ATLAS Top Physics Results

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Fermilab Wine and Cheese Seminar

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Motivation to Study Top Quark

Theoretical

- Heaviest of the known fundamental particles

  $m_t = 173.2 \pm 0.9$ GeV close to electroweak scale $\Rightarrow$ may play a special role in symmetry breaking
- Prompt decay is much shorter than QCD scale gives a unique opportunity to study spin, mass and couplings of a "bare quark"

  width $\Gamma = 1.42$ GeV and lifetime $\tau = 4.5 \times 10^{-25}$s $\ll \Lambda_{QCD}^{-1}$
- Largest contribution to quadratic divergences of SM Higgs mass comes from top quark loop $\Rightarrow$ physics beyond the Standard Model

  New top partners with same spin could fix the hierarchy problem

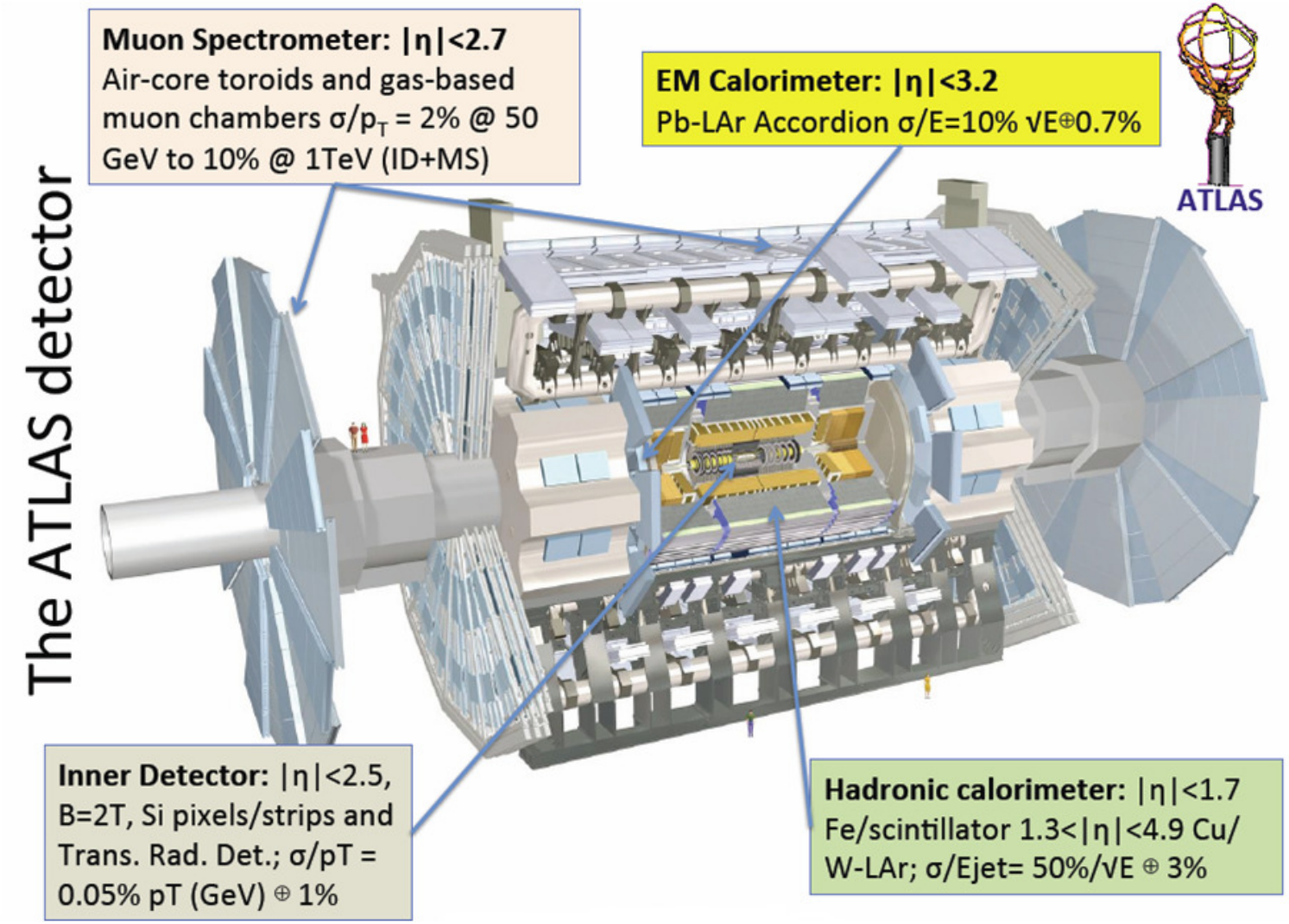
  X$\rightarrow t\bar{t}$: Topcolor or Little Higgs Z', g_{KK} from RS extra dimensions etc.

Experimental

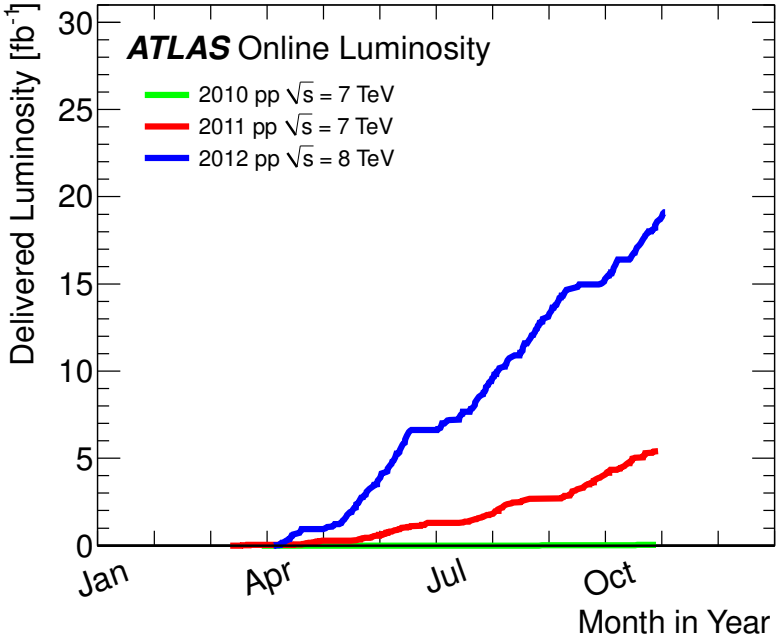
- LHC is a top factory. We can measure, search, calibrate with top quarks
- Well established experimental techniques to isolate and identify top quarks

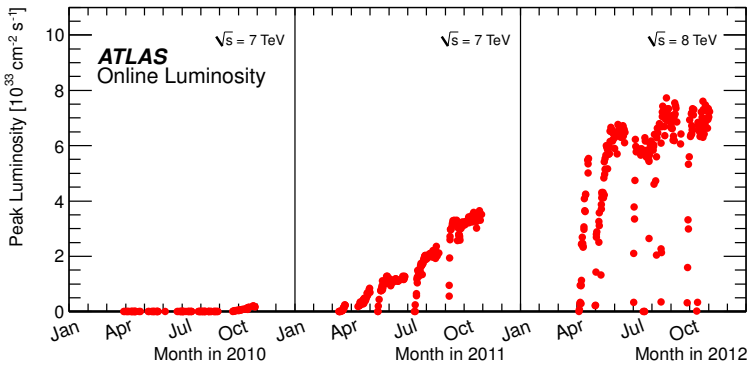
  New "boosted" reconstruction techinques gain importance at higher center-of-mass energies

ATLAS Detector



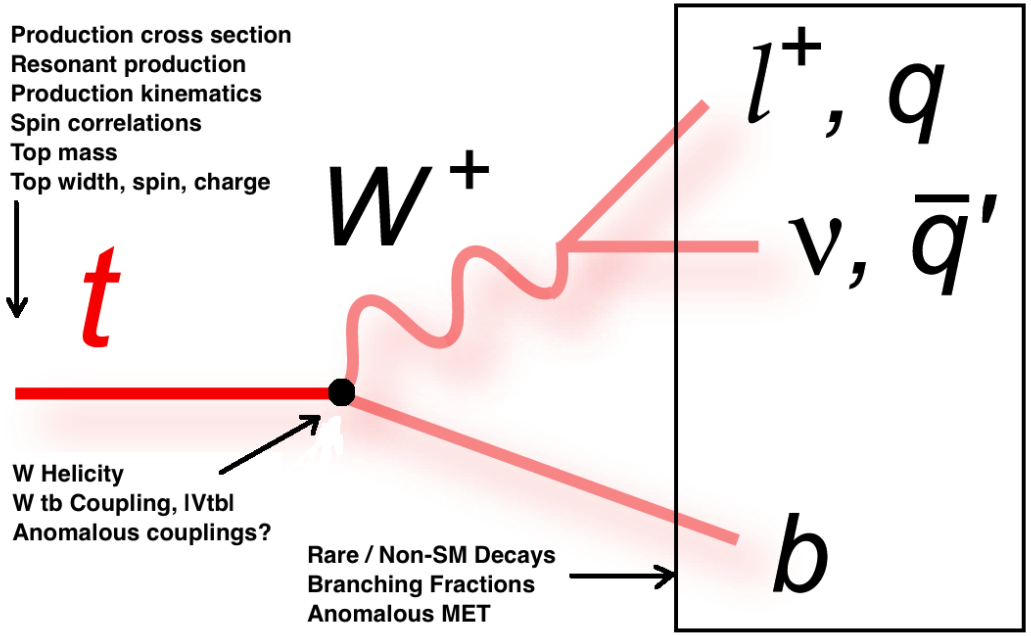
ATLAS Integrated Luminosity 2011 vs. 2012





