Smoking-Gun Signatures for Little Higgs Models at Hadron Colliders

Tao Han *
Univ. of Wisconsin–Madison/Fermilab
(Fermilab, Dec. 17, 2004)

*Collaborators: Heather Logan, Bob McElrath, Liantao Wang.

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Introduction and Motivation
Structure of Little Higgs Models
LH Phenomenology at Colliders
- really LH?
- which LH?

Conclusions

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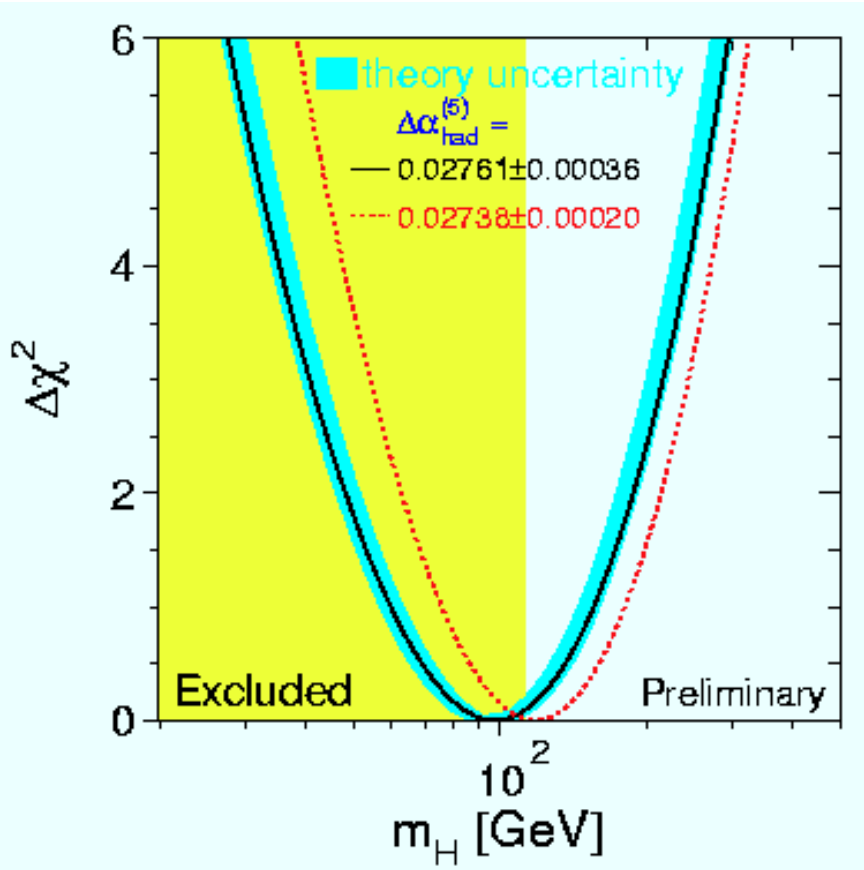
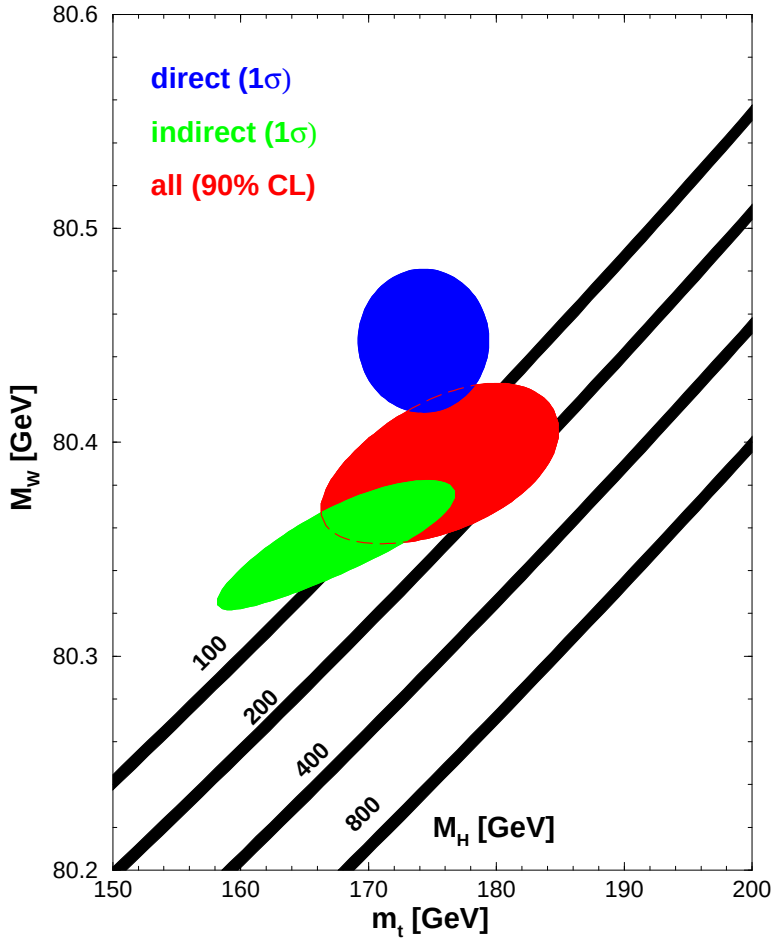
Introduction and Motivation

Precision EW data: SM with a light Higgs ?





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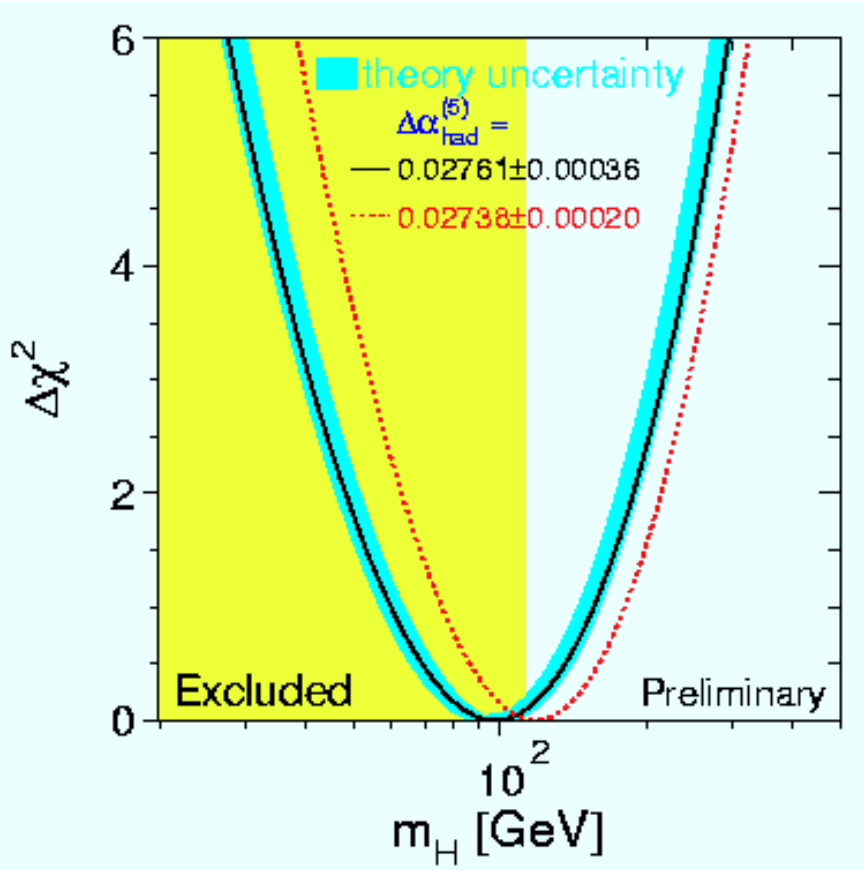
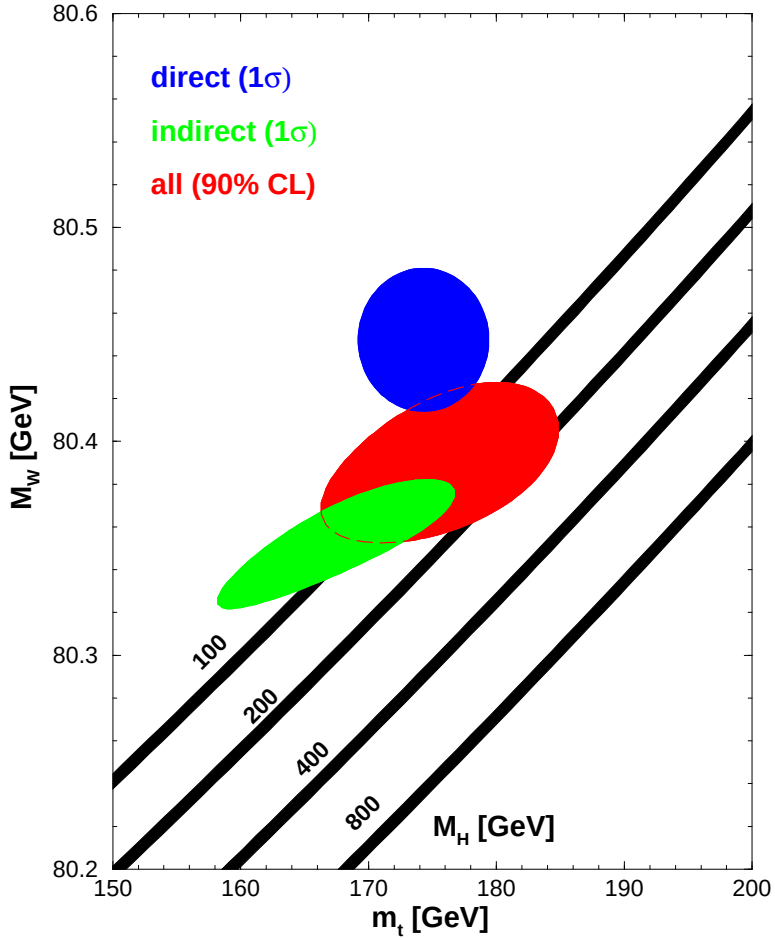




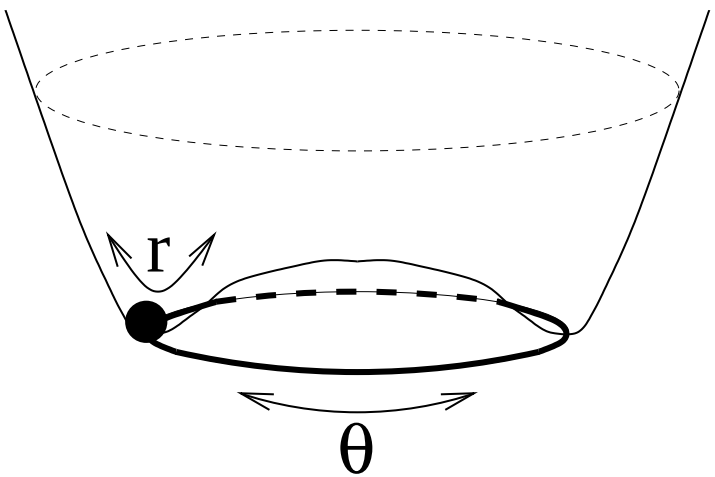
EW precision data: $m_H < 204$ GeV at 95% CL;* New fit: $m_H < 251$ GeV.

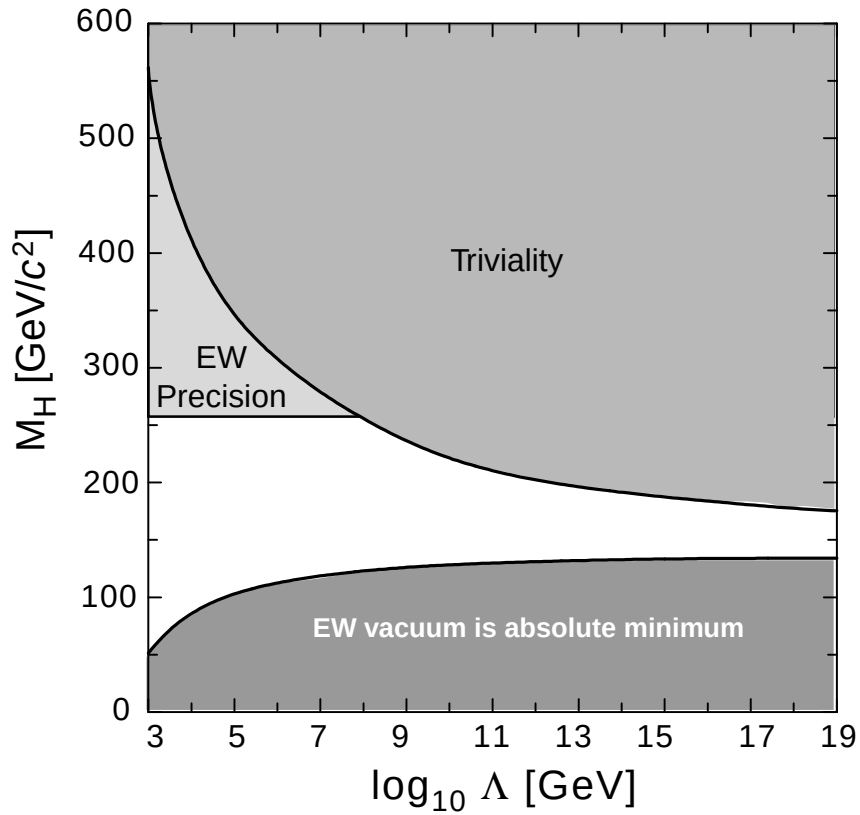
*LEP-EW; Hagiwara et al., PDG, 2002; J.Erler hep-ph/0212272.

SM as an effective theory ?

$$V = -\mu^2\Phi^2 + \lambda\Phi^4, \quad <\Phi>= \frac{v}{\sqrt{2}} = \sqrt{\frac{\mu^2}{2\lambda}}, \quad v^{-2} = \sqrt{2}\, G_F$$

$$m_H = \sqrt{2\lambda}\; v$$





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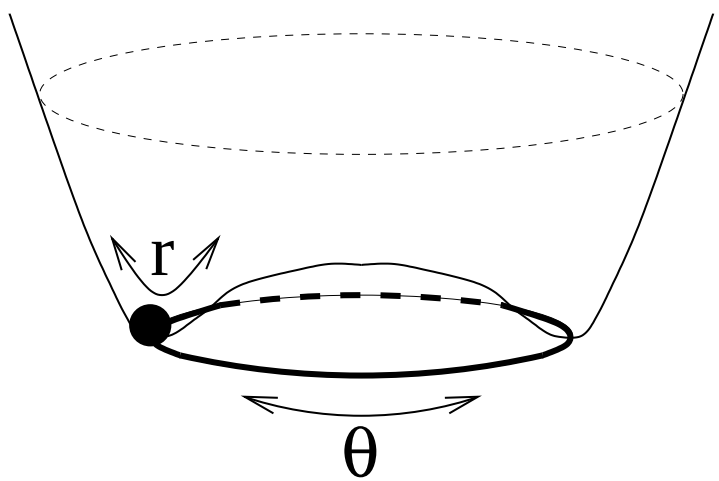
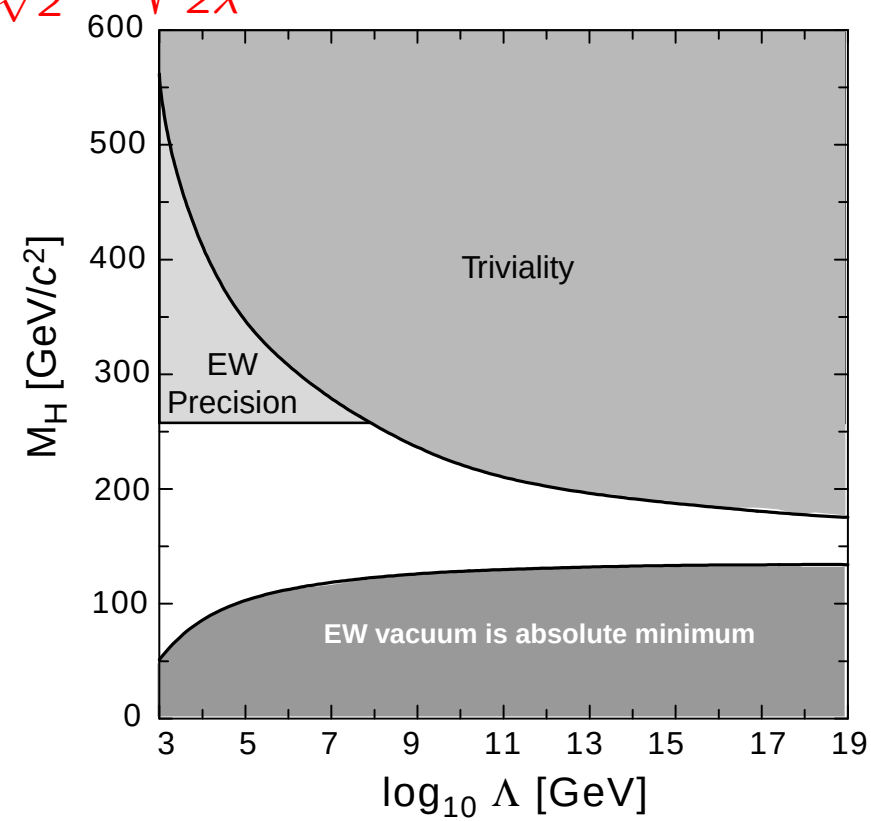




SM with a light H could be an effective theory to $\Lambda \sim M_{pl}$.*

a stable vacuum;

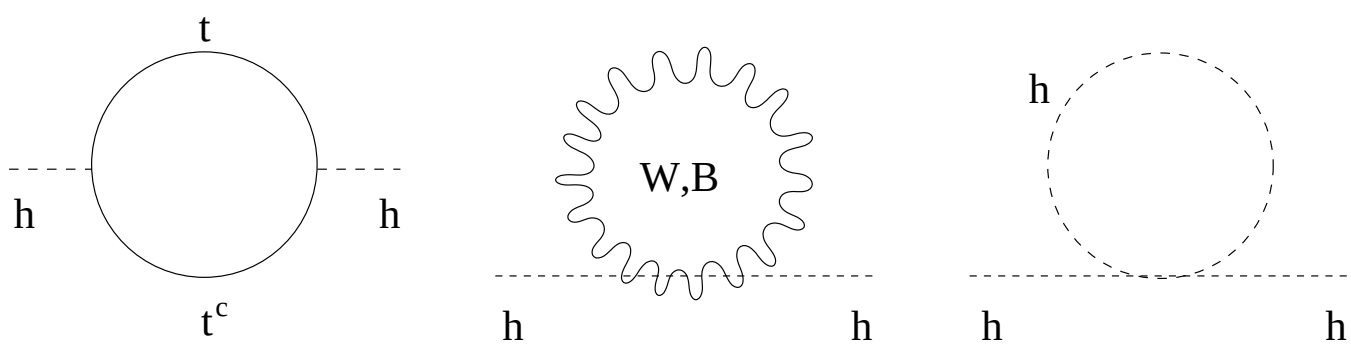
non-trivial interactions;

renormalizability ...

*figure from C. Quigg.

Unnatural ?

Due to quantum corrections, the Higgs mass is quadratically sensitive to the cutoff scale: $\sim \Lambda^2$.



