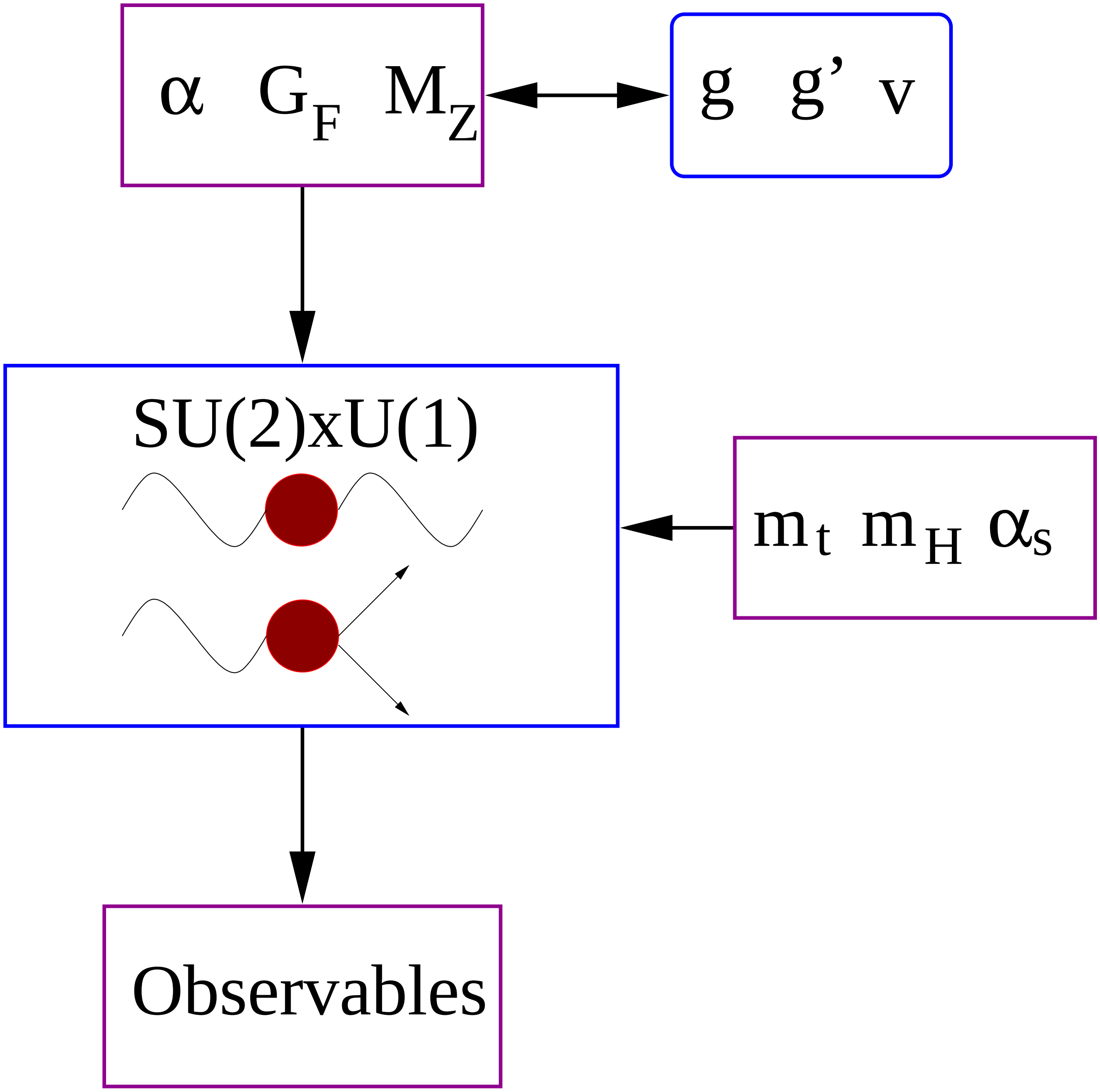
LINE DRIVE A Fermilab Series
of Linear Collider
Double-Headers

On the other hand . . .

1. **Physics without a Light Higgs Boson**
2. **The Need for Higher Energies**
3. **Lessons for a Linear Collider**
4. **Should we be one-handed?**

Light Higgs?

Higgs Mass Bounds From Precision EW Measurements



α G_F M_Z

g g' v

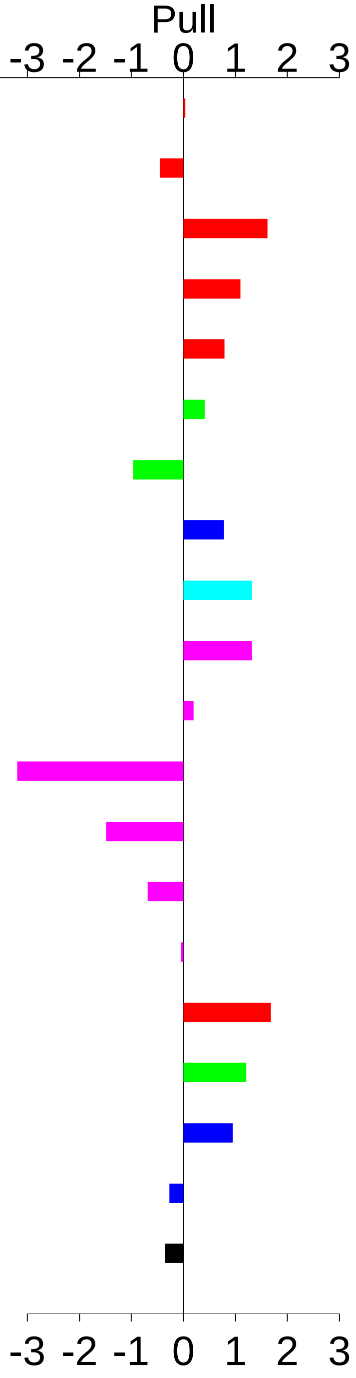
SU(2)xU(1)

