Exotic Heavy Quark Searches at the LHC

V. Erkcan Özcan

Boğaziçi University

On behalf of ATLAS and CMS Collaborations

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Outline

- Many BSM models predict new heavy quarks: GUTs, extra-dimensions, little Higgs, new SM-like generations, etc.
  - Can be vector-like, can have flavor-changing neutral current decays, including decays to a little Higgs, etc.
- Initial LHC searches focus mainly on new quarks that are pair-produced & that decay much in the same way as top.
  - Benchmark model - simplest extension of SM: 4th sequential generation of fermions.
- In this talk:
  - Motivation, searches for SM4(-like) quarks (dilepton b′, dilepton t′, semileptonic t′) and more exotic stuff
- Not in this talk: Channels studied with MC, but not yet in data

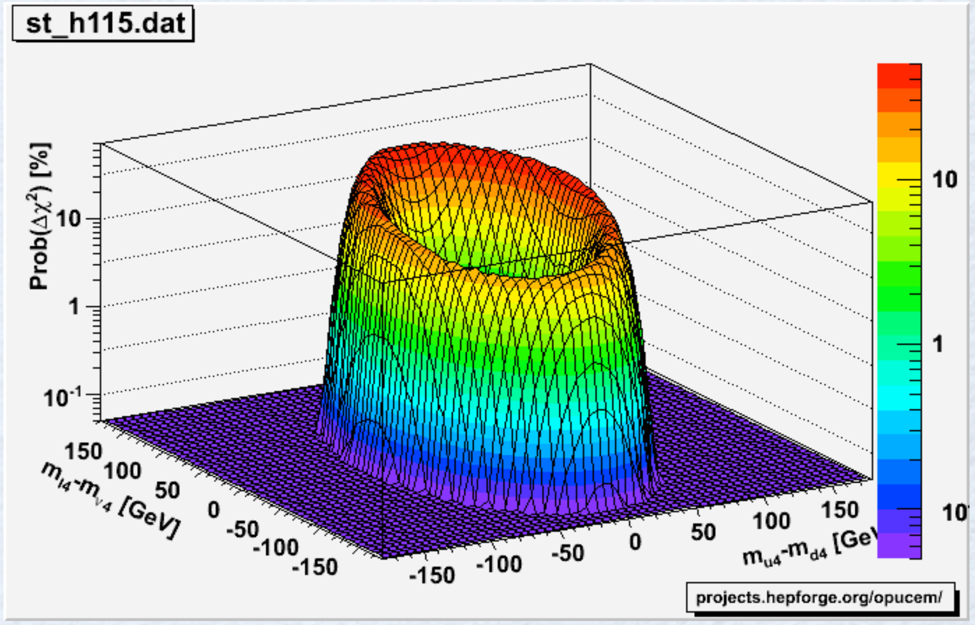
SM4

- Simplest extension of the SM:
  - Number of generations - not set in SM.
  - On the muon: “Who ordered that?” - I.I. Rabi
  - But then we got two full generations of fermions. So the real question: “Who decided not to order more?”
  - Incorrectly considered to have been overruled by EW precision data, recently shown to still have large possible parameter space.
- Many motivations for SM4:
  - Baryon asymmetry, dynamical EW symmetry breaking, SM flavor structure, dark matter neutrinos, help SUSY/technicolor/... to escape LEP/LHC limits, etc. etc.
  - From experimentalist POV: simple model - can provide benchmark MC for signature-based new quark/lepton searches, clear predictions, few free parameters, discover or reject at LHC...

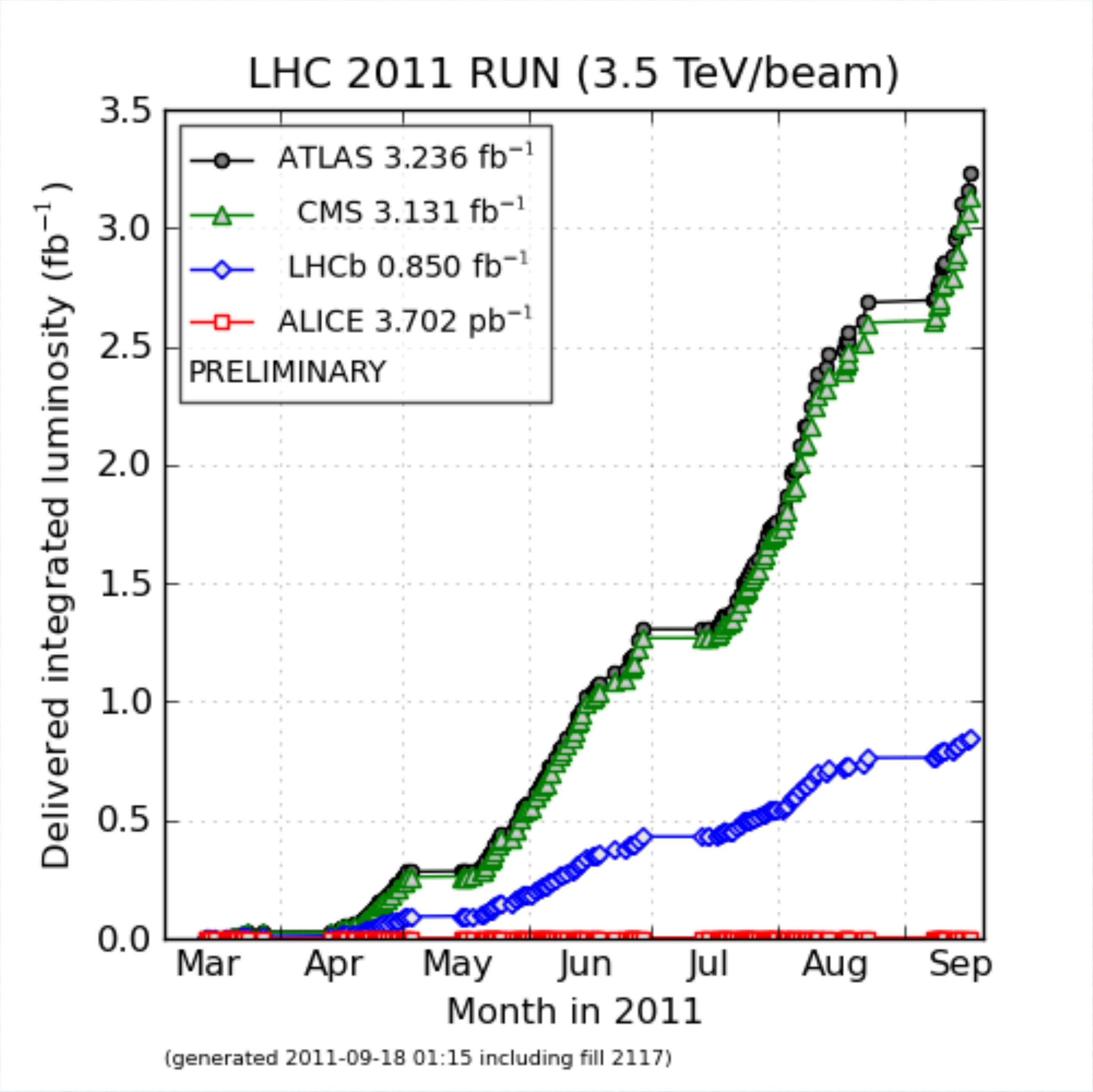
Upcoming 3rd WS in Istanbul, October 23-25

Search Channels

- As with top production, pair-production x-section is larger than that of single-production.
  - Exceptions: vector-like quarks, quarks with anomalous couplings, large mixing with other generations, etc.
- Commonly searched channels:
  - Down-type quark b′: pp -> b′b′ -> tWtW -> bWWbWW (because previous limits set $m_{b'} > m_t + m_W$)
  - Up-type quark t′: pp -> t′t′ -> bWbW (EW precision data favors $|m_{t'} - m_{b'}| < m_W$ particularly for light Higgs)
  - Similar channels with 4th gen. mixing with light generations.



Data



- LHC has already delivered over $3fb^{-1}$ of data at $\sqrt{s}$=7TeV to ATLAS and CMS each.
- The results here use only a fraction of this data:
  - Earliest analyses are based on ~$40pb^{-1}$ of 2010 data.
  - Summer 2011 results are based on $0.2\text{-}1fb^{-1}$.

TOOLS

- Common tools used for the searches:
  - Signal generated with Pythia or MadGraph (particularly when additional partons are considered)
    - Signal cross-sections are from HATHOR (approx. NNLO).
  - Backgrounds: CMS generates them also with Pythia, Madgraph.
    - ATLAS uses MC@NLO for tt background, Alpgen for V+jets, Herwig for dibosons.
    - k-factors for x-sections from MCFM, FEWZ.
  - Pythia (Herwig+Jimmy) is used for hadronization, fragmentation, parton showering, underlying event etc. by CMS (ATLAS).
  - Detector simulation is done with GEANT4.
    - When fake leptons are a source of background, data-driven determination is common. Based on loosening lepton ID criteria and extracting tight vs. loose efficiencies in control samples. => Common with many of top analyses.

CMS Search for B′

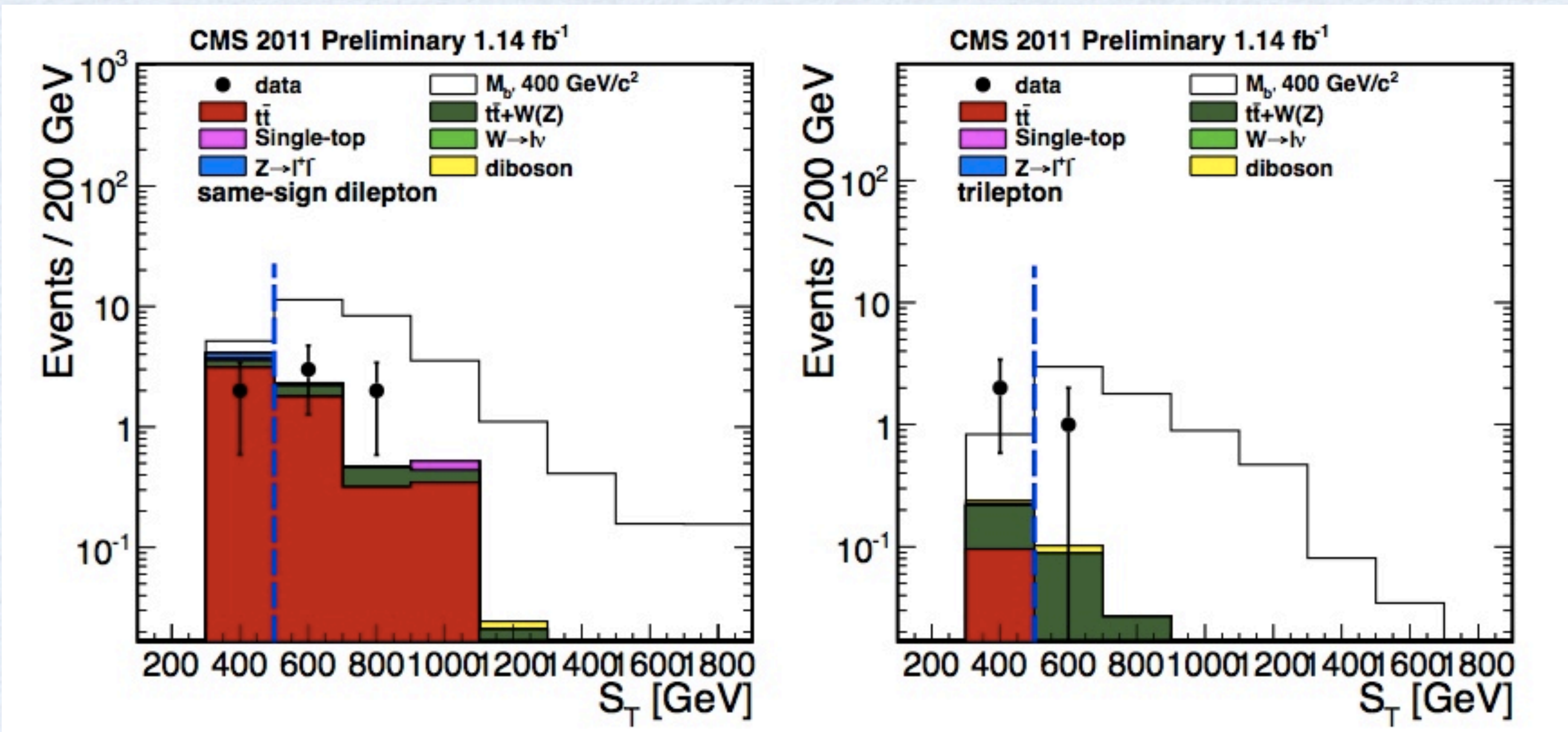
PAS EXO-11-036

- $b'b'$ -> tWtW -> bWWbWW
  - 2 SS or 3 isolated $l=e,\mu$ in final state (7.3% of total decays)
    - dilepton triggers (ε=92-99% dependent on FS)
    - $P_T^{e,\mu}>20$ GeV, $|\eta^{e,\mu}|<2.4$ (also reject $1.44<|\eta^e|<1.57$)
    - Lepton isolation: α^e=0.06-0.07 ; α^μ=0.15
      - [ΣE_T(within ΔR=0.3) - pileup contribution] < $\alpha^{e,\mu} \times PT^{e,\mu}$
    - For same-flavor leptons, Z-veto: $|m_{ll}-m_Z|>10$ GeV
  - Anti-kt R=0.5 jets with $P_T^j>25$ GeV, $|\eta^j|<2.4$
    b-tagging based on IP significance (50% tagging eff., 1% mistag)
    - $n_{jet}>=4(2)$ for 2SS/3 lepton channel ; $n_{b-jet}>=1$
  - $S_T = \Sigma P_T(\text{leptons}) + \Sigma P_T(\text{jets}) + E_T^{miss} > 500$ GeV

$M_{b'}$ [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

Backgrounds for B'

PAS EXO-11-036



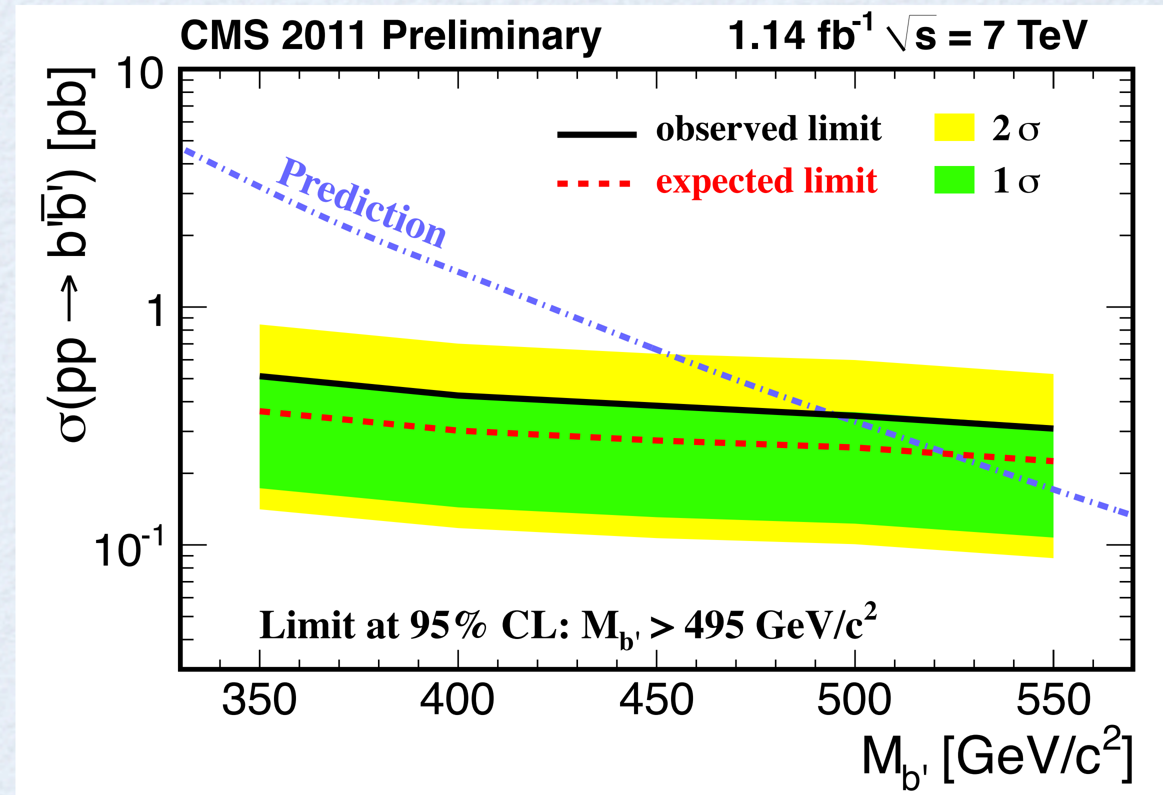
	total BG in signal region
2SS	4.4 ± 1.4
3	0.16 ± 0.09

