Beyond the Standard Model

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ICHEP Paris, July 2010

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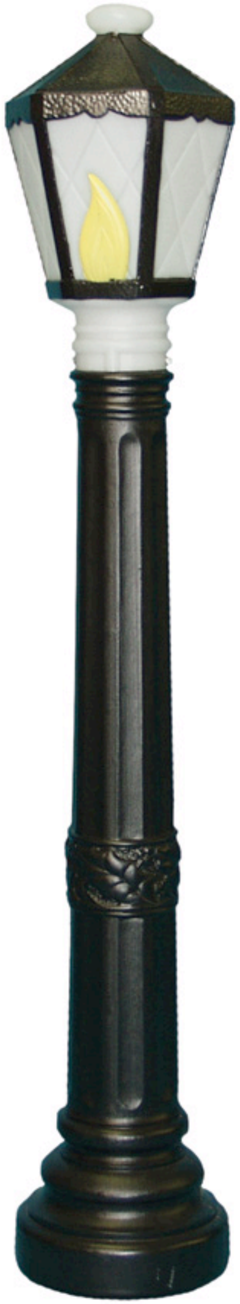
Some Recent Beyond the SM Themes

"LHC is most powerful street lamp in history"

"Anomalies need to be explained"

"Push theories to be complete and natural"

"LHC is most powerful street lamp in history"



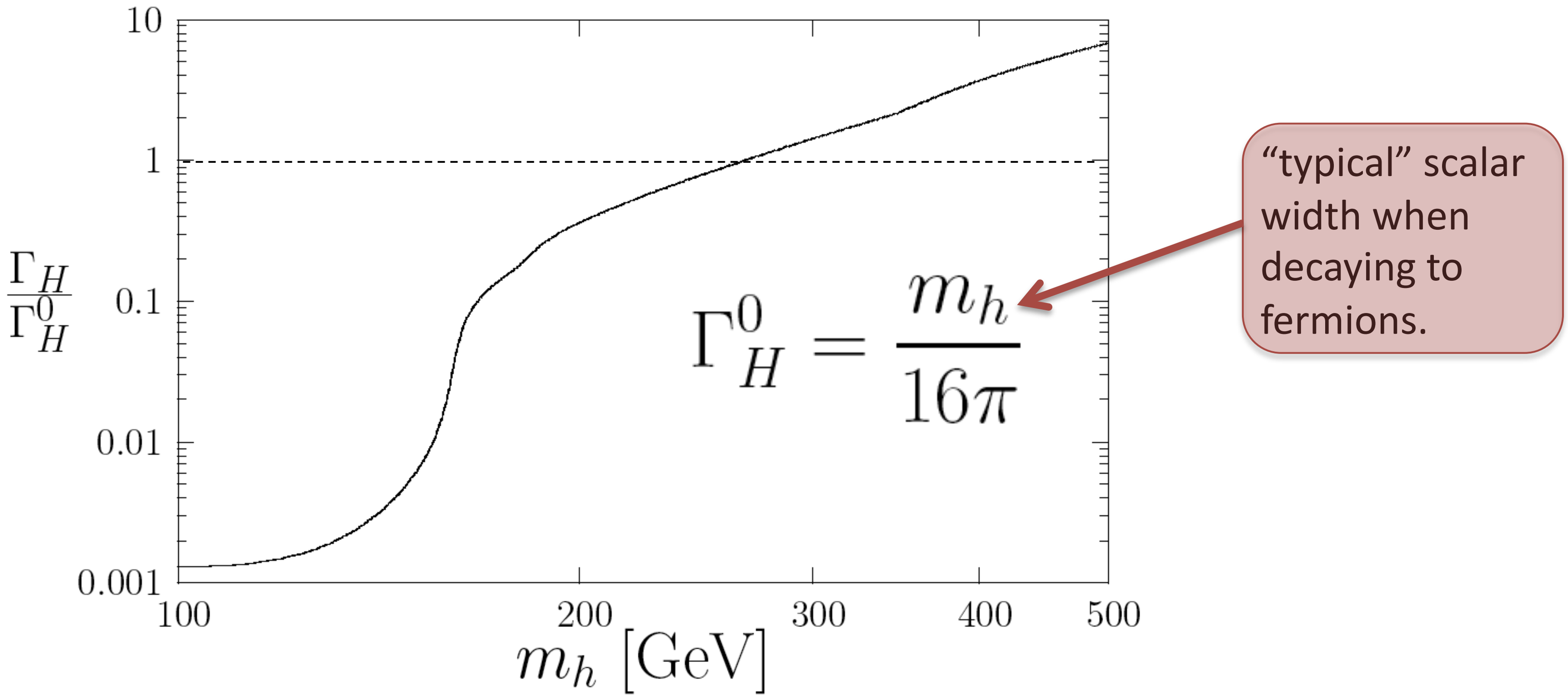
As the LHC has approached, many ideas to search under this lamppost have been developed.

*Hidden sectors (e.g., Y.Xie ICHEP talk)
*Exotic particles of various spin and gauge permutations (e.g., Berger ICHEP talk)
*Quirks (e.g., Xie ICHEP talk)
*Supermodels at early LHC (e.g., Ligeti ICHEP talk)
*Exotic Higgs decays (Several ICHEP talks)
*Many others

Experiment is suggesting that the Higgs boson may be light 115 GeV < m_h < 160 GeV

Light Higgs accidentally narrow

Largest BR of Higgs is to b quarks when $2m_b < m_h < 135$ GeV
Coupling of Higgs to bottom quark is $m_b/v < 1/50$.



Light Higgs boson especially susceptible to new decay modes.

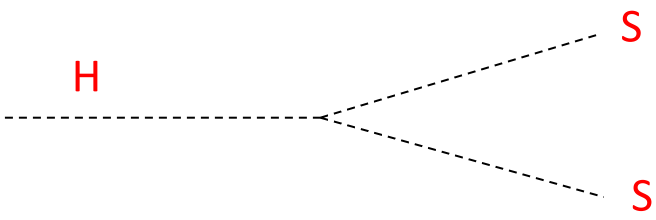
Ideas that impact narrow light Higgs

Hidden sector scalar φ mixing with Higgs boson (H-> φφ)
⇒Invisible width of the Higgs boson
Higgs dim-2 contributes to this special prospect!

Joshipura et al. '93 ;
Binoth, van der Bij, '97, etc
Many modern variants.

Most basic idea: addition of a real scalar field with Z_2. Simplest Dark Matter!

