Higgs Physics at LHC and future colliders

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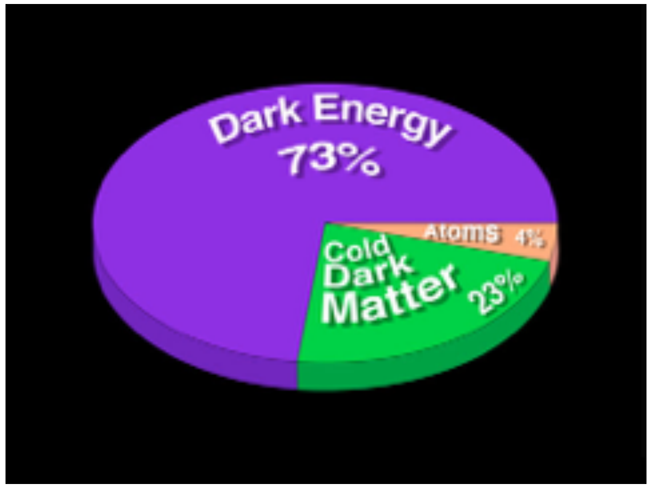
at Osaka Univ., on 6th Oct 2020

Big problem of Particle Physics 1 : dark matter

The SM particles can explain only 4% of the energy density of the universe

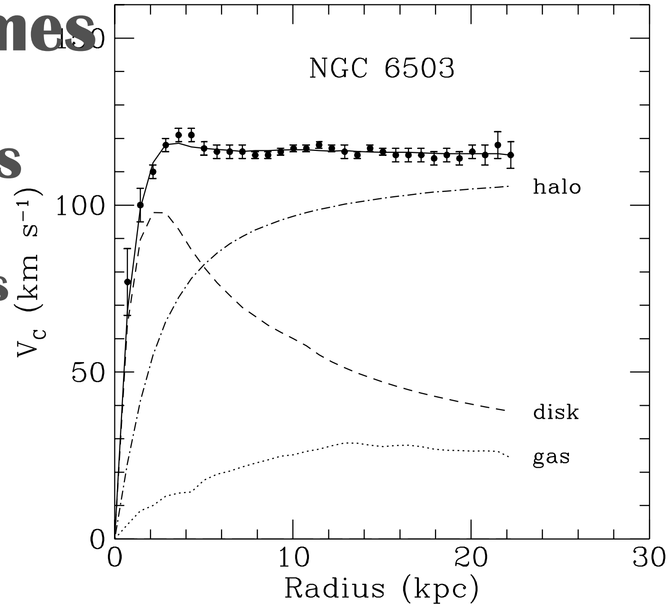
dark matter contributes about the 6 times

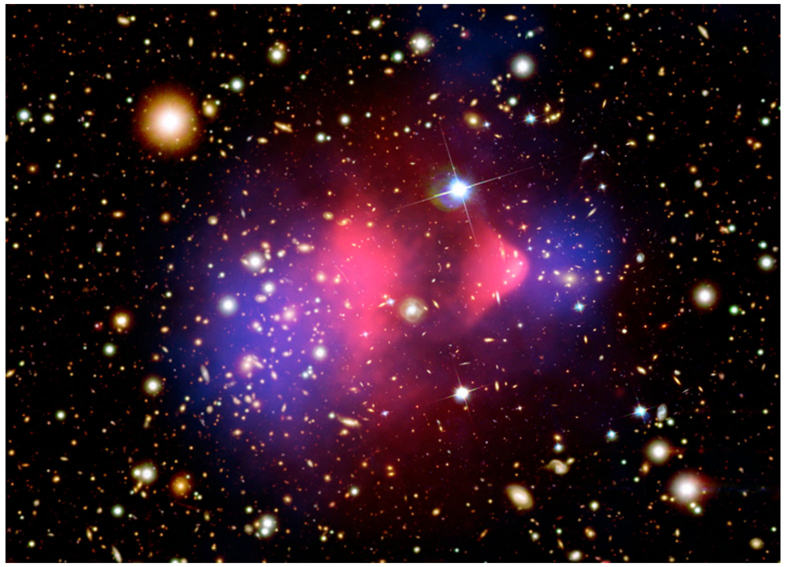


various observations

- **galaxy rotation curves**
- **cluster mergers**
- **N body simulations**
- **WMAP,BAO, etc**

$$\Omega_{\rm cdm}h^2 = 0.113$$

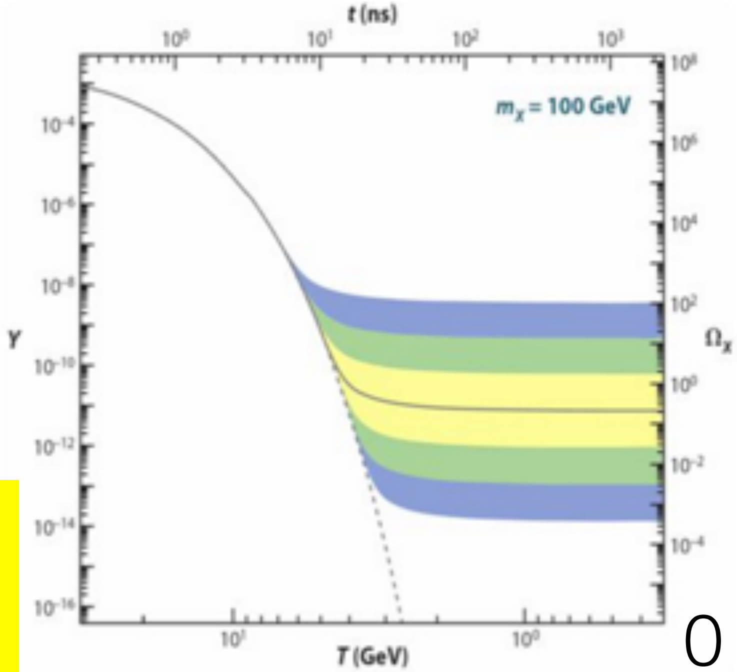




The Standard Model is not enough nad must be extended to explain the universe

Among various candidate for dark matter

WIMP (: weakly interacting massive particle) is the attractive candidate



Assuming thermally produced at early universe, the current abundance calculable

$$\Omega_\chi \sim \frac{0.1\text{pb}}{<\sigma_A v>}, \quad <\sigma_A v>\sim \frac{\alpha^2}{m_\chi^2} \sim 10^{-9}\text{GeV}^{-2},$$

$$\alpha_2 \sim 1/30 \rightarrow m_\chi \sim 1 \text{ TeV} \Rightarrow \text{new particle in TeV?}$$

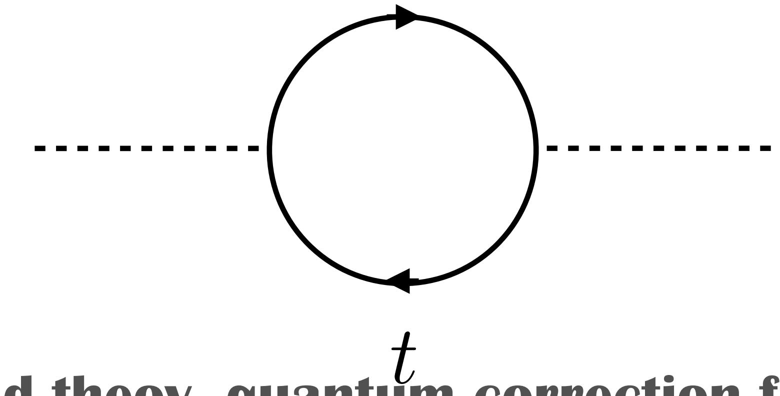
Assuming TeV scale mass, the abundance matches the observed one
⇒ we can expect the existence of new particles at TeV scale

Big problem of Particle Physics 2：fine tuning problem in higgs sector

Higgs：only one scalar particle in the SM

$$m_{h,\text{phys}}^2 = m_{h,\text{tree}}^2 + \delta m_h^2 \qquad \sim 125^2\text{GeV}^2 \sim 10^4\text{GeV}^2$$

$$\delta m_h^2 \sim$$



$$\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\text{SM}}^2 \sim 10^{38}\text{GeV}^2 (\Lambda_{\text{SM}} = m_{\text{Pl}}^2)$$

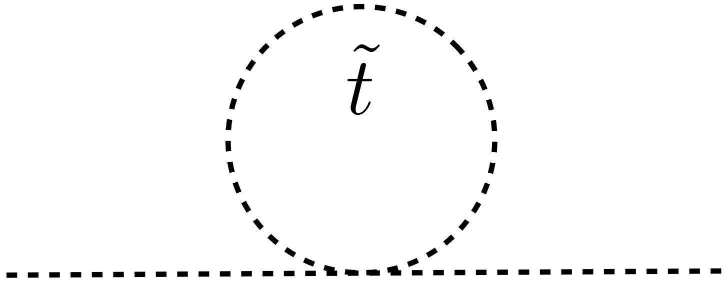
In quantum field theoy, quantum correction for a scalar particle naturally becomes the heaviest scale in theory.

⇒ **observed higgs mass unnatural**

Attractive solution : some symmetry exists, and existence of the partner particles (with the same couplings) , and their masses are below TeV scale

quadratic divergence is cancelled ⇒ existence of new particles at TeV scale expected

$$\delta m_h^2 \sim$$



$$\sim +\frac{3}{4\pi} y_t^2 \Lambda_{\text{SM}}^2$$

SUSY : plausible attractive candidate

since top loop is the largest,

expecially, top partner is important

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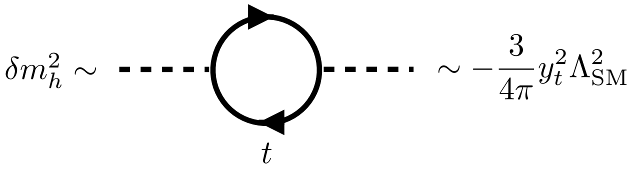
2 big problem in the SM

darkmatter

fine tuning



$$\delta m_h^2 \sim \quad \sim -\frac{3}{4\pi} y_t^2 \Lambda_{\mathrm{SM}}^2$$

indicates new particles at TeV scale

Especially, top partners, dark matters below TeV scale.

We can probe them at LHC. (directly or through Higgs measurements)

Its important before going into Higgs physics, assuming NP exists at all!

Naturalness

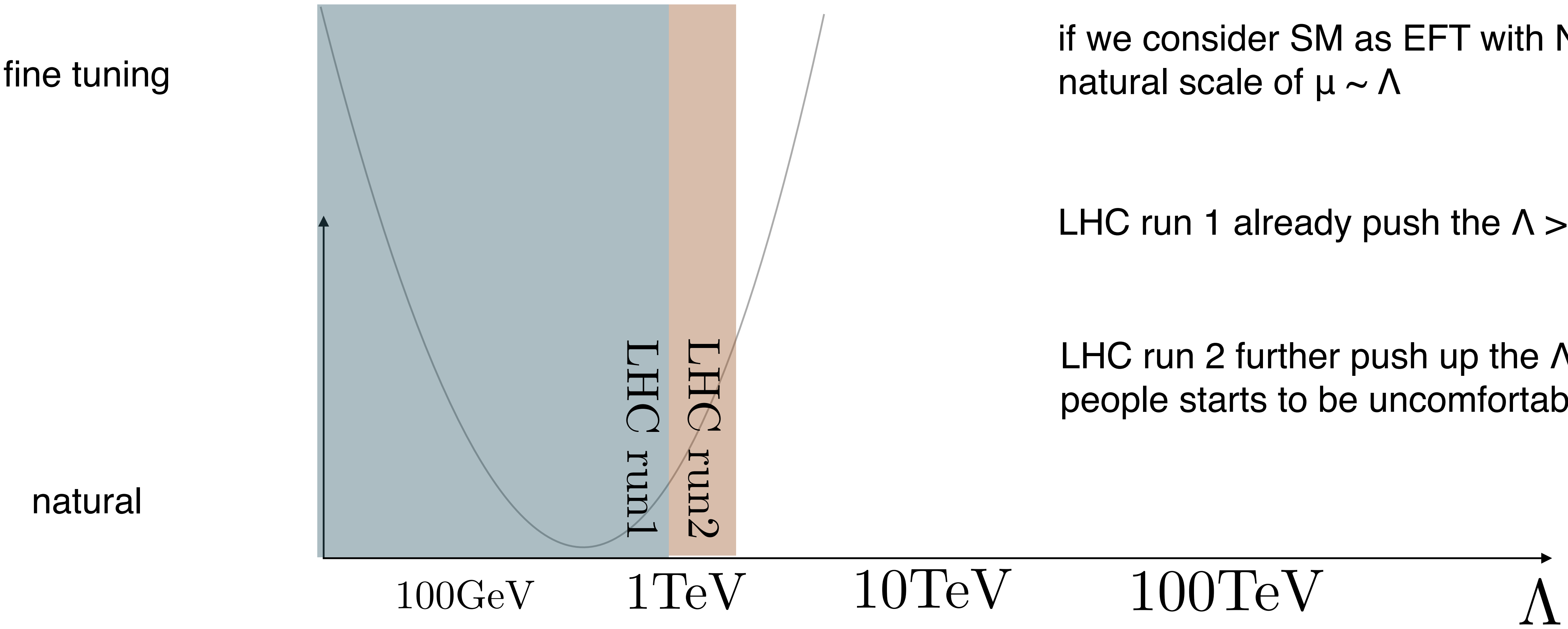
$$-\mathcal{L}_{\rm SM} = -\,\epsilon\Lambda^2 H^\dagger H$$

μ : only dimension full parameter ~ 100 GeV

d=2

$$+\,\mathcal{L}_{\rm kin} + gA_\mu \bar{f}\gamma^\mu f + y_{ij}\bar{f}_i H f_j + \lambda(H^\dagger H)^2$$

d=4



if we consider SM as EFT with NP scale Λ
natural scale of μ ~ Λ

LHC run 1 already push the Λ > 1 TeV

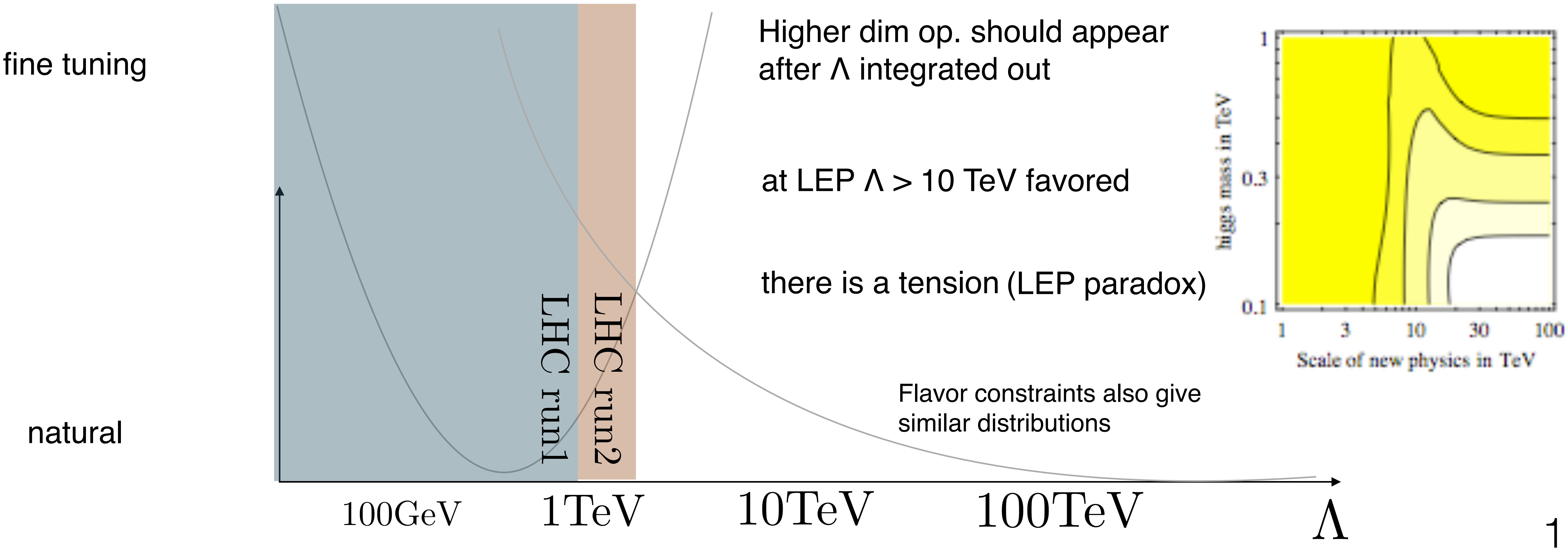
LHC run 2 further push up the Λ,
people starts to be uncomfortable

Naturalness

$$-\mathcal{L}_{\rm SM} = -\,\epsilon\Lambda^2 H^\dagger H$$ μ : only dimension full parameter ~ 100 GeV d=2

$$+\,\mathcal{L}_{\rm kin} + gA_\mu \bar{f}\gamma^\mu f + y_{ij}\bar{f}_i H f_j + \lambda(H^\dagger H)^2$$ d=4

$$+\frac{b_{ij}}{\Lambda}(LH)(LH) + \frac{c_{ij}}{\Lambda}(\bar{f}_i\sigma_{\mu\nu}f_j)G^{\mu\nu} + \frac{c_{ijkl}}{\Lambda^2}(\bar{f}_i f_j)(\bar{f}_k f_l)$$ d>4



Higher dim op. should appear after Λ integrated out

at LEP Λ > 10 TeV favored

there is a tension (LEP paradox)

Flavor constraints also give similar distributions

Naturalness

$$-\mathcal{L}_{\rm SM} = -\,\epsilon\Lambda^2 H^\dagger H$$

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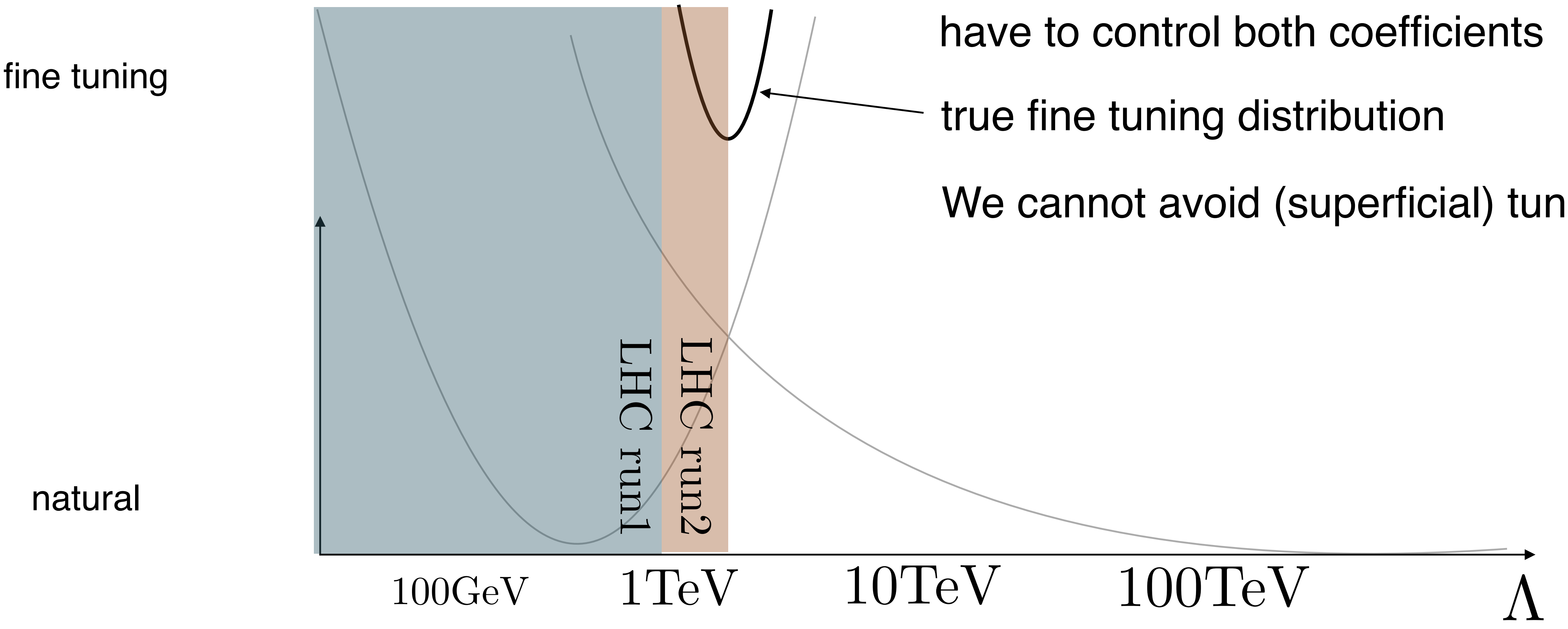
d>4



have to control both coefficients

true fine tuning distribution

We cannot avoid (superficial) tuning!

Naturalness

$$-\mathcal{L}_{\rm SM} = -\,\epsilon\Lambda^2 H^\dagger H$$

μ : only dimension full parameter ~ 100 GeV

d=2

$$+\,\mathcal{L}_{\rm kin} + g A_\mu \bar{f}\gamma^\mu f + y_{ij}\bar{f}_i H f_j + \lambda (H^\dagger H)^2$$

d=4

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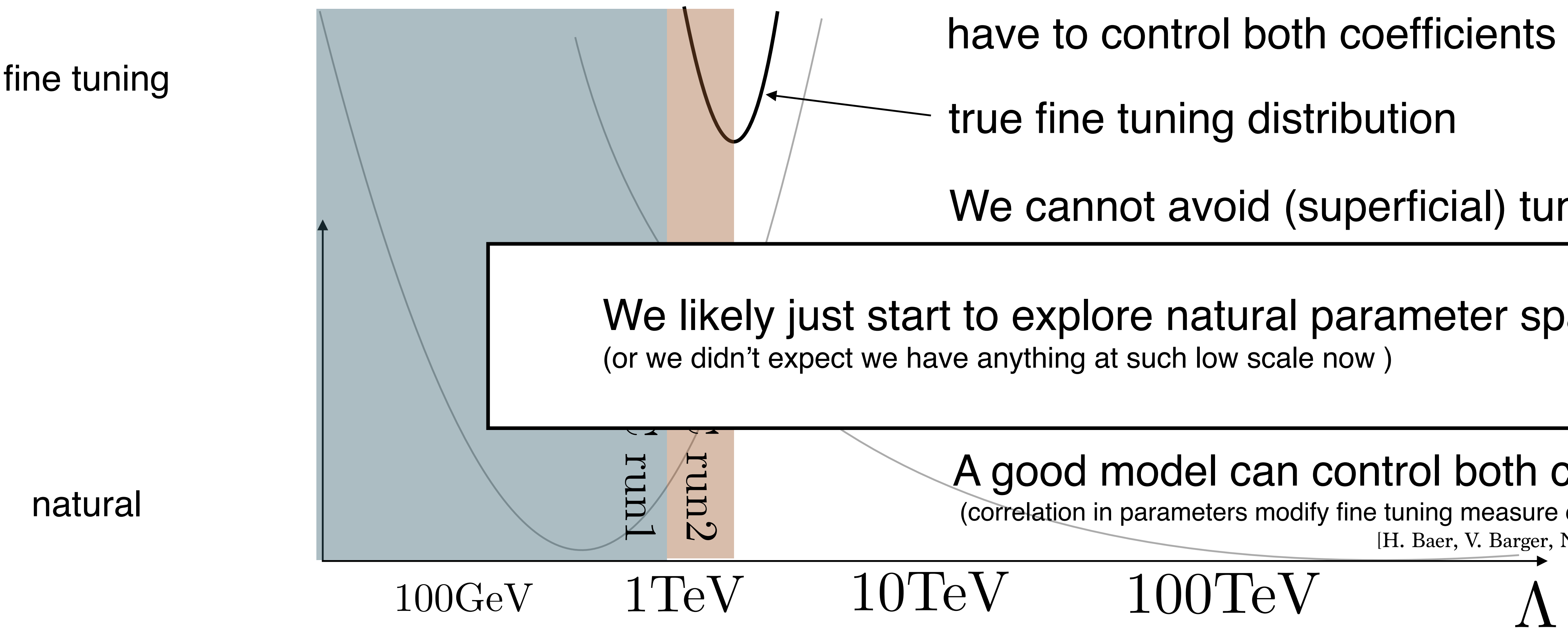
d>4



have to control both coefficients

true fine tuning distribution

We cannot avoid (superficial) tuning!

We likely just start to explore natural parameter space!
(or we didn’t expect we have anything at such low scale now)

A good model can control both cancelations
(correlation in parameters modify fine tuning measure dep. on models)
[H. Baer, V. Barger, N. Nagata, M. Savoy]

Schedule

2021/5~ run3

2027~2038: HL-LHC

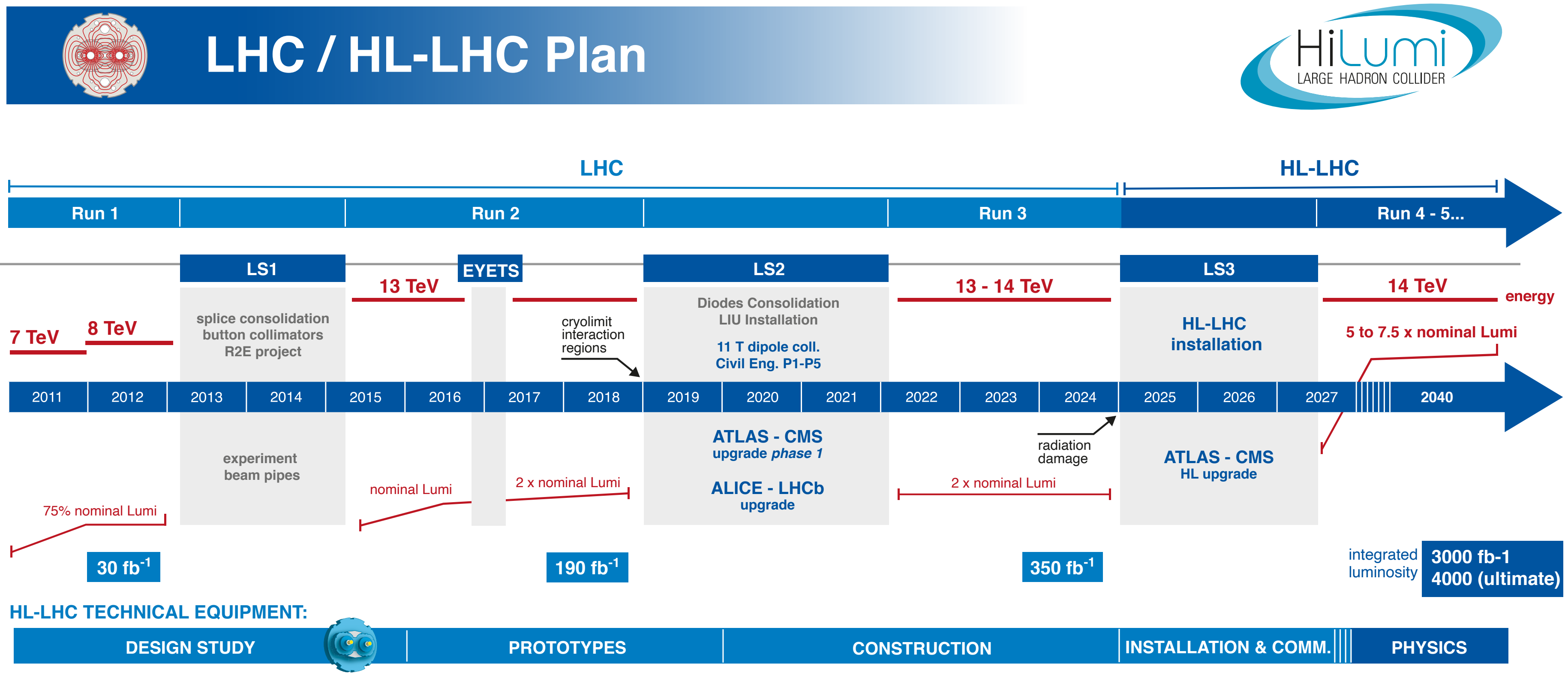
3 ab-1 planned

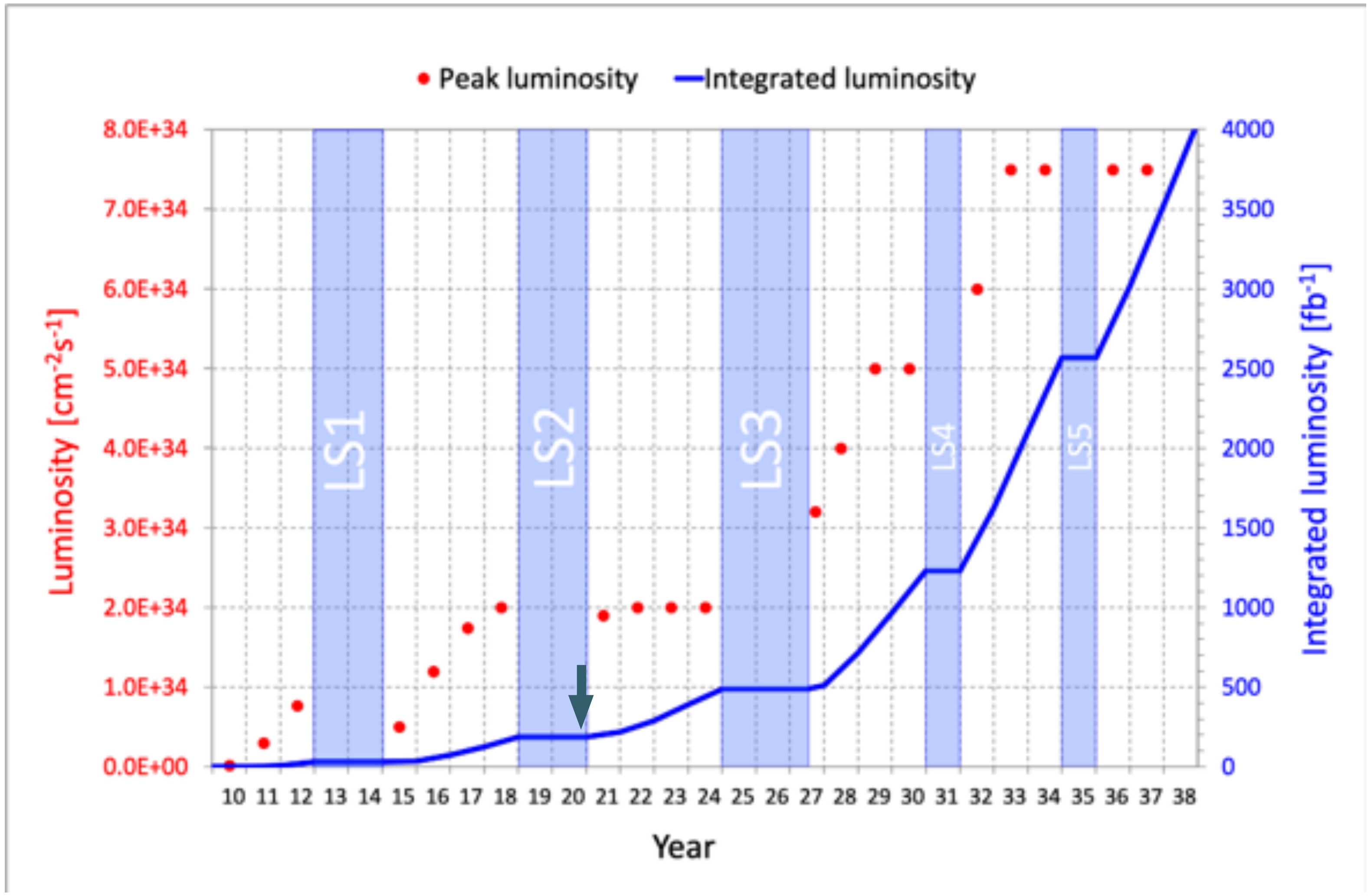
possibly up to 4 ab-1

Ultimate statistics O(20) times the current data (after 18years)

⇒ 20 times more particles produced

1. more heavy particles produced
2. precise distribution measurements
3. sensitivity for rare decays





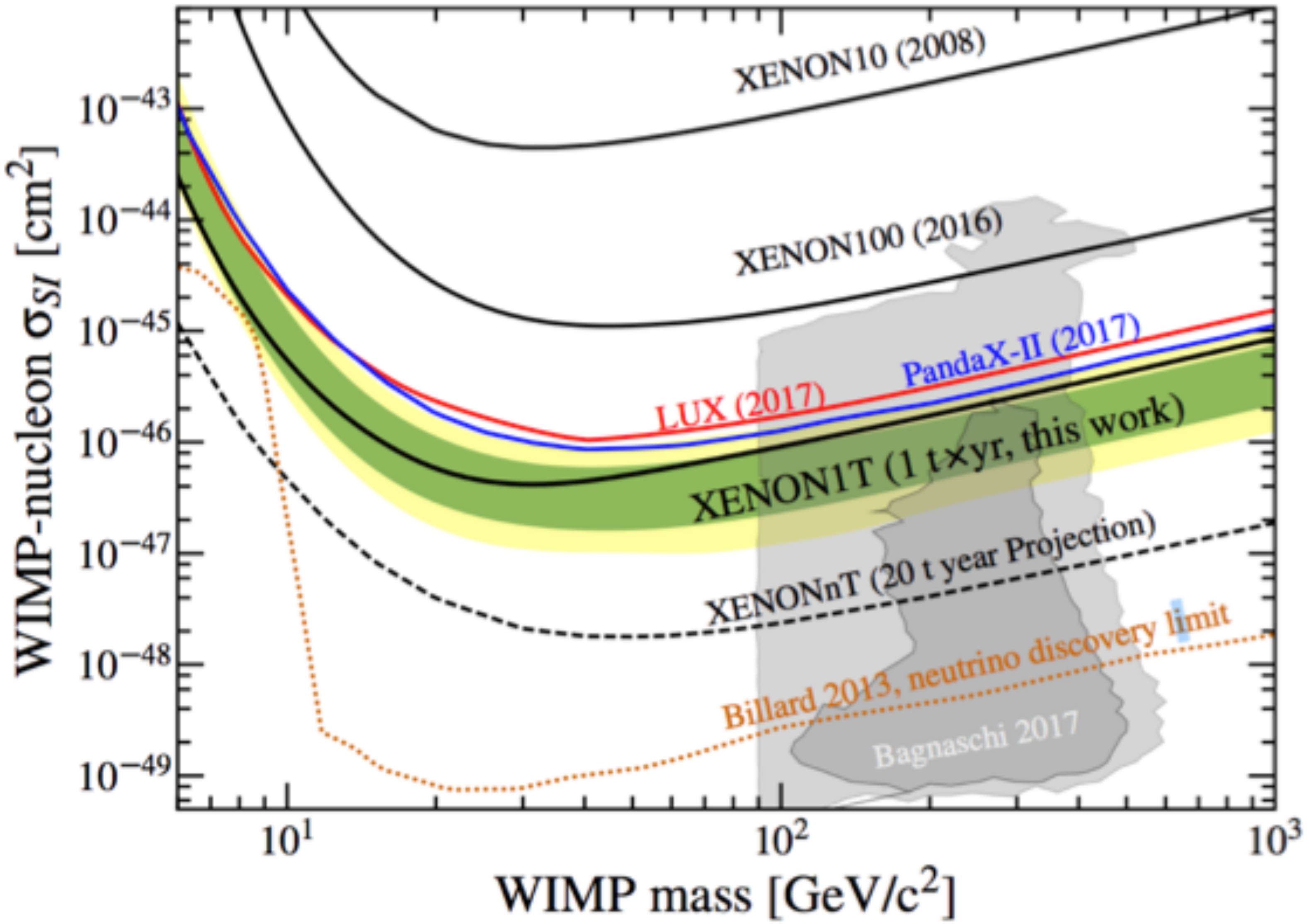
Dark matter direct detection experiments

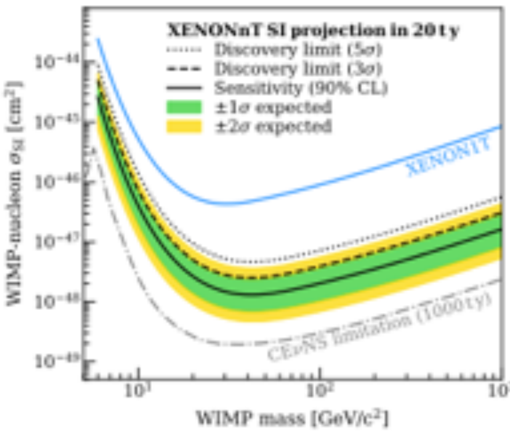
dark matter : existing new physics
an elementary particle plausible

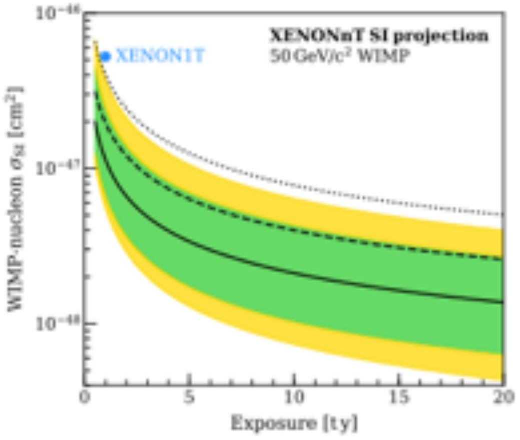
rapid progress of the sensitivity

the signal would be likely
found first

On the other hand,
even though the signal would
be found, we would like to test
at colliders anyway.



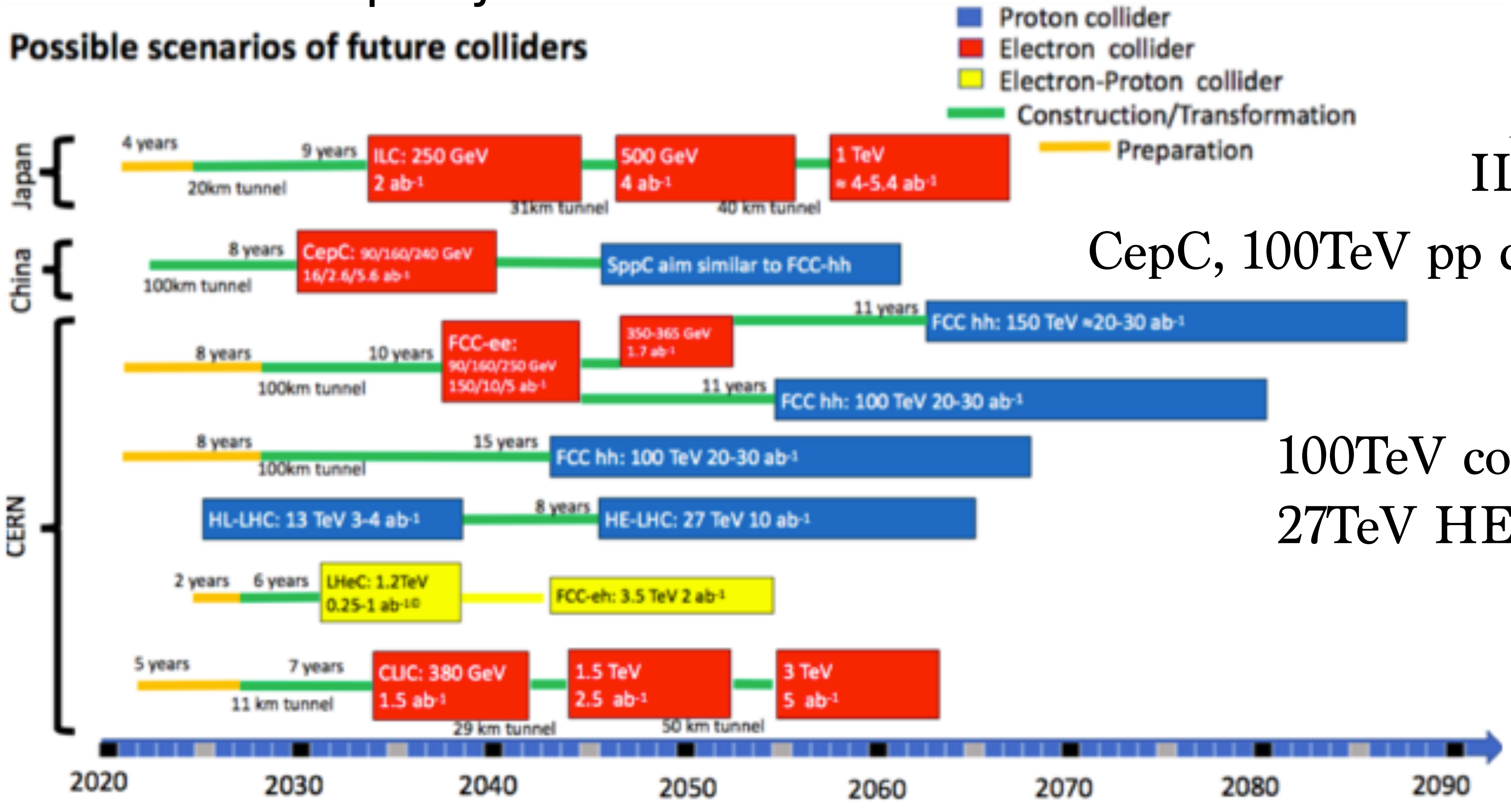




arXiv:2007.08796

XENON10	**XENON100**	**XENON1T**	**XENONnT**
2005 – 2007	2008 – 2016	2011 – 2018	2019 – 2023
15 cm drift TPC	30 cm drift TPC	100 cm drift TPC	150 cm drift TPC
Total: 25 kg	Total: 161 kg	Total: 3 200 kg	Total: 8 000 kg
Target: **14** kg	Target: **62** kg	Target: **2 000** kg	Target: **6 000** kg
Fiducial: 5.4 kg	Fiducial: 34/48 kg	Fiducial: 1 300 kg	Fiducial: 4 500 kg
Achieved (2007)	Achieved (2016)	Achieved (2018)	Projected (2022)
σ_{SI} = 8.8 · 10^{-44} cm^2	σ_{SI} = 1.1 · 10^{-45} cm^2	σ_{SI} = 4.1 · 10^{-47} cm^2	σ_{SI} = 1.6 x 10^{-48} cm^2
@ 100 GeV/c^2	@ 55 GeV/c^2	@ 30 GeV/c^2	@ 50 GeV/c^2

future collider projects after HL-LHC



The timeline for different scenarios for future colliders.

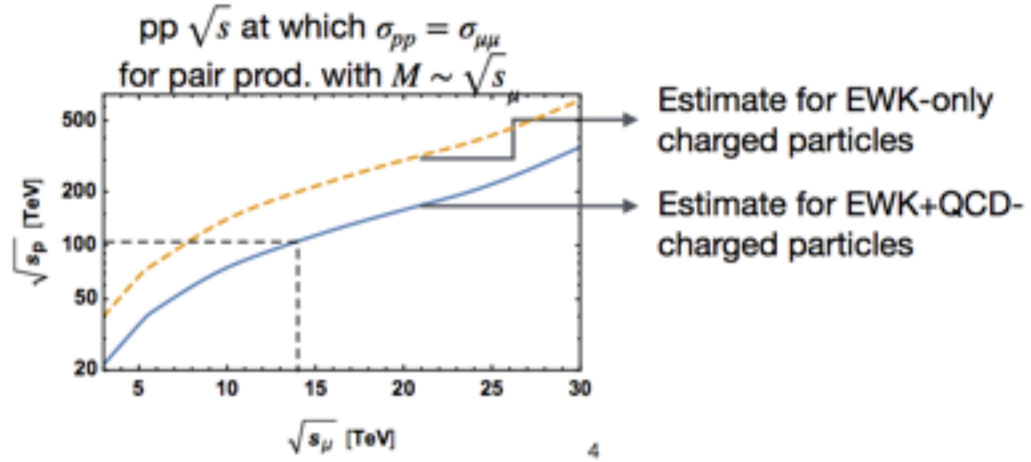
ILC 250

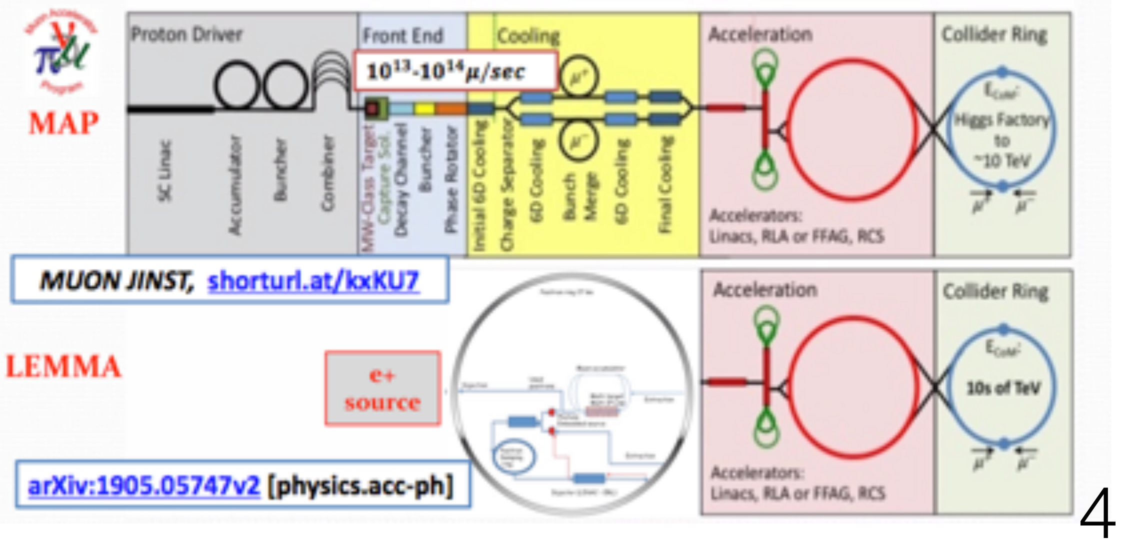
CepC, 100TeV pp collider

100TeV collider

27TeV HE-LHC

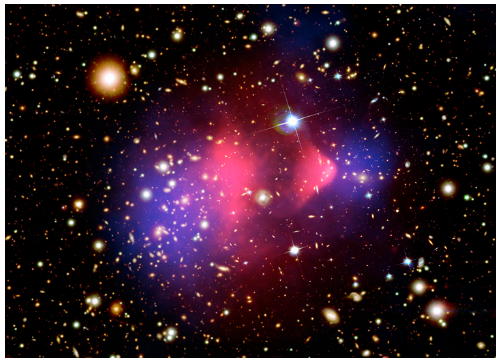
muon collider : e+e- promising?

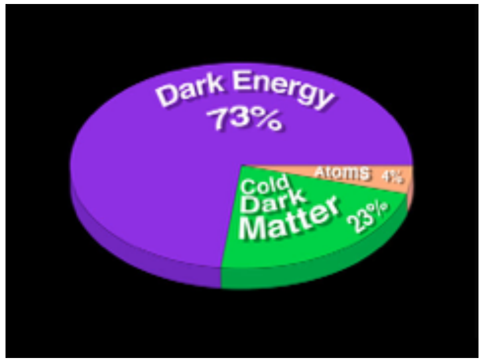




SUSY solves two big problems in particle physics

Existence of DM (serious problem)

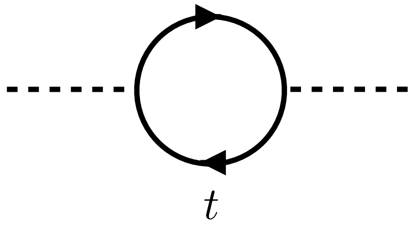




Naturalness (Fine tuning in Higgs sector)

$$m_{h,\mathrm{phys}}^2 = m_{h,\mathrm{tree}}^2 + \delta m_h^2 \sim 125^2\mathrm{GeV}^2 \sim 10^4\mathrm{GeV}^2$$

$\delta m_h^2 \sim$

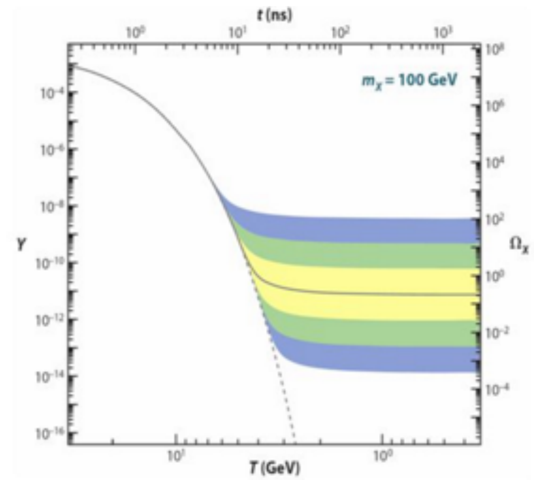


$$\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\mathrm{SM}}^2$$

$$\sim 10^{38}\mathrm{GeV}^2 (\Lambda_{\mathrm{SM}} = M_{\mathrm{Planck}})$$

$$\sim 10^{6}\mathrm{GeV}^2 (\Lambda_{\mathrm{SM}} = 1\mathrm{TeV})$$

TeV scale SUSY elegantly solve both problems



WIMP miracle

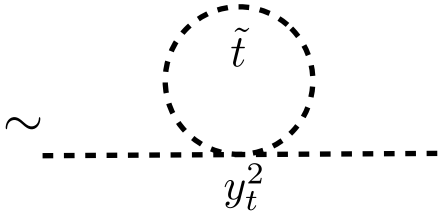
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{\alpha^2} \sim 10^9\mathrm{GeV}^2$$

neutralino DM

perfect WIMP DM

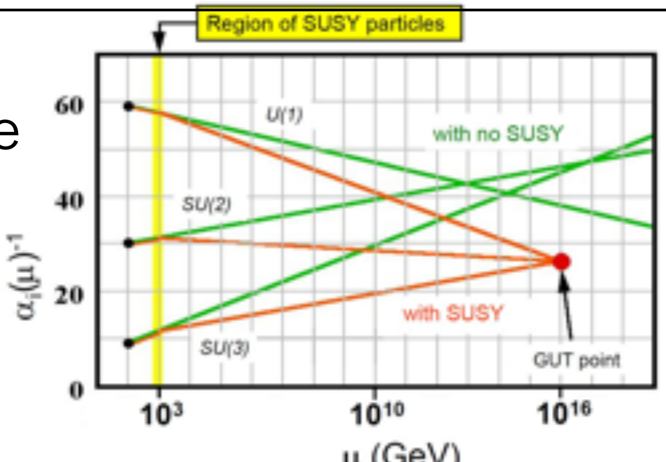
new partner particle, same coupling by symmetry

$\delta m_h^2 \sim$



$$\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$$

TeV sparticles make the gauge coupling unification happen at one scale



Even though LHC doesn't find new particles yet,
TeV scale SUSY is still the most attractive BSM

latest SUSY search results at LHC 13TeV ~ 137 fb^{-1}

based on simplified models

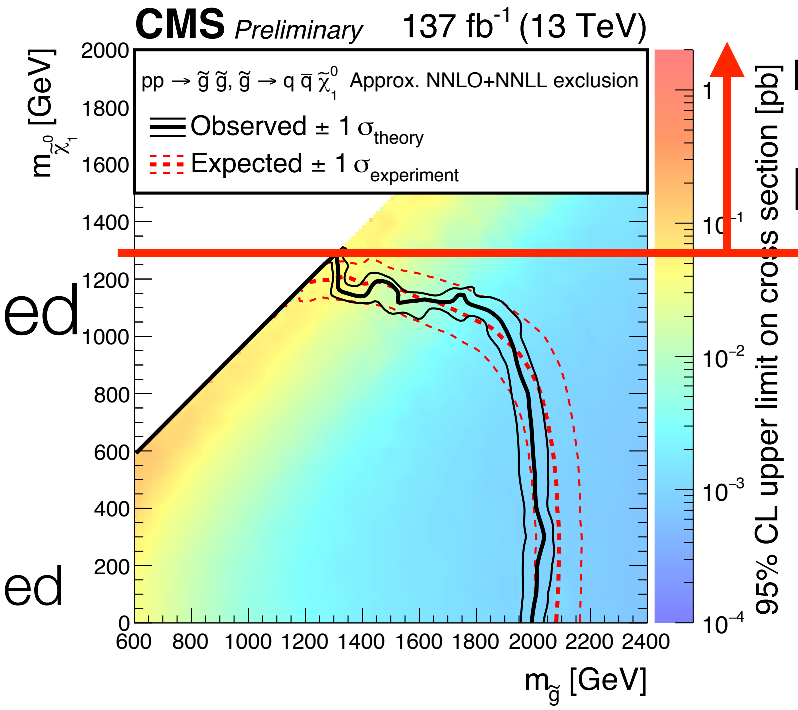
For massless LSP

~2 TeV gluino excluded

~1.8 TeV squarks excluded

~1.2 TeV stop excluded

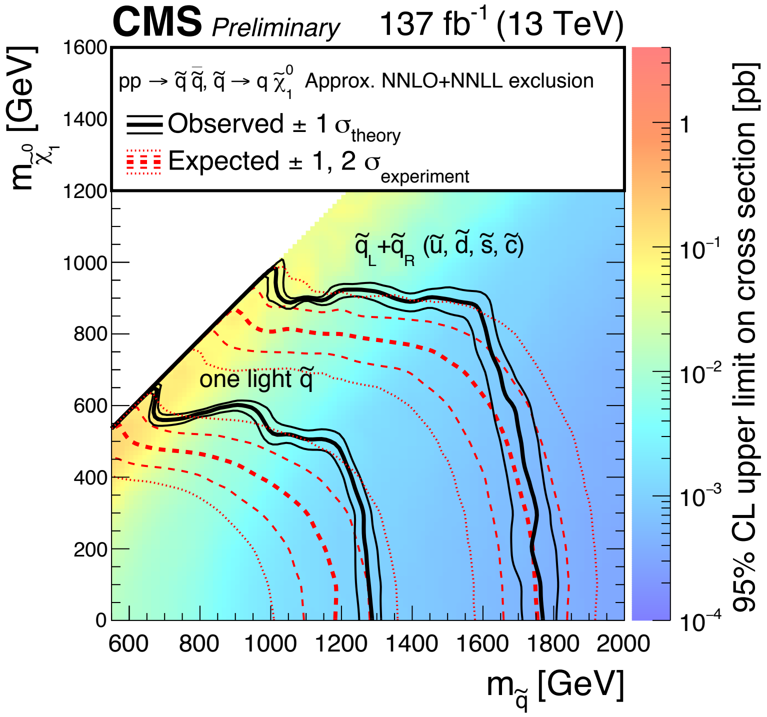
~700 GeV EWkino (W/Z) excluded
(highly depends on BR)

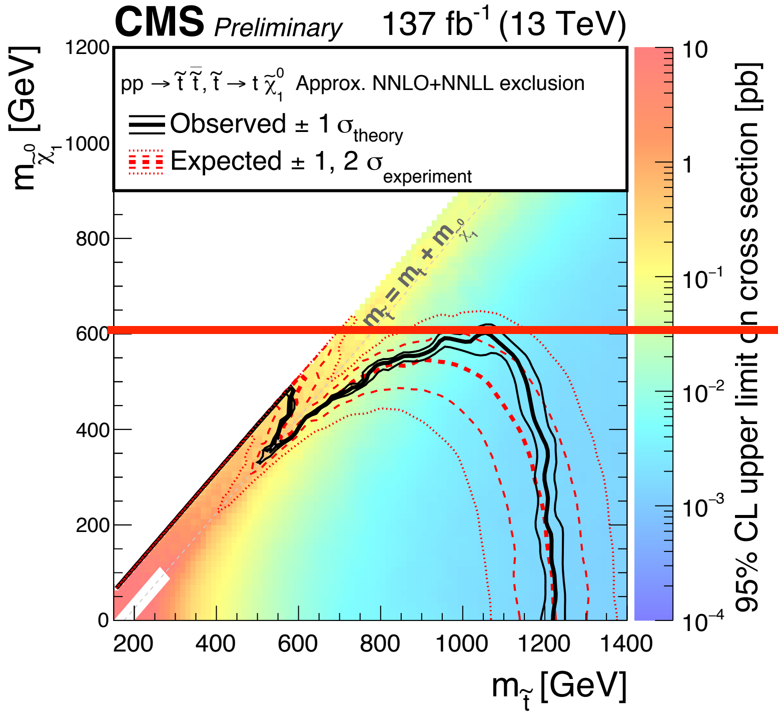


no constraint

LSP > 1.3TeV

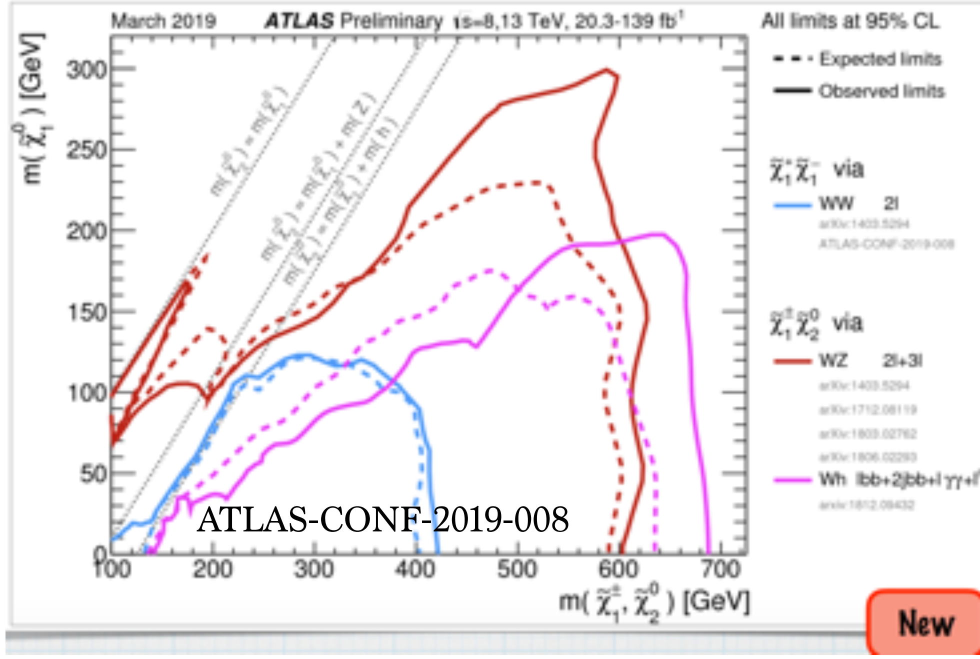
CMS-PAS-SUS-19-005





no constraint

LSP>600GeV



ATLAS-CONF-2019-008

Notice: no constraints when LSP mass is heavy enough

[ATL-COM-PHYS-2014-555]

SUSY search projection at 3 ab^{-1}

based on simplified models

For massless LSP

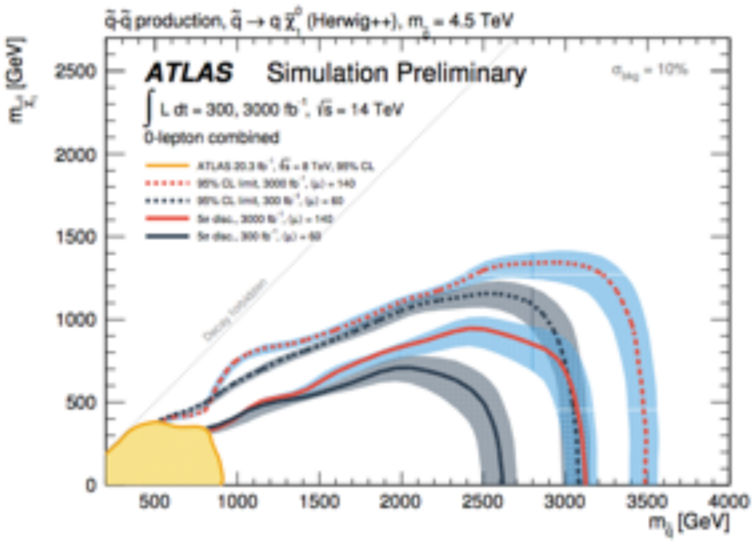
~3 TeV gluino excluded

~2.1-3.5 TeV squarks exclude

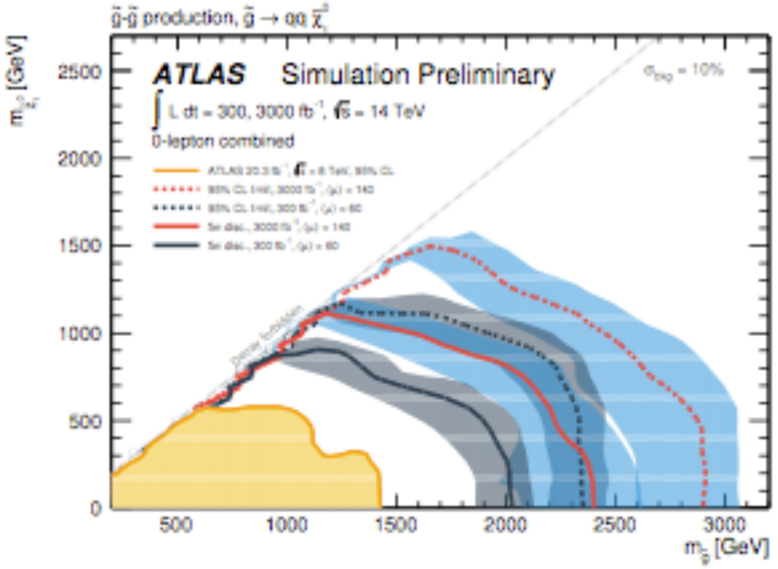
~1.6-1.7 TeV stop excluded

~1.1-1.3 TeV EWkino excluded
 (highly depends on BR)

