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Top Physics beyond the SM at the LHC

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Grenoble, Top workshop: from D0 to ATLAS, 2006

Outline

- SM introduction
- Top in BSM scenarios
- A different strategy: m_{tt} at the LHC
- Top & flavor physics: BSM from $V_{tb} < 1$
- Conclusions

Introduction

Definition of Standard Model top:

- It is the $SU(2)_L$ partner of the bottom.
- $t_L \Rightarrow T^3=+1/2$, t_R singlet.
- Its mass is obtained in the EWSB: $m_t = y_t v/\sqrt{2}$
- $Q_t=+2/3$ and is a color triplet.
- All couplings are fixed by the gauge structure.

It is just as all other quarks: what's so special about it?

Introduction

In the SM, it is the only quark with a "natural mass":

$$m_{top} = y_t\, v/\sqrt{2} \approx 174 \text{ GeV} \Rightarrow y_t \approx 1 \quad *$$

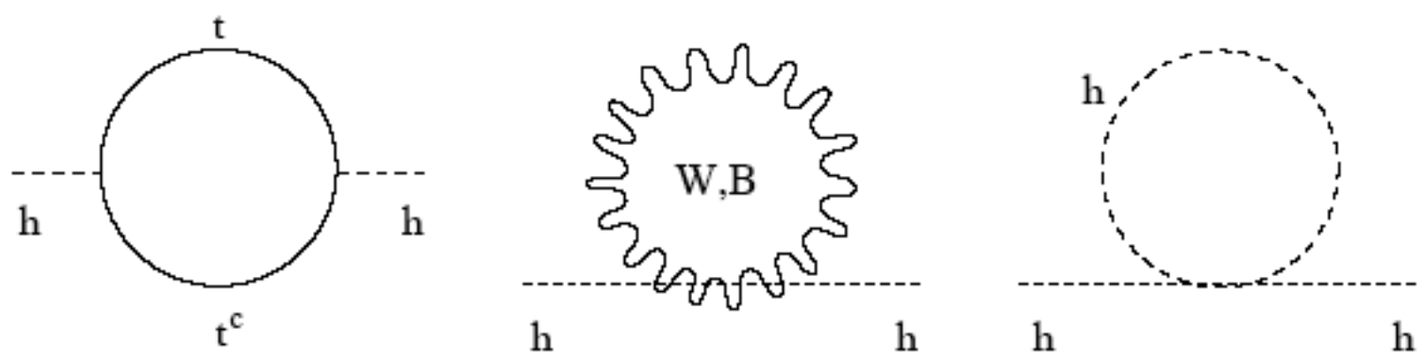
It "strongly" interacts with the Higgs sector!

This has led to the very prolific idea that top might have a special role in the EWBS!

*It also happens that $m_{top} \approx M_W + M_Z \approx 171$ GeV

Hierarchy problem

In fact, top dramatically affects the stability of the Higgs mass:

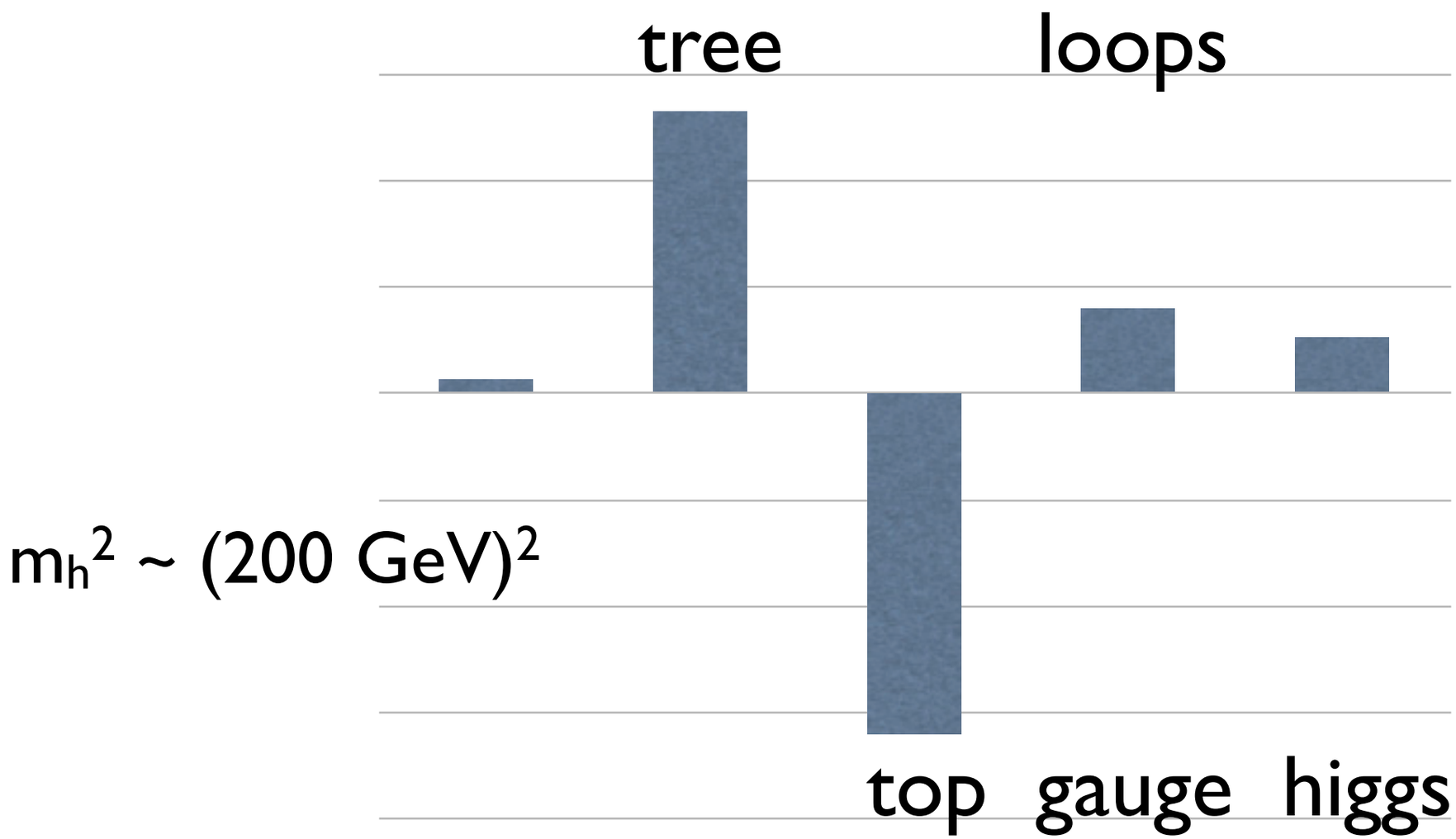


(a) (b) (c)

$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

$$(200\ \text{GeV})^2 = m_{H0}^2 + \left[-(2\ \text{TeV})^2 + (700\ \text{GeV})^2 + (500\ \text{GeV})^2\right] \left(\frac{\Lambda}{10\ \text{TeV}}\right)^2$$

Hierarchy problem



$$(200\ \mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\ \mathrm{TeV})^2 + (700\ \mathrm{GeV})^2 + (500\ \mathrm{GeV})^2\right]\left(\frac{\Lambda_{t,W,H}}{10\ \mathrm{TeV}}\right)^2$$

Definition of naturalness: less than 90% cancellation:

$$\Lambda_t \lesssim 3\ \mathrm{TeV} \quad \Lambda_W \lesssim 9\ \mathrm{TeV} \quad \Lambda_H \lesssim 12\ \mathrm{TeV}$$

* One can actually prove that this case in model independent way, i.e. that the scale associated with top mass generation is the same as that of EWSB.

Available solutions

There have been many different suggestions!
Fortunately, we can say that they group in 1+3 large classes:

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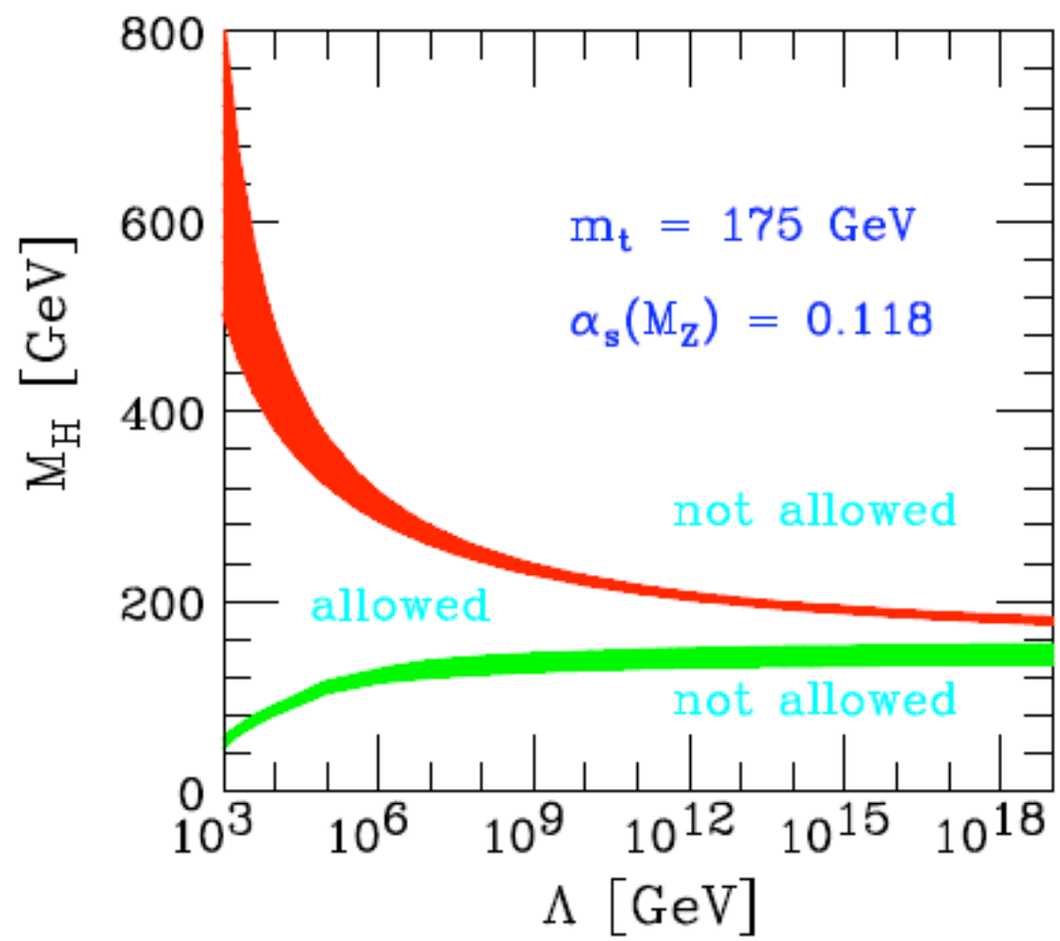
1. Denial: There is no problem. The SM is valid up to very high scale if the Higgs is either not too light or too heavy. Naturalness is our problem not Nature's. Pro's: none. Cons: a lot!



Available solutions

There have been many different suggestions!
Fortunately, we can say that they group in 1+3 large classes:

2. Weakly coupled model at the TeV scale:
Introduce new particles to cancel SM "divergences".

- This requires new particles to be related to the SM ones by some symmetry ⇒ partners.
- If we require less than 10% fine tuning, typical scale for top partners <2 TeV.
- All other particles might be heavier ⇒ first TeV the scale of new physics typically associated with top.
- Examples: SUSY (renormalizable), Little Higgs (EFT).
- Pro's: many. Con's: almost excluded.

Available solutions

There have been many different suggestions!
Fortunately, we can say that they group in 1+3 large classes:

3. Strongly coupled model at the TeV scale: New strong dynamics enters at ~1 TeV.

- Introduction of new (techni-) particles charged under a non-abelian group (not QCD). Higgs is composite.
- Top often enters as a player.
- Examples: Technicolor, Topcolor, Top see-saw, Small $N_T * N_f$ models
- Pro's: It has a strong physical motivation.
  Con's: not perturbative, difficult to make predictions. Typical problems are with EW precision fits and flavor physics.

Available solutions

There have been many different suggestions!
Fortunately, we can say that they group in 1+3 large classes:

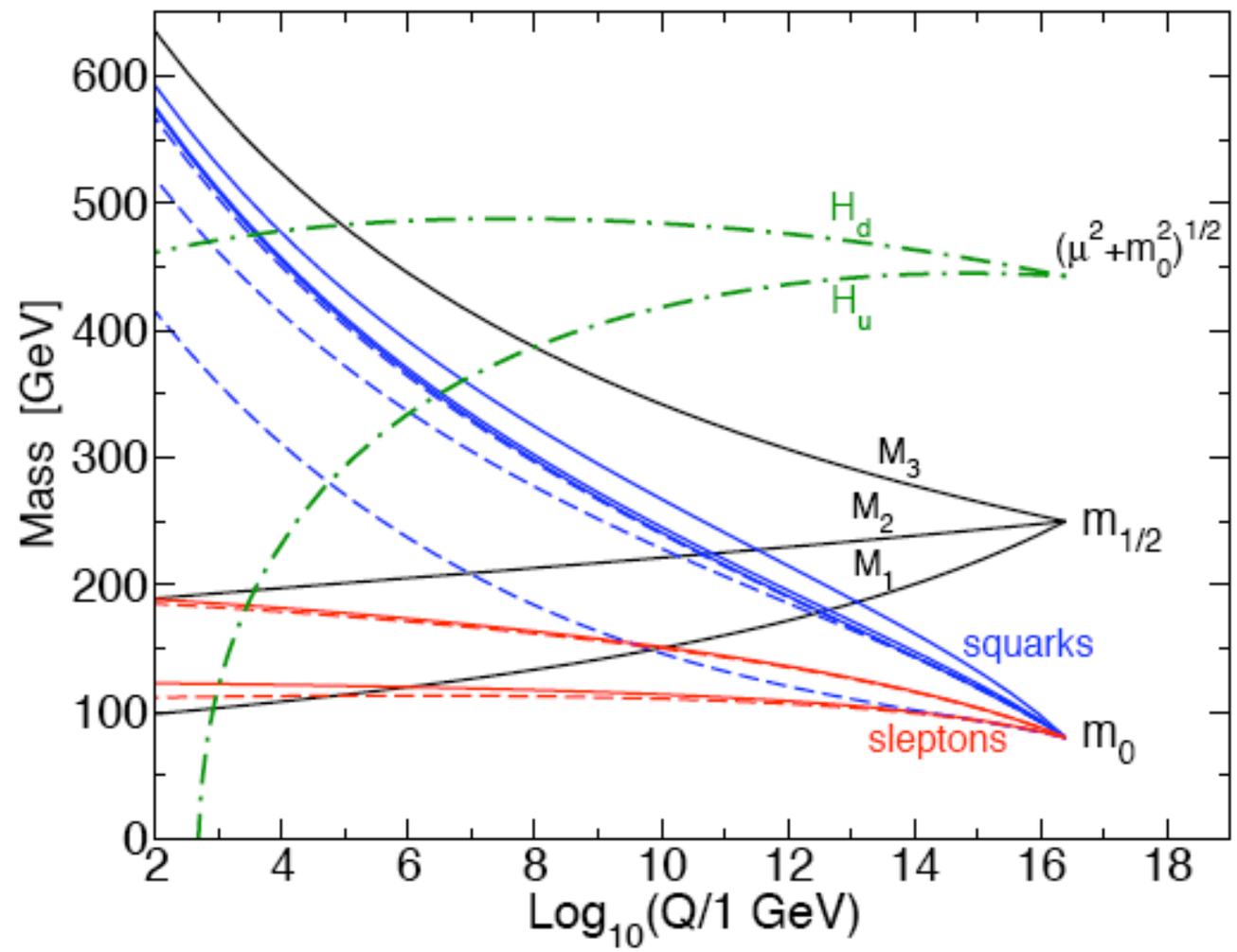
4. New space-time structure: Introduce extra space dimensions to lower the Planck scale cutoff to 1 TeV.

