4^{th} generation at LHC

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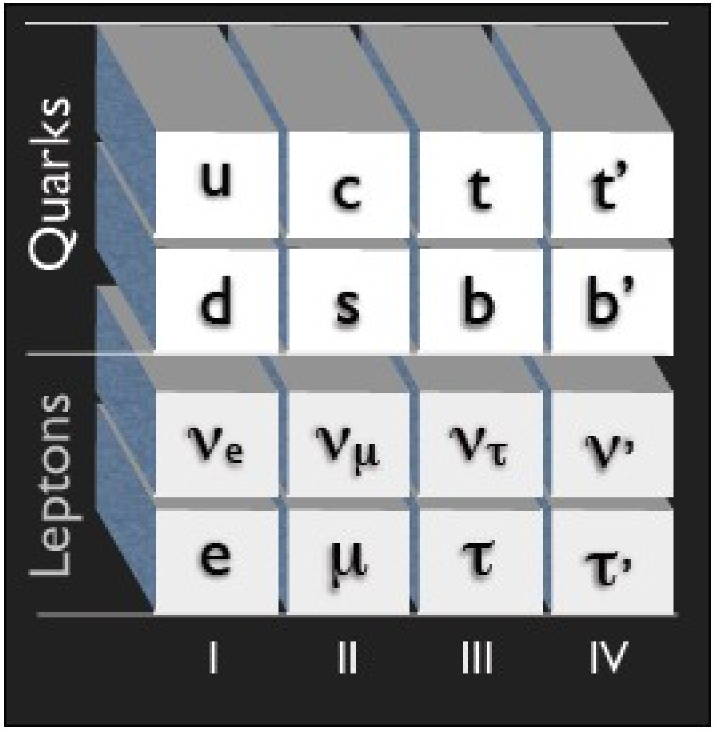
LAPP Annecy

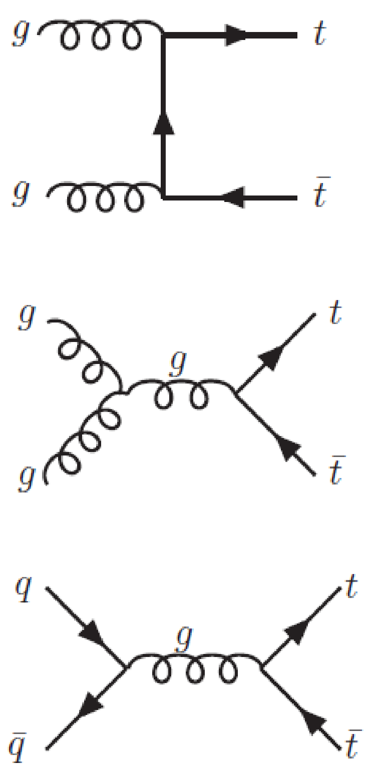
New heavy quarks

- 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
- <u>Benchmark model:</u>
  - Simplest extension of the SM: 4th sequential generation of fermions



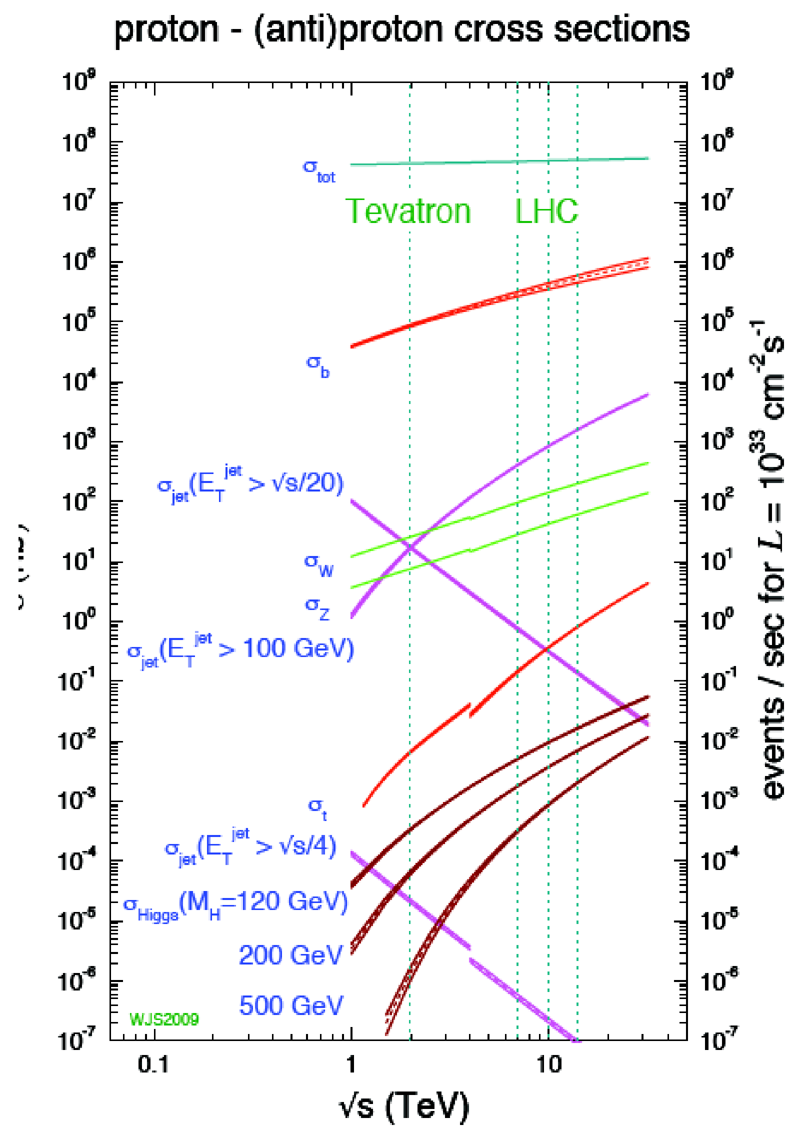
Top Quark Pair Production

- 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)



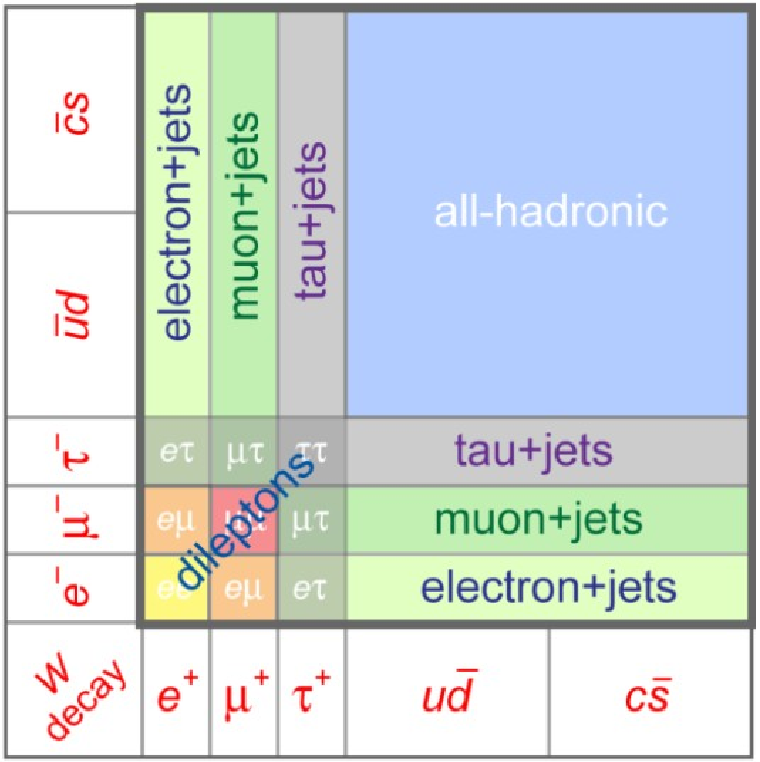
Dominant at the LHC (80%)

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%)



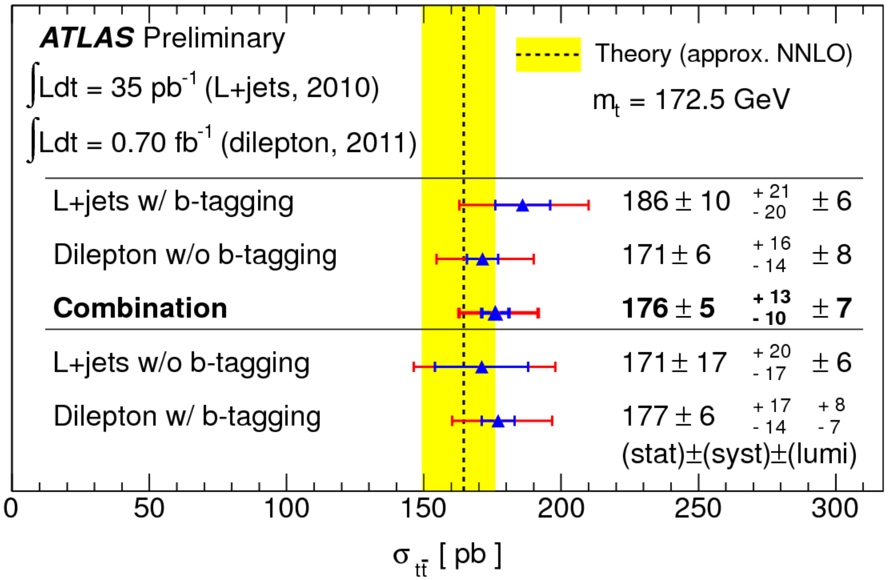
- The top-quark provides a virtual lab to search for new physics
  - Many tops have already been produced at LHC!!
  - Various properties of the top-quark have been measured
  - This helps us to provides procedures/tools to separate SM backgrounds from new physics

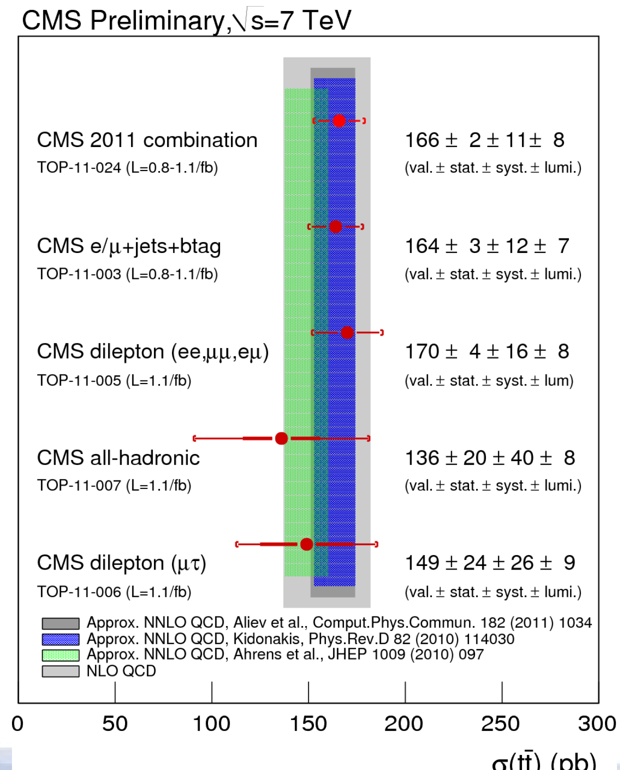
Top Quark Physic Status (cross sections only...)

- 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.

ATLAS

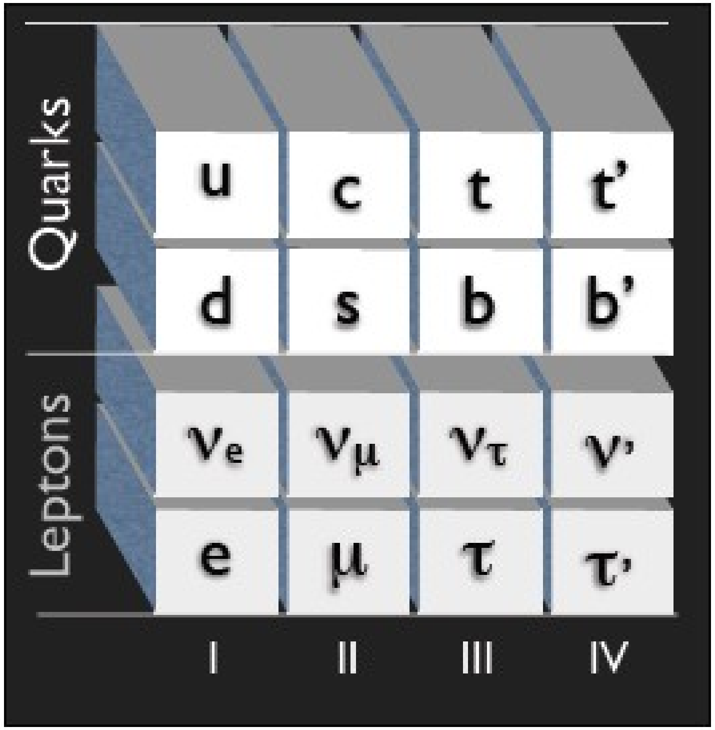
- CMS combine L+jets, dilepton, mu+tau, all hadronic (0.8-1.1fb-1) σ(ttbar) = 165.8 ± 2.2 (stat.) ± 10.6 (syst.) ± 7.8 (lumi.) pb.
- → results with more luminosity coming soon approaching theoretical errors!