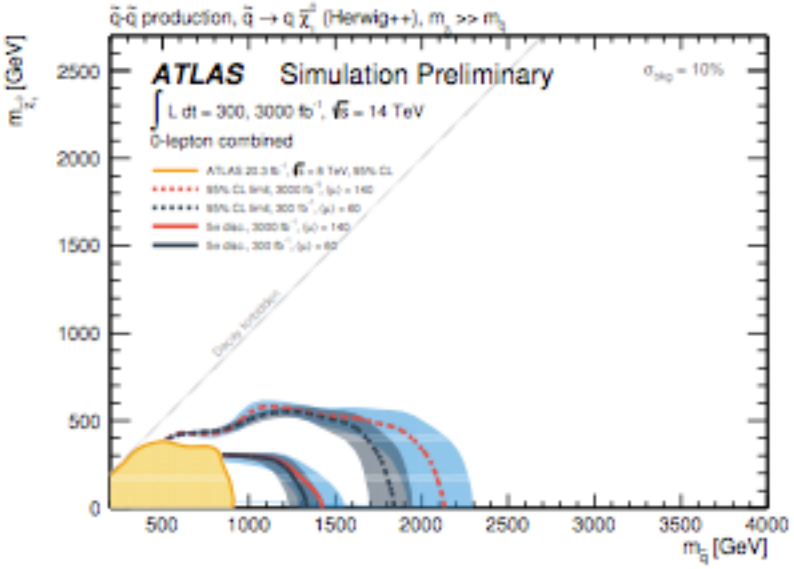
~0.7 TeV stau excluded



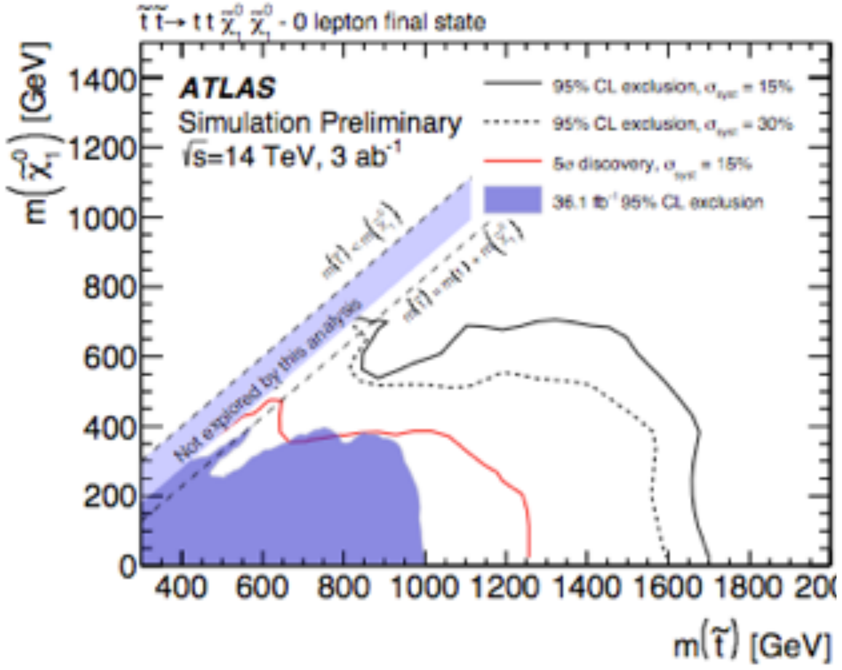
(c) $\tilde{q}\tilde{q}$, $m_{\tilde{g}}$ = 4.5 TeV

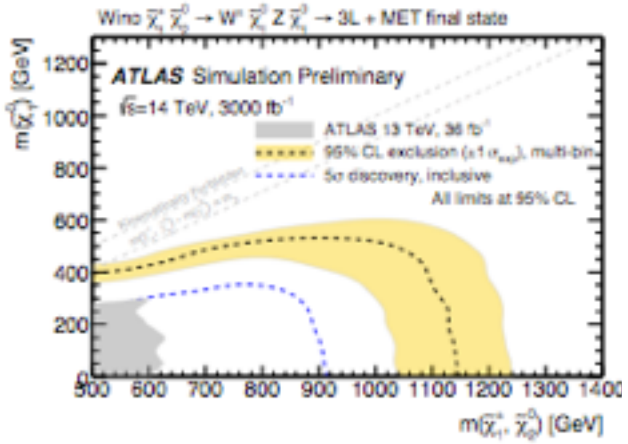


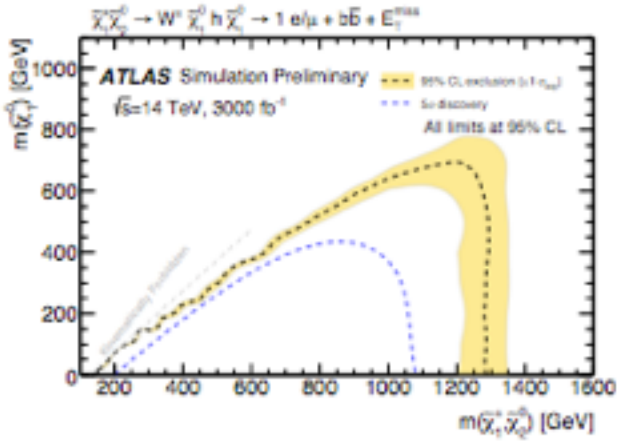
(a) $\tilde{g}\tilde{g}$

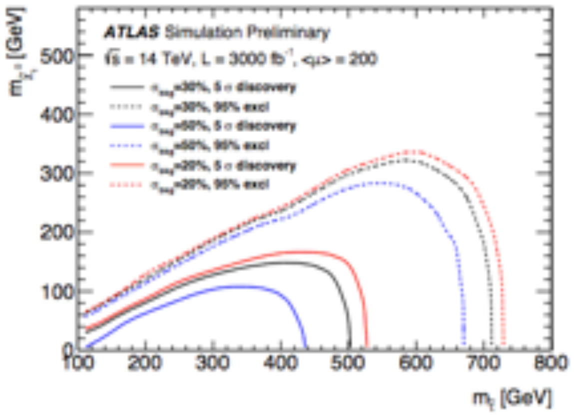


(b) $\tilde{q}\tilde{q}$, decoupled $\tilde{g}$









[arXiv:1812.07831]

Notice: no constraints when LSP mass is heavy enough

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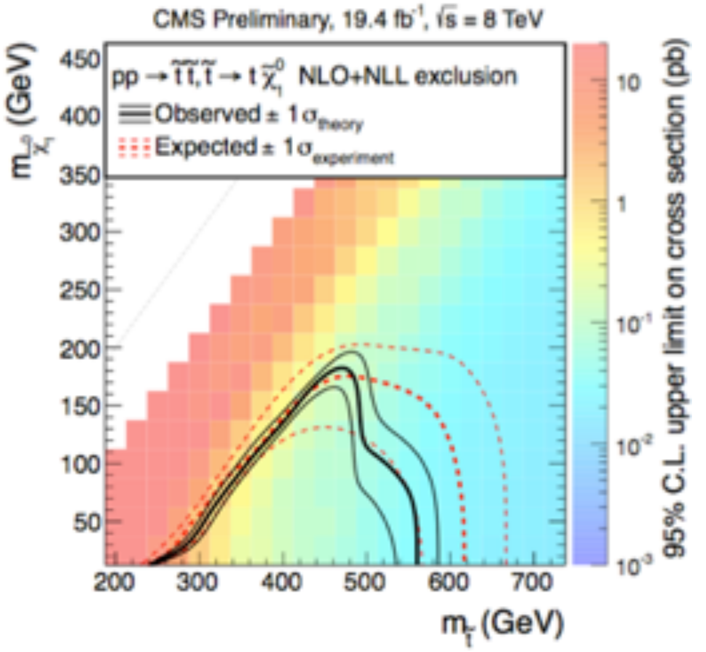
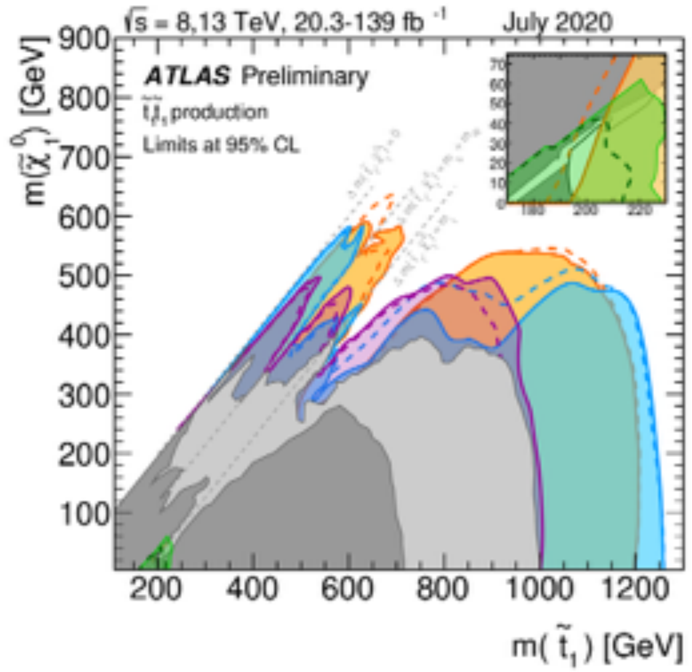
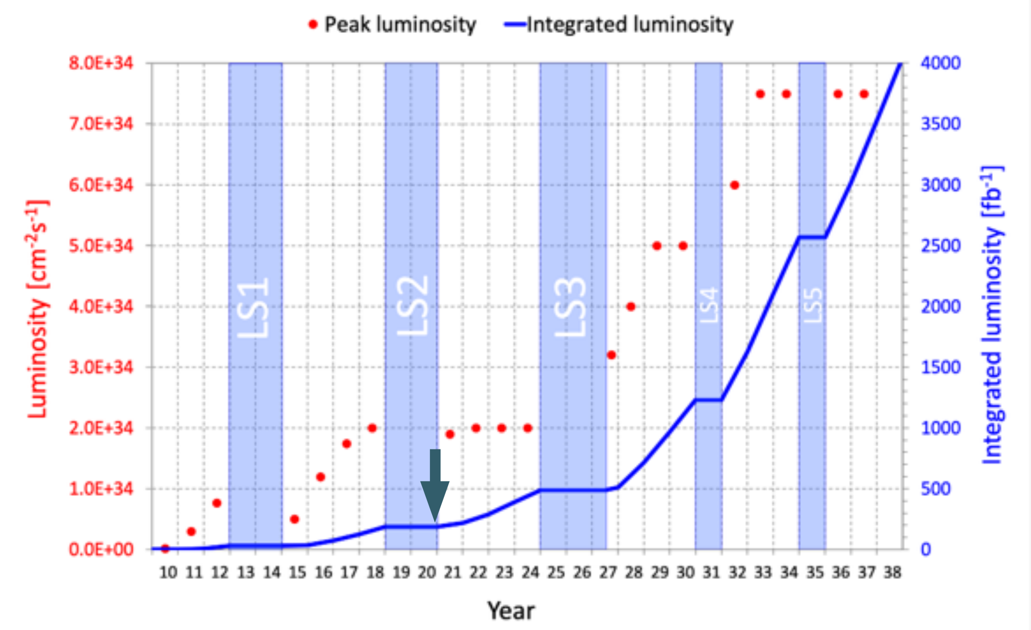
after LHC

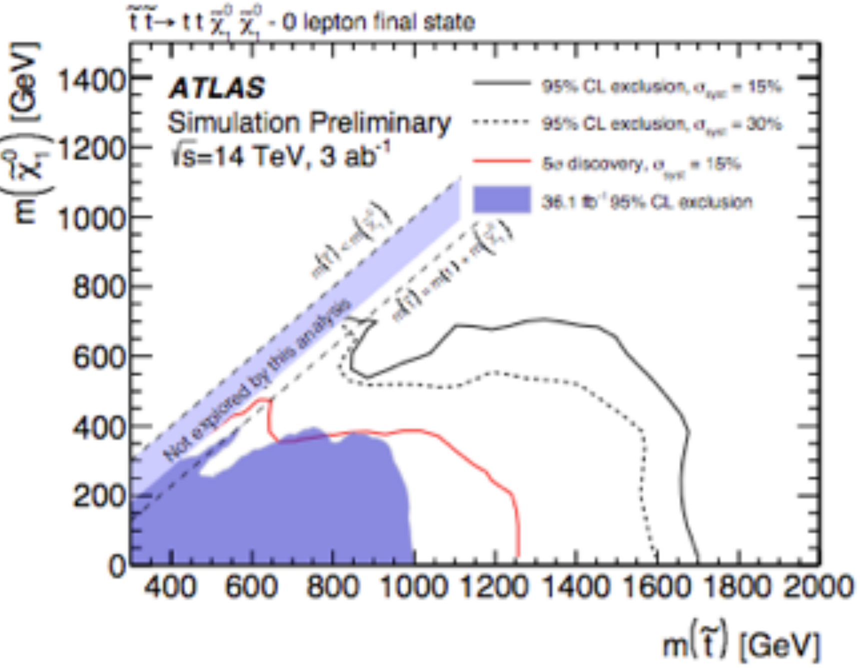
2021/5~ run3

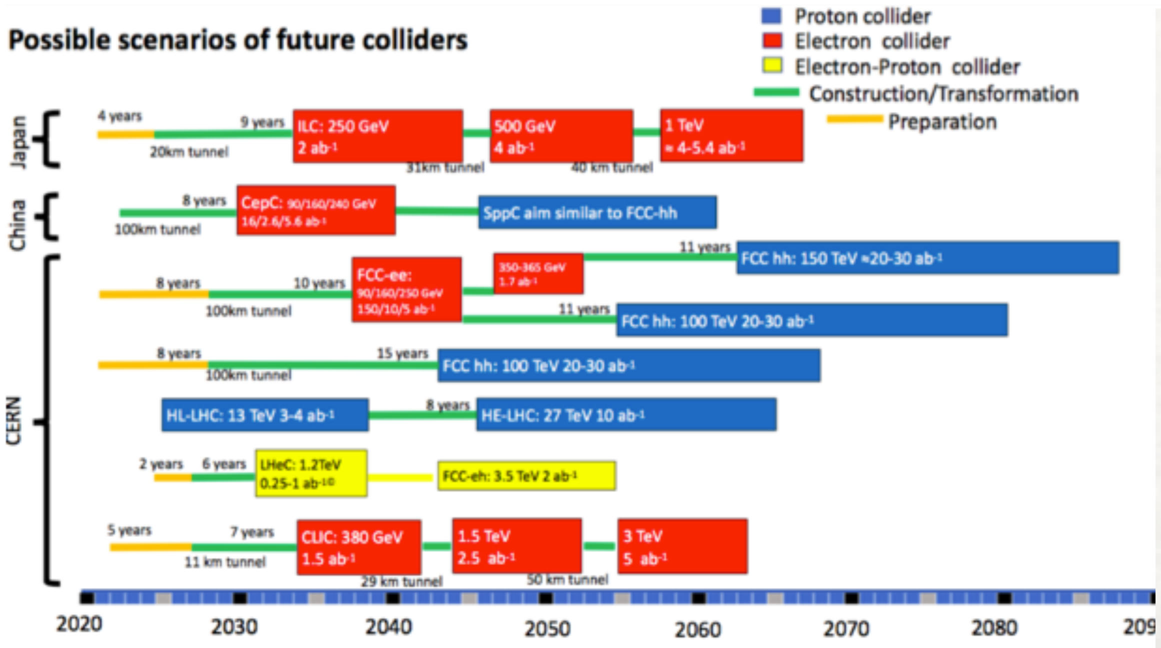
2027~2038: HL-LHC



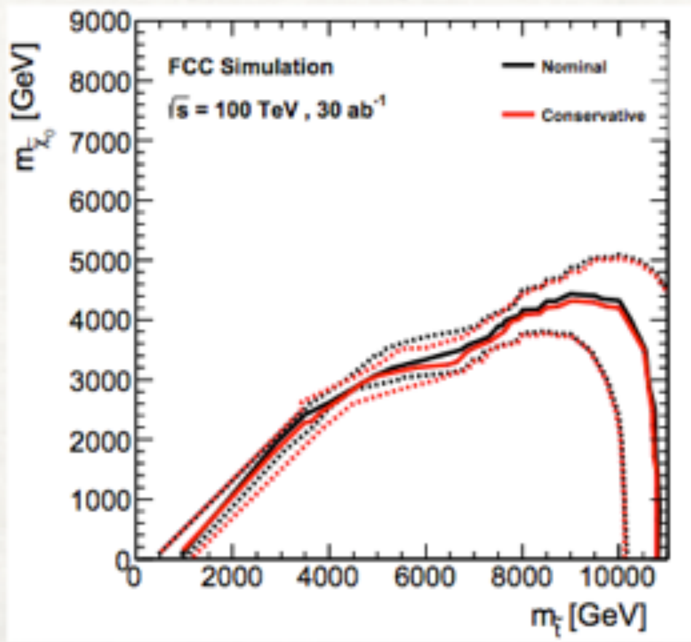








The timeline for different scenarios for future colliders.

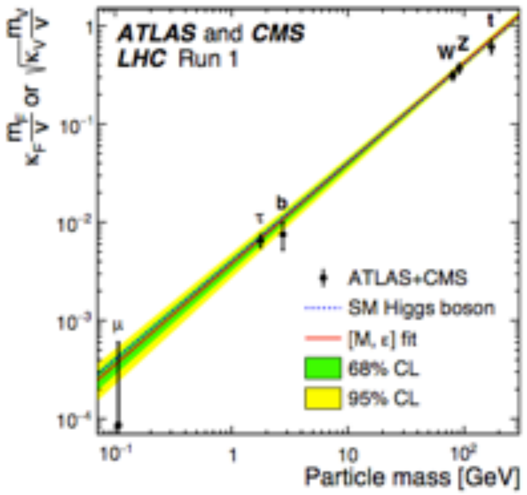


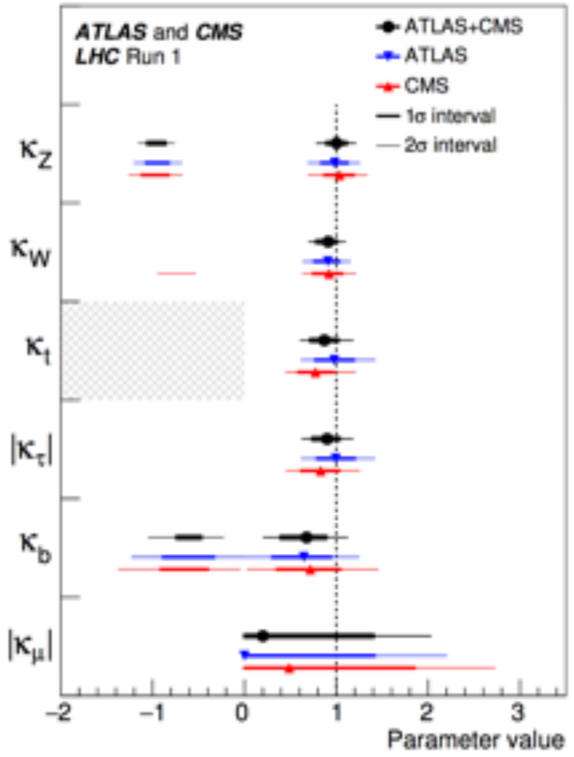
currently up to 1.2TeV excluded. HL-LHC 3ab-1 reaches 1.7TeV, FCC reaches 10TeV

SM like Higgs and no heavy Higgs

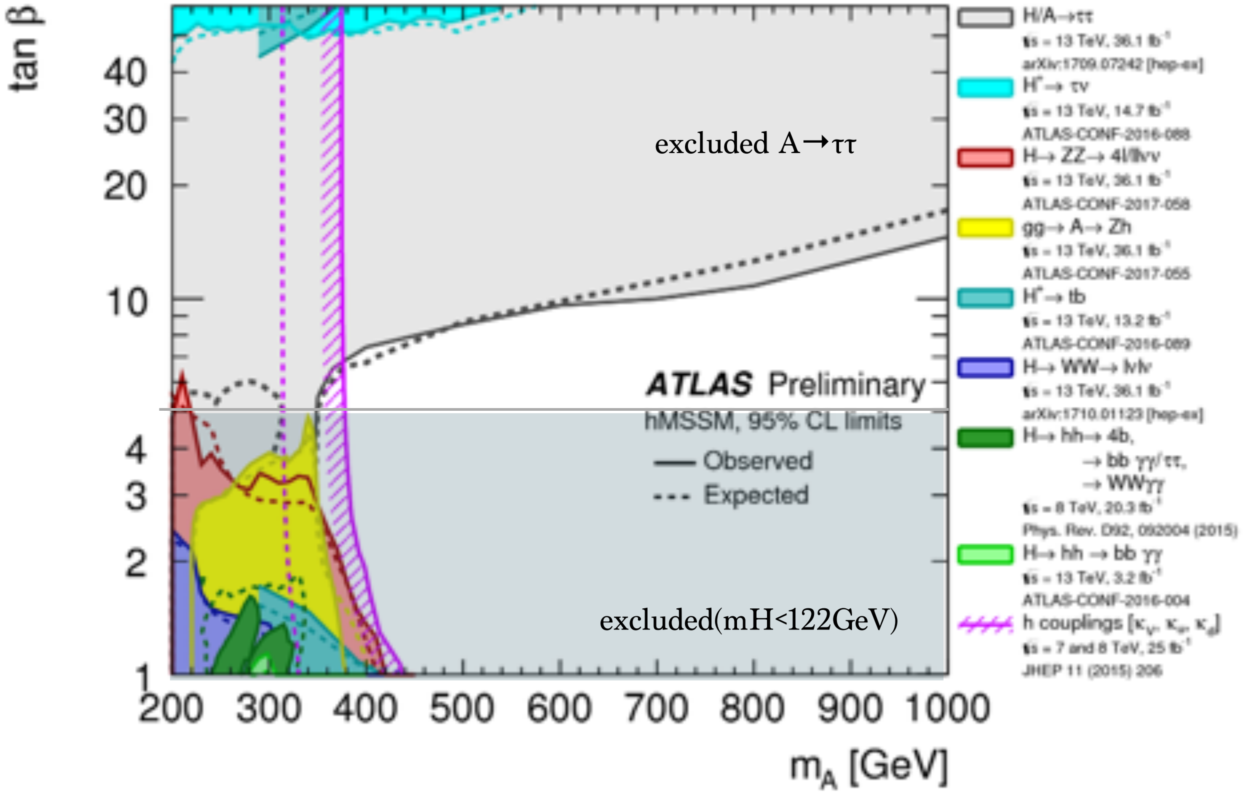
Higgs couplings measured
consistent to SM Higgs in 10-20%

also consistent to the MSSM higgs
in near decoupling limit





Heavy higgs searches



MSSM : 2HDM, additional Higgs expected

Unlike a general 2HDM, MSSM Higgs sector can be parameterized with $(m_A, \tan\beta)$

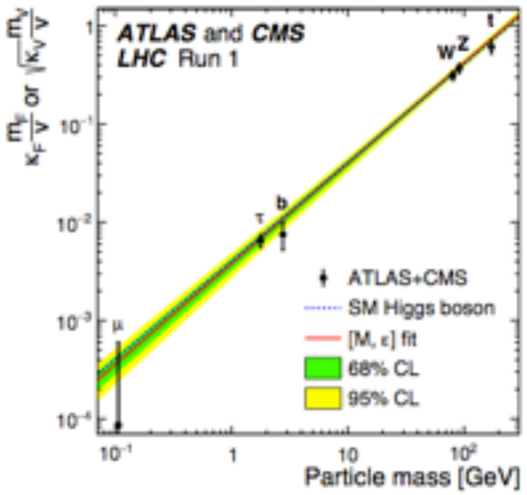
→ Light higgs coupling measurements already constrain $m_A \gtrsim 400\mathrm{GeV}$

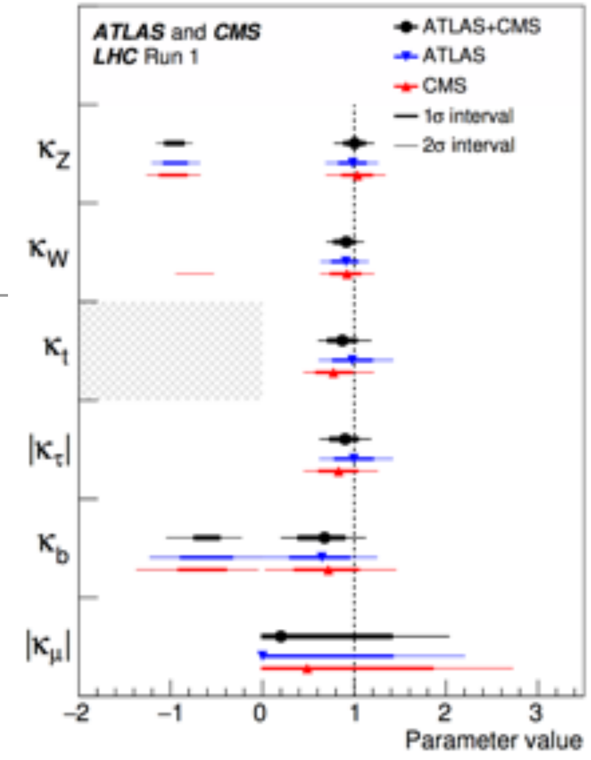
For large $\tan\beta$, bbA followed by $A \to \tau\tau$ dominates the sensitivity

Large parameter space is excluded, but also large region is still available

SM like Higgs and no heavy Higgs

Higgs couplings measured
consistent to SM Higgs in 10-20%





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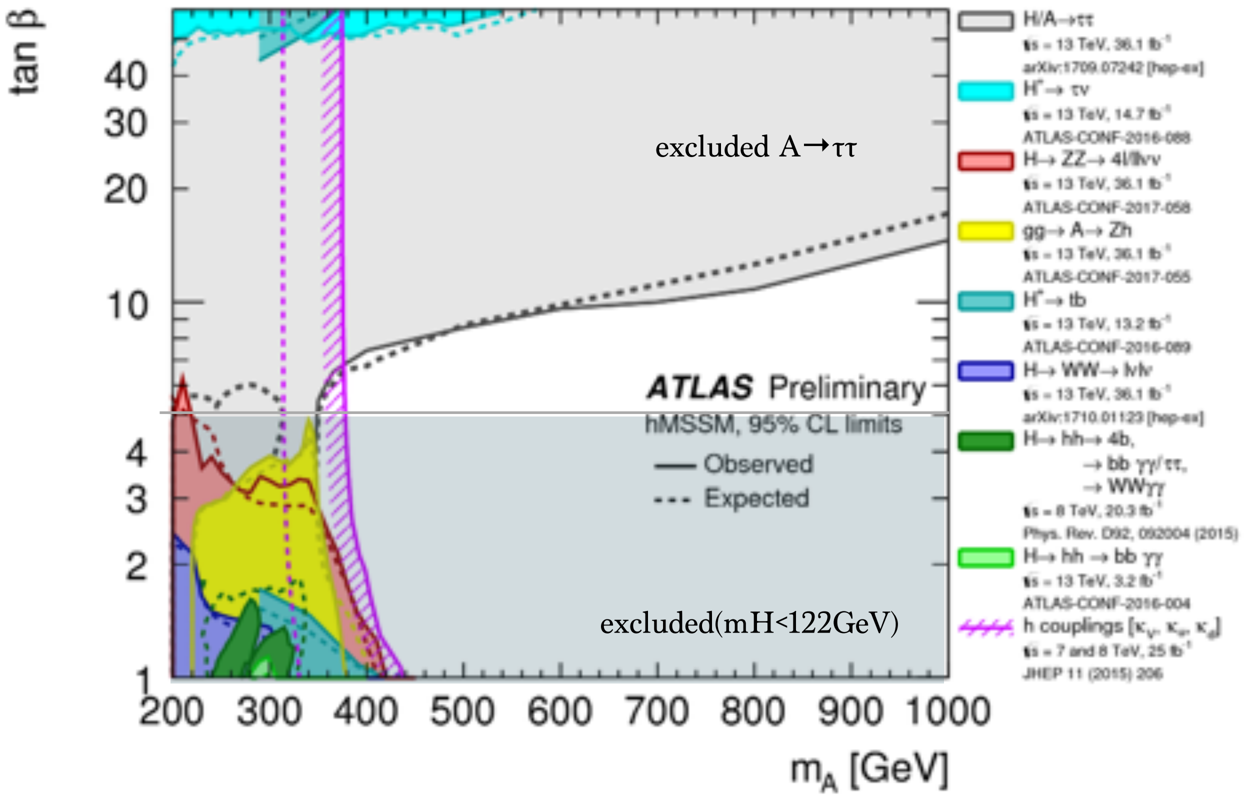
in near decoupling limit

Heavy higgs searches

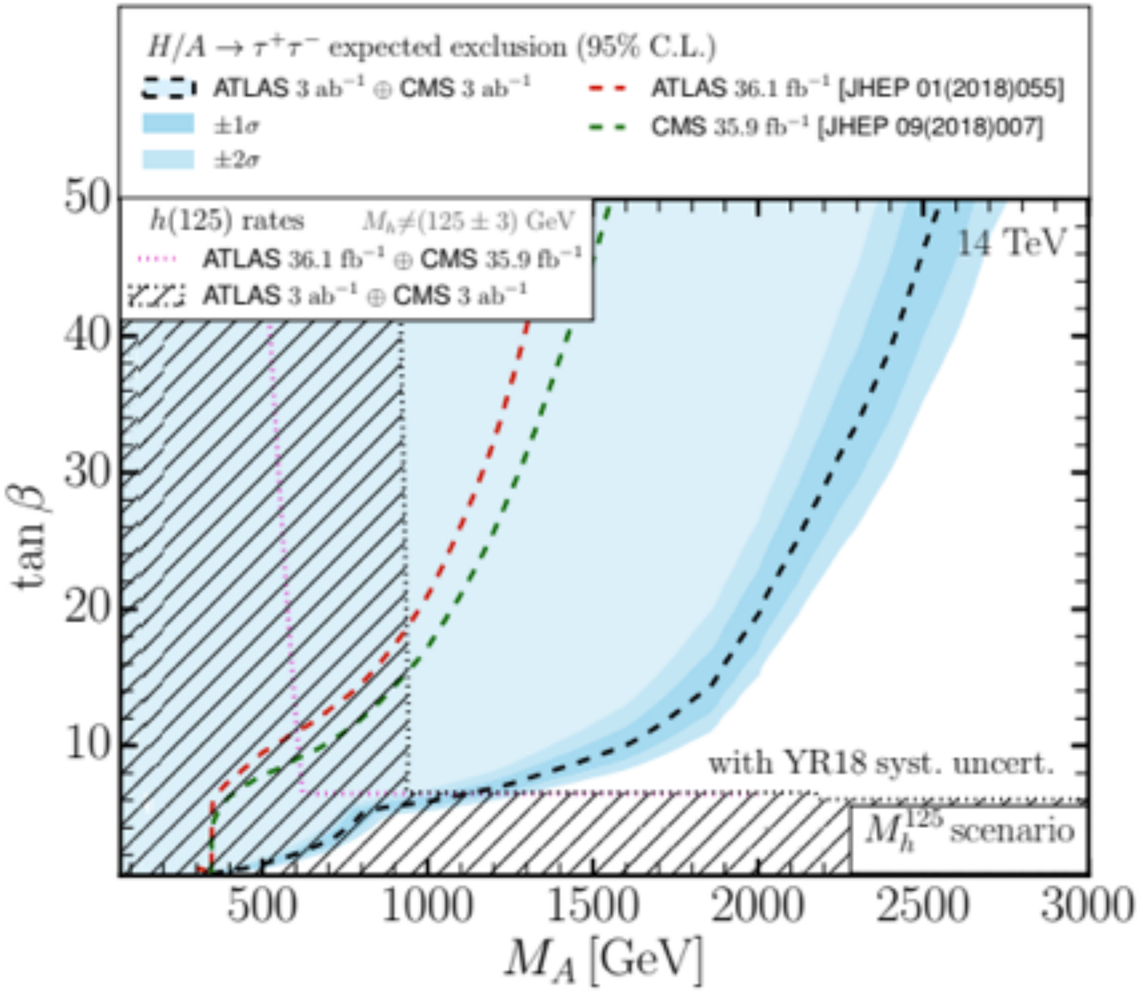


MS

Ur

ca

→



r

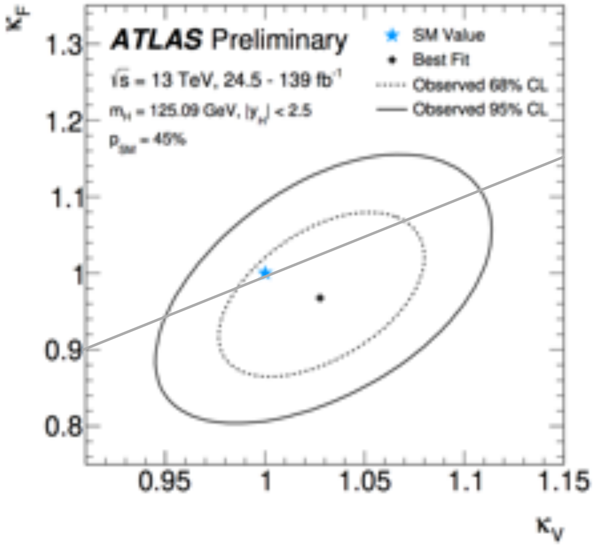
eady

For large tan β, bbA followed by $A \to \tau\tau$

Large parameter space is excluded, but a

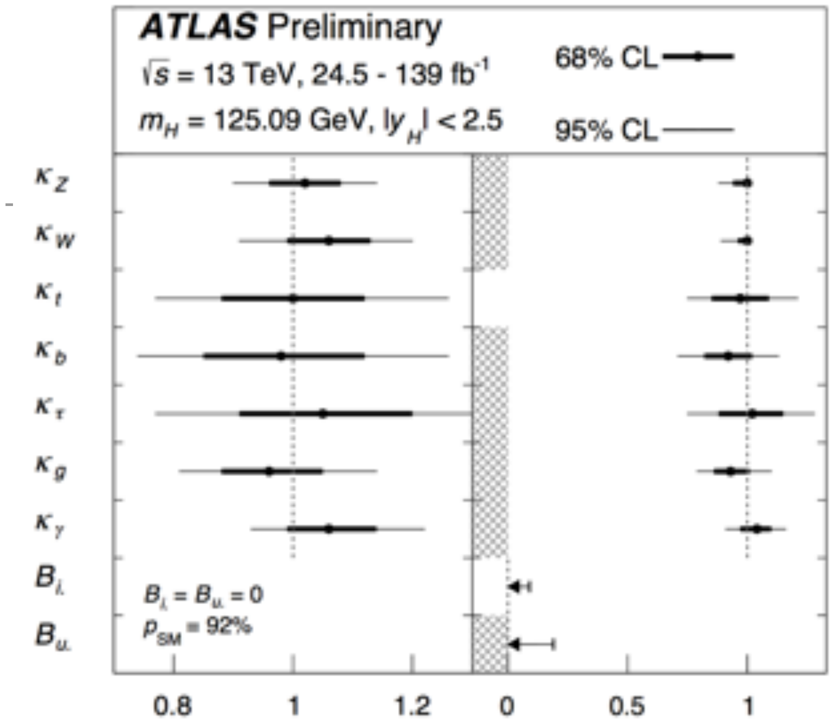
Kappa frameworks

$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}, \quad \kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

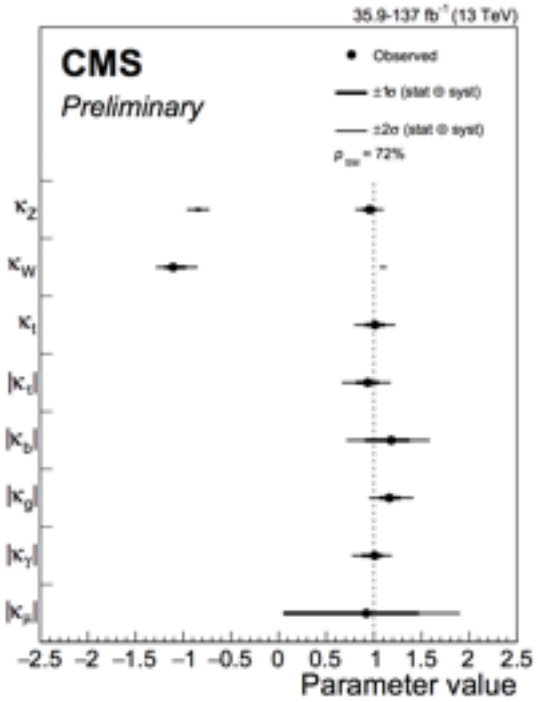


$\mu = 1.06 \pm 0.07$

ATLAS-CONF-2020-027

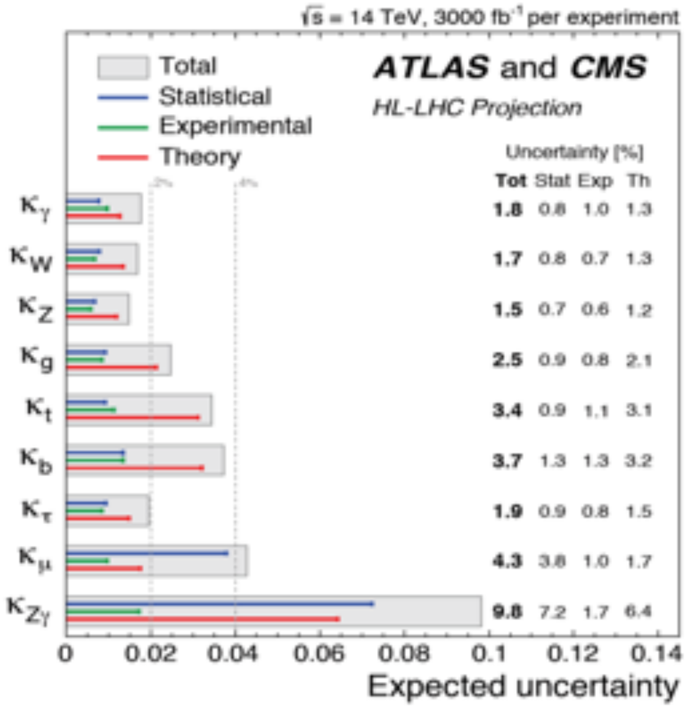


Production	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\mathrm{ggF})$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\mathrm{VBF})$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $-0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\mathrm{i.}} = B_{\mathrm{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$



Coupling modifiers κ_j			
		Uncertainty	
Parameters	Best-fit	Stat.	Syst.
κ_Z	$0.96^{+0.07}_{-0.07}$ $\left(^{+0.08}_{-0.08}\right)$	$^{+0.06}_{-0.06}$ $\left(^{+0.06}_{-0.06}\right)$	$^{+0.04}_{-0.05}$ $\left(^{+0.05}_{-0.05}\right)$
κ_W	$-1.11^{+0.14}_{-0.09}$ $\left(^{+0.09}_{-0.09}\right)$	$^{+0.13}_{-0.07}$ $\left(^{+0.07}_{-0.07}\right)$	$^{+0.05}_{-0.06}$ $\left(^{+0.06}_{-0.06}\right)$
κ_t	$1.01^{+0.11}_{-0.11}$ $\left(^{+0.10}_{-0.10}\right)$	$^{+0.06}_{-0.06}$ $\left(^{+0.06}_{-0.06}\right)$	$^{+0.09}_{-0.08}$ $\left(^{+0.08}_{-0.08}\right)$
κ_τ	$0.94^{+0.12}_{-0.12}$ $\left(^{+0.12}_{-0.11}\right)$	$^{+0.08}_{-0.11}$ $\left(^{+0.08}_{-0.07}\right)$	$^{+0.09}_{-0.06}$ $\left(^{+0.09}_{-0.08}\right)$
κ_b	$1.18^{+0.19}_{-0.27}$ $\left(^{+0.17}_{-0.16}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.13}_{-0.24}$ $\left(^{+0.11}_{-0.11}\right)$
κ_g	$1.16^{+0.12}_{-0.11}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.08}_{-0.08}$ $\left(^{+0.07}_{-0.07}\right)$	$^{+0.08}_{-0.08}$ $\left(^{+0.08}_{-0.07}\right)$
κ_γ	$1.01^{+0.09}_{-0.14}$ $\left(^{+0.09}_{-0.08}\right)$	$^{+0.07}_{-0.07}$ $\left(^{+0.07}_{-0.07}\right)$	$^{+0.06}_{-0.12}$ $\left(^{+0.05}_{-0.05}\right)$
κ_μ	$0.92^{+0.55}_{-0.87}$ $\left(^{+0.52}_{-0.96}\right)$	$^{+0.54}_{-0.87}$ $\left(^{+0.51}_{-0.95}\right)$	$^{+0.10}_{-0.01}$ $\left(^{+0.08}_{-0.08}\right)$

HIG-19-005-pas



Projected uncertainties on κ_i , combining ATLAS and CMS: total (grey box), statistical (blue), experimental (green) and theory (red).

~10% in Kappa at 139fb-1

2~4% in Kappa at 3ab-1

$$\Delta\kappa \sim \frac{v^2}{\Lambda^2} \to \Lambda \sim 750\ \mathrm{GeV}(10\%), 1.5\ \mathrm{TeV}(2.5\%)$$

Kappa frameworks with invisible width

$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H},$$

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\rm SM}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\rm SM}}$$

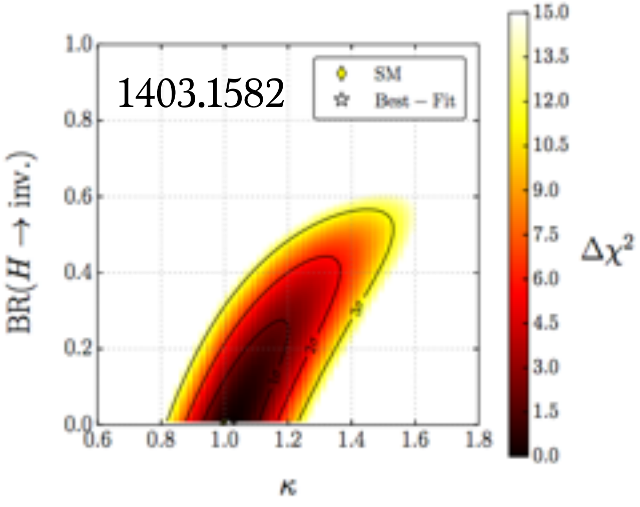
$$H \to \chi\chi$$

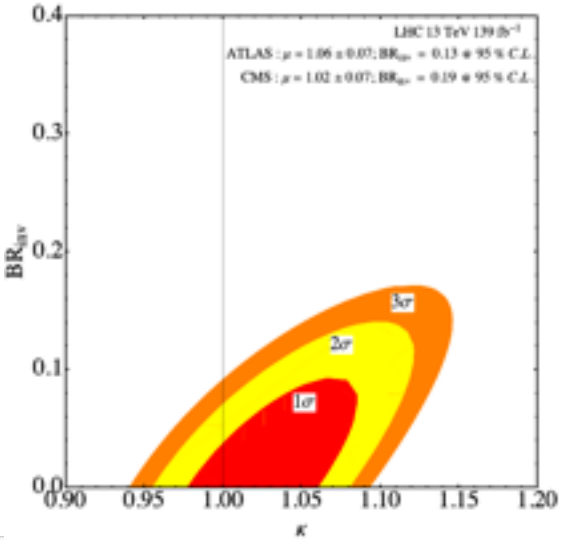
$$B_i = BR(H \to inv)$$

$$BR(H \to 4\nu) = 0.1\%$$

all visible signal strength unchanged under

$$\kappa^2 \cdot [1 - \mathrm{BR}(H \to \mathrm{NP})] = 1$$





Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
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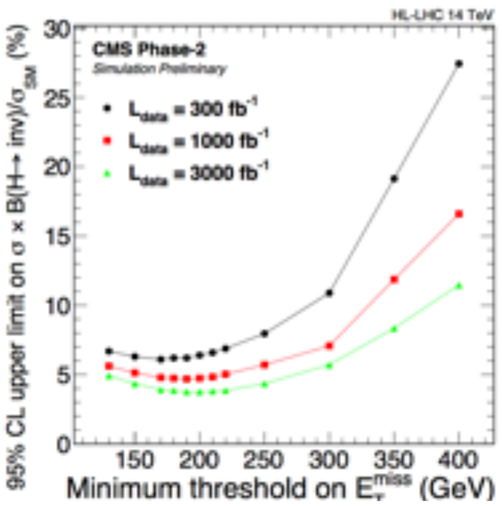
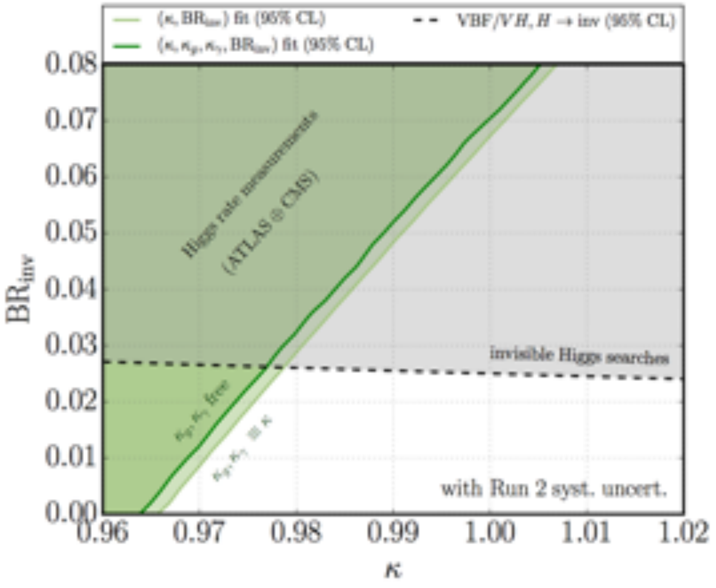
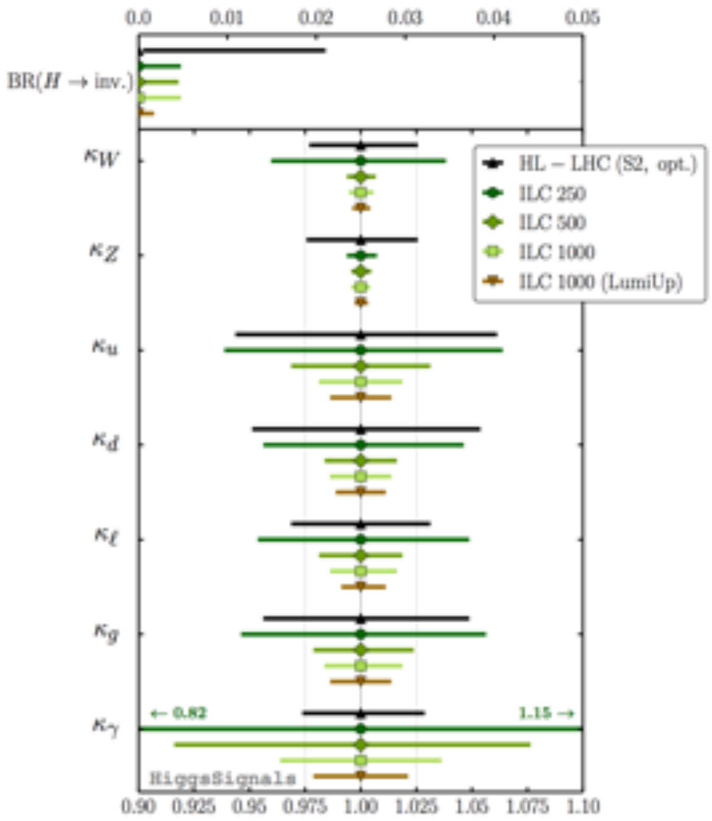
Total width ($B_{\rm i.} = B_{\rm u.} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$



$$(\mu_{\mathrm{VBF},VH} \cdot \mathrm{BR_{inv}})^{\text{HL-LHC}} \leq 2.5\%$$





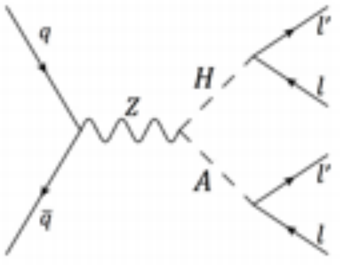
$$\Delta\kappa \sim \frac{v^2}{\Lambda^2} \to \Lambda \sim 750\ \mathrm{GeV}(10\%), 1.5\ \mathrm{TeV}(2.5\%)$$

What we can do at HL-LHC in Higgs physics ?

2027~2038: HL-LHC ⇒ 20 times more production of the particles

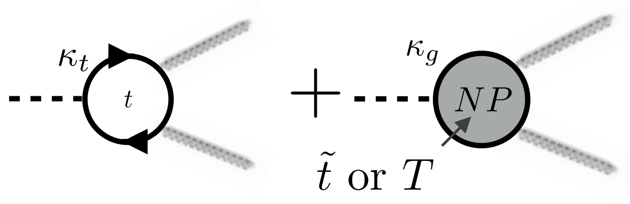
1. possibility of discovery of heavy particles

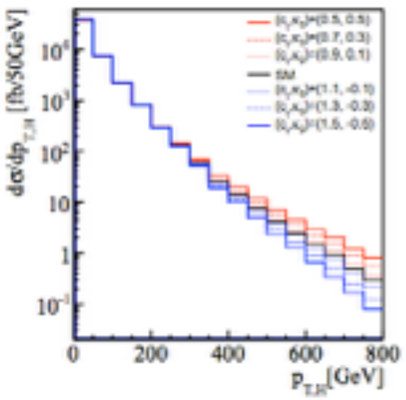
Heavy Higgs searches



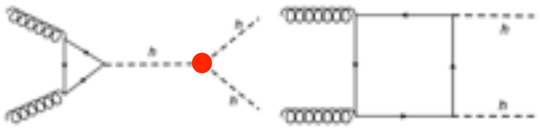
2. possibility of probing new physics effects using the distribution measurements

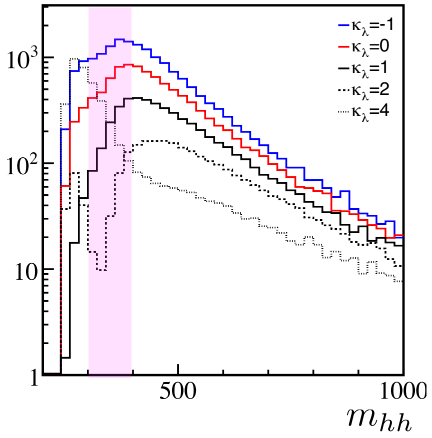
Boosted Higgs shapes





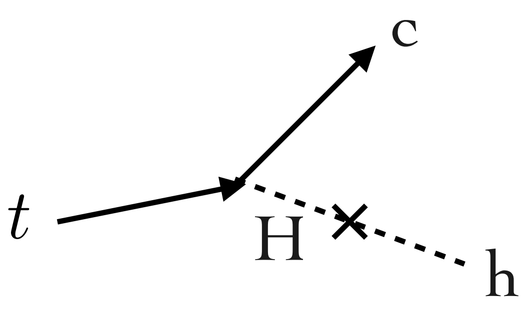
double-Higgs production

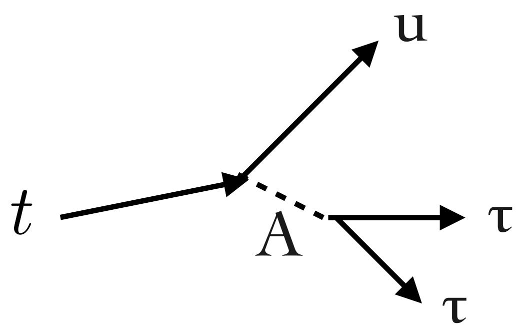




3. possibility of probing new physics effects using rare decays

Higgs rare decays, top rare decays





Muon g-2 : signature of BSM?

magnetic moment (potential term in a magnetic field)

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} \qquad \vec{\mu} = -g\frac{e}{2m}\vec{S}$$

$g = 2$ tree level, Dirac equation

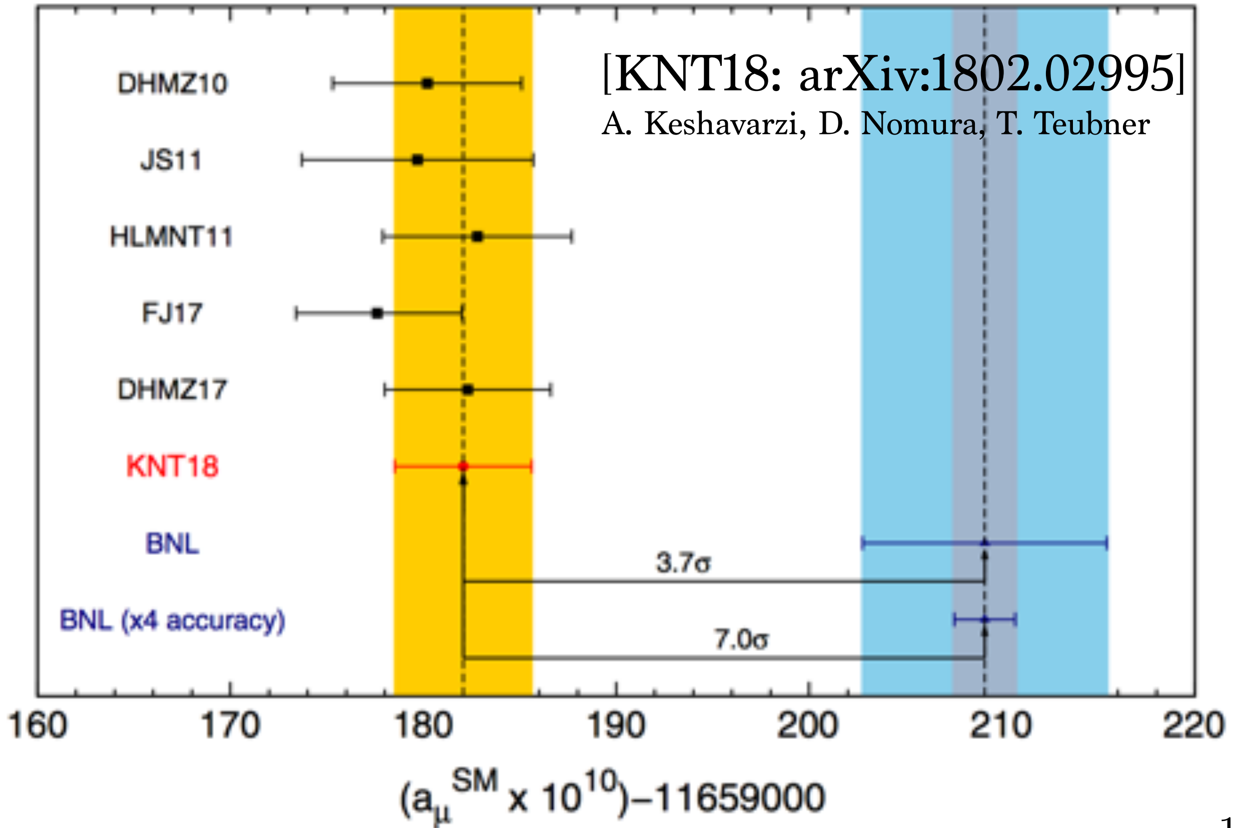
$g = 2.002\ 331$ QED, $\frac{\alpha}{\pi} = 0.00232\ldots$

$g = 2.002\ 331\ 83$ hadronic

$$g = 2.\underbrace{002\ 331\ 836\ 6}_{\text{anomalous magnetic moment}} \quad \text{EW}$$

$$a_\mu = (g_\mu - 2)/2$$

currently computed including 5-loop QED,
up to 9th digit reliable



[KNT18: arXiv:1802.02995]
A. Keshavarzi, D. Nomura, T. Teubner

$\times 10^{-10}$

Theory total	11659182.80 (4.94)	→	11659182.05 (3.56)
Experiment			11659209.10 (6.33)
Exp - Theory	26.1 (8.0)	→	27.1 (7.3)
Δa_μ	3.3σ	→	3.7σ

last year, estimate of the uncertainty reduced
the resulting significance increased

For long time, the 3σ level discrepancy observed

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} \sim \Delta a_\mu^{\rm EW} \sim \mathcal{O}(10^{-9})$$

$$\Delta a_\mu^{\rm NP} \sim \frac{g_{\rm NP}^2}{16\pi^2}\frac{m_\mu^2}{m_{\rm NP}^2}$$

Hint for BSM?
New physics at O(100GeV) ?

