ゲージヒッグス統一模型における安定なヒッグスボソン

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Y. Hosotani, MT, N.Uekusa (arXiv:1010.6135v2, and in progress)

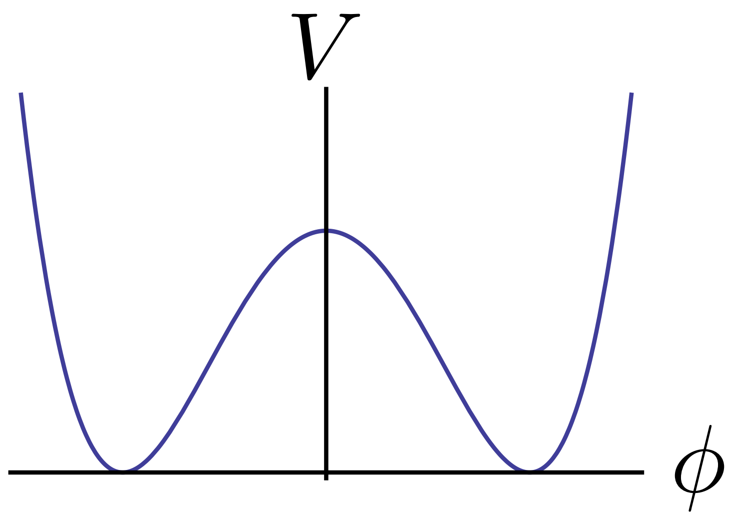
Introduction

Two big issues in particle physics

Electro-Weak Symmetry Breaking

Higgs mechanism:

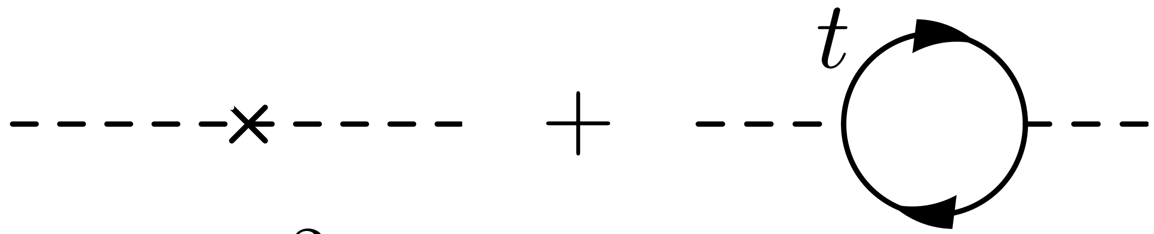
Not seen yet.



Naturalness and the hierarchy problem:

$$\Lambda \sim M_{\rm Pl} \sim 10^{18}\,{\rm GeV} \qquad \textbf{vs} \qquad M_{\rm weak} \sim 10^{3}\,{\rm GeV}$$

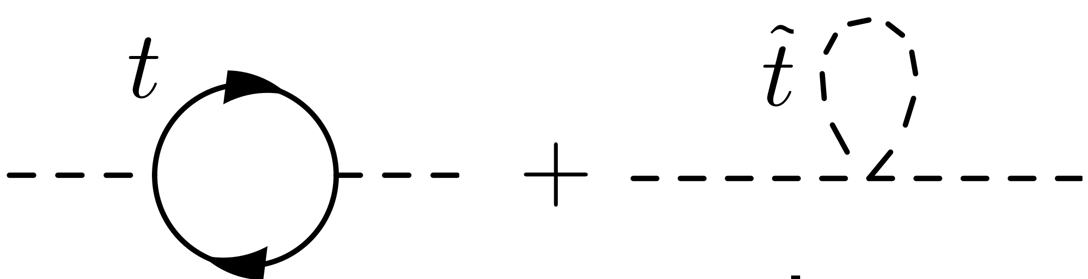
Radiative corrections to Higgs mass



m_0^2 $\qquad\qquad$ $\propto \Lambda^2$

$$\sim O((10^{18}\,\mathrm{GeV})^2) - O((10^{18}\,\mathrm{GeV})^2) \sim O((10^{3}\,\mathrm{GeV})^2)$$

A possible solution: Supersymmetry



$\sim \log \Lambda$

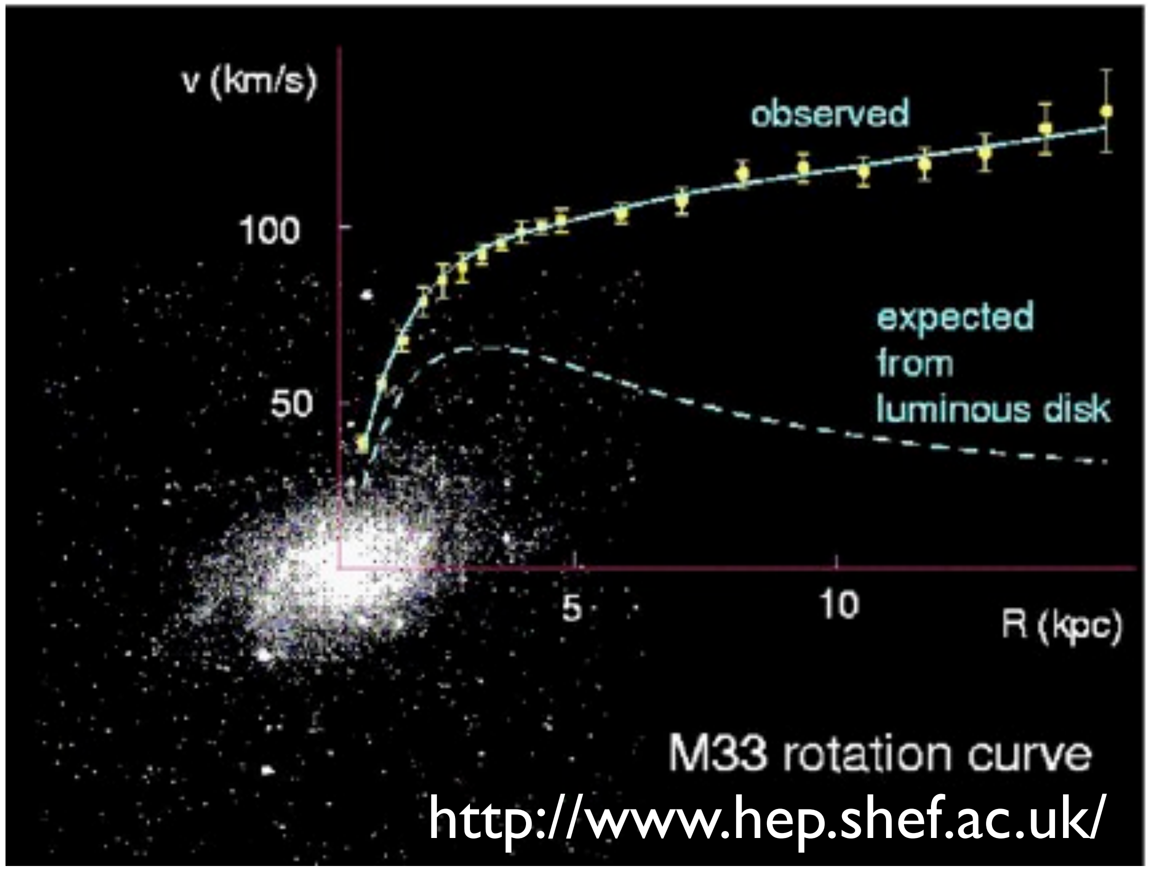
scalar top

An alternative solution:

Gauge-Higgs unification

Dark Matter

Rotation curves of galaxies: DM in galactic halo.

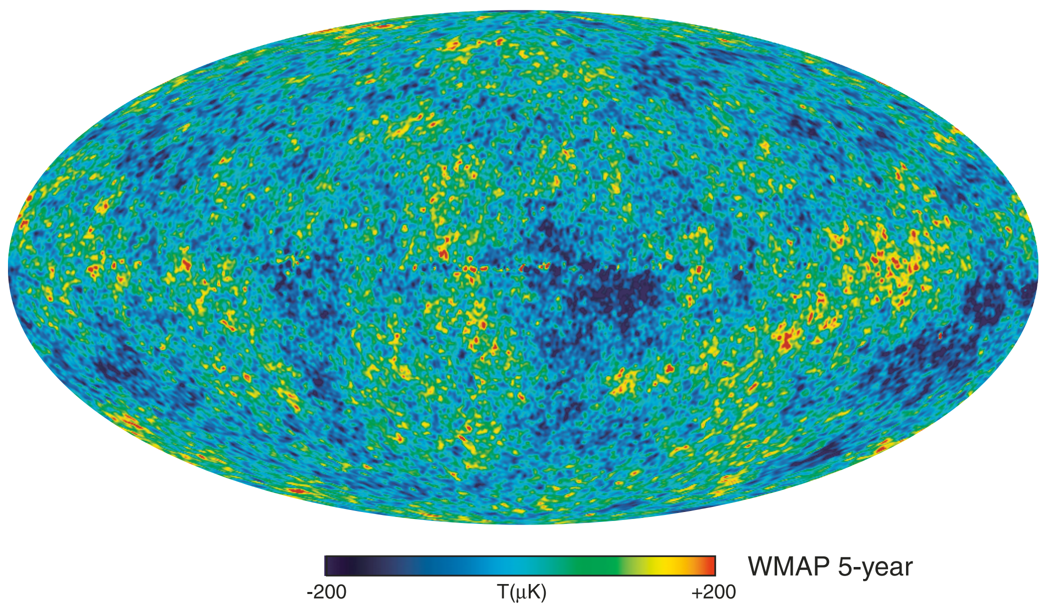


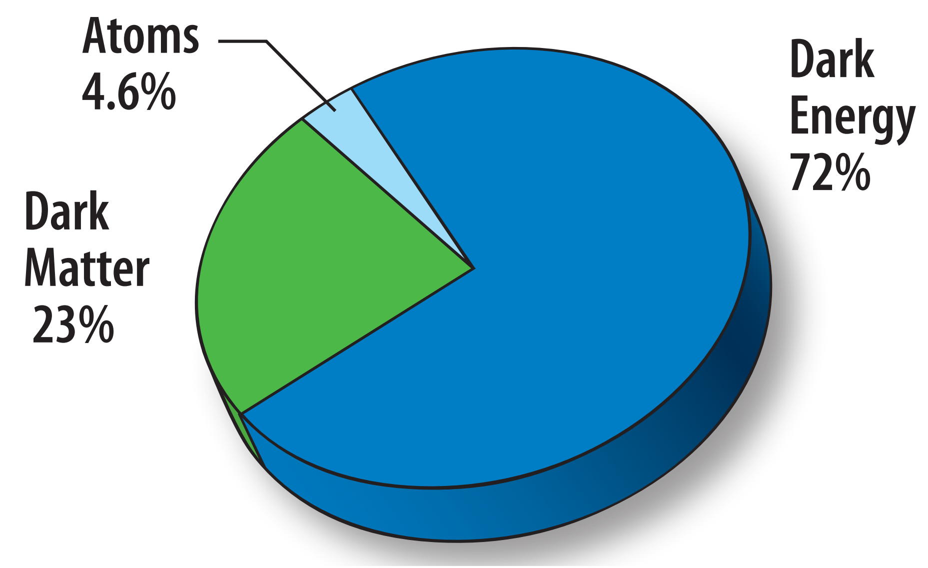
Other evidences:

cluster gas, gravitational lensing,
colliding clusters

Cosmic microwave background:

WMAP $\Omega_{\mathrm{CDM}} h^2 = 0.1131 \pm 0.0034$





http://map.gsfc.nasa.gov/

How particle physics explains the dark matter?

Supersymmetry → Neutralino

Gauge-Higgs unification → ?

Stable Higgs as Dark Matter (Dark Higgs scenario)

Questions on the dark Higgs scenario

How is it realized?

a gauge-Higgs unification model

Does it explain the relic abundance?

a constraint on Higgs mass

How do we confirm it?

collider phenomenology

Gauge-Higgs Unification

Gauge field in higher dimensions

Five-dimensional space-time: $x^M = (x^\mu, y)$

$x^\mu = (x^0, x^1, x^2, x^3)$

Gauge field: $A_M = (A_\mu, A_y)$

A_μ → 4D vector

A_y → 4D scalar ∋ Higgs

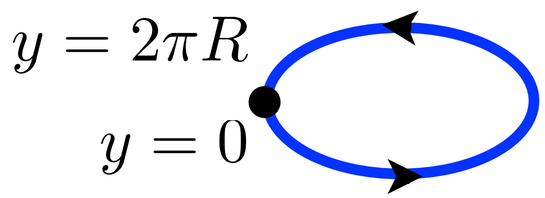
5D gauge inv. → Massless A_M

A potential solution to the naturalness problem!

Dynamical symmetry breaking

4D Higgs field: Wilson line (AB) phase

$M^4 \times S^1$ (multiply connected)



$$\hat{\theta}_H(x) \sim g \int_0^{2\pi R} A_y \, dy$$

$\langle \hat{\theta}_H \rangle \neq 0$ at quantum level.

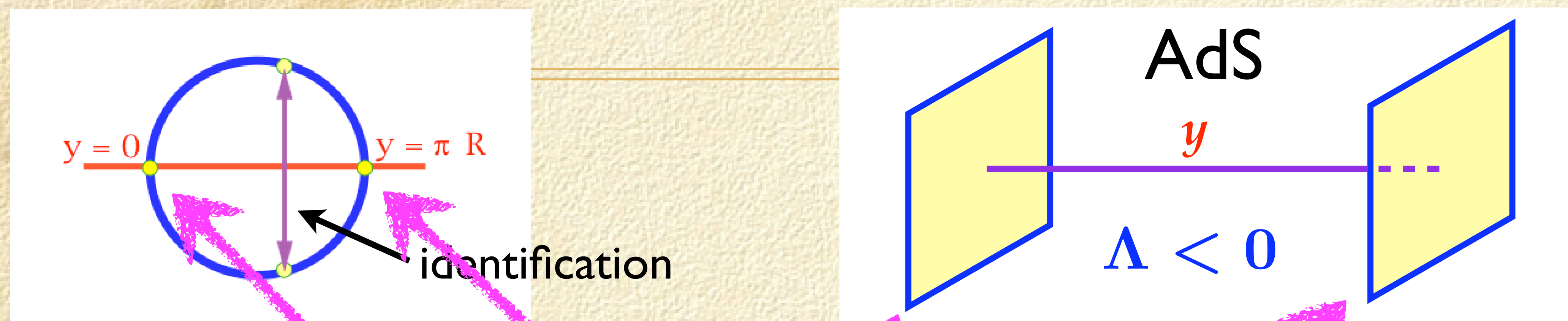
Nontrivial $V_{\text{eff}}(\hat{\theta}_H)$ at 1-loop.

