

LHC Phenomenology

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The big questions for the LHC era

Particle physics has many “big questions.”

I think the three most important ones that LHC can hope to answer are these:

What is the origin of mass?

Why is gravity so much weaker than the other forces?

What is the dark matter?

What is the origin of mass?

What is the origin of mass?

Left-handed fermions and right-handed fermions have different $SU(2)_L \times U(1)_Y$ quantum numbers.

Usual fermion mass term $\mathcal{L} = -m\bar{f}_R f_L$ is not gauge invariant.

Naive mass terms $\mathcal{L} = M^2 W^\mu W_\mu$ for W and Z bosons also violate gauge invariance.

Simplest way out: the **Higgs mechanism**.

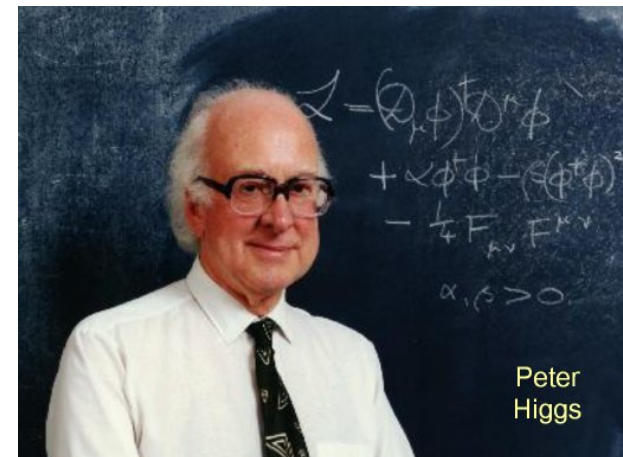
Introduce a scalar “Higgs” field H

- Doublet under $SU(2)_L$: $H = (\phi^+, \phi^0)^T$
- Carries $U(1)_Y$ hypercharge

Couplings of H :

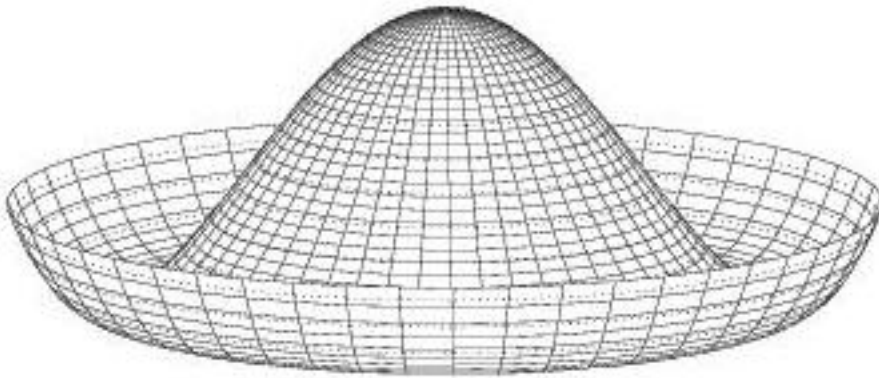
- To gauge bosons via the **covariant derivative**, $\mathcal{L} = |\mathcal{D}_\mu H|^2$.
- To itself via the **Higgs potential**, $-\mathcal{L} = V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$.
- To fermions via **Yukawa couplings**, $\mathcal{L} = y_f \bar{f}_R H^\dagger F_L$.

All these couplings are gauge invariant.



This works if we choose the signs of the terms in the Higgs potential: $V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$ with $\mu^2 < 0$ and $\lambda > 0$.

(why? SM gives no explanation.)



- Potential is symmetric under $SU(2)_L \times U(1)_Y$ gauge symmetry.
- Minimum is not at zero field value:

Universe must choose particular (non-symmetric) configuration.

This is **spontaneous symmetry breaking**.

Expand Higgs field about the minimum:

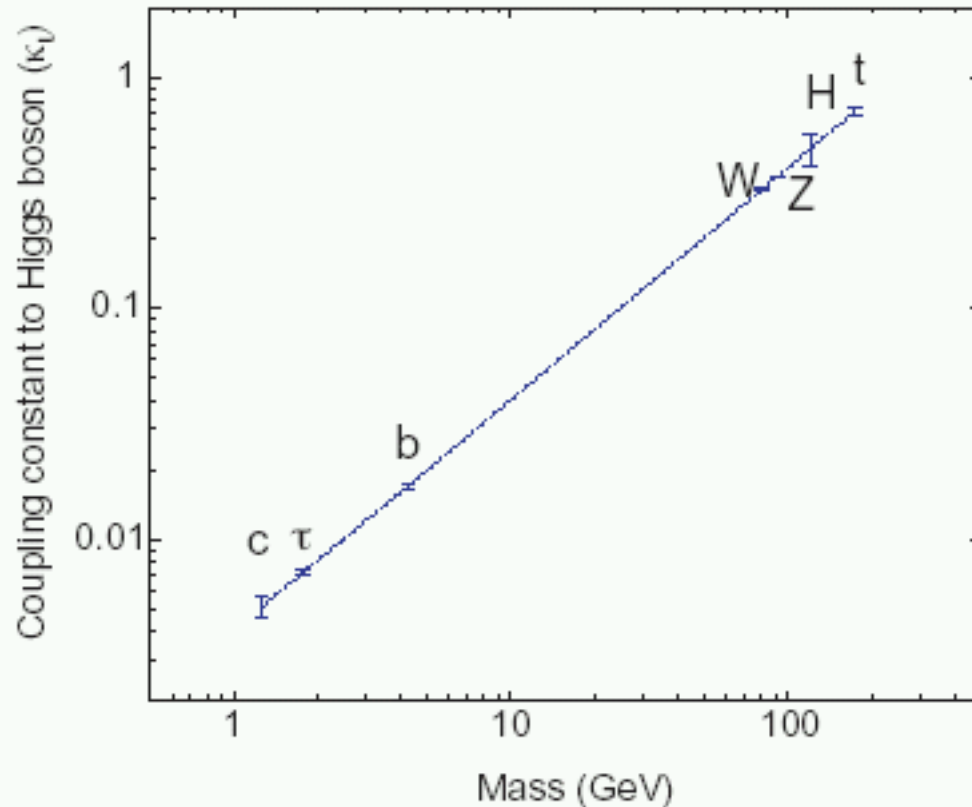
$$H = \begin{pmatrix} G^+ \\ (h + v)/\sqrt{2} + iG^0/\sqrt{2} \end{pmatrix}$$

Covariant derivative \rightarrow gauge boson masses and couplings to h :

$$\mathcal{L} = \frac{g^2}{4}(v+h)^2 W^{\mu+} W_{\mu}^- + \frac{g^2 + g'^2}{8}(v+h)^2 Z^{\mu} Z_{\mu}$$

Yukawa couplings \rightarrow fermion masses and couplings to h :

$$\mathcal{L} = \frac{y_f}{\sqrt{2}}(v+h)\bar{f}_R f_L + \text{h.c.}$$

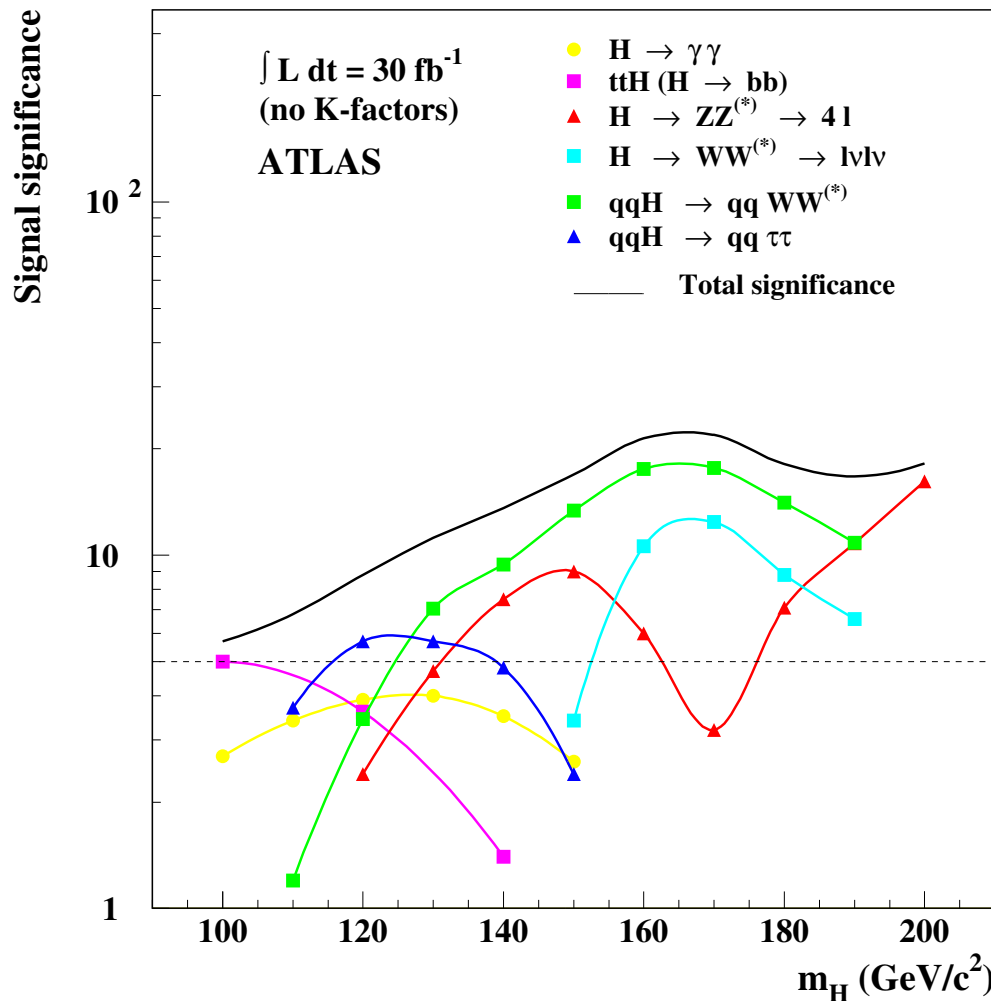


Mass of each particle is proportional to its Higgs coupling.

Slope is predicted by $v = 2M_W/g = 246$ GeV.

Test the SM Higgs mechanism by measuring the Higgs couplings to SM particles.

