4^{th} generation and heavy quarks at LHC

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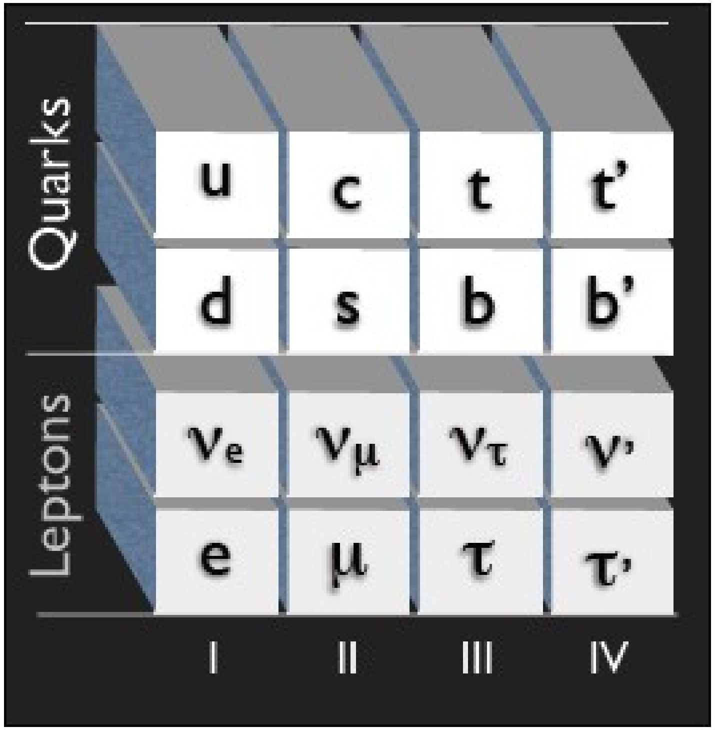
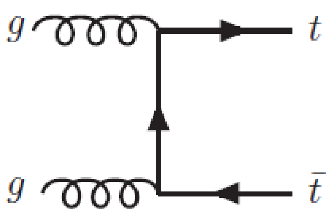
New heavy quarks

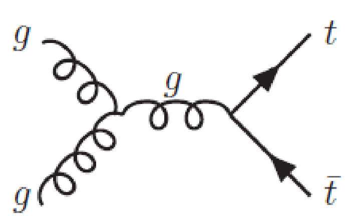
- Over the past decades, Standard Model (SM) has been very successful in describing all the experimental measurements using “only” three generations of quarks and lepton family
- Many BSM models predict new heavy quarks: Extra-dimension, little higgs, new SM like generations, GUTs, etc...
- → Can be vector like, can have flavor changing neutral current decays, etc...
- Initial searches at the LHC focus mainly on pair produced heavy quarks, decaying mostly like the top-quark
- Benchmark model:
  - Simplest extension of the SM: 4th sequential generation of fermions



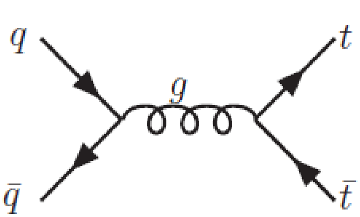
Top Quark Pair Production

- σ_{tt} (7 Tev LHC) ~ 165 pb (172.5 GeV, Moch, Uwer, Langenfeld (Phys. Rev. D78 (2008) 034003, arXiv:0907.2527) = 20 σ_{tt} (Tevatron)
- 5fb^{-1} @ 7 TeV already on tape
  → 825K ttbar pairs (~10 times Tevatron statistics)

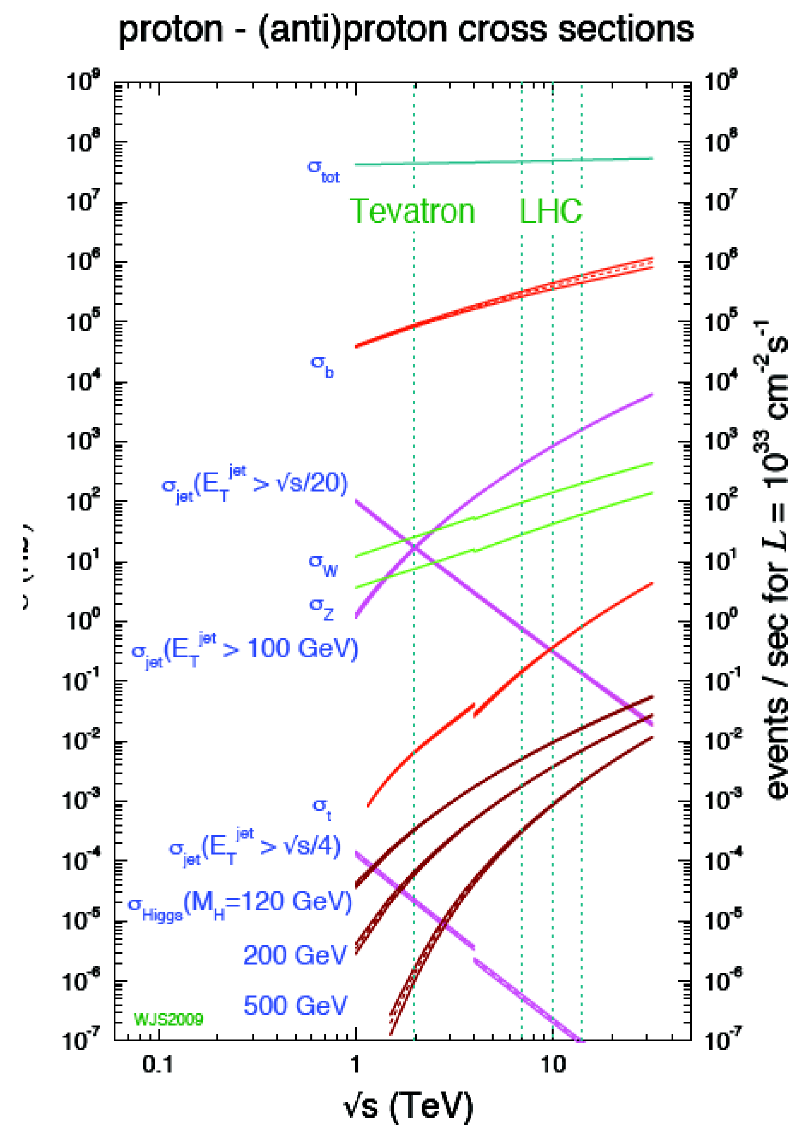




Dominant at the LHC (80%)

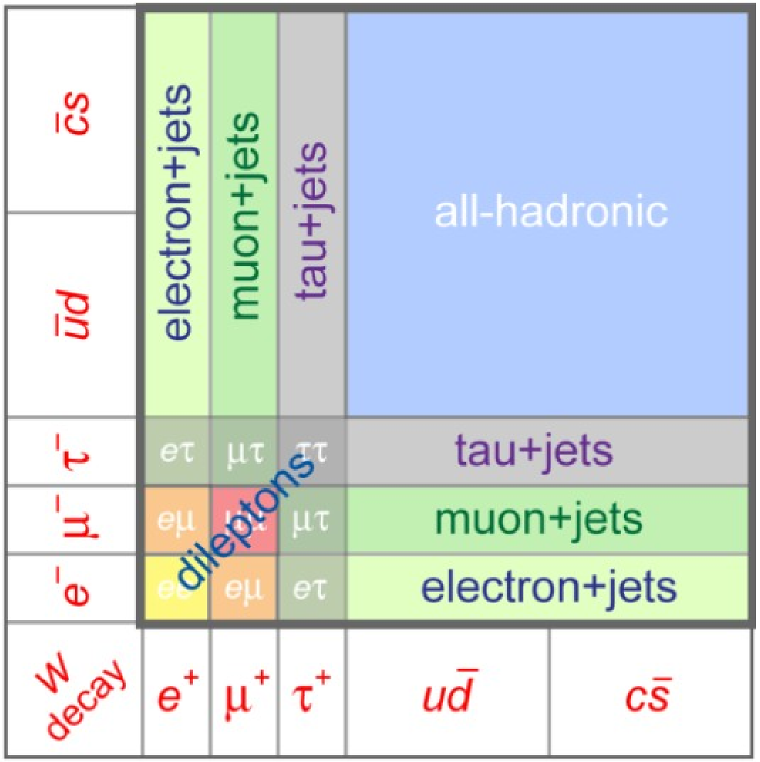


Dominant at the Tevatron



Top Quark Event Topology

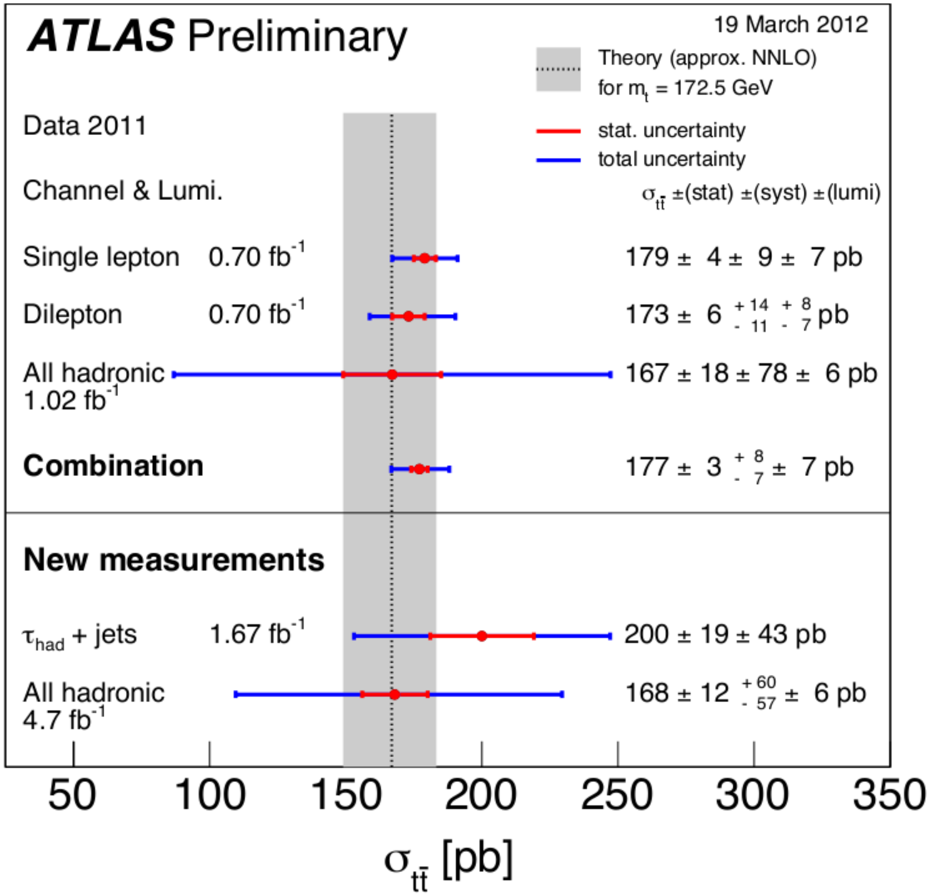
- Almost all top quarks decay to t → Wb
- Final states classified by W decay modes
  W → qq (2/3) or W → lν (1/3)
  - All hadronic (no W → lν) → 4/9 (~45%)
  - Semi-leptonic (1 W → lν) → 4/9 (only electron/muon considered → ~31%)
  - Di-leptonic (2 W → lν) → 1/9 (only electron /muon considered → ~5%)

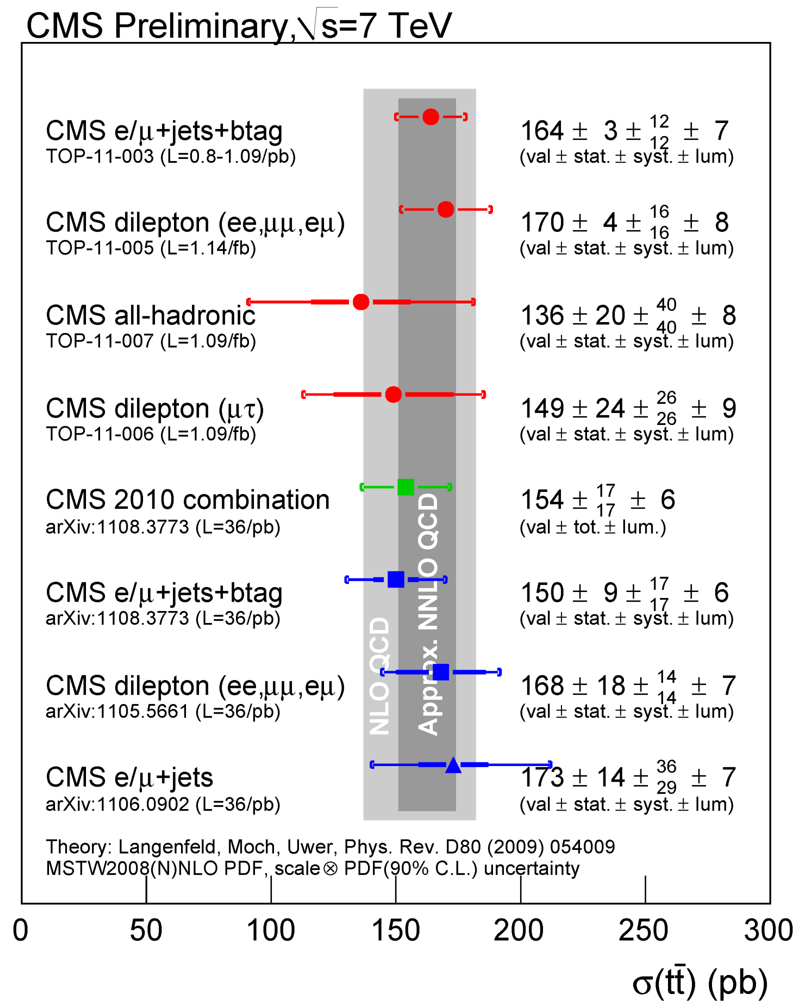


- The top-quark provides a virtual lab to search for new physics
  - Many tops have already been produced at LHC!!
  - Various properties of the top-quark have been measured
  - This helps us to provides procedures/tools to separate SM backgrounds from new physics

Top Quark Physic Status
(cross sections only...)

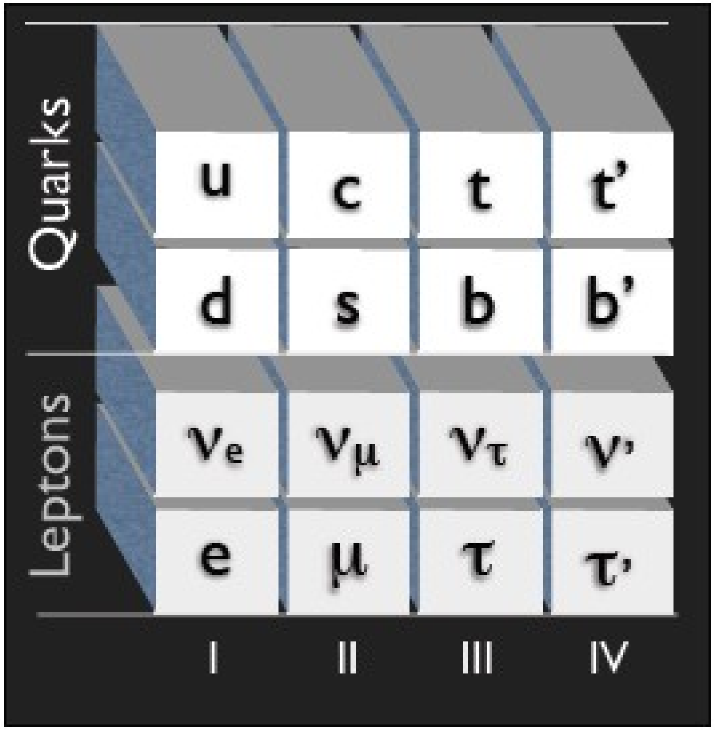
- → results now comparable with theoretical errors!!!





4^{th} generation quarks

- SM doesn't predict number of fermion generations:
  - Upper bound from QCD asymptotic freedom: number of families < 9 (<16 quarks).
  - CKM constraints fairly weak.
- SM4 = SM + 4^{th} generation family of fermions with 100 GeV < M < 600 GeV. Above 600 GeV large Yukawa couplings render model non-perturbative.
- In this talk will focus on heavy quarks
- Who ordered that?
  - Consistent w/ precision EW data and allowing for a heavier Higgs boson (up to ~500 GeV).
  - Extended CKM matrix could provide enough CP-violation to explain matter-antimatter asymmetry.
  - Can explain some anomalies in CP-violation measurements in B-physics.



$$\mathrm{CKM}_{4\times 4} = \begin{bmatrix} 0.97377\pm0.00027 & 0.2257\pm0.0021 & 0.00431\pm0.00030 & <0.044 \\ 0.230\pm0.011 & 0.957\pm0.095 & 0.0416\pm0.0006 & <0.46 \\ 0.0074\pm0.0008 & 0.0406\pm0.0027 & >0.78 & <0.47 \\ <0.063 & <0.46 & <0.47 & >0.57 \end{bmatrix}$$

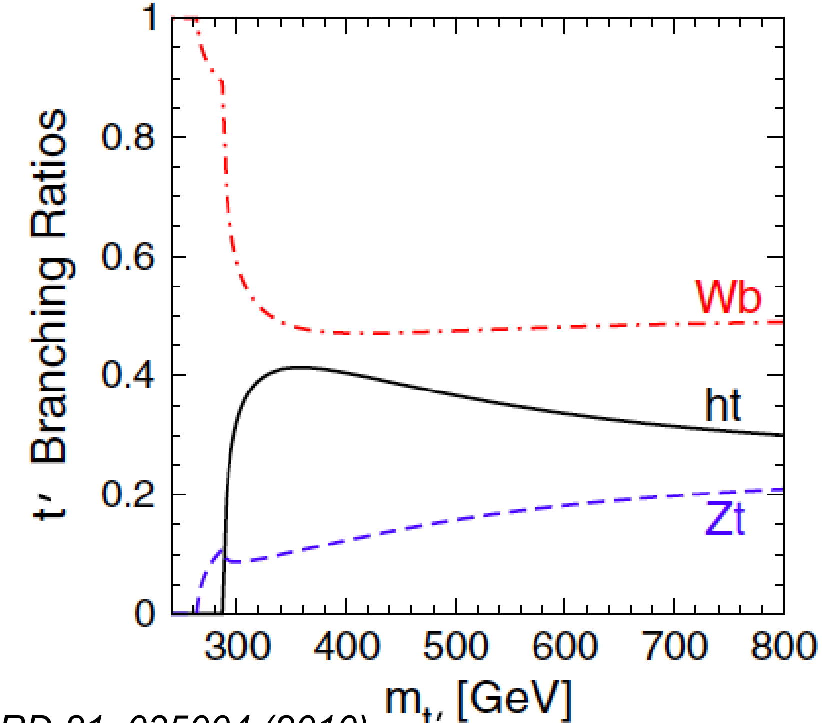
Vector like quarks

- Vector-like quarks: left and right components transform the same under $SU(2)_L$
- → can couple to SM particles without upsetting precision EW and flavor constraints.
- Vector-like quarks in a doublet need to be nearly degenerate in mass.
- Predicted by many models: extra-dimensions, Little Higgs, GUTs,…
- Since mixing with other quarks is ~m/M, they preferentially couple to the 3rd generation.
- Quite a few possibilities to explore! BRs can be quite model-dependent.

