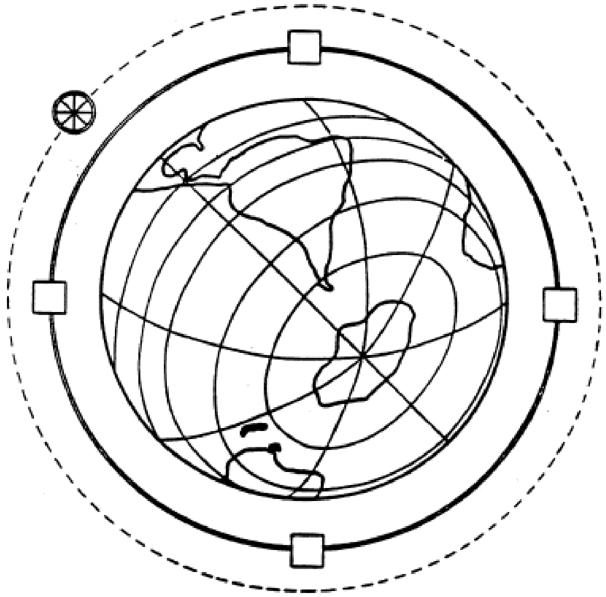


Physics at Very High Energies

1. **The Standard (Higgs) Model**
2. **Physics @ 1 TeV**
3. **Glimpses Beyond 1 TeV**
   - SUSY beyond 1 TeV
   - Composite Higgs
   - Technicolor
   - Extra Dimensions: The Brane World
4. **OR ELSE**
5. **Conclusions**

The Standard $SU(3)_C \times SU(2)_W \times U(1)_Y$ Model

Gauge Bosons: γ, $W^{\pm}$, Z^0, g

Fermions:

$$\begin{array}{c|ccc}
\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L & \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L & \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L & \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L \\
e_R & u_R & u_R & u_R \\
 & d_R & d_R & d_R \\
\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L & \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L & \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L & \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L \\
\mu_R & c_R & c_R & c_R \\
 & s_R & s_R & s_R \\
\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L & \begin{pmatrix} t \\ b_\theta \end{pmatrix}_L & \begin{pmatrix} t \\ b_\theta \end{pmatrix}_L & \begin{pmatrix} t \\ b_\theta \end{pmatrix}_L \\
\tau_R & t_R & t_R & t_R \\
 & b_R & b_R & b_R
\end{array}$$

BUT, $M_{W,Z} \neq 0$!

Universal Low-Energy Theorems:

$$\begin{aligned}
\mathcal{M}[W_L^+ W_L^- \to W_L^+ W_L^-] &= \frac{iu}{v^2} \\
\mathcal{M}[W_L^+ W_L^- \to Z_L Z_L] &= \frac{is}{v^2} \\
\mathcal{M}[Z_L Z_L \to Z_L Z_L] &= 0 \quad .
\end{aligned}$$

What dynamics cuts off growth in amplitude?

- New particles.
- Born approximation fails $\to$ strong interactions.
- Both.

Projecting onto the $I = J = 0$ channel

$$\mathcal{A}_{00} = \frac{s}{16\pi v^2} \approx \left(\frac{\sqrt{s}}{1.8\,\text{TeV}}\right)^2 \quad .$$

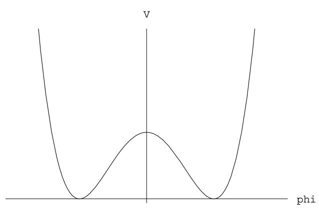
Dynamics of electroweak symmetry breaking must appear at energies less than $\mathcal{O}(1\ \text{TeV})$.

Review: The Higgs Model

Fundamental Scalar Doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad ,$$

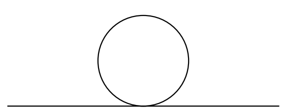
with potential:



$$V(\phi) = \lambda \left(\phi^\dagger \phi - \frac{v^2}{2} \right)^2 \quad ,$$

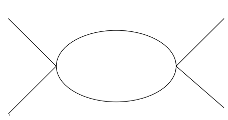
and $v \approx 246$ GeV.

- No fundamental scalars observed in nature!
- No explanation of Electroweak Symmetry Breaking
- Hierarchy and Naturalness Problem



$$\Rightarrow \; m_H^2 \propto \Lambda^2 \; .$$

- Triviality Problem



$$\Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0 \quad .$$

New realities?

Economist.com **SCIENCE & TECHNOLOGY**

New realities?

Oct 7th 2000

The "standard model" of the way the universe works is just about complete. Time to start looking for a new one

A HUNDRED years is a suspiciously round number. But if researchers at CERN, the European particle-physics laboratory near Geneva, turn out to be correct, it is exactly the period needed to build a model of how the universe works. Construction began in 1900 with Max Planck's publication of the first incarnation of quantum theory. Since then, and particularly with the development of high-energy particle accelerators in the 1930s and 1940s, the structure of matter has been probed in greater and greater detail while theorists have sought to impose order on what has been discovered. The result of their labours, now known as the standard model, will be complete-bar the odd dotting of "i"s and crossing of "t"s-with the discovery of a particle called the Higgs boson. This would round off the 18-strong menagerie of fundamental, irreducible particles required by the model. (The 17th, known as the tau neutrino, was announced two months ago by researchers at CERN's American rival, Fermilab.) And over the past few weeks indications have emerged from CERN that the Higgs is indeed a reality.

Time to start looking for a new one.

The "standard model" ... is just about complete.

Economist, Oct 7th 2000

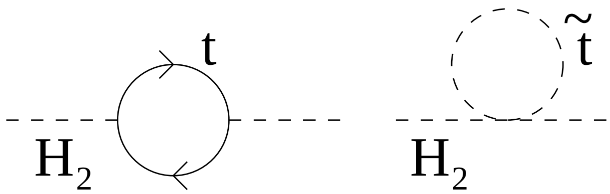
Three approaches @ 1 TeV:

- **Stabilize the Hierarchy** – Supersymmetry
- **Moderate the Hierarchy** – Composite Higgs
- **Eliminate the Hierarchy**
  1. Technicolor
  2. Low-Scale Gravity & Extra-dimensions

Physics at Very High Energies . . .

