Physics Beyond the SM and LHC Searches

"A (brief and not unweighted) random walk through the theory landscape"

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PPP Ph.D. Program, NBI, Copenhagen, Oct 3 2011

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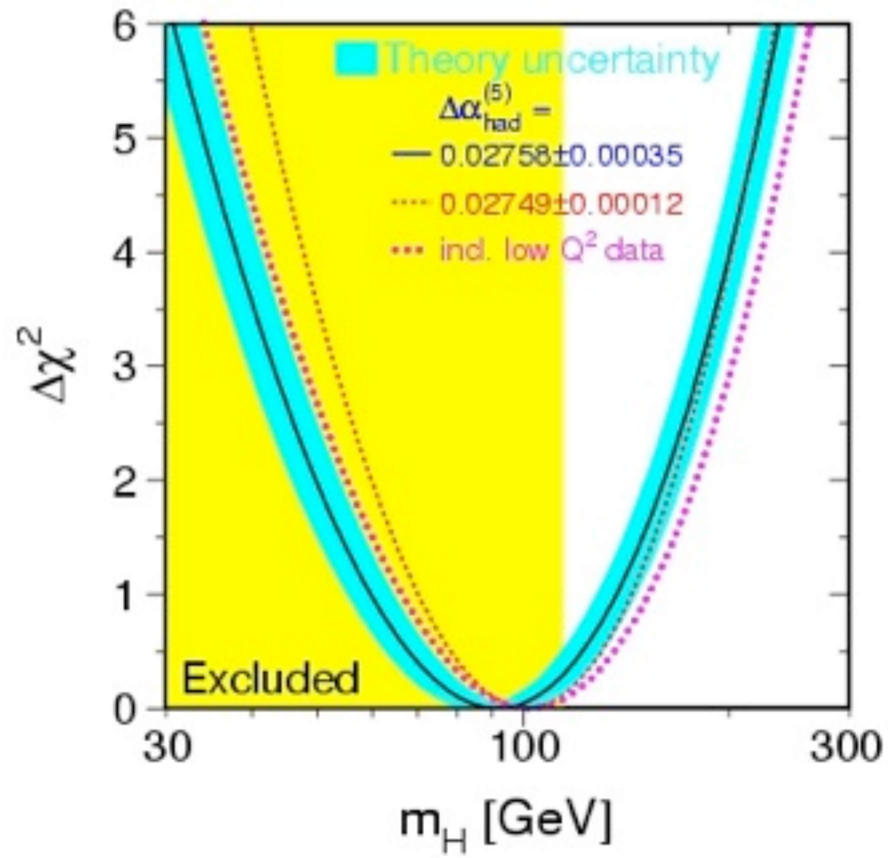
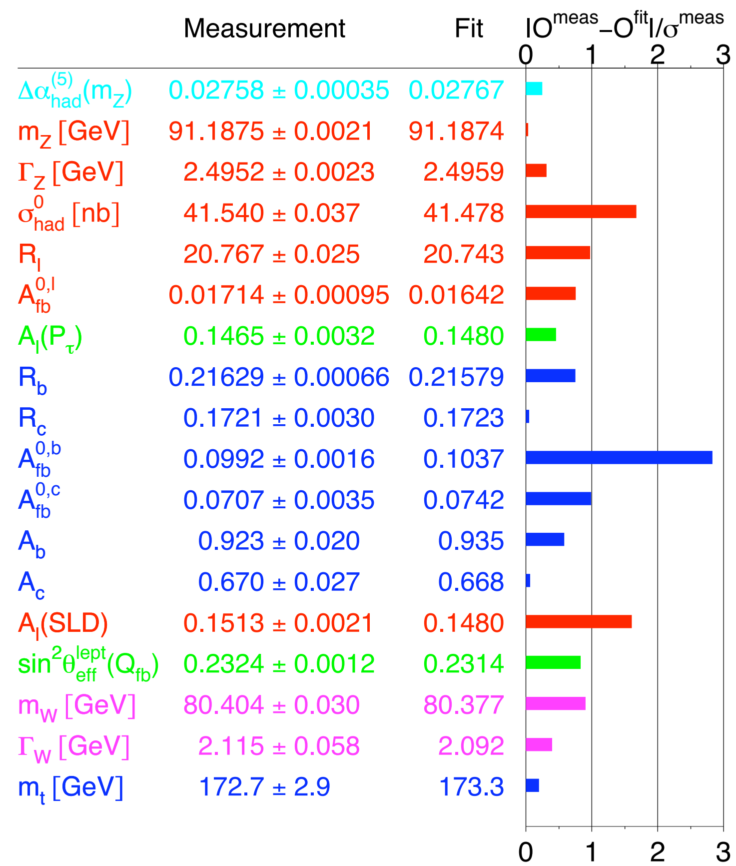
Introduction

- Standard Model: Electroweak gauge symmetry SU(2)xU(1) is fundamental, but spontaneously broken at low energies down to e&m U(1)
- Uncovering the mechanism of electroweak symmetry breaking (EWSB) is the central question for the LHC
- The Standard Model explanation of EWSB: Higgs phenomenon
- Postulate a new particle - the Higgs boson - of spin 0
- Vacuum is filled with Higgs condensate, which breaks the symmetry

Indirect Evidence for the Higgs

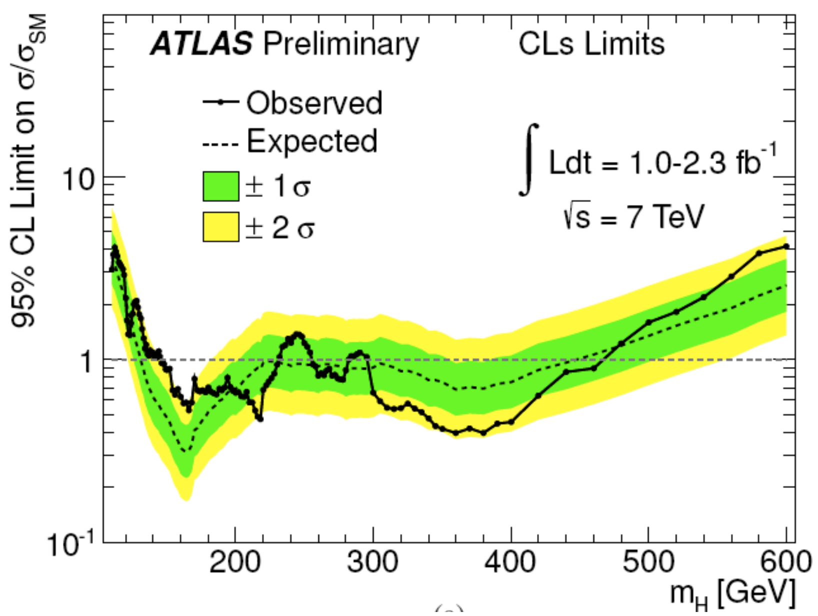


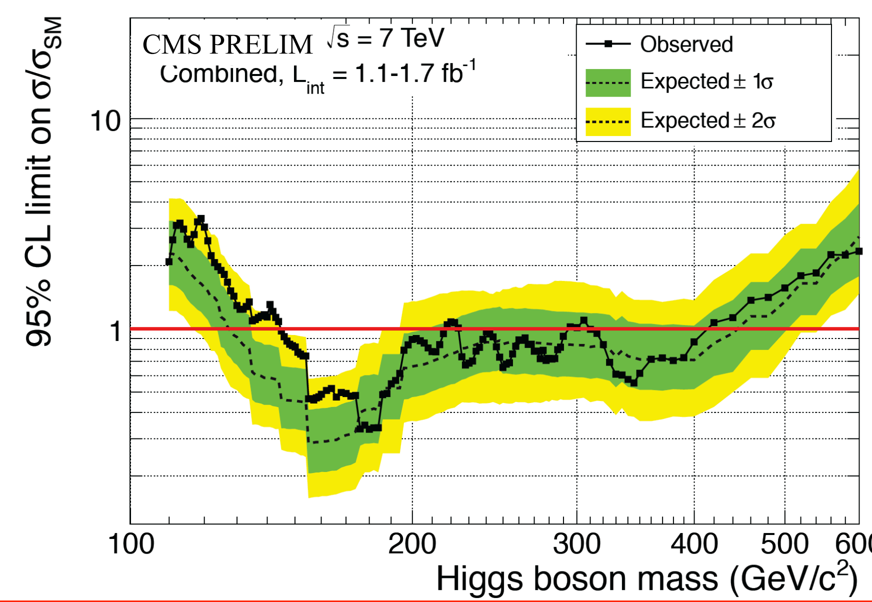


- Standard Model with a light Higgs provides a good fit to all data, indirect determination of H mass:

$$M_H < 186 \text{ GeV} \quad (95\% \text{ c.l.})$$

Direct Search for the Higgs





Expected exclusion mass range: 130 – 440 GeV
Observed exclusion mass range: 145-216, 226-288, 310-400 GeV

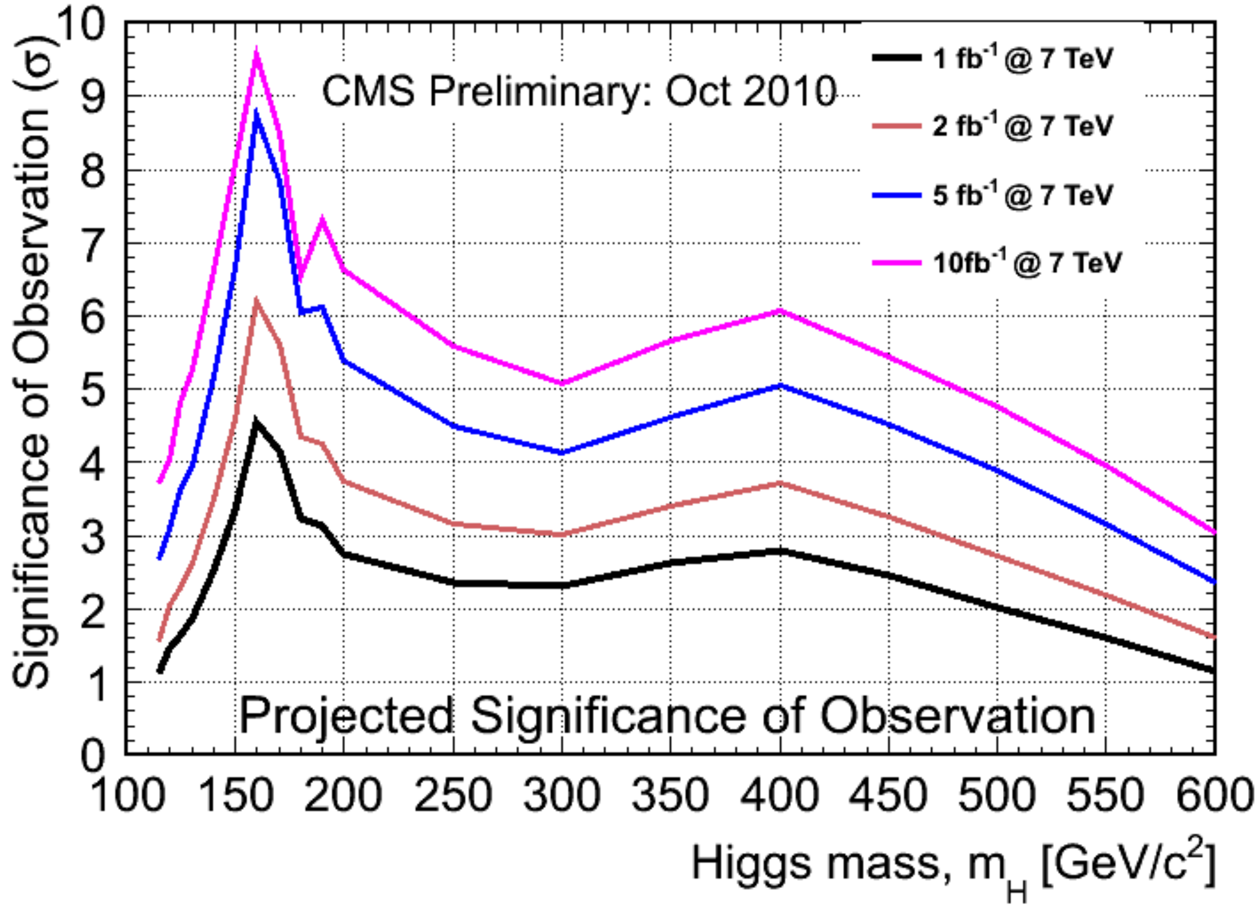
Standard Model Higgs boson mass excluded at 95% C.L.:

$146 < m_H < 232$, GeV
$256 < m_H < 282$ GeV
$296 < m_H < 466$ GeV

The exclusion Confidence Level (CLs) is about 99% in the region between 160 GeV and 220 GeV and exceeds 99% between 300 GeV and 420 GeV

[plots presented at Lepton-Photon Conference, August 2011]

Higgs Sensitivity : 1, 2, 5 and 10 fb^{-1} @ 7 TeV



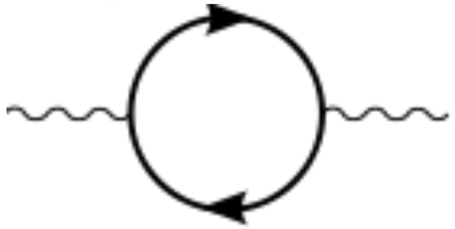
[V. Sharma, CMS, LP-11 talk]

