Elements of a Physics Case for HE LHC

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Do we want a higher energy LHC in the future?

First reaction is obvious…. YES

Nevertheless, we need to understand the potential physics gains of HE-LHC

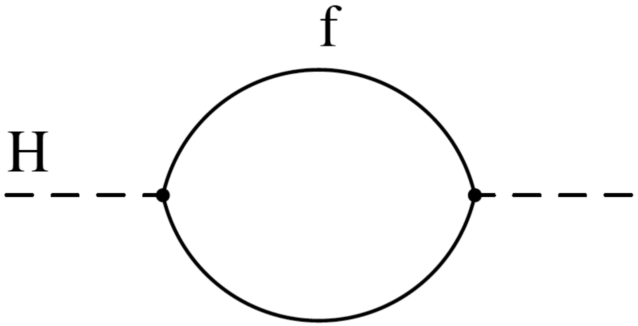
Emphasis here is on discovery capability, and not so much “precision study” capability (often associated with luminosity upgrades)

Outline a few thoughts worthy of more study, with focus on solution to “Naturalness Problem”.

Naturalness Problem connected to:

Higgs boson unstable to QM

A quantum loop is quadratically divergent. Higgs Mass, connected to Higgs vev, is unstable to the Highest mass scales in the theory.



$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 \quad \Rightarrow \quad \Lambda^2 \sim M_{Pl}^2 \; ?$$

Cures of the Naturalness Problem

1. Disallow all scalars in the theory (Technicolor).
2. Disallow higher mass scales (extra dimensions).
3. Symmetry cancels quadratic divergences (supersymmetry)

Technicolor

The quantum numbers of $\bar{Q}_L t_R$ are the same as the Higgs boson.

Assume new fermions exist with same quantum numbers as Standard Model, such that $\langle \bar{T}_L T_R \rangle \neq 0$.

Problems: Proliferation of Pseudo-Nambu Goldstone Bosons, challenges with precision measurements of Z decays, and difficulty giving both light quark and heavy quark masses.

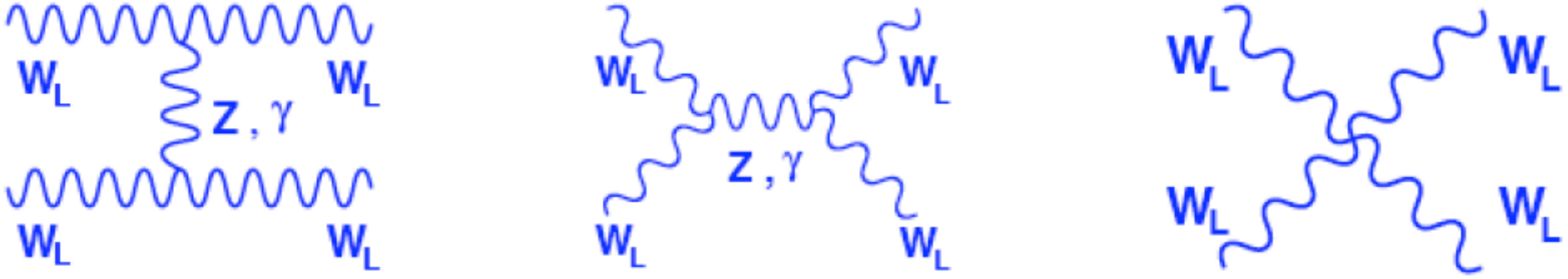
(BUT, not ruled out by any means and worth consideration….)

Traditional Primary Emphasis

A) Electroweak symmetry breaking is a mystery.

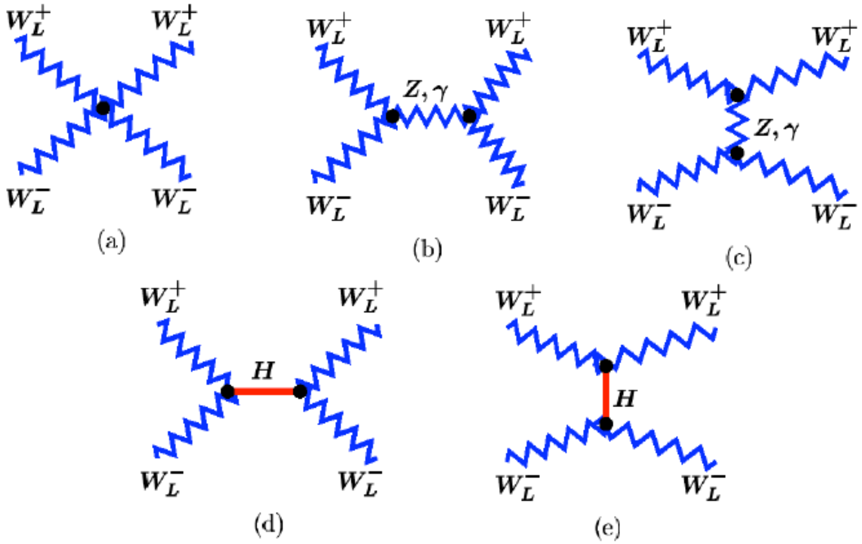
B) Symmetry breaking might produce Higgs boson or might not, depending on how hierarchy problem is solved

C) Longitudinal W scattering unitarized for E>1 TeV by Higgs or some other non-perturbative dynamics (techni-ρ meson)



$$\mathcal{A}_{\rm tree\ \ level} \sim \mathrm{E}^2_{\rm c.m.}/\mathrm{M}^2_{\rm W}$$