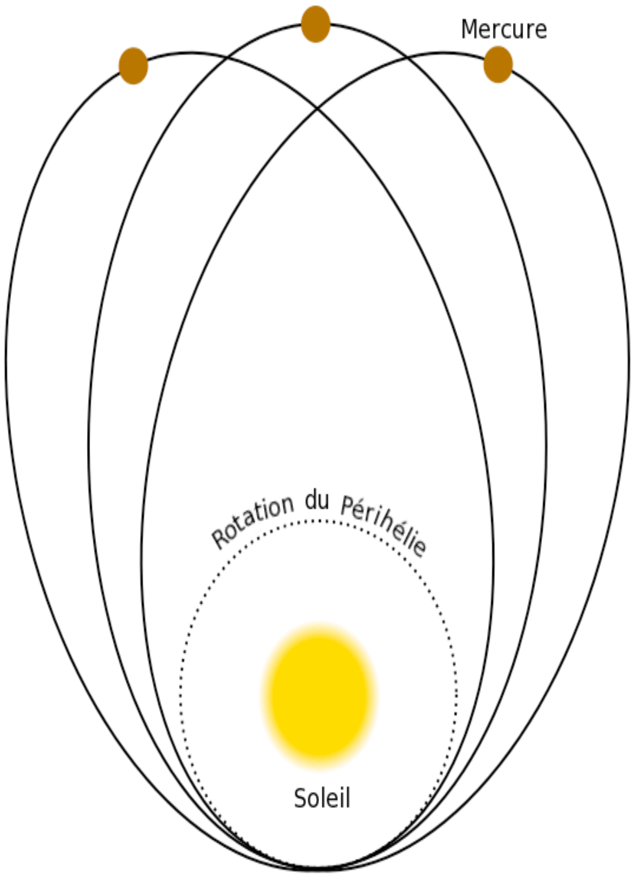
$$\mathcal{L} = \frac{M_S^2}{2} S^2 + \lambda S^2 |\Phi_{SM}|^2 + \cdots$$



U(1) Z' mixing with hypercharge, enabling H->Z'Z', where Z' decays to hidden states or SM fermions (H-> 4 leptons possible)

Exotic particle content coupling weakly to Higgs but dominating decay => Examples abound (e.g., Nandi ICHEP talk)

“Anomalies need to be explained”



wikimedia.com

Pamela positron excess

DAMA/LIBRA seasonal variation

g-2

B_s dimuon CP asymmetry

Neutrino vs. antineutrino properties

Top quark charge asymmetry

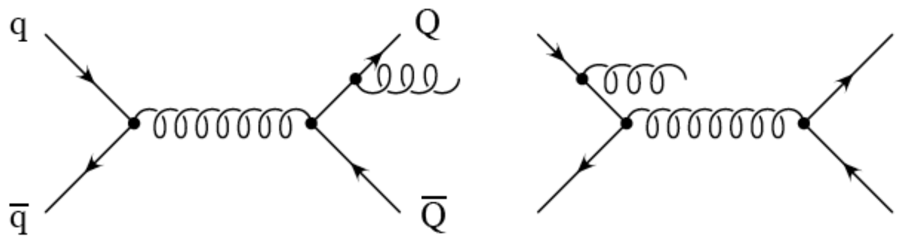
…

Standard Model Prediction

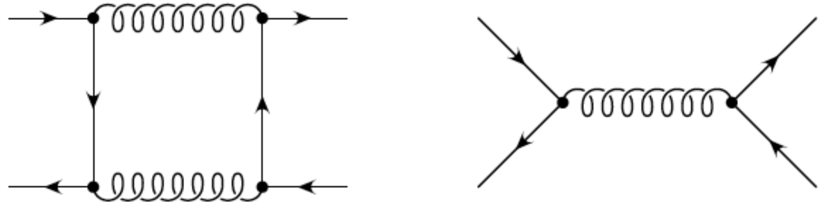
Asymmetry arises at α_s^3 order.

(Close analogy with QED α^3 asymmetry, Berends et al. 1973)

Interference of ISR with FSR:



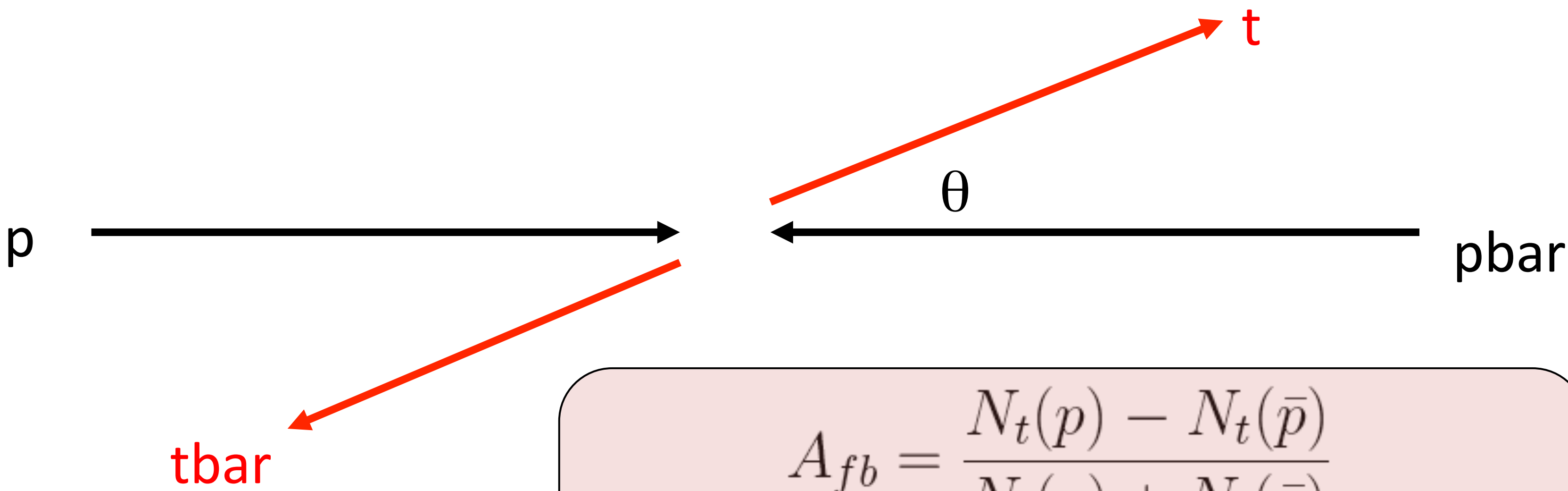
Interference of box with tree:



(Antuñano), Kühn, Rodrigo, PRD '99 (0709.1652)

