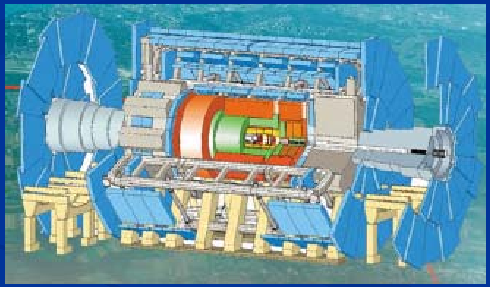
High p_T in 2015

(A Theorist's Perspective)

Tim M.P. Tait



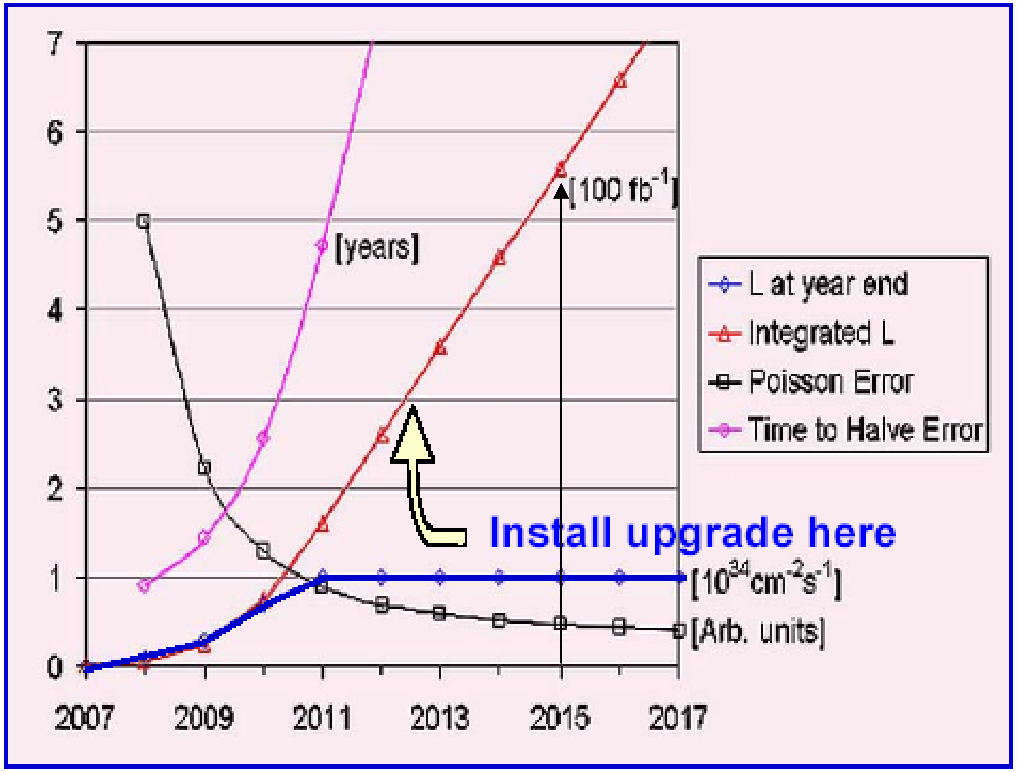
Argonne National Lab

Proton Driver Workshop
Fermilab
10/7/2004

Outline

- Introduction: Where will we be in 2015?
- Top Physics
- Higgs Physics
- Supersymmetry
- Extra Dimensions
- W's and Z's
- Summary

Luminosity?

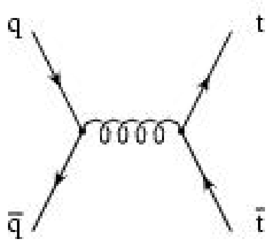


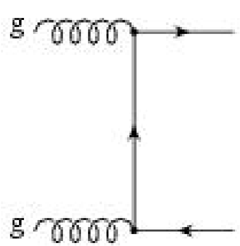
D. Green, HCP2004

- One low luminosity year: **~10 fb^{-1}**
- One high luminosity year: **~ 100 fb^{-1}**
- Start up? Calibration?
- So I will unfairly assume at 2015: six years of physics, half low and half high luminosities, a total of about **300 fb^{-1}**.
- With an upgrade, integrated luminosities of twice this large are claimed to be possible.
- Actual mileage will vary.

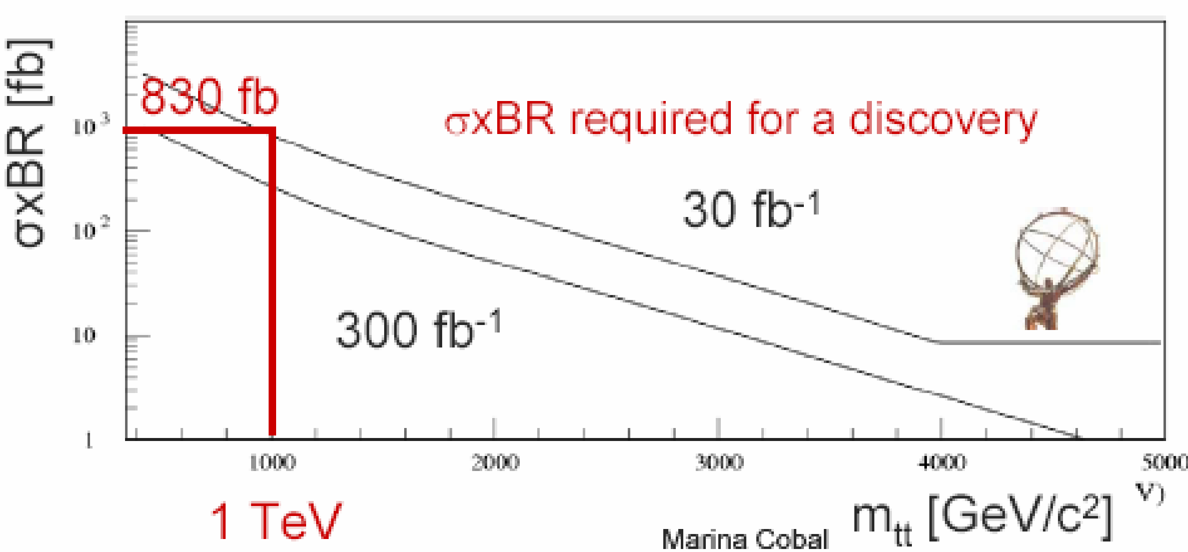
Top Physics

- QCD produces top in pairs
  - LHC will produce (many) millions of tops: top factory!
  - Also sensitive to new resonances, anomalous couplings, etc.
  - M_t could be measured down to ±1 GeV.
  - Large samples allow one to search for rare decays.