- No fine tuning anymore.
- Examples: ADD,RS,UED, Higgsless,...
- Pro's: very exciting and revolutionary.
- Con's: not very plausible.

SUSY

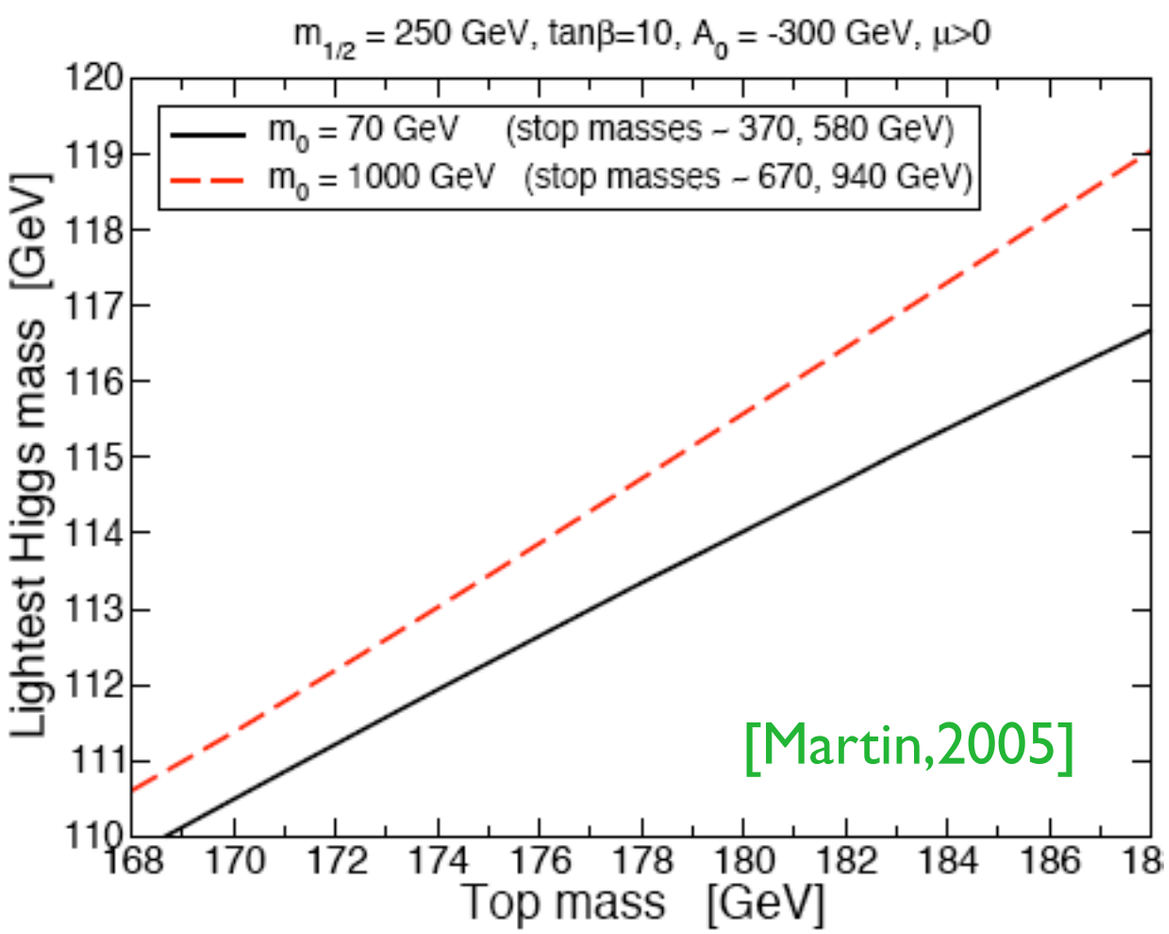
Main features relevant for top physics:

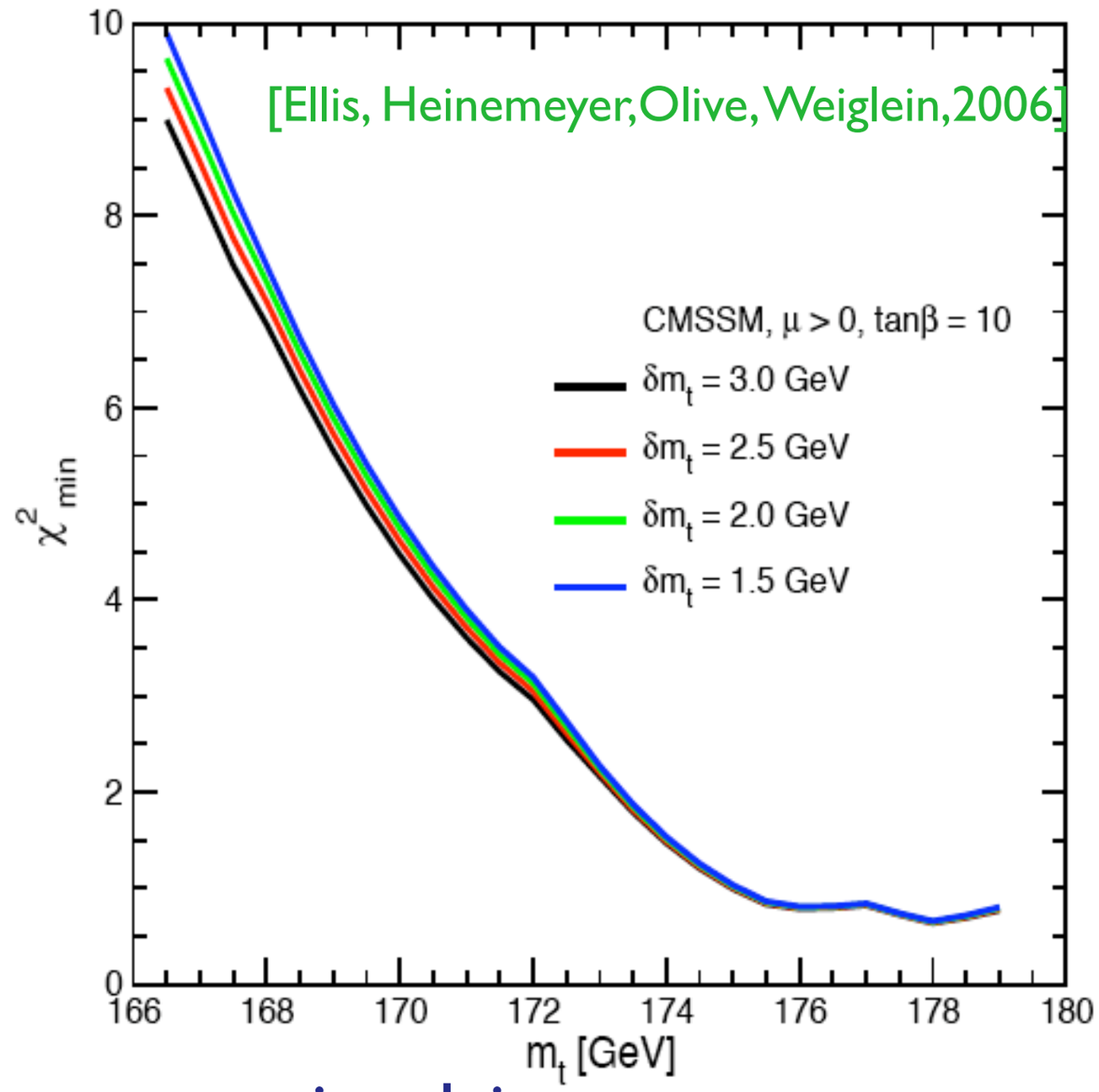
- Renormalizable theory, leading to gauge coupling unification.
- Two Higgs doublets, 5 physical states
- Top as scalar partner, the stop, which cancels its contribution to the Higgs mass. Typically the stop is the lightest squark.
- Large top Yukawa coupling drives EWSB by generating the right potential for the Higgs.
- In case of exact R symmetry SUSY particles have to be produced in pairs.



Top mass in SUSY

SUSY fans get more and more nervous as measurements from Tevatron drift to smaller m_{top} values...





In SUSY a plethora of phenomena involving top:
let's look only at 3 examples!

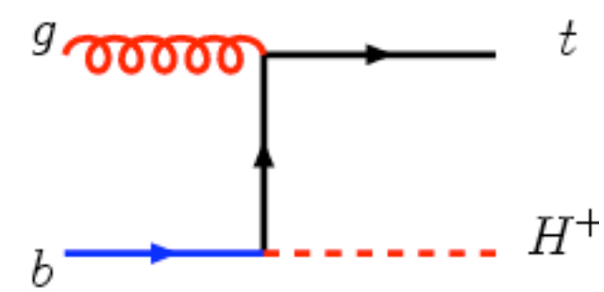
Susy example I: tH^+ production

Interest: Charged Higgs discovery

When $m_{H^+} > m_t$, no overlap with tt production, no TH need for a b-jet veto.

When $m_{H^+} < m_t$, tt production, with $t \rightarrow H^+b$ dominates. Overlap with $gb \rightarrow tH^+$ does not create a problem for discovery.

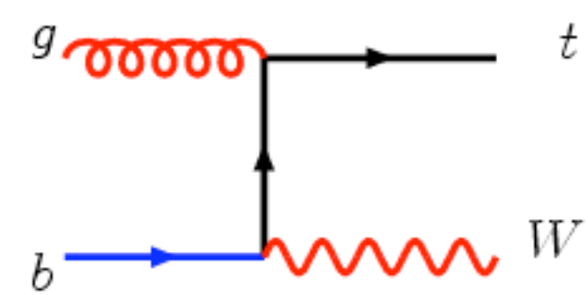
Need to be careful in the transition region $m_{H^+} \sim m_t$.



Interest: V_{tb} measurement

The Cinderella of the three channels. Not studied as much as s and t. Tiny at the Tevatron, sizeable at the LHC. It is similar to tt: it just has one b-jet less! Possible interesting signature: 2 leptons, missing Et, and exactly one b-jet. A b-jet veto is needed for a meaningful definition even at the TH level.
Focus on Vtb.

Important background when tt + jet veto is large (Ex: $gg \rightarrow H \rightarrow WW$).

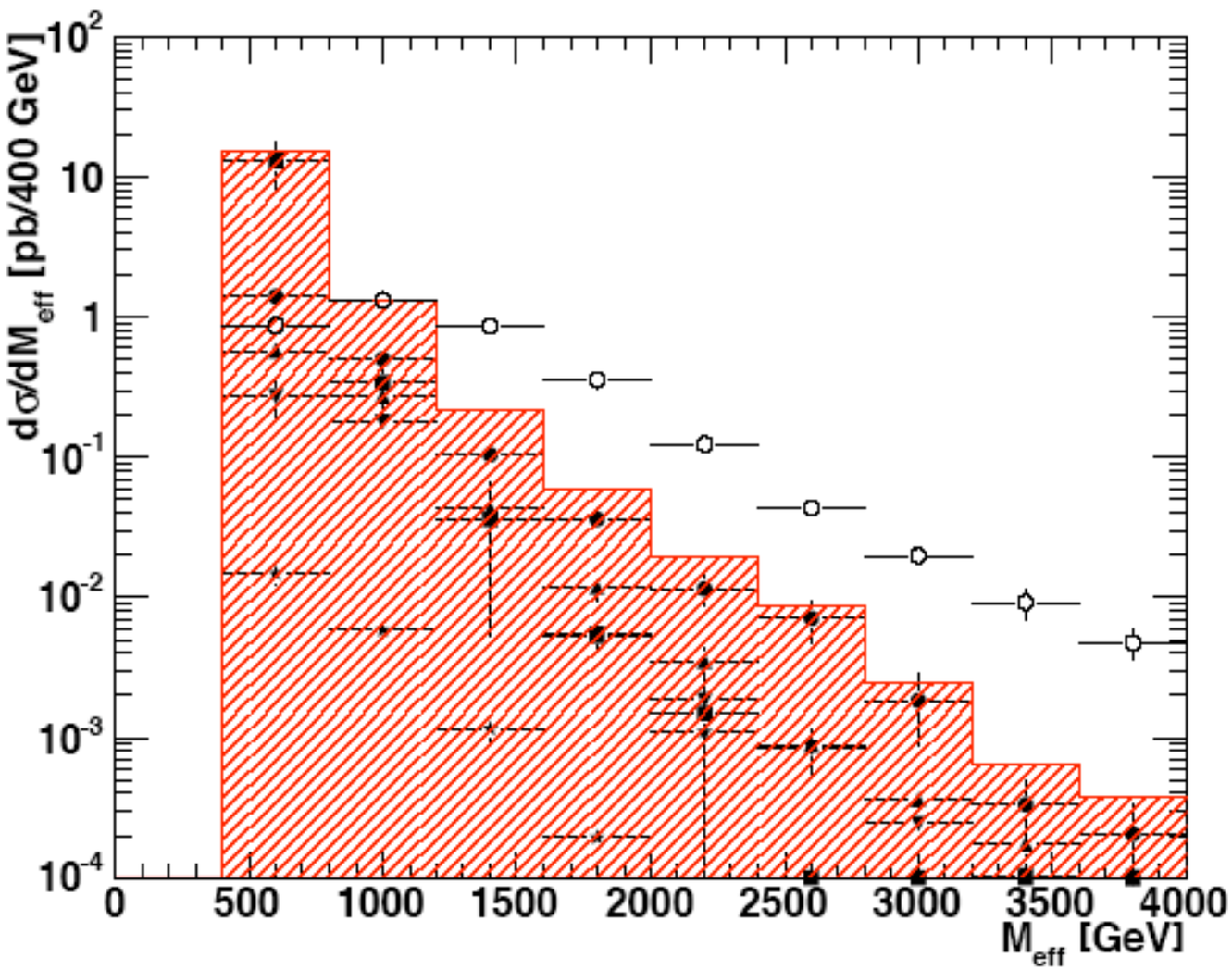


SUSY example II

[Kraml, Raklev, 2006]

$$\tilde{g}\tilde{g} \to t\bar{t}\tilde{t}_1\tilde{t}_1^*, t t\tilde{t}_1^*\tilde{t}_1^*, \bar{t}\bar{t}\tilde{t}_1\tilde{t}_1 \qquad m_{\tilde{t}_1} < m_t$$

$$pp \to \tilde{g}\tilde{g} \to bbl^{\pm}l^{\pm} + \text{jets} + E^T_{\text{miss}} \qquad \tilde{t} \to c\tilde{\chi}_1^0$$



Same-sign top quarks as a signature of light stops.

Very nice, typical SUSY inclusive signature: need for a very good control of the SM backgrounds.

Warning: Pythia (used here) is largely underestimating W,Z,tt + jets backgrounds. Matrix elements + PS and normalization to data needed.

