Latest results at the LHC

Koji Nakamura (KEK)
on behalf of ATLAS&CMS collaboration

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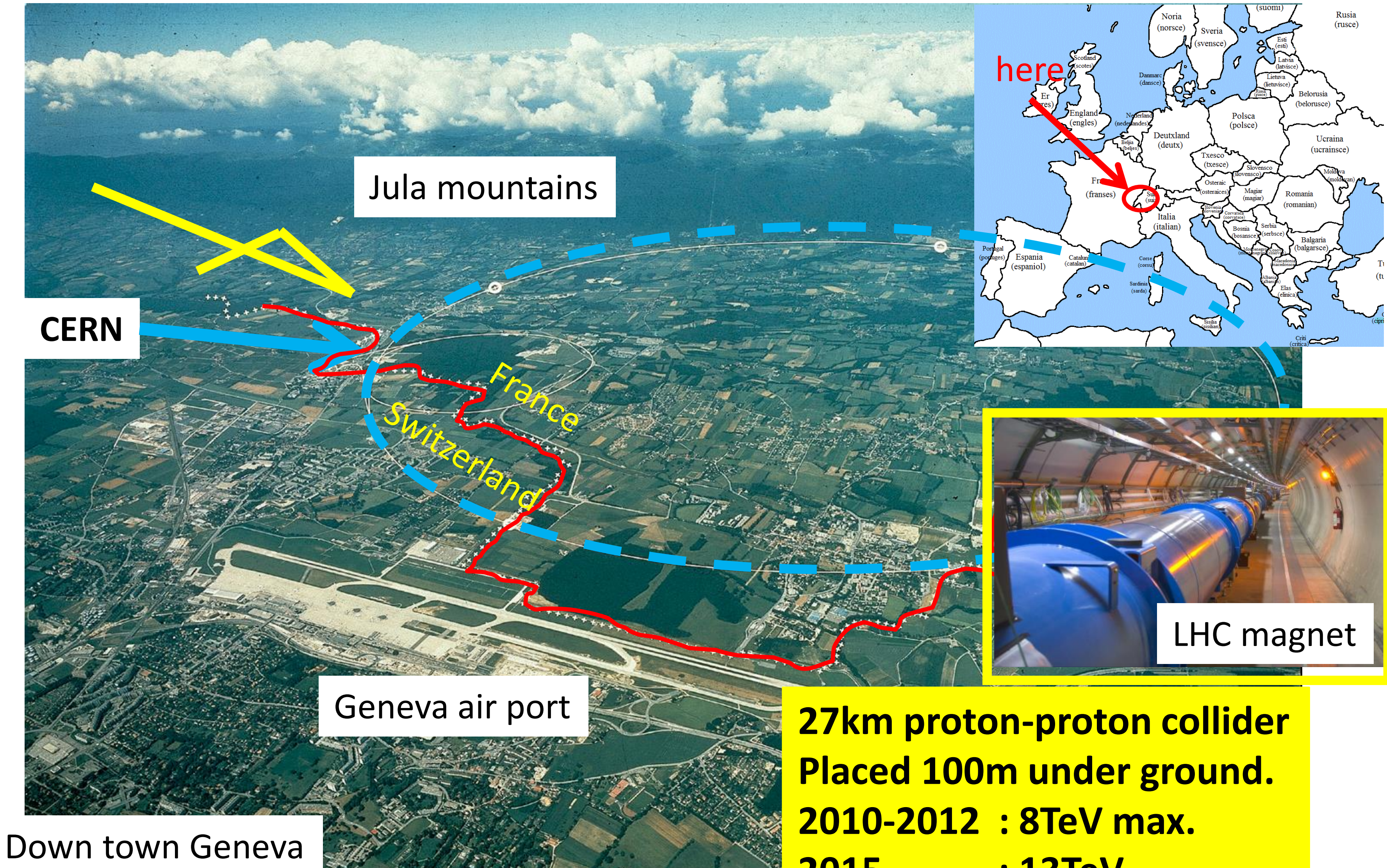
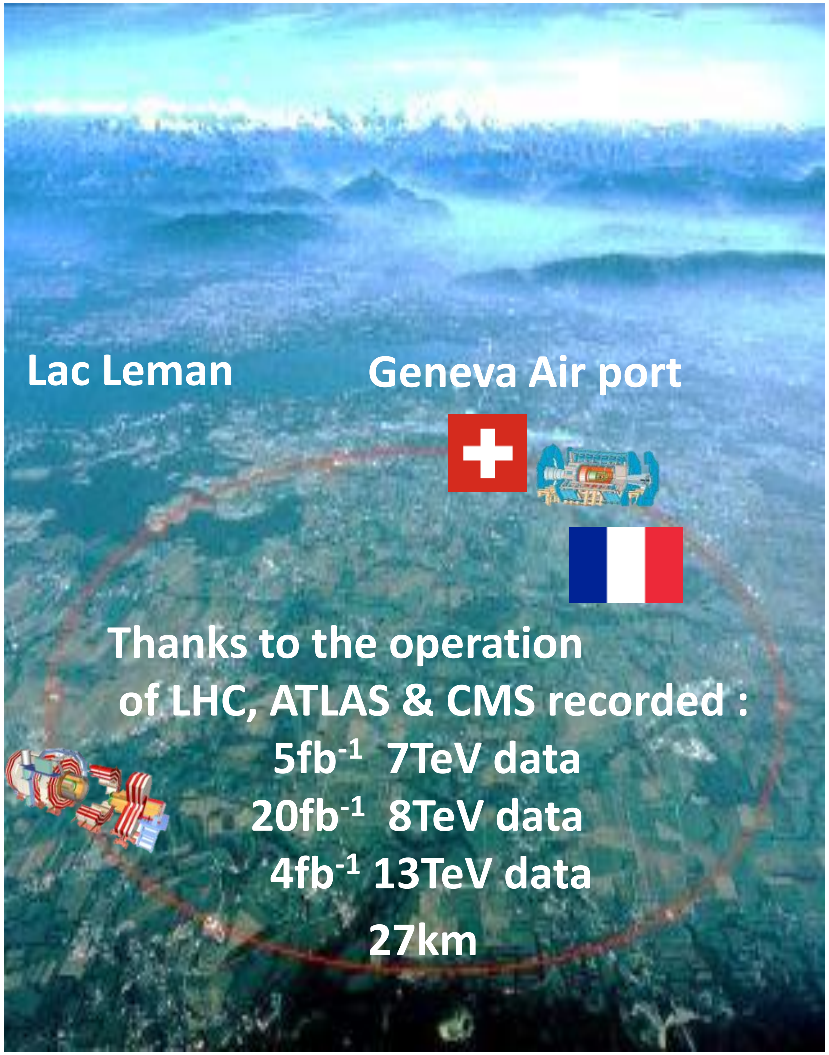
  - SUSY/Exotic results.
- Prospect for the future LHC and luminosity upgrade.

Large Hadron Collider (LHC)

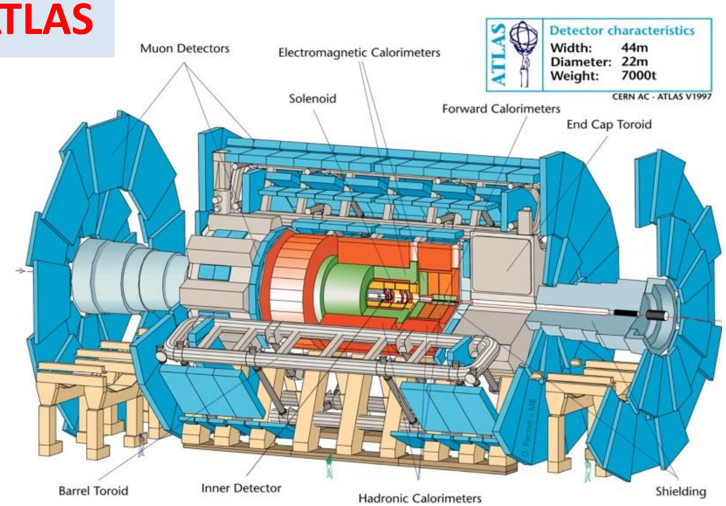


27km proton-proton collider
Placed 100m under ground.
2010-2012 : 8TeV max.
2015- : 13TeV

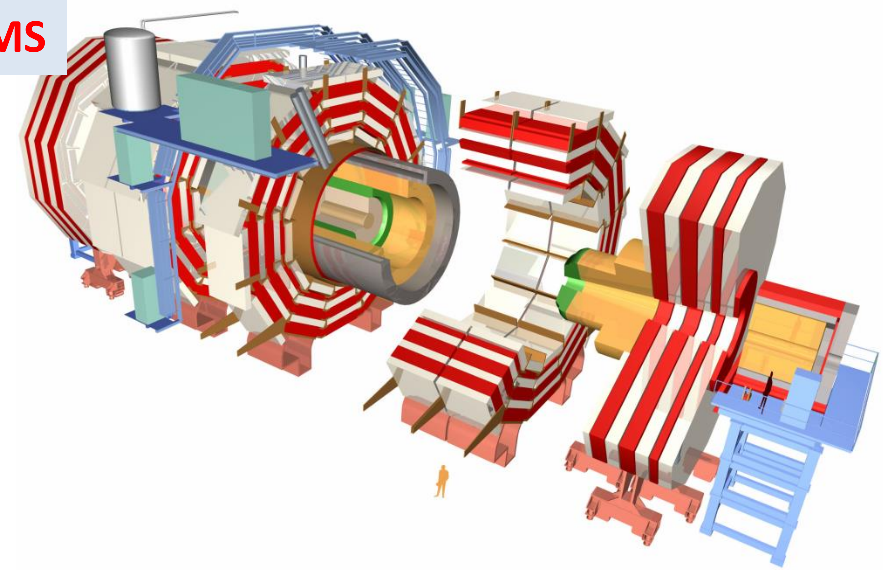
LHC and ATLAS/CMS experiment



ATLAS



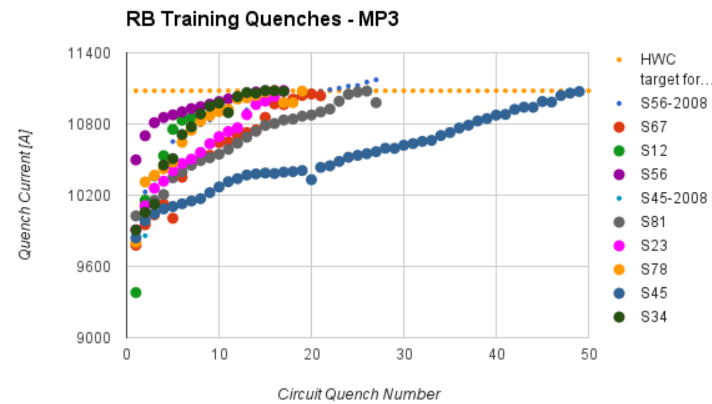
CMS

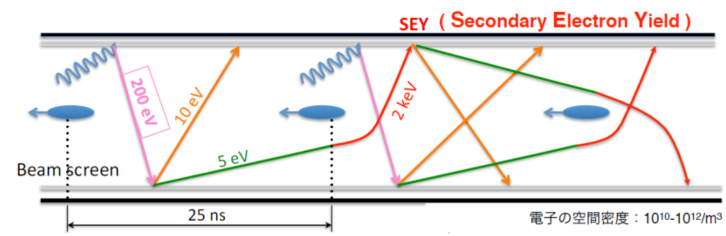


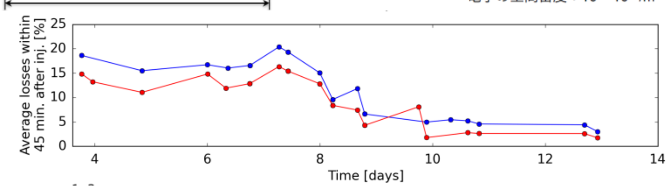
Status of the LHC machine after 8->13 TeV upgrade

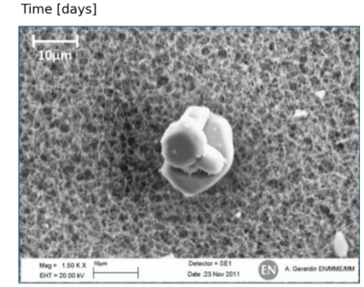
LHC operation in 2015

- Center-of-mass energy upgraded to 13TeV (6.5TeV x 6.5TeV)
  - Dipole magnet quench test done.
    - One sector spend 50 times quenches
    - This made slight delay of 13TeV col.
- Luminosity stayed low
  - Issue of Electron Cloud
    - First time experienced synchrotron radiation by proton collider !!
    - Scrubbing was necessary.
  - Unidentified Falling Object (UFO)



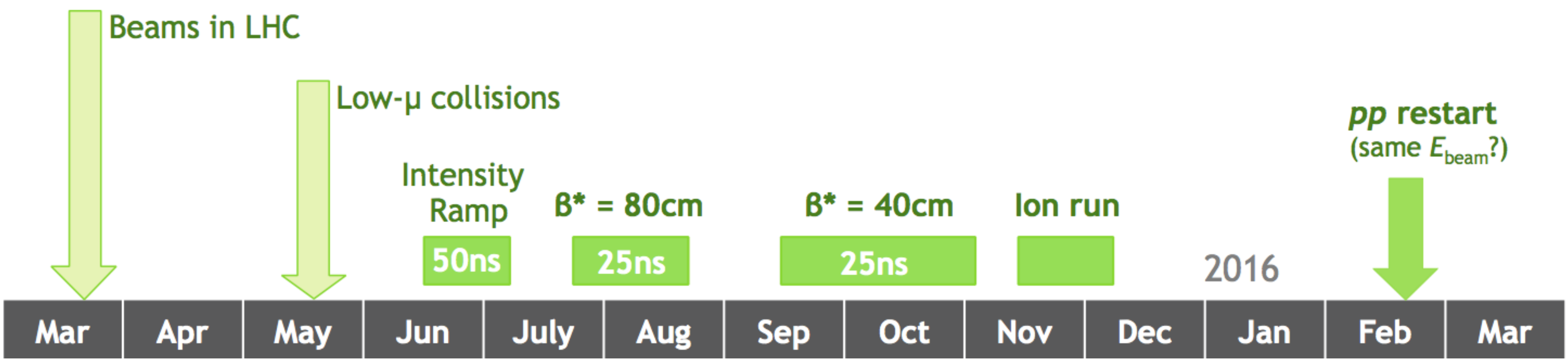






LHC operation in 2015

- Schedule at March 2015

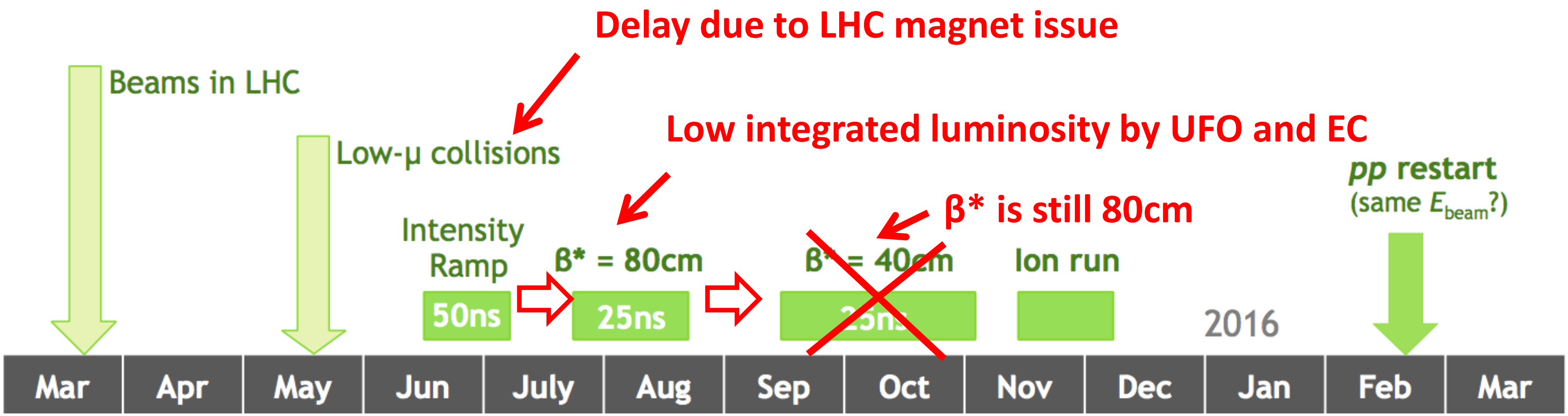


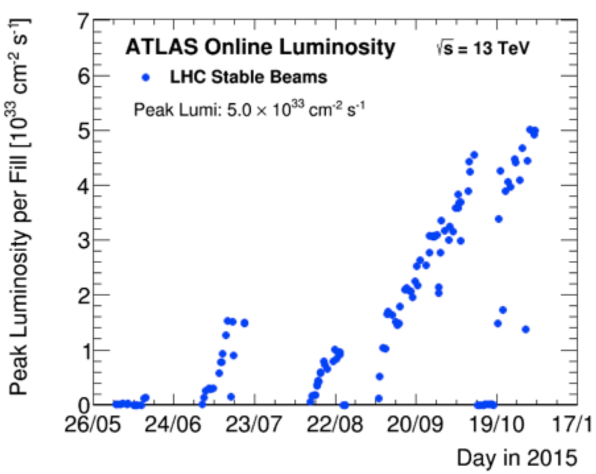
	3-4月	5月	6月	7-8月	9-11月	11-12月
Run Condition	Beam commissioning	Low-μ run	50ns beam β*=80cm	25ns beam β*=80cm	25ns beam β*=40cm	Heavy Ion
Luminosity for Phys.		(1fb^{-1})	1fb^{-1}	2-5fb^{-1}	5fb^{-1}	

About 10fb^{-1} in 2015 !?

LHC operation in 2015

- Schedule at March 2015→But in fact…





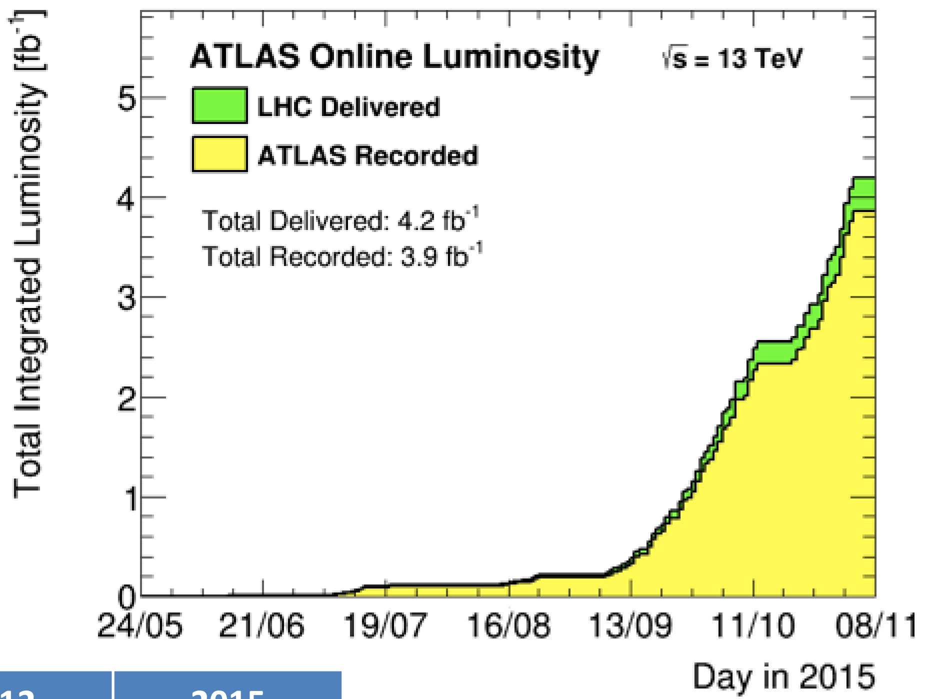
5月	6月	7-8月	9-11月	11-12月
Low-μ run	50ns beam β*=80cm	25ns beam β*=80cm	~~25ns beam β*=40cm~~	Heavy Ion
~~(1fb^{-1})~~	~~1fb^{-1}~~	~~2-5fb^{-1}~~ 0.2fb^{-1}	~~5fb^{-1}~~ 4fb^{-1}	

4.2fb^{-1}

About ~~10fb^{-1}~~ in 2015 !?

LHC operation in 2015

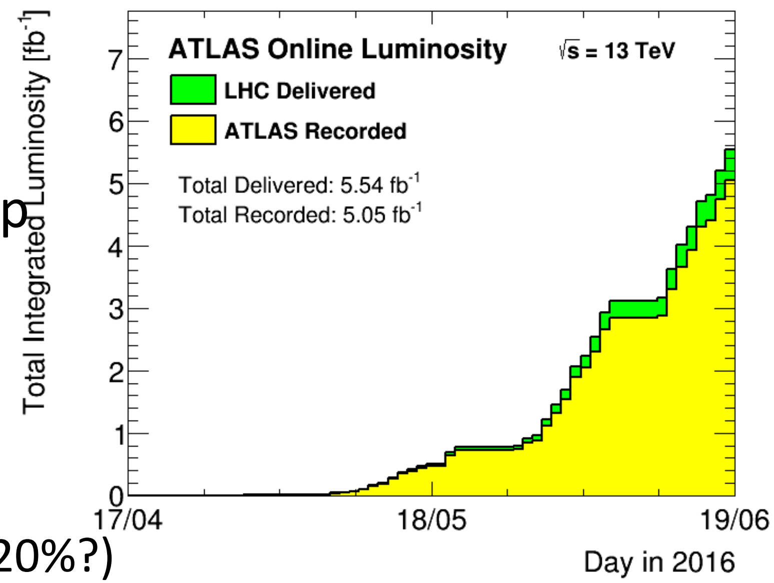
- Finally
  - ATLAS recorded 3.9fb^{-1} of data
  - **3.4fb^{-1} could be used for physics analysis.**



	Nominal	2012	2015
energy [TeV]	7	4	6.5
bunch spacing [ns]	25	50	25
beta* [cm] (crossing angle [urad])	55 (285)	60 (290)	80 (290)
max. number of bunches	2808	1380	2244/2232
Bunches / LHC injection	288	144	144(4x36)
peak luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/5	1.0	>0.7	~0.5

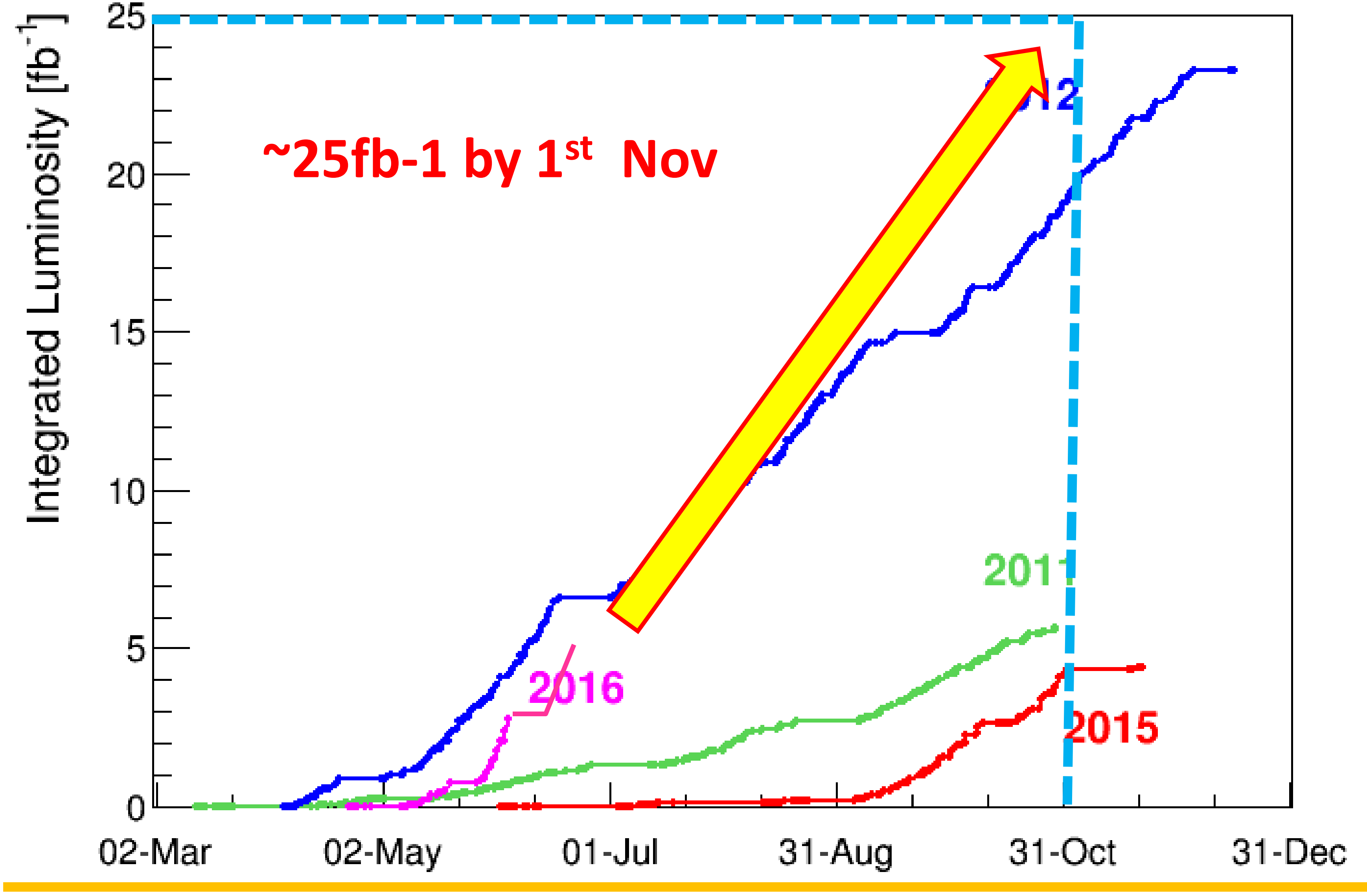
LHC operation in 2016

- Keep running with
  - Synchrotron radiation & e-cloud issue
    - Scrabbling was necessary.
  - UFO : loosen the threshold of beam dump
- New good and bad thing.
  - **Good : achieved β* to 40cm!**
    - Make luminosity twice!
  - **Bad : Vacume leak on SPS beam dump**
    - Limitation for the number of bunches. (10-20%?)
  - Small delay due to PS power supply issue etc…



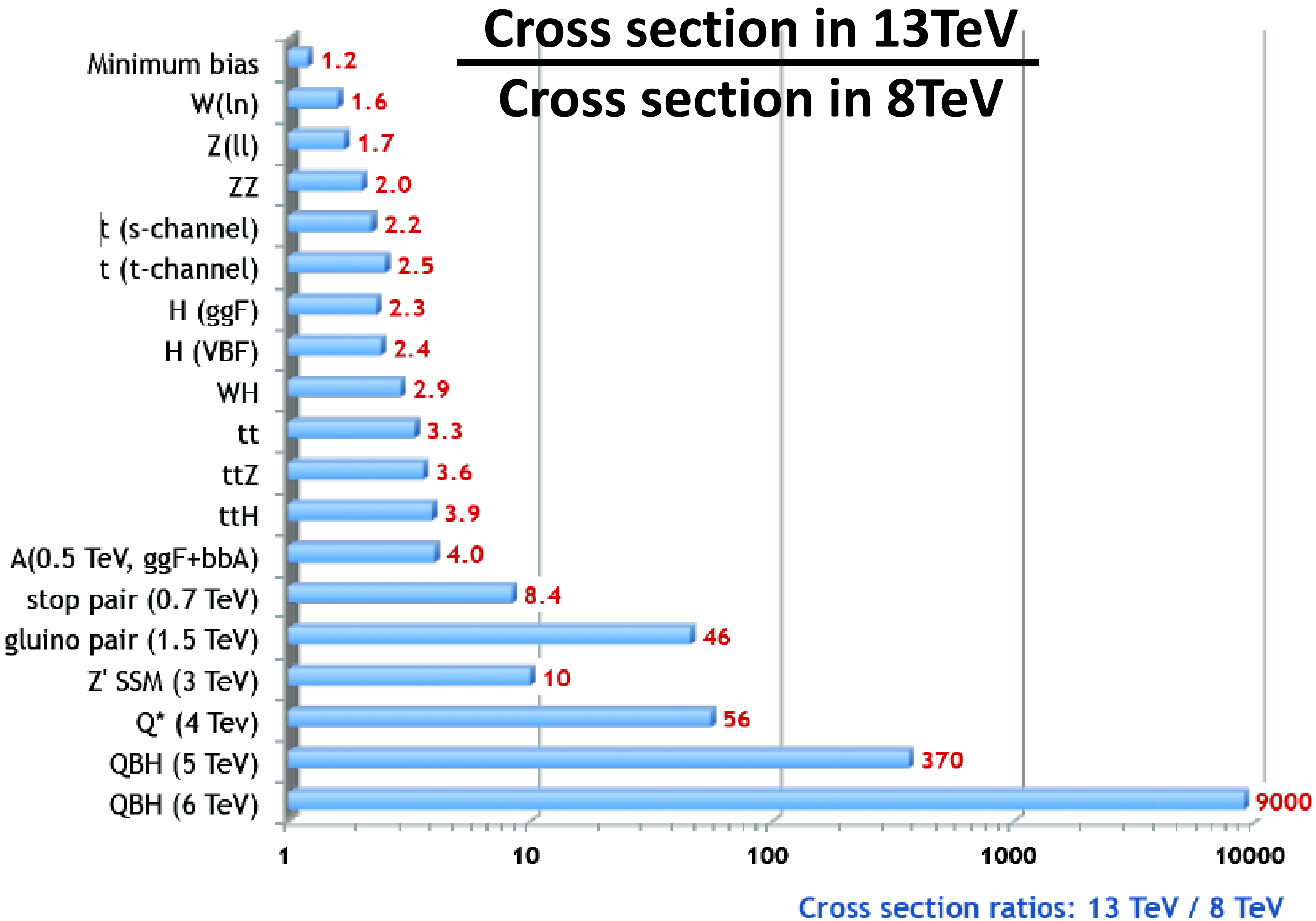
	Nominal	2012	2015	2016
energy [TeV]	7	4	6.5	6.6
bunch spacing [ns]	25	50	25	25
beta* [cm] (crossing angle [urad])	55 (285)	60 (290)	80 (290)	40 (370)
max. number of bunches	2808	1380	2244/2232	2040/2028
Bunches / LHC injection	288	144	144(4x36)	72 (1x72)
peak luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/5	1.0	>0.7	~0.5	0.8

Prospect of 2016



What different in 13TeV collision?

