Measurement of the top quark polarization in semi-leptonically decaying top-antitop pairs with the ATLAS detector

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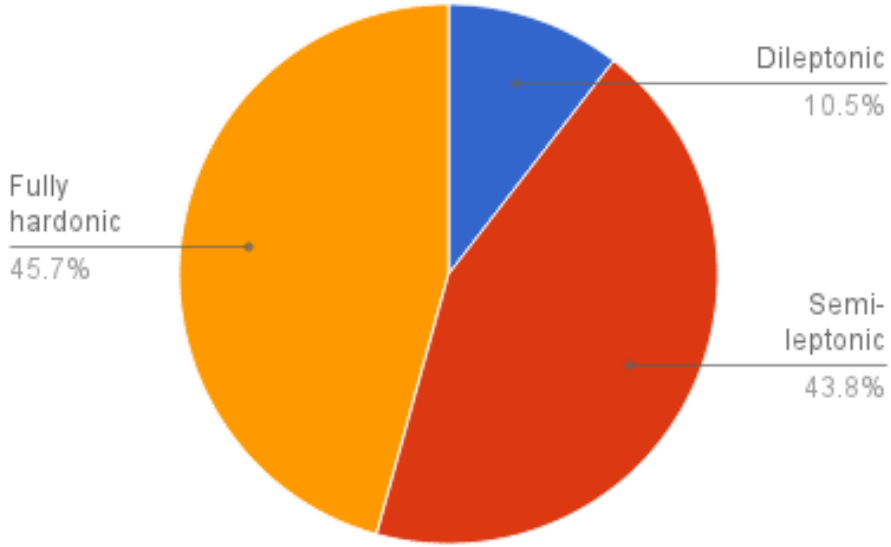
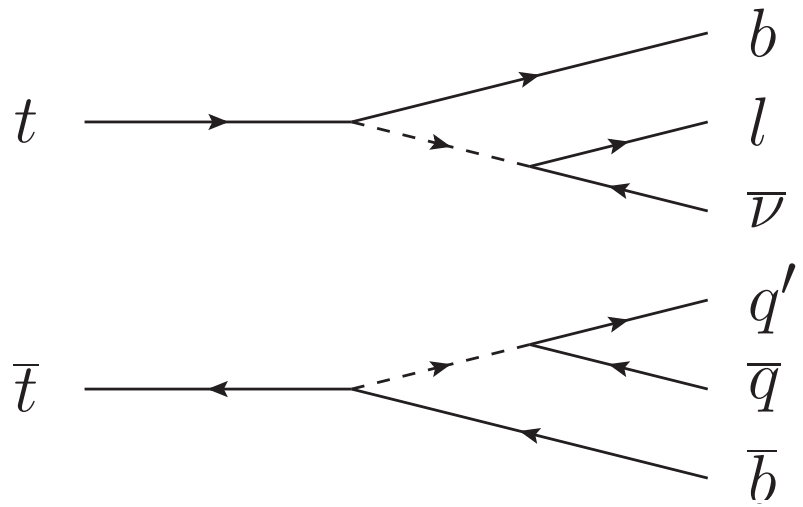
The top quark

Top Properties
$m_t = 173.5 \pm 1.0$ GeV
$\Gamma = 2.0^{+0.7}_{-0.6}$ GeV
$\tau \approx 3.3 \times 10^{-25}$ s

