Top Properties at the LHC

Jay Howarth: on behalf of the ATLAS and CMS Collaborations.
The story of top physics through the measurement of its properties.
TIMELINE OF TOP PHYSICS

Top Properties:
- Mass
- Width
- Charge
- Spin (Polarisation)
- Lifetime & Decay

Production Properties:
- Spin Correlation
- Charge Asymmetry
- Rare Processes

1995
2000
2005
2010
2015

ATLAS
CMS
DO
CDF
**Top Properties:**
- Mass
- Width
- Charge
- Spin (Polarisation)
- Lifetime & Decay

**Production Properties:**
- Spin Correlation
- Charge Asymmetry
- Rare Processes

**Already Had Some Great Talks!**
TIMELINE OF TOP PHYSICS


Top Properties:
- Mass
- Width
- Charge
- Spin (Polarisation)
- Lifetime & Decay

Production Properties:
- Spin Correlation
- Charge Asymmetry
- Rare Processes*

In this talk
Top Quark Discovered!

- The top quark is discovered by the CDF and D0 collaborations with a mass of ~ 175 GeV.
Lots of cross-section and Branching Ratio Studies

Properties need high stats to be sensitive…
First limits on charge by D0 (2007)

First Charge Asymmetry Measurements (2008)

CDF Starts to place limits on the Top Quark Width (2009)
TIMELINE OF TOP PHYSICS


LHC Turn ON!

The world’s first “top factory”, everyone gets excited…
Spin Correlations Observed

**ATLAS** excludes the possibility of spin-uncorrelated $\bar{t}t$ decays with more than 5$\sigma$. **CMS** see similar results a few months later.

(In fairness, **CDF** have been placing limits for a while and **DO** had first evidence)
ATLAS, CMS, D0, and CDF collectively publish dozens of properties papers in less than 3 years!
Properties measurements answer three things:

- Is it really a top quark?       (top quark charge)
- Is it the SM top quark?        (|V_{tb}| and width)
- Is it just the SM top quark?  (all properties, but $t\bar{t}\gamma$ as example)
Top Quark Charge

Is it really a top quark?
Did we really find the top?

• Two crucial components to the answer: charge and mass.
• Top mass is a free parameter in the SM (with a few constraints).
• Charge is not! Perfect to test if we’ve really found the isospin partner to the b-quark.

Observables:

• **CMS** measures an asymmetry \( A \) in terms of SM expectation \((SM = 2/3)\) and the exotic case \((XM = -4/3)\):

\[
A = \frac{1}{D_S} \frac{N_{SM} - N_{XM} - <N_{BG}>}{N_{SM} + N_{XM} - <N_{BG}>} \quad D_B
\]

• \( D_{S/B} \) = Dilution of signal(background)
• \(<N_{BG}>\) = Expected background events.
• \( N_{SM/XM} \) = Number of reconstructed events with SM(XM) charge.
Did we really find the top?

- Two crucial components to the answer: charge and mass.
- Top mass is a free parameter in the SM (with a few constraints).
- Charge is not! Perfect to test if we’ve really found the isospin partner to the b-quark.

Observables:

- **ATLAS** measures the charge directly, as well as a test statistic for hypothesis testing:

\[
\bar{Q} = (1 - r_b - r_t) \cdot Q_s + r_b \cdot Q_b + r_t \cdot Q_t
\]

- \(Q_{s/t/b} = Q_{b-jet} \cdot Q_\ell\)

- \(Q_{s/b/t} = \) Mean charge values for signal, background, and single top.
- \(r_{b/t} = \) fraction of background/single top events in signal selection.
ATLAS

\[ \int \mathcal{L} \, dt = 2.05 \, \text{fb}^{-1} \quad 7 \, \text{TeV} \]

- Lepton + Jets Channel
- 1 Isolated e(\mu) with \( E_T > 25 \, \text{GeV} \) (\( p_T > 20 \, \text{GeV} \))
- 4 or more jets with \( p_T > 25 \, \text{GeV} \)
- At least 1 b-tag (using MV-based tagger).
- \( E_T^{\text{miss}} > 20(35) \) for e(\mu) events.