- For 2-SS-lepton analysis: single-lepton events with an extra misidentified or non-isolated lepton, dilepton events with a charge-misidentified electron, or events with prompt same-sign dilepton ==> Main contribution from tt
- For 3-lepton analysis: dominated by processes with 3 prompt leptons, ie. tt+W(Z)
- Charge mis-id and "fake" lepton backgrounds estimated using data. (loose vs. tight lepton ID)

Results for B′

PAS EXO-11-036

	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



	total BG in signal region	observed events
2SS	4.4 ± 1.4	5
3	0.16 ± 0.09	1

- Using a Bayesian method with log-normal prior, and assuming BF(b′->tW) = 1 :
  - m(b′) > 495 GeV @ 95% CL

1.14 fb^{-1}

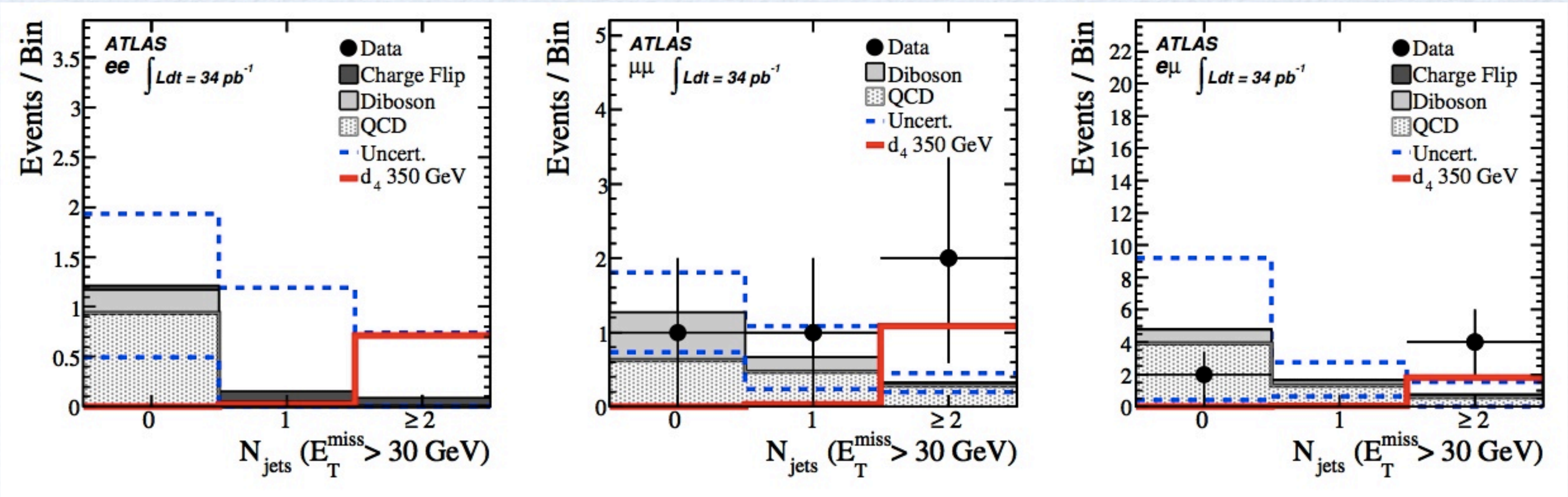
SS DiLeptons @ ATLAS

arXiv:1108.0366

- A generic search for two SS ee, eμ, μμ pairs (Limits on UED, SUSY, heavy Majorana neutrinos & b′ quarks)
- Selection very similar to CMS SS analysis, but without b-tag and S_T requirements.
  - 2 SS l=e,μ, with tight lepton ID
    - single lepton trigger
    - $P_T^{e,\mu}>20$ GeV, $|\eta^\mu|<2.5$, $|\eta^e|<1.37$ or $1.52<|\eta^e|<2.47$
    - Lepton isolation:
      - [ΣE_T(within $\Delta R=0.2$)] < $0.15 \times P_T^{e,\mu}$
    - In ee channel, Z-veto: $80<|m_{ee}-m_Z|<95$ GeV
  - Anti-kt R=0.4 jets with $P_T^j>30$ GeV, $|\eta^j|<2.5$
    - muons within $\Delta R=0.4$ of b-tagged jets of $P_T^j>20$ GeV vetoed
  - $E_T^{miss}>30$ GeV

SS DiLeptons

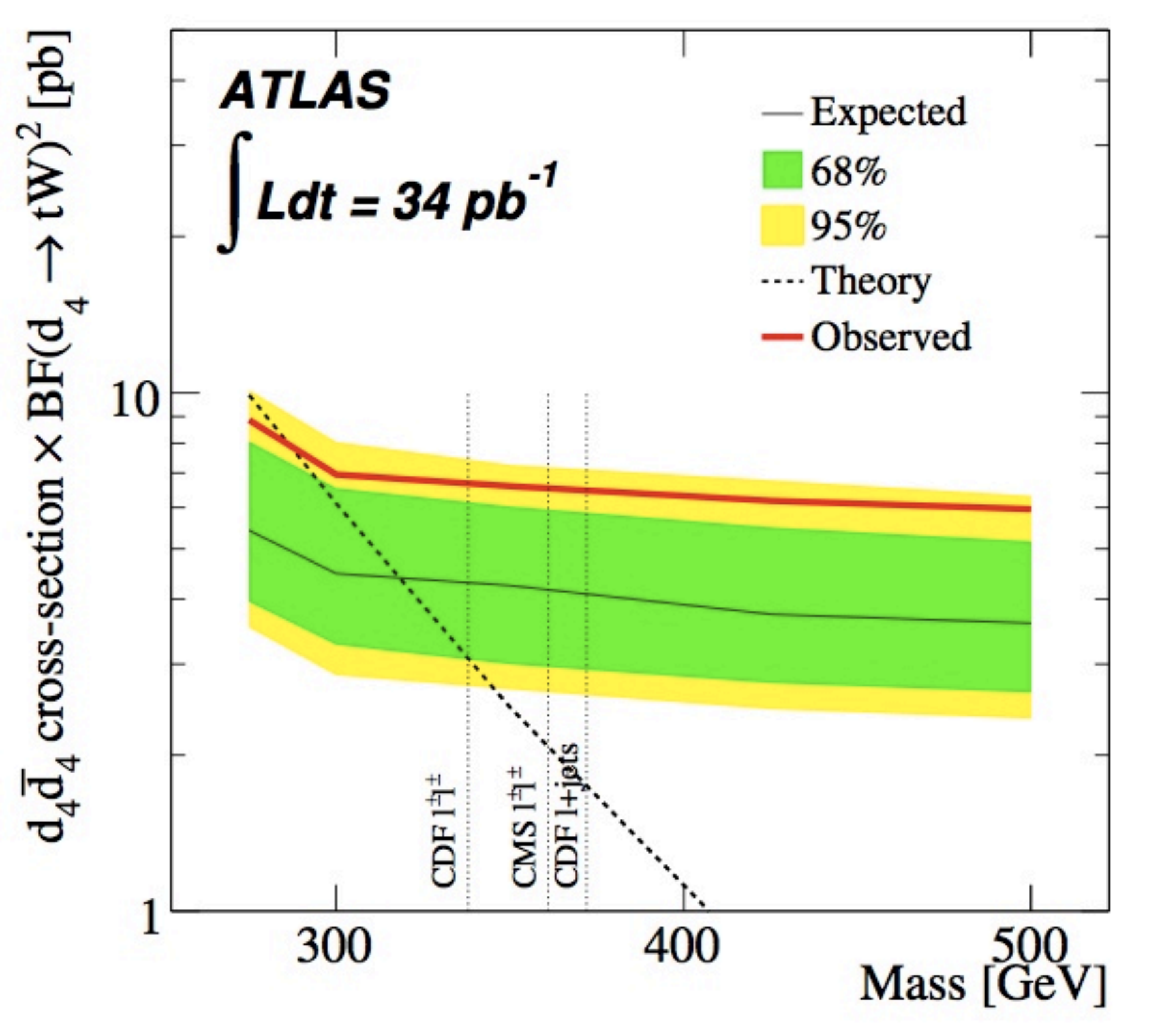
arXiv:1108.0366



- Backgrounds:
  - QCD - jets faking/creating isolated leptons (mainly from dijet & W+jets)
  - Charge Flip - electron charge mis-measurement
  - Diboson - irreducible SM background (mainly from WZ production)

SS DiLepton Results

arXiv:1108.0366



- Binned max likelihood fit, in three jet multiplicity bins (0, 1, 2+ jets).
- Assuming BF(b'->tW)=1, limits at 95% CL:
  - Expected limit: m(b')>330 GeV
  - Observed limit: m(b')>290 GeV

34 pb^{-1}

μμ channel has recently got updated to **1.6 fb^{-1}**, but the results have not been interpreted for a heavy quark yet. See ATLAS-CONF-2011-126

Search for T′

PAS EXO-11-050

- Much like a heavy top: t′t′ -> bWbW
  - Two decay channels: fully-leptonic, semi-leptonic
- The cuts for the fully-leptonic channel is very similar to those used in the b′ search. For example, from CMS:
  - 2 (or more) OS isolated l=e,μ in final state
    - dilepton triggers (ε=90-100% dependent on FS)
    - $P_T^{e,\mu}$>20 GeV, $|\eta^e|<2.4$, $|\eta^\mu|<2.4$
    - Lepton isolation: [ΣE_T(within ΔR=0.3)] < 0.15 × $P_T^{e,\mu}$
    - Z-veto: $|M_{ll}-m_Z|>10$ GeV
  - Anti-kt R=0.5 jets with P_T^j>30 GeV, $|\eta^j|<2.5$, separated from leptons b-tagging based on IP significance (50% tagging eff., 1% mistag)
    - $n_{jet}>=4$; $n_{b-jet}>=2$
  - E_T^{miss}>30GeV

Kinematic Cut on T′

PAS EXO-11-050

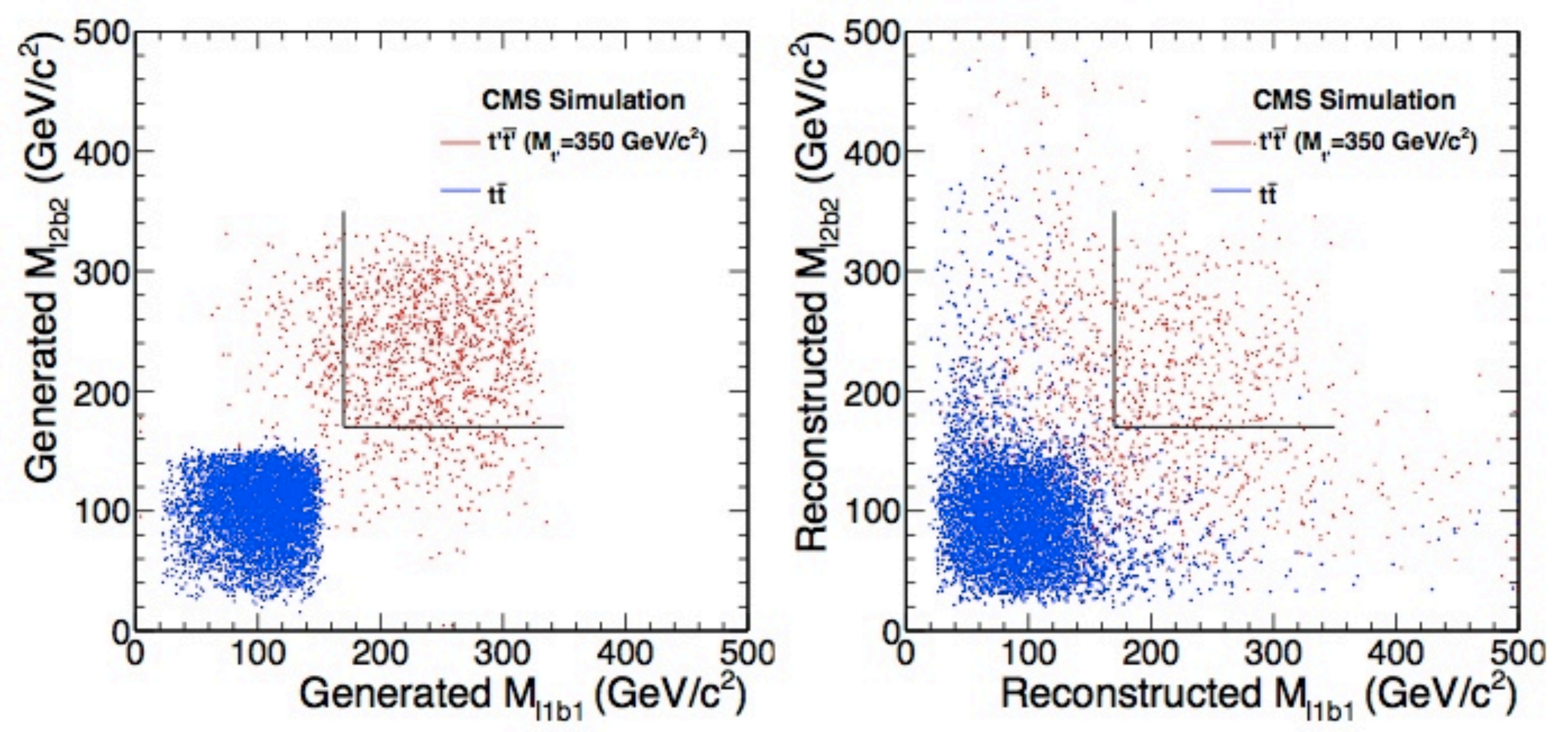
- After basic selection, fully-leptonic decays of tt dominate!

Sample	ee	$\mu\mu$	$e\mu$	all
$t'\bar{t}'$, $M_{t'} = 350\,\text{GeV}/c^2$	5.63 ± 0.41	5.63 ± 0.38	13.43 ± 0.61	24.69 ± 0.83
$t'\bar{t}'$, $M_{t'} = 400\,\text{GeV}/c^2$	2.51 ± 0.18	2.92 ± 0.19	6.33 ± 0.28	11.76 ± 0.38
$t'\bar{t}'$, $M_{t'} = 450\,\text{GeV}/c^2$	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

stat uncertainties only

- Use invariant masses of lepton and b-jet pairs as discriminant.

