New physics hunting with top quarks

Géraldine SERVANT, CERN-TH

based on collaborations with

- Céline Degrande, Jean-Marc Gérard, Christophe Grojean & Fabio Maltoni

1010.6304, JHEP
1104.1798, PLB + 1204.xxxx

- Léa Gauthier, Anne-Isabelle Etienvre (ATLAS, SPP, CEA Saclay)

in preparation (short preview in chapter 12 of 1005.1229 & in DESY-PROC-2010-01)

- Roberto Contino

0801.1679, JHEP

The top quark as a link to BSM

As today, still two paradigms for electroweak symmetry breaking:

- Weakly coupled New Physics (NP) at the TeV scale -> susy
- Strongly coupled NP at the TeV scale -> composite higgs

  Particularly motivated is the case in which the Higgs is the Goldstone Boson of a spontaneously broken global symmetry (a kind of pion from a new strong sector)

  = strong EW symmetry breaking with Partial Compositeness

$$\mathcal{L} = \mathcal{L}_{SM(\cancel{H})} + \mathcal{L}_{strong} + \mathcal{L}_{mix}$$

Quantum numbers of the Goldstones fixed by the symmetry breaking pattern in the strong sector:

G -> H

Higgs scalars as pseudo-Nambu-Goldstone bosons of new dynamics above the weak scale

New strong sector endowed with a global symmetry G spontaneously broken to H $\rightarrow$ delivers a set of Nambu Goldstone bosons

global symm. on u,d

strong int.

QCD: $SU(2)_L \times SU(2)_R \xrightarrow[SU(3)_c]{} SU(2)_V \supset U(1)_Q$

6 - 3 = 3 PNGB $\pi^{\pm}, \pi_0$

global symm. on techniquarks

Composite Higgs: $SO(6) \times U(1)_x \xrightarrow[SU(N_c)]{} SO(5) \times U(1)_Y \supset SU(2) \times U(1)_Y$

16 - 11 = 5 PNGB H, S

SO(5)/SO(4) -> SM Higgs
SO(6)/SO(5) -> SM + Singlet
SO(6)/SO(4) -> 2 Higgs Doublet Model

associated LHC tests

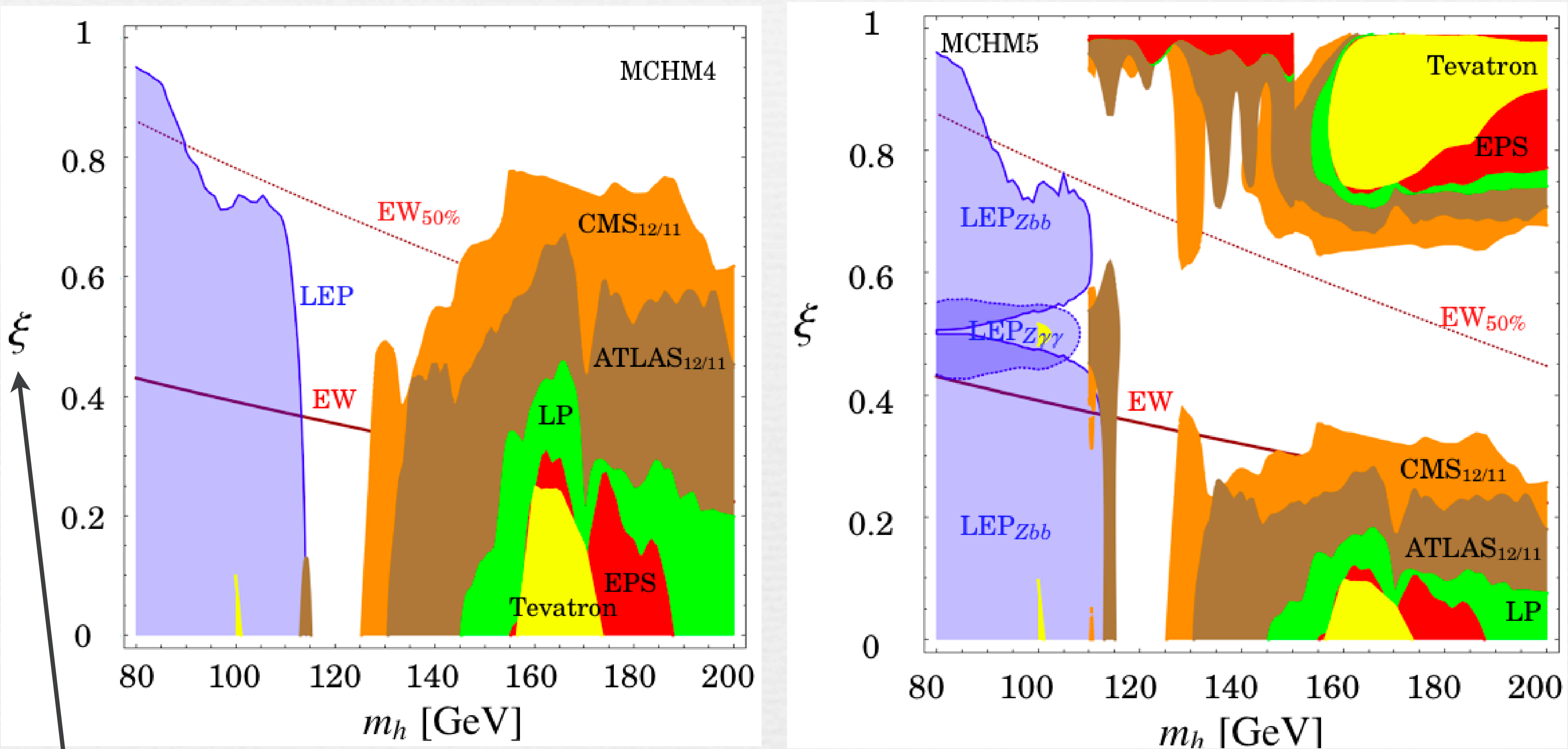
G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}}+\bar{\mathbf{4}}_{\mathbf{-2}}=2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7}=(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0}=(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3})=3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2})=2\times(\mathbf{2},\mathbf{2}),(\mathbf{2},\mathbf{2})+2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5}+\bar{\mathbf{4}}_{\mathbf{+5}}=2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$

-> Agashe, Contino, Pomarol'05

[Mrazek et al, 1105.5403]

Limits from Higgs searches on the composite Higgs for the two minimal composite higgs models

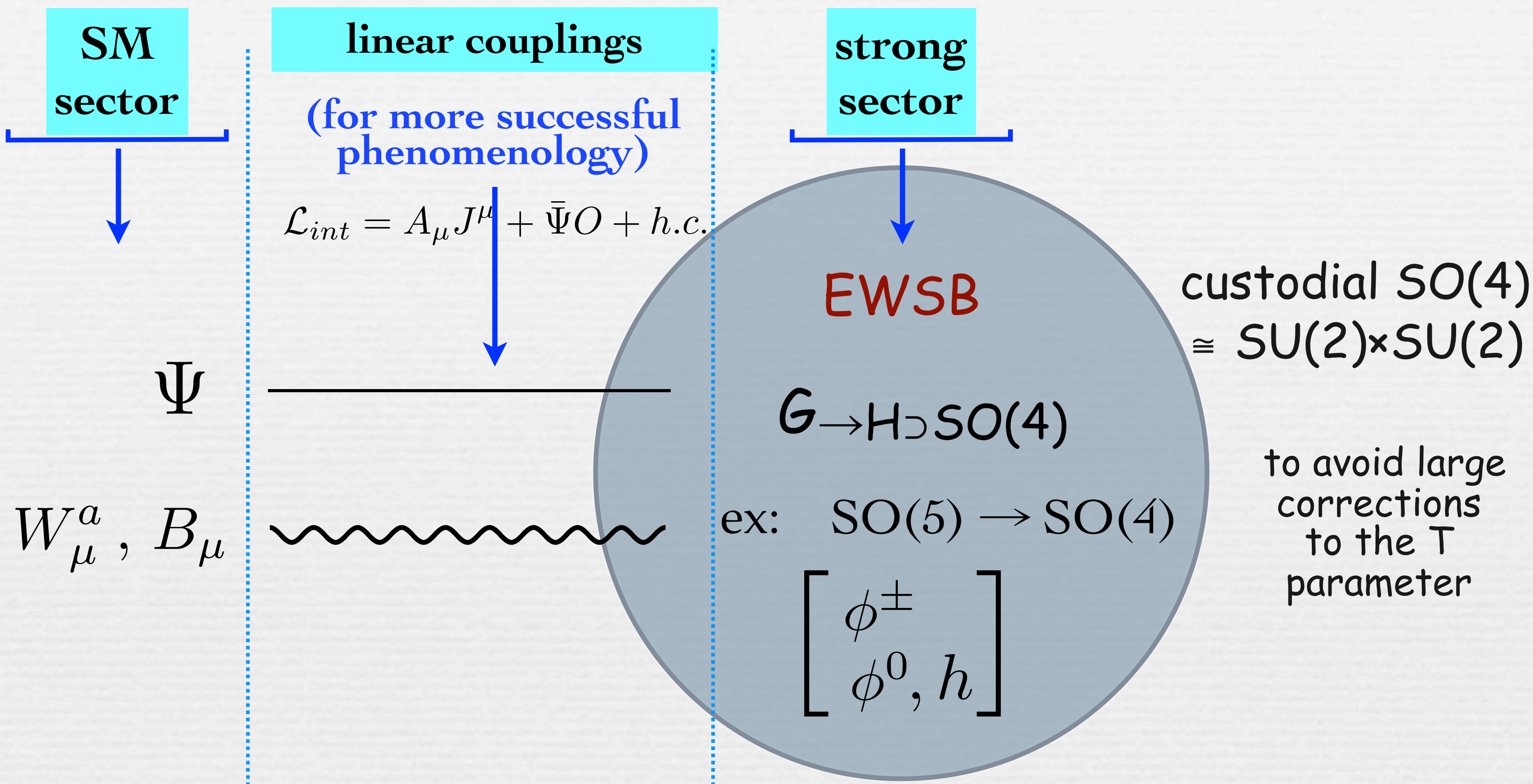
Espinosa et al, 1202.1286



= (v/f)^2, measures the amount of compositeness of the Higgs boson

(-> 0 in the SM elementary Higgs limit)

General structure -> Partial compositeness



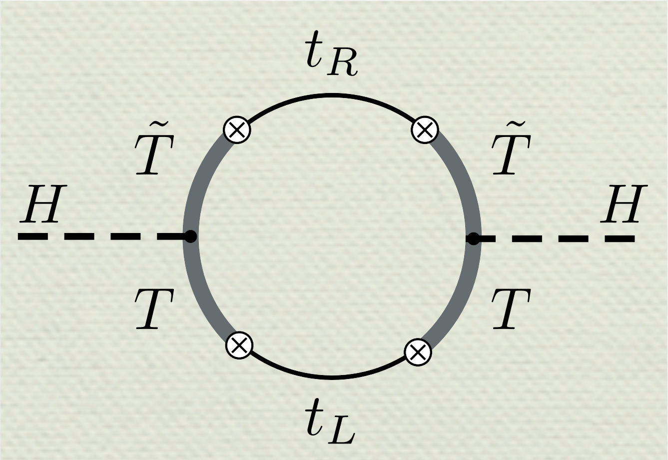
$$\mathcal{L}_{elementary} \qquad \mathcal{L}_{mix} \qquad \mathcal{L}_{composite}$$

$$\mathcal{L} = \bar{q}_L \,\partial\!\!\!/\, q_L + \bar{t}_R \,\partial\!\!\!/\, t_R + \Delta_L \,\bar{q}_L \,(T, B) + \Delta_R \,\bar{t}_R \tilde{T} + \mathrm{Tr}\,\{\bar{\mathcal{Q}}\,(\partial\!\!\!/ - M_{\mathcal{Q}})\,\mathcal{Q}\} + \bar{\tilde{T}}\,(\partial\!\!\!/ - M_{\tilde{T}})\,\tilde{T} + Y_* \,\mathrm{Tr}\{\bar{\mathcal{Q}}\,\mathcal{H}\}\,\tilde{T} + h.c$$

$\mathbf{2}$ $\mathbf{1}$

Naturalness implies light top partners

$$m_H^2 \sim \frac{3y_t^2}{8\pi^2} m_T^2$$



Elementary SM fermions mix with fermionic resonances of the strong sector

"Partial compositeness"

[Agashe, Contino & Pomarol '05]
[Kaplan, '80s]

After diagonalizing through a composite/elementary rotation:

$$\begin{pmatrix} q_L \\ Q_L \end{pmatrix} \longrightarrow \begin{pmatrix} \cos\varphi_L & -\sin\varphi_L \\ \sin\varphi_L & \cos\varphi_L \end{pmatrix} \begin{pmatrix} q_L \\ Q_L \end{pmatrix} \qquad \tan\varphi_{q_L} = \frac{\Delta_L}{M_2}$$

$$|SM> = \cos\varphi \; |elem> + \; \sin\varphi \; |comp>$$

and do the same for $\{t_R \leftrightarrow \tilde{T}\}$

SM Yukawa given by the composite components: $$y_t = Y_* \sin\varphi_{q_L} \sin\varphi_{t_R}$$

the larger the mixing, the larger the mass

Yukawa hierarchy comes from the hierarchy of compositeness

Third family most sensitive to strong dynamics

Essentially only the top talks to the new strong sector

Dual description in terms of higher-dimensional theories

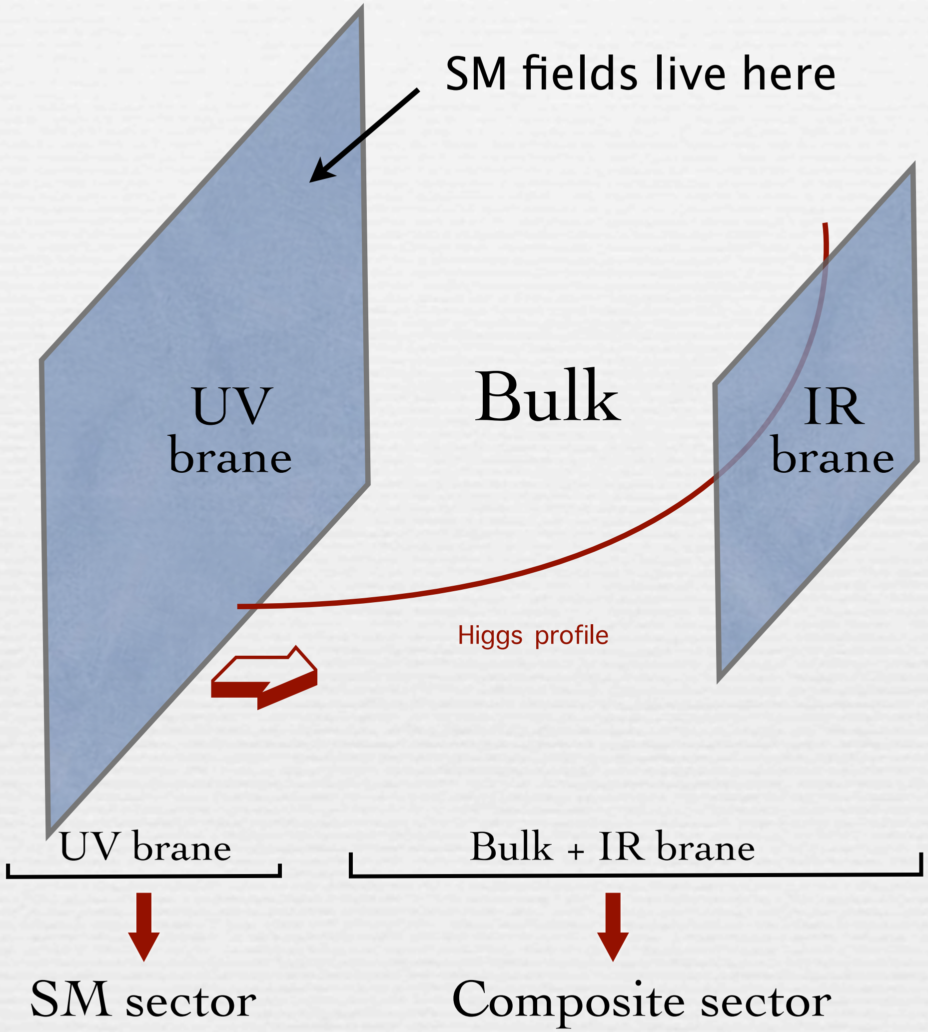
strong sector → warped extra dimension

→ UV completion

→ flavor addressed

resonances of the strong sector (heavy top partners) → Kaluza-Klein excitations

Example of strong dynamics: A warped extra dimension



$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

Light custodial partners of the top quark

$\mathbf{5} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$ 2 SU(2)_L doublets + 1 singlet

Custodial invariance of the strong sector implies larger multiplets of $SU(2)_L \times SU(2)_R \times U(1)_X$

- Heavy partners of (t_L, b_L) will form a $(2,2)_{2/3}$ [under $SU(2)_L \times SU(2)_R \times U(1)_X$

Composite (EW symm. break.) sector:

[mass mixing terms between the 2 sectors]

SM sector:

(t_L, b_L)

t_R

- $(Q, Q') = (\mathbf{2},\mathbf{2})_{2/3}$ $\quad Q = \begin{bmatrix} T \\ B \end{bmatrix}$

electric charge +5/3

$Q' = \begin{bmatrix} T_{5/3} \\ T_{2/3} \end{bmatrix}$ → "custodian"

- $(\mathbf{1},\mathbf{1})_{2/3} = \tilde{T}$

- $\mathcal{H} = (\mathbf{2},\mathbf{2})_0 = \begin{bmatrix} \phi_0^\dagger & \phi^+ \\ -\phi^- & \phi_0 \end{bmatrix}$

$$Y_* \, \mathrm{Tr}\{\bar{\mathcal{Q}}\,\mathcal{H}\}\,\tilde{T} + h.c$$

$$M_{Q'} = M_2 = M_Q \cos\varphi_{q_L}$$

$M_{Q'} \to 0$ for $\sin\varphi_{q_L} \to 1$

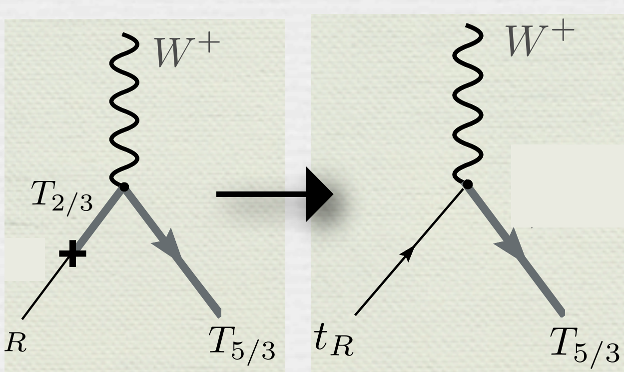
custodians become very light if SM top is largely composite

Before EW symmetry breaking:

$$\mathcal{L}_{yuk} = Y_* \sin\varphi_L \sin\varphi_R \left(\bar{t}_L \phi_0^\dagger t_R - \bar{b}_L \phi^- t_R\right) + Y_* \cos\varphi_L \sin\varphi_R \left(\bar{T}\phi_0^\dagger t_R - \bar{B}\phi^- t_R\right)$$
$$+ Y_* \sin\varphi_L \cos\varphi_R \left(\bar{t}_L \phi_0^\dagger \tilde{T} - \bar{b}_L \phi^- \tilde{T}\right) + Y_* \sin\varphi_R \left(\bar{T}_{5/3}\phi^+ t_R + \bar{T}_{2/3}\phi_0 t_R\right)$$
$$+ Y_* \cos\varphi_L \cos\varphi_R \left(\bar{T}_L \phi_0^\dagger \tilde{T}_R - \bar{B}_L \phi^- \tilde{T}_R\right) + Y_* \left(\bar{T}_R \phi_0^\dagger \tilde{T}_L - \bar{B}_R \phi^- \tilde{T}_L\right)$$
$$+ Y_* \cos\varphi_R \left(\bar{T}_{5/3}\phi^+ T_R + \bar{T}_{2/3}\phi_0 \tilde{T}_R\right) + Y_* \left(\bar{T}_{5/3}\phi^+ T_L + \bar{T}_{2/3}\phi_0 \tilde{T}_L\right) + \ldots$$

After EW symmetry breaking the charged 2/3 states mix in the $(T_{2/3}, \tilde{T}, T, t)_{L,R}$ basis

$$\mathcal{M}_{+2/3} = \begin{pmatrix} M_{(2,2)} & c_R\, r & 0 & s_R\, r \\ r & \dfrac{M_{(1,1)}}{c_R} & r & 0 \\ 0 & c_L c_R\, r & \dfrac{M_{(2,2)}}{c_L} & c_L s_R\, r \\ 0 & s_L c_R\, r & 0 & s_L s_R\, r \end{pmatrix}$$



-> the charged current interaction reads:

$$\mathcal{L} = \frac{g}{\sqrt{2}}\Big[\sin\theta_{T_{2/3}t_R}\, \bar{T}_{5/3}\gamma^\mu W_\mu^+ t_R + \sin\theta_{T_{2/3}t_L}\, \bar{T}_{5/3}\gamma^\mu W_\mu^+ t_L$$
$$+ \sin\theta_{TtR}\, \bar{B}\gamma^\mu W_\mu^- t_R + \sin\theta_{TtL}\, \bar{B}\gamma^\mu W_\mu^- t_L + h.c.\Big]$$

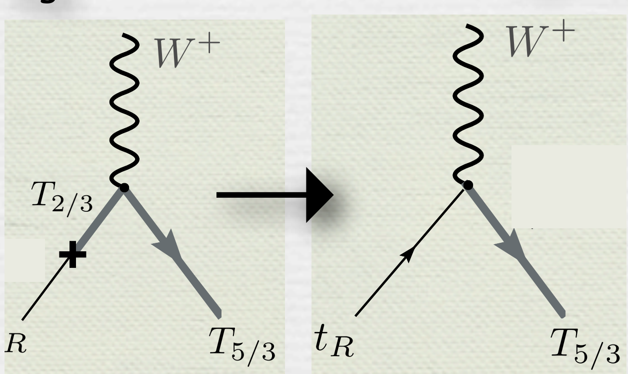
These new fermions couple strongly to the 3rd generation SM quarks plus one W_L , Z_L or h

$$\tan\varphi_L = \frac{\Delta_L}{M_Q} \qquad \tan\varphi_R = \frac{\Delta_R}{M_{\tilde{T}}}$$

$$Y_* \, \mathrm{Tr}\{\bar{\mathcal{Q}}\,\mathcal{H}\}\,\tilde{T} + h.c$$

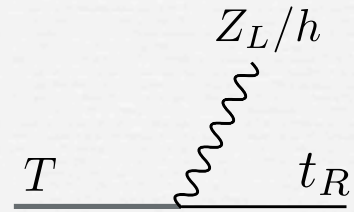
after rotating to mass eigen state basis

e.g



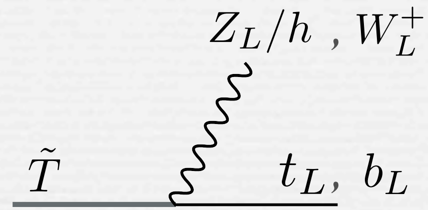
Single production and decays proceed via these couplings

Pair production proceeds via the usual QCD coupling

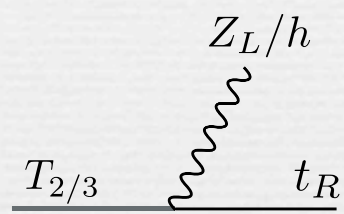


FCNC : absent for a 4th generation !

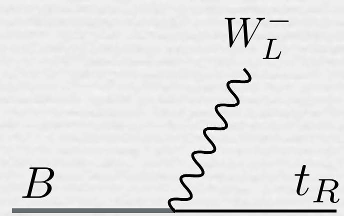
$Y_* \cos\varphi_L \sin\varphi_R$



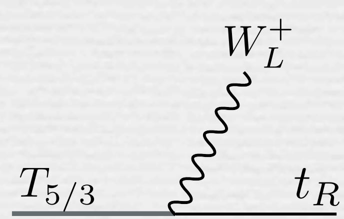
$Y_* \sin\varphi_L \cos\varphi_R$



$Y_* \sin\varphi_R$



$Y_* \cos\varphi_L \sin\varphi_R$

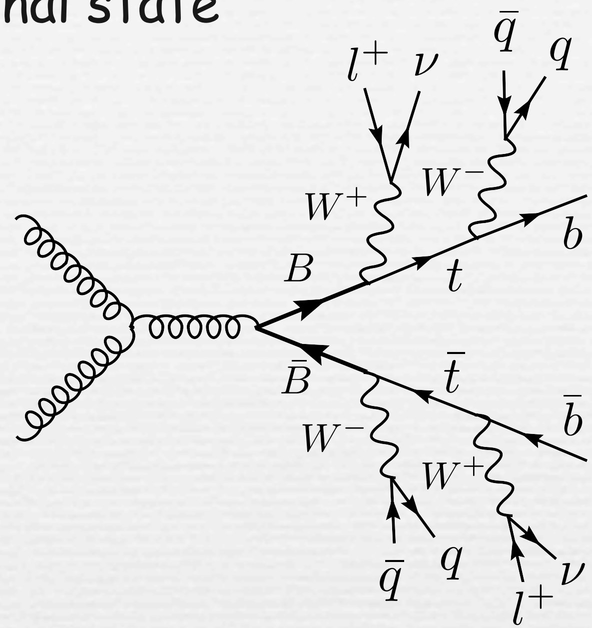


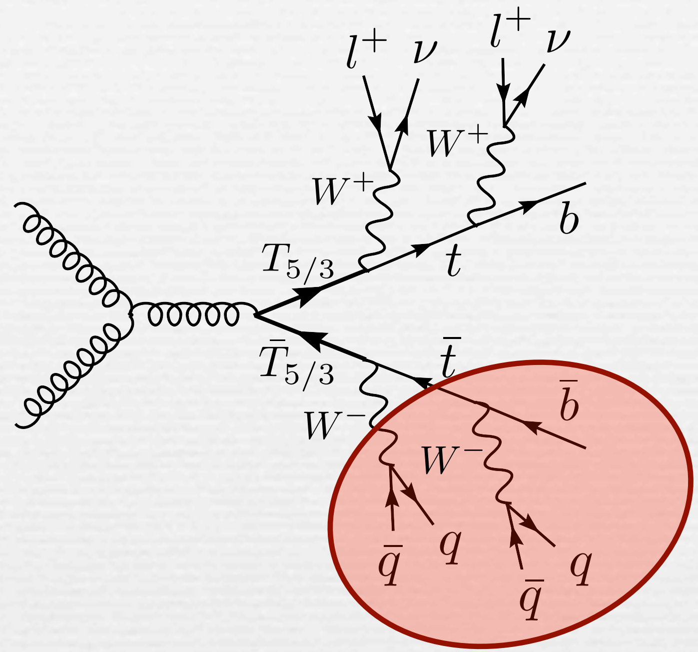
$Y_* \sin\varphi_R$

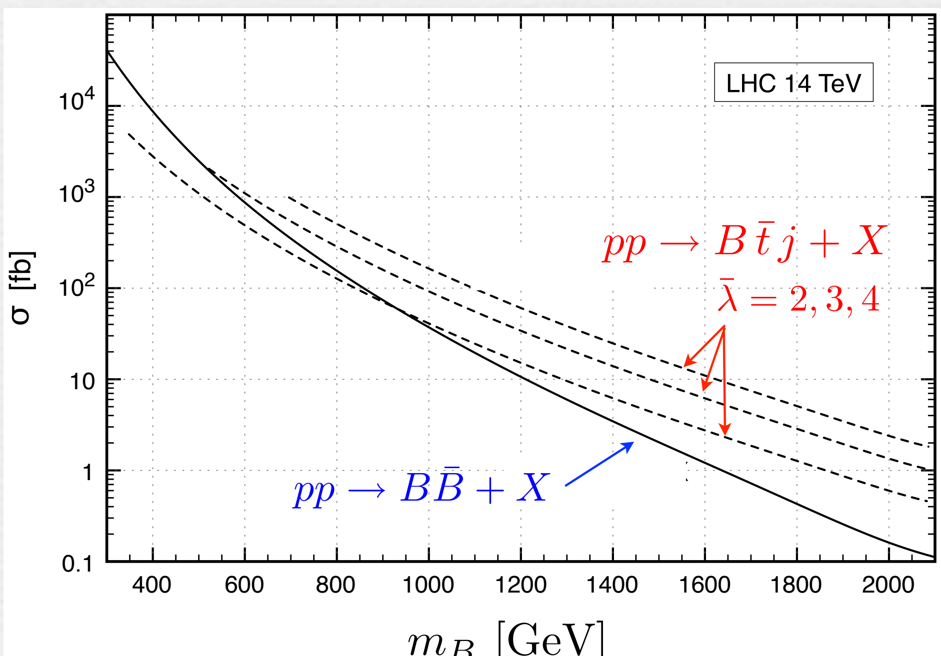
Look for $\bar{B}B$ and $T_{5/3}\,\bar{T}_{5/3}$ in same-sign dilepton final states

[Contino & Servant, '08]

$t\,\bar{t}$ WW final state

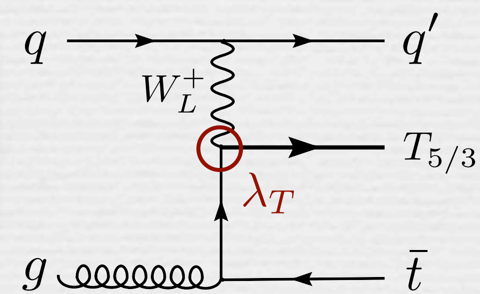






✔ For the $T_{5/3}$ case one can reconstruct the resonant (tW) invariant mass

Single production also relevant



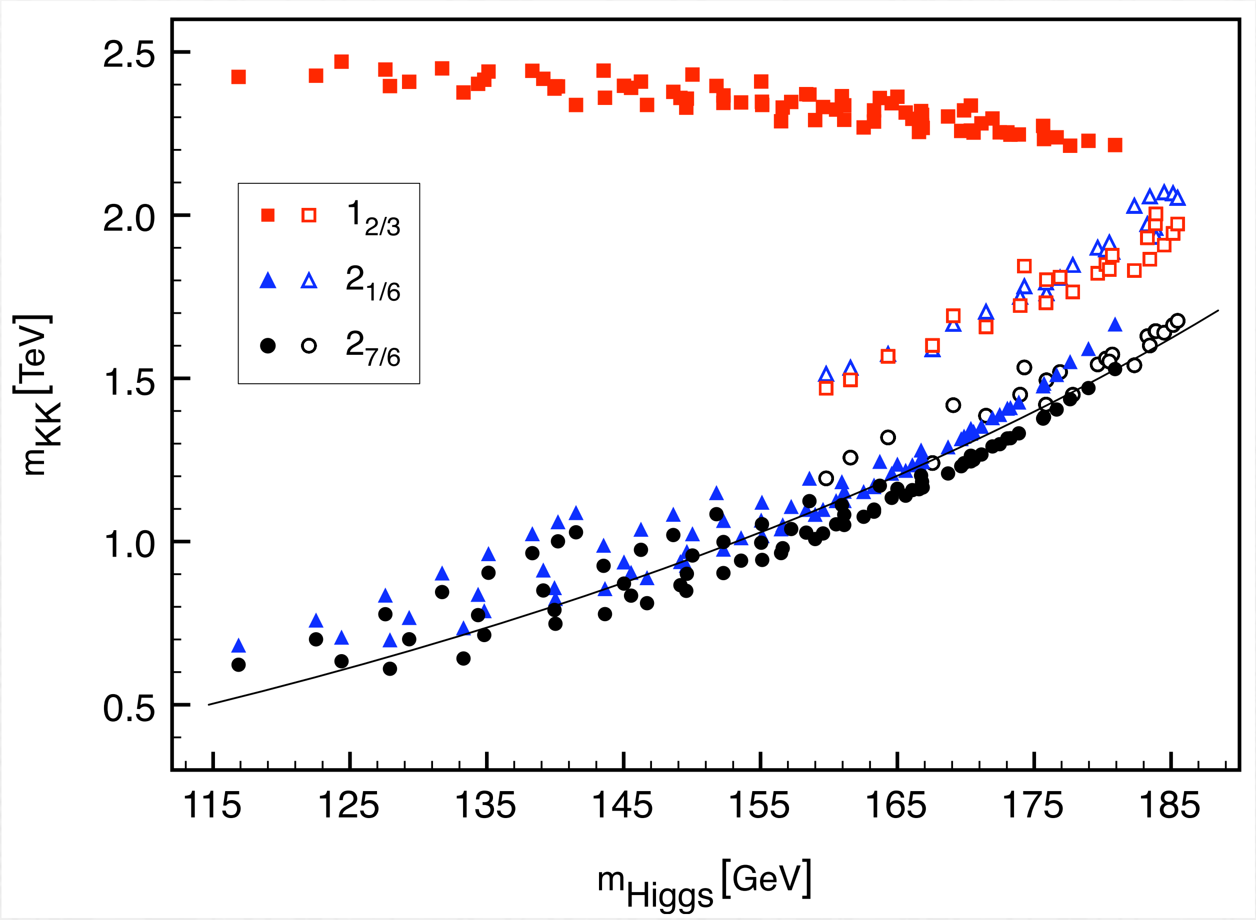
[Mrazek & Wulzer, '09]

Expected reach at 14 TeV: M~ 1.5 TeV

for study at 7 TeV see [Dissertori, Furlan, Moortgat, Nef '09]

Light Higgs wants light top partners

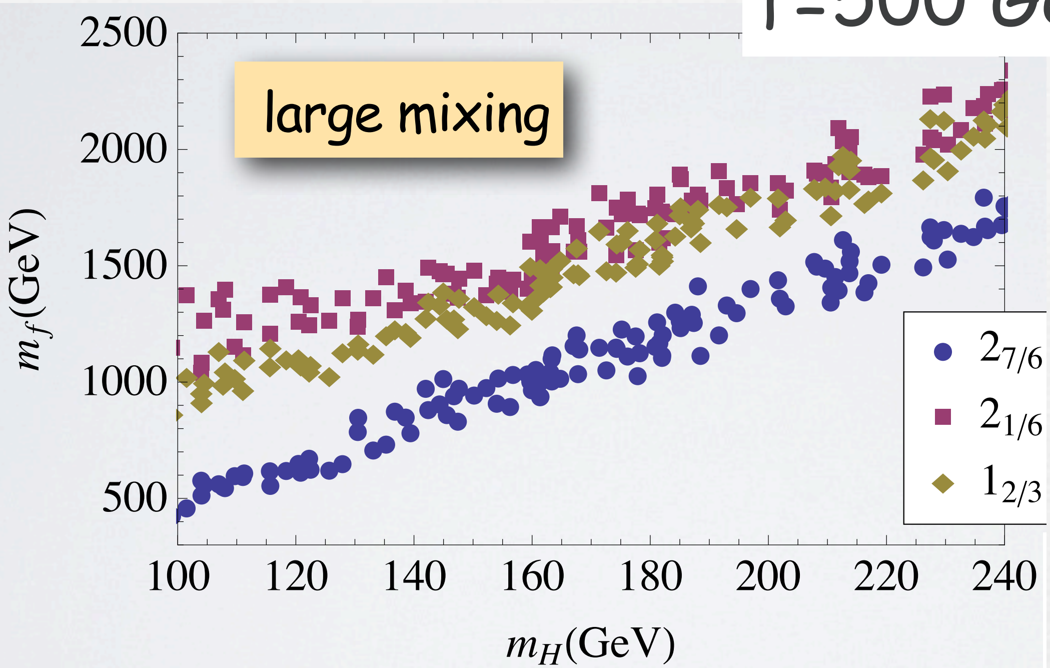
[Contino, Da Rold, Pomarol'06]