SUSY Beyond 1 TeV

SUSY is motivated by the Hierarchy Problem:



$$\rightarrow \delta m_H^2 \propto \log \Lambda^2 \ .$$

In the "minimal supersymmetric standard model" (MSSM) one introduces:

- Superpartners for all standard model particles: sfermions and gauginos.
- Two Higgs fields $H_1|_{+\frac{1}{2}}$ and $H_2|_{-\frac{1}{2}}$:
  1. Yukawa interactions arise from an *analytic* function (the superpotential) – cannot introduce $\tilde{H}$.
  2. Cancels potential $SU(2)$ anomaly.

Assume supersymmetry broken softly:

What are the masses of the superpartners?

M(ore)MSSM[†]

Naturalness requires $m_H \lesssim 1$ TeV.

SUSY protects electroweak scale if superpartners coupled most strongly to higgs $(\tilde{t}, \tilde{b_L}, \tilde{w}/\tilde{z}, \tilde{h})$ have masses $\lesssim 1$ TeV.

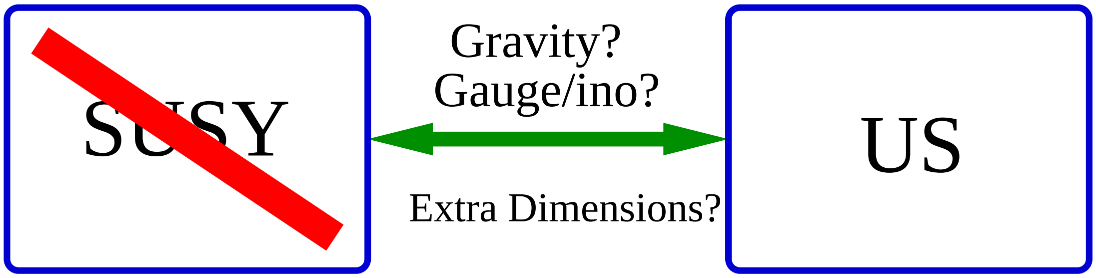
Mass scales:

1. Top squarks, left-handed bottom squark, weak gauginos, higgsinos have masses $\lesssim 1$ TeV.
2. Other squarks/sleptons contribute to weak scale at two-loops. Their masses must be $\lesssim 20$ TeV.
3. Gluino mass unspecified – $\mathcal{O}$(1TeV) in models.

Incomplete SUSY Spectrum ⇒ VLHC

[†] Cohen, Kaplan, and Nelson, `hep-ph/9607394`

SUSY Breaking



Interactions communicating SUSY breaking must be flavor-blind.

Gauge Mediation: Communication done through SM gauge interactions, possibly through an intermediate sector.

GMSB phenomenology at LHC generally easier than SUGRA models†.

Masses of particles in intermediate sector may be estimated from MSSM spectrum; could be as low as 10 TeV.

"Low-Scale" GMSB $\Rightarrow$ VLHC

† ATLAS Detector and Physics Performance TDR.

Composite Higgs

The Top-Quark Seesaw[†]:

$$\frac{m_t}{f_t} \simeq \frac{m_{quark}}{f_\pi} \approx 3 \quad \Rightarrow f_t \simeq 60\,\mathrm{GeV} \ll 250\,\mathrm{GeV} \ .$$

Seesaw: Mix with isosinglet χ:

$$\left(\overline{t_L} \quad \overline{\chi_L} \right) \begin{pmatrix} 0 & m_{t\chi} \\ \mu_{\chi t} & \mu_{\chi\chi} \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix} \ .$$

For $\mu_{\chi\chi} \gg m_{t\chi}, \mu_{\chi t}$

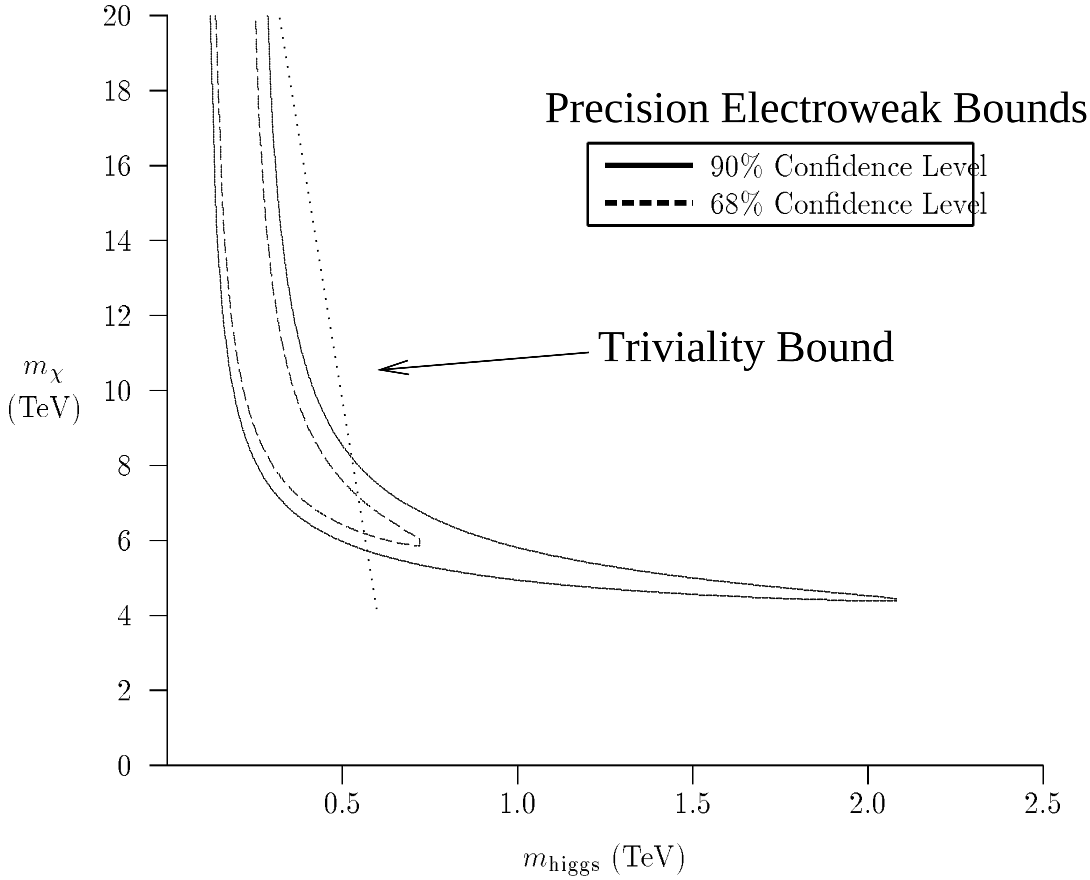
$$m_t \approx \frac{m_{t\chi}\mu_{\chi t}}{\mu_{\chi\chi}} \ ,$$

can have $m_{t\chi} \simeq 750$ GeV.

