Production of top quarks, jets and photons

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on behalf of the ATLAS and CMS Collaborations

Simon Fraser University

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Jet analyses
Properties of jet fragmentation at ATLAS [STDM-2017-16]

Measurement of observables sensitive to fragmentation functions $D_{q,g}^h(\zeta, \mu)$.

- Number of charged particles $\langle n_{\text{ch}} \rangle$ in jet.
- Momentum fraction $\zeta = p_{\text{ch}}^T / p_{\text{jet}}^T$.
- Transverse profile $p_{\text{T}}^{\text{rel}} = p_{\text{T}}^\text{ch} \sin \theta_{jc}$.
- Radial profile $\rho = 1/(2\pi rN_{\text{jet}})dn_{\text{ch}}/dr; \ r = \Delta R_{jc}$.
- Extraction of quark and gluon profiles from data.

\[\langle n_{\text{ch}} \rangle, \zeta, p_{\text{T}}^{\text{rel}}, \rho, \text{MC / Data}\]
Quark and gluon-like distributions obtained using two different methods

- Solve the system of equations for bin $i$ of each observable:
  \[
  h_i^f = f_q^f h_i^q + (1 - f_q^f) h_i^g; \quad h_i^c = f_q^c h_i^q + (1 - f_q^c) h_i^g
  \]

- Determine distributions for topics $T_1$ ($q$-like) and $T_2$ ($g$-like)
  \[
  h_i^{T_1} = \frac{h_i^f - \min_j \{h_j^f / h_j^c\} \times h_i^c}{1 - \min_j \{h_j^f / h_j^c\}}; \quad h_i^{T_2} = \frac{h_i^c - \min_j \{h_j^c / h_j^f\} \times h_i^f}{1 - \min_j \{h_j^c / h_j^f\}}
  \]
- Measurement of topology of the $b\bar{b}$ system.
- Trimmed anti-$k_t$ jet with $R = 1.0$ as a proxy for the gluon.
- Anti-$k_t$ track jets with $R = 0.2$ as proxies for $b$-quarks.
- Flavour fractions extracted from fits to signed impact parameter of tracks in both $b$-jets with respect to jet axis.

![Graph showing data and MC comparison](image)

**ATLAS** $\sqrt{s} = 13$ TeV, $L_{\text{int}} = 33$ fb$^{-1}$

<table>
<thead>
<tr>
<th>Component (pre-fit %, post-fit %)</th>
<th>Data (post-fit)</th>
<th>MC (pre-fit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L+C (45%, 34%)</td>
<td>BB</td>
<td>BB</td>
</tr>
<tr>
<td>B (34%, 50%)</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>BB (20%, 17%)</td>
<td>L+C</td>
<td>L+C</td>
</tr>
<tr>
<td>MC Uncertainty</td>
<td>Data</td>
<td>Data</td>
</tr>
</tbody>
</table>

**Flavor Fraction**

<table>
<thead>
<tr>
<th>$\Delta R(b,b)$</th>
<th>Data/MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>1.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Measured observables include:

- Angular distance $\Delta R_{bb} = \sqrt{(\Delta \eta_{bb})^2 + (\Delta \phi_{bb})^2}$
- Momentum sharing $z = p_{T2} / (p_{T1} + p_{T2})$
- Dimensionless mass $\rho = m_{bb} / p_T$
- Angle $\Delta \theta_{ppp,gbb}$ between jet-beam and $bb$ planes.

Significant disagreement at low $z$, “less polarization” is preferred.
Transverse thrust and thrust axis $\hat{n}_T$: $\tau_\perp = 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{Ti} \cdot \hat{n}_T|}{\sum_i p_{Ti}}$.

- $U$ and $L$ hemispheres: $\vec{p}_{Ti} \cdot \hat{n}_T > 0$ ($< 0$).

Define hemisphere coordinates: $\eta_X = \frac{\sum_{i \in X} p_{Ti} \eta_i}{\sum_{i \in X} p_{Ti}}$; $\phi_X = \frac{\sum_{i \in X} p_{Ti} \phi_i}{\sum_{i \in X} p_{Ti}}$.

$$B_X = \frac{1}{2P_T} \sum_{i \in X} p_{Ti} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}; \quad B_{\text{tot}} = B_U + B_L$$
- Total jet mass: $\rho_X = \frac{M_X^2}{P^2}$; $\rho_{tot} = \rho_U + \rho_L$

- Total transverse jet mass: $\rho_X^T = \frac{M_X^2}{P_T^2}$; $\rho_{tot}^T = \rho_U^T + \rho_L^T$

- Important test of the back-to-back and collinear regime (low thrust).
- Significant discrepancies observed in all variables across $p_T$ bins.
$\Delta \phi_{12}$ in back-to-back topologies at CMS [arXiv:1902.04374 (hep-ex)]

- Test of QCD at angles $\Delta \phi \lesssim \pi$, sensitive to resummation details.
- Two and three jet events studied ($p_{T1} > p_{T2} > 100$ GeV, $p_{T3} > 30$ GeV).
- Measurement of the normalized distribution of azimuthal difference $\Delta \phi_{12}$.
\( \Delta \phi_{12} \) in back-to-back topologies at CMS [arXiv:1902.04374 (hep-ex)]

- Comparison to LO+PS and NLO+PS are provided.
- In particular, Powheg (2 \( \rightarrow \) 2 and 2 \( \rightarrow \) 3) are studied.
- 2 and 3-jet measurements not simultaneously described by any model.