Unitarization



Simmons, '06

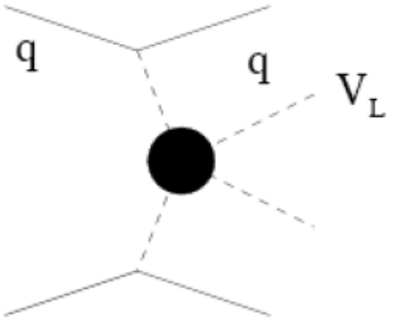
Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2-6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2}+\frac{15}{2}\cos\theta$
(d + e)	$-\frac{1}{2}-\frac{1}{2}\cos\theta$
Sum including (d+e)	$\mathbf{0}$

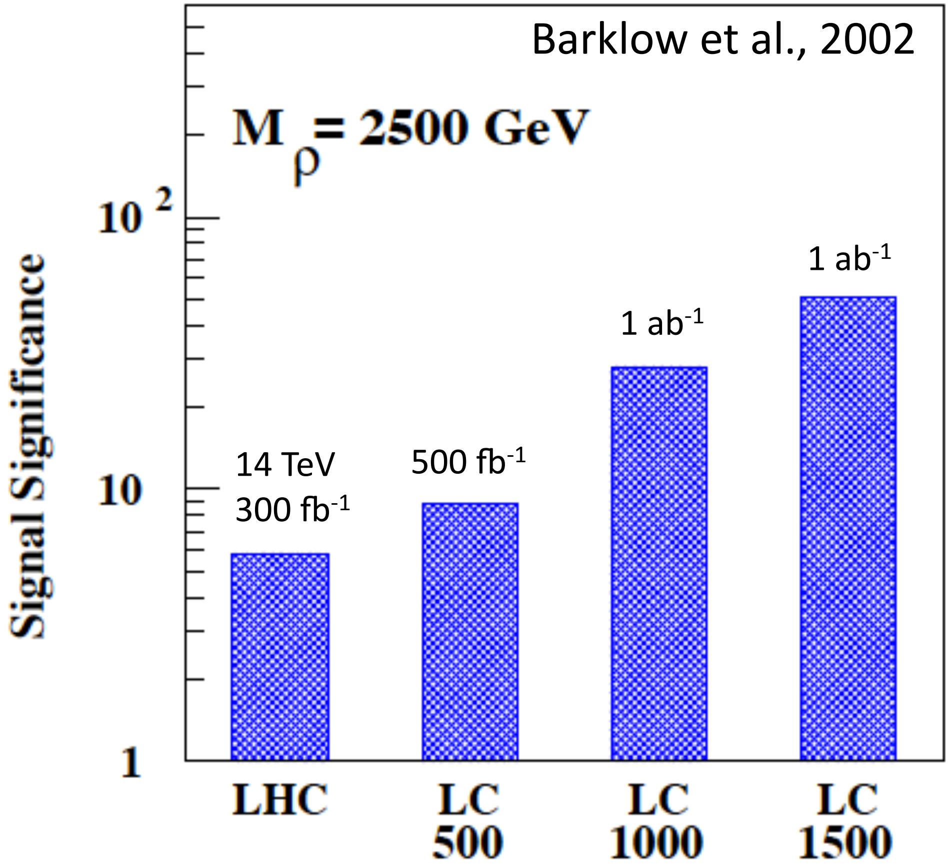
- ▶ $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\,v \simeq 1.0$ TeV
- ▶ If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow$ $E < \sqrt{4\pi}\,v \simeq 0.9$ TeV

In technicolor theories, the techni-ρ meson unitarizes $W_L W_L$ scattering, just as the ρ meson of QCD unitarizes ππ scattering.

M_ρ could be anywhere from ~1 TeV to ~3 TeV or even higher.

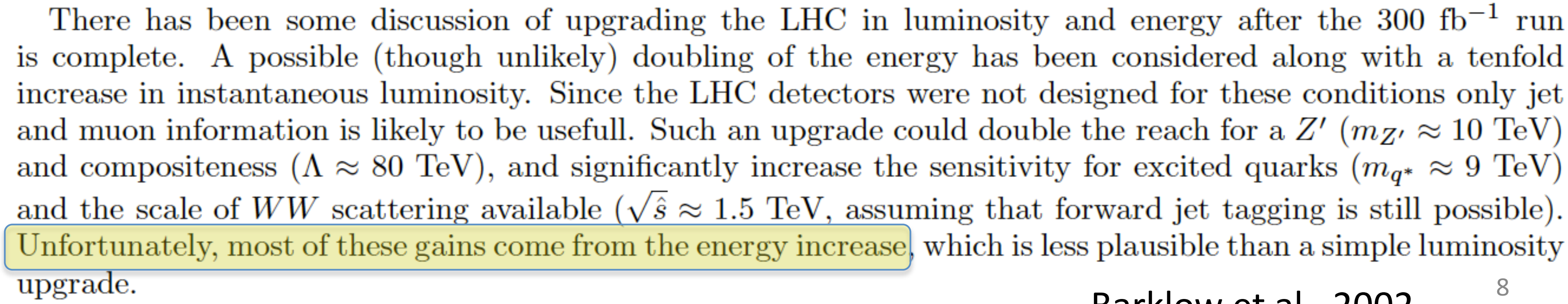
Collider Expectations




Barklow et al., 2002

Doubling energy would be good!

