Theory Overview

in the light of future hadron colliders

Tao Han
Univ. of Wisconsin - Madison

VLHC workshop, Fermilab, Oct. 16, 2003

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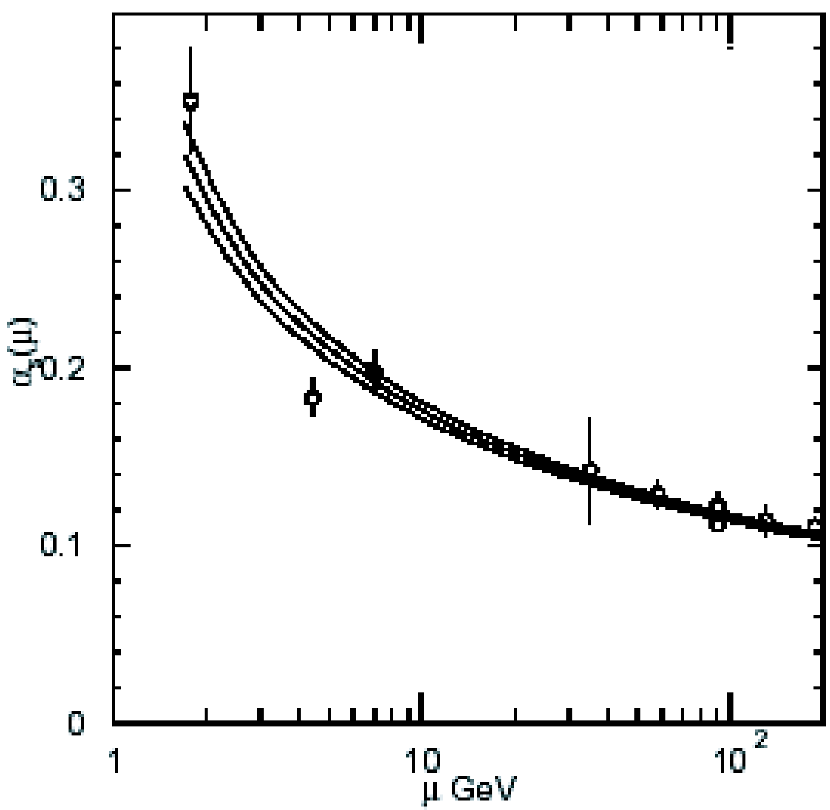
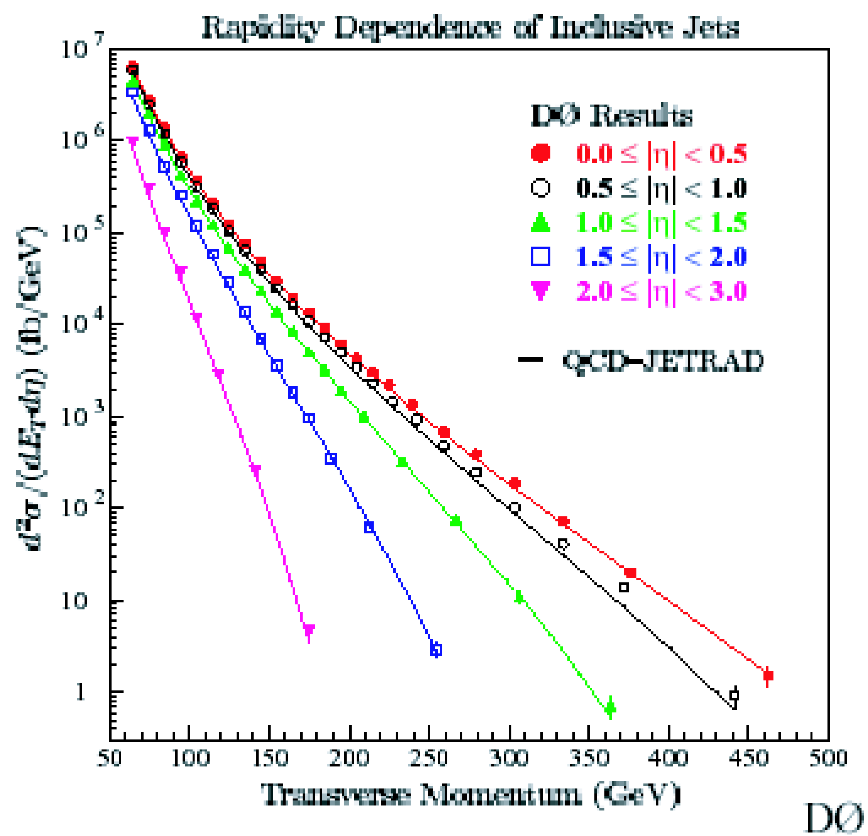
The Standard Model as It Is
The Need For Going Beyond SM
The Role of Future Hadron Colliders

The Standard Model
as a Low-Energy Effective Theory

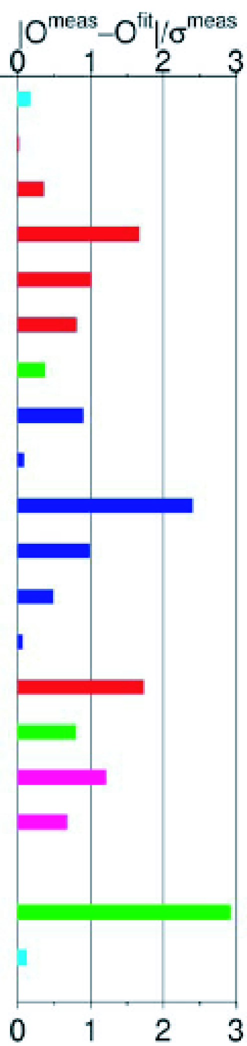
- $SU_c(3)$ QCD as the theory of strong interactions:





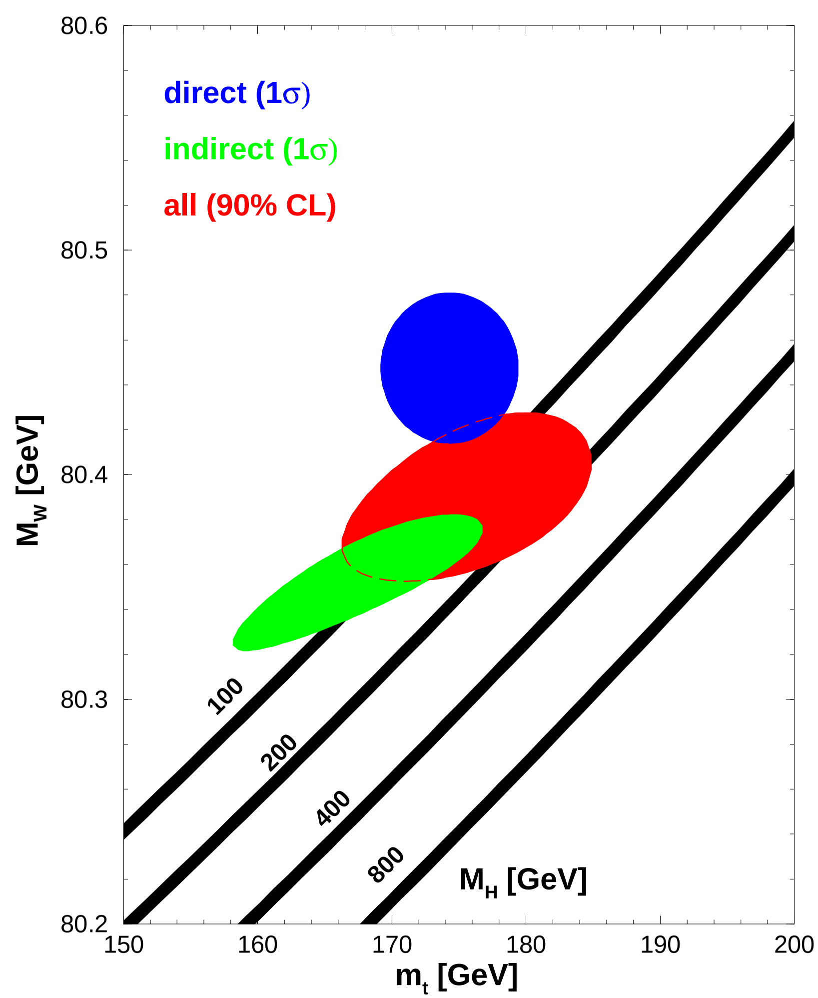
as well as significant progress in lattice gauge calculatioins.

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



Summer 2003

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	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_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	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
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1036
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	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



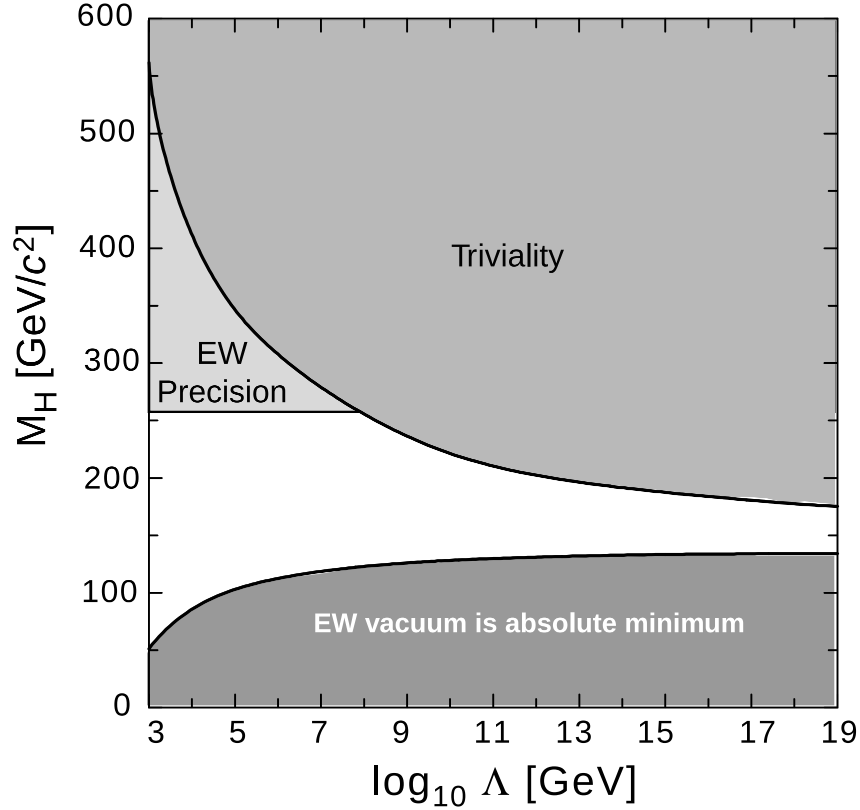
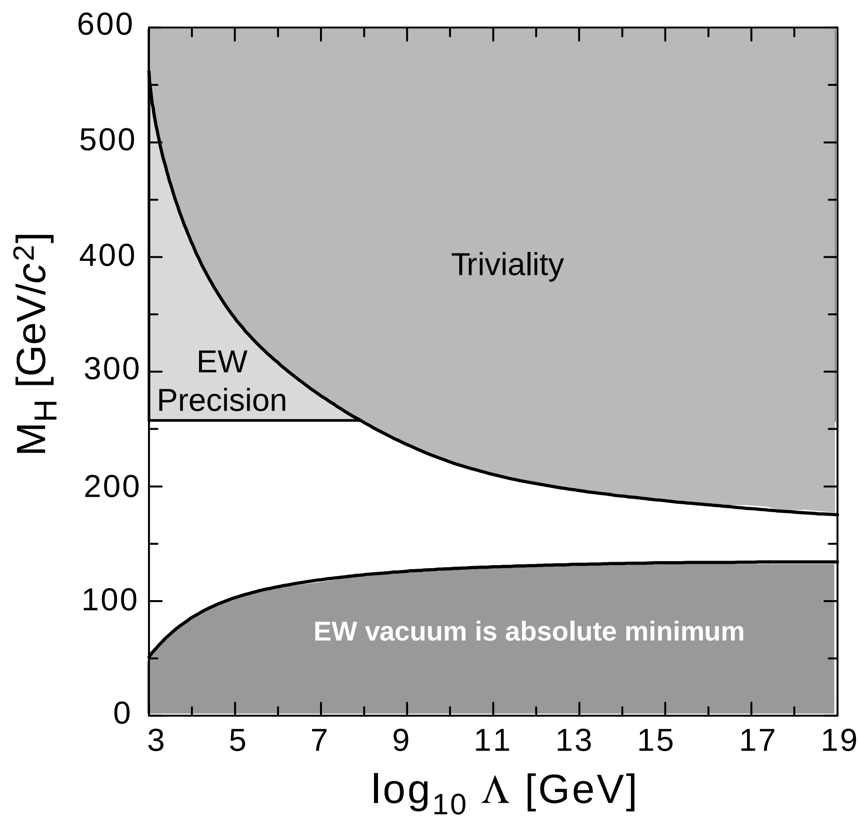


fig. from C. Quigg.

