Top Physics

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(University of British Columbia)
For many years, mankind hunted for a new particle...

- 1976: Discovery of Upsilon (Fermilab)
  - Contains a 5th quark - the b-quark
  - From family structure of SM
    - Expect a 6th quark - race to find it
- Petra (e+e-) at DESY, Hamburg, \( m_t > 23.3 \) GeV (1984)
- Tristan (e+e-) in Japan: \( m_t > 30.2 \) GeV (late 1980s)
- UA1@SPS at CERN: \( m_t > 44 \) GeV (1988)
- LEP (e+e-) at CERN: \( m_t > 45.8 \) GeV (1990)
- UA2@SPS: \( m_t > 69 \) GeV

**Electroweak precision data:**

\[
M_Z^2 = M_{Z}^{2\text{, order}} / (1 - \Delta)
\]

\[
\Delta \approx \ldots m_t^2 \ldots + \ldots \ln m_h \ldots
\]
Many years ago, in a land far far away

(22 years ago, at Fermilab)

By 1993, CDF and DØ were seeing interesting individual events, but at low statistical sensitivity.

A striking DØ dilepton event seen in its final limit paper [e (p_{T}=99\text{ GeV}), \mu (p_{T}=198\text{ GeV}), \text{MET (102 GeV)}, 2 \text{ jets, (E}_{T}=25, 22\text{ GeV})] was in a very low background region.

If hypothesize to be from top pair production (tt → (e\nu_j) (\mu\nu_j)), mass was consistent with M_{t}=(145-200)\text{ GeV}.

1992 CDF dilepton event: event with 2 energetic jets (one is b-tagged), isolated moderate p_{T} e and \mu, and substantial MET.

2 energetic jets (1 b-tagged @ CDF)
Isolated e and mu
Significant MET
The quest for a new particle finally came to an end

\( m_{\text{top}} = 176 \pm 8 \text{ (stat)} \pm 10 \text{ (syst)} \text{ GeV/c}^2 \)

\( \sigma_{\text{tt}} = 6.8^{+3.6}_{-2.4} \text{ pb} \)

\[ \text{Phys. Rev. Lett. 73, 225 (1994)} \]
\[ \text{Phys. Rev. Lett. 74, 2626 (1995)} \]

\( m_{\text{top}} = 199^{+19}_{-21} \text{ (stat)} \pm 22 \text{ (syst)} \text{ GeV/c}^2 \)

\( \sigma_{\text{tt}} = 6.4 \pm 2.2 \text{ pb} \)

\[ \text{Phys. Rev. Lett. 74, 2632 (1995)} \]
The world rejoiced!

March 2, 1995: Joint CDF/DØ seminar announcing the top quark discovery

Top quark discovery

Does it remind you of a recent picture from 2012?
Yet people kept looking near and far...
THE END

See special lecture next Friday by B. Klima

Or is it?
Content of these two lectures

- Why is the top still interesting?
- Top signatures
- Top cross section
  - Prediction
  - Inclusive
  - Differential
- Single top production any decay

- Top mass
- Other properties
- Searches for new physics with top quarks
What do we know about top

Experimentally confirmed facts:

- Top is the heaviest known fundamental particle
  - Mass $\sim 173$ GeV
- It is a quark (sees the strong force)
- Charge $\frac{2}{3}e$
- Spin $\frac{1}{2}$
- Decays almost exclusively to Wb
- Produced by strong and weak interactions

$$m_{top} = y_t v / \sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$
Why we still care about top

- Only place to study the properties of a bare quark
  - Lifetime < hadronisation
- Special role in EWSB?
- First place a new particle could be observed
  - Particularly if new particle couples to mass
- Top is a background to many other searches

\[
\tau_{\text{had}} \approx 2 \times 10^{-24} \text{s}
\]
\[
\tau_{\text{top}} \approx 5 \times 10^{-25} \text{s}
\]
The Problem:

\[ m_H^2 = m_{\text{bare}}^2 + \Delta m_H^2 \]

\[ \Delta m_H^2 \sim \frac{3}{(8\pi^2)} y_t^2 \Lambda^2 \]

If \( \Lambda \sim \text{Plank scale} \):

\[ m_H^2 \sim \Delta m_H^2 \times 10^{-32} \]

Possible Solutions:

A) SM only low energy effective theory

i.e. \( \Lambda \ll \text{Plank} \)