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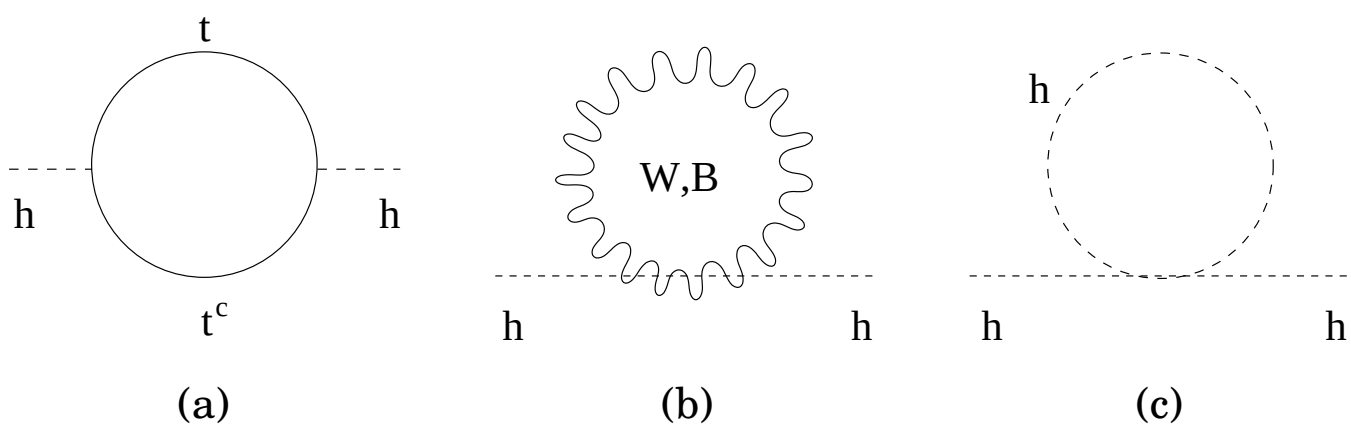

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$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

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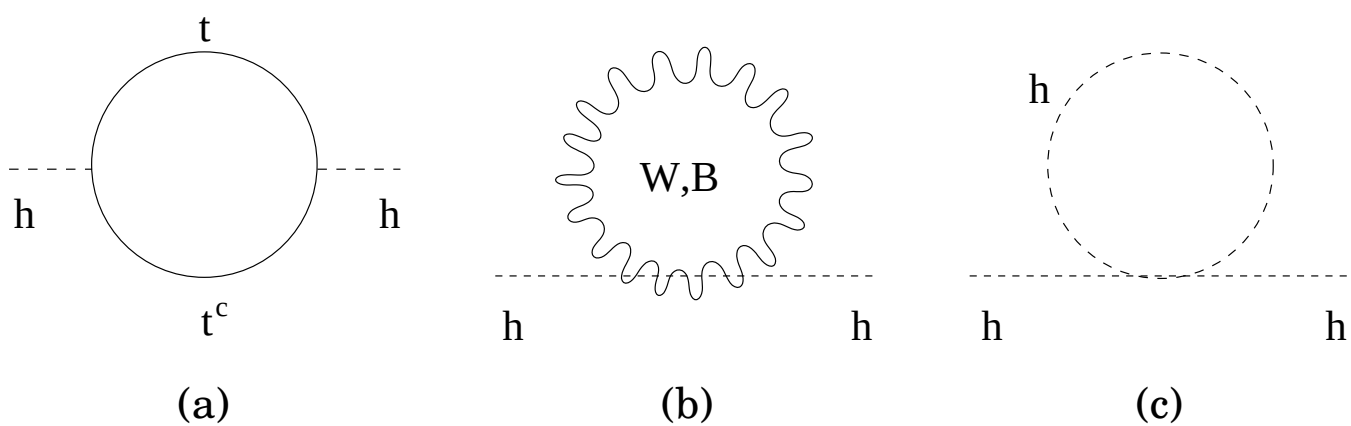

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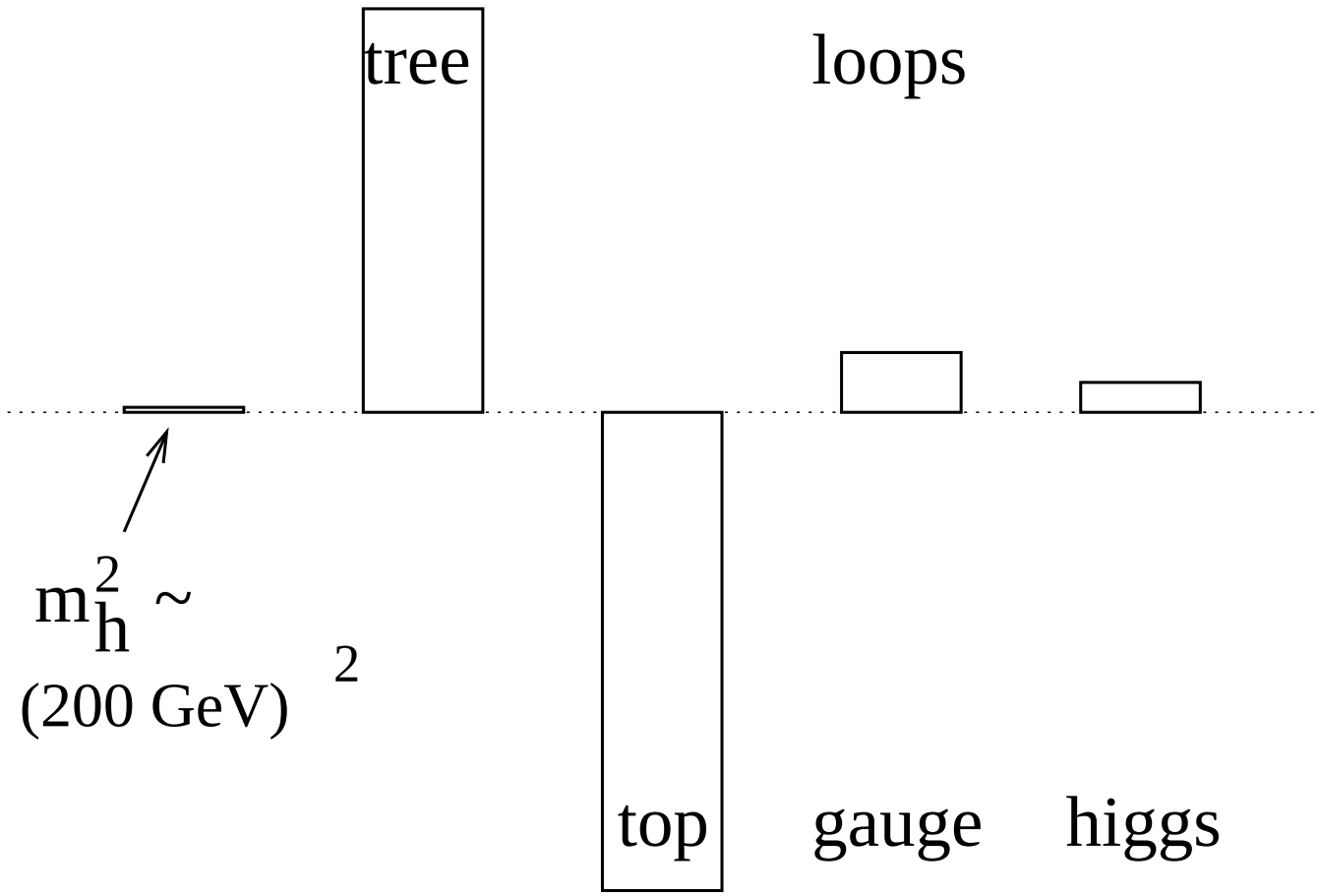
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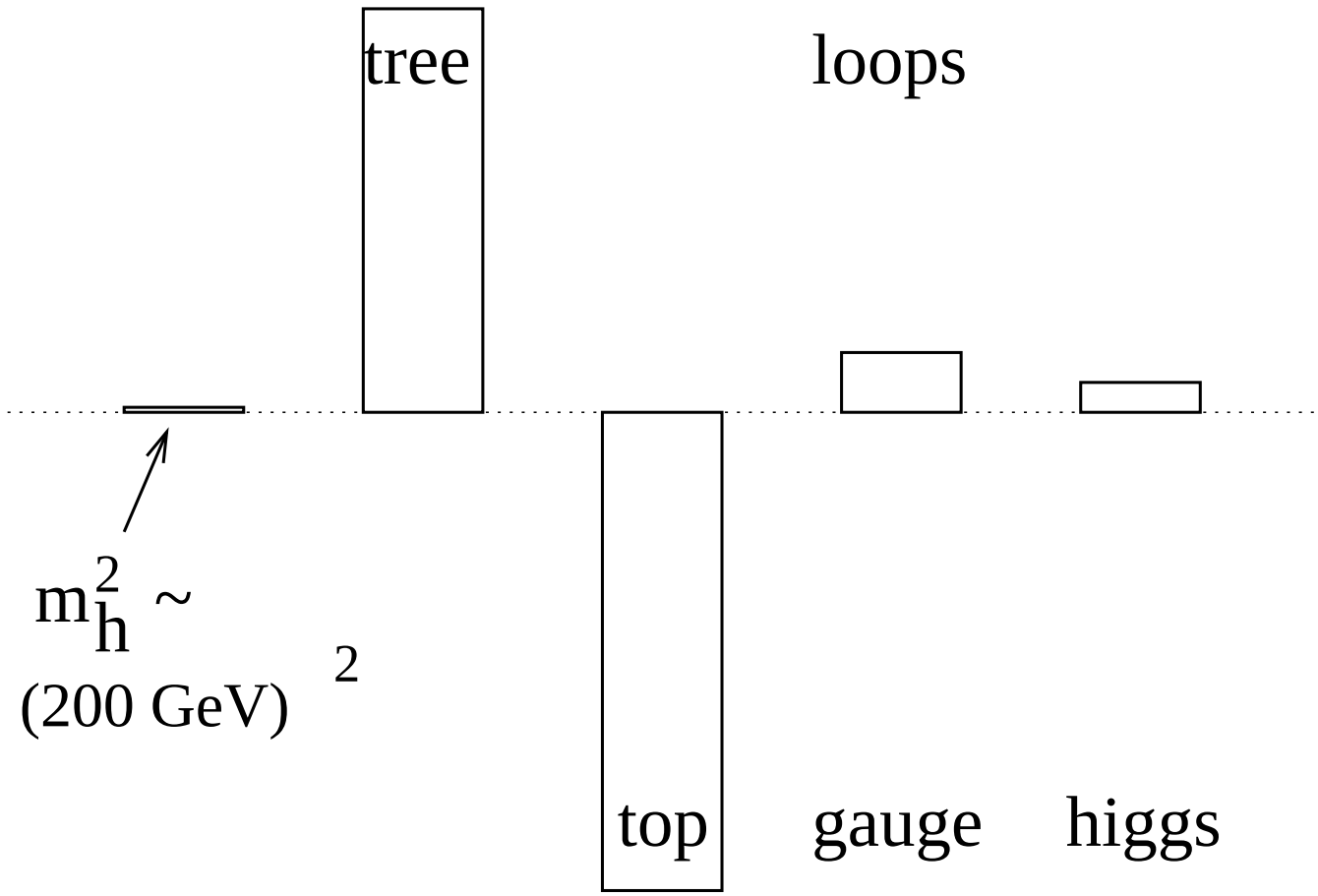

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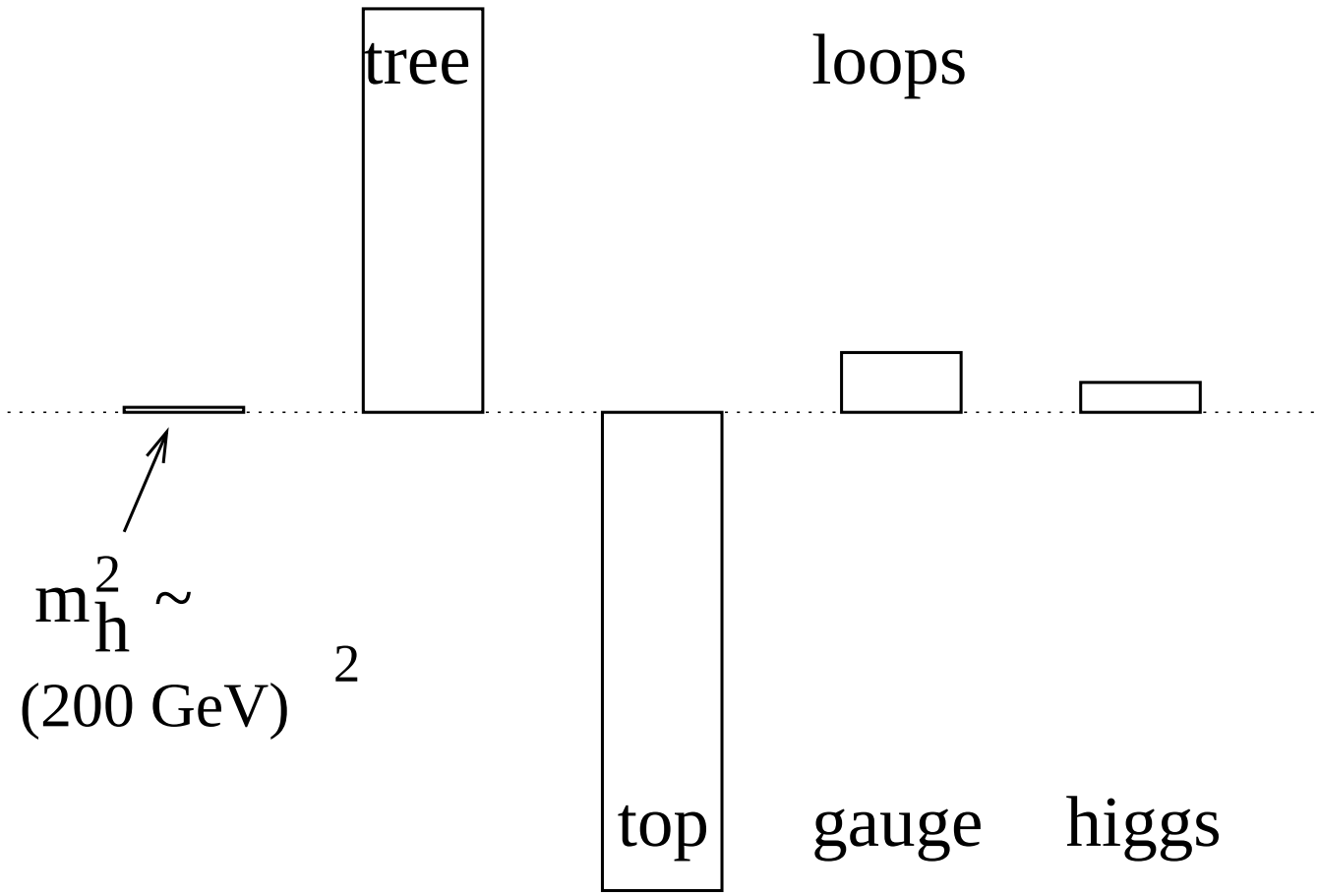

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Naturalness requirement: less than 90% cancellation on m_H^2

$$\Lambda_t \lesssim 3\ \mathrm{TeV} \quad \Lambda_W \lesssim 9\ \mathrm{TeV} \quad \Lambda_H \lesssim 12\ \mathrm{TeV}$$

Cancellation Mechanisms ?

- Veltman Point: non-correction to m_H (at one-loop)*

Let $$2M_W^2 + M_Z^2 + m_H^2 - \frac{4}{3}\sum_f N_C^f m_f^2 = 0$$

$\Rightarrow$ $m_H \simeq 320$ GeV. (accidental?)

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$\tilde{W}$ versus W

$\tilde{H}$ versus H

H_d versus H_u,

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lead to

$$\Delta m_H^2 \sim (M_{SUSY}^2 - M_{SM}^2)\frac{\lambda_f^2}{16\pi^2}\ln\left(\frac{\Lambda}{M_{SUSY}}\right)$$

Weak scale SUSY is natural if $M_{SUSY} \sim \mathcal{O}(1)$ TeV.

$\Rightarrow$ predict TeV scale new physics.

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The Little Higgs idea

- Higgs is a pseudo-Goldstone boson from global symmetry breaking (at scale $4\pi f$)[‡]
- Higgs acquires a mass radiatively at the EW scale v, by collective explicit breaking

[‡] Dimopoulos, Preskill, 1982; H.Georgi, D.B.Kaplan, 1984; T. Banks, 1984.

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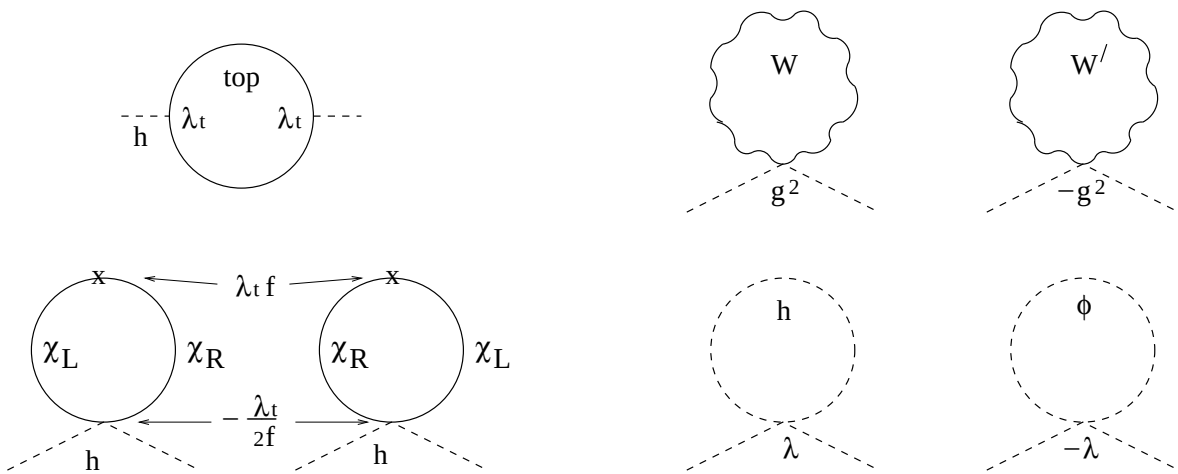
- Higgs acquires a mass radiatively at the EW scale v, by collective explicit breaking

- Consequently, quadratic divergences absent at one-loop level[*]

$$W, Z, B \leftrightarrow W_H, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$$

(cancellation among same spin states!)



An alternative way to keep H light (naturally)

[‡]Dimopoulos, Preskill, 1982; H.Georgi, D.B.Kaplan, 1984; T. Banks, 1984.

[*]Arkani-Hamed, Cohen, Georgi, hep-ph/0105239.

Model Construction

- Start from a Non-linear σ-model:

  a global symmetry G, a gauge symmetry $G^0 \subset G$.

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Naturalness requirement

If no large fine-tuning,

$$f \simeq \mathcal{O}(4\pi m_h) \simeq \text{ a few TeV} \left(\frac{m_h}{200 \text{ GeV}}\right).$$

Little Higgs Models

- Arkani-Hamed, Cohen, Georgi (The Moose in theory space) [hep-ph/0105239]

- Arkani-Hamed, Cohen, Katz, Nelson, Gregoire, Wacker (Minimal Moose) [hep-ph/0206020]

  Low energy theory: a 2HDM + complex scalar weak triplet + singlet

- Arkani-Hamed, Cohen, Katz, Nelson, "The Littlest Higgs Model" [hep-ph/0206021]

  $[SU(2) \times U(1)]^2$ gauged non-linear σ-model
  Low energy theory: doubled gauge and top-quark sector

- Low, Skiba, Smith (Antisymmetric Condensate) [hep-ph/0207243]

  $SU(6)/Sp(6)$ group structure Low energy theory: a 2HDM

- Kaplan, Schmaltz (a Simple Group model) [hep-ph/0302049]

  $SU(3)$ group structure; 2HDM; No new gauge parameters, many extra gauge bosons, more natural top cancellation

- S. Chang and J. Wacker (Little Higgs and Custodial $SU(2)$) [hep-ph/0303001]

  $SU(5)$ group structure; a 2HDM; more natural top cancellation

- H.-C. Cheng and I. Low [hep-ph/0308199]
  (TeV symmetry and the little hierarchy problem:
  introducing T-parity)

- E. Katz, J. Lee, A. Nelson, D. Walker [hep-ph/0312287]
  (A Composite Little Higgs Model
  with supersymmetric UV completion)

- ... ...

Before moving on to details ...

The Little Higgs models

- offer no more insight on flavor physics,
  but must respect stringent constraints from FCNC etc.[†]

$$\Lambda \gtrsim 75 \text{ TeV}.$$

$\Rightarrow$ Leave it to ultra-violet (UV) completion.

[†] R.K. Chivukula, N. Evans, E.H. Simmons, hep-ph/0204193.

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- are motivated by the "naturalness" argument.
  If adopting the "anthropic principle", then the motivation lost ...
  See a recent example for "fine-tuned" or "split SUSY"[‡]

[†] R.K. Chivukula, N. Evans, E.H. Simmons, hep-ph/0204193.

[‡] Arkani-Hamed, Dimopoulos, hep-th/0405159; Giudice, Romanino, hep-ph/0406088.

Example I: The Littlest Higgs Model*

A Non-linear σ-model with $G = SU(5)$:

$$\mathcal{L}_\Sigma = \frac{1}{2}\frac{f^2}{4}\mathrm{Tr}|\mathcal{D}_\mu \Sigma|^2, \qquad \Sigma = e^{2i\Pi/f}\Sigma_0,$$

where f is the condensate scale (the Goldstone-boson decay constant);
Σ, Σ_0, Π are 5×5 matrices.