m_t m_H α_s

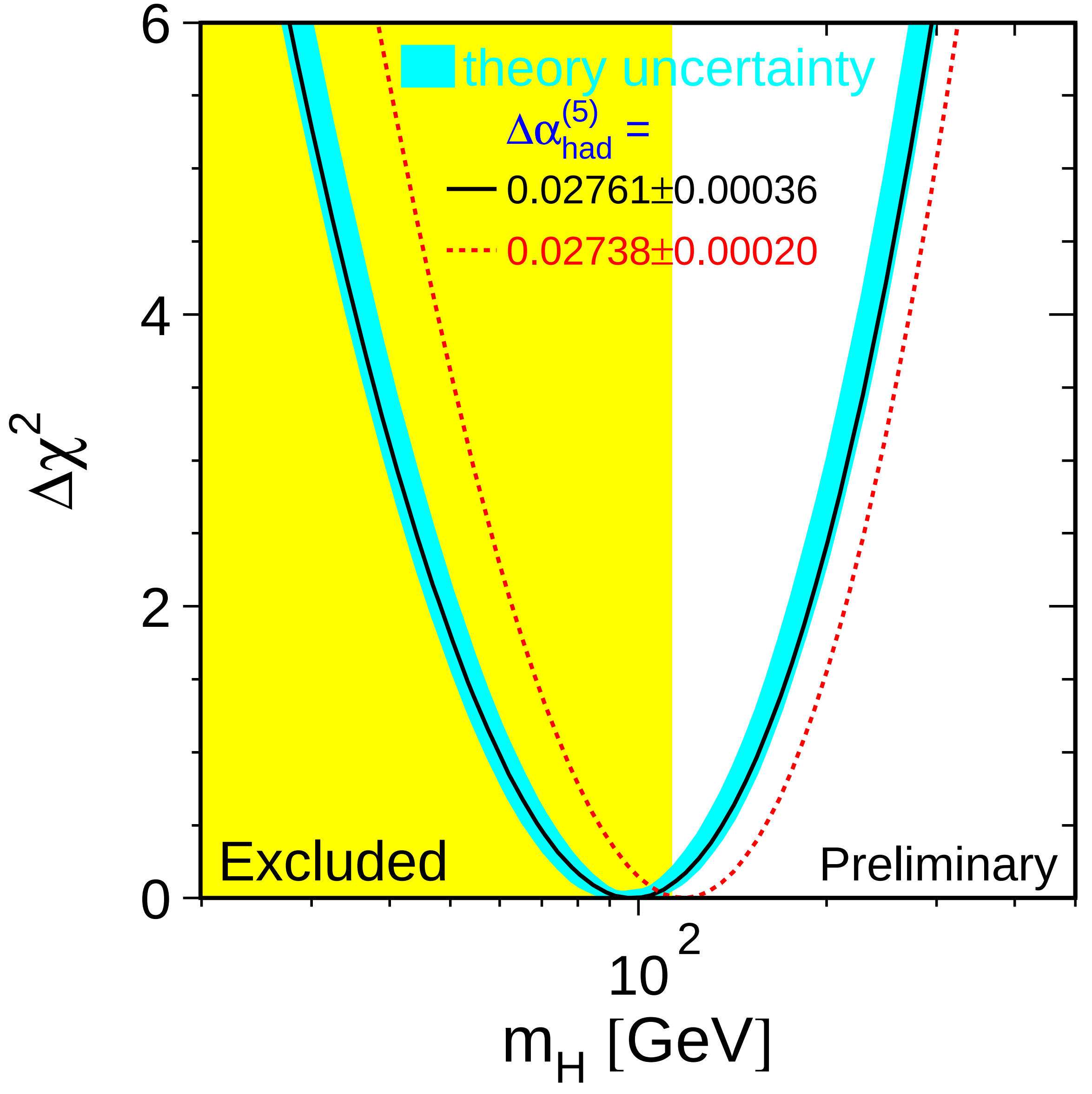
Observables

Winter 2001

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.04
Γ_Z [GeV]	2.4952 ± 0.0023	-.46
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.09
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.79
A_e	0.1498 ± 0.0048	.41
A_τ	0.1439 ± 0.0041	-.96
$\sin^2\theta^{lept}_{eff}$	0.2322 ± 0.0010	.78
m_W [GeV]	80.446 ± 0.040	1.32
R_b	0.21664 ± 0.00068	1.32
R_c	0.1729 ± 0.0032	.20
$A^{0,b}_{fb}$	0.0982 ± 0.0017	-3.20
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.48
A_b	0.921 ± 0.020	-.68
A_c	0.667 ± 0.026	-.05
A_l	0.1513 ± 0.0021	1.68
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.95
m_t [GeV]	174.3 ± 5.1	-.27
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.36



www.cern.ch/LEPEWWG/plots/winter2001/m01_show_pull.eps



Doesn't apply if new physics $E \simeq$ few TeV

http://www.cern.ch/LEPEWWG/plots/winter2001/m01_blueband.eps

The Triviality of the Standard Higgs Model

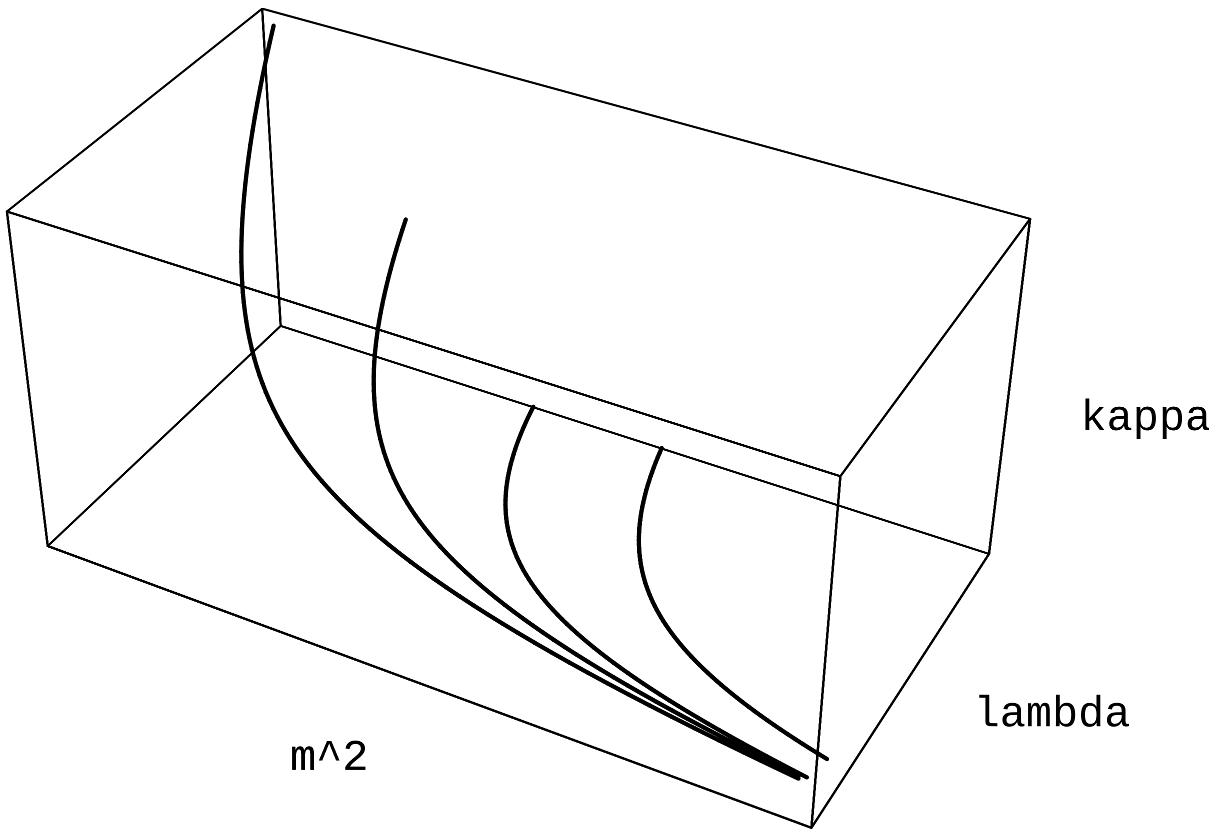
Define theory with a fixed UV-cutoff:

$$\begin{aligned}\mathcal{L}_\Lambda = \quad & D^\mu\phi^\dagger D_\mu\phi + m^2(\Lambda)\phi^\dagger\phi + \tfrac{\lambda(\Lambda)}{4}(\phi^\dagger\phi)^2 \\ & + \tfrac{\kappa(\Lambda)}{36\Lambda^2}(\phi^\dagger\phi)^3 + \ldots\end{aligned}$$

Integrate out states with $\Lambda' < k < \Lambda$:

$$\begin{aligned}\mathcal{L}_\Lambda &\Rightarrow \mathcal{L}_{\Lambda'} \\ m^2(\Lambda) &\rightarrow m^2(\Lambda') \\ \lambda(\Lambda) &\rightarrow \lambda(\Lambda') \\ \kappa(\Lambda) &\rightarrow \kappa(\Lambda')\end{aligned}$$

Consider evolution of couplings in the IR-limit....


kappa
lambda
m^2

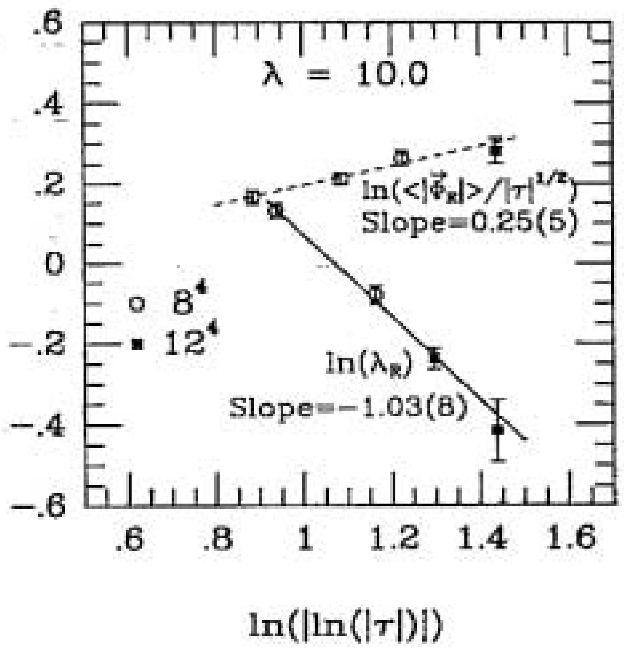
Consequences:

- $\kappa \to 0$ — “Renormalizability”, if $m_H \ll \Lambda$.
- $m^2 \to \infty$ — Naturalness/Hierarchy Problem:

$$\frac{\Delta m^2(\Lambda)}{m^2(\Lambda)} \propto \frac{v^2}{\Lambda^2}$$

- $\lambda \to 0$ — Triviality . . .

