Implications of LHC results for TeV scale physics:
WG3, March 26-30 2012

New fermions

Géraldine SERVANT, CERN-TH

Which (non-susy) new fermions ?

- 4th family in bad shape

- Top partners in PNGB composite Higgs models

- "exotic" (unusual quantum numbers and less straightforward connection to electroweak symmetry breaking)

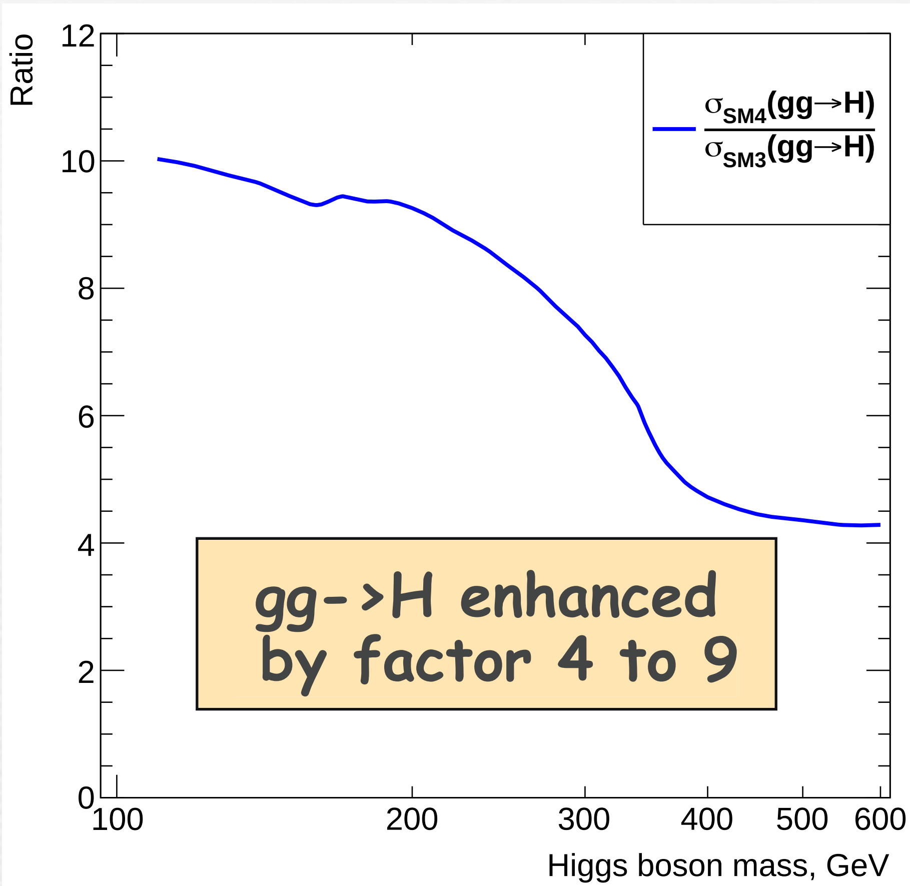
  e.g. "quirks"

For report:
focus on theoretical framework motivated by understanding the weak scale

New experimental results since last meeting on Dec. 9, 2011

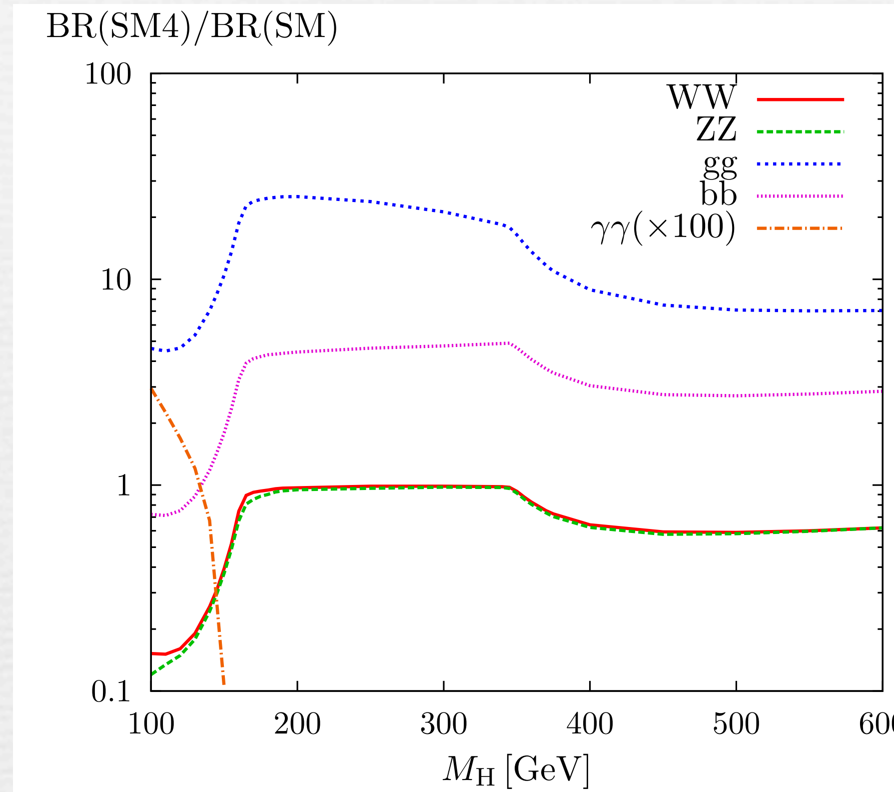
Constraint on 4th generation from Higgs searches

CMS PAS HIG-12-008



$$m_{b'} = m_{l'} = m_{\nu_l'} = 600\ \mathrm{GeV},$$

$$m_{t'} = m_{b'} + \left[1 + \frac{1}{5}\ln\left(\frac{M_H}{115\ \mathrm{GeV}}\right)\right] 50\ \mathrm{GeV}$$



decays in gluons and bb largely enhanced
→ supression of H→ 2 photons and
partially also H→WW and ZZ

The SM4 Higgs boson is excluded in the mass range 120-600 GeV at 95% CL and in the range 125-600 GeV at 99% CL

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.

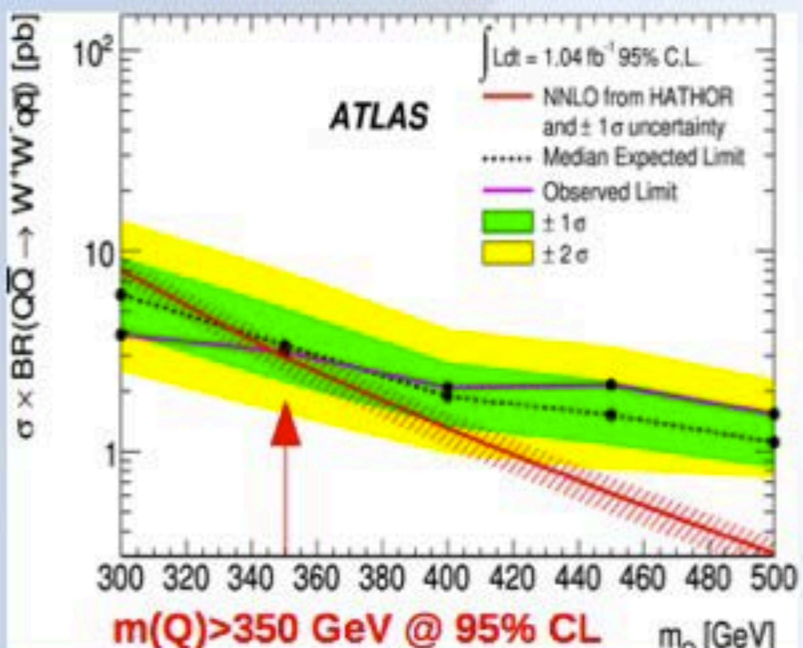
Selection criteria :

= 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'

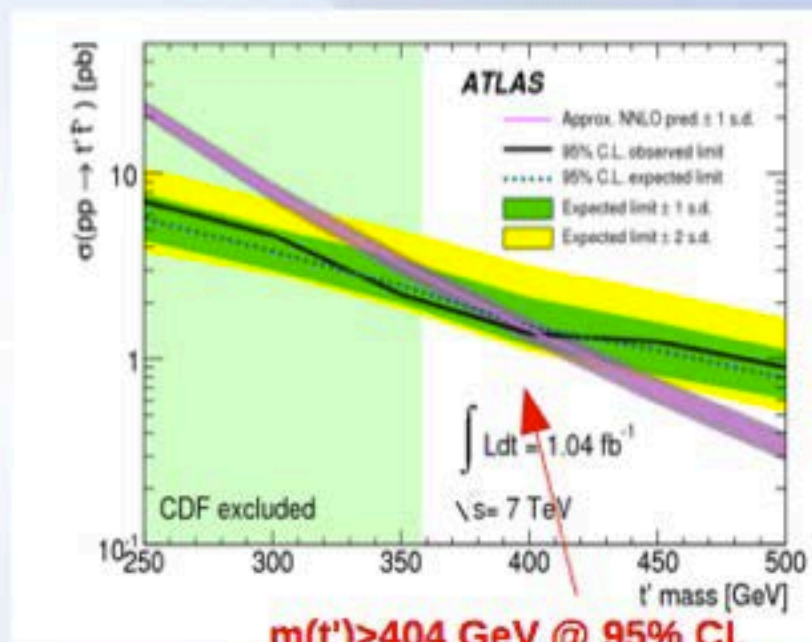
Only the range m(t') < (m_W – m(b')) is considered : t' → W^+q 100%

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

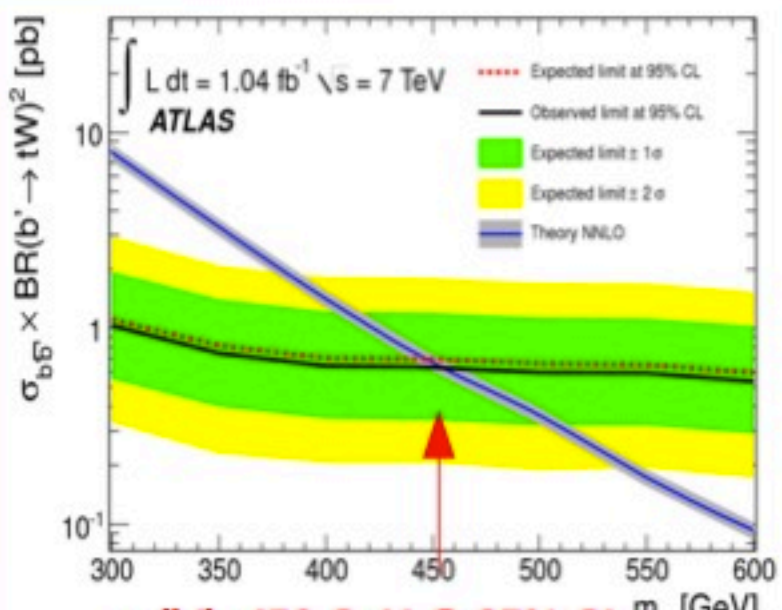
Selection criteria :

- = 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 : $b' \rightarrow tW$- 100%

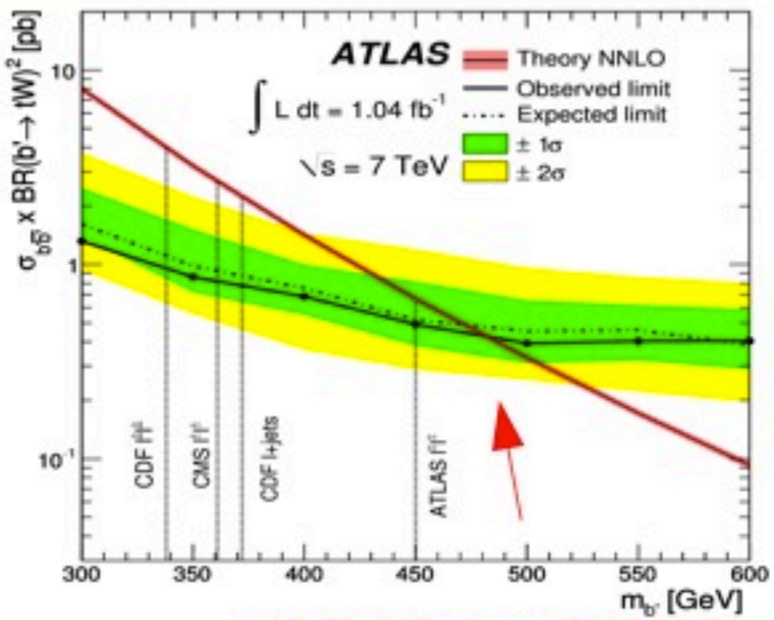
same-sign dilepton final state



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

arXiv : 1202.5520 [hep-ex]

lepton + jets final state



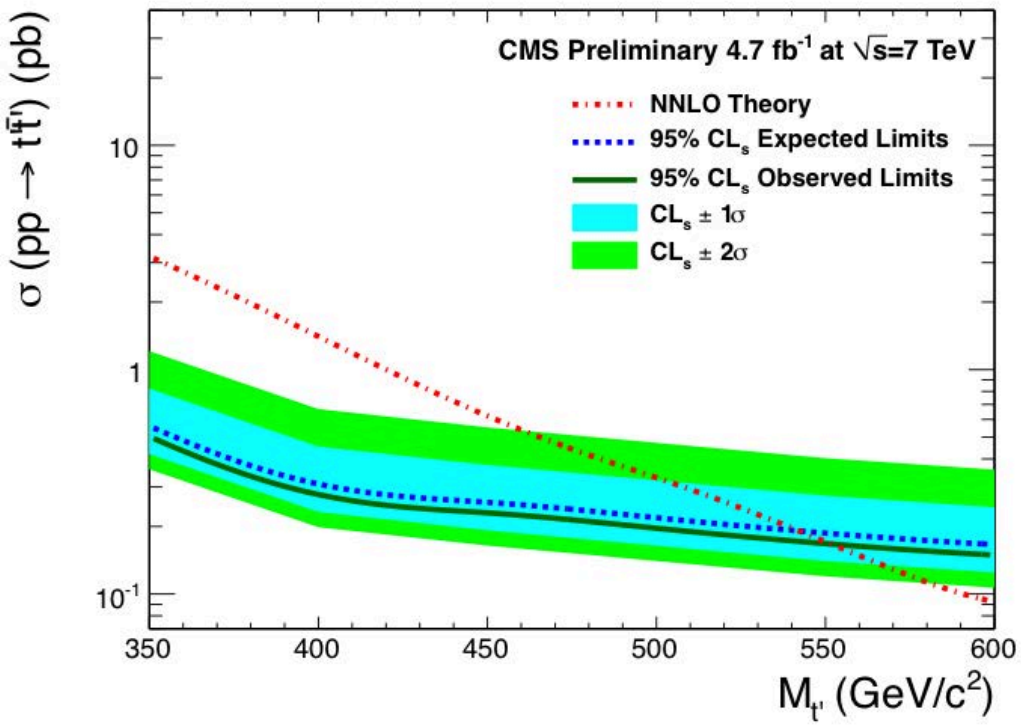
m(b')>480 GeV @ 95% CL

arXiv : 1202.6540 [hep-ex]