Hosotani mechanism, 1983

Gauge symmetry is dynamically broken.

Flat space and warped space

$M^4 \times (S^1/Z_2)$ | **Randall-Sundrum**



$$ds^2 = dx_\mu dx^\mu + dy^2 \quad \Rightarrow \quad ds^2 = e^{-2k|y|} dx_\mu dx^\mu + dy^2$$

Y. Hosotani

warp factor

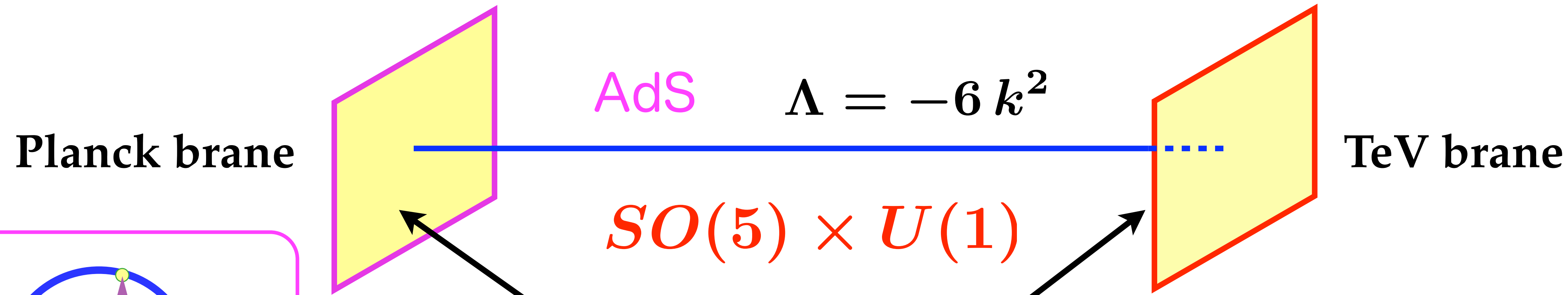
$e^{-k\pi R} \sim 10^{-15}$

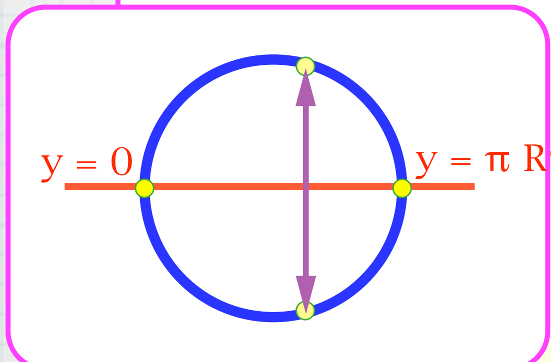
Two fixed points: $y = 0,\ y = \pi R$ → Two branes.

RS warped space → Realistic spectrum

An SO(5)xU(1) model on RS warped space

Agashe, Contino, Pomarol, 2005. Hosotani, Sakamura, 2006.
Medina, Shah, Wagner, 2007. Hosotani, Oda, Ohnuma, Sakamura, 2008.





$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x,-y) = P_0 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x,y) P_0^\dagger$$

$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x,\pi R - y) = P_1 \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x,\pi R + y) P_1^\dagger$$

Orbifold BC : $P_0\ ,\ P_1$

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Origin of the Higgs doublet

$$P_0 = P_1 = \begin{pmatrix} -1 & & & & \\ & -1 & & & \\ & & -1 & & \\ & & & -1 & \\ & & & & +1 \end{pmatrix}$$

$$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)$$

W Z γ

$A_\mu \sim$

Higgs

$$A_y \sim \begin{pmatrix} & & & & \phi_1 \\ & & & & \phi_2 \\ & & & & \phi_3 \\ & & & & \phi_4 \\ & & & & \end{pmatrix} \qquad \Phi = \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_4 - i\phi_3 \end{bmatrix}$$

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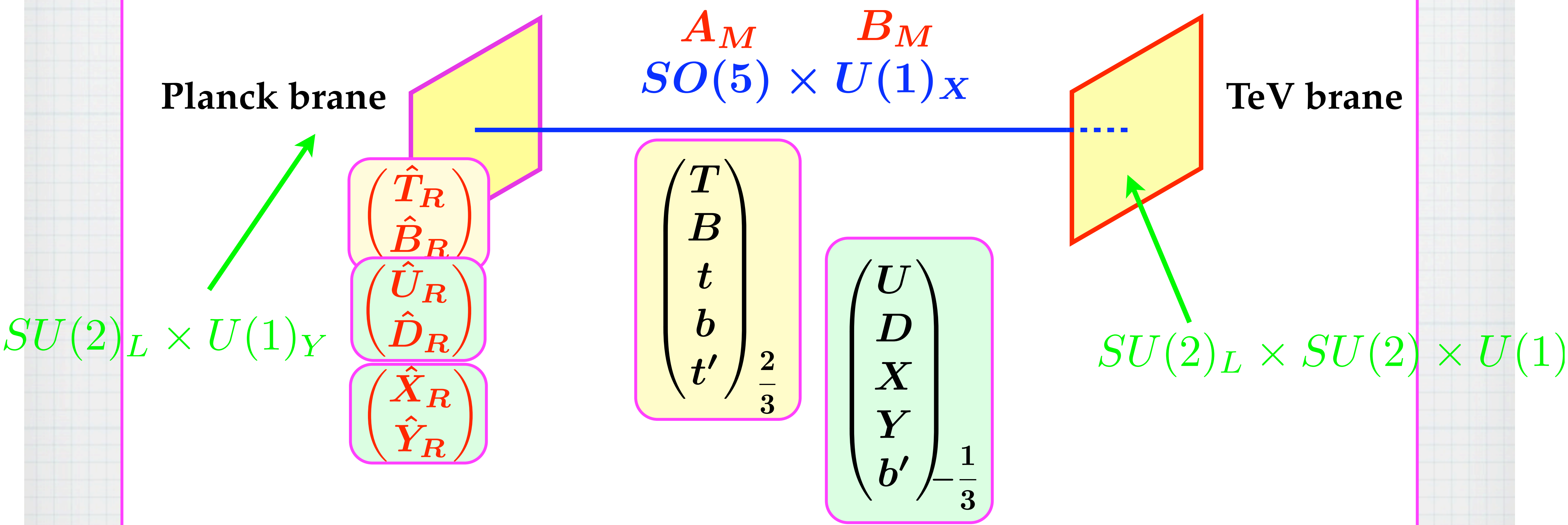
$$A_y(x^\mu, y) \sim \hat{\theta}_H(x^\mu) h_0(y) \hat{T}^4 + \cdots \qquad h_0(y) = h_0(-y)$$

SO(5)xU(1) Model on RS

YH, Oda, Ohnuma, Sakamura 2008
(YH, Noda, Uekusa 2009)



At low energies $\gamma\ ,\ W\ ,\ Z$ $\quad \begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad t'_R \quad b'_R \quad \cdots$

H

Y. Hosotani, 物理学会, 12 September 2009 - 2

Discrete symmetries

EWSB by Hosotani mechanism

4D Higgs field: Wilson line (AB) phase, $\hat{\theta}_H(x)$

→ Periodicity: $\mathcal{L}(\hat{\theta}_H) = \mathcal{L}(\hat{\theta}_H + 2\pi)$

Bulk fermions: vectors (and/or tensors) of SO(5), no spinors.

→ Reduction of period: $\mathcal{L}(\hat{\theta}_H) = \mathcal{L}(\hat{\theta}_H + \pi)$

Mirror reflection symmetry

$$y \to -y\,,\ \ A_y \to -A_y\,,\ \ \Psi \to \gamma_5 \Psi$$

→ Parity: $\mathcal{L}(\hat{\theta}_H) = \mathcal{L}(-\hat{\theta}_H)$

Effective Lagrangian at the Weak Scale

$$\mathcal{L}_{\rm eff} = -V_{\rm eff}(\hat{\theta}_H) - \sum_f m_f(\hat{\theta}_H)\bar{f}f + m_W^2(\hat{\theta}_H)W^{+\mu}W_\mu^- + \frac{1}{2}m_Z^2(\hat{\theta}_H)Z^\mu Z\mu$$

Symmetry implications:

$$V_{\rm eff}(\hat{\theta}_H + \pi) = V_{\rm eff}(\hat{\theta}_H) = V_{\rm eff}(-\hat{\theta}_H)\,,$$

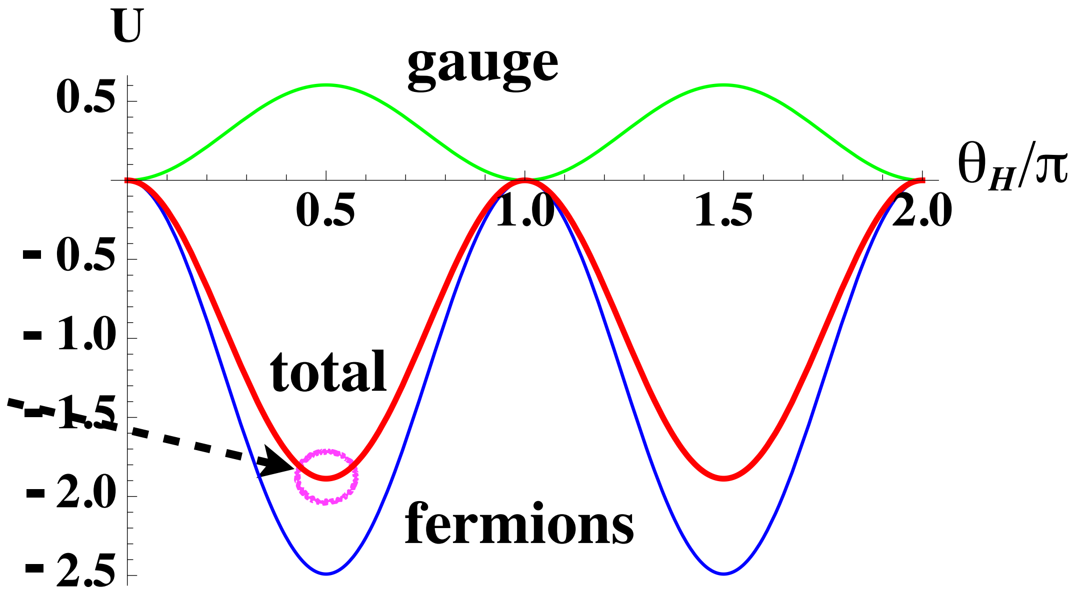
$$m_{W,Z}^2(\hat{\theta}_H + \pi) = m_{W,Z}^2(\hat{\theta}_H) = m_{W,Z}^2(-\hat{\theta}_H)\,,$$

$$m_f(\hat{\theta}_H + \pi) = -m_f(\hat{\theta}_H) = m_f(-\hat{\theta}_H)\,.$$

EWSB

Vacuum: Minimize $V_{\text{eff}}(\theta_H)$

$\theta_H = \pi/2\,.$



Physical Higgs:

$$\hat{\theta}_H(x) = \frac{\pi}{2} + \frac{H(x)}{f_H}\,.$$

$$f_H = 246\,\text{GeV}\;(\Leftarrow m_W = g f_H/2)$$

A new dynamical parity, H-parity,

$$\frac{\pi}{2} + \frac{H}{f_H} \xrightarrow[\hat{\theta} \to -\hat{\theta}]{} -\frac{\pi}{2} - \frac{H}{f_H} \xrightarrow[\hat{\theta} \to \hat{\theta} + \pi]{} \frac{\pi}{2} - \frac{H}{f_H}$$

$$H(x) \to -H(x)\,.$$

Effective Interactions

Integrating out KK modes,

$$m_W(\hat\theta_H) \sim \cos\theta_W m_Z(\hat\theta_H) \sim \frac{1}{2} g f_H \sin\hat\theta_H \ ,$$

$$m_a^F(\hat\theta_H) \sim \lambda_a \sin\hat\theta_H \ ,$$

$$\mathcal{L}_{\rm int} = -\frac{m_W^2}{f_H^2} H^2 W^{+\mu} W_\mu^- - \frac{m_Z^2}{2 f_H^2} H^2 Z^\mu Z_\mu + \sum_f \frac{m_f}{2 f_H^2} H^2 \bar f f + \cdots .$$