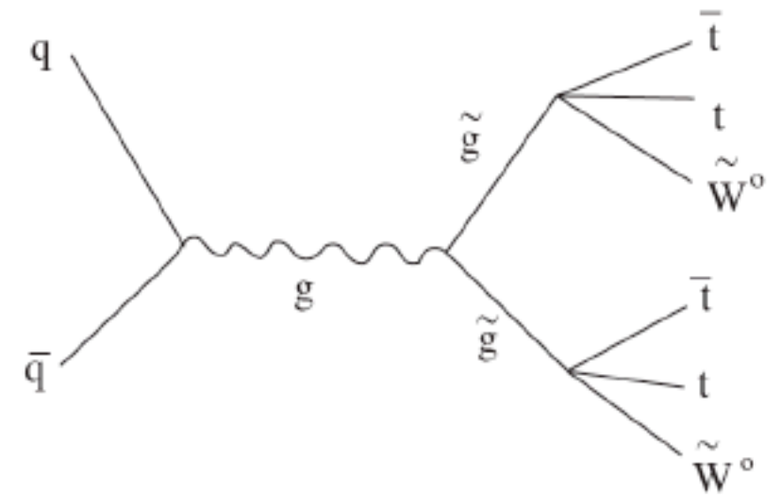
SUSY example III

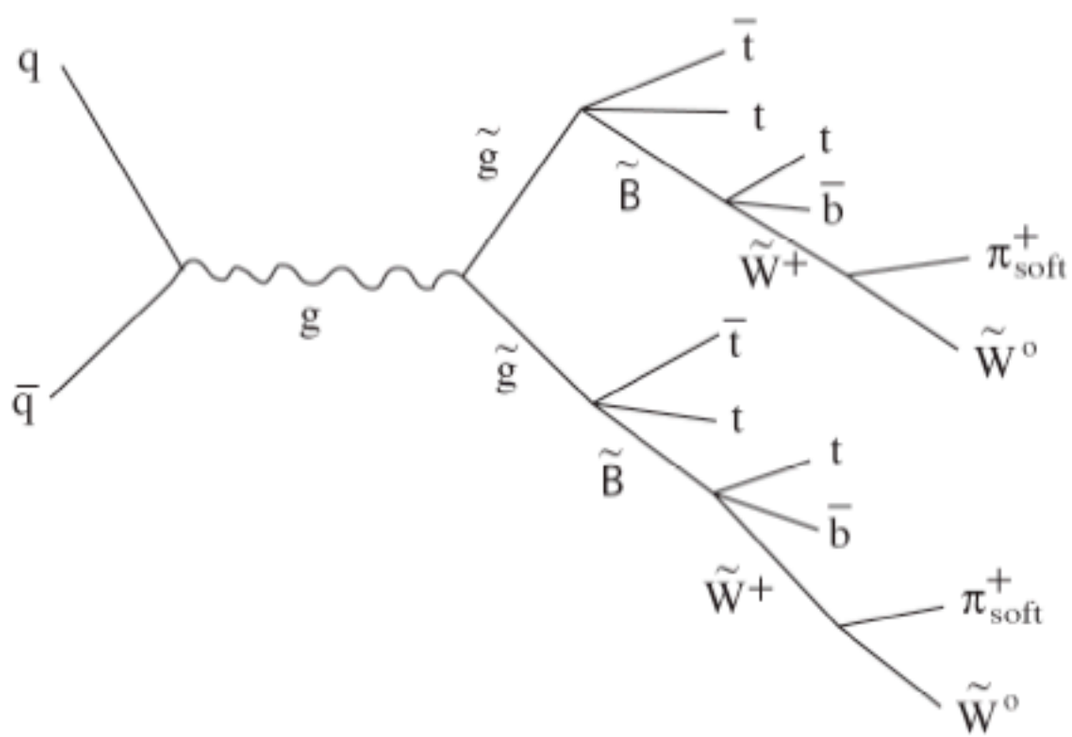
[Wells, 2006]

Schizophrenic SUSY:

$m_{scalars} \approx 30$ TeV, $m_{fermions} < 1$ TeV

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





Combinatoric/experimental Challenge.

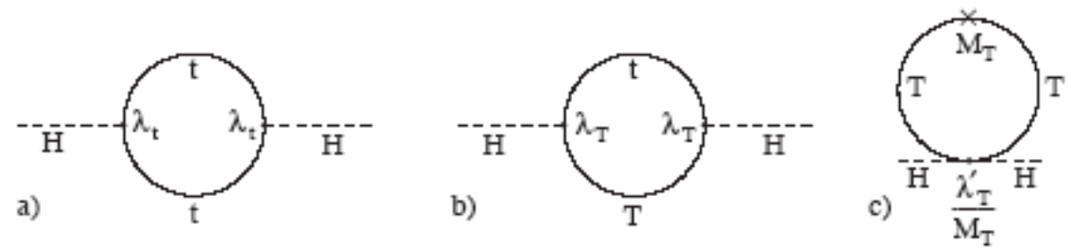
6 tops + 2 b's + 2 pions + MET

A theorist's dream = an experimentalist's nightmare !

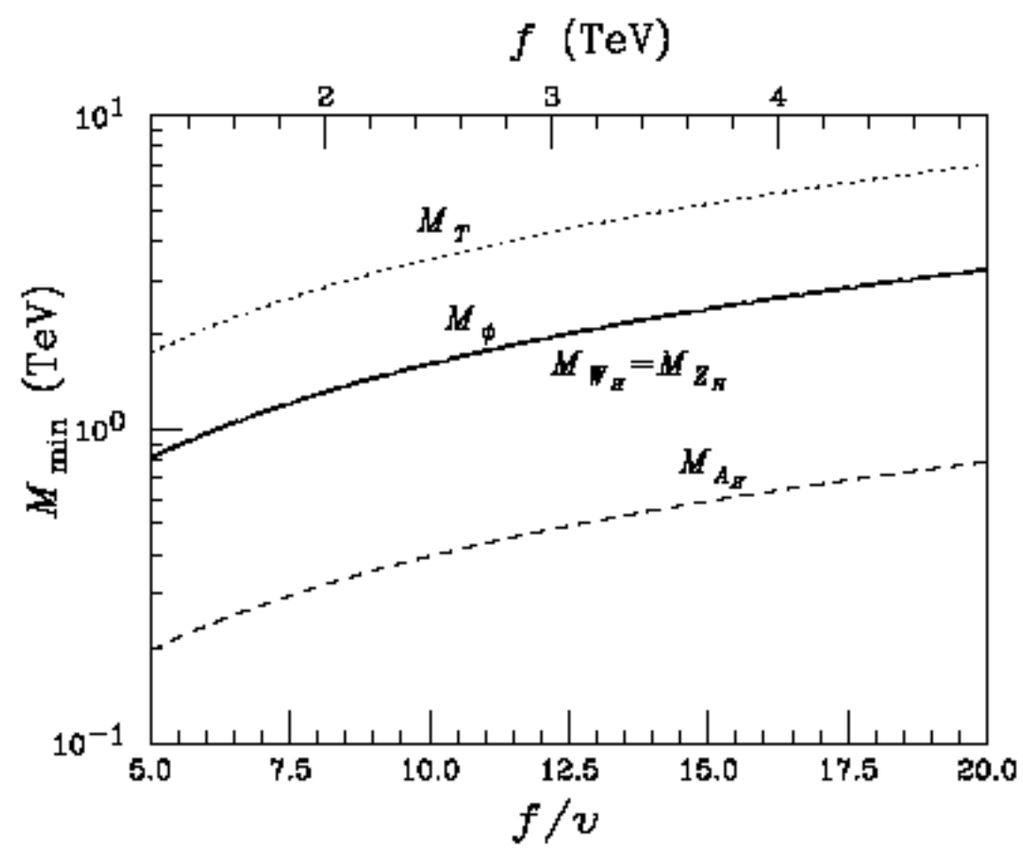
Little Higgs models

Main features relevant for top physics:

- Higgs field is a Goldstone boson resulting from breaking of a continuos symmetry
- Cancellation of quadratic divergence happens through same spin partners, thanks to the overall symmetry breaking patterns.
- Littlest Higgs predicts Vector like partner of a top at 1-2 TeV, EW gauge boson partners and a weak triplet scalar field.
- To solve problems with EW precision data, T parity for the EW gauge bosons has been included.
- Many variants exist with different phenomenology

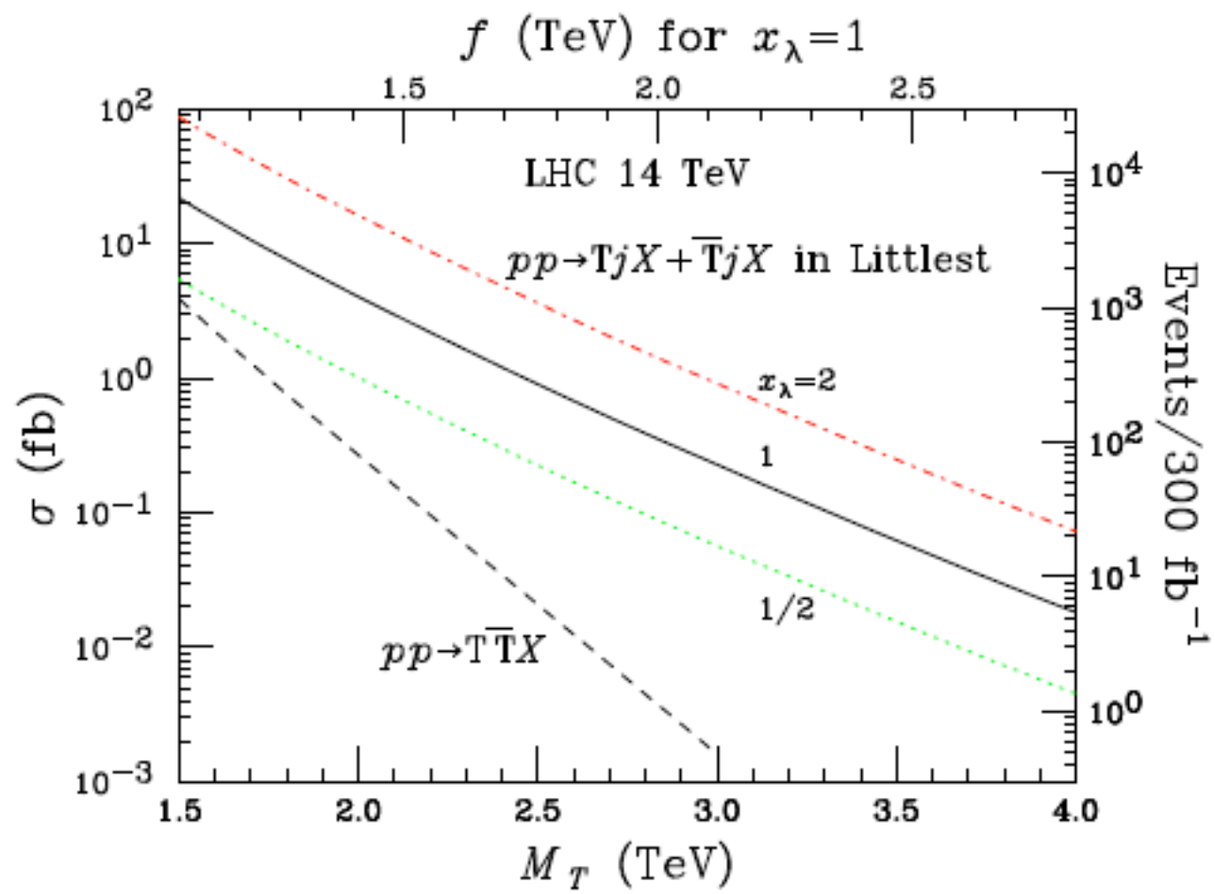


$$\lambda'_T = \lambda_t^2 + \lambda_T^2$$



Little Higgs: example I

- Production in pairs or singles of the partner of the top.
- CKM structure not affected.
- T →tH and tZ decays allowed
- EW precision measurements imply a rather large mass for the T.

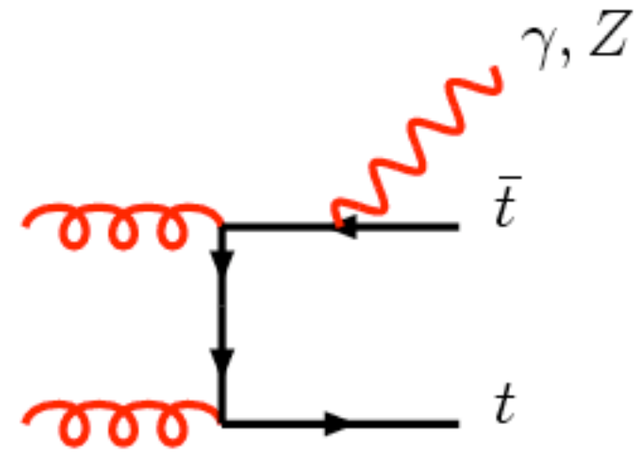


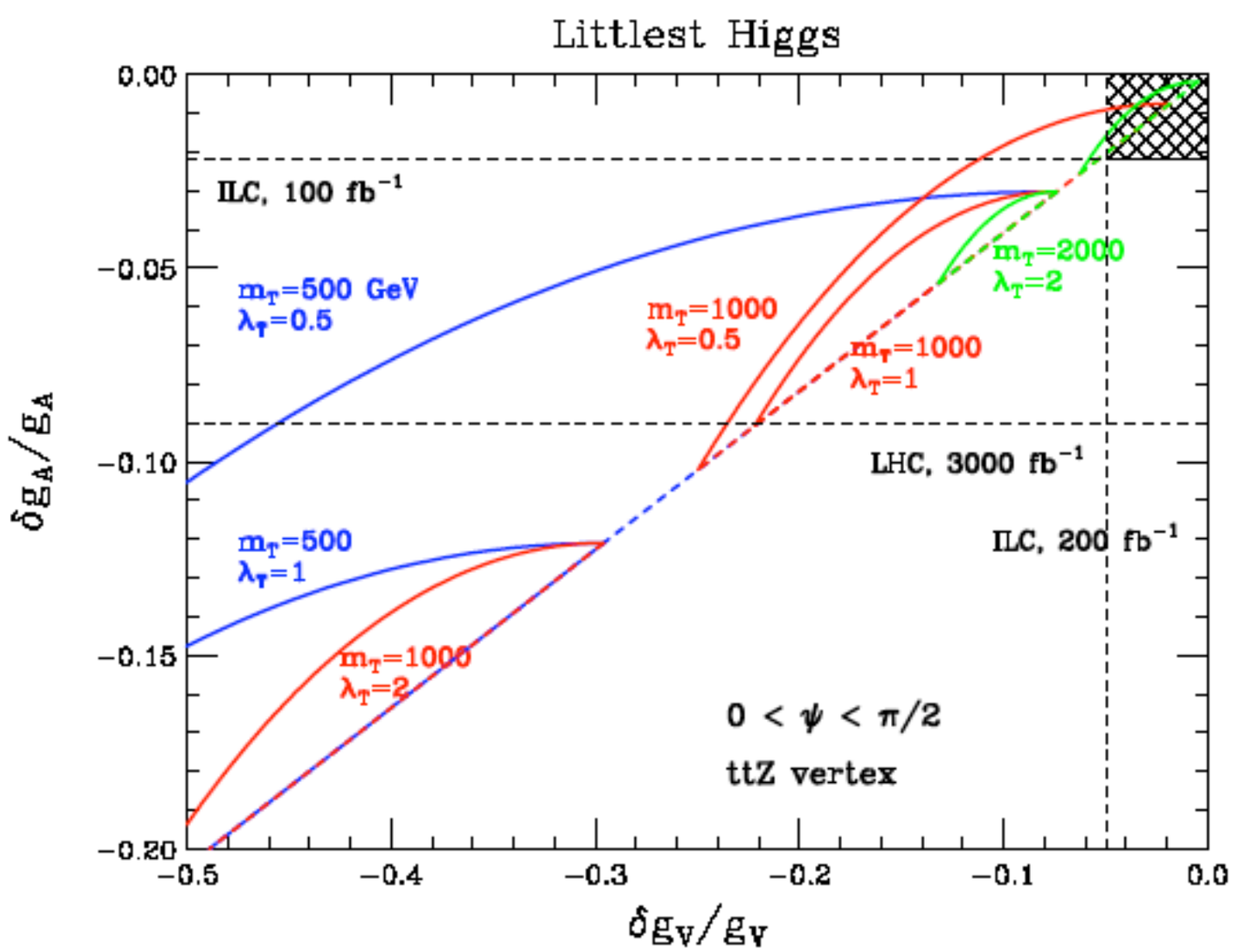
[Han, Logan, Wang, 2005]

Little Higgs: example II

For the charge, Q_t, one can measure $\sigma(tt\gamma)$: marginal at the Tevatron, good at the LHC. Only known at LO.

