Structure

- Introduction
- Angular Distributions
- Colour Flow
- Summary
Introduction
The Top Quark

- **Heaviest known elementary particle:**
  \[ m_t \sim 173 \text{GeV} \]

- **Standard Model:**
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime 0.5x10^{-24}s
    - **Bare quark** - no hadronisation
  - \(~100\% \) decay into Wb
  - Large coupling to SM Higgs boson
Top: From Discovery...

Discovered in 1995 by CDF and DØ at Fermilab (with few events)
...to Precision

Discovered in 1995 by CDF and DØ at Fermilab (with few events)

Situation today:
LHC $\rightarrow$ top quark factory!
- Many precision measurements possible!
Top Studies: Overview

- Top mass
- Top mass difference
- Top charge
- Lifetime
- Top width

- Branching ratios $|V_{tb}|$
- Anomalous coupling
- New/Rare decays

- Spin correlation
- Charge asymmetry
- Color Flow

- Production cross section
- Production kinematics
- Production via resonance
- New particles

- W helicity

s-, t- and Wt-channel production, properties and searches in single top events
Top Studies: Overview

- Top mass
- Top mass difference
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Top Quark Pair Production

At the Tevatron:

85% + 15%

At LHC:

14 TeV: 10% + 90%
7 TeV: 30% + 70%
Top Quark Pair Production

At the Tevatron:

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At LHC:

14 TeV: 10% + 90%
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Cross Sections:

<table>
<thead>
<tr>
<th>Collider</th>
<th>Cross section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (1.96 TeV)</td>
<td>$7.35^{+0.23}_{-0.27}$</td>
</tr>
<tr>
<td>LHC (7 TeV)</td>
<td>$177.3^{+10.1}_{-10.8}$</td>
</tr>
<tr>
<td>LHC (8 TeV)</td>
<td>$252.9^{+13.3}_{-14.5}$</td>
</tr>
<tr>
<td>LHC (13 TeV)</td>
<td>$831.8^{+40.3}_{-45.6}$</td>
</tr>
</tbody>
</table>

M. Czakon et al. arXiv:1112.5675
Final States in $t\bar{t}$

t$\rightarrow W^+ b W^- \bar{b}$: Final states are classified according to W decay

$B(t \rightarrow W^+ b) = 100\%$
Final States in $t\bar{t}$

$t\bar{t}\to W^+bW^-\bar{b}$: Final states are classified according to $W$ decay

$\mathcal{B}(t\to W^+b)=100\%$

**all-hadronic:**

$\geq 6$ jets (2 $b$-jets)

**dilepton:**

2 isolated leptons;

High missing $E_T$ from neutrinos;

2 $b$-jets

**lepton+jets:**

1 isolated lepton;

Missing $E_T$ from neutrino;

$\geq 4$ jets (2 $b$-jets)
Identification of b-Jets

- Important tool to increase $t\bar{t}$ purity
- $b$-hadron: travels some millimeters before it decays
- Neural Network (MV1) combines properties of displaced tracks and displaced vertices
Angular Distributions
Spin Correlations & Polarization

- Top quarks decay before fragmentation
  - Spin information is preserved
- Hadron colliders: top quarks produced un-polarized, but
  - New physics (NP) could induce polarization
    - e.g. NP causing forward-backward $t\bar{t}$ asymmetry → more left-handed tops
  - Correlation between top and antitop spin can be extracted
Measured spin correlation can change

- Due to different decay
- Due to different production

Spin correlation: test the full chain form production to decay!
Spin Correlation & Polarization

- Doubly differential cross section:

\[
\frac{1}{\sigma} \frac{d^2 \sigma}{d\cos \theta_1 d\cos \theta_2} = \frac{1}{4} \left( 1 \pm (\alpha P)_1 \cos \theta_1 \pm (\alpha P)_2 \cos \theta_2 - C \cos \theta_1 \cos \theta_2 \right)
\]

- \(\alpha_i\): spin analyzing power of decay product \(i\);
- \(\theta_i\): direction of daughter wrt. chosen axis