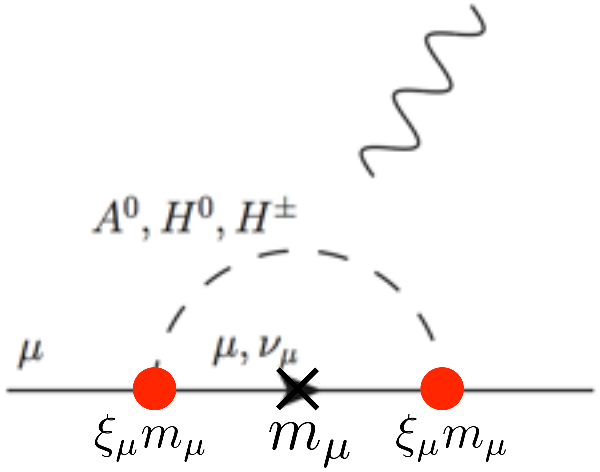
g-2 with LFV (ex. 2HDM)

$r_f^i = m_f^2/m_i^2$

$f_{h,H}(r) = \int_0^1 dx \frac{x^2(2-x)}{1-x+rx^2}, \quad f_A(r) = \int_0^1 dx \frac{-x^3}{1-x+rx^2}$

$f_{H^\pm}(r) = \int_0^1 dx \frac{-x(1-x)}{1-r(1-x)}.$

1-loop in 2HDM



compared with weak boson contributions suppressed by $\frac{m_\mu}{v} \sim 10^{-3}$

$$\Delta a_\mu^{1-\text{loop}} = \underbrace{\boxed{\frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}}}_{\sim 10^{-9}} \sum_i^{h,H,A,H^\pm} (\xi_\mu^i)^2 \underbrace{\frac{m_\mu^2}{m_i^2} f_i(r_f^i)}_{\sim 10^{-7}\ (m_H = 1\text{TeV})}$$

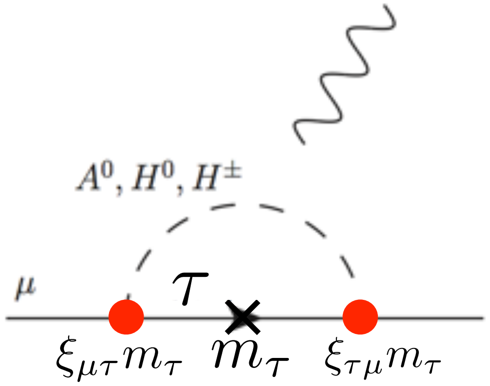
$\mathcal{O}(10^{-9})$ contribution required

cf.) muon-specific 2HDM [T. Abe, R. Sato, K. Yagyu, arXiv:1705.01469]

$\xi_\mu \sim 3000 \qquad m_H = 1\text{TeV}$

---

introducing LFV coupling has an advantage $m_\tau/m_\mu \sim 17$



➡ LFV enhance with $m_\tau^3/m_\mu^3 \sim 5000$, $\xi_{\mu\tau} \sim \xi_{\tau\mu} \sim 50$ required $\quad m_H = 1\text{TeV}$

consider the case only LFV couplings $\rho^{\mu\tau}, \rho^{\tau\mu}$ introduced for heavy higgses

Two Higgs Doublet Models (2HDM)

one additional Higgs doublet to the SM : new states $H, A, H^{\pm}$

$$\Phi_1 = \begin{pmatrix} H_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + ia_1) \end{pmatrix}, \Phi_2 = \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + ia_2) \end{pmatrix}$$

$$v_1^2 + v_2^2 = v_{\rm SM}^2 = (246{\rm GeV})^2$$

$$\tan\beta = v_2/v_1$$

appear as a low energy EFT in many well-motivated models (MSSM, Axion Models (PQ sym))

Yukawa interactions in general for both higgs doublets

$$\begin{aligned}\mathcal{L} = &-\bar{Q}_L^i H_1 y_d^i d_R^i - \bar{Q}_L^i H_2 \rho_d^{ij} d_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \tilde{H}_1 y_u^j u_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \tilde{H}_2 \rho_u^{jk} u_R^k \\ &-\bar{L}_L^i H_1 y_e^i e_R^i - \bar{L}_L^i H_2 \rho_e^{ij} e_R^j + \text{h.c..}\end{aligned}$$

$$\tilde{H} = (i\sigma_2)H^*$$

to avoid tree-level FCNC, certain parity structure is usually introduced (otherwise simultaneously not diagonalized)

however not necessary. we consider here g2HDM (new Yukawa matrices : free parameters, phenomenological analysis)

we consider only $\rho^{\mu\tau}, \rho^{\tau\mu}$

Heavy Higgses only couple via Hμτ vertex

cf) [Y. Abe, T. Toma and K. Tsumura, arXiv:1904.10908]

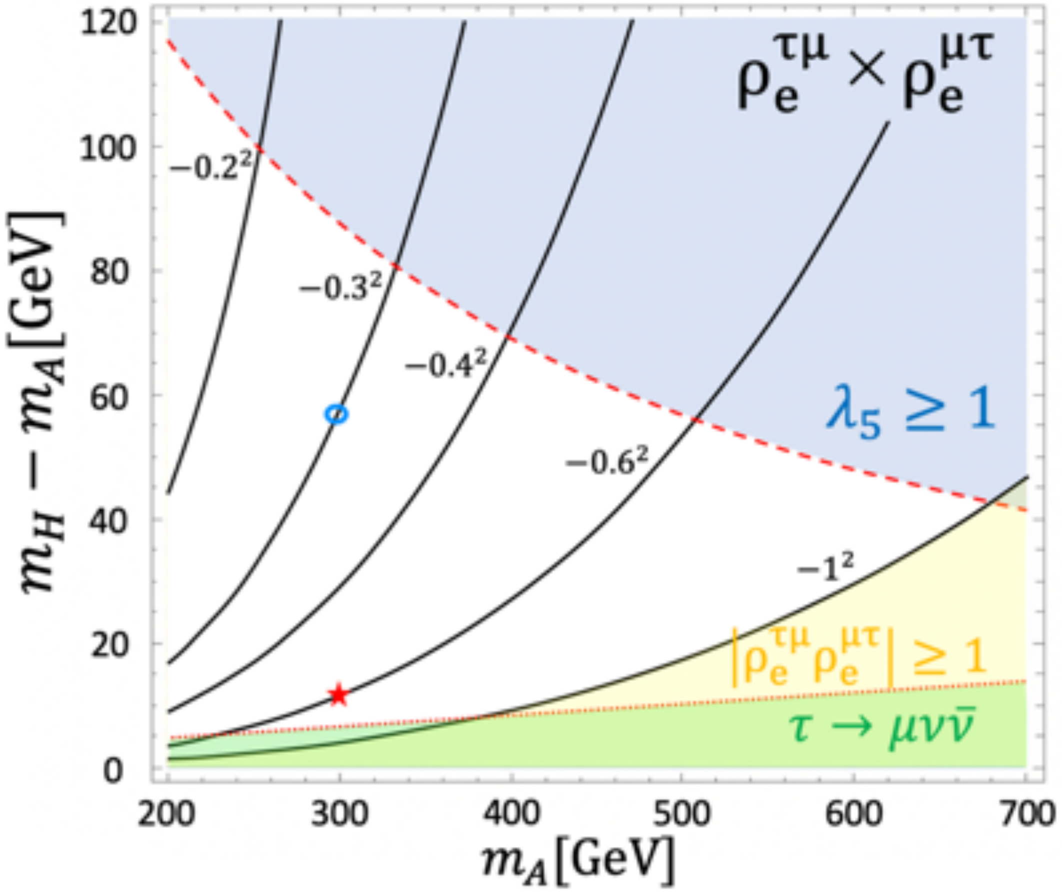
g-2 via lepton flavor violation

[S.Iguro, Y. Omura, MT JHEP 11 (2019) 130, arXiv:1907.09845]

g2HDM (new Yukawa matrices : free parameters, phenomenological analysis)

we consider only $\rho^{\mu\tau}, \rho^{\tau\mu}$ cf) [Y. Abe, T. Toma and K. Tsumura, arXiv:1904.10908]

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+\phi_1+iG}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2+iA}{\sqrt{2}} \end{pmatrix} \qquad \mathcal{L} = -\bar{\ell}_{Li} H_2 \rho^{ij} e_{Rj} + h.c.$$



$$\begin{aligned} \Delta a_\mu &\simeq -\frac{m_\mu m_\tau \rho_e^{\mu\tau}\rho_e^{\tau\mu}}{8\pi^2}\frac{\Delta_{H-A}}{m_A^3}\left(\ln\frac{m_A^2}{m_\tau^2} - \frac{5}{2}\right) \\ &\simeq -3\times10^{-9}\left(\frac{\rho_e^{\mu\tau}\rho_e^{\tau\mu}}{0.3^2}\right)\left(\frac{\Delta_{H-A}}{60[\text{GeV}]}\right)\left(\frac{300[\text{GeV}]}{m_A}\right)^3 \end{aligned}$$

H, A contributions cancel each other, total contributions $\propto \Delta_{H-A} = m_H - m_A$

controlled by Higgs potential, $V(H_i) = \lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1) + \{\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \text{h.c.}\} + \cdots$

$$m_H^2 \simeq m_A^2 + \lambda_5 v^2, \qquad m_{H^\pm}^2 \simeq m_A^2 - \frac{\lambda_4 - \lambda_5}{2}v^2,$$

we assume $m_A \leq m_H = m_{H^\pm}$ and require perturbativity, stability

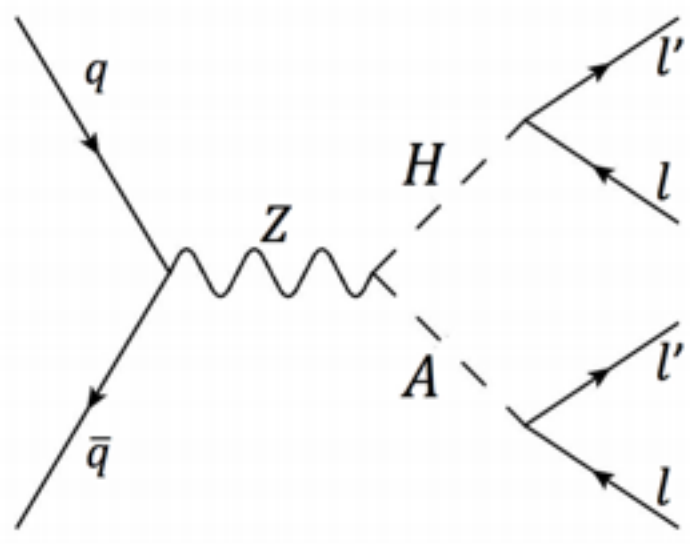
$$0 < \lambda_5 < 1 \qquad |\rho^{\mu\tau}|, |\rho^{\tau\mu}| < 1$$

the parameter region available to explain g-2 is finite

$$m_A \lesssim 700\text{GeV} \qquad \text{and} \qquad 10\text{GeV} \lesssim \Delta_{H-A} \lesssim 100\text{GeV}$$

g-2 via lepton flavor violation — LHC signatures

[S.Iguro, Y. Omura, MT JHEP 11 (2019) 130, arXiv:1907.09845]

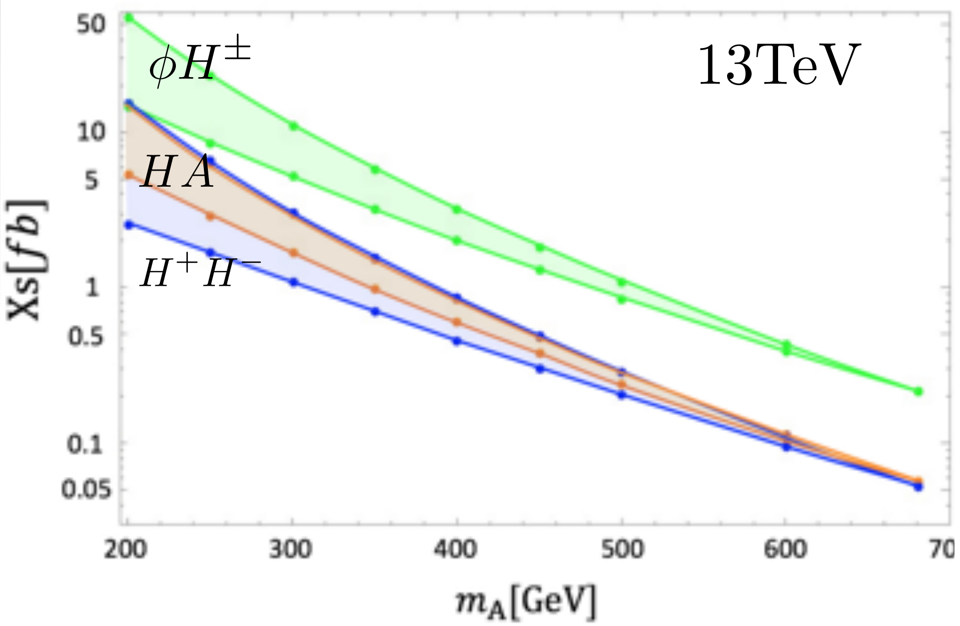


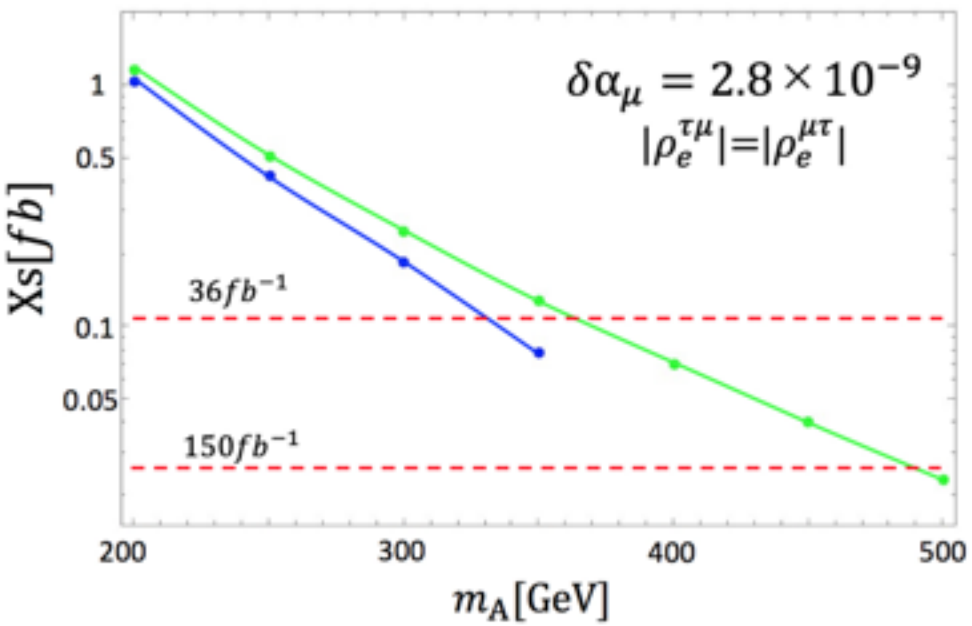
no QCD coupling : small but still sizable rate via SU(2) coupling

Heavy higgses produced in pair via Drell-Yan, HA, $\phi H^{\pm}$, and H^+H^-, where $\phi = H, A$.

$$BR(\phi \to \tau^+\mu^-) = BR(\phi \to \tau^-\mu^+) = 0.5,$$
$$BR(H^{\pm} \to \tau^{\pm}\nu) = 1 - BR(H^{\pm} \to \mu^{\pm}\nu) = \frac{|\rho_e^{\mu\tau}|^2}{|\rho_e^{\tau\mu}|^2 + |\rho_e^{\mu\tau}|^2} \equiv r.$$

they result in 4 leptons, 3 leptons, 2 leptons





multi-lepton $2\mu 2\tau$ channels

Especially $\mu^{\pm}\mu^{\pm}\tau^{\mp}\tau^{\mp}$

current data should already be sensitive at LHC up to 500 GeV

g-2 via LFV — mass reconstruction at LHC

[S.Iguro, Y. Omura, MT JHEP 11 (2019) 130, arXiv:1907.09845]

in future at 14 TeV, ~2fb (300 GeV) with 3 ab ⇒ ~ 6000 HA pair produced, other modes similarly produced

4 leptons from HA production

$\mu^\pm\mu^\pm\tau^\mp\tau^\mp$ same-sign di-muon di-tau (50%)

$\mu^+\mu^-\tau^+\tau^-$ opposite-sign di-muon di-tau (50%)

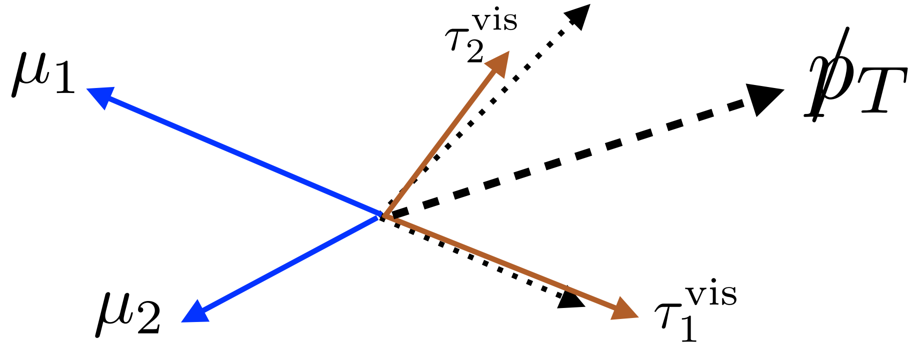
$\mathcal{O}(200-300)$ events for 3 ab^{-1}

OSOF pair gives the resonances (almost BG free)

τ-momentum : collinear approx.

$$\mathbf{p}_{\tau_i} = (1+c_i)\mathbf{p}^{\mathrm{vis}}_{\tau_i}$$

$$\not{\mathbf{p}}_T = c_1\mathbf{p}^{\mathrm{vis}}_{T,\tau_1} + c_2\mathbf{p}^{\mathrm{vis}}_{T,\tau_2} \qquad (c_1, c_2 > 0).$$



for $\mu^\pm\mu^\pm\tau^\mp\tau^\mp$

two possible combinations :

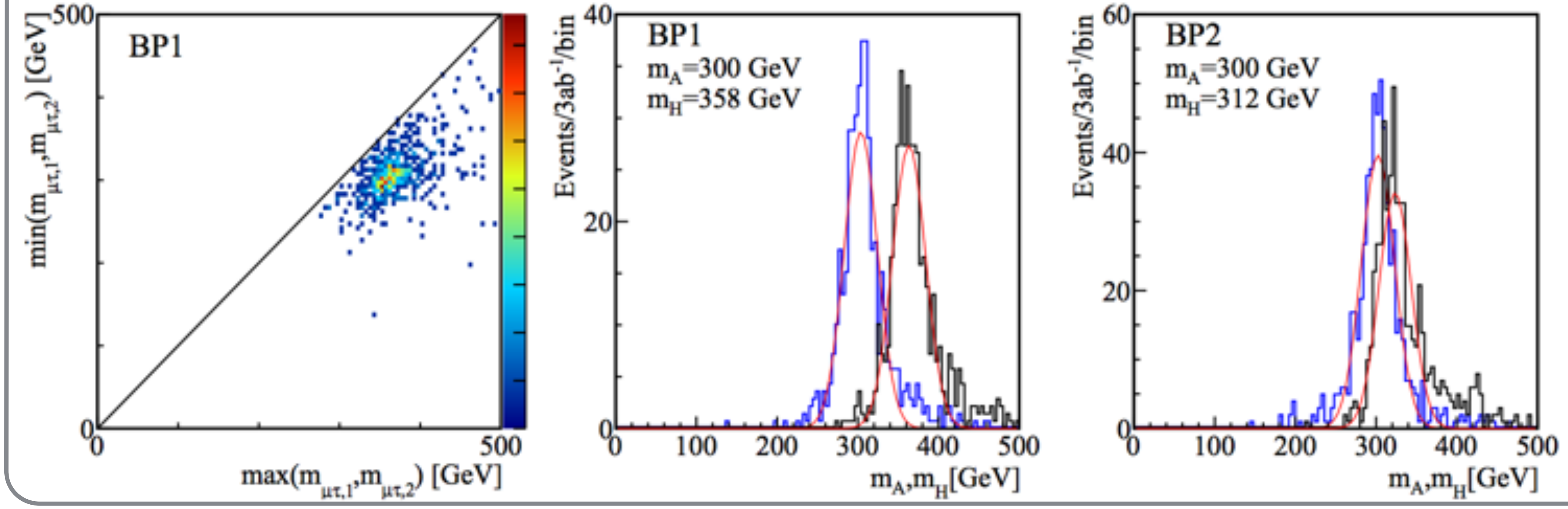
combination 1 : $m_{\mu_1\tau_1}$ and $m_{\mu_2\tau_2}$

combination 2 : $m_{\mu_1\tau_2}$ and $m_{\mu_2\tau_1}$

$\mu_1, \mu_2, \tau_1^{\mathrm{vis}}$, and τ_2^{vis} in p_T-order

select the one minimizing the sum of

$$\chi_i^2(m_A, m_H) = (m^{\mathrm{min}}_{\mu\tau,i} - m_A)^2/\sigma^2_{\mathrm{res}} + (m^{\mathrm{max}}_{\mu\tau,i} - m_H)^2/\sigma^2_{\mathrm{res}}$$



can reconstruct
two invariant masses
mA and mH

$$\sigma_{\mathrm{res}} \sim 20\mathrm{GeV}$$

cf.) $10\mathrm{GeV} \lesssim \Delta_{H-A} \lesssim 100\mathrm{GeV}$

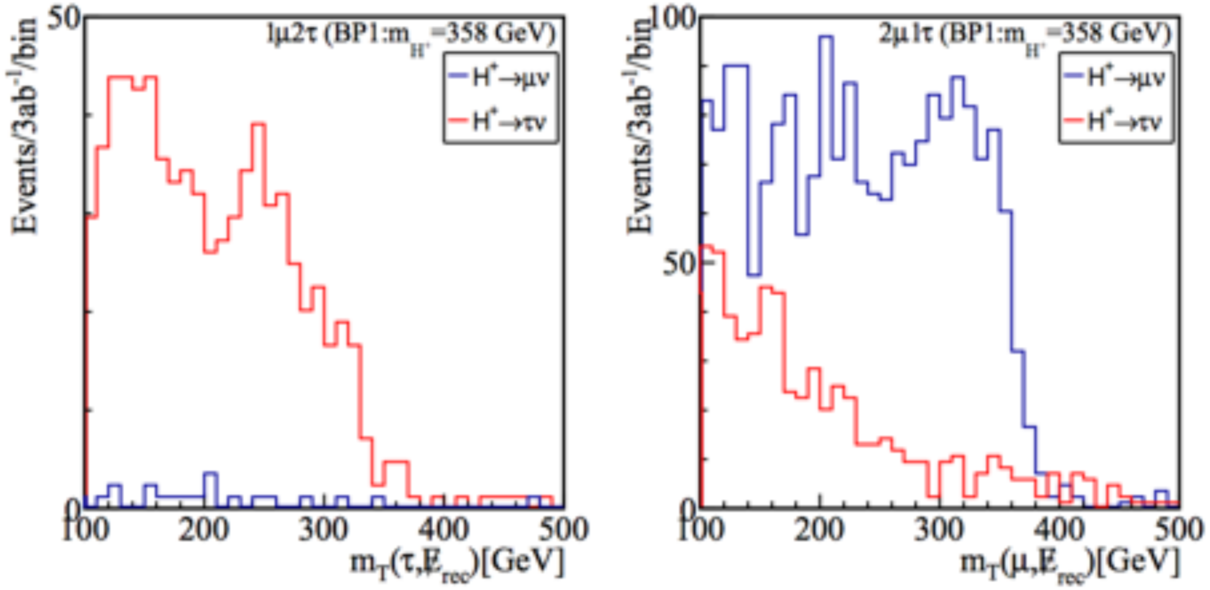
charged higgs mass
from 3 and 2 lepton modes

g-2 via LFV — mass reconstruction at LHC

charged Higgs mass can be reconstructed via 3 leptons from $\phi H^\pm$ production $\mu^\pm\tau^\mp\tau\nu$ and $\mu^\pm\tau^\mp\mu\nu$

ratio controlled by $BR(H^\pm\to\tau^\pm\nu)=1-BR(H^\pm\to\mu^\pm\nu)=\frac{|\rho_e^{\mu\tau}|^2}{|\rho_e^{\tau\mu}|^2+|\rho_e^{\mu\tau}|^2}\equiv r.$

part of τ-mode contribute to μ-mode



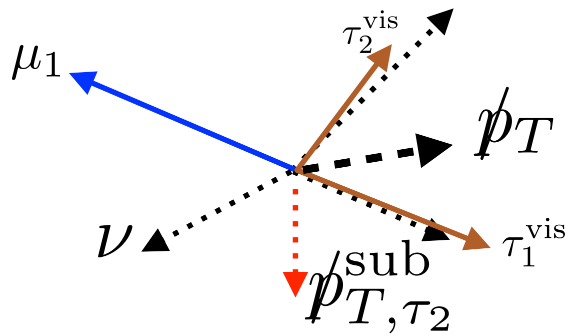
4 combinatorics : (production Φ=A, H) x (2 τμ combinations)

$$\mathbf{p}^{\rm rec}_{\tau_i}=(1+c_{\tau_i\phi})\mathbf{p}^{\rm vis}_{\tau_i},\quad (c_{\tau_i\phi}>0).$$

$$m^2_{\mu\tau_i^{\rm rec}}=(p_\mu+p^{\rm rec}_{\tau_i})^2=m^2_\phi,$$

$$\not{\mathbf{p}}^{\rm sub}_{T,\tau_i\phi}=\not{\mathbf{p}}_T-c_{\tau_i\phi}\mathbf{p}^{\rm vis}_{T,\tau}$$

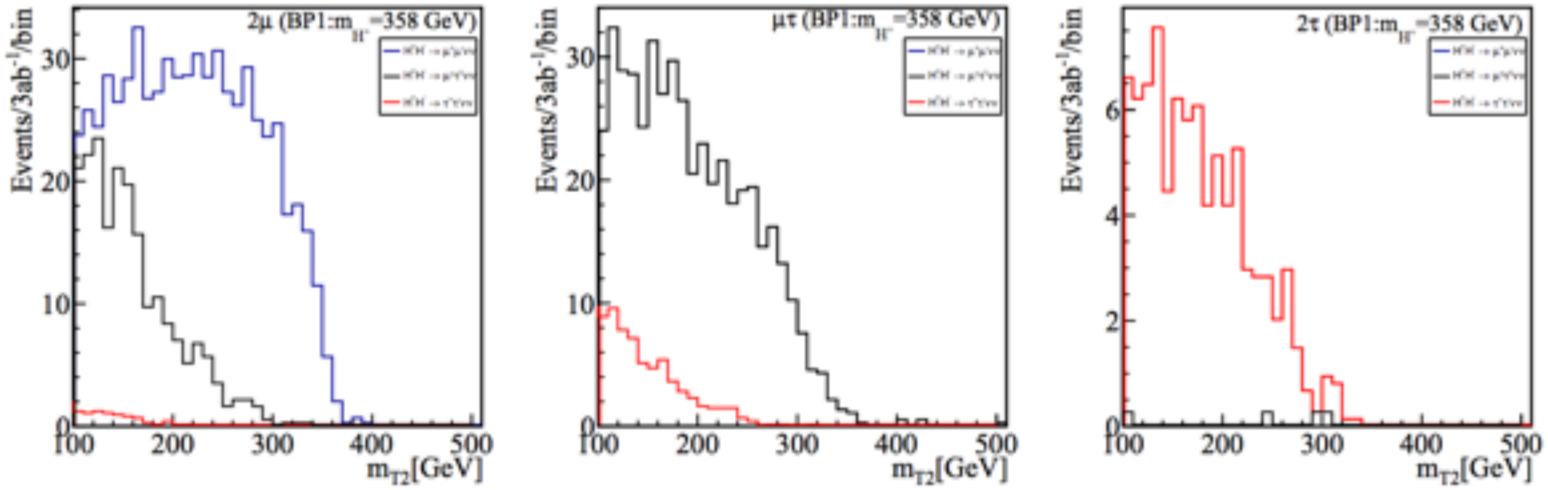
$$m_{T,\tau_i\phi}=m_T(\mathbf{p}^{\rm vis}_{\tau_{i'}},\not{\mathbf{p}}^{\rm sub}_{T,\tau_i\phi}),$$



taking the minimum of the 4 possibilities

$$m^{\rm min}_{T,\tau}=\min(m_{T,\tau_1 A},m_{T,\tau_1 H},m_{T,\tau_2 A},m_{T,\tau_2 H}).$$

also via 2 leptons from H^+H^- production



mH, mA, mH+ reconstructed
by 4,3,2 lepton events

event number ratios among various modes
sensitive to the BR

$$m_{T2}(\mathbf{p}_{\ell_1},\mathbf{p}_{\ell_2},\not{\mathbf{p}}_T)=\min_{\not{\mathbf{p}}_T=\not{\mathbf{p}}_{T,1}+\not{\mathbf{p}}_{T,2}}\{\max[m_T(\mathbf{p}_{\ell_1},\not{\mathbf{p}}_{T,1}),m_T(\mathbf{p}_{\ell_2},\not{\mathbf{p}}_{T,2})]\}$$

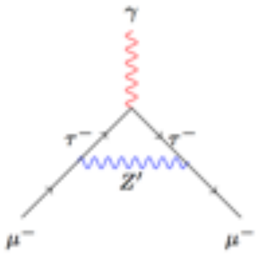
g-2 via LFV singlet

[S. Iguro, Y. Omura, M. T, arXiv: 2002.12728]

The previous searches using HA, etc. relay on the existence of the doublets
to explain g-2 via LFV, singlet extension is enough
In such cases, current collider constraints are very weak

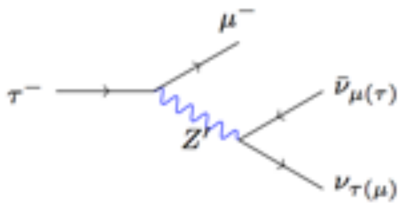
A famous example is the model with Z' [arXiv:1607.06832]

$$\mathcal{L}_{Z'} = g'_L\left(\bar\mu\gamma^\alpha P_L\tau + \bar\nu_\mu\gamma^\alpha P_L\nu_\tau\right)Z'_\alpha + g'_R\left(\bar\mu\gamma^\alpha P_R\tau\right)Z'_\alpha + \text{H.c.}\,,$$



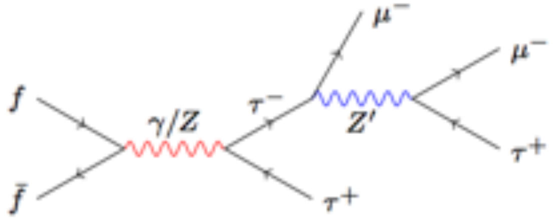
g-2 : LR term τ-mass enhanced

$$a_\mu \simeq \frac{1}{12\pi^2}\frac{m_\mu^2}{m_{Z'}^2}\left[3\,\mathrm{Re}(g'_L g'^*_R)\frac{m_\tau}{m_\mu} - |g'_L|^2 - |g'_R|^2\right]$$



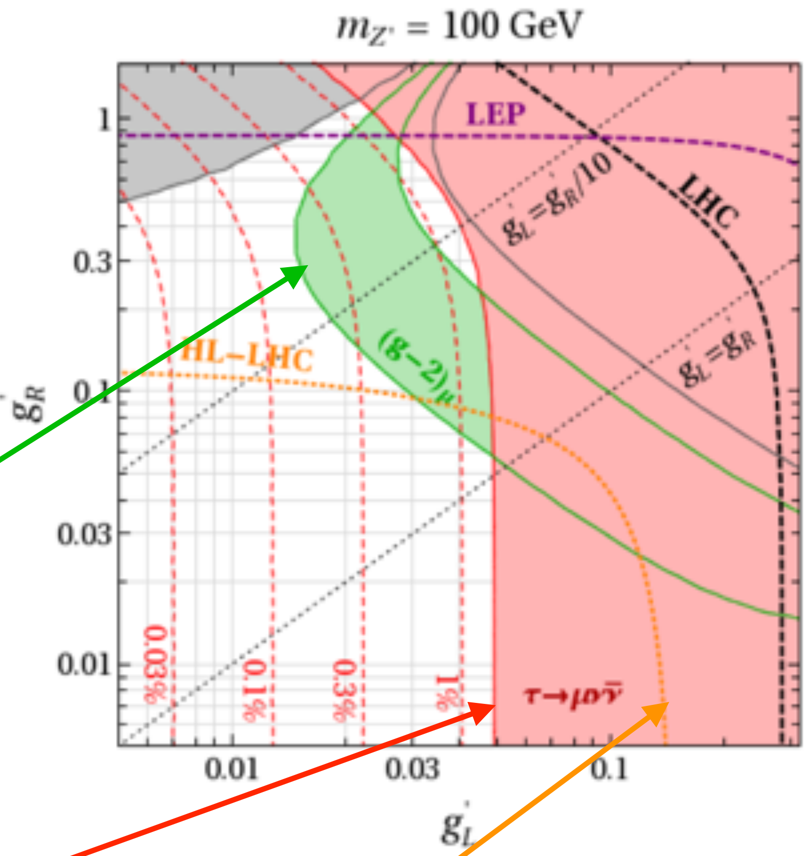
tau decay : L-enhanced by SM-interference

$$\frac{R_{\mu e}}{R_{\mu e}^{\rm SM}} = 1 + \frac{|g'_L|^2}{g_2^2}\frac{4m_W^2}{m_{Z'}^2} + \left(\frac{|g'_L g'_R|^2}{g_2^4} + \frac{|g'_L|^4}{g_2^4}\right)\frac{8m_W^4}{m_{Z'}^4}$$



$\tau\mu Z'$ production

$$\sigma \sim |g_L|^2 + |g_R|^2$$



g-2 : the product is constant

tau-decay : constraints weaker for $g_R \gg g_L$

colliders : mostly covered in future

g-2 via LFV singlet

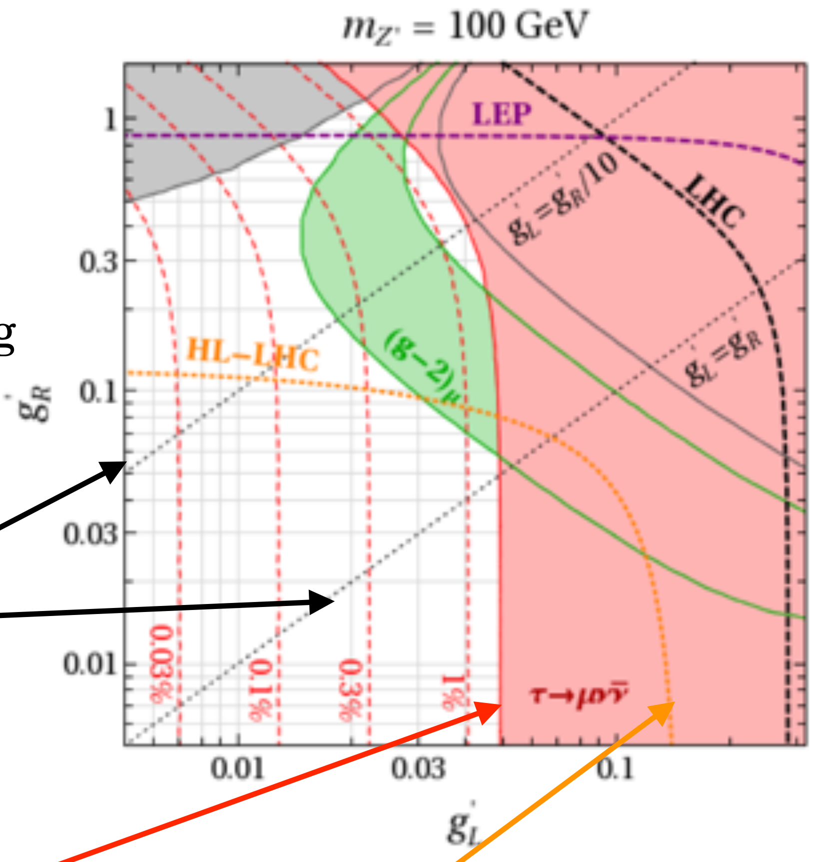
[S. Iguro, Y. Omura, M. T, arXiv: 2002.12728]

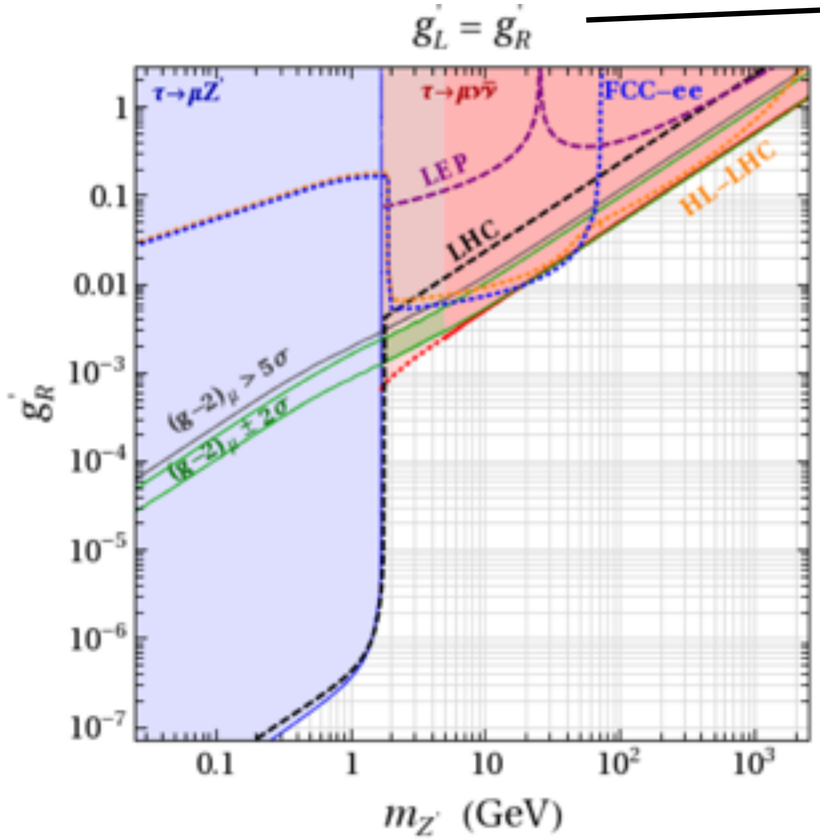
For the model with Z' as a function of Z' mass [arXiv:1607.06832]

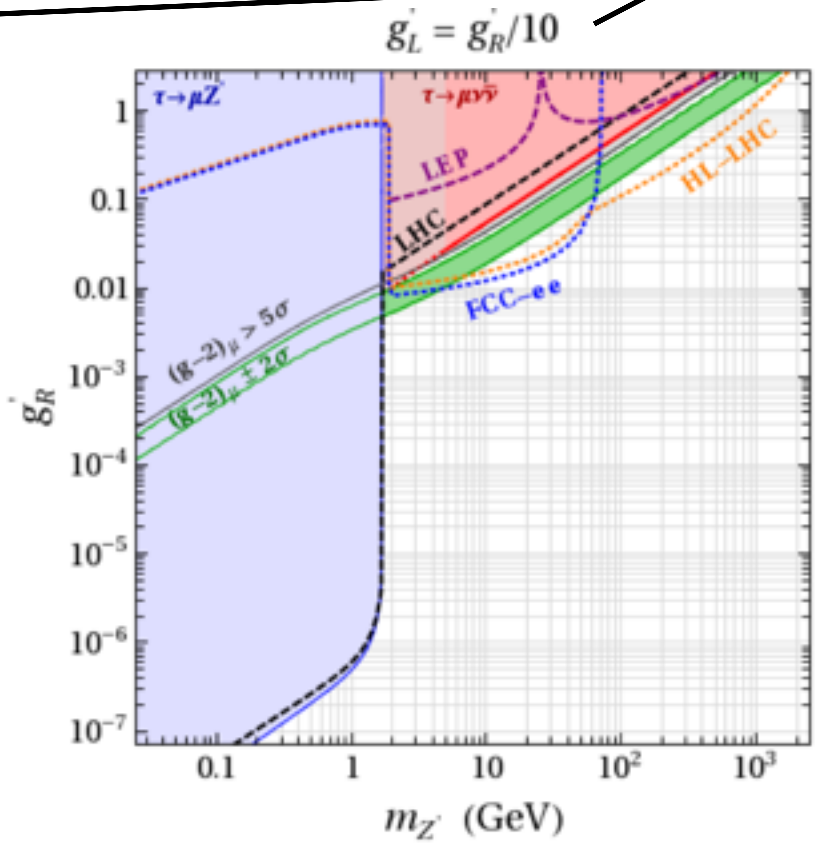
$g_L = g_R$ already excluded

$g_L = g_R/10$ still allowed $m_{Z'} \geq m_\tau - m_\mu$

in future, HL-LHC, FCC-ee will cover most of the remaining







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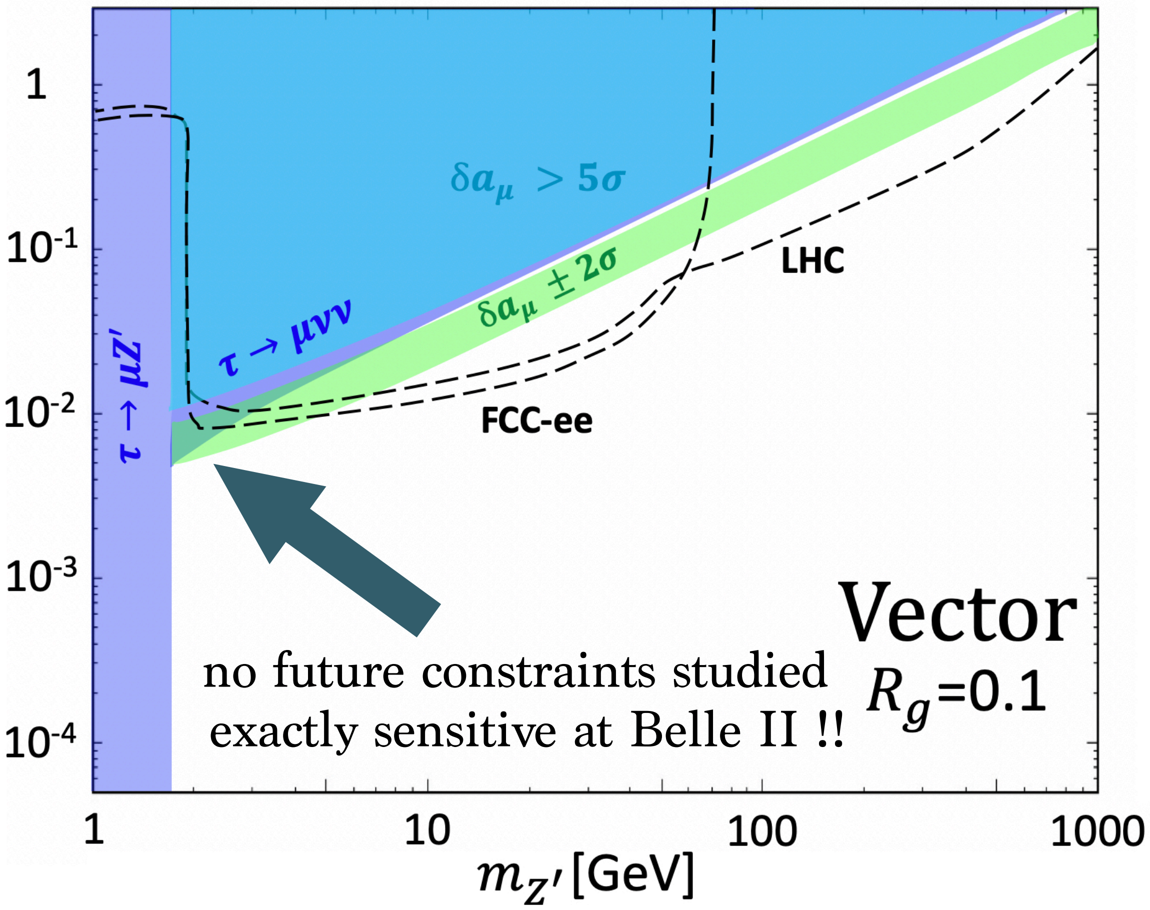
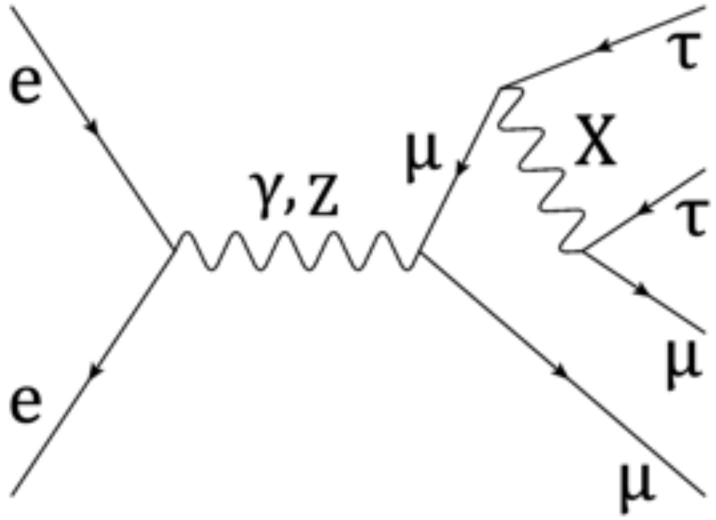


no future constraints studied
exactly sensitive at Belle II !!



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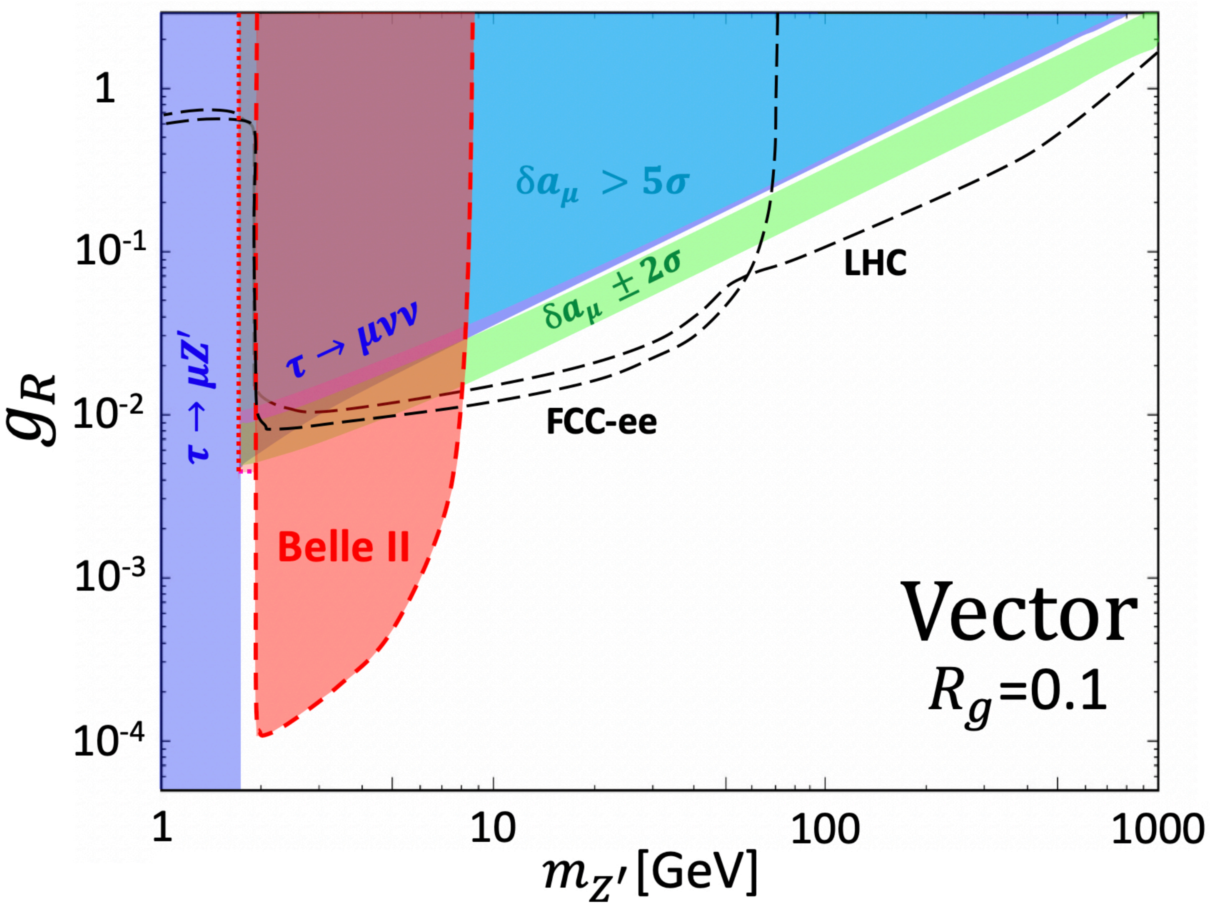

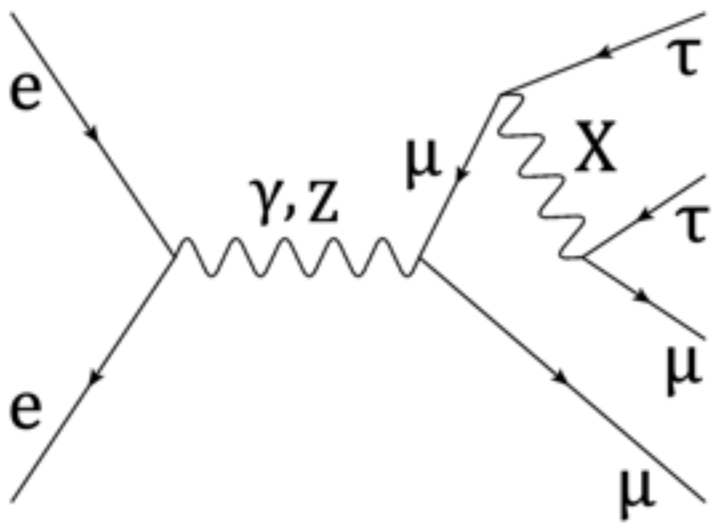

Belle II experiments will cover the remaining parameter space!

g-2 via LFV singlet

[S. Iguro, Y. Omura, M. T, arXiv: 2002.12728]

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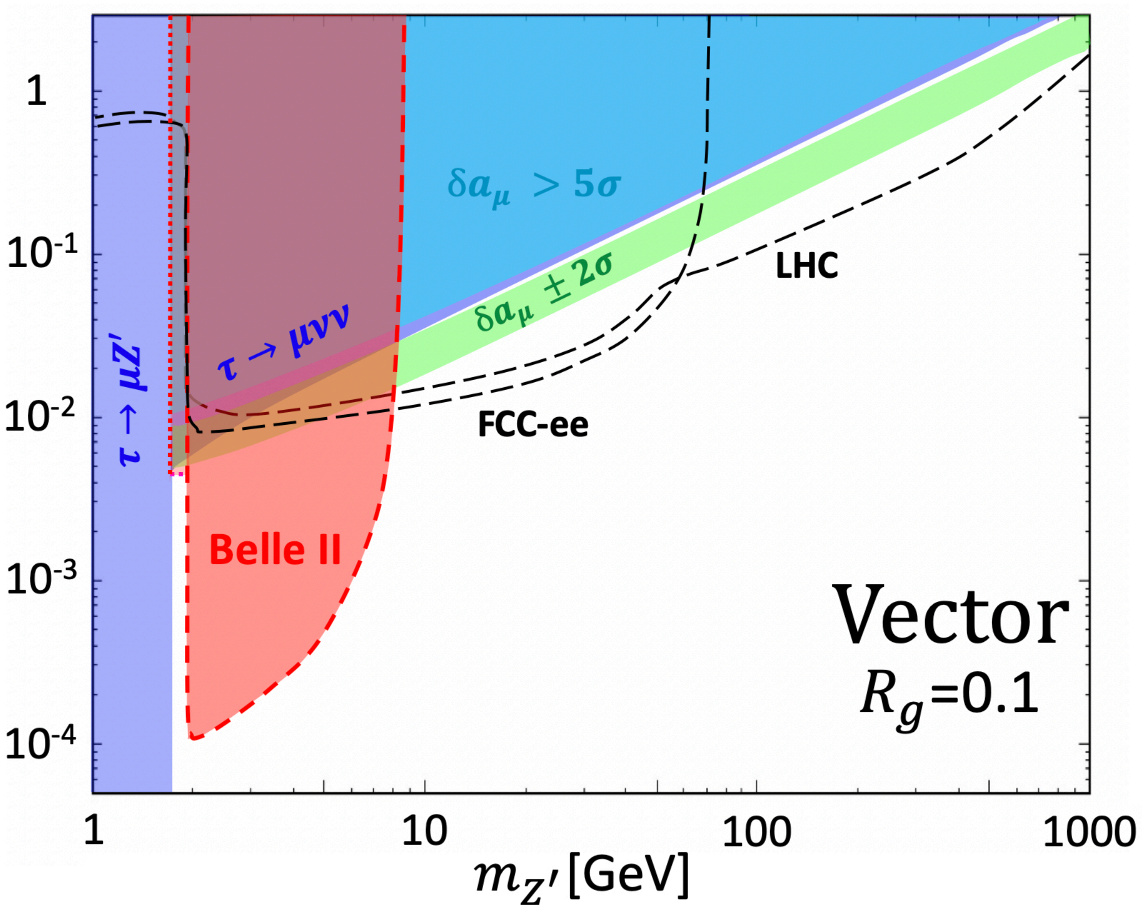
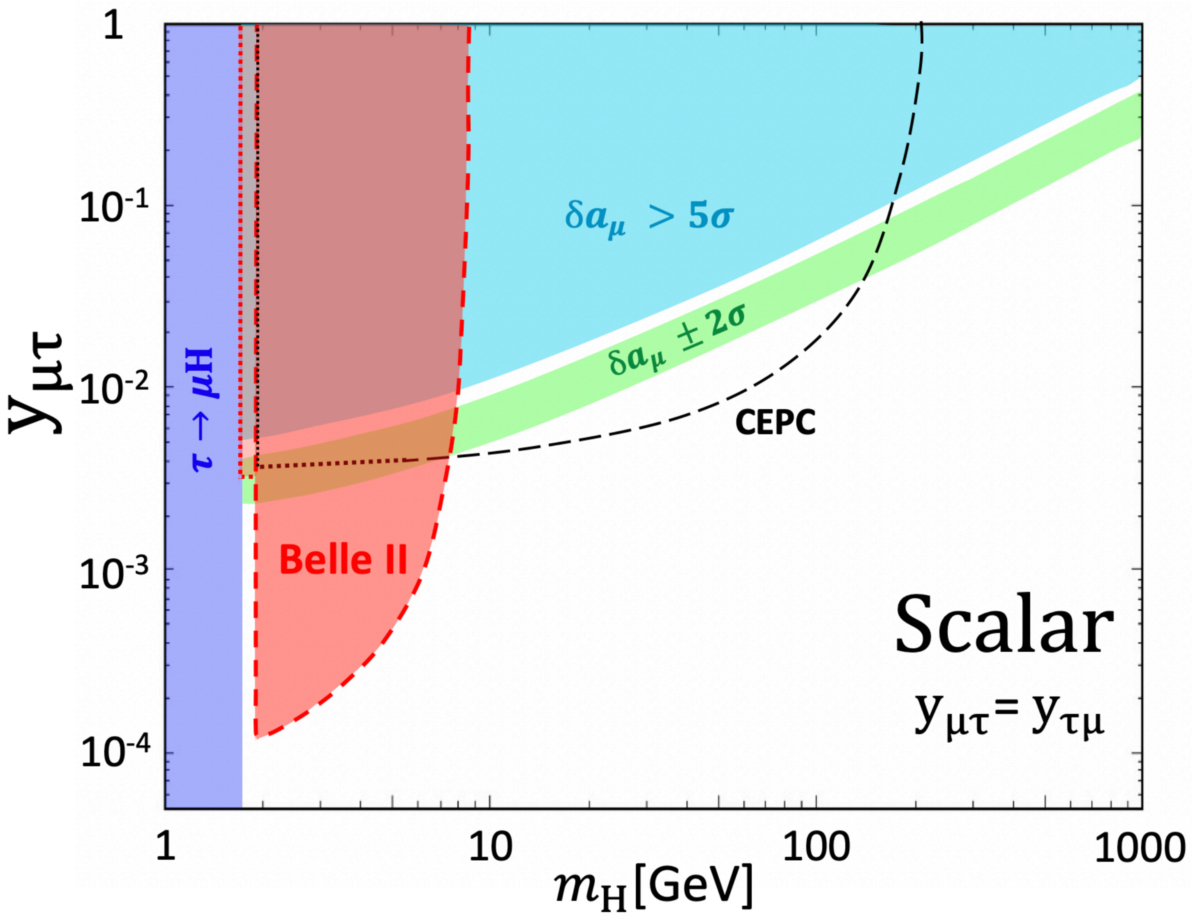




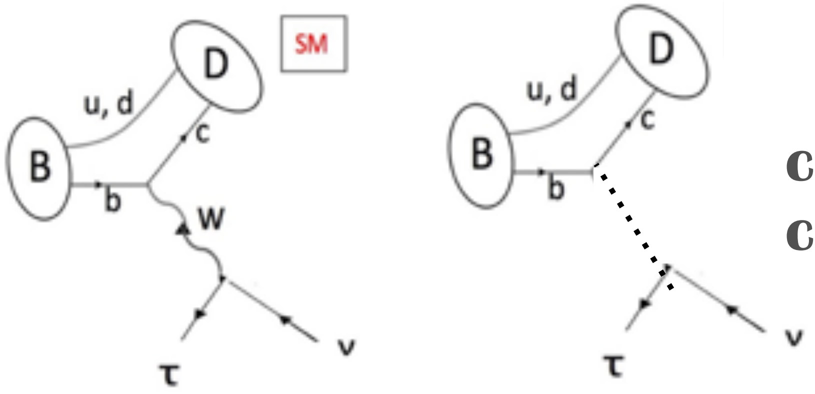
Belle II experiments will cover the remaining parameter space!

We have also studied scalar extension can be also covered

R(D) vs R(D(*)): signature of BSM?

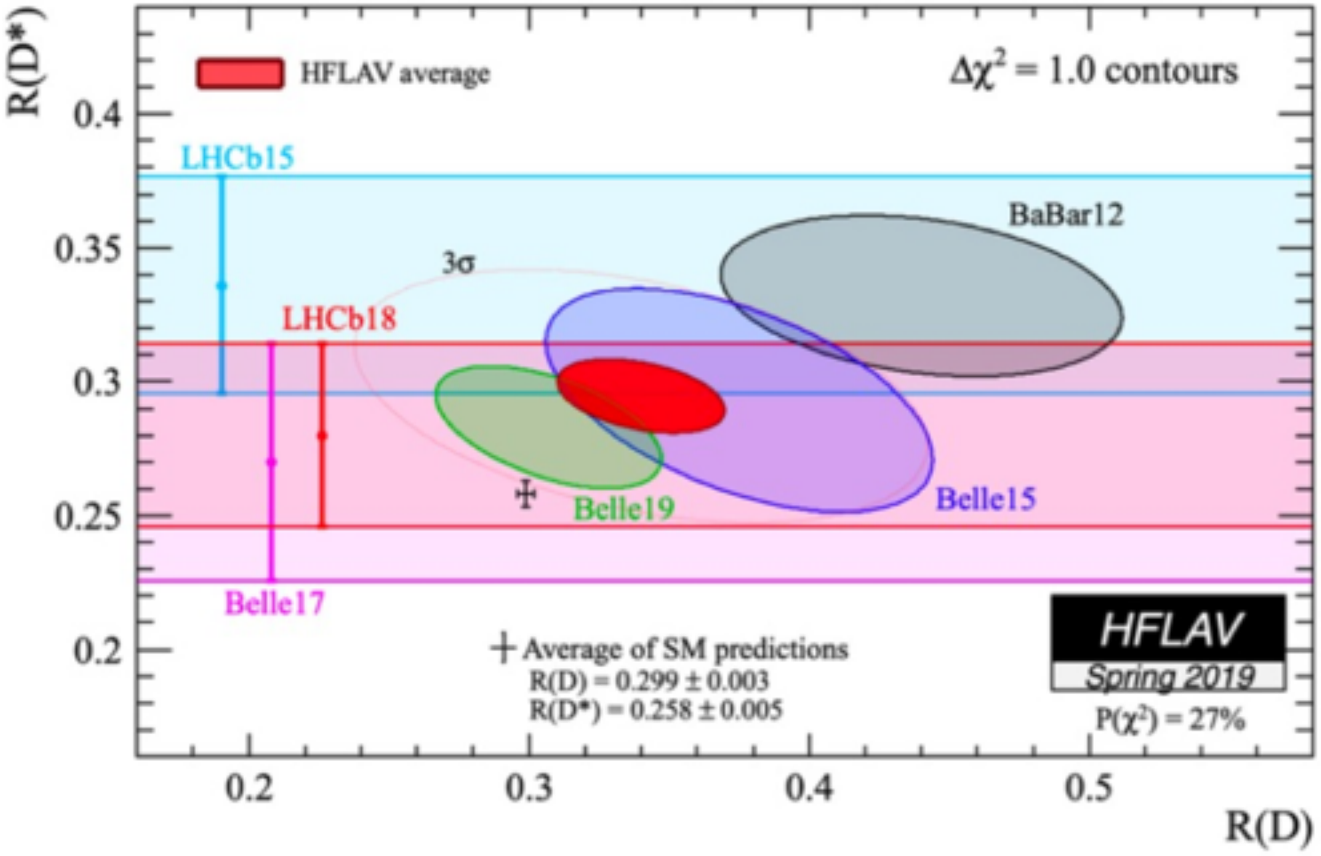
$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

∼3-4σ deviation reported



charged higgs can modify them

constrained by $BR(B_c \to \tau\nu)$ **but large uncertainty**



$$\mathcal{H}_{\text{eff}}^{b\to c\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{cb}\left[\left(1 + C_{V_L}\right)\mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R} + C_{S_R}\mathcal{O}_{S_R} + C_{S_L}\mathcal{O}_{S_L} + C_T\mathcal{O}_T\right] + \text{h.c.}.$$

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu b_{L,R})\left(\bar{\ell}_L\gamma_\mu\nu_{\ell L}\right), \quad \mathcal{O}_{S_{L,R}} = (\bar{c}\, b_{L,R})\left(\bar{\ell}_R\nu_{\ell L}\right), \quad \mathcal{O}_T = (\bar{c}\sigma^{\mu\nu}b_L)\left(\bar{\ell}_R\sigma_{\mu\nu}\nu_{\ell L}\right)$$

1D hyp.	best-fit	1σ range	2σ range	p-value (%)	pull$_{\text{SM}}$
C_V^L	0.07	[0.05, 0.09]	[0.04, 0.11]	44	4.0
C_S^R	0.09	[0.06, 0.11]	[0.03, 0.14]	2.7	3.1
C_S^L	0.07	[0.04, 0.10]	[−0.00, 0.13]	0.26	2.1
$C_S^L = 4C_T$	−0.03	[−0.07, 0.01]	[−0.11, 0.04]	0.04	0.7

[M. Blanke, A. Crivellin, T. Kitahara, M. Moscati, U. Nieste, I. Nisandzic]
arXiv: 1905.08253

$$C_X \sim \frac{v^2}{\Lambda^2}$$

Hint for BSM?

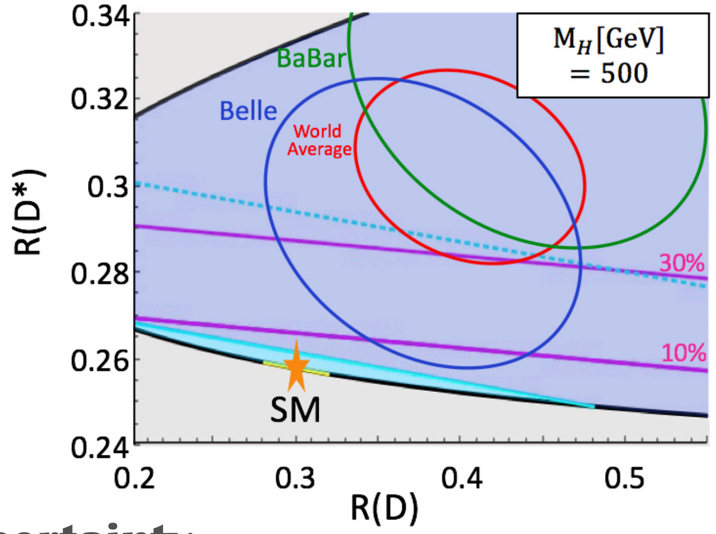
New particles below O(TeV)?