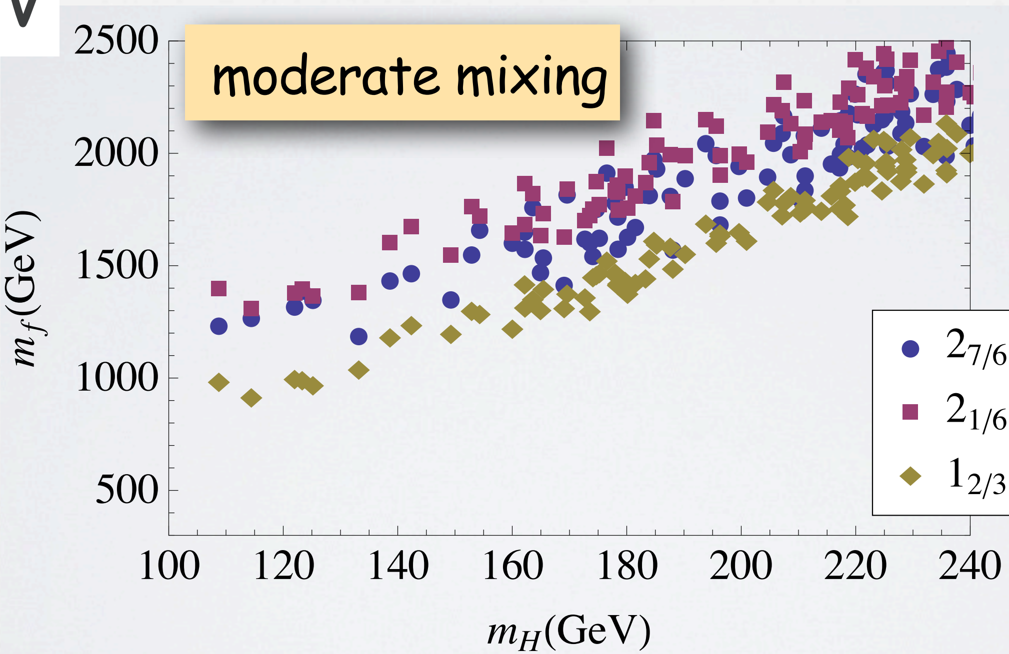


Light Higgs wants light top partners

[De Curtis, Redi, Tesi 1110.1613]

f=500 GeV



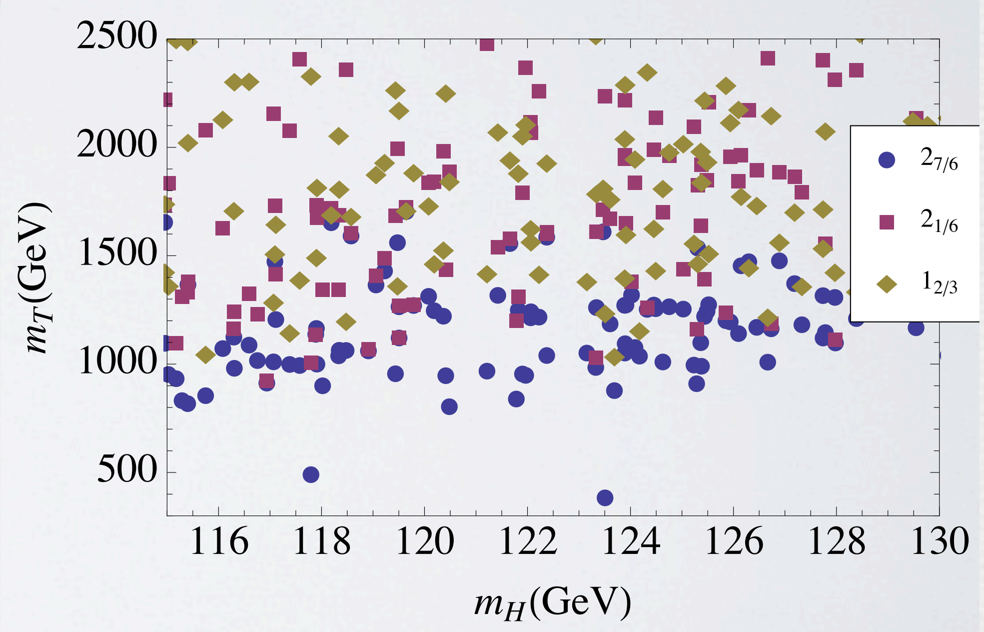


lightest fermion: doublet

lightest fermion: singlet

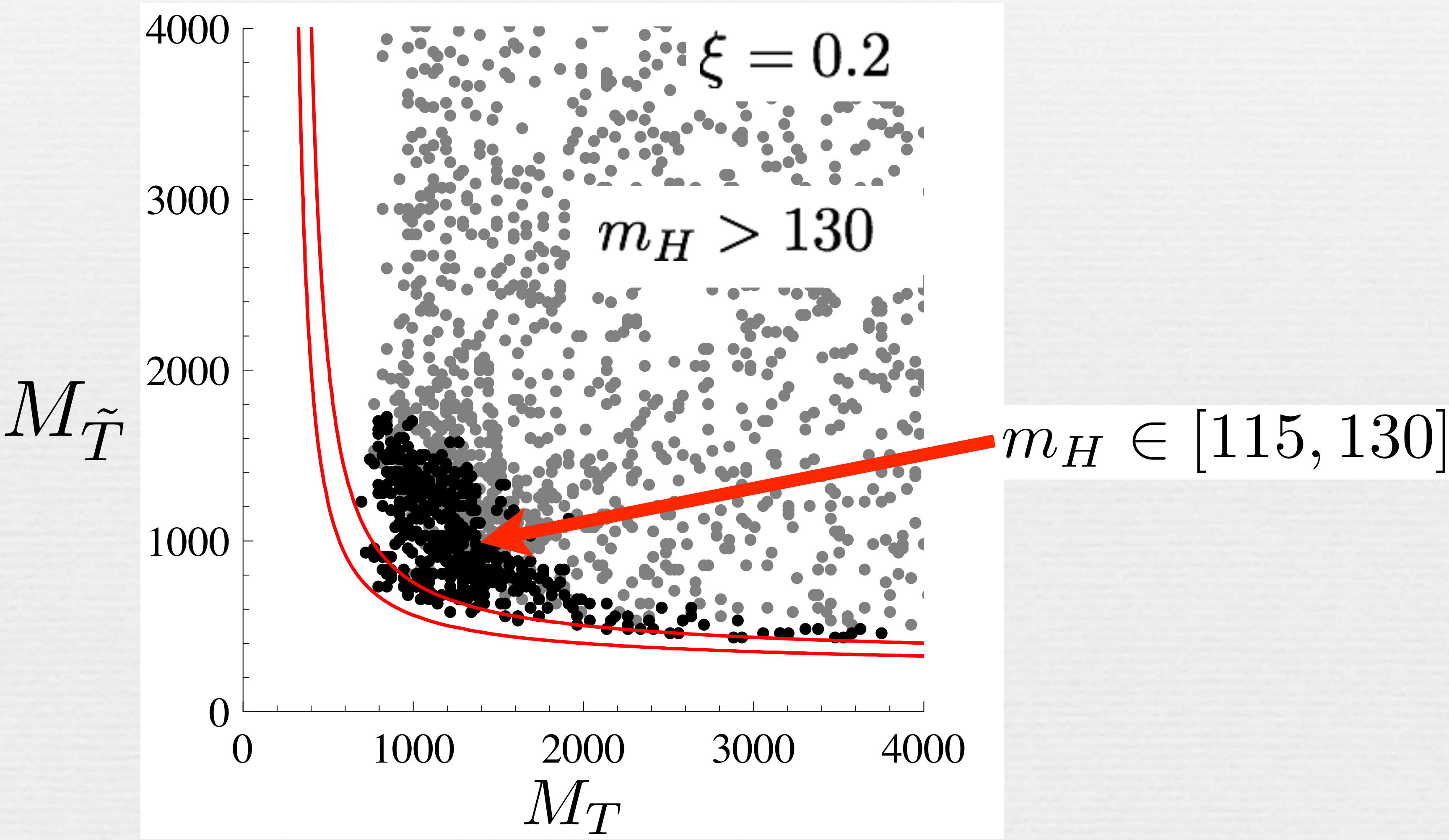
f=800 GeV

-> partners above experimental bound



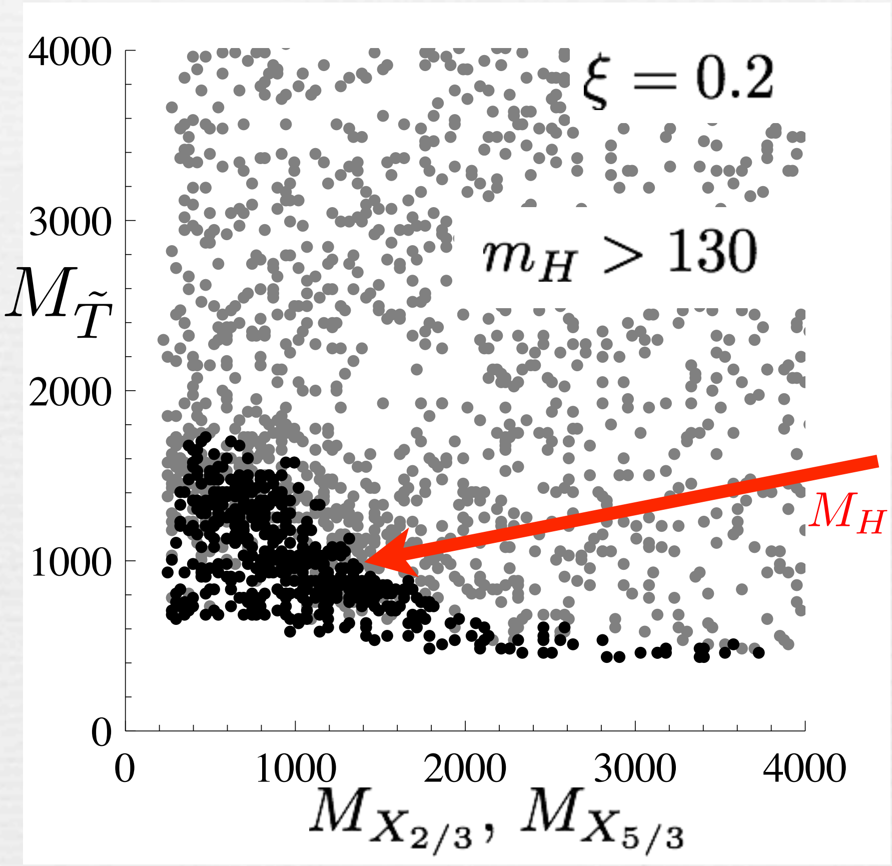
Light Higgs wants light top partners

[Panico & Wulzer, 1106.2719]

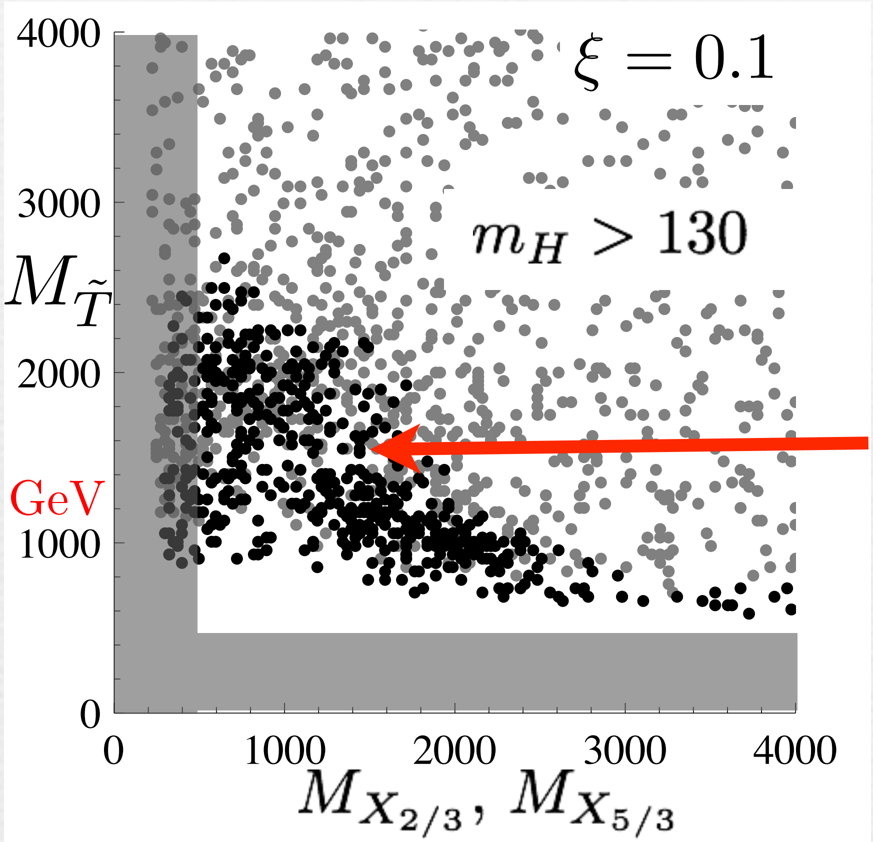


[Wulzer,2012]

Exotic bi-doublet is even lighter



$M_H \in [115 - 130]$ GeV



[Wulzer,2012]

Present constraints:
~ 550-600 GeV on the mass of b' and t'

[CMS L=1.14 fb-1]
PAS-EXO-11-036

$$B\bar{B} \to WtW\bar{t} \to l^{\pm}l^{\pm}\ b\ 3j\ E_T$$
$$\to lll\ b\ 1j\ E_T$$

$m_B > 495$ GeV

update at L=4.6 fb-1 $M_{b'} \gtrsim 600$ GeV

[CMS L=1.1 fb-1]
PAS-EXO-11-054

t'b -> bWb ; b't -> t_{bW}WbW ;
t't' -> bWbW ; b'b' -> t_{bW}Wt_{bW}W
$m_{t'} = m_{b'} > 490$GeV

[CMS L=4.7 fb-1] at least 1 lepton and 4 jets: $M_{t'} \gtrsim 560$ GeV
PAS-EXO-11-099

[CMS L=4.7 fb-1] dilepton $M_{t'} \gtrsim 552$ GeV
PAS-EXO-11-050

[CMS L=1.1 fb-1] T->tZ 3 leptons $M_T \gtrsim 475$ GeV
PAS-EXO-11-005

[ATLAS L=1.1 fb-1]

arXiv:1202.6540	1 lepton:	$M_{b'} \gtrsim 480$ GeV
arXiv:1202.5520	same-sign dilepton + 2 jets	$M_{b'} \gtrsim 450$ GeV
arXiv:1202.3389	dilepton + 2 jets	$M_{t'} \gtrsim 350$ GeV
arXiv:1202.3076	1 lepton:	$M_{t'} \gtrsim 404$ GeV

[ATLAS L=2 fb-1] arXiv:1204.1265 b'->bZ $M_{b'} \gtrsim 400$GeV

ATLAS limits on t'-> bW (with 1 fb^{-1})

Selection criteria :

= 2 opposite sign leptons (e,μ)
$|m_{LL} - m_Z| > 15$ GeV with $m_{LL} > 10$ GeV
n(jets) >= 2 jets
$E_T^{miss} > 60$ GeV for ee and μμ channel
$H_T = \Sigma p_T > 130$ GeV for eμ channel
$\Delta M(Q,\overline{Q})<25$ GeV
Mass-dependent requirements on H_T, E_T^{miss}, leading jet P_T and collinear mass are imposed as well to reduce the $t\bar{t}$ background.

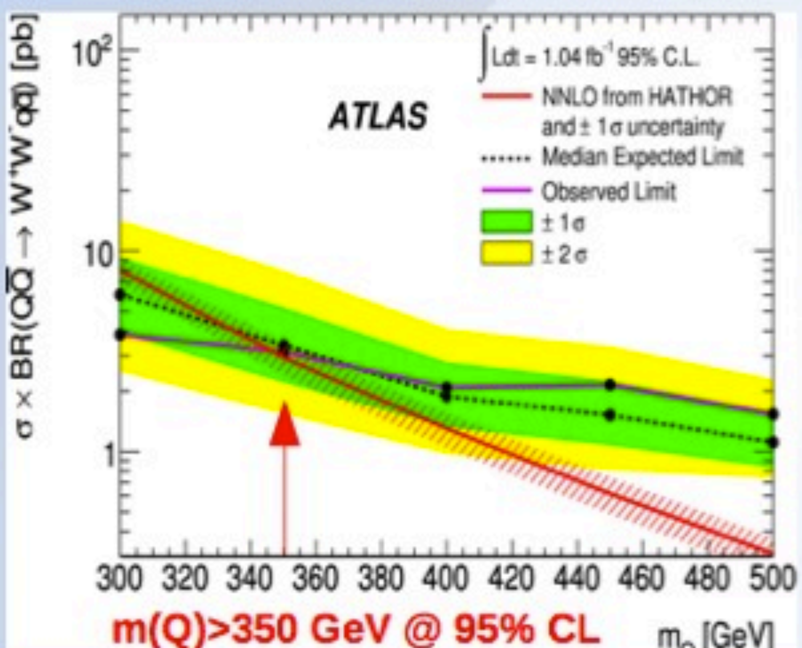
Selection criteria :

= 1 lepton (e,μ)
$E_T^{miss} > 35$ (20) GeV for e (μ) channel
$E_T^{miss} + m_T^{W} > 60$ GeV
n(jets) >= 3 jets with at least 1 b-jet
P_T(leading jet) > 60 GeV
P_T(jet) > 25 GeV

Exclusion Plots for the Q and t'

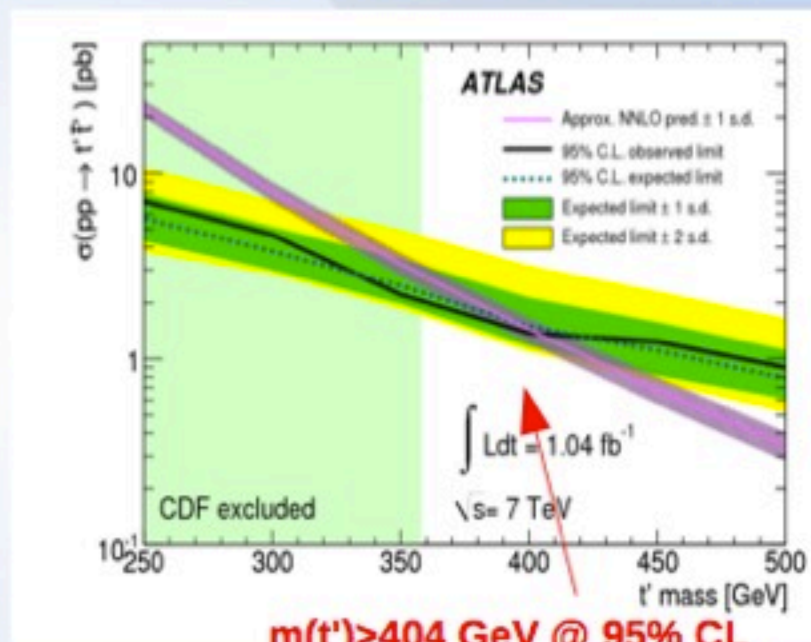
Only the range m(t') < (m_W – m(b')) is considered : t' → W^+q 100%

opposite-sign dilepton final state



arXiv : 1202.3389 [hep-ex]

lepton + jets final state



arXiv : 1202.3076 [hep-ex]

ATLAS limits on b'-> tW (with 1 fb^{-1})

Selection criteria :

>= 2 same sign leptons (e,μ)
$|m_{LL} - m_Z| > 10$ GeV with $m_{LL} > 10$ GeV
n(jets) >= 2 jets
$E_T^{miss} > 40$ GeV
$H_T = \Sigma p_T > 350$ GeV

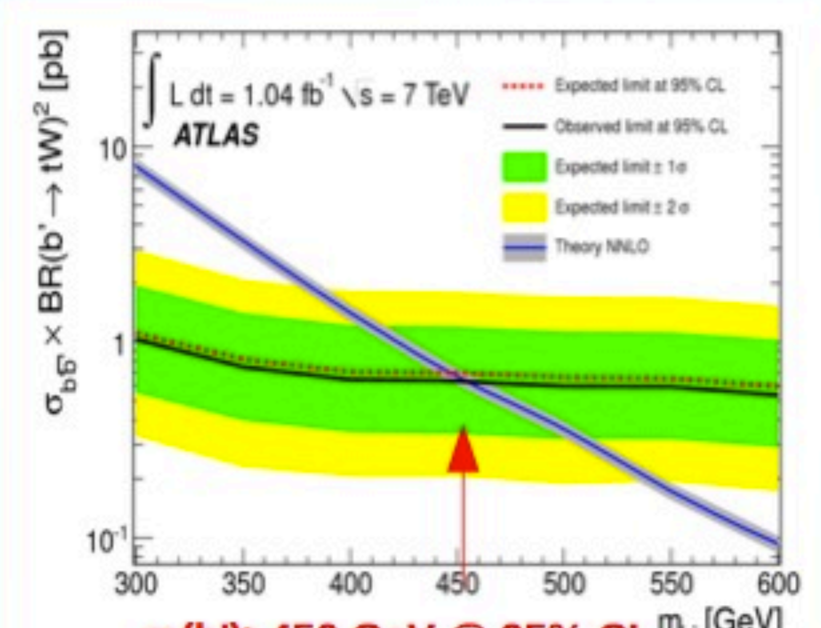
Selection criteria :

= 1 lepton (e,μ)
n(jets) >= 6 jets
$E_T^{miss} > 35$ (20) GeV for e (μ) channel
$m_T^W > 25$ GeV for e channel
$E_T^{miss} + m_T^W > 60$ GeV for μ channel

Exclusion Plots for the b'

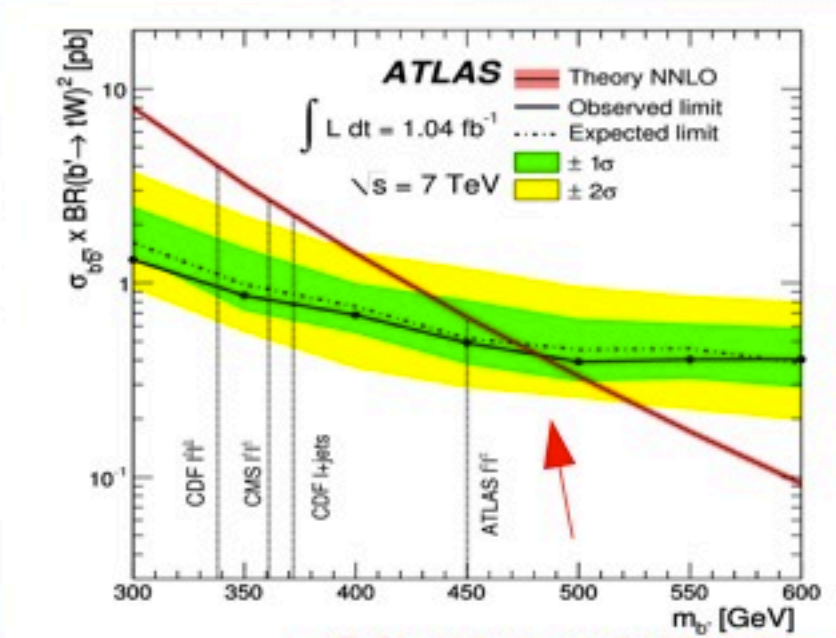
Only the range m(b') > (m(t) + m_W) is considered : b' → tW- 100%

same-sign dilepton final state



m(b')>450 GeV @ 95% CL

lepton + jets final state



m(b')>480 GeV @ 95% CL

arXiv : 1202.5520 [hep-ex]

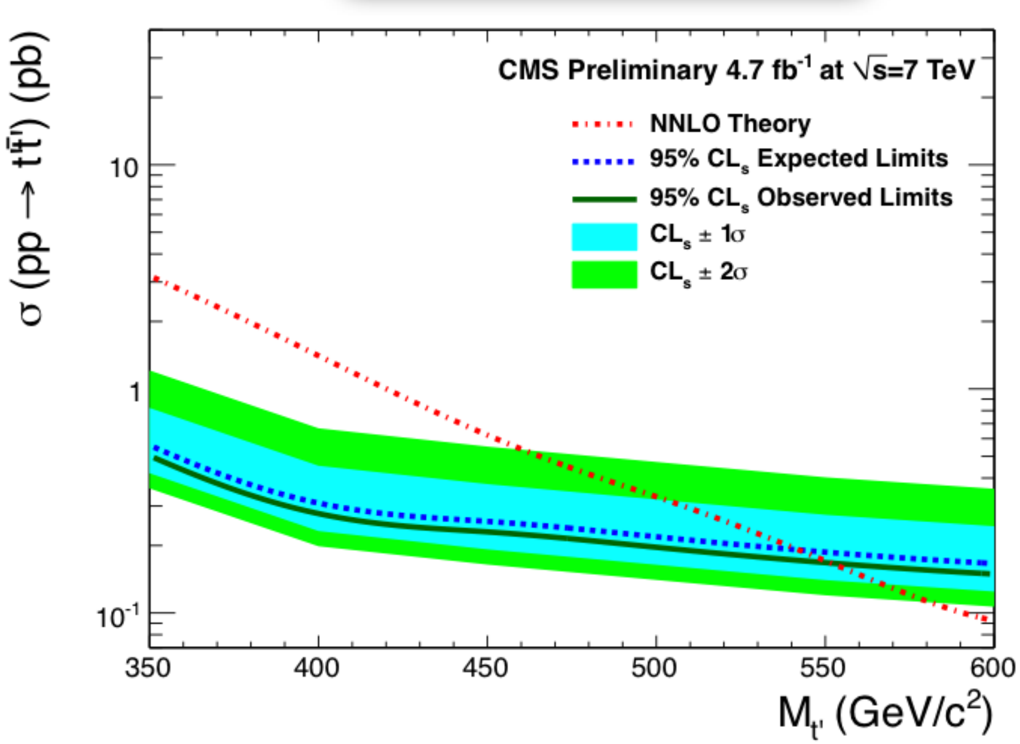
arXiv : 1202.6540 [hep-ex]

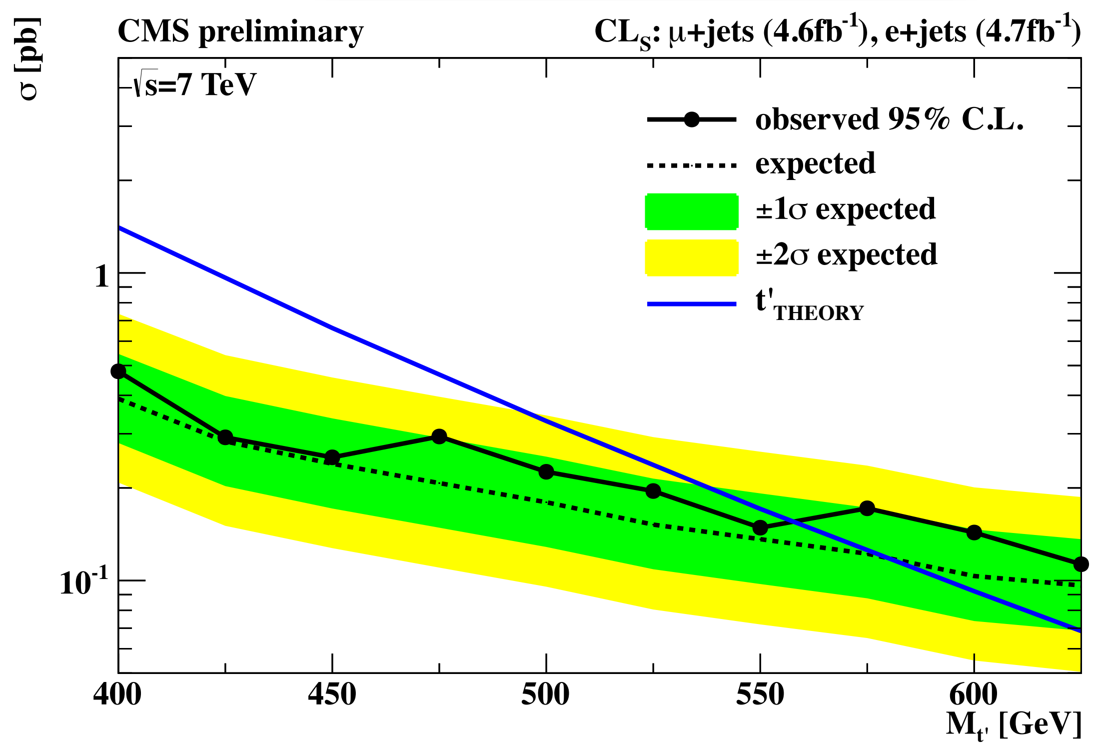
CMS limits on t'->bW (with 4.6 fb^{-1})

larger data set + stronger cuts: stronger limits

DILEPTON CHANNEL

1 LEPTON + 4 jets CHANNEL





$$M_{t'} \gtrsim 552 \text{ GeV}$$

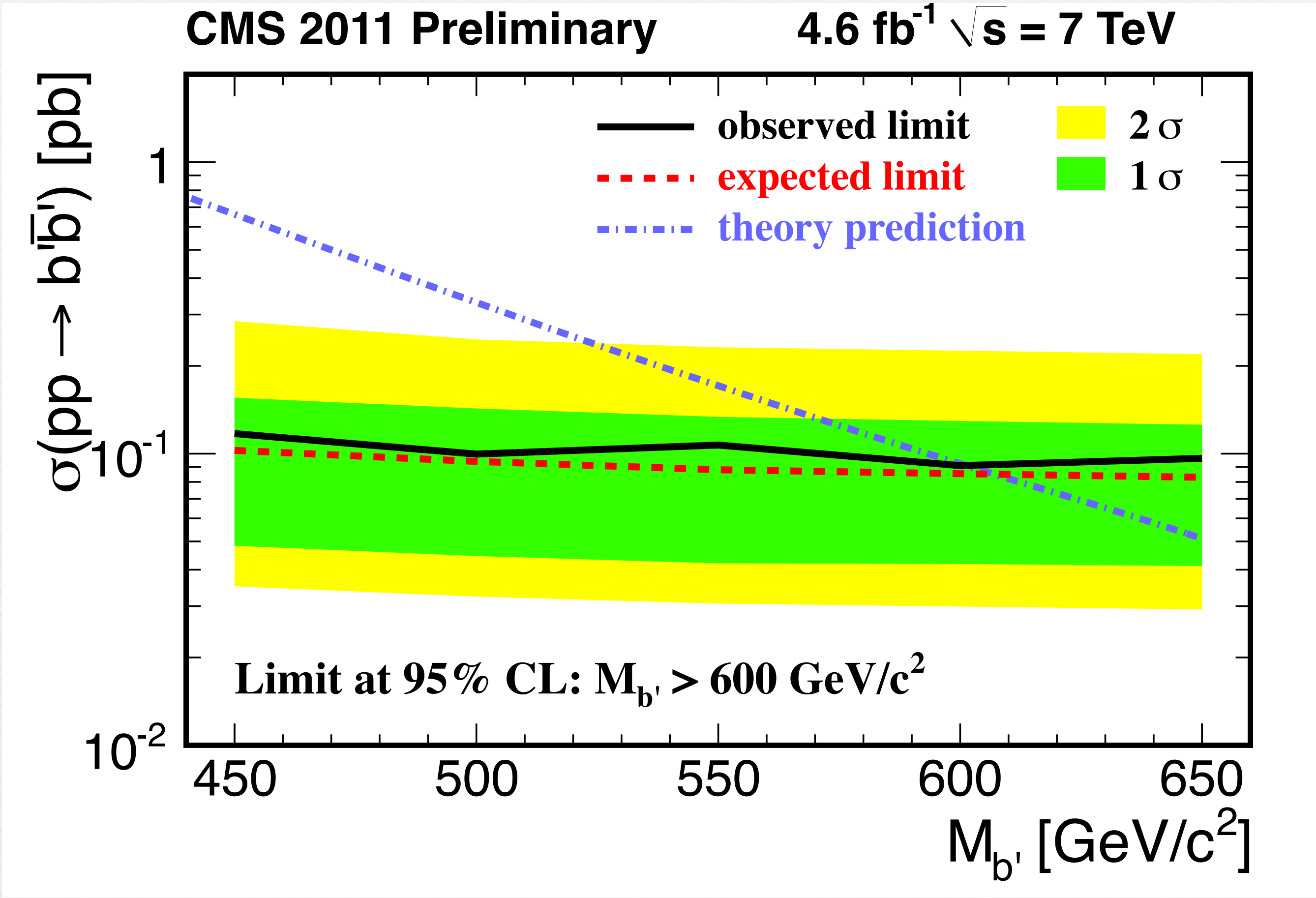
[CMS L=4.7 fb^{-1}]
PAS-EXO-11-050

$$M_{t'} \gtrsim 560 \text{ GeV}$$

[CMS L=4.7 fb^{-1}]
PAS-EXO-11-099

CMS limits on b'->tW (with 4.6 fb^{-1})

DILEPTON CHANNEL



[CMS L=4.6 fb^{-1}]
PAS-EXO-11-036

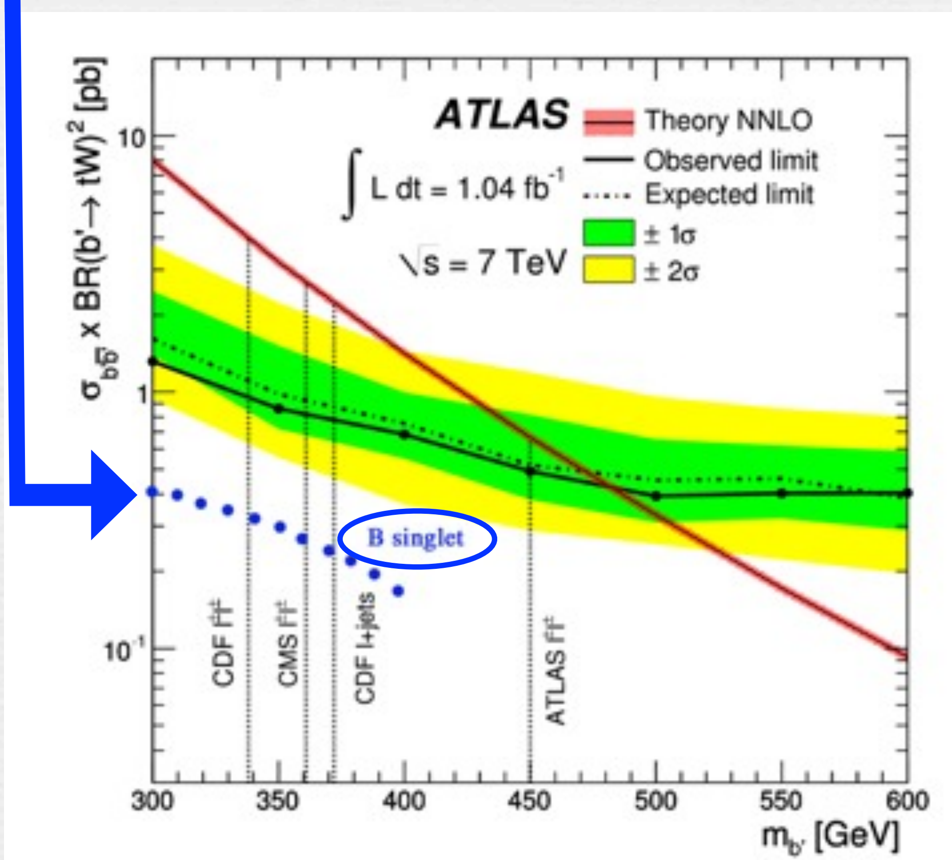
$$M_{b'} \gtrsim 600 \ \text{GeV}$$

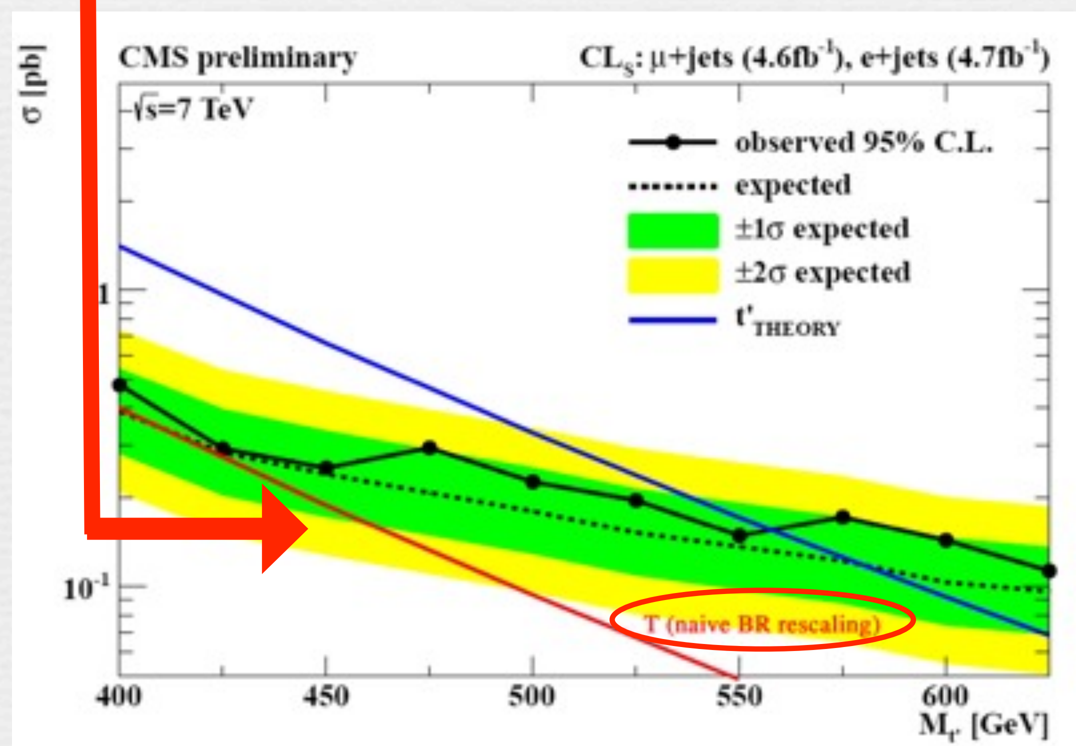
Note:

Presented limits assume 100% BR t' -> Wb and 100% BR b' -> Wt

Presented limits on b' apply to vector-like doublets, where B -> tW @ 100%, but not to singlets, which also decay into bZ and bH.