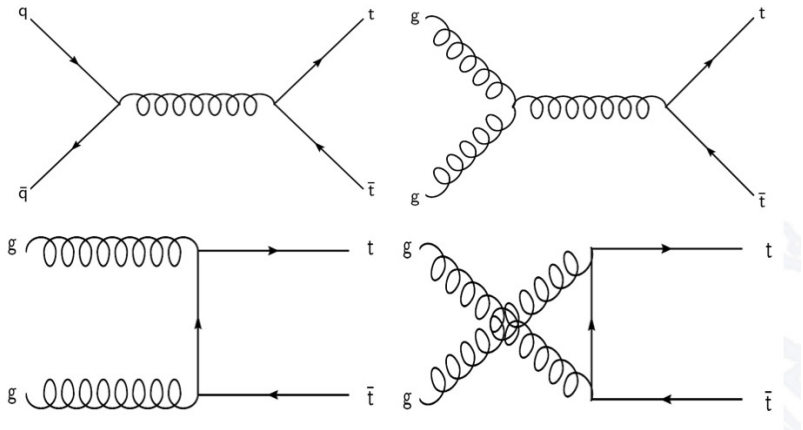
- Steady increase in integrated luminosity ~ 18 fb^{-1} on Nov 1 2012
- 2012 set a new record for instantaneous luminosity $7.73 \times 10^{33} cm^{-2} s^{-1}$
- Analyses and results shown today include dataset with $\sim 5\, fb^{-1}$ from 2011 (2012) datasets

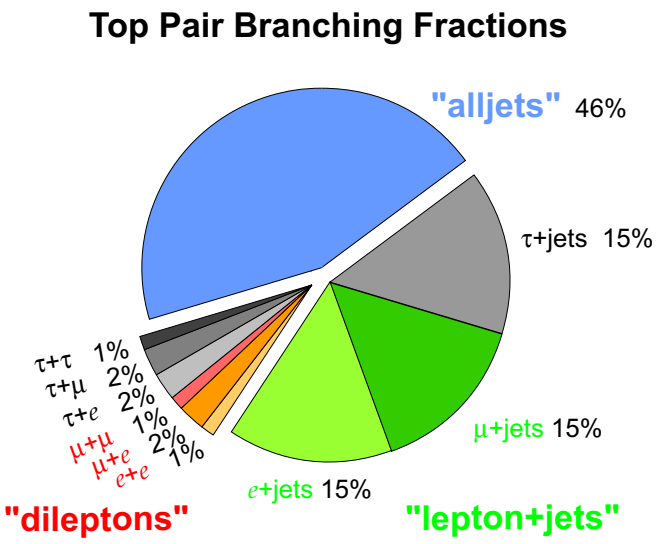
Overview



- Pair Production
  - Inclusive cross section
- Single Top
  - t-channel cross section
- Properties
  - Charge
- Pair properties
  - Spin correlation
  - Charge asymmetry
- New physics in top final states
  - Resonance searches

Top pair production and decay at LHC





- Production
  - gluon fusion: $gg \to t\bar{t}$ (90%) dominates at LHC
  - $q\bar{q}$ annihilation: $q\bar{q} \to t\bar{t}$ (10%)
- Decay
  - Branching ratio $\mathrm{Br}(t \to Wb) \sim 1$
  - t may decay leptonically ($t \to \ell\nu b$) or hadronically ($t \to qq'b$)
  - **alljets:** Br=46%, large multi-jet background
  - **lepton+jets:** Br=45%, intermediate background
  - **dileptons:** Br=9%, small multijet background

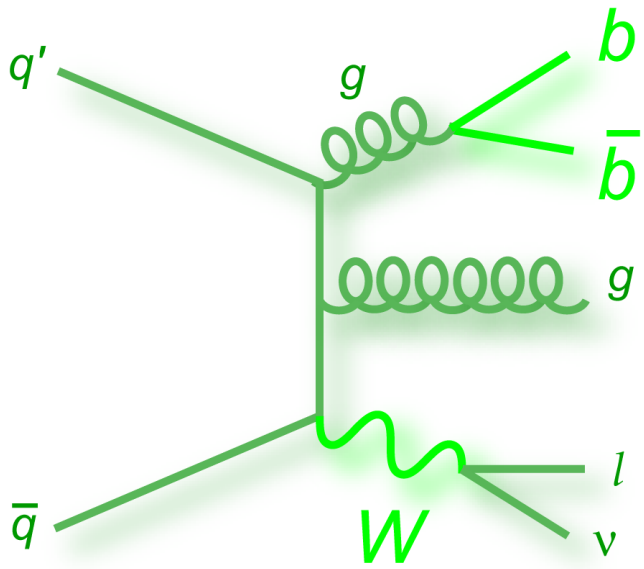
Object Reconstruction and Selection

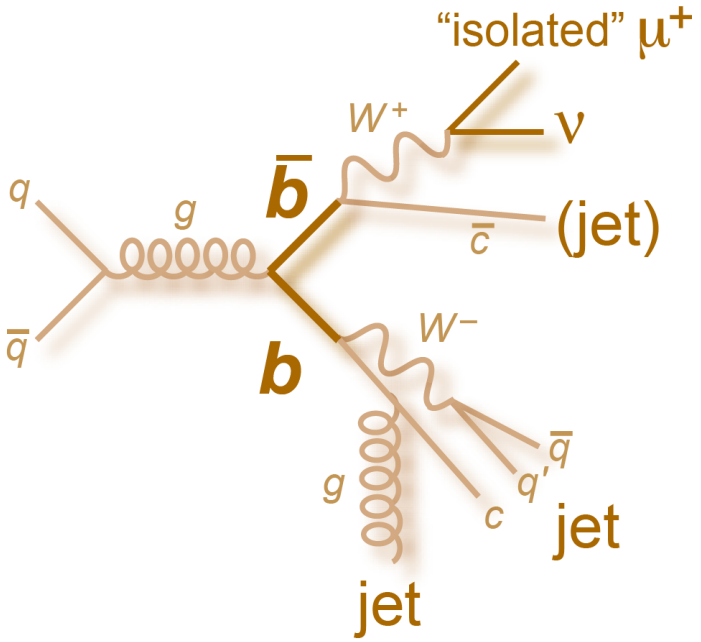
- electron
  - $E_T > 25$ GeV and isolated
  - $|\eta_{clus}| < 2.47$
  - require track association
- muon
  - $p_T > 20$ GeV and isolated
  - $|\eta| < 2.5$
  - require re-fitted (MS + ID) track
- jets
  - Anti-k_T R = 0.4 calibrated jets
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
  - $n_{jets} \geq 4$
  - ≥ 1 b-tagged jet
- $\not{E}_T$ from calorimeter cells in topological clusters

- Single-lepton Final State
  - lepton: $\ell \in e, \mu$
  - single e (μ) trigger, fat-jet trigger
  - $\not{E}_T > 35$ GeV, $m_{T,W} > 25$ GeV
  - $\not{E}_T > 20$ GeV, $\not{E}_T + m_{T,W} > 60$ GeV
- Di-lepton Final State
  - 2 leptons: $\ell, \ell \in ee, e\mu, \mu\mu$
  - single e(μ) trigger p_T >20 (18) GeV
  - $\geq$2 jets and = 2 OS leptons
  - $|m_Z - m_{\ell\ell}|$ >10 GeV
  - $\not{E}_T > 40$ GeV
  - $H_T > 130$ GeV in (in $e\mu$)

Background estimates (1)

- MC Modeling
  - backgrounds to $t\bar{t}$ include W+jets, single top, Z+jets, diboson production





Background estimates (2)

$W^{\pm}$ normalization estimated using charge asymmetry method

- Use $r \equiv \sigma(pp \to W^+)/\sigma(pp \to W^-)$
- $t\bar{t}$ QCD multijets, Z+jets are assumed charge symmetric.

$$N_{W^+} + N_{W^-} = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(D_{corr+} - D_{corr-})$$

- Jet electron template fit method
  - Jet-electrons are jets with high EM fraction($0.8 < f_{EM} < 0.95$) and $\geqslant 3$ tracks
  - Veto on real electrons and muons
  - Fit $\not{E}_T$ distribution in side-band ($\not{E}_T < 30$ (60) GeV and extract normalization of QCD background

$t\bar{t}$ Reconstruction / Limit setting

- Solving for neutrino p_z in single lepton channel
  - Solve for p_z of neutrino using lepton four-momentum and $\not{E}_T$
  - Scale $\not{E}_T$ if the discriminant is negative. Choose the smallest $|p_z|$ solution otherwise.
- Kinematic Fit in single lepton channel
  - Apply top and W-boson mass constraints (Breit-Wigner)
  - Use constraints from kinematics and particle properties
  - Parametrize detector effects using transfer functions $W(E_{calo}|E_{parton})$
  - Setup Likelihood function and maximize it in global (17 parameter) space
- Limit Setting
  - Limits usually set using CLs method
  - Occasionally Bayesian approach

Systematic uncertainties

- Normalization Uncertainties:
  - QCD: 60%, W/Z+jets, $t\bar{t}$ generator
- Shape Uncertainties: Jet energy scale/resolution, b-tagging $m_{t\bar{t}}$ shape, ISR/FSR
- Additional comparisons with MSTW2008nlo and CT10 PDF's for top (MC@NLO) samples
- Large-R jets: Simultaneously apply energy, mass and $k_{\perp}$-split scale uncertainties (by sub-structure group)
- b-tagging: parametrized in p_T of jet with increased b- and c-jet uncertainties for Large-R jet $p_T > 200$ GeV