If \( \Lambda \sim \text{TeV} \):

\[ \Delta m_H^2 \sim 0(m_H^2) \]

B) Add new particles (e.g. SUSY, top partners)

\( \sim t/T \)

loops cancel
Why we really still care about Top
TOP PRODUCTION AND DECAY
The focus of this paper is, on the one hand, to provide an up-to-date summary of the theoretical uncertainties on the total $t\bar{t}$ cross section, and on the other hand, to show how top quark data can be used to constrain the large-x gluon PDF. Indeed, unlike the Tevatron, top quark pair production at the LHC is dominated by $gg$ scattering, thus providing a complementary probe of the gluon PDF. As shown in Table 1, at the LHC the relative contribution of the $gg$ subprocess is between 85% and 90% depending on the beam energy, with $qq$ being about 10-15%, almost the opposite of the Tevatron. To illustrate the range of Bjorken-x's to which the top cross section is sensitive, the correlation between the $t\bar{t}$ production cross section and the up quark PDF is shown in Fig. 1 for the various cases that we will discuss in the paper: Tevatron Run II, LHC 7, 8 and 14 TeV. A correlation whose absolute magnitude is close to 1 indicates that variations of PDFs with a particular value of $x$ will in turn translate into cross-section variations. It is clear from Fig. 1 that for the LHC the top quark cross section directly probes the gluon in the range of $x$ between $x=0.1$ and $x=0.5$, where gluon PDF uncertainties are relatively large. The outline of this paper is as follows. In Sect. 2 we discuss the settings of the calculation and the treatment of the various theoretical uncertainties. In Sect. 3 we provide up-to-date predictions for the $t\bar{t}$ cross section at the Tevatron and LHC and compare with the most recent experimental data. In Sect. 4 we quantify the impact of the available top data on the gluon PDF, show how it reduces the gluon PDF's large-x uncertainties.
Pair Production

Things are a bit more complicated than that but let's start with the basics for now...
Top Decay

Top Pair Branching Fractions

- "alljets" 46%
- τ+jets 15%
- μ+jets 15%
- e+jets 15%
- "dileptons"
- "lepton+jets"
Shopping list
- 1 lepton
- Missing transverse momentum
- $\geq 4$ jets
  - 2 from b-hadrons

Backgrounds
- W+jets
- Single top
- Dibosons
- Z+jets
- QCD multi-jet ‘fakes’
Dilepton channel

Shopping list
- 2 leptons
- Missing transverse momentum
- ≥ 2 jets
  - 2 from b-hadrons

Backgrounds
- Z+jets
- Single top
- Dibosons
- QCD multi-jet ‘fakes’
All Hadronic channel

**Shopping list**
- 0 leptons
- No Missing transverse momentum
- $\geq 6$ jets
  - 2 from b-hadrons

**Backgrounds**
- QCD multi-jet

We sadly won’t be discussing this channel much in these lectures.
Relative merits

L+jets:
• Reasonable branching ratio
• Reasonable S/B
• Only 1 neutrino so can fully re-construct the ttbar system

dilepton:
• Lowest branching ratio
• Highest S/B
• 2 neutrinos so harder to re-construct the ttbar system

All hadronic:
• Highest branching ratio
• Lowest S/B
• Hard to determine backgrounds from QCD
• Reconstructing ttbar system: combinatorial complexity
Dilepton (emu) event display
L+jets event display
TOP PAIR PRODUCTION
CROSS SECTION
How far we have come!

Standard Model Production Cross Section Measurements

ATLAS Preliminary
Run 1 $\sqrt{s} = 7, 8$ TeV

LHC pp $\sqrt{s} = 7$ TeV
Theory

LHC pp $\sqrt{s} = 8$ TeV
Theory

Observed 4.5 – 4.9 fb$^{-1}$

Observed 20.3 fb$^{-1}$

$\sigma$ [pb$^{-1}$]

$0.1 < p_T < 2$ TeV
$0.3 < m_T < 5$ TeV

$\eta_T \geq 0$
$\eta_T \geq 1$
$\eta_T \geq 2$
$\eta_T \geq 3$
$\eta_T \geq 4$
$\eta_T \geq 5$
$\eta_T \geq 6$
$\eta_T \geq 7$

80 pb$^{-1}$
85 pb$^{-1}$

Total

$\gamma\gamma$, $ZZ$

$H \rightarrow WW$
$H \rightarrow VV$
$H \rightarrow W\gamma$
$H \rightarrow ZZ$

95% CL upper limit

Total

$W$ $Z$ $t\bar{t}$ $t\bar{t}$-chan total

$W$ $Z$ $t\bar{t}$ $W\gamma$ $W\gamma$ total fiducial fiducial fiducial fiducial fiducial