- At gen. level, very sharp distinction between signal & tt.
- At reco level, pair b and l based on min(ΔR).
- $m(l_i b_i) > 170$ GeV, i=1,2
  - $\varepsilon^{sig} \approx 40\%$
  - $\varepsilon^{tt} \approx O(0.001)$

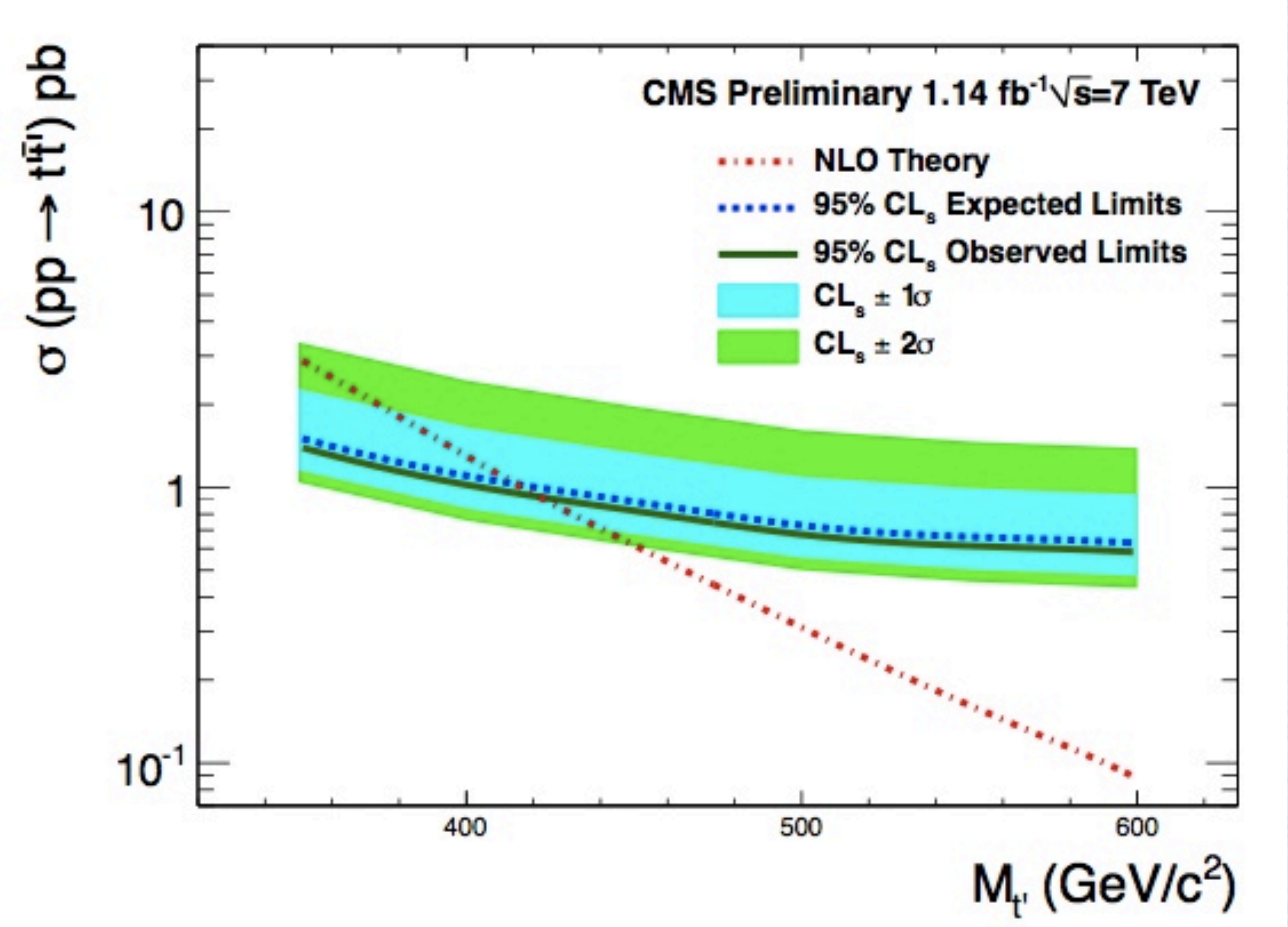


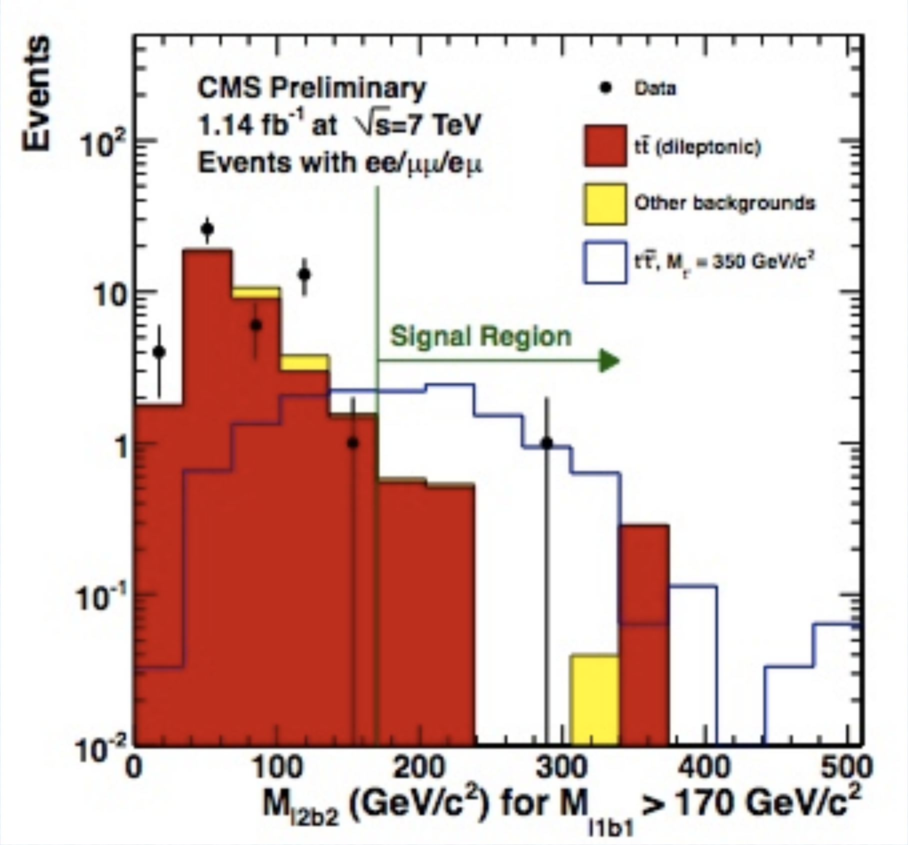
Fully-leptonic channel

Results for T'

PAS EXO-11-050

Sample	Yield	Prediction 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	



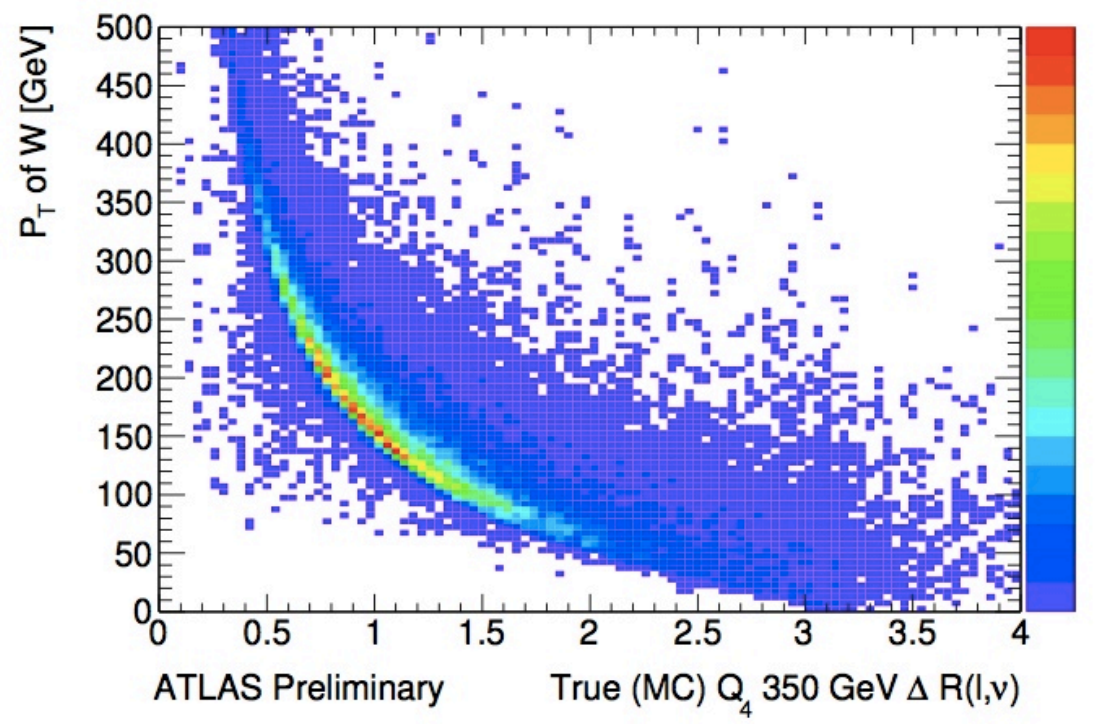


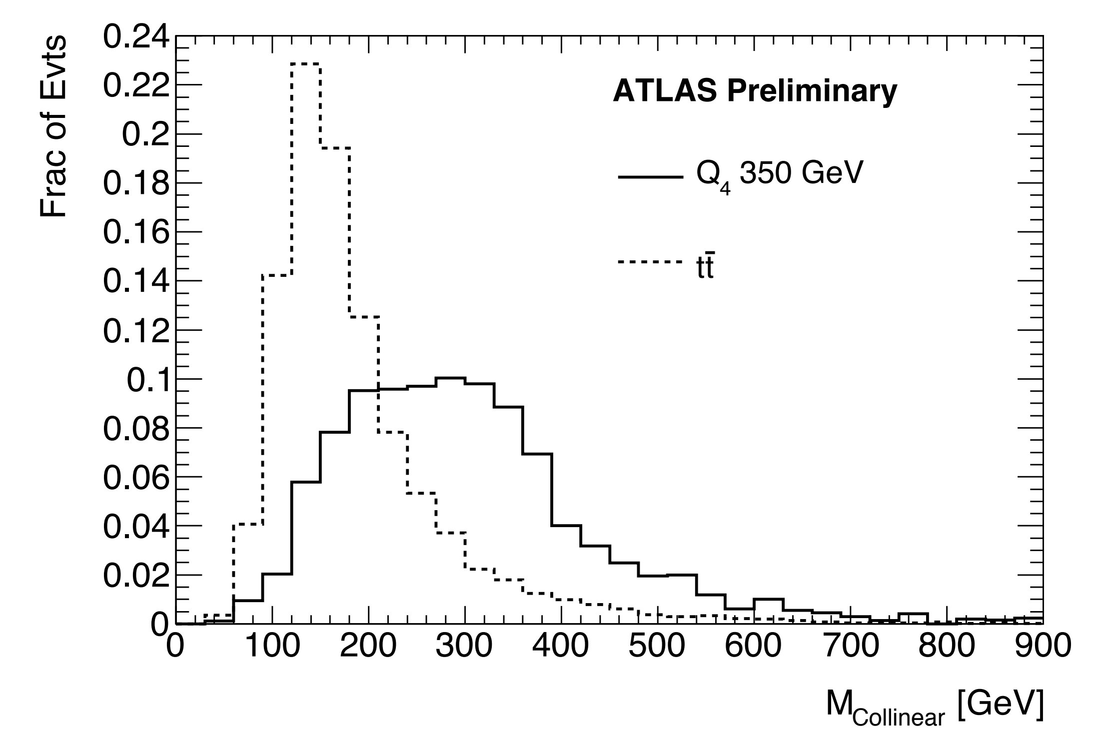
- Largest background (tt->ll) estimated from $m(l_i b_i)$ sidebands.
- Single event observed for 1.62 expected.
- Assuming BF(t'->bW) = 1 : m(t') > 422 GeV @ 95% CL

1.14 fb^{-1}

T′ Reconstruction

ATLAS-CONF-2011-022



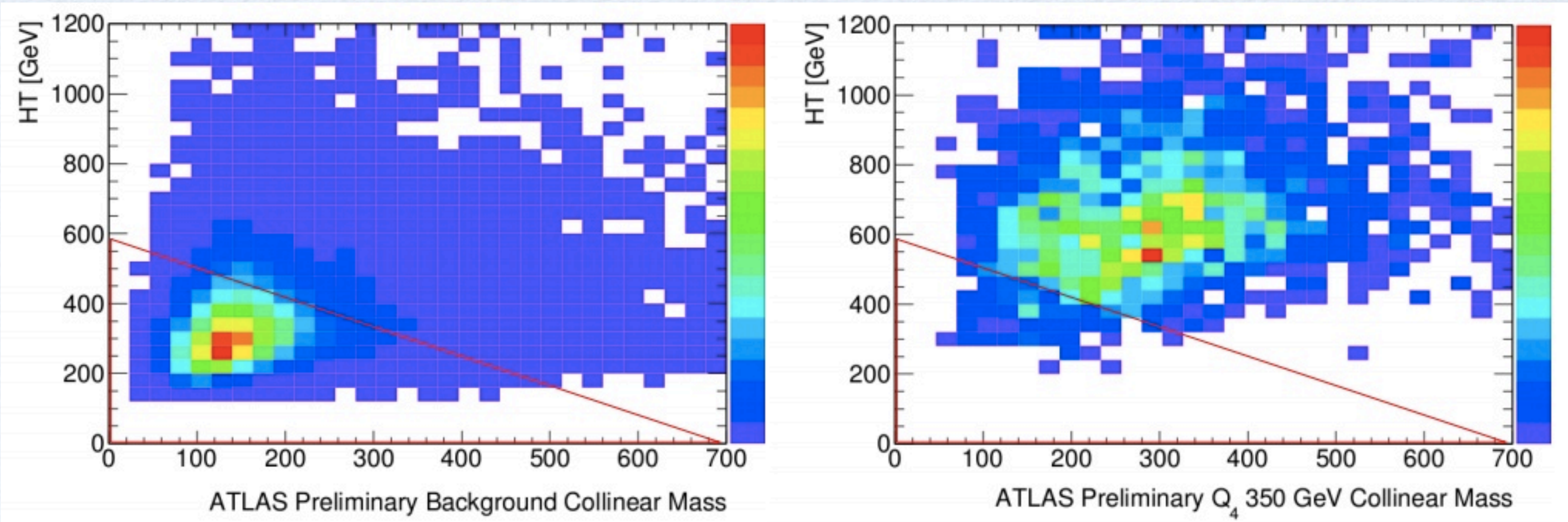


- No assumptions about quark mixing, ie. the final state is: t′t′ -> qWqW
- ATLAS tries to reconstruct two HQ masses ($m_{Collinear}$) in the event, from 4-momenta of jet+l+ν.
- high PT Ws => l & ν are approx. collinear.
- Reconstruct $|\Delta\eta(l,\nu)|$ and $|\Delta\Phi(l,\nu)|$ for each ν is a free parameter, allowed to vary in the range (0,1).
- Assume E_T^{miss} solely from 2 νs.
- Find $|\Delta\eta(l,\nu)|$, $|\Delta\Phi(l,\nu)|$ values and jet assignment which minimizes difference between two $m_{Collinear}$.

Fully-leptonic channel

T′ Kinematic Cuts

ATLAS-CONF-2011-022



- Triangular cut in H_T–$m_{Collinear}$ plane, optimized for various $m_{t'}$.
- S:B improved to be around 1:2.