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A subgroup is gauged:

$$G^0 = G_1 \otimes G_2 = [SU(2) \otimes U(1)]_1 \otimes [SU(2) \otimes U(1)]_2$$

with the co-variant derivative

$$\mathcal{D}_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^{2} \left[g_j W_j^a (Q_j^a \Sigma + \Sigma Q_j^{a\,\mathsf{T}}) + g'_j B_j (Y_j \Sigma + \Sigma Y_j^{\mathsf{T}}) \right]$$

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The Goldstone bosons:

The spontaneous symmetry breaking by

$$\langle \Sigma \rangle = \Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix}$$

Global: $SU(5) \Rightarrow SO(5)$, leading to 14 Goldstone bosons;

Gauged: $[SU(2) \otimes U(1)]_1 \otimes [SU(2) \otimes U(1)]_2 \Rightarrow SU(2)_L \otimes U(1)_Y$

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The fate of the Goldstone bosons

$1_0 \oplus 3_0$	4 Longitudinal modes of $Z_H, W_H^{\pm}, A_H$
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The h, ϕ are parameterized by

$$\Pi = \begin{pmatrix} 0 & h^\dagger/\sqrt{2} & \phi^\dagger \\ h/\sqrt{2} & 0 & h^\star/\sqrt{2} \\ \phi & h^{\mathsf{T}}/\sqrt{2} & 0 \end{pmatrix}, \quad h = (h^+,\ h^0), \quad \phi = \begin{pmatrix} \phi^{++} & \phi^+/\sqrt{2} \\ \phi^+/\sqrt{2} & \phi^0 \end{pmatrix}$$

Gauge Cancellation

Coupling of gauge bosons to Higgs is:

$$\begin{aligned}\mathcal{L}_\Sigma(W\cdot W) &= \frac{g^2}{4}\left[W^a_\mu W^{b\mu} - \frac{(c^2-s^2)}{sc}W^a_\mu W'^{b\mu}\right]\mathrm{Tr}\left[h^\dagger h\delta^{ab}\right] \\ &- \frac{g^2}{4}\left[W'^a_\mu W'^{a\mu}\right]\mathrm{Tr}\left[h^\dagger h\right]\end{aligned}$$

$$\begin{aligned}\mathcal{L}_\Sigma(B\cdot B) &= \frac{g'^2}{4}\left[B_\mu B^\mu - \frac{(c'^2-s'^2)}{s'c'}B_\mu B'^\mu\right]\mathrm{Tr}\left[h^\dagger h\right] \\ &- \frac{g'^2}{4}\left[B'_\mu B'^\mu\right]\mathrm{Tr}\left[h^\dagger h\right]\end{aligned}$$

The global symmetry ensures the new gauge bosons couple with $-g_i^2$!

New heavy quark and the $t - T$ Cancellation

Introduce a vector-like pair of colored fermions*

$$\tilde{t}: \ (3_c, 1_L)_{Y_i} \quad \text{and} \quad \tilde{t}'^c: \ (3_c, 1_L)_{-Y_i}.$$

The Lagrangian is:

$$\mathcal{L}_Y = \frac{1}{2}\lambda_1 f \epsilon_{ijk}\epsilon_{xy}\chi_i \Sigma_{jx}\Sigma_{ky} u_3'^c + \lambda_2 f \tilde{t}\tilde{t}'^c + \text{h.c.}$$

where $\chi_i = (b_3, t_3, \tilde{t})$, i, j, k run over 1...3, and x, y run over 4...5.

*B.A. Dobrescu, C.T. Hill. Phys.Rev.Lett.81,2634 (1998).

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- Due to the $SU(3)_1$ flavor symmetry, the λ_1 term guarantees the cancellation for the quadratic divergence:

$$-i\lambda_1(\sqrt{2}h^0 t_3 + if\tilde{t} - ih^0 h^{0*}\tilde{t}/f) \ u_3'^c + \text{h.c.}$$

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- The λ_2 term gives the mixing and the top-quark mass

$$m_t = \frac{\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}} \ v; \quad M_T = \sqrt{\lambda_1^2+\lambda_2^2} \ f, \qquad (x_\lambda = \lambda_1/\lambda_2).$$

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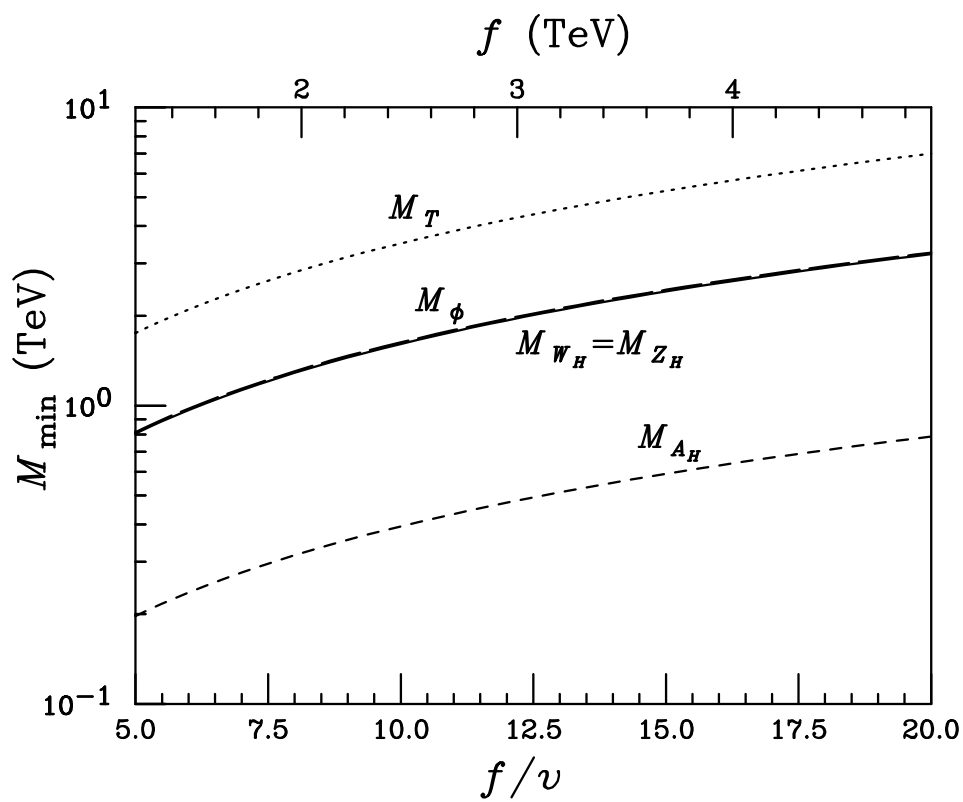
Independent model parameters

$\tan\theta = \frac{s}{c} = \frac{g_2}{g_1}$	New $SU(2)$ gauge coupling (or equivalently mixing angle θ)
$\tan\theta' = \frac{s'}{c'} = \frac{g_2'}{g_1'}$	New $U(1)$ gauge coupling (or equivalently mixing angle θ')
f	Symmetry breaking scale $\mathcal{O}$ (TeV)
v'	Triplet ϕ vacuum expectation value, $v'/v \lesssim v/4f$
m_H	Regular SM Higgs mass
M_T	Heavy vector top mass, we trade λ_2 for M_T

New heavy masses in LH:

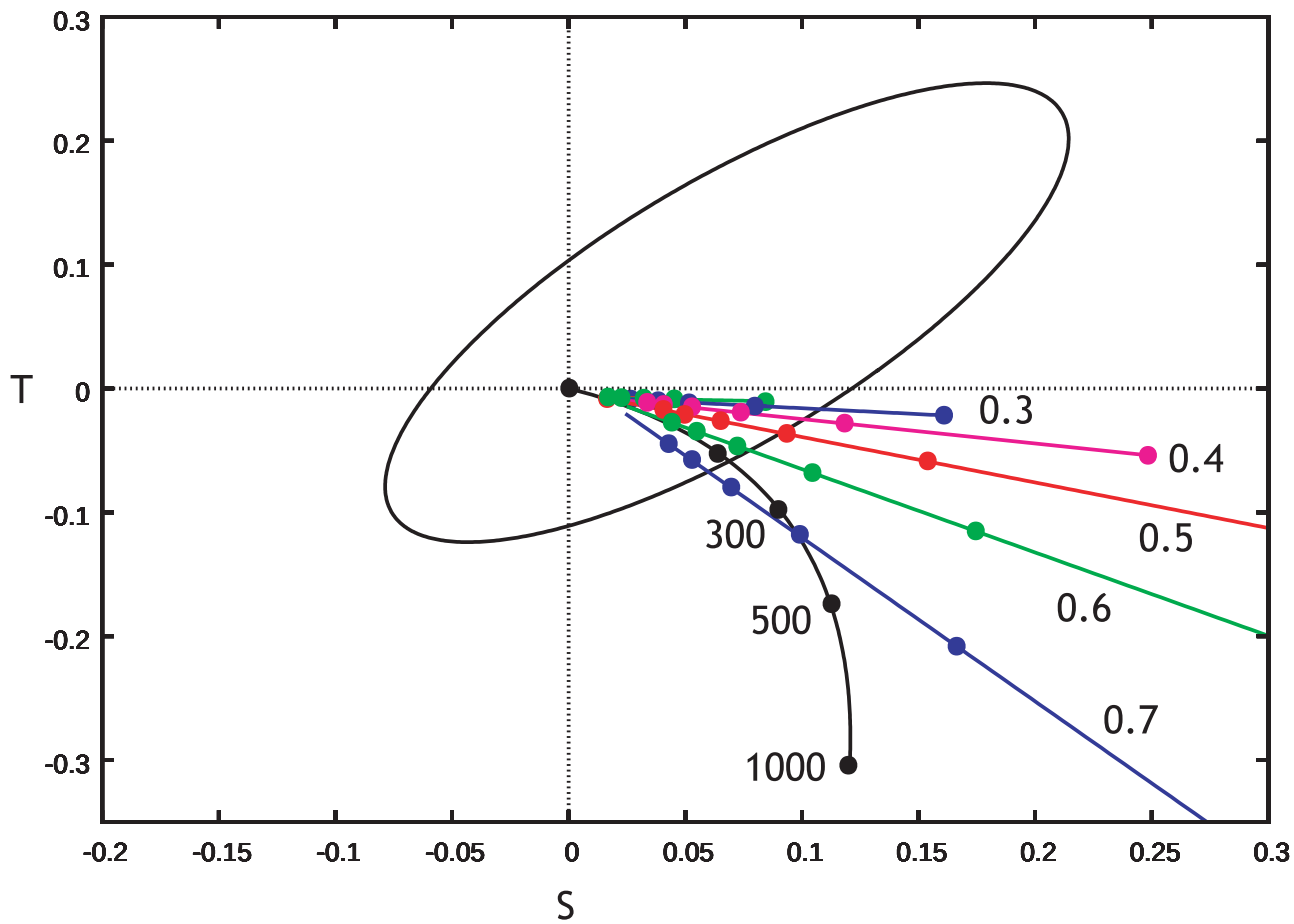
Heavy particles	Mass
A_H	$m_z^2 s_{\mathrm{W}}^2 \frac{f^2}{5 s'^2 c'^2 v^2}$
Z_H	$m_{\mathrm{W}}^2 \frac{f^2}{s^2 c^2 v^2}$
W_H	$m_{\mathrm{W}}^2 \frac{f^2}{s^2 c^2 v^2}$
$\phi^0, \pm, \pm\pm$	$\frac{2 m_H^2 f^2}{v^2} \frac{1}{1-(4 v' f/v^2)^2}$
T	$\sqrt{\lambda_1^2 + \lambda_2^2}\, f$



where $m_{\mathrm{W}} = gv/2$.

Electroweak Precision Constraints

(1). $W_H^{\pm}$, Z_H effects proportional to $c^2 = \cos^2\theta$:



Perelstein, Peskin, Pierce: `hep-ph/0310039`.

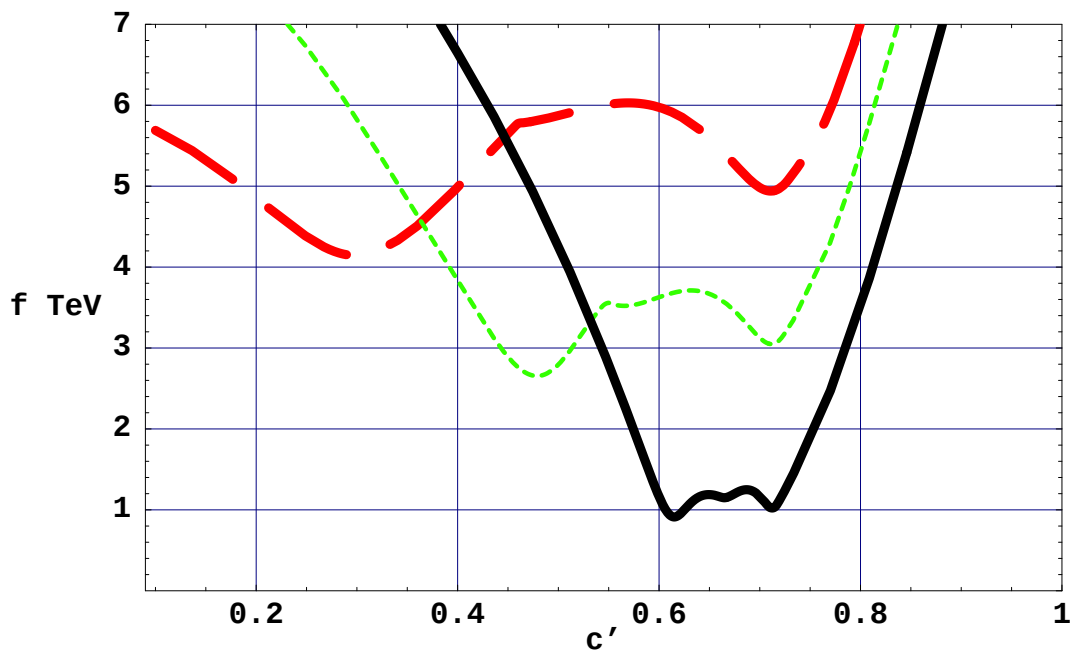
At 1σ level: $\cos\theta = 0.1,\ \ldots\ 0.7,\quad f = 1,\ 1.5,\ \ldots$ TeV inward.

(2). • Both $U(1)$'s violate the custodial $SU(2)$ symmetry

$$\frac{M^2_{W^\pm_L}}{M^2_{Z_L}} = c^2_{\rm W}\left[1 + \frac{v^2}{f^2}\frac{5}{4}(c'^2 - s'^2)^2 - 4\frac{v'^2}{v^2}\right].$$

• Csaki *et al.*, [hep-ph/0211124, 0303236]; Hewett *et al.*, [hep-ph/0211218]. They found, generically, $f > 3 - 4$ TeV at 95% CL.

• For certain choices of parameters: $c'^2 \approx s'^2$, $v' \ll v$ ...



Collider Phenomenology

Little Higgs itself? H_{SM} is THE LH.

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Only loop-induced effects*

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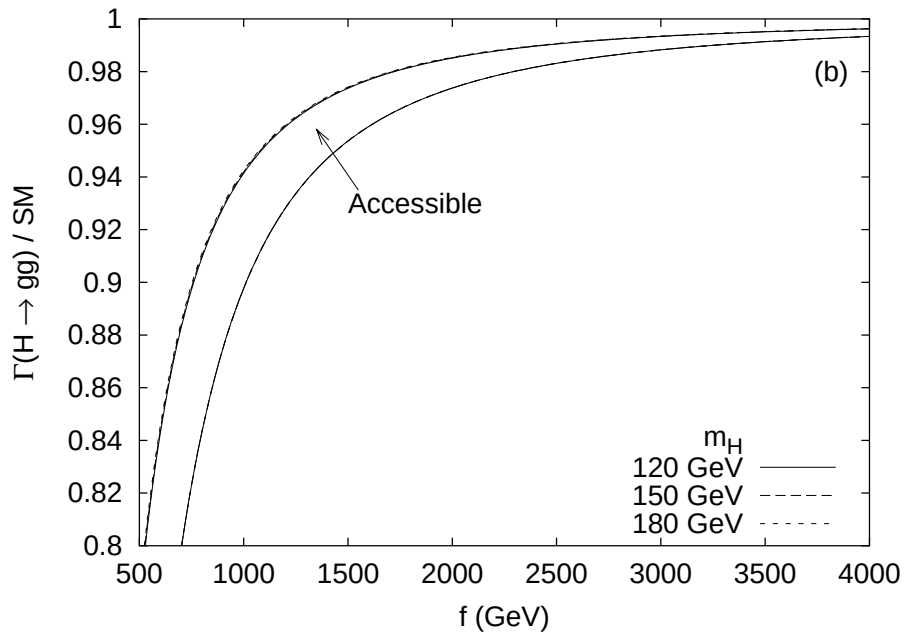
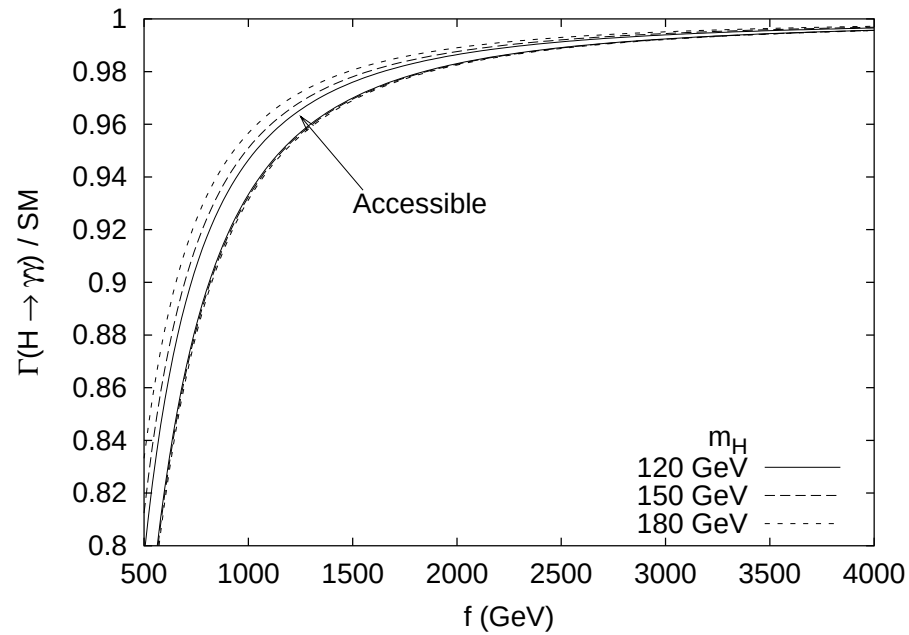
- $W_H^{\pm}$, T affect $H \to \gamma\gamma$





New effects scale like v^2/f^2, thus decouple at high scales.

*TH, H. Logan, B. McElrath, and L. Wang: `hep-ph/0302188`.