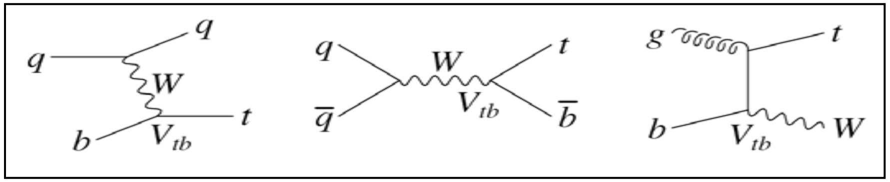
	Tevatron	LHC	
$t \to$	Run II	decay	production
$g\,q$	0.06%	1.6×10^{-3}	1×10^{-5}
$\gamma\,q$	0.28%	2.5×10^{-5}	3×10^{-6}
$Z\,q$	1.3%	1.6×10^{-4}	1×10^{-4}

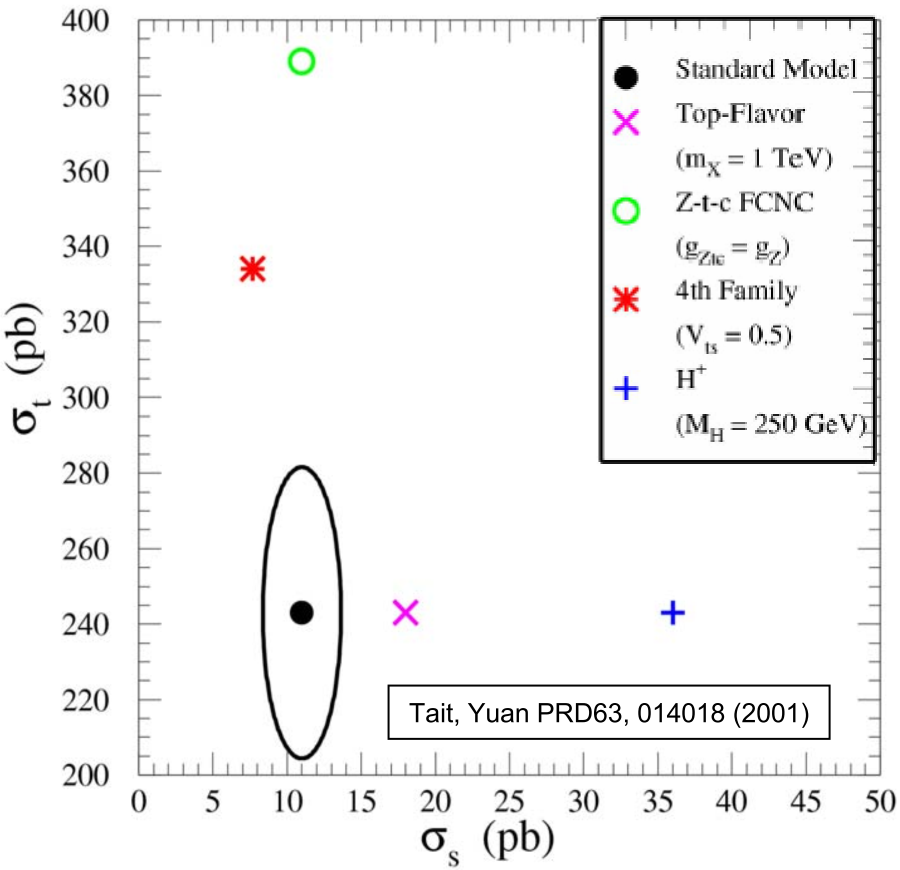


Marina Cobol HCP2004

Single Top

- Single top: the weak interactions!
  - Large m_t indicates top is a natural laboratory for EWSB
  - Single top is a direct measurement of the weak interactions
  - V_{tb} can be measured to **5%** (theory limited – Expt limits are **~2%**).
  - Three Production modes at hadron colliders
    - T-channel mode: largest at both Tevatron and LHC
    - S-channel mode: sizable at Tevatron, very difficult at LHC.
    - tW associated production: hopeless at Tevatron, can be done at LHC.
    - Each mode is sensitive to different kinds of physics beyond the SM.





Higgs @ LHC

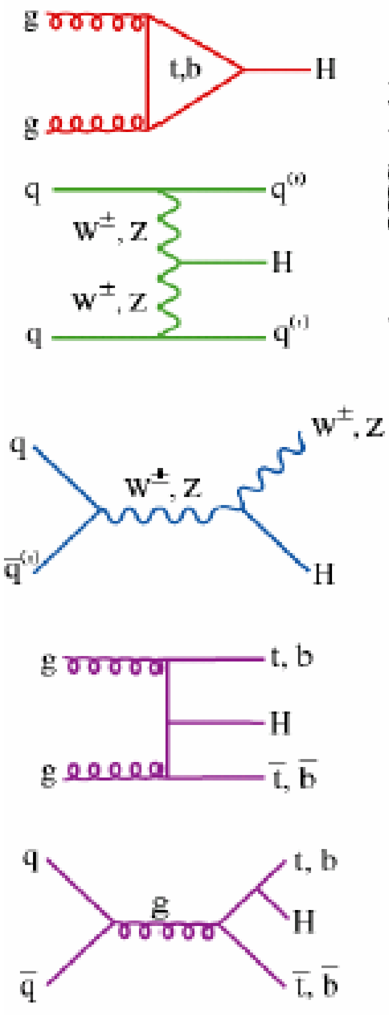
Gluon fusion: Huge!

