Limits on the Fourth Generation

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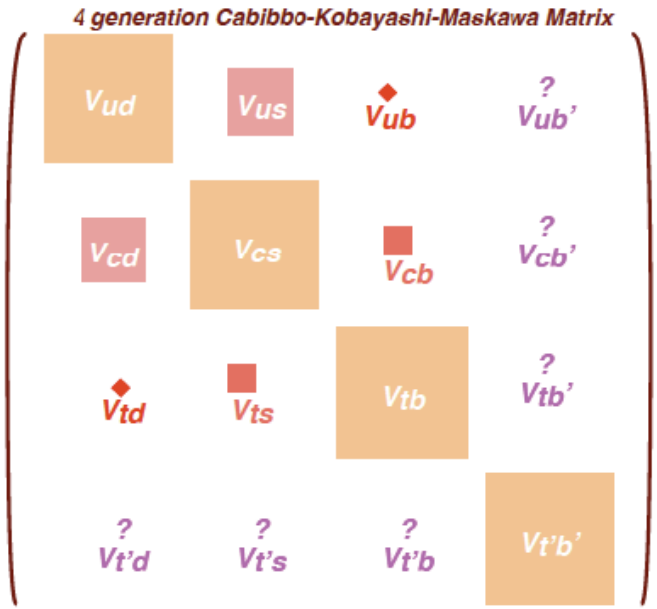
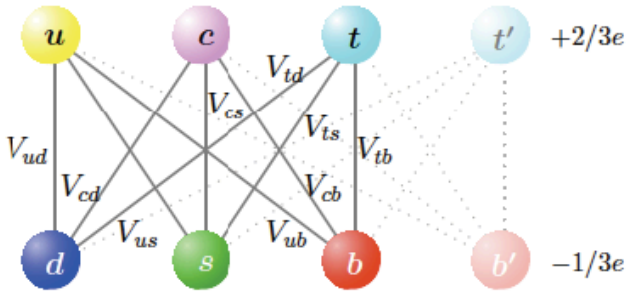
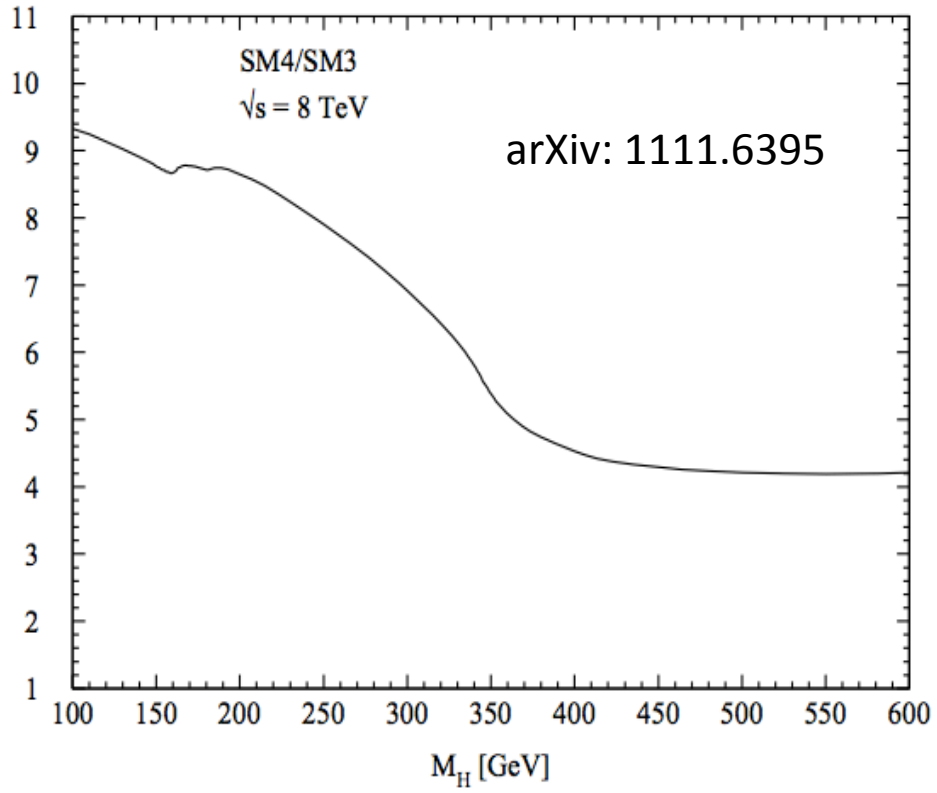
Sequential Fourth Generation

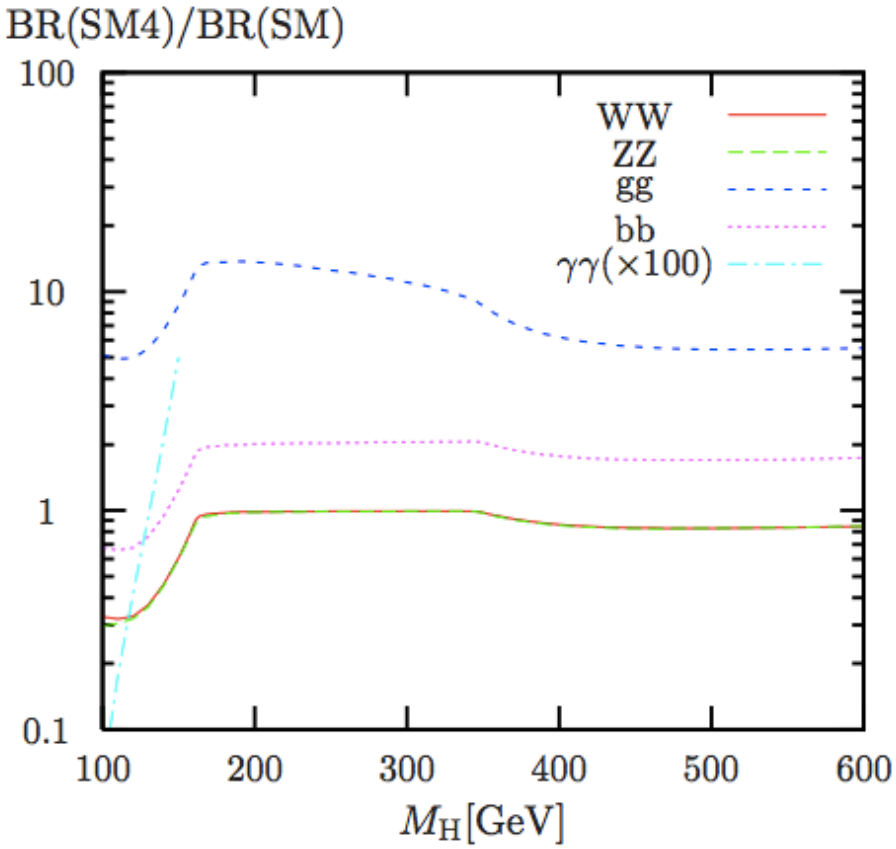
- The sequential fourth generation is a simplest extension of SM3
- Assuming the SM4 a new heavy up-type quark t′ is expected to decay into Wb (Wq) , and a new down-type quark b′ to decay into Wt (Wq)
- Electroweak precision measurement favor small mass splitting between 4th generation quarks $m(t') - m(b') < M_W$





Fourth Generation and Higgs

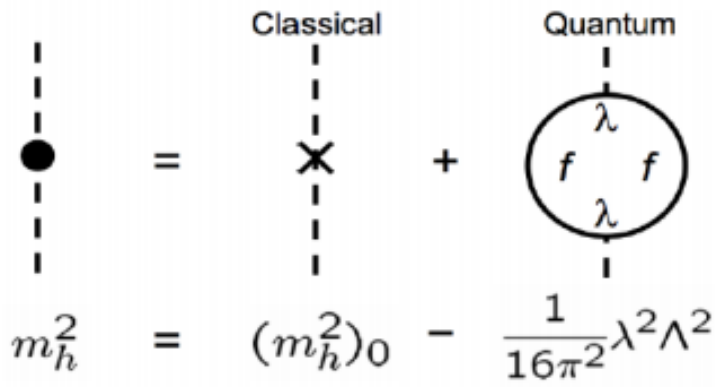




- Higgs cross section measurements in various channels disfavor sequential 4th generation, since this model predicts a specific hierarchy of signal strengths which are not supported by experimental results

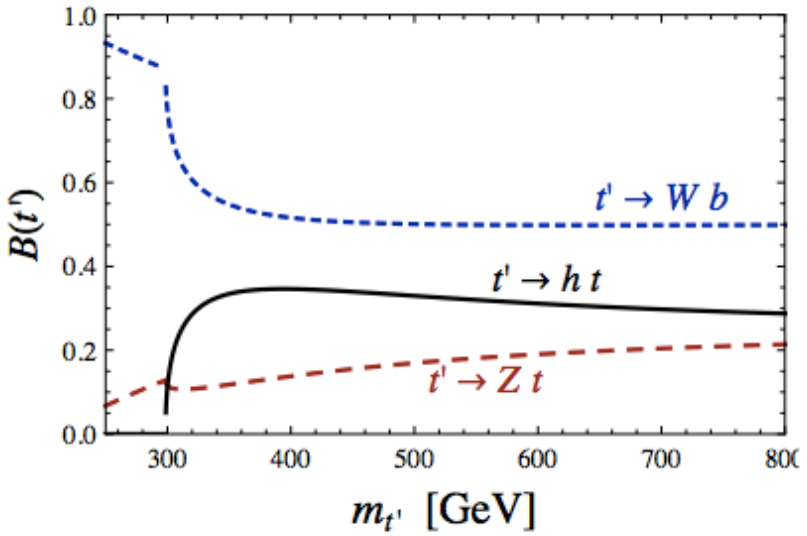
Vector-Like Quark

- Vector-like quarks, where both chiralities have the same transformations under the electroweak group SU(2)xU(1)
- Vector-like quarks appear in
  - Little Higgs model
  - Warped extra dimensions
  - Non-minimal super-symmetric extensions
- Cancel quadratic divergences in the Higgs mass induced by radiative corrections in top quark



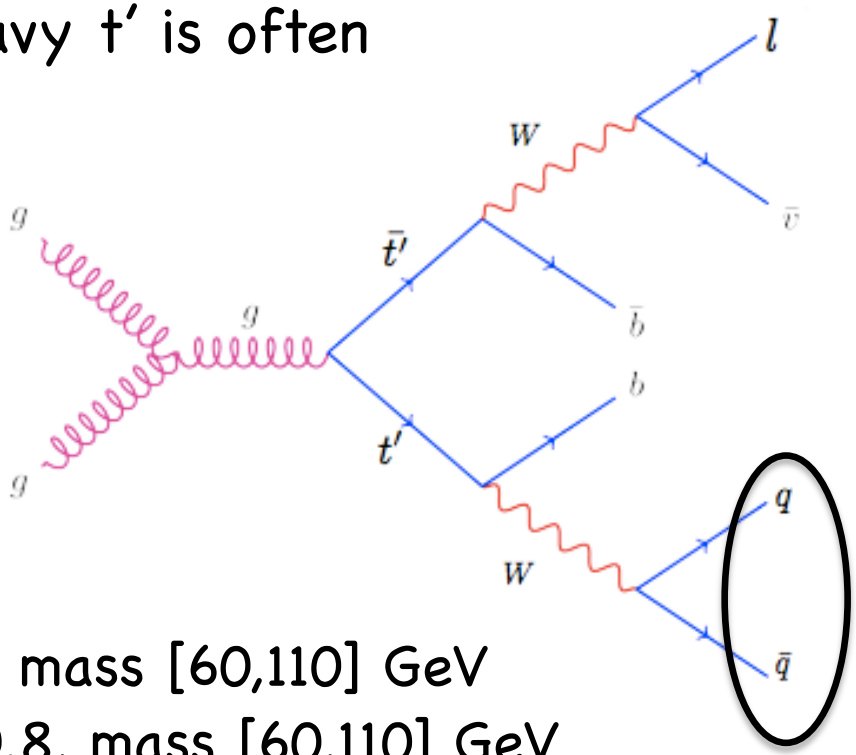
Vector-Like Quark

- Production at LHC:
  - Pair production via strong interactions
    - Cross sections based on HATHOR (Hadronic Top and Heavy quarks crOss section calculatoR)
  - Single production
- Decays (in most models couple to SM 3rd generation quarks):
  - t′ -> Wb and b′->Wt are complemented with FCNC decays t′->Zt, t′->Ht and b′->Zb, Hb, and also t′->tg, tγ at the next leading order diagrams
  - Weak-isospin singlet has three dominant decay modes
  - Weak-isosping doublet t′ decays into Zt, Ht



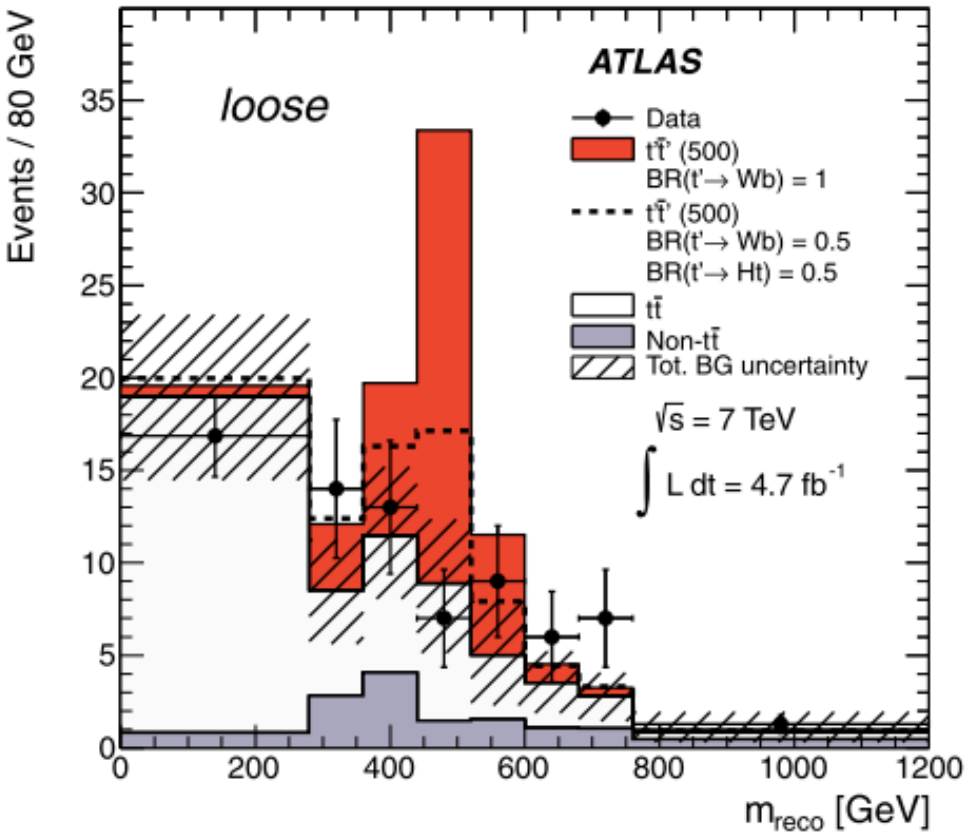
t′ → Wb (ℓ + jets)

