Theory overview of BSM top and Higgs interactions

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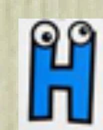
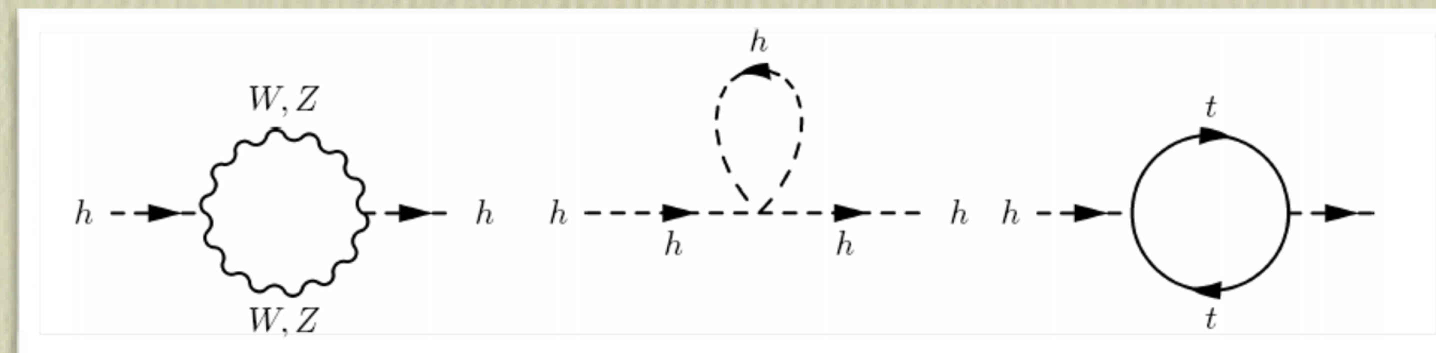
An ongoing long quest in just few lines

- Discovery of the  quark in 1995 at TeVatron
- The heaviest elementary particle, its mass affects precision EW fits
-  discovery in 2012 at the LHC and study of its properties
- Related large coupling of  and  : probe electroweak symmetry breaking
-  and  knowledge is driven by LHC measurements
- Good agreement with the SM and improved theoretical calculations
- Perfect tool to probe BSM physics

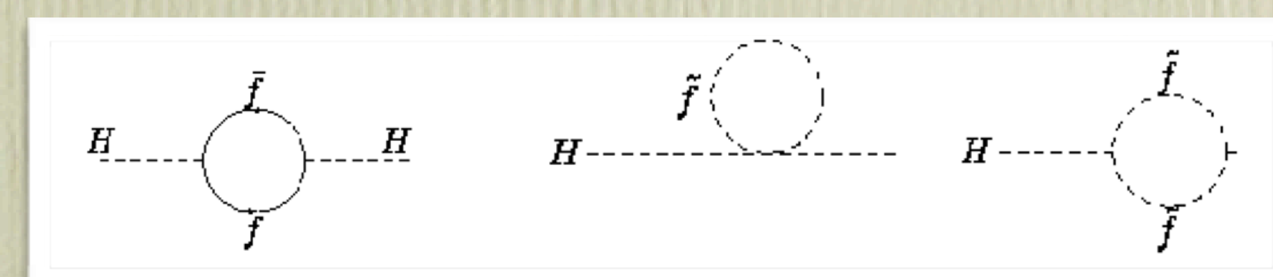
T is special for SM & BSM



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

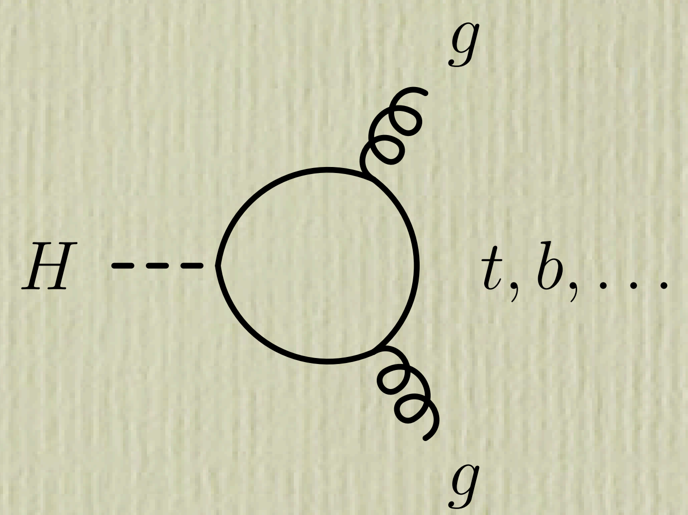
$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2 \approx -(0.2\ \Lambda)^2$$

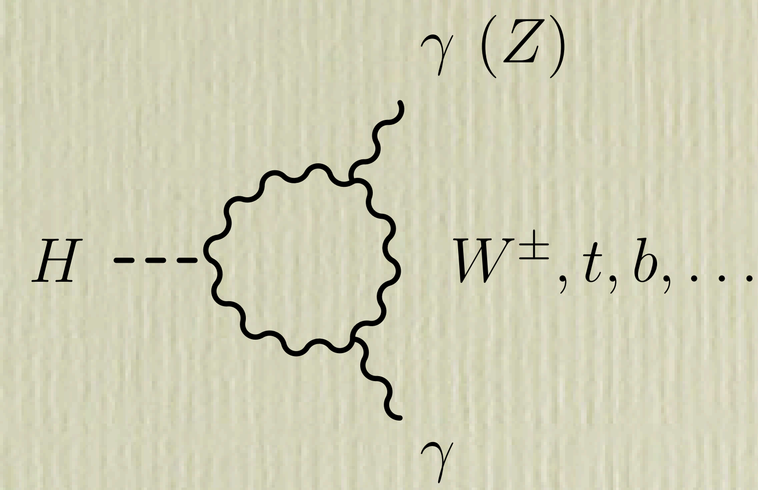
- In susy stop (top-partner) cancel the quadratic dependence



but not the only way! (see M.Peskin's theory keynote)

and in H couplings too





Example of a top normalised/inspired parameterisation:

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| \kappa_W \mathcal{A}_1(\tau_W) + C_t^\gamma \, 3 \left(\frac{2}{3}\right)^2 \mathcal{A}_{1/2}(\tau_t) \, [\kappa_t + \kappa_{\gamma\gamma}] + \dots \right|^2$$

$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_H^3}{16\sqrt{2}\pi^3} \left| C_t^g \frac{1}{2} \mathcal{A}_{1/2}(\tau_t) \, [\kappa_t + \kappa_{gg}] + \dots \right|^2$$

G.Cacciapaglia, A.D., J.Llodra-Perez 0901.0927
G.Cacciapaglia, A.D., G.Drieu La Rochelle, J.B.Flament 1210.8120

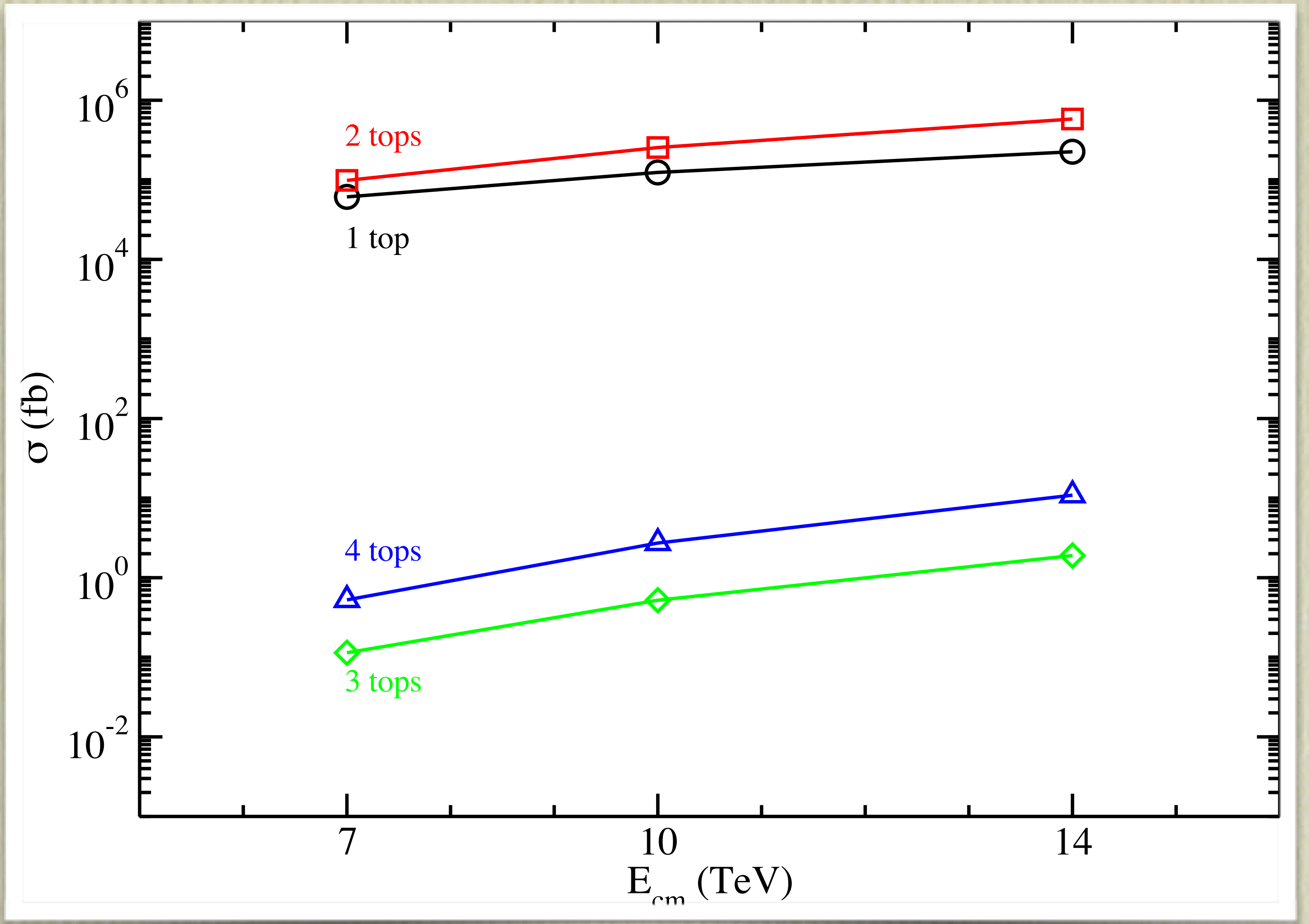
T is special for BSM physics

- Composite models (technicolor, effective lagrangians like little Higgs, topcolor...):
  - top effective 4 fermion operators
  - vector-like top partners
  - new coloured scalars
- Extra-dimensional models:
  - KK-modes of top and gluons
  - Xdim realisations of composite models