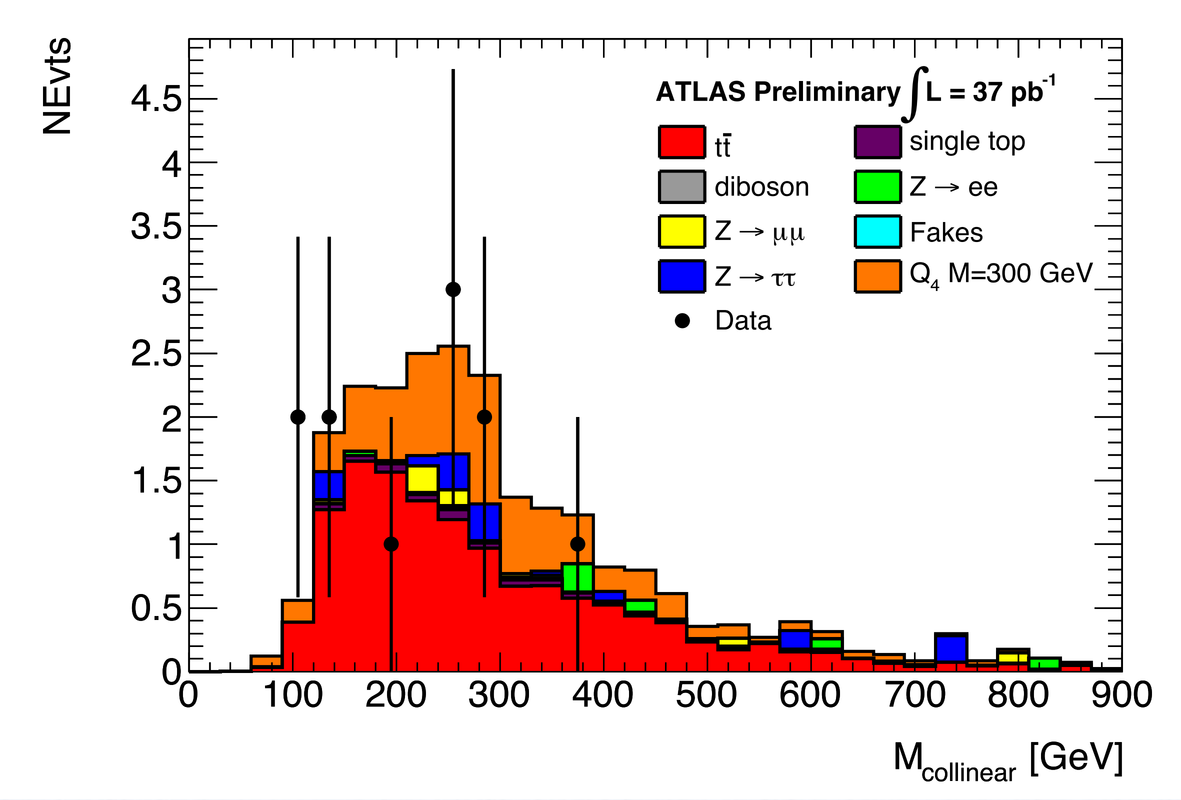
Q_4 Mass (GeV)	Final selection
250	$H_T > 500 - 0.7 \times M_{collinear}$
300	$H_T > 600 - 0.5 \times M_{collinear}$
350	$H_T > 600 - 0.2 \times M_{collinear}$
400	$H_T > 700 - 0.3 \times M_{collinear}$

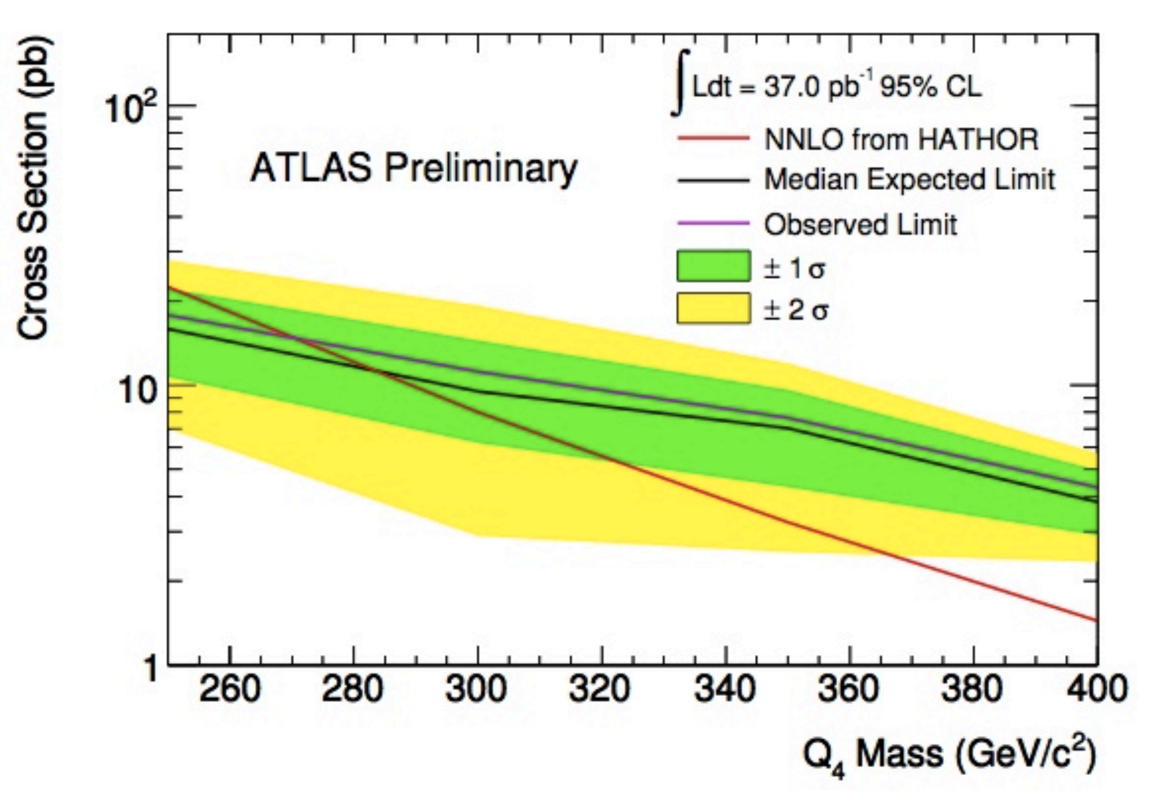
Fully-leptonic channel

Results for T′

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 max. likelihood to derive: m(t′) > 270GeV @ 95%CL. => Limit applicable to other exotic quark searches.

37 pb⁻¹

Search for T′

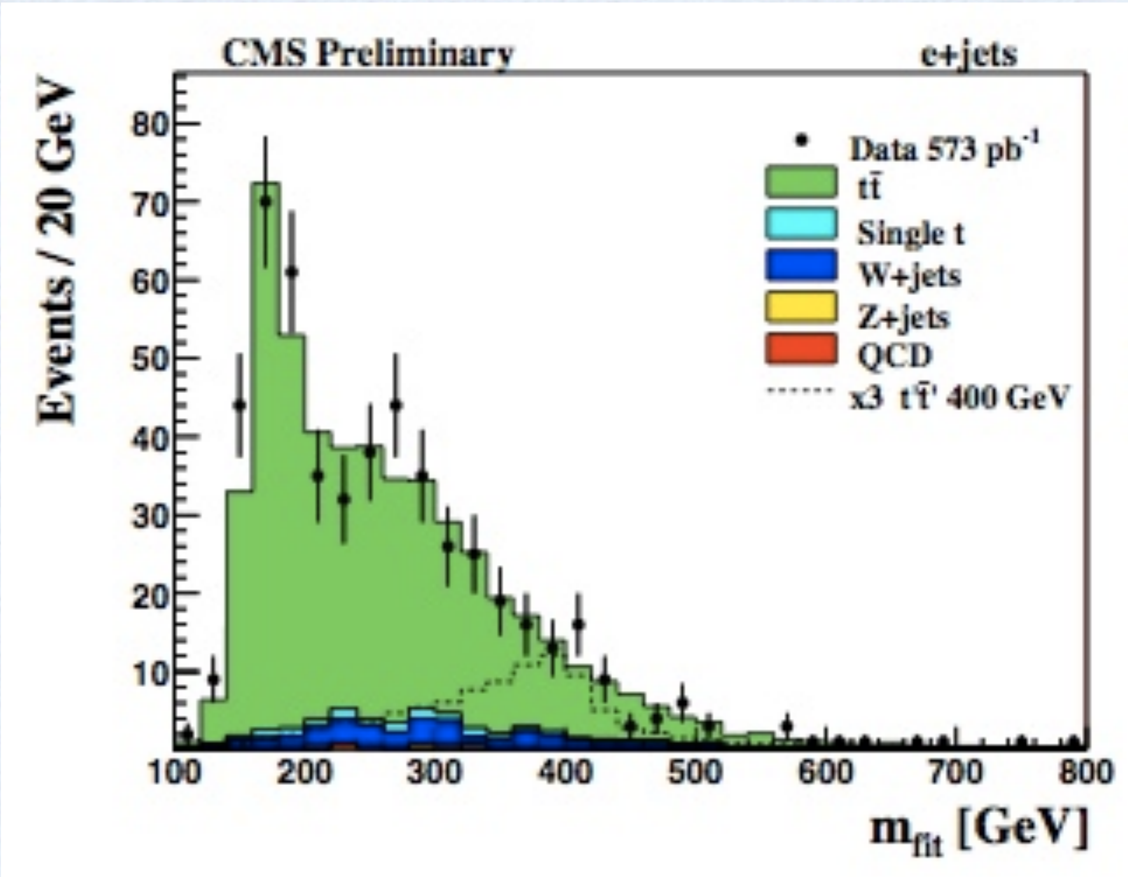
PAS EXO-11-051

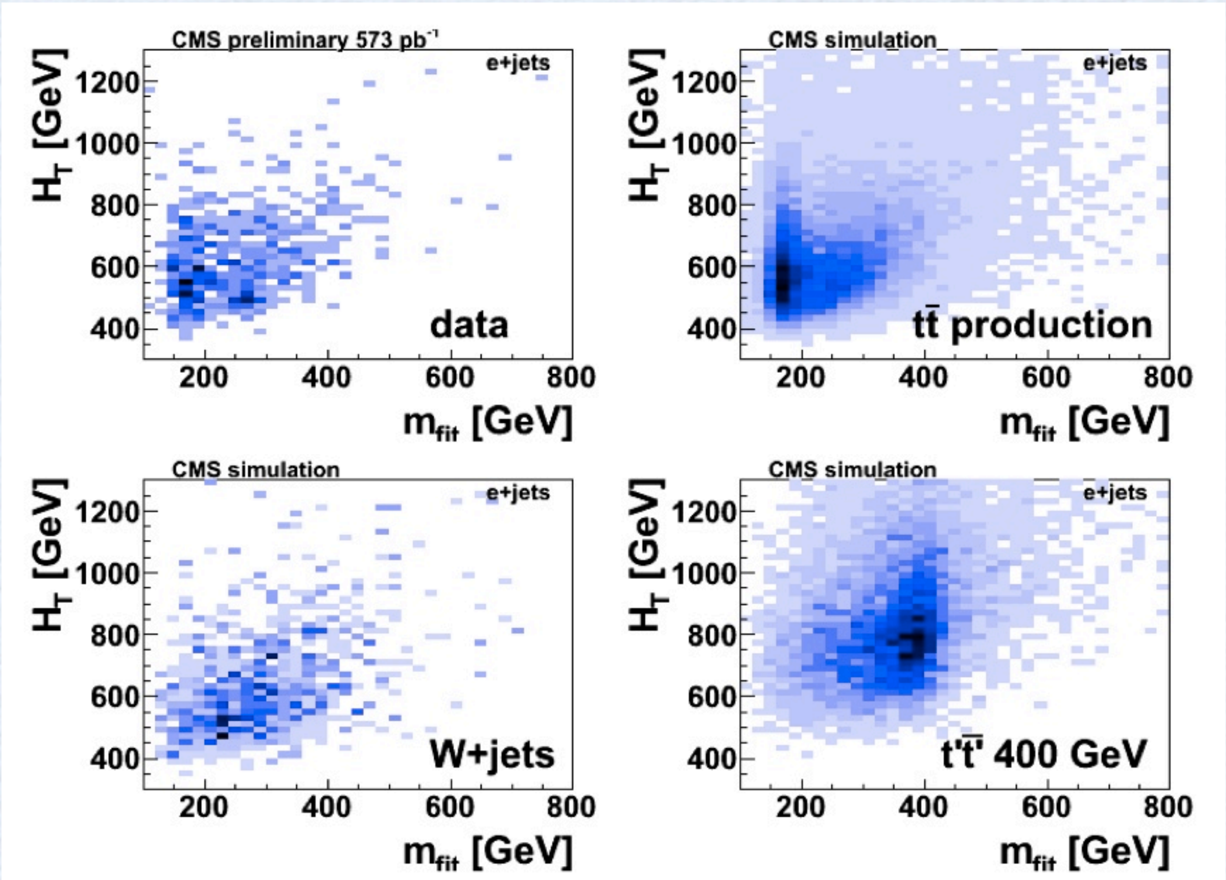
- Final state: t′t′ -> WbWb -> lνbjjb
- Cuts differ significantly from the dilepton case
  - P_T^e>30-45 GeV , $|\eta^e|$<2.5 (excluding transition region) or P_T^μ>35 GeV , $|\eta^\mu|$<2.1
  - At least four jets with P_T^j > 120, 90, 35, 35 GeV Jets within ΔR=0.3 of the lepton vetoed
  - At least one b-jet
  - E_T^{miss}>20GeV

Lepton + Jets Channel

Fitting for M(T′)

PAS EXO-11-051





e+jets channel shown as example

- Take four-jet combinations out of the hardest 5 jets.
- Use W mass contraints and the fact that the 2 reco t′ masses should be equal.
- Perform kinematic fit minimizing the χ^2 computed from the measured momenta of all final-state particles and their resolutions.
- Obtained t′ mass (m_{fit}) is used together with H_T for extracting yields.

Lepton + Jets Channel

RESULTS FOR T′

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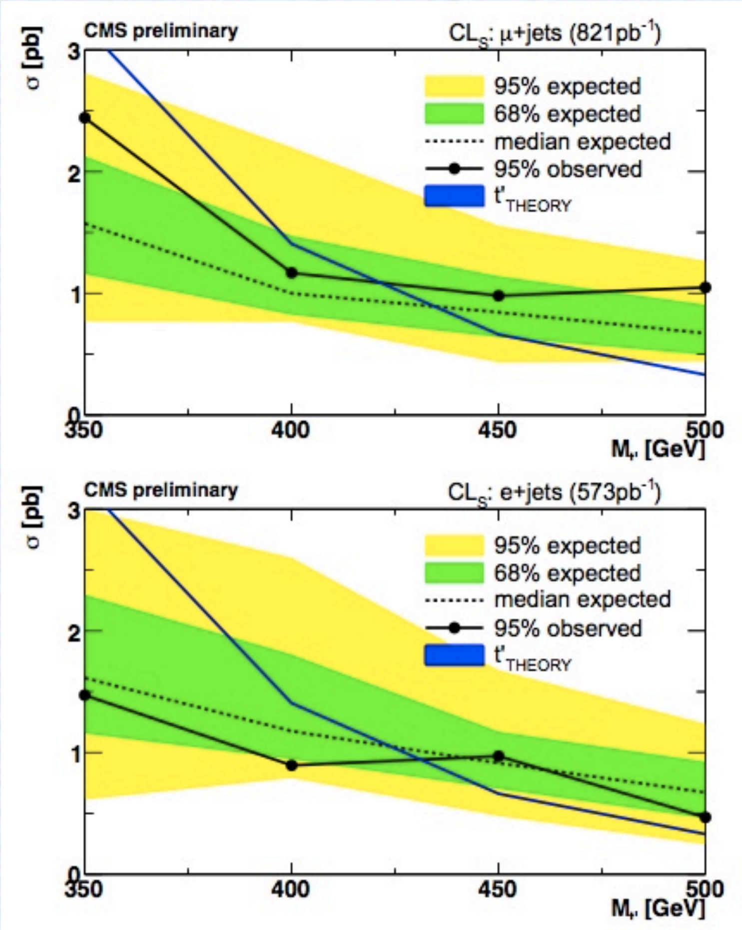
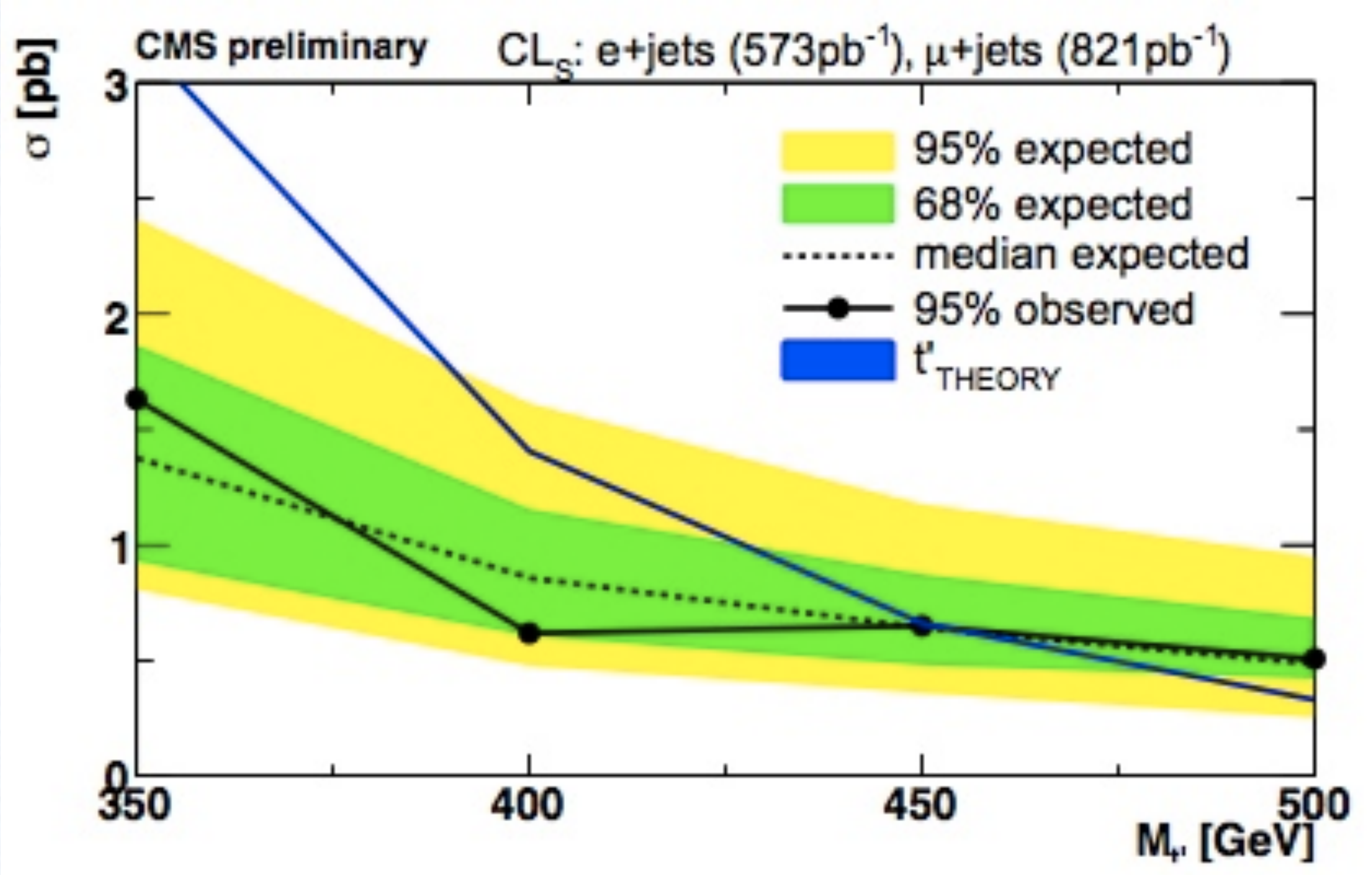