JHEP 11, 030 (2009) Triplets not included

	Label	Charge	Decay mode
T singlet	T_S	+2/3	$T \to W^+b$, Zt, Ht
B singlet	B_S	-1/3	$B \to W^-t$, Zb, Hb
(T,B) doublet	TB_d	(+2/3, -1/3)	$T \to W^+b$, Zt, Ht $B \to W^-t$, Zb, Hb
(X,T) doublet	XT_d	(+5/3, +2/3)	$X \to W^+t$ $T \to Zt$, Ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	$B \to Zb$, Hb $Y \to W^-b$

"Democratic"



PRD 81, 035004 (2010)

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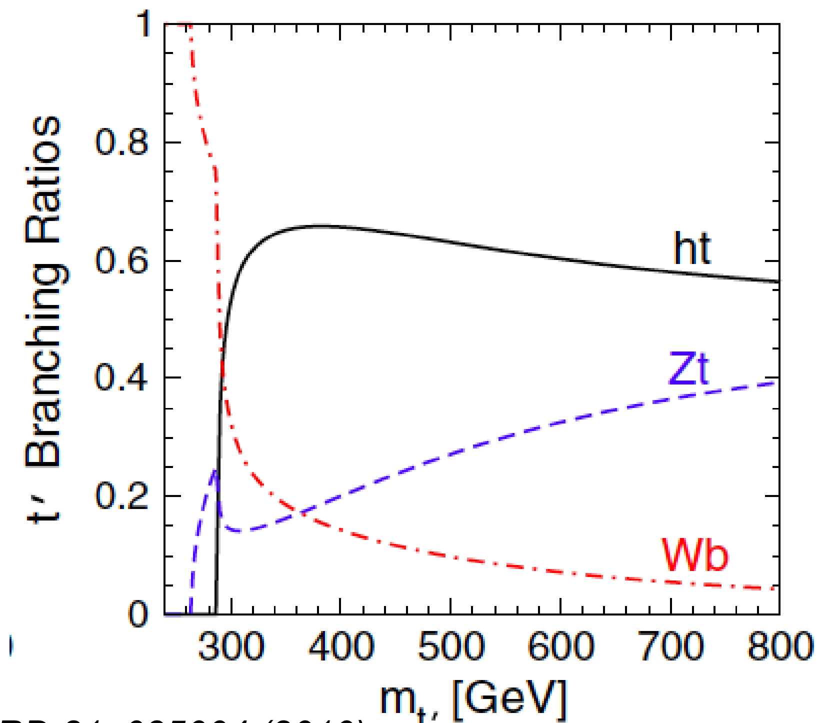
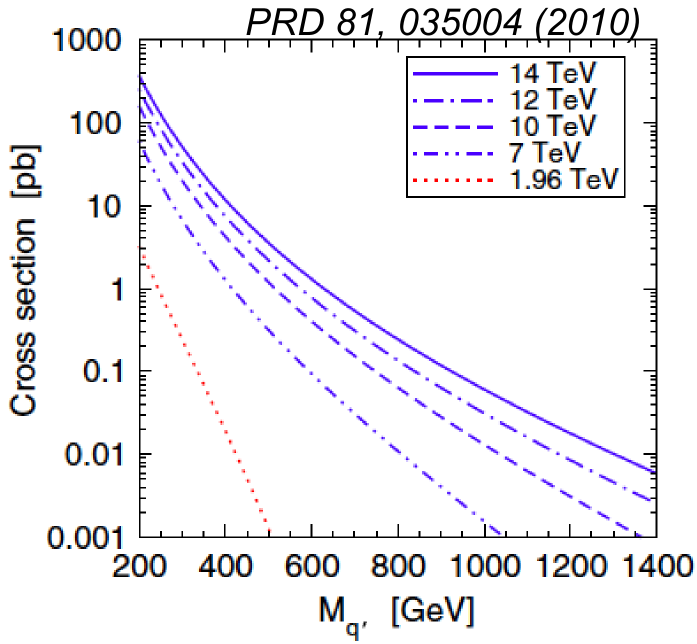
“W-phobic”

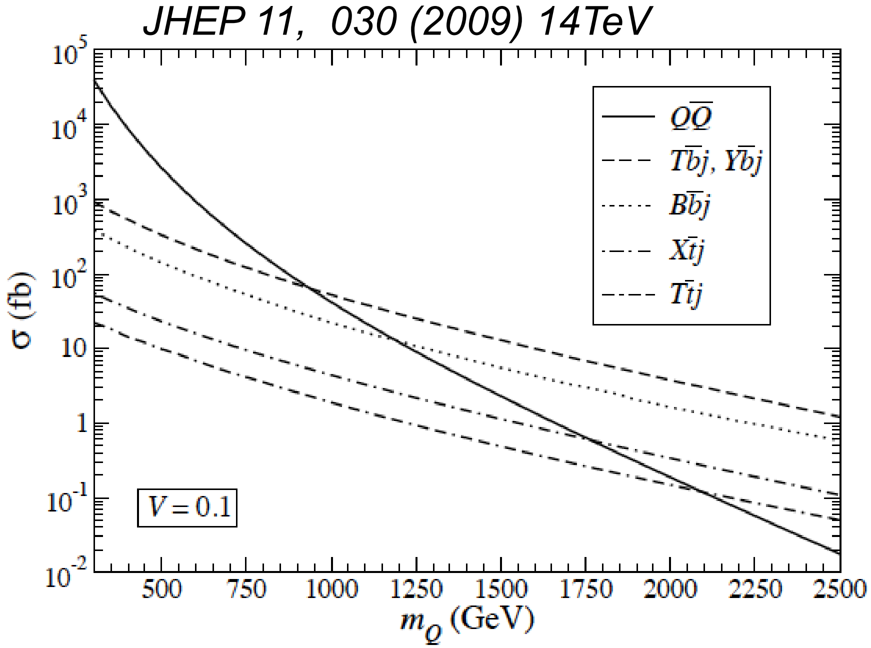


PRD 81, 035004 (2010)

Heavy quark production

- Up to masses ~1 TeV, dominant production is in pairs via the strong interaction:
- √s=7 TeV: σ(QQ) ~ 1.5 pb for m_Q~400 GeV vs σ(tt) = 160 pb
- √s=14 TeV: σ(QQ) ~ 8 pb for m_Q~400 GeV vs σ(tt) = 880 pb
- Many models involving vector-like quarks also have new heavy spin-1 colored particles (e.g G') which can enhance significantly the cross section.
- For masses above ~1 TeV the dominant production mode is single via the EW interactions (model-dep, but also opportunity to measure weak couplings of heavy quarks!).





Signatures: 4th generation quarks

- 4th Generation models have a restricted list of available signatures that simplify the search strategy: TT→WbWb, BB→tWtW → WbW WbW

				TB_d		
4 leptons						
	4l (0Z)			BB		
3 leptons	3l (0Z)			BB		
OS dileptons	l^+l^- (0Z)			TT,BB		
SS dileptons	$l^\pm l^\pm$			BB		
lepton+jets	$l^\pm$ (4j)			TT		
	$l^\pm$ (≥6j)			BB		

Signatures: vector like quarks

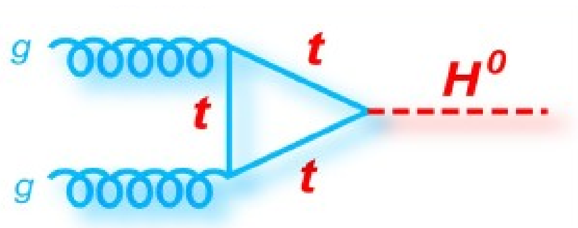
- If we consider VLQ models, there are many signatures that could be exploited, and which are ultimately needed to both enhance discovery potential and model discrimination.

		T_S	B_S	TB_d	XT_d	BY_d
4 leptons	4l (2Z)	TT	BB	TT,BB	TT	BB
	4l (1Z)	TT	BB	TT,BB	TT	BB
	4l (0Z)	TT	BB	TT,BB	TT,XX	BB
3 leptons	3l (1Z)	TT	BB	TT,BB	TT	
	3l (0Z)	TT	BB	TT,BB	TT,XX	
OS dileptons	l^+l^- (1Z)	TT	BB	TT,BB	TT	BB
	l^+l^- (0Z)	TT	BB	TT,BB	TT,XX	BB,YY
SS dileptons	$l^\pm l^\pm$		BB	BB	XX	
lepton+jets	$l^\pm$ (4j)	TT		TT	TT	YY
	$l^\pm$ ($\geq$6j)	TT	BB	TT,BB	TT,XX	

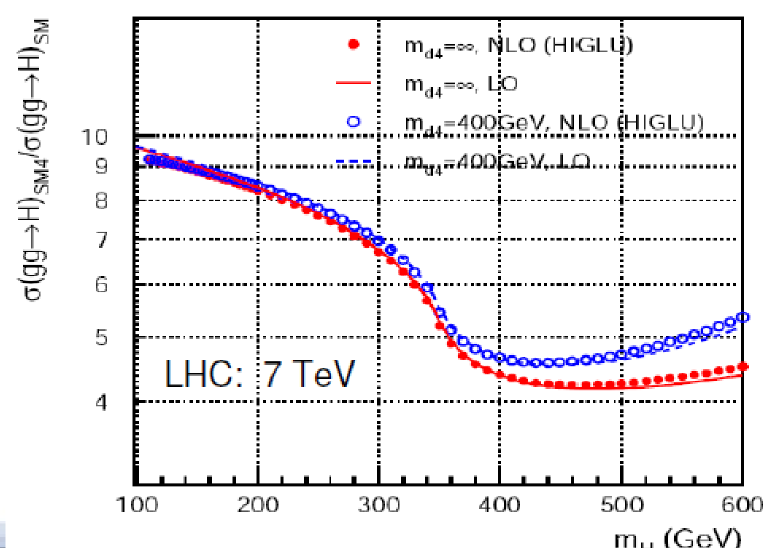
- Of course, some of them are more challenging or powerful than others…

Higgs and 4th generations 1/3

- 4th generation quarks can come with or without the Higgs boson
- If Higgs exist and considering SM4
  - Higgs couples to the new heavy quarks in the standard way
  - Substantial enhancement of the gg → H cross section
  - Leads to dramatic exclusion on the Higgs → 4th family in big trouble
- Data seems to indicate that both fourth family and SM Higgs cannot both exist
- If 4th family is discovered → SM Higgs is in deep troubles
- Also models of VLQ with a Higgs but suppression of SM branching ratio → Higgs only visible via heavy quark production

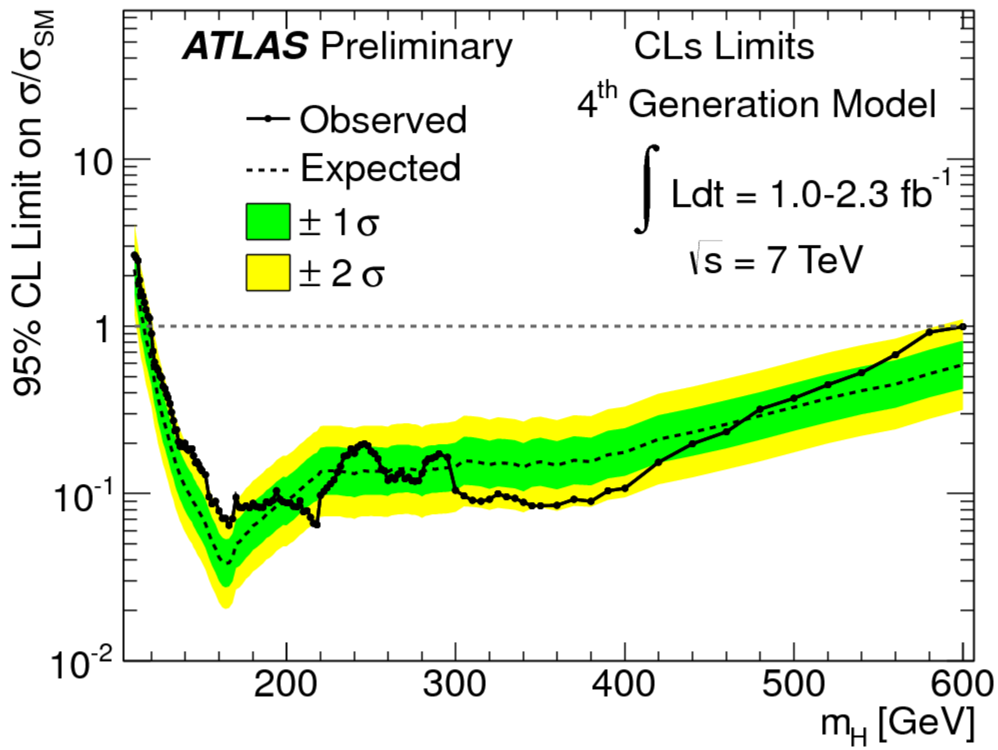


Ruan & Zhang (2011)



Higgs and 4th generations 2/3

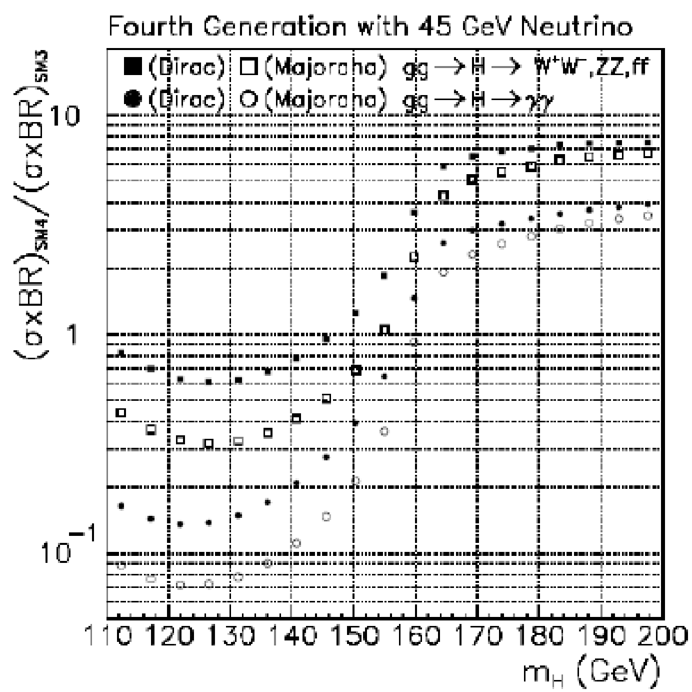
- What ATLAS did → consider 4th generation quarks/leptons with a mass of 600GeV
- Exclude Higgs boson with m(H) >119GeV and m(H)<593GeV
- If 125GeV excess is real → difficult to have a 4th generation quarks

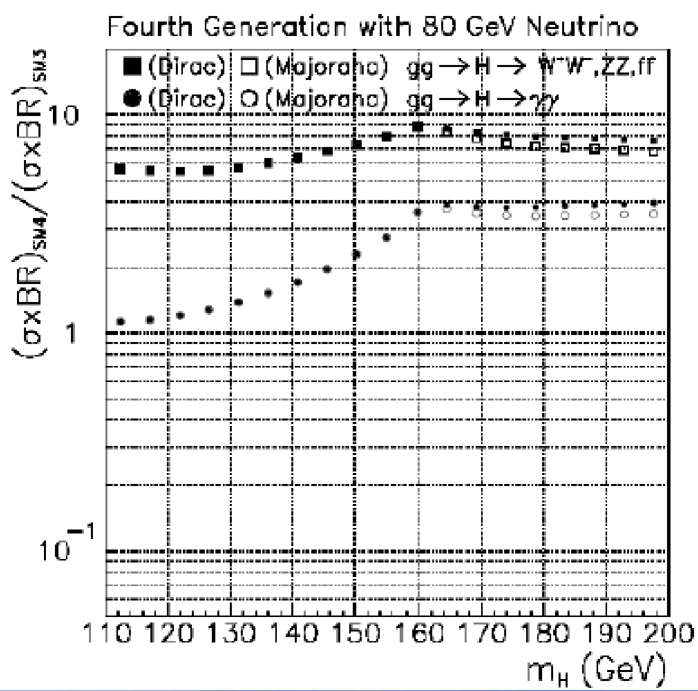


- → But, LHC limits not conservative

Higgs and 4th generations 3/3

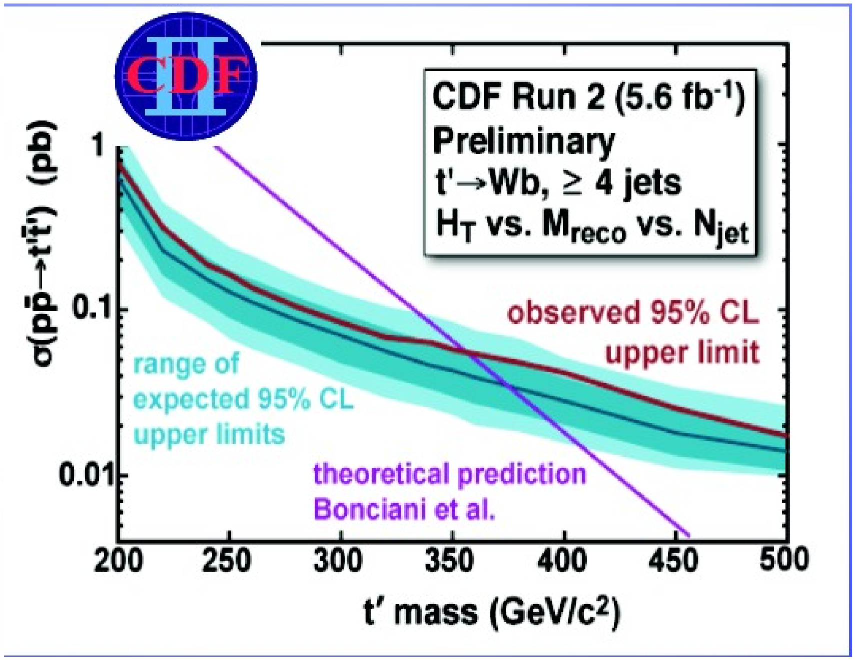
- But: Some room left for 4th generations and SM Higgs boson
  - 4th generation quarks also change the Higgs branching fractions
  - Heavy neutrino mass becomes a key parameter
  - SM4 with SM Higgs only possible
    - For very large Higgs masses > 600GeV
    - Small mass window → size depend on the heavy neutrino mass (Conservative limit from Z lineshape: Bulanov, Rozanov & Vysotsky (2003) m(ν4)> 46.7GeV)
    - → need to recalculate LHC Higgs limits with 4th generation for 46.7GeV heavy neutrino

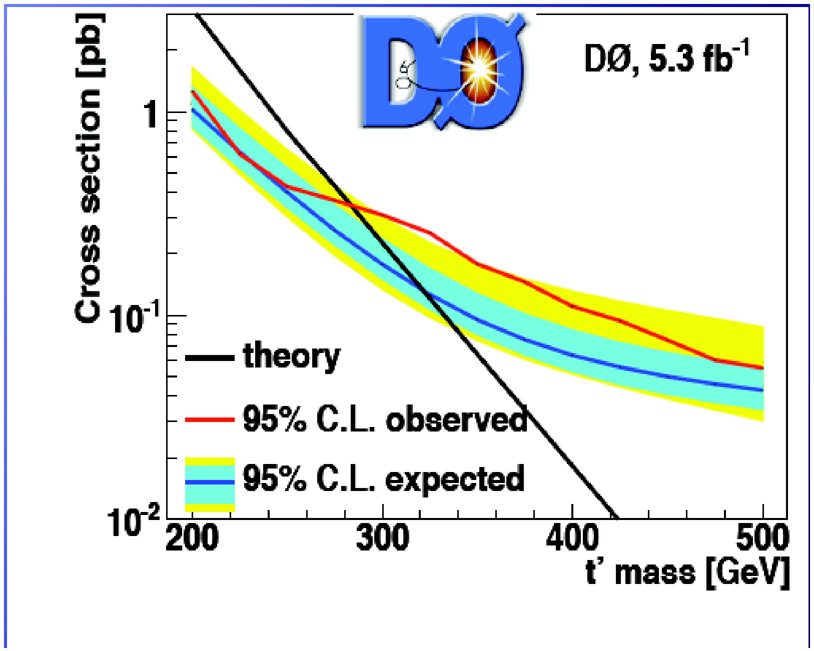




Tevatron Results t' (4^{th} gen)

- t' → Wb, L+jets Channel
- No signal consistent with t' pair production





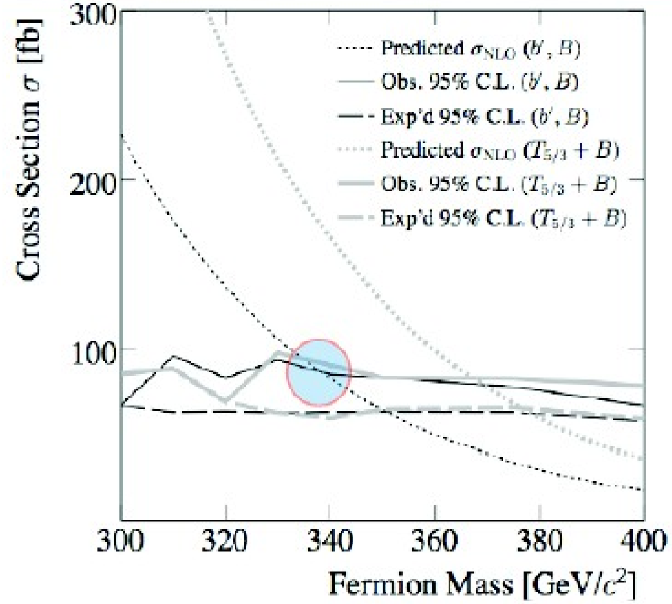
m(t') > 358GeV (CDF) @ 95%C.L.

m(t') > 285GeV (DO) @ 95%C.L.

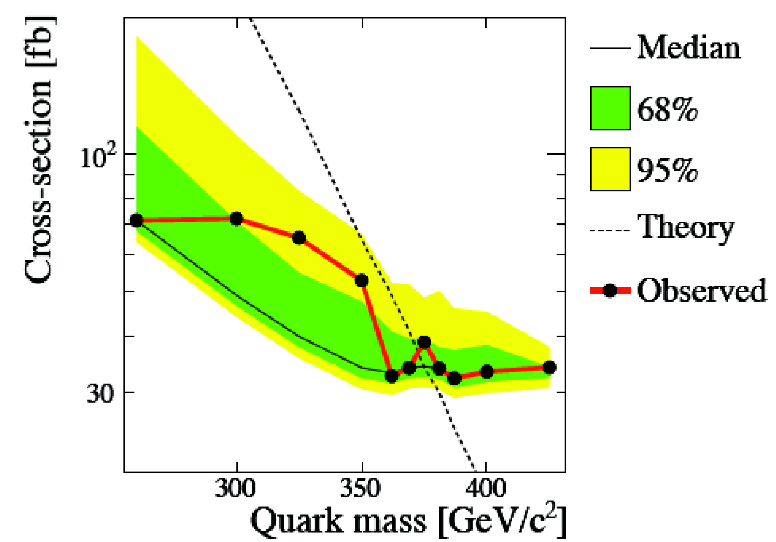
Tevatron Results b' (4^{th} gen)

- b' → Wt → WWb, L+jets Channel and same-signed leptons
- No signal consistent with b' pair production

Same-signed



Lepton+jets

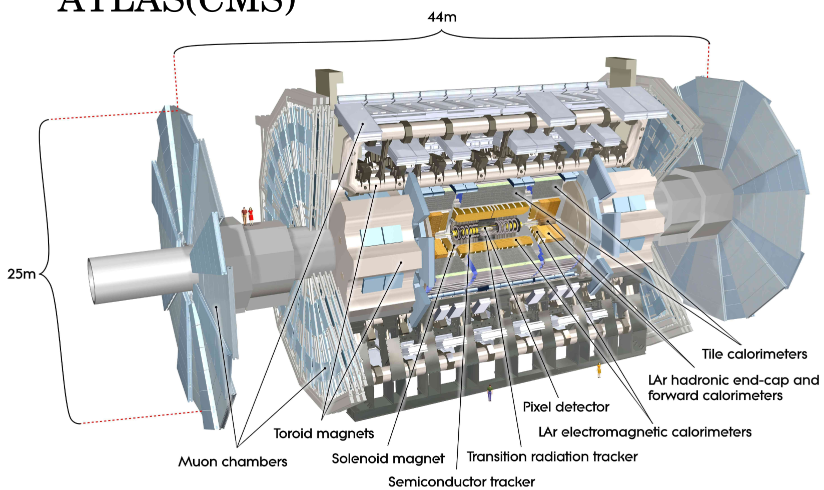


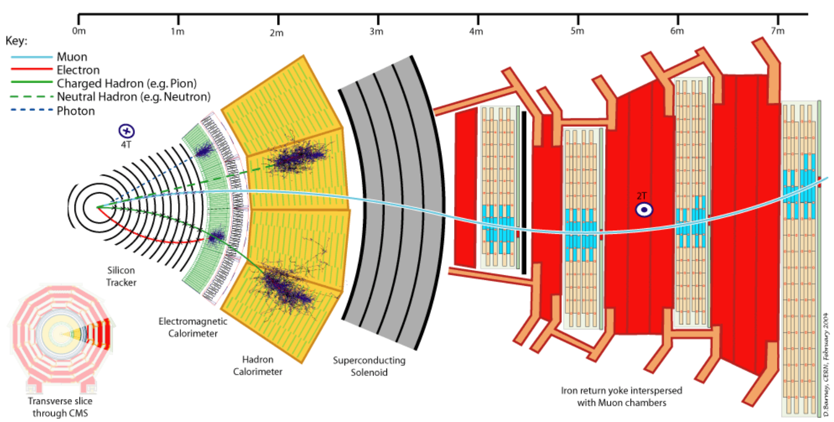
m(b') > 338GeV (CDF) @ 95%C.L.