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

larger data set + stronger cuts: stronger limits

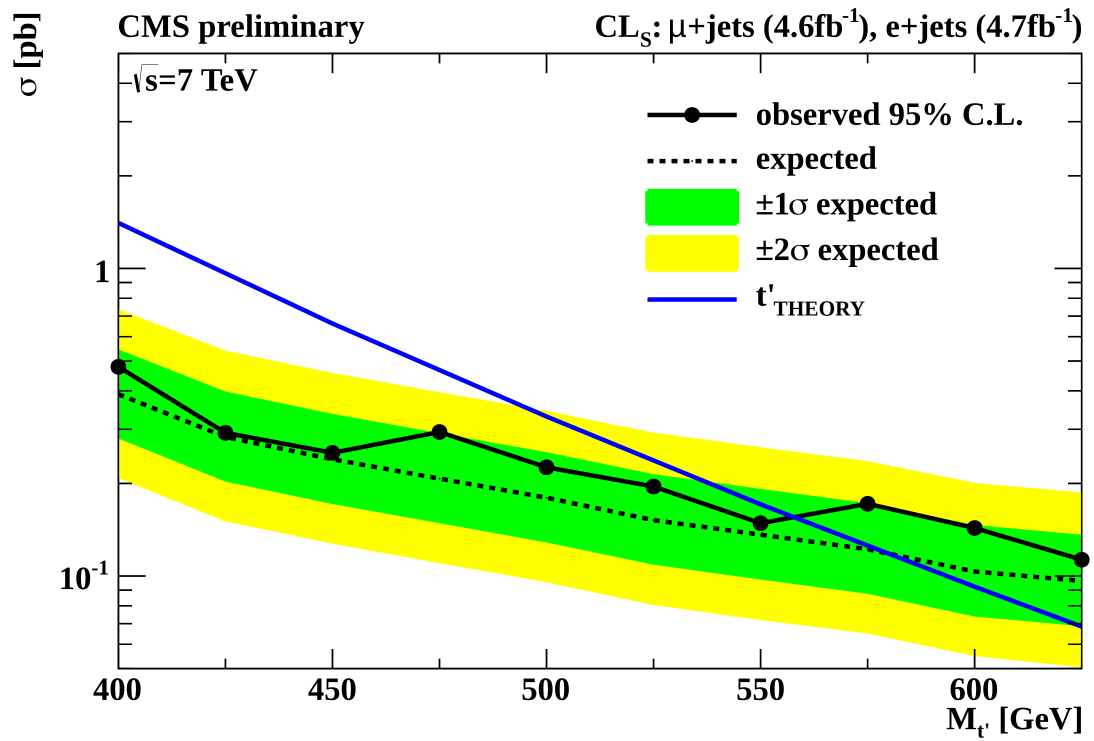
DILEPTON CHANNEL



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

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

1 LEPTON + 4 jets CHANNEL

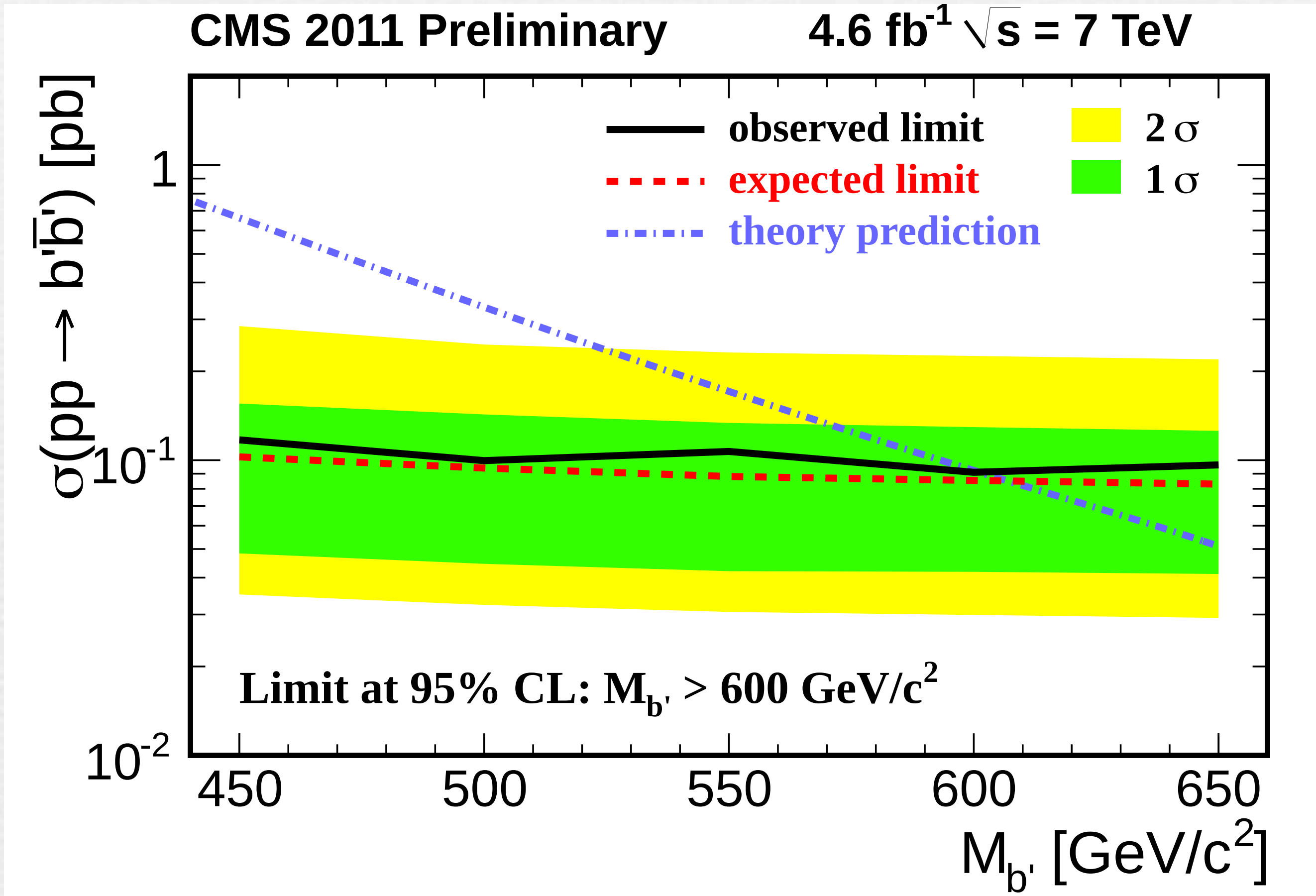


$$M_{t'} \gtrsim 560 \text{ GeV}$$

[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

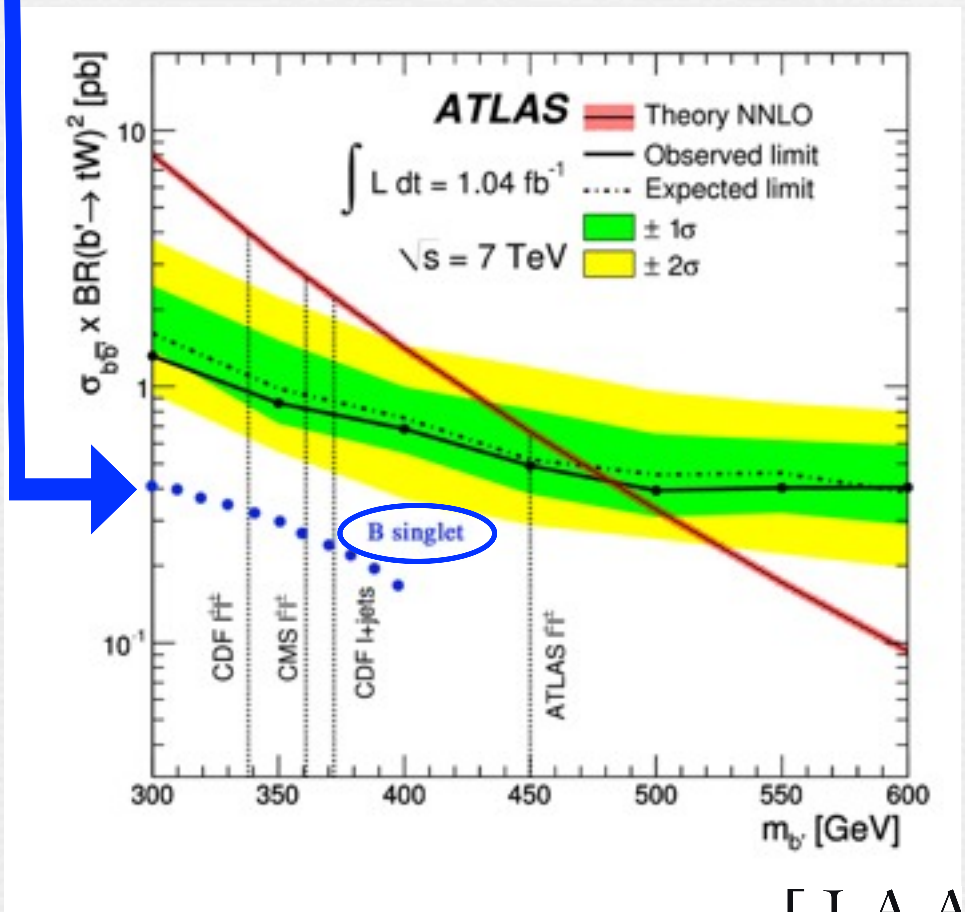
$$M_{b'} \gtrsim 600 \text{ GeV}$$

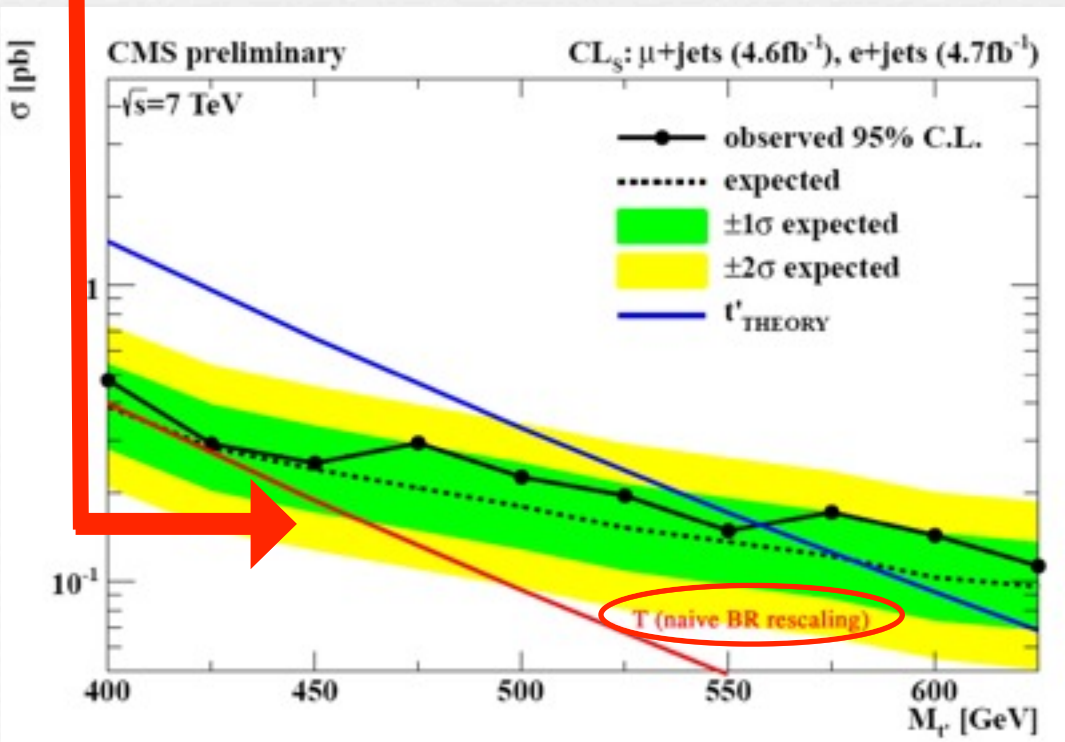
Note:

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



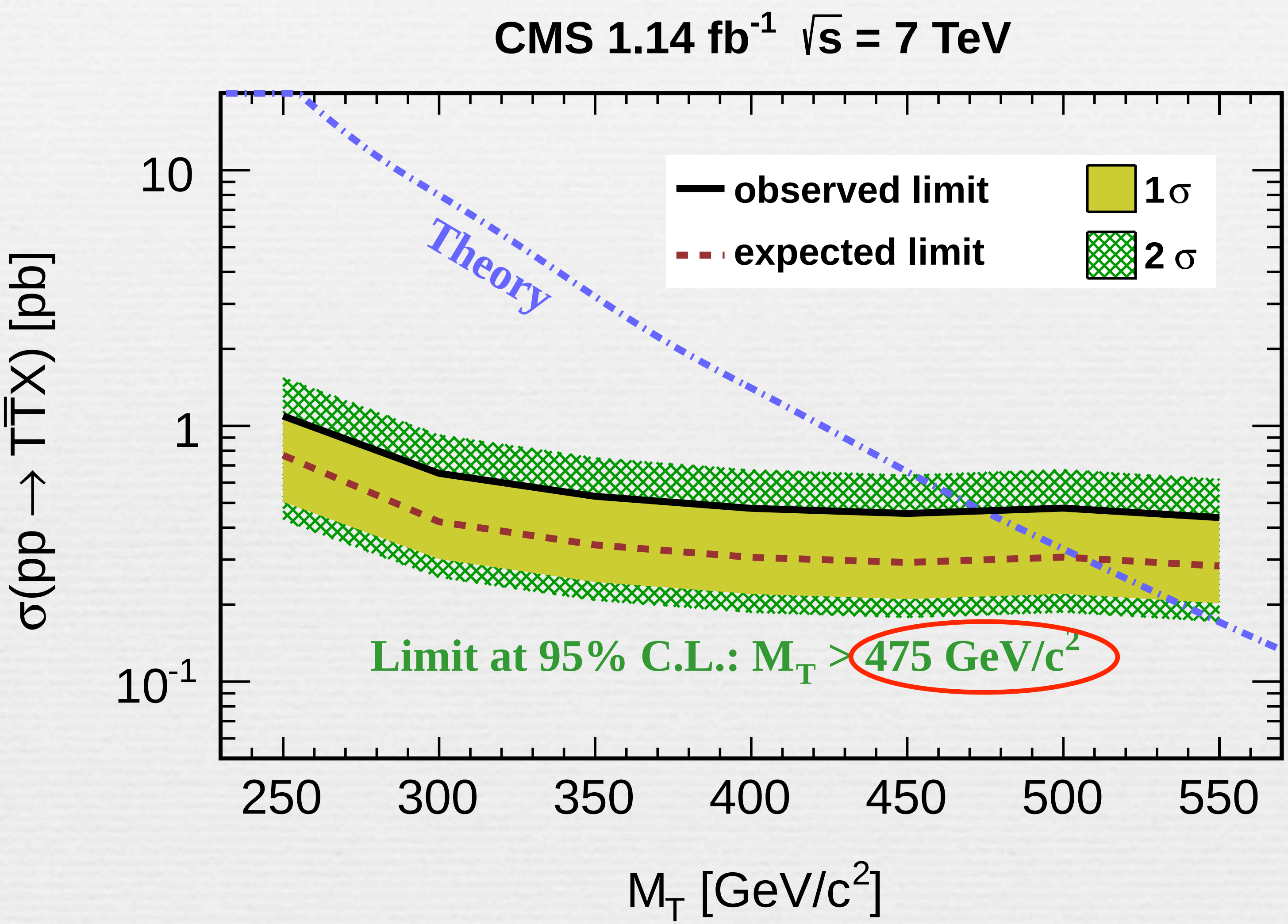


[J-A Aguilar-Saavedra]

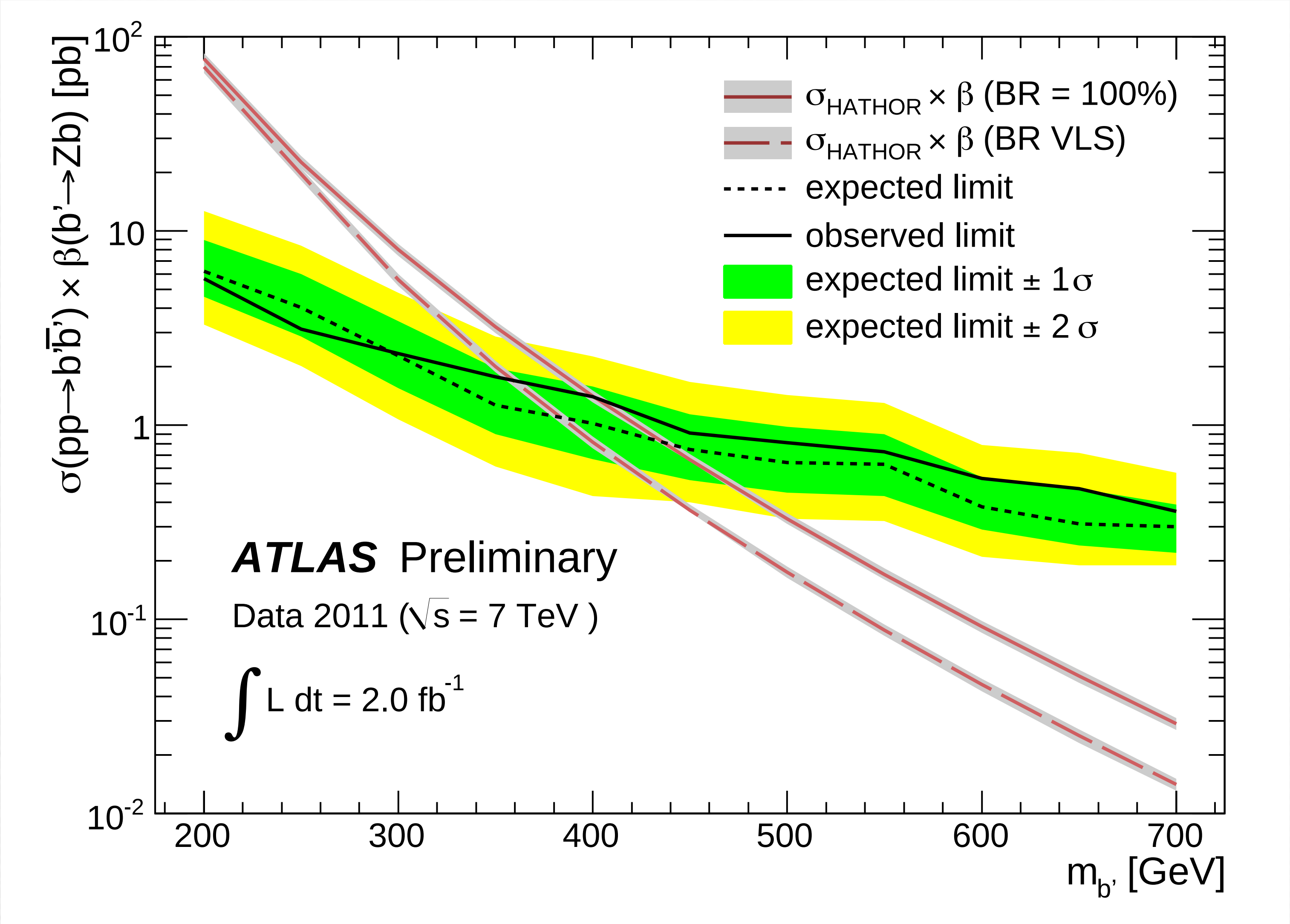
CMS limits on T->tZ

$pp \to T\bar{T}X$, 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})



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

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

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

[CMS L=1.14 fb^{-1}] $B\bar{B} \to WtW\bar{t} \to l^{\pm}l^{\pm}\ b\ 3j\ E_T$
PAS-EXO-11-036 $\to lll\ b\ 1j\ E_T$

$m_B > 495$ 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

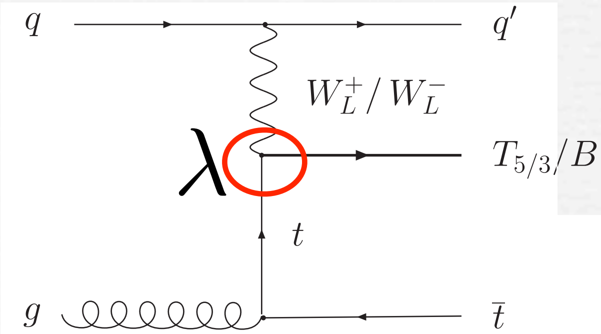
[CMS L=4.7 fb^{-1}] **dilepton** $M_{t'} \gtrsim 552$ GeV
PAS-EXO-11-050

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

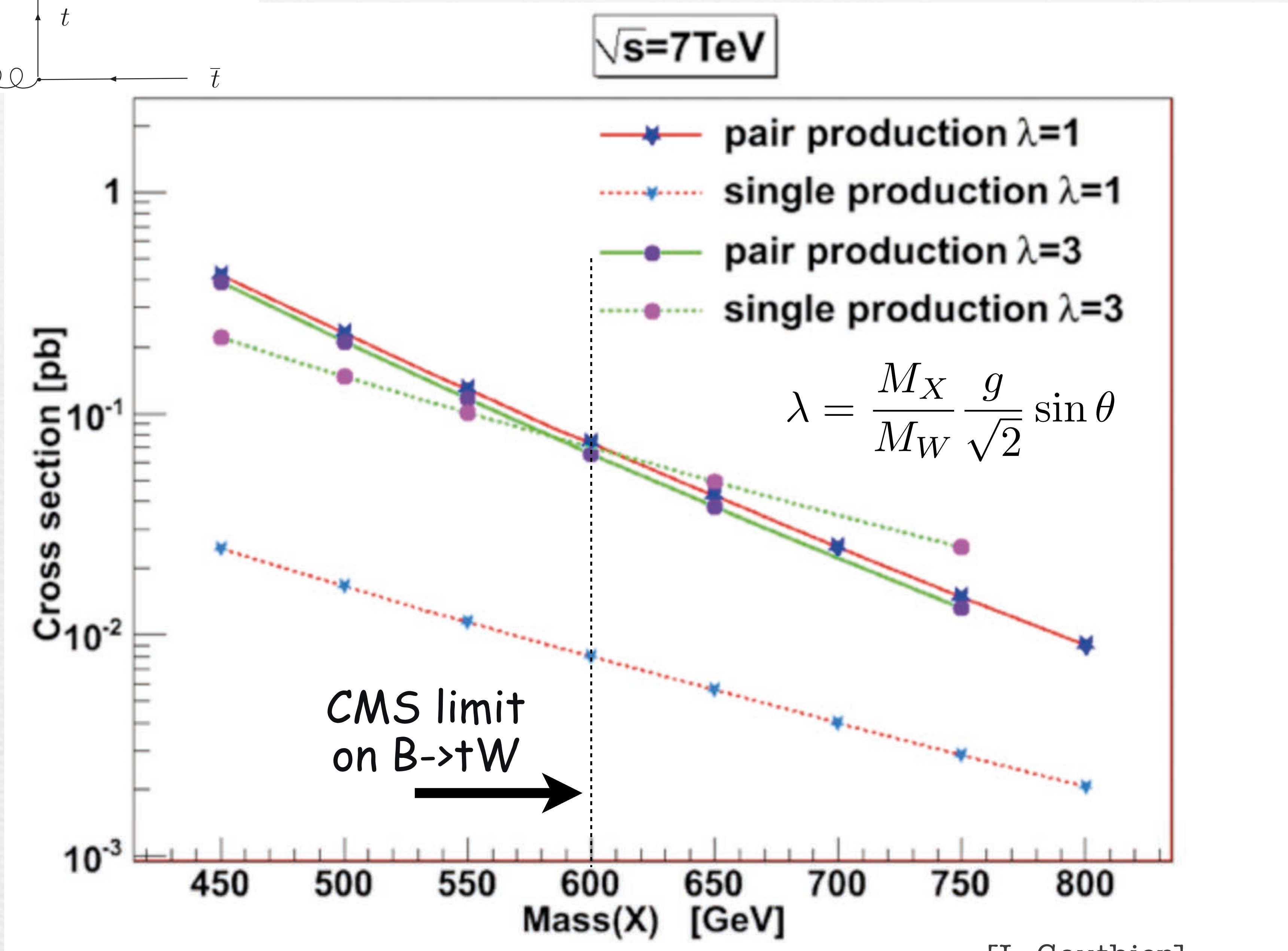
[ATLAS L=1.1 fb^{-1}]

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:1203.xxxx **b'->bZ** $M_{b'} \gtrsim 400$GeV



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



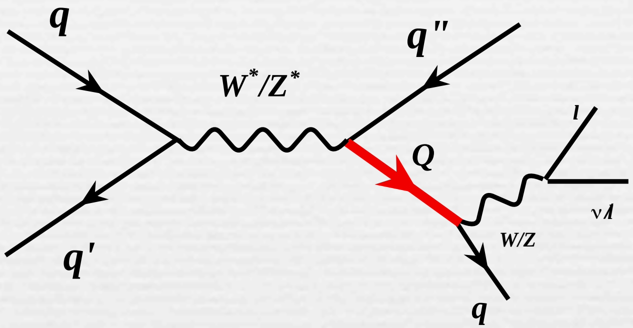
[L. Gauthier]

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

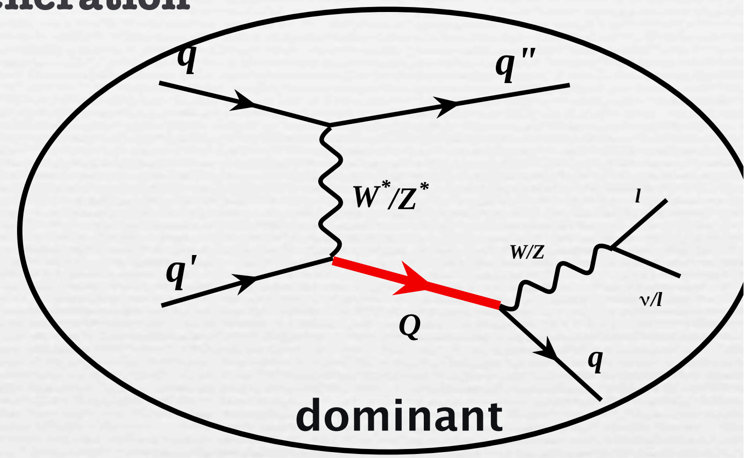
arXiv:1112.5755

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

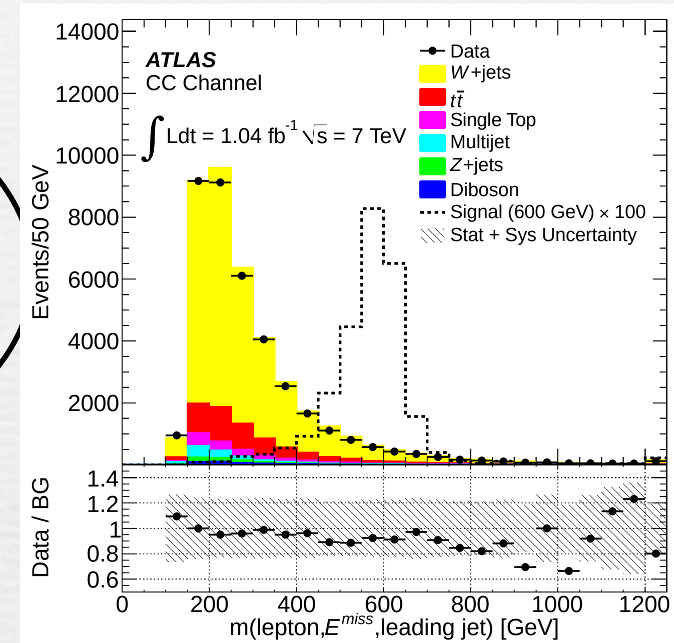
although new vector quarks expected to couple sizably only to third generation