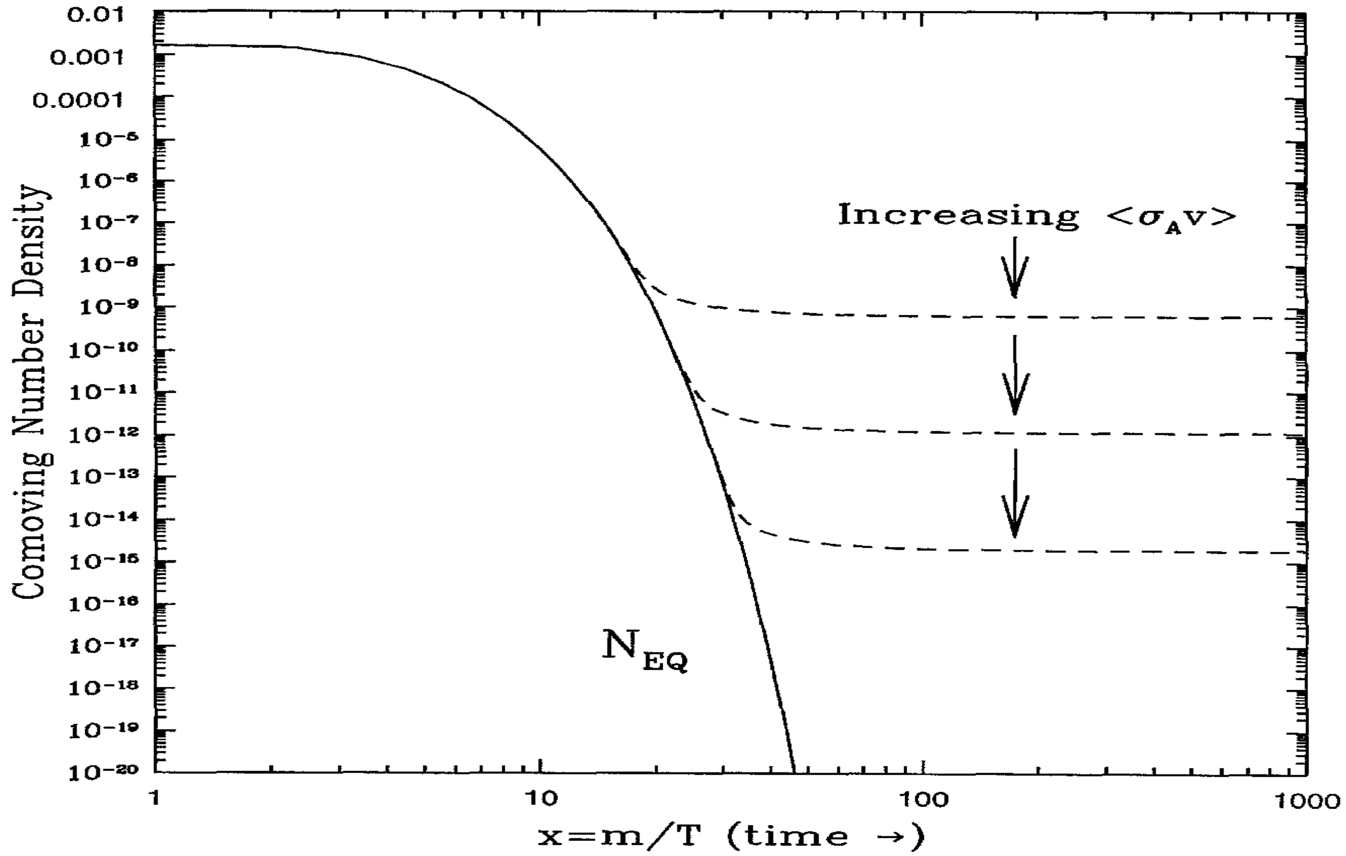
No odd powers of H .

Higgs is STABLE!

A good candidate for WIMP DM.

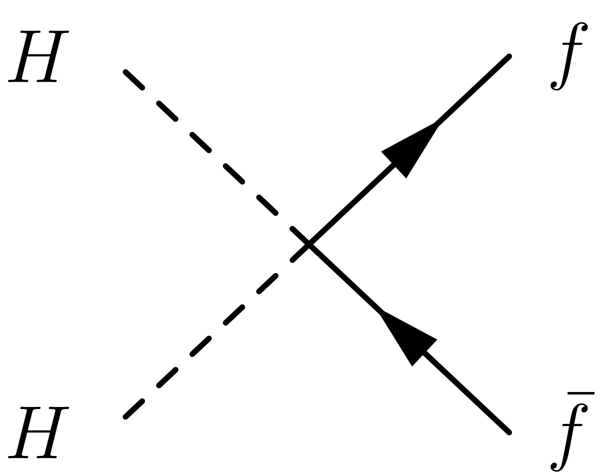
Dark Higgs

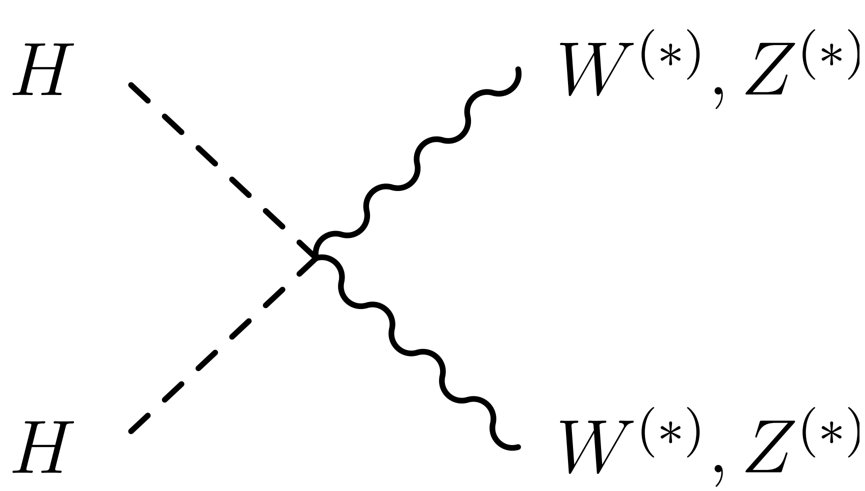
Relic Abundance

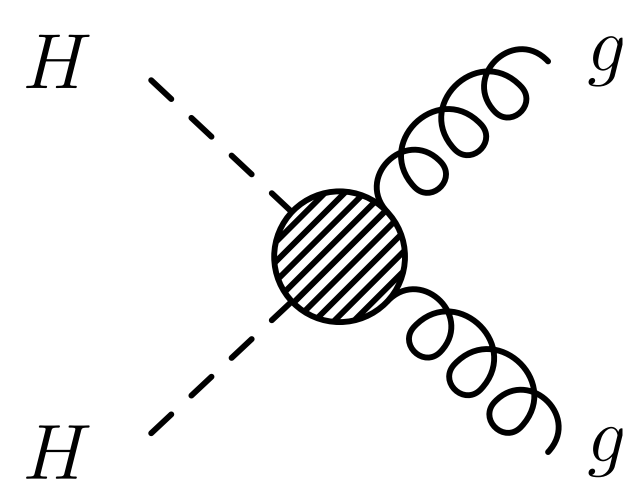


Kolb and Turner, 1989

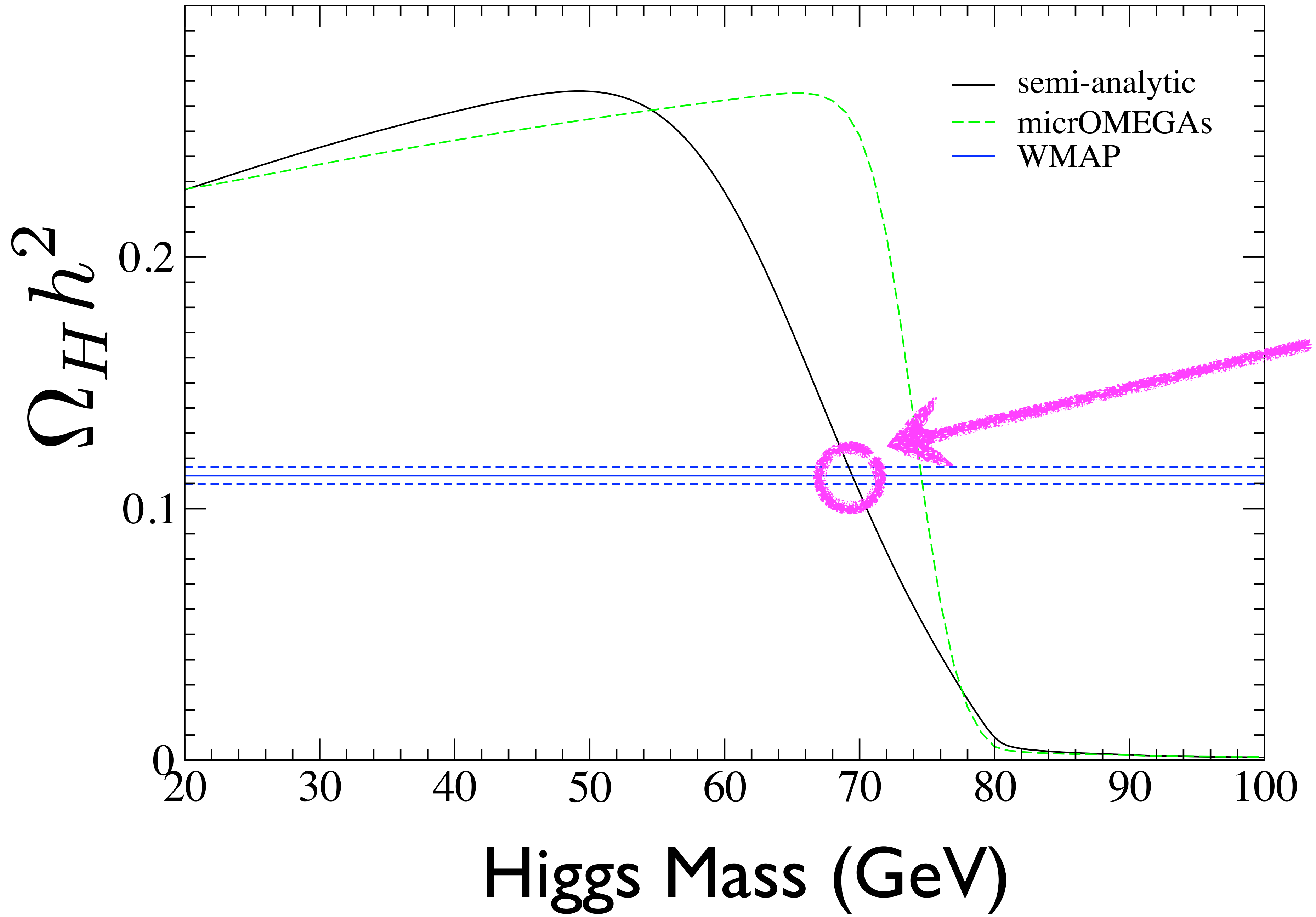
Annihilation processes:







Relic Abundance

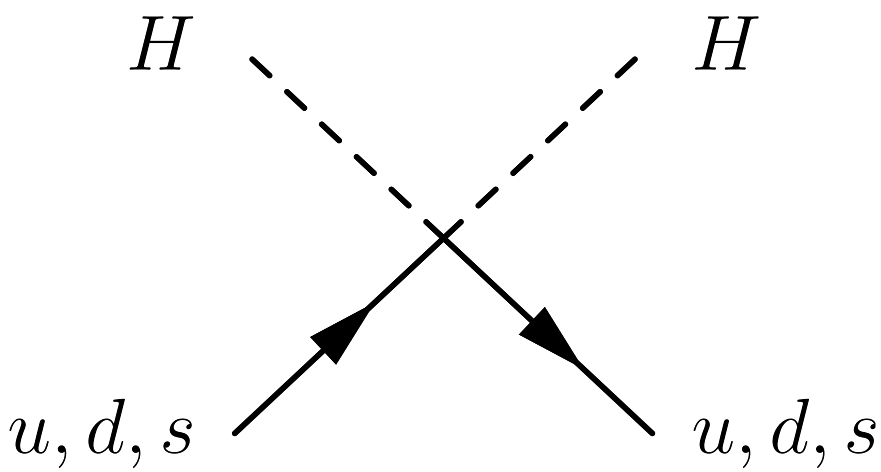


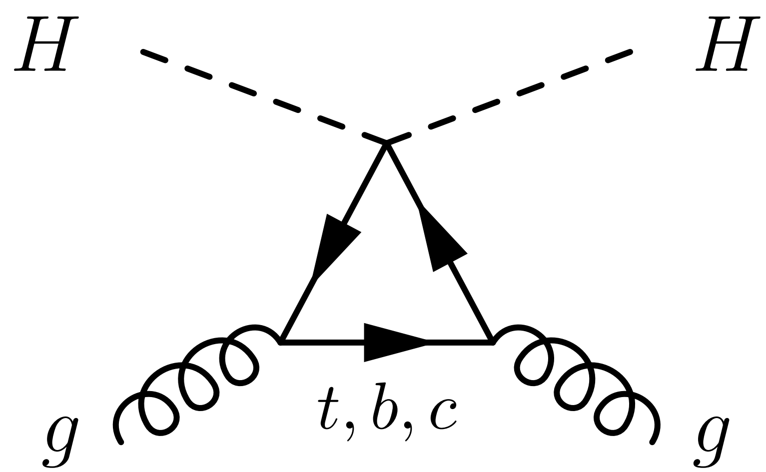
$m_H \sim 70\,\mathrm{GeV}$ favored.

