Top Quark Physics
Summary & Discussion

A. Jafari, P. Nason and R. Di Sipio

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Outline of Session

- Top as background (to Higgs)
- Top cross sections and distributions
- Top properties
- Rare processes

In the following, few highlights linked to each other to some extent.
The status of Top cross section measurements (Dell’Asta), in comparison with theoretical calculations (Czakon, Zaro, Siegert) is a good example of progress interplay in the experimental and theoretical aspects.

▶ Differential distributions in $t\bar{t}$ production are being constantly refined
▶ Differential distributions in single top begin to appear.
▶ NNLO calculation now extended to include top decay!
▶ Also new, from the theory side: **NNLO $t\bar{t}$ in $q_t$ subtraction**, Catani,Devoto,Grazzini,Kallweit,Mazzitelli,2019
▶ Investigation of top properties rely now upon very accurate calculations of cross sections.
$\bar{t}t$ (dilepton) multi-differential cross section

**New**

See talk by Lucio Cerrito

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Lidia Dell'Asta
TOP-YUKAWA COUPLING

Separate $N_{\text{jet}}$ Regions: $M_{\text{tt}}$ distribution in $\Delta y$ bins

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected 95% CL</th>
<th>Observed 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 jets</td>
<td>$Y_t &lt; 2.17$</td>
<td>$Y_t &lt; 2.59$</td>
</tr>
<tr>
<td>4 jets</td>
<td>$Y_t &lt; 1.88$</td>
<td>$Y_t &lt; 1.77$</td>
</tr>
<tr>
<td>5 jets</td>
<td>$Y_t &lt; 2.03$</td>
<td>$Y_t &lt; 2.23$</td>
</tr>
<tr>
<td>Combined</td>
<td>$Y_t &lt; 1.62$</td>
<td>$Y_t &lt; 1.67$</td>
</tr>
</tbody>
</table>

Ratio to predicted value: $Y_{\text{top}} < 1.67$ (95% C.L.)
SPIN CORRELATION

Previous ATLAS and CMS measurements have shown slightly stronger spin correlation in $\Delta\phi$ than expected in, but still consistent with, the Standard Model.

**Signature:** 2 isolated OS $e/\mu \& \geq 2$ jets ($\geq 1 \ b \ or \ \geq 2 \ b$).

**Method:** Inclusive ($\geq 1 \ b$) and $tt$-reconstructed ($\geq 2 \ b$) selections. Differential in $M_{tt}$, Parton and Particle Level.

**Azimuthal opening angle (detector level) - Inclusive Selection**

![Azimuthal opening angle (detector level) - Inclusive Selection](image)

**Pseudorapidity separation (det. level) - Inclusive Selection**

![Pseudorapidity separation (det. level) - Inclusive Selection](image)

**Systematic Bands:** uncertainties excluding PDFs and signal modelling

**Not self-normalised (NNLO scaling)**
**Signature**: 2 isolated OS e/μ (incl. same flav.) \& \( \geq 2 \) jets \((\geq 1 \ b)\).

**Method**: Normalised differential cross sections. Parton-level to full phase space.

\[
|\mathcal{M}(q\bar{q}/gg \to t\bar{t} \to (\ell^+\nu b)(\ell^-\bar{\nu}\bar{b}))|^2 \sim Tr[\rho R\bar{\rho}].
\]


- Each of the 15 coefficients extracted from normalised differential cross sections at parton level
- Also measured: \(|\Delta \phi_{\ell\ell}|\), the difference in azimuthal angle \(\phi\) between the two leptons in the laboratory frame
Exact NWA results @ NNLO

- Application in case of data/theory discrepancies

ATLAS-CONF-2018-027

NWA @ NNLO predictions

Behring, MC, Mitov, Papanastasiou, Poncelet `18
Exact NWA results @ NNLO

- Fine-tuned analysis reveals shortcomings in full phase space extrapolation

Negligible sensitivity to:
1. Top quark mass
2. Parton Distribution Functions
3. Electroweak effects
4. Radiation in the decay

Behring, MC, Mitov, Papanastasiou, Poncelet '19
Deviation of the order of few percent from predictions!

Theoretical NNLO results indicate that comparable variations in prediction are obtained by alternative choices of central scales.

Establishing-dismissing deviations linked to the choice of an “optimal” scale.

A question for everybody: where do we draw the line? What is our error?
My favourite words of wisdom from Kirill’s talk:

A mass parameter extracted from a measurement depends mostly on an observable rather than a simulation tool.