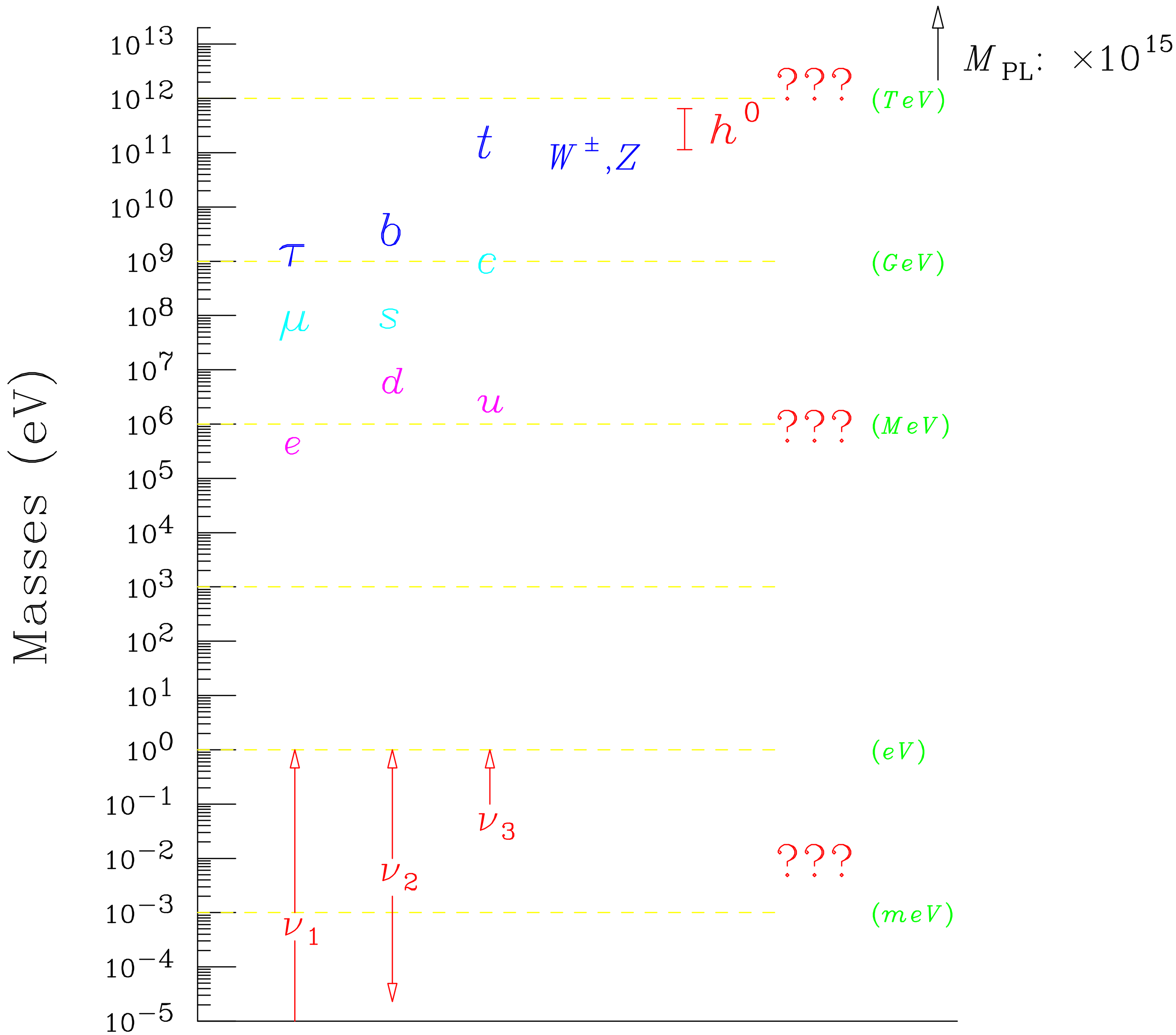


SM with a light H could be an effective theory to $\Lambda \sim M_{pl}$.

a stable vacuum;
non-trivial interactions;
renormalizability ...

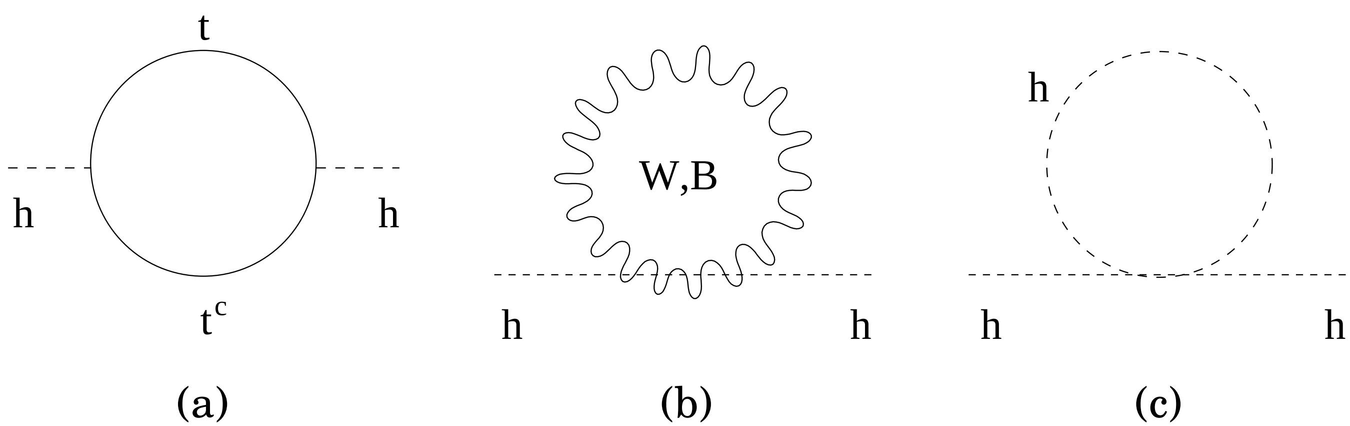
fig. from C. Quigg.

The Need For Going Beyond SM



The Large Hierarchy: $M_W - M_{pl}$

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



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

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

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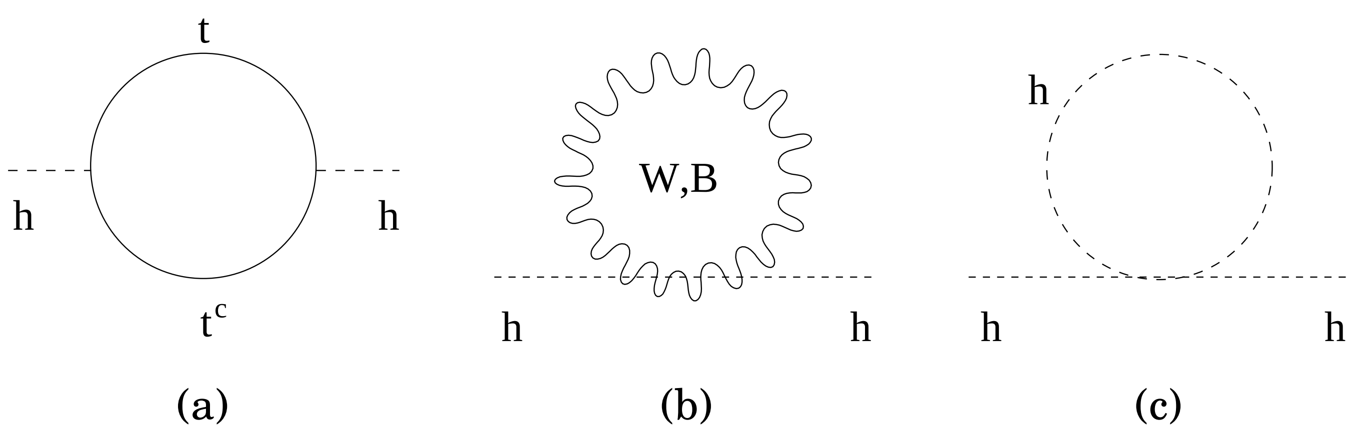

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If $\Lambda \sim M_{pl}$, it would need a 10^{-30}-level cancellation!

If requiring less than 90% cancellation, $\Lambda \lesssim 3$ TeV ($\sim 4\pi v$).

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

On the one hand, the "naturalness" argument prefers

$$\Lambda_{ew} \lesssim 4\pi v.$$

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.

†Chivukula, Evans, Simmons.

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$\Longrightarrow$ imply special structure or symmetry.

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Yet another 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!

Theoretical issues to understand:

- 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:
  gauge interactions;
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- Gravitation and cosmology: (see M. Turner)
  gravity and Planck scale physics;
  cosmology connections: inflation; dark matter; dark energy ...

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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 light new particles...

Other complementary experiments: non-colliders...

Our "theory bank"

(A). Weak-scale Supersymmetry:

A natural cancellation mechanism:

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

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

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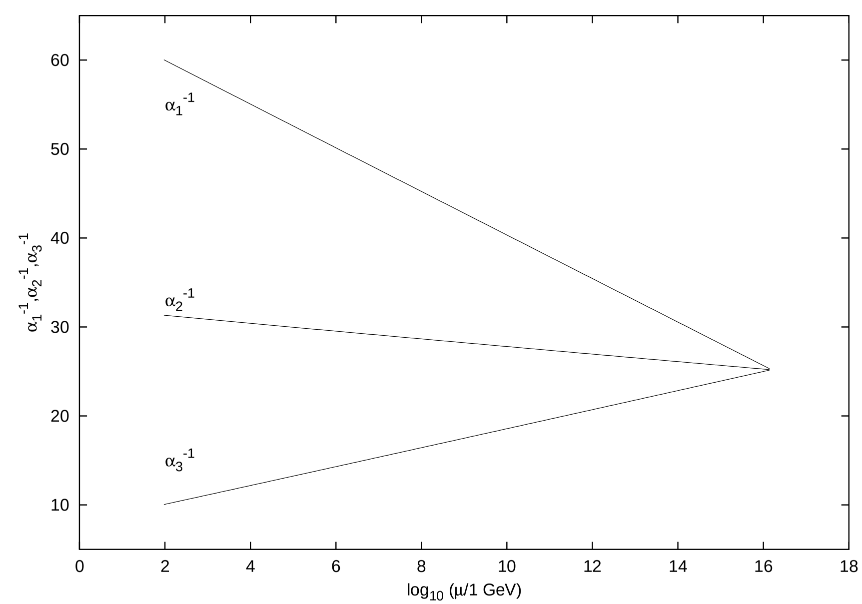
only if the "soft-SUSY breaking": $M_{SUSY} \sim \mathcal{O}(M_{SM})$.