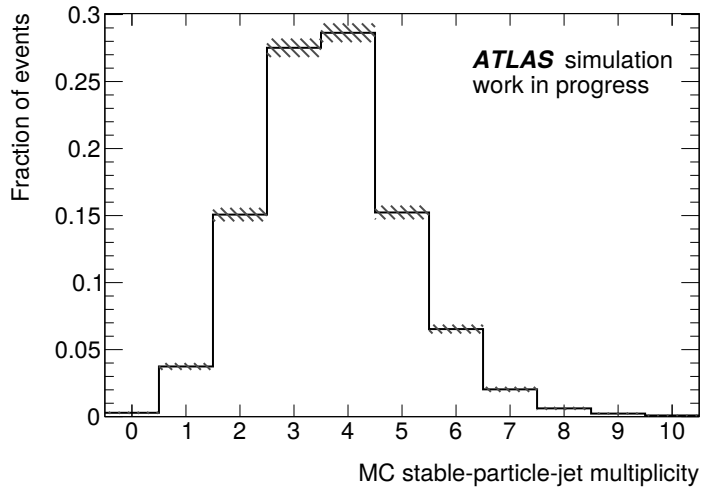


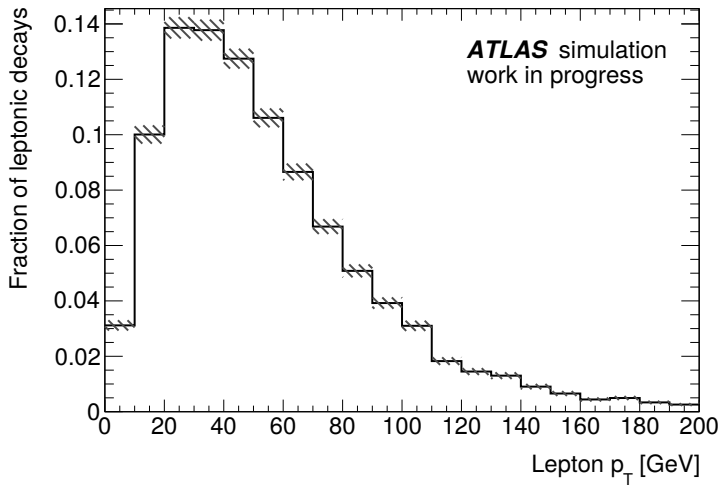
- Heaviest known fundamental particle.
- Lifetime is shorter than QCD timescale: no top bound states.
- **Decay products preserve the top's polarization state.**



Top-antitop event selection

- Exactly one electron or muon.
- 4 QCD jets.
- 2 b-tagged jets:
  - Neural network trained to identify b-quark decays.
  - Looks for b-quark decay's displaced vertex.
  - 70% working point misidentifies 1/137 light quarks jets.
- Significant missing transverse energy (MET) indicates the presence of a neutrino.

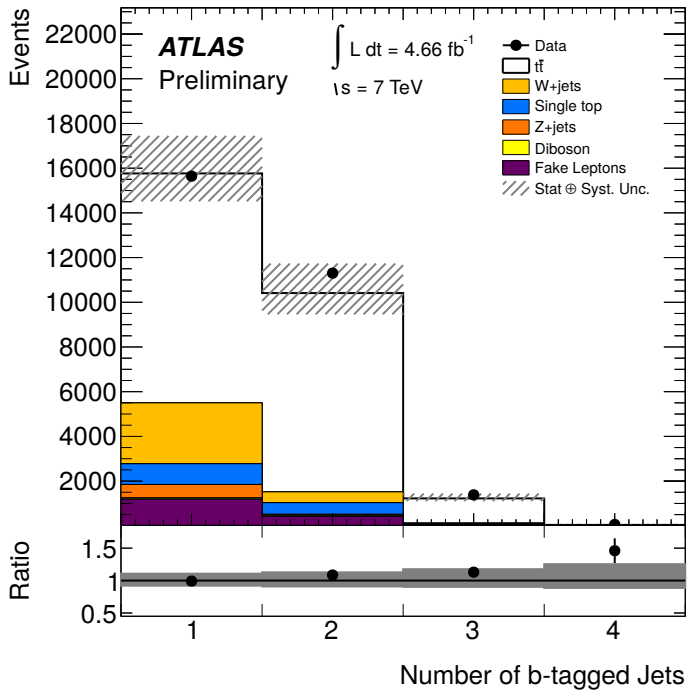




Simulation of $t\bar{t}$ production at $\sqrt{s} = 8$ TeV.

Backgrounds to top-antitop detections

- Processes which can create 4 jets, 1 lepton and MET are backgrounds.
- MET can arise from mis-measurement.
- QCD jet production σ is on the order 5×10^7 pb.
- QCD jets can be misidentified as leptons.
- Background processes are:
  - W boson and jets.
  - Z boson and jets.
  - Diboson.
  - Fake leptons (QCD).
  - Single top.



Number of b-tagged jets in electron events at $\sqrt{s} = 7$ TeV. Few b-tagged jets are observed in background events [1].