Presented limits on t' apply to charge -4/3 quarks in a doublet, but not to T singlets which also decay into tZ and tH



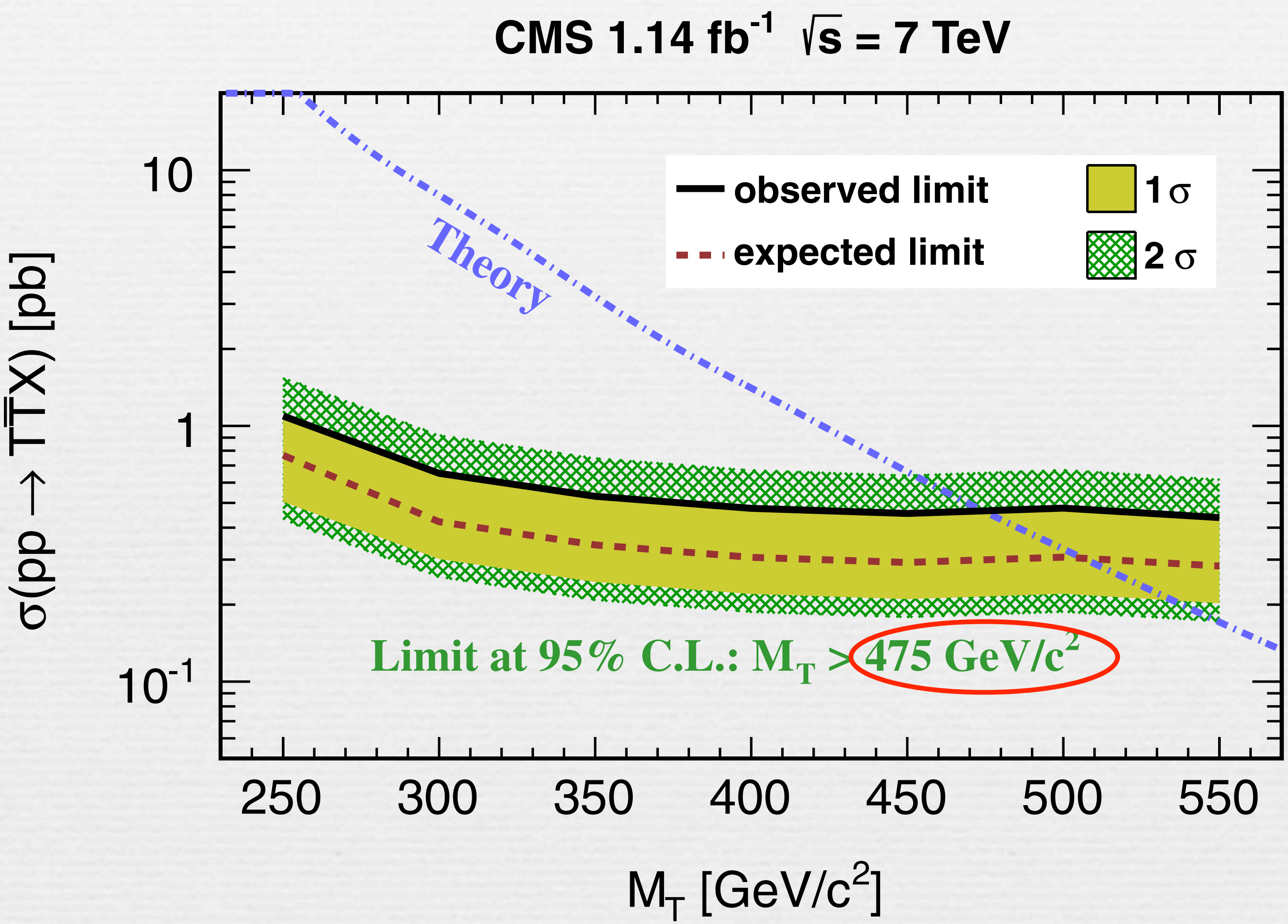


[J-A Aguilar-Saavedra]

CMS limits on T->tZ

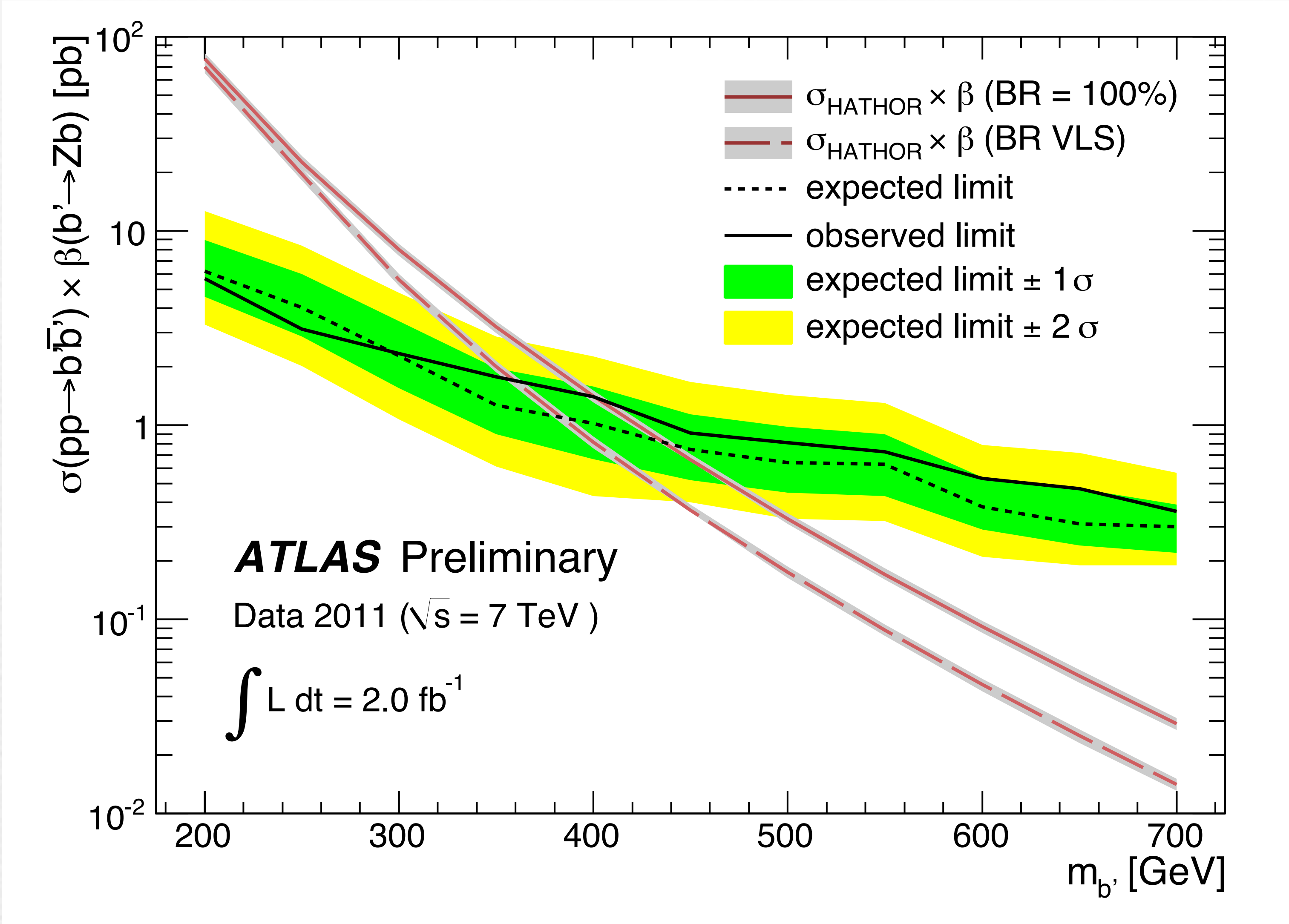
$pp \to T\bar{T}X$, with $T\bar{T} \to tZ\bar{t}Z \to b\bar{b}W^+W^-ZZ$

PRL **107,** 271802 (2011)



ATLAS limits on b'->bZ (with 2 fb^{-1})

b'b' → Zb + X with Z(→ee) + b-jet



$M \gtrsim 400\text{GeV}$ if BR=100%

$M \gtrsim 358\text{GeV}$ if B is singlet mixing with 3rd generation only

Prospects for T-> tH & B-> bH with H->bb

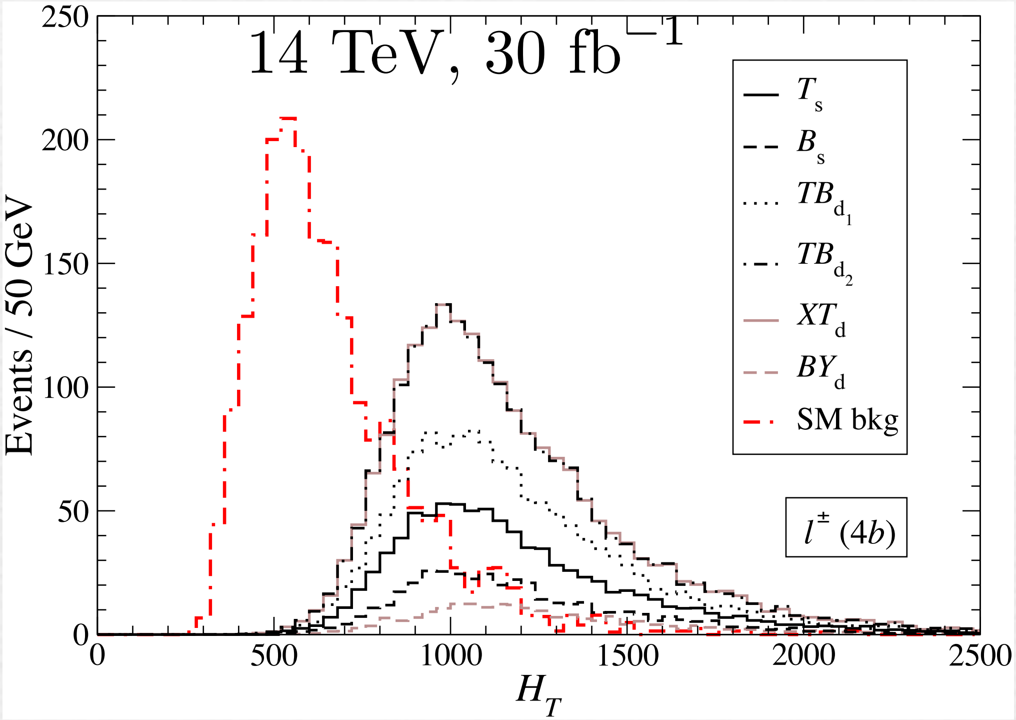
[Aguilar-Saavedra, 0907.3155]

$$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'\,,$$

$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

$$B\bar{B} \to HbW^+\bar{t} \to HbW^+W^-\bar{b}$$

$l^{\pm} + 4b$ final state

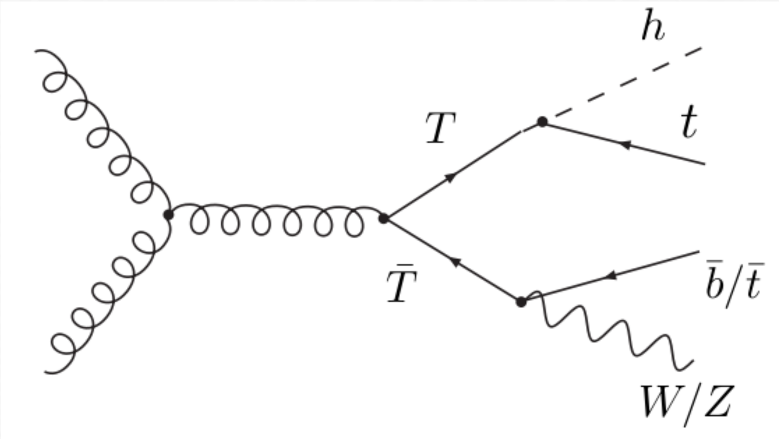


$$T\bar{T} \to HtH\bar{t} \to HW^+bHW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'\,,$$

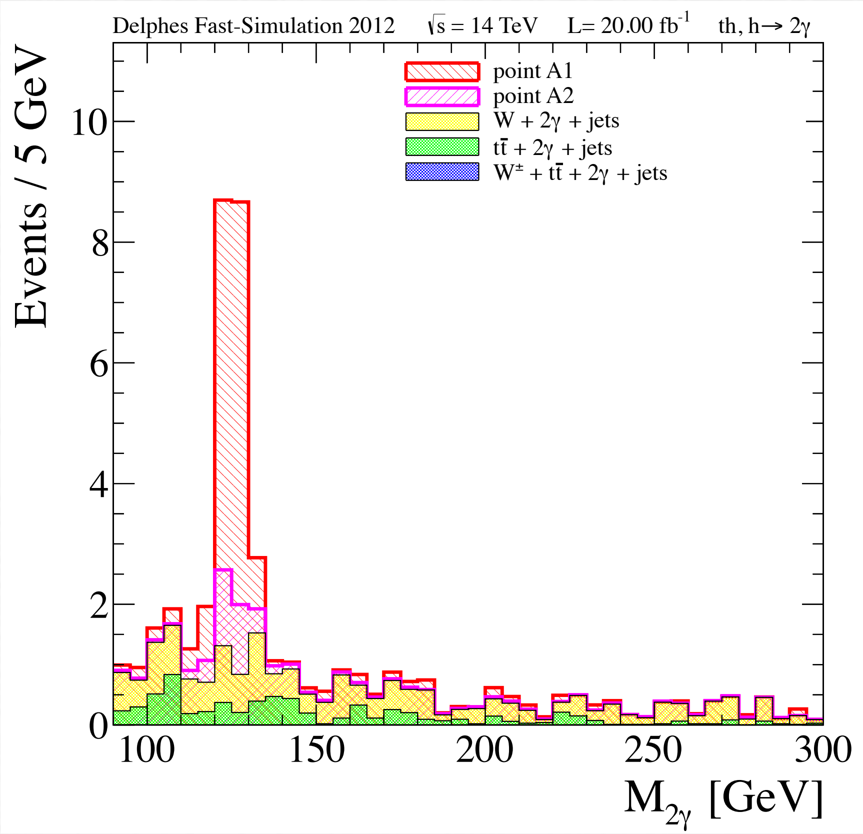
$l^{\pm} + 6b$ final state

Prospects for T->tH

[Azatov et al, Les Houches report, 1203.1488]
+ 1204.0455

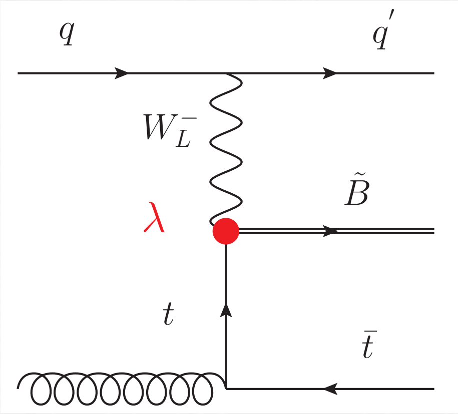


$$thbW/thtZ/thth,\ h \to \gamma\gamma$$



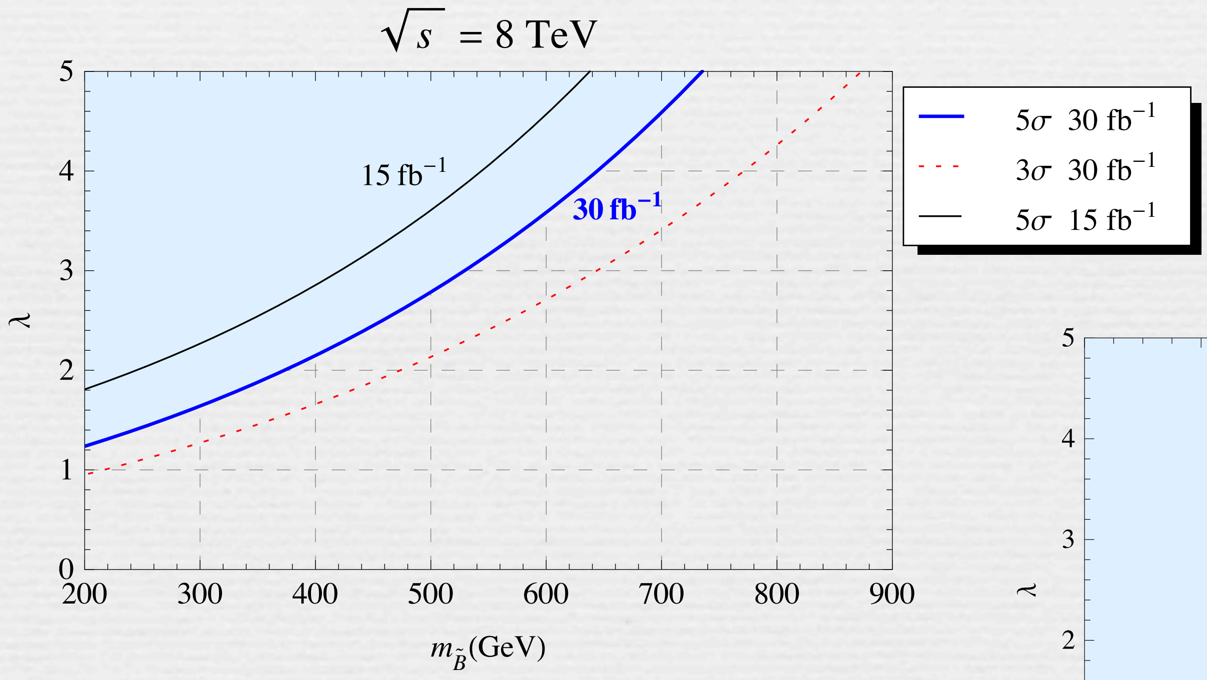
Prospects for B->bH

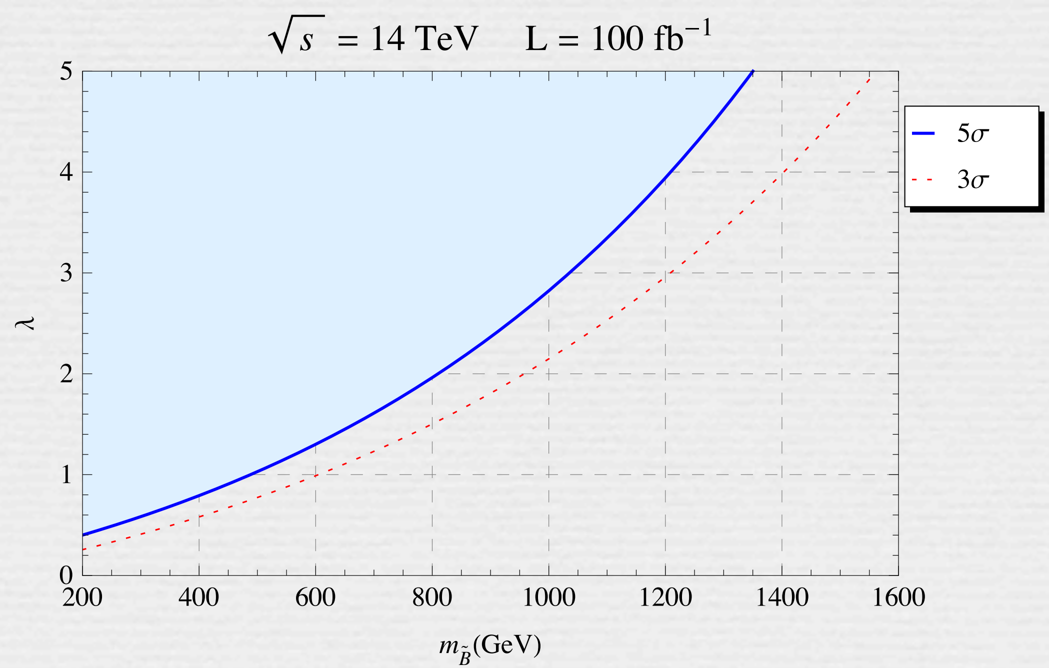
[Vignaroli 1204.0468]

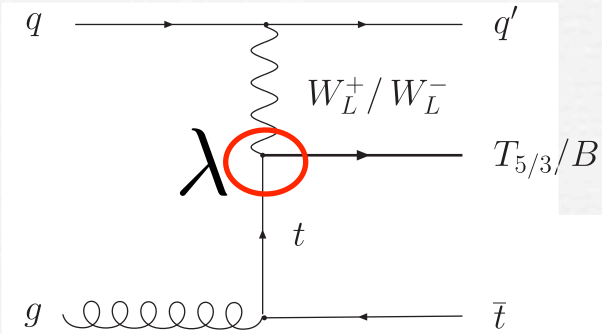


$$pp \to (\tilde{B} \to (h \to bb)b)t + X$$

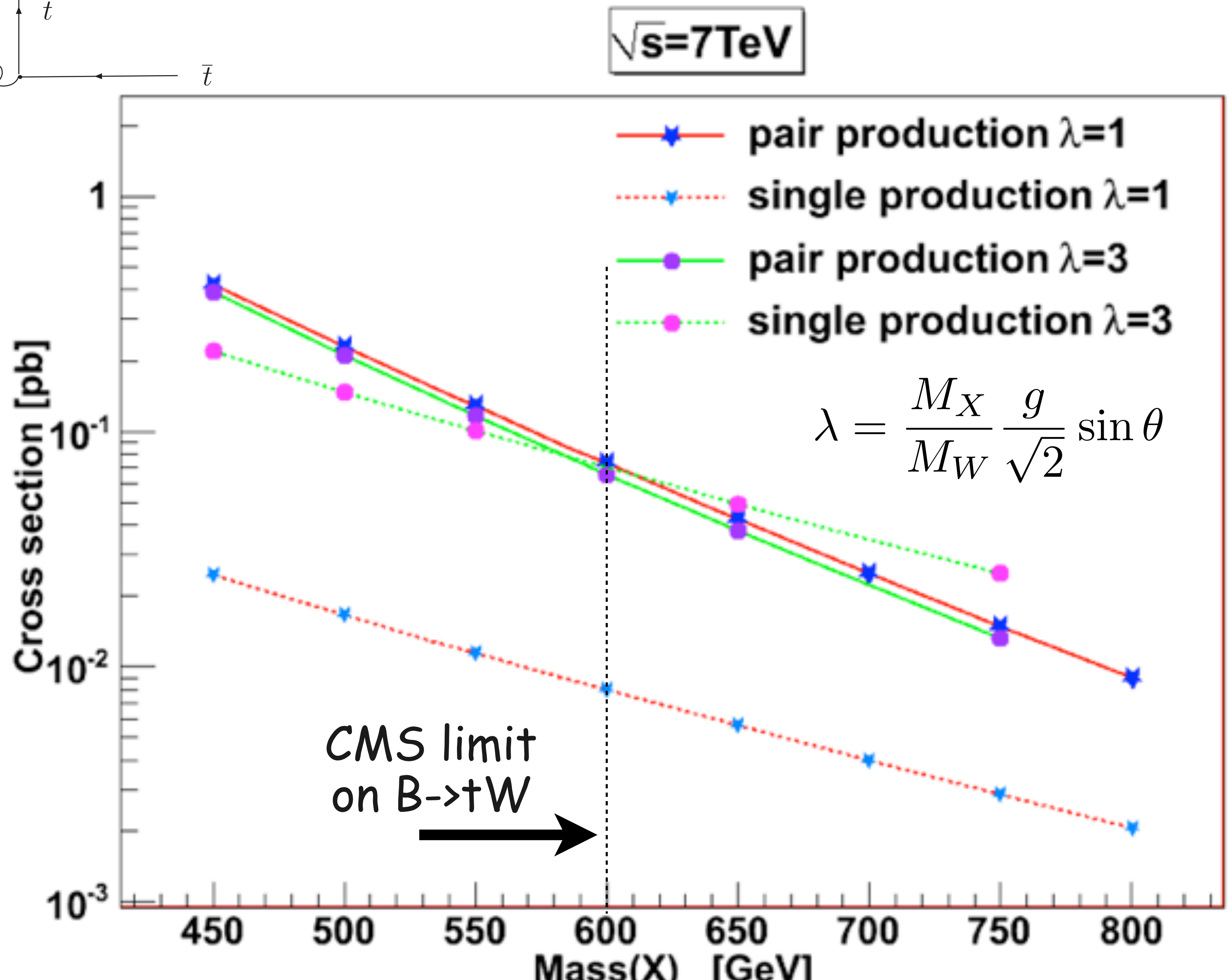
$$pp \to l^{\pm} + n\,jets + \not{E}_T\,, \qquad n \geq 4\,, \quad \text{At least 2 } b\text{-tag}$$







Single production may start to play an important role for M>~600 GeV



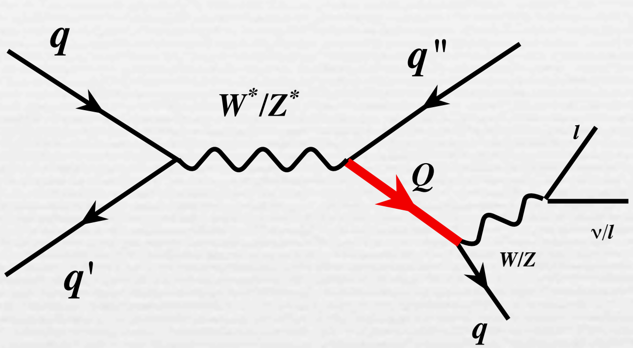
[L. Gauthier]

ATLAS search for singly produced vector-like coupled to light quarks

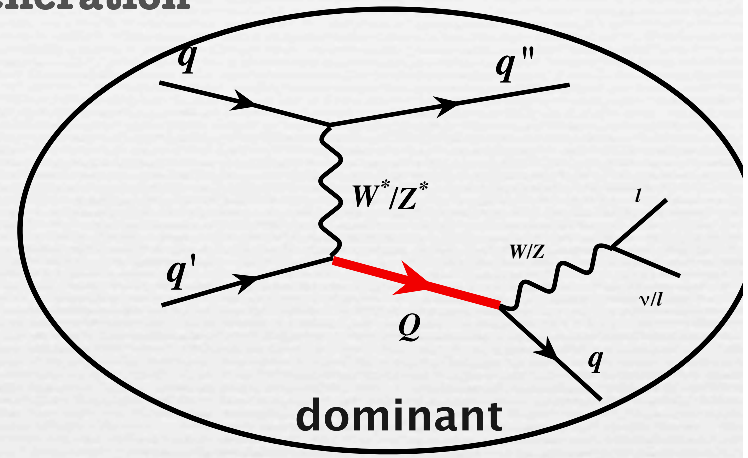
arXiv:1112.5755

$$pp \to Qq \to Wqq' \text{ and } pp \to Qq \to Zqq'$$

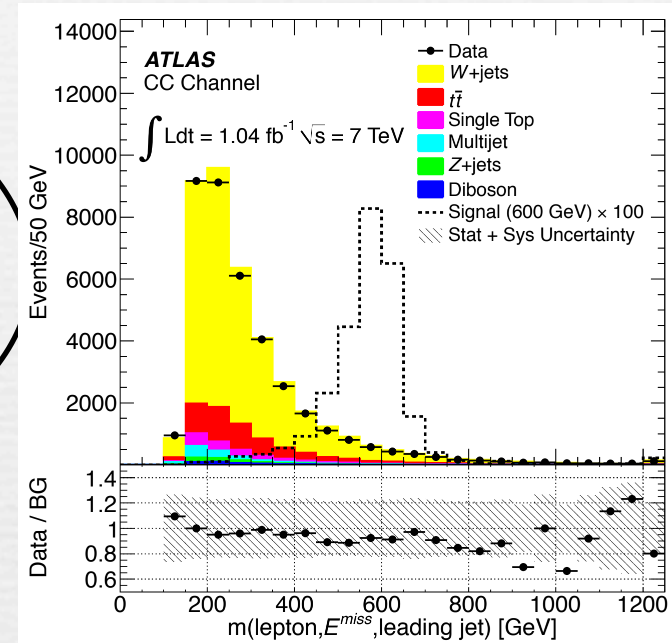
although new vector quarks expected to couple sizably only to third generation

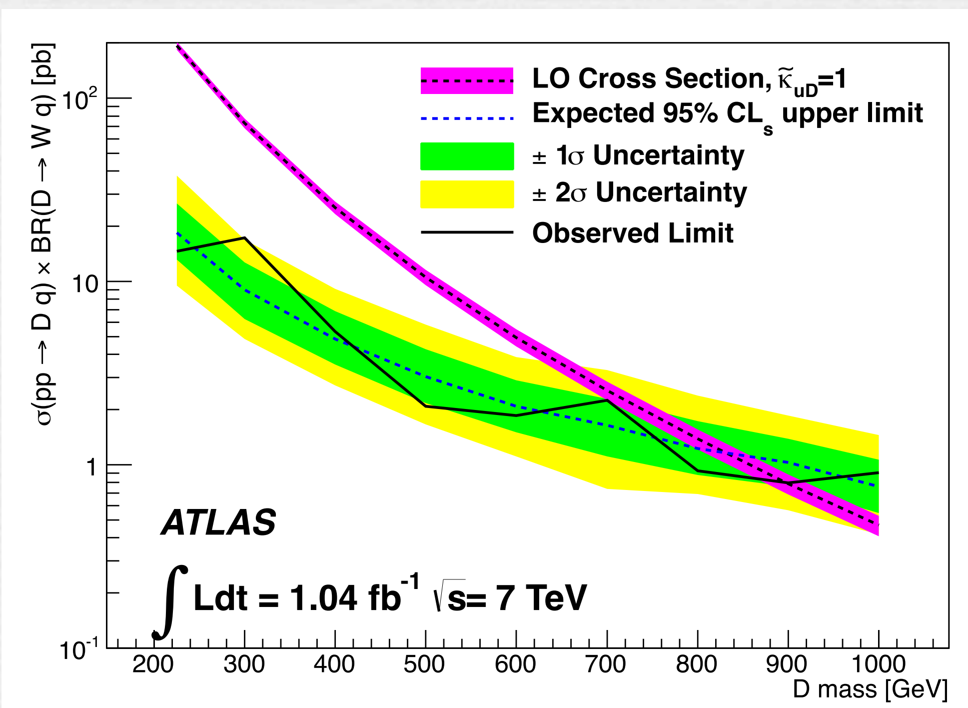


negligible



dominant





$$M > 900 \text{ GeV from CC}$$

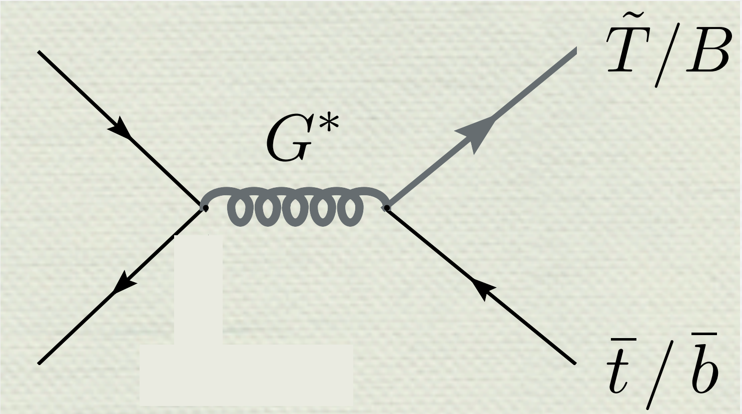
$$M > 760 \text{ GeV from NC}$$

Associated production (via a heavy gluon)

$$q\bar{q} \longrightarrow G^* \longrightarrow \tilde{T}\bar{t} + \tilde{B}\bar{b}$$

->Wbt̄ ->Wtb̄

[Bini, Contino , Parisse, Vignaroli, 1110.6058]
[Barcelo, Carmona, Masip, Santiago, 1110.5914]



same final state as tt̄

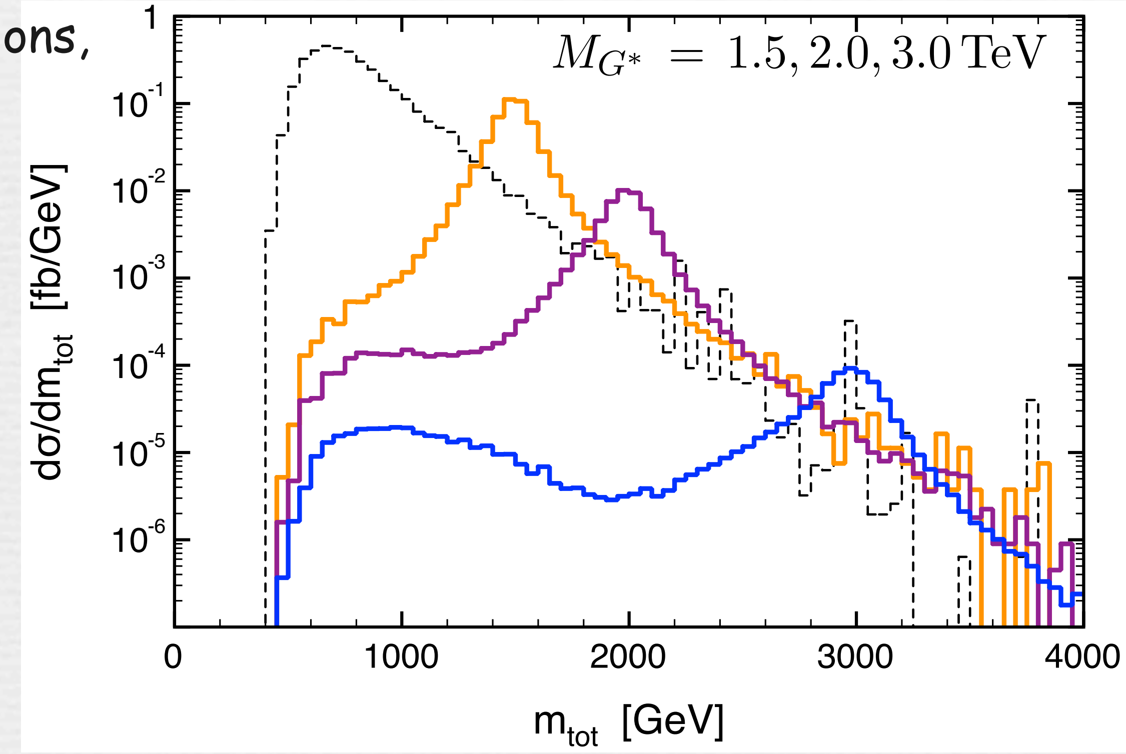
Mass reach depends on:

-the ratio $M_{G^*}/M_{\tilde{T},B}$

-on coupling between G* and the light fermions,

-on the top degree of compositeness

-> model-dependence



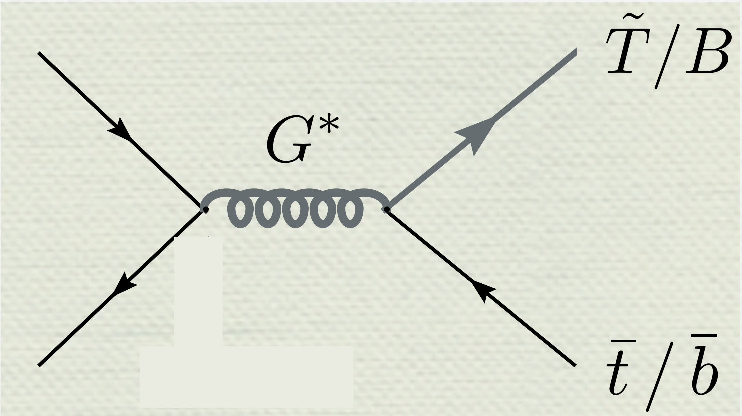
[Contino et al]

$$m_{tot} \equiv m(W_t b_t W_{\not{t}} b_{\not{t}})$$

Associated production (via a heavy gluon)

$$q\bar{q} \longrightarrow G^* \longrightarrow \underbrace{\tilde{T}\bar{t}}_{\text{->}Wb\bar{t}} + \underbrace{\tilde{B}\bar{b}}_{\text{->}Wt\bar{b}}$$

[Bini, Contino , Parisse, Vignaroli, 1110.6058]
[Barcelo, Carmona, Masip, Santiago, 1110.5914]



same final state as $t\bar{t}$

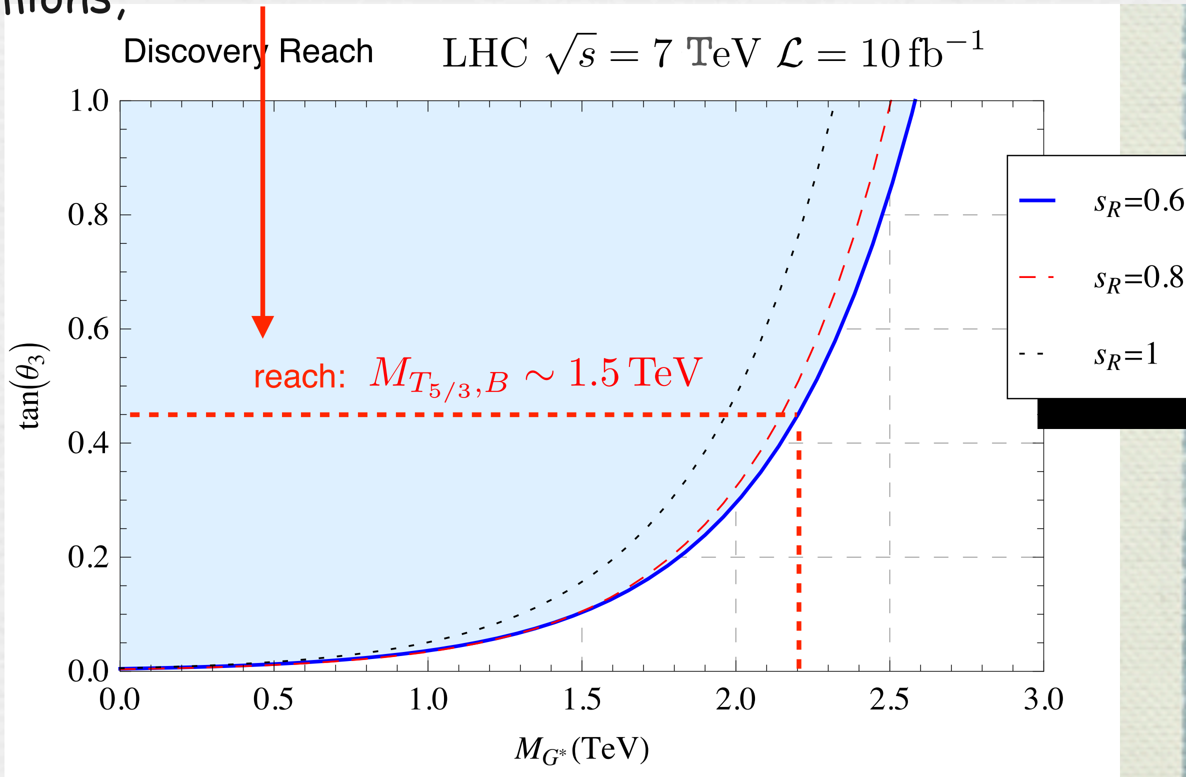
Mass reach depends on:

-the ratio $M_{G^*}/M_{\tilde{T},B}$

-on coupling between G* and the light fermions,

-on the top degree of compositeness

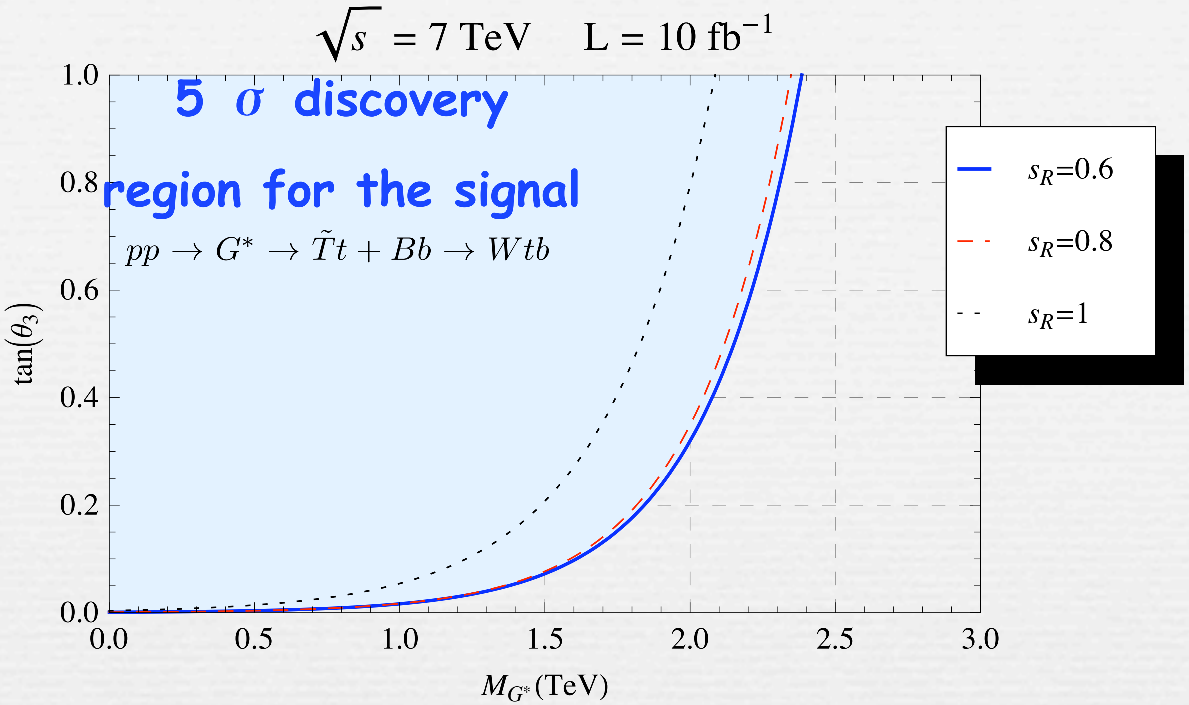
-> model-dependence



[Contino et al]

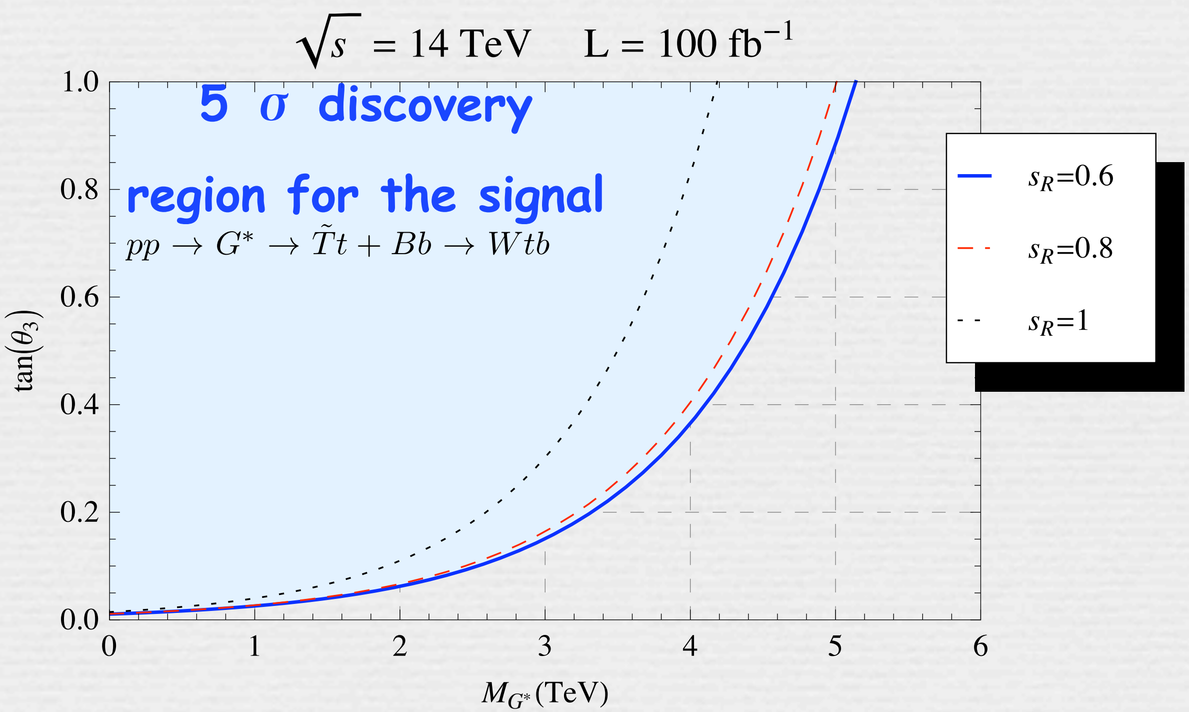
Much better reach
([1 - 1.4 TeV])
in comparison with the previous
single+pair production process

if $\dfrac{M_{G^*}}{M_{\tilde{T},B}} \sim 1.5$



$M_{G^*}/m_{\tilde{T}} = 1.5$ and $Y_* = 3$

almost 3 TeV reach for top partner!