- predict TeV scale new physics: (see I. Hinchliffe)
  light Higgs bosons, SUSY partners...
- imply a (possible) grand desert in $M_{SUSY} - M_{GUT}$, and unification
- radiative EWSB:

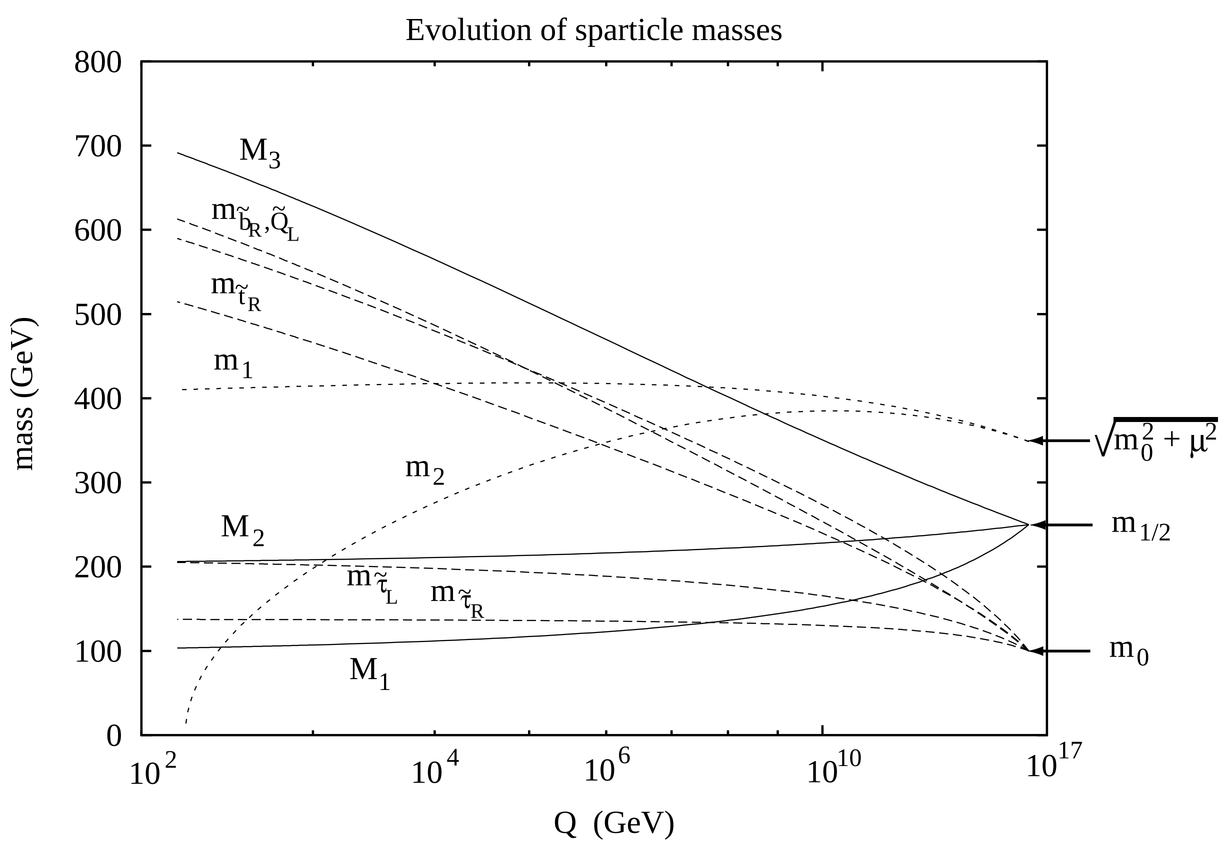
$$M_Z^2/2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2.$$



What about M_{SUSY}?

Merely (124?) unknown parameters, and most part of the para-space is inconsistent with observations.

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



The Little Hierarchy persists:

[*] $m_{\tilde{q}} \gtrsim$ several TeV or $m_{\tilde{q}_i}$ highly degenerate.

- "inverted hierarchy":[†] $m_{\tilde{t}} \sim 1$ TeV; $m_{\tilde{q}_{1,2}} \gtrsim 4$ TeV.

- "focus point" scenario:[‡]
  Heavy m_0, so that $\tilde{q}$, $\tilde{l}$ several TeV.
  H_u insensitive to m_0; low μ keep the naturalness.

- "more minimal MSSM"[*]
  New scale $F \approx 5 - 20$ TeV, so that $m_{\tilde{t}} \ll m_{\tilde{q}_{1,2}}$.

- ... ...

[*] Arkani-Hamed, Schmaltz; TH, Kribs, McElrath.

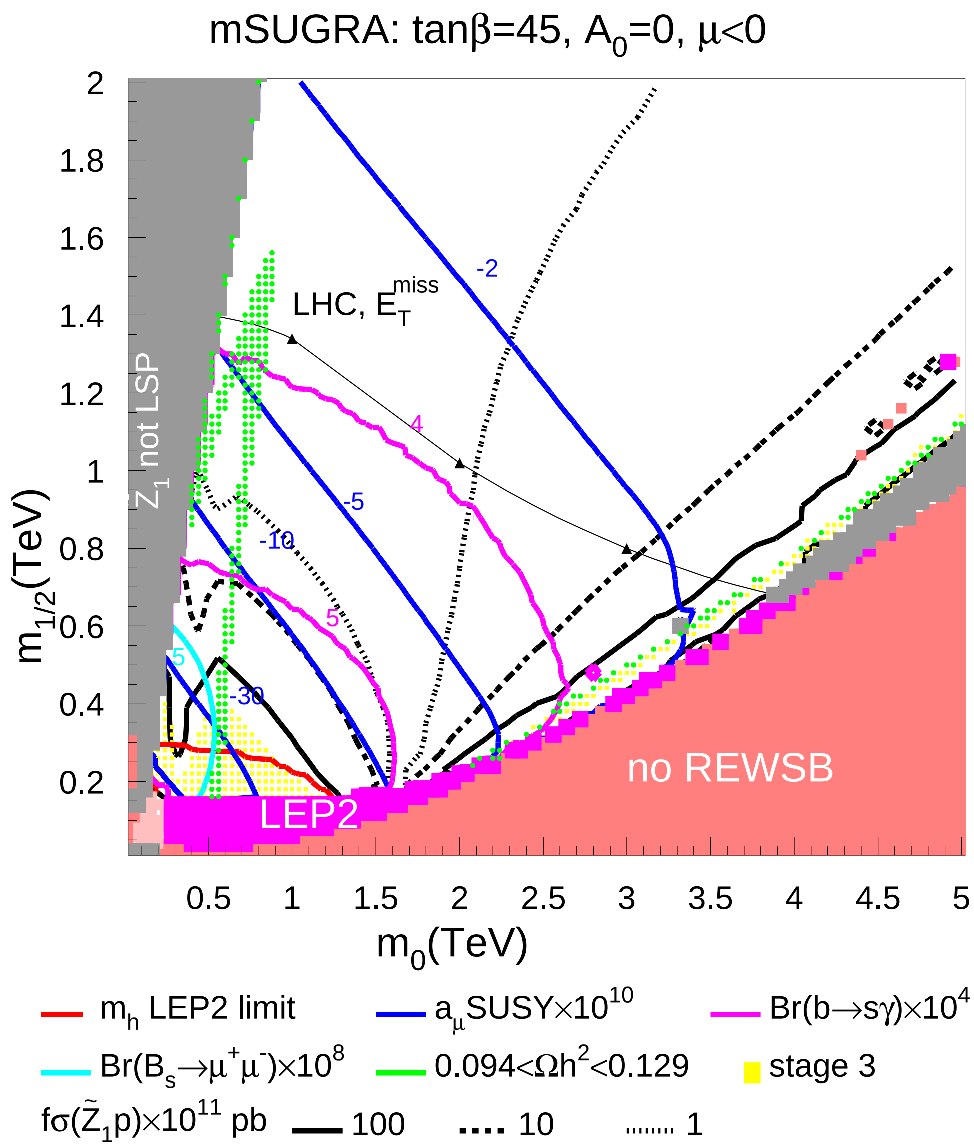
[†] Bagger, Feng, Polonsky, Zhang

[‡] Feng, Matchev, Moroi

[*] Cohen, Kaplan, Nelson.

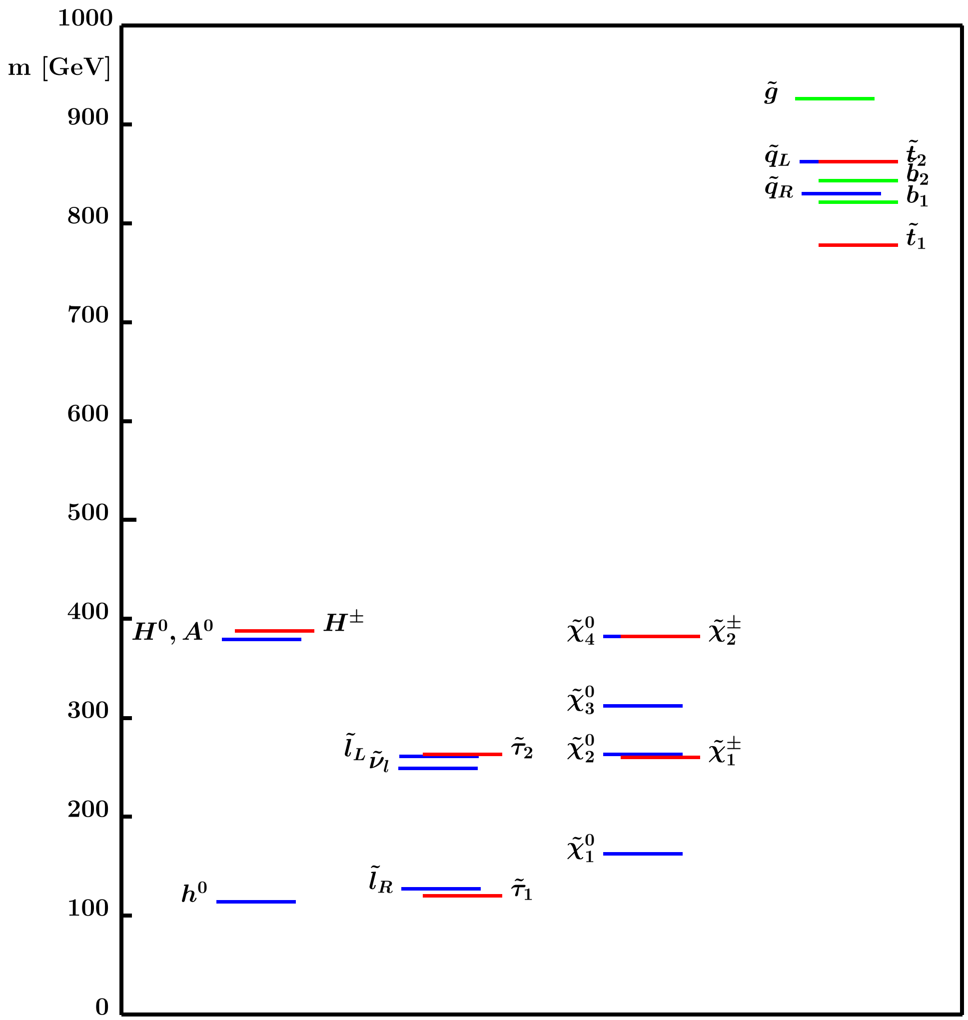
LHC may NOT guarantee a SUSY discovery: *

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



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

- Gauge mediation scenario: F, M, $\tan\beta$, and N_M



Squarks and gluinos are typically heavier;

There is the messenger sector to explore: $M_\Phi \sim \mathcal{O}(few - 100\ \text{TeV})$.

