Production of top quarks, jets and photons

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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 $p_{\text{T}}^{\text{rel}} = p_{\text{ch}}^T \sin \theta_{jc}$.
- Radial profile $\rho = 1/(2\pi rN_{\text{jet}}) dn_{\text{ch}}/dr; \quad r = \Delta R_{jc}$.
- Extraction of quark and gluon profiles from data.

![Graph 1](image1.png)

![Graph 2](image2.png)
Properties of jet fragmentation at ATLAS [STDM-2017-16]

Quark and gluon-like distributions obtained using two different methods

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

- Determine distributions for topics $T_1$ ($q$-like) and $T_2$ ($g$-like)
  \[ h_i^{T_1} = \frac{h_i^f - \min_j \{ h_j^f / h_j^c \} \times h_i^c}{1 - \min_j \{ h_j^f / h_j^c \}} \]
  \[ h_i^{T_2} = \frac{h_i^c - \min_j \{ h_j^c / h_j^f \} \times h_i^f}{1 - \min_j \{ h_j^c / h_j^f \}} \]
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.

**Figure 1**: Plot showing the measured flavor fractions for $b\bar{b}$ events with $0.25 < \Delta R(b,\bar{b}) < 0.3$ in the ATLAS detector. The measurement is compared to data and simulations, with uncertainties shown.

**Figure 2**: Scatter plot of $s_{d_0}^{sub}(j_1)$ vs. $\Delta R(b,\bar{b})$ showing the data (post-fit) and MC (pre-fit) distributions for different flavor components. The data are unfolded to correct for detector effects. The figure demonstrates the agreement between data and simulation within uncertainties.
$g \to b\bar{b}$ at small angles in ATLAS [Phys. Rev. D 99, 052004 (2019)]

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 $\Delta \theta_{ppg,gbb}$ 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: $\eta_X = \frac{\sum_{i \in X} p_{Ti} \eta_i}{\sum_{i \in X} p_{Ti}}$; $\phi_X = \frac{\sum_{i \in X} p_{Ti} \phi_i}{\sum_{i \in X} p_{Ti}}$

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

- Total transverse jet mass: \( \rho_T^X = \frac{M_X^2}{P_T^2} \); \( \rho_{T\text{tot}} = \rho_T^U + \rho_T^L \)

Important test of the back-to-back and collinear regime (low thrust).

Significant discrepancies observed in all variables across \( p_T \) bins.
Test of QCD at angles $\Delta \phi \lesssim \pi$, sensitive to resummation details.

Two and three jet events studied ($p_{T1} > p_{T2} > 100 \text{ GeV, } p_{T3} > 30 \text{ GeV}$).

Measurement of the normalized distribution of azimuthal difference $\Delta \phi_{12}$. 

![Graphs showing distribution of $\Delta \phi_{12}$ for different jet multiplicities and transverse momenta ranges.]
Comparison to LO+PS and NLO+PS are provided.
In particular, Powheg (2 → 2 and 2 → 3) are studied.
2 and 3-jet measurements not simultaneously described by any model.
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 $D_{13/8}^{\gamma,Z} = R_{13/8}^\gamma / R_{13/8}^{Z,\text{fid}}$.

### Graphs

**ATLAS**

- 8 TeV, 20.2 fb$^{-1}$ and 13 TeV, 3.2 fb$^{-1}$
- Relative uncertainty in $R_{13/8}^\gamma$
- $1.56 < |\eta_\gamma| < 1.81$

**ATLAS Simulation**

- $\sqrt{s} = 8$ TeV and 13 TeV
- Relative uncertainty in $R_{13/8}^\gamma$
- $1.56 < |\eta_\gamma| < 1.81$

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

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

**Correlated components:**
- complete correlation model
- no correlation assumed
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

- $E_T^\gamma > 190$ GeV and $|y^\gamma| < 2.5$.
- $p_T^{\text{jet}} > 30$ GeV and $|y^{\text{jet}}| < 2.4$.
- BDT to discriminate from background, validated with isolation sidebands.

**Inclusive $\gamma$**

**$\gamma$+jets**

![Graphs showing differential cross-sections for inclusive $\gamma$ and $\gamma$+jets events.](image-url)
Comparison of inclusive $\gamma$ (top) and $\gamma$+jet (bottom) to NLO pQCD (JetPhox)

**Figure 1:**
- **Top Panel:** Comparison of inclusive $\gamma$ to NLO pQCD (JetPhox) for $|\gamma'| < 0.8$.
  - Theory/Data ratio vs. $E_T$ (GeV) for different $E_T$ bins.
  - Data stat. uncertainty, Data total unc., NLO JETPHOX scale unc., NLO JETPHOX total unc.
  - CMS Preliminary
  - Theory/Data ratio vs. $E_T$ (GeV) for different $E_T$ bins.

**Figure 2:**
- **Top Panel:** Comparison of inclusive $\gamma$+jet to NLO pQCD (JetPhox) for $2.1 < |\gamma'| < 2.5$.
  - Theory/Data ratio vs. $E_T$ (GeV) for different $E_T$ bins.
  - Data stat. uncertainty, Data total unc., NLO JETPHOX scale unc., NLO JETPHOX total unc.
  - CMS Preliminary
  - Theory/Data ratio vs. $E_T$ (GeV) for different $E_T$ bins.

**Figure 3:**
- **Top Panel:** Comparison of inclusive $\gamma$+jet to NLO pQCD (JetPhox) for $|\gamma'| < 1.44$, $|\gamma'| < 1.5$, $p_T^{jet} > 30$ GeV.
  - Theory/Data ratio vs. $E_T$ (GeV) for different $E_T$ bins.
  - Data stat. uncertainty, Data total unc., NLO JETPHOX scale unc., NLO JETPHOX total unc.
  - CMS Preliminary
  - Theory/Data ratio vs. $E_T$ (GeV) for different $E_T$ bins.