- Electron: \( m_{T}(W) > 25 \, \text{GeV} \)
- Muon: \( m_{T}(W) + E_T^{\text{miss}} > 60 \, \text{GeV} \)

CMS

\[ \int \mathcal{L} \, dt = 4.60 \, \text{fb}^{-1} \quad 7 \, \text{TeV} \]

- Muon + Jets Channel
- All objects reconstructed using particle flow.
- 1 Isolated \( \mu \) (\( p_T > 26 \, \text{GeV} \))
- 4 or more jets (\( p_T > 30 \, \text{GeV} \))
- At least 2 b-tags (using a vertex significance tagger)
B-Jet Charge Identification: “Track Weighting Technique”

Track Selection:
- \( p_T > 1 \) GeV
- \( |\eta| < 2.5 \)
- \( \Delta R_{(\text{track,bjet})} < 0.25 \)
- At most 10 highest \( p_T \) tracks

\[
Q_{\text{b jet}} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^\kappa}{\sum_i |\vec{j} \cdot \vec{p}_i|^\kappa}
\]

- \( q_i = \) Track charge
- \( p_i = \) Track momentum
- \( \vec{j} = \) B-jet axis
- \( \kappa = \) b-bbar separation parameter \((0.5)\)
Lepton — B-Jet Assignment:

- Invariant mass of correct lepton — b-jet pair shouldn’t exceed top quark mass.

\[ M(\ell, \ bjet_A) < m_{cr} \]

and

\[ M(\ell, \ bjet_B) > m_{cr} \]

- \( m_{cr} \) is optimised for efficiency and purity, with an optimal value of 155 GeV.

"Invariant Mass Technique"

Efficiency = 28 %

Purity = 81 %
**B-Jet Charge Identification:** "Soft Muon Tagging"

\[
BR(b \rightarrow \mu + \nu + X) \approx 11\% \\
BR(b \rightarrow c \rightarrow \mu + \nu + X) \approx 10\%
\]

- Transverse momentum of muon, relative to jet axis, sensitive to source of muon.
- Optimal cut point \( p_{T, \text{rel}} > 0.85 \text{ GeV} \).
- 74.5% ± 2.7% of events with soft muon have correct charge assignment.
Lepton — B-Jet Assignment:  "Invariant Mass Technique"

• Invariant mass of one selected b-jet and two other jets closest to m_{top} defines hadronic b.

• Invariant mass of muon and other b-jet must be less than 150 GeV.

• Charge of leptonic top is sum of the lepton-jet charge.

Efficiency = ~60 %
Purity = 80 %
• **ATLAS** describes b-jet $p_T$ well in both electron and muon channels.

• Good data/MC agreement for preselection and after charge assignment in **CMS** analysis, illustrated in the soft muon $p_T$ spectrum.
• Both observables also clearly agree with the SM expectation.
\[ Q_{\text{meas.}} = 0.64 \pm 0.02 \text{ (stat.)} \pm 0.08 \text{ (syst.)} \quad A_{\text{meas.}} = 0.97 \pm 0.12 \text{ (stat.)} \pm 0.31 \text{ (syst.)} \]

- Both experiments strongly favour the SM hypothesis.
- **ATLAS** explicitly quote exclusion of the non-SM hypothesis at more than 8\(\sigma\) in each channel (**CMS** see similar but don’t quote exactly).
- Both **ATLAS** and **CMS** results are dominated by modelling uncertainties.
Top Quark Charge

Is it really a Top Quark?

Looks like it
Indirect $|V_{tb}|$

Is it the SM top quark?
Definition:

\[ V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.041 & 0.999 \end{bmatrix} \]

- Magnitude of top-bottom charged current proportional to \(|V_{tb}|\), which should dominate over off-diagonal elements (i.e. \(|V_{tb}| \sim 1\))

\[ \mathcal{R} = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} \quad q = (b, s, d) \quad \mathcal{R} = |V_{tb}|^2 \]

- When combined with single top, t-channel production, possible to indirectly measure top-quark partial width.
Event Selection:

- Dilepton events.
- Opposite charged, isolated leptons (e, µ, p_T > 20 GeV).
- At least 2, no more than 4, anti-k_T 0.5 jets (p_T > 30 GeV).
- 15 GeV Z window veto (ee, µµ only).
- Invariant mass > 12 GeV.
- E_T^{miss} > 40 GeV (ee, µµ only).
Extraction:

- Profile likelihood fit using 36 different equations in terms of:
  - \( \epsilon_b \) — b-tag efficiency
  - \( \epsilon_q \) — misID efficiency
  - \( \epsilon_{q^*} \) — misID rate