- Simultaneous fit to the H_T-m_{fit} histograms of the e&μ channels to obtain limits with CLs. Nuisance parameters to take into account jet E-scale, σ_{tt}, contribution from EW backgrounds, uncertainties on lepton ID eff, b-tagging eff.
  - 95%CL lower limit assuming B(t′->Wb)=1 : m(t′)>450 GeV

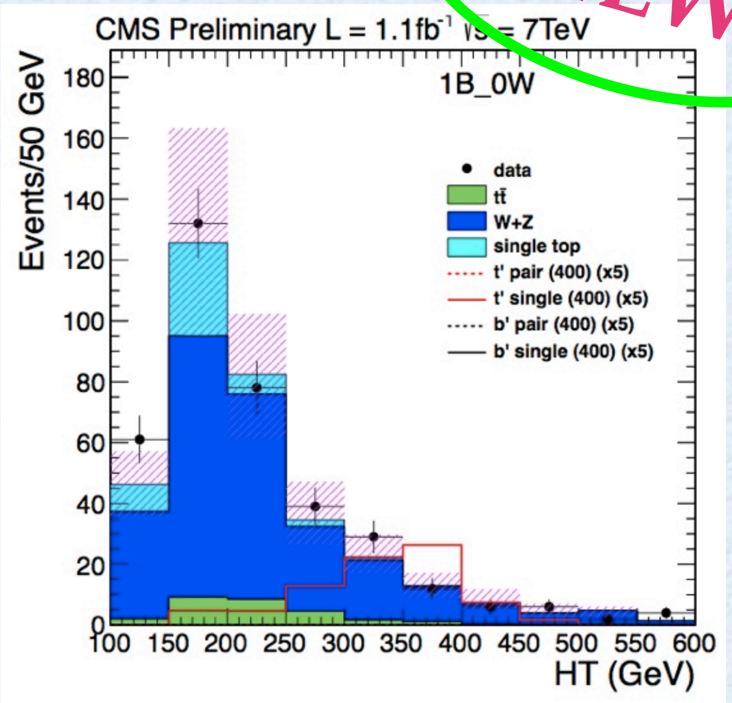
573 pb^{-1} e+jets
821 pb^{-1} μ+jets

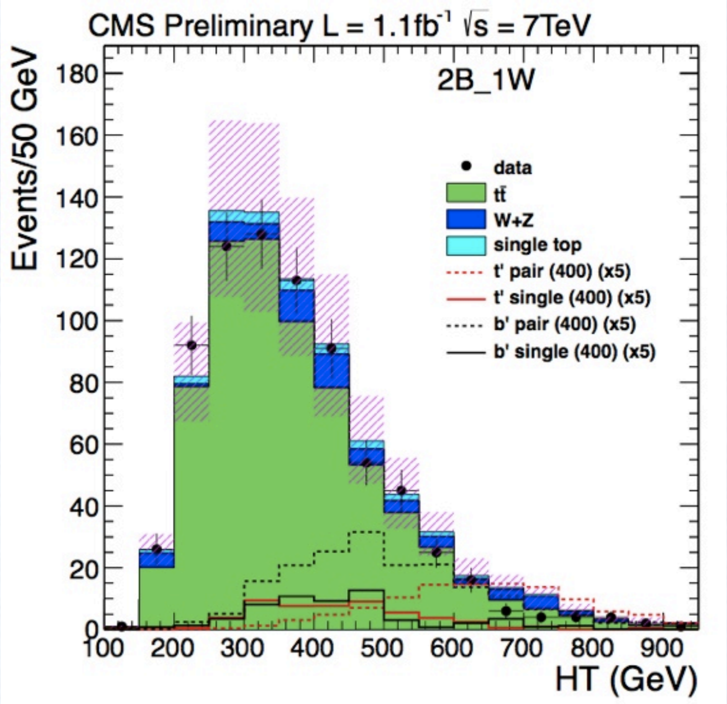
4G Inclusive Search

PAS EXO-11-054

NEW

- Inclusive analysis including single and pair-production of degenerate 4th gen. quarks
  - t′b -> bWb ; b′t -> t_{bW}WbW ;
    t′t′ -> bWbW ; b′b′ -> t_{bW}Wt_{bW}W
- Search carried in 6 subsamples, based on $n_{b\text{-}jet}$ and $n_{W\to qq}$, and with slightly different selection requirements:
  - {1,2+}B_0W: mainly single t′ production
  - 1B_1W, 2+B_{1,2,3+}W: mainly pair production
- Isolated muon with P_T^{μ}>40GeV and |η|<2.1, vetoes on extra leptons.
- H_T is used as discriminating variable and a fit is performed to 6 subsamples together.





4G Inclusive Results

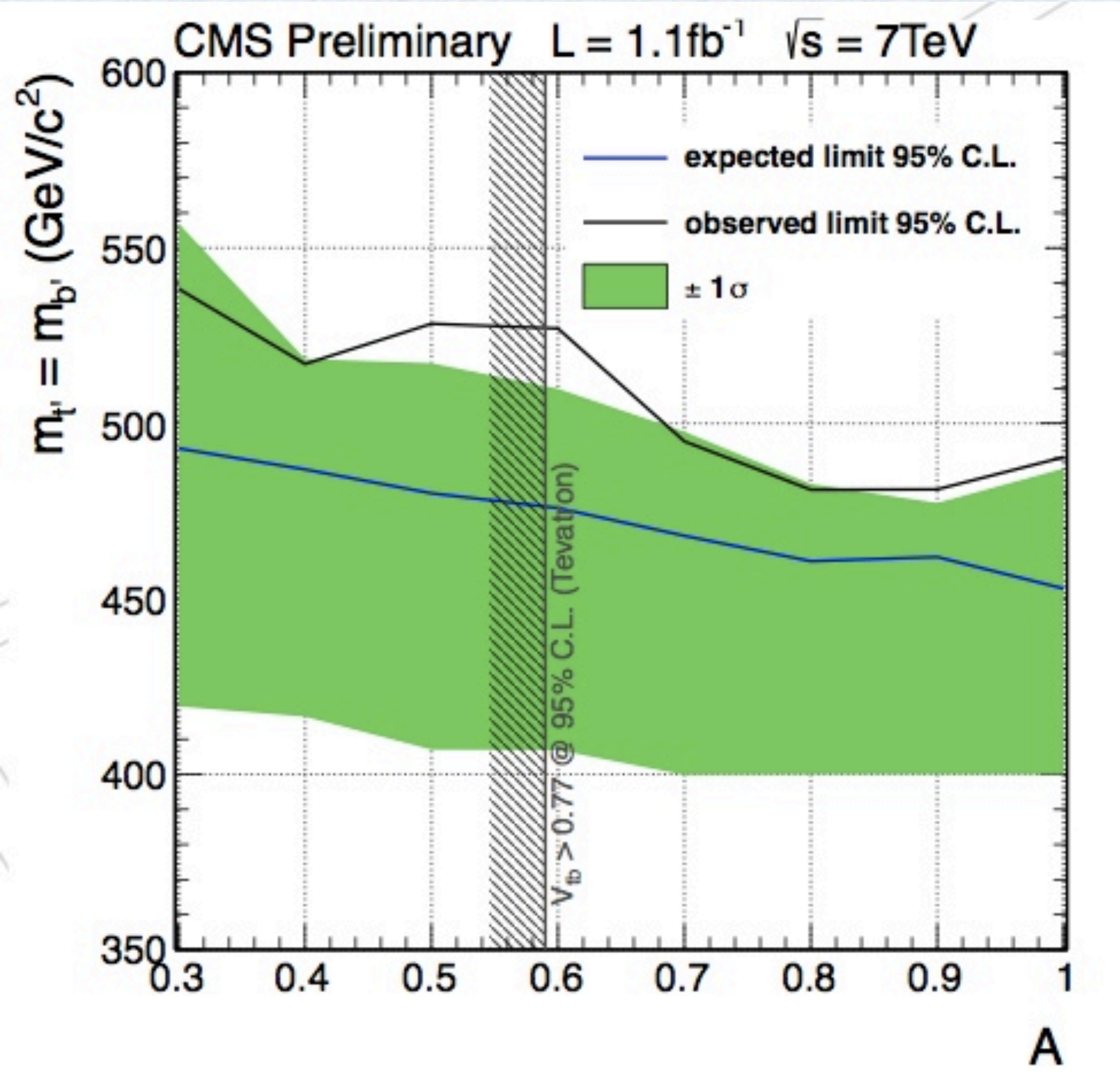
PAS EXO-11-054

NEW

- Results presented in the (A, m_{q4}) plane, where mq4 is the degenerate mass of the quarks, $A=|V_{tb}|^2$.

$$\mathrm{CKM4} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & \sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

- Using CL_S, obtained 95% CL limit for minimal off-diagonal mixing (A≈1): $m_{t'}=m_{b'} > 490\text{GeV}$



For more details, see poster by Petra Van Mulders.

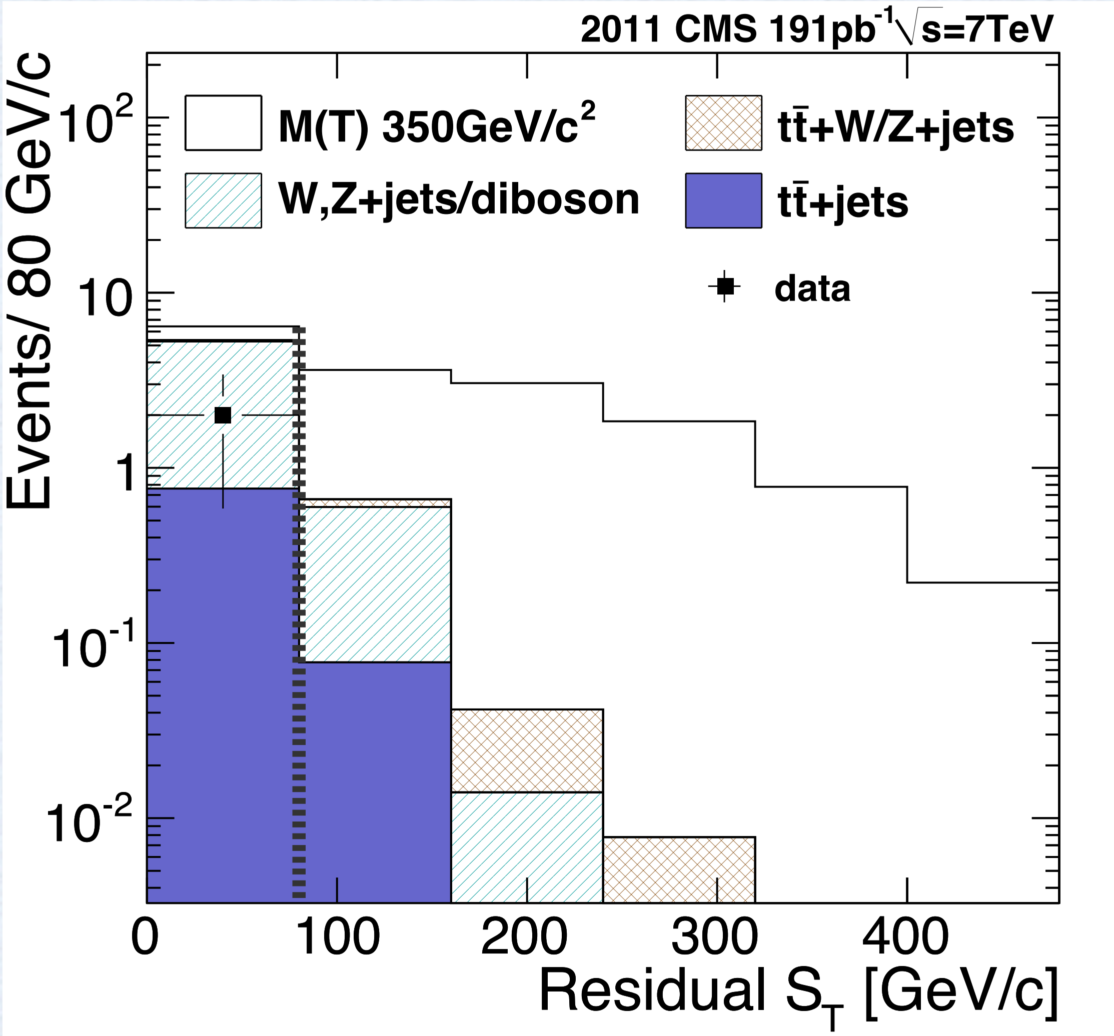
1.1 fb⁻¹

FCNC Top-Like T

PAS EXO-11-005

- Vector-like quarks from composite Higgs models, little Higgs, extra dimensions, etc. can have FCNC decays.
- If m(H)>m(T)-m(t), the dominant (only) decay channel can be T->tZ.