For the weak coupling to the Z, measure $\sigma(ttZ)$: feasible at the LHC. Only known at LO. Baur, Juste, Orr, Rainwater '04





[Berger, Perelstein,Petriello 2005]

$$\delta g_R^{Zt} = 0$$

$$\delta g_L^{Zt} = \frac{\lambda_T^2 v^2 g_A^Z}{m_T^2}$$

$$\delta g_R^{Zg} = \frac{v^2}{4f^2}\frac{c_\psi^2 s_\psi^2}{c_W^2 - s_W^2} g_R^Z,$$

$$\delta g_L^{Zg} = \frac{v^2}{4f^2}\left[2 g_A^Z s_\psi^4 + g_R^Z \frac{c_\psi^2 s_\psi^2}{c_W^2 - s_W^2}\right]$$

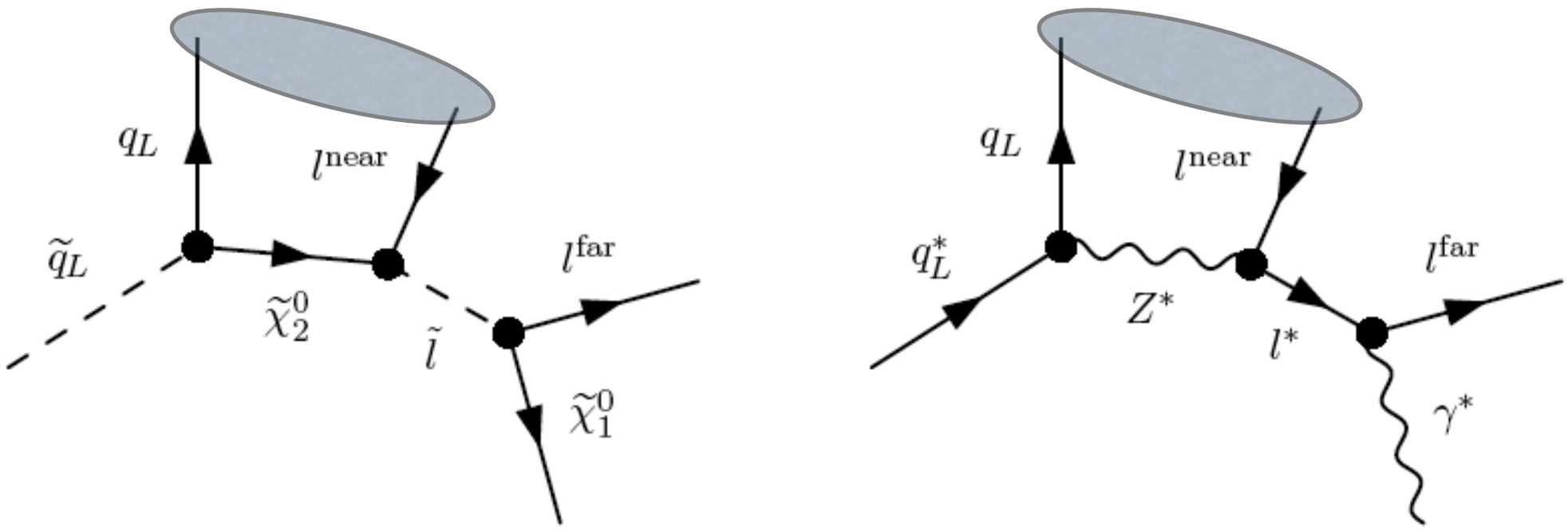
Modified space-time

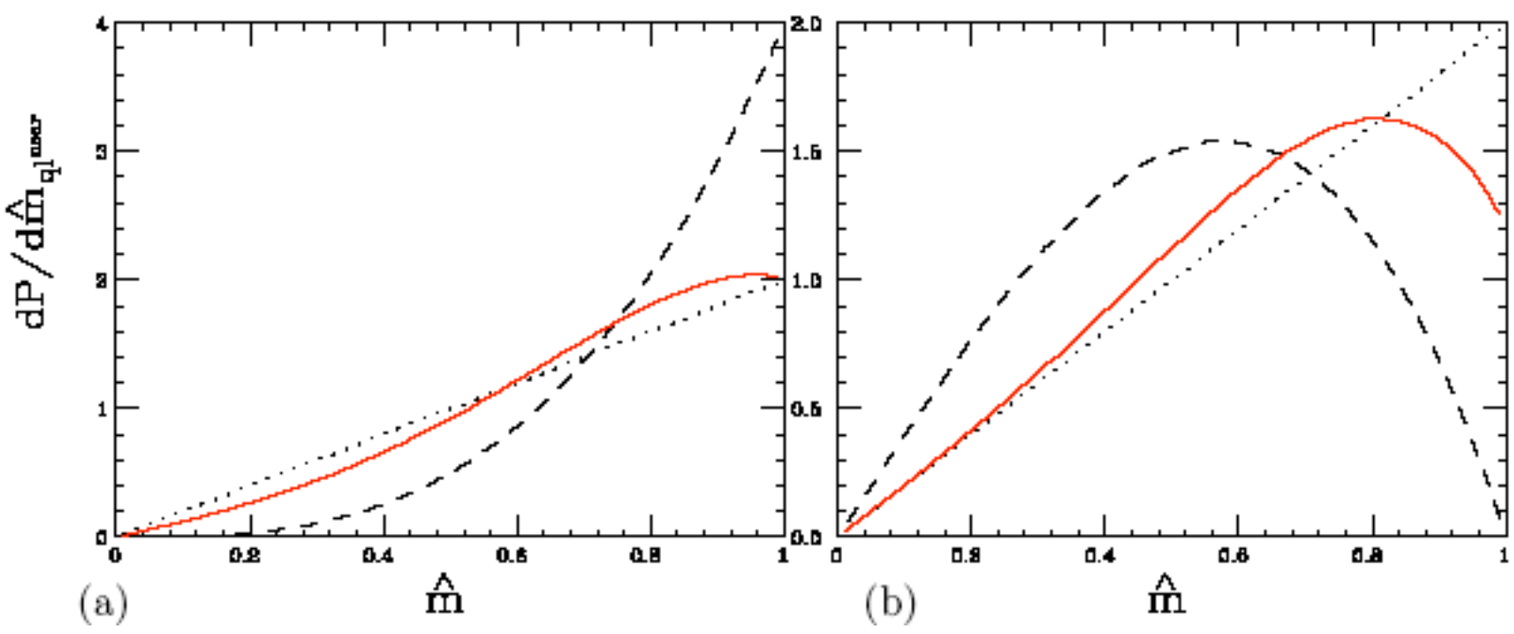
Main features relevant for top physics:

- Large extra space dimensions reduce effective gravity scale to TeV
- Models are characterized by extra dimensions warped or flat and by where the SM partcicles leave.
- Common feature: Fourier modes of the bosonic fields - Kaluza-Klein excitations of gravitons.
- Phenomenology is model dependent (ADD,RS,UED,Higgless,...) and top does not play any special role.
- In some models, like UED, some or all SM particles propagate uniformly in the bulk (flat ED) and each of them has KK excitation associated to it. Even in this case a top might have a heavier partner.

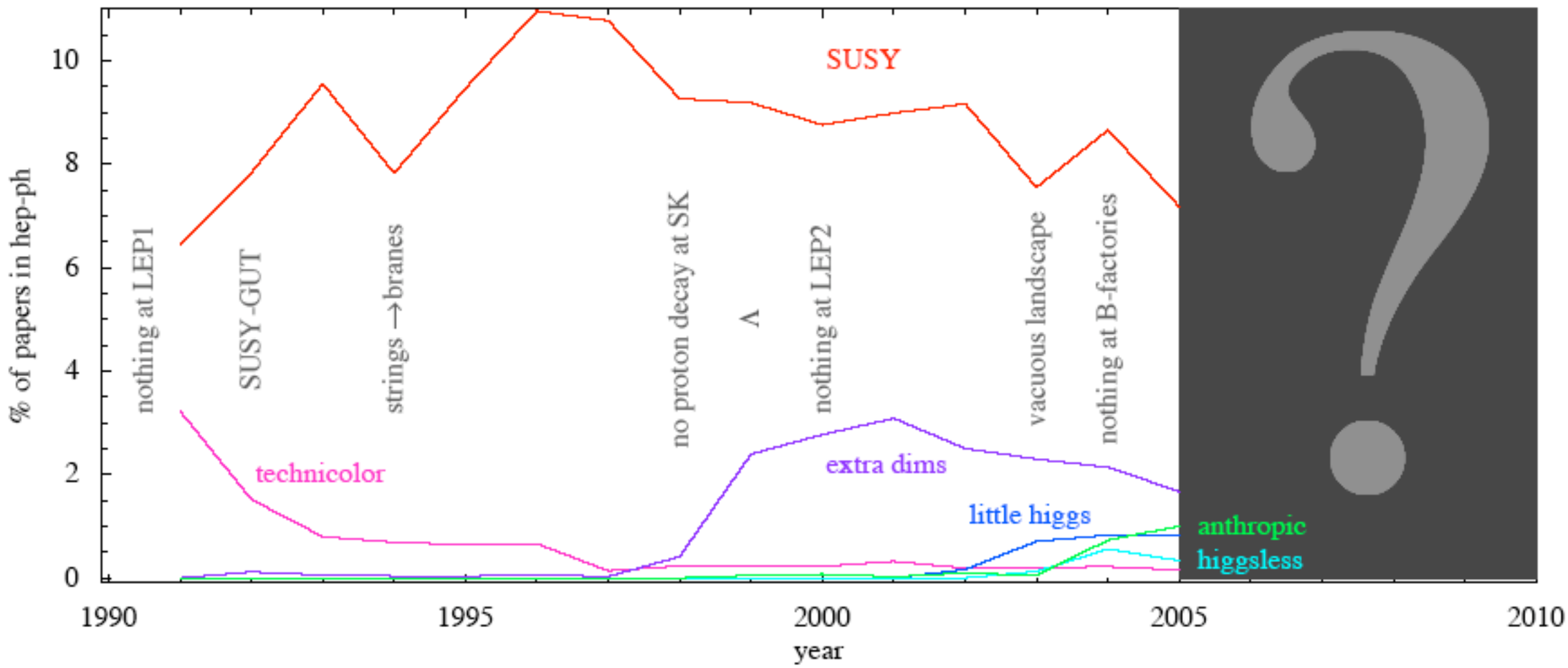
Spin correlations: SUSY vs UED

[Smillie, Webber, 2005]





More and more models available...



[Strumia, IFAE, 2006]

Th: Trend to balkanization.

Exp: Increased demand for multi-purpose MC tools able to simulate "any" model.

Reasonal approach while waiting for data:

Focus on signatures and use new models as templates to sharpen our swords

Outline

- SM introduction
- Top in BSM scenarios
- A different strategy: m_{tt} at the LHC
- Top & flavor physics: BSM from $V_{tb} < 1$
- Conclusions

Top & flavor physics: V_{tb}

The study of flavor physics and the structure of CP violation in the SM offers a complementary way to the direct search of new physics at colliders.

Tree-level FC processes in the SM are via charged-currents interactions

$$J_\mu^+ = \bar{u}_L \gamma_\mu d_L \overset{\text{mass eigenstates}}{\Longrightarrow} J_\mu^+ = \bar{U}_L \gamma_\mu \mathbf{V}_{\text{CKM}} D_L$$

Direct tree-level dominated process measurements lead to:

$$|\mathbf{V}_{\text{CKM}}| = \begin{pmatrix} 0.9738 \pm 0.0005 & 0.2200 \pm 0.0026 & (3.67 \pm 0.47) \times 10^{-3} \\ 0.224 \pm 0.012 & 0.996 \pm 0.013 & (41.3 \pm 1.5) \times 10^{-3} \\ ? & ? & ? \end{pmatrix}$$

$$\delta_{\text{CKM}} = (71 \pm 16)^\circ.$$

At present we have no direct information on each of the CKM elements of third line!

Top & flavor physics: V_{tb}

It is the hypothesis of unitarity of the CKM which contraints the V_{ti} matrix elements

$$|V_{td}| \simeq 0.0048 - 0.014, \quad |V_{ts}| \simeq 0.037 - 0.043, \quad |V_{tb}| \simeq 0.9990 - 0.9992$$

$$\mathcal{O}(\lambda^3) \qquad \mathcal{O}(\lambda^2) \qquad \mathcal{O}(1)$$

where $\lambda \simeq 0.22$. $\longrightarrow$ but true only for 3 generations.

For example, the most recent CDF measurements on B_s mixing

$$\Delta M_s = 17.33^{+0.42}_{-0.21}(\text{stat.}) \pm 0.07(\text{syst.})\text{ps}^{-1} \quad \text{CDF collab.}$$

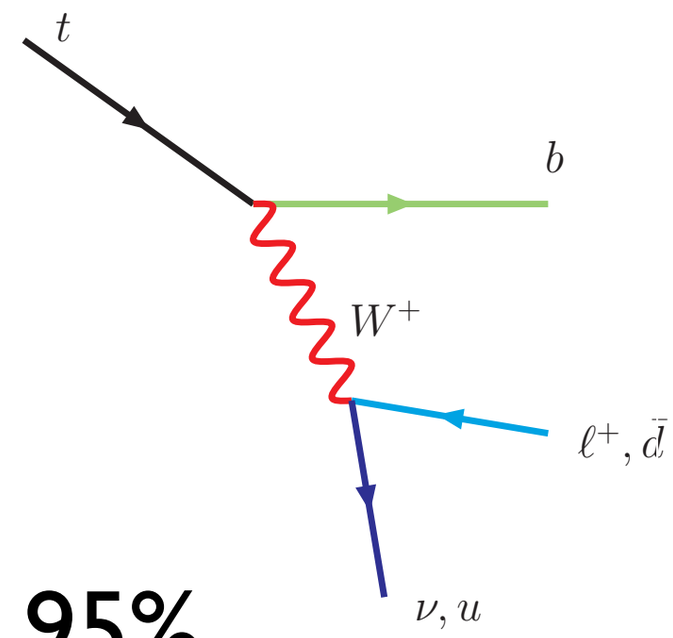
is a good agreement with the SM prediction

$$0.20 < |V_{td}/V_{ts}| < 0.22.$$

$\longrightarrow$ but true only if box diagram is new physics free.

Top & flavor physics: V_{tb}

V_{ti} from Tevatron



Top can decay into a real W $\Rightarrow$ $\Gamma_t \approx$ GF m_t^3 ($|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2$)

but we don't measure the width only the branching ratio:

$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

>0.61 at 95%

$1.12^{+0.21}_{-0.19}(\text{stat})^{+0.17}_{-0.13}(\text{syst})$, CDF, $1.03^{+0.19}_{-0.17}$ (stat + syst), DØ

$\longrightarrow$ but this indicates only small $|V_{ts}|/|V_{tb}|$ and $|V_{td}|/|V_{tb}|$ and the absolute size of V_{tb} is not constrained *at all*.