$T_f \sim 3\,\mathrm{GeV}$

$10^{-27}\mathrm{cm}^3/\mathrm{s}$	$b\bar{b}$	$W^{(*)}W^{(*)}$	$Z^{(*)}Z^{(*)}$
$\sigma v\|_{v\to 0}$	7.3	11	1.5

Direct Detection $HN \to HN$





$$\mathcal{L}_{\rm eff} \simeq \frac{H^2}{2f_H^2}\left[\sum_{q=u,d,s} m_q \bar{q}q - \frac{\alpha_s}{4\pi} G^a_{\mu\nu} G^{a\,\mu\nu}\right]$$

$$\longrightarrow \quad \mathcal{L}_{HN} \simeq \frac{2+7f_N}{9}\,\frac{m_N}{2f_H^2}\,H^2 \bar{N} N$$

$$f_N = \sum_{q=u,d,s} \langle N | m_q \bar{q} q | N \rangle / m_N \simeq 0.1 \sim 0.3$$

Spin-Independent Cross Section

CDMS II

arXiv:0912.3592

Local DM density

$\rho_0 = 0.3\,\mathrm{GeV/cm^3}$

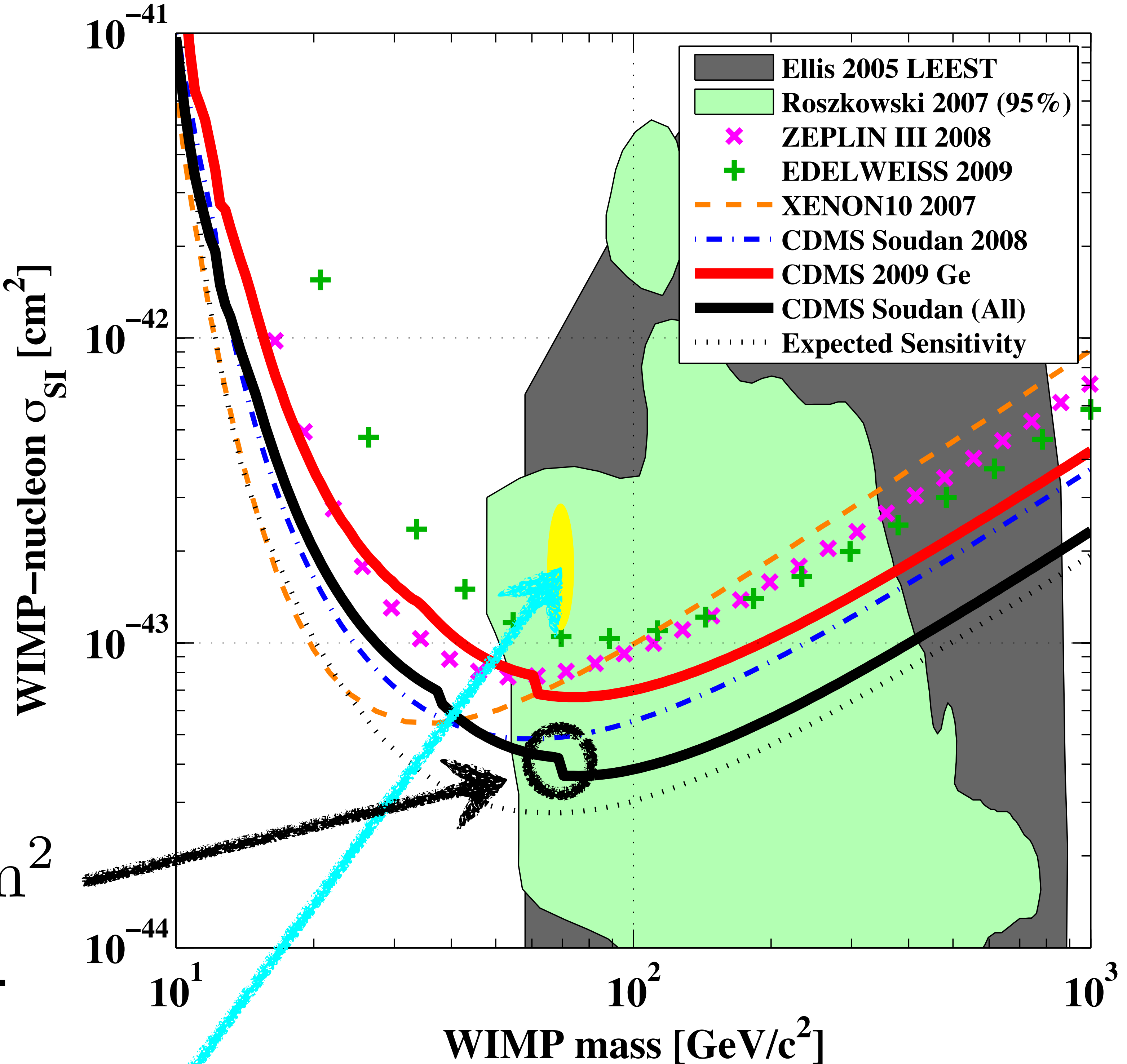
assumed in exps.

For $m_H = 70\,\mathrm{GeV}$

Exp. bound:

$\sigma_{\mathrm{SI}} \lesssim 3.8 \times 10^{-44}\,\mathrm{cm}^2$

90% CL

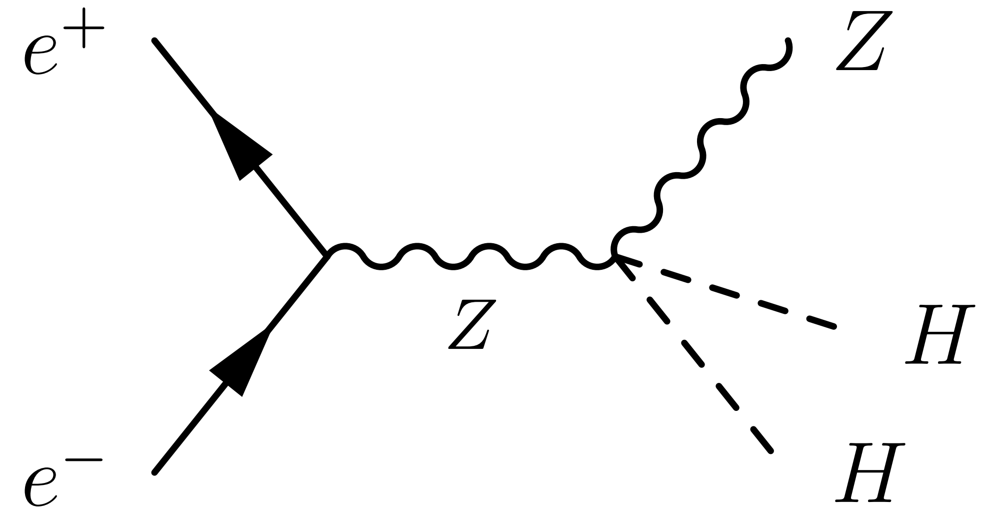


Dark Higgs

Prediction: $\sigma_{\mathrm{SI}} \simeq (1.2 - 2.7) \times 10^{-43}\,\mathrm{cm}^2$

Collider Signals

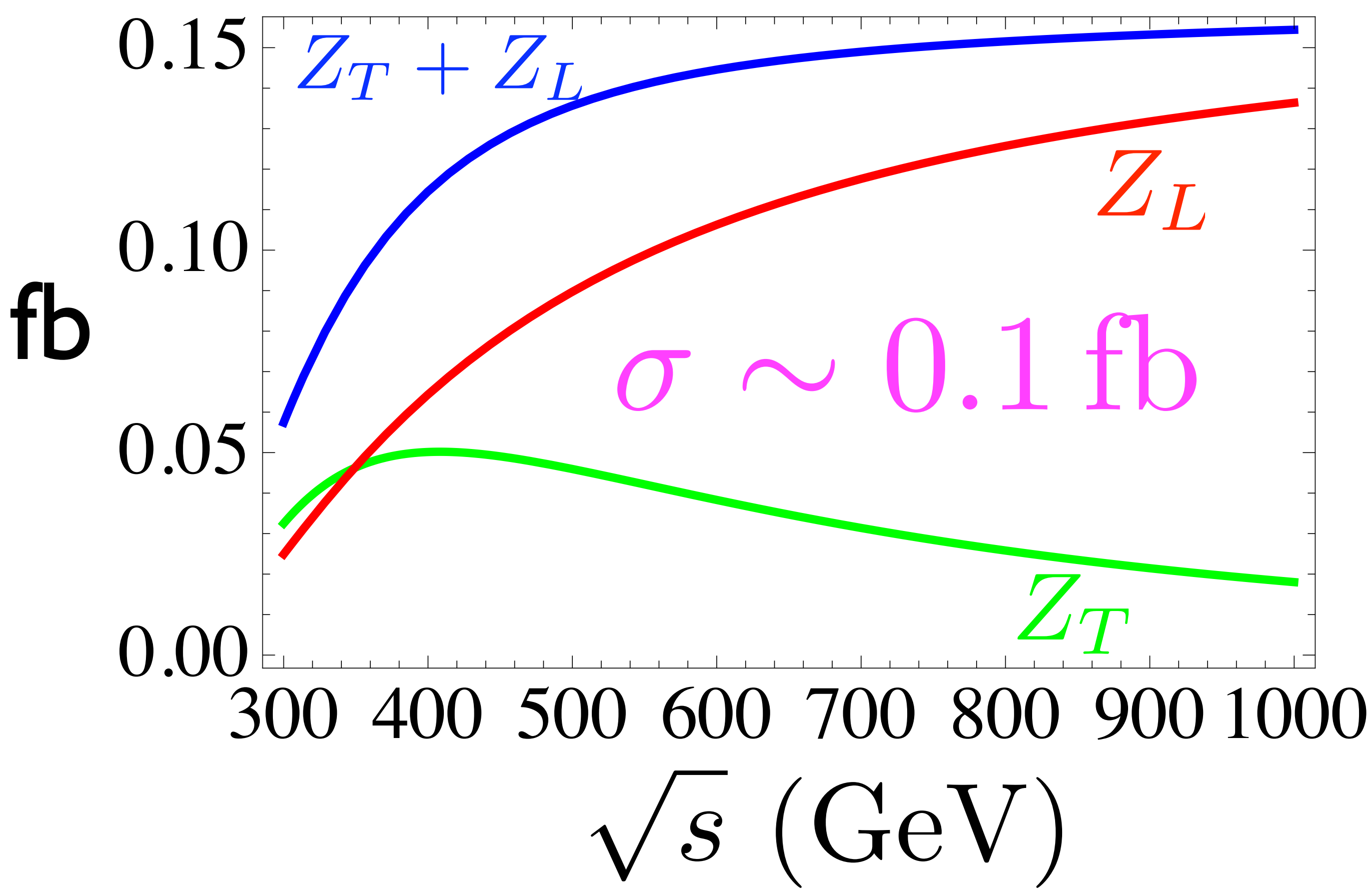
Higgs pair production at Linear Collider



Signal: $e^+e^- \to ZHH$

H's are missing.

total cross section for $m_H = 70\,\mathrm{GeV}$



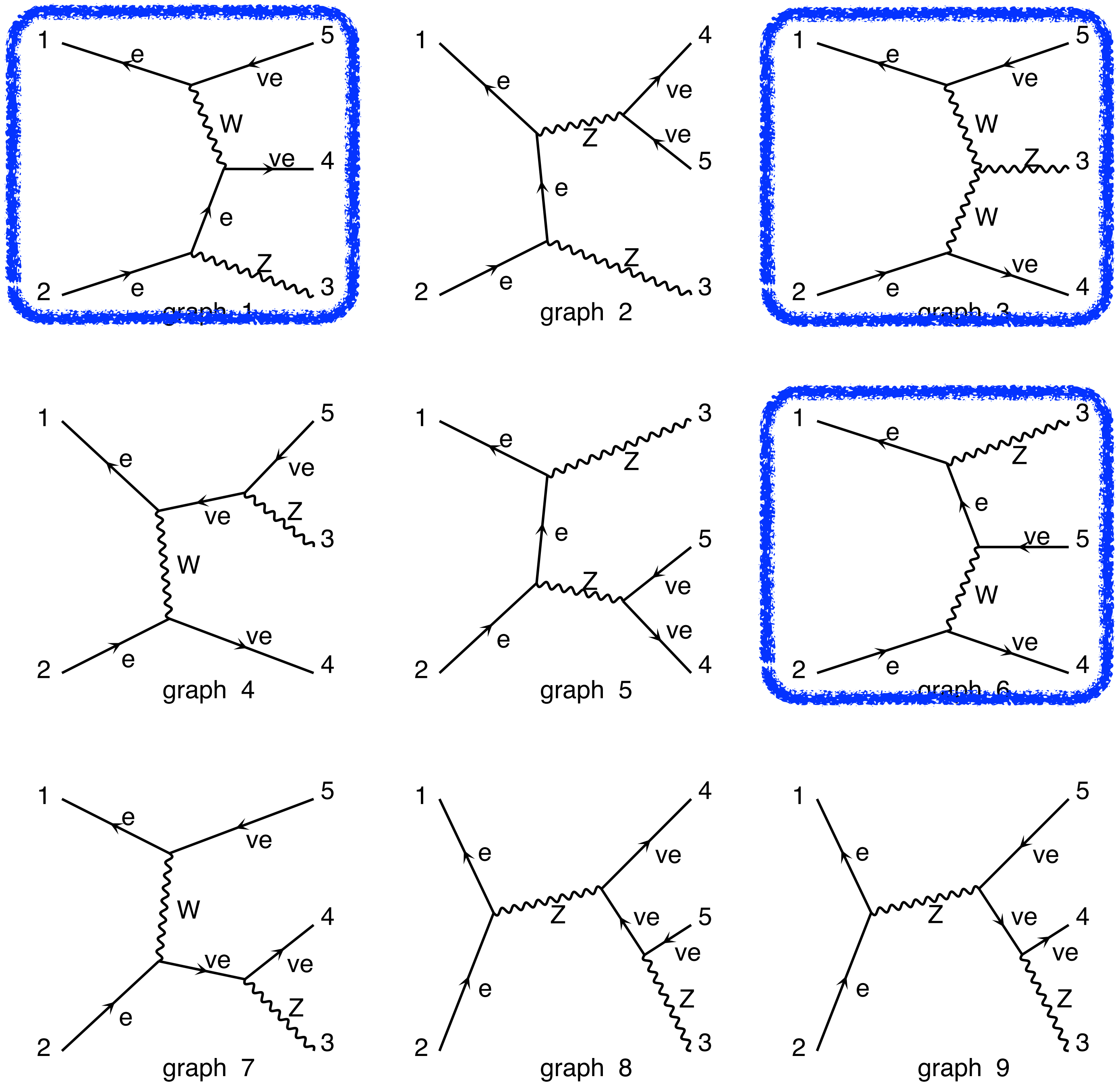
Z_L violates the unitarity unless $s/m_{\mathrm{KK}}^2 \ll 1$.

$m_{\mathrm{KK}} \sim 1.5\,\mathrm{TeV}$

$\sqrt{s} = 500\,\mathrm{GeV}$ in the following.