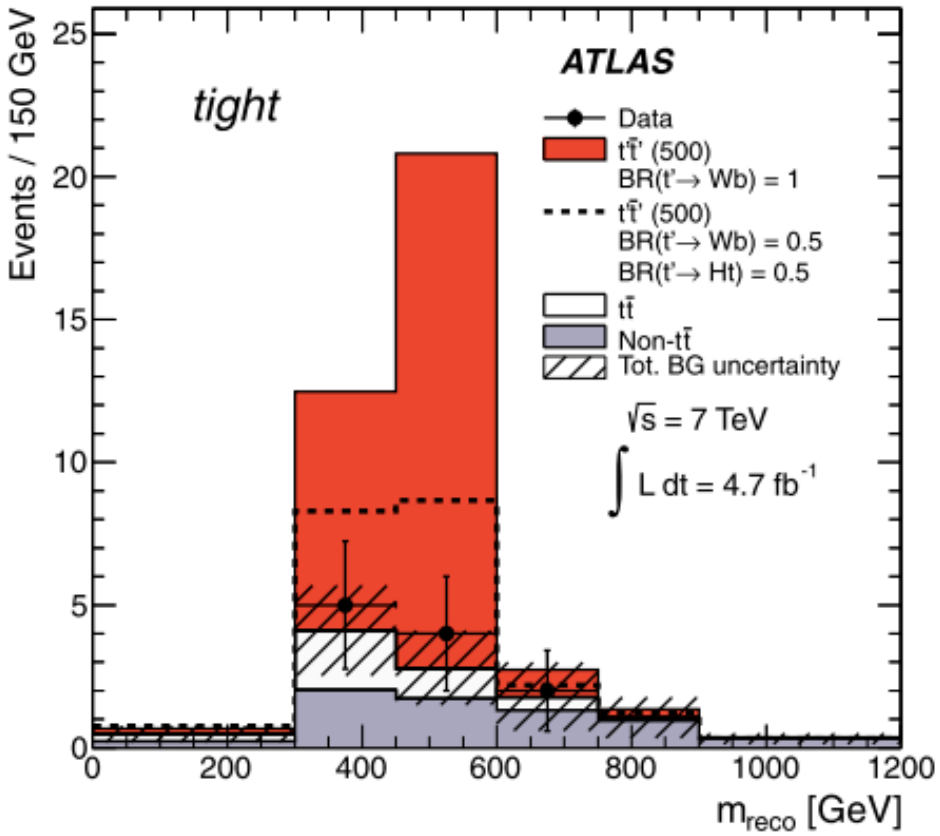
- Exploits the fact that W-boson from heavy t′ is often reconstructed as a single jet
- Event Selection:
  - e/μ , p_T > 25/20 GeV
  - ≥ 3/4 jets, ≥ 1 b-tag, $W_{had}^{typeI/II}$
  - Missing E_T > 35/20 GeV
  - E_T^{Miss} + m_T > 60 GeV
- Hadronic W reconstruction:
  - W_{had}^{typeI} – single jet, p_T > 250 GeV, jet mass [60,110] GeV
  - W_{had}^{typeII} – di-jet, p_T > 150 GeV, ΔR < 0.8, mass [60,110] GeV
- $H_T = p_T^{\ell}$ + Missing E_T + $\sum p_T^{jets}$ > 750 GeV,
- $\Delta R(\ell\nu)$ < 1.4, $b_{1,2}$ p_T > 160/60 GeV
- Tight Selection:
- min $\Delta R(W_{had,}\ b_{1,2})$ > 1.4, min $\Delta R(\ell,\ b_{1,2})$ > 1.4



PLB 718 (2013) 1284

t′ → Wb (ℓ + jets)





- Reconstructed Mass of t′ quark
- Tight Selection used for limit setting using CL_S

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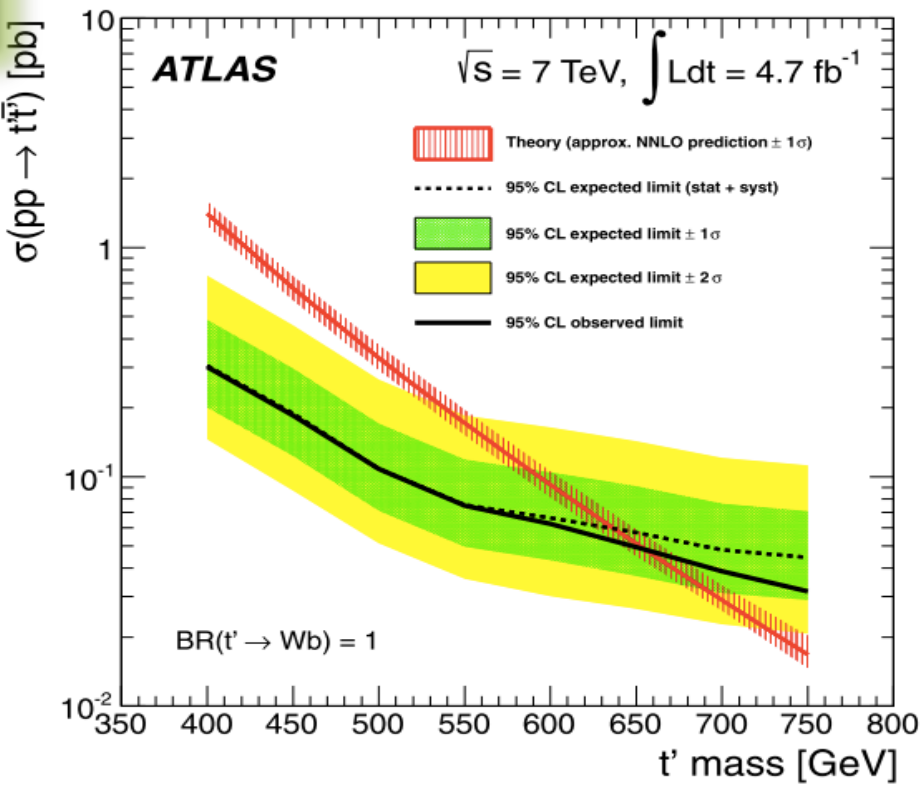
t′ → Wb (ℓ + jets)

$M_{t'}$ > 656 GeV @ 95 % C.L.
BR (t′→Wb) = 100%

MOST STRINGENT LIMIT TO-DATE



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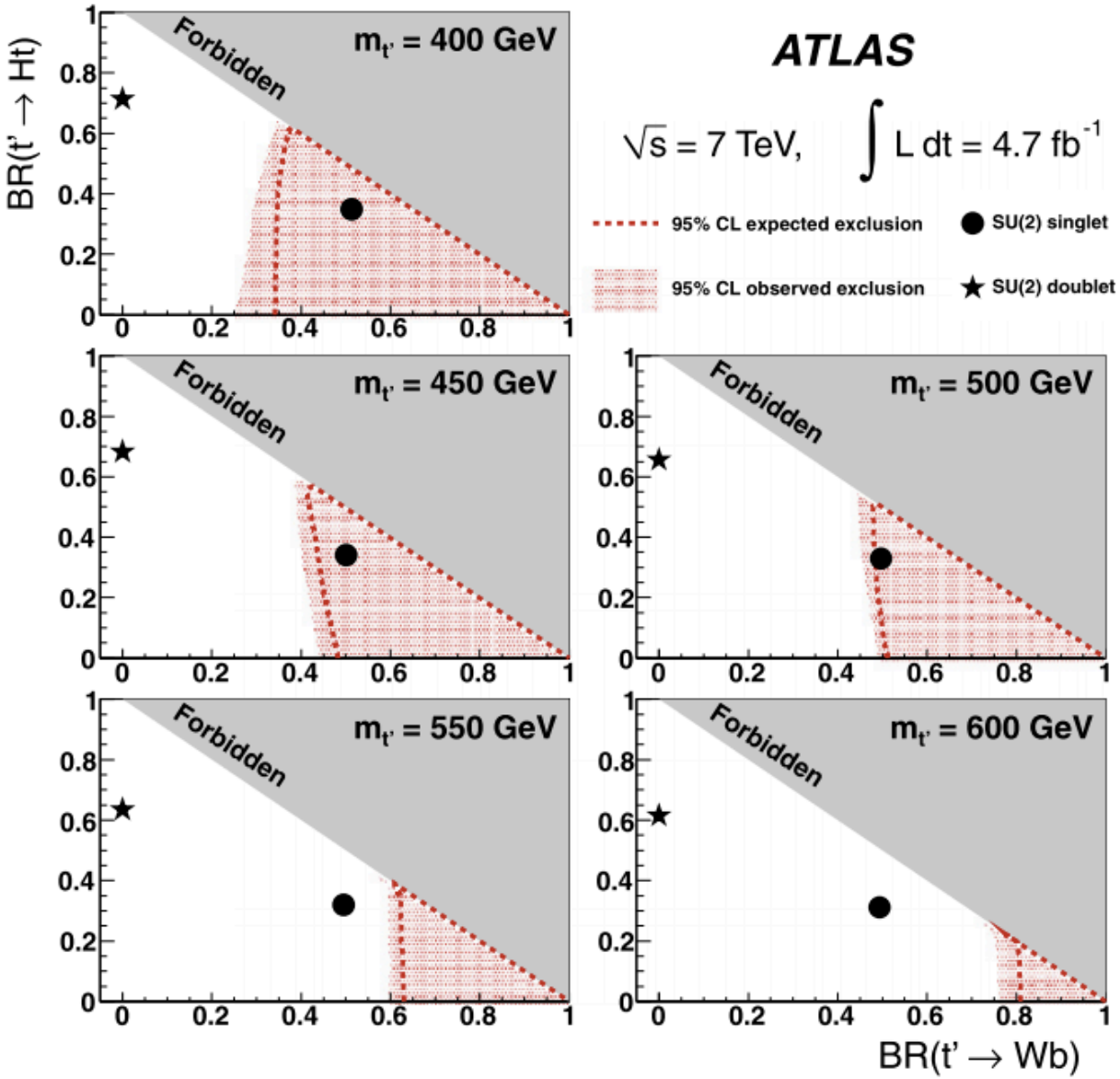
t′ → Wb, Ht, Zt (ℓ + jets)



- BR(Zt) = 1- BR(Wb)-BR(Ht)

For $M_{t'}$ = 550 GeV
BR (t′ → Wb) < 0.63
@ 95 % C.L.

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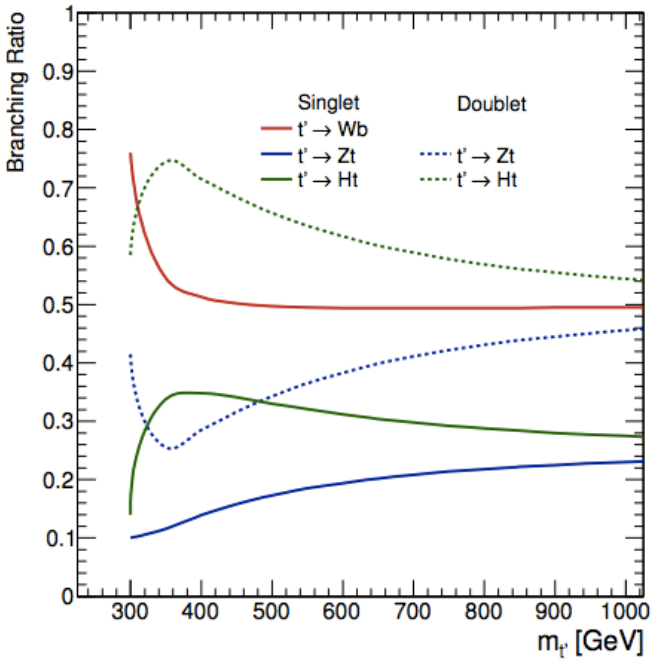
t′ → Ht (ℓ + jets)

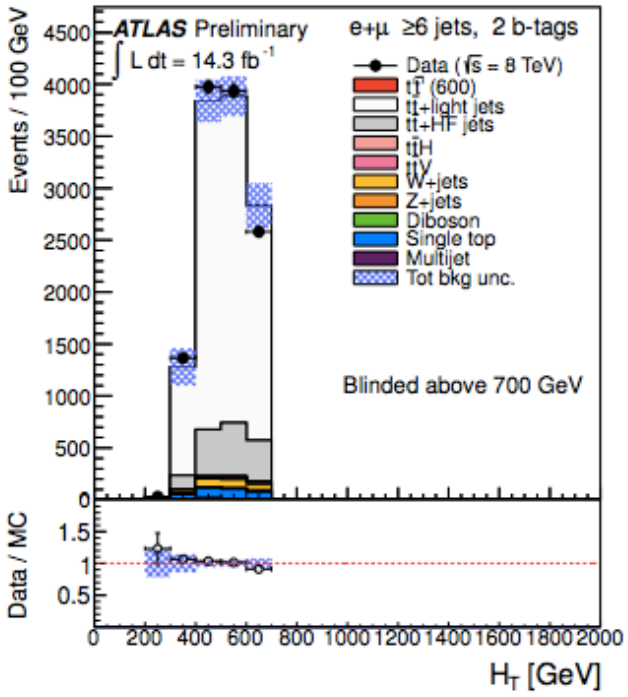
- Search for singlet and doublet t′ quarks

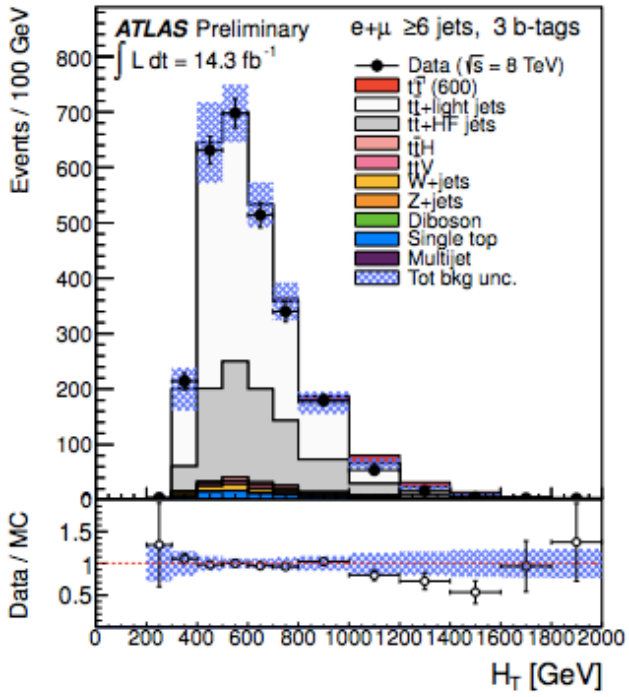


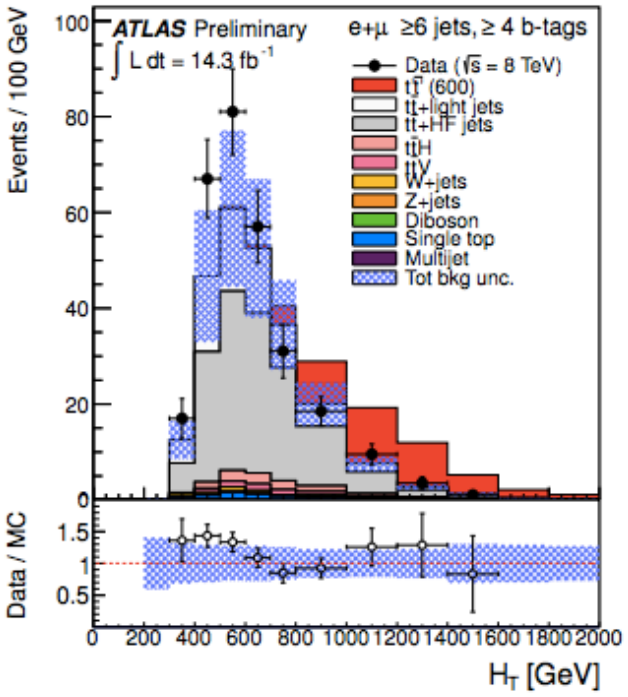
- Event Selection:
  - One lepton e/μ
  - ≥ 3/4 jets, ≥ 2 b-tags,
  - Missing E_T > 20 GeV
  - E_T^{Miss} + m_T > 60 GeV
- Analysis Strategy:
  - Events are classified based on # of b-tags (2,3, ≥ 4)
- For 2-b-tag events $H_T = p_T^{\ell}$ + Missing E_T + $\sum p_T^{jets}$ < 700 GeV to assure orthogonality to t′->Wb search

ATLAS-CONF-2013-018

t′ → Ht (ℓ + jets)