First we need to discover the Higgs (if it exists).
 If the Higgs is Standard Model-like, LHC will discover it



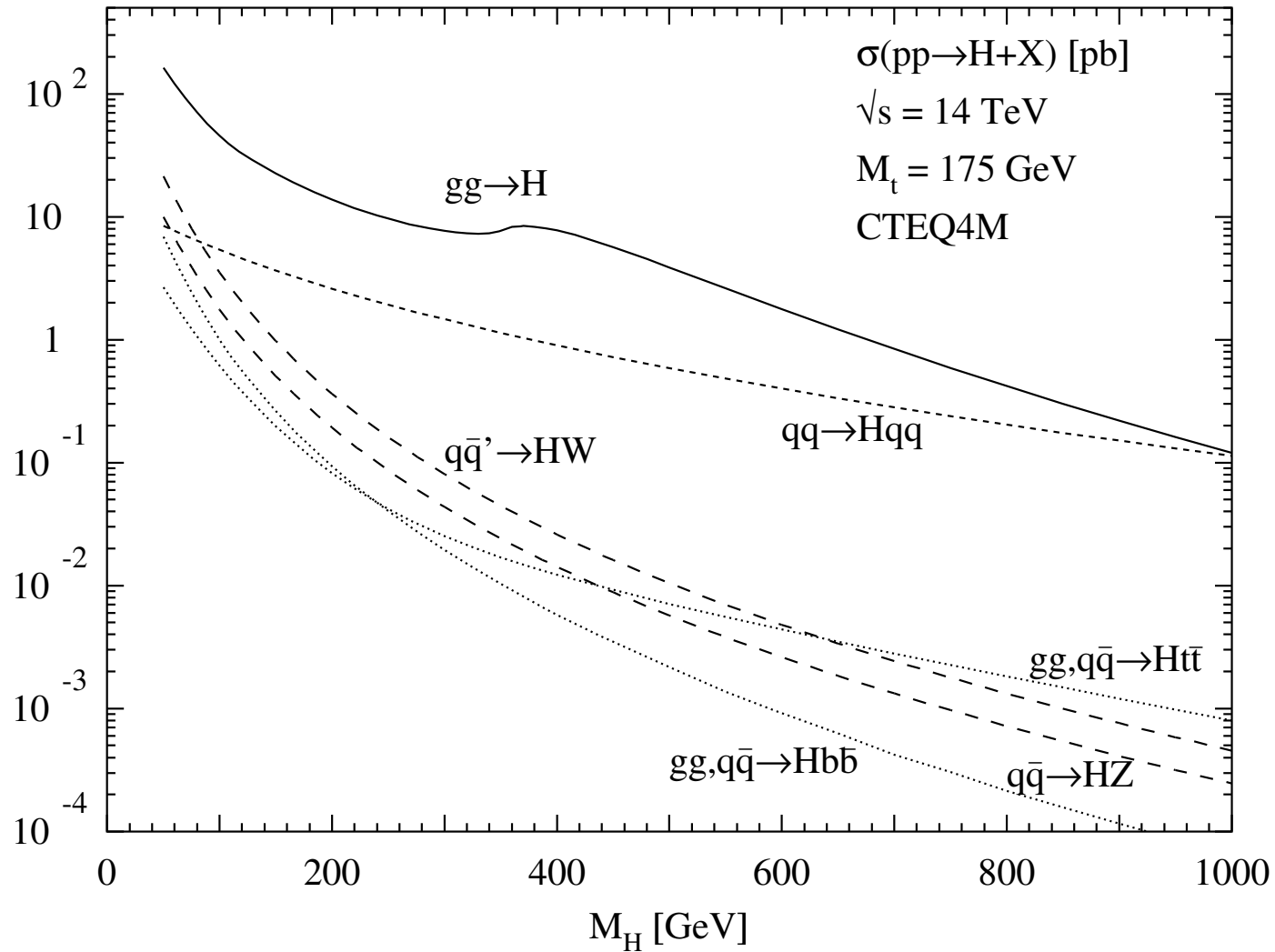
Updates:

- $H \rightarrow \gamma\gamma$ better once K-factors included
- ttH backgrounds bigger than expected: no longer a discovery channel

CMS reach is similar

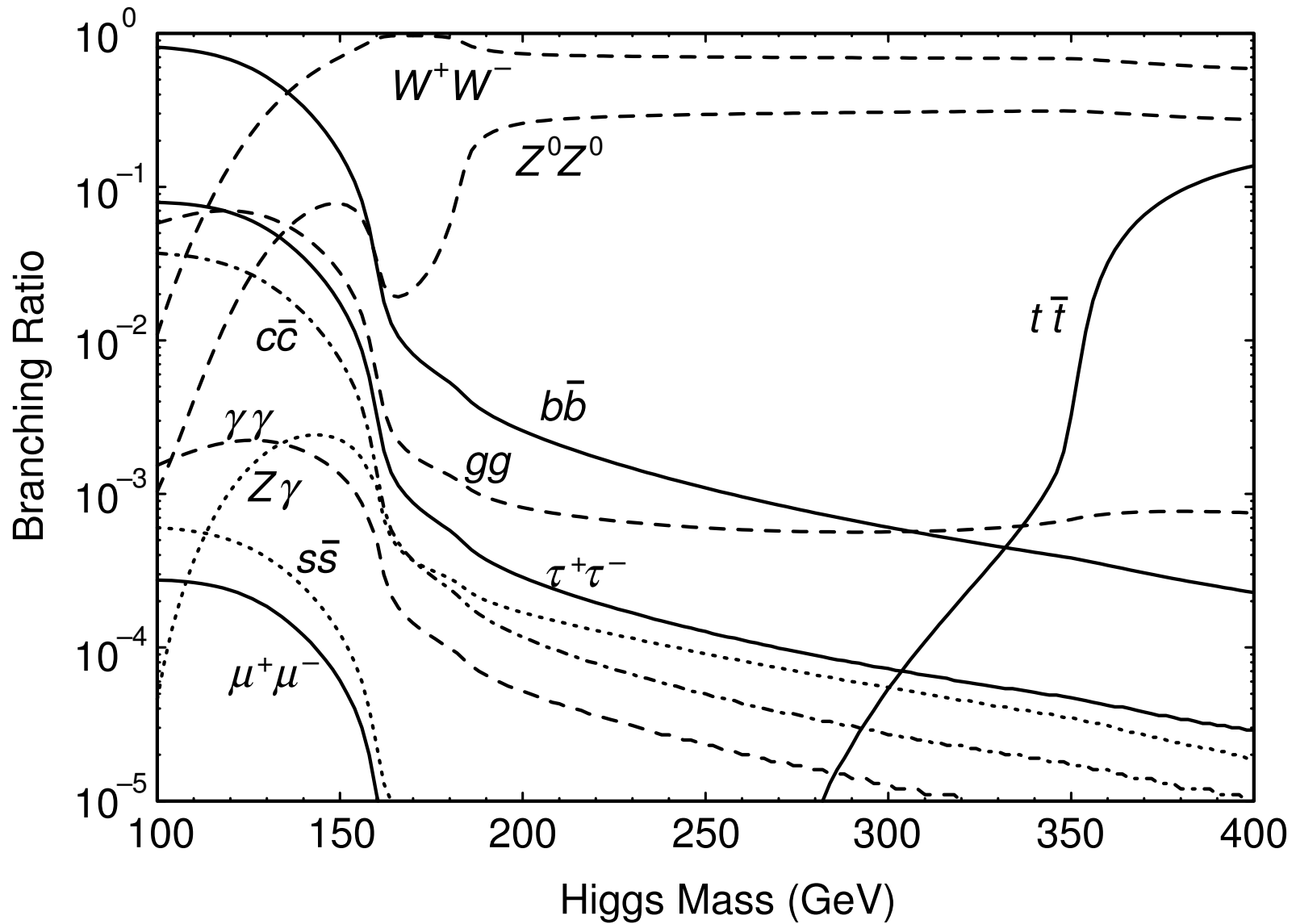
S. Asai et al., Eur. Phys. J. C 32S2, 19 (2004)

Higgs couplings determine production cross sections



M. Spira, Fortsch. Phys. 46, 203 (1998)

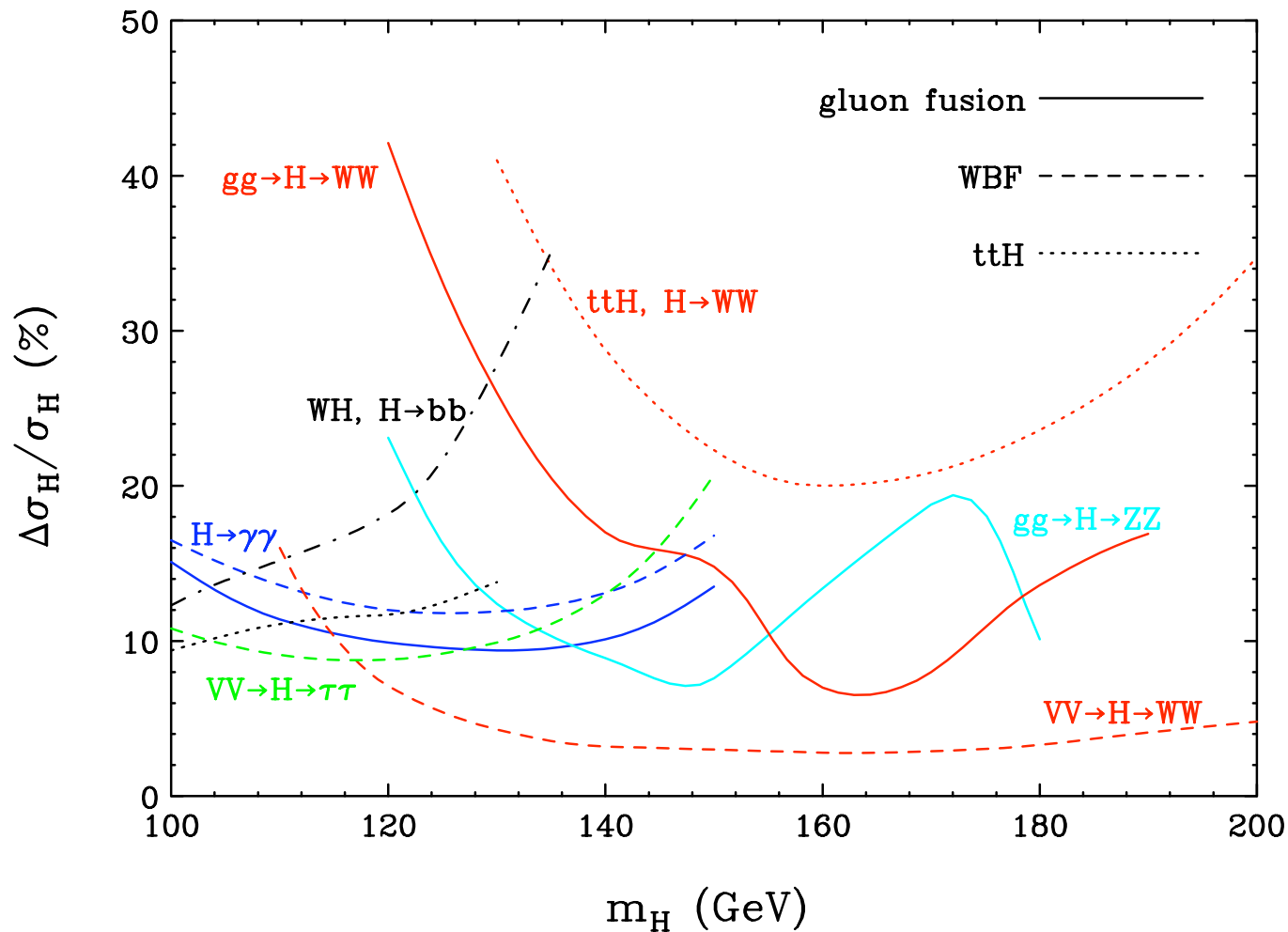
Higgs couplings determine **decay branching ratios**



HDECAY

→ Higgs couplings determine **rates in each channel**.

