4th generation at LHC

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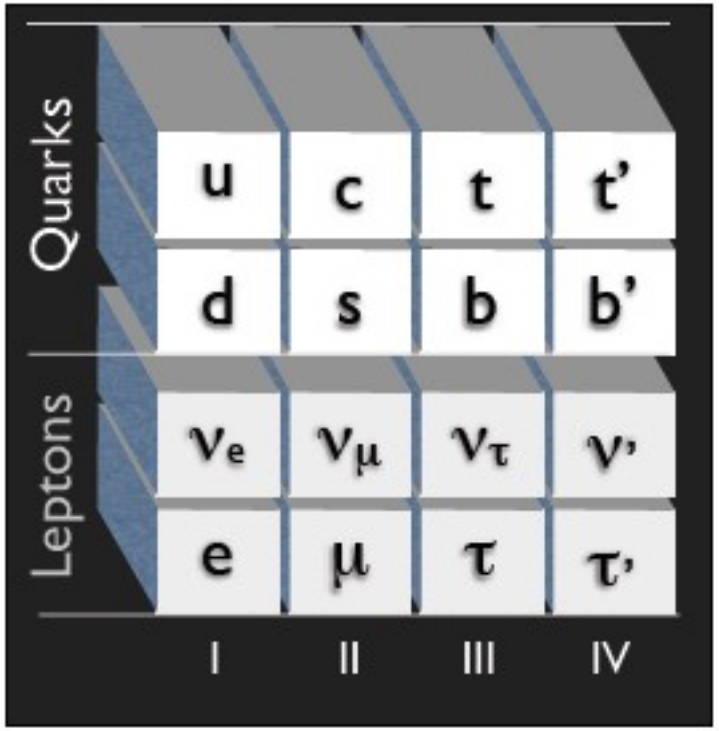
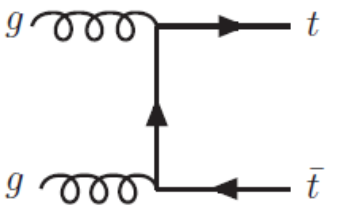
New heavy quarks

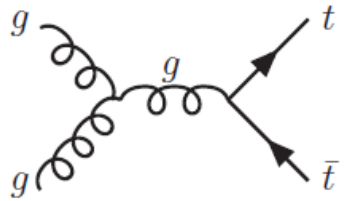
- Over the past decades, Standard Model (SM) has been very successful in describing all the experimental measurements using "only" three generations of quarks and lepton family
- Many BSM models predict new heavy quarks: Extra-dimension, little higgs, new SM like generations, GUTs, etc...
- → Can be 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



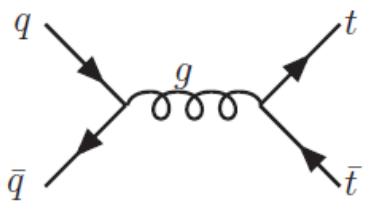
Top Quark Pair Production

- 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)

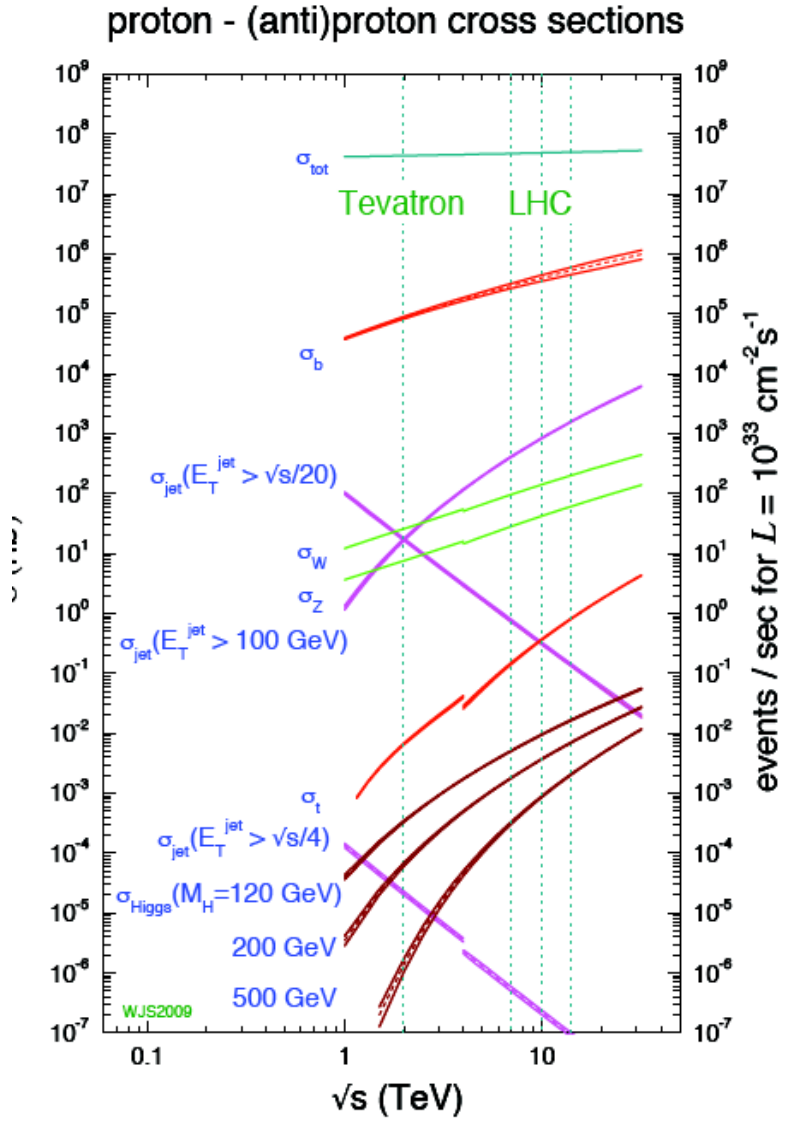




Dominant at the LHC (80%)

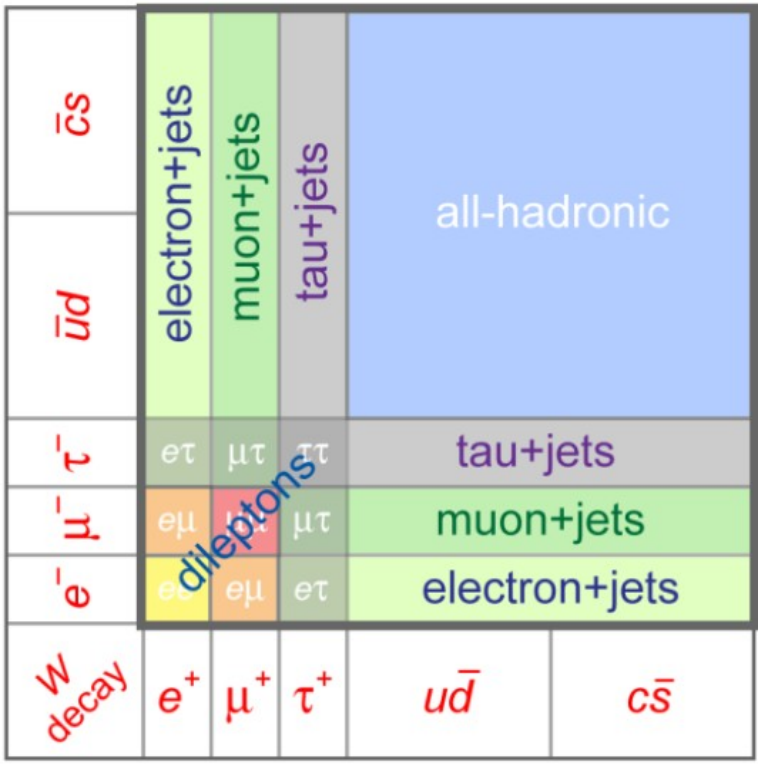


Dominant at the Tevatron



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%)

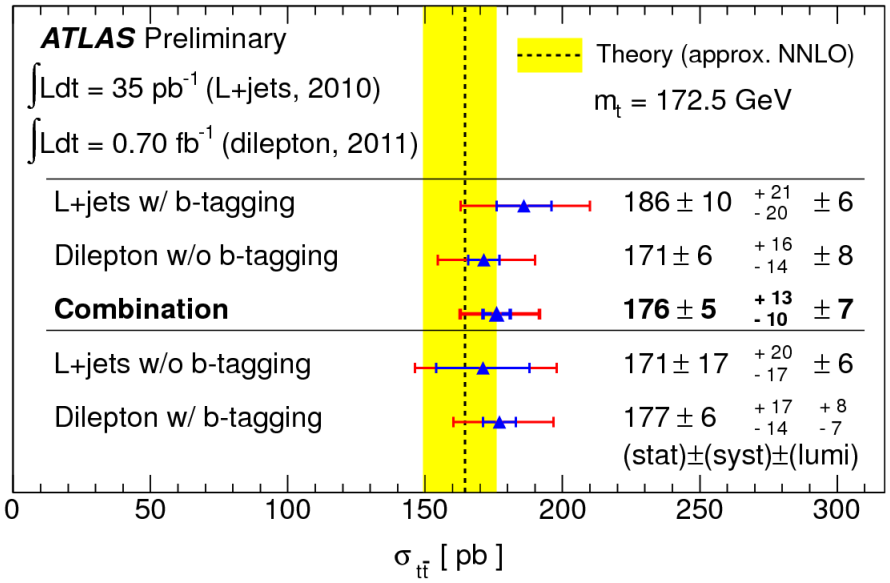


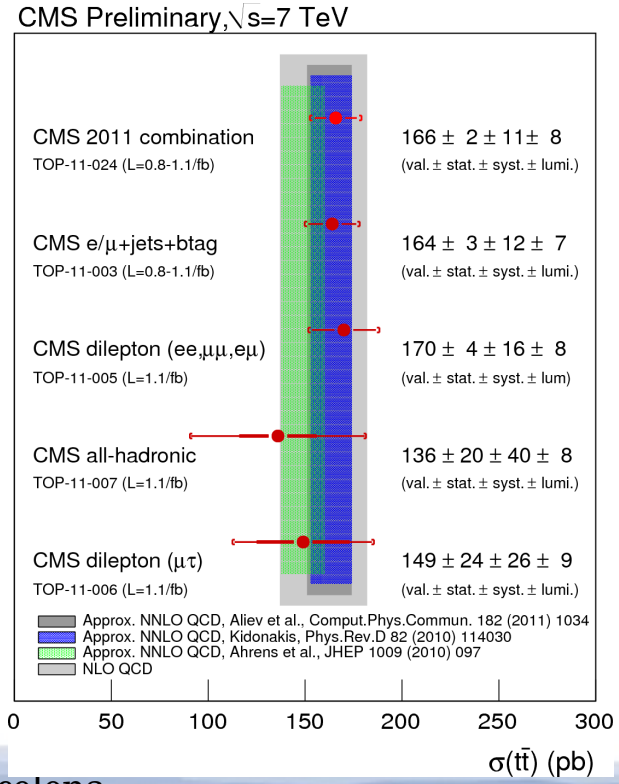
- The top-quark provides a virtual lab to search for new physics
  - Many tops have already been produced at LHC!!
  - Various properties of the top-quark have been measured
  - This helps us to provides procedures/tools to separate SM backgrounds from new physics

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

ATLAS

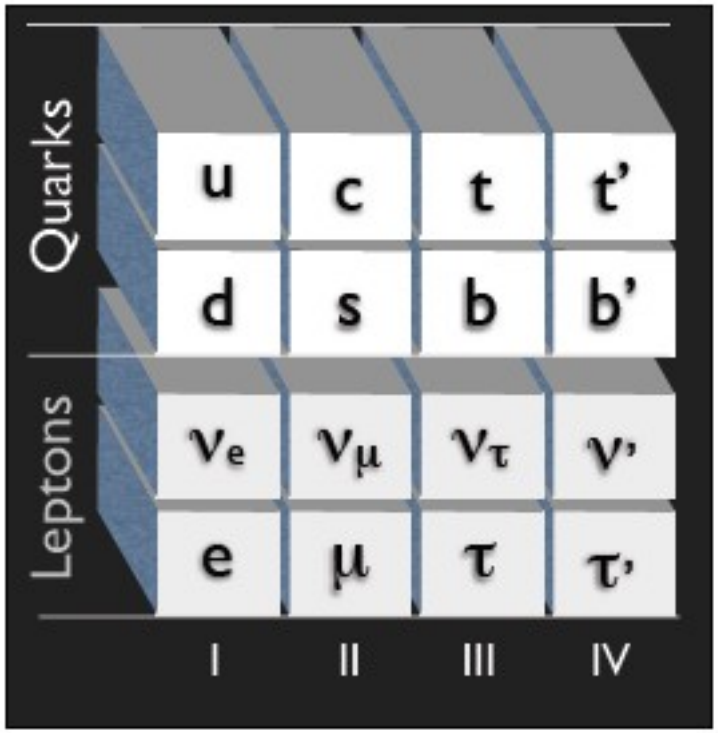
- Single lepton: (0.7fb-1) σ(ttbar) = 179.0 +9.8–9.7 (stat+syst) ±6.6(lumi.)pb
- Dilepton: (0.7fb-1) : σ(ttbar) = 177 ±6 (stat.)+17-14 (sys.) ±8 (lum.)pb
- Combination (L+jets 35pb-1 and DL 0.7fb-1 no btag): σ(ttbar) = 176 ±5(stat.) +13-10(syst.) ±7 (lumi.)pb.
- CMS combine L+jets, dilepton, mu+tau, all hadronic (0.8-1.1fb-1) σ(ttbar) = 165.8 ± 2.2 (stat.) ± 10.6 (syst.) ± 7.8 (lumi.) pb.
- → results with more luminosity coming soon approaching theoretical errors!