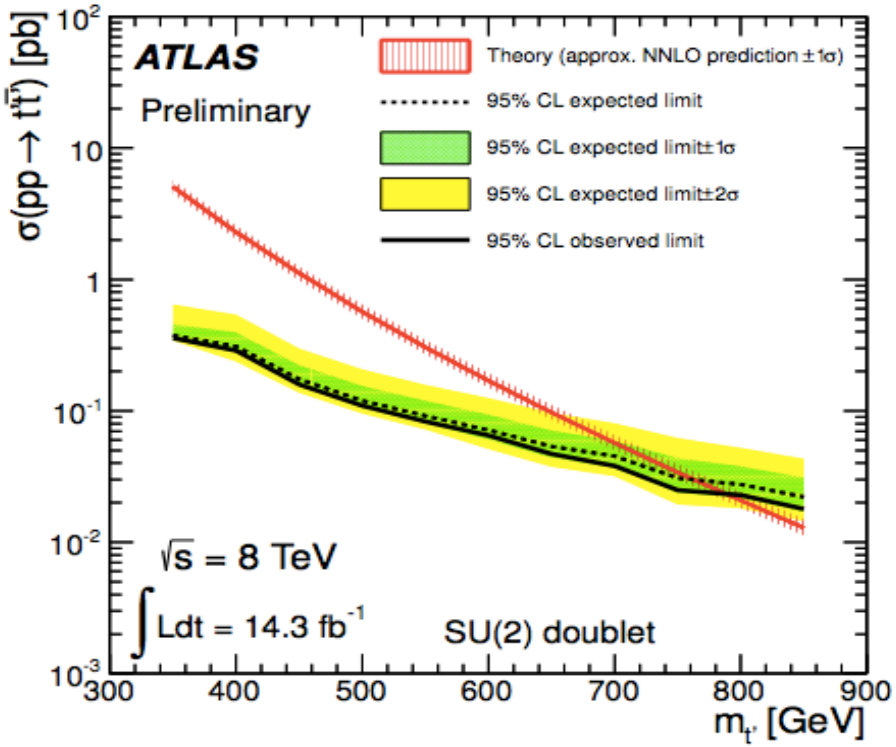




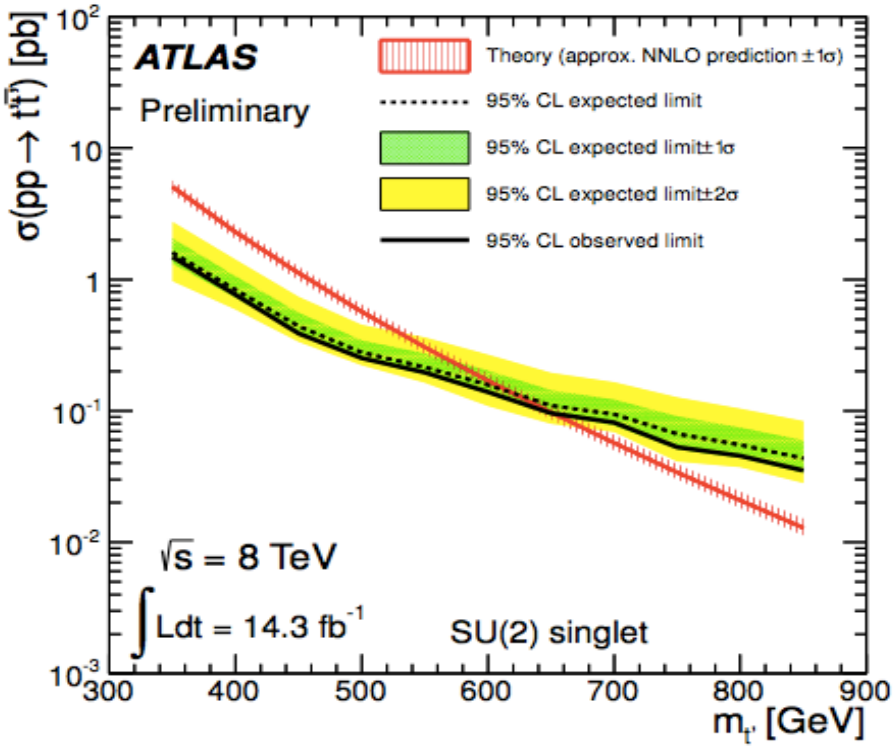
ATLAS-CONF-2013-018

t′ → Ht (ℓ + jets)

$M_{t'}$ > 790 GeV @ 95 % C.L.
SU(2) doublet



$M_{t'}$ > 640 GeV @ 95 % C.L.
SU(2) singlet



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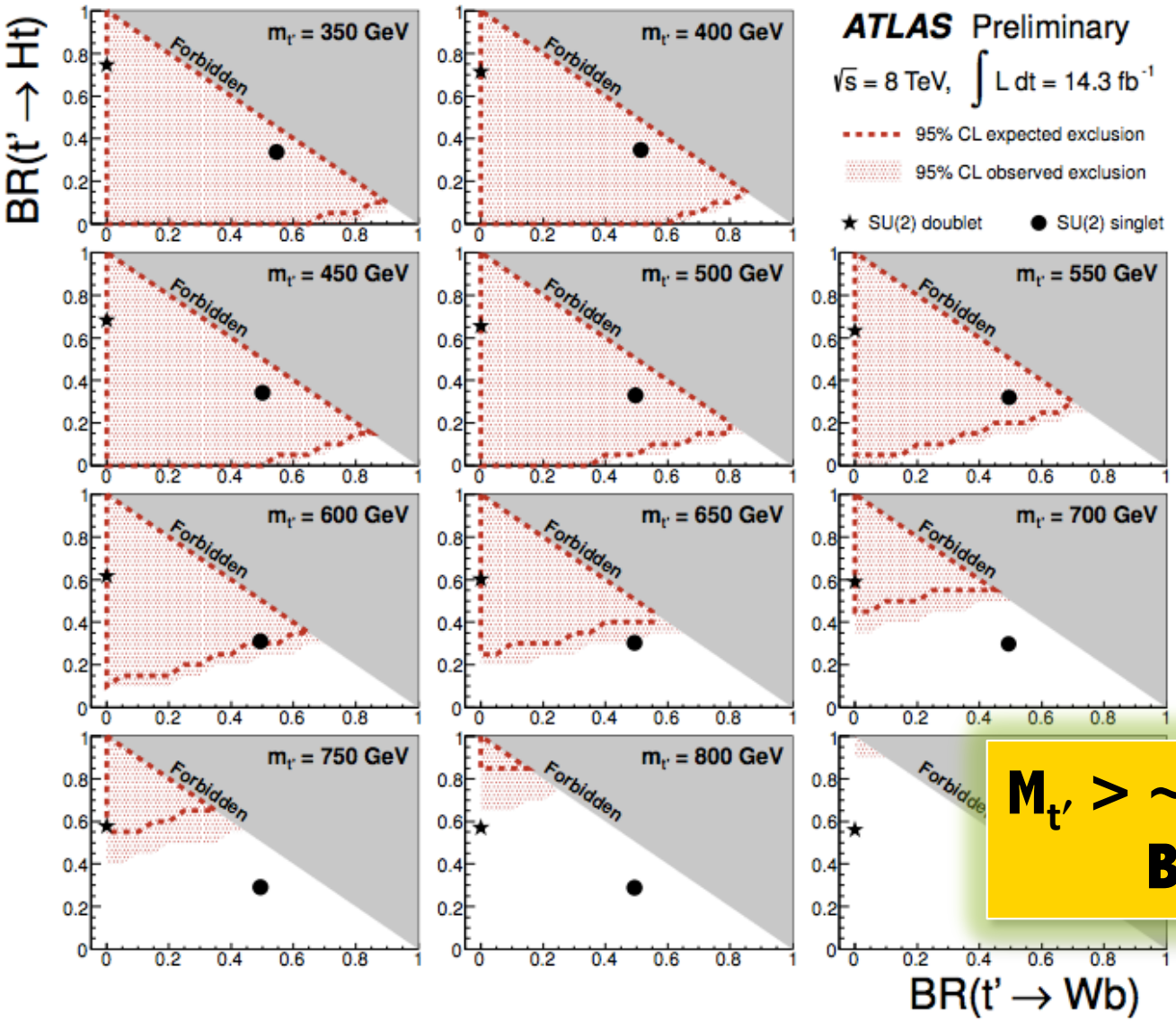
t′ → Ht (ℓ + jets)

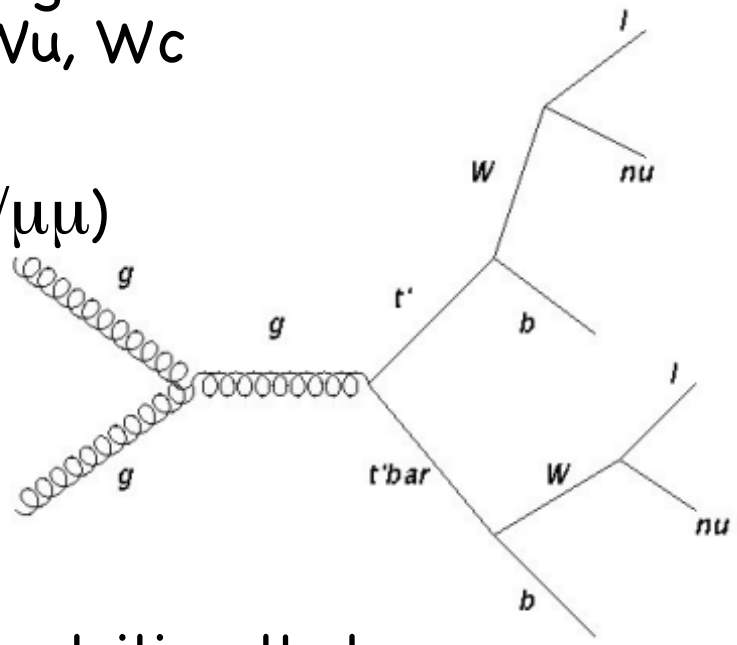


$M_{t'}$ > ~850 GeV @ 95 % C.L.
BR (t′→Ht) = 100%

ATLAS-CONF-2013-018

t′,b′ ➔ Wq (di-lepton)

- Search for decays into quarks of first two generations or a bottom quark : t′-> Wd, Ws, Wb or b′ -> Wu, Wc
- Event Selection:
  - Two opposite sign high p_T leptons (ee/eμ/μμ)
  - Z/γ -> ee/μμ veto
  - ≥ 2 jets
  - $H_T = \sum p_T^{\ell} + \sum p_T^{jets} > 130$ GeV
- Analysis Strategy:
  - Perform kinematic mass reconstruction exploiting that neutrinoes approximately collinear with leptons
  - Take an average of two reconstructed masses, keep events if they are within 25 GeV

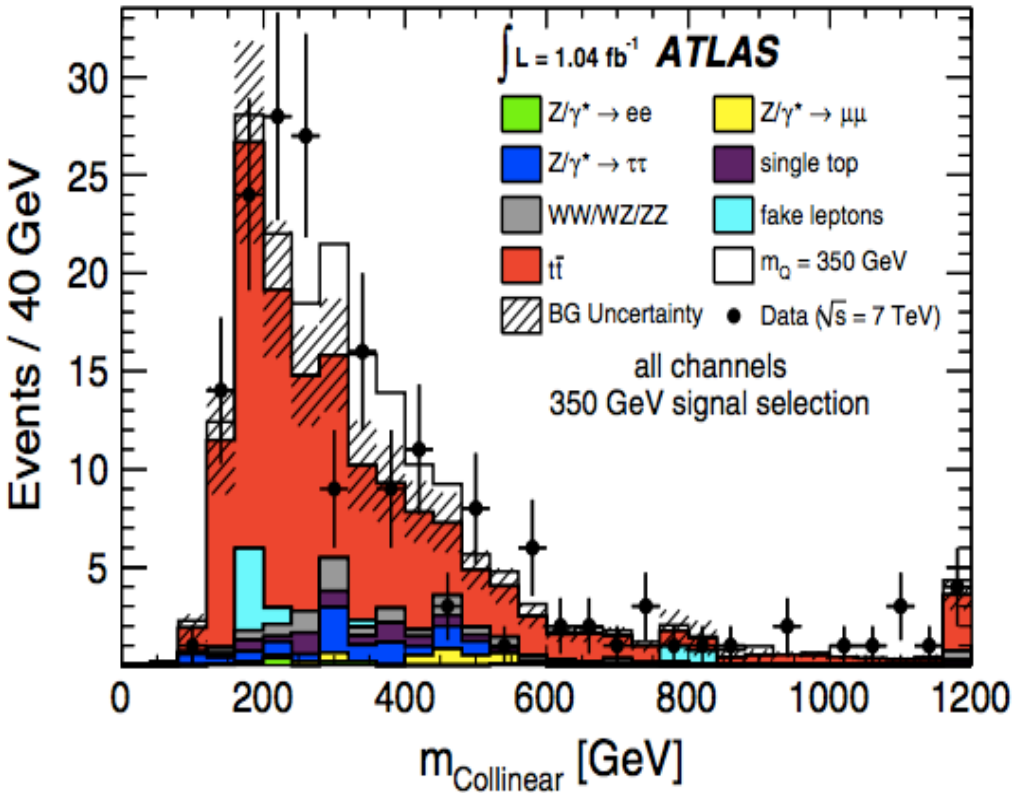


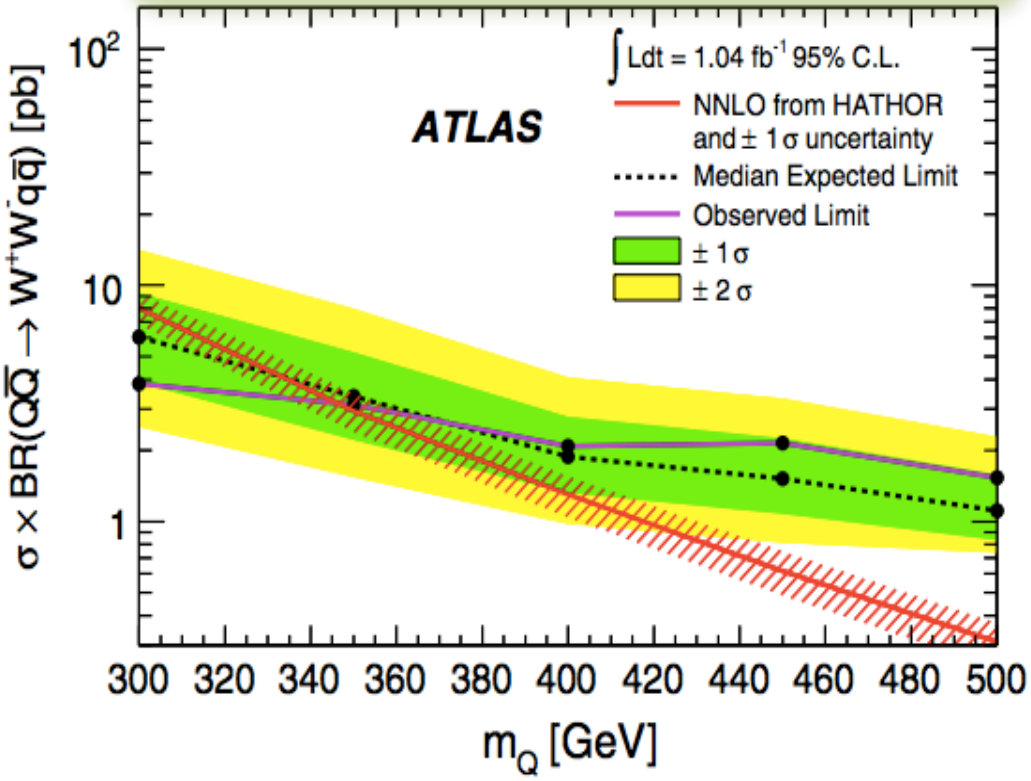
PRD 86 (2012) 012007

t′,b′ ➔ Wq (di-lepton)