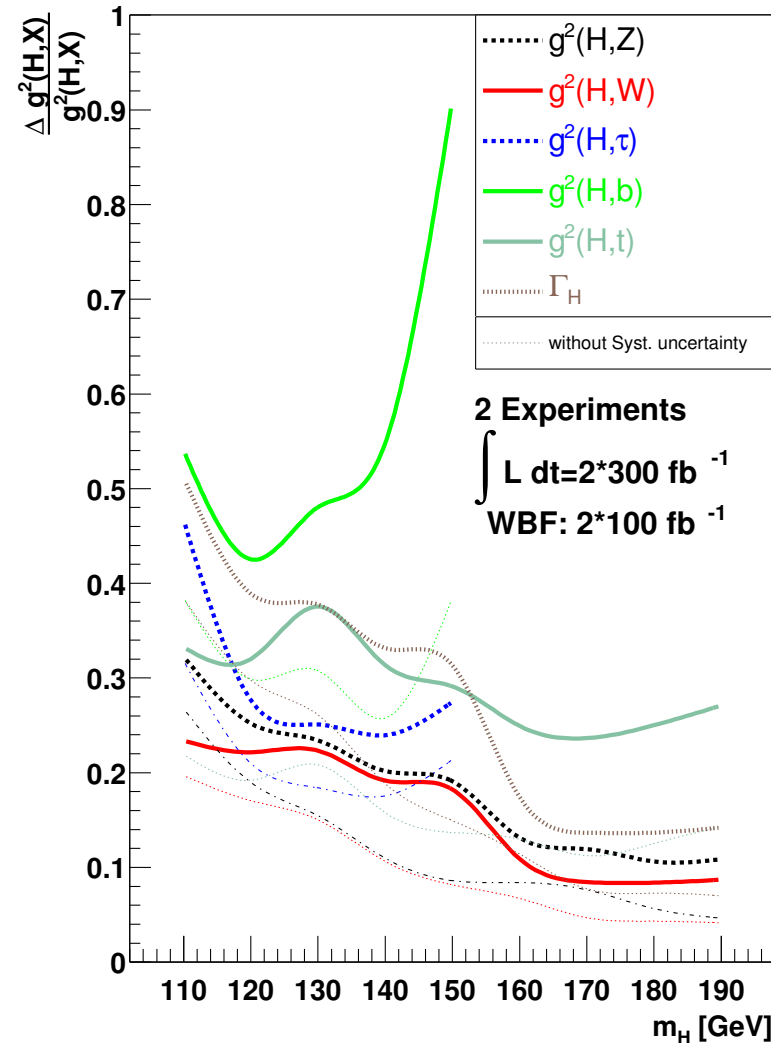
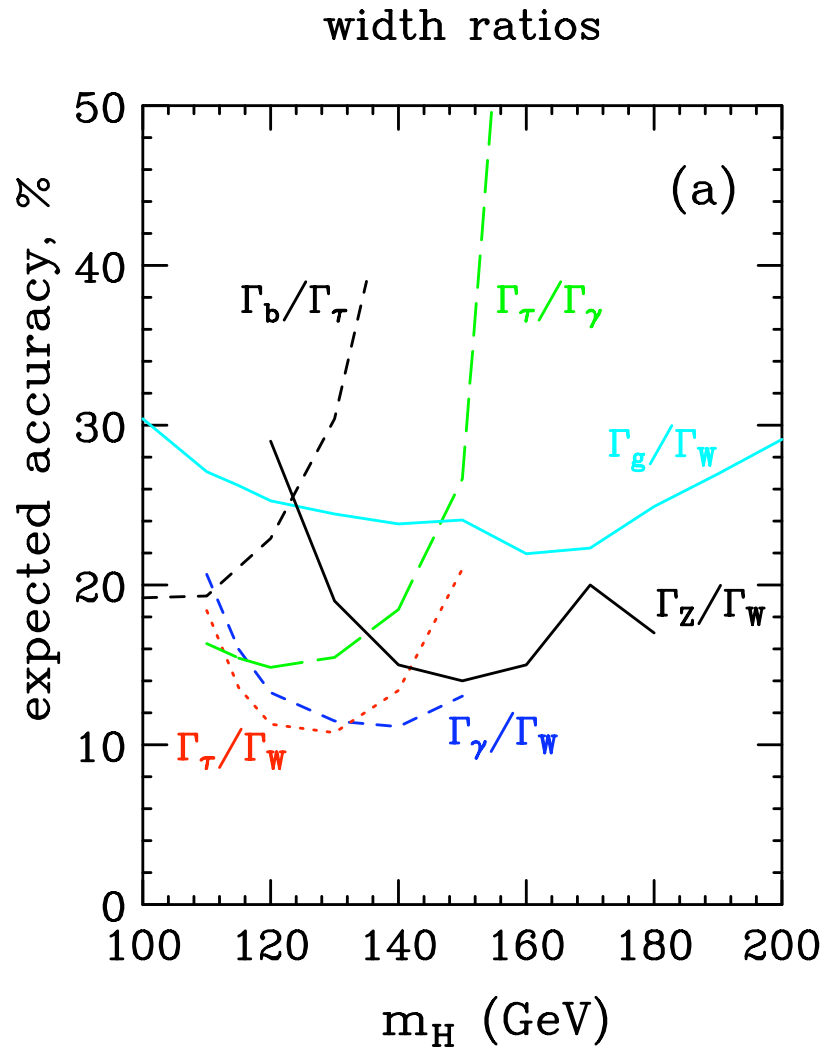
Test of the SM Higgs couplings: measure Higgs rates at LHC



LHC, 200 fb^{-1} (except 300 fb^{-1} for $ttH, H \rightarrow bb, WH, H \rightarrow bb$). Zeppenfeld, hep-ph/0203123

Ratios of rates give ratios of partial widths.

Add theory assumption: $hWW, hZZ \leq \text{SM} \rightarrow$ fit Higgs coups.

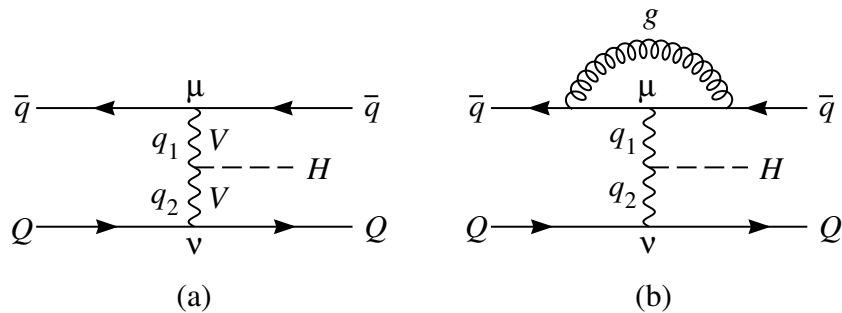


[L] 200 fb^{-1} (except 300 fb^{-1} for $ttH(\rightarrow bb)$, $WH(\rightarrow bb)$). Zeppenfeld, hep-ph/0203123

[R] Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld, hep-ph/0406323

Measure tensor structure of HVV coupling in VBF:

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$T^{\mu\nu} = a_1 g^{\mu\nu} + a_2 (q_1 \cdot q_2 g^{\mu\nu} - q_1^\nu q_2^\mu) + a_3 \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\mathcal{L}_I \sim HV_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

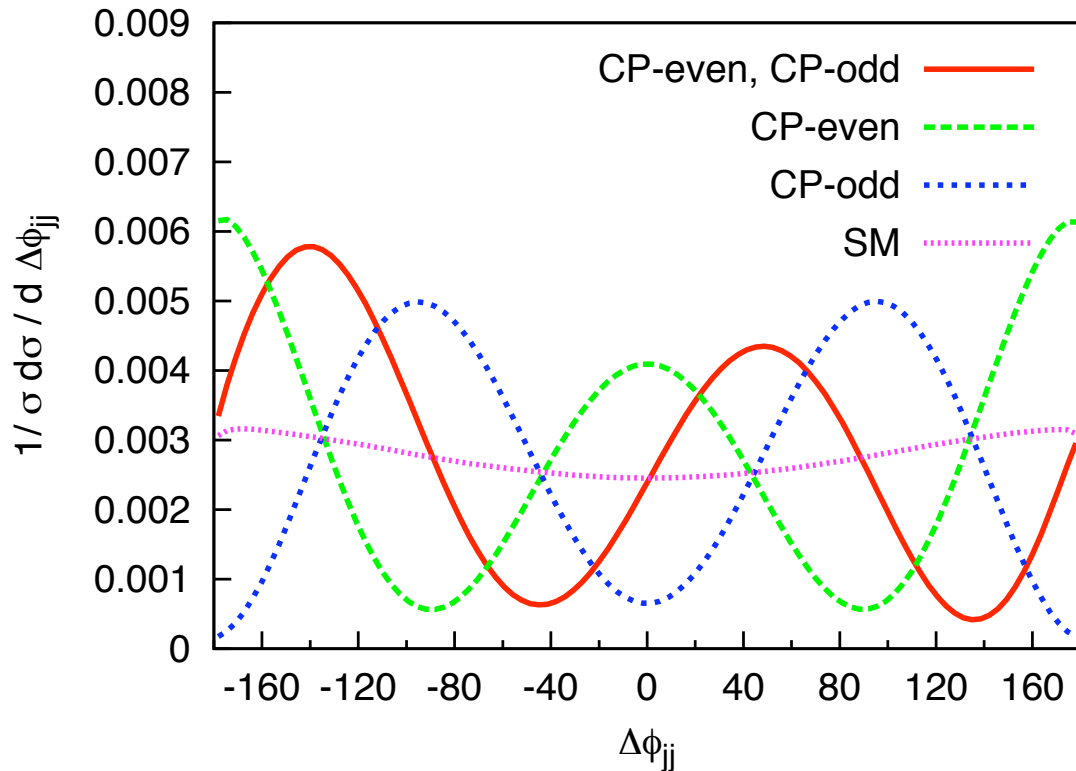
CP even $\mathcal{L}_{eff} \sim HV_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\mathcal{L}_{eff} \sim HV_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

HVV vertex structure gives different distributions in jj azimuthal angle $\Delta\phi$:



mixed CP case:
 $a_2 = a_3, a_1 = 0$

pure CP-even case:
 a_2 only

pure CP odd case:
 a_3 only

Figy, Hankele, Klämke, & Zeppenfeld, hep-ph/0609075

$HV^\mu V_\mu$ structure is “smoking gun” for Higgs mechanism EWSB.