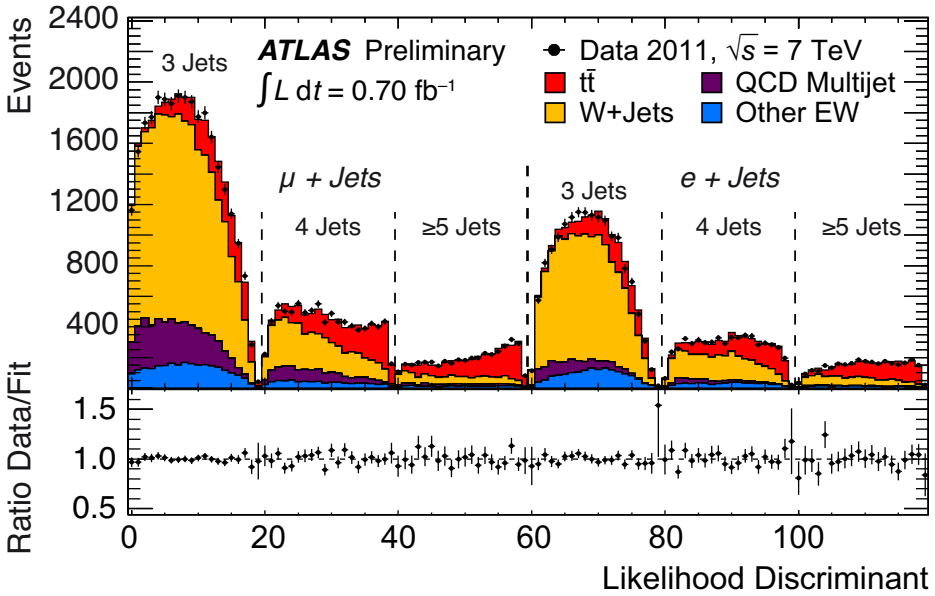
Inclusive cross section

- Pair Production
- Single Top
- Properties
- Pair properties
- New physics in top final states

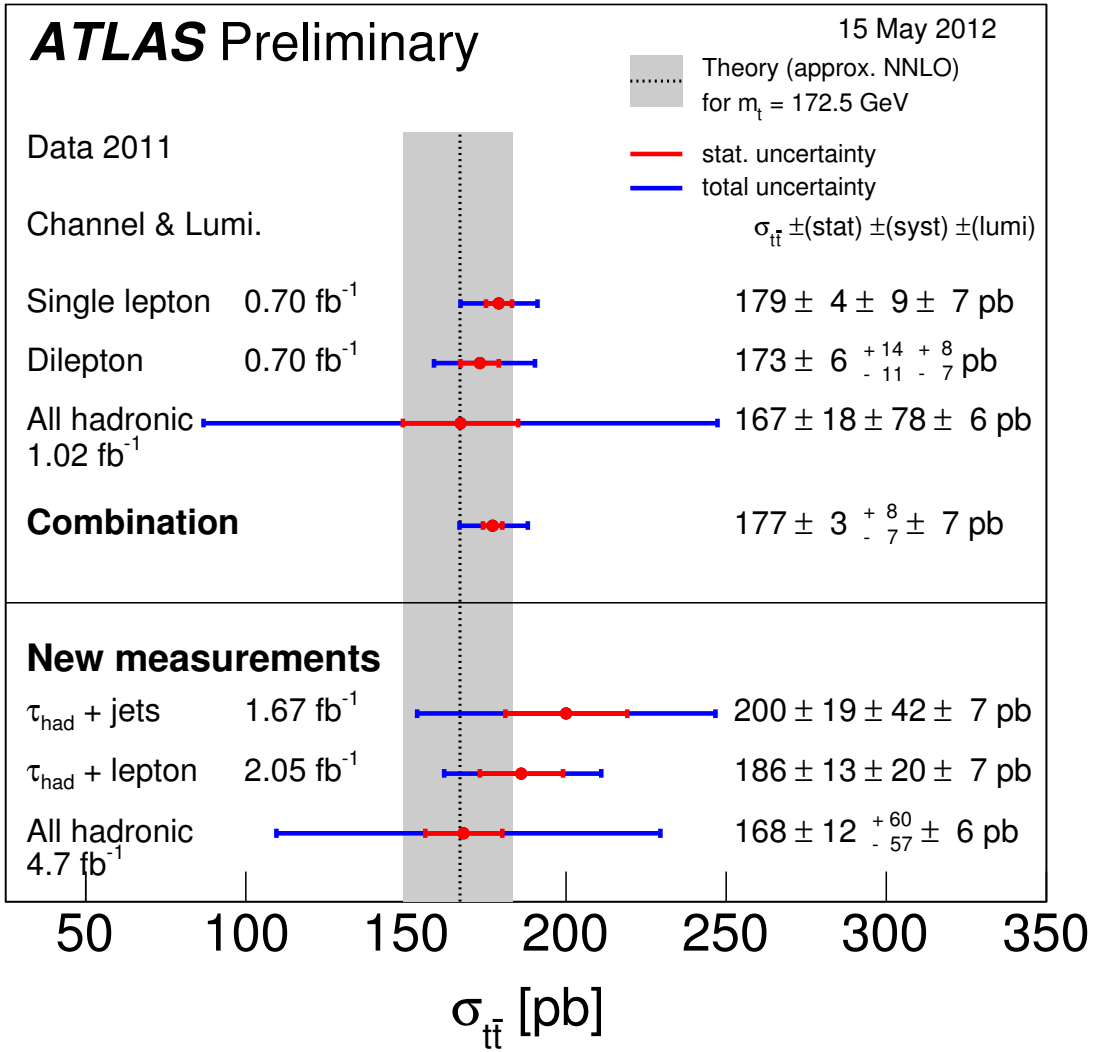
Inclusive $t\bar{t}$ production cross section (1)

ATLAS-CONF-2011-121 ($\mathcal{L} = 0.7 fb^{-1}$ $\sqrt{s} = 7$ TeV)

- Most precise ATLAS inclusive cross section measurement
- Event selection
  - Single isolated lepton $\ell \in e, \mu$, large $\not{E}_T$ and $\geqslant 3$ jets, no b-tag
- Method to extract signal
  - Likelihood discriminant from kinematic variables
  - Use signal and background templates and perfrom a maximum likelihood fit to data simultaneously on all six channels
  - Result $\sigma_{t\bar{t}} = 179.0^{+7.0}_{-6.0}(\mathrm{stat} + \mathrm{syst}) \pm 6.6(\mathrm{lumi})$ pb



Inclusive $t\bar{t}$ production cross section (2)



Single top t-channel cross section

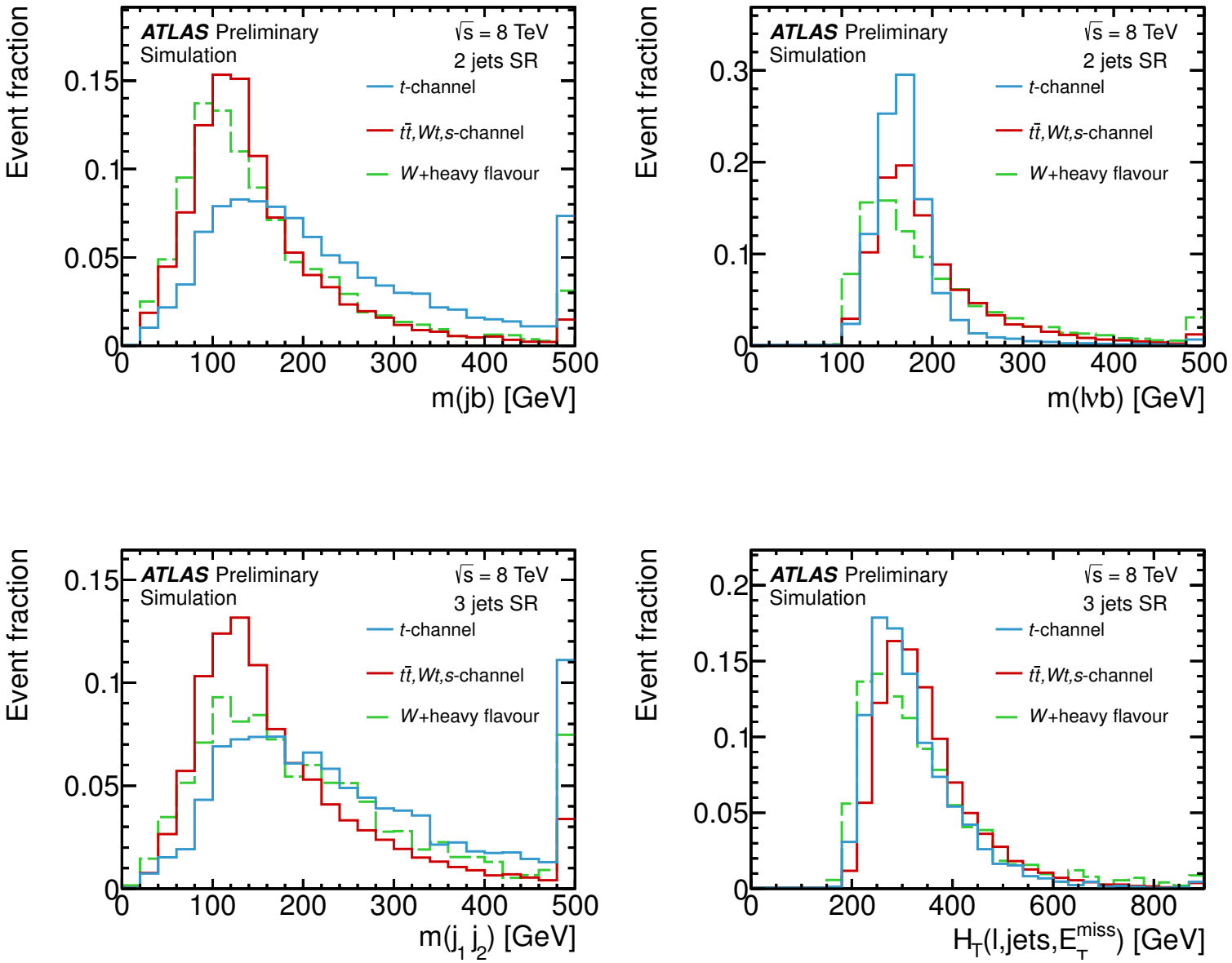
- Pair Production
- Single Top
- Properties
- Pair properties
- New physics in top final states

Single top t-channel cross section (1)