MOST STRINGENT LIMIT TO-DATE

M_Q > 350 GeV @ 95 % C.L.
BR (Q➔Wq) = 100%

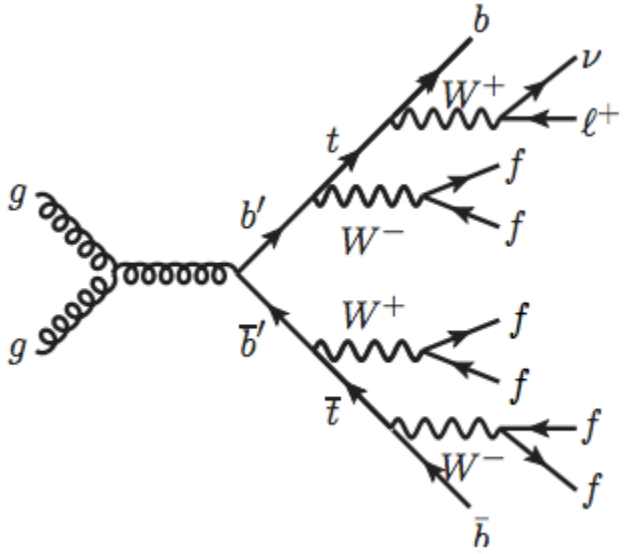




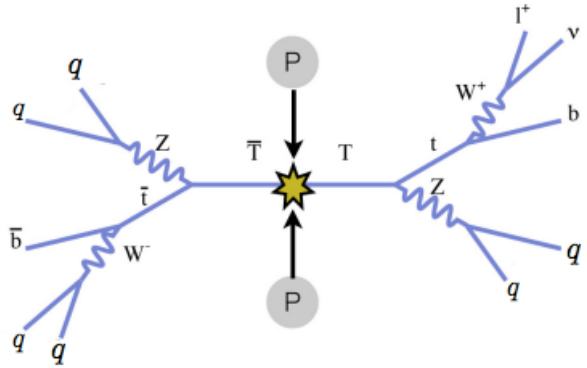
PRD 86 (2012) 012007

b′ → Wt (ℓ + jets)

- Event Selection:
  - e/μ , p_T > 30 GeV
  - ≥ 4 jets, ≥ 1 b-tag
  - Missing E_T > 20 GeV



- Analysis Strategy:
  - Perform a fit to $S_T = p_T^{\ell}$ + Missing E_T + $\sum p_T^{\text{jets}}$ for different jet multiplicity bins (N_{jets} = 4, 5, 6, ≥ 7)
  - Results can also be interpreted for t′->tZ



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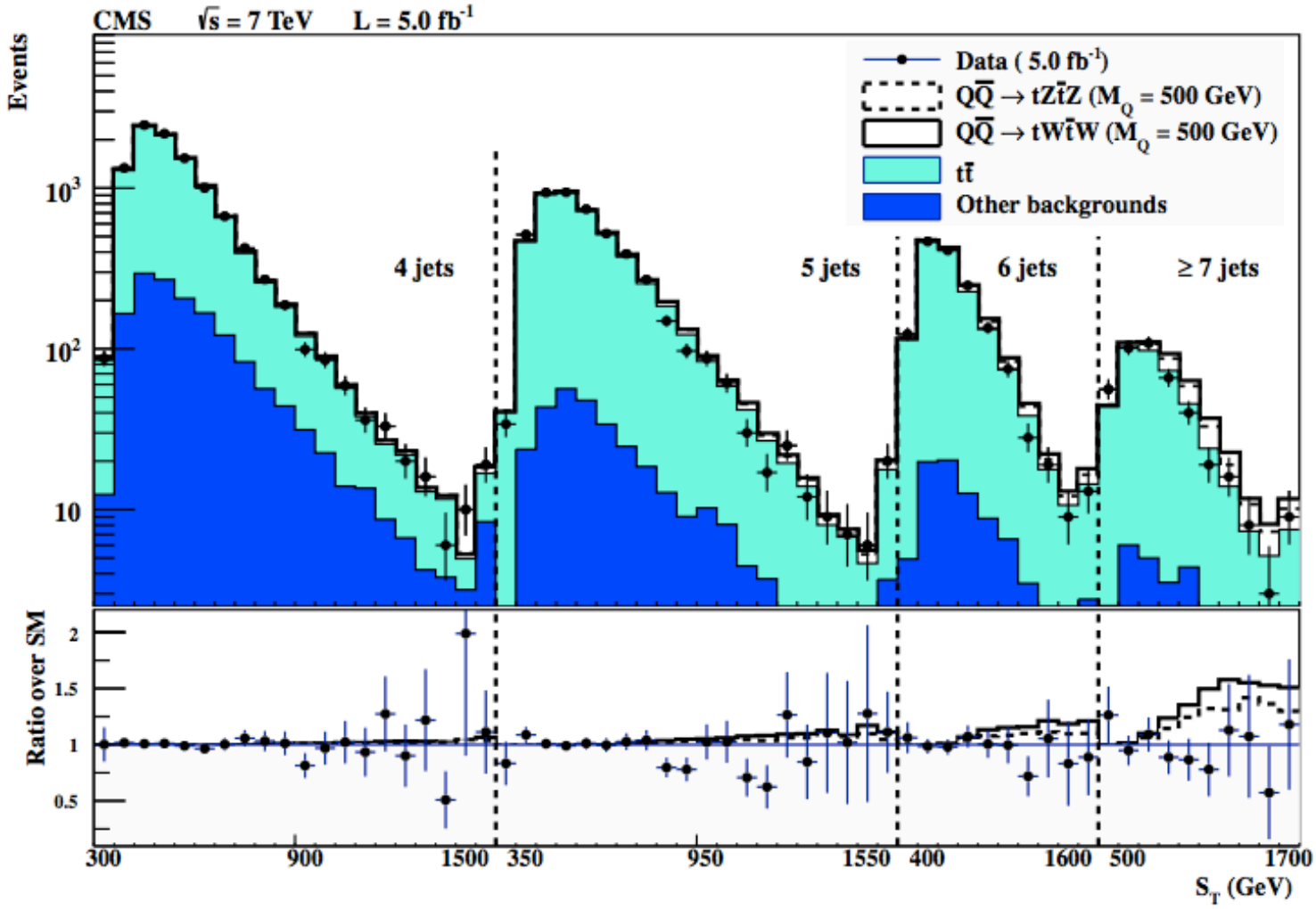
b′ → Wt, t′ → Zt (ℓ + jets)



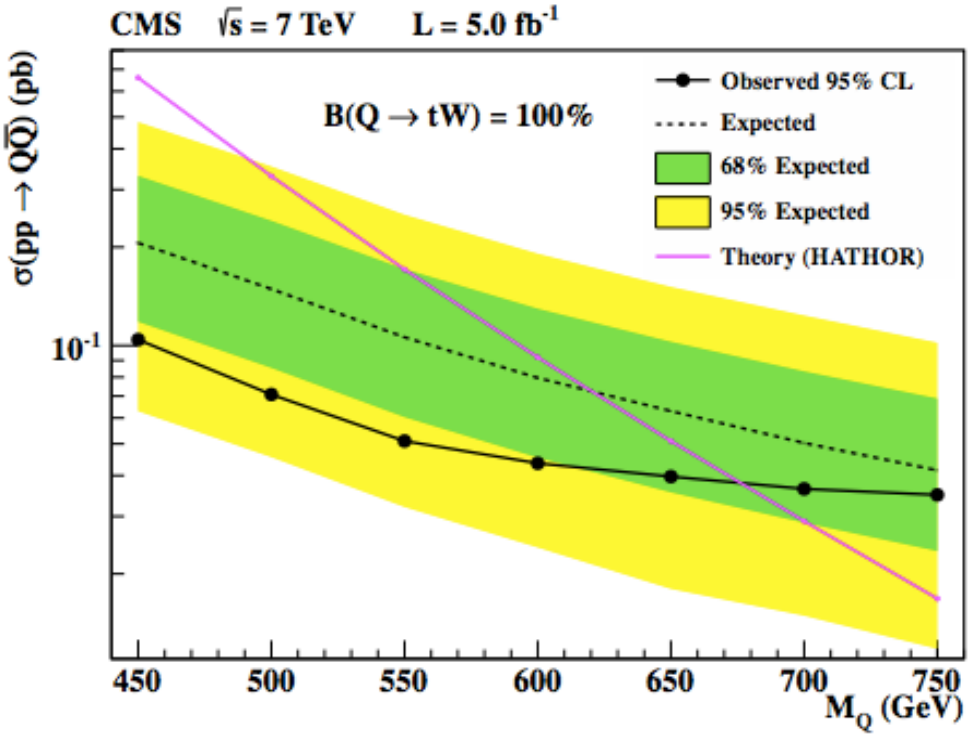
JHEP 01 (2013) 154

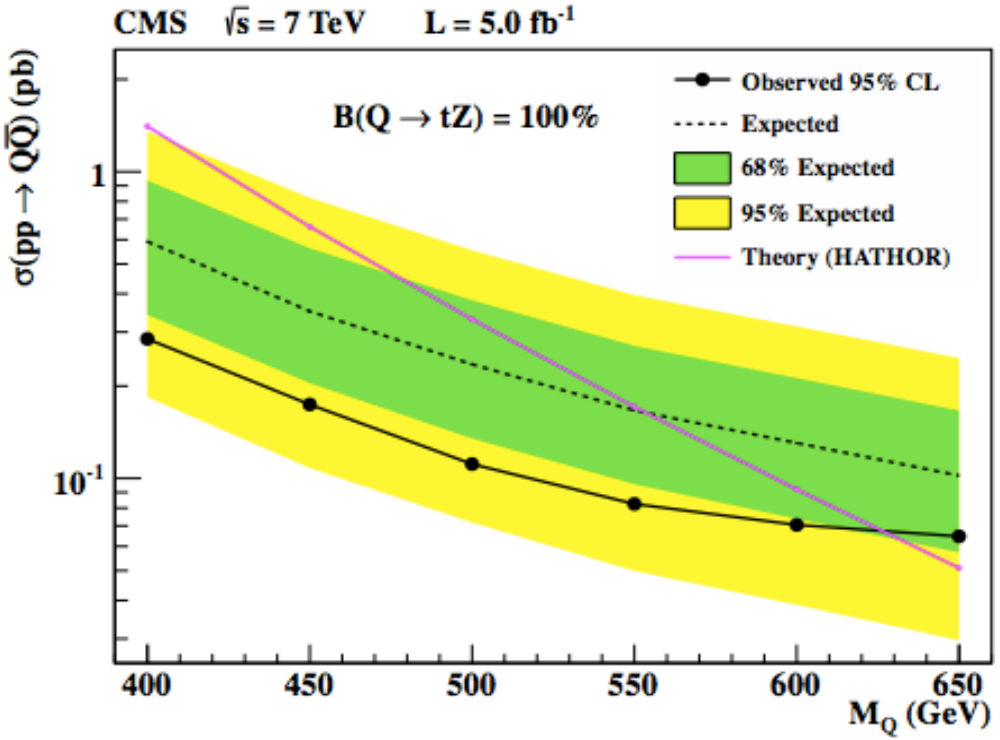
b′ → Wt, t′ → Zt (ℓ + jets)

$M_{b'}$ > 675 GeV @ 95 % C.L.
BR (b′→Wt) = 100%

$M_{t'}$ > 625 GeV @ 95 % C.L.
BR (t′→Zt) = 100%

MOST STRINGENT LIMIT TO-DATE





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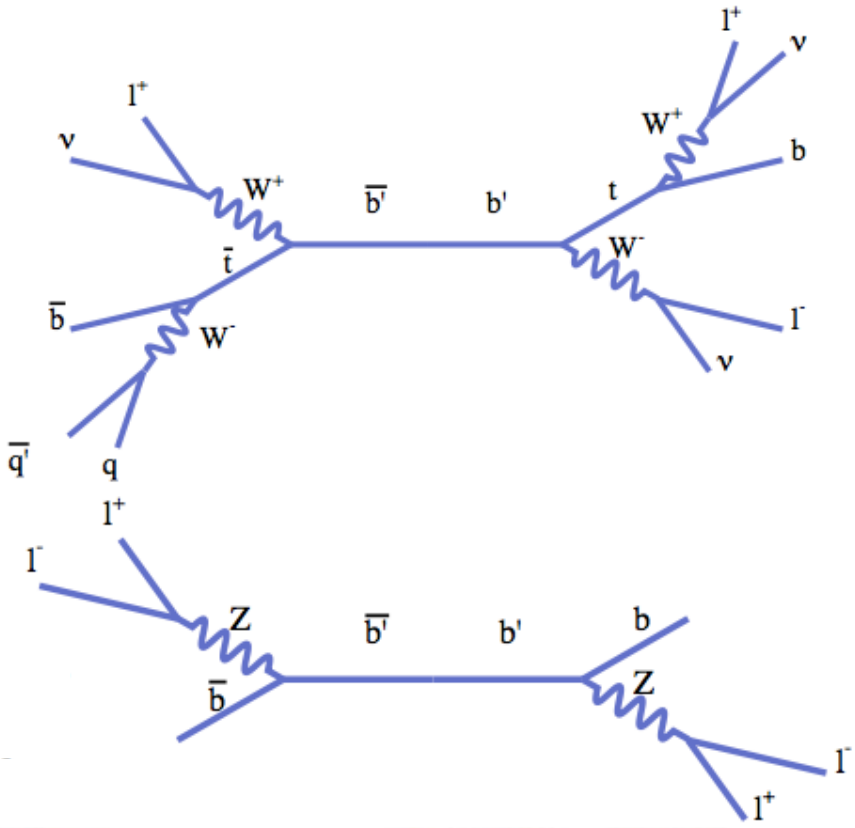
b′ ➔ Wt, Zb (multi-lepton)

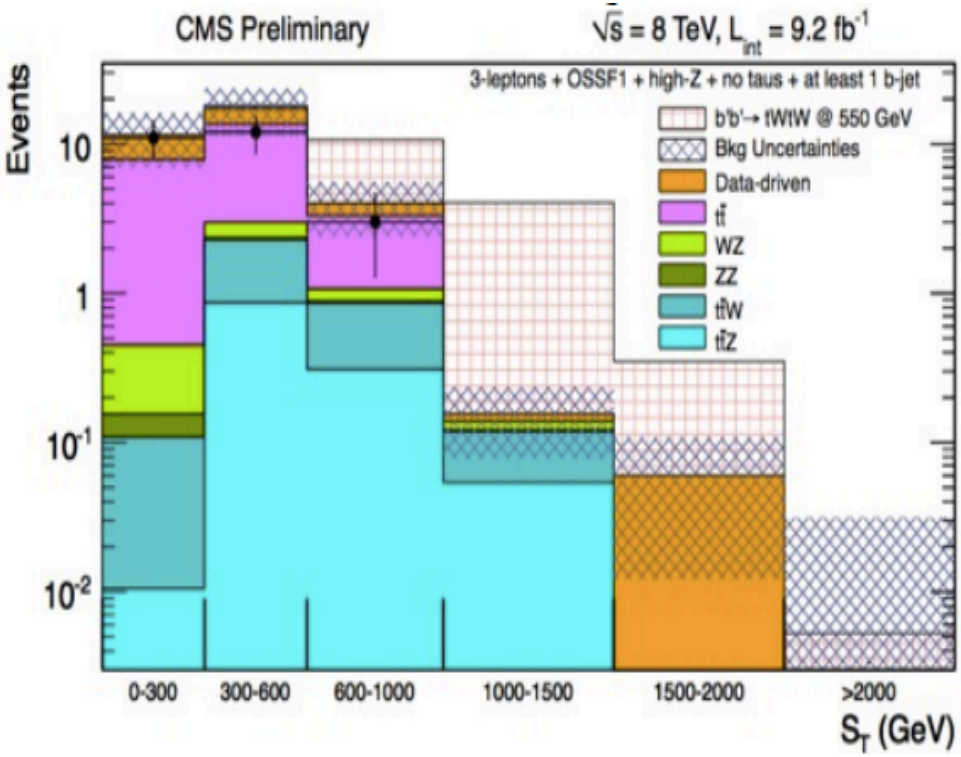
- Event Selection:
  - ≥ 3 leptons (e,μ) , p_T > 20,10,10 GeV
  - γ^* -> ee/μμ veto
  - ≥ 1 b-jet

