FORWARD PRODUCTION MEASUREMENTS WITH LHCb

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Outline

• LHCb detector

• Forward production measurements
  • Forward energy flow
  • Central exclusive production (CEP)
    • CEP of $J/\psi$ and $\psi(2S)$
    • CEP of charmonium pairs
  • Production ratios of identified particles

• Summary
LHCb detector

- Single arm spectrometer
- Stations: $2 < \eta < 5$
  - Vertex locator (VELO)
    Both forward and backward
    20 $\mu$m IP resolution for $p_T > 2$ GeV/c
  - 4 tracker stations & 4 Tm integrated field
    0.4%-0.6% momentum resolution
  - Calorimeters
  - RICH detectors
    $\epsilon(K \rightarrow K) \sim 95\%$ for $(\pi \rightarrow K) \sim 5\%$
  - Muon system
    Muon Identification $\epsilon \sim 97\%$ MisID $\sim 2\%$

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Forward Energy Flow

- **Motivation**
  - Energy Flow (EF): Average energy per event in a given $\eta$ interval

\[
\frac{1}{N_{\text{int}}} \frac{dE_{\text{total}}}{d\eta} = \frac{1}{\Delta \eta} \left( \frac{1}{N_{\text{int}}} \sum_{i=1}^{N_{\text{part}, \eta}} E_{i, \eta} \right)
\]

- Sensitive to parton radiation and multiple parton interaction
- Tests of event generators – collider and cosmic ray models

- **Data sample**
  - 0.1 nb^{-1} low pile-up data collected at 7 TeV
  - At least one VELO track required in the trigger
Forward Energy Flow

• Analysis Strategy
  • Measurement with tracks $2 \text{ GeV}/c < p < 1 \text{ TeV}/c$
  • Four different event classes
    • Inclusive minimum bias – at least one track with $p > 2 \text{ GeV}/c$
    • Hard-scattering – at least one track with $p_T > 3 \text{ GeV}/c$
    • Diffractive enriched – no backward tracks
    • Non-diffractive enriched – at least one backward track
  • Corrected to particle level
    • Charged energy flow – only tracking information (no PID; $E \approx p$).
    • Total energy flow – data-constrained MC estimate of neutral component (Calorimeter information)
  • Systematics dominated by model uncertainty and selection cuts
Charged Energy Flow vs. PYTHIA

- Energy Flow increases with momentum transfer
  \( \text{EF}_{\text{diff}} < \text{EF}_{\text{incl}} < \text{EF}_{\text{ndiff}} < \text{EF}_{\text{hard}} \)

- PYTHIA6 underestimates charged EF for all event classes at high \( \eta \)

- PYTHIA8 – best agreement for diffractive enriched events, yet it overestimates EF in hard scattering ones

- Same conclusions apply for the total EF (backups)

  EPJC73 (2013) 2421
Charged Energy Flow vs. cosmic ray models

- Cosmic-ray interaction models tend to overestimate the EF.
- SYBILL and EPOS give the best description for MB inclusive events.
- SYBILL gives good agreement in all 4 LHCb event classes except at high η for hard scattering events.
- Total energy flow given in backups.

EPJC73 (2013) 2421
Central exclusive production

- **CEP:** protons remain intact
  \[ h_1(p_1) + h_2(p_2) \rightarrow h_1(p_1') + X + h_2(p_2') \]

- **Physics motivation:** tests of QCD
  - Pomeron – γ interactions
  - Double pomeron exchange (pomeron-pomeron fusion)

- **CEP at LHCb**
  - Elastic scattering with intact and un-tagged protons

Observed

Fractional momentum of the parton \( x \sim 5 \times 10^{-6} \)
**CEP study at LHCb**

- **Two key subsystems for CEP study at LHCb**
  - **Vertex locator**
    - Precise track and vertex reconstruction
    - LHCb is “forward spectrometer”? VELO also has coverage for backward track reconstruction
  - **Scintillator Pad Detector (SPD)**
    - Provides input to hardware trigger
    - Used primarily as multiplicity detector
CEP of $J/\psi$ and $\psi(2S)$

- **Data sample**
  - 930 pb$^{-1}$ collected at 7 TeV
  - Events with less than 10 SPD hits triggered