- All of EWSB due to $\langle \bar{t}t \rangle \neq 0$! No PGBs.
- Typical Scales of interactions: O(5 TeV)
- Top-Gluons & Z′
- Extra Singlet-Quarks
- Composite Higgs field, primarily $\bar{\psi}_L \chi_R \ldots$

[†]B. A. Dobrescu & C. T. Hill, hep-ph/9712319

Limits on Seesaw Higgs Mass†



Seesaw yields a model of a composite Higgs boson.

Larger Higgs masses are allowed at 68% and 90% CL, because* of non-zero contribution to T.

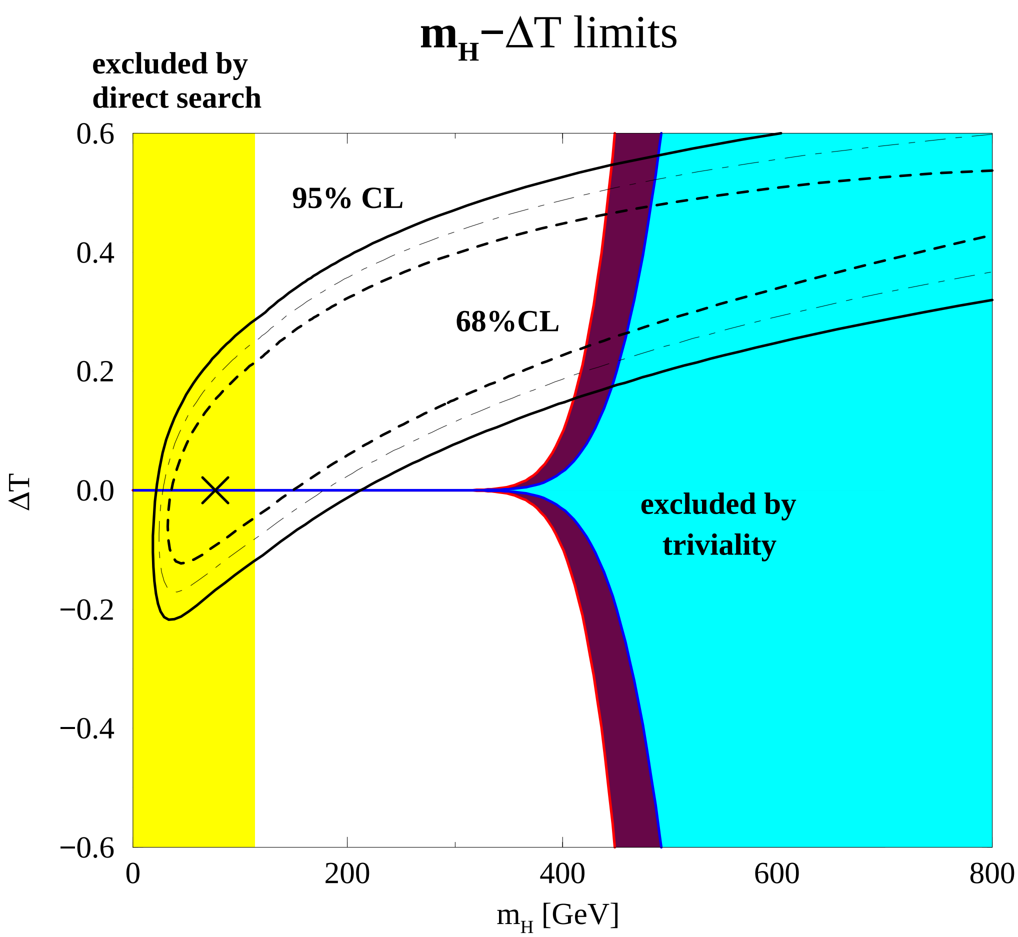
†H. Collins *et. al.*, `hep-ph/9908330`

*R.S.C. & N. Evans, `hep-ph/9907414`

Limits on a Composite Higgs Boson

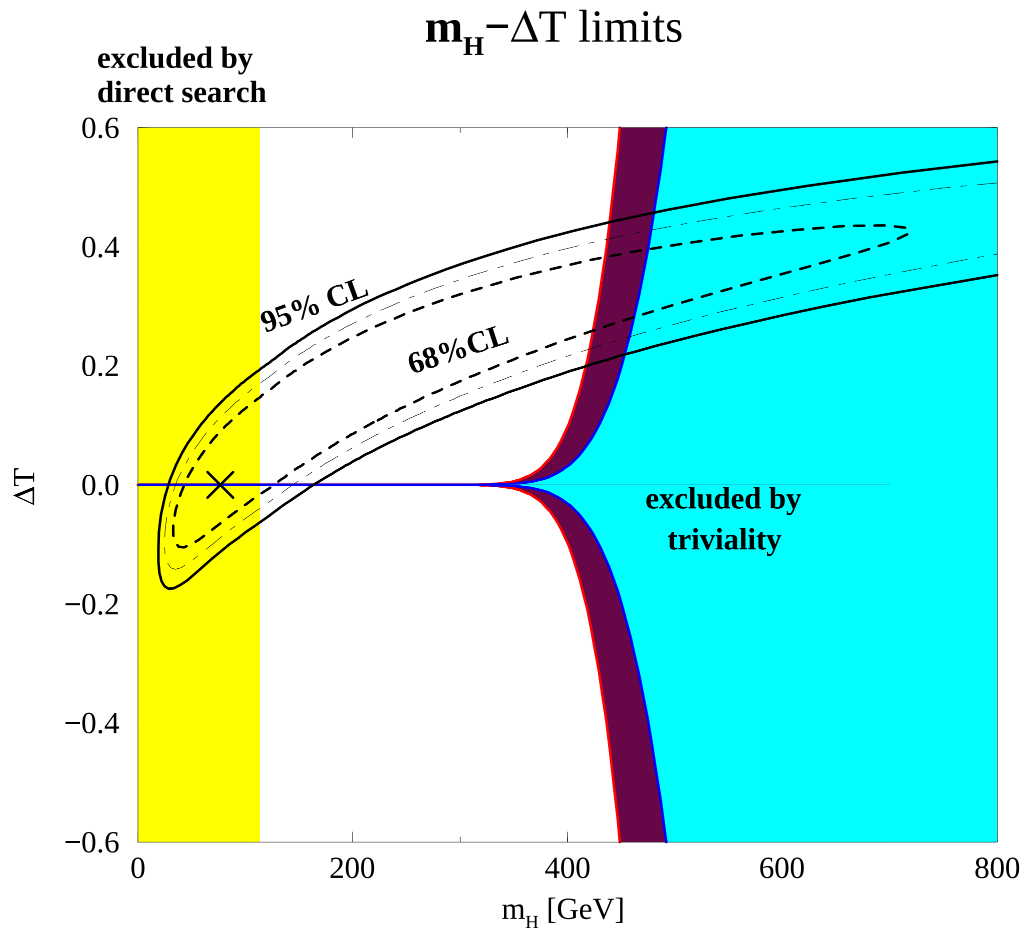
From triviality, we see that the Higgs model with a "heavy" Higgs boson can only be an effective theory valid below some high-energy scale Λ.

As the Higgs becomes heavier, the scale Λ *decreases*. Hence, the expected size of contributions to T *grow* $\Rightarrow$ consider ($\Delta\chi^2$, 2 dof) limits in $(m_H, \Delta T)$ plane:



Future Prospects

