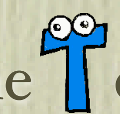
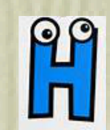
When the T is not "single": THeoretical overview

Aldo Deandrea
Université Lyon 1 & IUF

top LHC-France 2014 - April 8th 2014 - @IPNL

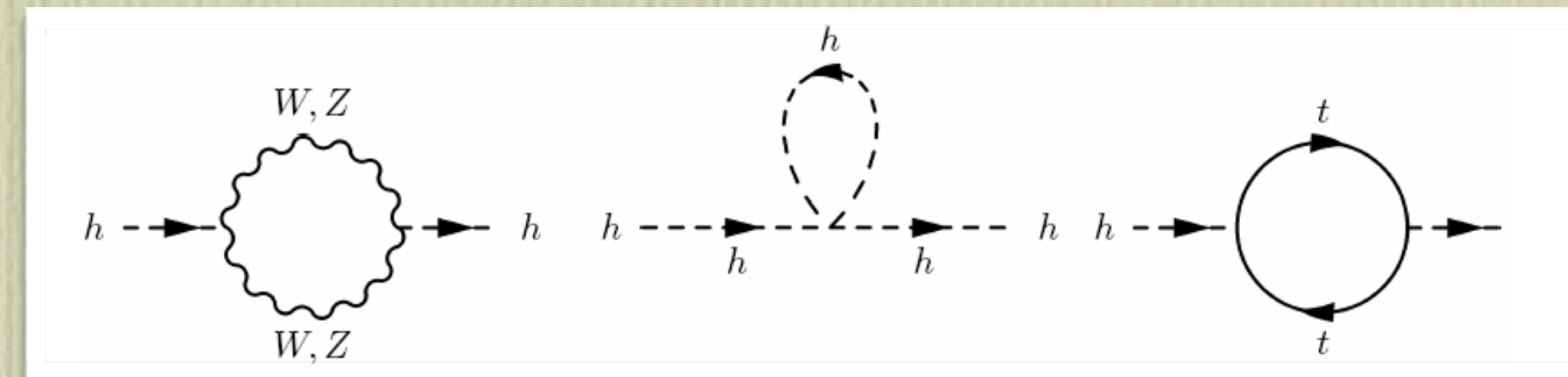
An experimental and theory hot subject (a long quest in just few lines)

- Discovery of the  quark in 1995 at TeVatron in pair production
- The heaviest elementary particle, its mass affects precision EW fits
-  vacuum stability (with a wild extrapolation though...)
- Related large coupling to the  : probe electroweak symmetry breaking
- Now  data is driven by LHC measurements
- Good agreement with the SM (except large FB asymmetry in $t\bar{t}$ @ TeVatron)
- Perfect tool to probe BSM physics

Look for BSM in  physics

- precision top mass measurements
- single top (see next session, very promising for BSM)
- $t\bar{t}$ observables
- 3 tops and more (multi-tops)
- same charge tops
- monotop
- asymmetries
- heavy top partners (vector-like)

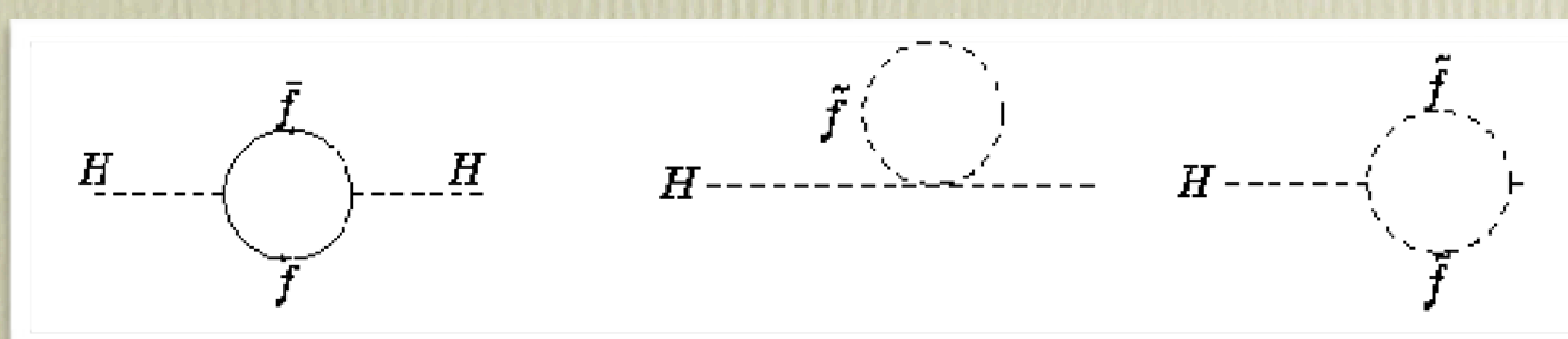
T is special for SM & BSM



- top enters the loop correction to the Higgs mass with a large contribution

$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2 \approx -(0.2\ \Lambda)^2$$

- In susy stop (top-partner) cancel quadratic dependence



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“Natural” theories

$$m^2 = m_0^2 \left(1 + a(\lambda, g) \log \frac{\Lambda^2}{m_0^2}\right) + b(\lambda, g)\Lambda^2$$

- natural if $b(\lambda,g)=0$ by a symmetry
- can be natural if Λ is a physical cut-off (ex. compositness)
- quasi-natural if $b(\lambda,g)=0$ perturbatively (ex. at one-loop in Little Higgs for top contribution)
- tuned: any special value you like, even $m_0=0$ $\Lambda=0$ (classically conformal)

T is special for BSM physics

- Composite models (technicolor, effective lagrangians like little Higgs, topcolor...):
  - top effective 4 fermion operators
  - vector-like top partners
- Extra-dimensional models:
  - KK-modes of top and gluons
  - Xdim realisations of composite models
  - in warped models wave function profile superposition “explains” Yukawa strength

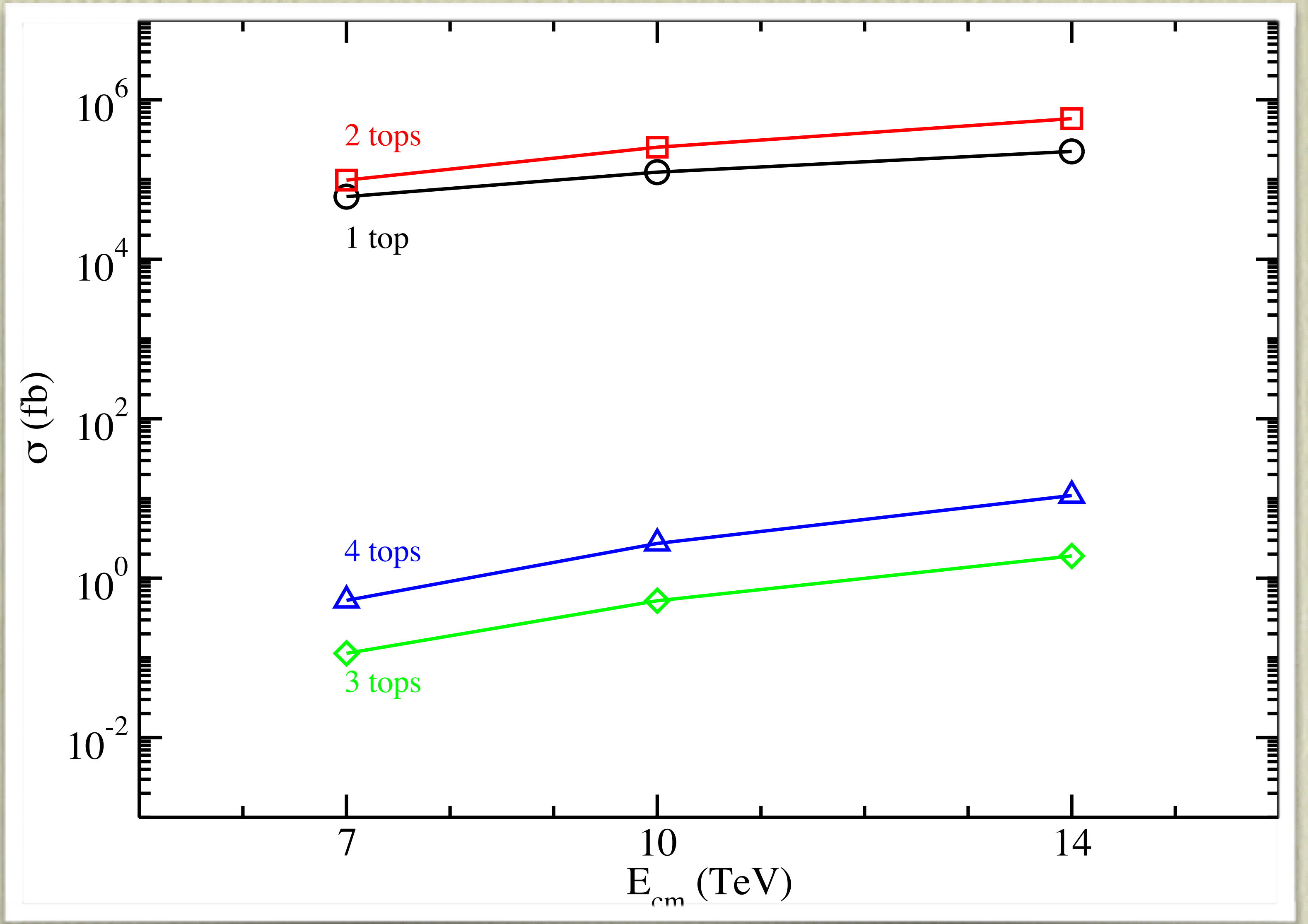
BSM uses of the top quark

- triggering electroweak symmetry breaking
- top-color, top see-saw models
- top partners (scalars in susy, fermionic in composite models, little higgs, extra-dimensional models)
- mixing of the top with new (vector-like) heavy quarks
- flavour changing couplings
- new particles may couple to the top quark (heavy gluon, Z'...)
- top-Higgs interactions, top portal sectors

Counting T's and BSM physics

- Very simple plan for the talk:
  - 2 tops (modifications to $t\bar{t}$ and $\bar{t}\bar{t}$)
  - 3 tops (MSSM, Z',topcolor...)
  - 4 tops (many BSM models studies)
  - 6 tops
  - 8 tops (and why we stop here)
- Exception to the previous rule: monotop

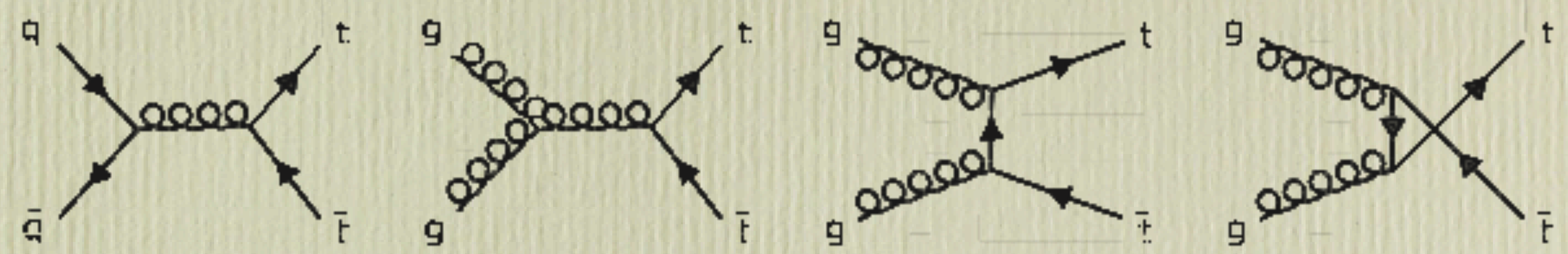
SM cross sections



from 1001.0221
Barger et al.

