Soft and high-$p_T$ QCD

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on behalf of the LHC collaborations

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Science & Technology
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Introduction

- LHC probes QCD at all scales

Elastic collisions $\iff$ multi-TeV jet production

- Rich variety of physics
  - Non-perturbative physics
  - Differential cross sections
  - Fragmentation functions and PDFs
  - Underlying event
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ALICE $pp \rightarrow \{\pi^0, \eta\} \rightarrow \gamma\gamma$ arXiv:1708.08745

- Transverse mass ($m_T$) scaling of $\pi^0$ and $\eta$ production
- New input to fragmentation functions above TeV scale
- Experimental challenge: low $p_T$ $\gamma$ reconstruction

$$\pi^0 = \langle u\bar{u}, d\bar{d}\rangle$$
$$\eta = \langle u\bar{u}, d\bar{d}, s\bar{s}\rangle$$

- PHOS (PHOton Spectrometer) $\phi < 60^\circ$ coverage too low for $\eta \rightarrow \gamma\gamma$
- PCM = photon conversion method
- PHOS and EMCal triggers used

\[ \varepsilon = 2\pi \Delta y A_{\text{rec}} \]
\[ \text{ALICE simulation} \]
\[ pp, \quad \bar{\psi} = 8 \text{ TeV} \]
\[ \pi^0 \rightarrow \gamma\gamma \]
\[ \eta \rightarrow \gamma\gamma \]

\[ 0.3 \quad 1 \quad 2 \quad 3 \quad 5 \quad 6 \quad 7 \quad 10 \]
\[ 30 \quad 40 \]
\[ p_T \ (\text{GeV/c}) \]

\[ 10^3 \quad 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \quad 10^{10} \]

- PCM
- PCM-EMC
- EMC
- PHOS
ALICE $\{\pi^0, \eta\} \rightarrow \gamma\gamma$ arXiv:1708.08745

- Two Component Model (TCM) fit used
- Largest NLO uncertainty is $\mu$ choice
- Previous ALICE $\pi^0$ at 7 TeV part of DSS14 FF
ALICE $\{\pi^0, \eta\} \rightarrow \gamma\gamma$ arXiv:1708.08745

- Pythia with Monash 2013 tune best describes data
- FF DSS07 ($\eta$), DSS14 ($\pi^0$)
- Good agreement with NLO calculation
- $\pi^0/\eta$ ratio deviates from $m_T$ scaling by $6.2\sigma$ for $p_T < 3.5$ GeV

Agreement within uncertainties for NA27, PHENIX and ALICE data from $\sqrt{s} = 27.5$ GeV to 8 TeV
**ALICE unidentified hadron production**  
**Preliminary figures**

- Measure charged hadron spectra in tracklet multiplicity classes
- Observe enhancement relative to minimum bias data for $N_{\text{tracklets}} > 20$

![Graph 1](ALI-PREL-136980)

- More details [here](ALI-PREL-136996)
BEC between identical bosons enhanced when bosons are close in phase space

- Seen in ratio of correlated and reference correlation functions $\rho$:

$$C_2(Q) = \frac{\rho_{\text{identical}}(Q)}{\rho_{\text{non-identical}}(Q)} \sim [1 + e^{-RQ}](1 + \delta Q)$$

- $Q^2 = -(p_1 - p_2)^2$
- $\delta Q = $ long-distance correlation effects
- $R = $ effective source radius
- $\lambda = $ “chaoticity”, strength of effect
- Select non-identical bosons by mixing events

- Measure

$$r_d(Q) \equiv \frac{C_2^{\text{data}}(Q)}{C_2^{\text{MC}}}$$

to incorporate Coulomb and spin effects

- Investigate dependence on event activity

![Graph showing number of reconstructed PVs vs. Velo track multiplicity per PV]
LHCb Bose-Einstein correlations  \texttt{arXiv:1709.01769}

- Use LHCb PID to select 98% pure $\pi$ sample
- Effective source radius $R$ increases with $n_{\text{ch}}$, chaoticity $\lambda$ decreases
- Fit quality not perfect: need different parameterisation?
- Compatible with ATLAS results (limited rapidity overlap)
CMS Bose-Einstein correlations at 13 TeV

- Comprehensive comparison of BEC results with double ratio, cluster subtraction, hybrid cluster subtraction (arXiv:1712.07198)
- Compatibility between 7 TeV CMS and ATLAS results

![Graphs showing CMS Preliminary results for HCS Method - pp @ 13 TeV and CMS - pp @ 7 TeV](image1)

![Graphs showing CMS Preliminary results for ATLAS - pp @ 7 TeV](image2)
ATLAS ordered hadron chains 1709.07384

- Inspired by string model of hadronisation
- Helicity suppresses collinear $q \to gg$ and $g \to gg$ emission $\to$ helical QCD string
- Construct hadron chains algorithmically from particles (assume pions)
- Minimum bias dataset
ATLAS ordered hadron chains 1709.07384