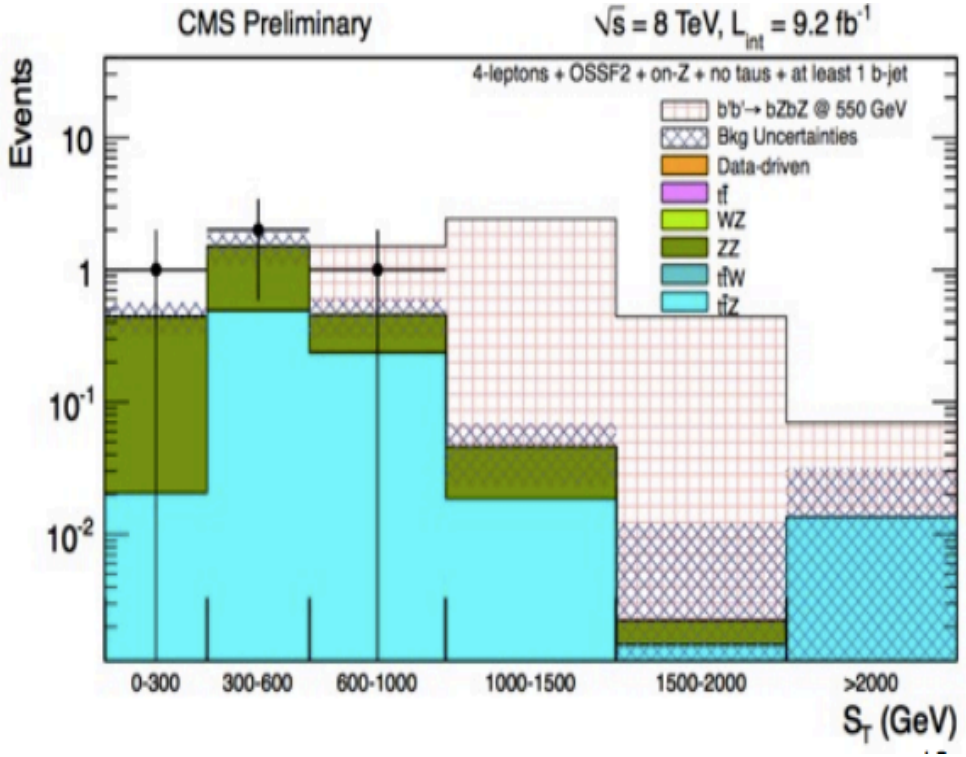
- Analysis Strategy:
  - Classify events based on number of leptons, hadronic taus, b-jets, pair of leptons consistent with Z boson
  - 240 exclusive channels
  - Data-driven background estimate for non-prompt leptons
  - Perform a fit to
  - $S_T = \Sigma\, p_T^{\ell}$ + Missing E_T + $\Sigma\, p_T^{jets}$



CMS-PAS-SUS-12-027

b′ ➔ Wt, Zb (multi-lepton)





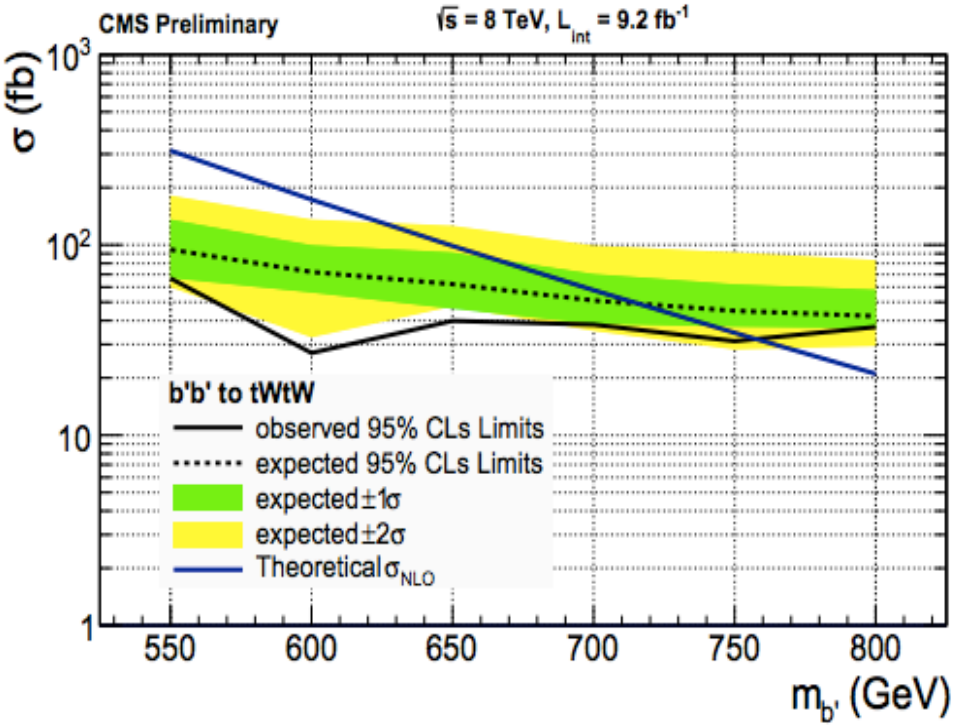
CMS-PAS-SUS-12-027

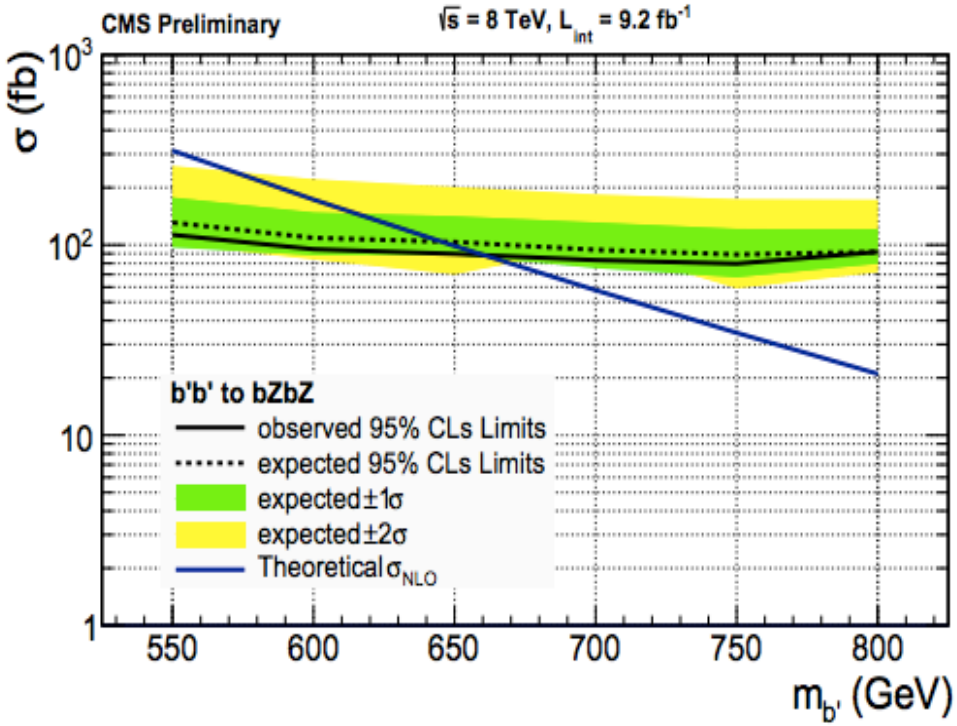
b′ ➔ Wt, Zb (multi-lepton)

$M_{b'}$ > 760 GeV @ 95 % C.L.

$M_{b'}$ > 660 GeV @ 95 % C.L.

MOST STRINGENT LIMITS TO-DATE

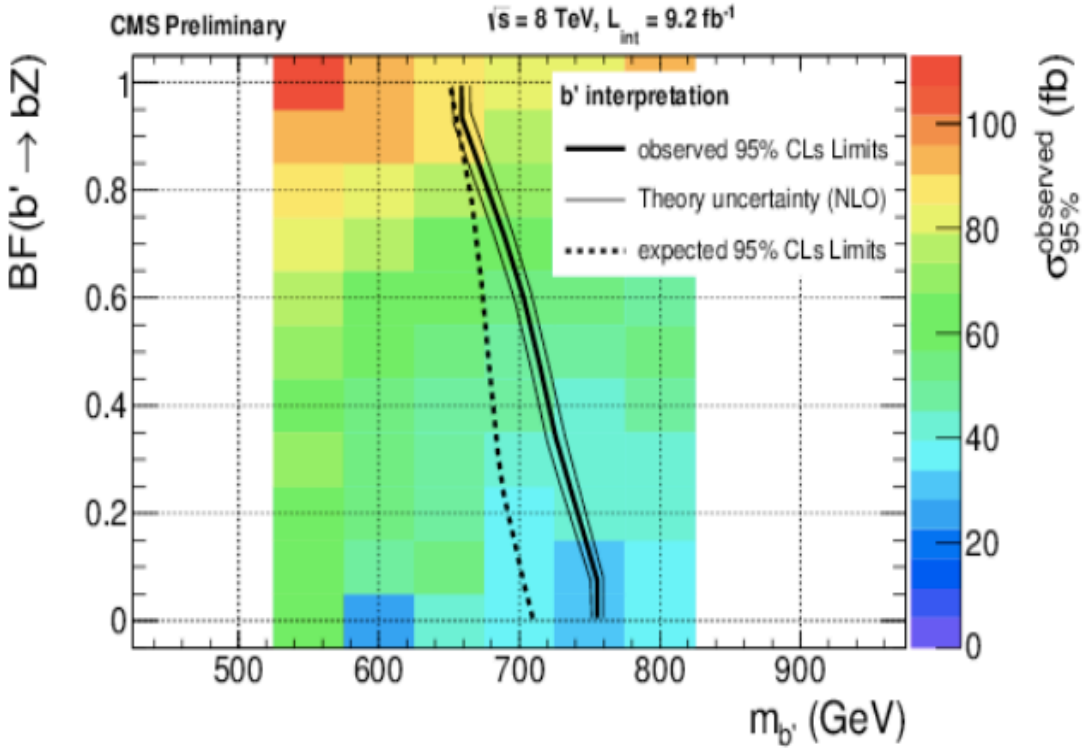


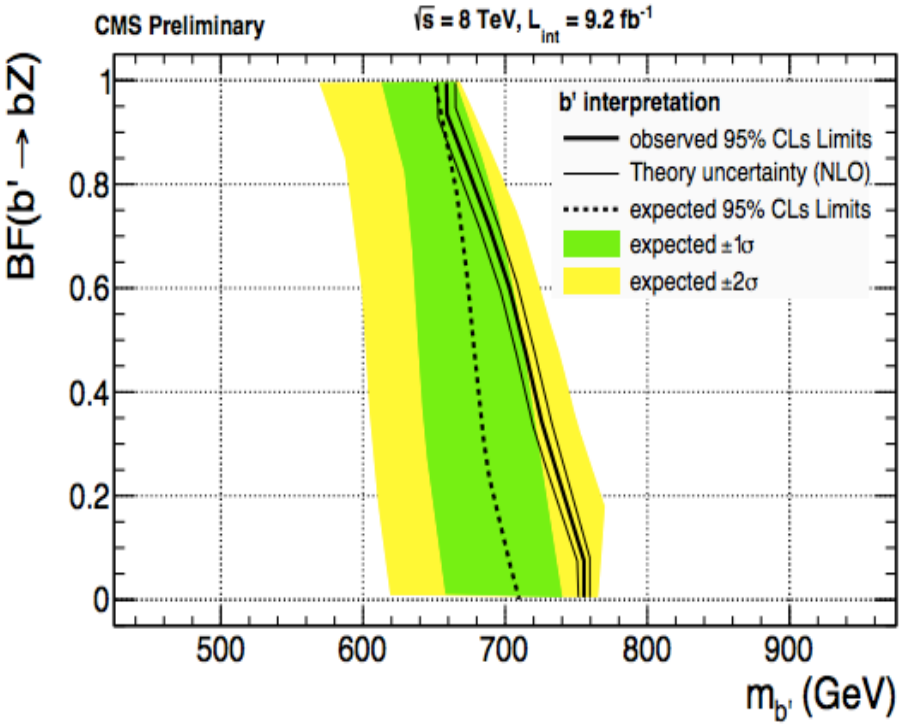


CMS-PAS-SUS-12-027

b′ ➔ Wt, Zb (multi-lepton)

$M_{b'}$ > 715 GeV @ 95 % C.L.
BR(Wt) =BR(Zb) = 0.5





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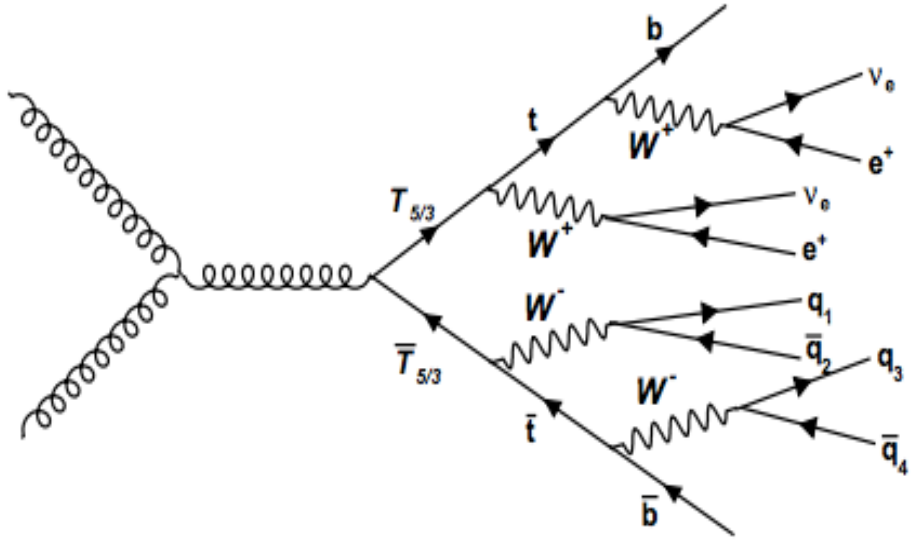
b′ ➔ Wt (same-sign di-lepton)



Background	# of Events
tt+W/Z	5.2 ± 0.9
Di-boson	1.7 ± 0.5
Non-prompt	1.0 ± 0.6
Charged MisID	1.5 ± 0.4
Total Exp.	9.3 ± 1.3
Observed	15

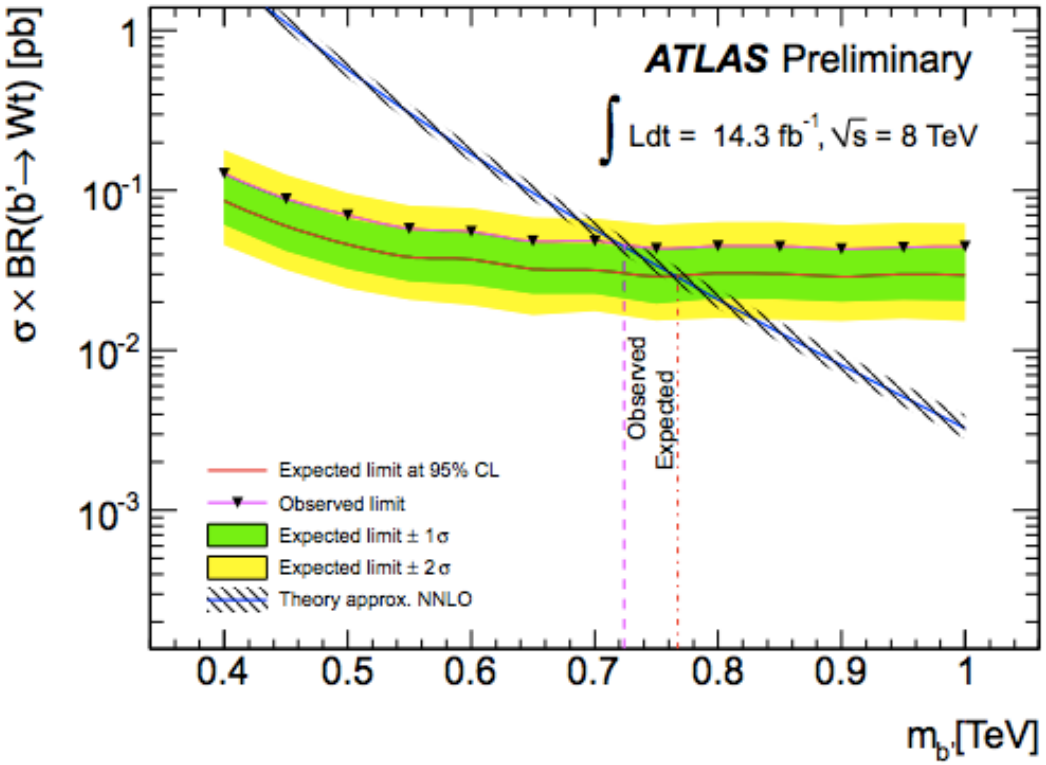
- Event Selection:
  - 2 same-sign leptons (e,μ), p_T > 25 GeV
  - γ* -> ee/μμ veto
  - ≥ 2 jets, ≥ 1 b-tag
  - Missing E_T > 40 GeV
  - $H_T = \Sigma\, p_T^{\ell} + \Sigma\, p_T^{jets} > 650$ GeV

