Soft and diffractive physics at LHCb

Dermot Moran (University of Manchester)
On behalf of the LHCb collaboration
Overview

• The LHCb detector
• Energy Flow (EF) definition and physics motivation
• Measurements of charged and total EF
• Central Exclusive Production (CEP) physics motivation
• Measurements of CEP in the dimuon channel
• Summary
The LHCb detector

Forward arm spectrometer designed to study b physics

Operates in a low $\mu$ environment (~1.5 in 2010)
Possible to investigate low $p_T$ process at high $\eta$ (study soft QCD)
Typical event at LHCb

<table>
<thead>
<tr>
<th>VELO XZ</th>
<th>VELO XY</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="VELO XZ Image" /></td>
<td><img src="image2" alt="VELO XY Image" /></td>
</tr>
</tbody>
</table>

- Long tracks reconstructed in the forward region
- Resolution of long tracks $\frac{dp}{p} \sim 0.4\%$
- Backward tracks can also be reconstructed in the VELO (used to ID diffractive events)
Energy flow: definition and physics motivation

Average energy created in a particular interval of $\eta$ per inelastic pp collision
(normalised to the $\eta$ bin size)

\[
N_{\text{int}} = \# \text{ Inelastic pp collisions}
\]

\[
N_{\text{part, } \eta} = \# \text{ Stable particles in } \eta \text{ bin}
\]

\[
E_{i, \eta} = \text{ Energy of an individual particle}
\]

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

Forward EF sensitive to the amount of parton radiation and
Multi Parton Interactions (MPI)
MPI is predominant source of UE but not well understood
Measurement may allow discrimination between MPI models
+ determine important parameters for existing models

LHCb analysis uses reconstructed tracks and photons to measure EF
(LHCb-CONF-2012-012)
Energy Flow analysis outline

Charged EF measured with tracks (Primary measurement)
Use momentum of Long tracks with 2<P<1000 GeV/c
Approximation P = E used (PID not required)

Charged EF is corrected to account for detector effects
Ratio of MC predictions at generator and detector level

Neutral EF from Charged EF (data) and Neutral EF/Charged EF Ratio (MC)
Factor introduced to account for data MC mismatch

Total EF (Neutral+Charged) measured with low pile-up MB data at 7 TeV
(~ 6 million events, 5% pile-up)

4 event classes
Inclusive MB: at least 1 long track
Hard scattering: MB with at least 1 long track with P_T>2 GeV/c
Diffractive enriched: MB with no backward tracks
Non-diffractive enriched: MB with at least 1 backward track
Total EF Vs. PYTHIA tunes

Error bars show systematic uncertainty
(Statistical uncertainties are negligible)

Pythia based models underestimate EF at large $\eta$ and overestimate at low $\eta$
EF increases with momentum transfer of underlying pp process
Total EF Vs. PYTHIA tunes

Diffractive EF described best by PYTHIA 8

Non-diffractive and diffractive EF underestimated by PYTHIA models
Total EF Vs. Cosmic-ray models

Inclusive MB EF best described by SYBILL (out of all models)

Hard scattering EF at large $\eta$ best described by QGSJETII-03 (out of all models)
Diffractive EF description from SYBILL is competitive with PYTHIA 8
Non-diffractive EF is best described by SYBILL (out of all models)
Systematic uncertainties

Model dependance of correction factors dominates systematic uncertainty
Smallest uncertainty at high $\eta$ where measurement is most sensitive to MPI
Exclusive dimuon candidate at LHCb

Just 2 long tracks (identified as muons) and no backward tracks
Exclusive dimuon physics motivation

Protons go down beam pipe so signal is 2 muons (+photon) and rapidity gaps

Diphoton dimuon production ideal for luminosity measurement
Exclusive J/Ψ measurement allows search for Odderon
Exclusive Xc allows test of CEP Higgs predictions
Both J/Ψ and Xc measurements allow probe of gluon at low x

(LHCb-CONF-2011-022)
Inelastic background

Gluon emissions and proton dissociation

Additional particles may not be detected in LHCb
Central object generally has a higher Pt than for signal
Events passing low multiplicity dimuon trigger in 2010
(Total Lumi collected in 2010 = 37 pb⁻¹)

Just 2 forward tracks and no backward tracks
Pile-up events rejected
**J/Ψ inelastic background**

Fit exclusive J/Ψ candidate $p_T$ spectrum

Inelastic background taken from data

Signal from Superchic which uses $\exp(-b p_T^2)$ form

Slope $b$ estimated from explicit calculation using HERA data: $6.1 \pm 0.3$ GeV$^{-2}$

Fit gives $b = 5.8 \pm 1$ GeV$^{-2}$

Require DiMuon $p_T < 900$ MeV
Exclusive J/Ψ and Ψ(2S) measurements

Measurements correspond to cross-section times branching ratio where the decay products are in the LHCb acceptance.

\[ \sigma_{J/\Psi \rightarrow \mu^+ \mu^-} = 307 \pm 21 \pm 33 \pm 17 \text{ pb} \]
\[ \sigma_{\Psi(2S) \rightarrow \mu^+ \mu^-} = 7.8 \pm 1.3 \pm 1.0 \pm 0.4 \text{ pb} \]

Statistical + systematic + luminosity uncertainties are given.