- \(P\): polarization
- \(C\) spin correlation;
Spin Correlation & Polarization

- Doubly differential cross section:

\[ \frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4} \left( 1 \pm (\alpha P)_1 \cos\theta_1 \pm (\alpha P)_2 \cos\theta_2 - C \cos\theta_1 \cos\theta_2 \right) \]

- \( \alpha_i \): spin analyzing power of decay product \( i \);
- \( \theta_i \): direction of daughter wrt. chosen axis
- \( P \): polarization
- \( C \) spin correlation; \( C = A_{\alpha_1 \alpha_2} \)

<table>
<thead>
<tr>
<th>( \alpha_{i/j} ) (LO)</th>
<th>b</th>
<th>lepton</th>
<th>d</th>
<th>u</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.41</td>
<td>1.00</td>
<td>1.00</td>
<td>-0.31</td>
</tr>
<tr>
<td>( \alpha_{i/j} ) (NLO)</td>
<td>-0.39</td>
<td>0.998</td>
<td>0.93</td>
<td>-0.31</td>
</tr>
</tbody>
</table>

\[ A = \frac{N (\uparrow\uparrow) + N (\downarrow\downarrow) - N (\uparrow\downarrow) - N (\downarrow\uparrow)}{N (\uparrow\uparrow) + N (\downarrow\downarrow) + N (\uparrow\downarrow) + N (\downarrow\uparrow)} \]
Spin Correlations: Stop

- Simple azimuthal angle: $\Delta \varphi = |\varphi_1 - \varphi_2|$
  - No kinematic reconstruction needed!
- Extract spin correlation using MC with SM spin correlation, and without spin correlation
  - Extract $f_{SM}$ with template fit to different observables
- Result:
  $$f_{SM} = 1.20 \pm 0.14 \text{(stat + syst)}$$

Spin Correlations: Stop

- Test also stop pair production
  - For $m_{\text{stop}} \sim m_{\text{top}}$
  - Looks like no-correlation $t\bar{t}$

Spin Correlations: Stop

- $\tilde{t}\tilde{t}$ production, $\tilde{t}\rightarrow b f f \tilde{\chi}_1^0 / \tilde{t}\rightarrow c \tilde{\chi}_1^0 / \tilde{t}\rightarrow W b \tilde{\chi}_1^0 / \tilde{t}\rightarrow t \tilde{\chi}_1^0$

**ATLAS Preliminary**
- $t\bar{s}=13$ TeV
- $t0L 13.2$ fb$^{-1}$ [CONF-2016-077]
- $t1L 13.2$ fb$^{-1}$ [CONF-2016-050]
- $t2L 13.3$ fb$^{-1}$ [CONF-2016-076]
- MJ 3.2 fb$^{-1}$ [1604.07773]
- Run 1 [1506.08616]

- $m_{\tilde{t}_1}$ [GeV]
- $m_{\tilde{\chi}_1}$ [GeV]

- Observed limits
- Expected limits
- All limits at 95% CL
Spin Correlations: Stop

Kinematically challenging region
Spin Correlations: Stop
Spin Density Matrix

- Many more spin correlation and polarization results by Tevatron experiments, ATLAS and CMS
  - Issue: no 1-to-1 correspondence to spin density matrix
- Construct system of orthogonal axes → extract polarization, spin correlations and cross correlations

![Diagram of orthogonal axes](image)

- Normal to production plane
- "Helicity"
- Orthogonal to other two axes
## Spin Density Matrix