- **Selection**
  - Exact one primary interaction (24% of total sample)
  - No backward tracks
  - No photons

- **Mass fit**
  - Signal – Crystal Ball
  - Background - Exponential
  - 55895 $J/\psi$ and 1565 $\psi(2S)$
CEP of $J/\psi$ and $\psi(2S)$

- **Background**
  - Feed-down
    - Estimated using other exclusive productions and simulation
  - Inelastic (dominant)
    - Estimated using collision data
    - Fit to $p_T^2$

Regge theory

![Regge theory diagrams](b) (c) (d)
CEP of $J/\psi$ and $\psi(2S)$

- Integrated cross-sections
  
  $\sigma_{pp \rightarrow J/\psi \rightarrow \mu^+ \mu^-}(2.0 < \eta_{\mu^\pm} < 4.5) = 291 \pm 7\text{(stat.)} \pm 19\text{(sys.)}\text{ pb}$
  
  $\sigma_{pp \rightarrow \psi(2S) \rightarrow \mu^+ \mu^-}(2.0 < \eta_{\mu^\pm} < 4.5) = 6.5 \pm 0.9\text{(stat.)} \pm 0.4\text{(sys.)}\text{ pb}$
  
- Comparison with theoretical predictions: good agreement

CEP of $J/\psi$ and $\psi(2S)$

- Differential cross-sections

Theory from PRD88,017504(2013) and PRD78,014023(2013)

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CEP of $J/\psi$ and $\psi$(2S)

- Exclusive production in $pp$ collisions is related to photoproduction

\[
\frac{d\sigma}{dy}_{pp\rightarrow pJ/\psi\ p} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow J/\psi\ p}(W_+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow J/\psi\ p}(W_-)
\]

- Derive $\sigma_{\gamma p \rightarrow J/\psi\ p}(W_\pm)$ from the results using a power-law relationship determined by the H1 collaboration

\[
\sigma_{\gamma p \rightarrow J/\psi\ p}(W) = 81(W/90\ \text{GeV})^{0.67}\ \text{nb}
\]

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Good agreement
CEP of charmonium pairs

- **Motivation**  
  - Production via exchange of two pomerons  
  - Help to understand charmonium pair production

- **Data sample**  
  - 3 fb\(^{-1}\) collected at both 7 and 8 TeV, average energy 7.6 TeV

- **Selection**  
  - Exactly four forward tracks  
  - At least three identified muons  
  - \(J/\psi\) and \(\psi(2S)\) within [-200, 65] MeV from nominal mass
CEP of charmonium pairs

- **Invariant mass**
  
  ![Invariant mass plots](image)

- **Result**
  
  - 37 $J/\psi J/\psi$ and 5 $J/\psi \psi(2S)$ candidates found

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CEP of charmonium pairs

- Results

\[ \sigma^{J/\psi J/\psi} = 58 \pm 10 \text{(stat)} \pm 6 \text{(syst)} \text{ pb}, \]
\[ \sigma^{J/\psi J/\psi (2S)} = 63^{+27}_{-18} \text{(stat)} \pm 10 \text{(syst)} \text{ pb}, \]
\[ \sigma^{\psi (2S) \psi (2S)} < 237 \text{ pb}, \]
\[ \sigma^{\chi_{c0} \chi_{c0}} < 69 \text{ nb}, \]
\[ \sigma^{\chi_{c1} \chi_{c1}} < 45 \text{ pb}, \]
\[ \sigma^{\chi_{c2} \chi_{c2}} < 141 \text{ pb} \]

- Comparison between inclusive and exclusive

\[ \frac{\sigma^{J/\psi J/\psi}}{\sigma^{J/\psi}} \bigg|_{\text{inclusive}} = \left( 5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0} \right) \times 10^{-4} \]
\[ \frac{\sigma^{J/\psi J/\psi}}{\sigma^{J/\psi}} \bigg|_{\text{exclusive}} = (2.1 \pm 0.8) \times 10^{-3} \]

- Comparison with theory

CEP: 24 ± 9 pb
Theory: 8 – 36 pb

\[ \frac{\sigma^{(J/\psi \psi (2S))}}{\sigma^{(J/\psi J/\psi)}} = 1.1^{+0.5}_{-0.4} \]

