Particle Production in the Forward Region

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OVERVIEW

MEASUREMENTS
Forward Energy Flow
Double Charm Production
Central Exclusive Production
Perspectives from the Ion Pilot Run

SUMMARY
**Charged Energy Flow**

\[
\frac{1}{n_{\text{Interaction}}} \frac{d E_{\text{Charged}}}{d \eta} = \frac{1}{\Delta \eta} \frac{1}{n_{\text{Interaction}}} \sum_{i=1}^{n_{\text{Particles}, \eta}} E_{i, \eta}
\]

**Data**

- Low pile up (≈ 5%) data of about 100 \( \mu b^{-1} \) at \( \sqrt{s} = 7 \) TeV.

The measurement uses tracks with \( 2 \) GeV < \( p < 1 \) TeV but data are corrected to represent the total (charged) Energy Flow at particle level.

**Simulation**

- **Pythia 6.4 + EvtGen + Photos** using three tunes: LHCb; Perugia 0; and Perugia NOCR
- **Pythia 8.135** (default tune)
- **Epos 1.99, Qgsjet01, QgsjetII-03 and Sibyll 2.1**
LHC collides two beams – cosmic rays hit the atmosphere at rest.

$$\sqrt{s_{\text{LHC}}} = 2 \cdot E_{\text{LHC}}$$

$$\sqrt{s_{\text{Cosmic Ray}}} \approx \sqrt{2 \cdot E_{\text{Cosmic Ray}} \cdot m}$$

LHC can probe pp interactions as if 25 PeV protons hit protons in the atmosphere and test Cosmic Ray simulations.
Event Classes

**Minimum Bias inclusive**
At least one track with $p > 2$ GeV and $1.9 < \eta < 4.9$.

**Hard Scattering**
At least one track with $p_T > 3$ GeV and $1.9 < \eta < 4.9$.

**Diffractive enriched**
No track within $-3.5 < \eta < -1.5$.

**Non-diffractive enriched**
At least one track within $-3.5 < \eta < -1.5$. 
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![Diagram showing particle production in LHCb](image-url)
Sybill and EPOS give good description for most of the distributions but not for the diffractive enriched.

All comparisons with default tunes.
Pythia 8 gives best description of most of the distributions but overshoots for the hard scatter.
Double Charm Production

\[ \frac{dN}{d(m_{\mu^+\mu^-})} \]

\[ \frac{1}{1\text{ MeV/c}^2} \]

\[ J/\psi \rightarrow \mu^+\mu^- \]

LHCb
\[ \sqrt{s} = 7 \text{ TeV} \]
\[ \int \mathcal{L} = 355 \text{ pb}^{-1} \]

LHCB-PAPER-2012-003 (J. High Energy Phys. 06 (2012) 141)
INTRODUCTION

We measure pairs of $J/\psi$ and open charm hadrons and pairs of two open charm hadrons the in the following final states:

- $J/\psi \rightarrow \mu\mu$
- $D_0 \rightarrow K^-\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$
- $D_s^+ \rightarrow [K^-K^+]_\Phi\pi^+$
- $\Lambda_c^+ \rightarrow pK^-\pi^+$

These processes are sensitive to charmonium production mechanism, double parton scattering and intrinsic charm. $C$ denotes $D_0, D^+, D_s^+$ or $\Lambda_c^+$ Charge conjugated states are included throughout this section.

More details in backup.
**Open Charm Candidates**

**Signal Yields**

\[
\begin{align*}
J/\psi & \quad 49.57 \cdot 10^6 \\
D^0 & \quad 65.77 \cdot 10^6 \\
D^+ & \quad 33.25 \cdot 10^6 \\
D_s^+ & \quad 3.59 \cdot 10^6 \\
\Lambda_c^+ & \quad 637 \cdot 10^3
\end{align*}
\]

The fraction of c-hadrons originating from b decays is estimated between 1.3%($D^0$) and 4.5%($\Lambda_c^+$).

\[\int \mathcal{L} = 355 \text{ pb}^{-1} \text{ at } 7 \text{ TeV}\]
D^0\bar{C} AND D^0C CANDIDATES
Double Charm Production

$D^0\bar{C}$ and $D^0C$ Candidates
RESULTS

Compared to LO predictions from $gg \rightarrow c\bar{c}c\bar{c}$.