$H$ $WZ$ $ZZ$ $Z\gamma$ $t\bar{t}W$ $t\bar{t}Z$ $t\bar{t}\gamma$

$Z_{jj}$ EWK $W_{YY}$ $W_{WW}$ $W_{ZZ}$ $W_{WW}$ $W_{WW}$

$W_{WW}$ $W_{WW}$ $W_{WW}$ $W_{WW}$ $W_{WW}$ $W_{WW}$

$n_{\text{jet}}$=0

$\eta_T \leq 3.0$

$|y| < 3.0$

$y < 3.0$
Calculations

\[
\sigma = \sum_{i,j=q,\bar{q},g} \int dx_1 \, dx_2 \, f_i(x_1, Q^2) \cdot \bar{f}_j(x_2, Q^2) \cdot \hat{\sigma}(Q^2)
\]

- Sum over incoming partons i, j
- Momentum fraction for incoming parton
- PDF for incoming parton
- "partonic" cross section
Partonic cross section

- Need to calculate everything that goes into $Y$
- Use perturbative expansion of $Y$ in orders of strong coupling constant ($\alpha_s$)
  - $\alpha_s \sim 0.1$ so series should converge

$$\sigma (q\bar{q}/gg \rightarrow t\bar{t} + X) = H^{(0)} + \alpha_s H^{(1)} + \alpha_s^2 H^{(2)} + \ldots$$

**Leading order (LO) term**, proportional to $\alpha_s^2$

**Next-to-leading order (NLO) term**, proportional to $\alpha_s^3$

**Next-to-next-to-leading order term**, proportional to $\alpha_s^4$
Leading Order

Each vertex contributes $\sqrt{\alpha_s}$

$\alpha_s =$ strong force (QCD) coupling constant
Next to Leading Order

Extra gluon - results in extra jet of hadrons in detector (more later)
Calculate all allowed processes

+ infinite number of diagrams

2
Leading order

Contains all terms proportional to $\alpha_s^2$
Next to Leading order

Contains all terms proportional to $\alpha_s^2$ and $\alpha_s^3$
State of the art: NNLO

- Latest-greatest for the inclusive ttbar cross section: NNLO
- Latest-greatest for differential ttbar cross section: NLO
  - Expect NNLO differential distributions in a matter of months!

<table>
<thead>
<tr>
<th>Collider</th>
<th>$\sigma_{\text{tot}}$ [pb]</th>
<th>scales [pb]</th>
<th>pdf [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>7.164</td>
<td>$+0.110 (1.5%)$  $-0.200 (2.8%)$</td>
<td>$+0.169 (2.4%)$  $-0.122 (1.7%)$</td>
</tr>
<tr>
<td>LHC 7 TeV</td>
<td>172.0</td>
<td>$+4.4 (2.6%)$  $-5.8 (3.4%)$</td>
<td>$+4.7 (2.7%)$  $-4.8 (2.8%)$</td>
</tr>
<tr>
<td>LHC 8 TeV</td>
<td>245.8</td>
<td>$+6.2 (2.5%)$  $-8.4 (3.4%)$</td>
<td>$+6.2 (2.5%)$  $-6.4 (2.6%)$</td>
</tr>
<tr>
<td>LHC 14 TeV</td>
<td>953.6</td>
<td>$+22.7 (2.4%)$  $-33.9 (3.6%)$</td>
<td>$+16.2 (1.7%)$  $-17.8 (1.9%)$</td>
</tr>
</tbody>
</table>
State of the art

- Tevatron combined* 1.96 TeV (L=8.8 fb⁻¹)
- ATLAS dilepton 7 TeV (L=4.6 fb⁻¹)
- CMS dilepton 7 TeV (L=2.3 fb⁻¹)
- ATLAS l+jets* 7 TeV (L=0.7 fb⁻¹)
- CMS l+jets 7 TeV (L=2.3 fb⁻¹)
- ATLAS dilepton 8 TeV (L=20.3 fb⁻¹)
- CMS dilepton 8 TeV (L=5.3 fb⁻¹)
- LHC combined eµ* 8 TeV (L=5.3-20.3 fb⁻¹)
- ATLAS l+jets 8 TeV (L=20.3 fb⁻¹)
- CMS l+jets* 8 TeV (L=2.8 fb⁻¹)