**Figure 4:**
- **Top Panel:** Comparison of inclusive $\gamma$+jet to NLO pQCD (JetPhox) for $1.57 < |\gamma'| < 2.5$, $1.5 < |\gamma'| < 2.4$, $p_T^{jet} > 30$ GeV.
  - Theory/Data ratio vs. $E_T$ (GeV) for different $E_T$ bins.
  - Data stat. uncertainty, Data total unc., NLO JETPHOX scale unc., NLO JETPHOX total unc.
  - CMS Preliminary
  - Theory/Data ratio vs. $E_T$ (GeV) for different $E_T$ bins.
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 $\chi = e^{(|y_t - y_{\bar{t}}|)}$**

![Graph of Collins-Soper angle $\cos \theta^*$](image1)

![Graph of Angular distance $\chi$](image2)

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ATLAS
$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
Fiducial phase space

<table>
<thead>
<tr>
<th>Data</th>
<th>POWHEG+Py8</th>
<th>POWHEG+H7</th>
<th>MG5_aMC@NLO+Py8</th>
<th>Sherpa 2.2.1</th>
</tr>
</thead>
</table>

![ATLAS Graph](image3)

![ATLAS Graph](image4)
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:

$$|p_{\text{out}}^t| = \frac{p_{\text{had}}^t \cdot \left| \frac{p_{\text{lep}}^t \times \hat{z}}{|p_{\text{lep}}^t \times \hat{z}|} \right|}{|p_{\text{lep}}^t|}$$
Combined fit to $e^+e^-, \mu^+\mu^-$ and $e^\pm\mu^\mp$ channels.

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

$\sigma_{t\bar{t}} = 815 \pm 2 \text{ (stat.)} \pm 29 \text{ (sys.)} \pm 20 \text{ (lumi.)}$ from $m_t$, $\sigma$ simultaneous fit.

**PDF set** $\alpha_s(m_Z)$
- ABMP16: $0.1139 \pm 0.0023 \text{ (fit + PDF)} +0.0014 \text{ (scale)}$
- NNPDF3.1: $0.1140 \pm 0.0033 \text{ (fit + PDF)} +0.0021 \text{ (scale)}$
- CT14: $0.1148 \pm 0.0032 \text{ (fit + PDF)} +0.0018 \text{ (scale)}$
- MMHT14: $0.1151 \pm 0.0035 \text{ (fit + PDF)} +0.0020 \text{ (scale)}$

**PDF set** $m_t^{\text{pole}}$ [GeV]
- ABMP16: $169.9 \pm 1.8 \text{ (fit + PDF + } \alpha_s) +0.8 \text{ (scale)}$
- NNPDF3.1: $173.2 \pm 1.9 \text{ (fit + PDF + } \alpha_s) +0.9 \text{ (scale)}$
- CT14: $173.7 \pm 2.0 \text{ (fit + PDF + } \alpha_s) +0.9 \text{ (scale)}$
- MMHT14: $173.6 \pm 1.9 \text{ (fit + PDF + } \alpha_s) +0.9 \text{ (scale)}$
Differential cross sections versus a large variety of observables.

Comparison to high-order predictions in QCD

- Full NNLO + $\alpha^3_{\text{EW}}$ (LUXQED17)
- Full NNLO + double resummation (NNLO+NNLL')
- Approximate N$^3$LO @ NNLL.
- Approximate NNLO.

![Graph](image)

**CMS** 35.9 fb$^{-1}$ (13 TeV)

**CMS** 35.9 fb$^{-1}$ (13 TeV)

**Dilepton, parton level**

- Data
- POWHEGv2 + PYTHIA8
- POWHEGv2 + HERWIG++
- MG5_aMC@NLO + PYTHIA8 [FxFx]

- Stat ⊕ Syst
- Stat

**m_{t\bar{t}} [GeV]**

**p_{T} [GeV]**
$t\bar{t}$ multi-differential cross sections at CMS [arXiv:1904.05237 (hep-ex)]

- Dilepton channels $ee$, $e\mu$, $\mu\mu$.
- Cross sections as a function of pairs of variables:
  \[
  \{p_T(t), y_t, M_{t\bar{t}}, \Delta y_{t\bar{t}}, \Delta \phi_{t\bar{t}}, p_T(t\bar{t})\}
  \]
- Triple-differential cross sections of jet multiplicity $N_{jet}$
- Extraction of strong coupling $\alpha_s$, top mass $m_t$ and PDFs.

![Graph showing the distribution of cross sections](image)

- **CMS**
  - $300 < M(t\bar{t}) < 400$ GeV
  - $400 < M(t\bar{t}) < 500$ GeV
  - $500 < M(t\bar{t}) < 650$ GeV
  - $650 < M(t\bar{t}) < 1500$ GeV

- **35.9 fb$^{-1}$ (13 TeV)**
  - Ratio of data to signal
  - Ratio of data to other
  - Non-$t\bar{t}$
  - Syst. unc.

- **POW+PYT, $\chi^2=21$**
- **POW+HER, $\chi^2=22$**
- **MG5+PYT, $\chi^2=29$**
- **POW+PYT unc.**

- **Events / 100 GeV**
  - Data
  - t$t$ signal
  - t$t$ other
  - Non-t$t$
  - Syst. unc.
Values of strong coupling and top pole mass obtained from NLO QCD analysis:

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

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.