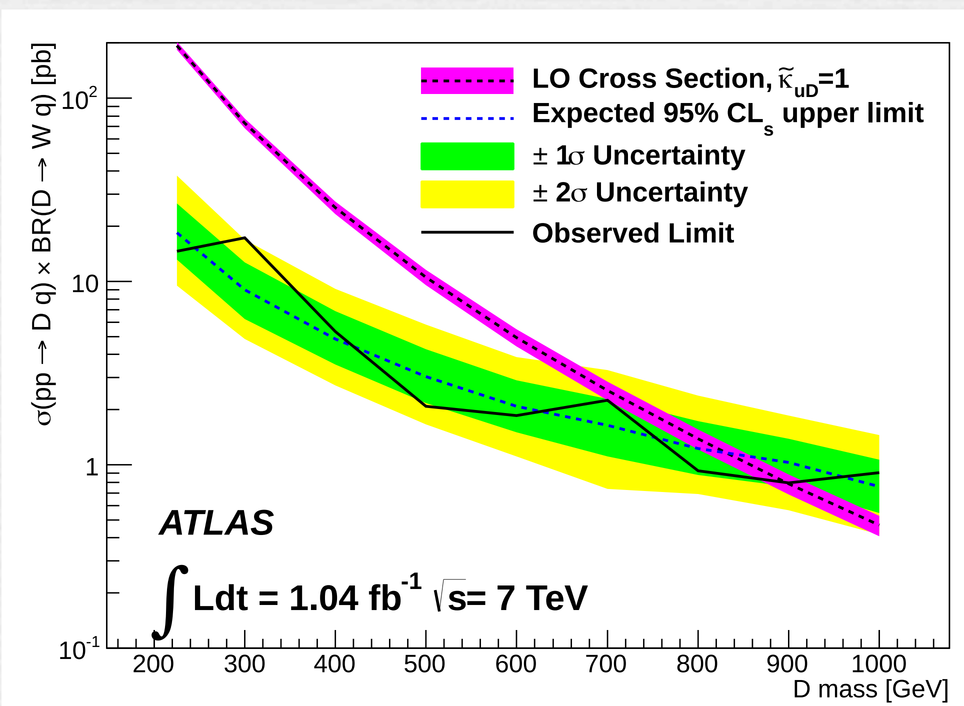


negligible



dominant





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

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

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

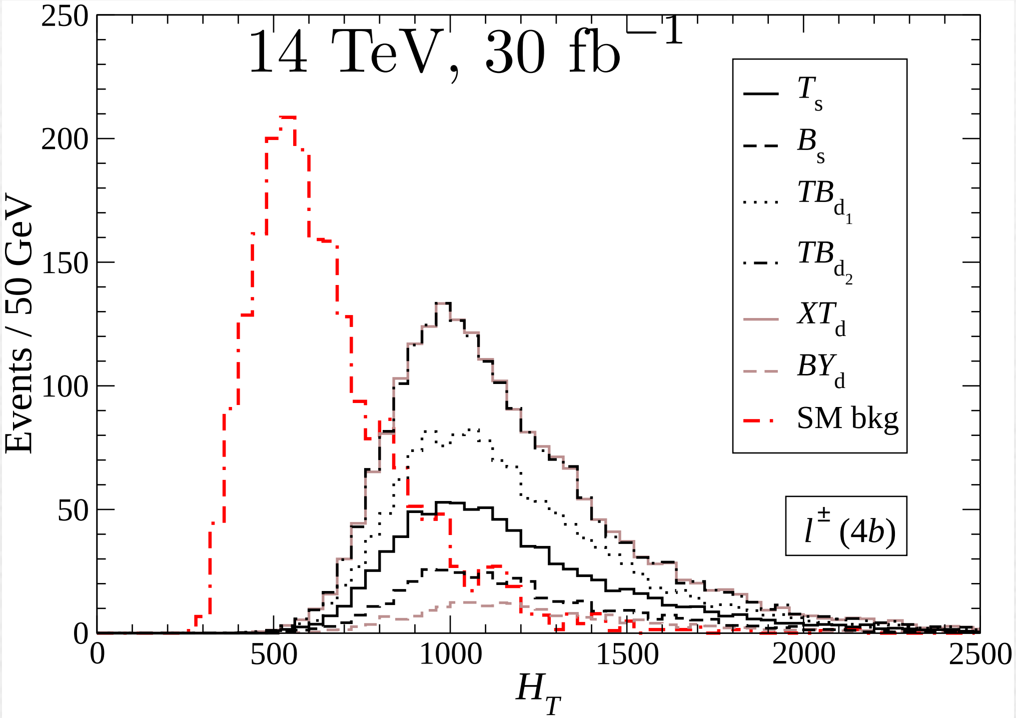
[Aguilar-Saavedra, 0907.3155]

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

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

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

$l^\pm + 4b$ final state

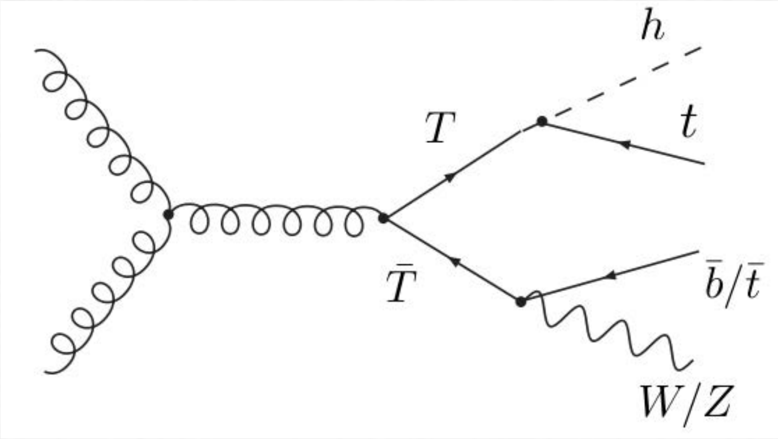


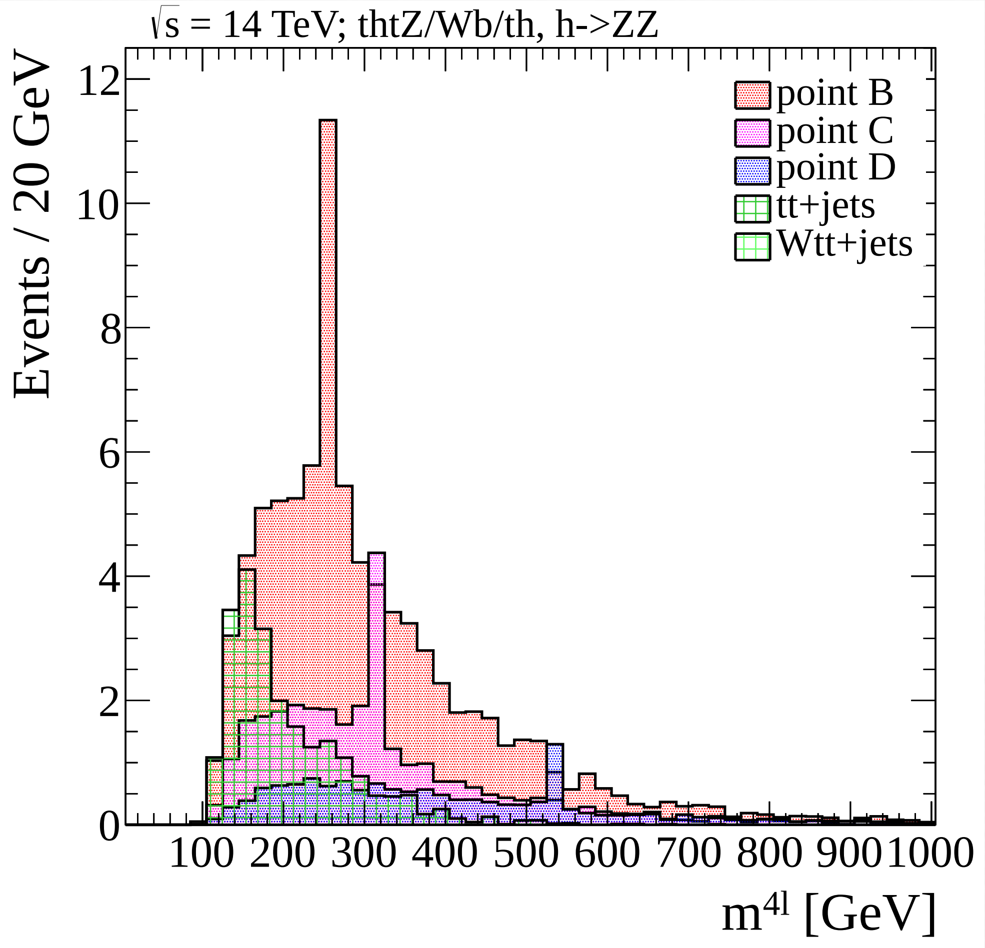
$$T\bar{T} \to HtH\bar{t} \to HW^+bHW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$

$l^\pm + 6b$ final state

Prospects for T->tH with heavy Higgs

[Azatov et al,
Les Houches report, 1203.1488]





$$M_H = 255, 320, 540\ \text{GeV}$$

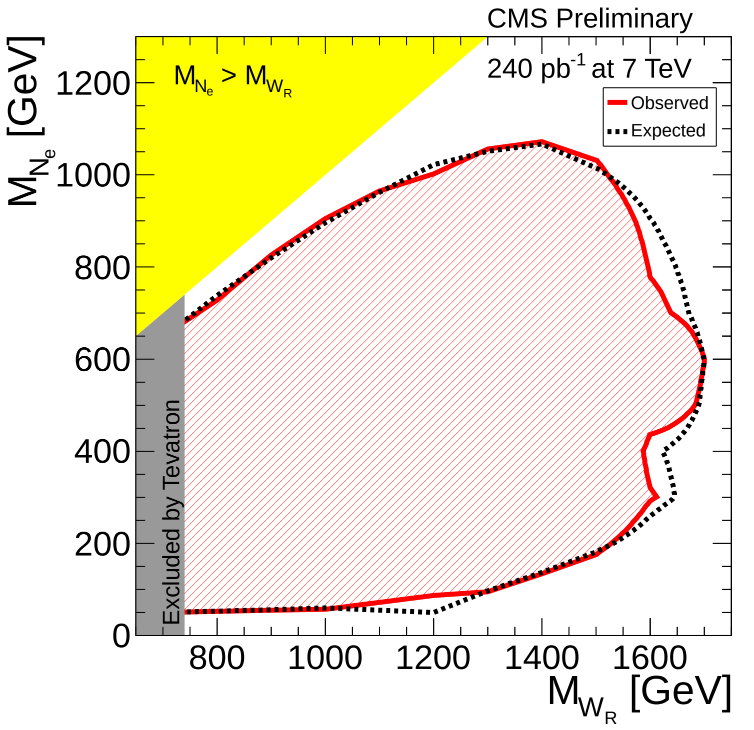
Heavy Leptons

Heavy neutrinos:

In SM with Left-Right symmetry

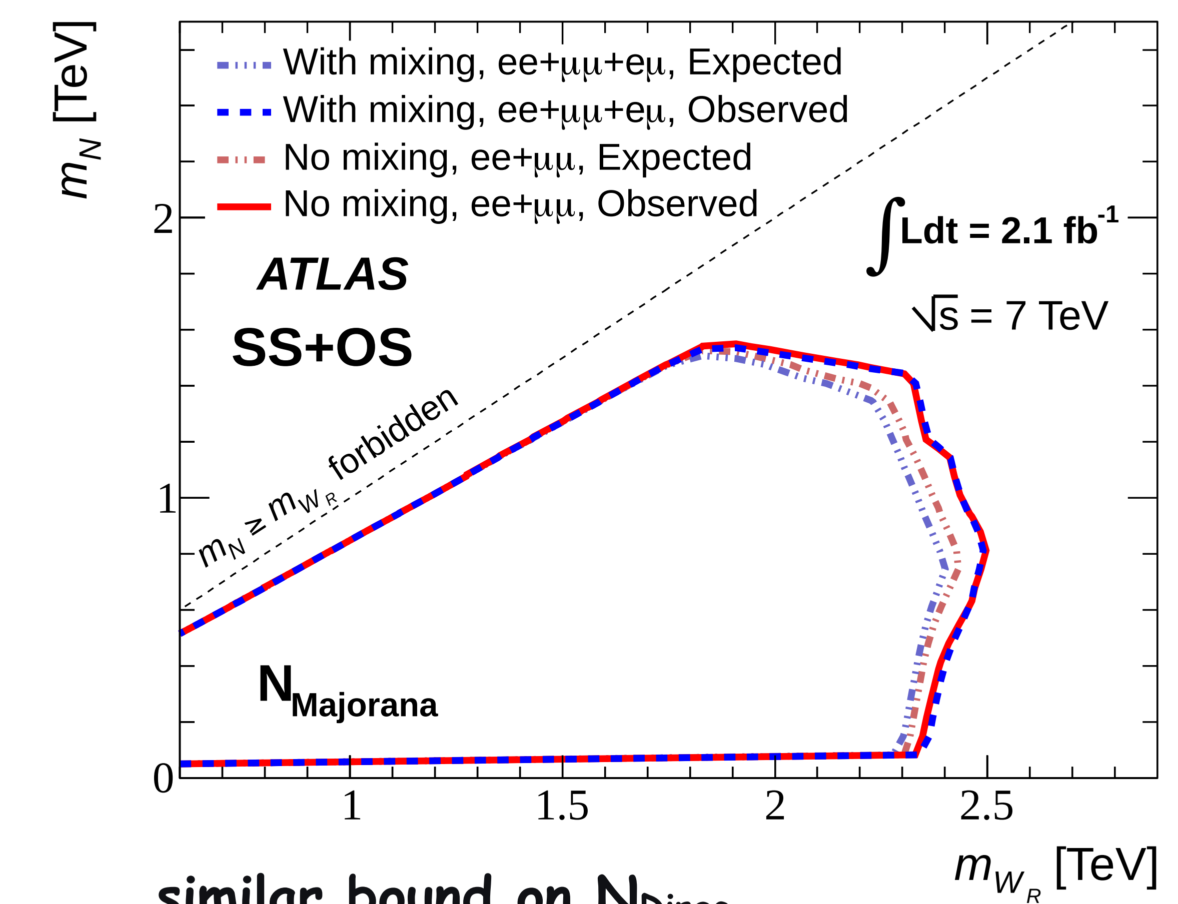
$$pp \to W_R + X \to N_\ell + \ell + X. \qquad W_R \to \ell_1 N_\ell \to \ell_1 \ell_2 W_R^* \to \ell_1 \ell_2 jj \quad (\ell = e, \mu)$$