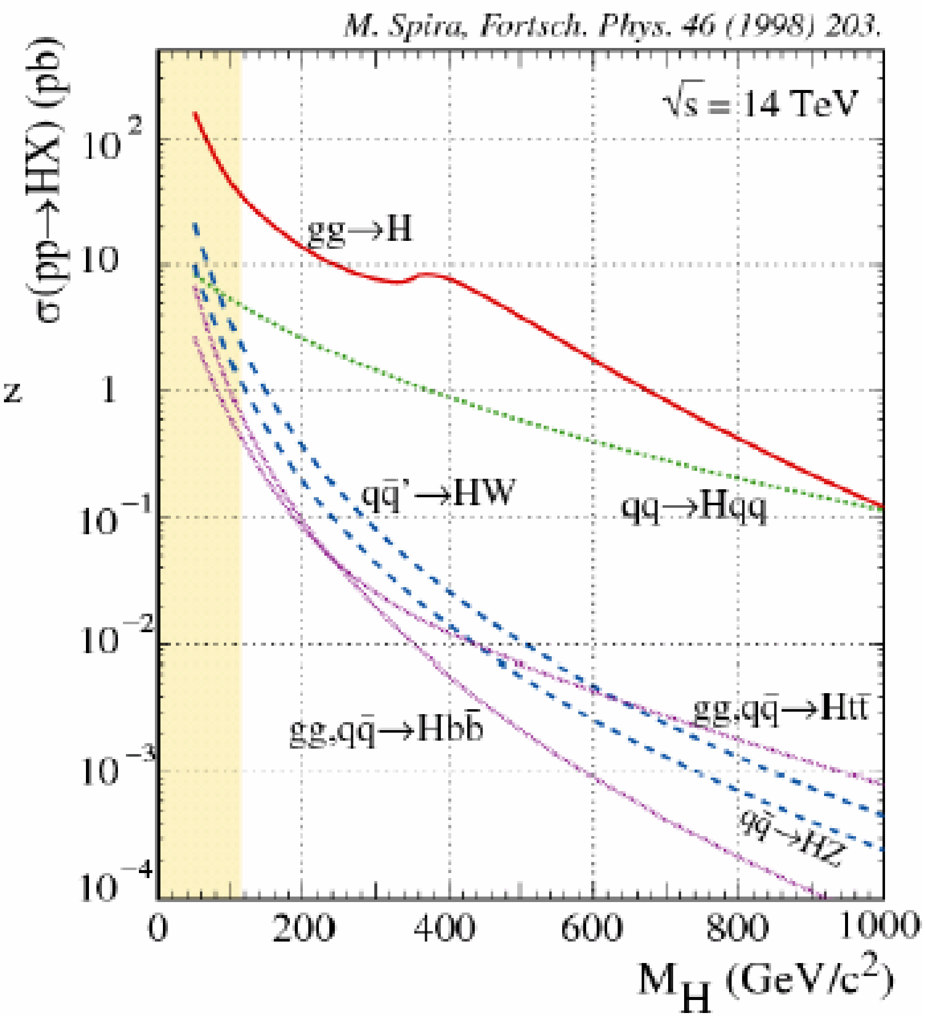
Weak boson fusion:
Testing W-W-H

WH production:
Hard at LHC,
Dominant at Tevatron

t t H: Testing y_t

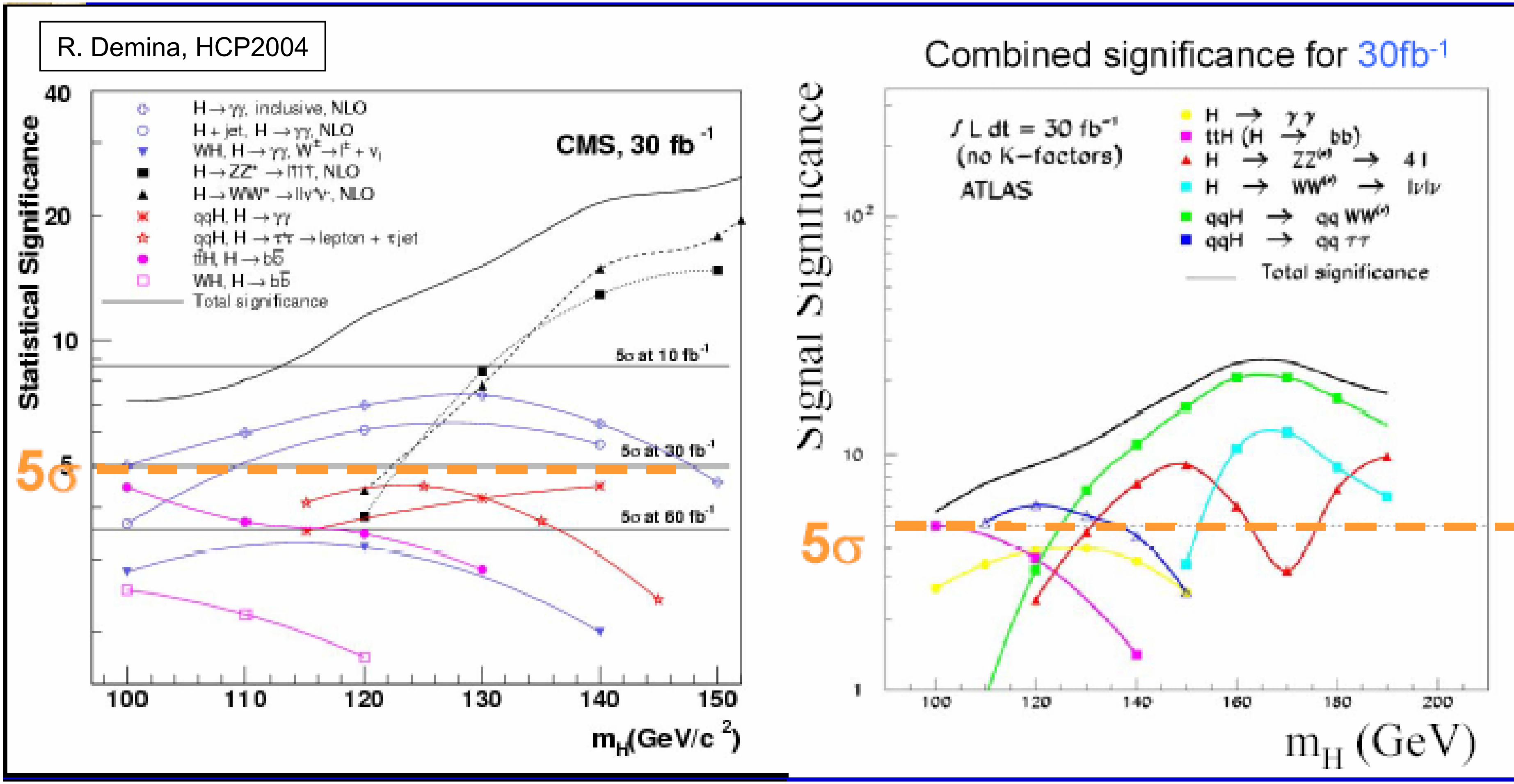
b b H: Beyond the SM





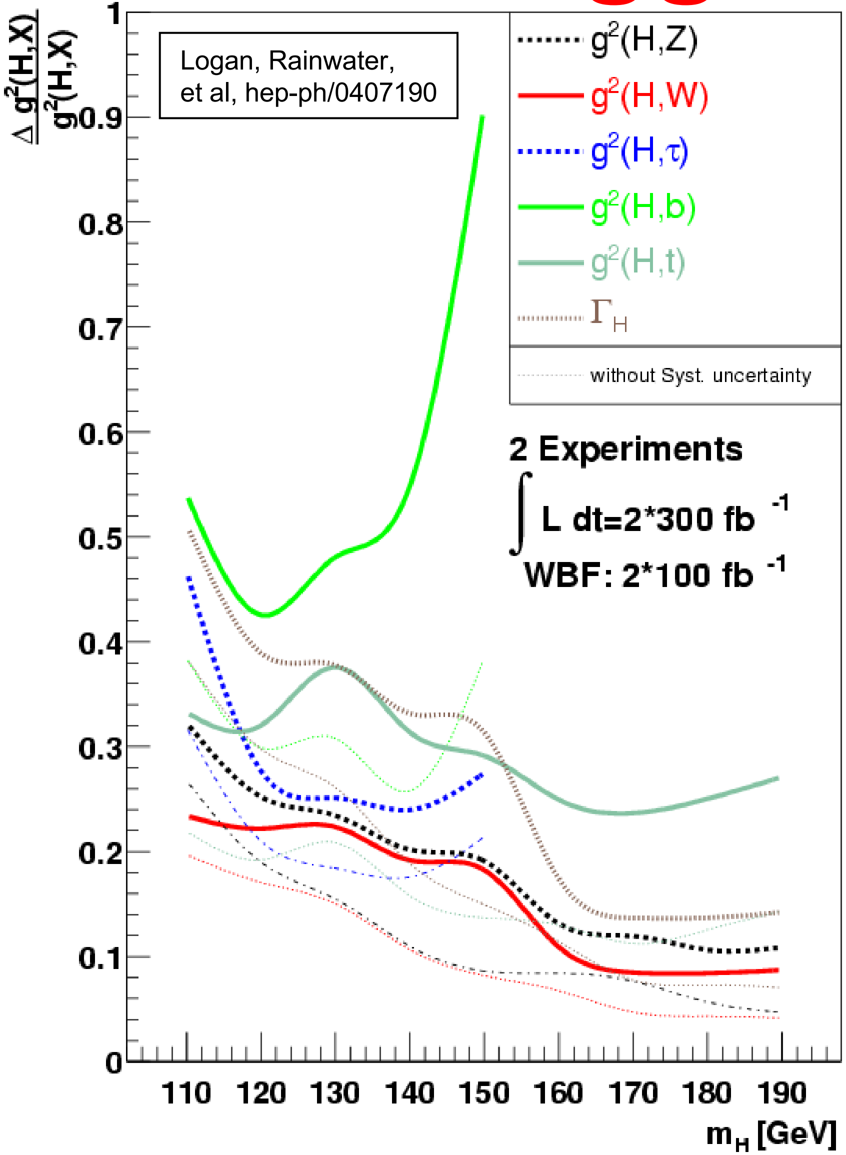
A variety of production and decay modes are available at the LHC.