Measured cross-sections are consistent with theoretical predictions:
L. Motyka & G. Watt, W. Schäfer & A. Szczurek, SuperChic, Starlight

Ratio of Ψ(2S) to J/Ψ: 0.19 +/- 0.03
Starlight prediction: 0.16
Schafer & Szczurek prediction: 0.2
HERA: 0.166 +/- 0.012
CDF: 0.14 +/- 0.05
J/Ψ production $\sigma$ as a function rapidity

### J/Ψ production cross-section

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>2-2.25</th>
<th>2.25-2.5</th>
<th>2.5-2.75</th>
<th>2.75-3</th>
<th>3-3.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{d\sigma}{dy}$ (J/Ψ)</td>
<td>3.2 ± 0.8 ± 0.9</td>
<td>4.5 ± 0.5 ± 0.8</td>
<td>5.3 ± 0.4 ± 0.9</td>
<td>4.4 ± 0.3 ± 0.7</td>
<td>5.5 ± 0.3 ± 0.8</td>
</tr>
</tbody>
</table>

- **Absorptive correction**
- **Photon Energy spectrum**

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

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

### Assumption

Assume power law behaviour for photoproduction $\sigma(W) = (aW^\delta)$

Fit of $*$ to the differential data gives:

$$a = 0.8^{+1.2}_{-0.5} \text{ nb} \quad \delta = 0.92 \pm 0.15$$

Consistent with HERA data ($a = 3 \text{ nb}$ and $\delta = 0.72$)
J/Ψ photoproduction $\sigma$

Differential cross-sections transformed into photoproduction cross-sections

$$\sigma_{\gamma p \rightarrow V p}(W^{\pm}) = \frac{1/r(y) \frac{d\sigma}{dy_{pp \rightarrow pVp}} - k_{\mp} \frac{dn}{dk_{\mp}} \sigma_{\gamma p \rightarrow V p}(W^{\mp})}{k_{\pm} \frac{dn}{dk_{\pm}}}$$

LHCb Preliminary

- H1
- ZEUS
- Power Law fit to HERA data
- LHCb ($W^+$ solutions)
- LHCb ($W^-$ solutions)
- Power Law fit to LHCb data
Exclusive diphoton dimuons and $X_c$ measurements

**Dimuons with mass > 2.5 GeV**
+ mass cuts to remove $J/\Psi$ and $\Psi(2S)$

**$J/\Psi$ + photon mass**

- $\sigma_{X_{c0}\rightarrow\mu+\mu-\gamma} = 9.3 \pm 2.2 \pm 3.5 \pm 1.8 \text{ pb}$
- $\sigma_{X_{c1}\rightarrow\mu+\mu-\gamma} = 16.4 \pm 5.3 \pm 5.8 \pm 3.2 \text{ pb}$
- $\sigma_{X_{c2}\rightarrow\mu+\mu-\gamma} = 28.0 \pm 5.4 \pm 9.7 \pm 5.4 \text{ pb}$

- $\sigma_{\gamma\gamma\rightarrow\mu+\mu-} = 67 \pm 10 \pm 5 \pm 15 \text{ pb}$
Conclusions

• Forward EF has been measured for inclusive MB, hard scattering, diffractive and non-diffractive enriched events
• PYTHIA based generators underestimate the data at large $\eta$ while most of the cosmic-ray models overestimate it, except for diffractive events
• SYBILL gives best description of the inclusive MB and non-diffractive EF
• Exclusive $J/\Psi$, $\Psi(2S)$, $X_c$ and diphoton produced dimuons have been measured at LHCb
• Cross-sections are consistent with theoretical predictions
• $J/\Psi$ photoproduction cross-section has been determined and is consistent with HERA
BACKUP
Charged EF Vs. PYTHIA tunes
Charged EF Vs. Cosmic-ray models
J/Ψ and Ψ(2S) candidates

Number of forward tracks in events with no backward tracks

Ψ(2S) -> J/Ψ + X estimated from Superchic
J/Ψ and Ψ(2S) candidates

Number of Photons in events with no backward tracks and 2 forward tracks

\[ X_c \rightarrow J/Ψ + \gamma \] estimated from Superchic
Inelastic $J/\Psi$ background
Exclusive J/ψ b estimation