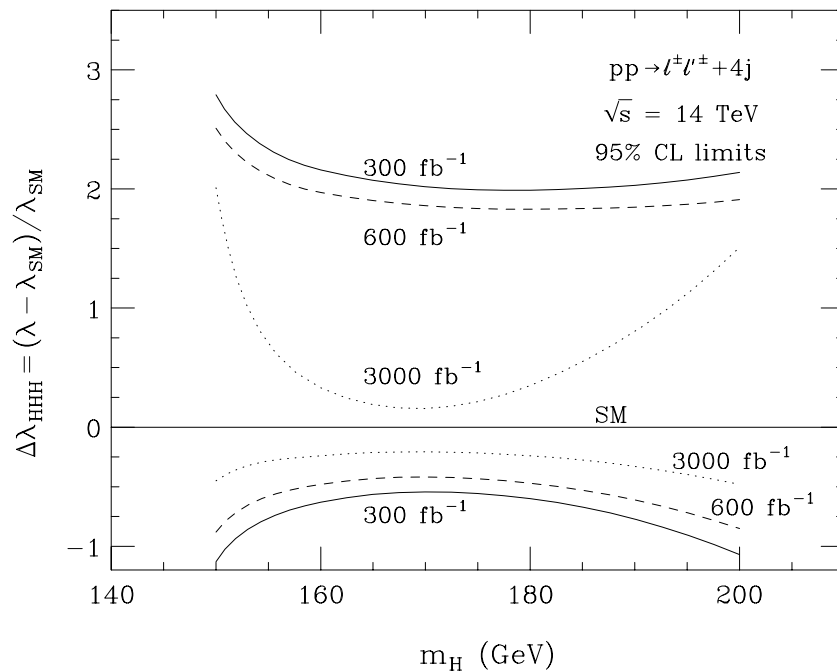
Check for CP violation and/or loop-induced $HV^{\mu\nu} V_{\mu\nu}$ structure.

Test structure of the Higgs potential $V = \mu^2 H^\dagger H + \lambda(H^\dagger H)^2$:

Measure the **triple-Higgs coupling**

$gg \rightarrow HH \rightarrow WWWW$ at LHC

- diagrams include $gg \rightarrow H^* \rightarrow HH$ via triple-Higgs coupling.



1σ : $+100\%$ w/ 300 fb^{-1}
 -30%

for M_H between $155 \sim 200 \text{ GeV}$

Baur, Plehn, Rainwater, hep-ph/0211224

Also $gg \rightarrow HH \rightarrow bb\gamma\gamma$ at lower M_H : somewhat worse sensitivity.

Baur, Plehn, Rainwater, hep-ph/0310056

What is the origin of mass?

LHC will be able to:

- discover a SM(-like) Higgs
- test key features of the Higgs mechanism of electroweak symmetry breaking and mass generation

But the Higgs sector of the Standard Model introduces another problem...

Why is gravity so much weaker
than the other forces?

Why is gravity so much weaker than the other forces?

This is really a question of energy scales.

Newton's constant: $G_N = 1/M_{\text{Planck}}^2$

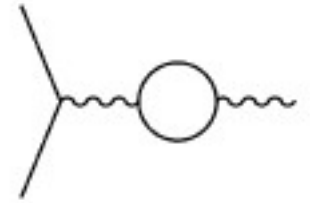
Dimensions of $[\text{mass}]^{-2}$: nonrenormalizable theory

Analogous to 4-Fermi theory: $f\bar{f} \rightarrow f\bar{f}$ via contact interaction

Fermi's constant: $G_F = g^2/4\sqrt{2}M_W^2 = 1/\sqrt{2}v^2$

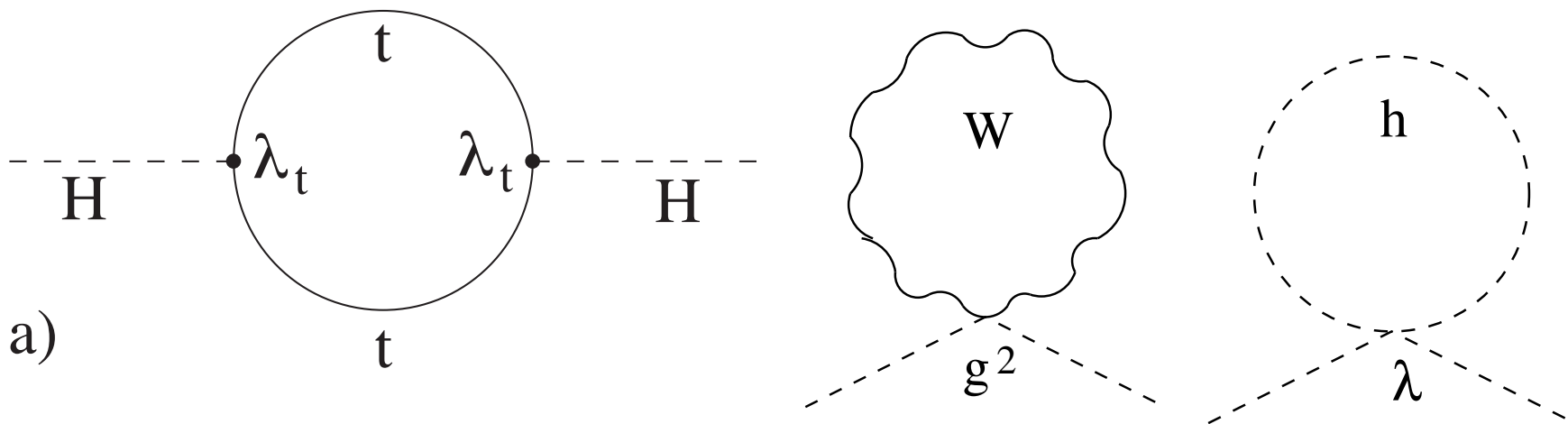
Why is the weak scale so much lower than the Planck scale?

Gauge couplings “run” because of vacuum polarization:



$$\alpha_s(Q) = \alpha_s(\mu) / [1 + (b/2\pi)\alpha_s(\mu) \log(Q/\mu)]$$

Mass term in Higgs potential $V = \mu^2 H^\dagger H + \lambda(H^\dagger H)^2$ also runs:



But this running is quadratic, not logarithmic: $\mu^2 = \mu_0^2 + \Delta\mu^2$ with

$$\Delta\mu^2 = -\frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{9}{64\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \dots$$

Scalar mass term is the only parameter that runs quadratically.

$$\Delta\mu^2 = -\frac{3}{8\pi^2}y_t^2\Lambda^2 + \frac{9}{64\pi^2}g^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots$$

“Natural” prediction: $\mu^2 \sim \mu_0^2 \sim \Delta\mu^2$

Setting the cutoff $\Lambda \sim M_{\text{Planck}}$, this gives a prediction for μ^2 1,000,000,000,000,000,000,000,000,000,000 times too large.

The second-worst prediction in all of physics? (after the cosmological constant :)

The vast difference in scale between M_{Planck} and M_W is the **Hierarchy Problem**.

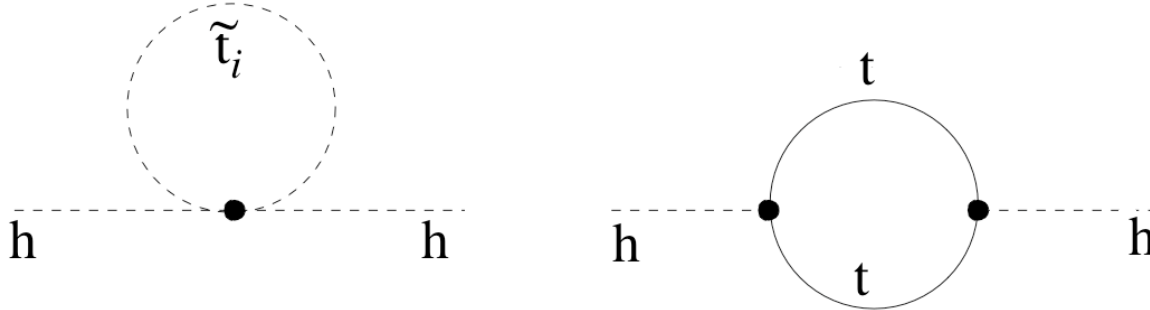
Solution(s):

- Have μ_0^2 cancel $\Delta\mu^2$ to 30 decimal places? (Extreme fine tuning...)
- Lower the SM cutoff Λ to \sim TeV scale; introduce New Physics above this scale that stabilizes the hierarchy.

Two main classes of solutions to the hierarchy problem:

1) Supersymmetry

SUSY relates μ^2 to a fermion mass, which only runs logarithmically. Guarantees cancellation between SM loop diagrams and SUSY loop diagrams.



2) Composite Higgs

Higgs is some kind of bound state (“meson”) of fundamental fermions, held together by a new force that gets strong at the TeV scale. Above a TeV there are no fundamental scalars, so no hierarchy problem.

[Includes extra-dimension / RS models by AdS/CFT duality.]

Generic models of New Physics tend to be fairly tightly constrained by [electroweak precision data](#).

New particles contribute to measured SM processes e.g. $f\bar{f} \rightarrow f\bar{f}$

Can parameterize their effect in terms of [dimension-6 operators](#)

$$\mathcal{L} = \frac{1}{[\Lambda_{\text{eff}}^{\text{NP}}]^2} \mathcal{O}_{\text{dim6}} + \dots$$

suppressed by an [effective cutoff scale](#) $[\Lambda_{\text{eff}}^{\text{NP}}]^2$.

EW precision data constrain $\Lambda_{\text{eff}}^{\text{NP}}$ to be above 1.3 ~ 17 TeV depending on the operator.