A_{FB}(th) = 3.8 +- 0.6 %

Top Asymmetry at the Tevatron



$$A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}$$

$N_i(j) = \#$ of particle i in direction of particle j

Assuming CP

$N_{\bar{t}}(p) = N_t(\bar{p})$ which implies $A_c = A_{fb}$ where $A_c = \frac{N_t(p) - N_{\bar{t}}(p)}{N_t(p) + N_{\bar{t}}(p)}$

Measurements Reported

$$A_{FB} = 0.20 \pm 0.11^{stat} \pm 0.047^{syst} \; (0.695\; fb^{-1} \;\text{CDF T. Schwarz Thesis})$$

$$A_{FB} = 0.19 \pm 0.09^{stat} \pm 0.02^{syst} \; (0.9\; fb^{-1} \;\text{D0 0712.0851})$$

$$A_{FB} = 0.17 \pm 0.07^{stat} \pm 0.04^{syst} \; (1.9\; fb^{-1} \;\text{CDF 0806.2472})$$

* $$A_{FB} = 0.193 \pm 0.065^{stat} \pm 0.024^{syst} \; (3.2\; fb^{-1} \;\text{CDF 9724, 17 Mar 2009})$$

A_{FB}=0.150 +- 0.050 +- 0.024 (5.3 fb^{-1} A. Eppig CDF ICHEP, July 2010)
D0 Expt also reporting ~2σ effect (4.2 fb^{-1} V. Shary D0 ICHEP, July 2010)

Large BSM contribution difficult: Illustrate with Axigluons

So-called chiral color theories of various origins.

$SU(3)_L$ x $SU(3)_R$ breaks to $SU(3)_c$
Leaving 8 massive axigluons.
Coupling is QCD strength but with γ^5

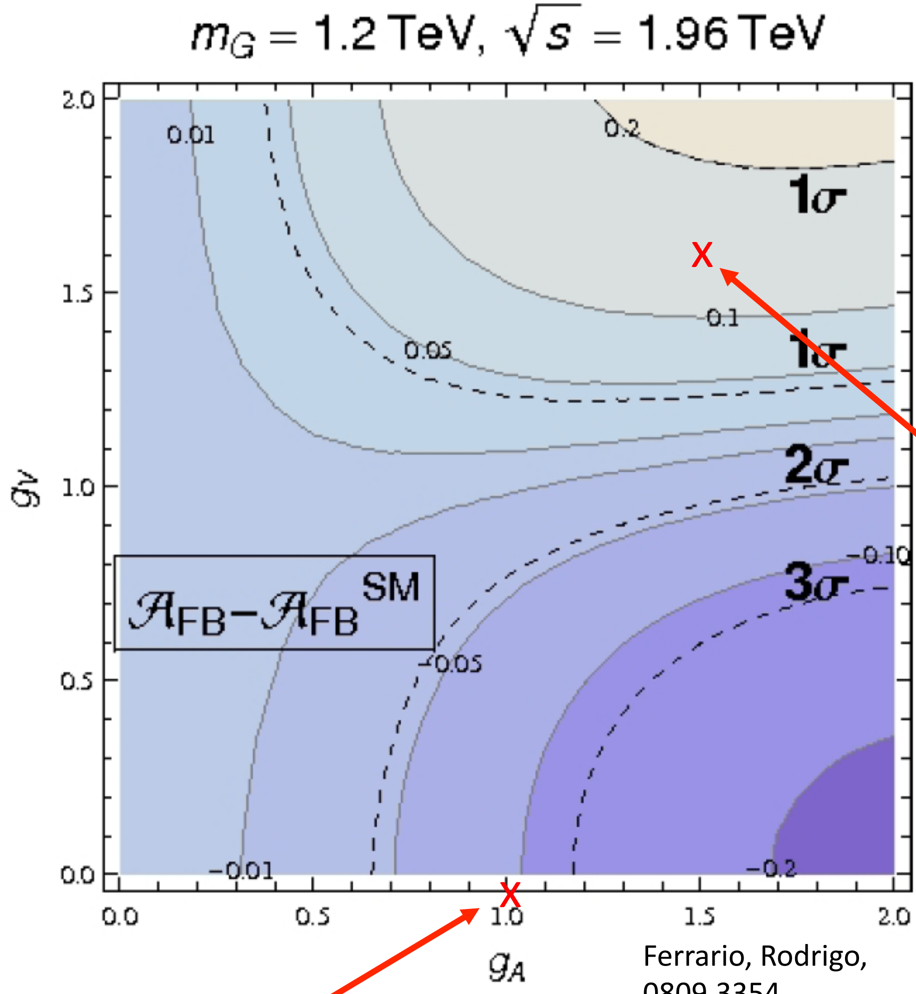
Maximal charge asymmetry as tree-level $\bar{t}\gamma^\mu\gamma^5 t$ is relative C odd to $\bar{t}\gamma^\mu t$.

Problem is the asymmetry goes wrong way!

A_{FB} = - 0.13 for m_A = 1 TeV

Limit on pure axigluon from $A_{FB}(t)$ may be stronger than from direct searches.