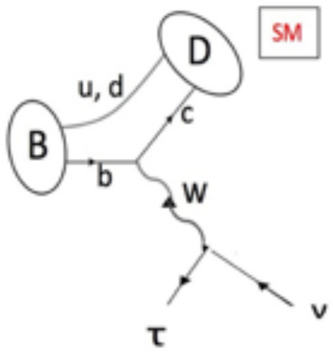
test of flavor anomaly at LHC

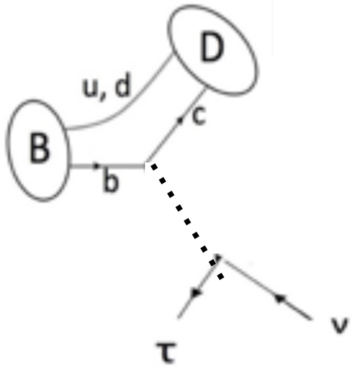
Syuhei Iguro (Nagoya U.), Yuji Omura (KMI, Nagoya), MT
JHEP 03 (2019) 076 arXiv:1810.05843

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

∼3-4σ deviation reported



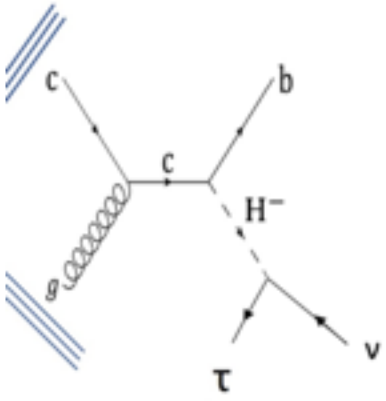


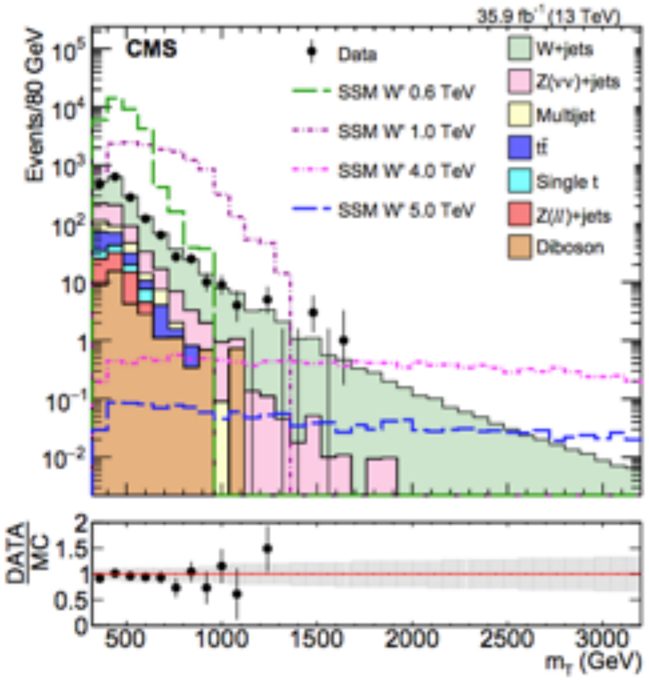


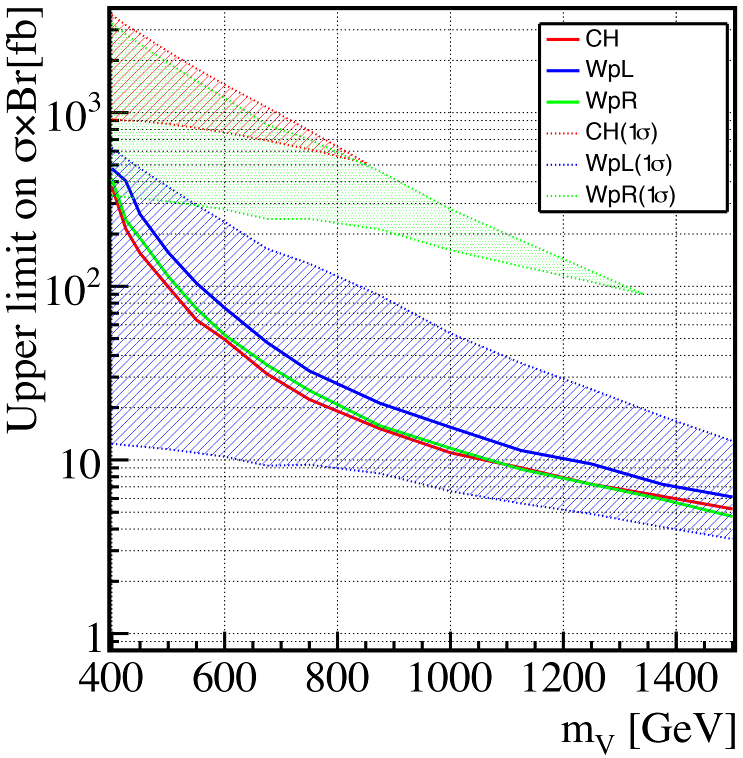
charged higgs can solve it

constrained by $BR(B_c \to \tau\nu)$ but large uncertainty

At LHC τν searches already set stronger bound for such a charged higgs







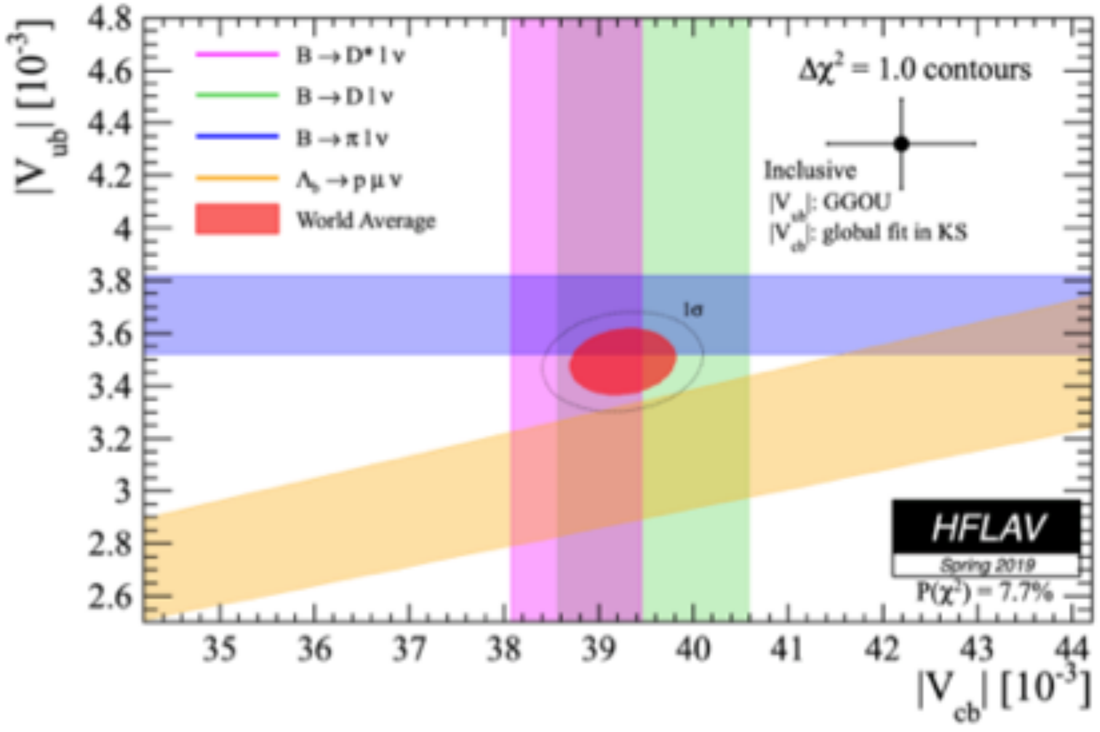
test of flavor anomaly at LHC

S. Iguro, , MT, R. Watanabe [arXiv:20XX.XXXXX to appear]

Vub, Vcb determinations from exclusive, inclusive analyses have discrepancy

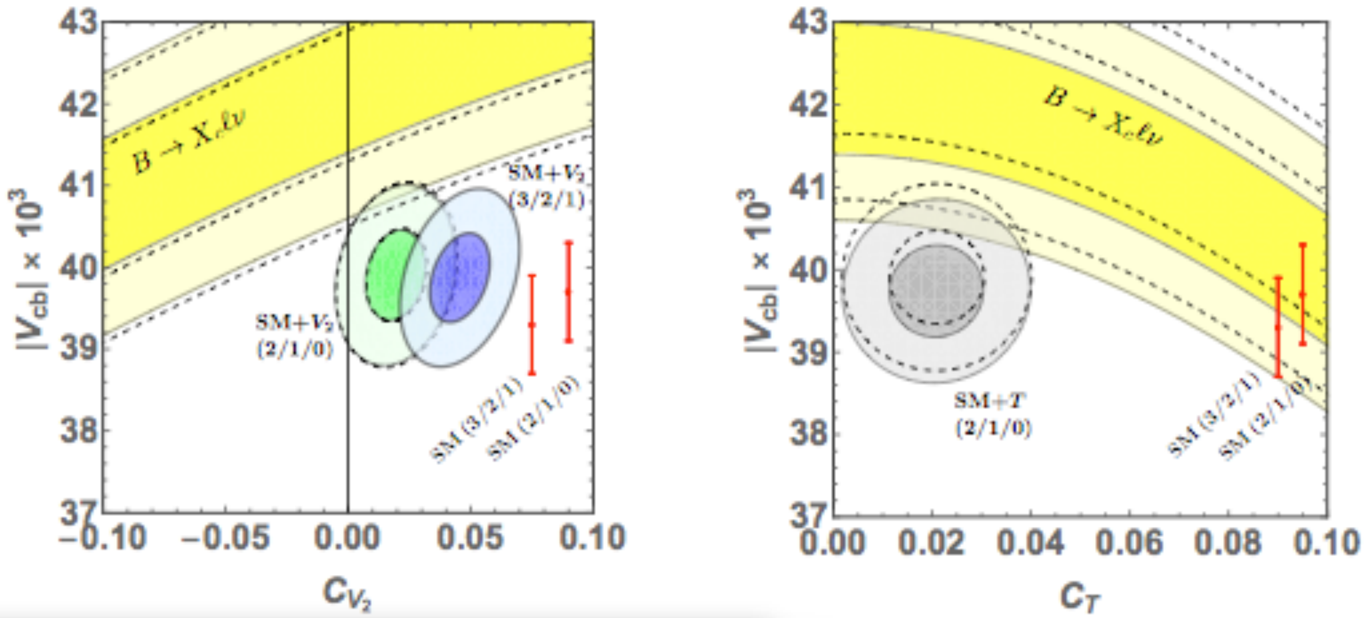
NP contributions might better accommodate the situation also in cbeν, cbμν, ubeν, ubμν couplings

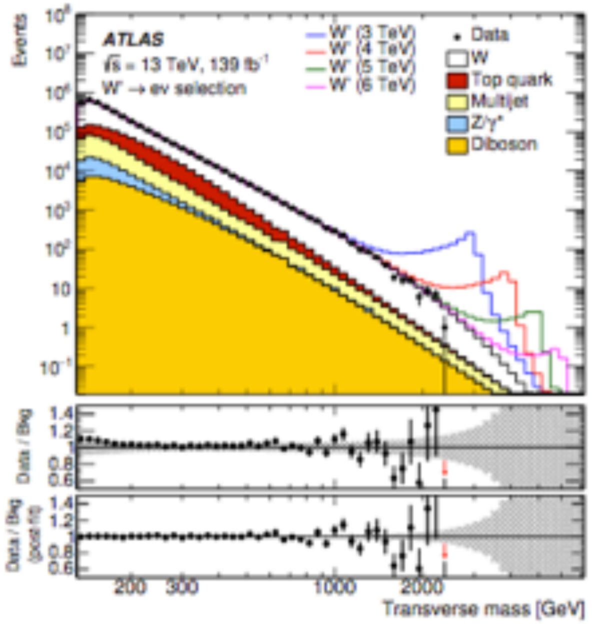
(again at least O(TeV) new particles allowed)

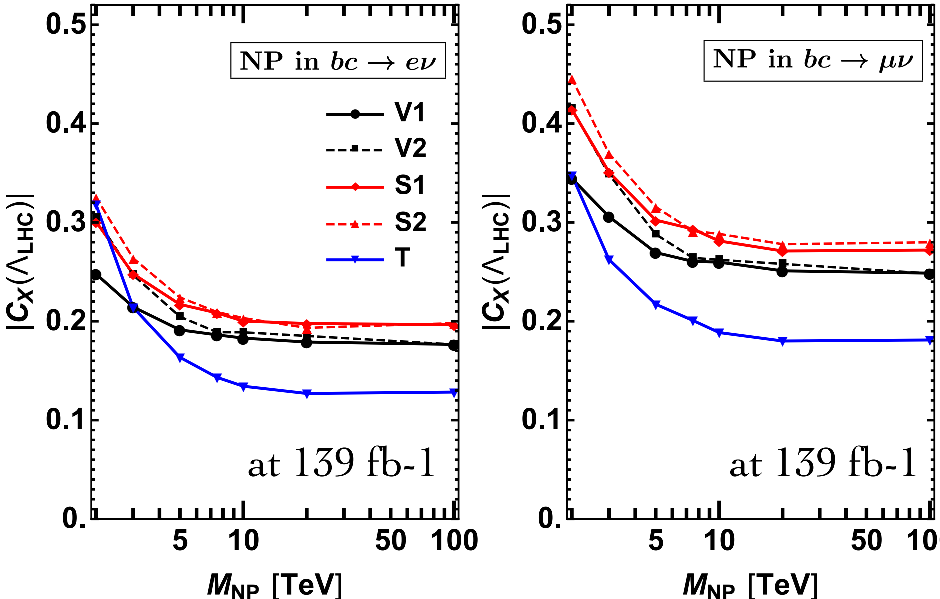


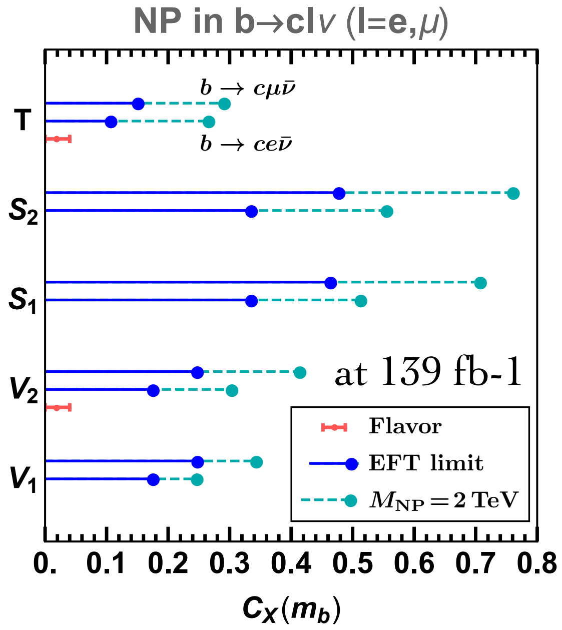
$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}}V_{cb}\Big[(\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) + C_{V_2}(\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L\nu_\ell) + C_T(\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell)\Big], \quad (1)$$

S Iguro, R. Watanabe [arXiv:2004.10208 [hep-ph]].









We consider the UV models to generate the op. at LHC

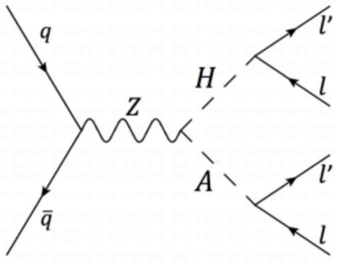
found rather sensitive to M_NP

What we can do at HL-LHC in Higgs physics ?

2027~2038: HL-LHC ⇒ 20 times more production of the particles

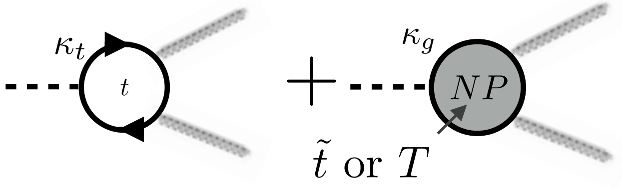
1. possibility of discovery of heavy particles

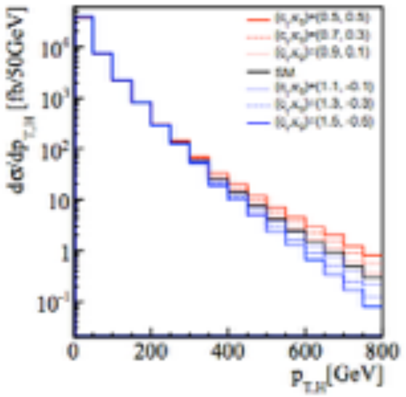
Heavy Higgs searches



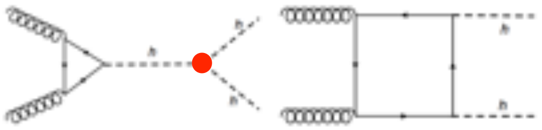
2. possibility of probing new physics effects using the distribution measurements

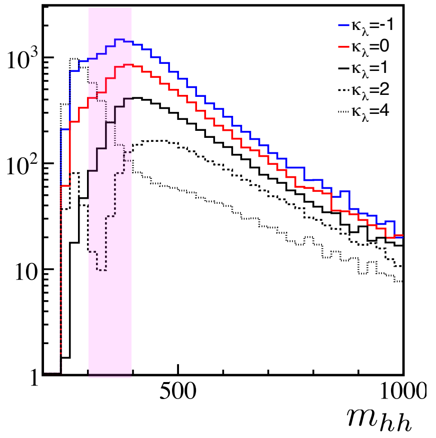
Boosted Higgs shapes





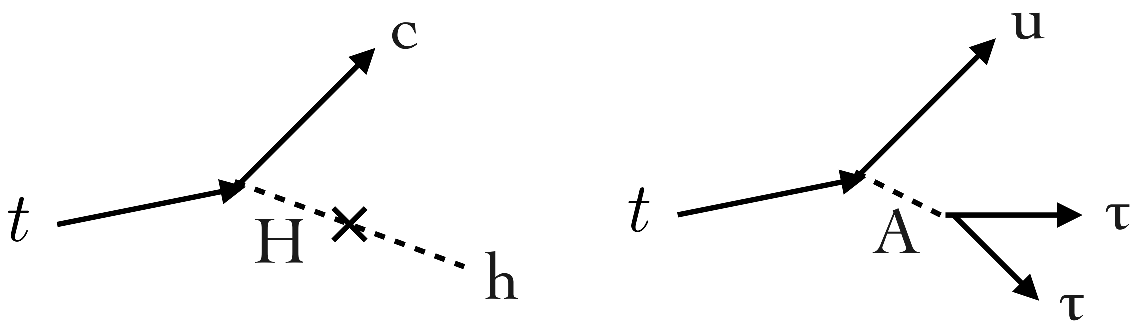
double-Higgs production





3. possibility of probing new physics effects using rare decays

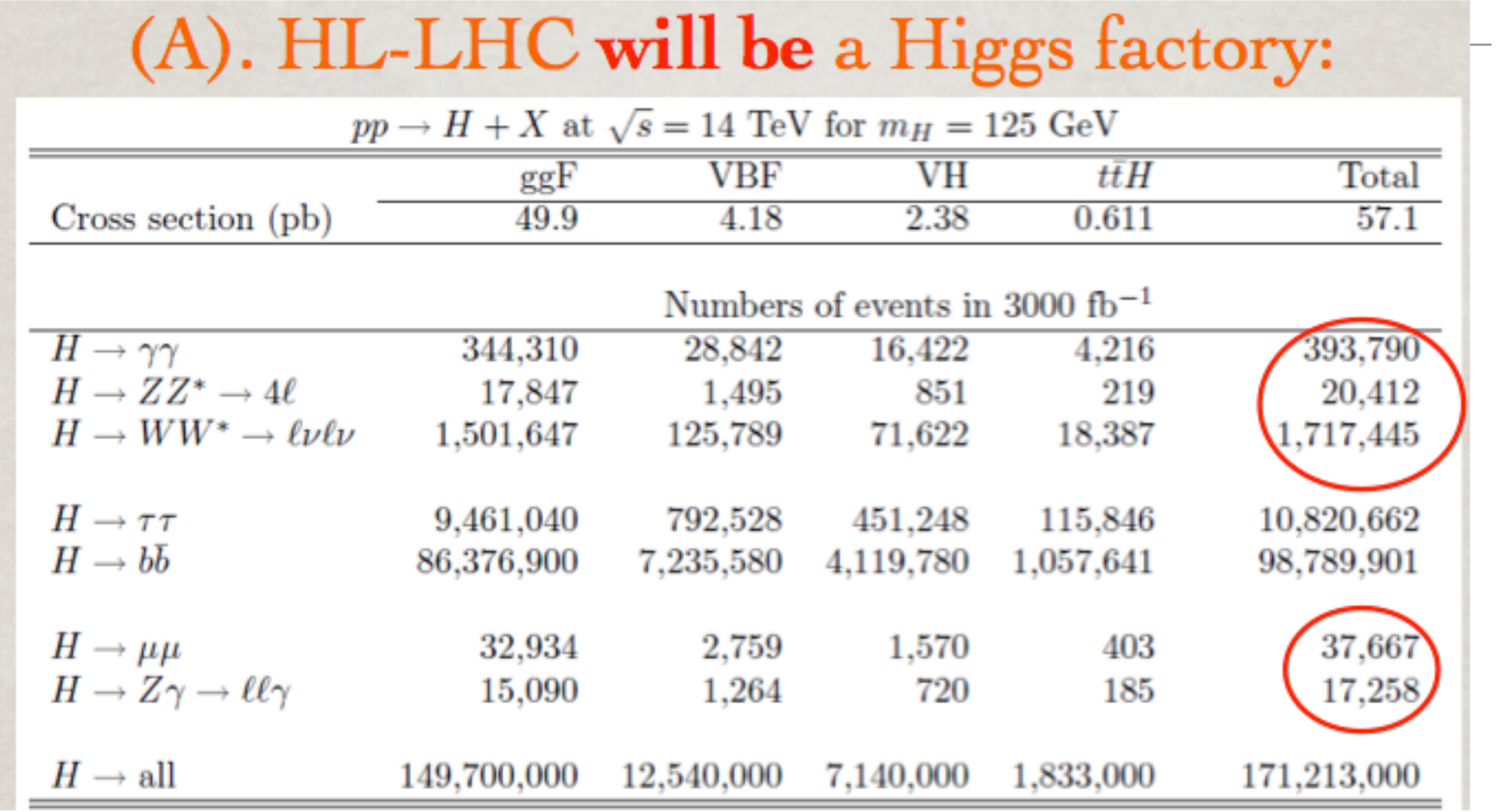
Higgs rare decays, top rare decays



Higgs Factory

~2-4 % precision expected

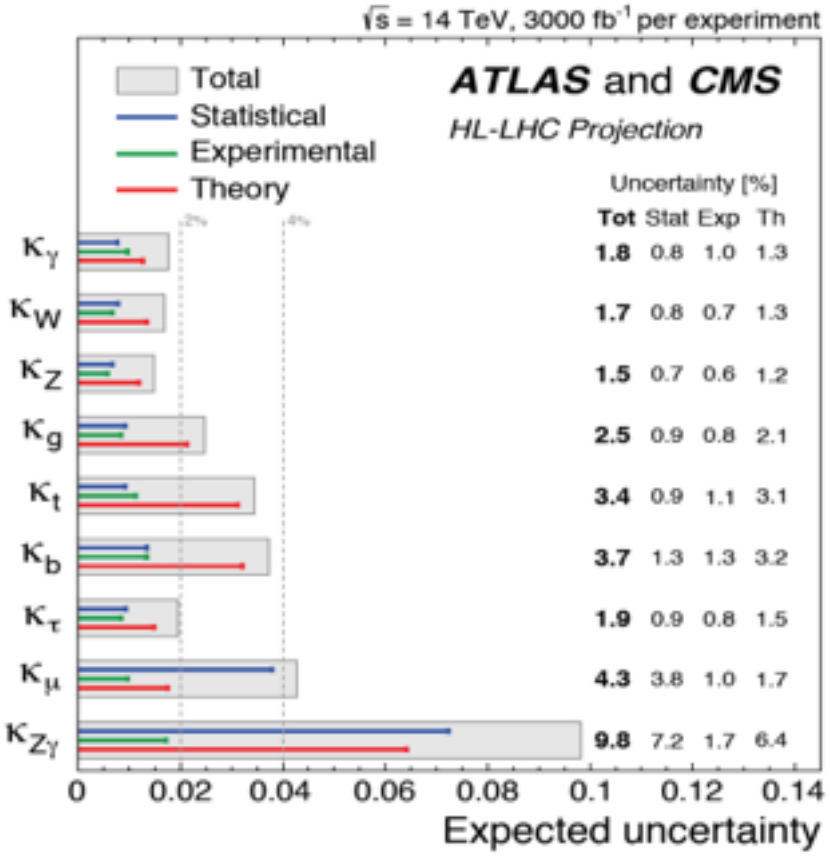
~2.5 % BR(invisible) (13% at 139fb-1)



(A). HL-LHC **will be** a Higgs factory:

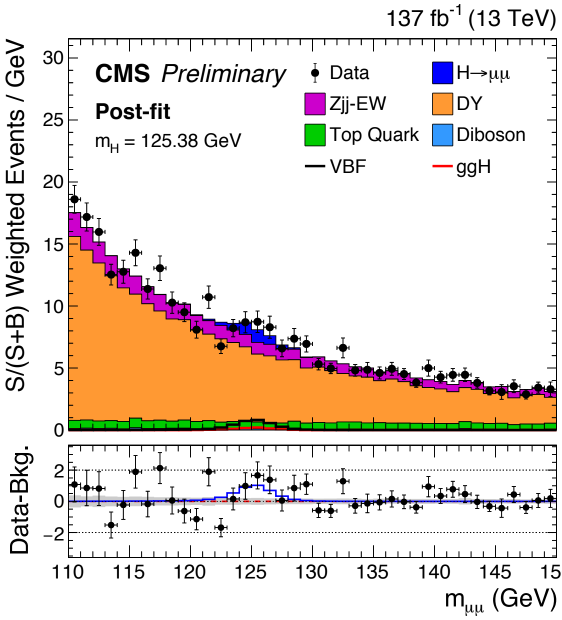
$pp \to H + X$ at $\sqrt{s} = 14$ TeV for $m_H = 125$ GeV

	ggF	VBF	VH	$t\bar{t}H$	Total
Cross section (pb)	49.9	4.18	2.38	0.611	57.1
	Numbers of events in 3000 fb^{-1}				
$H \to \gamma\gamma$	344,310	28,842	16,422	4,216	393,790
$H \to ZZ^* \to 4\ell$	17,847	1,495	851	219	20,412
$H \to WW^* \to \ell\nu\ell\nu$	1,501,647	125,789	71,622	18,387	1,717,445
$H \to \tau\tau$	9,461,040	792,528	451,248	115,846	10,820,662
$H \to b\bar{b}$	86,376,900	7,235,580	4,119,780	1,057,641	98,789,901
$H \to \mu\mu$	32,934	2,759	1,570	403	37,667
$H \to Z\gamma \to \ell\ell\gamma$	15,090	1,264	720	185	17,258
$H \to$ all	149,700,000	12,540,000	7,140,000	1,833,000	171,213,000

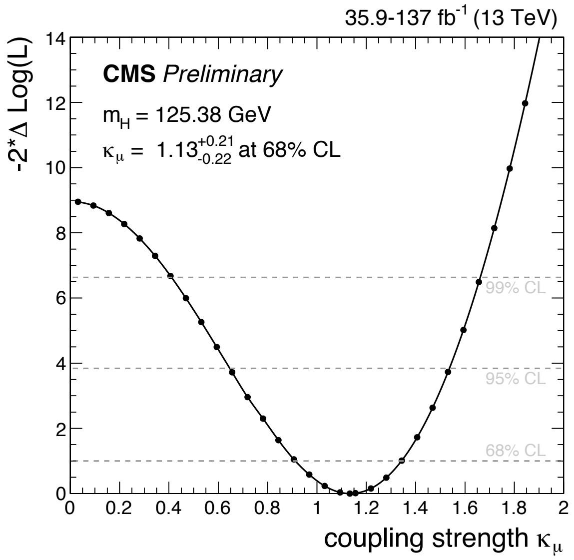


Projected uncertainties on κ_i, combining ATLAS and CMS: total (grey box), statistical (blue), experimental (green) and theory (red).

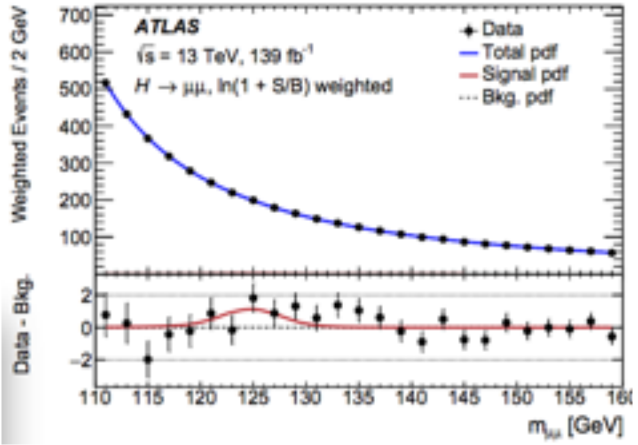
CMS-PAS-HIG-19-006

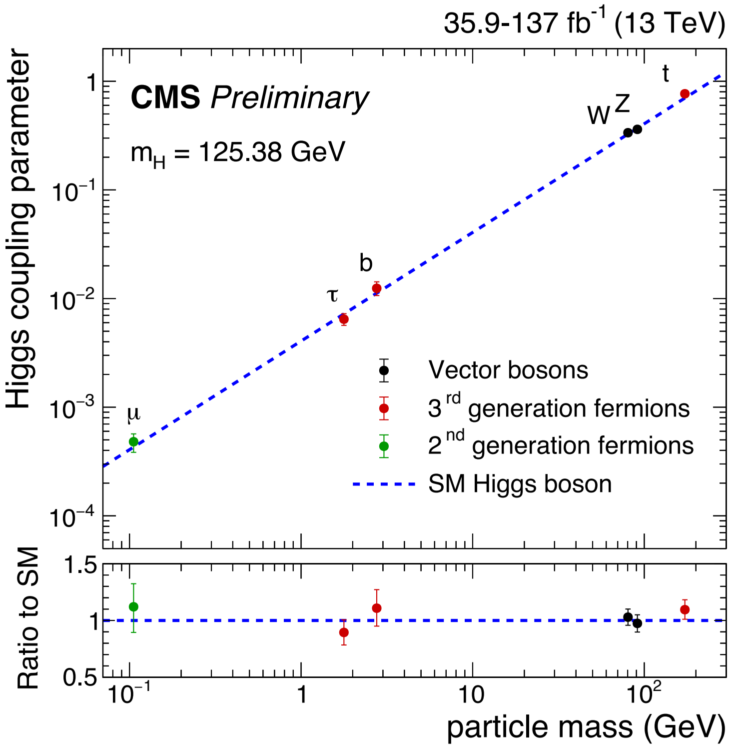


muon yukawa evidence has been achieved !



arXiv:2007.07830





top partner indirect searches

ggH coupling: most important for Higgs production, by top-loop
higgs cross section ⇒ top yukawa indirect measurement

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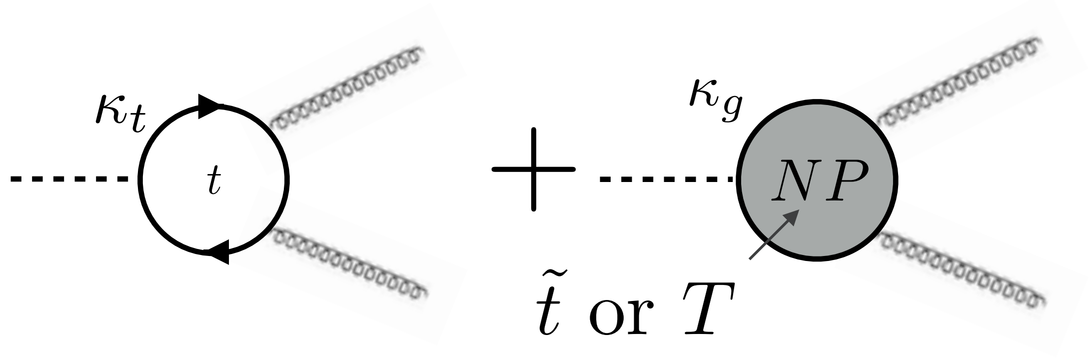
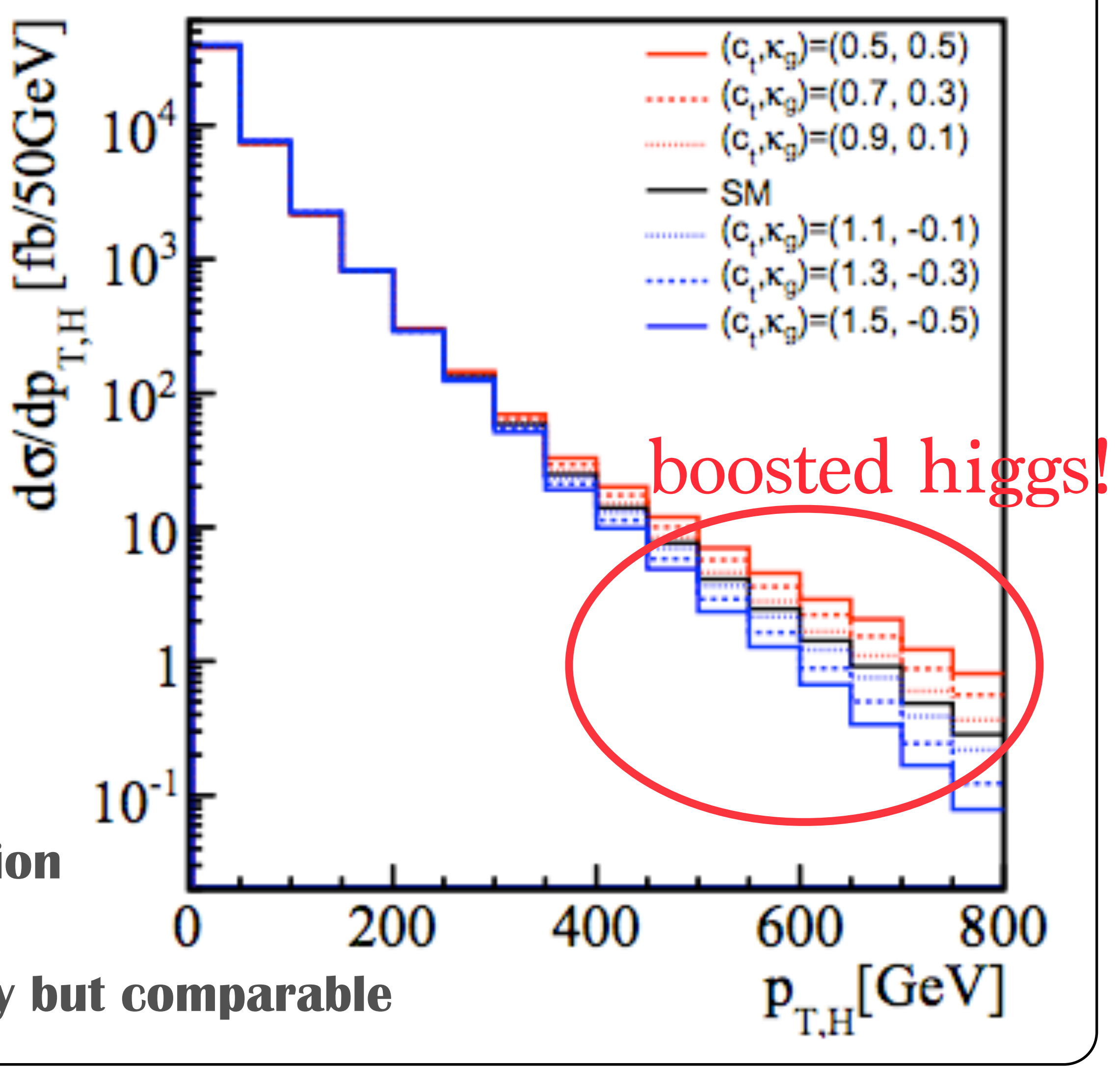
[M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant]

However, if top-partner exists, we cannot distinguish top-partner loop effects from top-loop effects

to solve the degeneracy,
top yukawa direct measurements required (ttH measurements)





different momentum dependence
⇒ we can solve the degeneracy using Higgs pT distribution
we estimated the sensitivity at LHC
complimentary to ttH measurement, weaker sensitivity but comparable

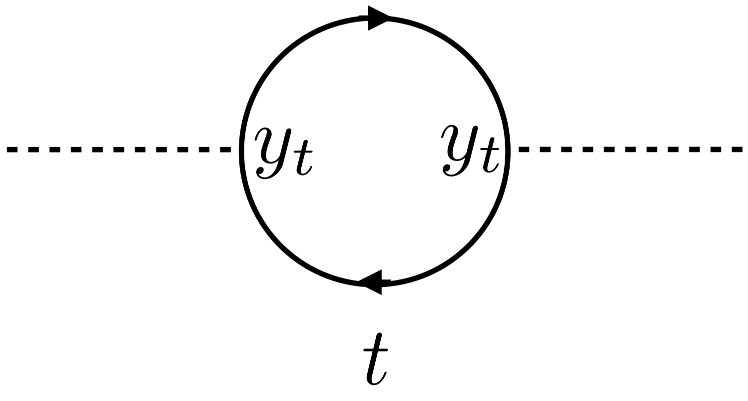
Higgs： $50\ \text{pb} \times 3 \cdot 10^3 \text{fb}^{-1} \sim 10^8$

one of good examples of precision physics, which the overwhelming high statistics at LHC makes possible

Fine tuning problem

Higgs: only scalar elementary particle in the SM

$\delta m_h^2 \sim$



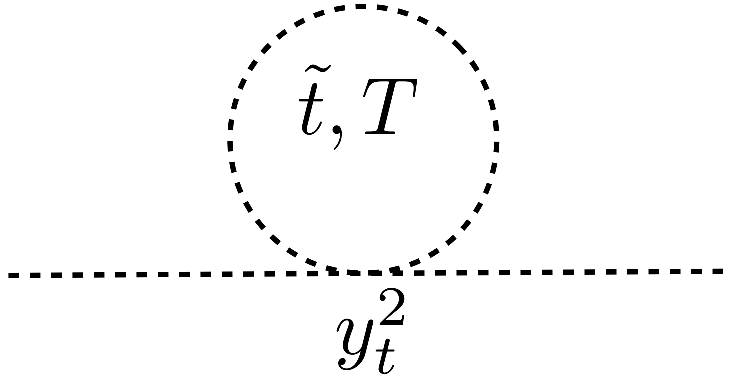
$$\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\mathrm{SM}}^2 \sim 10^{38}\mathrm{GeV}^2(\Lambda_{\mathrm{SM}} = m_{\mathrm{Pl}})$$
$$\sim 10^{6}\mathrm{GeV}^2(\Lambda_{\mathrm{SM}} = 1\mathrm{TeV})$$

$$m_{h,\mathrm{phys}}^2 = m_{h,\mathrm{tree}}^2 + \delta m_h^2 \qquad \sim 125^2\mathrm{GeV}^2 \sim 10^4\mathrm{GeV}^2$$

Higgs mass receives quantum corrections of the order of highest mass scale

⇨ New physics should appear around TeV scale to avoid fine tuning

$\delta m_h^2 \sim$

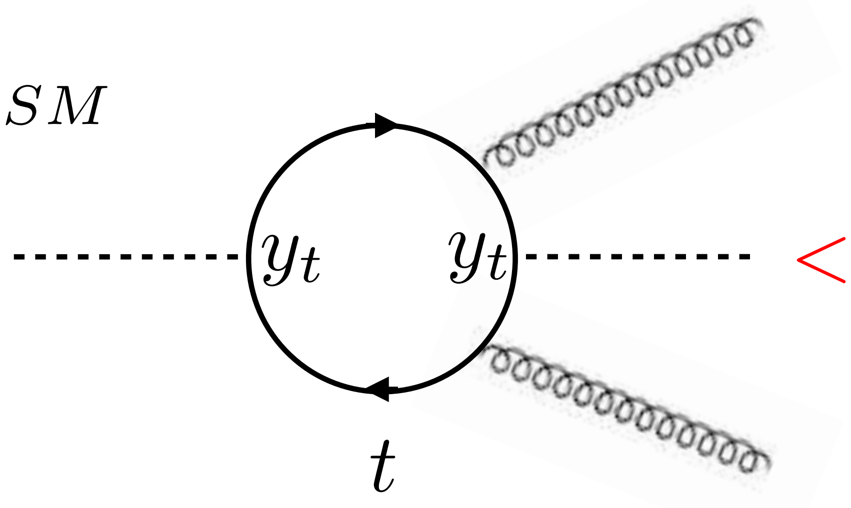


$$\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$$

new particle, same coupling by symmetry SUSY: popular candidate
or Higgs as pNGB: Composite Higgs, strong int. at f, Top partner

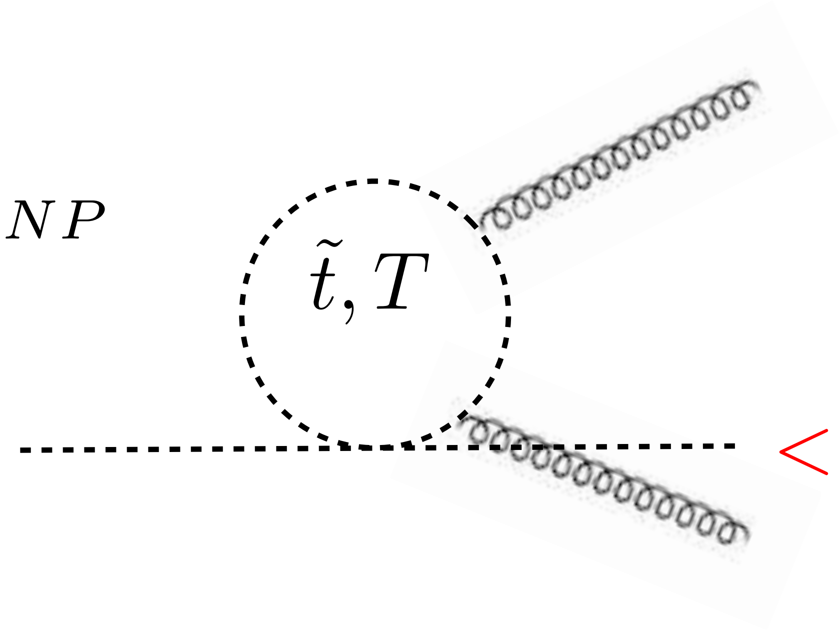
Top partners affect higgs couplings?

$\mathcal{M}(h \to gg)_{SM}$



$< h >= v$

$\mathcal{M}(h \to gg)_{NP}$



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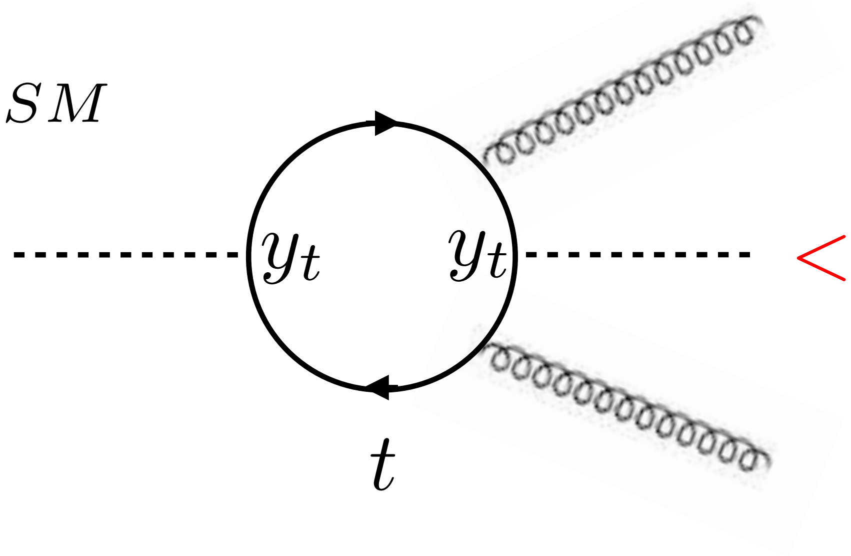


$< h >= v$

$$\Gamma(h \to gg) = \frac{\alpha_s m_h^3}{128\pi^2} |\mathcal{A}_{gg}|^2$$

$$\mathcal{A}_{gg} = \frac{1}{v} \sum_q A_{1/2}(\tau_q)$$

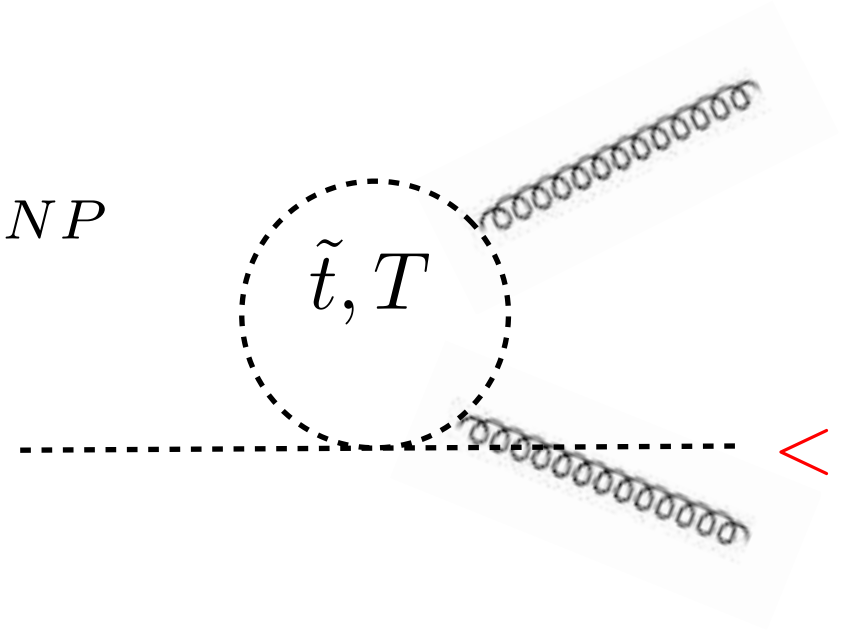
$$\tau = 4m_q^2/m_H^2$$

$$A_{1/2}(\tau) = 2\tau[1 + (1-\tau) f(\tau)] \quad \to \frac{4}{3}$$

$$f(\tau) = \arcsin^2 \sqrt{1/\tau} \quad (\tau \geq 1)$$

$$f(\tau) = -\frac{1}{4} \log \left[\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi \right]^2 \quad (\tau < 1)$$

$\mathcal{M}(h \to gg)_{NP}$



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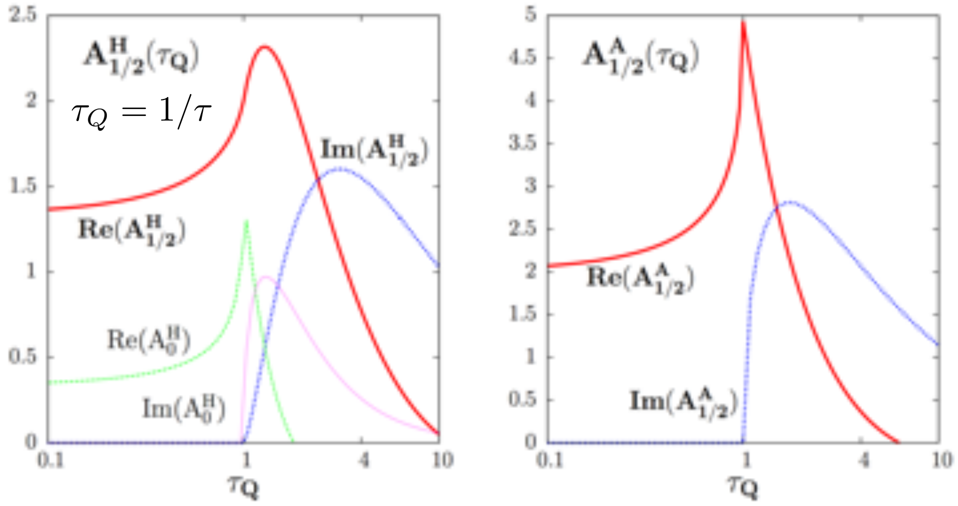

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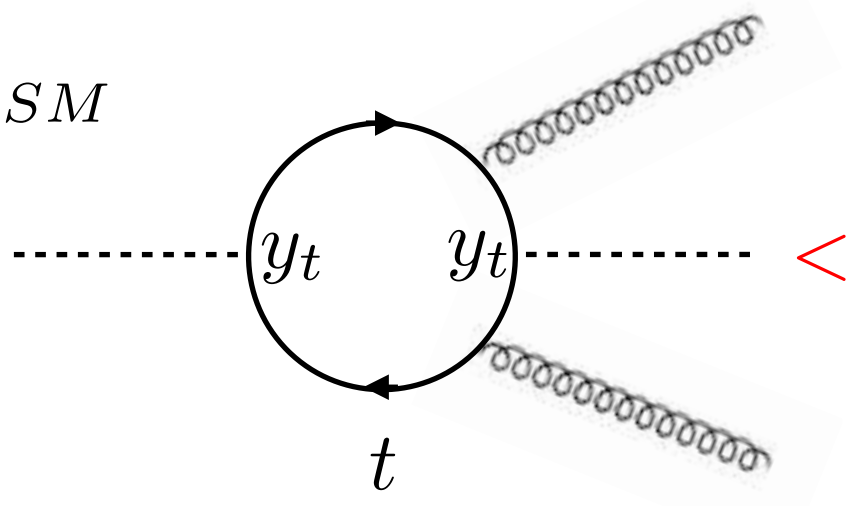

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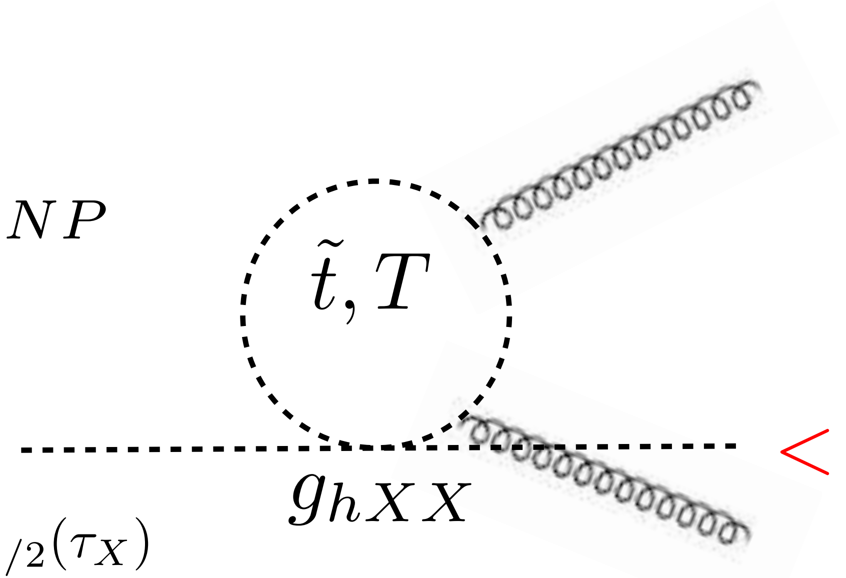
$\mathcal{M}(h \to gg)_{NP}$



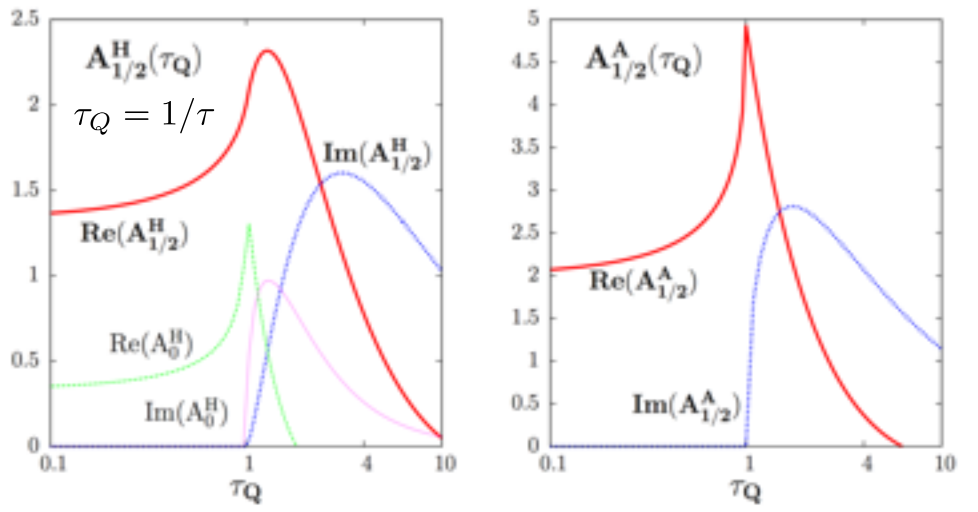
$< h >= v$

$$\Delta\mathcal{A}_{gg} = \frac{g_{hXX}}{m_X}A_{1/2}(\tau_X)$$

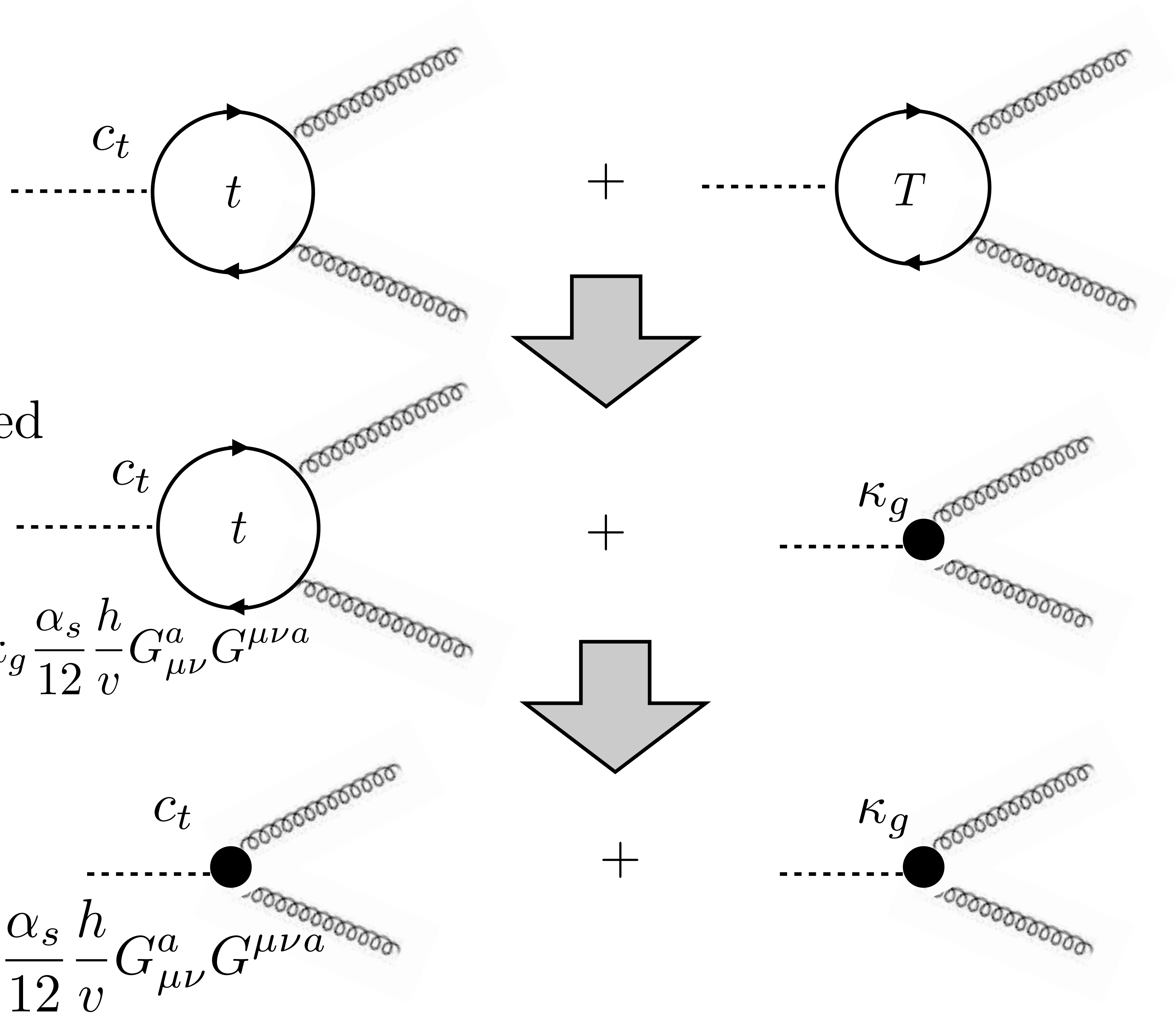
$$\Delta\mathcal{A}_{gg} = \frac{g_{hXX}}{2m_X^2}A_{0,1}(\tau_X)$$

$$A_1(\tau) = -[2 + 3\tau + 3\tau(2-\tau)f(\tau)] \to -7$$

$$A_0(\tau) = -\tau[1 - \tau f(\tau)] \quad \to \frac{1}{3}$$



Effective Lagrangian for higgs physics



UV theory

top partner decoupled

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - c_t \frac{m_t}{v} \bar{t}th + \kappa_g \frac{\alpha_s}{12} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu a}$$

$$\kappa_g^{\text{eff}} = c_t + \kappa_g$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + (c_t + \kappa_g) \frac{\alpha_s}{12} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu a}$$

what we measure in inclusive $H \to gg$

Off-shell gluon breaks top loops

arXiv:1405.4295 M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant

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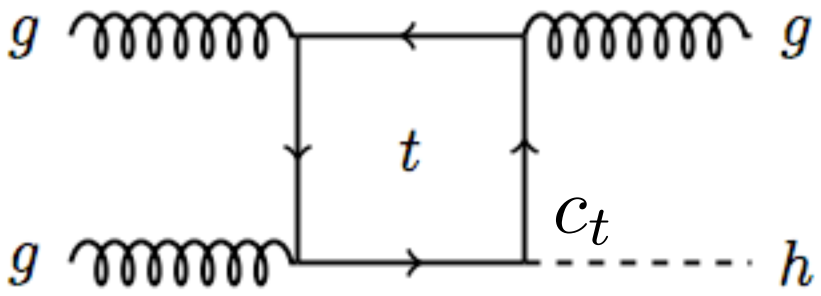
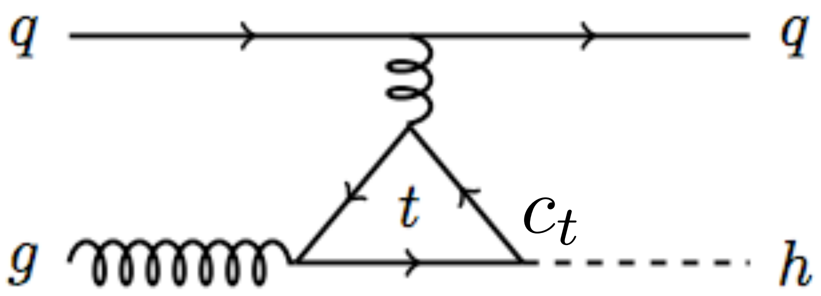
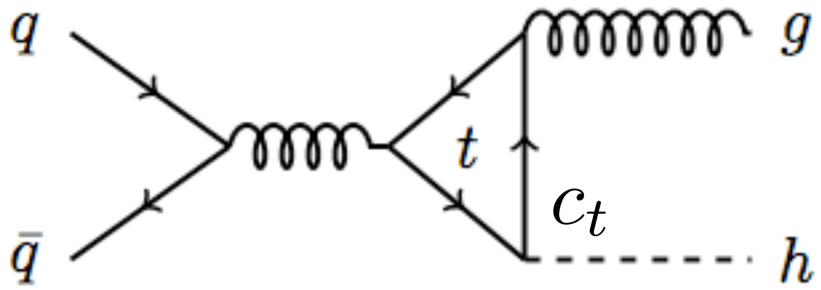
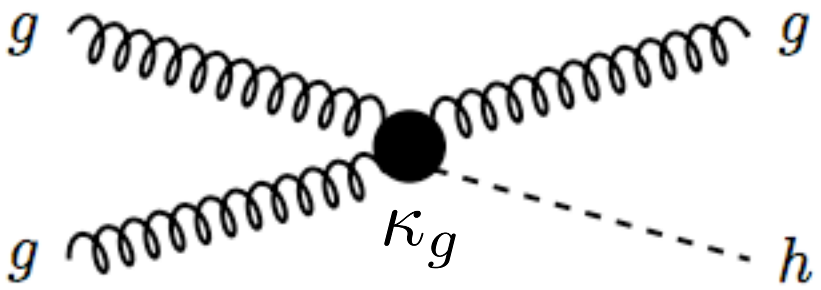
$$\mathcal{M}(c_t, \kappa_g) = c_t \mathcal{M}(m_t) + \kappa_g \mathcal{M}(\infty)$$









on-shell gluon amplitude has only scale m_H
(only τ_X is sensitive to the mass but very weak)

gluon off-shellness can probe the mass scale in the loop.