Operator(s)	shift	M_W	Z-pole	DIS	Q_W	$e^+e^- \rightarrow f\bar{f}$ (LEP2)	$e^+e^- \rightarrow W^+W^-$
O_{WB}	α, M_Z		✓	✓	✓	✓	✓
O_h	M_Z						
O_{ll}^t	G_F			✓		✓	
O_{ll}^s, O_{le}				✓		✓	
O_{ee}						✓	
$O_{lq}^s, O_{lq}^t, O_{lu}, O_{ld}$				✓	✓	✓	
O_{eq}, O_{eu}, O_{ed}					✓	✓	
O_{hl}^t	G_F		✓	✓	✓	✓	✓
O_{hl}^s, O_{he}			✓	✓	✓	✓	✓
$O_{hu}, O_{hd}, O_{hq}^s, O_{hq}^t$			✓	✓	✓	✓	
O_W							✓

Han & Skiba, [hep-ph/0412166](#)

EW precision constraints push $\Lambda_{\text{eff}}^{\text{NP}}$ well above “natural” TeV scale, especially for strongly coupled NP.

- This is the source of difficulties with, e.g., Technicolor.

Called the “**little hierarchy**” problem: EW precision typically gives tight constraints on NP models.

But SUSY is not tightly constrained...

Biggest corrections come from tree-level exchange. Superpartners odd under **R-parity**: only exchanged in loops!

$$1/[\Lambda_{\text{eff}}^{\text{NP}}]^2 \rightarrow 1/16\pi^2[\Lambda^{\text{NP}}]^2 \quad \longrightarrow \quad \Lambda^{\text{NP}} \sim 0.1 \Lambda_{\text{eff}}^{\text{NP}}$$

If the model has a parity like this, EW precision constraints are no longer an issue.

- Little Higgs with T-parity
- Universal Extra Dimensions (KK-parity)

If little hierarchy bothers you, then expect a “TeV-scale parity”.

- Pair production of new particles
- Cascade decays to a stable “LTP” ← !

What is the dark matter?

What is the dark matter?

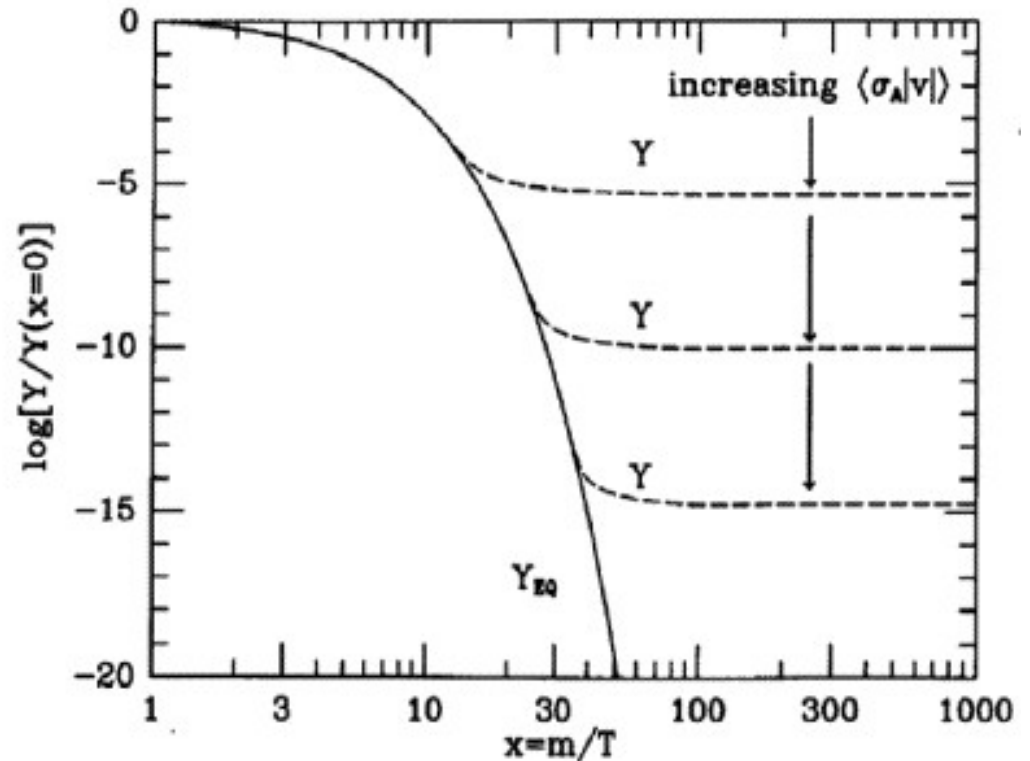
Need a stable neutral particle.

Thermal production in the early universe followed by freeze-out:

Typical annihilation cross section: $\langle\sigma v\rangle \sim g^4/16\pi M^2$

Observed DM abundance:
need $\sigma v \sim 1$ pb

If $g \sim$ weak interactions,
get $M \sim 100$ GeV.



Kolb & Turner

A WIMP is a natural dark matter candidate!

TeV-scale parity makes it (more or less) automatic.

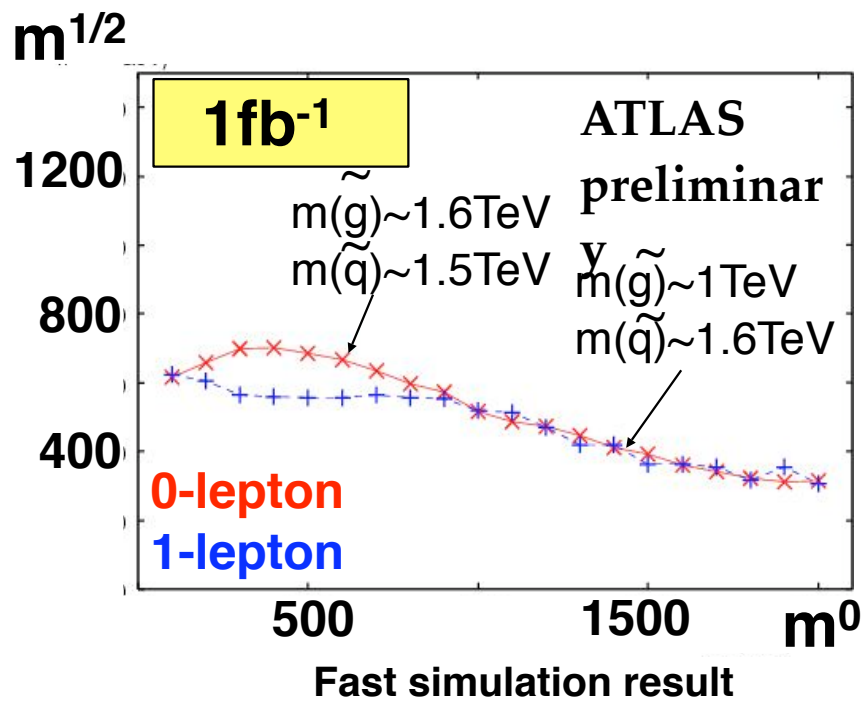
...but DM could still be something completely unrelated, like an axion.

Lightning survey of
Beyond-the-Standard-Model
LHC phenomenology

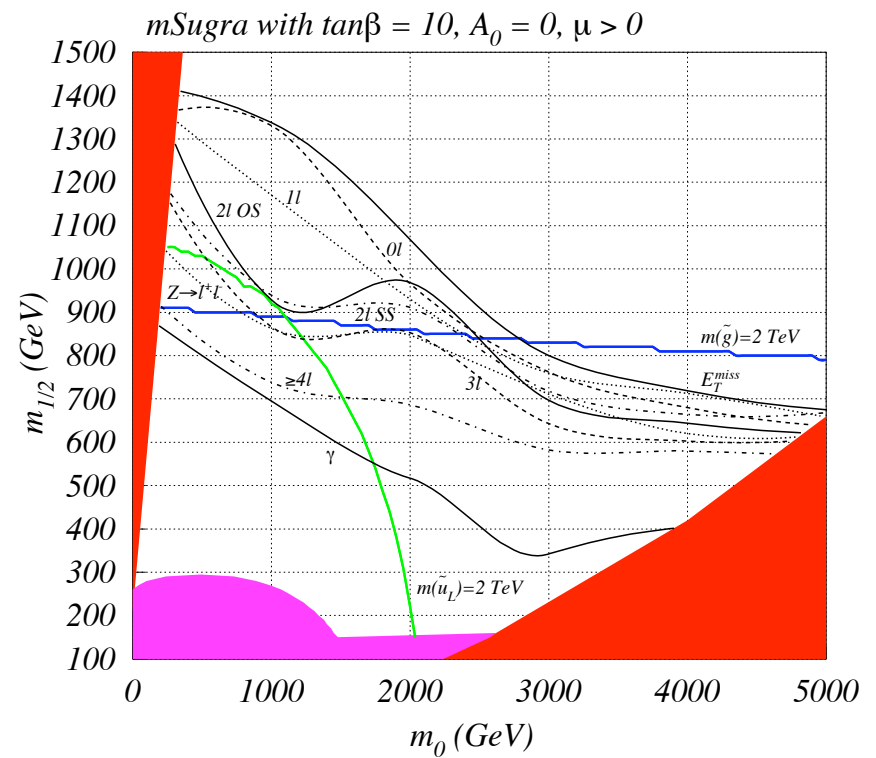
Supersymmetry

Generic channel is jets + missing energy from squark and gluino production.