Ratios – Results

Double Parton Scattering

\[
\sigma_{\text{DPS}}(C_1 C_2) = \begin{cases} 
\frac{1}{2} \frac{\sigma(C_1) \times \sigma(C_1)}{\sigma_{\text{eff}}} 
, & \text{for } C_1 = C_2 \\
\frac{\sigma(C_1) \times \sigma(C_2)}{\sigma_{\text{DPS}}^{\text{eff}}} 
, & \text{for } C_1 \neq C_2.
\end{cases}
\]

\[
\sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb (Tevatron)}
\]


Agreement only in J/ψ case.

(J. High Energy Phys. 06 (2012) 141)
Selection: Two Muons and nothing else! Protons disappear undetected down the beam pipe. $\int \mathcal{L} = 1 \text{ fb}^{-1}$ at 7 TeV.

LHCB-PAPER-2012-044 (Accepted for publication in J. Phys. G)
Motivation

- $\gamma\gamma$ initial state is forbidden by parity conservation.
- So this result is complementary to the CEP $\chi_{c,0,1,2}$ published in LHCb-CONF-2011-022.

Backgrounds

- Feed down from $\chi_c$ estimated with SUPERCHIC.
- Non exclusive $J/\psi$ production.
- Non resonant $\gamma\gamma \rightarrow \mu^+\mu^-$ QED process.
Background Estimation

- Signal shape from **SUPERCHIC**.
- Background shape extrapolated from data.
- Normalisation fixed using a fit to the $p_T$ distribution.
- Signal region with $p_T < 900$ MeV

More details in backup.
Feed-down from $\chi_c$ and $\psi(2S)$

Processes producing peaking background:

- $\chi_c \rightarrow J/\psi \gamma$
- $\psi(2S) \rightarrow J/\psi \gamma$

with the $\gamma$ not reconstructed.
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- $\chi_c \rightarrow J/\psi \gamma$
- $\Psi(2S) \rightarrow J/\psi \gamma$

with the $\gamma$ not reconstructed.

- The fraction of events where the other decay product was not reconstructed was estimated from simulations.
- The normalisation was fixed w.r.t the measured rates of these particles.
- The fraction of $J/\psi$ events from $\chi_c$ is $9.0 \pm 0.8\%$ and $1.8 \pm 0.3$ from $\Psi(2S)$. 

Feed-down from $\chi_c$ and $\Psi(2S)$
LHCb measured the cross section of the exclusive production of $J/\psi$ and $\Psi(2S)$ to

\[ \sigma_{pp \rightarrow J/\psi (\rightarrow \mu^+ \mu^-)} = 307 \pm 21 \pm 36 \text{ pb} \]
\[ \sigma_{pp \rightarrow \Psi(2S) (\rightarrow \mu^+ \mu^-)} = 7.8 \pm 1.3 \pm 1.0 \text{ pb} \]
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\end{align*}
\]

Predictions

- Gonçalves and Machado
- STARLIGHT
- Motyka and Watt
- SUPERChIC
- Schäfer and Szczurek
What can we do with Ions?

First look at the pilot run from Autumn 2012.

LHCB-CONF-2012-034
Particle Production in LHCb Measurements Perspectives from the Ion Pilot Run

Strangeness Production

LHCb Preliminary

\[ p_A \text{ collisions - all} \]
\[ \sqrt{s_{\text{NN}}}=5.02 \text{ TeV} \]
\[ 2.5<y_{\text{cm}}<4.5 \]
\[ p_T>0.2 \text{ GeV/c} \]

signal: 138719 ± 677 entries
1780370 primary vertices

LHCb Preliminary

\[ p p \text{ collisions} \]
\[ \sqrt{s_{pp}}=8 \text{ TeV} \]
\[ 2.5<y_{\text{cm}}<4.5 \]
\[ p_T>0.2 \text{ GeV/c} \]

signal: 50567 ± 323 entries
1133226 primary vertices

Track resolution is similar in pPb$^{82}$ collisions and pp collisions.
The RICH system can identify charged Kaons in proton - Ion collisions.
The RICH system can identify anti protons in proton - Ion collisions.
LHCb as fixed Target experiment?
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Introducing SMOG
LHCb as fixed Target experiment?
Introducing SMOG
Events are selected from \((\text{proton} - \text{empty}), (\text{empty} - \text{Pb}^{82})\) and \((\text{proton} - \text{Pb}^{82})\) bunch crossings.

