Flavor and Top Physics - WG1

Theoretical Summary

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Flavor in the LHC Era

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Outline

- Theoretical Motivation
- New physics in top interactions: Wtb, V_{tb}, neutral interactions.
- Flavor changing neutral interactions of the top: $FCNCs$ in top decay and production.
- Signals of new physics strongly coupled to the top: discovering a theory of flavor at the LHC

Physics Beyond the SM and the Top quark

- The top is the least tested quark.
- We will have very large data samples at the LHC.
- It might play a role in EWSB
  - Through radiative breaking (SUSY, Little Higgs models)
  - Through new strong interactions (Topcolor)
- Electroweak Symmetry breaking is strongly coupled to the top:

$$y_t \sim \sqrt{2}\frac{m_t}{v} \sim O(1)$$

- Are there other states strongly coupled to the top ?
  - Maybe associated with EWSB, or
  - Maybe associated with the origin of fermion masses (or at least with m_t).

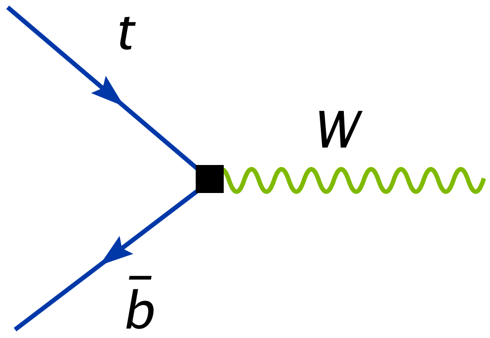
Physics Beyond the SM and the Top

Two ways to study the top:

- New physics above a scale Λ is integrated out. Leads to anomalous couplings of top with gauge bosons, Higgs, rare top decays, etc.
- New states strongly coupled to top, are produced and then decay to top pairs, single top.

Charged Anomalous Couplings

- The Wtb coupling:

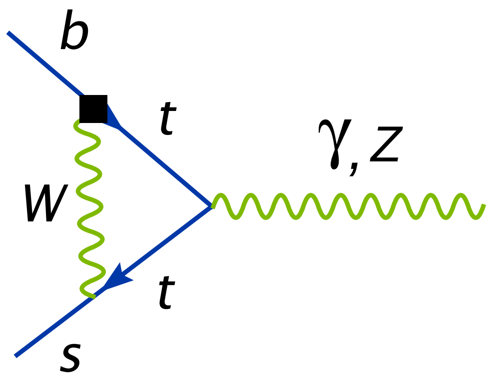


$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \mathrm{h.c.}\,,$$

- Dim-4 (V_L,V_R), and Dim-5 (g_L,g_R) anomalous Wtb couplings

Charged Anomalous Couplings

- Constraints from B physics: $b \to s\gamma$ and $b \to s\ell^+\ell^-$.



- Leading operator for $b \to s\gamma$ is

$$O_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}$$

Wilson coefficient receives the anomalous coupling contribution

Charged Anomalous Couplings

- Branching ratio for $E_\gamma > 1.6$ GeV, and matching scale $\mu_0 = 160$ GeV, is (M. Misiak)

$$\begin{aligned} \mathcal{B}(B \to X_s\gamma) \times 10^4 &= (3.15 \pm 0.23) - 4.14\,(V_L - V_{tb}) + 411\,V_R \\ &- 53.9\,g_L - 2.12\,g_R - 8.03\,C_7^{(p)}(\mu_0) \\ &+ \mathcal{O}\left[\left(V_L - V_{tb}, V_R, g_L, g_R, C_7^{(p)}\right)^2\right], \end{aligned}$$

- To be compared to

$$\mathcal{B}(\bar{B} \to X_s\gamma) = \left(3.55 \pm 0.24\,{}^{+0.09}_{-0.10} \pm 0.03\right) \times 10^{-4}$$

Charged Anomalous Couplings

- This results in bounds on V_L, V_R, g_L, g_R

	$V_L - V_{tb}$	V_R	g_L	g_R	$C_7^{(p)}(\mu_0)$
upper bound	0.04	0.0024	0.003	0.08	0.02
lower bound	-0.24	-0.0004	-0.018	-0.46	-0.12

at 95% C.L., each obtained with all others vanishing.

- If all allowed, no significant bound from $b \to s\gamma$.
- Need to update study including $b \to s\ell^+\ell^-$, and $B^0 - \bar{B}^0$ mixing.
- For ATLAS sensitivity see *Nuno Castro's* talk.

V_{tb} from Single Top Production

(J. Alwall, J. Frederix, J. M. Gerard, A. Giammanco, M. Herquer, E. Kou, V. Lemaitre, F. Maltoni)

- Need direct measurement of V_{tb}. Tevatron measurement of

$$R \equiv \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

  translated into $|V_{tb}|$ if unitarity assumed.

- Measurements give: $R = 1.12^{+0.27}_{-0.23}$ (CDF) $R = 1.12^{+0.19}_{-0.17}$ (D0)

$$\Rightarrow R > 0.61$$ at 95% C.L.