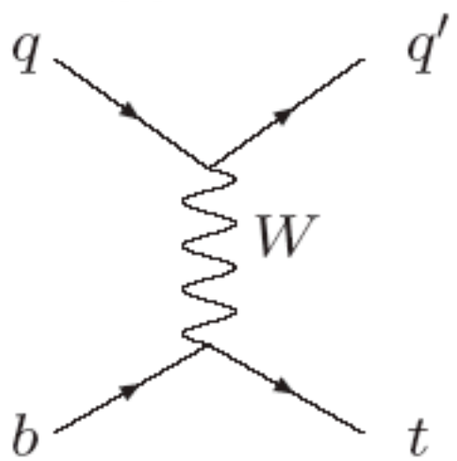
Top & flavor physics: V_{tb}

V_{ti} from Tevatron

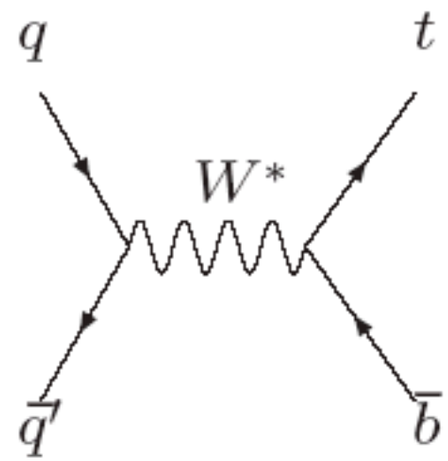
We can gain direct access from the single top measurements:

Inclusion of s, d quark contributions to t- and s-channel:

$$\sigma(pp \to tX) = |V_{td}|^2\sigma_d + |V_{ts}|^2\sigma_s + |V_{tb}|^2\sigma_b$$
$$\sigma(pp \to tX) = (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2)\sigma^{\text{s-channel}}$$



(d and s?)



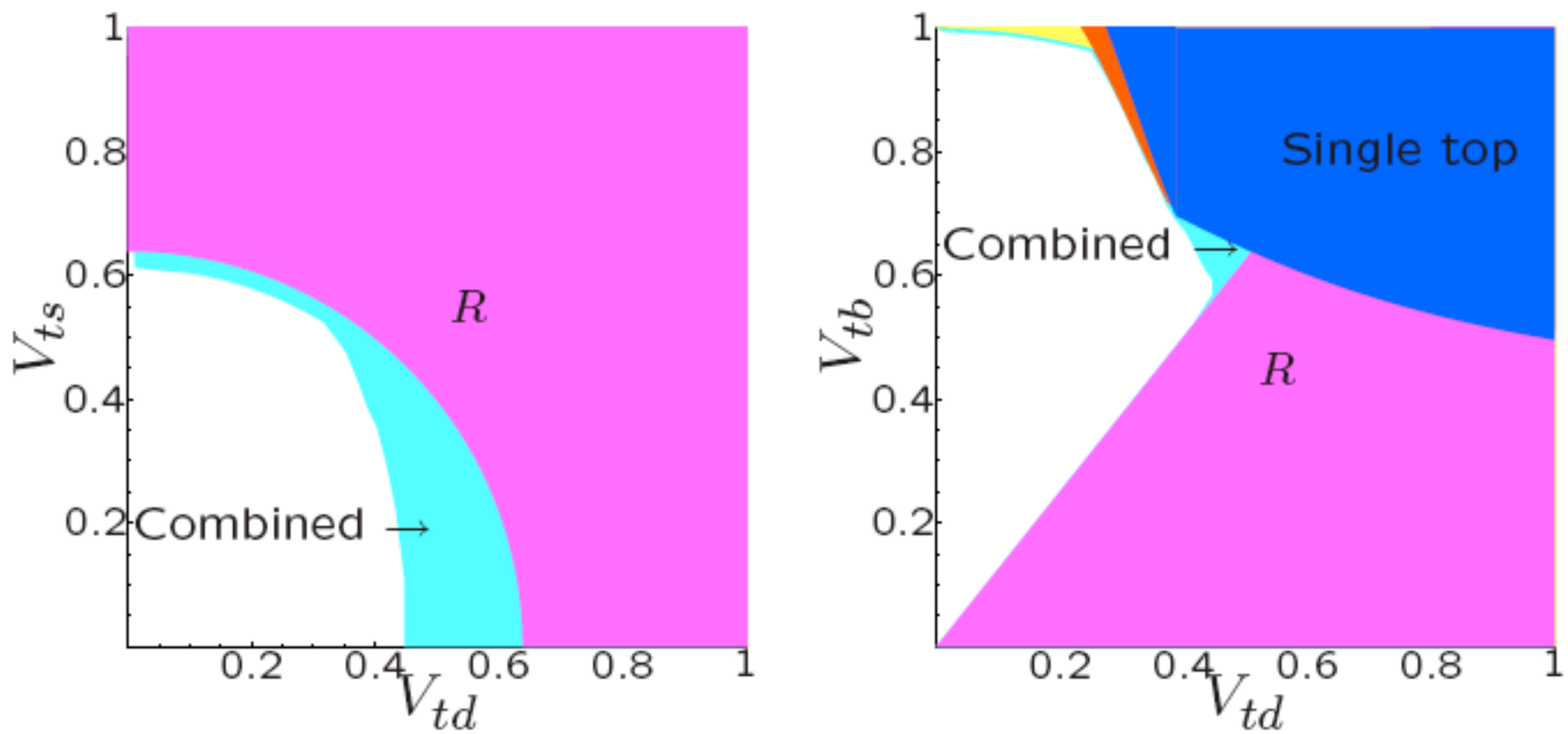
Using the present limits from CDF

$$\sigma^{\text{t-channel}} < 3.2\text{pb}; \qquad \sigma^{\text{s-channel}} < 3.1\text{pb}$$

taking into account the different Br's and combining them with R we obtain

Top & flavor physics: V_{tb}

V_{ti} from Tevatron



[Alwall et al. , CP3, 2006]

Conclusion Vtb is (mildly) constrained constrained from Tevatron direct measurements. At present this is only a TH exercise. It would be nice to see similar plots done by CDF and D0....

Up to this point the analysis is completely model independent. Can we obtain more stronger constraints but considering models as general as possible?

Top & flavor physics: V_{tb}

Breaking of 3x3 unitarity requires extra-fermions.
Two choices:

1. vector-like quark (b' or t'): 3 x 4 or 4 x3 CKM (includes Little Higgs)

2. fourth generation (b' and t'): 4 x 4 CKM

Precision EW measurements, flavor physics, and direct bounds can be combined together to constraint V_{ti} if NO other new physics is included except for the above.

Let's look at case 1. which is more unusual...

Top & flavor physics: V_{tb}

Let us consider:

$(u_i,d_i)_L$ u_{iR} d_{iR} plus t'_L t'_R or b'_L b'_R as $SU(2)_L$ singlets

Some interesting properties:

1. Neutral current couplings change
2. Tree-level FCNC are introduced
3. All new couplings are fixed by the gauge structure and the CKM matrix

$$J^0_\mu \supset -\frac{g}{2\cos\theta_w}(\bar{u}_{iL}\mathbf{V}\mathbf{V}^\dagger\gamma_\mu u_{iL} + \bar{d}_{iL}\mathbf{V}^\dagger\mathbf{V}\gamma_\mu d_{iL})$$
$$J^+_\mu \supset -\frac{g}{\sqrt{2}}(\bar{u}_{iL}\mathbf{V}\gamma_\mu d_{iL} + h.c.)$$

Neutral current constraints ⇒ constraints on CKM matrix

Top & flavor physics: V_{tb}

3 x 4 and 4 x 3 matrices contain three extra mixing angles:
$\Gamma(Z \to$ hadrons) is saturated by the SM processes, therefore:

1) b' mixing to the other quarks are strongly suppressed. $\longrightarrow$ an extension to $\mathbf{V}_{3\times4}$ does not modify V_{tb} much.

2) t' mixing to the other quarks are strongly suppressed *apart from $t - t'$ mixing*.

As a result:

$$\mathbf{V}_{4\times3} = \begin{pmatrix} 1_{2\times2} & 0 \\ 0 & \mathbf{U}^{\dagger}_{2\times2} \end{pmatrix} \begin{pmatrix} \mathbf{V}^{(\mathrm{CKM})}_{3\times3} \\ 0 \end{pmatrix}; \mathbf{U} = R_{34}(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}.$$

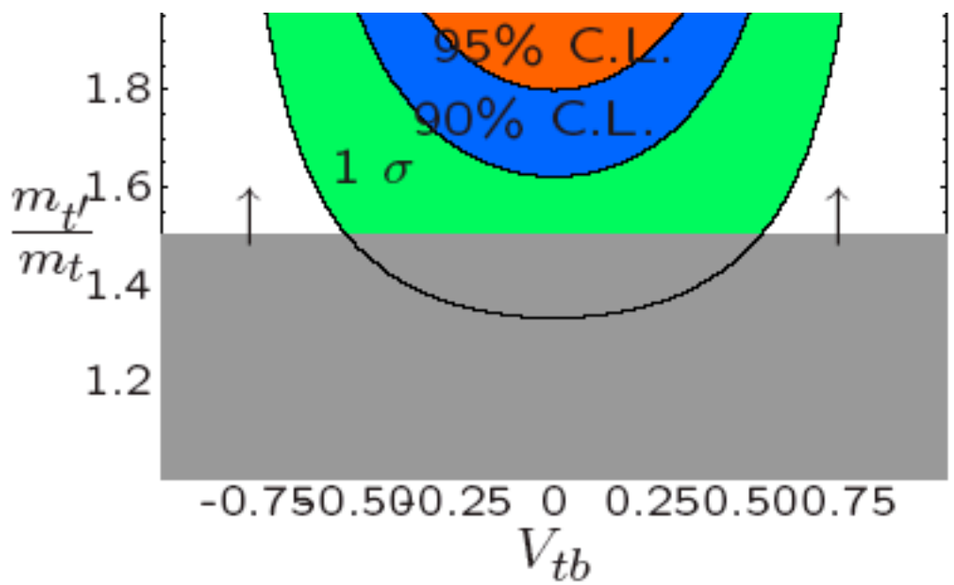
which leads to

$$V_{ti} = V^{(\mathrm{CKM})}_{ti} \cos\theta \quad V_{t'i} = V^{(\mathrm{CKM})}_{ti} \sin\theta \quad i = (d, s, b)$$

☞ With this kind of *scaling factor*, R is unity and $|V_{td}/V_{ts}|$ is SM.

Top & flavor physics: V_{tb}

The most important indirect constraints come from $B \to X_s \gamma$



$|V_{tb}| > 0.53$ at 1σ

- EW precision data: T value is approximately obtained as

$$T > 1.1 \sin^2\theta \quad \text{for} \quad m_{t'} > 258\text{GeV}$$

which actually leads to a very strong constraint

$$|V_{tb}| > 0.89 \quad \text{for} \quad T = 0.23$$

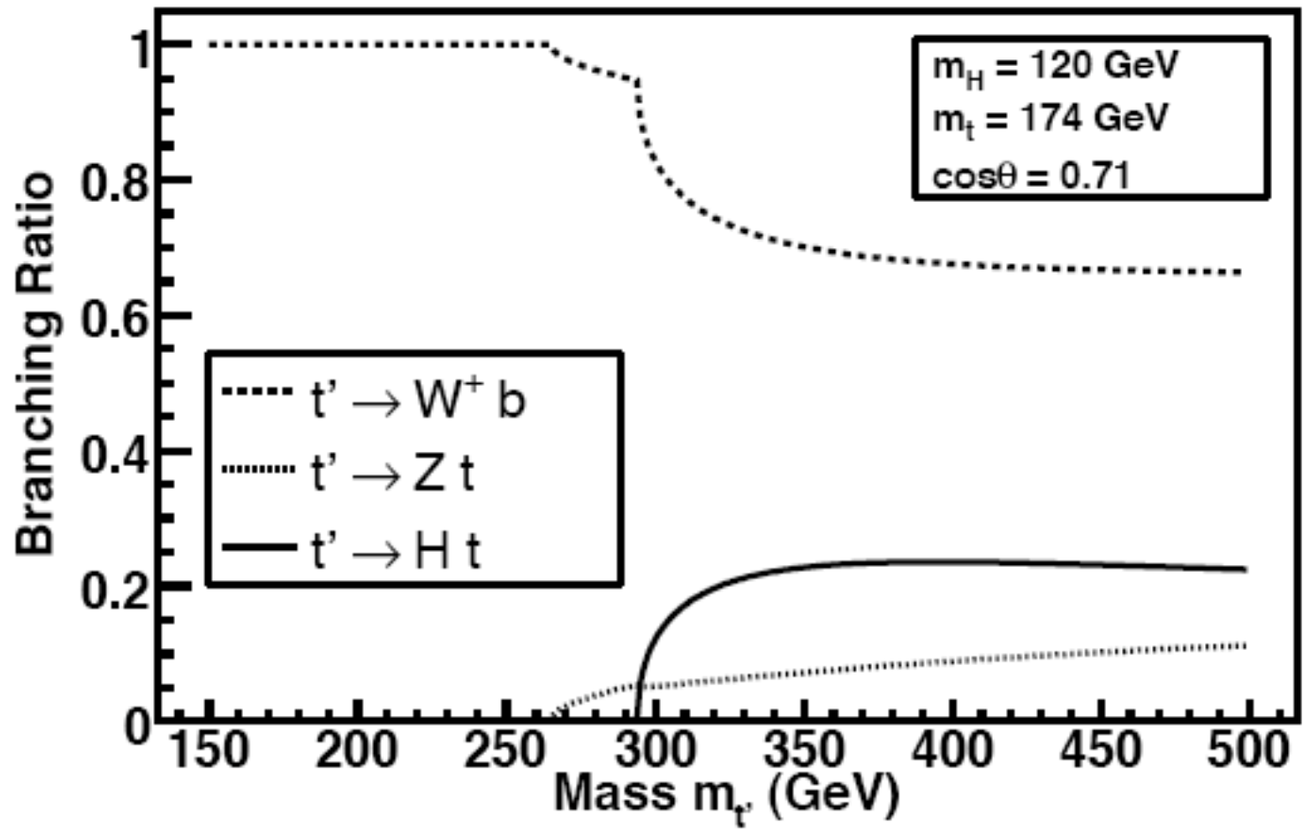
even though direct information on the Higgs mass would be needed to have a more robust limit.