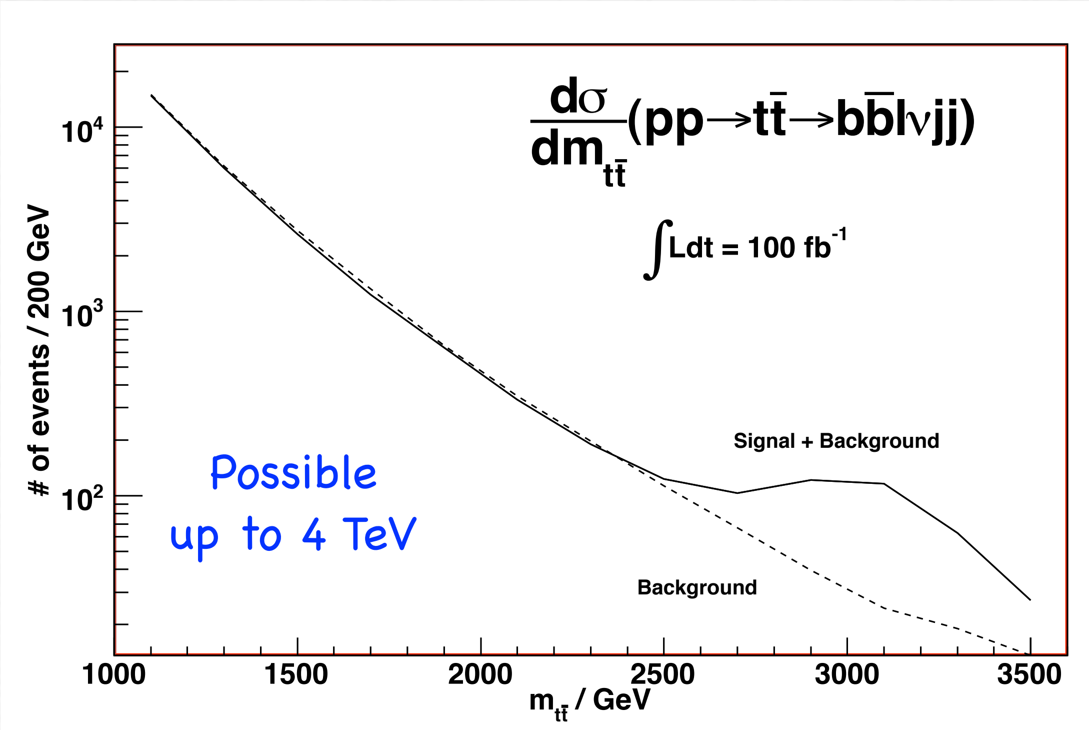


[Bini, Contino , Parisse, Vignaroli, 1110.6058]

Other signature: Gluonic resonance

$$pp \to G^* \to t\bar{t}$$

decay mainly into tops which have sizable coupling to the strong sector



Agashe et al

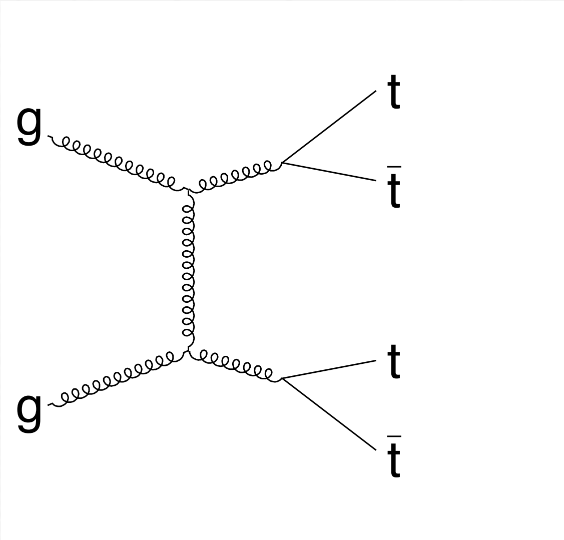
Let us now imagine the top partners are too heavy to be accessible at the LHC (i.e >~1.5-2 TeV), and heavy gluons also too heavy (>~4 TeV)

Where shall we search for signs of top compositeness ?

Four-top events at the LHC

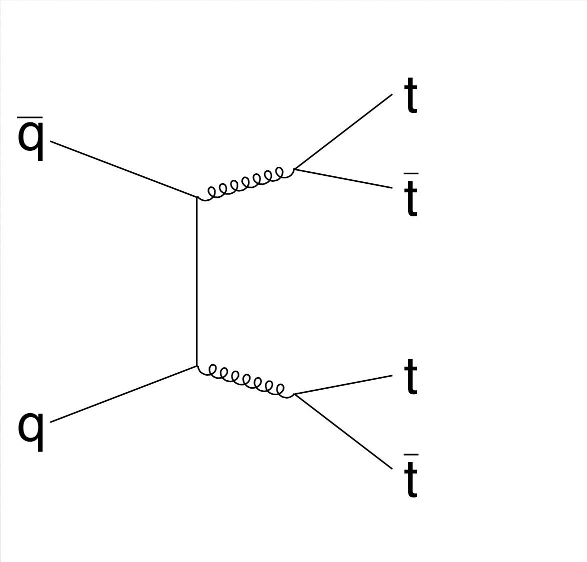
spectacular events with 12 partons in the final state

Four-top production in the Standard Model



88 %

+



+ ....

σ_{LHC} ~ 7.5 fb @ 14 TeV

σ_{LHC} ~ 0.2 fb @ 7 TeV

$\sigma_{tevatron}$ < 10^-4 fb

⇛ 4 top final state sensitive to several classes of new TeV scale physics

e.g. SUSY (gluino pair production with $\tilde{g} \rightarrow t\,\bar{t}\,\chi_0$)

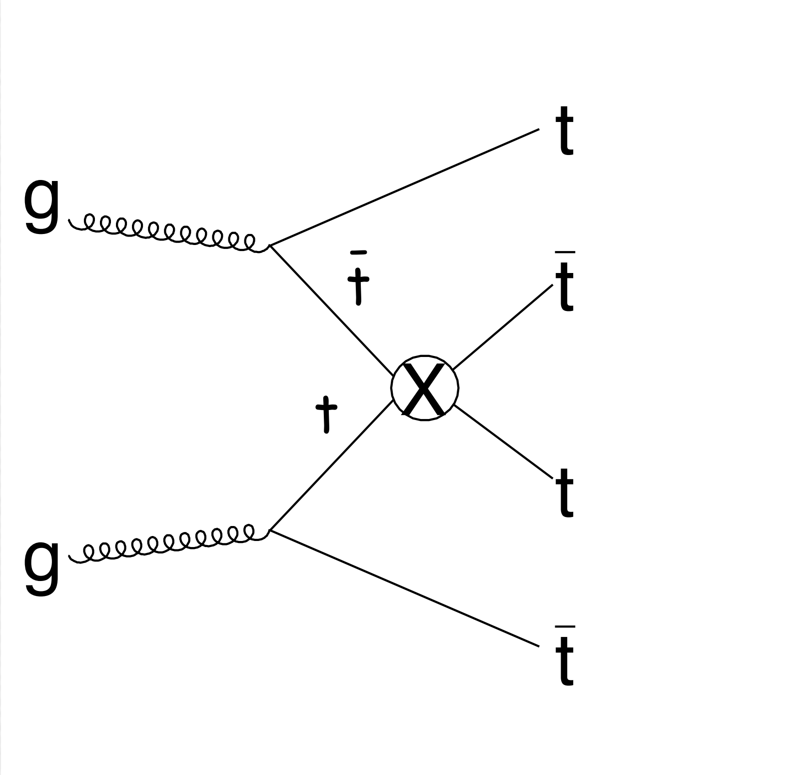
top compositeness

well-motivated class of composite higgs models where new heavy resonances have a preference for the top quark

Low energy effective theory approach

After integrating out heavy resonances, we are left with higher dimensional operators such as $$\frac{1}{\Lambda^2}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$$

leading to:



[Pomarol-Serra,'08]
[Lillie-Shu-Tait,'08]

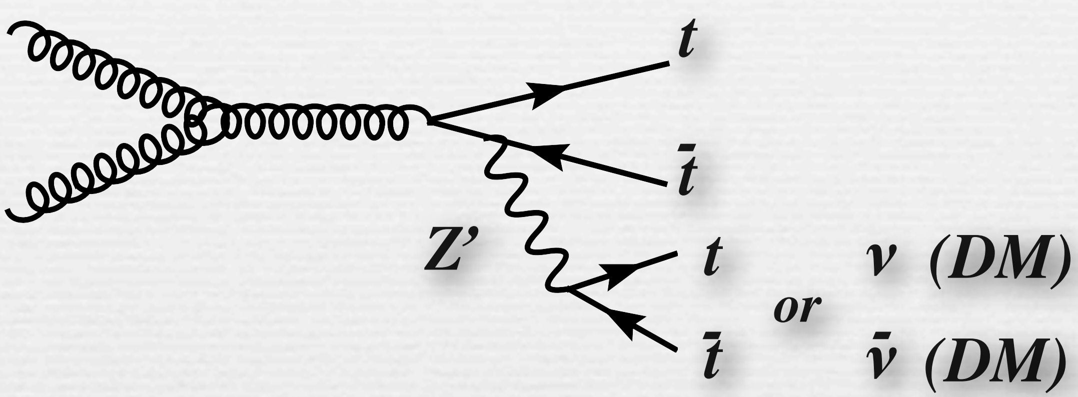
Four-top events from a top-philic and Dark Matter-philic Z'

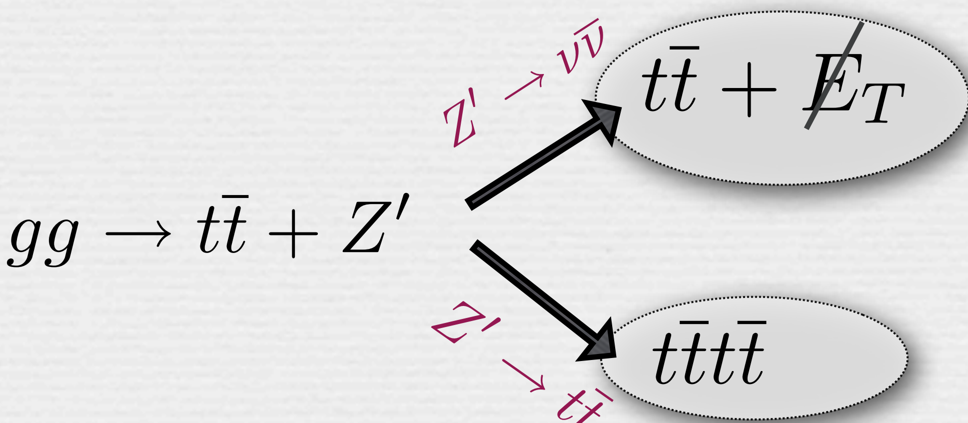
Jackson, Servant, Shaughnessy,Tait, Taoso,'09

Z' has suppressed couplings to light quarks

-> no observable $t\,\bar{t}$ resonances

instead:





A simple UV completion

All SM fermions are uncharged under U(1)'

Add $\tilde{T}$ (vector-like) charged under U(1)' with same gauge SM quantum numbers as t_R

to realize coupling of top quark to Z' and h:

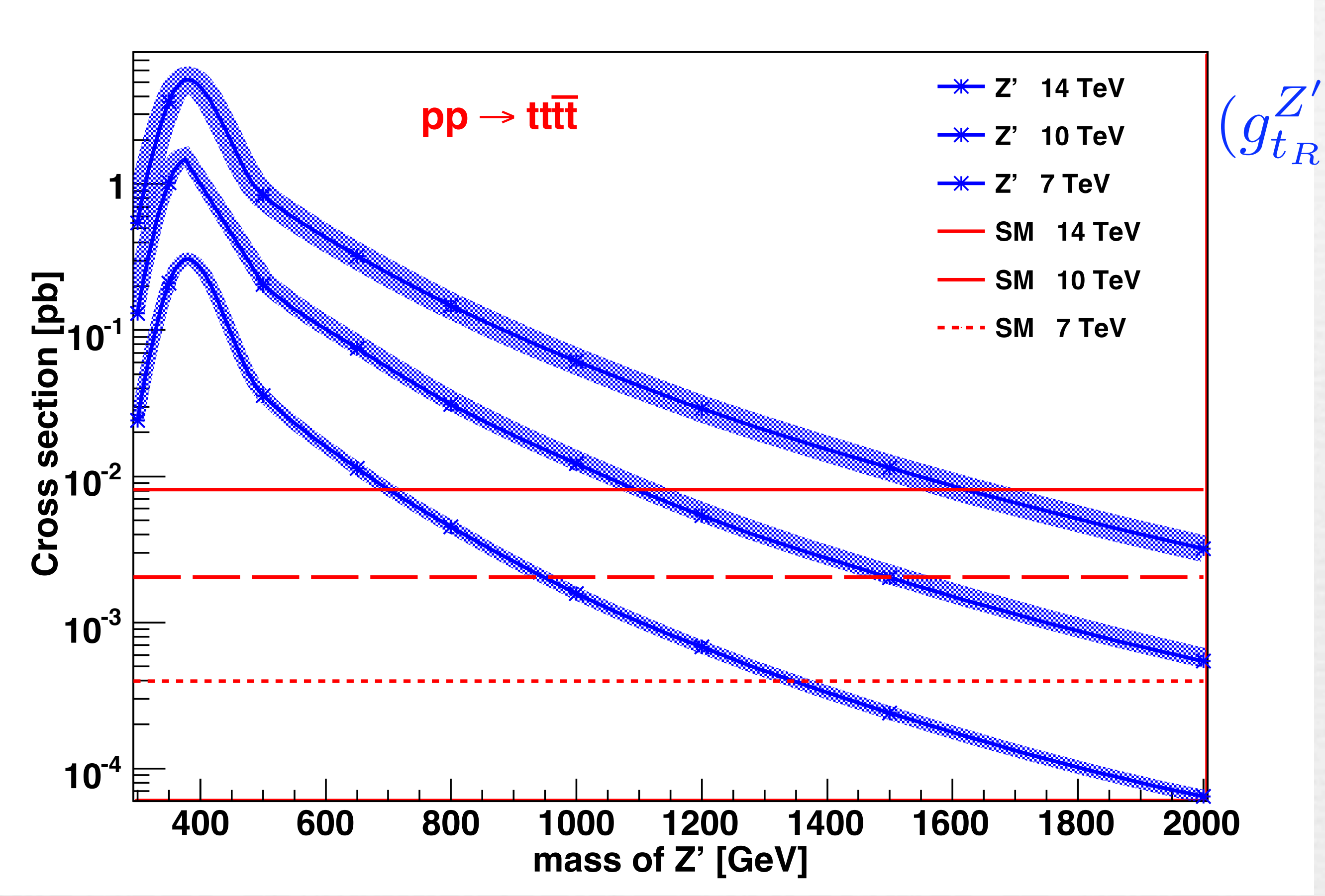
$$y H \overline{Q}_3 t_R + \mu \overline{\tilde{T}}_L \tilde{T}_R + Y \Phi \overline{\tilde{T}}_L t_R$$

higgs of U(1)'

the light mass eigen state identified with top quark is an admixture of t and $\tilde{T}$

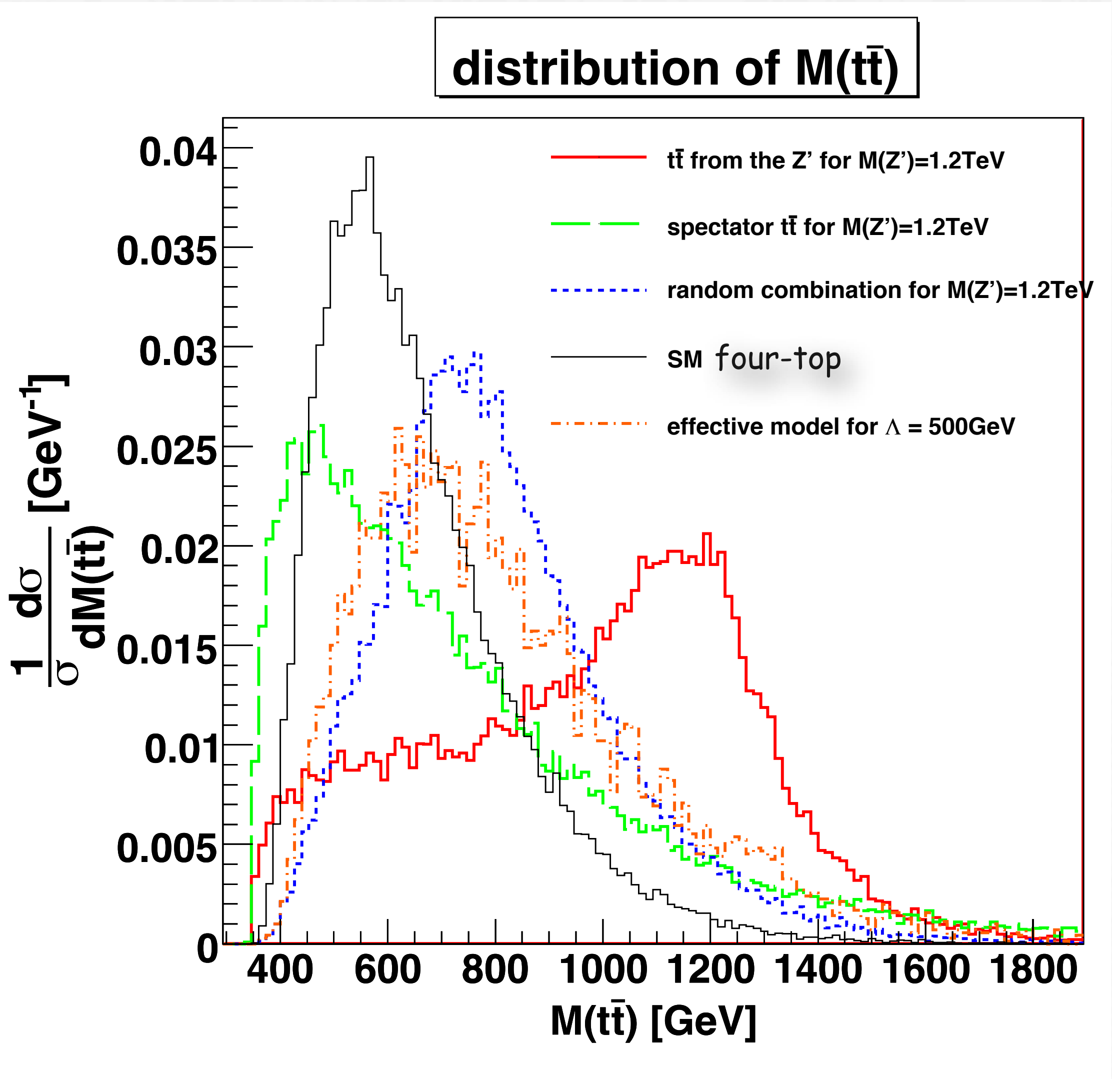
production cross section at the LHC

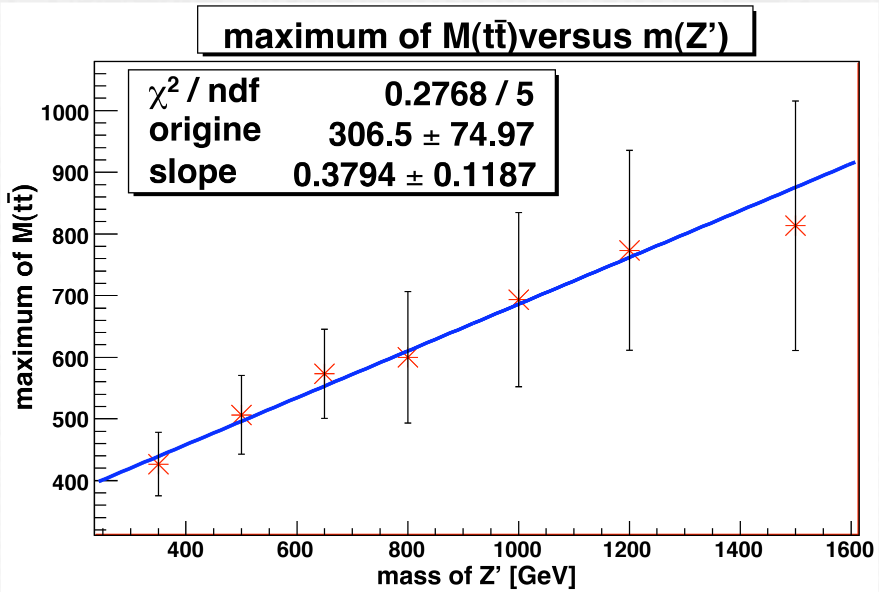
Use top-philic Z′ as benchmark model



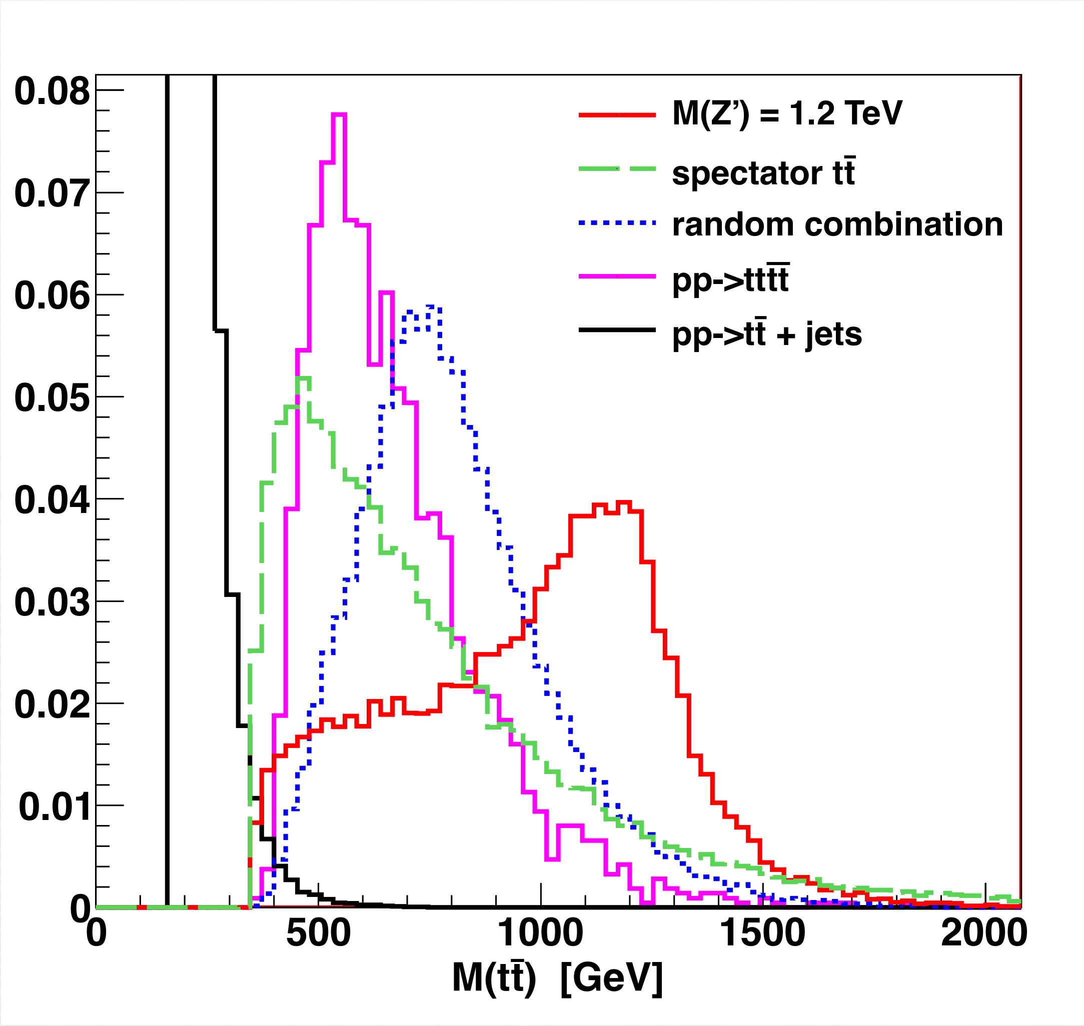
$(g_{t_R}^{Z'} = 3)$

$t\,\bar{t}$ invariant mass





for random combination


M(Z') = 1.2 TeV
spectator $t\bar{t}$
random combination
pp->$tt\bar{t}\bar{t}$
pp->$t\bar{t}$ + jets
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
500
1000
1500
2000
M($t\bar{t}$) [GeV]

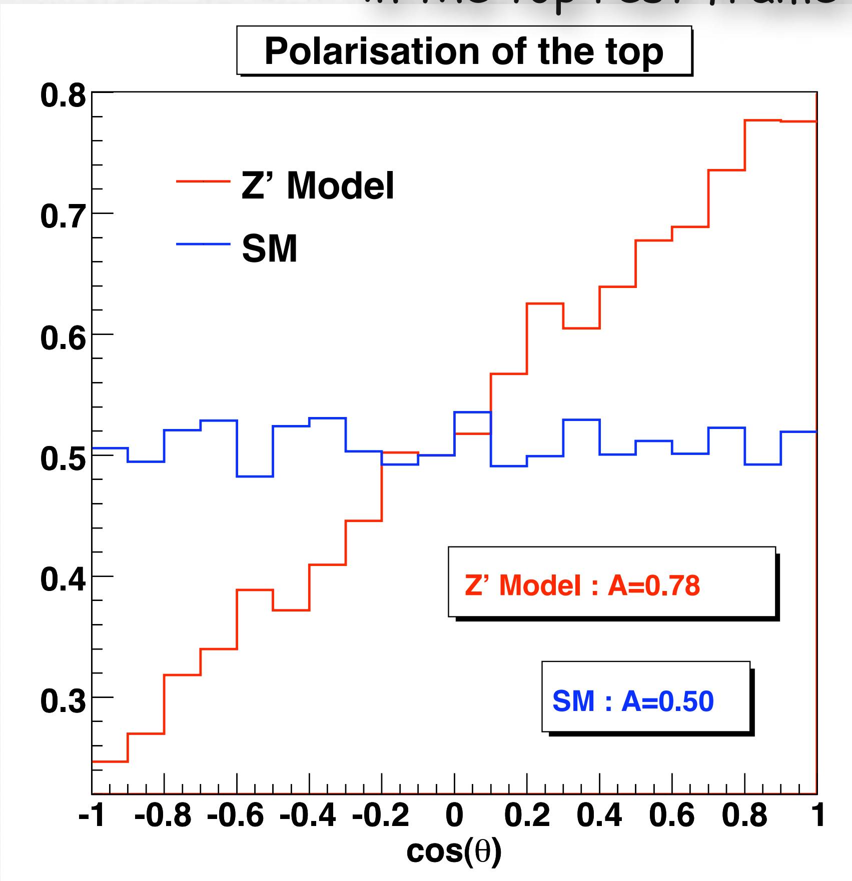
top polarization

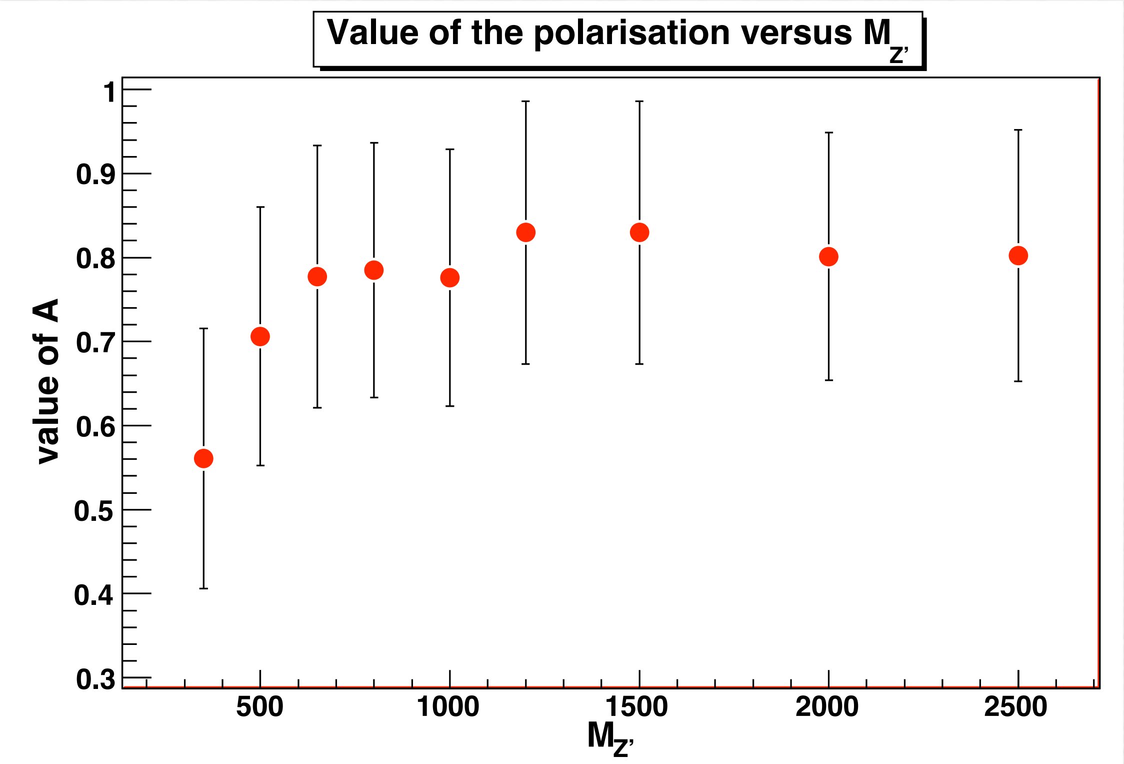
In the models of interest, 4-top production yields an excess of right-handed tops

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{A}{2}(1+\cos\theta) + \frac{1-A}{2}(1-\cos\theta)$$

A: fraction of RH tops

θ is the angle between the direction of the (highest p_T) lepton in the top rest frame and the direction of the top polarisation





background in same-sign dilepton channel @LHC

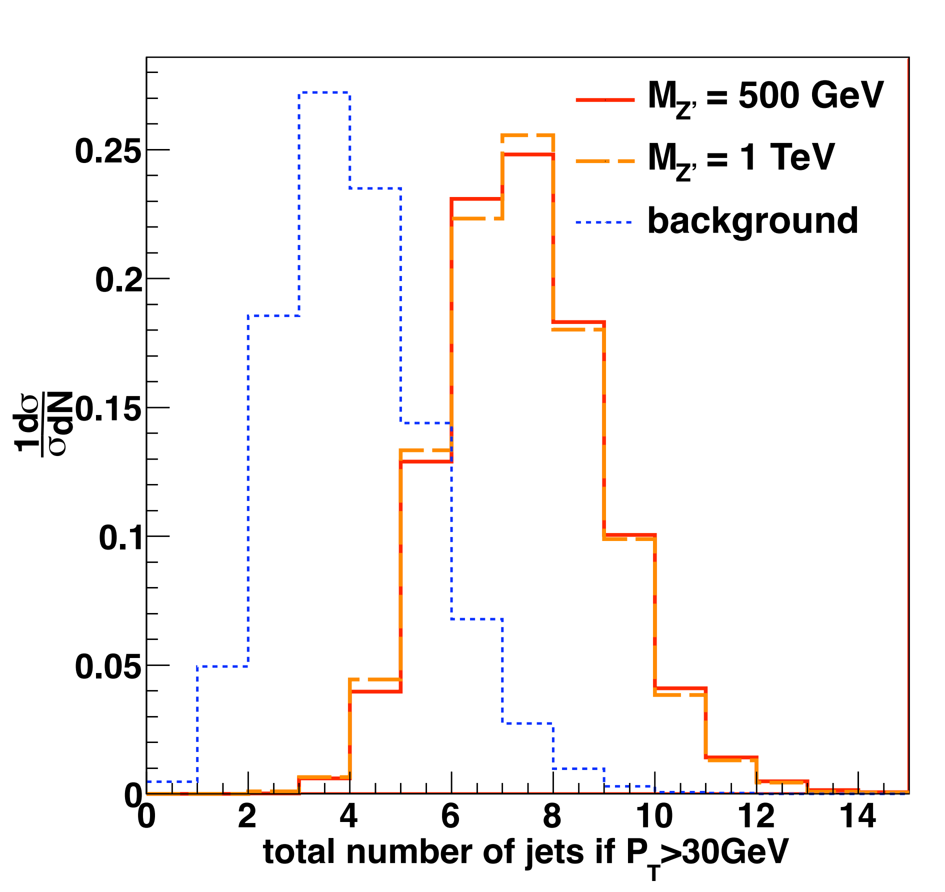
final state: $\ell^{\pm}\,\ell^{\pm}$ + n jets + $\not{E}_T$

(of which 4 are b-jets)

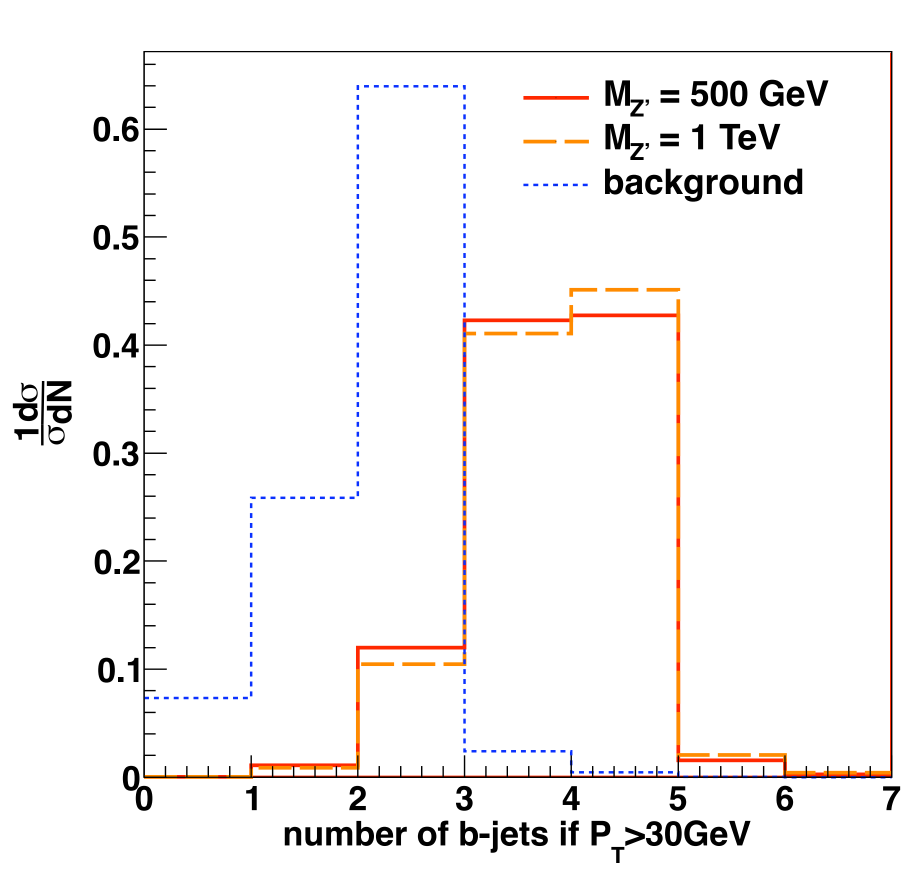
process	σ [fb]	$\sigma.BR(l^{\pm}l^{\pm})$ [fb]
signal m(Z')=500GeV	838	35
signal m(Z')=1TeV	61	2.6
signal + 1jet m(Z')=500GeV	164	6.9
signal + 1jet m(Z')=1TeV	21.5	0.9
$tt\bar{t}\bar{t}$	7.5	0.3
$t\bar{t}W^+W^- + 0,1,2jets$	450	13.7
$t\bar{t}W^{\pm} + 0,1,2,3jets$	595	18.4
$W^+W^-W^{\pm} + 0,1,2jets$	603	18.7
$W^{\pm}W^{\pm} + 0,1,2,3jets$	340	15.5
$t\bar{t}$	442 657	203
$t\bar{t}$ + 1 jet	315 999	145
$t\bar{t}$ + 2 jets	182 868	84
$t\bar{t}$ + 3 jets	101 057	46
$t\bar{t}$ + 4 jets	36 236	17

