Physics Beyond the Standard Model

— the Electroweak sector and more...

Tao Han
Univ. of Wisconsin - Madison

CTEQ Summer School, Madison (June 27, 2004)

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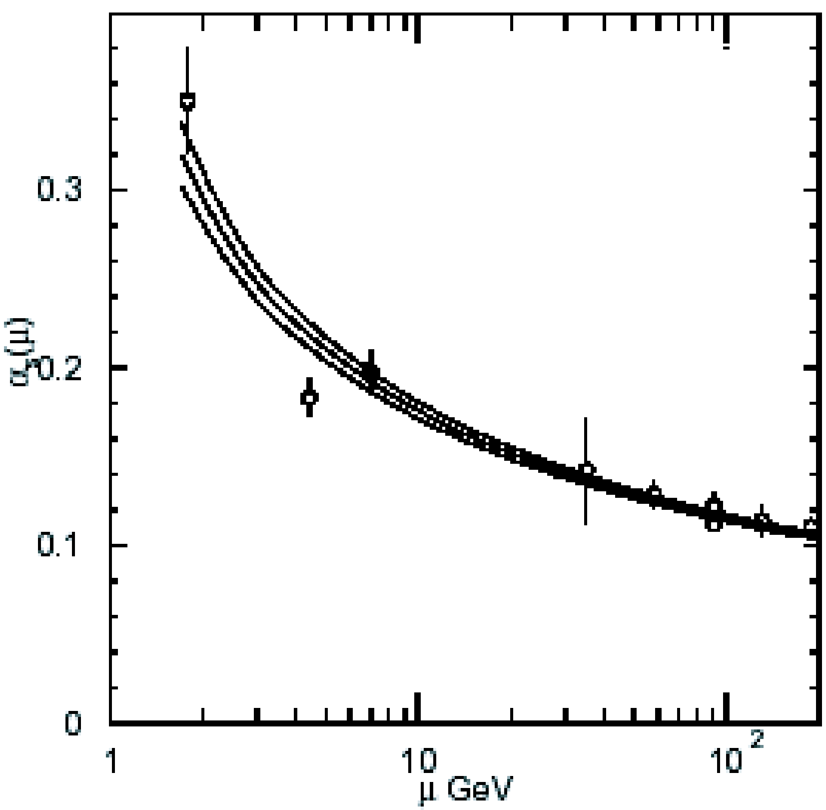
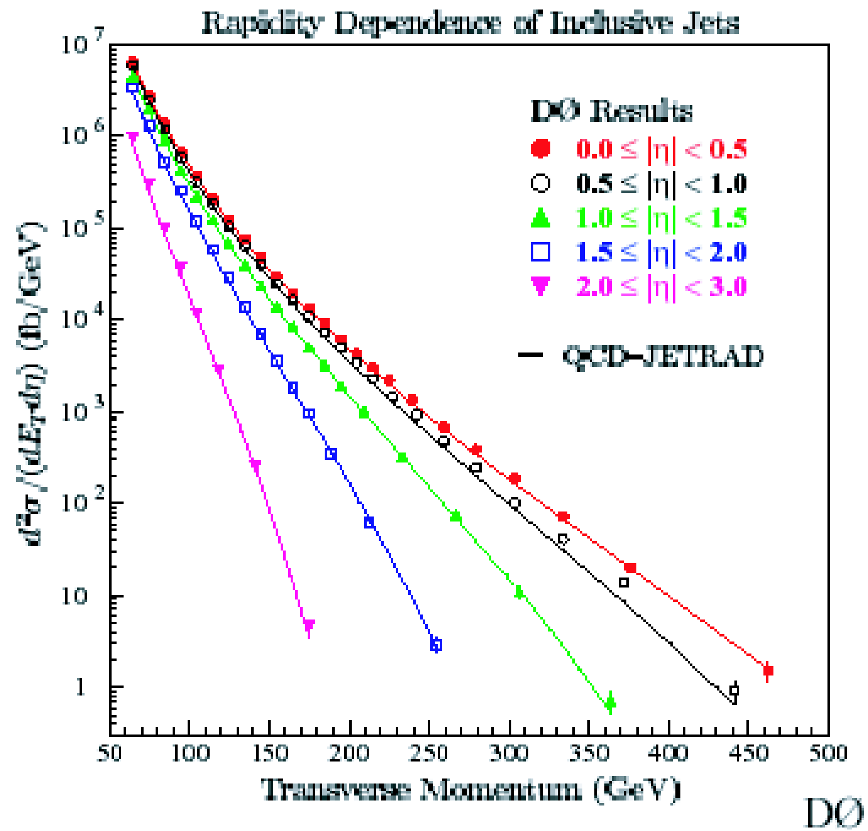
The Standard Model as It Is
The Need For Going Beyond SM
Our “Theory Bank”
Their Signals at the LHC

The Standard Model
as a Low-Energy Effective Theory

- $SU_c(3)$ QCD as the theory of strong interactions:





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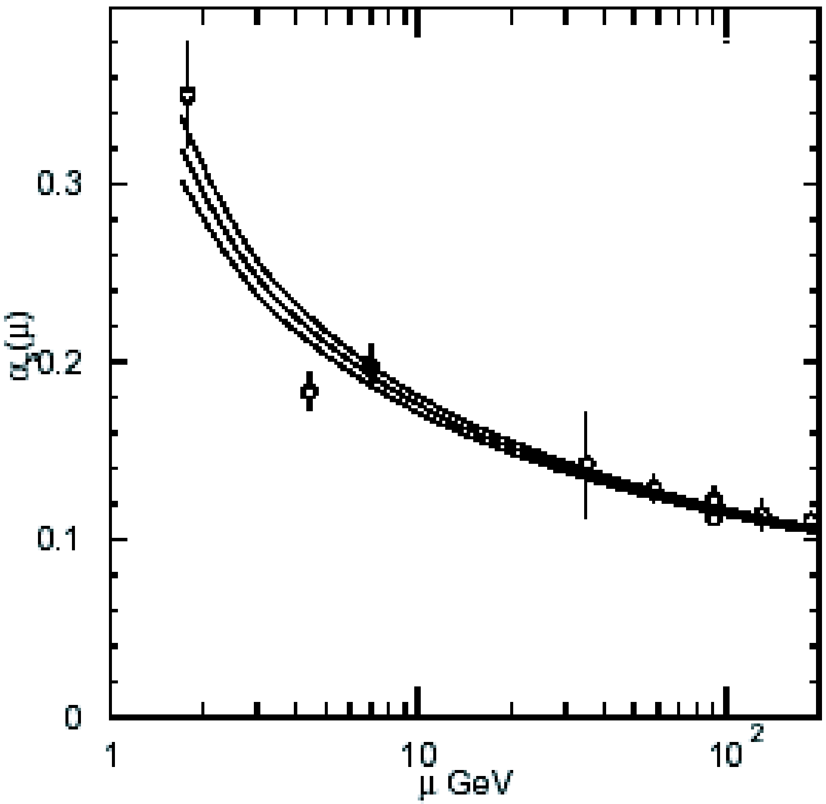
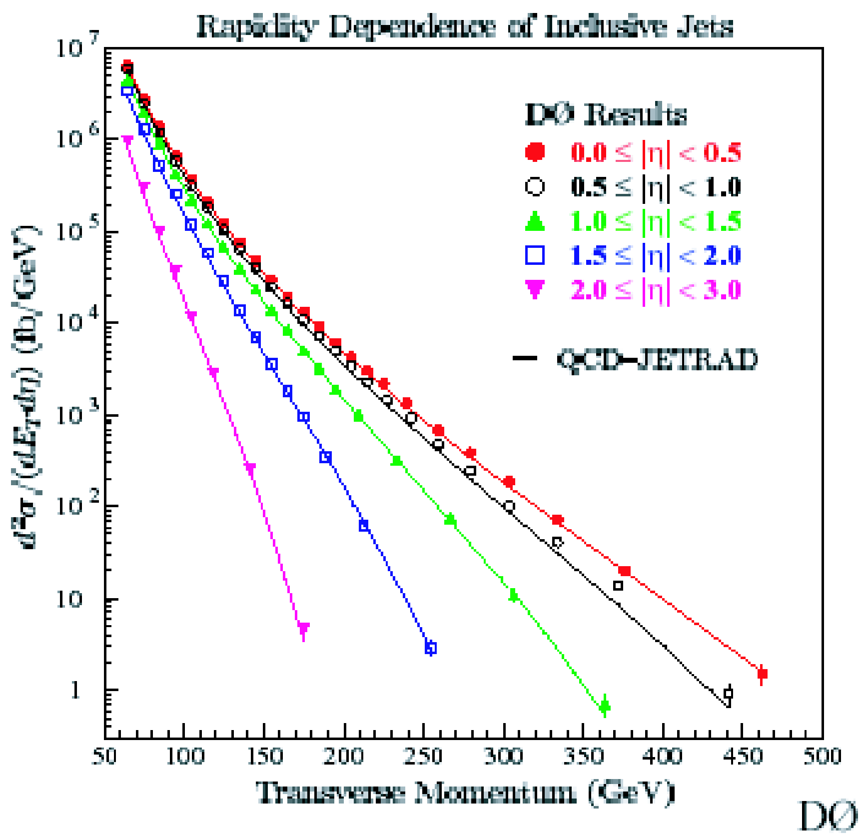




QCD remarkably successfful:

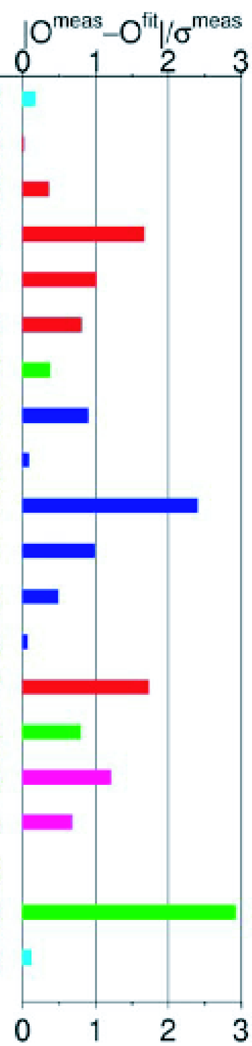
Perturbative QCD well tested and formed foundation for HEP;

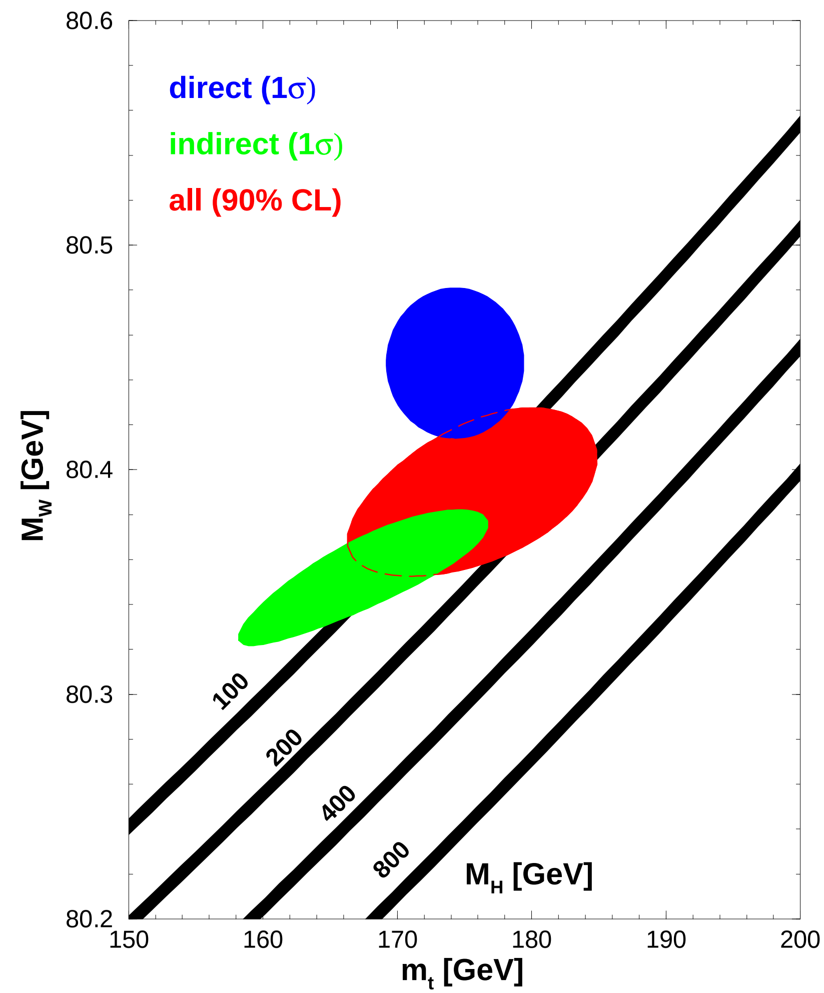
Significant progress in lattice gauge calculatioins.