4^{th} 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 + 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.



$$\mathrm{CKM}_{4\times4} = \begin{bmatrix} 0.97377\pm0.00027 & 0.2257\pm0.0021 & 0.00431\pm0.00030 & <0.044 \\ 0.230\pm0.011 & 0.957\pm0.095 & 0.0416\pm0.0006 & <0.46 \\ 0.0074\pm0.0008 & 0.0406\pm0.0027 & >0.78 & <0.47 \\ <0.063 & <0.46 & <0.47 & >0.57 \end{bmatrix}$$

Vector like quarks

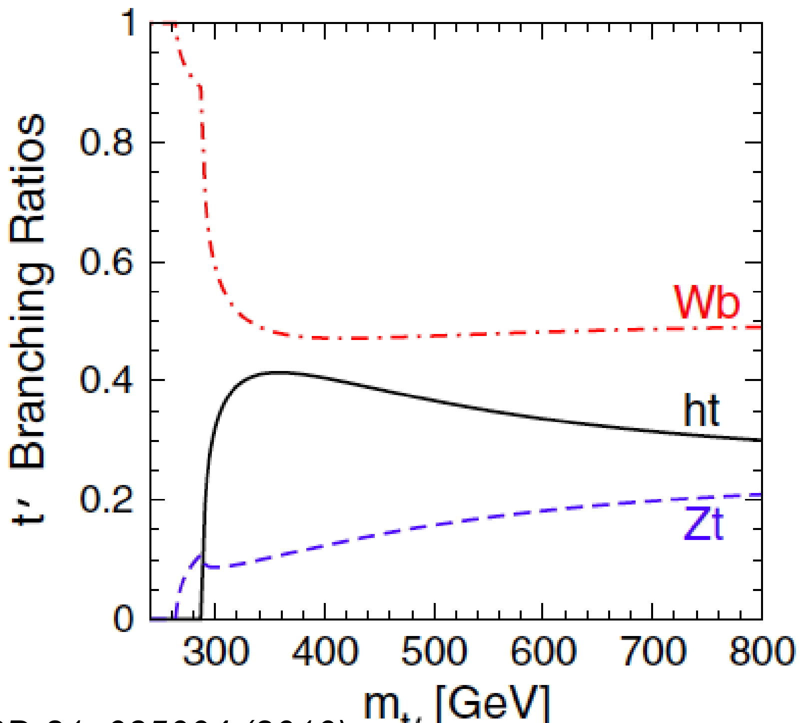
- Vector-like quarks: left and right components transform the same under $SU(2)_L$
- → can couple to SM particles without upsetting precision EW and flavor constraints.
- Vector-like quarks in a doublet need to be nearly degenerate in mass.
- Predicted by many models: extra-dimensions, Little Higgs,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

"Democratic"



PRD 81, 035004 (2010)

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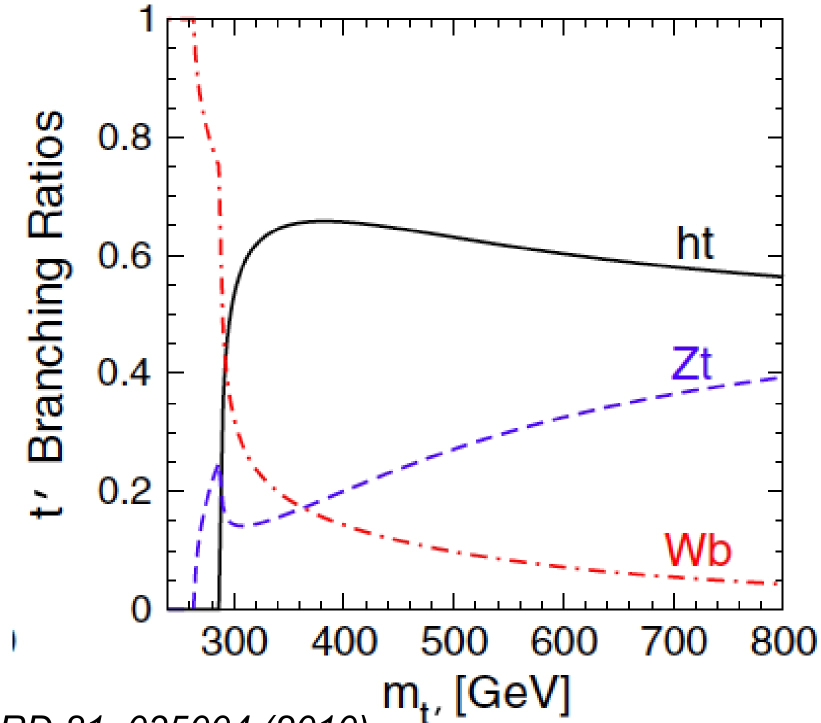
(X,T) doublet	XT_d	(+5/3, +2/3)	$X \rightarrow W^+t$ $T \rightarrow$ Zt, Ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	$B \rightarrow$ Zb, Hb $Y \rightarrow W^-b$

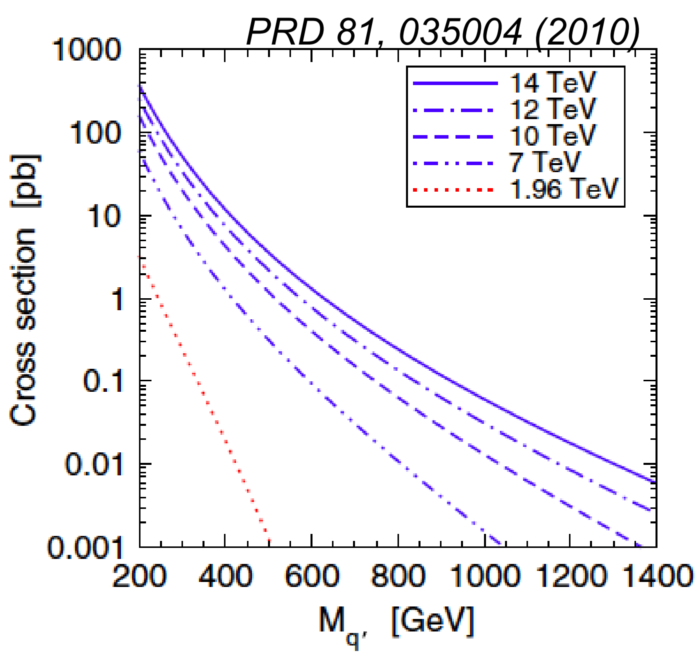
“W-phobic”

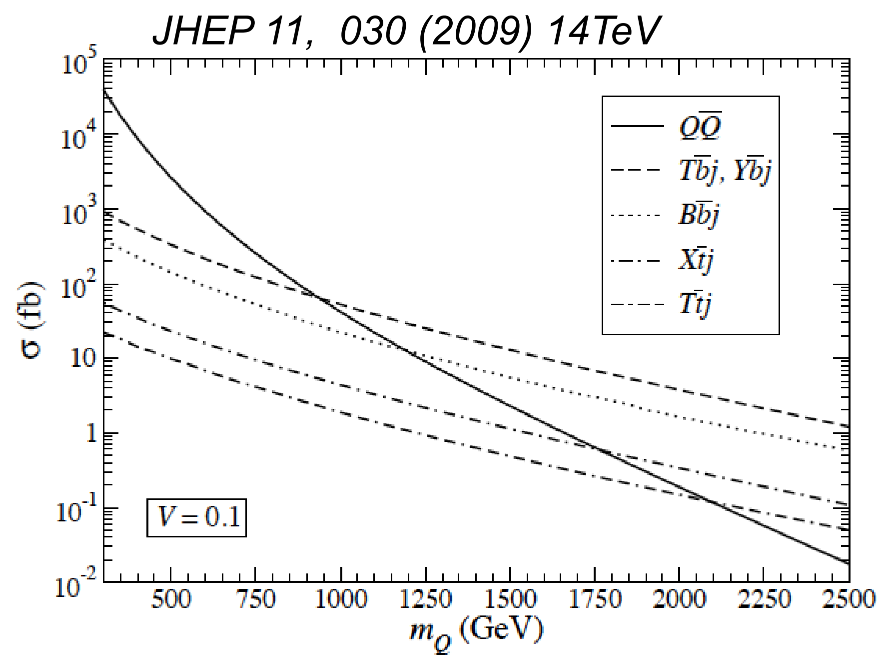


PRD 81, 035004 (2010)

Heavy quark production

- Up to masses ~1 TeV, dominant production is in pairs via the strong interaction:
- $\sqrt{s}$=7 TeV: σ(QQ) ~ 1.5 pb for m_Q~400 GeV vs σ(tt) = 160 pb
- $\sqrt{s}$=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: 4^{th} generation quarks

- 4^{th} 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	

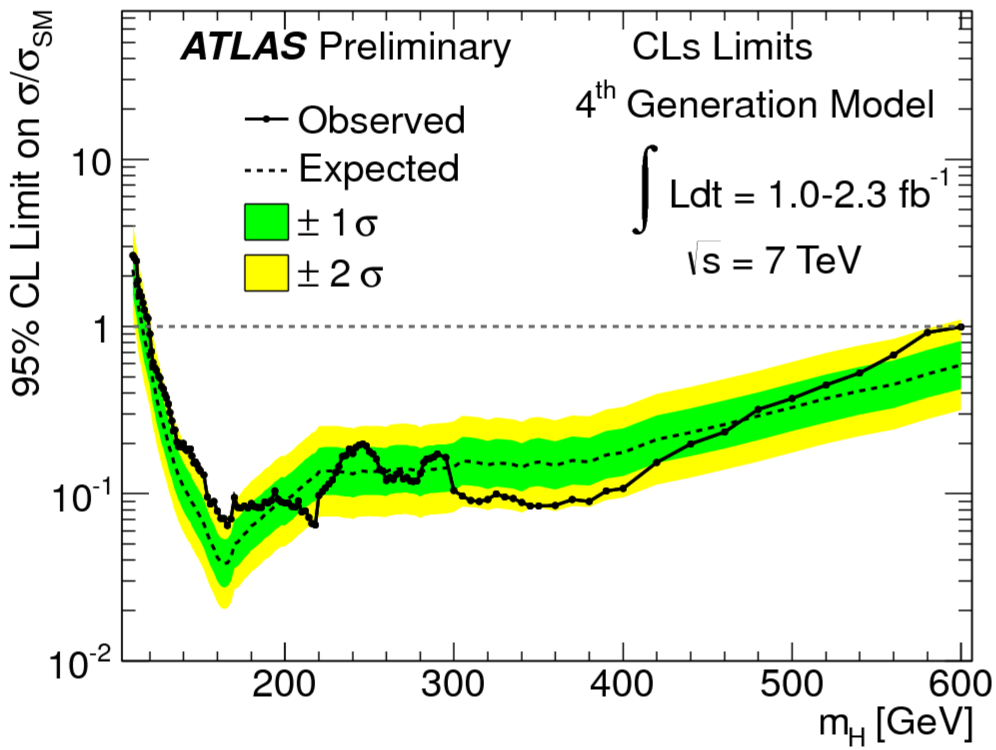
- Of course, some of them are more challenging or powerful than others…

Higgs and 4^{th} generations 1/2

- 4^{th} 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 $gg \rightarrow H$ cross section
  - Leads to dramatic exclusion on the Higgs → 4^{th} family in big trouble
- Data seems to indicate that both fourth family and SM Higgs cannot both exist
- If 4^{th} 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