* Preliminary

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004

\( m_{\text{top}} = 172.5 \text{ GeV} \), PDF + uncertainties according to PDF4LHC

\( \sqrt{s} \) [TeV]
Tevatron Run II, $\sqrt{s}=1.96$ TeV

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$N_{\text{exp}}$</th>
<th>$\sigma(p\bar{p} \rightarrow t\bar{t})$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF dilepton</td>
<td>8.8 fb$^{-1}$</td>
<td>7.09 ± 0.83 ± 0.49 ± 0.67</td>
</tr>
<tr>
<td>CDF ANN lepton+jets</td>
<td>4.6 fb$^{-1}$</td>
<td>7.82 ± 0.56 ± 0.38 ± 0.41</td>
</tr>
<tr>
<td>CDF SVX lepton+jets</td>
<td>4.6 fb$^{-1}$</td>
<td>7.32 ± 0.71 ± 0.36 ± 0.61</td>
</tr>
<tr>
<td>CDF all-jets</td>
<td>2.9 fb$^{-1}$</td>
<td>7.21 ± 1.28 ± 0.50 ± 1.18</td>
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<td>CDF combined</td>
<td>≤ 8.8 fb$^{-1}$</td>
<td>7.63 ± 0.50 ± 0.31 ± 0.39</td>
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<tr>
<td>D0 dilepton</td>
<td>5.4 fb$^{-1}$</td>
<td>7.36 ± 0.85 ± 0.31 ± 0.39</td>
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<td>D0 lepton+jets</td>
<td>5.3 fb$^{-1}$</td>
<td>7.90 ± 0.74 ± 0.20 ± 0.56</td>
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<td>D0 Combined</td>
<td>≤ 5.4 fb$^{-1}$</td>
<td>7.56 ± 0.59 ± 0.20 ± 0.56</td>
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Tevatron Combined

$\sigma(p\bar{p} \rightarrow t\bar{t})$ [pb] ≤ 8.8 fb$^{-1}$ with $m_t = 172.5$ GeV

7.60 ± 0.41 ± 0.20 ± 0.36


ttbar cross section

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sigma_{\text{total}}$ [pb]</th>
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<tr>
<td>ATLAS, $t\bar{t}$ b → X</td>
<td>1.7 ± 0.7 ± 0.3</td>
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<tr>
<td>ATLAS, dilepton (*)</td>
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<td>ATLAS, all jets (*)</td>
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<tr>
<td>LHC combined (Sep 2012)</td>
<td>1.7 ± 0.7 ± 0.3</td>
</tr>
</tbody>
</table>

Effect of LHC beam energy uncertainty: 3.3 pb (not included in the figure)

$\Delta \sigma_{\text{exp}} \sim 3.9\%$

$\Delta \sigma_{\text{the}} \sim 5.4\%$
ttbar cross section

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\sigma(p\bar{p} \rightarrow t\bar{t}) [pb]
ttbar cross section: dilepton

$$tt \rightarrow e\mu\nu\bar{\nu}b\bar{b}$$

$$N_1 = L\sigma\epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_{b1}$$

$$N_2 = L\sigma\epsilon_{e\mu} \epsilon_b^2 C_b + N_{b2}$$

- Efficiency for $b$-jet from top quark to be in the detector & reconstructed by ATLAS
- Efficiency for leptons to be in the detector & reconstructed by ATLAS
- Term to account for correlations between the two $b$-jets

Measure $N_1$ and $N_2 \rightarrow$ extract $\epsilon_b$ and $\sigma$

- Analysis designed to be as insensitive as possible to large detector uncertainties
- Takes as much information as possible from the detector
ttbar cross section: dilepton