4th generation quarks

- SM doesn't predict number of fermion generations:
  - Upper bound from QCD asymptotic freedom: number of families < 9.
  - CKM constraints fairly weak.
- SM4 = SM + 4th 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.



$$CKM_{4\times4} = \begin{bmatrix} 0.97377 \pm 0.00027 & 0.2257 \pm 0.0021 & 0.00431 \pm 0.00030 & < 0.044 \\ 0.230 \pm 0.011 & 0.957 \pm 0.095 & 0.0416 \pm 0.0006 & < 0.46 \\ 0.0074 \pm 0.0008 & 0.0406 \pm 0.0027 & > 0.78 & < 0.47 \\ < 0.063 & < 0.46 & < 0.47 & > 0.57 \end{bmatrix}$$

Vector like quarks

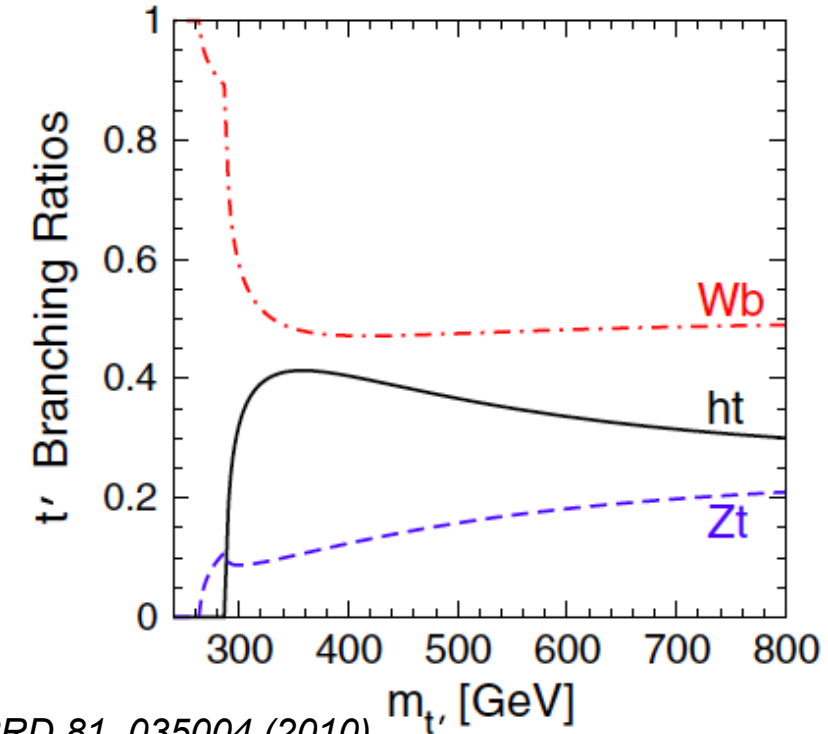
- Vector-like quarks: left and right components transform the same under $SU(2)_L$
- → can couple to SM particles without upsetting precision EW and flavor constraints.
- Vector-like quarks in a doublet need to be nearly degenerate in mass.
- Predicted by many models: extra-dimensions, Little Higgs, 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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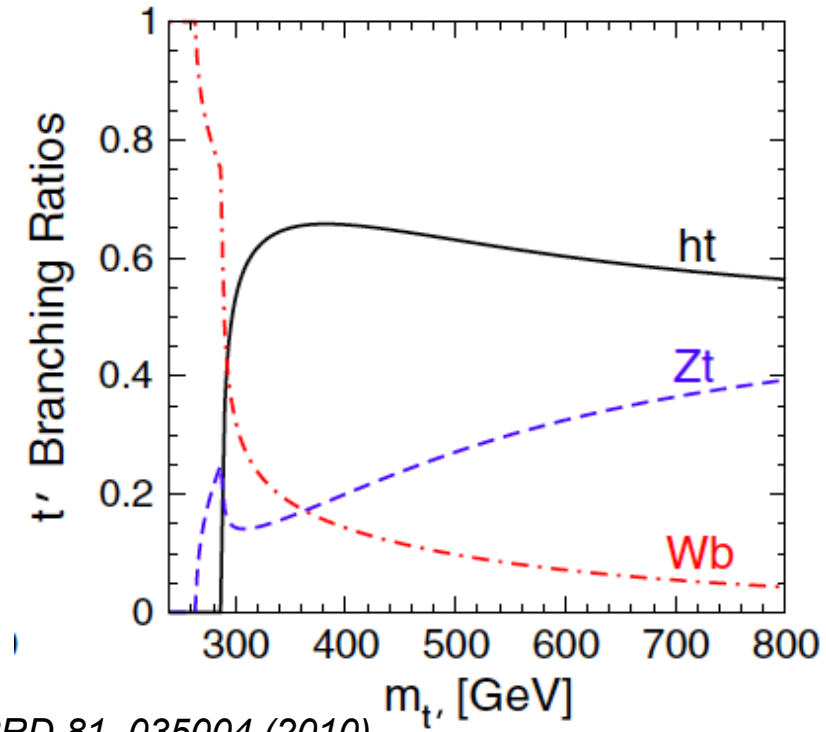
(X,T) doublet	XT_d	(+5/3, +2/3)	X→W^+t T→Zt, Ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	B→Zb, Hb Y→W^-b

"W-phobic"

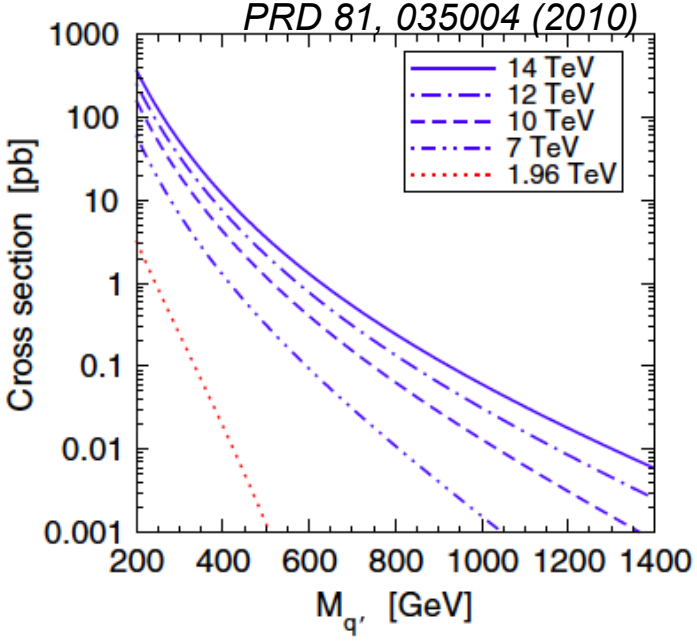


PRD 81, 035004 (2010)

Heavy quark production

- Up to masses ~1 TeV, dominant production is in pairs via the strong interaction:
- $\sqrt{s}$=7 TeV: $\sigma(QQ)$ ~ 1.5 pb for m_Q~400 GeV vs $\sigma(tt)$ = 160 pb
- $\sqrt{s}$=14 TeV: $\sigma(QQ)$ ~ 8 pb for m_Q~400 GeV vs $\sigma(tt)$ = 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!).

PRD 81, 035004 (2010)



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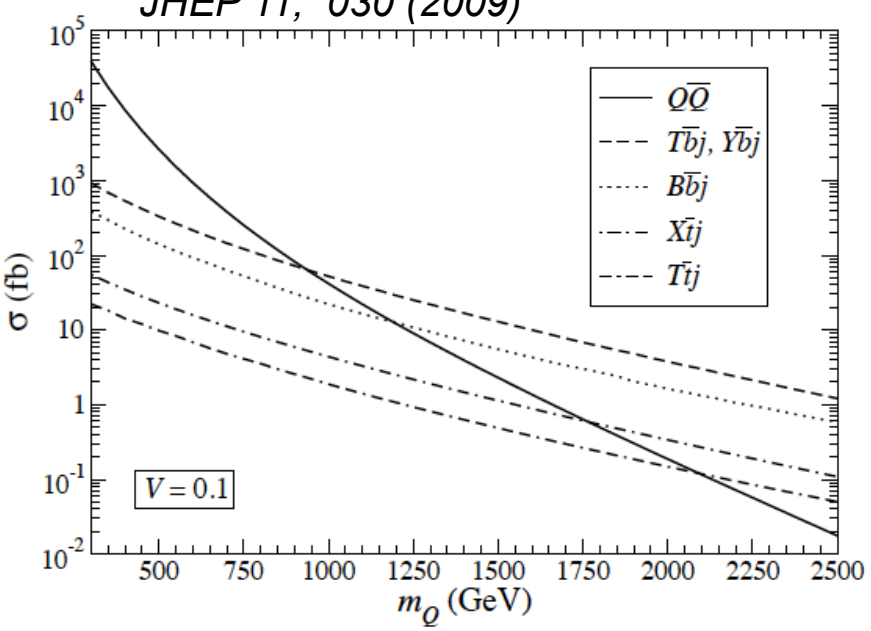


Signatures: 4th generation quarks

- 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		
	$l^\pm$ (4j)			TT		
lepton+jets	$l^\pm$ (≥6j)			BB		

Signatures: vector like quarks

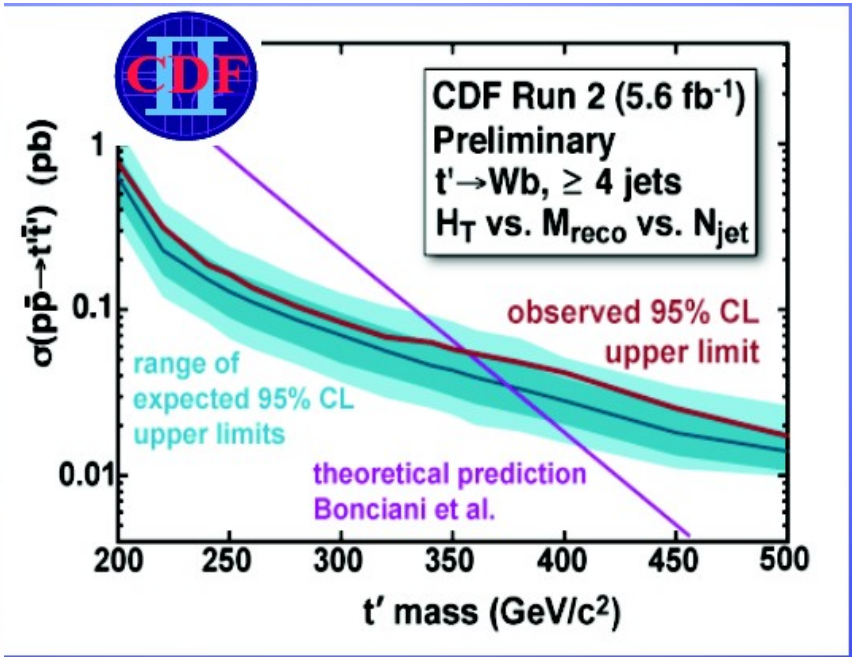
- If we consider VLQ models, there are many signatures that could be exploited, and which are ultimately needed to both enhance discovery potential and model discrimination.

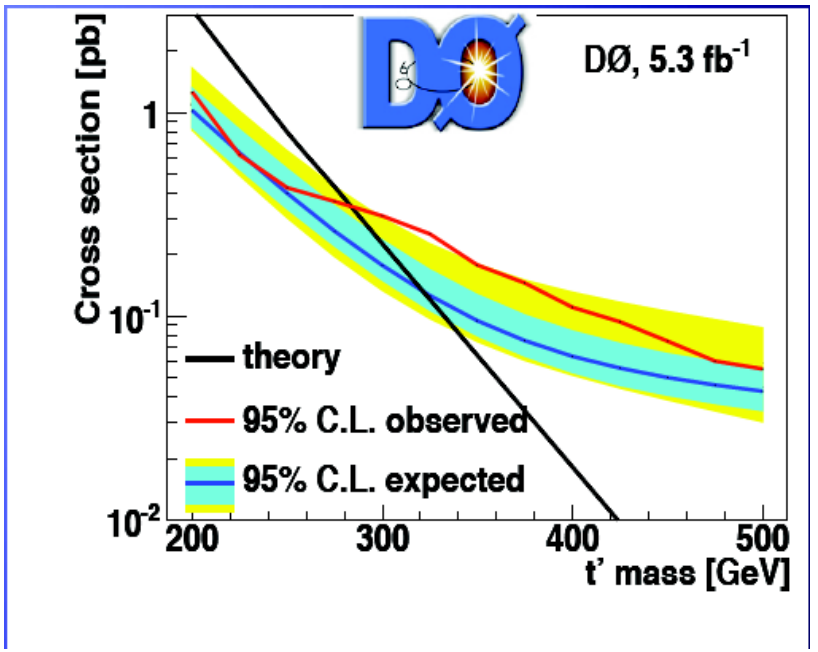
	T_S	B_S	TB_d	XT_d	BY_d
4 leptons: 4l (2Z)	TT	BB	TT,BB	TT	BB
4 leptons: 4l (1Z)	TT	BB	TT,BB	TT	BB
4 leptons: 4l (0Z)	TT	BB	TT,BB	TT,XX	BB
3 leptons: 3l (1Z)	TT	BB	TT,BB	TT	
3 leptons: 3l (0Z)	TT	BB	TT,BB	TT,XX	
OS dileptons: l^+l^- (1Z)	TT	BB	TT,BB	TT	BB
OS dileptons: l^+l^- (0Z)	TT	BB	TT,BB	TT,XX	BB,YY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

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

Tevatron Results t'

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





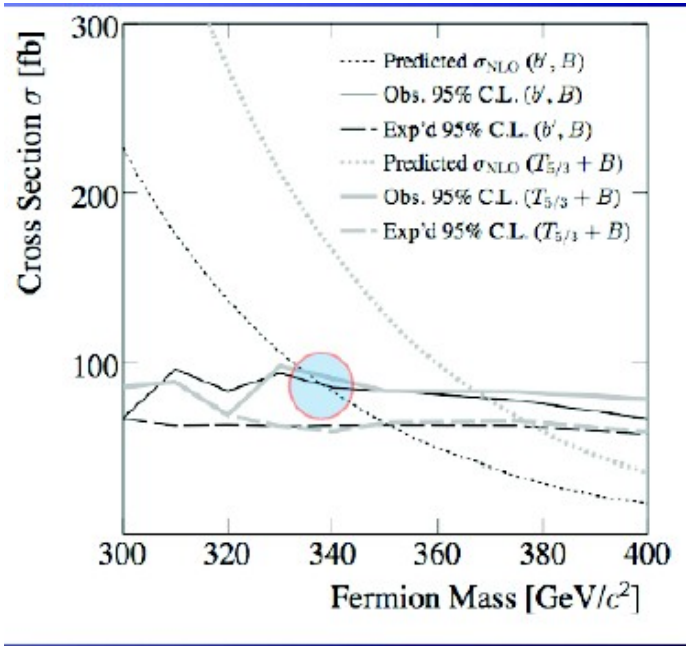
m(t') > 358GeV (CDF) @ 95%C.L.