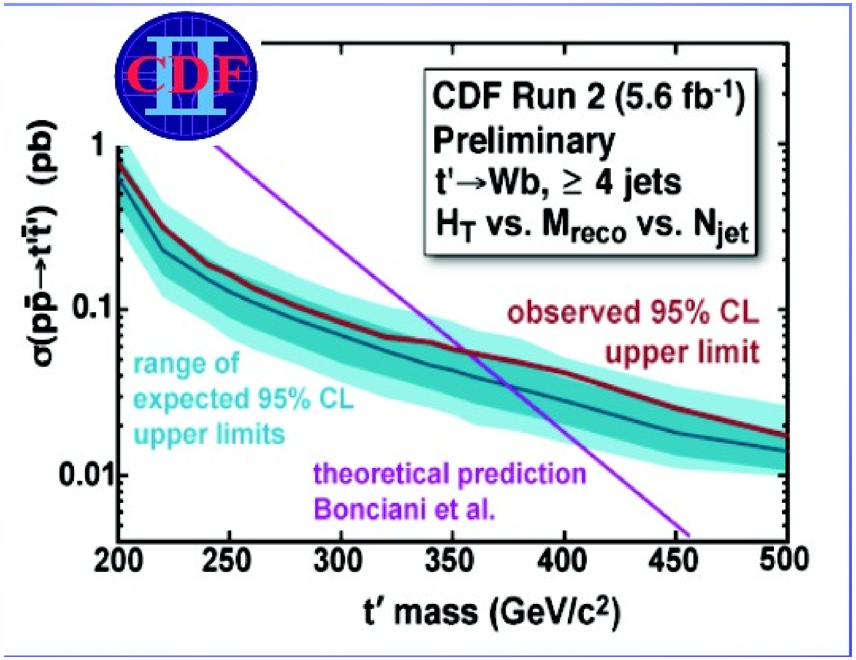
Higgs and 4th generations 2/2

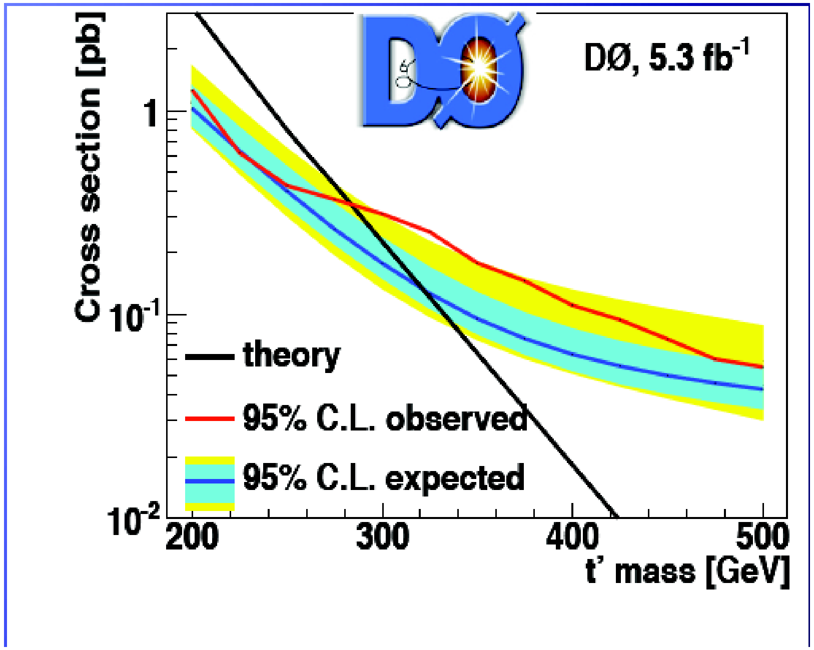
- What ATLAS did → consider a 4th generation quark with a mass of 600GeV
- Exclude Higgs boson with mH >119GeV and mH<593GeV
- If 125GeV excess is real → no 4th generation quarks :(



Tevatron Results t' (4th gen)

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





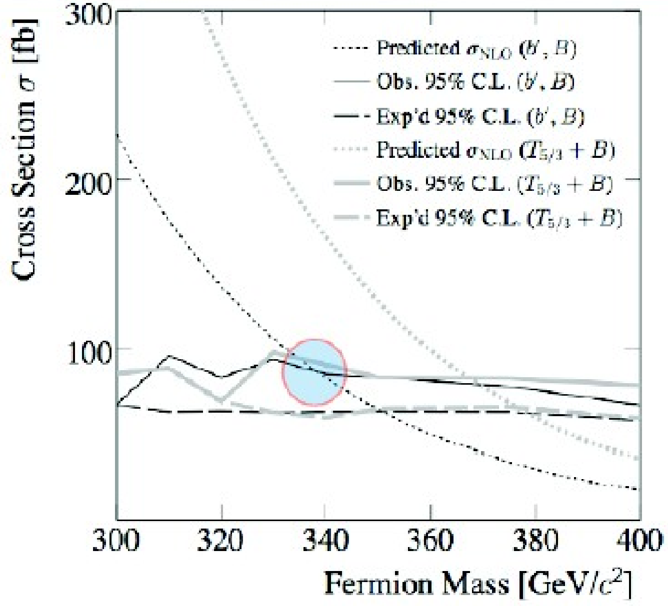
m(t') > 358GeV (CDF) @ 95%C.L.

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

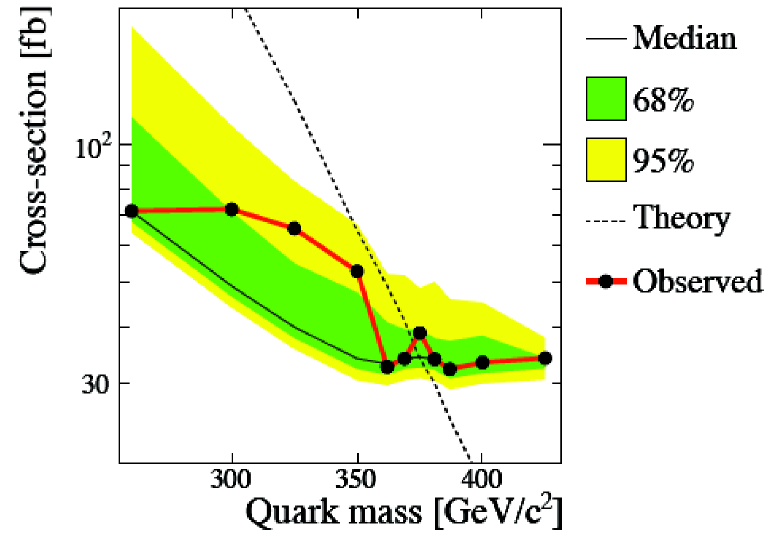
Tevatron Results b' (4^{th} gen)

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

Same-signed



Lepton+jets

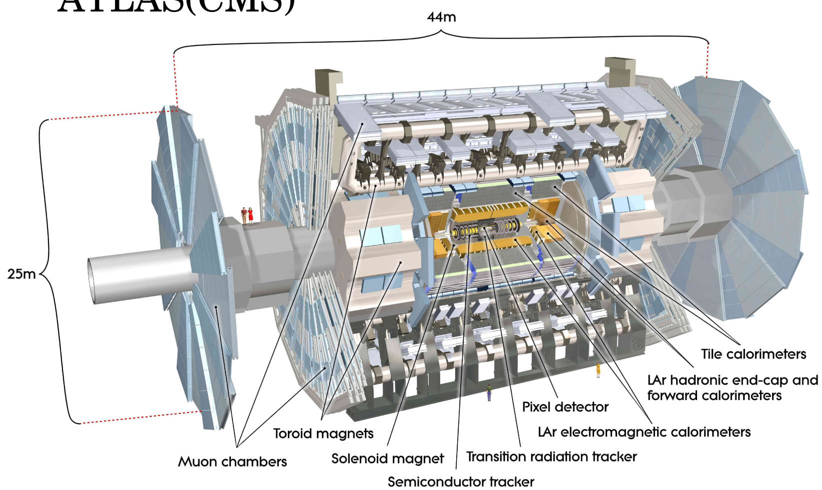


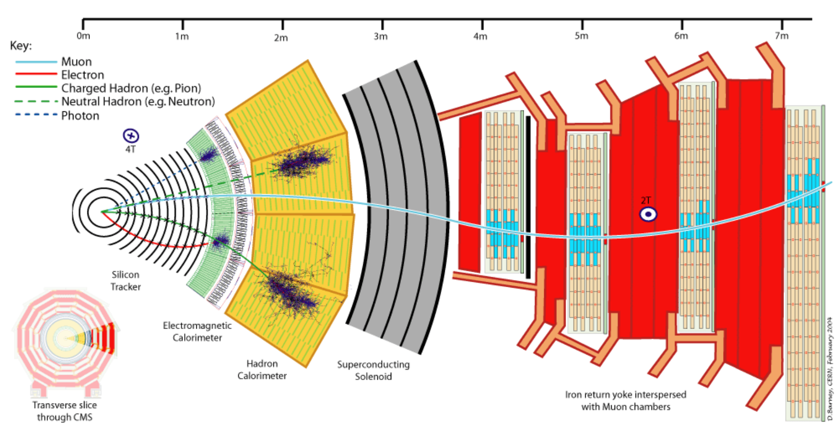
m(b') > 338GeV (CDF) @ 95%C.L.

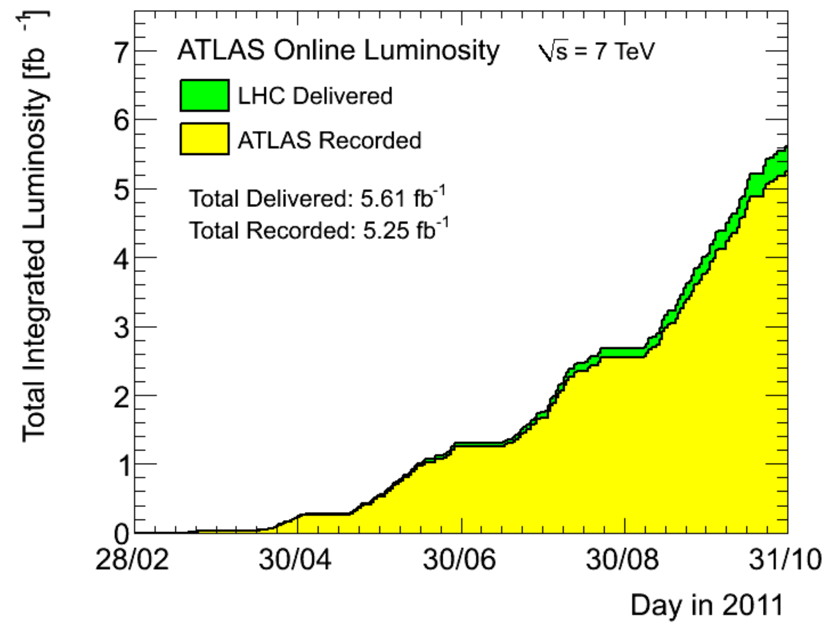
m(b') > 372GeV (CDF) @ 95%C.L.

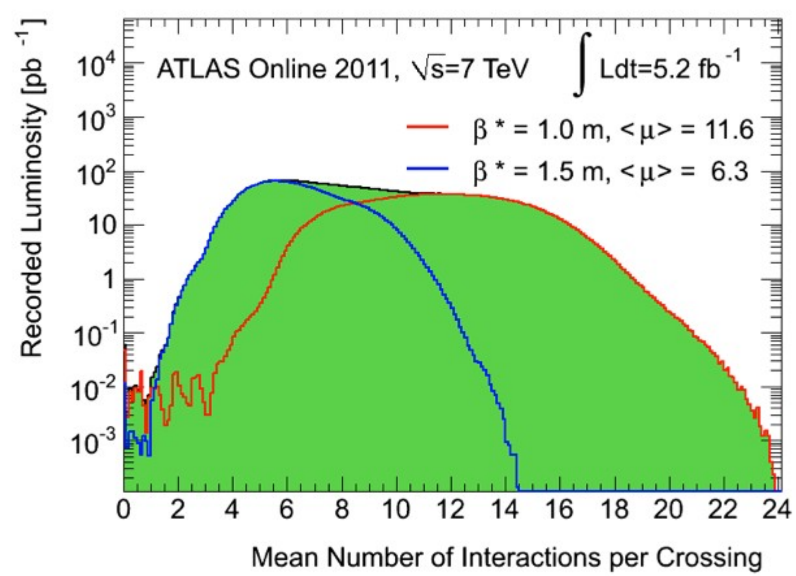
Detectors and LHC Data

- 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)









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)
- 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 [%]	same-sign dilepton yield	trilepton efficiency [%]	trilepton 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

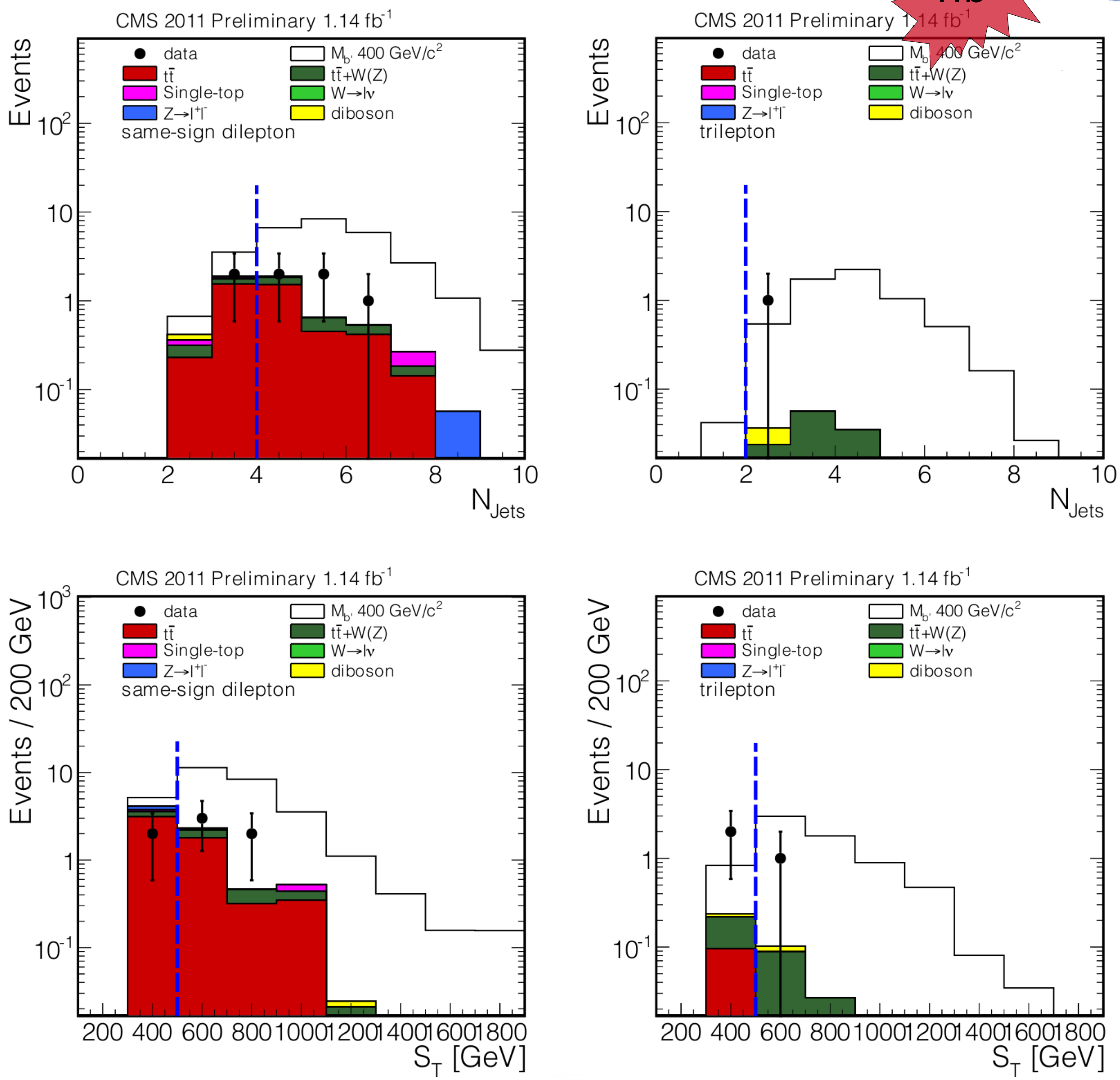
CMS – Search for b' 2/3

PAS-EXO-11-036

1fb^{-1}

- <u>Backgrounds:</u>
  - 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
- <u>Expected/observed yields:</u>