(B). Dynamical approach/Little Higgs:

- Technicolor/Extended Technicolor: (see K. Lane)
  In TC, EWSB by techni-fermion condendation:

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

$\Longrightarrow$ predicts new strong dynamics at the TeV scale:

$$\pi_T,\ \eta_T,\ \rho_T,\ \omega_T \ldots$$

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When generalizing to ETC to incorporate fermion masses,*
it is phenomenologically difficult for generating

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

and large $m_q \sim \frac{\Lambda_{TC}^3}{\Lambda_{ETC}^2} > 100$ MeV.

$\Longrightarrow$ new strong dynamics with multi scales?
The Little Hierarchy persists!

*Eichten and Lane;
For a review, Hill and Simmons

- Top quark special ? $m_t \approx v/\sqrt{2} = 174$ GeV.

"Topcolor/Top-seesaw" :

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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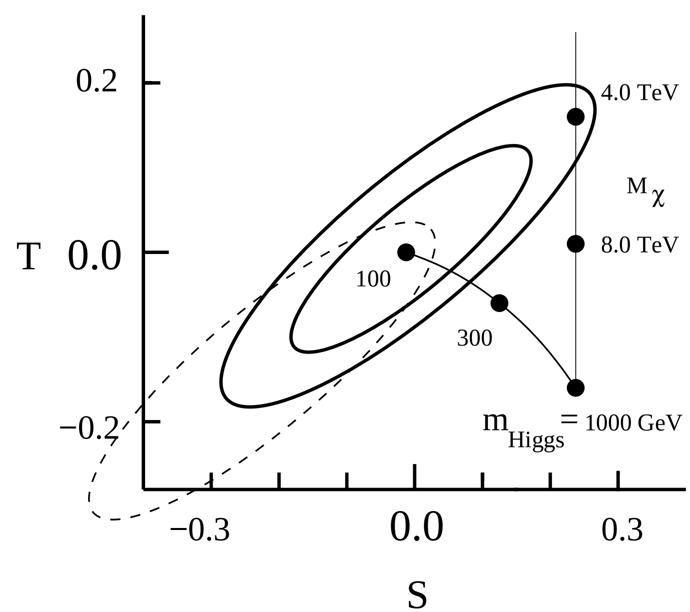

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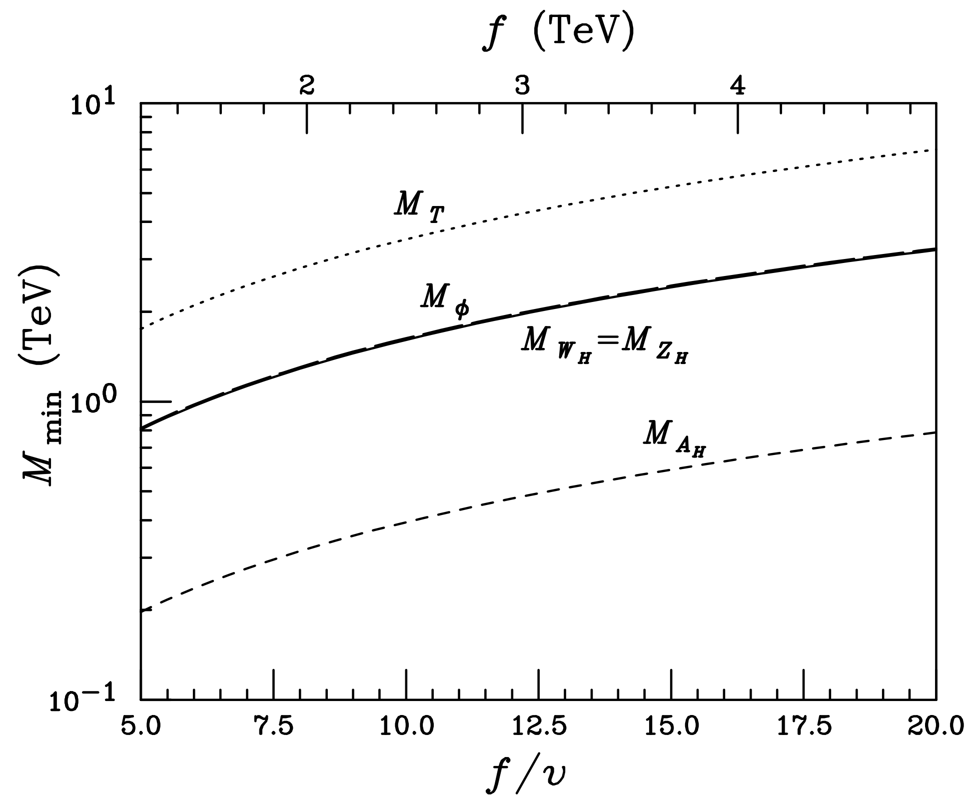
- Little Higgs: as a pseudo Nambu-Goldstone boson (see G. Kribs)

  New symmetries introduced to cancel the (1-loop) quadratic divergence.

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	$m_W^2\ \frac{f^2}{s^2c^2v^2}$
$\phi^{0,\ \pm,\ \pm\pm}$	$\frac{2m_H^2f^2}{v^2}\ \frac{1}{1-(4v'f/v^2)^2}$
A_H	$m_z^2 s_W^2\ \frac{f^2}{5s'^2c'^2v^2}$



$(m_h \approx 115$ GeV$)$

(C). Extra-dimensions: (see G. Giudice, T. Rizzo, S. Nandi)

- With the help of extra-dimensions, low-scale gravity/string theories resolve the large hierarchy:

$$M_S^{n+2} \sim M_{PL}^2 / R^n \longrightarrow \mathcal{O}(1 \text{ TeV}^2).$$

New states predicted: KK, stringy, and winding modes

$$M_n^2 \sim \frac{n_k^2}{R^2}, \quad n_s M_S^2, \quad n_w^2 R^2 M_S^4.$$

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- TeV-Scale Black Holes: For a black hole of mass M_{BH}, its size is

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

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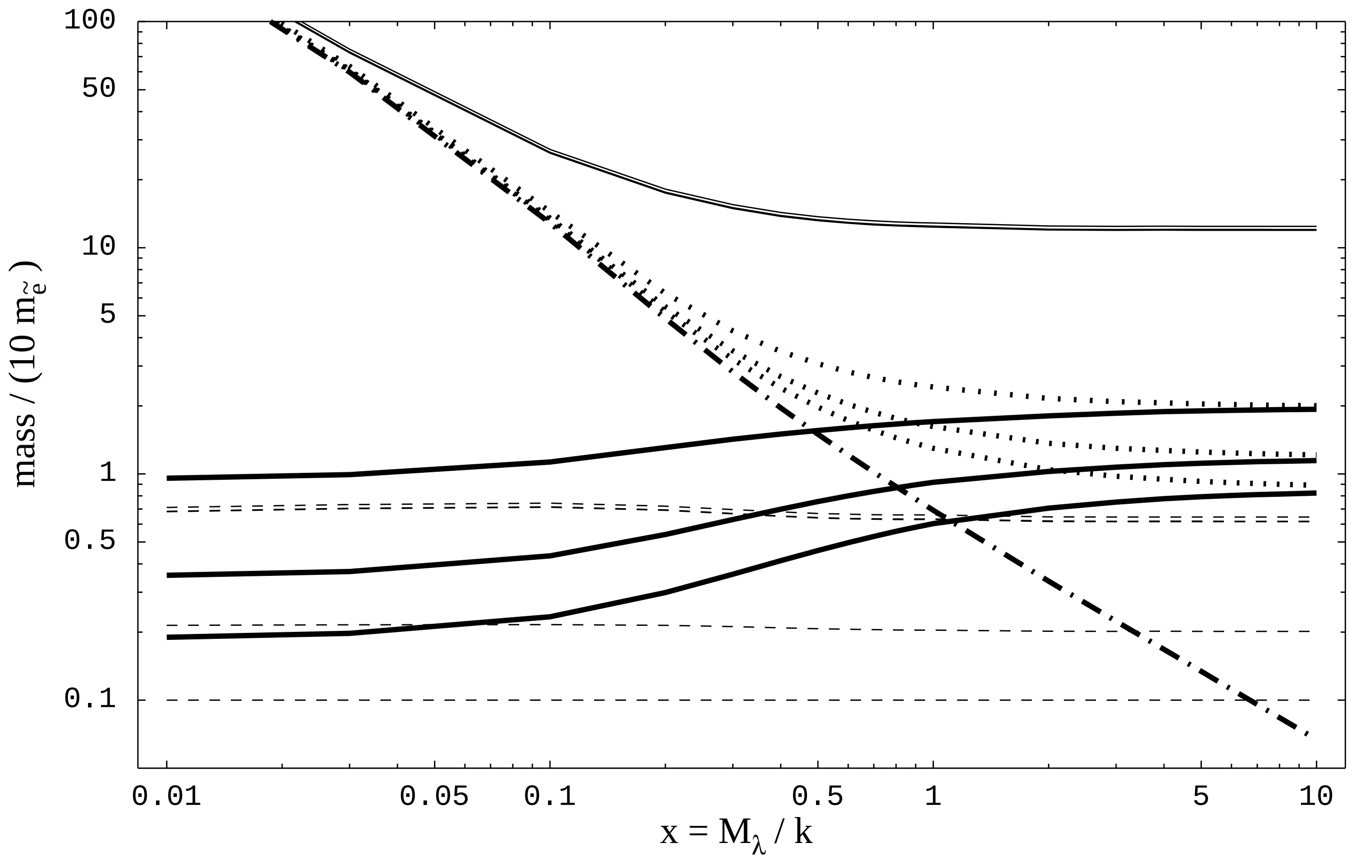
However, proton stability imposes bound on M_D.
e.g. $\ell - q$ separated scenario,*

$$L \gtrsim \frac{10}{M_D} \quad \Rightarrow \quad M_D \gtrsim 10\ \text{TeV}.$$

*Arkani-Hamed, Schmaltz; TH, Kribs, McElrath.