LHC, 1 fb^{-1}

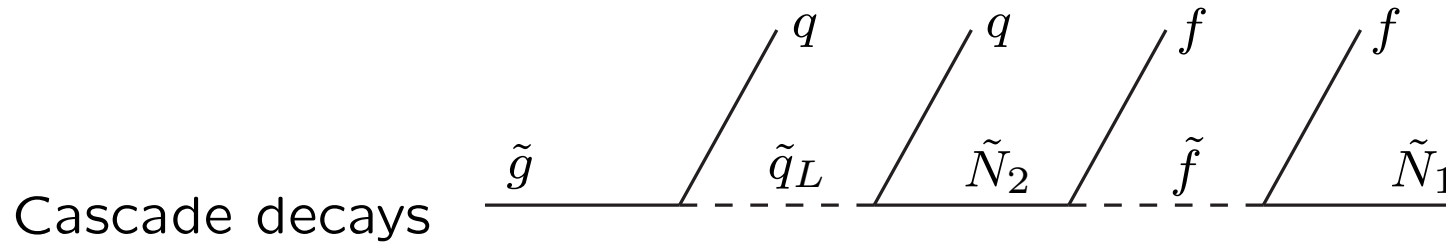


100 fb^{-1}

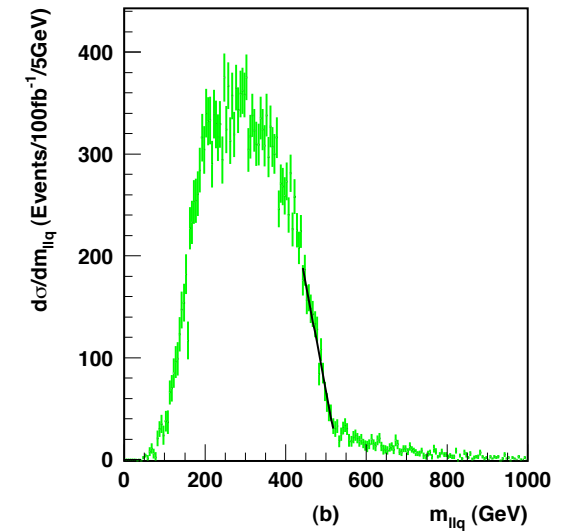
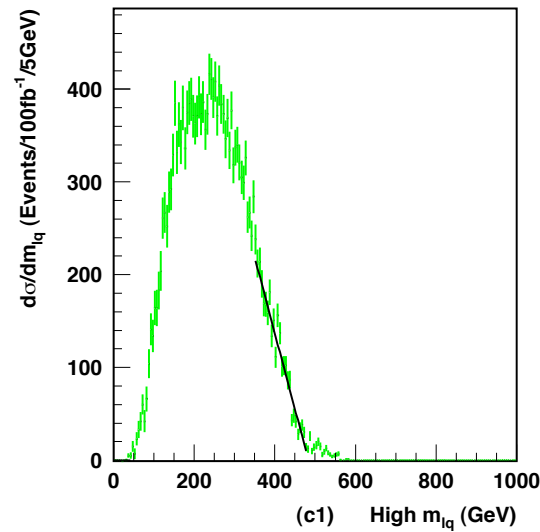
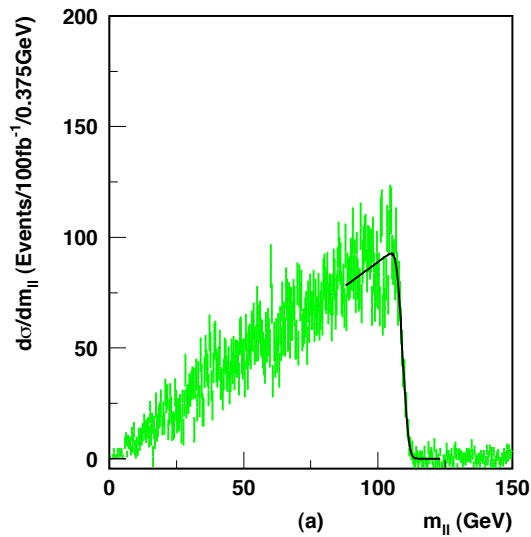


Supersymmetry: key measurements

1) Mass spectrum



Use **kinematic edges** to get mass differences in decay chain



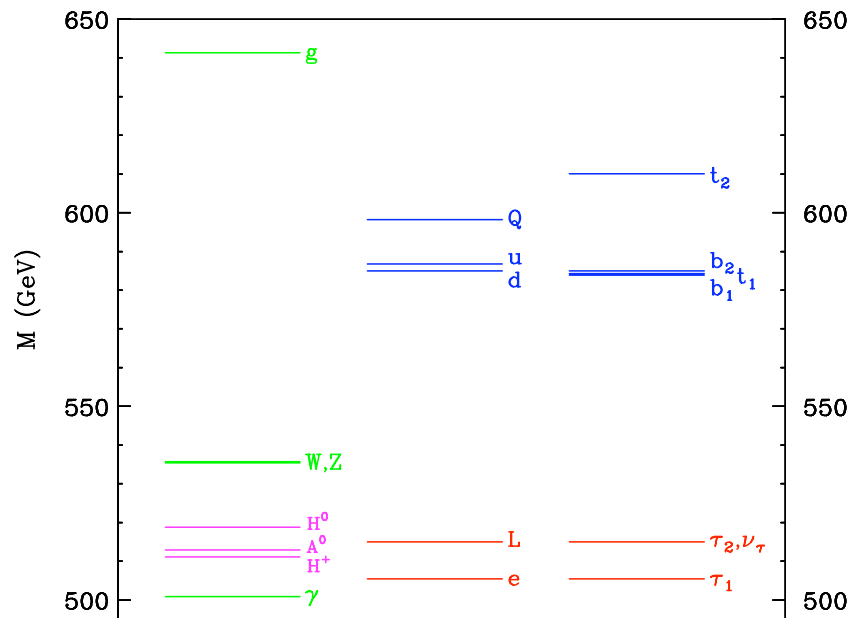
Supersymmetry: key measurements

2) Spin of superpartners

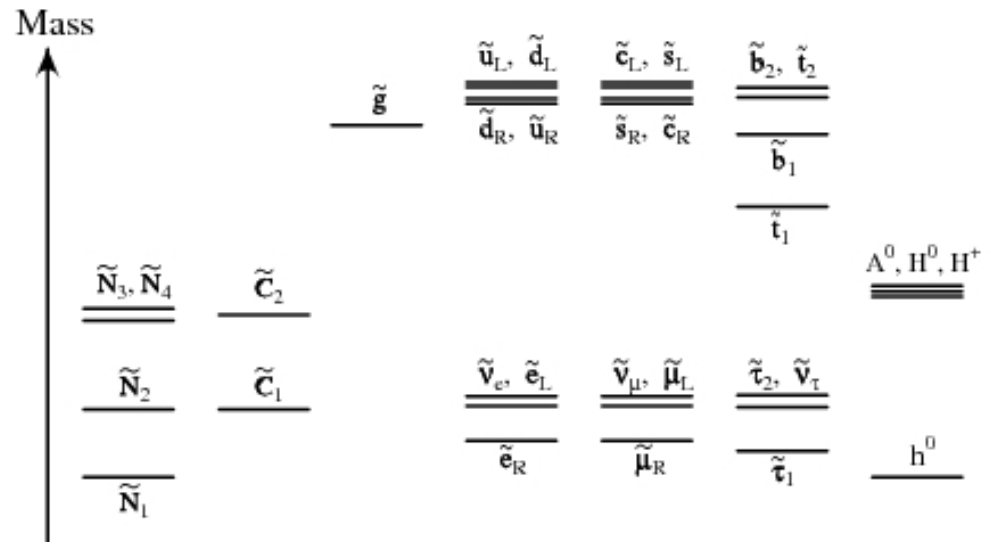
Universal Extra Dimensions can mimic SUSY

Stable “LKP” → jets + missing energy signatures.

UED, $L = (500 \text{ GeV})^{-1}$



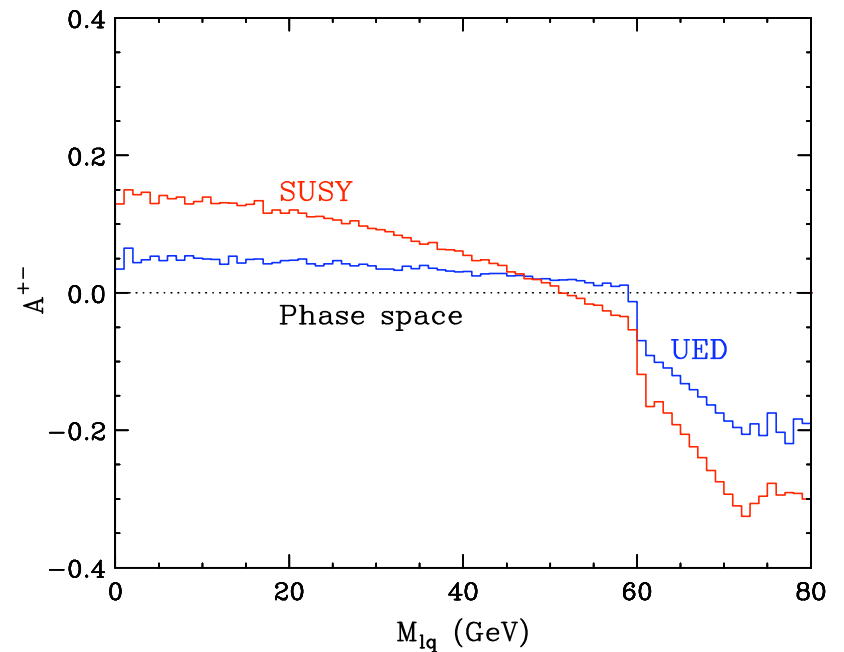
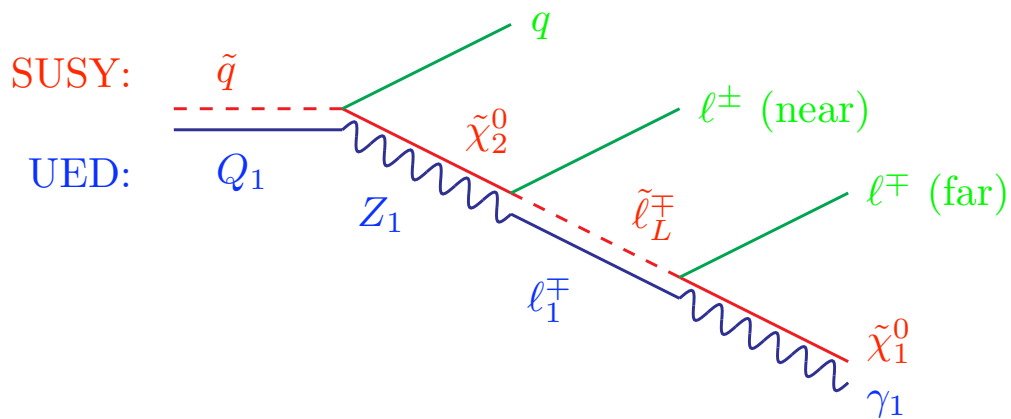
MSUGRA



Supersymmetry: key measurements

2) Spin of superpartners

Need to be clever to find distinguishing observables!
Kinematic distributions, etc.