$t\bar{t}$+jets with charge mis-ID is the main background (more precisely ttbar+ 2 hard jets)

of jets

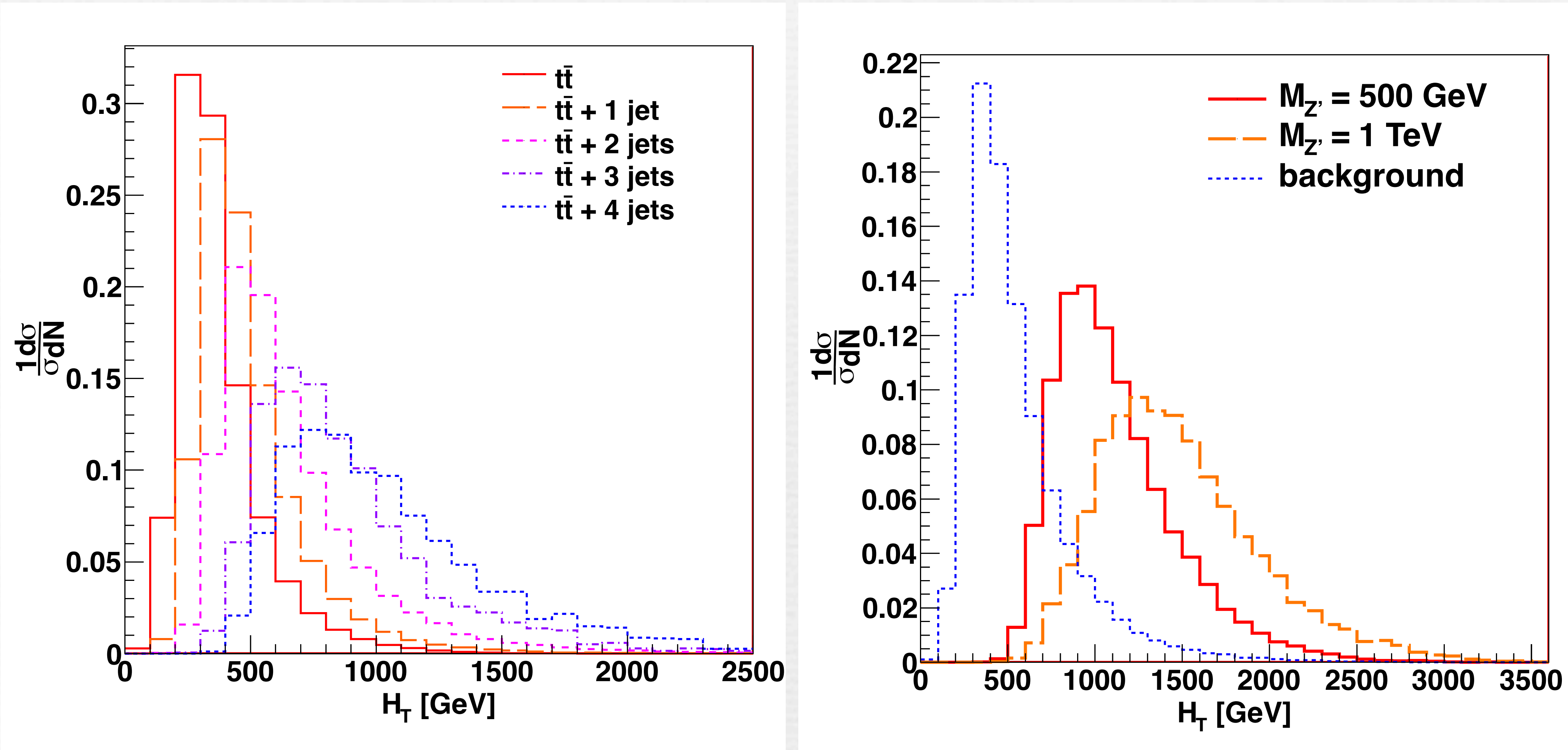


$M_{Z'}$ = 500 GeV
$M_{Z'}$ = 1 TeV
background
$\frac{1}{\sigma}\frac{d\sigma}{dN}$
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
12
14
total number of jets if P_T>30GeV



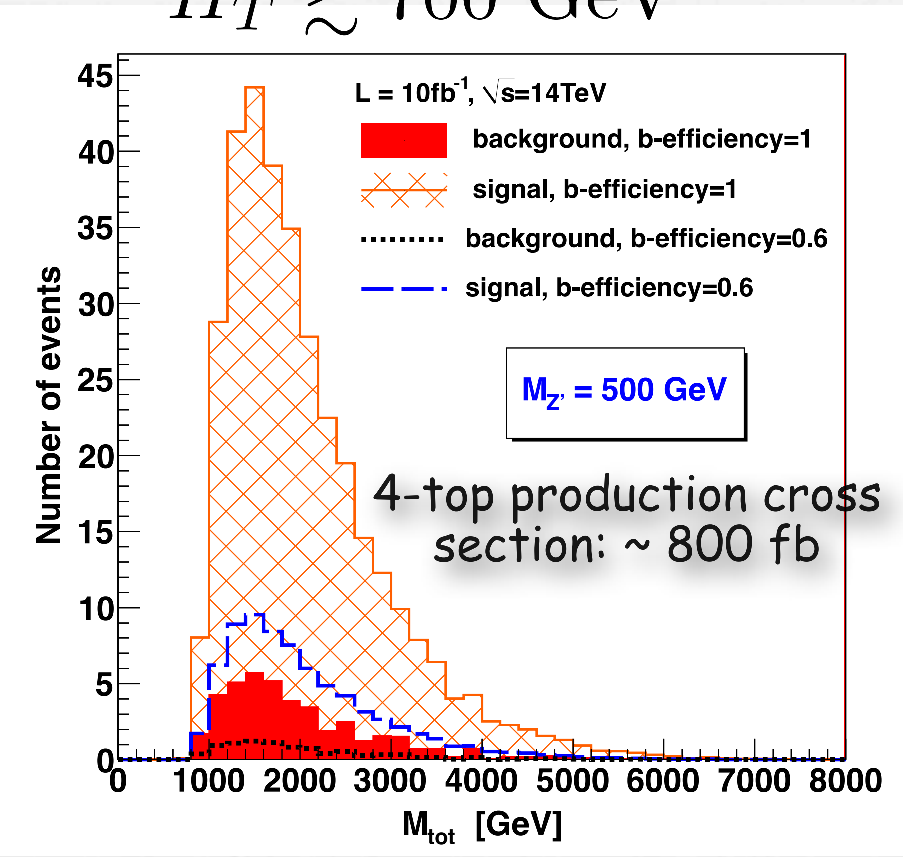
$M_{Z'}$ = 500 GeV
$M_{Z'}$ = 1 TeV
background
$\frac{1}{\sigma}\frac{d\sigma}{dN}$
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
number of b-jets if P_T>30GeV

Distinguishing variable

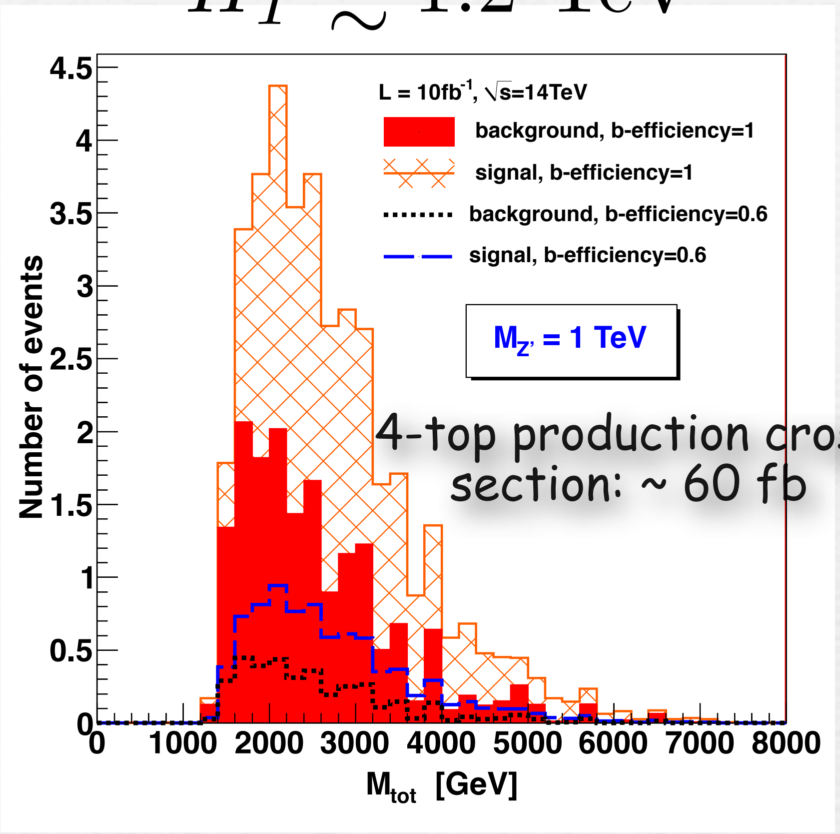


$$n_j \geq 6,\, p_T > 30 \text{ GeV} \qquad n_{\text{b jets}} \gtrsim 3$$

$H_T \gtrsim 700$ GeV



$H_T \gtrsim 1.2$ TeV



$\sim\ 20\ \sigma$

5σ excess luminosity

$\sim 1\ \text{fb}^{-1}$

$\sim 2\ \sigma$

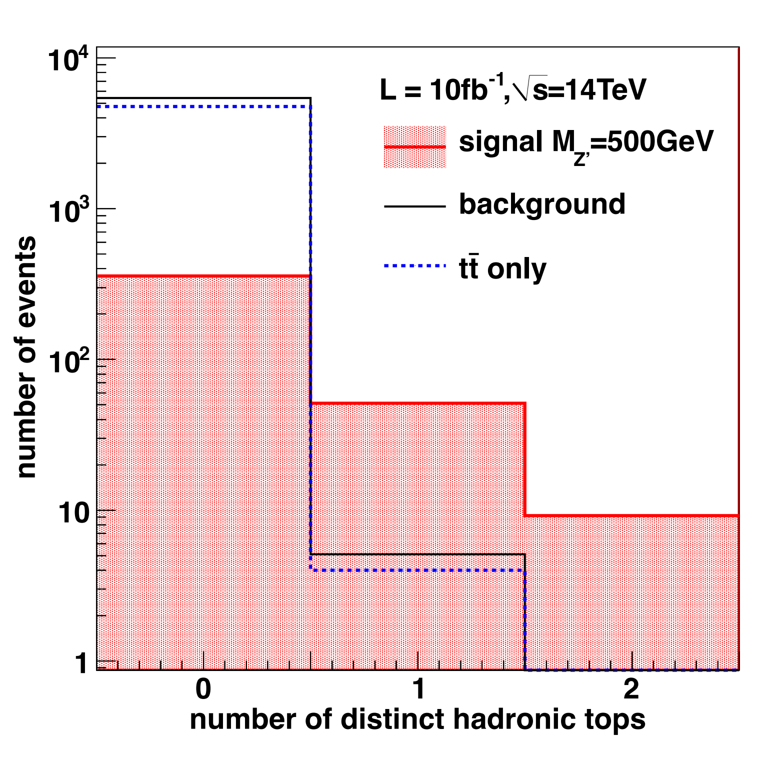
5σ excess luminosity

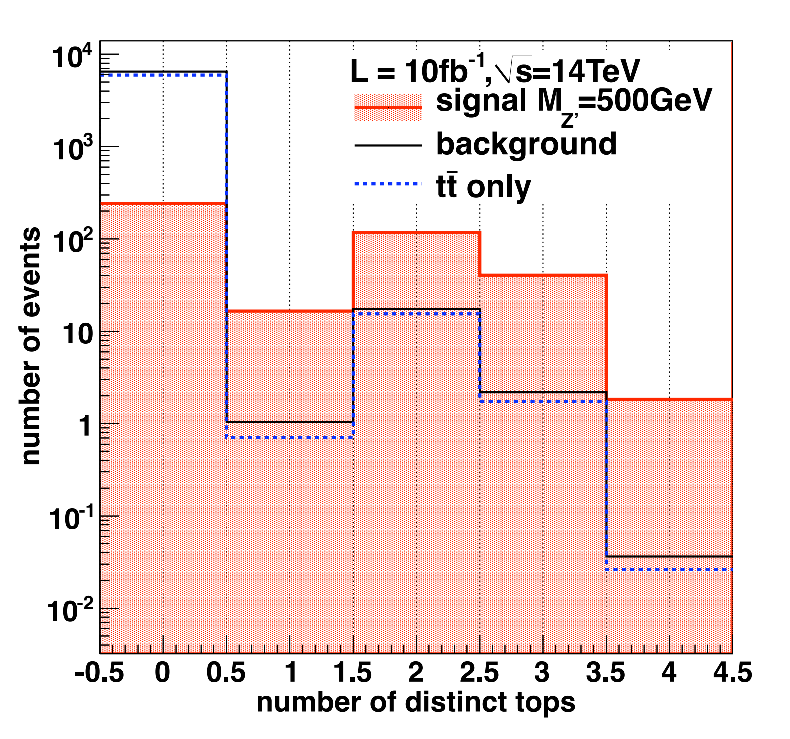
$\sim 45\ \text{fb}^{-1}$

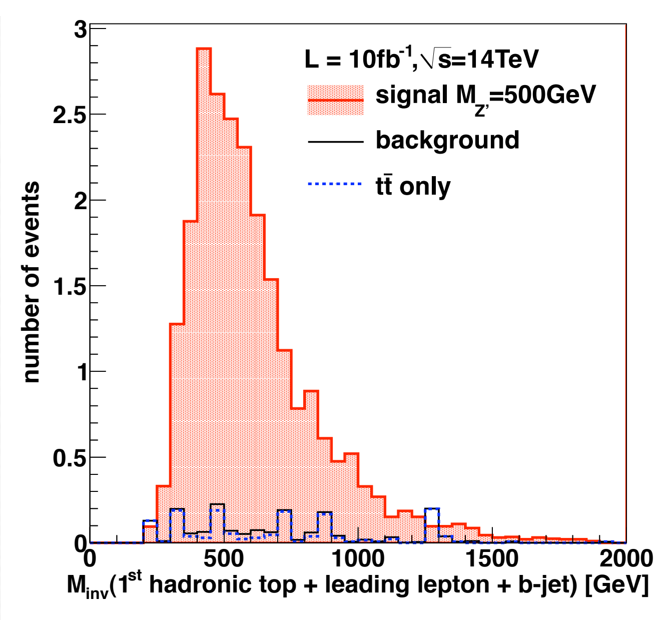
top reconstruction

With cut $nb_{jet} \geq 6$ and $nb_{bjet} \geq 3$:

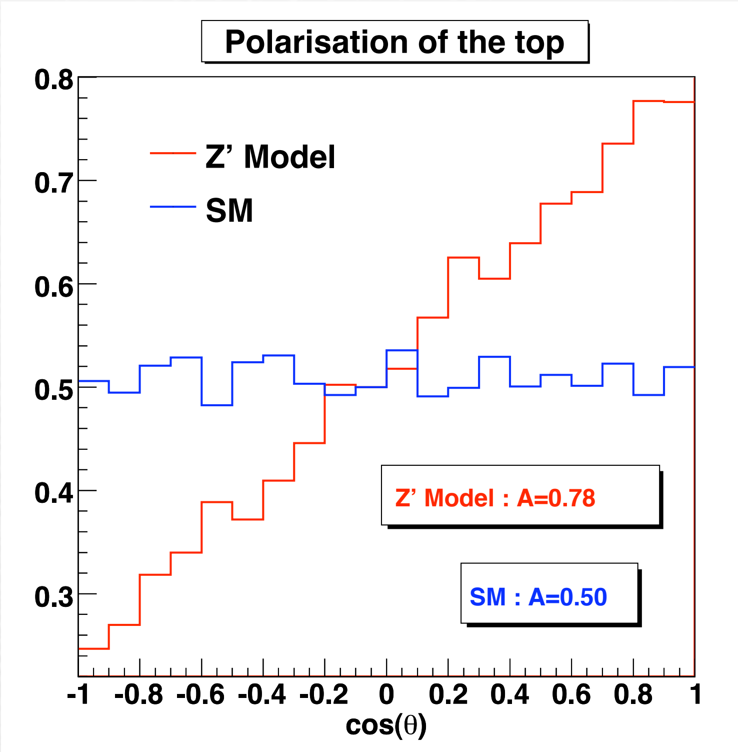
after finding the 2 leptonic tops

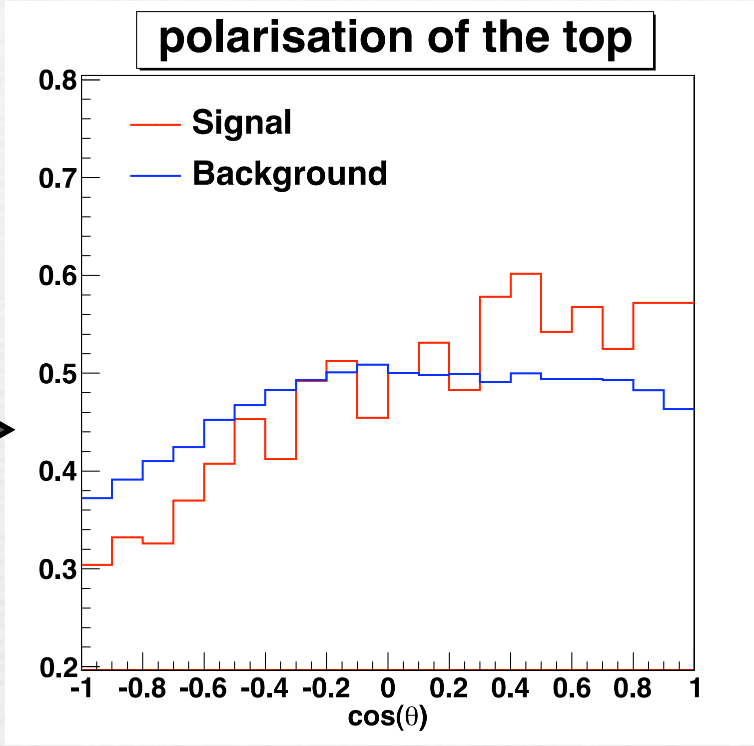






Back to top polarisation
(requires top momentum reconstruction)



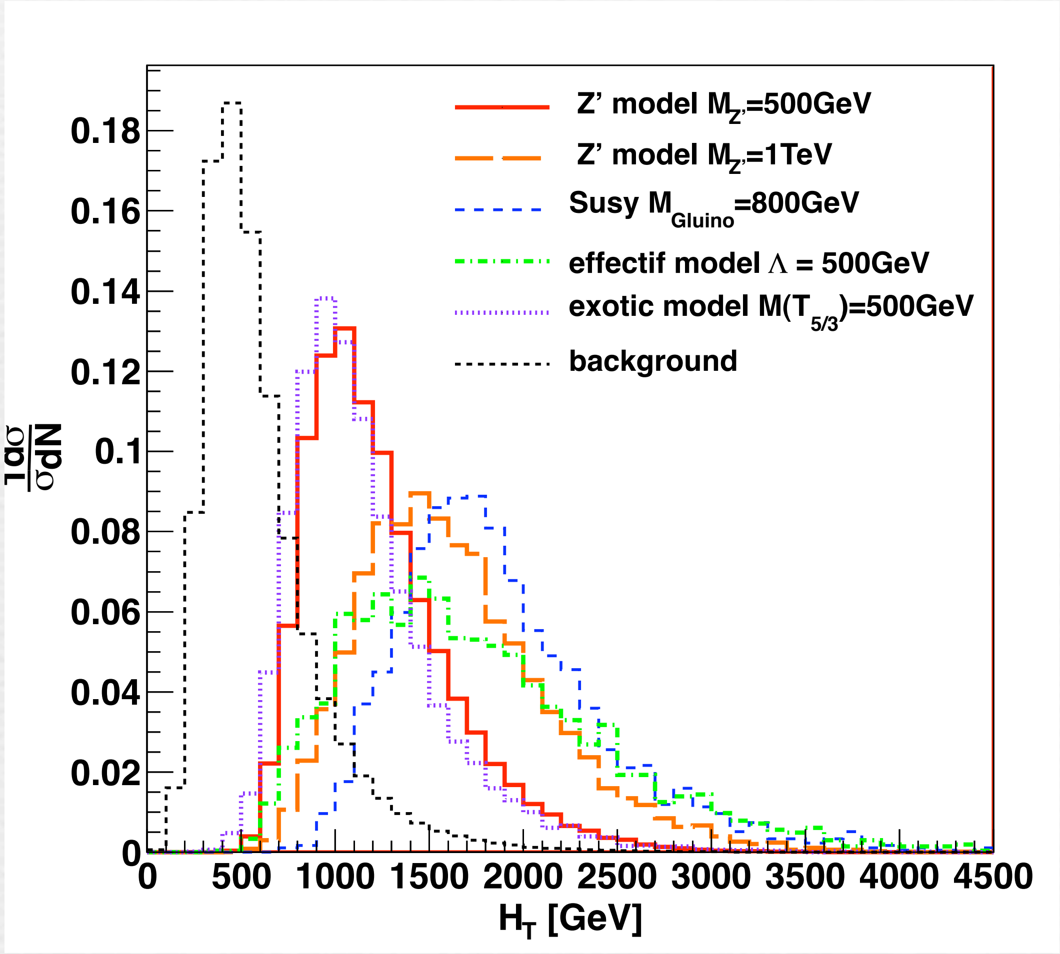


at generator level

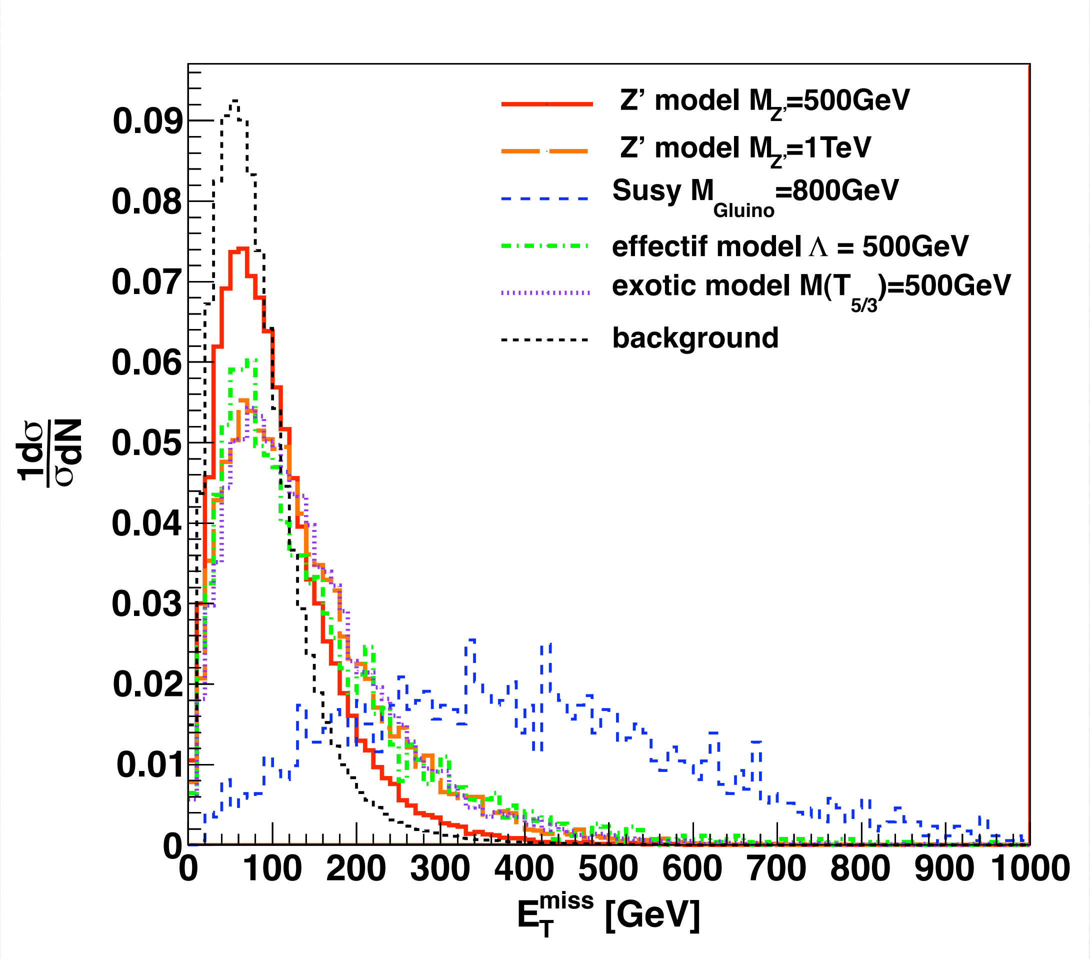
after top reconstruction

in 1-lepton channel

four-top events from different models

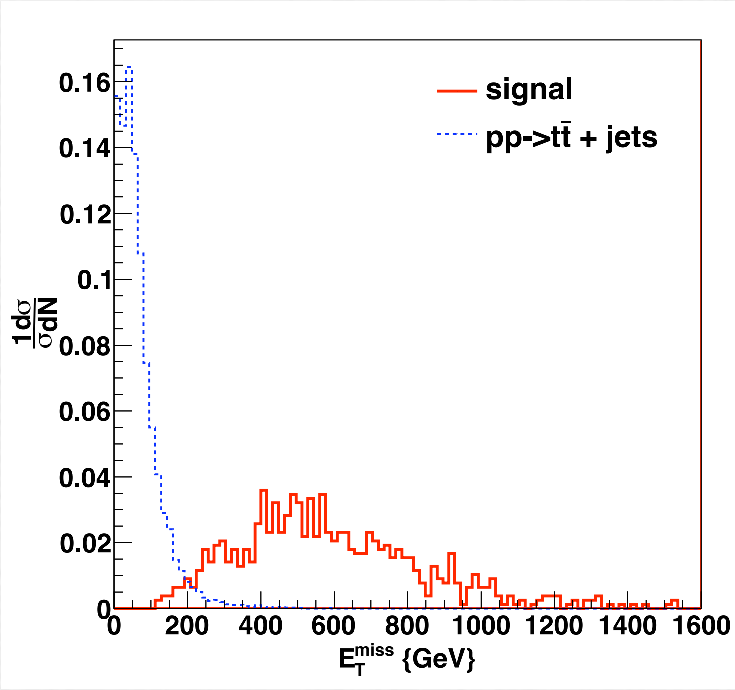


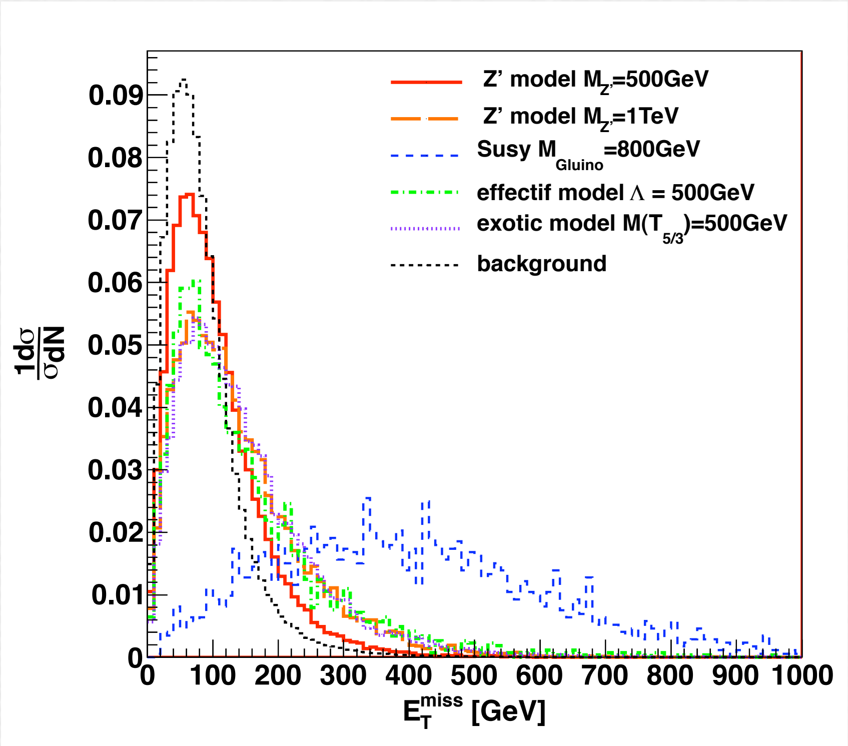
four-top events from gluino pair production is easily distinguishable



large E_Tmiss

four-top events from gluino pair production

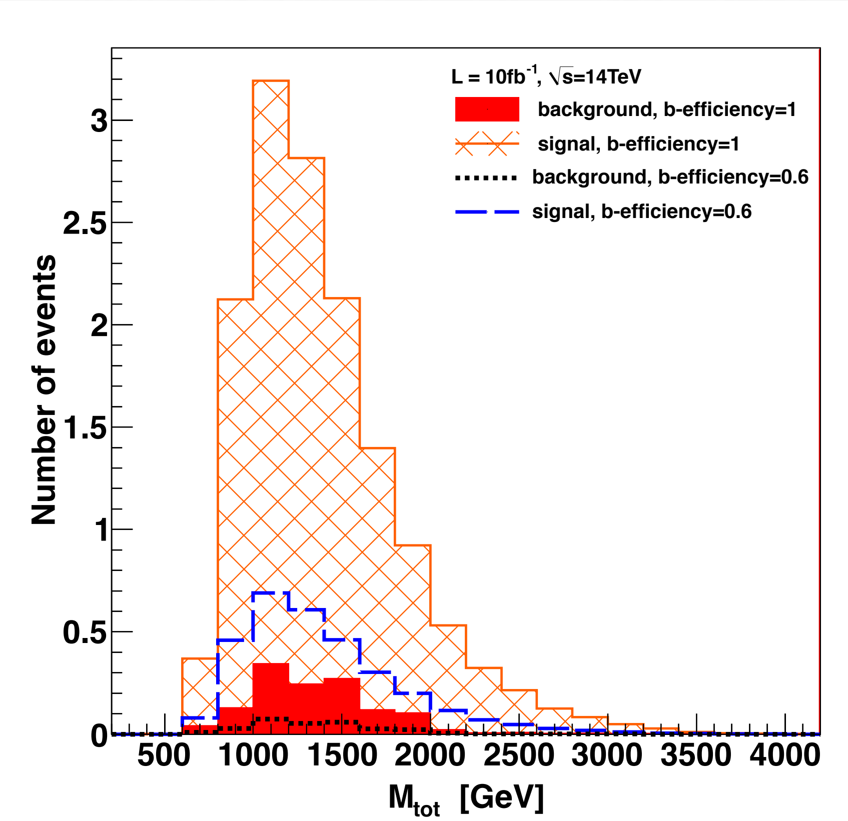




M=800 GeV

four-top events at 7 TeV

process	σ [fb]	$\sigma.BR(l^{\pm}l^{\pm})$ [fb]
signal m(Z')=500GeV	41	1.7
$tt\bar{t}\bar{t}$	0.74	0.031
$t\bar{t}$	93 142	42.7
$t\bar{t}$ + 1 jet	71 746	32.90
$t\bar{t}$ + 2 jets	37 190	17.06
$t\bar{t}$ + 3 jets	15 851	7.27
$t\bar{t}$ + 4 jets	4 215	1.93



$$nb_{jets} \geq 6,\ nb_{bjets} \geq 3,\ H_T > 500GeV$$

with 10 /fb:

S= 3

B= 0.3

The top quark-Dark Matter connection

if the WIMP hypothesis is correct: likely to be connected to the physics of EW symmetry breaking and Dark Matter may have enhanced couplings to massive states

A very simple effective theory

Jackson, Servant, Shaughnessy,Tait, Taoso,'09
see also Belanger-Pukhov-Servant '07

The WIMP is a Dirac fermion, ν , singlet under the SM,

charged under a new spontaneously broken U(1)'.

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + M^2_{Z'} Z'_\mu Z'^\mu + i\bar{\nu}\gamma^\mu D_\mu \nu + g^t_R \bar{t}\gamma^\mu P_R Z'^\mu t + \frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu}_Y$$

$$D^\mu \quad \equiv \quad \partial_\mu - i\left(g^\nu_R P_R + g^\nu_L P_L\right) Z'^\mu$$

The only SM particle charged under the Z' is the top quark

There is no SM state the WIMP can decay into: ν is stable.

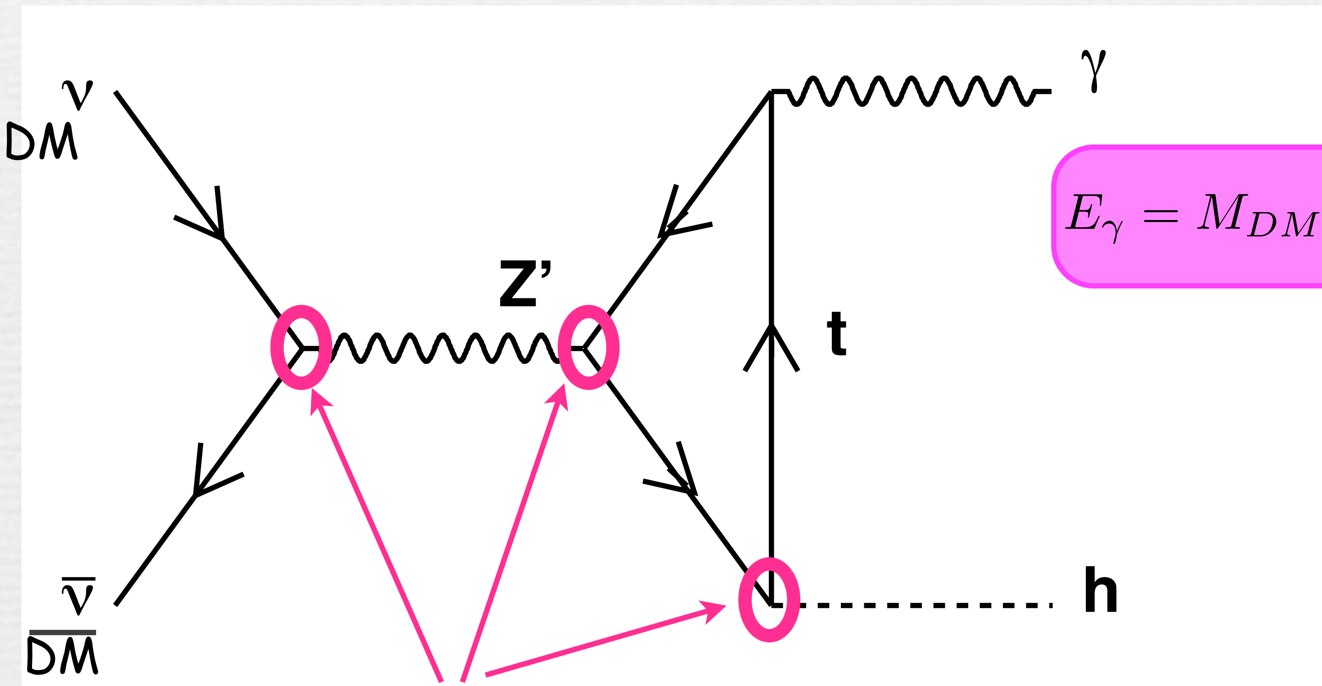
This model can be UV completed as an SO(10) RS model — Agashe_Servant '04

More generally, in models of partial fermion compositeness, natural to expect that only the top couples sizably to a new strongly interacting sector.

Seeing the light from Dark Matter

Jackson, Servant, Shaughnessy,Tait, Taoso,’09

Dirac Dark Matter annihilation into γ H

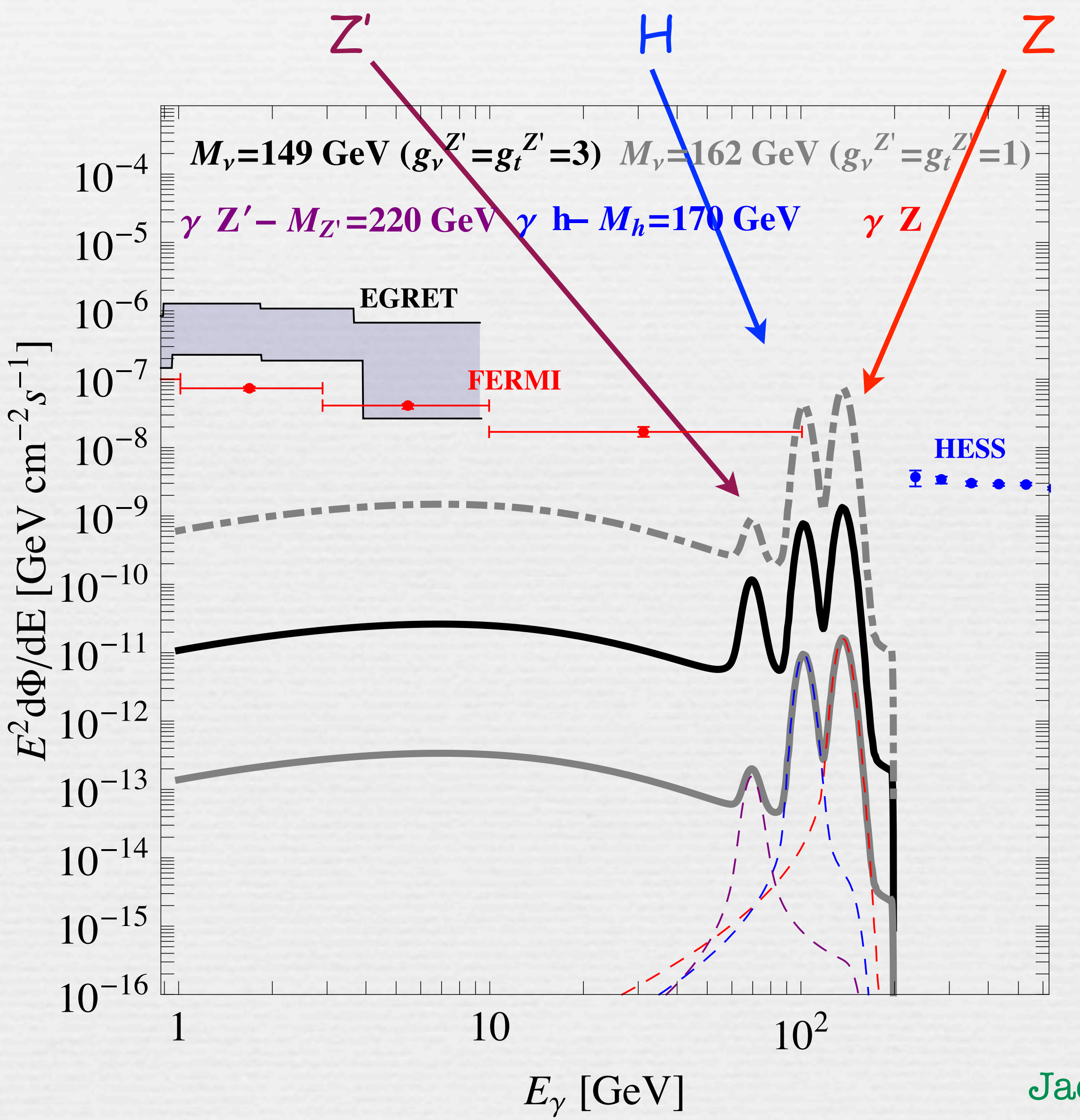


$$E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)$$

~ O(1) couplings

Higgs in Space!