LC background $e^+e^- \to Z\nu\bar{\nu}$

Diagrams by MadGraph



BG cross section with $M_{\rm miss} \geq 120\,{\rm GeV}$

$$\sigma_{\rm BG} \simeq 311\,{\rm fb}$$

Need polarizations!

beams and Z

LC with polarizations

Ideal case: $e^+_L e^-_R \to Z_L HH\,,\ Z_L \nu\bar{\nu}$

$\sigma_{\rm signal} \simeq 0.12\,{\rm fb}$ vs $\sigma_{\rm BG} \simeq 0.42\,{\rm fb}$

$|\cos\theta| < 0.6$ is applied.

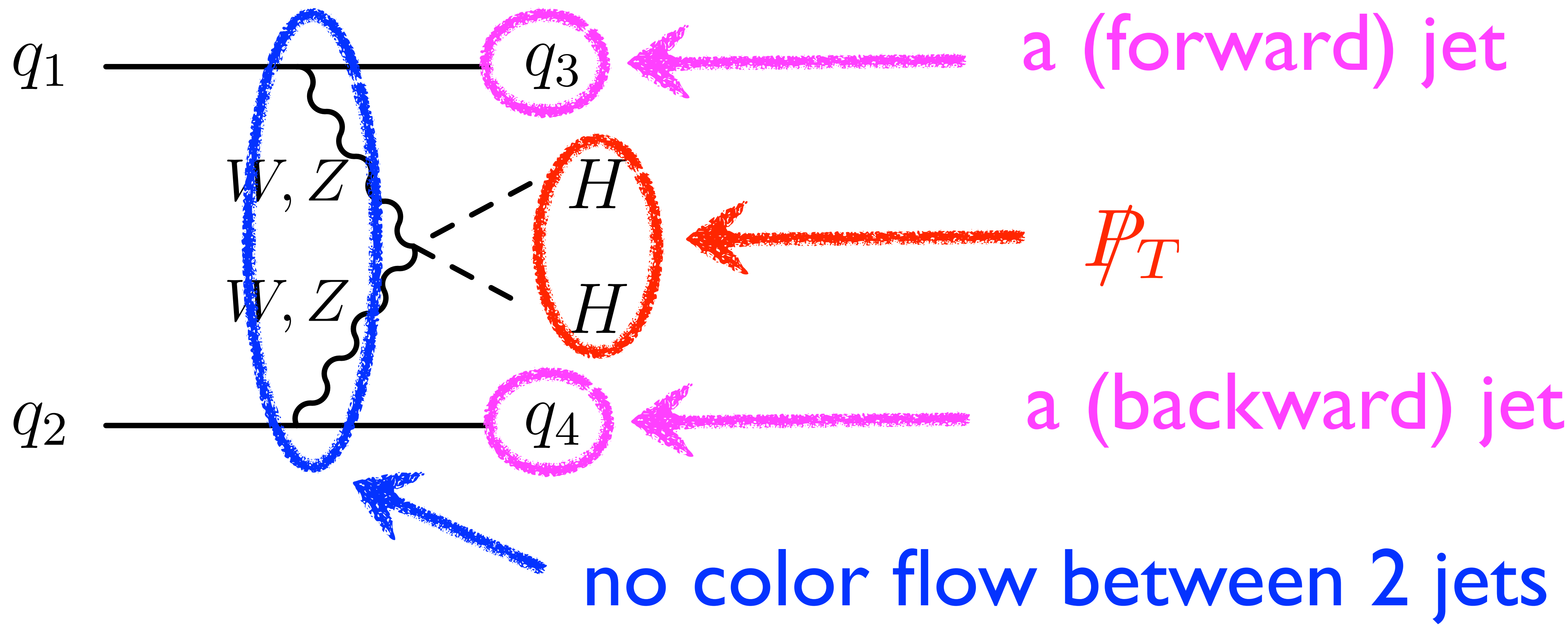
Significance: $\mathcal{S} \equiv \dfrac{N_{\rm signal}}{\sqrt{N_{\rm signal} + N_{\rm BG}}}$

$$\mathcal{S} = 1.4\sqrt{L/100\,{\rm fb}^{-1}}$$

A few (or more) ${\rm ab}^{-1}$ is required!

Higgs pair production at LHC

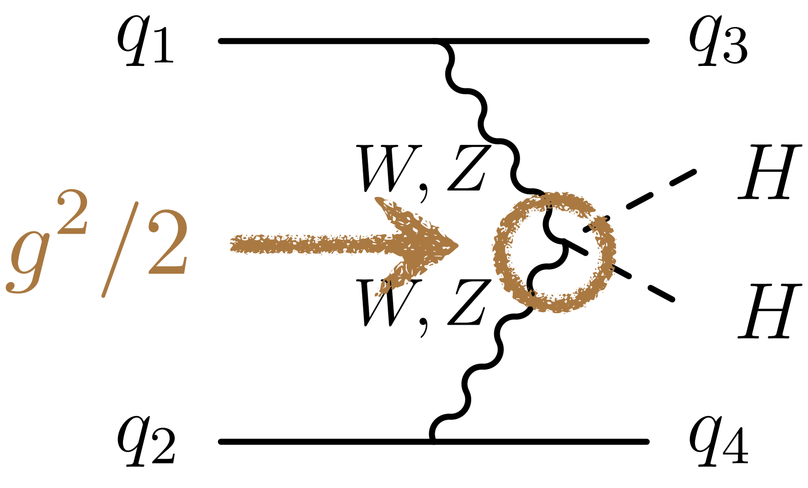
Signal: Weak boson fusion

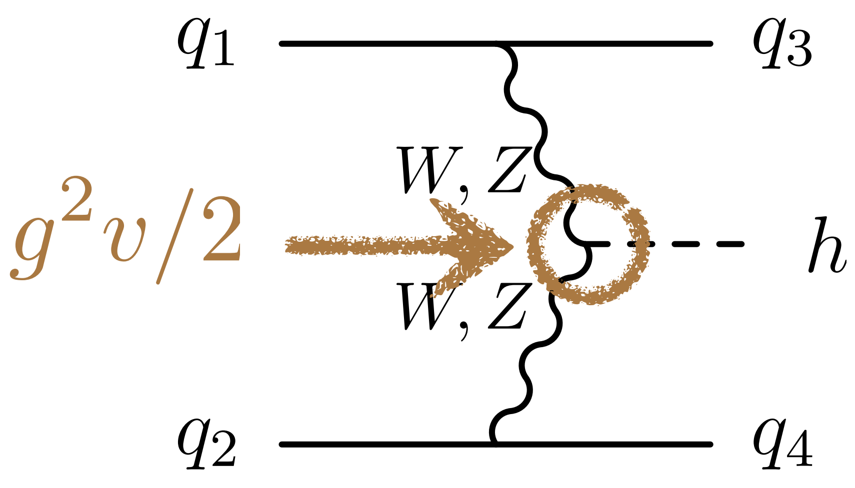


Background: Wjj, Zjj, jjj

→ Similar as invisible Higgs search

Signal cross section at LHC





$$\frac{d\sigma_{HH}}{dm_{HH}^2} = \frac{\bar{\beta}_f}{32\pi^2 v^2} \sigma_h |_{m_h^2 = m_{HH}^2}$$

in the SM

$$\sigma_{HH} \sim 1.5\,\text{fb}$$

$$\sigma_{BG} \simeq 167\,\text{fb}$$

$$\mathcal{S} \sim 1.2\sqrt{L/100\,\text{fb}^{-1}}$$

Éboli, Zeppenfeld

$p_T^j > 40$ GeV, $|\eta_j| < 5.0$,

$|\eta_{j1} - \eta_{j2}| > 4.4$, $\eta_{j1} \cdot \eta_{j2} < 0$,

$\not{p}_T > 100$ GeV.

$M_{jj} > 1200$ GeV, $\phi_{jj} < 1$.

More on H parity

SO(5) algebra

$SU(2)_L$ $SU(2)_R$ $SO(5)/SO(4)$

$$A_M = \sum_{I=1}^{10} A_M^I T^I = \sum_{a_L=1}^{3} A_M^{a_L} T^{a_L} + \sum_{a_R=1}^{3} A_M^{a_R} T^{a_R} + \sum_{\hat{a}=1}^{4} A_M^{\hat{a}} T^{\hat{a}}$$

$$[T^{a_L}, T^{b_L}] = i\epsilon^{abc} T^{c_L} \quad , \quad [T^{a_R}, T^{b_R}] = i\epsilon^{abc} T^{c_R} \quad , \quad [T^{a_L}, T^{b_R}] = 0 \quad ,$$

$$[T^{\hat{a}}, T^{\hat{b}}] = \frac{i}{2}\epsilon^{abc}(T^{c_L} + T^{c_R}) \quad ,$$

$$[T^{\hat{a}}, T^{b_L}] = -\frac{i}{2}\delta^{ab} T^{\hat{4}} + \frac{i}{2}\epsilon^{abc} T^{\hat{c}} \quad , \quad [T^{\hat{a}}, T^{b_R}] = +\frac{i}{2}\delta^{ab} T^{\hat{4}} + \frac{i}{2}\epsilon^{abc} T^{\hat{c}} \quad ,$$

$$[T^{a_L}, T^{\hat{4}}] = -\frac{i}{2} T^{\hat{a}} \quad , \quad [T^{a_R}, T^{\hat{4}}] = +\frac{i}{2} T^{\hat{a}} \quad , \quad [T^{\hat{a}}, T^{\hat{4}}] = \frac{i}{2}(T^{a_L} - T^{a_R})$$

$$(a, b, c = 1 \sim 3) \ .$$

Invariant under $\Omega_H = \mathrm{diag}\,(1, 1, 1, -1, 1) \in O(5)$

$$\{T^{a_L}, T^{a_R}, T^{\hat{a}}, T^{\hat{4}}\} \longrightarrow \{T^{a_R}, T^{a_L}, T^{\hat{a}}, -T^{\hat{4}}\}$$

Typical mode expansion

5D mode func.

4D field

$$\tilde{A}_\mu(x,z) = \sum_{n=0}^{\infty}{}^{d}\, W_\mu^{(n)} \left\{ N_W(\lambda_n)\frac{T^{-_L}+T^{-_R}}{2} + \cos\theta_H N_W(\lambda_n)\frac{T^{-_L}-T^{-_R}}{2} - \frac{\sin\theta_H}{\sqrt{2}} D_W(\lambda_n) T^{\hat{-}} \right\} + \text{h.c.}$$

$$+ \sum_{n=1}^{\infty}{}^{s}\, W_\mu^{\prime(n)} \left\{ -\cos\theta_H N_{W'}(\lambda_n)\frac{T^{-_L}+T^{-_R}}{2} + N_{W'}(\lambda_n)\frac{T^{-_L}-T^{-_R}}{2} \right\} + \text{h.c.}$$

$$+ \sum_{n=0}^{\infty}{}^{s}\, A_\mu^{\gamma(n)} h_\gamma(\lambda_n)(T^{3_L}+T^{3_R}) + \sum_{n=1}^{\infty}{}^{s}\, A_\mu^{\hat{4}(n)} h_A(\lambda_n) T^{\hat{4}} + \cdots$$

$$\tilde{A}_z(x,z) = \sum_{n=1}^{\infty}{}^{s} \sum_{a=1}^{3} S^{a(n)} h_S^{LR}(\lambda_n)\frac{T^{a_L}+T^{a_R}}{\sqrt{2}} + \sum_{n=0}^{\infty}{}^{s}\, H^{(n)} h_H^{\wedge}(\lambda_n) T^{\hat{4}} + \cdots$$

$$\theta_H = \pi/2$$

$W_\mu^{(n)},\ A_\mu^{\gamma(n)},\ S^{a(n)}$ $\quad P_H$ **even**

$W_\mu^{\prime(n)},\ A_\mu^{\hat{4}(n)},\ H^{(n)}$ $\quad P_H$ **odd**

H-even KK particle production

Model parameters

EW parameters: $k,\ g_A,\ g_B,\ z_L = e^{kL}$

EW inputs: $m_Z,\ \alpha,\ \sin^2\theta_W$

$$z_L \longrightarrow m_H$$

$z_L = e^{kL}$	$\sin^2\theta_W$	k(GeV)	$m_{\rm KK}$(GeV)	$c_{\rm top}$	m_H(GeV)	$m_W^{\rm tree}$(GeV)
10^{15}	0.2312	4.666×10^{17}	1,466	0.432	135	79.82
10^{10}	0.23	3.799×10^{12}	1,194	0.396	108	79.82
10^{5}	0.2285	2.662×10^{7}	836	0.268	72	79.70

Spectrum

KK gluon

Table 14: KK gluon masses $m_{G^{(n)}}$ in unit of GeV.

$z_L \setminus n$	1	2	3	4	5
10^{15}	1143.4	2597.79	4060.29	5524.61	6989.61
10^{10}	939.287	2123.35	3313.67	4505.36	5697.54
10^{5}	676.998	1508.23	2342.77	3177.87	4013.1

KK W

Table 15: KK W boson masses $m_{W^{(n)}}$ in unit of GeV.

$z_L \setminus n$	1	2	3	4	5
10^{15}	1132.69	1799.15	2586.69	3284.74	4049.02
10^{10}	926.031	1468.74	2109.46	2677.61	3299.47
10^{5}	657.626	1038.84	1487.22	1885.54	2320.8

KK Z

Table 16: KK Z boson masses $m_{Z^{(n)}}$ in unit of GeV.

$z_L \setminus n$	1	2	3	4	5
10^{15}	1129.49	1802.53	2583.37	3288.13	4045.64
10^{10}	922.087	1472.93	2105.3	2681.86	3295.21
10^{5}	651.946	1045.02	1480.99	1892.00	2314.27

Focus on the first KK Z.