<table>
<thead>
<tr>
<th>( \sqrt{s} )</th>
<th>Uncertainty (inclusive ( \sigma_{tt} ))</th>
<th>( \Delta \epsilon_{e\mu}/\epsilon_{e\mu} ) (%)</th>
<th>( \Delta C_b/C_b ) (%)</th>
<th>( \Delta \sigma_{tt}/\sigma_{tt} ) (%)</th>
<th>( \Delta \epsilon_{e\mu}/\epsilon_{e\mu} ) (%)</th>
<th>( \Delta C_b/C_b ) (%)</th>
<th>( \Delta \sigma_{tt}/\sigma_{tt} ) (%)</th>
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<tbody>
<tr>
<td>Data statistics</td>
<td>1.69</td>
<td>0.71</td>
<td>0.72</td>
<td>1.43</td>
<td>0.65</td>
<td>-0.57</td>
<td>1.22</td>
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<td>( t\bar{t} ) modelling</td>
<td>0.71</td>
<td>-0.72</td>
<td>1.43</td>
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<td>-0.57</td>
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<td>Single-top ( Wt ) cross-section</td>
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<td>0.72</td>
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<td>( Z + ) jets extrapolation</td>
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<td>0.74</td>
<td>0.37</td>
<td>-</td>
<td>0.37</td>
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<td>Jet energy resolution</td>
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<td>Jet reconstruction/vertex fraction</td>
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<td>( b )-tagging</td>
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<td>Analysis systematics (( \sigma_{tt} ))</td>
<td>1.56</td>
<td>0.75</td>
<td>2.27</td>
<td>1.66</td>
<td>0.59</td>
<td>2.26</td>
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<td>Integrated luminosity</td>
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<td>LHC beam energy</td>
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<td>-</td>
<td>1.79</td>
<td>-</td>
<td>-</td>
<td>1.72</td>
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<tr>
<td>Total uncertainty (( \sigma_{tt} ))</td>
<td>1.56</td>
<td>0.75</td>
<td>3.89</td>
<td>1.66</td>
<td>0.59</td>
<td>4.27</td>
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</table>
Towards differential distributions...
It’s even more complicated

- Matrix element (hard)
- Parton Shower
- Multiple interactions
- Fragmentation and hadronisation
- QED radiation
MC IN TOP EVENTS
Simplest generators: LO

- Hard Process is only LO processes

- Radiation only from parton shower
  - Resummation valid for collinear and soft emissions

Pythia, Herwig, AcerMC, ...
NLO generators

- Hard Process includes NLO processes
  - First emission now in the hard process
    - Expect better modelling
  - Additional radiation from parton shower
    - Need matching procedure to avoid double-counting

**MC@NLO, Powheg**
Multi-leg generators (LO and NLO)

• Hard Process includes up to N additional emissions

• No loop processes in LO!
• First N emission now in the hard process
  • Expect better modelling
• Additional radiation from parton shower
  • Need matching procedure to avoid double-counting
• NLO versions (e.g. aMC@NLO_MG5, Sherpa) available
  • Experiments starting to use them
DIFFERENTIAL CROSS SECTIONS
Short break...

Alison Lister, HCP 2015
Unfolding: Parton vs Particle

Matrix Element calculation (usually perturbative)

Fragmentation, parton shower, hadronisation, PDFs,... (often non-perturbative)

Matrix Element calculation

Fragmentation, parton shower, hadronisation, PDFs,... (often non-perturbative)
Unfolding: Parton vs Particle

Easier to calculate

Closer to what we measure

What we measure

Parton

Particle

Reco

ATLAS Preliminary
20.3 fb^{-1}, 1s = 8 TeV, μ+jets
Unfolding: step-by-step guide

- Start with a relevant detector level distribution
Unfolding: step-by-step guide

• Start with a relevant detector level distribution (reco)
• Build matrix of reco level vs particle level variable
  • Are they the optimal variable definitions to use?

**ATLAS Simulation Preliminary**

- Sufficiently diagonal?
- Tails not too large?
- Think the MC can model it well?
Unfolding: step-by-step guide

- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
  - If corrections are small: maybe bin-by-bin correction is enough?
  - Invert the matrix
    - Sadly not usually stable...
  - Pick one of the many unfolding procedures on the market (RooUnfold)
    - Single Value decomposition
      - Strength of the regularisation parameter?
    - Bayesian Unfolding (iterative unfolding)
      - Number of iterations?
      - ... many many more...
Unfolding: step-by-step guide

• Start with a relevant detector level distribution (reco)
• Build matrix of particle level vs reco level variable
• Choose unfolding method
  • Check for biases in the method / stability
    • Closure
    • Stress-tests
      • e.g. change truth distribution, check can still infold
Unfolding: step-by-step guide

- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
- Correct for efficiency loss
  - Reconstructed objects not identical to particle level ones
  - Object reconstruction efficiency
  - Detector resolution
Unfolding: step-by-step guide

- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
- Correct for efficiency loss
- Get unfolded distribution!!!!
  - Compare to your favorite generators
  - Hope it teaches you something useful
Unfolding: step-by-step guide

- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
- Correct for efficiency loss
- Get unfolded particle level distribution
- If also unfold to parton level
  - 2\textsuperscript{nd} unfolding matrix
  - 2\textsuperscript{nd} efficiency correction
Unfolding: step-by-step guide

- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
- Correct for efficiency loss
- Get unfolded particle level distribution
- If also unfold to parton level
  - 2\textsuperscript{nd} unfolding matrix
  - 2\textsuperscript{nd} efficiency correction
  - Get unfolded distribution
Unfolding: Parton vs Particle

**Parton**

**Particle**

---

**ATLAS Preliminary**

20.3 fb⁻¹, s = 8 TeV

**ATLAS Preliminary**

20.3 fb⁻¹, s = 8 TeV

**Reco**

**Data**

**Single lepton**

**Single top**

**W+jets**

**Z+jets**

**Diboson**

---

**MC / Data**

**top quark p_T [GeV]**

---

**MC / Data**

**top-jet candidate p_T [GeV]**

---

**Events / GeV**

---

**20.3 fb⁻¹, s = 8 TeV, μ+jets**
Unfolding: Parton vs Particle

**Parton**

**Particle**

ATLAS Preliminary

20.3 fb⁻¹, 1s = 8 TeV

Easier to calculate

Closer to what we measure

What we measure

Reco

ATLAS Preliminary

20.3 fb⁻¹, 1s = 8 TeV, μ+jets

Data / MC

Events / GeV

Data / MC
Unfolding: Parton vs Particle

**ATLAS Preliminary**

20.3 fb⁻¹, 1s = 8 TeV

**Reco**

Data
- Single lepton
- Dilepton
- Single top
- W+jets
- Multijet
- Z+jets
- Diboson

**Events / GeV**

Data / MC

**Relative Uncertainty [%]**

- Total Uncertainty
- Large-R JES photon+jet
- Large-R JES topology
- B-tagging
- Data statistics
- Signal modeling

**Top quark p_T [GeV]**

**Particle top-jet candidate p_T [GeV]**

**ATLAS-CONF-2014-057**
Unfolding: Parton vs Particle

Which is better?

- Depends what you want to do with it...For example
- Comparison to fixed order predictions
  - Needs to be at parton level
- PDF fitting
  - Needs to be at parton level
- Constraining some of the parameters of the MC (‘tuning’)  
  - Particle level if preferred
    - Lower uncertainties
    - Usually smaller MC dependent corrections
- My personal take: do both (when / where relevant) and make everyone happy!
Differential cross section

- Unfolding to parton level
- Top is defined in MC as the top quark right before it decays
- Comparing to fixed order calculations
Differential cross section

- Unfolding to particle level
- Select ttbar events with 1 lepton and >=3 jets
- Look at additional jets
- Constrain amount of additional radiation
Differential cross section

- Unfolding to particle level
- Reconstruct top at particle level
  - ‘pseudo-top’
- Use same algorithm at reco level

- Constrain MC parameters
Differential cross section

- Unfolding to particle level
- Don’t always need to reconstruct the tops

CMS, 19.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV

- Data
- MadGraph+Pythia6
- MC@NLO+Herwig6
- Powheg+Pythia6
- Powheg+Herwig6

Theory/Data

Differential cross section

- Comparing to PDFs
  - Parton or particle level

- Need to be parton level to be used in PDF fit
  - Work ongoing...

Transverse momenta of parton-level top quarks

Rapidity of parton-level $t\bar{t}$ system
Tails (New Physics?)

CMS, 19.7 fb\(^{-1}\) at \(\sqrt{s} = 8\) TeV

- Improving the modelling uncertainties in ttbar production can help to see new physics!

\[\text{arXiv:1505.04480}\]
\[\text{arXiv:1505.07018}\]
Constraining PDF

- ttbar events already used in some PDF fits
  - So far only inclusive cross section
  - Probes gluon PDF in region x=0.1-0.5
  - Where PDF uncertainty is large

![Correlation between PDFs and Cross-Section](image)

**Figure 5**

**Ratio to NNPDF2.3 NNLO, \( \alpha_s = 0.118 \)**

**Table**

<table>
<thead>
<tr>
<th>( Q^2 ) = 100 GeV^2</th>
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<tbody>
<tr>
<td>g_{(x, Q^2)}</td>
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<td>NNPDF2.3</td>
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**arXiv:1303.7215**