V_{tb} from Single Top Production

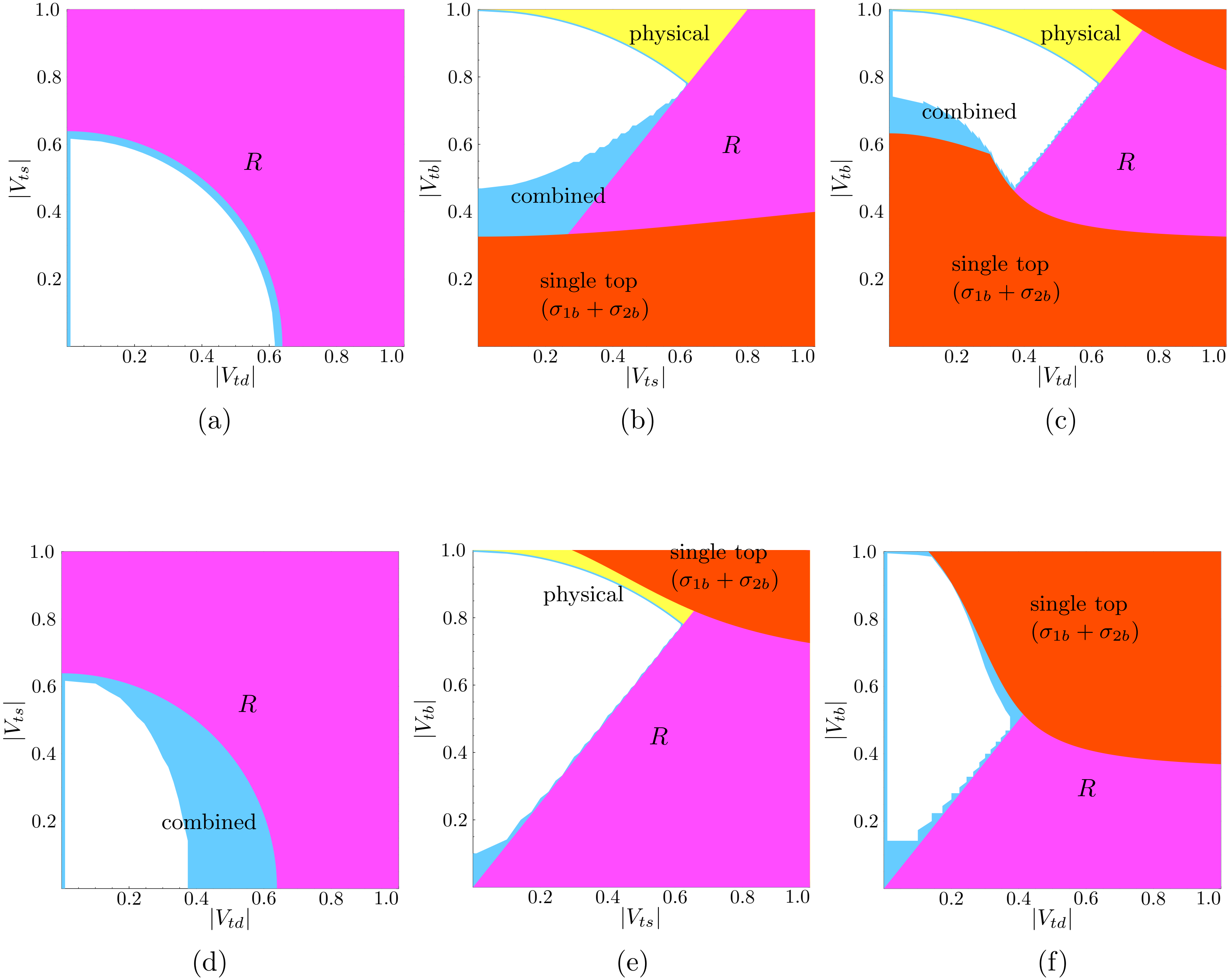
- New D0 measurement of single top:

$$\begin{aligned} \sigma^{\rm s-ch} + \sigma^{\rm t-ch} &= 4.9 \pm 1.4 \text{ pb} \\ \sigma^{\rm s-ch} &= 1.0 \pm 0.9 \text{ pb} \\ \sigma^{\rm t-ch} &= 4.2^{+1.8}_{-1.4} \text{ pb} \end{aligned}$$

- Plus the CDF upper bounds:

$$\begin{aligned} \sigma^{\rm s-ch} + \sigma^{\rm t-ch} &< 2.7 \text{ pb} \\ \sigma^{\rm s-ch} &< 2.5 \text{ pb} \\ \sigma^{\rm t-ch} &< 2.3 \text{ pb} \end{aligned}$$

V_{tb} from Single Top Production



V_{tb} from Single Top Production

- Message: Still considerable room for extra fermions mixing with SM fermions
- LHC with $10 fb^{-1}$ should measure $|V_{tb}|$ with 5% (CMS study).