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

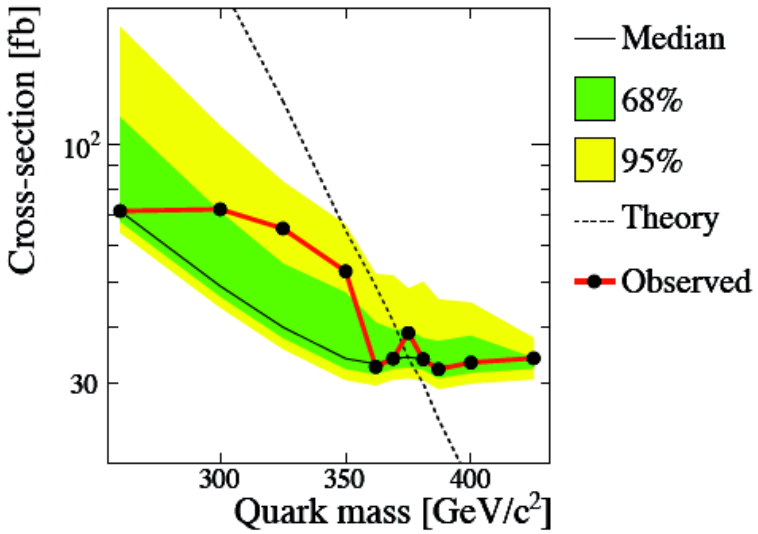
Tevatron Results b'

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

Same-signed



Lepton+jets

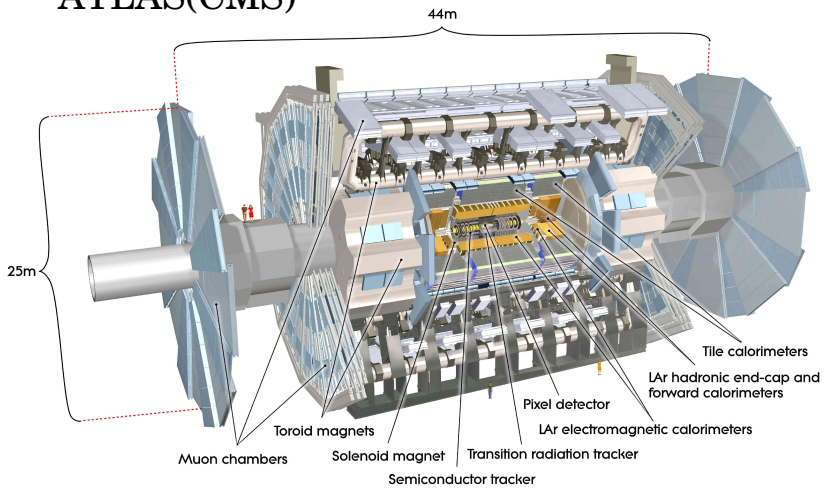


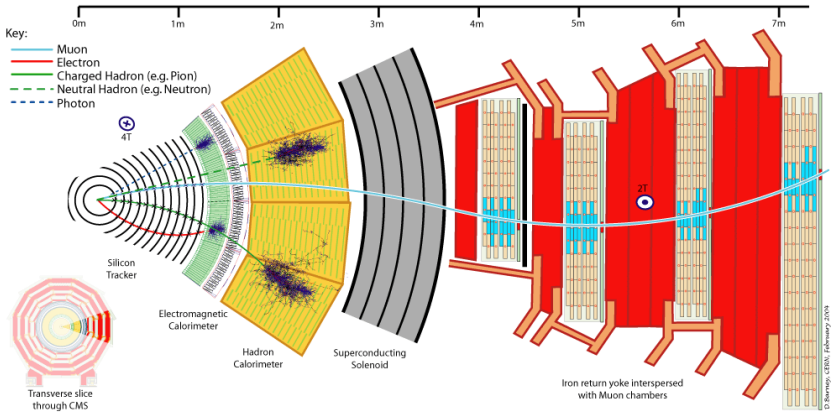
m(b') > 338GeV (CDF) @ 95%C.L.

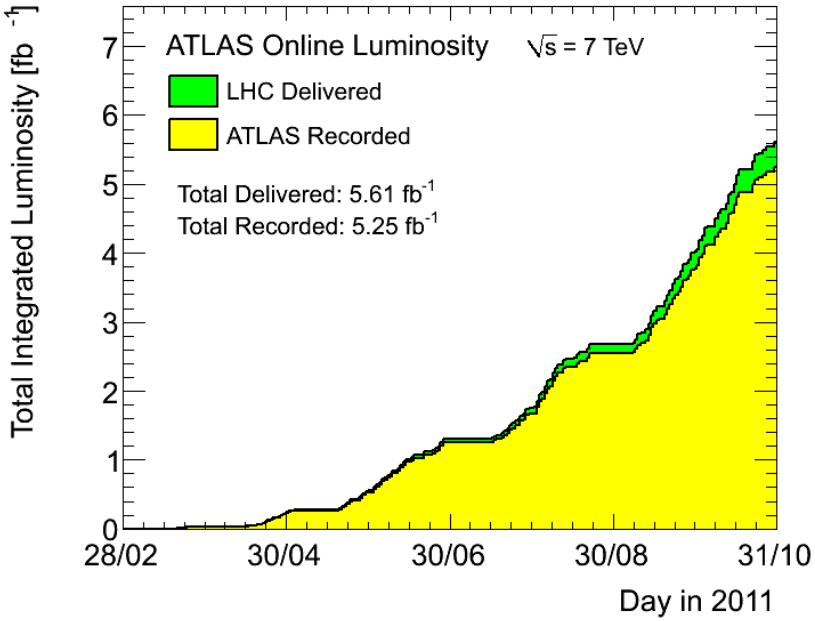
m(b') > 372GeV (CDF) @ 95%C.L.

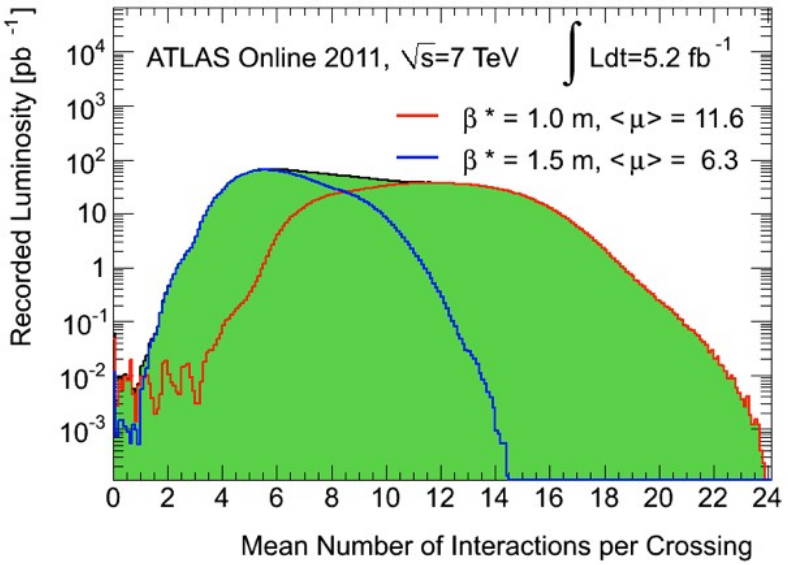
Detectors and LHC Data

- 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)









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

- ATLAS results → https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
  - Search for Up-Type Fourth Generation Quarks in the Dilepton plus Jets Channel (37pb-1, ATLAS-CONF-2011-022)
  - Inclusive search for same-sign dilepton signatures in pp collisions at √s= 7 TeV with the ATLAS detector (35pb-1, arXiv:1108.0366)
  - Search for New Phenomena in ttbar Events With Large Missing Transverse Momentum (1.04fb-1, arXiv:1109.4725)
  - 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)
  - Search for Up-Type Fourth Generation Quarks in the Lepton plus Jets Channel (1.04fb-1) (not yet public, under approval process, not showing details)
- CMS results → https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
  - Search for a Heavy Bottom-like Quark (1.14fb-1, CMS PAS EXO-11-036)
  - Search for a Heavy Top-like Quark in the Dilepton Final state (1.14fb-1, PAS-EXO-11-050)
  - Search for pair production of a fourth-generation t' quark in the lepton-plus-jets channel (0.82-0.57 fb-1, PAS-EXO-11-051)
  - 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 √s= 7 TeV (1.14fb-1, arXiv:1109.4985)

CMS – Search for b' 1/3

PAS-EXO-11-036

1fb^{-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-sign dilepton efficiency [%]	yield	trilepton efficiency [%]	yield
350	3.20	1.16 ± 0.15	42	0.33 ± 0.06	12
400	1.41	1.36 ± 0.17	22	0.42 ± 0.06	6.7
450	0.662	1.51 ± 0.18	11	0.45 ± 0.07	3.4
500	0.330	1.57 ± 0.19	5.9	0.48 ± 0.07	1.8
550	0.171	1.80 ± 0.22	3.5	0.57 ± 0.08	1.1

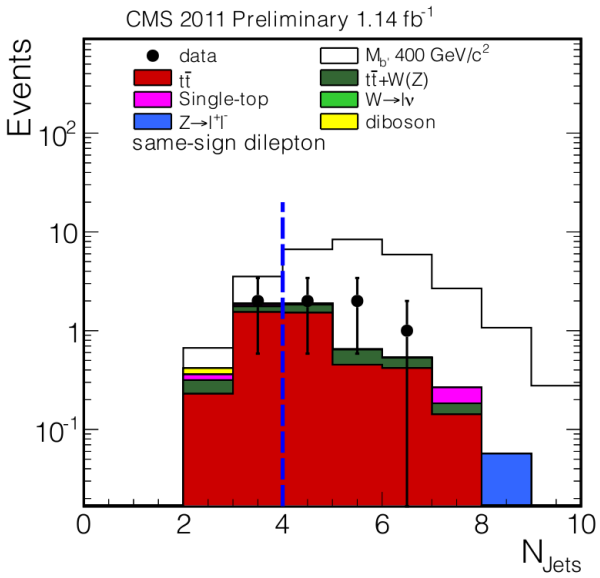
CMS – Search for b' 2/3

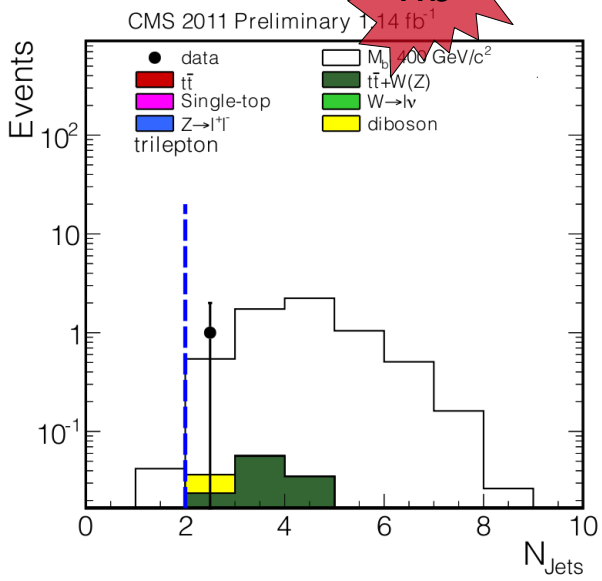
PAS-EXO-11-036

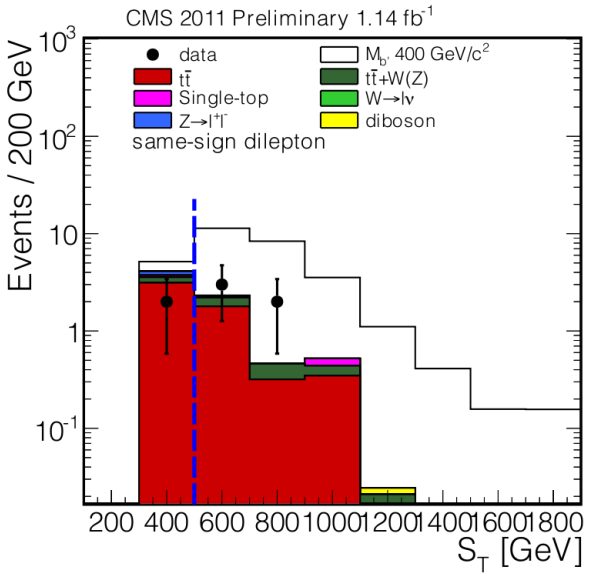
1fb^{-1}

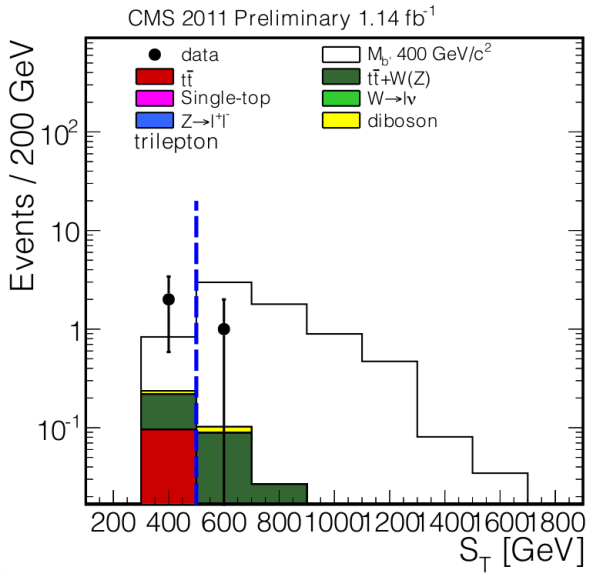
- Backgrounds:
  - Same sign 2 leptons → main contribution is from ttbar
  - 3 leptons; main contribution tt+W(Z)
- Good modeling of the data, no sign of any excess → set limits
- Expected/observed yields:

	Total BG in signal region	Data
2SS	4.4 +/- 1.4	5
3 lepton	0.16 +/- 0.09	1









CMS – Search for b' 3/3

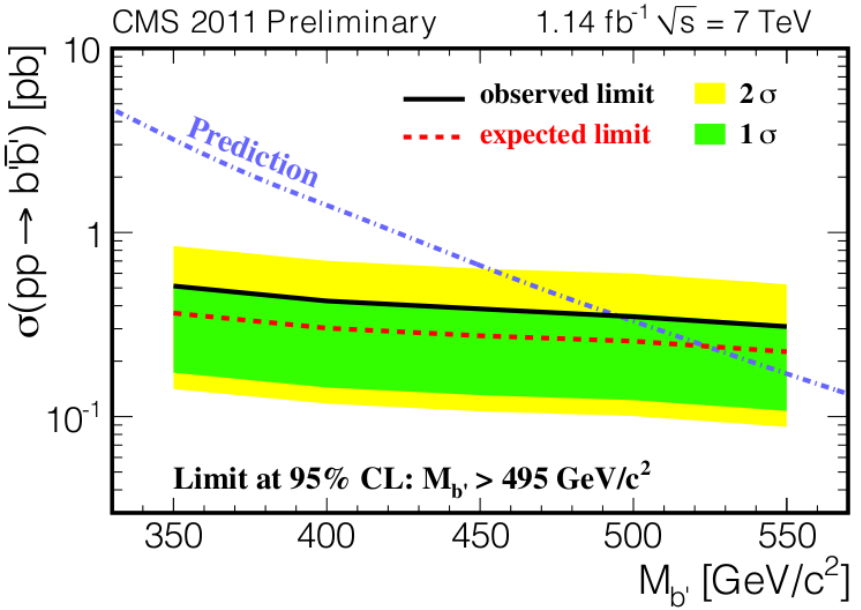
PAS-EXO-11-036

1fb^{-1}

- Limits extracted using a cut and count method
- Bayesian method with log-normal prior for integration over the nuisance parameters
- Observed limit: m(b') > 495GeV @ 95%CL

	Total BG in signal region	Data
2SS	4.4 +/- 1.4	5
3 lepton	0.16 +/- 0.09	1

	same-sign dilepton		trilepton	
	$\Delta\epsilon/\epsilon$	ΔB	$\Delta\epsilon/\epsilon$	ΔB
Accuracy of control-sample method	-	1.02	-	-
Control sample statistics	-	0.49	-	-
Integrated Luminosity	4.5%	0.03	4.5%	0.007
Background normalization	-	0.39	-	0.059
Lepton selection	4.4 – 4.5%	0.03	6.2 – 6.5%	0.010
b-tagging	10%	0.07	10%	0.016
Pile-up events	2.3%	0.35	3.4%	0.053
Jet energy scale	1.4 – 3.2%	0.12	0.4 – 4.3%	0.008
Jet energy resolution	0.8 – 2.4%	0.51	0.6 – 3.5%	0.010
Missing energy resolution	0.1 – 3.1%	0.10	0.6 – 6.0%	0.014
Trigger	2.3%	0.07	2.3%	0.004
PDF	0.3 – 0.7%	0.06	0.7 – 1.8%	0.005
Simulated sample statistics	3.1 – 4.0%	0.05	5.6 – 7.4%	0.025
Total	12 – 13%	1.4	14 – 17%	0.09



ATLAS – Same sign dileptons 1/3

arXiv:1108.0366

35pb^{-1}

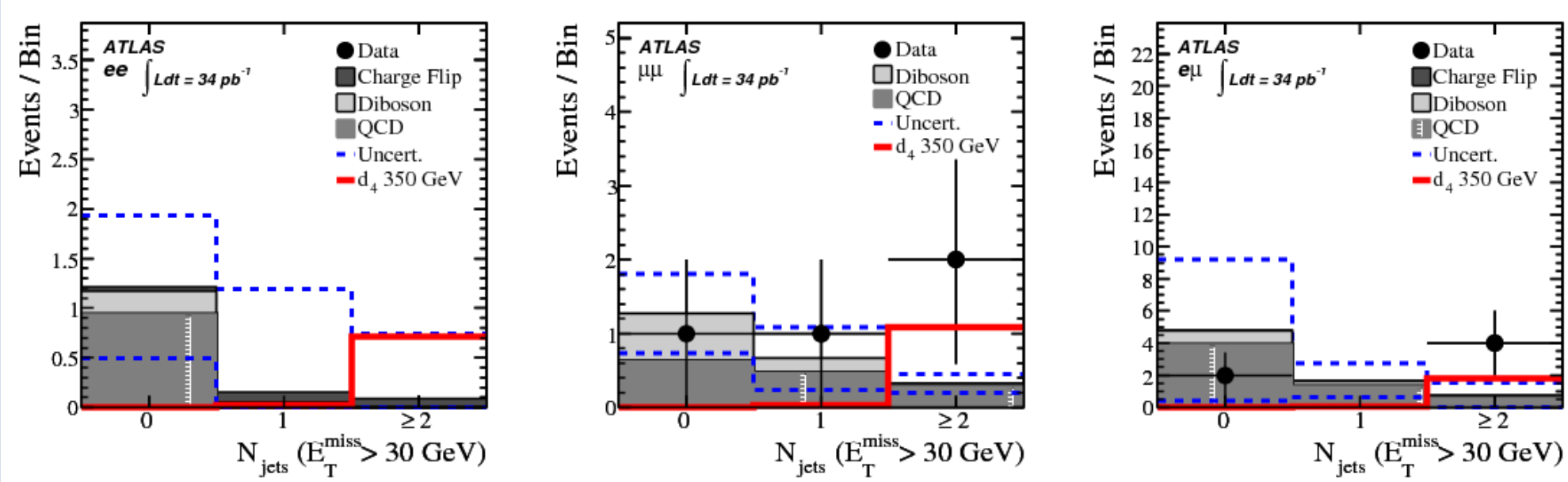
- This analysis present the search for two same sign leptons (ee/eμ/$\mu\mu$)
- Inclusive search for new physics → limits on heavy Majorana neutrinos, UED, b'
- Selection:
  - 2 same sign leptons with tight identification criteria
  - Single lepton trigger
  - Lepton pT > 20GeV; muon $|\eta| < 2.5$; electron $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - Lepton isolation: $\Sigma ET(\Delta R<0.2) < 0.15*pT$
  - Jets: Anti-kt 0.4, pt> 30GeV, $|\eta| < 2.5$
  - ETMiss > 30 GeV

ATLAS – Same sign dileptons 2/3

arXiv:1108.0366

35pb^{-1}

- Background sources in the SM:
  - QCD → jets faking/creating isolated leptons
  - Charge Mis-Identification
  - Diboson → irreducible background
- Data/Monte Carlos modeling is shown in the njet distribution:
  - This is the variable used for limit setting



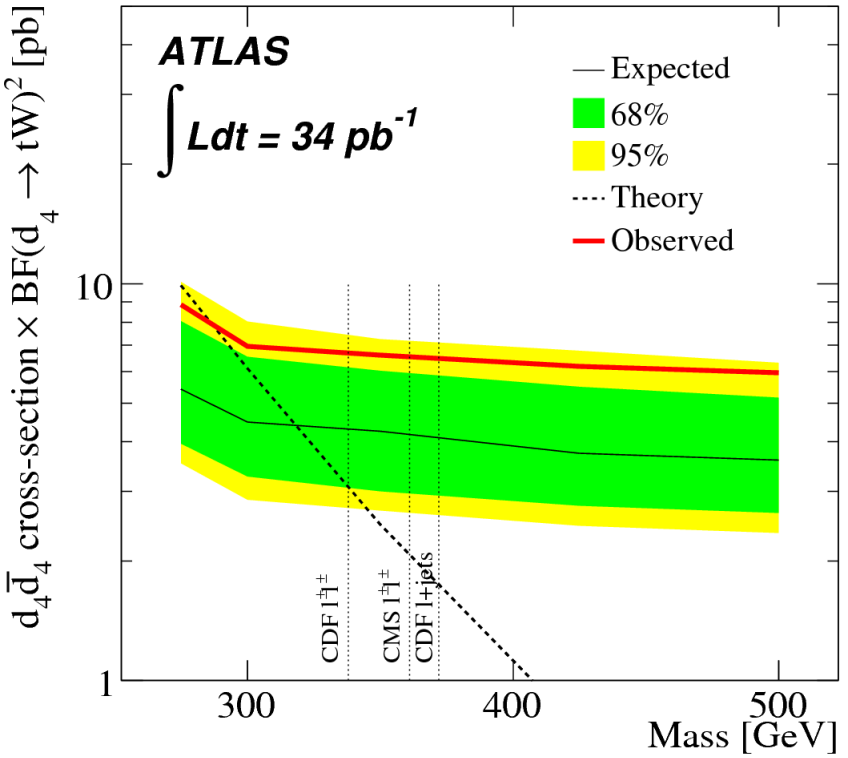
ATLAS – Same sign dileptons 3/3

arXiv:1108.0366

35pb^{-1}

- A 3 bin template is used for limit setting → njet = 0,1 and ≥2
- Limits are set using the Feldman-Cousins prescription
- Confidence level interval are build using a Likelihood ratio test statistic
- Assuming BR(b' → tW) = 1 → m(b') > 290GeV @ 95% C.L.

Analysis with 1fb-1 under ATLAS internal circulation



CMS – Search for t' dilepton 1/3

PAS-EXO-11-050

1fb^{-1}

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

- Selection:
  - 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 > 30GeV

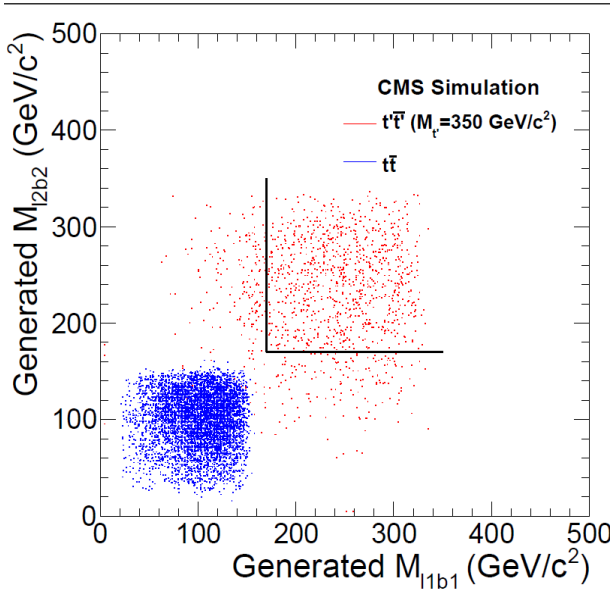
CMS – Search for t' dilepton 2/3

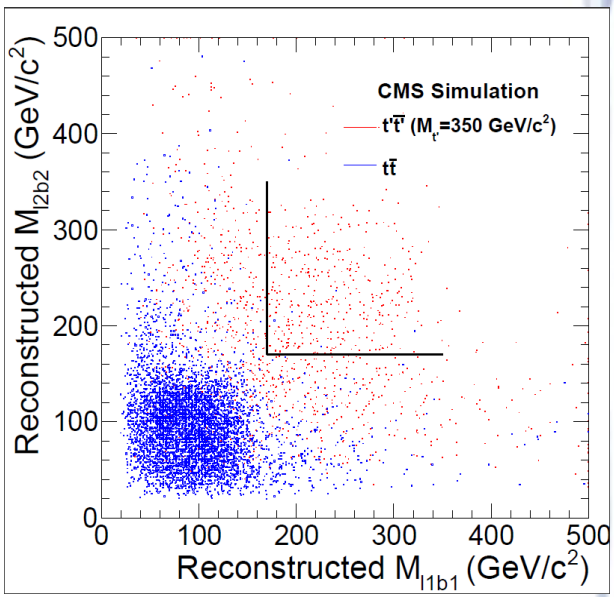
PAS-EXO-11-050

1fb^{-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 two masses
  - → signal efficiency ~ 40%
  - → ttbar very small...