- $SU_L(2) \otimes U_Y(1)$ EW theory and precision measurements:

Summer 2003

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
Q_W(Cs)	-72.84 ± 0.46	-72.90





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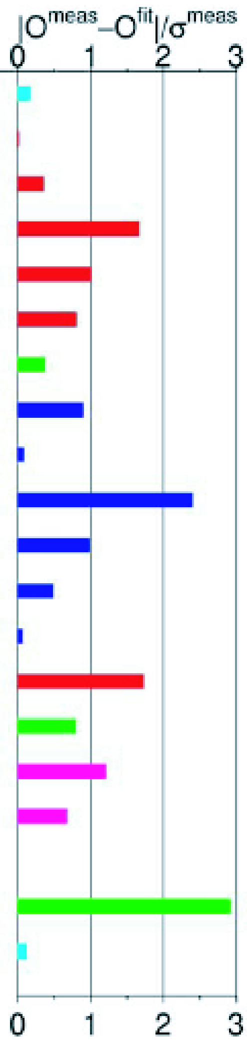
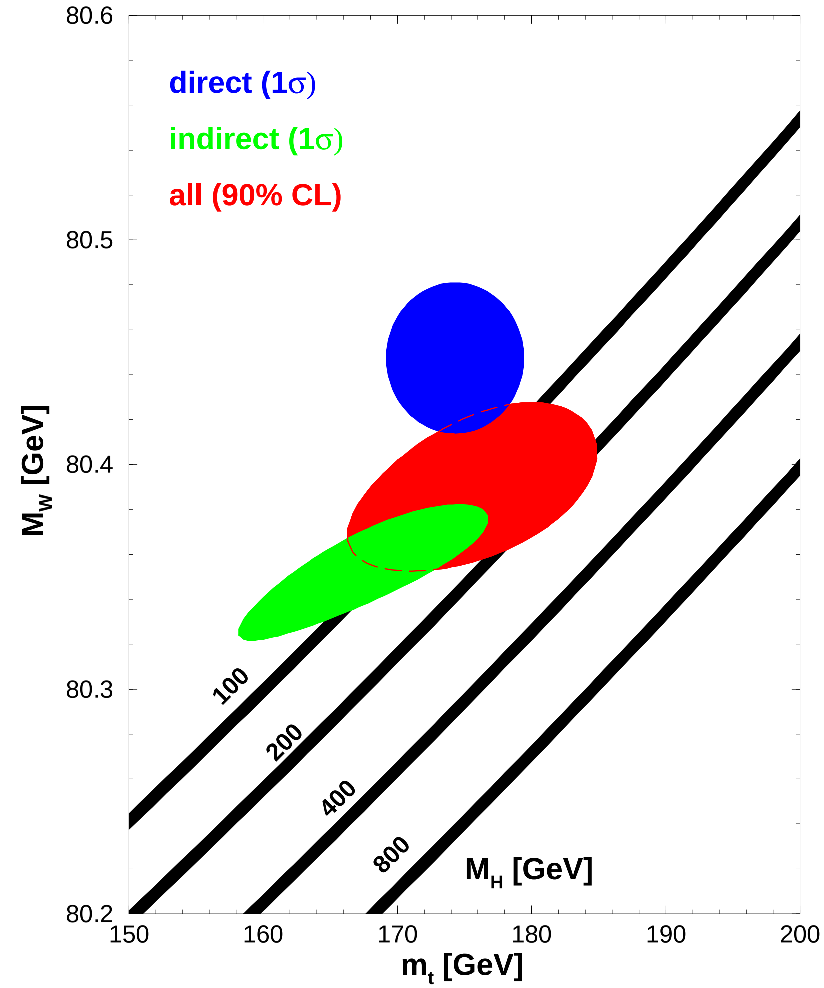


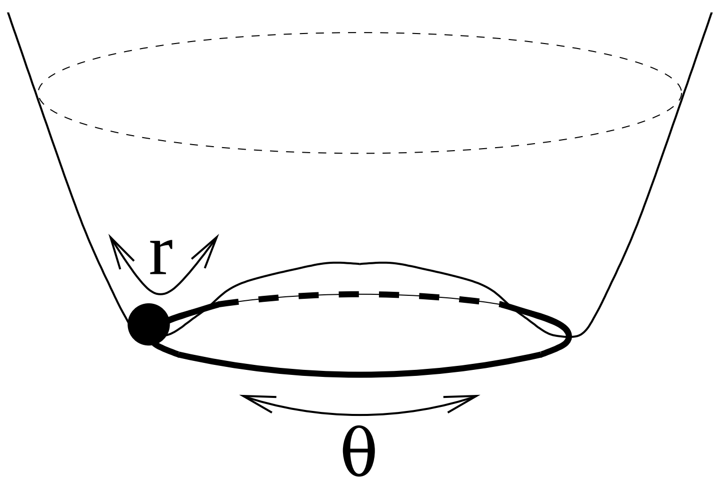


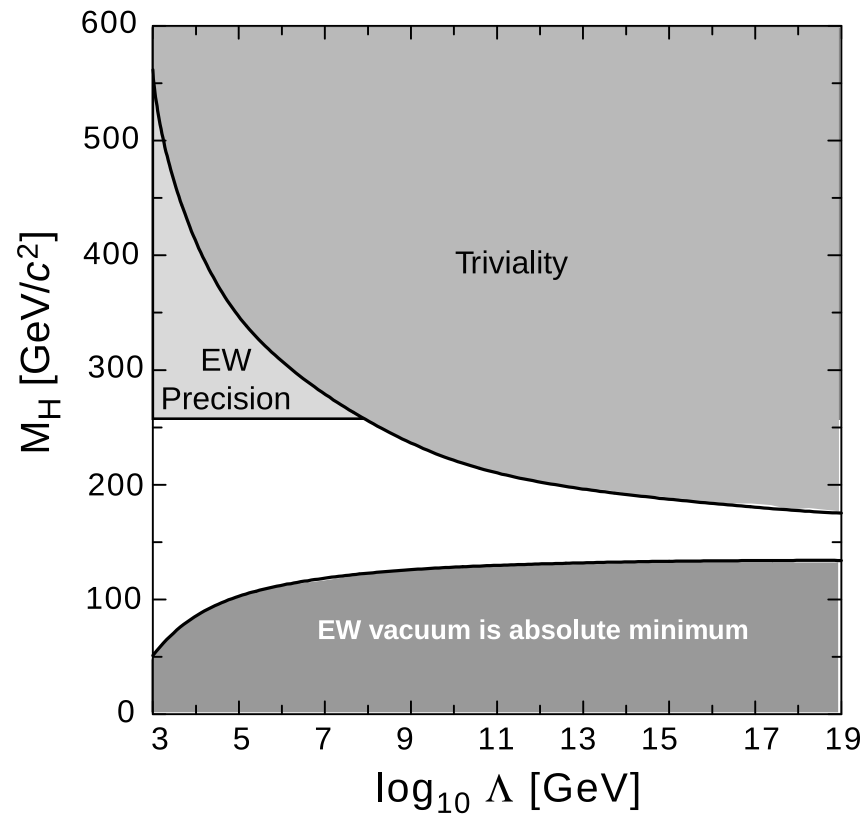
EW precision data: $m_H < 251$ GeV at 95% CL with $m_t = 178$ GeV.

• 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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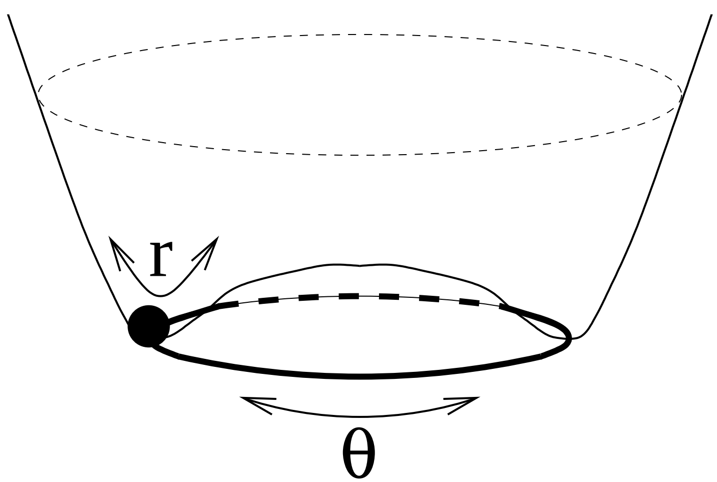
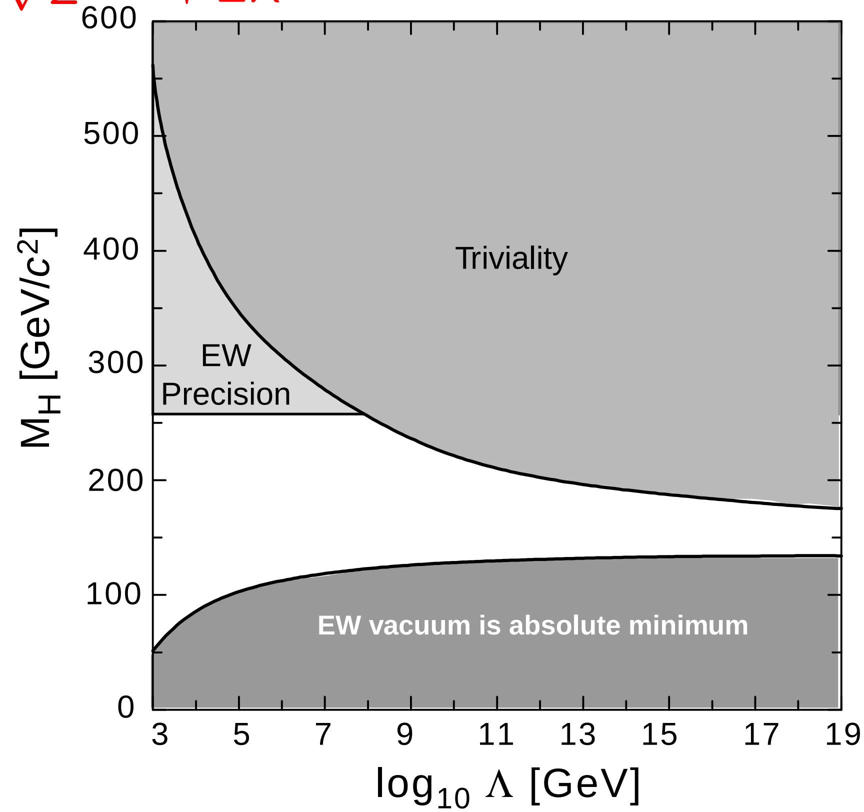




All couplings $g_{2,3}$, $\sin^2\theta_W$, g_f and masses $\sim g_i v$ are in place. SM with a light H could be an *effective theory* to $\Lambda \sim M_{pl}$.