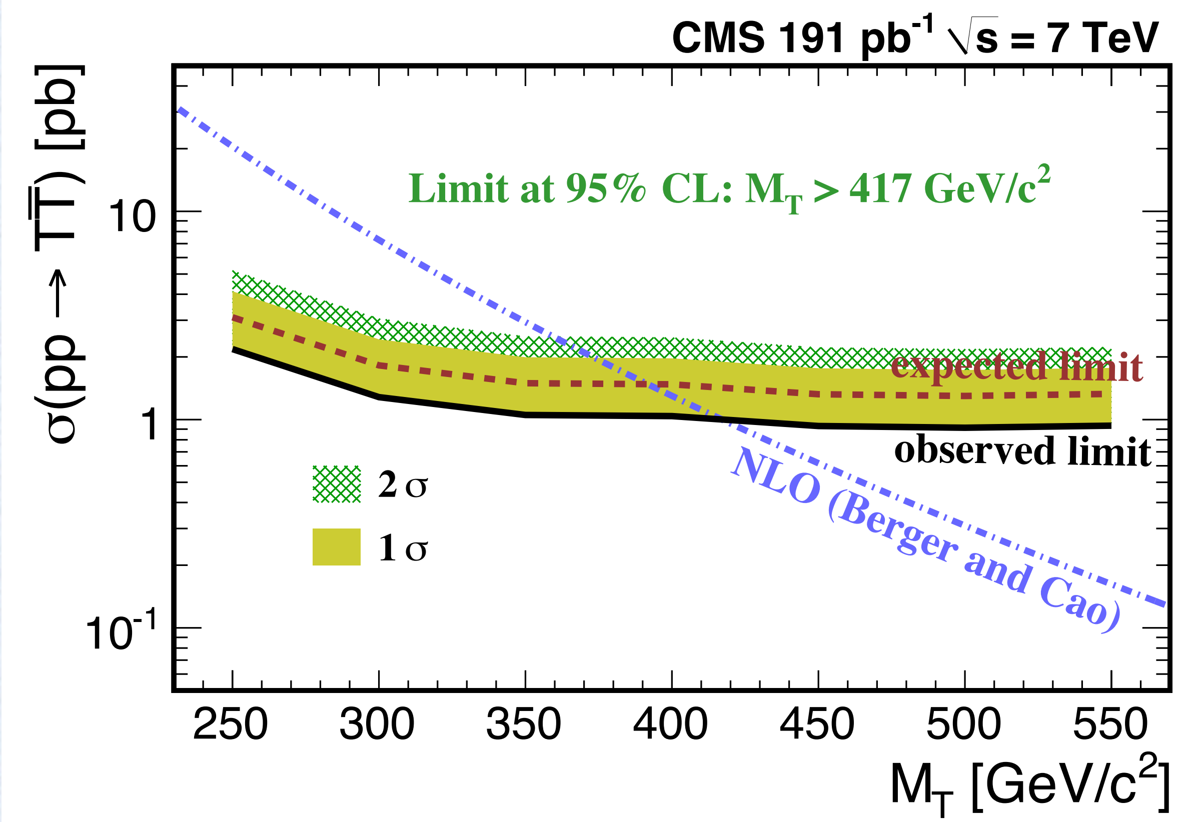
- Complex final state with low backgrounds.
    - pp -> TT -> tZtZ -> bW bW ZZ
    - P_T^e>20 GeV, P_T^μ>15 GeV, well-measured, isolated (within cone ΔR=0.3)
    - One leptonic Z: OSSF leptons, 60 < $|m_{ll}|$ < 120 GeV
    - At least one additional lepton, and 2+ jets
    - residual $S_T \equiv \Sigma E_T$(jets beyond the hardest two, leptons beyond the hardest two) > 80 GeV



Limits on FCNC T

PAS EXO-11-005

Process	Cross-section (pb)	ϵ[%]	Yield
$T\bar{T}$, $M(T) = 250$ GeV/c^2	20.5 (NLO)	14.5 ± 3.0	30.4
$T\bar{T}$, $M(T) = 300$ GeV/c^2	7.29 (NLO)	24.6 ± 5.0	18.4
$T\bar{T}$, $M(T) = 350$ GeV/c^2	2.94 (NLO)	29.9 ± 6.8	8.99
$T\bar{T}$, $M(T) = 400$ GeV/c^2	1.30 (NLO)	30.3 ± 6.9	4.03
$T\bar{T}$, $M(T) = 450$ GeV/c^2	0.617 (NLO)	33.8 ± 7.7	2.13
$T\bar{T}$, $M(T) = 500$ GeV/c^2	0.310 (NLO)	34.4 ± 7.9	1.09
$T\bar{T}$, $M(T) = 550$ GeV/c^2	0.162 (NLO)	33.6 ± 7.9	0.56
$t\bar{t}$ + jets	158 (CMS)	$(2.6 \pm 2.0) \times 10^{-4}$	0.08
Z + jets	2.9×10^3 (CMS)	$(6.3 \pm 5.4) \times 10^{-5}$	0.35
WZ inclusive	18.0 (NLO)	$(3.3 \pm 0.5) \times 10^{-3}$	0.12
ZZ inclusive	5.9 (NLO)	$(5.9 \pm 0.6) \times 10^{-3}$	0.07
$t\bar{t}$ + W + jet	0.144 (LO)	$(1.3 \pm 1.3) \times 10^{-2}$	0.004
$t\bar{t}$ + Z + jet	0.094 (LO)	$(5.4 \pm 1.3) \times 10^{-1}$	0.10
Expected background from simulated samples			0.71
Background with two real leptons (data-driven)			0.45 ± 0.28
Background with three real leptons (simulated)			0.28 ± 0.11
Sum (estimated background)			0.73 ± 0.31
Data (191 pb^{-1})			0



- Estimated background: 0.73 events. No observed events.
- Bayesian upper limits computed with flat prior and assuming B(T->tZ) = 1:
  - m(T) > 417 GeV at 95% CL

191 pb^{-1}

The results have just been updated to 1.14 fb^{-1}, and the limit is now m(T)>475 GeV.

Top Partners

arXiv:1109.4725

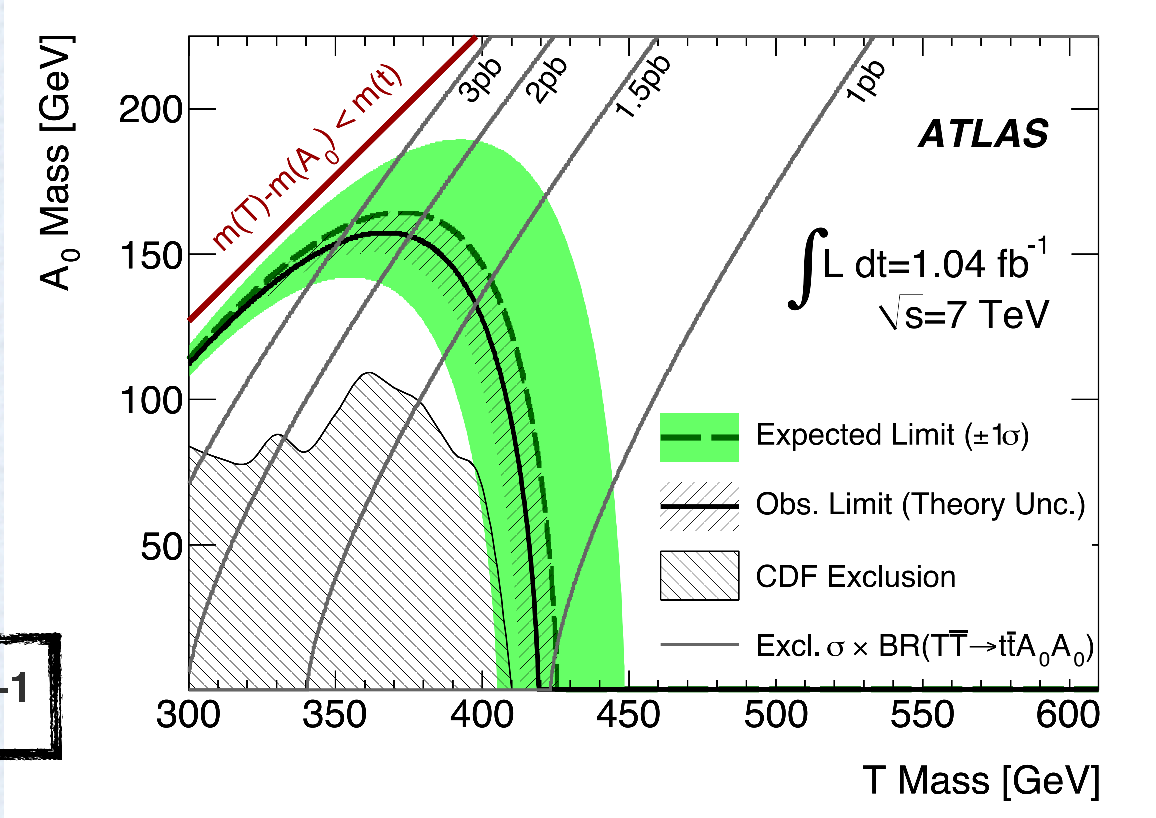
- A word on exotic top partners that decay T->tA_0.
  - A_0 is a stable, neutral scalar; hence E_T^{miss}.
  - In most models, T is quark-like (Q=⅔, spin=½, produced in gluon-fusion & qq annihilation).
  - Ex: Little Higgs with T-parity conservation, UED models with KK parity, stops decaying to t & neutralino.
- Exactly one electron(muon) with P_T>25(20) GeV. Veto on extra leptons with P_T>15 GeV, on isolated tracks with P_T>12 GeV.
- At least 4 jets with P_T>25 GeV.
- E_T^{miss}>100 GeV, m_T>150 GeV.
- Estimated bkg = 101±16
  Observed events = 105
- Assuming B(T->tA_0)=100%, exclude at 95% CL:

  m(T)<420 GeV for m(A_0)<10 GeV.

  330<m(T)<390 GeV for m(A_0)<140 GeV.

1.04 fb^{-1}

Source	*N(evts)*
di-lept. tt	62 ± 15
single-lept. tt / W+jets	33.1 ± 3.8
multi-jet	1.2 ± 1.2
single t	3.5 ± 0.8
Z+jets	0.9 ± 0.3
dibosons	0.9 ± 0.2
Total	101 ± 16
Data	105



Top Quark Charge

ATLAS-CONF-2011-141

NEW

- "Top" quark could be an exotic quark with Q=-4/3.
- Measurement of top quark charge in high-purity tt sample.
  - Candidate semi-leptonic tt events chosen with the same criteria as ATLAS tt charge asymmetry note, ATLAS-CONF-2011-106.
  - electron events: P_T^e>25 GeV, E_T^{miss}>35 GeV, m_T^W>25 GeV
  - muon events: P_T^μ>20 GeV, E_T^{miss}>20 GeV, $E_T^{miss}+m_T^W$>60 GeV
  - 4+ jets with P_T^j>20 GeV, at least one of which is b-tagged
- Two techniques:
  - Track charge weighting: Use correlation between charge of b-quark and the charges of tracks in the b-jet. Require a 2nd b-jet in event. (About 2200 events with 90% tt purity).
  - Soft lepton: charge of lepton from semileptonic B-hadron decays. Require a muon with P_T>4GeV that is within ΔR=0.4 cone of a jet. (About 1700 events with 80% tt purity).

Charge Determination

ATLAS-CONF-2011-141

NEW

Track charge weighting

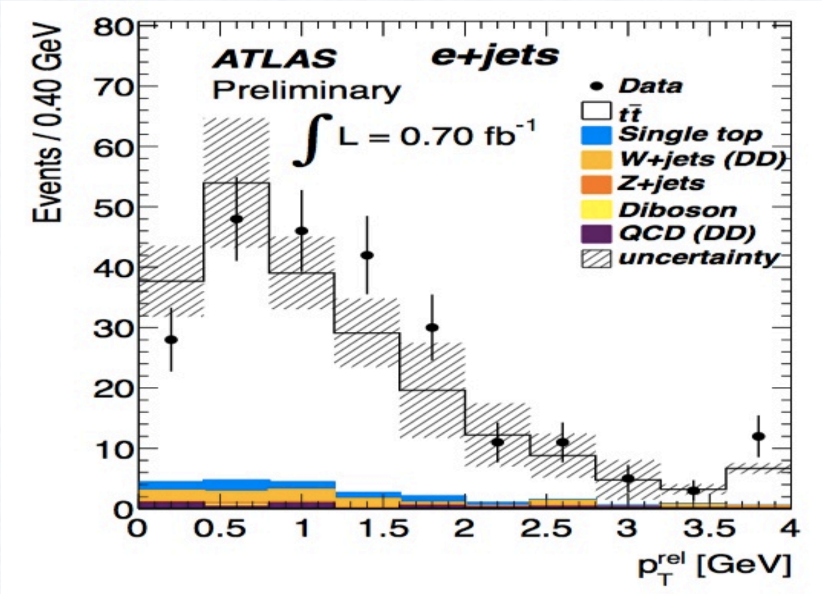
- b-jet charge is defined as:

$$Q_{b\,jet} = \frac{\sum_i q_i |\vec{j}\cdot\vec{p_i}|^\kappa}{\sum_i |\vec{j}\cdot\vec{p_i}|^\kappa}$$

  - q_i = charge, $\mathbf{p}_i$ = momentum of track i, that is within ΔR=0.25 of the b-jet axis, **j**. κ=0.5
  - Up to 10 tracks with P_T>1GeV enter the computation.
- Discriminating variable: $Q_{comb} = Q_{bjet} \times Q_{lepton}$
  - Matching of the lepton and the b-jet is based on checking the invariant mass of lepton and b-jet: m(l,b-jet), since this cannot be larger than m_{top}.

Soft muon tag

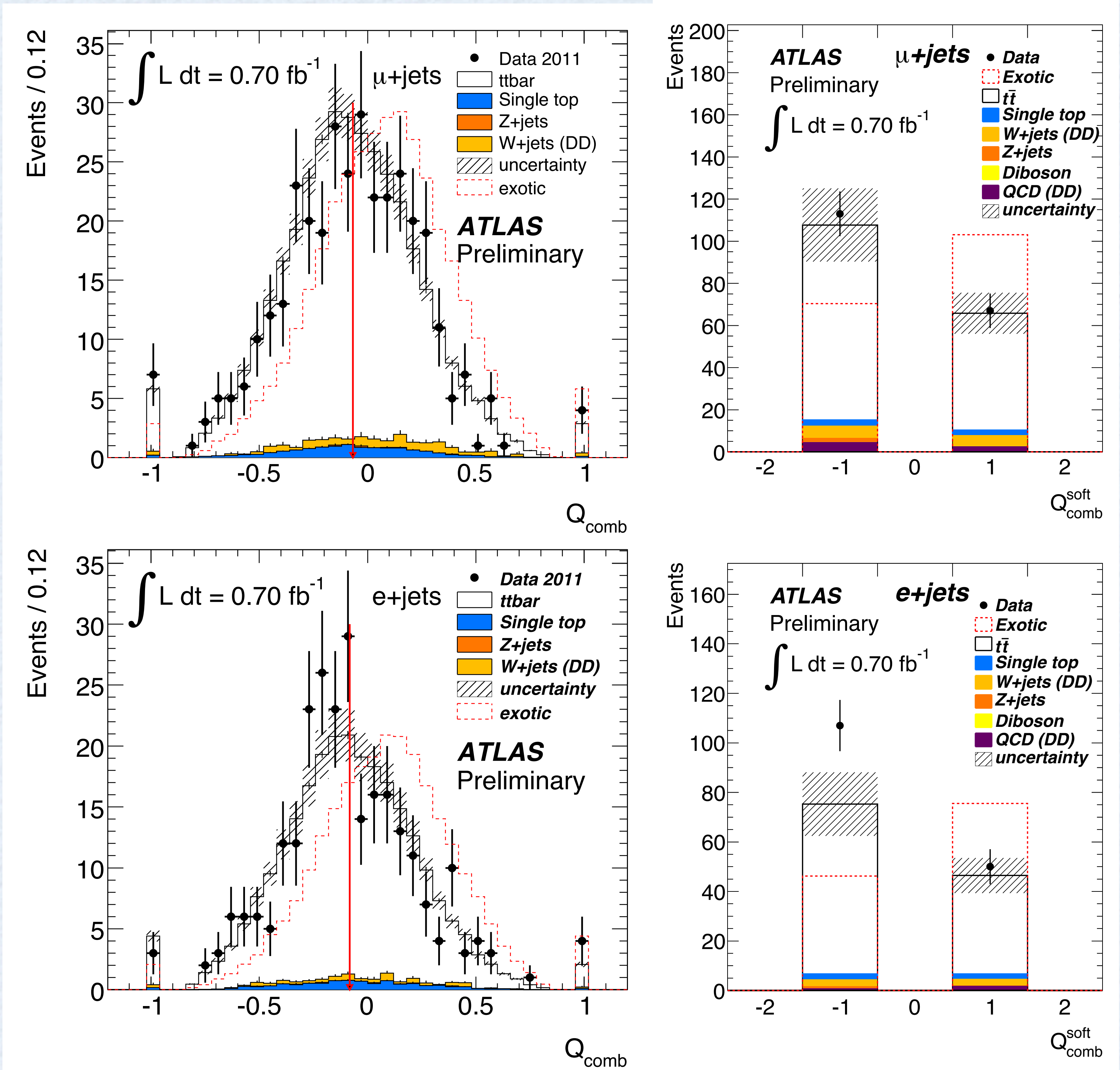
- b-jet charge is based on the charge of a soft muon identified:
  - A kinematic likelihood fitter determines event topology.
  - Jet with highest likelihood of coming from leptonically decaying top is selected.
  - Search for a μ of P_T^{rel}>0.8 GeV in the selected jet.