Regge Theory Prediction: \( b \) increases with \( W \)

\[
b = b_0 + 4\alpha' \ln \frac{W}{W_0}
\]

2 \( W \) values for each bin of rapidity

Measured at HERA

Weight \( b \) values (1 for each \( W \)) by photon flux

\[
(W^\pm)^2 = M \sqrt{s} \exp \pm y.
\]

<table>
<thead>
<tr>
<th>( y )</th>
<th>( W_1 )</th>
<th>( W_2 )</th>
<th>( b_1 )</th>
<th>( b_2 )</th>
<th>weight 1</th>
<th>weight 2</th>
<th>( &lt; b &gt; )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.125</td>
<td>426.0</td>
<td>50.9</td>
<td>6.2</td>
<td>4.5</td>
<td>0.70</td>
<td>0.30</td>
<td>5.73</td>
</tr>
<tr>
<td>2.375</td>
<td>482.8</td>
<td>44.9</td>
<td>6.3</td>
<td>4.4</td>
<td>0.72</td>
<td>0.28</td>
<td>5.81</td>
</tr>
<tr>
<td>2.625</td>
<td>547.1</td>
<td>39.6</td>
<td>6.4</td>
<td>4.3</td>
<td>0.74</td>
<td>0.26</td>
<td>5.89</td>
</tr>
<tr>
<td>2.875</td>
<td>619.9</td>
<td>35.0</td>
<td>6.5</td>
<td>4.2</td>
<td>0.75</td>
<td>0.25</td>
<td>5.98</td>
</tr>
<tr>
<td>3.125</td>
<td>702.4</td>
<td>30.9</td>
<td>6.6</td>
<td>4.1</td>
<td>0.77</td>
<td>0.23</td>
<td>6.06</td>
</tr>
<tr>
<td>3.375</td>
<td>796.0</td>
<td>27.2</td>
<td>6.7</td>
<td>4.0</td>
<td>0.78</td>
<td>0.22</td>
<td>6.15</td>
</tr>
<tr>
<td>3.625</td>
<td>901.9</td>
<td>24.0</td>
<td>6.8</td>
<td>3.9</td>
<td>0.79</td>
<td>0.211</td>
<td>6.24</td>
</tr>
<tr>
<td>3.875</td>
<td>1022.0</td>
<td>21.2</td>
<td>6.9</td>
<td>3.8</td>
<td>0.80</td>
<td>0.20</td>
<td>6.34</td>
</tr>
<tr>
<td>4.125</td>
<td>1158.1</td>
<td>18.7</td>
<td>7.0</td>
<td>3.7</td>
<td>0.81</td>
<td>0.19</td>
<td>6.42</td>
</tr>
<tr>
<td>4.375</td>
<td>1312.3</td>
<td>16.5</td>
<td>7.1</td>
<td>3.6</td>
<td>0.82</td>
<td>0.18</td>
<td>6.51</td>
</tr>
</tbody>
</table>

6.1 \( \pm \) 0.3 GeV\(^{-2}\)
Inclusive J/Ψ background

![Graph showing the number of events versus the number of forward tracks with two different conditions: Backward rapidity gap required (red dots) and Backward rapidity gap not required (black dots). The graph is labeled with LHCb Preliminary.]
Preliminary results

Efficiencies determined from Simulation

Effective Luminosity $L_{\text{eff}}$ depends on trigger efficiencies and on the average number of interactions per beam crossing $\mu$

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>3.5 %</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.7 %</td>
</tr>
<tr>
<td>Trigger</td>
<td>4 %</td>
</tr>
<tr>
<td>Tracking $\epsilon$</td>
<td>2 % (1% per $\mu$)</td>
</tr>
<tr>
<td>Identification $\epsilon$</td>
<td>5 % (2.5% per $\mu$)</td>
</tr>
<tr>
<td>Selection $\epsilon$</td>
<td>1%</td>
</tr>
<tr>
<td>Non resonant background ($\psi(2S)$ analysis)</td>
<td>3%</td>
</tr>
<tr>
<td>$\psi(2S)$ background ($J/\psi$ analysis)</td>
<td>0.3%</td>
</tr>
<tr>
<td>$\chi_c$ background ($J/\psi$ analysis)</td>
<td>0.8%</td>
</tr>
<tr>
<td>Precision of dimuon $p_T$ fit</td>
<td>6 %</td>
</tr>
<tr>
<td>Signal shape of dimuon $p_T$ fit</td>
<td>6 %</td>
</tr>
<tr>
<td>Background shape of dimuon $p_T$ fit</td>
<td>6 %</td>
</tr>
</tbody>
</table>