Radiative Corrections

- Quantum mechanics allows for energy non-conservation for short periods of time:

$$\Delta E \Delta t \sim \hbar$$

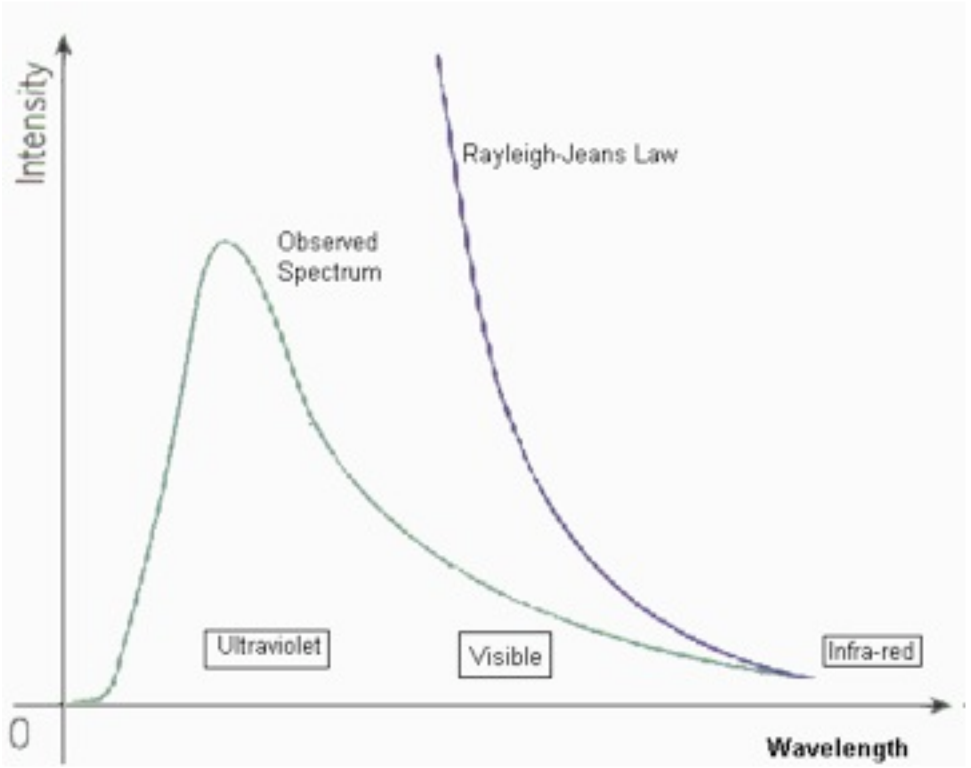
- A particle-antiparticle pair may spontaneously appear from the vacuum, and then disappear after $\Delta t < 1/M$
- The vacuum is full of such "virtual" pairs!
- The virtual pairs can interact with particles: this is described by Feynman diagrams with loops ("radiative corrections")



- Computing radiative corrections involves integration over the lifetime of the virtual pair, in principle down to t=0 (or equivalently energy up to infinity)

Beyond the SM

- Computing radiative corrections in most quantum field theories (including the SM) involves integrals which diverge at high virtual energies
- Mathematically, this can be dealt with by renormalization
- Physically, divergences mean that we're applying the theory in a regime where it is no longer valid!



Expect a deeper layer of structure beneath the SM!

Light Higgs → NP at TeV!

- No elementary spin-0 particles are known to exist: scalar mass is unstable with respect to radiative corrections

- In SM,

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$v^2 = \frac{\mu^2}{\lambda}, \quad m_h^2 = 2\mu^2$$

- Renormalization:

$$\mu^2(M_{\rm ew}) = \mu^2(\Lambda) + c_1 \frac{1}{16\pi^2}\Lambda^2 + c_2 \frac{1}{16\pi^2} \log\left(\frac{\Lambda}{M_{\rm ew}}\right) + \text{finite}$$

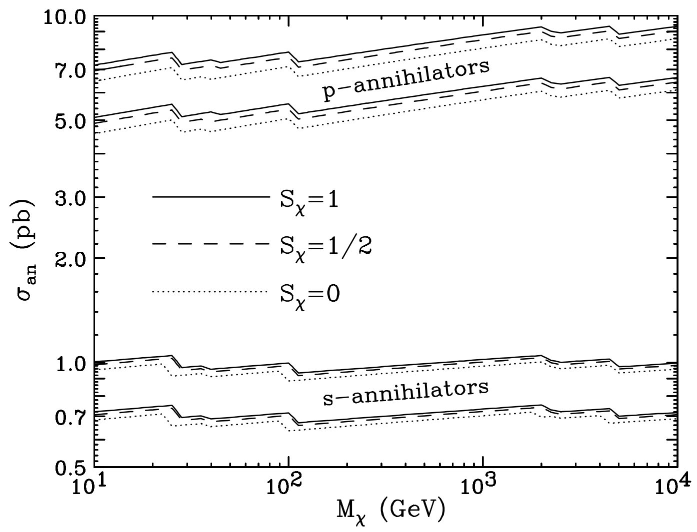
with $c_1 \sim 1$ and Λ is the scale where loop integrals are cut off by new physics

- Expect $\mu \sim \Lambda/(4\pi)$ ➡ $\Lambda \sim 1 \text{ TeV}$ (naturalness)

[But NB: $\Lambda \sim 10 \text{ TeV}$ if 1% fine-tuning is allowed!]

Thermal Dark Matter

- Dark matter (non-luminous, non-baryonic, non-relativistic matter) well-established by a variety of independent astro observations, ~20% of the universe
- None of the SM particles can be dark matter
- Assume new particle, in thermal equilibrium with the cosmic plasma in the early universe
- Measured DM density ⇨ interaction cross section DM-SM



$$\sigma \approx 1 \text{ pb} \sim \frac{\alpha}{(\text{TeV})^2}$$

independent hint for new physics at the TeV scale!

[figure: Birkedal, Matchev, MP, hep-ph/0403004]

Options for New Physics @ TeV

- Models with light Higgs, addressing naturalness:
  - New particles, related to SM by symmetry, cut off loops (ex. SUSY, Little Higgs, gauge-higgs unification)
  - Higgs not elementary, bound state resolved at ~TeV (ex. warped [Randall-Sundrum] extra dimensions)
  - Point-like SM particles resolved as TeV-scale strings (ex. large extra dimensions)
- Models without light Higgs, necessarily strongly-coupled at the TeV scale (ex.: Technicolor, Higgsless)
- Models that do not improve naturalness, but have other interesting features or unusual signatures (ex. hidden valley, unparticles, split SUSY)

Supersymmetry

- In supersymmetric theories scalar masses do not receive quadratic divergences
- SUSY not symmetry of nature ⇨ must be broken
- "Soft" breaking at the TeV scale ⇨ loops cut off at the TeV scale, naturalness restored
- "Minimal" supersymmetric SM (MSSM): superpartner for each SM d.o.f., plus 2nd Higgs doublet and its superpartners

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

Table 7.1: The undiscovered particles in the Minimal Supersymmetric Standard Model (with sfermion mixing for the first two families assumed to be negligible).

34 new particles waiting to be discovered!

[table: S. Martin, hep-ph/9709356]

SUSY as an Extra (Fermionic) Dimension

- Grassmann (anticommuting) numbers:

  $\theta : \{\theta_1, \theta_2\} = 0 \Rightarrow \theta^2 = 0$ cf normal numbers: $x : [x, y] = 0$

- In quantum field theory, fields of fermions (e.g. electrons) are Grassmann-valued - Pauli exclusion principle built in!

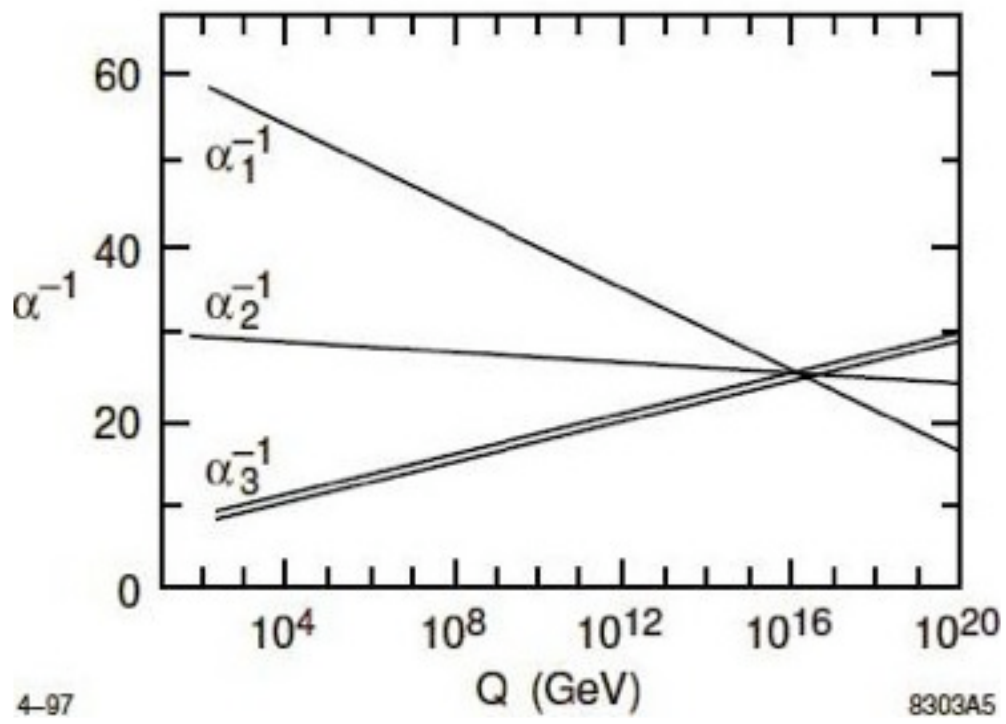
- Imagine a space with 1 or more G-valued coordinates, in addition to the usual 4: superspace

- "Superfield" lives in this superspace: $\Phi(x^\mu, \theta)$

- Taylor expand to obtain usual 4D fields: $\Phi(x^\mu, \theta) = \phi(x) + \theta\psi(x)$

- Supersymmetry is the generalization of Poincare group (rotations, translations, boosts) to this new superspace

Gauge Coupling Unification: a Hint for Supersymmetry?



- The three lines do not meet in the SM (but, considering the extrapolation range, come close!)
- There is at least one example of non-SUSY model where unification occurs with roughly same precision

MSSM and Its 100 Parameters

- Arbitrary soft terms ⇨ O(100) free parameters, affecting spectrum, branching ratios, etc.

$$\begin{aligned}\mathcal{L}_{\rm soft}^{\rm MSSM} &= -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)\\ &\quad -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right)\\ &\quad -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger\\ &\quad - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.\end{aligned}$$

- Models of SUSY breaking "predict" some parameters (or relations among them), reduce the freedom

- But: Many such models (e.g. gravity mediation, gauge mediation, anomaly mediation, etc.), each has strengths and weaknesses, no clear "winner" emerged over ~25 years of model-building ⇨ NEED DATA!!!