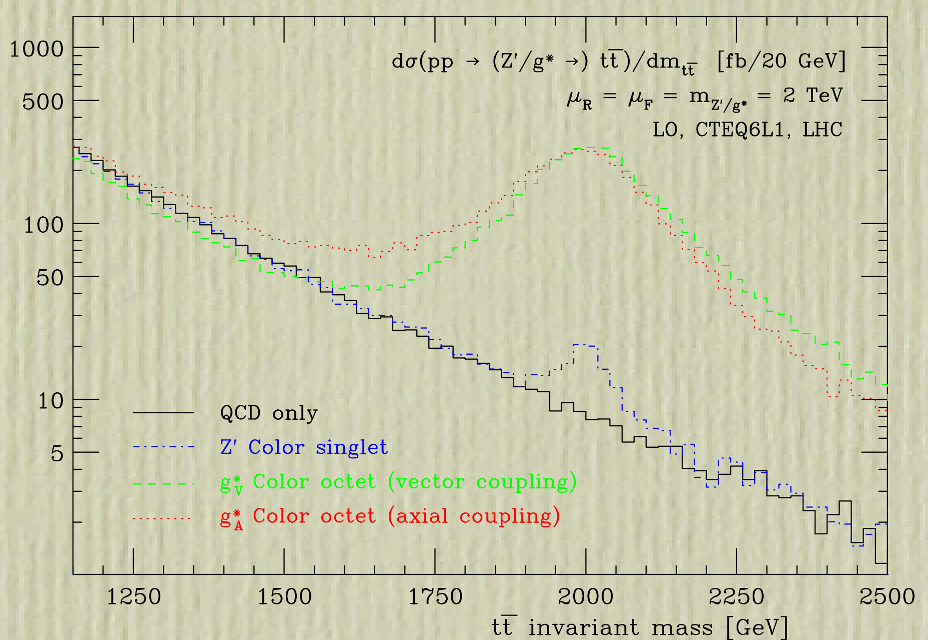
- multi-top (more than 2) cross-sections are small in the SM ~ fb while can be enhanced in BSM

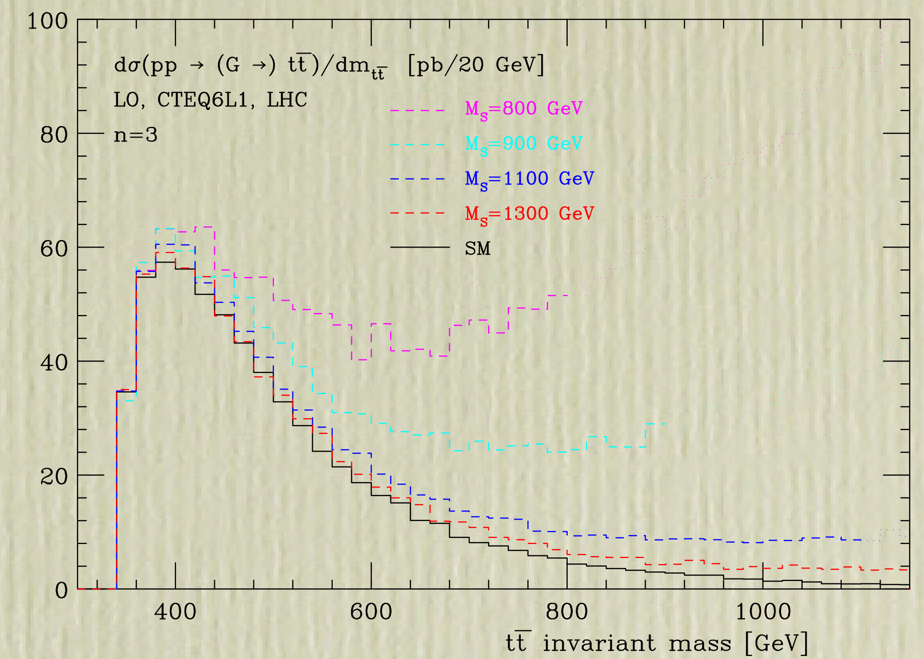
T-Tbar



- $t\bar{t}$ strong production with large and well measured cross-section and shape
- gluon fusion dominant (90% at 14 TeV LHC)
- detailed theoretical description available
- BSM in resonant and non-resonant effects
- $t\bar{t}$ invariant mass is particularly sensitive to BSM

T-Tbar in BSM





from 0712.2355 Frederix & Maltoni

- resonant contributions from:
  - spin 0, 1, 2
  - color singlets, octets
  - parity even and odd states

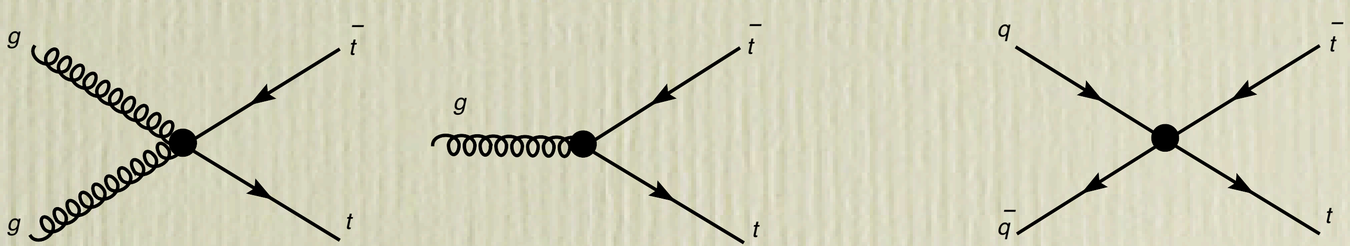
T-Tbar in BSM

- generic BSM effects in the top sector can also be encoded in effective operators

- for $t\bar{t}$ production 2 classes (Degrande et al. 1010.6304)