Perturbative analysis, but nonperturbative investigations show the same* behavior:



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[*] J. Kuti, *et. al.*, PRL 61 (1988) 678

Implications of Triviality

- The Standard Higgs model is, at best, a low-energy effective theory valid below a scale Λ characteristic of the underlying physics.

- Dashen & Neuberger: Given $m_H^2 = 2\lambda(m_H)v^2$, there is an *upper* bound on Λ. An *estimate* of this bound can be obtained by integrating the one-loop β-function, which yields

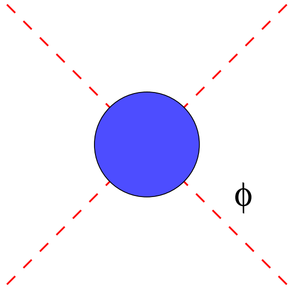
$$\Lambda \lesssim m_H \exp\left(\frac{4\pi^2 v^2}{3m_H^2}\right) ,$$

- Constraints on the underlying physics will result in a lower bound on Λ and will give rise to an upper bound on m_H.

T, S, and U in Composite Higgs Models

$T=0$ at tree-level in standard model because of an *accidental* “custodial” symmetry. In general the underlying high-energy physics *will not* respect custodial symmetry.

Leading custodial-symmetry violating operator:



$$\Rightarrow \frac{b\kappa^2}{2!\,\Lambda^2}\left(\phi^\dagger \overleftrightarrow{D}^\mu \phi\right)^2 ,$$

where κ measures size of couplings of composite Higgs field, and b=$\mathcal{O}(1)$.

This gives rise to ($\Delta\rho = \varepsilon_1 = \alpha T$)

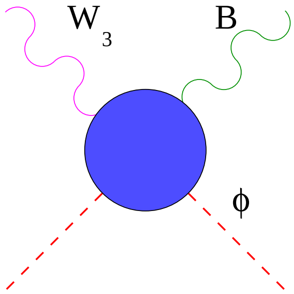
$$|\Delta T| = |b|\kappa^2 \frac{v^2}{\alpha(M_Z)\Lambda^2} \gtrsim \frac{|b|\kappa^2\, v^2}{\alpha(M_Z^2)\, m_H^2}\, \exp\left(-\frac{8\pi^2 v^2}{3m_H^2}\right) ,$$

where $v \approx 246$ GeV.

Current limits imply $|T| \lesssim 0.5$, and hence

$\Lambda \gtrsim 4\,\mathrm{TeV}\cdot\kappa$. (For $\kappa \simeq 4\pi$, $m_H \lesssim 450$ GeV.)

The leading contribution to S arises from



$$\Rightarrow -\frac{a}{2!\,\Lambda^2}\left\{[D_\mu, D_\nu]\phi\right\}^\dagger [D^\mu, D^\nu]\phi\ .$$

This gives rise to ($\varepsilon_3 = \frac{\alpha S}{4\sin^2\theta_W}$)

$$\Delta S = \frac{4\pi a v^2}{\Lambda^2}\ .$$

NB: The size of these effects is very different.

$$\frac{\Delta S}{\Delta T} = \frac{a}{b}\left(\frac{4\pi\alpha}{\kappa^2}\right) = \mathcal{O}\left(\frac{10^{-1}}{\kappa^2}\right)\ .$$

Even for $\kappa \simeq 1$, $|\Delta S| \ll |\Delta T|$.

Furthermore in a strongly coupled theory, which would give rise to a composite Higgs, we expect $\kappa = \mathcal{O}(4\pi)$. *In QCD, for example,* $g_\rho \simeq 6$.

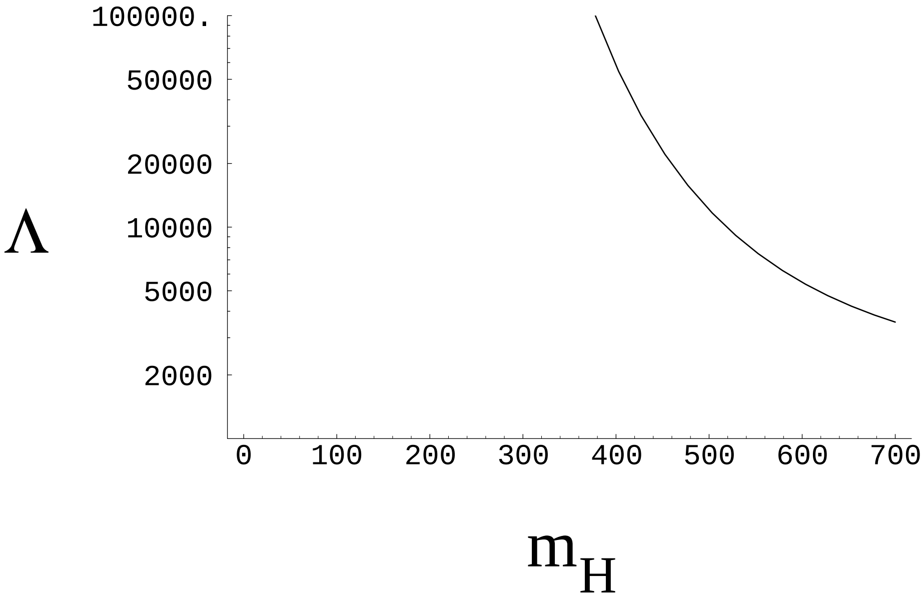
Likewise: U ($\varepsilon_2 = -\frac{\alpha U}{4\sin^2\theta_W}$) arises from

$$\frac{c g^2 \kappa^2}{\Lambda^4}(\phi^\dagger W^{\mu\nu}\phi)^2$$

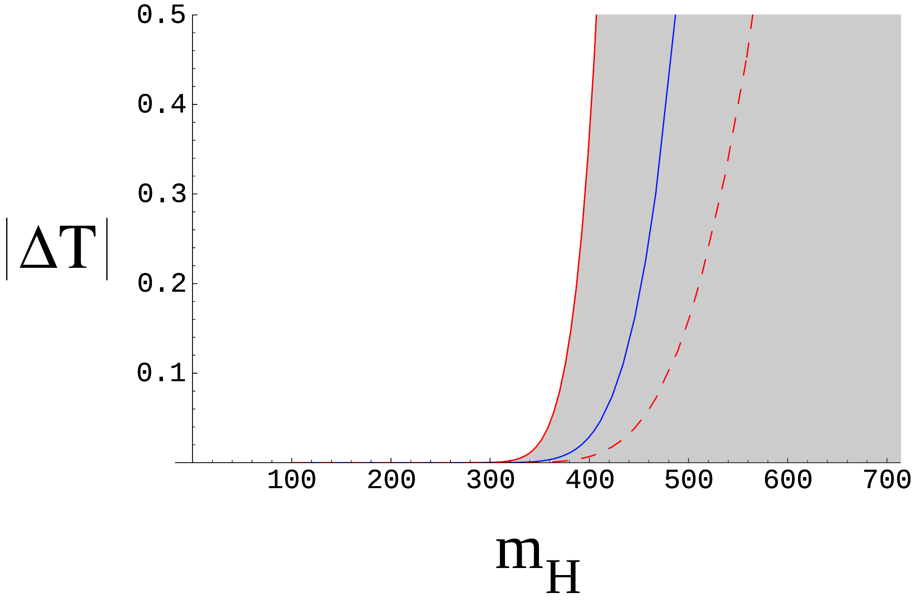
and is much smaller than T.

Putting It All Together …

The larger m_H, the lower Λ …



…and the larger ΔT!