Try more general g_V-g_A couplings



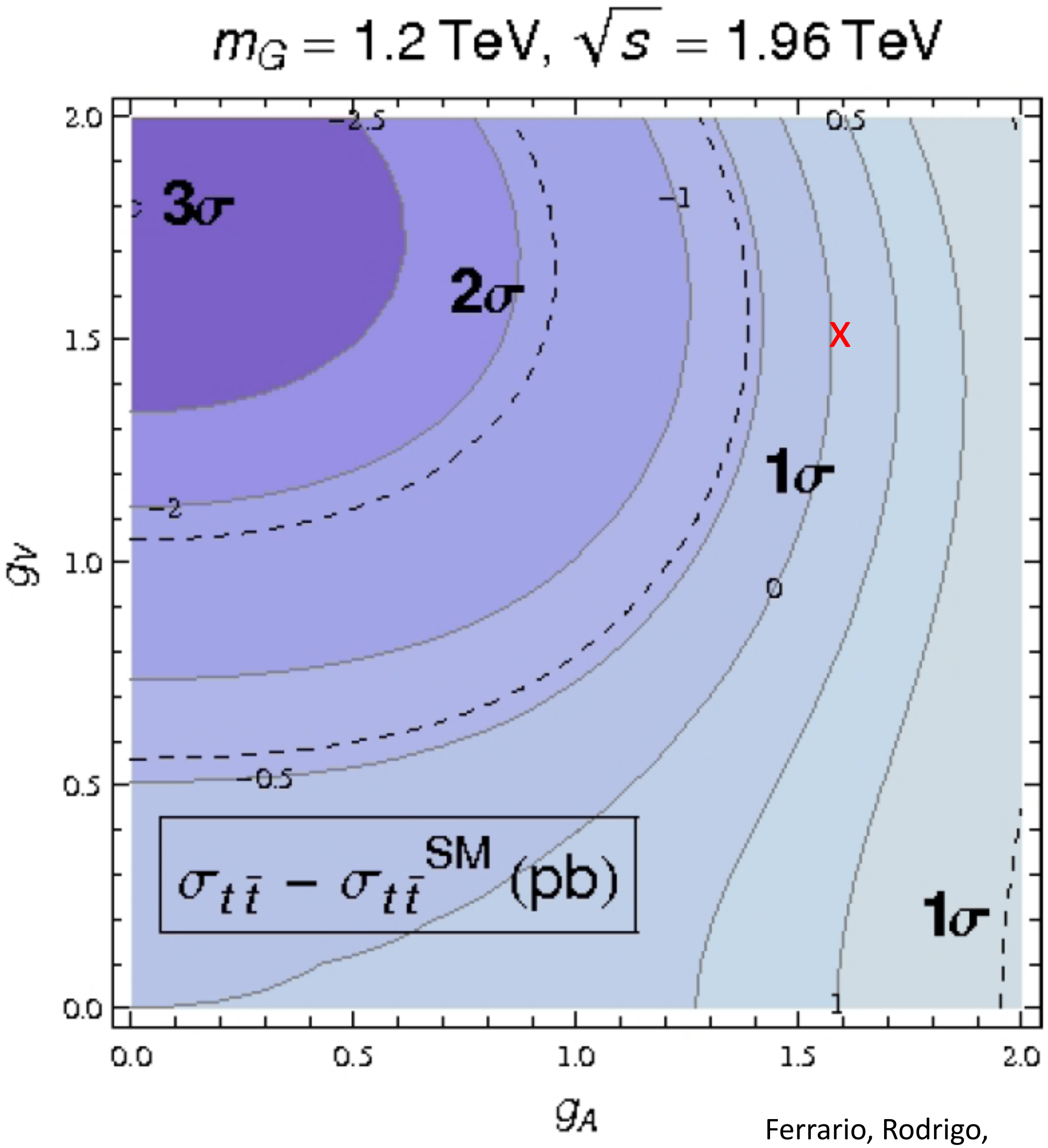
Couplings are with respect to the QCD gauge coupling.

This point looks good!

Ferrario, Rodrigo, 0809.3354

Pure axigluon coupling (large negative contribution to A_{FB})

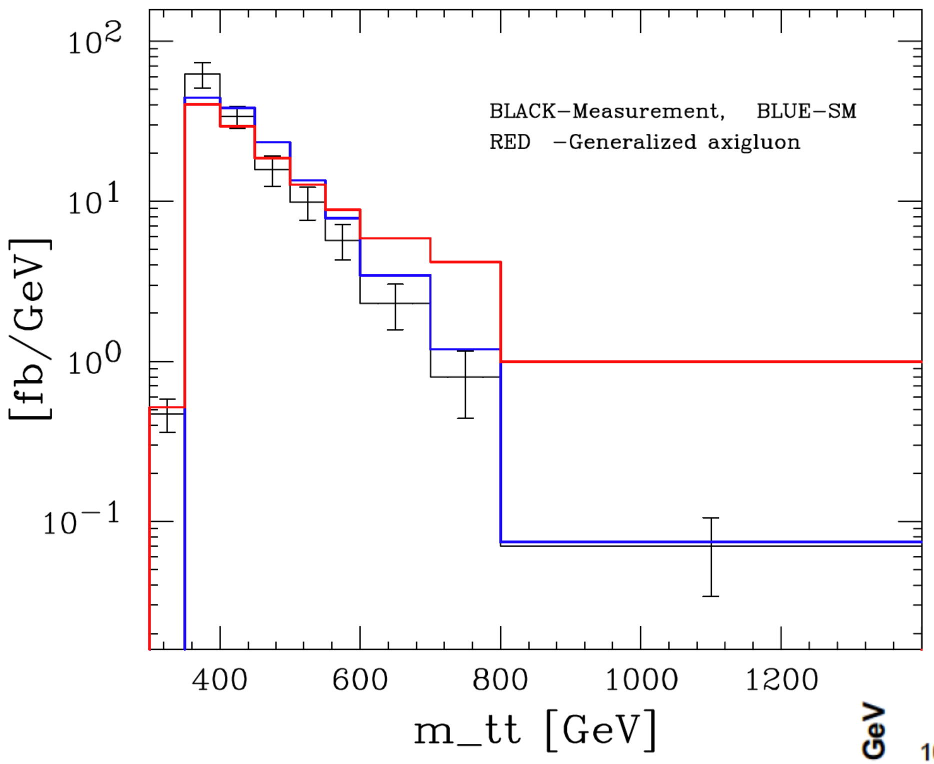
Top cross-section constraint



Consistency with total rate is ok.

Ferrario, Rodrigo, 0809.3354

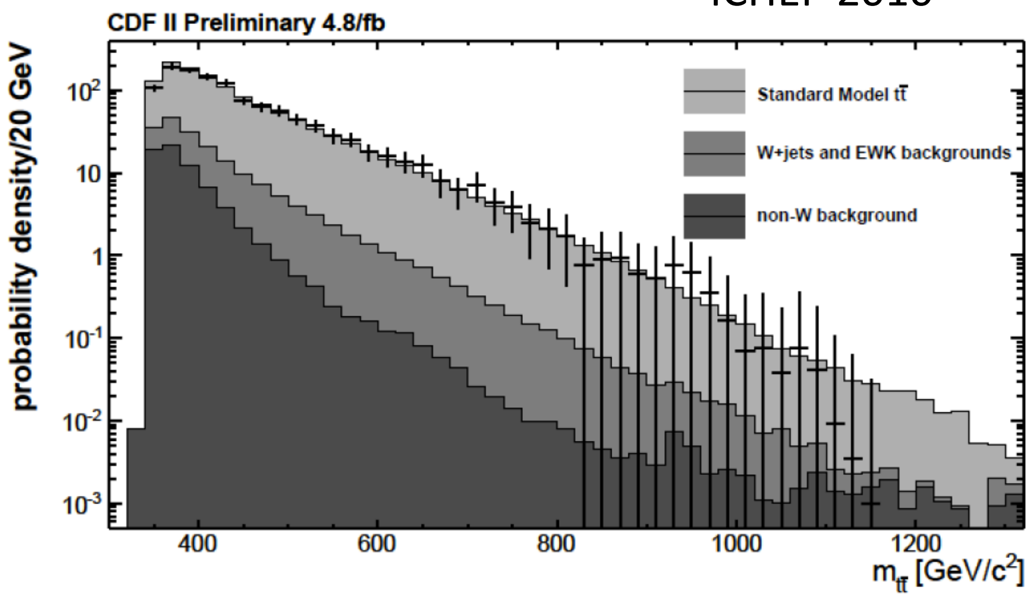
Generic Problem: Difficulty with differential cross-section



Red line: M_X=1.2 TeV g_V=1.65 g_A=1.55

Data from CDF, "Measurement of the ttbar differential cross section … in 2.7 fb^{-1} of CDF II Data", CDF note 9602 (11 Nov 08).