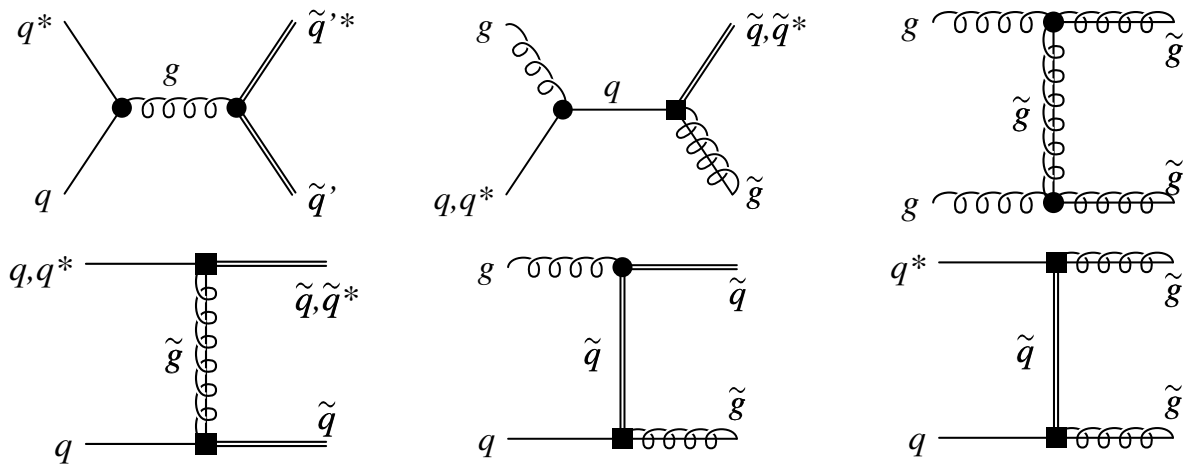


Datta, Kong & Matchev, hep-ph/0509246

Supersymmetry: key measurements

3) Coupling relations

gauge couplings \leftrightarrow gaugino Yukawa couplings



Freitas & Skands, hep-ph/0606121

Requires ILC input for squark decay BRs.

Supersymmetry: variations

MSSM – minimal model

Want to measure mass spectrum

→ SUSY breaking mechanism!

NMSSM – extra Higgs singlet & neutralino

Can't just fit to MSSM assumptions

Supersymmetric Fat Higgs model – heavier Higgs spectrum

Compositeness at high scale

Higgs phenomenology very different than MSSM

Composite Higgs

Venerable example: [Technicolor](#)

No Higgs per se; Goldstones are composites (“pions”)

Strongly coupled: can't calculate reliably

Calculate by analogy with QCD: too large effect on EW precision observables

Hard to make top quark heavy enough

New understanding: [AdS/CFT correspondence](#)

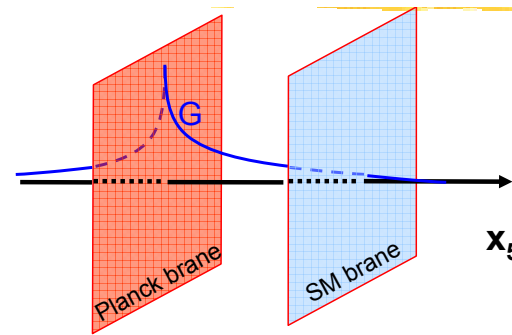
Strongly coupled theories are [dual](#) to warped extra dimensional theories, like Randall-Sundrum model

Warped 5-dim theories are calculable!

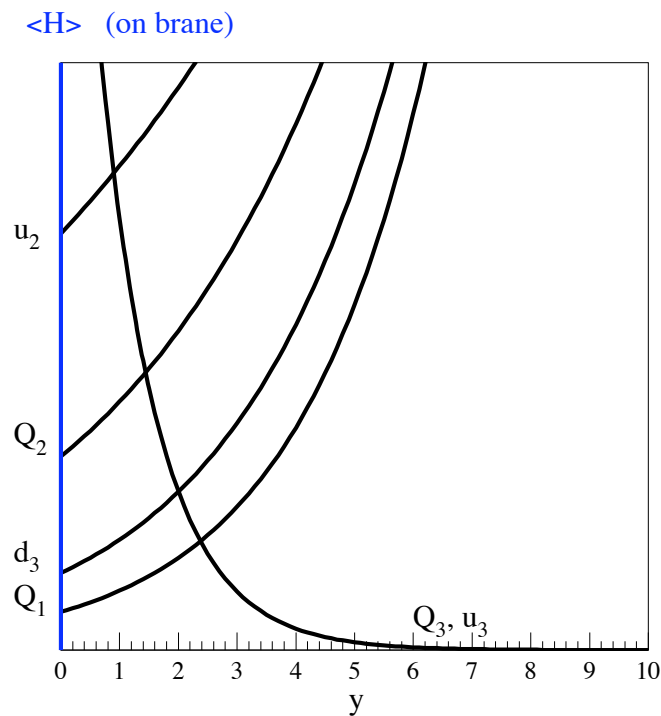
Composite states \leftrightarrow states near IR brane

Composite Higgs: Randall-Sundrum model

Has a physical Higgs state
Higgs lives on IR brane
Higgs is composite

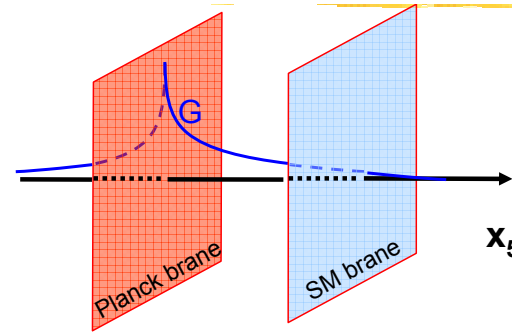


5-dim fermion wavefunction overlaps give natural explanation for exponential hierarchy of fermion masses



Composite Higgs: Randall-Sundrum model

Has a physical Higgs state
Higgs lives on IR brane
Higgs is composite



Z' , KK gluon

- Decays preferentially to $t\bar{t}$: TeV resonances in top pairs!
- Enhanced coupling to right-handed top

t' , other KK quarks

- Single production via qW , qZ fusion
Cross section larger than pair production for heavy masses
- Decays back to qW , qZ

Composite Higgs: Higgsless model

Minimal effective theory, supposed to be dual to technicolor

New W' , Z' gauge bosons \sim TeV:

- KK excitations from extra dimension

- Techni-rho type composite states

New states couple more strongly to top than to lighter fermions:

- Top lives near the IR brane

- Top is mostly-composite mixture

Composite Higgs: Little hierarchy

EW precision forces compositeness scale relatively high:
Have to fine tune a little to get Higgs light enough

Little Higgs models: use symmetries to make the Higgs lighter

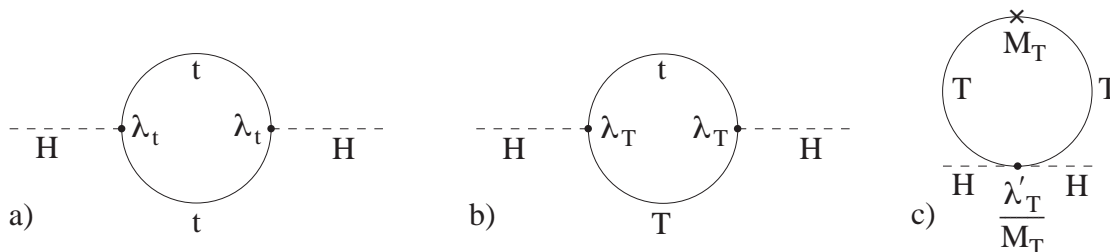
Eliminate one-loop Higgs mass corrections

$$\Delta\mu^2 \sim (g^2/16\pi^2)^2 \Lambda^2 \text{ instead of } (g^2/16\pi^2)\Lambda^2$$

Push compositeness scale up to 10 TeV without finetuning

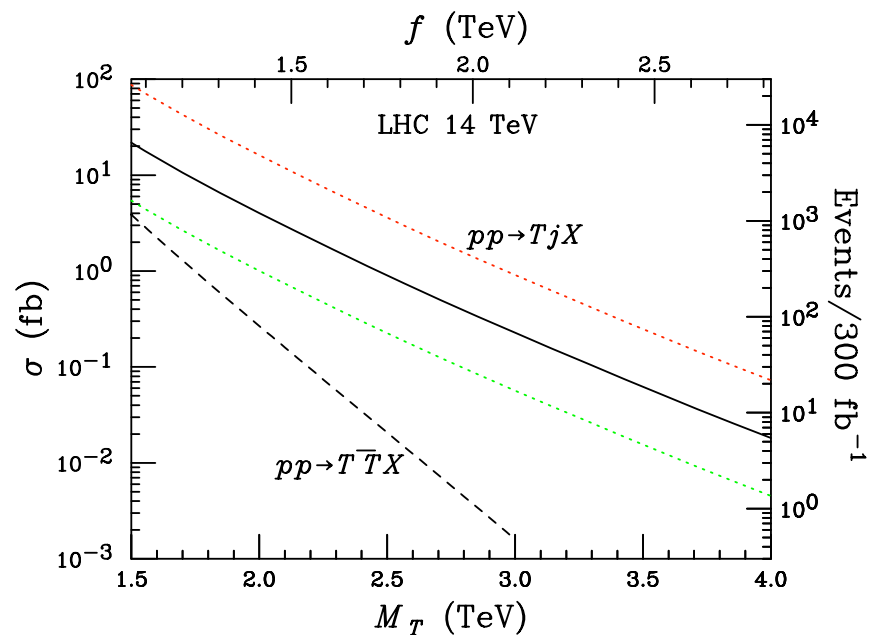
Need new particles at 1 TeV to cancel one-loop μ^2 corrections

Top partner T :