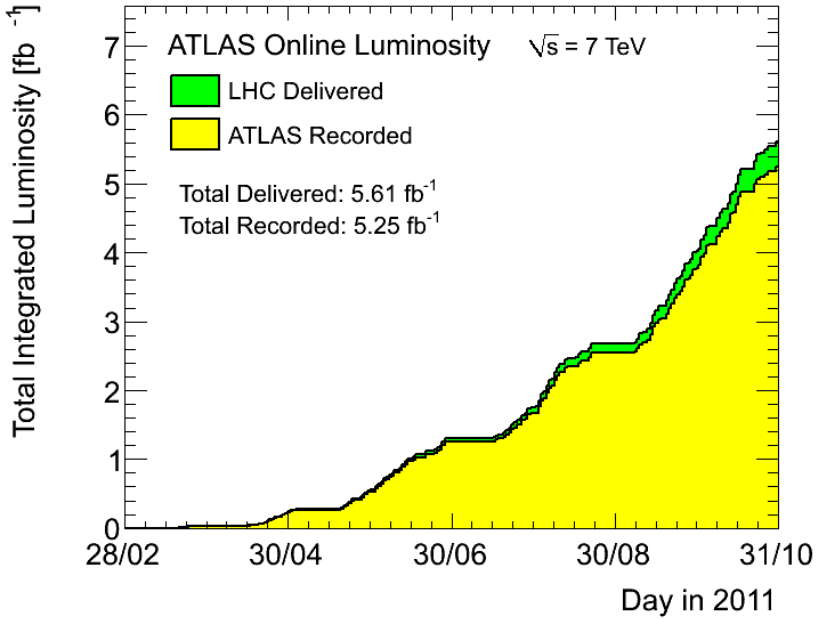
m(b') > 372GeV (CDF) @ 95%C.L.

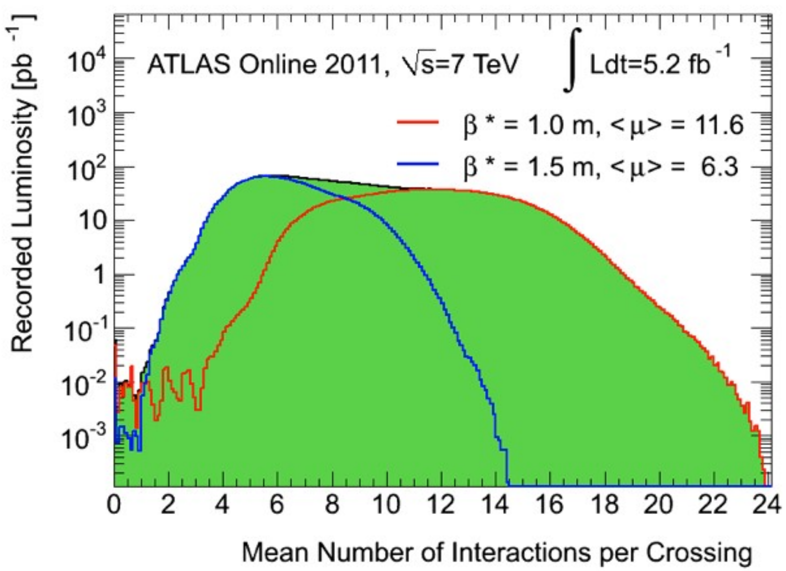
Detectors and LHC Data

- Data collected in 2011 → up to 5.25 fb^{-1}
- Maximum instantaneous luminosity 3.5 x 10^{-33} $cm^{-2}s^{-1}$
- Pileup up to nvtx = 24 (depending on the LHC)
- Luminosity uncertainty down to 3.4(4.5)% in ATLAS(CMS)









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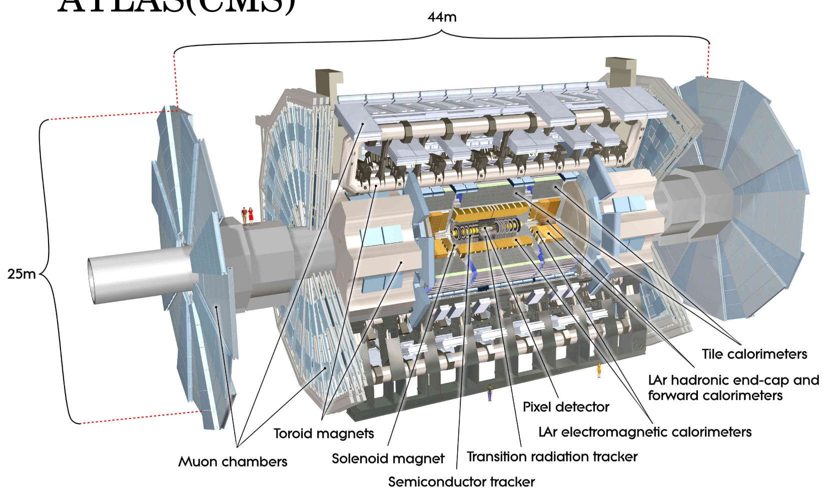
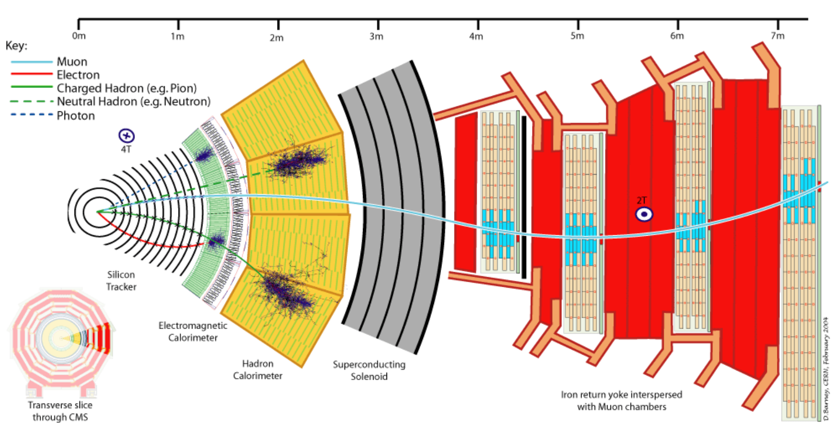
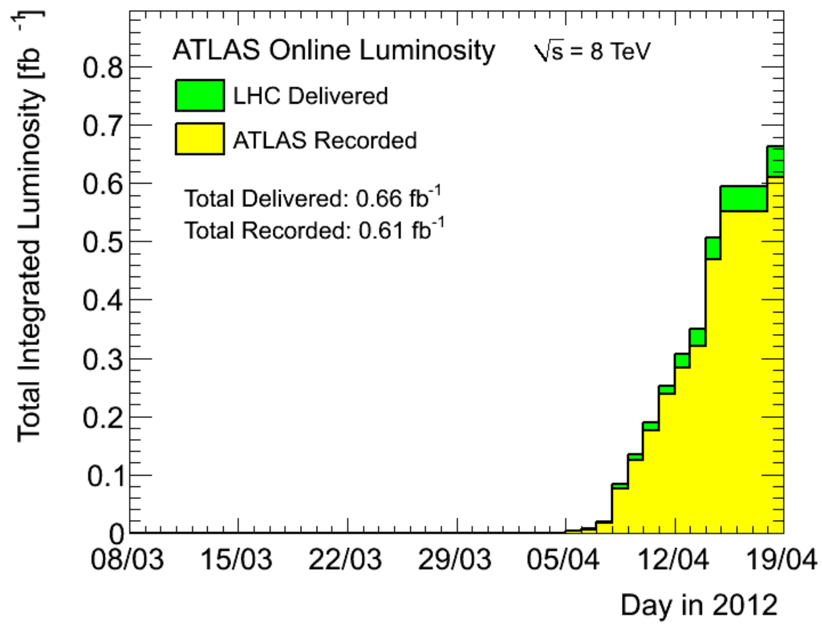
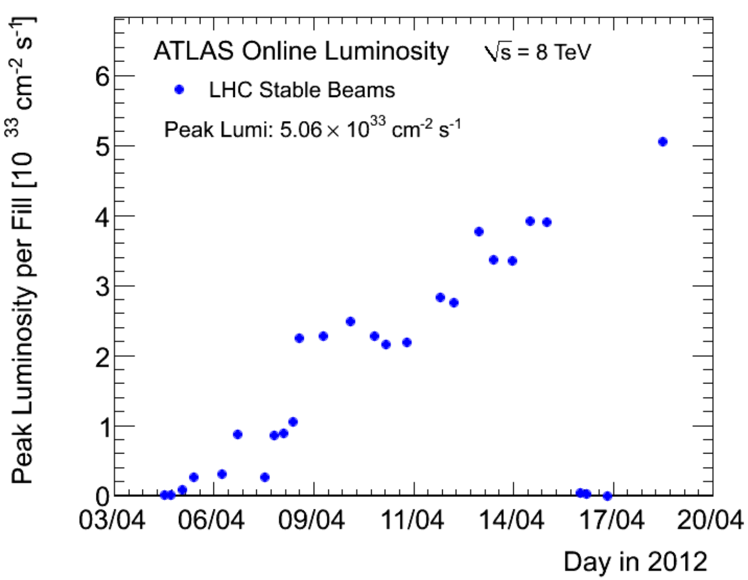








Monte-Carlos

- Signal generated with Pythia or MadGraph (ATLAS/CMS)
- Signal cross-sections from HATHOR (NNLO approximation)

- Backgrounds:
  - ATLAS: MC@NLO for ttbar, single top, Alpgen for W/Z+jets, Herwig for dibosons
  - CMS: Pyhtia, MadGraph
  - For fake leptons: Obtained via data-driven techniques → loosening the lepton ID criteria and extracting tight vs loose efficiencies in control samples

Results Covered In This Talk

- CMS results → https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
  - Search for a Heavy Bottom-like Quark (4.9 fb-1, arXiv:1204.1088)
  - Search for a Heavy Top-like Quark in the Dilepton Final state (5 fb-1, arXiv:1203.5410)
  - Search for the pair production of a fourth-generation up-type t' quark in events with a lepton and at least four jets (4.6 fb-1, PAS-EXO-11-099)
  - Inclusive search for a fourth generation of quarks (1.1 fb-1, PAS-EXO-11-054)
  - Search for a Vector-like Quark with Charge 2/3 in t+Z Events from pp collisions at $\sqrt{s}$= 7 TeV (1.14fb-1, arXiv:1109.4985)

Results Covered In This Talk

- ATLAS results → https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
  - Search for pair production of a heavy quark decaying to a W boson and a b quark in the lepton+jets channel with the ATLAS detector (1.04fb-1, arXiv:1202.3076)
  - Search for pair-produced heavy quarks decaying to Wq in the two-lepton channel at sqrt(s) = 7 TeV with the ATLAS detector (1.04fb-1, arXiv:1202.3389)
  - Search for same-sign top-quark production and fourth-generation down-type quarks in pp collisions at sqrt(s) = 7 TeV with the ATLAS detector (1.04fb-1, arxiv:1202.5520)
  - Search for down-type fourth generation quarks with the ATLAS Detector in events with one lepton and high transverse momentum hadronically decaying W bosons in sqrt(s)=7 TeV pp collisions (1.04fb-1, arxiv:1202.6540)
  - Search for New Phenomena in ttbar Events With Large Missing Transverse Momentum (1.04fb-1, arXiv:1109.4725)
  - Search for pair production of a new quark that decays to a Z boson and a bottom quark with the ATLAS detector (2.0fb-1, approved plots)
  - Search for a heavy vector-like quark coupling to light quarks in proton-proton collision at √s= 7 TeV with the ATLAS detector (1.04 fb-1, arXiv:1112.5755)

BB → WtWt 1/3

arXiv:1204.1088

5fb^{-1}

- b'b' → tWtW → WbW WbW
  - 2 same sign or three isolated leptons (e/mu) in the final state → 7.3% of the decay
  - Dilepton triggers → 92% (mu/mu), 96% (e/mu), >99% (e/e)
- Selection criteria:
  - Muons: pT>20GeV, $|\eta|<2.4$; isolation ΣET(ΔR<0.3) – pileup < 0.15*pT
  - Electron: pT>20GeV, $|\eta|<2.4 \notin 1.44 < |\eta| < 1.57$; isolation ΣET(ΔR<0.3) – pileup < 0.06*pT
    - Select event with 2 opposite sign leptons or three leptons (2 of them opposite charge)
  - For same flavor leptons → Z mass veto: |mll – mZ| > 10GeV
  - B-tagging based on IP significance → 50% b-tag efficiency; 1% mistag rate; nbjet≥1
  - Jets clustered using PF particles and Anti-kt with a cone of 0.5; pt > 25GeV; $|\eta|<2.4$
    - Same sign lepton → njets≥4; 3 lepton channel njets≥2
  - ST = scalar sum of jet pT, lepton pT, MET, should be > 500GeV
- Signal selection efficiency:

$M_{b'}$ [GeV/c^2]	Cross section [pb]	Same-charge dilepton efficiency [%]	Same-charge dilepton yield	Trilepton efficiency [%]	Trilepton yield
450	0.662	1.52 ± 0.13	49	0.47 ± 0.05	15
500	0.330	1.64 ± 0.14	26	0.51 ± 0.05	8.2
550	0.171	1.71 ± 0.14	14	0.56 ± 0.05	4.7
600	0.0923	1.69 ± 0.14	7.6	0.60 ± 0.06	2.7
650	0.0511	1.71 ± 0.15	4.3	0.63 ± 0.06	1.6

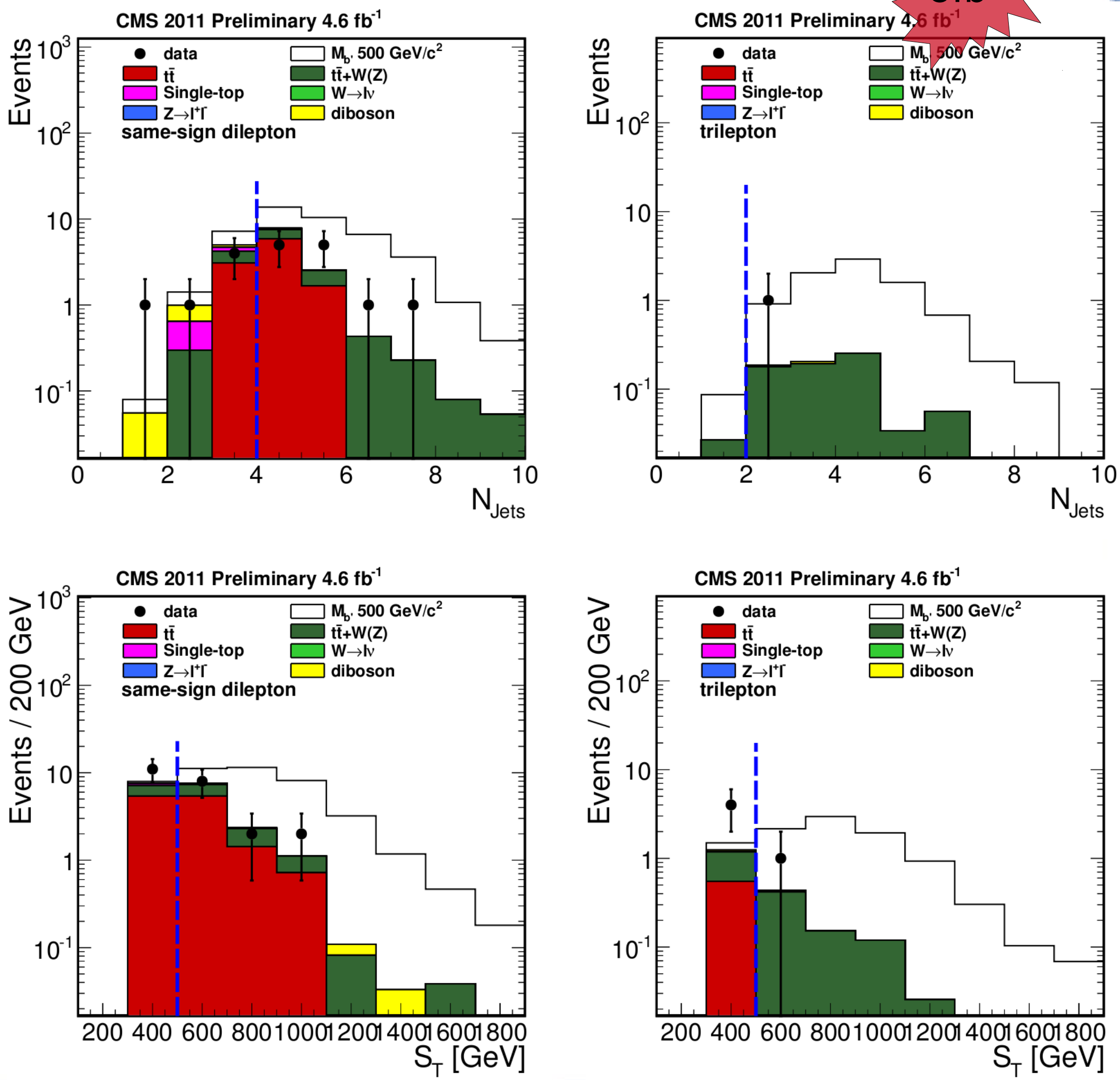
BB → WtWt 2/3

arXiv:1204.1088

$5fb^{-1}$

- Backgrounds:
  - Same sign 2 leptons → main contribution is from ttbar
  - 3 leptons; main contribution tt+W(Z)
- Good modeling of the data, no sign of any excess → set limits
- Expected/observed yields:

	Total BG in signal region	Data
2SS	11.4 +/- 2.9	12
3 lepton	0.78 +/- 0.21	1



BB → WtWt 3/3

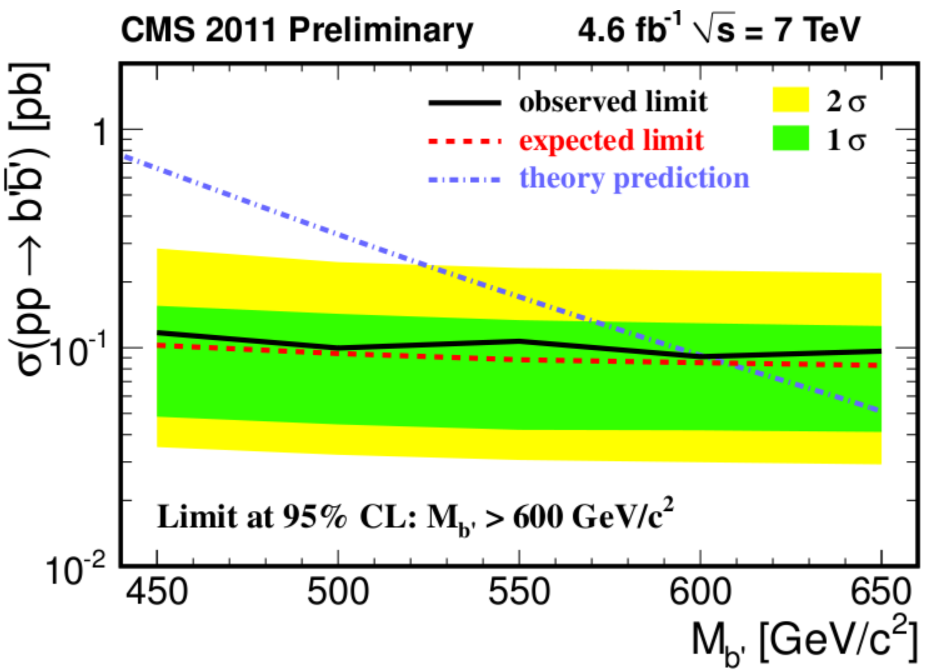
arXiv:1204.1088

5fb^{-1}

- Limits extracted using a cut and count method
- Modified frequentist method used to extract limits
- Observed limit: m(b') > 611GeV @ 95%CL

	Total BG in signal region	Data
2SS	11.4 +/- 2.9	12
3 lepton	0.78 +/- 0.21	1

	Same-charge dilepton		Trilepton	
	$\Delta\epsilon/\epsilon$ [%]	ΔB	$\Delta\epsilon/\epsilon$ [%]	ΔB
Accuracy of control-sample method	-	2.63	-	-
Control sample statistics	-	0.76	-	-
b-tagging	6.7	0.35	6.7	0.08
Lepton selection	3.3	0.03	4.9 – 5.1	0.04
Background normalization	-	0.74	-	0.12
Pile-up events	0.5	0.13	0.6	0.03
Jet energy scale	1.1 – 2.0	0.31	0.3 – 1.0	0.02
Jet energy resolution	0.3 – 1.4	0.22	0.3 – 0.9	0.02
Missing energy resolution	0.1 – 0.7	0.38	0.1 – 2.2	0.07
Trigger	1.4	0.11	0.7	0.01
PDF	0.4 – 1.9	0.26	0.4 – 1.3	0.03
Simulated sample statistics	2.7 – 3.4	0.26	4.5 – 6.5	0.12
Integrated luminosity	2.2	0.24	2.2	0.05
Total	8.6 – 9.0	2.9	10 – 11	0.21