- Energy upgrade from 8TeV to 13TeV makes…



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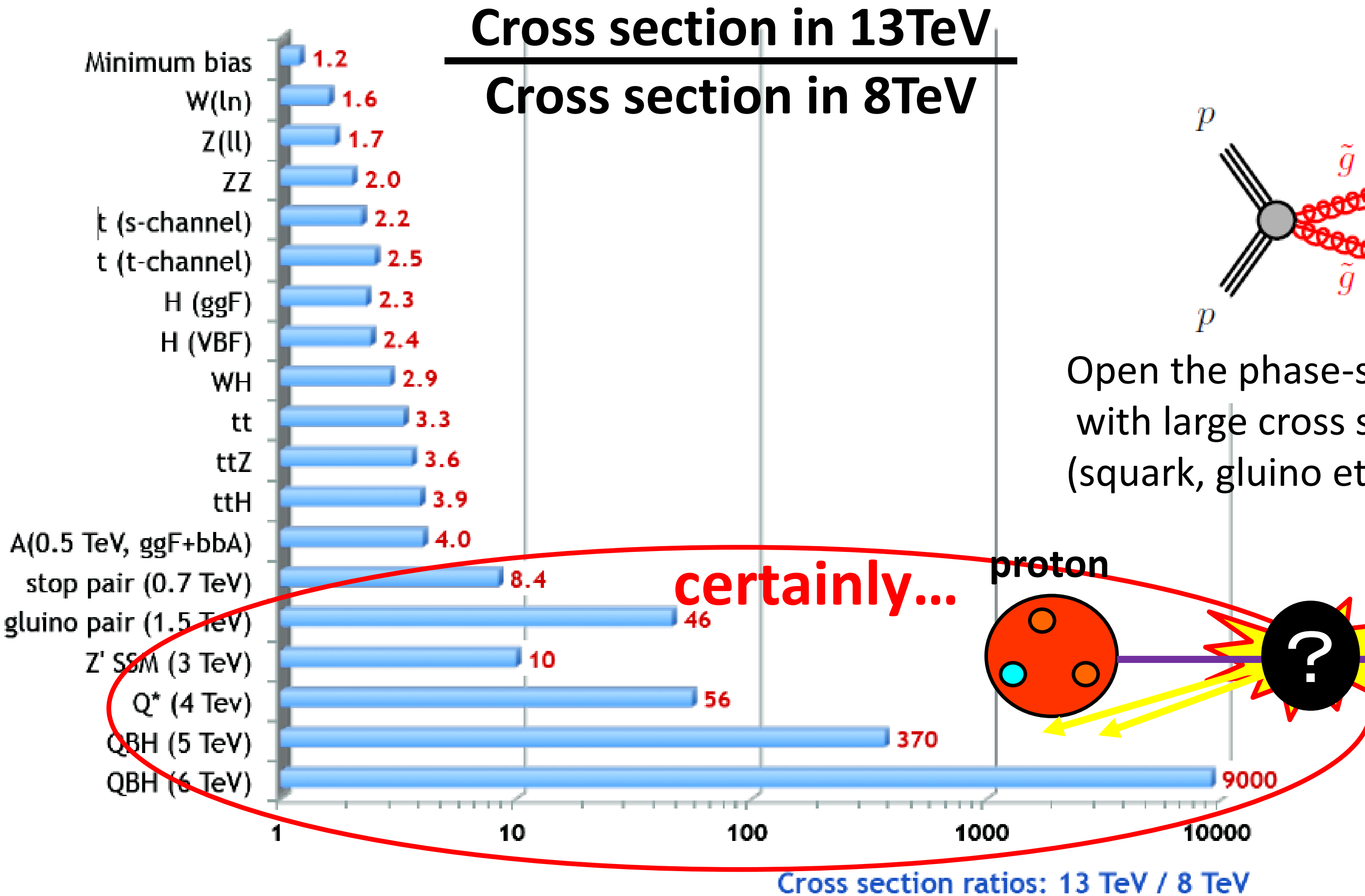
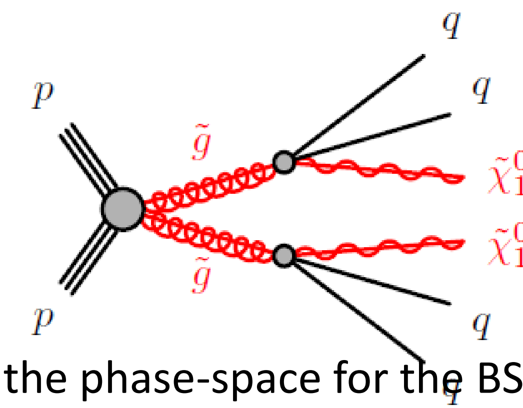
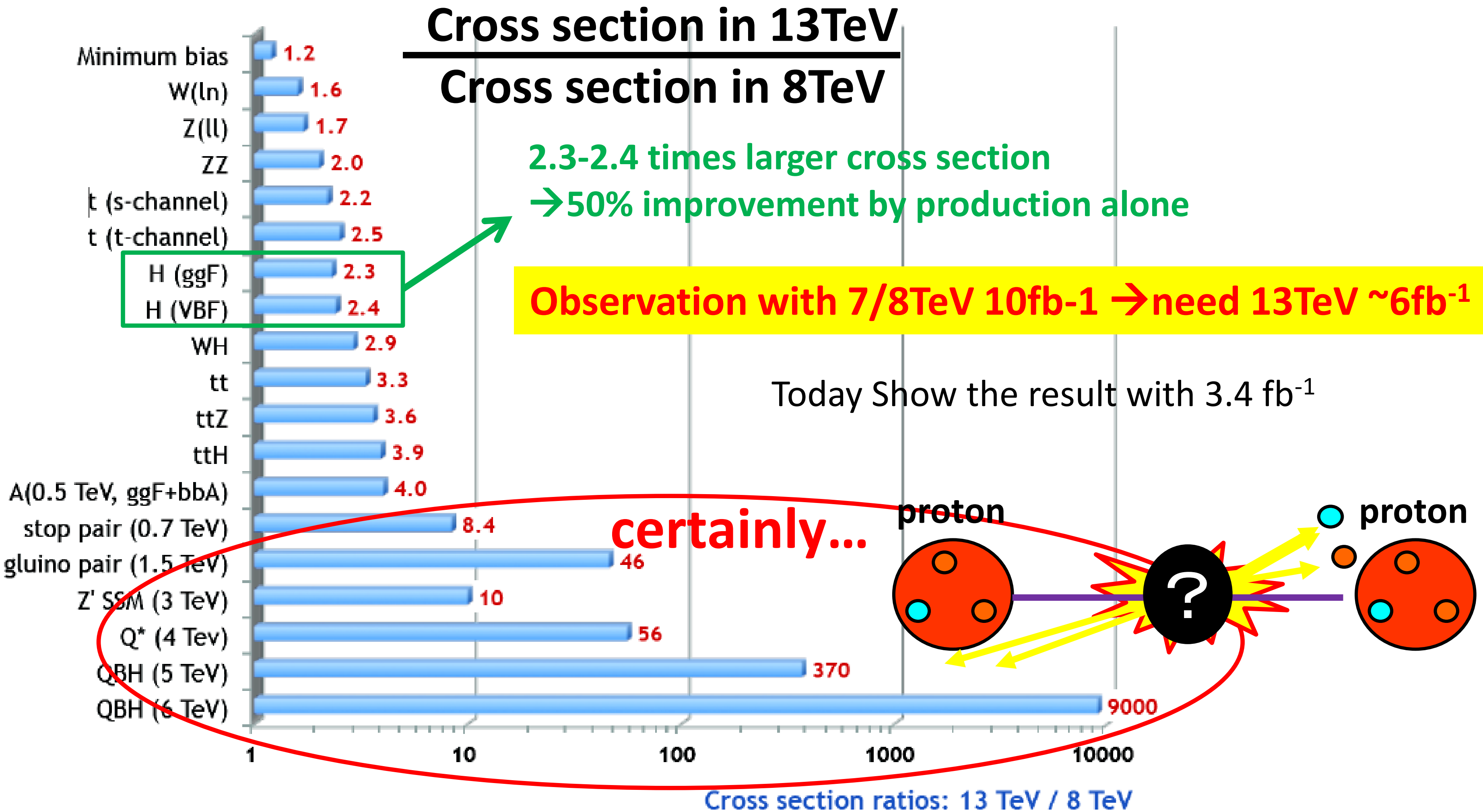




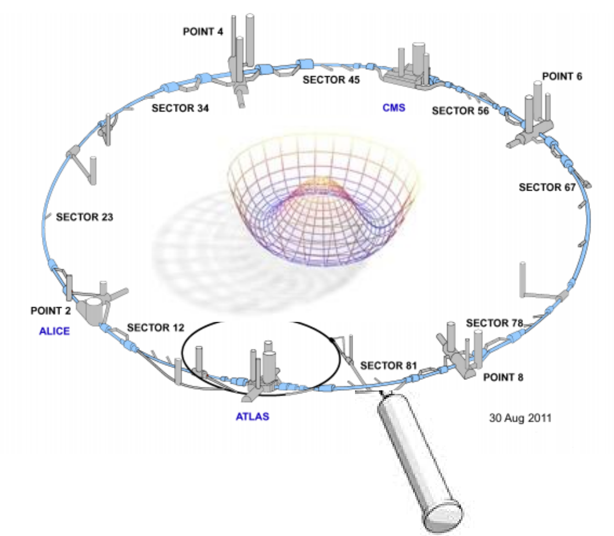
Open the phase-space for the BSM with large cross section (squark, gluino etc)

What different in 13TeV collision?

- Energy upgrade from 8TeV to 13TeV makes…



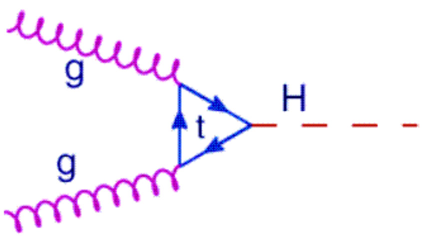
Published result at the LHC run2



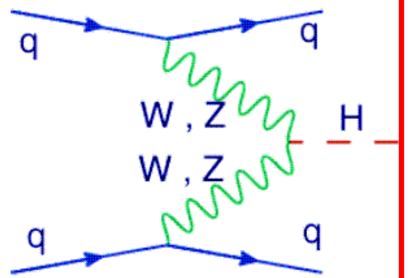
- Re-observation of Higgs boson?
- Are the excess in VV and γγ real?
- SUSY/Exotic results.

Higgs production and decay @ LHC

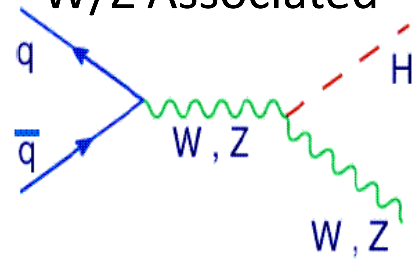
Gluon Fusion(ggF)



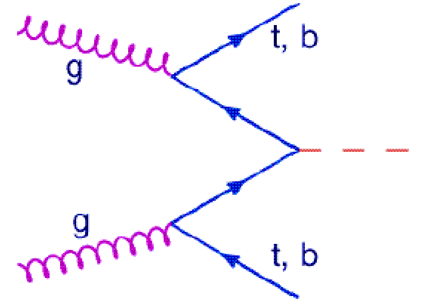
Vector Boson Fusion



W/Z Associated



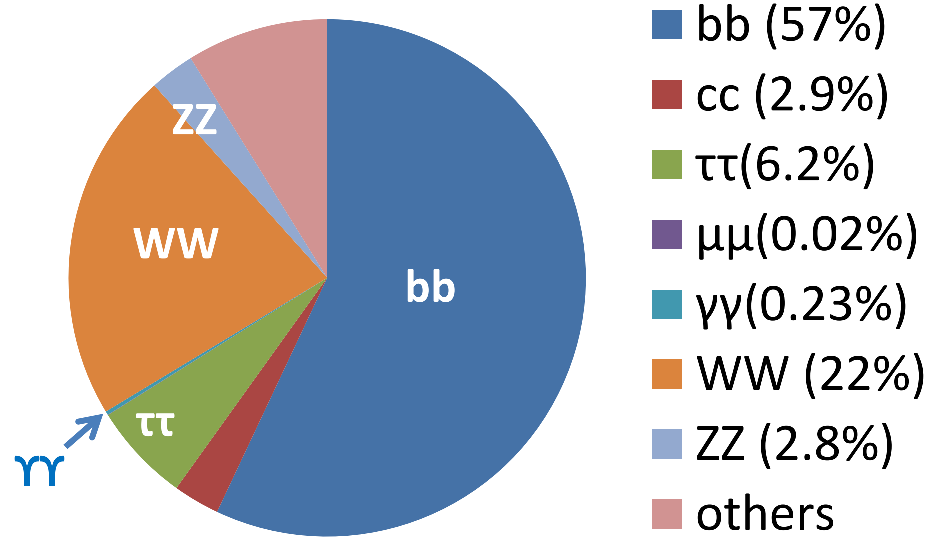
tt/bb Associated



Process	8TeV σ [pb]	14TeV σ [pb]
Gluon Fusion	**19.1**	**49.9**
Vector Boson Fusion	**1.57**	**4.18**
W/Z Associated	1.11	2.39
tt/bb Associated	0.128	0.611

8TeV @125.5GeV
14TeV @125GeV

@125.5GeV



Run 1 results

Channel	Signal strength [μ]		Signal significance [σ]	
	from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	5.0	5.6
	$(^{+0.26}_{-0.24})$	$(^{+0.24}_{-0.22})$	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
	$(^{+0.33}_{-0.27})$	$(^{+0.31}_{-0.26})$	(5.5)	(6.8)
$H \to WW$	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
	$(^{+0.21}_{-0.20})$	$(^{+0.23}_{-0.20})$	(5.8)	(5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
	$(^{+0.37}_{-0.33})$	$(^{+0.31}_{-0.29})$	(3.3)	(3.7)
$H \to bb$	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
	$(^{+0.39}_{-0.37})$	$(^{+0.45}_{-0.43})$	(2.7)	(2.5)
$H \to \mu\mu$	-0.7 ± 3.6	0.8 ± 3.5		
	(± 3.6)	(± 3.5)		
ttH production	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
	$(^{+0.72}_{-0.66})$	$(^{+0.88}_{-0.80})$	(1.6)	(1.3)

- Classify the Higgs search/measurement study by decay modes.

Run 1 results

Channel	Signal strength [μ]		Signal significance [σ]	
	from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	$1.15^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.12^{+0.25}_{-0.23}$ $\left(^{+0.24}_{-0.22}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ \to 4\ell$	$1.51^{+0.39}_{-0.34}$ $\left(^{+0.33}_{-0.27}\right)$	$1.05^{+0.32}_{-0.27}$ $\left(^{+0.31}_{-0.26}\right)$	6.6 (5.5)	7.0 (6.8)
$H \to WW$	$1.23^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.91^{+0.24}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.35}$ $\left(^{+0.37}_{-0.33}\right)$	$0.89^{+0.31}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	$0.62^{+0.37}_{-0.36}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.42}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		
ttH production	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.72}_{-0.66}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.88}_{-0.80}\right)$	2.7 (1.6)	3.6 (1.3)

20-30%

30-40%

5σ!

3σ!

- Classify the Higgs search/measurement study by decay modes.
- **5σ observation of γγ, ZZ and WW channel.**
- **Need more data for H->bb and gg->ttH production.**
- Longer time project for H->μμ (HL-LHC?)

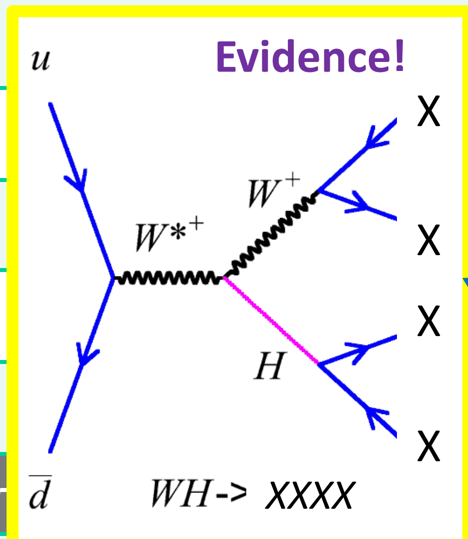
Results Production and Decay (sensitivity)

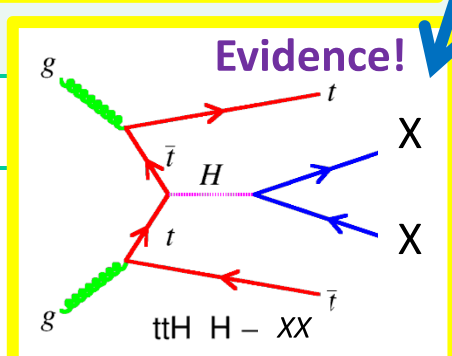
Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \rightarrow \tau\tau$	**5.5**	5.0
$H \rightarrow bb$	2.6	3.7

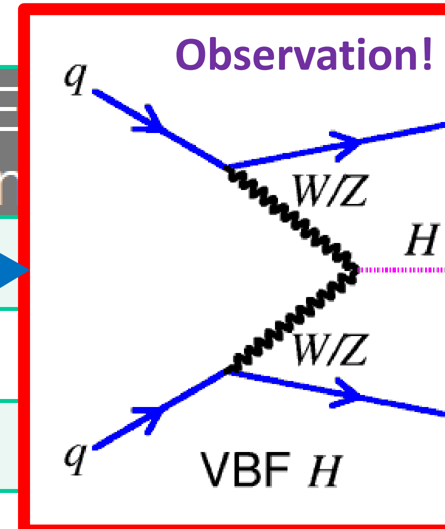
Results Production and Decay (sensitivity)

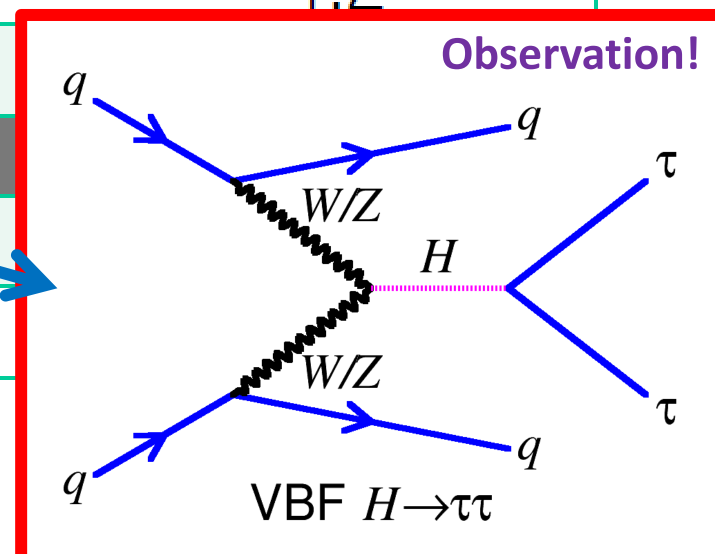
After ATLAS & CMS combination !

Production process	Observed Significance(σ)	E… Sign…
VBF	**5.4**	
WH	2.4	
ZH	2.3	
VH	3.5	4.2
ttH	4.4	
Decay chann…		
H→ττ	**5.5**	
H→bb	2.6	







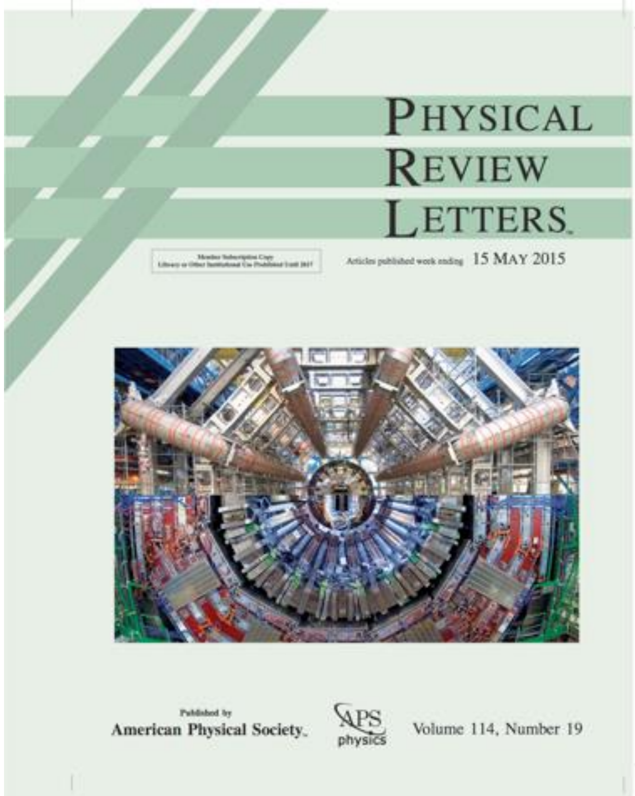


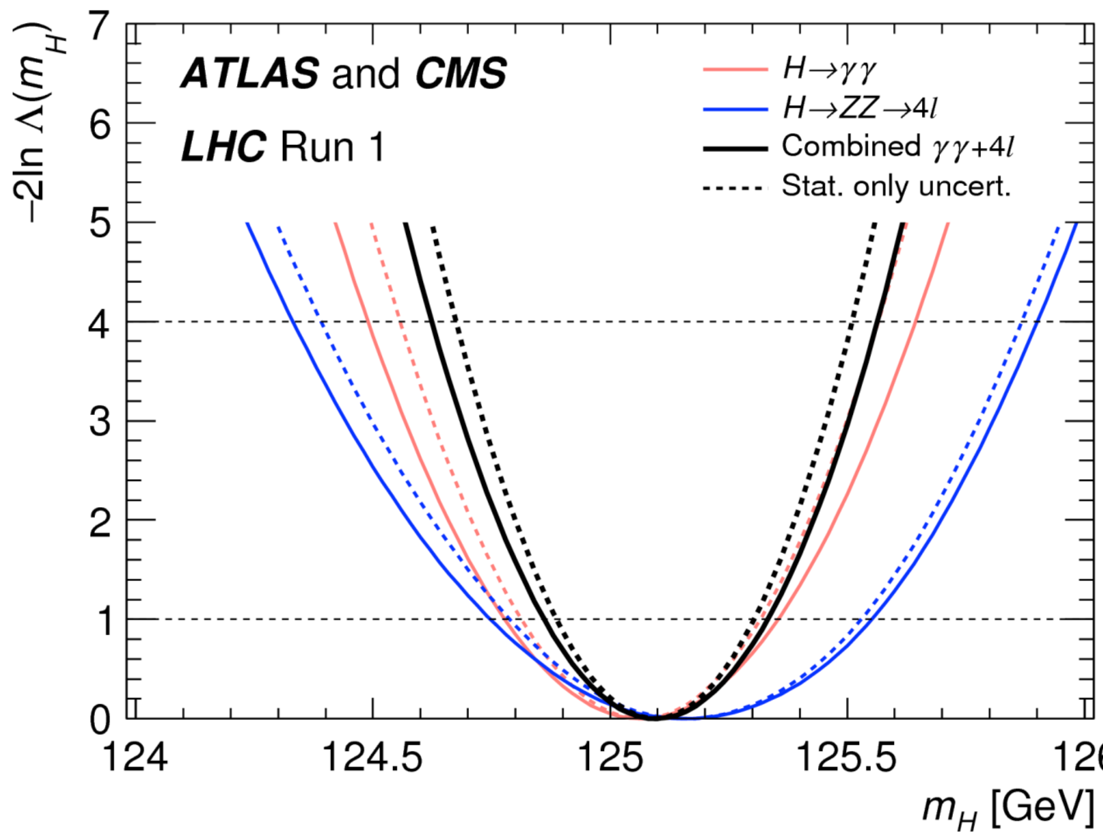
Mass of observed Boson

- ATLAS & CMS has been published in March 2015

M_H = 125.09 ± 0.24 GeV [±0.21 (stat.) ±0.11(syst.)]

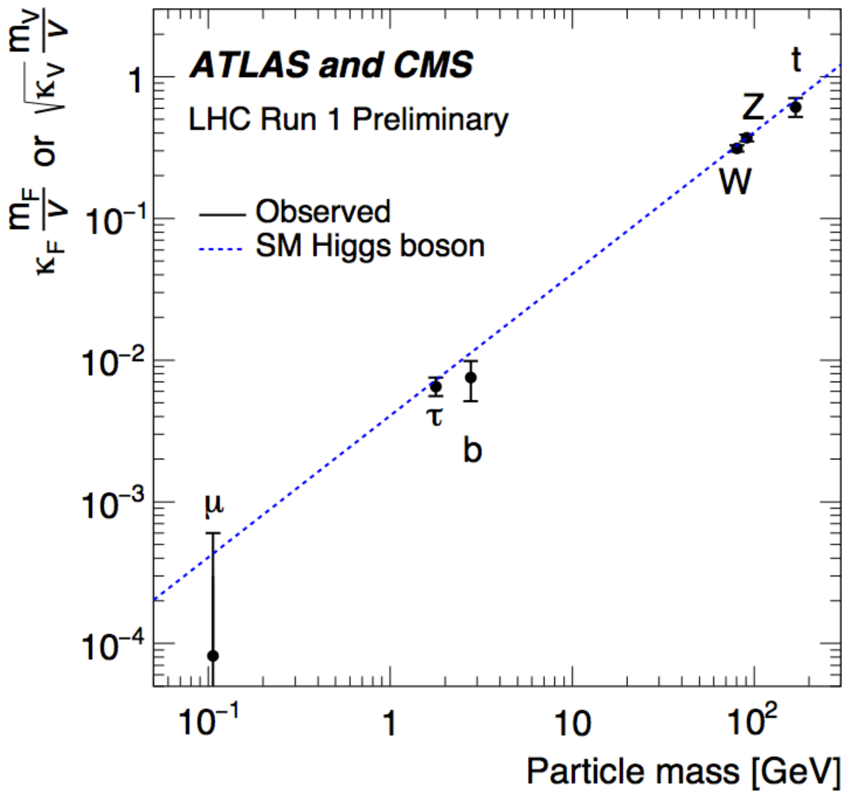
  - This result was important to measure coupling deviation from SM

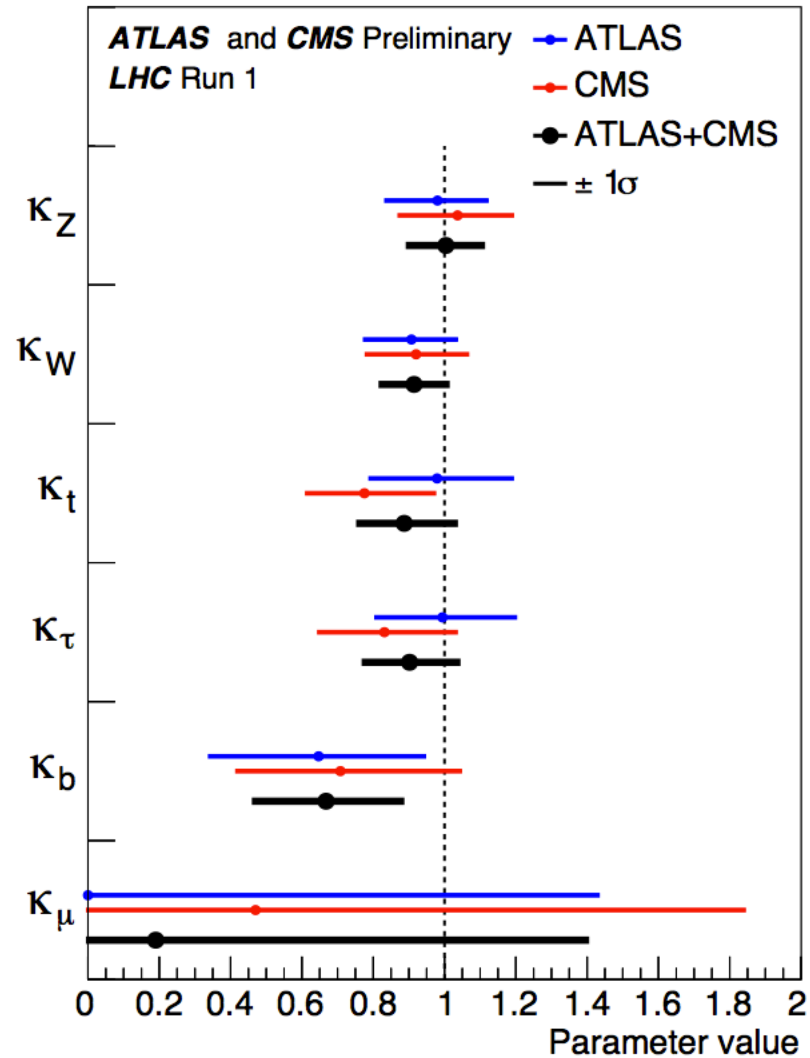




Constraints on Higgs coupling

- Assume only SM physics in loops, no invisible Higgs decays
- Fit for scaling parameters for Higgs coupling to : W, Z ,b, t, τ, μ





Before Higgs result… Top re^3-observation

- Top pair production

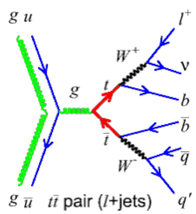
Dilepton

$$\sigma_{t\bar{t}} = 803 \pm 7\ (\text{stat}) \pm 27\ (\text{syst}) \pm 45\ (\text{lumi}) \pm 12\ (\text{beam})\ \text{pb}$$

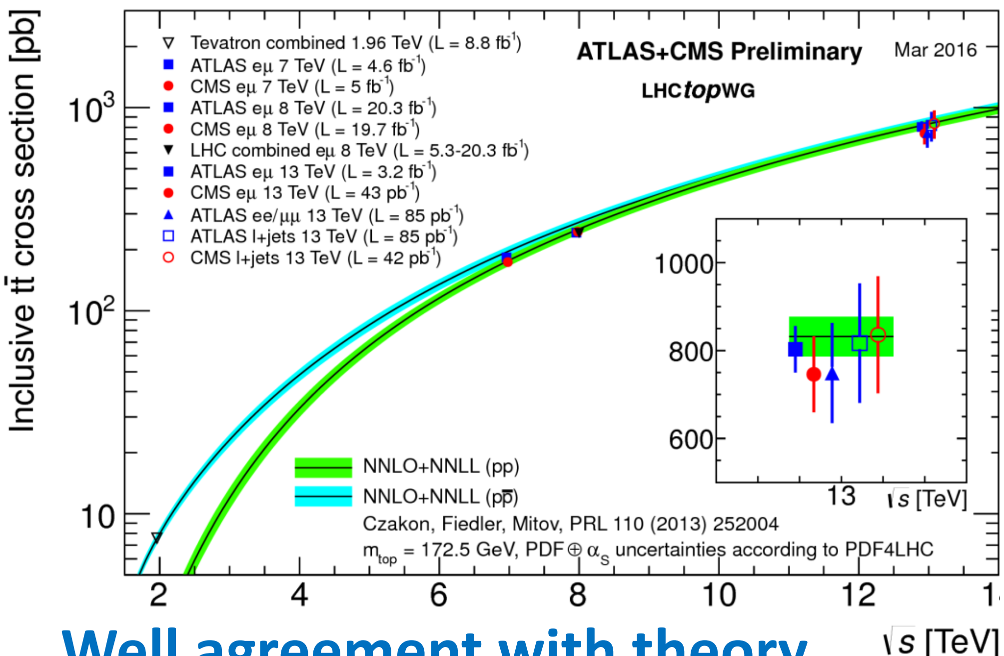
$$\sigma_{t\bar{t}} = 749 \pm 57\ (\text{stat}) \pm 79\ (\text{syst}) \pm 74\ (\text{lumi})\ \text{pb}$$

Lepton+jets

$$\sigma_{t\bar{t}} = 817 \pm 13\ (\text{stat}) \pm 103\ (\text{syst}) \pm 88\ (\text{lumi})\ \text{pb}$$



Theory Prediction 832^{+40}_{-46} pb.



Well agreement with theory

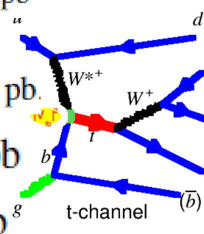
- Single top production

Top Quark

$$\sigma(tq) = 133 \pm 6\,(\text{stat.}) \pm 24\,(\text{syst.}) \pm 7\,(\text{lumi.})\ \text{pb}$$

Anti-Top Quark

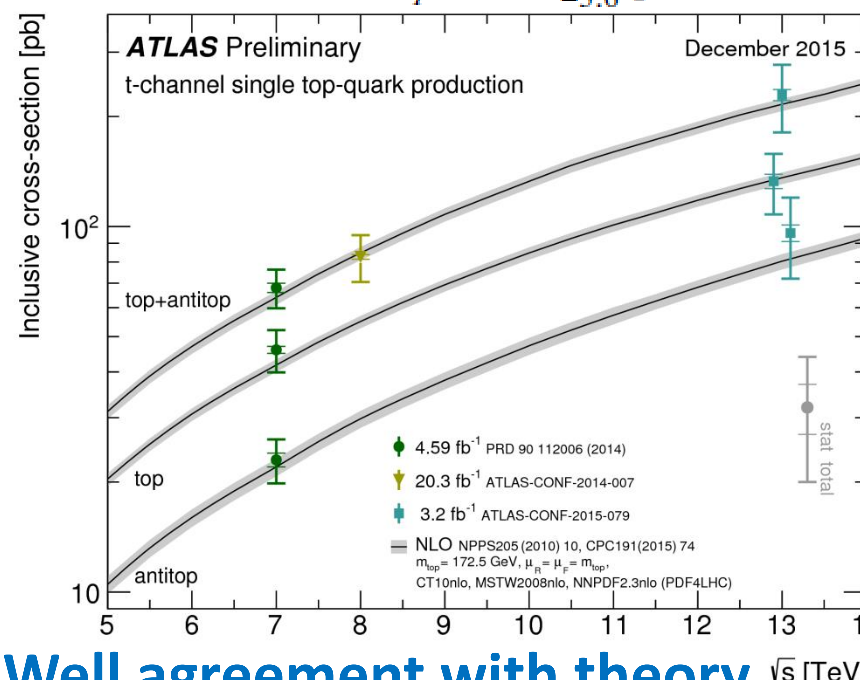
$$\sigma(\bar{t}q) = 96 \pm 5\,(\text{stat.}) \pm 23\,(\text{syst.}) \pm 5\,(\text{lumi.})\ \text{pb}.$$



Theory Prediction

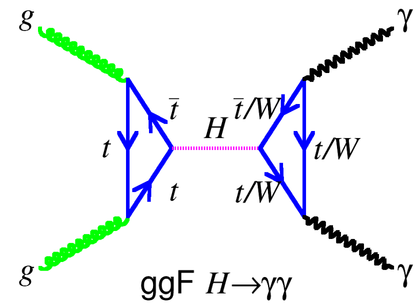
$$\sigma_{tq} = 136.0^{+5.4}_{-4.6}\ \text{pb}$$

$$\sigma_{\bar{t}q} = 81.0^{+4.1}_{-3.6}\ \text{pb}$$

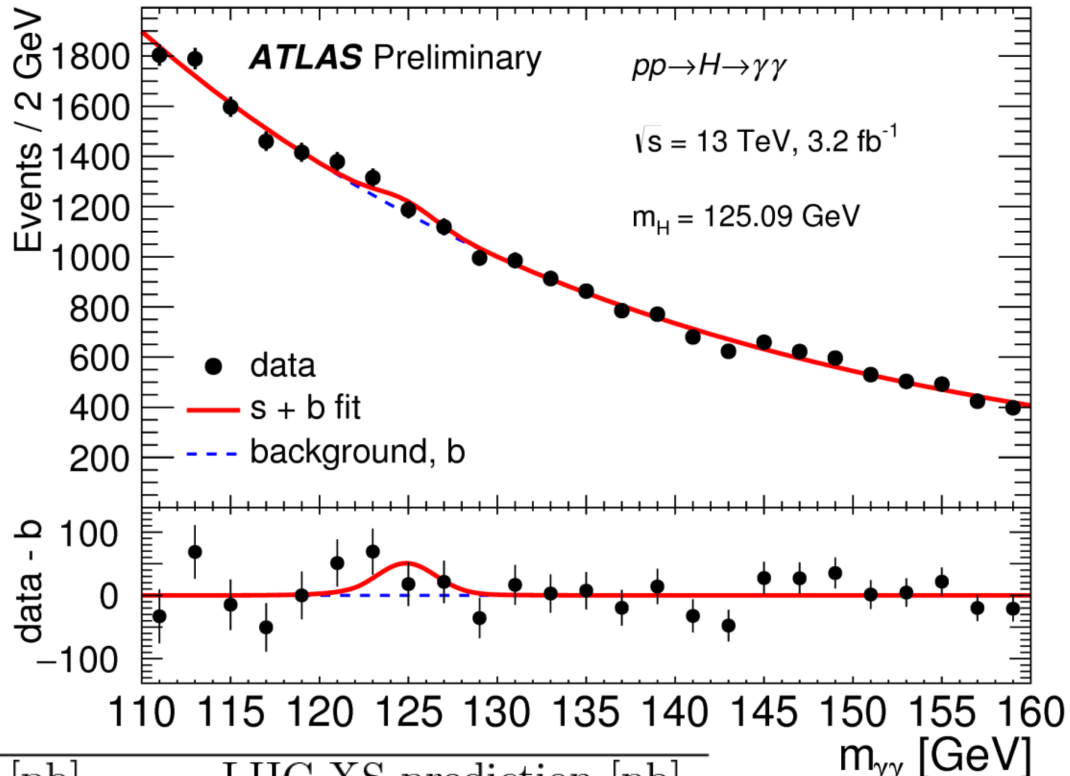


Well agreement with theory

H→γγ

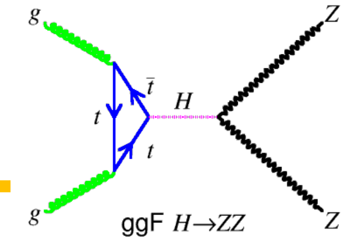


- di-photon spectrum in 3.2fb^{-1} data
  - SignalはCrystal Ball + Gaussian
  - Fit background shape by analytical function
- Rate of Real γγ in baackground is 78%
- $N_{sig} = 113 \pm 74^{+43}_{-25}$
- **Result:**
  - **1.5σ(1.9σ) obs(exp)**