	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

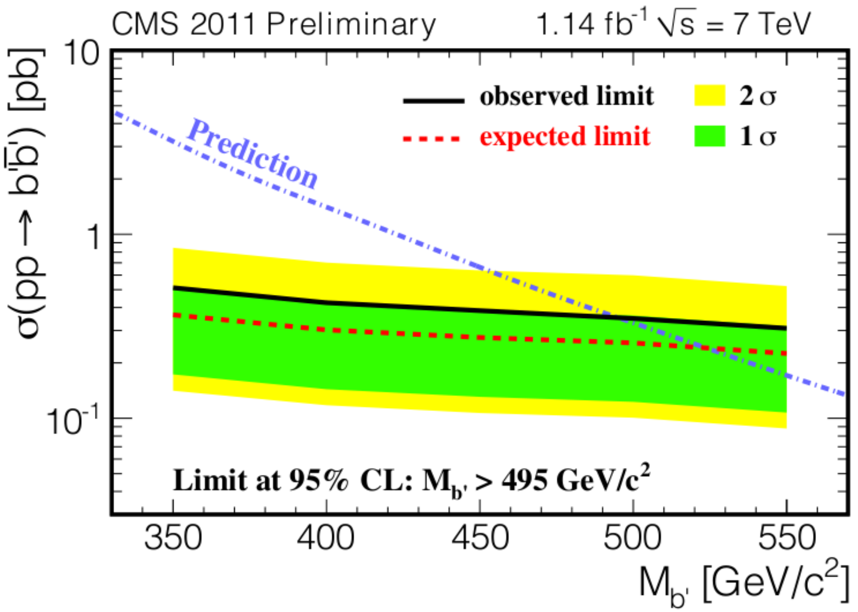
PAS-EXO-11-036

$1fb^{-1}$

- 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

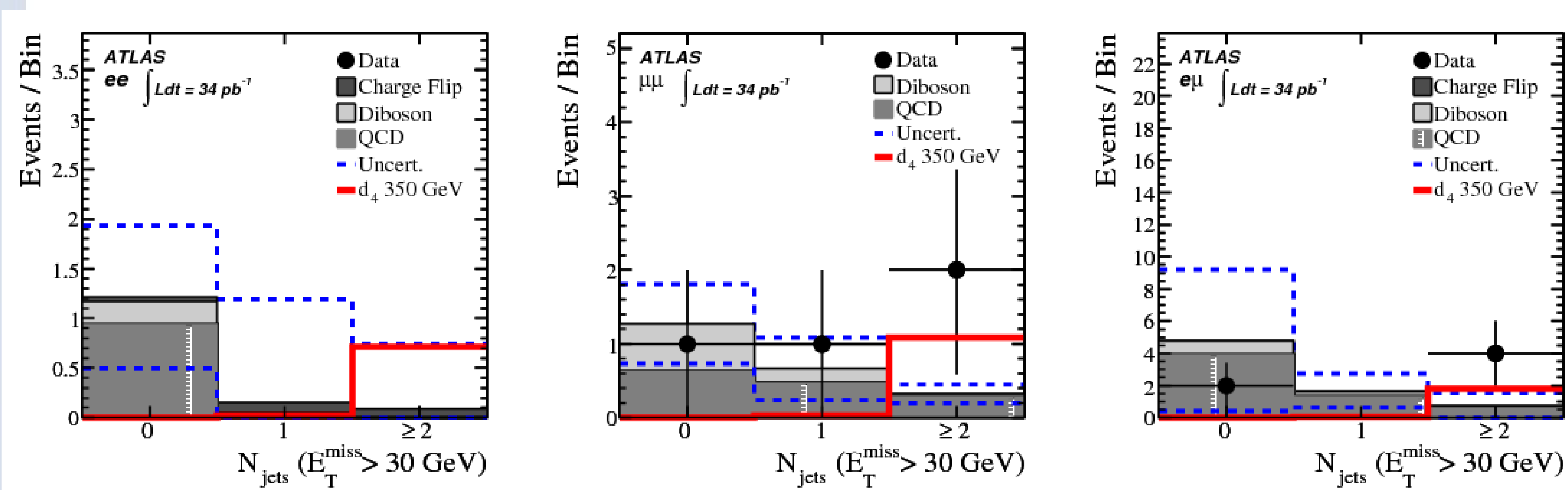
ATLAS – Same sign dileptons 2/3

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



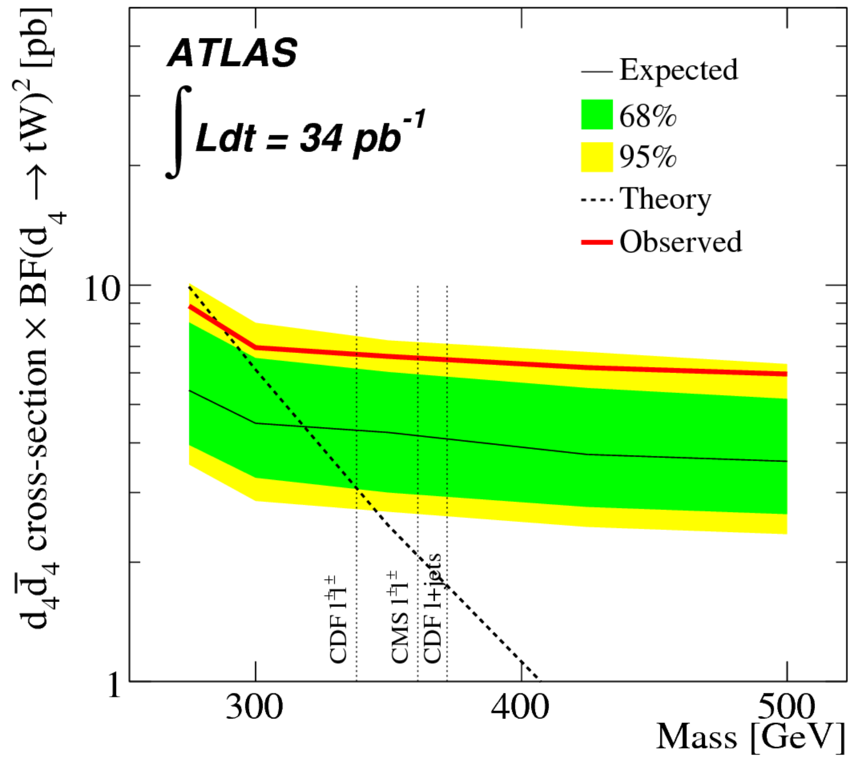
ATLAS – Same sign dileptons 3/3

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

$1 fb^{-1}$

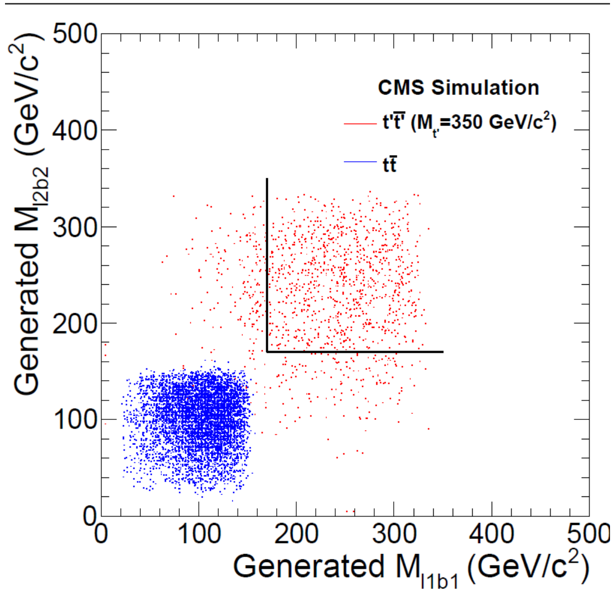
- Signal region:
  → after basics selection ttbar dominates...

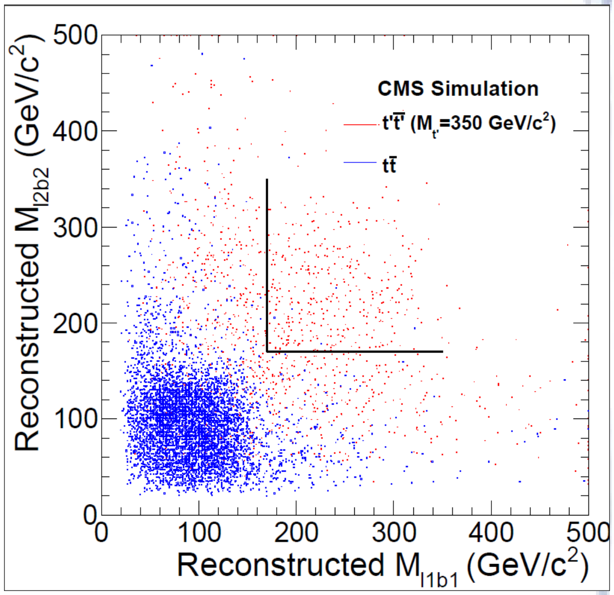
- The invariant mass of lepton and b-jet is used as discriminant

- 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	$\mu\mu$	$e\mu$	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