- Search strategies must be designed with this in mind - "cover" the 120-dimensional parameter space as well as experimental limitations allow

SUSY: Generic Predictions

- Extra discrete symmetry - R parity - imposed to avoid rapid proton decay (may be relaxed, but very artificial)
- All SM states R-even, superpartners R-odd ⟹ lightest superpartner (LSP) stable
- Strong limits on colored/charged relics in the universe prefer neutral LSP (also a WIMP dark matter candidate!)
- Generic signature: missing energy in every event with superpartner production
- Inclusive search for stable (neutral or not) objects plus high-pT jets and/or leptons is the best mod.-ind. strategy
- Production cross sections for strongly interacting superpartners - gluinos and squarks - are usually the largest (could be 1 - 10 pb ⟹ $10^4 - 10^5$ events/year at the LHC)

- Direct decays ("guaranteed") give jets+MET:

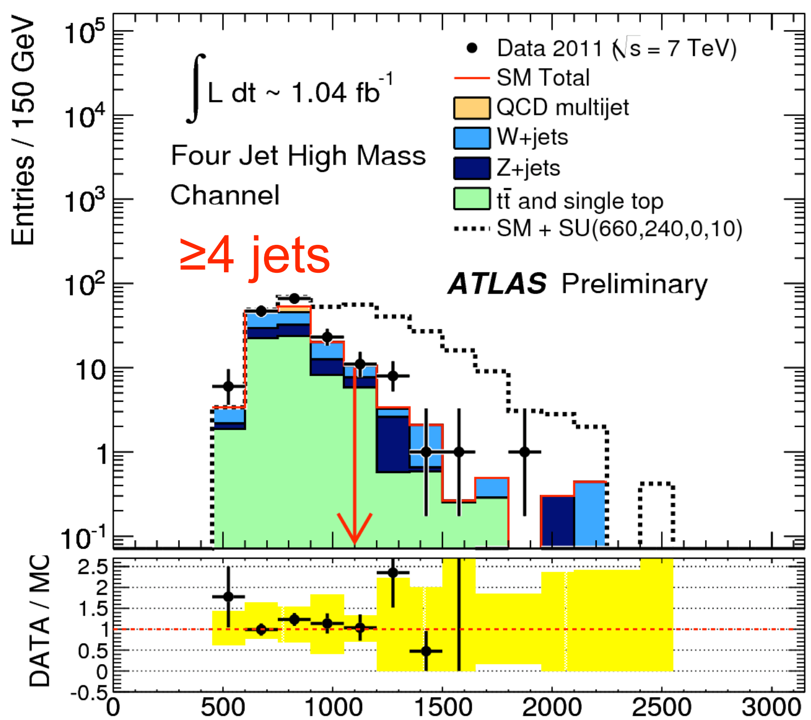
$$\tilde{q} \rightarrow q + \chi_1^0 \quad , \tilde{g} \rightarrow q\bar{q}\chi_1^0$$

- Cascade decays (spectrum-dependent) may give lepton(s) +jets+MET: for example

$$\tilde{q} \rightarrow q + \chi_2^0, \quad \chi_2^0 \rightarrow \mu^+ + \tilde{\mu}^-, \quad \tilde{\mu}^- \rightarrow \mu^- + \chi_1^0$$

iff $M(\tilde{q}) > M(\chi_2^0) > M(\tilde{\mu}) > M(\chi_1^0)$

H_T = scalar sum of all jet E_T

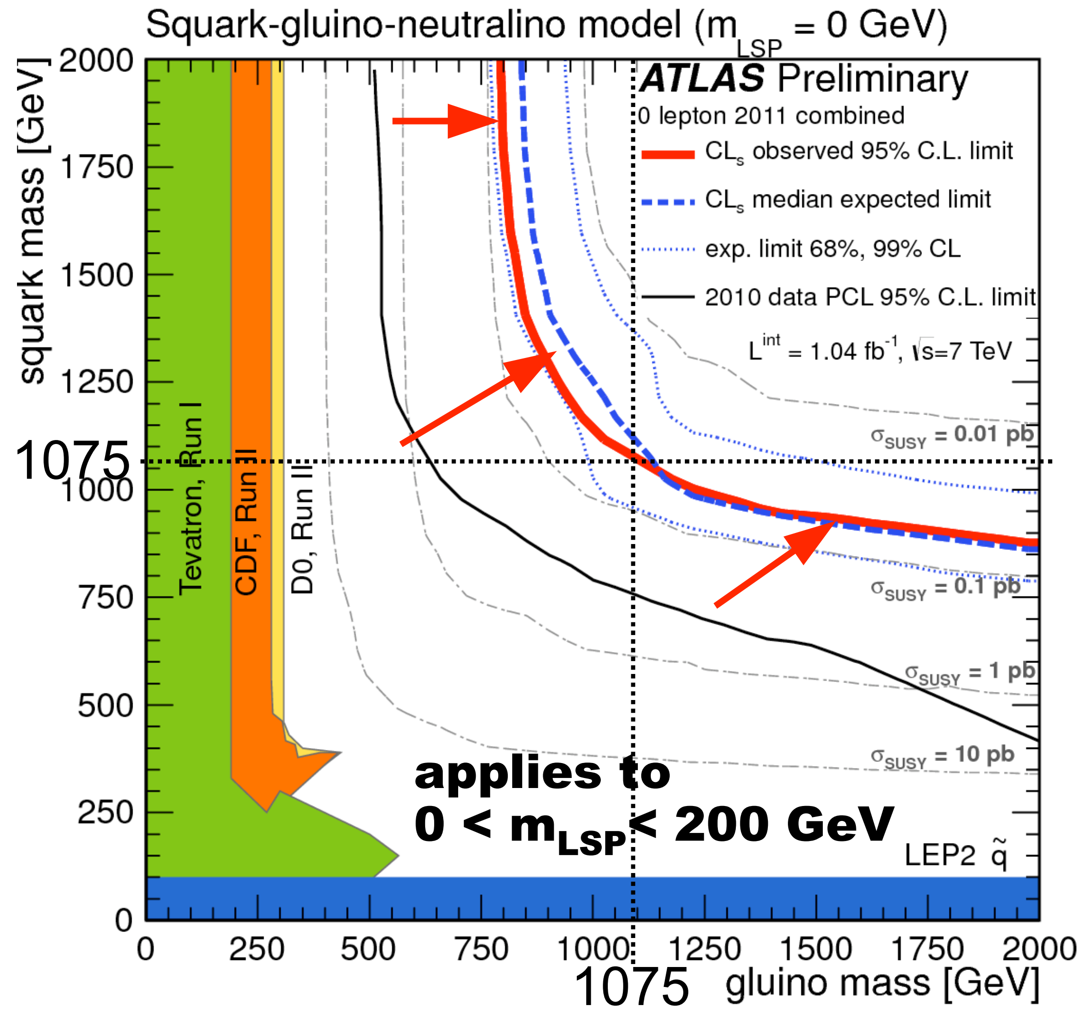


$m_{eff} = H_T$ + Missing E_T [GeV]

SM: Etmiss from neutrinos:

$$Z \rightarrow \nu\bar{\nu} \ , t\bar{t}, \ldots$$

"Reality": Etmiss from detector malfunctioning, jet energy mismeasurements, etc.



So, the bounds on gluino and squark masses are already above 1 TeV

Does this imply that SUSY is “disfavored” (i.e. sparticles must be too heavy to eliminate fine-tuning)?

Plot credit: H. Bachacou talk at LP-11

BBC NEWS

SCIENCE & ENVIRONMENT

27 August 2011 Last updated at 02:41 ET

LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.

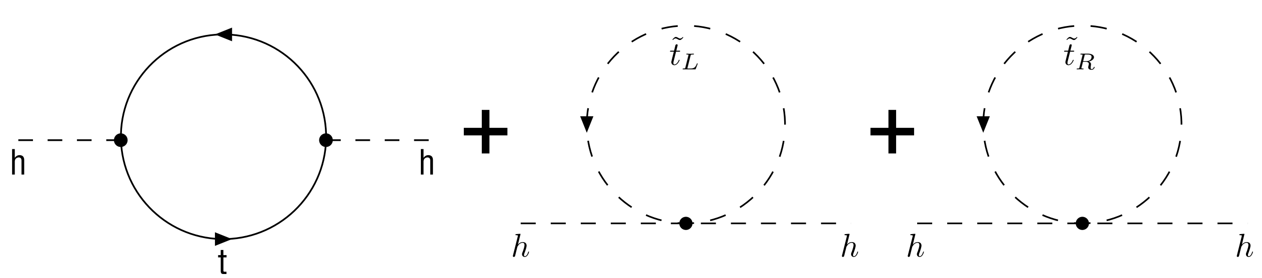
Light Higgs → NP at TeV!

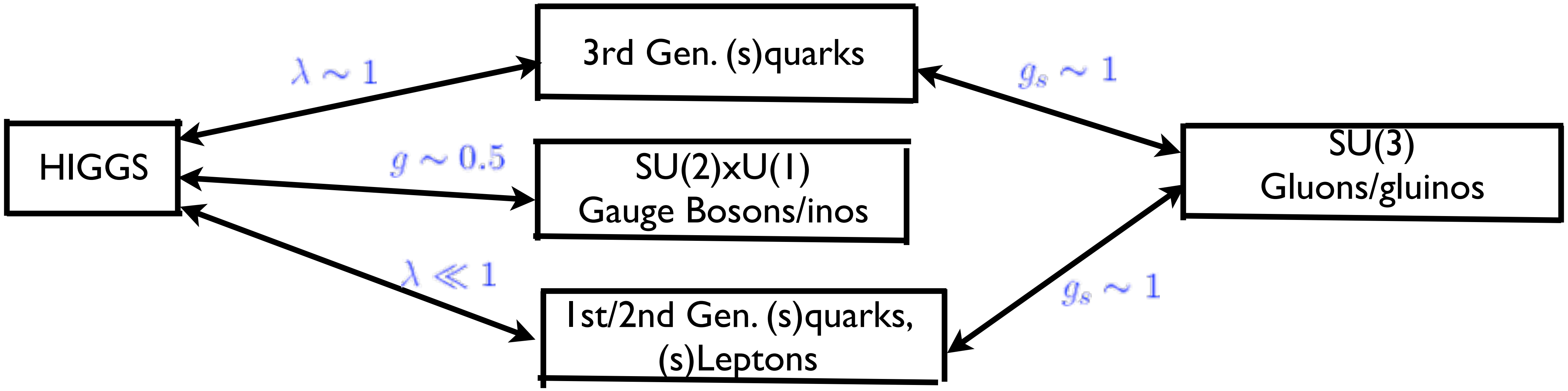
- Renormalization:

$$\mu^2(M_{\rm ew}) = \mu^2(\Lambda) + c_1 \frac{1}{16\pi^2}\Lambda^2 + c_2 \frac{1}{16\pi^2} \log\left(\frac{\Lambda}{M_{\rm ew}}\right) + \text{finite}$$

where Λ is the scale where loop integrals are cut off by new physics

- Expect $\mu \sim \Lambda/(4\pi)$ ⇨ $\Lambda \sim 1\ \mathrm{TeV}$ (naturalness) **IF** $c_1 \sim 1$
- However, c_1 depends on the coupling constants and different particles in loops contribute differently!





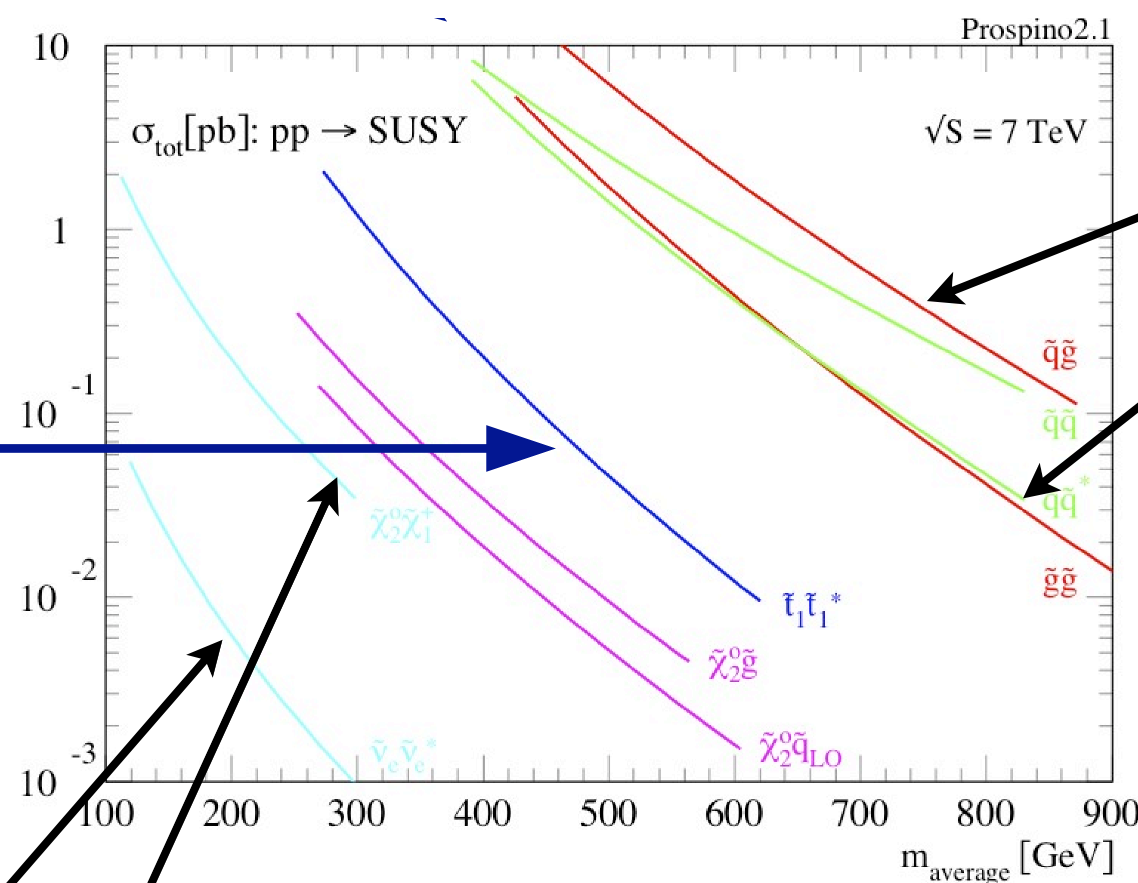
- So: only Higgsinos and 3rd gen. squark really must be below TeV
- Other squarks/sleptons may be a factor of 5 or more heavier with no effect on fine-tuning
- Gluino first appears at 2 loops, suppressing its effect on fine-tuning

What About the LHC?