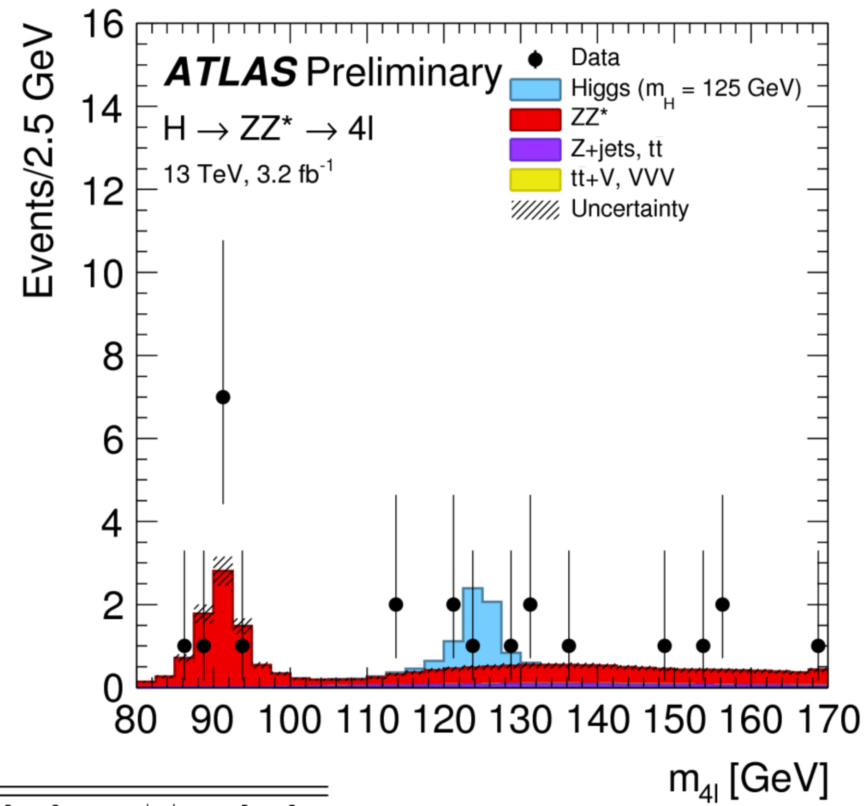


$\sqrt{s}$	Measured total cross section [pb]	LHC-XS prediction [pb]
7 TeV	35 ± 12 (stat.) ± 4 (syst.) ± 1 (lumi.)	17.5 ± 1.6
8 TeV	30.5 ± 7.1 (stat.) $^{+2.6}_{-2.5}$ (syst.) ± 0.9 (lumi.)	22.3 ± 2.0
13 TeV	40 ± 26 (stat.) $^{+16}_{-10}$ (syst.) ± 2 (lumi.)	$50.9\ ^{+4.5}_{-4.4}$

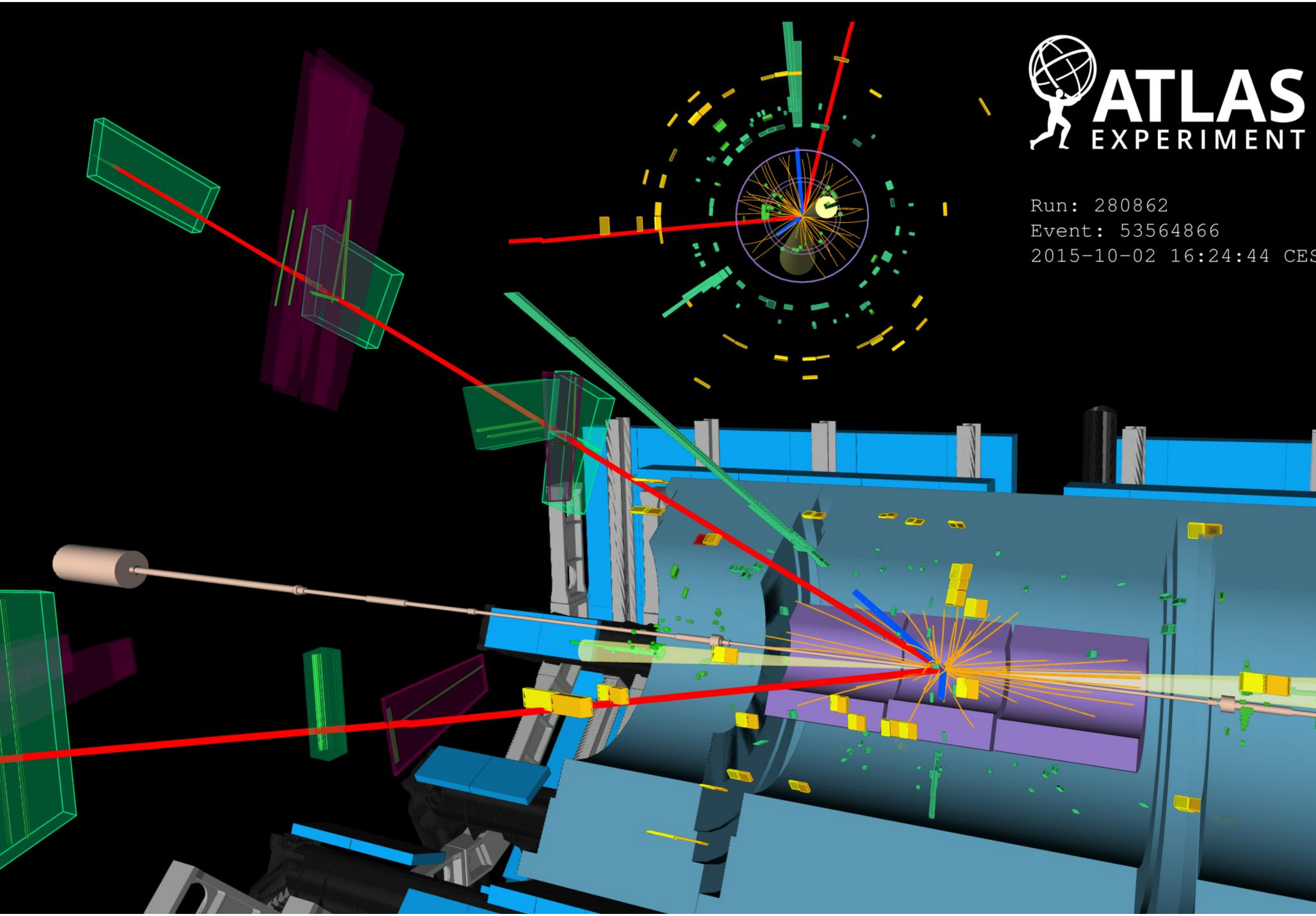
H→ZZ(*)



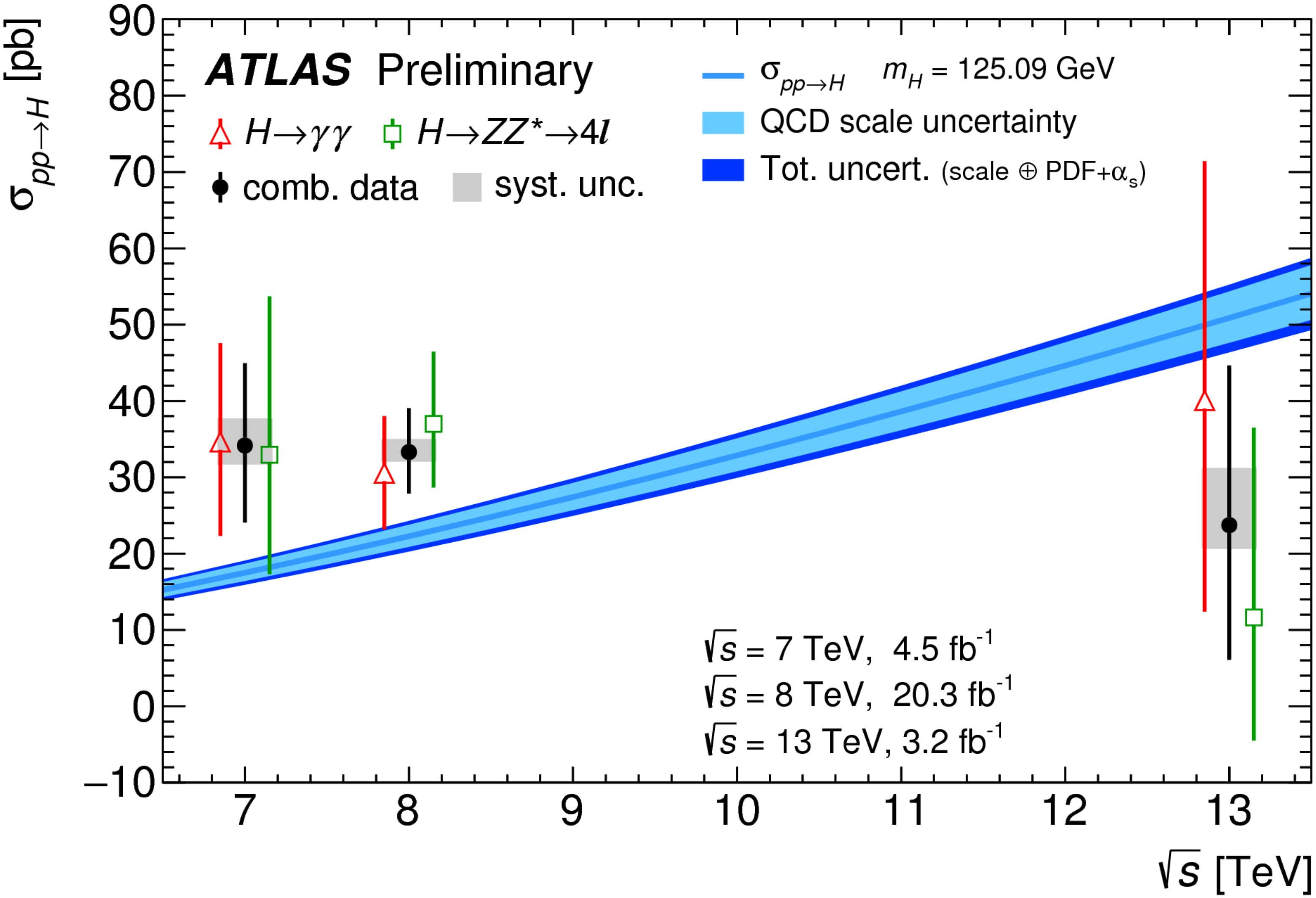
- m_{4l} spectrum
- $118<m_{4l}<129$GeV
  - Signal exp =4.57±0.54
  - Bkg exp = 2.1±0.2
  - Observed 4 event.
- $N_{sig}^{fit}=1^{+2.3}_{-1.5}$
- **Result :**
  - **0.7σ(2.8σ) obs(exp)**



Data set [TeV]	N_s	$\sigma^{fid}_{4\ell}$ [fb]	σ^{fid}_{theory} [fb]	σ^{tot} [pb]	σ^{tot}_{theory} [pb]
7	$4.5^{+2.8}_{-2.2}$	$1.9^{+1.2}_{-0.9}$	1.03 ± 0.11	33^{+21}_{-16}	17.5 ± 1.6
8	$24.0^{+6.0}_{-5.3}$	2.1 ± 0.5	1.29 ± 0.13	37^{+9}_{-8}	22.3 ± 2.0
13	$1.0^{+2.3}_{-1.5}$	$0.6^{+1.3}_{-0.9}$	2.74 ± 0.28	12^{+25}_{-16}	$50.9^{+4.5}_{-4.4}$


ATLAS
EXPERIMENT
Run: 280862
Event: 53564866
2015-10-02 16:24:44 CES

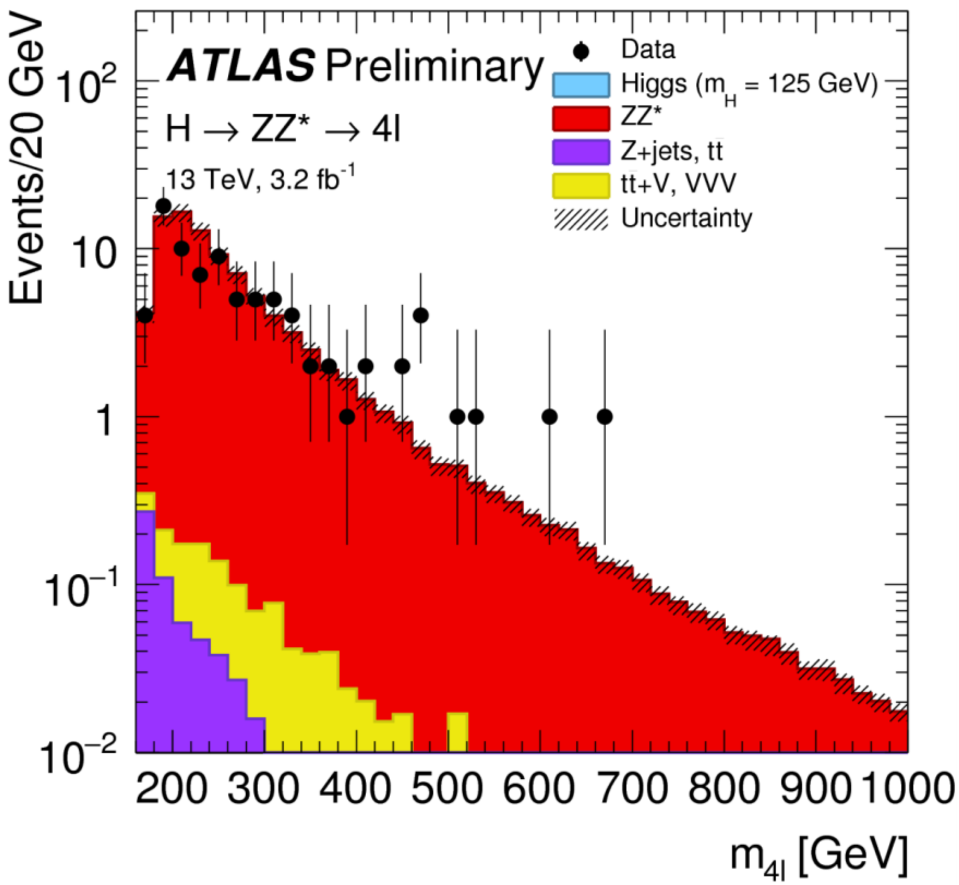
In summary

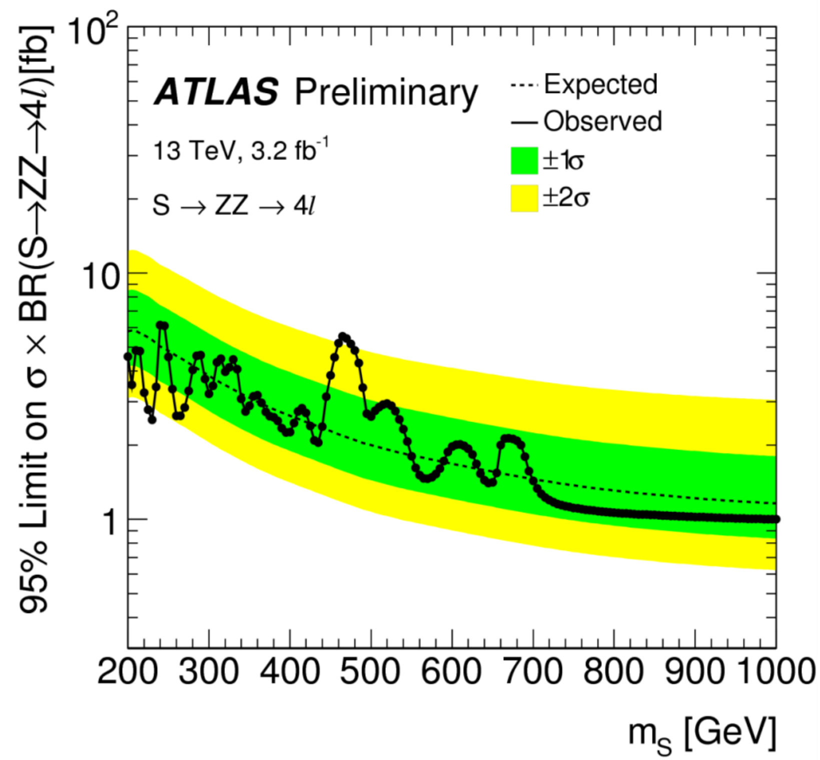


ATLAS Preliminary
H→γγ
H→ZZ*→4l
comb. data
syst. unc.
σ_pp→H m_H = 125.09 GeV
QCD scale uncertainty
Tot. uncert. (scale ⊕ PDF+α_s)
√s = 7 TeV, 4.5 fb^-1
√s = 8 TeV, 20.3 fb^-1
√s = 13 TeV, 3.2 fb^-1
σ_pp→H [pb]
√s [TeV]

H→ZZ : High Mass resonance

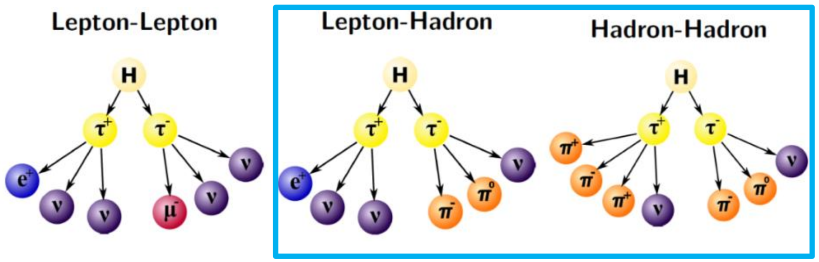
- Extended search reason to 1TeV   no significant excess observed
- Set 95%CL limit on σ x BR(s→ZZ→4l)

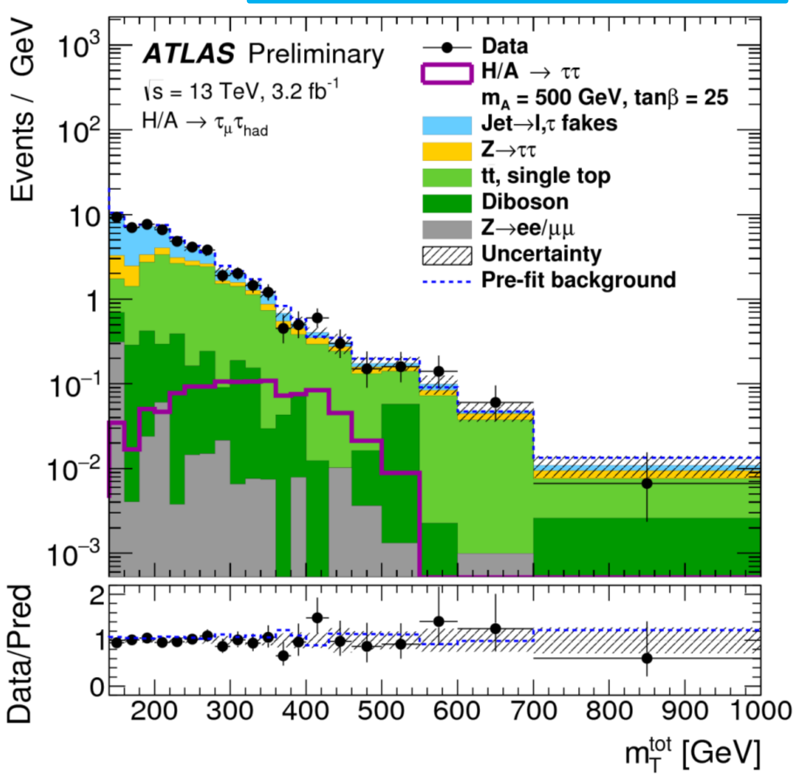


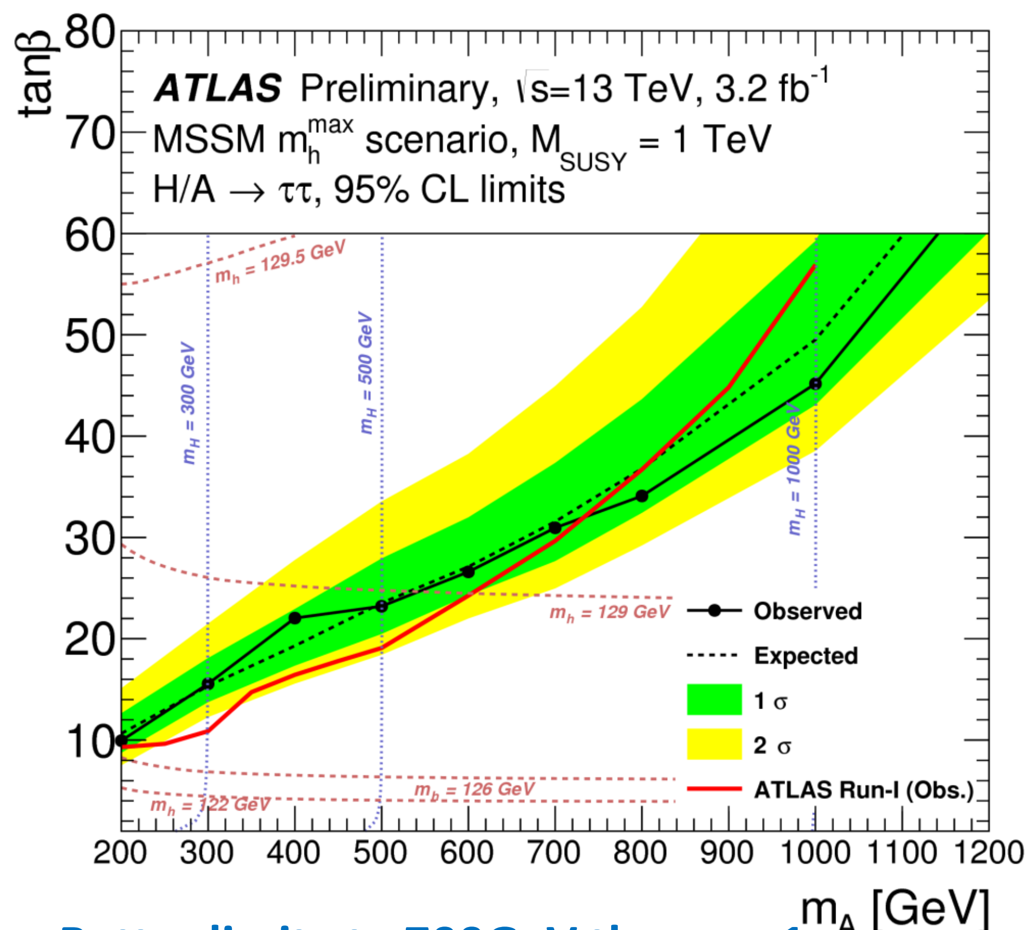


MSSM A→ττ

- To early for SM Higgs H→ττ but possible for MSSM



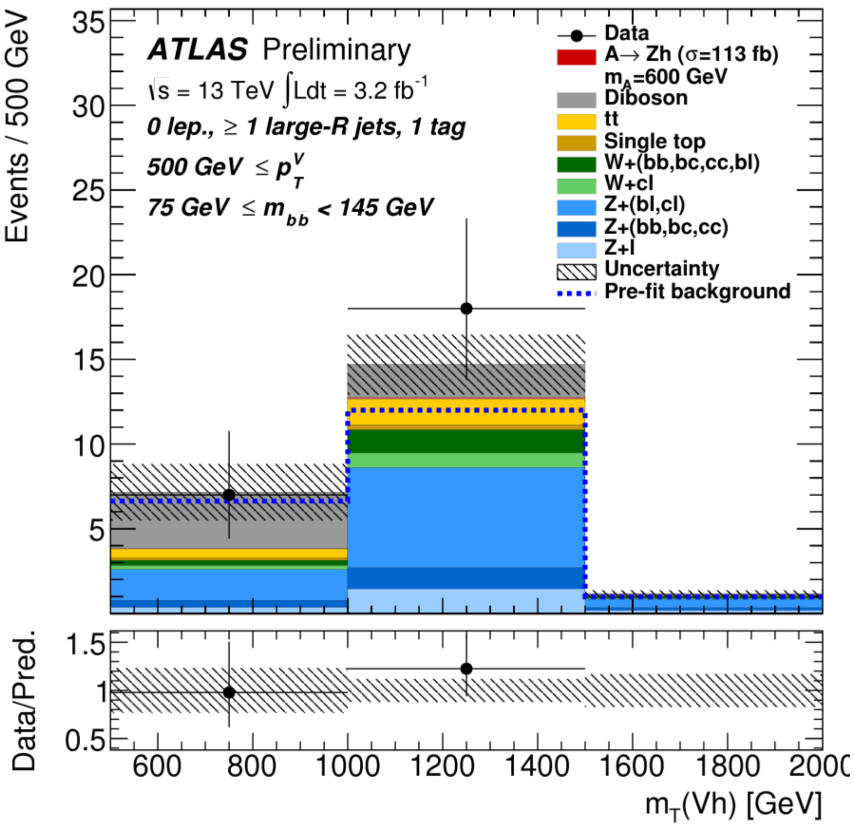


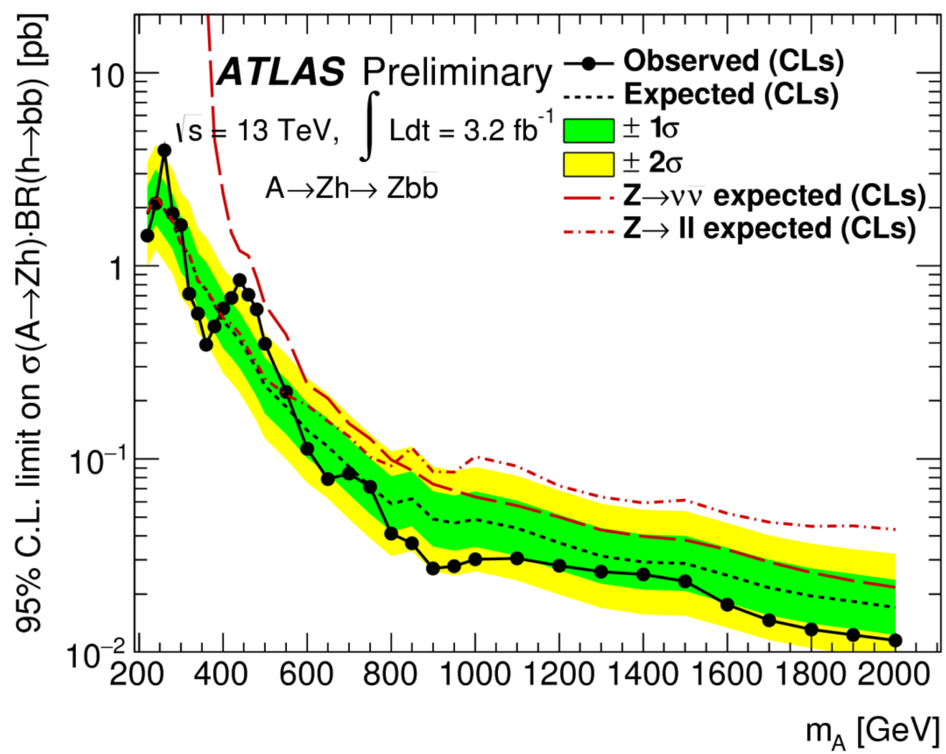


Better limit at >700GeV than run1

MSSM A→Zh

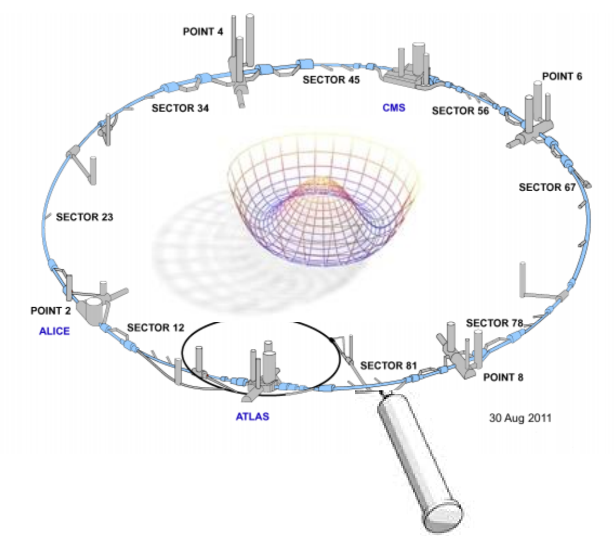
- Extended SM ZH→llbb,ννbb analysis to High mass.
- In pTZ>500GeV analysis H→bb treated as 1 fat jet (boost)





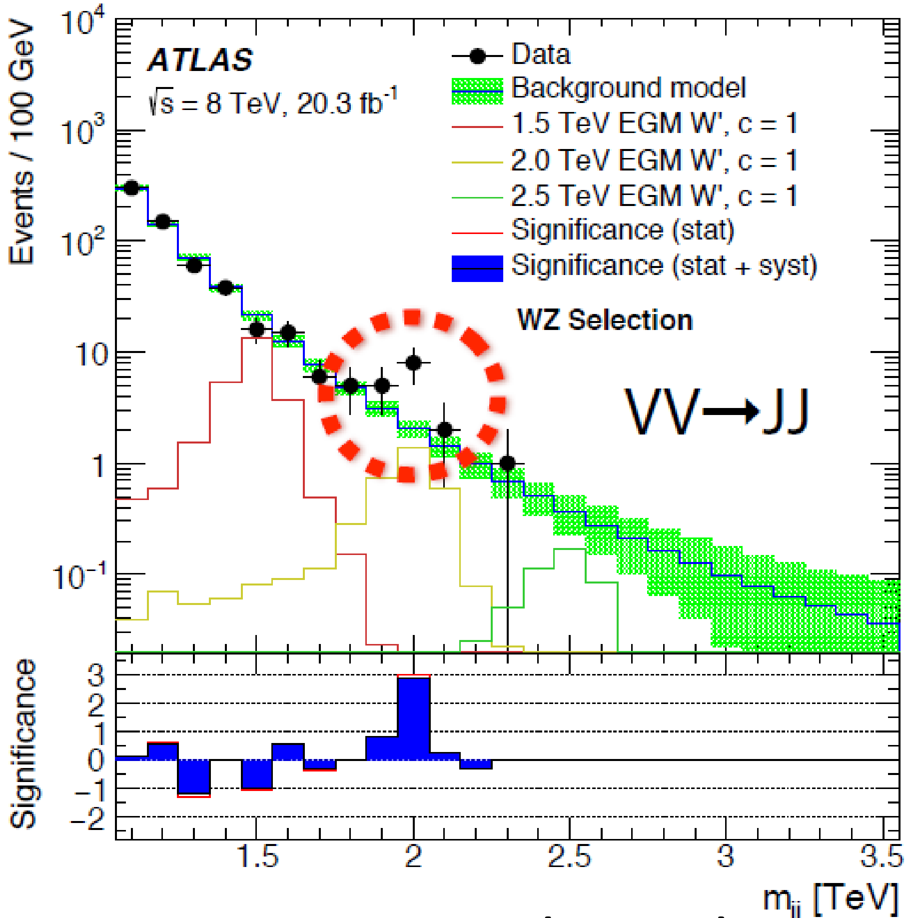
Better limit at >800GeV than run1

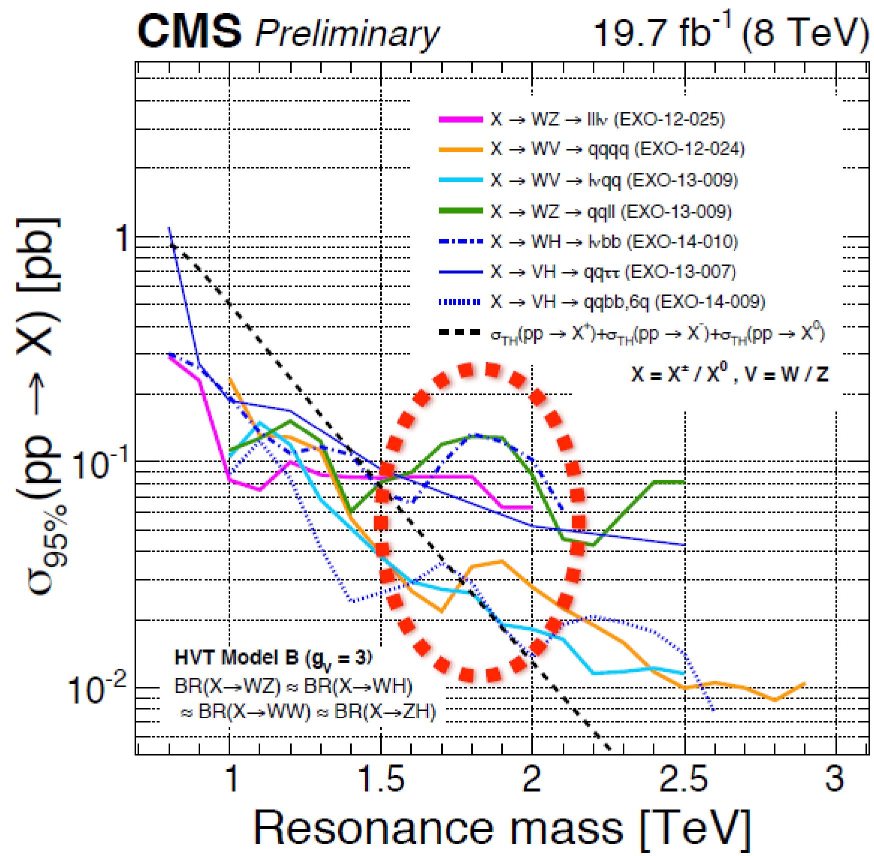
Published result at the LHC run2



- Re-observation of Higgs boson?
- Are the excess in VV and γγ real?
- SUSY/Exotic results.