Example: 2-Jet Events:

\[
\mathcal{P}_{2j,2t,2d} = \mathcal{R}^2 \epsilon_b^2 + 2\mathcal{R}(1 - \mathcal{R})\epsilon_b\epsilon_q + (1 - \mathcal{R})^2 \epsilon_q^2
\]

\[
\mathcal{P}_{2j,2t,1d} = \mathcal{R}^2 \epsilon_b \epsilon_{q^*} + \mathcal{R}(1 - \mathcal{R})(\epsilon_b + \epsilon_q)\epsilon_{q^*} + (1 - \mathcal{R})^2 \epsilon_q \epsilon_{q^*}
\]

\[
\mathcal{P}_{2j,2t,1d} = \epsilon_{q^*}^2
\]
Results:

\[ R_{ee} = 0.997 \pm 0.007 \pm 0.035 \]
\[ R_{\mu\mu} = 0.996 \pm 0.007 \pm 0.034 \]
\[ R_{e\mu} = 1.015 \pm 0.003 \pm 0.031 \]
\[ R_{\text{comb.}} = 1.014 \pm 0.003 \pm 0.032 \]

(Other Results)

\[ R_{\text{CDF (dilepton)}} = 0.870 \pm 0.070 \]
\[ R_{\text{D0 (1+jets)}} = 0.900 \pm 0.040 \pm 0.035 \]

Assuming Unitarity:

\[ |V_{tb}| = 1.007 \pm 0.016 \]

• Each channel, as well as combined result, consistent with SM expectation and with one-another.

• Replacing R with |V_{tb}| in the fit, also gives result consistent with SM expectation.

• CMS R results relative uncertainty of 3.1%.
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Assuming Unitarity:

\[ |V_{tb}| = 1.007 \pm 0.016 \]

• Dominant systematic uncertainties come from top quark mass assumption, and b-tagging efficiency.
**Top Width:**

\[ \Gamma_t = \frac{\sigma_{t-ch}}{\mathcal{B}(t \rightarrow Wb)} \cdot \frac{\Gamma(t \rightarrow Wb)}{\sigma_{t-ch}^{\text{theory}}} \]

- Where \( \sigma_{t-ch} \) are the measured or “theory” t-channel cross sections.
- Assuming top quark mass of 172.5 GeV, the predicted width is \( \Gamma_t = 1.329 \)
- Measurement performed using 7 TeV single top theoretical predictions and measurements from CMS:

\[ \Gamma_t = 1.36 \pm \text{(stat.)} \pm^{0.14}_{0.11} \text{(syst.)} \]

- Dominant uncertainty from single top measurement (9.2% of 10.4%)
Indirect $|V_{tb}|$

Is it the SM top quark?

Seems so
Associated Photon Production

Is it a window into new physics?
Motivation:

• Top couplings are not diluted by hadronisation, and could be altered by BSM models (first evidence for \(tt\gamma\) reported by CDF).

• \(tt\gamma\) measurements can constrain composite top-quark models as well as excited top-quark models (\(t^* \rightarrow t\gamma\)).

• **ATLAS** measures a fiducial cross-section \(\times\) Branching ratio of single lepton channel.

• **CMS** measures ratio to \(tt\) production and extrapolate to cross-section measurement, again in single-lepton channel.
**t\(\bar{t}\)\(\gamma\): EVENT SELECTION**

\[ \int \mathcal{L} \, dt = 4.60 \text{ fb}^{-1} \quad 7 \text{ TeV} \]

- Lepton + jets channel (similar to charge, see backup)
- Photons are selected with:
  \[ E_T > 25 \text{ GeV} \]
  \[ |\eta| < 2.47 \]
  \[ |\eta| < 1.52 \text{ & } |\eta| > 1.37 \]
  \[ |m(\gamma \ell) - m(Z)| > 5 \text{ GeV} \]
  \[ \Delta R(\gamma, \ell) > 0.7 \]
  \[ \Delta R(\gamma, j) < 0.5 \text{ (reject event)} \]

- Photons from non-hadron parent.
- Leptons(photons) required to have:
  \[ p_T > 20 \text{ GeV}, \; |\eta| < 2.5(2.37) \]
- Electrons are dressed with photons in cone of 0.1.
- Dilepton and tau events considered non-fiducial.
CMS: Preselection

\[
\int \mathcal{L} \, dt = 19.7 \text{ fb}^{-1} \quad 8 \text{ TeV}
\]