Other things that we get out:

- Things seem difficult because they are!
- Don’t say: we just measure the Monte Carlo mass, let the theorists sort it out ...
- Don’t be afraid to think!
TOP QUARK MASS: INDIRECT

Final values determined from a simultaneous fit to $m_{\text{top}}$, PDF, $\alpha_S$ in XFITTER

Triple-differential cross section and NLO prediction with best-fit $m_{\text{top}}$, $\alpha_S(m_Z)$, PDFs

$\alpha_S(m_Z) = 0.1135 \pm 0.0016 (\text{fit}) + 0.0002 (\text{model}) + 0.0008 (\text{param}) + 0.0011 (\text{scale}) = 0.1135 + 0.0021 (\text{total}),$

$m_t^{\text{pole}} = 170.5 \pm 0.7 (\text{fit}) \pm 0.1 (\text{model}) + 0.0 (\text{param}) \pm 0.3 (\text{scale}) \text{ GeV} = 170.5 \pm 0.8 (\text{total}) \text{ GeV}.$
TOP QUARK MASS: DIRECT/INDIRECT

**Signature**: 2 isolated OS e/μ & ≥2 jets (≥1 b). Multi-categories

**Method**: (1) Fit to multi differential distributions for the direct top mass via dependence in the signal acceptance, efficiency and $m_{b\text{min}}$. (2) Use theoretical calculation of the absolute cross section to determine the indirect top mass (MSbar- and pole- schemes) and $\alpha_s(M_Z)$

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**CMS**

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

### $\mathcal{O}_{t\bar{t}}$

- **MMHT14nnlo**
  $\alpha_s(m_Z) = 0.1181$

- **CT14nnlo**
  $\alpha_s(m_Z) = 0.1181$

- **NNPDF3.1nnlo**
  $\alpha_s(m_Z) = 0.1181$

- **ABMP16nnlo**
  $\alpha_s(m_Z) = 0.1160$

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**Direct top mass from the acceptance/efficiency dependence, and $m_{b\text{min}}$:**

$$172.33 \pm 0.14 \text{ (stat)} \pm 0.66 \pm 0.72 \text{ (syst)} \text{ GeV}$$

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**Fit for the indirect MSbar mass, then converted to the pole mass scheme:**

<table>
<thead>
<tr>
<th>PDF set</th>
<th>$m_t^{\text{pole}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABMP16</td>
<td>$169.9 \pm 1.8$ (fit + PDF + $\alpha_s$) $^{+0.8}_{-1.2}$ (scale)</td>
</tr>
<tr>
<td>NNPDF3.1</td>
<td>$173.2 \pm 1.9$ (fit + PDF + $\alpha_s$) $^{+0.9}_{-1.3}$ (scale)</td>
</tr>
<tr>
<td>CT14</td>
<td>$173.7 \pm 2.0$ (fit + PDF + $\alpha_s$) $^{+0.9}_{-1.4}$ (scale)</td>
</tr>
<tr>
<td>MMHT14</td>
<td>$173.6 \pm 1.9$ (fit + PDF + $\alpha_s$) $^{+0.9}_{-1.4}$ (scale)</td>
</tr>
</tbody>
</table>
Multidifferential: Is NLO really enough for that precision?

What is driving the error so small? Where does the mass come from?
Single Top and more!

Dominant modes precisely measured, $|V_{tb}|$ determined

Rare $t + Z$: Obs by CMS $>5\sigma$!

Rare $t + \gamma$: Evidence!
Single Top and more!

**ATLAS**
\[
\sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1}
\]
\[
pp \rightarrow \ell^+ \ell^- b \bar{b} + X
\]

**CMS Preliminary**
\[
e/\mu + \text{jets}, \ 36 \text{ fb}^{-1} (13 \text{ TeV})
\]

**Pred./Data**
\[
1/\sigma \times \frac{d\sigma}{dp_T} (1/\text{GeV})
\]

**Parton-level top quark p_T (GeV)**

- Data
- POWHEG4FS
- aMC@NLO4FS
- aMC@NLO5FS

**tt-tW interference**

**top p_T test in another phase space**
Tops! Tops! Tops!

Four-tops production: complex topology, background to ttH, possibly enhanced by BSM

Observed (expected) upper limit:
47 (33) fb, i.e. $5.1 (3.6^{+2.9}_{-1.8}) \times \text{SM}$

Full Run2 dataset!
Tops! Tops! Tops!

Four-tops production: complex topology, background to ttH, possibly enhanced by BSM

Observation: 47 (33)

Single lep.

SS dilep. JHEP12 (2018) 039

36.1 fb$^{-1}$ SS dilep. / trilep. [JHEP12 (2018) 039]
36.1 fb$^{-1}$ Combined

CMS

35.8 fb$^{-1}$ Single lep. / OS dilep. [CMS PAS TOP-17-019]
35.9 fb$^{-1}$ Combined

137 fb$^{-1}$ SS dilep. / trilep. [CMS PAS TOP-18-003]

NLO QCD NLO QCD+EW [JHEP02 (2018) 031]
Many interesting new results, both in rare processes and in the most common ones.

Most debatable issues in very well measured ones (precision is hunting us?).

Spin correlations: 5% effect! Is theory that accurate? What attitude should we have towards theory errors? Does EFT interpretation help in using theoretical progress in the most productive way?

Top mass: what attitude? The traditional one (MC mass vs Pole or MSbar mass) is not very productive ... (see also Hang,P.N.,Corcella,Yokoya in the High Luminosity-High Energy workshop report).

Fiducial phase-space differential cross sections combination a la Higgs?