Couplings

Table 25: The couplings of the first KK Z boson with charged leptons, $g_{fI}^{(Z_1)}\sqrt{L}/g_A$.

z_L	eL	μL	τL	eR	μR	τR
10^{15}	0.0310237	0.0310238	0.0310529	2.52033	2.42011	2.35629
10^{10}	0.0382222	0.0382224	0.0382616	2.13663	2.03326	1.96297
10^{5}	0.0549348	0.0549354	0.0550174	1.62351	1.53169	1.45818

Table 26: The couplings of the first KK Z boson with left-handed quarks, $g_{fL}^{(Z_1)}\sqrt{L}/g_A$.

z_L	u	c	t	d	s	b
10^{15}	−0.0399184	−0.0399209	−0.206095	0.0488131	0.048804	−0.558474
10^{10}	−0.0491807	−0.0491842	−0.256412	0.0601393	0.0601274	−0.672188
10^{5}	−0.0706849	−0.0706938	−0.386896	0.0864351	0.0864104	−0.927167

Table 27: The couplings of the first KK Z boson with right-handed quarks, $g_{fR}^{(Z_1)}\sqrt{L}/g_A$.

z_L	u	c	t	d	s	b
10^{15}	−1.65847	−1.58714	−1.4692	0.829233	0.793569	0.723936
10^{10}	−1.40259	−1.32685	−1.1796	0.701297	0.663427	0.579202
10^{5}	−1.06424	−0.991935	−0.754189	0.532119	0.495967	0.376702

Table 24: The couplings of the first KK W boson with leptons, $g_{fL}^{(W_1)}\sqrt{L}/g_A$ and the couplings of the first KK Z boson with neutrinos, $g_{fL}^{(Z_1)}\sqrt{L}/g_A$.

z_L	$e\nu_e$	$\mu\nu_\mu$	$\tau\nu_\tau$	ν_e	ν_μ	ν_τ
10^{15}	−0.138009	−0.138008	−0.137939	−0.0577078	−0.0577075	−0.0576242
10^{10}	−0.170013	−0.170012	−0.169923	−0.0710978	−0.0710974	−0.0709898
10^{5}	−0.244187	−0.244186	−0.24403	−0.102185	−0.102184	−0.101988

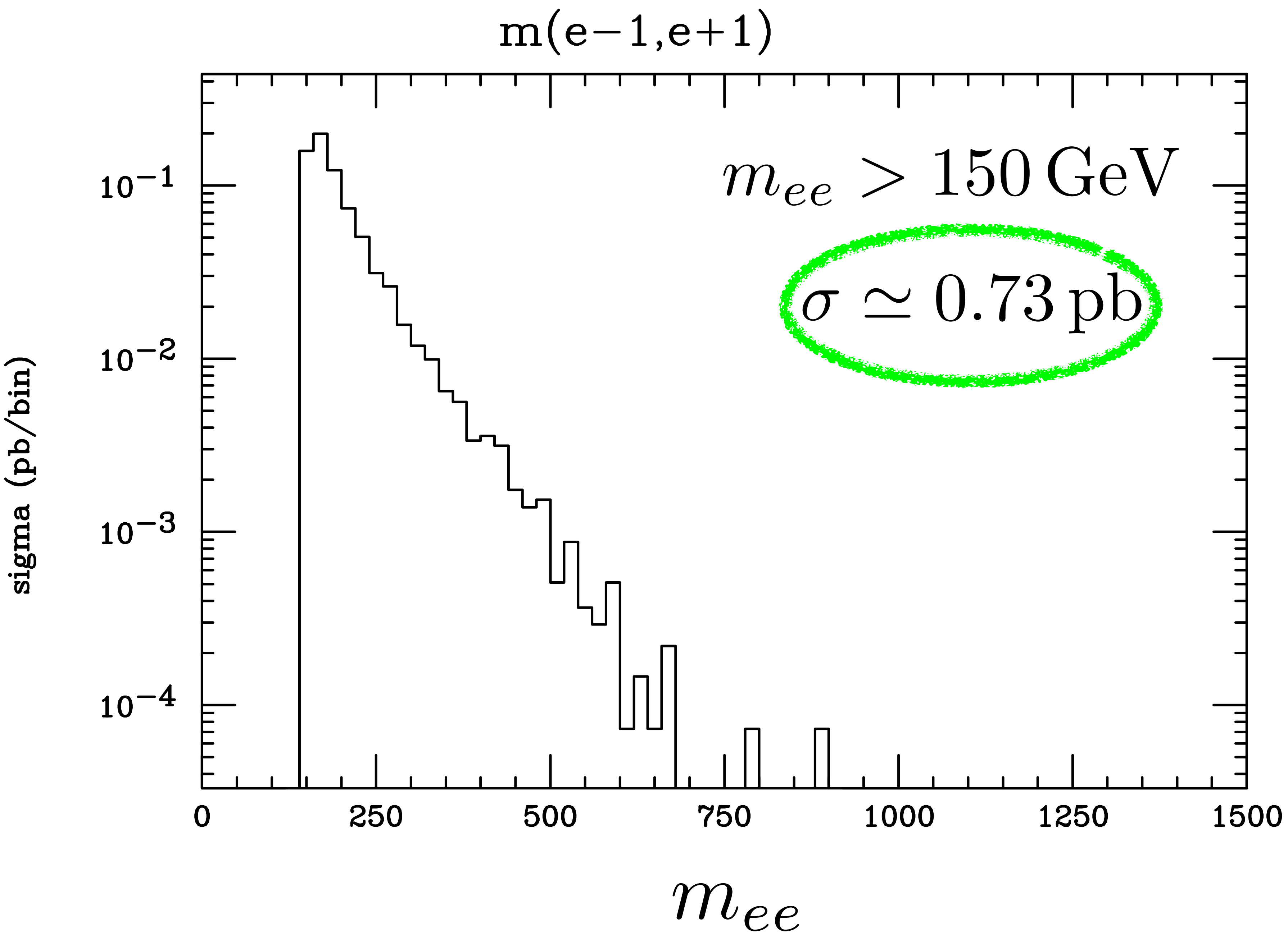
Decay width and BR

Table 28: First KK Z boson decay: the branching fraction and the total width.

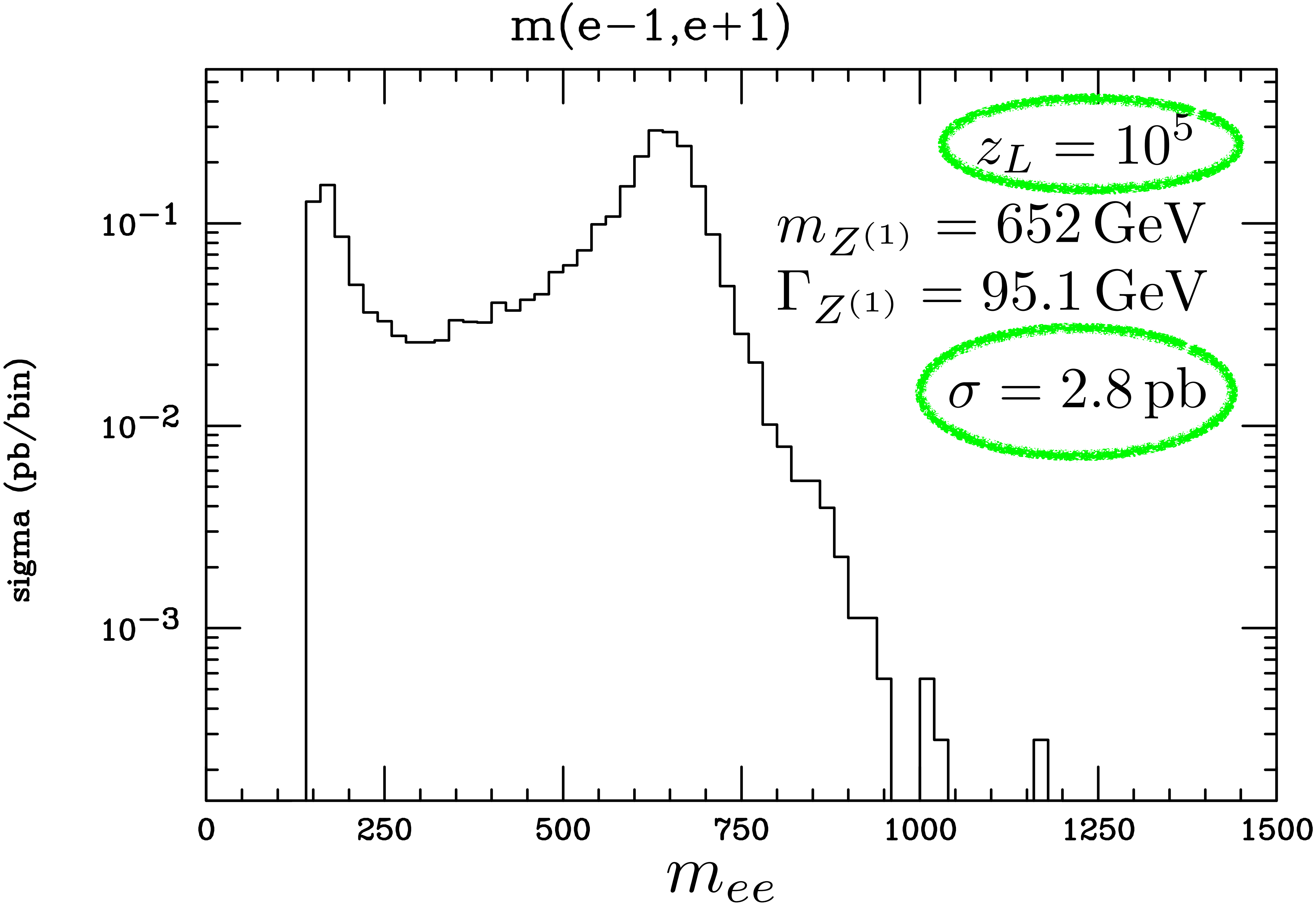
z_L	10^{15}	10^{10}	10^{5}
e (%)	14.1396	14.18	13.253
μ (%)	13.0376	12.8416	11.798
τ (%)	12.3591	11.9693	10.6941
$\nu_e + \nu_\mu + \nu_\tau$ (%)	0.0222139	0.0470403	0.157124
$(u+c)/2$ (%)	17.6028	17.3854	16.0203
$(d+s+b)/3$ (%)	3.68474	4.40884	7.27081
c (%)	16.8299	16.4225	14.9003
b (%)	5.58161	7.3338	15.0894
t (%)	14.1818	12.9648	10.2446
$u+d+s+c$ (%)	40.6781	40.6636	38.7638
total width (GeV)	371.761	217.536	95.0912

