# Top Quark Pair Properties with ATLAS

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## Motivation:

- Heaviest of the known fundamental particles

  $m_t = 173.2 \pm 0.9$ GeV close to the EW scale
- Decay occurs before hadronization process "bare quark"

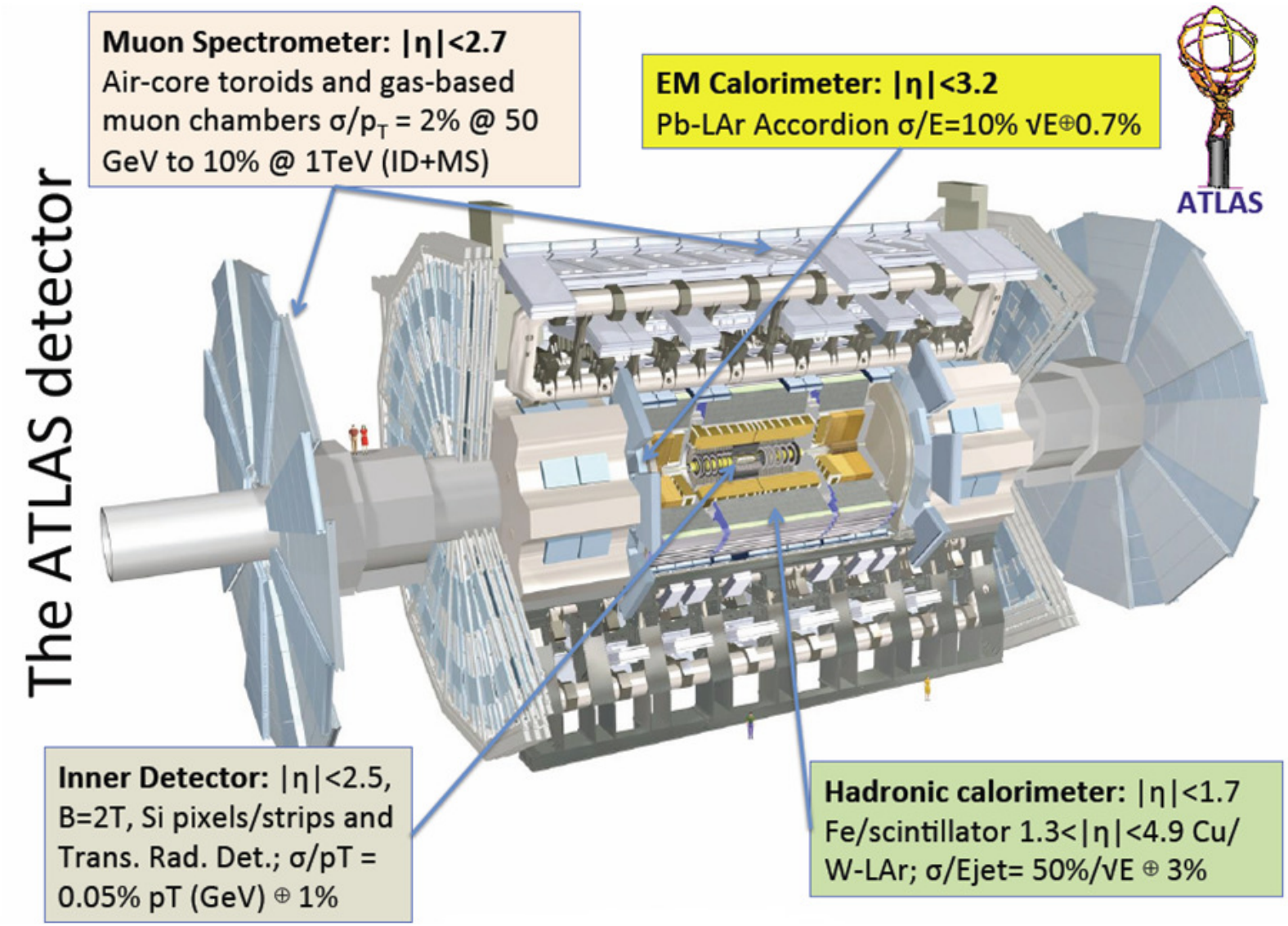
  width $\Gamma = 1.42$ GeV and lifetime $\tau = 4.5 \times 10^{-25}$s $\ll \Lambda_{QCD}^{-1}$
- Window into physics beyond the Standard Model