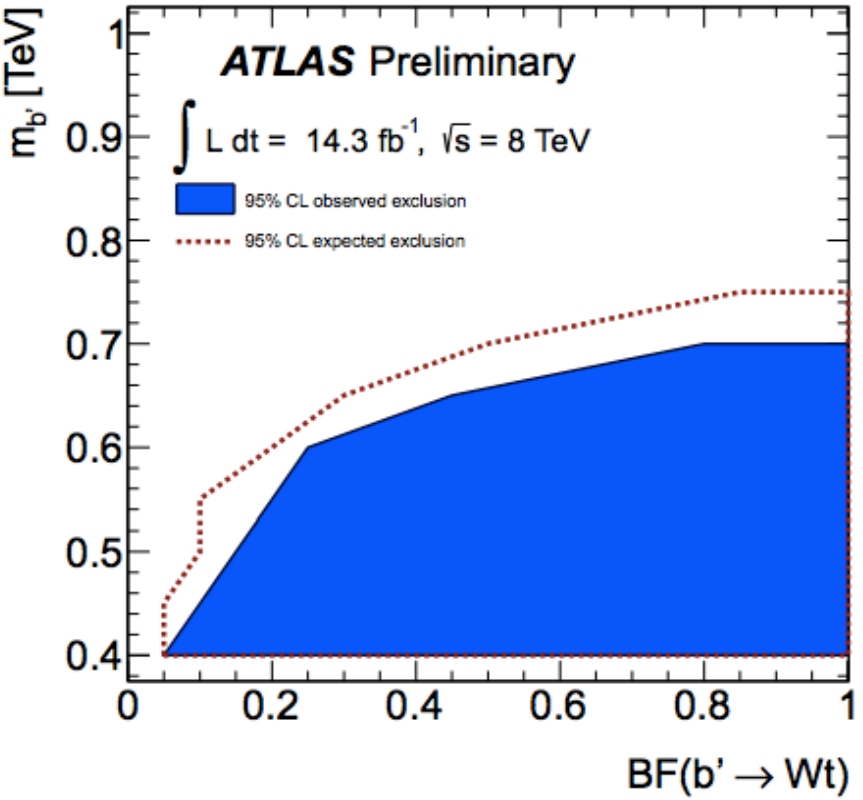
ATLAS-CONF-2013-051

b′ → Wt, Wq (same-sign di-lepton)

$M_{b'}$ > 720 GeV @ 95 % C.L.

- Limits on the chiral 4-th generation quarks, assuming b'->Wt and Wq



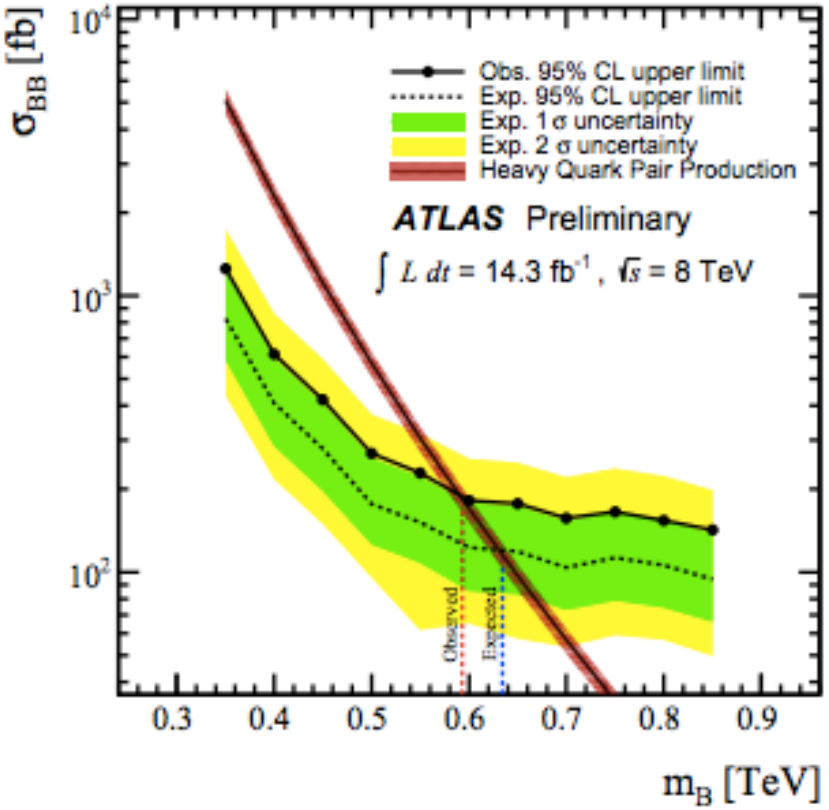


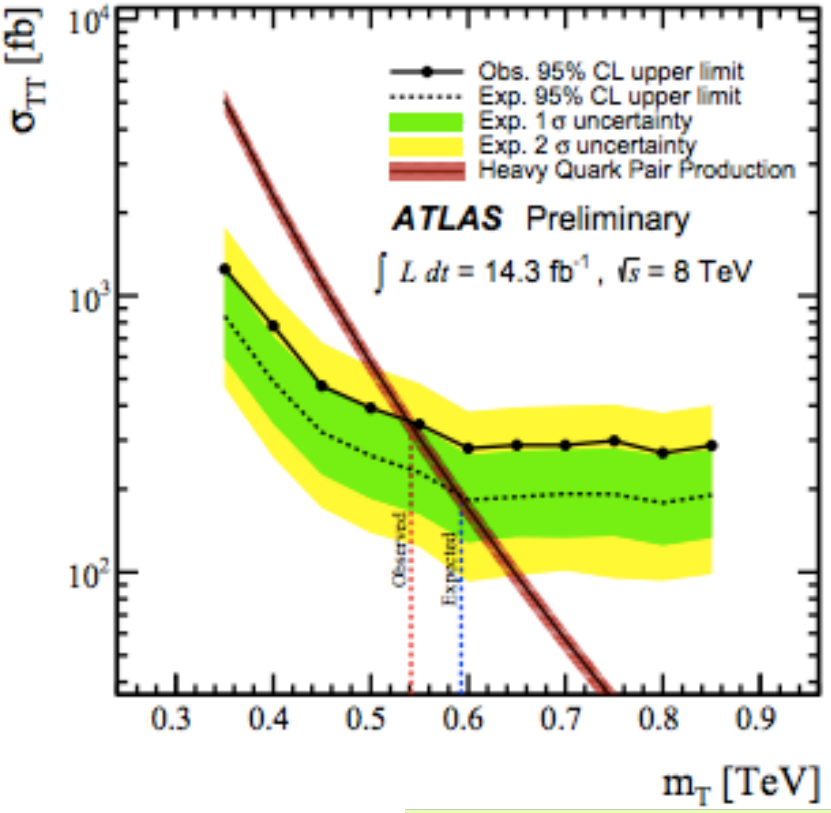
ATLAS-CONF-2013-051

b′ and t′ (same-sign di-lepton)

$M_{b'}$ > 590 GeV @ 95 % C.L.
b′ SU(2) singlet

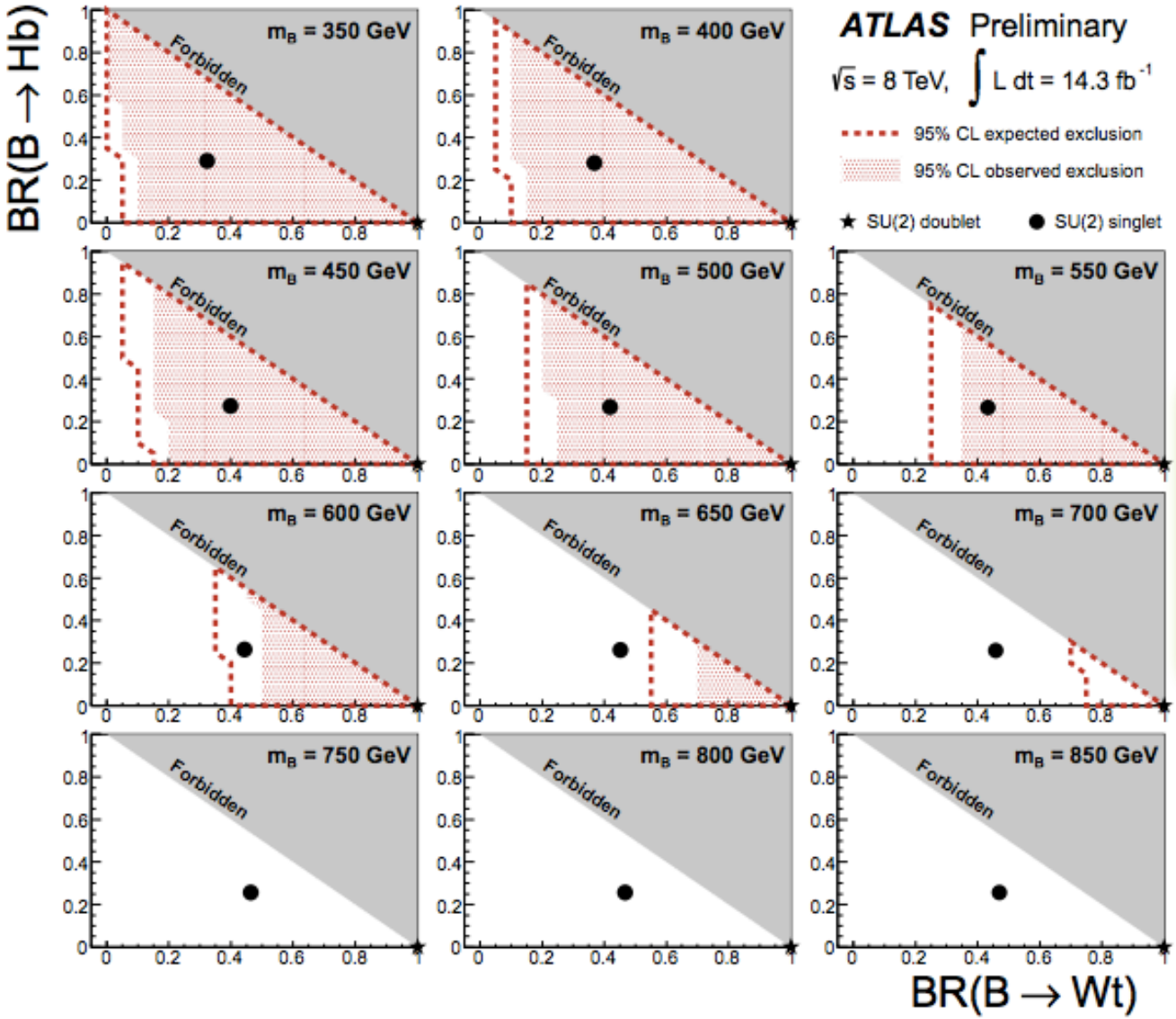
$M_{t'}$ > 540 GeV @ 95 % C.L.
t′ SU(2) singlet





ATLAS-CONF-2013-051

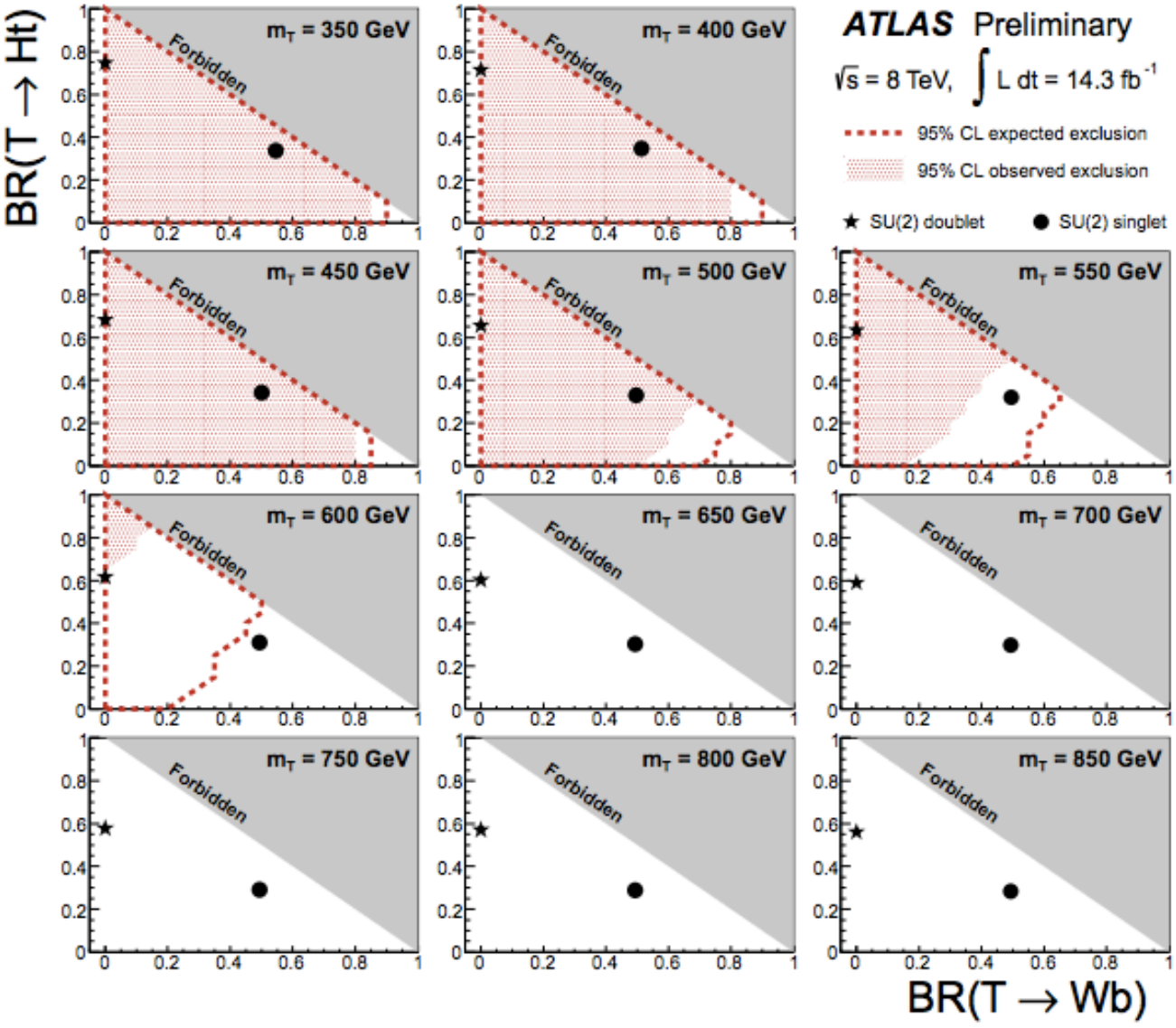
b′ (same-sign di-lepton)



For $M_{b'}$ = 550 GeV
BR (b′ → Wt) < 0.35
@ 95 % C.L.