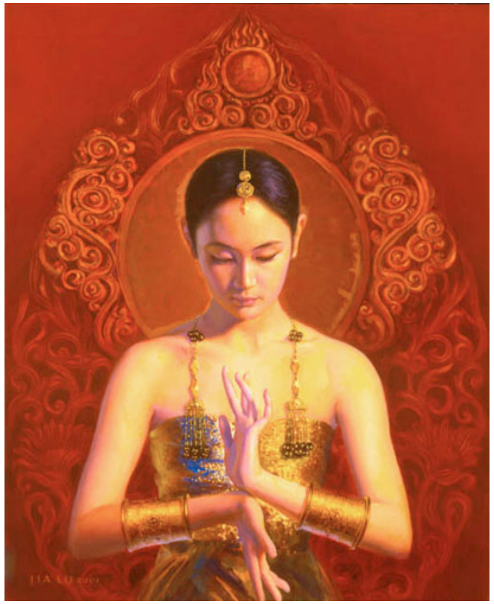
ICHEP 2010



BSM Ideas to increase A_{FB}(top)

General Axigluon papers [Antunano, Ferrario, Kuhn, Rodrigo: several papers]
Warped RS KK Gluons [Djouadi, Moreau, Richard, Singh: 0906.0604]
t-channel Z’ coupling to up-top [Jung, Murayama, Pierce, JW: 0907.4112]
W' Boson coupling to top and down quark [Cheung, Keung, Yuan: 0908.2589]
Axigluons [Frampton, Shu, Wang: 0911.2955]
t-channel color sextet or triplet scalar exchange [Shu, Tait, Wang: 0911.3237]
Color triplet diquarks [Arhrib, Benbrik, Chen: 0911.4875]
GUT light colored scalars [Dorsner, Fajfer, Kamenik, Kosnik: 0912.0972]
‘Model independent’ Dim-6 Effective operators [Jung, Ko, Lee, Nam: 0912.1105]
R-parity violating t-channel process [Cao, Heng, Wu, Yang: 0912.1447]
W' and Z' left-right model [Barger, Keung, Yu: 1002.1048]
Axial vector exotic gluon [Cao, McKeen, Rosner, Shaughnessy, Wagner: 1003.3461]
Axigluons don't work [Chivukula, Simmons, Yuan: 1007.0260]

Ko, ICHEP Talk



Jia Lu, “Completeness”

“Push theories to be complete and natural”

*Constructing natural theories with dark matter and baryogenesis

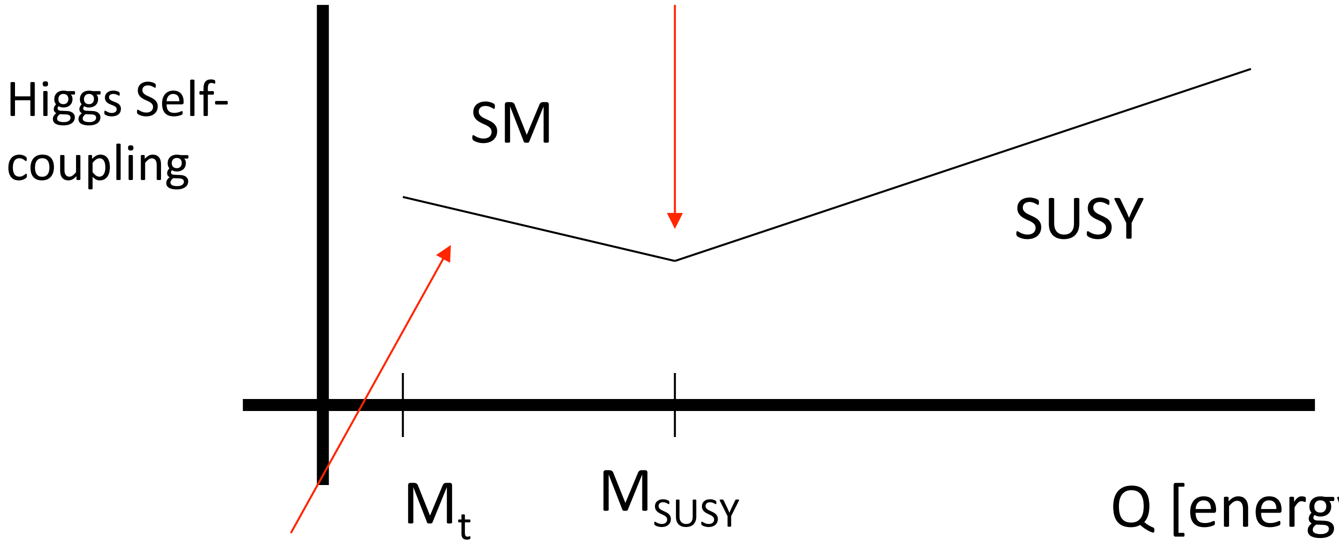
*Ameliorating Flavor constraints in RS Warped Extra dimensions

*Subtle finetunings in Little Higgs theories (Grinstein ICHEP talk)

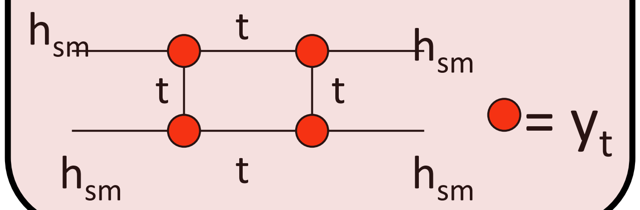
*Natural Lightest Higgs mass > 115 GeV in supersymmetry (Lodone ICHEP talk)

Understanding Lightest Higgs Mass Computation

$$\lambda(M_{SUSY}) = \frac{1}{8}(g^2 + g'^2)\cos^2 2\beta$$



$$\frac{d\lambda}{d\log Q} = -\frac{3}{4\pi^2} y_t^4 + \cdots$$



$$\begin{aligned} m_h^2 &= 2\lambda v^2 = 2\left(\lambda(M_{SUSY}) + \frac{3}{4\pi^2} y_t^4 \log\frac{M_{SUSY}}{M_t}\right) v^2 \\ &= M_Z^2 \cos^2 2\beta + \frac{3M_t^4}{\pi^2 v^2}\log\frac{M_{SUSY}}{M_t} \end{aligned}$$