Counting 's and BSM physics

- Simple plan (but skip some of those already extensively covered at this conference):
  - 1 top (single top, monotop)
  - 2 tops (modifications to $t\bar{t}$ and $\bar{t}\bar{t}$)
  - 3 tops (MSSM, Z'...)
  - 4 tops (many BSM studies)
  - 6 tops
  - 8 tops (and why we stop here)

SM cross sections



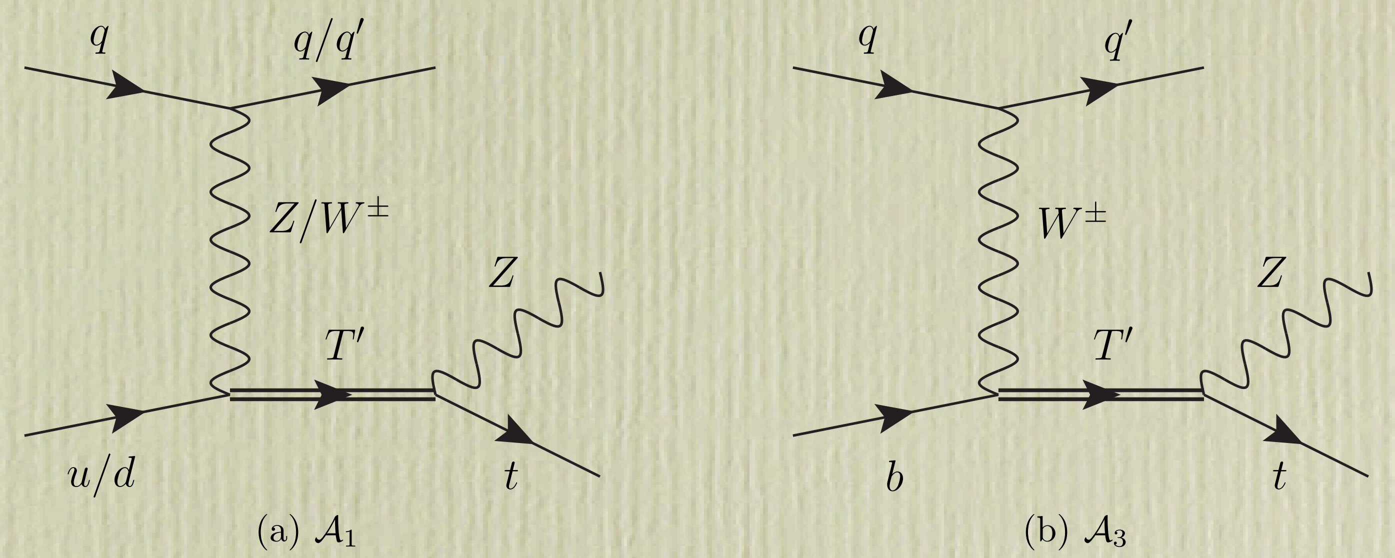
from 1001.0221
Barger et al.

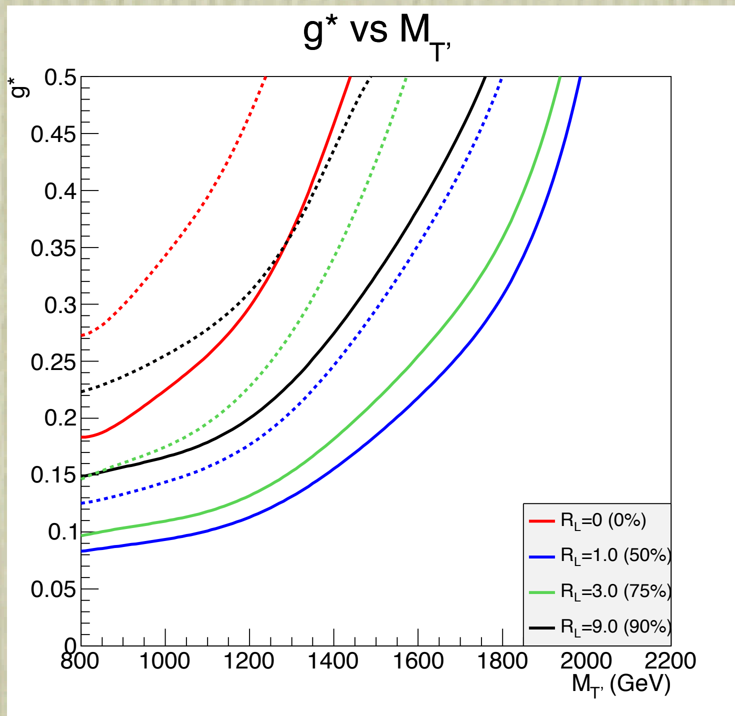
- multi-top (more than 2) cross-sections are small in the SM ~ fb while can be enhanced in BSM

Single top

- A full session already dedicated to it
- Main implications for BSM:
  - search for FCNC
  - modification of the Wtb coupling
  - W' → tb
  - b* → t W

Single top and T'→tZ





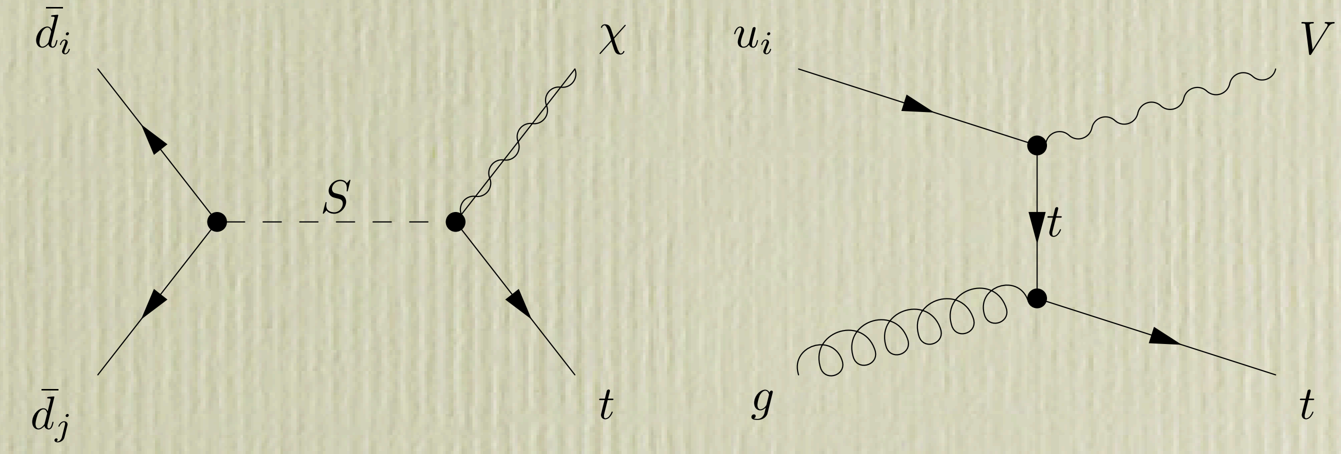
Also recast as FCNC limit on Ztq coupling

1411.7587 L.Basso, J.Andrea (trilepton channel)

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, with SM embedding, see I.Boucheneb et al. 1407.7529

Monotop - resonant

- spin zero couples to spinors with opposite chirality, but **φ_1** is a singlet, **φ_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, **φ_1** ok, but **φ_2** into t plus a multiplet (so not only a neutral 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 on the decay side χ can go to X^μ b, no monotop!