Neutral Anomalous Couplings

- Many models of EWSB predict a few percent deviation in the $Zt\bar{t}$ coupling. How well do we know it?
- For instance, Dim-4 operators:

$$\mathcal{L} = -\frac{g}{2c_W}\bar{t}\gamma^\mu\left(N_L^t P_L + N_R^t P_R\right) t\, Z_\mu$$

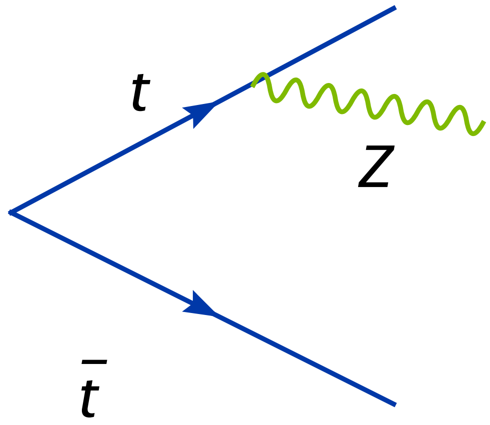
- Bounds from T, R_b:

$$\begin{aligned} T &\sim N_R^t - N_L^t + V_L \\ R_b &\sim N_L^t - \frac{1}{4} N_R^t \end{aligned}$$

- $b \to s\ell^+\ell^-$ about to be constraining (need better than 10% in the Br).

Neutral Anomalous Couplings

- Many BSM theories give “sizable” deviation of up to a few $\%$
- How well can we measure $Zt\bar{t}$?

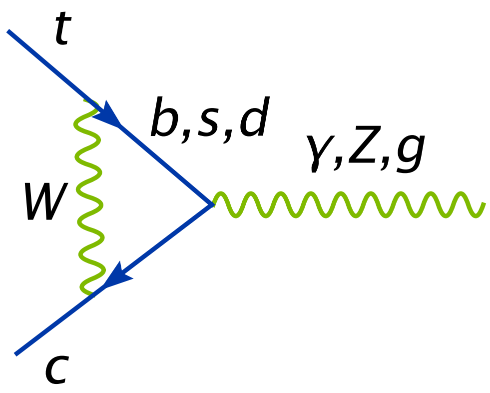


At the LHC, very hard to get better than 10% (U. Baur et al.).

- Need to make use of $b \to s\ell^+\ell^-$.

Flavor Changing Neutral Currents of the Top

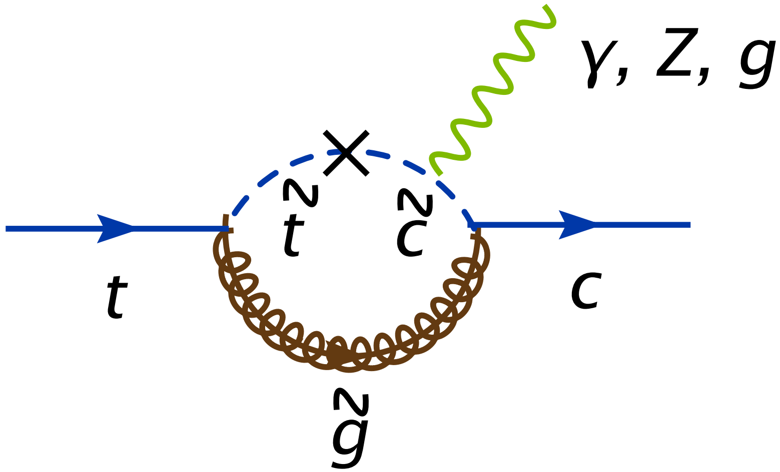
- In the SM, $t \to cV$ is greatly suppressed:



- E.g. $t \to c\gamma$ vs. $b \to s\gamma$:
  - Top mode is more efficiently GIM suppressed: $(m_b/M_W)^2$ instead of $(m_t/M_W)^2$.
  - Top mode competes with $t \to bW$, which is $O(1)$ w.r.t. to $\lambda \sim \theta_C$. $b \to s\gamma$ vs. $b \to c\ell\nu$, $O(\lambda^2)$.
  - QCD not so important in $t \to c\gamma$.
- Typical SM predictions $Br(t \to cV) \sim (10^{-14} - 10^{-12})$

FCNCs of the Top - SUSY

- Squark mixing induces FCNC at one loop: δ_{23}^{LL}, δ_{23}^{RR}, δ_{23}^{LR}



- Branching ratios as large as $Br(t \to c\gamma) \sim 10^{-5}$ if LR mixing allowed.