$H + \text{j}:\quad p_{T,H}$ distribution is the observable

Off-shell gluon breaks top loops

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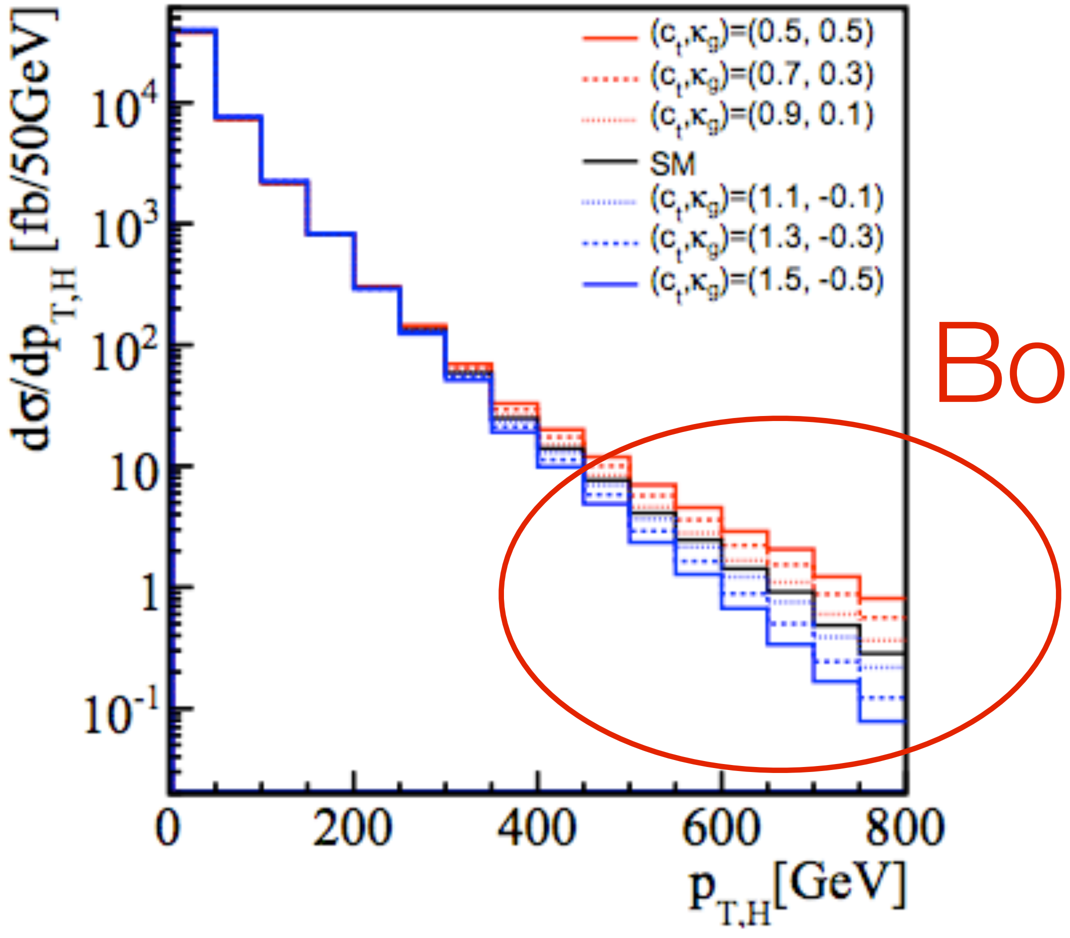
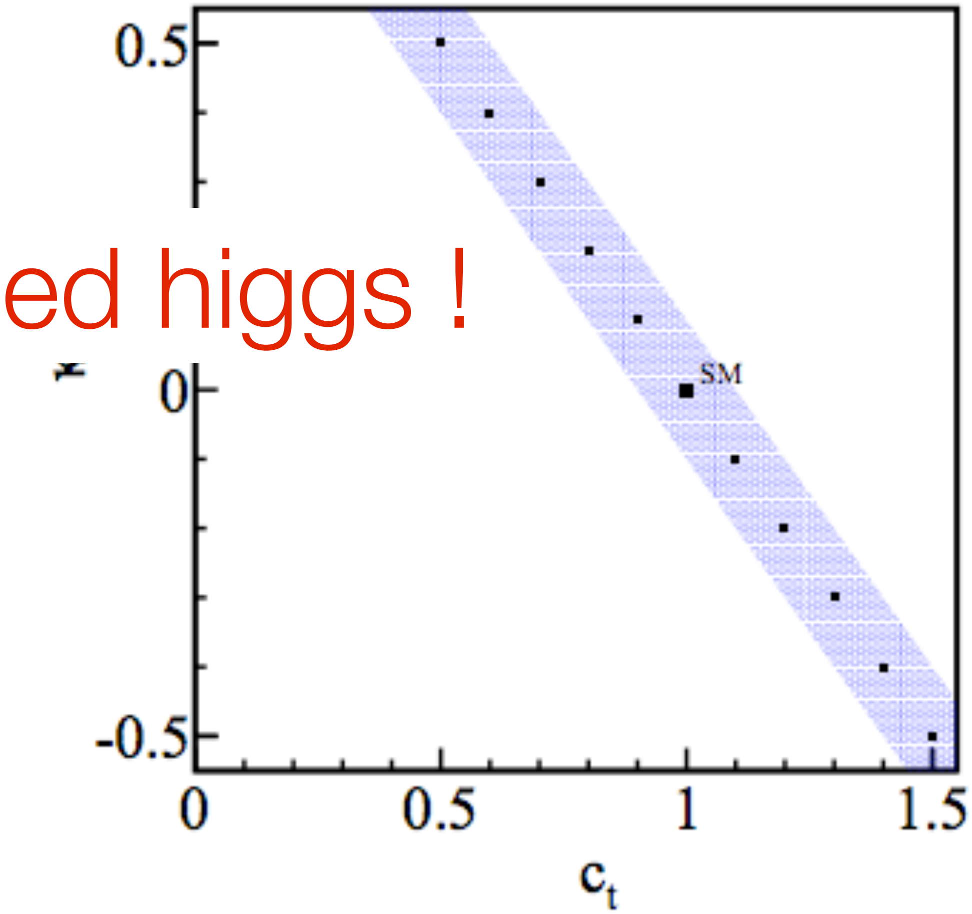
$$\mathcal{M}(c_t, \kappa_g) = c_t \mathcal{M}(m_t) + \kappa_g \mathcal{M}(\infty)$$



Boosted higgs !



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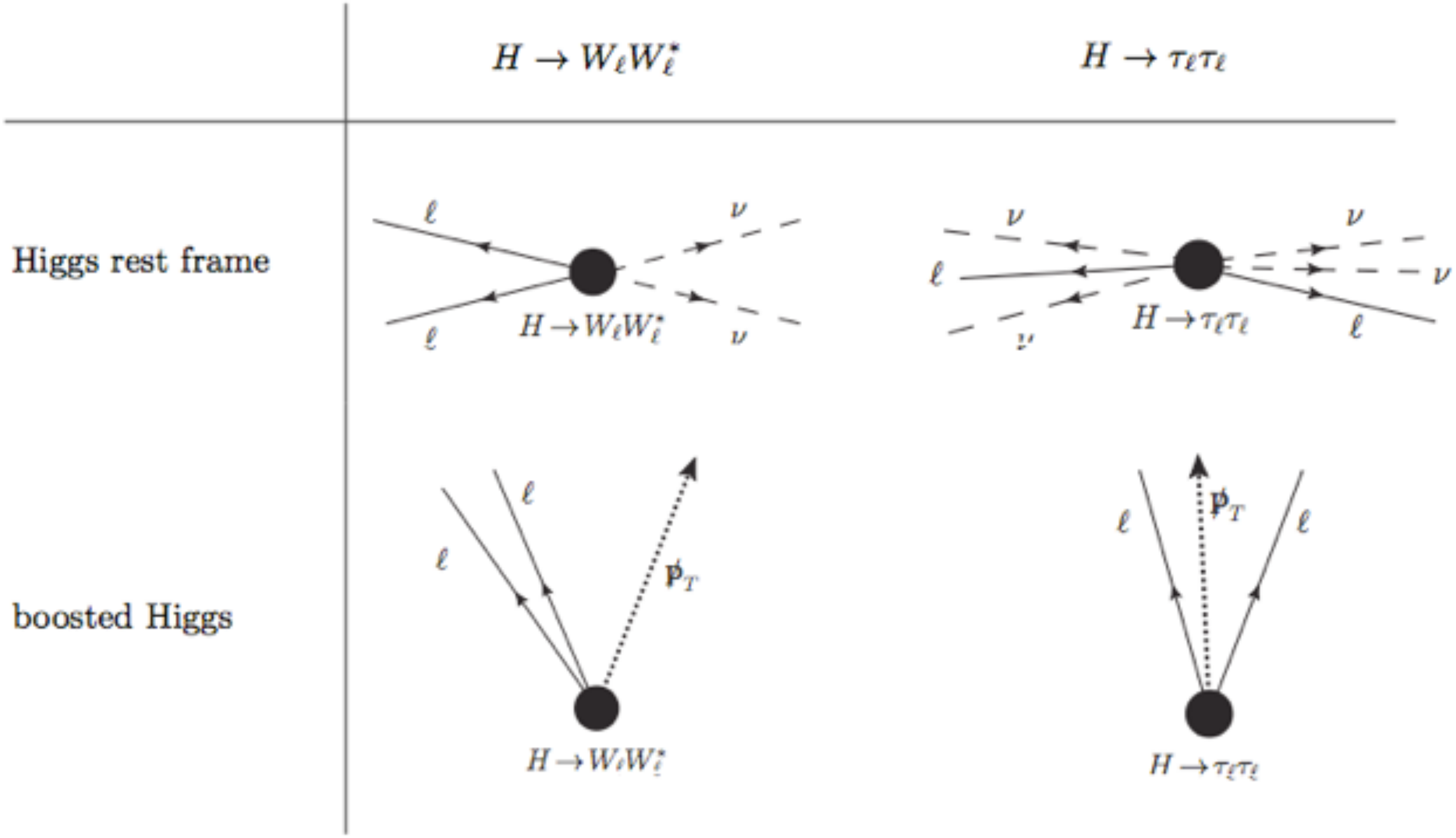
gluon off-shellness can probe the mass scale in the loop.

H + j : $p_{T,H}$ distribution is the observable

How higgs boost helps

arXiv:1405.4295 M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant

For 125 GeV higgs, $BR(b\bar{b}) \sim 60\%$, $BR(W^+W^-) \sim 20\%$, $BR(\tau^+\tau^-) \sim 6\%$,



$H \to \tau\tau$ BR is large and can reconstruct using $\not{E}_T$

Collinear approx. $\mathbf{p}_\nu = \alpha \mathbf{p}_\ell \;\; (\alpha > 0)$ thanks to $m_\tau \ll m_H$

We consider di-lepton channel $(ee, e\mu, \mu\mu) + \not{E}_T$ from $\tau\tau$

How far can we measure under BG presence?

$H \to \tau\tau$ ($p_{T,H} > 0$ GeV)	3.15 pb

BG: WW+jets, Z+jets, $t\bar{t}$+jets,

WW+jets: 2 jets merged, $p_{T,j_1} > 150$ GeV, $W \to e, \mu, \tau$	0.6 pb
Z+jets: 2 jets merged, $p_{T,j_1} > 150$ GeV, only $Z \to \tau\tau$	10 pb
$t\bar{t}$+jets: 0 + 1 jet merged	918 pb

Basic selection cut:

$$n_\ell = 2, \text{ opposite-sign, } m_{\ell\ell} > 20\text{GeV}, \; p_{T,H}^{\text{rec}} > 200 \text{ GeV}, \; n_j^{\text{fat}} = 1, \; n_b = 0$$

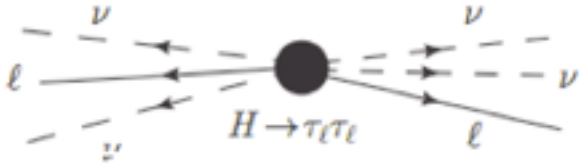
$$\mathbf{p}_{T,H}^{\text{rec}} = \mathbf{p}_{T,\ell_1} + \mathbf{p}_{T,\ell_2} + \not{\mathbf{p}}_T$$

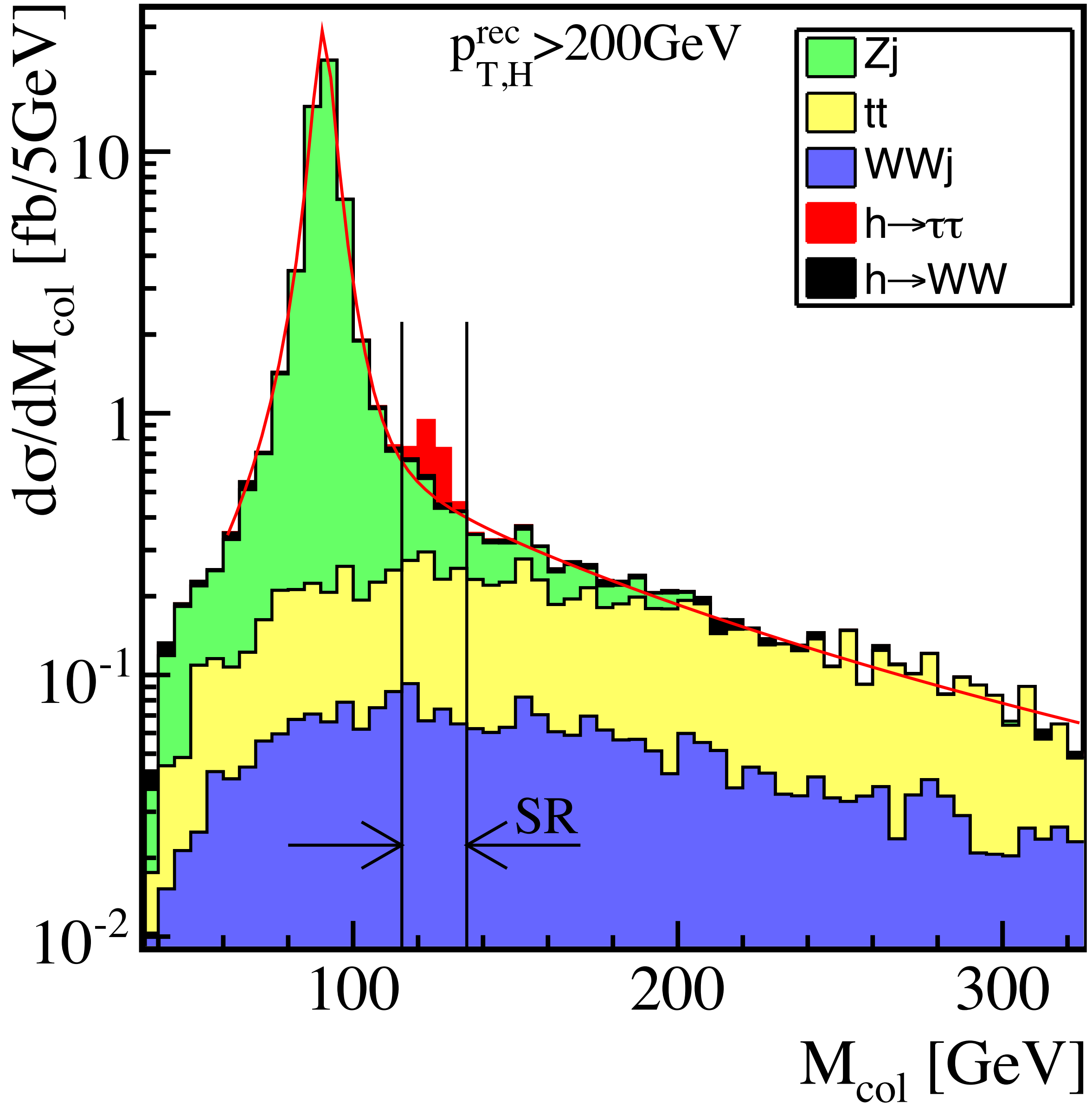
How boost helps, M_col distribution

Collinear approx.

$$\not{\mathbf{p}}_T = \mathbf{p}_{T,\nu_1} + \mathbf{p}_{T,\nu_2}$$

$$\mathbf{p}_{\nu_1} = \alpha_1 \mathbf{p}_{\ell_1}, \ \mathbf{p}_{\nu_2} = \alpha_2 \mathbf{p}_{\ell_2} \qquad (\alpha_1, \alpha_2 > 0)$$





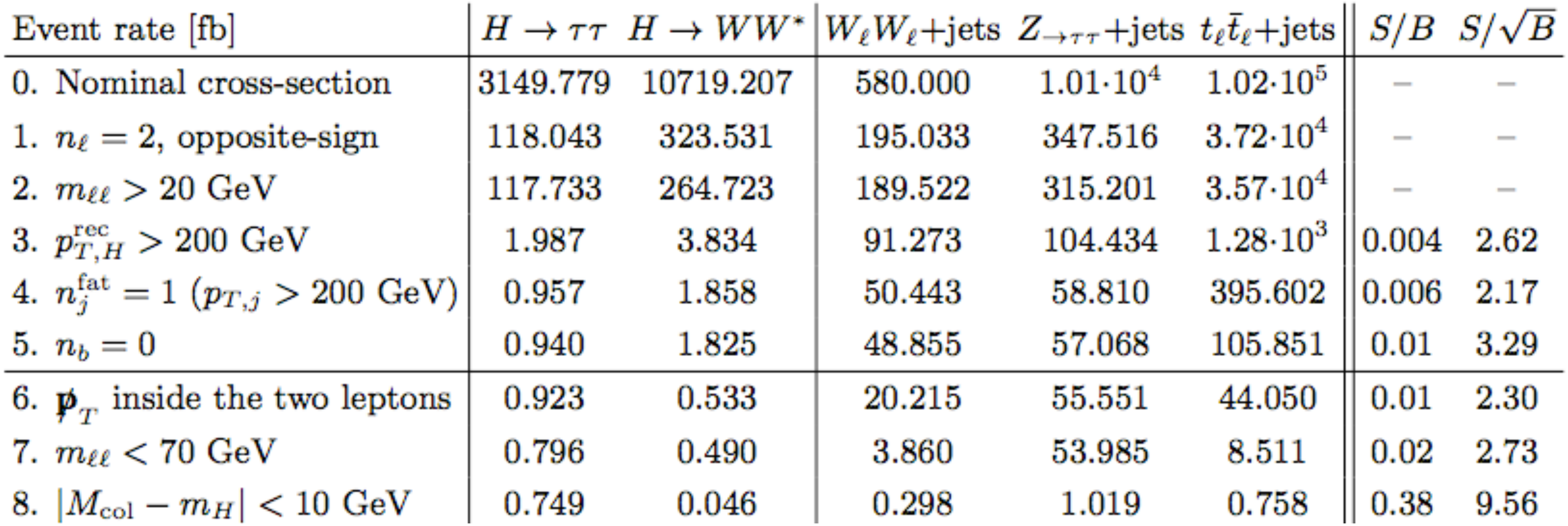
$$p_{\rm col} = p_{\nu_1} + p_{\nu_2} + p_{\ell_1} + p_{\ell_2}$$

$$M^2_{\rm col} = p^2_{\rm col}$$

thanks to $m_\tau \ll m_H$

We see also $m_Z \to \tau\tau$ peak

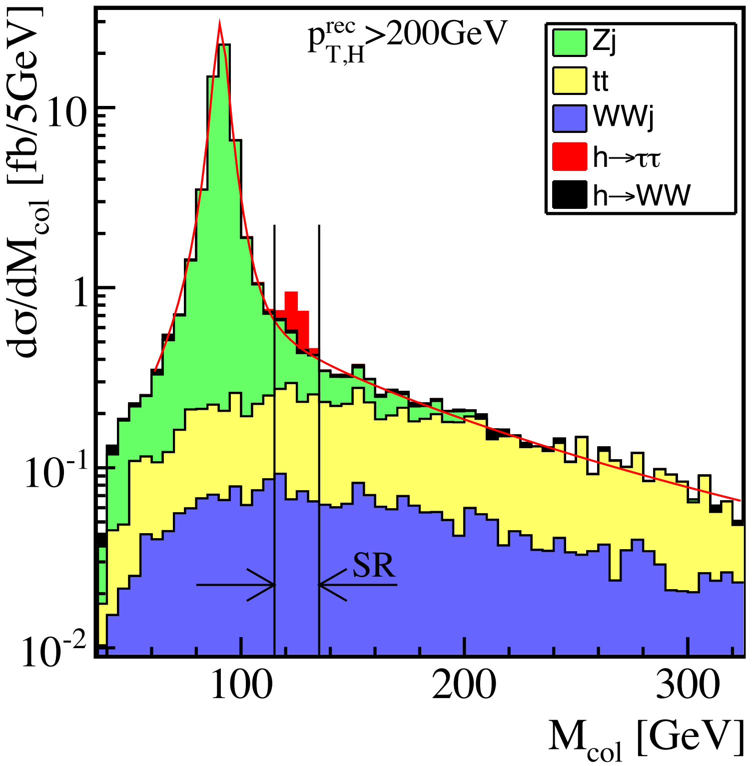
H to tau tau results



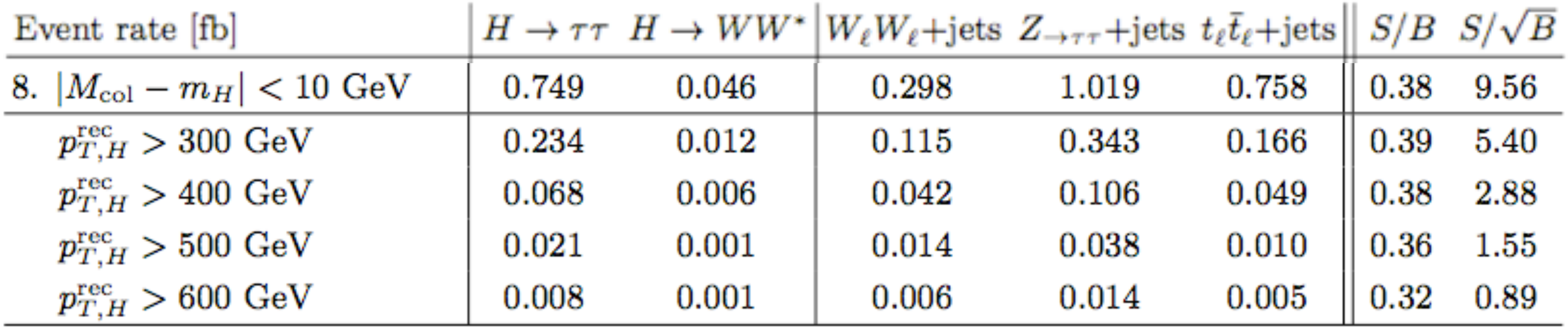
Event rate [fb]	$H \to \tau\tau$	$H \to WW^*$	$W_\ell W_\ell$+jets	$Z_{\to\tau\tau}$+jets	$t_\ell \bar{t}_\ell$+jets	S/B	$S/\sqrt{B}$
0. Nominal cross-section	3149.779	10719.207	580.000	$1.01 \cdot 10^4$	$1.02 \cdot 10^5$	–	–
1. $n_\ell = 2$, opposite-sign	118.043	323.531	195.033	347.516	$3.72 \cdot 10^4$	–	–
2. $m_{\ell\ell} > 20$ GeV	117.733	264.723	189.522	315.201	$3.57 \cdot 10^4$	–	–
3. $p_{T,H}^{\text{rec}} > 200$ GeV	1.987	3.834	91.273	104.434	$1.28 \cdot 10^3$	0.004	2.62
4. $n_j^{\text{fat}} = 1$ ($p_{T,j} > 200$ GeV)	0.957	1.858	50.443	58.810	395.602	0.006	2.17
5. $n_b = 0$	0.940	1.825	48.855	57.068	105.851	0.01	3.29
6. $\not{p}_T$ inside the two leptons	0.923	0.533	20.215	55.551	44.050	0.01	2.30
7. $m_{\ell\ell} < 70$ GeV	0.796	0.490	3.860	53.985	8.511	0.02	2.73
8. $\lvert M_{\text{col}} - m_H \rvert < 10$ GeV	0.749	0.046	0.298	1.019	0.758	0.38	9.56

$$S/B \sim 0.4,\ S/\sqrt{B} \sim 10 \text{ for } 300\ \text{fb}^{-1}$$

$H \to \tau\tau$ is visible



Higgs PT distribution



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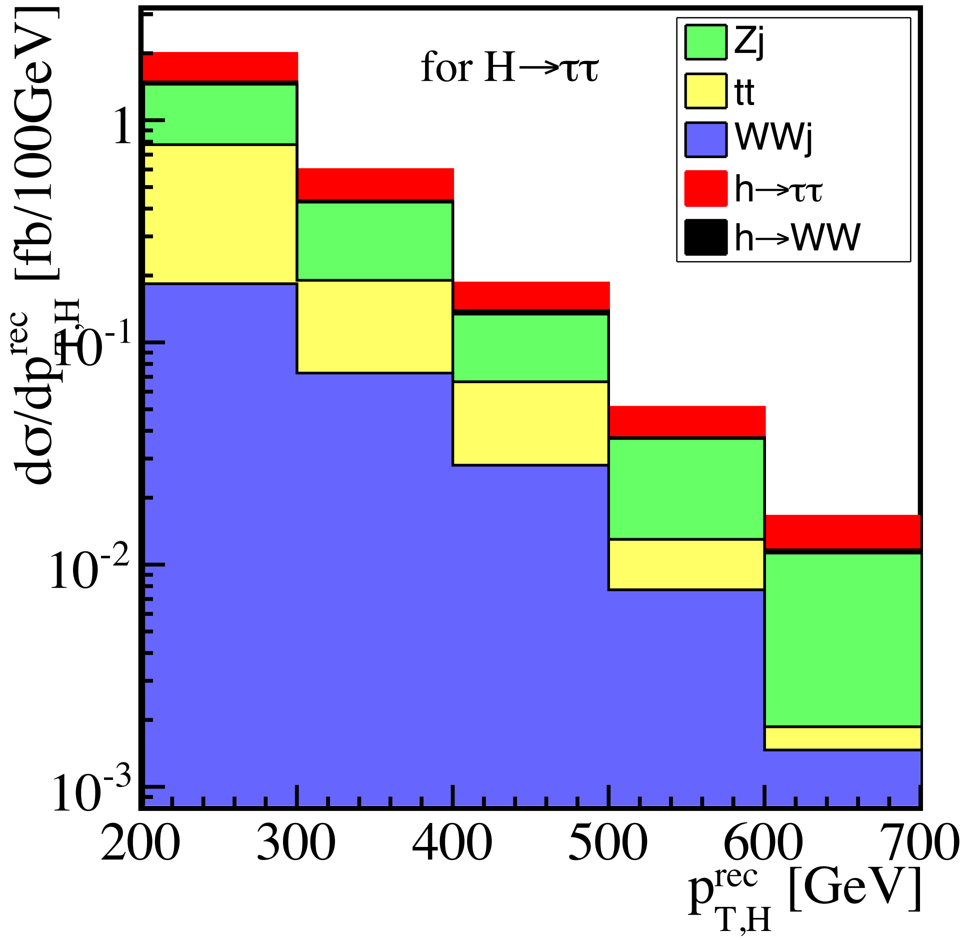
8. $\lvert M_{\mathrm{col}} - m_H \rvert < 10$ GeV	0.749	0.046	0.298	1.019	0.758	0.38	9.56
$p_{T,H}^{\mathrm{rec}} > 300$ GeV	0.234	0.012	0.115	0.343	0.166	0.39	5.40
$p_{T,H}^{\mathrm{rec}} > 400$ GeV	0.068	0.006	0.042	0.106	0.049	0.38	2.88
$p_{T,H}^{\mathrm{rec}} > 500$ GeV	0.021	0.001	0.014	0.038	0.010	0.36	1.55
$p_{T,H}^{\mathrm{rec}} > 600$ GeV	0.008	0.001	0.006	0.014	0.005	0.32	0.89

H momentum is reconstructed, we can observe $p_{T,H}$ dependence



error	$300fb^{-1}$	$3ab^{-1}$
$\sigma(p_{T,H} > 200\mathrm{GeV})$	12%	4%
$\sigma(p_{T,H} > 300\mathrm{GeV})$	22%	7%
$\sigma(p_{T,H} > 400\mathrm{GeV})$	41%	13%

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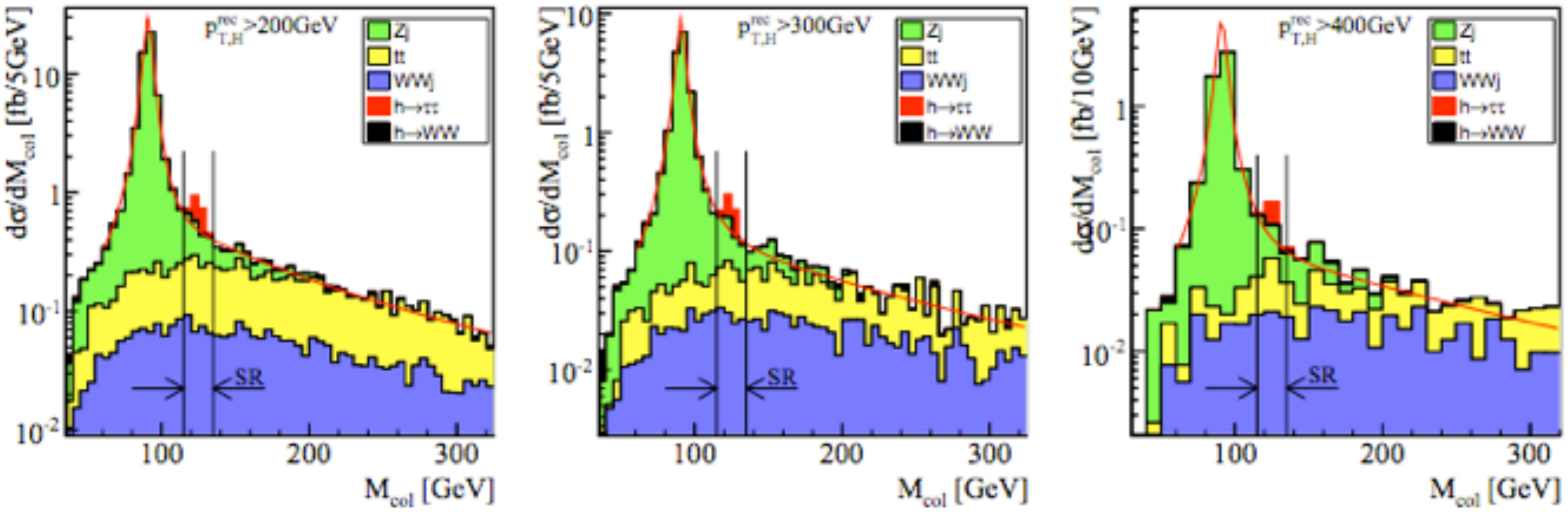
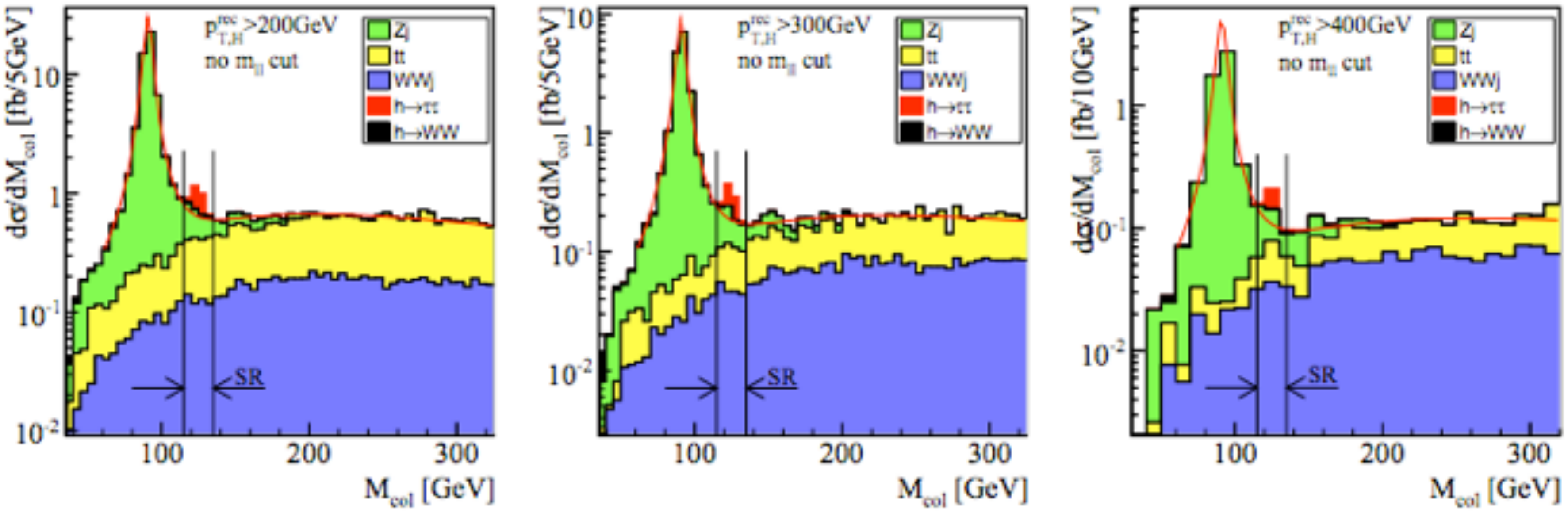


beautiful side band



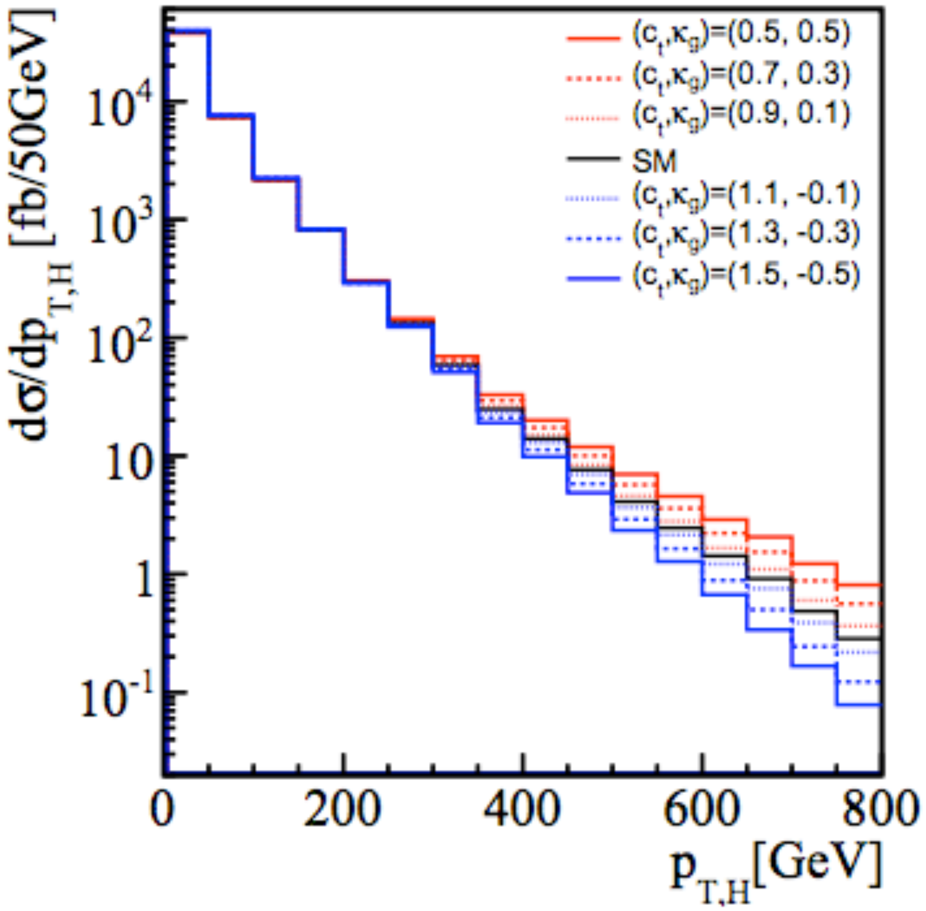
removing $m_{\ell\ell}$ cut

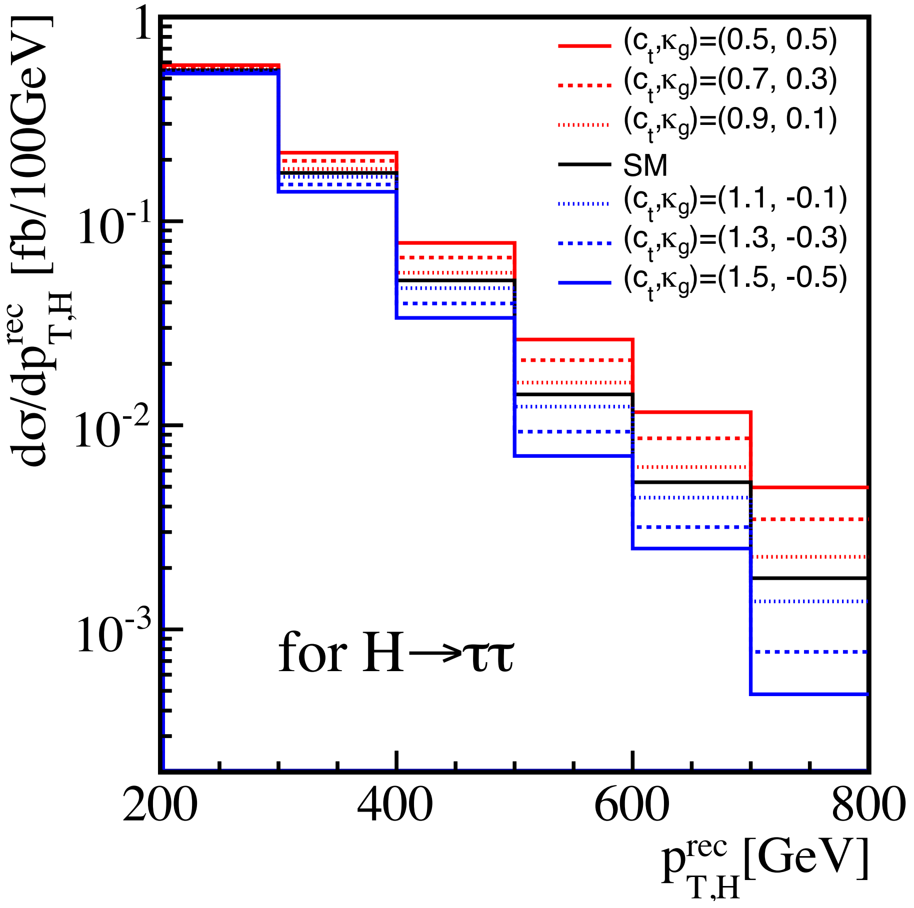
WW, $t\bar{t}$ contribution

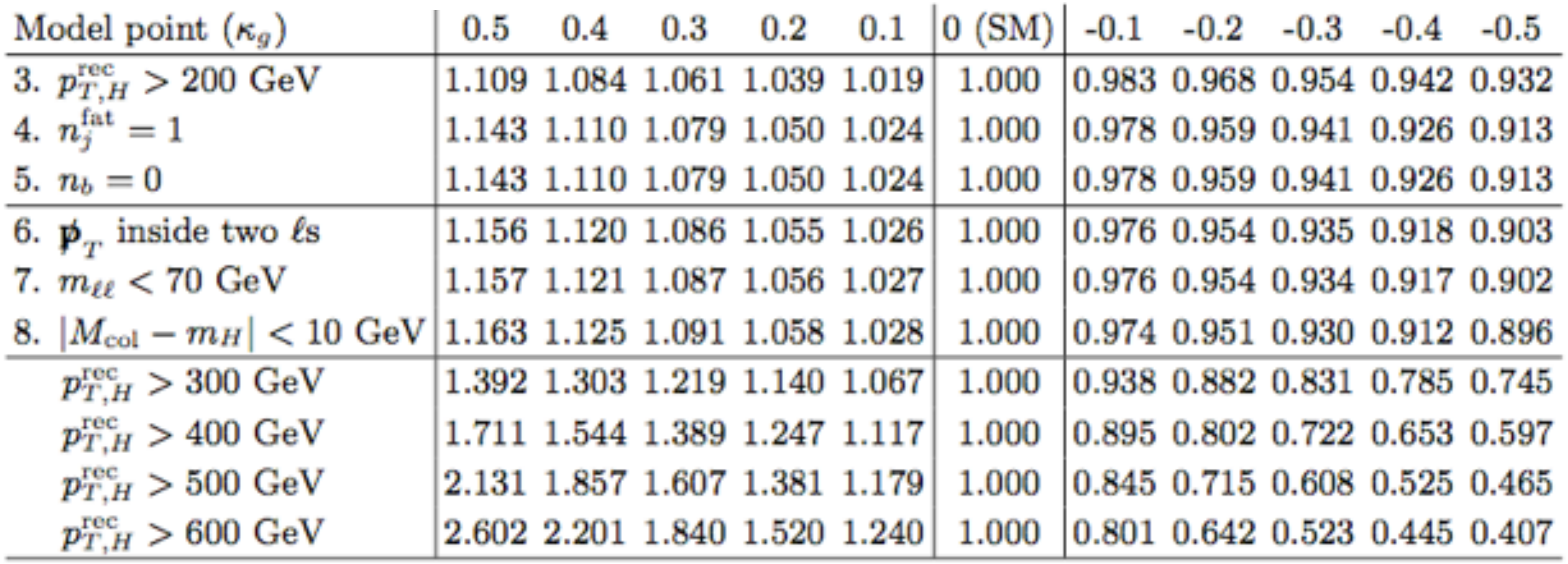
we can estimate

New physics sensitivity

With the same cut flow, enhanced in high $p_{T,H}$ since optimised for boosted H







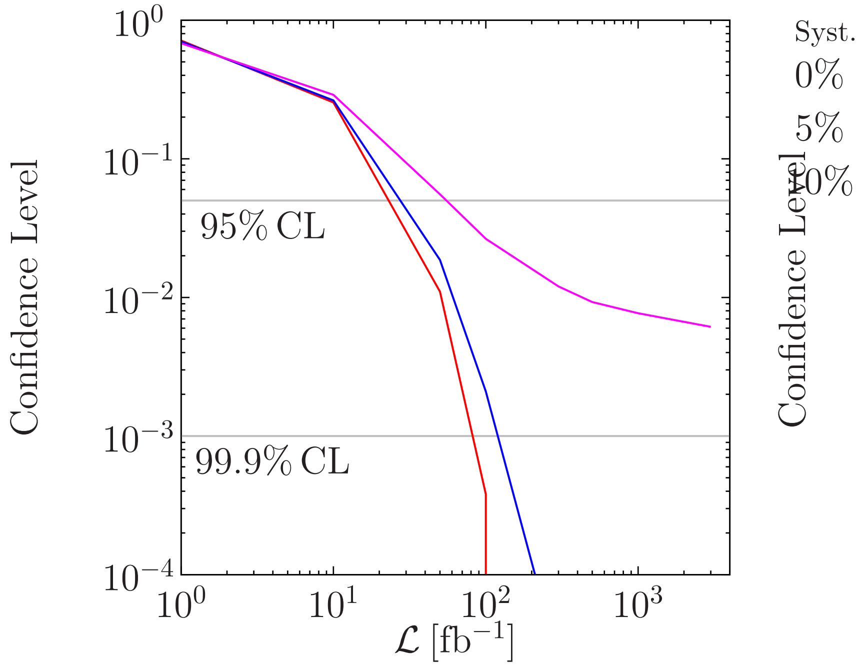
Model point (κ_g)	0.5	0.4	0.3	0.2	0.1	0 (SM)	-0.1	-0.2	-0.3	-0.4	-0.5
3. $p^{rec}_{T,H} > 200$ GeV	1.109	1.084	1.061	1.039	1.019	1.000	0.983	0.968	0.954	0.942	0.932
4. $n_j^{fat} = 1$	1.143	1.110	1.079	1.050	1.024	1.000	0.978	0.959	0.941	0.926	0.913
5. $n_b = 0$	1.143	1.110	1.079	1.050	1.024	1.000	0.978	0.959	0.941	0.926	0.913
6. $\not{p}_T$ inside two ℓs	1.156	1.120	1.086	1.055	1.026	1.000	0.976	0.954	0.935	0.918	0.903
7. $m_{\ell\ell} < 70$ GeV	1.157	1.121	1.087	1.056	1.027	1.000	0.976	0.954	0.934	0.917	0.902
8. $\lvert M_{col} - m_H\rvert < 10$ GeV	1.163	1.125	1.091	1.058	1.028	1.000	0.974	0.951	0.930	0.912	0.896
$p^{rec}_{T,H} > 300$ GeV	1.392	1.303	1.219	1.140	1.067	1.000	0.938	0.882	0.831	0.785	0.745
$p^{rec}_{T,H} > 400$ GeV	1.711	1.544	1.389	1.247	1.117	1.000	0.895	0.802	0.722	0.653	0.597
$p^{rec}_{T,H} > 500$ GeV	2.131	1.857	1.607	1.381	1.179	1.000	0.845	0.715	0.608	0.525	0.465
$p^{rec}_{T,H} > 600$ GeV	2.602	2.201	1.840	1.520	1.240	1.000	0.801	0.642	0.523	0.445	0.407

$\kappa_g > 0$ enhance in high $p_{T,H}$

$\kappa_g < 0$ deficit in high $p_{T,H}$

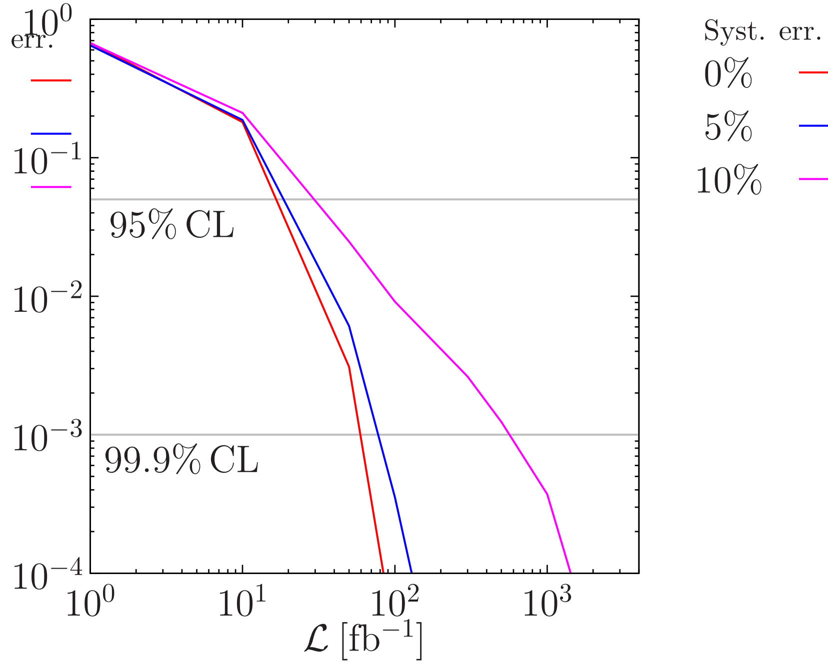
New physics sensitivity

SM vs. BG



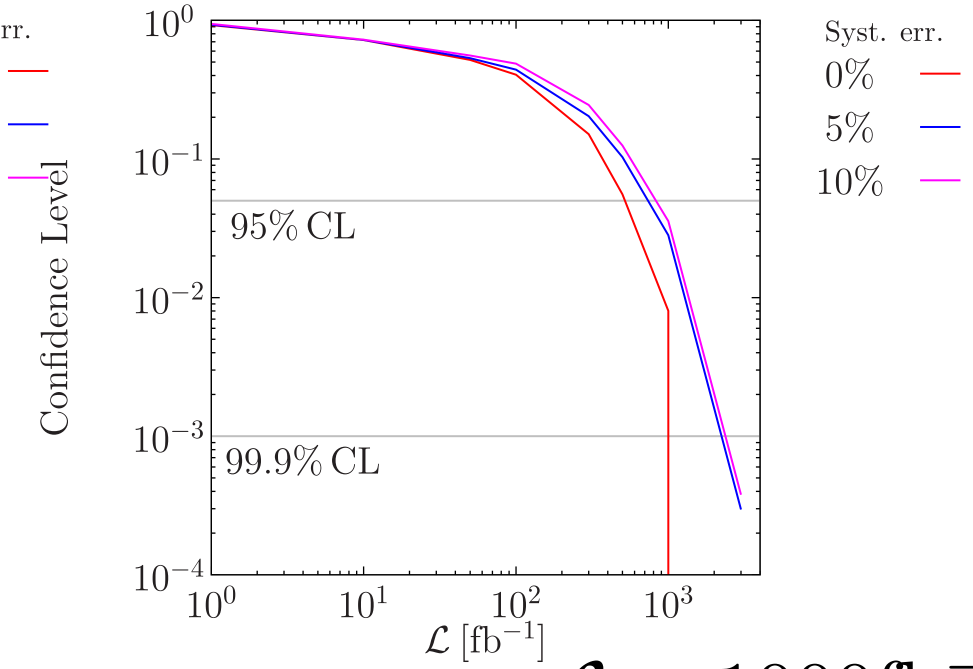
$\mathcal{L} = 20 \sim 60\text{fb}^{-1}$

$\kappa_g = 0.5 \text{ vs. BG}$



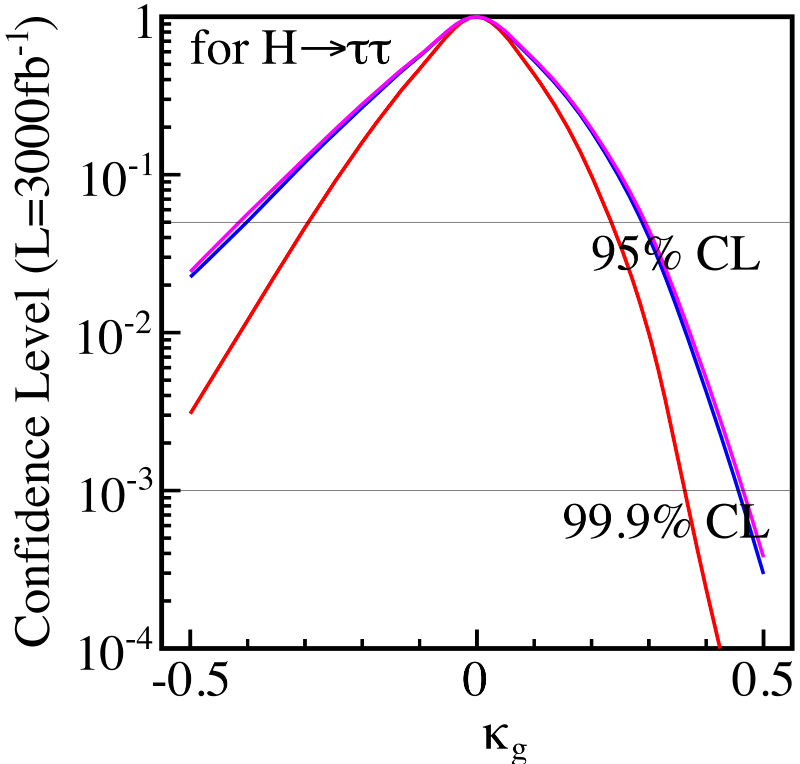
$\mathcal{L} = 15 \sim 30\text{fb}^{-1}$

$\kappa_g = 0.5 \text{ vs. SM}$



$\mathcal{L} = 1000\text{fb}^{-1}$

$\kappa_g < 0$: deficit is difficult to distinguish



with 3000 fb^{-1}, $\kappa_g < -0.29$ and $\kappa_g > 0.24$ excluded

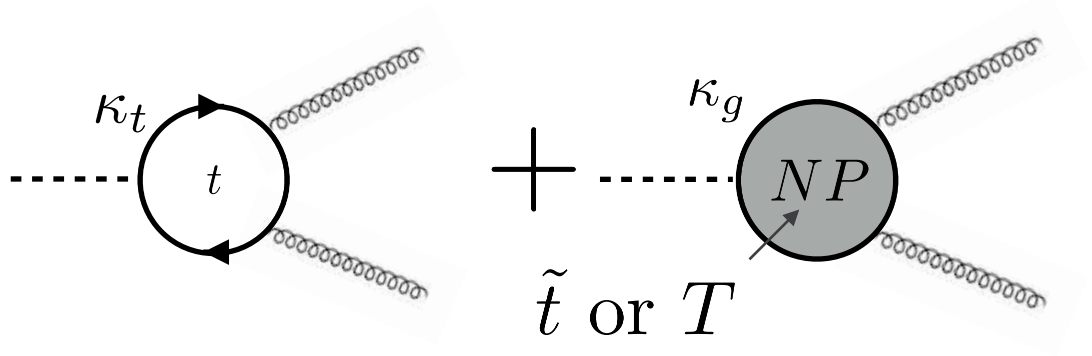
with 10% sys. err., $\kappa_g < -0.4$ and $\kappa_g > 0.3$ excluded

top partner indirect searches

ggH coupling: most important for Higgs production, by top-loop
higgs cross section ⇒ top yukawa indirect measurement

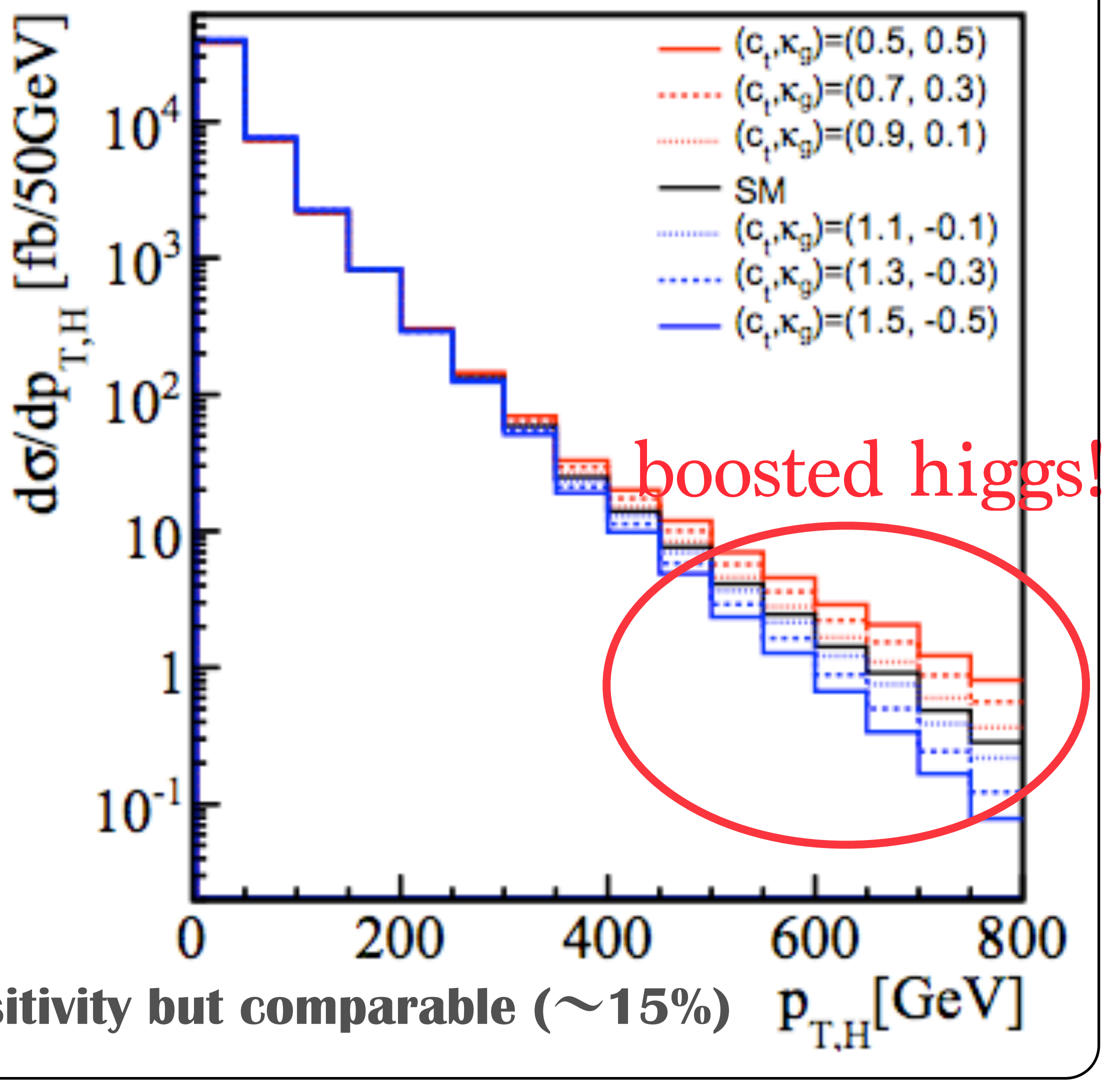
However, if top-partner exists, we cannot distinguish
top-partner loop effects from top-loop effects

to solve the degeneracy,
top yukawa direct measurements required (ttH measurements)



different momentum dependence
⇒ we can solve the degeneracy using Higgs pT distribution
we estimated the sensitivity at LHC
complimentary to ttH measurement (∼10%), weaker sensitivity but comparable (∼15%)

Eur.Phys.J. C74 (2014) no.10, 3120
[M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant]

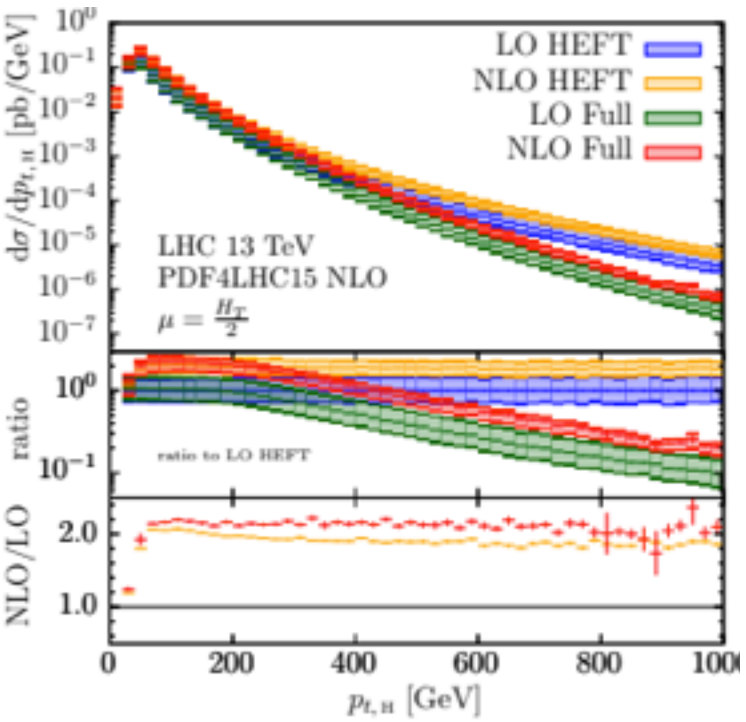


Higgs： $50\ \mathrm{pb} \times 3 \cdot 10^3 \mathrm{fb}^{-1} \sim 10^8$

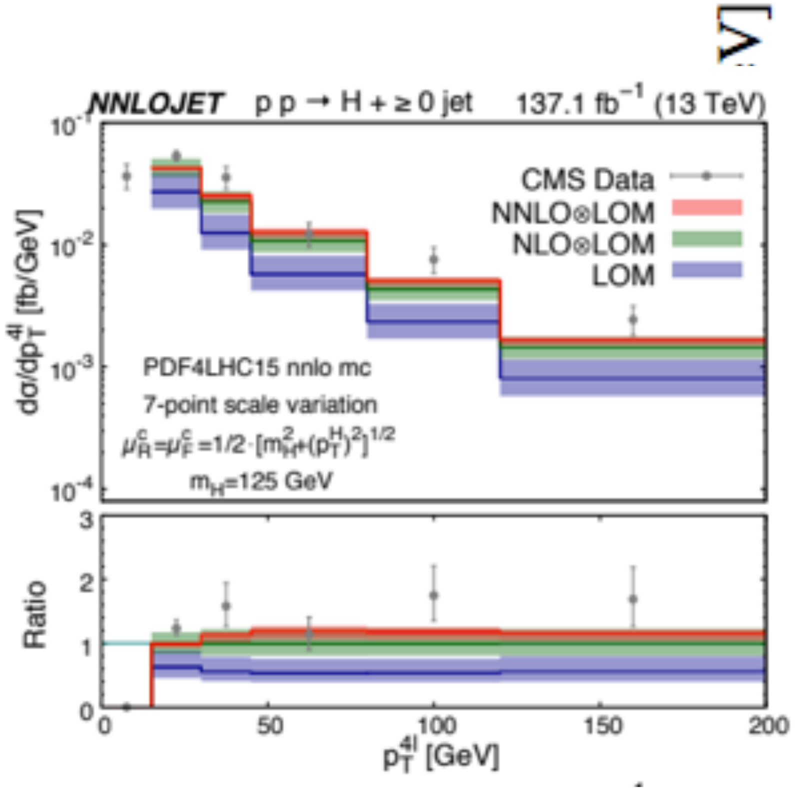
one of good examples of precision physics, which the overwhelming high statistics at LHC makes possible

top partner indirect searches

[Jones, Kerner, Luisoni]
arXiv:1802.00349



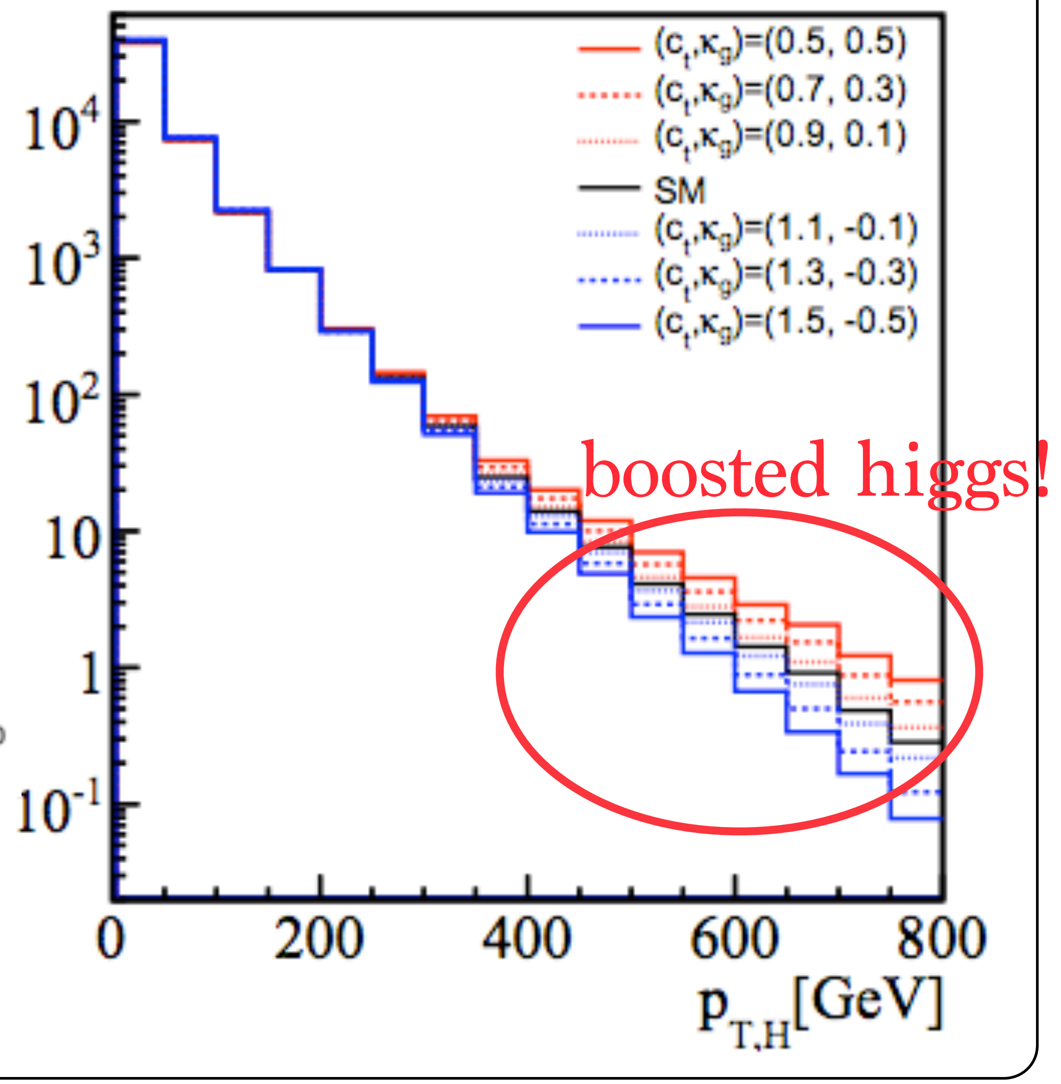
finite mt effects
important also in NLO



NNLO QCD for 2 to 2 process
[Chen, Gehrmann, Glover, Huss]

arXiv:1905.13738

Eur.Phys.J. C74 (2014) no.10, 3120
[M. Schlaffer, M. Spannowsky, MT, A. Weiler, C. Wymant]

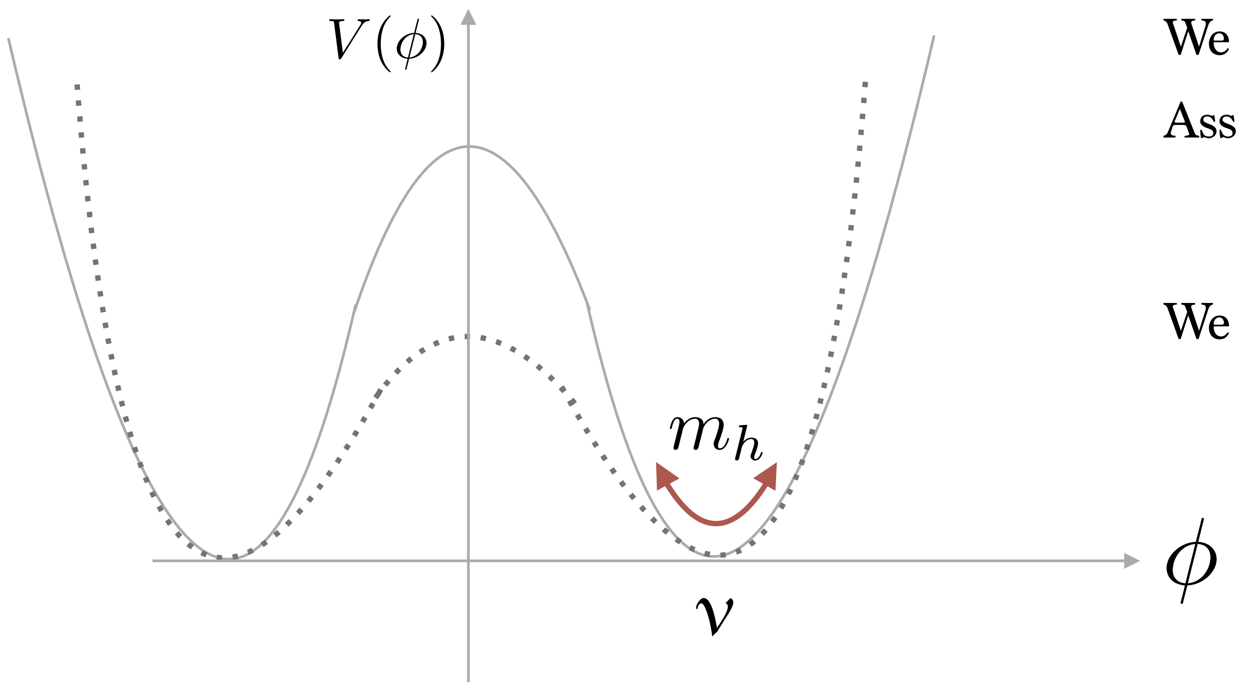


boosted higgs!