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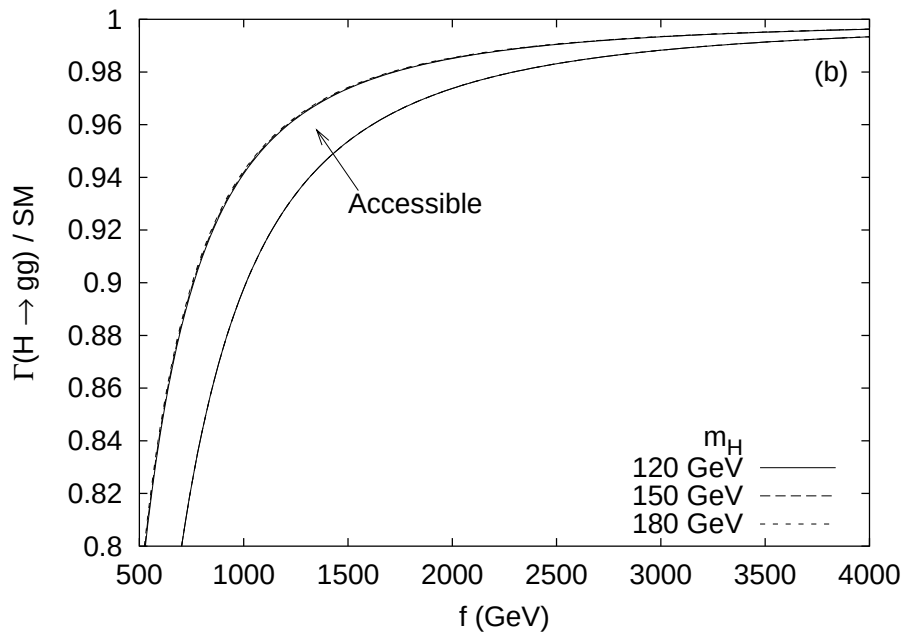
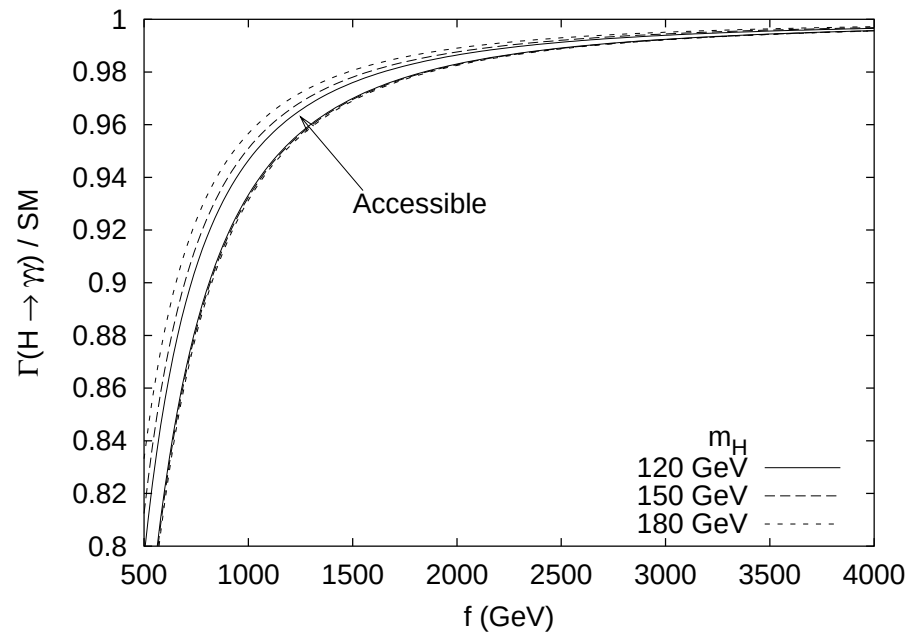




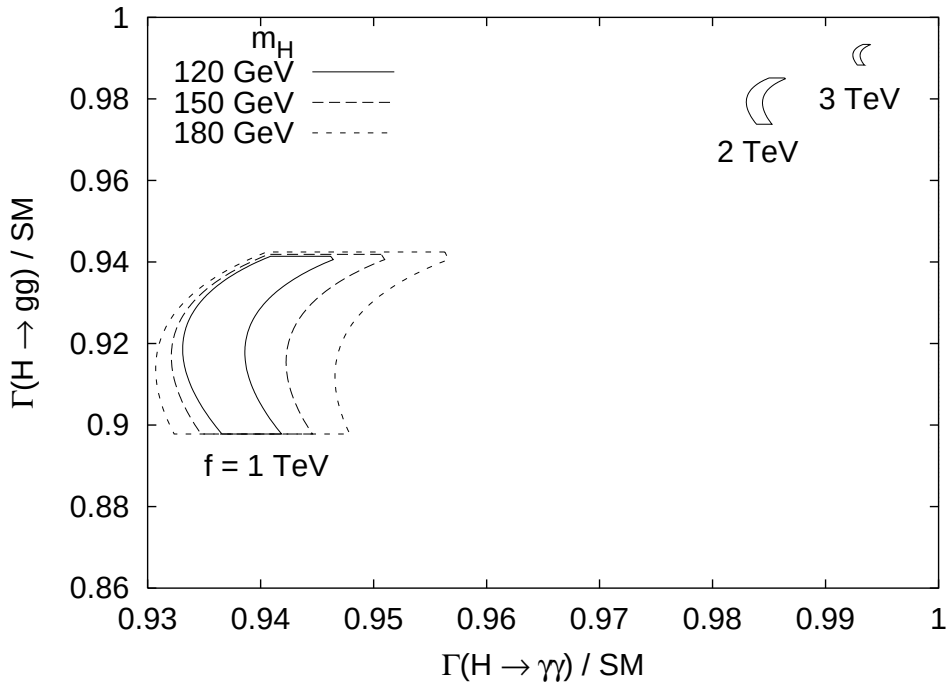
New effects scale like v^2/f^2, thus decouple at high scales.

For $f \sim 1$ TeV, $H \to gg$ reduced by $6 \sim 10\%$;

$H \to \gamma\gamma$ reduced by $5\% \sim 7\%$.

*TH, H. Logan, B. McElrath, and L. Wang: `hep-ph/0302188`.

Correlation between $H \to gg$ and $H \to \gamma\gamma$:



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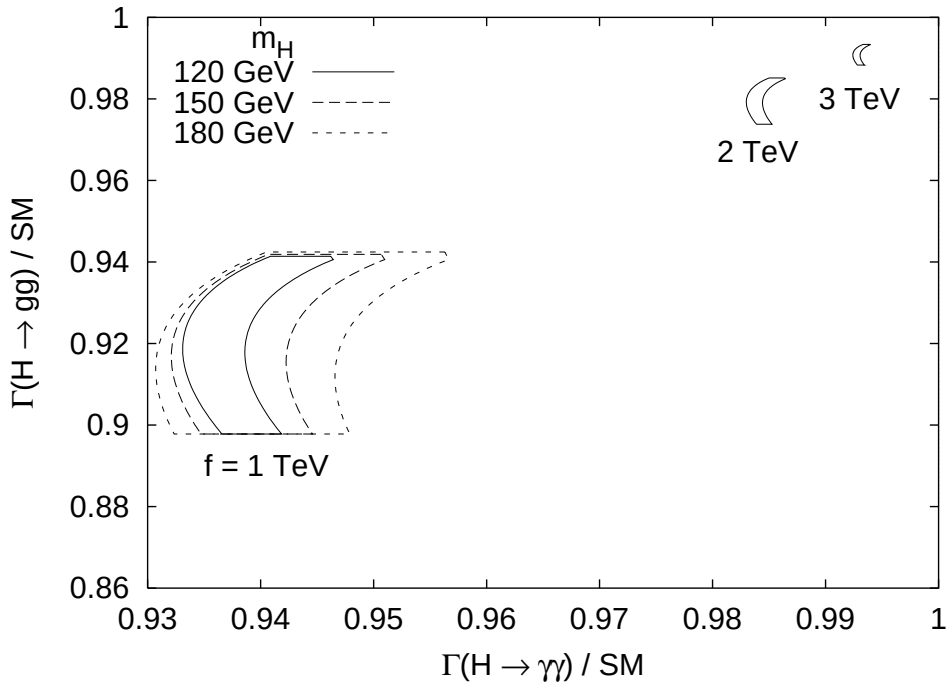
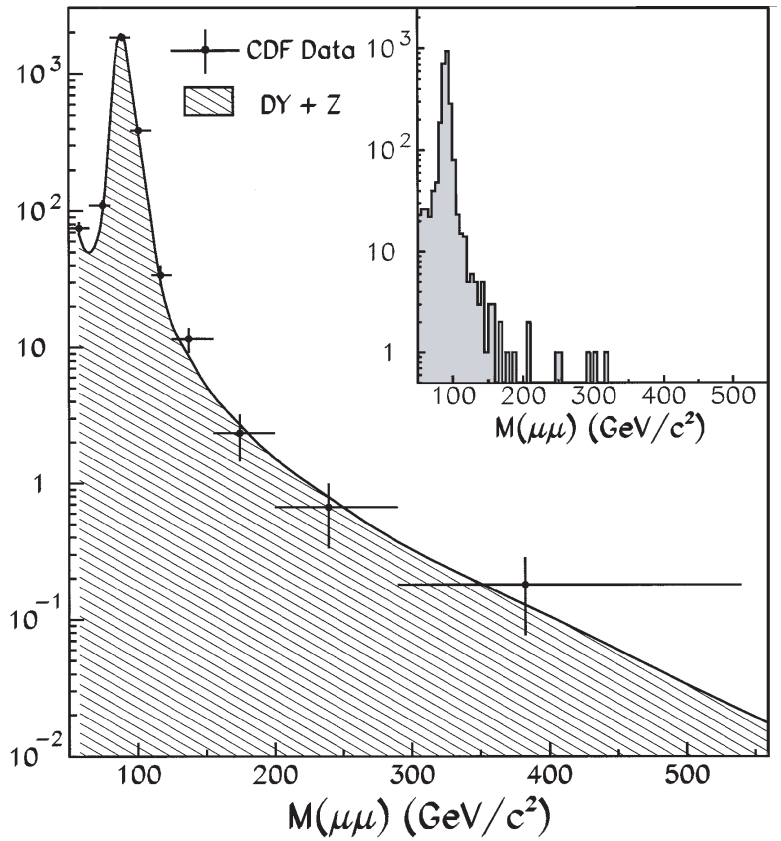


While the LHC and ILC could be sensitive to $f \sim 650$ GeV, a photon collider could probe deviation for $H \to \gamma\gamma$ to $f \approx 1.1$ (0.7) TeV at 2σ (5σ).

Recall Tevatron searches for a $Z' \to \mu^+\mu^-$ [e.g. CDF, PRL 79, (1997)]:



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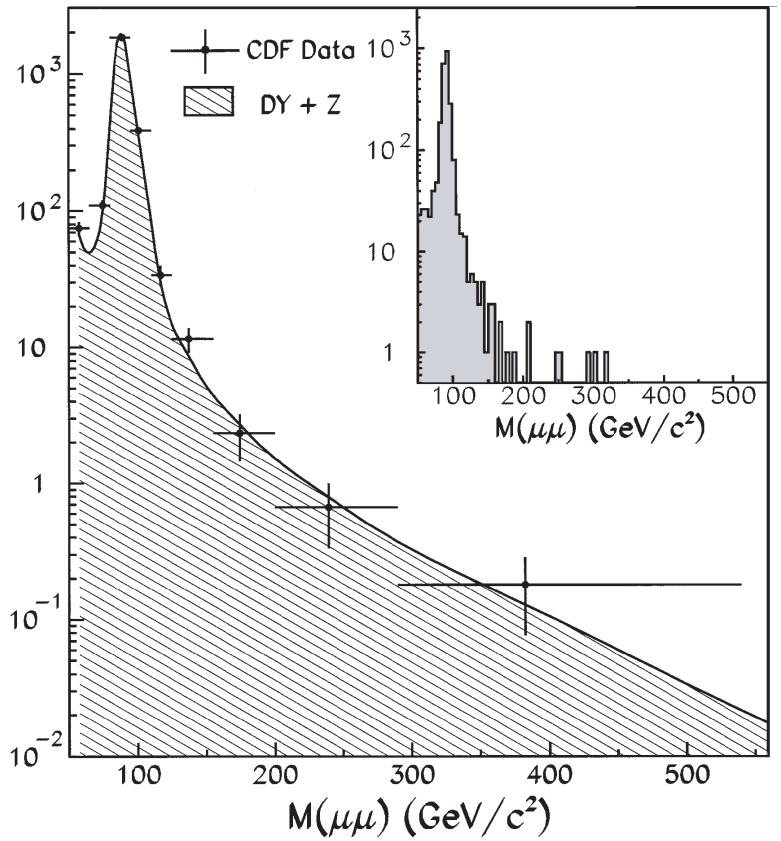

including:

$$p\bar{p} \to Z, \gamma \to \mu^+\mu^- X,$$
$$p\bar{p} \to W^+W^- \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu X,$$
$$p\bar{p} \to b\bar{b} \to \mu^+\mu^- + hadrons + X,$$
$$p\bar{p} \to t\bar{t} \to W^+b\ W^-\bar{b} \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu b\bar{b}\ X.$$

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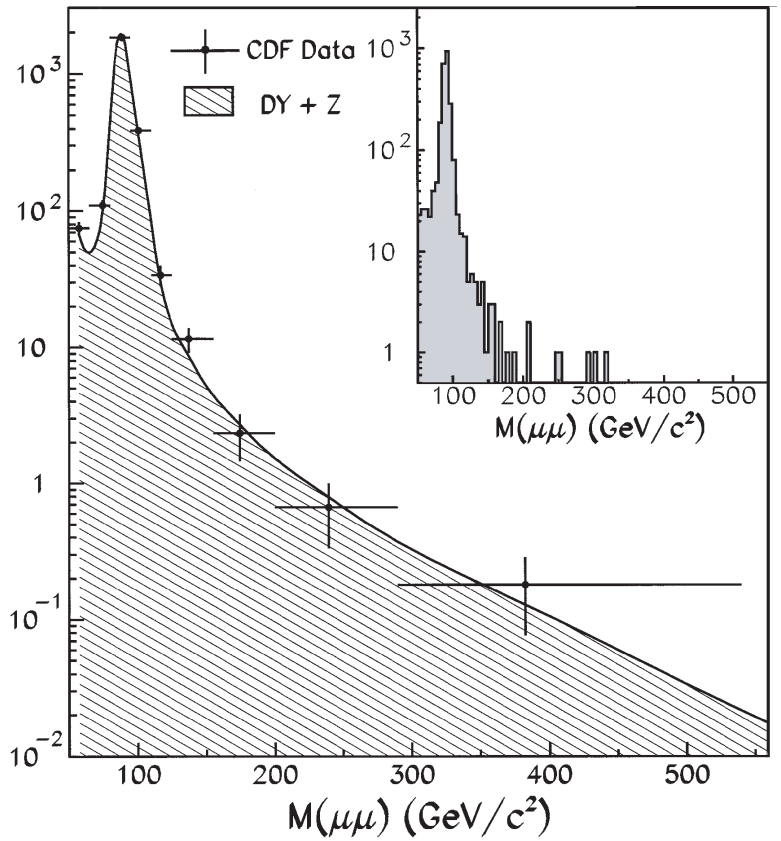

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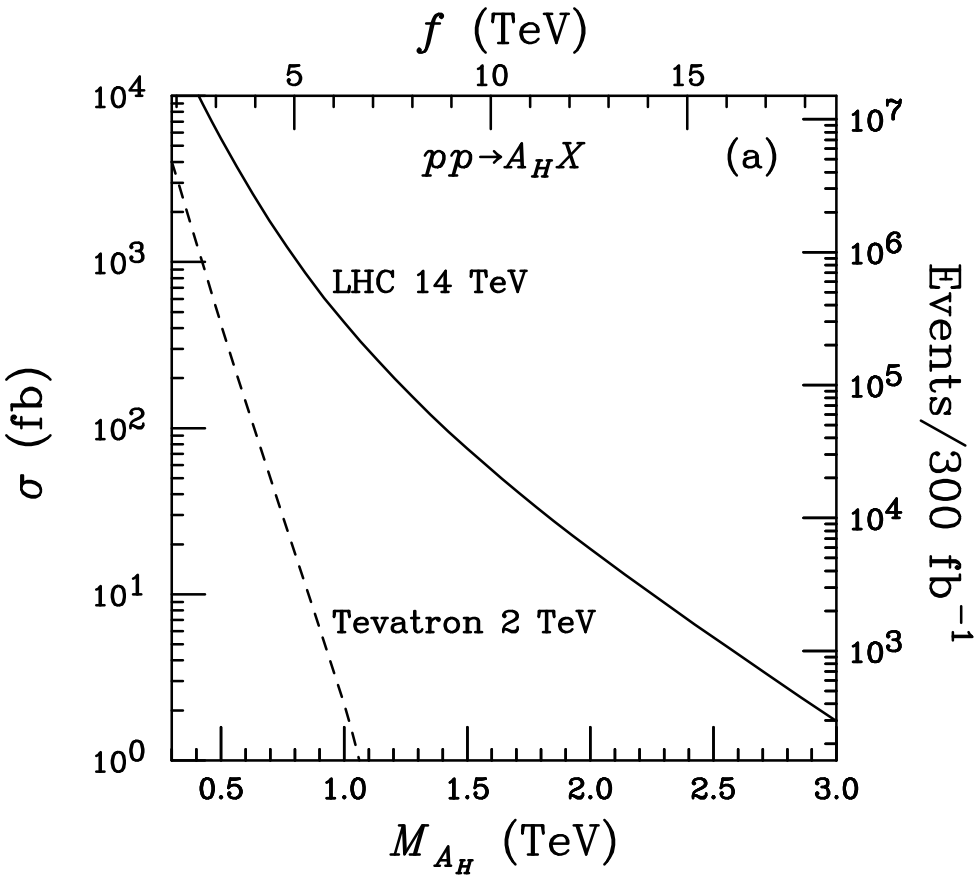
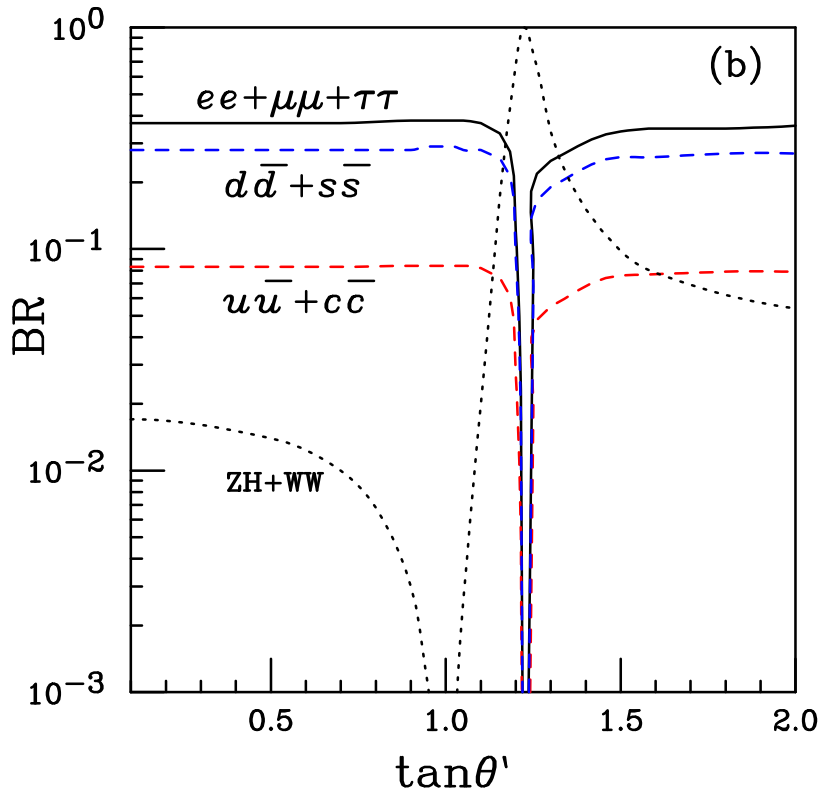
$p\bar{p} \to t\bar{t} \to W^+b\ W^-\bar{b} \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu b\bar{b}\ X.$
$\sigma < 40$ fb $\Rightarrow$ $M_{Z'} > 600$ GeV.

For a recent consideration, M. Carena, A. Daleo, B. Dobrescu, T. Tait, `hep-ph/0408098`.