8TeV di-boson results



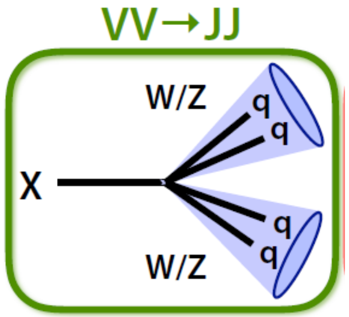


- Excess in Run1 (8TeV) : Say final word by 13TeVdata
- “J” : boost jet (mearged 2jet)→ boost boson-tagging

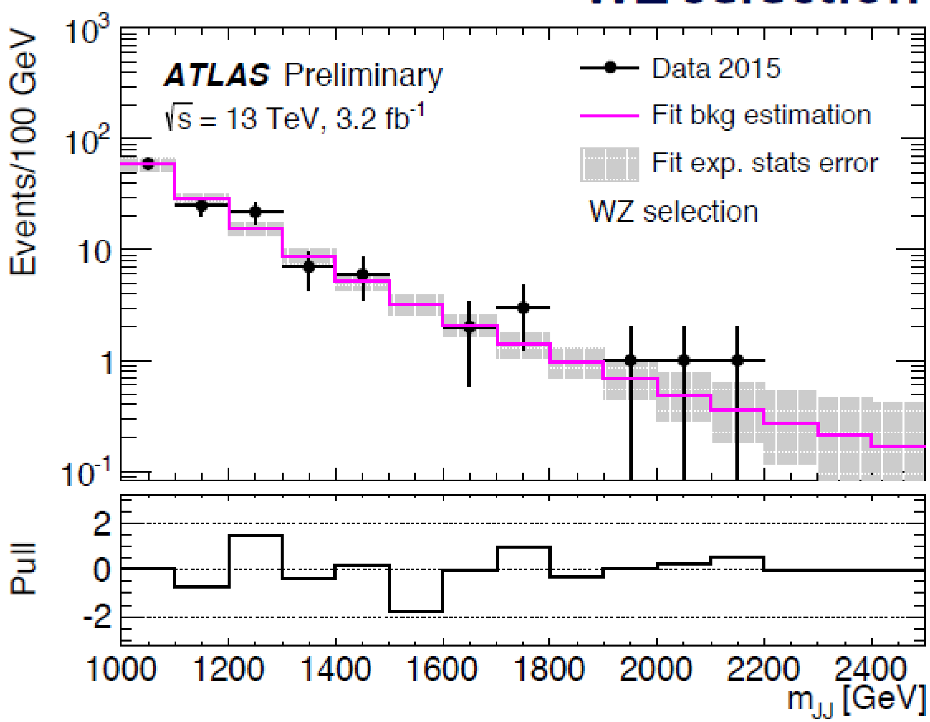
VV→JJ analysis @ 13TeV

- Repeated the same analysis as 8TeV with 13TeV data.
- Classify WZ,WW,ZZ selection by m_{qq}

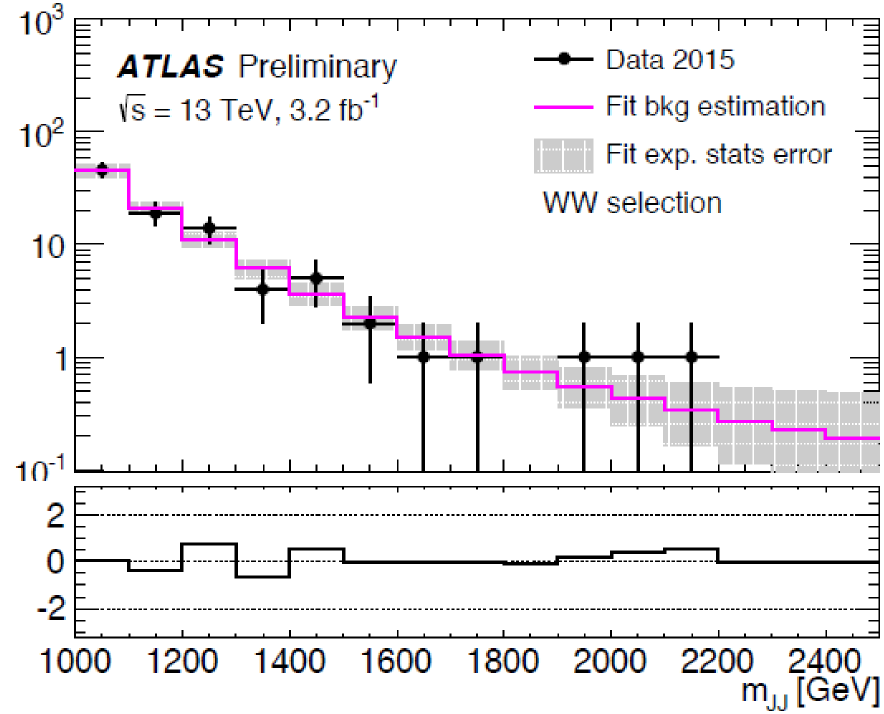
→No significant excess at 2TeV…



WZ selection



WW selection

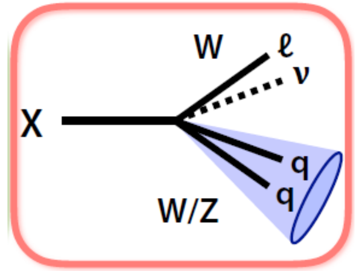


VV → Leptonic decay

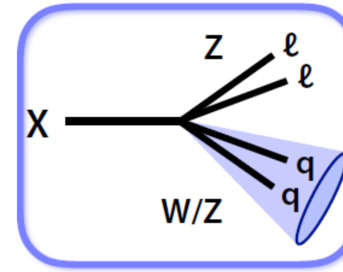
- In addition to VV→JJ, analized leptonic decay channel

→ No significant excess

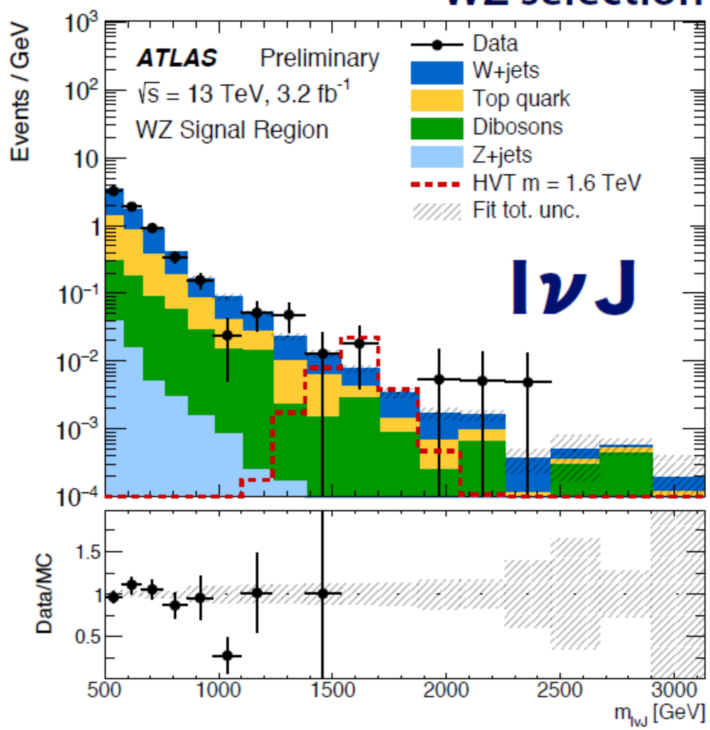
WW/WZ→lνJ



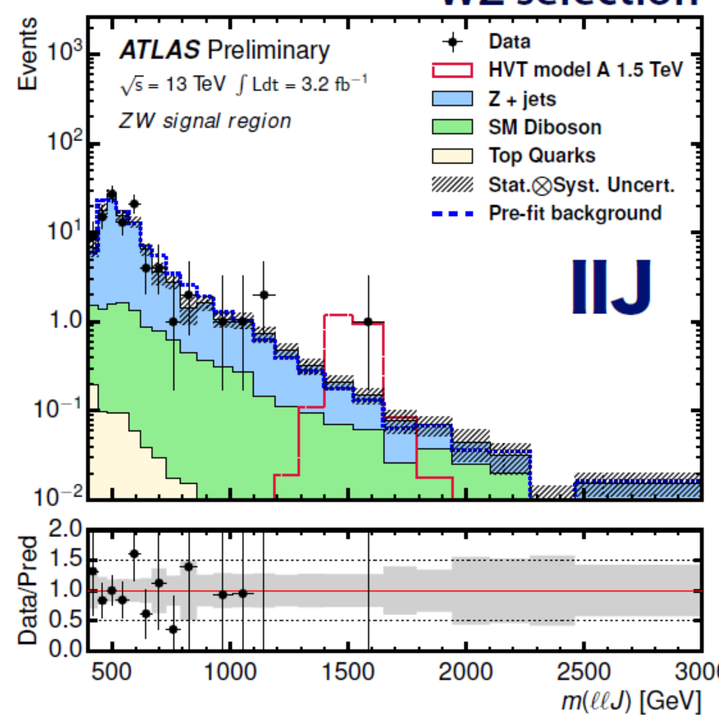
ZW/ZZ→llJ



WZ selection



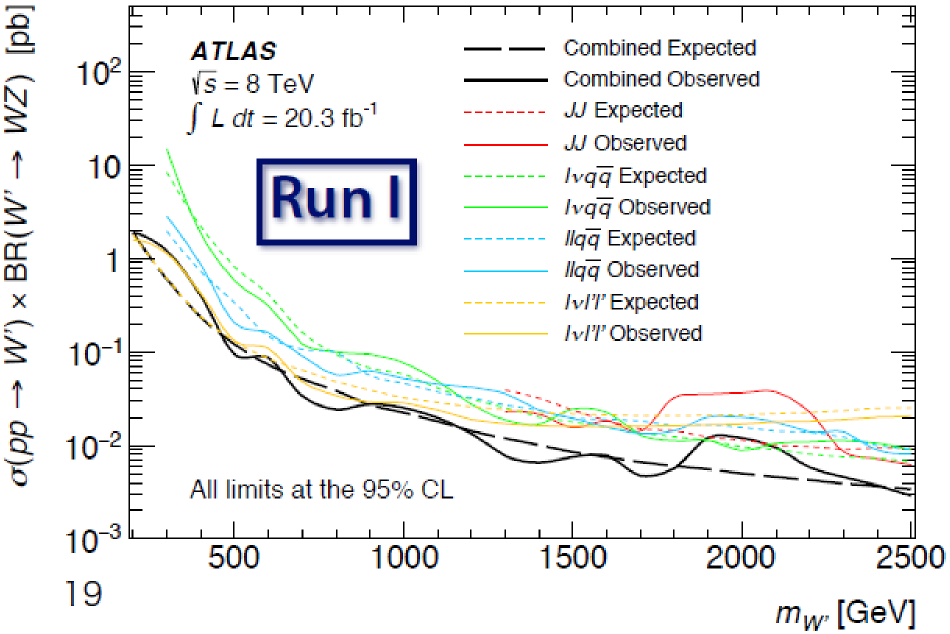
WZ selection

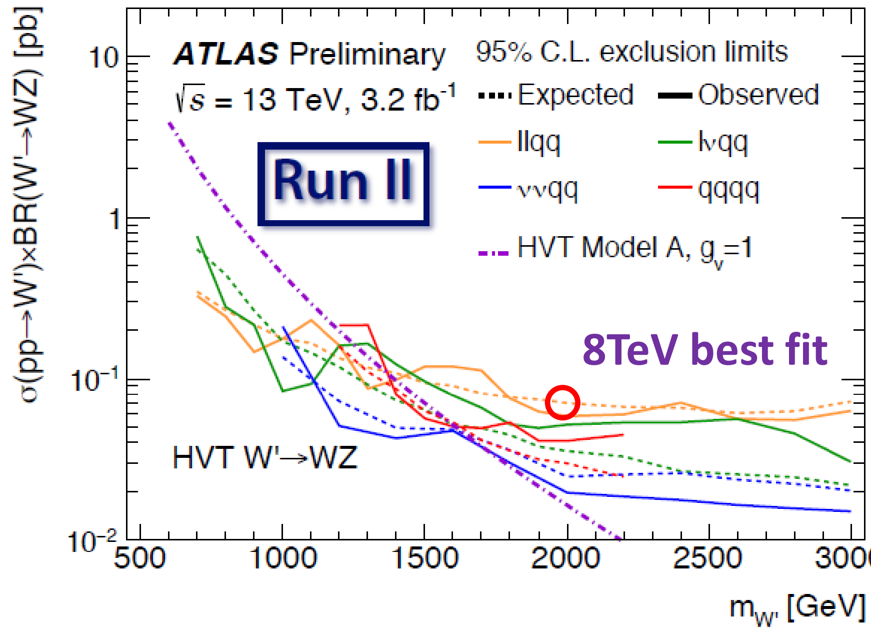


Have the 8TeV excess excluded ?

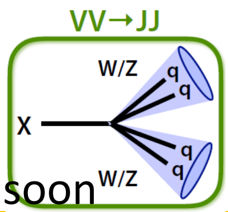
- Extrapolated 8TeV excess to 13TeV production cross section by using Proton PDF assuming (qq→X and gg→X)

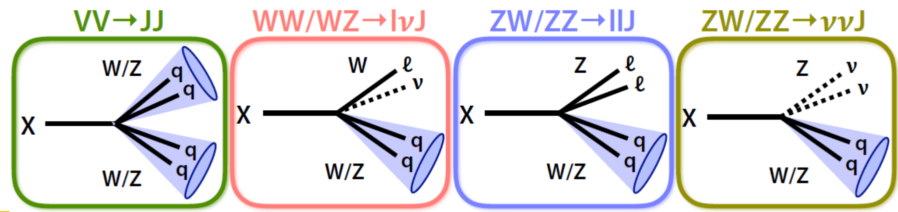
Best fit : σ x BR(W'→WZ) ~ 7 fb @ 2TeV —8→13TeV→ 10-15倍 : 70-100fb @ 2TeV





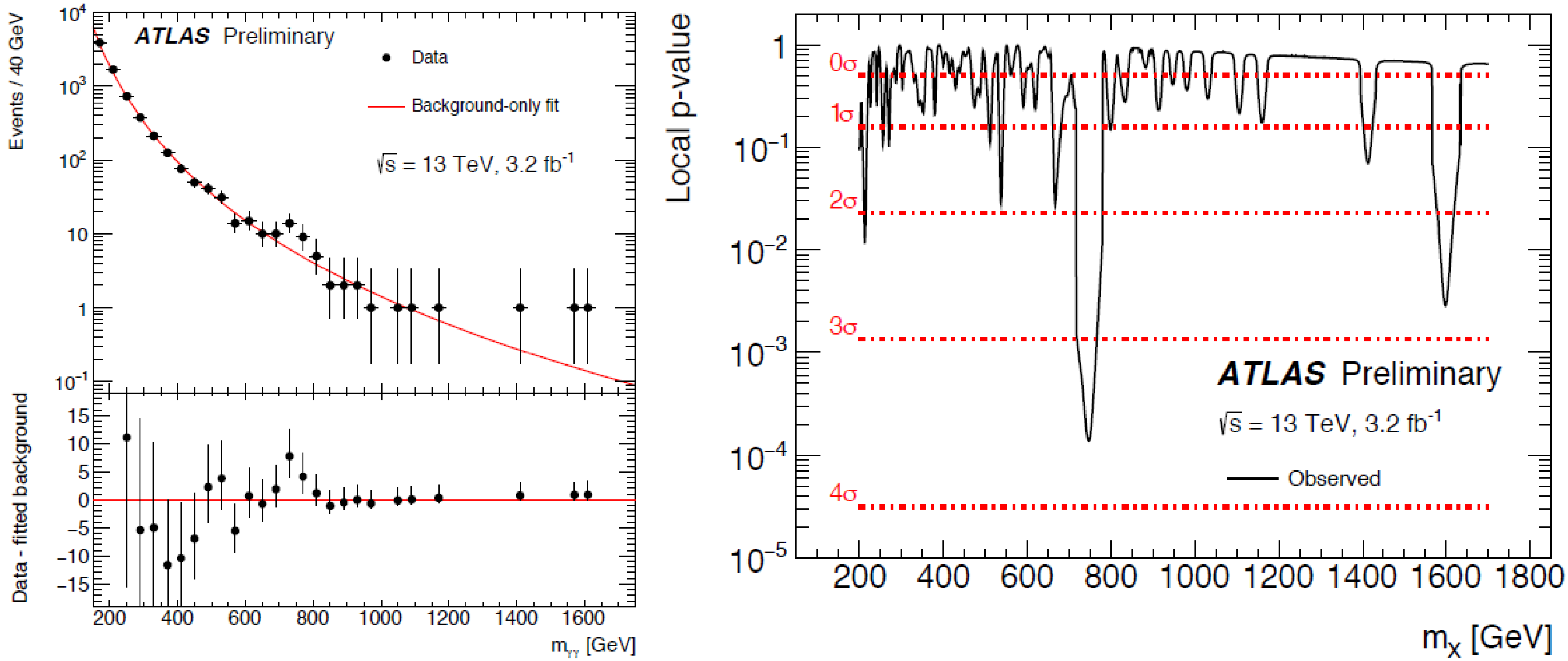
Almost excluded





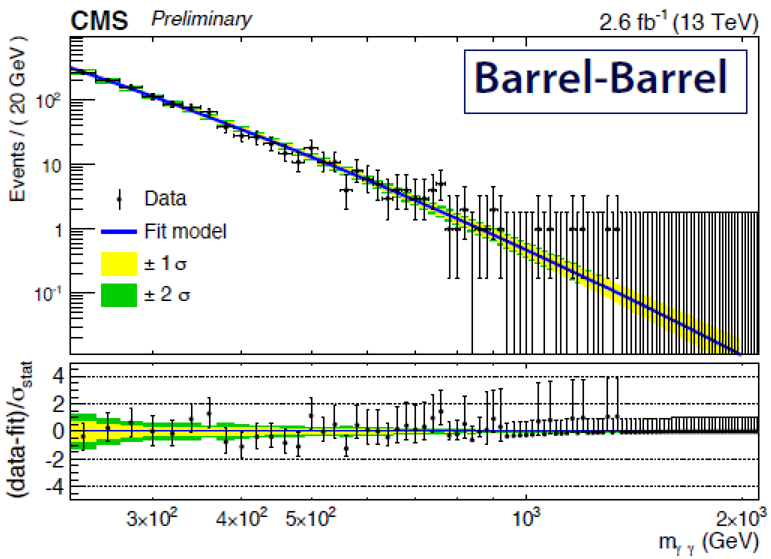
→combination will be available soon

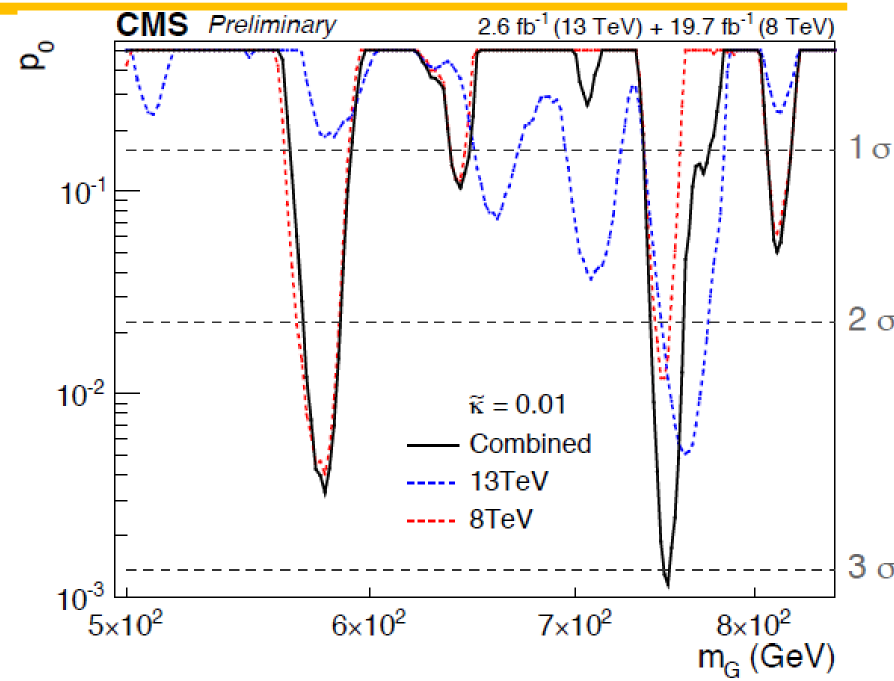
Di-Photon analysis (Dec 2015)

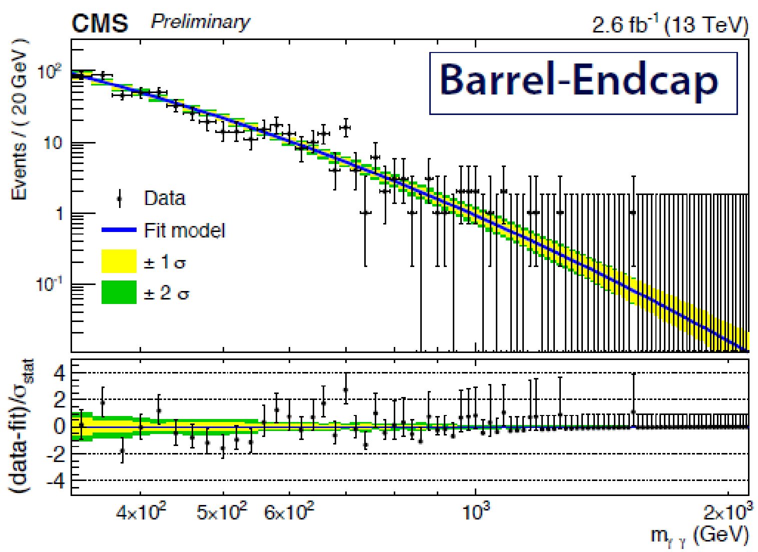


- Di-boson (750GeV) excess : local(global)3.9(2.3)σ
- Width : Γ/m=6% (Γ=45GeV)

Di-Photon analysis (Dec 2015)







- Saw small excess in Barrel-Barrel event (not for Barrel-Endcap event)
- Show excess for both 8TeV and 13TeV but different mass.
- 13TeV : Local(global) 2.6(<1.2)σ@760GeV
- 8TeV : Local (global) 3.0(<1.7)σ @750GeV

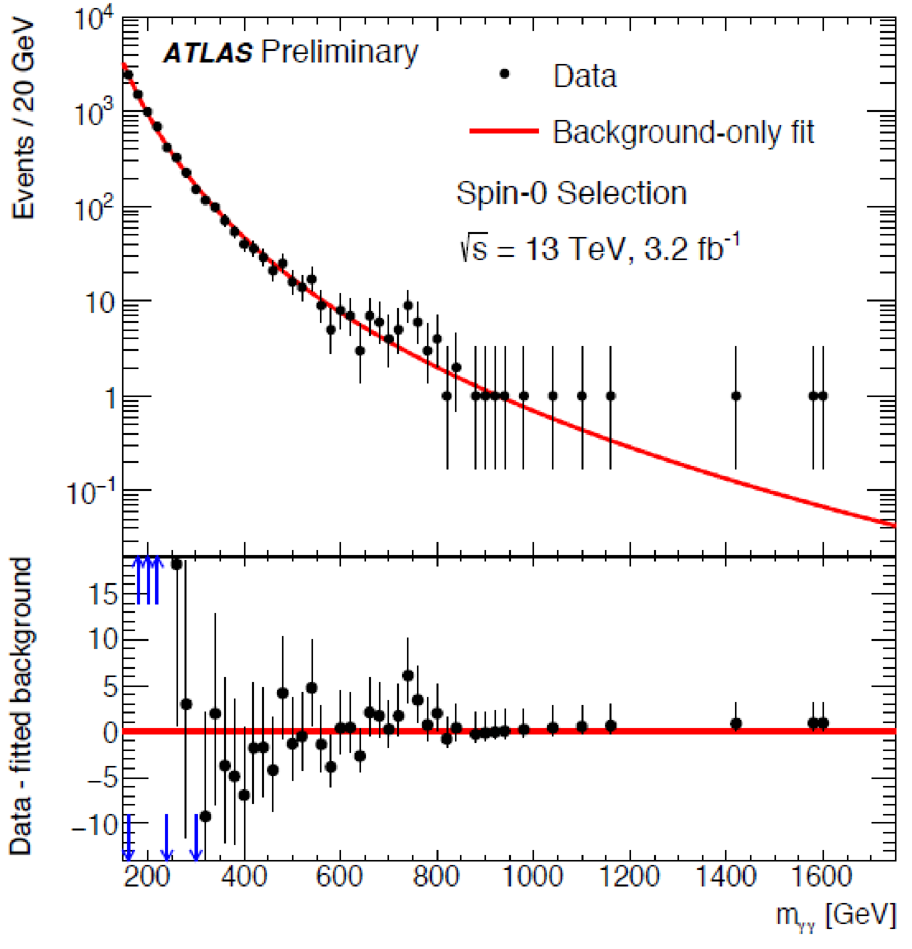
  for κ/M_{Pl}=0.01(RS Graviton) i.e. narrow

Re-analysis for Moriond

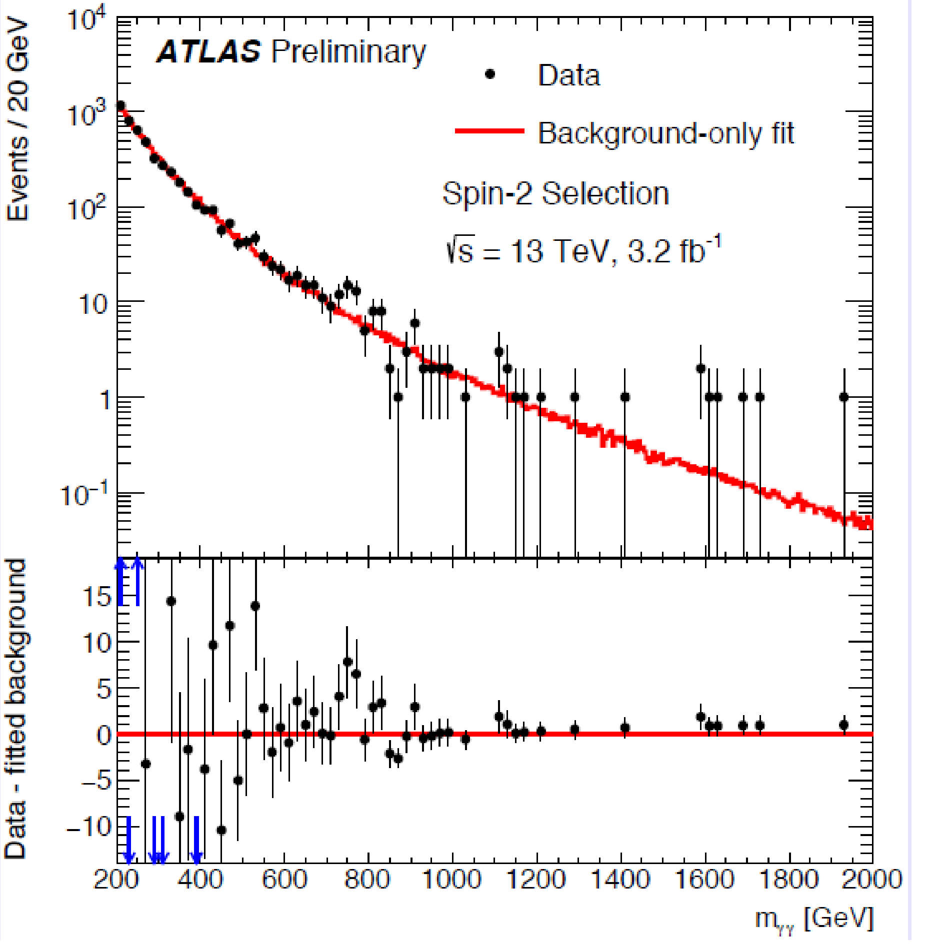
- Two type of analysis : Spin-0 Higgs and Spin-2 Graviton (Originally Spin-2 analysis is very loose selection to target for very high mass region >3TeV)
- Common selection
  - Tight photon ID with Diphoton trigger
- Spin0 Higgs analysis
  - **$E_T^{\gamma1(2)} > 0.4(0.3) m_{\gamma\gamma}$**
    - 750GeVで$E_T^{\gamma1} > 300$GeV
- Spin2 Graviton analysis
  - **$E_T^{\gamma1,2} > 55$GeV**
    - Looser cut than Spin0, high acceptance to the Forward Event.

Re-analysis for Moriond

- Spin-0 Higgs analysis

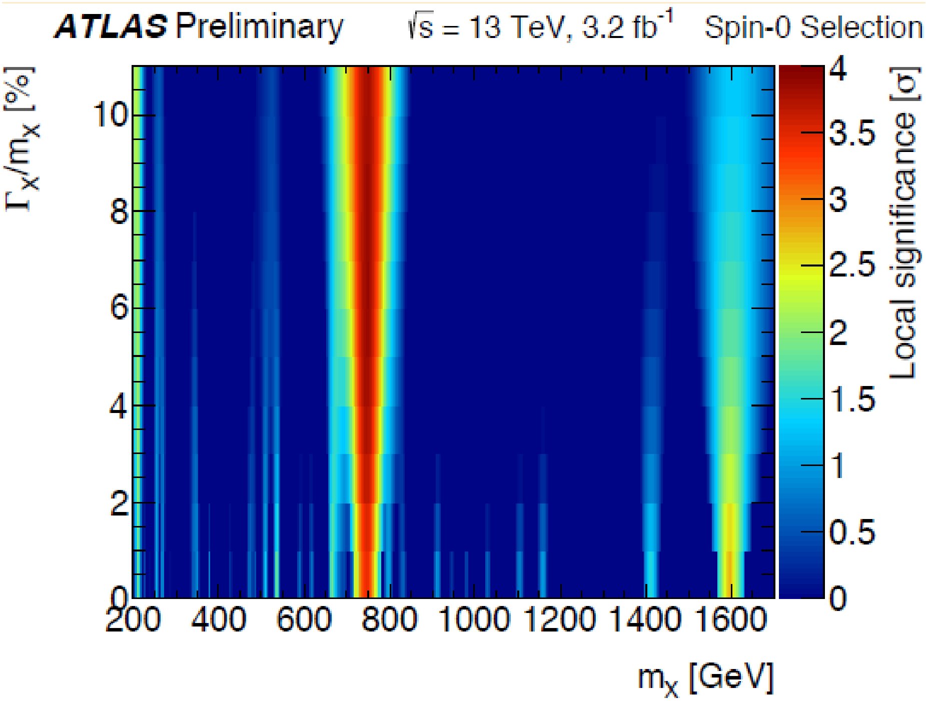


- Spin-2 Graviton analysis

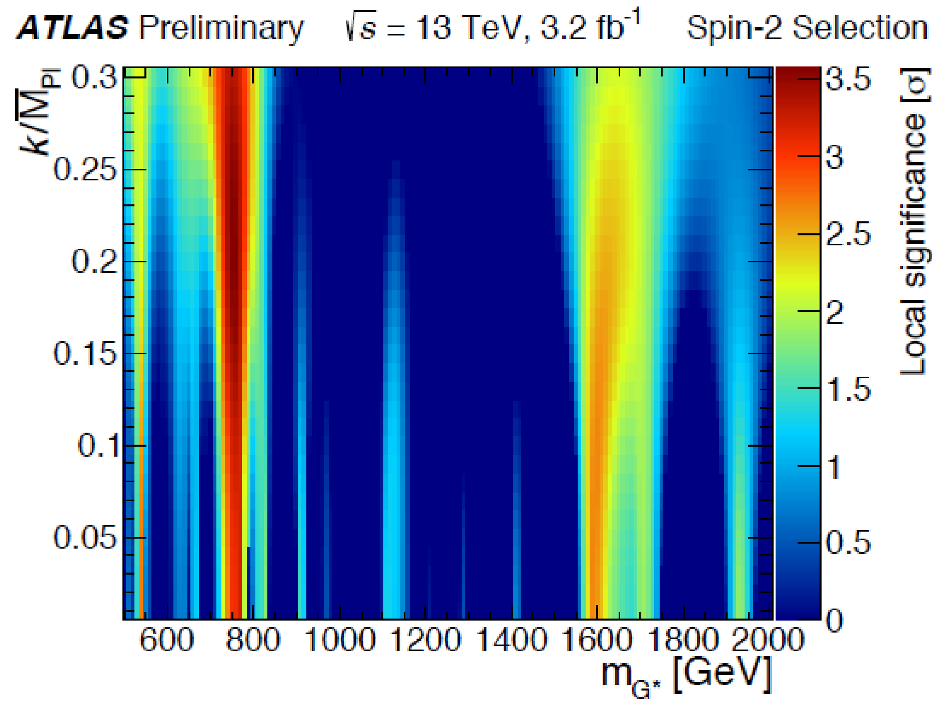


Re-analysis for Moriond

- Spin-0 Higgs analysis



- Spin-2 Graviton analysis

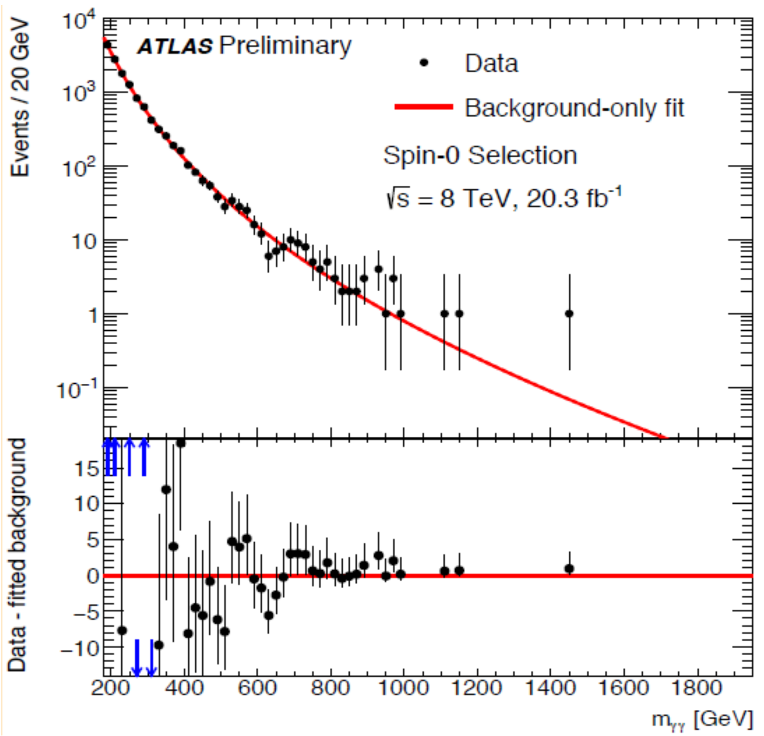


Local (global) 3.9(2.0)σ
@ 750GeV, Γ/m=6% (Γ=45GeV)