Stops have small cross sections:

$\sigma(\tilde{t}\tilde{t}^*) \approx 30$ fb

at 500 GeV

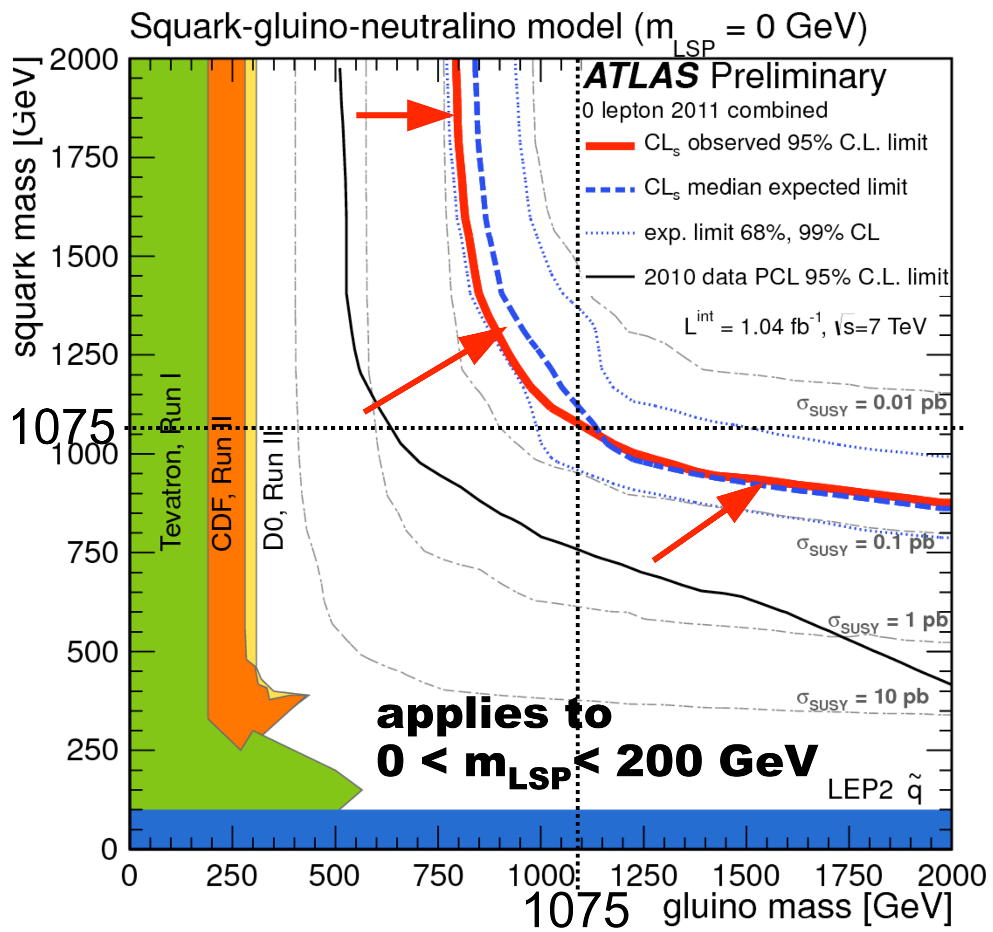


All searches so far rely on producing gluinos and/or 1st, 2nd gen. squarks, different decay channels

Chargino/neutralino (e.g. higgsino) cross sections are even smaller

Plot credit: H. Bachacou talk at LP-11

LHC Searches



Plot credit: H. Bachacou talk at LP-11

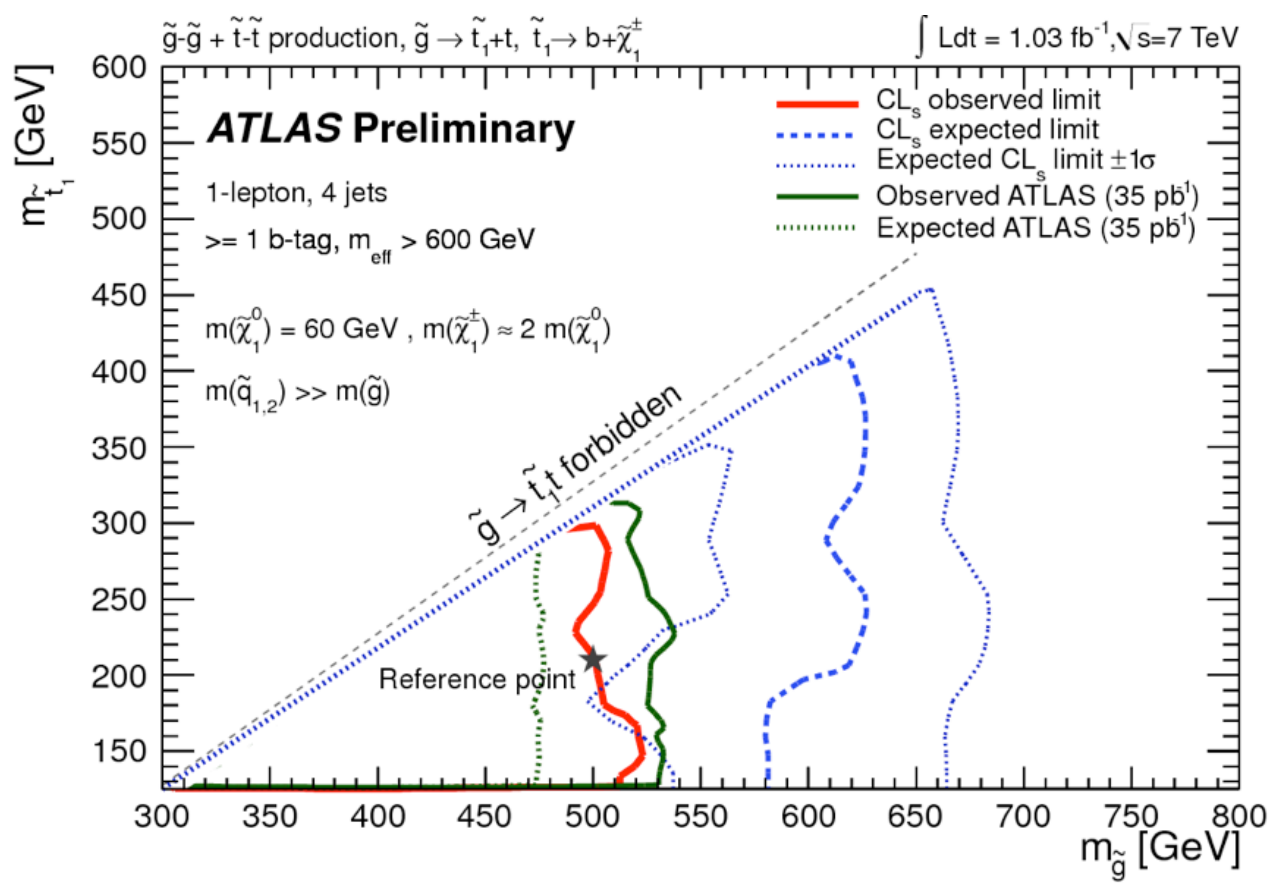
BOTTOM LINE: 1st/2nd gen. squark/gluino bounds have essentially NO impact on fine-tuning in the MSSM

[Not so in specific SUSY breaking models, e.g. where three gen. of squarks have common mass term at some scale]

LHC Searches

Don't they search for stops?

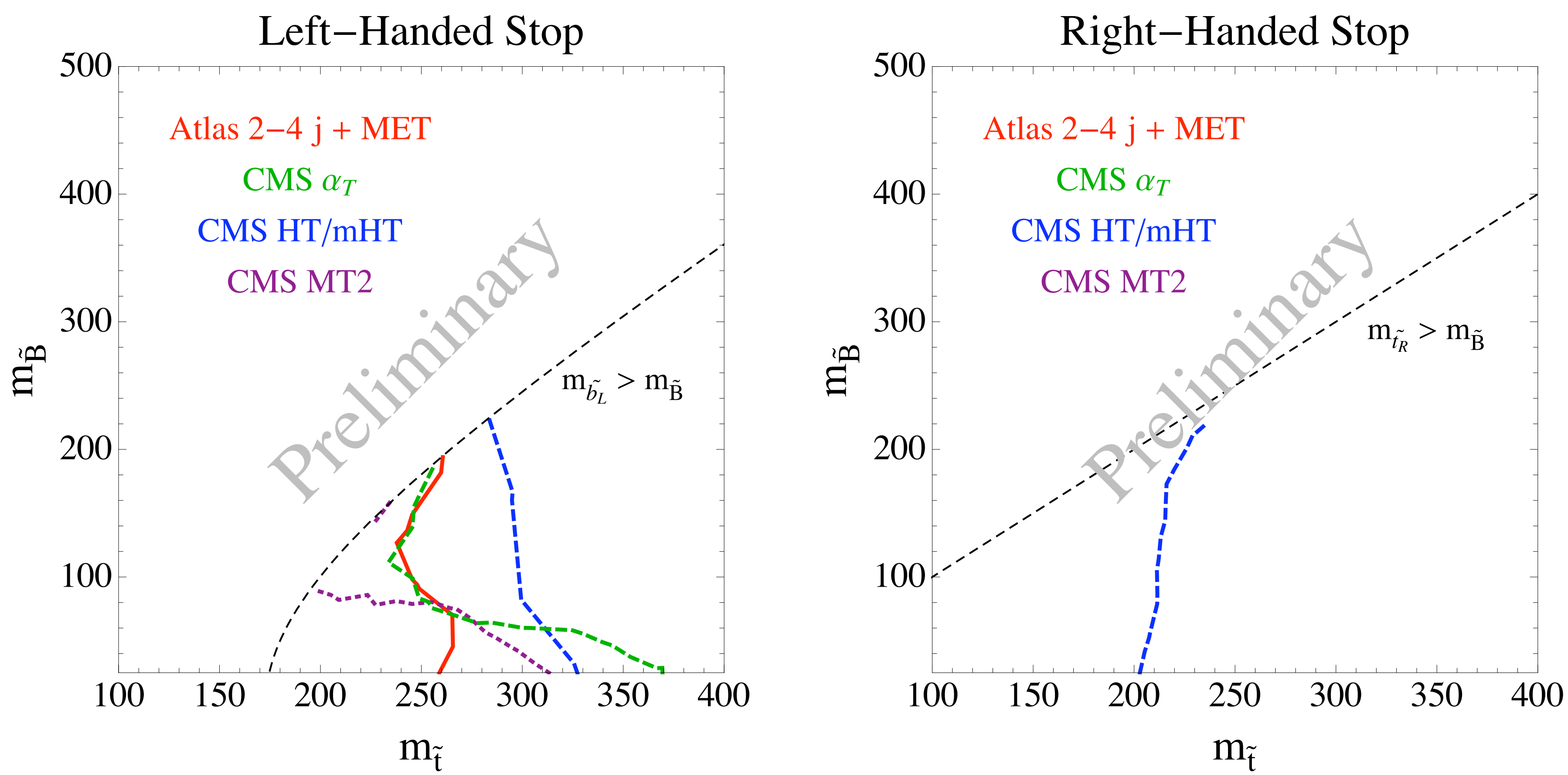
ATLAS-CONF-2011-130 17 August 2011



$m_{\tilde{g}} \gtrsim 500\,\mathrm{GeV}$ $\quad m_{\tilde{t}} \gtrsim\ ?$

This search relies on gluino pair-production to make stops,
and has no impact on fine-tuning so far

Wouldn't stops show up in other channels? Yes, but the limits so far are not strong enough to impact fine-tuning



[Re-interpretation of 1 fb-1 searches presented at summer conferences, by Papucci, Ruderman, Toro and Weiler]

- Good news: SUSY, as a solution to the hierarchy problem, is alive and well despite lack of LHC discovery so far

MSSM, Higgs and Naturalness

- Non-observation of the Higgs at LEP2 presents a significant problem for the MSSM
- At tree level, a firm upper bound (ind. of 120 parameters) on the mass of the lighter CP-even Higgs boson: $m(h^0) < M_Z$
- Experimentally, $m(h^0) > 114\ \mathrm{GeV}$ (except corners)
- Loop corrections to $m(h^0)$ must be large (25%)
- Same loops induce large corrections to Higgs vevs, which need to be canceled precisely - fine-tuning of O(1%)
- In any case, $m(h^0) \leq 135\ \mathrm{GeV}$ in the MSSM - will be tested within a year!
- Caveat: If SUSY is realized, it may well be a non-minimal version (e.g. extra scalars coupled to the Higgs sector, non-standard Higgs phenomenology)

MSSM Pheno: Some Caveats

- Caveat 1: R-parity may be broken (e.g. either L or B would be sufficient to ensure proton stability) ⟹ no MET signature

- Caveat 2: next-to-lightest SUSY particle (nLSP) may be long-lived enough to decay outside of the detector ($10^{10}\ \mathrm{yrs} > \tau_{\mathrm{nLSP}} > 10^{-8}\ \mathrm{sec}$) ⟹ no missing energy, a massive charged-particle (CHAMP) track or a decay of a particle stopped inside the detector instead

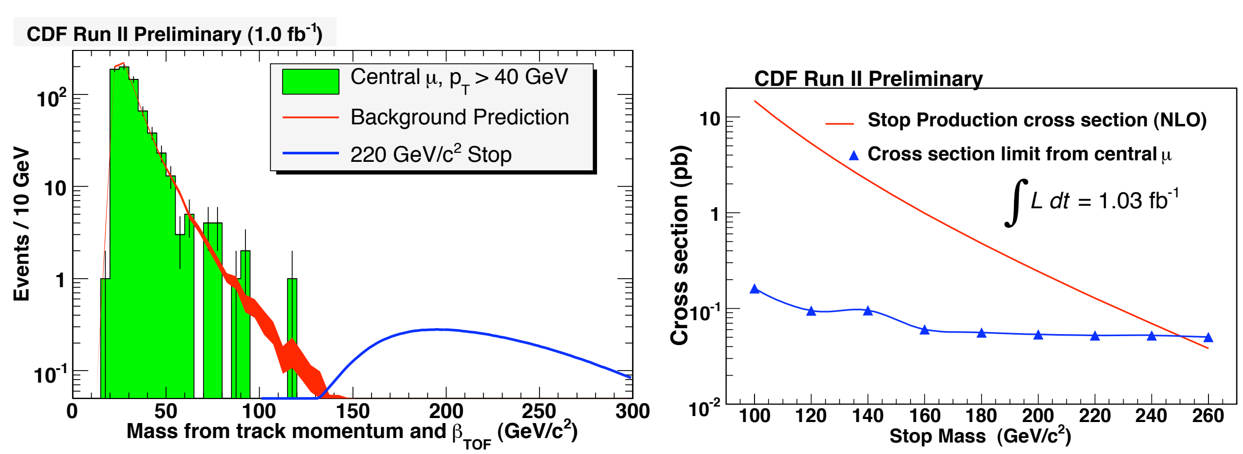


Figure 11: Spectrum of the mass calculated from the momentum and time of flight for CDF muon candidates (left). CDF limits on the production cross section versus stop mass of long-lived stop particles (right).