Monotop - nonresonant

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

- 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

LHC monotop analyses

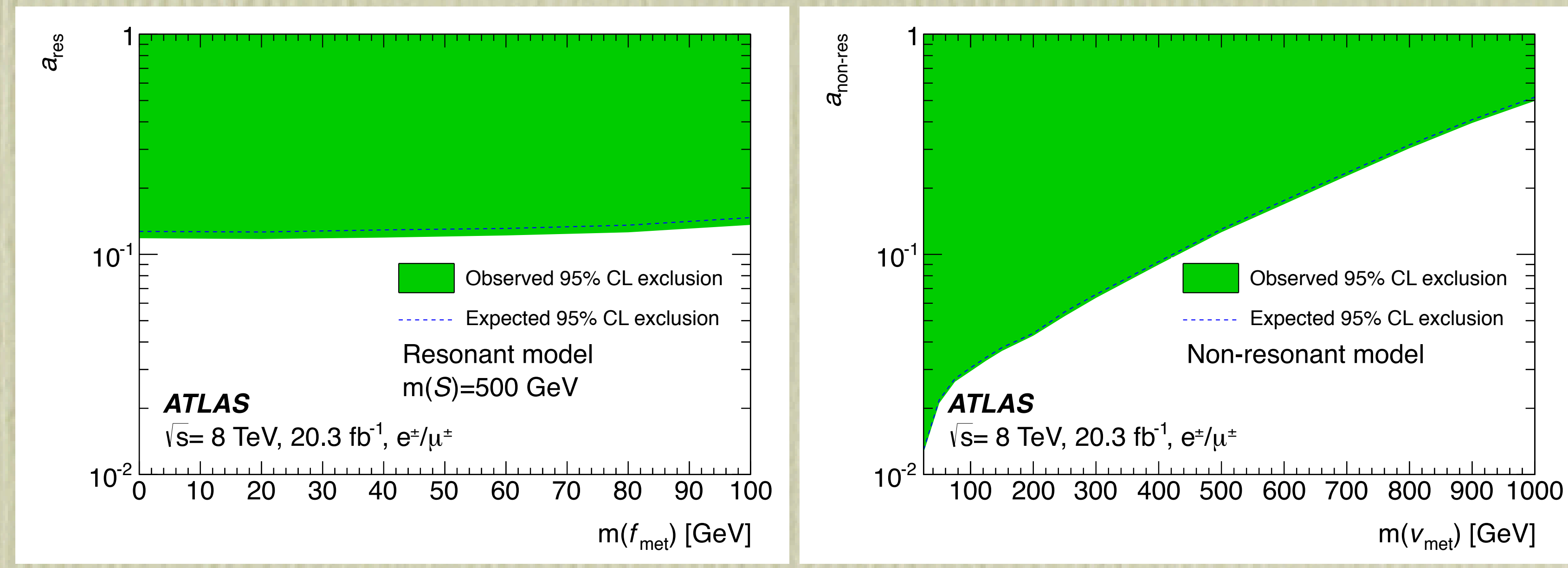


figure from 1410.5404
CERN-PH-EP-2014-231

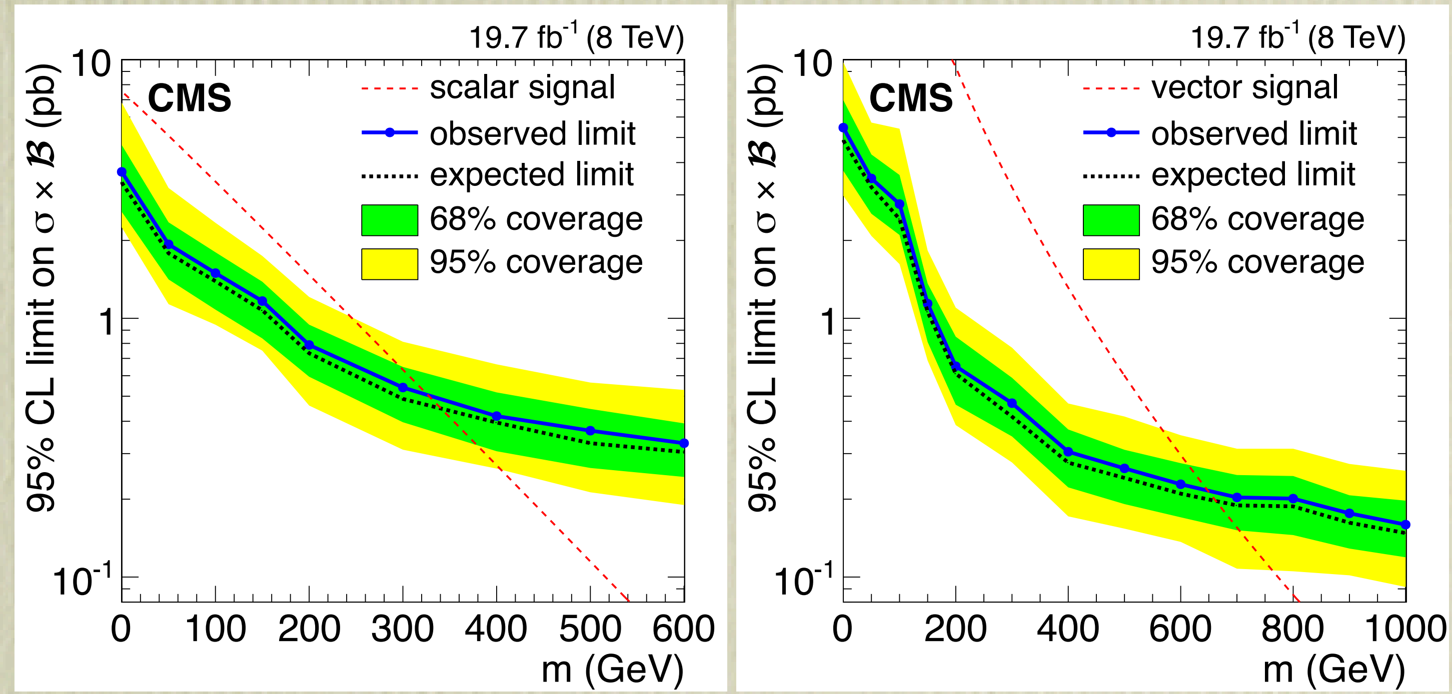
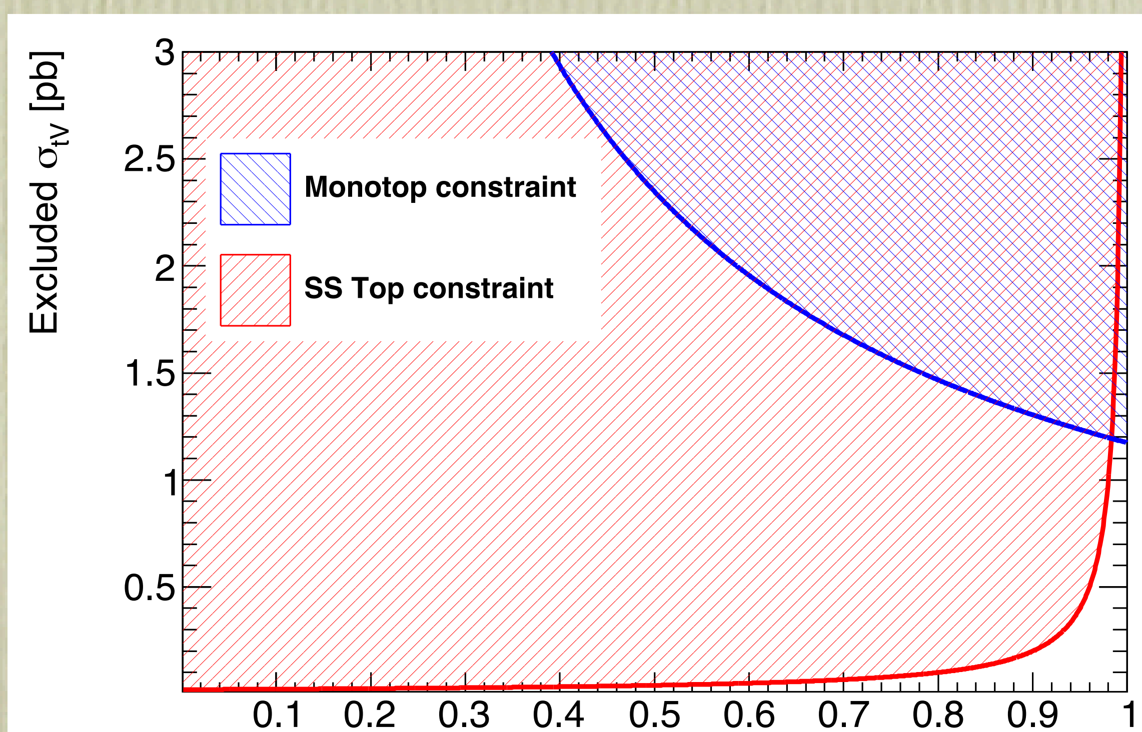