Assumes favorable narrow resonance $M_\pi > M_\rho/2$

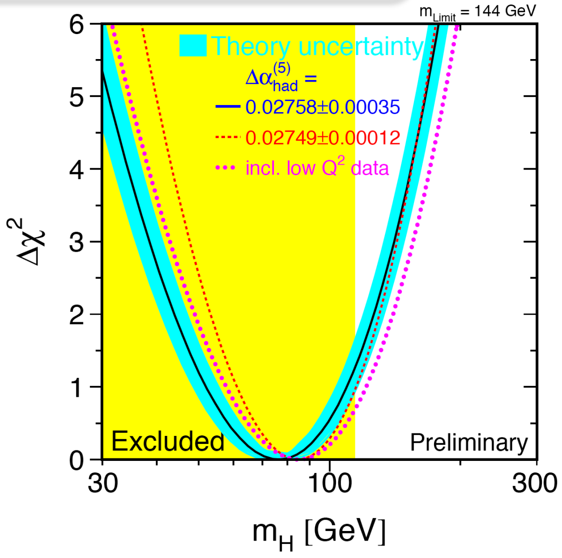

There has been some discussion of upgrading the LHC in luminosity and energy after the 300 fb^{-1} run is complete. A possible (though unlikely) doubling of the energy has been considered along with a tenfold increase in instantaneous luminosity. Since the LHC detectors were not designed for these conditions only jet and muon information is likely to be usefull. Such an upgrade could double the reach for a Z' ($m_{Z'} \approx 10$ TeV) and compositeness ($\Lambda \approx 80$ TeV), and significantly increase the sensitivity for excited quarks ($m_{q^*} \approx 9$ TeV) and the scale of WW scattering available ($\sqrt{\hat{s}} \approx 1.5$ TeV, assuming that forward jet tagging is still possible). Unfortunately, most of these gains come from the energy increase, which is less plausible than a simple luminosity upgrade.

Barklow et al., 2002

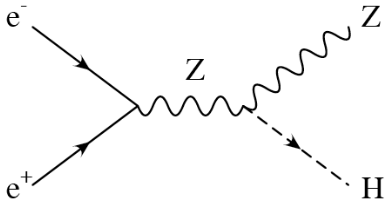
Perhaps to be given less emphasis….

Interesting further ideas in this vein: Higgsless theories, top condensate, etc.
But perhaps less emphasis is in order given recent expt results.

Higgs boson mass upper limit (95% CL) from precision Electroweak is less than 180 GeV.



Lower limit from lack of direct signal at LEP 2 is about 115 GeV.



Tevatron 95% exclusion 160 GeV < m_h < 170 GeV

Experiment Summary: 115 GeV < m_h < 160 GeV or 170 GeV < m_h < 180 GeV

In other words, Higgs boson (or equivalent dynamics) is likely to be LIGHT and PERTURBATIVE electroweak interactions are expected.

Large Extra Dimensions

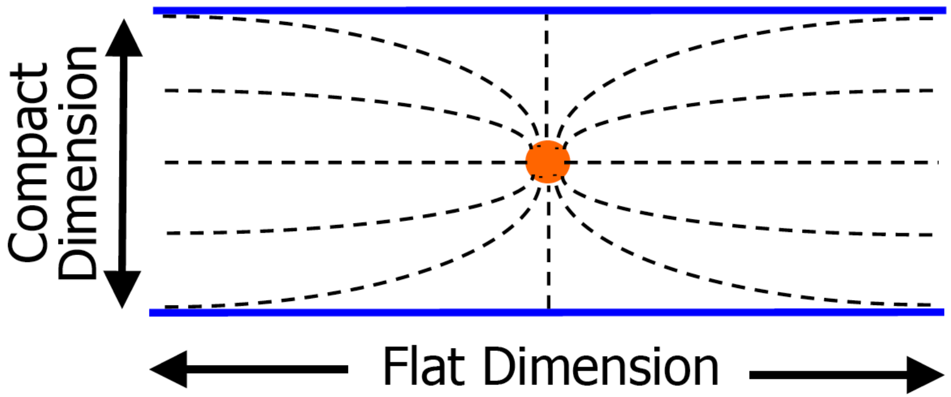
Quadratic divergence ok if no high scales!

But gravity surely exists, with its high Planck Scale --
Much larger than any known SM particle mass.

$$\frac{M_{Pl}}{m_t} \sim 10^{16}$$

How can this hierarchy be explained?

Extra Dimensions may
Explain large Planck Mass.
(Arkani-Hamed, Dimopoulos, Dvali)

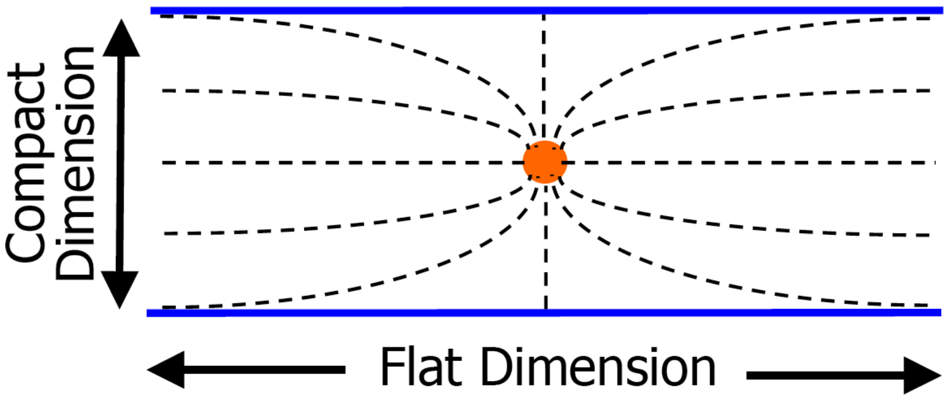


Landsberg, 2001

Strength of Gravity

$$V(r) \sim \frac{1}{V_n M_D^{n+2}} \frac{m_1 m_2}{r} \quad \text{for } r \gg R$$

Large Planck mass is fake. Comes from large Extra-dimension Volume.