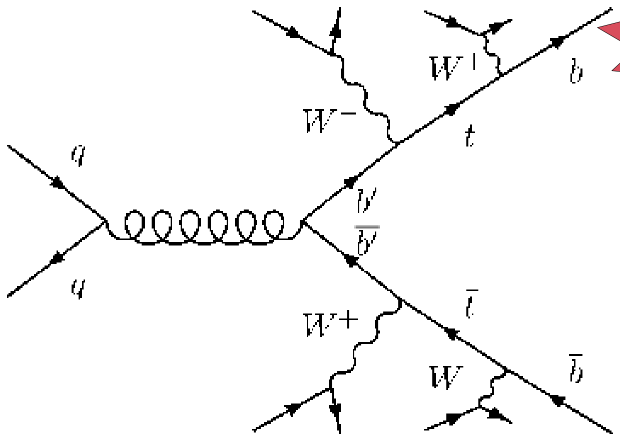


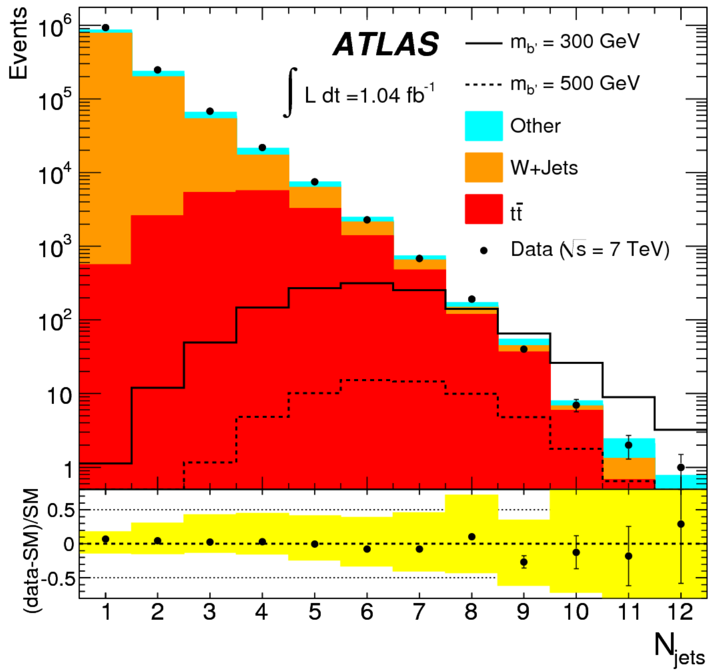
BB → WtWt (single lepton) 1/3

arXiv:1202.6540

1fb^{-1}

- Final state b'b' → WtWt → WWbWWb → 1lep+MET+ ≥6jets
- <u>Event selection:</u>
  - Exactly 1 lepton (electron or muon) with tight selection criteria
  - Lepton pT > 20(25)GeV muon(electron); muon $|\eta| < 2.5$; electron $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - ETMiss > 20(35) GeV; muon(electron)
  - ETMiss + MTW(lep) > 60GeV
  - ≥6jets with pT > 25GeV and $|\eta| < 2.5$
- No b-tagging requirements
- High jet multiplicity → suppress background
- Identify high pT W bosons (close-by jets)



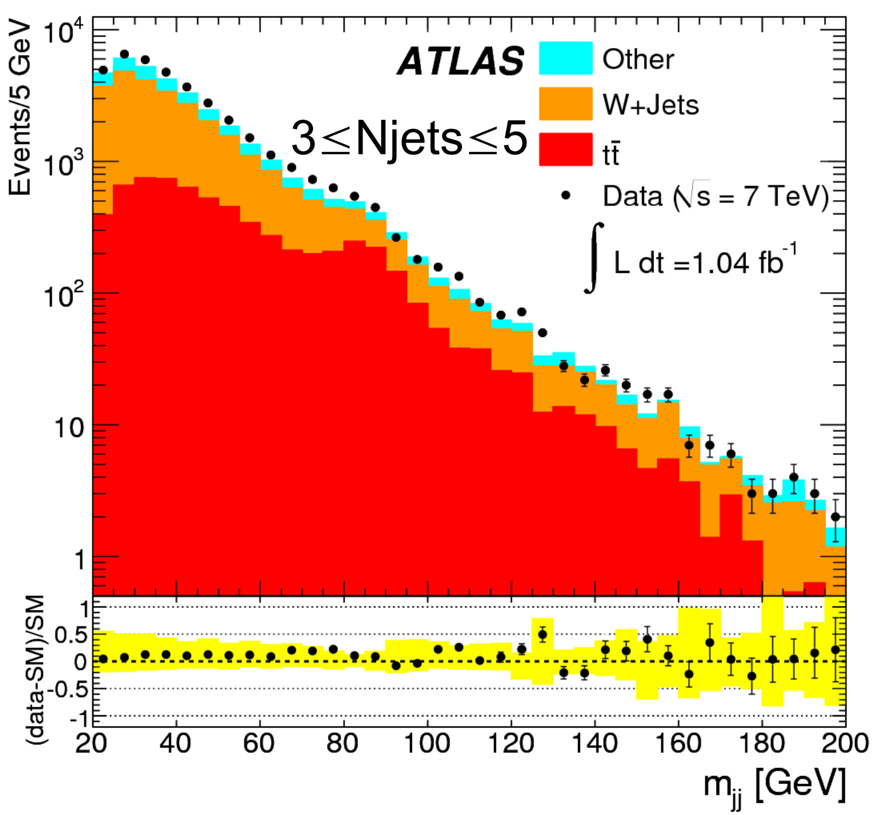


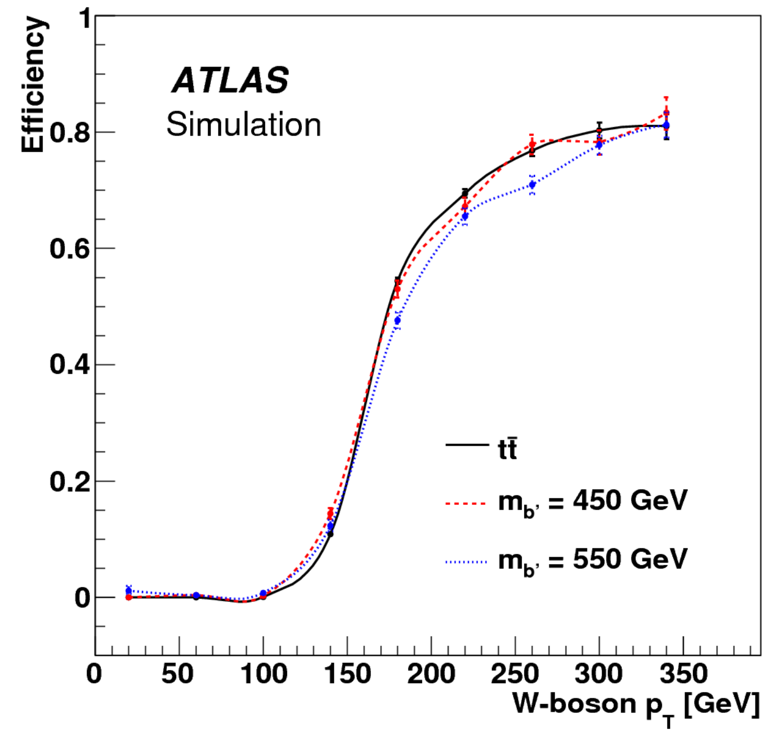
BB → WtWt (single lepton) 2/3

arXiv:1202.6540

$1fb^{-1}$

- Analysis based on high pT hadronic W (2 jets collimated)
- Pair jets if DR(j,j) < 1
- Count the number of W with 70<MW<100GeV
  - → >75% efficient for pt(W)>250GeV
- Very good Background modeling in several signal free regions



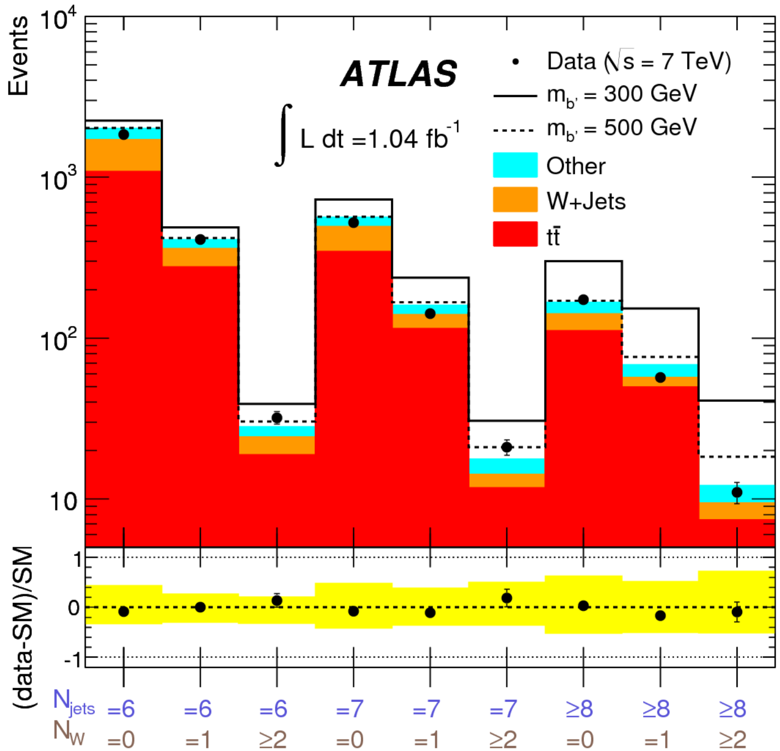


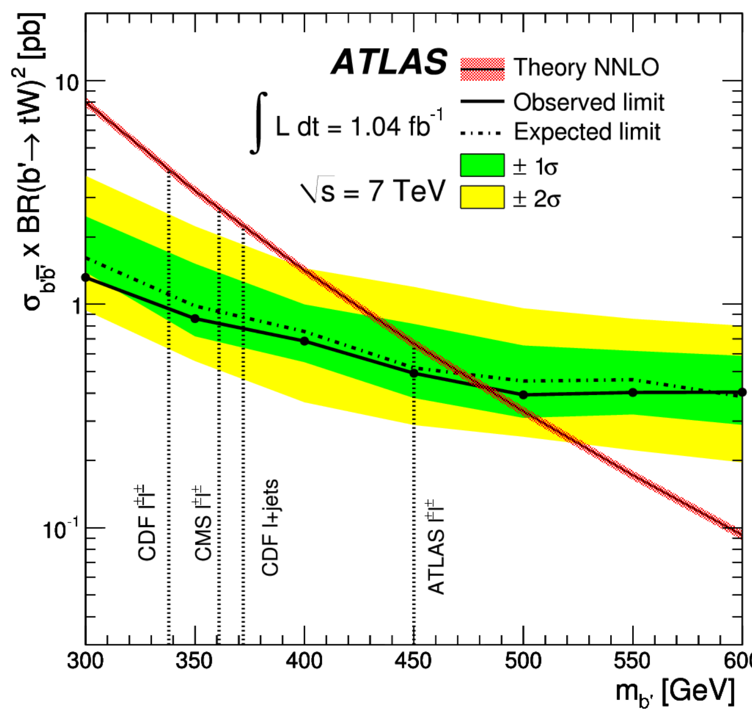
BB → WtWt (single lepton) 3/3

arXiv:1202.6540

1fb^{-1}

- Data in agreement with SM expectations → Set limits
- Number of hadronic W boson candidate (0,1, ≥2) for 3 jet bins (6, 7, ≥8)
- Mclimit used (Cls method with profile likelihood fit)
- Assuming BR(b' → tW) = 1 → m(b') > 480GeV @ 95% C.L.





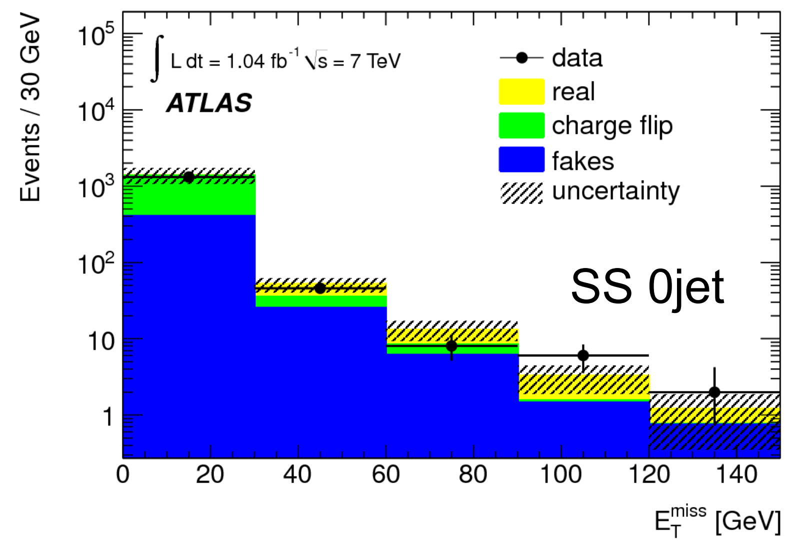
Applicable to VLQ
B → W-t (Q=-1/3) and
X → W+t (Q=+5/3)

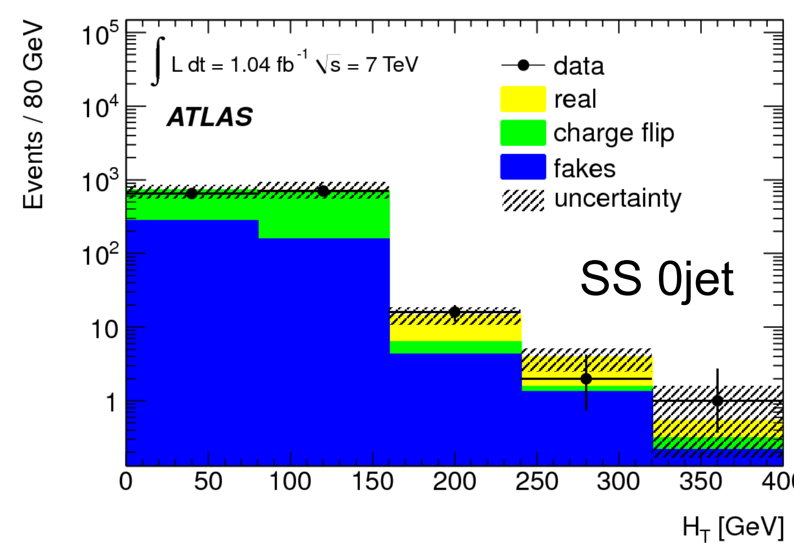
BB → WtWt (SS dileptons) 1/3

arXiv:1202.5520

1fb^{-1}

- Final state b'b' → WtWt → WWbWWb → 2SS leptons, MET, ≥2jets
- Search for two same sign leptons (ee/eμ/$\mu\mu$)
- Signature: 2 SS leptons, MET, >=2jets
- Pre-Selection:
  - 2 same sign leptons with tight identification criteria
  - Single lepton trigger
  - Lepton pT > 20(25)GeV muon(electron); muon $|\eta| < 2.5$; electron $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - ee/mumu → Mll > 15GeV and $|$Mll - MZ$|$>10GeV
  - Jets: 2 Anti-kt 0.4, pt> 20GeV, $|\eta| < 2.5$
  - ETMiss > 40 GeV
- No b-tagging requirements



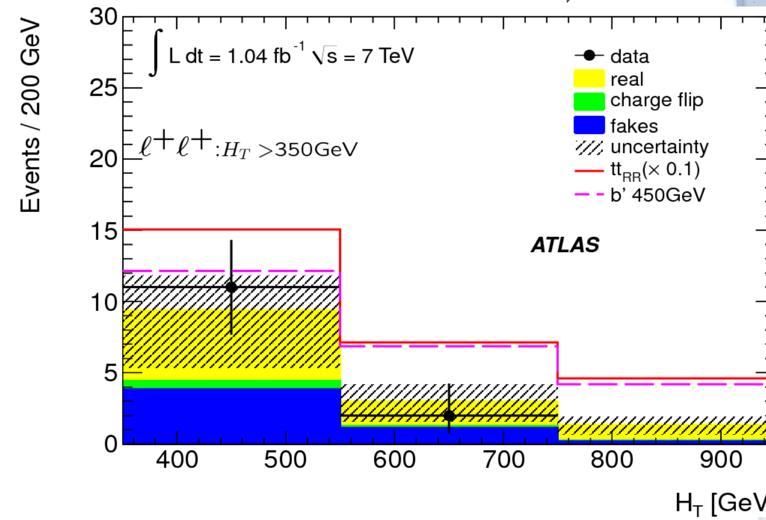


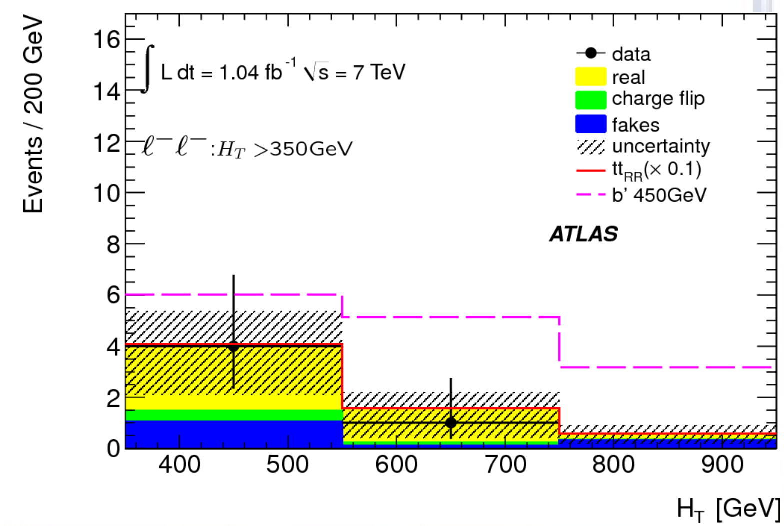
BB → WtWt (SS dileptons) 2/3

arXiv:1202.5520

$1\,fb^{-1}$

- Background sources in the SM:
  - Diboson (MC) → irreducible background (Real leptons)
  - Ttbar, Wjets → one fake lepton or charge filp → data driven
- Dominant systematics:
  - Jet energy scale and resolution
  - Fake lepton background
  - Charge flip background
- Strategy:
  - Signal region → HT > 350GeV (scalar sum of leptons and jets)
  - Low background search → accurate estimations
  - Cut and count analysis





BB → WtWt (SS dileptons) 3/3

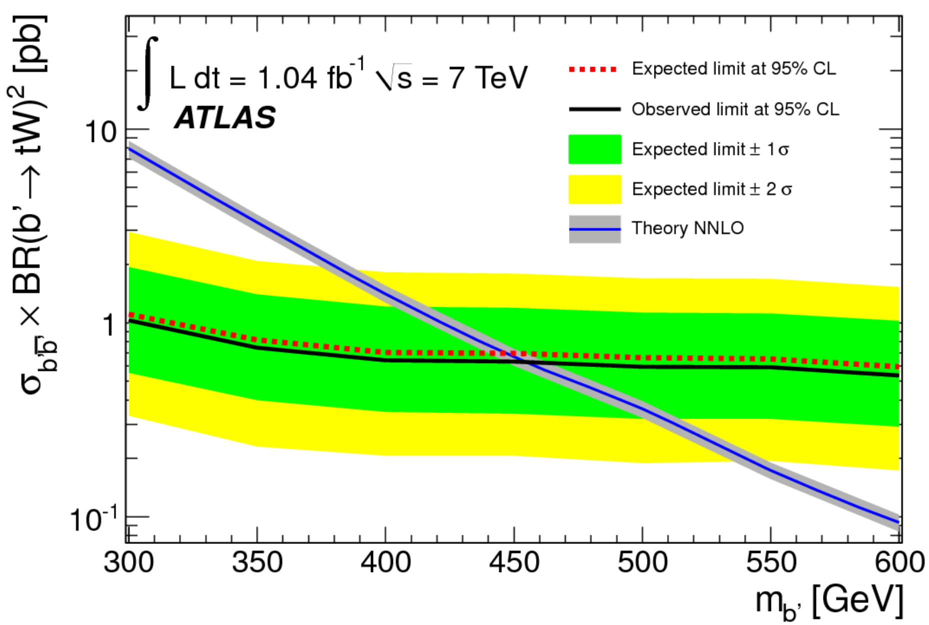
arXiv:1202.5520

$1fb^{-1}$

- A single bin counting experiment is used to set limit
- Data in agreement with SM expectations
- Limits setting using Collie package
- Confidence level interval are build using a Likelihood ratio test statistic
- Assuming BR(b' → tW) = 1 → m(b') > 450GeV @ 95% C.L.

	e^-e^-	$\mu^-\mu^-$	$e^-\mu^-$
Fake	$0.2 \pm 0.3 \pm 0.1$	$0.7 \pm 0.3^{+0.6}_{-0.3}$	$0.5 \pm 0.2^{+0.7}_{-0.3}$
Charge flip	$0.3 \pm 0.1^{+0.3}_{-0.1}$	$0 \pm 0^{+0.01}_{-0}$	$0.3 \pm 0.1^{+0.2}_{-0.1}$
Real	$0.8 \pm 0^{+0.3}_{-0.6}$	$1.0 \pm 0^{+0.4}_{-0.6}$	$2.3 \pm 0^{+0.8}_{-1.9}$
Total	$1.4 \pm 0.3^{+0.4}_{-0.6}$	$1.7 \pm 0.3 \pm 0.7$	$3.1 \pm 0.2^{+1.1}_{-1.9}$
Data	1	2	2
b' 450 GeV	$1.8 \pm 0 \pm 0.3$	$2.1 \pm 0 \pm 0.3$	$4.3 \pm 0 \pm 0.5$

	e^+e^+	$\mu^+\mu^+$	$e^+\mu^+$
Fake	$0.8 \pm 0.6^{+0.2}_{-0.4}$	$1.0 \pm 0.3^{+0.6}_{-0.4}$	$3.3 \pm 1.1^{+1.6}_{-1.4}$
Charge flip	$0.3 \pm 0.1^{+0.3}_{-0.1}$	$0 \pm 0^{+0.01}_{-0.0}$	$0.4 \pm 0.1^{+0.3}_{-0.1}$
Real	$1.9 \pm 0^{+0.7}_{-1.5}$	$1.6 \pm 0^{+0.7}_{-0.9}$	$4.4 \pm 0^{+1.3}_{-3.1}$
Total	$3.0 \pm 0.6^{+0.8}_{-1.5}$	$2.6 \pm 0.3^{+0.9}_{-1.1}$	$8.1 \pm 1.1^{+2.2}_{-3.4}$
Data	2	1	10
b' 450 GeV	$1.8 \pm 0 \pm 0.3$	$2.7 \pm 0 \pm 0.4$	$5.0 \pm 0 \pm 0.7$



Applicable to VLQ
B → W-t (Q=-1/3) and
X → W+t (Q=+5/3)

TT → WbWb (OS dilepton) 1/3

arXiv:1203.5410

5fb^{-1}

- Search for heavy top-like: t't' → WbWb → lνb lνb (l=e/μ)

- <u>Selection:</u>
  - 2 (or more) opposite sign leptons; pt>20GeV; $|\eta|$< 2.4
  - Dilepton triggers efficiency → 100, 95, 90% for ee, eμ, $\mu\mu$, respectively
  - Lepton isolation → ΣET(ΔR<0.3) < 0.15*pT
  - Z mass veto for ee, $\mu\mu$ → removed event if 76 < Mll < 106GeV or Mll<12GeV
  - Jets: Anti-kt R=0.5; pT>30GeV; $|\eta|$< 2.5 (separated by ΔR>0.4 from selected leptons)
    - At least 2 jets and at least two of them b-tag
  - ETMiss > 50GeV

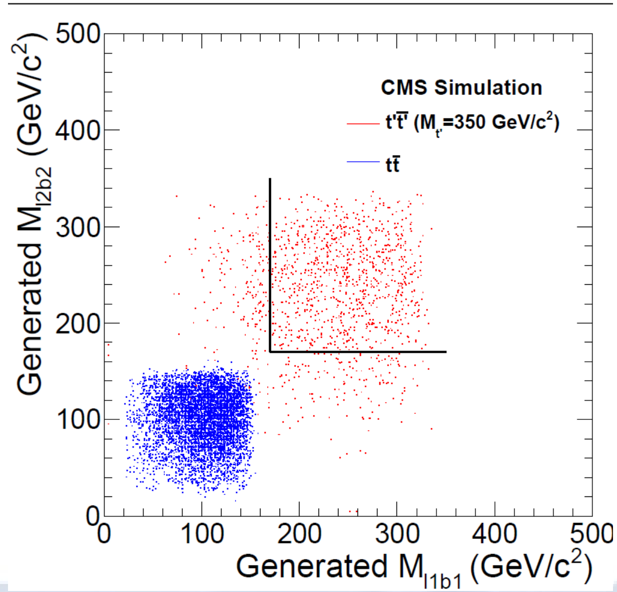
TT → WbWb (OS dilepton) 2/3

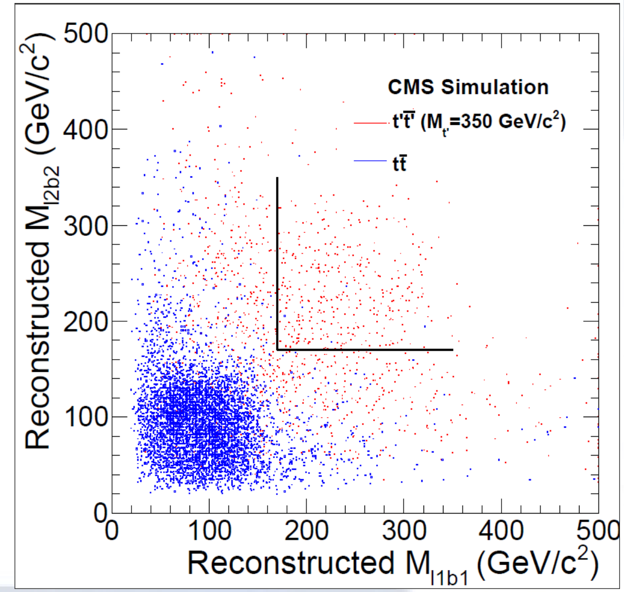
arXiv:1203.5410

5fb^{-1}

- Signal region:
  → after basics selection ttbar dominates...
- The invariant mass of lepton and b-jet is used as discriminant
- At generator level:
  → clear distinction between t' and top
- At reconstruction level:
  → pairing done with min(ΔR) between lepton and bjet
- Mlb > 170GeV is applied for the minumum
  - → signal efficiency ~ 50%
  - → ttbar very small...