FCNCs of the Top - SUSY

We can also consider the single top production induced by this FCNC vertices

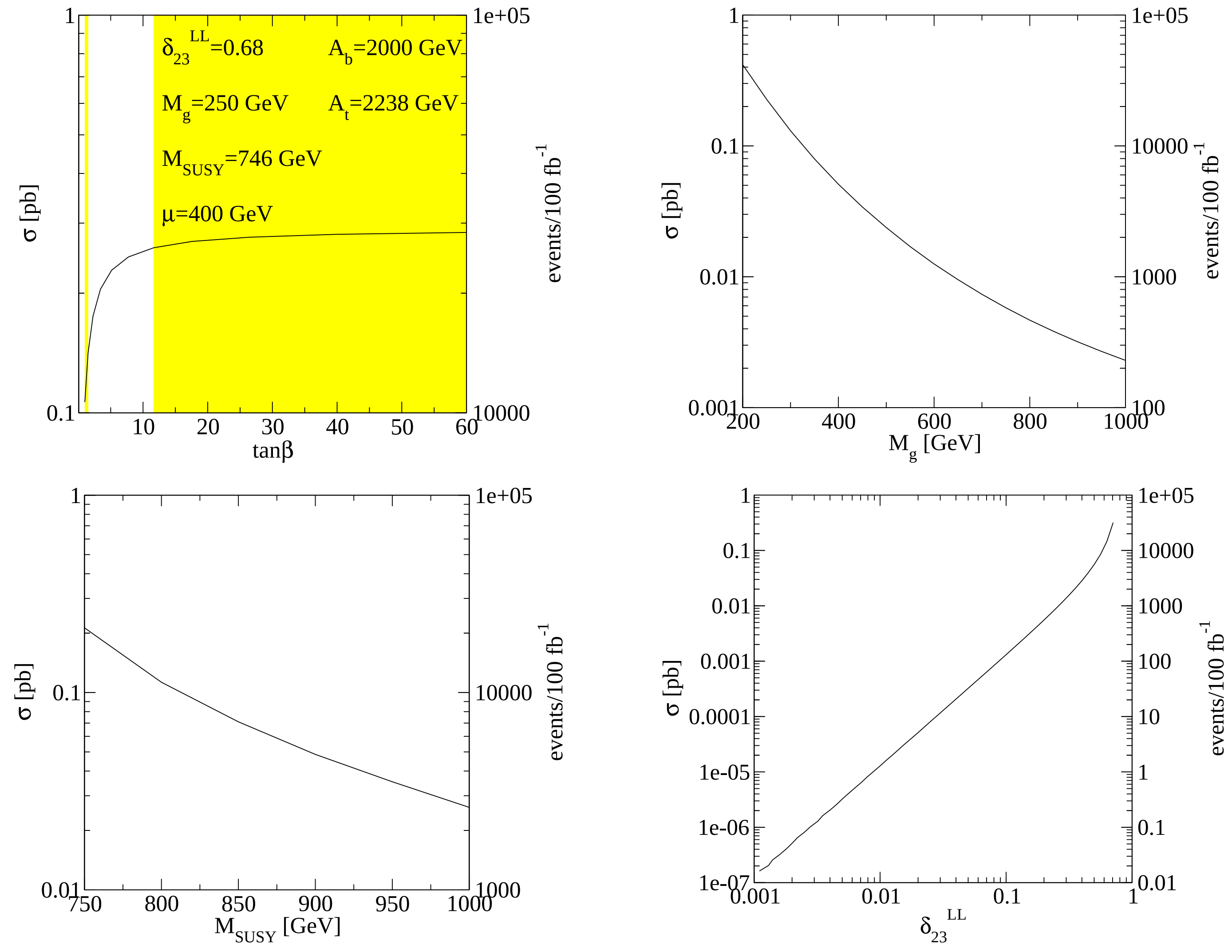
Particularly $t\,c\,g$ (J. Guasch, W. Hollik, S. Peñaranda, J. Solà)

- Compute $\sigma_{tc} \equiv \sigma(pp \to t\bar{c})$:

$$\sigma_{tc} \sim \left(\delta_{23}^{(t)LL}\right)^2 \frac{m_t^2 (A_t - \mu/\tan\beta)^2}{M_{\rm SUSY}^4} \frac{1}{m_{\tilde{g}}^2}$$

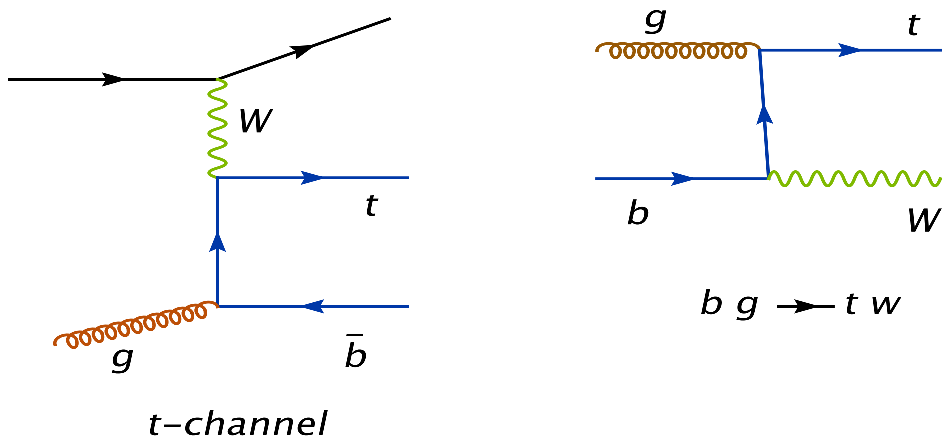
- Correlations with $b \to s\gamma$:
  - $\tan\beta$
  - μ
  - $\delta_{23}^{(t)LL}$ related to $\delta_{23}^{(t)LL}$ through CKM rotation.

