Soft QCD measurements in the forward acceptance at the LHC

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– on behalf of the LHCb collaboration –

Outline

- The LHCb experiment
- Energy flow and multiplicities
- Identified particles
- Drell-Yan production
- Summary and outlook
1. The LHCb Experiment

**RICH1 & RICH2**
\[ \varepsilon(K \to K) \sim 95\% \]
\[ \pi \to K \text{ mis-id: } \sim 5\% \]

**Calorimeters**
\[ \text{ECAL: } \sigma_{E/E} \sim 1\% + 10\%/\sqrt{E[GeV]} \]

**VELO**
\[ \sigma_{IP} \sim 20 \mu m \]

**Tracking System**
\[ \Delta p/p = 0.4\%@5 \text{ GeV/c} \]
\[ \text{to } 0.6\%@100 \text{ GeV/c} \]

**Muon System**
\[ \varepsilon(\mu \to \mu) \sim 97\% \]
\[ \pi \to \mu \text{ mis-id: } 1 \sim 3\% \]
Data taking history

- data taking efficiency 93%
- instantaneous luminosity up to $L = 4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$
  - twice design value at double the nominal bunch spacing
  - luminosity leveling for LHCb by beam steering
- a total of about $2 \times 10^{14}$ pp-collisions scrutinized

<table>
<thead>
<tr>
<th>year</th>
<th>int.luminosity</th>
<th>E[TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>6.8 $\mu$b$^{-1}$</td>
<td>0.9</td>
</tr>
<tr>
<td>2010</td>
<td>0.3 nb$^{-1}$</td>
<td>0.9</td>
</tr>
<tr>
<td>2010</td>
<td>37 pb$^{-1}$</td>
<td>7</td>
</tr>
<tr>
<td>2011</td>
<td>0.1 pb$^{-1}$</td>
<td>2.76</td>
</tr>
<tr>
<td>2011</td>
<td>1 fb$^{-1}$</td>
<td>7</td>
</tr>
<tr>
<td>2012</td>
<td>2 fb$^{-1}$</td>
<td>8</td>
</tr>
<tr>
<td>2013</td>
<td>1.3 nb$^{-1}$</td>
<td>5 (pA)</td>
</tr>
<tr>
<td>2013</td>
<td>0.6 nb$^{-1}$</td>
<td>5 (pA)</td>
</tr>
<tr>
<td>2013</td>
<td>3.3 pb$^{-1}$</td>
<td>2.76</td>
</tr>
</tbody>
</table>
2. **Energy Flow and Multiplicities**

→ **Energy Flow (EF): average energy per event in a given \( \eta \)-interval**

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

→ part of underlying event
→ sensitive to multi-parton interactions & parton radiation
→ comparison to PYTHIA 6, PYTHIA 8 and cosmic ray models (generators used to model cosmic ray induced air showers)

❖ analysis for different event classes:

- inclusive minimum bias: \( \geq 1 \) tracks with \( \eta \in [1.9, 4.9] \) and \( p > 2 \text{ GeV/c} \)
- hard scattering: inclusive &\& \( \geq 1 \) tracks with \( p_T > 3 \text{ GeV/c} \)
- diffractive enriched: inclusive &\& 0 tracks with \( \eta \in [-3.5, -1.5] \)
- non-diffractive enriched: inclusive &\& \( \geq 1 \) tracks with \( \eta \in [-3.5, -1.5] \)
total \( EF = (\text{charged}+\text{neutral})EF \)

- Energy Flow increases with momentum transfer
  \( EF_{\text{diff}} < EF_{\text{incl}} < EF_{\text{ndiff}} < EF_{\text{hard}} \)
- Highest sensitivity at large \( \eta \)
- Uncertainties:
  - Dominated by systematics
  - Smallest at large \( \eta \)

**PYTHIA 6:** Energy Flow is
  - Overestimated at small \( \eta \)
  - Underestimated at large \( \eta \)
  PYTHIA 8.135 default:
  - Except for hard scattering, the Energy Flow is well described for all samples
models not tuned to LHC(b)

- EPOS & SIBYLL: good description of EF for inclusive and non-diffractive events
- QGSJET models: overestimated EF for inclusive and non-diffractive events; good description of hard scattering
- best description by SIBYLL
- all models underestimate the EF of diffractive events
Charged particle multiplicities