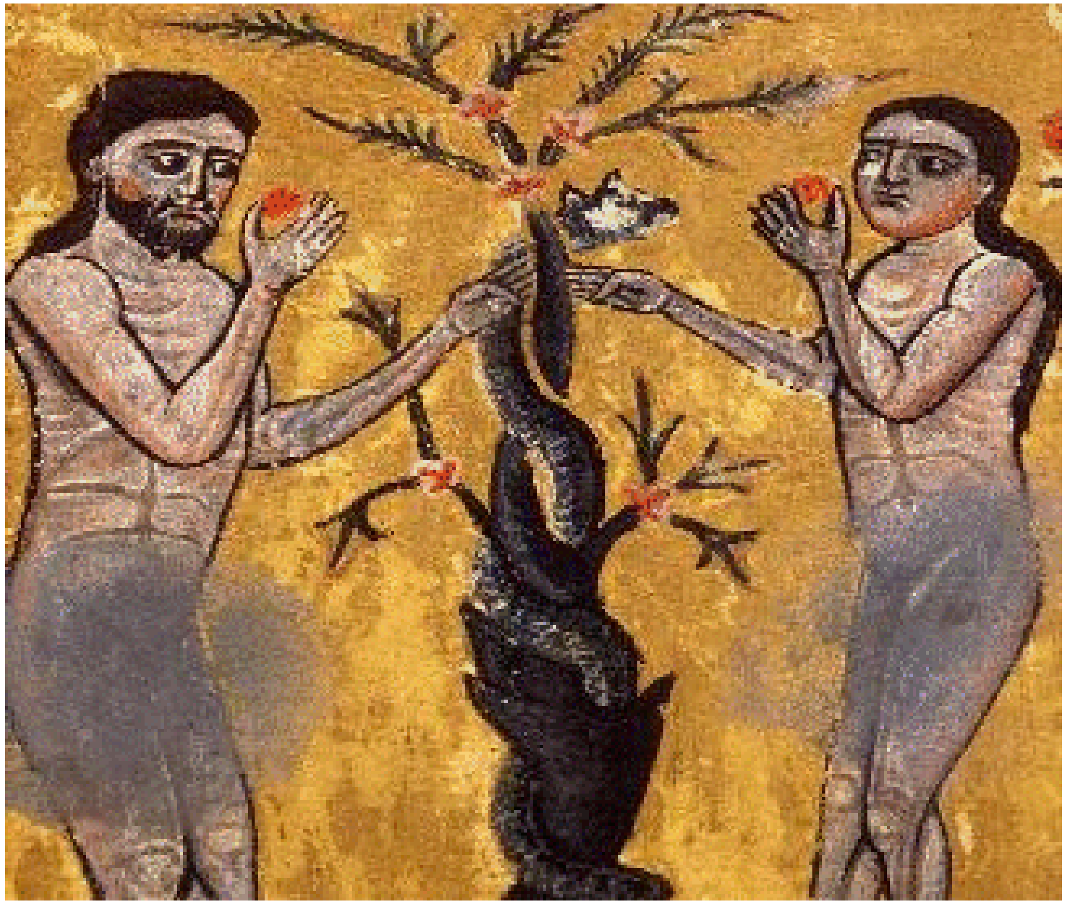
a stable vacuum;

non-trivial interactions;

renormalizability ...

Q: Would you need physics beyond the Standard Model?

A: ... ...



(The Garden of Aden)

The Need For Going Beyond SM ?

Vastly Separated Scales for Fundamental Interactions:

- QCD condensate: f_π

  At the scale Λ_{QCD}, the interaction becomes non-perturbative:

$$f_\pi \propto \langle \bar{q}_L q_R \rangle_0^{1/3} \sim 100 \text{ MeV}.$$

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  Empirically (Fermi's weak interaction) and theoretically (EWSB):

  $$v = \frac{1}{(\sqrt{2}\, G_F)^{1/2}} = \frac{2M_W}{g} \approx 250 \text{ GeV}.$$

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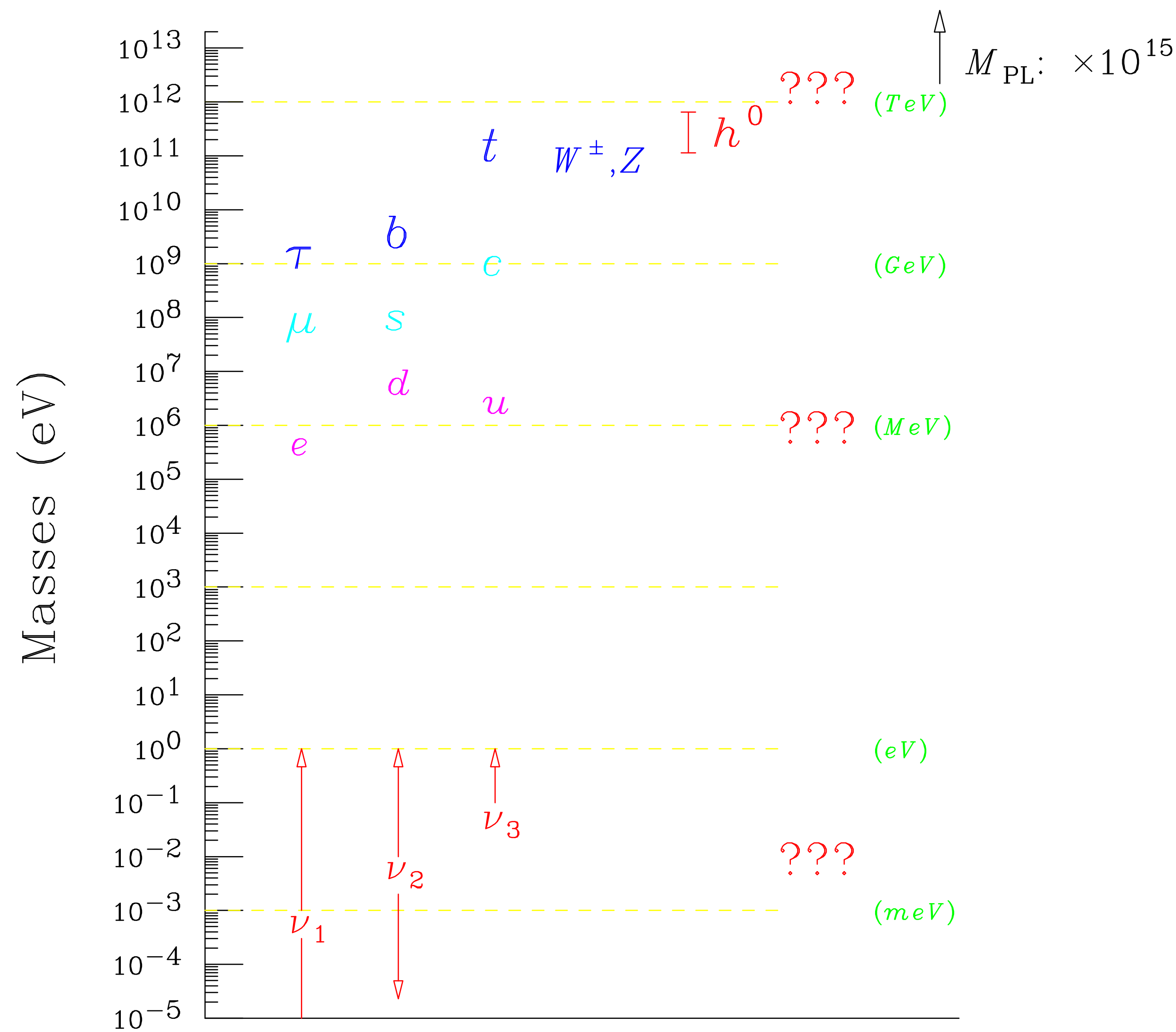
- Quantum Gravity?

  $$M_{Pl} = \frac{\hbar c}{\sqrt{G_N}} \approx 10^{19} \text{ GeV}.$$

  We have NO clue about it ...

Mass Spectrum in a Wide Range:



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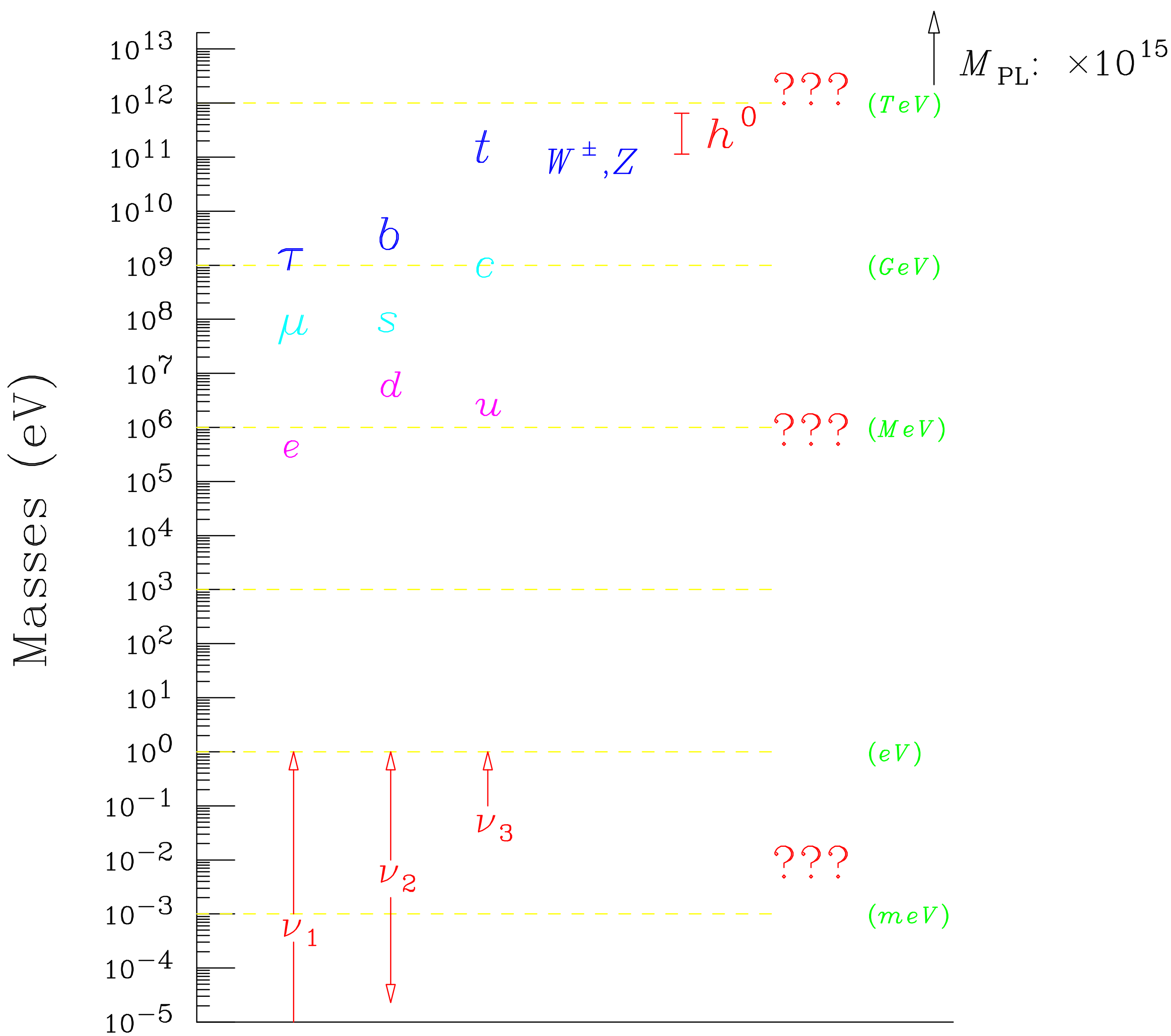
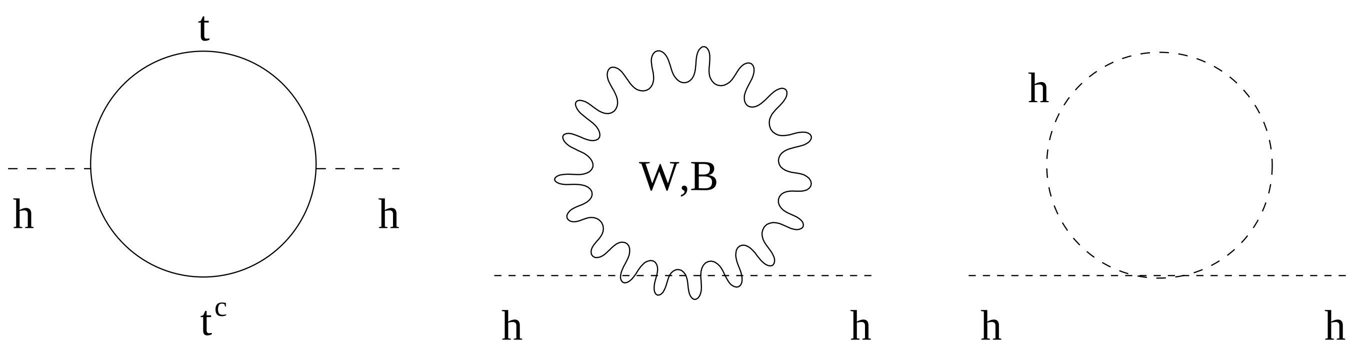