- SUSY GUTs with extra-dimensions *



- dashed (bottom up): $m_{\tilde{e}}$, $m_{\tilde{l}}$ and $m_{\tilde{q}}$, $m_{\tilde{u}}$, $m_{\tilde{d}}$ nearly degenerate.
- thick solid: MSSM gauginos; • dot-dashed: XY gauginos;
- dotted: 321 gaugino KK modes; • thin solid: XY and 321 KK gauge.

*Hall, Nomura; Nomura, Smith.

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Fermion masses and mixing remain the most challenging tast!

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- Attempts in ETC/Walking TC/Topcolor assisted TC/Top-seesaw ...
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- SUSY GUTs relations,
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(D). The flavor sector:

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Further experiments for more hints.

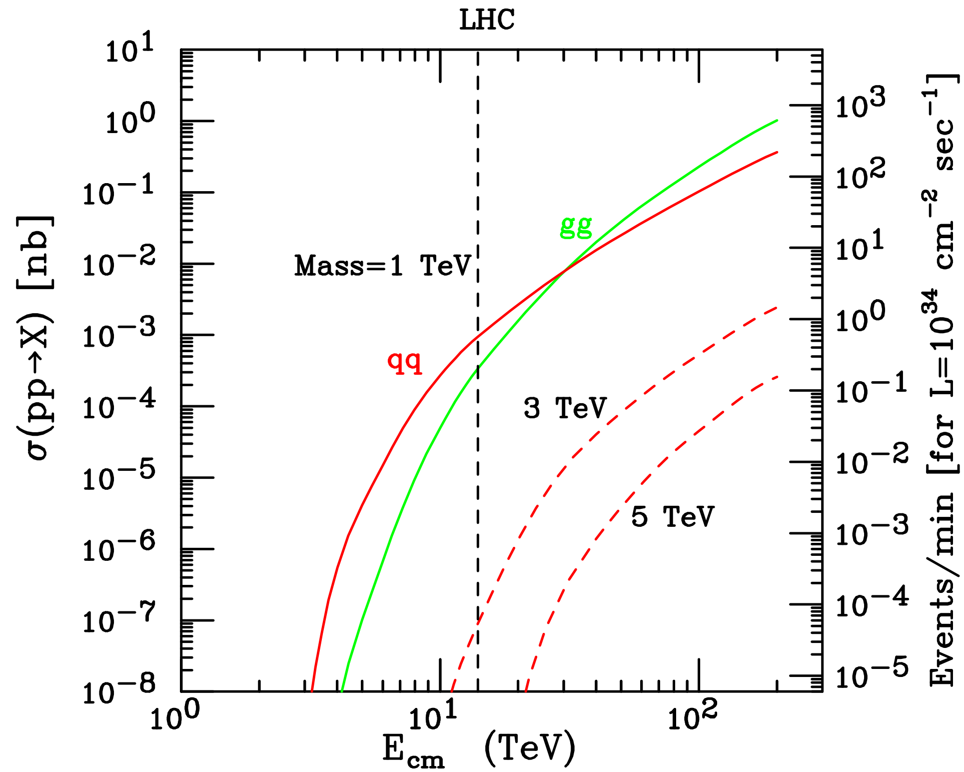
Physics at Future Hadron Colliders

For any scenario beyond SM, VLHC WILL contribute:

- SUSY needs VLHC:

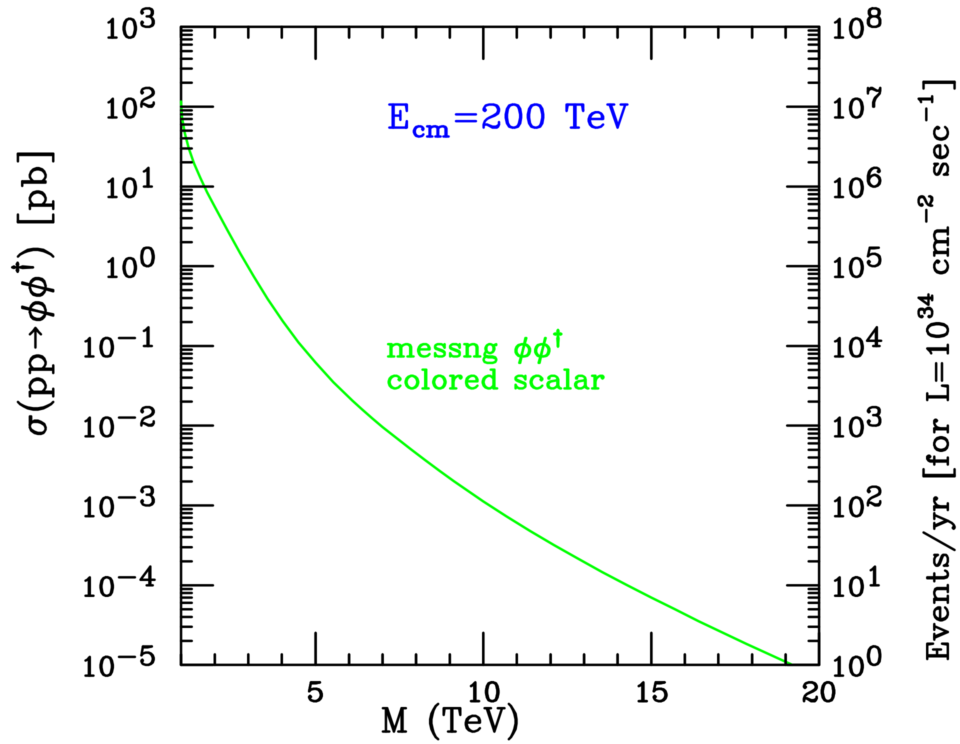
(a) Multi-TeV Squarks $\tilde{u}$, $\tilde{d}$: the inverse-hierarchy scenario

$\tilde{t}$ is at $\mathcal{O}$(1 TeV) (naturalness); while $\tilde{q}$ are at $\mathcal{O}$(5 TeV) (FCNC)



(b) SUSY Breaking Messengers:

$$M_\Phi \sim \mathcal{O}(few - 100 \text{ TeV}).$$



If the messenger number is conserved, then the Lightest Messenger Particle (LMP) is stable, leading to

$$\Phi' \to \Phi_0 V \to E^{miss} + W, Z, \gamma, g.$$

interesting signal; large SM bckgrnds ...

If Φ, $\bar{\Phi}$ couple to SM multiplets (fermions...), then

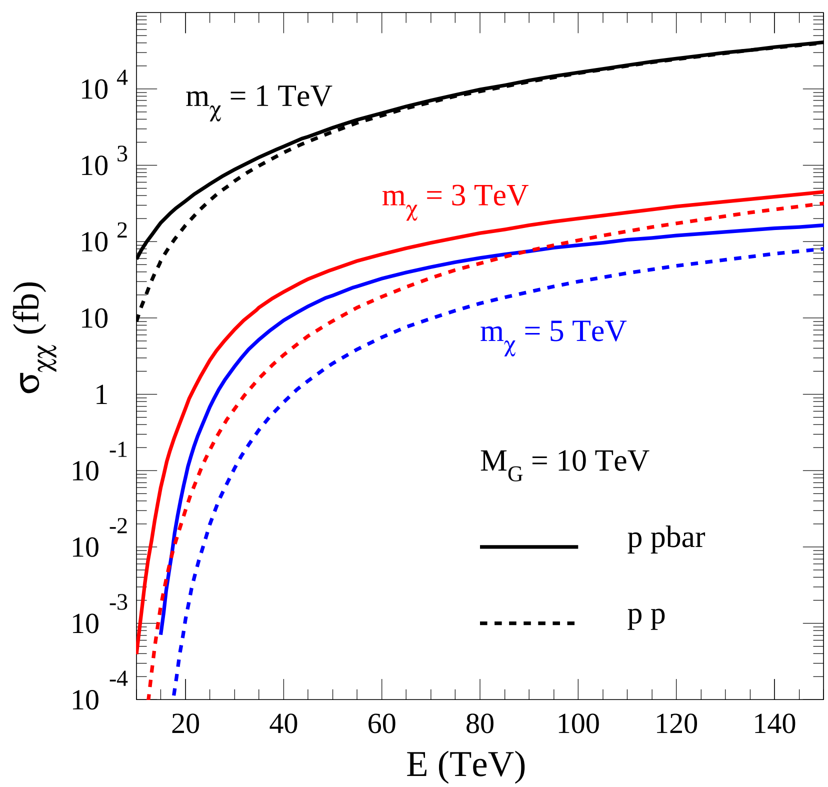
$$\Phi_0 \to e + \bar{\mu},\ \tilde{q}_i + \tilde{q}_j,\ h + \tilde{q}, \text{ etc.}$$

(almost like R_p violating interactions)

which would lead to spectacular new experimental signatures!

- Strong dynamics needs VLHC:

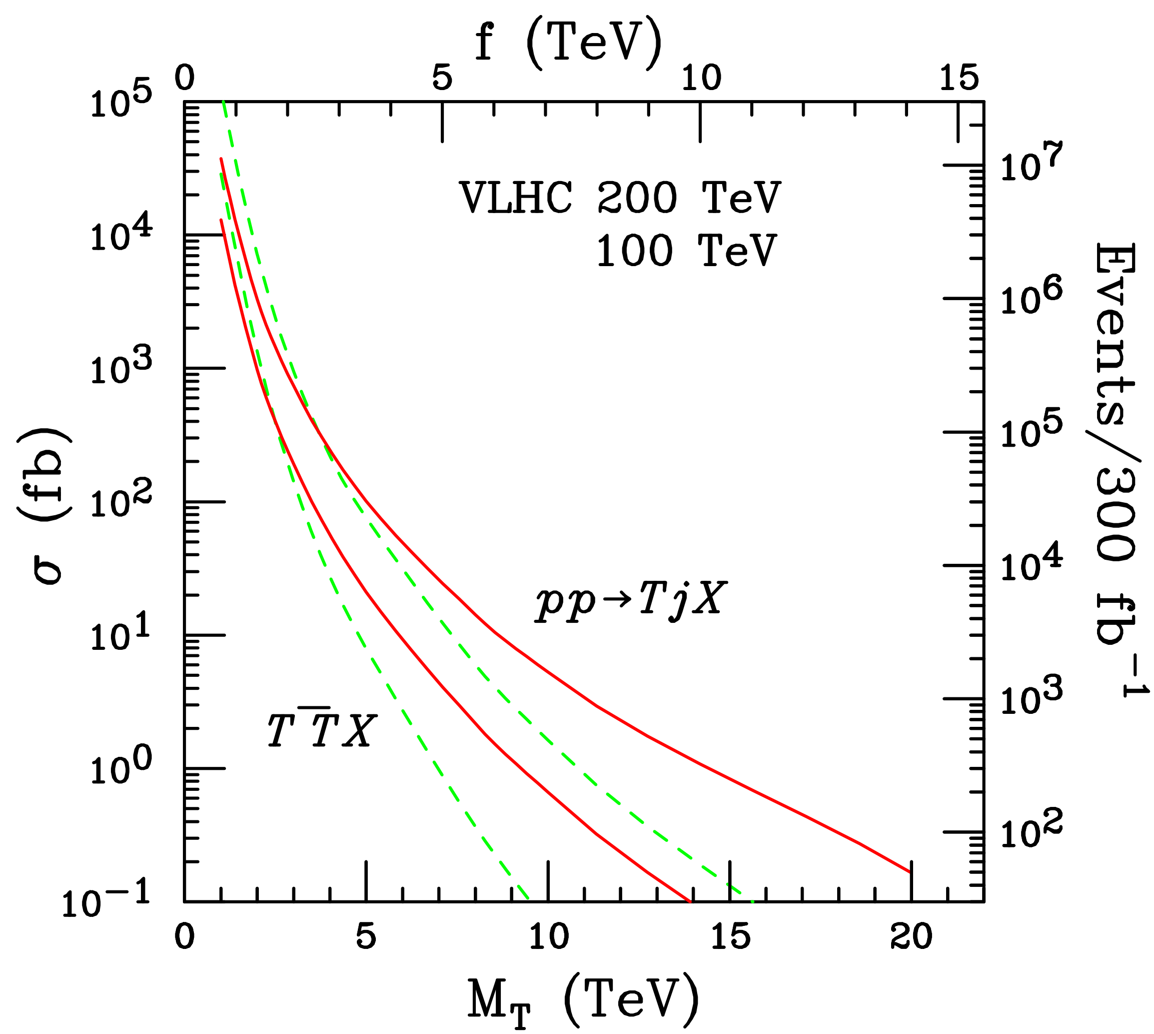
(a) Top-Seesaw: the "top-partners" χ_R, χ_L, with $M_\chi \sim$TeV.*



$\Longrightarrow$ with $\chi_{R,L} \to th,\ bW...$, good signatures.