Higgs Discovery



If the Higgs is there, and remotely SM-like (or MSSM-like), we should have observed it by 2015. Combination of production/decay modes are essential.

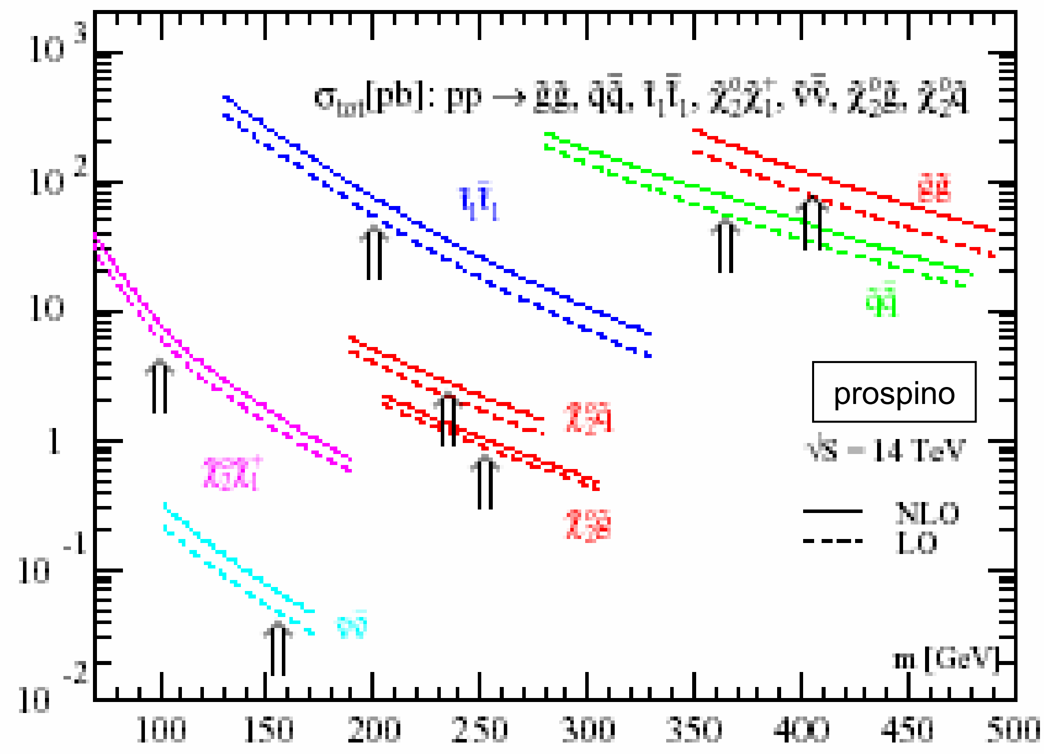
Higgs Couplings



- But **IS** it a Higgs?
- This question in detail requires determining spin, CP, and couplings.
- These are all challenging for LHC.
- A crucial EWSB question is the H-W-W and H-Z-Z couplings.
- LHC is hurt by the lack of a useful WH production mode. (WBF helps).
- Even at high luminosities, measurements rarely get better than **20%.**
- This plot assumes **no** systematic uncertainties.
- Large $\mathbf{m_H}$ is very difficult.

SUSY

- If nature is supersymmetric as a solution to the hierarchy problem, super-partners should have masses no larger than several 100 GeV.
- The minimal model has a Higgs mass less than about 135 GeV.
- LHC will copiously produce colored super-partners, which will cascade down to the Lightest Supersymmetric Particle.



SPS1a	LHC $\Delta^{(1)}$	$\Delta^{(2)}$	SoftSusy
m_0	4.0	4.6	98 ± 4.6
$m_{1/2}$	1.8	2.8	253 ± 2.9
$\tan\beta$	1.3	3.4	11.6± 3.4
A_0	31.8	50.5	14.7± 14.2

δexp → $\Delta^{(1)}$; δ(exp+theory) → $\Delta^{(2)}$

T. Plehn, hep-ph/0410063

mSUGRA SPS1a:

M_0 = 100 GeV
$M_{1/2}$ = 250 GeV
tan β = 10
A_0 = -100 GeV

Beyond mSUGRA?

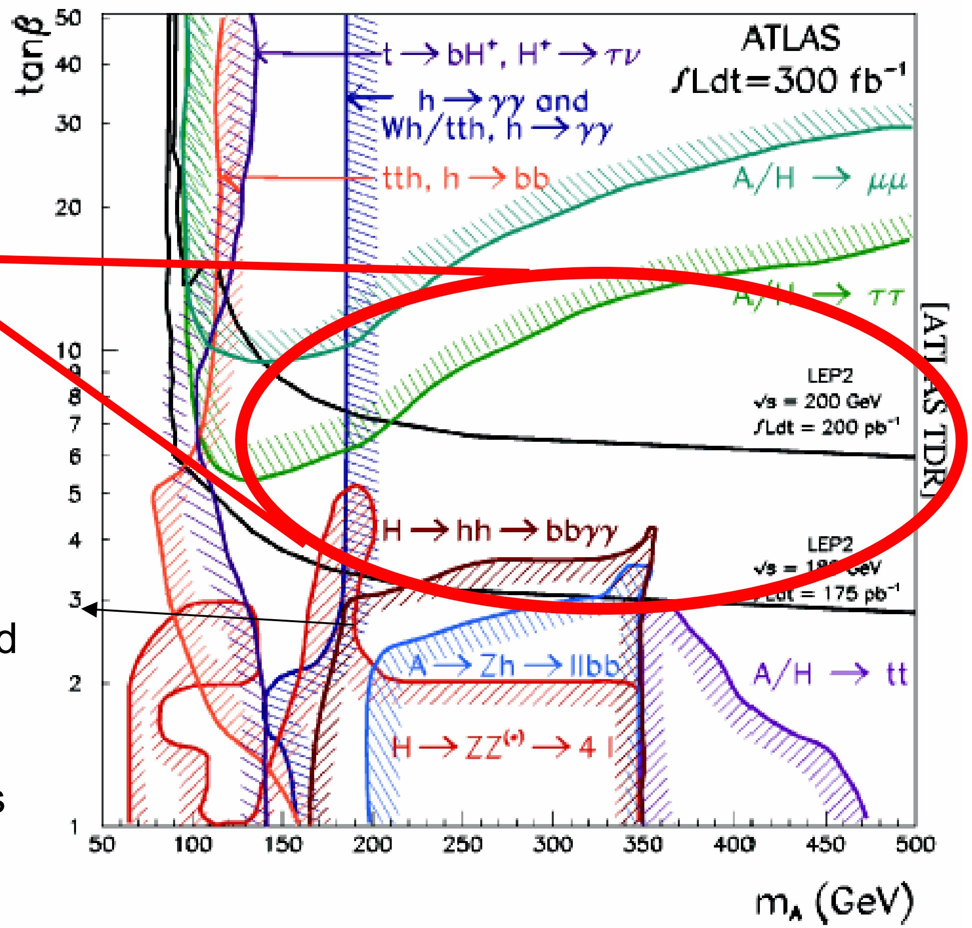
- Ultimately, we want to use the measurements of SUSY breaking parameters to infer the mechanism of SUSY breaking.
  - mSUGRA, GMSB, AMSB, $\tilde{g}$MSB, Scherk-Schwarz, …?
- In the study mentioned above, the LHC measured the gluino mass and light squark masses. It managed to extract the light neutralino masses from the decay kinematics.
- It did not observe the stops, or the heavier chargino or neutralinos.
- Generically the LHC has trouble with the Higgsinos, because they don't appear in cascade decays of light squarks.
- This leads to gaps in the spectrum, making it difficult to extract the underlying soft masses.
- If SUSY exists, we should have seen it by 2015 but may not yet perfectly understand its nature…