Top & flavor physics: V_{tb}

CDF Run II gives:

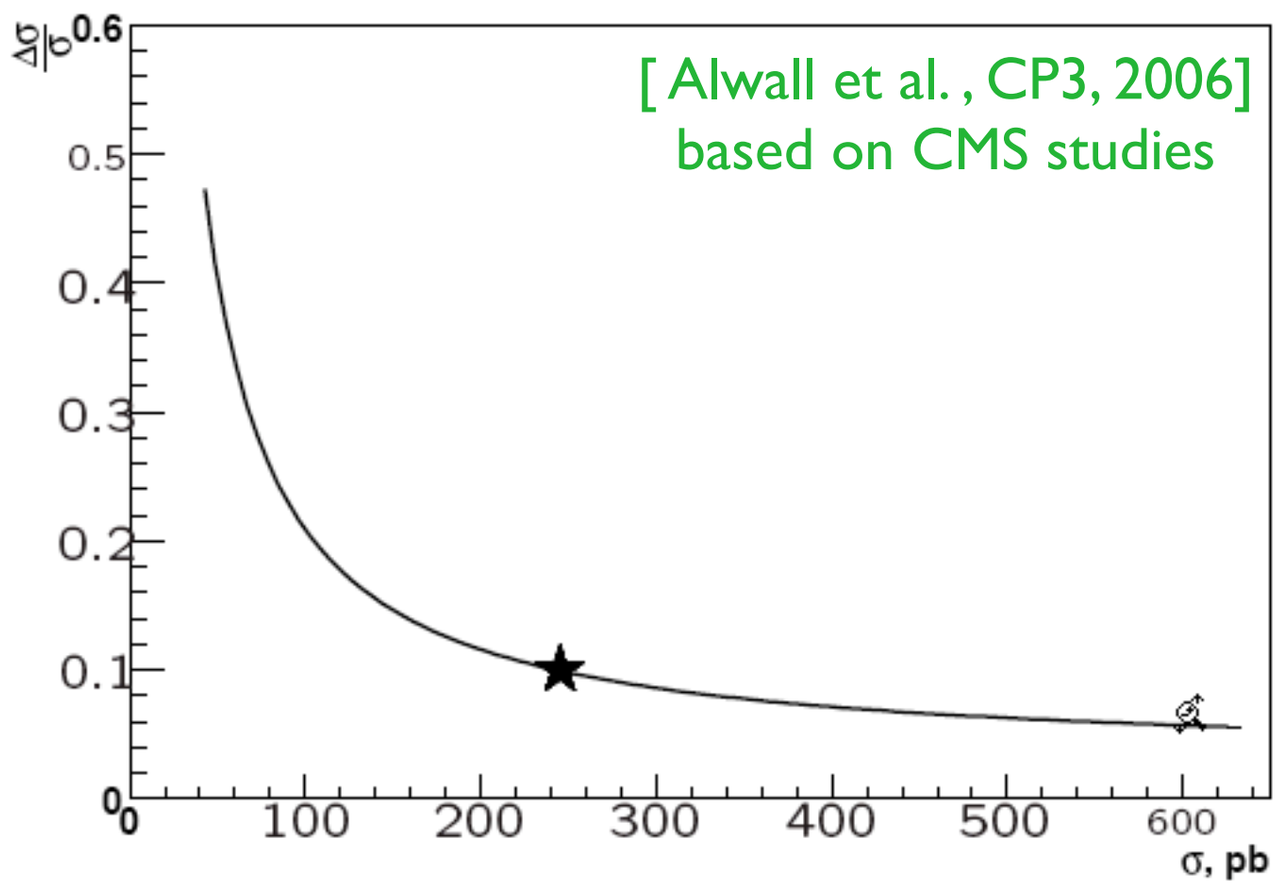
$$m_{t'} > 258\text{GeV} \quad 95\% \text{ C.L.}$$

where it was assumed Br(t'→Wq)=1. In a vector-like quark model t' has rather large FCNC decay t'→Zt/Ht when kinematically allowed.



Top & flavor physics: V_{tb}

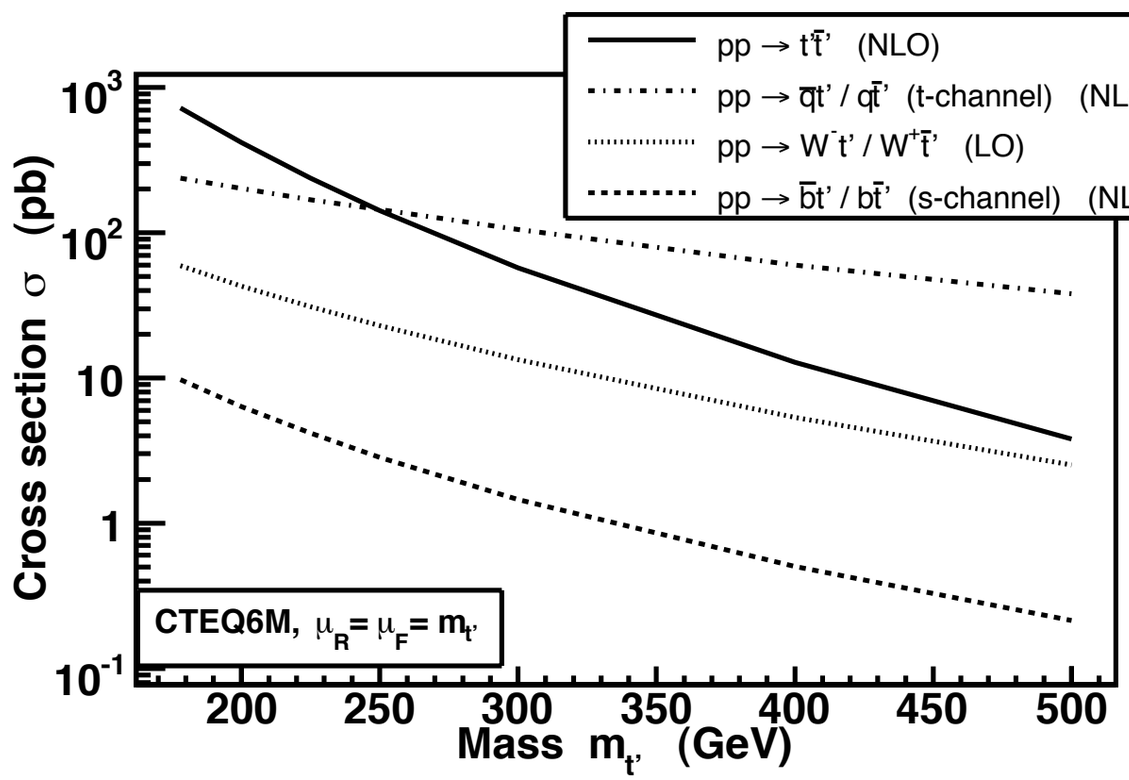
Prospects on the extraction of V_{tb} at LHC, mainly from t-channel indicate a 5% error with 10 fb^{-1} integrated luminosity, for V_{tb}=1 !



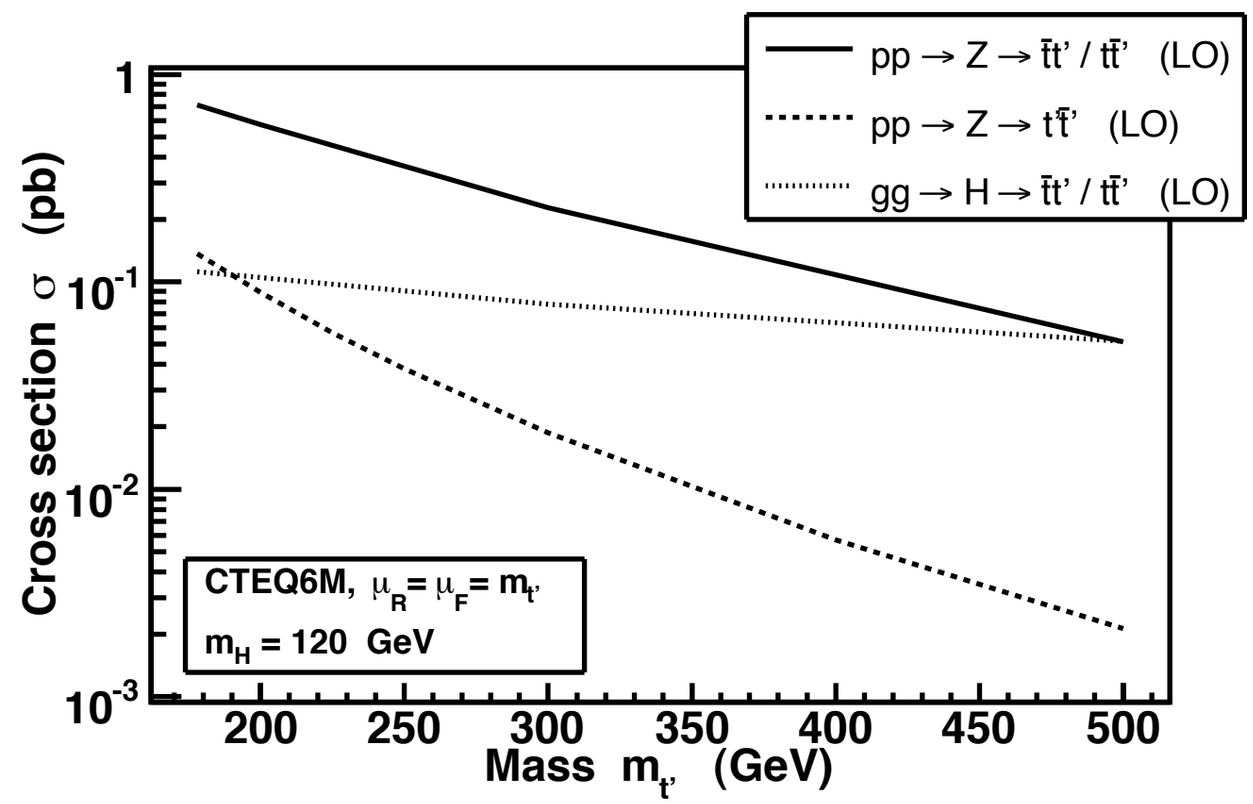
Top & Top' at the LHC

[Alwall et al. , CP3, 2006]

A vector-like quark leads to very interesting signatures. In the Little Higgs the mass of a t' is very high, but in general smaller masses cannot be yet excluded.



t't'and single t' processes.
If kinematically allowed,
the FCNC t'→tZ decay can
lead to clean signatures.



FCNC associated production
mechanism for tt'.

Conclusions

- The top quark is the best probe of EWSB and fermion mass generation.
- We have direct and indirect strategies to go after BSM physics associated to the top quark.
- A common feature of BSM models is to have one (or more) partners to the top (examples: SUSY, Little Higgs, NewTechicolor).
- Measurement of all top properties (mass, couplings, spin) is our first aim: will confirm its nature and/or hint to physics BSM.
- Experimental side: optimal situation!
  Tevatron: steady increase of luminosity+experience overcomes small rates and calls for sophisticated analysis.
  LHC: huge statistics→ top is day-1 physics with an amazing phenomenology.

Conclusions

- On the theory side, many developments and on-going efforts:

  a. More models to be challenged with
     ⇒ more templates for experimental studies

     ⇒ wider range of applications, more flexibility = less model dependence.

  b. General tools and frameworks available to simulate "any" new model, from the Lagrangian to the event level.

  c. Predictions for complex backgrounds are continuosly improved.

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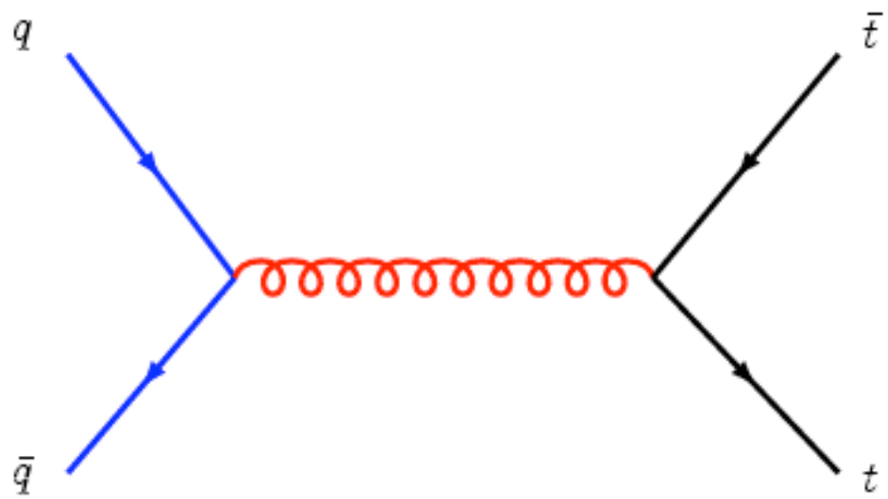
We just need... data!

Outline

- SM introduction
- Top in BSM scenarios
- A different strategy: m_{tt} at the LHC
- Top & flavor physics: BSM from $V_{tb} < 1$
- Conclusions

FROM TEV TO LHC

Tevatron



85% of the total cross section

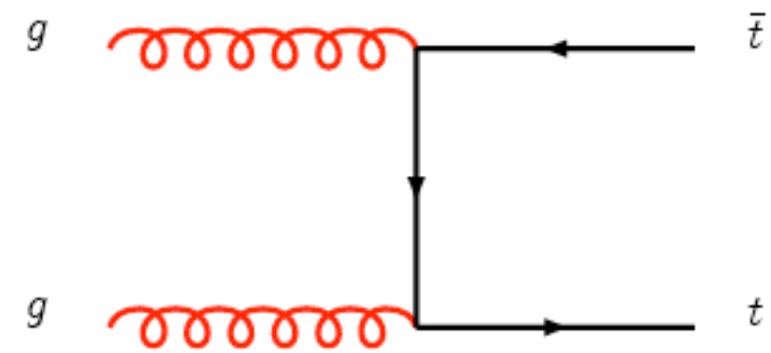
10 tt pairs per day

60% of the time there is extra radiation so that pt(tt)>15 GeV.

tt are produced closed to threshold, in a $^3S_1[8]$ state. Same spin directions. 100% correlated in the off-diagonal basis.

Worry because of the backgrounds: (W+jets, WQ+jets,WW+jets)

LHC



90% of the total cross section

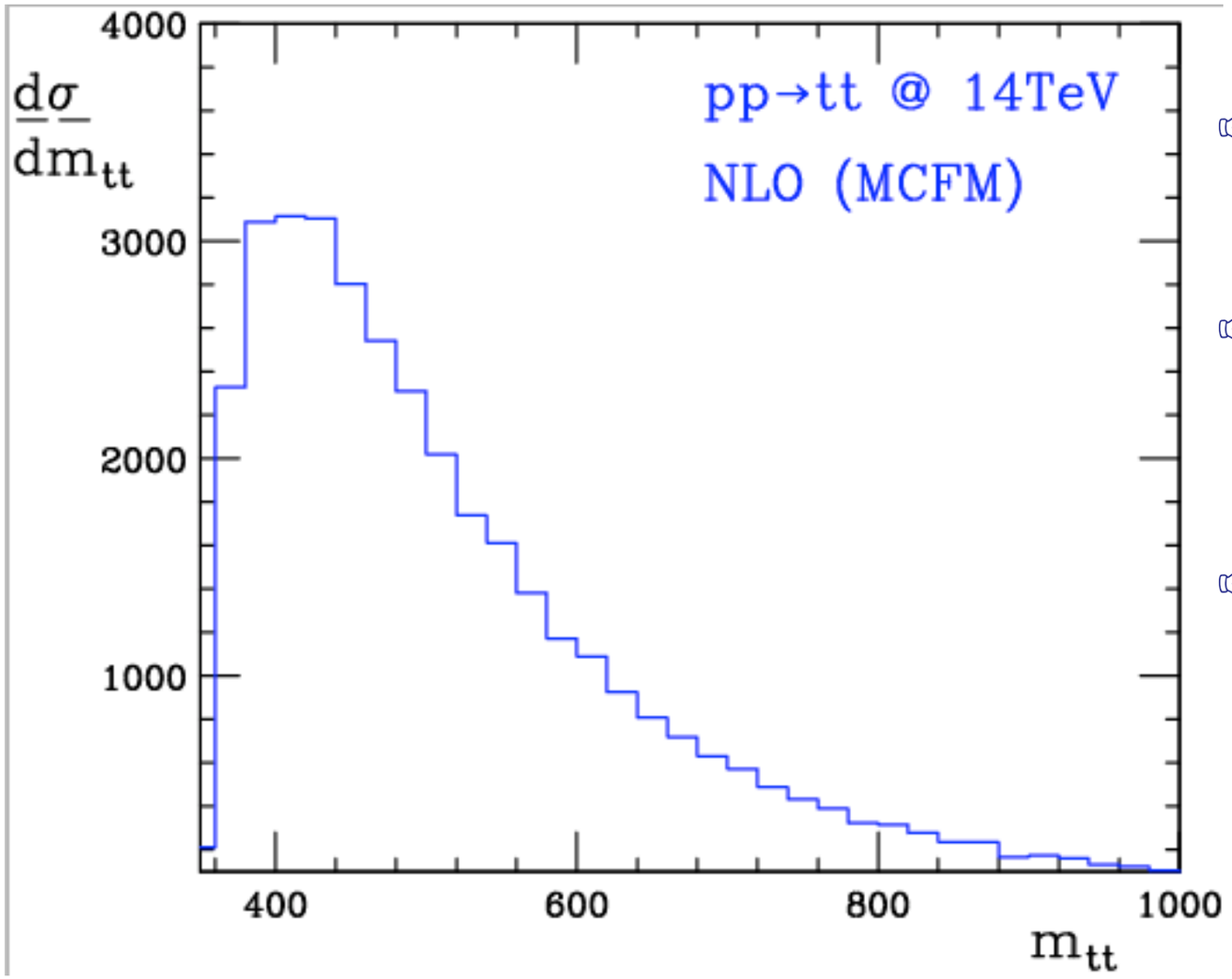
1 tt pair per second

Almost 70% of the time there is extra radiation so that pt(tt)>30 GeV.

tt can be easily produced away from threshold. On threshold they are $^1S_0$ state, with opposite spin directions. No 100% correlation.