- Fit to string model gives maximum triplet hadron chain mass
  \(M_{3h} < 575 \pm 20\) MeV

- Enhanced correlation of like-sign vs. opposite-sign pairs at low \(Q\) can be explained by ordered hadron chains
CMS underlying event in $Z \rightarrow \mu\mu$ \cite{arXiv:1711.04299}

- ISR/FSR dominant at high $p_T^{\mu\mu}$
- Agrees with tunes based on lead track/jet measurements $\rightarrow$ UE independent of hard process

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CMS underlying event in $t\bar{t} \rightarrow e\mu + \text{jets}$ CMS-PAS-TOP-17-015

- Yesterday’s signal is today’s UE hard process
- Interesting event topology: many different physics objects
CMS underlying event in $t\bar{t} \rightarrow e\mu + \text{jets}$ CMS-PAS-TOP-17-015

- Measuring UE properties at $\mu_R, \mu_F \approx 2m_t$
- Comparisons with a range of generators, tunes and settings
High $p_T$ QCD ($m_{jj} = 9.3$ TeV)
High $p_T$ QCD ($m_{jj} = 6.14$ TeV)
Jet reconstruction (K. Pachal, Performance I)

- Uses particle flow (define and follow all particles through detector)
- CMS jet energy uncertainties DP-2016-020
- Uses topological cell clustering based on signal and noise thresholds
- ATLAS jet energy uncertainties arXiv:1703.09665

< 2% uncertainty for 100 GeV < \( p_T < 2 \) TeV!
ATLAS inclusive jet and dijet cross sections arXiv:1711.02692

- Inclusive jets: $p_T > 100$ GeV, $|y| < 3$
- Better agreement with NNLO
  - $p_T^{\text{jet}}$: weight each jet in event according to $\mu_R = \mu_F = p_T^{\text{jet}}$
  - $p_T^{\max}$ scale choice overestimates: see backup

**ATLAS**

$L = 81 \text{nb}^{-1} - 3.2 \text{fb}^{-1}$

$\sqrt{s} = 13 \text{TeV}$

anti-$k_t$, $R=0.4$

- Theory/Data
- $L = 81 \text{nb}^{-1} - 3.2 \text{fb}^{-1}$
- $\sqrt{s} = 13 \text{TeV}$
- anti-$k_t$, $R=0.4$
- $\mu_R = \mu_F = P_T^{\text{jet}}$
- NLO MMHT 2014 NLO
- NNLO MMHT 2014 NNLO
ATLAS inclusive jet and dijet cross sections arXiv:1711.02692

- Dijets: $p_T > 75$ GeV, $p_T^1 + p_T^2 > 200$ GeV
- Excellent agreement across a broad $p_T$ and $y$ range
- All PDFs overestimate slightly at high $p_T$ and $2.5 < y^* = |y^1 - y^2| < 3$
Azimuthal correlations

- Azimuthal angles between jets are sensitive to ISR, FSR
- Testing ground for pQCD, MC tunes

Measure $\Delta \phi_{2j}^{\text{min}}$ maximised by

- $2\pi/3$, 3 jets
- $\pi/2$, 4 jets

- Interesting for $\geq 3$ jets, infrared safe
CMS azimuthal correlations arXiv:1712.05471

- PH-2J - PowHeg, 2-jet NLO mode
- $\Delta \phi_{1,2}$ and $\Delta \phi_{2j}^{\text{min}}$ have complementary kinematics
CMS azimuthal correlations \( \Delta \phi_{1,2} \)

- Exclude \( \Delta \phi < \pi/2 \): large \( t\bar{t} \) and \( W/Z + \text{jet backgrounds} \)
- Best overall description given by MC@NLO in Herwig7

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**CMS**

**Number of Jets ≥ 3**

- Anti-\( k_T \) R = 0.4
- Experimental uncertainty

**Number of Jets ≥ 4**

- Anti-\( k_T \) R = 0.4
- Experimental uncertainty

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

**Ratio to data**

- \( 800 < p_T^{\text{max}} < 1000 \) GeV
- \( p_T^{\text{max}} > 1000 \) GeV

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**Stewart Martin-Haugh (RAL)**

**Soft and high-\( p_T \) QCD**

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CMS azimuthal correlations \( \Delta \phi_{2j}^{\text{min}} \)

- PH-2J with Herwig7 and Pythia8 PS models \( \Delta \phi_{2j}^{\text{min}} \) best
- Compare with LO generators (Pythia8, Herwig++, MadGraph (2 \( \to \) 4))
ATLAS jet azimuthal decorrelations arXiv:1805.04691

- Measure

\[ R_{\Delta \phi}(H_T, y^*, \Delta \phi_{\text{max}}) = \frac{\frac{d^2 \sigma_{\text{dijet}}(\Delta \phi_{\text{dijet}} < \Delta \phi_{\text{max}})}{dH_T dy^*}}{\frac{d^2 \sigma_{\text{dijet}}(\text{inclusive})}{dH_T dy^*}} \]