Sample	ee	$\mu\mu$	eμ	all
$t'\bar{t}'$, $M_{t'} = 350\,\mathrm{GeV}/c^2$	5.63 ± 0.41	5.63 ± 0.38	13.43 ± 0.61	24.69 ± 0.83
$t'\bar{t}'$, $M_{t'} = 400\,\mathrm{GeV}/c^2$	2.51 ± 0.18	2.92 ± 0.19	6.33 ± 0.28	11.76 ± 0.38
$t'\bar{t}'$, $M_{t'} = 450\,\mathrm{GeV}/c^2$	1.45 ± 0.09	1.53 ± 0.09	3.27 ± 0.14	6.25 ± 0.19
$t\bar{t} \to \ell^+\ell^-$	167.46 ± 5.85	178.88 ± 5.71	445.45 ± 9.30	791.79 ± 12.38
$t\bar{t} \to$ fake	3.35 ± 0.85	0.19 ± 0.19	5.81 ± 1.04	9.35 ± 1.36
W + jets	< 2	< 2	< 2	< 2
DY$\to \ell^+\ell^-$	2.23 ± 1.39	2.15 ± 1.66	< 1	4.38 ± 2.17
Di-boson	0.04 ± 0.01	0.14 ± 0.07	0.14 ± 0.07	0.31 ± 0.10
Single top	2.63 ± 0.28	2.41 ± 0.26	7.03 ± 0.45	12.06 ± 0.59
Total simulated background	175.70 ± 6.08	183.76 ± 5.96	458.43 ± 9.37	817.88 ± 12.66
Data	184	182	512	878





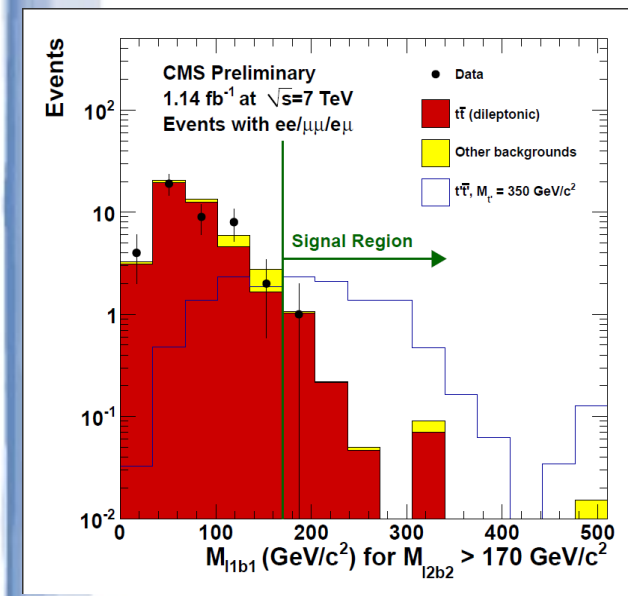
CMS – Search for t' dilepton 3/3

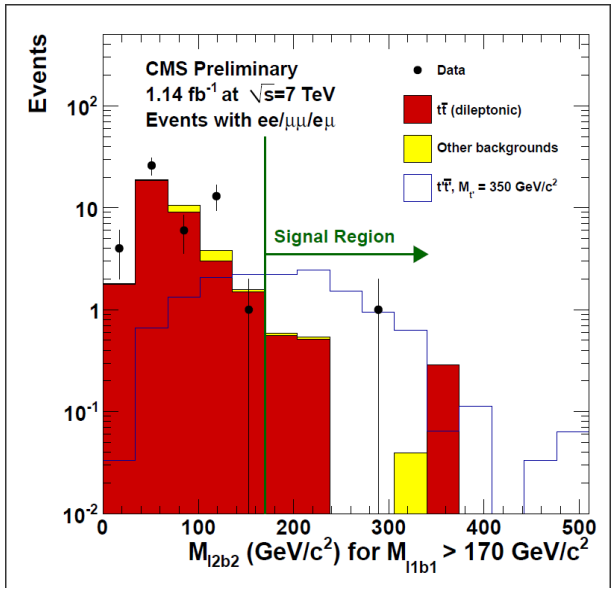
PAS-EXO-11-050

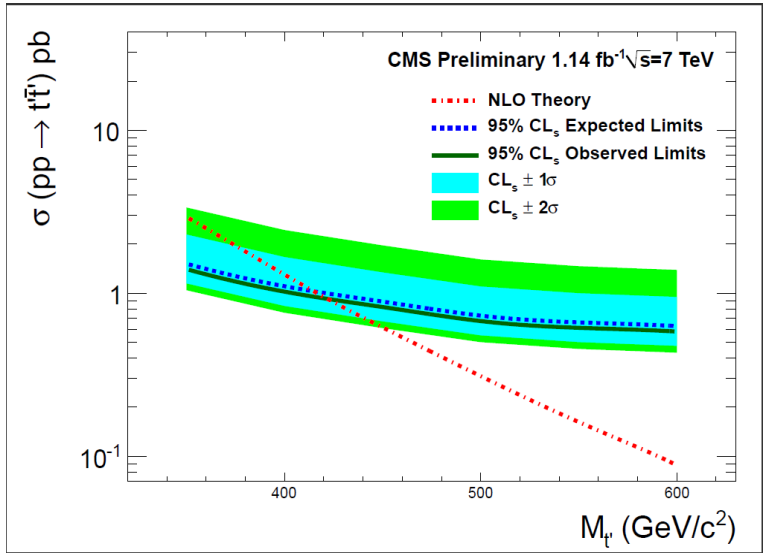
1fb^{-1}

- 1 event observed; 1.62 expected
- 95% CL Limits extracted using Cut and count
- Observed limit → m(t') > 422GeV @ 95% CL

Sample	Yield	Source
$t\bar{t} \to \ell^+\ell^-$	1.35 ± 0.67	Data
Fake leptons	$0.0^{+0.4}_{-0.0}$	Data
DY$\to e^+e^-$ or $\mu^+\mu^-$	$0.07^{+0.13}_{-0.07}$	Data
DY$\to \tau^+\tau^-$	0.11 ± 0.11	Simulation
Di-boson	0.02 ± 0.02	Simulation
Single top	0.07 ± 0.04	Simulation
Total prediction	$1.62^{+0.80}_{-0.70}$	
Data	1	







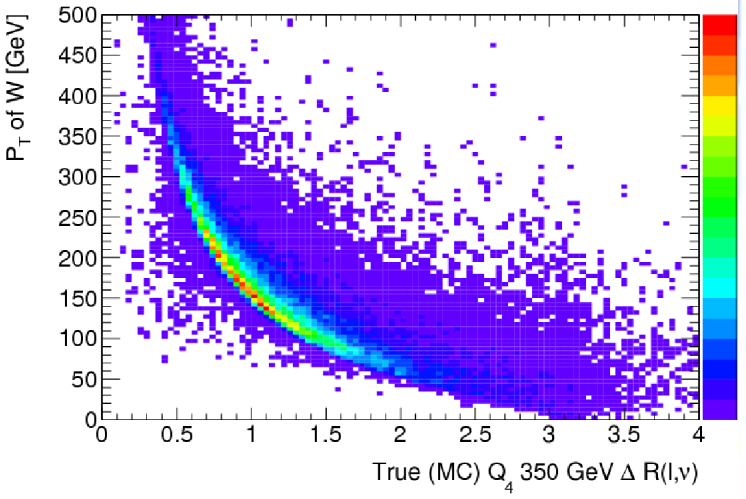
ATLAS – Search for t' dilepton 1/3

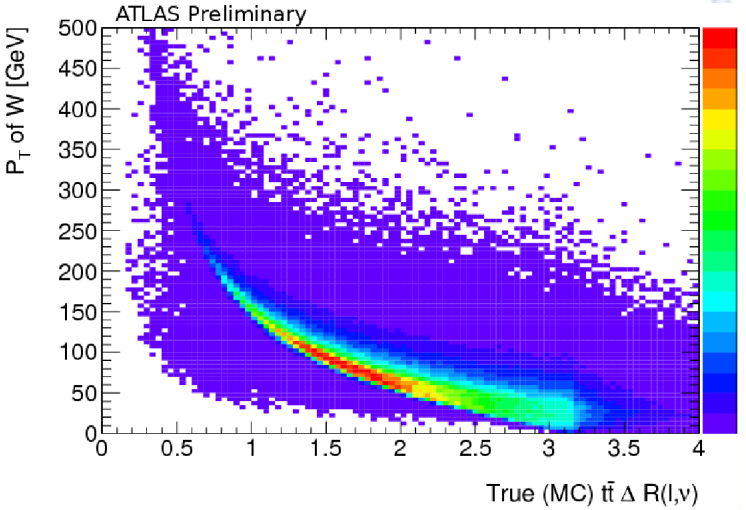
35pb^{-1}

- 1st search ever in this channel!!
- For this analysis, no assumption about the quark mixing in the final state t' → Wq

ATLAS-CONF-2011-022

- Baseline selection:
  - Excatly 2 leptons pT > 20GeV; muon $|\eta| < 2.5$; electron $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - Lepton isolation: $\Sigma ET(\Delta R<0.2) < 4GeV$
  - Jets: Anti-kt 0.4, pt> 20GeV, $|\eta| < 2.5$ → at least 2 jets
  - ETMiss > 40 GeV (ee/$\mu\mu$); HT(MET+lep pt) > 130GeV (eμ)
  - For ee/$\mu\mu$ → Mll > 15GeV; |Mll – MZ| > 10GeV
- Reconstruction of the heavy quark masses:
  - At high W pT → neutrino and lepton ~ collinear
  - Reconstruct both neutrinos by assuming solely contribution to MET
  - 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)



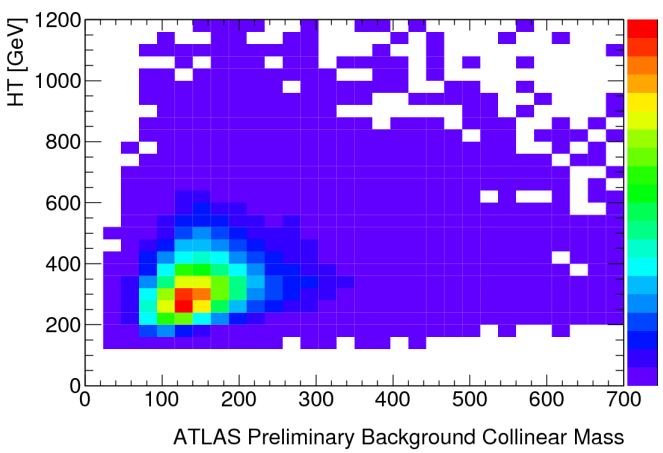


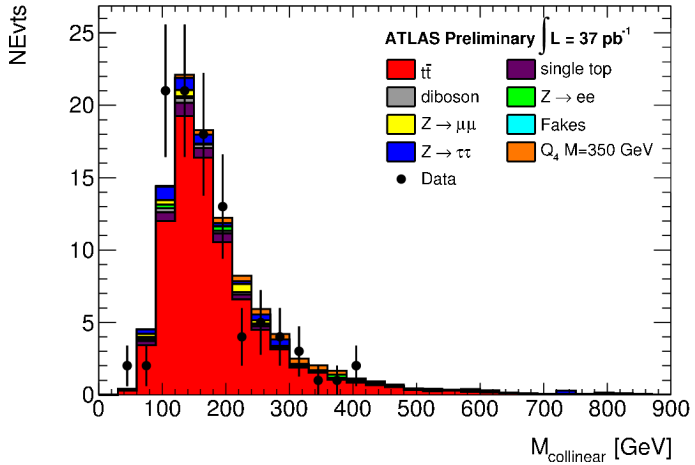
ATLAS – Search for t' dilepton 2/3

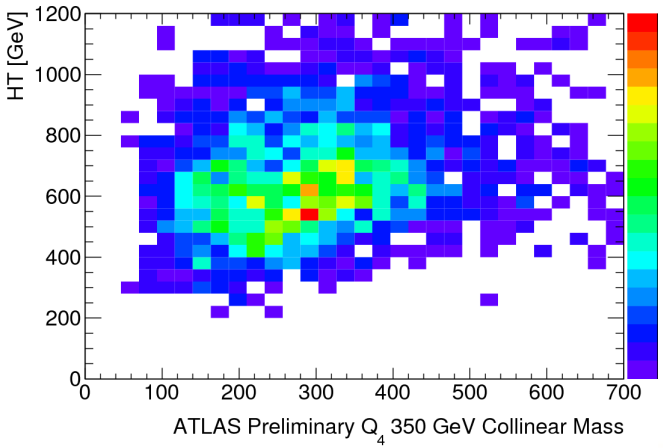
35pb^{-1}

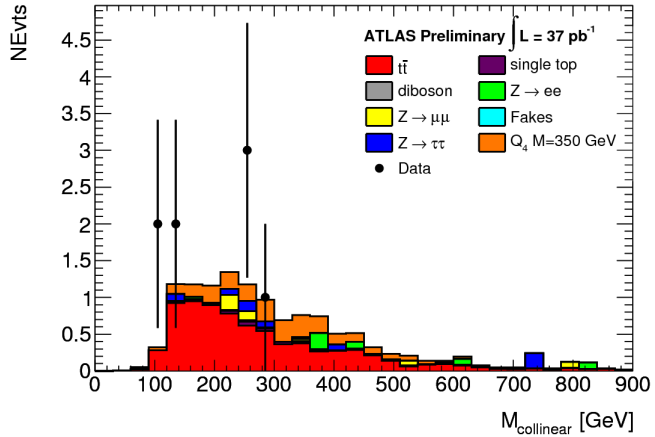
ATLAS-CONF-2011-022

Q_4 Mass (GeV)	Final selection
250	$H_T > 500 - 0.7 \times M_{collinear}$
300	$H_T > 600 - 0.5 \times M_{collinear}$
350	$H_T > 600 - 0.2 \times M_{collinear}$
400	$H_T > 700 - 0.3 \times M_{collinear}$









- 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

ATLAS – Search for t' dilepton 3/3

35pb^{-1}

ATLAS-CONF-2011-022

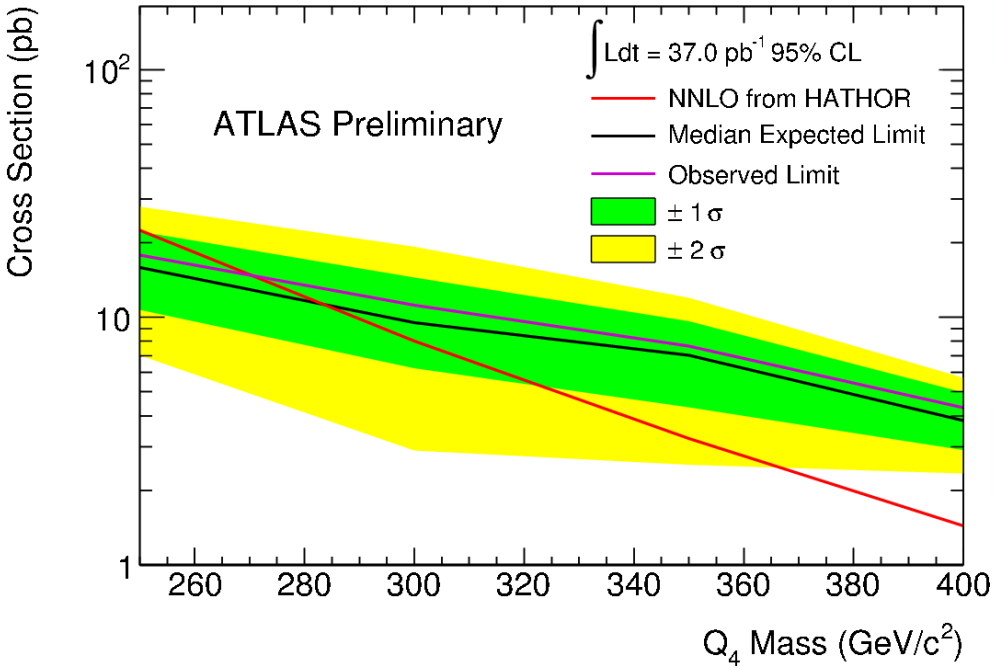
Q_4 Mass [GeV/c^2]	250	300	350	400
Total BG	40.4 ± 0.7 ± 3.9	16.8 ± 0.5 ± 1.7	10.1 ± 0.4 ± 1.0	6.3 ± 0.4 ± 0.8
Signal	20.7 ± 0.5 ± 1.9	7.1 ± 0.2 ± 0.3	3.0 ± 0.1 ± 0.2	1.4 ± 0.1 ± 0.1
Observed	40	11	8	5