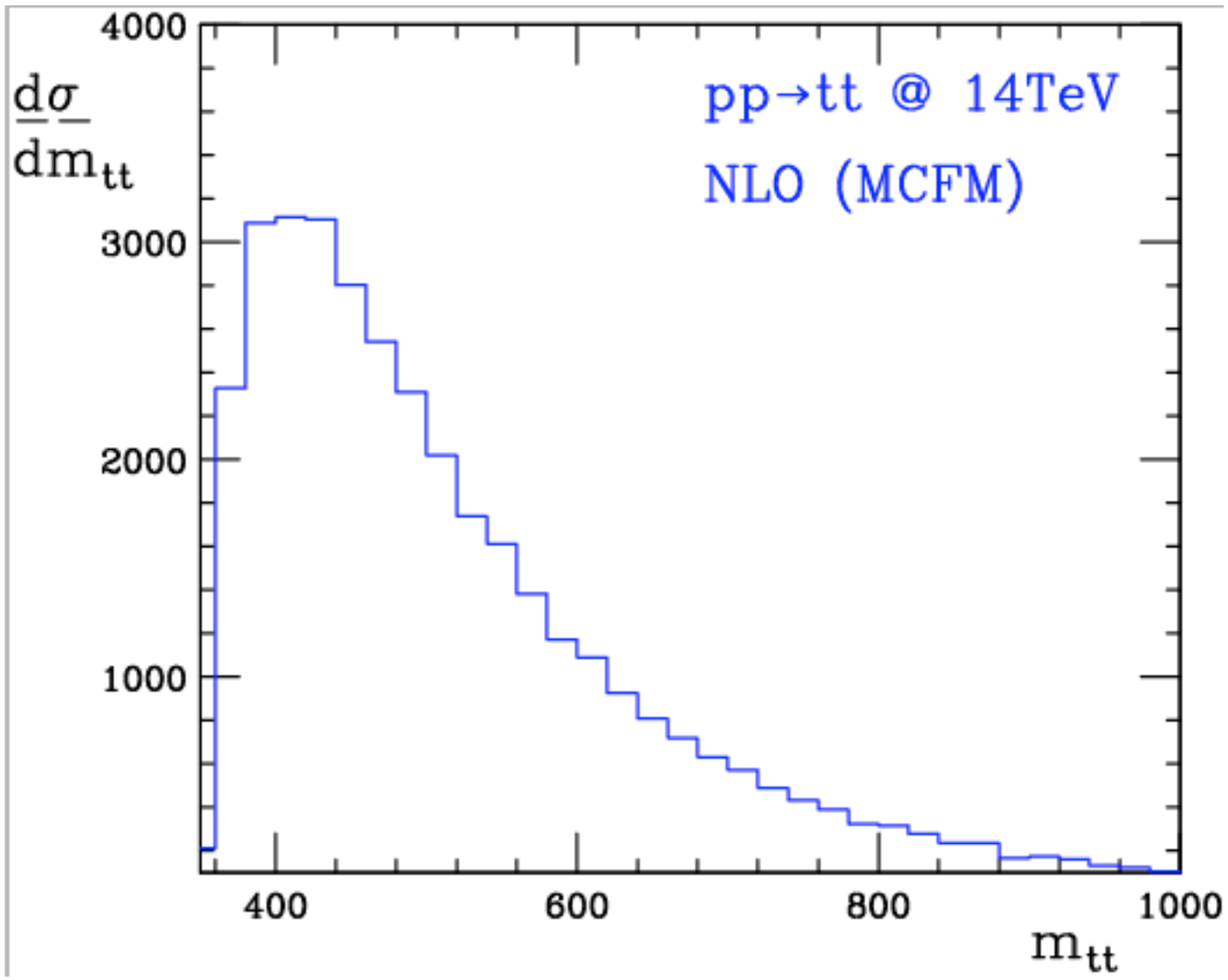
Worry because IT is a background!

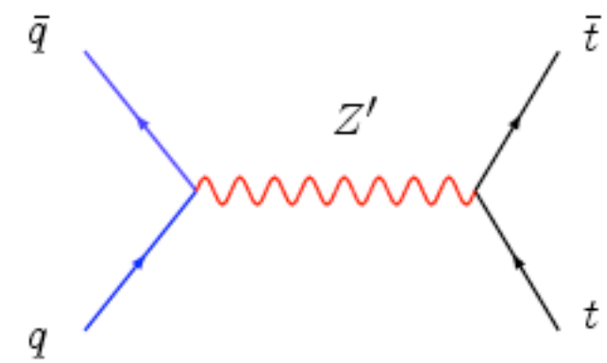
m_{tt} as a BSM physics observatory

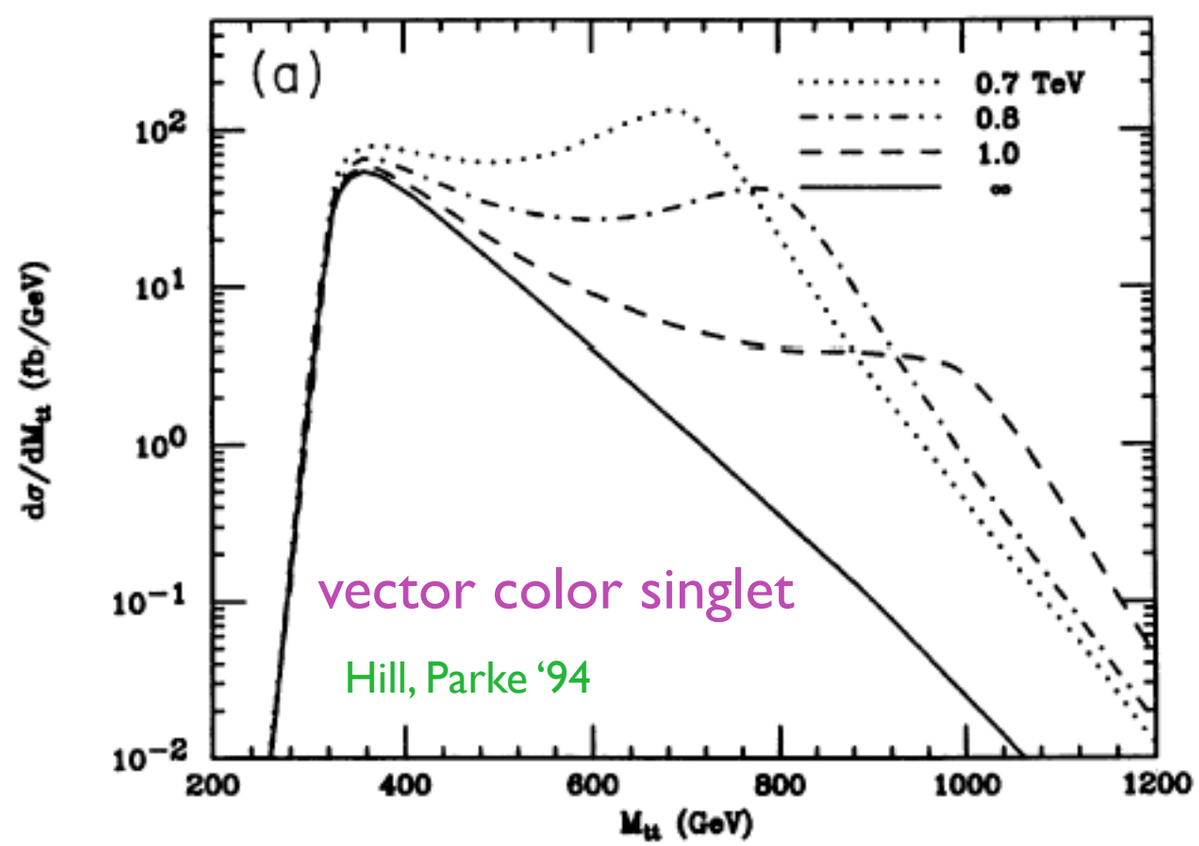


- Distribution known at NLO, including the matching with the shower (in MC@NLO).
- Very interesting SM study. The peak of the distribution is sensitive to the top mass. Possibility for a joint σ and m_t measurement.
- In the high mass-invariant tail, fully hadronic events look like two jet events: different systematics for m_t measurement.

m_{tt} as a BSM physics observatory

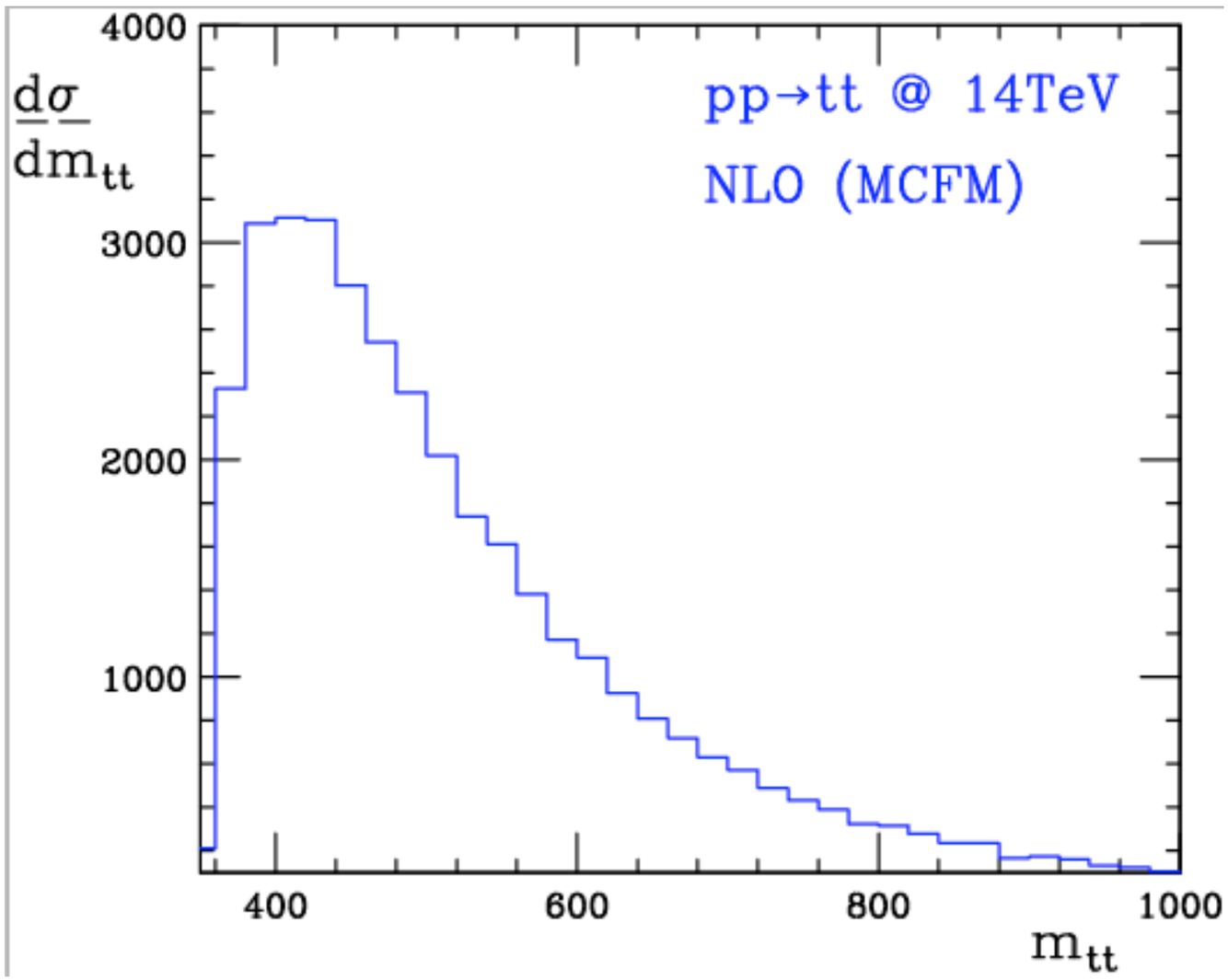


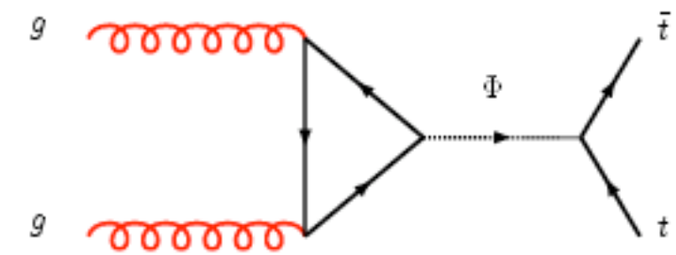


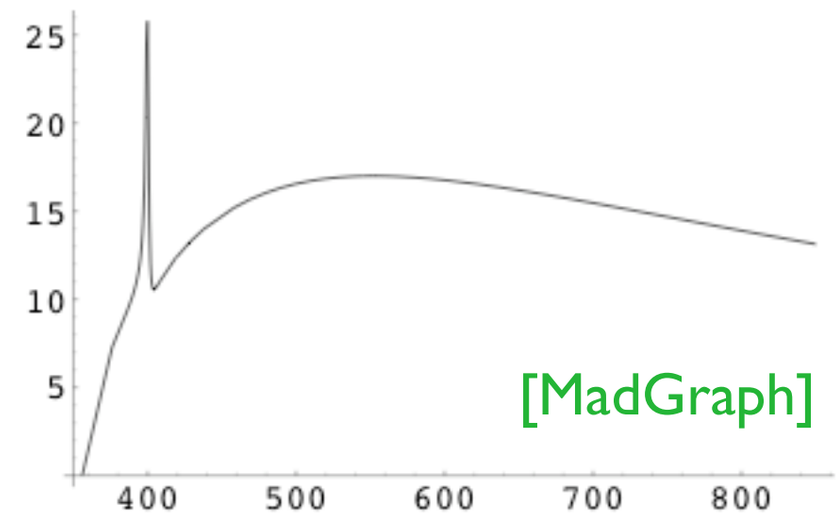


The best of all possible discoveries: a peak in the invariant mass distribution!
Similar results are obtained if a colored vector is exchanged.