Higgs boson mass

In minimal supersymmetry the lightest Higgs mass is computable:

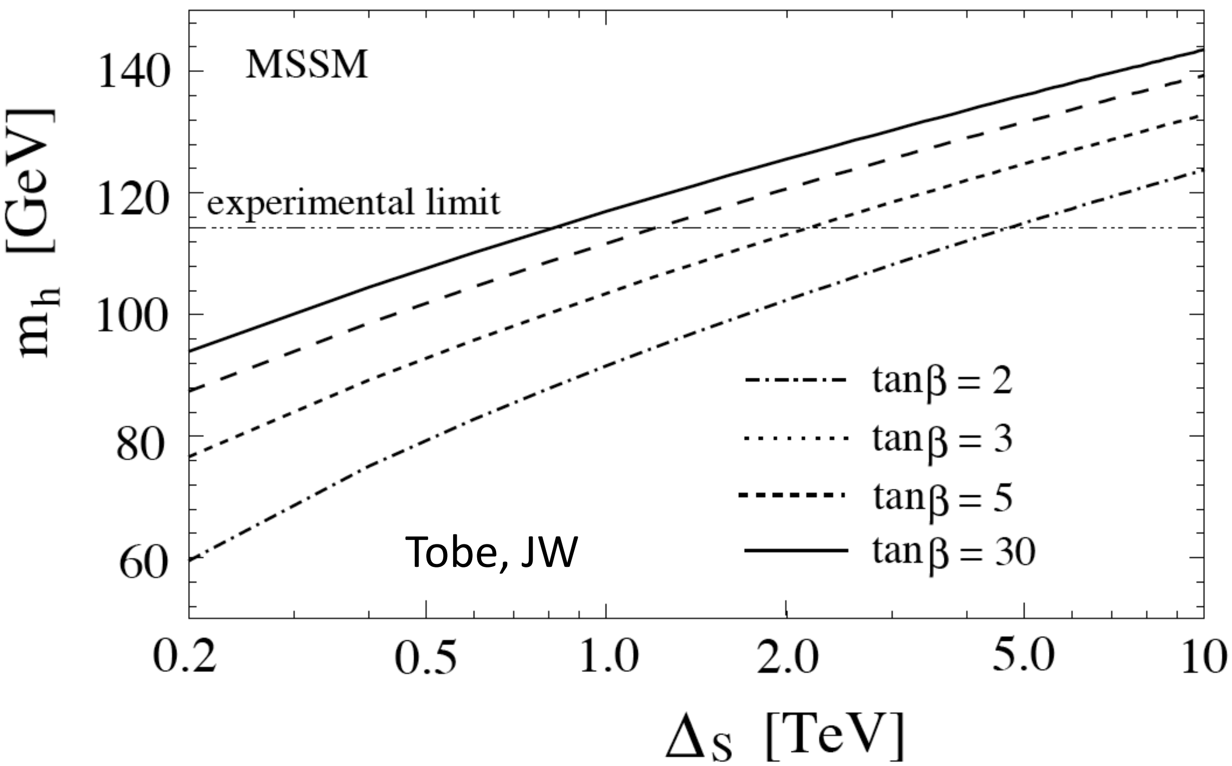
$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \log \frac{\tilde{m}_t^2}{m_t^2} + \cdots$$

Tree-level value is bounded by $m_Z = 91\,\mathrm{GeV}$. Current lower limit on Higgs boson mass is $114\,\mathrm{GeV}$. Thus, we need $\sim (70\,\mathrm{GeV})^2$ contribution from quantum correction.

Need $\tilde{m}_t \gtrsim 5\,\mathrm{TeV}(0.8\,\mathrm{TeV})$ for $\tan\beta = 2(30)$

Log-sensitivity keeps m_h below the Precision EW bound (~ 200 GeV)

Lightest Higgs Mass in the MSSM



$$
\begin{aligned}
m_h^2 &= M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2} \ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{3m_t^2}{v^2} c_{\tilde{t}}^2 s_{\tilde{t}}^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln \frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2} + \cdots \\
&\equiv M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \ln \frac{\Delta_S^2}{m_t^2} \quad \text{where } \Delta_S^2 \gtrsim m_{\tilde{t}_1} m_{\tilde{t}_2}
\end{aligned}
$$

What's wrong with heavier superpartners?

Terms in the EW scalar potential are governed by supersymmetry breaking scale.

m_{Hu} and m_{Hd} are susy breaking masses with, e.g. squark mass contributions induced by RGE.

Minimizing EW potential with large susy breaking m_{Hu} and m_{Hd} that churns out a small m_Z is a 'finetuning'

$$\mu^2 + \frac{m_Z^2}{2} = \frac{m_{H_d}^2 - \tan^2\beta\, m_{H_u}^2}{\tan^2\beta - 1}$$

Extra Singlet Solution to Higgs Mass Problem

Introduce a SM singlet and a Z_3 symmetry to the superpotential:

$$W = \lambda S H_u H_d + \lambda' S^3 + \cdots$$

ϕ^4-like contributions to Higgs mass arise from $F_S^\dagger F_S$ contributions to the scalar potential.

The Higgs mass bound then becomes

Normal radiative Corrections.