- Binned maximum likelihood used to set limit on the production cross section (Feldmans Cousins principle used to build the confidence band)

  Template fit using the Mcoll distribution

- Observed limit m(t') > 270GeV @ 95%CL

Source	Effect	Size [%]
Electron trigger and reconstruction	Yield	1.6%
Electron ID	Yield	2-9%
Muon ID and reconstruction	Yield	0.3%
Muon trigger	Yield	0.1-1.3%
Electron energy scale	Shape	0.6%
Muon momentum scale	Shape	0.1%
Jet energy scale	Shape and Yield	12%
Gluon radiation	Shape and Yield	15%
Signal cross-section	Yield	14%
Background cross-sections	Yield	5-30%
Fake lepton background	Shape and Yield	50%
Luminosity	Yield	11%



Result using 1fb-1 of 2011 data is under internal review
Paper will be published

CMS – Search for t' single-lepton 1/3

PAS-EXO-11-051

0.5-0.8fb^{-1}

- Final state t't' → WbWb → qqb lνb

- Selection:
  - Isolated Electron pt > 30 – 45 GeV (trigger threshold changed) $|\eta|<2.4 \notin 1.44<|\eta|<1.57$
  - Isolated Muon pt > 35 GeV $|\eta|<2.1$
  - Jets: Anti-kt R=0.5 → 4 jets 120, 90, 35, 35 GeV
  - MET > 20GeV
  - At least 1 btag jet

process	cross section	e+jets eff.	μ+jets eff.
$t'\bar{t}'$			
$m_{t'} = 350$ GeV	3.20 pb	$3.7 \pm 0.4\%$	$4.5 \pm 0.3\%$
$m_{t'} = 400$ GeV	1.41 pb	$4.3 \pm 0.4\%$	$5.2 \pm 0.4\%$
$m_{t'} = 450$ GeV	0.66 pb	$4.8 \pm 0.4\%$	$5.6 \pm 0.4\%$
$m_{t'} = 500$ GeV	0.33 pb	$5.0 \pm 0.4\%$	$5.8 \pm 0.4\%$

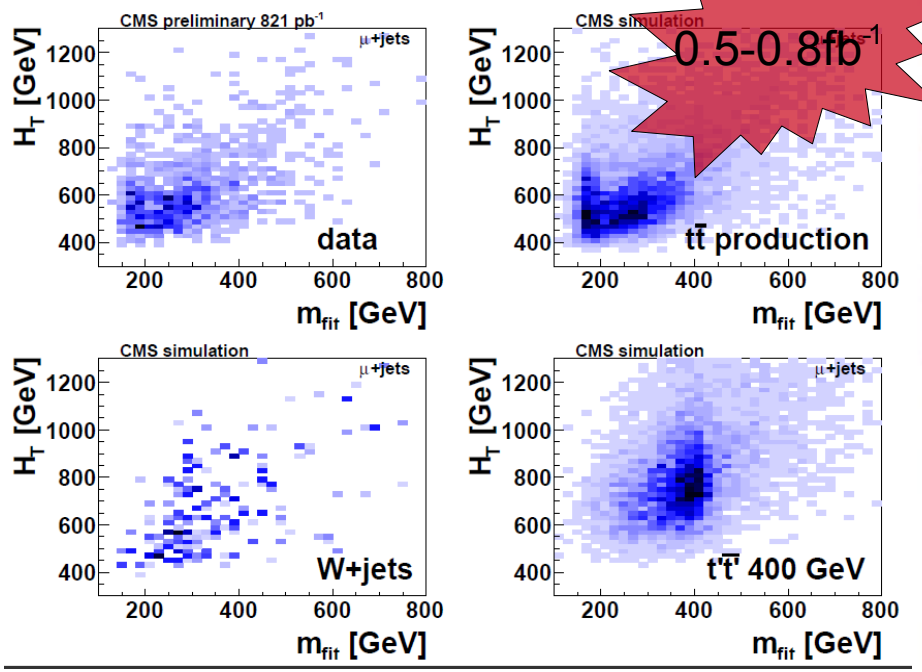
CMS simulation

process	cross section	e+jets events	μ+jets events
$\mathcal{L}$		573 pb^{-1}	821 pb^{-1}
data		520	1054
$t\bar{t}$	158 pb	456 ± 91	907 ± 114
single t	33 pb	14.5 ± 3.5	30 ± 6
W+jets	30 μb	33.3 ± 8.2	106 ± 25
Z+jets	2.9 μb	4.5 ± 1.2	2.6 ± 2.6
WW, WZ, ZZ	67 pb		2.1 ± 0.6
multijets		2.5 ± 1.2	5.7 ± 5.5
total background		510 ± 103	1054 ± 145

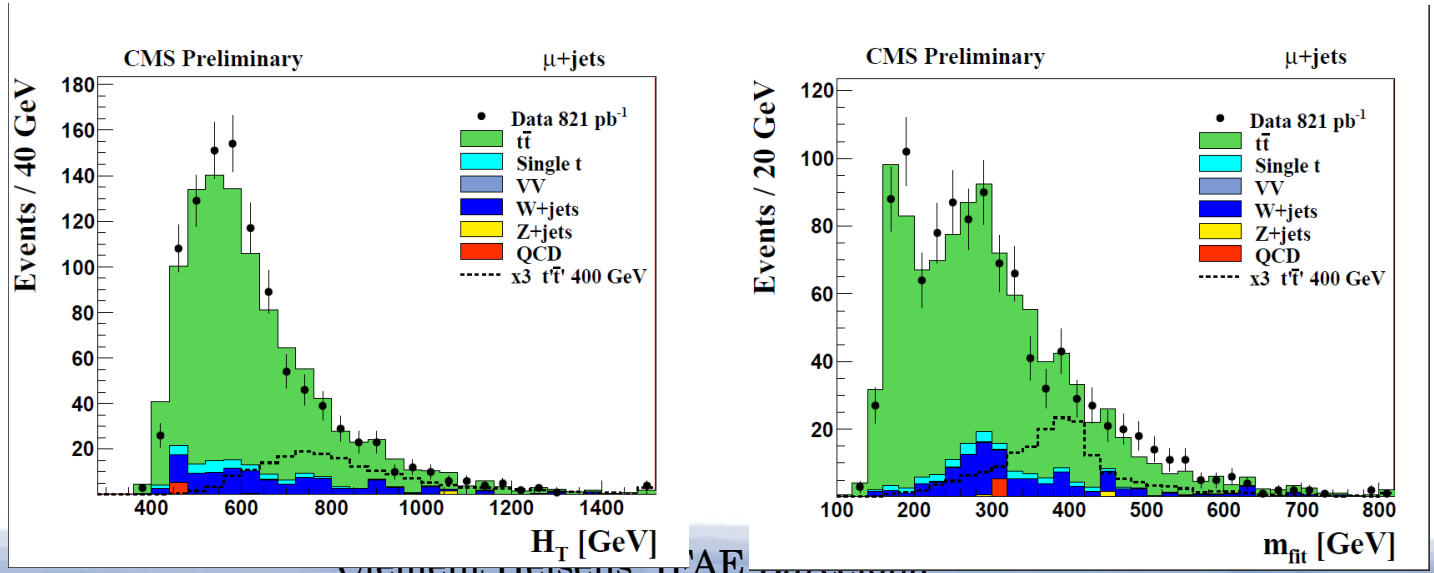
CMS – Search for t' single-lepton 2/3

- Mass reconstruction → take four-jet combination out of the hardest 5 jets
- Use the W mass constraint and leptonic/hadronic t' mass should be equal
- 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

PAS-EXO-11-051



0.5-0.8fb^{-1}

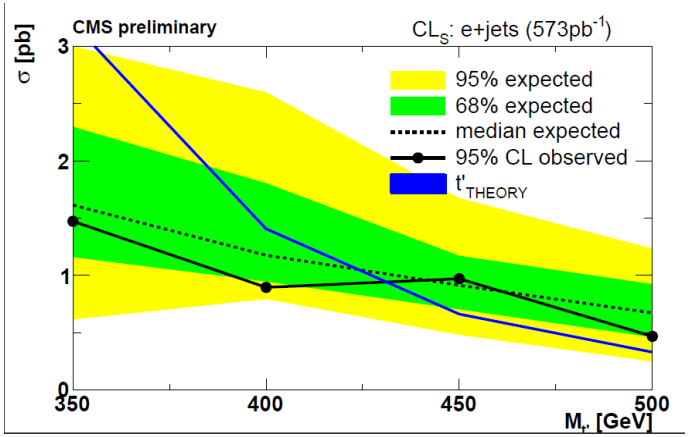


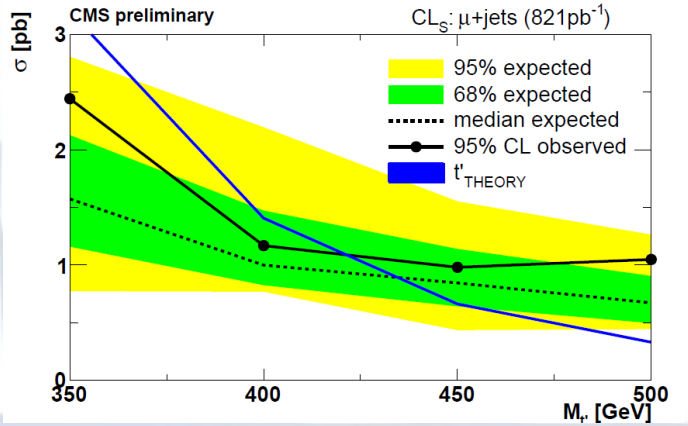
CMS – Search for t' single-lepton 3/3

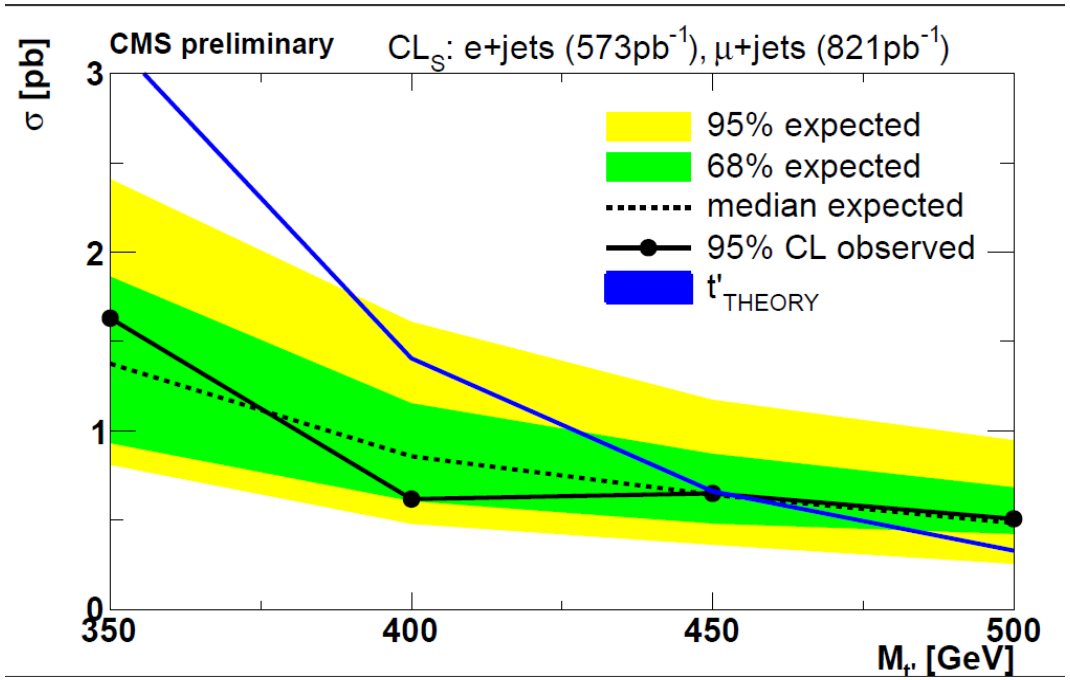
PAS-EXO-11-051

0.5-0.8fb^{-1}

- CLs method used to set limits on the t't' production cross section
- Assuming BR(t' → Wb) = 1 → m(t') > 450GeV @ 95%CL

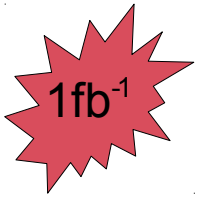






ATLAS – Search for t' single-lepton 1/2

Not yet public...