KK Z at Tevatron: $p\bar{p} \to Z^{(1)} X \to e^- e^+ X$

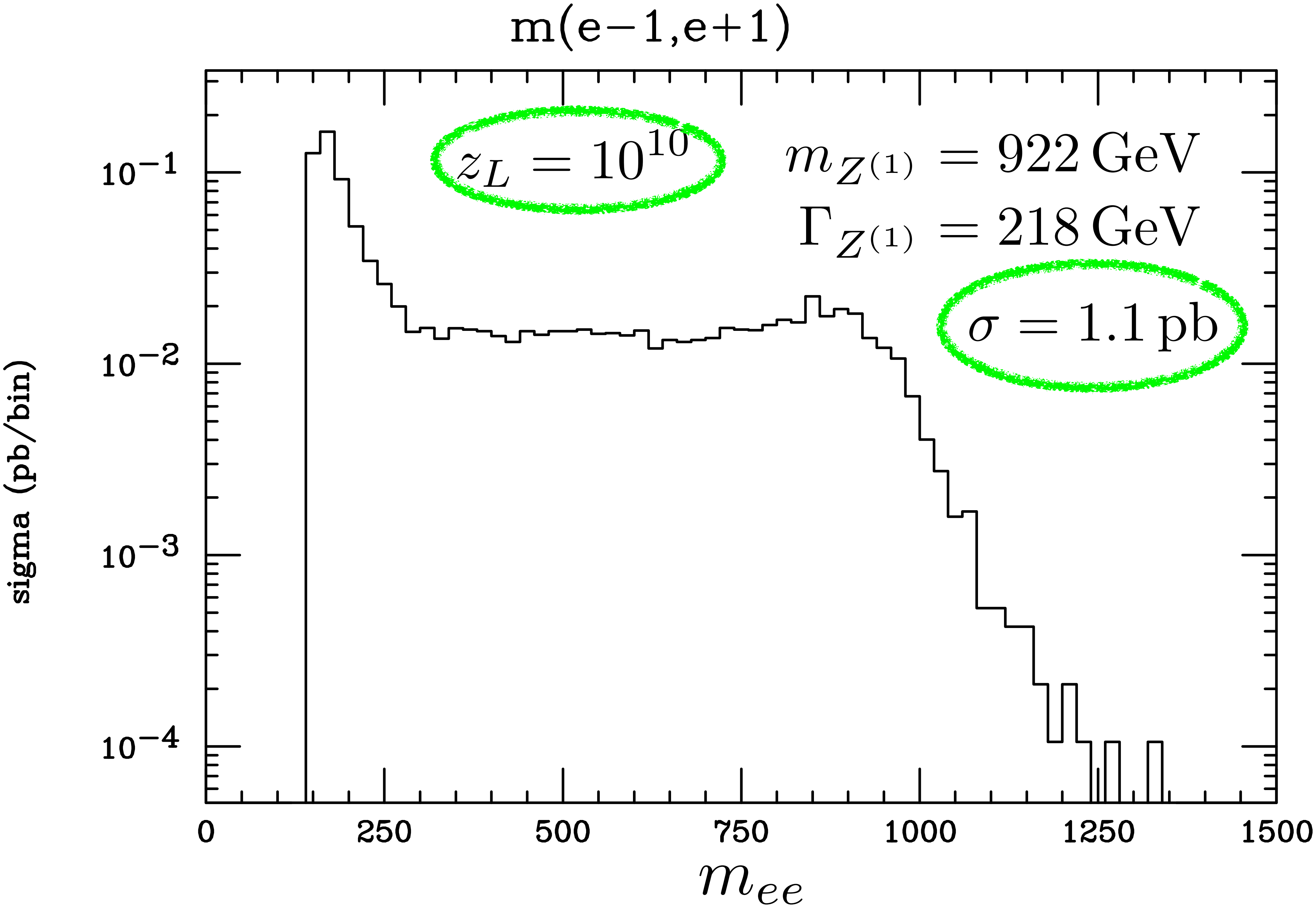
Background: $p\bar{p} \to e^- e^+ X$



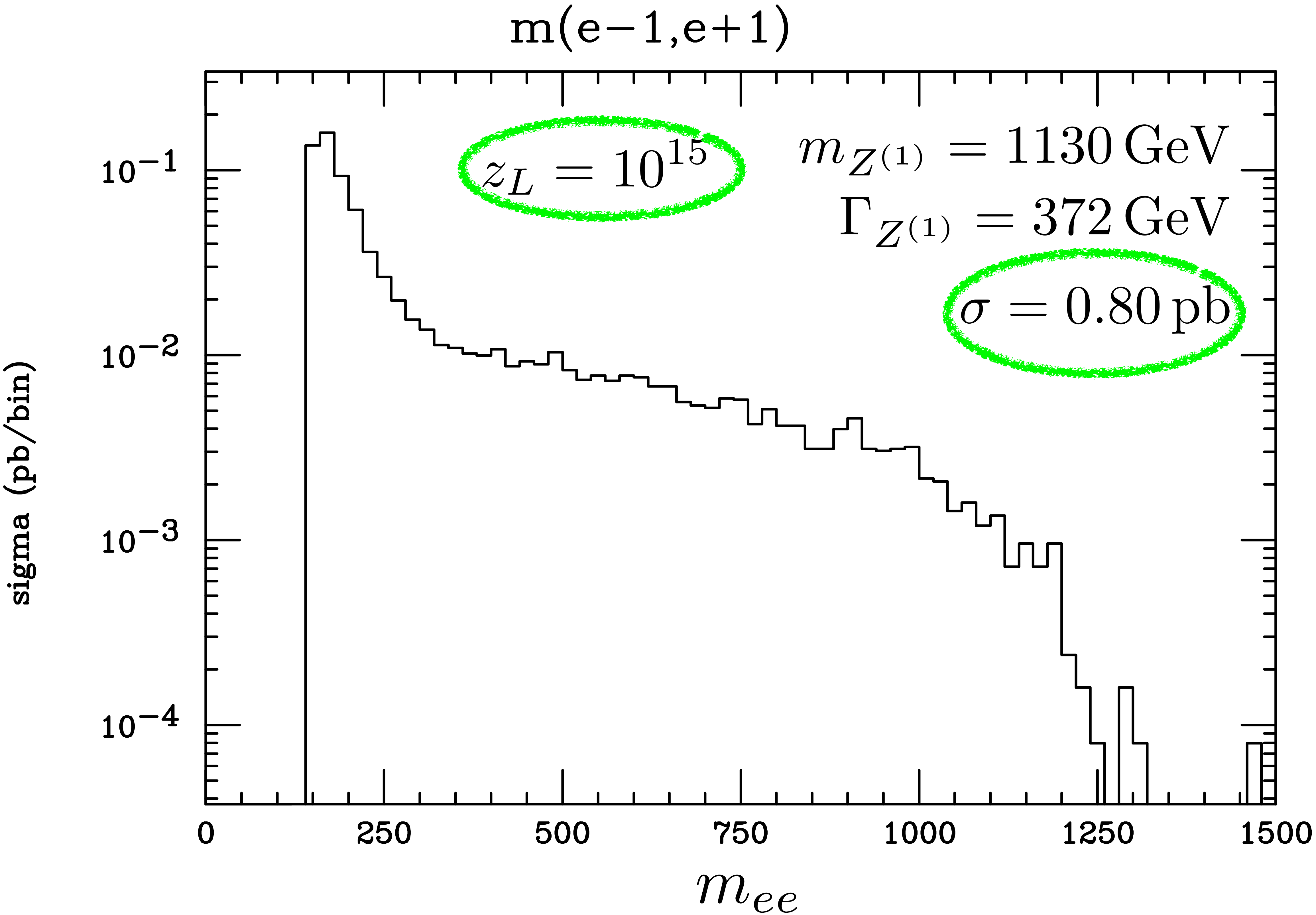
$$p\bar{p} \to Z^{(1)} X \to e^- e^+ X$$



$$p\bar{p} \to Z^{(1)} X \to e^- e^+ X$$



$$p\bar{p} \to Z^{(1)}X \to e^- e^+ X$$



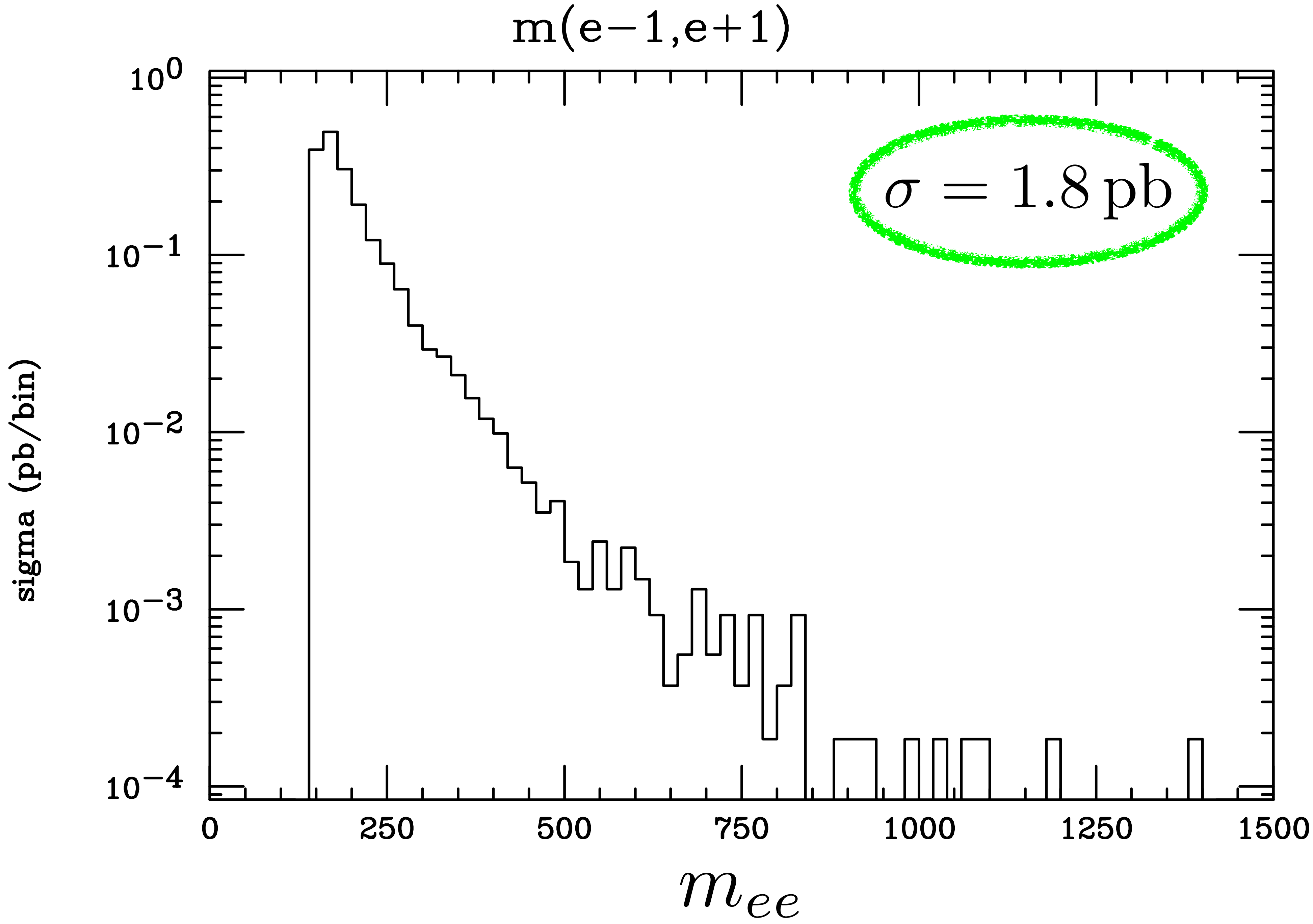
Significance at Tevatron $L = 2.5\,\mathrm{fb}^{-1}$

z_L	10^5	10^{10}	10^{15}
$\mathcal{S}$	121	22	4

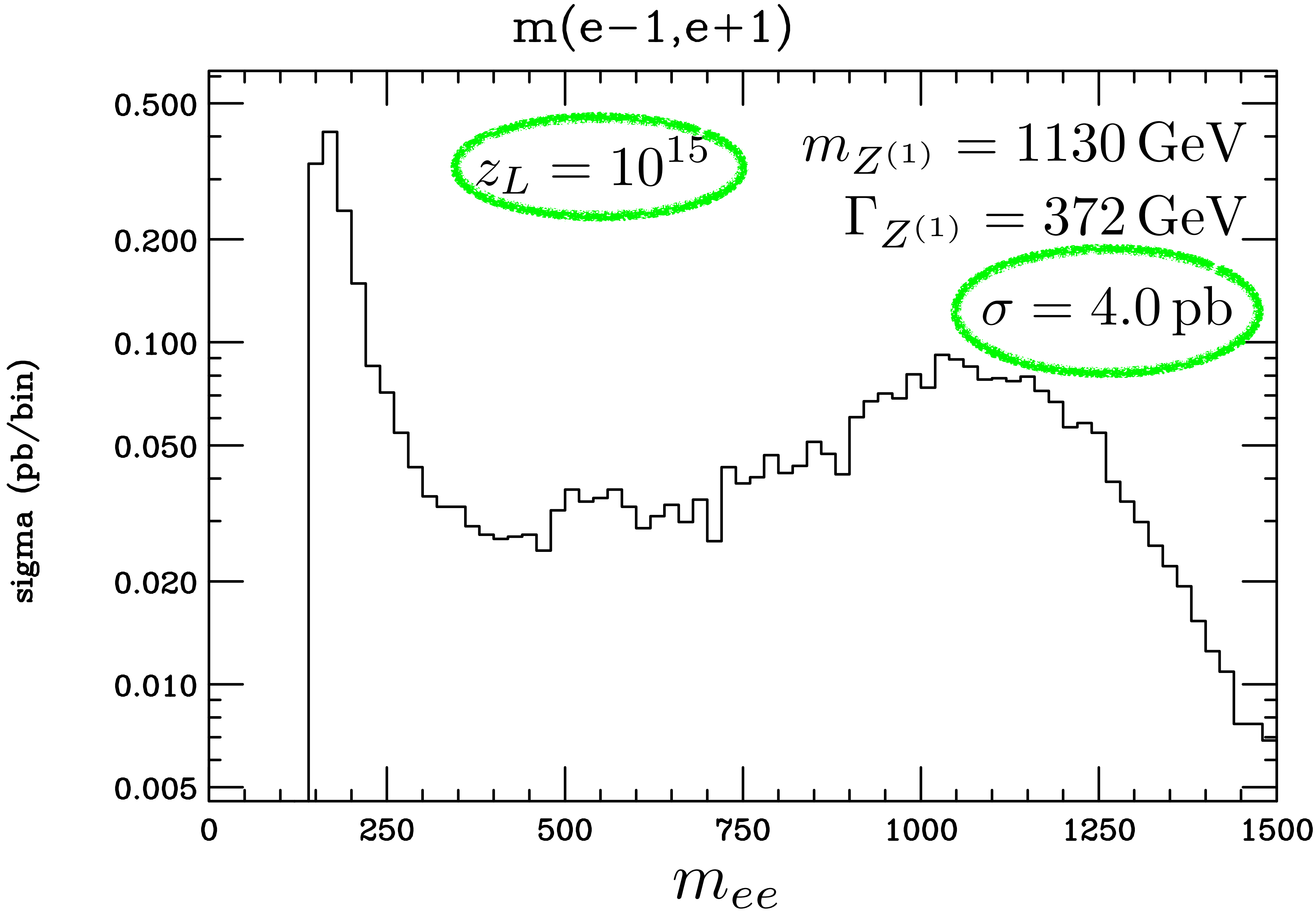
disfavored (121, 22)

KK Z at LHC: $pp \to Z^{(1)} X \to e^- e^+ X$

Background: $pp \to e^- e^+ X$



$$pp \to Z^{(1)} X \to e^- e^+ X$$



Significance at LHC $\sqrt{s} = 7\,\mathrm{TeV}$

$$\mathcal{S} = 5.1\sqrt{\frac{L}{10\,\mathrm{pb}^{-1}}}$$

Summary

- Stable Higgs in gauge-Higgs unifiction is a viable candidate of dark matter.

  Dark Higgs scenario

- $m_H \sim 70\,\mathrm{GeV}$ is predicted.

- Direct detection is likely.

  Exp. limits depend on the local DM density, ρ_0 .

  $\rho_0 \simeq 0.04 \sim 0.6\,\mathrm{GeV/cm^3}$

- We need a few ab^{-1} or more.

  both for LHC and LC.