Sample	ee	$\mu\mu$	$e\mu$	all
$t'\overline{t'}$, $M_{t'} = 400\,\mathrm{GeV}/c^2$	10.6 ± 0.9	13.9 ± 1.0	29.4 ± 1.5	53.9 ± 2.0
$t'\overline{t'}$, $M_{t'} = 500\,\mathrm{GeV}/c^2$	3.0 ± 0.2	3.3 ± 0.2	6.7 ± 0.4	12.9 ± 0.5
$t'\overline{t'}$, $M_{t'} = 600\,\mathrm{GeV}/c^2$	0.9 ± 0.1	1.0 ± 0.1	2.2 ± 0.1	4.1 ± 0.2
$t\bar{t} \to \ell^+\ell^-$	488 ± 11	615 ± 12	1472 ± 19	2575 ± 25
$t\bar{t} \to$ other	7.2 ± 1.3	0.5 ± 0.3	10.5 ± 1.6	18.2 ± 2.1
W + jets	< 1.9	< 1.9	< 1.9	< 1.9
DY$\to \ell^+\ell^-$	2.9 ± 1.5	1.6 ± 1.0	0.6 ± 0.5	5.1 ± 1.8
Diboson	0.5 ± 0.1	1.1 ± 0.2	1.9 ± 0.2	3.6 ± 0.3
Single top quark	15.6 ± 1.0	19.5 ± 1.1	46.9 ± 1.7	82.0 ± 2.2
Total background	514 ± 11	637 ± 12	1532 ± 19	2683 ± 25
Data	510	615	1487	2612





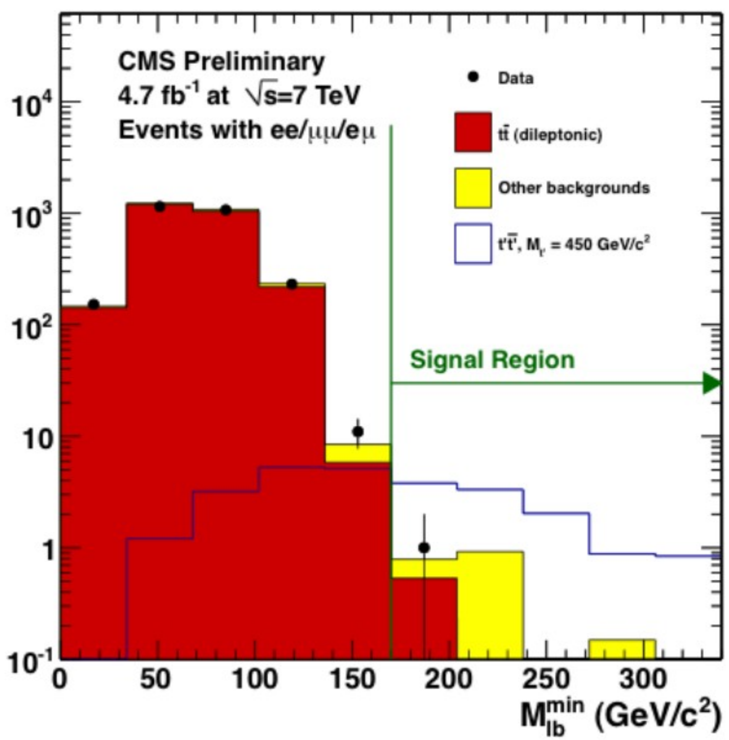
TT → WbWb (OS dilepton) 3/3

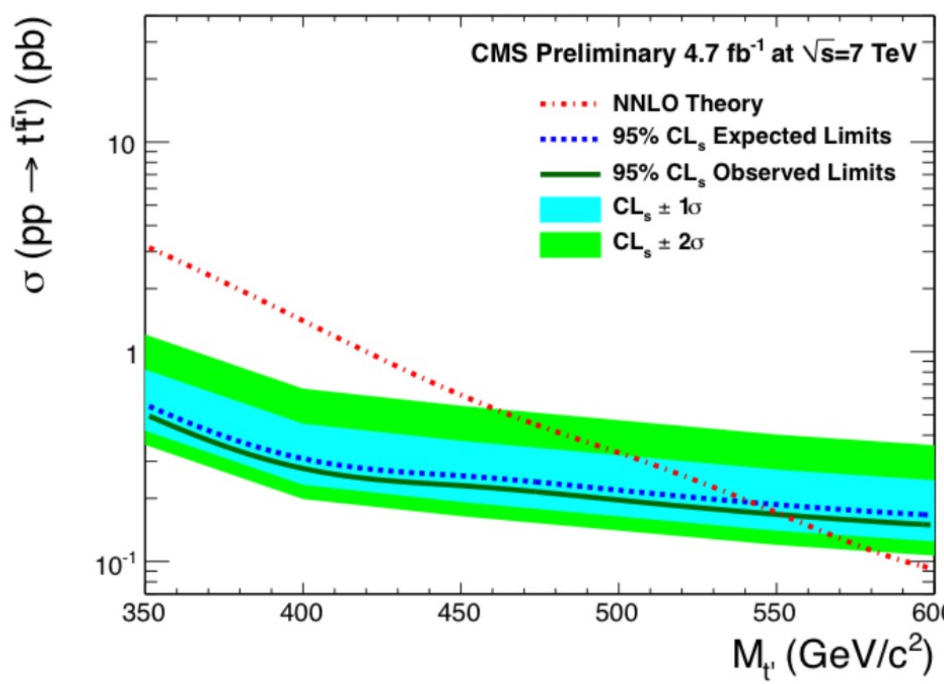
arXiv:1203.5410

5fb^{-1}

- 1 event observed; 1.8 +/- 1.1 expected
- 95% CL Limits extracted using Cut and count
- Observed limit m(t')>552GeV @ 95%CL

$t'\overline{t}'$ sample	ee	$\mu\mu$	eμ	all
$M_{t'} = 400\,\mathrm{GeV}/c^2$	3.5 ± 0.5	5.5 ± 0.6	11.2 ± 0.9	20.1 ± 1.2
$M_{t'} = 500\,\mathrm{GeV}/c^2$	1.4 ± 0.2	1.9 ± 0.2	3.3 ± 0.2	6.7 ± 0.4
$M_{t'} = 600\,\mathrm{GeV}/c^2$	0.6 ± 0.1	0.6 ± 0.1	1.3 ± 0.1	2.5 ± 0.1





TT → WqWq (OS dilepton) 1/3

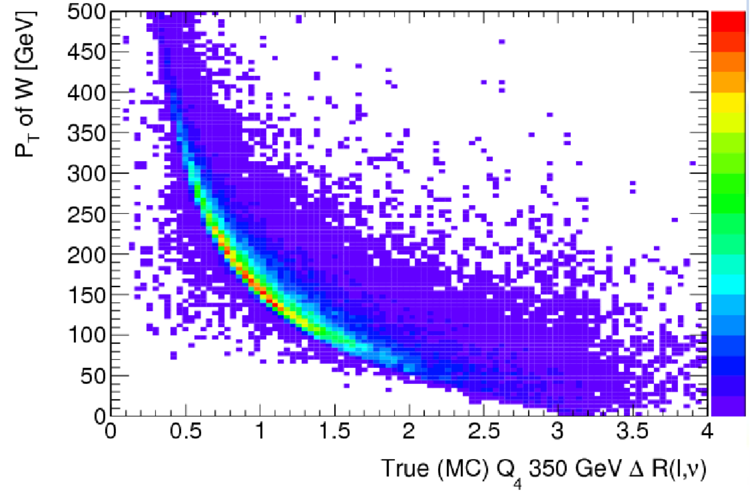
1fb^{-1}

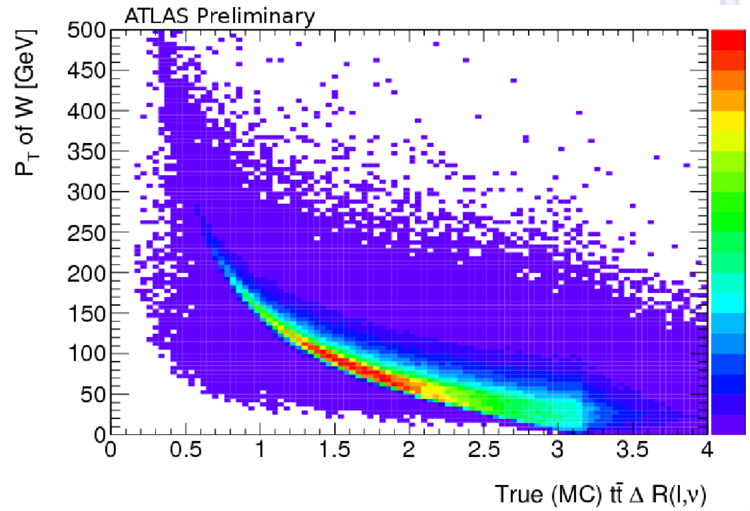
arXiv:1202.3389

- Final state t't' → WqWq → lνq lνq
- No assumption about the quark mixing t' → Wq

- <u>Baseline selection:</u>
  - Exactly 2 leptons pT > 20GeV; muon |η|< 2.5; electron |η| < 2.47 ∉ 1.37 <|η|< 1.52
  - Lepton isolation: ΣET(ΔR<0.2) < 3.5GeV
  - Jets: Anti-kt 0.4, pt> 25GeV, |η|< 2.5 → at least 2 jets
  - ETMiss > 60 GeV (ee/μμ); HT(MET+lep pt) > 130GeV (eμ)
  - For ee/μμ → Mll > 15GeV; |Mll – MZ| > 10GeV

- <u>Reconstruction of the heavy quark masses:</u>
  - At high W pT → neutrino and lepton ~ collinear
  - Reconstruct both neutrinos by assuming solely contribution to MET
  - Reconstruct |Δη(l,ν)| and |ΔΦ(l,ν)| for each neutrino as a free parameter → range [0,1]
  - Find the |Δη(l,ν)| and |ΔΦ(l,ν)| values and jet assignment that minimizes the differences between the two masses (collinear mass) and keep events with |m1-m2|<25GeV





TT → WqWq (OS dilepton) 1/3

1fb^{-1}

arXiv:1202.3389

- Final state t't' → WqWq → lνq lνq
- No assumption about the quark mixing t' → Wq

- <u>Baseline selection:</u>
  - Exactly 2 leptons pT > 20GeV; muon $|\eta|$< 2.5; electron $|\eta|$ < 2.47 ∉ 1.37 <$|\eta|$< 1.52
  - Lepton isolation: ΣET(ΔR<0.2) < 3.5GeV
  - Jets: Anti-kt 0.4, pt> 25GeV, $|\eta|$< 2.5 → at least 2 jets
  - ETMiss > 60 GeV (ee/$\mu\mu$); HT(MET+lep pt) > 130GeV (eμ)
  - For ee/$\mu\mu$ → Mll > 15GeV; |Mll – MZ| > 10GeV

- <u>Reconstruction of the heavy quark masses:</u>
  - At high W pT → neutrino and lepton ~ collinear
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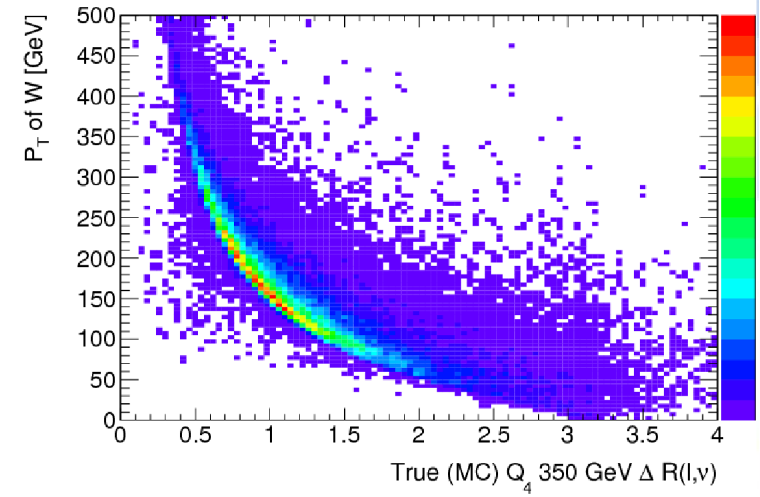
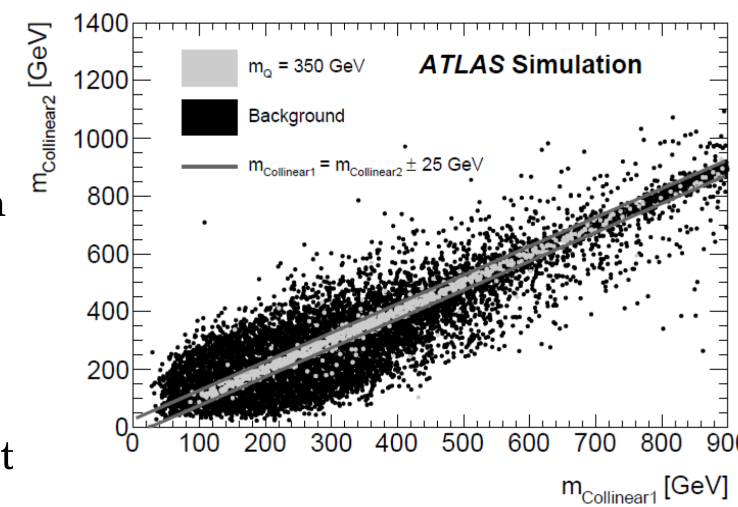
  - Reconstruct $|\Delta\eta(l,\nu)|$ and $|\Delta\Phi(l,\nu)|$ for each neutrino as a free parameter → range [0,1]
  - Find the $|\Delta\eta(l,\nu)|$ and $|\Delta\Phi(l,\nu)|$ values and jet assignment that minimizes the differences between the two masses (collinear mass) and keep events with |m1-m2|<25GeV



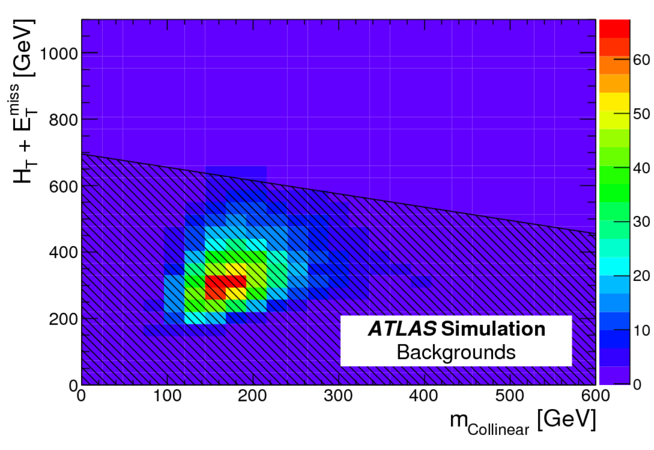


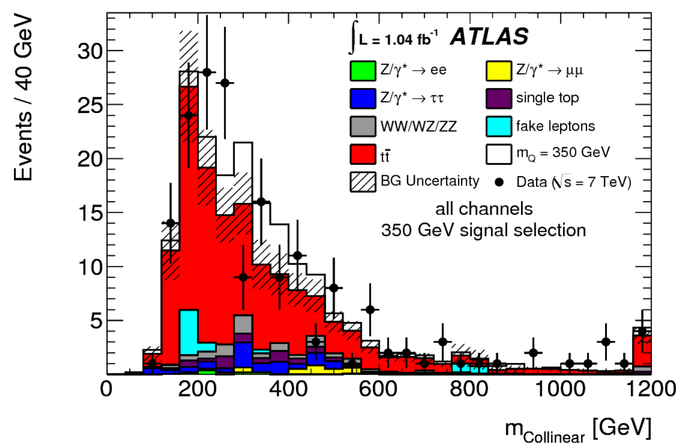
TT → WqWq (OS dilepton) 2/3

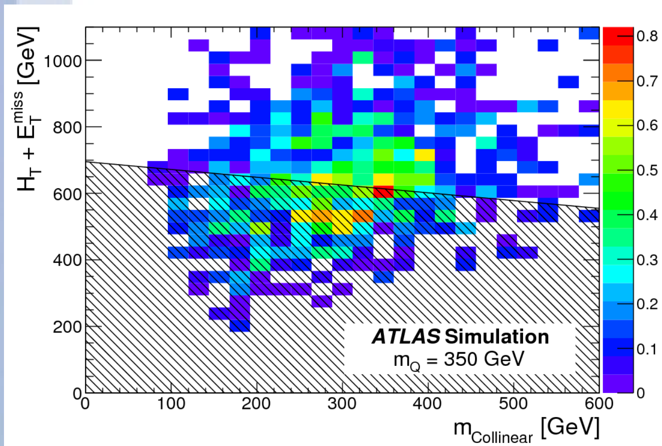
$1\,\mathrm{fb}^{-1}$

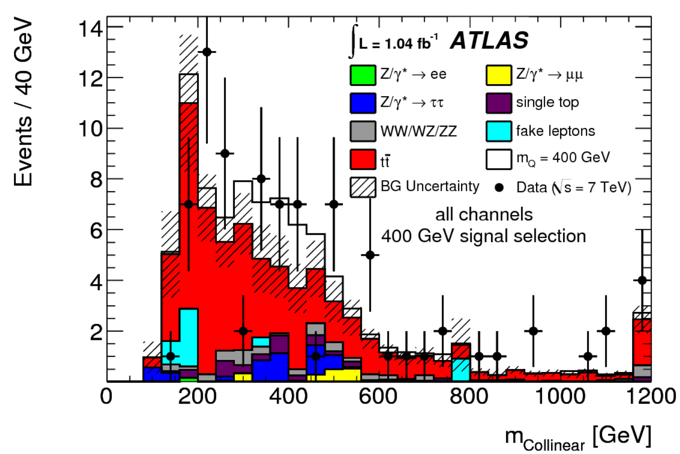
m_Q (GeV)	Triangle Requirement (GeV)
300	$H_T + E_T^{miss} > 610 - 0.4 \times m_{Collinear}$
350	$H_T + E_T^{miss} > 700 - 0.4 \times m_{Collinear}$
400	$H_T + E_T^{miss} > 790 - 0.4 \times m_{Collinear}$
450	$H_T + E_T^{miss} > 880 - 0.4 \times m_{Collinear}$
500	$H_T + E_T^{miss} > 970 - 0.4 \times m_{Collinear}$

m_Q (GeV)	Jet p_T (GeV)	E_T^{miss} (GeV)
300	Leading jet $p_T >$ 80	—
350	Leading jet $p_T >$ 120	—
400	Leading jet $p_T >$ 130	$E_T^{miss} > 70$
450	Leading jet $p_T >$ 130	$E_T^{miss} > 70$
500	Leading jet $p_T >$ 130	$E_T^{miss} > 70$









- Final selection:
  → triangular cut in the Mcoll – HT plane (= Hthad + lepton pT + MET)
- Optimized for each t' mass
  → improve the signal/background discrimination
- → Mcoll after triangular cut is used to discriminate signal and background