FCNCs of the Top - SUSY



SUSY Contributions to Single Top Production

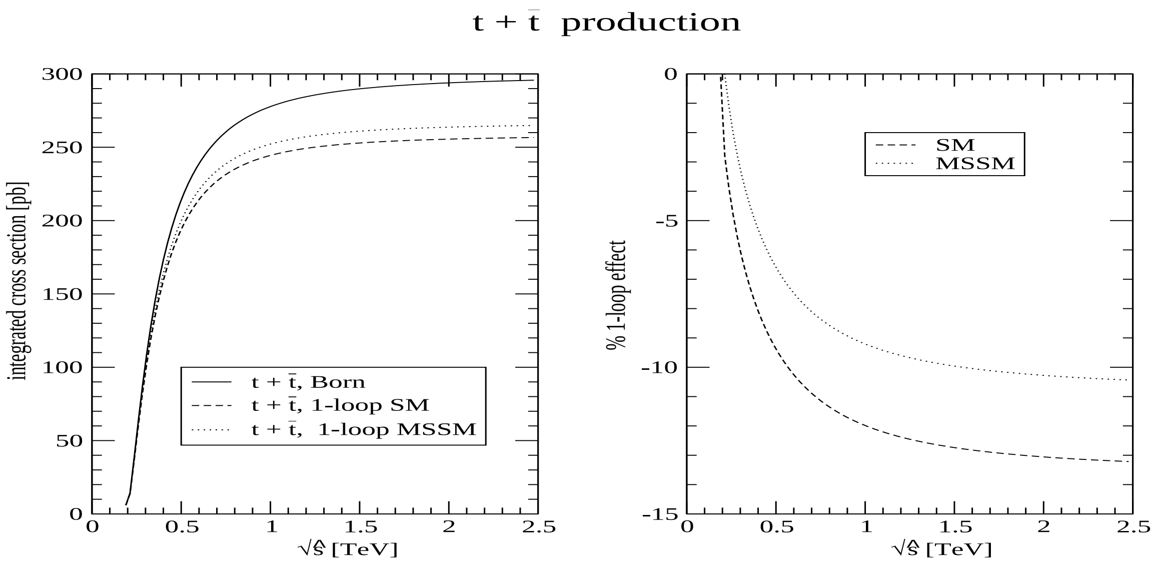
Compute the NLO electroweak (SM and SUSY) contributions
(M. Beccaria, G. Macorini, F. M. Renard and C. Verzegnassi)



- t channel (W-gluon fusion): Largest $\sim 250\ pb$ ($\sim 6\%$ SM QCD correction).
- Associated production ($bg \to tW$): $\sim 30\ pb$ (10% SM QCD, 6% SUSY QCD).
- s-channel: $\sim 10\ pb$ (50% SM QCD correction).

EW Corrections to Single Top Production

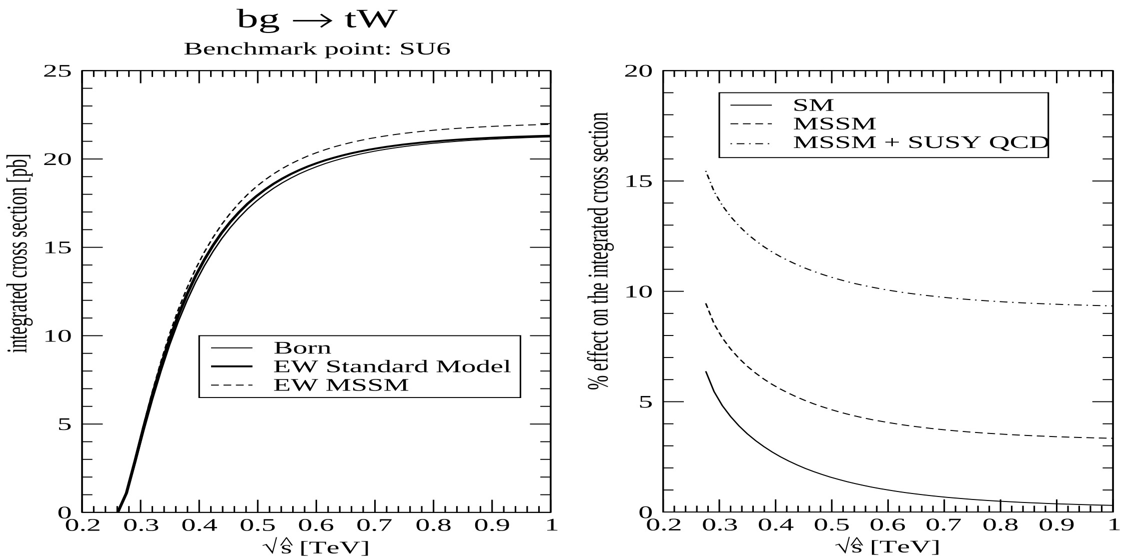
t-channel (W-gluon fusion)



- True SUSY effect is small here: $\lesssim 2\%$.
- One loop SM EW correction is large: $\sim 13\%$. Larger than the SM NLO QCD effect.