Sparticle	Expected precision (100 fb^{-1})
$\tilde{q}_L$	± 3%
$\tilde{\chi}^0_2$	± 6%
$\tilde{l}_R$	± 9%
$\tilde{\chi}^0_1$	± 12%

Dan Tovey, HCP2004

SUSY Higgses

- The MSSM is a two Higgs doublet model
  - 5 physical scalars: h^0, H^0, A^0, $H^{\pm}$
  - ATLAS can cover much of the mA-tan b plane with 300 fb-1.
  - However, there are regions where only one SM-like Higgs is seen.
  - LEP helps too.
  - Beyond the minimal model?
    - Fine-tuning arguments disfavor the minimal model.
    - Top mass is crucial.
    - We need to understand the reach for large m_h and non-standard signatures.
    - CP violation in the minimal model can lead to holes where no Higgs is seen.



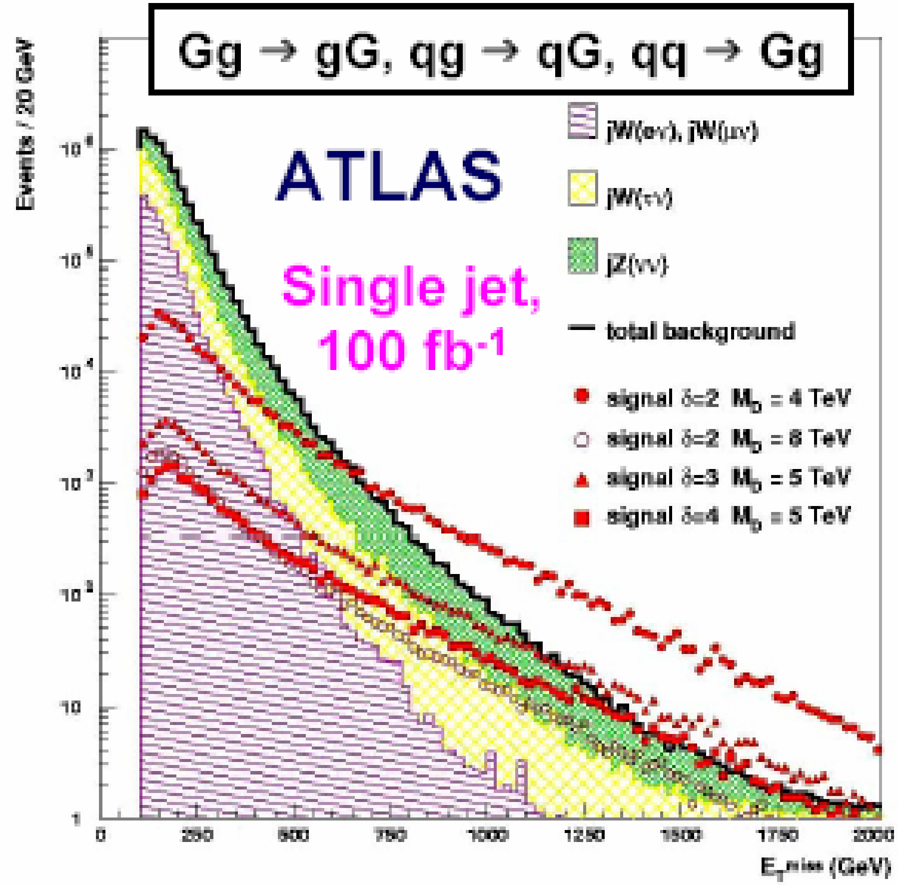
Carena, Mrenna, Pilaftsis, Wagner hep-ph/0211467

Extra Dimensions

- Extra dimensions come in many different types
  - "Large" (ADD): SM on a brane, gravity in the bulk
  - "Warped" (RS): SM on a brane or in bulk, curved extra dimension
  - "Universal" (ACD): All of SM in bulk
- They have different signatures:
  - Large extra dimensions have a "continuum" of graviton KK modes. Observables at large energies tend to smoothly deviate from SM backgrounds. They can either be produced and escape or mediate processes virtually.
  - Warped extra dimensions have narrow, strongly coupled graviton KK modes. They can appear as resonances in SM processes.
  - Universal extra dimensions have KK modes for all SM particles. The Lightest KK Particle is stable and appears as missing energy. (It could play the role of dark matter…). Like in SUSY with R-parity, they are pair-produced.

Large Extra Dimensions

- KK emission
  - Graviton escapes from the brane as missing energy.
  - The result is a mono-jet signature.
  - Signal rates depend on the number of extra dimensions and fundamental Planck scale (~TeV).
- Black Holes!
  - Low string scale allows one to produce string balls or black holes.
  - They decay "thermally", into high multiplicity events.



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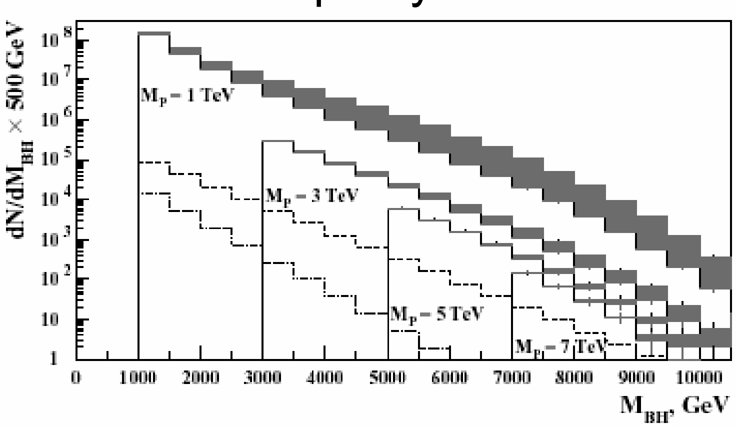
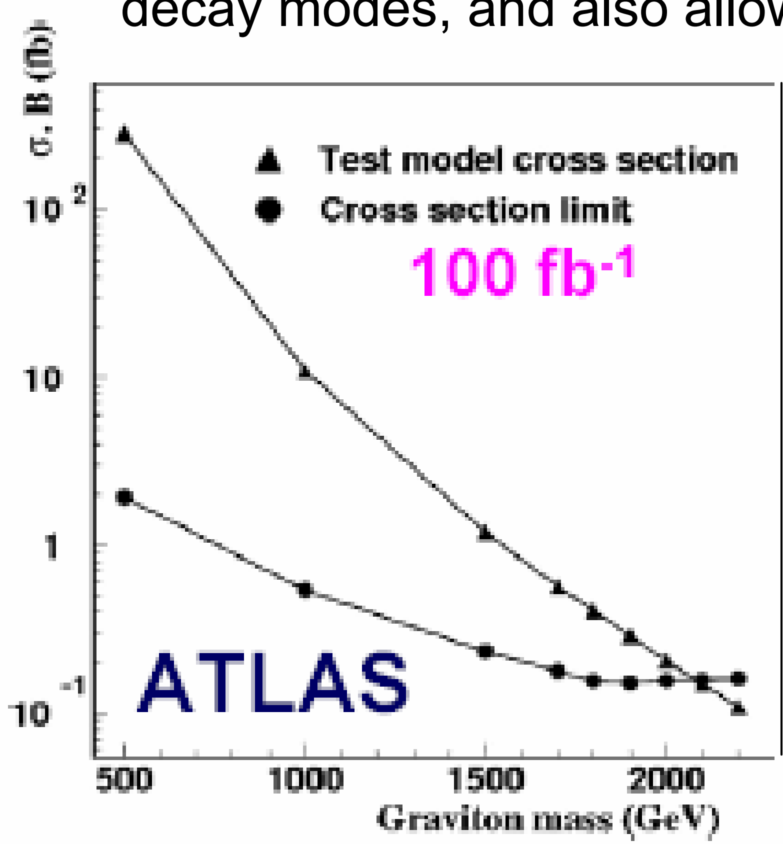