EW scale: $v \approx \mathcal{O}(1\ \text{TeV})$; $m_\nu : 10^{-15}$ down ? $M_{pl} : 10^{15}$ up ?.

The Large Hierarchy: all way up to M_{pl}

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



(a) (b) (c)

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

$$(200 \text{ GeV})^2 = m_{H0}^2 + \left[-(2000 \text{ GeV})^2 + (700 \text{ GeV})^2 + (500 \text{ GeV})^2\right] \left(\frac{\Lambda}{10 \text{ TeV}}\right)^2$$

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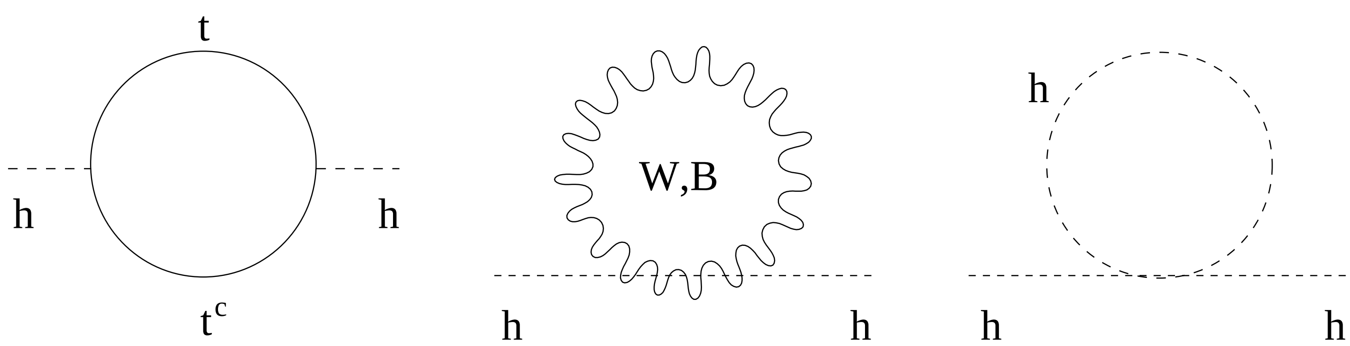

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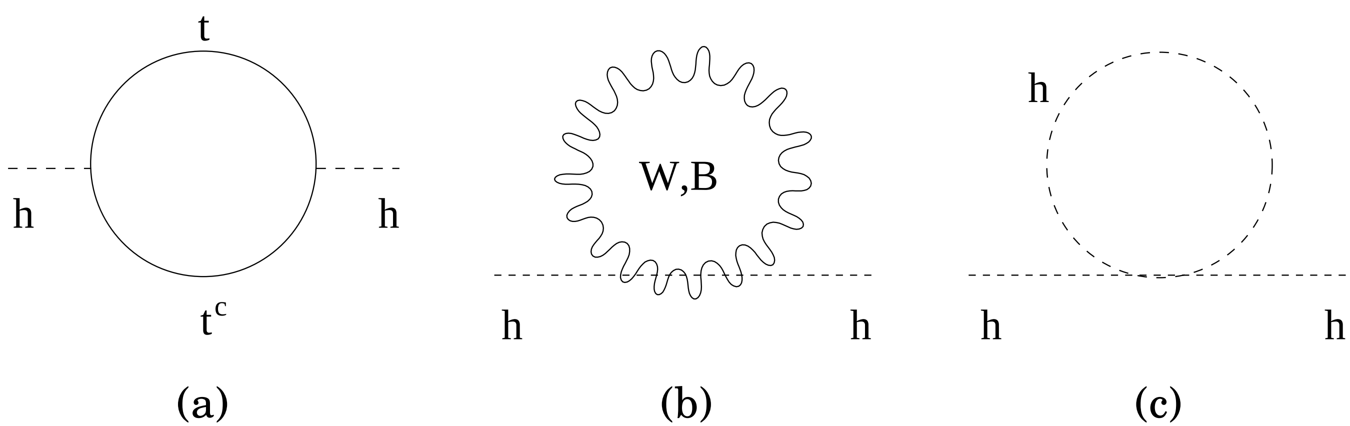

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Naturalness requirement: New physics appears at or below 3 TeV.

Yet Another Large Hierarchy: all way down to m_ν

- The simplest (Majorana) neutrino mass term

$$\frac{y_\nu}{\Lambda} HLHL \sim y_\nu \, \frac{v^2}{\Lambda} \, \overline{(\nu_L)^c} \, \nu_L.$$

Taking $m_\nu \lesssim 1$ eV,

$$\Longrightarrow \; \Lambda \sim y_\nu \, \frac{2v^2}{m_\nu} \gtrsim y_\nu \; (10^{14} \text{ GeV}).$$

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The smaller the fermion masses are, the larger the new physics scale is!

Physics way beyond the SM!

The "Little Hierarchy": $4\pi v - \Lambda_{new}$

On the one hand, the "naturalness" argument prefers

$\Lambda_{ew} \lesssim 4\pi v$, just like in QCD: $\Lambda_{QCD} \lesssim 4\pi f_\pi$.

On the other hand,

- EW precision data indicate "decoupling" behavior [*]

  $$\Lambda_{ew} \gtrsim 2 - 10 \text{ TeV}.$$

  (based on generic dim-6 operators.)

- FCNC ($K^0 - \bar{K}^0$ mixing etc.) constraints set

  $$\Lambda_{flavor} \gtrsim 70 - 100 \text{ TeV}.$$

  (based on generic strong dynamics,[†] or generic MSSM[‡])

[*] Barbieri, Strumia, hep-ph/9905281.

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$\Longrightarrow$ imply special structure or symmetry.

Physics just beyond the SM!

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Theoretical issues to address:

- Vastly different mass scales:
  - EW gauge symmetry breaking;
  - charged fermion masses;
  - neutrino masses.
- Nontrivial fermion structure:
  - three fermion generations;
  - quark small mixing; neutrino (nearly) maximal mixing;
  - CP violation.
- Unified description:
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$\Longrightarrow$ All indicate the need for physics beyond the SM.

Our “theory bank”

Let’s focus on the EWSB sector.

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(A). Dynamical approach for mass generation:

- Technicolor: a lesson from QCD
  SU(N_{TC}) gauge theory, TC fermions $Q = U, D, ...$
  EWSB by TC-fermion condendation at Λ_{TC}:

$$v \sim \langle \overline{Q_L} Q_R \rangle^{1/3} \sim 246 \text{ GeV}.$$

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× leads to too large radiative corrections:

$$S \approx 0.25 N_{TC}, \text{ while } S_{exp} \sim -0.07 \pm 0.11.$$

× no fermion masses.

- Extended Technicolor:* for fermion mass generation
  G_{ETC} gauge theory, ETC fermions: $U, D, ..., \quad u, d...$
  After intrgrating out ETC gauge bosons at the scale Λ_{ETC},
  with TC-fermion condensate,SM fermion mass generated:

$$m_f \sim \langle \overline{Q_L} Q_R \rangle / \Lambda_{ETC}^2 \sim \Lambda_{TC}^3 / \Lambda_{ETC}^2.$$

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For a review, Hill and Simmons

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$\times$ a devastating problem:

On the one hand: small FCNC: $\frac{1}{\Lambda_{ETC}} < \frac{1}{10^3 \text{ TeV}}$.

on the other hand, heavy quark $m_c \sim 1$ GeV $\Rightarrow \Lambda_{ETC} < 30 \times \frac{\Lambda_{TC}}{1 \text{ TeV}}$

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$\Longrightarrow$ Non-QCD like: Walking TC

TC gauge coupling running very slowly.

$\langle \overline{Q_L} Q_R \rangle$ almost constant over $\Lambda_{TC} - \Lambda_{ETC}$.

$\langle \overline{Q_L} Q_R \rangle_{ETC}$ enhanced by 100–1000.

*Eichten and Lane;
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- "Topcolor/Top-seesaw": Top quark special ?

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Introducing an additional fermion pair $\chi_L,\ \chi_R$:

(1) topcolor[*] generates the condensation $H \sim (\bar{\chi}_R t_L,\ \bar{\chi}_R b_L)$

$\Rightarrow$ EWSB and a heavy Higgs $m_H \sim 1$ TeV.

(2) topseesaw[§] leads to a SM t, and a heavy state χ, with $M_\chi \approx 4$ TeV.

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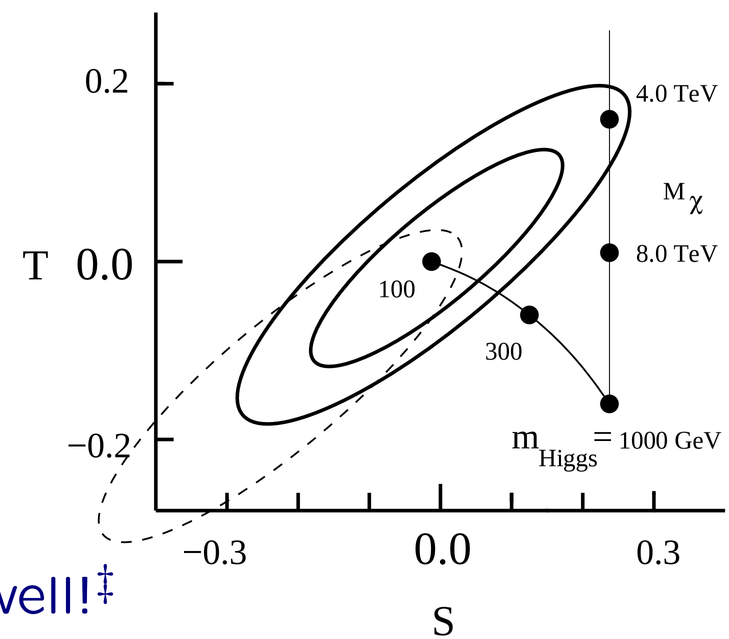

fit EW precision data well![‡]

[*]C. Hill.