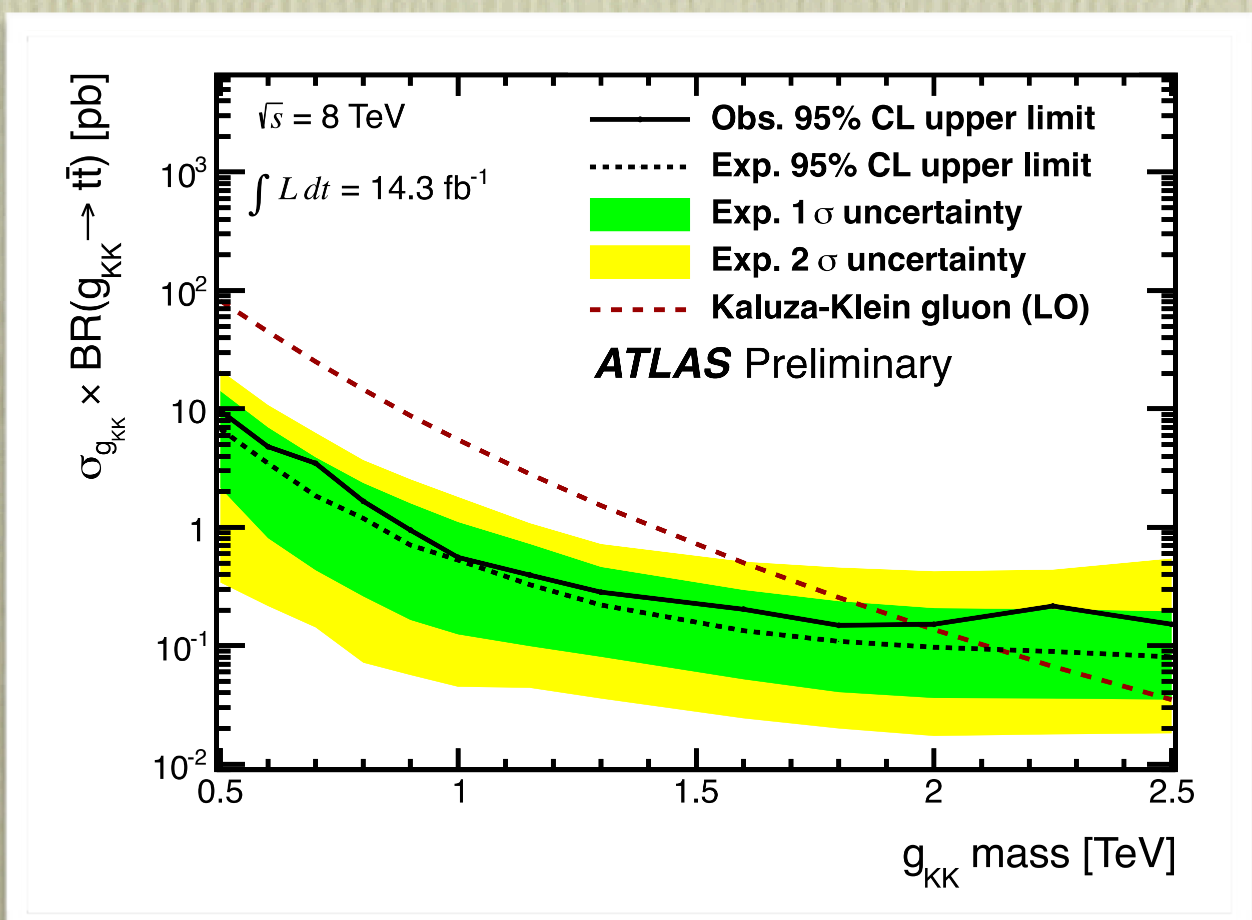
    - $t\bar{t}g$, $t\bar{t}gg$

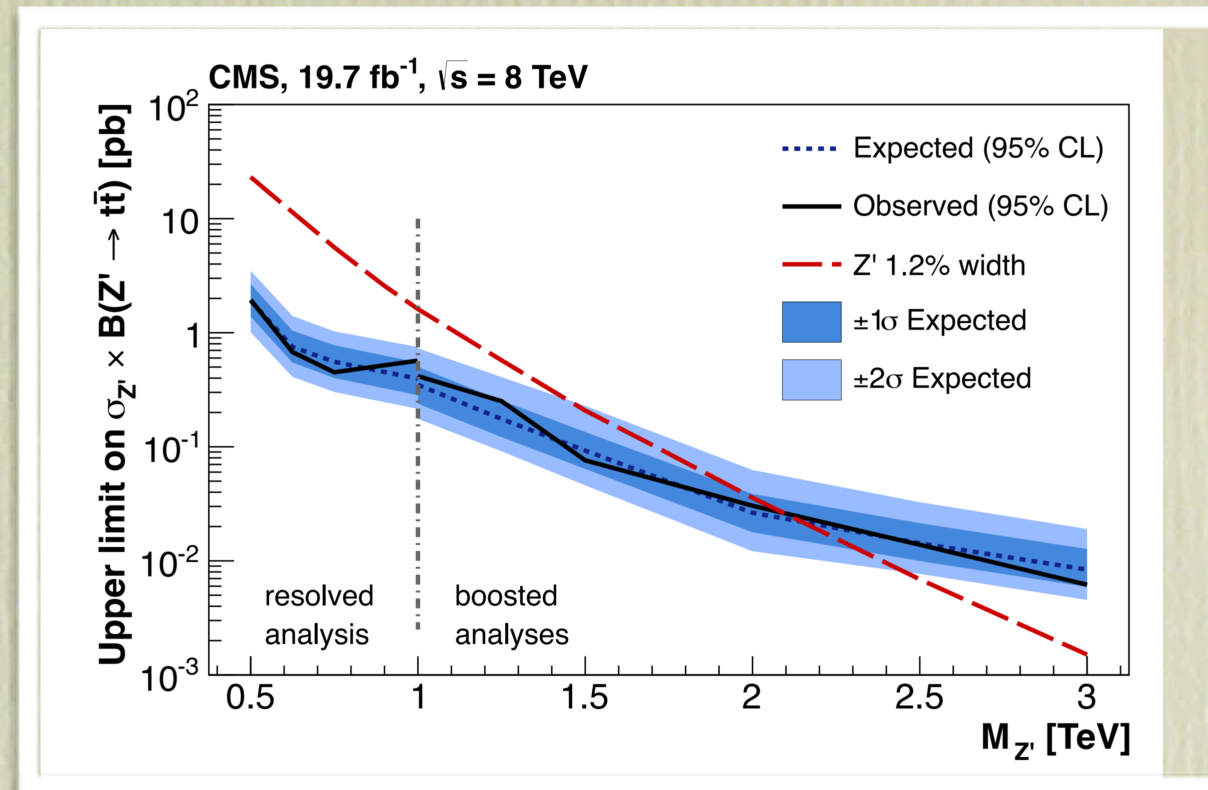
    - 4 quark operators
      ($t\bar{t}$ and 2 light quarks)



T-Tbar exclusions examples

from ATLAS-CONF-2013-052

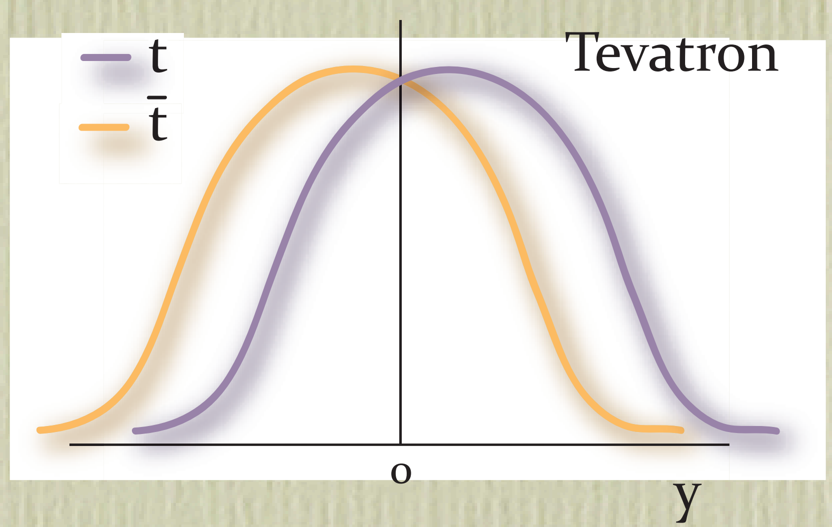


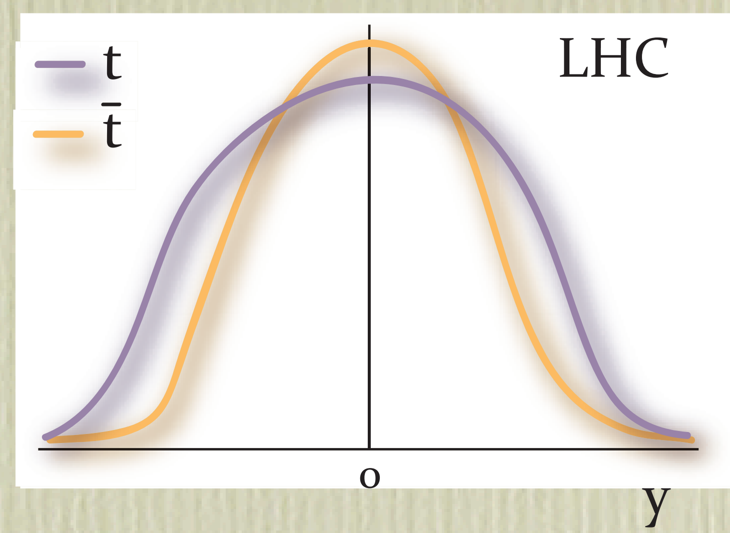


from CMS 1309.2030

Model	Observed Limit	Expected Limit
Z', $\Gamma_{Z'}/M_{Z'} = 1.2\%$	2.1 TeV	2.1 TeV
Z', $\Gamma_{Z'}/M_{Z'} = 10\%$	2.7 TeV	2.6 TeV
RS KK gluon	2.5 TeV	2.4 TeV

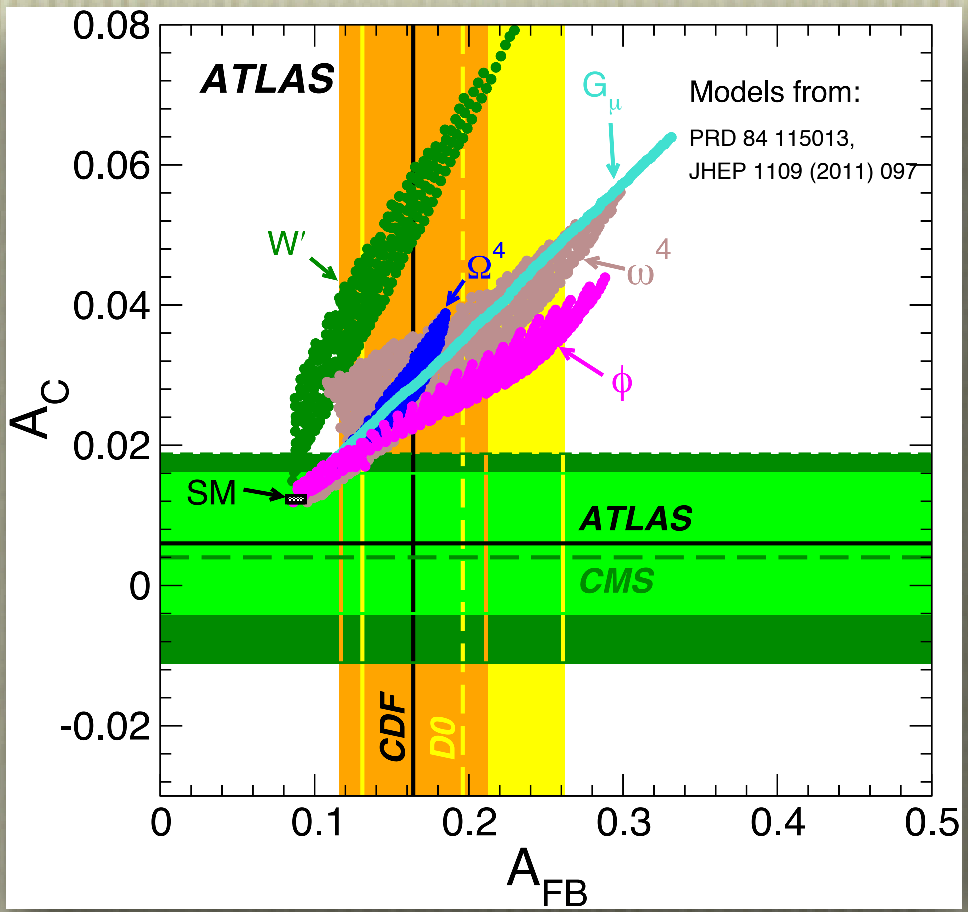
T-T bar charge asymmetry

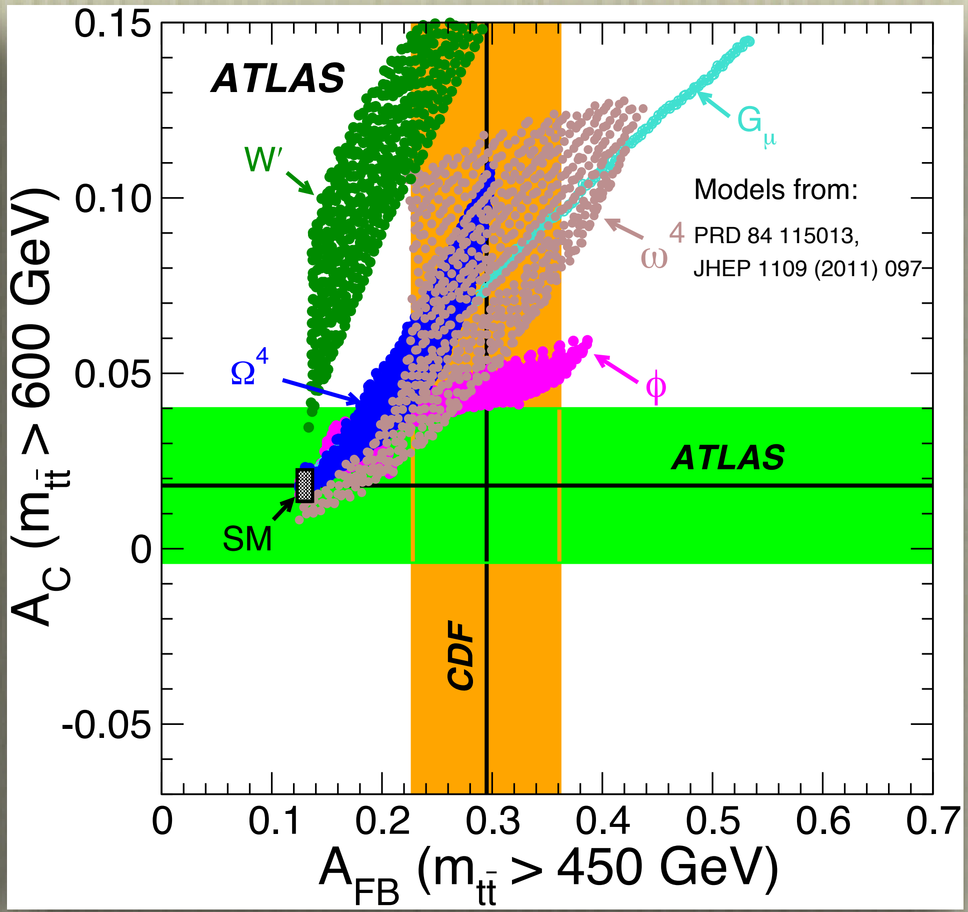




- TeVatron: q (anti-q) mostly from proton (antiproton) → A_{FB}
- LHC: average quark momentum fraction $x_q > x_{anti\text{-}q}$ → central-peripheral asymmetry A_C
- BSM: new particles with different V,A couplings affect asymmetries