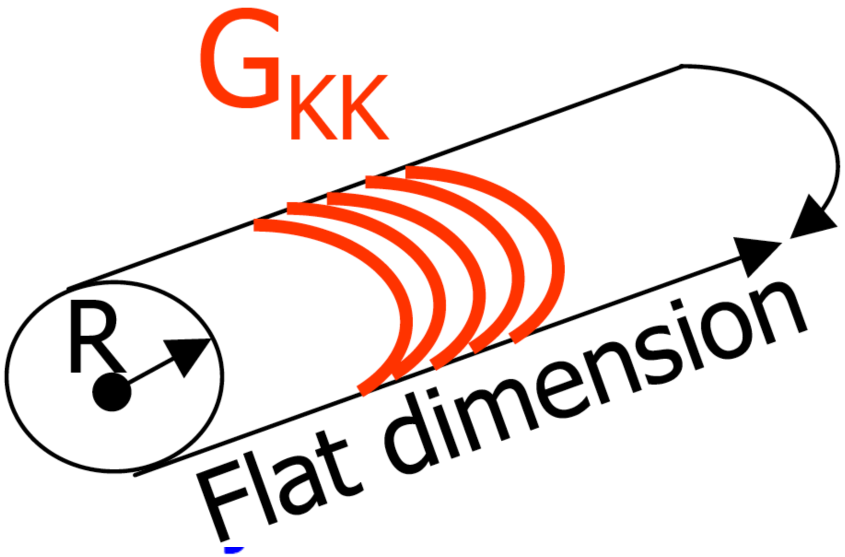


Landsberg, 2001

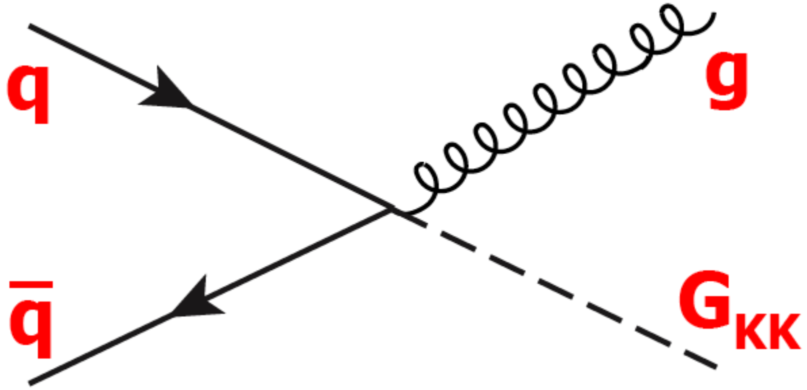
$$M_{Pl}^2 = V_n M_D^{n+2}$$

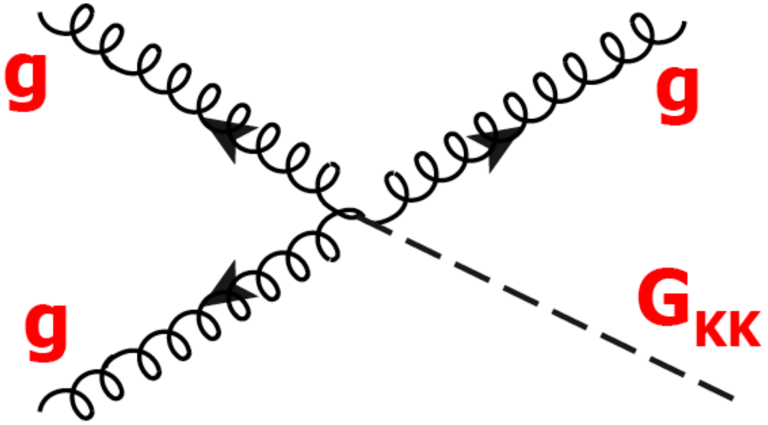
M_D is ~ TeV if Xdim solves the hierarchy problem

Implications of Large Extra Dimensions



Kaluza-Klein copies of
The graviton accessible
At high-energy colliders.





Landsberg, 2001

KK Graviton cross-sections

Cross section of producing one KK gravition $\sigma_{KK} \sim \frac{1}{M_{Pl}^2}$

KK Gravitons are spaced closed to each other. There are approximately $(ER)^n$ KK gravitions with mass < E.

So, total gravitons cross-section up to energy E is

$$\sigma_{allKK} \sim \frac{(ER)^n}{M_{Pl}^2}$$

But $R^n = M^2_{pl}/M_D^{2+n}$, which means total cross-section is

$$\sigma_{allKK} \sim \frac{1}{M_D^2}\left(\frac{E}{M_D}\right)^n$$

Fast growth with energy….