  X$\rightarrow t\bar{t}$: Topcolor or little Higgs $Z'$, $g_{KK}$ from RS extra dim. etc.
- LHC is a top factory - copious production, $\sigma(pp \rightarrow t\bar{t}) \sim 177$pb
- Tevatron measured an excess on $t\bar{t}$ asymmetry ($A_{FB}$) - test it at LHC

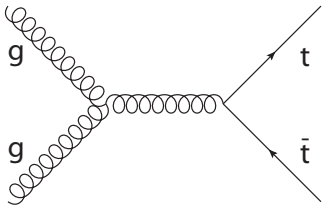
## Outline:

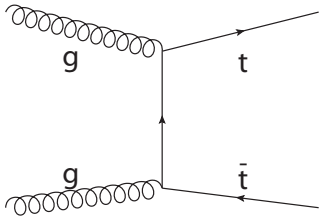
- Top pair production and decay
- Searches for $t\bar{t}$ resonances in lepton plus jets and di-lepton channels
- Observation of spin correlation in $t\bar{t}$ events
- Measurement of charge asymmetry in $t\bar{t}$ production
- Summary

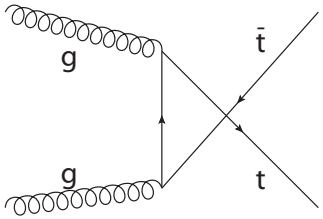
# ATLAS Detector

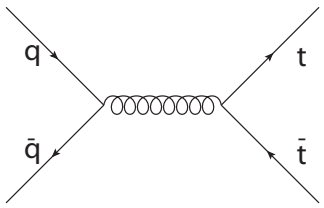


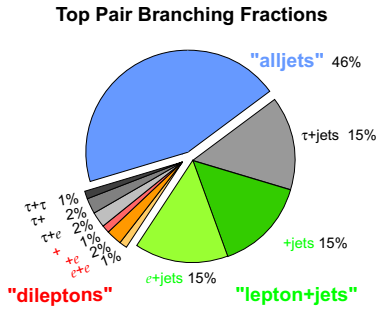
# Top pair production and decay




- 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:** $\mathrm{Br}$=46%, large multi-jet background
  - **lepton+jets:** $\mathrm{Br}$=45%, intermediate background
  - **dileptons:** $\mathrm{Br}$=9%, small multijet background

# Object Reconstruction and Selection

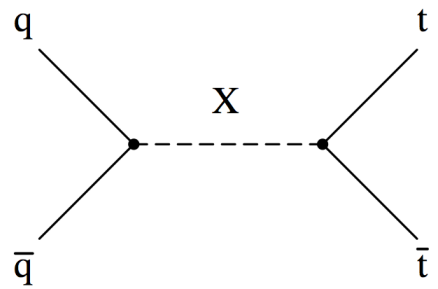
- electron
  - $E_T > 25$ GeV and isolated
  - $|\eta_{clus}| < 2.47$
  - require track association
- muon
  - $p_T > 20$ GeV and isolated
  - $|\eta| < 2.5$
  - require re-fitted (MS + ID) track
- jets
  - Anti-$k_T$ R = 0.4 calibrated jets
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
  - $n_{jets} \geq 4$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

- Single-lepton Final State
  - lepton: $\ell \in e, \mu$
  - single e ($\mu$) trigger $p_T$ >20 (18) GeV
  - $\not\!\!E_T > 35$ 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($\mu$) 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 $e\mu$)

# Search for $t\bar{t}$ resonances in lepton plus jets channel

**ATLAS-CONF-2012-029 ($\mathcal{L} = 2.05 fb^{-1}$)**

- Production of top pairs via unknown mediator X at the LHC (e.g. $Z', g_{KK}$)