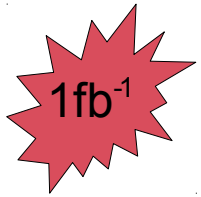


- As in CMS: Final state t't' → WbWb → jjb lνb
- Strategy:
  - Stay as close as possible to the top group selection
  - Relatively low jet pT, and lepton pT
  - Using the btagging (≥1bjet 70% efficiency)
- 1D kinematic Likelihood fit
  - Reconstructed top mass
  - 3 jet bin: just the invariant mass of the 3 jets
  - >=4 jets: using KLFitter (see many talks about performance)
    - Using leading 4 jets only
    - Floating 'top' mass
    - Only constrain both 'sides' to be similar

} Helps to constraint systematics with profiling

ATLAS – Search for t' single-lepton 2/2

Not yet public...



- Systematics treated as nuisance parameters
- ATLAS list of systematics is very conservative respect to CMS (23 sources considered, 13 are profiled; CMS 7 systematics, no ttbar modeling)
- A profile likelihood ratio is performed combining 3jet exclusive/4 jet inclusive channel for at least 1btag jet and electron and muon channels
- Full results will be made public soon, under ATLAS internal review

CMS – Inclusive search for a 4th generation 1/3

PAS-EXO-11-054

1fb^{-1}

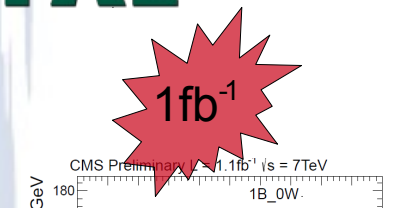
- This analysis presents the inclusive search of 4th generation up-down type quark from pair or single production (t'b → Wb b; b't → WbW Wb; t't' → WbWb; b'b' → WbW WbW)

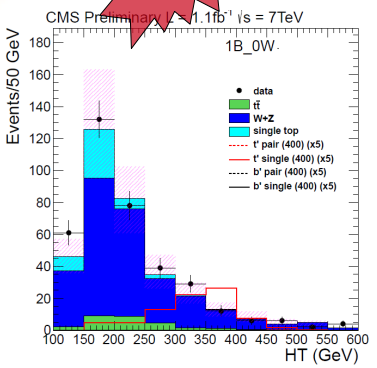
- Search is performed in the muon channel:
  - 1 isolated muon pt> 40 GeV; $|\eta| < 2.1$; veto other isolated muons pT >10GeV, $|\eta|<2.5$; veto electrons pt>20GeV; $|\eta|<2.5$
  - Jets pt> 30GeV; $|\eta| < 2.5$; ≥1 to be a b-tag ($|\eta| < 2.4$ tracker acceptance)
  - MET>40GeV to reduce QCD multijet

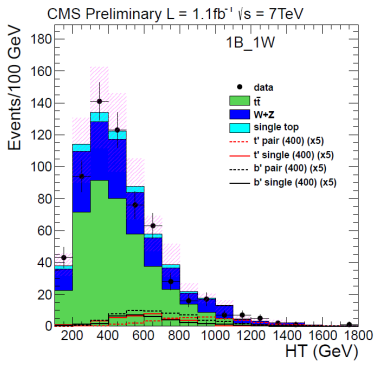
- Search performed in 6 subsamples, based on nb-jet (==1, ≥2) ; nWhad (==0, ==1, ==2, ≥3)
  - 1B_0W → single t' with 1 fwd/1central bjet; ==1 forward jet ($2.4<|\eta|<5$) pT>30GeV
  - 2B_0W → single t' with 2central bjets; ==0 forward jet ($2.4<|\eta|<5$) pT>30GeV
  - 1B_1W → t't' tt pair production with 1 b-jet failing ID; ≥3 jets in addition of the btag
  - 2B_1W
  - 2B_2W → one additional bjet at least 2, 4, 6 additional jets
  - 2B_3W

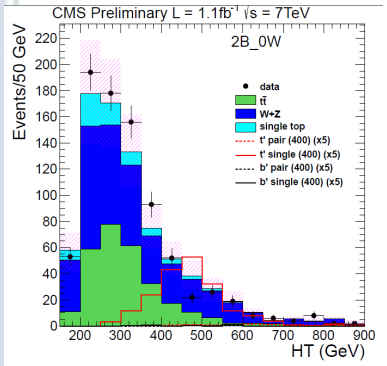
CMS – Inclusive search for a 4th generation 2/3

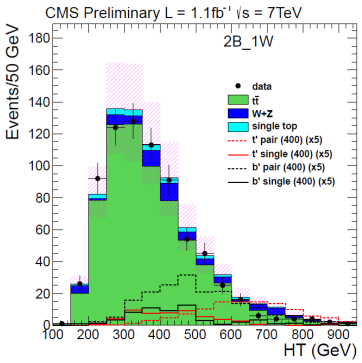
PAS-EXO-11-054

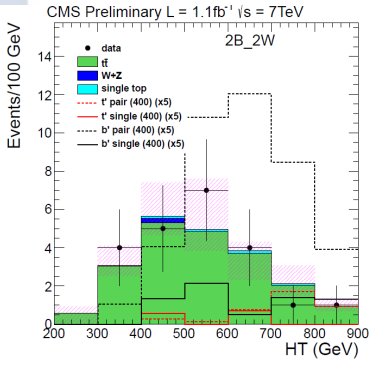


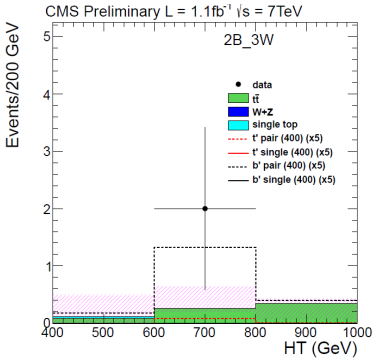












- HT discriminant is used = scalar sum of MET, muon pT, btag jets, Whad pT
- HT is sensitive to the presence of 4th generation quark
- A 4th generation quark would appear in the high tails of the HT distribution
- The 6 channels are combined into a single template histogram
- The 4 different signals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

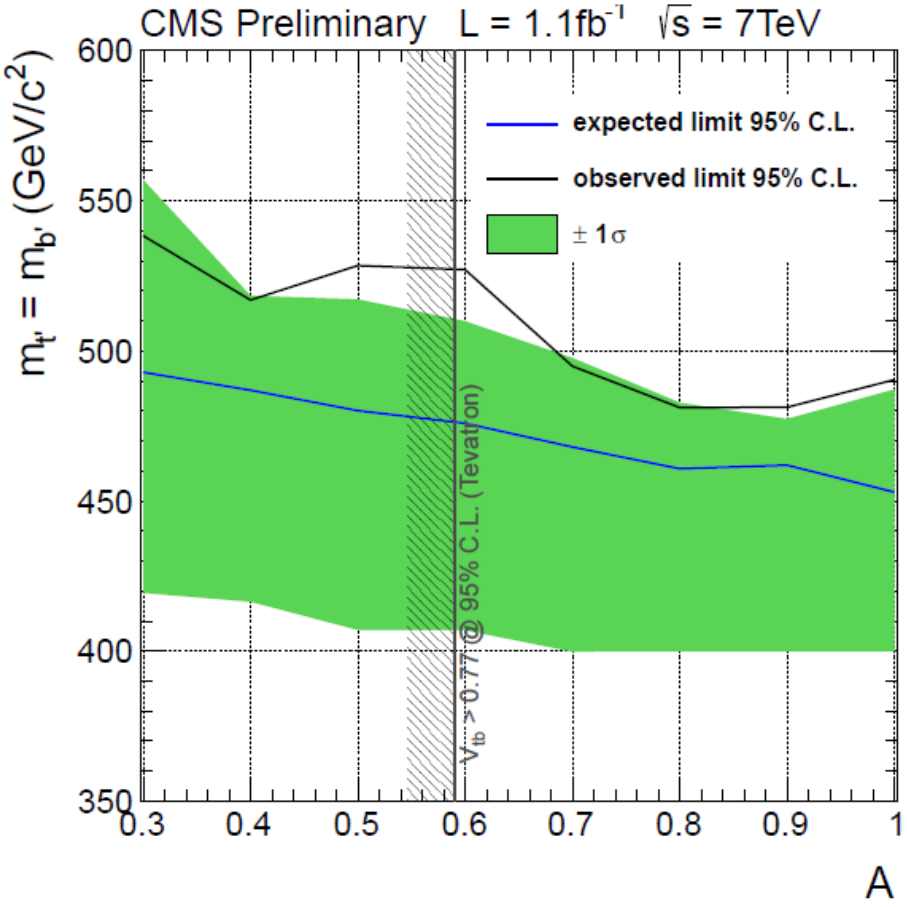
CMS – Inclusive search for a 4th generation 3/3