ATLAS-CONF-2013-051

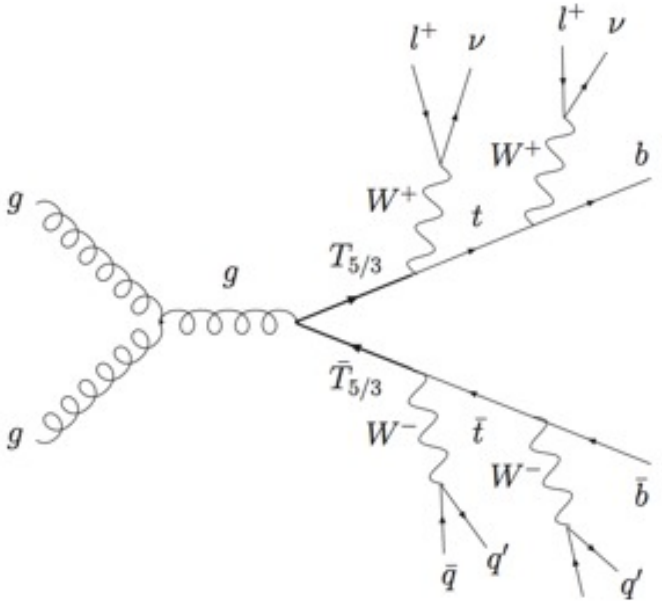
t′ (same-sign di-lepton)



ATLAS-CONF-2013-051

$T^{5/3} \rightarrow Wt$ (same-sign di-lepton)

- Event Selection:
  - 2 same-sign leptons (e,μ), p_T > 30 GeV
  - γ* -> ee/μμ veto
  - $N_{constituents} \geq 5$
  - $H_T = \Sigma\, p_T^{\ell} + \Sigma\, p_T^{jets} > 900$ GeV
- Boosted W-bosons and top-quarks are identified using CA8 jets and jet substructure algorithms
- W-boson:
  - $N_{subjets} = 2$, $60 < m_{jet} < 130$ GeV
- Top-quark:
  - $N_{subjets} = 3$, $140 < m_{jet} < 250$ GeV,
  - Min $m_{pair\text{-}wise} > 50$ GeV



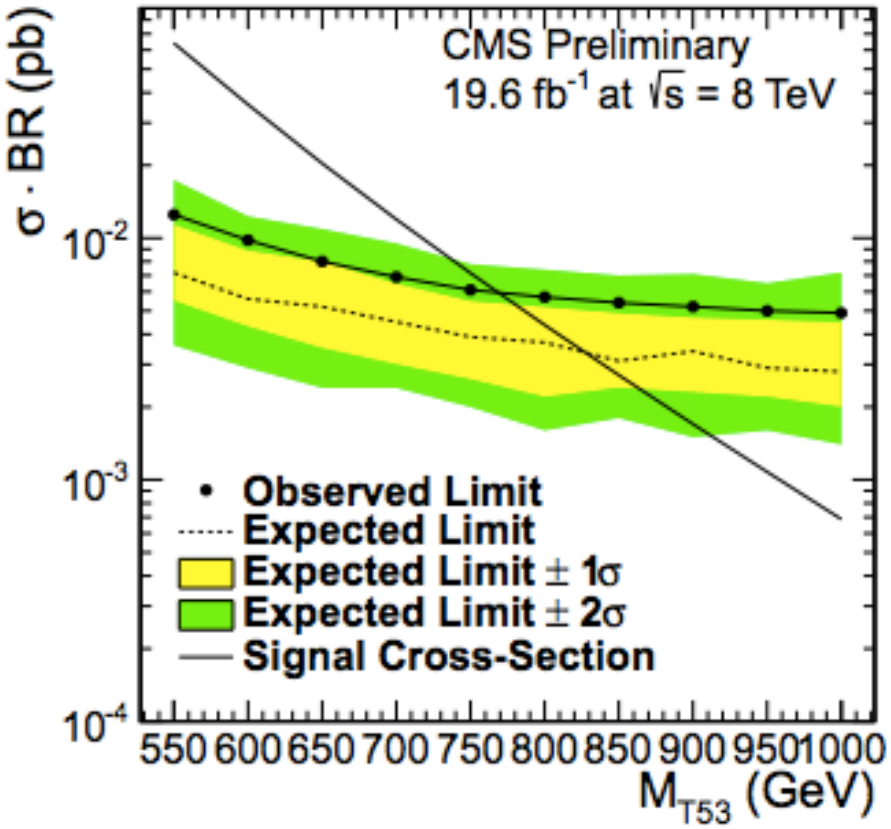
CMS-PAS-B2G-12-012

$T^{5/3} \rightarrow Wt$ (same-sign di-lepton)

MOST STRINGENT LIMIT TO-DATE

$M_{T\,5/3}$ > 770 GeV @ 95 % C.L.

Backgrounds	# of Events
Prompt	3.9 ± 0.8
Non-prompt	2.6 ± 1.8
Charge MisID	0.1 ± 0.0
Total Exp.	6.6 ± 2.0
Observed	11



CMS-PAS-B2G-12-012

Inclusive Search for Chiral 4th Generation

- Inclusive search assuming degenerate masses $m_{t'} = m_{b'}$
- BR(t'->Wb) = BR(b'->Wt) = 100%
- Simplified CKM4 matrix

$$\mathrm{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & \sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

- Event Selection:
- ≥ 1 leptons (e,μ) , p_T > 40 GeV
- ≥ 1 jet , ≥ 1 b-tag , p_T > 30 GeV
- Missing E_T > 40 GeV
- Events classified based on # of W bosons

1W	2W	3W	4W
t'b	t't'	b't + b't'	b'b'

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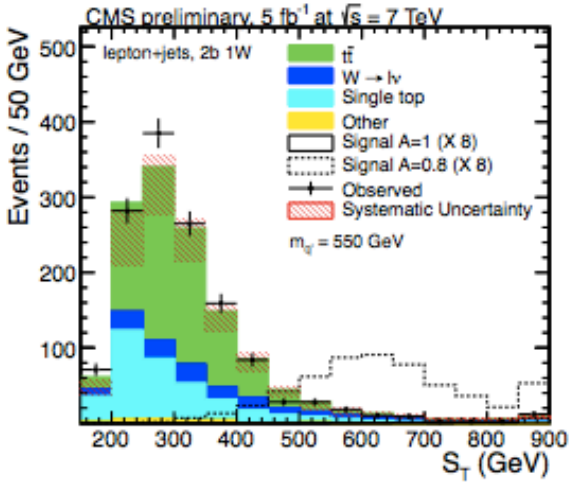
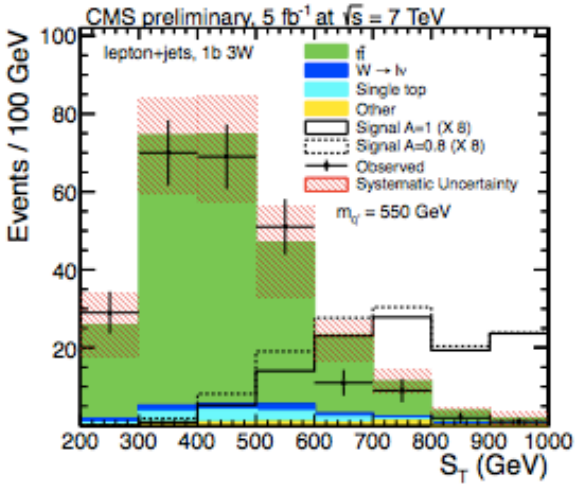
Inclusive Search for Chiral 4th Generation

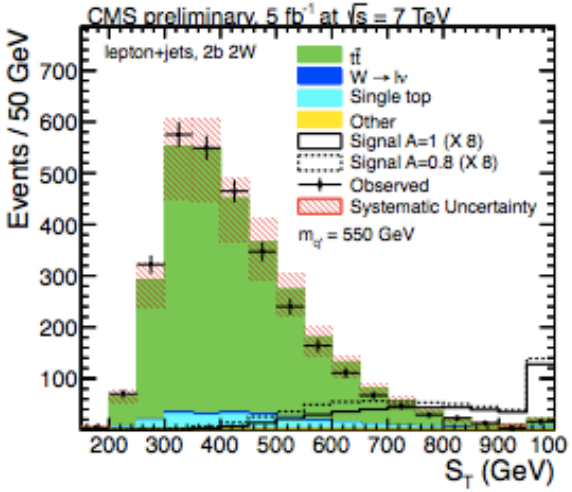
2b1W



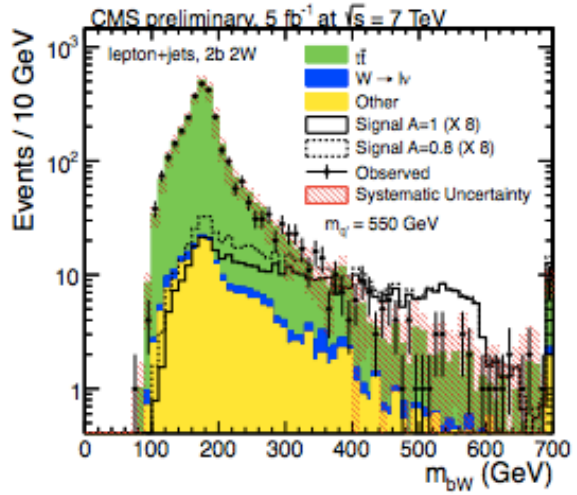
1b3W



2b2W



2b2W



- Fit to $S_T = p_T^{\ell} +$ Missing $E_T + p_T^{b} + p_T^{j} + \Sigma\, p_T^{W\text{-had}}$
- in single-lepton 1W and 3W channels
- 2D-fit in 1ℓ 2W
- Counting-experiment
  - In 1ℓ 4W,
  - Same-sign dilepton
  - and tri-lepton channels

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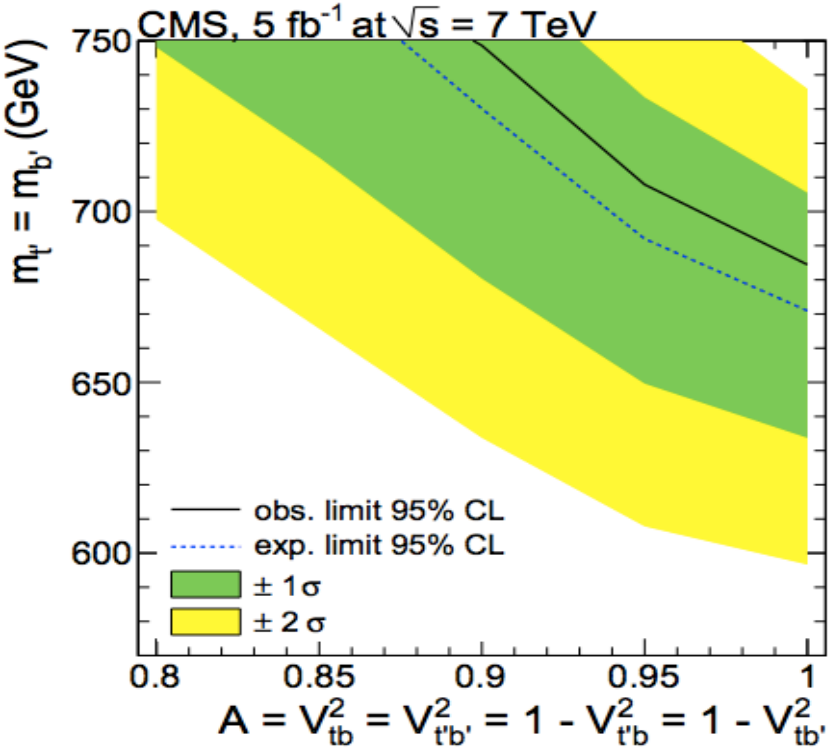
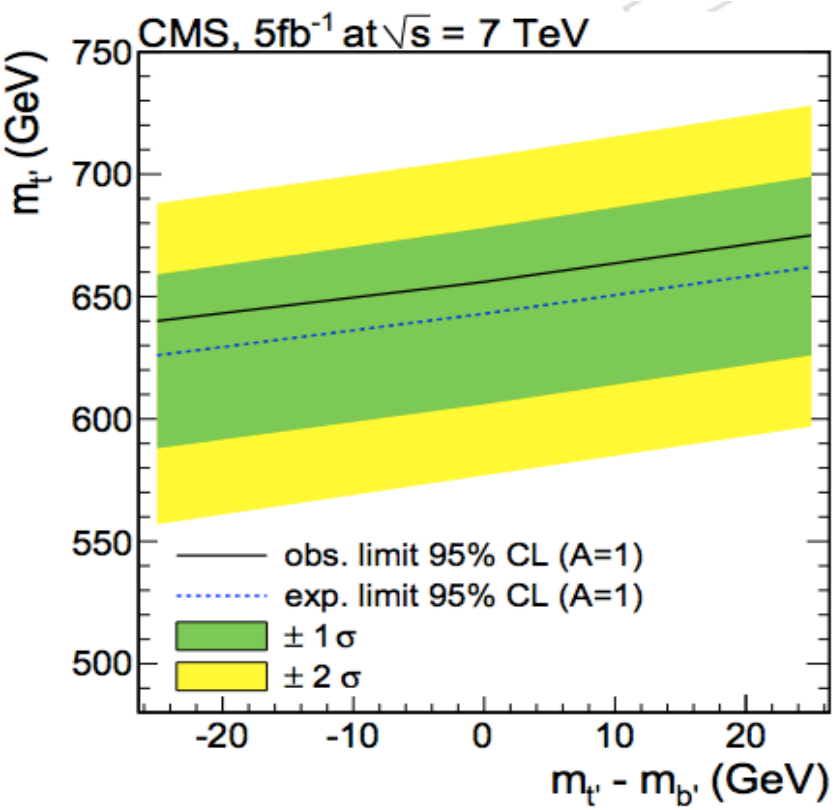
Inclusive Search for Chiral 4th Generation

$M_{t'} = M_{b'} > 685$ GeV @ 95 % C.L.

- Assume no t'b' electroweak production for non-degenerate masses





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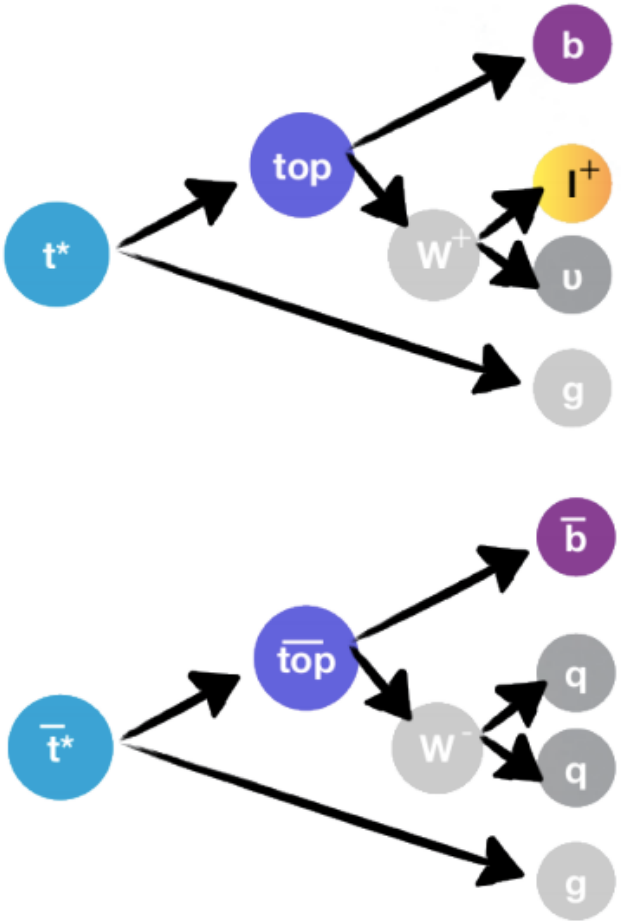
t* → tg (ℓ + jets)

- Search for t*, spin 3/2 quark
- Event Selection:
  - e/μ , p_T > 30/26 GeV
  - ≥ 6 jets, ≥ 1 b-tag
- Analysis Strategy:
  - Kinematic t*-quark mass reconstruction
    - m(ℓν) = m(qq) = M_W
    - m(ℓνb) = m(qqb) = M_{top}
    - m(ℓνbg) = m(qqbg) = M_{reco}
    - Construct and minimize χ^2