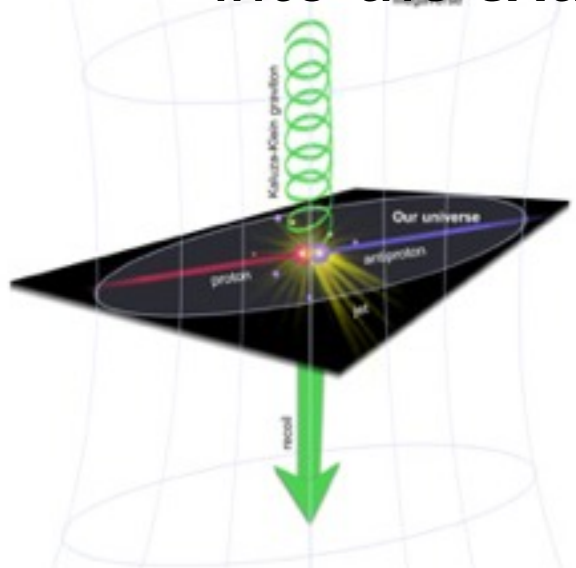
[figure credit: T. Adams, arXiv: 0808.0728]

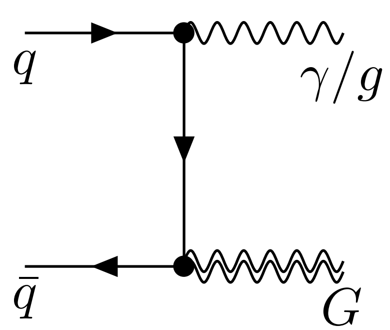
Quantum Gravity at TeV

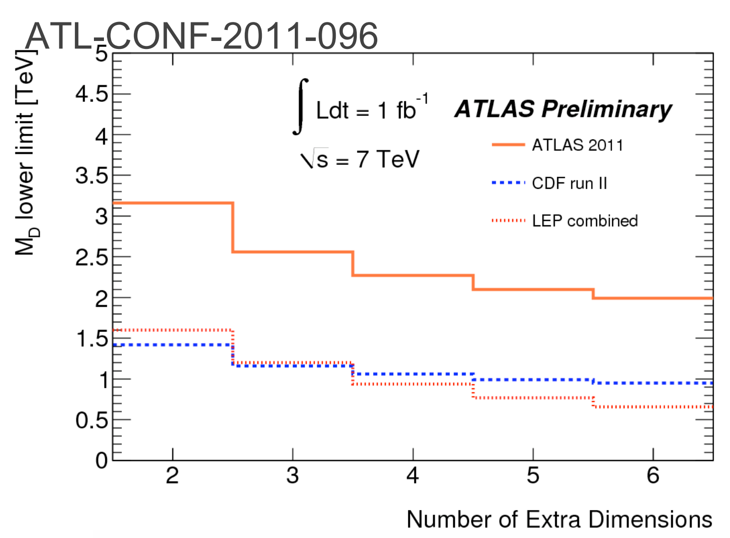
- In string theory, all divergent integrals cut off at M_S : Higgs and other particles turn into finite-size strings!
- If $M_S \sim 1 \text{ TeV}$, there is no hierarchy problem! But $M_S \sim M_{\text{Pl}}$
- ADD model: SM on a 4D "brane" inside higher-D space, with extra dimensions compactified with

$$R \sim M_{\text{Pl}}^{-1} \left(\frac{M_{\text{Pl},4}}{M_{\text{Pl}}} \right)^{2/n} \gg M_{\text{Pl}}^{-1}$$

- At $E < M_{\text{Pl}}$, missing energy signature due to graviton emission into the extra dimensions





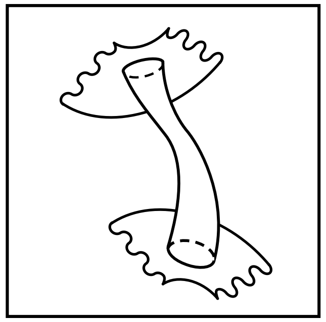


[Mirabelli, MP, Peskin, hep-ph/9811337, PRL82:2236]

Black Holes & Strings at LHC?

- If two partons collide at super-plankian energies $E \gg M_{\rm Pl}$, a black hole must form
- Given existing constraints on $M_{\rm Pl}$, it seems pretty unlikely that the LHC will probe the region $E \gg M_{\rm Pl}$ [Meade, Randall, 0708:3017]
- In any (weakly coupled) string theory, Regge excitations of SM particles lie below Planck scale $M_n = \sqrt{n} M_S, \quad M_S < M_{\rm Pl}$
- Reggeons appear as s-channel resonances in SM scattering processes: Easy to see, more realistic target than BHs

[Cullen, MP, Peskin, hep-ph/0001166, PRD62:055012]



- Distinguish from Zprimes etc.: spin (e.g. first "Regge gluon" is spin-2!)
- Excited Reggeons have spin > 2, at present not handled by general-purpose MC generators!

QCD Redux: Composite Higgs, Technicolor, and Their Cousins

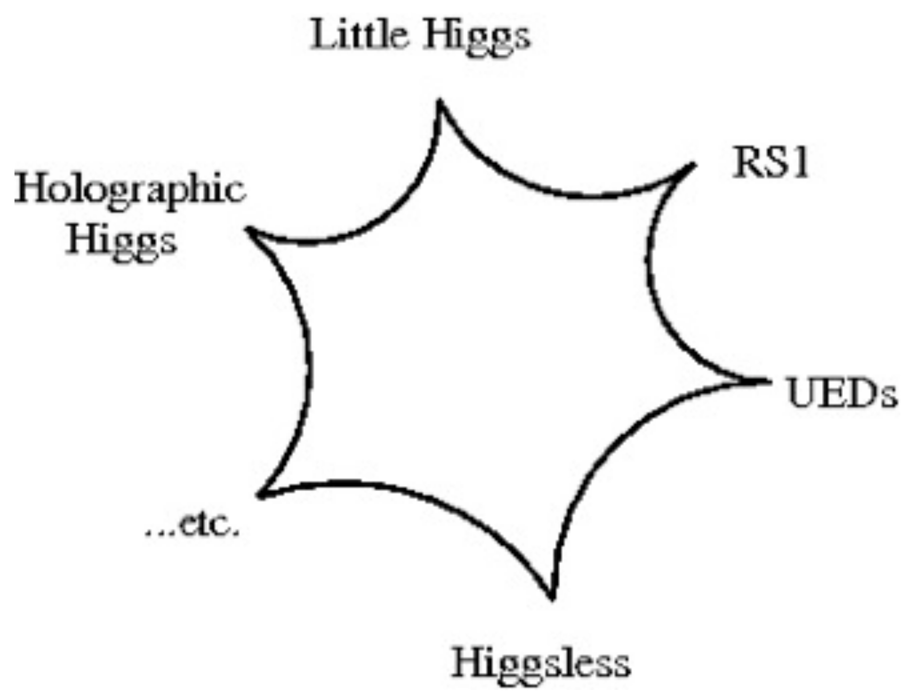


figure credit: Ian Low

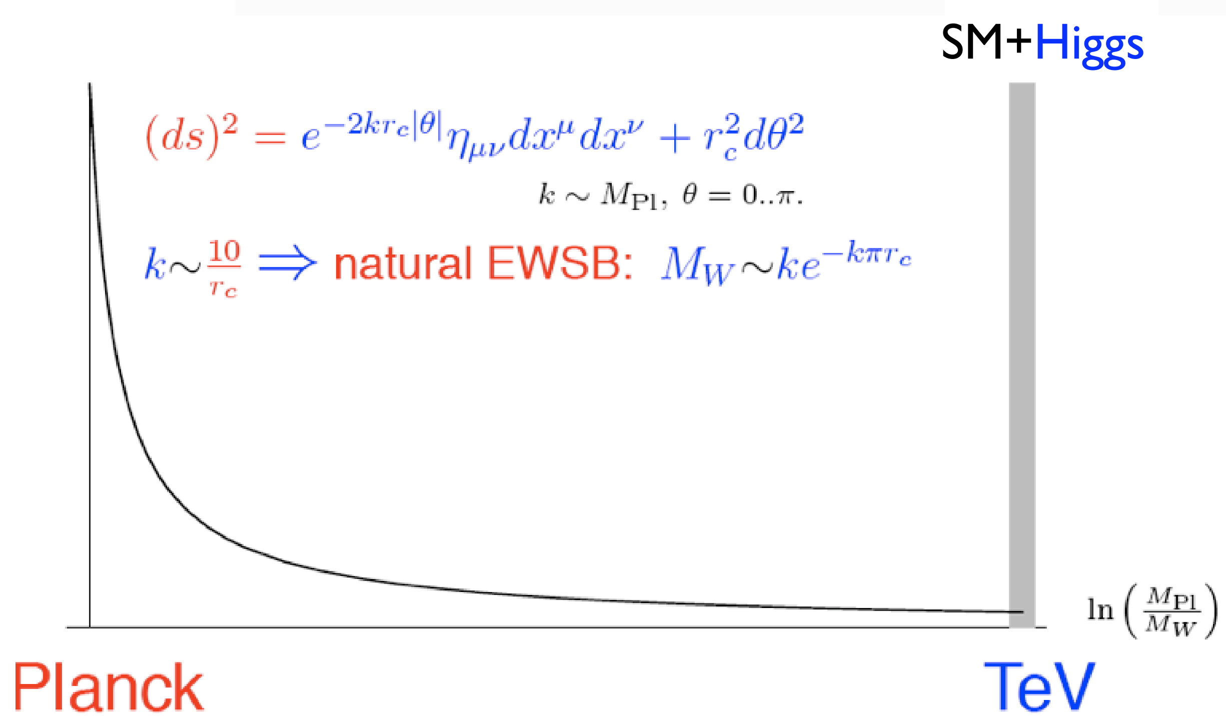
- All these models involve new strong dynamics at TeV (or 10 TeV), a la QCD confinement at GeV, but with interesting new twists!