figure from 1410.1149
CMS-B2G-12-022
a-parameter set to 0.1

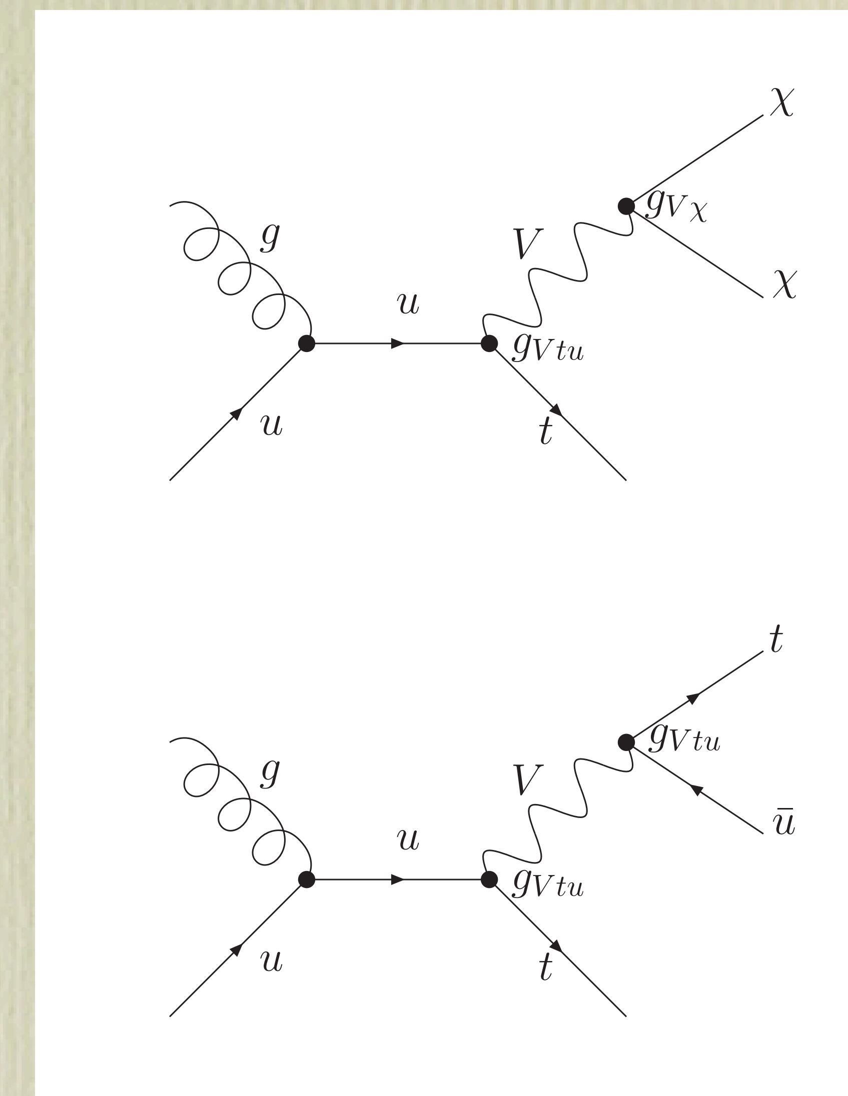
Other constraints for monotop

$$\sigma_{monotop} = \sigma_{tV} \times BR[V \to \chi\chi]$$

$$\sigma_{SStop} = \sigma_{tV} \times \frac{1 - BR[V \to \chi\chi]}{2}$$



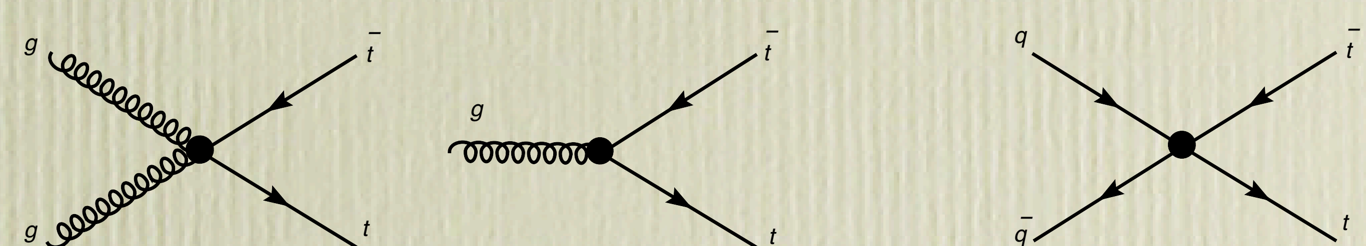
Br (V→χχ)



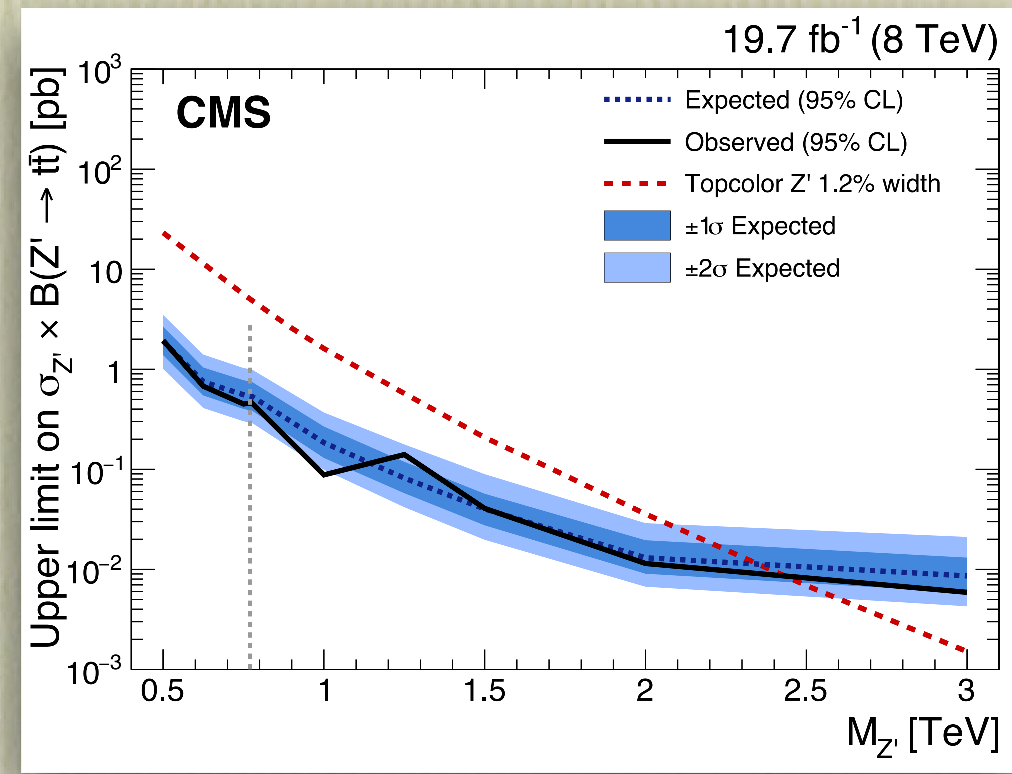
figures from T.Megy

T-Tbar in BSM

- Resonant contributions from:
    - spin 0, 1, 2
    - color singlets, octets
    - parity even and odd states
- Effective operator description (Degrande et al. 1010.6304)
    - $t\bar{t}g$, $t\bar{t}gg$
    - 4 quark operators ($t\bar{t}$ and 2 light quarks)