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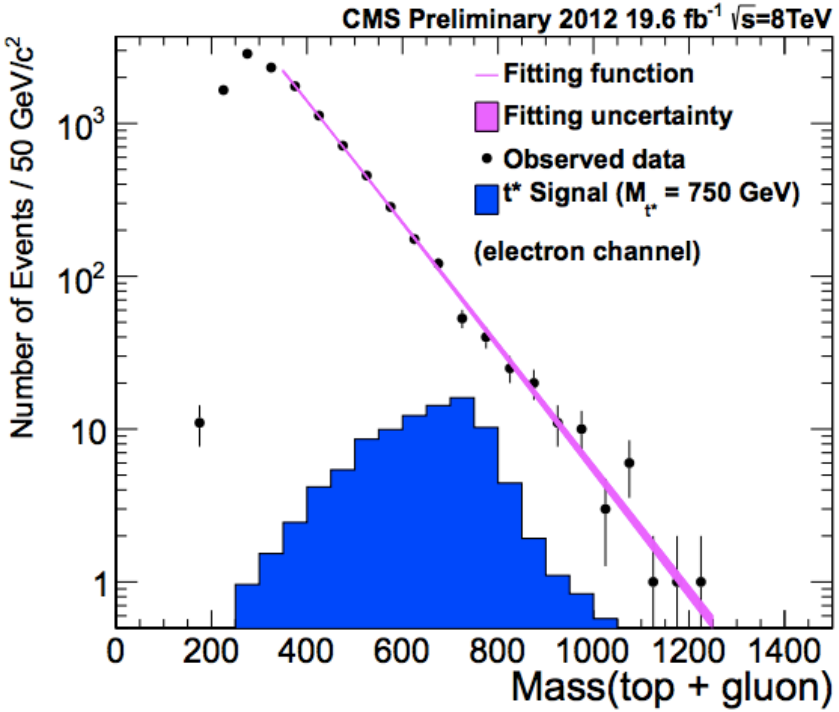
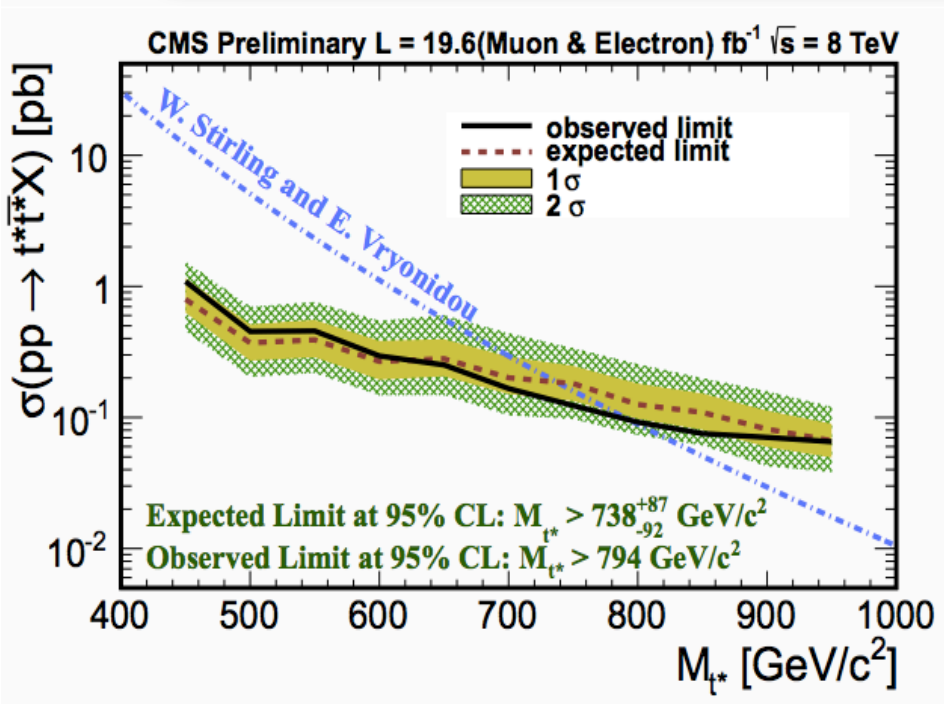
t* → tg (ℓ + jets)

- Data-driven to estimate background contribution in the signal region: $bg(m) = \frac{a}{1+e^{(m-b)/c}}$

FIRST SEARCH

M_{t^*} > 794 GeV @ 95 % C.L.

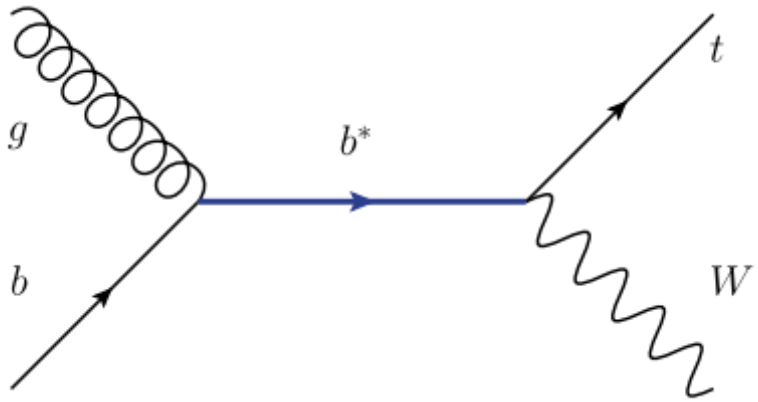




CMS-PAS-B2G-12-014

Search for single b* ➔ Wt

- Search for excited bottom quark, which is produced via chromomaganetic interaction and decaying electroweakly
- Event Selection:
  - Dilepton
    - Two opposite sign high p_T leptons ($ee/e\mu/\mu\mu$) , ≥ 1 jet,
    - Missing E_T > 50 GeV
    - Z/γ -> $ee/\mu\mu/\tau\tau$ veto
    - Discriminating variable: H_T
  - ℓ + jets
    - Lepton (e/μ), p_T > 25 GeV
    - ≥ 4 jets, ≥ 1 b-tag
    - Missing E_T > 30/25 GeV
    - m_T^W > 30 GeV
    - Discriminating variable: reconstructed mass



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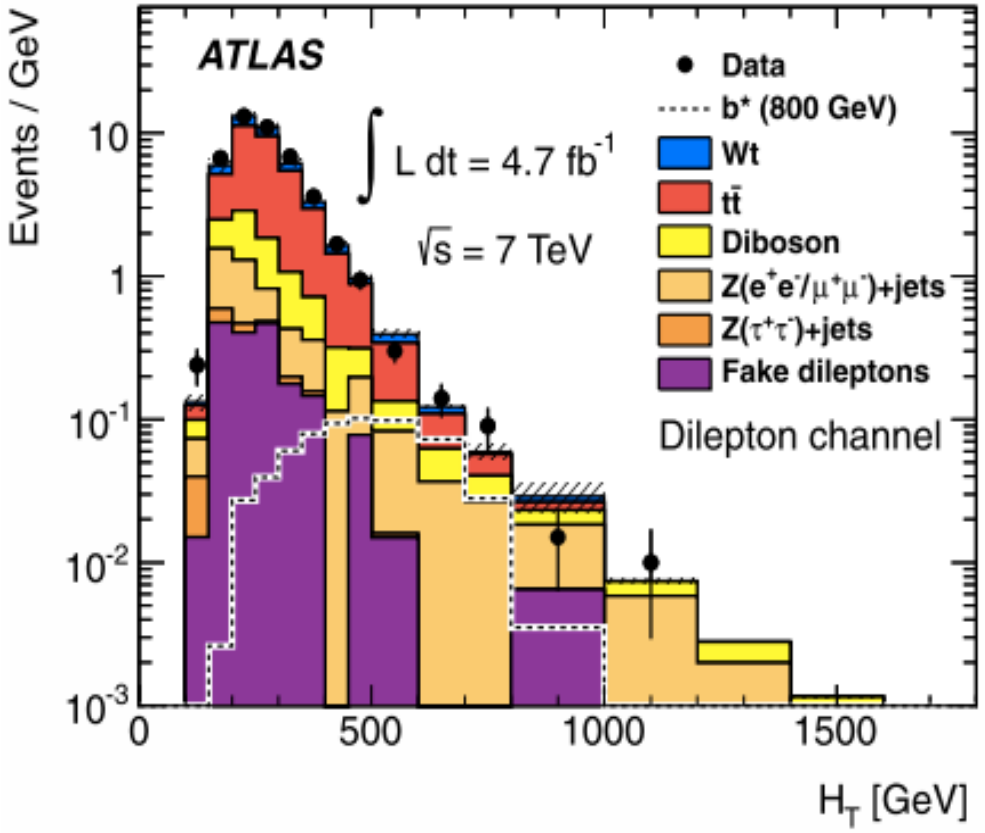
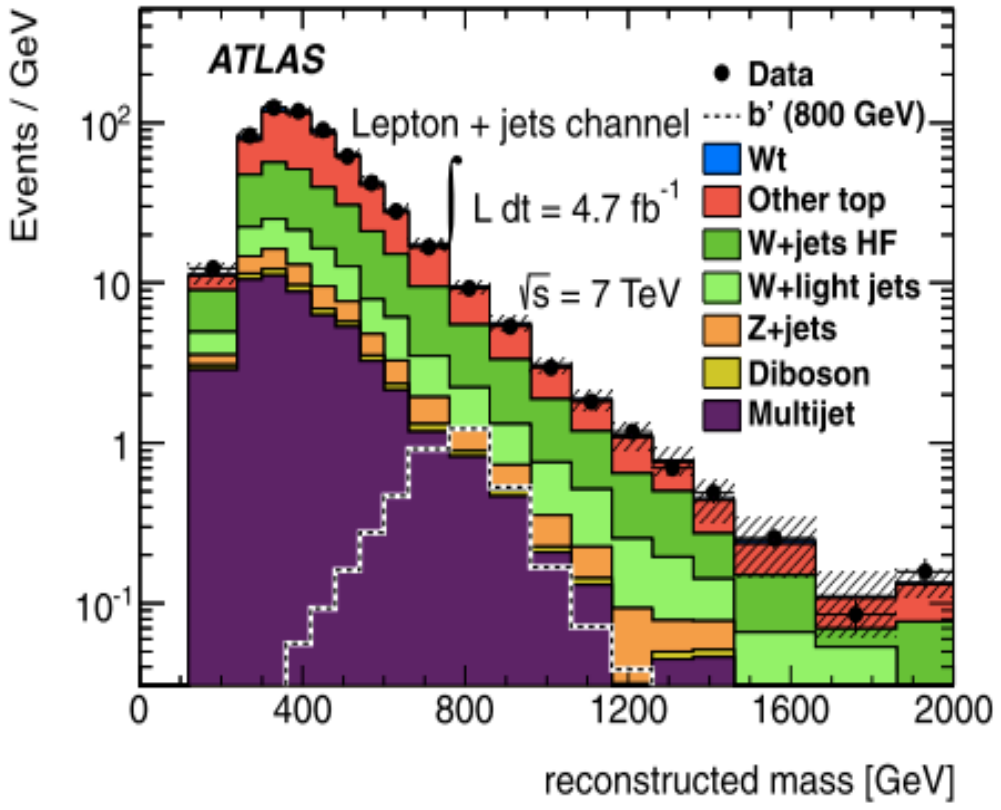
Search for single b* ➔ Wt





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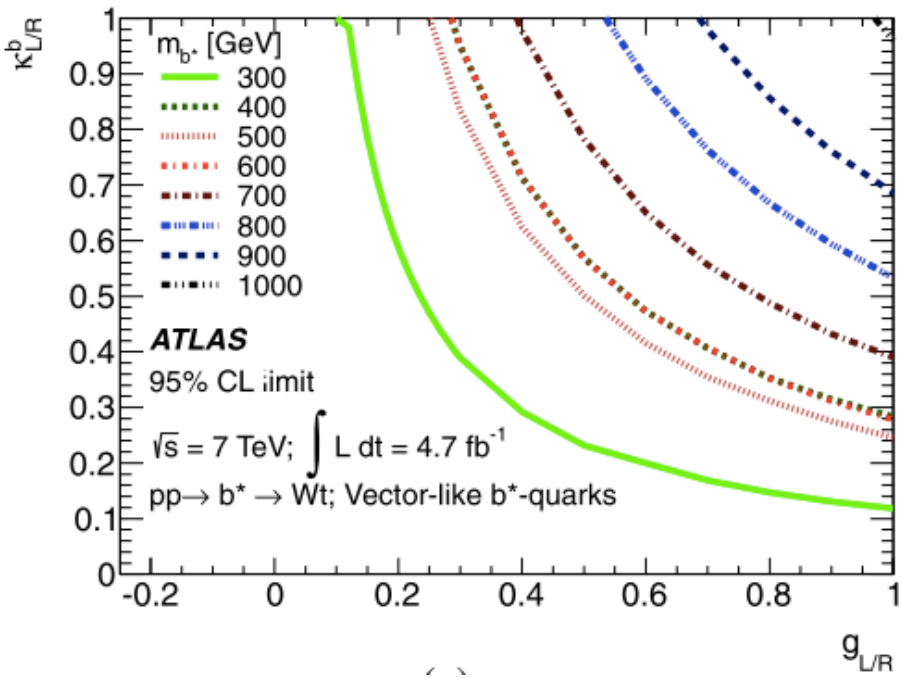
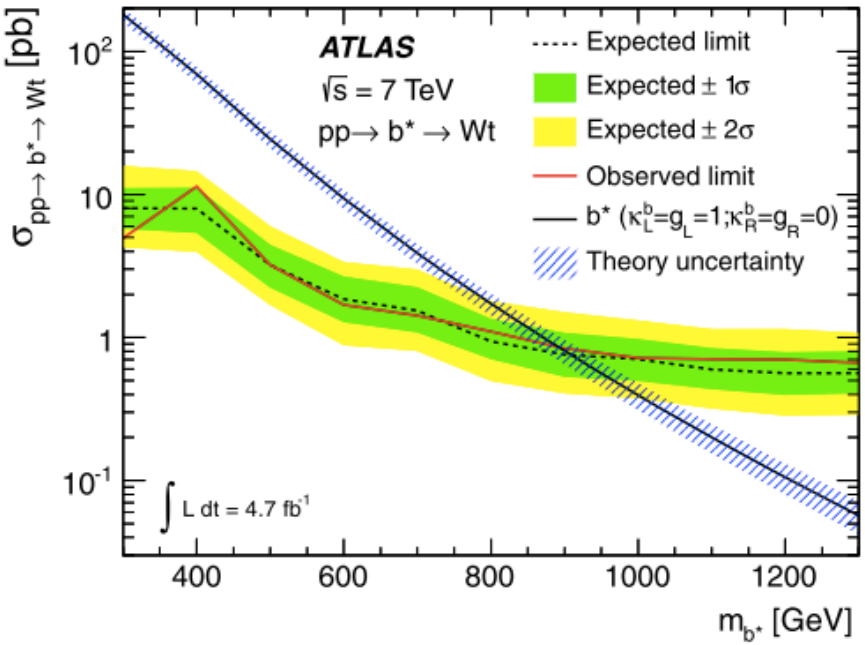
Search for single b* ➔ Wt

First Search

- For purely left-handed b* and unit strength chromomagnetic coupling

M_{b^*} > 870 GeV @ 95 % C.L.





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Summary

Mass, Dominant Decay	Limit @ 95% C.L.	Experiment, Channel
m(t′), t′ ➔ Wb	> 656 GeV	ATLAS, l+jets
m(t′), t′ ➔ Ht	>~850 GeV	ATLAS, l+jets
m(t′), t′ ➔ Zt	> 625 GeV	CMS, l+jets
m(t′,b′), t′, b′ ➔ Wq	> 350 GeV	ATLAS, OS dilepton
m(b′), b′ ➔ Wt	> 760 GeV	CMS, multi-lepton
m(b′), b′ ➔ Zb	> 660 GeV	CMS, multi-lepton
Inclusive t′, b′	> 685 GeV	CMS, multi-channel
m(t′), SU(2) singlet	> 640 GeV	ATLAS, l+jets
m(b′), SU(2) singlet	> 590 GeV	ATLAS, SS dilepton
m(t′), SU(2) doublet	> 790 GeV	ATLAS, l+jets
m(t′), t′ ➔ tg	> 794 GeV	CMS, l+jets

Conclusions

- Both CMS and ATLAS have a rich physics program on searches for heavy exotic quarks
- Many new analysis and interpretations using 8 TeV dataset of 20 fb^{-1} are underway
- Stay tuned for new results !

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Muito obrigado pela vossa atenção !