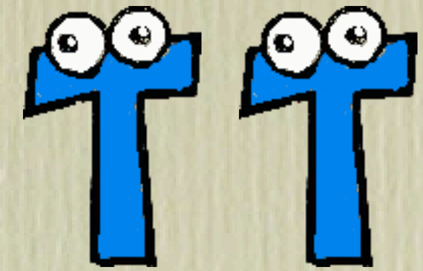
T-Tbar charge asymmetry

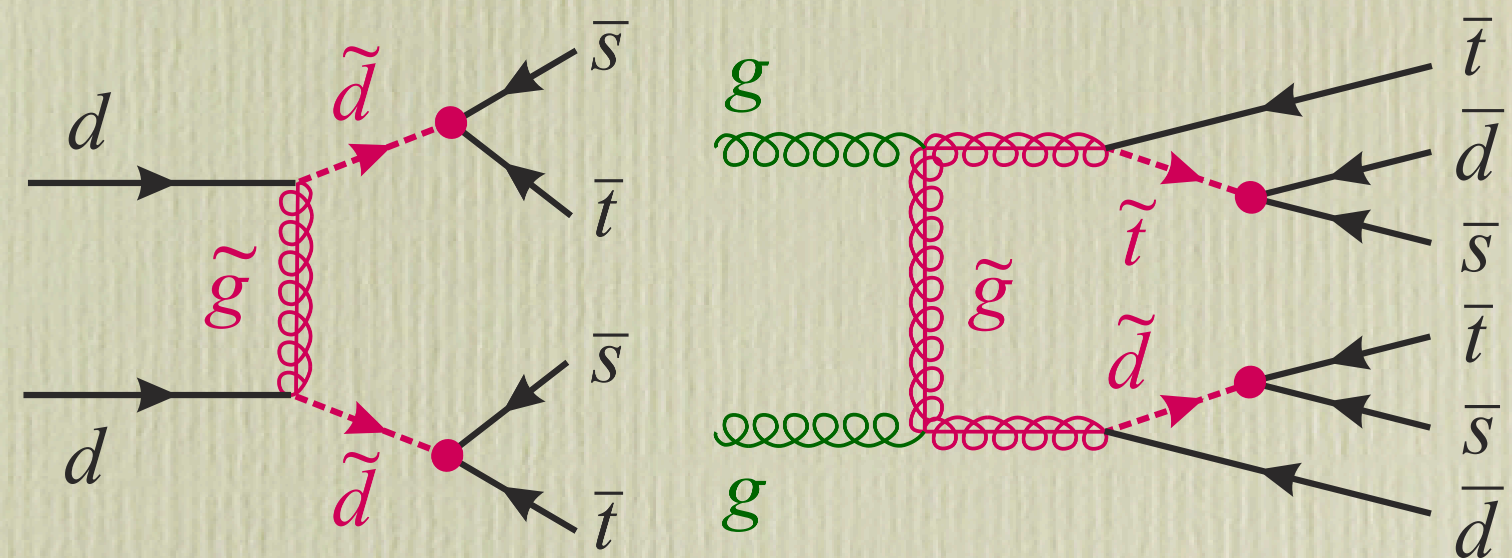




from ATLAS 1311.6724

LHC compatible with SM expectations

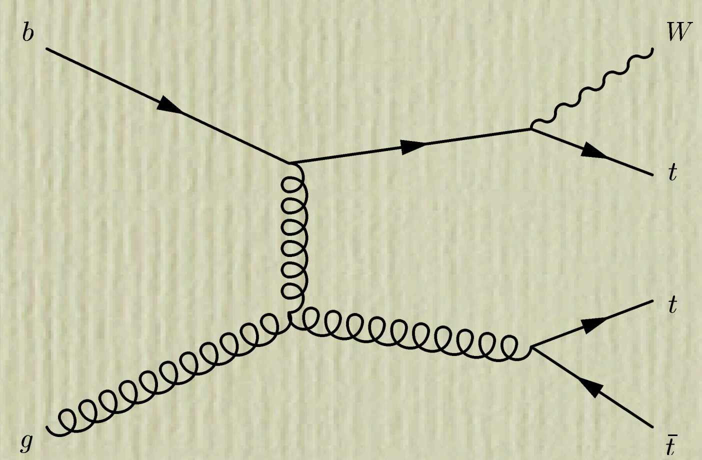
Same charge 

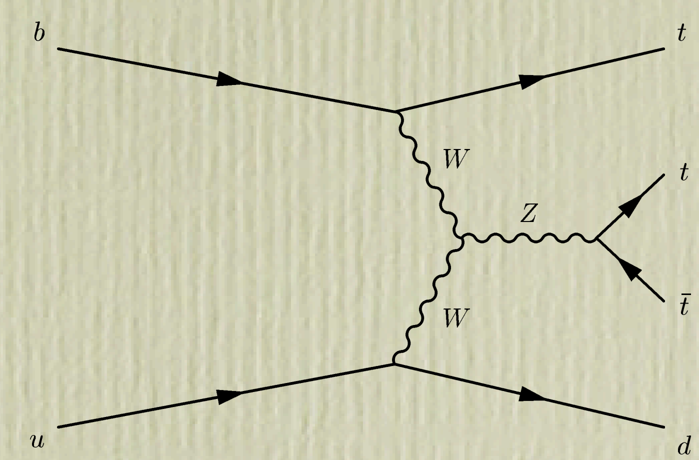


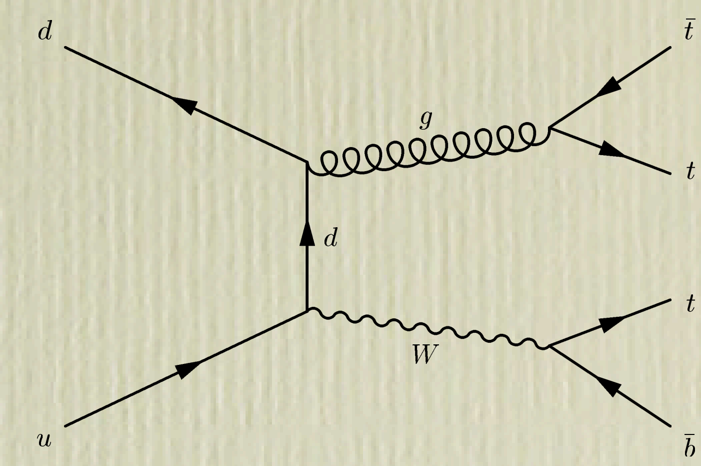
- Example in RPV models (from Durieux et al. 1210.6598)

- @LHC qq initial states dominate over qbar-qbar ones and this asymmetry propagates in the final state

3 Ts in the SM



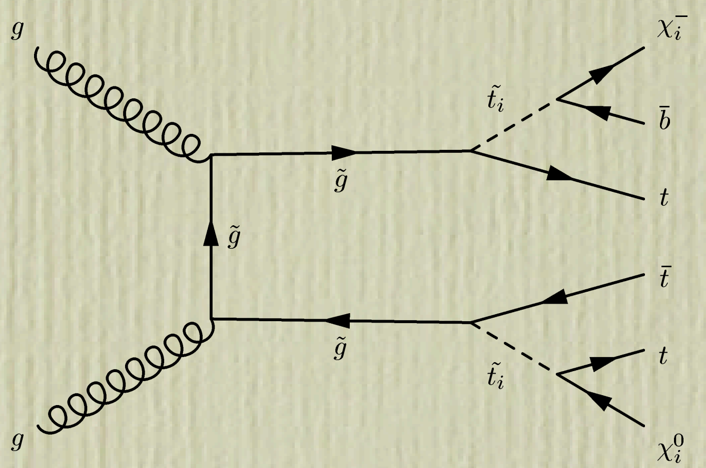




from 1001.0221
Barger et al.

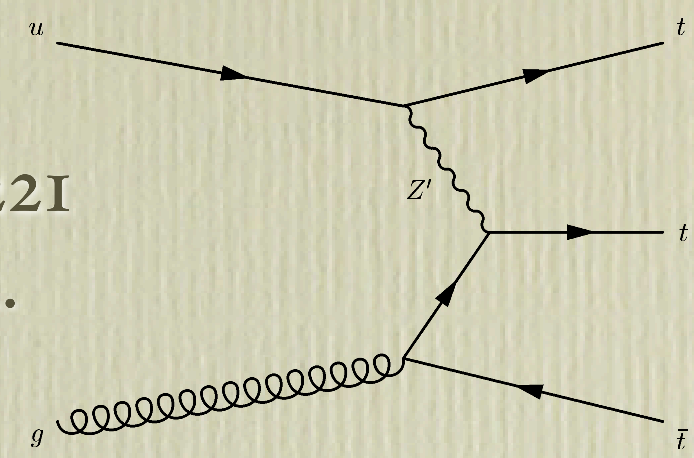
- 1.9 fb @ 14TeV LHC
- odd number of tops requires the tbW vertex
- 3 tops + (W, jets, b)

3 Ts examples in BSM



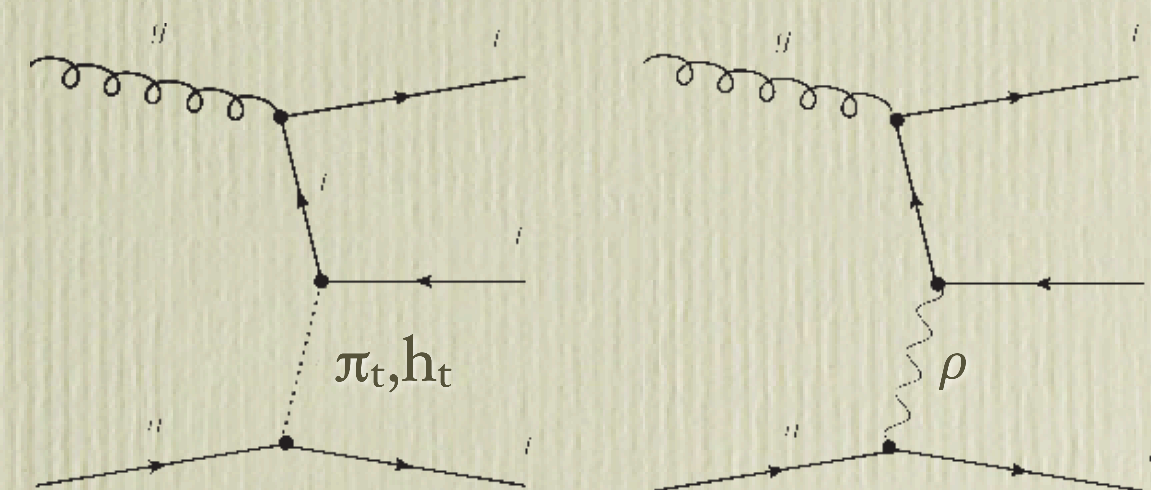
susy

from 1001.0221
Barger et al.