Top polarization

- Strong force vertex couples equally to left and right spin states: $g_s \lambda\gamma$.
- Strongly produced $t\bar{t}$ pairs are produced with **zero net polarization** in the standard model.
- Double differential distribution of polar angles of $t\bar{t}$ decay products (parity conserving case):

$$\frac{1}{\sigma}\frac{\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 + \alpha_1 P_1 \cos\theta_1 + \alpha_2 P_2 \cos\theta_2 - C\cos\theta_1\cos\theta_2\right)$$

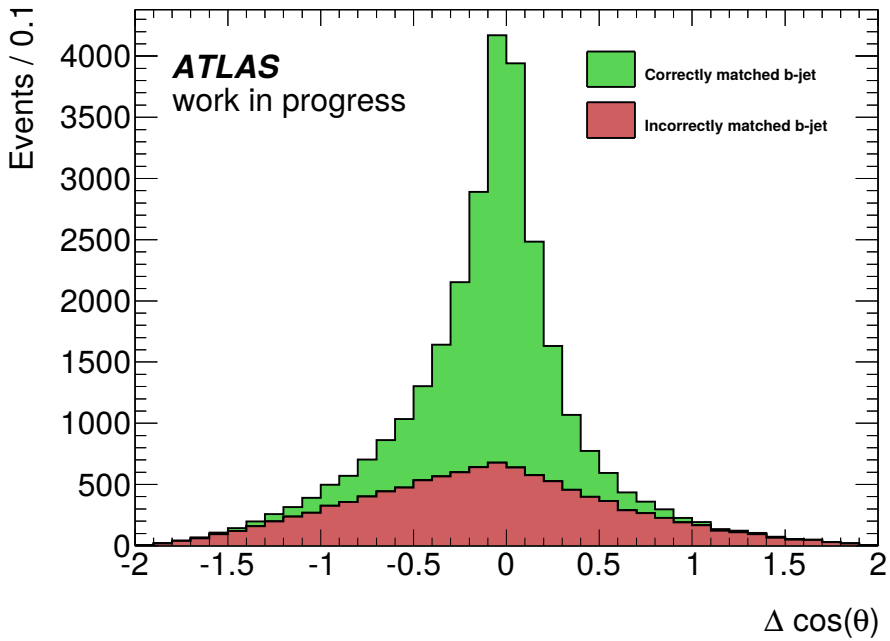
- P is the polarization of top quark.
- $\cos\theta$ is the polar angle of the decay products relative to the top quark's direction.
- α is the spin analyzing power (1 for leptons).
- C is the spin correlation.

Reconstructing the top's frame

- Two event permuatations are found by exchanging the b jets.
- Permutation closest to the top mass is selected by minimizing:

$$\left(\sqrt{(\boldsymbol{\nu}+\mathbf{l}+\mathbf{b_l})^2}-m_{\text{top}}\right)^2+\left(\sqrt{(\mathbf{q_1}+\mathbf{q_2}+\mathbf{b_h})^2}-m_{\text{top}}\right)^2$$

- $\boldsymbol{\nu}_{x,y}$ is determine from the MET.
- $\boldsymbol{\nu}_z$ is calculated from 4-momentum conservation.



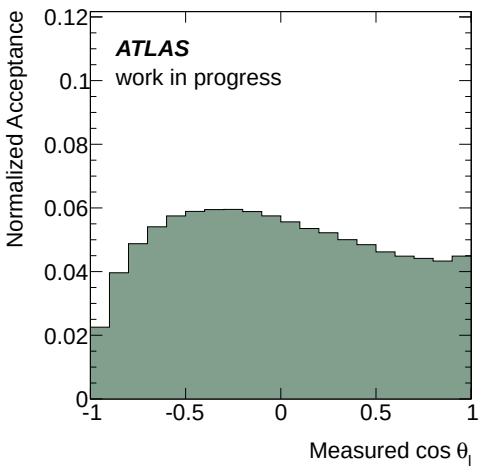
Difference between reconstructed and Monte-Carlo generated $\cos\theta$ in the electron channel at $\sqrt{s}=8$ TeV.