- Discriminating variable: $Q_{comb}^{soft} = Q_{soft\mu} \times Q_{lepton}$

Results on Exotic Charge

ATLAS-CONF-2011-141



- Observed charge distribution is in good agreement with SM.
- Mean value of Q_{comb} and Q_{comb}^{soft} is used to define a test statistic.
- Q=-4/3 hypothesis excluded at more than 5σ.

	$\langle Q_{comb}^{soft} \rangle$
SM	-0.234 ± 0.011
Exotic	$+0.209 \pm 0.011$
Measured	-0.31 ± 0.07

	$\langle Q_{comb} \rangle$
SM	-0.082 ± 0.020
Exotic	$+0.083 \pm 0.020$
Measured	-0.082 ± 0.015

NEW

0.70 fb^{-1}

Conclusions

- ATLAS and CMS is searching for new heavy quarks in multiple decay channels.
  - Most stringent constraints so far on 4th generation quarks (assuming dominant mixing with 3rd gen.).
    - $M(t') > 450$ GeV ; $M(b') > 495$ GeV ; $M(q_4) > 490$ GeV
  - Limits on (m_T, m_{A0}) plane for top-partners decaying to top+E_T^{miss}:
    - $m(T) \gtrsim 400$ GeV for $m(A_0) < 100$ GeV.
  - A "top" quark with exotic charge of $Q=-4/3$ has been excluded at more than 5σ.
- Some of these analyses are still with 2010 data, updates are in the pipeline, and are likely to improve the search range significantly.
  - With $5 fb^{-1}$, the 4th gen. limits can be pushed by another 50-80GeV.

Backups

SM4, Why Not?

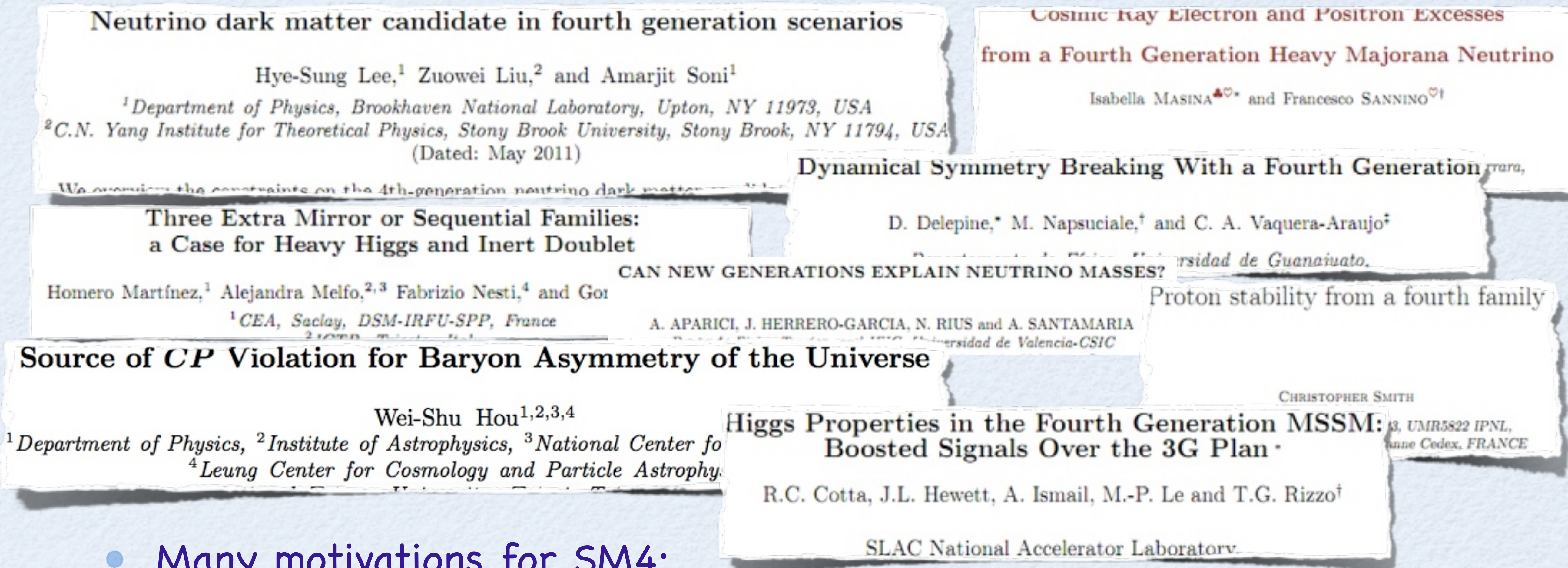
- Number of generations - not set in SM.
  - On the muon: "Who ordered that?" - I.I. Rabi
  - But then we got two full generations of fermions. So the real question: "Who decided not to order more?"
- But why was it so unpopular for a while?
  - Pre-neutrino oscillation days: Neutrinos were massless & LEP found N(neutrino lighter than $m_Z/2$)=3.

> An extra generation of ordinary fermions is excluded at the 99.95% CL on the basis of the S parameter alone, corresponding to $N_F = 2.92 \pm 0.27$ for the number of families. This result assumes that there are no new contributions to T or U and therefore that any new families are degenerate. In principle this restriction can be

From PDG 2004

  - PDG thought EW oblique parameters were inconsistent with extra generations - as the calculation assumed a fully "degenerate" 4th generation. (In the meantime, there were papers showing the full EW fit allowed a non-degenerate 4th generation!)

Why SM4?


Neutrino dark matter candidate in fourth generation scenarios

Hye-Sung Lee,[1] Zuowei Liu,[2] and Amarjit Soni[1]

[1]Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA
[2]C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794, USA
(Dated: May 2011)

Cosmic Ray Electron and Positron Excesses from a Fourth Generation Heavy Majorana Neutrino

Isabella Masina and Francesco Sannino

Dynamical Symmetry Breaking With a Fourth Generation

D. Delepine,* M. Napsuciale,† and C. A. Vaquera-Araujo‡

Three Extra Mirror or Sequential Families: a Case for Heavy Higgs and Inert Doublet

Homero Martínez,[1] Alejandra Melfo,[2,3] Fabrizio Nesti,[4] and Gor

[1]CEA, Saclay, DSM-IRFU-SPP, France

CAN NEW GENERATIONS EXPLAIN NEUTRINO MASSES?

A. APARICI, J. HERRERO-GARCIA, N. RIUS and A. SANTAMARIA

Universidad de Valencia-CSIC

Proton stability from a fourth family

Christopher Smith

Source of CP Violation for Baryon Asymmetry of the Universe

Wei-Shu Hou[1,2,3,4]

[1]Department of Physics, [2]Institute of Astrophysics, [3]National Center fo
[4]Leung Center for Cosmology and Particle Astrophys

Higgs Properties in the Fourth Generation MSSM: Boosted Signals Over the 3G Plan

R.C. Cotta, J.L. Hewett, A. Ismail, M.-P. Le and T.G. Rizzo†

SLAC National Accelerator Laboratory

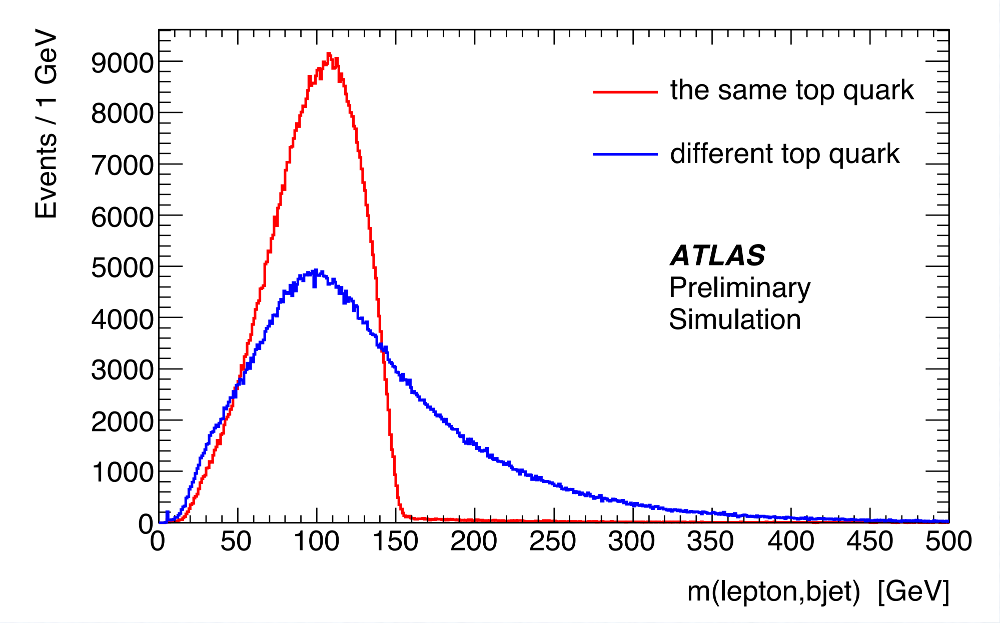
- Many motivations for SM4:
  - Baryon asymmetry, dynamical EW symmetry breaking, SM flavor structure, dark matter neutrinos, help SUSY/technicolor/… to escape LEP/LHC limits, etc. etc.
  - <u>From experimentalist POV</u>: simple model - can provide benchmark MC for signature-based new quark/lepton searches, clear predictions, few free parameters, discover or reject at LHC…

Upcoming 3rd WS in Istanbul, October 23-25

Track Charge Weighting

ATLAS-COM-CONF-2011-163

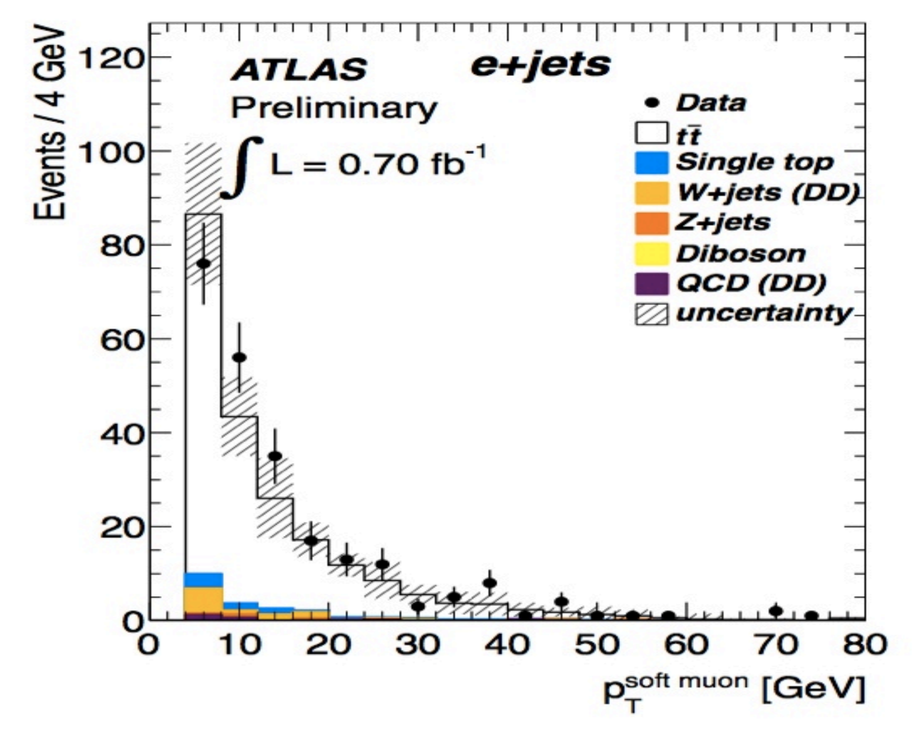
- b-jet charge is defined as: $Q_{bjet} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^{\kappa}}{\sum_i |\vec{j} \cdot \vec{p}_i|^{\kappa}}$
  - q_i = charge, $\mathbf{p}_i$ = momentum of track i, that is within ΔR=0.25 of the b-jet axis, **j**. κ=0.5
  - Up to 10 tracks with P_T>1GeV enter the computation.
- Discriminating variable: $Q_{comb} = Q_{bjet} \times Q_{lepton}$
  - To match lepton and b-jet, look at invariant mass of lepton and b-jet: m(l,b-jet)
  - Take only those events in which m(l,b-jet)>155GeV for one b-jet and m(l,b-jet)<155GeV for the other b-jet.

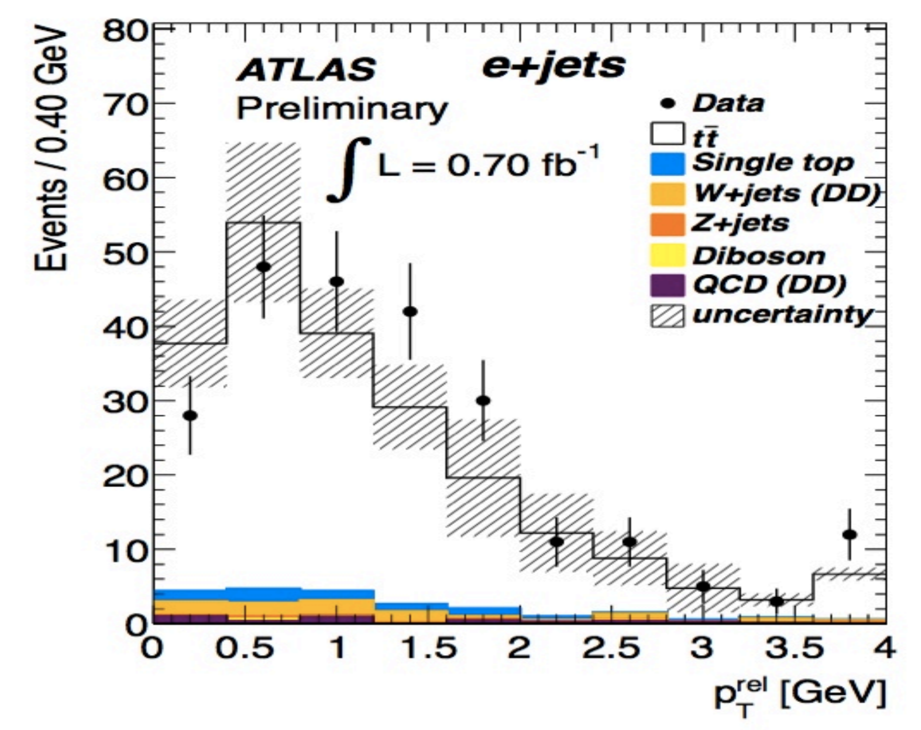


Soft Muon Charge

ATLAS-COM-CONF-2011-163

- A kinematic likelihood fitter determines event topology.
- Jet with highest likelihood of coming from leptonically decaying top is selected.
- Search for a μ of P_T^{rel}>0.8 GeV in the selected jet.
- Then define discriminating variable:
  $Q_{comb}^{soft} = Q_{soft\mu} \times Q_{lepton}$