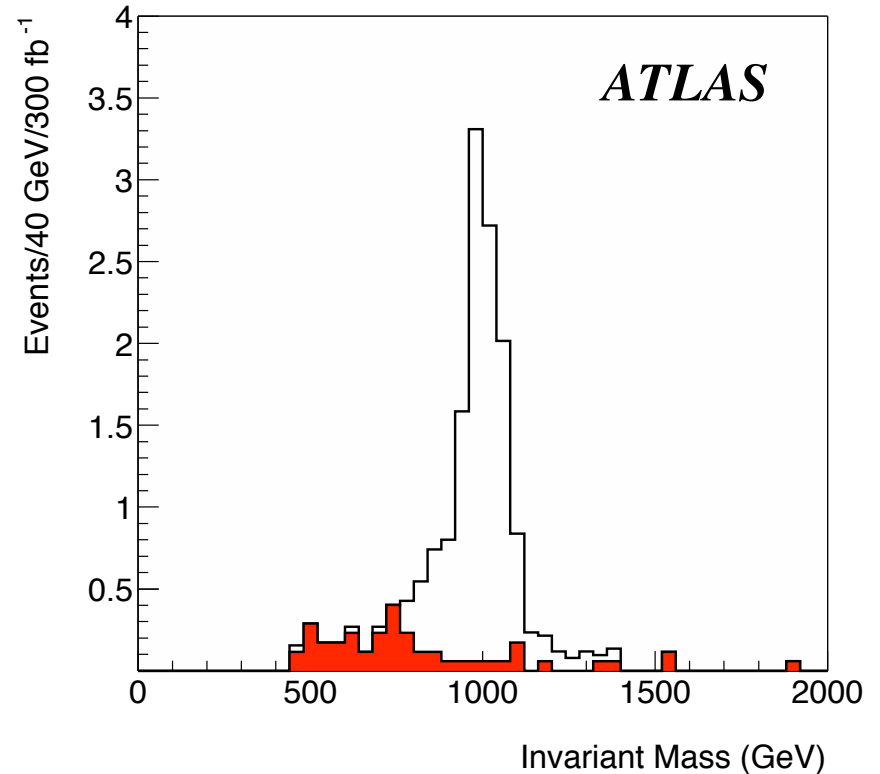
Composite Higgs: Little Higgs

Top partner T : Production



Han, McElrath, H.L. & Wang, hep-ph/0301040

Decay to tZ



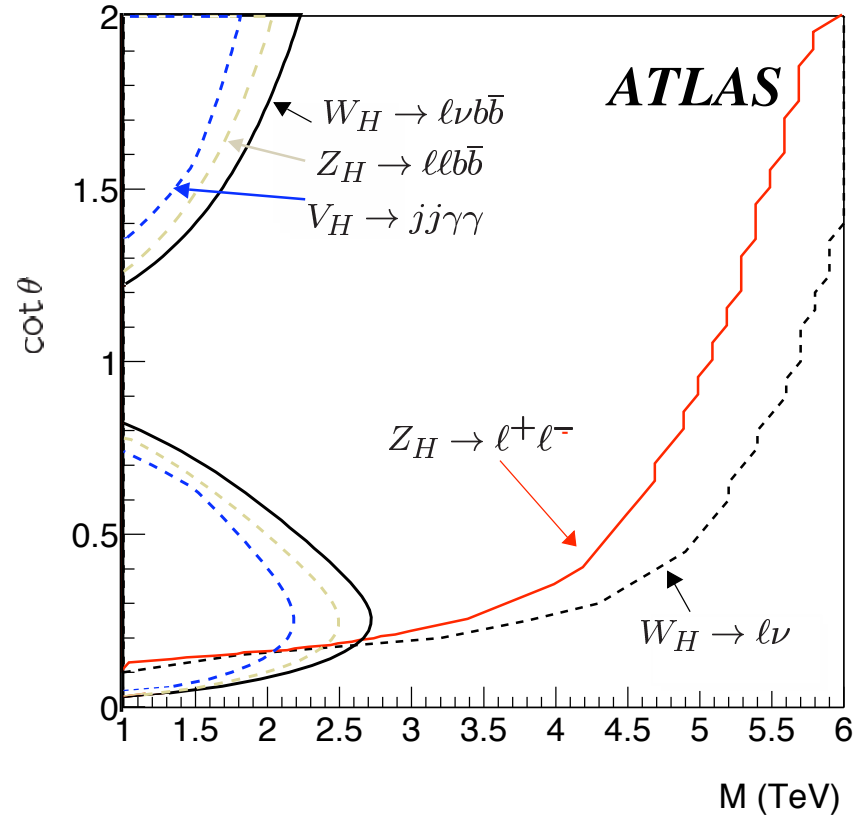
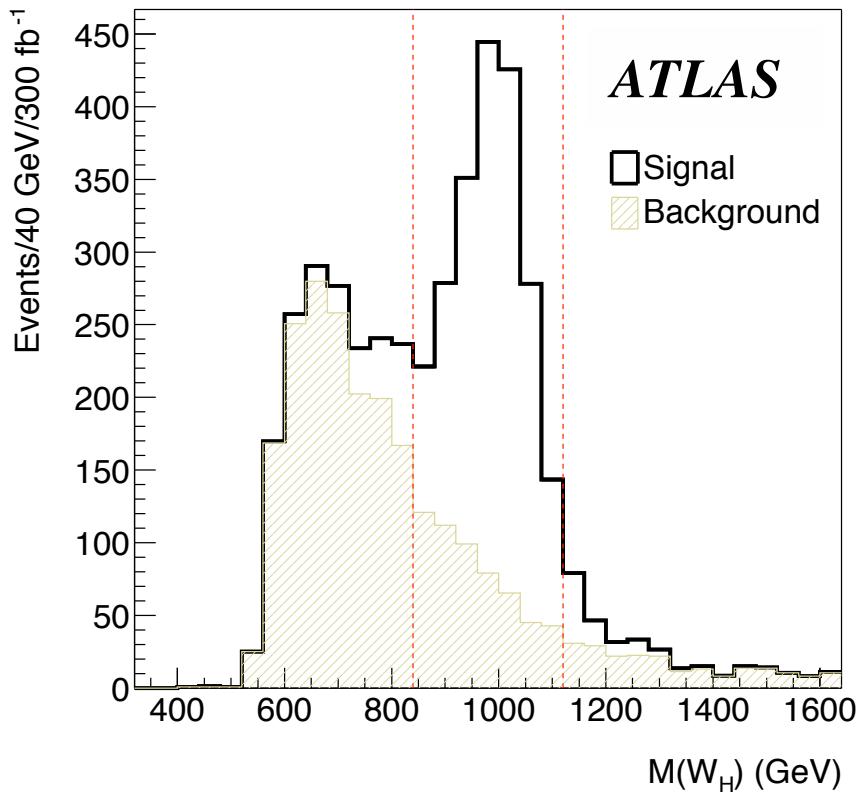
Azuelos et al, hep-ph/0402037

Characteristic signature for new singlet quark coupled to Higgs & top.

Composite Higgs: Little Higgs

Gauge partners W_H, Z_H (and sometimes B_H):

$W_H \rightarrow Wh$ characteristic signature 5σ discovery w/ 300 fb^{-1} :



Azuelos et al, hep-ph/0402037

$Z_H \rightarrow \ell^+\ell^-$, $W_H \rightarrow l\nu$ characteristic signatures for generic new gauge bosons.

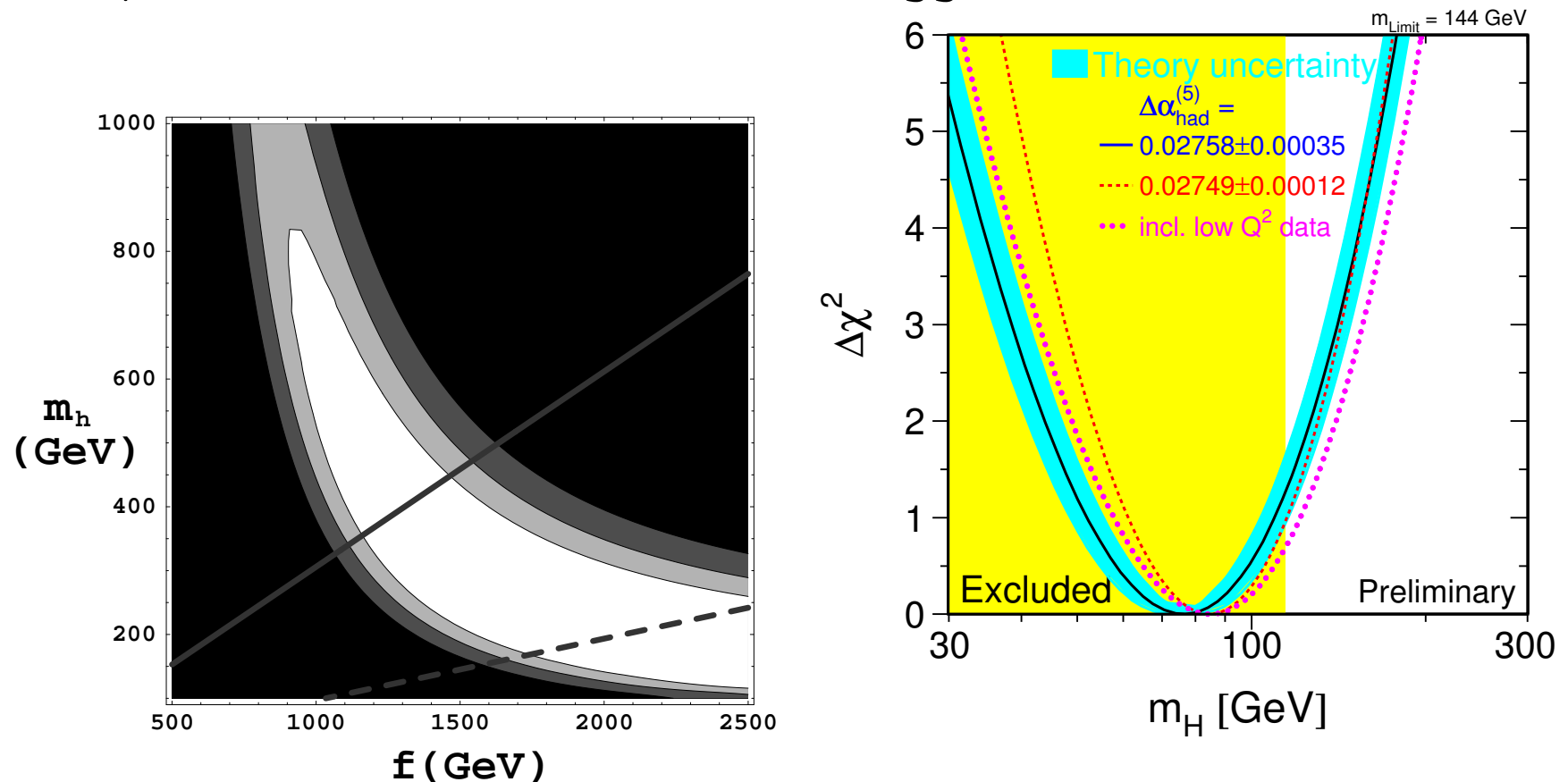
Composite Higgs: Little Higgs with T-parity

A kind of “deconstructed” UED: Looks more like SUSY!

Looser electroweak constraints \rightarrow lighter new particles

T-parity \rightarrow pair production, stable “LTP” (dark matter)

EW precision allows much heavier Higgs than SM



Hubisz, Meade, Noble, Perelstein, hep-ph/0506042

Outlook

LHC begins in less than a year.

Best chance to answer big questions of particle physics.

What is the origin of mass?

- Discover SM(-like) Higgs
- Measure key Higgs properties

Why is gravity so much weaker than the other forces?

- New Physics at TeV scale to stabilize the hierarchy
- Many many possibilities; wide range of common signatures

What is the dark matter?

- EW-scale WIMP gives right relic density
- New TeV-scale parity to make it stable
- End of decay chain: missing energy signal