july 2011



CMS PAS EXO-11-002

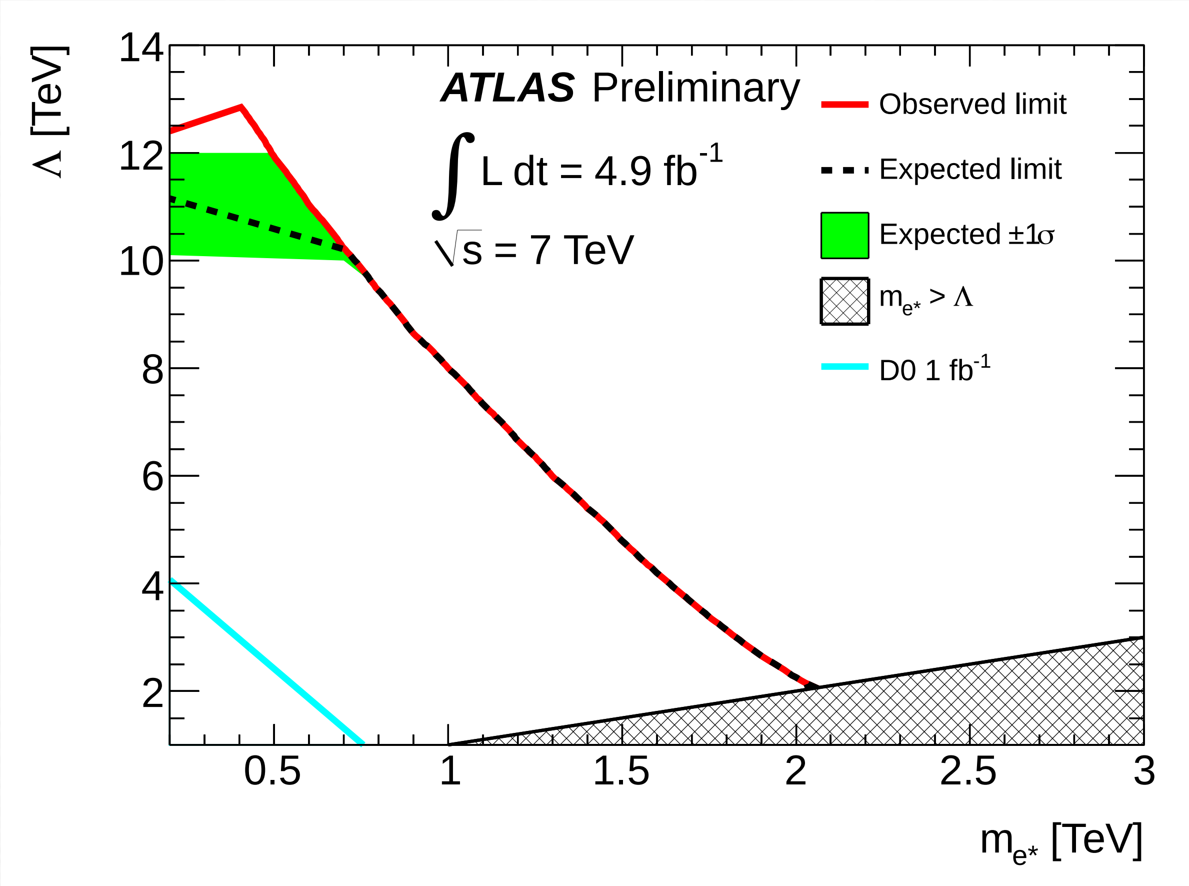
march 2012



similar bound on N_{Dirac}

Excited leptons:

$$\mathcal{L}_{\rm GM} = \frac{1}{2\Lambda}\bar{\ell}^*_R \sigma^{\mu\nu}\left[g f \frac{\tau^a}{2} W^a_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}\right]\ell_L + h.c.,$$



ATLAS-CONF-2012-008

For $e\gamma$ resonance in $ee\gamma$ events

relevant for vector-like lepton triplet models, e.g.Delgado et al. 1105.5417, Panella et al 1201.3764

End of experimental update

As today, still two paradigms for EW symmetry breaking:

- Weakly coupled NP at the TeV scale -> susy

- Strongly coupled NP at the TeV scale -> composite higgs or higgsless

Particularly motivated is the case in which the Higgs is a light remnant of strong dynamics as 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

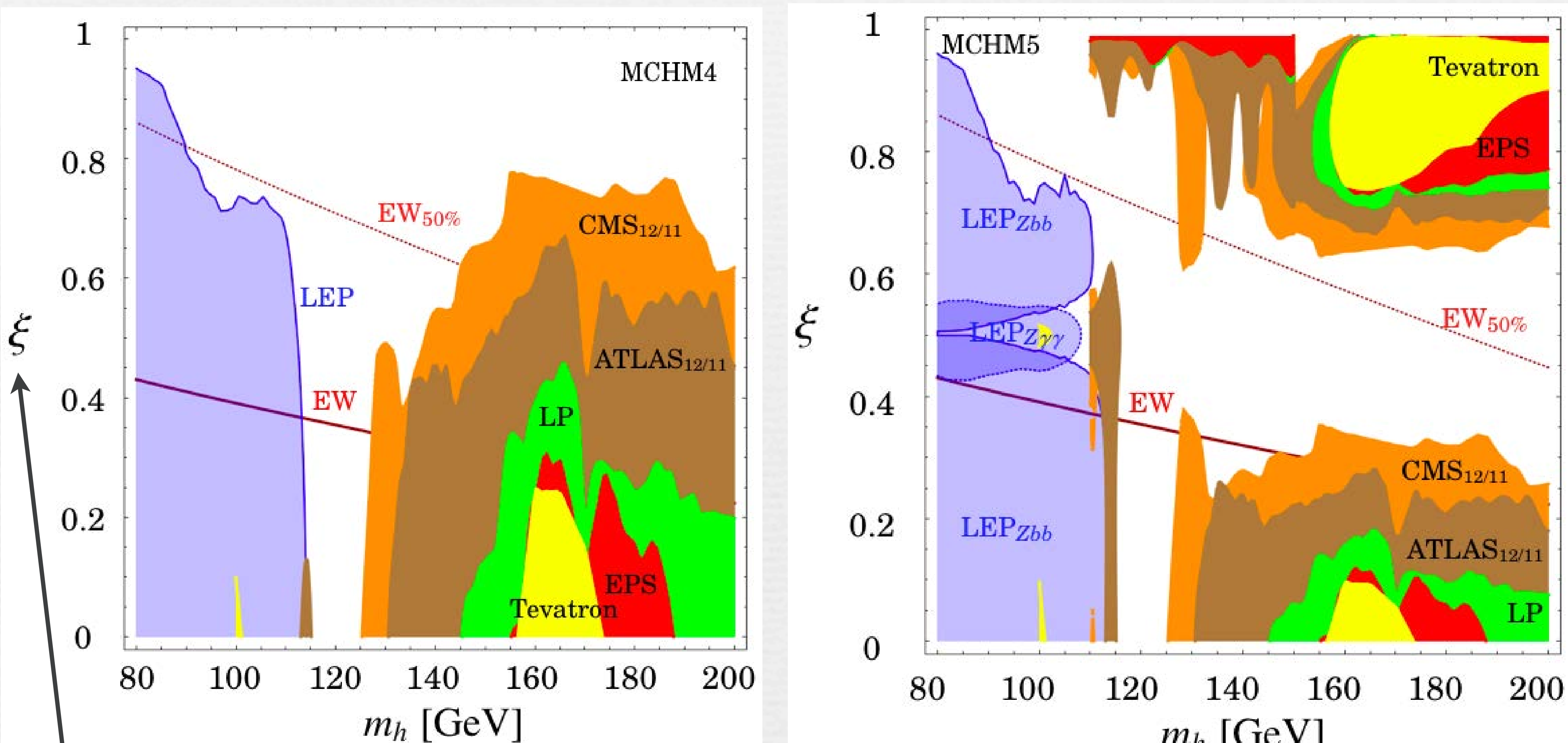
G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}}+\mathbf{\bar{4}_{-2}}=2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
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	$\mathbf{4}_{-5}+\mathbf{\bar{4}_{+5}}=2\times(\mathbf{2},\mathbf{2})$
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

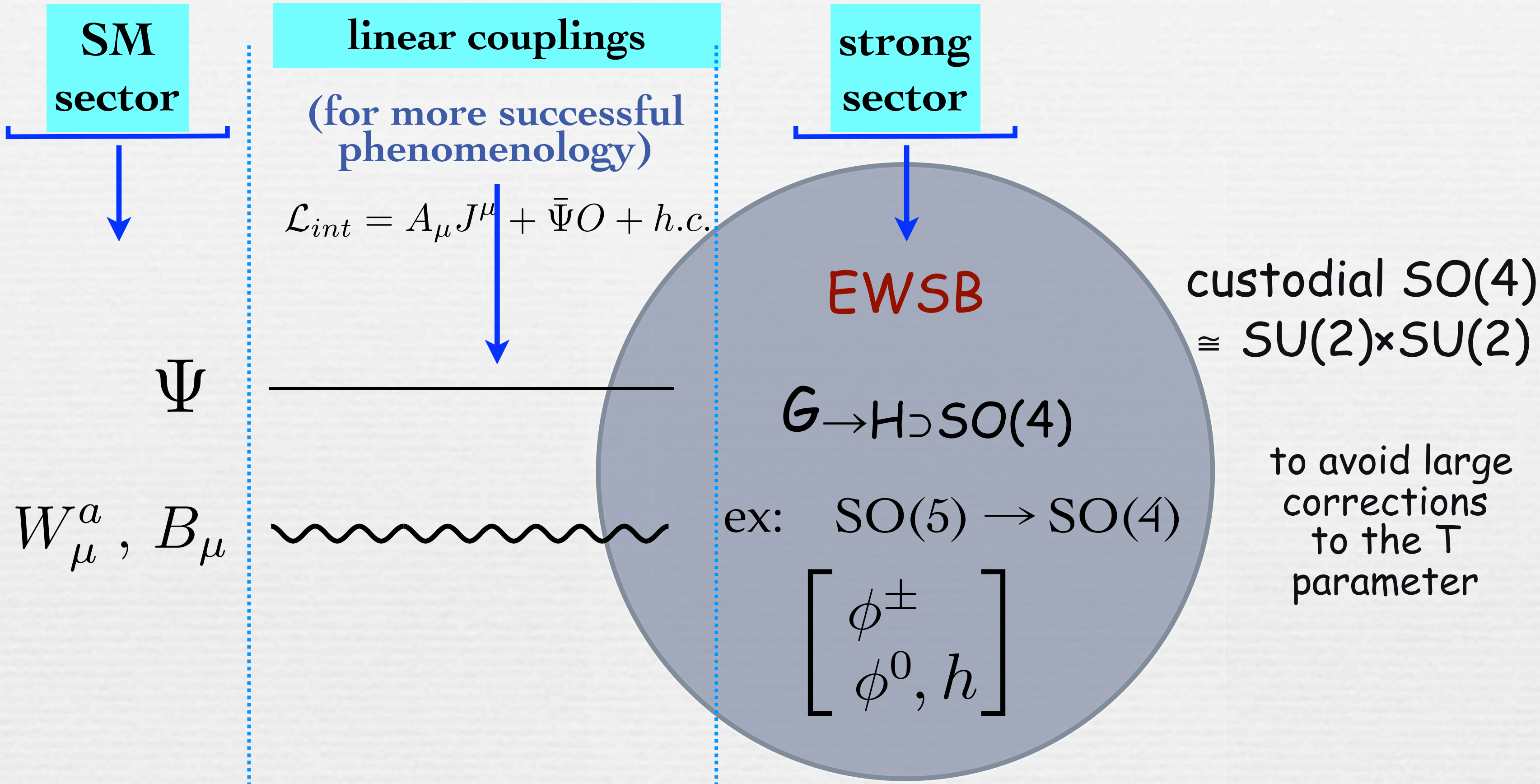
Espinosa et al, 1202.1286



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

(-> 0 in the SM elementary Higgs limit)