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[‡]H.-J. He, C. Hill, T. Tait.

- A less ambitious approach: Little Higgs Models
  Accept the existence of a light Higgs;
  keep the Higgs boson "naturally" light (at 1-loop level).

† 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

† 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!)

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

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† Higgs is a pseudo-Goldstone boson from global symmetry breaking (at scale $4\pi f$)‡

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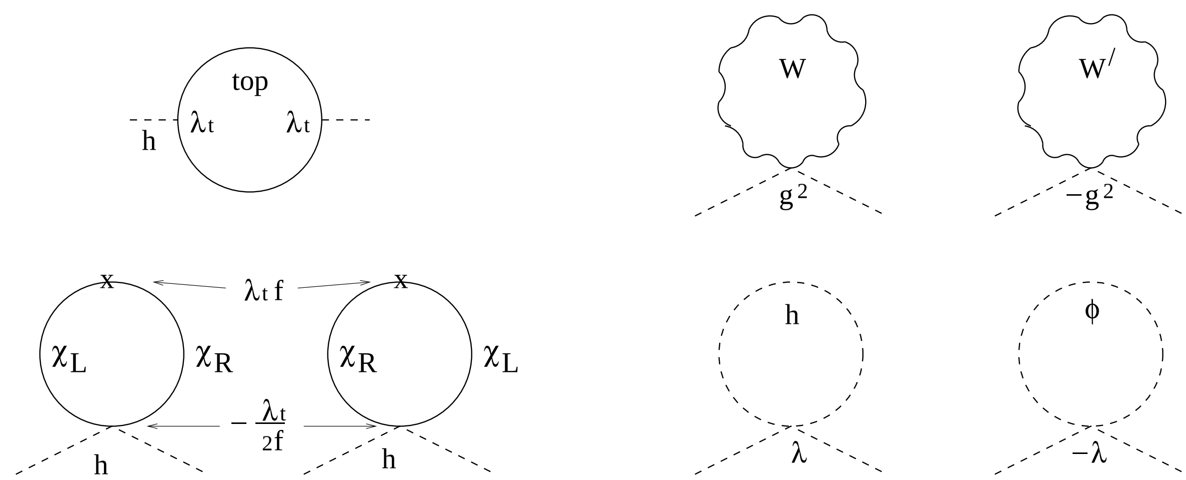
† Consequently, quadratic divergences absent at one-loop level*

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

(cancellation among same spin states!)



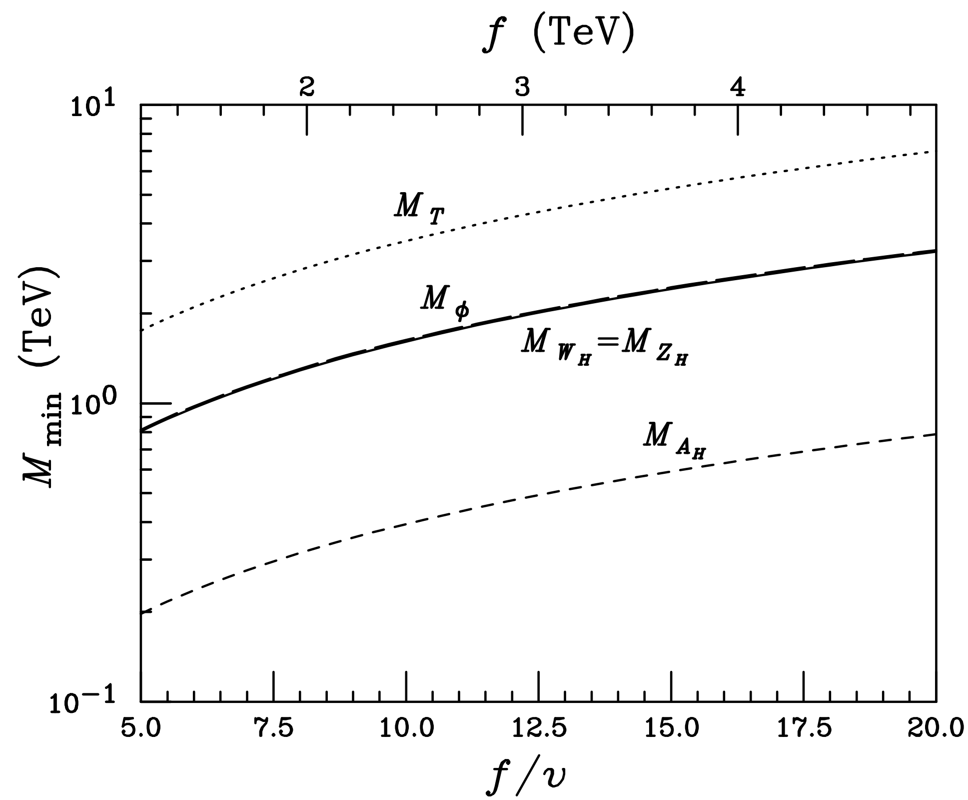
An alternative way to keep H light (naturally)

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

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

New heavy states in the littlest Higgs:

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



($m_h \approx 115$ GeV)

(B). Weak-scale Supersymmetry:

A natural cancellation mechanism:

Symmetry between *opposite* spin & statistics

$\tilde{t}$ versus t

$\tilde{W}$ versus W

$\tilde{H}$ versus H

H_d versus H_u,

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H_d versus H_u,

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

Weak scale SUSY stabilizes the hierarchy $M_W - M_{pl}$

only if the "soft-SUSY breaking": $M_{SUSY} \sim \mathcal{O}(M_{SM})$.

$\surd$ predict TeV scale new physics:

light Higgs bosons H^0, A^0, $H^\pm$; SUSY partners $\tilde{W}^\pm$..., $\tilde{g}$, $\tilde{q}$, $\tilde{l}^\pm$...

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$$M_Z^2/2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2.$$

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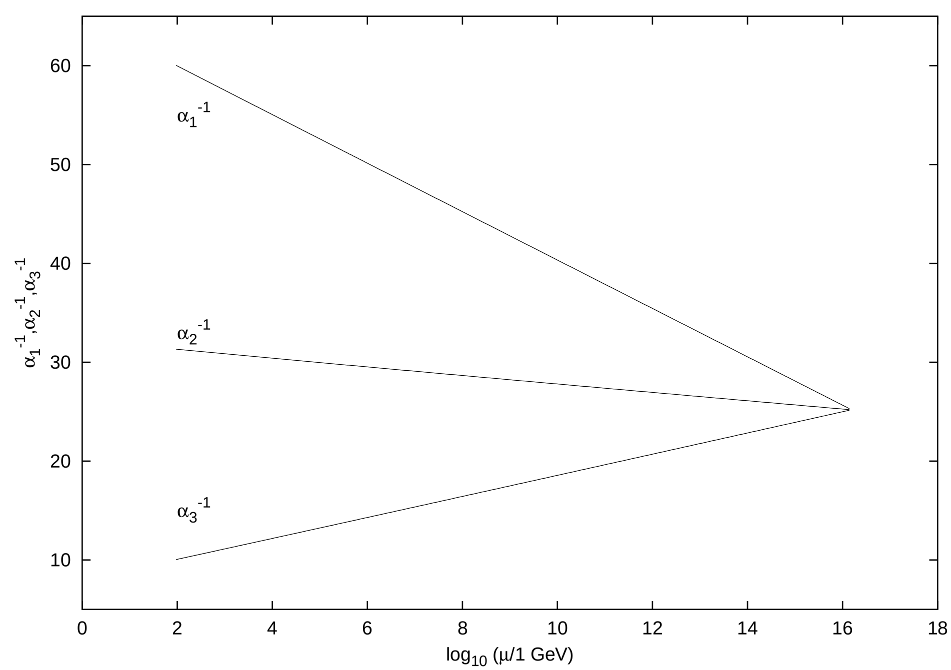

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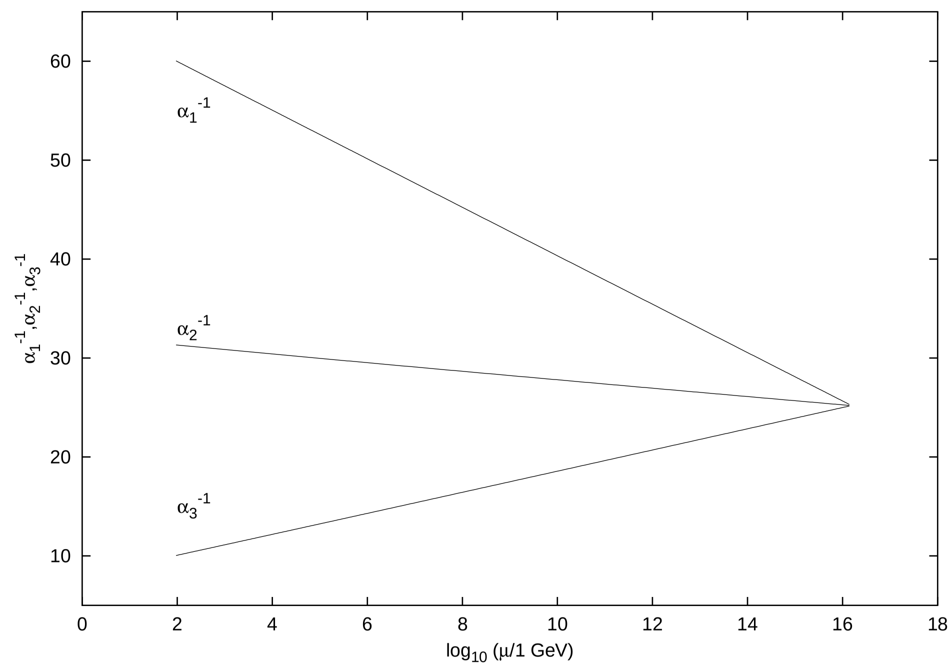

√ The "LSP" is a good dark matter candidate $\tilde{\chi}^0 \sim \tilde{B}$.

What about M_{SUSY}?

× Supersymmetry breaking mechanism is unknown.
Merely (124?) free parameters;
most part of the parameter-space ruled out.

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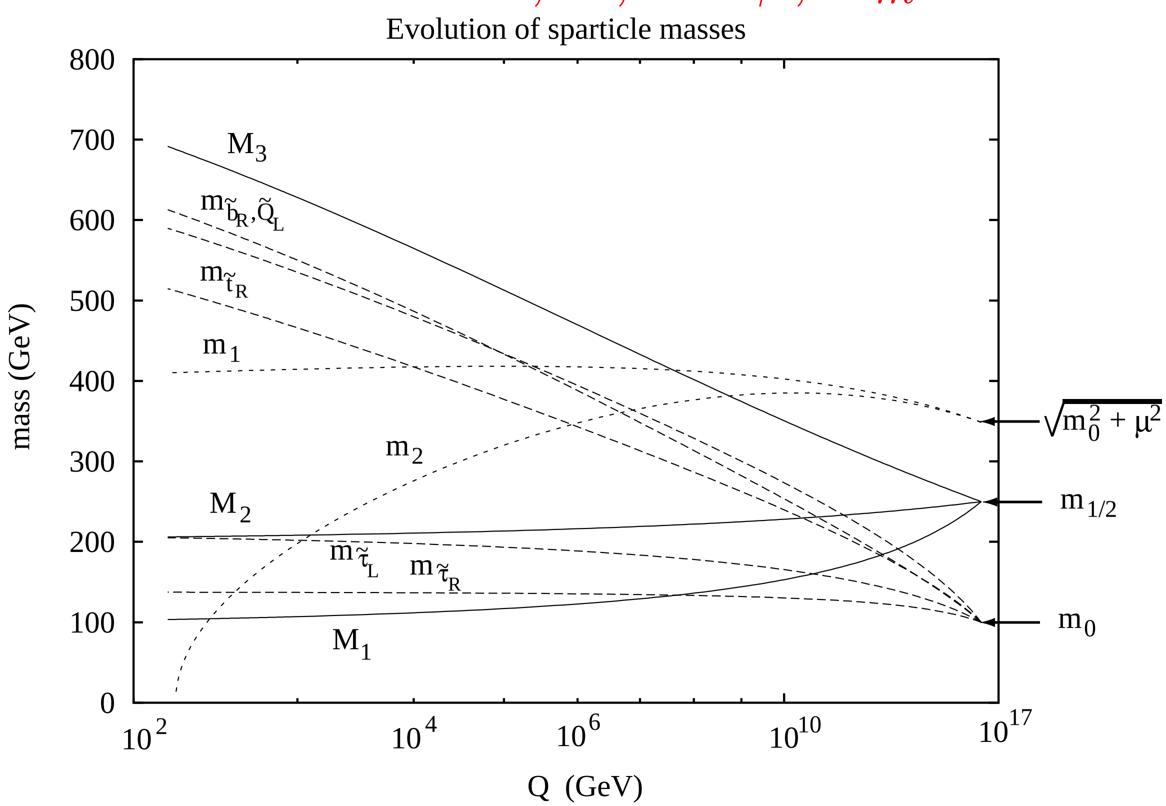
Assumption on the parameters: SUSY breaking in a hidden sector

(*) mSUGRA scenario: m_0, $m_{1/2}$, A, $\tan\beta$, and $sign(\mu)$

(*) Gauge mediation scenario: M, F, $\tan\beta$, n_m.