γ-ray lines from the Galactic Center $\Delta\Omega = 10^{-5}$ sr



Spectra for parameters leading to correct relic density and satisfying direct detection constraints

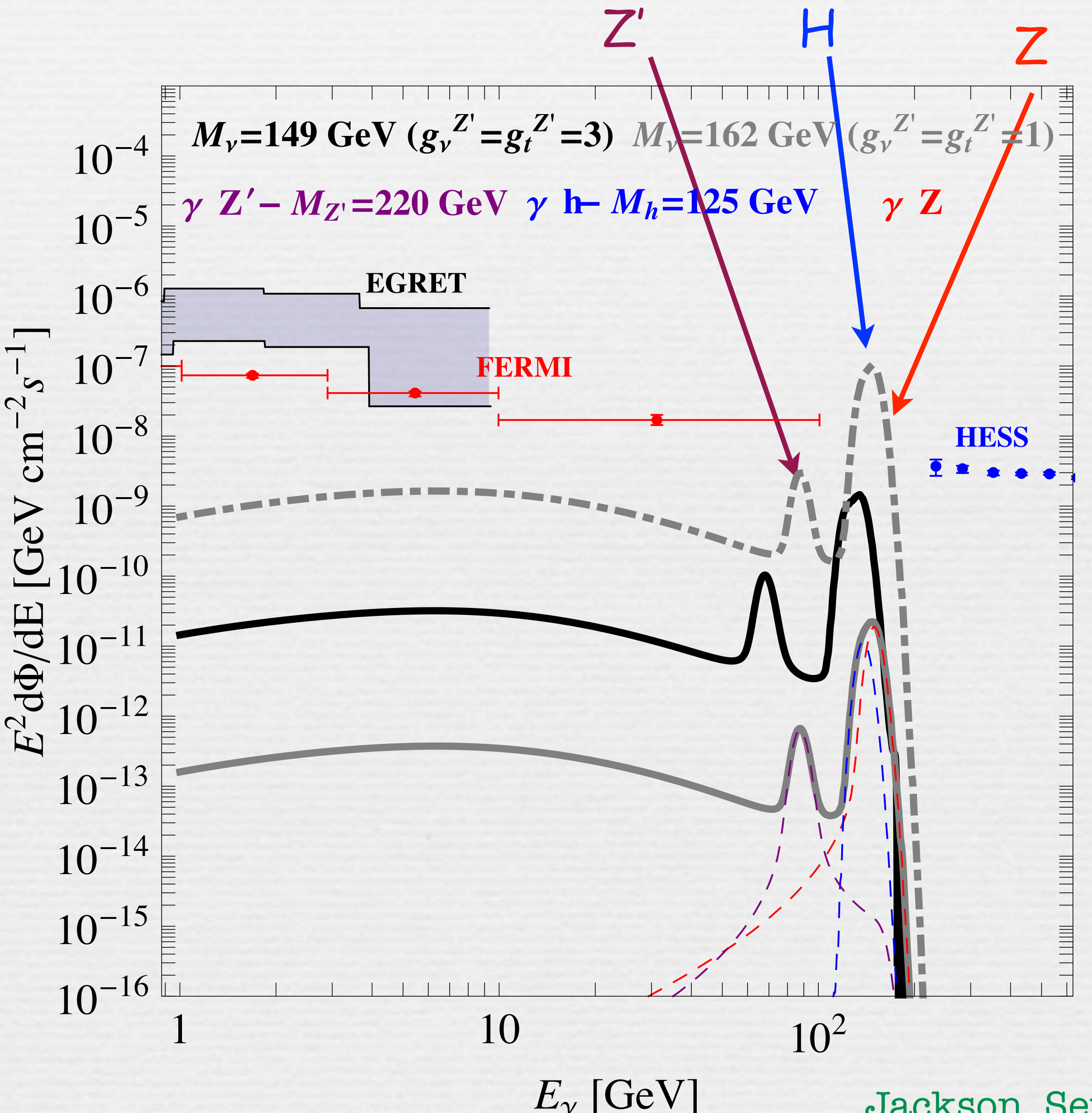
NFW profile

adiabatically contracted

Jackson, Servant, Shaughnessy,Tait, Taoso,'09 and a very recent claim ...

"A Tentative γ -Ray Line With E~ 130 GeV from Dark Matter Annihilation at the Fermi Large Area Telescope."

[Weniger 1204.2797]



The additional line due to Z' disappears if the Z' is heavier than 300 GeV

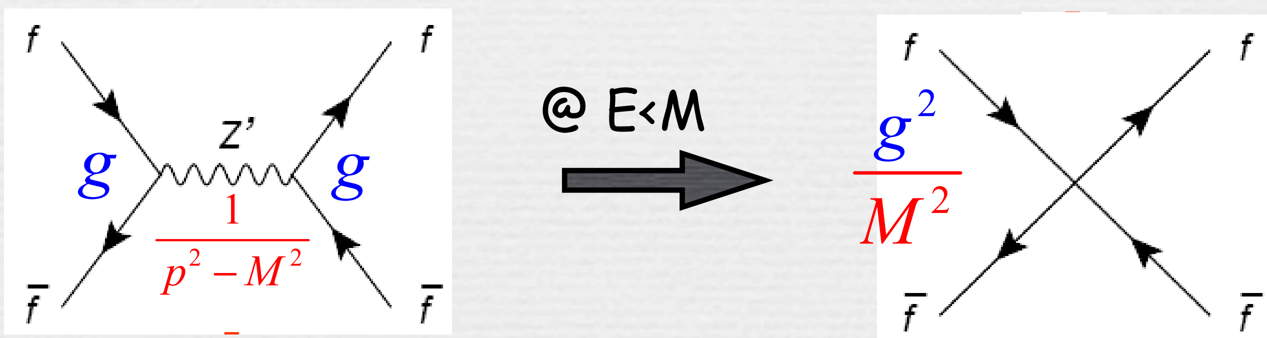
Jackson, Servant, Shaughnessy,Tait, Taoso,'09

If gauge resonances are heavier -> Effective Field Theory (EFT) approach

EW precision data together with constraints from flavour physics make plausible if not likely that there exists a mass gap between the SM degrees of freedom and any new physics threshold.

In this case, new physics can be integrated out and simply gives new (higher dimensional) interactions among the SM degrees of freedom

effective 4-fermion interaction



$$L = L_{SM} + \frac{g^2}{M^2}\bar{\psi}\psi\bar{\psi}\psi$$

$$\dim = 6$$

in the rest of the talk:

no bias on what the TeV new physics should be

Low-energy effective field theory approach to BSM

Buchmuller-Wyler '86

New interactions are assumed to respect all symmetries of the SM.

> 60 operators

$$L = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

$$\mathrm{dim} = \quad \leq 4 \qquad\qquad 6$$

Good news: Only a few operators contribute to top quark physics

Our goal:

study new physics in $t\bar{t}$ final state in the most general model-independent approach

Dimension 6 operators for top physics

Zhang & Willenbrock'10, Aguilar-Saavedra '10 , Degrande & al '10 ...

There are only 15 relevant operators:

CP-even

operator	process
$O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$	top decay, single top
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with real coefficient)	top decay, single top
$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$	single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi G} = \frac{1}{2}(\phi^+ \phi) G^A_{\mu\nu} G^{A\mu\nu}$	$gg \to t\bar{t}$
7 four-quark operators	$q\bar{q} \to t\bar{t}$

c_{hg}

c_{Vv}
c_{Aa}
c_{Av}

CP-odd

operator	process
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_{\tilde{G}} = g_s f_{ABC} \tilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi\tilde{G}} = \frac{1}{2}(\phi^+ \phi) \tilde{G}^A_{\mu\nu} G^{A\mu\nu}$	$gg \to t\bar{t}$

We will only consider those which affect top pair production **at tree level by interference with the SM** (QCD) amplitudes (we neglect weak corrections)

Dimension 6 operators for top physics

Zhang & Willenbrock'10, Aguilar-Saavedra '10 , Degrande & al '10

There are only 15 relevant operators:

top-philic operators: modifying top couplings and not only-gluon couplings

CP-even

operator	process
$O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$	top decay, single top
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}$ (with real coefficient)	top decay, single top
$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$	single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi G} = \frac{1}{2}(\phi^+\phi)G^A_{\mu\nu}G^{A\mu\nu}$	$gg \to t\bar{t}$
7 four-quark operators	$q\bar{q} \to t\bar{t}$

c_{hg}

c_{Vv} c_{Aa} c_{Av}

CP-odd

operator	process
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_{\tilde{G}} = g_s f_{ABC} \tilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi\tilde{G}} = \frac{1}{2}(\phi^+\phi)\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$gg \to t\bar{t}$

We will only consider those which affect top pair production **at tree level by interference with the SM** (QCD) amplitudes (we neglect weak corrections)

Effective Field Theory for Top Quark Pair production

Degrande & al '10

We calculate top pair production at order O(1/Λ^2)

$$|M|^2 = |M_{SM}|^2 + 2\Re(M_{SM}M^*_{NP}) + \mathscr{O}\left(\frac{1}{\Lambda^4}\right)$$

i.e. we assume new physics manifests itself at low energy only through operators interfering with the SM

We focus on top-philic new physics (and therefore ignore interactions that would only affect the standard gluon vertex $\mathcal{O}_G = f_{ABC}G^A_{\mu\nu}G^{B\,\nu\rho}G^{C\,\mu}_{\rho}$)

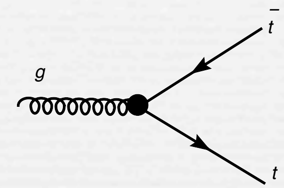
We are left with only two classes of dim-6 gauge invariant operators (when working at order O(1/Λ^2))

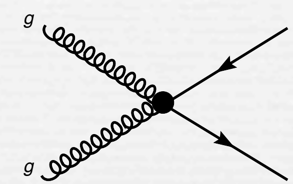
Effective Field Theory for Top Quark Pair production

We are left with only two classes of dim-6 gauge invariant operators (when working at order $O(1/\Lambda^2)$)

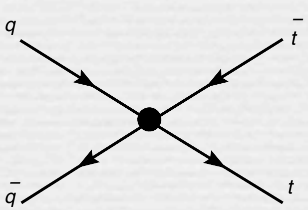
- op. with t, $\bar{t}$ and one or two gluons (chromomagnetic moment)

$$\mathcal{O}_{hg} = \left[\left(H\bar{Q}\right)\sigma^{\mu\nu}T^A t\right] G^A_{\mu\nu}$$





- 4-fermion op.



$\bar{L}L\bar{L}L$:

$$\mathcal{O}^{(8)}_{Qu} = \left(\bar{Q}\gamma^\mu T^A Q\right)\left(\bar{u}\gamma_\mu T^A u\right),$$
$$\mathcal{O}^{(8)}_{Qd} = \left(\bar{Q}\gamma^\mu T^A Q\right)\left(\bar{d}\gamma_\mu T^A d\right),$$
$$\mathcal{O}^{(8)}_{tq} = \left(\bar{q}\gamma^\mu T^A q\right)\left(\bar{t}\gamma_\mu T^A t\right),$$

$\bar{R}R\bar{R}R$:

$$\mathcal{O}^{(8)}_{tu} = \left(\bar{t}\gamma^\mu T^A t\right)\left(\bar{u}\gamma_\mu T^A u\right),$$
$$\mathcal{O}^{(8)}_{td} = \left(\bar{t}\gamma^\mu T^A t\right)\left(\bar{d}\gamma_\mu T^A d\right),$$

$\bar{L}L\bar{R}R$:

$$\mathcal{O}^{(8,1)}_{Qq} = \left(\bar{Q}\gamma^\mu T^A Q\right)\left(\bar{q}\gamma_\mu T^A q\right),$$
$$\mathcal{O}^{(8,3)}_{Qq} = \left(\bar{Q}\gamma^\mu T^A \sigma^I Q\right)\left(\bar{q}\gamma_\mu T^A \sigma^I q\right),$$

$\bar{L}R\bar{L}R$:

$$\mathcal{O}^{(8)}_{d} = \left(\bar{Q}T^A t\right)\left(\bar{q}T^A d\right),$$

: negligible (QCD is chirality diagonal)

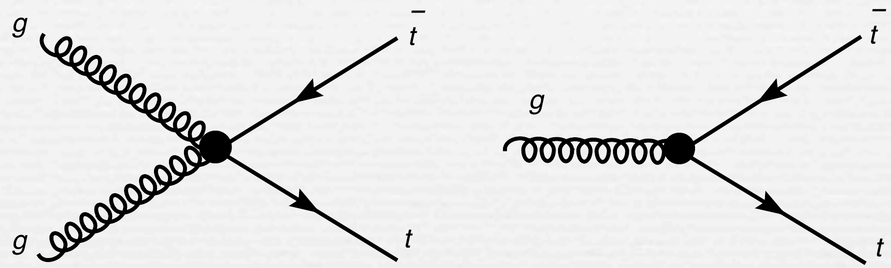
however only 7 independent operators

top pair production in EFT at order $O(1/\Lambda^2)$

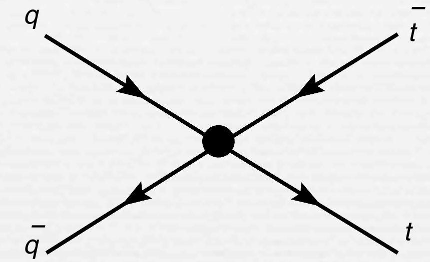
we assume new physics manifests itself at low energy only through operators interfering with the SM

$$|M|^2 = |M_{SM}|^2 + 2\Re(M_{SM}M_{NP}^*) + \mathscr{O}\left(\frac{1}{\Lambda^4}\right)$$

New vertices:

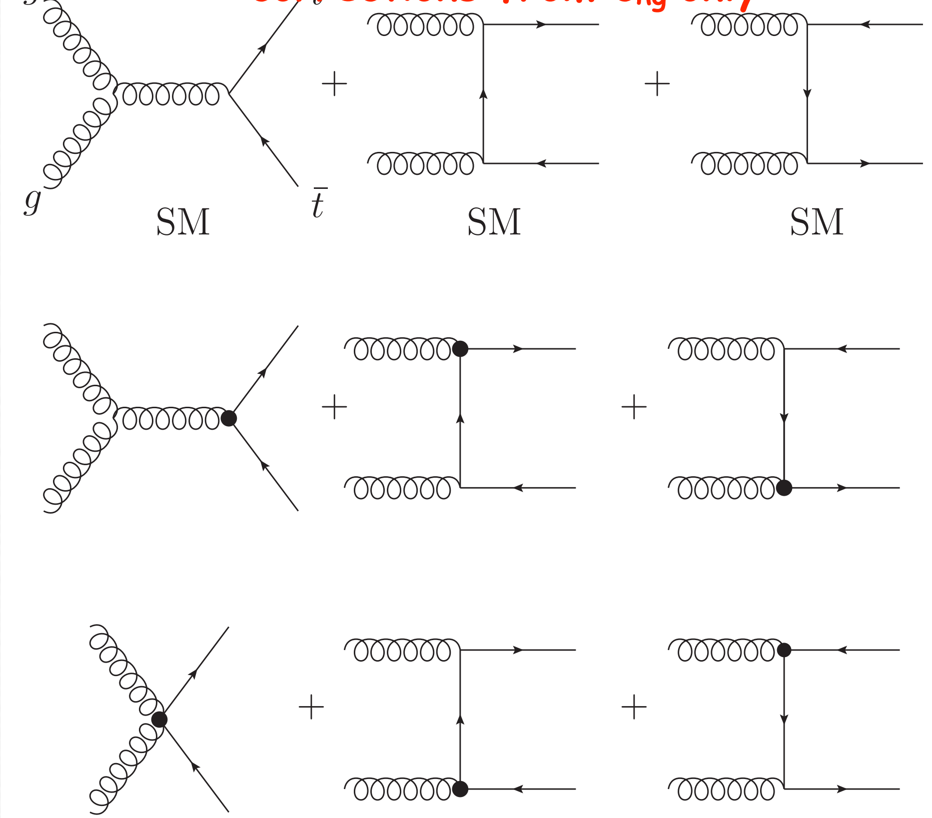


Chromomagnetic operator $\mathcal{O}_{hg} = (H\bar{Q})\sigma^{\mu\nu}T^A t\, G^A_{\mu\nu}$

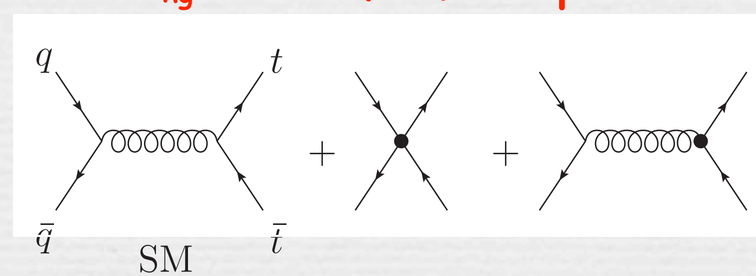


Four-fermion operators

top pair production from gluon fusion: corrections from c_{hg} only



top pair production from q anti-q annihilation: corrections from both c_{hg} and 4-fermion operators



gluon fusion (contribution from one operator only)

The new physics and SM contributions for gluon fusion have a common factor

$$\frac{d\sigma}{dt}(gg \to t\bar{t}) = \frac{d\sigma_{SM}}{dt} + \sqrt{2}\alpha_s g_s \frac{v m_t}{s^2}\frac{c_{hg}}{\Lambda^2}\left(\frac{1}{6\tau_1\tau_2} - \frac{3}{8}\right)$$

$$\frac{d\sigma_{SM}}{dt}(gg \to t\bar{t}) = \frac{\pi\alpha_s^2}{s^2}\left(\frac{1}{6\tau_1\tau_2} - \frac{3}{8}\right)(\rho + \tau_1^2 + \tau_2^2 - \frac{\rho^2}{4\tau_1\tau_2})$$

Common factor mainly responsible for the shape of the distributions

$$\tau_1 = \frac{m_t^2 - t}{s}, \quad \tau_2 = \frac{m_t^2 - u}{s}, \quad \rho = \frac{4m_t^2}{s}$$

t: Mandelstam variable related to θ angle

(between incoming parton and outgoing top quark)

$$m_t^2 - t = \frac{s}{2}(1 - \beta\cos\theta)$$

The operator O_{hg} can hardly be distinguished from the SM in gluon fusion

Distortions in the shape of the distributions can only come from $q\,\bar{q}$ annihilation → small effect at LHC

$q\,\bar{q}$ annihilation (contribution from the 8 operators)

Only two linear combinations of 4-fermion operators actually contribute to the differential cross section after averaging over the final state spins

some vector combination of operators that is symmetric under q <-> $\bar{q}$

some axial combination of operators is asymmetric under q <-> $\bar{q}$

$$\frac{d\sigma}{dt}(q\bar{q}\to t\bar{t}) = \frac{d\sigma_{SM}}{dt}\left(1+\frac{c_{Vv}\pm\frac{c'_{Vv}}{2}}{g_s^2}\frac{s}{\Lambda^2}\right)+\frac{1}{\Lambda^2}\frac{\alpha_s}{9s^2}\left(\left(c_{Aa}\pm\frac{c'_{Aa}}{2}\right)s(\tau_2-\tau_1)+4g_s c_{hg}\sqrt{2}vm_t\right)$$

even part in the scattering angle θ comes from $\bar{t}\gamma^\mu T^A t\bar{q}\gamma^\mu T^A q$

odd part in the scattering angle θ comes from $\bar{t}\gamma^\mu\gamma_5 T^A t\bar{q}\gamma^\mu\gamma_5 T^A q$

This dependence vanishes after integration over t

vector combination of the light quarks involving the RH and LH top quarks

axial combination of the light quarks involving the RH and LH top quarks

$$c_{Vv} = c_{Rv} + c_{Lv} \qquad \longleftarrow\text{u+d}\longrightarrow \qquad c_{Aa} = c_{Ra} - c_{La}$$

$$c'_{Vv} = (c_{tu}-c_{td})/2 + (c_{Qu}-c_{Qd})/2 + c_{Qq}^{(8,3)} \qquad \longleftarrow\text{u-d}\longrightarrow \qquad c'_{Av} = (c_{tu}-c_{td})/2 - (c_{Qu}-c_{Qd})/2 - c_{Qq}^{(8,3)}$$

$$\text{with}\quad \begin{cases} c_{Rv} = c_{tq}/2 + (c_{tu}+c_{td})/4 \\ c_{Lv} = c_{Qq}^{(8,1)}/2 + (c_{Qu}+c_{Qd})/4 \end{cases}$$

$$\text{with}\quad \begin{cases} c_{Ra} = -c_{tq}/2 + (c_{tu}+c_{td})/4 \\ c_{La} = -c_{Qq}^{(8,1)}/2 + (c_{Qu}+c_{Qd})/4. \end{cases}$$

total cross section

Tevatron

$$\sigma\left(pp\to t\bar{t}\right)/\mathrm{pb} \;=\; 6.15^{+2.41}_{-1.61} + \left[\left(0.87^{+0.23}_{-0.16}\right) c_{Vv} + \left(1.44^{+0.47}_{-0.33}\right) c_{hg} + \left(0.31^{+0.08}_{-0.06}\right) c'_{Vv}\right]\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 .$$

LHC 7 TeV

$$\sigma\left(pp\to t\bar{t}\right)/\mathrm{pb} = 94^{+22}_{-17} + \left[\left(4.5^{+0.7}_{-0.6}\right) c_{Vv} + \left(25^{+7}_{-5}\right) c_{hg} + \left(0.48^{+0.068}_{-0.056}\right) c'_{Vv}\right]\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

LHC 14 TeV

$$\sigma\left(pp\to t\bar{t}\right)/\mathrm{pb} \;=\; 538^{+162}_{-115} + \left[\left(15^{+2}_{-1}\right) c_{Vv} + \left(144^{+34}_{-25}\right) c_{hg} + \left(1.32^{+0.12}_{-0.12}\right) c'_{Vv}\right]\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 .$$

u+d (isospin 0)

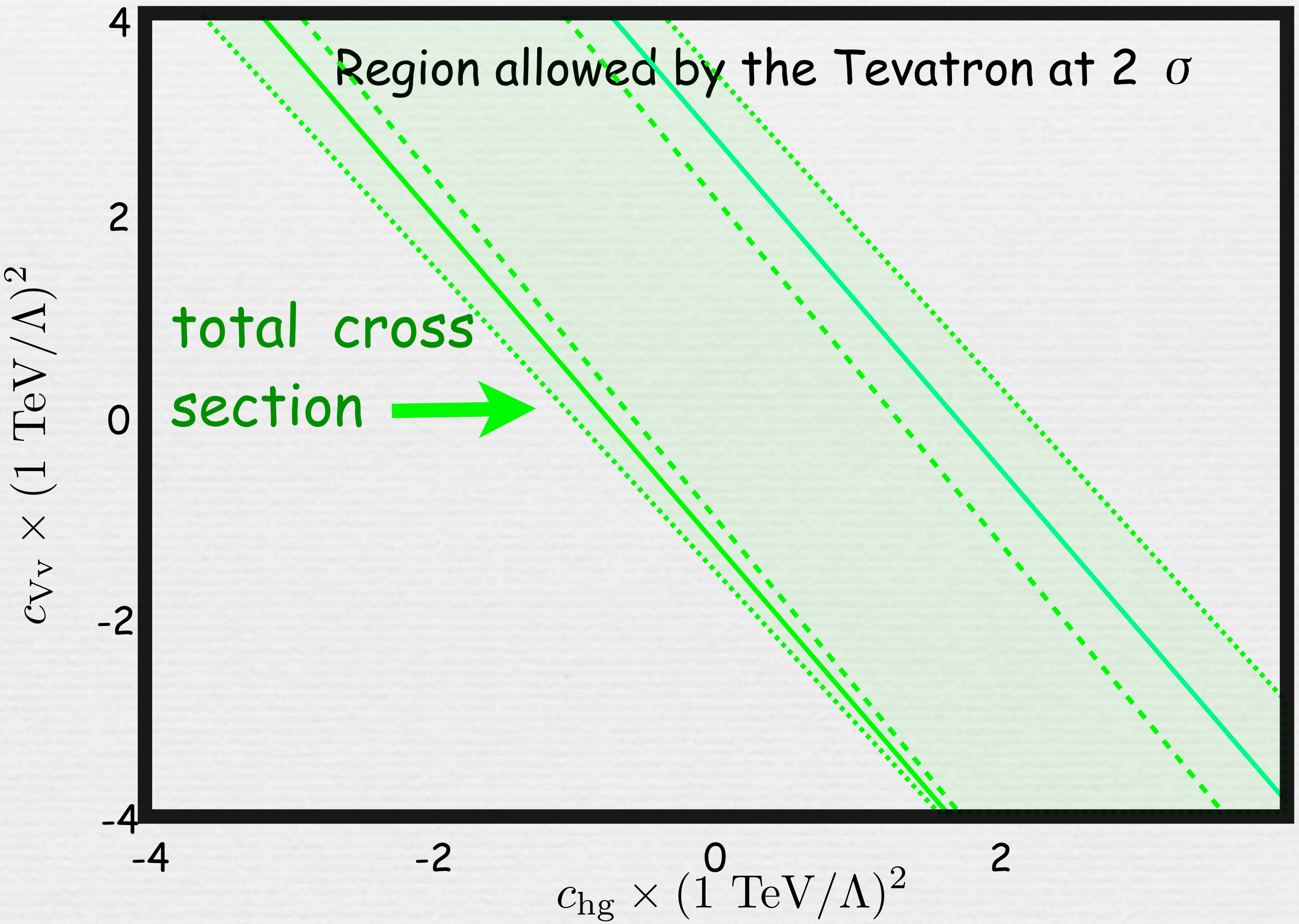
chromo magnetic moment

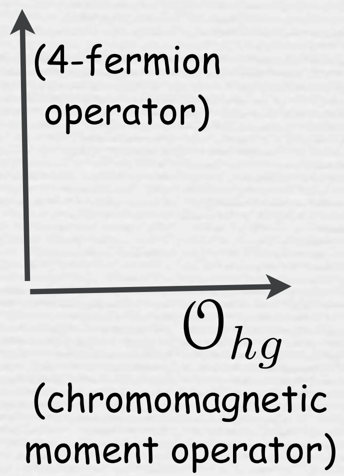
u-d (isospin 1)

LO with CTEQ6L1 pdfs
In fits, we'll use NLO+NLL SM results but in interference, we'll keep LO SM amplitude

Tevatron constraints

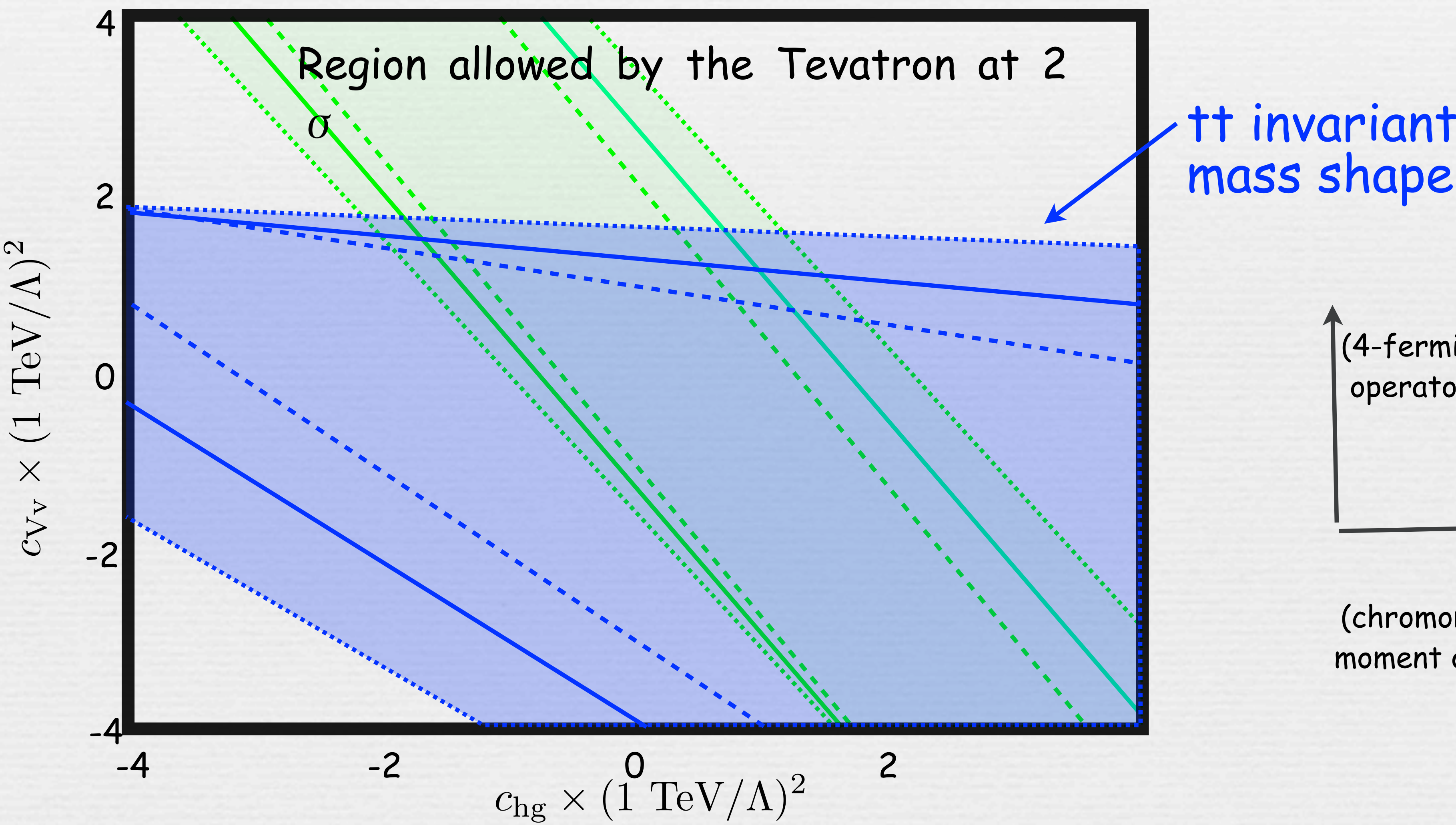
The $p\bar{p}$ -> $t\bar{t}$ total cross section at Tevatron depends on both c_{hg} and c_{Vv} and constrains thus a combination of these parameters.

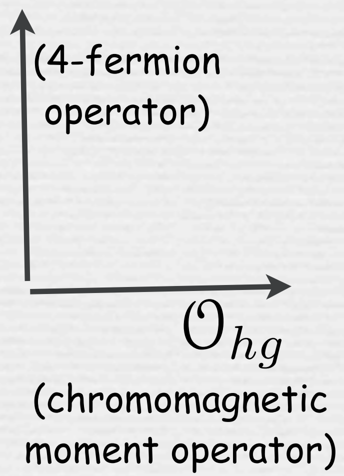




Tevatron constraints

The $p\bar{p} \rightarrow t\bar{t}$ total cross section at Tevatron depends on both c_{hg} and c_{V_v} and constrains thus a combination of these parameters.

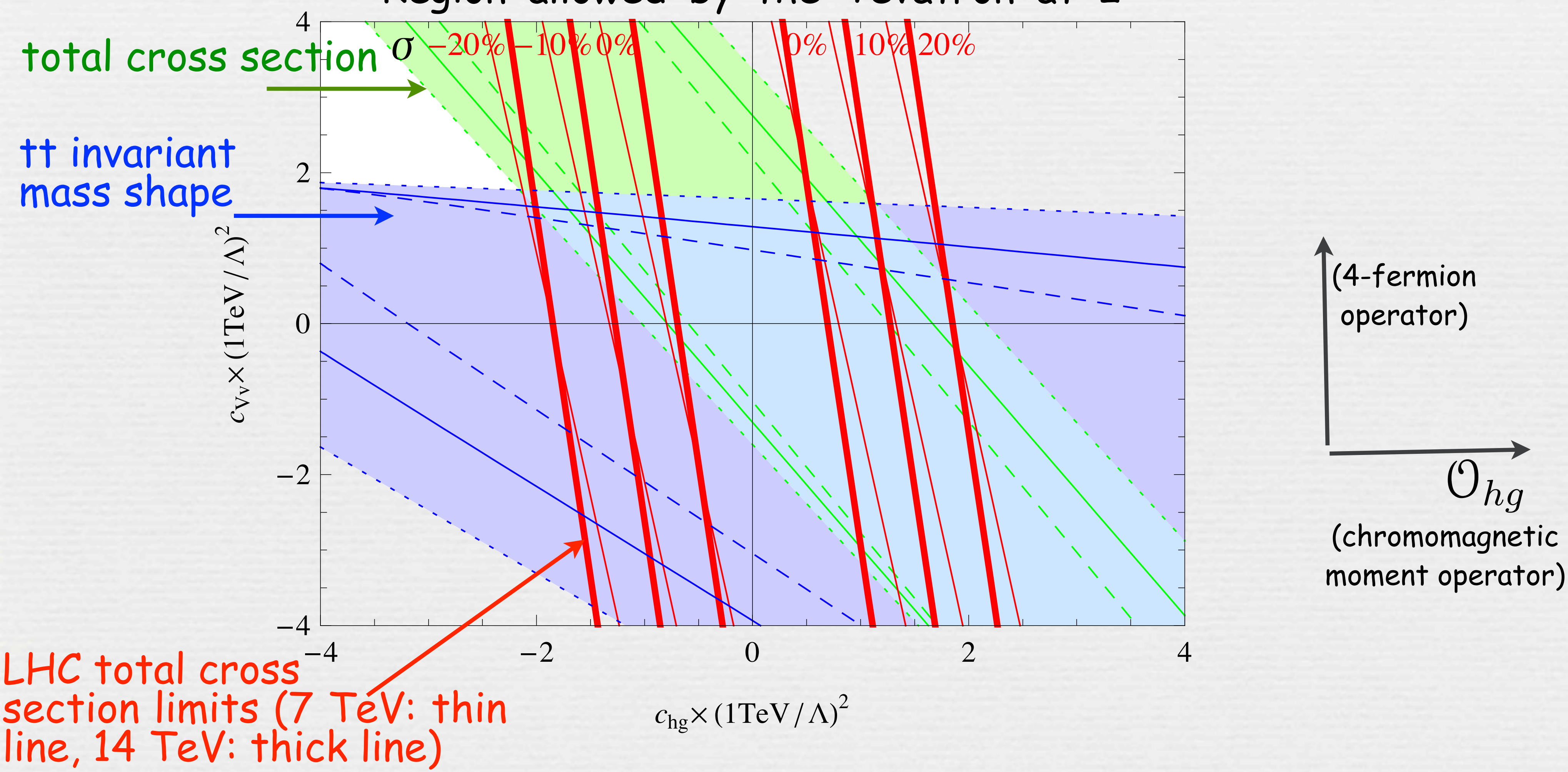




The LHC - Tevatron complementarity

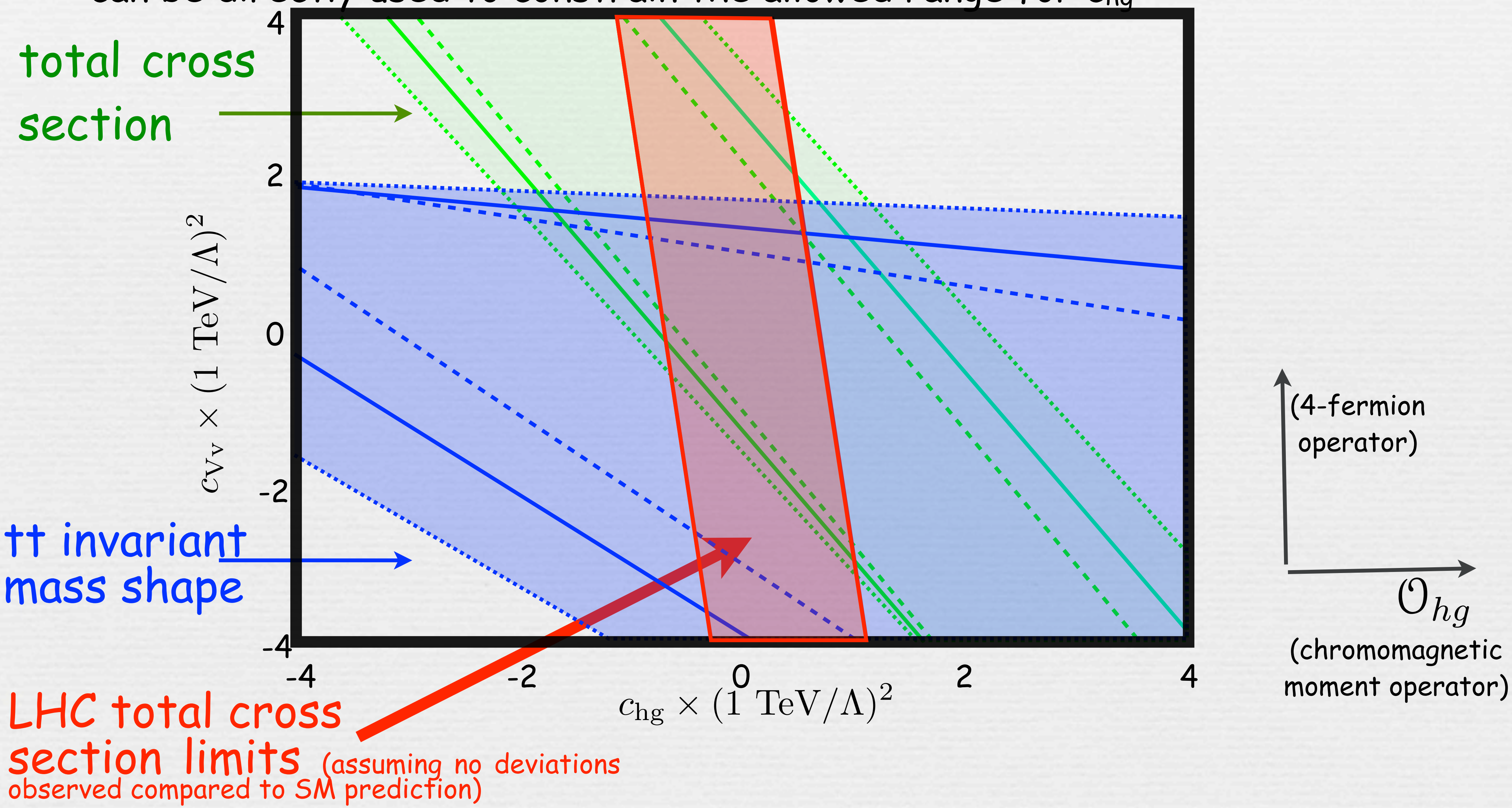
- The Tevatron cross section depends on both c_{hg} and c_{Vv} and constrains thus a combination of these parameters.
- At the LHC, the pp -> $t\bar{t}$ total cross section mostly depends on c_{hg} and can be directly used to constrain the allowed range for c_{hg}