<table>
<thead>
<tr>
<th>Expectation values</th>
<th>NLO predictions</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^k_+$</td>
<td>0.0030 ± 0.0010</td>
<td>$\cos \theta^k_+$</td>
</tr>
<tr>
<td>$B^k_-$</td>
<td>0.0034 ± 0.0010</td>
<td>$\cos \theta^k_-$</td>
</tr>
<tr>
<td>$B^n_+$</td>
<td>0.0035 ± 0.0004</td>
<td>$\cos \theta^n_+$</td>
</tr>
<tr>
<td>$B^n_-$</td>
<td>0.0035 ± 0.0004</td>
<td>$\cos \theta^n_-$</td>
</tr>
<tr>
<td>$B^r_+$</td>
<td>0.0013 ± 0.0010</td>
<td>$\cos \theta^r_+$</td>
</tr>
<tr>
<td>$B^r_-$</td>
<td>0.0015 ± 0.0010</td>
<td>$\cos \theta^r_-$</td>
</tr>
<tr>
<td>$C(k,k)$</td>
<td>0.318 ± 0.003</td>
<td>$\cos \theta^k_+ \cos \theta^k_-$</td>
</tr>
<tr>
<td>$C(n,n)$</td>
<td>0.332 ± 0.002</td>
<td>$\cos \theta^n_+ \cos \theta^n_-$</td>
</tr>
<tr>
<td>$C(r,r)$</td>
<td>0.055 ± 0.009</td>
<td>$\cos \theta^r_+ \cos \theta^r_-$</td>
</tr>
<tr>
<td>$C(n,k) + C(k,n)$</td>
<td>0.0023</td>
<td>$\cos \theta^n_+ \cos \theta^k_+ + \cos \theta^k_+ \cos \theta^n_-$</td>
</tr>
<tr>
<td>$C(n,k) - C(k,n)$</td>
<td>0</td>
<td>$\cos \theta^n_+ \cos \theta^k_+ - \cos \theta^k_+ \cos \theta^n_-$</td>
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<tr>
<td>$C(n,r) + C(r,n)$</td>
<td>0.0010</td>
<td>$\cos \theta^n_+ \cos \theta^r_+ + \cos \theta^r_+ \cos \theta^n_-$</td>
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<td>$C(n,r) - C(r,n)$</td>
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</tr>
<tr>
<td>$C(r,k) + C(k,r)$</td>
<td>−0.226 ± 0.004</td>
<td>$\cos \theta^r_+ \cos \theta^k_+ + \cos \theta^k_+ \cos \theta^r_-$</td>
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<tr>
<td>$C(r,k) - C(k,r)$</td>
<td>0</td>
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</table>
Spin Density Matrix

- Analysis in dilepton final state
- Unfolding to particle and parton level

JHEP 03 (2017) 113
Spin Density Matrix

- Unfolding using fully bayesian unfolding
- Example response matrix for unfolding to parton level
  - Bin optimization taking into account expected statistical uncertainty and bias

<table>
<thead>
<tr>
<th>Bin Optimization</th>
<th>ATLAS Simulation</th>
<th>$\sqrt{s} = 8$ TeV</th>
<th>$\cos\theta^p$, $\cos\theta^n$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$[0.8, 1.0]$</td>
<td>$[0.25, 0.6]$</td>
<td>$[0.0, 0.25]$</td>
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<td>$[0.25, 0.6]$</td>
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<td>$[-0.6, -0.25]$</td>
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</tbody>
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Reconstructed Bins

07.03.2018
Spin Density Matrix

- Particle level:

  Transverse polarization

  Transverse spin correlations
Spin Density Matrix

**ATLAS** \( \sqrt{s} = 8 \text{ TeV} - 20.2 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Polarisations</th>
<th>JHEP 12 (2015) 026</th>
<th>result ± (stat+det) ± (mod)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_{+}^{k} )</td>
<td>-0.044 ± (0.027) ± (0.026)</td>
<td></td>
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<td>( B_{-}^{k} )</td>
<td>-0.064 ± (0.030) ± (0.023)</td>
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<tr>
<td>( B_{+}^{n} )</td>
<td>-0.018 ± (0.023) ± (0.024)</td>
<td></td>
</tr>
<tr>
<td>( B_{-}^{n} )</td>
<td>0.023 ± (0.024) ± (0.034)</td>
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</tr>
<tr>
<td>( B_{+}^{f} )</td>
<td>0.039 ± (0.030) ± (0.029)</td>
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<td>( B_{-}^{f} )</td>
<td>0.033 ± (0.029) ± (0.045)</td>
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</table>

**Spin Correlations**

<table>
<thead>
<tr>
<th>Correlation</th>
<th>ATLAS</th>
<th>JHEP 12 (2015) 026</th>
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<tr>
<td>( C(k,k) )</td>
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<td>0.296 ± (0.072) ± (0.057)</td>
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<tr>
<td>( C(n,n) )</td>
<td></td>
<td>0.304 ± (0.038) ± (0.047)</td>
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</tr>
<tr>
<td>( C(r,r) )</td>
<td></td>
<td>0.086 ± (0.075) ± (0.122)</td>
<td></td>
</tr>
</tbody>
</table>