- **Multiplicity measurement with momentum information**
  - Kinematics: $p_T > 0.2$ GeV/$c$, $p > 2$ GeV/$c$, $2.0 < \eta < 4.8$
  - Low-pileup ($< 4\%$) minimum-bias pp sample at $\sqrt{s} = 7$ TeV
  - Systematic uncertainties 1-10\% - dominant contribution from dead material

- Charged particle density per event vs $\eta$

  ![Graphs showing charged particle density per event vs $\eta$](image)

  - PYTHIA 6 and PHOJET (not tuned to LHC) underestimate densities
  - Satisfactory description by PYTHIA 8.180 (LHC tune) and HERWIG++
  - Best models underestimate density at low $\eta$ and overestimate at large $\eta$
charged particle density per event vs $p_T$

kinematics: $p > 2 \text{ GeV/c}$, $2.0 < \eta < 4.8$

→ most PYTHIA 6 models and PHOJET too low, but shape OK
→ too soft distribution for PYTHIA 6 LHCb-tune
→ reasonable description by PYTHIA 8.180
→ normalization OK but too soft spectrum for HERWIG++
:: kinematics: $p > 2 \text{GeV/c}, \ p_T > 0.2 \text{GeV/c}, \ 2.0 < \eta < 4.8$

- too few charged particles in PHOJET and PYTHIA 6 tunes
- PYTHIA 8.180 and HERWIG++ (tuned to central LHC data) do best
- none of the models studied is fully able to describe all distributions
3. IDENTIFIED PARTICLES

→ particle production ratios as a function of $y$ and $p_T$

- antiparticle/particle ratios and ratios of different particle species

\[
\frac{\pi^-}{\pi^+}, \frac{K^-}{K^+}, \frac{\bar{p}}{p}, \frac{\bar{\Lambda}}{\Lambda} \quad \text{and} \quad \frac{K^+ + K^-}{\pi^+ + \pi^-}, \frac{p + \bar{p}}{\pi^+ + \pi^-}, \frac{p + \bar{p}}{K^+ + K^-}, \frac{\bar{\Lambda}}{K^0_S}
\]

- many systematic uncertainties cancel
- mainly information about the hadronization process:
  → baryon number transport from $\bar{p}/p$ and $\bar{\Lambda}/\Lambda$
  → baryon suppression from baryon/meson ratios
  → strangeness suppression from kaon/pion ratios

❖ experimental aspects:

➢ results based on $0.3 \text{ nb}^{-1}$ at $\sqrt{s} = 0.9 \text{ TeV}$ and $1.8 \text{ nb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$
➢ PID efficiencies from $K^0_S \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p\pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ and $\phi \rightarrow K^+ K^-$
➢ dominant uncertainties from PID due to limited size of calibration sample
Antiparticle/particle ratios

$\sqrt{s} = 0.9 \text{ TeV}$  $\sqrt{s} = 7 \text{ TeV}$  $\sqrt{s} = 0.9 \text{ TeV}$  $\sqrt{s} = 7 \text{ TeV}$

→ charge ratio drops towards larger rapidities (proton beam)
→ effect more pronounced at higher $p_T$
→ general behavior reproduced by all PYTHIA 6 tunes
\[ \frac{(K^+ + K^-)}{(\pi^+ + \pi^-)} \quad \sqrt{s} = 0.9 \text{ TeV} \]
\[ \frac{(\bar{p} + p)}{(\pi^+ + \pi^-)} \quad \sqrt{s} = 7 \text{ TeV} \]

- strangeness suppression very similar to baryon suppression
- less suppression at larger \( p_T \)
- reasonable description only by LHCb-tune of PYTHIA 6
\( \sqrt{s} = 0.9 \text{ TeV} \) \hspace{1cm} \( \sqrt{s} = 7 \text{ TeV} \)

\( \Lambda/K_S \) significantly reduced baryon suppression at large \( p_T \)

→ all considered PYTHIA 6 tunes fail to describe the strangeness-data
Baryon number transport

\[ \sqrt{s} = 0.9 \, \text{TeV} \]

\[ \sqrt{s} = 7 \, \text{TeV} \]