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

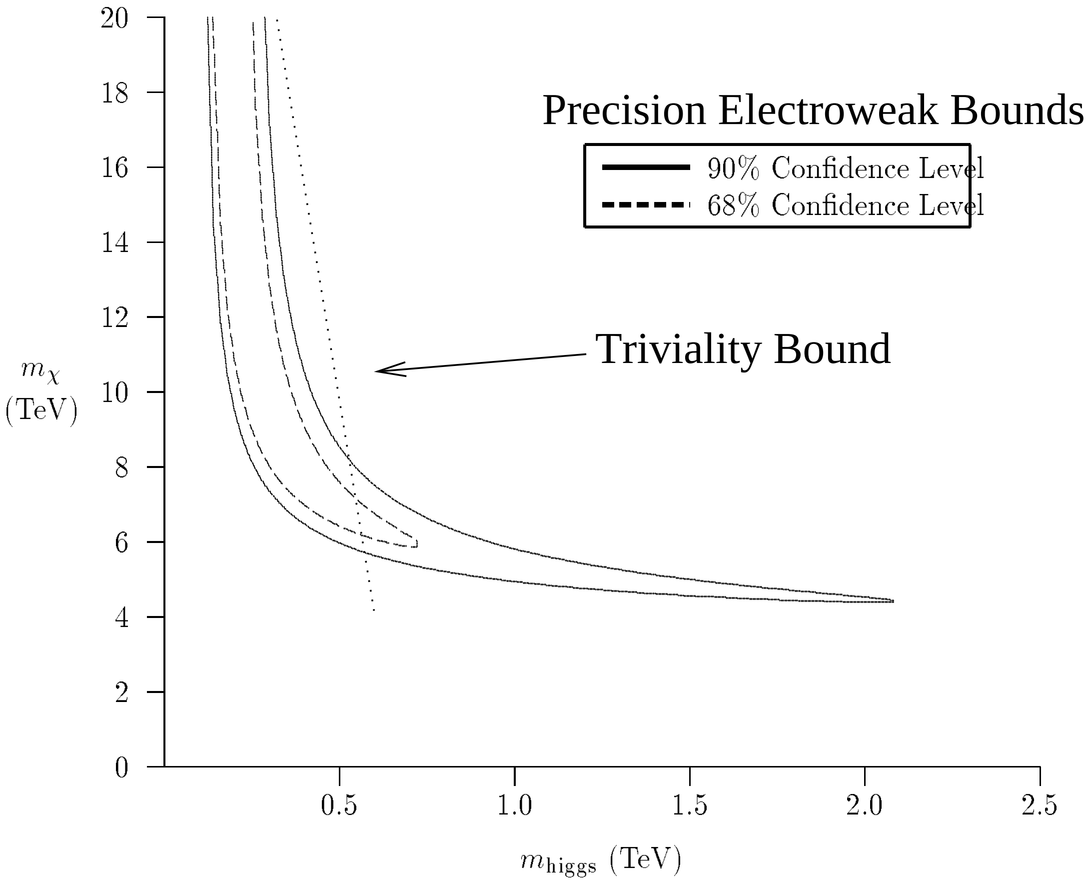
$$m_t \approx \frac{m_{t\chi}\mu_{\chi t}}{\mu_{\chi\chi}}\ ,$$

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 Weak-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.

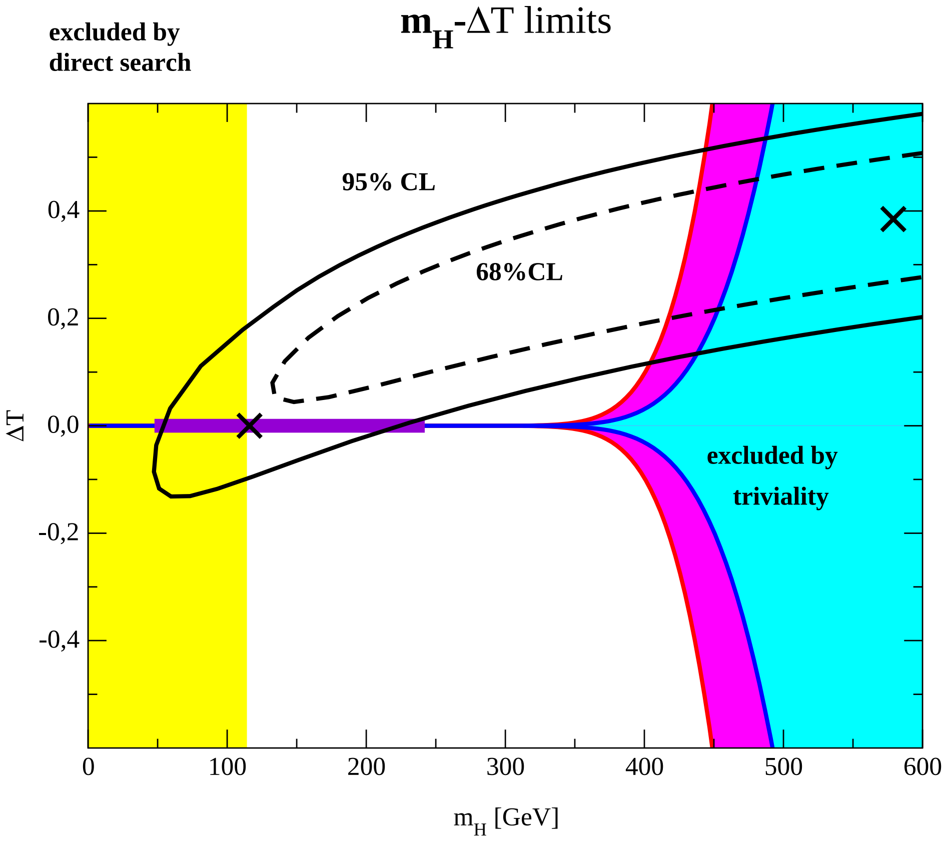
Larger Higgs masses are allowed at 68% and 90% CL, because[*] of non-zero contribution to T.

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

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

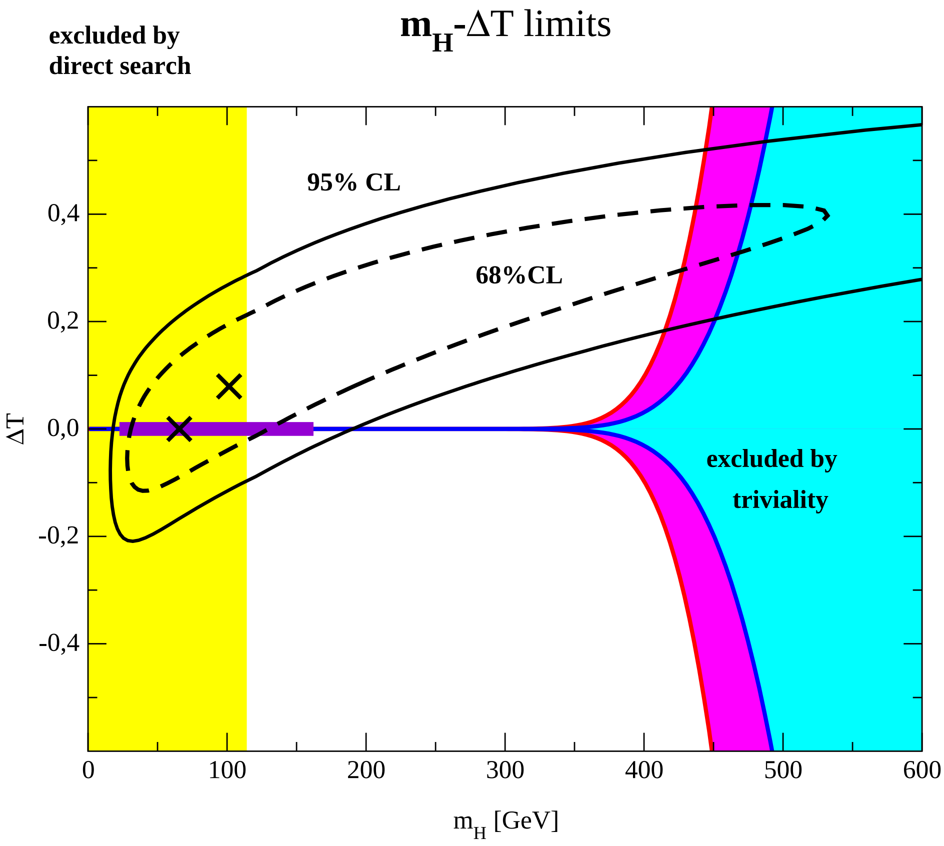
Limits on a Composite Higgs Boson

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:



$A_{fb}^{0,b}$ (and $\Delta\alpha^{(5)}_{\rm had}$ and α_s) has changed this curve significantly!

Fit Without* $\mathbf{A}_{fb}^{0,b}$



Heavy/Composite Higgs ⇒ Higher Energies

*M. Chanowitz, `hep-ph/0104024`

Higher Energies

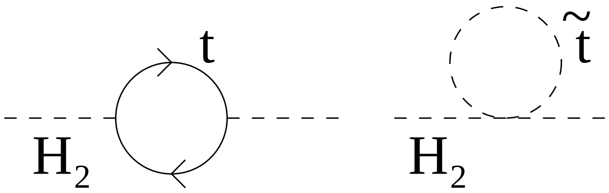
Three approaches @ 1 TeV:

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

Physics at $\mathcal{O}(10\ \text{TeV})\ldots$

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.
    3. “Higgs” light in minimal model & **also nonminimal if perturbative unification assumed!**.

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.