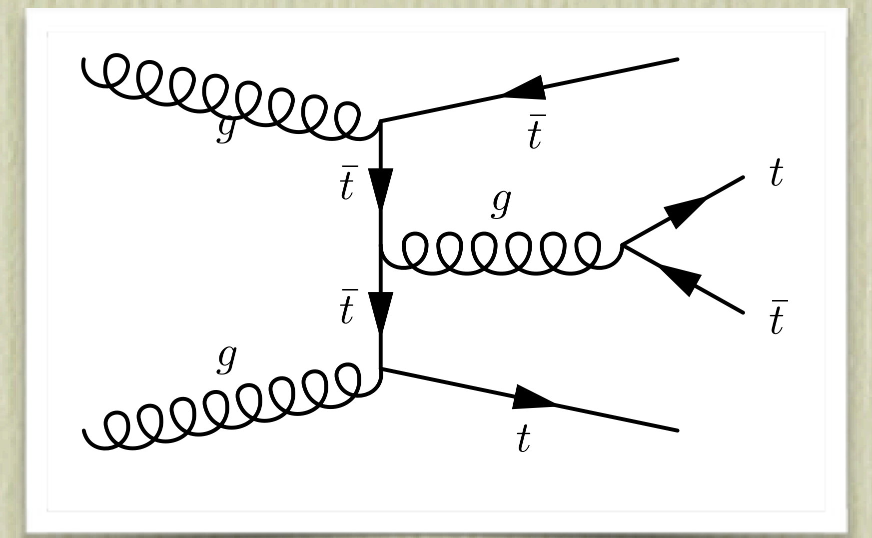
Z’

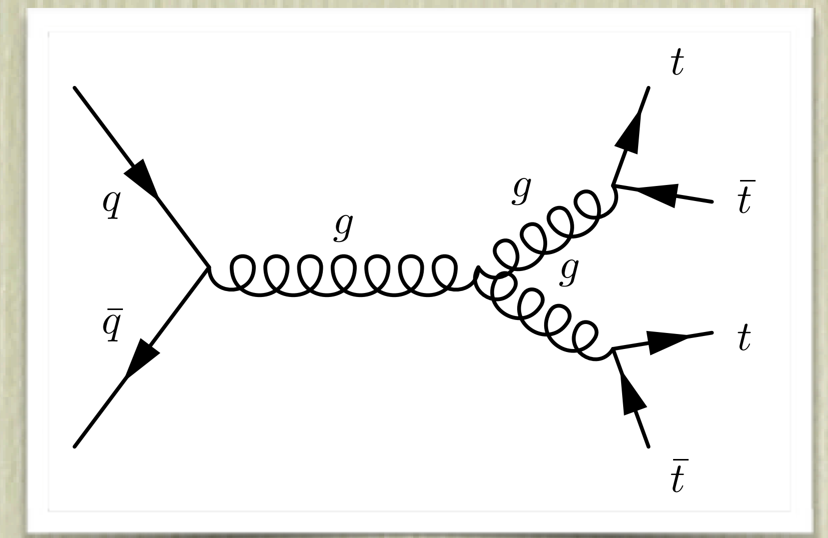
topcolor
from 1203.2321



- in susy can be enhanced if light stops and not too heavy gluino
- Z’ signal is due to FCNC vertex (Z’ should be leptophobic)
- simple topcolor models also face FCNC limits

4 Ts in the SM





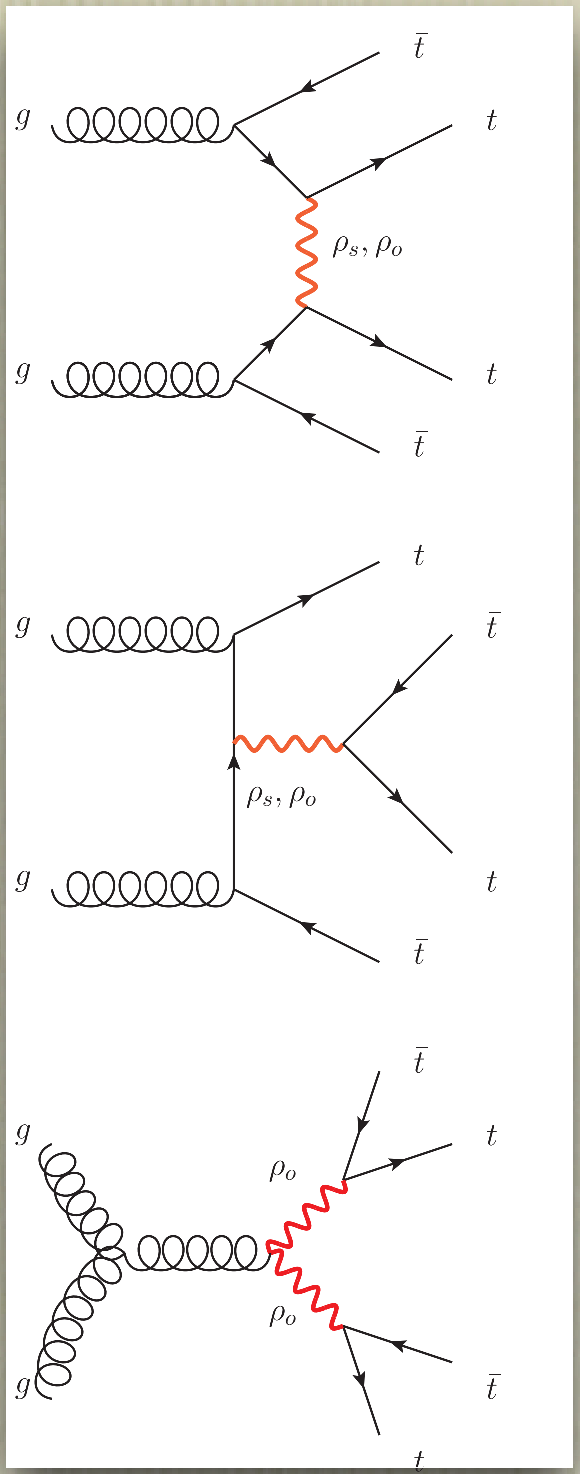
- gg dominant on qqbar at LHC
- small cross-section in the SM (0.5 fb @7 TeV)

4Ts in BSM

- quite a number of BSM models (SS tt applies too, see 1203.5862):
    - heavy gluon (octect)
    - heavy photon (color singlet) (ex. 2-xdim models) pair produced and decaying to $t\bar{t}\,t\bar{t}$

Aguilar-Saavedra & Santiago 1112.3778

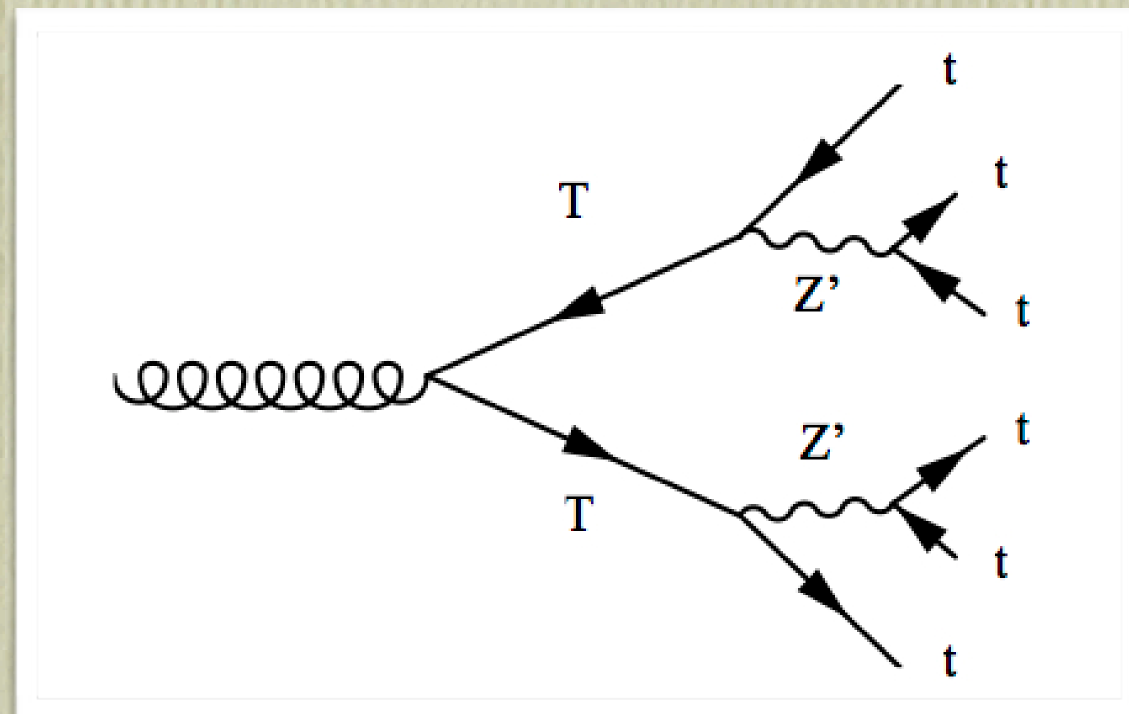
Cacciapaglia et al. 1107.4616



multi  s in BSM

- multitops = more than 4 top quarks in the final state
- how many tops at LHC can be detected (in a single event)? surely (much) less than $\sqrt{s}/m_t \sim 80$ at 14 TeV LHC
- are 6, 8... tops constrained by present measurements? can have more?
- what BSM physics?
- ongoing work with G.Cacciapaglia and N.Deutschmann