- Muon + jets channel (similar to charge, see backup)
- 1 Isolated \( \mu \)
  \( (p_T > 26 \text{ GeV}, |\eta| < 2.1) \)
- At least 4 jets
  \( (p_T > 55, 45, 35, 20 \text{ GeV}) \)
- Events rejected if electron reconstructed with
  \( (p_T > 20 \text{ GeV}, |\eta| < 2.5) \)

CMS "vis" Selection

- Photons selected with
  \( (E_T > 20 \text{ GeV}, |\eta| < 1.444) \)
- Photons are rejected if
  \( \Delta R(\gamma, \mu \text{ or jet}) < 0.7 \)

Analysis uses preselection in denominator for ratio calculation, and visible (vis) photon selection in ratio numerator.
Both **ATLAS** and **CMS** see good agreement in the photon transverse energy spectrum.
Isolation:

- In both ATLAS and CMS, the signal selection has a high percentage of non-prompt photons.

- Non-prompt photons are those originating from charged hadron decays, and not from the $t\bar{t}\gamma$ signal.
**Extraction:**

- Quantity of correctly identified prompt-photons extracted using binned likelihood fit to charged hadron isolation.

\[
R \equiv \frac{\sigma_{\bar{t}t + \gamma}}{1} \cdot \frac{1}{\sigma_{tt}} \equiv \frac{R_{\text{vis}}^\text{vis}}{\epsilon_{\gamma}} = \frac{N_{\text{sig}}}{\epsilon_{\text{vis}} \epsilon_{\gamma}} \cdot \frac{1}{N_{\text{presel}} \cdot \pi_{tt}}
\]

- \( R_{\text{vis}} \) = observed ratio
- \( \epsilon_{\text{vis}} \) = selection efficiency
- \( N_{\text{presel}} \) = number of \( \bar{t}t \) selected events before photon selection
- \( \pi_{tt} \) = purity of preselected \( \bar{t}t \) events
- \( \epsilon_{\gamma} \) = efficiency for photon to enter preselection
- \( \epsilon_{\text{vis}} \) = efficiency for photon to pass photon selection

- Templates derived from MC (using MC history to differentiate real and fake).
Extraction:

- Number of signal events extracted using template fit to photon-track isolation variable.
- Prompt photon template derived from Z events in data.
- Non-prompt photon template derived from di-jet events with inverted EM shower cuts.
- Cross section calculated using:

\[ \sigma_{t\bar{t}+\gamma}^{\text{fid.}} = \frac{N_s}{\epsilon \cdot L} \]
Results: **ATLAS**

\[
\sigma_{t\bar{t}+\gamma}^{\text{fid}} \times \text{BR} = 63 \pm 8 \ (\text{stat.})^{+17}_{-13} \ (\text{syst.}) \pm 1 \ (\text{lumi.}) \ \text{fb}
\]

\[
\sigma_{t\bar{t}+\gamma}^{\text{fid \ theory}} \times \text{BR} = 48 \pm 10 \ \text{fb}
\]

5.3 \sigma \text{ significance from the zero hypothesis}

Results: **CMS**

\[
R = (1.07 \pm 0.07 \ (\text{stat.}) \pm 0.27 \ (\text{syst.})) \times 10^{-2}
\]

\[
\sigma_{t\bar{t}+\gamma} = 2.4 \pm 0.2 \ (\text{stat.}) \pm 0.6 \ (\text{syst.}) \ \text{pb}
\]

\[
\sigma_{t\bar{t}+\gamma}^{\text{theory}} = 1.8 \pm 0.5 \ \text{pb}
\]

Dominated by jet modelling uncertainties (17%)

Dominated by background modelling uncertainties (23%)

- Both experiments observed agreement with the SM expectation.
Associated Photon Production

Is it a window into new physics?

Perhaps, but not yet
**Conclusions:**

- Top quark properties have been extensively probed during Run1 at the LHC.
- Every observed property agrees with the SM expectation.

**Prognosis?**

- Either we’re really really good at predicting top properties, or new physics is hiding at a higher scale, or its contributions are more subtle than we’ve probed so far.
- Story isn’t over yet! Many more Run1 results in the pipeline, and Run2 about to start.
Backup
ATLAS Results:

- Charge: http://arxiv.org/abs/1307.4568
- $tt\gamma$: http://arxiv.org/abs/1502.00586

CMS Results:

- Charge: http://inspirehep.net/record/1260686
- Width: http://arxiv.org/abs/1404.2292
- $tt\gamma$: http://inspirehep.net/record/1278650
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<th>Source</th>
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