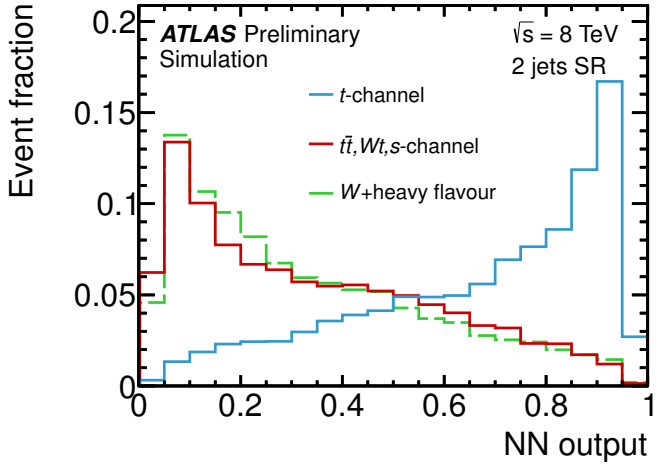
ATLAS-CONF-2012-132 ($\mathcal{L} = 5.8 fb^{-1}$ $\sqrt{s} = 8$ TeV)

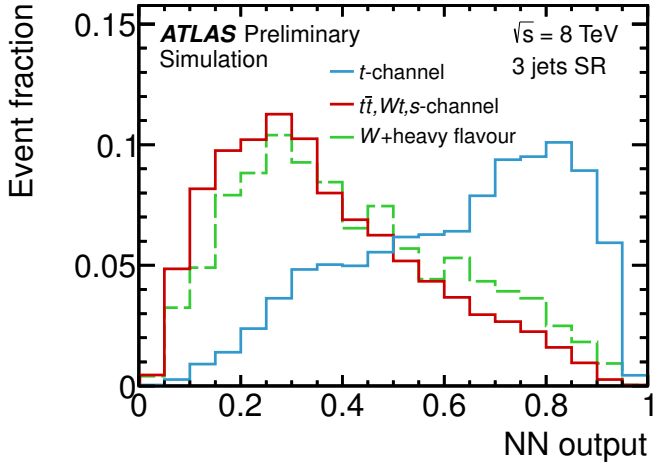
- Event selection
  - Single isolated lepton $\ell \in e, \mu$
  - $\not{E}_T$
  - 2 or 3 jets with exactly one b-tag
- Background modeling
  - W+jets, Z+jets, diboson $t\bar{t}$, modeled using MC
  - QCD multijet production data-driven approach
- Signal extraction
  - Neural network (NN) based discriminant using 11 variables
  - Variables chosen to get best discrimination power
    - $m(jb)$, $m(\ell\nu b)$, $|\eta(j)|$, $m_T(\ell\nu)$ etc. for 2 jets
    - $m(j1, j2)$, $H_T(\ell, jets, \not{E}_T)$, $m(j1, j3)$, etc. for 3 jets
- Fit using simultaneous likelihood fit to NN discriminant in both channels
- Also extract coupling at the Wtb-vertex
- W polarization is sensitive Wtb-vertex $\Rightarrow$ limits on anomalous contributions

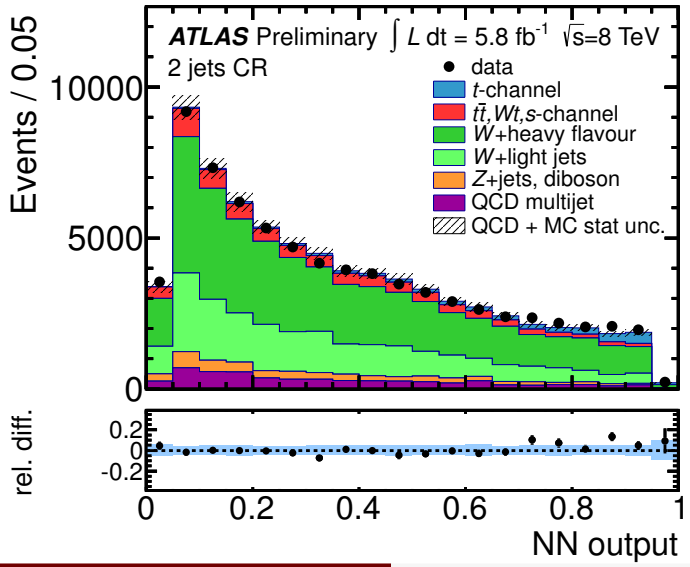
Single top t-channel cross section (2)

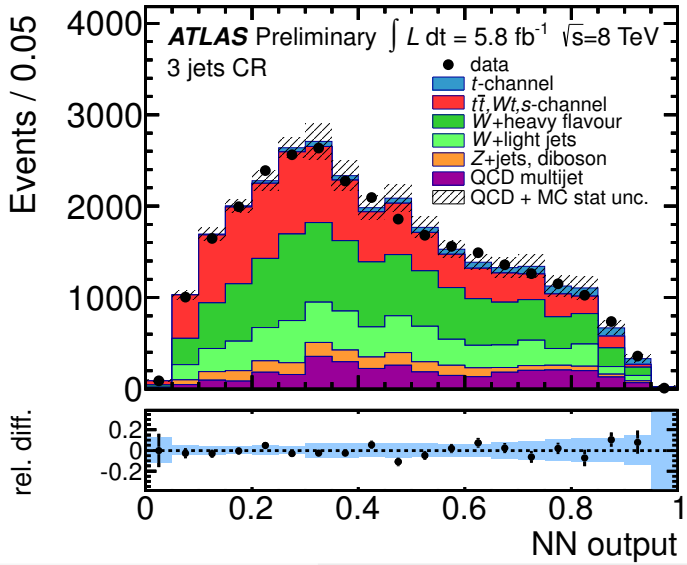


Single top t-channel cross section (3)



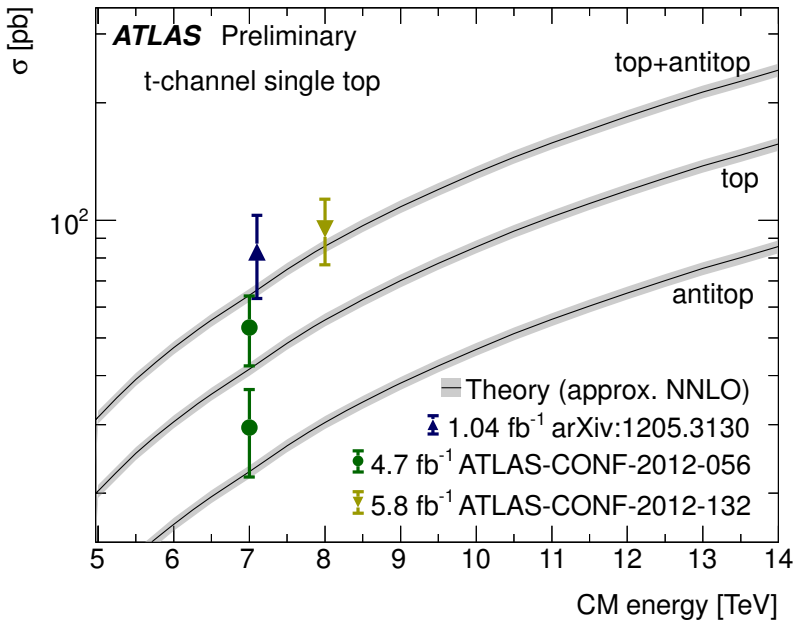






Single top t-channel cross section (4)

- $\sigma(t) = 95 \pm 2(\text{stat.}) \pm 18(\text{syst.})$ pb (Agrees well with SM)
- Wtb-vertex $|V_{tb}| = 1.04^{0.10}_{-0.11}$
- 95% CL lower limit on $|V_{tb}| = 0.80$



Top charge

- Pair Production
- Single Top
- Properties
- Pair properties
- New physics in top final states

Top quark charge measurement (1)

ATLAS-CONF-2011-141 ($\mathcal{L}$ = 0.7fb^{-1} $\sqrt{s}$ = 7 TeV)

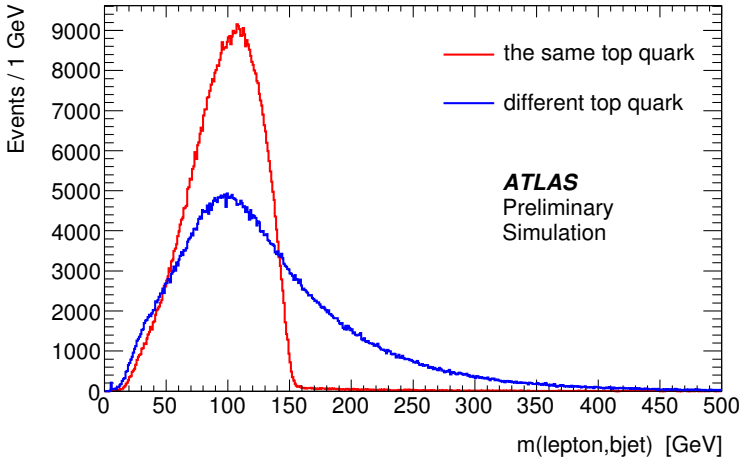
- Measurement of charge of top decay products to infer its charge

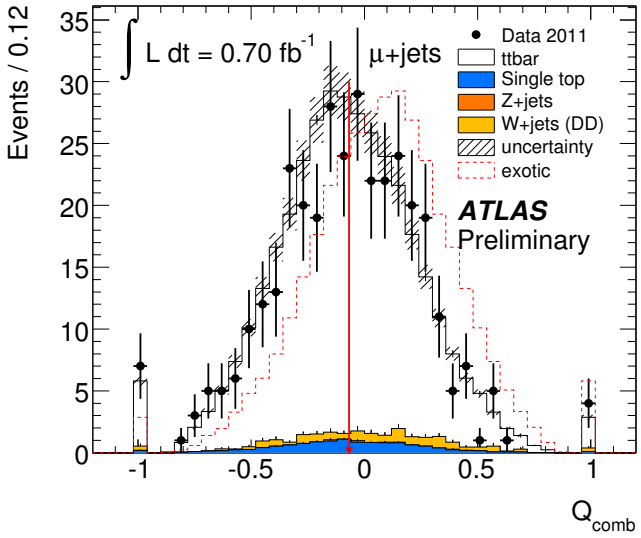
$$t^{(2/3)} \to b^{(-1/3)} + W^{(+1)}, \;\; W^{+} \to \ell^{+}, \nu_{\ell} \;\; (\mathrm{SM})$$
$$\tilde{t}^{(-4/3)} \to b^{(-1/3)} + W^{(-1)}, \;\; W^{-} \to \ell^{-}, \bar{\nu}_{\ell} \;\; (\mathrm{Exotic})$$