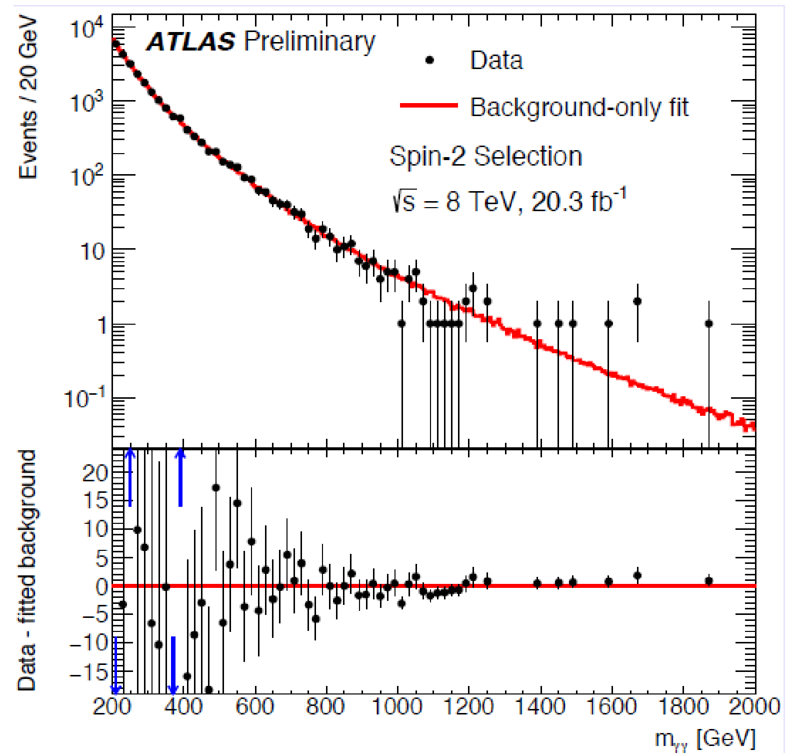
Local (global) 3.6(1.8)σ
@ 750GeV, Γ/m=7% (κ/M_{Pl}=0.2)

8TeV data re-analysis

- Spin-0 Higgs analysis



- Spin-2 Graviton analysis

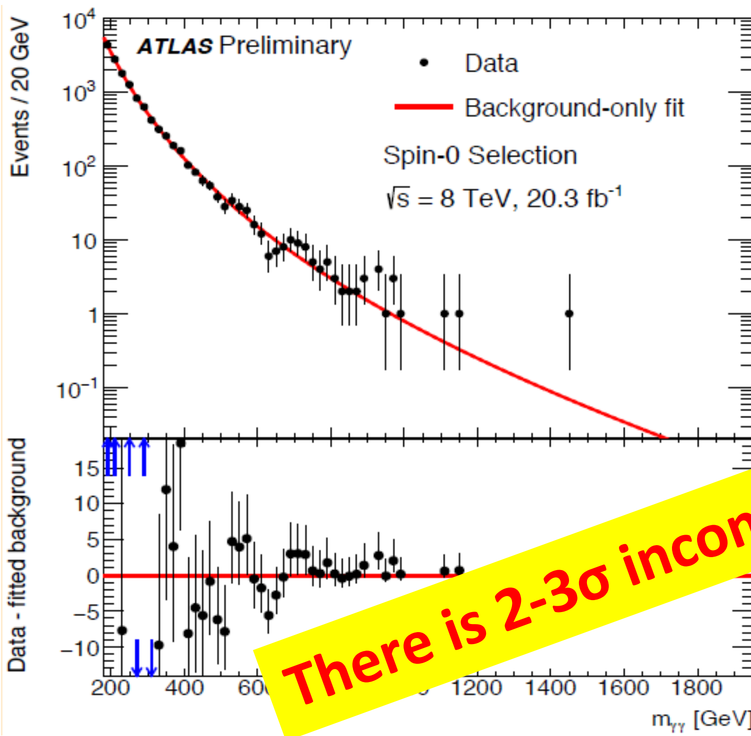


Local 1.9σ @ 750GeV, Γ/m=6% (Γ=45GeV)
Compatibility with 13TeV
gg(qq) process 1.2(2.1)σ

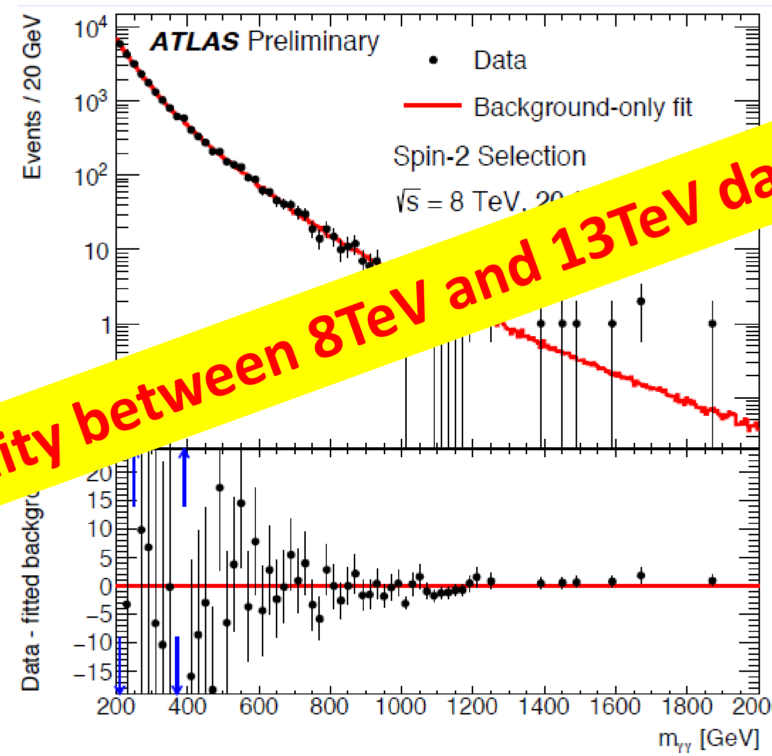
No significant excess
Compatibility with 13TeV
gg(qq) process 2.7(3.3)σ

8TeV data re-analysis

- Spin-0 Higgs analysis



- Spin-2 Graviton analysis



There is 2-3σ incompatibility between 8TeV and 13TeV data

Local 1.9σ @ 750GeV, Γ/m=6% (Γ=45GeV)

Compatibility with 13TeV gg(qq) process 1.2(2.1)σ

No significant excess

Compatibility with 13TeV gg(qq) process 2.7(3.3)σ

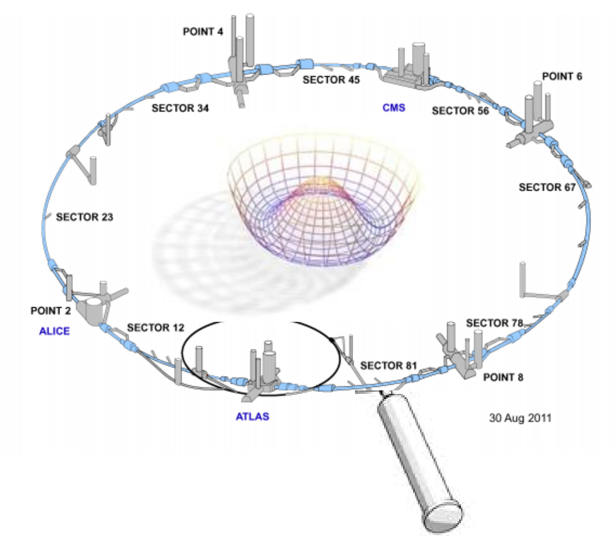
What we saw in 2016 data?

- To say final word…

What we saw in 2016 data?

- To say final word…
  - **Sorry, I can't show anything…**
    - – Unblinded 2.6fb^{-1} data last week, though.
      - **Not enough data to reach conclusion (2/3 x run1).**
    - – Will show results in ICHEP conference…
      - **With higher statistics for sure.**

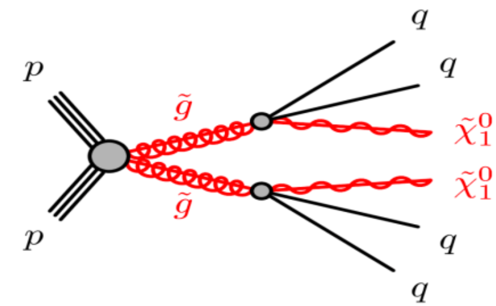
Published result at the LHC run2

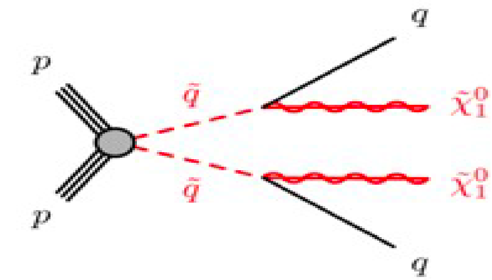


- Re-observation of Higgs boson?
- Are the excess in VV and γγ real?
- SUSY/Exotic results.

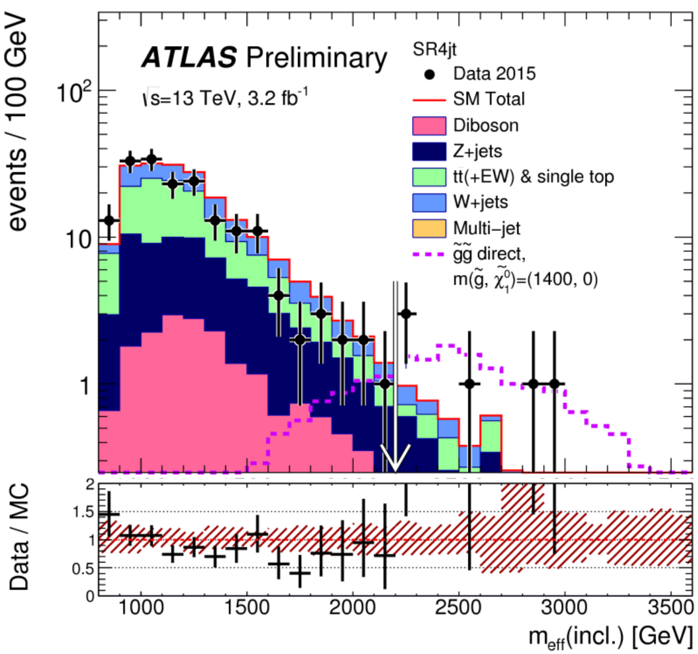
Squark and Gluino searches (1,2 gen)

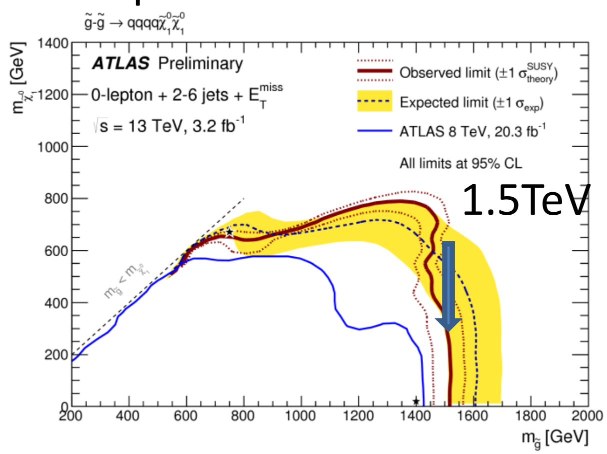
- **Huge cross section, quite exiting to see the first result after upgraded collider energy.**
- (2-6)Jets + large MET
- Dominant background : Z(→νν)+jets, Top

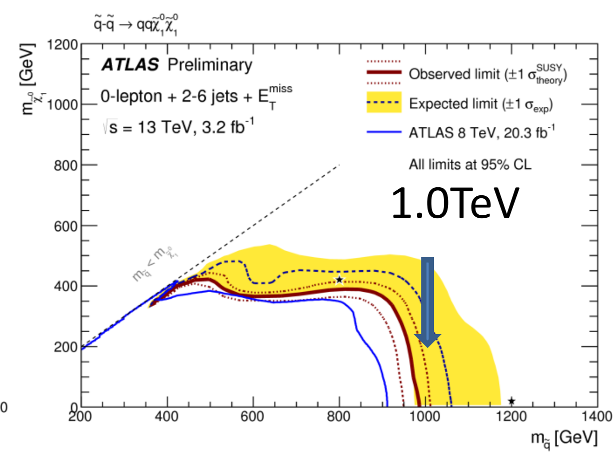




No significant excess observed.
excluded
gluino : <1.5TeV
squark : < 1.0TeV

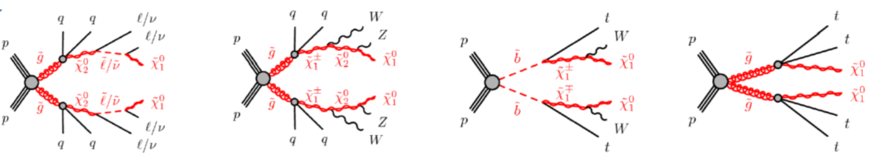


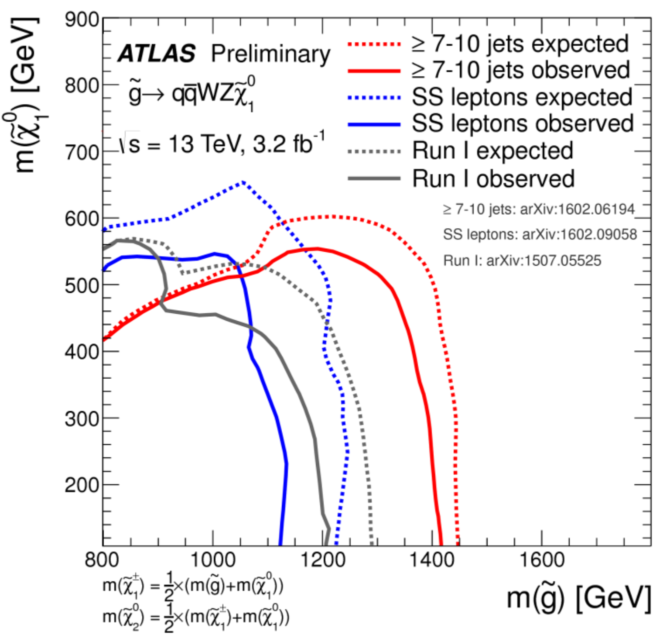




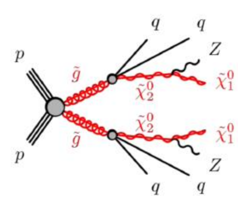
>=2 lepton channel

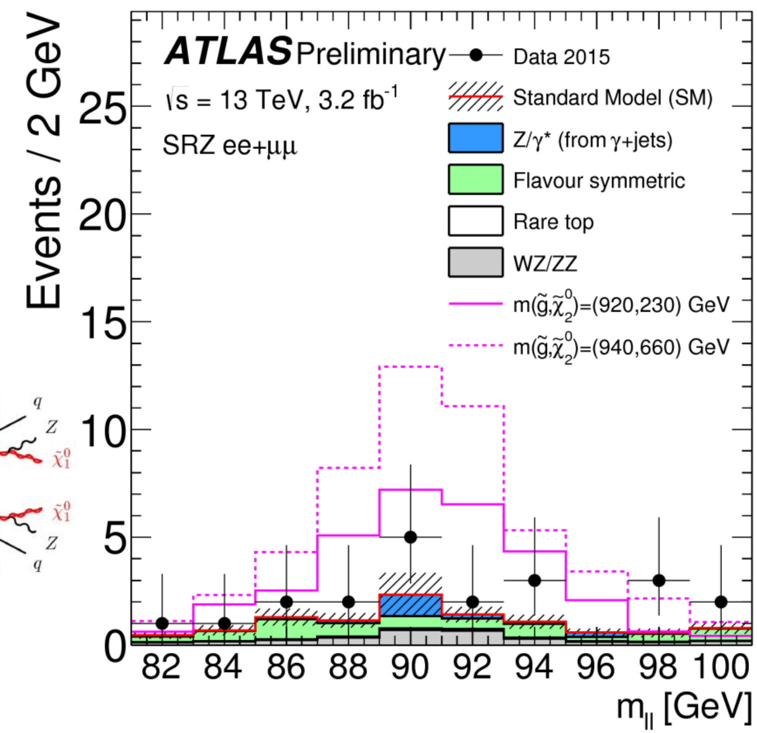
- 2 same-sign leptons
  - Small SM Bkg
  - No significant excess





- 2 opposite-sign leptons
  - gluino/squark assosiated with Z
  - Run1: 3(1.7)σ excess for ee(μμ)
  - Run2: 2.2σ excess !?
    - 21 event (bkg 10.3±2.3)
  - Too small excess if Run1 excess is real





Prospect of 300 and 3000fb^{-1}

No New results so if time allows

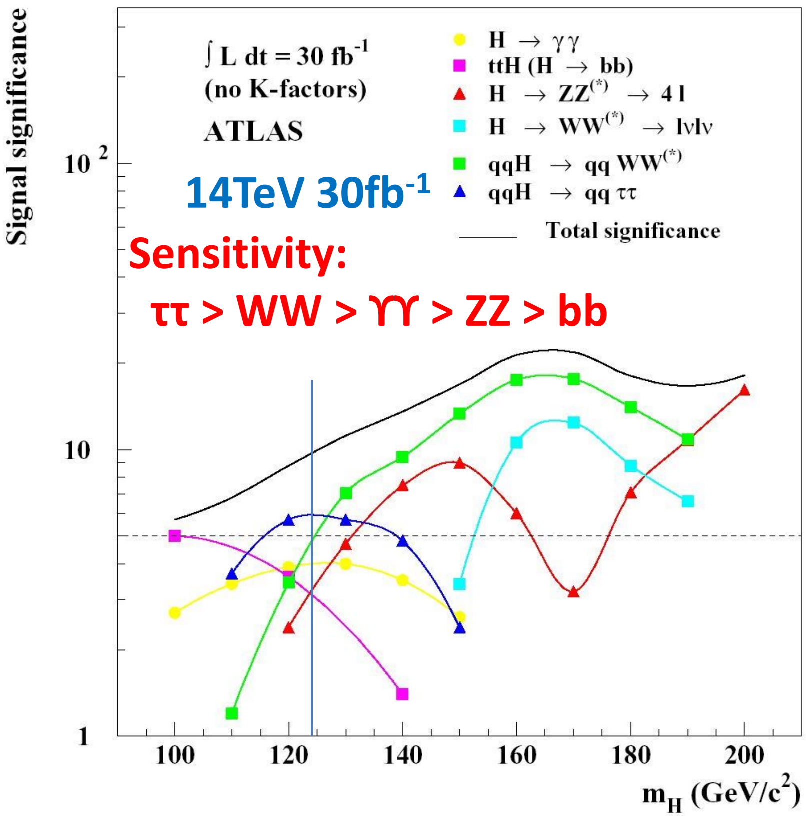
My personal view…

Not assuming the improvement of identification algorithm etc…
Extremely simpler analysis assumed than current Run1 resutls
So the result is very conservative and pessimistic case…

Lesson and leaned

Before experiment…

arXiv:hep-ph/0402254



ATLAS 2011+2012 Full data

$5fb^{-1}$(7TeV)+$20fb^{-1}$(8TeV)

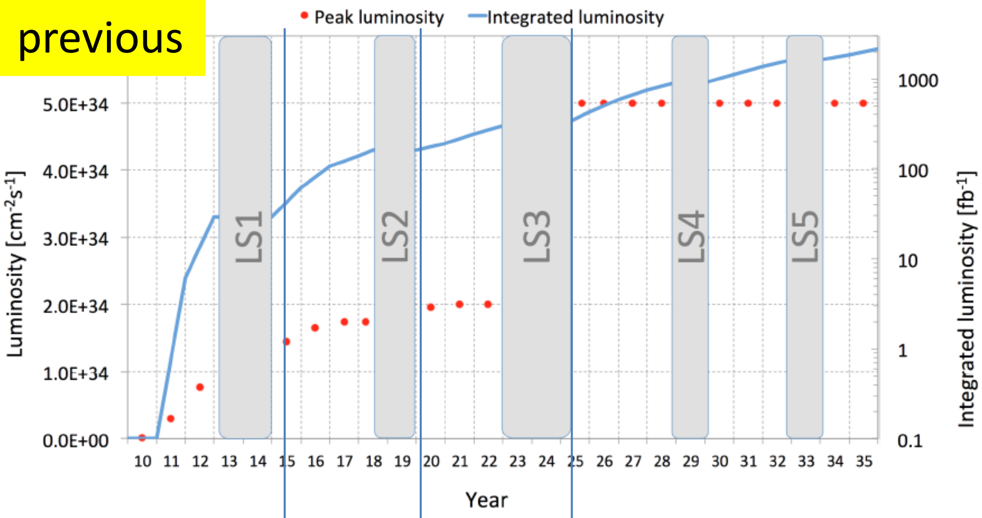
Decay channel	Expected sensitivity	Observed Sensitivity
ggF,(VBF):H→ZZ	6.2σ	8.1σ
ggF,VBF:H→ϒϒ	4.6σ	5.2σ
ggF,VBF:H→WW	5.8σ	6.1σ
(ggF),VBF:H→ττ	3.4σ	4.5σ
VH,H→bb	2.6σ	1.4σ
H→μμ	<7.2xSM	<7.0xSM
ttH:H→bb	<2.2xSM	<3.4xSM

Prospect of before starting experiment…

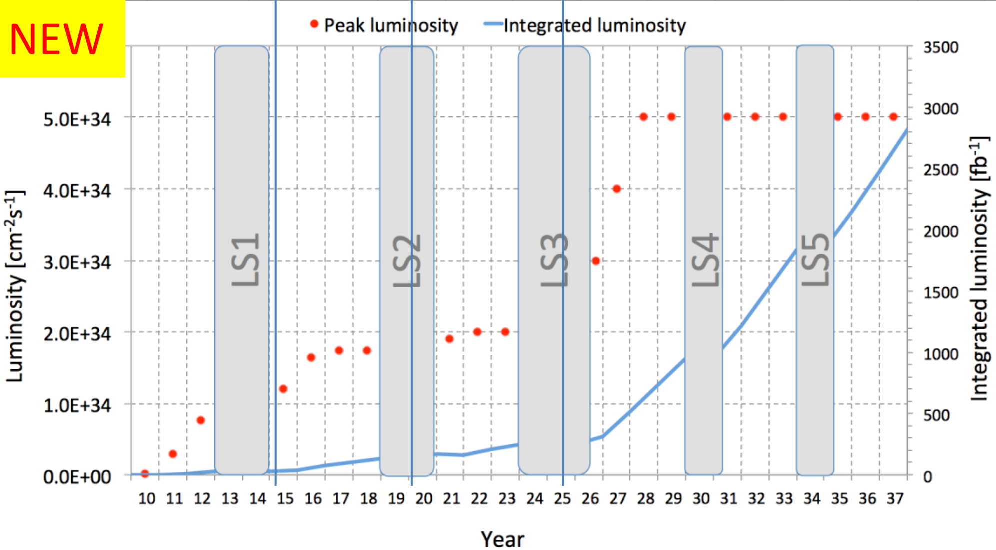
Much better results observed!!

Schedule changed

previous



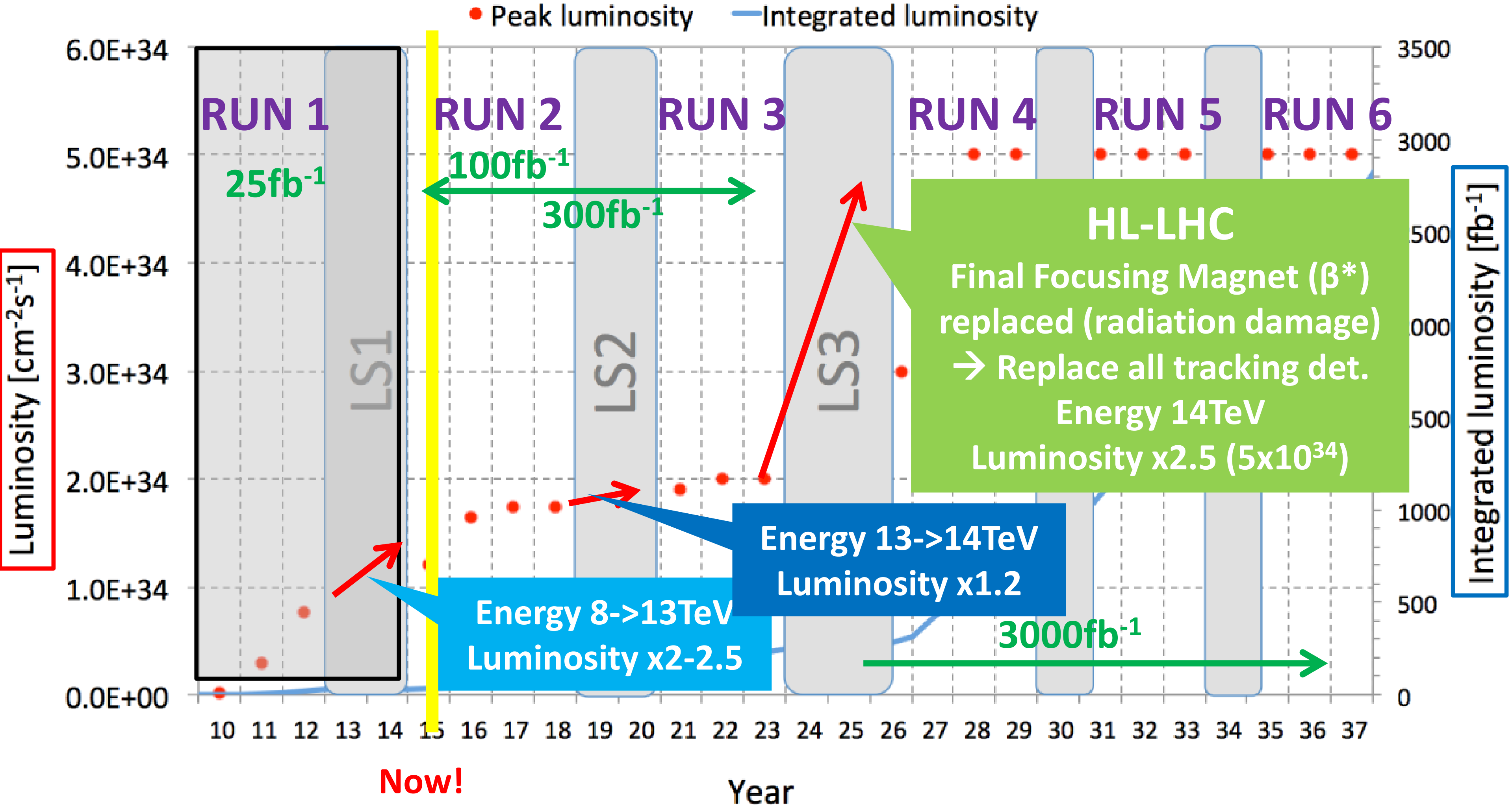
NEW



- Long shutdown (LS2&LS3) schedule is officially shifted 1-2 years.
  - Run3 starts 2021
  - HL-LHC starts 2026

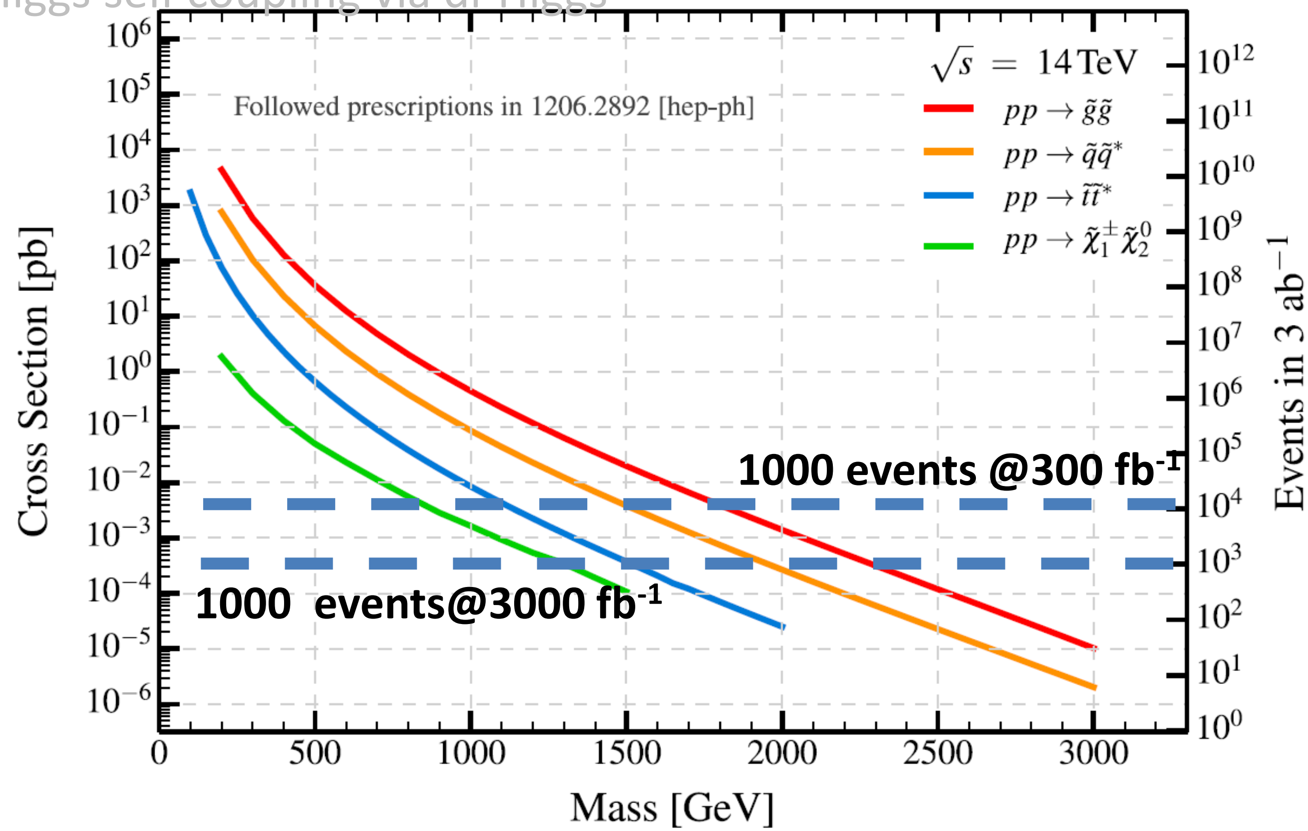
Upgrade schedule

- A bit complicated…



Physics motivation of HL-LHC

- Really need 300→3000fb^{-1} upgrade?
  - New Physics searches
  - Higgs searches and measurement
    - **Coupling measurement, search for rare decay**
    - Search for the Higgs self coupling via di-Higgs events.