SUSY Contributions to Single Top Production

Associated production ($bg \to tW$)



- The SUSY effect can be large here: as much as $\lesssim 13\%$, depending on the energy.
- The pure NLO EW SM effect is negligible.
- Complementarity between t-channel and associated production.

FCNCs of the Top - Higgs

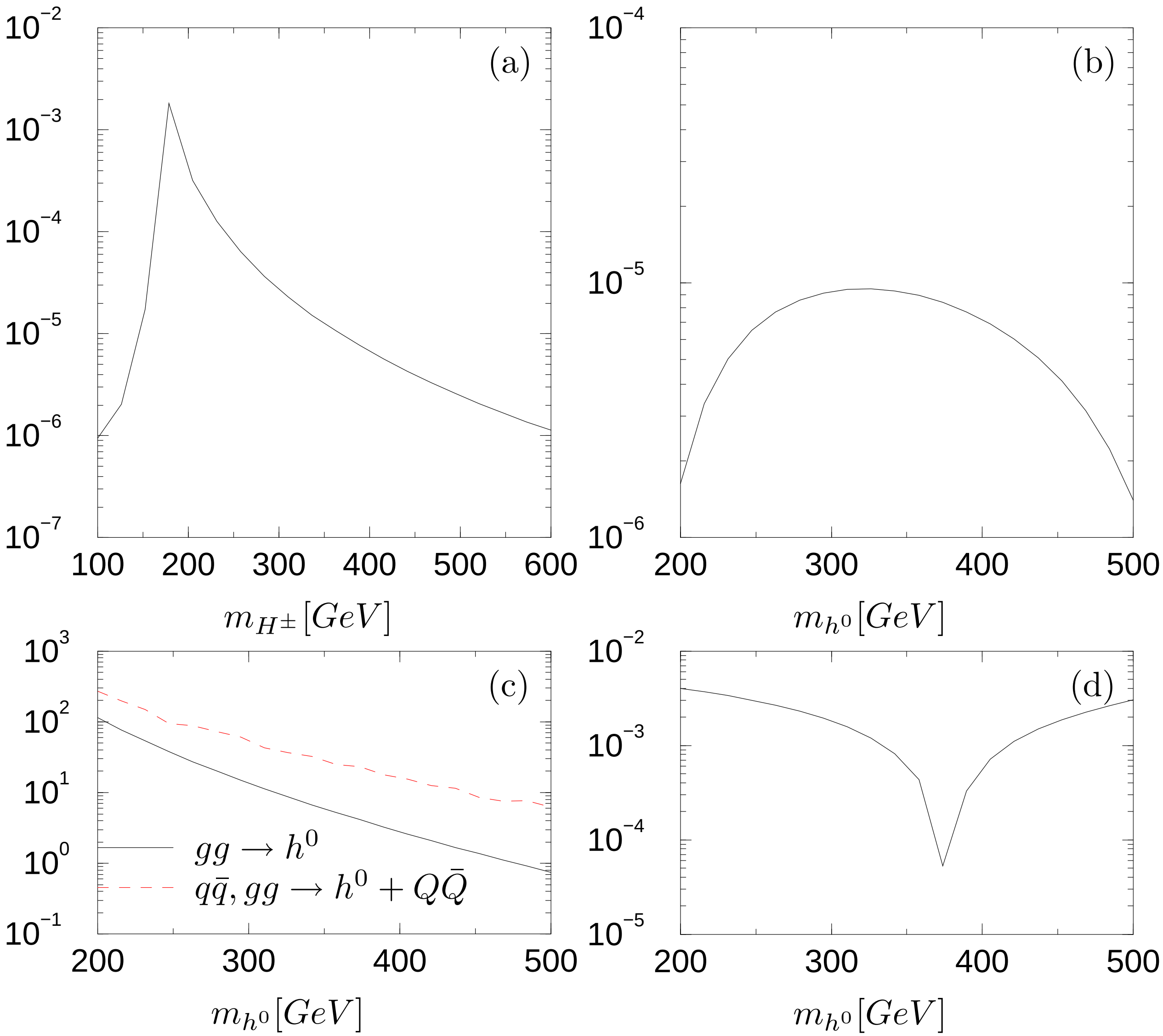
Loop induced FCNC decays Higgs bosons into a top in a 2HDM (S. Béjar, J. Guasch, J. Solà)