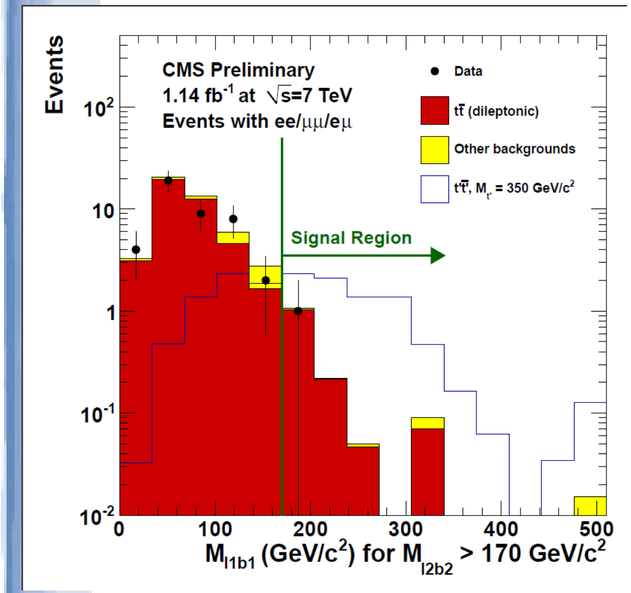
CMS – Search for t' dilepton 3/3

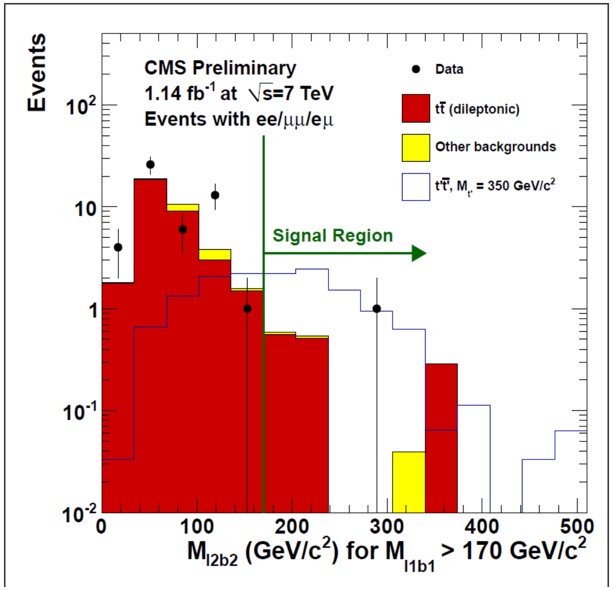
PAS-EXO-11-050

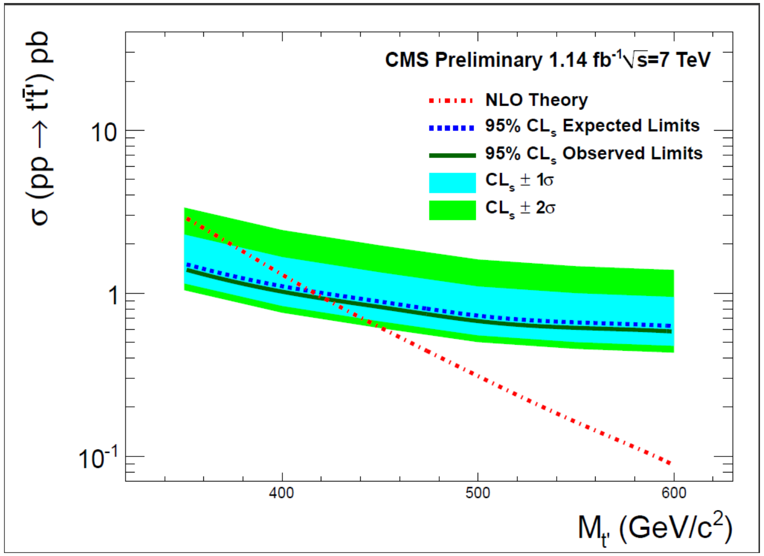
$1 fb^{-1}$

- 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

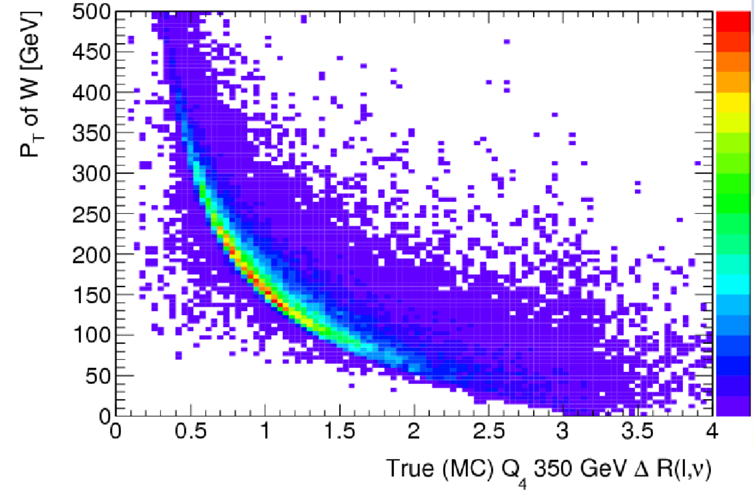
35pb^{-1}

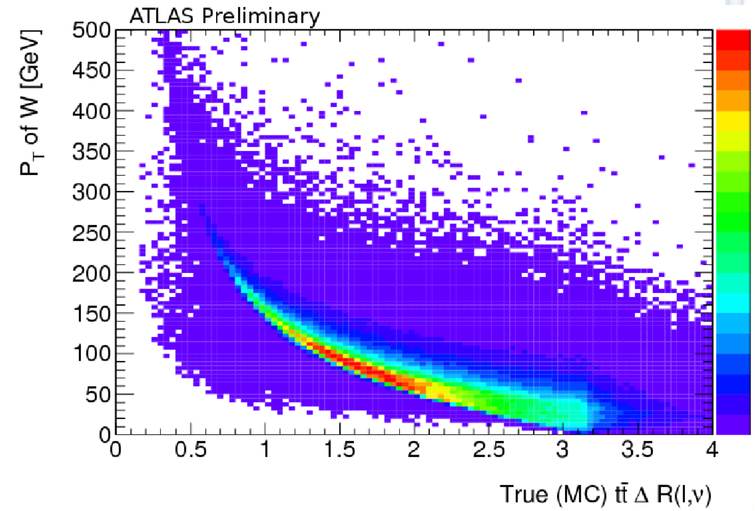
ATLAS-CONF-2011-022

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

- <u>Baseline selection:</u>
  - Excatly 2 leptons pT > 20GeV; muon $|\eta|$< 2.5; electron $|\eta|$ < 2.47 $\notin$ 1.37 <$|\eta|$< 1.52
  - Lepton isolation: ΣET(ΔR<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

- <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 $|\Delta\eta(l,\nu)|$ 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)



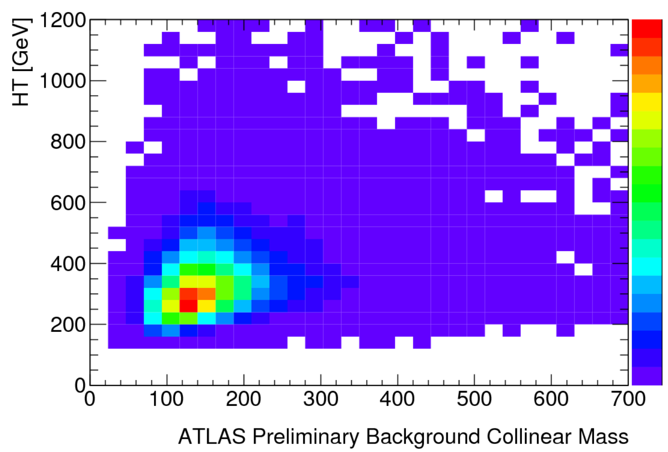


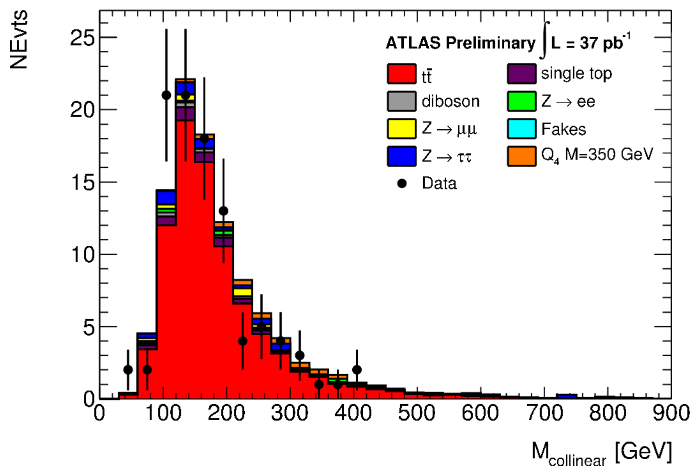
ATLAS – Search for t' dilepton 2/3

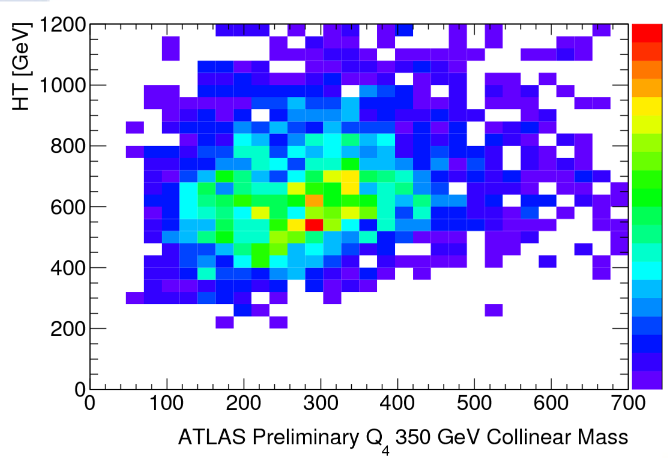
35pb^{-1}

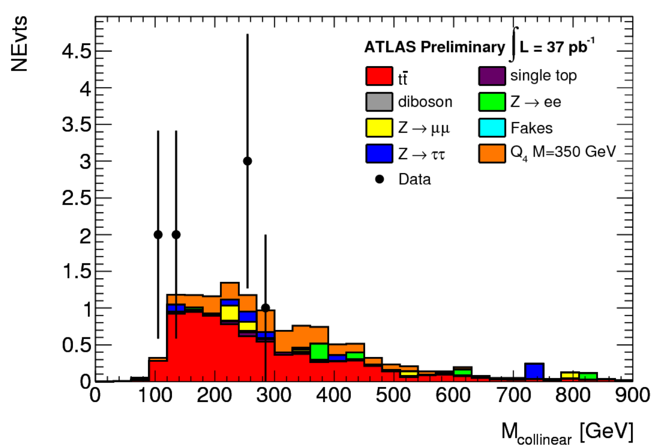
ATLAS-CONF-2011-022

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}

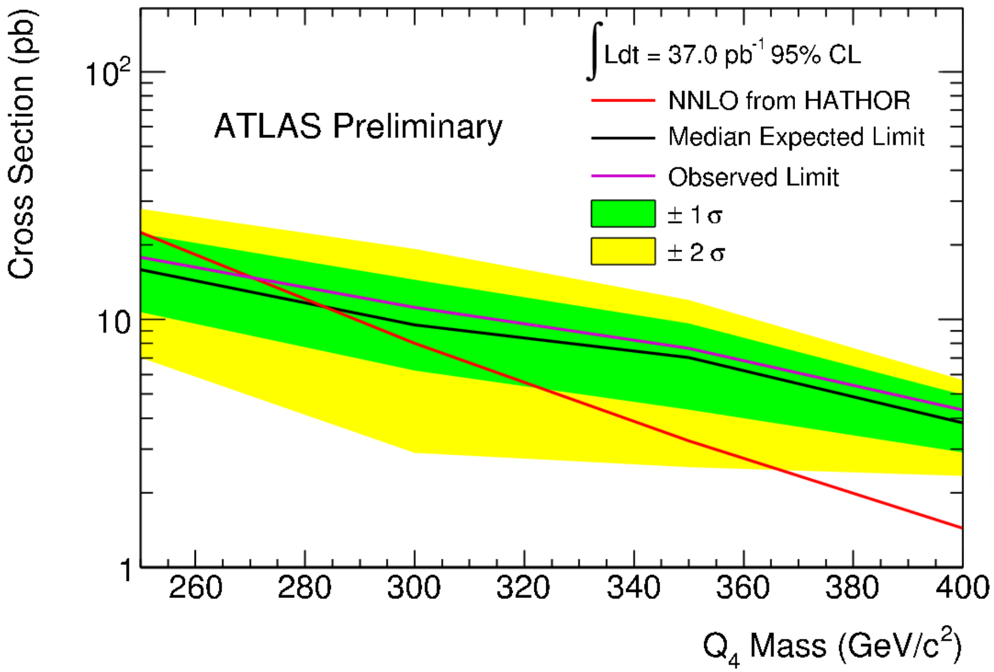
ATLAS-CONF-2011-022

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	$5.0 \pm 0.4\%$	$5.8 \pm 0.4\%$