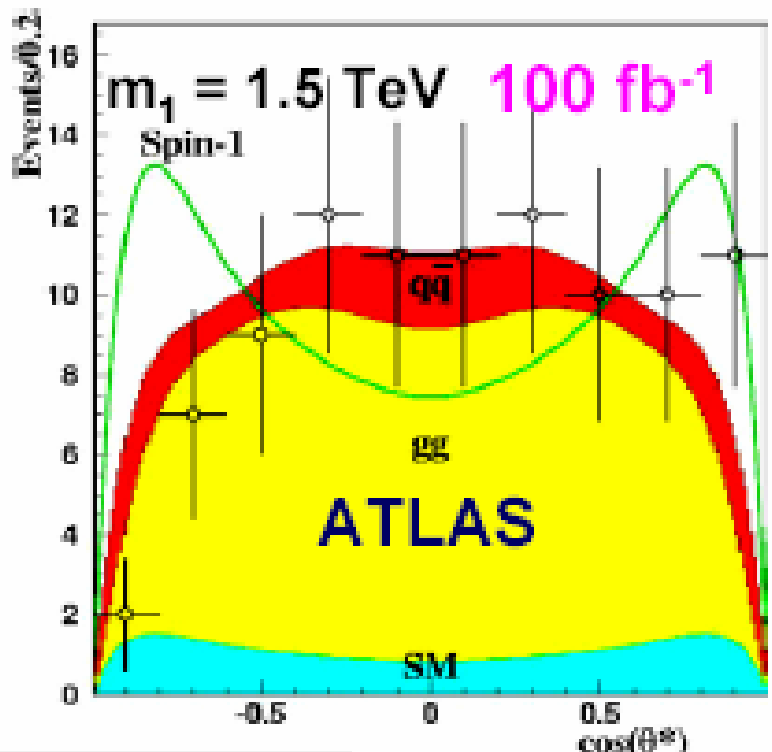
Dimopoulos, Landsberg hep-ph/0106295

M_D^{max} (E_T>1 TeV, 100 fb^{-1}) = 9.1, 7.0, 6.0 TeV for δ=2,3,4

Warped Extra Dimension

- KK gravitons are fairly narrow and couple strongly: appear as resonances.
- If their spin-2 nature can be discovered, this would be a strong clue as to the nature of the resonance (i.e. not like a Z').
- Some models have SM in the bulk: this will change the graviton decay modes, and also allow new states to be discovered.





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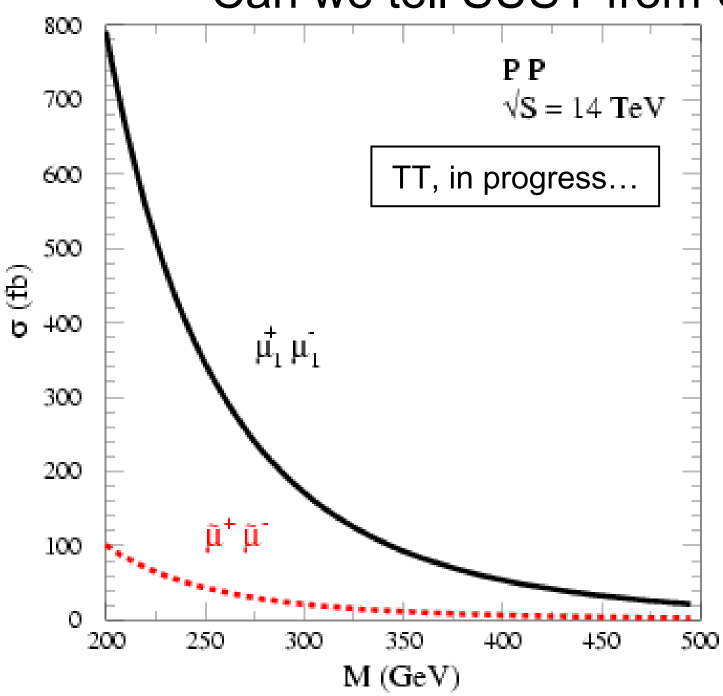
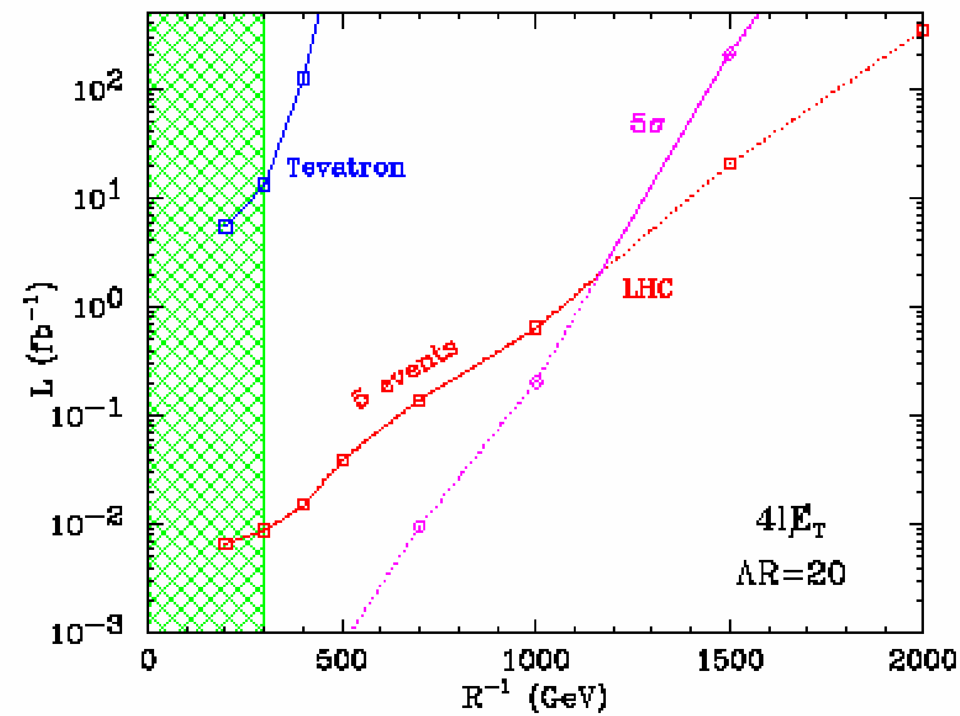
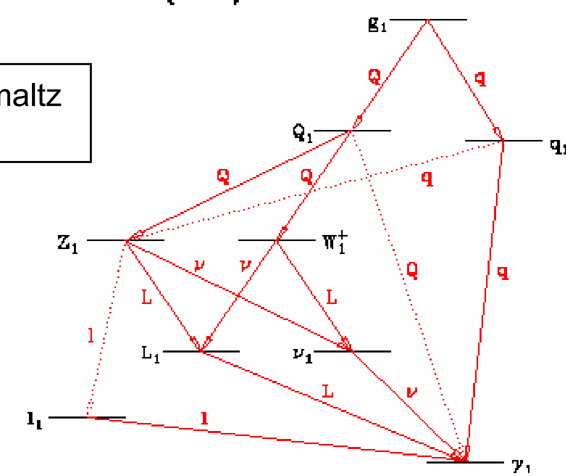
Universal Extra Dimensions

- The "SUSY" of extra dimensions!
  - KK modes must be pair-produced, and decay into the LKP: missing energy.
  - There is an entire tower of KK modes and they have the same spin as their SM counter-parts.
  - Can we tell SUSY from UED?