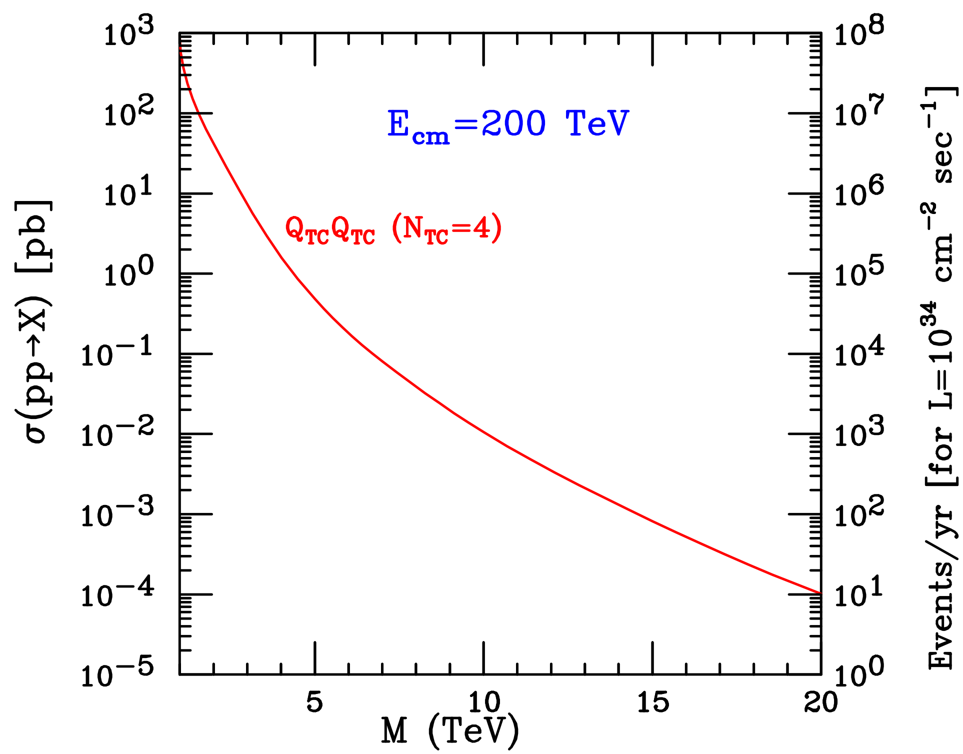
*Tim Tait

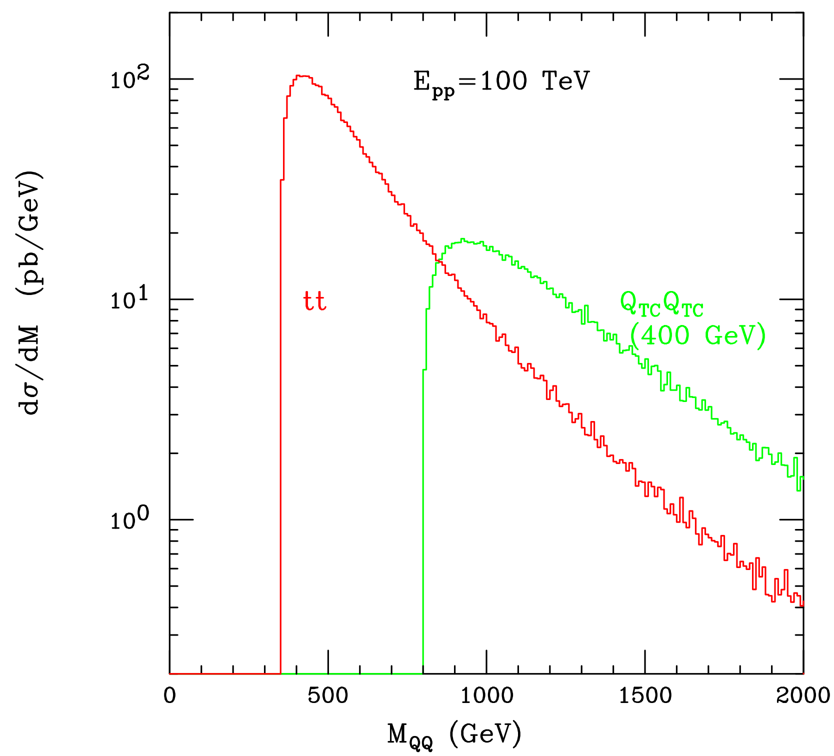
(b) Little Higgs: the "top-partner" T:



$\Longrightarrow$ with $T \to th,\ tZ,\ bW,$ good signatures.

(c) Heavy Techni-quarks: U_{TC}, D_{TC}...



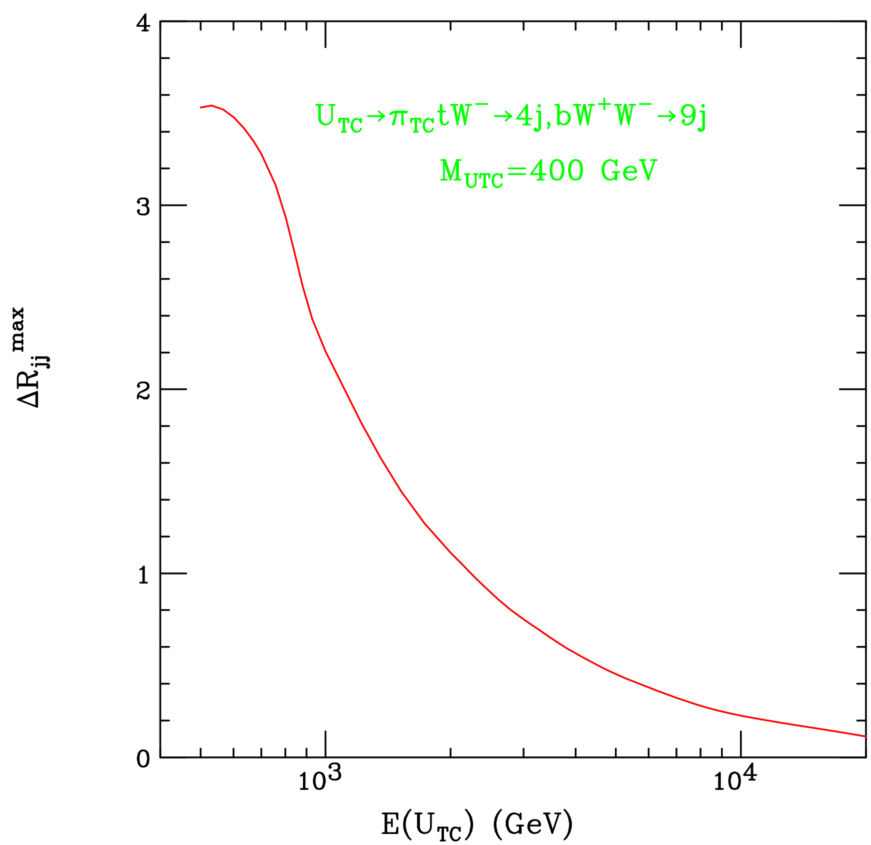


The production rate is comparable or higher than $pp \to t\bar{t}$!

Technicolor Manifeso:

$$pp \to U_{TC}\bar{U}_{TC}X \to \text{two very mass jets!}$$

At high energies, *e.g.*, $U_{TC} \to \pi^+_{TC} t W^- \to 4j, bW^+, f\bar{f}' \to 9j$



$\Longrightarrow$ a massive (not always fat) jet!

(d) Strongly-interacting Electroweak Sector:

If no $h_i/SUSY$ found at the LHC, $W_L W_L$ Scattering must reveal new dynamics

- $\Lambda_{EW}(W_L W_L \to W_L W_L) \sim \sqrt{8\pi}\, v \sim 1.2$ TeV.

$\sqrt{s_W} \sim 2$ TeV $\Rightarrow$ $\sqrt{s_f} > 4$ TeV $\Rightarrow$ $\sqrt{s_p} > 65$ TeV

$$\frac{\sigma(W_L^+ W_L^- \to W_L^+ W_L^-)}{\sigma(W_L^+ W_L^- \to Z_L Z_L)} \begin{cases} \sim 2 & \text{scalar } H^0, \\ \gg 1 & \text{vector } \rho^0_{TC}, \\ \sim 2/3 & \text{LET } \sqrt{s} \ll M. \end{cases}$$

SEWS signal rates with 100 fb^{-1}:

$W^+W^- \to W^+W^-$	1 TeV scalar	$M \to \infty$
14 TeV	2000	900
200 TeV	8×10^5	4×10^5

-

$$\Lambda_f(WW \to f\bar{f}) = \frac{8\pi v^2}{3 m_f} \sim \begin{cases} 3 \text{ TeV} & m_t = 175 \text{ GeV} \\ 97 \text{ TeV} & m_b = 5 \text{ GeV}. \end{cases}$$

(e) Contact Interactions: Compositeness?