If $\Delta m_t = 2$ GeV and $\Delta M_W = 30$ MeV:



Heavy/Composite Higgs $\Rightarrow$ VLHC

Technicolor

$SU(N_{TC})$ strong/confining theory,

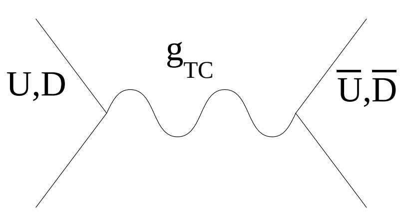
$$\Psi_L = \begin{pmatrix} U \\ D \end{pmatrix}_L \qquad U_R, D_R$$

with massless fermions

$$\mathcal{L} = \bar{U}_L i\not{D} U_L + \bar{U}_R i\not{D} U_R + \bar{D}_L i\not{D} D_L + \bar{D}_R i\not{D} D_R$$

Like QCD in m_u, $m_d \to 0$ limit:

- Chiral $SU(2)_L \times SU(2)_R$ symmetry
- Dynamically broken $SU(2)_L \times SU(2)_R \to SU(2)_V$
- Pions: $\pi^{\pm}, \pi^0 \Leftrightarrow W_L^{\pm}, Z_L$

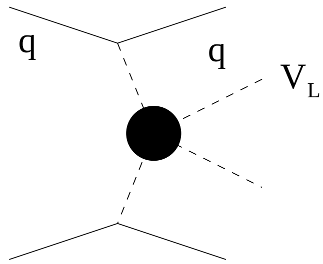


$$\to \langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle \neq 0 \,.$$

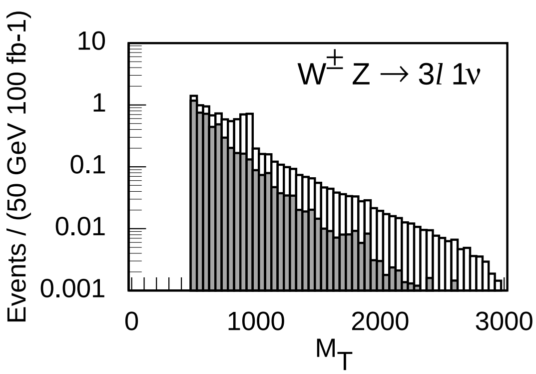
- $F_{TC} \Leftrightarrow v_i$
- Resonances: ρ_T & ω_T $[m^2 \propto F^2]$

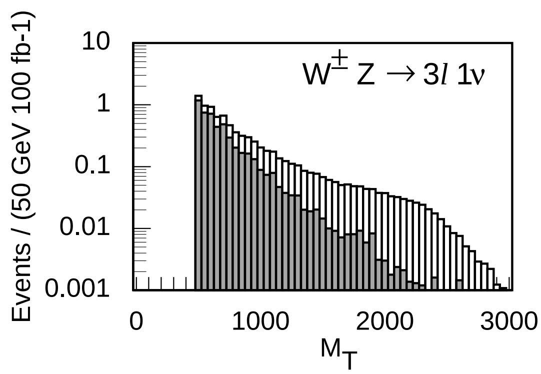
“Classic” Technicolor at the LHC[†]

Gauge-Boson Scattering:



For $M_{\rho_{TC}} = 1.0 \text{ TeV}, 2.5 \text{ TeV}$:



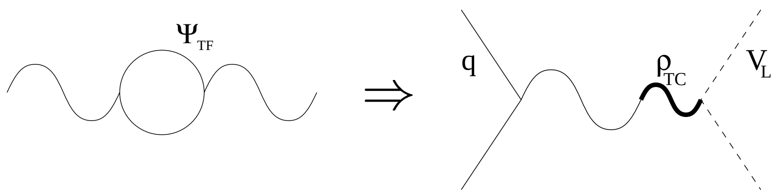


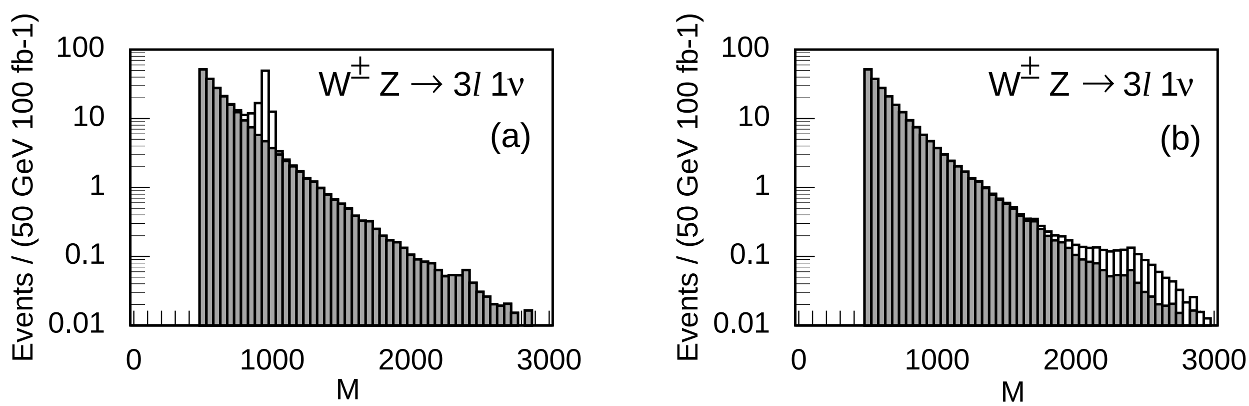
leptonic cuts	jet cuts
$\lvert y(\ell)\rvert < 2.5$	$E(j_{tag}) > 0.8$ TeV
$p_T(\ell) > 40$ GeV	$3.0 < \lvert y(j_{tag})\rvert < 5.0$
$p_T^{\text{miss}} > 50$ GeV	$p_T(j_{tag}) > 40$ GeV
$p_T(Z) > \frac{1}{4} M_T$	$p_T(j_{veto}) > 60$ GeV
$M_T > 500$ GeV	$\lvert y(j_{veto})\rvert < 3.0$

* J. Bagger *et. al.*, `hep-ph/9306256, 9504426`

"Classic" Technicolor at the LHC†

Gauge-Boson — Vector Meson Mixing:

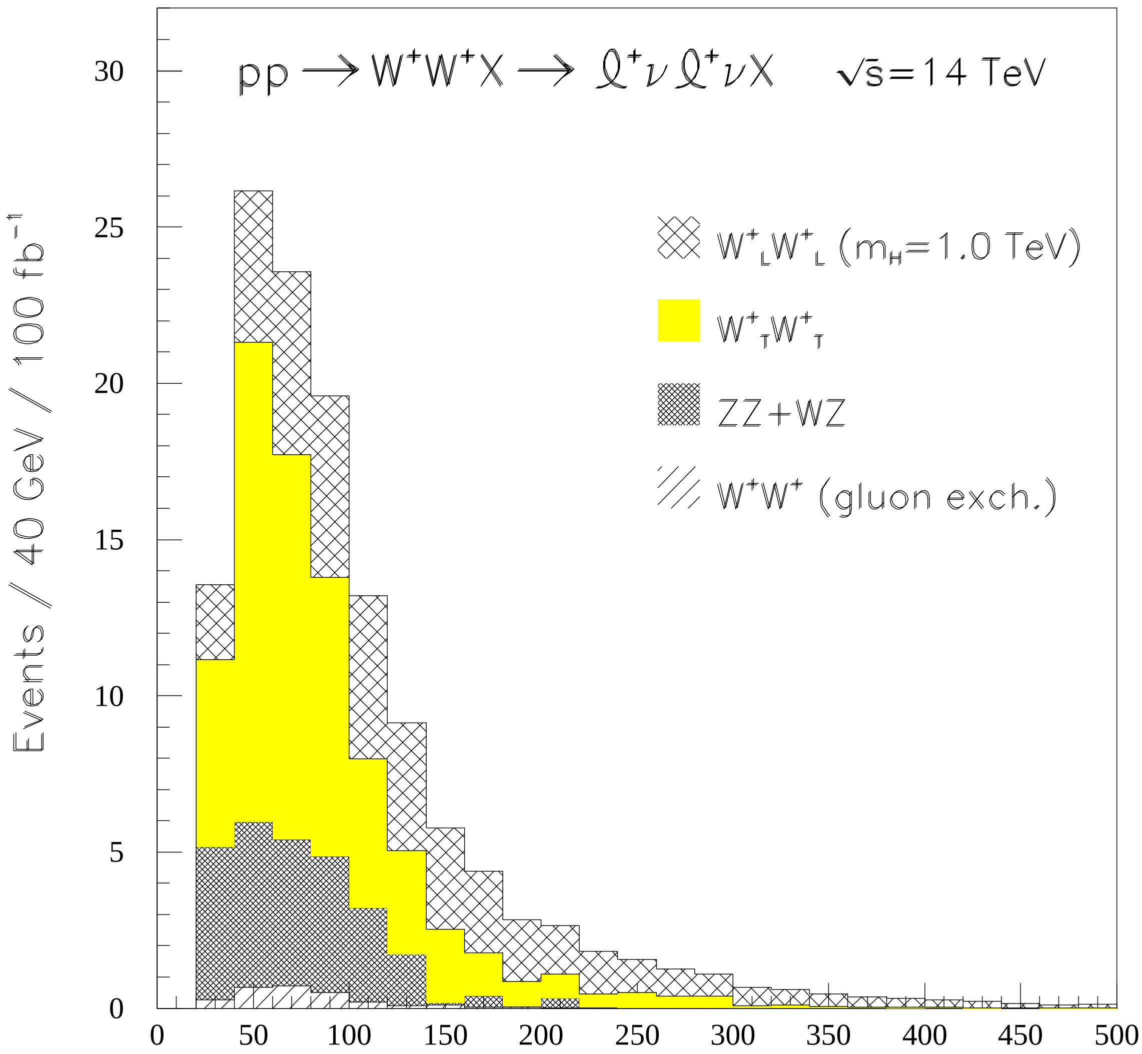




*M. Golden, *et. al.*, `hep-ph/9511206`

Strong WW Scattering at the LHC†

Non-Resonant Scattering:



† ATLAS Collaboration, CERN/LHCC/94-43.