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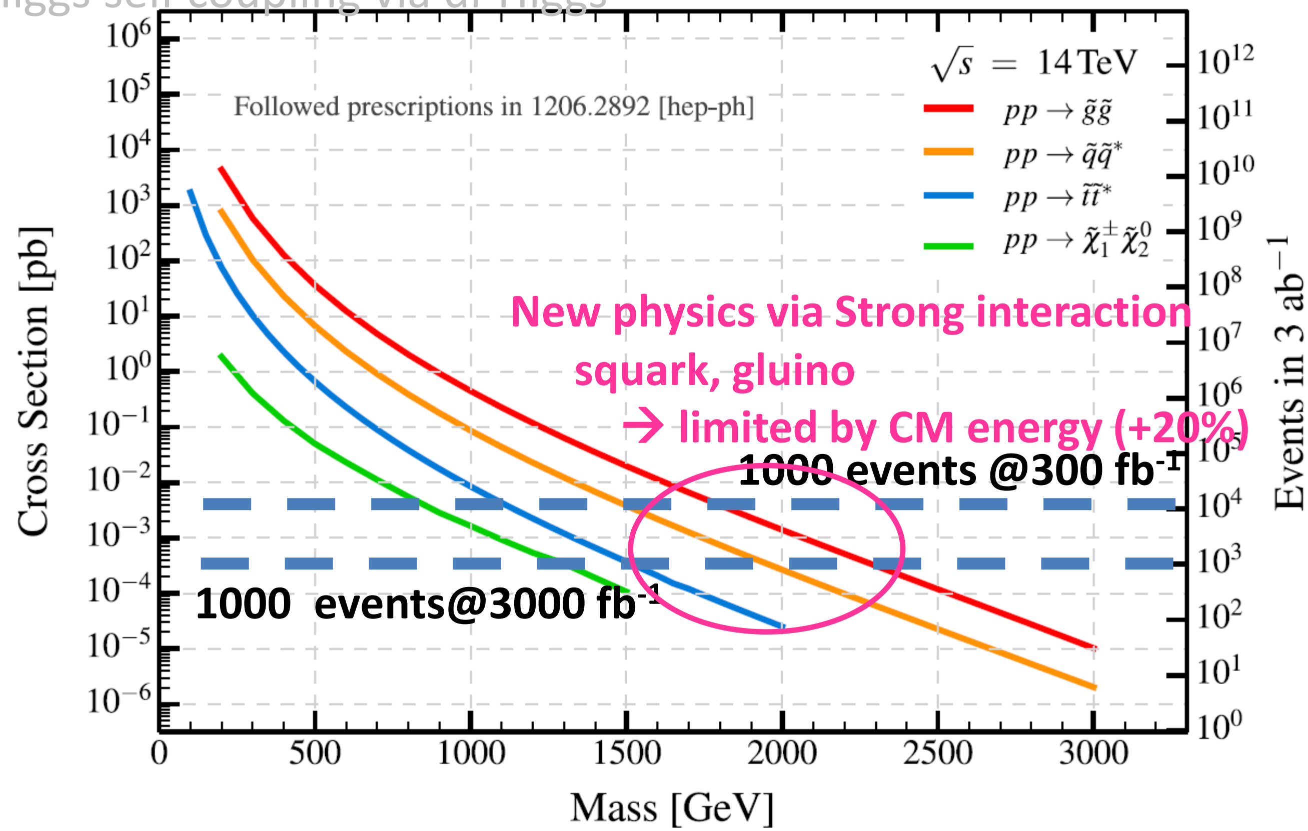

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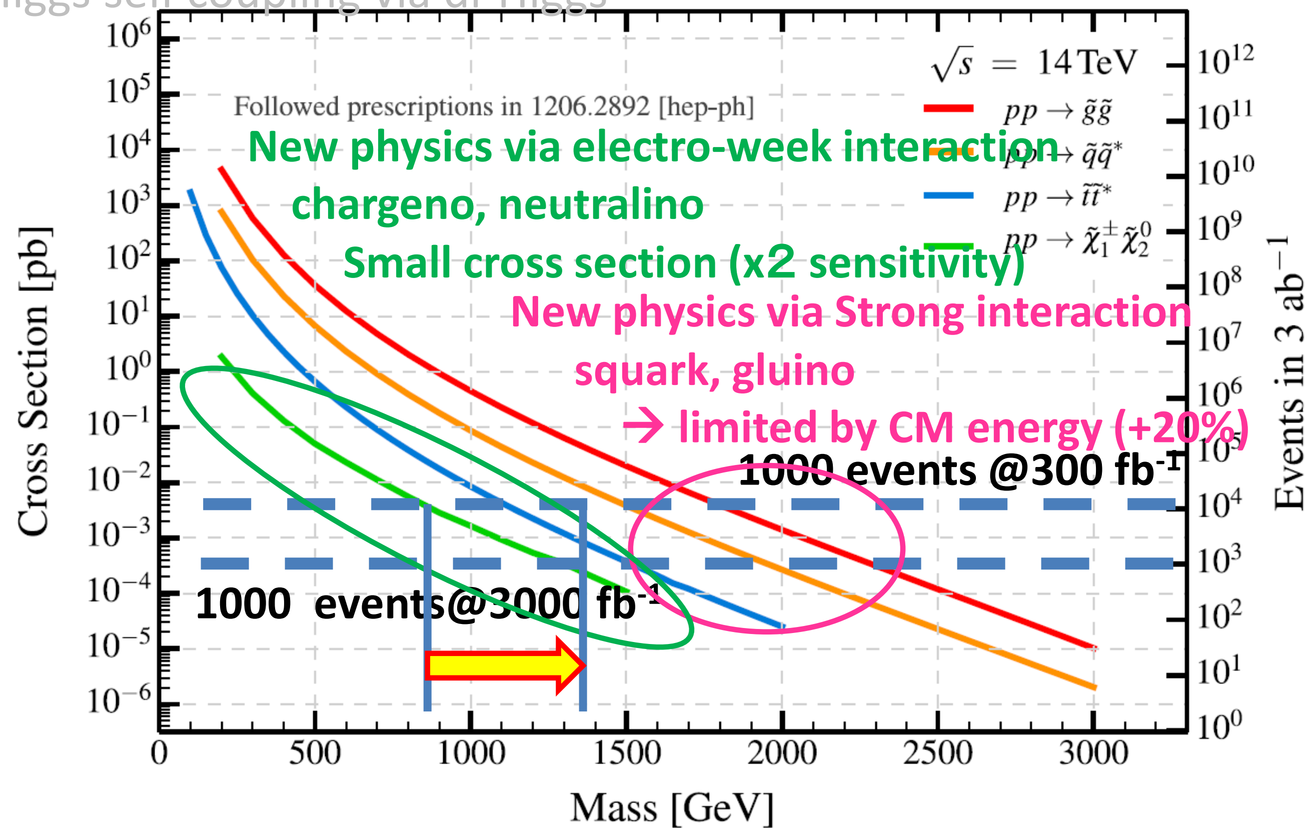

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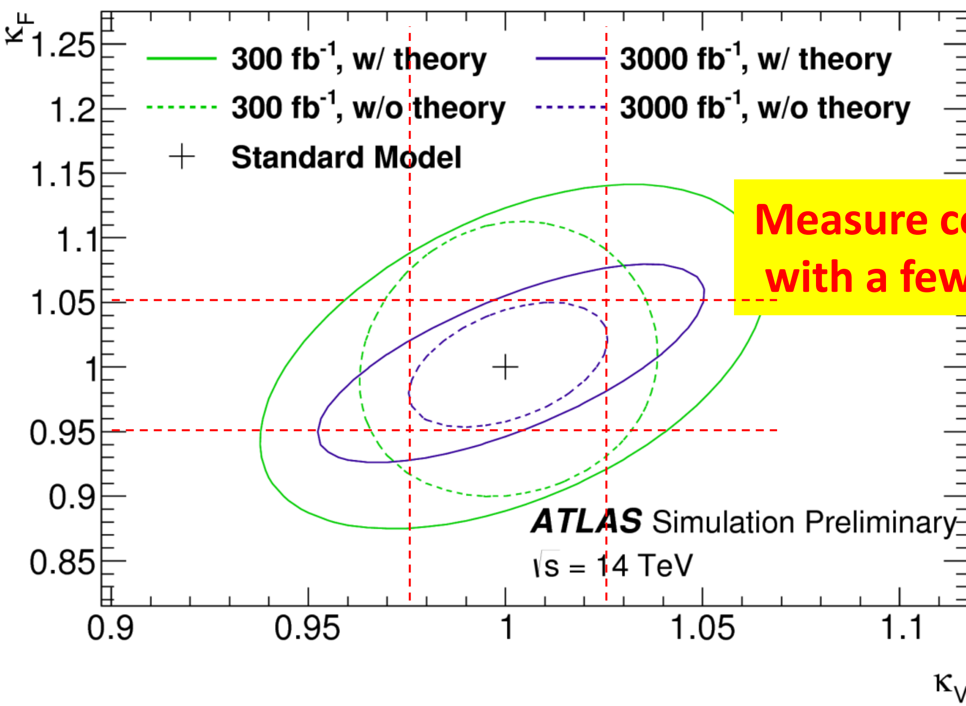
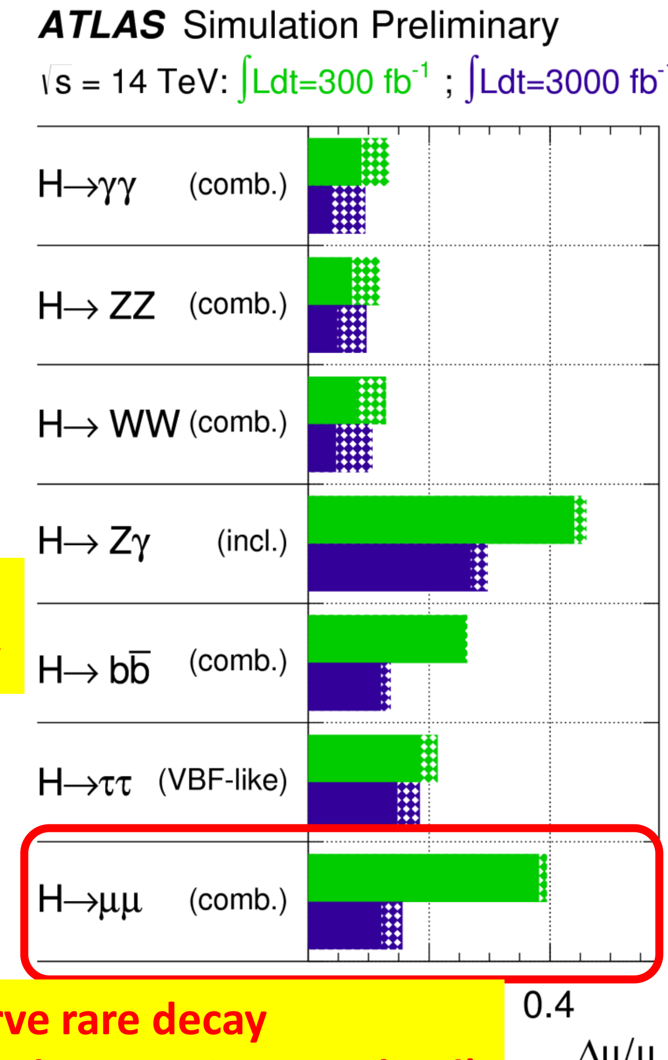


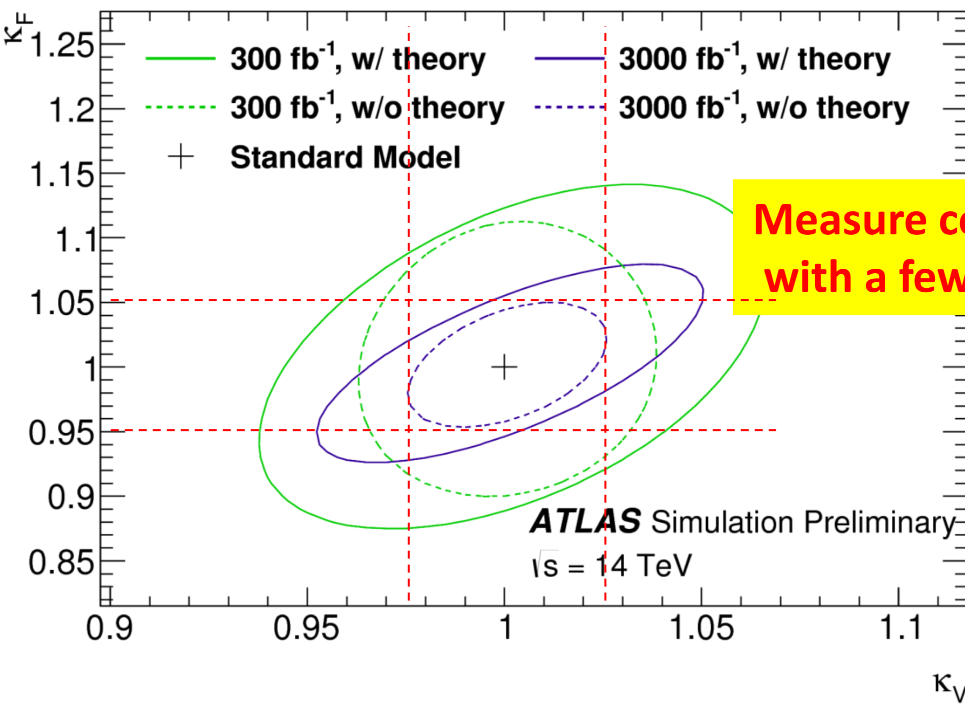
Measure coupling with a few % accuracy



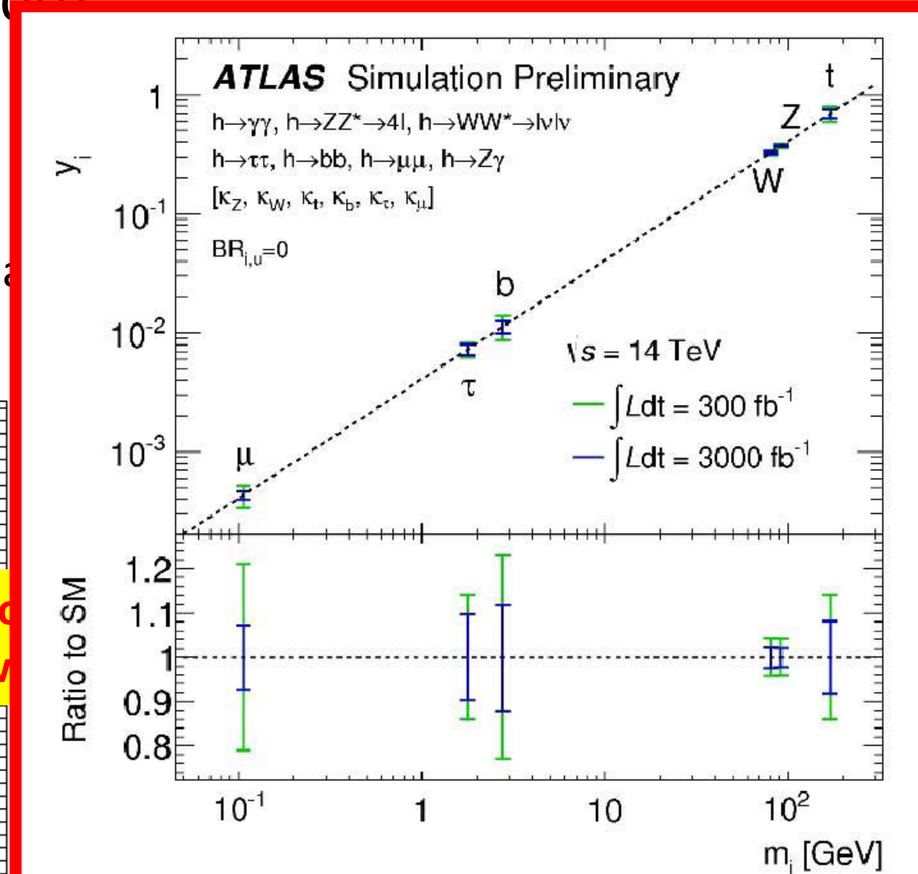
Observe rare decay
(Second generation coupling!)

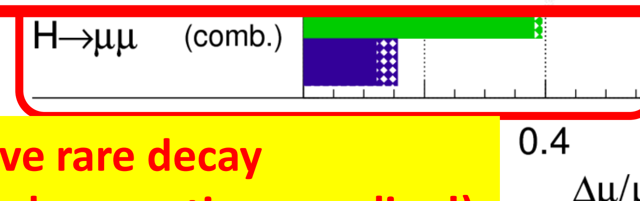
Physics motivation of HL-LHC

- Really need 300→3000fb^{-1} upgrade?
  - New Physics searches
  - Higgs searches and measurement
    - **Coupling measurement, search for**
    - Search for the Higgs self coupling via
      events.



Measure co
with a few



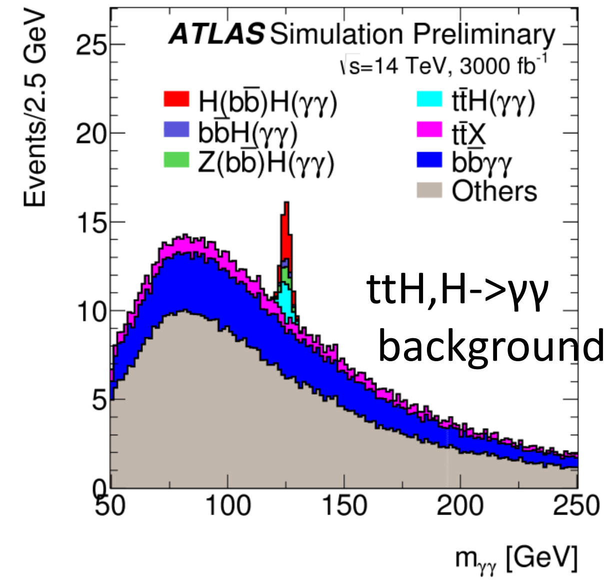


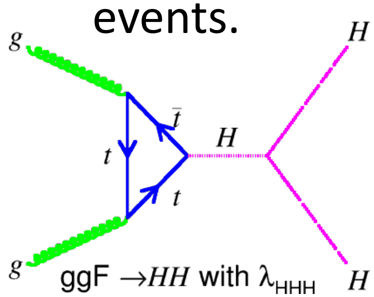
Observe rare decay
(Second generation coupling!)

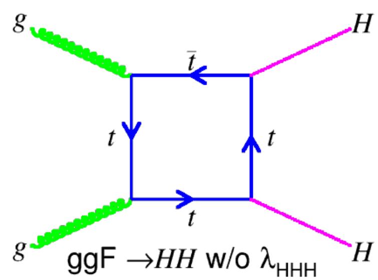
Physics motivation of HL-LHC

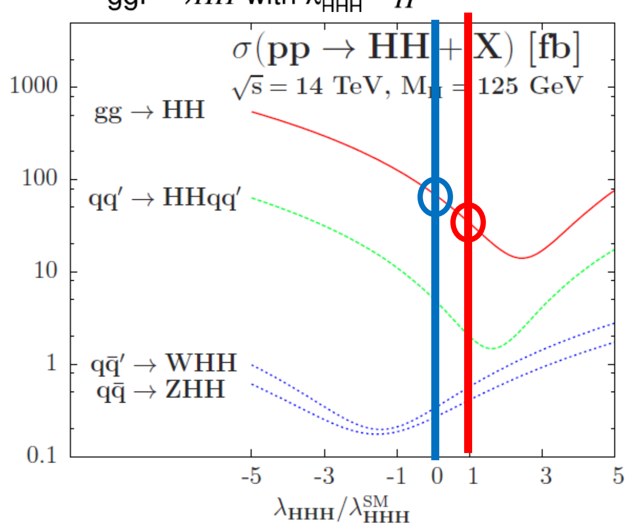
- Really need 300→3000fb^{-1} upgrade?
  - New Physics searches
  - Higgs searches and measurement
    - **Coupling measurement, search for rare decay**
    - Search for the Higgs self coupling via di-Higgs events.

Most sensitive : gg→HH→bbγγ









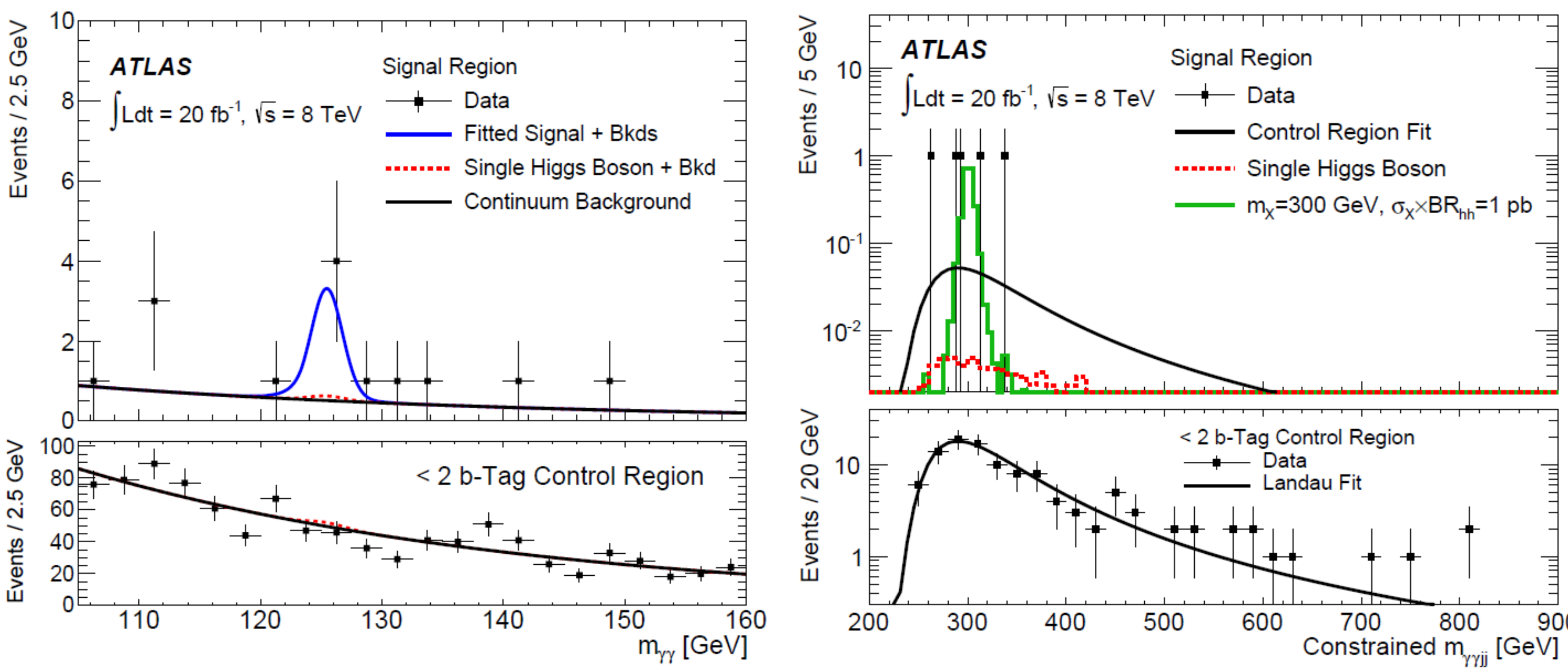
Amount of self coupling changes interference of triangle and box diagram

	gg->HH σ [fb^{-1}] @ 14TeV
$\lambda_{HHH}/\lambda^{SM}_{HHH}$=1	34 fb^{-1}
$\lambda_{HHH}/\lambda^{SM}_{HHH}$=0	71 fb^{-1}
$\lambda_{HHH}/\lambda^{SM}_{HHH}$=2	16 fb^{-1}

gg→HH→bbγγ only
1.3 σ (@ SM HH)
→ **Exclude λ_{HHH}=0**
→ **improvement**
→ **3σ with combination**

Run 1 result – Search for self coupling

- HH→γγbb search
  - **4 event excess in $m_{\gamma\gamma}$ distribution after bb selection**
  - 2.4σ excess (σ~1pb, 30 times bigger than σ_{HH}=34fb^{-1})
  - Not excluded possibility of an excess of $M_{\gamma\gamma jj}$~300GeV



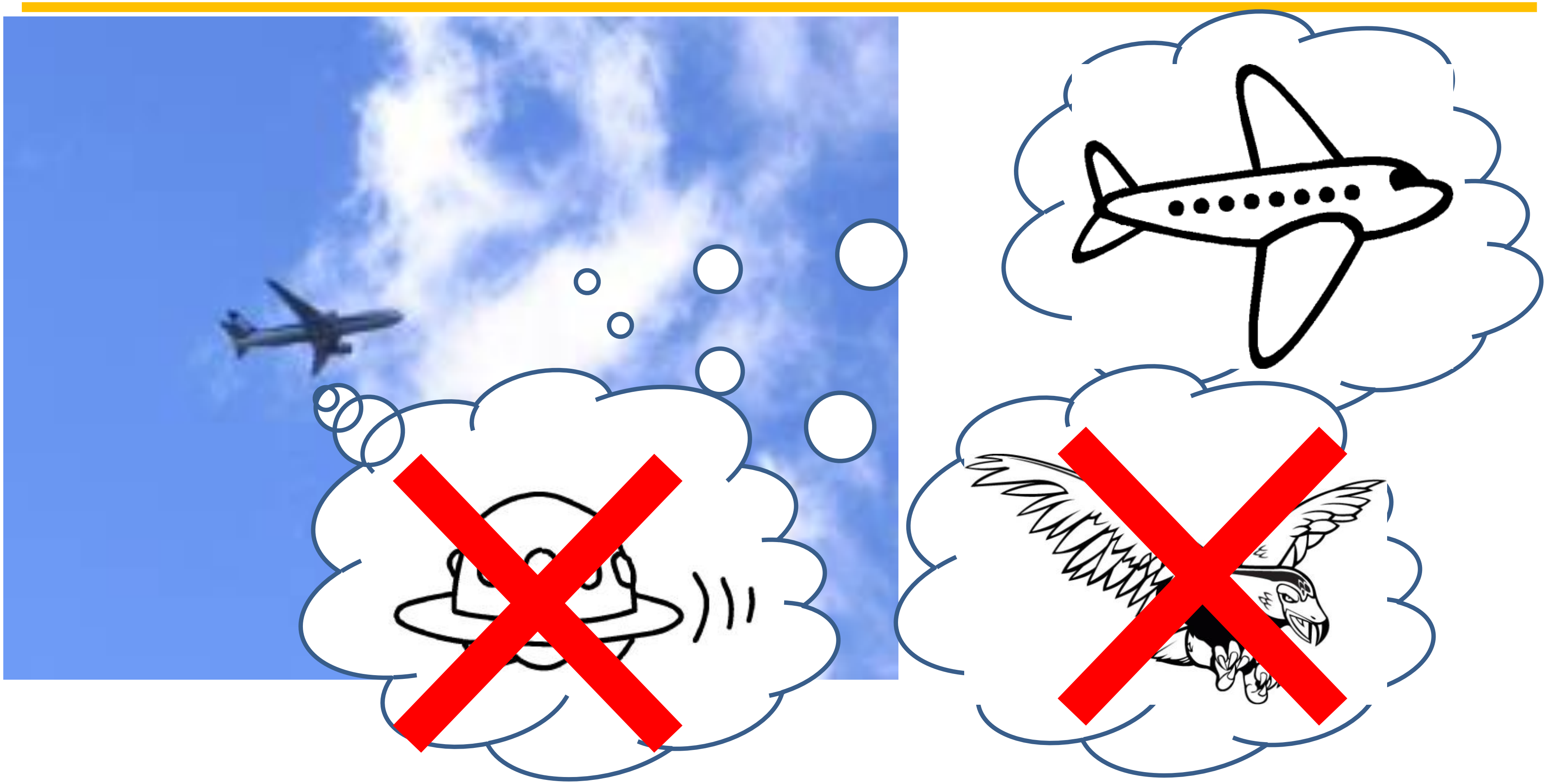
We observed something in July 2012

- **Indeed the observation was clear! (6σ)**

We observed something in July 2012

- **Indeed the observation was clear!**
- **But still not sure what it is.**

With full dataset in 2012

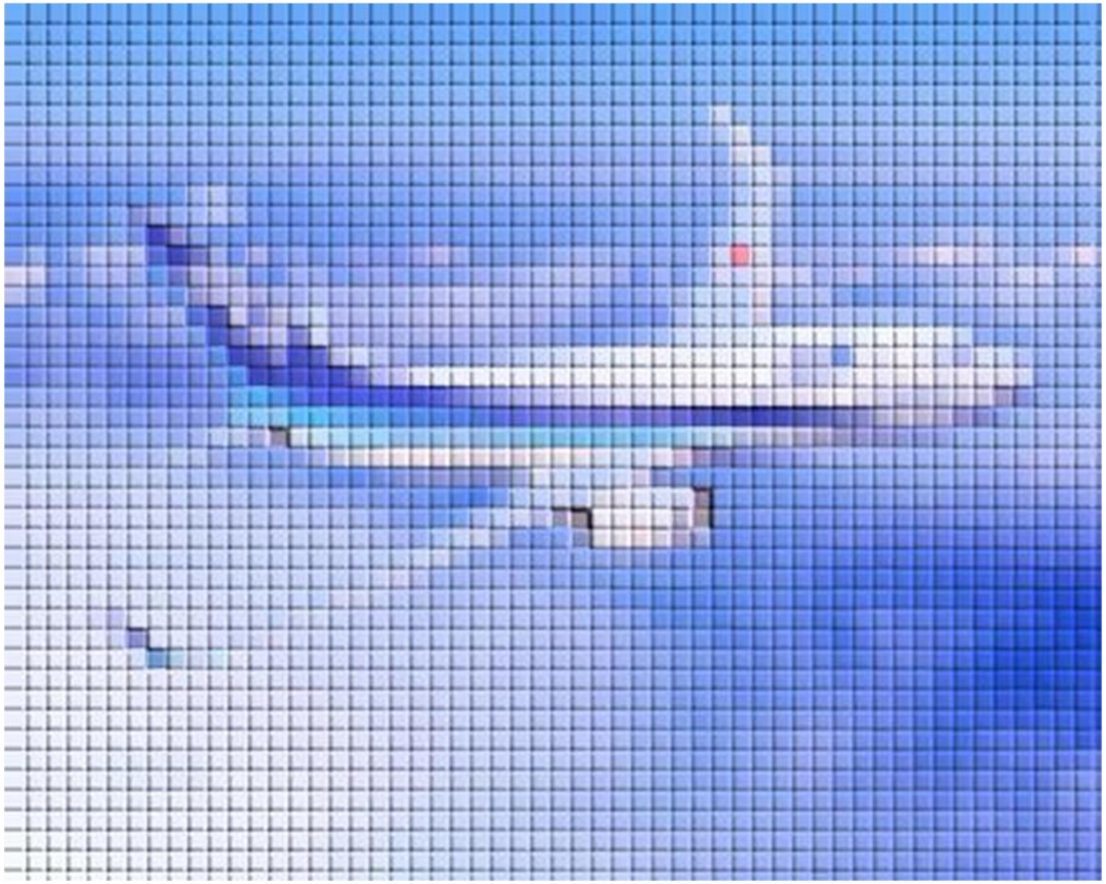


But also found that nothing around…

LHC after 2yr shutdown

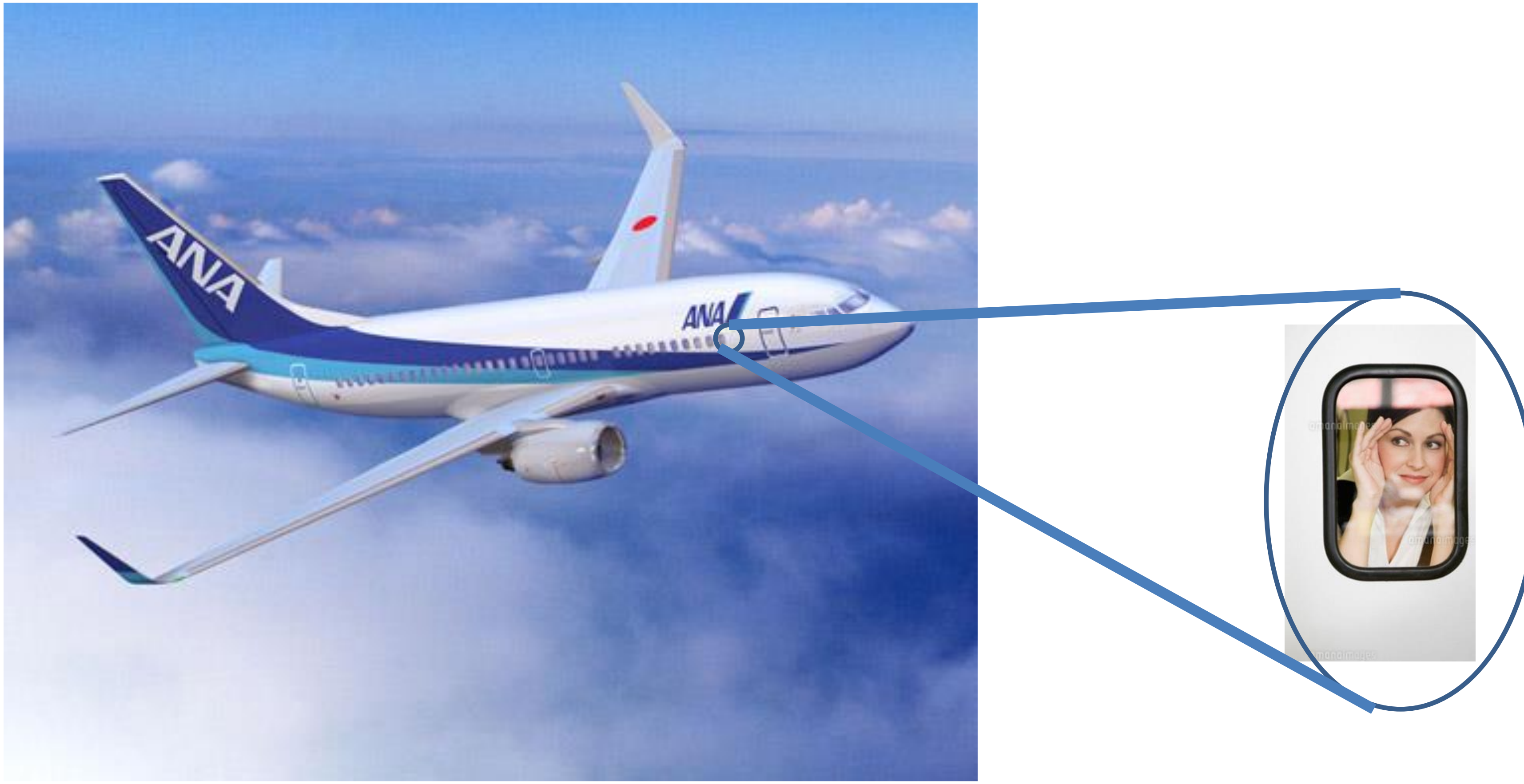
- **Potentially we have tool to see what kind of air plane there.**

LHC after 2yr shutdown



- **Potentially we have tool to see what kind of air plane there.**
- **But still need more data to see concrete picture.**

HL-LHC and next generation exp.



Should we know who is sitting on the plane ?

HL-LHC and next generation exp.

Should we know who is sitting on the plane ?