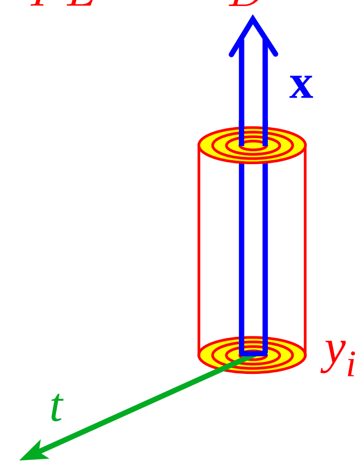


(C). Extra-dimensions:
A new approach to the hierarchy problem

- Large Extra-dimension Scenario; ADD*

In a world with $D = 4 + n$ dimensions, the 4-dim Planck scale is related to the D-dim one M_D as

$$M_{PL}^2 \sim M_D^{n+2} V_n.$$



*N. Arkani-Hamed, Dimopoulos, Dvali

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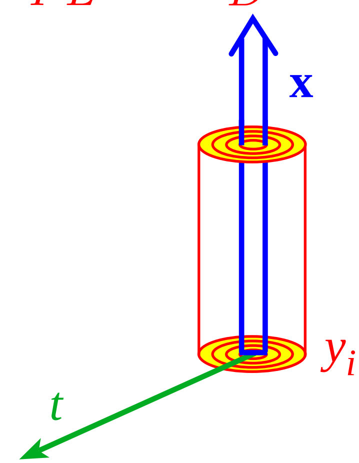

Thus the fundamental scale:

$$M_D \sim (M_{pl}^2 / V_n)^{n+2} \longrightarrow \mathcal{O}(1\ \text{TeV}).$$

or the radius:

$$R \sim \frac{M_{pl}^{2/n}}{M_D^{2/n+1}} \approx \begin{cases} \mathcal{O}(0.1\ mm) & \text{for } n = 2 \\ \mathcal{O}(1.0\ fm) & \text{for } n = 7 \end{cases}$$

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- "Warped" Extra-dimension Scenario; the Randall-Sundrum model

In a 5-dim space, Randall and Sundrum found a static solution of the form:*

$$ds^2 \sim e^{-2ky}\ \eta_{\mu\nu}\ dx^\mu dx^\nu - dy^2,$$

where k is the curvature scale in the 5^{th}-dim.

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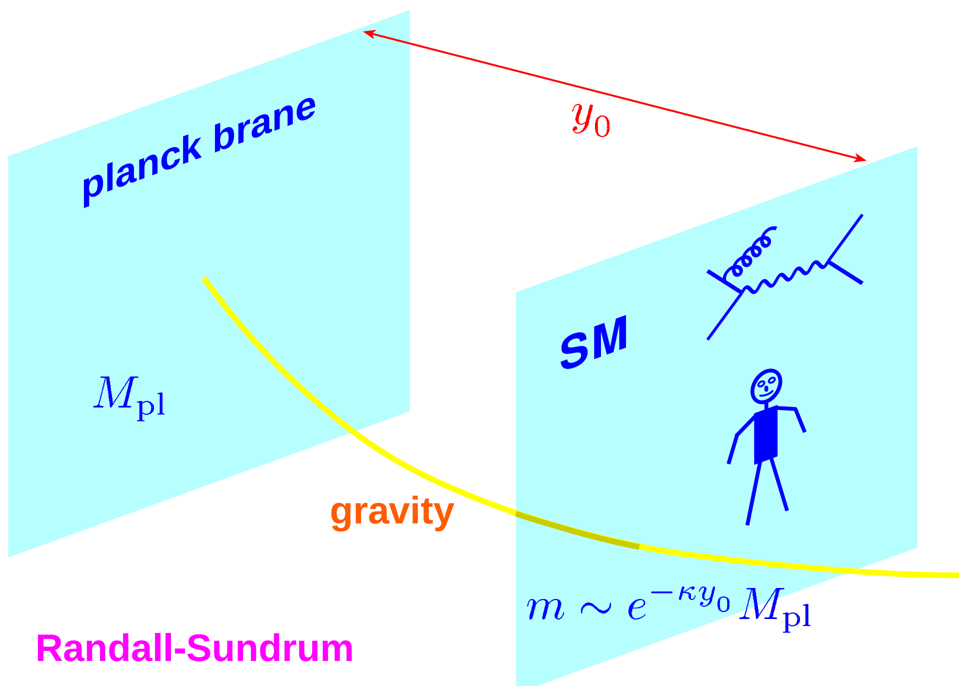
The extra dimension y is “warped”.



$$M = e^{-ky} M_{pl}.$$

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  Symmetry breaking by boundary conditions/terms

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5d SUSY GUTs model, with SUSY/GUT symmetry breaking by orbifolding on the boundary.

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5d non-SUSY model, with gauge symmetry breaking by orbifolding/boundary condition.
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Particularly interesting: AdS/CFT correspondence

5d AdS theory $\Longleftrightarrow$ 4d strongly interacting walking TC!

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- Observable signatures for extra-dim models:

▷ At “low” energies

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$(4+n)-$dim physics directly probed, and gravity effects observable:* mainly via light KK gravitons of mass

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or whatever propagate there ⇒ an effective theory (SM+KK).

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▷ Intermediate energy regime $E \sim M_D$: stringy states significant:† s-channel poles as resonances:†

$$\mathcal{M}(s,t) \sim \frac{t}{s - M_n^2}, \quad M_n = \sqrt{n} M_S.$$

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†G. Shui and H. Tye (1998); K. Benakli (1999).

† Accomando, Antoniadis, Benakli (2000); Cullen, Perelstein, Peskin (2000).

▷ At "trans Planckian" energies $E > M_D, M_S$:
$(4+n)$–dim physics directly probed;
gravity dominant: black hole production[‡]

$$\sqrt{s} = M_{BH} > M_D \text{ for } b < r_{bh}.$$

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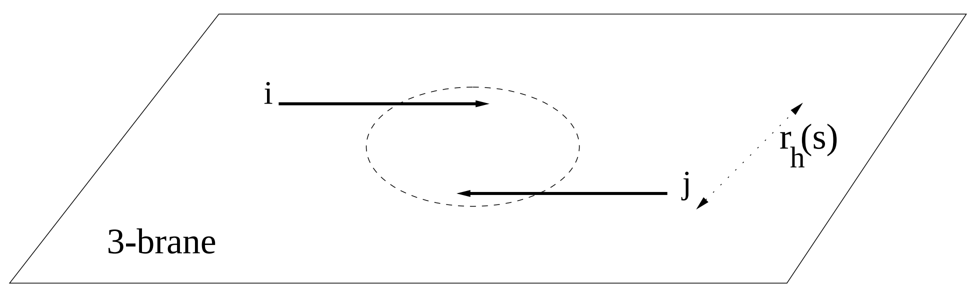
$$r_{bh} = \frac{1}{\sqrt{\pi} M_D} \left[\frac{M_{BH}}{M_D} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right) \right]^{\frac{1}{n+1}} \to M_{BH}/M_{pl}^2 \text{ in 4d}$$
$$\sigma = \pi r_{bh}^2.$$



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Yet more to come:

Tevatron: EW, top sector, Higgs (?), new particle searches...

LHC: Higgs studies, comprehensive new particle searches...

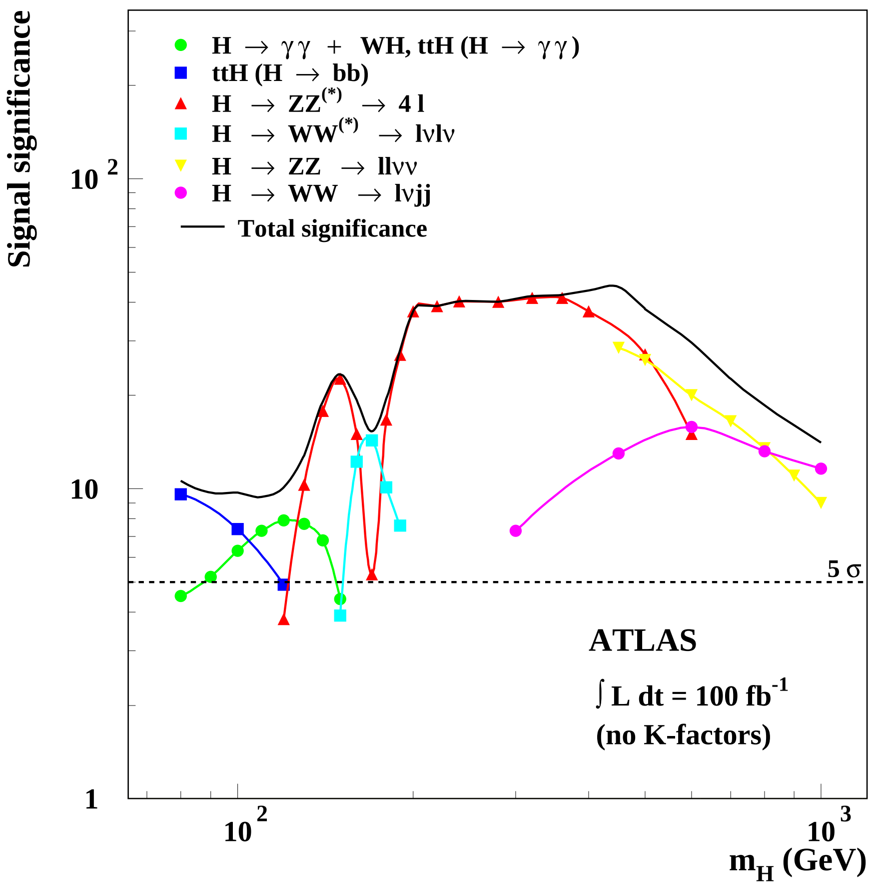
LC: more on top sector, precision Higgs and new light particles...