The heavy A_H signal at hadron colliders

- A_H should be the lightest new state;
- DY production rate large





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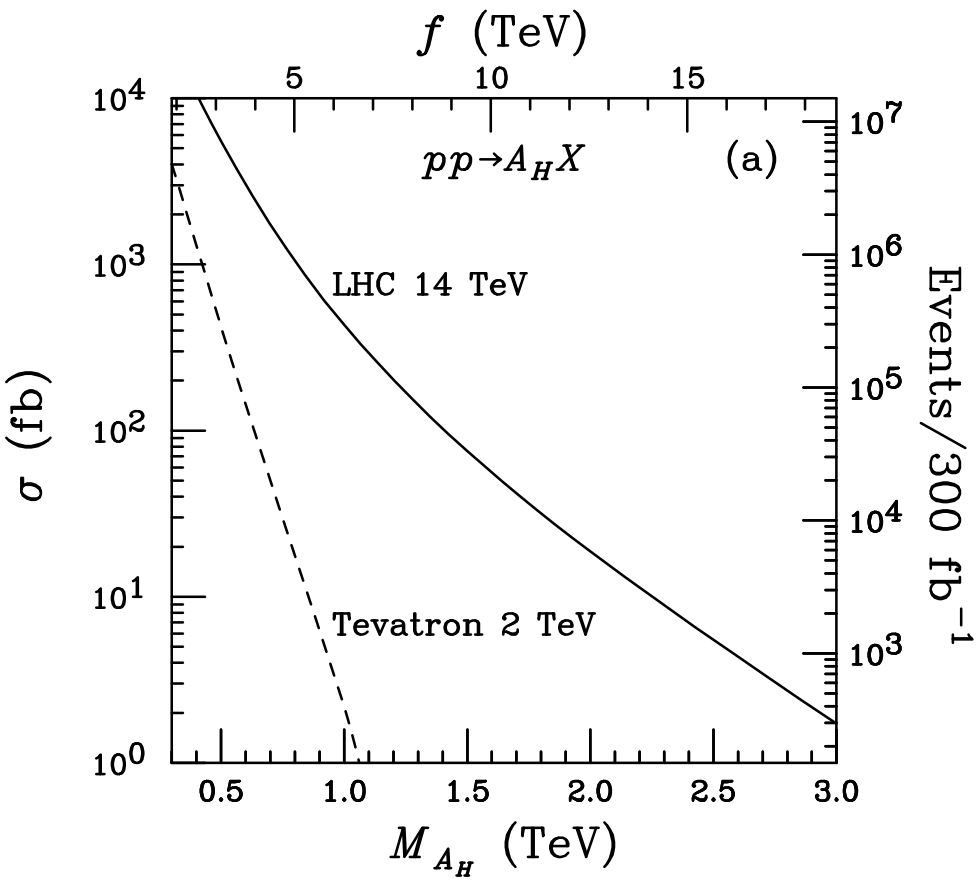

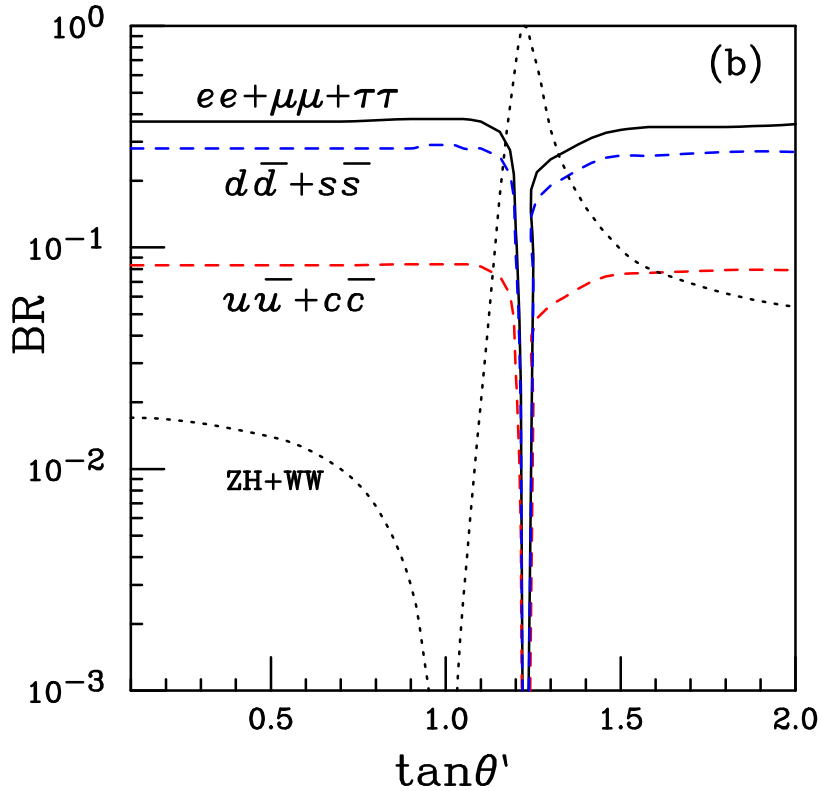

Tevatron: $M_{A_H} > 0.5$ TeV or $f > 3$ TeV;*
LHC: $M_{A_H} \sim 3$ TeV or $f \sim 18$ TeV.

*Hewett, Petriello, Rizzo, hep-ph/0211218.

A_H signal not most robust for LH idea

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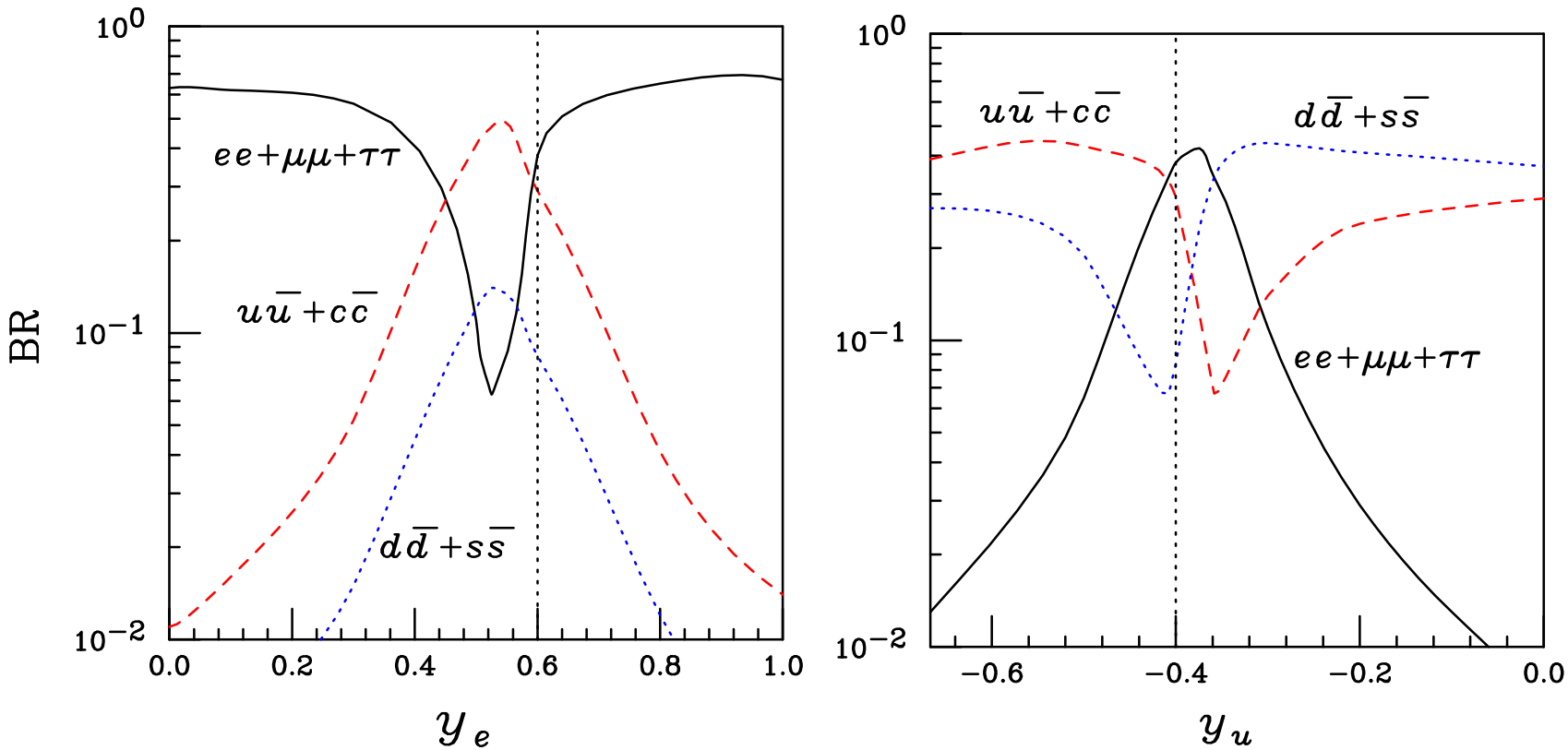
- fermionic couplings depend on $U(1)$ charges



$\tan\theta' = 1$

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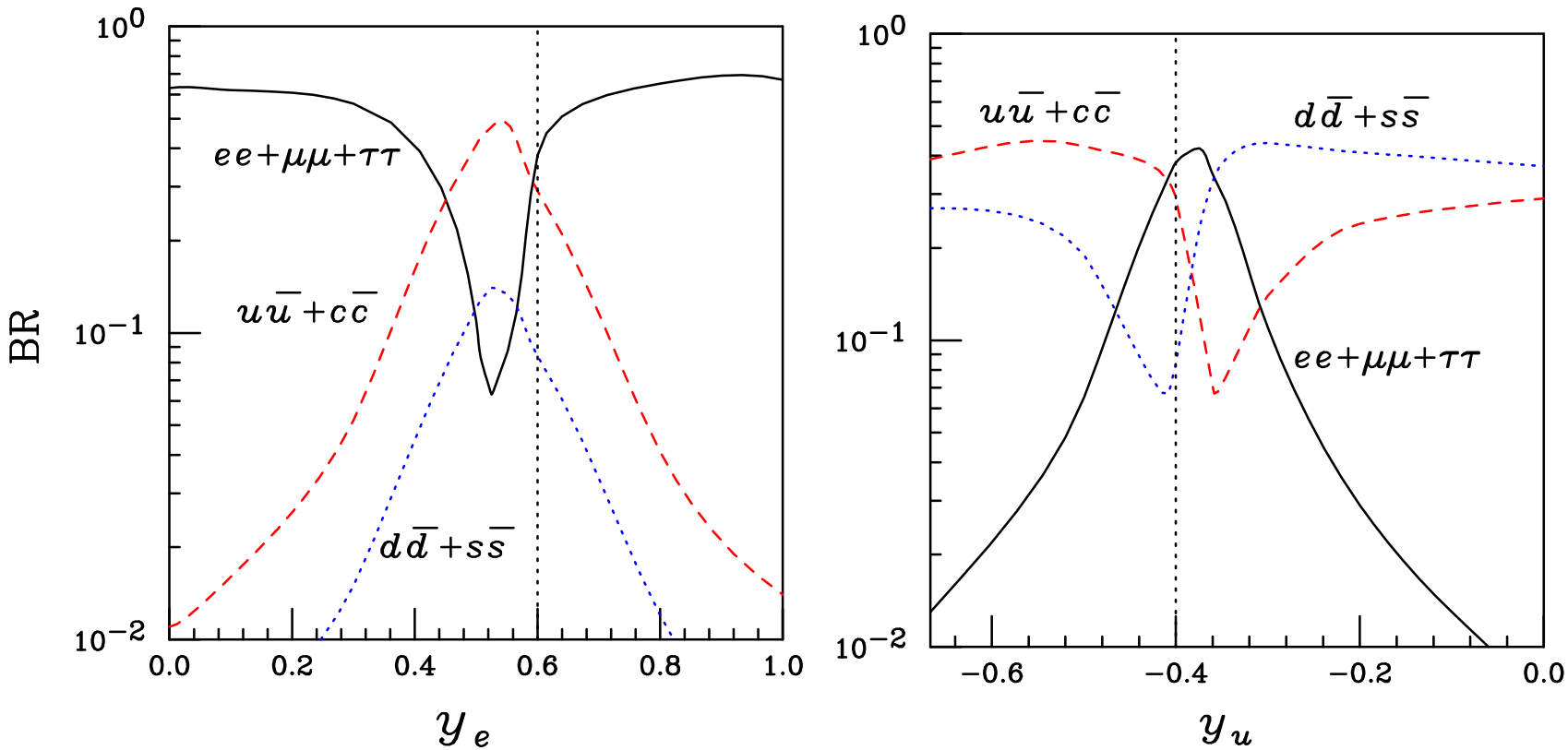

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$BR(A_H)$ may change by as much as 50.

even decouples from the SM fermions when $\tan\theta' = Y_1/Y_2$.

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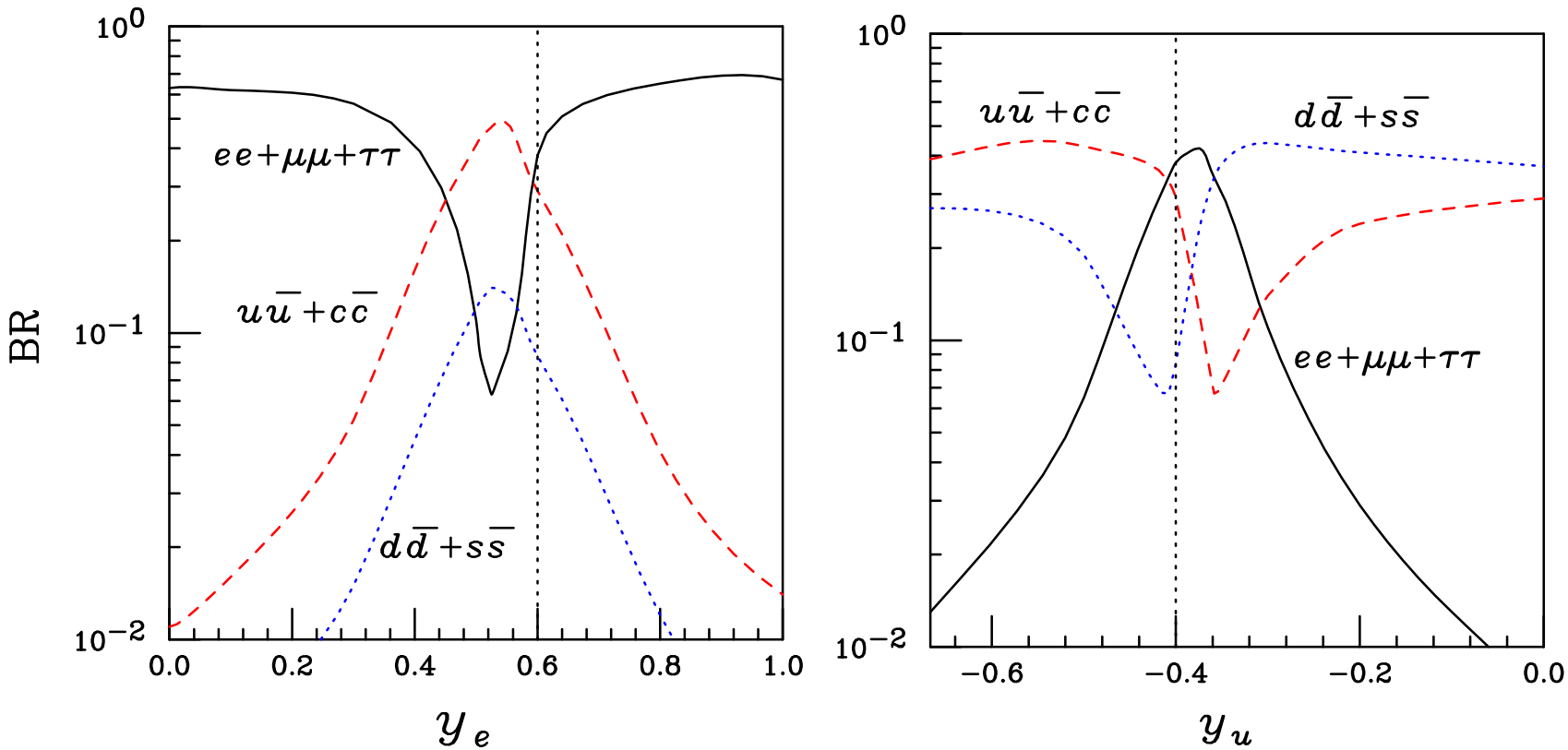

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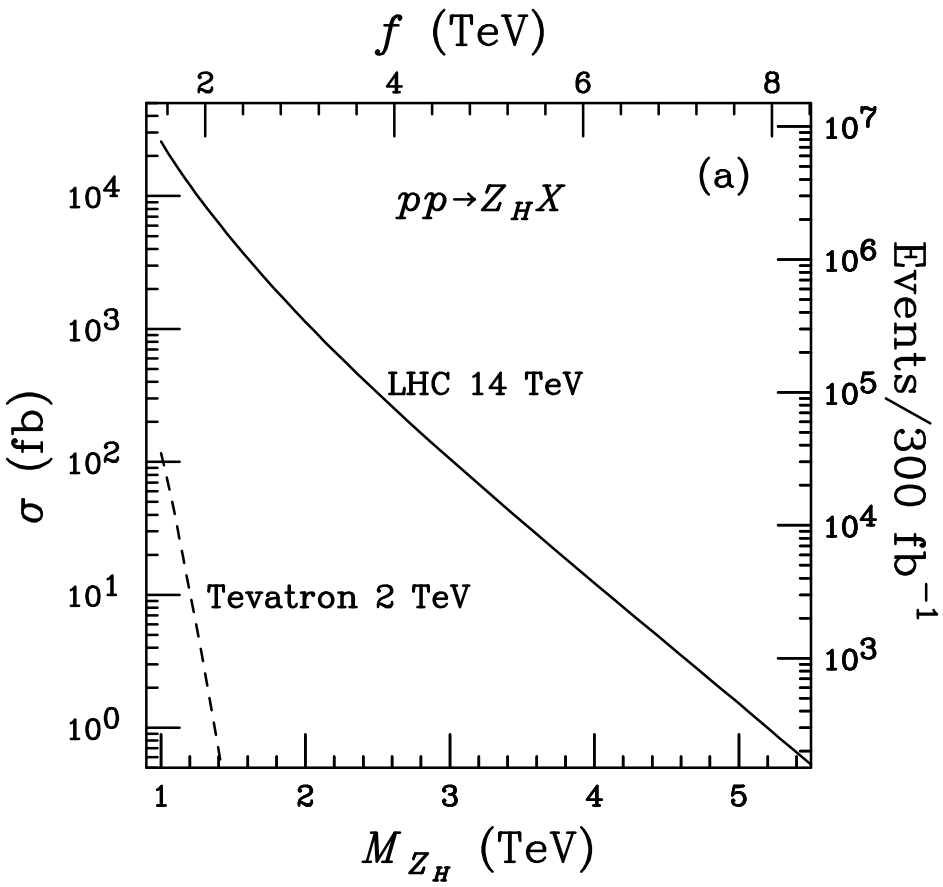
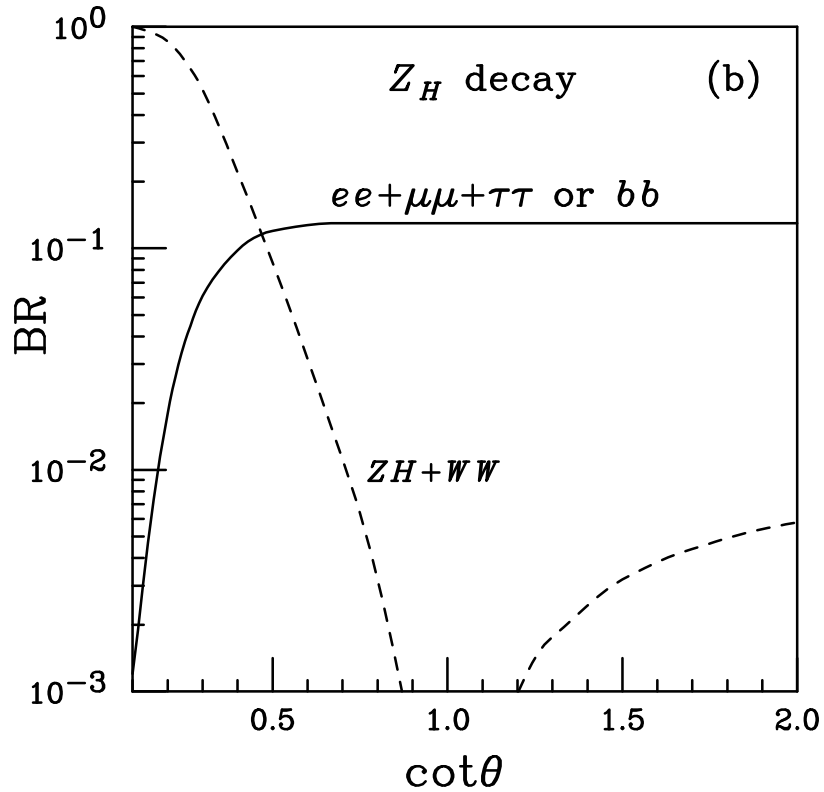
you may find a gun, but ...

The heavy Z_H signal at hadron colliders *

- Z_H/W_H rebust new state
- DY production rate large





*TH, H. Logan, B. McElrath, and L. Wang: hep-ph/0301040.