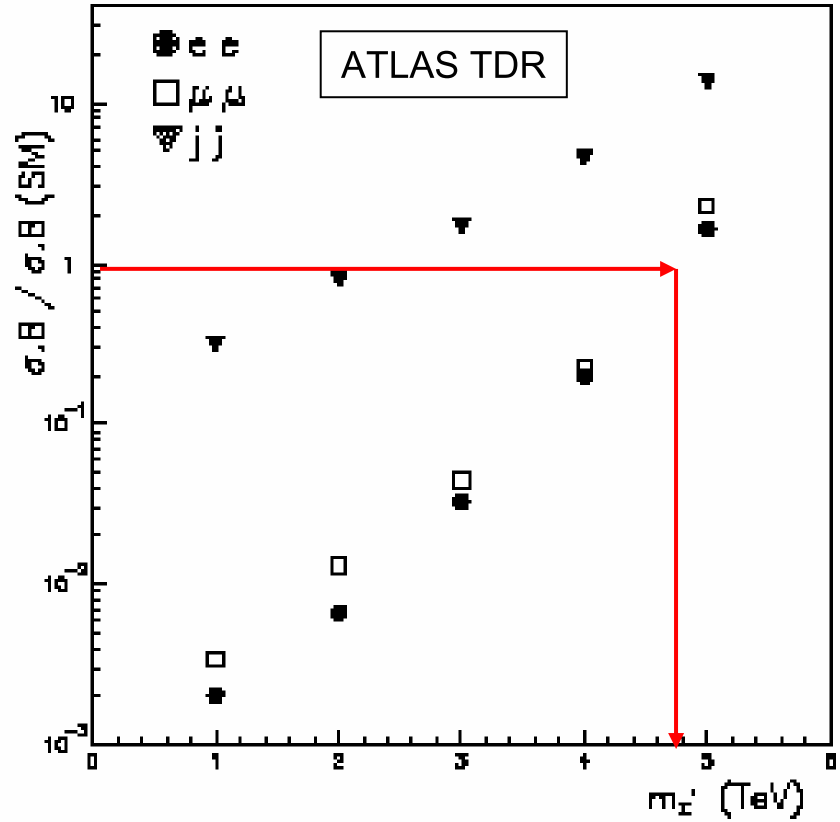
Cheng, Matchev, Schmaltz
hep-ph/0205314



Tim Tait

Z’

- Z’s are ubiquitous
  - **GUT**s with gauge groups (*S0(10), E_6*, …)
  - **Extra dimensions** with gauge fields in the bulk have copies of γ, Z, which are massive, neutral vector particles.
  - Theories like Topcolor uses them to drive **EWSB**.
  - The **Little Higgs** theories use massive vector particles to cancel quadratic divergences in the Higgs mass induced by W and Z.
  - New **SUSY** theories use them to survive the LEP II bound on $\mathbf{m_h}$.
  - Angular correlations can reveal the spin 1 nature of the resonance.



New Model-independent parameterization:
Carena, Daleo, Dobrescu, TT, hep-ph/04090809

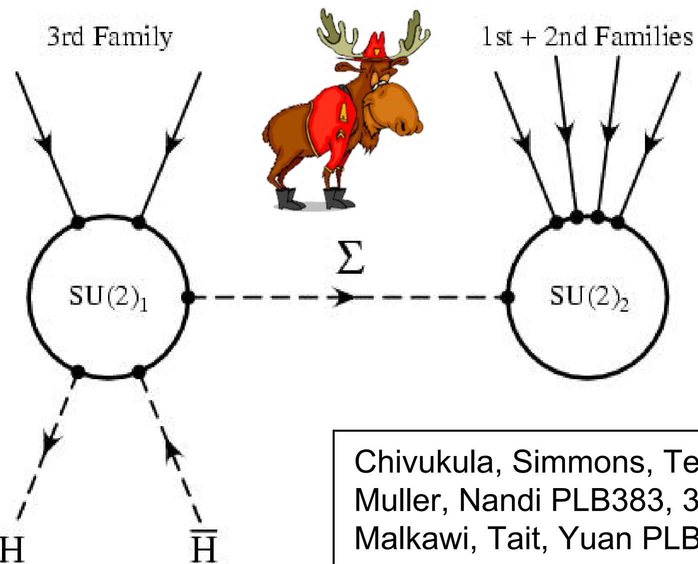
$$\sigma\left(p\bar{p} \to Z'X \to \ell^+\ell^- X\right) = \frac{\pi}{48s}\left[c_u w_u + c_d w_d\right]$$

$$c_u = g_Z^2\left(z_q^2 + z_u^2\right)\mathrm{BR}(Z' \to \ell^+\ell^-) \quad c_d = g_Z^2\left(z_q^2 + z_d^2\right)\mathrm{BR}(Z' \to \ell^+\ell^-)$$

W'

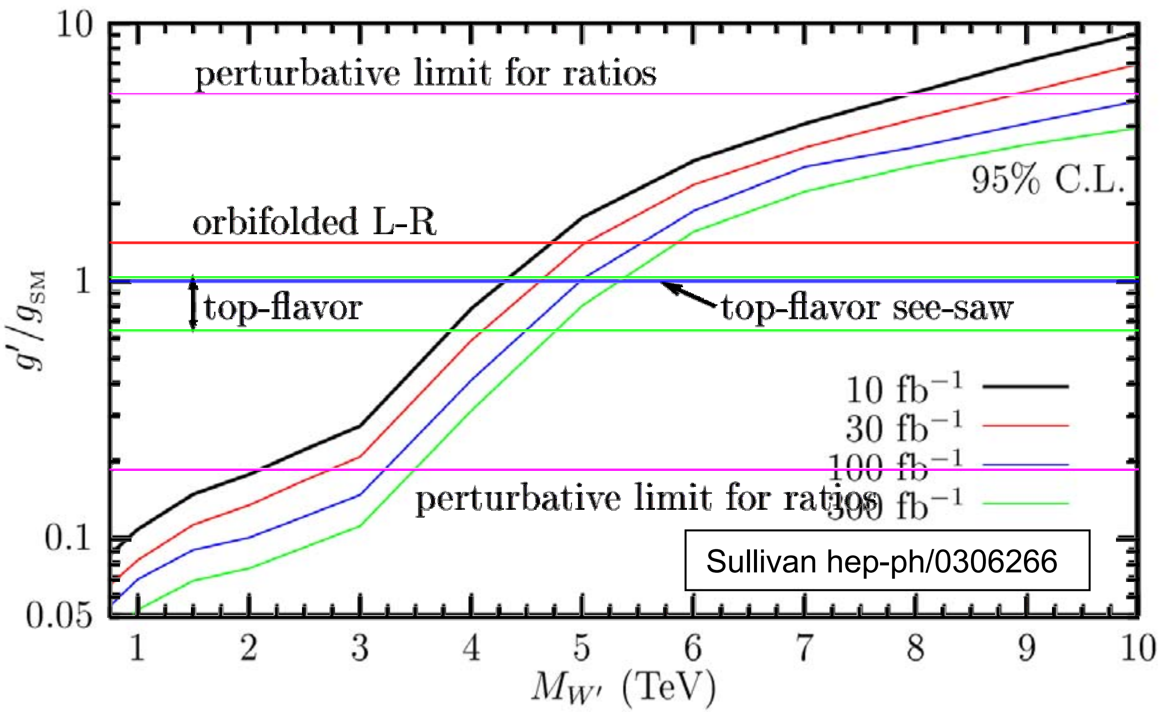
An interesting theory has:
$SU(2)_1 \times SU(2)_2 \times U(1)_Y$