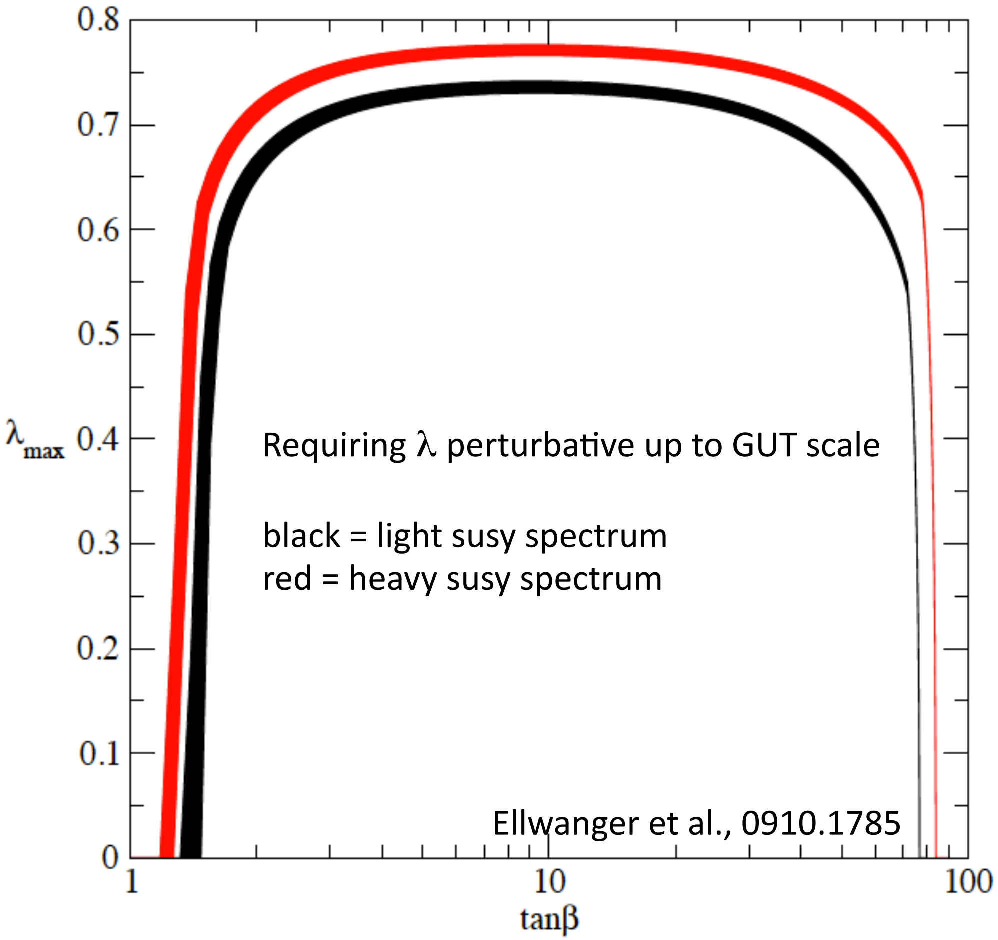
$$m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta m_{h,rad}^2$$

Assuming λ perturbative up to unification scale ($M_U \simeq 2 \times 10^{16}$ GeV), gives predictions for the "reasonable upper limit" of lightest Higgs in NMSSM.

RGE: $16\pi^2 \frac{d\lambda^2}{dt} = \lambda^2 \left(3h_t^2 + 3h_b^2 + h_\tau^2 + 4\lambda^2 + 2\kappa^2 - g_1^2 - 3g_2^2\right)$

$$h_t = \frac{1}{\sin\beta} \frac{m_t}{v} \qquad h_b = \frac{1}{\cos\beta} \frac{m_b}{v}$$

RGE depends on tanβ



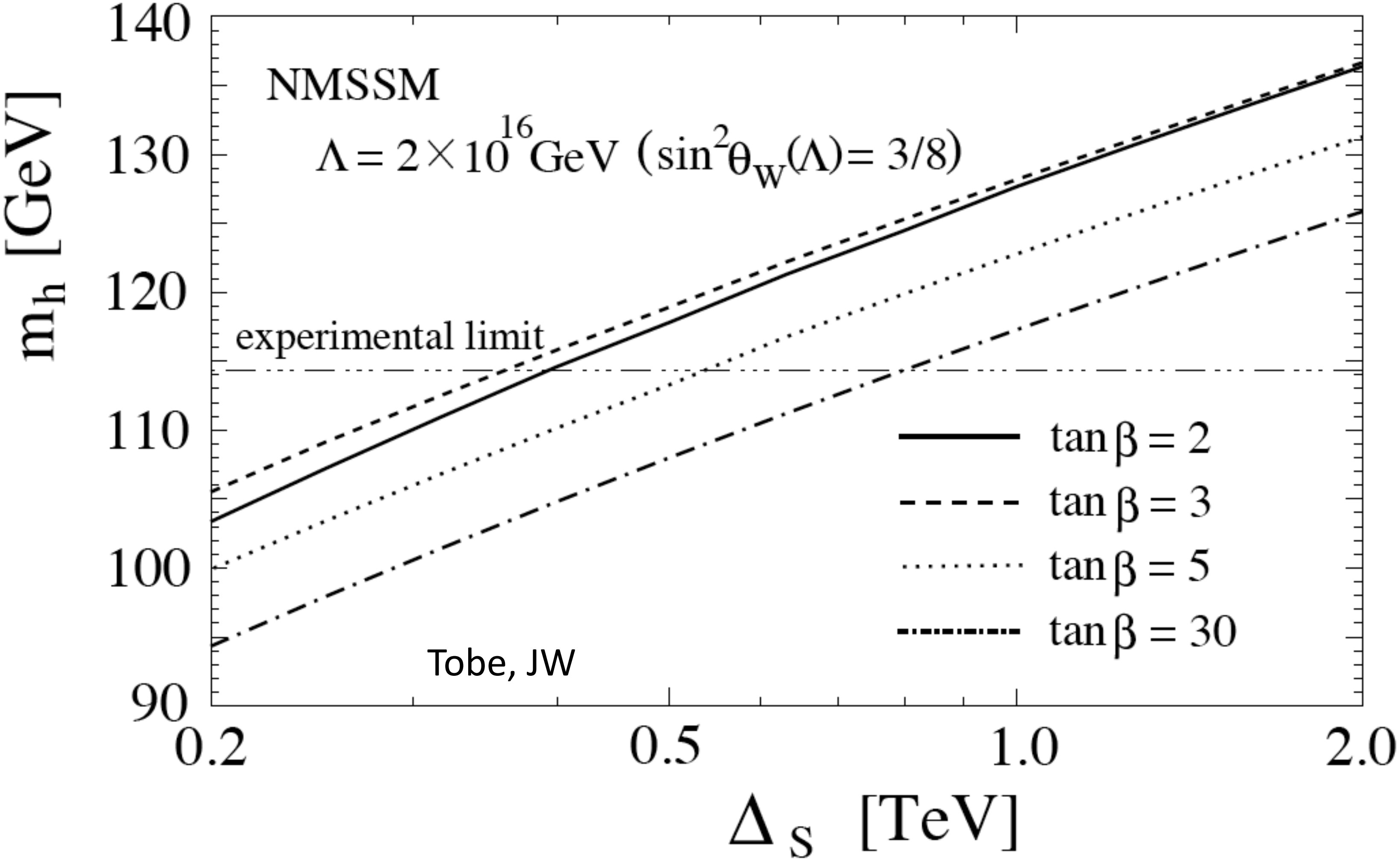
Perturbativity bounds on NMSSM

RGE forces λ(Q) to increase its value as the scale Q increases.

This bounds $\lambda<\lambda_{max}$ at $Q=m_h$ if we require that $\lambda<4\pi$ at $Q=M_{GUT}$, which in turn puts upper limit on the Higgs mass.