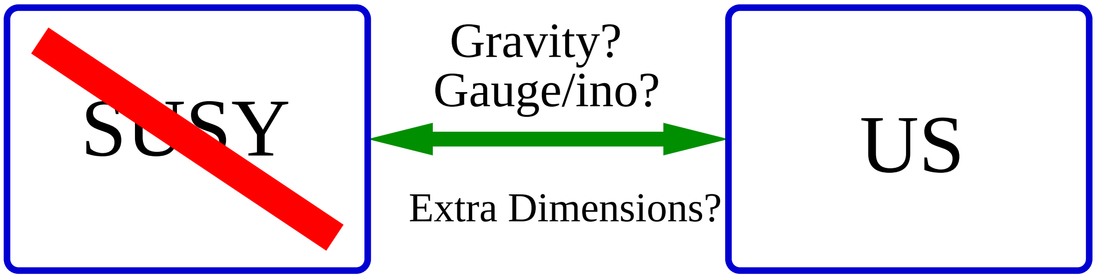
Mass scales:

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 – $\mathcal{O}(1\mathrm{TeV})$ in models.

Incomplete SUSY Spectrum ⇒ Higher Energies

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

SUSY Breaking



~~SUSY~~

Gravity?
Gauge/ino?

Extra Dimensions?

US

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 ⇒ Higher Energies

[†] ATLAS Detector and Physics Performance TDR.

Technicolor

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

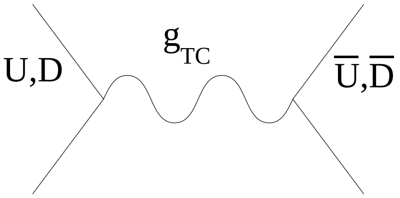
$$\Psi_L = \begin{pmatrix} U \\ D \end{pmatrix}_L \qquad U_R, D_R$$

with massless fermions

$$\begin{aligned} \mathcal{L} &= \bar{U}_L i\not{D} U_L + \bar{U}_R i\not{D} U_R + \\ &\quad \bar{D}_L i\not{D} D_L + \bar{D}_R i\not{D} D_R \end{aligned}$$

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: $\pi^\pm, \pi^0 \Leftrightarrow W_L^\pm, Z_L$

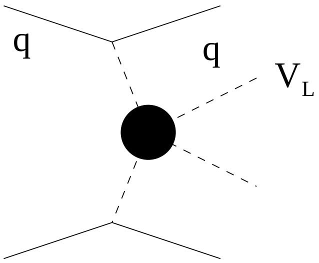


$$\to \langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle \neq 0\,.$$

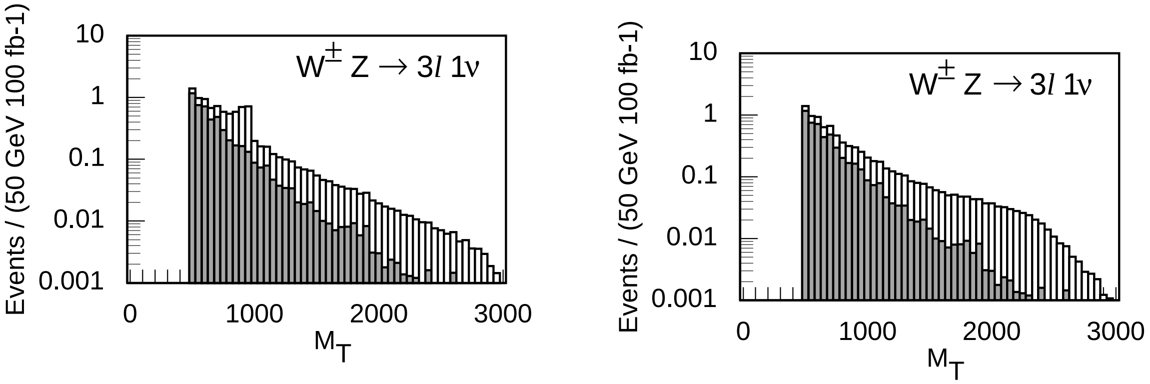
- $F_{TC} \Leftrightarrow v_i$
- Resonances: ρ_T & ω_T $[m^2 \propto F^2]$

"Classic" Technicolor at the LHC†

Gauge-Boson Scattering:



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

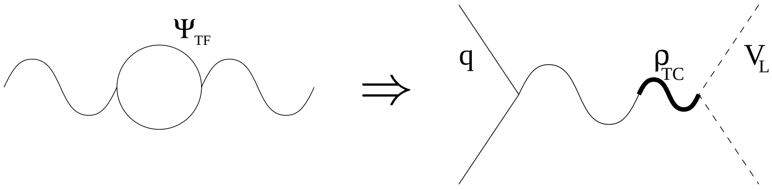


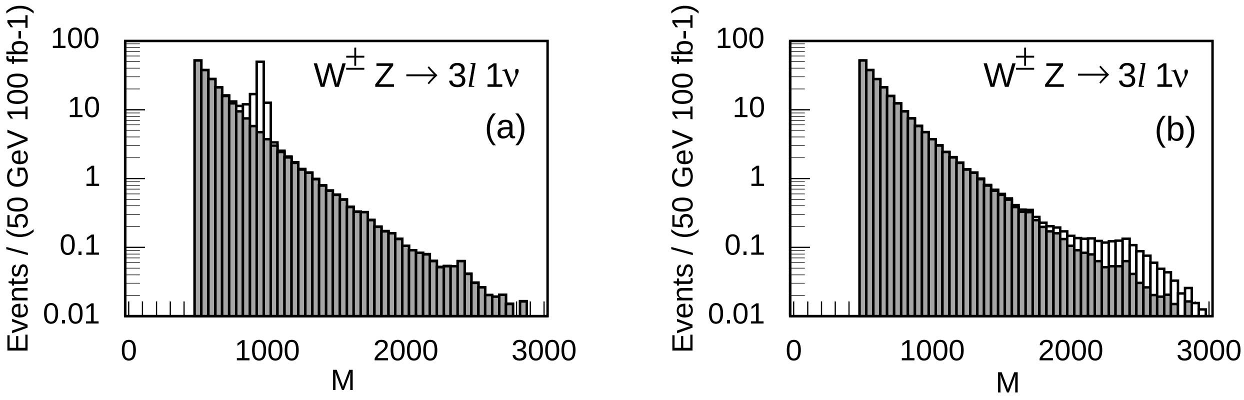
leptonic cuts	jet cuts
$\lvert y(\ell)\rvert < 2.5$	$E(j_{tag}) > 0.8$ TeV
$p_T(\ell) > 40$ GeV	$3.0 < \lvert y(j_{tag})\rvert < 5.0$
$p_T^{\text{miss}} > 50$ GeV	$p_T(j_{tag}) > 40$ GeV
$p_T(Z) > \frac{1}{4}M_T$	$p_T(j_{veto}) > 60$ GeV
$M_T > 500$ GeV	$\lvert y(j_{veto})\rvert < 3.0$

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

“Classic” Technicolor at the LHC[†]

Gauge-Boson — Vector Meson Mixing:

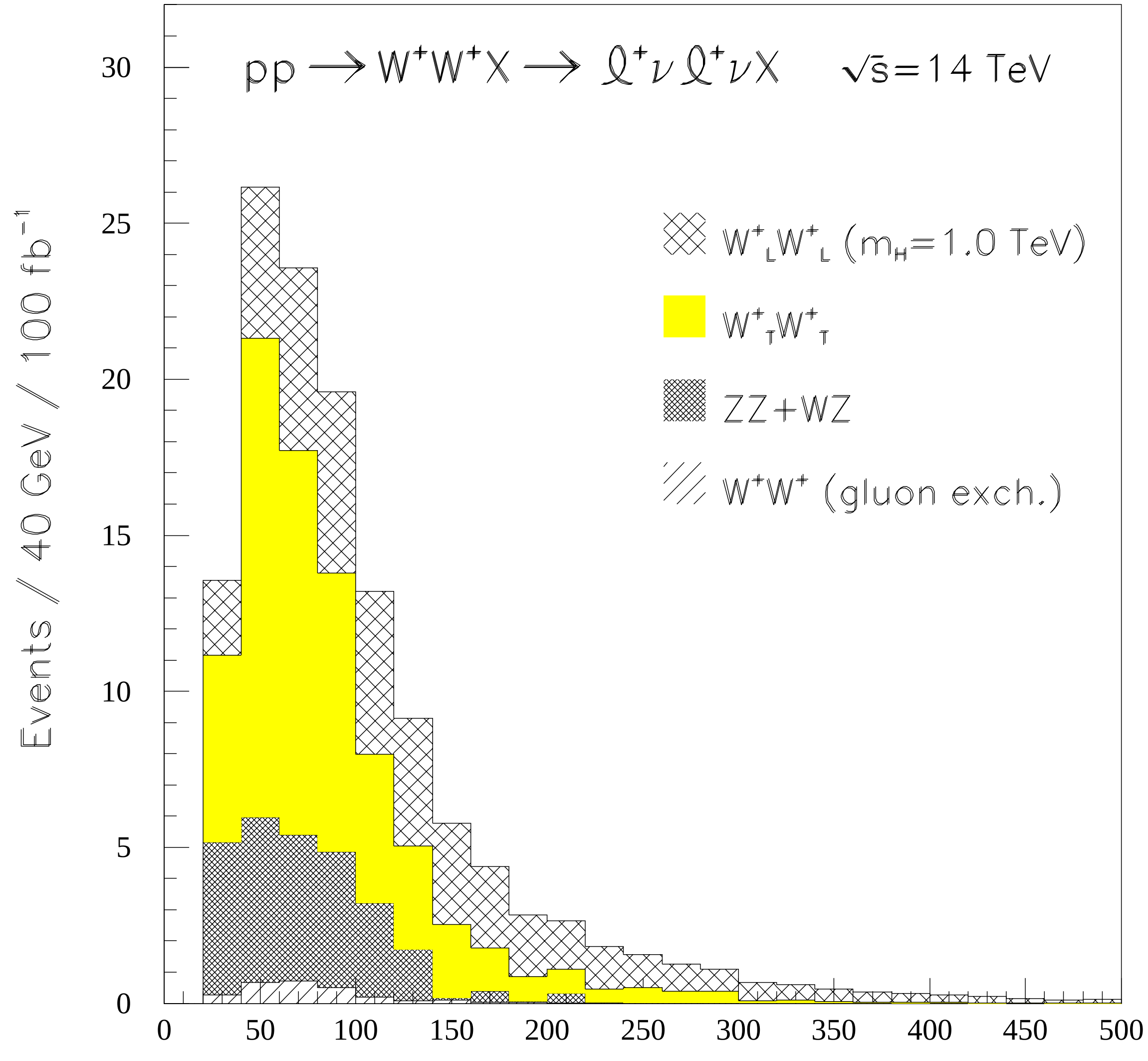




[*] M. Golden, *et. al.*, `hep-ph/9511206`

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.

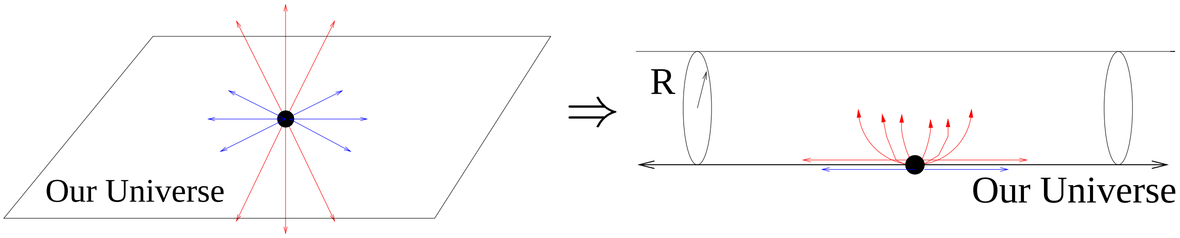
New Strong Dynamics!

Strong WW Scattering⇒Higher Energies

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.



New View: $4+n$ dimensions, lower "Planck" scale

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

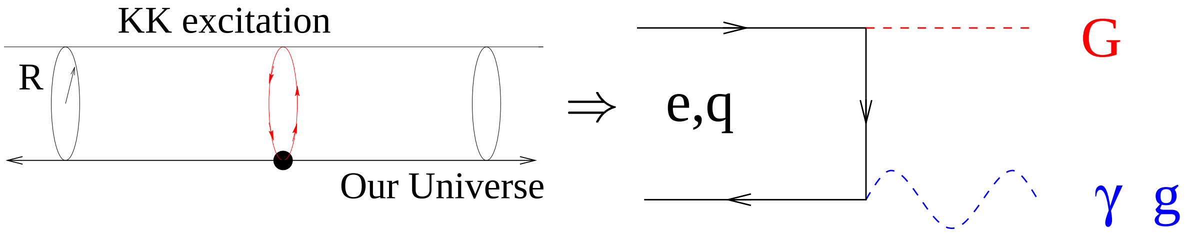
Hence $M_{Pl}^2 \propto M^{2+n}\, R^n$. Consider $M = 1$ TeV:

- $n = 2 \Rightarrow R = \mathcal{O}(1\,\mathrm{mm})$ & $R^{-1} \simeq 10^{-4}\,\mathrm{eV}$
  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, ...`

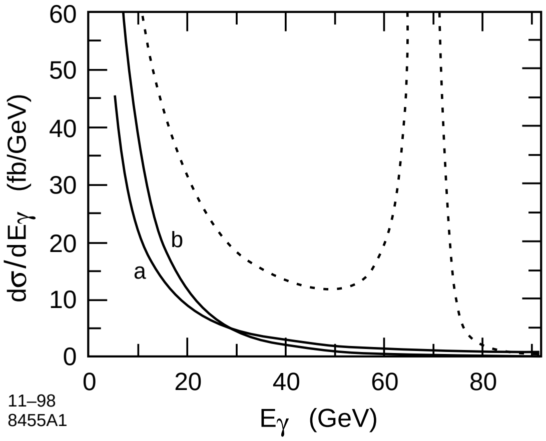
"Large" Signatures

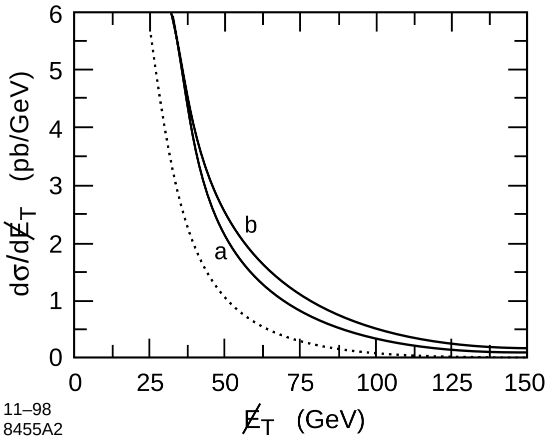
KK excitations of the graviton:



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

Collider Signatures:

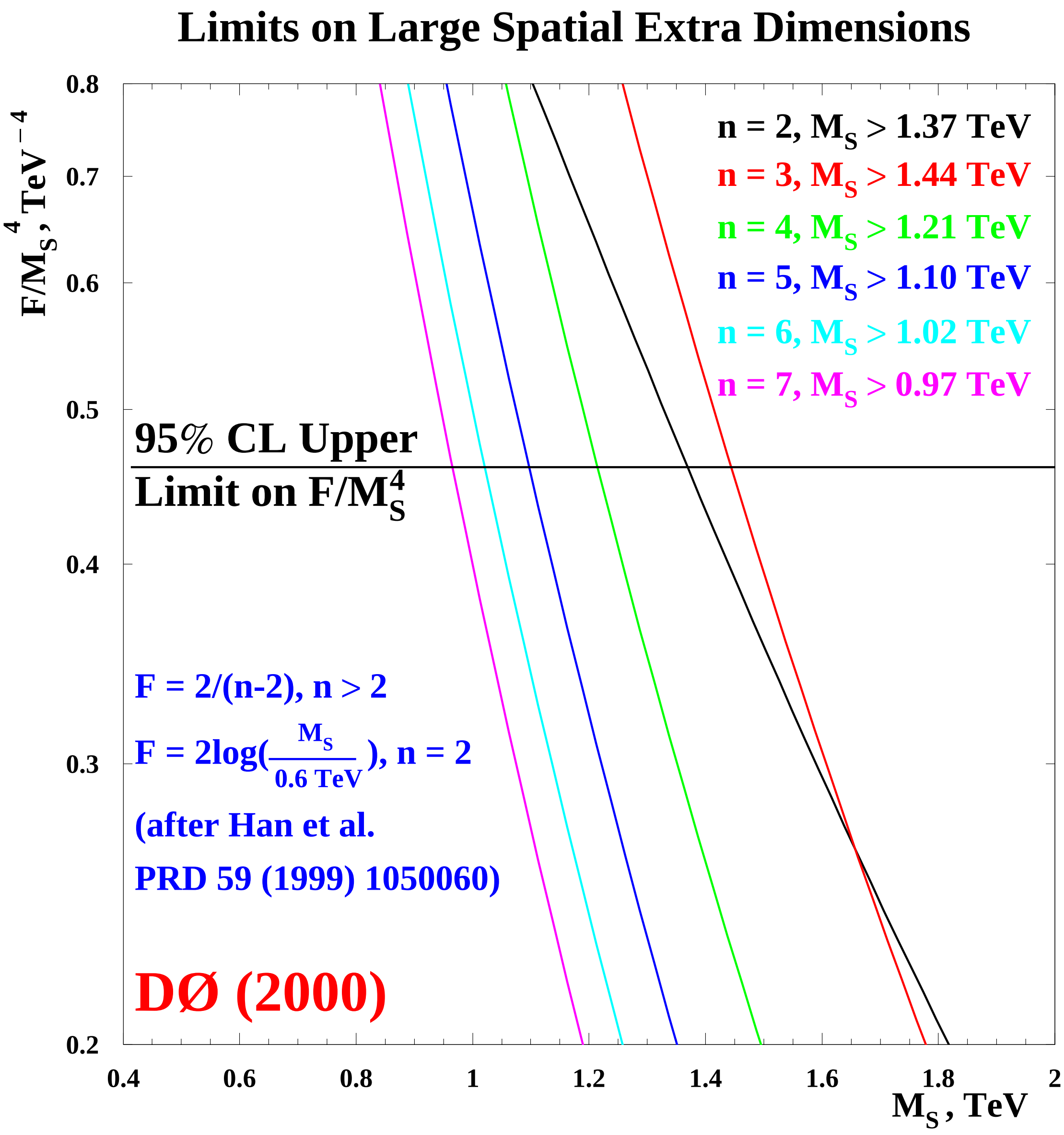




Collider	(95% CL)	M $(n=2)$	M $(n=4)$	M $(n=6)$
Present:	LEP 2	1200	730	520
	Tevatron	750	610	610
Future:	Tevatron	1300	900	810
	LC	7700	4500	3100
	LHC	4500	3400 (5000*)	3300

Mirabelli, Perelstein, & Peskin `hep-ph/9811337` *Hinchliffe/ATLAS

Virtual Exchange*:



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*DØ, `hep-ex/0008065`

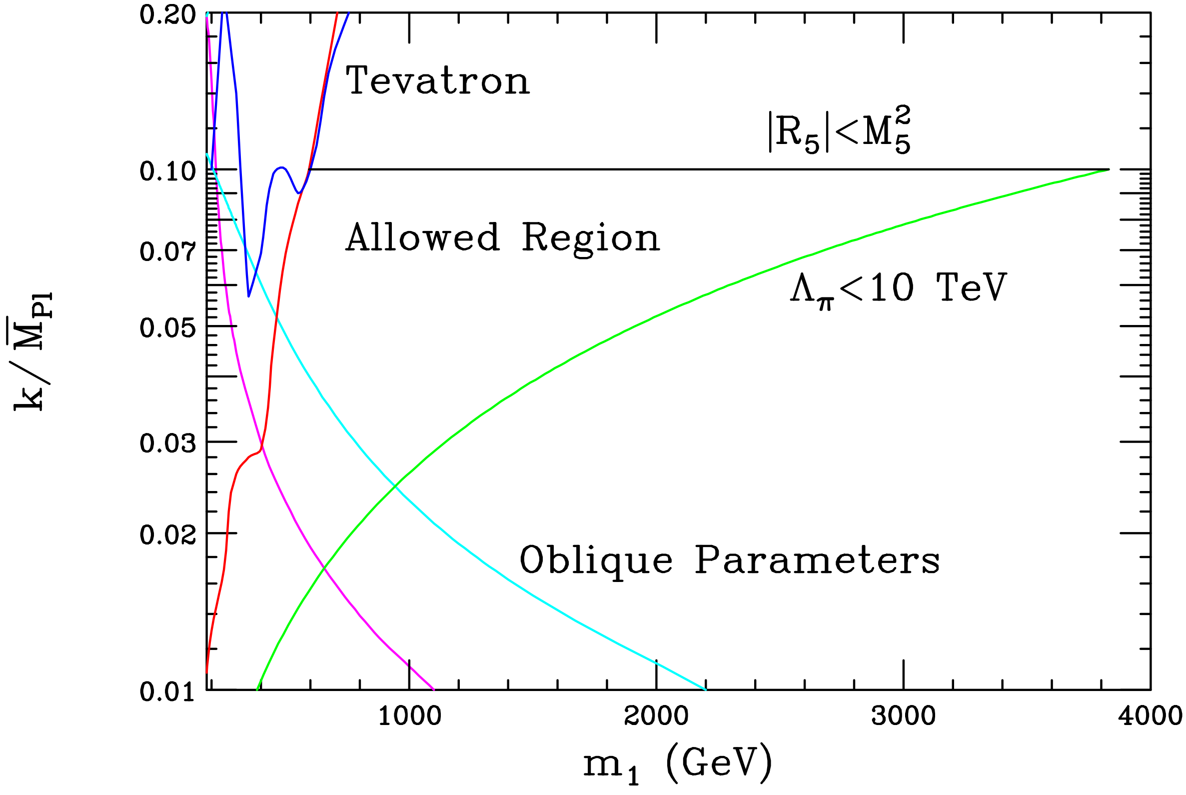
Small Dimensions: Warped Geometry[†]

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 $\varphi = \pi$.

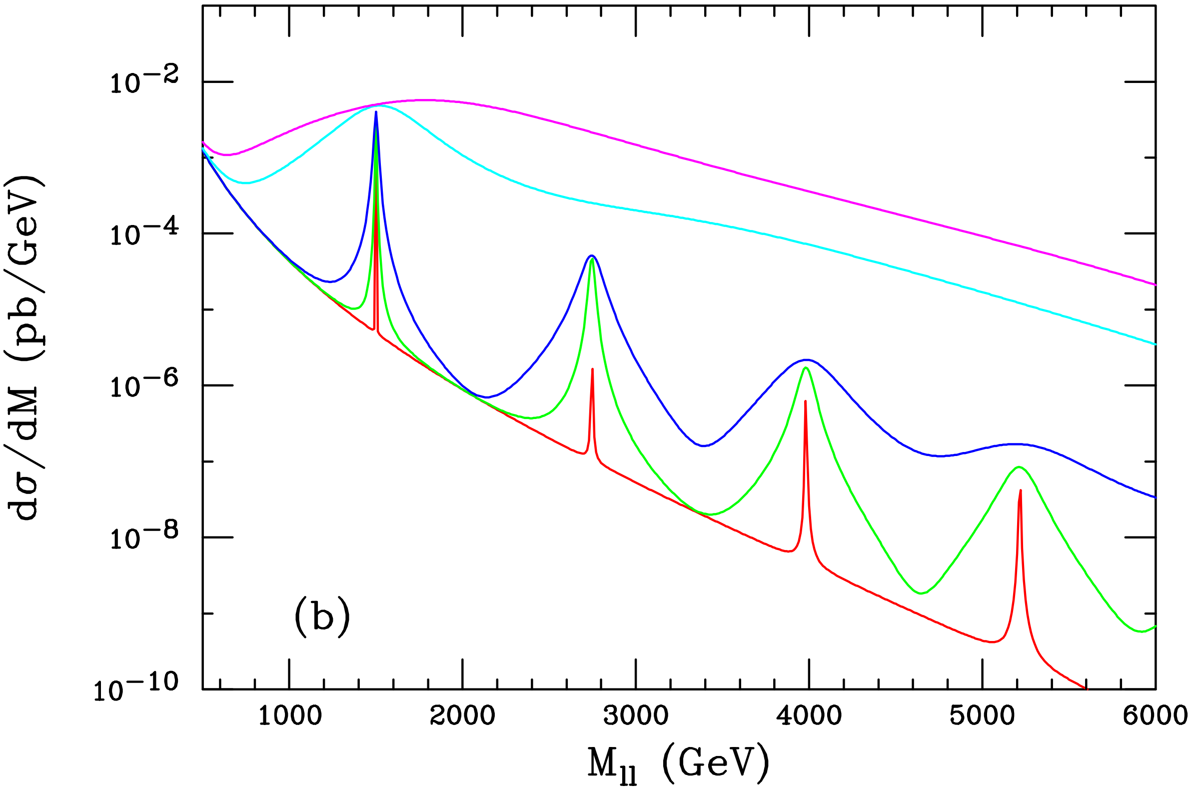
Yields cutoff $\Lambda_\pi \simeq M_{Pl}\, e^{-kr_c\pi}$ for SM!