07.03.2018

Yvonne Peters
Spin Density Matrix

### ATLAS

$\sqrt{s} = 8$ TeV - 20.2 fb$^{-1}$

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<td>$C(k,k)$</td>
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<td>$B^-_s$</td>
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<td>$C(n,n)$</td>
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<tr>
<td>$B^+_n$</td>
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<tr>
<th>Experiment</th>
<th>$\sqrt{s}$</th>
<th>Method</th>
<th>$B^+_s$</th>
<th>$B^-_s$</th>
<th>$C(k,k)$</th>
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<tr>
<td>ATLAS</td>
<td>8 TeV</td>
<td>Unfolding</td>
<td>$-0.044 \pm 0.038$</td>
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<td>CMS [16]</td>
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<td>Unfolding</td>
<td>$-0.022 \pm 0.058$</td>
<td>$0.278 \pm 0.084$</td>
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</tr>
<tr>
<td>ATLAS [11]</td>
<td>7 TeV</td>
<td>Template fit</td>
<td>$-0.035 \pm 0.040$</td>
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<td>ATLAS [10]</td>
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<td>Template fit</td>
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<td>D0 [17]</td>
<td>1.96 TeV</td>
<td>Template fit</td>
<td>$-0.102 \pm 0.061$</td>
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### Spin Density Matrix

**ATLAS** $\sqrt{s} = 8$ TeV - 20.2 fb$^{-1}$

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<td>$B_+^r$</td>
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**Measured for the first time**

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<td>$0.315 \pm 0.078$</td>
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</table>
Spin Density Matrix

- Cross correlations measured for the first time

- Overall agreement with the SM

- Sensitive to different NP effects (e.g. CP-violating effects)
Spin Correlations & 2HDM

- Spin observables can be used to search for heavy Higgs bosons (for example)

![Graph showing spin observables and 2HDM scenarios](image-url)
Top Events as a Laboratory
Quarks carry QCD color charge
- But only colour singlets can be observed
  - For example W, Z, or bound states like hadrons

Partons carrying color are color connected to partons with anti-colour

Hadronization: Particles building up between colour-connected partons

Gluon: color octet
Quark: color triplet
Jets carry color, and are thus **color connected** to each other.

- Pairing of connection depends on nature of decaying particles.

Particles created during hadronization should be concentrated along angular region spanned by the color connected partons.

- Transverse jet profiles should not be round.
- Shape influenced by direction of color flow!
Color Flow between Jets

- Jets carry color, and are thus color connected to each other
  - Pairing of connection depends on nature of decaying particles

- Particles created during hadronization should be concentrated along angular region spanned by the color connected partons
  - Transverse jet profiles should not be round
  - Shape influenced by direction of color flow!

**Example:**
- Singlet: $t\bar{t}H$
- Octet: $t\bar{t}g$
Color Flow Observable

Construct a local observable, constructed from particles within a chosen jet cone: **Jet pull**

- Pick a pair of jets in the event
- Build vectorial sum of jet components:

\[ \vec{p} = \sum_i \frac{E_T^i}{E_T^{\text{jet}}} \vec{r}_i \]

- \( \vec{r}_i \): position of jet component \( i \) relative to center of jet
- \( E_T^i \): transverse energy of component \( i \)
- \( E_T^{\text{jet}} \): transverse energy of jet

\[ \Delta \phi = \phi - \phi_{J_1} \]

\[ \Delta y = y - y_{J_1} \]

**Gallicchio, Schwartz, PRL 105, 022001 (2010)**
Color Flow Observable

Construct a local observable, constructed from particles within a chosen jet cone: **Jet pull**

- Pick a pair of jets in the event
- Build vectorial sum of jet components:

\[ \vec{p} = \sum_i \frac{p_T^i |r_i|}{p_T^{jet}} \vec{r}_i \]

- \( \vec{r}_i \): position of jet component \( i \) relative to center of jet
- \( p_T^i \): transverse momentum of component \( i \)
- \( p_T^{jet} \): transverse momentum of jet