6 Ts in BSM



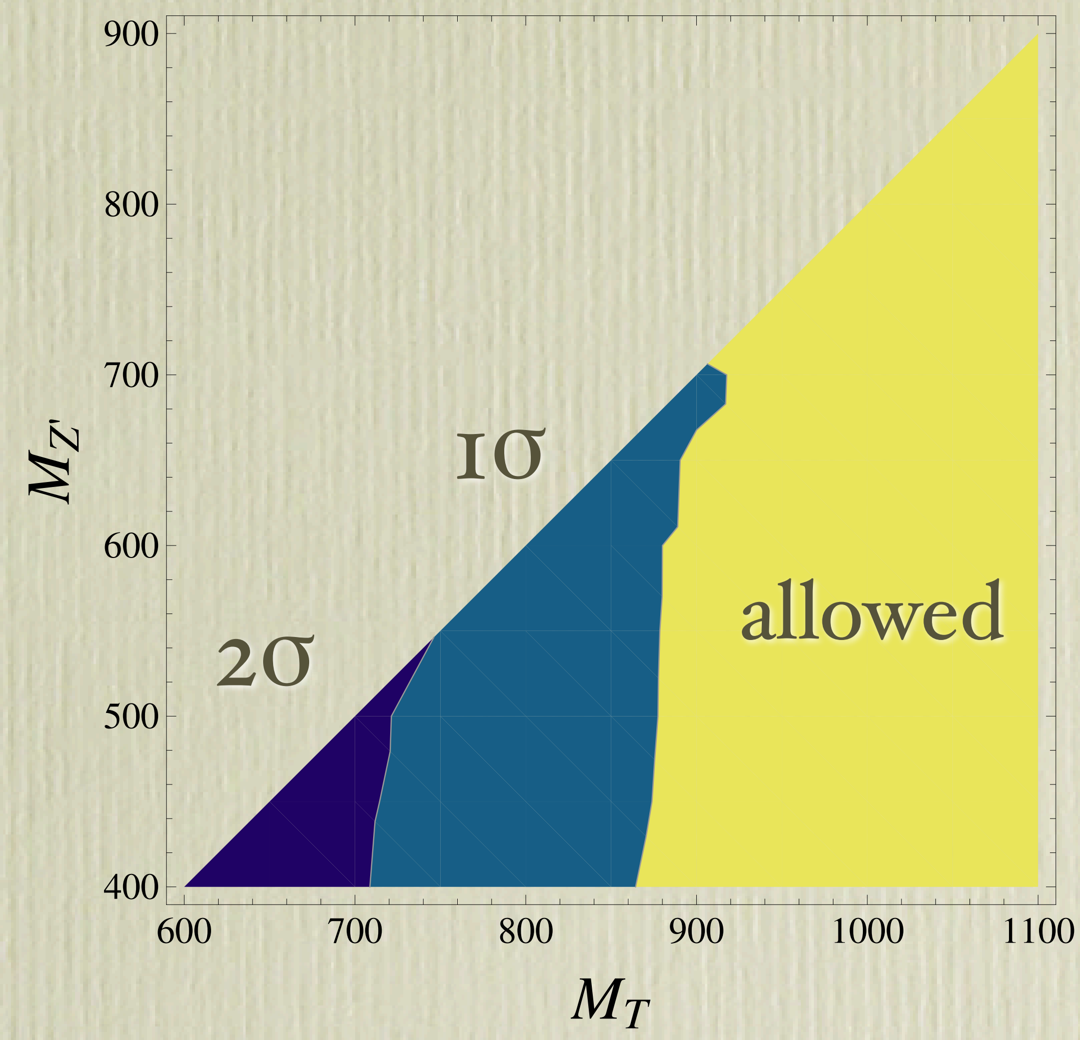
	$R_{Z'}$	R_T
R_1	$\mathbf{1}$	$\mathbf{3}$
R_2	$\mathbf{8}$	$\mathbf{3}$
R_3	$\mathbf{8}$	$\bar{\mathbf{6}}$
R_4	$\mathbf{8}$	$\mathbf{15}$

- you just need a T (top-partner) and a Z’ ($m_T > m_{Z'} + m_t$)
- coloured Z’ is more constrained
- possible colour SU(3) embeddings in the table

6 s bounds

- if Z' coloured just check your 4 top analysis (Z' pair production is larger, $m_T > m_{Z'} + m_t$ and typically colour factor advantage)

- if Z' colour singlet 2SSL give bounds: (recasting CMS 1212.6194)



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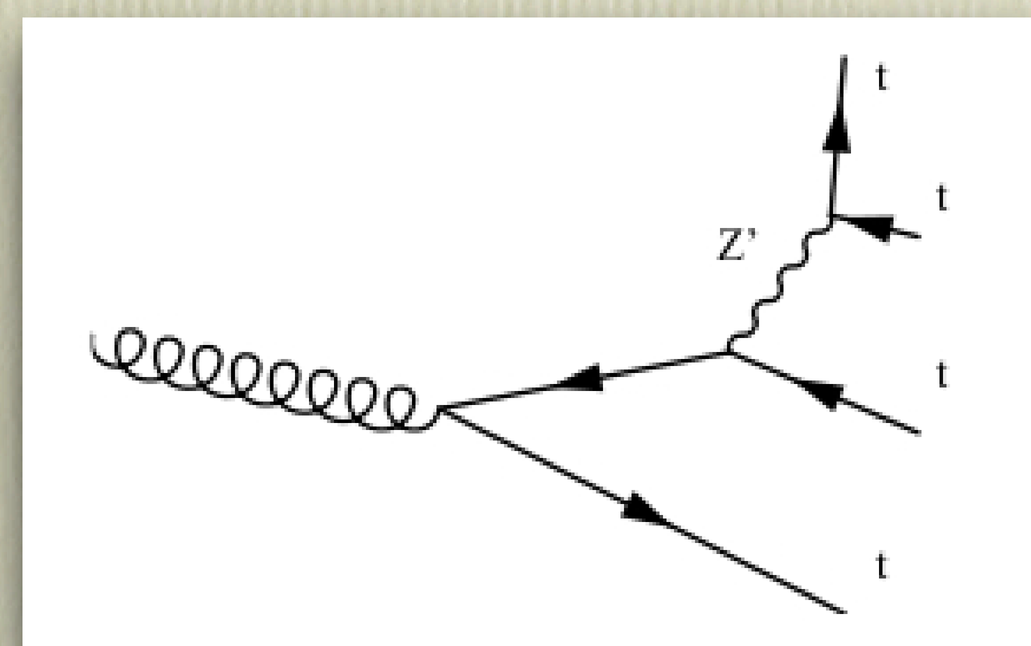
8 s in BSM

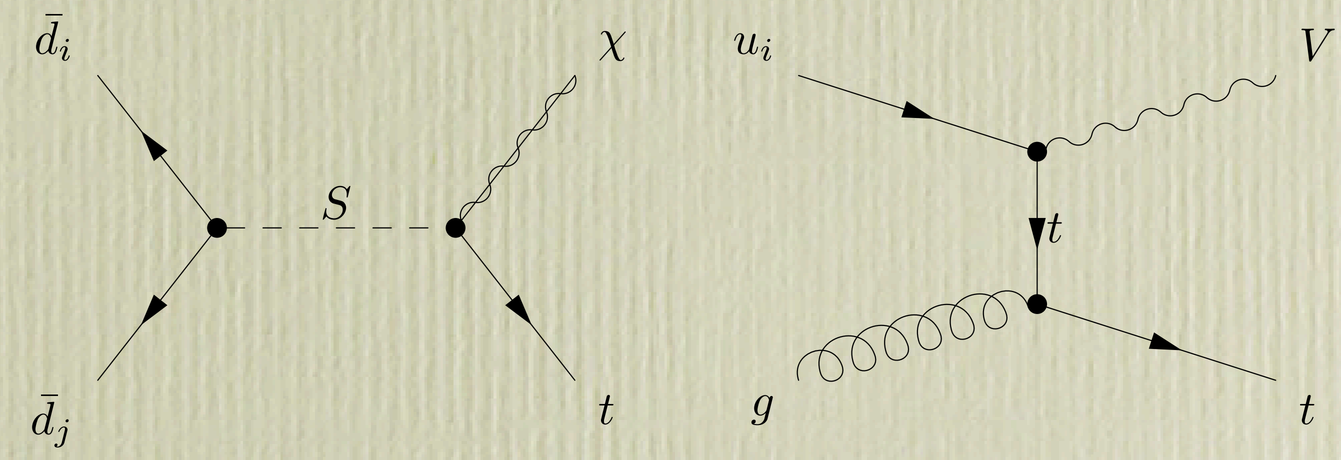
- you need a ϱ, a T and a Z’ ($m_\varrho > m_T > m_{Z'} + m_t$)
- ϱ octet, T triplet and Z’ singlet (all previous cases also possible but constrained as in 6 tops)
- 8 tops from pair production of ϱ colour octets
- no bounds from present 2SSL data for a 800 GeV ϱ (bkg compatible)
- closing the window on top multiplicity is a matter of int. luminosity and dedicated searches



Monotop

- production of a single top plus missing energy (not necessarily a DM particle), first introduced in 1106.6199 (J.Andrea, B.Fuks, F.Maltoni)

- can be resonant (coloured boson, as R violating SUSY) or flavour changing:



- general effective Lagrangian description, but what SM embedding? (ongoing work with Boucheneb, Cacciapaglia, Fuks; ATLAS analysis underway)

Monotop - resonant

- spin zero couples to spinors with opposite chirality, but $\boldsymbol{\varphi}_1$ is a singlet, $\boldsymbol{\varphi}_2$ a triplet of SU(2), so two different fields:

$$\lambda_S^1 \varphi_1 \bar{d}_R^C d_R + \lambda_S^2 \varphi_2 \bar{d}_L^C d_L$$

- similar argument in decay: need t plus a singlet, $\boldsymbol{\varphi}_1$ ok, but $\boldsymbol{\varphi}_2$ into t plus a multiplet (so not only a neutral long-lived state).

- spin 1 couples to spinors with same chirality:

$$\lambda_V^1 X^\mu \bar{d}_L^C \gamma_\mu d_R + \lambda_V^2 X^\mu \bar{d}_R^C \gamma_\mu d_L$$

so X^μ is (2,1/6) and χ can decay to X^μ b, no monotop!