Higgs： $50 \text{ pb} \times 3 \cdot 10^3 \text{fb}^{-1} \sim 10^8$

one of good examples of precision physics, which the overwhelming high statistics at LHC makes possible

Higgs potential shape



We know the local structure around the VEV (v and mh)

Assuming the simple potential V(Φ)= $\lambda\phi^4 + \mu\phi^2$

$$V(h) = \frac{\lambda}{4}h^4 + \lambda v h^3 + \cdots = \frac{\lambda_4}{4!}h^4 + \frac{\lambda_3}{3!}h^3 +$$

We should have the relation

$$\lambda_4 = 6\lambda$$

$$\lambda_3 = 6\lambda v = \frac{3m_h^2}{v}$$

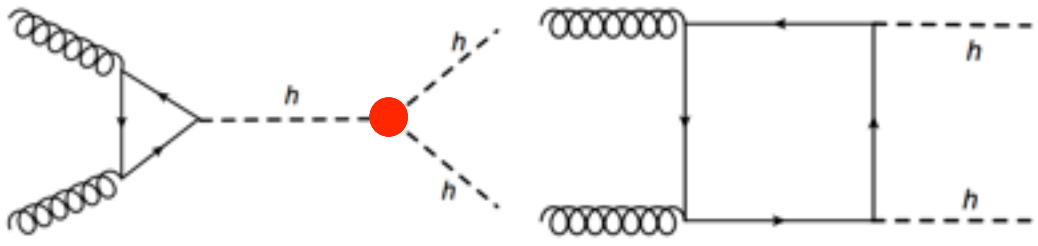
$$\lambda_{\rm SM} \approx 1/8.$$

EW Baryogenesis : strong 1st phase transition required
⇒ 50-70% deviation in Higgs triple coupling

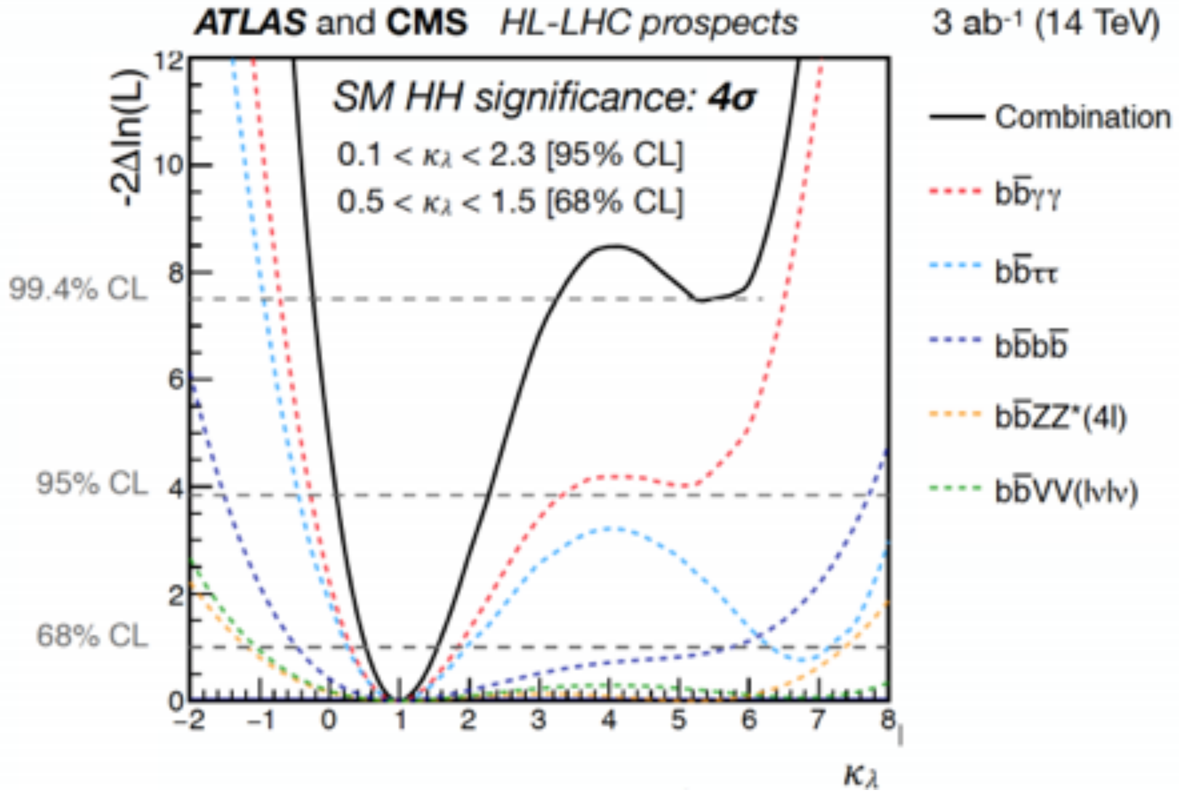
$$\lambda_3 = \frac{3m_h^2}{v} + \frac{6v^3}{\Lambda^2} \gtrsim 1.7\lambda_{3,\rm SM}$$

[C. Grojean, G. Servant, J. Wells]

HH pair production



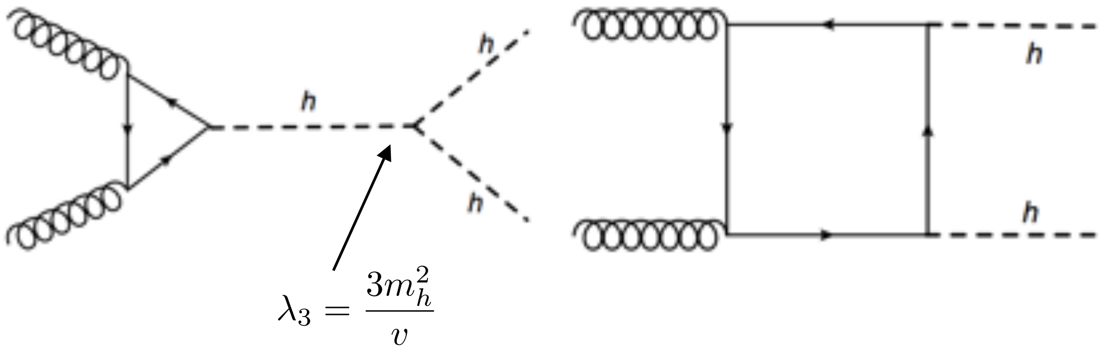
bbγγ mode is best channel



50% measurement is not enough to judge EWBG

three phase space

strong destructive interference



$\lambda_3 = \frac{3m_h^2}{v}$

$$\mathcal{M} = \kappa_\lambda y_t \mathcal{M}_\triangle + y_t^2 \mathcal{M}_\square$$

$$m_{hh}^{(\mathrm{th})} \approx 2m_h$$

$$\frac{\alpha_s}{12\pi v}\left(\frac{\kappa_\lambda \lambda_{\mathrm{SM}}}{s-m_h^2} - \frac{1}{v}\right) \rightarrow \frac{\alpha_s}{12\pi v^2}(\kappa_\lambda - 1) \overset{\mathrm{SM}}{=} 0\,.$$

$$\frac{\alpha_S}{12\pi} G^{\mu\nu}G_{\mu\nu} \log(1+\frac{h}{v})$$

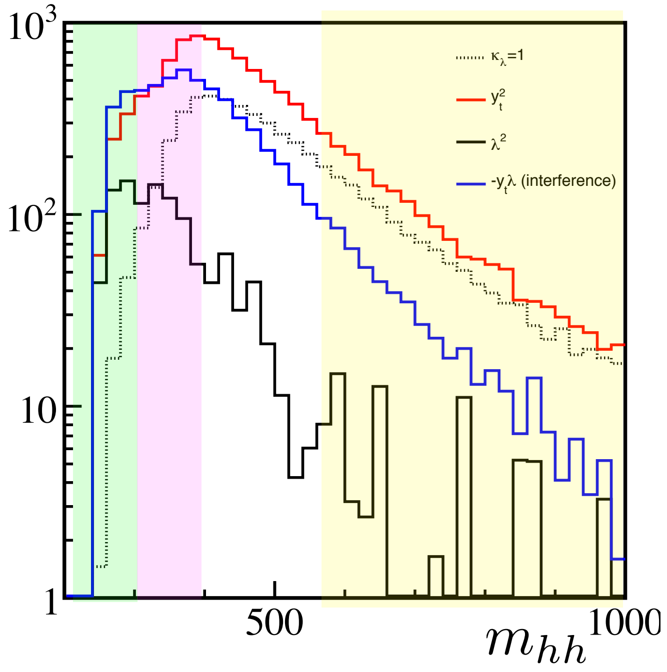
$$\log(1+\frac{h}{v}) = \frac{h}{v} - \frac{h^2}{2v^2} + \cdots$$

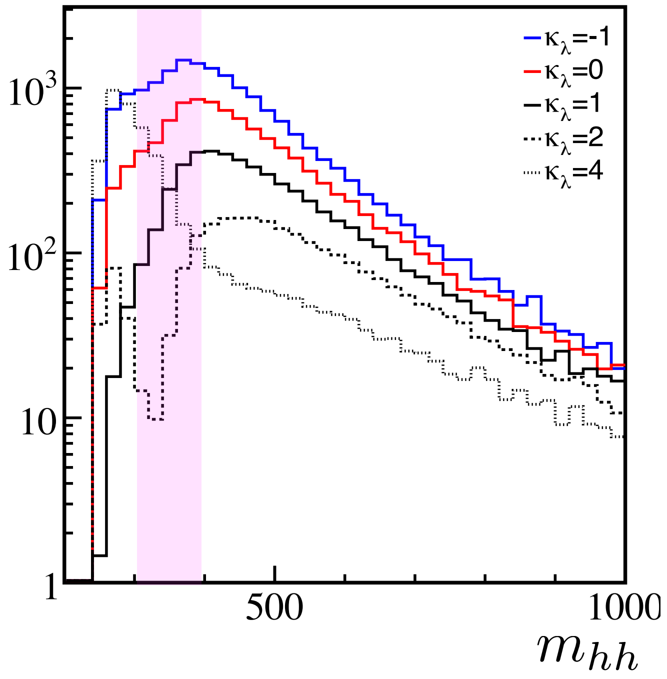
$$m_{hh}^{(\mathrm{abs})} \approx 2m_t\,.$$

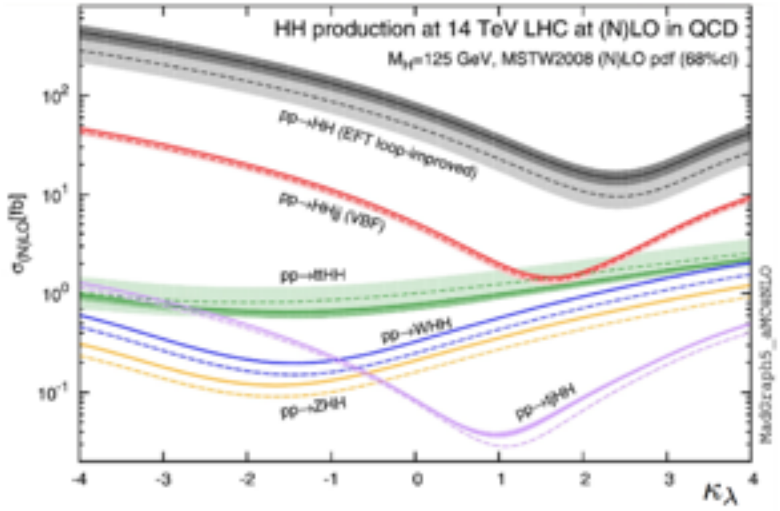
absorptive imaginary parts lead to a significant dip

$$m_{hh}^{(\mathrm{high})} \gg m_h, m_t\,.$$

box contributions decay slower





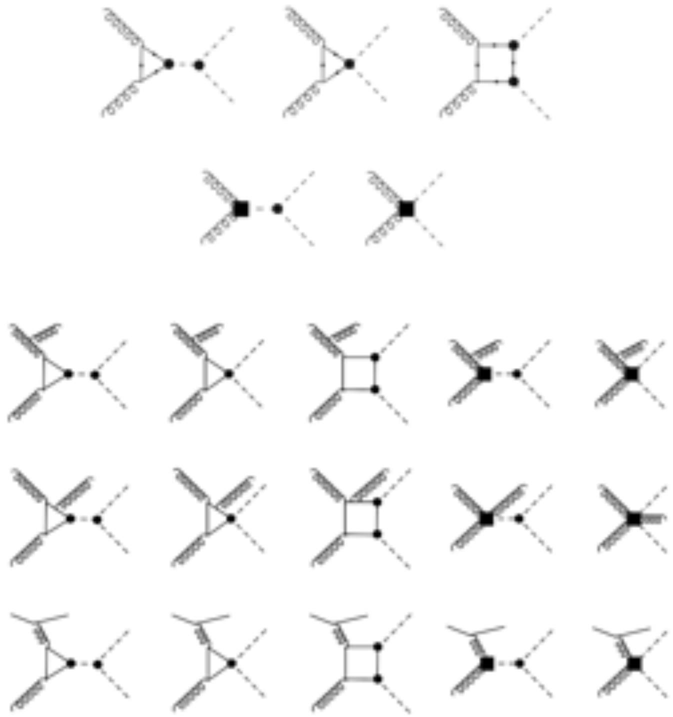


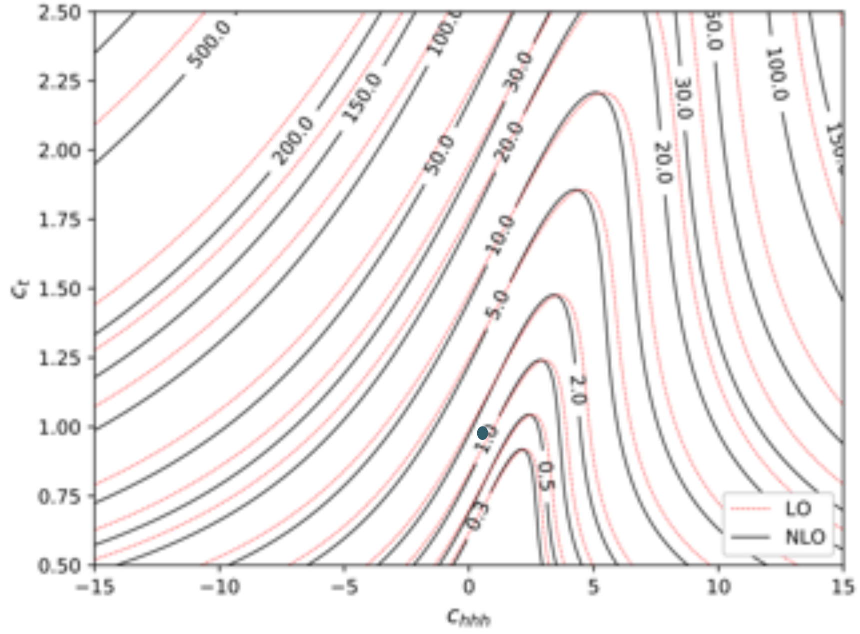
Since they are scalar particles, only m_{hh} distribution has the information at LO.

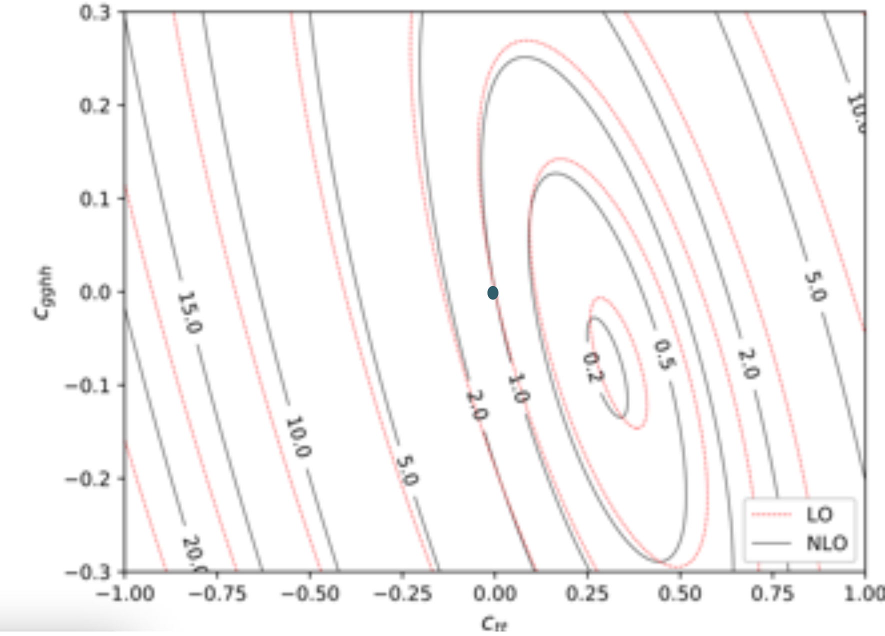
Theory prediction at NLO

include EFT couplings and full mt dependence [arXiv: 1806.05162]

$$\mathcal{L} \supset -m_t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v}+c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}\,.$$



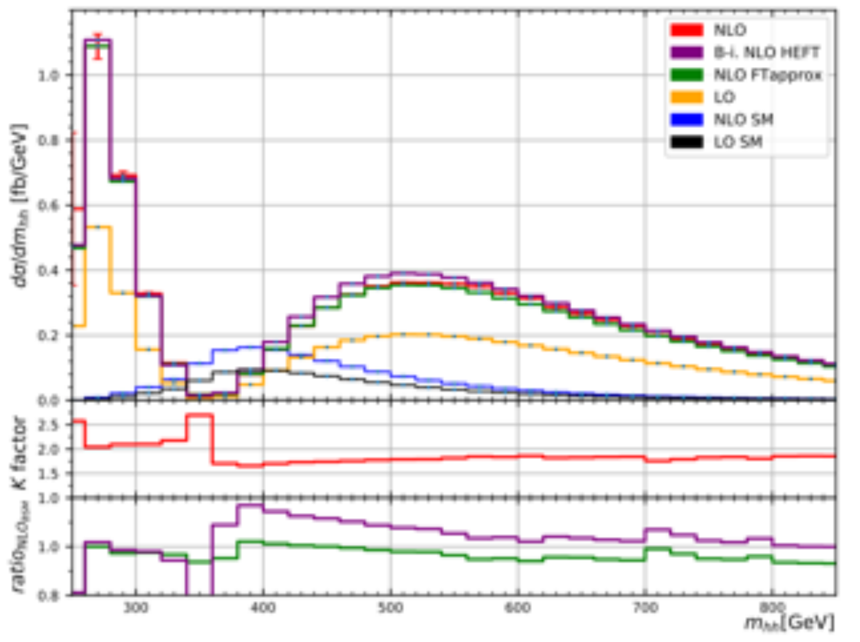




$$\sigma/\sigma_{SM} = A_1\,c_t^4 + A_2\,c_{tt}^2 + A_3\,c_t^2c_{hhh}^2 + A_4\,c_{ggh}^2c_{hhh}^2 + A_5\,c_{gghh}^2 + A_6\,c_{tt}c_t^2 + A_7\,c_t^3c_{hhh} + A_8\,c_{tt}c_t\,c_{hhh} + A_9\,c_{tt}c_{ggh}c_{hhh} + A_{10}\,c_{tt}c_{gghh} + A_{11}\,c_t^2c_{ggh}c_{hhh} + A_{12}\,c_t^2c_{gghh} + A_{13}\,c_tc_{hhh}^2c_{ggh} + A_{14}\,c_tc_{hhh}c_{gghh} + A_{15}\,c_{ggh}c_{hhh}c_{gghh}\,. \tag{2.7}$$

$$\Delta\sigma/\sigma_{SM} = A_{16}\,c_t^3c_{ggh} + A_{17}\,c_tc_{tt}c_{ggh} + A_{18}\,c_tc_{ggh}^2c_{hhh} + A_{19}\,c_tc_{ggh}c_{gghh} + A_{20}\,c_t^2c_{ggh}^2 + A_{21}\,c_{tt}c_{ggh}^2 + A_{22}\,c_{ggh}^3c_{hhh} + A_{23}\,c_{ggh}^2c_{gghh}\,.$$

$c_{hhh} = 7.5, c_t = 1, c_{tt} = -1, c_{ggh} = c_{gghh} = 0.$

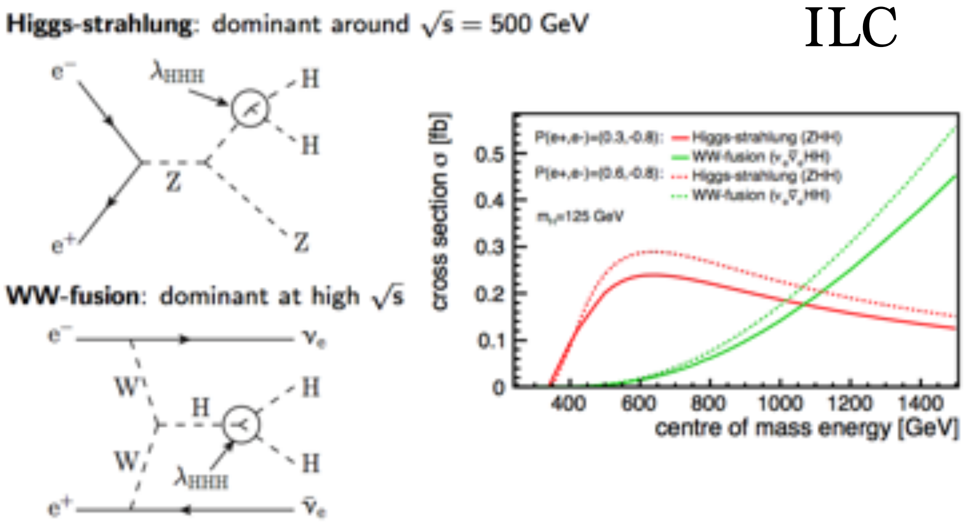


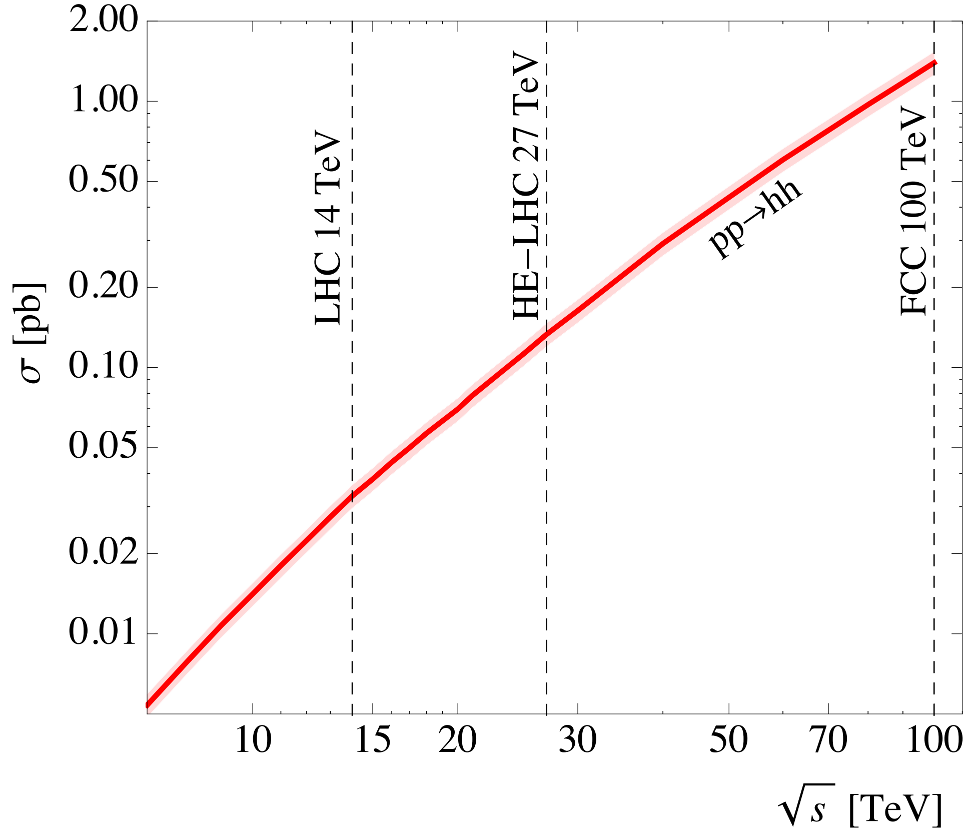
K-factor can be large up to 3, depending on the phase space

differential distribution for 23terms available at arxiv

HE-LHC and 100 TeV colliders

1. the 27 TeV high-energy LHC (HE-LHC) with an integrated luminosity of 15 ab^{-1},
2. a 100 TeV hadron collider with 30 ab^{-1}, under consideration at CERN (FCC-hh) [18] and in China (SppC) [19].





in cross section compared with 14TeV

factor 4 (27TeV)

factor 40 (100TeV)

in event numbers

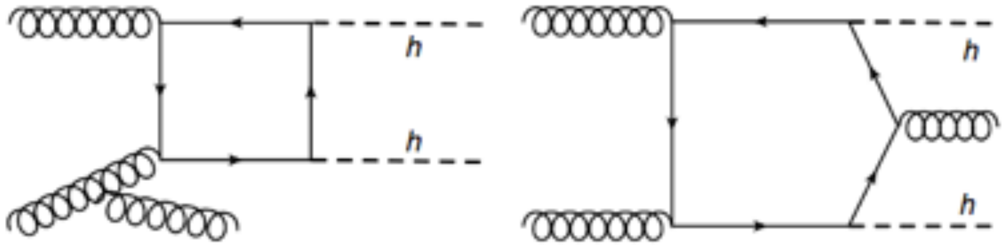
x20 x20

14 TeV → 27 TeV → 100 TeV

properly simulate the 3rd jet important

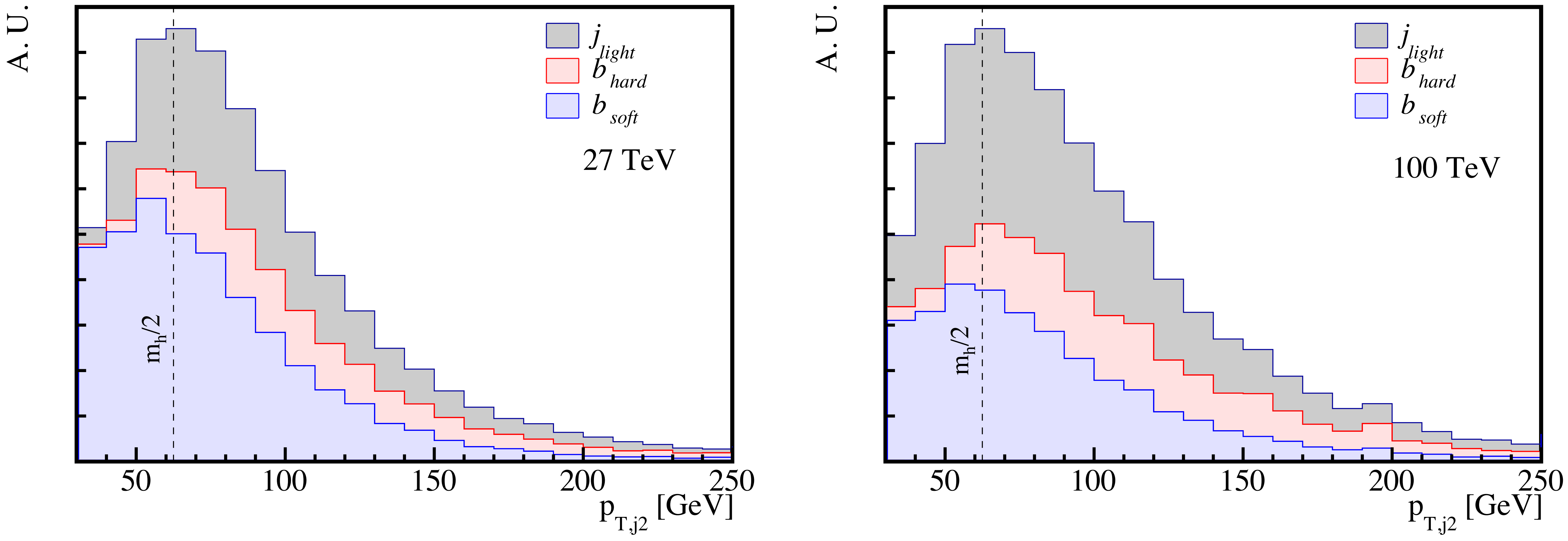
All Signal/BG samples simulated with 1 additional jet in MLM matching

$$pp \to hh \to b\bar{b}\,\gamma\gamma + X.$$



two H decay products not always found in the hardest two jets (b from H has intrinsic pT ~ 60GeV)

origin of the second jet for 27 TeV and 100 TeV



Requiring two b-tags in three hardest jets important! (50% acceptance higher)

Event selection

two photons, two b-jets

$$\epsilon_{\gamma\to\gamma} = 0.863 - 1.07\cdot e^{-p_{T,\gamma}/34.8\ \text{GeV}}\ ,$$

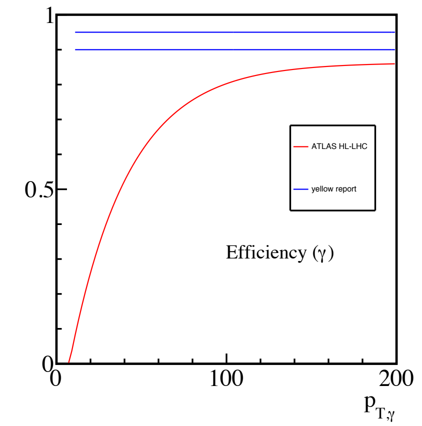
$$\epsilon_{j\to\gamma} = \begin{cases} 5.3\cdot 10^{-4}\exp\left(-6.5\left(\frac{p_{T,j}}{60.4\ \text{GeV}}-1\right)^{2}\right)\ , \\ 0.88\cdot 10^{-4}\left[\exp\left(-\frac{p_{T,j}}{943\ \text{GeV}}\right)+\frac{248\ \text{GeV}}{p_{T,j}}\right]\ , \end{cases}$$

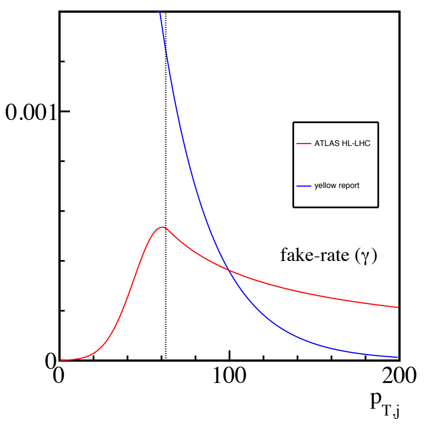
pT<65GeV

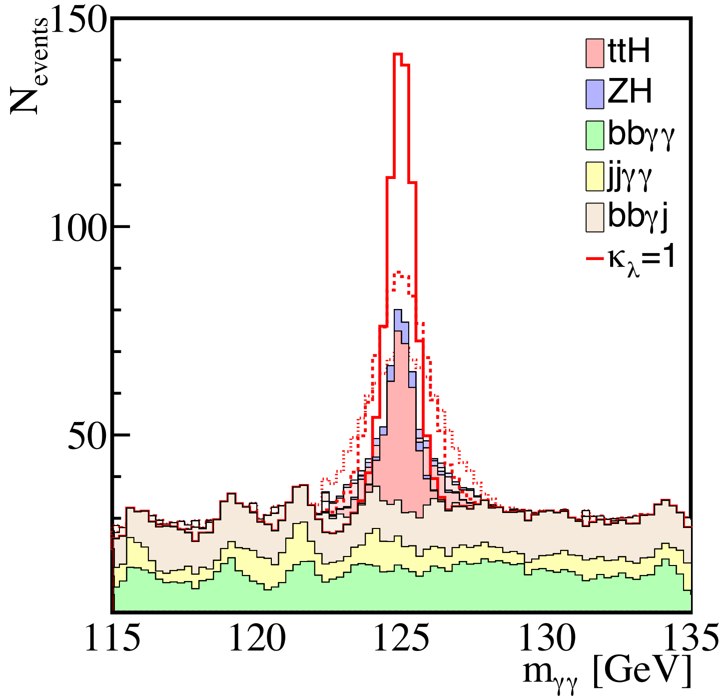
pT>65GeV

reducing fake photon important (esp. low pT)

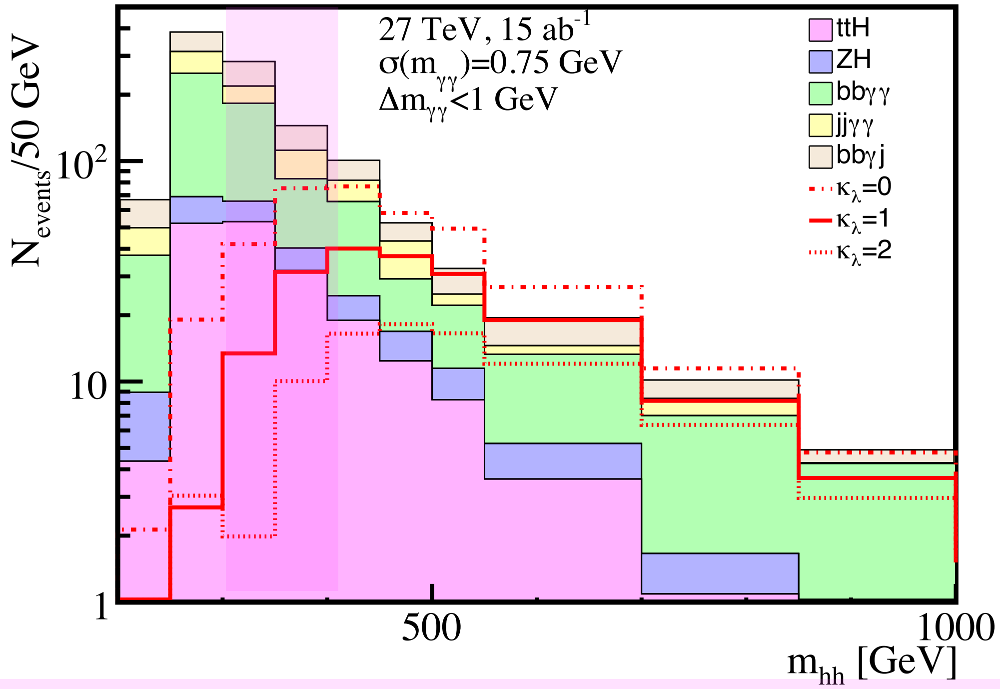
both pairs provide higgs mass

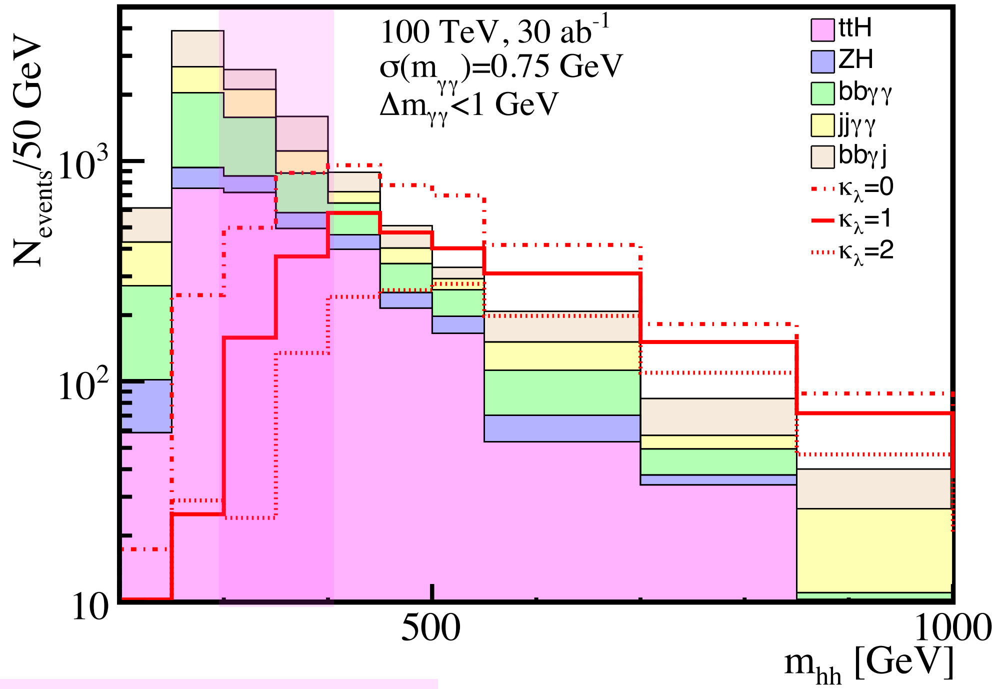






Higgs Signal/BG: peaked
continuum BG: flat
(controllable by side-bands)





characteristic structure should appear in low m_{hh} region

but very difficult to access it due to too huge BG (cf. using jet recoil)

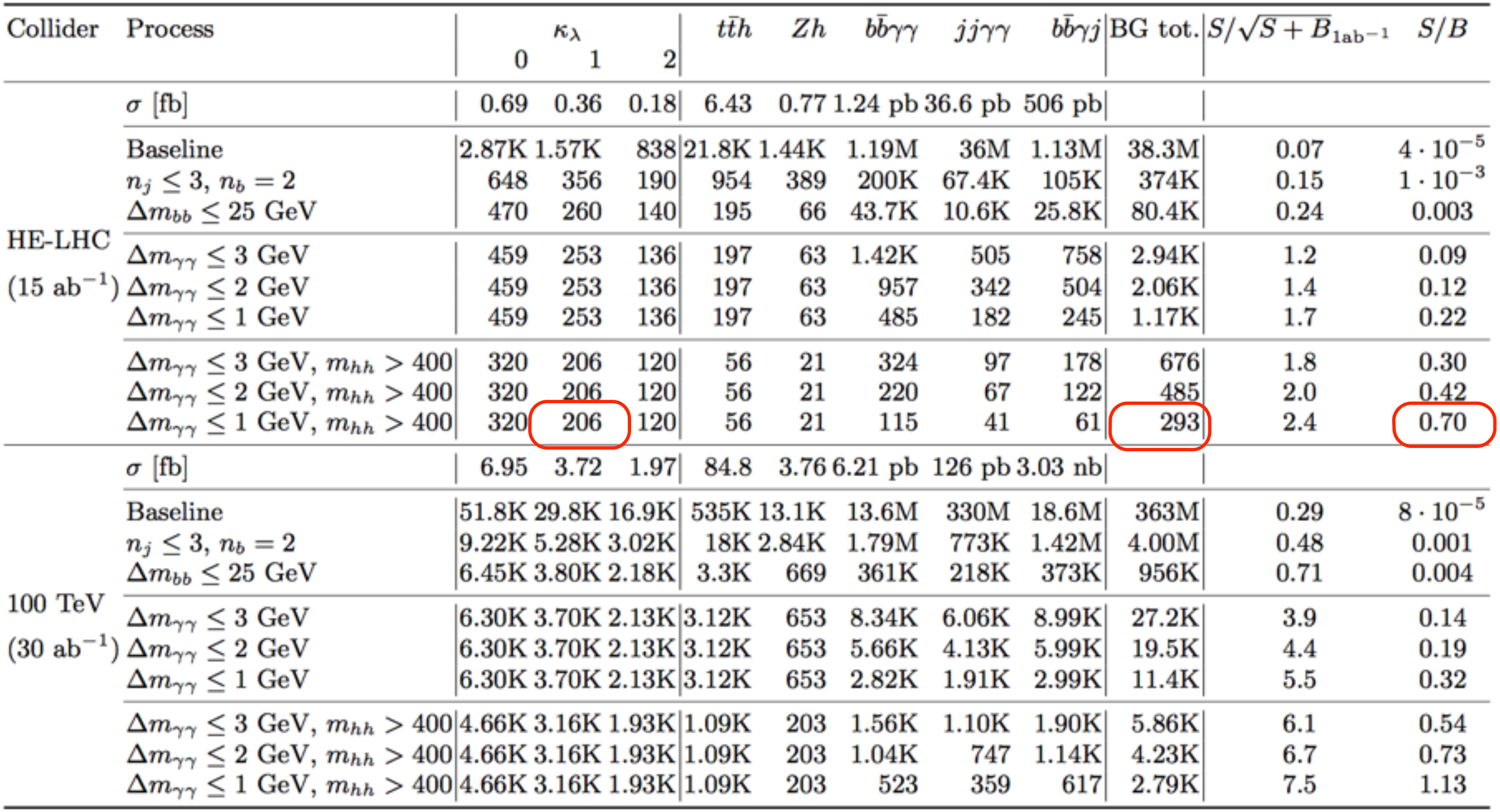
JHEP 1502 (2015) 016
[A. Barr, M. Dolan, C. Englert,
D. Ferreira de Lima, M. Spannowsky]

We have to require $m_{hh} > 400\text{GeV}$

Results

Baseline: $p_{T,j} > 30$ GeV, $|\eta_j| < 2.5$,
$p_{T,\gamma} > 30$ GeV, $|\eta_\gamma| < 2.5$,
$\Delta R_{\gamma\gamma,\gamma j,jj} > 0.4$.

$\epsilon_b = 70\%$ $\epsilon_c = 15\%$ $\epsilon_j = 0.3\%$



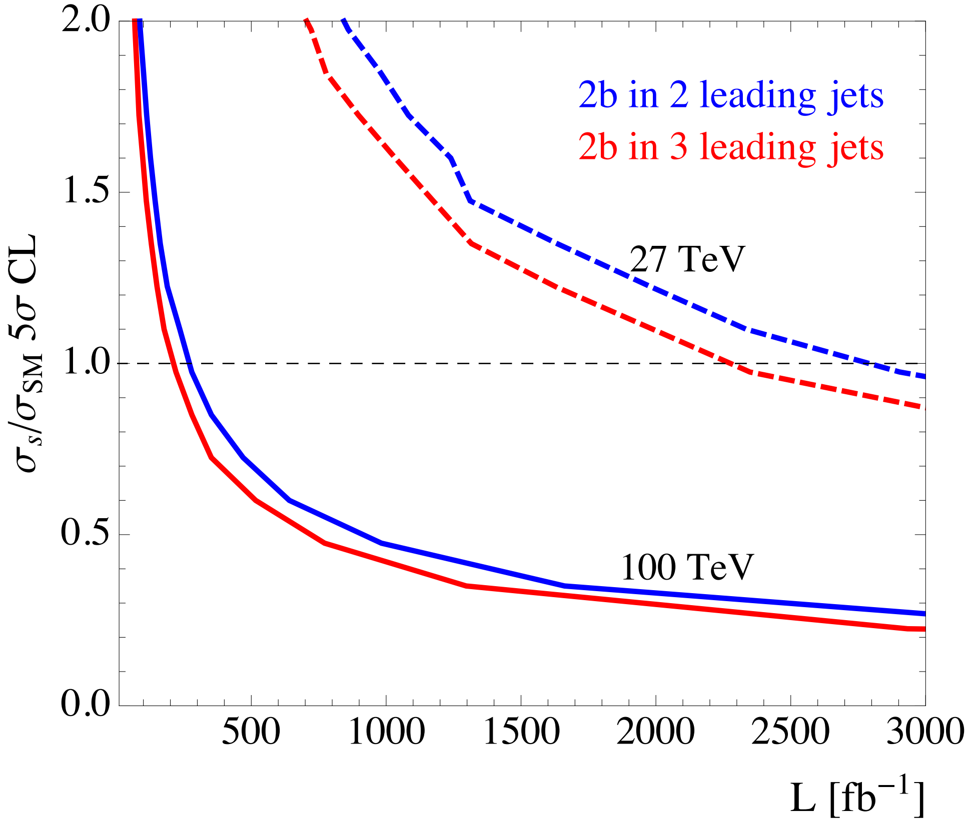
Collider	Process	κ_λ			$t\bar{t}h$	Zh	$b\bar{b}\gamma\gamma$	$jj\gamma\gamma$	$b\bar{b}\gamma j$	BG tot.	$S/\sqrt{S+B}_{1\text{ab}^{-1}}$	S/B
		0	1	2								
HE-LHC ($15\ \text{ab}^{-1}$)	σ [fb]	0.69	0.36	0.18	6.43	0.77	1.24 pb	36.6 pb	506 pb			
	Baseline	2.87K	1.57K	838	21.8K	1.44K	1.19M	36M	1.13M	38.3M	0.07	$4\cdot10^{-5}$
	$n_j \leq 3$, $n_b = 2$	648	356	190	954	389	200K	67.4K	105K	374K	0.15	$1\cdot10^{-3}$
	$\Delta m_{bb} \leq 25$ GeV	470	260	140	195	66	43.7K	10.6K	25.8K	80.4K	0.24	0.003
	$\Delta m_{\gamma\gamma} \leq 3$ GeV	459	253	136	197	63	1.42K	505	758	2.94K	1.2	0.09
	$\Delta m_{\gamma\gamma} \leq 2$ GeV	459	253	136	197	63	957	342	504	2.06K	1.4	0.12
	$\Delta m_{\gamma\gamma} \leq 1$ GeV	459	253	136	197	63	485	182	245	1.17K	1.7	0.22
	$\Delta m_{\gamma\gamma} \leq 3$ GeV, $m_{hh} > 400$	320	206	120	56	21	324	97	178	676	1.8	0.30
	$\Delta m_{\gamma\gamma} \leq 2$ GeV, $m_{hh} > 400$	320	206	120	56	21	220	67	122	485	2.0	0.42
	$\Delta m_{\gamma\gamma} \leq 1$ GeV, $m_{hh} > 400$	320	206	120	56	21	115	41	61	293	2.4	0.70
100 TeV ($30\ \text{ab}^{-1}$)	σ [fb]	6.95	3.72	1.97	84.8	3.76	6.21 pb	126 pb	3.03 nb			
	Baseline	51.8K	29.8K	16.9K	535K	13.1K	13.6M	330M	18.6M	363M	0.29	$8\cdot10^{-5}$
	$n_j \leq 3$, $n_b = 2$	9.22K	5.28K	3.02K	18K	2.84K	1.79M	773K	1.42M	4.00M	0.48	0.001
	$\Delta m_{bb} \leq 25$ GeV	6.45K	3.80K	2.18K	3.3K	669	361K	218K	373K	956K	0.71	0.004
	$\Delta m_{\gamma\gamma} \leq 3$ GeV	6.30K	3.70K	2.13K	3.12K	653	8.34K	6.06K	8.99K	27.2K	3.9	0.14
	$\Delta m_{\gamma\gamma} \leq 2$ GeV	6.30K	3.70K	2.13K	3.12K	653	5.66K	4.13K	5.99K	19.5K	4.4	0.19
	$\Delta m_{\gamma\gamma} \leq 1$ GeV	6.30K	3.70K	2.13K	3.12K	653	2.82K	1.91K	2.99K	11.4K	5.5	0.32
	$\Delta m_{\gamma\gamma} \leq 3$ GeV, $m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	1.56K	1.10K	1.90K	5.86K	6.1	0.54
	$\Delta m_{\gamma\gamma} \leq 2$ GeV, $m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	1.04K	747	1.14K	4.23K	6.7	0.73
	$\Delta m_{\gamma\gamma} \leq 1$ GeV, $m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	523	359	617	2.79K	7.5	1.13

including 3rd jets in the analysis important

narrowing di-photon mass range effective to reach S/B ~ 1.
(the resolution 0.75, 1.5, 2.25 GeV assumed corresponding to the 1,2,3 GeV range)
[Note: 1.5GeV is already achieved at the LHC.]

4th jet veto mainly for reducing ttH BG.

Two important comments

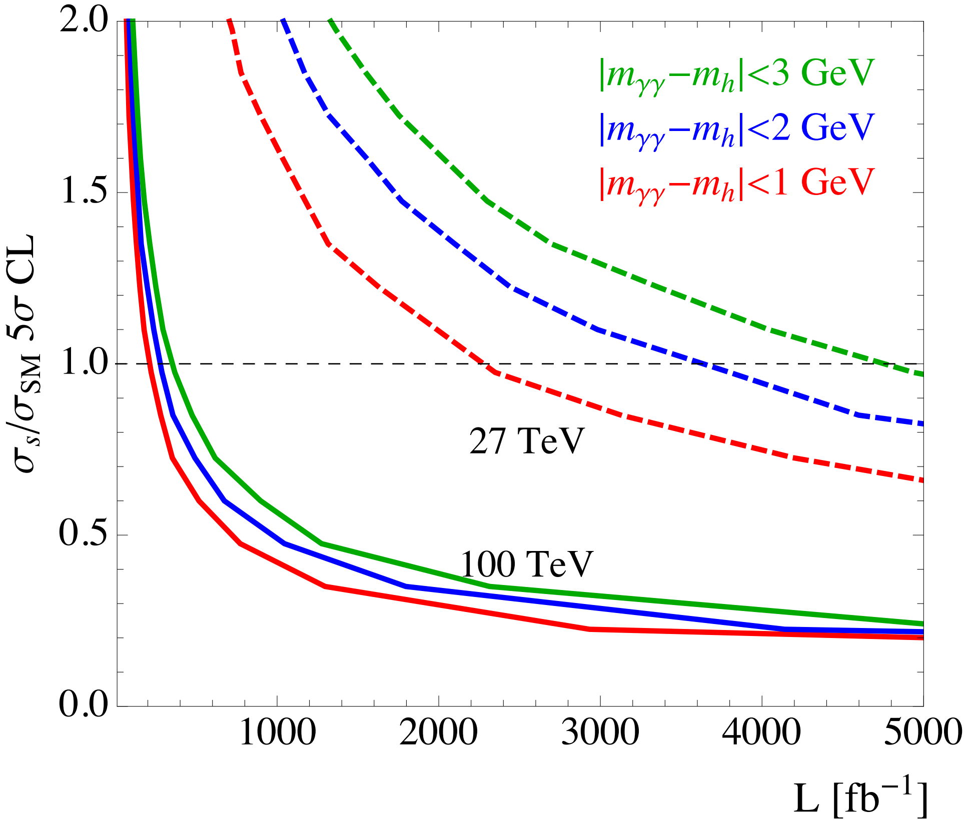


sub-samples (bb, bbj) and (jbb, bjb)

including b-tag in 3rd jet clearly improves the sensitivity

The 5σ measurement for HE-LHC is

$2.8\ \text{ab}^{-1}$ to below $2.3\ \text{ab}^{-1}$



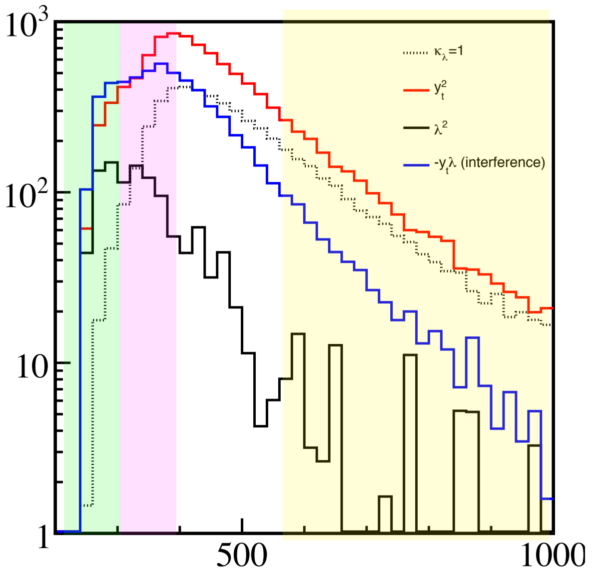
for Higgs self coupling sensitivity
photon invariant mass resolution most important

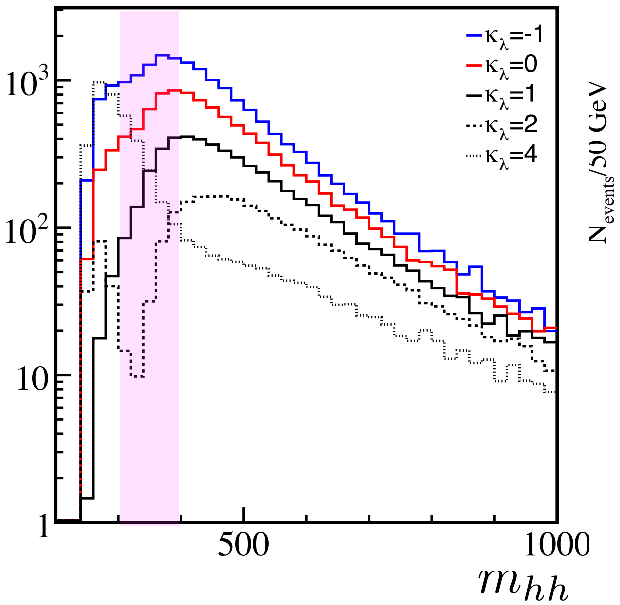
(the resolution 0.75, 1.5, 2.25 GeV assumed
corresponding to the 1,2,3 GeV range)
[1.5 GeV is already achieved at LHC]

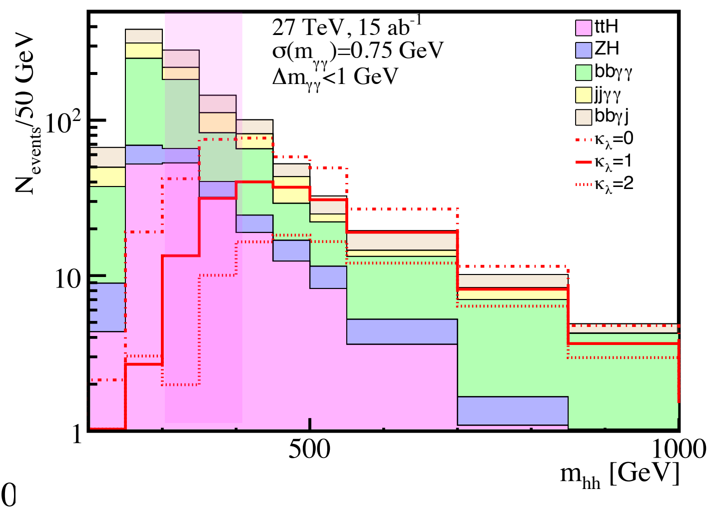
important for detector design

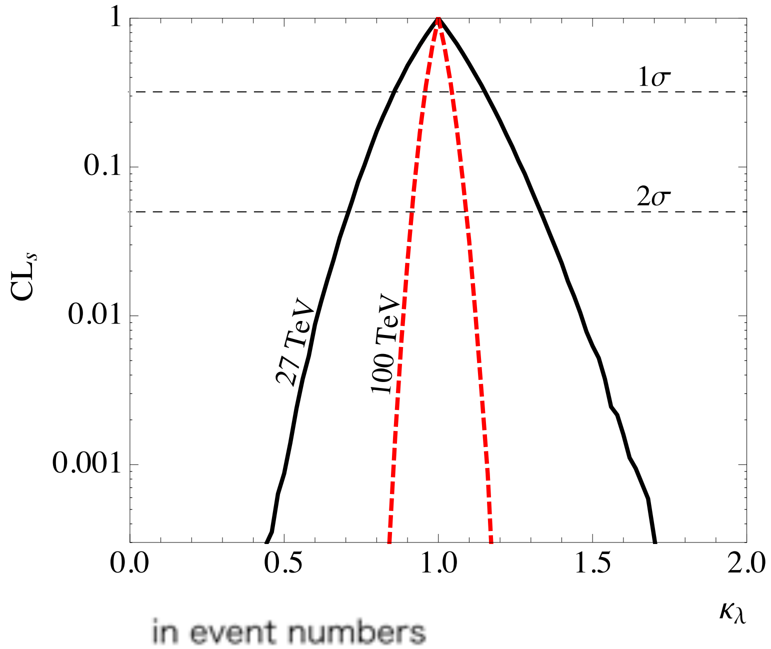
study for future colliders

D. Goncalves, T. Han, F. Kling, T. Plehn, MT
[Phys. Rev. D 97, 113004 (arXiv:1802.04319)]







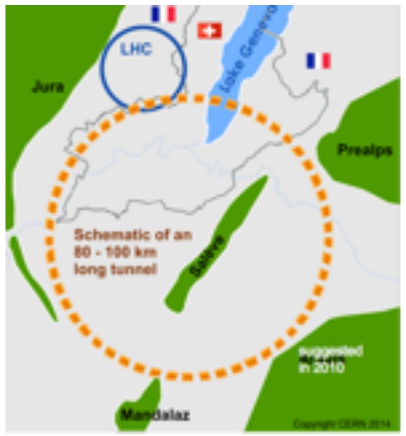


in event numbers

14 TeV $\xrightarrow{\times 20}$ 27 TeV $\xrightarrow{\times 20}$ 100 TeV

HL–LHC sensitivity 50% ⇔ HE-LHC (27TeV) 15% (100TeV: 5%)

We first in the world estimate the sensitivity at 27TeV (including ISR-jet effects) : important input for the future decision making



CERN/China future colliders

HE-LHC: 27 TeV 2040〜

FCC : 100TeV 2043〜

(late 2017, energy of HE option is determined as 27TeV)

at some point we have to decide either way,
study needed for the decision making important

EW Baryogenesis : strong 1st phase transition required
⇒ 50-70% deviation in Higgs triple coupling

whether we can exclude ? (question to answer yes-no)

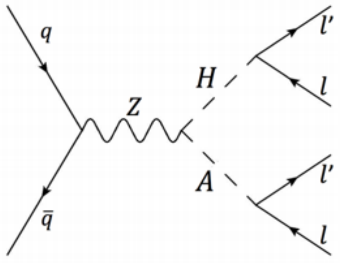
We have shown 27TeV would be enough to answer it

What we can do at HL-LHC in Higgs physics ?