- \( R_{\Delta \phi} \) is a function of several aspects of QCD
  - \( H_T/2 \): hard scale
  - \( y^* = |y_1 - y_2| \): kinematics
  - \( \Delta \phi_{\text{max}} \): hardness of additional jet production

- Choose data points with good theory prediction for \( \alpha_S \) determination
Calculate running with renormalisation group equation

1 σ below world average $\alpha_S^{PDG} = 0.1181 \pm 0.0011$

Highest measured $\alpha_S(Q)$ value to date
Soft drop jet grooming: decluster jet constituents (calo-clusters): see A. Larkoski’s talk

\[
\frac{\min(p_T^{j_1}, p_T^{j_2})}{p_T^{j_1} + p_T^{j_2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta
\]

Can construct precise observables insensitive to e.g. non-global logarithms

ATLAS measured scaled jet mass \( \rho = m_{\text{soft drop}}/p_T^{\text{ungroomed}} \) for \( R = 0.8 \) jets

Keep energy scale \( z_{\text{cut}} = 0.1 \) to avoid \( z_{\text{cut}} \) resummation, vary \( \beta \in 0, 1, 2 \)
Select dijet events with $p_T^{j_1} > 600$ GeV, $p_T^{j_2}/p_T^{j_1} < 1.5$

Unfold to detector-level simulation: substantial differences between truth and reconstructed distributions

Uncertainties vary widely with $\rho$

High $\rho$: jet constituent energy scale dominates

Low $\rho$: MC modelling dominates
Normalise $\sigma$ to resummation region ($-3.7 < \log_{10}(\rho^2) < -1.7$)

$\beta \in 1, 2 \rightarrow$ less soft radiation is subtracted

- $\log_{10}(\rho^2) < -3.7$
- $-3.7 < \log_{10}(\rho^2) < -1.7$
- $\log_{10}(\rho^2) > -1.7$

- NP
- LO+NNLL
- NLO+NLL

\[
\log_{10}(\rho^2) < -3.7
\]

\[
-3.7 < \log_{10}(\rho^2) < -1.7
\]

\[
\log_{10}(\rho^2) > -1.7
\]
Conclusions

▶ Thanks to all the collaborations for such an impressive range of results
▶ Sorry I couldn’t include everything!
▶ Please join the QCD parallel sessions to learn more
Backup: ALICE detector
Backup: Cluster subtraction in Bose-Einstein correlations

- Use only single ratios
- Fit opposite-sign correlation function to phenomenological function
- Exclude resonances from fit
Three datasets used:

- 0.9 TeV, \( n_{ch} \geq 2 \), \( \approx 4.5 \)M events
- 7 TeV, \( n_{ch} \geq 2 \), \( \approx 10 \)M events
- 7 TeV, \( n_{ch} \geq 150 \), \( \approx 18 \)k events

\( R \) and \( \lambda \) are \( \approx \) independent of energy to within uncertainties

First evidence for saturation of \( R \) at high multiplicity, as predicted by pomeron-based models.
2 Event and object selection

The ATLAS detector covers almost the whole solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. It is described in detail elsewhere [11]. For the measurements presented in this paper, the tracking devices and the trigger system are of particular importance. The innermost pixel layer, the insertable B-layer (IBL) [12,13], was added between Run 1 and Run 2 of the LHC, around a new thinner (radius of 25 mm) beam pipe. It is composed of 14 azimuthal lightweight staves, each of them made of 12 silicon planar sensors in its central region and 2 × 4 3D sensors at the ends. The pixel sizes are smaller than for the other pixel layers giving better longitudinal impact parameter resolution. The smaller radius gives rise to better transverse impact parameter resolution. Furthermore new service quarter panels have been implemented which significantly reduce the material at the boundaries of the active tracking volume.

This analysis uses the same dataset and follows the ATLAS charged particle distribution analysis [14] regarding event and track selections. Events were collected from colliding proton bunches where the Minimum Bias Trigger Scintillators recorded one or more counters above threshold on either side of the detector.

The data sample corresponds to an integrated luminosity of $170 \mu b^{-1}$. The only additional requirement for this analysis was the presence of a leading track with a $p_T$ of at least 1 GeV. This requirement results in a fully efficient trigger, hence no trigger requirement is imposed in MC events.

To reduce the contribution from background events and additional interactions, events are required to contain a primary vertex [15] and no second vertex with four or more tracks. The rate of background events from non-colliding beams is estimated to be less than 0.01% and the contribution from tracks from additional interactions is less than 0.01% after this requirement.

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**Figure 1**: Definition of UE regions as a function of the azimuthal angle with respect to the leading track.
Jet substructure technique “soft drop”: insensitive to non-global logarithms

1. Start with usual \textit{anti} \( - k_T \) jet
2. Re-cluster with Cambridge-Aachen
3. Traverse the clustering tree backwards
4. Remove branch points that don’t satisfy soft drop condition

\[
\frac{\min(p_T^{j_1}, p_T^{j_2})}{p_T^{j_1} + p_T^{j_2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)
\]