Region allowed by the Tevatron at 2



The LHC - Tevatron complementarity

- The Tevatron cross section depends on both c_{hg} and c_{Vv} and constrains thus a combination of these parameters.
- At the LHC, the pp -> $t\bar{t}$ total cross section mostly depends on c_{hg} and can be directly used to constrain the allowed range for c_{hg}

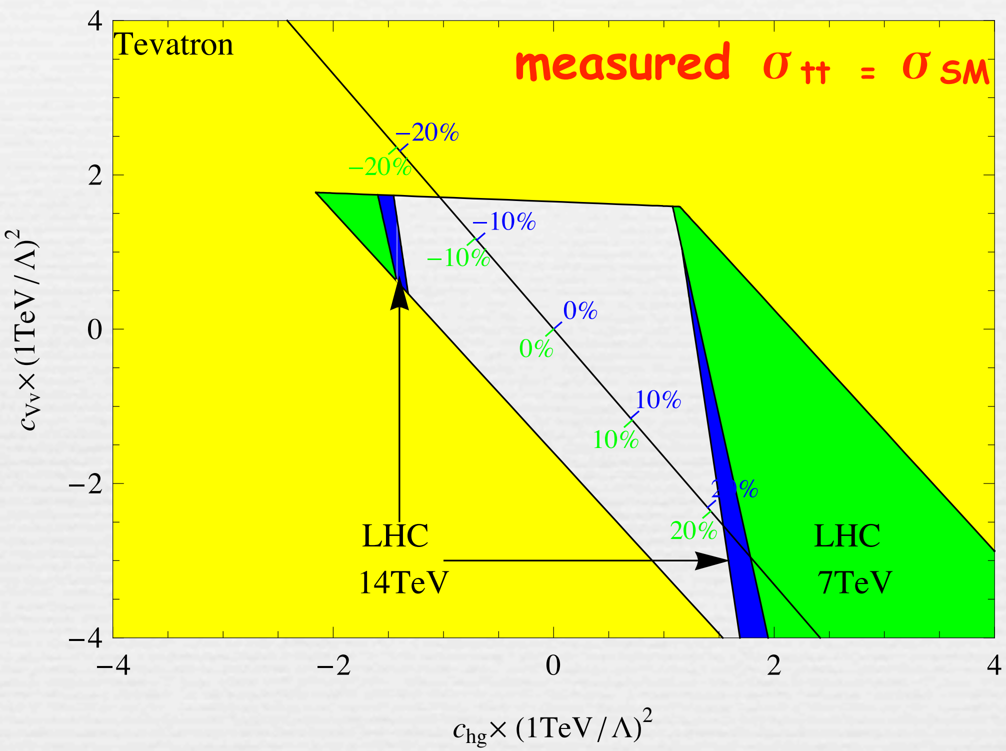


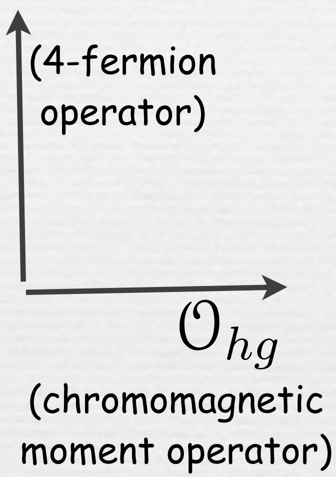
Constraining Non-resonant New Physics in top pair production

[Degrande, Maltoni, Gérard, Grojean, Servant'10]

yellow region is excluded by Tevatron

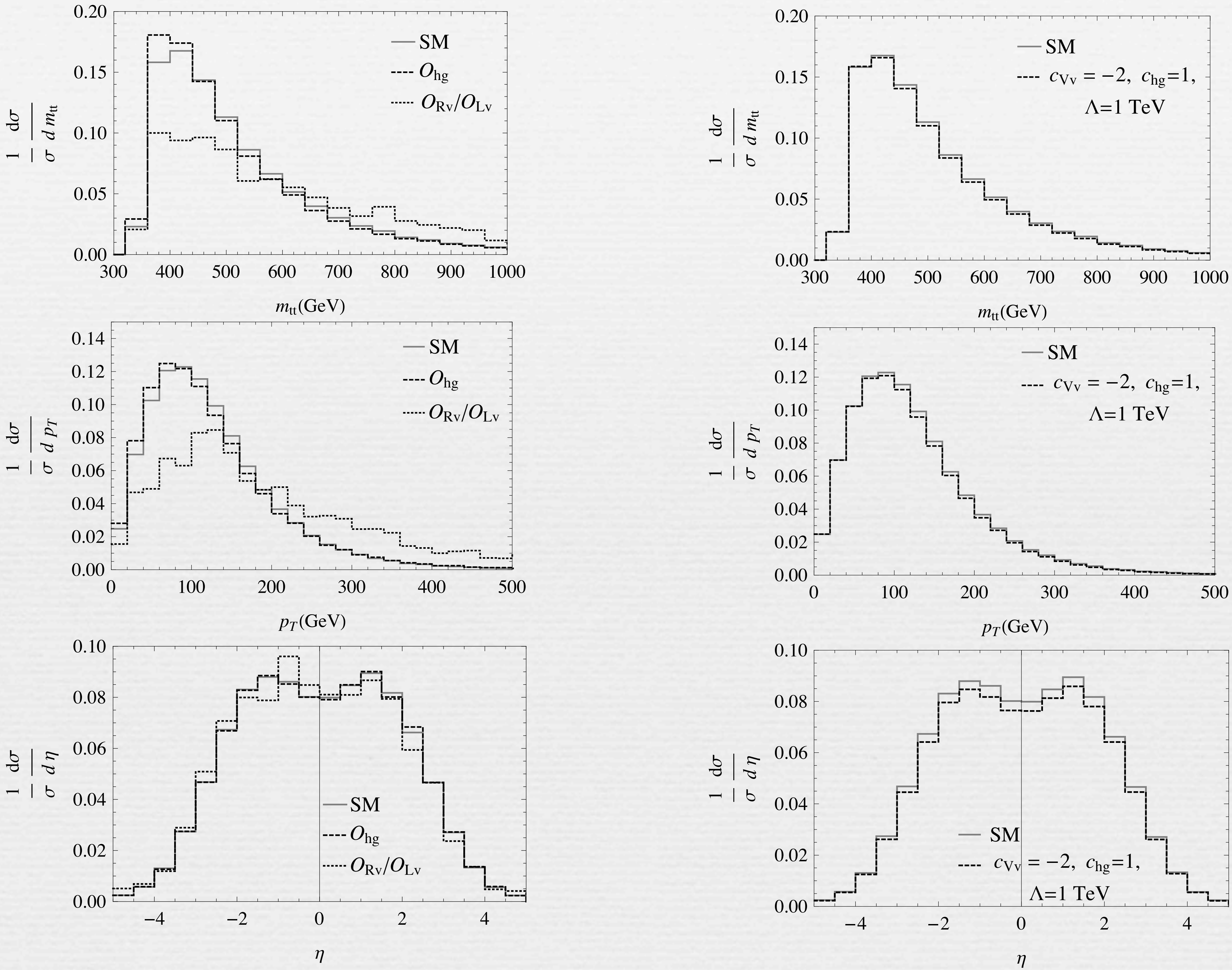
green (blue) region excluded by LHC at 7 TeV (14 TeV) after a precision of 10% is reached on σ_{tt}





A 10% uncertainty on the total cross section at the LHC already rules out a large region of parameter space

Minor effect on shapes of distributions at the LHC



Domain of validity of results

1) when O(1/Λ^4) terms are subdominant

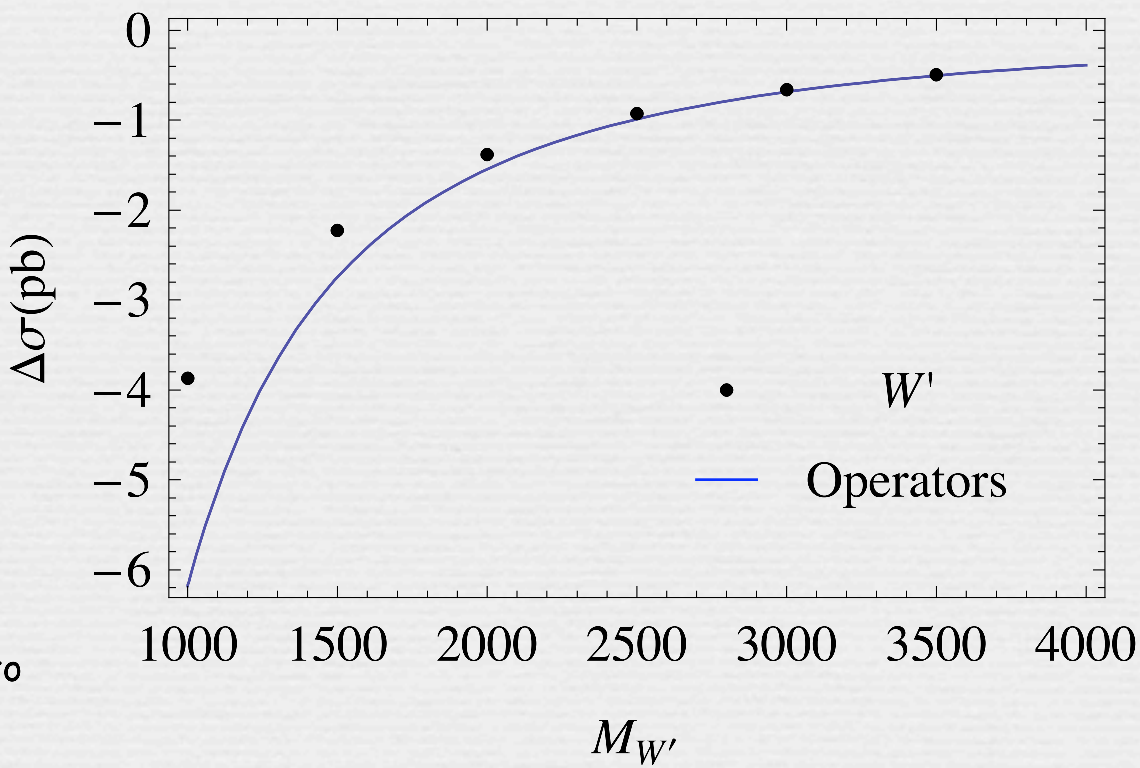
At the Tevatron, our results apply to a region of parameter space bounded by

$$|c_i|\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \lesssim 7$$

At the LHC, since the center of mass energy is larger, the reliable region shrinks to $|c_{hg}|\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \lesssim 3$ and $|c_{Vv}|\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \lesssim 2$

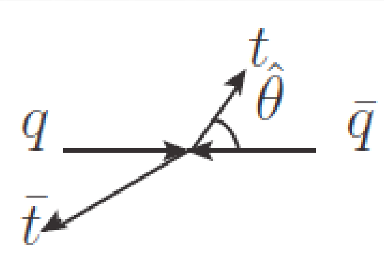
2) For which typical mass scale does the effective field theory treatment apply?

-> ~ 1.5 TeV



correction to SM cross section at the LHC due to a W' and comparison with EFT computation

Effective Field Theory Approach to the Forward-Backward asymmetry



$$A_{FB} \equiv \frac{\sigma\left(\cos\theta_t > 0\right) - \sigma\left(\cos\theta_t < 0\right)}{\sigma\left(\cos\theta_t > 0\right) + \sigma\left(\cos\theta_t < 0\right)}$$

$$A_{FB}^{\rm SM} = 0.05 \pm 0.015. \qquad\qquad A_{FB}^{\rm EXP} = 0.15 \pm 0.05({\rm stat}) \pm 0.024({\rm syst}),$$

-> top quarks are preferentially emitted in the direction of the incoming quark

$$\frac{d\sigma}{dt}(q\bar{q} \to t\bar{t}) = \frac{d\sigma_{SM}}{dt}\left(1 + \frac{c_{Vv} \pm \frac{c'_{Vv}}{2}}{g_s^2}\frac{s}{\Lambda^2}\right) + \frac{1}{\Lambda^2}\frac{\alpha_s}{9s^2}\left(\left(c_{Aa} \pm \frac{c'_{Aa}}{2}\right)s(\tau_2 - \tau_1) + 4g_s c_{hg}\sqrt{2}vm_t\right)$$

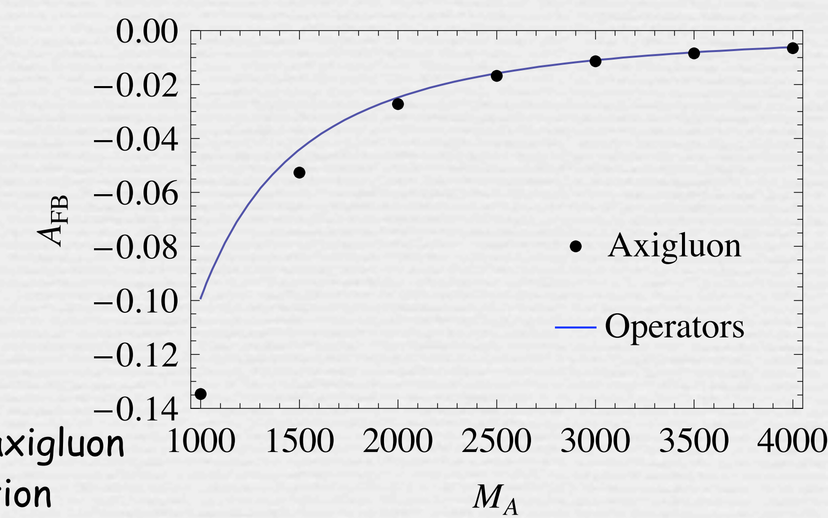
$$\delta A_{FB}^{\dim 6} = \left(0.0342^{+0.016}_{-0.009}\, c_{Aa} + 0.0128^{+0.0064}_{-0.0036}\, c'_{Aa}\right) \times \left(\frac{1\ {\rm TeV}}{\Lambda}\right)^2$$

[Degrande, Maltoni, Gérard, Grojean, Servant'10]

C_{Aa} and C'_{Aa} are only constrained by the asymmetry and not by the total cross section or the invariant mass distribution

Link to axigluon models:

$$c_{Aa}/\Lambda^2 = -2g_A^q g_A^t/m_A^2$$



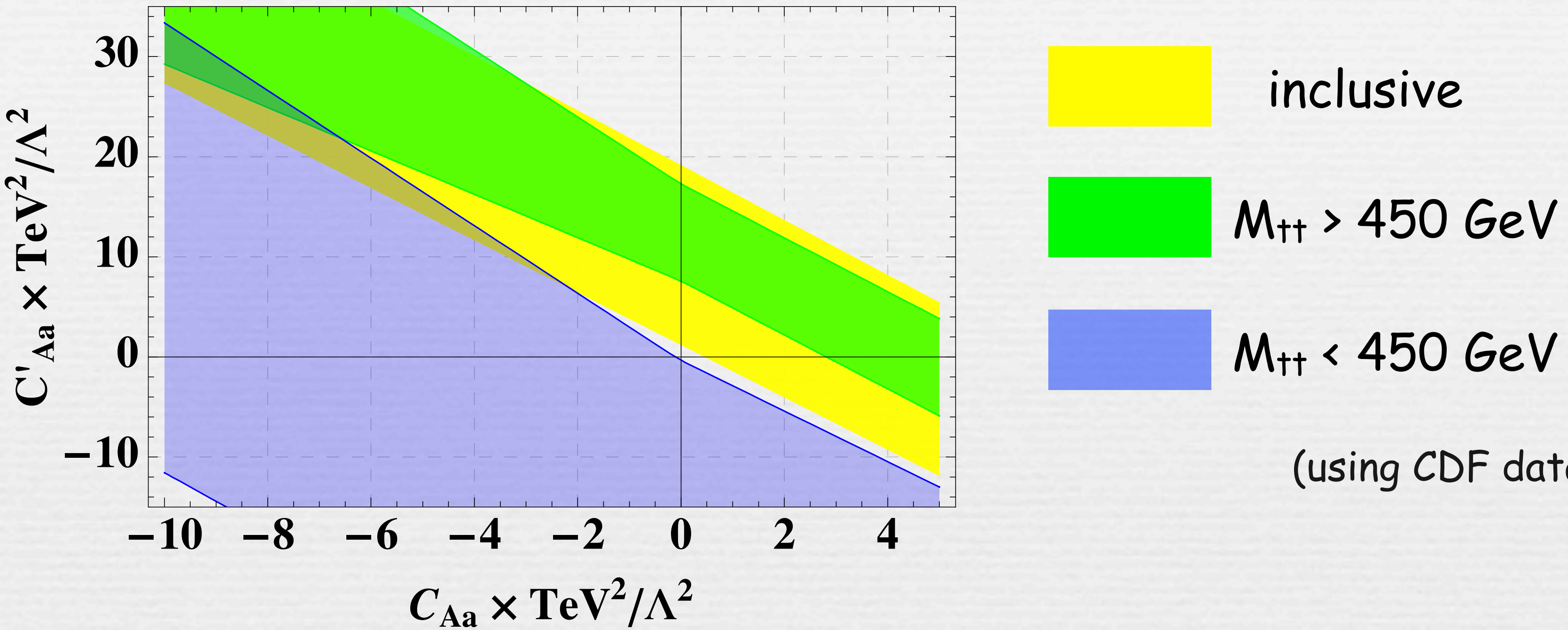
AFB prediction at the Tevatron due to an axigluon and comparison with the EFT computation

Most general expression at order $O(\Lambda^{-2})$

$$\delta A(m_{t\bar{t}} < 450\ \text{GeV}) = \left(0.023^{+3}_{-1} c_{Aa} + 0.0081^{+6}_{-4} c'_{Aa}\right)\left(\frac{1\ \text{TeV}}{\Lambda}\right)^2,$$

[Degrande et al'10,'11]

$$\delta A(m_{t\bar{t}} \geqslant 450\ \text{GeV}) = \left(0.087^{+10}_{-9} c_{Aa} + 0.032^{+4}_{-3} c'_{Aa}\right)\left(\frac{1\ \text{TeV}}{\Lambda}\right)^2.$$



(using CDF data)

Including $O(\Lambda^{-4})$ terms can alleviate the tension. See analysis by Aguilar-Saavedra & Perez-Victoria, **1103.2765** and Delaunay et al, **1103.2297**.

$$\sigma(t\bar{t}) = \sigma_{SM} + \delta\sigma_{int} + \delta\sigma_{quad} \quad \Rightarrow \quad \delta\sigma_{int} + \delta\sigma_{quad} \simeq 0$$

consistent to ignore SM×Dim 8 terms if c is large

This requires $A_{new} \sim -2A_{SM}$ ⇒ $t\bar{t}$ tail at LHC

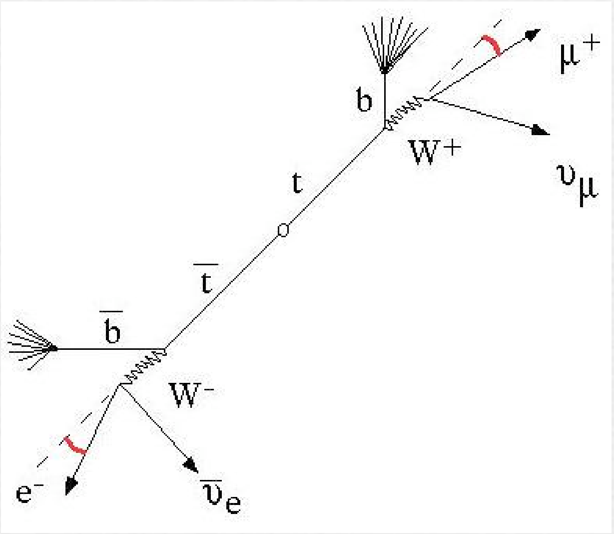
more details in JA Aguilar-Saavedra's talk

Spin correlations

The three observables σ, $d\sigma/dm_{t\bar{t}}$ and A_{FB} are unable to disentangle between theories coupled mainly to right- or left-handed top quarks. However, spin correlations allow us to determine which chiralities of the top quark couple to new physics, and in the case of composite models, whether one or two chiralities of the top quark are composite.

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + C\cos\theta_+\cos\theta_- + b_+\cos\theta_+ + b_-\cos\theta_-\right)$$

θ_+ (θ_-) is the angle between the charged lepton l^+ (l^-) resulting from the top (antitop) decay and some reference direction $\vec{a}$ ($\vec{b}$).



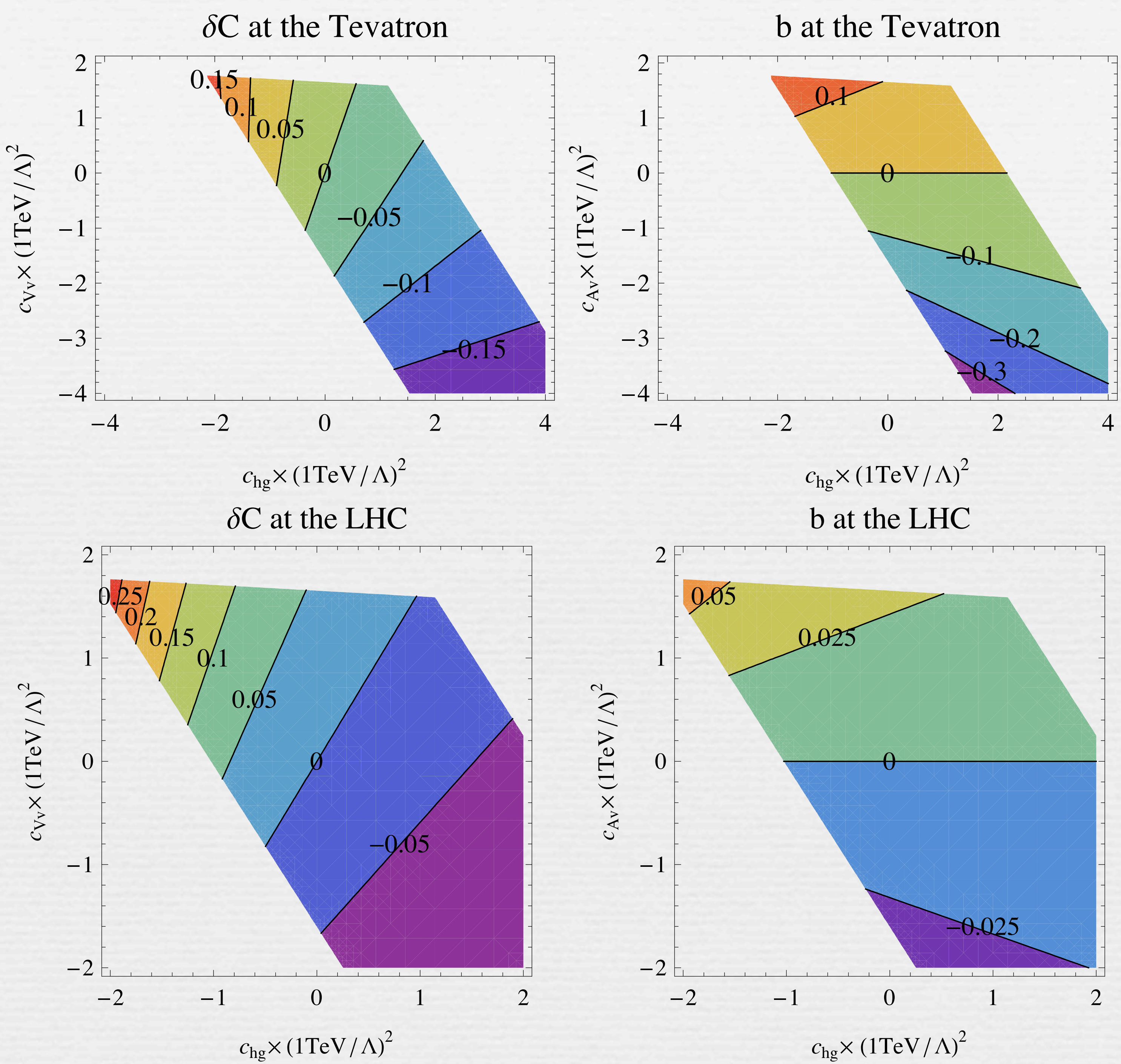
$$\begin{aligned} C &= \frac{1}{\sigma}\left(\sigma_{RL} + \sigma_{LR} - \sigma_{RR} - \sigma_{LL}\right), \\ b_+ &= \frac{1}{\sigma}\left(\sigma_{RL} - \sigma_{LR} + \sigma_{RR} - \sigma_{LL}\right), \\ b_- &= \frac{1}{\sigma}\left(\sigma_{RL} - \sigma_{LR} - \sigma_{RR} + \sigma_{LL}\right). \end{aligned}$$

$$C \times \sigma/\text{pb} = 2.82^{+1.06}_{-0.72} + \left[\left(0.37^{+0.10}_{-0.08}\right)c_{hg} + \left(0.50^{+0.13}_{-0.10}\right)c_{Vv}\right] \times \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2,$$

$$b \times \sigma/\text{pb} = \left(0.45^{+0.12}_{-0.09}\right)c_{Av} \times \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2,$$

allows to distinguish between LH and RH quarks

proportional to $c_{Rv} - c_{Lv}$



δC at the Tevatron
b at the Tevatron
δC at the LHC
b at the LHC
$c_{Vv} \times (1\mathrm{TeV}/\Lambda)^2$
$c_{Av} \times (1\mathrm{TeV}/\Lambda)^2$
$c_{hg} \times (1\mathrm{TeV}/\Lambda)^2$
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
0.1
0
−0.1
−0.2
−0.3
0.25
0.2
0.15
0.1
0.05
0
−0.05
0.05
0.025
0
−0.025

Spin correlations

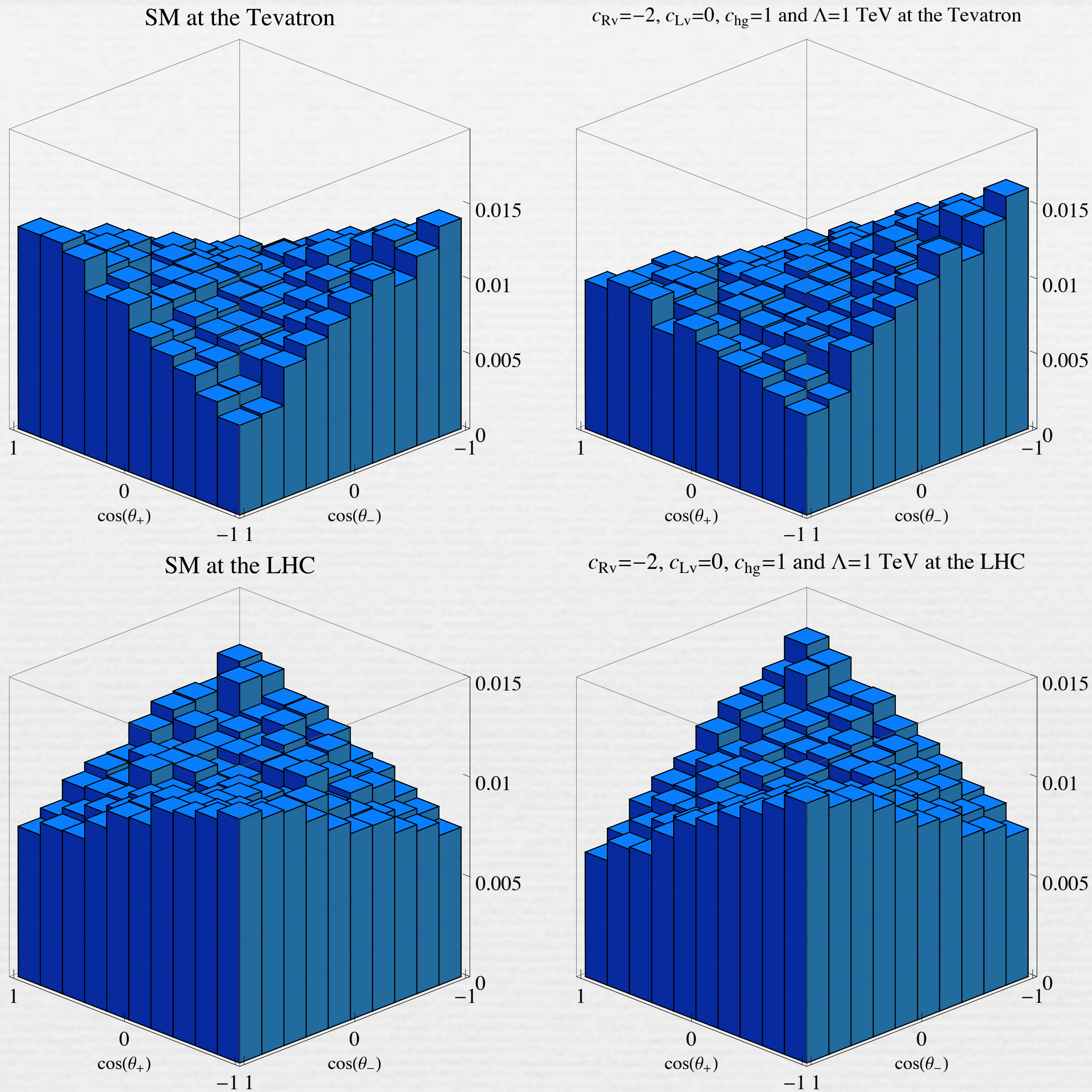


Figure 11: Distribution of events at the Tevatron/LHC (top panel/bottom panel) for the SM (on the left) and for $c_{Rv} = -2$, $c_{Lv} = 0$, $c_{hg} = 1$ and $\Lambda = 1$ TeV (on the right) with $\mu_F = \mu_R = mt$.

Summary

Non-resonant top philic new physics can be probed using measurements in top pair production at hadron colliders

This model-independent analysis can be performed in terms of 8 operators. Observables depend on different combinations of only 4 parameters:

$$\sigma(gg \to t\bar{t}), d\sigma(gg \to t\bar{t})/dt \quad \leftrightarrow \quad c_{hg}$$

$$\sigma(q\bar{q} \to t\bar{t}) \quad \leftrightarrow \quad c_{hg}, c_{Vv}$$

$$d\sigma(q\bar{q} \to t\bar{t})/dm_{tt} \quad \leftrightarrow \quad c_{hg}, c_{Vv}$$

$$A_{FB} \quad \leftrightarrow \quad c_{Aa}$$

$$\text{spin correlations} \quad \leftrightarrow \quad c_{hg}, c_{Vv}, c_{Av}$$

Note:

Previous studies had looked at the phenomenology of **part of** the operators

e.g:

	Zhang et al, 1008.3869	Kumar et al, 0901.3808	Cao et al, 1003.3461	Jung et al, 0912.1105	Hioki et al, 0910.3049
	Ref. [24]	Ref. [19]	Ref. [51]	Ref. [20]	Ref. [21]
c_{hg}	$2C_{tG}$	$g_1 g_s$			$\frac{1}{2}C^{33}_{uG\phi}$
c_{Vv}	$\frac{1}{4}\left(C^1_u+C^2_u+C^1_d+C^2_d\right)$	$-g_2 g_s^2(*)$	$\frac{g_s^2}{4}(\kappa^u_R+\kappa^d_R+\kappa^u_L+\kappa^d_L)(*)$	$\frac{g_s^2}{2}(C_1+C_2)$	
c_{Aa}	$\frac{1}{4}\left(C^1_u-C^2_u+C^1_d-C^2_d\right)$		$\frac{g_s^2}{4}(\kappa^u_R+\kappa^d_R+\kappa^u_L+\kappa^d_L)(*)$	$\frac{g_s^2}{2}(C_1-C_2)$	
c'_{Vv}	$\frac{1}{2}\left(C^1_u+C^2_u-C^1_d-C^2_d\right)$		$\frac{g_s^2}{2}(\kappa^u_R-\kappa^d_R+\kappa^u_L-\kappa^d_L)(*)$		
c'_{Aa}	$\frac{1}{2}\left(C^1_u-C^2_u-C^1_d+C^2_d\right)$		$\frac{g_s^2}{2}(\kappa^u_R-\kappa^d_R+\kappa^u_L-\kappa^d_L)(*)$		

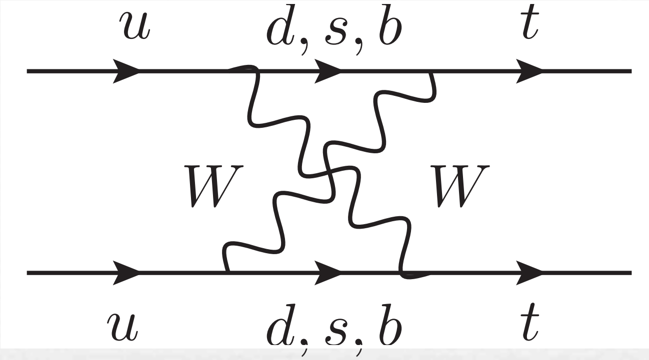
Listed all operators
although did not study
the phenomenology

Effective Field Theory Approach to Same-sign top pair production

Like-sign top pair production is a golden channel for early discovery at the LHC

uu->tt is absent in the SM at tree level

SM contribution to uu->tt ~ $|V_{ub}|^4$



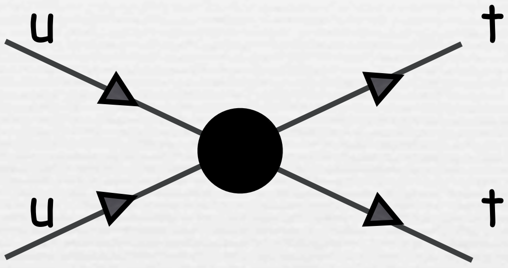
Five Effective Operators for Same-Sign Top-Pair Production

Degrande et al, 1104.1798
Aguilar-Saavedra, 1008.3562

$$\mathcal{L}^{qq\to tt}_{\mathrm{dim}=6} = \frac{1}{\Lambda^2}\left(c_{RR}\mathcal{O}_{RR} + c^{(1)}_{LL}\mathcal{O}^{(1)}_{LL} + c^{(3)}_{LL}\mathcal{O}^{(3)}_{LL} + c^{(1)}_{LR}\mathcal{O}^{(1)}_{LR} + c^{(8)}_{LR}\mathcal{O}^{(8)}_{LR}\right) + h.c.$$

$$\mathcal{O}_{RR} = [\bar{t}_R\gamma^\mu u_R][\bar{t}_R\gamma_\mu u_R],$$
$$\mathcal{O}^{(1)}_{LL} = [\bar{Q}_L\gamma^\mu q_L][\bar{Q}_L\gamma_\mu q_L],$$
$$\mathcal{O}^{(3)}_{LL} = [\bar{Q}_L\gamma^\mu\sigma^a q_L][\bar{Q}_L\gamma_\mu\sigma^a q_L],$$

$$\mathcal{O}^{(1)}_{LR} = [\bar{Q}_L\gamma^\mu q_L][\bar{t}_R\gamma_\mu u_R],$$
$$\mathcal{O}^{(8)}_{LR} = [\bar{Q}_L\gamma^\mu T^A q_L][\bar{t}_R\gamma_\mu T^A u_R]$$



$c_{LL} = c^{(1)}_{LL} + c^{(3)}_{LL}$

$O^{(1)}_{LL}$ and $O^{(3)}_{LL}$ contain $[\bar{b}_L\gamma^\mu d_L][\bar{b}_L\gamma_\mu d_L]$ which contributes to B_d mixing

and are therefore constrained: $|c_{LL}|\,(1\ \mathrm{TeV}/\Lambda)^2 < 2.1\ 10^{-4}$

pp -> tt cross section

$$\frac{d\sigma}{dt} = \frac{1}{\Lambda^4}\Bigg[\left(|c_{RR}|^2 + |c_{LL}|^2\right)\frac{(s-2m_t^2)}{3\pi s}$$

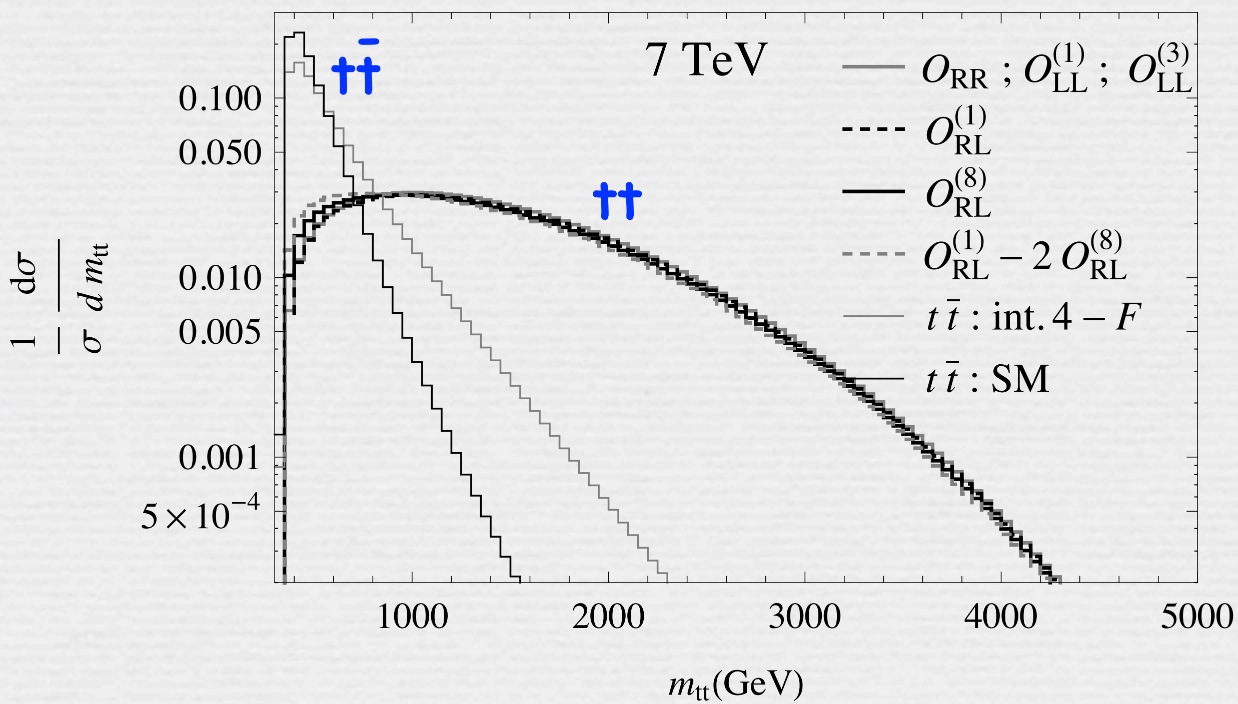
$$+\left(|c^{(1)}_{LR}|^2 + \frac{2}{9}|c^{(8)}_{LR}|^2\right)\frac{(m_t^2-t)^2+(m_t^2-u)^2}{16\pi s^2}$$

$$-\left(|c^{(1)}_{LR}|^2 + \frac{8}{3}\Re\left(c^{(1)}_{LR}c^{(8)*}_{LR}\right) - \frac{2}{9}|c^{(8)}_{LR}|^2\right)\frac{m_t^2}{24\pi s}\Bigg].$$