General structure -> Partial compositeness

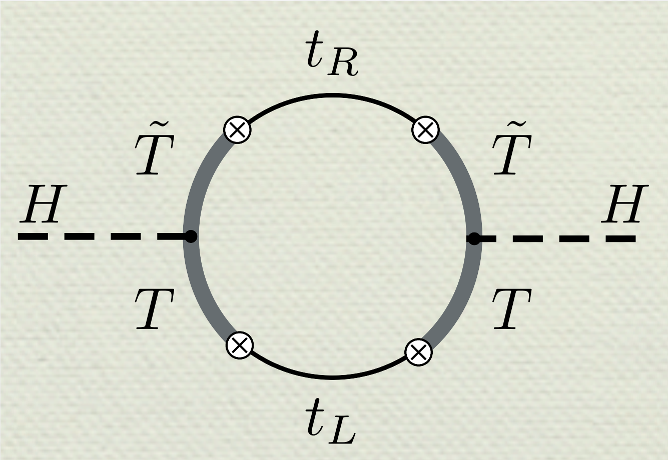


$$\mathcal{L}_{elementary} \qquad \mathcal{L}_{mix} \qquad \mathcal{L}_{composite}$$

$$\mathcal{L} = \bar q_L \not\partial q_L + \bar t_R \not\partial t_R + \Delta_L \bar q_L (T,B) + \Delta_R \bar t_R \tilde T + \mathrm{Tr}\{\bar{\mathcal{Q}}(\not\partial - \underset{\mathbf{2}}{M_{\mathcal{Q}}})\mathcal{Q}\} + \bar{\tilde T}(\not\partial - \underset{\mathbf{1}}{M_{\tilde T}})\tilde T + Y_* \mathrm{Tr}\{\bar{\mathcal{Q}}\,\mathcal{H}\}\,\tilde T + h.c$$

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

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

"Partial compositeness"

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

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:

SM sector:

[mass mixing terms between the 2 sectors]

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

(t_L, b_L)

t_R

electric charge +5/3

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

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

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

custodians become very light if SM top is largely composite

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

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

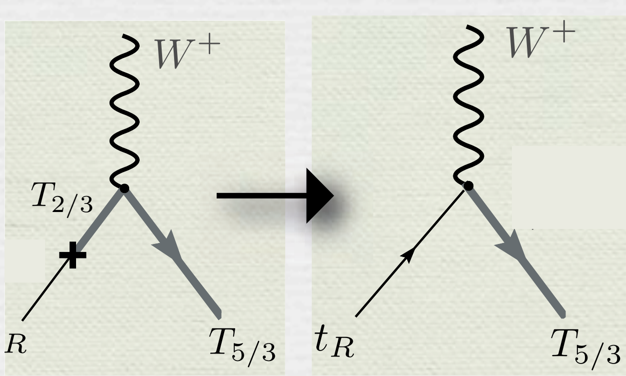
$$Y_* \,\mathrm{Tr}\{\bar{\mathcal{Q}}\,\mathcal{H}\}\,\tilde{T} + h.c$$

Before EW symmetry breaking:

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

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

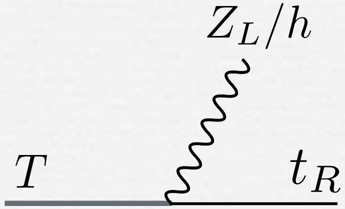
$$\mathcal{M}_{+2/3} = \begin{pmatrix} M_{(2,2)} & c_R\, r & 0 & s_R\, r \\ r & \dfrac{M_{(1,1)}}{c_R} & r & 0 \\ 0 & c_L c_R\, r & \dfrac{M_{(2,2)}}{c_L} & c_L s_R\, r \\ 0 & s_L c_R\, r & 0 & s_L s_R\, r \end{pmatrix}$$



-> the charged current interaction reads:

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

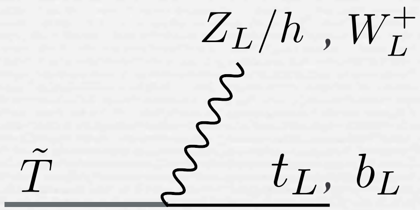
These new fermions couple strongly to the 3rd generation SM quarks plus one W_L , Z_L or h



FCNC : absent for a 4th generation !

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

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

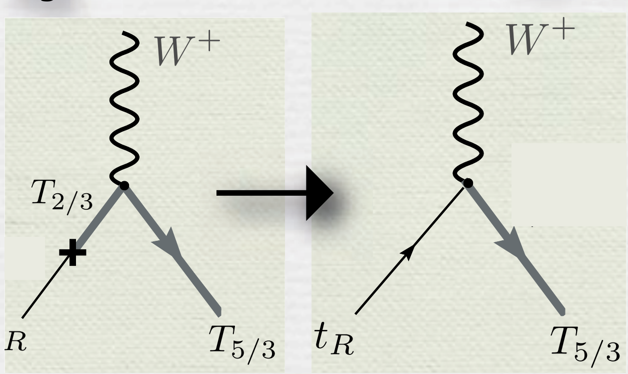


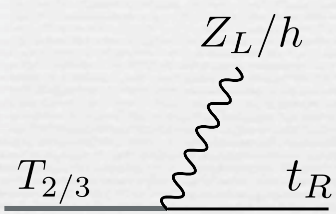
$Y_* \sin\varphi_L \cos\varphi_R$

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

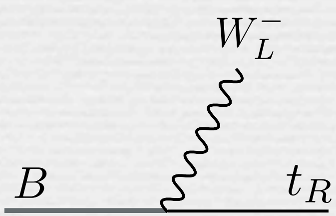
after rotating to mass eigen state basis

e.g

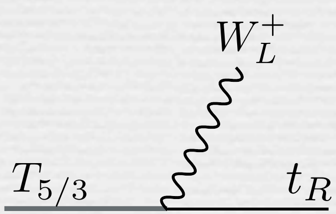




$Y_* \sin\varphi_R$



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



$Y_* \sin\varphi_R$

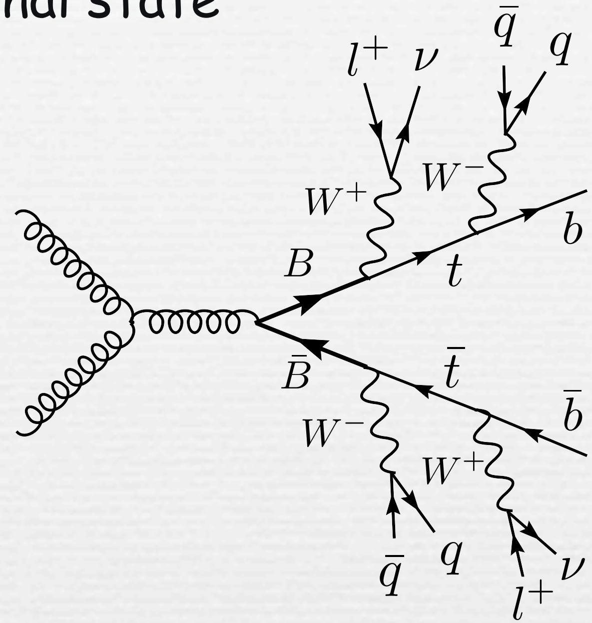
Single production and decays proceed via these couplings

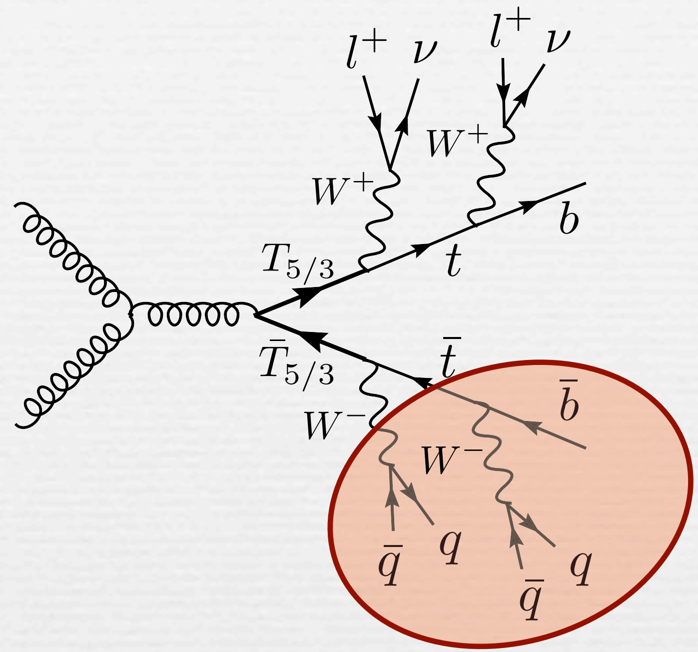
Pair production proceeds via the usual QCD coupling

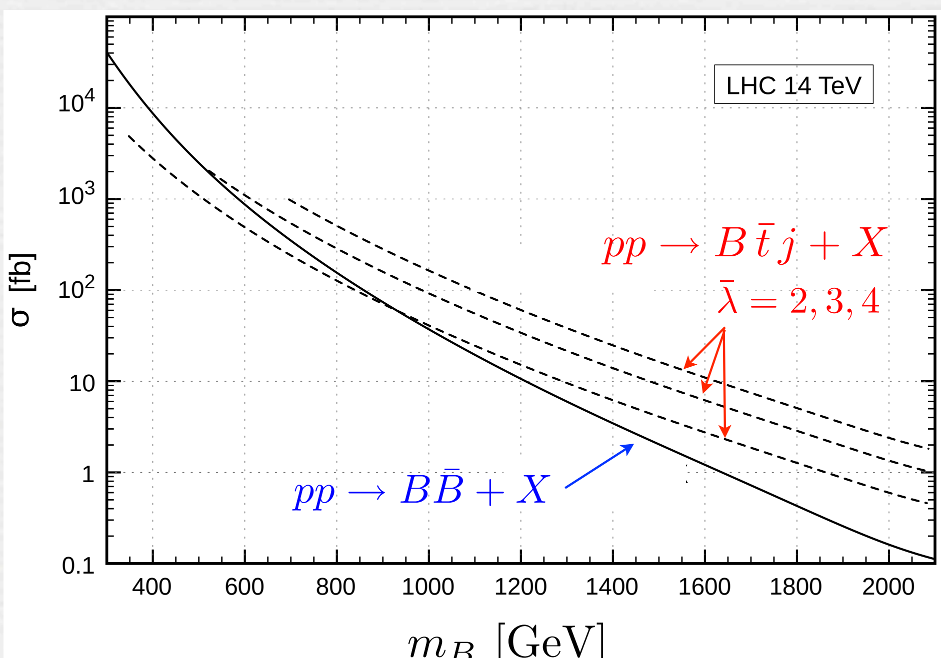
Look for $\bar{B}B$ and $T_{5/3}\,\bar{T}_{5/3}$ in same-sign dilepton final states

[Contino & Servant, '08]

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

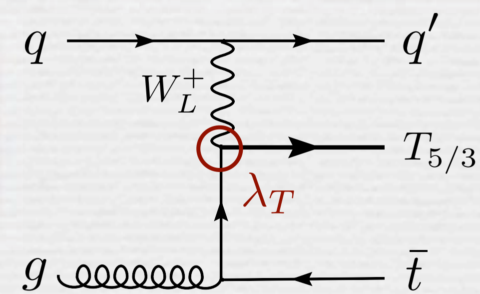






✔ For the $T_{5/3}$ case one can reconstruct the resonant (tW) invariant mass

Single production also relevant



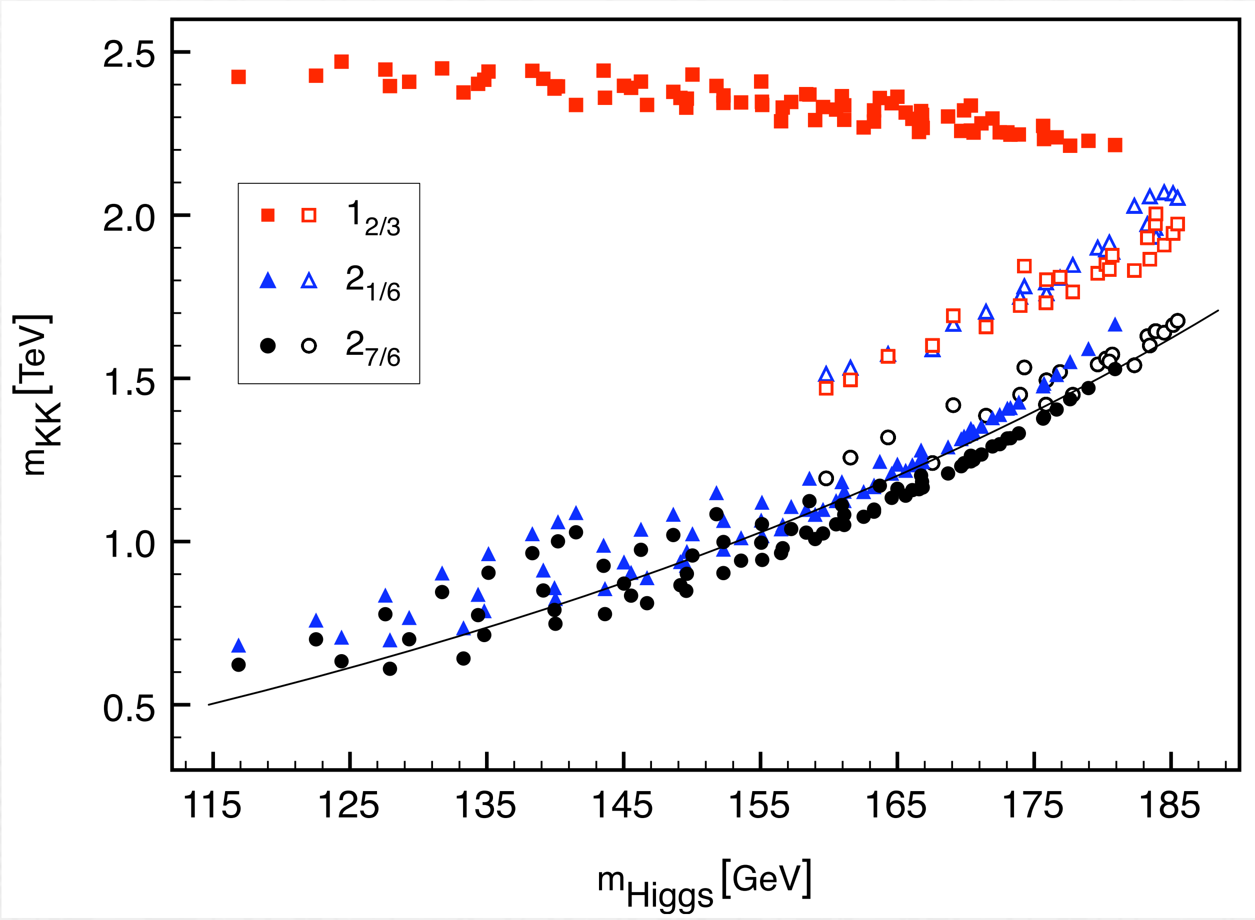
[Mrazek & Wulzer, '09]