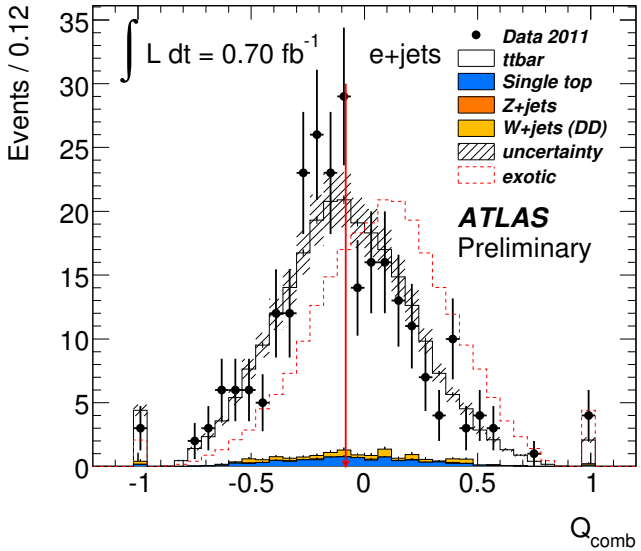
- Event Selection
  - Single isolated lepton $\ell \in e, \mu$
  - $\not{E}_T$
  - $\geqslant$ 4 jets with $\geqslant$ 1b-tag
- Method to extract signal $t \to W^{+}, b$, $\bar{t} \to W^{-}, \bar{b}$
  1. Charge of W boson determined through its leptonic decay
  2. Charge of b quark using two different methods
     - Charge weighted sum of of tracks belonging to the b-jet
     - Using semi-leptonic B-hadron decays ($b \to c, u + W^{-}, W^{-} \to \ell^{-}, \bar{\nu}_{\ell}$)

Top quark charge measurement (2)

- Charge weighting
  - Find lepton, b-jet assignment using their invariant mass
  - $m(\ell, bjet_a) < m_{cr}$ and $m(\ell, bjet_b) > m_{cr}$
  - $m_{cr} = 155$ GeV (optimized)
  - Define combined charge $Q_{comb} = Q_{b-jet} \times Q_\ell$

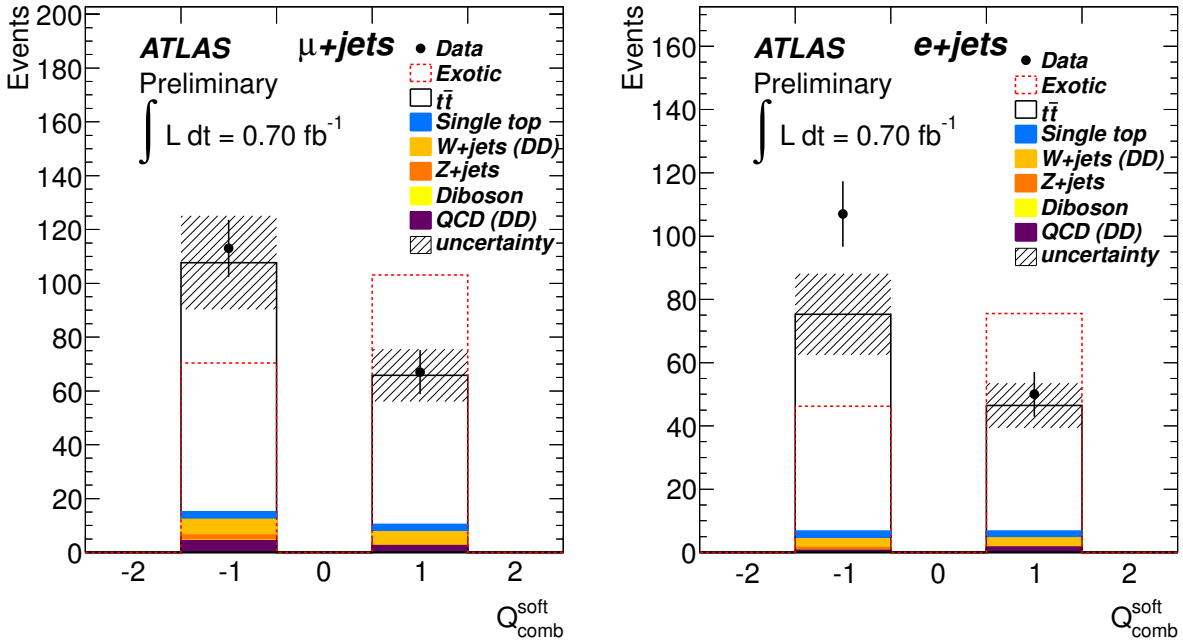






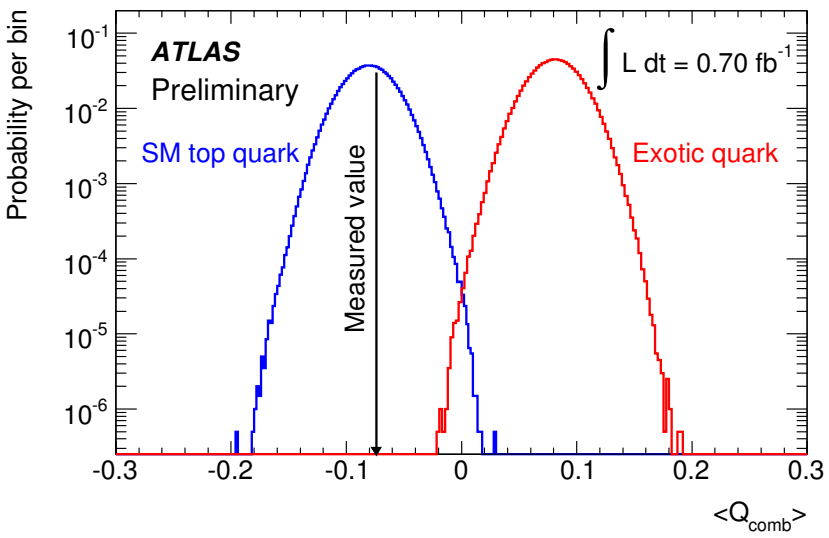
Top quark charge measurement (3)

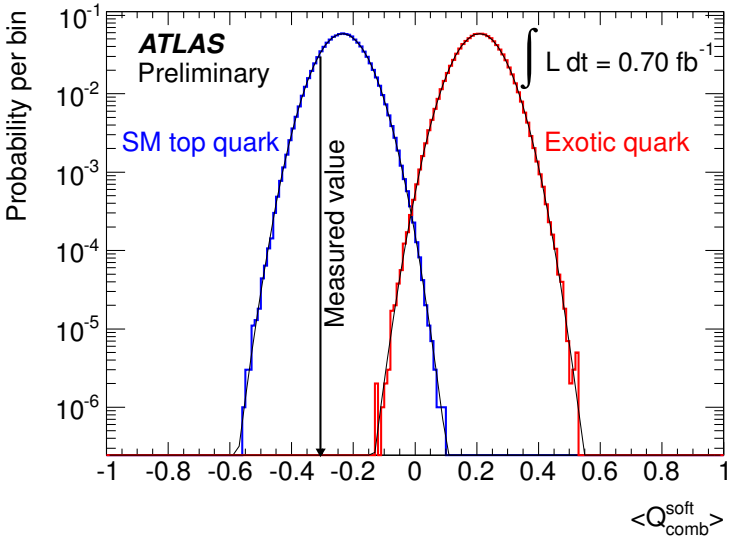
- Use semi-leptonic decays of B-hadrons
  $BR(b \to \mu + \nu + X) \sim 11\%$ (same charge), soft ($p_T(\mu)$ >4 GeV)
- Suppress other sources ($B \to D, B^0 \to \bar{B}^0$)
  $BR(b \to c \to \mu + \nu + X) \sim 10\%$ (opposite charge)
  Require $p_T^{rel} > 800$ MeV to suppress background
- Use Kinematic fitter to pair b-quark and lepton
- Define combined charge $Q_{comb}^{soft} = Q_{\mu}^{soft} \times Q_{\ell}$



Top quark charge measurement (4)

- Combined charge in good agreement with SM for both methods
- Set limits for exotic quark with likelihood approach comparing to SM
- Exotic scenario excluded at more than 5σ





Spin correlation

- Pair Production
- Single Top
- Properties
- Pair properties
- New physics in top final states

Observation of spin correlation in $t\bar{t}$ events

Observation of spin correlation would

- confirm spin 1/2 of top quark
- set the upper limit on lifetime and lower bound on width
- probe presence of non-standard interactions like Higgs decay

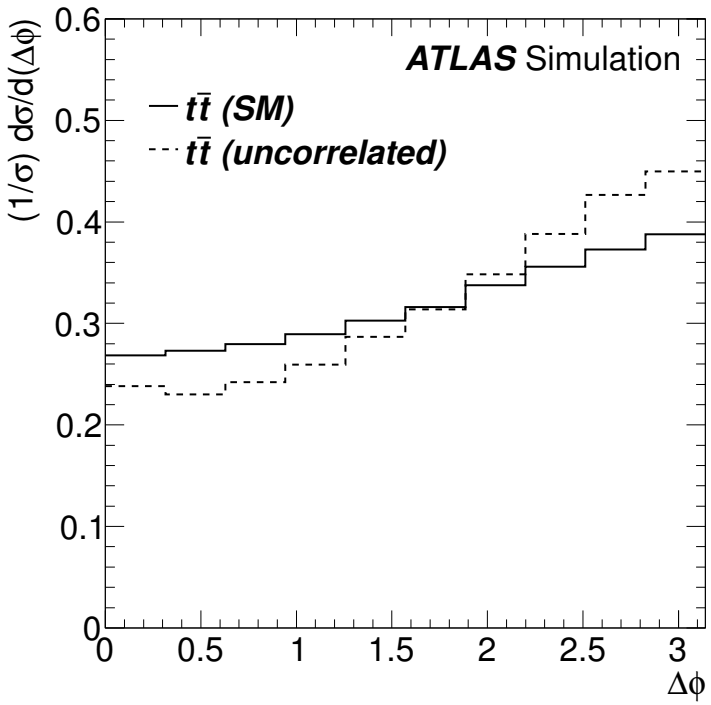
- Observable: $\Delta\phi = |\phi_{\ell^+} - \phi_{\ell^-}|$ dilepton mode
- Primary backgrounds:
  - $t\bar{t}$, single top (MC@NLO), $Z/\gamma^* \to \ell\ell$ (ALPGEN), Small background (W+jets)
- Spin correlation coefficient:

$$A^{SM}_{helicity} = 0.32, \quad A^{SM}_{maximal} = 0.44$$

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

arXiv:1203.4081 ($\mathcal{L} = 2.1 fb^{-1}$)