Walking-Technicolor

If $\beta(\alpha_{TC}) \simeq 0$ all the way from Λ_{TC} to M_{ETC}, *i.e.* if the TC-coupling "walks" $\Rightarrow \gamma_m(\mu) \cong 1$

$$m_{q,l} = \frac{g^2_{ETC}}{M^2_{ETC}} \times \left(\langle \overline{T}T \rangle_{ETC} \cong \langle \overline{T}T \rangle_{TC} \frac{M_{ETC}}{\Lambda_{TC}} \right)$$

FCNCs $\Rightarrow M_{ETC}/\Lambda_{TC} \gtrsim 100 - 1000$

$$m_{q,l} \lesssim \frac{50 - 500\,\mathrm{MeV}}{N_D^{3/2}\theta^2_{sd}}$$

enough to accommodate s and c quarks.

How can $\beta(\alpha_{TC}) \simeq 0$?

- Many fermions
- Fermions in different TC representations.

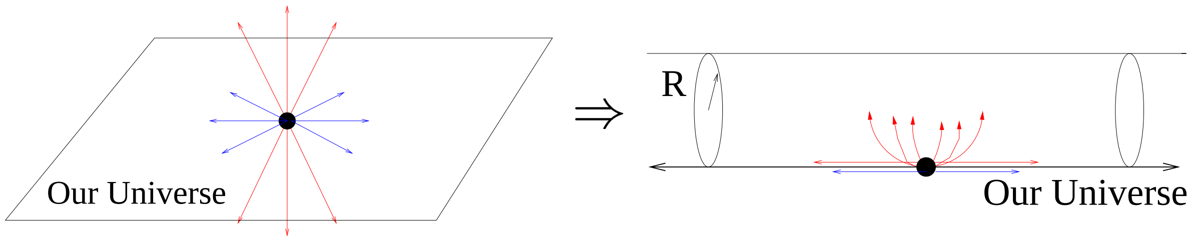
New Strong Dynamics!

Strong WW Scattering$\Rightarrow$VLHC

Extra Dimensions: the Brane World

Large Extra Dimensions:

Conventional View: Quantum Gravity irrelevant for $E \ll M_{Pl} \simeq 1.2 \times 10^{19}$ GeV.



n extra dimensions, lower the "Planck" scale

$$V_{Grav}(r) \propto \begin{cases} \frac{m_1 m_2}{M_{Pl}^2\, r} & r \gg R \\ \frac{m_1 m_2}{M^{2+n}\, r^{n+1}} & r \ll R \end{cases}$$

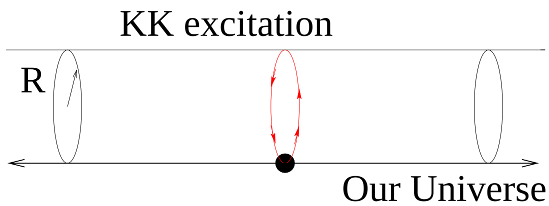
Hence $M_{Pl}^2 \propto M^{2+n}\, R^n$. Consider $M = 1$ TeV:

- $n = 2 \Rightarrow R = \mathcal{O}(1\,\mathrm{mm})$ & $R^{-1} \simeq 10^{-4}\,\mathrm{eV}$
  SuperNovae require $M \geq 50$ TeV for $n = 2$
- $n = 6 \Rightarrow R = \mathcal{O}(10^{-12}\,\mathrm{cm})$ & $R^{-1} \simeq 10\,\mathrm{MeV}$

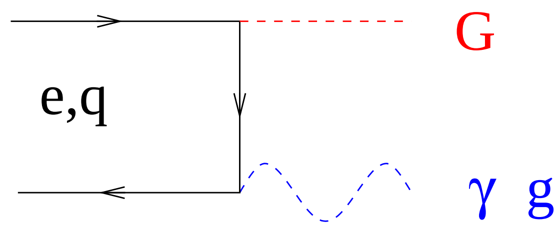
Antoniadis, Lykken, Dudas, Gerghetta, Arkani-Hamed, Dimopoulos, Dvali, Shiu, Tye, Kakushadze, Sundrum, ...

“Large” Signatures

KK excitations of the graviton:

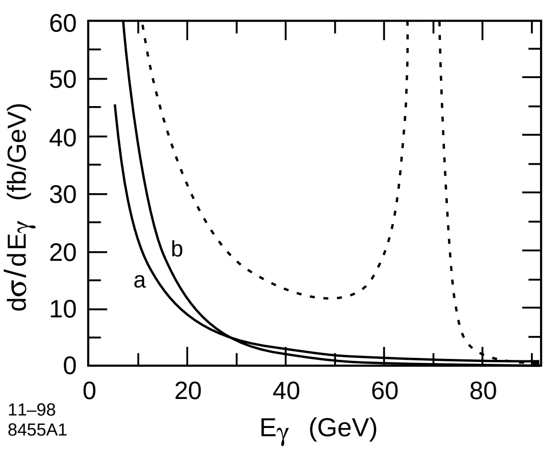


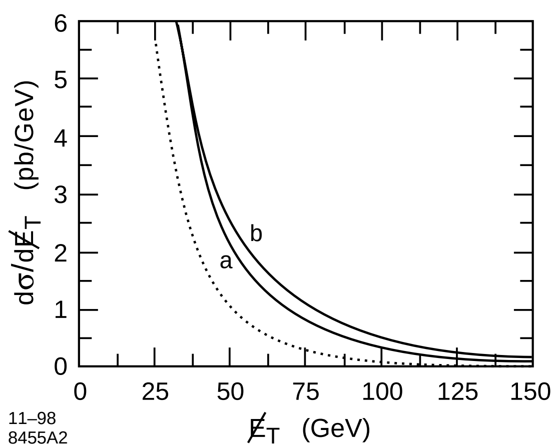
$\Rightarrow$



$\delta\mathcal{L} = -(8\pi G_N)^{1/2} G_{\mu\nu} T^{\mu\nu}$ but Many States!