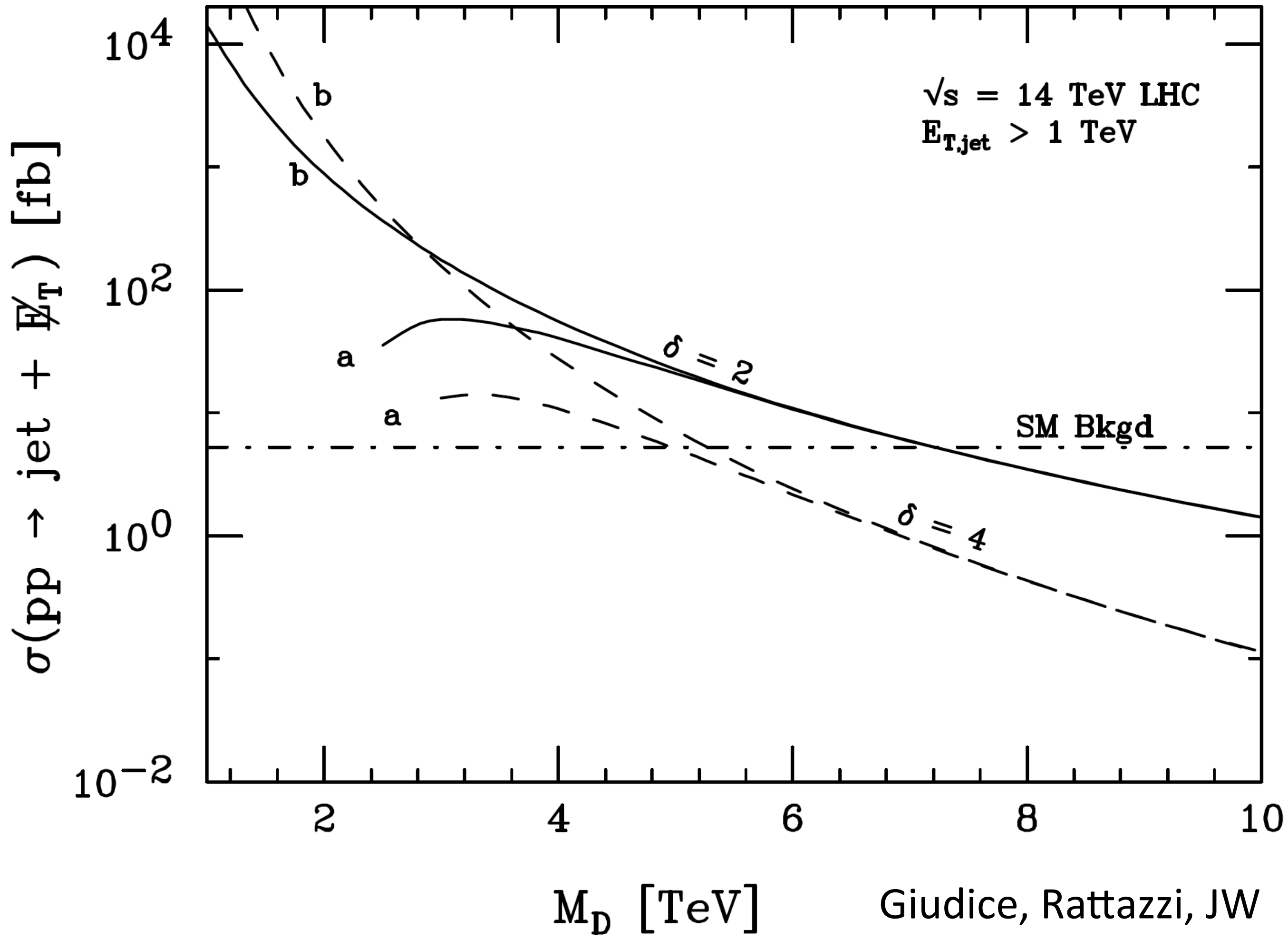
Compare this cross-section, with E^n growth,

$$\sigma_{allKK} \sim \frac{1}{M_D^2}\left(\frac{E}{M_D}\right)^n$$

With the usual cross-section growths of other theories

$$\sigma \sim \frac{1}{E^2}$$

Higher energy extremely helpful



Giudice, Rattazzi, JW

This plot: Keep energy fixed, but vary M_D.

Yet, illustrates how sensitive cross-sec is to ratio of E/M_D.

Higher energy pays huge dividends!

Energy and Extra Dimensions

other studies to propose

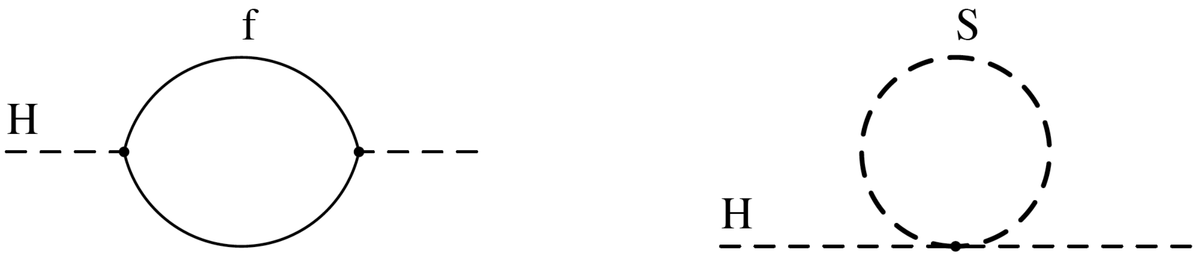
Shown that HE extremely valuable for graviton emissions

Many more benefits possible amenable to careful study:

- Non-linear gravity objects (NGOs = Black holes, string balls, etc.)
- String Regge excitations
- Transplanckian scattering (calculable in $E>>M_D$ limit!)
- Multi-TeV gravitons and gauge bosons in Randall-Sundrum warped extra dimension