Monotop - nonresonant

- the flavour changing boson V should be long-lived or have invisible decay V→$\chi\chi$

- spin zero: ϕ a doublet of SU(2), disfavoured

$$\phi\ (y_1\, \bar{t}_R u_L + y_2\, \bar{u}_R t_L)$$

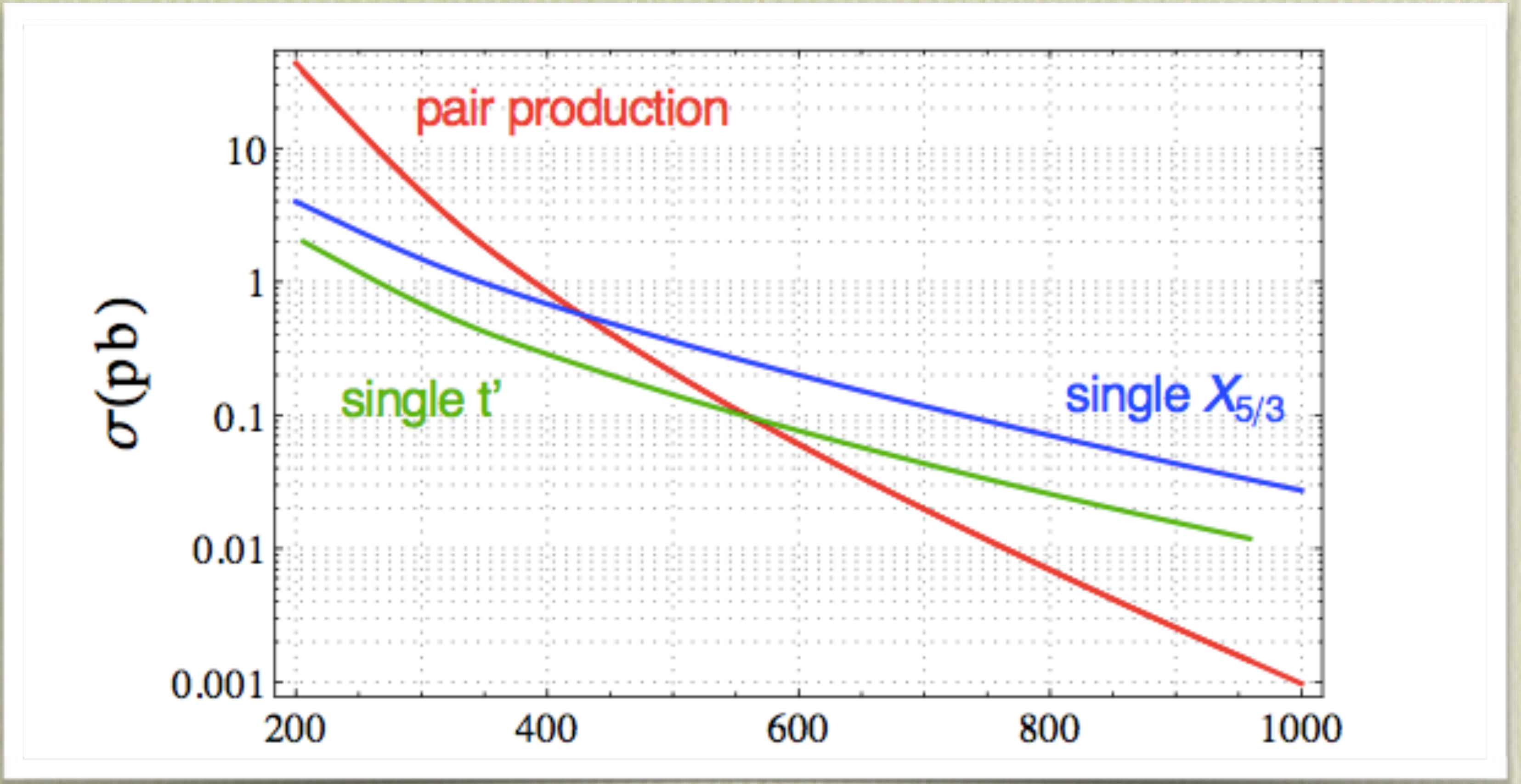
- spin 1, can be singlet

$$a_R V_\mu \bar{t}_R \gamma^\mu u_R + a_L V_\mu (\bar{t}_L \gamma^\mu u_L + \bar{b}_L \gamma^\mu d_L)$$

- χ as a DM candidate is constrained both by relic abundance and by LHC

beyond T: vector-like quarks

- Unique window to test models (Xdim, composite, Little Higgs, SUSY)
- Reach at LHC substantial and only partially exploited
- Mixings with all the 3 SM generation important (production/decay)
- Single production dominant with present mass bound at LHC (~700 GeV)



why vector-like quarks?

- top partners are expected in many extensions of the SM (composite/Little higgs models, Xdim models)
- they come in complete multiplets (not just singlets)
- theoretical expectation is a not too heavy mass scale M ($\sim$TeV) and mainly coupling to the 3rd generation
- Present LHC mass bounds $\sim$ 700 GeV
- Mixings bounded by EWPT, flavour…

Simplest multiplets (and SM quantum numbers)

	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(t') (b')	$\begin{pmatrix} X \\ t' \end{pmatrix}$ $\begin{pmatrix} t' \\ b' \end{pmatrix}$ $\begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix}$ $\begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	1/6 7/6 -5/6	2/3 -1/3
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}}\bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}}\bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}}\bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}}\bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}}\bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		
Free parameters		4 $M + 3 \times \lambda^i$	4 or 7 $M + 3\lambda_u^i + 3\lambda_d^i$	4 $M + 3 \times \lambda^i$

Simplified Mixing effects (t-T sector only)

- Yukawa coupling generates a mixing between the new state(s) and the SM ones

- Type 1 : singlet and triplets couple to SM L-doublet
  - Singlet ψ = (1, 2/3) = U : only a top partner is present
  - triplet ψ = (3, 2/3) = {X, U, D} , the new fermion contains a partner for both top and bottom, plus X with charge 5/3
  - triplet ψ = (3, −1/3) = {U, D, Y} , the new fermions are a partner for both top and bottom, plus Y with charge −4/3

$$\mathcal{L}_{\text{mass}} = -\frac{y_u v}{\sqrt{2}}\,\bar{u}_L u_R - x\,\bar{u}_L U_R - M\,\bar{U}_L U_R + h.c.$$

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & x \\ 0 & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

Simplified Mixing effects (t-T sector only)

- Type 2 : new doublets couple to SM R-singlet
- SM doublet case ψ = (2, 1/6) = {U, D} , the vector-like fermions are a top and bottom partners
- non-SM doublets ψ = (2, 7/ 6) = {X, U} , the vector-like fermions are a top partner and a fermion X with charge 5/3
- non-SM doublets ψ = (2, -5/ 6) = {D,Y} , the vector-like fermions are a bottom partner and a fermion Y with charge -4/3

$$\mathcal{L}_{\text{mass}} = -\frac{y_u v}{\sqrt{2}} \bar{u}_L u_R - x\, \bar{U}_L u_R - M\, \bar{U}_L U_R + h.c.$$

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & 0 \\ x & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

Mixing 1VLQ (doublet) with the 3 SM generations

$$M_u = \begin{pmatrix} \tilde{m}_u & & & \\ & \tilde{m}_c & & \\ & & \tilde{m}_t & \\ x_1 & x_2 & x_3 & M \end{pmatrix} = V_L \cdot \begin{pmatrix} m_u & & & \\ & m_c & & \\ & & m_t & \\ & & & M \end{pmatrix} \cdot V_R^\dagger$$

$$V_L \implies M_u \cdot M_u^\dagger = \begin{pmatrix} \tilde{m}_u^2 & & & x_1^* \tilde{m}_u^2 \\ & \tilde{m}_c^2 & & x_2^* \tilde{m}_c^2 \\ & & \tilde{m}_t^2 & x_3 \tilde{m}_t^2 \\ x_1 \tilde{m}_u & x_2 \tilde{m}_c & x_3 \tilde{m}_t & |x_1|^2 + |x_2|^2 + x_3^2 + M^2 \end{pmatrix}$$

$m_q \propto \tilde{m}_q$

mixing is suppressed by quark masses

$$V_R \implies M_u^\dagger \cdot M_u = \begin{pmatrix} \tilde{m}_u^2 + |x_1|^2 & x_1^* x_2 & x_1^* x_3 & x_1^* M \\ x_2^* x_1 & \tilde{m}_c^2 + |x_2|^2 & x_2^* x_3 & x_2^* M \\ x_3 x_1 & x_3 x_2 & \tilde{m}_t^2 + x_3^2 & x_3 M \\ x_1 M & x_2 M & x_3 M & M^2 \end{pmatrix}$$

mixing in the right sector present also for $\tilde{m}_q \to 0$

flavour constraints for q_R are relevant

Mixing with more VL multiplets

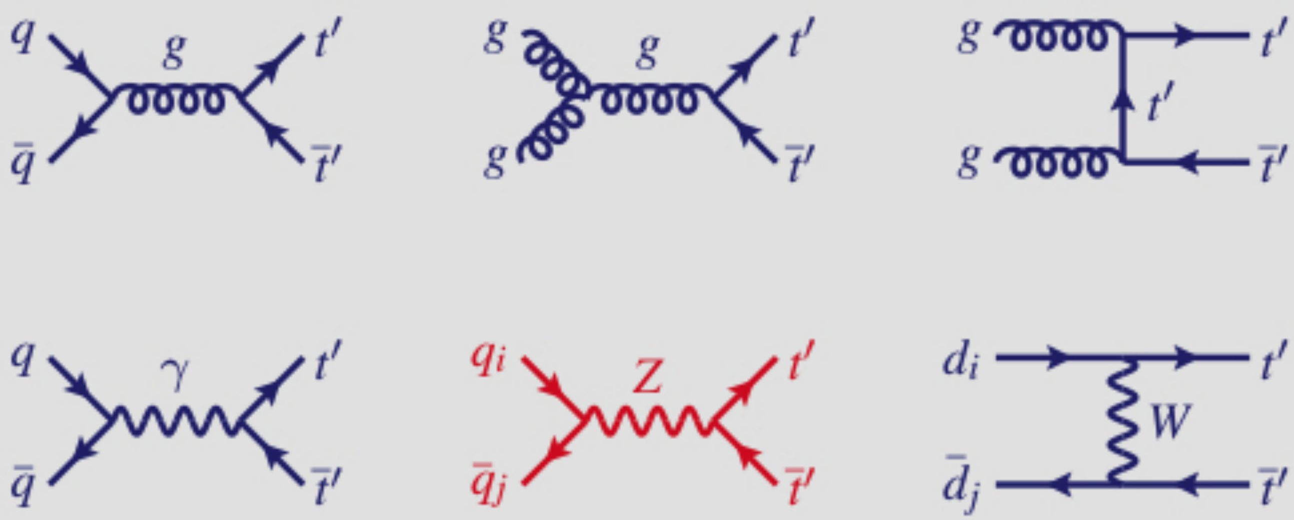
ArXiv:1305.4172 M.Buchkremer et al.