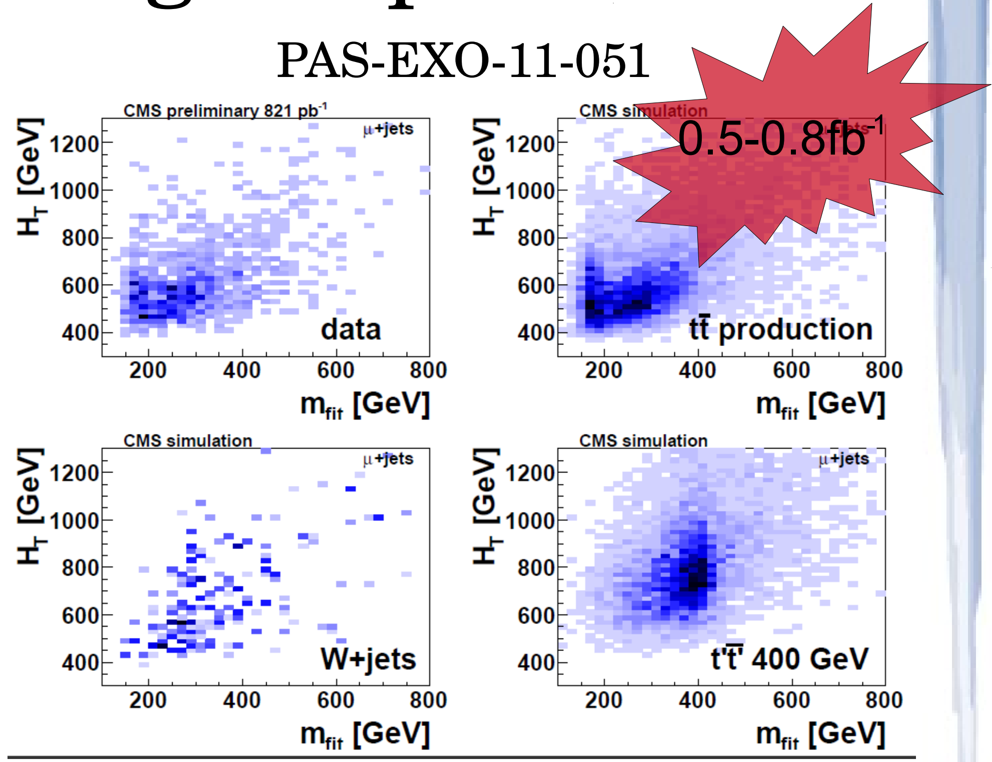
CMS simulation

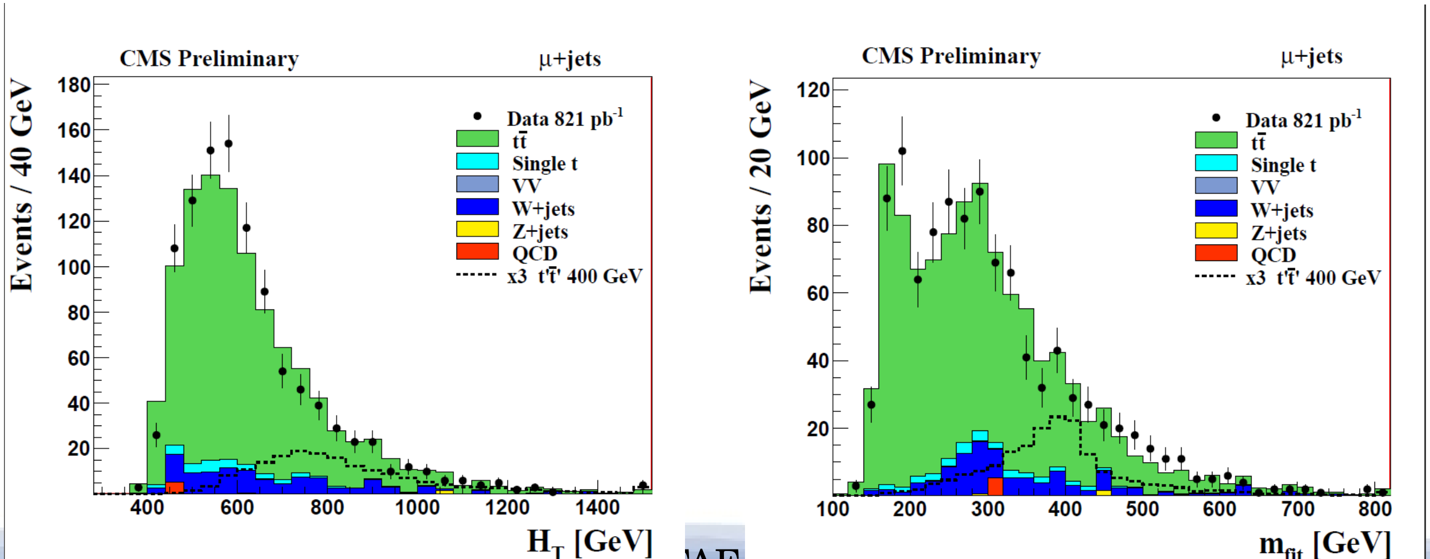
process	cross section	e+jets events	μ+jets events
$\mathcal{L}$		573 pb^{-1}	821 pb^{-1}
data		520	1054
$t\bar{t}$	158 pb	456 ± 91	907 ± 114
single t	33 pb	14.5 ± 3.5	30 ± 6
W+jets	30 μb	33.3 ± 8.2	106 ± 25
Z+jets	2.9 μb	4.5 ± 1.2	2.6 ± 2.6
WW,WZ,ZZ	67 pb		2.1 ± 0.6
multijets		2.5 ± 1.2	5.7 ± 5.5
total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

CMS – Search for t' single-lepton 2/3

PAS-EXO-11-051

- 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





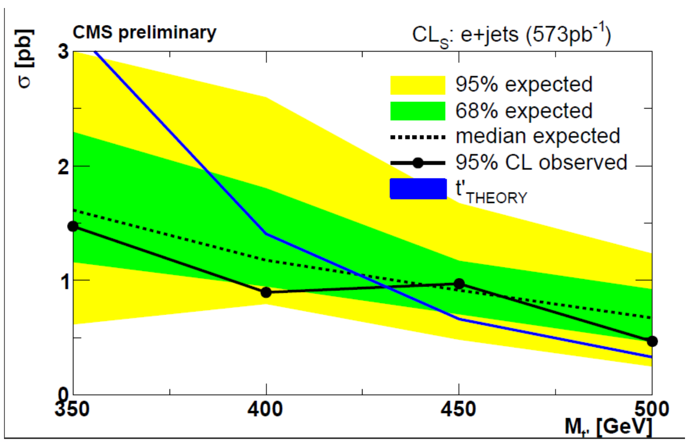
CMS – Search for t' single-lepton 3/3

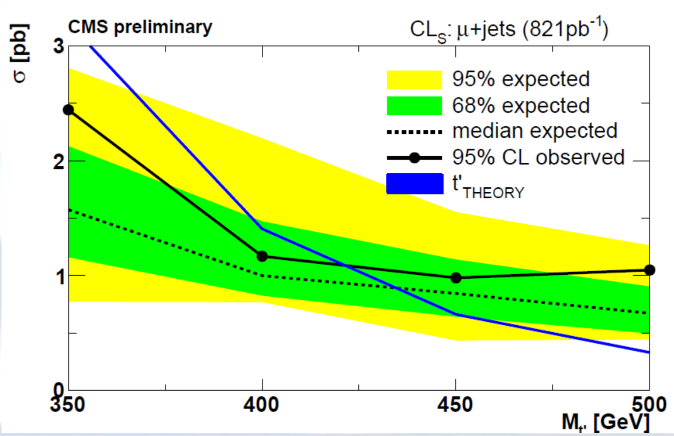
PAS-EXO-11-051

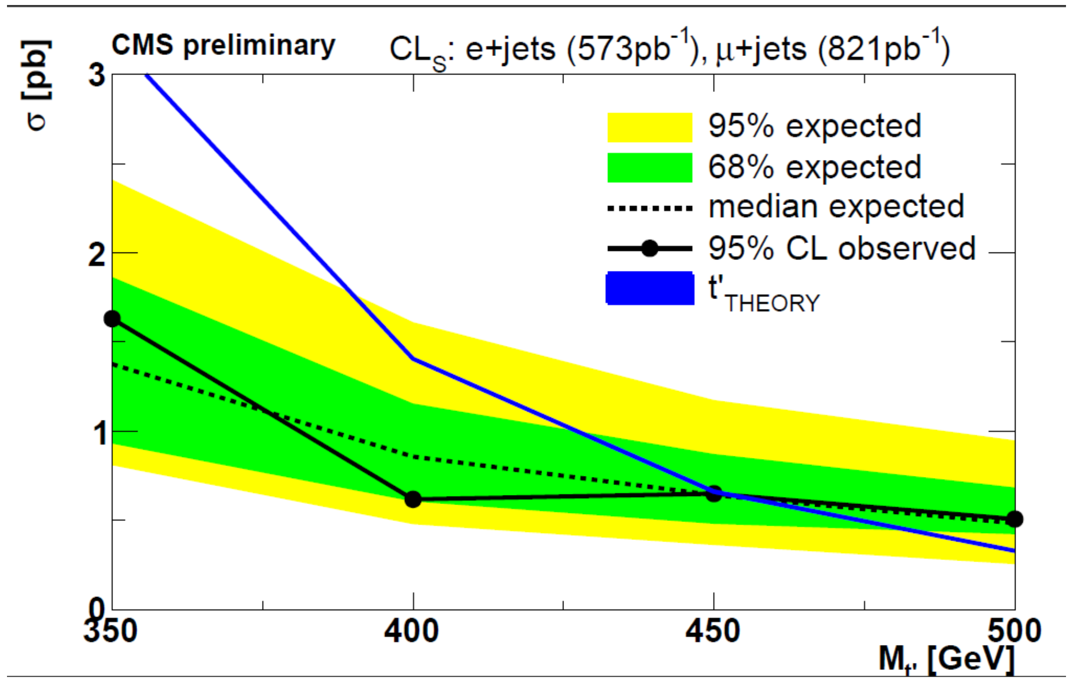
0.5-0.8fb^{-1}

- 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 1/3

Just made public!

1fb^{-1}

- 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 (60/25/25), and lepton pT (e/mu 25/20)
  - 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 (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

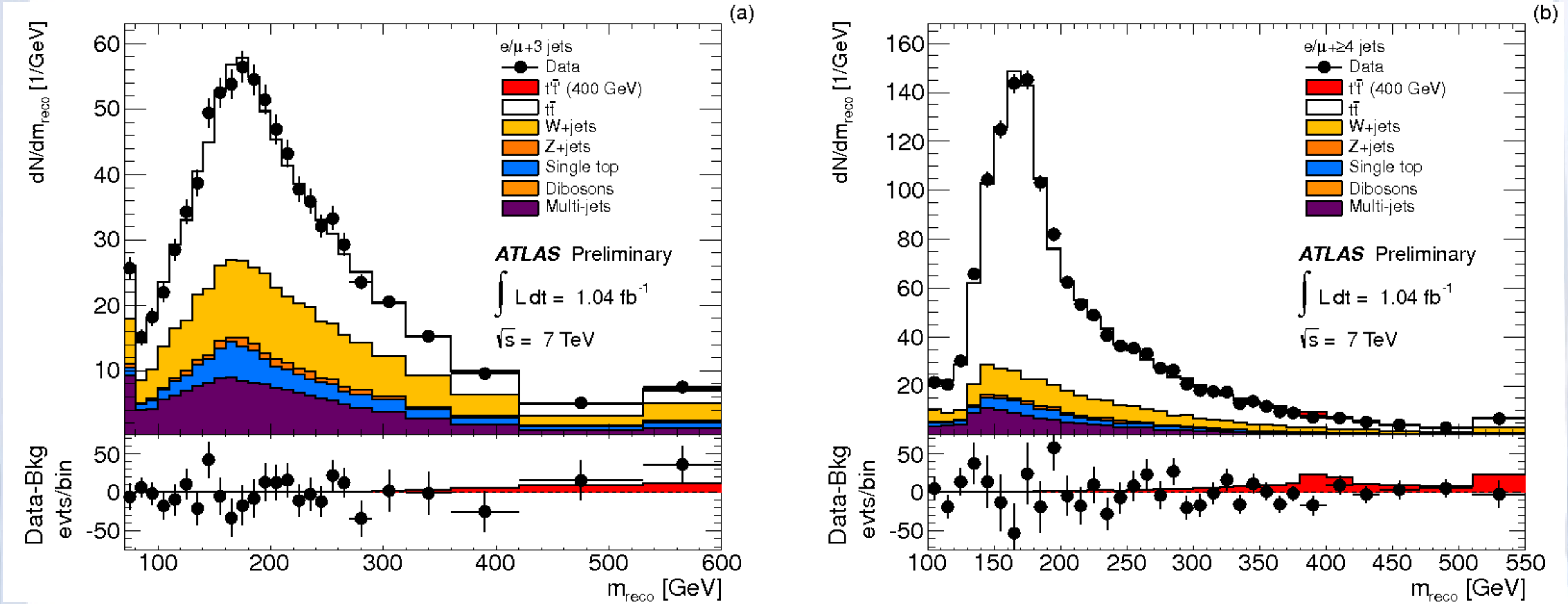
- Use mclimit package to set CLs limits
  - Modified package:
    - Extrapolation methods
    - Added functionality for running tests et

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

Just made public!

$1fb^{-1}$

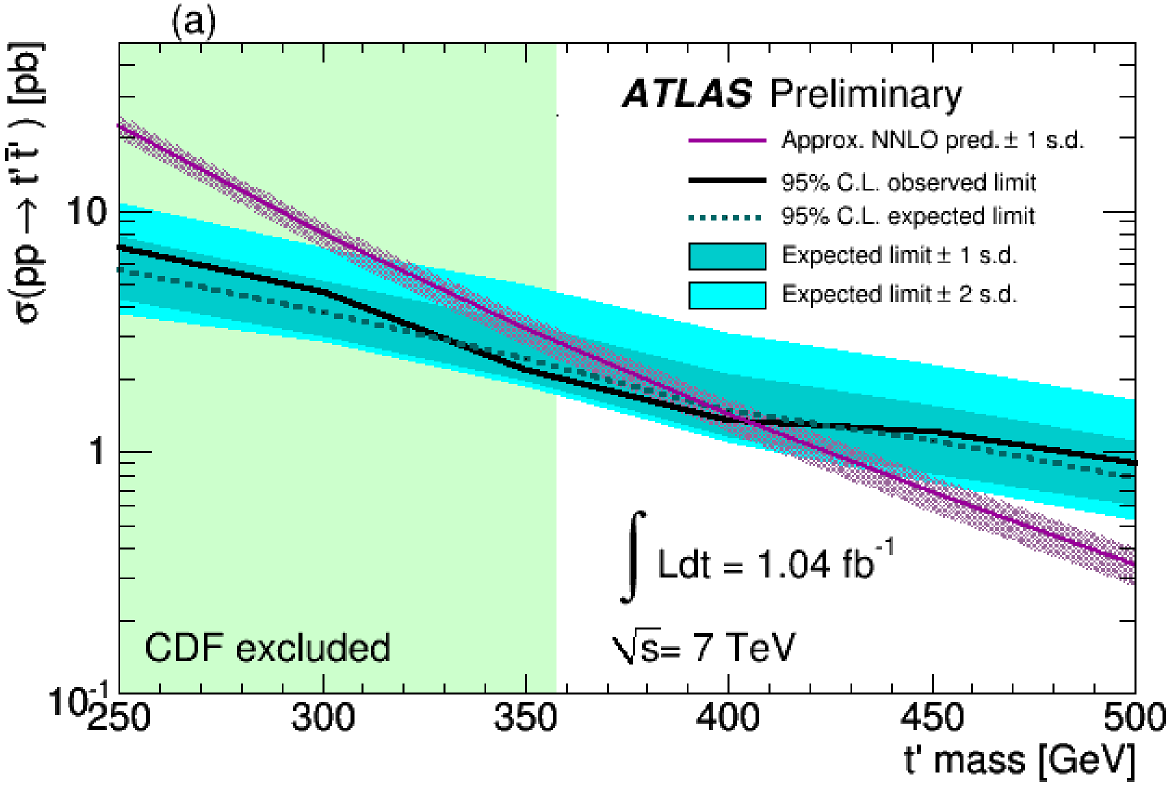
- Systematics treated as nuisance parameters
- ATLAS list of systematics is very conservative respect to CMS (23 sources considered, 13 are profiled; CMS 7 systematics, no ttbar modeling)
- A profile likelihood ratio is performed combining 3jet exclusive/4 jet inclusive channel for at least 1btag jet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