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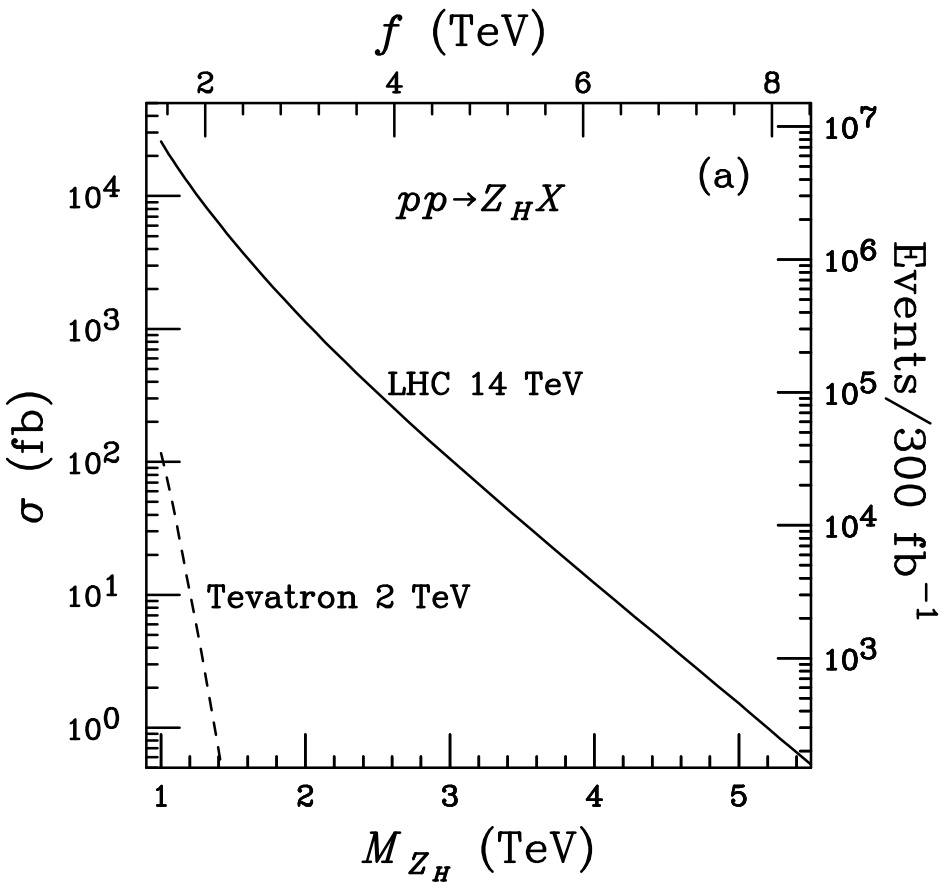

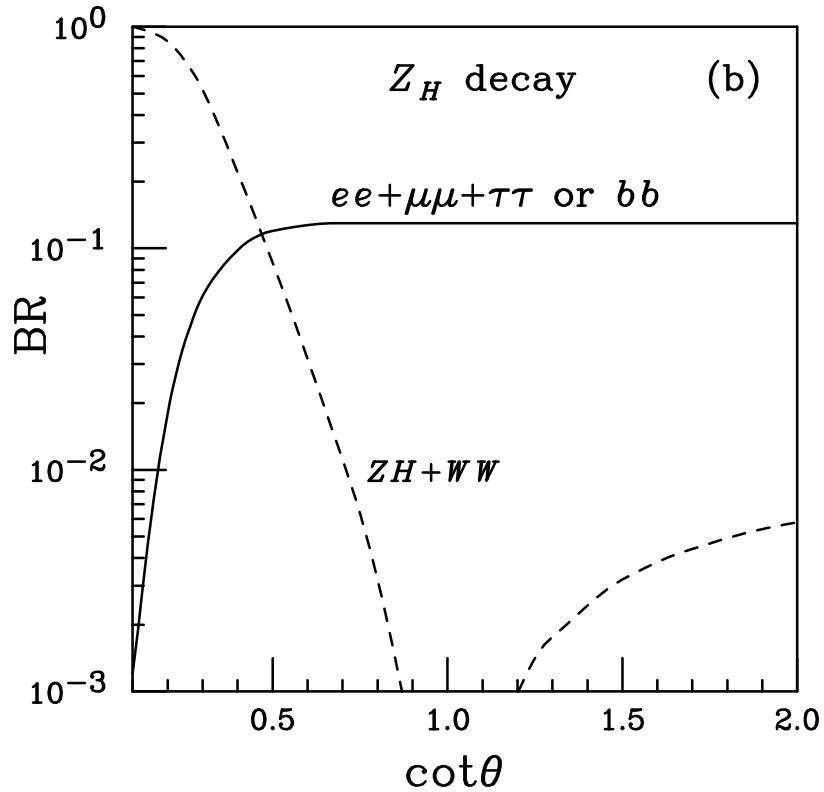

Tevatron: marginal accessibility $M_{Z_H} \lesssim 1$ TeV;
LHC: $M_{Z_H} \sim 5$ TeV or $f \sim 8$ TeV.

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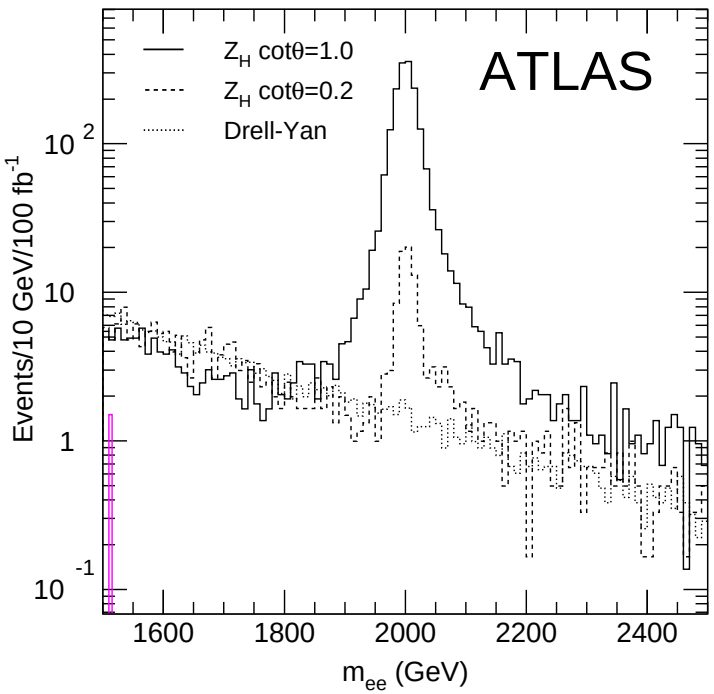
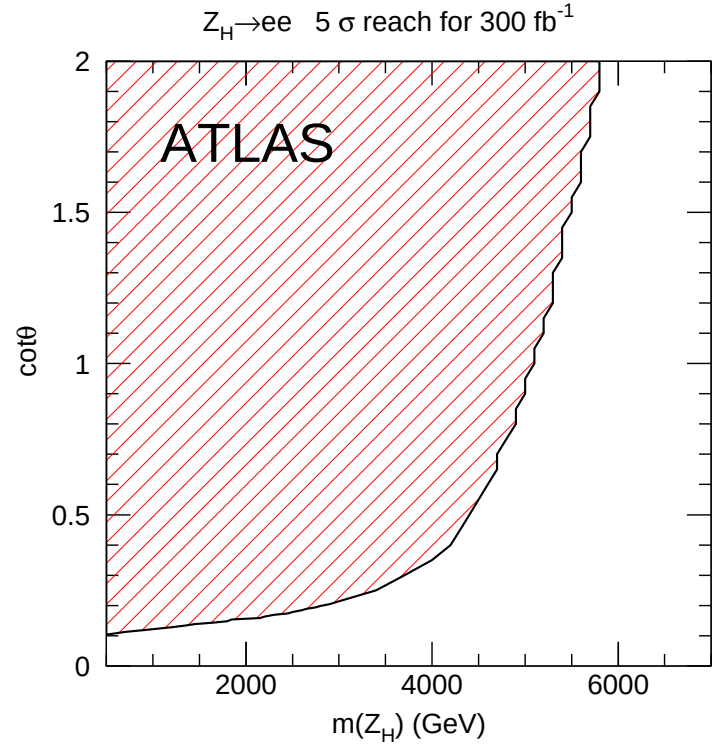
ATLAS simulations for $Z \to \ell^+\ell^-$:*





Reach $M_{Z_H} \sim$ several TeV for $\cot\theta > 0.1$:

*G. Azuelos et al.: `hep-ph/0402037`.

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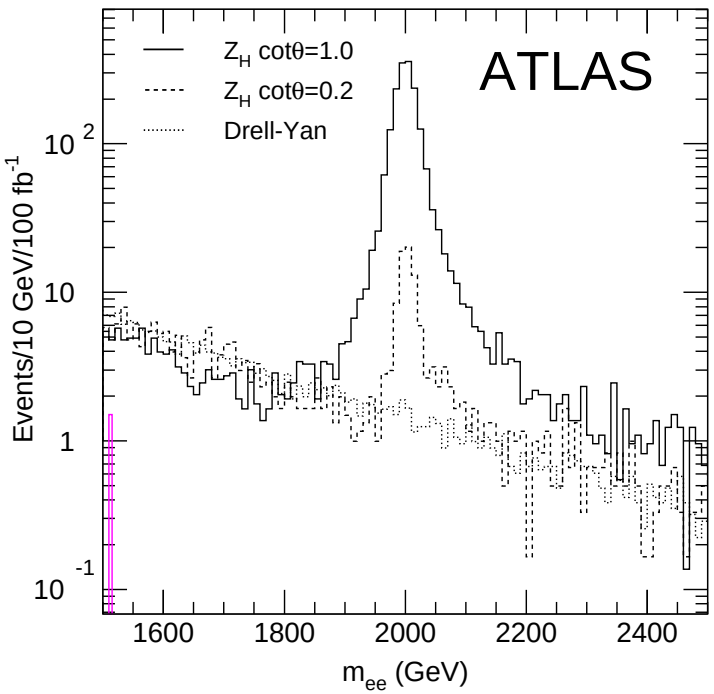
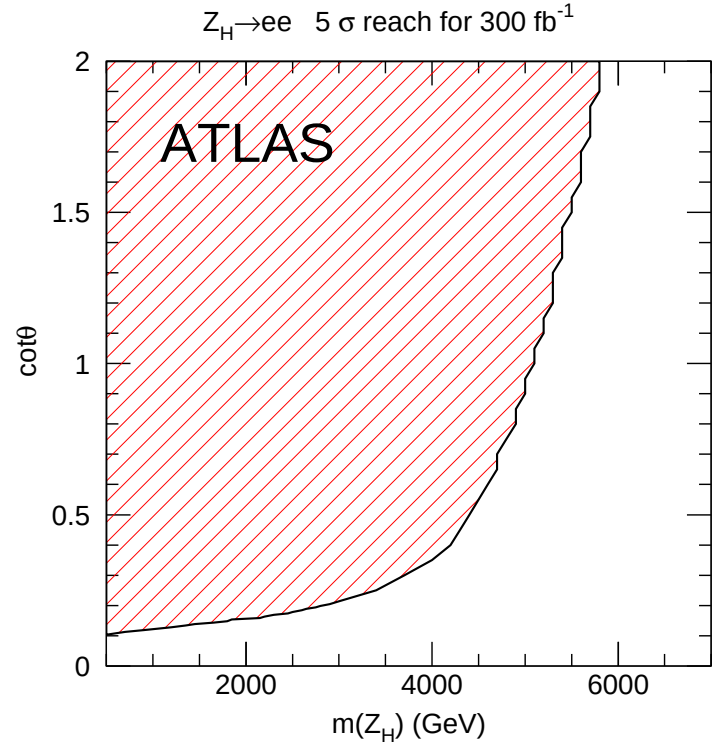




Reach $M_{Z_H} \sim$ several TeV for $\cot\theta > 0.1$:

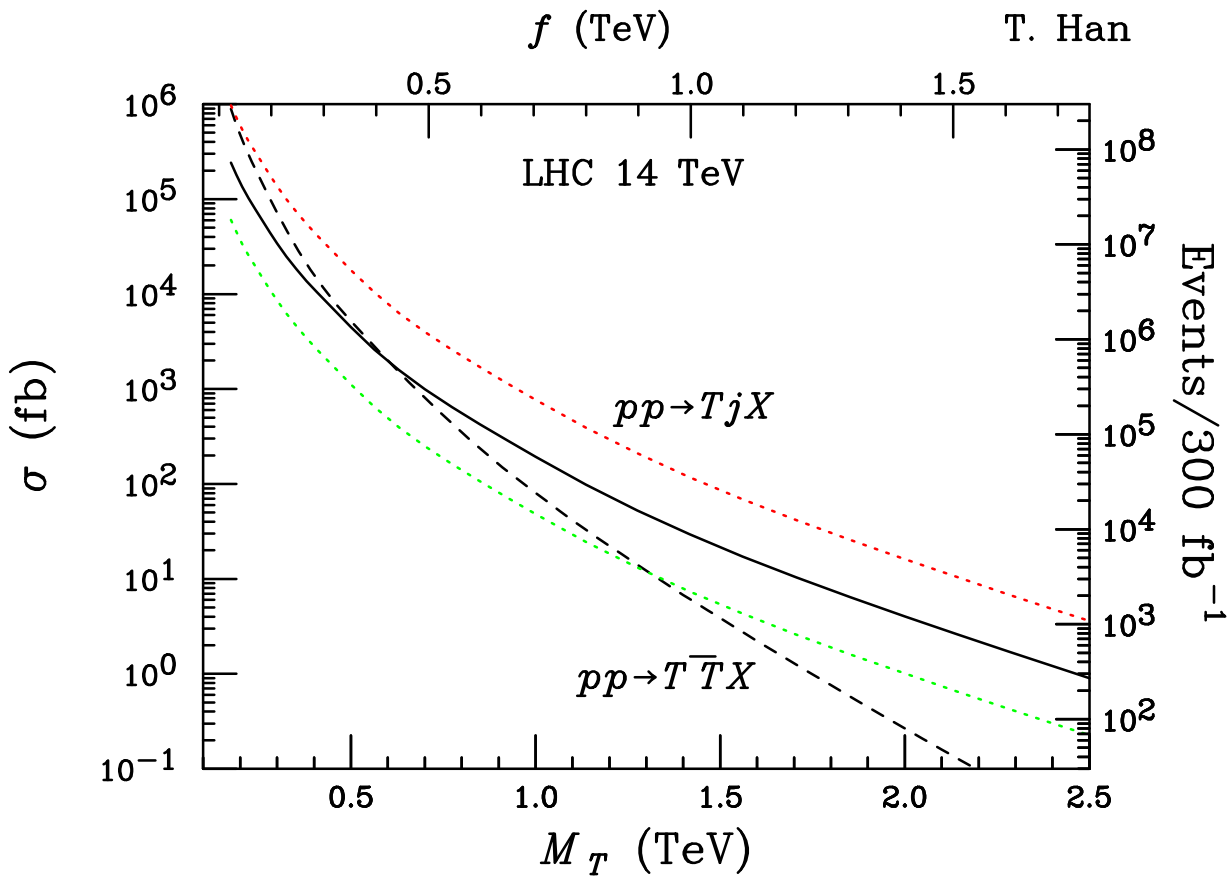
Cross-sectiions measure $\cot\theta$: $N(\ell^+\ell^-)$ versus $N(Zh)$.†

Mass peak M_{Z_H} determines f.

*G. Azuelos et al.: `hep-ph/0402037`.

†Burdman, Perelstein, Pierce: `hep-ph/0212228`.

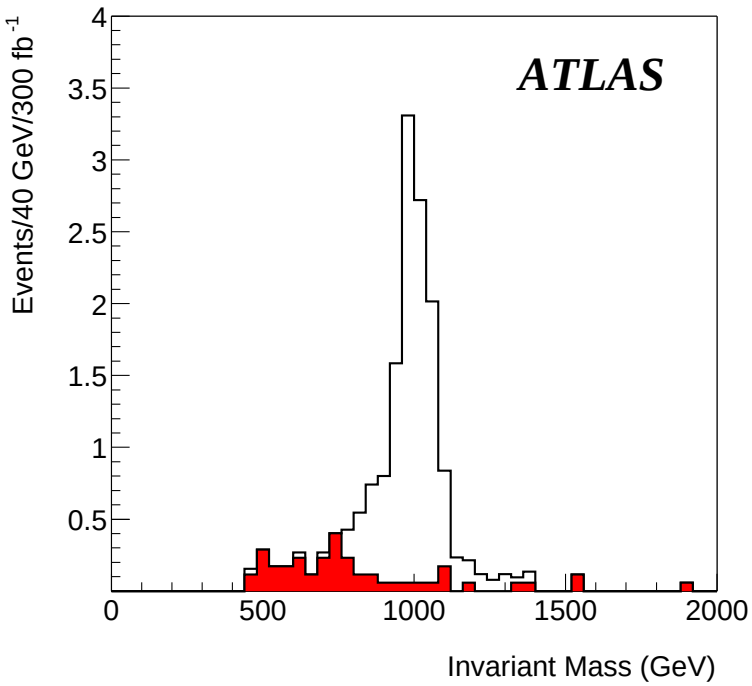
The heavy T signal at the LHC

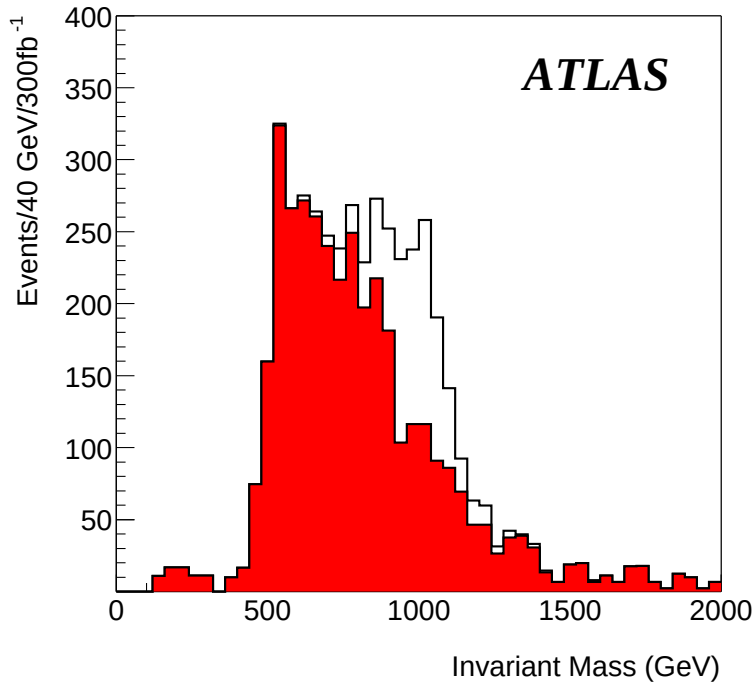


$gg \to T\bar{T}$ phase-space suppression;
$qb \to q'T$ via t-channel $W_L b \to T$. †

†D. Dicus and S. Willenbrock, PRD (1986); C.-P. Yuan PRD (1990); ... ...

ATLAS simulations for $T \to tZ,\ bW$:*





Reach $M_T \sim 1$ (2) TeV for $x_\lambda = 1$ (2).

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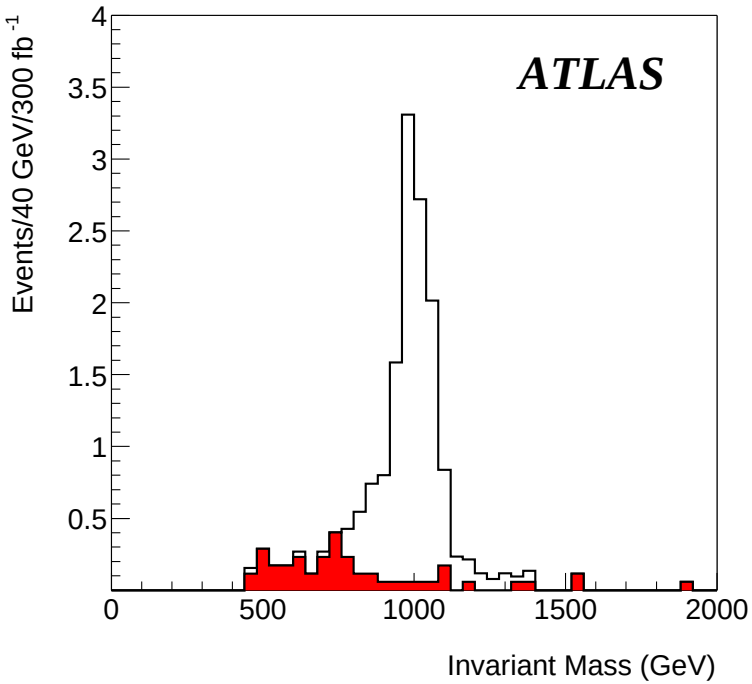

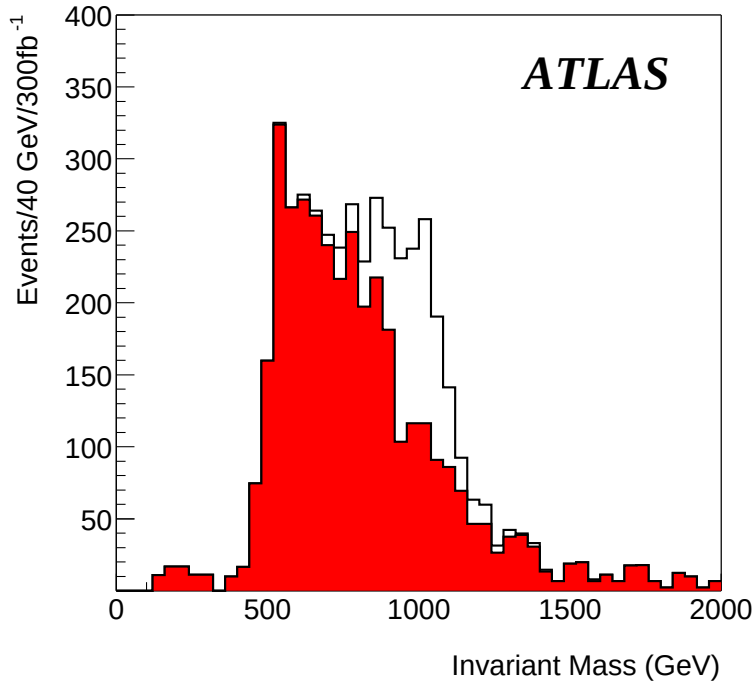

Reach $M_T \sim 1$ (2) TeV for $x_\lambda = 1$ (2).