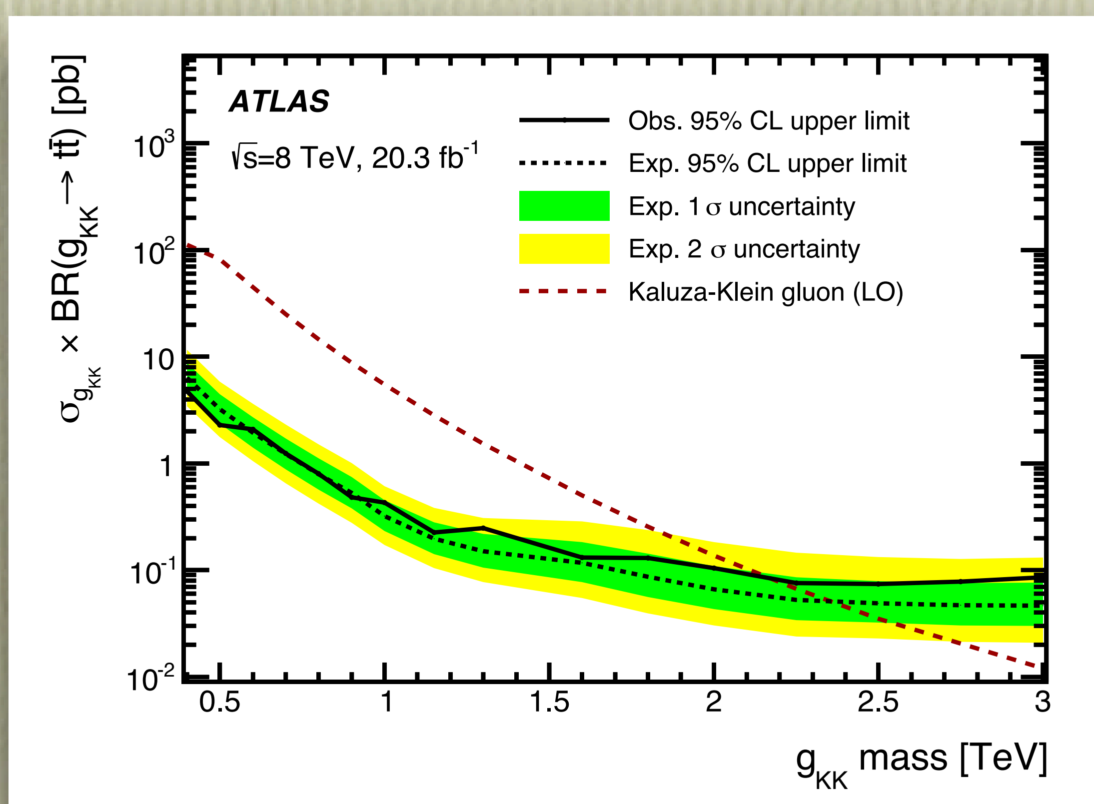


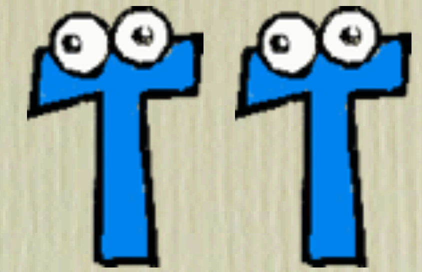
T-Tbar exclusions examples

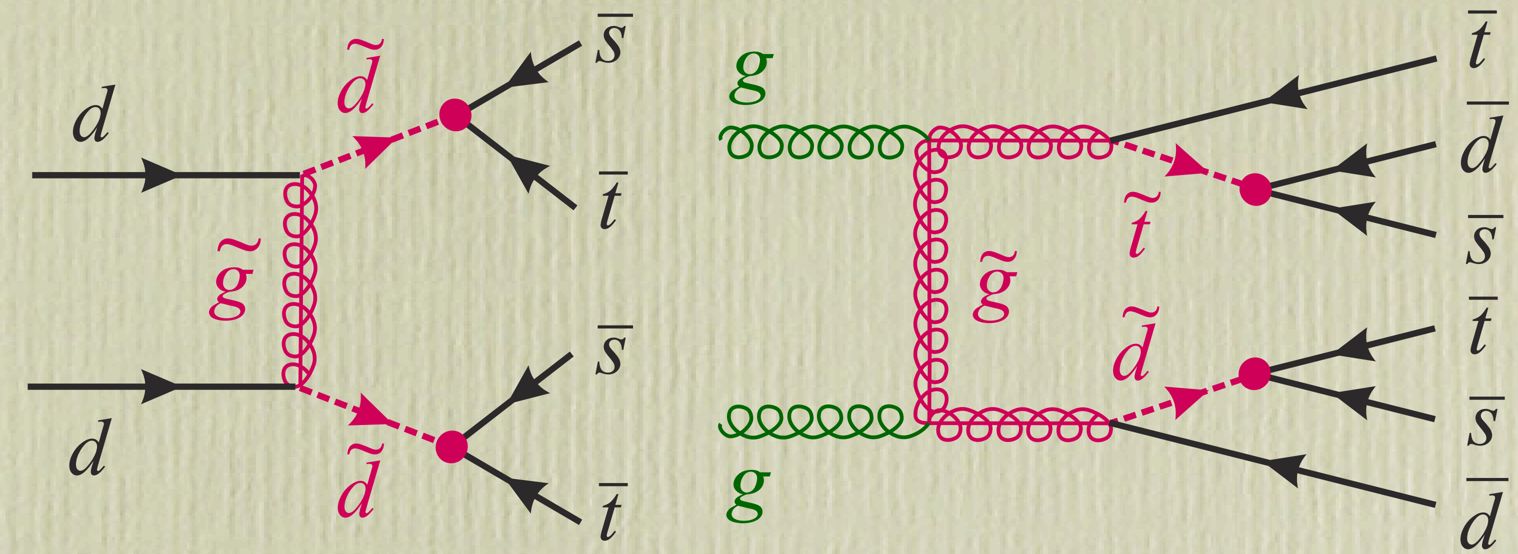


from CMS 1506.03062

from ATLAS 1505.07018

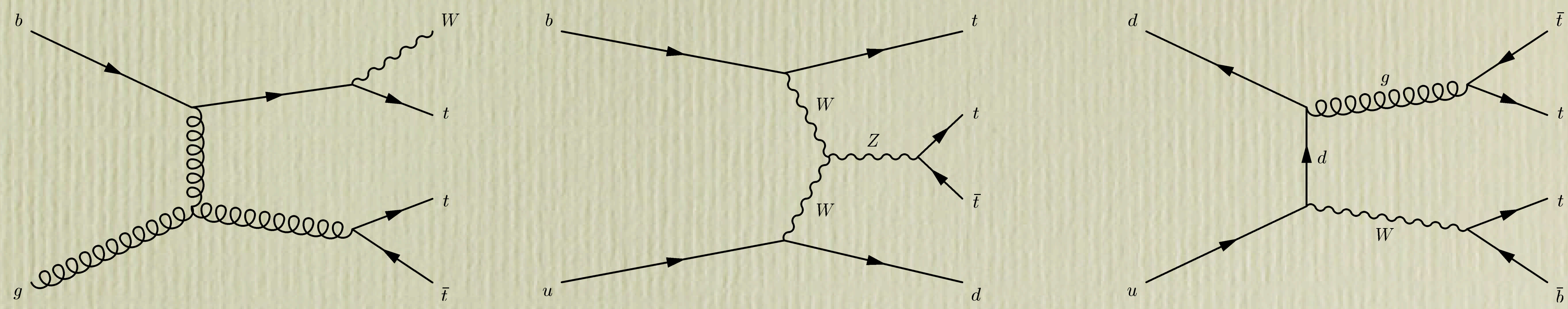


Same charge: 



- Example in RPV models (from G.Durieux, C.Smith 1307.1355)
- @LHC qq initial states dominate over qbar-qbar ones

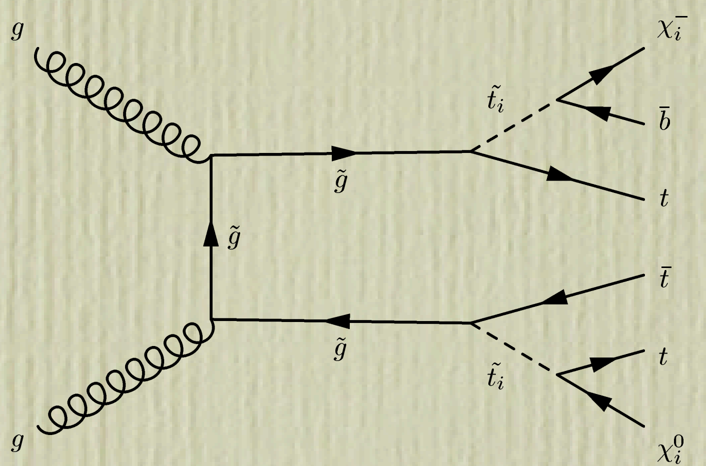
3 Ts in the SM



from 1001.0221
Barger et al.

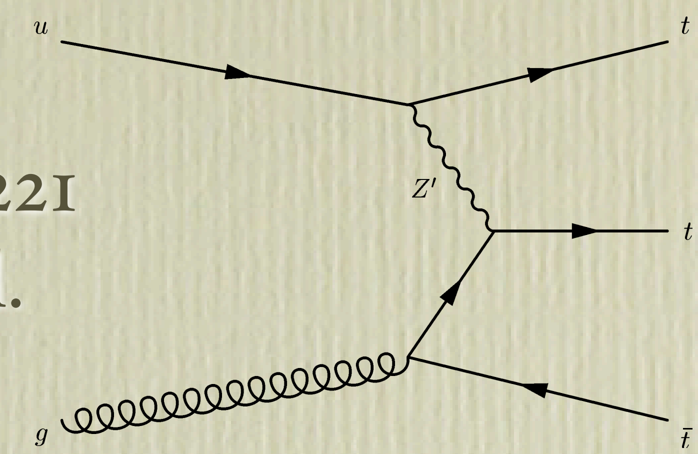
- 1.9 fb @ 14TeV LHC
- odd number of tops requires the tbW vertex
- 3 tops + (W, jets, b)

3  s examples in BSM



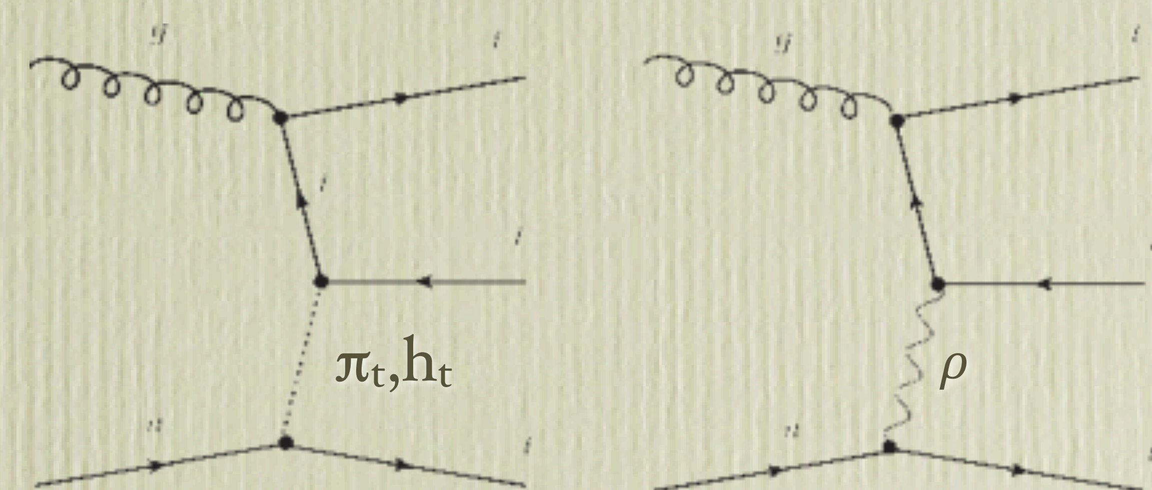
susy

from 1001.0221
Barger et al.



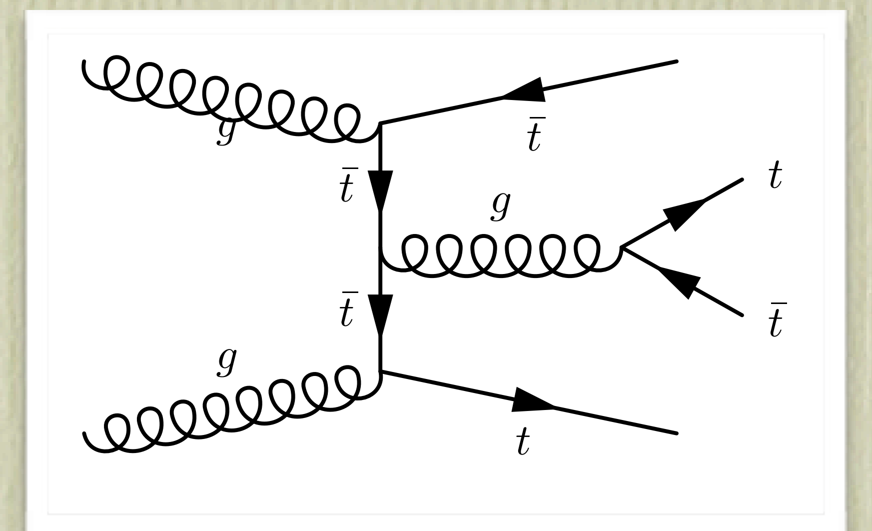
Z'