- Compute

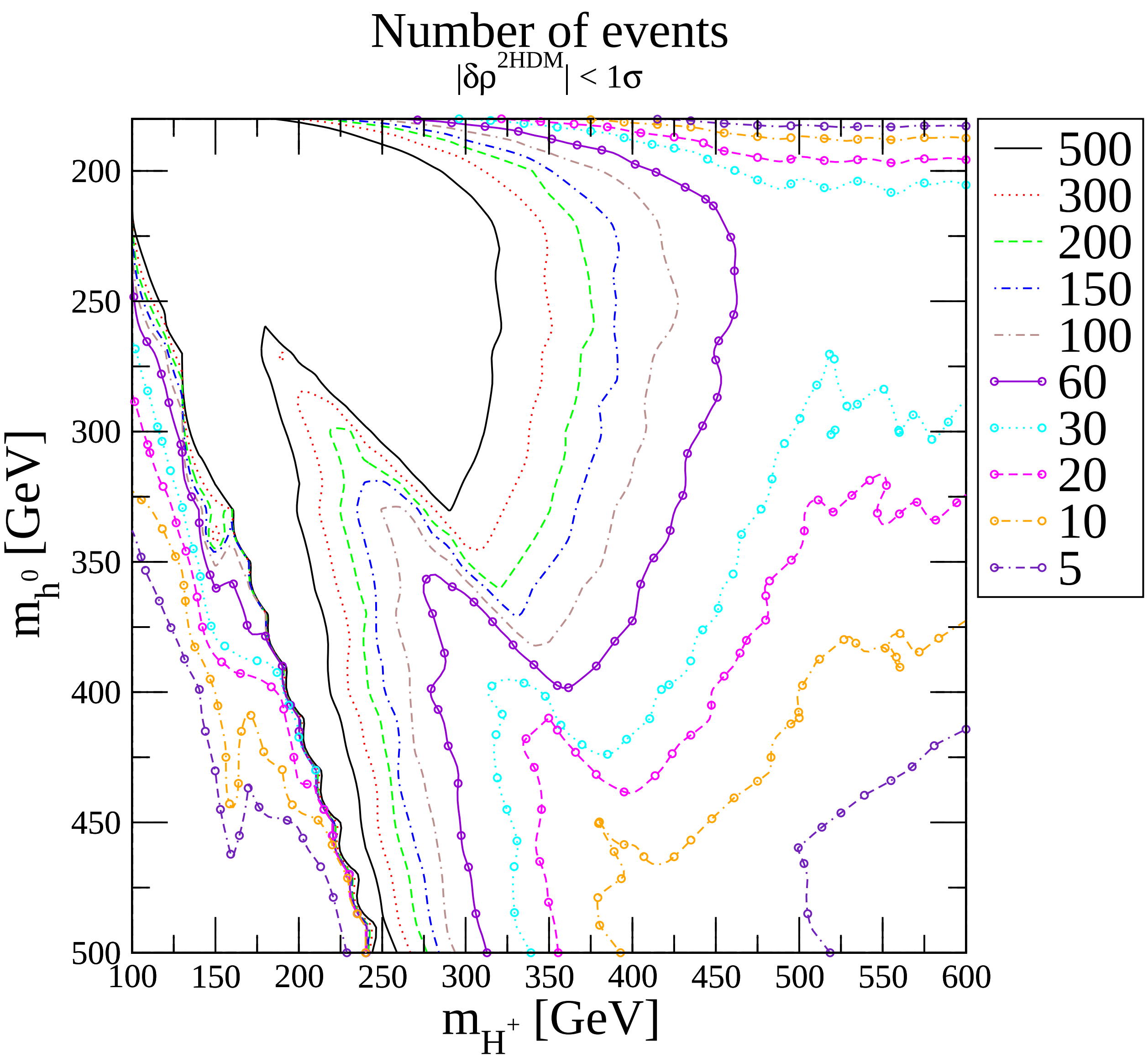
$$\sigma(pp \to h \to tc) = \sigma(pp \to hX)\, Br(h \to tc)$$

- Taking into account constraints from
  - $b \to s\gamma$: $m_{H^\pm} \gtrsim 350\ GeV$,
  - perturbativity: $0.1 \lesssim \tan\beta \lesssim 60$,
  - custodial symmetry: $|\delta\rho^{\mathrm{2HDM}}| \lesssim 0.1\%$
- For the 2HDMII, sizable branching ratios for lightest CP-even into tc

FCNCs of the Top - Higgs



FCNCs of the Top - Higgs



New Physics and Top production

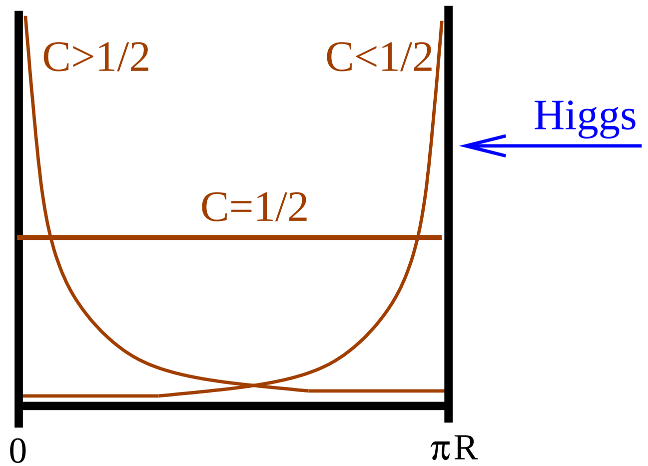
- Also consider direct production of new physics strongly coupled to top
- Typically, associated to the origin of fermion masses
- Example: Warped Extra Dimensions (Randall-Sundrum) with matter and gauge fields in 5D bulk:

localization of fermions $\leftrightarrow$ fermion mass hierarchy

- $\Rightarrow$ in addition to solving the Hierarchy Problem, Theory of Flavor. What are the signals ? All over flavor physics ?
- Is there a signal at the LHC ? (P. Aquino, O. Eboli, G.B.)