Supersymmetry

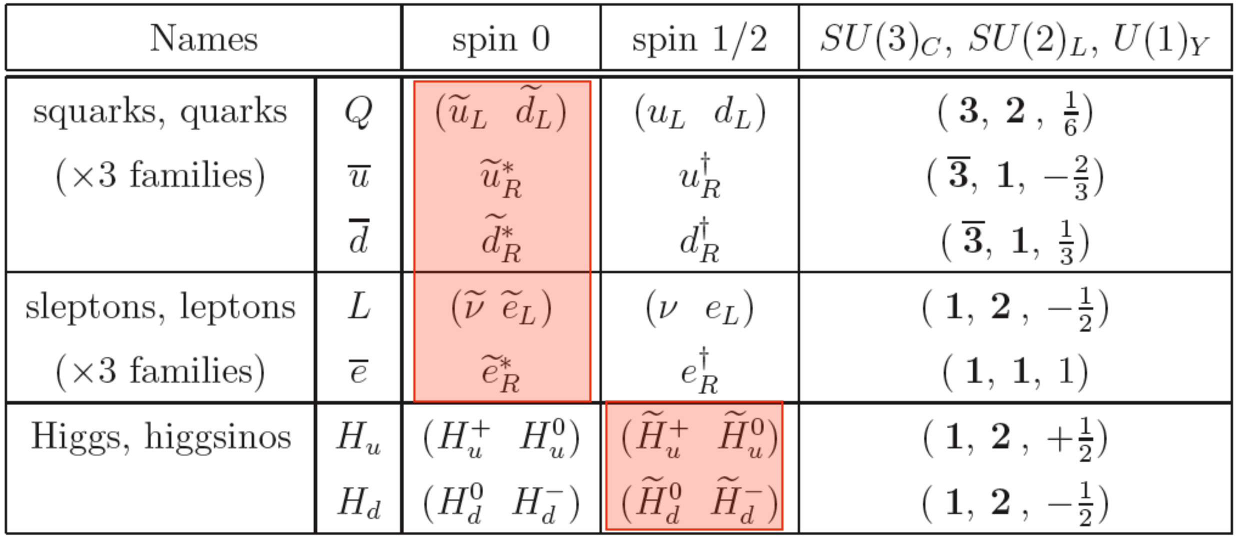
Symmetry cancels the quadratic divergence, making solutions natural.



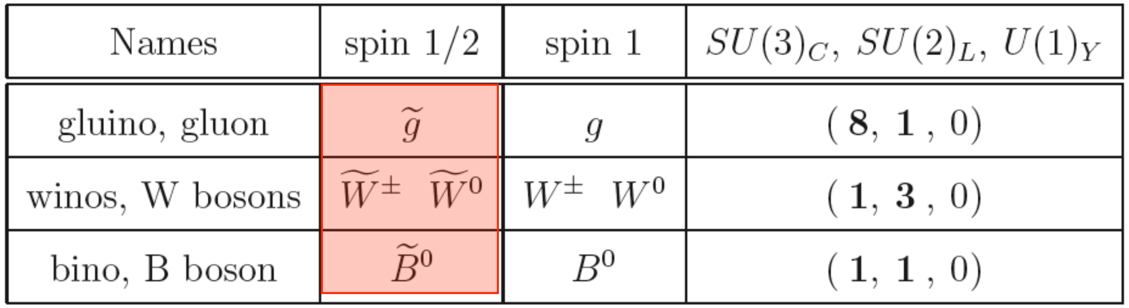
Martin, hep-ph/9709356

$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 - \frac{\alpha_f}{4\pi}\Lambda^2 \sim 0 + \cdots$$

The Particle Spectrum of Minimal Supersymmetry



Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\ \mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\ \mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$



Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\ \mathbf{8},\ \mathbf{1}\ ,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\ \mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$

Excellent source from which to learn the fundamentals.

Scalar Superpartners highlighted in red.

SUSY Primer: Martin, hep-ph/9709356v5 (Dec 08)

Description of SUSY Breaking

SUSY breaking resides in <F> of chiral multiplet

$$X = x + \sqrt{2}\psi\theta + F\theta^2$$

This leads to gravitino mass: $m_{3/2}^2 \sim \frac{F^\dagger F}{M_{\rm Pl}^2}$

Gravitino is spin 3/2 particle. ψ is the absorbed ±1/2 spin component (goldstino).

Gaugino masses: $\int d^2\theta \frac{X}{M_{\rm Pl}} \mathcal{W}\mathcal{W} \sim m_{3/2}\lambda\lambda$

Scalar masses: $\int d^2\theta d^2\bar{\theta} \frac{X^\dagger X}{M_{\rm Pl}^2} \Phi_i^\dagger \Phi_i \rightarrow m_{3/2}^2 \phi_i^* \phi_i$

Everybody $\sim m_{3/2}$, and $m_{3/2} \sim m_W$ for naturalness.