Collider Signatures:





Collider	(95% CL)	M ($n=2$)	M ($n=4$)	M ($n=6$)
Present:	LEP 2	1200	730	520
	Tevatron	750	610	610
Future:	Tevatron	1300	900	810
	LC	7700	4500	3100
	LHC	4500	3400 (5000*)	3300

Mirabelli, Perelstein, & Peskin hep-ph/9811337

*Hinchliffe/ATLAS

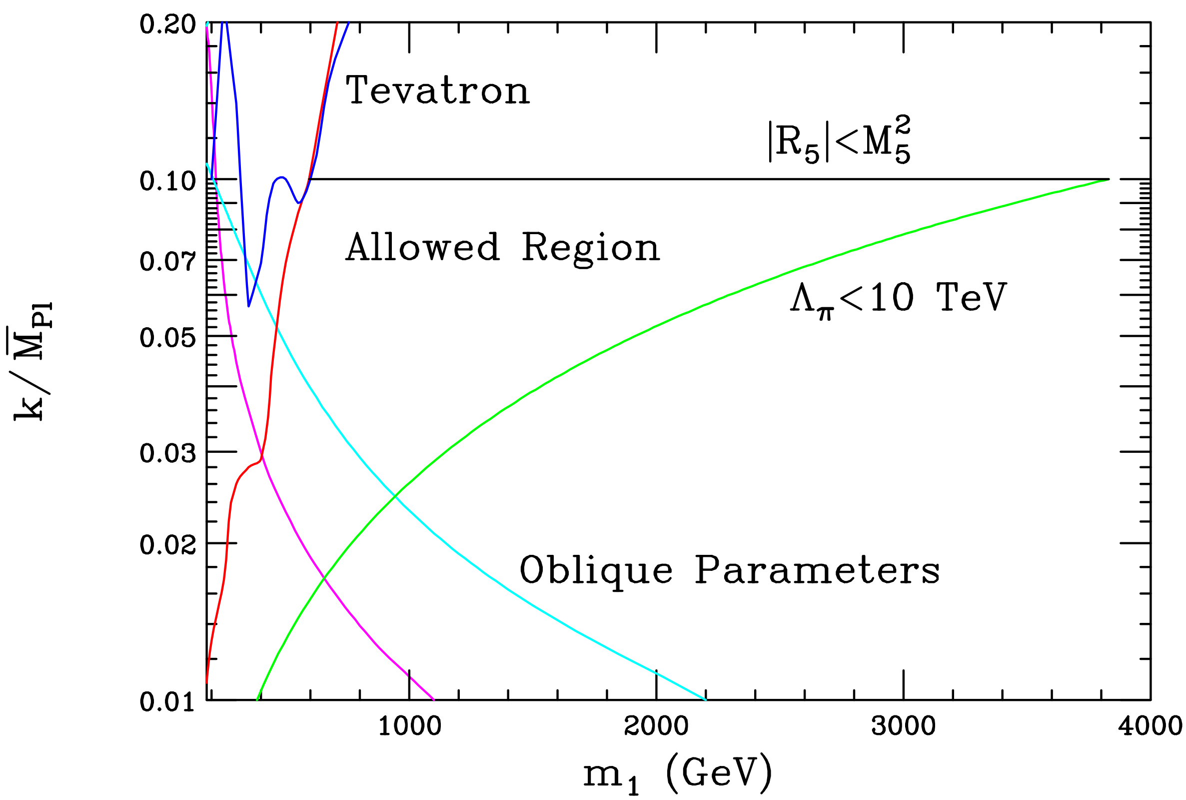
Small Dimensions: Warped Geometry†

Hierarchy from 5-d AdS geometry:

$$ds^2 = e^{-2kr_c|\varphi|}d^2x_4 + r_c^2 d\varphi^2 \ ,$$

gravity localized at $\varphi = 0$, SM at $\varphi = \pi$.

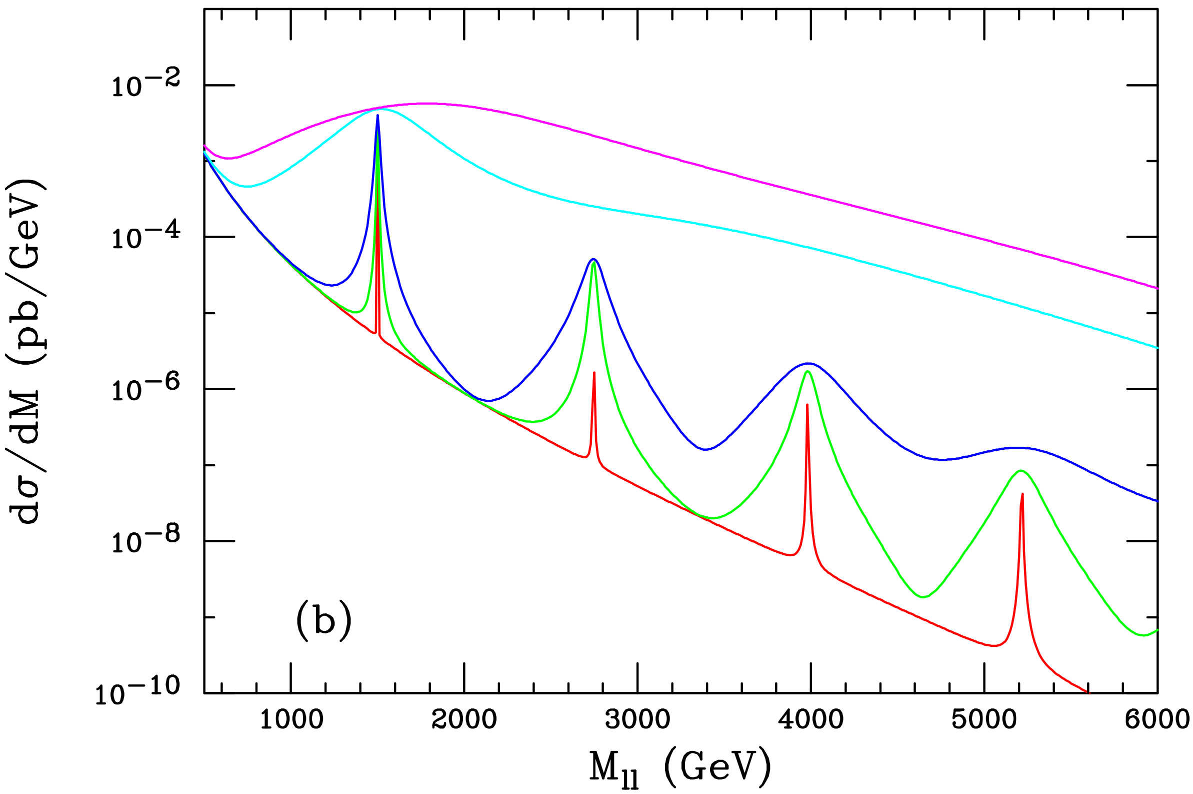
Yields cutoff $\Lambda_\pi \simeq M_{Pl}\, e^{-kr_c\pi}$ for SM!