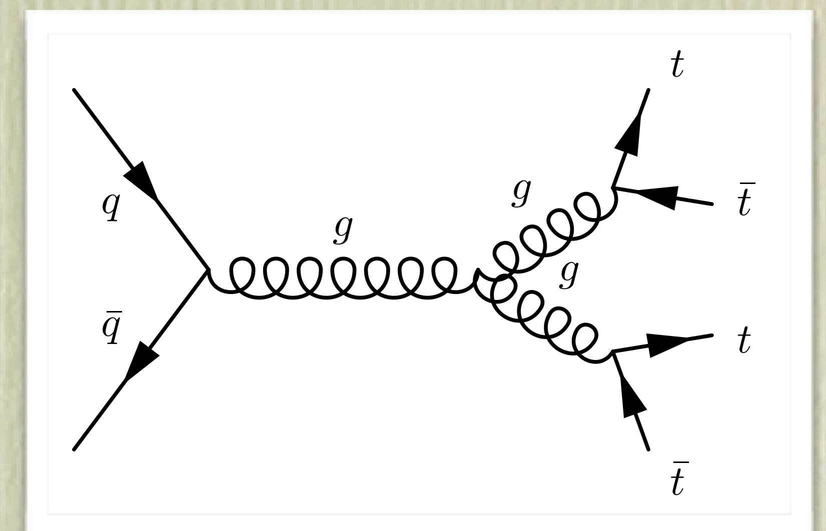
topcolor
from 1203.2321



- 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  s in the SM



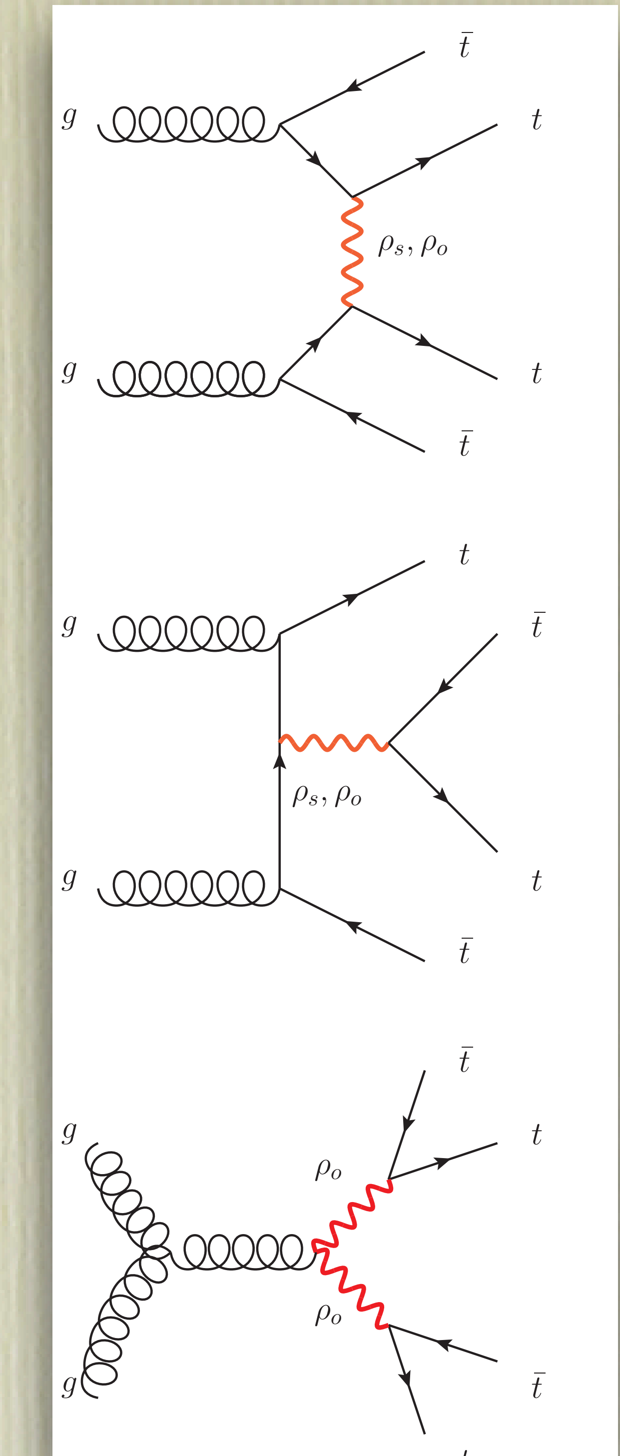


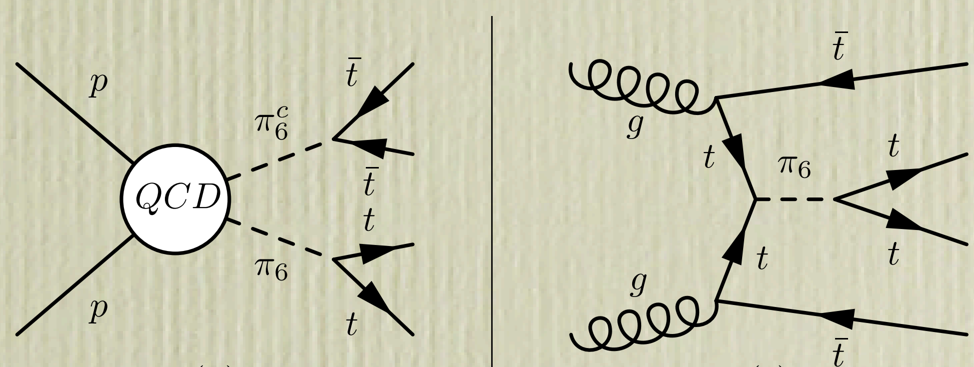
- gg dominant on qqbar at LHC
- small cross-section in the SM (0.5 fb @7 TeV)

4Ts in BSM

- quite a number of BSM models (SS tt applies too, see 1203.5862):
  - heavy gluon (octect)
  - heavy color singlet pair produced and decaying to $t\bar{t}\,t\bar{t}$
  - heavy color sextet decaying to $\bar{t}\bar{t}$, tt
  - σ<32 fb @95% CL (CMS 1409.7339)

Aguilar-Saavedra & Santiago 1112.3778



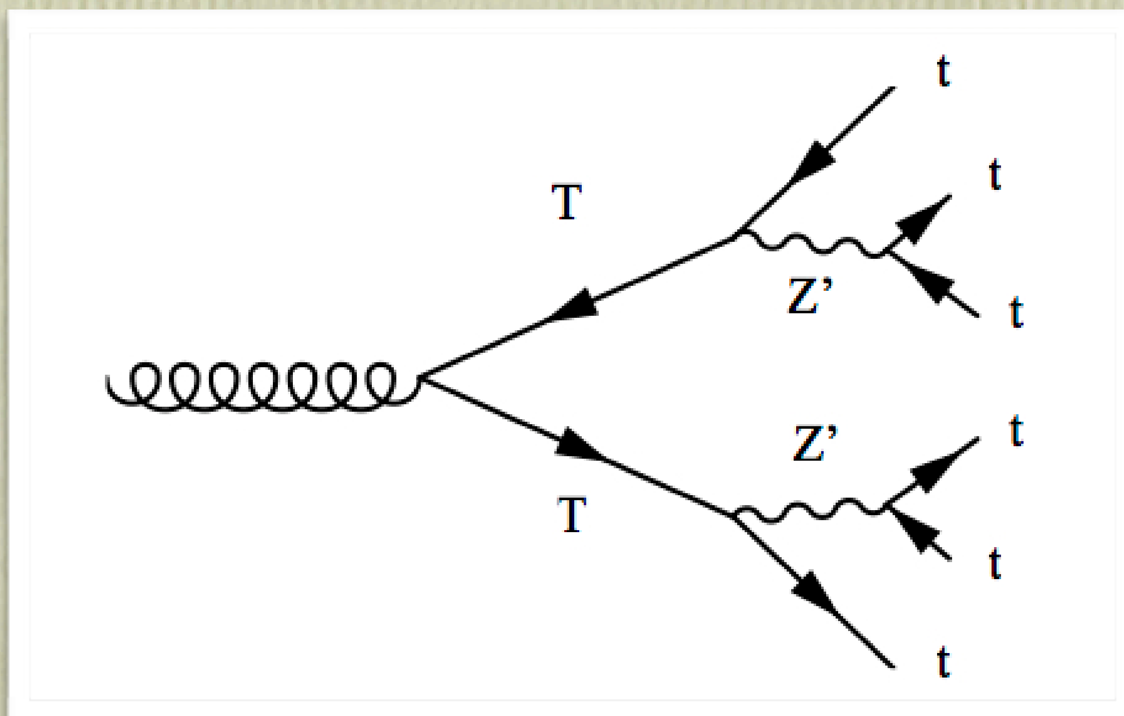


Cacciapaglia et al. 1107.4616, 1507.02283

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 $\sqrt{s}/m_t \sim 75$ at 13 TeV LHC
- are 6, 8... tops constrained by present measurements? can have more?
- what BSM physics?

6 Ts in BSM



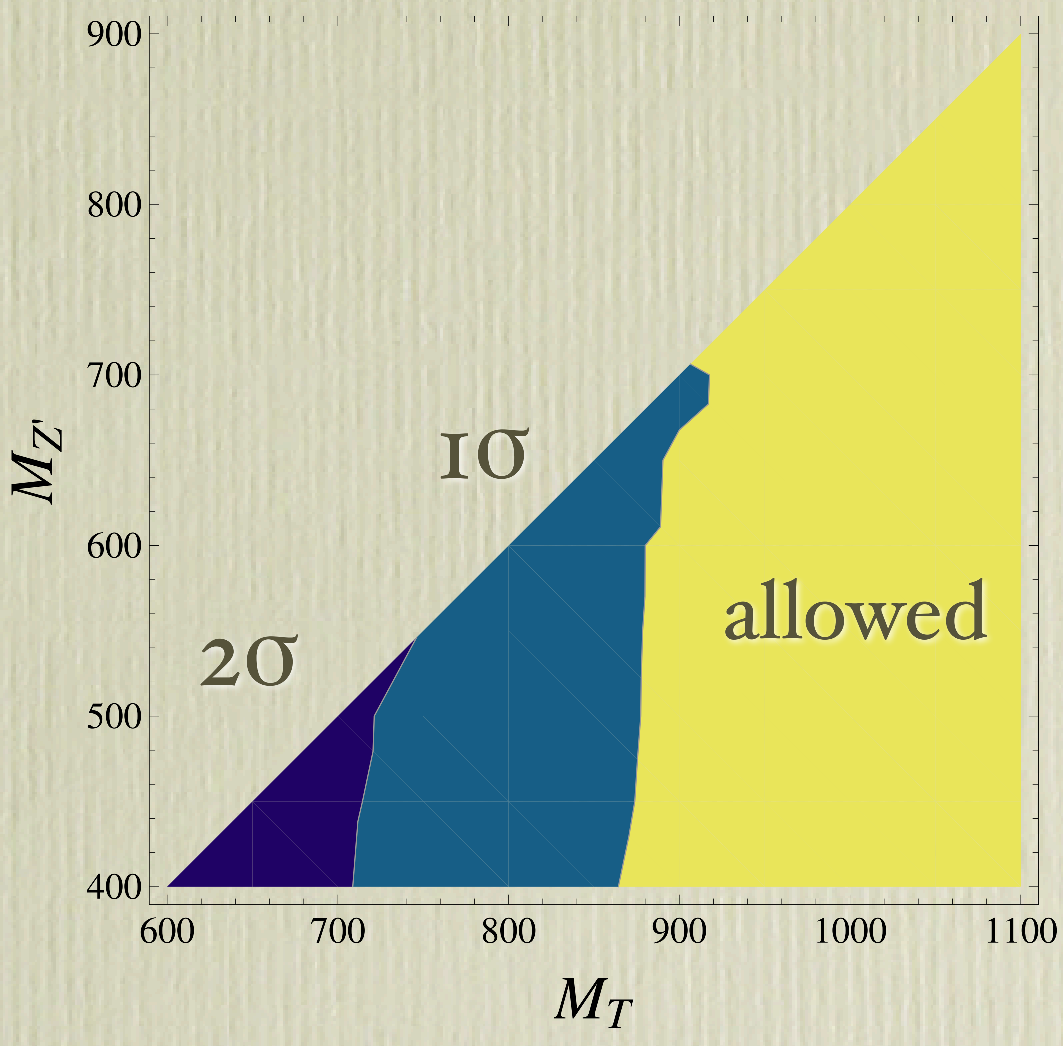
	$R_{Z'}$	R_T
R_1	$\mathbf{1}$	$\mathbf{3}$
R_2	$\mathbf{8}$	$\mathbf{3}$
R_3	$\mathbf{8}$	$\bar{\mathbf{6}}$
R_4	$\mathbf{8}$	$\mathbf{15}$