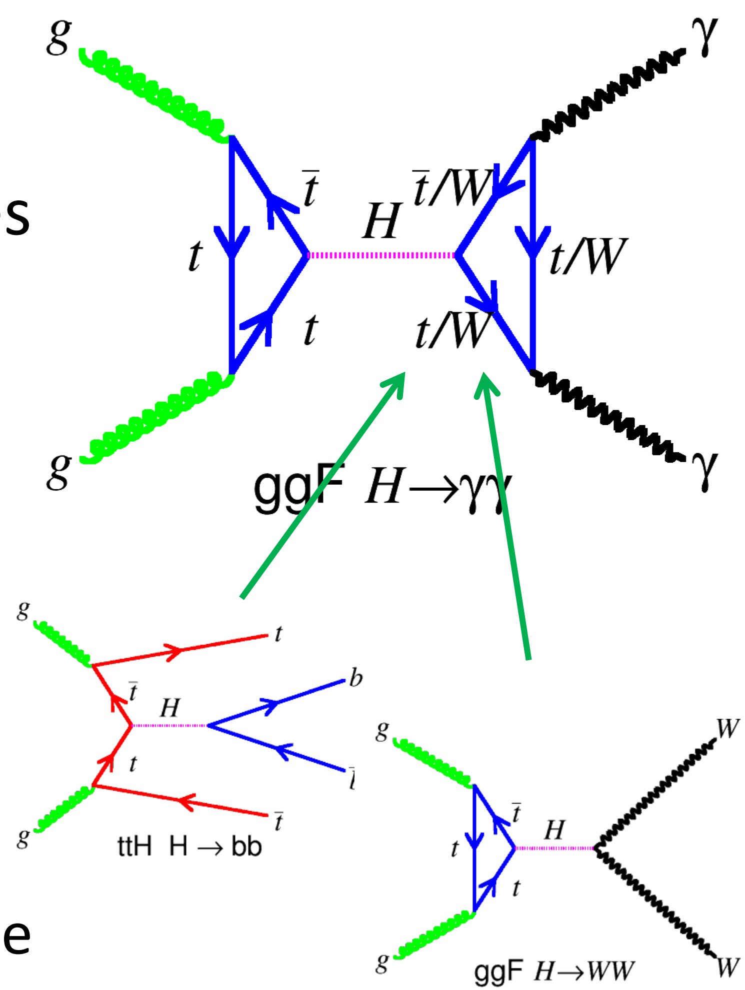
Or should we search for another flying object?

backup

Difficulty of coupling measurement

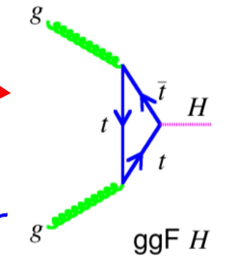
- **Define κ parameters** for each HVV and Hff coupling, noted as κ_V and κ_f (e.g. κ_t κ_b κ_τ κ_Z κ_W)
- Some loop process have interferences among loop particles.
  - SM assumption used :

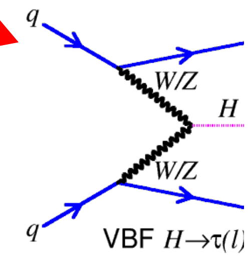
    (e.g. $\kappa_\gamma^2 = 1.59\cdot\kappa_W^2\ 0.07\cdot\kappa_t^2 - 0.66\cdot\kappa_W\kappa_t$)
  - LHC have potential to measure individual κ and test the interference term.
- Need to assume Full width of Higgs boson but can perform fit with the unknown or invisible component.
  - Test if unknown or invisible is negligible

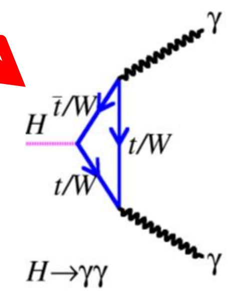


Interference in Higgs production and decay

Production	Loops	Interference	Multiplicative factor	
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	–	$W-t$	$\sim$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim$	$3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim$	κ_b^2
Partial decay width				
Γ^{ZZ}	–	–	$\sim$	κ_Z^2
Γ^{WW}	–	–	$\sim$	κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2
Total width for $BR_{BSM} = 0$				
Γ_H	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

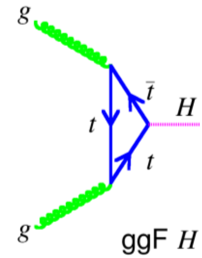


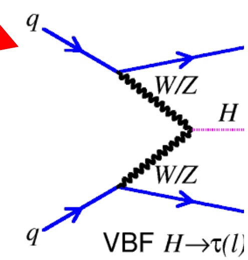




Interference in Higgs production and decay

Production	Loops	Interference	Multiplicative factor	
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06\cdot\kappa_t^2 + 0.01\cdot\kappa_b^2 - 0.07\cdot\kappa_t\kappa_b$
$\sigma(VBF)$	–	–	$\sim$	$0.74\cdot\kappa_W^2 + 0.26\cdot\kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim$	$2.27\cdot\kappa_Z^2 + 0.37\cdot\kappa_t^2 - 1.64\cdot\kappa_Z\kappa_t$
$\sigma(ttH)$	–	–	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	–	$W-t$	$\sim$	$1.84\cdot\kappa_t^2 + 1.57\cdot\kappa_W^2 - 2.41\cdot\kappa_t\kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim$	$3.4\cdot\kappa_t^2 + 3.56\cdot\kappa_W^2 - 5.96\cdot\kappa_t\kappa_W$
$\sigma(bbH)$	–	–	$\sim$	κ_b^2
Partial decay width				
Γ^{ZZ}	–	–	$\sim$	κ_Z^2
Γ^{WW}	–	–	$\sim$	κ_W^2





HUGE interference

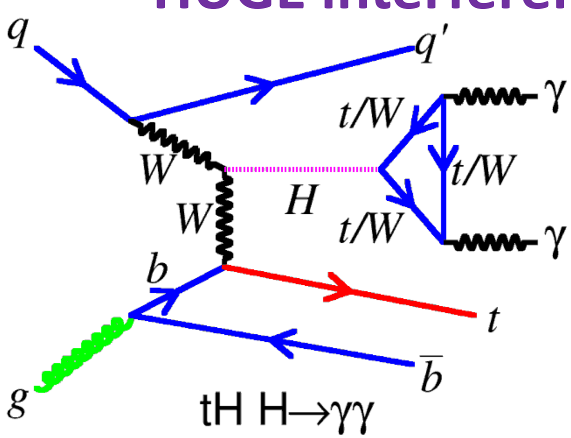
$- 0.66\cdot\kappa_W\kappa_t$

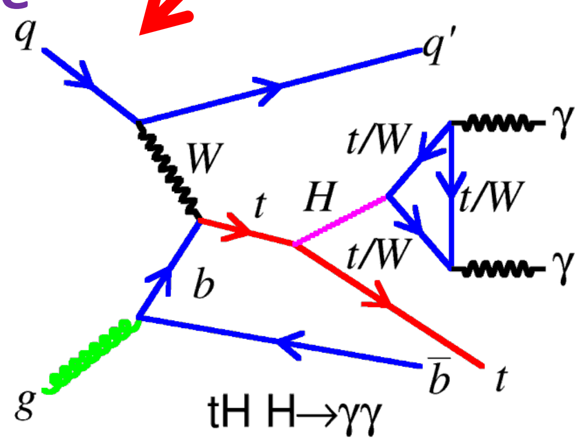
$+ 0.09\cdot\kappa_g^2 +$

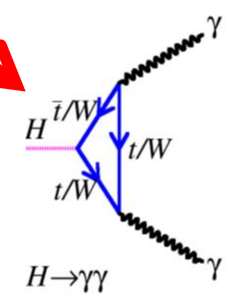
$+ 0.03\cdot\kappa_c^2 +$

$16\cdot\kappa_{Z\gamma}^2 +$

$22\cdot\kappa_\mu^2$







ATLAS and CMS combination

- All the matrix of Decay / production modes are included except :
  - ggF/VBF H->bb (difficulty of trigger and background rejection)
  - VH/ttH H-> μμ (Too small signal yield).
- Full combination describes ~ 580 signal&control regions from both experiment.
  - Total 4200 nuisance parameters (Systematic uncertainties) are included.
  - Detector and acceptance related NPs are de-correlated.
  - Theory(PDF, Scale, BRs) uncertainty are correlated btw experiments.

Decay / Production	Untagged	VBF	VH	ttH
$H\rightarrow\gamma\gamma$				
$H\rightarrow ZZ\rightarrow 4l$				
$H\rightarrow WW\rightarrow 2l2\nu$				
$H\rightarrow\tau\tau$				
$H\rightarrow bb$				
$H\rightarrow\mu\mu$				

Bottom Yukawa coupling

- Yb @ 13/14TeV

Major search was VH,H->bb process in Run1

Adding 13TeV 10fb^{-1}is enough for evidence

→7TeV+8TeV+13TeV : 3σ(expected)

Note : low observed in 7+8TeV data…

May need full 2016 data？

New sensitive channel ttH, H→bb in run2

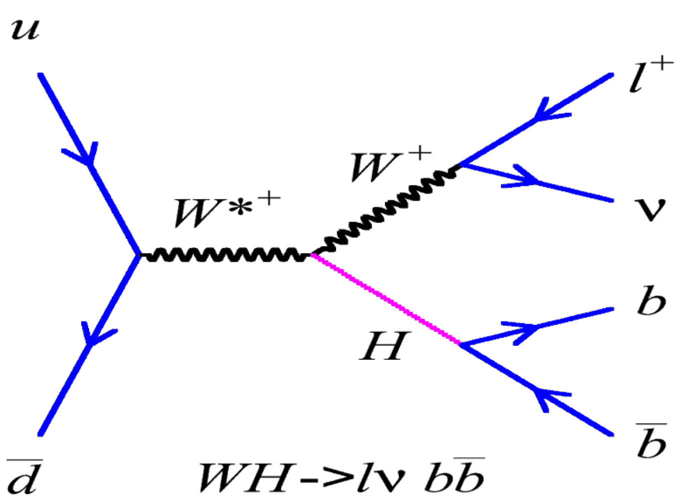
Minor channel in run1 due to small xsec.

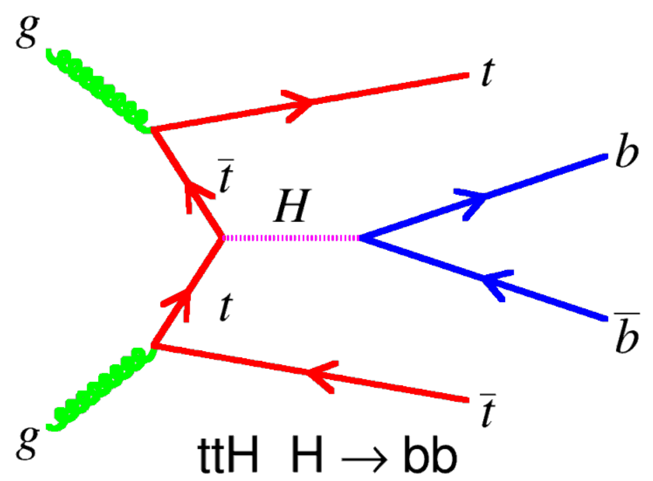
3.9 times bigger xsec in 13TeV collisions!

Need 13TeV 40 fb^{-1} to claim 3σ(expected)

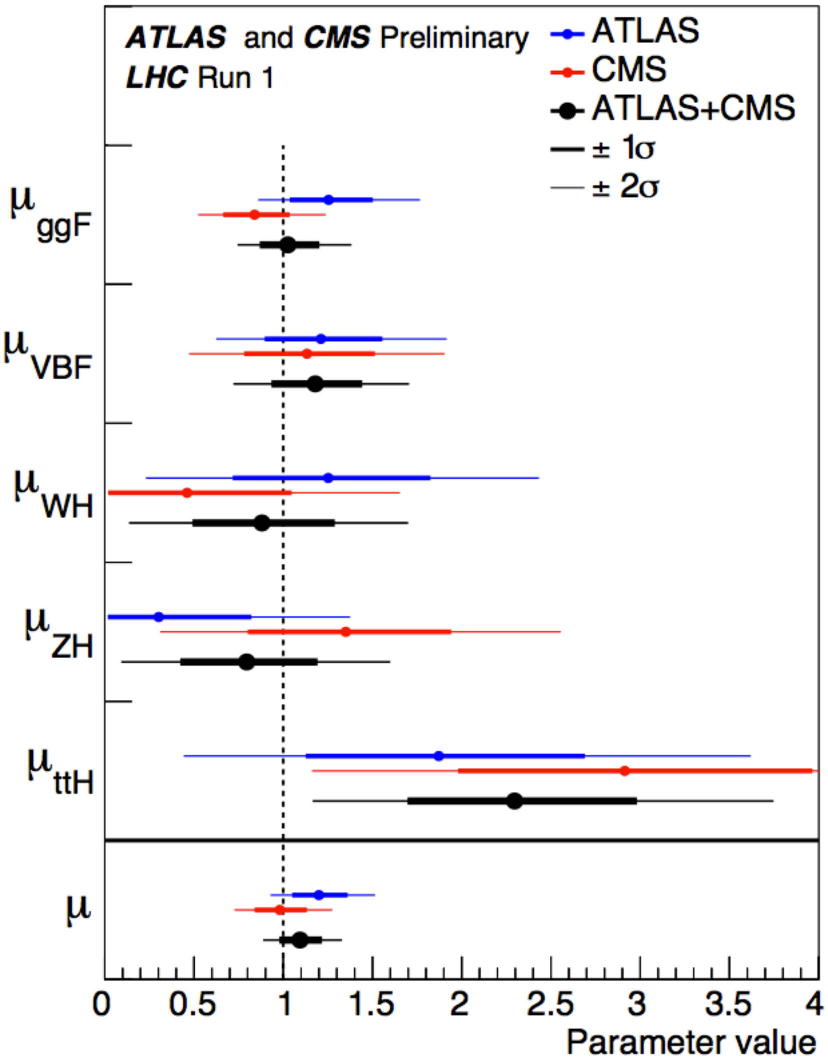
Possibly evidence in full 2016 data？

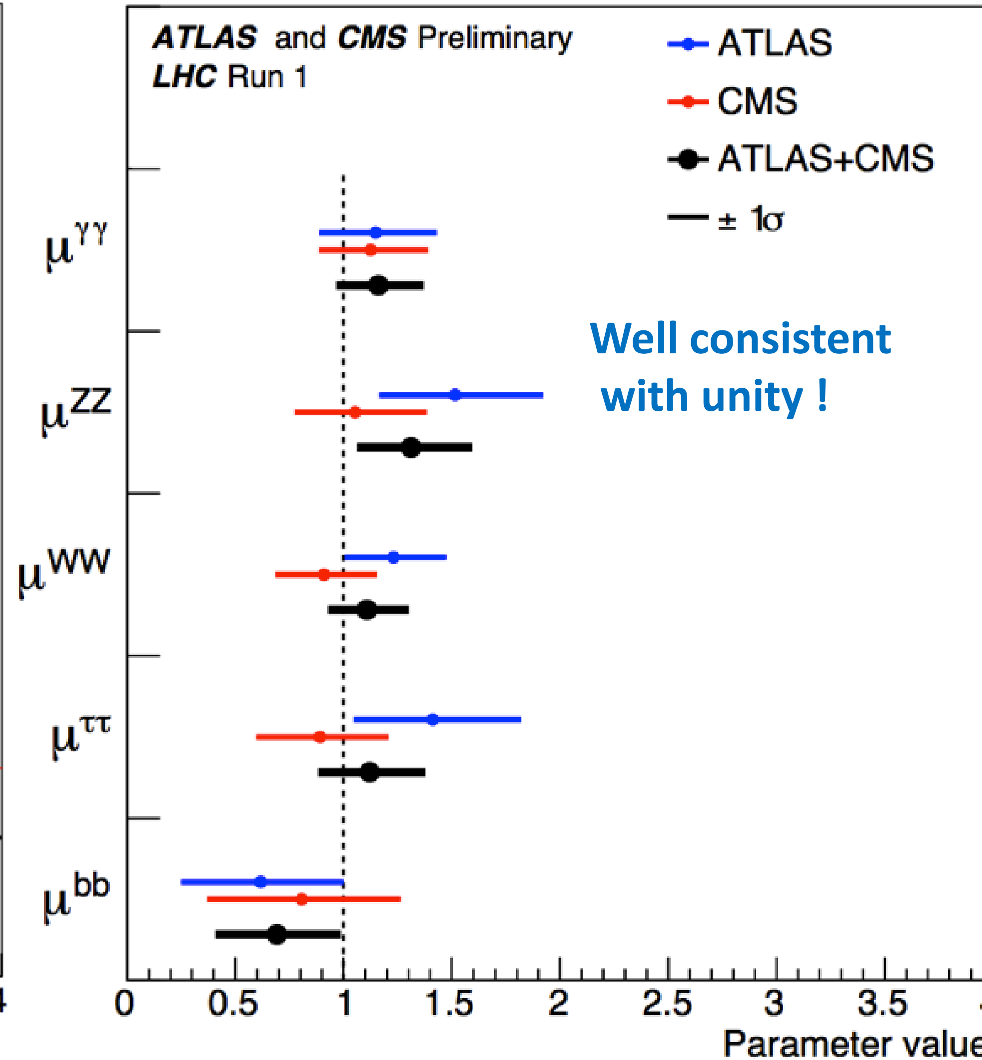
Can claim Yt observation at the same time!





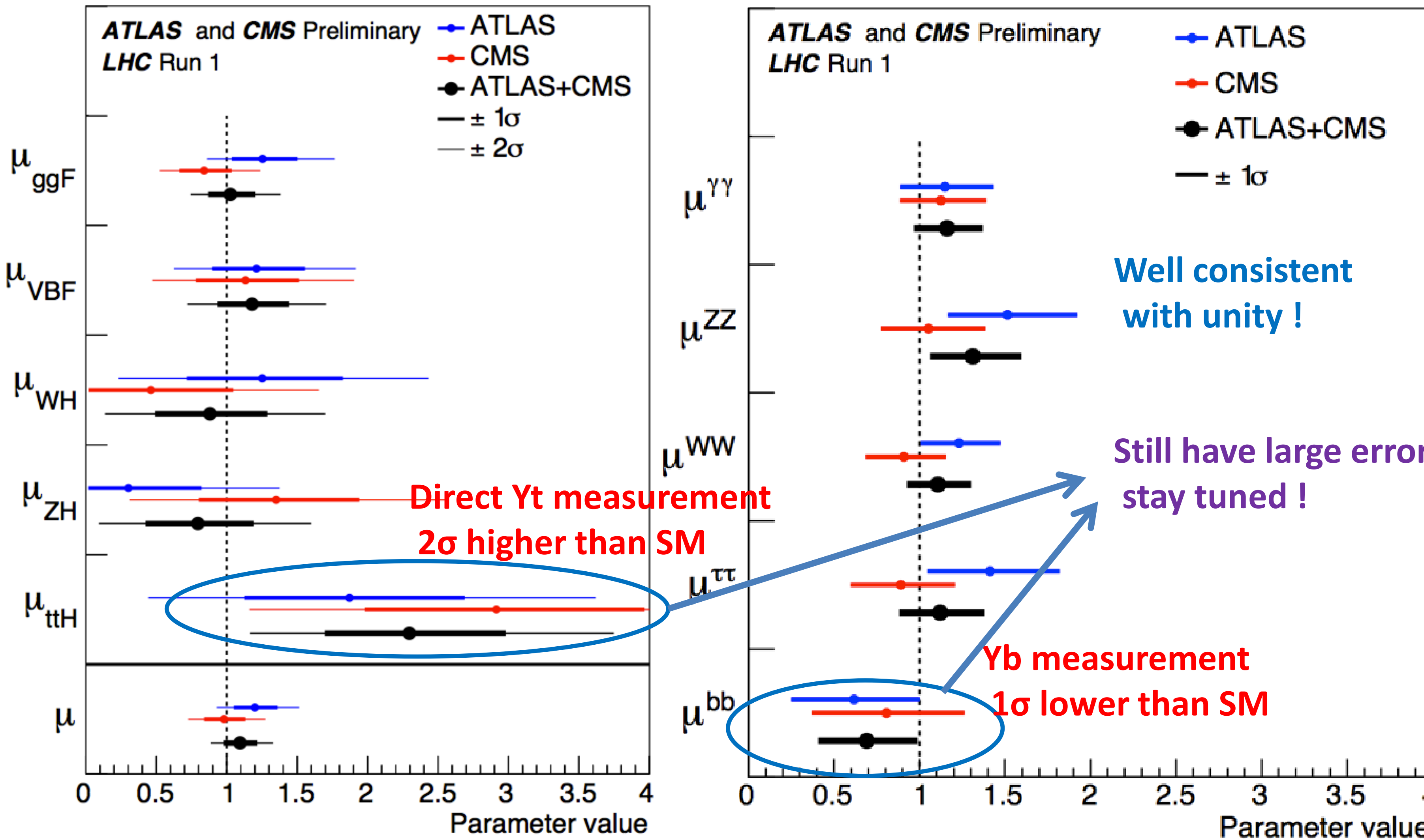
Results Production and Decay (strength)





Well consistent with unity !

Results Production and Decay (strength)



The Grobal Signal Strength

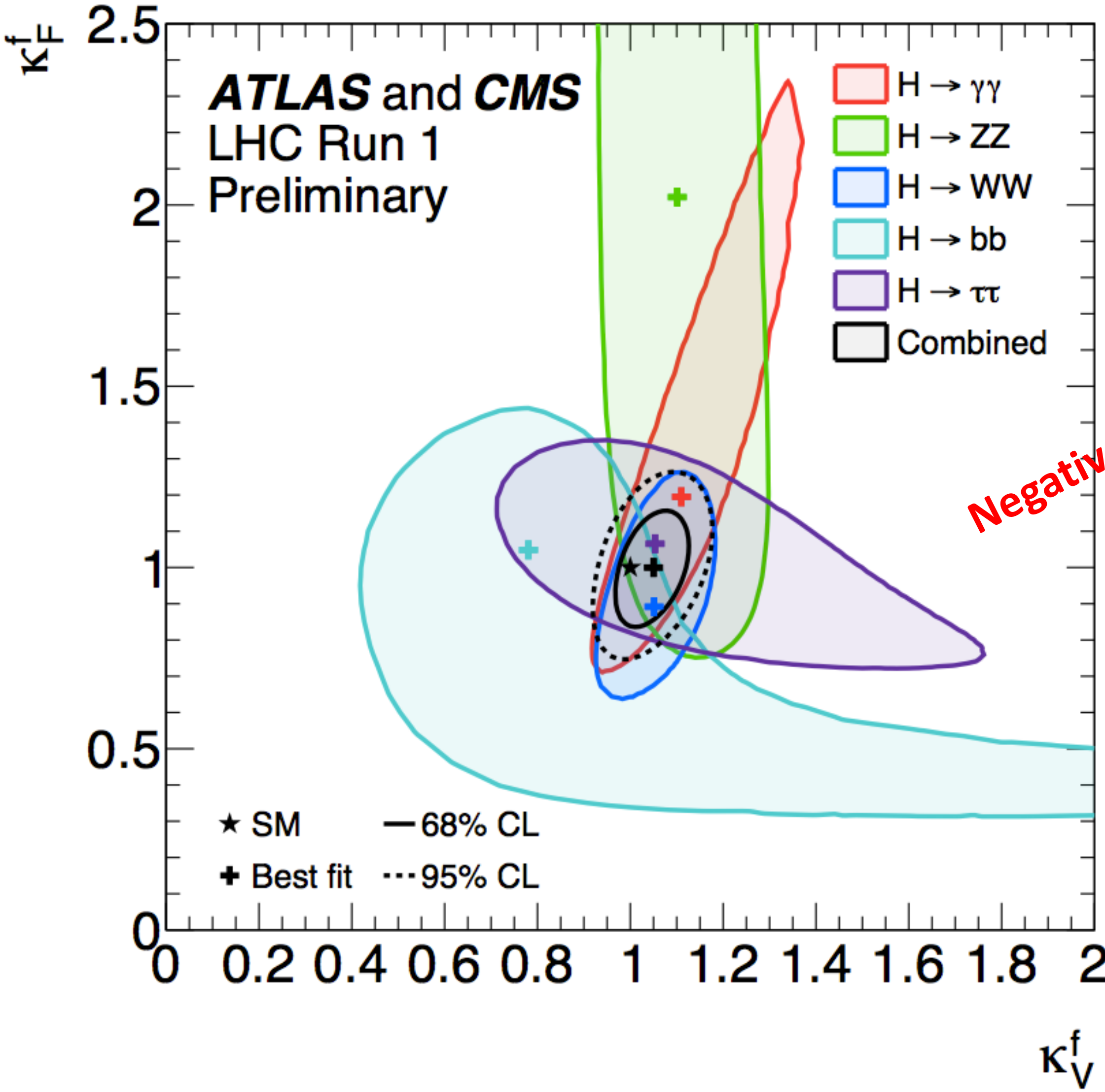
- Assuming SM ratio of production cross section and decay rate :

$$\mu = 1.09^{+0.11}_{-0.10}$$

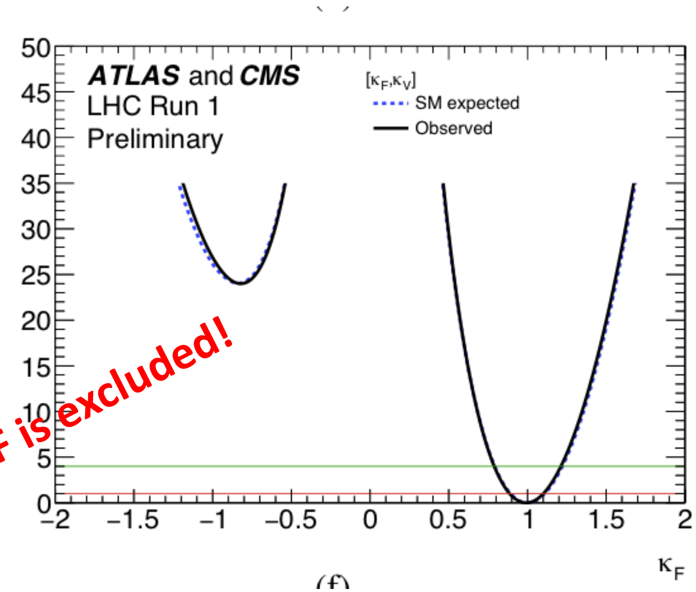
$$= 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig})$$

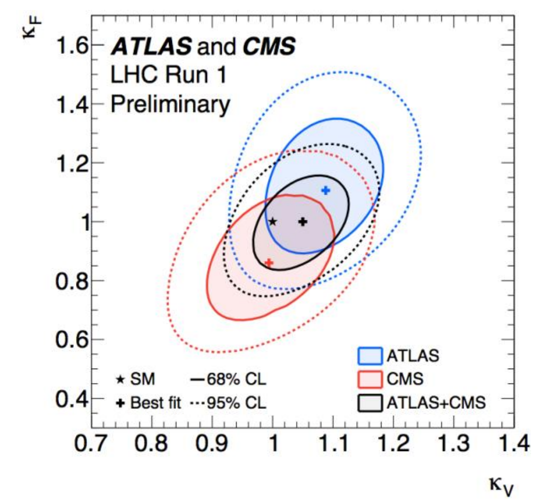
Stat uncertainty and signal theory systematics are the same size.
(Signal Theory uncertainty is dominated by ggF cross section.)

Fermion v.s. Boson coupling



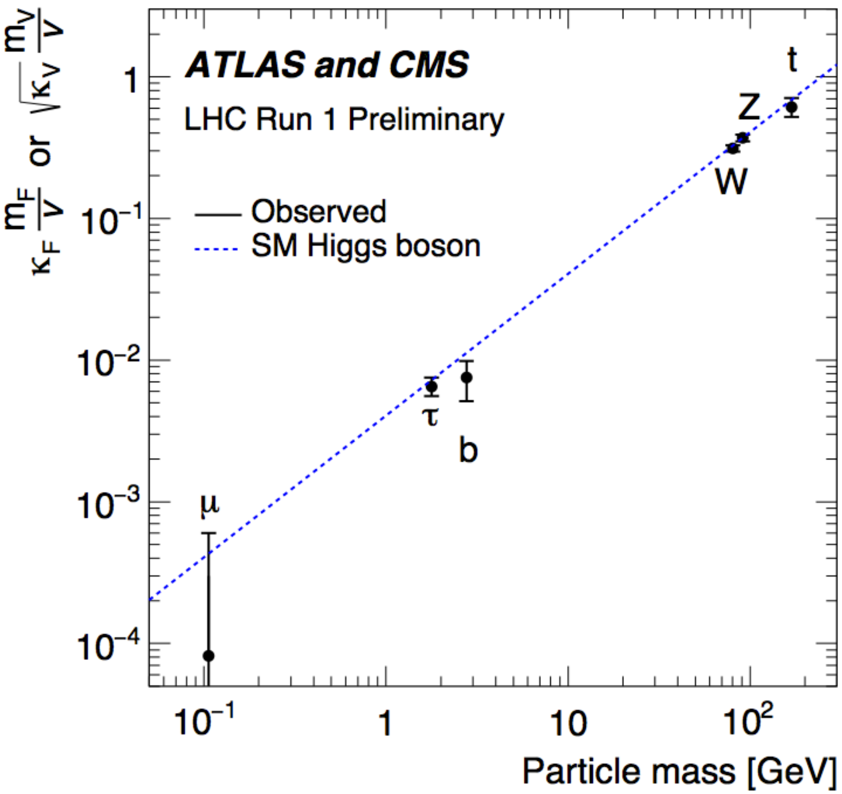
Negative κF is excluded!

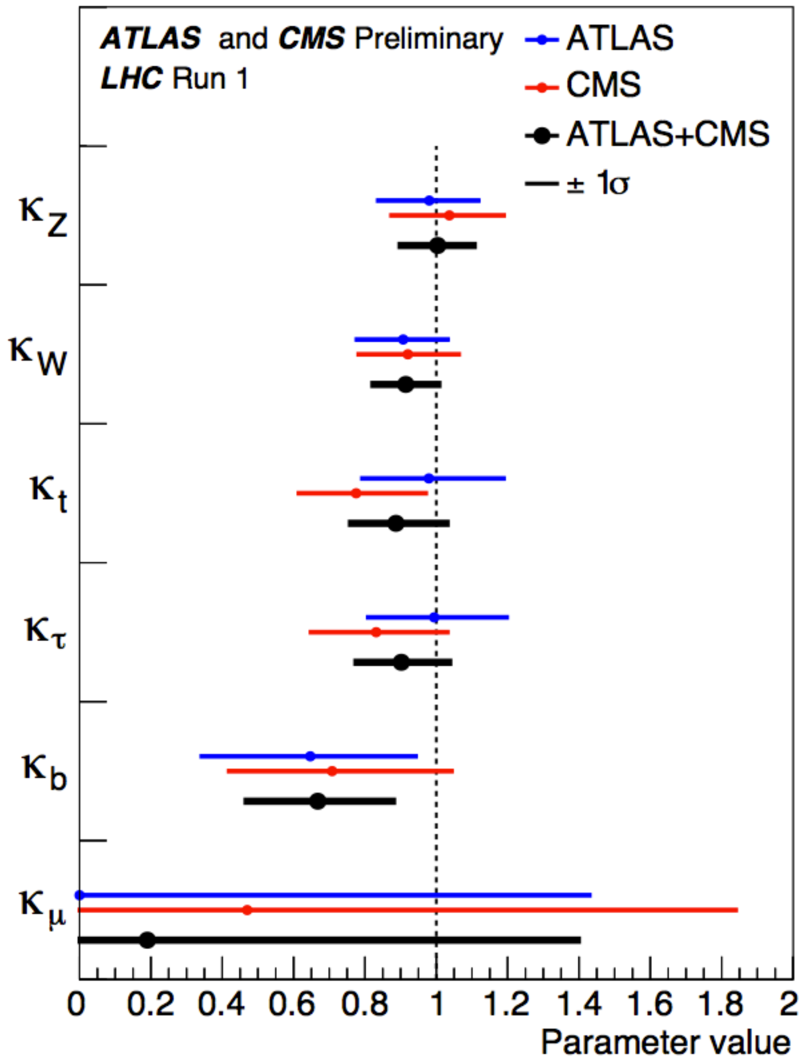




Constraints on Higgs coupling

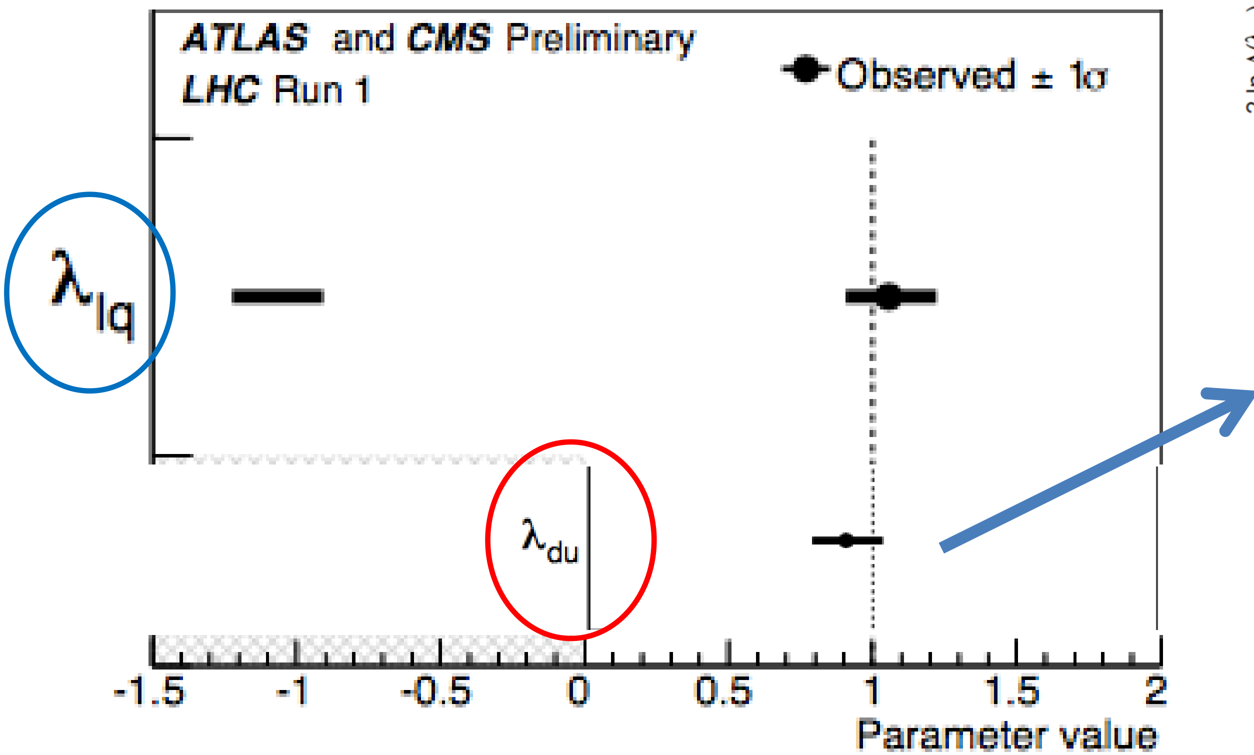
- Assume only SM physics in loops, no invisible Higgs decays
- Fit for scaling parameters for Higgs coupling to : W, Z ,b, t, τ, μ

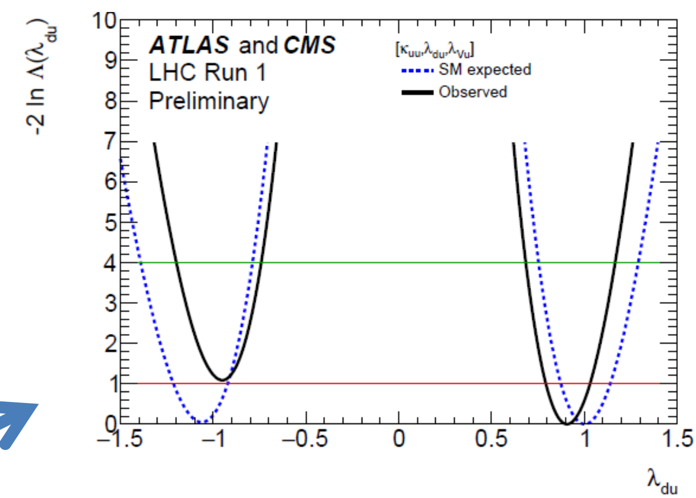




Constraints on Higgs coupling

- Several BSM physics modify the coupling ratio between up-type and down-type fermion coupling, and lepton and quark couplings

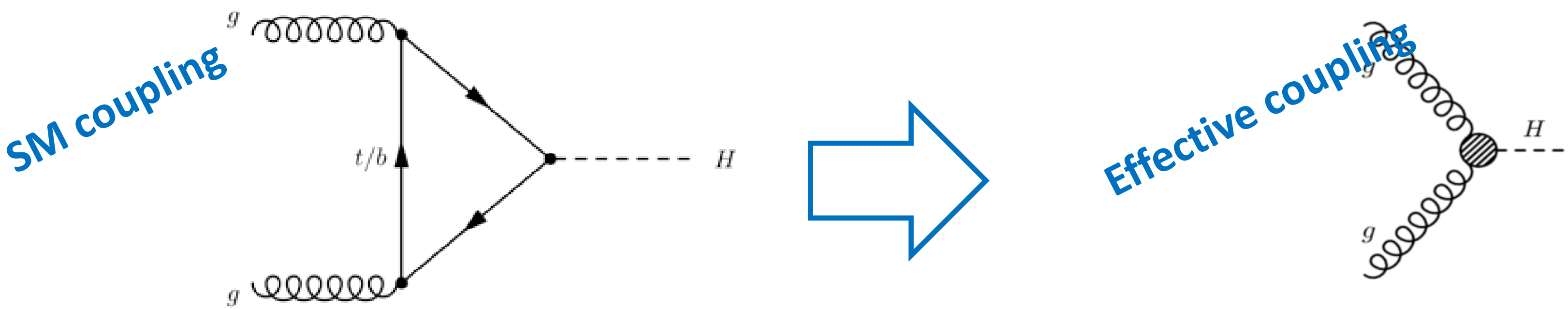




Slight preference of positive solution due to the low BR_{bb} and high σ(ttH).

Probing BSM Higgs coupling

- Results which showed already are assuming SM coupling and no BSM contribution to the loop and extra decay. → Fit without this assumption allow to probe new physics effect!
  - Used effective coupling instead of SM loop coupling.