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

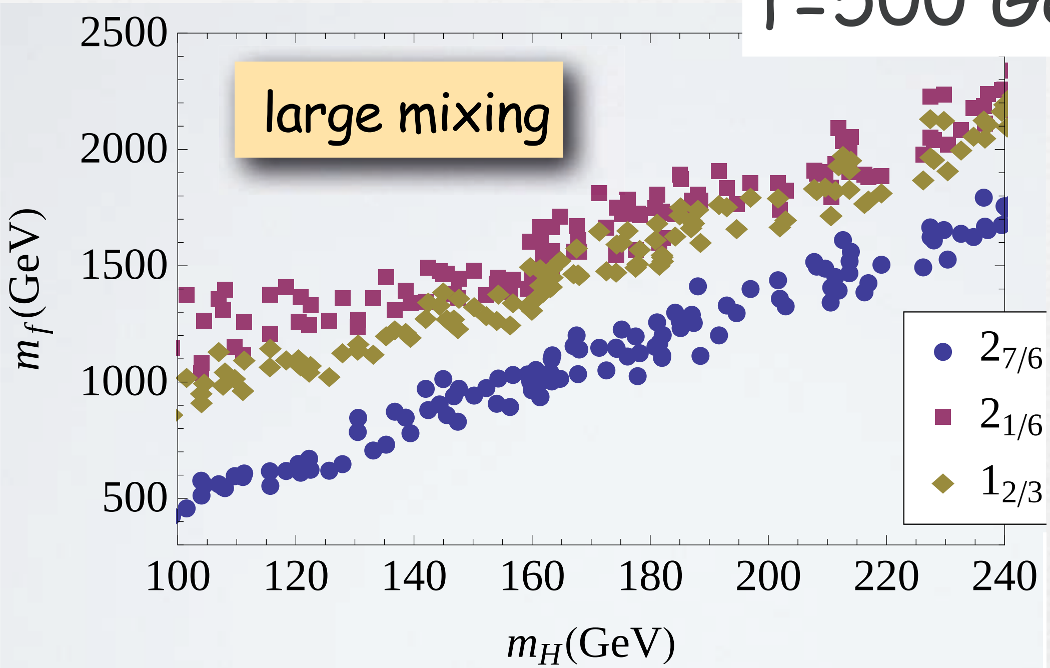
[Contino, Da Rold, Pomarol'06]



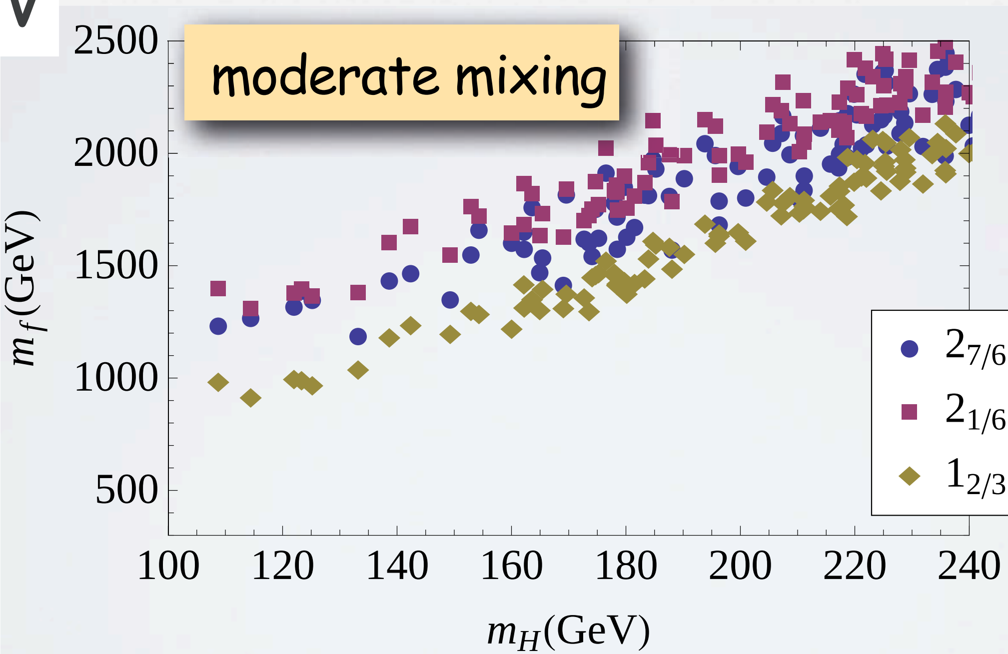
Light Higgs wants light top partners

[De Curtis, Redi, Tesi 1110.1613]

f=500 GeV



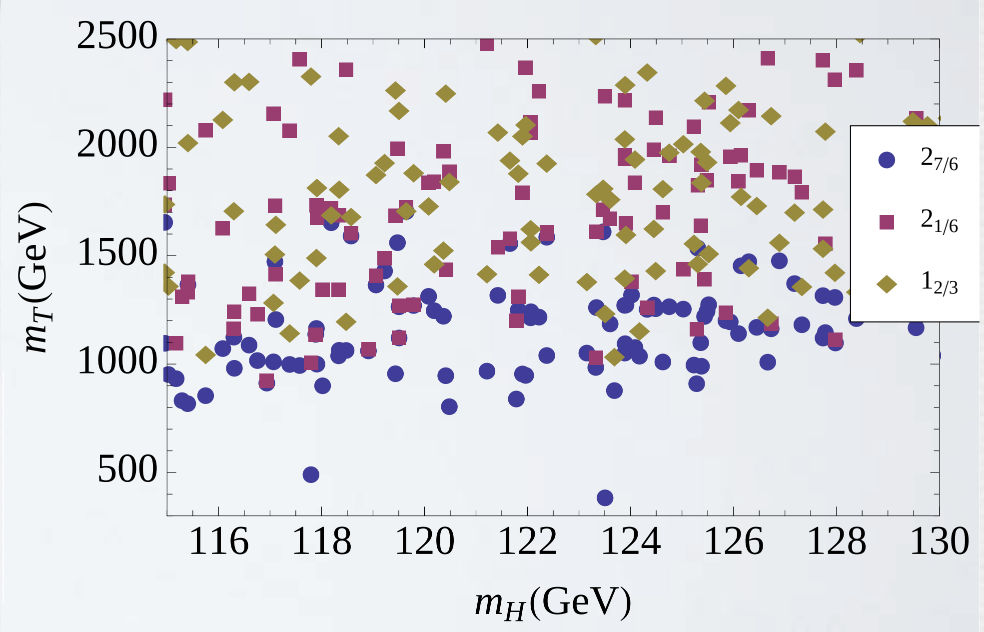
lightest fermion: doublet



lightest fermion: singlet

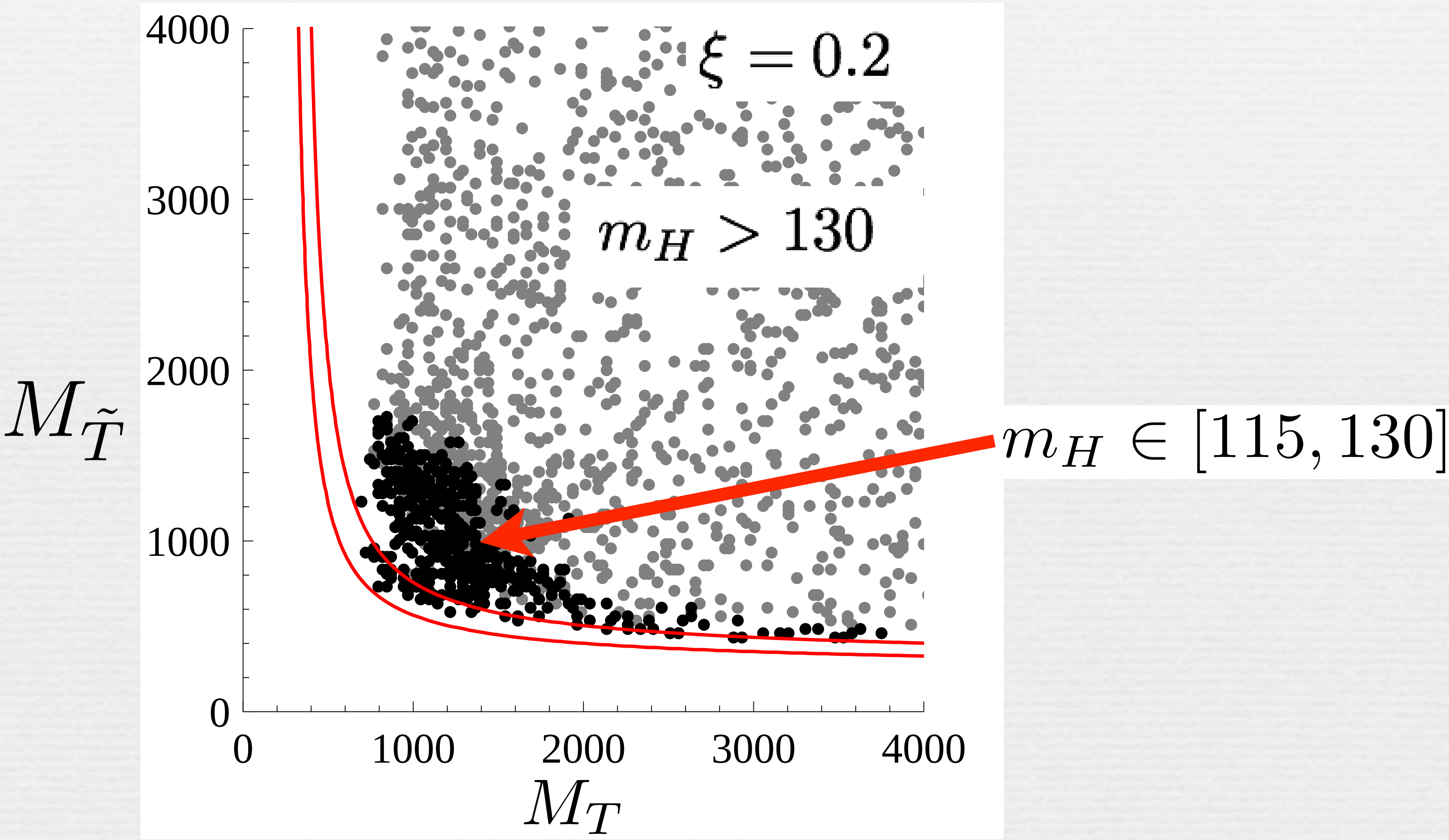
f=800 GeV

-> partners above experimental bound



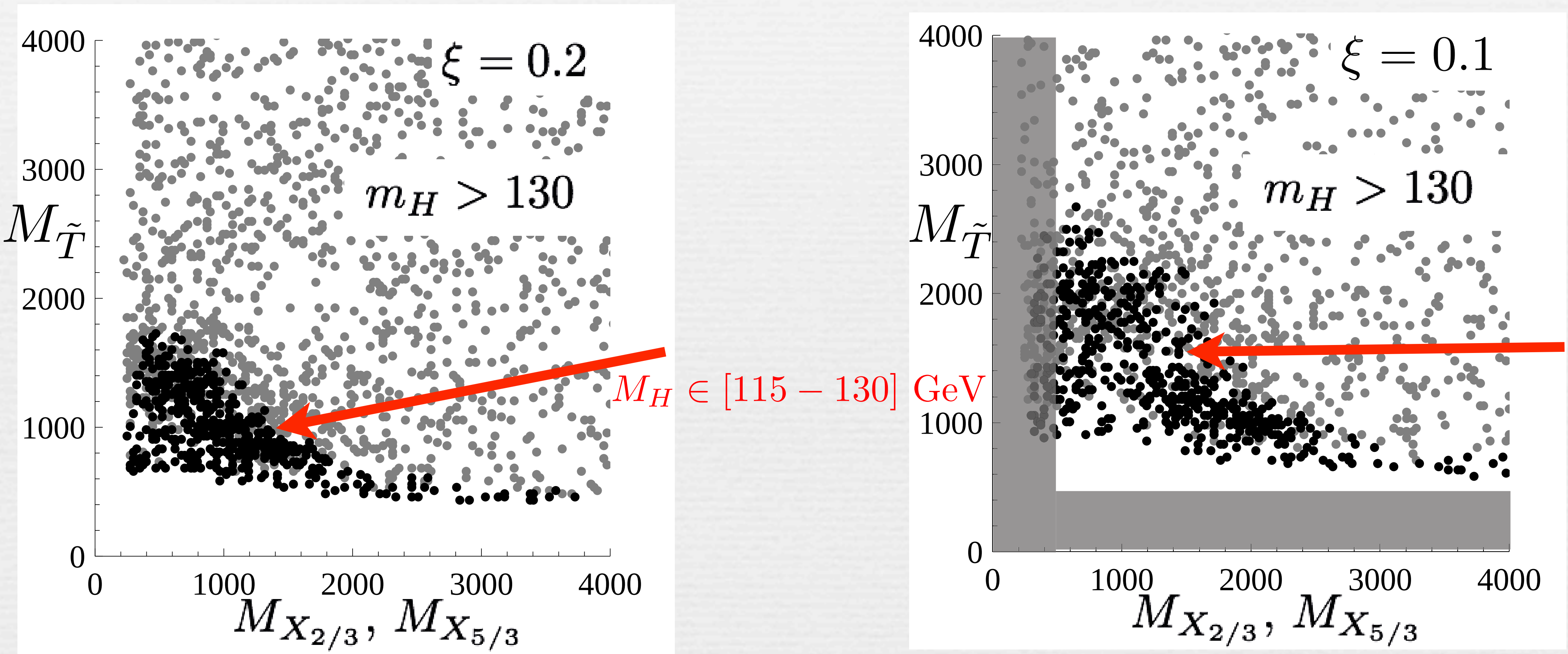
Light Higgs wants light top partners

[Panico & Wulzer, 1106.2719]