- 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)

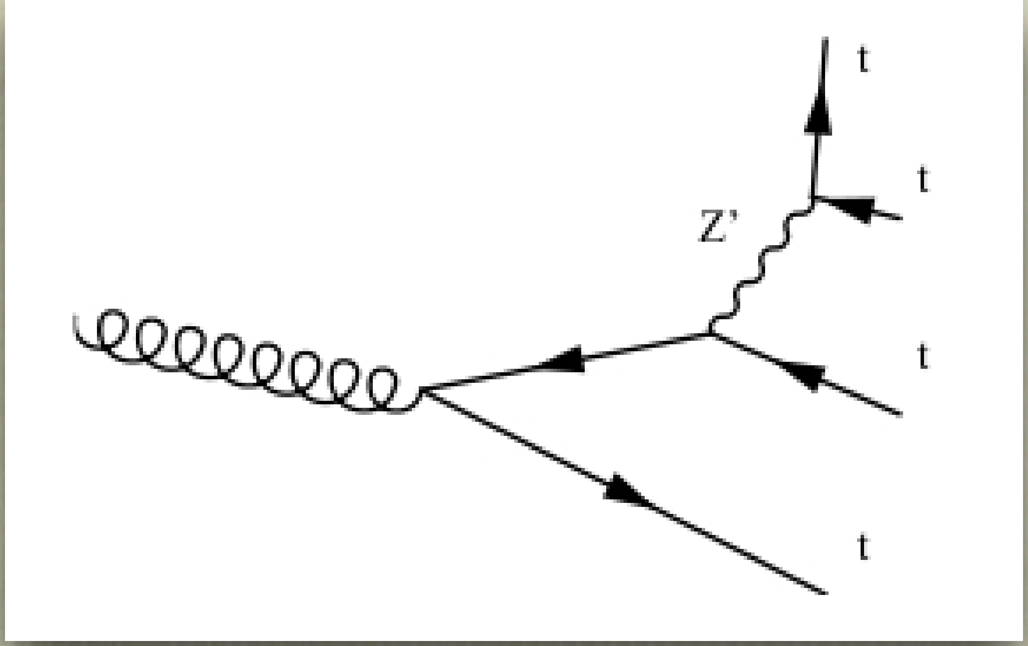
- if Z' is colour singlet 2SSL give bounds: (ex. recasting CMS 1212.6194)



1405.6119 A.D., N.Deutschmann

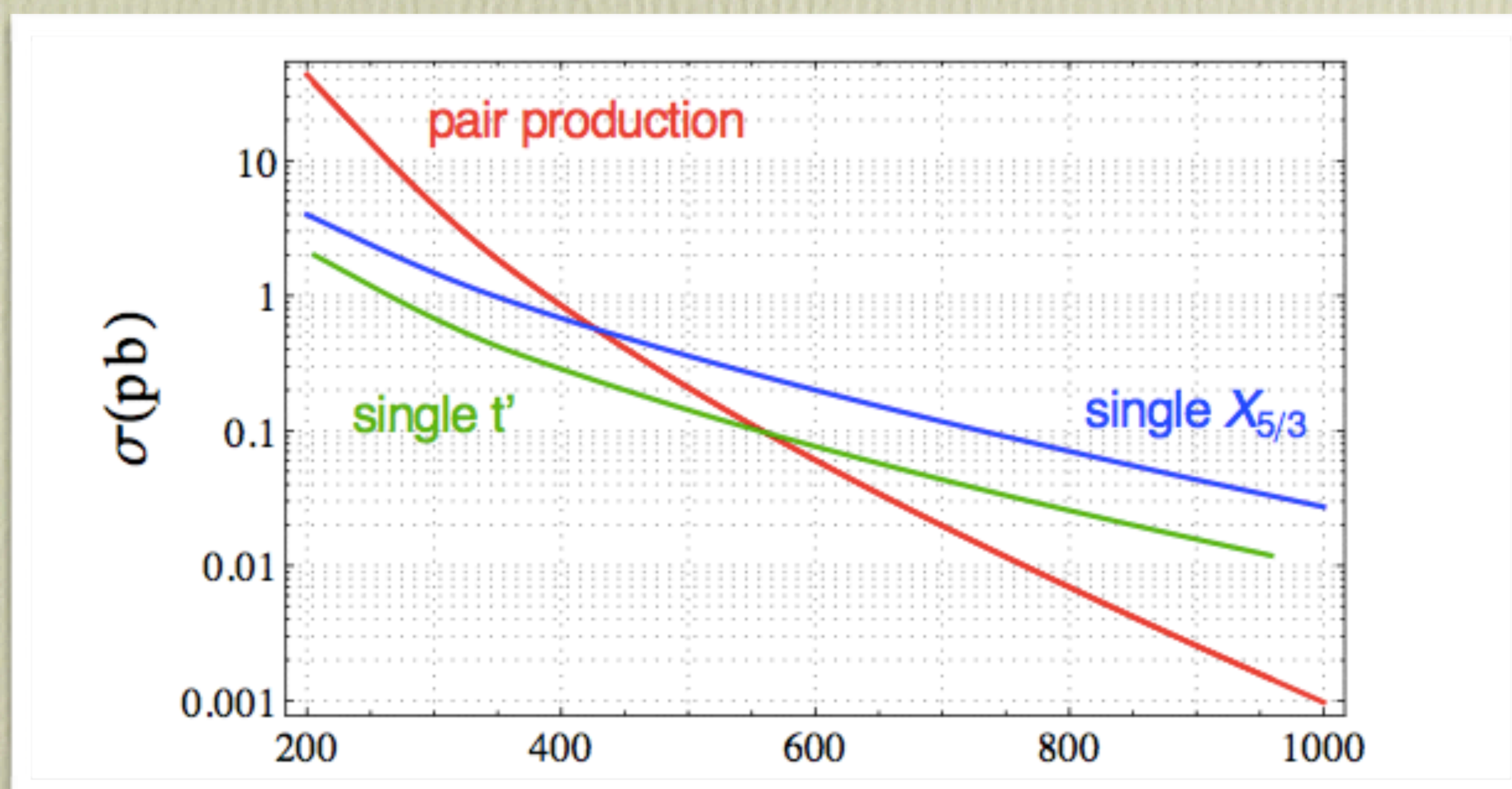
8 Ts in BSM

- 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



beyond  : vector-like quarks

- Unique window to test models (Xdim, composite, Little Higgs, SUSY) and good theoretical motivation
- Reach at LHC substantial and only partially exploited
- Mixings with all the 3 SM generations important (production/decay)
- Single production dominant with present mass bound at LHC (~800 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 only singlets)
- theoretical expectation is a not too heavy mass scale M (∿TeV) and mainly coupling to the 3rd generation
- Present LHC mass bounds ∿ 800 GeV
- Mixings bounded by EWPT, flavour…
- Note: in realistic composite models also scalars and vectors are expected.