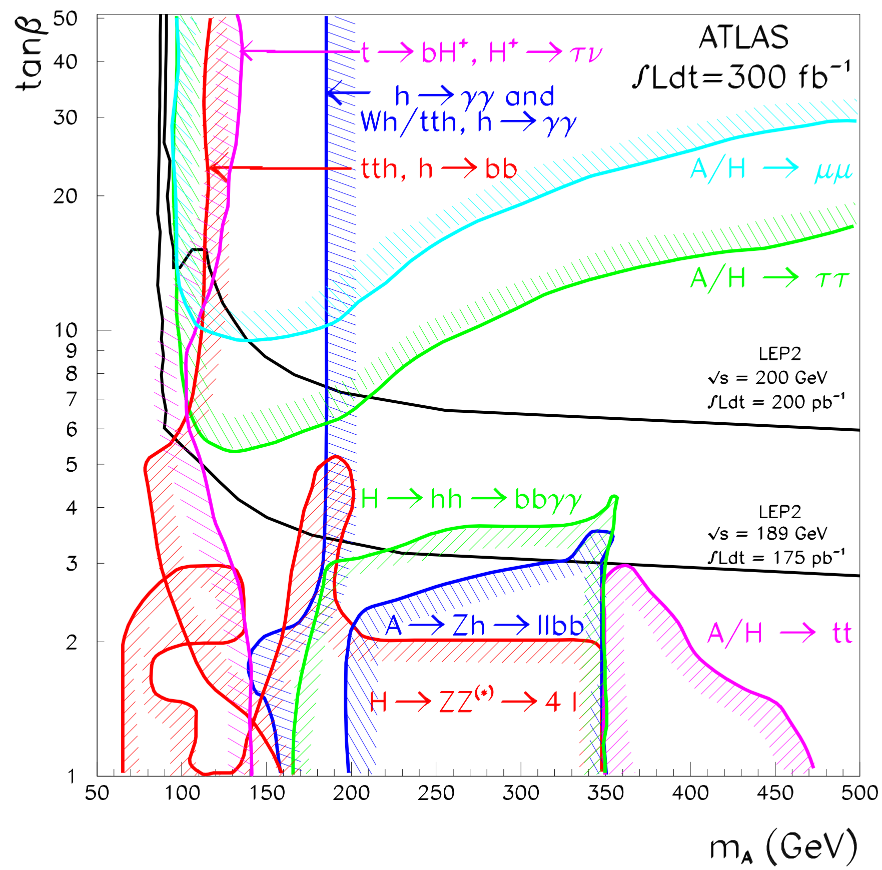
Other complementary experiments: non-accelerators ...

New Physics at Future Hadron Colliders

For any scenario beyond SM, LHC WILL contribute:

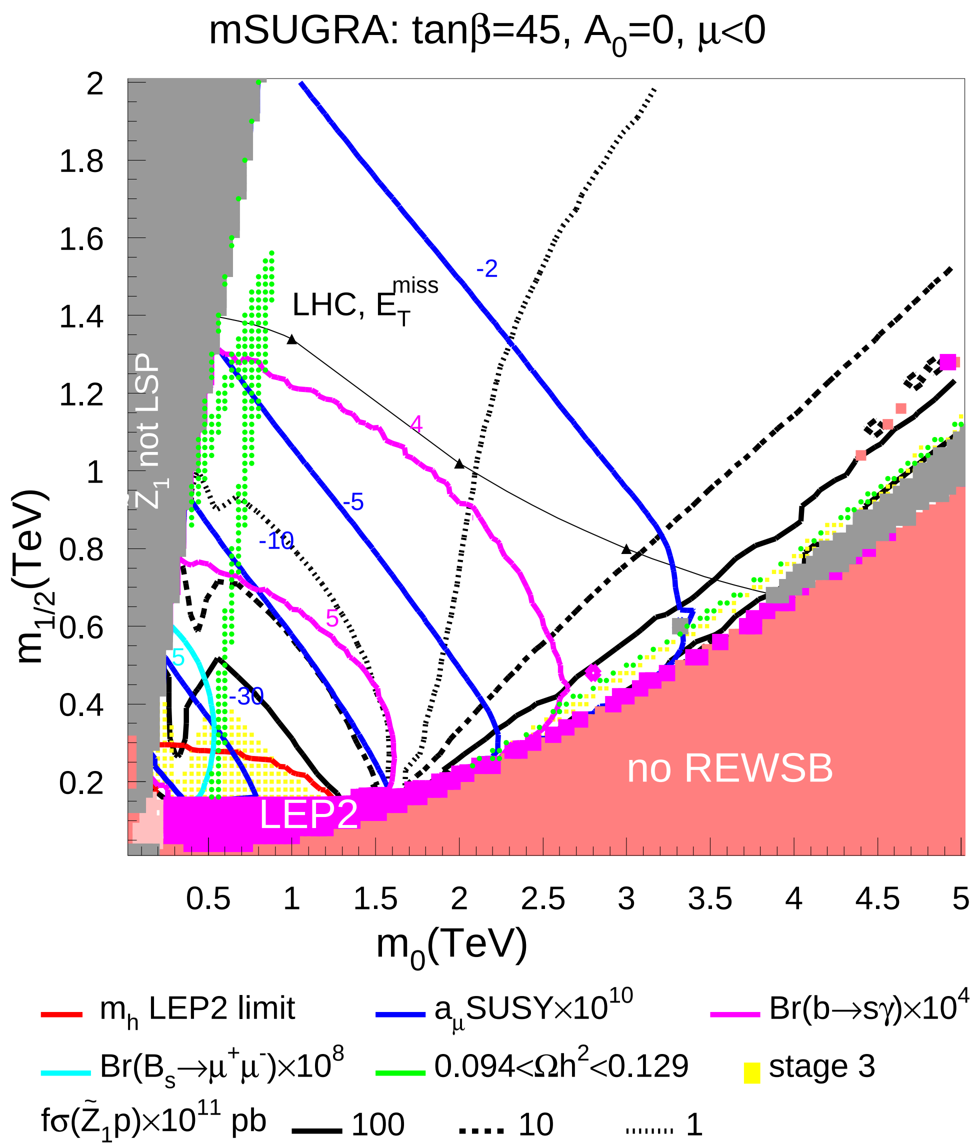
- Higgs fully covered at the LHC:





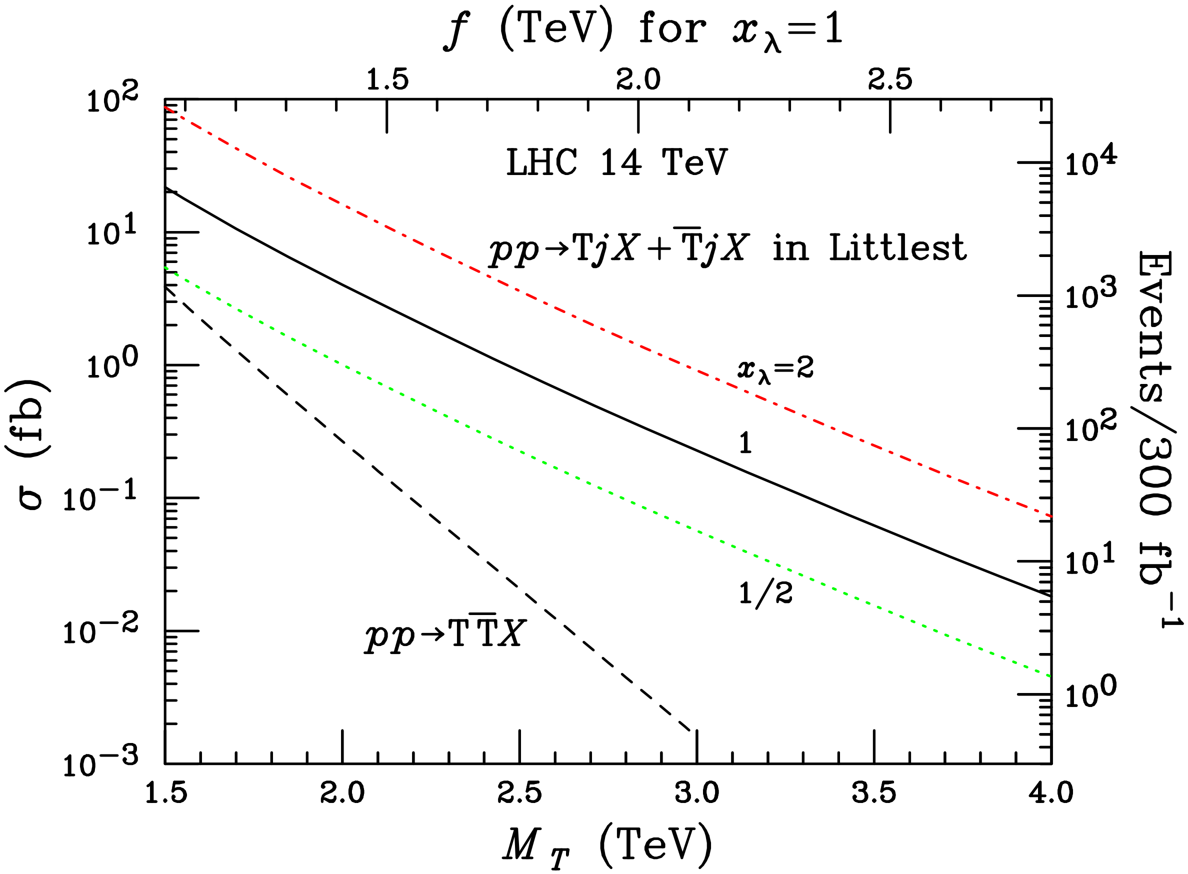
- LHC will have great chance for SUSY discovery: *

$m_0 > 4000$ GeV, $m_{1/2} > 1400$ GeV, $\tan\beta \gtrsim 45$.



*Baer, Balazs, Belyaev, O'Farrill, hep-ph/0305191.

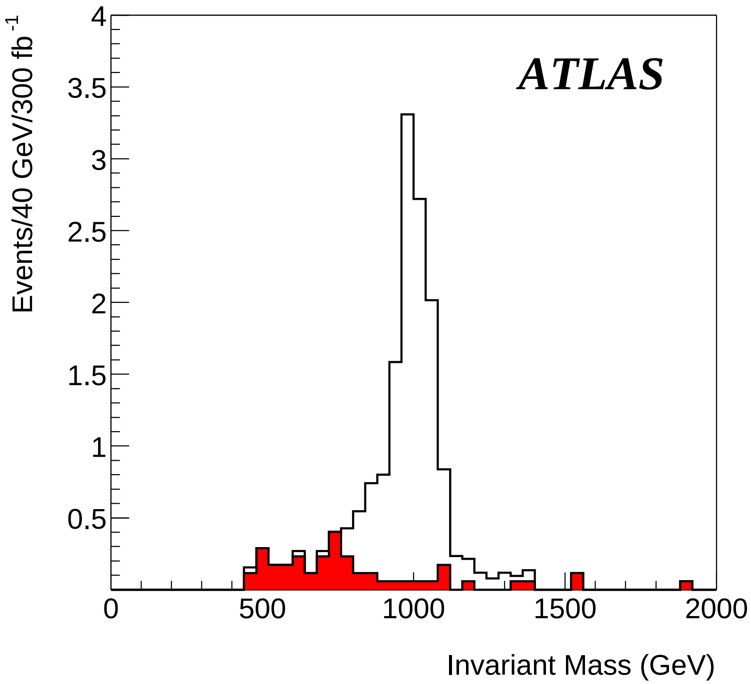
- LH: The heavy T signal at LHC

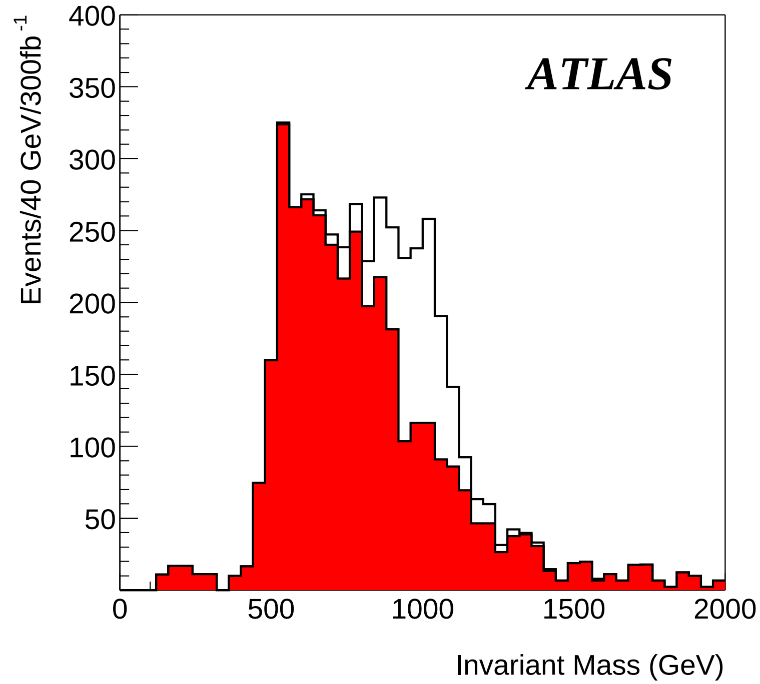


$gg \to T\bar{T}$ phase-space suppression;

$qb \to q'T$ via t-channel $W_L b \to T$.