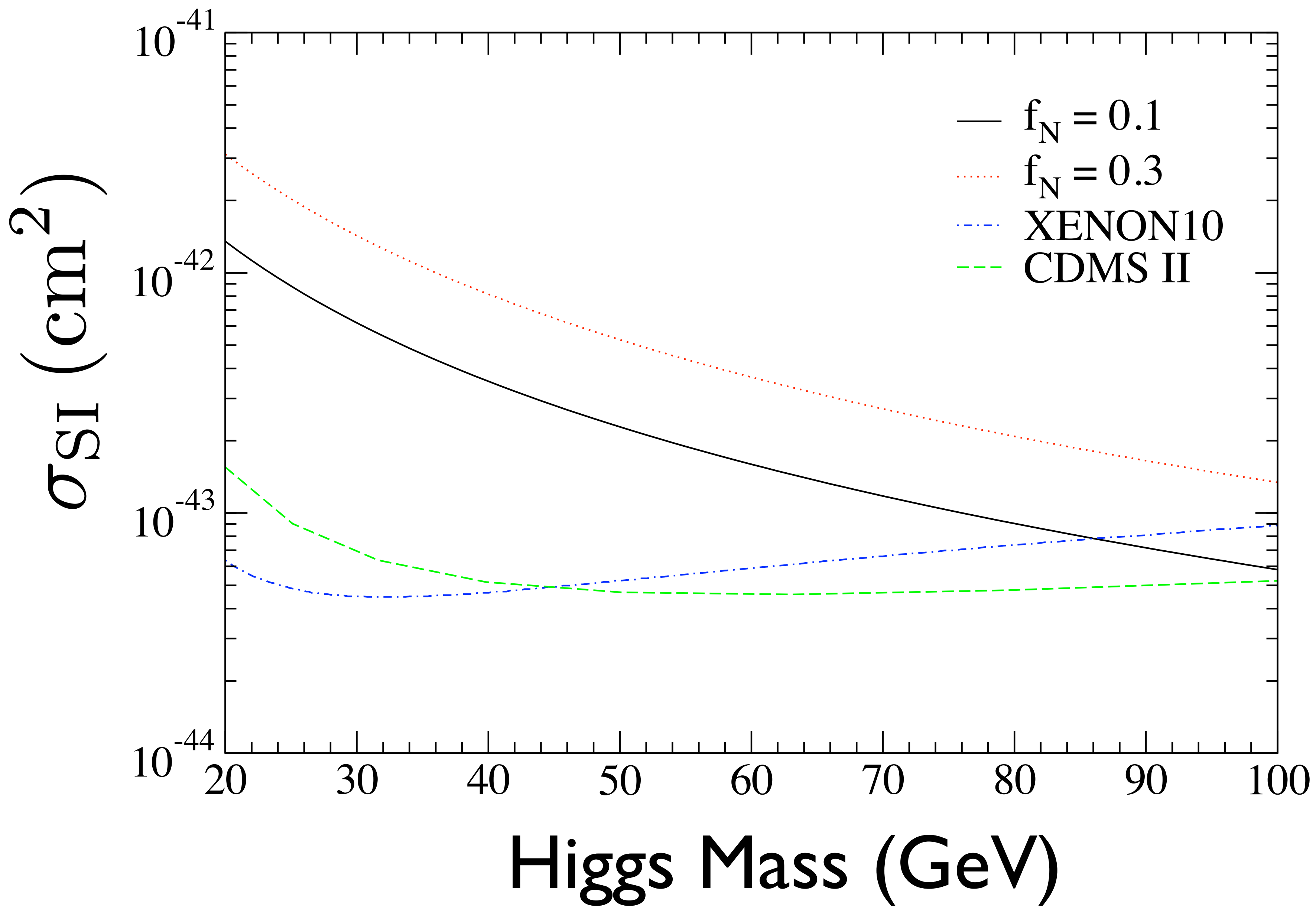
- The first KK Z production at Tevatron suggests a larger warp factor. $z_L \sim 10^{15}$
- Dark Higgs seems difficult at the present model.

  $m_H = 135\,\mathrm{GeV}$ for $z_L = 10^{15}$
- The first KK Z production may be discovered at LHC with $10\,\mathrm{pb}^{-1}$ even for $z_L = 10^{15}$.

Thank you.

Backup Slides

Spin-Independent Cross Section



Local DM density

$$\rho_0 = 0.3\,\mathrm{GeV/cm^3}$$

assumed in exps.

For $m_H = 70\,\mathrm{GeV}$

Prediction: $\sigma_{\rm SI} \simeq (1.2 - 2.7) \times 10^{-43}\,\mathrm{cm}^2$

Exp. bound: $\sigma_{\rm SI} \lesssim 3.8 \times 10^{-44}\,\mathrm{cm}^2$

Uncertainties in the direct detection

Local density of CDM (not measured)

$\rho_0 = 0.3\,\mathrm{GeV/cm^3}$

assumed in the experiments.

$\rho_0 = 0.2 \sim 0.6\,\mathrm{GeV/cm^3}$

reasonable for smooth halo.

$\rho_0 \sim 0.04\,\mathrm{GeV/cm^3}$ (Kamionkowski and Koushiappas)

possible for non-smooth halo.

Effective Higgs coupling $HH\bar{f}f$

may be altered in more general models.

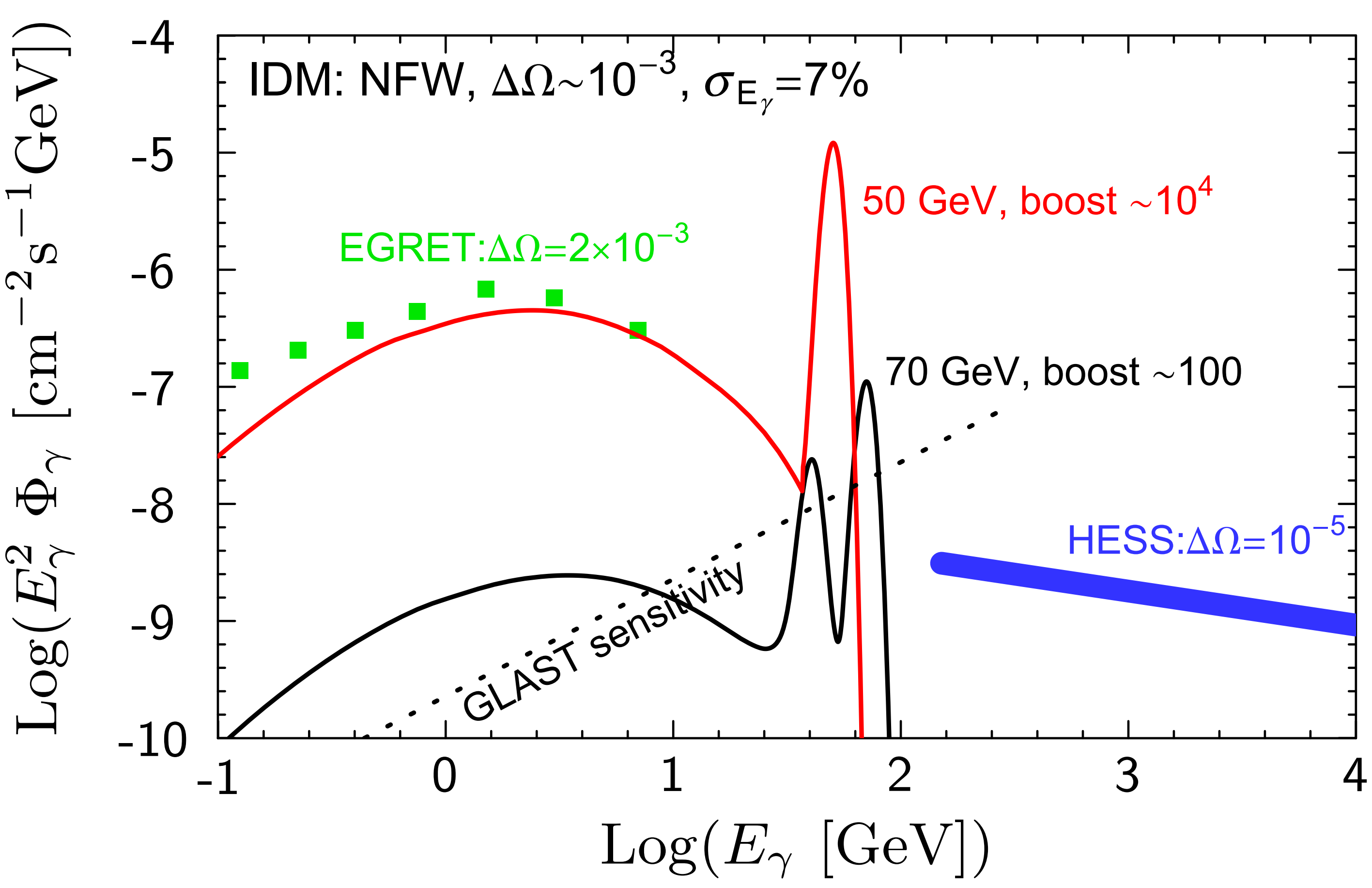
Astrophysical Signals

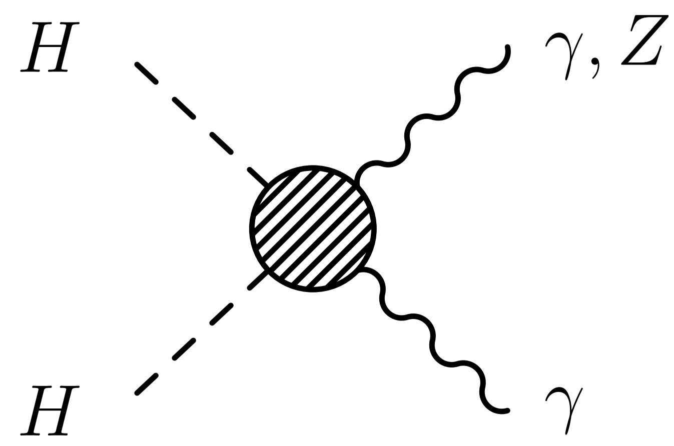
$HH \to \gamma\gamma,\ \gamma Z$ in the Galactic halo.

Two (nearly) monochromatic gamma lines.

$$E_\gamma = m_H (\simeq 70\mathrm{GeV})\,, m_H - m_Z^2/(4m_H)(\simeq 40\mathrm{GeV})$$

$$\sigma_{\gamma\gamma(\gamma Z)}\, v|_{v\to 0} \simeq 4.3(5.4) \times 10^{-29}\mathrm{cm}^3/\mathrm{s}$$





cf. Inert Doublet Model

Gustafsson et al.

Stable Higgs as Dark Matter (Dark Higgs scenario)

謎の2粒子 正体は同じ!?

「暗黒物質はヒッグス」

阪大教授 新理論

宇宙構成の定説覆す可能性

ノーベル賞学者、南部陽一郎博士の理論から存在が予測された粒子「ヒッグス」が、宇宙を満たす謎の物質「ダークマター（暗黒物質）」と同じものであるという新理論を、大阪大の細谷裕教授がまとめた。この〝2粒子〟は素粒子物理の最重要テーマで、世界中で発見が競われている。ダークマターは安定で壊れないが、ヒッグスは素粒子の基本法則「標準理論」ではすぐに壊れるとされ、新理論は従来の宇宙の成り立ちを説明する定説を覆すもの。証明されれば宇宙は5次元以上あることになり、人工ブラックホールの創出も可能になるかもしれない。

南部博士が1960年に提唱し、授賞理由になった「対称性の自発的破れ」を基にヒッグスが提唱されたが未発見。宇宙誕生直後にでき、他粒子はヒッグスに衝突して動きにくくなり質量を持つとされる。一方、宇宙は光を出さず安定なダークマターで満ちていると予想されている。

細谷教授は、宇宙が時間と3次元空間の4次元ではなく、5次元以上であると考え、様々な粒子が力を及ぼしあう理論を考えた。その結果「ヒッグスは崩壊せず、電荷を持たない安定した存在」となった。

欧州にある世界最大の加速器（LHC）では最大の課題としてヒッグスの検出実験が行われる。標準理論では「観測可能」だが、細谷理論では観測不能。新たな実験手法で検証が可能になるという。一方、ダークマターも09年末、発見の可能性が報告されたが、細谷理論と矛盾しないという。

細谷教授は09年秋、来日した南部博士に新理論を説明。南部博士は「今まで誰も気づかなかったヒッグス粒子に対する見方は十分あり得る」と評価したという。

小林富雄・東京大教授（素粒子実験）の話「美しく素晴らしいアイデア。数年で新理論を検証できる可能性もある」

標準理論 物質の成り立ちや力の働き方を説明する素粒子理論。宇宙の四つの力のうち重力を除いた電磁気力と弱い力、強い力を説明する。南部博士の理論などが基礎になっている。

Yomiuri newspaper,
the front page
on Jan. 5, 2010.

Table 3: The couplings of Z boson with left-handed quarks, $g_{fL}^{(Z)}\sqrt{L}/g_A$.

z_L	u	c	t	d	s	b
10^{15}	0.348452	0.348132	0.32172	−0.425887	−0.425887	−0.42639
10^{10}	0.349467	0.349467	0.307934	−0.427336	−0.427336	−0.428457
10^{5}	0.352916	0.352914	0.253315	−0.431553	−0.431553	−0.435986

Table 4: The couplings of Z boson with right-handed quarks, $g_{fR}^{(Z)}\sqrt{L}/g_A$.

z_L	u	c	t	d	s	b
10^{15}	−0.15643	−0.156388	−0.183737	0.0782151	0.0781938	0.0781582
10^{10}	−0.15765	−0.157568	−0.200882	0.0788248	0.0787836	0.0786987
10^{5}	−0.161498	−0.161279	−0.268141	0.0807492	0.0806393	0.0802678

Table 6: The couplings of Z bosons with charged leptons, $g_{fI}^{(Z)}\sqrt{L}/g_A$.

z_L	eL	μL	τL	eR	μR	τR
10^{15}	−0.270677	−0.270677	−0.270674	0.234664	0.234605	0.234569
10^{10}	−0.271598	−0.271598	−0.271594	0.236509	0.236398	0.236324
10^{5}	−0.274278	−0.274278	−0.274267	0.242328	0.242053	0.24183

Table 5: The couplings of W boson with leptons, $g_{fL}^{(W)}\sqrt{L}/g_A$ and the couplings of Z boson with neutrinos, $g_{fL}^{(Z)}\sqrt{L}/g_A$.

z_L	$e\nu_e$	$\mu\nu_\mu$	$\tau\nu_\tau$	ν_e	ν_μ	ν_τ
10^{15}	1.00533	1.00533	1.00533	0.503492	0.503492	0.503492
10^{10}	1.00792	1.00792	1.00792	0.505205	0.505205	0.505206
10^{5}	1.01535	1.01535	1.01534	0.51019	0.51019	0.510191