**Legend**
- Pull Vector \( \vec{P}_1 \)
- Jet Connection Vector \( \vec{C}(J_1, J_2) \)
- Pull Angle (\( J_1 \) w.r.t. \( J_2 \))
- Constituent of \( J_1 \) (size weighted by \( p_T \))

\[ \Delta \phi = \phi - \phi_{J_1} \]
\[ \Delta y = y - y_{J_1} \]

Gallicchio, Schwartz, PRL 105, 022001 (2010)
Colour Flow in Top

- Top events as laboratory to test new tools

- Jets carry color, and are thus color connected to each other
  - Pairing of connection depends on nature of decaying particles

Gallichio, Schwartz, PRL 105, 022001 (2010)

Jet pull: vectorial sum of components within each jet → jet pull angle: angle wrt. connection line of pair of jets
Colour Flow in Top

- Consider 4 variables in semileptonic $t\bar{t}$ events (>1 b-tagged jet)
  
  - Two non-b-tagged jets:
    - Relative jet pull angles
    - Jet pull magnitude

  - Two b-tagged jets
    - Relative jet pull angle
Analysis

- Correct distributions for detector effects
- 13 TeV analysis: use only track-jets
  - Have shown to have better resolution than calorimeter jets in 8 TeV analysis

PLB 750, 475-493 (2015)
Results for W daughters

- Correction to stable particle-level (iterative Bayesian unfolding)

- Relative jet pull angles for jets from W boson

- Colour-flipped model disfavoured by the data
Results for W daughters

- Correction to stable particle-level (iterative Bayesian unfolding)

- MC modeling quite poor for these observables
Results for Magnitude and b-Pull

- Jet pull magnitude and pull angle of b-jets:
  - Data seems to favor “wider” jets
  - Jet pull: potential to search for NP
    - Mc modeling required?!
Summary

- Top Quark Physics: Probing the heaviest known elementary particle!
  - Precision measurements of polarization and spin correlations
    - probing the full top production and decay chain ever more precise
  - Jet pull: accessing colour-flow information between jets → information on colour-nature of mother particle

- Everything compatible with SM so far

- Tops were, are and stay awesome → much to learn about the SM and beyond
BACKUP
FBU principle: apply Bayes theorem and give posterior probability for different possible spectra

Elements needed:
- input: $\Delta |y|$ distribution in background subtracted data
- efficiency and response matrix taken from the signal sample (Powheg)
- output: posterior distribution for the asymmetry

We take the mean as central value and the smallest interval covering 68% of the integral as the uncertainty.
Define “pseudo-tops” on particle level

- In fiducial region
- Easy to reproduce for theorists!

Pseudo-top:

- Use particles with mean lifetime $> 3 \times 10^{-11}$ s
- Leptons: use “dressed lepton”: leptons are used together with photons in their vicinity
- Jets: anti-$k_T$ with $R=0.4$ applied on stable particles (not leptons or neutrinos)
  - Presence of $b$-hadron with $p_T>5$ GeV: jet is taken as a $b$-jet
Differential

- $\ell$+jets channel: selection

- Exactly 1 lepton (e or $\mu$)
  - e: $p_T > 25$ GeV, $|\eta| < 2.47$ & !(1.37 < $|\eta|$ < 1.52)
  - $\mu$: $p_T > 25$ GeV, $|\eta| < 2.5$

  - Missing $p_T$ for neutrino ($E_T$): $>30$ GeV

- $\geq 4$ jets with $p_T > 25$ GeV; $|\eta| < 2.5$

  - $\geq 2$ jets b-tagged
- Top reconstruction

Leptonic pseudo-top:
- construct leptonically decaying W from lepton and $E_T^{\text{miss}}$
- b-jet with smallest $\Delta R$ to lepton
Differential

- **Top reconstruction**

  **Leptonic pseudo-top:**
  - construct leptonically decaying $W$ from lepton and $E_T^{\text{miss}}$
  - $b$-jet with smallest $\Delta R$ to lepton

  **Hadronic pseudo-top:**
  - construct $W$ from remaining two highest-$p_T$ jets
  - use remaining $b$-jet
# Colour Flow: Systematics

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<th>System</th>
<th>$\Delta \theta_P (j_1^W, j_2^W)$ [%]</th>
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