Composite Higgs

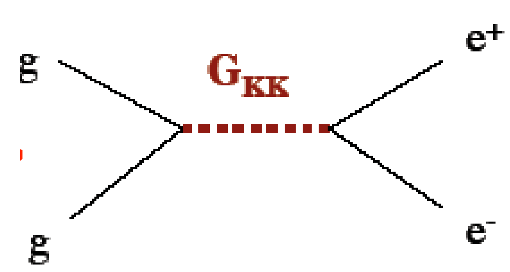
- Many spin-0 particles exist in nature - mesons
- They are composite, made of spin-1/2 quarks, bound by QCD strong force
- Above the QCD confinement scale, the good degrees of freedom are quarks ⇨ no hierarchy problem!
- Can the Higgs be a meson bound by a new strong force?
- Old idea, but difficult to build models - non-perturbative physics!
- New insight: AdS/CFT duality ⇨ some strongly coupled 4D models are "dual" to weakly coupled, calculable models with an extra dimension!
- Setup: Randall-Sundrum (RS) 5D model

Warped (RS) Extra Dimension

- Original model had the SM on the TeV brane, solves the hierarchy problem



- New states: KK gravitons at the TeV scale
- Couplings: $\mathcal{L} \sim \dfrac{1}{(\mathrm{TeV})^2} T_{\mu\nu} G^{\mu\nu}_{\rm KK}$



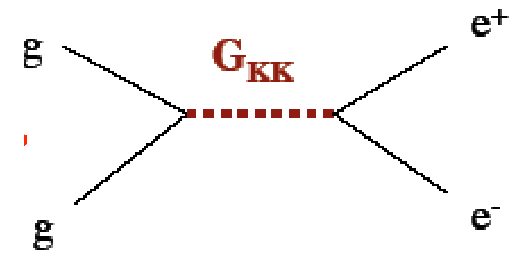
Kaluza-Klein Particles from Extra Dimensions

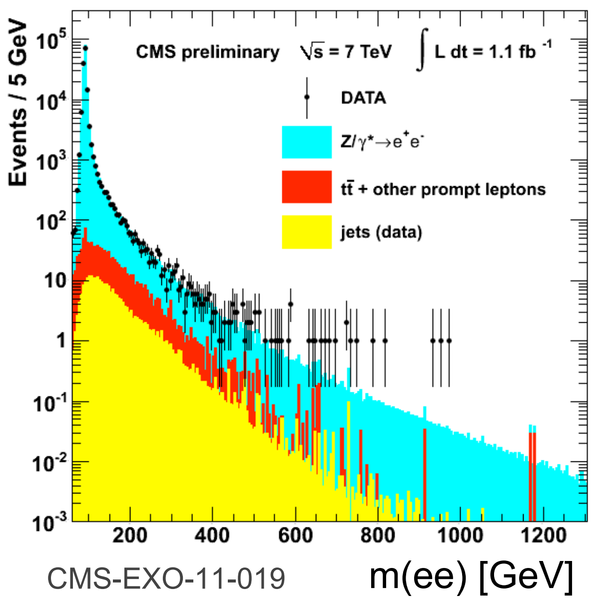
- Suppose that space-time has an extra spatial dimension, which is circular, with radius R
- Free field can be decomposed into momentum eigenstates (waves): $\phi \sim e^{i(p\cdot x+p_5 y)}$
- Periodicity ⇨ momentum quantization: $p_5(2\pi R) = 2\pi n$ ⇨ $p_5 = \frac{n}{R}$
- Fourier expansion = Kaluza-Klein decomposition:

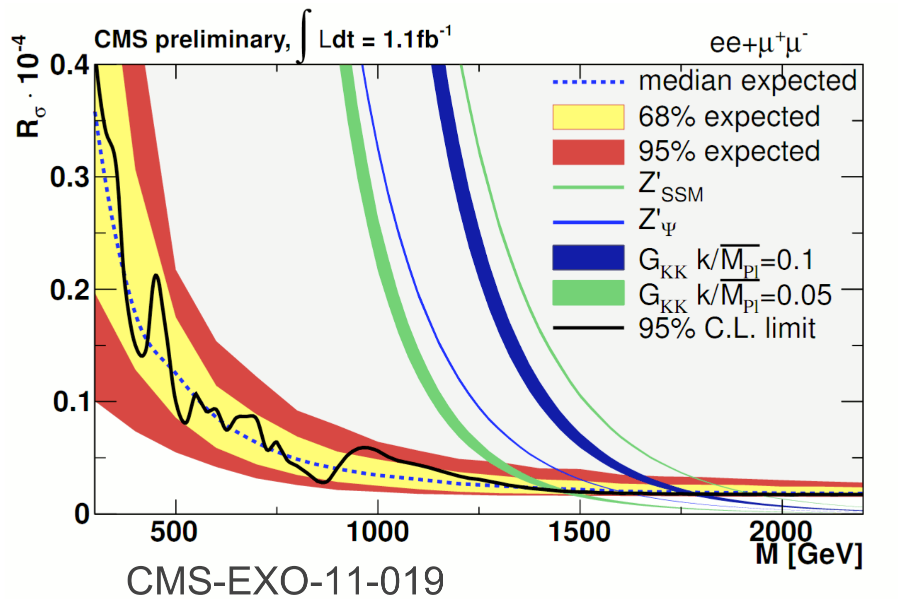
$$\phi(x,y) \sim \sum_{n=0}^{\infty} \phi^n(x)\; e^{iny/R}$$

- Each KK mode behaves like a 4D particle, with mass $M_n = \frac{n}{R}$
- SM fields can be fundamentally 5D, if $\frac{1}{R} > 500\ \mathrm{GeV}$

RS: LHC Searches





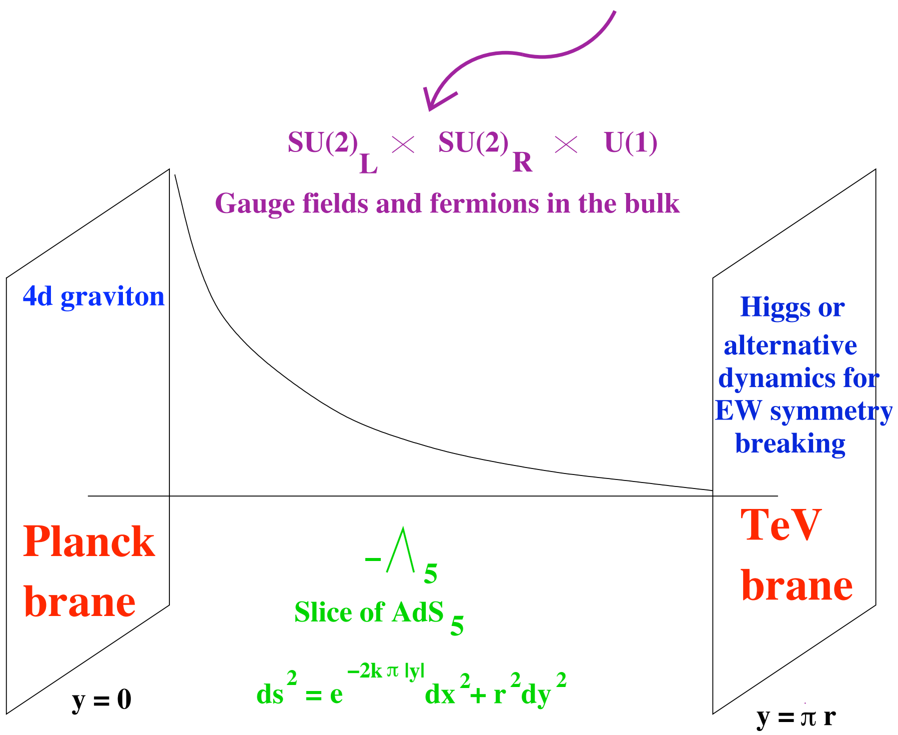


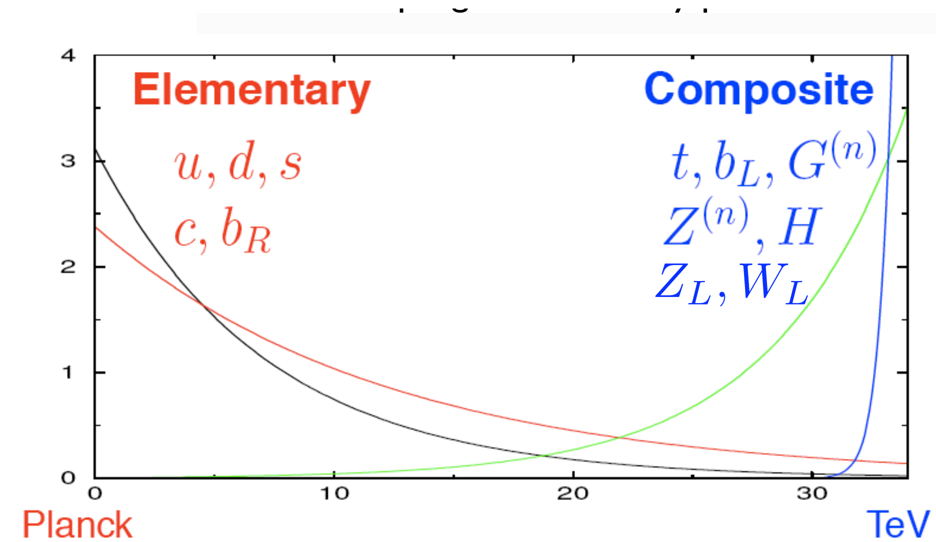
RS graviton (k/M_{Pl} = 0.1):
m(G) > 1.8 TeV at 95% C.L.

[a similar bound is obtained from 2-photon resonance search]

RS with Bulk Matter

- It was subsequently realized that models with SM gauge fields and fermions in the "bulk" are more interesting:





- natural solution to fermion mass hierarchy problem

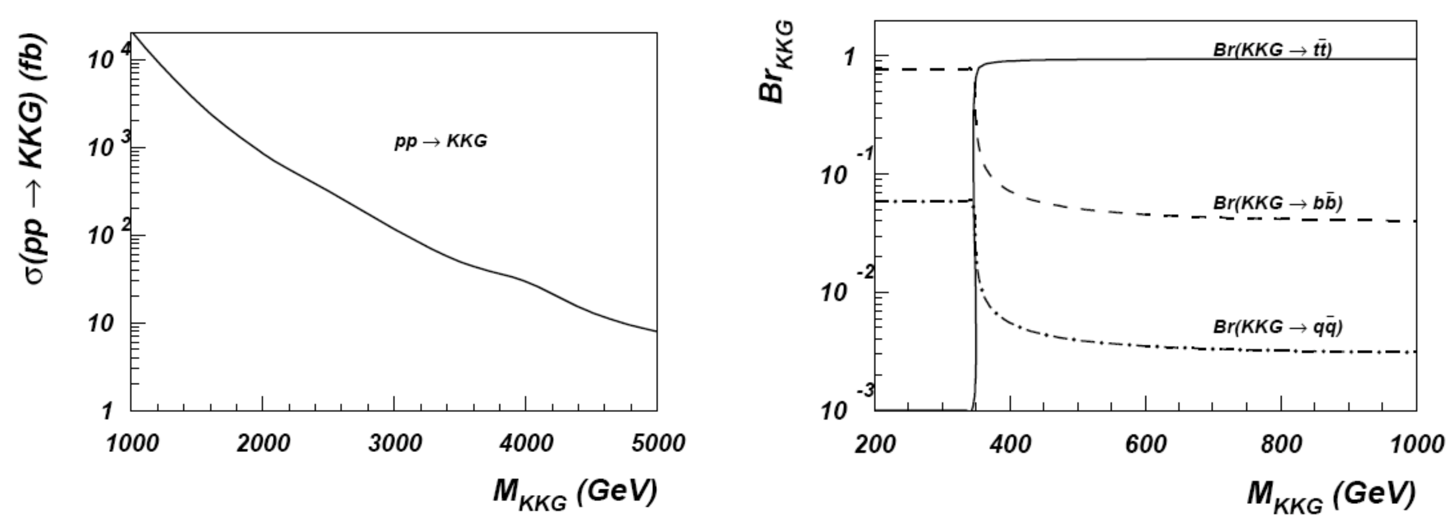
- natural suppression of flavor-changing neutral currents

- possibility of gauge coupling unification, as in the MSSM

figure credits: G. Perez, G. Servant

RS with Bulk Matter: Pheno

- Good: all SM states now have KK modes!
- Bad: the KKs do not couple to light quarks and leptons much...
- Worse: PEW constraints force KK masses > 3 TeV or so
- KK gluon is probably the easiest target at the LHC

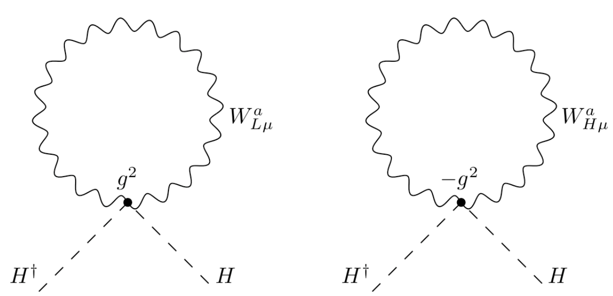


Agashe et. al., hep-ph/0612015; Lillie et.al., hep-ph/0701166

Final state: A pair of highly-boosted tops ("top jets"?)

Gauge-Higgs Unification

- A zero-mass photon does not require fine-tuning - mass is protected by gauge symmetry
- In a 5D theory, the gauge field $A_M(x) \to A_\mu(x), A_5(x)$
- If the 5th dimension is infinite, A_5 is naturally massless!
- After compactification, $m(A_5) \sim 1/R$ ⇨ good if $1/R \sim M_W \sim M(W')$
- Higgs mass quadratic divergences are canceled by KK modes:



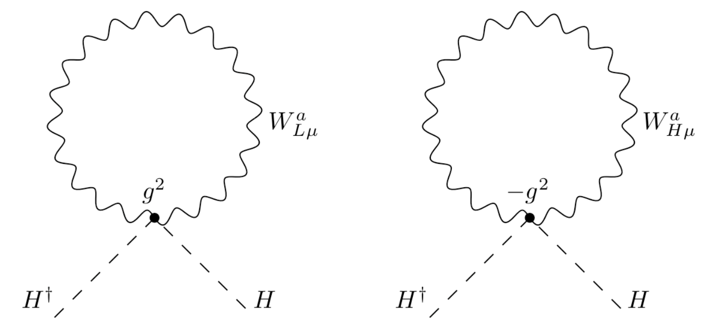
- A realistic GHU implementation, using a warped extra dimension, predicts KK states at 2 TeV and $m_h < 140$ GeV

[Agashe, Contino, Pomarol, hep-ph/0412089]

Little Higgs

- Quadratic divergence cancellation by same-spin states can also occur in a purely 4D theory - Little Higgs

[LH ⟺ effective theory of the first two KK modes in GHU!]