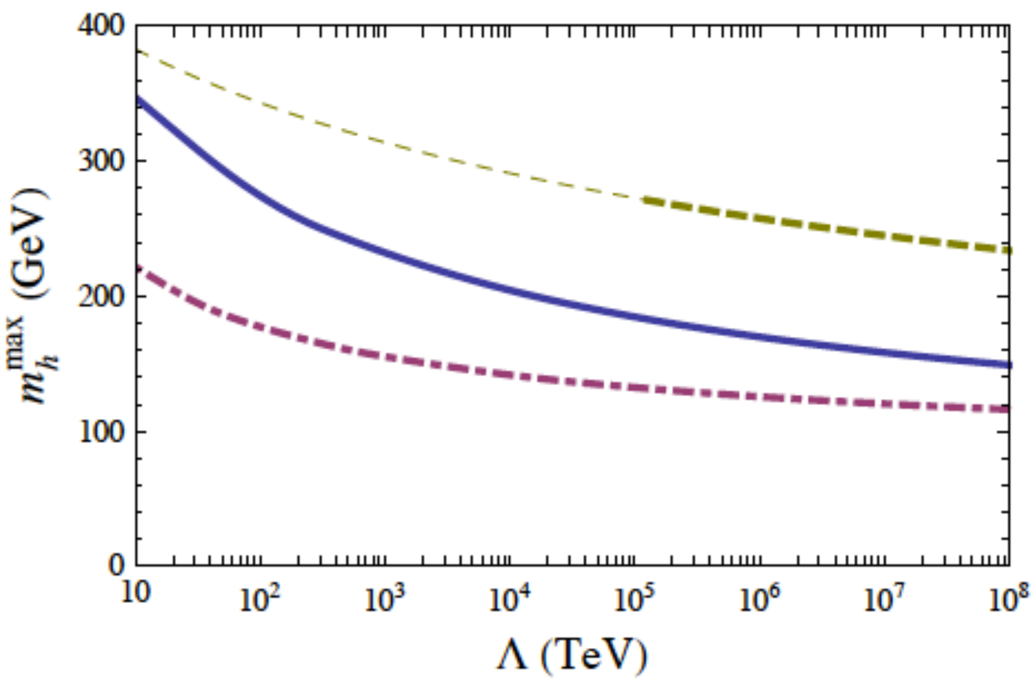
$$m_h^2 \leq m_Z^2 (\cos^2 2\beta + \frac{2\lambda_{max}^2}{g^2+g'^2} \sin^2 2\beta)$$

Easier to get m_h>114 GeV now



Relaxing Perturbativity Constraint

Allow $\lambda(Q)$ coupling to blow up at a much smaller scale Λ.
$\lambda(m_h)$ can then be much higher, allowing m_h much higher.



Advantages:

-Can ameliorate flavor problem using heavy 1st and 2nd generation squarks

-Higgs boson mass above 115 GeV limit without 'unnaturally' large mass superpartners.

Disadvantages:

-Theory not perturbative up to 'high scale'

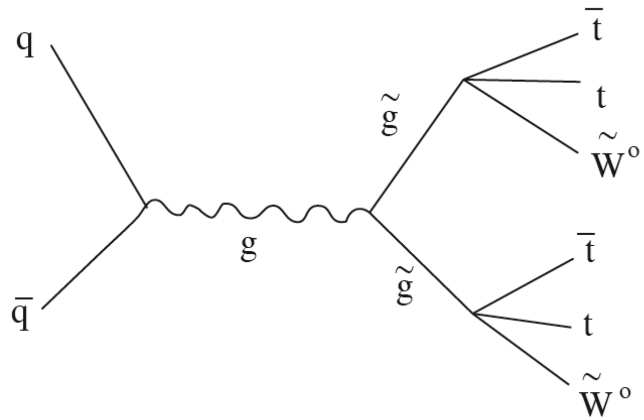
-Apparent perturbative gauge coupling unification just a mirage?

Barbieri et al., '10
Lodone ICHEP talk →

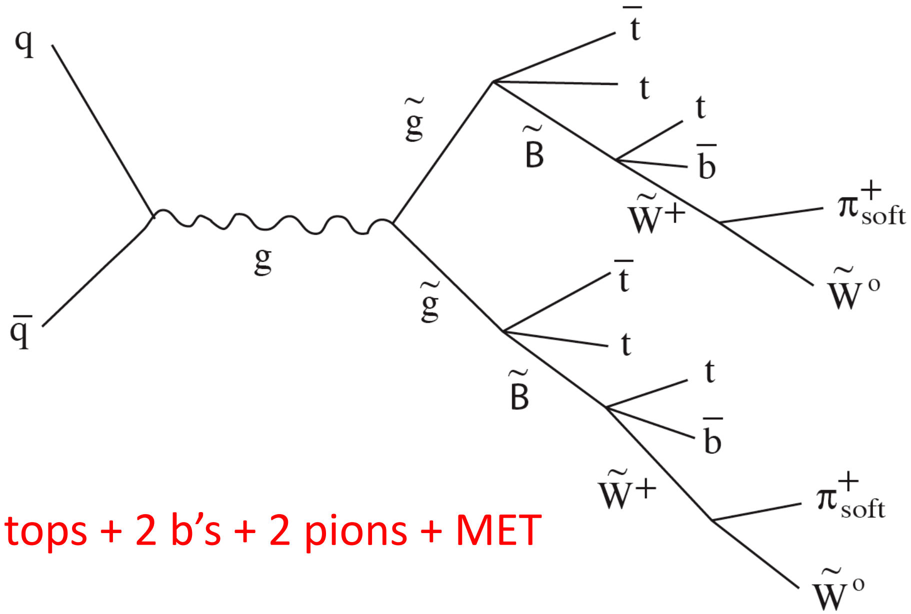
The connection to flavor leads to gluino pair production followed by decays to four tops plus missing energy.

Light stops and sbottoms implications: High multiplicity tops+MET events

Simplest event type: 4 top quarks plus missing energy. Can the missing energy be measured?



Ubiquitous four top events, with bino LSP or wino LSP (as shown).



6 tops + 2 b's + 2 pions + MET

Similar 4top signature for other theories:
- -Split SUSY
- -Strongly coupled top condensate
- -KK gluons in low-scale RS models

Conclusion

Experimental progress has played key role in the rise or demise of various Beyond the SM theories.

Continual efforts since we wish to “explain more”. Questions refine with more knowledge and insight.

Much anticipation for further results from all experiments, including at the high-energy frontiers of the Tevatron and LHC.

Mort Kunstler, “Lewis and Clark”