![Graph showing comparison between PH-2J + PYTHIA8, PH-3J + PYTHIA8, and PH-2J + Herwig++]

anti-\( k_T \) R=0.4

Inclusive 2-jet

Total exp. unc.

PH-2J + PYTHIA8

PH-3J + PYTHIA8

PH-2J + Herwig++

CMS

Prediction/Data (normalised 2-jet cross section)

- 200 < \( p_T^{\text{max}} \) < 300 GeV
- 400 < \( p_T^{\text{max}} \) < 500 GeV
- 600 < \( p_T^{\text{max}} \) < 700 GeV
- 800 < \( p_T^{\text{max}} \) < 1000 GeV
- \( p_T^{\text{max}} > 1200 \) GeV

- 300 < \( p_T^{\text{max}} \) < 400 GeV
- 500 < \( p_T^{\text{max}} \) < 600 GeV
- 700 < \( p_T^{\text{max}} \) < 800 GeV
- 1000 < \( p_T^{\text{max}} \) < 1200 GeV

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

R=0.4

Total exp. unc.

PH-2J + PYTHIA8

PH-3J + PYTHIA8

PH-2J + Herwig++
Photon analyses
Photon cross section ratios 13 / 8 TeV [JHEP 04 (2019) 093]

- Ratio of two measurements: [JHEP 08 (2016) 005, PLB 770 (2017) 473]
- Reduction of uncertainties by considering their correlations:
  - Experimental uncertainties below 5% in the full $E_T^\gamma$ range ($\gamma$ES).
  - Theoretical uncertainties below 2% in the full $E_T^\gamma$ range (scale).
- Ratios come in two flavours:
  - Ratio of double-differential cross sections: $R_{13/8}^\gamma$ versus $E_T^\gamma$ and $|y^\gamma|$
  - Double ratio to Z fiducial cross sections $D_{13/8}^{\gamma,Z} = R_{13/8}^\gamma/R_{13/8}^{Z,fid}$.

### Graphs

**ATLAS**
- 8 TeV, 20.2 fb$^{-1}$ and 13 TeV, 3.2 fb$^{-1}$
- $1.56 < |\eta^\gamma| < 1.81$

Relative uncertainty in $R_{13/8}^\gamma$

**ATLAS Simulation**
- $\sqrt{s} = 8$ TeV and 13 TeV
- $1.56 < |\eta^\gamma| < 1.81$

Relative uncertainty in $R_{13/8}^\gamma$

Uncertainties:
- Scale variation
- $\alpha_s$
- PDF
- Beam energy
- Total

Systematic uncertainty $\gamma$ES
- uncorrelated $\oplus$ extra2015

Correlated components:
- complete correlation model
- no correlation assumed

### Uncertainties Table

<table>
<thead>
<tr>
<th>Component</th>
<th>ATLAS 8 TeV 20.2 fb$^{-1}$</th>
<th>ATLAS 13 TeV 3.2 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>y^\gamma</td>
<td>&gt; 1$</td>
</tr>
<tr>
<td>$</td>
<td>y^\gamma</td>
<td>&lt; 1$</td>
</tr>
</tbody>
</table>

Javier Llorente
Production of top quarks, jets and photons
Comparison of ratios to NLO QCD (+NNLO for Z)

Recent NNLO predictions for $\gamma$ production [arXiv:1904.01044 (hep-ph)]
Measurement of isolated photons inclusively and in association with jets

- \( E_T^\gamma > 190 \text{ GeV} \) and \( |y^\gamma| < 2.5 \).
- \( p_T^{\text{jet}} > 30 \text{ GeV} \) and \( |y^{\text{jet}}| < 2.4 \).

BDT to discriminate from background, validated with isolation sidebands.

### Inclusive \( \gamma \)

### \( \gamma + \text{jets} \)
Comparison of inclusive $\gamma$ (top) and $\gamma$+jet (bottom) to NLO pQCD (JetPhox)

**CMS Preliminary**

$2.26 \text{ fb}^{-1}$ (13 TeV)

- $|y'| < 0.8$
- $|y| < 1.5$, $p_{T,\gamma} > 30$ GeV

**Theory / Data**

- Data stat. uncertainty
- Data total unc.
- NLO JETPHOX scale unc.
- NLO JETPHOX total unc.

