Recent Soft QCD Measurements at LHCb

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for LHCb Collaboration

• Inelastic $pp$ cross-section
  JHEP 06 (2018) 100
  arXiv:1803.10974

• $J/\psi$ production in jets
  arXiv:1701.05116

• $b\bar{b}$ correlations
  JHEP 1711 (2017) 030
  arXiv:1708.05994

• Bose-Einstein correlations
  JHEP 12 (2017) 025
  arXiv:1709.01769
Complementarity of LHCb

- Angular acceptance of LHCb complementary to ATLAS/CMS

- Vertex Locator
  - 8 mm from LHC beam

- Particle ID systems
  - RICH π/K/p ID

2<\eta<5

4.3 Muon system based particle identification

The identification of a track reconstructed in the tracking system as a muon is based on the association of hits around its extrapolated trajectory in the muon system [82]. A search is performed for hits within rectangular windows around the extrapolation points where the x and y dimensions of the windows are parameterised as a function of momentum at 53.
Inelastic $pp$ cross-section

- Fundamental observable in $pp$ collisions
  - Accelerators, cosmic rays induced air showers, transport of cosmic rays in interstellar medium
- Dominant processes in inelastic $pp$ interaction

- Non-Diffractive (ND)
- Single-Diffractive (SD)
- Double-Diffractive (DD)

- Measure fraction of non-empty events
Method: Inelastic $pp$ cross-section

- Data sample
  - 10.7 nb$^{-1}$ collected in 2015 at 13 TeV
- Unbiased triggers
  - Leading bunches in LHC bunch-trains
  - Random events accepted
  - Avoid background from previous crossing
- Selection
  - $\geq 1$ long-lived charged particle in acceptance

- Fiducial cross-section

$$\sigma_{acc} = \frac{(\mu - \mu_{bkg})N_{evt}}{L_{tot}}$$

$\mu$: average number of interactions per events

Obtained from fraction of empty events and corrected for detector inefficiency and wrongly reconstructed tracks

Chris Parkes, ICHEP, July 2018
**Results:** Inelastic $pp$ cross-section

- Fiducial cross-section
  \[ \sigma_{\text{acc}} = 62.2 \pm 0.2 \text{ (syst.)} \pm 2.5 \text{ (lumi.) } \text{mb} \]

- Extrapolate to full phase-space using simulation
  \[ \sigma_{\text{inel}} = 75.4 \pm 3.0 \text{ (expt.)} \pm 4.5 \text{ (extrap.) } \text{mb} \]

Agreement with ATLAS & TOTEM measurements made in different $\eta$ ranges

![Graph showing inelastic cross-sections at 7 TeV and 13 TeV](image)
J/ψ production in jets

- Many NRQCD calculations predict large transverse polarisation for J/Ψ that is not observed in data
  - Direct production, leading to largely isolated J/Ψ
  - Could be explained by quarkonium production in parton-shower, leading to non-isolated J/Ψ
- Utilise prompt and b-hadron decay J/ψ in jets
- Measure a proxy for isolation

\[ z(J/\psi) = \frac{P_T(J/\psi)}{P_T(\text{Jet containing } J/\psi)} \]

- Studies radiation accompanying quarkonia
- First measurement of this quantity in prompt J/ψ
**Method:** $J/\psi$ production in jets

- **Prompt and b-hadron decay** $J/\psi$ separated using a pseudo-decay time in $P_{T}(\text{jet}), z(J/\psi)$ bins

• Utilises real-time-analysis strategy
  – Facilitated no $p_{T}(J/\psi)$ requirements
• Only one $pp$ reconstructed vertex for resolution
• $z(J/\psi)$ corrected for selection efficiencies and unfolded for detector response.
Results: \( J/\psi \) production in jets

- **Prompt** \( J/\psi \) are much less isolated than predicted
  - High \( p_T \) \( J/\psi \) predominantly produced in parton shower?
  - Could explain long-standing transverse polarisation puzzle

- **B-hadron decay** \( J/\psi \) in good agreement with Pythia

\[ d\sigma / d\sigma \]
bb correlations

- Kinematic correlations between heavy quark & anti-quark probe production mechanism
  - Gluon splitting, Flavour-creation, Flavour excitation
  - Previous studies of open charm have identified contributions from all three processes
- Previously measured by CMS & ATLAS
- LHCb study in its forward acceptance at 7/8 TeV
  - Uses $b \rightarrow J/\psi X$ decays
  - Differential cross-section as function of kinematic variables, for ranges of $J/\psi$ transverse momenta
Results: $b\bar{b}$ correlations

- $|\Delta \Phi^*|$ difference in azimuthal angle $b$-hadrons
- $|\Delta \eta^*|$ difference in pseudorapidity $b$-hadrons
- Probe production mechanism
  - Agreement with Pythia(LO) and POWHEG(NLO), suggests small NLO effects
  - Unlike charm no large contribution from gluon splitting seen (small $|\Delta \Phi^*|$)

Plots down to $P_T \geq 2$ GeV and range of kinematic variables in paper
Bose-Einstein correlations

• Enhancement of production of identical bosons (like-sign pions) close in phase-space
  – Understand emission volume in hadronization
  – First study in $pp$ forward region
  – Pion identification with RICH

Correlation Function: $C_2(Q) = \frac{N(Q)^{\text{same}}}{N(Q)^{\text{ref}}}$

where $Q^2$ is four-momenta difference squared of the two pions
Method: Bose-Einstein correlations

\[ C_2(Q) = N(1 + \lambda e^{-R \cdot Q}) \times (1 + \delta \cdot Q) \]

- Levy Parametrisation + long-range correlations:
  - \( C_2(Q) \): Normalisation
  - \( \delta \): Long-range correlations