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

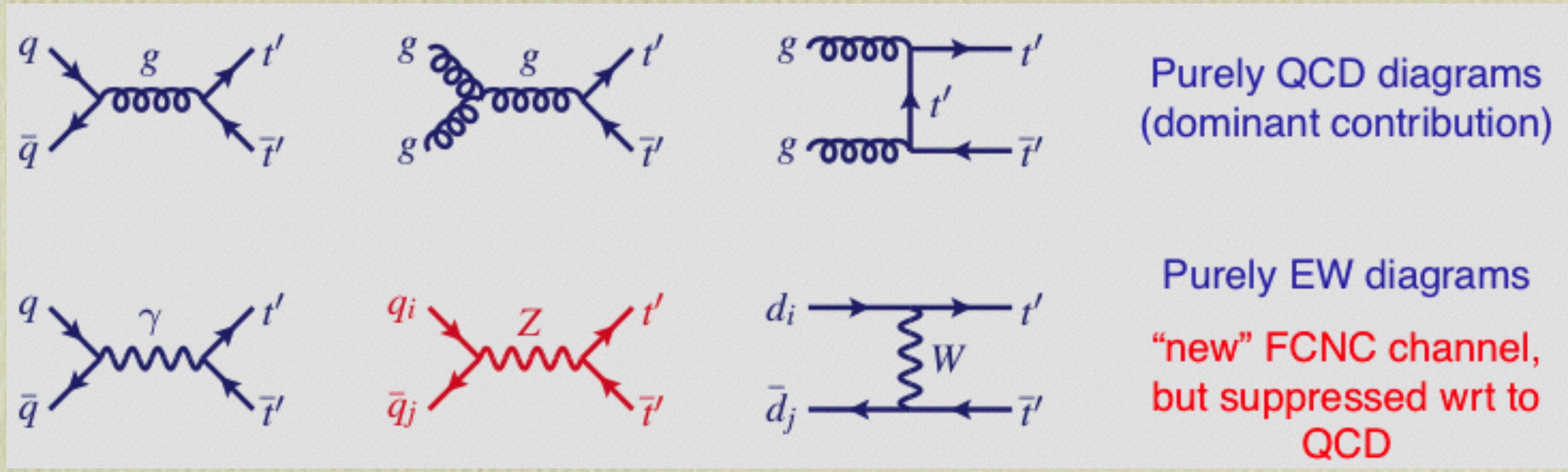
integer isospin multiplets

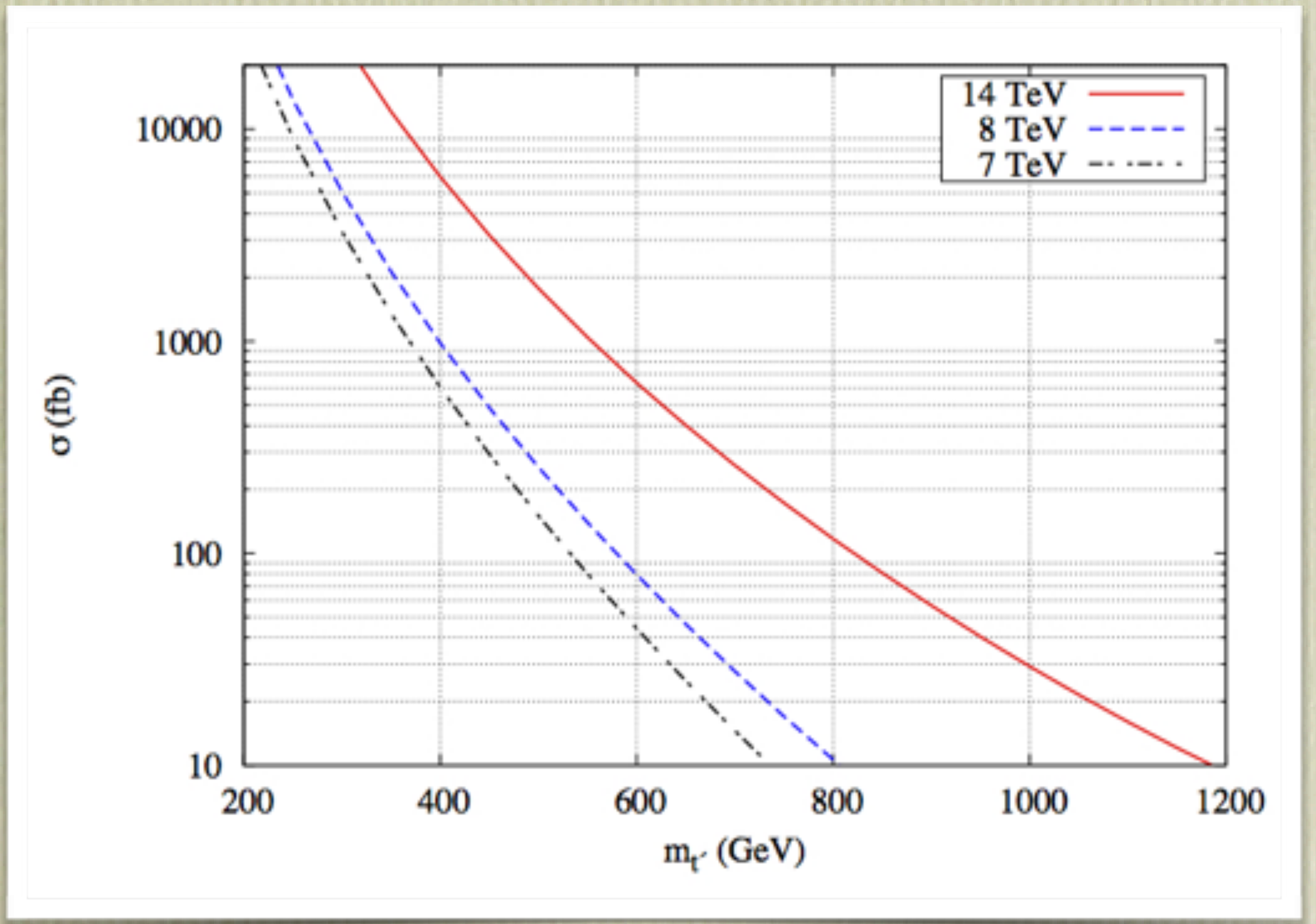
ArXiv:1305.4172 M.Buchkremer et al.

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

semi-integer isospin multiplets

Pair production





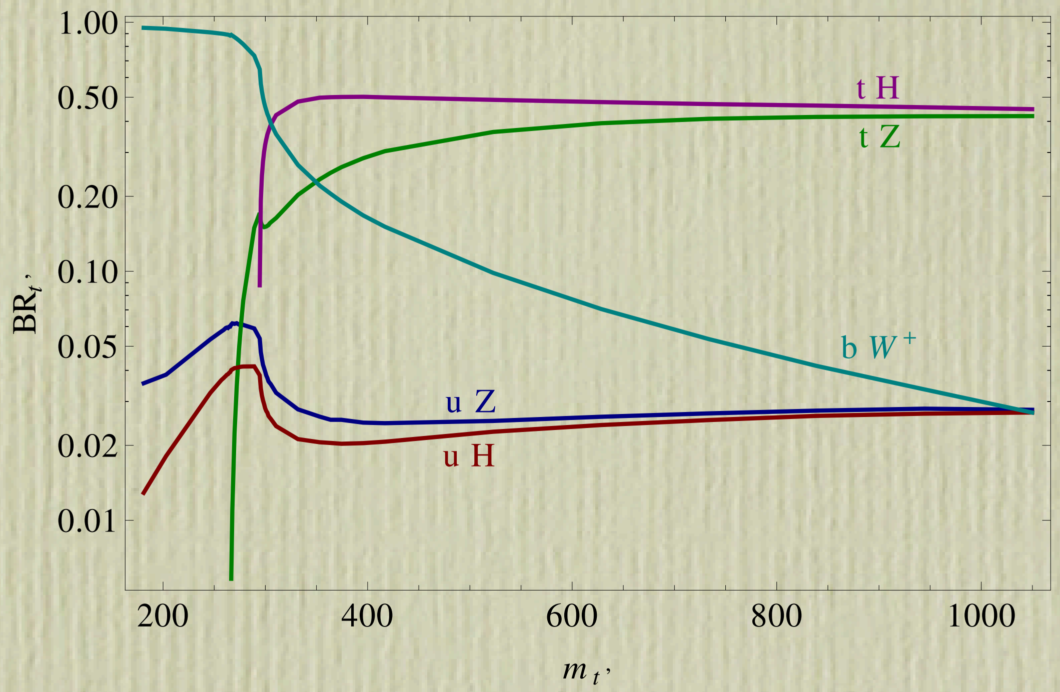
Pair production for t'
of the non-SM doublet
pp → t' t @ LHC

T’ decays

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

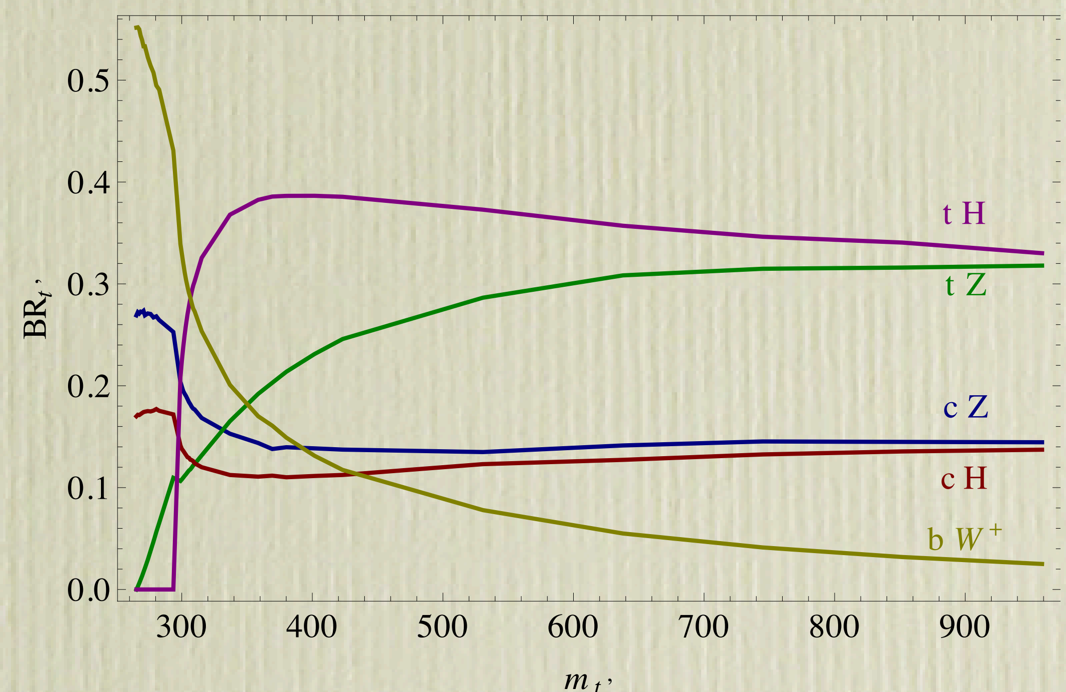
t’	Wb	Zt	ht
Singlet, Triplet Y=2/3	50%	25%	25%
Doublet, Triplet Y=-1/3	0%	50%	50%

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 and Higgs are a privileged gate to test BSM physics
- precision measurements era is now
- 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