Soft QCD measurements in the forward acceptance at the LHC

Michael Schmelling – MPI for Nuclear Physics

– on behalf of the LHCb collaboration –

Outline

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

QCD 14

17th HIGH-ENERGY PHYSICS
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IN QUANTUM CHROMODYNAMICS (QCD)

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Pseudorapidity acceptance
 $2 < \eta < 5$

RICH1 & RICH2
 $\epsilon(K \rightarrow K) \sim 95\%$
 $\pi \rightarrow K$ mis-id: $\sim 5\%$

Calorimeters

ECAL: $\sigma_E/E \sim 1\% + 10\%/\sqrt{E[\text{GeV}]}$

VELO
 $\sigma_{IP} \sim 20 \mu\text{m}$
for high- p_T tracks
bwd acc. $-4 < \eta < -1.5$

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

Muon System
 $\epsilon(\mu \rightarrow \mu) \sim 97\%$
 $\pi \rightarrow \mu$ mis-id: $1 \sim 3\%$

Data taking history

LHCb Integrated Luminosity

year	int.luminosity	E[TeV]
2009	$6.8 \mu\text{b}^{-1}$	0.9
2010	0.3 nb^{-1}	0.9
2010	37 pb^{-1}	7
2011	0.1 pb^{-1}	2.76
2011	1 fb^{-1}	7
2012	2 fb^{-1}	8
2013	1.3 nb^{-1}	5 (pA)
2013	0.6 nb^{-1}	5 (Ap)
2013	3.3 pb^{-1}	2.76

- 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 2×10^{14} pp-collisions scrutinized

2. ENERGY FLOW AND MULTIPLICITIES

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

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

- 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:** ≥ 1 tracks with $\eta \in [1.9, 4.9]$ and $p > 2 \text{ GeV}/c$
- **hard scattering:** inclusive & ≥ 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 & ≥ 1 tracks with $\eta \in [-3.5, -1.5]$

Energy Flow: data vs PYTHIA

→ $total\ EF = (charged + neutral) EF$

■ Energy Flow increases with momentum transfer

$$EF_{diff} < EF_{incl} < EF_{ndiff} < EF_{hard}$$

■ highest sensitivity at large η

■ uncertainties:

→ dominated by systematics

→ smallest at large η

PYTHIA 6: Energy Flow is

- overestimated at small η
- underestimated at large η

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

→ multiplicity measurement with momentum information

- kinematics: $p_T > 0.2 \text{ GeV}/c$, $p > 2 \text{ GeV}/c$, $2.0 < \eta < 4.8$
- low-pileup ($< 4\%$) minimum-bias pp sample at $\sqrt{s} = 7 \text{ TeV}$
- systematic uncertainties 1-10% - dominant contribution from dead material

❖ charged particle density per event vs η

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- 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 η and overestimate at large η

❖ 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 PYTHIA6 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

$$\frac{\pi^-}{\pi^+}, \frac{K^-}{K^+}, \frac{\bar{p}}{p}, \frac{\bar{\Lambda}}{\Lambda} \quad \text{and} \quad \frac{K^+ + K^-}{\pi^+ + \pi^-}, \frac{p + \bar{p}}{\pi^+ + \pi^-}, \frac{p + \bar{p}}{K^+ + K^-}, \frac{\bar{\Lambda}}{K_S^0}$$

- 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 nb^{-1} at $\sqrt{s} = 0.9 \text{ TeV}$ and 1.8 nb^{-1} at $\sqrt{s} = 7 \text{ TeV}$
- PID efficiencies from $K_S^0 \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p \pi^-$, $\bar{\Lambda} \rightarrow \bar{p} \pi^+$ and $\phi \rightarrow K^+ K^-$
- dominant uncertainties from PID due to limited size of calibration sample

Antiparticle/particle ratios

$$\pi^-/\pi^+$$

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

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

$$K^-/K^+$$

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

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

- charge ratio drops towards larger rapidities (proton beam)
- effect more pronounced at higher p_T
- general behavior reproduced by all PYTHIA 6 tunes

Strangeness and baryon suppression

$$(K^+ + K^-)/(\pi^+ + \pi^-)$$

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

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

$$(\bar{p} + p)/(\pi^+ + \pi^-)$$

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

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

- ➔ strangeness suppression very similar to baryon suppression
- ➔ less suppression at larger p_T
- ➔ reasonable description only by LHCb-tune of PYTHIA 6

Strange-baryon suppression

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

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

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- significantly reduced baryon suppression at large p_T
- all considered PYTHIA 6 tunes fail to describe the strangeness-data

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

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

JHEP08(2011)034

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

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→ 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/π ratio but not ϕ cross-section

4. DRELL-YAN PRODUCTION

→ *LHCb physics reach*

❖ kinematics

$$x_1 x_2 = \frac{m^2}{s} \quad \text{and} \quad \frac{x_1}{x_2} = e^{2y}$$

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

- $q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+ \mu^-$
- 37 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 PYTHIA 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 $5 \text{ GeV}/c^2$ 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_S^0 production in pp collisions at $\sqrt{s} = 0.9$ TeV
- PLB703(2011)267 Measurement of the inclusive ϕ 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/ψ 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/ψ 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/ψ production in pp collisions at $\sqrt{s} = 2.76$ TeV
- JHEP06(2013)064 Production of J/ψ and Υ mesons in at $\sqrt{s} = 8$ TeV
- JPG40(2013)045001 Exclusive J/ψ and $\psi(2S)$ production at 7 TeV