Measuring the top's polarization

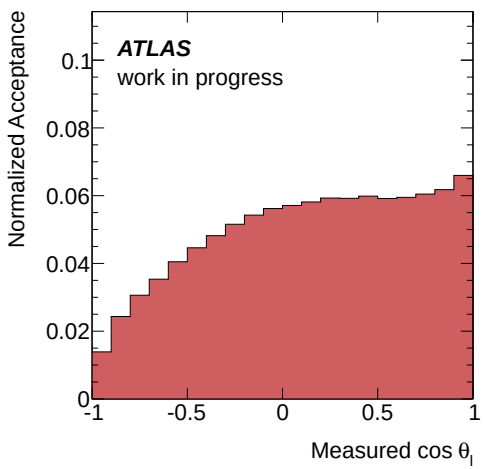
- Templates of positive (P) and negative (N) polarization are created.
- For each bin i of $\cos\theta$, the acceptance is measured (a_i).
- The template value of each bin is obtained by re-weighting its events by $1 \pm \cos\theta$ (simplified for this presentation).

$$\begin{aligned} S_i &= f P_i + (1-f) N_i \\ &= f a_i (1+\cos\theta_i) + (1-f) a_i (1-\cos\theta_i) \\ &= a_i \left\{1 + (2f-1)\cos\theta_i\right\} \end{aligned}$$

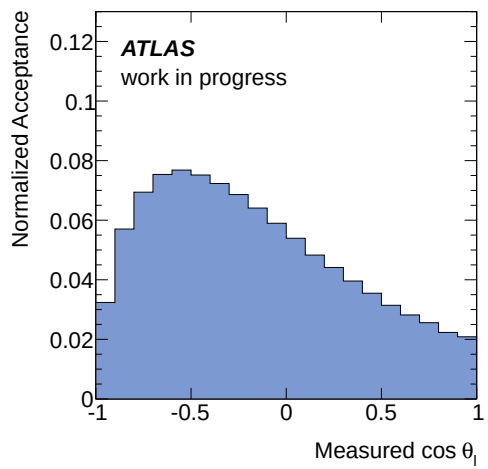
$F_i = a_i$



$P_i = a_i(1+\cos\theta)$



$N_i = a_i(1-\cos\theta)$

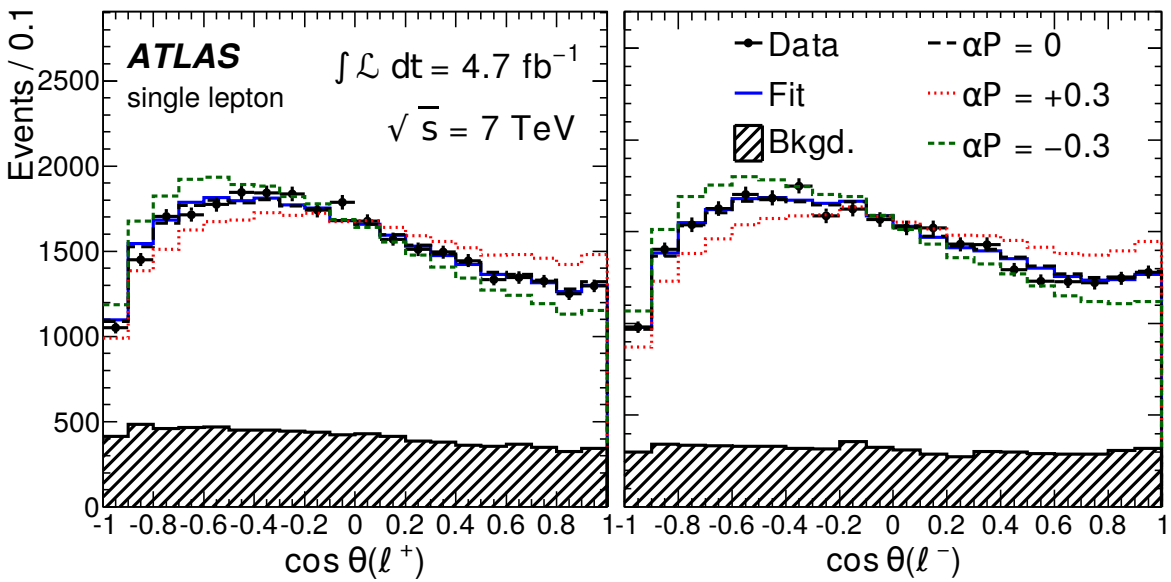


Measurement of the top's polarization

- $\sqrt{s} = 7$ TeV measurement of the parity conserving $t\bar{t}$ polarization in semi-leptonic decays:

$$-0.034 \pm 0.017^{+0.038}_{-0.037}$$

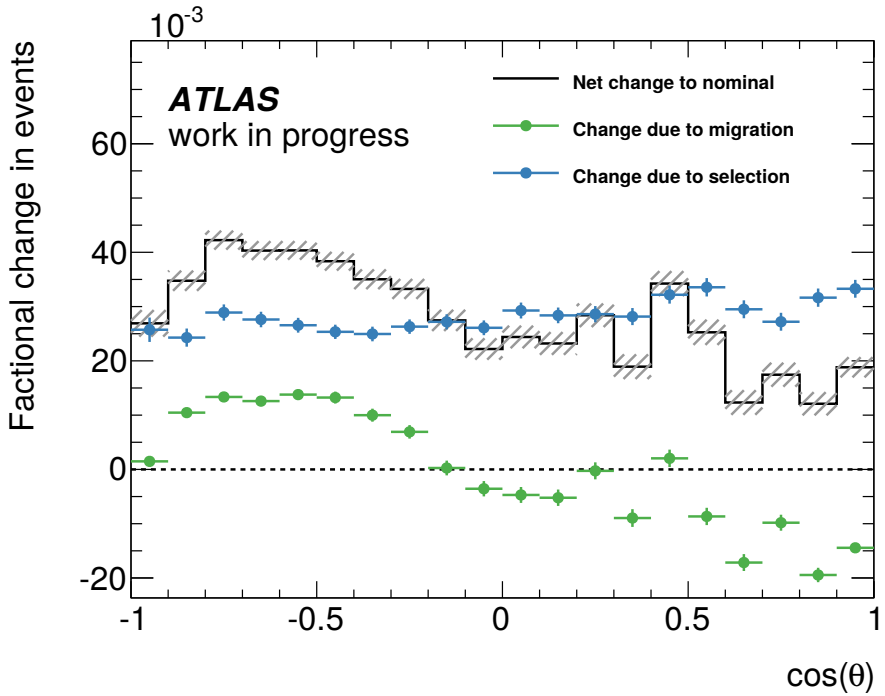
- Nearly 3/4 of the systematic uncertainty arises from jet modelling uncertainty.



$\sqrt{s} = 7$ TeV parity conserving polarization measurement [2].

Uncertainties in the measurement

- Impact of jet energy uncertainty:
  - Migration between bins of $\cos\theta$.
  - Change in jet permutation choice.
  - Change in acceptance of events.
- Mitigation strategies:
  - Optimize bin size (shape resolution vs. migration).
  - Cut at higher $m_{t\bar{t}}$ where selection is less sensitive to jet energy.
  - Decouple reconstruction method from jet energy.



Fractional change to the $\cos\theta$ template after applying a jet energy systematic uncertainty shift at $\sqrt{s} = 8$ TeV.

Summary

- Top quark allows probing of quantities with precise predictions from the standard model.
- $\sqrt{s} = 8$ TeV LHC data provides unprecedented statistics for precise measurement of $t\bar{t}$ properties.
- Top polarization has been measured at $\sqrt{s} = 7$ TeV and is consistent with the standard model prediction.
- Measurement at $\sqrt{s} = 8$ TeV is underway.
- Statistical uncertainty is smaller, and systematic uncertainties can be reduced.
- More stringent bounds can be placed on $t\bar{t}$ polarization.