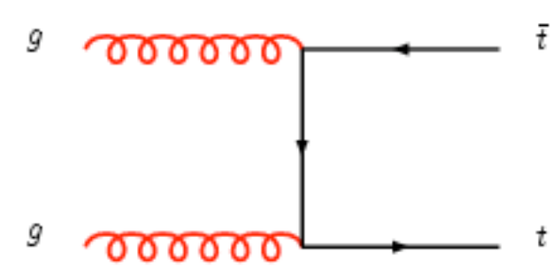
m_{tt} as a BSM physics observatory



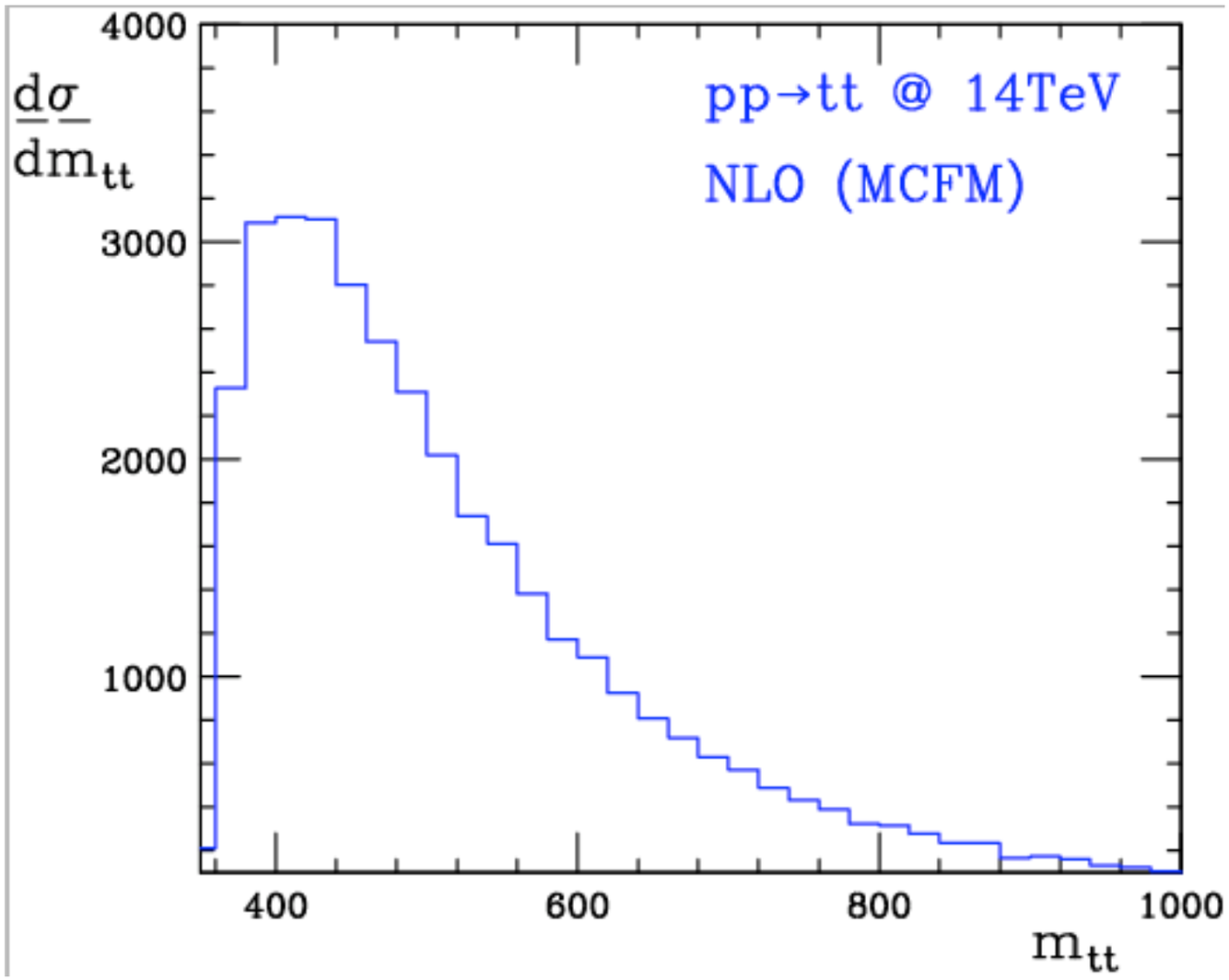


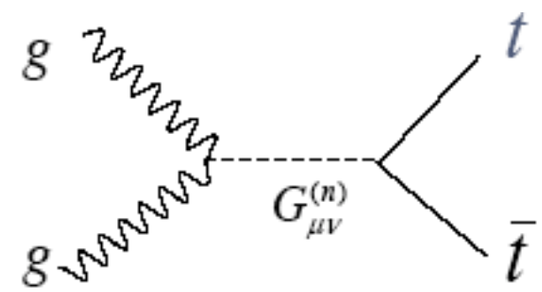


Non-trivial behavior (peak-dip) due to the interference between the signal and the background, only if top width dominated by $\Phi \to tt$.

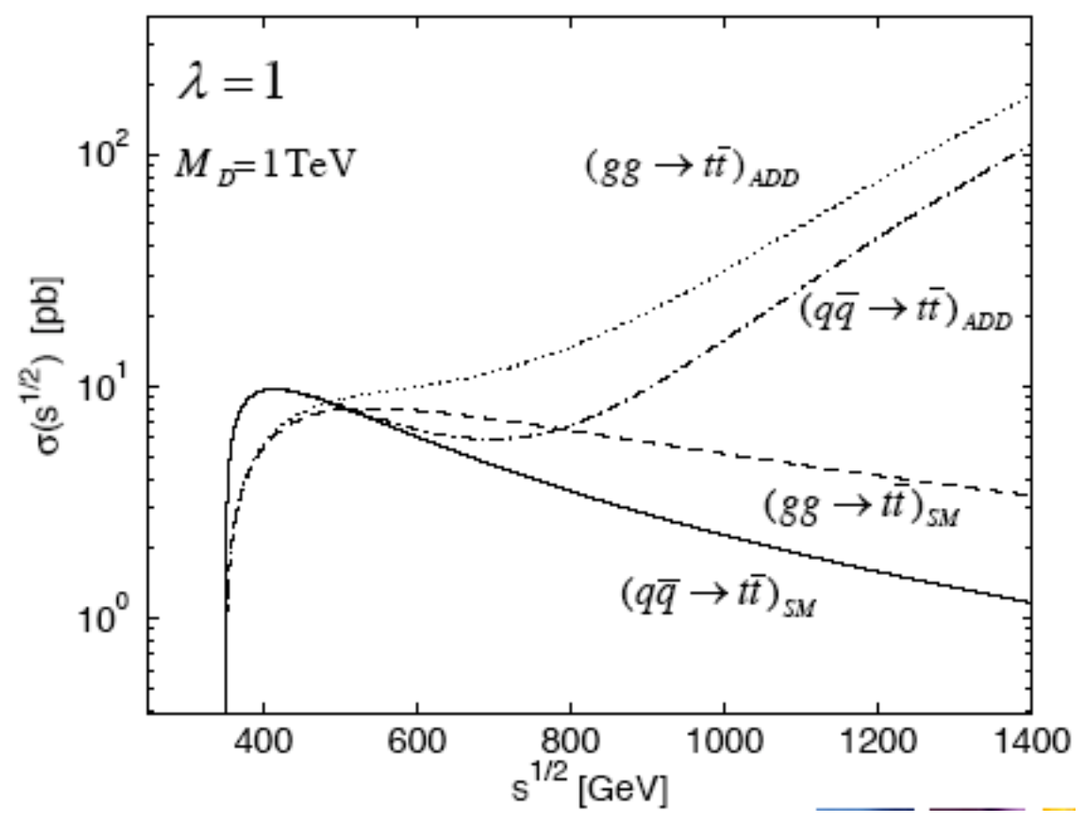


m_{tt} as a BSM physics observatory



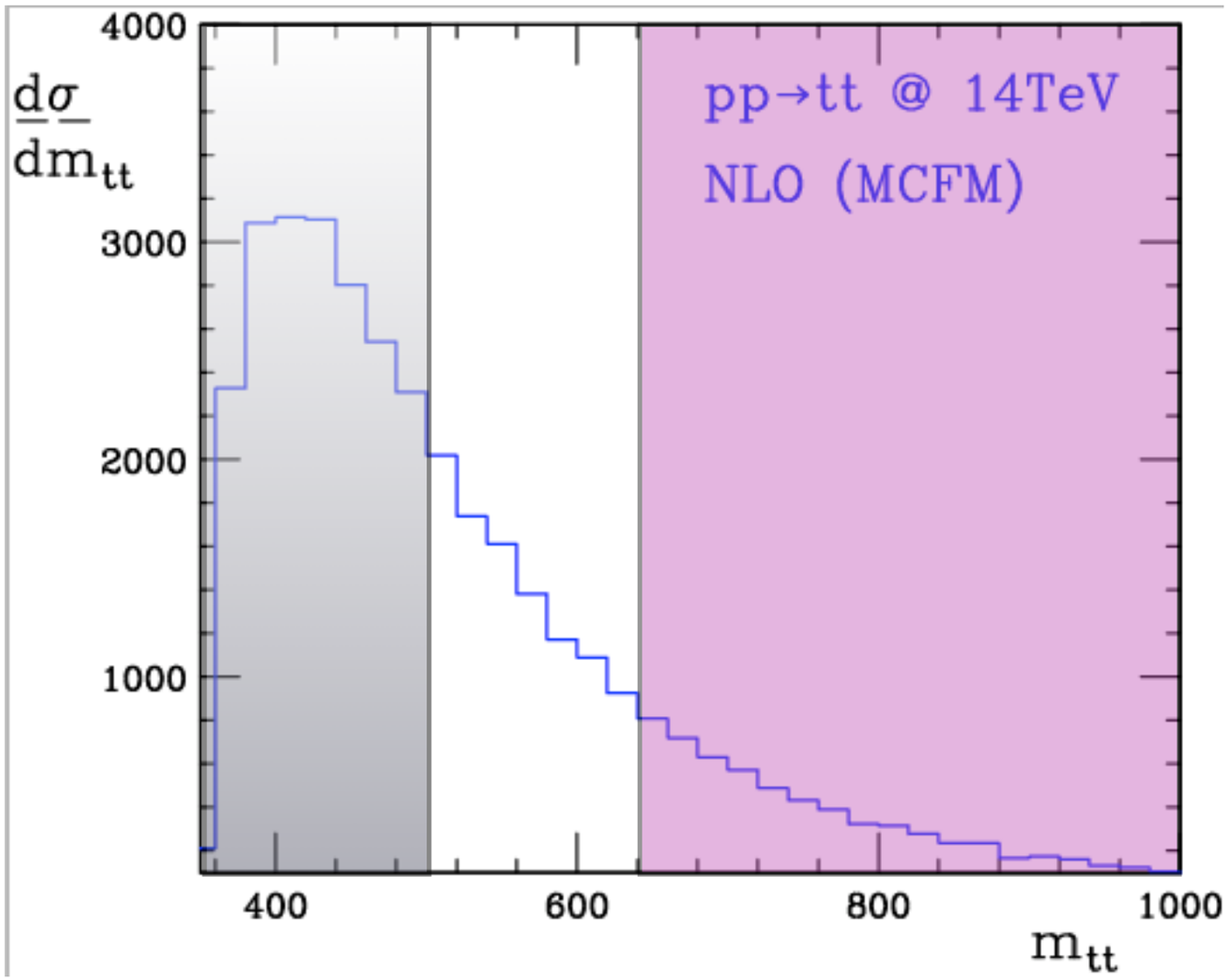


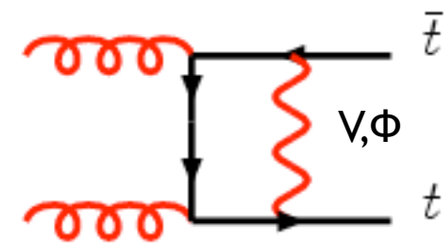
[Arai,Okada,Smolek,Simak 2005]



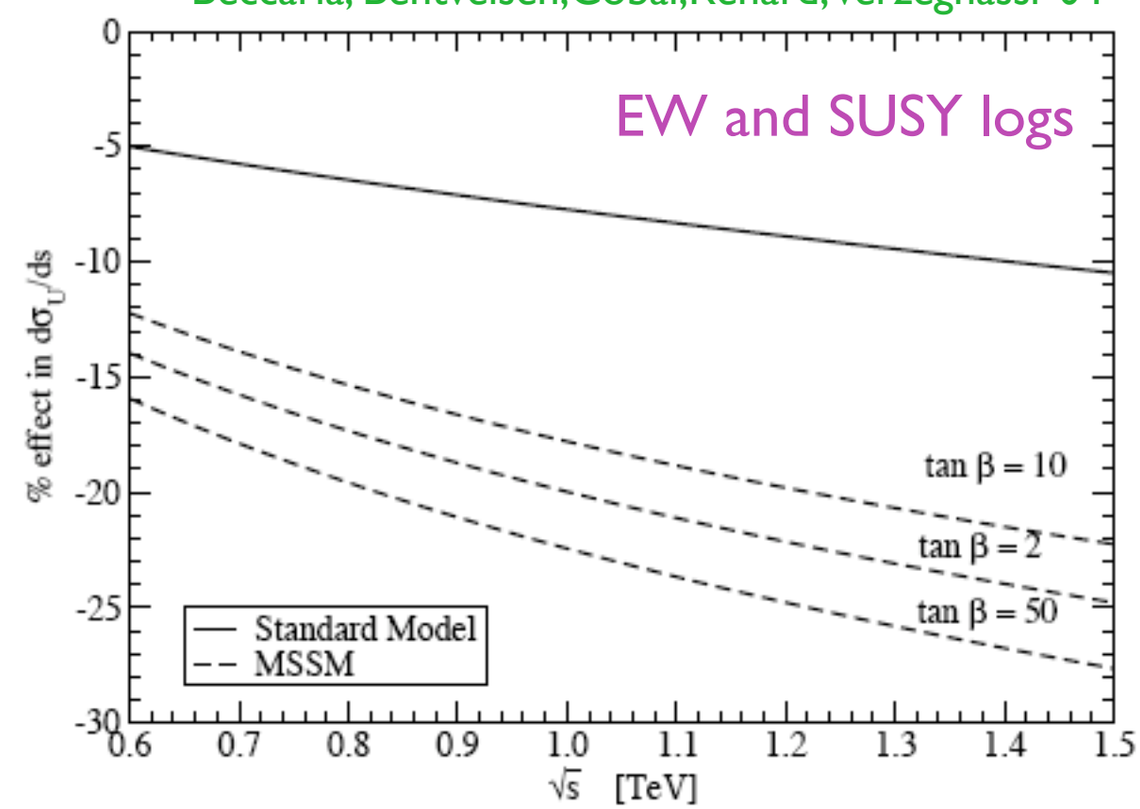
In a UED scenario the cross section into tt may even start to violate unitarity due to the exchange of a KK graviton.

m_{tt} as a BSM physics observatory





Beccaria, Bentvelsen, Cobal, Renard, Verzegnassi '04



CP violation:

$t_L\bar{t}_L \to t_R\bar{t}_R$

Schmidt and Peskin, '92

P violation:

$t_R\bar{t}_L \to t_L\bar{t}_R$

Kao and Wackeroth, '00

Indirect measurement: difference in normalization and shape