Heavy bosons and quark/lepton sub-structure lead to 4-fermion contact interactions:

$$4\pi\frac{\kappa}{\Lambda^2}\ \bar{\psi}_{f1}\Gamma_\mu\psi_{f1}\ \bar{\psi}_{f2}\Gamma^\mu\psi_{f2}$$

The best channel at hadron colliders is the DY process:

$$pp \to \gamma^*, Z \to e^+e^-/\mu^+\mu^- + X$$

The Sensitivity to the "composite scale Λ" goes like

$$\frac{s^2}{\Lambda^4},$$

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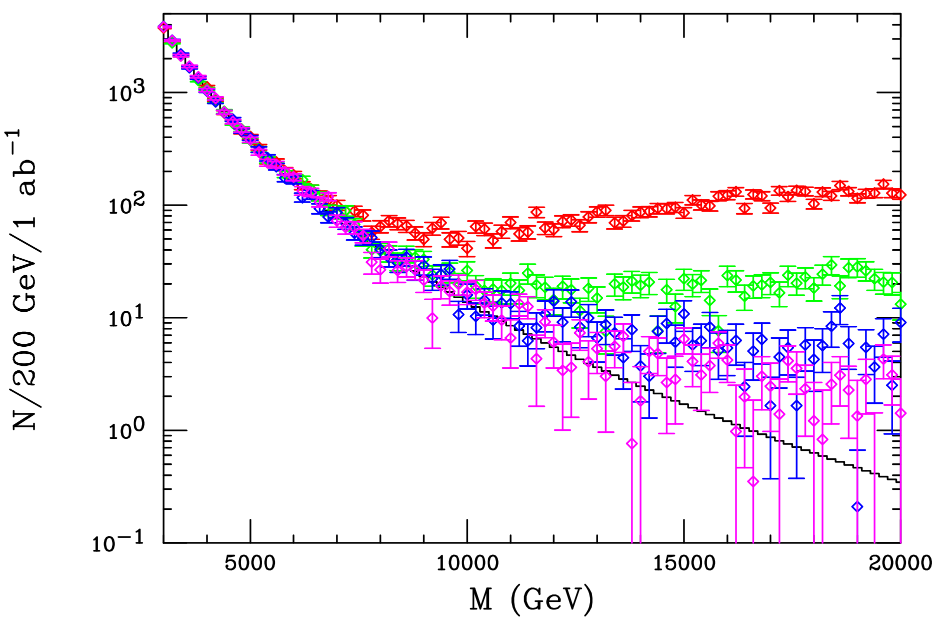
so that Tevatron→LHC→VLHC:

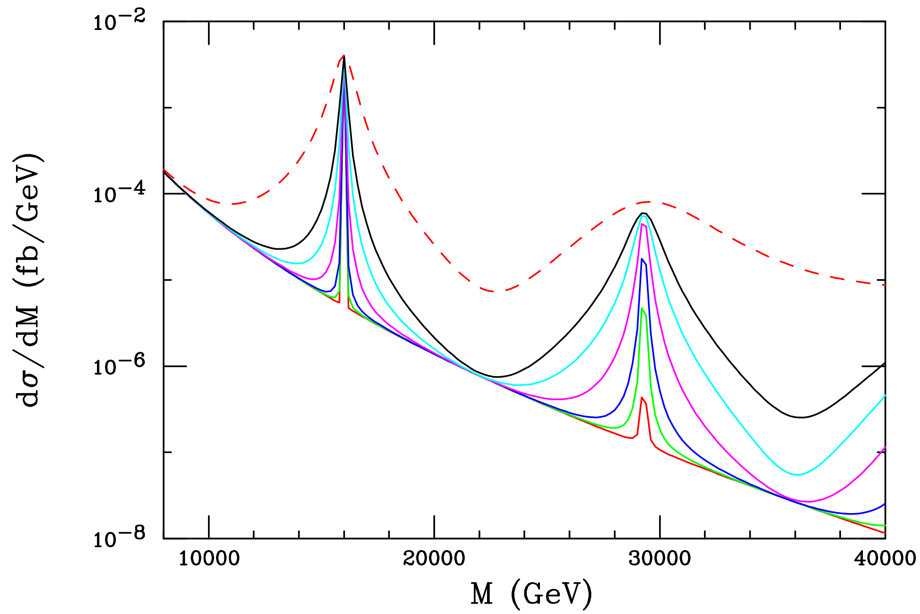
$$\frac{(1.8\ \text{TeV})^4}{(3\ \text{TeV})^4} \sim \frac{(14\ \text{TeV})^4}{(25\ \text{TeV})^4} \sim \frac{(100\ \text{TeV})^4}{(170\ \text{TeV})^4}$$

170 TeV ⇒ 10^{-18} cm ! should cover the "little hierarchy".

• Deep into extra-dimensions at VLHC:

(a) Large extra-dim ADD & warped extra-dim RS: *





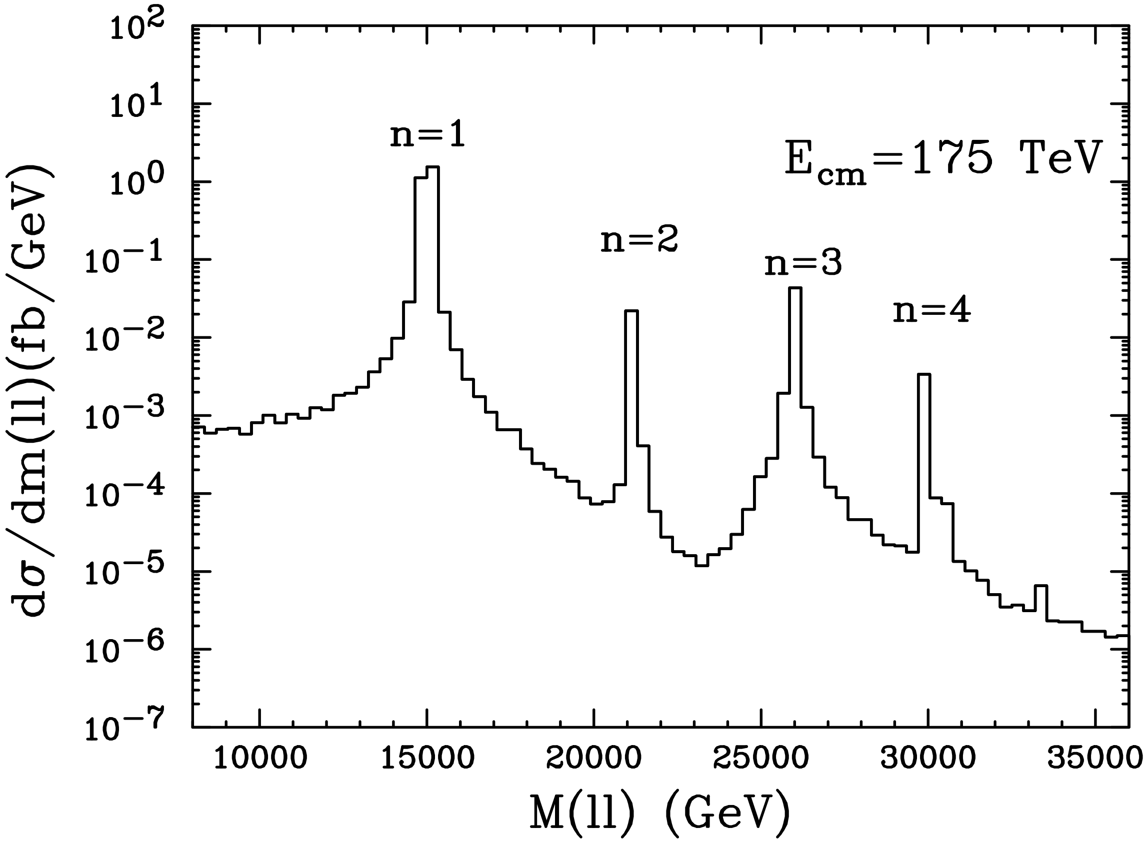
left: ADD with $M_\star = 20,\ 25,\ 30,\ 35$ TeV;

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

*T. Rizzo

(b) Low-scale string resonances: *

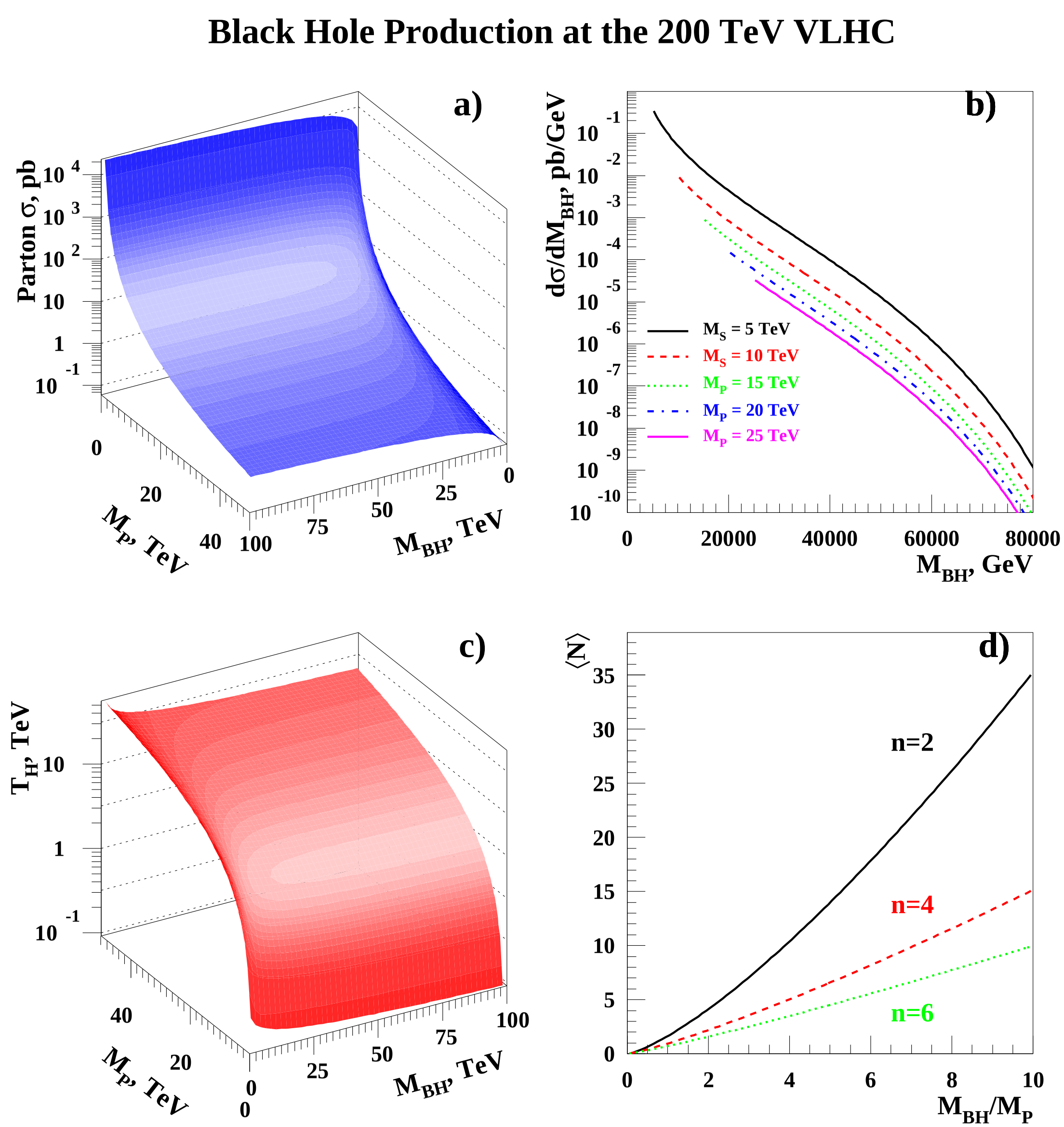
$$pp \to S_J^n\ X \to l^+ l^- X$$



String state masses $M_S^{(n)} = \sqrt{n}\ M_S = \sqrt{n}$ 15 TeV.