Trigger \(p-\text{Ne}\) events and \(\text{Pb}-\text{Ne}\) events using beam gas trigger.

Beam gas events can be statistically subtracted so using SMOG does not interfere with collision data.
Proton Neon Collisions @ $\sqrt{s} = 87$ GeV

$\bar{\Lambda} \rightarrow \bar{p}\pi^+$

$\Lambda \rightarrow p\pi^-$

$K_S^0 \rightarrow \pi^+\pi^-$

$\phi \rightarrow K\bar{K}$

LHCB-CONF-2012-034
Particle Production in LHCb Measurements
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**Integrated Luminosity**

These events were taken from the pilot run with only $569 \text{ mb}^{-1}$ with SMOG and $361 \text{ mb}^{-1}$ without SMOG.
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We have taken much more data recently!

Results are not yet public.
Summary

LHCb measurements are sensitive to many different aspects of forward particle production.

LHCb measured charged– and neutral Forward Energy Flow.

LHCb measures exclusive dimuon states.

LHCb measured significant Double Charm production in the forward region in 17 modes.

There are many other measurements available.

Perspectives

The ion data shown here correspond only to the proton Ion pilot run in autumn 2012.

The ion run that has finished on February 10th includes more luminosity and more beam configurations.
Backup

Measurements
Forward Energy Flow
Double Charm Production
Central Exclusive Production
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Summary
Selection

Requirements on basic particles:
- $\mu^\pm \ p_T > 650$ MeV
- $h^\pm \ p_T > 250$ GeV $\land 2 < \eta < 5 \land \chi^2_{\text{Impact Parameter}} > 9$
- $\pi^\pm, K^\pm \ 3.2 < p < 100$ GeV
- $p, \bar{p} \ 10 < p < 100$ GeV

The particle hypothesis is determined from the RICH detectors.

Requirements on Open Charm and Charmonium candidates:
- $3 < p_T < 12$ GeV (lower cut not on $J/\psi$)
- $2 < y < 4$
- $\chi^2_{\text{Impact Parameter}} < 9$

The sample is further purified with requirements on $\chi^2_{\text{Vertex}}$, $\chi^2_{\text{Impact Parameter}}$, and $\chi^2_{\text{Fit Decay Hypothesis}}$. (back)
Combination

- $c$-hadron candidates are combined in pairs.
- A fit with the hypothesis of two prompt $c$-hadrons from the same primary vertex is performed.
- $\chi^2 / n_{dof} < 5$ is required.
- Purity from fit to $\chi^2$ distribution.
- Efficiencies mostly from data.

$\chi^2_{\text{global}} / \text{ndf}$
Other Properties of the di-charm candidates

Available Measurements

- invariant mass
- $\Delta \phi$
- $\Delta y$
- $p_T$

Correlation was studied.
**Background Estimation**

- Use $p_T$ distribution to discriminate against non exclusive background.
- Fit Novosibirsk function to the $p_T$ distributions.
- Extrapolate linearly to two tracks.
- Restrict signal region to $p_T < 900$ MeV.
**J/γ production as a function of rapidity**

Differential cross section re-calculated in 10 rapidity bins

Results can then be compared to H1/ZEUS data using known photon flux for a photon of energy \( k \)

\[
\frac{d\sigma}{dy_{pp\to pV_p}} = r(y) \left[ k_+ \frac{dn}{dk_+} \sigma_{γp\to VP}(W^+) + k_- \frac{dn}{dk_-} \sigma_{γp\to VP}(W^-) \right]
\]

Absorptive correction

\[
r(y) = 0.85 - \frac{0.1|y|}{3}
\]

Photon Energy spectrum

\[
\frac{dn}{dk} = \frac{\alpha_{em}}{2\pi k} \left[ 1 + \left( 1 - \frac{2k}{\sqrt{s}} \right)^2 \right] \left( \log A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3} \right)
\]

For each point there are two solutions for \( W \), the photon-proton c.m. energy

→ use power law behaviour for photoproduction \( s(W) = aW^d \)

Fit to the differential data gives

\[
a = 0.8^{+1.2}_{-0.5} \text{ nb}
\]

\[
\delta = 0.92 \pm 0.15
\]

→ Consistent with HERA data