- In LH, Higgs is a Goldstone boson arising from a global symmetry breaking [a la pions in QCD]

- If the global symmetry is exact, $m_h = 0$ naturally!

- Goldstones only interact derivatively ⟹ need to break the global symmetry explicitly by gauge and Yukawa interactions

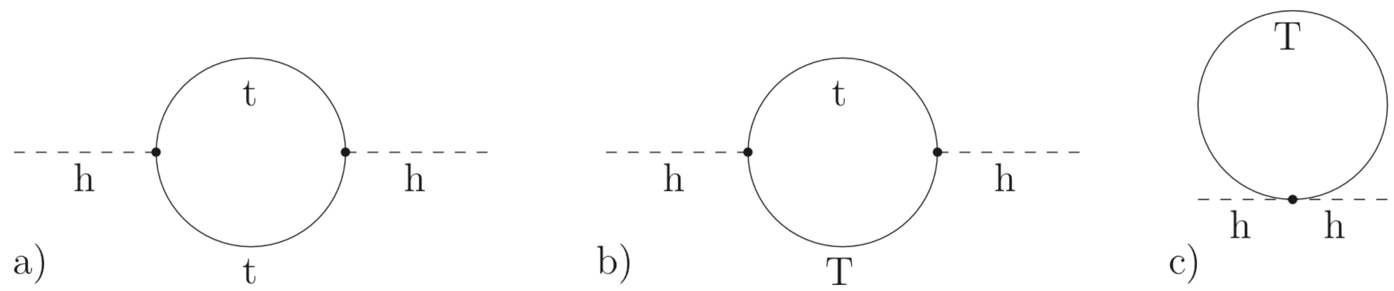
- Generically explicit breaking reintroduces quadratic divergences

- "Collective" breaking pattern in LH avoids quad. div. at one loop

[Arkani-Hamed, Cohen, Georgi, 2002]

EWSB in Littlest Higgs Model

- Higgs mass is dominated by top and Top loops:



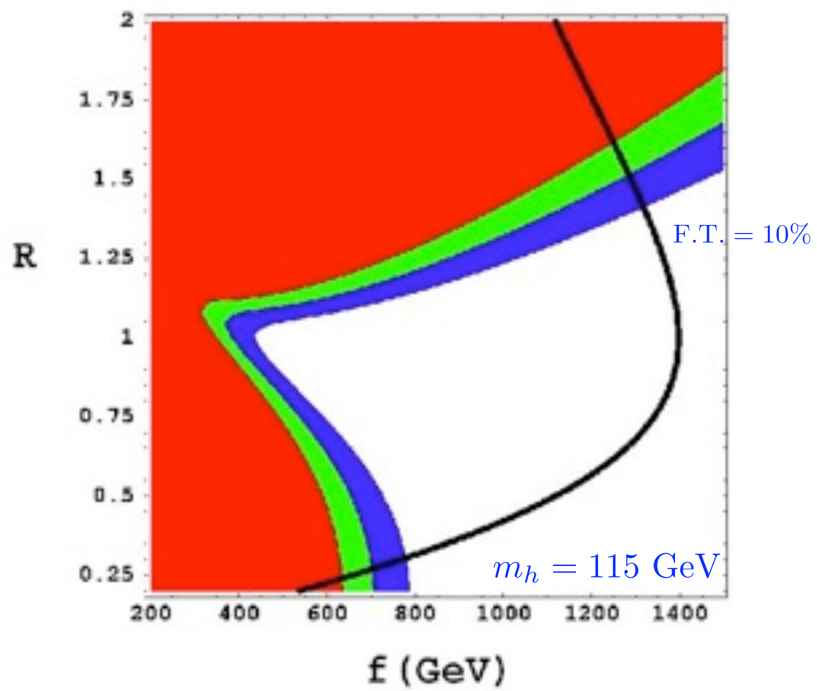
- This contribution is log-divergent and negative:

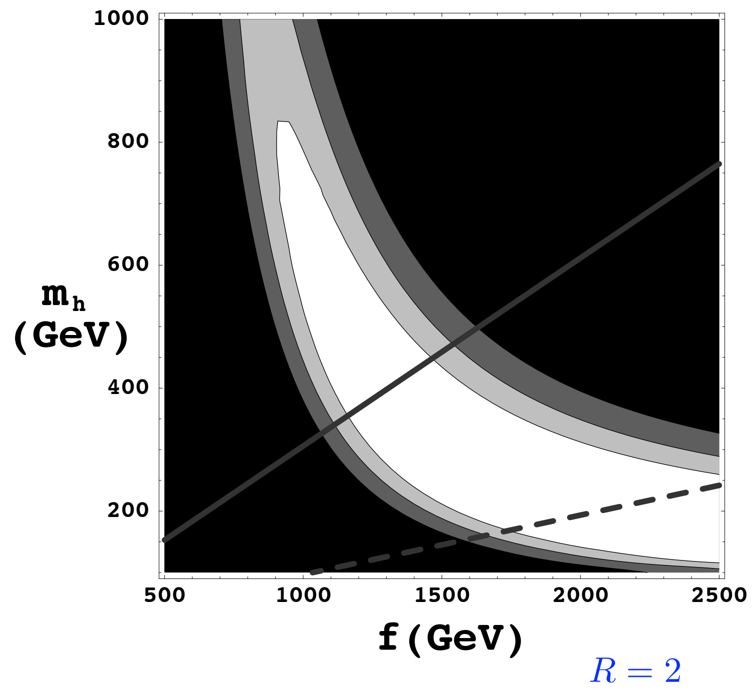
$$m_{\rm t}^2(H) = -\frac{3\lambda_t^2 M_T^2}{8\pi^2} \log \frac{\Lambda^2}{M_T^2} \ .$$

- All other contributions are generically subdominant
- EWSB is triggered radiatively - simple mechanism!
- Similar to the MSSM but with no tree-level potential at all - e.g. no μ problem!

Little Higgs and T Parity

- LH models are weakly coupled at the TeV scale, predictive!
- The "first-generation" LH models strongly disfavored by precision electroweak data
- Best solution: introduce "T Parity": new TeV-scale particles T-odd and only appear in loops in PEWO [a la R parity of the MSSM]
- Littlest Higgs with T Parity (LHT) passes PEW tests without significant fine-tuning

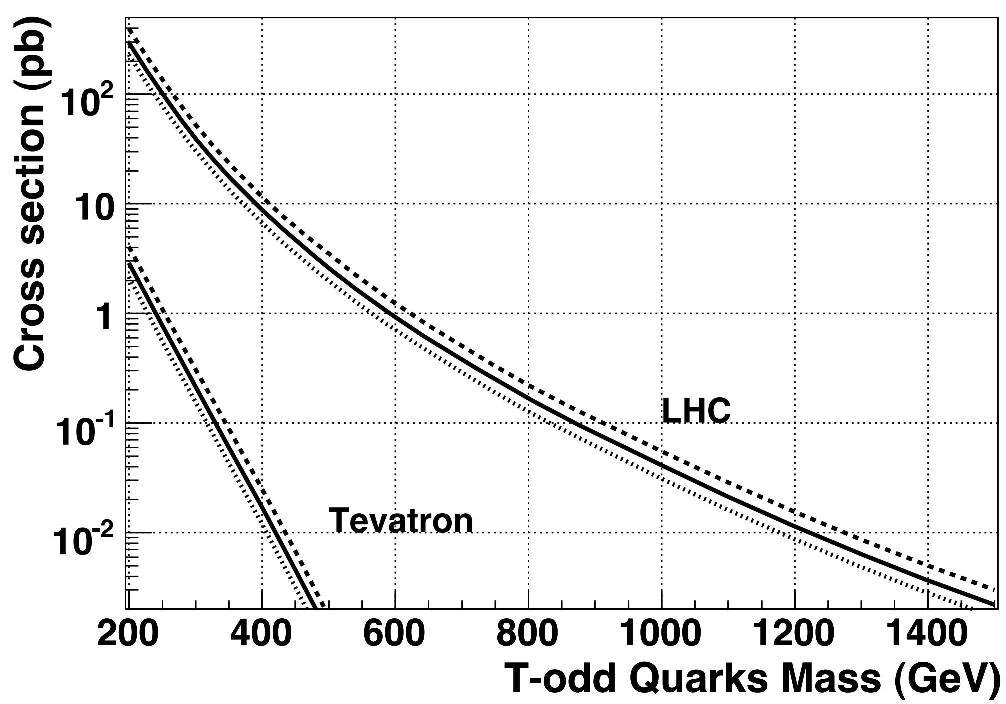




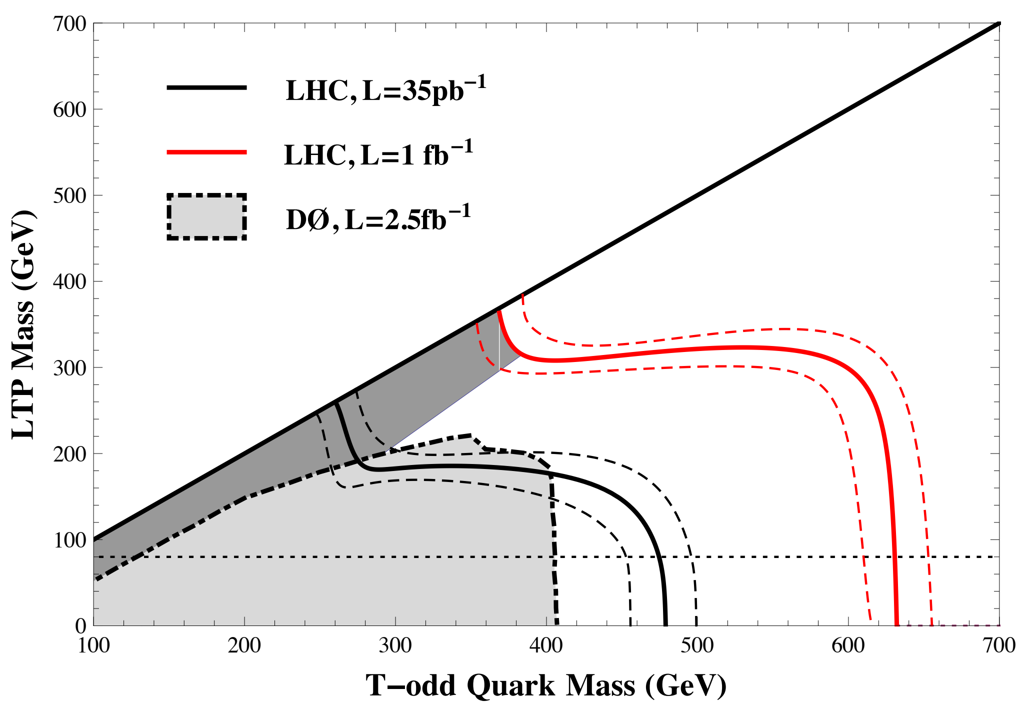
[Hubisz, Meade, Noble, MP, hep-ph/0506042]

LHT Collider Phenomenology

- The Lightest T-Odd Particle (LTP) is stable, typically the neutral, spin-1 "heavy photon" - WIMP DM candidate
- Symmetry structure forces introduction of T-odd partners for each SM (weak doublet) fermion - "T-quarks" and "T-leptons"
- Hadron collider signature: T-quark production, decays to LTP+jets



[Carena, Hubisz, MP, Verdier, 2006]



[MP, Shao, 2011]

A "SUSY look-alike" candidate!

LHT or SUSY?