*TH, P. Burikham

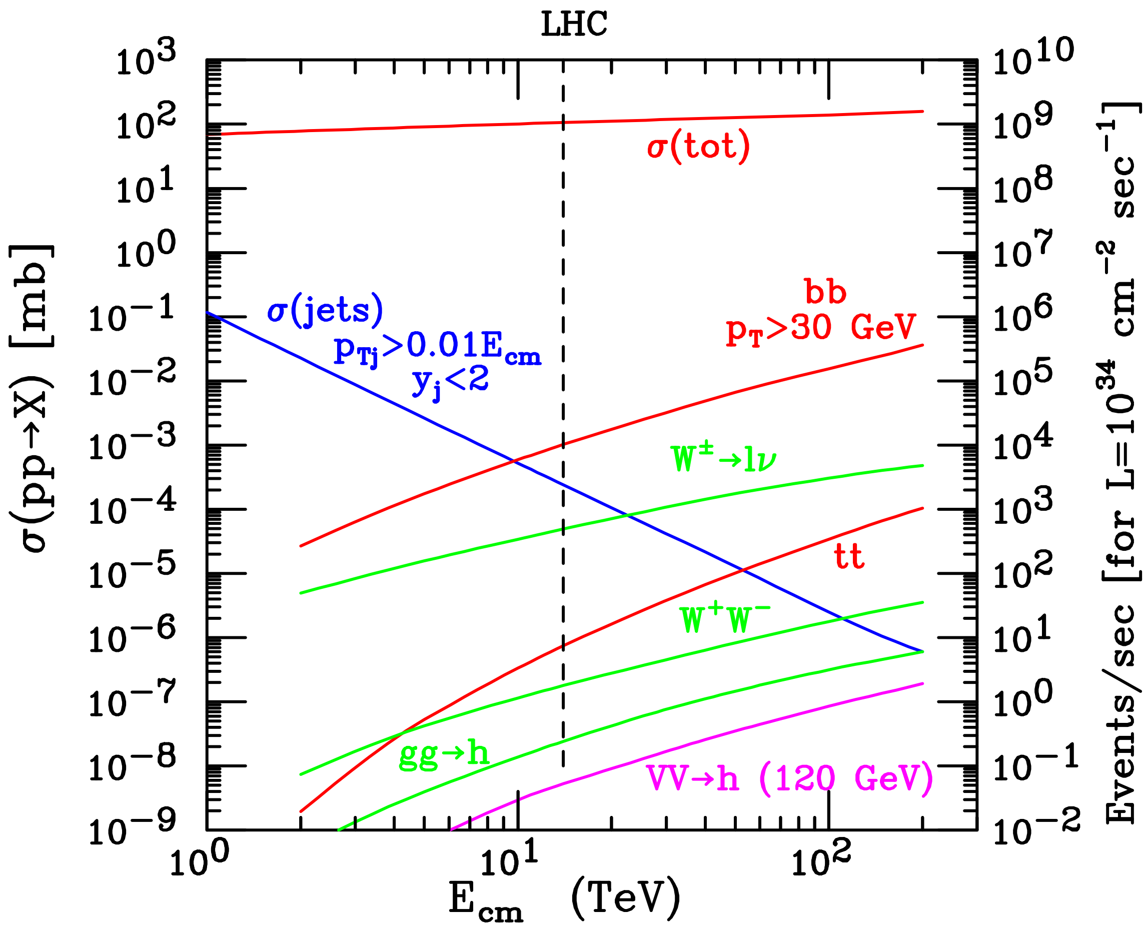
(c)



At $\sqrt{s} = 200$ TeV, $\sigma(M_B > 25$ TeV$) = 3$ pb. *

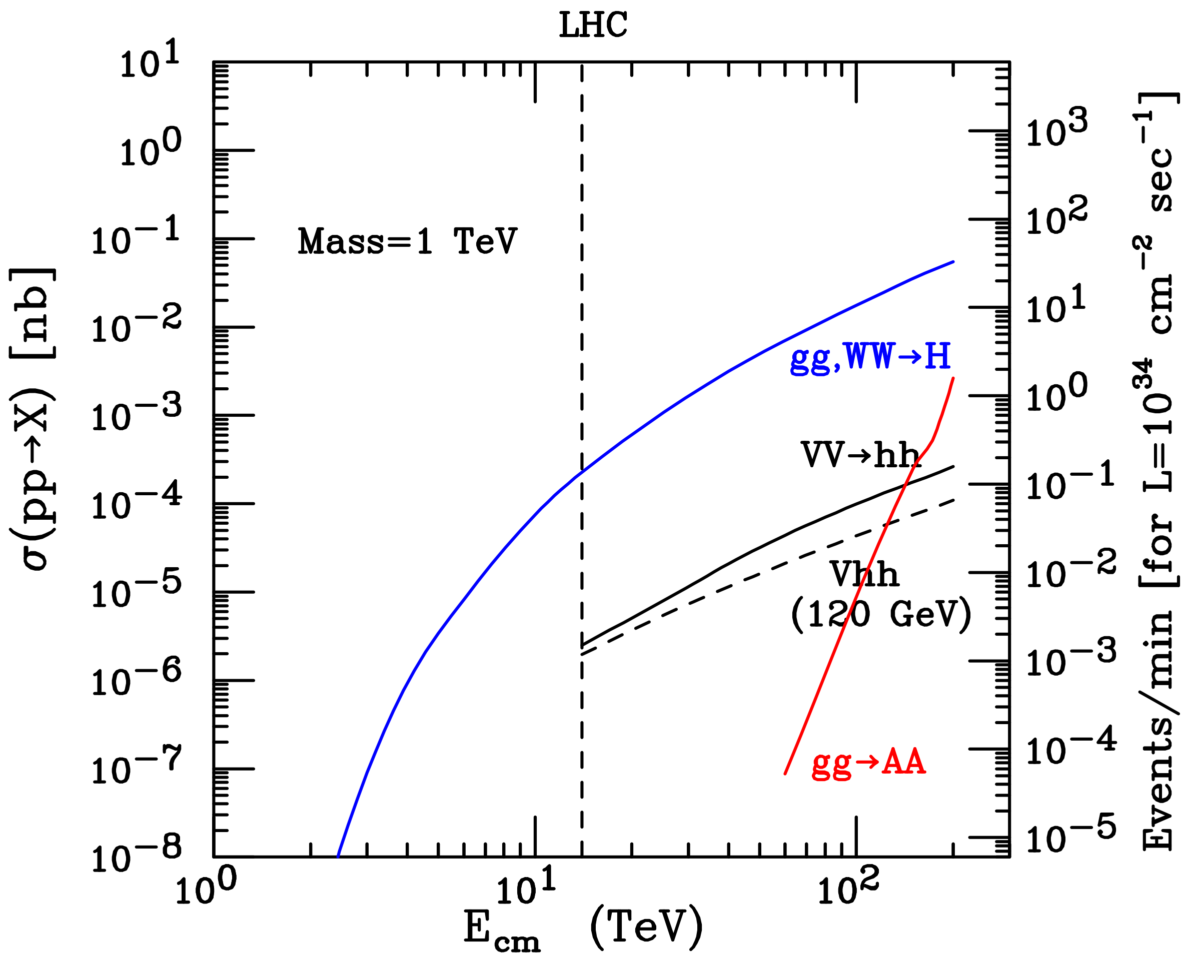
*Greg Landsberg

- Bread & butter SM physics:



- Total pp cross section as expected ?
- 10-100 times more W/Z, WW, $t\bar{t}$...;
- Rare processes like $h \to \mu^+\mu^-$? (D. Rainwater)

More Higgses: $pp \to Vhh; WW \to hh$ (see D. Rainwater) and a very heavy "Higgs" (1 TeV)



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For $0\nu2\beta$ decay,

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Produce it at highest energies:

$$u + u \rightarrow d + d\ W^+ W^+ \rightarrow dd\ \ell_1^+ \ell_2^+ .$$

Since

$$\mathcal{M} \sim \sum_i U^\star_{\ell_1 i} U_{i \ell_2}\ \frac{\lambda_i m_{\nu_i}}{p^2 - m^2_{\nu_i}}$$

then

$$\mathcal{M} \sim \begin{cases} \sum_i U^\star_{\ell_1 i} U_{i \ell_2}\ \lambda_i\ \frac{m_{\nu_i}}{E} & \text{for } m_\nu^2 \ll p^2, \\ \sum_i U^\star_{\ell_1 i} U_{i \ell_2}\ \lambda_i\ \frac{E}{M_R} & \text{for } M_R^2 \gg p^2. \end{cases}$$

Multi-W, H production via Sphalerons (see A. Ringwald)

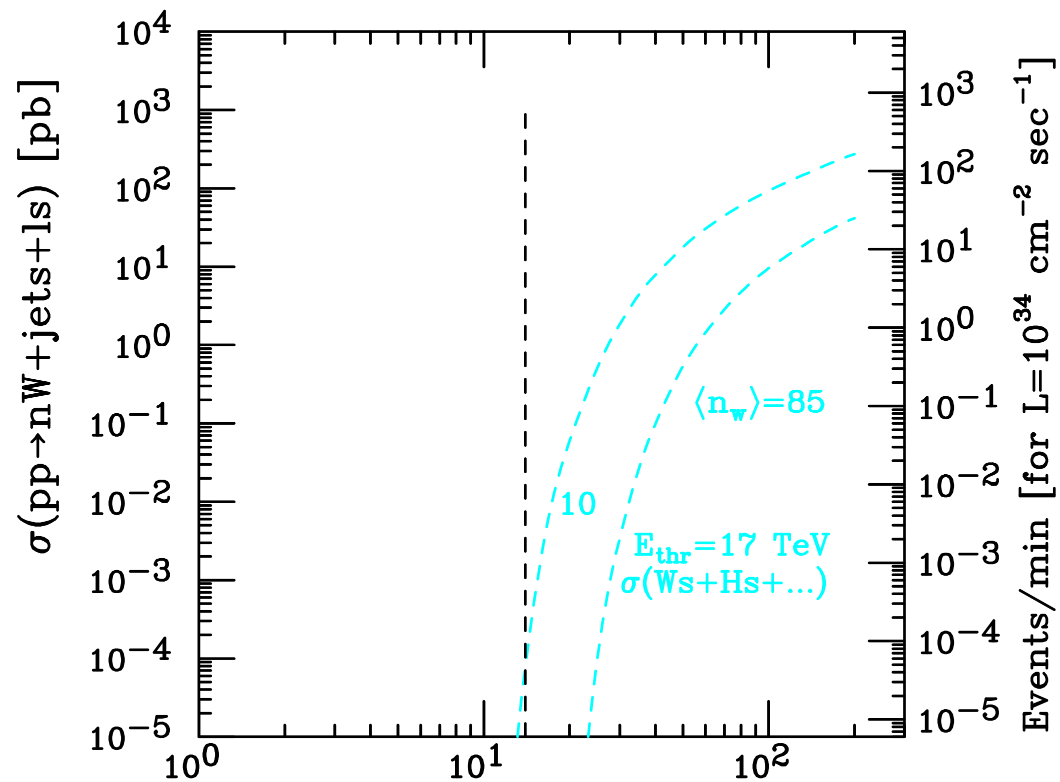
Electroweak instantons/sphalerons induce $B+L$ violating transitions

$$qq \to 7\bar{q} + 3\bar{\ell} + n_w W^{\pm} + n_h H$$

with total cross section

$$\sigma(tot) \sim e^{-2\pi/\alpha_w} \; e^{\alpha_w s/M_W^2} \leq \frac{16\pi}{s}.$$

$\Rightarrow$ Enhanced for $\sqrt{s} > M_W/\alpha_w$, bound by unitarity.



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Go for the energy frontier!