[Wulzer,2012]

Exotic bi-doublet is even lighter



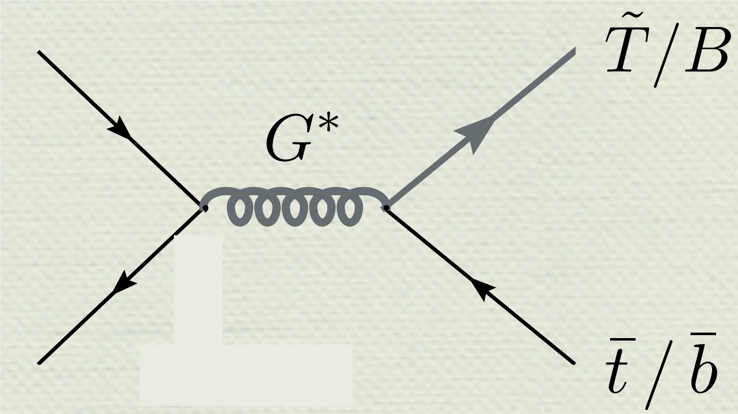
[Wulzer,2012]

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 $t\bar{t}$

Mass reach depends on:

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

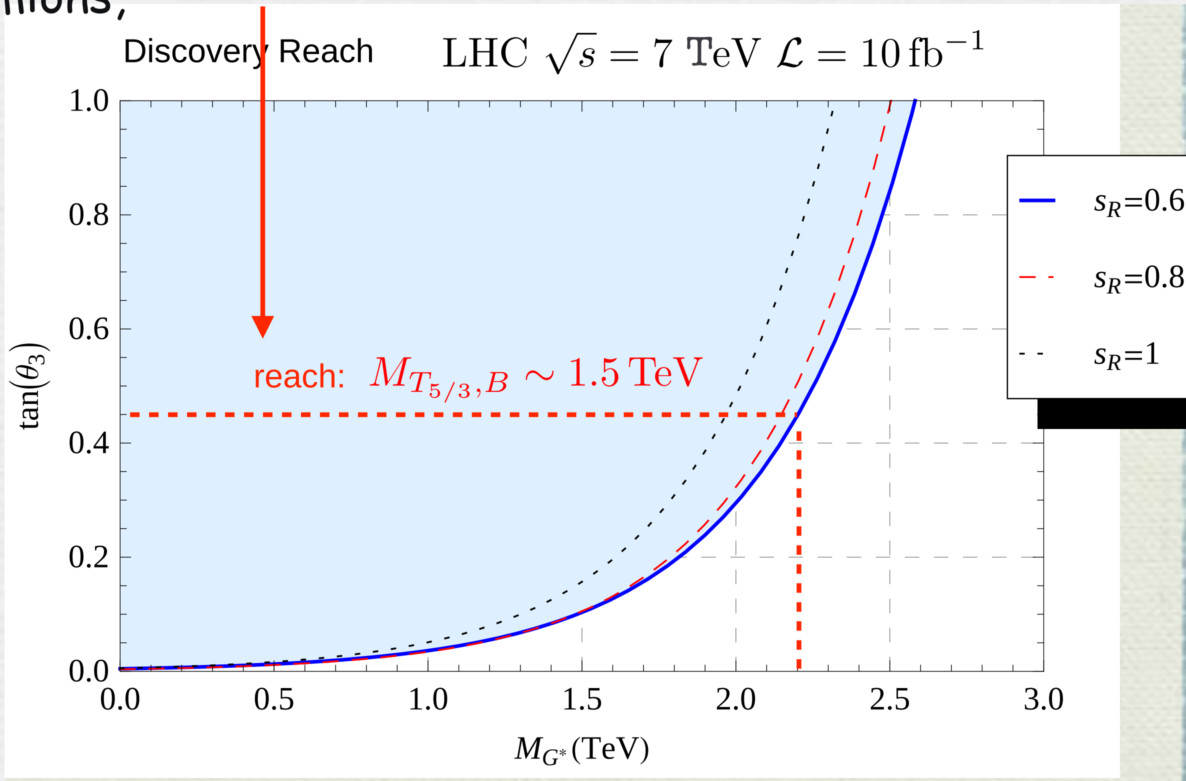
-on coupling between G* and the light fermions,

-on the top degree of compositeness

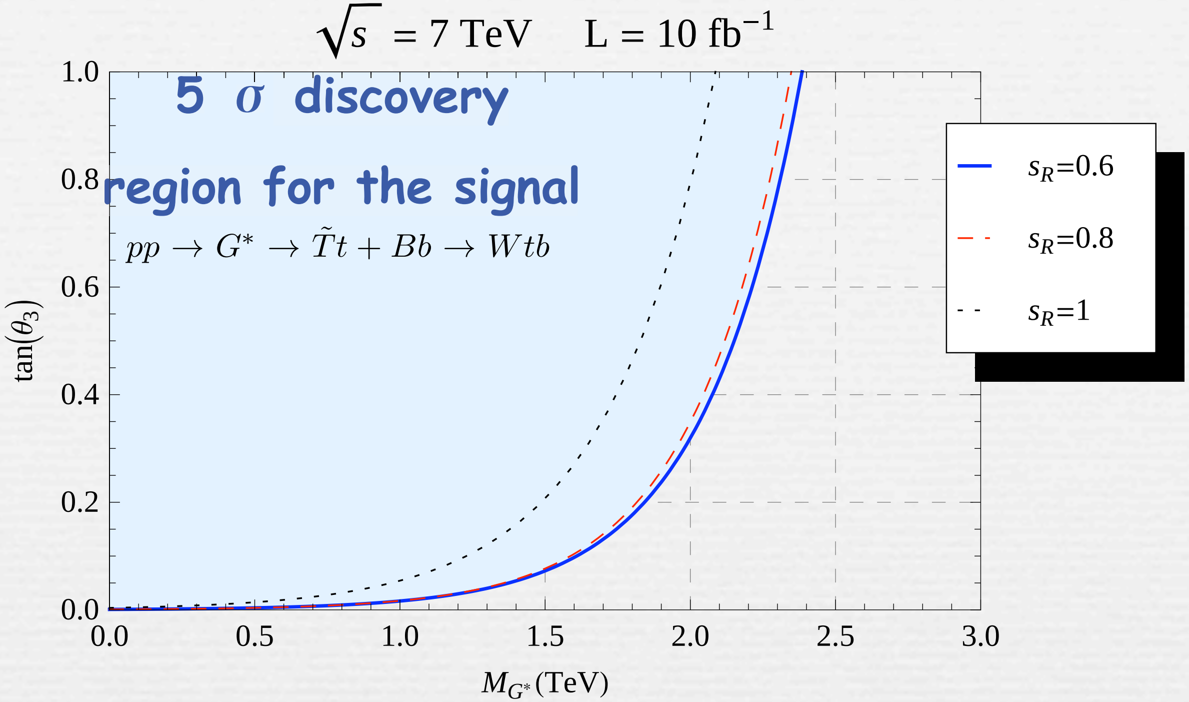
-> model-dependence

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

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

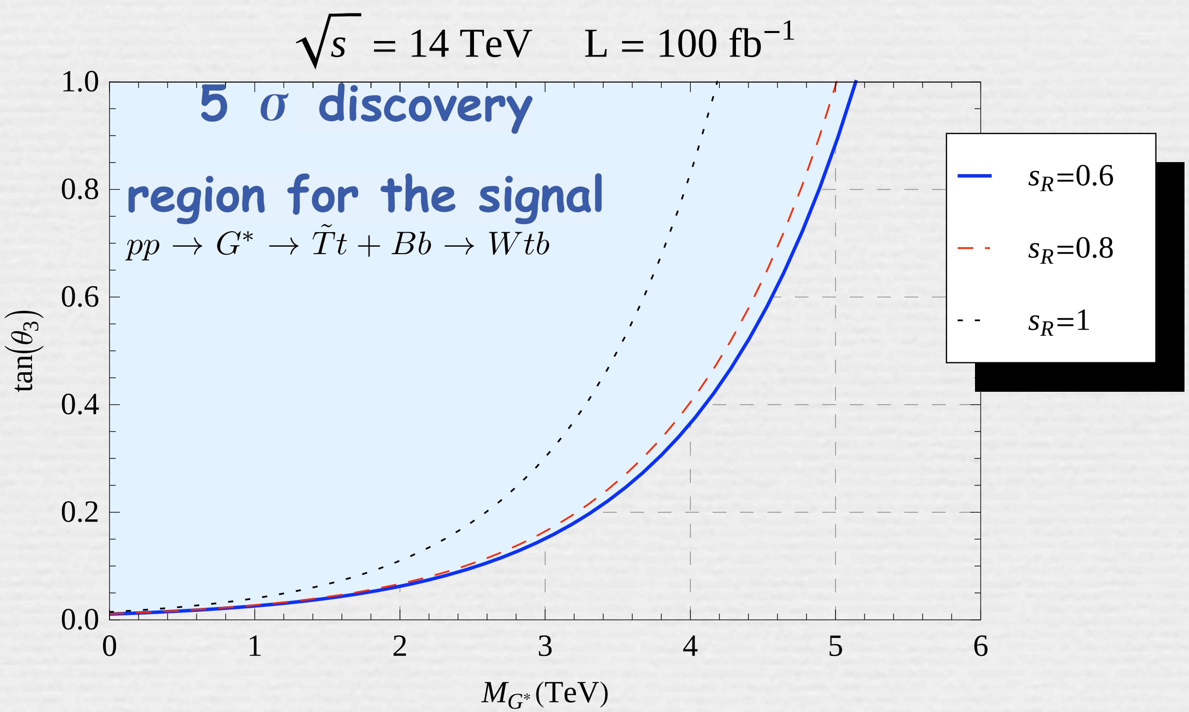


[Contino et al]



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

almost 3 TeV reach for top partner!

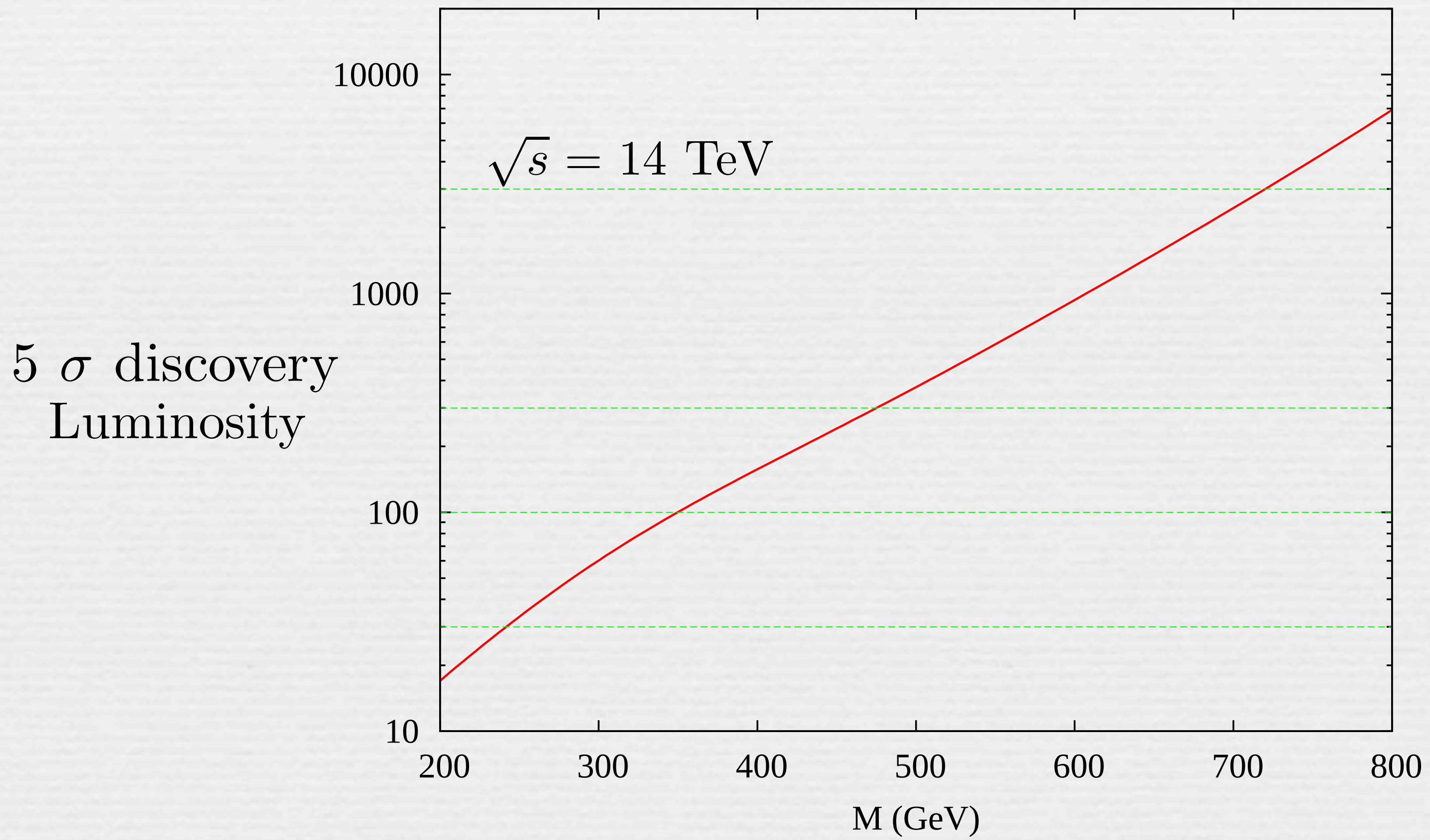


[Bini, Contino , Parisse, Vignaroli, 1110.6058]

Finally: new leptonic resonances

new lepton doublets at the LHC (tau custodians)

[Del Aguila, Carmona, Santiago, 1007.4206]



not particularly encouraging

Summary (same as last time)

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

your feedback on the content of the 4-page report is welcome