† Randall & Sundrum, `hep-ph/9905221`

* Davoudiasl, Hewett, Rizzo, `hep-ph/0006041`

KK states in Drell-Yan at LHC*:

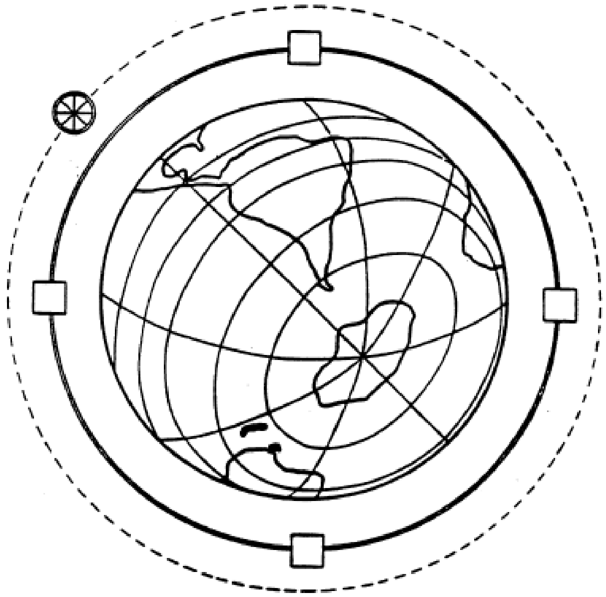


Extra-D Signals at LHC ⇒ "Strings" at VLHC

* Davoudiasl, Hewett, Rizzo, `hep-ph/0006041`

OR ELSE:

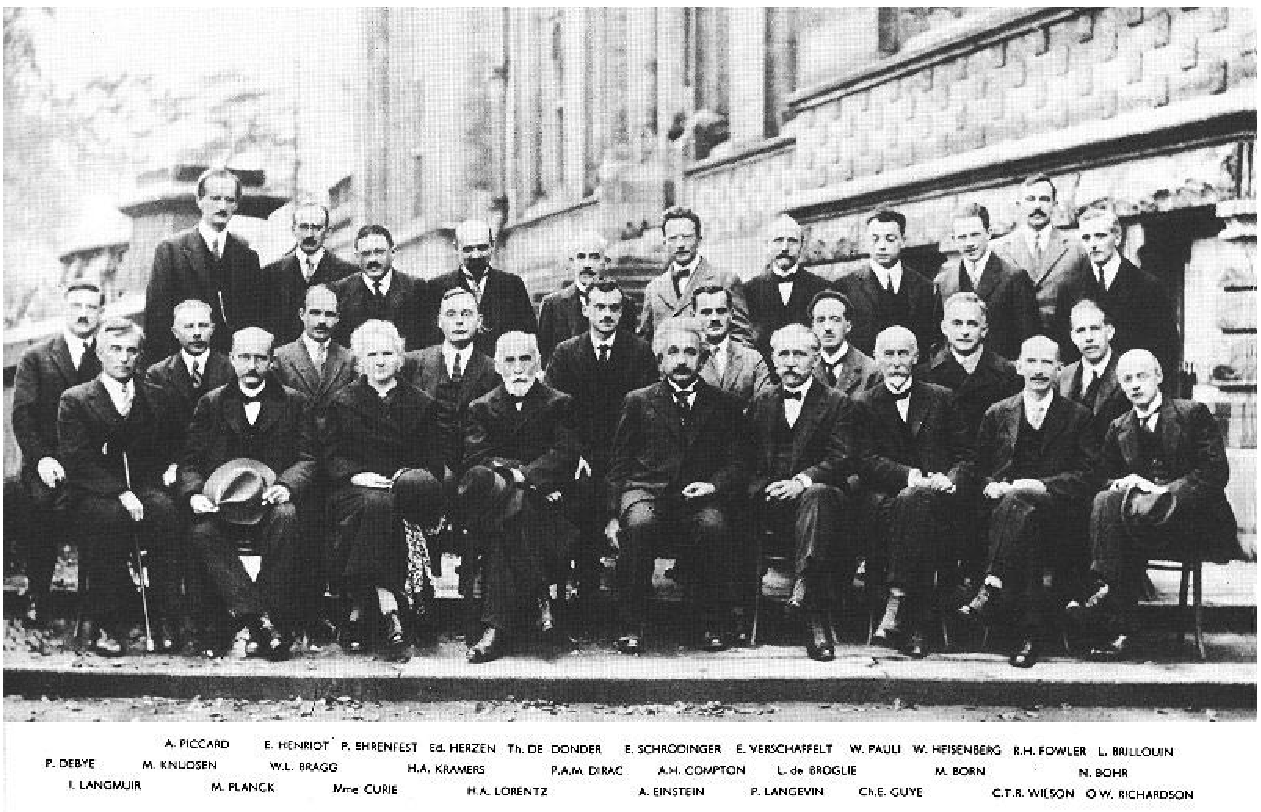
Desert above 1 TeV



Physics at Very High Energies

1. **The Standard Model**
   "Everything we know now"
2. **Physics @ 1 TeV**
   "Why we are clueless"
3. **Glimpses Beyond 1 TeV**
   "Sheer Speculation"
4. **OR ELSE**
   "The Pessimistic View"
5. **Conclusions**
   "We Need Experimental Guidance"

LHC will complete the last revolution . . .



. . . the VLHC will start the next one!