Challenges for Low-Energy SUSY

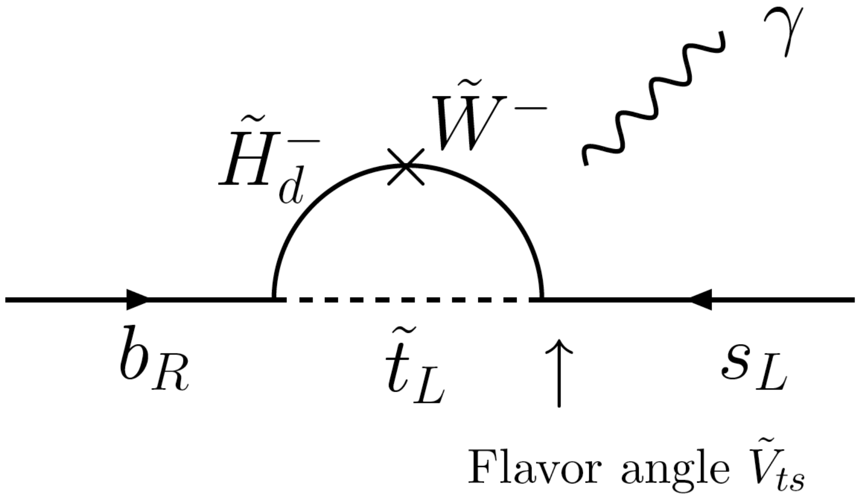
Throw a dart into Minimal SUSY parameter space,
And what do you get?

*Observable predictions would be
Incompatible with experiment.*

Briefly review these challenges ….

Flavor Changing Neutral Currents

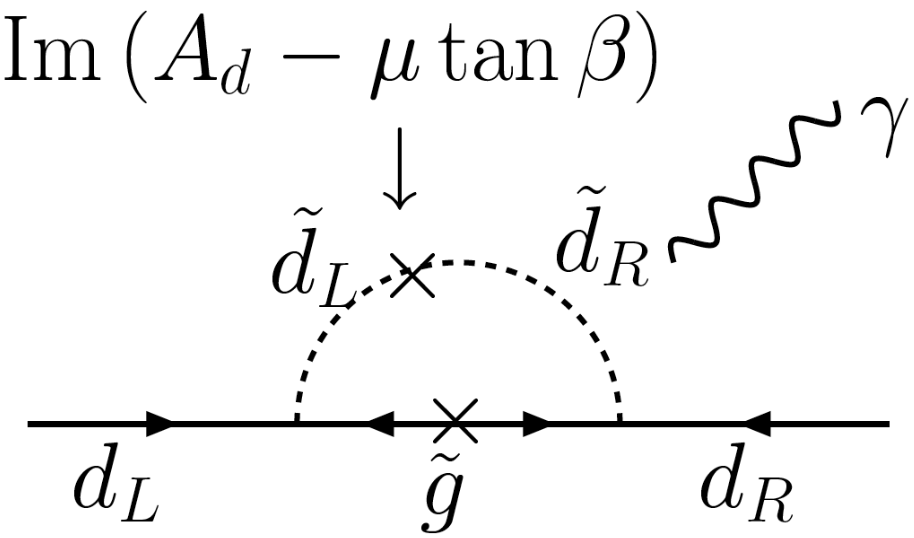
Random superpartner masses and mixing angles would generate FCNC far beyond what is measured:



However: heavy scalars would squash these FCNCs

CP Violation

Supersymmetry has many new sources of CP violation:



Large unless CP angle small or scalar masses heavy.

Theory home to these ideas:

Non-singlet SUSY breaking

SUSY breaking accomplished by non-singlet.

Scalars don’t care:

$$\int d^4\theta \frac{X^\dagger X}{M_{\rm Pl}^2} Q^\dagger Q \Longrightarrow \frac{F^\dagger F}{M_{Pl}^2}\tilde{Q}^\dagger \tilde{Q} \quad (m_{\tilde{Q}}^2 \simeq F^\dagger F/M_{\rm Pl}^2)$$

On the other hand, gauginos do care:

$$\int d^2\theta \frac{X}{M_{\rm Pl}^2} WW \quad \text{not gauge invariant} \;\; M_\lambda = 0$$

Assuming cosmological constant = 0 (I.e. tiny) the gravitino mass is

$$m_{\tilde{G}}^2 = \frac{F^\dagger F}{M_{\rm Pl}^2}$$

Mass Spectrum

In this case, leading contribution to gaugino mass can be, e.g., the AMSB contribution:

$$M_\lambda = \frac{\beta(g_\lambda)}{g_\lambda} m_{\tilde{G}}$$

(Randall, Sundrum;
Giudice, Luty, Murayama, Rattazzi)

The complete spectrum is

(light gauginos)

$$\begin{aligned} M_3 &\simeq M_{\tilde{G}}/40 \\ M_2 &\simeq M_{\tilde{G}}/320 \\ M_1 &\simeq M_{\tilde{G}}/120 \end{aligned}$$

Ratios of scalar/gaugino can be altered significantly, but hierarchy may be generic.

LSP is Wino!

$$M_{\tilde{Q}} \sim M_{\tilde{e}} \sim M_{\tilde{G}}$$

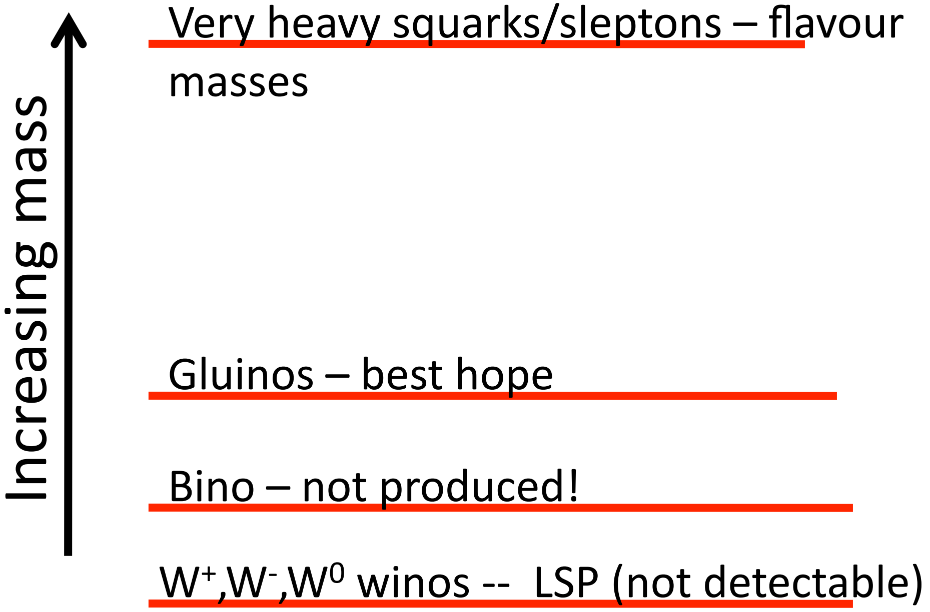
(Heavy scalars)