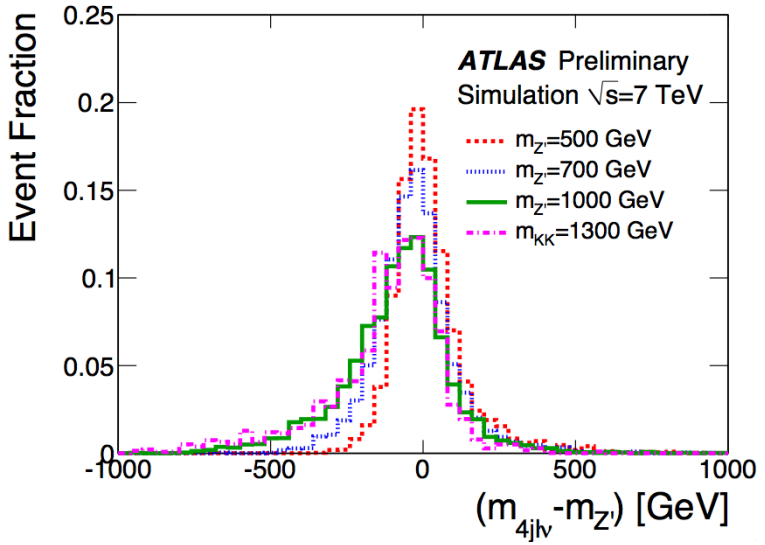

- Event selection:
  - $n_{jets} \geq 3$ if any jet with $m_j > 60$ GeV
  - $n_{jets} \geq 4$ otherwise
  - leading jet with $p_T > 60$ GeV
  - $\geq 1$ $b$-tagged jet

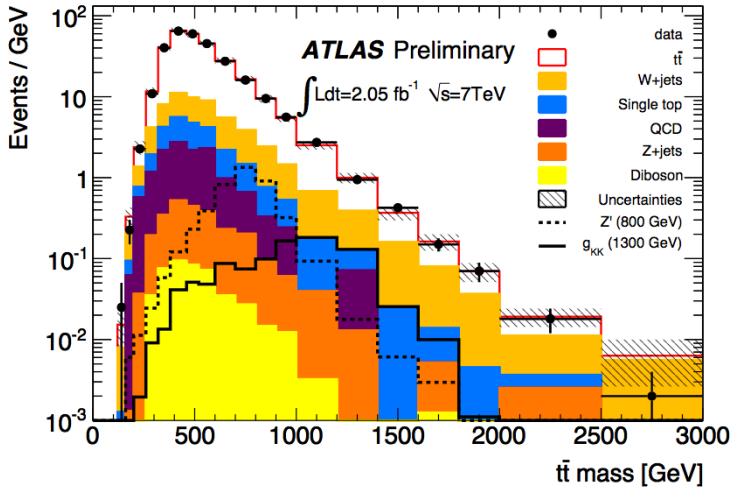
- Benchmark models for X$\rightarrow t\bar{t}$:
  - Leptophobic Topcolor $Z'$
    $\Gamma/M = 1.2\%$
  - Kaluza-Klein gluon ($g_{KK}$)
    $\Gamma/M = 15.3\%$ (RS models)
- Primary backgrounds:
  - $t\bar{t}$, single top (MC@NLO)
  - W+jets (ALPGEN) normalized to Data
  - QCD multi-jet (fake lepton) estimated using data-driven template

# Search for $t\bar{t}$ resonances in lepton plus jets channel

$t\bar{t}$ mass reconstruction

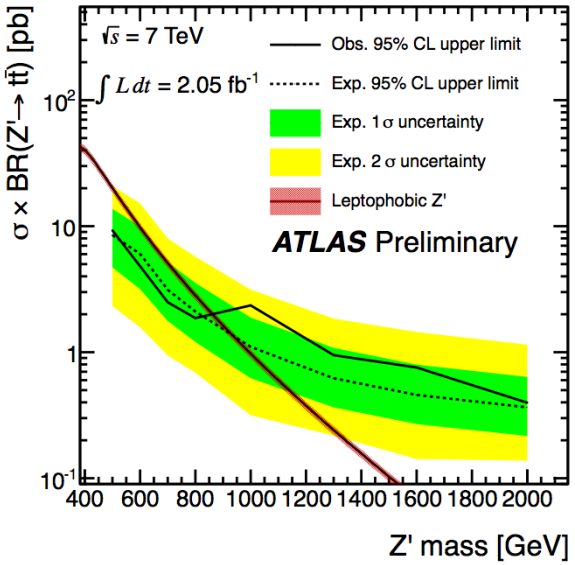
- $m_{t\bar{t}}$ is derived from lepton, $\not{E}_T$ and leading 3 or 4 jets
- $\nu$ $p_z$ is determined using W mass constraint
- If no jet has $m_j > 60$ GeV: 3 or 4 jets considered are close to lepton or (other jet)
- If jet has $m_j > 60$ GeV:
  - hadronic $t$ formed by high-mass jet + closest jet
  - leptonic $t$ formed by $\ell$ + closest jet