This model has been called "**Topflavor**": a separate weak interaction for the 3rd family.



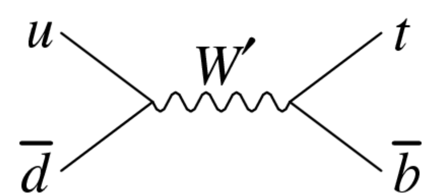
- Topflavor: **$W' \rightarrow t\,\bar{b}$**

Simmons, **PRD55, 5494 (1997)**



Sullivan hep-ph/0306266

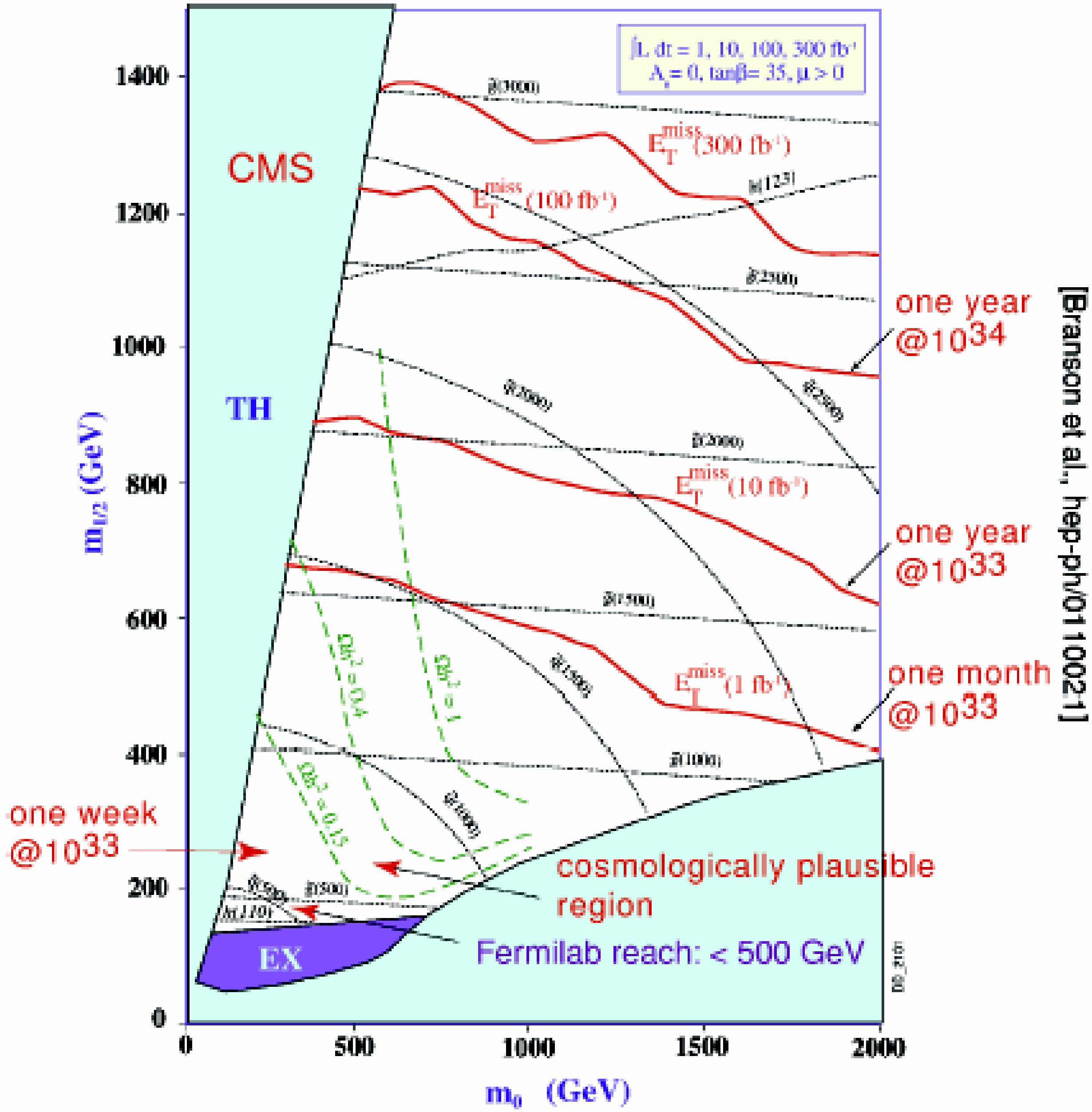
Chivukula, Simmons, Terning PRD53, 5258 (1996)
Muller, Nandi PLB383, 345 (1996)
Malkawi, Tait, Yuan PLB385, 304 (1996)
Batra, Delgado, Kaplan, Tait, JHEP 0402,043 (2004)



Summary

- In 2015 the LHC will have made great progress in exploring the high energy frontier.
  - Anomalous top physics should be discovered or bounded to 10^{-3} or so.
- If there is a SM-like (or MSSM-like) Higgs, probably we'll know.
  - Couplings could be measured to 10% (if we're lucky) or not measured (if we're not so lucky…)
  - Is it really the Higgs?
- If nature is supersymmetric, some sparticles should be seen.
  - Gluinos, squarks, some neutralinos/charginos seen and measured.
  - Higgsinos, sleptons, and maybe stops may be unknown.
  - SUSY Higgses may or may not be seen.
- Extra dimensions should be seen as KK modes, black holes, etc…
  - Black holes are messy.
  - UED represents a challenge to distinguish from SUSY
  - Z's/W's could be seen. How well will we know their interactions?
- We should have strong clues to EWSB, but a lot more to do!

Supplementary Slides



CMS
TH
EX
∫L dt = 1, 10, 100, 300 fb⁻¹
A₀ = 0, tanβ = 35, μ > 0
E_T^miss (300 fb⁻¹)
E_T^miss (100 fb⁻¹)
E_T^miss (10 fb⁻¹)
E_T^miss (1 fb⁻¹)
one year @10^34
one year @10^33
one month @10^33
one week @10^33
cosmologically plausible region
Fermilab reach: < 500 GeV
[Branson et al., hep-ph/0110021]
m_1/2 (GeV)
m_0 (GeV)
0
200
400
600
800
1000
1200
1400
0
500
1000
1500
2000