Collider Implications of Heavy Flavor Supersymmetry

Example spectrum:

M2 = 100 GeV
M1 = 300 GeV
M3 = 700 GeV

$M_{3/2}$~$M_{\text{scalars}} >> M_{\text{gauginos}}$



Very heavy squarks/sleptons – flavour masses

Gluinos – best hope

Bino – not produced!

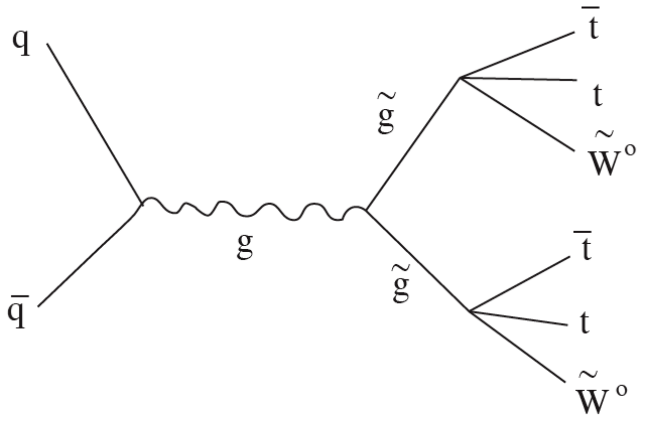
W^+,W^-,W^0 winos -- LSP (not detectable)

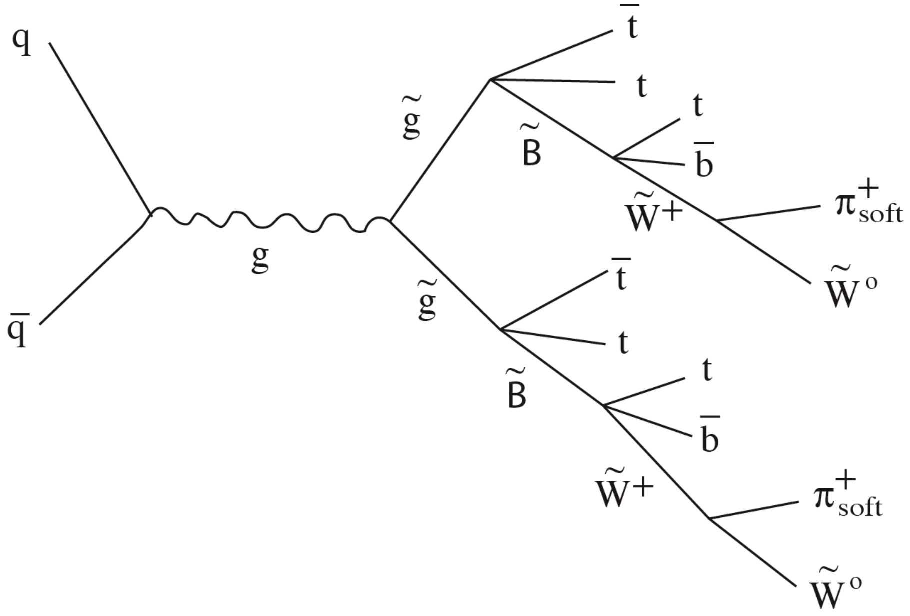
- Scalars are out of LHC reach!
- Binos are not produced
- Higgs mass predicted to be above current limit (but <140 still)
- Winos not directly detectable
- gluino pair production give colliders hope

LHC or HE-LHC can discover susy through gluinos:

High multiplicity tops+MET events

Simplest event type: 4 top quarks plus missing energy.





Combinatoric/experimental Challenge.

6 tops + 2 b’s + 2 pions + MET

Toharia, JW

Scalar superpartner discoveries

Scalar superpartners are unlikely to be directly produced at LHC in this framework.

In general, scalars are heavier than fermion superpartners across many variants of susy model building. Generic prospect.

Need high energy to produce directly these heavy squarks.

Perhaps best bet is gaugino + squark production. Suggest careful study of the various prospects at HE LHC. May be one of principle motivators for HE LHC upgrade.

Keep in mind, may have rough idea of where scalar masses are through LHC experiments (Higgs mass, gluino decay widths, etc.).

Conclusions

We have reviewed science gains that would be important if nature chooses any one of the three theory approaches to the Naturalness Problem.

Each idea has its higher energy needs:

Technicolour: Heavy techni-rho resonances, and $V_L V_L$ scattering sensitivities

Extra dimensions: Graviton emission sensitivity, KK graviton resonance searches (Warped), and KK gauge boson production.

Supersymmetry: direct measurement of heavy squarks