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





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

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

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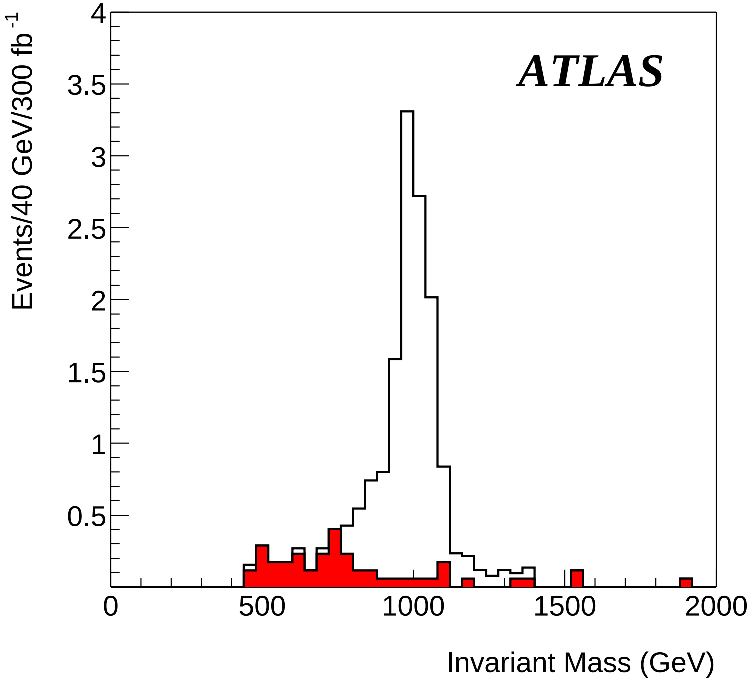
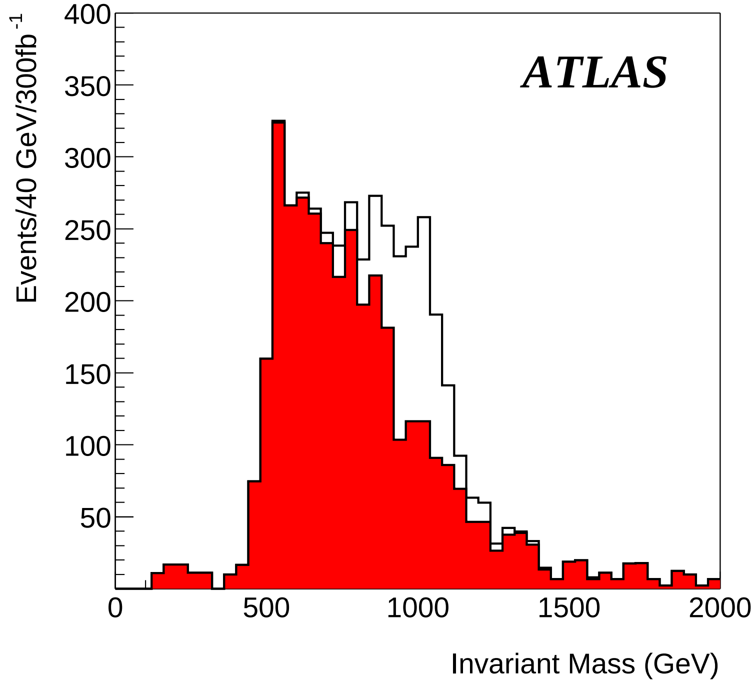




Reach $M_T \sim 1\ (2)$ TeV for $x_\lambda = 1\ (2)$.

Cross-sectiions measure coupling x_λ.

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

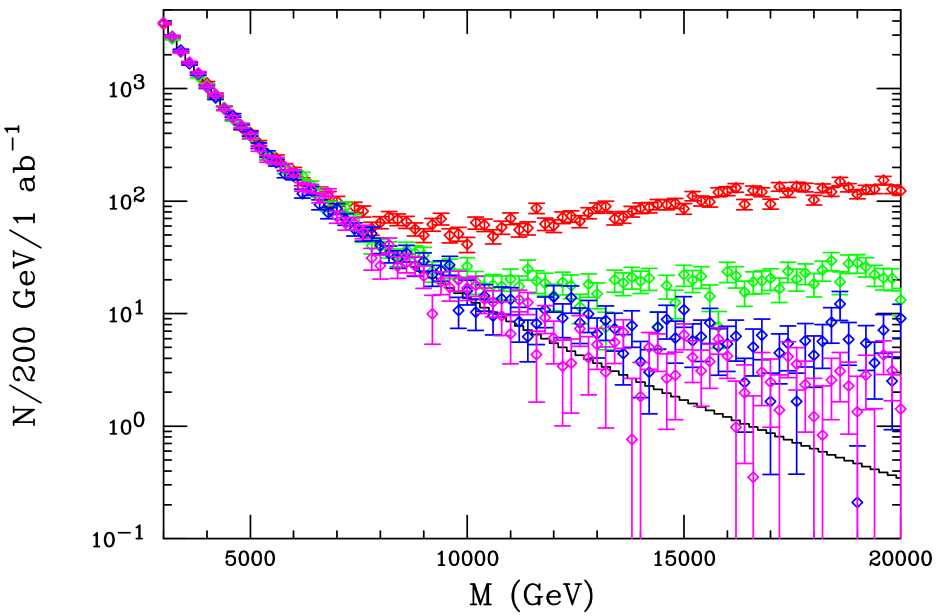
$\Longrightarrow$ check consistency with f from M_{Z_H}.*

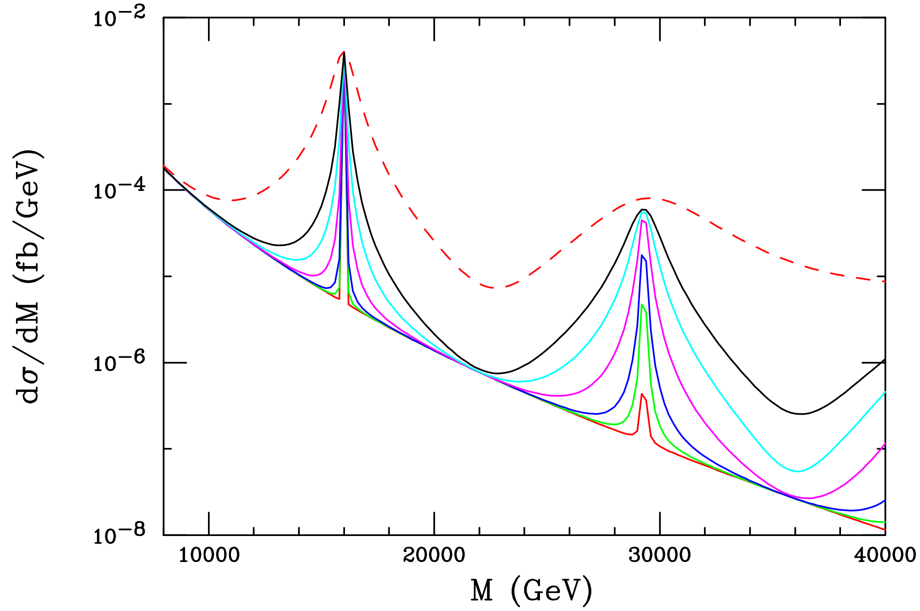
*G. Azuelos et al.: hep-ph/0402037.

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

- Deep into extra-dimensions at the LHC:

Large extra-dim ADD & warped extra-dim RS: *



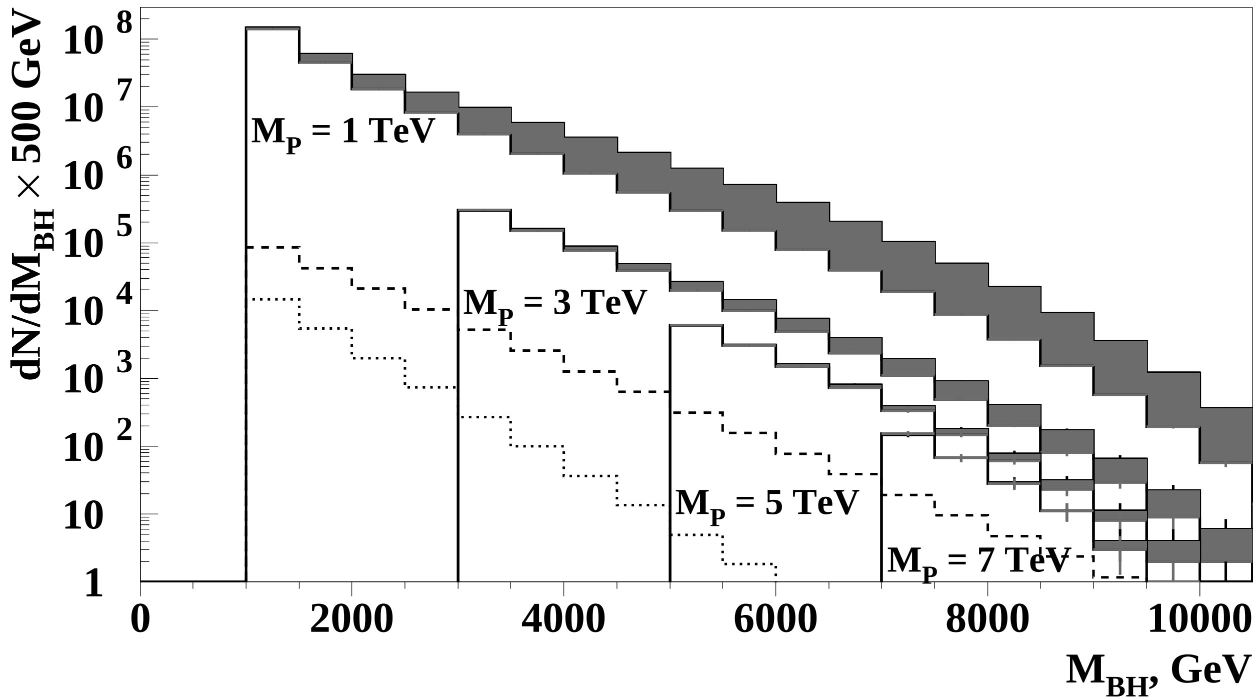


left: ADD with $M_\star = 20,\ 25,\ 30,\ 35$ TeV;

right: RS with $M_{KK} = 16$ TeV.

*T. Rizzo

Black hole to ℓ and γ events at the LHC: *



*Greg Landsberg

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- Only experiments can tell.

Go For The LHC!