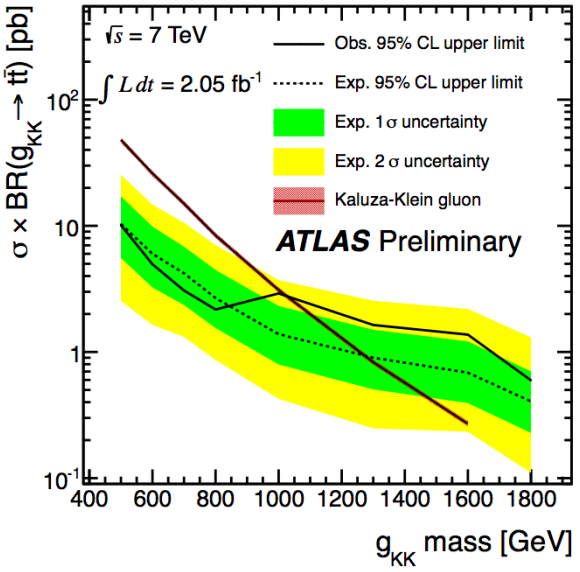


# Search for $t\bar{t}$ resonances in lepton plus jets channel

- Dominant systematic uncertainties
  - Normalization:
    - QCD: 50%
    - W/Z+jets 48%
    - $t\bar{t}$ +7/-9.6%
  - Shape: Jet energy scale/resolution, $b$-tagging $m_{t\bar{t}}$ shape, ISR/FSR
- Exclusion Limits
  - Derived from binned $m_{t\bar{t}}$ variable using Bayesian method
  - $500 < m_{Z'} < 860$ [GeV]
  - $500 < m_{g_{KK}} < 1025$ [GeV]