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

Just made public! $1fb^{-1}$

- No sign of excess → set limits
  - 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



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

1fb^{-1}

PAS-EXO-11-054

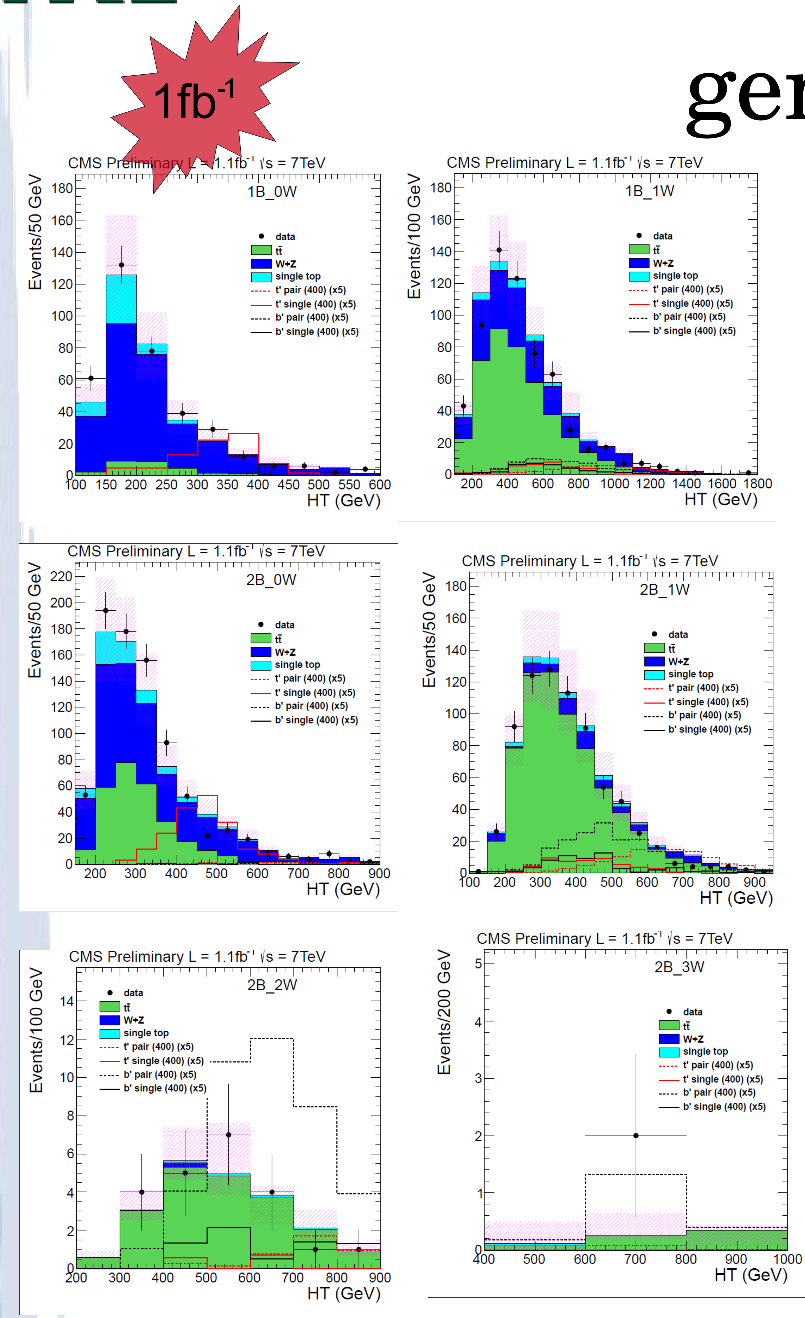
- This analysis presents the inclusive search of 4th generation up-down type quark from pair or single production (t'b → Wb b; b't → WbW Wb; t't' → WbWb; b'b' → WbW WbW)

- <u>Search is performed in the muon channel:</u>
  - 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

- <u>Search performed in 6 subsamples, based on nb-jet (==1, ≥2) ; nWhad (==0, ==1, ==2, ≥3)</u>
  - 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

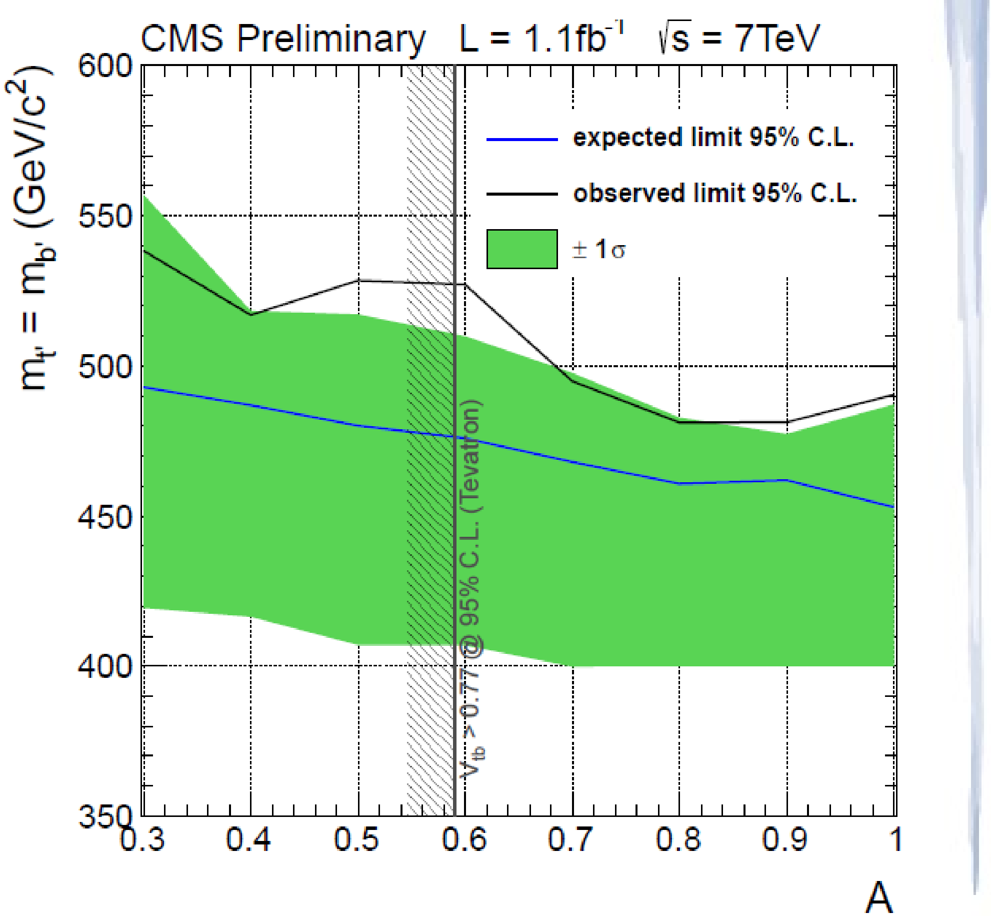
CMS – Inclusive search for a 4th generation 3/3

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

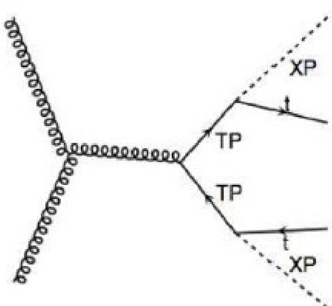
1fb^{-1}

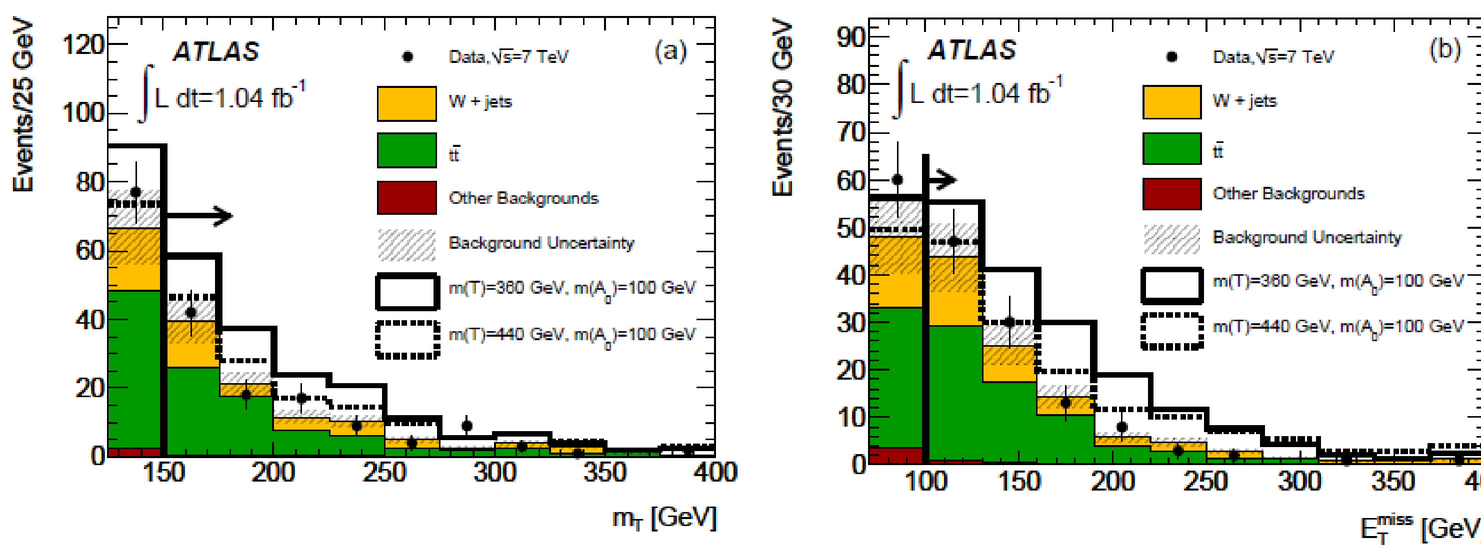
arXiv:1109.4725

- Search for anomalous MET in tt (single lepton) events

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

- Benchmark: TT pair with $T \rightarrow tA_0$
  - 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