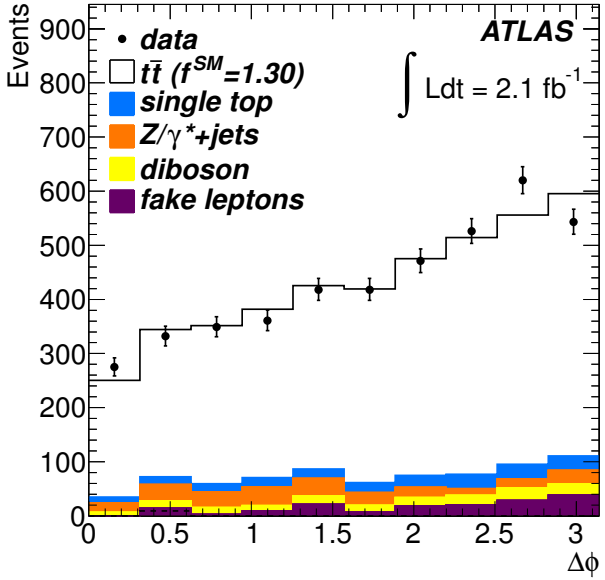
- Define SM fraction f^{SM} and uncorrelated fraction f^{UC} with $f^{SM} + f^{UC} = 1$
- SM vs uncorrelated at parton level

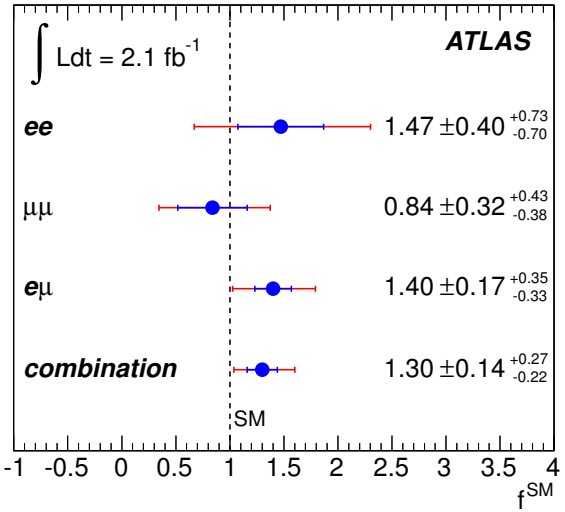


Observation of spin correlation in $t\bar{t}$ events

- Systematic uncertainties:
  - jet calibration (up to 9%), ISR/FSR (4.5%), PDF (8%)
  - generator(8%), data/MC template statistics (14%/9%)
- Fit Results:
  - Binned likelihood fit to $\Delta\phi$ using MC

$$
\begin{aligned}
f^{SM} &= 1.30 \pm 0.14^{+0.27}_{-0.22} \\
A_{helicity} &= 0.42 \pm 0.04^{+0.09}_{-0.07} \\
A_{maximal} &= 0.57 \pm 0.06^{+0.12}_{-0.10}
\end{aligned}
$$





Charge asymmetry

- Pair Production
- Single Top
- Properties
- Pair properties
- New physics in top final states

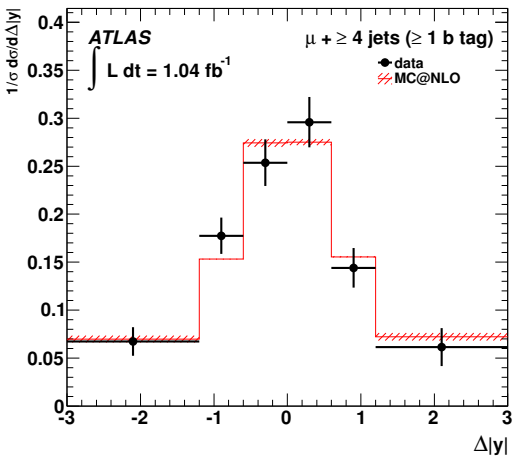
Measurement of charge asymmetry in $t\bar{t}$ events

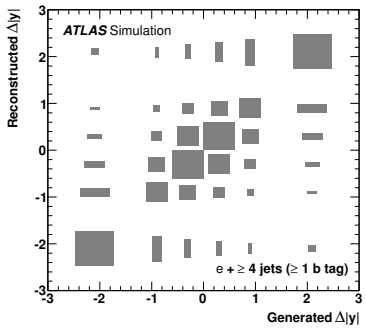
arXiv:1203.4211 ($\mathcal{L} = 1.04 fb^{-1}$)

- Observable: $\Delta|y| = |y_t| - |y_{\bar{t}}|$; semi-leptonic channel
- $gg \to t\bar{t}$ production is symmetric where as $q\bar{q} \to t\bar{t}$ is asymmetric at NLO and $A_C^{SM} < 0$, $\bar{t}$ are produced more centrally than t

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

- $t\bar{t}$ system is reconstructed using a top likelihood which selects correct object combination on MC with high efficiency
- Resulting $\Delta|y|$ distribution is unfolded using Bayesian approach

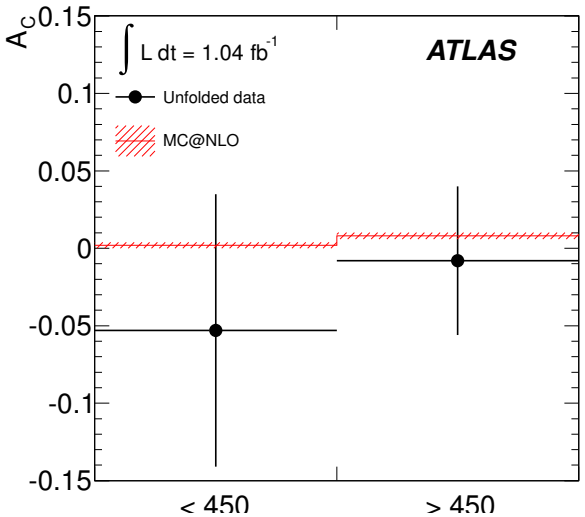




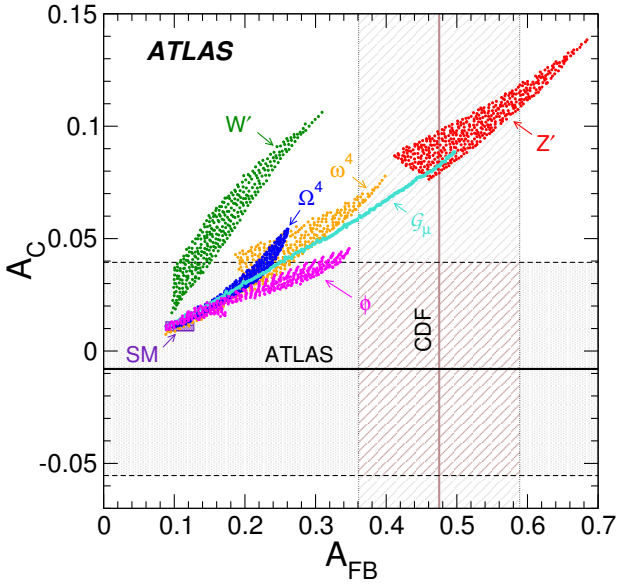
Measurement of charge asymmetry in $t\bar{t}$ production

A_C Fit Results:

$$-0.018 \pm 0.028\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst})$$
$$-0.053 \pm 0.070\,(\mathrm{stat}) \pm 0.054\,(\mathrm{syst})\,(\mathrm{m}_{\mathrm{t\bar{t}}} < 450\,\mathrm{GeV}$$
$$-0.008 \pm 0.035\,(\mathrm{stat}) \pm 0.032\,(\mathrm{syst})\,(\mathrm{m}_{\mathrm{t\bar{t}}} > 450\,\mathrm{GeV}$$



- In good agreement with SM predictions
- Results disfavor models with flavor-changing Z' and W' proposed to explain Tevatron's A_{FB} measurements



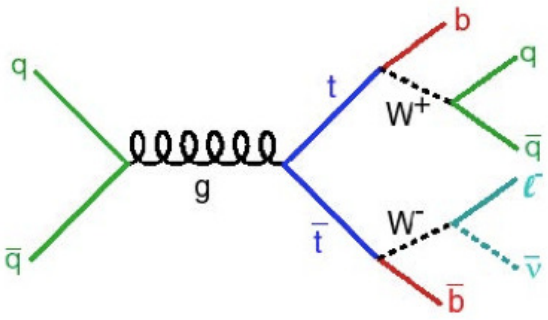
Top Resonances

- Pair Production
- Single Top
- Properties
- Pair properties
- New physics in top final states

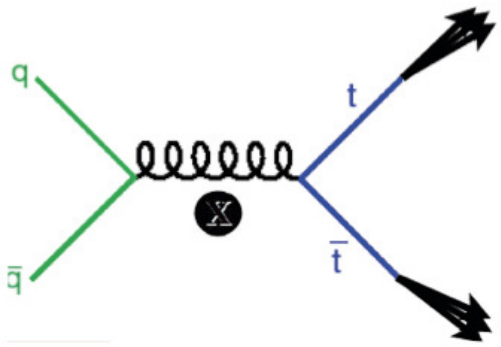
Search for $t\bar{t}$ resonances (1)

ATLAS-CONF-2012-136 ($\mathcal{L}$ = 4.66fb^{-1} $\sqrt{s}$ = 7 TeV)