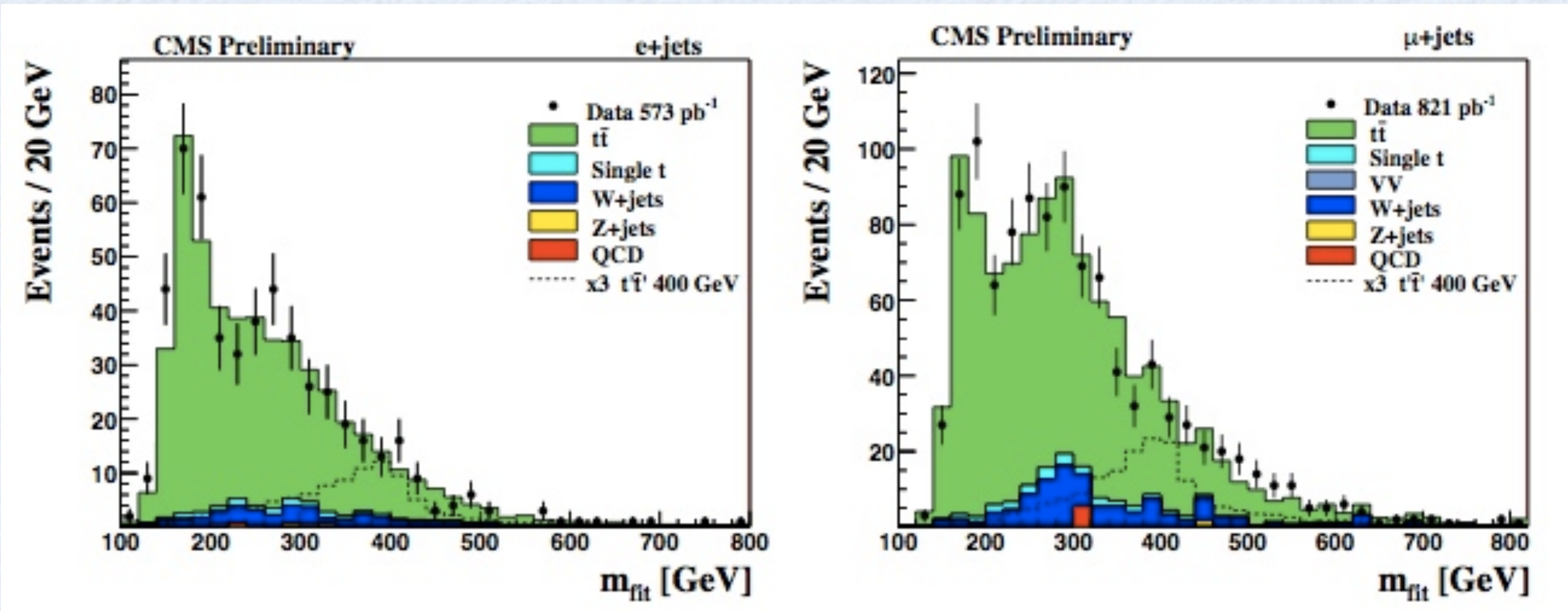


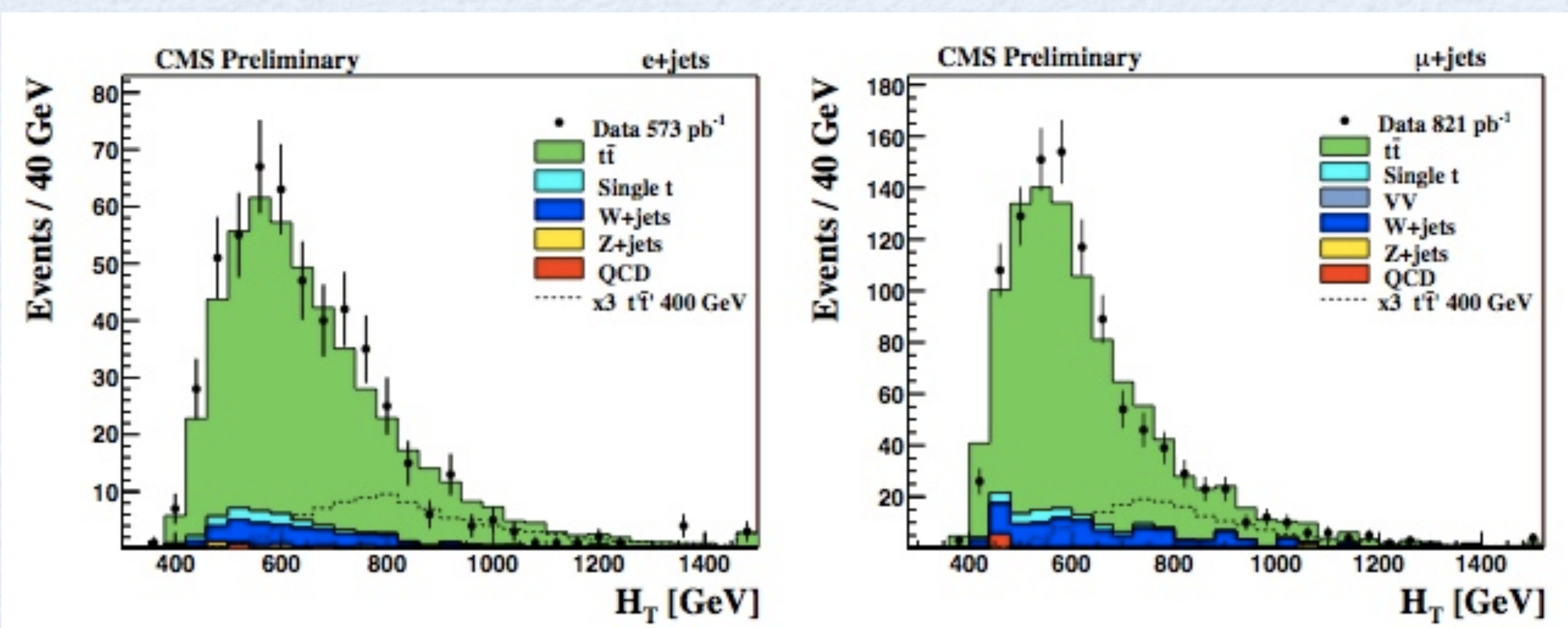


Fitting for M(T′)

Lepton + Jets Channel

PAS EXO-11-051





- Take four-jet combinations out of the hardest 5 jets. (Slightly different assignment for μ channel.)
- Use W mass contraints and the fact that the 2 reco t′ masses should be equal.
- Perform kinematic fit minimizing the χ^2 computed from the measured momenta of all final-state particles and their resolutions.

TOP PARTNERS (OLD)

ATLAS-CONF-2011-036

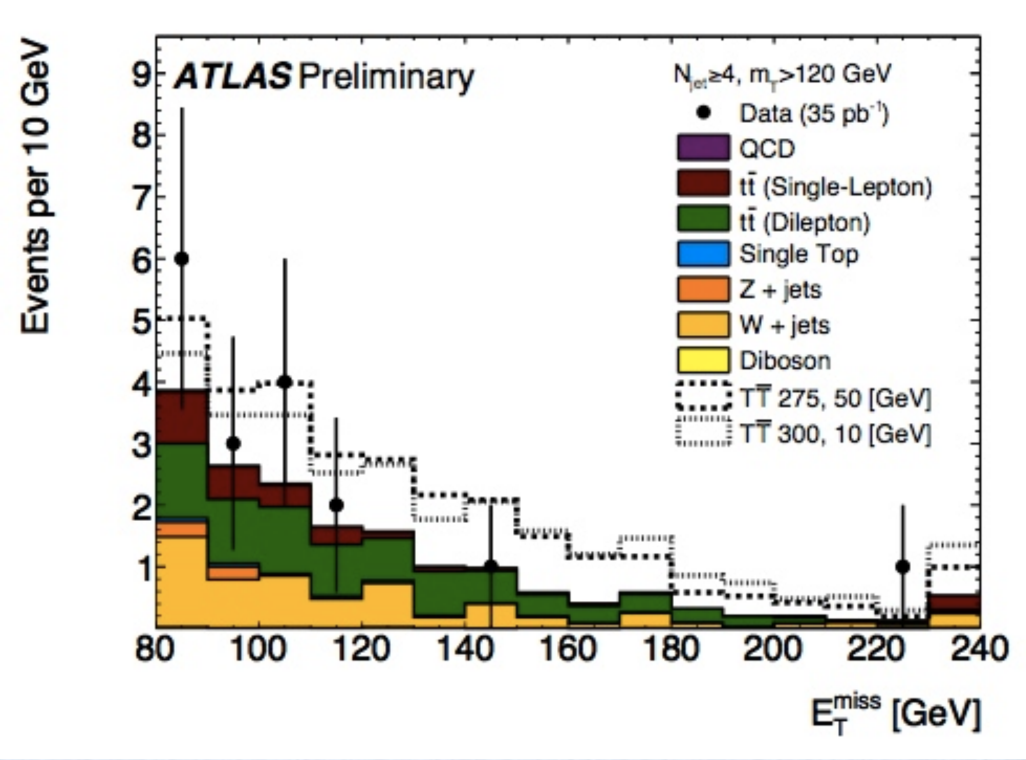
- A word on exotic top partners that decay T->tA_0.
  - A_0 is a stable, neutral scalar; hence E_T^{miss}.
  - In most models, T is quark-like (Q=⅔, spin=½, produced in gluon-fusion & qq annihilation).
  - Ex: Little Higgs with T-parity conservation, UED models with KK parity, stops decaying to t & neutralino.
- Exactly one lepton with P_T>20 GeV. Veto on (loose) leptons with P_T>15 GeV, on isolated tracks with P_T>12 GeV.
- At least 4 jets with PT>20 GeV.
- E_T^{miss}>80 GeV, m_T>120 GeV.
- Estimated bkg = 17.2
  Observed events = 17
- Exclude at 95% CL:

  m(T)=300 GeV for m(A_0)<10 GeV.

  m(T)=275 GeV for m(A_0)<50 GeV.

35 pb^{-1}

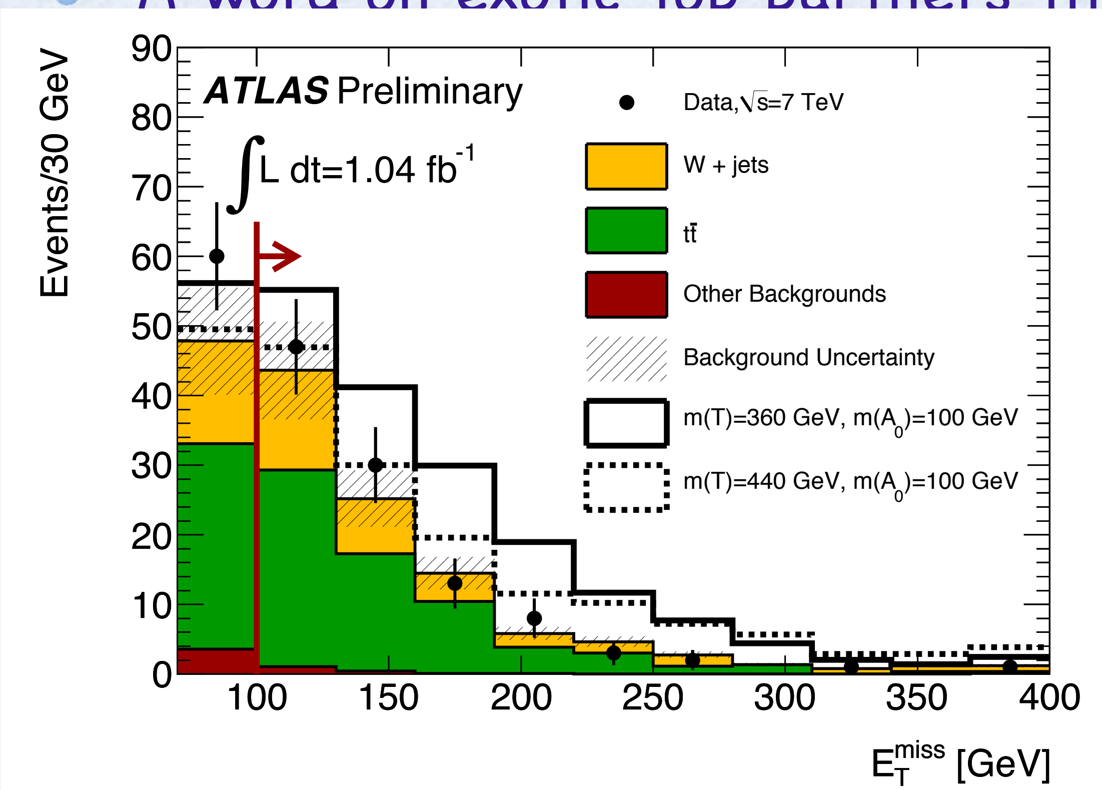
Source	Yield
Single-Lepton $t\bar{t}/W$	8.4 ± 1.6
Dilepton $t\bar{t}$	7.6 ± 2.0
Z+jets	0.4 ± 0.1
Dibosons	$0.2 \pm <0.1$
Single Top	0.4 ± 0.1
QCD	0.2 ± 0.6
Total Background	17.2 ± 2.6
Data	17



Top Partners (old)

ATLAS-CONF-2011-036

- A word on exotic top partners that decay T->tA_0.



…ence E_T^{miss}.

… (Q=⅔, spin=½, produced in …

…conservation, UED models

Source	Yield
Single-Lepton $t\bar{t}/W$	8.4 ± 1.6
Dilepton $t\bar{t}$	7.6 ± 2.0
Z+jets	0.4 ± 0.1
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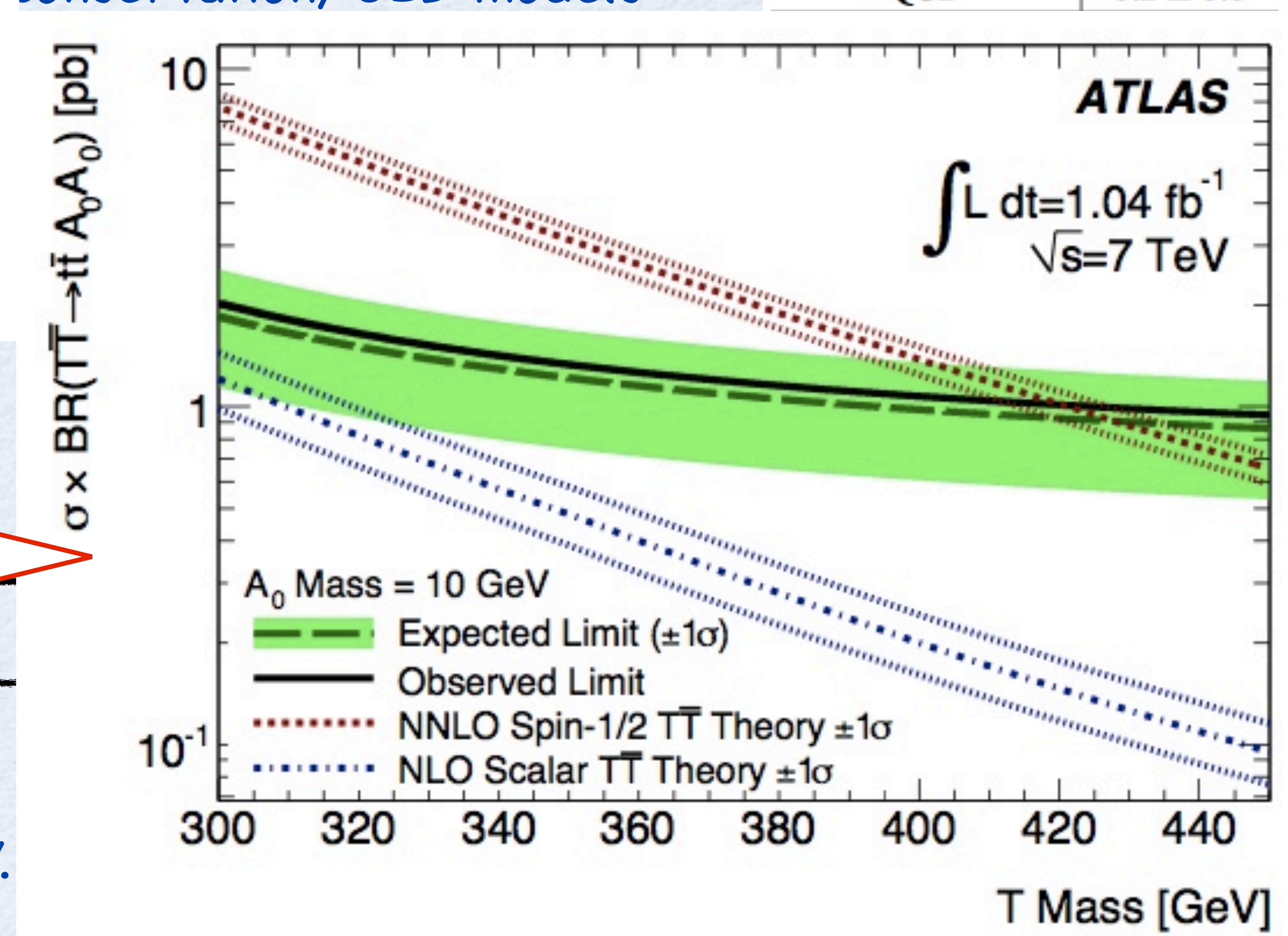

- E_T^{miss}>80 GeV, m_T>120 GeV.
- Es…
  O…
- Ex…
  m(T)=300 GeV for m(A_0)<10 GeV.
  m(T)=275 GeV for m(A_0)<50 GeV.

Updated result:
m(T) > 420 GeV