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$1.57 < |y'| < 2.5$, $1.5 < |y| < 2.4$, $p_{T,\gamma} > 30$ GeV

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$|y| < 2.5$, $|y'| < 1.5$

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<table>
<thead>
<tr>
<th>$E_T$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times 10^2$</td>
</tr>
<tr>
<td>Theory / Data</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>Data total unc.</td>
</tr>
<tr>
<td>NLO JETPHOX scale unc.</td>
</tr>
<tr>
<td>NLO JETPHOX total unc.</td>
</tr>
</tbody>
</table>
Top quark analyses
- Fully hadronic $t\bar{t}$ events in boosted regime
- Two $R = 1.0$ jets with $p_T > 350$ GeV, $|\eta| < 2.0$, $|m_J - m_t| < 50$ GeV.
- Both jets are associated to a small ($R = 0.4$) $b$-tagged jet ($\Delta R_{JJ} < 1.0$)
- Multijet background estimated in a data-driven way.

Collins-Soper angle $\cos \theta^*$

Angular distance $\chi = e^{|\gamma_t - \gamma_{\bar{t}}|}$

\begin{align*}
\text{ATLAS} & \\
\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} & \\
\text{Fiducial phase space} & \\
\end{align*}

\begin{align*}
\frac{1}{\sigma_{\text{fit}} \cdot d \chi_t^i} & \\
\text{Prediction} & \\
\text{Data} & \\
\end{align*}
Single lepton channel $e$ or $\mu$ with $p_T > 25$ GeV, $|\eta| < 2.5$.

Jets reconstructed with $R = 0.4$, $p_T > 25$ GeV and $|\eta| < 2.5$.

Out-of-plane momentum: $|p^t_{\text{out}}| = \left| \vec{p}^t_{\text{had}} \cdot \frac{\vec{p}^t_{\text{lep}} \times \hat{z}}{|\vec{p}^t_{\text{lep}} \times \hat{z}|} \right|$
Combined fit to $e^+e^−$, $μ^+μ^−$ and $e^±μ^±$ channels.

Likelihood fit to extract $σ_{t\bar{t}}$, $α_s(m_Z)$ and $m_t$.

$σ_{t\bar{t}} = 815 ± 2 \text{ (stat.)} ± 29 \text{ (sys.)} ± 20 \text{ (lumi.)}$ from $m_t$, $σ$ simultaneous fit.
Differential cross sections versus a large variety of observables.

Comparison to high-order predictions in QCD

- Full NNLO + $\alpha_3^{3\text{EW}}$ (LUXQED17)
- Full NNLO + double resummation (NNLO+NNLL’)
- Approximate N$^3$LO @ NNLL.
- Approximate NNLO.
Dilepton channels $ee$, $e\mu$, $\mu\mu$.

Cross sections as a function of pairs of variables:

$$\{p_T(t), y_t, M_{t\bar{t}}, \eta_{t\bar{t}}, \Delta\phi_{t\bar{t}}, p_T(t\bar{t})\}$$

Triple-differential cross sections of jet multiplicity $N_{jet}$

Extraction of strong coupling $\alpha_s$, top mass $m_t$ and PDFs.

$\begin{array}{c}
\text{CMS} \\
\text{35.9 fb}^{-1} (13 \text{ TeV})
\end{array}$

$$\begin{array}{c}
\text{1/} \sigma \frac{d\sigma}{dp_T(t\bar{t})} \text{ [GeV]}^{-1} \\
\text{Ratio}
\end{array}$$

$\begin{array}{c}
300 < M(t\bar{t}) < 400 \text{ GeV} \\
400 < M(t\bar{t}) < 500 \text{ GeV} \\
500 < M(t\bar{t}) < 650 \text{ GeV} \\
650 < M(t\bar{t}) < 1500 \text{ GeV}
\end{array}$

$\begin{array}{c}
\text{Events / 100 GeV} \\
\text{Ratio}
\end{array}$

$\begin{array}{c}
\text{Data, dof=15} \\
\text{POW+PYT, } \chi^2=21 \\
\text{POW+HER, } \chi^2=22 \\
\text{MG5+PYT, } \chi^2=29 \\
\text{POW+PYT unc.}
\end{array}$

$\begin{array}{c}
\text{Data, dof=15} \\
\text{POW+PYT, } \chi^2=21 \\
\text{POW+HER, } \chi^2=22 \\
\text{MG5+PYT, } \chi^2=29 \\
\text{POW+PYT unc.}
\end{array}$
Values of strong coupling and top pole mass obtained from NLO QCD analysis:

- $\alpha_s(m_Z) = 0.1135 \pm 0.0016$ (fit) $^{+0.0002}_{-0.0004}$ (mod.) $^{+0.0008}_{-0.0001}$ (par.) $^{+0.0011}_{-0.0005}$ (scale)
- $m_t^{\text{pole}} = 170.5 \pm 0.7$ (fit) $\pm 0.1$ (mod.) $^{+0.0}_{-0.1}$ (par.) $\pm 0.3$ (scale)

Uncertainties estimated according to the general approach of HERAPDF2.0
Summary and conclusions

- New results on jet, photon and top quark production have been presented.
- Higher order theoretical predictions have been recently developed, in particular for photon and top production.
- In general, good qualitative agreement is observed with the state of the art theoretical predictions.
- Some significant discrepancies are also observed for some jet observables (event shapes).
- Huge ongoing effort from both ATLAS and CMS to provide new measurements. Stay tuned for future updates!
- See next talk by C. Pollard for another nice set of jet substructure and top measurements.