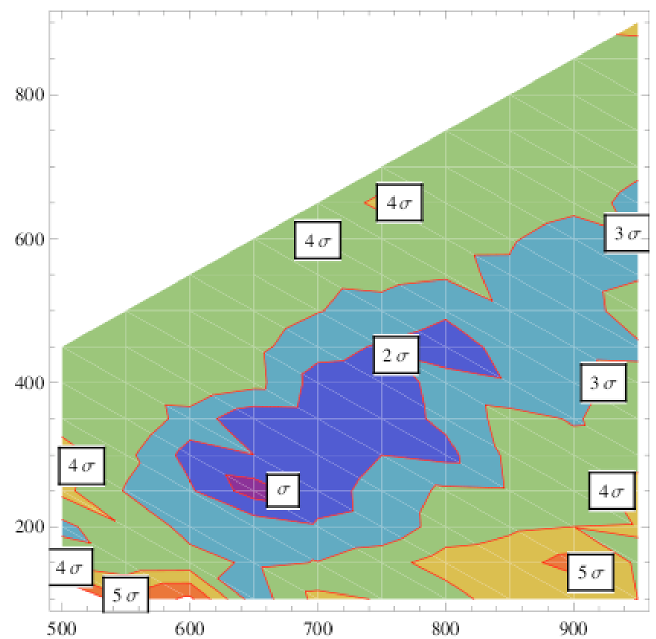
[Hallenbeck, MP, Spethmann, Thom, Vaughn, arXiv: 0812.3135]

- Only looked at one channel, generic in both models

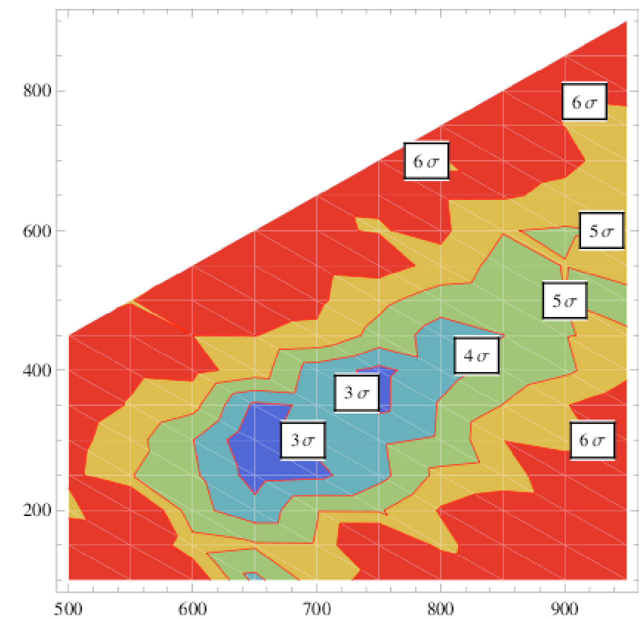
$$pp \to Q'\bar{Q}', Q' \to qB' \quad \Rightarrow \quad 2j + \mathrm{MET}$$

- Simulated SUSY+SM sample = "data", try to fit with LHT+SM, varying LHT parameters (T-quark and LTP masses)

- Fit to 10 observables: $\langle p_T \rangle, \langle H_T \rangle$, moments, asymmetries



200 pb-1



1 fb-1

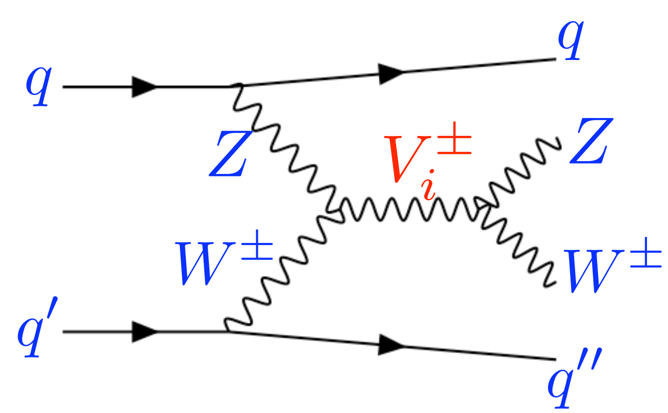
[This study point is now ruled out... Still, the strategy may well be useful]

What if There is No Higgs?

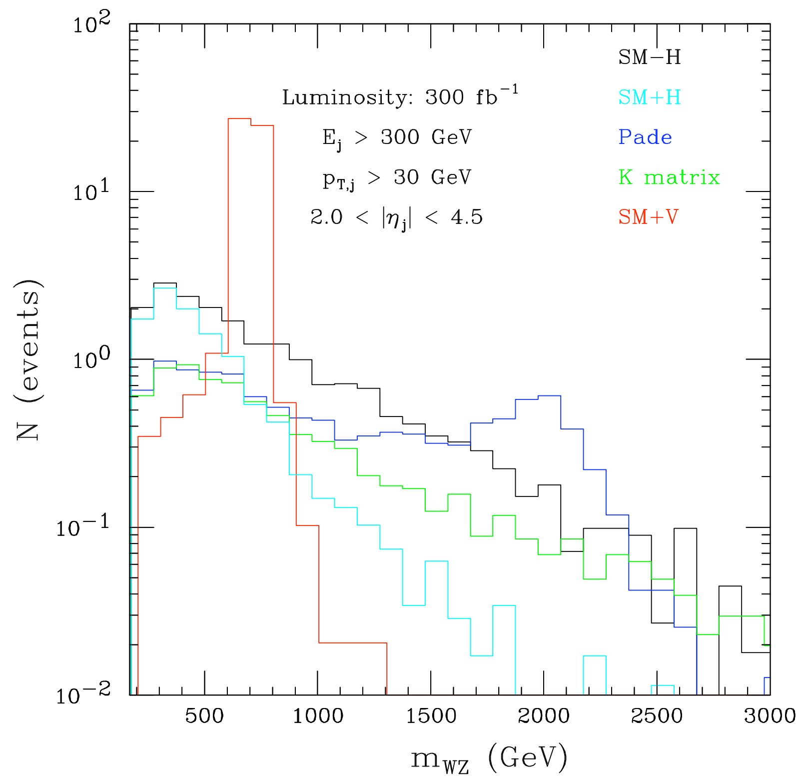
- If physics at TeV scale is strongly coupled, a symmetry-breaking condensate can exist without a physical Higgs boson in the theory - technicolor!
- TC with QCD-like dynamics at TeV is strongly disfavored by precision electroweak data
- Difficult to explore model space due to strong coupling
- New insight: AdS/CFT duality ⇨ some strongly coupled 4D models are "dual" to weakly coupled, calculable models with an extra dimension!
- 5D "Higgsless" models have been constructed, with EWSB by boundary conditions in RS-like setup, passes precision electroweak tests with ~1% fine-tuning
- Fermion masses can be straightforwardly incorporated

Higgsless Phenomenology

- Best place to search for all higgsless models is W/Z scattering
- Unitarity must be restored, typically resonances appear
- 5D Higgsless model predicts narrow, light (sub-TeV) resonances



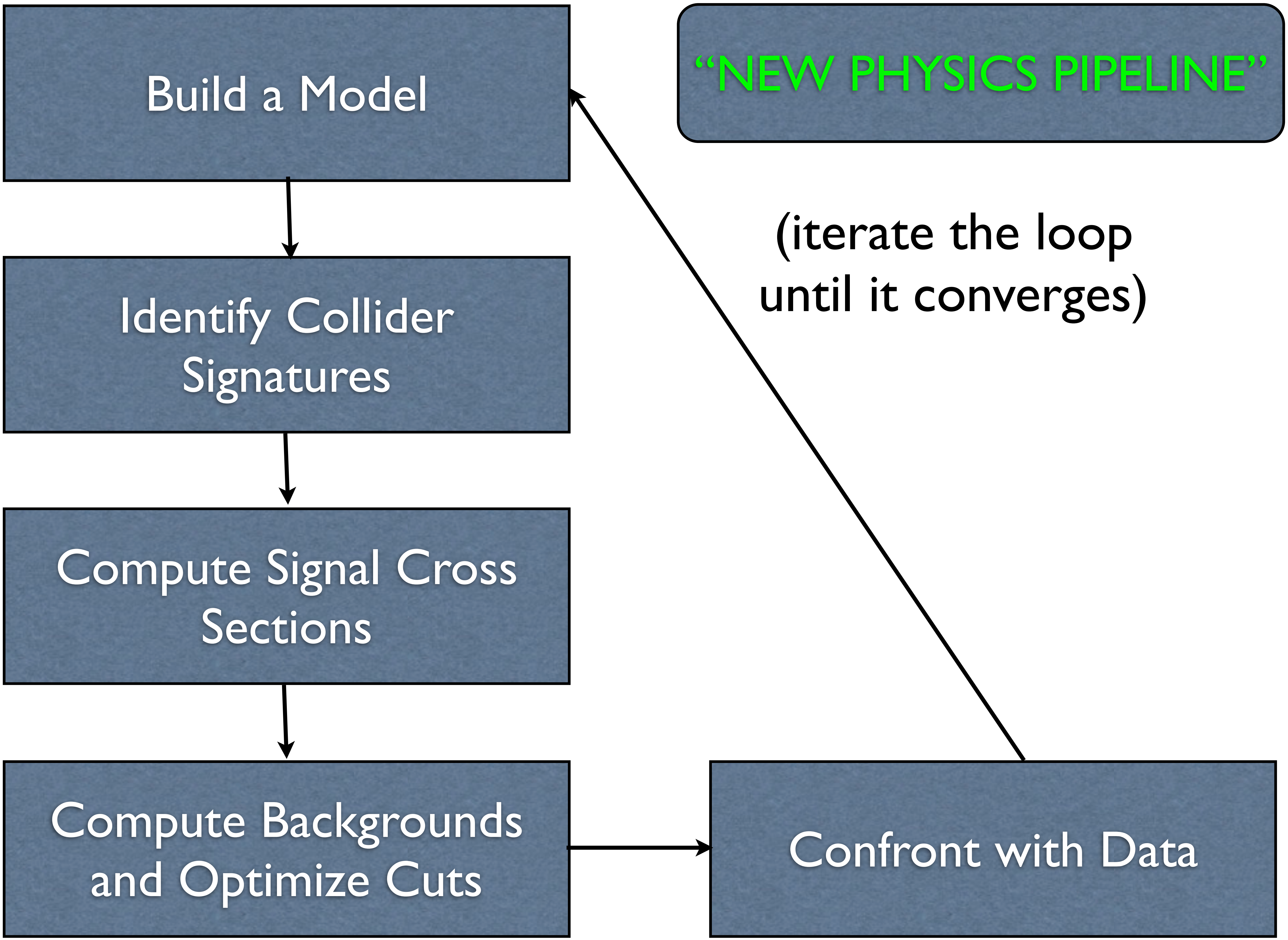
[Birkedal, Matchev, MP, hep-ph/0412278]



Gold-Plated Channel: 2j+3l+Et_miss

Closing Remarks

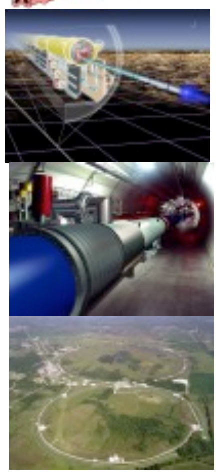
- Since the SM became accepted (~30 years), theorists have been able to provide very precise guidance for new physics searches at the energy frontier (e.g. W, Z, top)
- This is NOT the case in the BSM physics hunt:
  - Number of "ideas" is finite (SUSY, xdim, TC, ...)
  - Number of "implementations" is essentially infinite
  - Number of "free parameters" in each implementation is typically large
- Inclusive (signature-based whenever possible) searches are the best bet
- "Model space" will evolve very quickly once there is evidence for BSM in the data!


"NEW PHYSICS PIPELINE"
Build a Model
Identify Collider Signatures
Compute Signal Cross Sections
Compute Backgrounds and Optimize Cuts
Confront with Data
(iterate the loop until it converges)

Monte Carlo Tools for BSM

- Monte Carlo predictions from models are essential for theory/experiment connection
- Old model: MC developers implement models in general-purpose generators, users use these tools (slow!)
- New model (over the last ~3-4 years):
  - users implement models in parton-level matrix element generators (e.g. Madgraph), output Les Houches Accord-compatible files
  - LHA files are passed on to the rest of the simulation chain (same as SM, except if long-lived BSM states)

[theory.fnal.gov/mc4bsm/]



Monte Carlo Tools for Beyond the Standard Model Physics

6th Workshop: MAR 22 - 24 , 2012 (CORNELL)

ORGANIZERS e-mail: mc4bsm.AT.nbi.dk

RESOURCES:

- BSM tool repository
- Les Houches Accord for BSM Generators
- Video Lectures on Monte Carlo for the LHC
- Summary of MC4BSM-1 Discussion sessions

RELATED WORKSHOPS:

- TOOLS 2010

5th workshop: APR 14-16, 2010 (NBI, COPENHAGEN)

Organizing committee: Poul Henrik Damgaard, Christophe Grojean, Peter Hansen, Jørgen Beck Hansen, Rasmus Mackeprang, Konstantin Matchev, Stephen Mrenna, Maxim Perelstein, Peter Skands.

4th workshop: APRIL 3-4, 2009 (UC DAVIS)

Organizing committee: Hsin-Chia Cheng, Christophe Grojean, Konstantin Matchev, Stephen Mrenna, Maxim Perelstein, Peter Skands.

3rd workshop: MARCH 10-11, 2008 (CERN)

Organizing committee: Georges Azuelos, Christophe Grojean, Jay Hubisz, Borut Kersevan, Joe Lykken, Fabio Maltoni, Konstantin Matchev, Filip Moortgat, Stephen Mrenna, Maxim Perelstein, Peter Skands, James Wells.

2nd workshop: MARCH 21-24, 2007 (PRINCETON)

Organizing committee: Jay Hubisz, Konstantin Matchev, Stephen Mrenna, Maxim Perelstein, Peter Skands.

1st workshop: MARCH 20-21, 2006 (FERMILAB)

Organizing Committee: Marcela Carena, Mu Chun Chen, Bogdan Dobrescu, Chris Hill, Jay Hubisz, Joe Lykken, Konstantin Matchev, Stephen Mrenna, Maxim Perelstein, Jose Santiago, Peter Skands.

Conclusions

- The mechanism which breaks electroweak symmetry remains a fundamental, unsolved mystery
- All natural models of EWSB predict new physics at the TeV scale
- Tevatron is at the frontier, discovery possible every day
- LHC is on its way!
- Lots of interesting possibilities - exciting physics ahead!
- Widely open theory space brings challenges as well:
  - Making sure no new physics is missed (triggers, cuts)
  - Experiment-theory communication issues