2027~2038: HL-LHC ⇒ 20 times more production of the particles

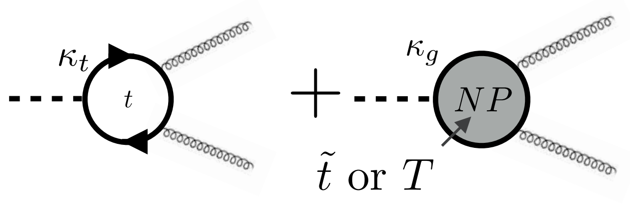
1. possibility of discovery of heavy particles

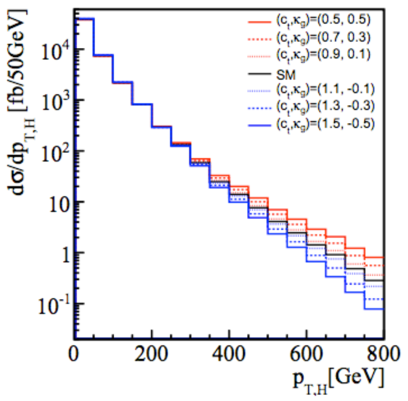
   Heavy Higgs searches



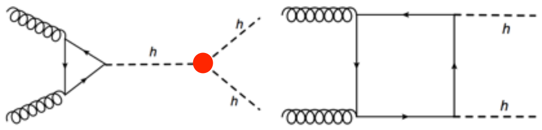
2. possibility of probing new physics effects using the distribution measurements

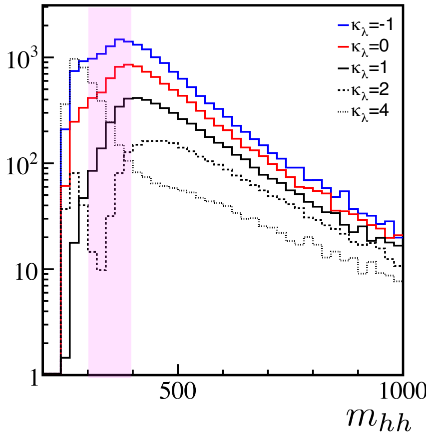
   Boosted Higgs shapes





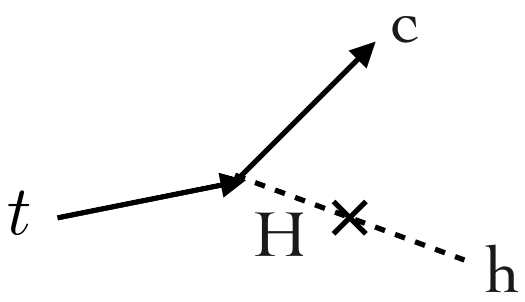
double-Higgs production

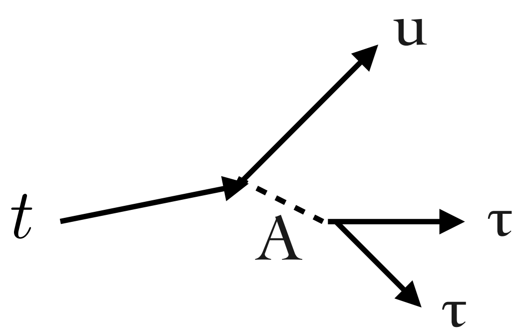




3. **possibility of probing new physics effects using rare decays**

   Higgs rare decays, top rare decays

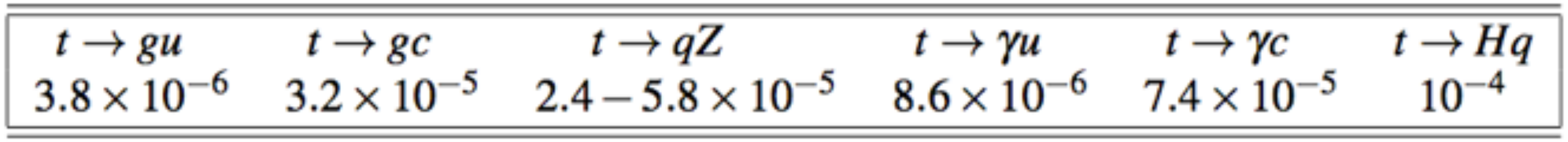




top factory

Top pair copiously produced : 1nb x 3ab^{-1}= 3 x 10^{9} pairs

Top FCNC 95%C. L. reach at 3ab^{-1}



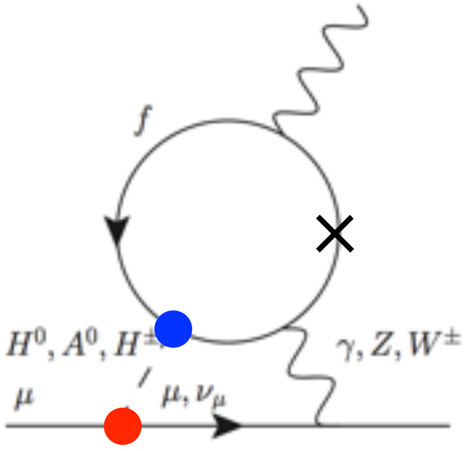
$t \to gu$	$t \to gc$	$t \to qZ$	$t \to \gamma u$	$t \to \gamma c$	$t \to Hq$
3.8×10^{-6}	3.2×10^{-5}	$2.4 - 5.8 \times 10^{-5}$	8.6×10^{-6}	7.4×10^{-5}	10^{-4}

a variant axion model to predict t -> ch (top-specific 2HDM) [C-W Chian, H. Fukuda, MT, T. T. Yanagida] JHEP 11 (2015) 057

[C-W Chian, H. Fukuda, MT, T. T. Yanagida] Phys. Rev. D 97, 035015 (2018)

We consider very light pseudo-scalar A in a variant axion model to explain muon g-2. (u-type lepton-specific 2HDM)

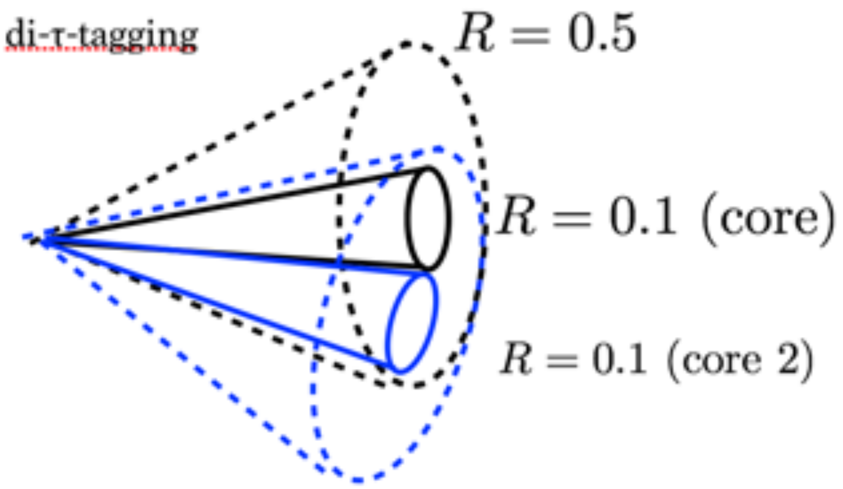
[C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]Phys.Rev.D 98 (2018) 9, 095020



$$\propto m_\mu m_f^2 / m_H^2$$

boosted A → ττ from top decays

di-τ-tagging

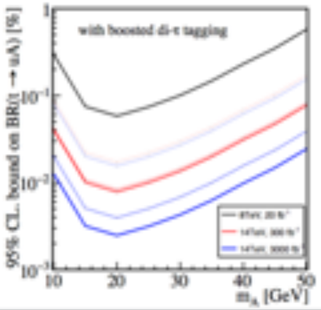


mutual isolation

[A. Katz, M. Son, B. Tweedie, PRD 83, 114033(2011).]

if core 1 is removed, the rest is τ-tagged

if core 2 is removed, the rest is also τ-tagged



For *mA*=15GeV

BR(*t*→*uA*) < 0.08%

(10% by CMS study)

0.003-0.01% in future

2HDM as the solution for strong CP problem

Strong CP problem

θ-vacuum

$$|\theta> = \sum_{n=-\infty}^{\infty} e^{in\theta}|n> \Leftrightarrow \mathcal{L}_\theta = \frac{g^2\theta}{32\pi^2}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

$$\theta_{\rm eff} = \theta + \arg\det[M^u M^d]$$

Why $\theta_{\rm eff} < 10^{-11}$?

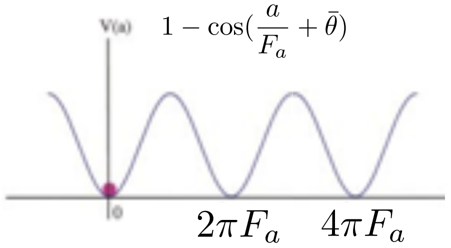
PQ solution with axion

assume spontaneously broken U(1) $\eta e^{i\theta_{PQ}} \sim \eta + ia$ to introduce axion field

triangle diagram (N: n. of coupled quarks), $\delta\mathcal{L} = -\frac{g^2}{32\pi^2}N\frac{a}{\eta}G^{\mu\nu}\tilde{G}_{\mu\nu}$ induced

after QCD PT, $< G^{\mu\nu}\tilde{G}_{\mu\nu} > \sim \Lambda^4_{\rm QCD}$ the potential

$$\theta_{\rm eff} = \theta + \arg\det[M^u M^d] + \frac{< a >}{F_a}$$



$\bar{\theta} = \theta_{\rm strong} + \theta_{\rm EM}$

very attractive, *a* also play a good CDM role

$a' \equiv a + \bar{\theta}F_a$

invisible axion models

KSVZ

heavy Q introduced $\mathcal{L}_Q = -y_Q\bar{Q}_L\Phi Q_R + \text{h.c.}$

(no problem but no low energy phenomenology, not interesting)

$N_{DM} = 1$

(Kim 1979, Shifman, Vainshtein, Zakharov 1980)

ZDFS

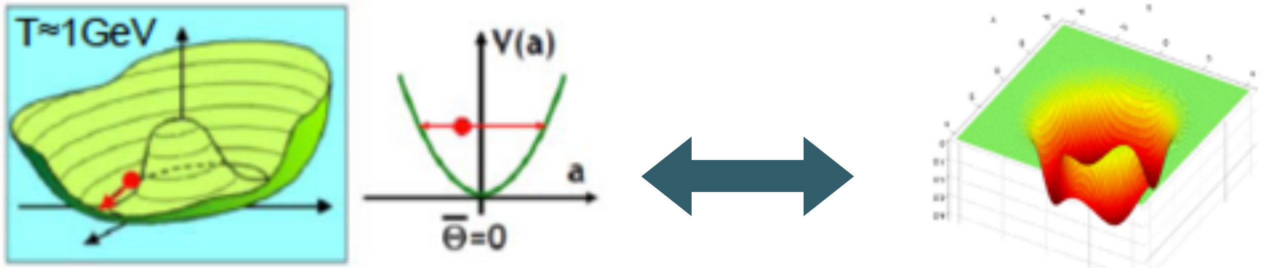
two Higgs doublet model

$\Phi_1^\dagger\Phi_2\sigma^2$ $N_{DM} = 6$

$m\Phi_1^\dagger\Phi_2\sigma$ $N_{DM} = 3$

(Zhitnitsky1980,
Dine, Fischler, Srednicki 1981)

mismatch due to the different periodicity



in θ space

in $\frac{a}{\eta} = \frac{a}{NF_a}$ space

Variant Axion model

domain wall problem absent if only 1 quark coupled to PQ-Higgs $N_{DM} = 1$

[R.D. Peccei, T.T. Wu and T. Yanagida, Phys. Lett. B172, 435 (1986)]

g-2 in Lepton-specific 2HDM with VAM

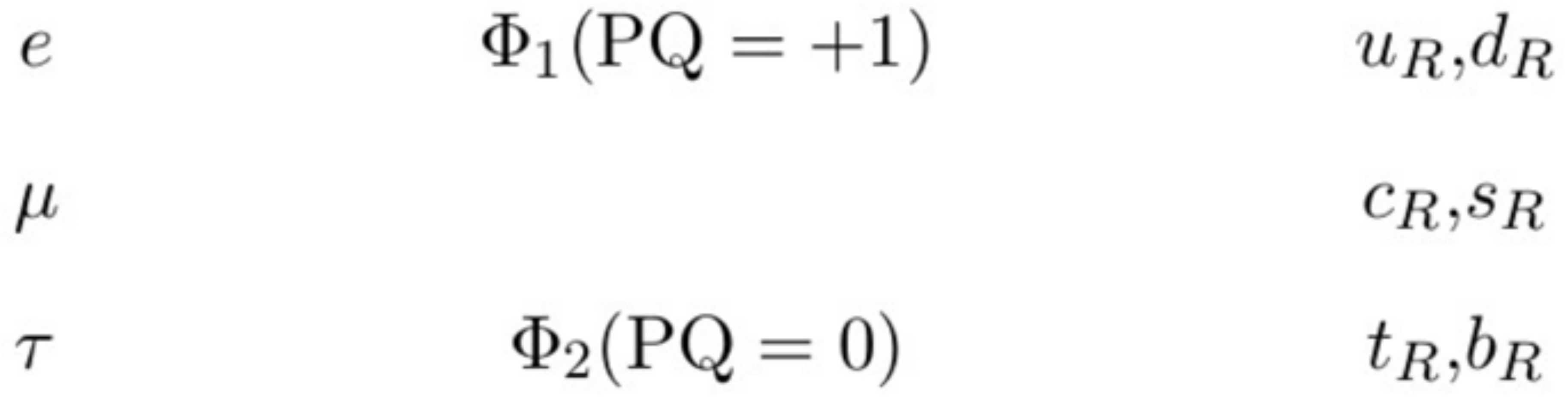
[C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]Phys.Rev.D 98 (2018) 9, 095020

VAM is a 2HDM at low energy, there is a choice which one quark is PQ charged.

quark sector : domain wall problem ⇒ only one q_R PQ charged

lepton sector : lepton yukawa has to be enhanced for muon g-2 ⇔ corresponding VEV is small (tanβ>>1)

(lepton sector is irrelevant to domain wall problem)



e	$\Phi_1(\mathrm{PQ}=+1)$	u_R, d_R
μ		c_R, s_R
τ	$\Phi_2(\mathrm{PQ}=0)$	t_R, b_R

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[C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]Phys.Rev.D 98 (2018) 9, 095020

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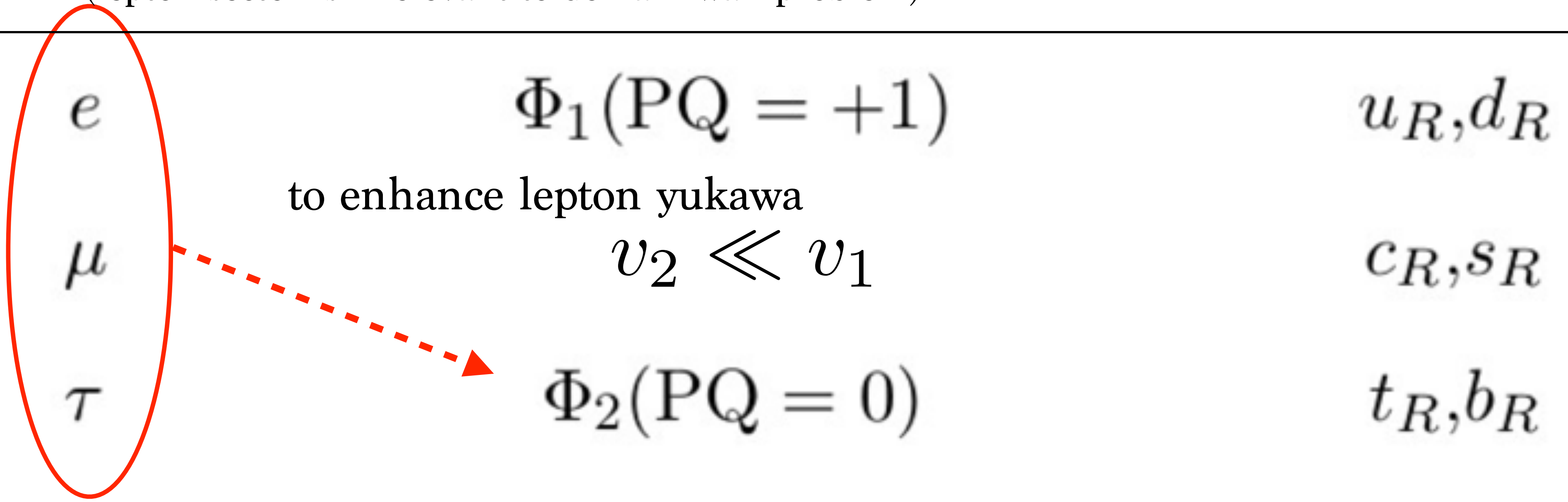

e $\quad$ $\Phi_1(\mathrm{PQ}=+1)$ $\quad$ u_R, d_R

to enhance lepton yukawa

μ $\quad$ $v_2 \ll v_1$ $\quad$ c_R, s_R

τ $\quad$ $\Phi_2(\mathrm{PQ}=0)$ $\quad$ t_R, b_R

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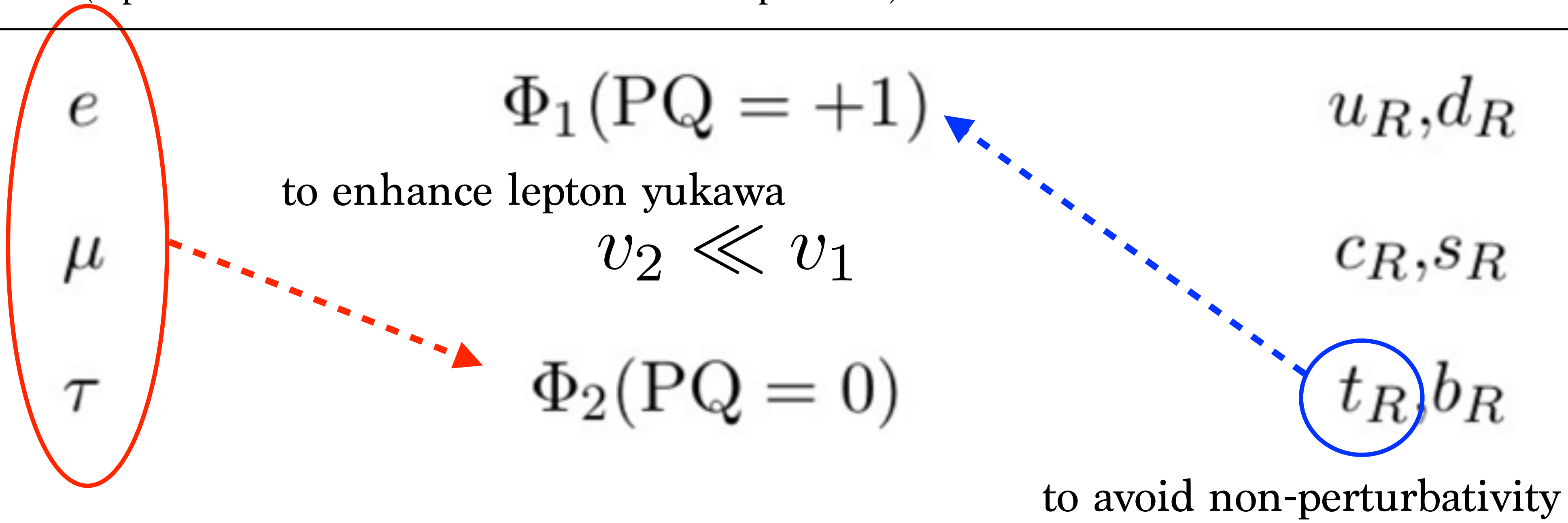

e

μ

τ

$\Phi_1(\mathrm{PQ} = +1)$

to enhance lepton yukawa

$v_2 \ll v_1$

$\Phi_2(\mathrm{PQ} = 0)$

u_R, d_R

c_R, s_R

t_R, b_R

to avoid non-perturbativity

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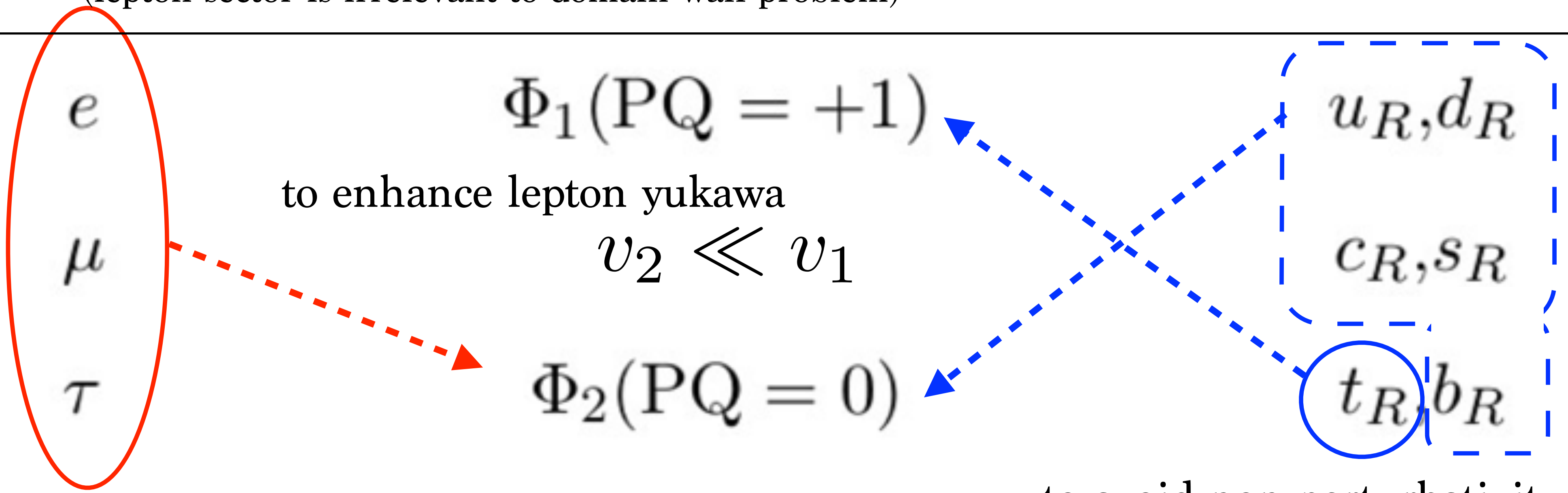

e

μ

τ

$\Phi_1(PQ=+1)$

to enhance lepton yukawa

$v_2 \ll v_1$

$\Phi_2(PQ=0)$

u_R, d_R

c_R, s_R

t_R, b_R

to avoid non-perturbativity

to avoid domain wall

the 3rd gen. part becomes identical to the type II 2HDM ⇒ very constrained by LHC via bbA production

also by Bs→μμ

⇒ not viable possibility

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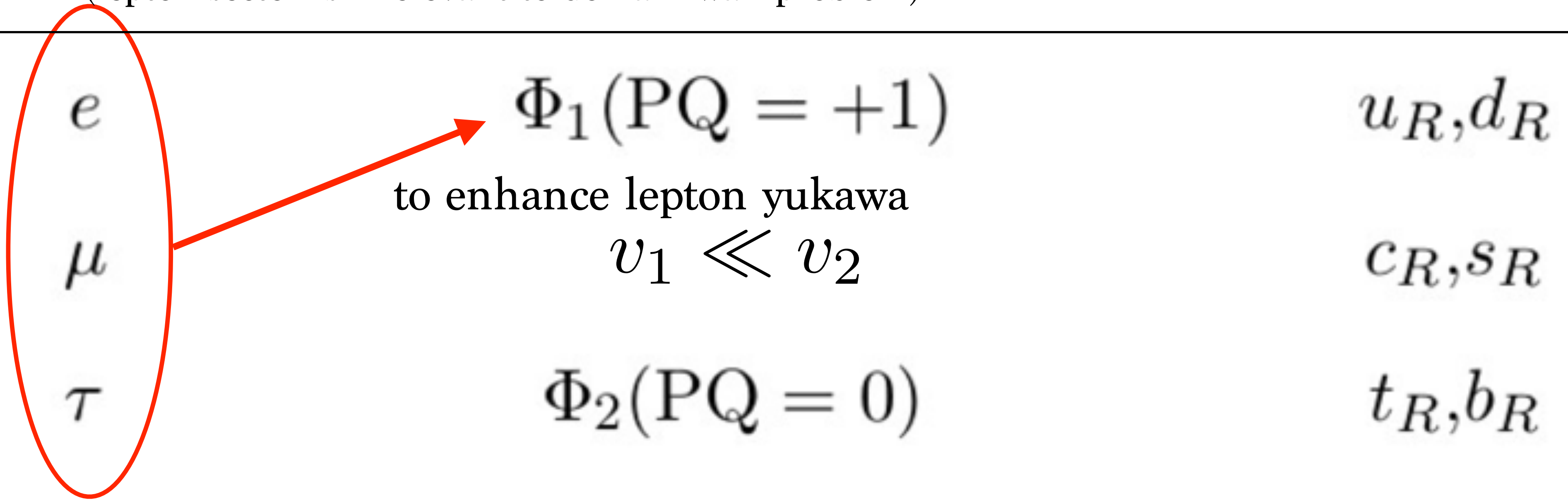

e

μ

τ

$\Phi_1(PQ=+1)$

to enhance lepton yukawa

$v_1 \ll v_2$

$\Phi_2(PQ=0)$

u_R, d_R

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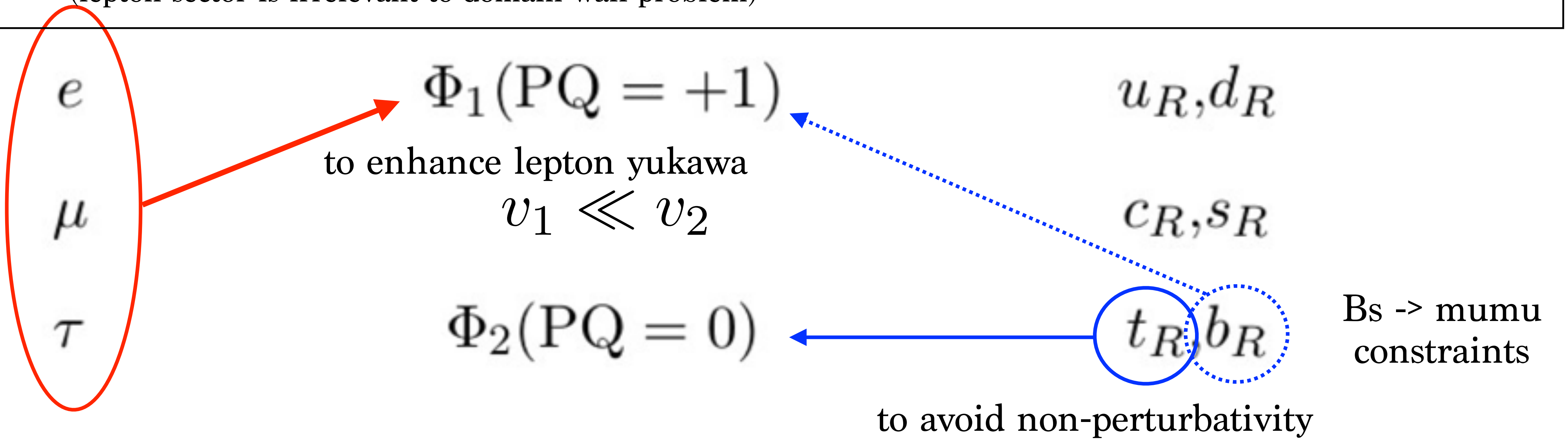

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$\Phi_2(PQ=0)$

u_R, d_R

c_R, s_R

t_R, b_R

Bs -> mumu constraints

to avoid non-perturbativity

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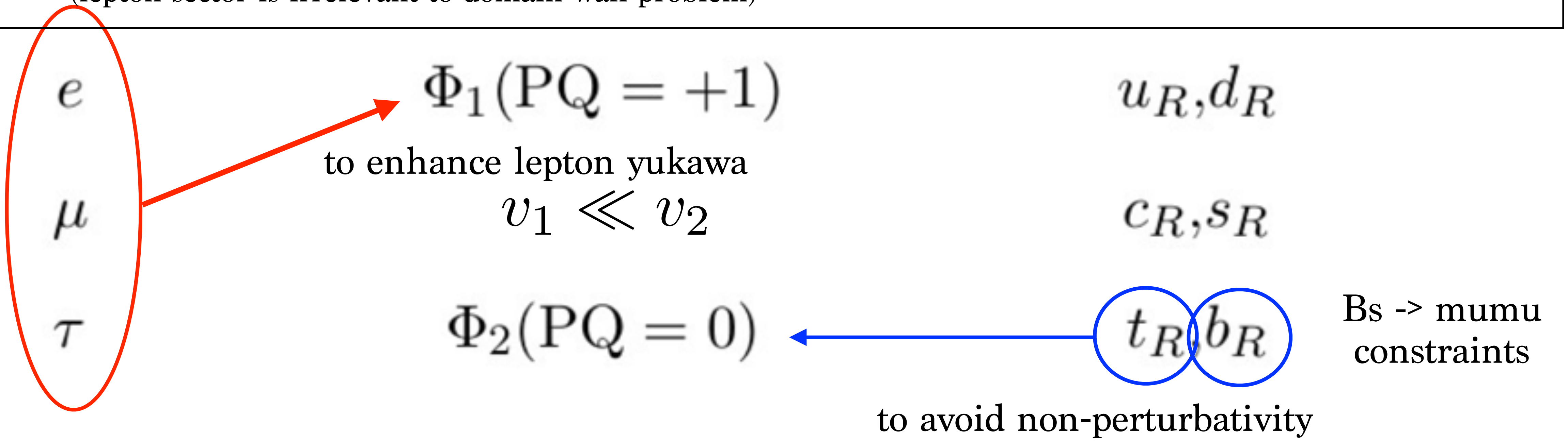

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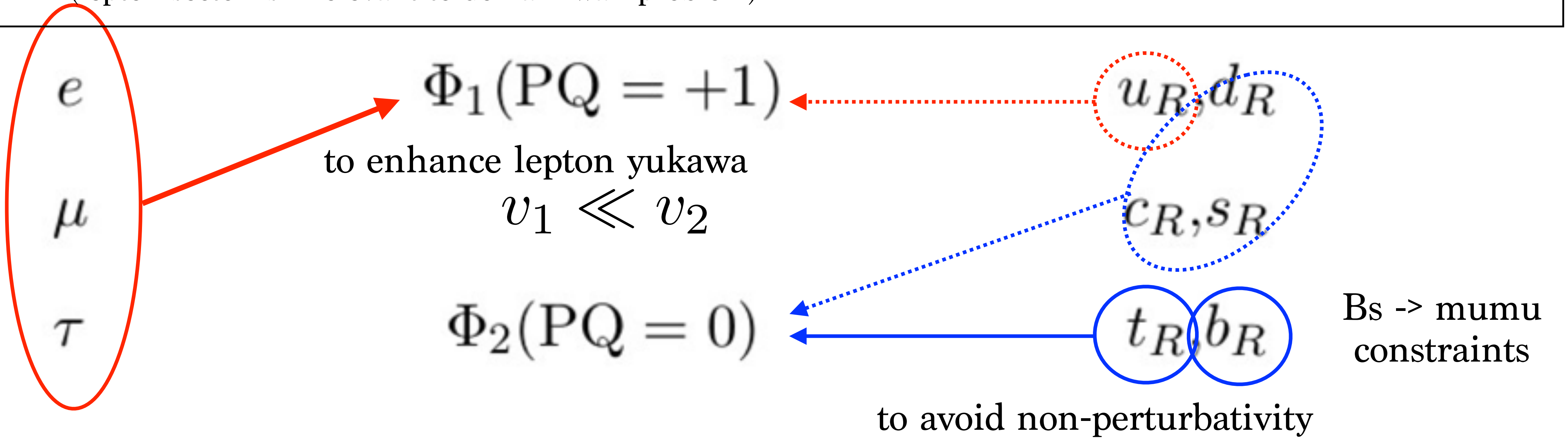


e

μ

τ

$\Phi_1(PQ = +1)$

to enhance lepton yukawa

$v_1 \ll v_2$

$\Phi_2(PQ = 0)$

u_R, d_R

c_R, s_R

t_R, b_R

Bs -> mumu constraints

to avoid non-perturbativity

several choices, but up-specific is most interesting possibility

charm-specific : opposite sign for g-2

down/strange-specific : very constrained by Kaon physics

up-type specific Variant Axion model

[C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida] Phys.Rev.D 98 (2018) 9, 095020

$$\begin{array}{ccccccccc} \Phi_1 & \Phi_2 & u_R & c_R & t_R & d_R & Q_L & \ell_R & L_L \\ + & - & - & + & + & + & + & - & + \end{array}$$

when we take up-type VAM,
top/charm/up FCNC is the generic prediction

For up-specific VAM,

Φ_2 only couple with u_R, e_R

$$L^u = -\Phi_1 \bar{u}_{Ra}[Y_{u1}]_{ai} Q_i - \Phi_2 \bar{u}_{R3}[Y_{u2}]_i Q_i + \text{h.c.}$$

$$Y_{u1} = \begin{pmatrix} * & * & * \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad Y_{u2} = \begin{pmatrix} 0 & 0 & 0 \\ * & * & * \\ * & * & * \end{pmatrix} ,$$

mix with β

Higgs basis
(only Φ^{SM}has a VEV)

$$\mathcal{L} = -\,\Phi^{\text{SM}} \bar{u}_{Rj}[Y_u^{\text{SM}}]_{ji} Q_i - \Phi' \bar{u}_{Ra}[Y'_u]_{ji} Q_i$$

$$Y'_u = -s_\beta Y_{u1} + c_\beta Y_{u2} = \begin{pmatrix} -\tan\beta & & \\ & \cot\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{\text{SM}}$$

$$\boxed{Y'_e = -\tan\beta \;\; Y_e^{\text{SM}}},$$

$$Y'_d = \cot\beta \;\; Y_d^{\text{SM}} .$$

diagonalizing mass matrix

$$Y_u^{\prime,\text{diag}} = \begin{pmatrix} -\tan\beta & & \\ & \cot\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{\text{diag}} + (\tan\beta + \cot\beta) H_u Y_u^{\text{diag}},$$

$$H_u = V_u \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} V_u^\dagger - \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} = \begin{pmatrix} \frac{\cos\rho_u - 1}{2} & 0 & \frac{\sin\rho_u}{2} \\ 0 & 0 & 0 \\ \frac{\sin\rho_u}{2} & 0 & \frac{1-\cos\rho_u}{2} \end{pmatrix} .$$

consider u-t mixing for simplicity

$$\boxed{\zeta_{uu} \equiv -\tan\beta - (\tan\beta + \cot\beta)\frac{\cos\rho_u - 1}{2} ,}$$

$$\zeta_{cc} \equiv \cot\beta ,$$

$$\zeta_{tt} \equiv \cot\beta - (\tan\beta + \cot\beta)\frac{1 - \cos\rho_u}{2} ,$$

$$\zeta_{ut} = \zeta_{tu} = (\tan\beta + \cot\beta)\frac{\sin\rho_u}{2} .$$

$$\xi^h_{ff'} \equiv s_{\beta-\alpha}\delta_{ff'} + c_{\beta-\alpha}\zeta_{ff'} ,$$

$$\xi^H_{ff'} \equiv c_{\beta-\alpha}\delta_{ff'} - s_{\beta-\alpha}\zeta_{ff'} ,$$

$$\xi^A_{ff'} \equiv (2T_3^f)\zeta_{ff'} ,$$

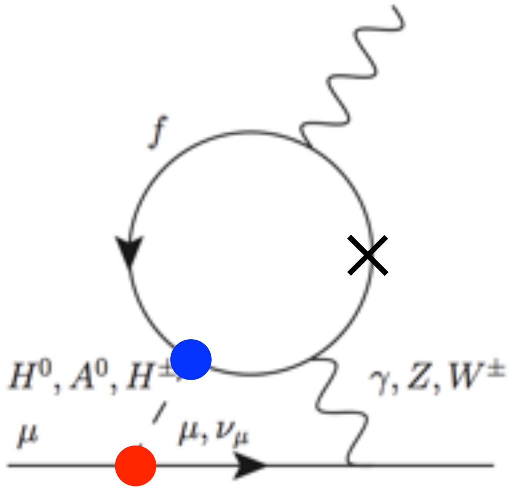
leptons and up: tan beta enhanced

FV $\propto\sim \sin\rho\tan\beta$

mixing eff. : ζ_{uu}:$-\tan\beta$ $\nearrow$, ζ_{tt} :$^{\cot\beta}\searrow$$-\tan\beta$

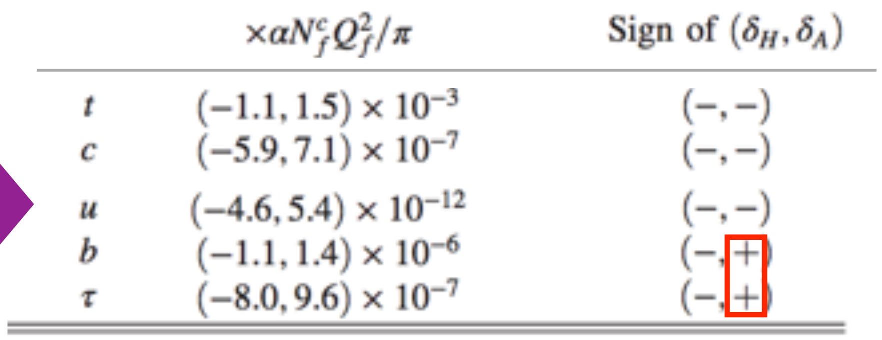
g-2 in Lepton-specific 2HDM with VAM

[C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida] Phys.Rev.D 98 (2018) 9, 095020



$$\propto m_\mu m_f^2/m_H^2$$

$$\Delta a_\mu^{\rm BZ} = \underbrace{\boxed{\frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}}}_{\sim 10^{-9}} \boxed{\frac{\alpha_{\rm EM}}{\pi} \sum_i^{h,H,A} \sum_f^{t,b,c,\tau} N_f^c Q_f^2 \xi_\mu^i \xi_f^i \frac{m_f^2}{m_i^2} g_i(r_f^i)}$$



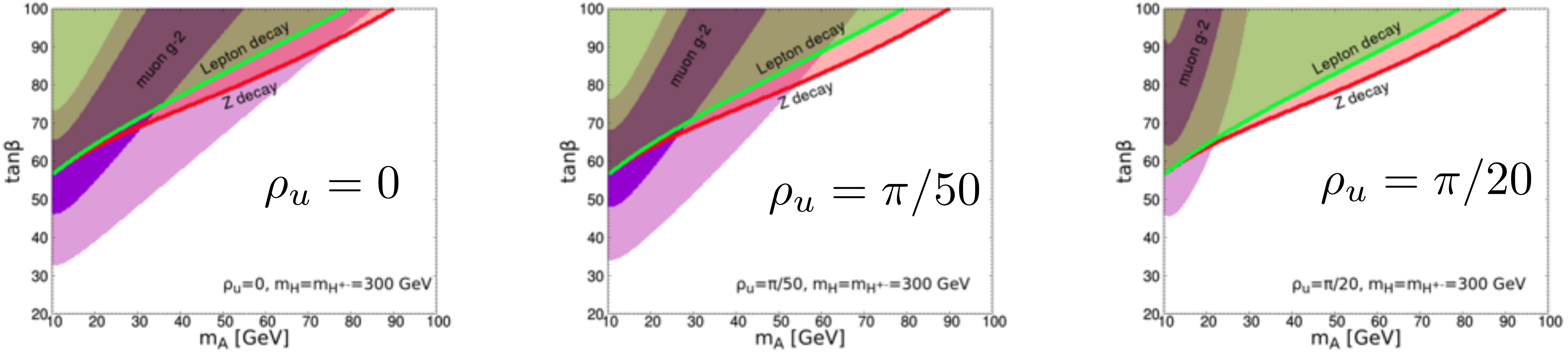
	$\times \alpha N_f^c Q_f^2/\pi$	Sign of (δ_H, δ_A)
t	$(-1.1, 1.5) \times 10^{-3}$	$(-,-)$
c	$(-5.9, 7.1) \times 10^{-7}$	$(-,-)$
u	$(-4.6, 5.4) \times 10^{-12}$	$(-,-)$
b	$(-1.1, 1.4) \times 10^{-6}$	$(-,\boxed{+})$
τ	$(-8.0, 9.6) \times 10^{-7}$	$(-,\boxed{+})$

opposite sign contributions -tan β enhanced for up-type ⇒ only up negligible

LFV doesn’t contribute directly to g-2, but affects the diagonal elements

FV $\propto\sim \sin\rho\tan\beta$

mixing eff. : $\zeta_{uu}{:}_{-\tan\beta} \nearrow, \zeta_{tt} :^{\cot\beta} \searrow_{-\tan\beta}$



switching on LFV coupling induces negative top-loop contribution ⇒ rather disfavored by g-2

but acceptable as long as a small mixing

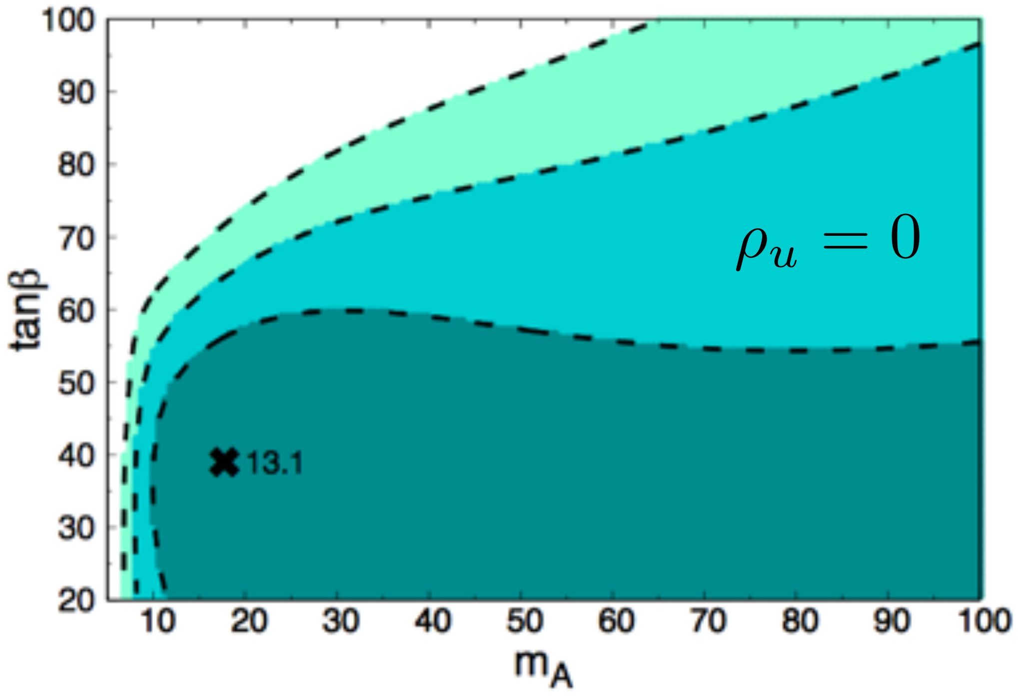
g-2 in Lepton-specific 2HDM with VAM

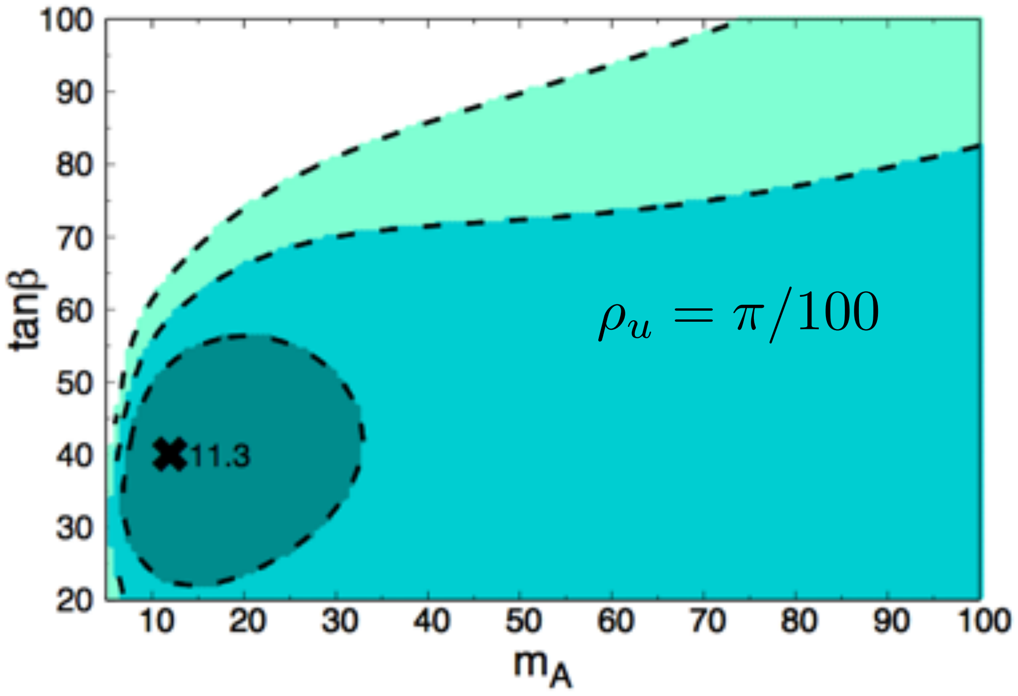
[C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida] Phys.Rev.D 98 (2018) 9, 095020

Bs→μμ observation exhibit a slight deficit from the SM prediction

$$\bar{R}_{s\mu} \equiv \frac{\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-)_{\mathrm{EXP}}}{\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}}} = 0.79 \pm 0.20$$

$$\frac{\mathcal{M}}{\mathcal{M}^{\mathrm{SM}}} = 1 + \frac{\mathcal{M}^{u\mathrm{VAM}}}{\mathcal{M}^{\mathrm{SM}}} \sim 1 - 0.21\xi_{tt}^{A}\xi_{\mu\mu}^{A}\left(\frac{15\mathrm{GeV}}{m_A}\right)^2 \sim 1.21 - 0.05\rho_u^2\tan^2\beta$$





for combined χ^2-fit including Bs→μμ, small mixing $\rho_u = \pi/100$ slightly improves the fit

mA ~ 15GeV, tanβ~40, $\rho_u \sim 0.03$ will give a best fit

[C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida] Phys.Rev.D 98 (2018) 9, 095020

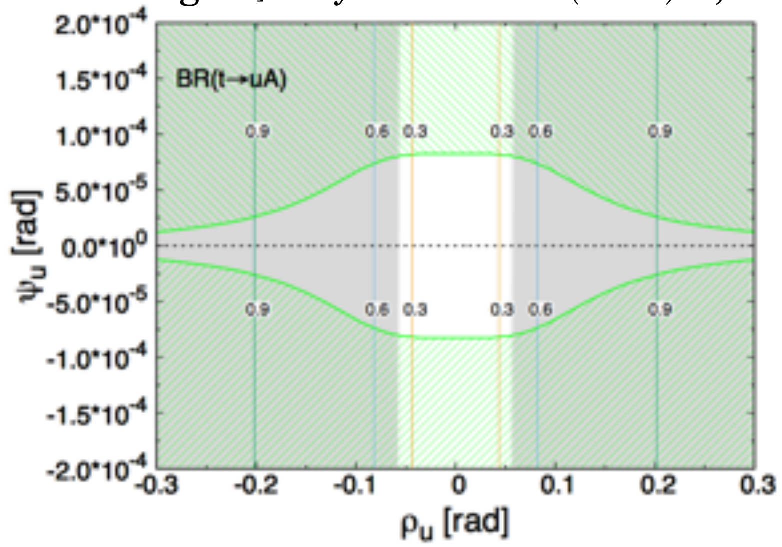
$t \to u A \, , A \to \tau \, \tau$

even for a slight mixing ρ~0.03 induces large *BR(t*→*uA)* ~O(10%)

$$\Gamma_{t \to uA/cA} \propto\sim \sin^2 \rho_u \tan^2 \beta$$

A decays dominantly to $\tau\tau$ about 100%

important signal from top pair production : $t\bar{t} \to t\bar{u}A, A \to \tau\tau$



$\Gamma_{t,\mathrm{tot}} \leq 2.5\mathrm{GeV} \to BR(t \to uA/cA) \lesssim 40\%$ $|\rho_u| \lesssim 0.06$

recast the LHC searches for *bbA*, *A*→$\tau\tau$, in the context of MSSM (type II)

(CMS at 8TeV in μτ, eτ, eμ modes)

kinematics is different between *tuA* and *bbA*

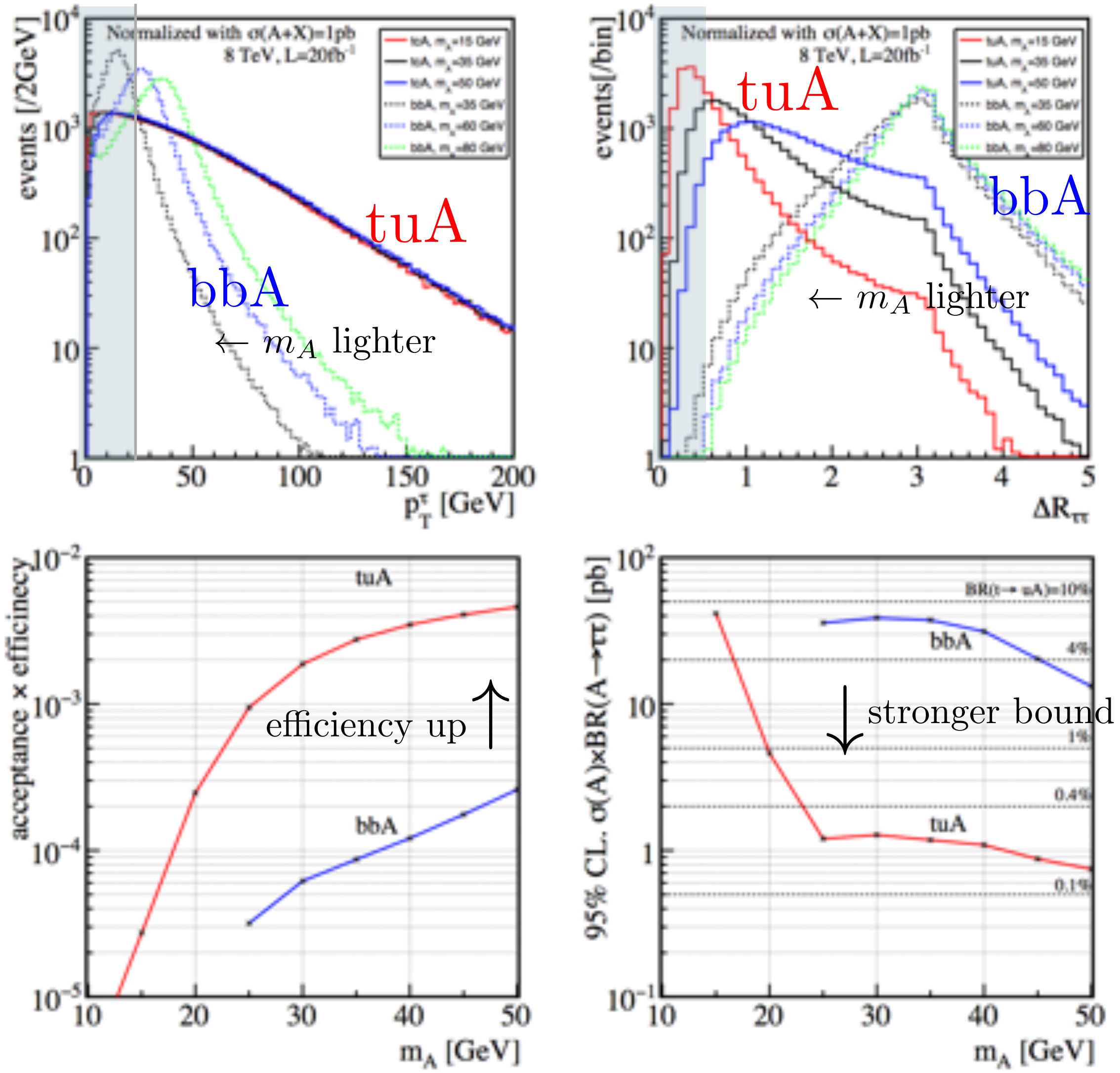
— efficiency for *tuA*

higher due to $p_{T,\tau}$ cut

quickly goes down as $m_A \to 0$ due to ΔR cut

we estimate 8 TeV sensitivity,

BR(t→*uA)* < 0.2% (*mA*>25GeV), 10% (*mA*=15GeV) : marginal

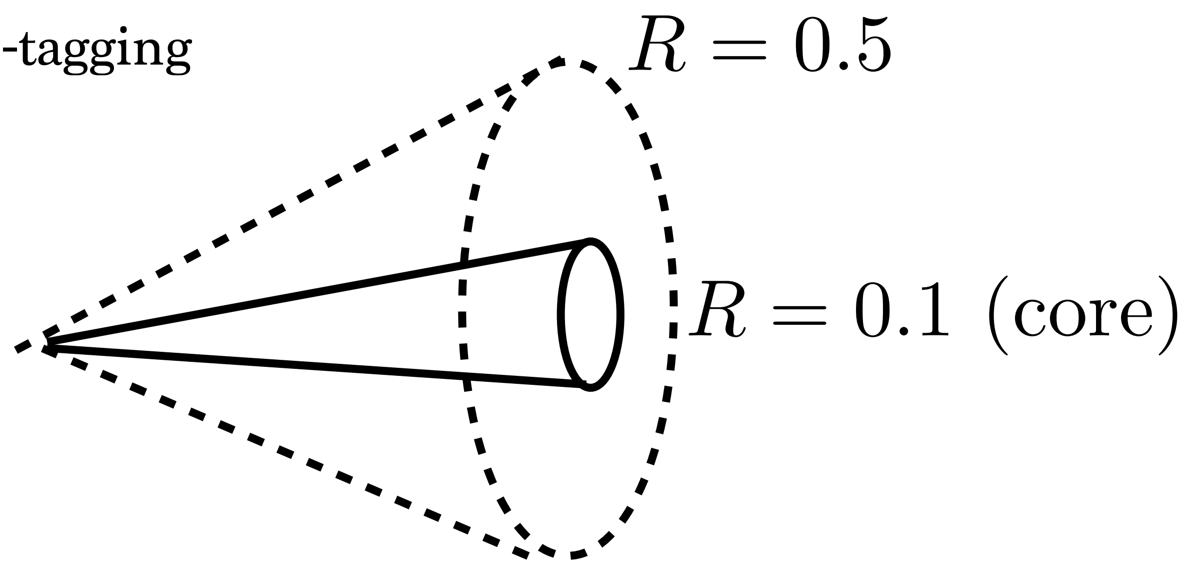


boosted A → $\tau\ \tau$

[C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida] Phys.Rev.D 98 (2018) 9, 095020

The reason for rapid drop of the efficiency is due to the overlapping τ's due to the boost

τ-tagging

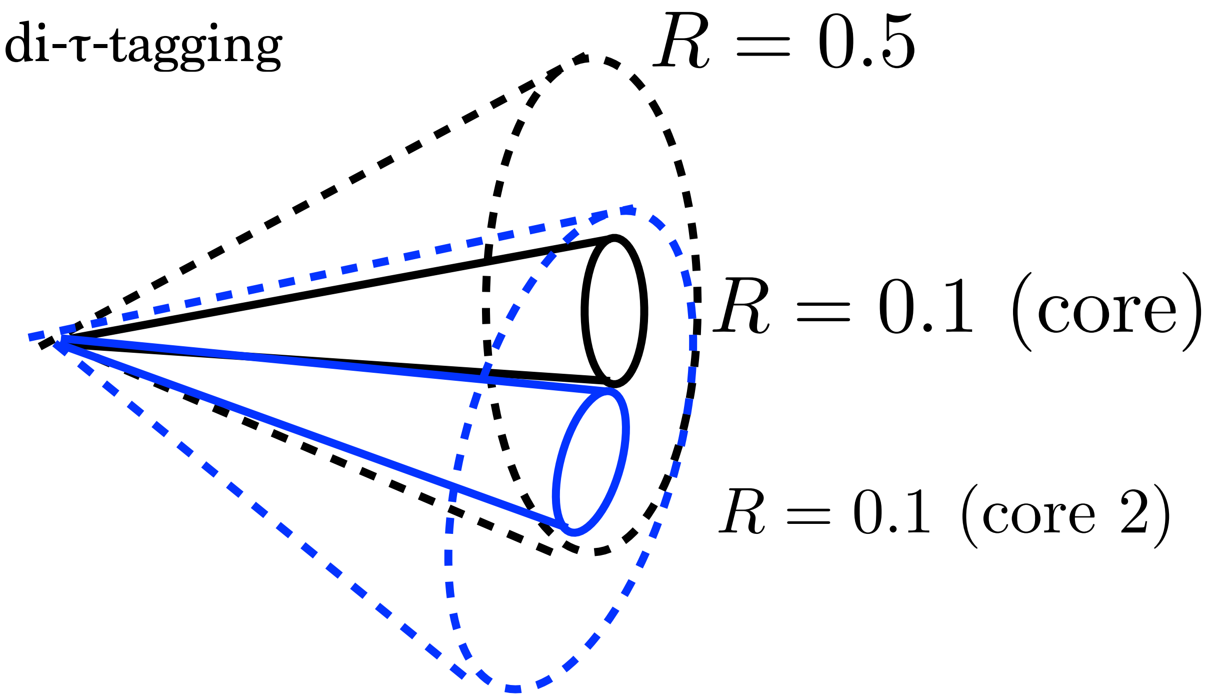


require energy deposit in the core part

$$f = \frac{E(R = 0.1)}{E(R = 0.5)} > 0.95$$

for boosted tau pair the usual isolation fails

di-τ-tagging

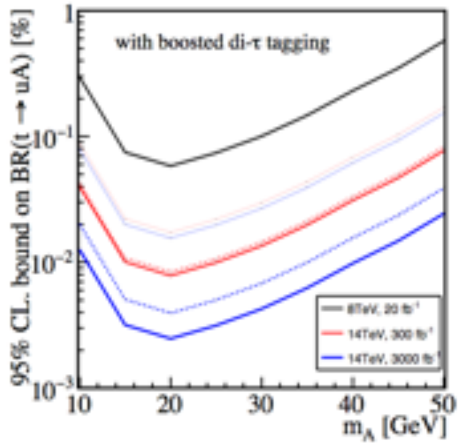


mutual isolation

[A. Katz, M. Son, B. Tweedie, PRD 83, 114033(2011).]

if core 1 is removed, the rest is τ-tagged

if core 2 is removed, the rest is also τ-tagged



For *mA*=15GeV

BR(*t*→*uA*) < 0.08%

(10% by CMS study)

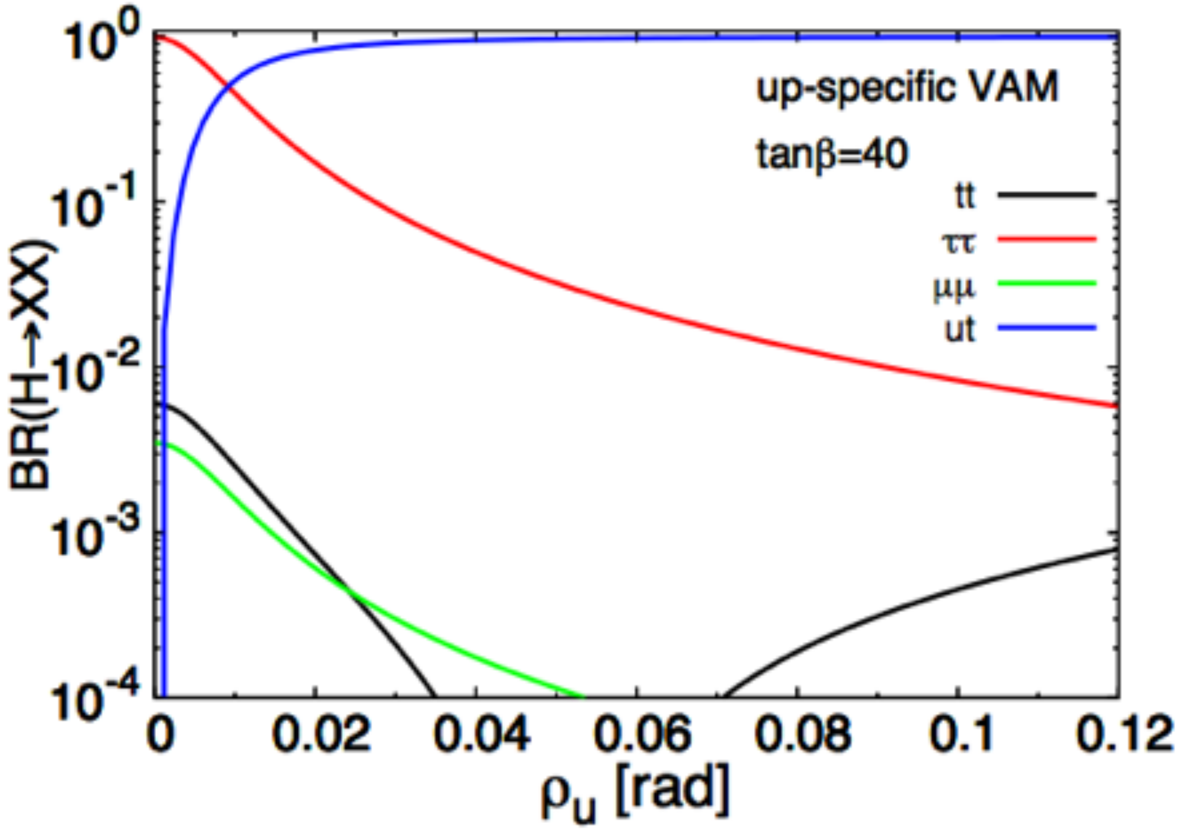
0.003-0.01% in future

Flavor violating Heavy higgs decays

[C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida] Phys.Rev.D 98 (2018) 9, 095020

For $m_H \gg m_t$ and tan $\gg 1$, we have

$$\frac{BR(H \to tu)}{BR(H \to \tau\tau)} \sim \frac{m_t^2}{m_\tau^2}\frac{3\sin^2\rho_u}{2} \simeq (120 \cdot \sin\rho_u)^2$$



the flavor-violating decay $H \to tu$ dominates for $\rho_u \gtrsim 1/120$.

$$\mathcal{L} \supset \sum_{f,f'}^{u,c,t,d,s,b,e,\mu,\tau} -\frac{m_{f'}}{v}(\xi^h_{ff'} h \bar{f}_R f'_L + \xi^H_{ff'} H \bar{f}_R f'_L + i\xi^A_{ff'} A^0 \bar{f}_R f'_L) + \text{h.c},$$

$$\xi^h_{ff'} \equiv s_{\beta-\alpha}\delta_{ff'} + c_{\beta-\alpha}\zeta_{ff'} ,$$

$$\xi^H_{ff'} \equiv c_{\beta-\alpha}\delta_{ff'} - s_{\beta-\alpha}\zeta_{ff'} ,$$

$$\xi^A_{ff'} \equiv (2T_3^f)\zeta_{ff'} ,$$

$$\zeta_{ff'} = \begin{array}{ll} \cot\beta\,\delta_{ff'} & (\text{for } f = d, s, b) , \\ -\tan\beta\,\delta_{ff'} & (\text{for } f = e, \mu, \tau) \end{array}$$

$$\zeta_{uu} \equiv -\tan\beta - (\tan\beta + \cot\beta)\frac{\cos\rho_u - 1}{2} ,$$

$$\zeta_{cc} \equiv \cot\beta ,$$

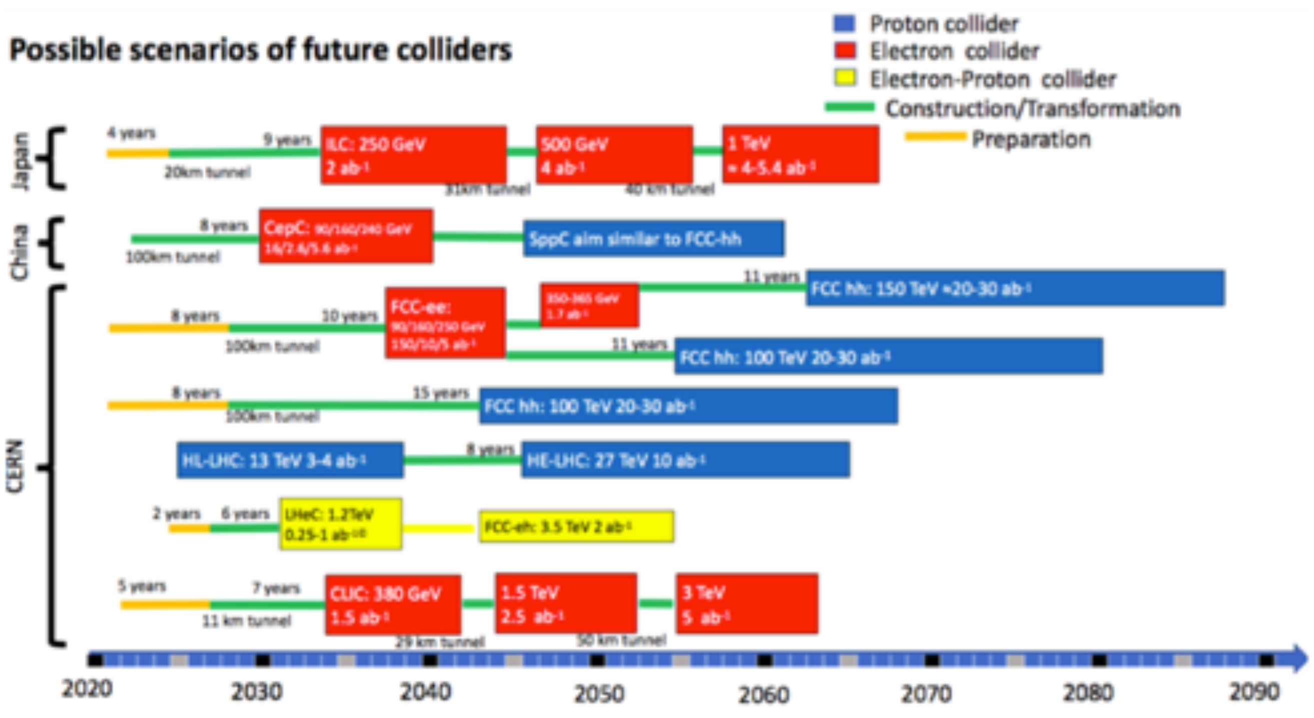
$$\zeta_{tt} \equiv \cot\beta - (\tan\beta + \cot\beta)\frac{1 - \cos\rho_u}{2} ,$$

$$\zeta_{ut} = \zeta_{tu} = (\tan\beta + \cot\beta)\frac{\sin\rho_u}{2} .$$

very striking signature of the up-specific Variant Axion Model

LHeC

arXiv: 2007.14491



The timeline for different scenarios for future colliders.