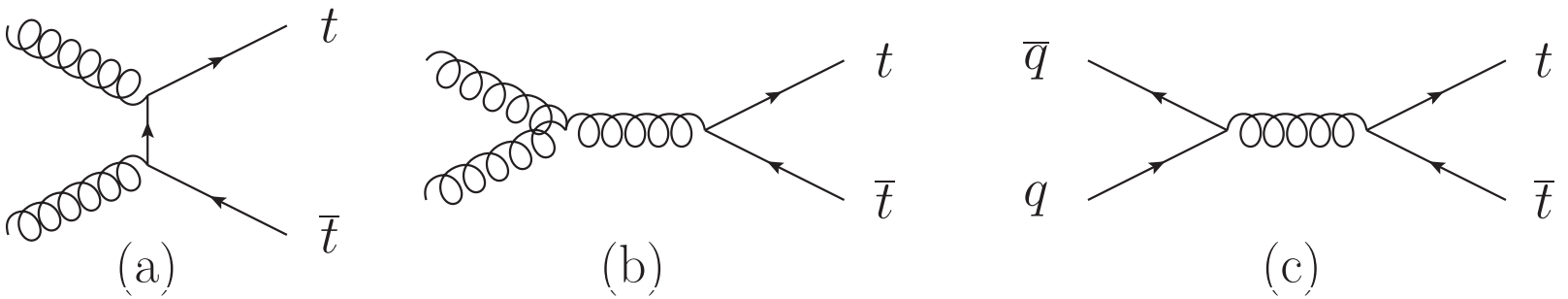
References

ATLAS Collaboration.
Measurement of top quark polarisation in $t\bar{t}$ events with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$.
Technical Report ATLAS-CONF-2012-133, CERN, Geneva, Sep 2012.

ATLAS Collaboration.
Measurement of top quark polarization in top-antitop events from proton-proton collisions at s = 7 TeV using the ATLAS detector.
Phys. Rev. Lett., 111(arXiv:1307.6511. CERN-PH-EP-2013-101):232002. 19 p, Jul 2013.

Backup

Collider production of top-antitop pairs



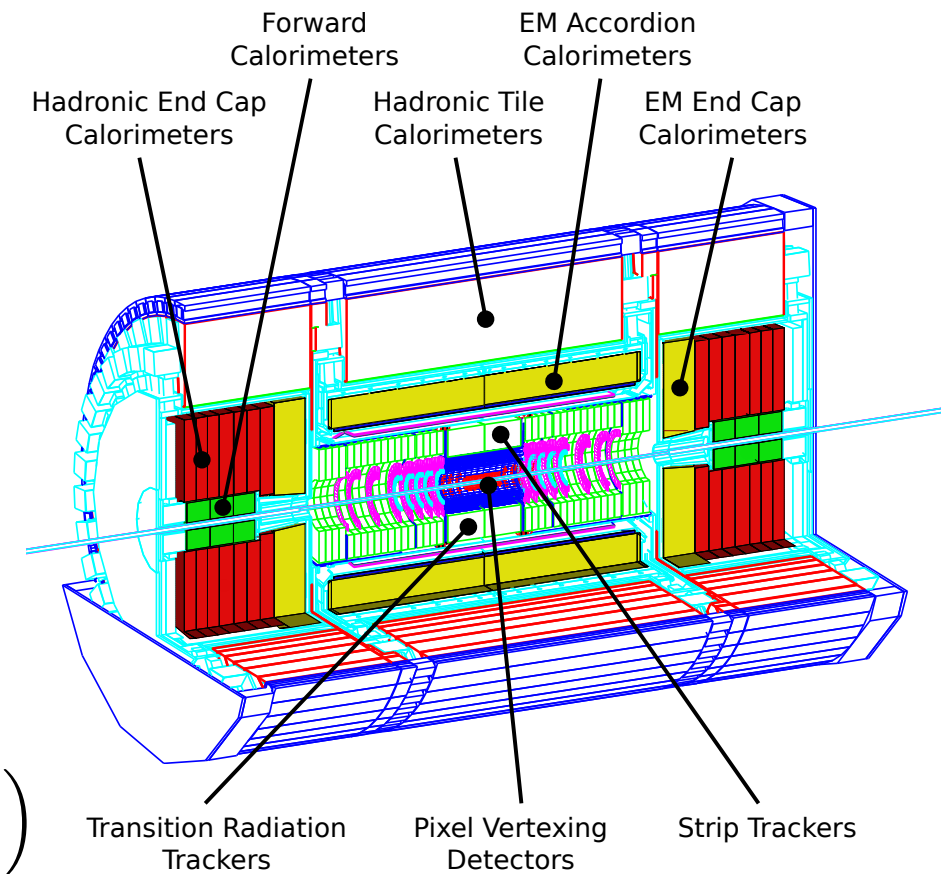
Experiment	$\sqrt{s}$ [TeV]	$\sigma_{t\bar{t}} \pm \sim 5\%$ [pb]	$t\bar{t}$ pairs $\pm \sim 5\%$
Tevatron	1.96	7.24	79 000
LHC	7	177	960 000
LHC	8	253	5 800 000

- Gluon fusion (a, b) dominates with the **LHC** pp initial state: 80% of $t\bar{t}$ production at $\sqrt{s} = 7$ TeV.
- $q\bar{q}$ annihilation (c) dominates with the **Tevatron** $p\bar{p}$ initial state: 85% of $t\bar{t}$ production.