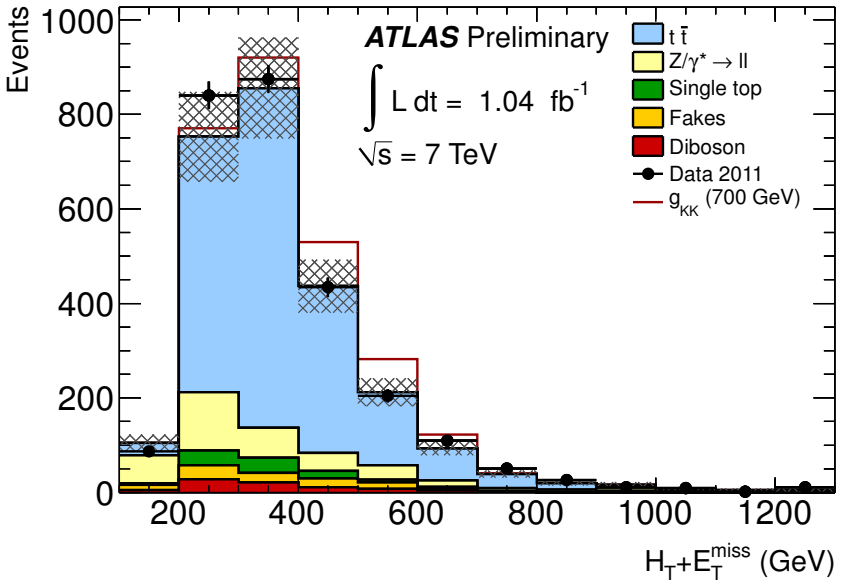


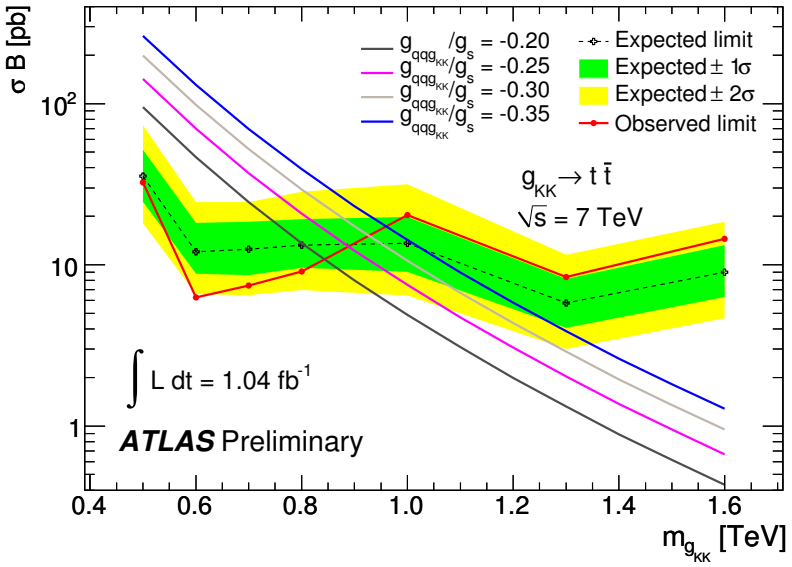



# Search for $t\bar{t}$ resonances in di-lepton channel

**ATLAS-CONF-2011-123 ($\mathcal{L} = 1.04 fb^{-1}$)**

- 3 channels: $(\ell, \ell) \in ee, \mu\mu, e\mu$
- Observable: $H_T + \not{E}_T$ with $H_T = \sum_\ell p_T^\ell + \sum_{jets} p_T^{jet}$
- Normalization to data in control region with Z in its mass window
- Primary backgrounds:
  - $t\bar{t}$, single top (MC@NLO), $Z/\gamma^* \rightarrow \ell\ell$ (ALPGEN), Small background (W+jets)
- Systematic uncertainties:
  - jet calibration, ISR/FSR, generator, lepton efficiency
- Limits:
  - Observed lower limits: $m_{g_{KK}}$ from 0.8 to 1.02 TeV



# 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

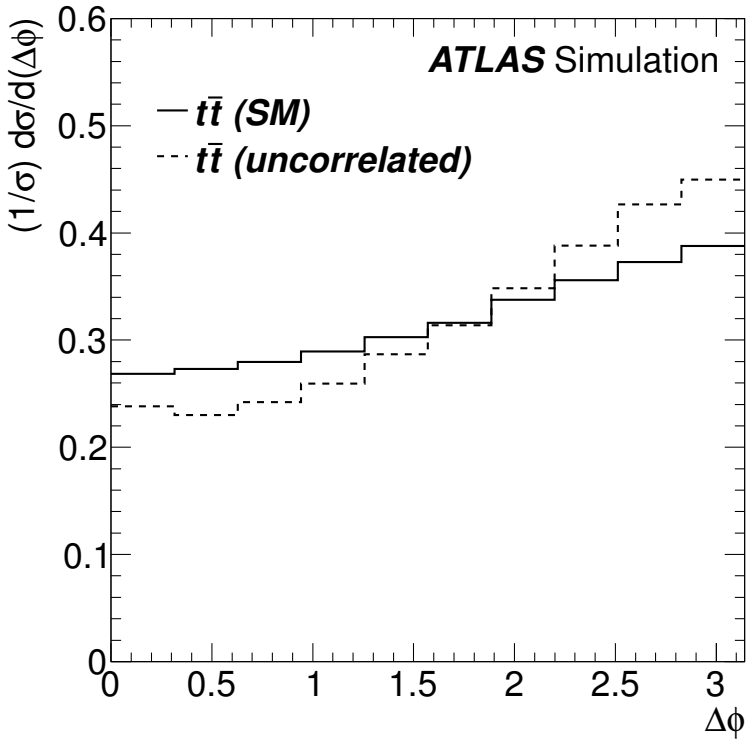
- Observable: $\Delta\phi = |\phi_{\ell^+} - \phi_{\ell^-}|$ dilepton mode
- Primary backgrounds:
  - $t\bar{t}$, single top (MC@NLO), $Z/\gamma^* \rightarrow \ell\ell$ (ALPGEN), Small background (W+jets)
- Spin correlation coefficient:

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

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

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

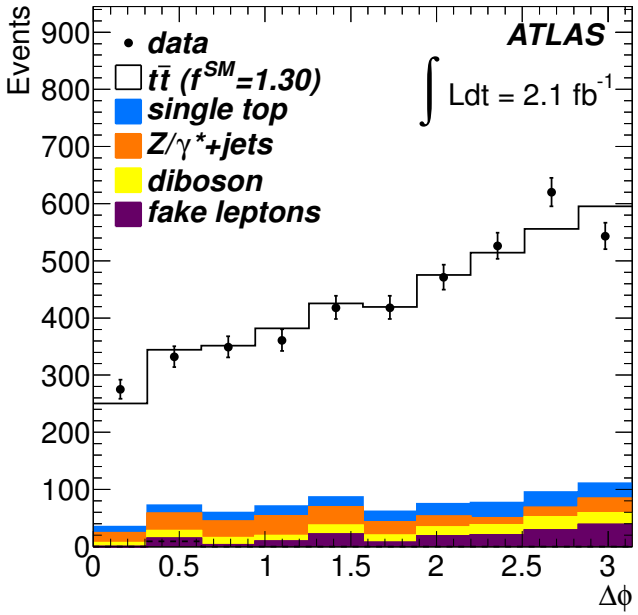
- Define SM fraction $f^{SM}$ and uncorrelated fraction $f^{UC}$ with $f^{SM} + f^{UC} = 1$
- SM vs uncorrelated at parton level