- all considered PYTHIA 6 tunes fail to describe observed \( y \)-dependence
- behavior as a function of \( \Delta y \) is independent of \( \sqrt{s} \) for \( \bar{\Lambda}/\Lambda \) and \( \bar{p}/p \)

Soft QCD measurements at LHCb - Identified particles
M. Schmelling, QCD14
**$\phi$-meson production**

- **higher sensitivity to direct strangeness production**

- clean experimental signature $\phi \rightarrow K^+ K^-$

- cross-section underestimated by PYTHIA 6 tunes
- shapes in $y$ and $p_T$ not reproduced by the models
- LHCb-tune of PYTHIA 6 describes $K/\pi$ ratio but not $\phi$ cross-section
4. **Drell-Yan Production**

→ *LHCb physics reach*

- **kinematics**
  
  \[ x_1 x_2 = \frac{m^2}{s} \text{ and } \frac{x_1}{x_2} = e^{2y} \]

- small masses test small \( x \)
- forward rapidity means large asymmetries in \( x \) and thus sensitivity to even smaller values

- **LHCb allows to probe PDFs in a completely unexplored regime!**
Drell-Yan results

Drell-Yan di-muon cross-section vs invariant mass (LHCb-CONF-2012-013)

- $q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-$
- $37 \text{ pb}^{-1}$ recorded in 2010
- $5 < M_{\mu\mu} < 120 \text{ GeV}/c^2$
- isolated high-$p_T$ muons

- template-fits to isolation distribution of signal and background
- leading order predictions systematically too low
- NLO predictions in good agreement with the data
5. SUMMARY AND OUTLOOK

→ **LHCb has a wide QCD-related physics program.**

- studies of global event properties
  - energy flow and multiplicities not well described by PYTHA 6 tunes
  - cosmic ray models not tuned to HEP data do surprisingly well
  - better overall description by PYTHIA 8 and Herwig++

- production measurements for identified particles
  - antiparticle/particle ratios generally well described
  - strangeness and baryon suppression too strong in PYTHIA 6 tunes
  - baryon number transport not described by PYTHIA 6 tunes
  - baryon number transport with rapidity difference independent of $\sqrt{s}$

- Drell-Yan production
  - measurements to masses as low as 5 GeV/$c^2$ and $x \sim 10^{-5}$
  - good agreement with NLO predictions

❖ **many results with valuable input for model tuning!**

and more . . .
Selected results on forward production

- **global event properties of pp collisions**
  - EPJC73(2013)2421 Measurement of the forward energy flow at $\sqrt{s} = 7$ TeV
  - EPJC74(2014)2888 Measurement of charged particle multiplicities at $\sqrt{s} = 7$ TeV

- **light quarks and strangeness in pp collisions**
  - PLB693(2010)69 Prompt $K_0^S$ production in pp collisions at $\sqrt{s} = 0.9$ TeV
  - PLB703(2011)267 Measurement of the inclusive $\phi$ cross-section at $\sqrt{s} = 7$ TeV
  - JHEP08(2011)034 Measurement of $V^0$ production ratios at $\sqrt{s} = 0.9$ and 7 TeV
  - EPJC72(2012)2168 Prompt hadron production ratios at $\sqrt{s} = 0.9$ and 7 TeV

- **proton-lead collisions at $\sqrt{s_{NN}} = 5$ TeV**
  - JHEP02(2014)072 Study of $J/\psi$ production and cold nuclear matter effects

- **open charm and charmonium in pp collisions**
  - NPB871(2013)1 Prompt charm production in pp collisions at $\sqrt{s} = 7$ TeV
  - EPJC71(2011)1645 $J/\psi$ production in pp collisions at $\sqrt{s} = 7$ TeV
  - EPJC72(2012)2100 $\psi(2S)$ meson production in pp collisions at $\sqrt{s} = 7$ TeV
  - JHEP02(2013)041 $J/\psi$ production in pp collisions at $\sqrt{s} = 2.76$ TeV
  - JHEP06(2013)064 Production of $J/\psi$ and $\Upsilon$ mesons in at $\sqrt{s} = 8$ TeV
  - JPG40(2013)045001 Exclusive $J/\psi$ and $\psi(2S)$ production at 7 TeV