- Many BSM models predict new particles that couple strongly to top quark pairs.
- Experimental mass resolution $\mathcal{O}(10\%)$
- Leptophobic topcolor Z'
  - Spin 1, color singlet, narrow resonance ($\Gamma/m_{Z'}$=1.2%)
- Kaluza-Klein gluon (g_{KK}) from Randall-Sundrum models
  - Spin1, color octet, wide resonance ($\Gamma/m_{g_{KK}}$=15%)
- Look for bump in m_{tt} spectrum

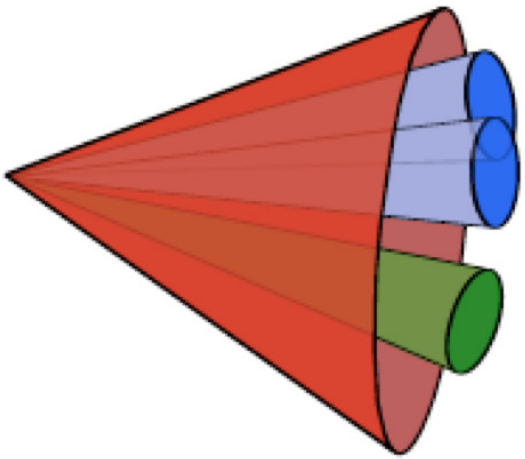


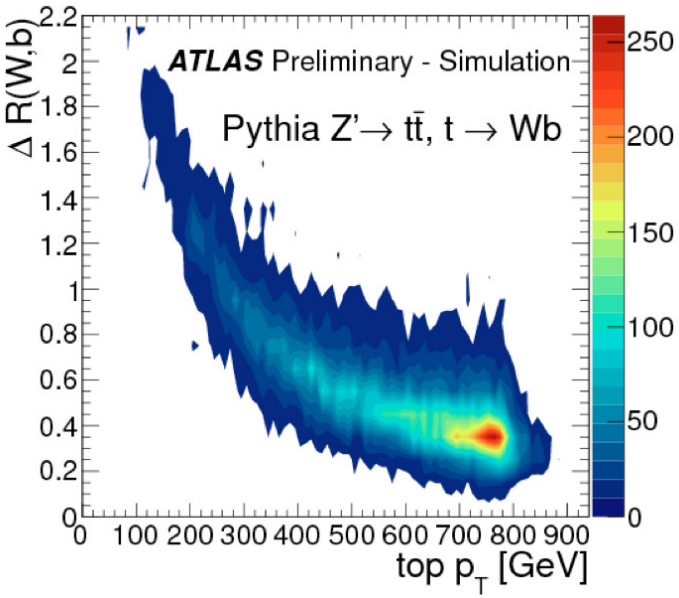
"Resolved"



"Boosted"

Search for $t\bar{t}$ resonances (2)

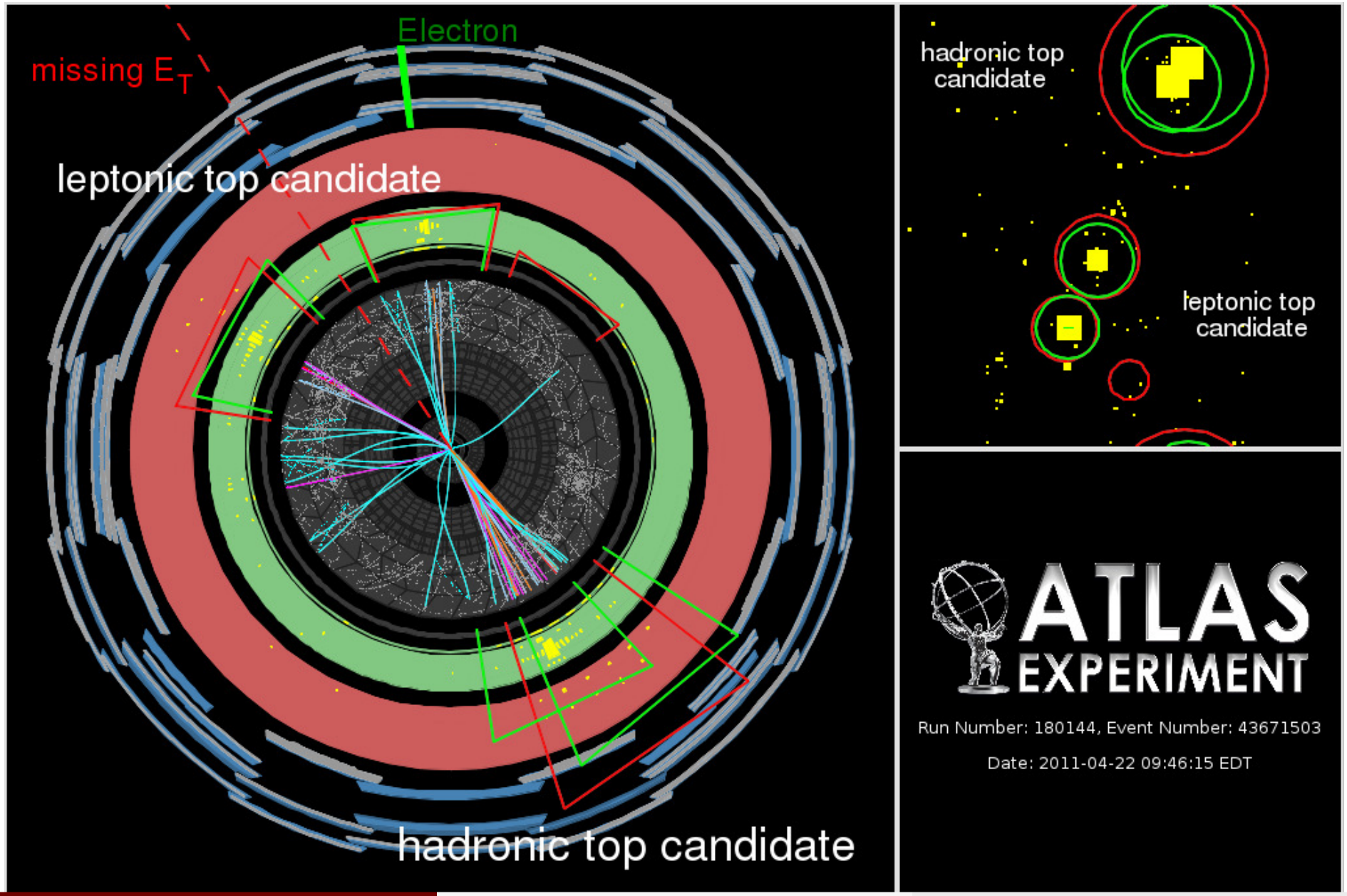




- Use jets with large radii (e.g, Anti-k$_T$, R=1.0) to collect all products of hadronic top decay
- Rule of thumb: $\Delta R \sim 2M/p_T$
- Use jet-substructure techniques to infer presence of W and top inside of "fat jet"

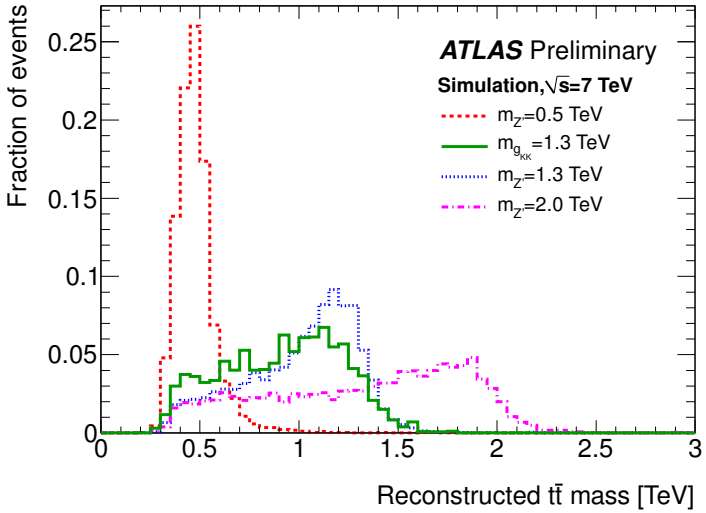
- Jets with larger radii suffer more from contamination by underlying event and pile-up
- Use techniques such as grooming remove soft radiation

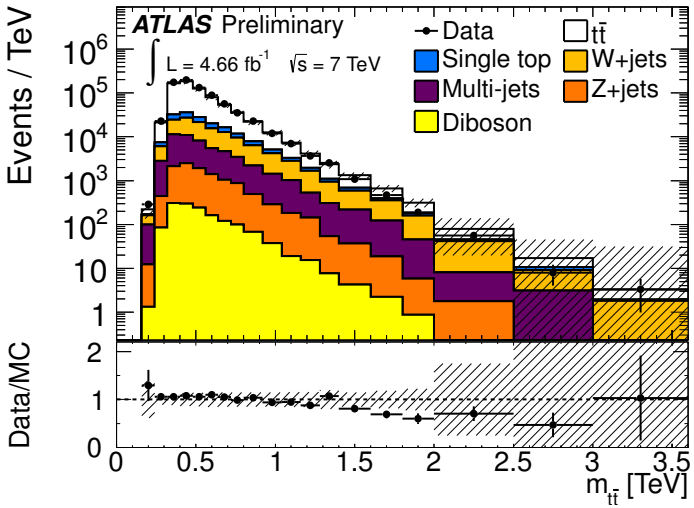
Search for $t\bar{t}$ resonances (3)

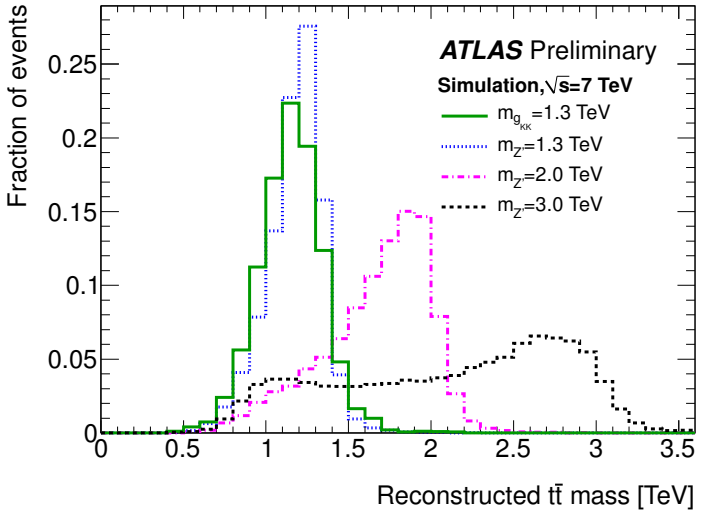


Search for $t\bar{t}$ resonances (4)