[†] 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 Higher Energies

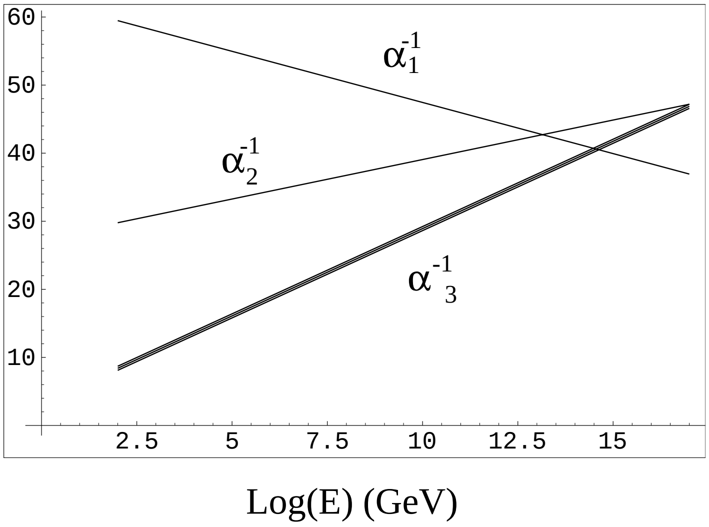
[*] Davoudiasl, Hewett, Rizzo, `hep-ph/0006041`

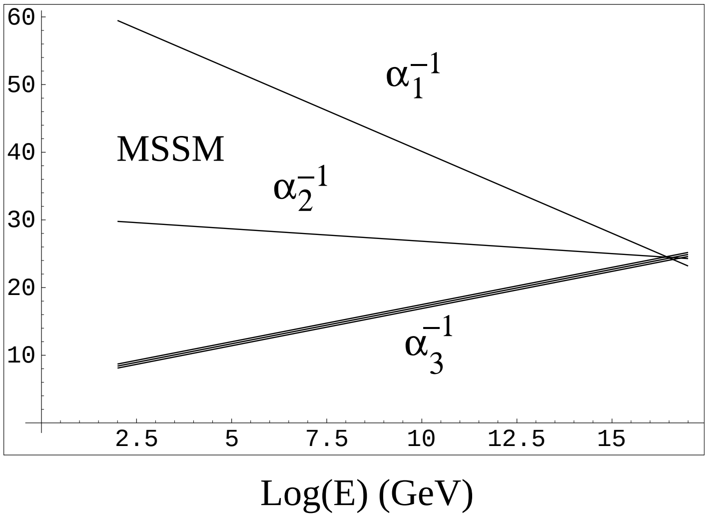
OR ELSE:

Desert above 1 TeV?

SUSY GUTS

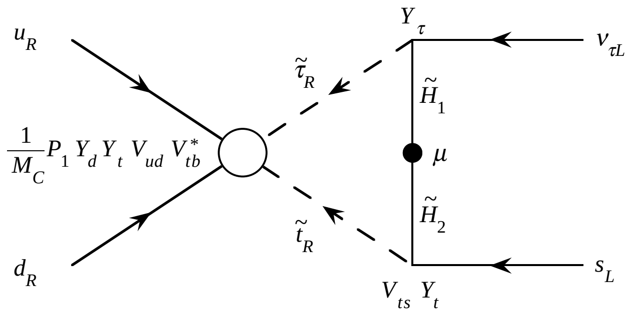
$$SU_C(3) \times SU_W(2) \times U_Y(1) \supset SU(5)$$





$$\frac{\tau_P}{B(P \to e^+ \pi^0)} > 1.6 \times 10^{33} \text{ yr (90\% CL)}$$

But Minimal SUSY $SU(5)$ is Dead*!



$\tan\beta \simeq 2.5$:

$$\left(\frac{M_C}{1.1 \times 10^{17}\ \text{GeV}}\right) \gtrsim \left(\frac{\tau^{\exp}(p \to K^+ \bar{\nu})}{1.7 \times 10^{33}\ \text{yr}}\right)^{\frac{1}{2}} \left(\frac{1\ \text{TeV}}{m_{\tilde{f}}}\right)$$

$\tan\beta \gtrsim 5$:

$$\left(\frac{M_C}{8.8 \times 10^{17}\ \text{GeV}}\right) \gtrsim \left(\frac{\tau^{\exp}(p \to K^+ \bar{\nu})}{1.7 \times 10^{33}\ \text{yr}}\right)^{\frac{1}{2}} \left(\frac{1\ \text{TeV}}{m_{\tilde{f}}}\right) \left(\frac{\tan\beta}{10}\right)^2$$

$M_C \gg 10^{16}$ GeV $\Rightarrow$ no coupling unification.

Minimal SUSY $SO(10)$ is on life-support.[†]

[*] Goto and Nihei `hep-ph/9808255` &

Babu and Strassler `hep-ph/9808447`

[†] Dermmsek, Mafi & Raby `hep-ph/0007213`

Lessons

Lessons for a Linear Collider:

A linear collider with $\sqrt{s} = 300 - 500$ GeV and sufficient luminosity

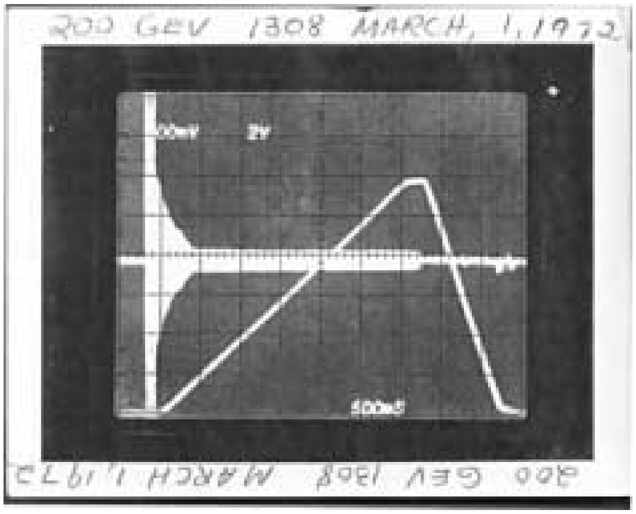
- **may** be able to **produce and directly study** the particle(s) responsible for electroweak symmetry breaking if they are light or
- **can** make precision measurements which probe the **indirect effects** if these particles are heavy.

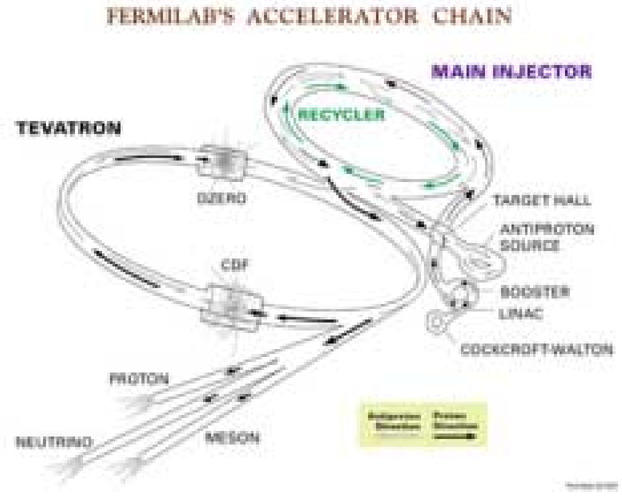
However:

1. There is no **direct** evidence that any/all of the particles associated with electroweak symmetry breaking are light.
2. The indirect evidence is **weak** - and has gotten weaker over the last year!
3. Regardless of the origin of electroweak symmetry breaking, the **direct study of (partonic) collisions at $\mathcal{O}$(10 TeV) will likely be required.**

How we build a LC is more important than initial energy!

- **Upgradability:** 1 TeV or higher – issues include beam optics and final focus, and accommodation new acceleration mechanisms.





How we build a LC is more important than location!

- **Globalization:** *HEPAP White Paper* – "…we expect that at most one of each type of energy frontier facility would be built. Further, a balance in siting new accelerators worldwide is healthy for the field."

1. We need to construct a **coordinated & coherent** international HEP program.
2. **The Future is Now!** Can we coordinate upcoming worldwide B-, K-, ν-programs?

“On the other hand . . . ”

Give me a one-handed economist [physicist]!
All my economists [physicists] say,
“on one hand... on the other.”