Flavor Models in WED

- $O(1)$ flavor breaking in bulk can generate fermion mass hierarchy:



  Fermions localized toward the TeV brane can have larger Yukawas, Those localized toward the Planck brane have highly suppressed ones.

- But fermions at $\simeq \pi R \Rightarrow$ strong couplings to 1st KK gauge bosons. E.g: 3rd generation quarks might have large couplings $\rightarrow$ flavor violation.

Signals for a Theory of Flavor

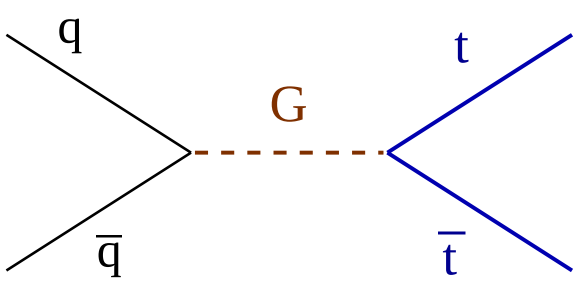
- Assume a generic RS bulk model:
  - Bulk fermions and gauge bosons.
  - Bulk masses ($c's$) $\Rightarrow$ Fermion masses / CKM.
- Model(s) satisfy all EWPC (S, T, $Z \to b\bar{b}$, etc.).
- Assume typical masses $m_{KK} \simeq O(1)$ TeV

How do we test this flavor theory at the LHC ?

Signals for Flavor Violation

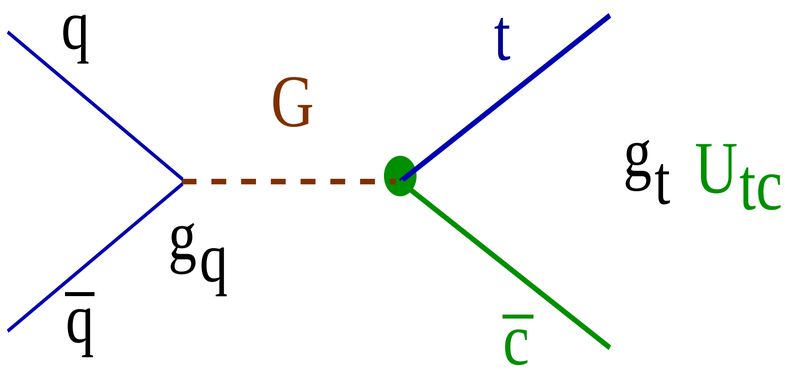
What is the best signal for flavor violation ?

- Flavor diagonal vertices:



Compare $t\bar{t}$ resonances with light quark resonances.
Observing these is hard.

Single Top Production at High Invariant Mass



- Signal: t + jet, very large invariant mass (>1.5 TeV).
- Use $t \longrightarrow b\ell\nu$.
- Typically few hundred fb^{-1}.

Single Top Production at High Invariant Mass

Results for $U_R^{tq} = 1$.

Process	$M_G = 1$ TeV			$M_G = 2$ TeV		
	σ – Cut I	σ – Cut II	σ – Cut III	σ – Cut I	σ – Cut II	σ – Cut III
$pp \to tj$	148 fb	103 fb	103 fb	5.10 fb	2.18 fb	2.18 fb
$pp \to Wjj$	243 fb	42.0 fb	21.0 fb	25.4 fb	3.79 fb	0.95 fb
$pp \to Wbb$	11.1 fb	4.07 fb	3.19 fb	0.97 fb	0.45 fb	0.06 fb
$pp \to tb$	1.53 fb	0.70 fb	0.61 fb	0.04 fb	0.02 fb	0.02 fb
$pp \to t\bar{t}$	44.4 fb	15.1 fb	14.2 fb	1.60 fb	0.29 fb	0.24 fb
Wg fusion	32.0 fb	5.23 fb	5.23 fb	1.20 fb	0.10 fb	0.10 fb

Single Top Production at High Invariant Mass

Reach in U_R^{tq}

M_G [TeV]	$30 fb^{-1}$	$100 fb^{-1}$	$300 fb^{-1}$
1	0.24	0.18	0.14
2	0.65	0.50	0.36

Conclusions/Outlook

- The top quark is a natural window to physics beyond the SM
  - Its mass is of the order of the weak scale $m_t \sim v$
  - It is strongly coupled to the (mystery) Higgs sector
  - It appears to be involved in EWSB
- The LHC will have access to lots of top quarks
  - We can measure its couplings with precision $\Rightarrow$ constrain heavy new physics through loops, tree-level suppressed interactions: Wtb, V_{tb}, neutral couplings, FCNCs, etc.
  - Check for consistency of emerging picture at the TeV scale (e.g.: corrections to single top in the MSSM).
- It will have access to the energy frontier: new physics states might couple strongly to top. Maybe even a window to the theory of flavor.