- Anti-k_T (R=1.0) jet with $p_T >$ 350 GeV, $\geqslant 1$ b-tag
- $m_t > 100$ GeV $\sqrt{d_{12}} > 40$ GeV
- Lepton isolation: shrink cone size with lepton p_T
- Trigger on fat jets

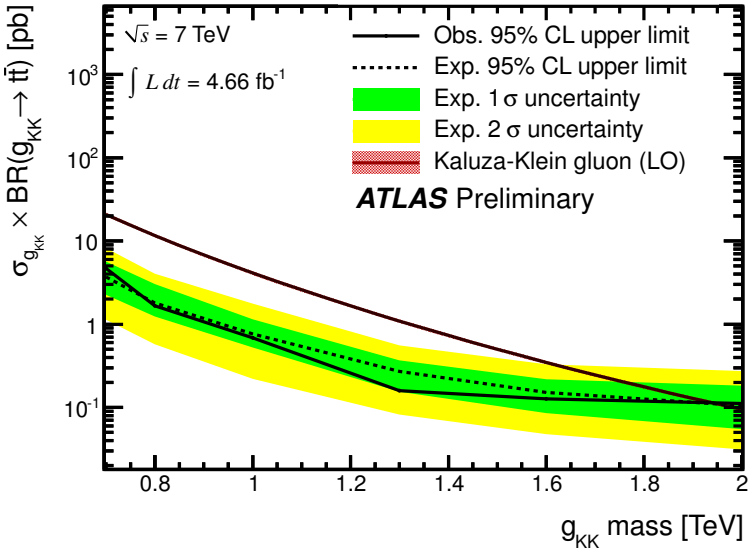


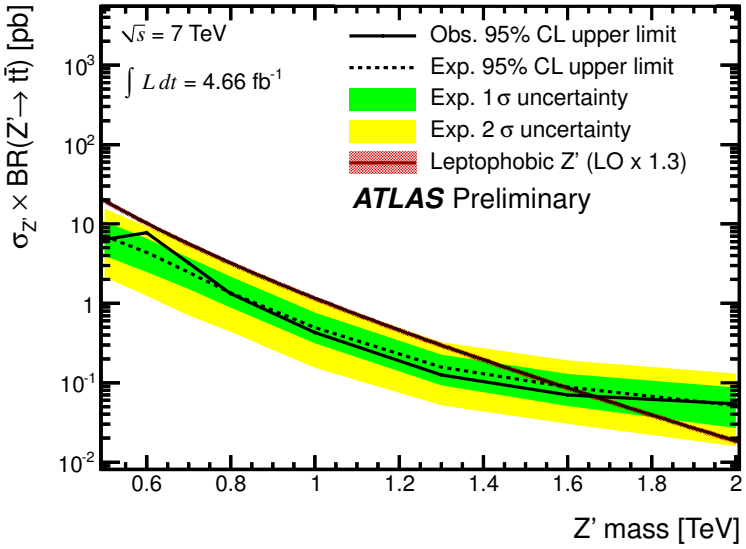




Search for $t\bar{t}$ resonances (5)

- $0.6 < m(g_{KK}) < 1.94$ and $0.5 < m(Z') < 1.66$ TeV excluded at 95%CL





Mass	stat+syst KK gluon (pb)				stat+syst. Z' (pb)			
(GeV)	Obs.	Exp.	-1σ	$+1\sigma$	Obs.	Exp.	-1σ	$+1\sigma$
500						7.08	3.97	10.82
600						4.37	2.50	6.54
700	4.67	3.70	2.27	5.63	3.21	2.46	1.51	3.78
800	1.67	1.81	1.24	3.02	1.32	1.36	0.89	2.17
1000	0.68	0.76	0.53	1.14	0.43	0.50	0.31	0.77
1300	0.16	0.27	0.16	0.37	0.13	0.16	0.09	0.23
1600	0.13	0.15	0.09	0.22	0.07	0.09	0.05	0.13
2000	0.11	0.11	0.06	0.18	0.05	0.05	0.03	0.09
3000					0.03	0.03	0.02	0.04

Summary

- Top pairs offer a rich phenomenology. Many analyses carried out in ATLAS with top quarks
- A few measurements, search results using top/top-pairs shown today
- ATLAS is exploring the TeV frontier with tops, carrying out precision measurements of top quark properties
  - Inclusive pair production cross section and single top t-channel consistent with SM predictions
  - Charge measurement consistent with SM expectation
  - First observation of spin correlation and charge asymmetry measurement in good agreement with SM predictions
  - Disfavors some models proposed to explain Tevatron's A_{FB} measurements
  - No evidence of $X \to t\bar{t}$ yet
- Increased energy ($\sqrt{s} = 8$ TeV) and statistics beneficial for searches and measurements. Many results foreseen in Moriond 2013 timescale
- Details of results
  - ATLAS Top results

References

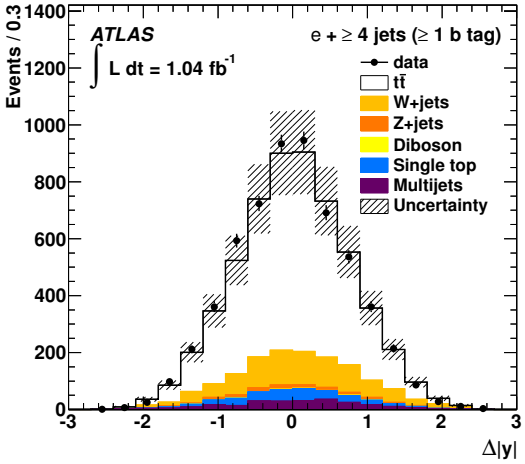
- A Search for $t\bar{t}$ Resonances in the Lepton Plus Jets Channel using 2.05 fb^{-1} pp Collisions at $\sqrt{s} = 7$ TeV CDS 1430738
- A Search for $t\bar{t}$ Resonances in the Dilepton Channel in 1.04 fb^{-1} of pp Collisions at $fb^{-1} = 7$ TeV CDS 1376423
- Observation of spin correlation in $t\bar{t}$ events from pp collisions at $\sqrt{s}$ = 7 TeV using the ATLAS detector arXiv:1203.4081
- Measurement of the charge asymmetry in top quark pair production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector arXiv:1203.4211

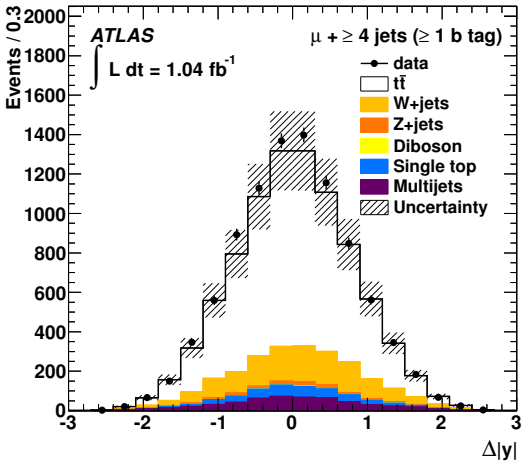
BACKUP - Top Object Reconstruction

- Electrons:
  - Clusters of energy deposits in EM calorimeter are reconstructed and associated to charged particle tracks in the inner detector.
- Muons:
  - Track segments are reconstructed in the muon chambers (spectrometer) and segments are combined starting from the outermost layer. They are fitted to account for material effects.
  - Inner detector charged particle tracks are matched to the fitted spectrometer tracks.
- Jets:
  - Clusters of energy deposits in EM and hadronic calorimeter cells are combined using the Anti-k_T algorithm with distance parameter R = 0.4
- Missing E_T ($\not{E}_T$):
  - Formed using a vector sum of all jets, electron and muon candidates and all the unassigned cells in the calorimeter.

BACKUP - Measurement of charge asymmetry in $t\bar{t}$ production

- Preliminary result, Oct 2011 [ATL-COM-PHYS-2011-1386]
- $\mathcal{L} = 1.04 fb^{-1}$
- $t\bar{t}$: semi-leptonic mode $\ell \in e, \mu$
- Observable: $\Delta|y| = |y_t| - |y_{\bar{t}}|$
- Event selection:
  - e channel: $\not{E}_T > 35$ GeV and $m_{T,W} > 25$ GeV
  - μ channel: $\not{E}_T > 20$ GeV and $\not{E}_T + m_{T,W} > 60$ GeV
  - require $n_{jets} \geq 4$ with p_T >25 GeV
  - Require at least one b-tagged jet





BACKUP - Inclusive cross section

$H_{T,3p}$ is the transverse momentum of all but two leading jets, normalized to the sum of absolute values of all longitudinal momenta in the event

$$H_{\mathrm{T,3p}} = \frac{\sum_{i=3}^{N_{\mathrm{jets}}} |p_{\mathrm{T},i}^2|}{\sum_{j=1}^{N_{\mathrm{objects}}} |p_{z,j}|},$$

where p_T is the transverse momentum and p_z the longitudinal momentum. The sum over all objects includes the charged lepton, neutrino and up to four leading jets.

Aplanarity A: 1.5 times the smallest eigenvalue of the momentum tensor defined as

$$M_{ij} = \frac{\sum_{k=1}^{N'_{\mathrm{objects}}} p_{ik} p_{jk}}{\sum_{k=1}^{N'_{\mathrm{objects}}} p_k^2},$$

where p_{ik} is the i-th momentum component and p_k is the modulus of the momentum of object k, and the sum is over the momenta of up to four leading jets and the charged lepton.