TT → WqWq (OS dilepton) 3/3

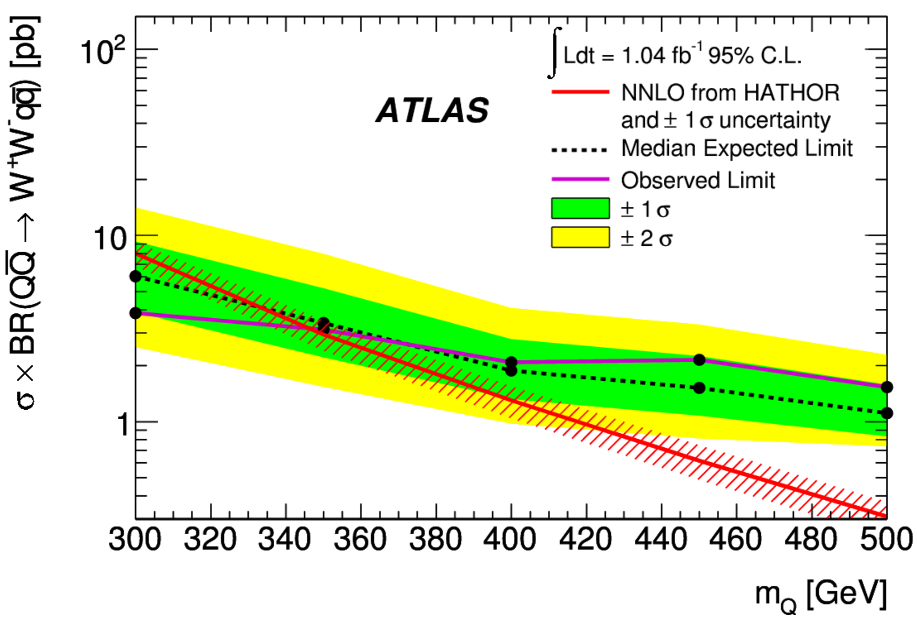
1fb^{-1}

arXiv:1202.3389

- Binned maximum likelihood used to set limit on the production cross section; Template fit using the Mcoll distribution

- Observed limit m(t') > 350GeV @ 95%CL

Source	$+1\sigma$ Unc.	-1σ Unc.
Lepton trigger	1 %	1 %
Lepton ID and reconstruction	2 %	<1 %
Jet reconstruction	3 %	3 %
Jet energy resolution	2 %	2 %
Jet energy scale	13 %	11 %
μ momentum resolution	2 %	2 %
μ momentum scale	1 %	2 %
e energy resolution	1 %	1 %
e energy scale	<1 %	<1 %
e isolation pileup term	1 %	1 %
e isolation p_T term	<1 %	<1 %
E_T^{miss} uncertainties	1 %	<1 %
LAr readout problem	2 %	2 %
ISR/FSR: $t\bar{t}$	8 %	5 %
MC generator: $t\bar{t}$	1 %	<1 %
MC fragmentation/model: $t\bar{t}$	1 %	1 %
Drell-Yan model	7 %	7 %



Applicable to to VLQ
T → Wq(q=d,s,b) B → Wq(q=u,c)
and Y → W-b

$TT \rightarrow WbWb$ (single-lepton) 1/3

PAS-EXO-11-099

5fb^{-1}

- Final state $t't' \rightarrow WbWb \rightarrow qqb\ l\nu b$
- Selection:
  - Isolated Electron pt > 35 GeV $|\eta|<2.4 \notin 1.44 < |\eta| < 1.57$
  - Isolated Muon pt > 35 - 42 GeV (depending on the running period) $|\eta|<2.1$
  - Jets: Anti-kt R=0.5 → 4 jets 120, 90, 50(35), 35 GeV electron(muon)
  - MET > 20GeV
  - At least 1 btag jet

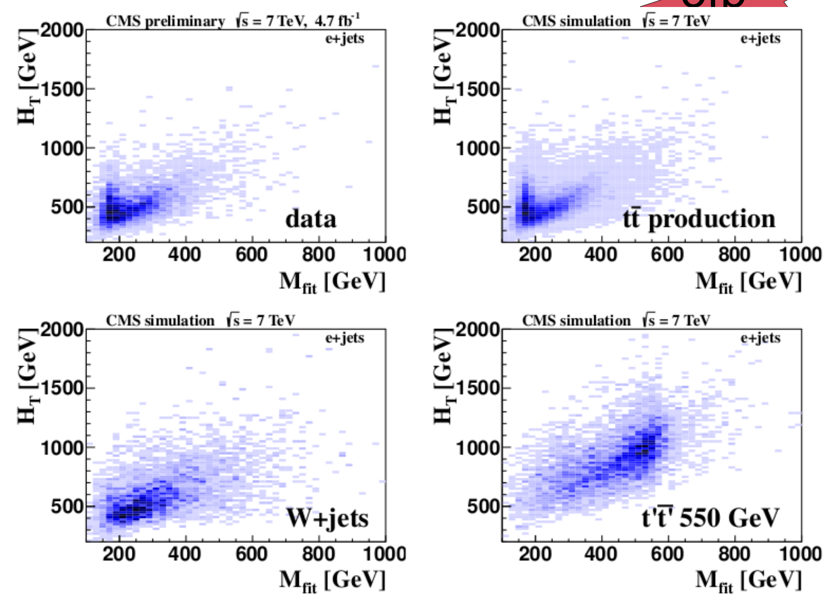
		e+jets events	μ+jets events
$\mathcal{L}$		4683 pb^{-1}	4601 pb^{-1}
data		4734	6448
background process	cross section		
$t\bar{t}$	165.8 pb	4000 ± 33	5536 ± 45
single t	33 pb	196 ± 3	316 ± 5
W+jets	30 μb	434 ± 13	709 ± 48
Z+jets	2.9 μb	46 ± 5	51 ± 6
WW,WZ,ZZ	67 pb	–	14 ± 1
multijets		73 ± 3	5 ± 5
total background		4749 ± 36	6631 ± 67

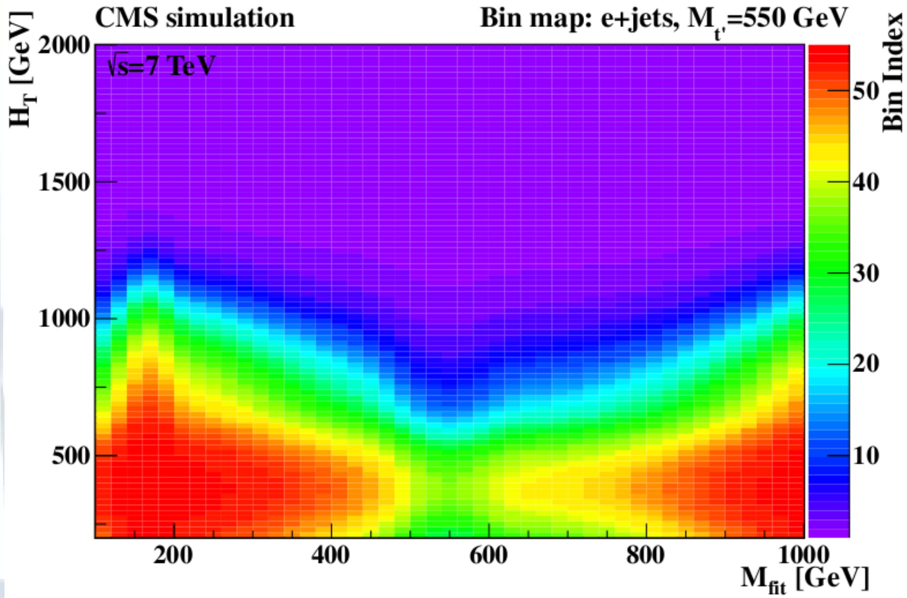
TT → WbWb (single-lepton) 2/3

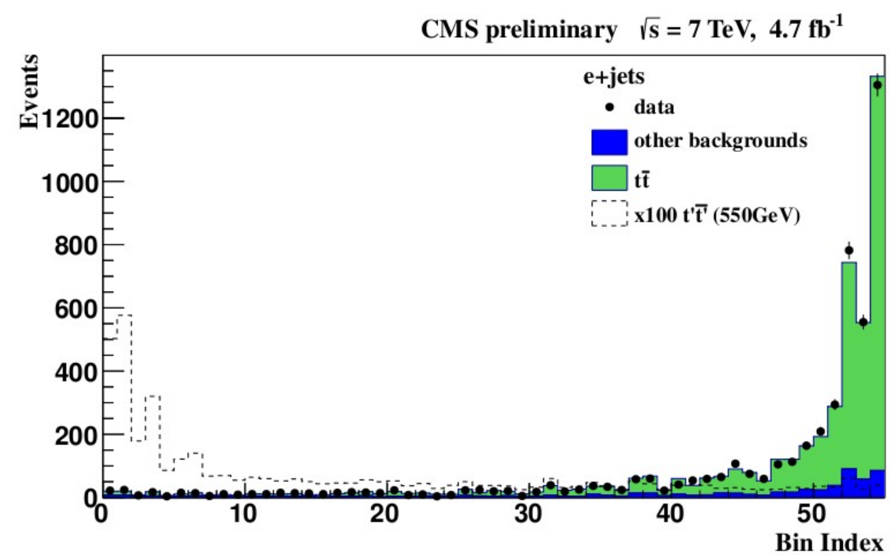
- A kinematic fit is performed by minimizing a chi2 from the measured momenta of all the particles and their resolutions
- Fitted t' mass is used together with HT → 2D discriminant unfolded in a 1D
- Unfolding method:
  - Order bins in a 1D S/B histogram
  - Merge adjacent bins until the fractional statistical uncertainty is below 20% for both signal and background templates

PAS-EXO-11-099

$5fb^{-1}$







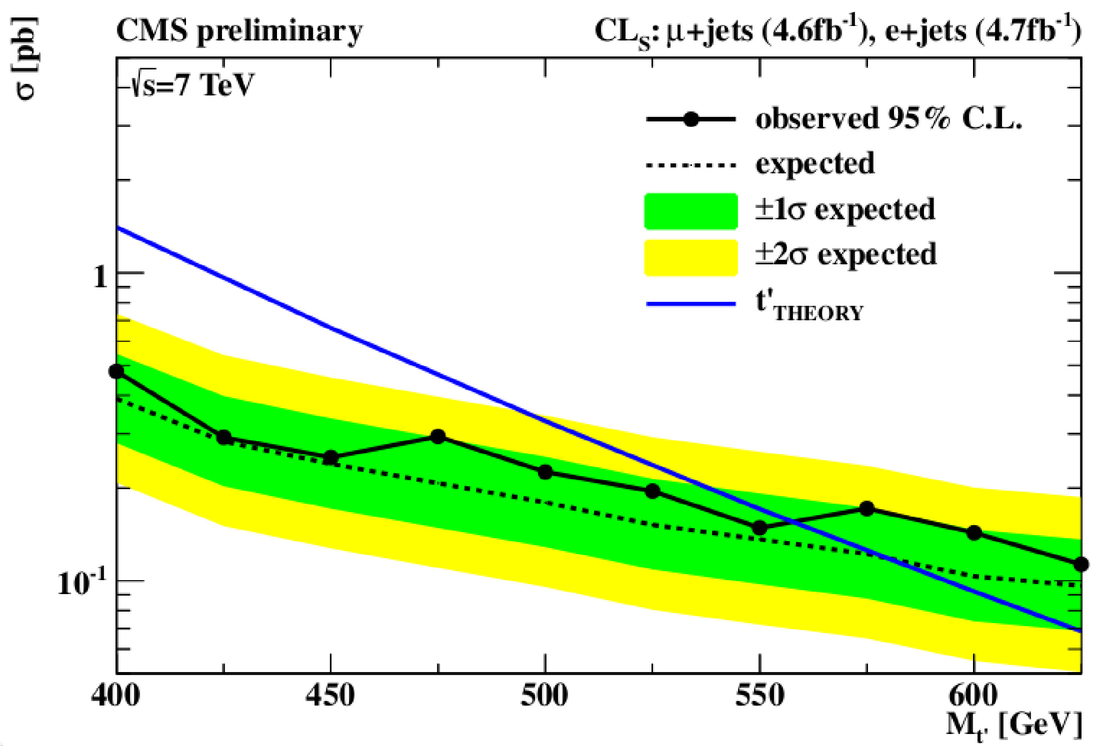
TT → WbWb (single-lepton) 3/3

PAS-EXO-11-099

5fb⁻¹

$M_{t'}$ (GeV)	cross section (pb)	e+jets eff. (%)	μ+jets eff. (%)
400	1.41	4.3 ± 0.1	5.4 ± 0.1
425	0.96	4.4 ± 0.1	5.6 ± 0.1
450	0.66	4.7 ± 0.1	6.0 ± 0.1
475	0.46	4.7 ± 0.1	6.1 ± 0.1
500	0.33	4.8 ± 0.1	6.2 ± 0.1
525	0.24	4.7 ± 0.1	6.4 ± 0.1
550	0.17	4.9 ± 0.1	6.5 ± 0.1
575	0.13	4.7 ± 0.1	6.6 ± 0.1
600	0.092	4.7 ± 0.1	6.6 ± 0.1
625	0.069	4.8 ± 0.1	6.5 ± 0.1

- CLs method used to set limits on the t't' production cross section
- Assuming BR(t' → Wb) = 1
  → m(t') > 550GeV @ 95%CL



$TT \rightarrow WbWb$ (single-lepton) 1/3

arXiv:1202.3076

1fb^{-1}

- Final state t't' → WbWb → jjb lνb
- Strategy: → stay as close as possible to the top group selection → loose selection
- Event selection:
  - Single lepton triggers
  - Exactly 1 leptons pT > 20GeV; muon $|\eta|< 2.5$; electron $|\eta|< 2.47 \notin 1.37 <|\eta|< 1.52$ (veto the other flavor)
  - Jets: Anti-kt 0.4, pt> 25GeV, $|\eta|< 2.5$ → at least 3 jets; leading jet pT > 60GeV
  - ETMiss > 20 (30)GeV muon (electron); ETMiss + MTW > 60GeV
  - Using the btagging (≥1bjet 70% efficiency, optimize to get best S/sqrt(B))
- 1D kinematic Likelihood fit
  - Reconstructed top mass
  - 3 jet bin: just the invariant mass of the 3 jets
  - >=4 jets: using KLFitter
    - Using leading 4 jets only
    - Floating 'top' mass
    - No Btagging information used
    - Only constrain both 'sides' to be similar

Helps to constraint systematics with profiling

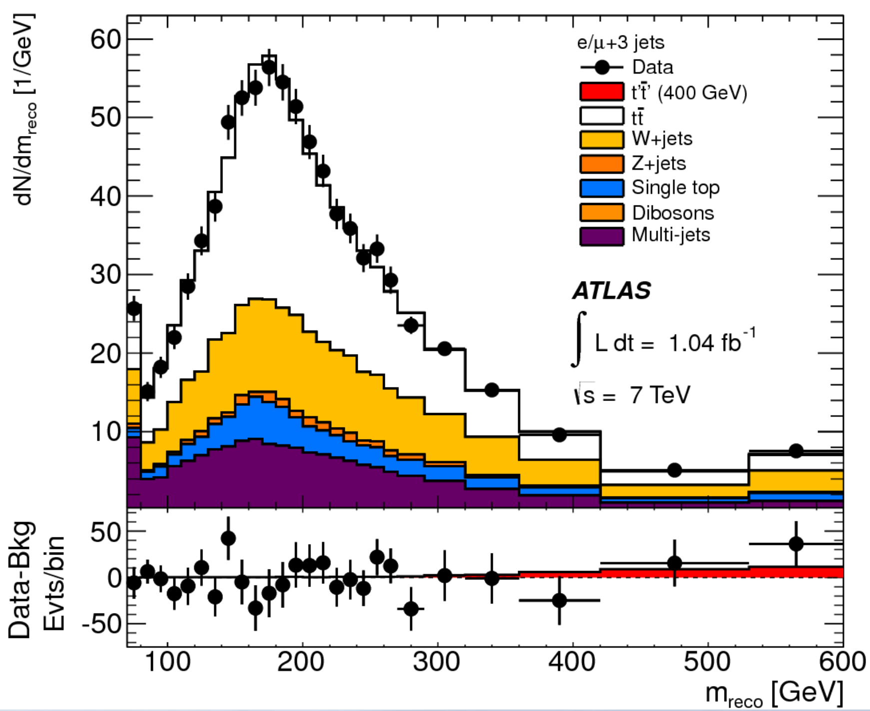
TT → WbWb (single-lepton) 2/3

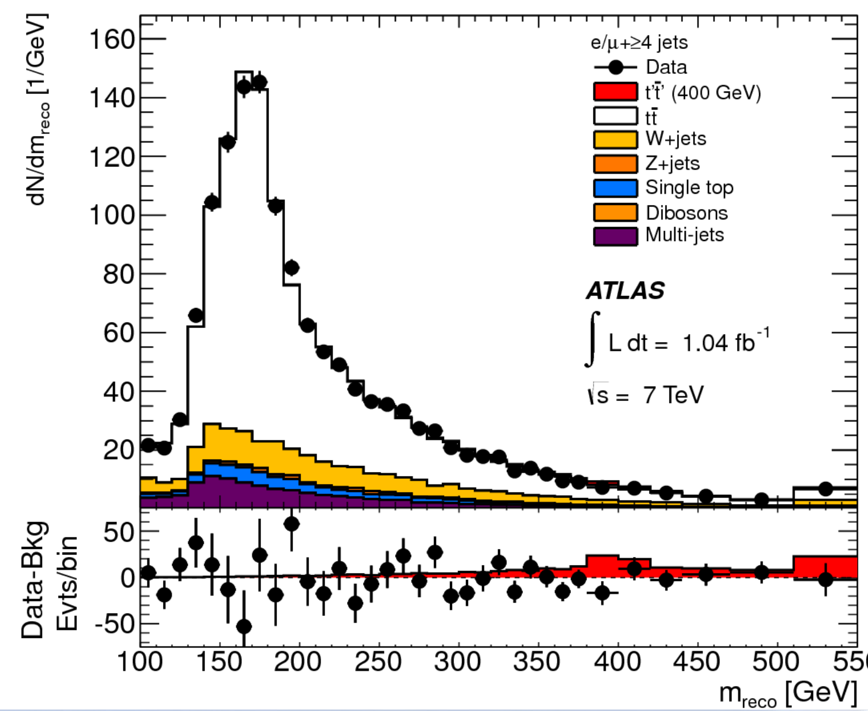
arXiv:1202.3076

$1fb^{-1}$

- Systematics treated as nuisance parameters
- Dominant systematics: Jet energy scale; ttbar modeling: ISR/FSR, NLO generator (*), fragmentation model (*) (*) = Not profiled
- A profile likelihood ratio is performed combining 3jet exclusive/4 jet inclusive channel for at least 1btag jet and electron and muon channels

	e+3 jets	μ+3 jets	e+$\geq$4 jets	μ+$\geq$4 jets
$t\bar{t}$	2320 ± 460	3000 ± 630	4470 ± 920	5900 ± 1200
W+jets	1440 ± 790	2200 ± 1200	830 ± 580	1160 ± 790
Z+jets	92 ± 53	118 ± 62	86 ± 56	83 ± 46
Single top	382 ± 68	554 ± 94	262 ± 70	325 ± 79
Dibosons	28 ± 7	37 ± 11	12 ± 5	17 ± 5
Multi-jet	520 ± 520	550 ± 550	320 ± 320	340 ± 340
Total prediction	4800 ± 1000	6500 ± 1500	6000 ± 1100	7800 ± 1400
Data	4533	6421	6145	8149
$t'\bar{t}'$(400 GeV)	20.0 ± 3.3	21.0 ± 3.6	102.0 ± 10.5	98.1 ± 11.1





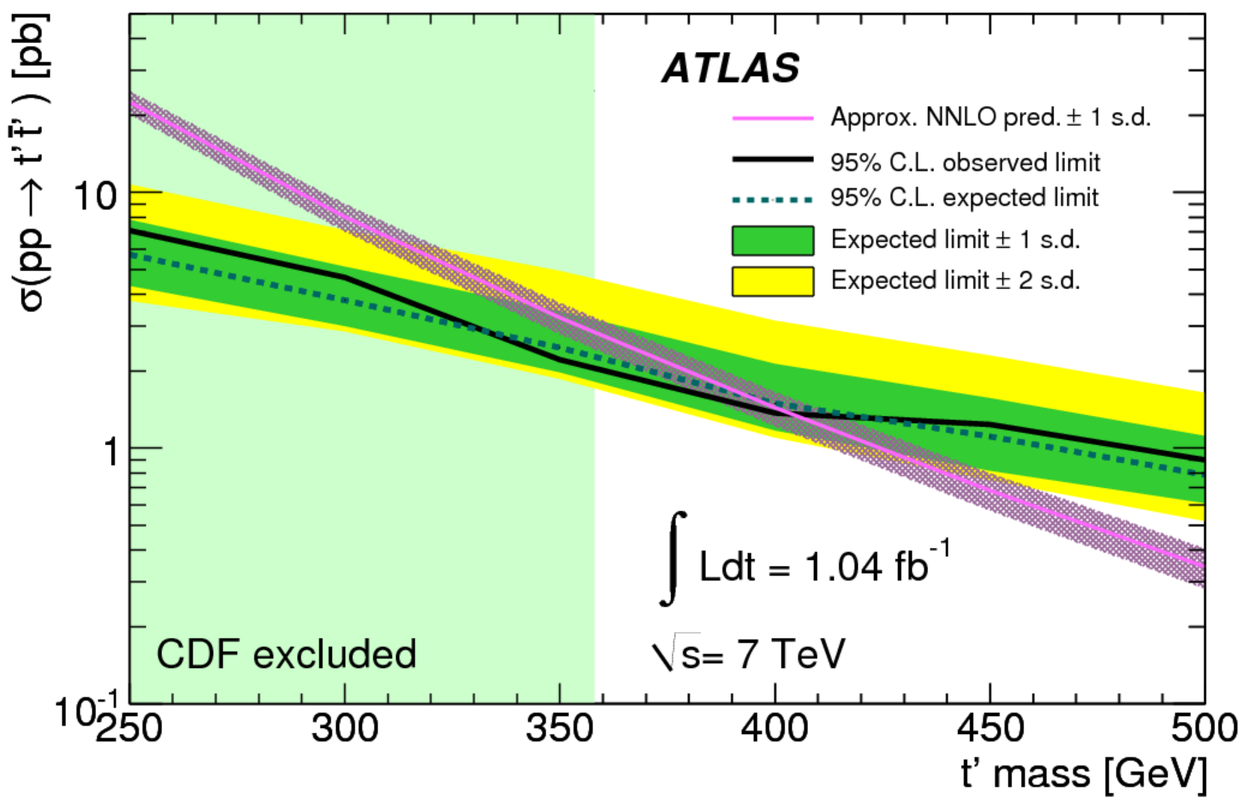
TT → WbWb (single-lepton) 3/3

arXiv:1202.3076

1fb^{-1}

- No sign of excess → set limits (mclimit)
  - Combined limit: electron/muon =3/⩾4jets → 4 orthogonal channels
  - Observed limit: $m_{t'}$ > 404GeV @ 95% C.L. Expected limit: 394GeV
  - Observed limit is within 1σ of the expected in the full mass range considered