1fb^{-1}

PAS-EXO-11-054

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

- 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



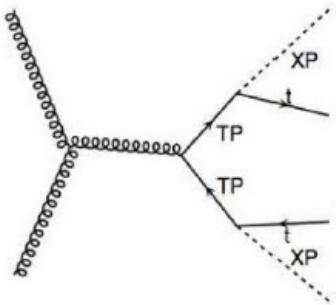
ttbar + Anomalous E_T^{miss} 1/2

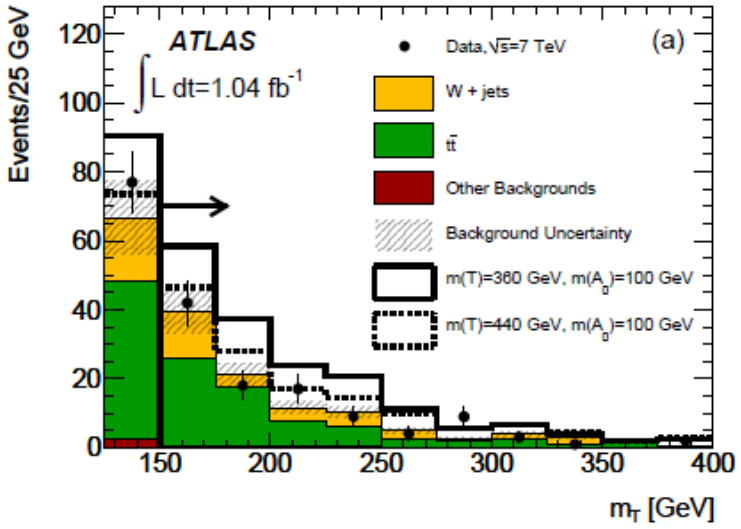
1fb^{-1}

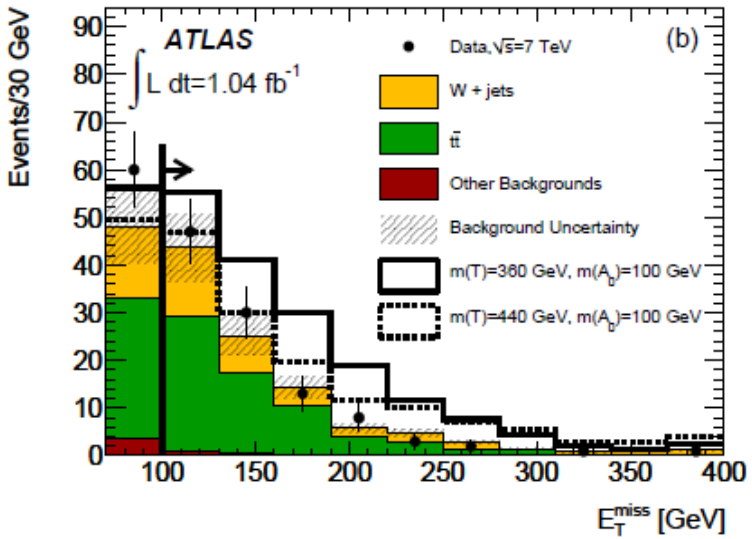
arXiv:1109.4725

- 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





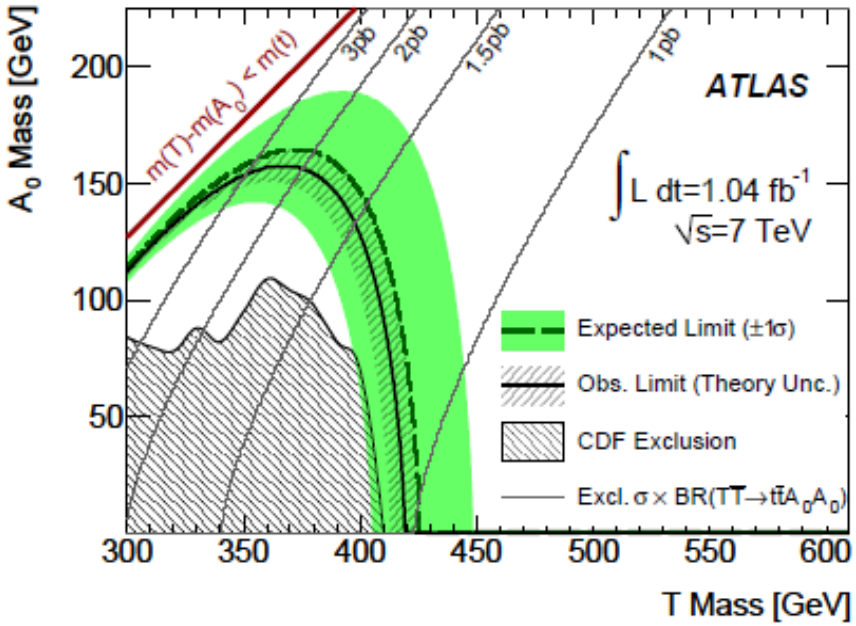


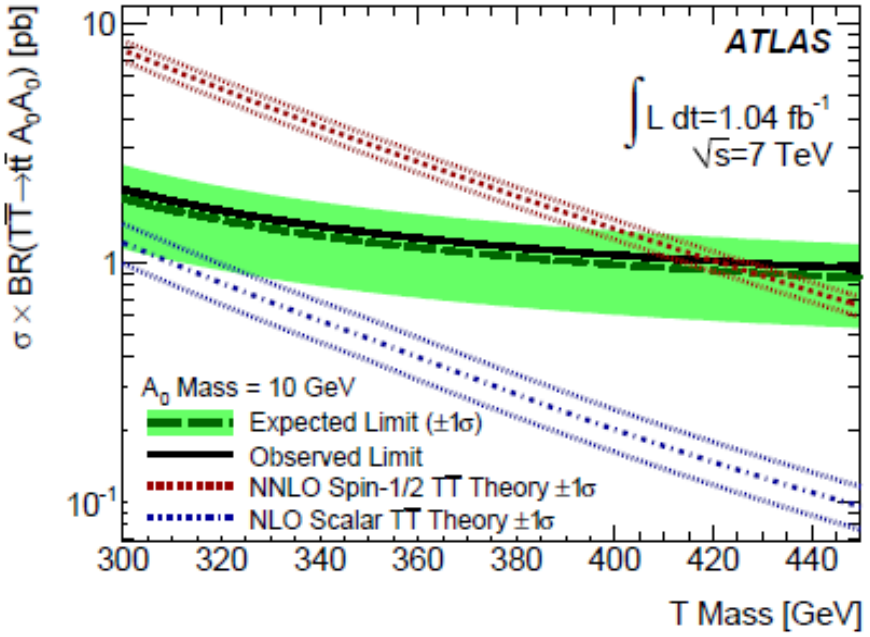
ttbar + Anomalous E_T^{miss} 2/2

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



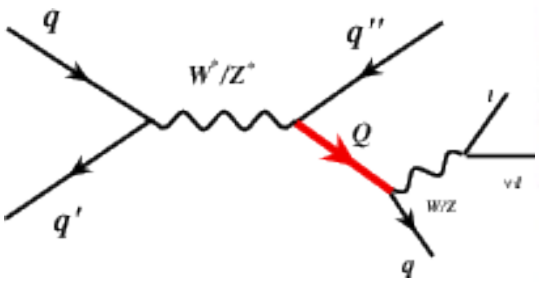


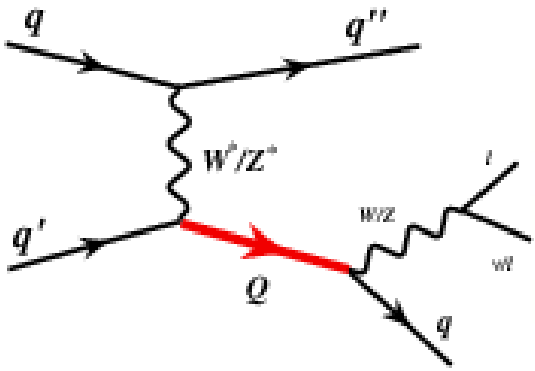
Search for VLQ (single prod.) 1/3

arXiv:1112.5755

1fb^{-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 = (v/mQ)K'qQ
  - q is any light quark; Q is VLQ, mQ VLQ mass
  - v 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



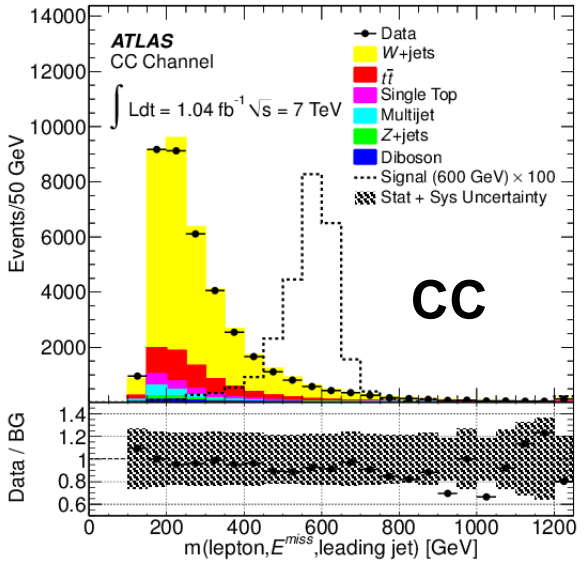


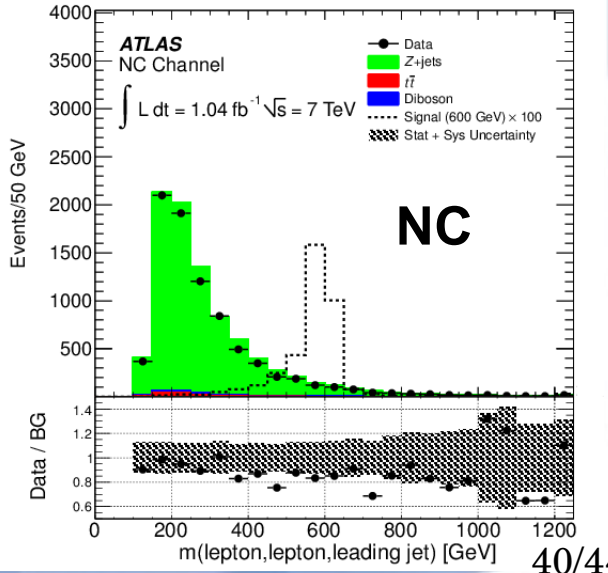
Search for VLQ (single prod.) 2/3

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
- Charge Current:
  - Exactly one lepton
  - E_t^{miss} > 50GeV
  - At least 2 jets with pT > 50, 25 GeV
  - $|\Delta\eta|>1$ leading jet pT and 2nd or 3rd jet
  - $m_T(W)$ > 40GeV
  - $\Delta\Phi(l,E_T^{miss})$ > 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)
- Neutral Current:
  - Exactly two opposite charged same-flavor leptons
  - 66 <M_{ll} <116GeV , 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

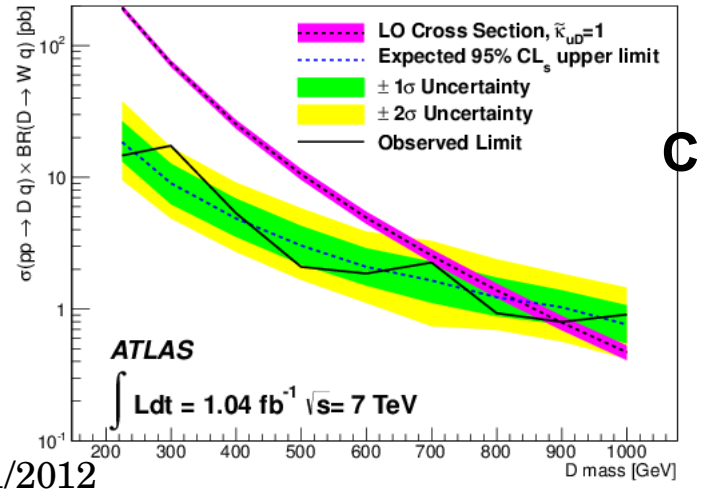
arXiv:1112.5755

1fb^{-1}

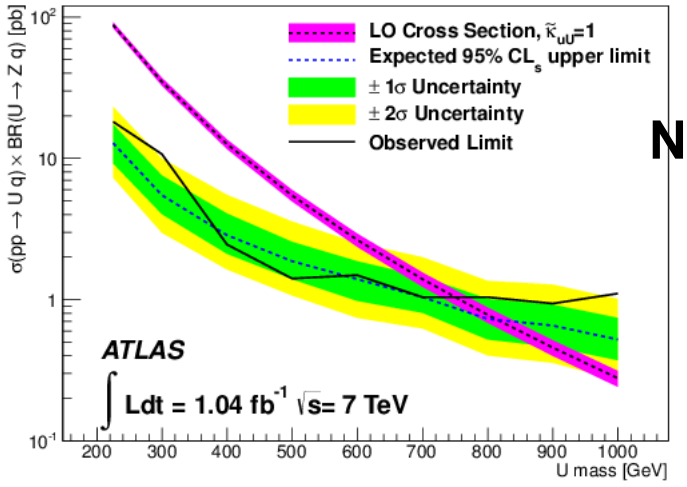
- Cls method and binned maximum Likelihood
- Search performed by searching a signal peak on top of a smooth background
- No evidence of VLQ found
- Assuming K'uU = K'uD = 1 set limits → mVLQ > 900(760) GeV for CC(NC) @95%C.L.
- Tevatron limits → K'uU=1 690GeV (100% BR CC) ; K'uD=sqrt(2) 550GeV (100%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

Process	Electron channel	Muon channel
W+jets	14500 ± 100 ± 4400	16600 ± 100 ± 5000
$t\bar{t}$	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
$t\bar{t}$	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



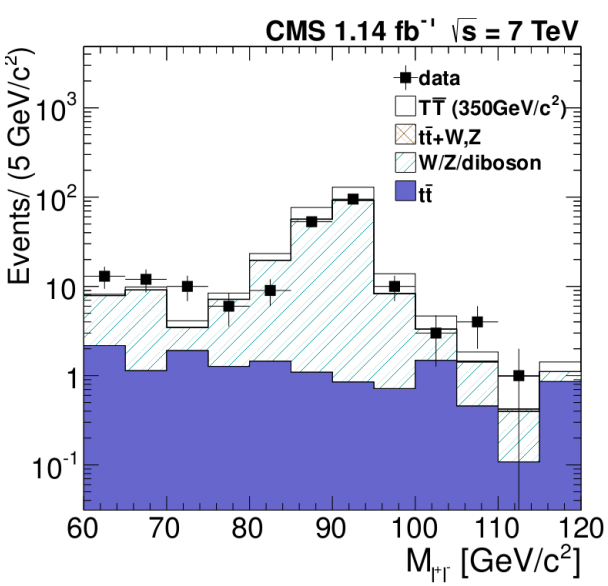
NC

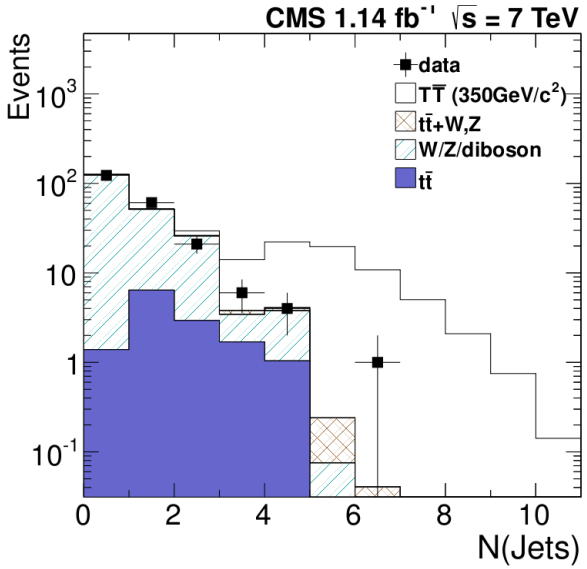
Search for VLQ in t+Z (pair prod.)1/2

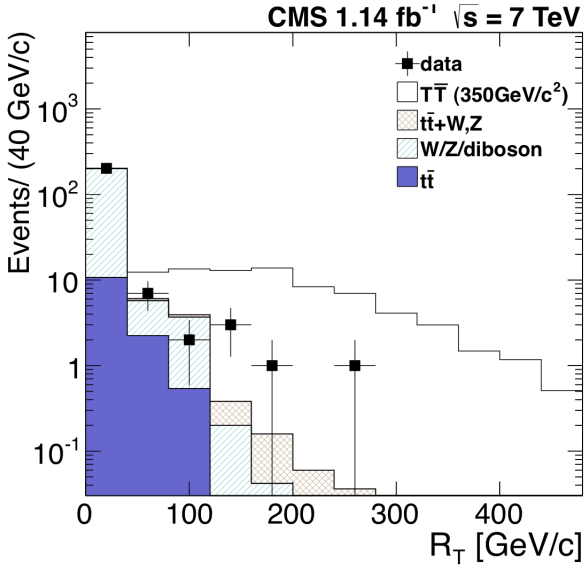
arXiv:1109.4985

1fb^{-1}

- Search for a pair-produced heavy vector like quark T (VLQ) with charge 2/3
- 100% BR T → tZ; pp → TT → tZtZ → 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 → 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)







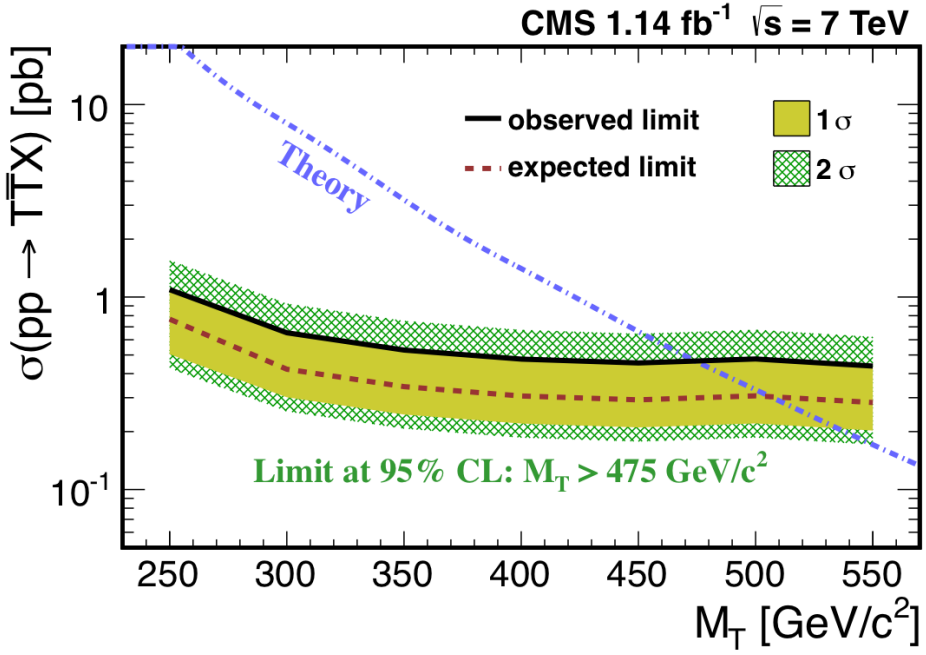
Search for VLQ in t+Z (pair prod.)2/2

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



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 :(
- Some analysis still based on 2010 dataset, but are being updated (in the pipeline for approval)
- Improvement expected for Moriond ~ factor of 4 in luminosity
- 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).
- Lots of fun coming soon :)
- Apologies for any relevant topics omitted due to time limitations

Bonus Slides