integer isospin multiplets

$$\mathcal{L}_{\text{mass}} = \bar{q}_L \cdot \left(\begin{array}{ccc|ccc|ccc} \mu_1 & 0 & 0 & 0 & \dots & 0 & x_{1,n_d+4} & \dots & x_{1,N} \\ 0 & \mu_2 & 0 & 0 & \dots & 0 & x_{2,n_d+4} & \dots & x_{2,N} \\ 0 & 0 & \mu_3 & 0 & \dots & 0 & x_{3,n_d+4} & \dots & x_{3,N} \\ \hline y_{4,1} & y_{4,2} & y_{4,3} & M_4 & 0 & 0 & & & \\ \vdots & \vdots & \vdots & 0 & \ddots & 0 & & \omega_{\alpha\beta} & \\ y_{n_d+3,1} & y_{n_d+3,2} & y_{n_d+3,3} & 0 & 0 & M_{n_d+3} & & & \\ \hline 0 & 0 & 0 & & & & M_{n_d+4} & 0 & 0 \\ \vdots & \vdots & \vdots & & \omega'_{\alpha\beta} & & 0 & \ddots & 0 \\ 0 & 0 & 0 & & & & 0 & 0 & M_N \end{array}\right) \cdot q_R + h.c.$$

semi-integer isospin multiplets

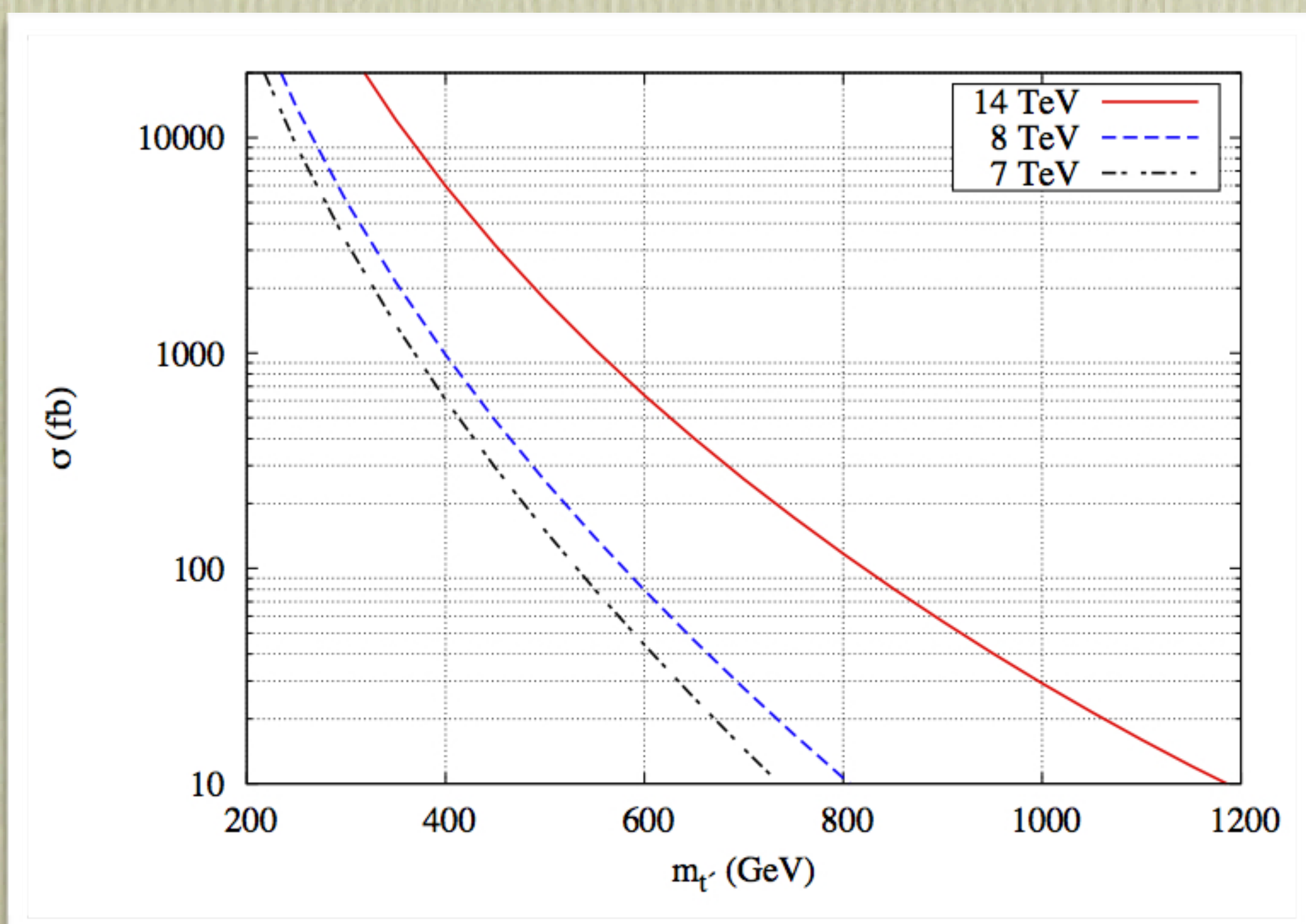
Pair production



Purely QCD diagrams (dominant contribution)

Purely EW diagrams

"new" FCNC channel, but suppressed wrt to QCD



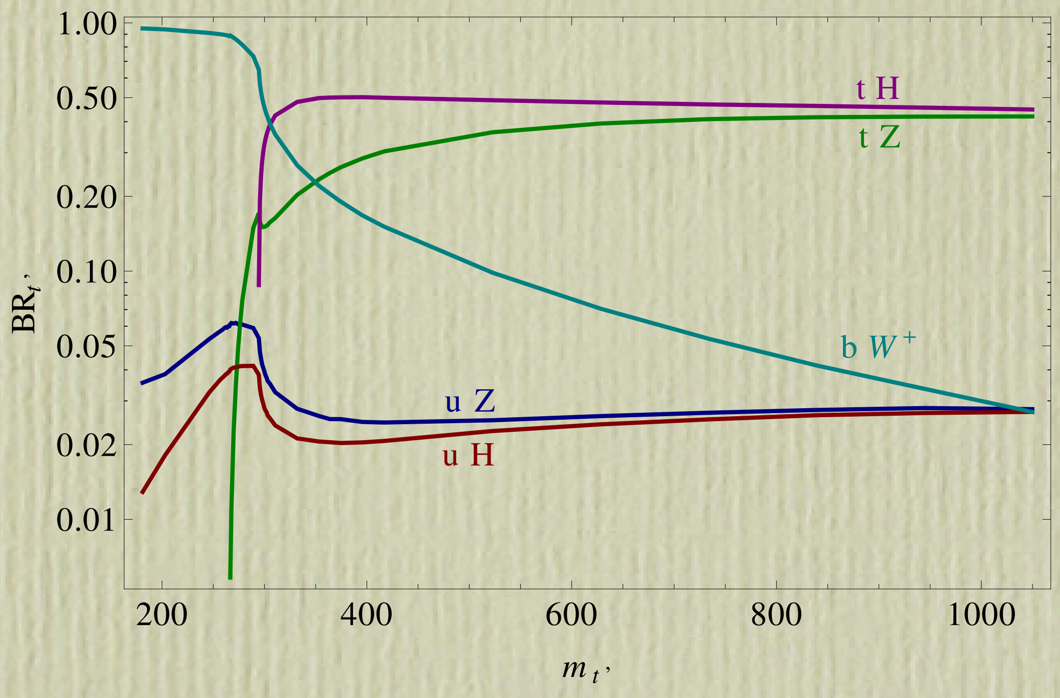
Pair production for t' of the non-SM doublet pp → t' t @ LHC

T' decays

Decay modes never 100% in one channel, in the limit of the equivalence theorem, dictated by the multiplet representation :

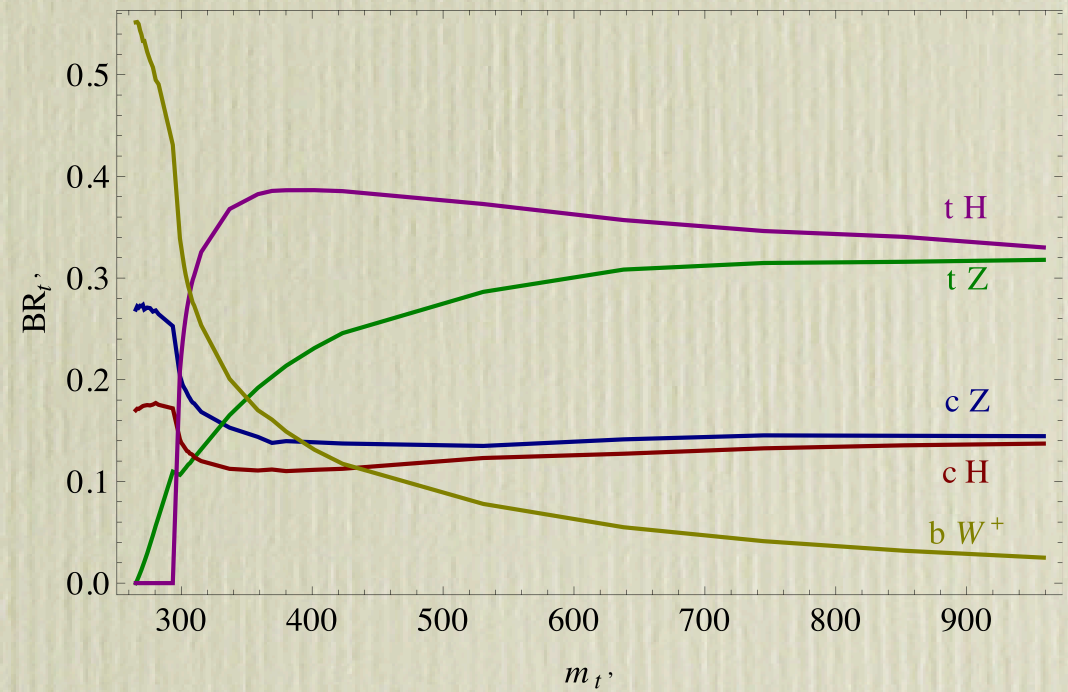
t'	Wb	Zt	ht
Singlet, Triplet Y=2/3	50%	25%	25%
Doublet, Triplet Y=-1/3	~0%	50%	50%

T' decays ($X^{5/3}$,T') multiplet



Mixing mostly with top
V_R^{41} maximal

Mixing mostly with top
V_R^{42} maximal



In all cases T' → bW
NOT dominant for allowed masses

Conclusions

- top quark plays a special role in SM and BSM
- top quark is a privileged gate to test BSM physics
- precision measurements era is now
- new multi-top channels can give extra information
- monotop is an interesting but constrained scenario
- top partners are a rich sector to explore to discover or constrain BSM physics