Applicable to VLQ
Y → W-b (Q=-4/3)



Inclusive search for a 4^{th} generation 1/3

PAS-EXO-11-054

1fb^{-1}

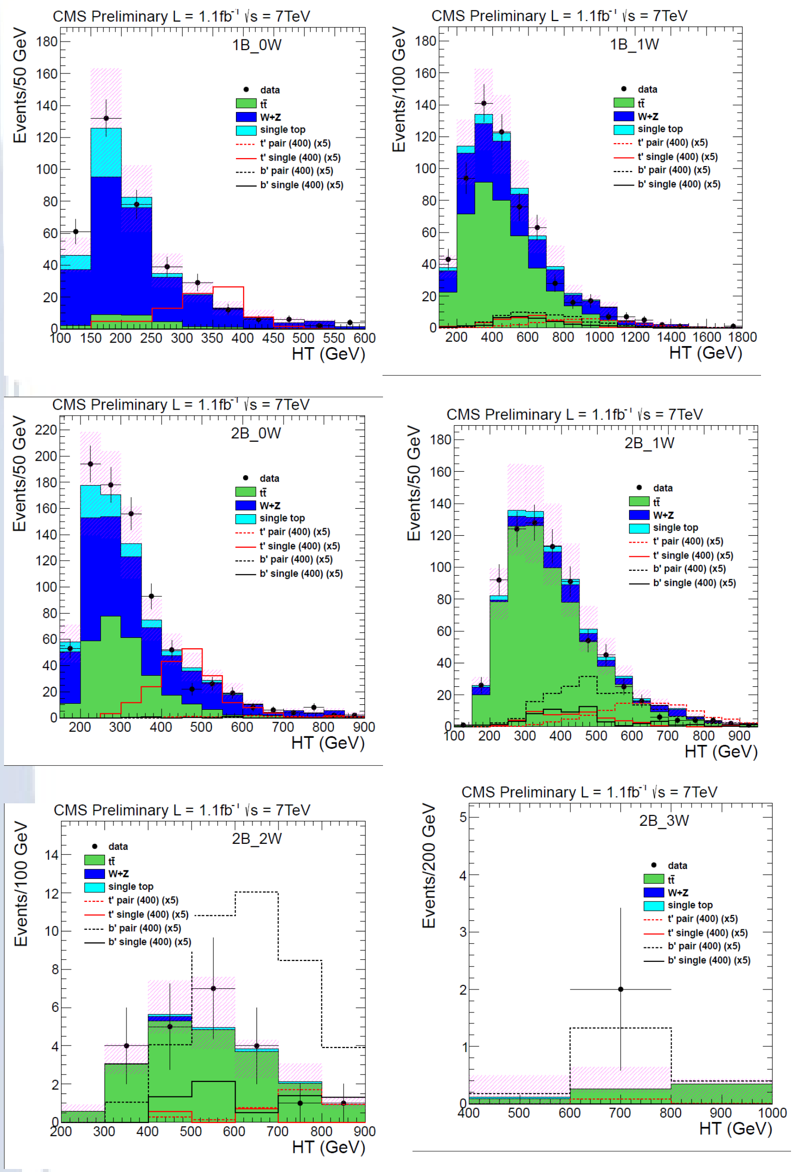
- This analysis presents the inclusive search of 4^{th} generation up-down type quark from pair or single production (t'b → Wb b; b't → WbW Wb; t't' → WbWb; b'b' → WbW WbW)

- Search is performed in the muon channel:
  - 1 isolated muon pt> 40 GeV; $|\eta|$ < 2.1; veto other isolated muons pT >10GeV, $|\eta|$<2.5; veto electrons pt>20GeV; $|\eta|$<2.5
  - Jets pt> 30GeV; $|\eta|$ < 2.5; ≥1 to be a b-tag ($|\eta|$ < 2.4 tracker acceptance)
  - MET>40GeV to reduce QCD multijet

- Search performed in 6 subsamples, based on nb-jet (==1, ≥2) ; nWhad (==0, ==1, ==2, ≥3)
  - 1B_0W → single t' with 1 fwd/1central bjet; ==1 forward jet (2.4<$|\eta|$<5) pT>30GeV
  - 2B_0W → single t' with 2central bjets; ==0 forward jet (2.4<$|\eta|$<5) pT>30GeV
  - 1B_1W → t't' tt pair production with 1 b-jet failing ID; ≥3 jets in addition of the btag
  - 2B_1W
  - 2B_2W
  - 2B_3W

  → one additional bjet at least 2, 4, 6 additional jets

Inclusive search for a 4th generation 2/3



PAS-EXO-11-054

1fb^{-1}

- HT discriminant is used = scalar sum of MET, muon pT, btag jets, Whad pT
- HT is sensitive to the presence of 4th generation quark
- A 4th generation quark would appear in the high tails of the HT distribution
- The 6 channels are combined into a single template histogram
- The 4 different signals processes are added into a single distribution for the signal

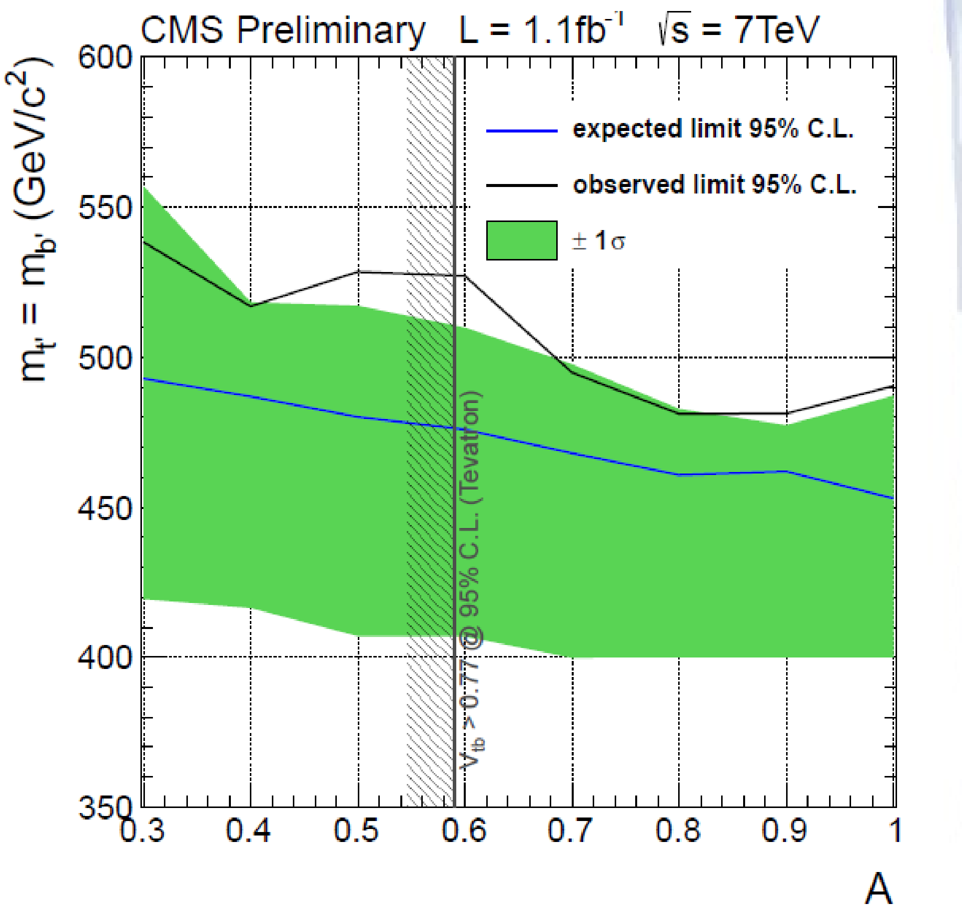
Inclusive search for a 4^{th} generation 3/3

PAS-EXO-11-054

$1fb^{-1}$

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

- Different templates of signal are made for each value of A and masses of the new quark
- The results are presented in the plane (A, mq4), where mq4 is the degenerate mass of the quarks, A = |Vtb|2
- Using the CLs method is used to set limits together with a profile likelihood template fit
- For minimal off diagonal mixing, (A~1) between the third and the fourth generation, mt' = mb' > 490GeV @ 95%CL



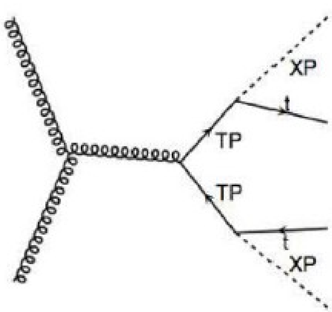
TT → tA0tA0 (tt + E_t^{miss}) 1/2

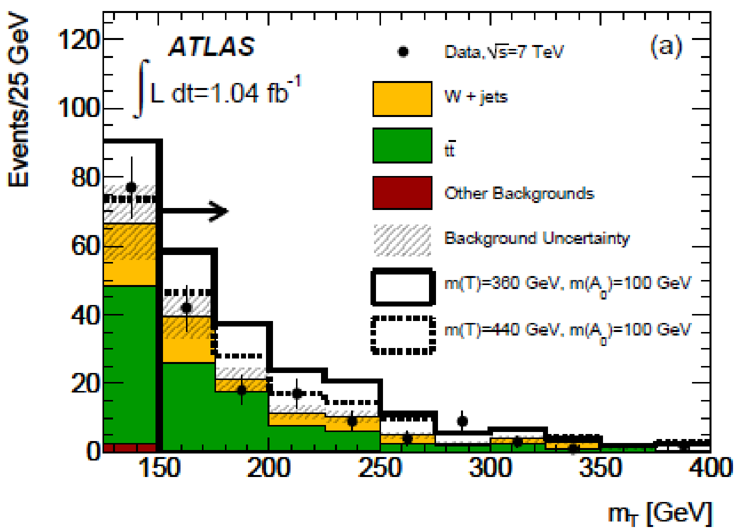
1fb^{-1}

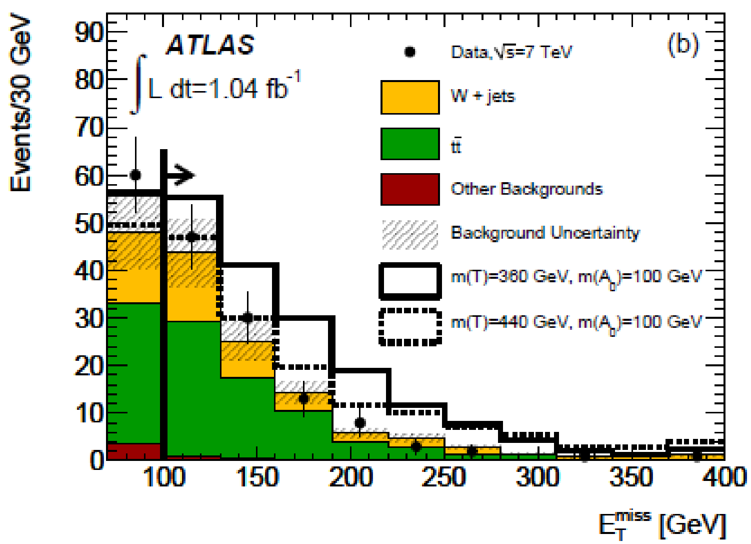
arXiv:1109.4725

- Search for anomalous MET in tt (single lepton) events
- Benchmark: TT pair with T → tA_0
  - A_0 is a dark matter candidate
  - Enhanced cross section due to spin states
- Signal region:
  - E_T^{miss} > 100GeV, m_T>150GeV, dilepton veto, p_T>15GeV, tracks, loose electrons

Source	Number of events
Dilepton $t\bar{t}$	62 ± 15
Single-lepton $t\bar{t}/W$+jets	33.1 ± 3.8
Multi-jet	1.2 ± 1.2
Single top	3.5 ± 0.8
Z+jets	0.9 ± 0.3
Dibosons	0.9 ± 0.2
Total	101 ± 16
Data	105







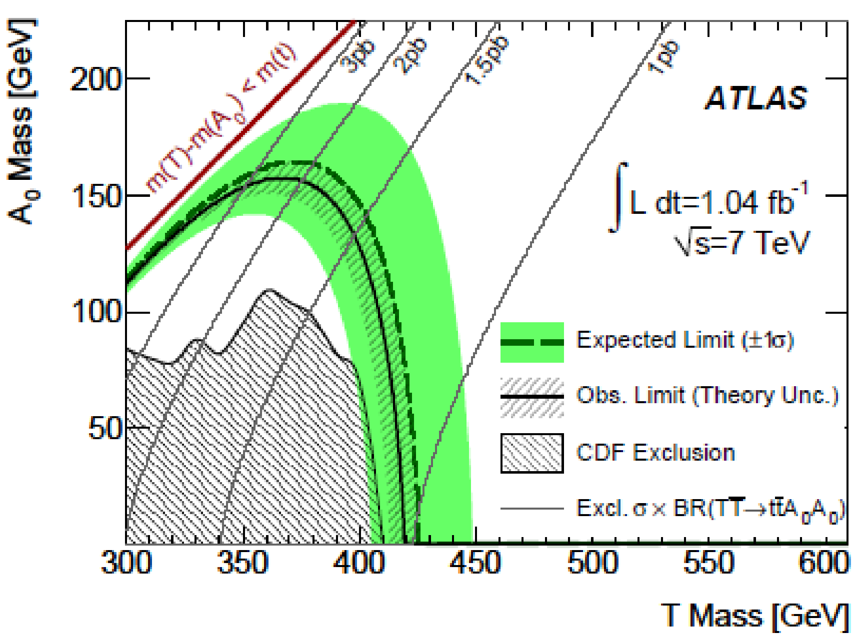
$T\bar{T} \rightarrow tA0\bar{t}A0$ $(t\bar{t} + E_t^{miss})$ 2/2

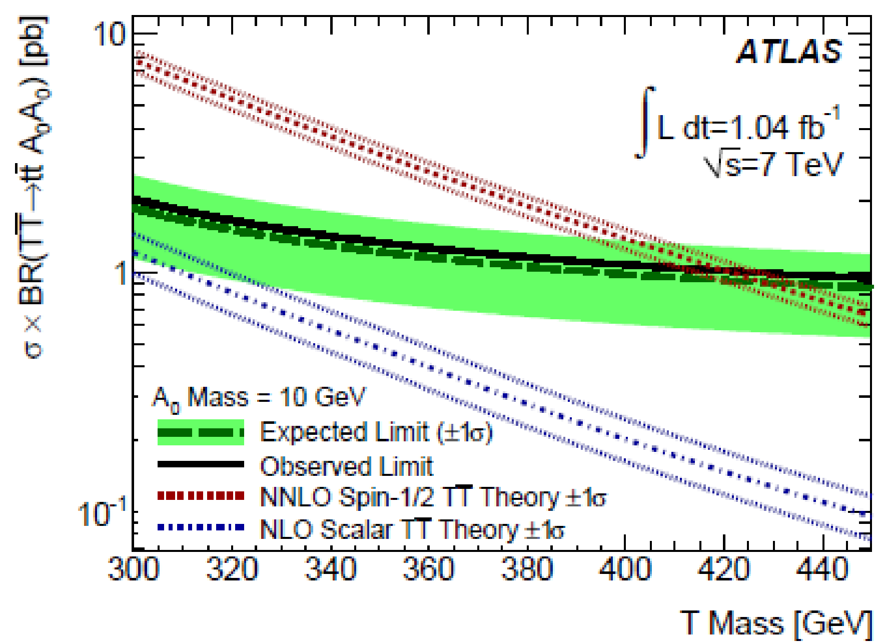
$1fb^{-1}$

arXiv:1109.4725

- Assuming BR(T → tA0) = 1
- Cut and count method used to set limit using frequentist confidence intervals
- 95% CL limits on TT pair production cross section (depend on A0 and T masses)
  - m(T) < 420 GeV for m(A0) < 10GeV
  - 330 < m(T) < 390 GeV for m(A0) < 140GeV

Could be applied to VLQ
TT → WbZt, ZtZt (with Z → $\nu\nu$)
TT → Wb Ht (H invisible)



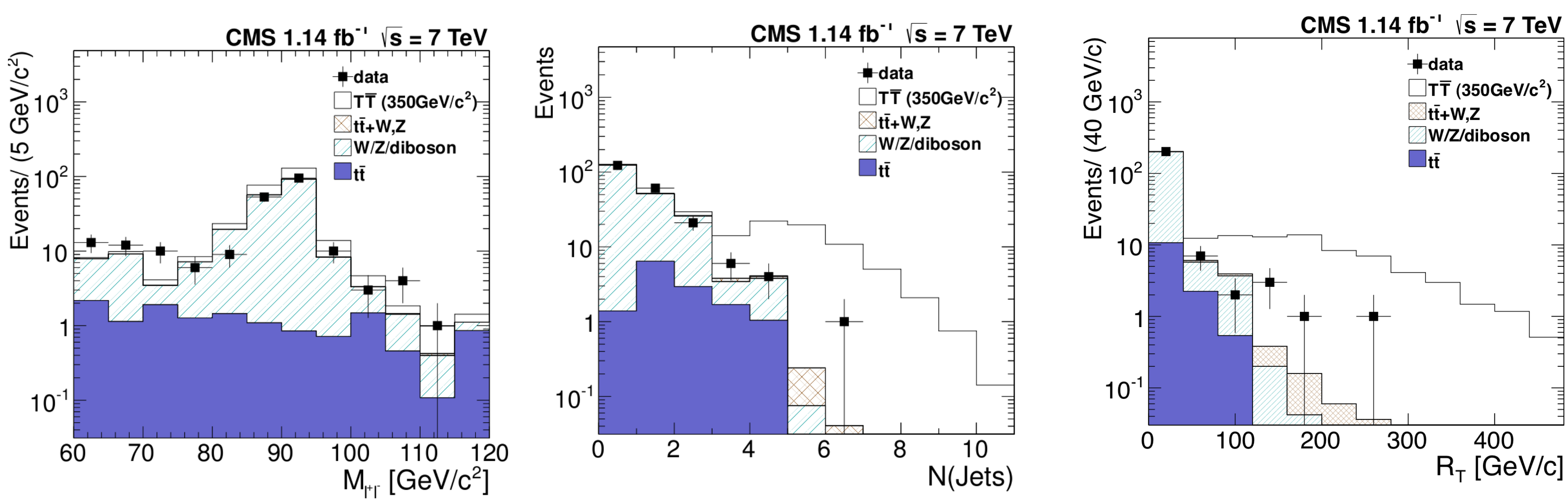


Search for VLQ in t+Z (pair prod.)1/2

arXiv:1109.4985

$1fb^{-1}$

- Search for a pair-produced heavy vector like quark T (VLQ) with charge 2/3
- 100% BR $T \rightarrow tZ$; $pp \rightarrow TT \rightarrow tZtZ \rightarrow WbZWbZ$
- Muon, pT > 15GeV and $|\eta|<2.4$
- Electron > 20GeV and $|\eta|<2.5 \notin 1.44 < |\eta| < 1.57$
- Jets from particle flow, antikt 0.5; pT>25GeV, $|\eta| < 2.4$
- One leptonic $Z \rightarrow$ 2 OS, same flavored leptons (e or mu) 60 < Mll < 120GeV
- At least 3 leptons and at least 2 jets
- RT > 80GeV, with RT = ΣpT(jet i) + ΣpT(lepton i) ($i \neq 1,2$)



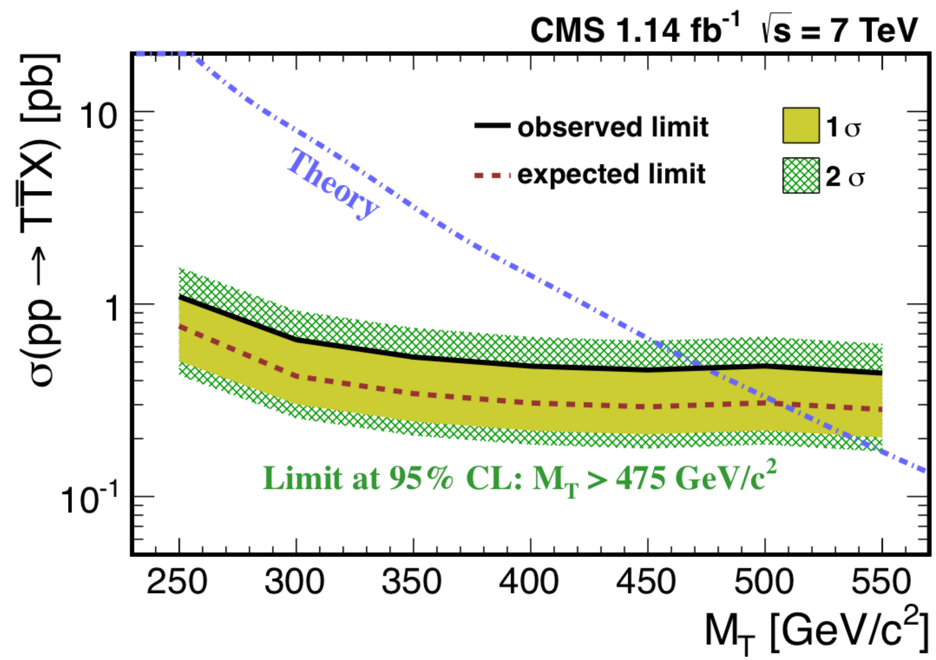
Search for VLQ in t+Z (pair prod.)2/2

arXiv:1109.4985

$1fb^{-1}$

- After full event selection two types of backgorund remains:
  - Events with 2 prompt leptons and a non prompt lepton from a jet (B_{2l}) → data driven
  - Events with 3 prompt leptons (B_{3l}) tt+Z, diboson → from MC
- Seven events observed in data, compatible with SM expectation → no evidence of VLQ
- Upper limit on the cross section calculated using a Bayesian method
- Assuming a BR of 100% T → tZ set limits on the cross section
- Exclude m(VLQ)< 475GeV @ 95% C.L.