Theory: 0.5

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First observed

Inelastic included
Production ratios of identified particles

- Antiparticle/particle ratios
  - Ratio drops at large rapidity, especially at higher $p_T$
  - Reasonable agreement with all considered MC tunes

$\frac{\pi^-}{\pi^+}$

$\frac{K^-}{K^+}$

Measured at 0.9 and 7 TeV

Production ratios of identified particles

- Baryon to Meson Ratio and Light Baryon Suppression
- LHCb MC agrees better
- PYTHIA6 Perugia tunes underestimate the ratio
- Smaller baryon suppression in high $p_T$. Similar qualitative trend in $\bar{\Lambda}/K^0_s$ measurement


Production ratios of identified particles

- Baryon number transport

Measured at 0.9 and 7 TeV  
Rapidity loss $\Delta y = y_{\text{beam}} - y_{\text{particle}}$  
First measured in this $\Delta y$ range  
Complementary to ALICE data


Agree with Perugia NOCR better

Production ratios of identified particles

- Baryon number transport

Measured at 0.9 and 7 TeV
Rapidity loss $\Delta y = y_{\text{beam}} - y_{\text{particle}}$
First measured in this $\Delta y$ range
Complementary to ALICE data


Similar dependence seen in strange baryon production
Behavior as a function of $\Delta y$ is independent of $\sqrt{s}$

Summary

• **Forward energy flow** has been measured. PYTHIA8 provides better description. Cosmic ray shower models describe minimum bias data well.

• **Exclusive $J/\psi$ and $\psi(2S)$ cross-sections** have been measured at LHCb. Results are consistent with theory and photo-production results from HERA.

• **First observation** of CEP with pairs of S-wave charmonium at LHCb. Upper limits calculated for pairs of P-wave charmonium.

• Production ratio for identified particles have been measured. Baryon number transport and baryon suppression are not well described by PYTHIA tunes.
Total EF estimate

For each $\Delta \eta$, main assumption:

$$\Delta E_{Neutral, PV} \propto \Delta E_{Charged, PV}$$

at collision's primary vertex (PV), hence after unfolding with detection efficiency and acceptance.

$$\Delta E_{Neutral, PV} = \Delta E_{Charged, PV} \times \frac{\Delta E_{Neutral, gen}}{\Delta E_{Charged, gen}}$$

where $\Delta E_{Neutral, gen}$ and $\Delta E_{Charged, gen}$ are the generator results for these quantities in corresponding $\Delta \eta$.

Extra correction:

$$\Delta E_{Neutral, PV} = \Delta E_{Charged, PV} \times \frac{\Delta E_{Neutral, gen}}{\Delta E_{Charged, gen}} \times \frac{1 + R_{data, RECO}}{1 + R_{MC, RECO}}$$

where

$$R_{data, RECO} = \frac{\Delta E_{calorimeter, data}}{\Delta E_{Charged raw, data}}$$

and

$$R_{MC, RECO} = \frac{\Delta E_{calorimeter, simulated}}{\Delta E_{Charged raw, simulated}}$$

- $EF_{calorimeter, data}$ - measured energy flow through calorimeter in data;
- $EF_{calorimeter, simulated}$ - reconstructed energy flow through calorimeter in simulation;
- $EF_{Charged raw, data}$ - raw estimate of charge energy flow in data, before unfolding to PV;
- $EF_{Charged raw, simulated}$ - reconstructed energy flow for charged particles in simulation.
Total EF vs. PYTHIA

- Total energy flow for all 4 event classes; LHCb data vs. PYTHIA tunes results;

- PYTHIA8 agrees with diffractive events, but not with the hard $p_T$ events, where it overestimates the energy flow;

- PYTHIA6 underestimates the energy flow at high-$\eta$ for all cases.

- No PYTHIA tune describes all 4 components;
- PYTHIA8 give best agreement in general.
Total EF vs. cosmic ray model

- Total energy flow for all 4 event classes; LHCb data vs. cosmic ray model;

- QGSJET models overestimates the soft $p_T$ component in MB inclusive and non-diffractive;

- SYBILL reproduces the best all 4 cases, this time there is a more pronounced disagreement in last 2 high-$\eta$ bins for the hard component.
CEP of charmonium: $J/\psi \, \psi(2S)$ mass