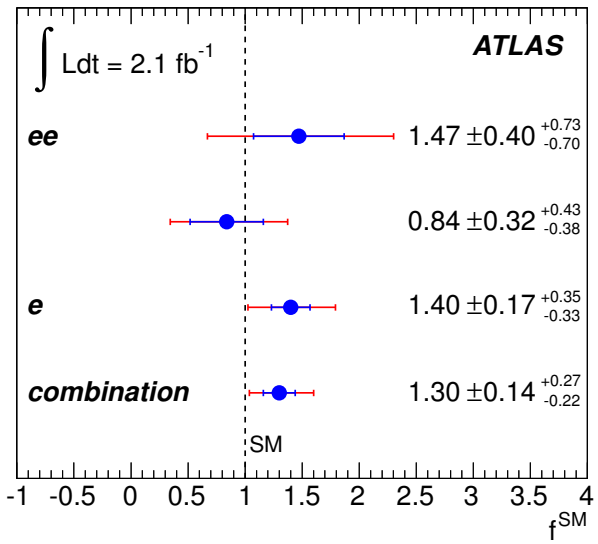


# Observation of spin correlation in $t\bar{t}$ events

- 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

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



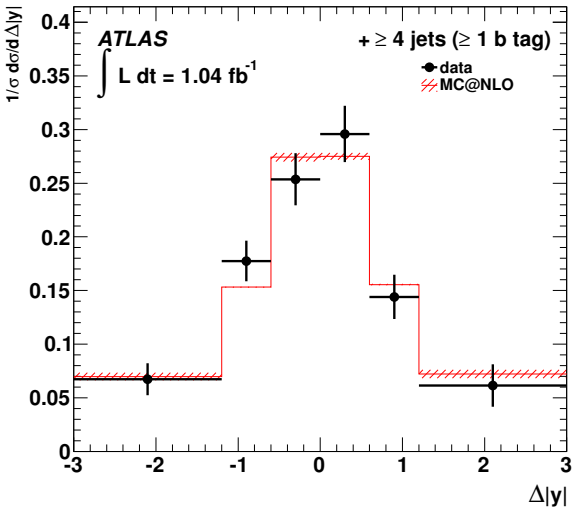



# Measurement of charge asymmetry in $t\bar{t}$ events

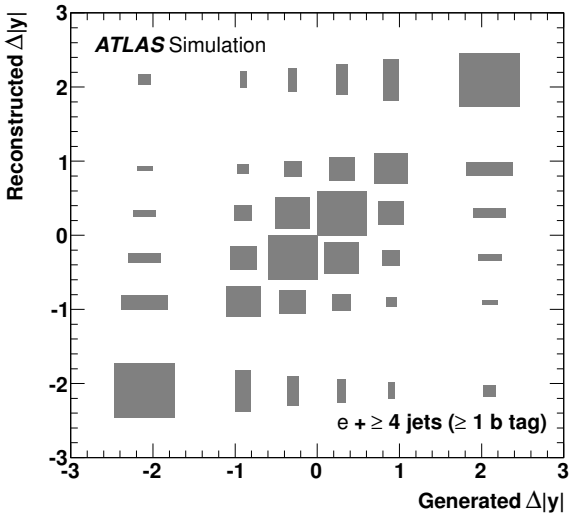
arXiv:1203.4211 ($\mathcal{L} = 1.04 fb^{-1}$)

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

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



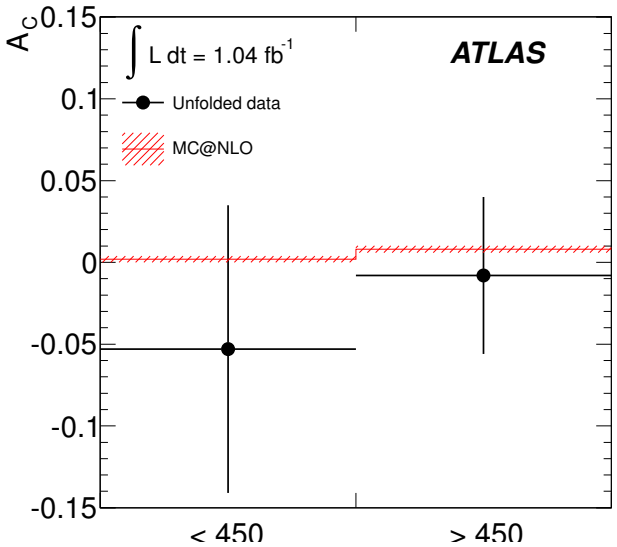

- $t\bar{t}$ system is reconstructed using a top likelihood which selects correct object combination on MC with 74% efficiency
- Resulting $\Delta|y|$ distribution is unfolded using iterative Bayesian approach



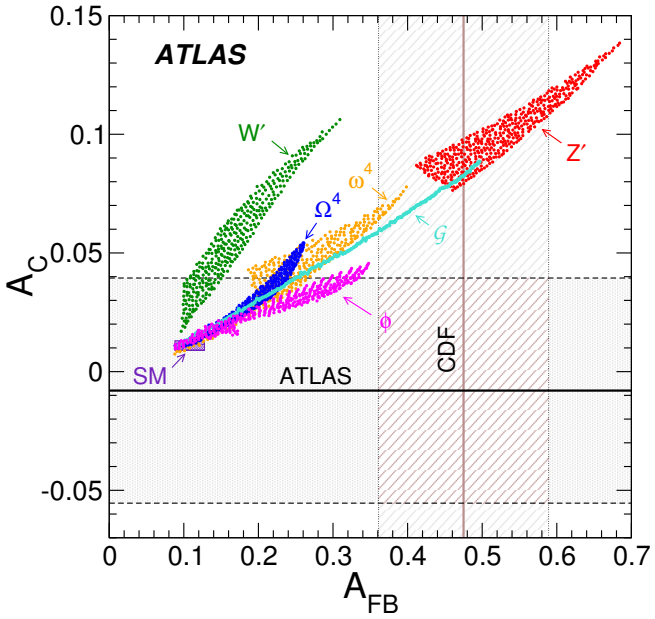
# Measurement of charge asymmetry in $t\bar{t}$ production

$A_C$ Fit Results:

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




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



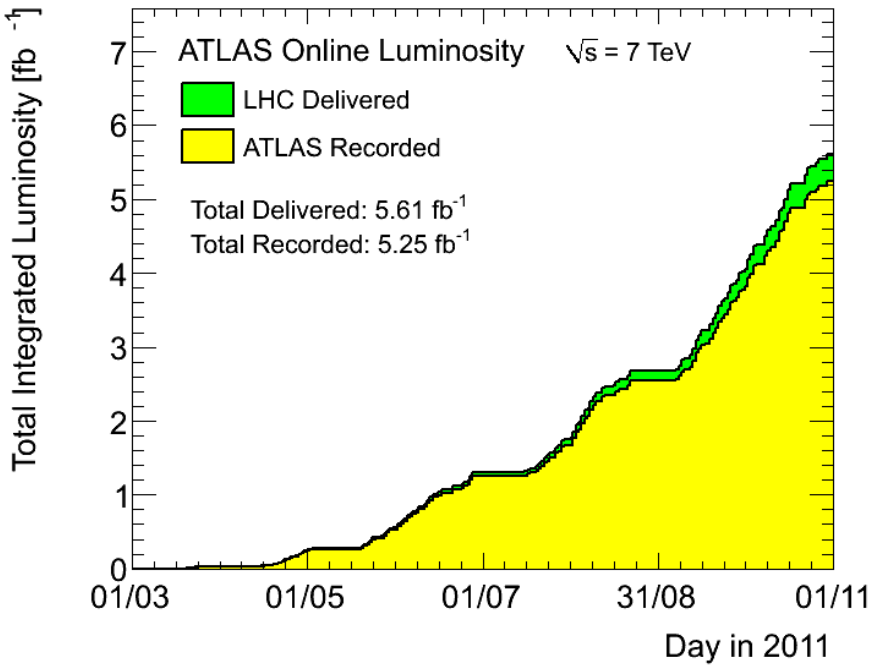
# Summary

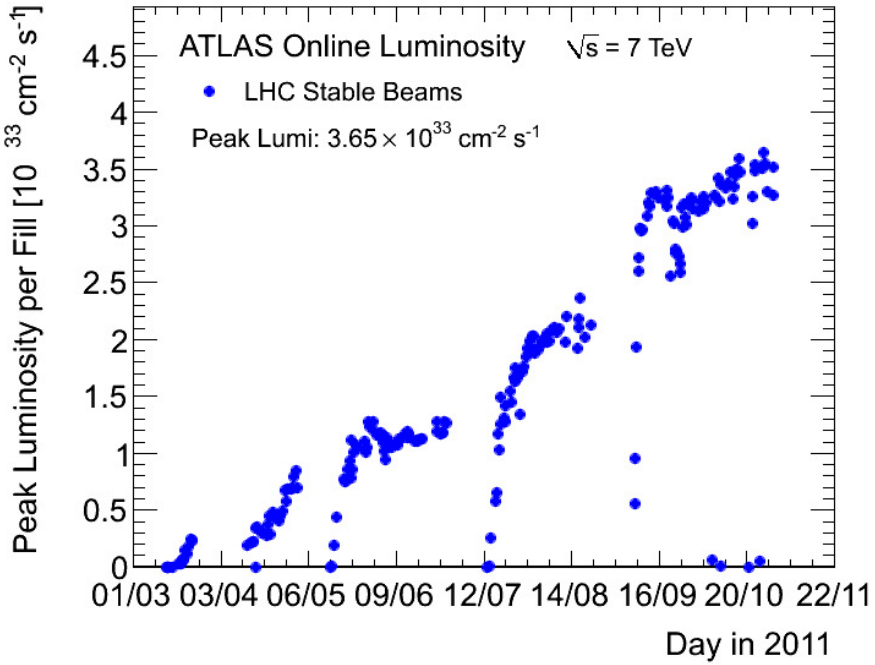
- Top pairs offer a rich phenomenology. Many analyses carried out in ATLAS with top quarks
- A few measurements, search results using top pairs shown today
  - No evidence of $X \rightarrow t\bar{t}$.
  - First observation of spin correlation and charge asymmetry measurement in good agreement with SM predictions
  - Disfavors some models proposed to explain Tevatron's $A_{FB}$ measurements
- More results with $5\,\mathrm{fb}^{-1}$ to come
- Increased energy ($\sqrt{s} = 8$ TeV) and statistics beneficial for searches and measurements
- Details of results
  - ATLAS Top results
  - ATLAS Exotics 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 - ATLAS 2011 Integrated Luminosity




- Steady and significant increase in instantaneous luminosity in 2011
- Integrated luminosity recorded by ATLAS in 2011 reached 5.3 $fb^{-1}$ with 5.6 $fb^{-1}$ delivered by LHC with stable beams
- Analyses and results shown today include dataset with 1 to 2 $fb^{-1}$ integrated luminosities

# 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
  - $\mu$ 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