Channel	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	Total
$B_{2\ell}$	$0.2^{+0.3}_{-0.2}$	0.8 ± 0.5	0.9 ± 0.4	1.1 ± 0.5	3.0 ± 0.8
$B_{3\ell}$	0.3 ± 0.1	0.3 ± 0.1	0.5 ± 0.2	0.5 ± 0.2	1.6 ± 0.5
B_{total}	0.5 ± 0.3	1.1 ± 0.5	1.4 ± 0.5	1.7 ± 0.6	4.6 ± 1.0
Data	0	2	2	3	7

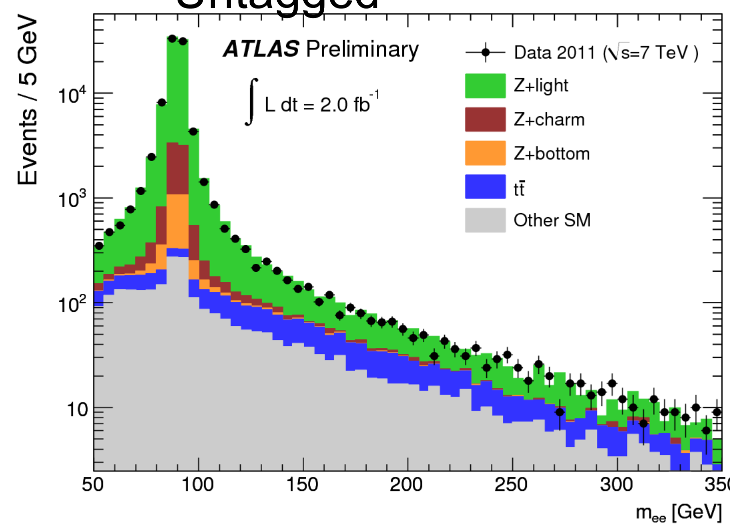


BB → Zb+X (OS dileptons) 1/3

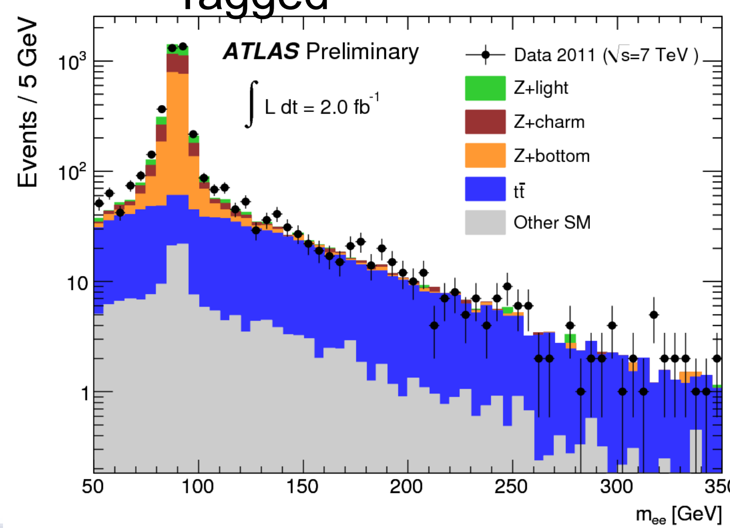
- Final state BB → Zb + X → llb + X
- Focus on a least one B → Zb
- Using only electron channel: Z → ee
- <u>Preselection:</u>
  - Single electron trigger (95%)
  - ≥2 OS electrons
  - electron pT > 25GeV $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - ≥1jet with pT>25GeV (antikt04)
  - ≥1 bjet (60% efficiency)

$2fb^{-1}$

Untagged



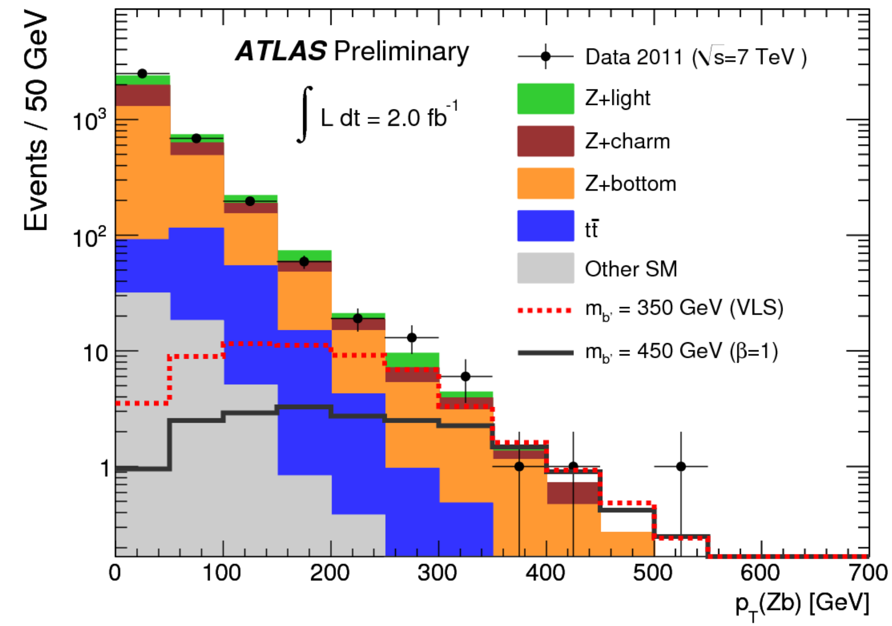
Tagged



BB → Zb+X (OS dileptons) 2/3

$2fb^{-1}$

- Exploit boosted configuration of the Zb system
- Z candidate → 2OS electrons satisfying |Mee – MZ|<15GeV (take the closest to MZ)
- B → Zb formed with Z and highest pT b jet
- Final selection:
  - pT (Zb) > 150GeV → heavy quarks produced with large pT

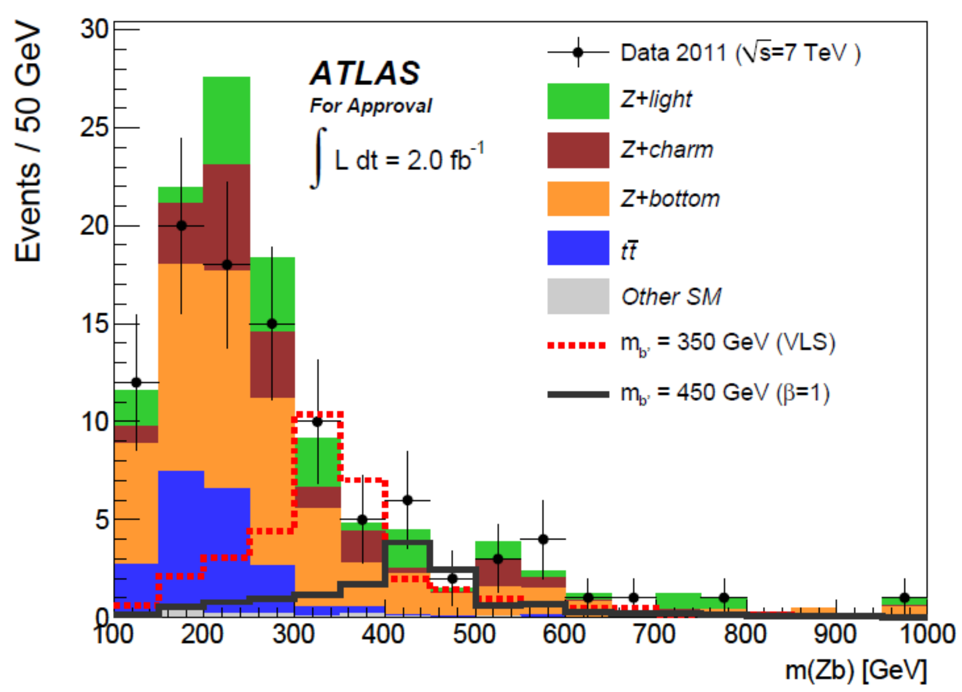


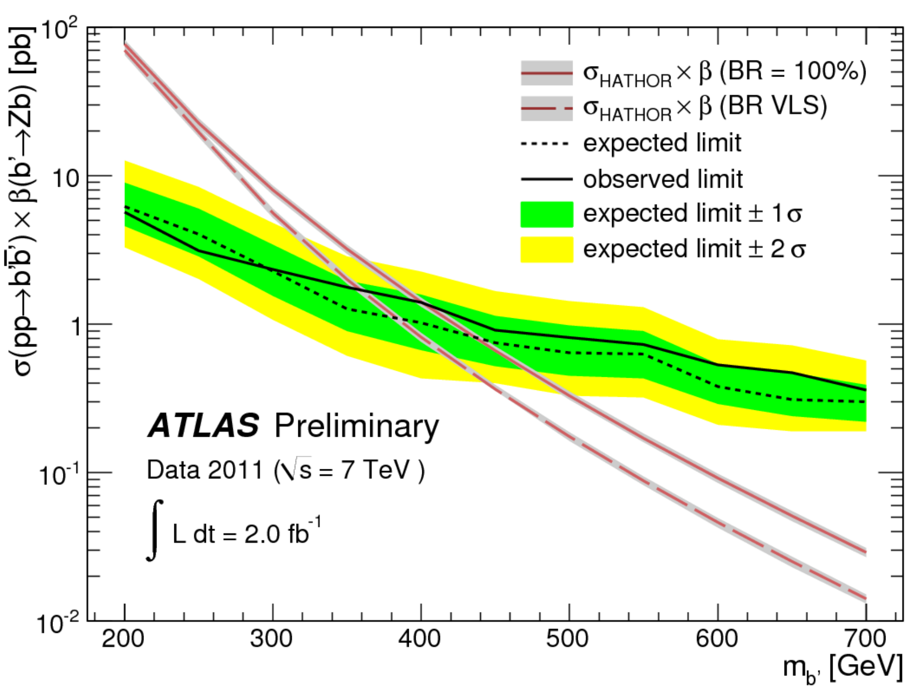
Source	$Z+\geq 1$ jet	$Z+\geq 1$ b-jet	$p_T(Zb) > 150$ GeV
Z+light	74400 ± 7300	590 ± 140	19 ± 7
Z+charm	5340 ± 520	870 ± 210	18 ± 7
Z+bottom	2540 ± 250	1710 ± 270	52 ± 17
$t\bar{t}$	320 ± 40	220 ± 40	20 ± 4
Other SM	1010 ± 280	70 ± 20	1.6 ± 0.4
Total SM	83600 ± 8100	3460 ± 580	110 ± 30
Data	**80519**	**3466**	**100**
$m_{b'} = 350$ GeV	110 ± 12	93 ± 11	55 ± 7
$m_{b'} = 450$ GeV	27 ± 3	20 ± 2	14 ± 2

BB → Zb+X (OS dileptons) 3/3

2fb^{-1}

- Final discriminant M(Zb)
- 2 scenarios → maximal mixing β=1; Vector Like Singlet (VLS) solely mixing with 3rd generation (mass dependent β=0.9-0.5/200-700GeV)
- SM Higgs mass of 125GeV assumed
- Set limits with mclimit
- m(b') > 400 (358) GeV @ 95%C.L. For beta=1 (VLS)



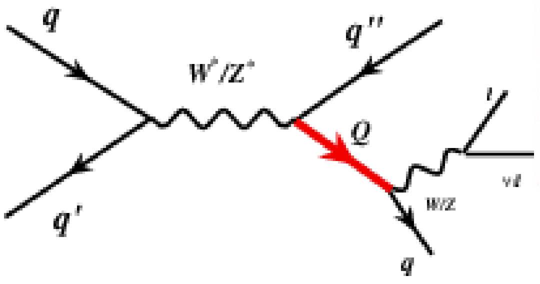


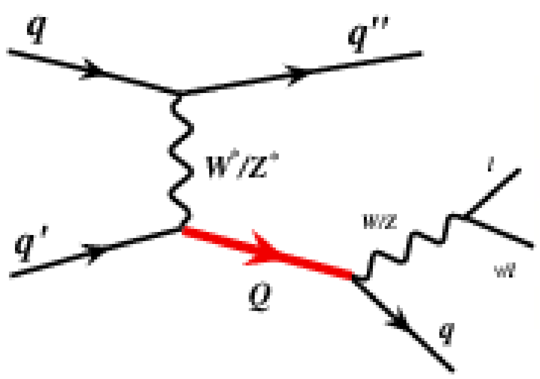
Search for VLQ (single prod.) 1/3

arXiv:1112.5755

$1\,fb^{-1}$

- Search for vector like quarks (VLQ)Q singly produced both in
  - Charged Current (CC) pp → Qq → Wqq'
  - Neutral Curent (NC) pp → Qq → Zqq'
- Assuming only leptonic decays of the gauge boson
- Both S and T channels contribute to the signal cross section
- Assume VLQ couples to first two generation only (2 degenerate VLQ doublets)→ potentially strong signal at the LHC
- Couplings KqQ = (ν/mQ)K'qQ
  - q is any light quark; Q is VLQ, mQ VLQ mass
  - ν Higgs vev
  - K'qQ → the model dependence of the qVQ vertex (V = W or Z)
- Consider only VLQs U and D of charge +2/3 and -1/3



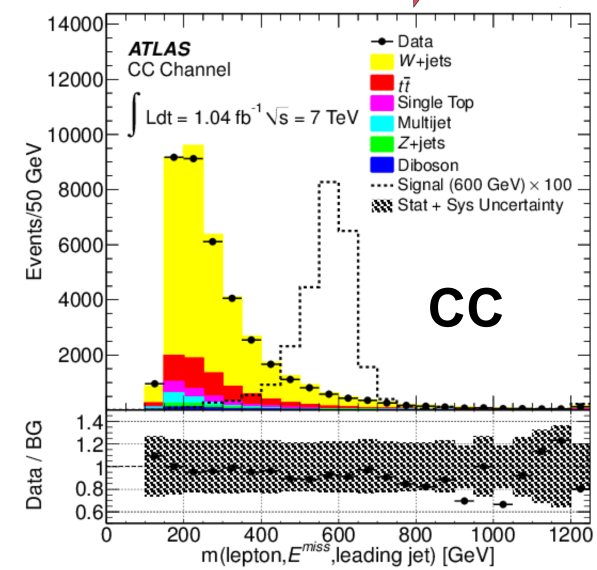


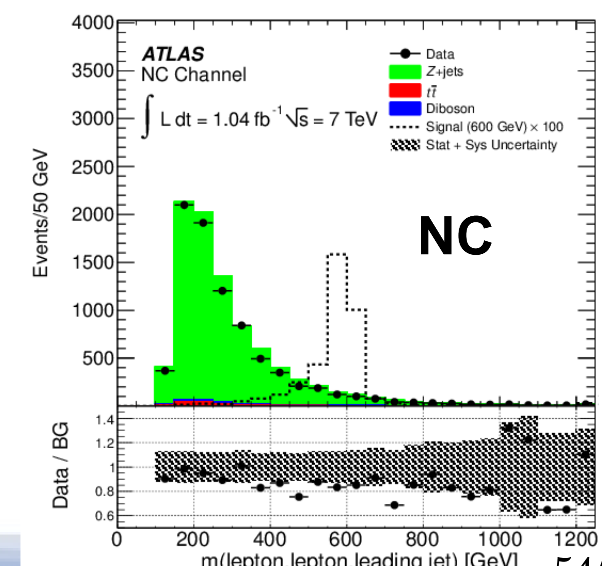
Search for VLQ (single prod.) 2/3

arXiv:1112.5755

$1fb^{-1}$

- Event selection, considering electron and muon leptons:
- Single lepton triggers
- Isolated electron, pT > 25GeV, $|\eta|<2.47 \notin 1.37<|\eta|<1.52$
- Isolated muon, pT > 25GeV, $|\eta|<2.5$
- Jets reconstructed with antiKT0.4
- <u>Charge Current:</u>
  - Exactly one lepton
  - $E_t^{miss} > 50$GeV
  - At least 2 jets with pT > 50, 25 GeV
  - $|\Delta\eta|>1$ leading jet pT and 2[nd] or 3[rd] jet
  - $m_T(W) > 40$GeV
  - $\Delta\Phi(l,E_T^{miss}) > 2.4$ (expect boosted Ws)
  - VLQ mass → m(W,jet) with leading jet pT (ν pz chosen to give the largest $|\Delta\eta|$ between neutrino and leading jet pT)
- <u>Neutral Current:</u>
  - Exactly two opposite charged same-flavor leptons
  - $66 < M_{ll} < 116$GeV , pT(l,l) > 50GeV (expect boosted Zs)
  - At least 2 jets with pT> 25GeV
  - VLQ mass → m(l,l,jet) with leading jet pT





Search for VLQ (single prod.) 3/3

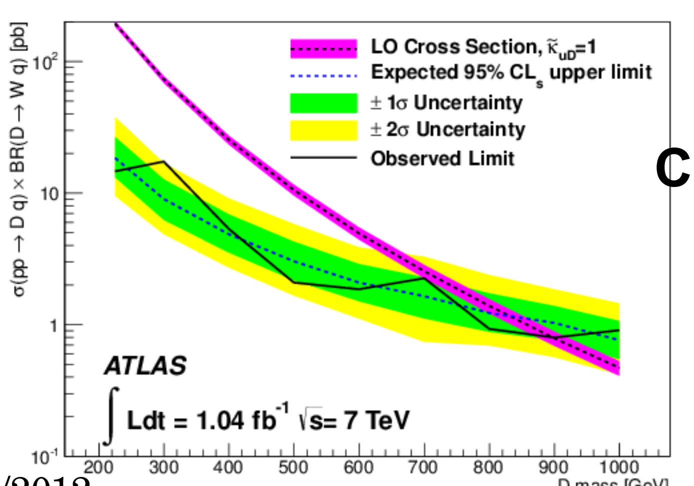
arXiv:1112.5755

$1fb^{-1}$

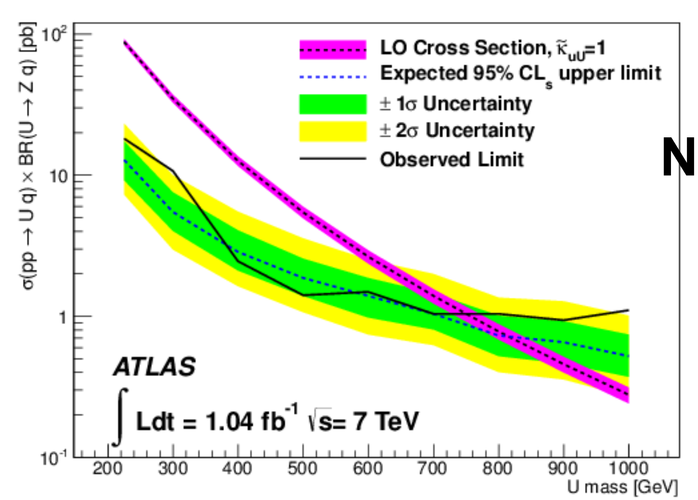
- Cls method and binned maximum Likelihood
- Search performed by searching a signal peak on top of a smooth background
- No evidence of VLQ found
- Assuming K'uU = K'uD = 1 set limits → mVLQ > 900(760) GeV for CC(NC) @95%C.L.
- Tevatron limits → K'uU=1 690GeV (100% BR CC) ; K'uD=sqrt(2) 550GeV (100% BR NC)

Process	Electron channel	Muon channel
W+jets	14500 ± 100 ± 4400	16600 ± 100 ± 5000
tt	2360 ± 50 ± 270	2530 ± 50 ± 290
Single Top	700 ± 30 ± 120	740 ± 27 ± 120
Multijet	670 ± 30 ± 270	340 ± 20 ± 410
Z+jets	128 ± 11 ± 90	432 ± 21 ± 170
Diboson	174 ± 13 ± 53	198 ± 14 ± 62
Expected Total Background	18500 ± 100 ± 4400	20900 ± 100 ± 5100
Data	17302	20668
Expected Signal, D(225 GeV)	2360 ± 50 ± 350	2380 ± 50 ± 400
Expected Signal, D(600 GeV)	133 ± 12 ± 10	133 ± 12 ± 11
Expected Signal, D(1000 GeV)	14 ± 4 ± 1	14 ± 4 ± 1

Process	Electron Channel	Muon Channel
Z+jets	3250 ± 60 ± 430	5350 ± 70 ± 700
tt	58 ± 8 ± 3	90 ± 9 ± 5
Diboson	38 ± 6 ± 4	58 ± 8 ± 4
Expected Total Background	3350 ± 60 ± 430	5500 ± 70 ± 700
Data	3105	5070
Expected Signal, U(225 GeV)	192 ± 14 ± 9	339 ± 18 ± 19
Expected Signal, U(600 GeV)	15 ± 3.9 ± 0.6	23 ± 4.8 ± 0.7
Expected Signal, U(1000 GeV)	1.9 ± 1.4 ± 0.1	2.7 ± 1.6 ± 0.1



CC



NC

Summary of the results

- 4th generation:
  - b'b' → Wt (100% BR) 611GeV
  - t't' → Wb (100% BR) 552GeV
  - Inclusive search (mt' = mb') 490GeV
- Vector like quarks:
  - TT → tZ (100% BR) 475GeV
  - TT → tZ + X 358 - 400GeV
  - T → Wq (no coupling to 3rd generation) 900GeV
  - T → Zq (no coupling to 3rd generation) 750GeV

Producing model independent results

- For the most part LHC searches so far have been, not only model-dependent, but often in the context of unrealistic models, e.g.:
  - Assume BR=1 for particular heavy quark decay modes.
  - Neglect additional signals that would be present in any realistic model (e.g. in 4^{th} gen models there are two quarks, not one which in principle can contribute in the signal region depending on the final event selection and observable used).
- Given the large number of possible signatures to explore, it's hard to imagine we can in general design "model-indep" searches for VLQs, but we can sometimes alleviate some of the model assumptions by carefully designing the search.
- A good example: QQ → Zb+X
  - Leptonic Z allows to focus on Q decay modes containing Z bosons with small contamination from other decay modes.
  - Reconstructed Zb system "enough" to suppress backgrounds and build a sensitive observable so don't really need to look at the "rest of the event".

  Designing event selections which are very inefficient for most but a subset of decay modes may also be a way to have a "cleaner" interpretation (e.g. SS dileptons mainly sensitive to B/X quarks, l+6 b-tag searches only sensitive to T → tH, etc).
- In the case of 4th gen models, it's possible to relax assumptions on the VQq elements (e.g. by not using b-tagging requirements or producing limits on BR vs mQ plane).

Conclusion and Outlook

- ATLAS and CMS have performed the search for new heavy quarks in several decay channels
  - Search for new heavy quarks made a lot of quick progress at LHC
  - LHC limits are now the most stringent ones
  - Unfortunately no sign of new physic yet :(
- Our program of heavy quark searches is barely covering the tip of the iceberg….
- We have a nice set of searches focusing on pair production but much territory remains to be explored (NC decay modes, boosted topologies, single production, etc).
- Very exciting prospects ahead!
  - Factor of 5 increase in statistics from analyses (2011 dataset).
  - Also reoptimized/broader scope analyses and new channels!
  - Up to 15 fb1 at $\sqrt{s}$=8 TeV by then end of 2012.
- Apologies for any relevant topics omitted due to time limitations

Bonus Slides