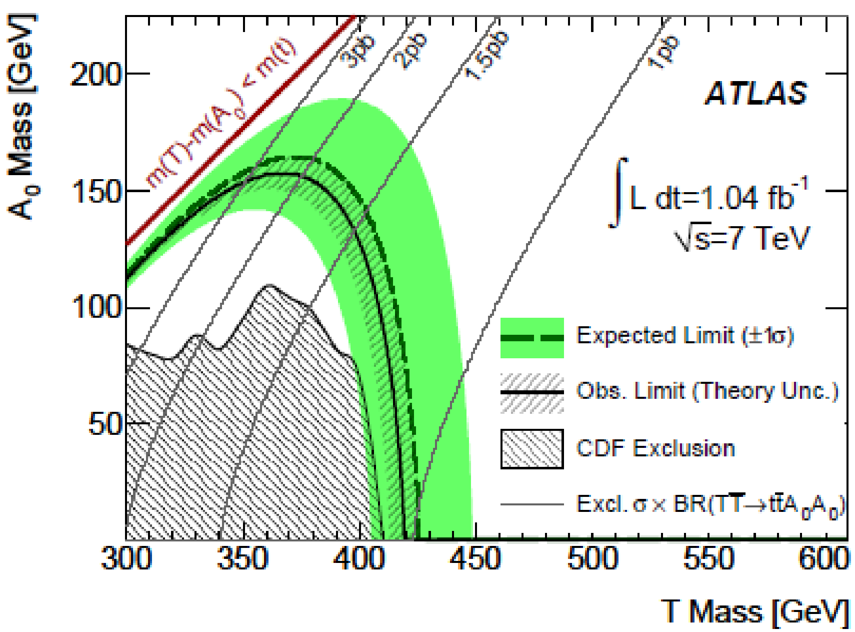


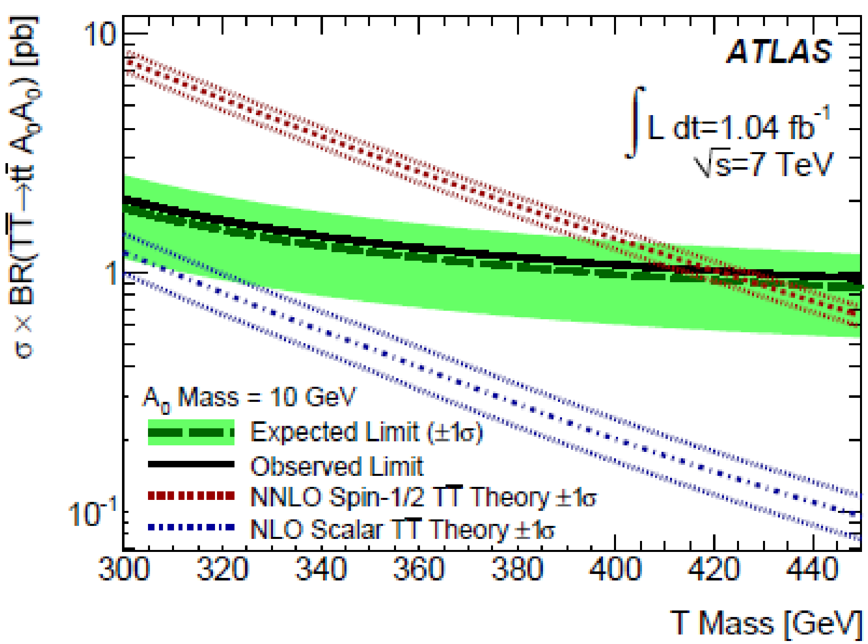
ttbar + Anomalous E_T^{miss} 2/2

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



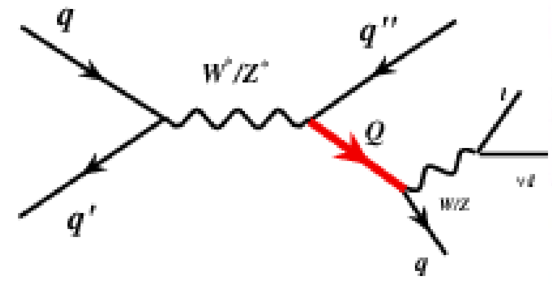


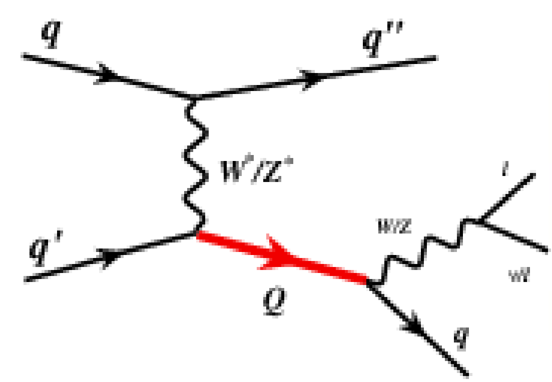
Search for VLQ (single prod.) 1/3

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 = (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



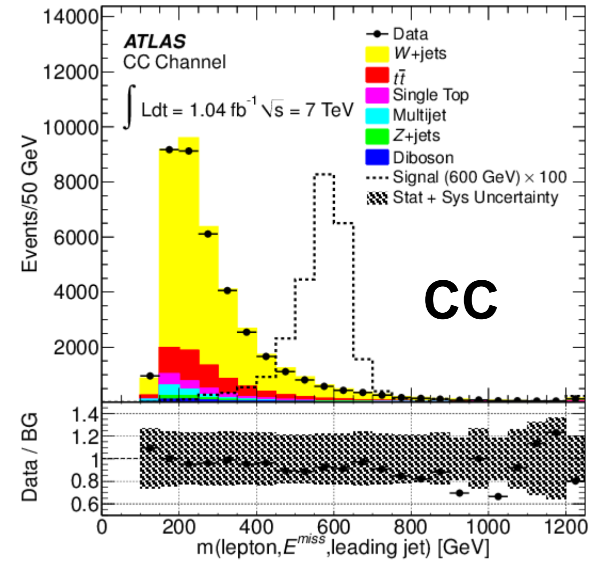


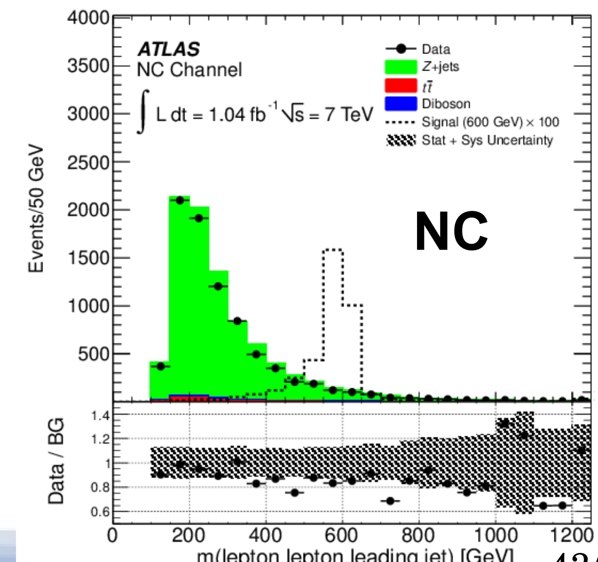
Search for VLQ (single prod.) 2/3

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} > 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)
- <u>Neutral Current:</u>
  - 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

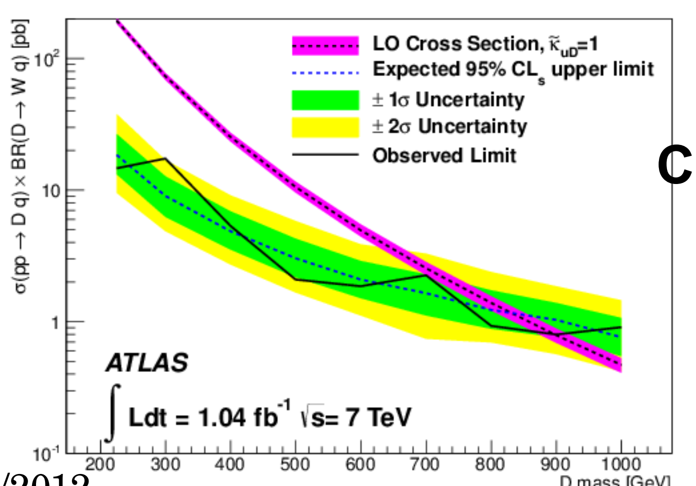
arXiv:1112.5755

1fb^{-1}

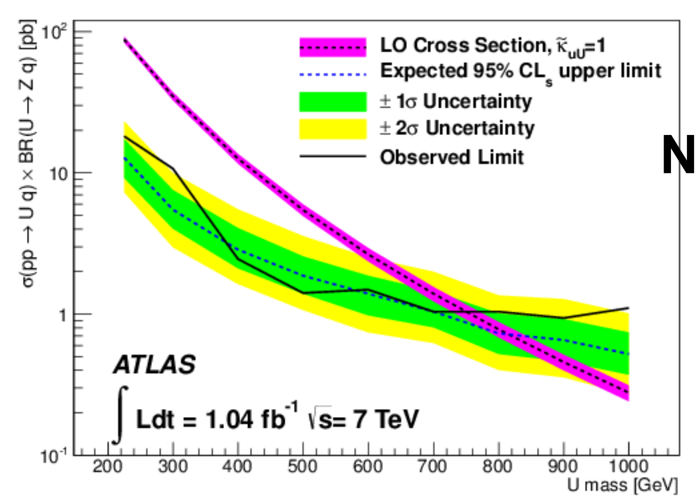
- Cls method and binned maximum Likelihood
- Search performed by searching a signal peak on top of a smooth background
- No evidence of VLQ found
- Assuming K'uU = K'uD = 1 set limits → mVLQ > 900(760) GeV for CC(NC) @95%C.L.
- Tevatron limits → K'uU=1 690GeV (100% BR CC) ; K'uD=sqrt(2) 550GeV (100%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



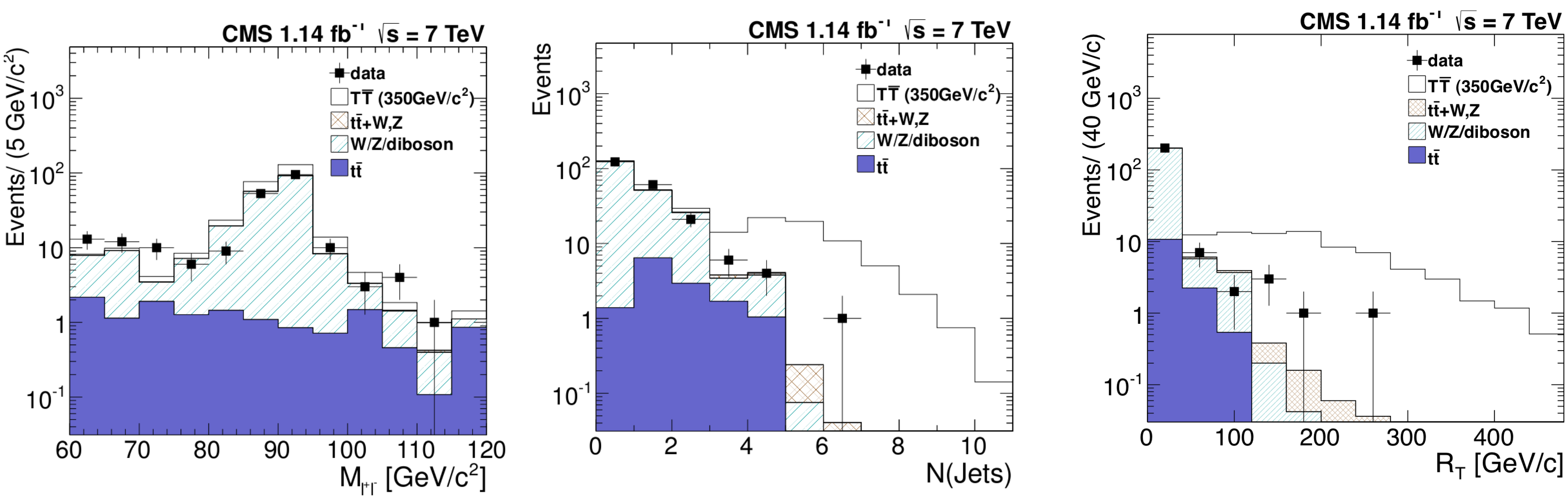
NC

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 $T \to tZ$; $pp \to TT \to tZtZ \to WbZWbZ$
- 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 $Z \to 2$ OS, same flavored leptons (e or mu) $60 < Mll < 120$GeV
- At least 3 leptons and at least 2 jets
- RT > 80GeV, with $RT = \Sigma pT(\text{jet } i) + \Sigma pT(\text{lepton } i)$ $(i \neq 1,2)$



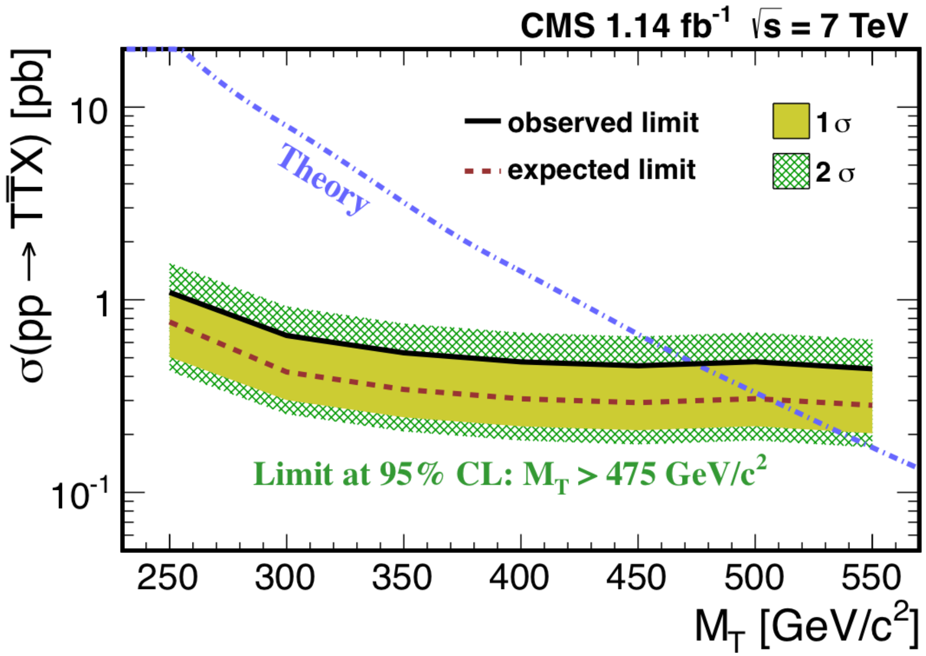
Search for VLQ in t+Z (pair prod.)2/2

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



Summary of the results

- 4th generation:
  - b'b' → Wt (100% BR) 495GeV
  - t't' → Wb (100% BR) 450GeV
  - Inclusive search (mt' = mb') 490GeV
- Vector like quarks:
  - TT → tZ (100% BR) 475GeV
  - 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 4th 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 :(
- 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