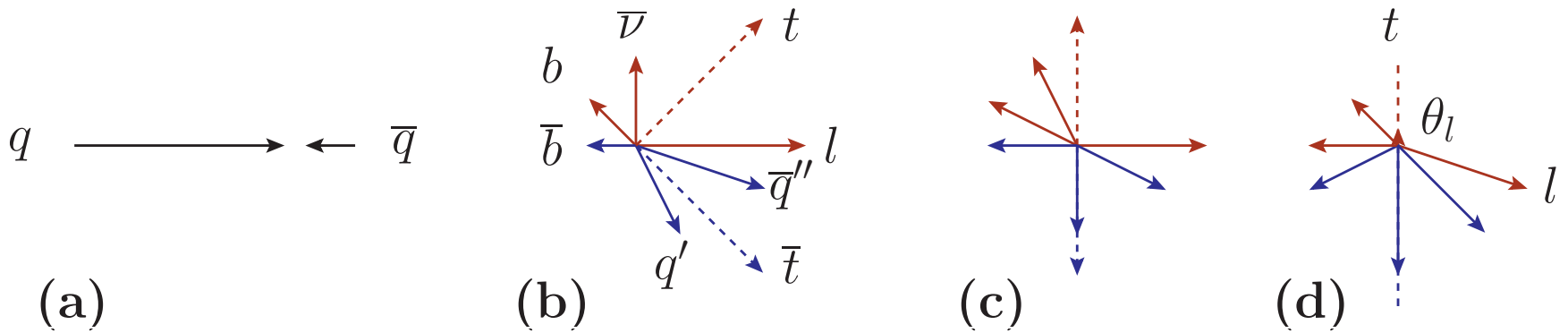
The ATLAS detector

- Semil-leptonic top analysis uses the following physics objects:
- **QCD jets**: tracks + EM + hadronic calorimeters
- **Electroms**: tracks + EM calrimeter
- **Muon**: muon spectrometer
- Missing transverse energy (**MET**):

$$-\sum\left(\overrightarrow{\mathrm{lep}_E}+\overrightarrow{\gamma_E}+\overrightarrow{\mathrm{jet}_E}+\overrightarrow{\mathrm{calo}_E}\right)$$



Measuring the polar angle



$q\bar{q}$ annihilation

$t\bar{t}$ decay products (lab frame)

$t\bar{t}$ rest frame

t rest frame

- Polar angle θ is measured in the top's rest frame.
- Leptonic b-quark must be identified to reconstruct tops rest frame.
- Neutrino p_z must be calculated.

Template fit

- Contents of bin i given polarization P (up to a normalization factor):

$$S_i = 1 + P\cos\theta_{1i} + P\kappa + C\cos\theta_{1i}\kappa$$
$$\kappa \equiv \sum \cos\theta_2$$

- Fit from a sum of positive and negative polarization:

$$\begin{aligned}
S_i = \quad & f\left(1 + \cos\theta_{1i} + \kappa + C\cos\theta_{1i}\kappa\right) + \\
& (1-f)\left(1 - \cos\theta_{1i} - \kappa + C\cos\theta_{1i}\kappa\right) \\
= \quad & f + f\cos\theta_{1i} + f\kappa + fC\cos\theta_{1i}\kappa + \\
& 1 - \cos\theta_{1i} - \kappa + C\cos\theta_{1i}\kappa + \\
& -f + f\cos\theta_{1i} + f\kappa - fC\cos\theta_{1i}\kappa \\
= \quad & 1 + 2f\cos\theta_{1i} - \cos\theta_{1i} + 2f\kappa - \kappa + C\cos\theta_{1i} \\
= \quad & 1 + (2f-1)\cos\theta_{1i} + (2f-1)\kappa + C\cos\theta_{1i} \\
& \Rightarrow P = 2f - 1
\end{aligned}$$