Cross-sectiions measure coupling x_λ.

Mass peak M_T determines f : $v/f = m_t/M_T(x_\lambda + x_\lambda^{-1})$

$\Longrightarrow$ check consistency with f from M_{Z_H}.*

*G. Azuelos et al.: `hep-ph/0402037`.

*Perelstein, Peskin, Pierce: `hep-ph/0310039`.

Which Little Higgs model?

Example II: A Simple Group Model*

A non-linear σ-model:

Global symmetry: $[SU(3)]^2 \Rightarrow [SU(2)]^2$, leading to 10 Goldstone bosons;

Gauge symmetry: $SU(3) \otimes U_X(1) \Rightarrow SU(2)_L \otimes U(1)_Y$

*D.E. Kaplan and M. Schmaltz: hep-ph/0302049.

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The fate of the Goldstone bosons:

5 Longitudinal modes of $Z', X^{\pm}, Y_0, \overline{Y_0}$;
h doublet;
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Features:

All interactions are fixed by SM gauge couplings;
Z' is like Z_H; $X^{\pm}$ like $W_H^{\pm}$.

*D.E. Kaplan and M. Schmaltz: hep-ph/0302049.

Fermions promoted to

triplet $\mathbf{3}$: (u, d, U), (c, s, C), (t, b, T),

leading to T, C, U 3 heavy fermions.

But this "universal" assignment is $SU(3) \otimes U_X(1)$ anomalous.

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An "anomaly-free" assignment proposed *

$\bar{\mathbf{3}}$: $(d, -u, D)$, $(s, -c, S)$; $\mathbf{3}$: (t, b, T),

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*O.C. Kong hep-ph/0307250; hep-ph/0312060.

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leading to T, S, D 3 heavy fermions.

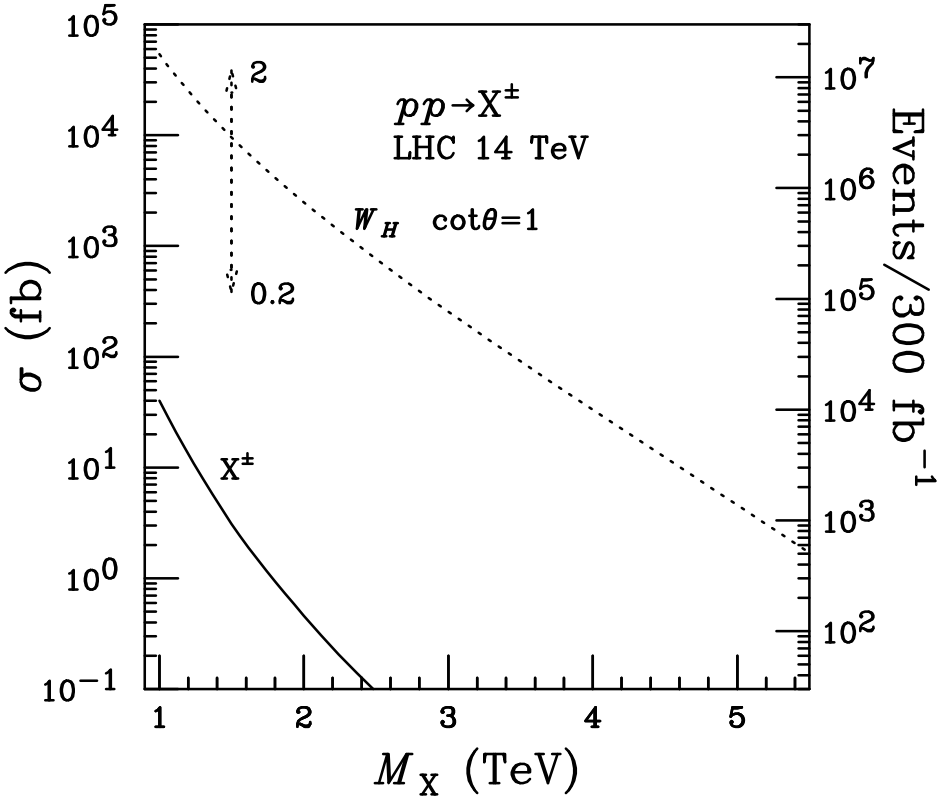
Features:

Two condensates are needed (2 vev's) f_1, f_2;
(X^+, Y_0), $(\overline{Y_0}, X^-)$ couplings to SM fermions suppressed by
$\frac{1}{t_\beta}\frac{v}{f}$, $\quad t_\beta = \frac{f_2}{f_1} > 1$.

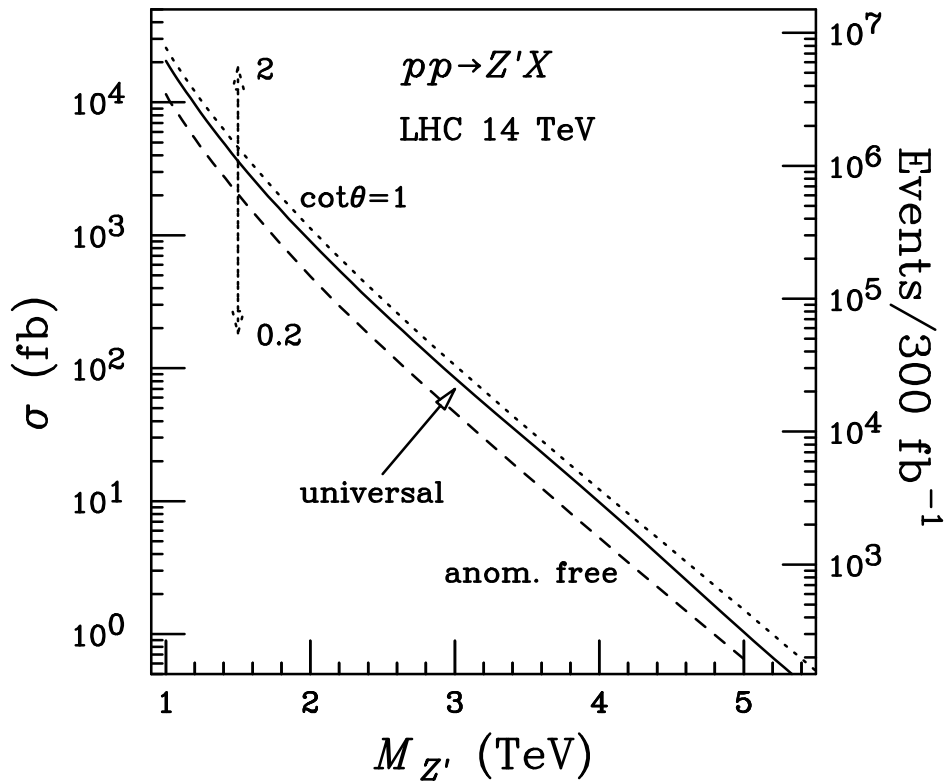
*O.C. Kong hep-ph/0307250; hep-ph/0312060.

Which LH? Gauge sector signatures

- $W_H^{\pm}$ versus $X^{\pm}$



- Z_H versus Z'



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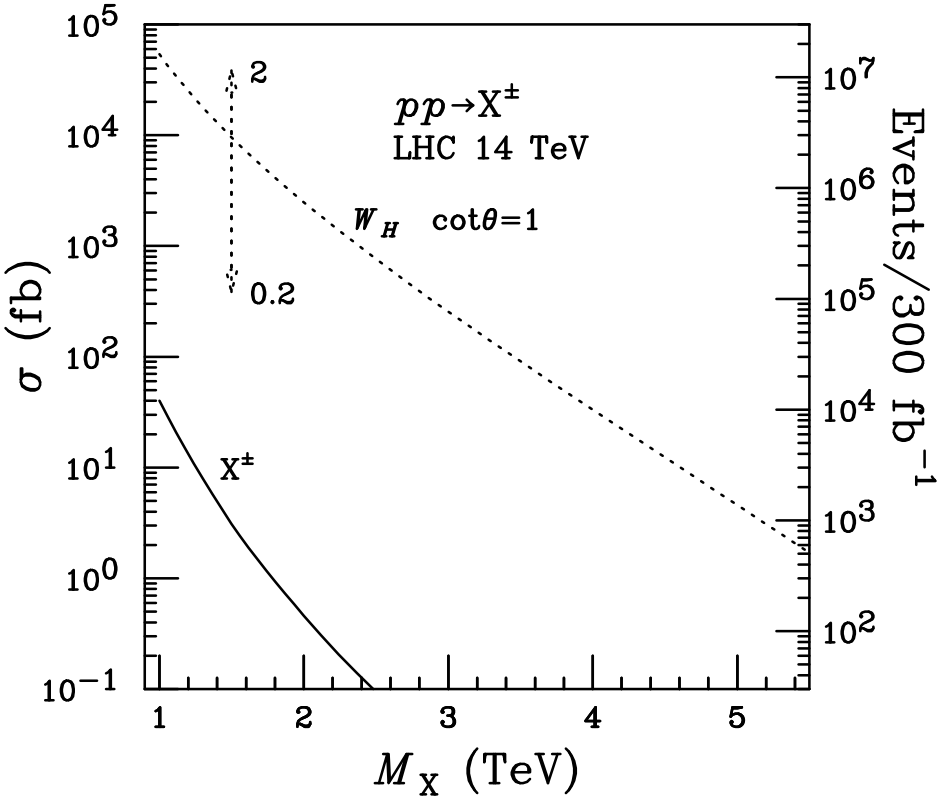
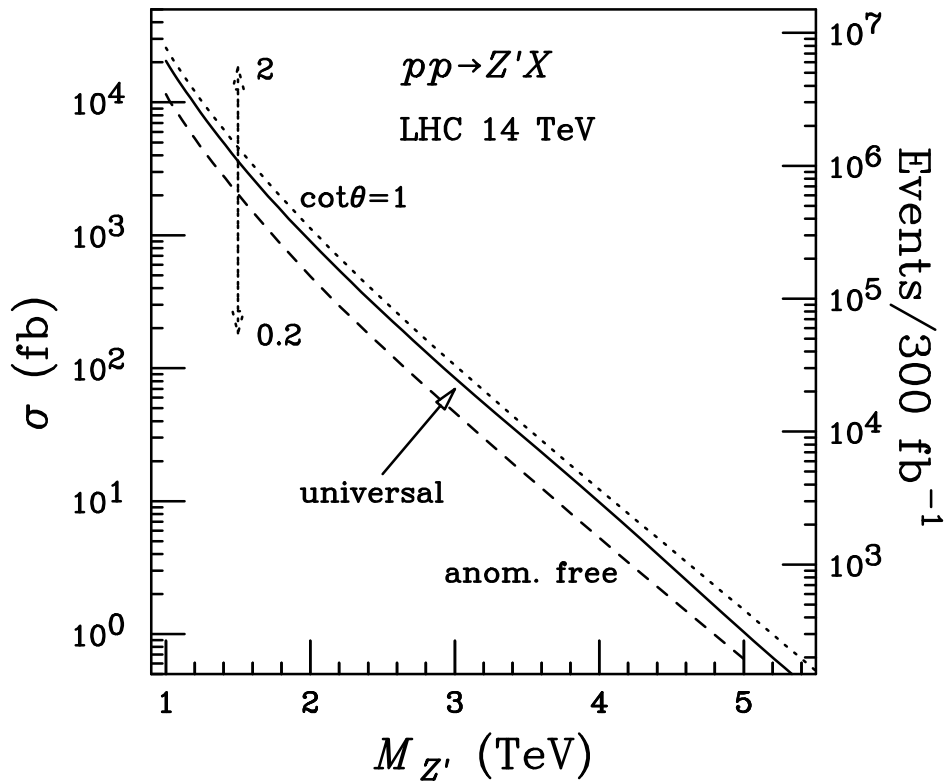


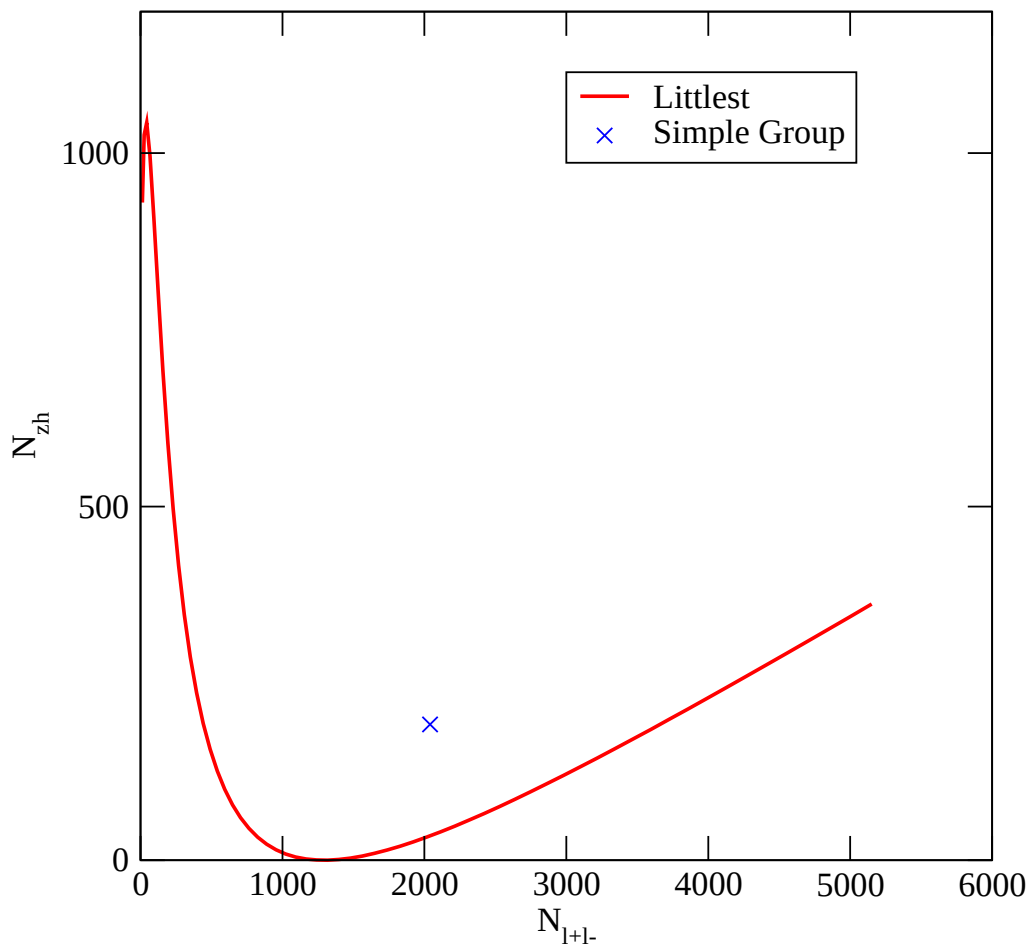


Littlest: Strong $W_H^\pm$ signal; Simple-group: no $X^\pm$;

$M_{Z_H,Z'} \sim 5$ TeV or $f \sim 8$ TeV.

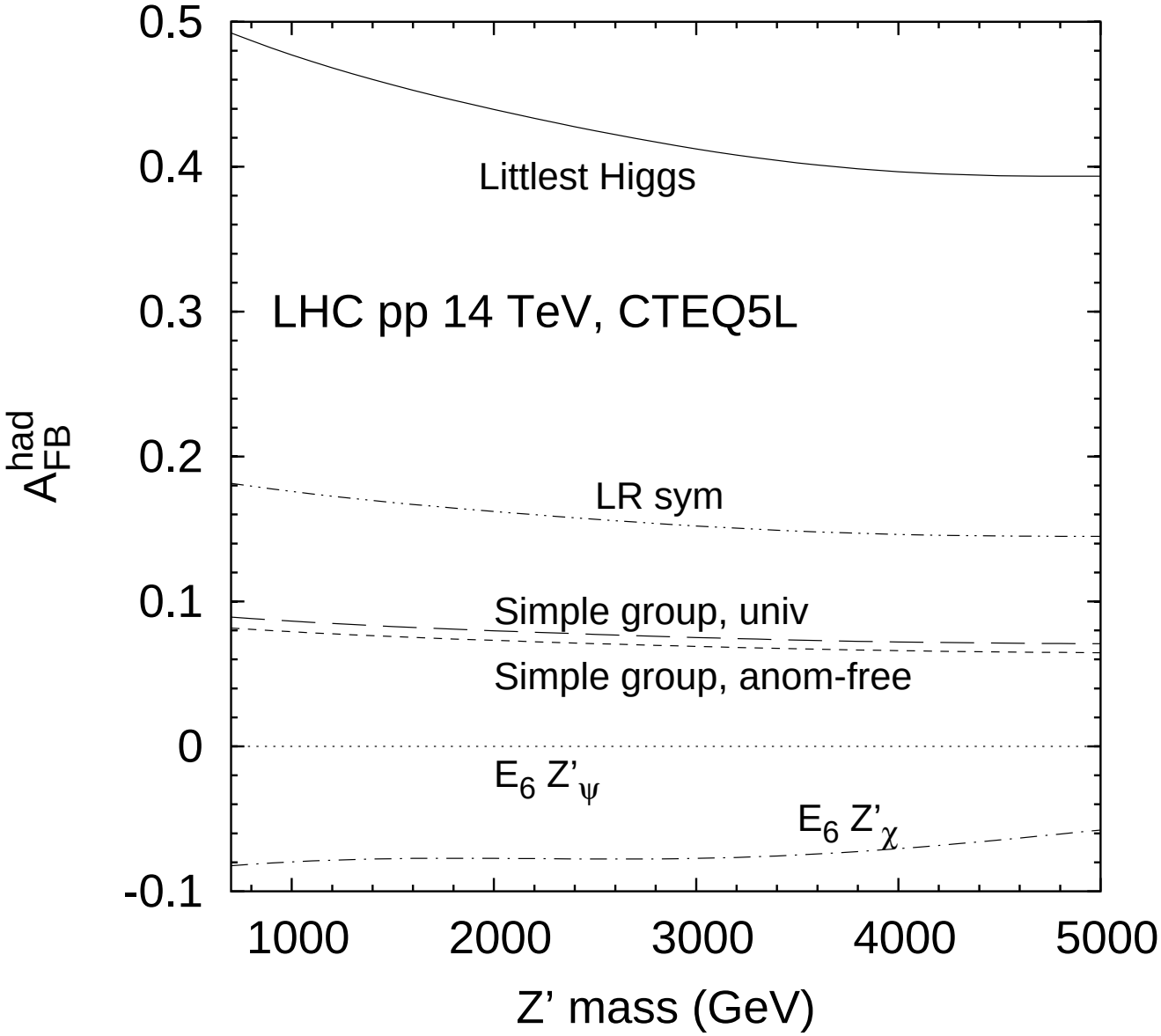
N_{ZH} versus $N_{\ell\ell}$:

Z_H depends on $\cot\theta$; Z' fixed by SM gauge couplings:



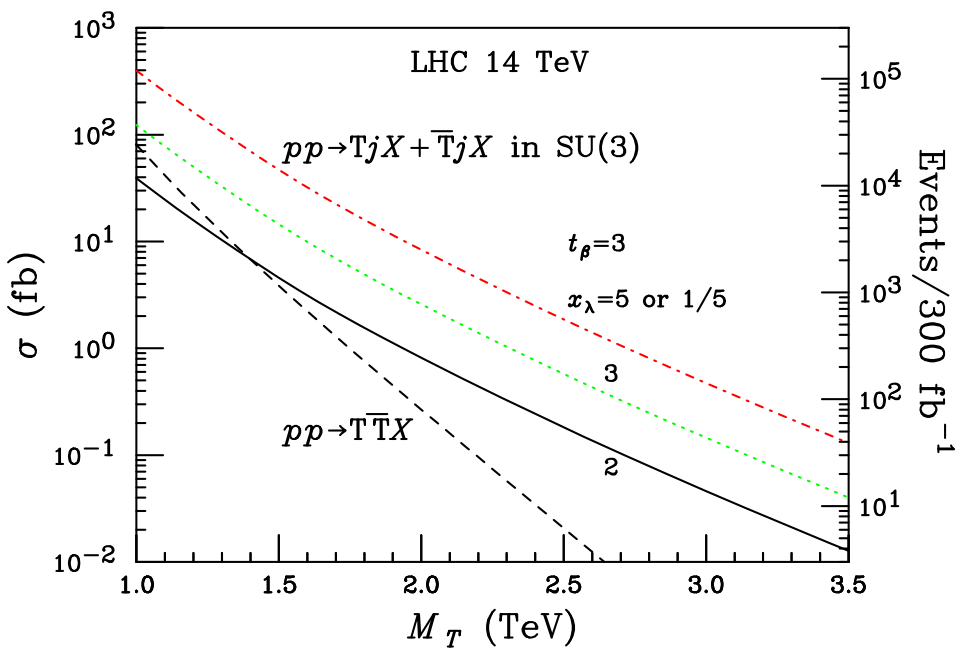
Significant differences for FB asymmetry among Z's:

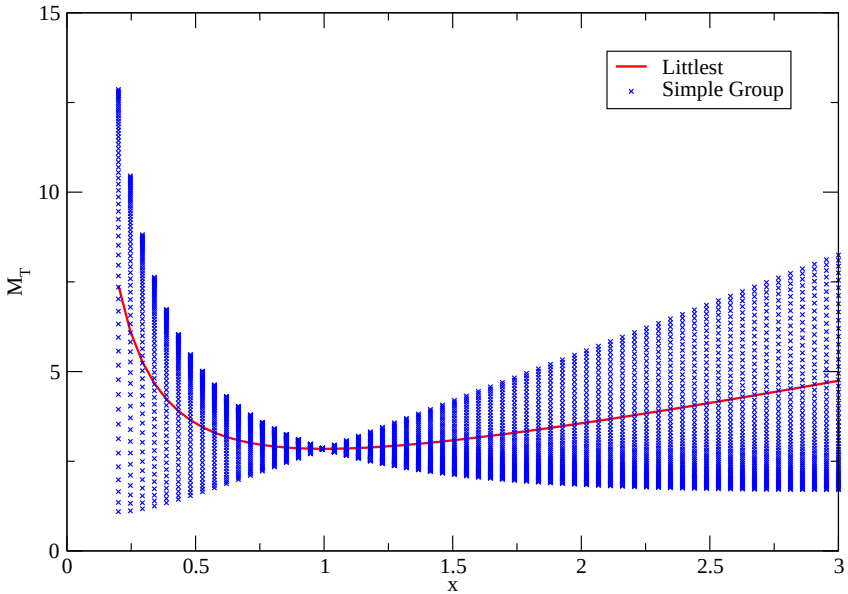
$$A_{FB}^{i,f} = \frac{3}{4} A_i A_f, \quad A_i = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}.$$



Which LH? Heavy quark sector signatures

- T_{LH} versus T_{su3}:





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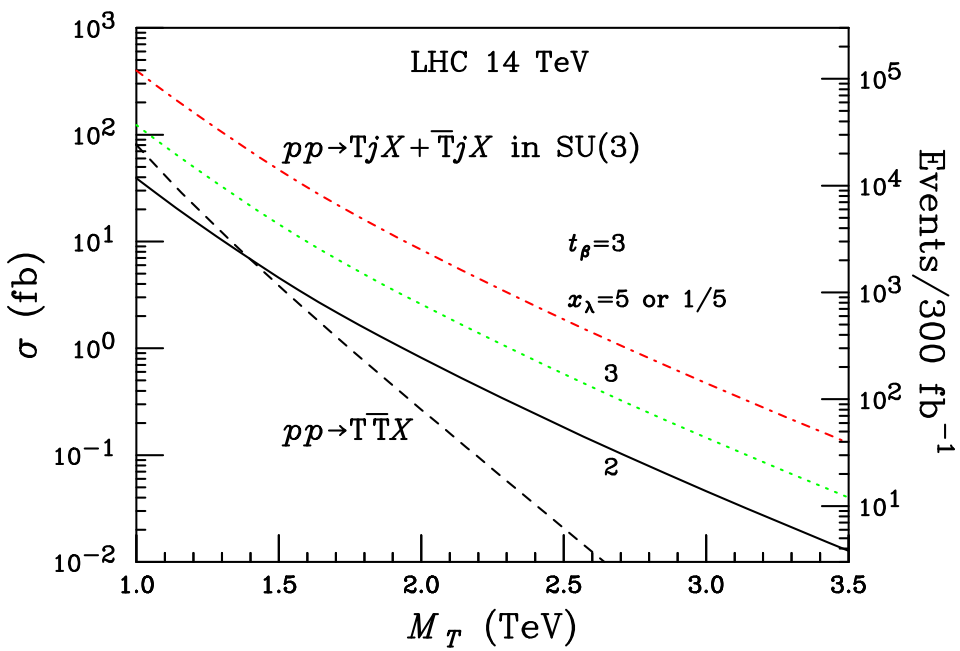

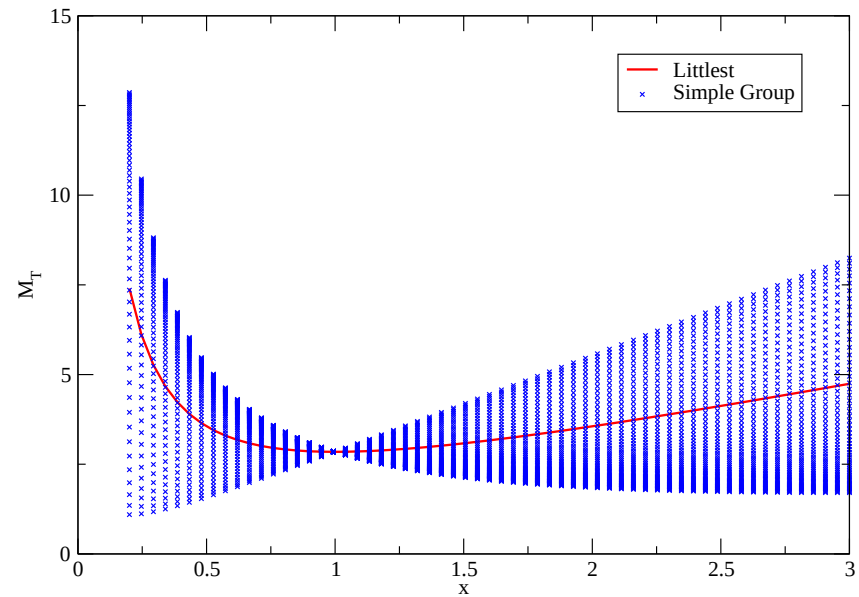

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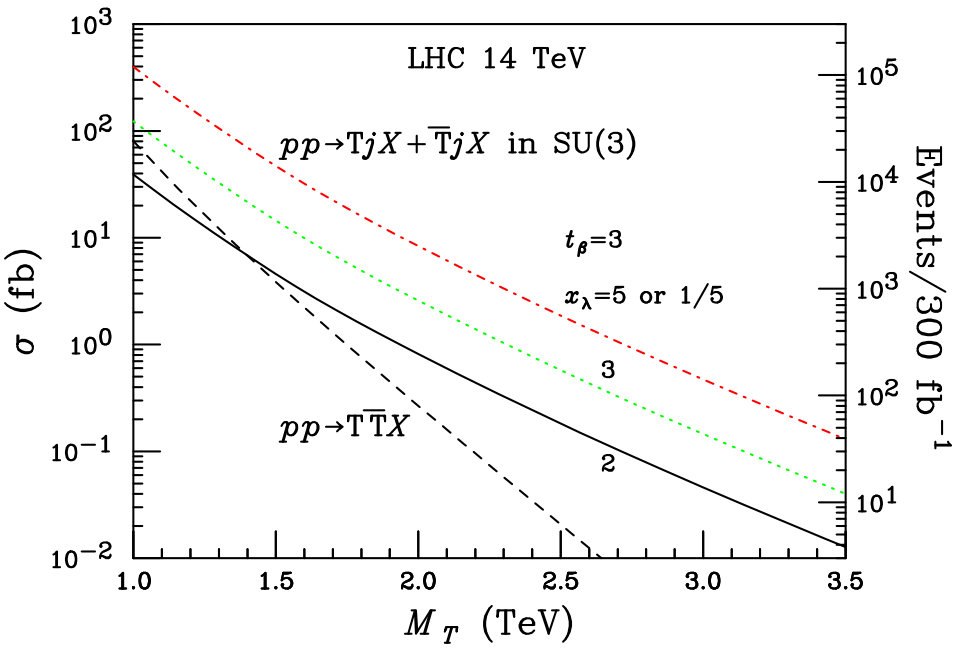

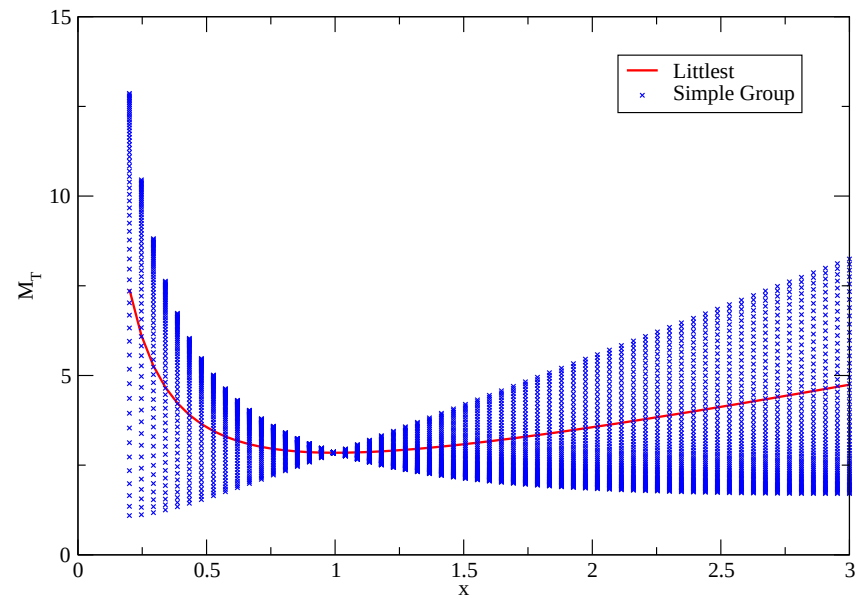

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SU(3):† $M_T/m_t = \frac{2f}{v}\frac{x_\lambda^2+t_\beta^2}{x_\lambda(1+t_\beta^2)}, \quad t_\beta = \frac{f_2}{f_1}.$

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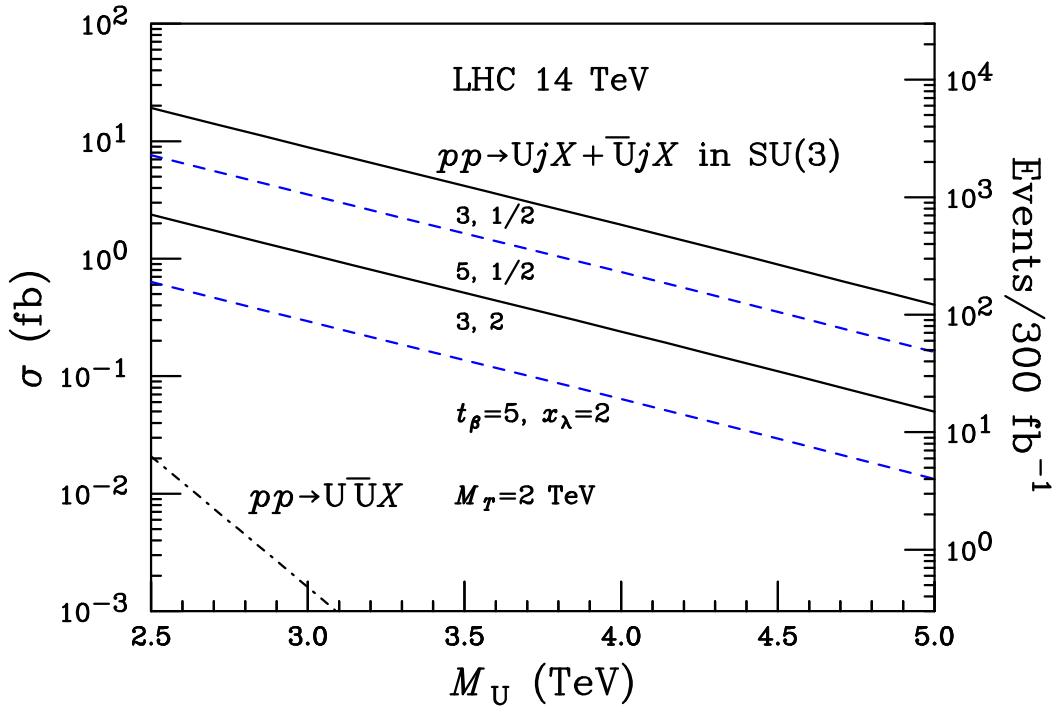
†TH, H. Logan, L.T. Wang, to appear.

Must observe $W^+ d \to U$ or $W^- u \to D$:



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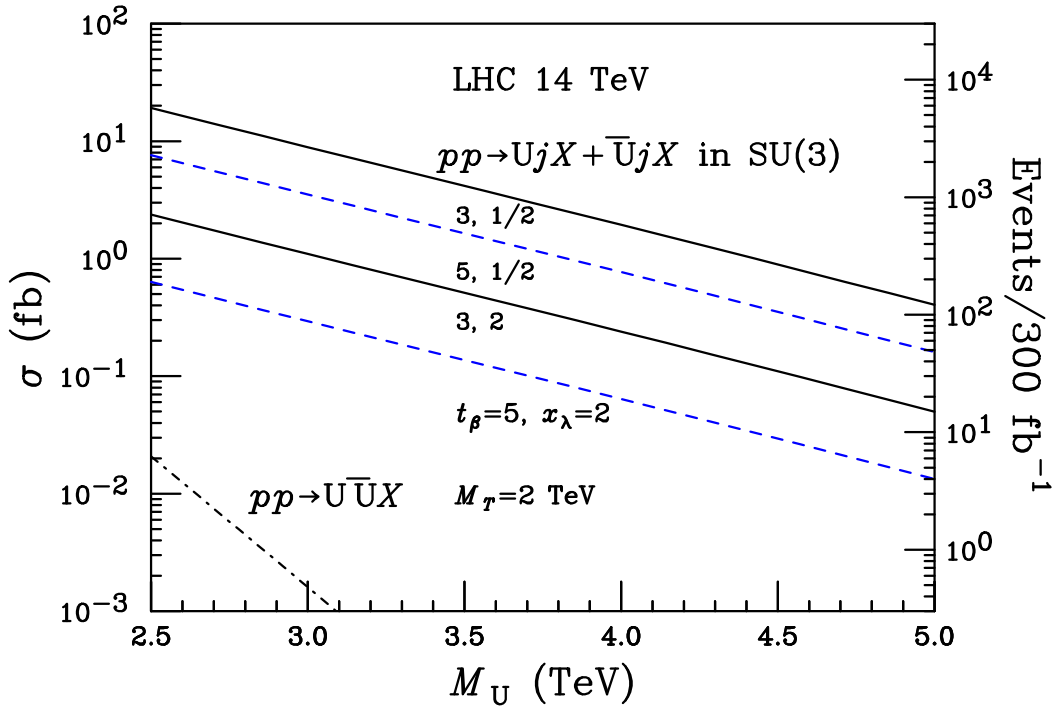

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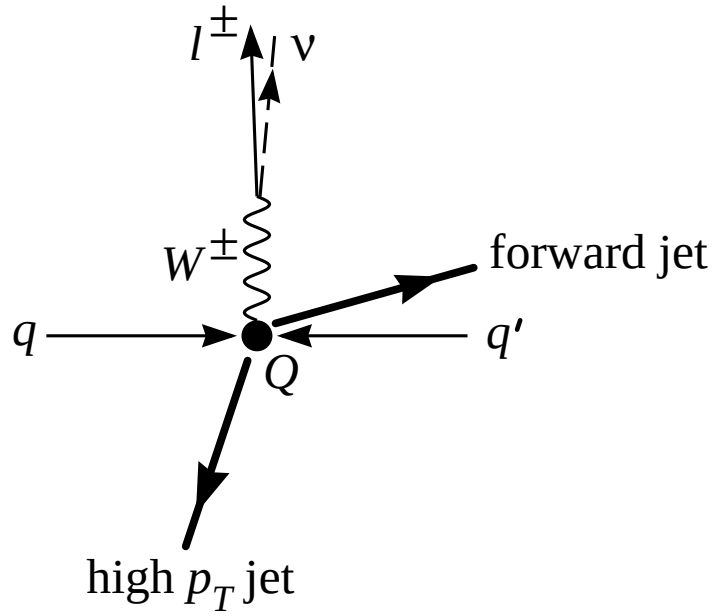
Important to note:

- $\sigma_U \approx 10\sigma_{\bar{U}}$; $\sigma_D \approx 10\sigma_{\bar{D}}$;
- $U \to d\ell^+\nu \Rightarrow$ sequential fermion embedding;
  $D \to u\ell^-\bar{\nu} \Rightarrow$ anomaly-free fermion embedding.

Kinematical features: $W^+ d \to U \to \ell^+ \nu j$:



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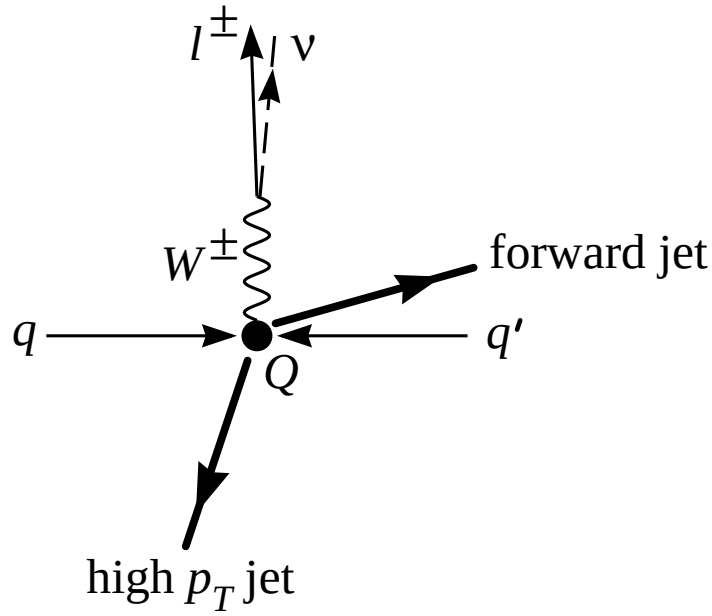

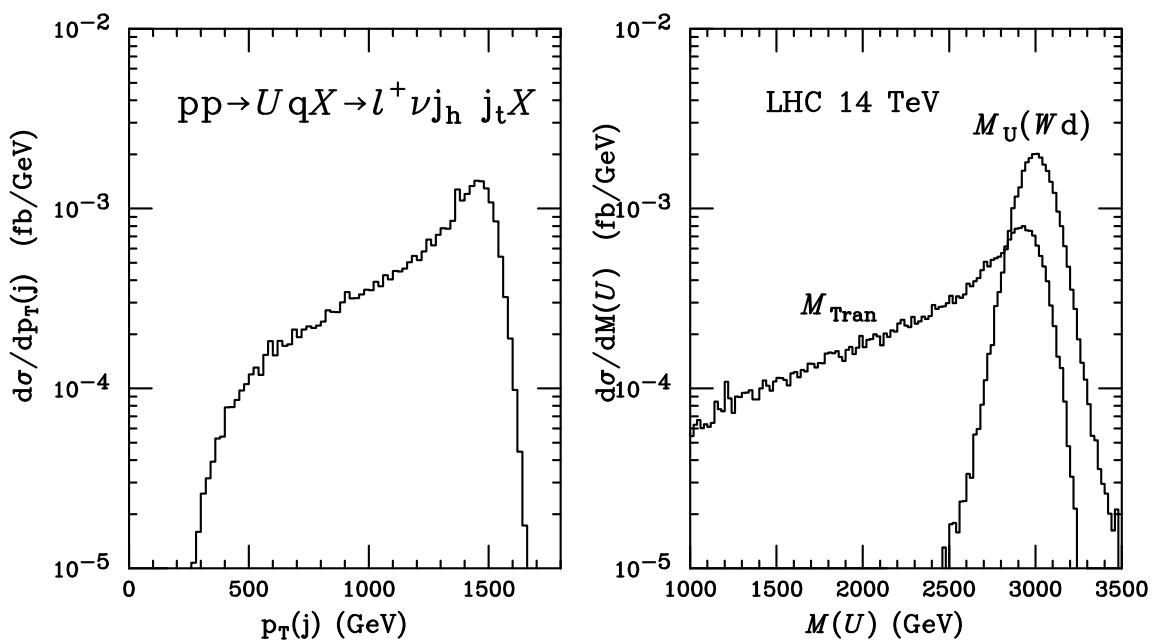

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  Experimental side: TeV $e^{\pm}, \mu^{\pm}$, very fast W, Z decays ...