CDR default e-beam : 60GeV $\sqrt{s} = 1.3$ TeV

new default : 50 GeV (initially 30GeV)

$$\sqrt{s} = 1.2 \text{ TeV}$$

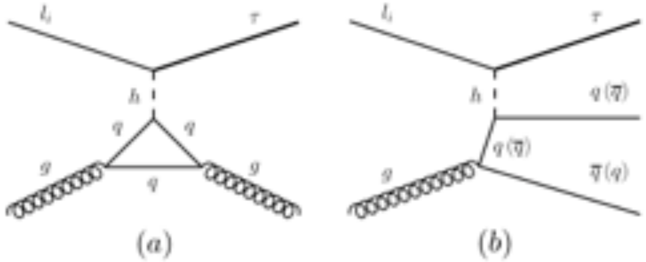
$$\mathcal{O}(1)\text{ab}^{-1}/\text{year}$$

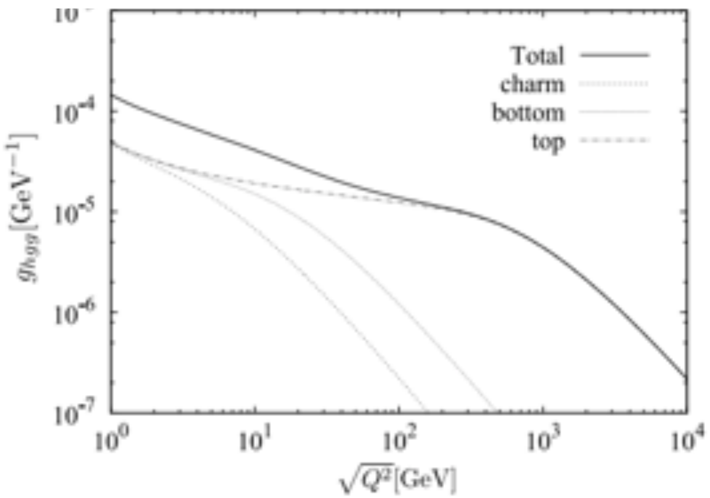
DIS, better determination of PDF

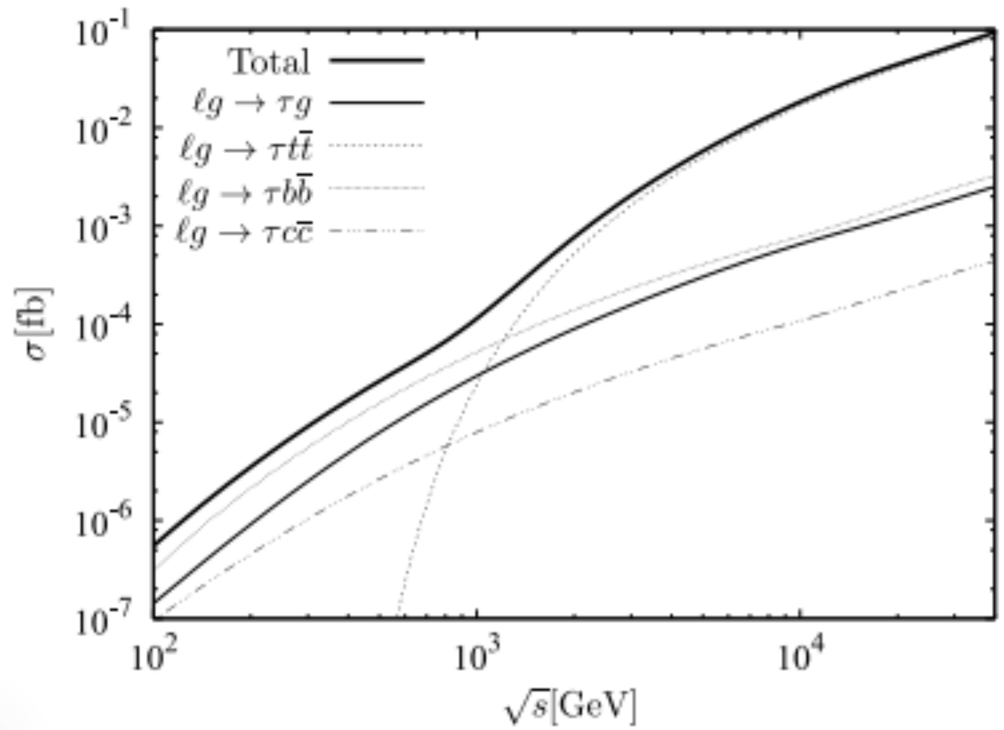
it would reduce the systematic uncertainty of the data obtained at HL-LHC

Higgs mediated CLFV scattering

MT, Y. Uesaka, M. Yamanaka
Phys. Lett. B 772, 279-282 (2017) [arXiv:1705.01059]







For maximally allowed coupling,

$$\sqrt{|\rho_{e\tau}|^2 + |\rho_{\tau e}|^2} = 2.4 \times 10^{-3}$$

$\mathcal{O}(100)$events would be produced

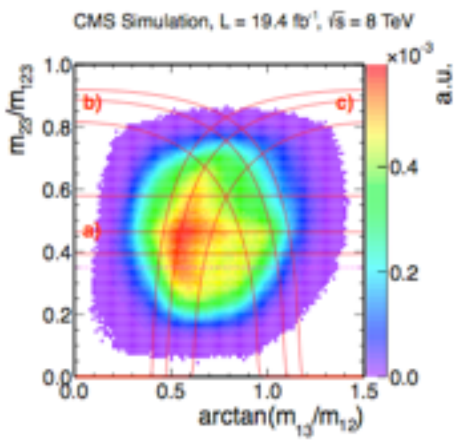
Remark

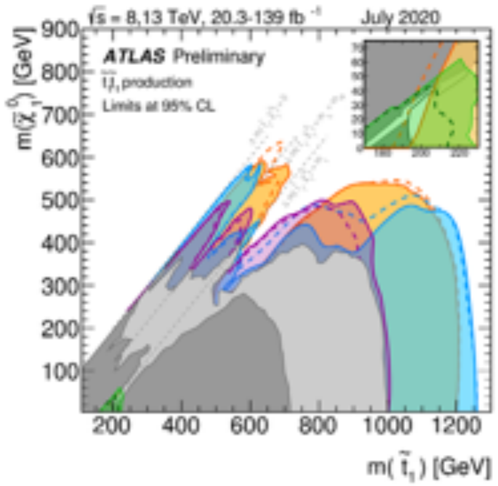
motivated by the problems of the SM, focusing on TeV scale new particles.

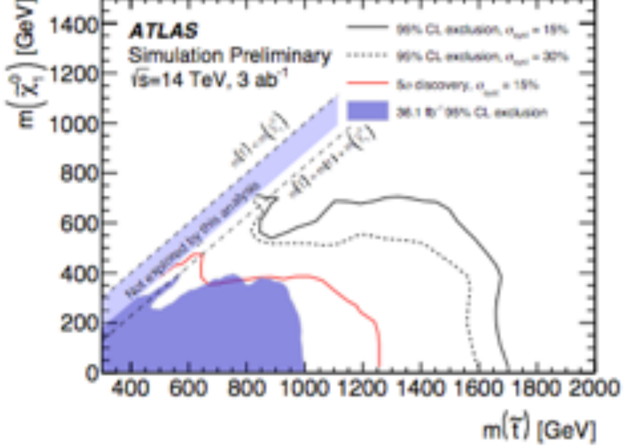
If new particles exist, how can we probe them ?

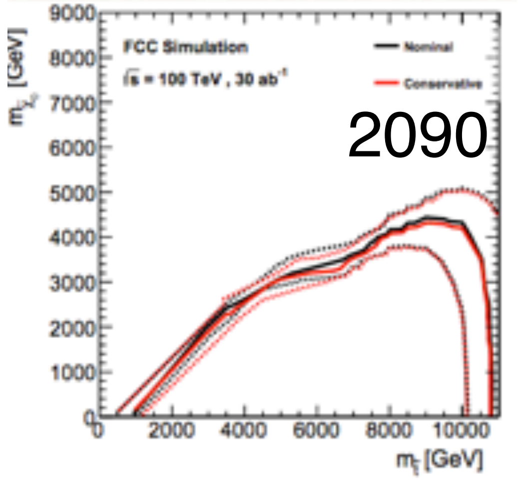
With high stats of LHC, we can probe new particles.

Phenomenology: we would like to test the hypothesis in the real world







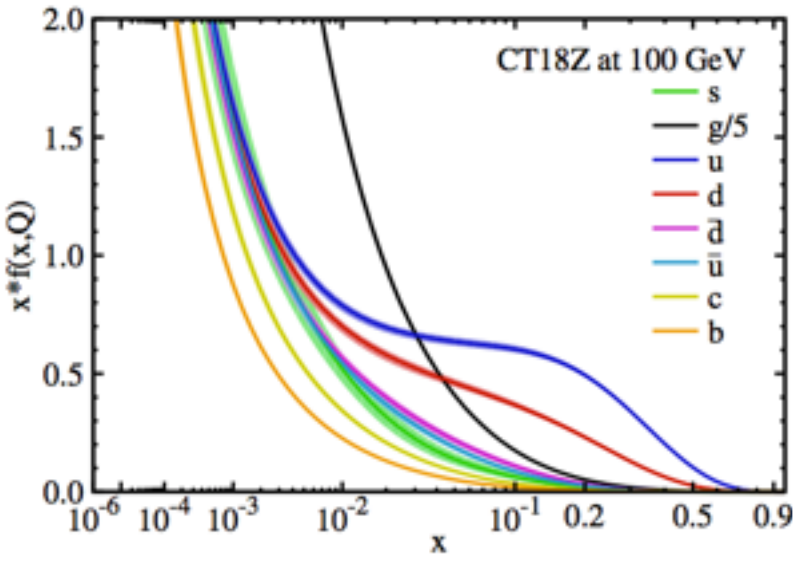


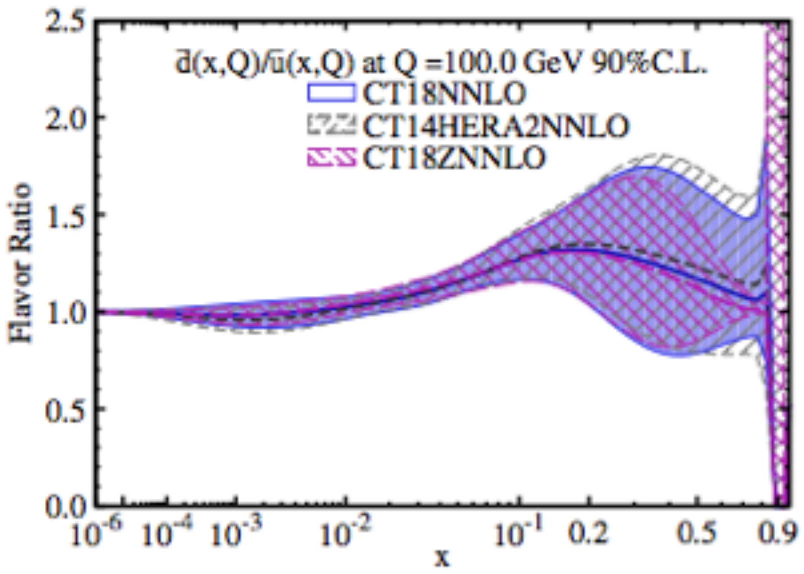
problem : **the type of researches that if new particles exist, how we can probe them** → **unrealistic waiting time**

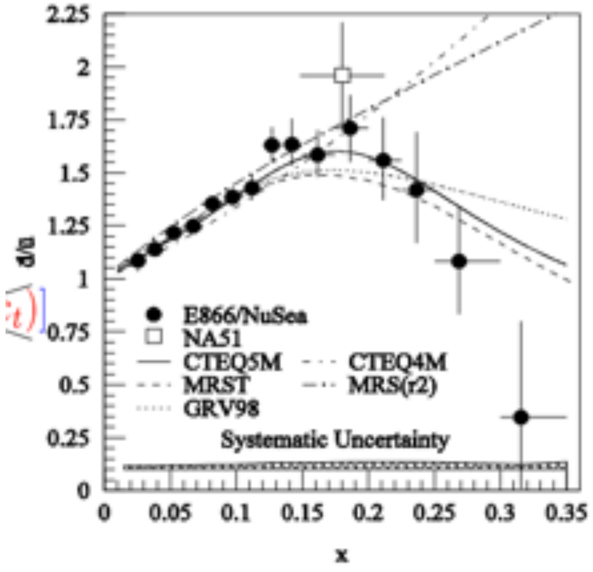
It's time to learn from data.

interesting facts possibly hidden in uncertainty

ex.) dbar/ubar ratio in PDF in proton







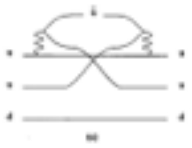
$$\bar{d} > \bar{u}$$

Once measured unexpectedly different

From gluon splitting, we expected dbar=ubar

since p(uud) , $g \to u\bar{u}$ suppressed by Pauli exclusion principle

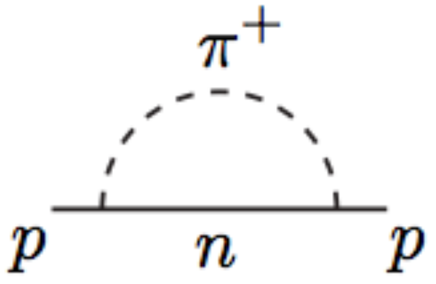
Field, Feynman, Phys. Rev. D15 (1977) 2590



explicit calculation gives 1% difference, and $\bar{u} > \bar{d}$

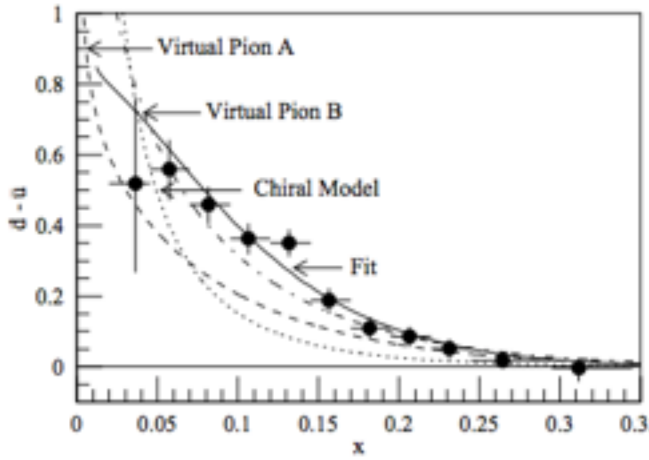
Ross, Sachrajda, Nucl. Phys. B149 (1979) 497
Steffens, Thomas, Phys. Rev. 55 (1997) 900

It seems due to Pion cloud $uud \to (udd)(u\bar{d}) \to uud$



Sullivan, Phys. Rev. D5 (1972) 1732
Thomas, Phys. Lett. 126B (1983) 97

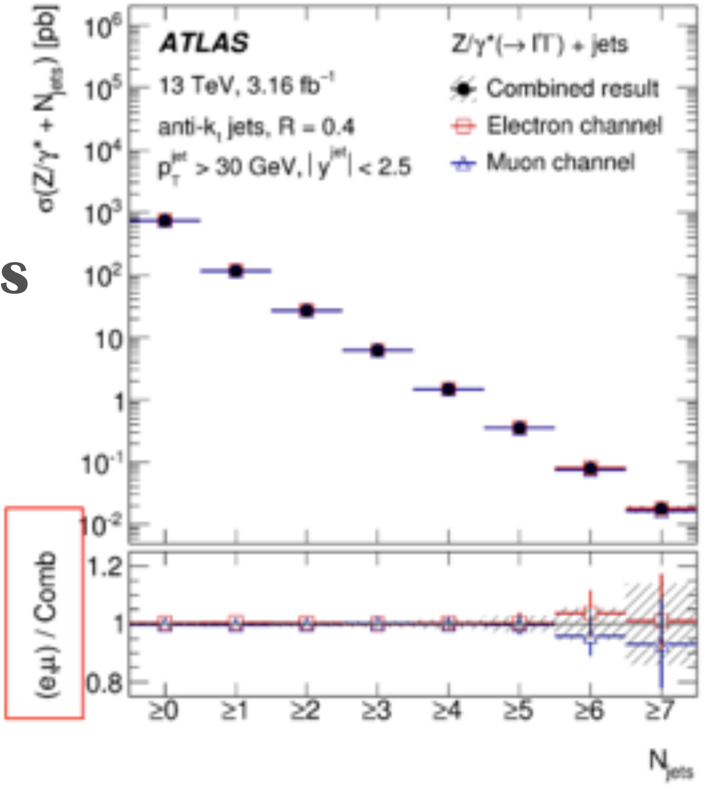
$$\bar{d} > \bar{u}$$

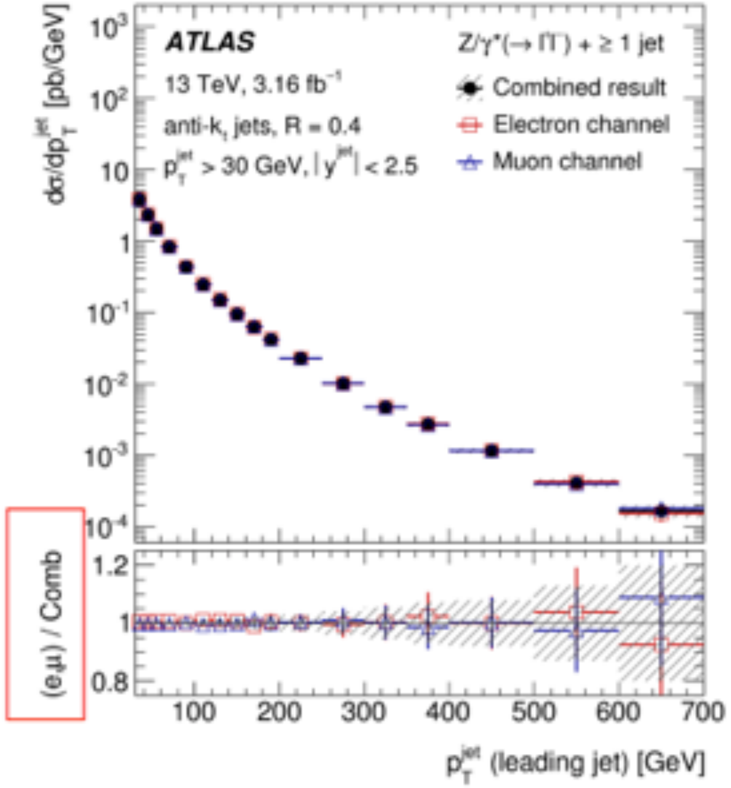


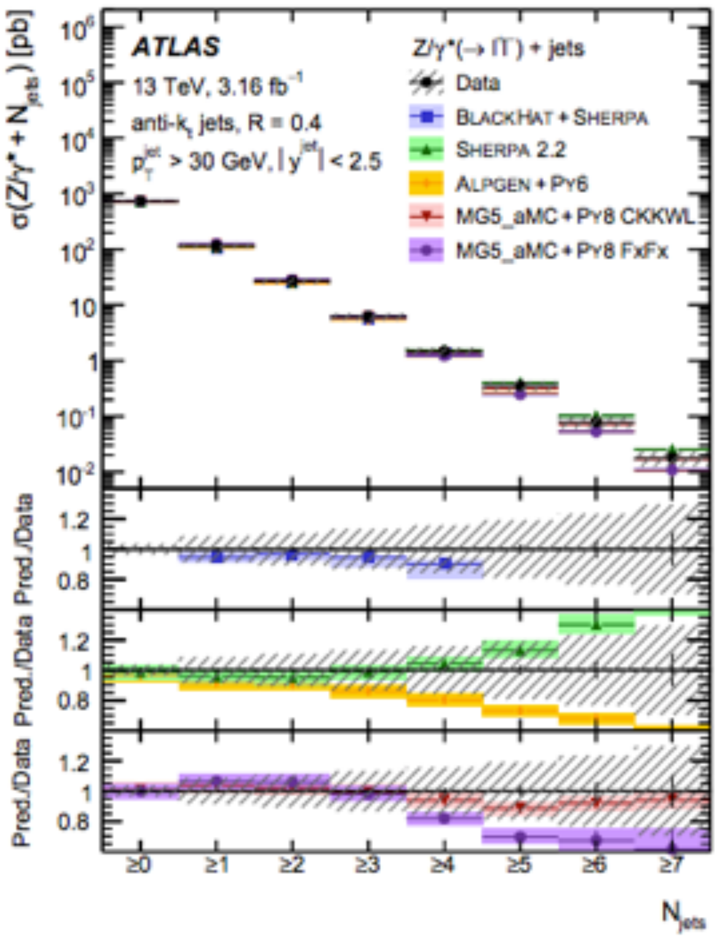
LHC is a W, Z, top, Higgs factory

W,Z: 100nb, tt:1nb, H:50pb $\Rightarrow \sim 10^{11}, 10^{9}, 10^{8}$ **at 3ab-1**

Z + n jets

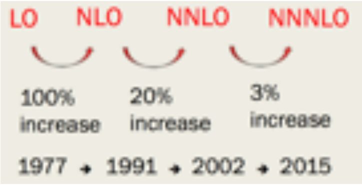






theory cannot reproduce all, but data exist

cf） Higgs cross section



For example, correlation among 4 jets, we might be able to check or to find new facts? With 1d plots not enough, however, 2d plots would be already difficult to understand.

Can we find new facts with Machine Learning as a tool ?

Machine Learning for Jet physics

A. Chakraborty, S.-H. Lim, M. M. Nojiri, MT
JHEP 07 (2020) 111[arXiv:2003.11787]

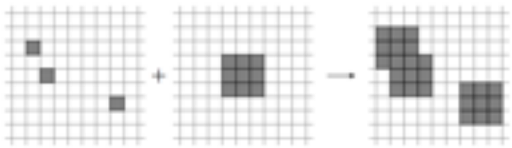
Using the ML developed for Image recognition CNN, top jet vs. QCD jet from jet images as inputs

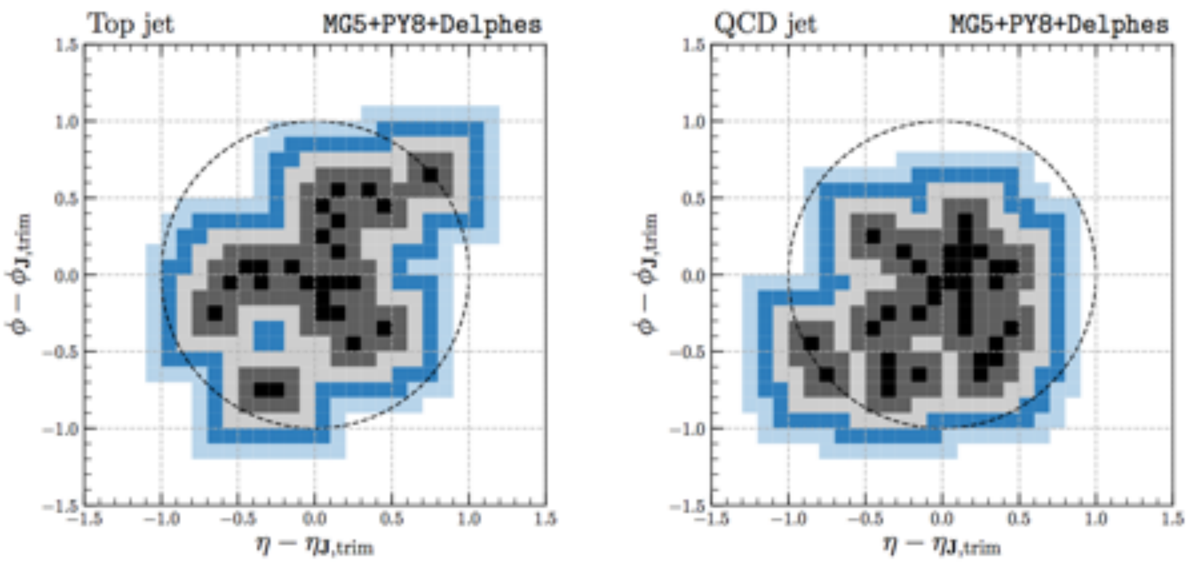
It is known that it is better than the conventional approaches

To understand what is important in CNN, we divide inputs into 2 categories and construct DNN and compared

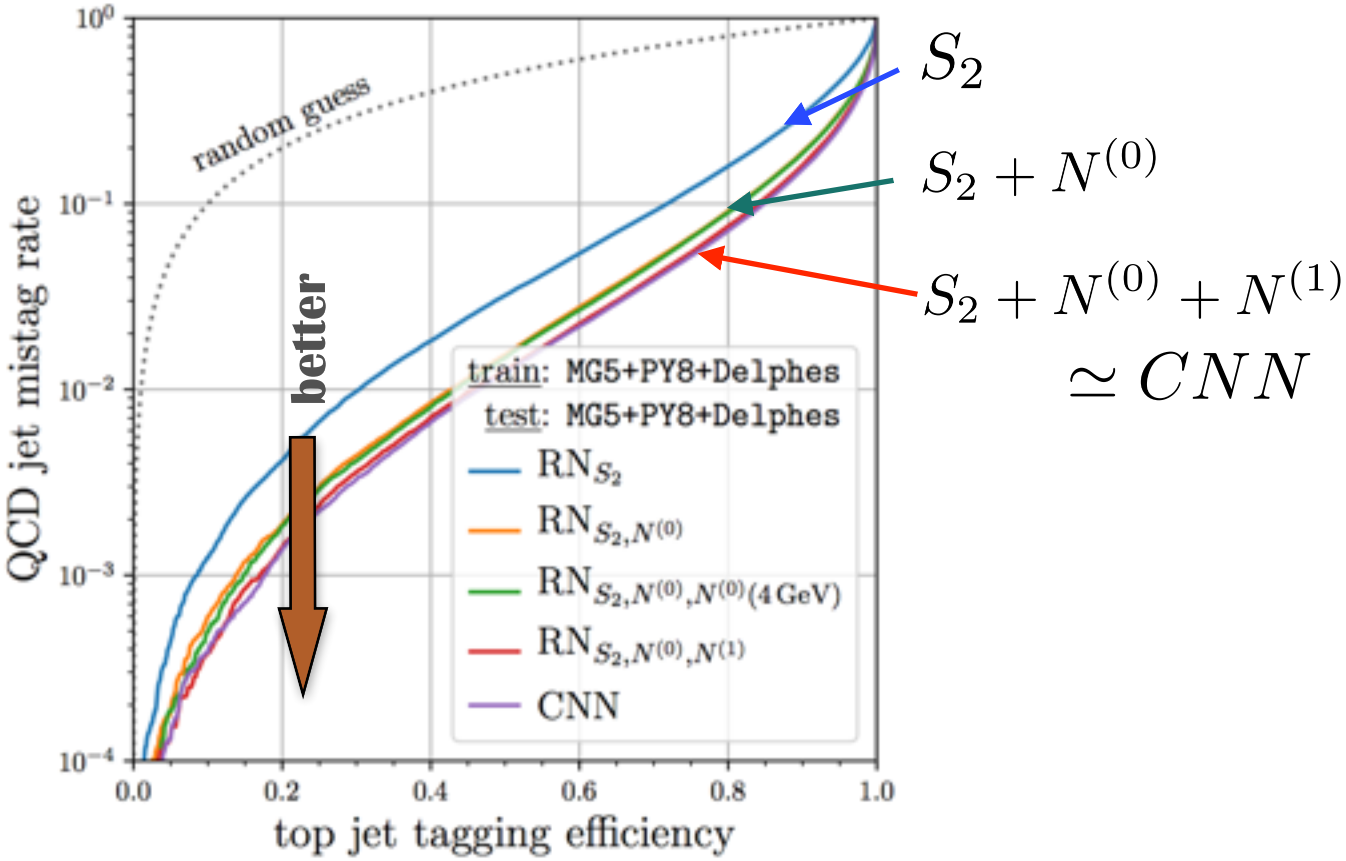
- **2point correlation** S_2 **(pQCD based, traditional variable)**
- **calorimeter hit** $N^{(0)}$**, and an extension** $N^{(1)}$ **(non-perturbative quantities)**

$N^{(0)} \to N^{(1)}$:





QCD jet : more hits and denser



We show adding $N^{(0)}, N^{(1)}$ **DNN approaches the performance of the CNN**
non-perturbative quantities affects the separation

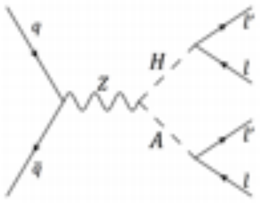
Summary

Naturalness : we probably just enter the natural parameter space finally
lots of opportunities at LHC

Higgs physics at HL-LHC, future colliders

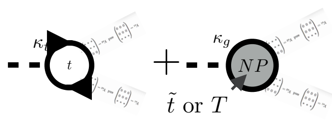
1. Heavy higgs states searches

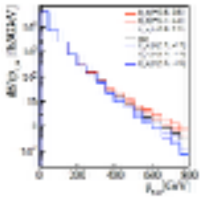
flavor anomalies : gradually sensitive at LHC

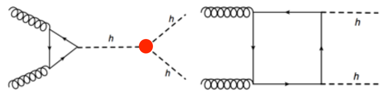


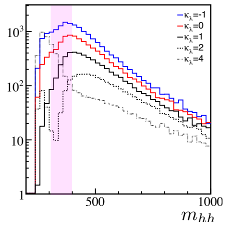
2.3. Higgs factory / top factory

2. pT distribution :





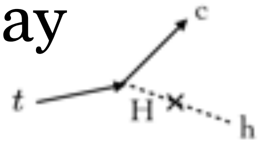


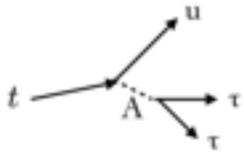


different pT bin gives independent information

3. rare decays :

interesting to consider FV higgs/top decay





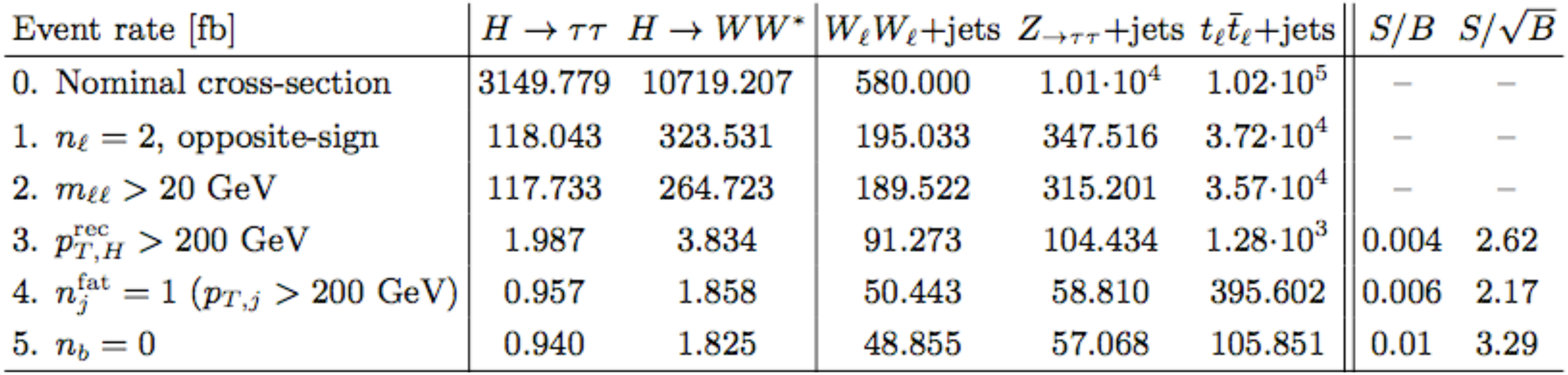
It is time to learn from data, ML helps?

If you are interested in this direction, please contact me.

takeuchi@kmi.nagoya-u.ac.jp

Backup

Cut flow



Event rate [fb]	$H \to \tau\tau$	$H \to WW^*$	$W_\ell W_\ell$+jets	$Z_{\to\tau\tau}$+jets	$t_\ell \bar{t}_\ell$+jets	S/B	$S/\sqrt{B}$
0. Nominal cross-section	3149.779	10719.207	580.000	$1.01 \cdot 10^4$	$1.02 \cdot 10^5$	–	–
1. $n_\ell = 2$, opposite-sign	118.043	323.531	195.033	347.516	$3.72 \cdot 10^4$	–	–
2. $m_{\ell\ell} > 20$ GeV	117.733	264.723	189.522	315.201	$3.57 \cdot 10^4$	–	–
3. $p_{T,H}^{\text{rec}} > 200$ GeV	1.987	3.834	91.273	104.434	$1.28 \cdot 10^3$	0.004	2.62
4. $n_j^{\text{fat}} = 1$ ($p_{T,j} > 200$ GeV)	0.957	1.858	50.443	58.810	395.602	0.006	2.17
5. $n_b = 0$	0.940	1.825	48.855	57.068	105.851	0.01	3.29

Basic selection cut:

$$n_\ell = 2,\ \text{opposite-sign},\ m_{\ell\ell} > 20\text{GeV},\ p_{T,H}^{\text{rec}} > 200\ \text{GeV},\ n_j^{\text{fat}} = 1,\ n_b = 0$$

$$\mathbf{p}_{T,H}^{\text{rec}} = \mathbf{p}_{T,\ell_1} + \mathbf{p}_{T,\ell_2} + \not{\mathbf{p}}_T$$

WW, Z, $t\bar{t}$ contribute at similar level

How accurate λ measurement would be interesting ?

EWSB phase transition at early universe

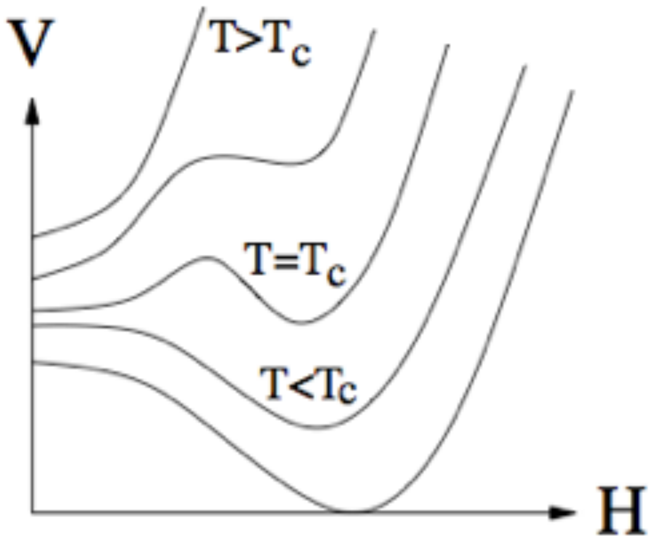
finite temp. effective higgs potential

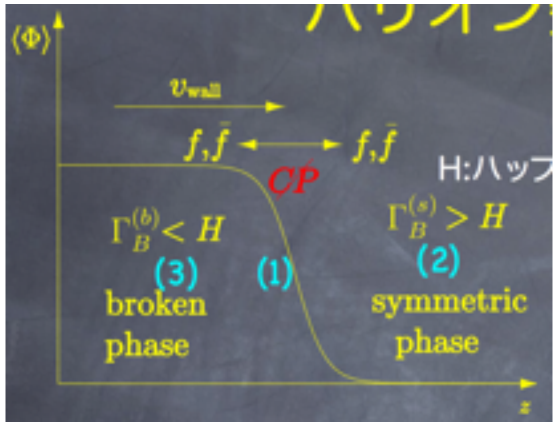
$$V(h) = \frac{\lambda}{4}h^4 + \lambda v h^3 + \cdots = \frac{\lambda_4}{4!}h^4 + \frac{\lambda_3}{3!}h^3 +$$

$$V_{\rm tot} \cong m_H^2(T)H^2 - ETH^3 + \lambda H^4$$

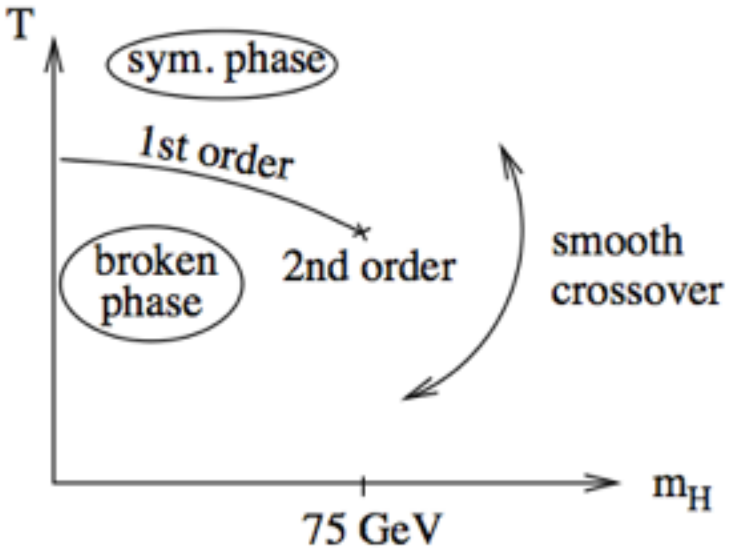
in the SM $\lambda_{\rm SM} \approx 1/8.$

$$\lambda_4 = 6\lambda \qquad \lambda_3 = 6\lambda v = \frac{3m_h^2}{v}$$





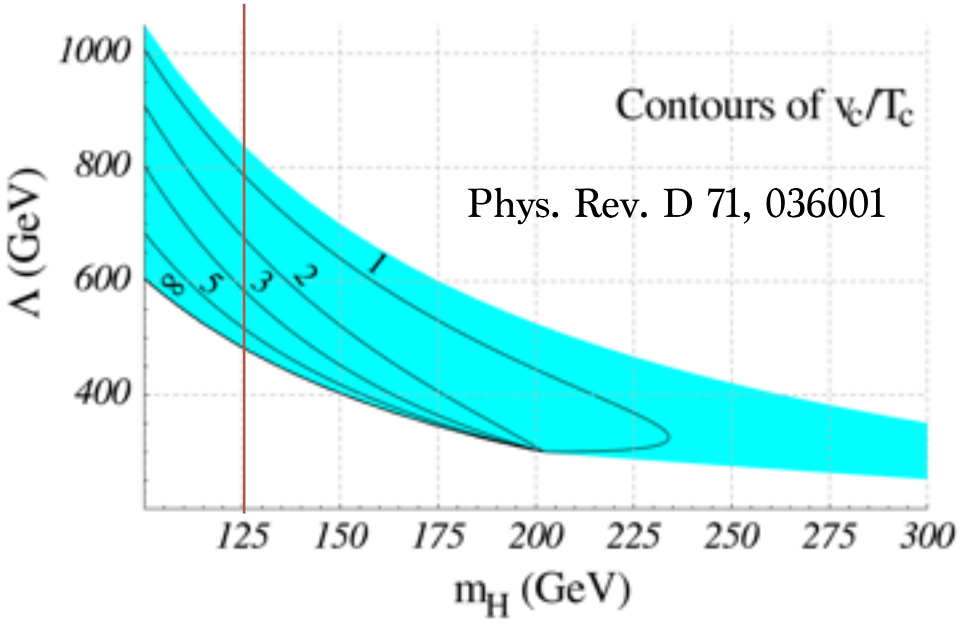
For EW baryogenesis successful strong 1st order PT (vc/Tc > 1) required (necessary condition)

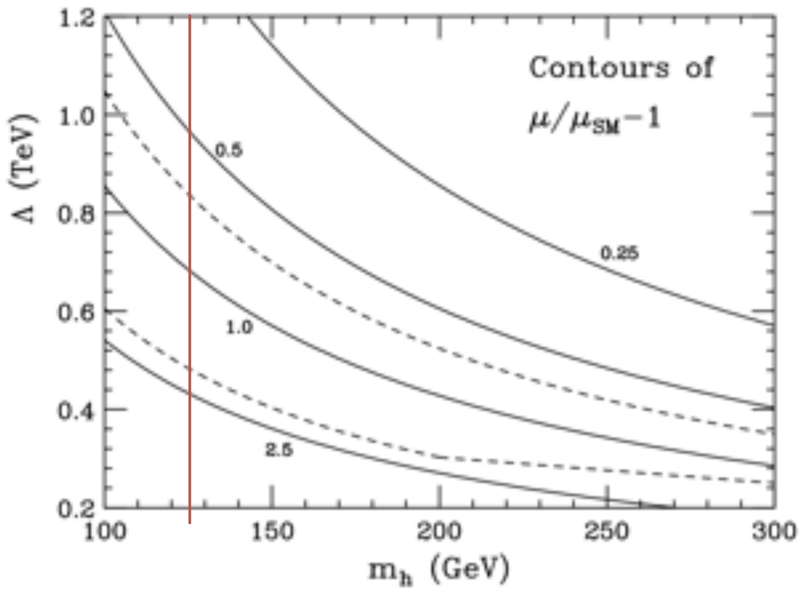


125 GeV Higgs is too heavy for EWBG successful

Considering new physics by dim.6 op.

$$V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \frac{1}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3$$





strong 1st order PT → O(1) deviation in λ_3 required

[C. Grojean, G. Servant, J. Wells]

$$\lambda_3 = \frac{3m_h^2}{v} + \frac{6v^3}{\Lambda^2} \gtrsim 1.7\lambda_{3,\rm SM}$$

To exclude this EWBG scenario, 70% level measurements required for λ_3

the statement is rather general

[Phys.Rev. D97 (2018) no.7, 075008
M. Reichert, A. Eichhorn, H. Gies, J. M. Pawlowski, T. Plehn, M. M. Scherer]

$$V_{k=\Lambda} = \frac{\mu^2}{2}\phi^2 + \frac{\lambda_4}{4}\phi^4 + \Delta V,$$

$$\Delta V_6 = \lambda_6 \frac{\phi^6}{\Lambda^2}, \qquad \Delta V_8 = \lambda_6 \frac{\phi^6}{\Lambda^2} + \lambda_8 \frac{\phi^8}{\Lambda^4},$$

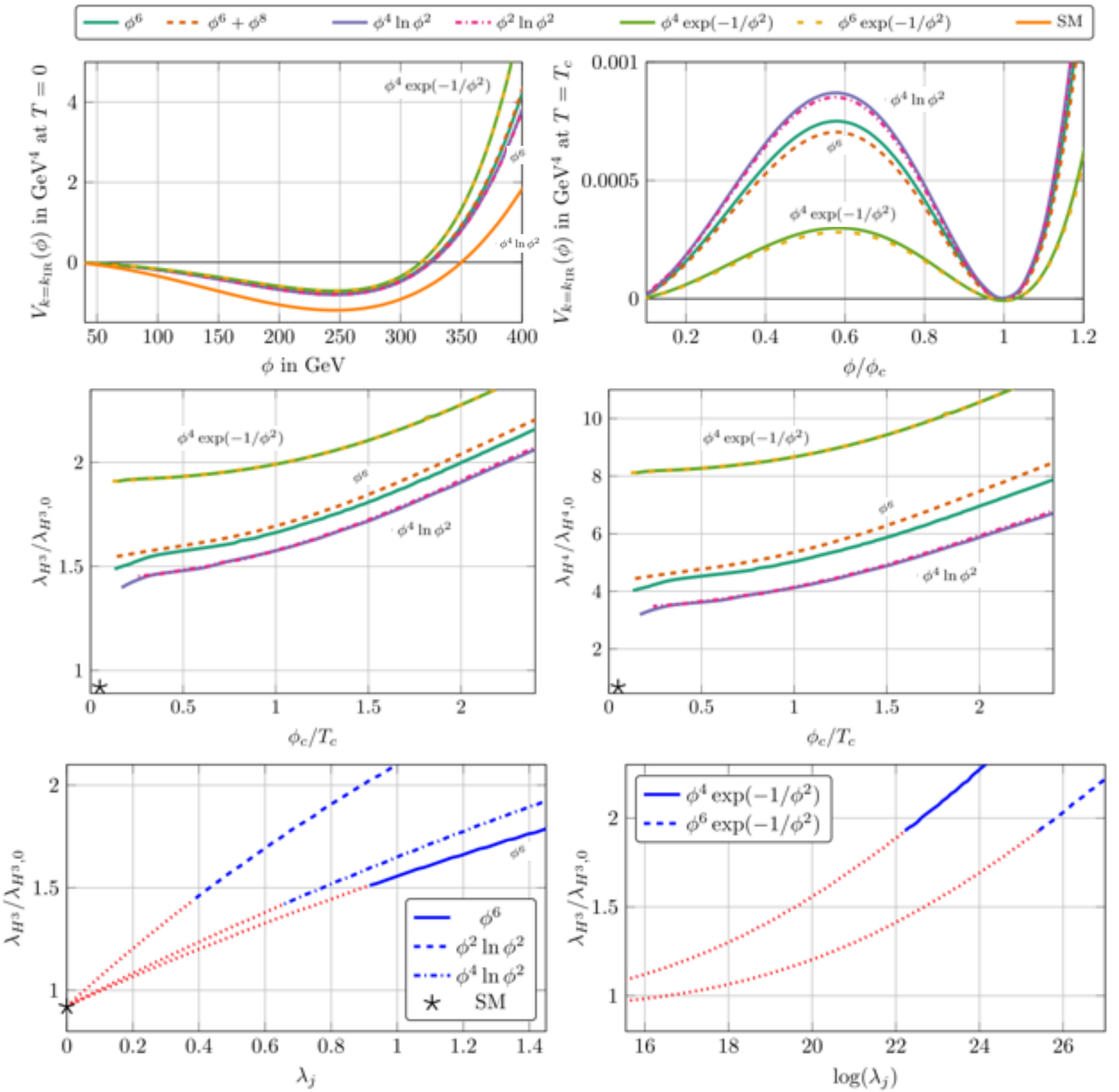
$$\Delta V_{\ln,2} = -\lambda_{\ln,2} \frac{\phi^2 \Lambda^2}{100} \ln \frac{\phi^2}{2\Lambda^2},$$

$$\Delta V_{\ln,4} = \lambda_{\ln,4} \frac{\phi^4}{10} \ln \frac{\phi^2}{2\Lambda^2},$$

$$\Delta V_{\exp,4} = \lambda_{\exp,4} \phi^4 \exp\left(-\frac{2\Lambda^2}{\phi^2}\right),$$

$$\Delta V_{\exp,6} = \lambda_{\exp,6} \frac{\phi^6}{\Lambda^2} \exp\left(-\frac{2\Lambda^2}{\phi^2}\right).$$

Considering 3 types of potentials

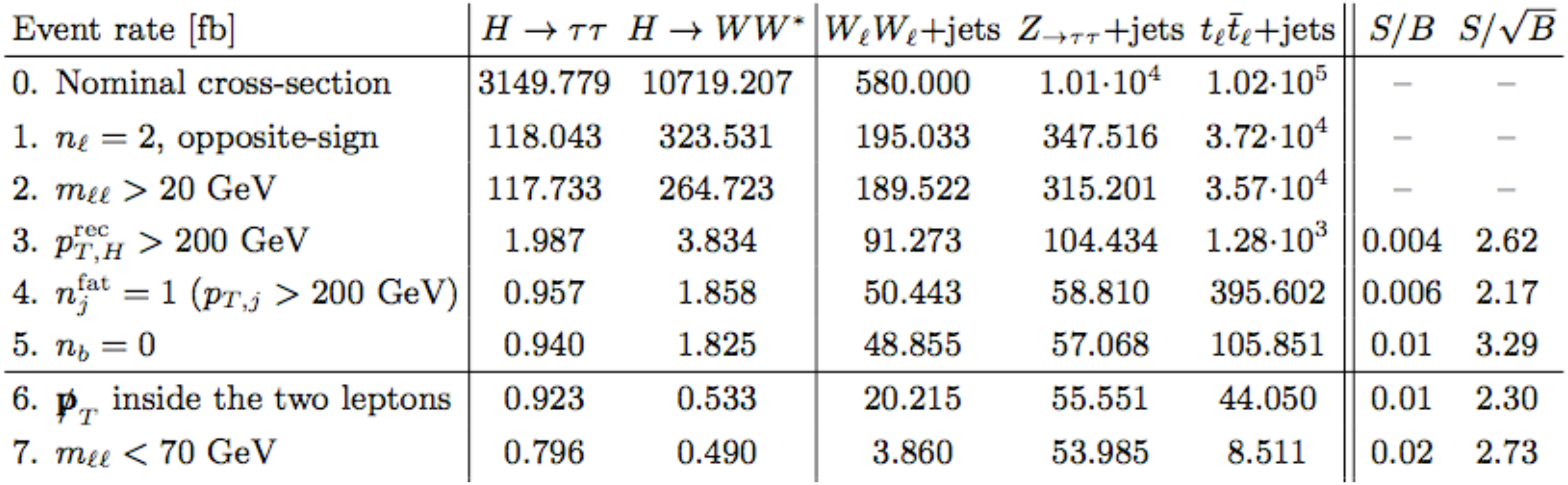


strong 1st order PT → O(1) deviation in λ_3 required

$$\lambda_3 = \frac{3m_h^2}{v} + \frac{6v^3}{\Lambda^2} \gtrsim 1.7\lambda_{3,\rm SM}$$

To exclude this EWBG scenario, 70% level measurements required for λ_3

Cut flow



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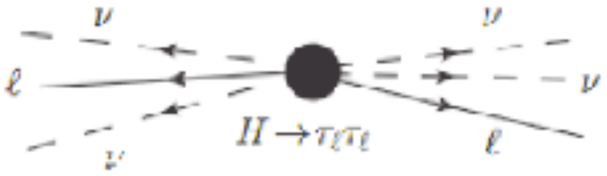
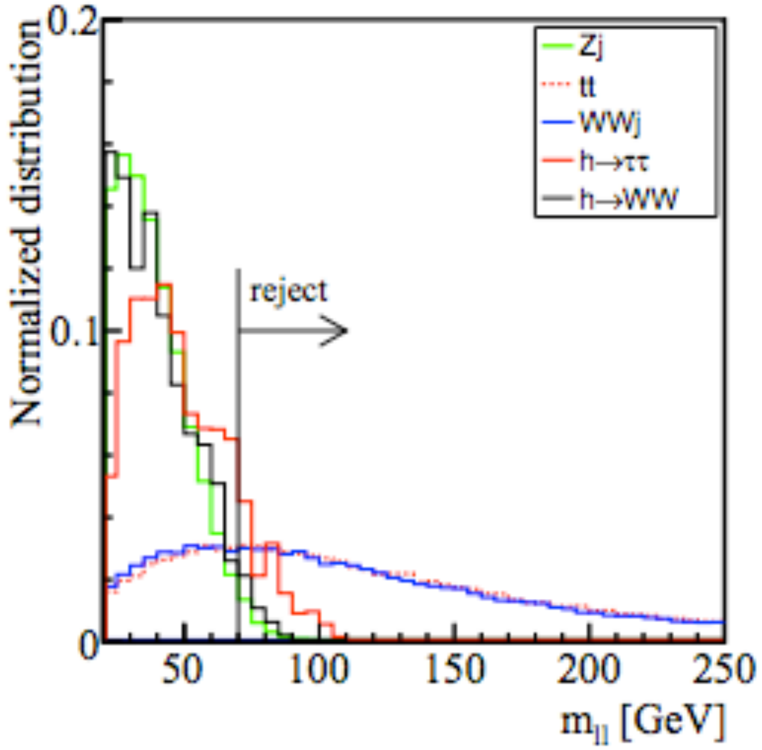
5. $n_b = 0$	0.940	1.825	48.855	57.068	105.851	0.01	3.29
6. $\not{p}_T$ inside the two leptons	0.923	0.533	20.215	55.551	44.050	0.01	2.30
7. $m_{\ell\ell} < 70$ GeV	0.796	0.490	3.860	53.985	8.511	0.02	2.73





Z+jets becomes dominant BG

Strong CP problem

QCD Lagrangian contains the total derivative term: θ-term

$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \quad \longleftrightarrow \quad |\theta>= \sum_{n=-\infty}^{\infty} e^{in\theta}|n> \quad \theta\text{-vacuum}$$

$|n>\rightarrow|m>$ but $|\theta>\rightarrow|\theta>$ gauge inv.

Note that θ is physical $0 \leq \theta < 2\pi$

Furthermore, chiral tr. $q \rightarrow e^{i\alpha\gamma_5} q$ induces $\theta \rightarrow \theta - 2\alpha$

massive fermion mass term is also changed.

$$\theta_{\rm eff} = \theta + \arg\det[M^u M^d] \quad \text{is invariant under the chiral tr.}$$

$$\propto \arg\det[v^6 Y^u Y^d]$$

θeff can be measured from Neutron EDM $|d_n| = 4.5 \times 10^{-15}\theta_{\rm eff}\,e{\rm cm}$

$$|d_n^{\rm obs}| < 2.9 \times 10^{-26} e{\rm cm}$$

Why $\theta_{\rm eff} < 10^{-11}$?

while the origin of θ and arg M is completely different

Fine tuning problem

Peccei-Quinn mechanism and domain wall problem

[R. D. Peccei, H. R. Quinn, PhysRevLett.38.1440]

If the theory has $U(1)_{PQ}$, which spontaneously breakdowns to provide axion, at η.

Due to the anomaly, $\mathrm{U}(1)_{PQ}$ current is not conserved, $\partial^\mu j_\mu^{\mathrm{PQ}} = -\frac{g^2}{32\pi^2} A G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$,

$\eta e^{i\theta_{PQ}} \sim \eta + ia$

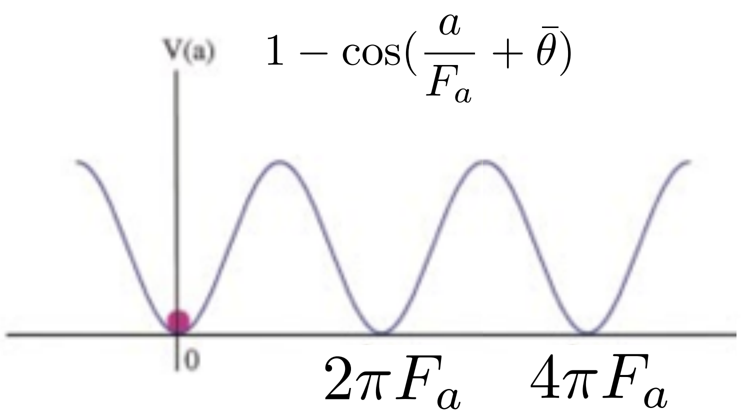
$\frac{a}{\eta} \to \frac{a}{\eta} + \epsilon$ induces $\delta\mathcal{L} = -\frac{g^2}{32\pi^2} \epsilon A G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$, induce the potential in the effective Lagrangian

$$\boxed{\mathcal{L}_{\mathrm{eff}} = -\frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} - \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{g^2}{32\pi^2} \frac{a}{F_a} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{\bar{\theta} g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu}}$$

$$F_a = \eta / A$$

A depends on the model ($\sim N$)

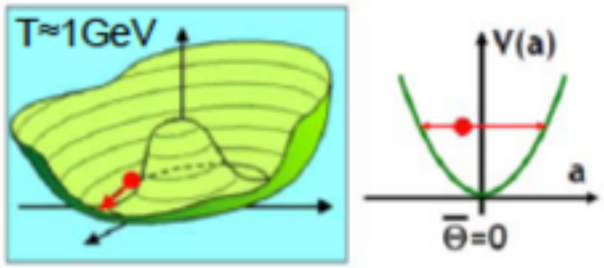
at low temperature, QCD instanton effects give an axion a potential and minimizing it gives $< a >= -\bar{\theta} F_a$.



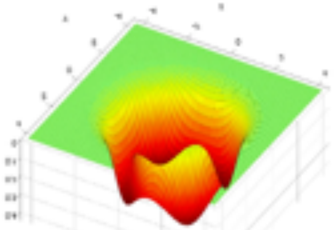
$\bar{\theta} = \theta_{\mathrm{strong}} + \theta_{\mathrm{EM}}$

$a' \equiv a + \bar{\theta} F_a$

in theta space



in <a> space



$\theta_{\mathrm{eff}} = \bar{\theta} + \frac{<a>}{F_a} = \frac{<a'>}{F_a} = 2n\pi (n = 1, \dots, N)$

$U(1)_{PQ} \to Z_N, \quad N = |\sum_{PQ} (2q_i + u_i + d_i)|$

$N_{\mathrm{DW}} = N_{\mathrm{PQ}}$ [C.Q. Geng, J. N. Ng, PhysRevD.41.3848]

Variant Axion model $N_{\mathrm{PQ}} = 1$ is free from the domain wall problem

[R.D. Peccei, T.T. Wu and T. Yanagida, Phys. Lett. B172, 435 (1986)]
[C-R Chen, P. Frampton, F. Takahashi, T. T. Yanagida JHEP1006(2010)059]