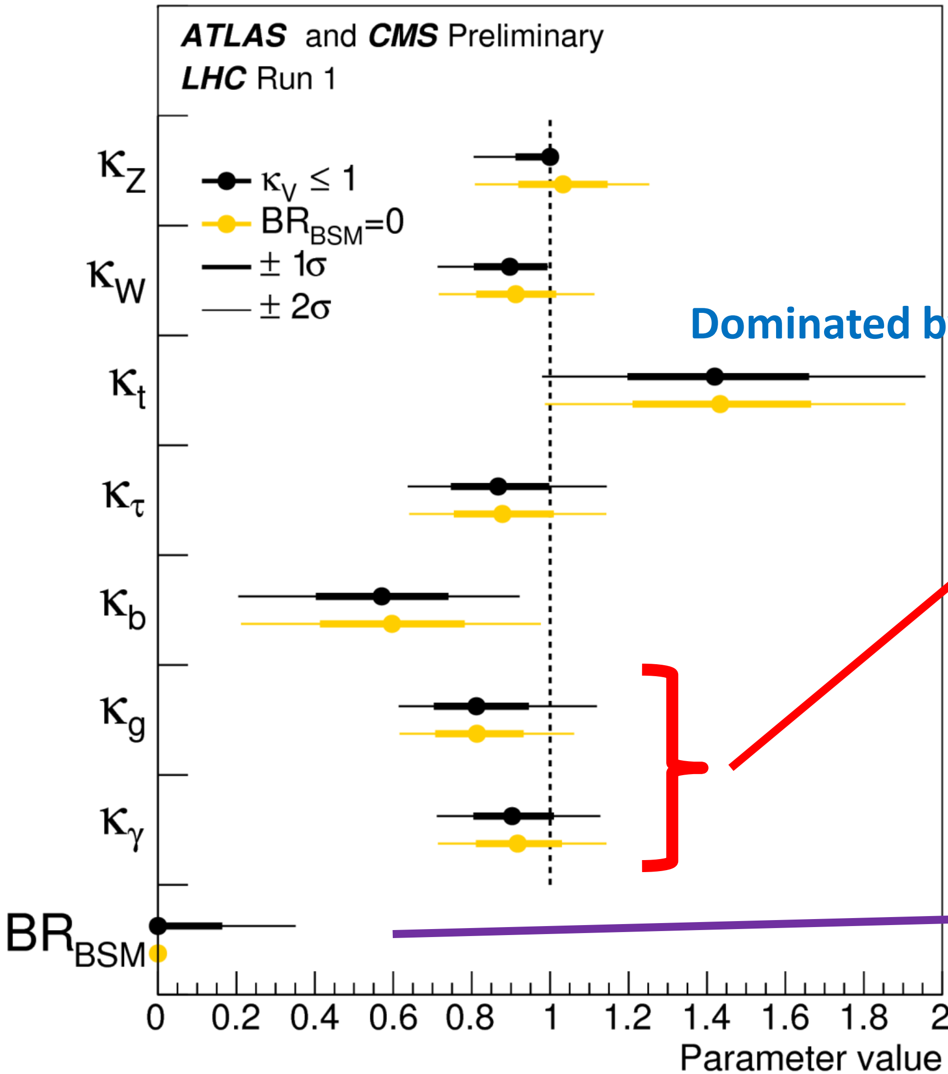


$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$ $\kappa_g{}^2$

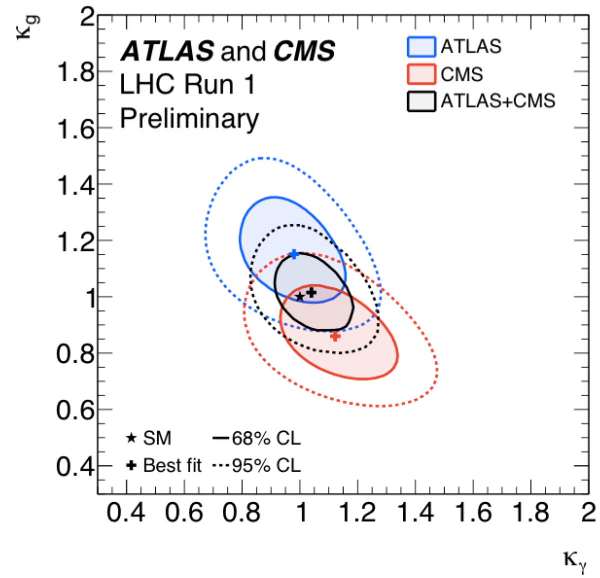
  - Allowing BSM Higgs decay (invisible and unknown etc.) to increase total width.

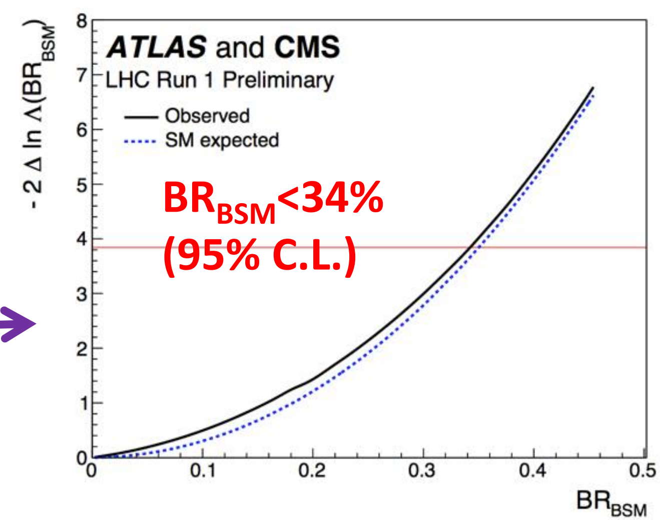
$$\Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

Probing BSM Higgs coupling



Dominated by ttH xsec





BR_{BSM}<34% (95% C.L.)

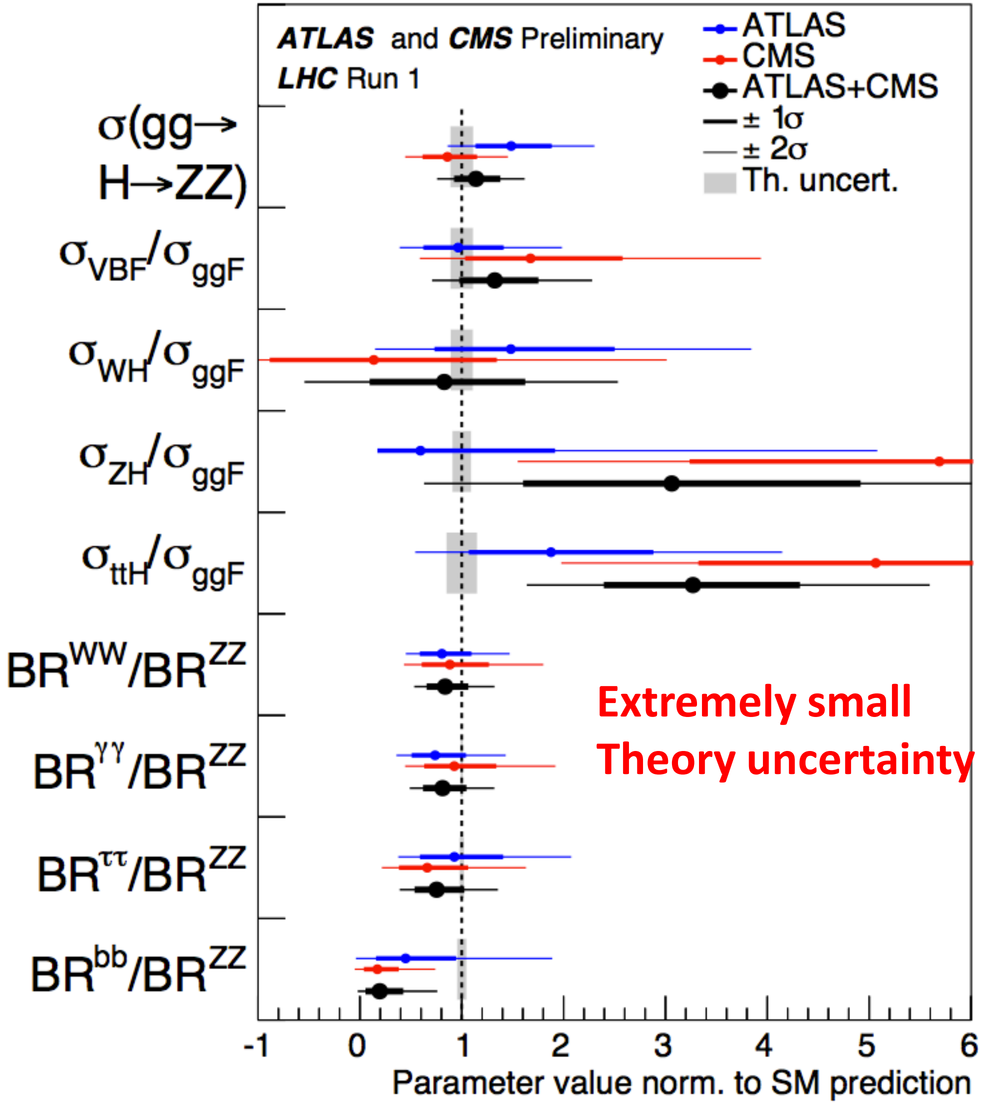
More generic parametrization

- To make **more general parametrization**, i.e. minimum number of assumption and with minimum exposure to theory uncertainties.
- Most generic model is signal strength model with ratio (no assumption of full width):

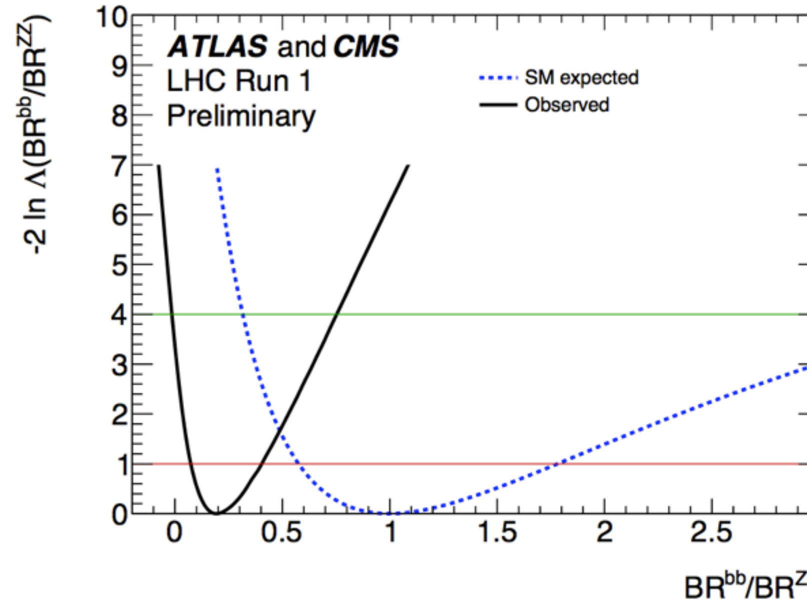
$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right),$$

  – Choose ggF→ZZ as reference since it is cleanest channel and has smallest experimental systematic uncertainty.
  – These ratio exposure to dominant theoritical uncertainty on inclusive cross section

Result of generic model fitting

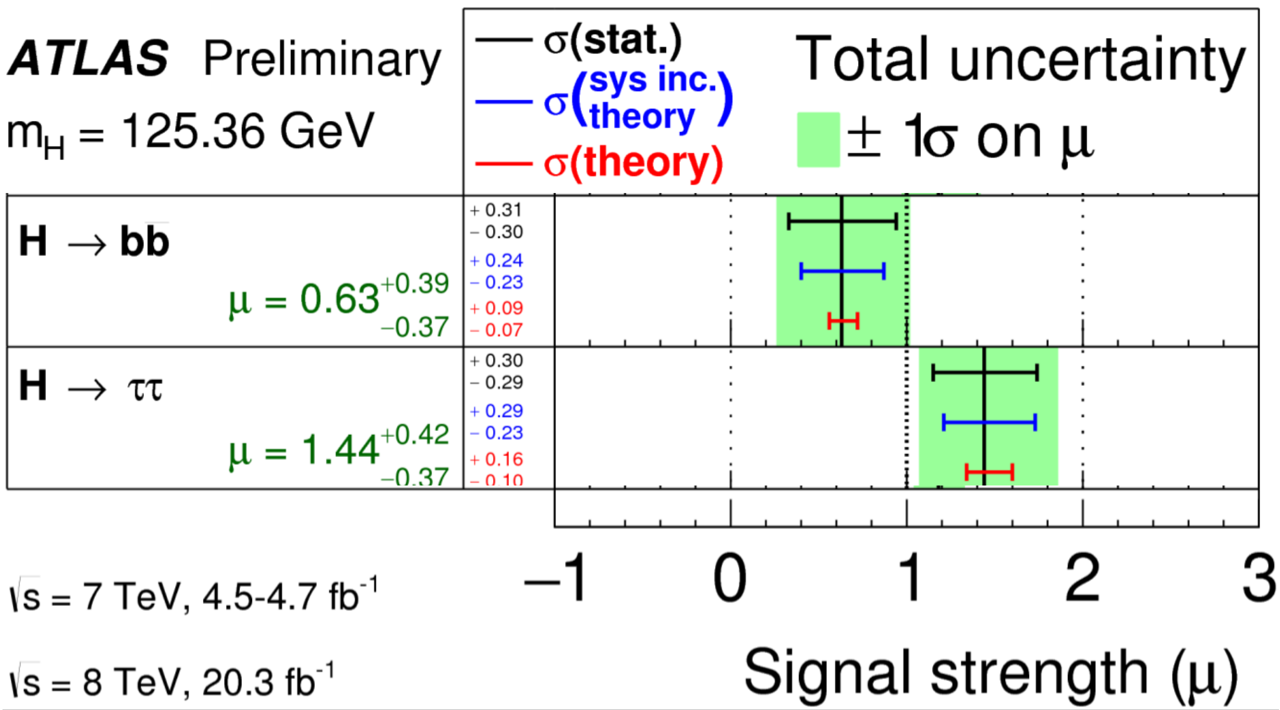


- Largest discrepancy from SM observed for BR^{bb}/BR^{ZZ} at level of 2.4σ.
  - Driven by combination of **high ttH->leptons, ZH→ZZ and low VH→bb**



Discussion about theory systematics

- For the H→bb and ττ measurement, for instance, statistics and background normalization systematics are dominant uncertainty in μ. (these are reducible.)
- **Theory cross section and branching ratio uncertainty is 8-15% level.**
  - Of cause LHC is hadron collider so production cross section (e.g. ggF) have huge uncertainty.
  - But in bb and tautau measurement , VH and VBF is dominant production process and which have relatively lower uncertainty(4%). → **Non negligible BR uncertainty exists.**



Discussion about theory systematics

- Higgs BR uncertainty which currently we are assigning to all of our results :

	BR	Uncert[%]	Uncert[%]
$H \to bb$	0.577000	3.21	-3.27
$H \to \tau\tau$	0.063200	5.71	-5.67
$H \to \mu\mu$	0.000219	6.01	-5.86
$H \to cc$	0.029100	12.17	-12.21
$H \to ss$	0.000246	4.88	-4.86
$H \to tt$	0.000000	0	0
$H \to gg$	0.085700	10.22	-9.98
$H \to \gamma\gamma$	0.002280	4.98	-4.89
$H \to Z\gamma$	0.001540	9.01	-8.83
$H \to WW$	0.215000	4.26	-4.2
$H \to ZZ$	0.026400	4.28	-4.21
ΓH[GeV]	4.07E-03	3.97	-3.93

Evaluated by **HDECAY&Prophecy4F**

The uncert. are defined as a linear sum of PU and THUs.
PU … parametric uncertainty.
α_S, Δm_b, Δm_c and Δm_t
THU … Theoritical uncertainty.
QCD and EW scale

Are these irreducible ???

- Uses pole-mass for charm and bottom
  - How to reduce this ?

Parameter	Central value	Uncertainty	$\overline{\text{MS}}$ masses $m_q(m_q)$
$\alpha_s(M_Z)$	0.119	± 0.002	
m_c	1.42 GeV	± 0.03 GeV	1.28 GeV
m_b	4.49 GeV	± 0.06 GeV	4.16 GeV
m_t	172.5 GeV	± 2.5 GeV	165.4 GeV

- THU uncertainty is ~2%
  - Is reducible by higher order calculation ?

Table 2: Estimated theoretical uncertainties from missing higher orders.

Partial width	QCD	electroweak	total
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	~ 1–2% for $M_H \lesssim 135$ GeV	$\sim 2\%$
$H \to \tau^+\tau^-/\mu^+\mu^-$		~ 1–2% for $M_H \lesssim 135$ GeV	$\sim 2\%$
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim 2$–5% for $M_H < 500$ GeV	$\sim 5\%$
		$\sim 0.1(\frac{M_H}{1\ \text{TeV}})^4$ for $M_H > 500$ GeV	~ 5–10%
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$
		$\sim 0.17(\frac{M_H}{1\ \text{TeV}})^4$ for $M_H > 500$ GeV	~ 0.5–15%

- **Break down of branching ratio uncertainties.**

Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to bb$	122	2.30	-2.3% $+2.3\%$	$+3.2\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
	126	2.36	-2.3% $+2.3\%$	$+3.3\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
	130	2.42	-2.4% $+2.3\%$	$+3.2\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
$H \to \tau^+\tau^-$	122	$2.51 \cdot 10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
	126	$2.59 \cdot 10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
	130	$2.67 \cdot 10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
$H \to \mu^+\mu^-$	122	$8.71 \cdot 10^{-4}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
	126	$8.99 \cdot 10^{-4}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	-0.1% -0.0%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
	130	$9.27 \cdot 10^{-4}$	$+0.1\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.0%	$+2.0\%$ -2.0%
$H \to c\bar{c}$	122	$1.16 \cdot 10^{-1}$	-7.1% $+7.0\%$	-0.1% $+0.1\%$	$+6.2\%$ -6.0%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
	126	$1.19 \cdot 10^{-1}$	-7.1% $+7.0\%$	-0.1% $+0.1\%$	$+6.2\%$ -6.1%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
	130	$1.22 \cdot 10^{-1}$	-7.1% $+7.0\%$	-0.1% $+0.1\%$	$+6.3\%$ -6.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
$H \to gg$	122	$3.25 \cdot 10^{-1}$	$+4.2\%$ -4.1%	-0.1% $+0.1\%$	$+0.0\%$ -0.0%	-0.2% $+0.2\%$	$+3.0\%$ -3.0%
	126	$3.57 \cdot 10^{-1}$	$+4.2\%$ -4.1%	-0.1% $+0.1\%$	$+0.0\%$ -0.0%	-0.2% $+0.2\%$	$+3.0\%$ -3.0%
	130	$3.91 \cdot 10^{-1}$	$+4.2\%$ -4.1%	-0.1% $+0.2\%$	$+0.0\%$ -0.0%	-0.2% $+0.2\%$	$+3.0\%$ -3.0%

Are these irreducible ???

- Uses pole-mass for charm and bottom
  - How to reduce this ?

Parameter	Central value	Uncertainty	$\overline{\text{MS}}$ masses $m_q(m_q)$
$\alpha_s(M_Z)$	0.119	±0.002	
m_c	1.42 GeV	±0.03 GeV	1.28 GeV
m_b	4.49 GeV	±0.06 GeV	4.16 GeV
m_t	172.5 GeV	±2.5 GeV	165.4 GeV

- THU
  - –

Tab

Partial width			
$H \to b\bar{b}/c\bar{c}$			
$H \to \tau^+\tau^-/\mu$			
$H \to t\bar{t}$			
$H \to gg$			
$H \to \gamma\gamma$			
$H \to Z\gamma$			
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$
		$\sim 0.17(\frac{M_H}{1\ \text{TeV}})^4$ for $M_H > 500$ GeV	~ 0.5–15%

- **Break down of branching ratio uncertainties.**

Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
	122	2.30	−2.3% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
$H \to bb$	126	2.36	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%

Δm_t	THU
+0.0% −0.0%	+2.0% −2.0%
+0.0% −0.1%	+2.0% −2.0%
+0.1% −0.1%	+2.0% −2.0%
+0.1% −0.1%	+2.0% −2.0%
+0.1% −0.1%	+2.0% −2.0%
+0.0% −0.1%	+2.0% −2.0%
+0.1% −0.0%	+2.0% −2.0%
+0.0% −0.1%	+2.0% −2.0%
+0.0% −0.1%	+2.0% −2.0%
+0.1% −0.1%	+2.0% −2.0%
−0.2% +0.2%	+3.0% −3.0%
−0.2% +0.2%	+3.0% −3.0%
−0.2% +0.2%	+3.0% −3.0%

Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
	122	2.30	−2.3% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
$H \to bb$	126	2.36	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
	130	2.42	−2.4% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
	122	$2.51 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+2.0% −2.0%
$H \to \tau^+\tau^-$	126	$2.59 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
	130	$2.67 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%

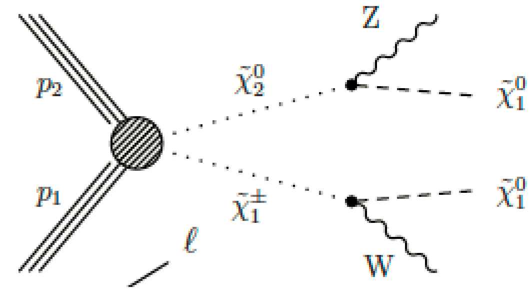
This should be critical for ILC…

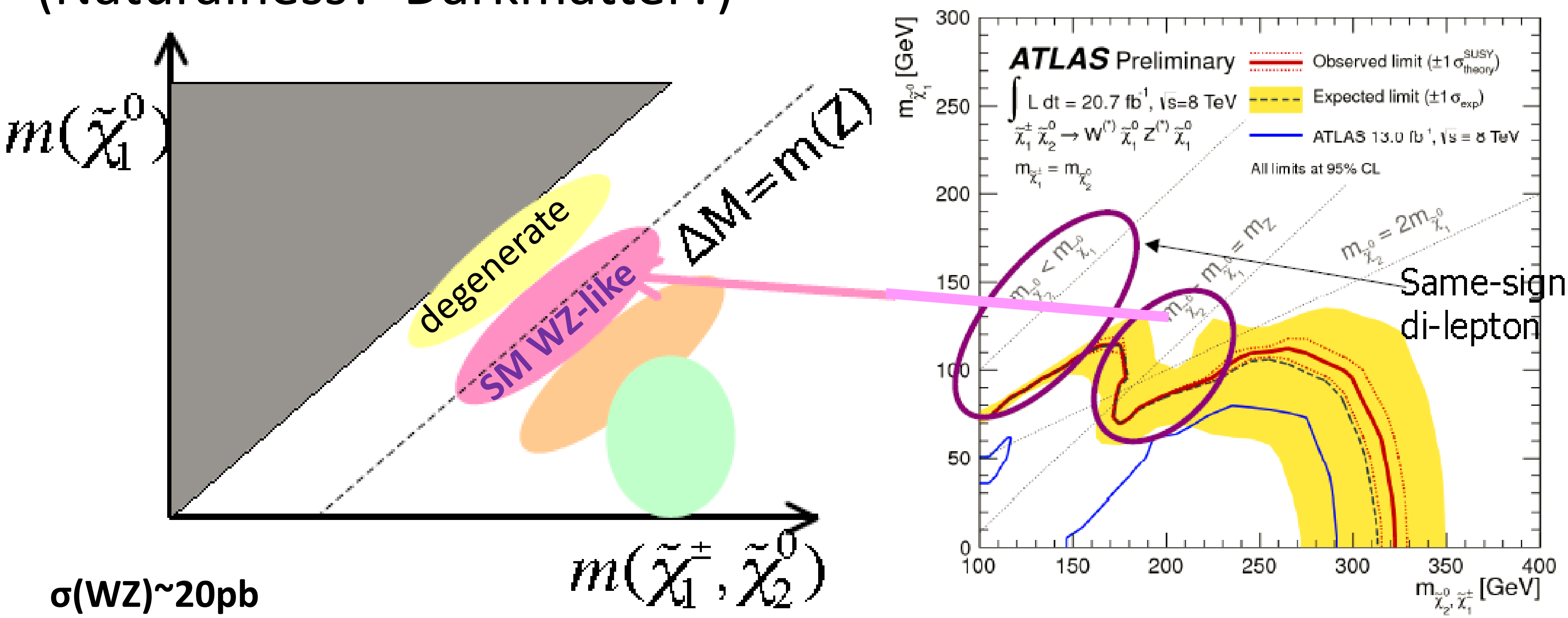
EW Gaugino search

- Direct Gaugino search

  In case sqark gluino are too heavy

  Light EW gaugino is expected
  (Naturalness? Darkmatter?)



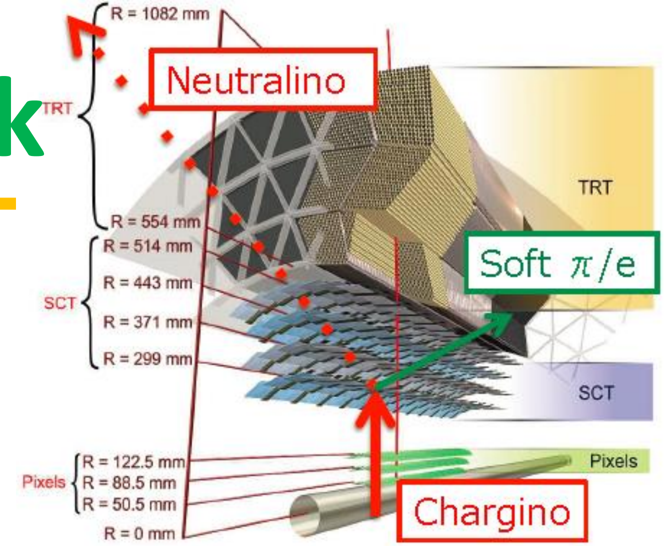


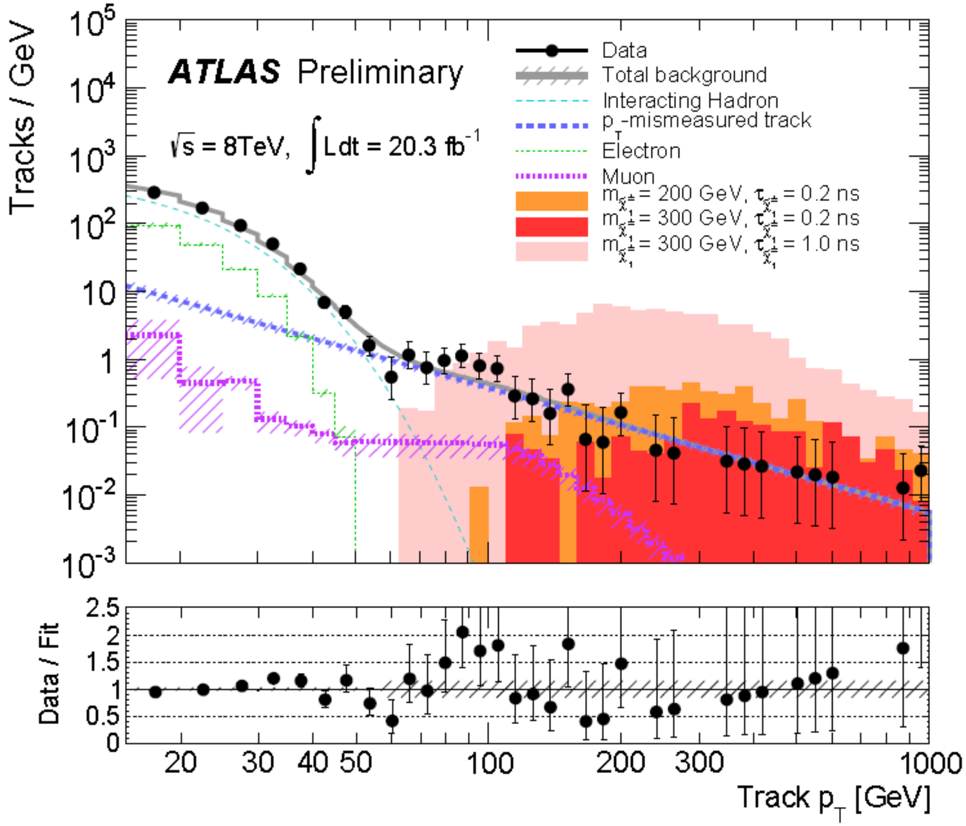
σ(WZ)~20pb

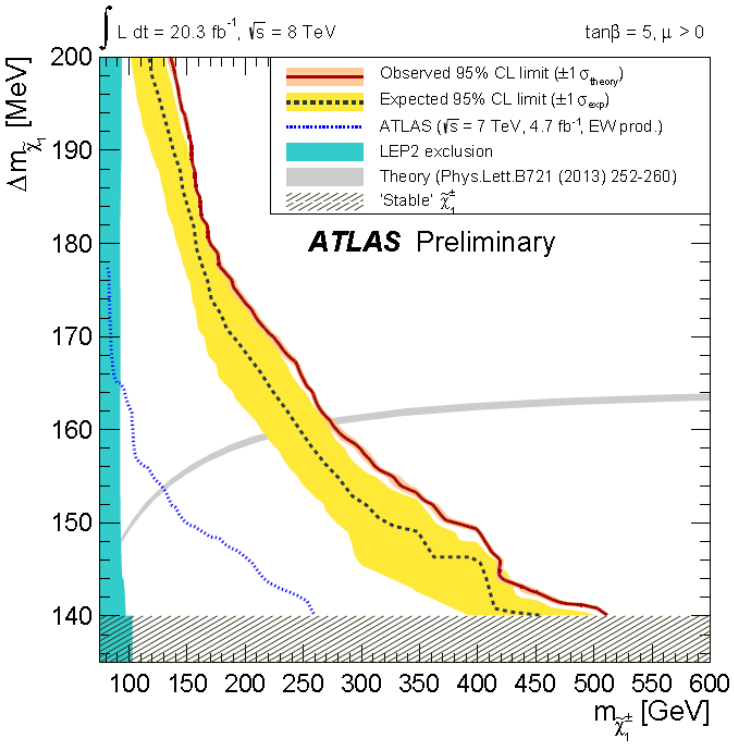
σ($\tilde{\chi}^{\pm}$, $\tilde{\chi}^{0}$)~0.5pb @200GeV

Disappearing track

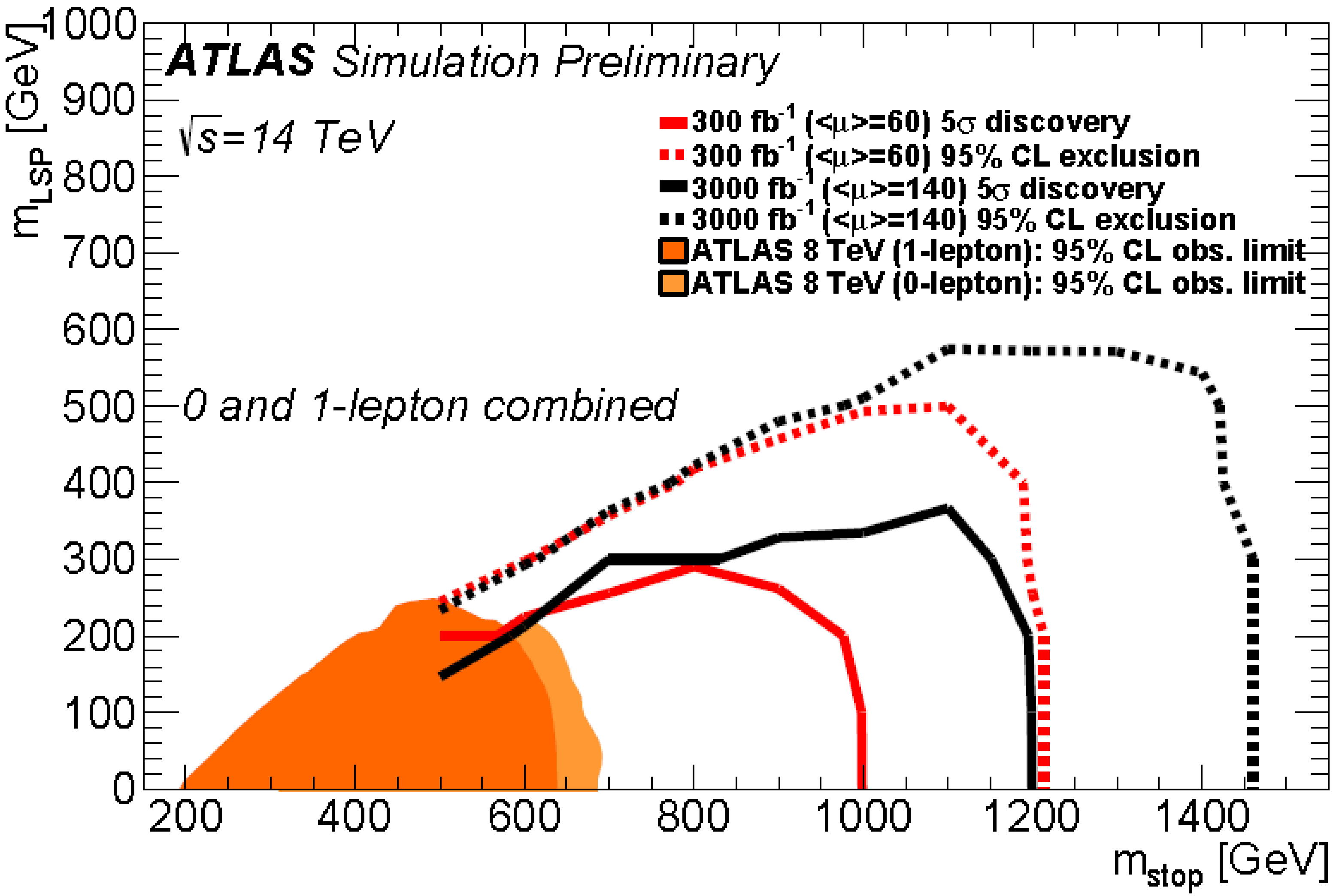
- The mass of $\tilde{\chi}^{\pm}$and $\tilde{\chi}^{0}$are degenerating ($\Delta m_{\tilde{\chi}_1}$ ~160MeV), $\tilde{\chi}^{\pm}$ have long lifetime (cτ~o(1)cm)
- **$\tilde{\chi}^{\pm}$ decayed in the ATLAS inner tracking detector then observed as disappearing track.**







Stop @300/3000fb^{-1}



Chargeno/neutralino @ 300/3000fb-1