σ grows like ~ s

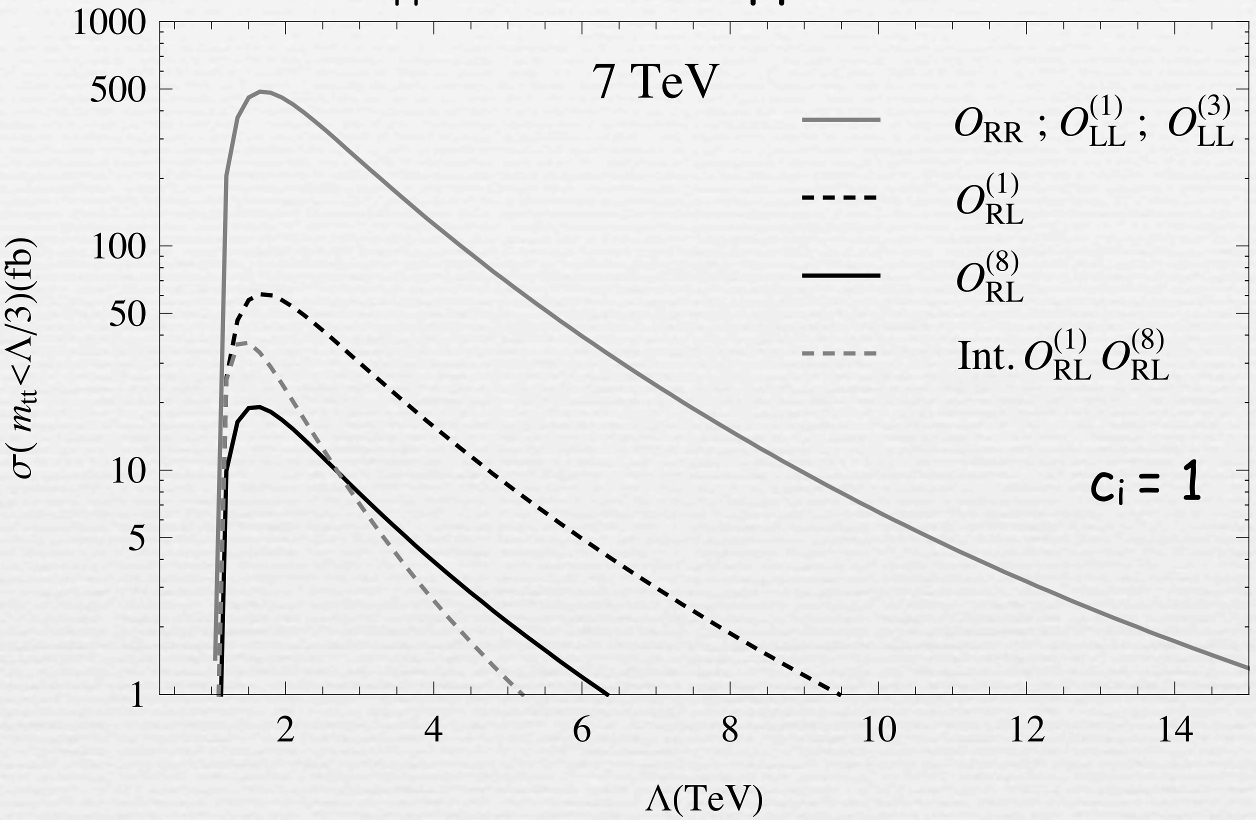
~ m_t^2

A large part of the cross section at the LHC comes from the region where m_{tt} ~ 1 TeV, where the $1/\Lambda$ cannot be trusted for Λ ~ 1TeV



(no such concern at the Tevatron where m_{tt} <~ 500 GeV)

$\sigma_{pp\to tt}$ with an upper cut on M_{tt}



For Λ ~ 2 TeV and c~ 1, cross sections are of order O(pb) at 7 TeV

Spin correlations

Very efficient to discriminate among the contributions from the various operators which have a well-defined chirality structure and no interference with the SM is possible

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left[1 + C\cos\theta_1\cos\theta_2 \ + b(\cos\theta_1 + \cos\theta_2)\right],$$

$$C = \frac{1}{\sigma}(\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}),$$
$$b = \frac{1}{\sigma}(\sigma_{++} - \sigma_{--}),$$

$$\begin{array}{rll} \mathcal{O}_{RR} & C = 1 & b = 0.997 \\ \mathcal{O}_{LL}^{(1)}, \mathcal{O}_{LL}^{(3)} & C = 1 & b = -0.997 \\ \mathcal{O}_{LR}^{(1)}, \mathcal{O}_{LR}^{(8)} & C \approx 1 & b \approx 0 \end{array}$$

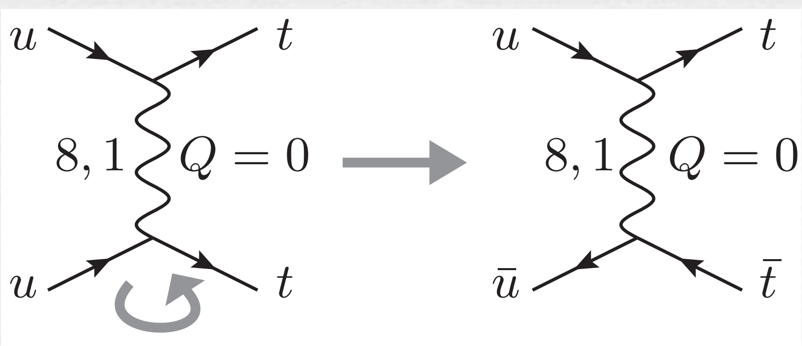
Link to resonant models

In general, no relation exists between same and opposite sign top pair production i.e. c_{RR}, c_{LL}, $c_{LR}^{(1)}$, $c_{LR}^{(8)}$ cannot be related to c_{Vv}, c_{Aa}

$$\mathcal{L}^{q\bar{q}\to t\bar{t}} = \left(\frac{c_{Vv}}{2} \pm \frac{c'_{Vv}}{4}\right)[\bar{t}\gamma_\mu T^a t][\bar{q}\gamma_\mu T^a q] + \left(\frac{c_{Aa}}{2} \pm \frac{c'_{Aa}}{4}\right)[\bar{t}\gamma_\mu\gamma_5 T^a t][\bar{q}\gamma_\mu\gamma_5 T^a q]$$

t-channel

Spin	SU(3)	SU(2)	Y	c_{RR}	$c_{LL}^{(1)}$	$c_{LL}^{(3)}$	$c_{LR}^{(1)}$	$c_{LR}^{(8)}$
1	1	1	0	$-\frac{1}{2}$	$-\frac{\xi^2}{2}$		$-\xi$	
1	8	1	0	$-\frac{1}{6}$	$-\frac{\xi^2}{24}$	$-\frac{\xi^2}{8}$		$-\xi$
0	1	2	$\frac{1}{2}$				$-\frac{1}{6}\xi$	$-\xi$
0	8	2	$\frac{1}{2}$				$-\frac{2}{9}\xi$	$\frac{1}{6}\xi$
1	1	3	0			$-\frac{\xi^2}{2}$		
1	8	3	0		$-\frac{3}{8}\xi^2$	$\frac{5}{24}\xi^2$		



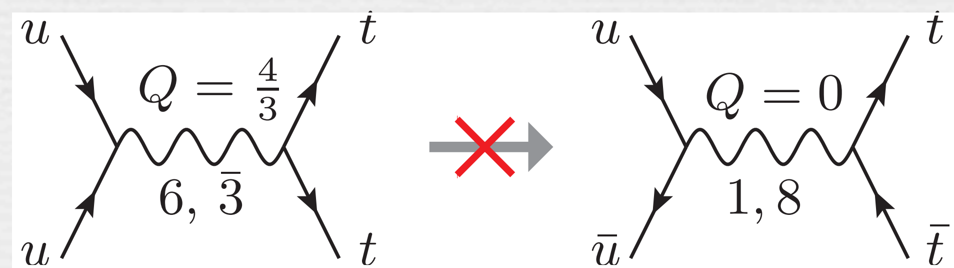
link to AFB in ttbar

$|c_{Vv}| = |c_{Aa}|$, $|c'_{Vv}| = |c'_{Aa}|$

Spin	SU(2)	Y	c_{Vv}	c'_{Vv}	c_{Aa}	c'_{Aa}
1	1	0	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	-1
0	2	$\frac{1}{2}$	$-\frac{1}{2}\left(\lvert\xi\rvert^2 + \frac{1}{2}\right)$	$-\frac{1}{2}$	$\frac{1}{2}\left(\lvert\xi\rvert^2 + \frac{1}{2}\right)$	$\frac{1}{2}$

s-channel

Spin	SU(3)	SU(2)	Y	c_{RR}	$c_{LL}^{(1)}$	$c_{LL}^{(3)}$	$c_{LR}^{(1)}$	$c_{LR}^{(8)}$
1	$\bar{3}$	2	$\frac{5}{6}$				$-\frac{1}{6}$	$\frac{1}{2}$
1	6	2	$\frac{5}{6}$				$-\frac{1}{3}$	$-\frac{1}{2}$
0	6	1	$\frac{4}{3}$	$\frac{1}{4}$				
0	6	3	$\frac{1}{3}$		$-\frac{3}{8}$	$-\frac{1}{8}$		



Connection with composite top models

In models of composite tops, the operators contributing directly to top pair production are subdominant compared to four-top operators (from Naive Dimensional Analysis)

$$\frac{1}{\Lambda^2}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$$

(The dominant operators are those which contain only fields from the strong sector, scale as g_ρ^2)

$1 \lesssim g_\rho \lesssim 4\pi$

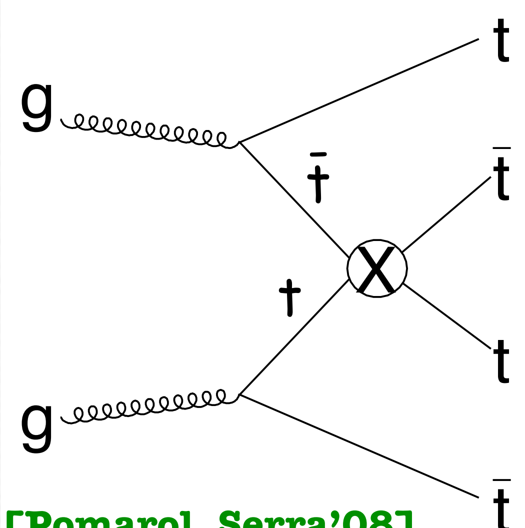
coupling of the strong sector

4-fermion op. contributing directly to $t\bar{t}$ production scale at best as g_ρ while O_{hg} scales as g_ρ^{-1}

In this case, a much better probe of the dominant dynamics is the direct production of four top quarks

spectacular events with 12 partons in the final state

typical LHC cross sections at 14 TeV: 10 - 100 fb



[Pomarol, Serra'08]
[Lillie, Shu, Tait '08]

$t\bar{t}b\bar{b}$ and $t\bar{t}t\bar{t}$ production at the LHC

if only t_R is composite

$$\mathcal{O}_R = (\bar{t}\gamma^\mu t)(\bar{t}\gamma_\mu t)\,.$$

$$\mathcal{O}_R^{(8)} = 1/3\,\mathcal{O}_R$$

if only t_L is composite

$$\mathcal{O}_L^{(1)} = (\bar{Q}\gamma^\mu Q)(\bar{Q}\gamma_\mu Q)$$

$$\mathcal{O}_L^{(8)} = (\bar{Q}\gamma^\mu T^A Q)(\bar{Q}\gamma_\mu T^A Q)$$

if both t_L and t_R are composite

$$\mathcal{O}_S^{(1)} = (\bar{Q}t)(\bar{t}Q)$$

$$\mathcal{O}_S^{(8)} = (\bar{Q}T^A t)(\bar{t}T^A Q)$$

cross sections at 14 TeV assuming

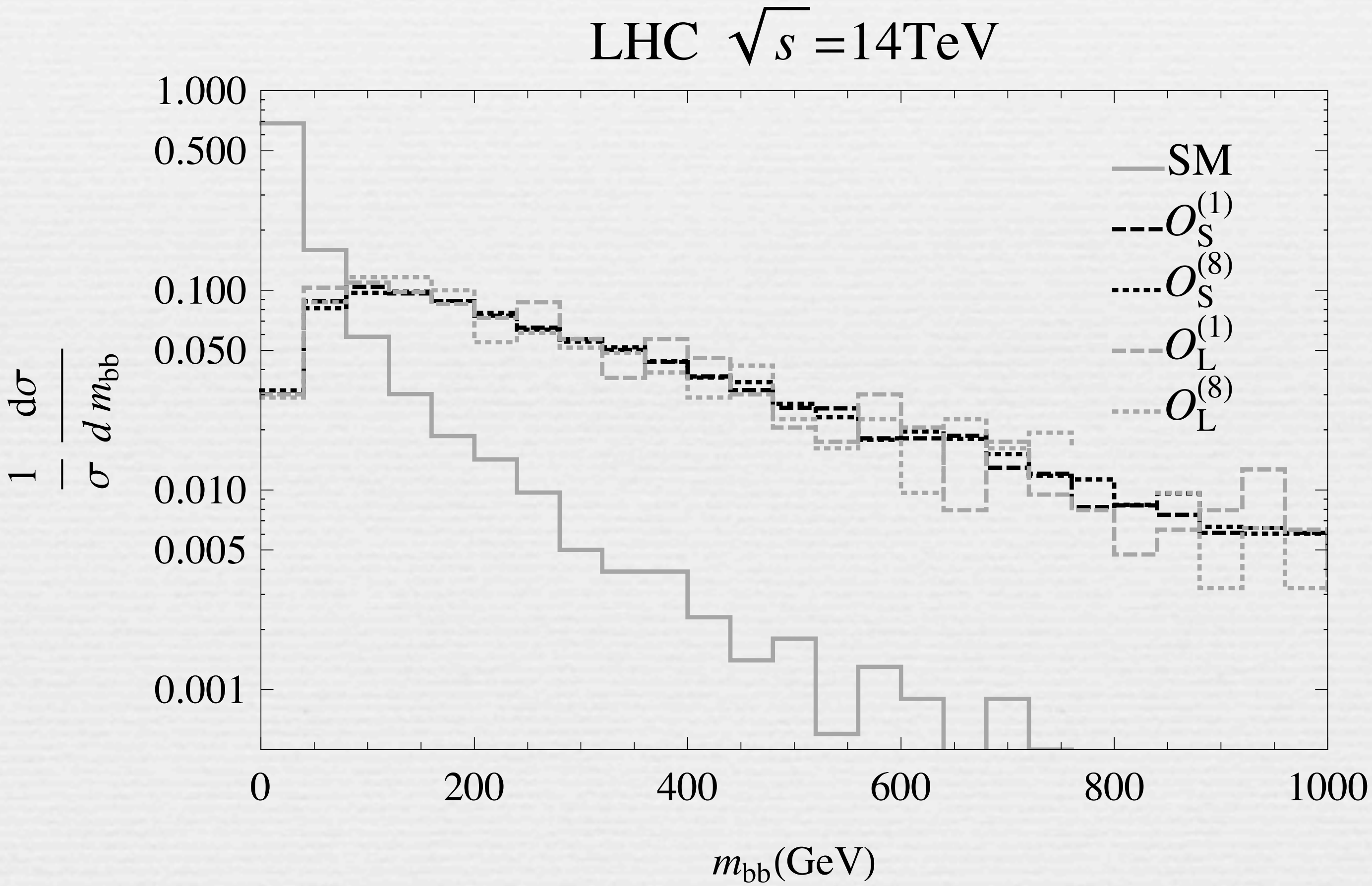
$$c_i = 4\pi$$

Λ= 1 TeV

	σ_{4t} (fb)	$\sigma_{4t}^{\Lambda^{-2}}$ (fb)	$\sigma_{4t}^{\Lambda^{-4}}$ (fb)	$\sigma_{t\bar{t}b\bar{b}}$ (pb)	$\sigma_{t\bar{t}b\bar{b}}^{\Lambda^{-2}}$ (pb)	$\sigma_{t\bar{t}b\bar{b}}^{\Lambda^{-4}}$ (pb)	$\sigma_{t\bar{t}b\bar{b}}^{\text{cut}}$ (pb)	$\sigma_{t\bar{t}b\bar{b}}^{\text{cut}}/\sigma_{4t}$
SM	4.86	-	-	7.2	-	-	0.348	71.6
$\mathcal{O}_R^{(1)}$	-	2.7	138	-	-	-	-	-
$\mathcal{O}_S^{(1)}$	-	2.9	48	-	<1.1	7.60	4.40	92
$\mathcal{O}_S^{(8)}$	-	0.49	11	-	<0.2	1.28	0.76	71
$\mathcal{O}_L^{(1)}$	-	2.7	138	-	<0.5	3.61	2.12	15.6
$\mathcal{O}_L^{(8)}$	-	0.91	15	-	0.49	0.77	0.42	28.2

$t\bar{t}b\bar{b}$

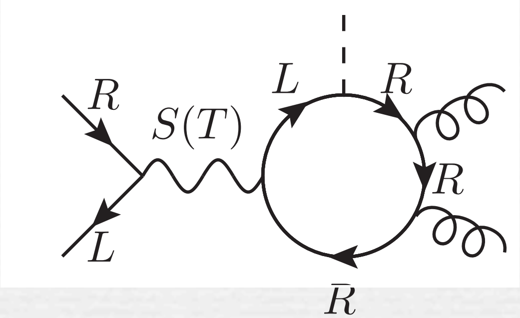
$b\,\bar{b}$ pair produced with invariant mass larger than in the SM



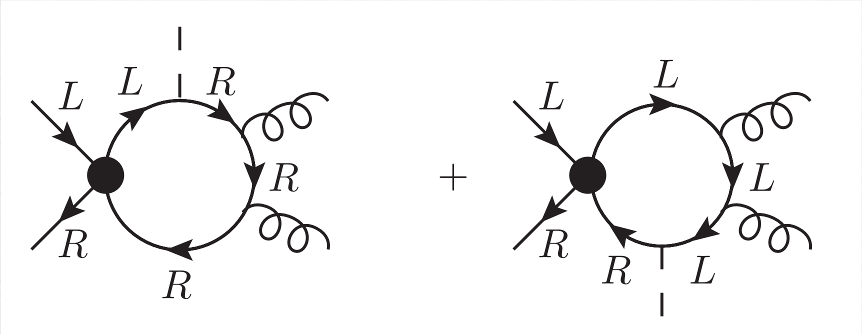
only relevant if t_L is composite (constrained scenario)

Testing O_{hg}

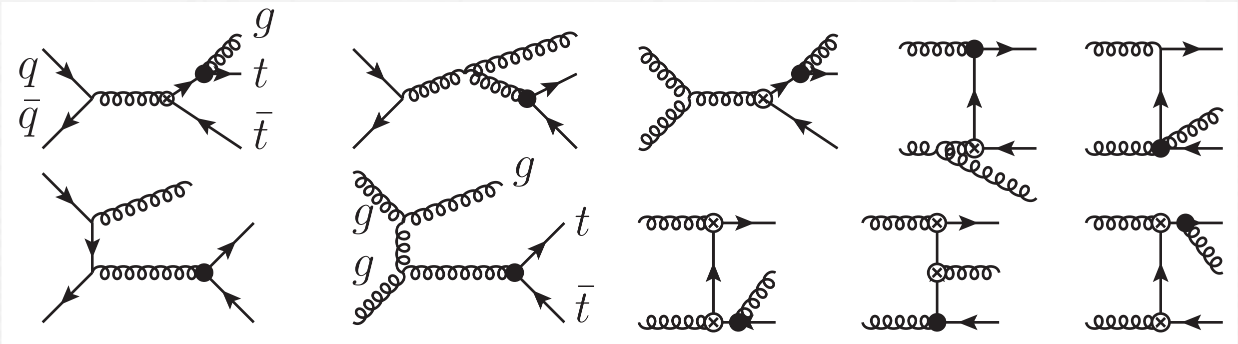
1-loop generation of the chromo-magnetic operator

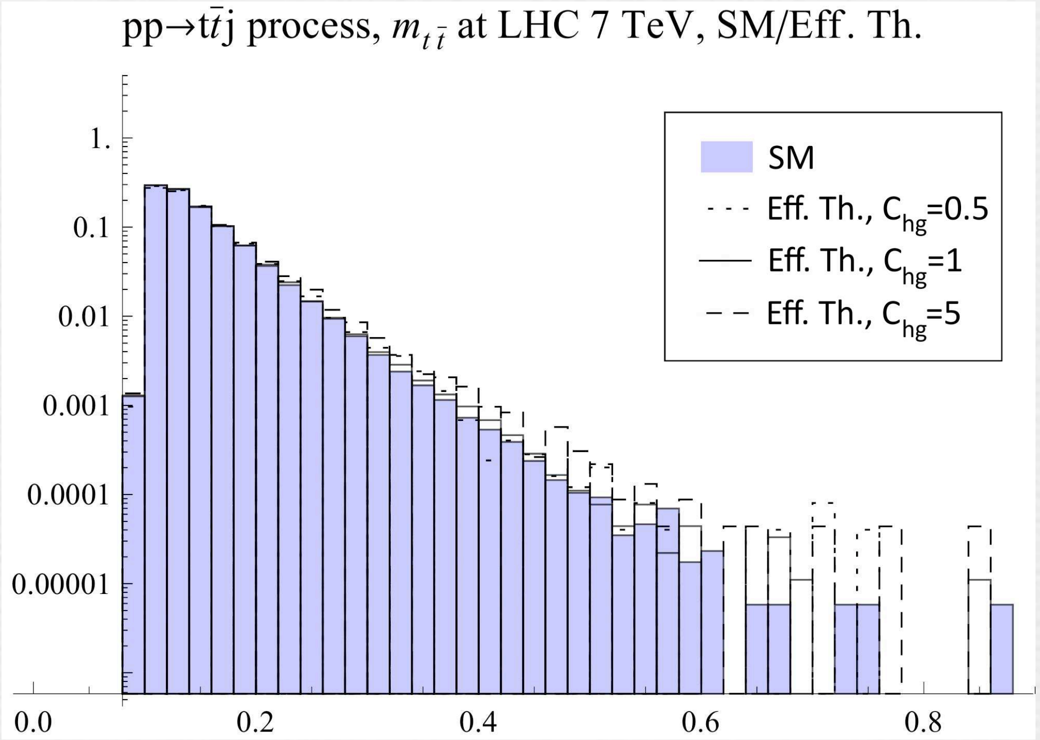


$$(H\bar{Q}t)\,(H\bar{Q}t) \Longrightarrow \delta c_{hg}$$



$t\bar{t}$ + jets



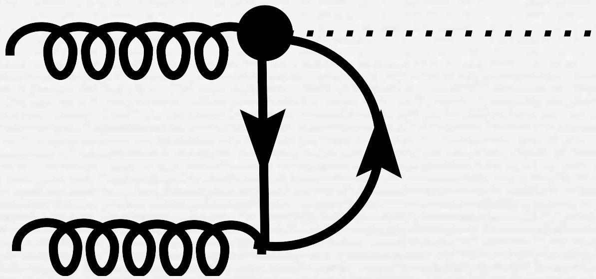
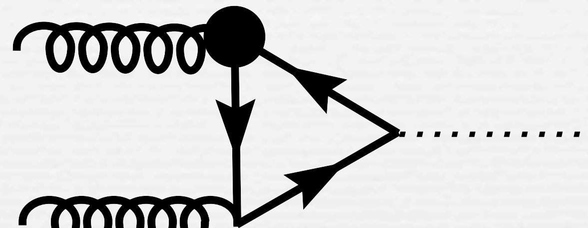
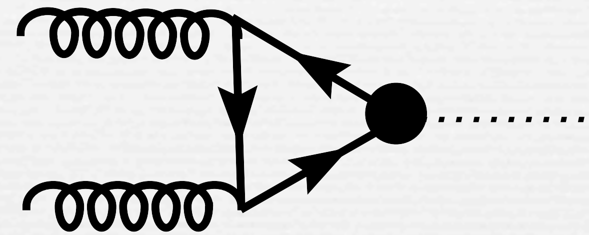


$$\frac{2M_{t\bar{t}}}{\sqrt{s}}$$

[Flament'11]

Constraints from higgs searches on top-philic new physics

Degrande et al, to appear

$$\mathcal{O}_{hg} = \left(\bar{Q}_L H\right)\sigma^{\mu\nu}T^a t_R G^a_{\mu\nu}$$

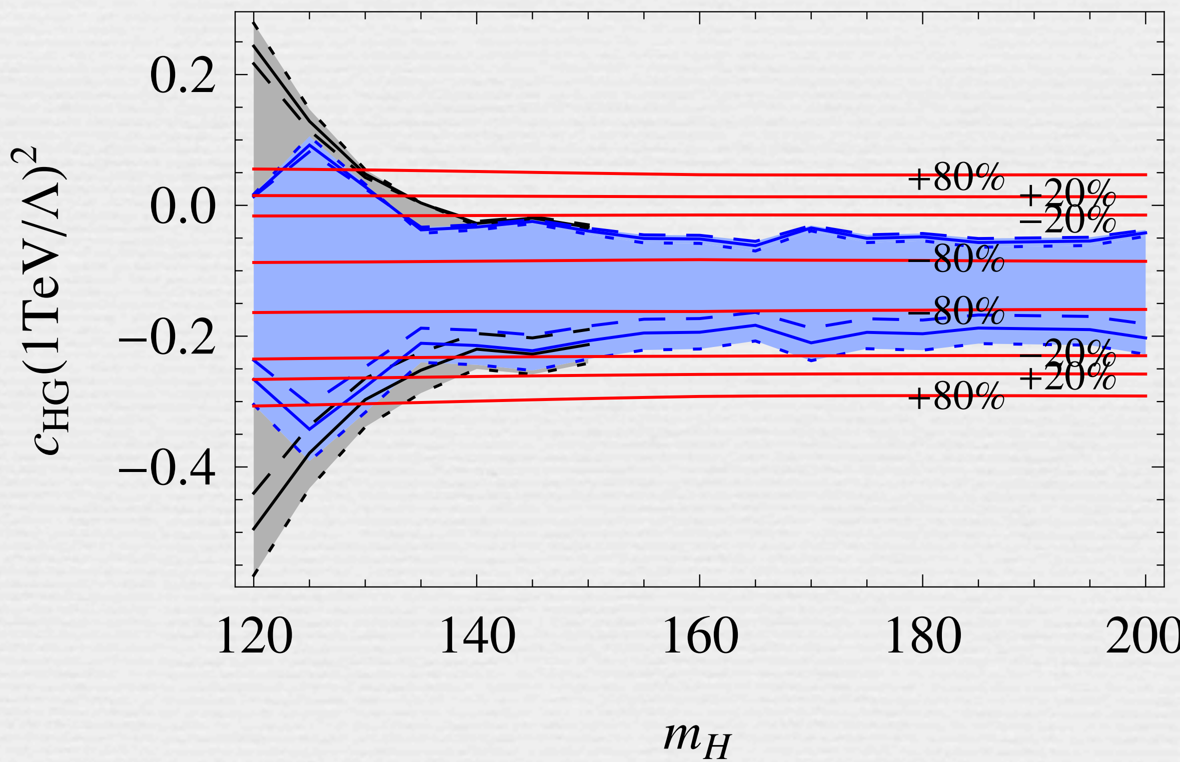
$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R$$

$$\mathcal{O}_H = \partial_\mu \left(H^\dagger H\right)\partial^\mu \left(H^\dagger H\right)$$

$$\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$

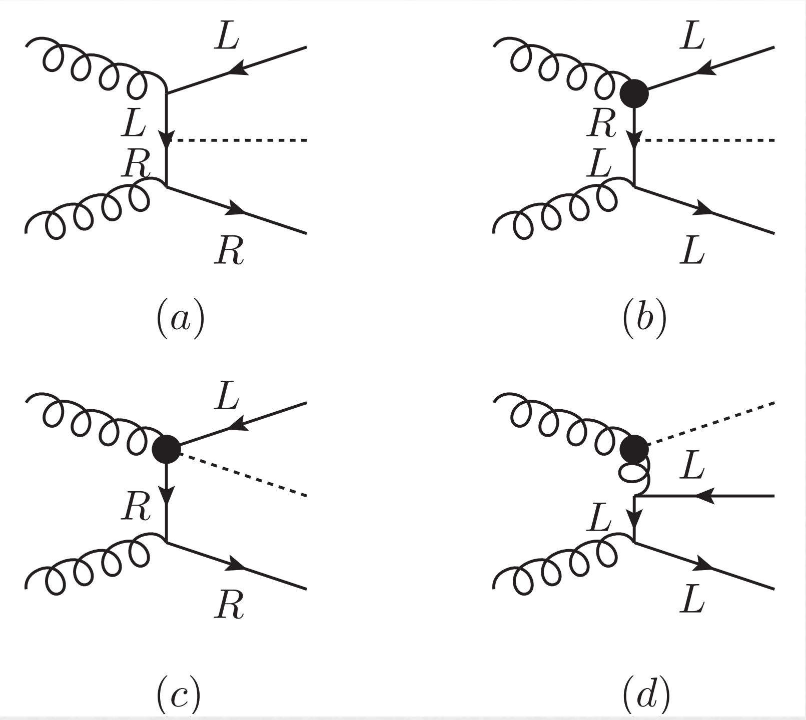
$$\delta c_{HG} \approx 0.03 \Re c_{hg} - 0.006 c_y$$

$$c_y = c_H + \frac{v}{\sqrt{2}m_t}\Re\left(c_{Hy}\right)$$



Using $t\bar{t}h$ to constrain the chromomagnetic operator

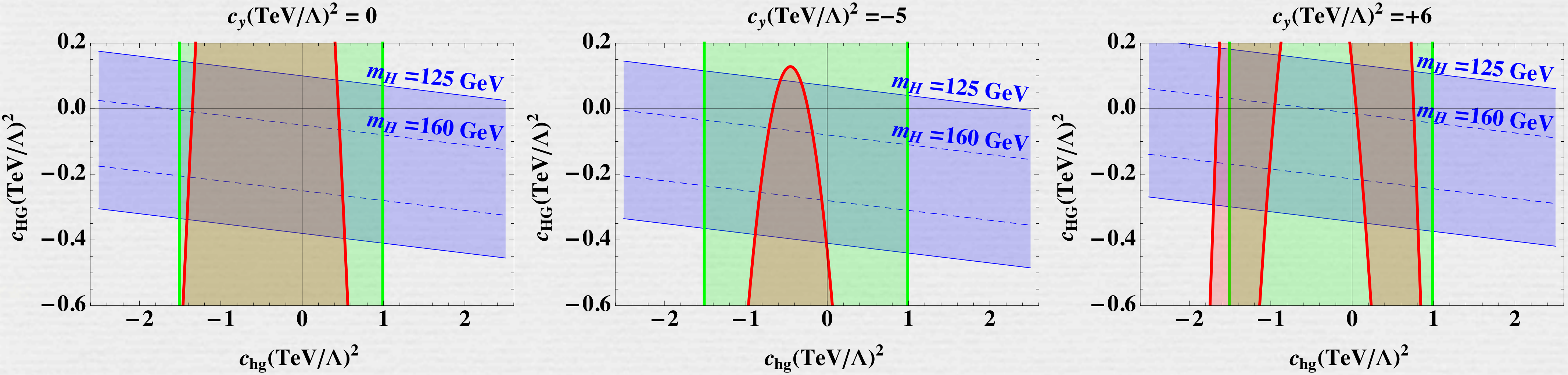
Degrande et al, to appear



constraints from h production

constraints from tt production

constraints from tth production



The top quark-baryogenesis connection

Baryogenesis without ~~B~~ nor ~~L~~ nor CP~~T~~

Possible if dark matter carries baryon number

Farrar-Zaharijas hep-ph/0406281
Agashe-Servant hep-ph/0411254

In a universe where baryon number is a good symmetry, Dark matter would store the overall negative baryonic charge which is missing in the visible quark sector

Matter Anti-matter asymmetry of the universe:

characterized in terms of the baryon to photon ratio

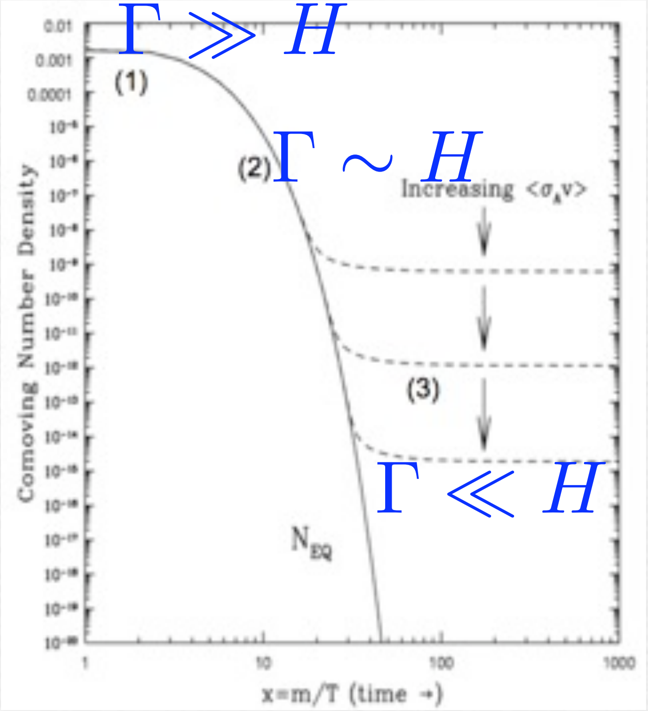
$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ 6. 10^{-10}

The great annihilation between nucleons & anti-nucleons

$$n + \bar{n} \to \pi + \pi \to \gamma + \gamma + \ldots$$

occurs when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T} / m_\pi^2 \sim H \sim \sqrt{g_*} T^2 / m_{Pl}$



corresponding to a freeze-out temperature T_F ~ 20 MeV

In absence of an asymmetry:

$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

10^9 times smaller than observed, and there are no antibaryons
-> need to invoke an initial asymmetry

10 000 000 001 Matter	10 000 000 000 Anti-matter

1
(us)

Similarly, Dark Matter may be asymmetric

$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

Does this indicate a common dynamics?

If $n_{dm} - \overline{n}_{dm} \propto n_b - \overline{n}_b$

then $$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{(n_{dm} - \overline{n}_{dm})m_{dm}}{(n_b - \overline{n}_b)m_b} \sim C\frac{m_{dm}}{m_b}$$

conservation of global charge: $$Q_{\mathrm{DM}}(n_{\overline{\mathrm{DM}}} - n_{\mathrm{DM}}) = Q_b(n_b - n_{\bar{b}})$$

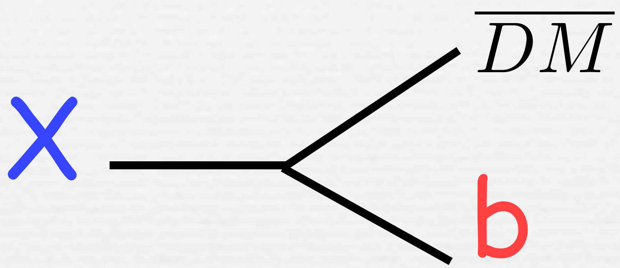
if efficient annihilations: $$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{Q_b}{Q_{dm}}\frac{m_{dm}}{m_b} \longrightarrow$$ typical expected mass ~ GeV

two possibilities:

1) asymmetries in baryons and in DM generated simultaneously

2) a pre-existing asymmetry (either in DM or in baryons) is transferred between the two sectors

asymmetry between b and $\bar{b}$ is created via the
out-of-equilibrium and CP-violating decay :



$$Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\bar{b}})$$

out-of equilibrium and CP violating decay of X sequesters the anti baryon number in the dark sector, thus leaving a baryon excess in the visible sector

If efficient annihilation between DM and $\overline{DM}$, and b and $\bar{b}$

$$\rho_{\rm DM} = m_{\rm DM} n_{\overline{\rm DM}} \approx 6\rho_b \rightarrow m_{\rm DM} \approx 6\frac{Q_{\rm DM}}{Q_b}\ {\rm GeV}$$

A unified explanation for DM and baryogenesis

$$\Omega_b \approx \frac{1}{6}\Omega_m$$

turns out to be quite natural in warped GUT models...

GUT baryogenesis at the TeV scale !

Agashe-Servant-Tulin in progress

Proton stability & Stable GUT partner in Warped GUTs

Agashe-Servant'04

DM is RH neutrino from 16 of SO(10)

$$\begin{pmatrix} Q'_L \\ u^c_R \\ d^c_R \\ L'_L \\ e'^c_R \\ \nu'^c_R \end{pmatrix}$$

multiplet has B=1/3

number of color indices

bulk fermion with (-+) BC -> light!

stable under $Z_3 : \Phi \longrightarrow \Phi \; e^{2\pi i \left[B - \frac{\alpha - \overline{\alpha}}{3}\right]}$

Has enhanced couplings to TeV KK modes (such as Z') and top quark

UV	SO(10)	IR
light SM fermions	warping →	t_R Higgs DM

Z_3 symmetry in the SM:

Agashe-Servant'04

number of color indices

$$\Phi \longrightarrow \Phi\, e^{2\pi i \left[B - \frac{(\alpha - \bar{\alpha})}{3} \right]}$$

conserved in any theory where baryon number is a good symmetry

any non-colored particle that carries
baryon number will be charged under Z_3

e.g warped/composite GUTs

Summary 1

So far ATLAS and CMS papers related to searches for heavy b′, t′ ... remained mainly motivated by fourth generation

However, the search for heavy top partners is strongly motivated by models of Higgs compositeness, that will survive in the next few years

The presence of light top partners constitutes the most visible manifestation of the composite Higgs scenario

Summary II

Effective field theory approach to BSM:
characterizes new physics in a model-independent way,
useful to set bounds on non-resonant new physics

2011 LHC data already rules out large region of parameter space

New constraints on the 4-fermion and the chromomagnetic operators and more to come (looking forward to the measurement of $t\bar{t}$ invariant mass distribution)

complementarity between Higgs, $t\bar{t}$ and $t\bar{t}H$ production

Models of top compositeness can lead to zero signal at 7-8 TeV while non-zero signals (4 top production + top partners production) at 14 TeV