- Double ratio data/simulation
  - Account for imperfections in reference sample
  - Perform analysis as a function of number of charged particles
    Activity: low, medium, high

\[ r_d(Q) = \frac{C_2(Q)^{\text{Data}}}{C_2(Q)^{\text{MC}}} \]

- R: Radius of source (spherical, static)
- \( \lambda \): Chaoticity (0-coherent, 1-chaotic)
Results: Bose-Einstein correlations

- Source size **increases** with activity • \( \lambda \) **decreases** with activity

\[ R \text{ [fm]} \]

\begin{tabular}{ccc}
LHCb & \( \sqrt{s} = 7 \text{ TeV} \) & \\
\hline
\hline
low activity & \n_{ch}: [8-18] & \\
medium activity & [19-35] & \\
high activity & [36-96] & \\

\end{tabular}

\[ \lambda \]

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\end{tabular}

- \( R, \lambda \) trends comparable with those seen in other experiments
- Values appear somewhat lower in LHCb forward acceptance than in central region of ATLAS
Summary: Recent Soft QCD at LHCb

- Inelastic $pp$ cross-section in LHCb acceptance
  - Good agreement with determinations from other rapidity ranges
- **Prompt J/ψ** production
  - Much less isolated than Pythia predicts
- $b\bar{b}$ correlations
  - Agreement with Pythia/POWHEG
- Bose-Einstein correlations
  - Observed in like-sign pions in forward $pp$
Backup
Stability: Inelastic $pp$ cross-section at 13 TeV

Statistical errors only, systematics inferred from spread
Luminosity: Inelastic $pp$ cross-section at 13 TeV

- Continuous online monitoring of number of interactions with at least two tracks in the vertex detector
  \[ L = N_1 N_2 \nu_{\text{rev}} \Omega, \quad \Omega = 2c \int \rho_1(x, y, z, t) \rho_2(x, y, z, t) \, dx \, dy \, dz \, dt. \]

- Direct method calibration using beam-gas imaging
  - Reconstruct interaction vertices of beam and gas nuclei
  - Angles, positions, shapes of beams
Mass fit: $J/\psi$ Production in Jets

$20 < p_T\text{(jet)} < 30 \text{ GeV}$
$0.4 < z(J/\psi) < 0.5$

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

- Data
- Total Fit
- $J/\psi$
- Background

$m(\mu^+\mu^-) [\text{GeV}]$
Results: $b\bar{b}$ Correlations

**a)**
- **POWHEG**
- **PYTHIA**
- uncorrelated $b\bar{b}$

**b)**
- LHCb
- $\sqrt{s} = 7.8$ TeV
- $p_{T}^{J/\psi} > 2$ GeV/c

**c)**
- $\frac{1}{R} \frac{d\sigma}{d\Delta\phi}$

**d)**
- $\frac{1}{R} \frac{d\sigma}{d\Delta\eta}$

**e)**
- $A_{T}$

**f)**
- $\frac{1}{R} \frac{d\sigma}{d\Delta p_{T}^{J/\psi}}$
- $m^{J/\psi, J/\psi}$ [GeV/c$^2$]
- $p_{T}^{J/\psi, J/\psi}$ [GeV/c]
Results: $b\bar{b}$ Correlations

LHCb

$\sqrt{s} = 7.8$ TeV

$p_T^{J/\psi} > 3$ GeV/$c$

$\frac{d\sigma}{d\Delta\phi^{*}}$ vs $|\Delta\phi^{*}| / \pi$

$\frac{d\sigma}{d\Delta\eta^{*}}$

$\mathcal{A}_T$

$\frac{d\sigma}{d m^{J/\psi J/\psi}}$ [GeV/$c^2$]

$\frac{d\sigma}{d p_T^{J/\psi}}$ vs $p_T^{J/\psi}$ [GeV/$c^2$]

arXiv:1708.05594
Results: $b\bar{b}$ Correlations
Results: $b\bar{b}$ Correlations

a) POWHEG

b) PYTHIA

c) uncorrelated $b\bar{b}$

LHCb

$\sqrt{s} = 7,8$ TeV

$p_T^{J/\psi} > 7$ GeV/c

$|\Delta\phi^*| / \pi$

$|\Delta\eta^*|$

$A_T$

$m_{J/\psi \to J/\psi}$ [GeV/$c^2$]

$1/\Delta p_T^{J/\psi, J/\psi}$

$1/\Delta p_T^{J/\psi, J/\psi}$ [GeV/$c$]
Coulomb Effect: Bose-Einstein Correlations

- Coulomb effect not simulated
- Corrected by applying Gamov penetration factor

\[ G_2(Q) = \frac{2\pi \zeta}{e^{2\pi \zeta} - 1}, \text{ where } \zeta = \pm \frac{am}{Q} \]
Event Multiplicity: Bose-Einstein Correlations

- BEC parameters depend on total multiplicity
- VELO track multiplicity ($N_{ch}$ used)
- Unfolded to account for acceptance

![Graph showing the distribution of VELO track multiplicities per PV]

<table>
<thead>
<tr>
<th>VELO $N_{ch}$</th>
<th>activity class</th>
<th>unfolded $N_{ch}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10</td>
<td>(52-100)%</td>
<td>8-18</td>
</tr>
<tr>
<td>11-20</td>
<td>(15-52)%</td>
<td>19-35</td>
</tr>
<tr>
<td>21-60</td>
<td>(0-15)%</td>
<td>36-96</td>
</tr>
</tbody>
</table>

**track multiplicities unfolded using PYTHIA 8 (in $2 < \eta < 5$)**

LHCb $\sqrt{s} = 7$ TeV