LHCb: Diffractive studies through energy flow and other soft QCD measurements

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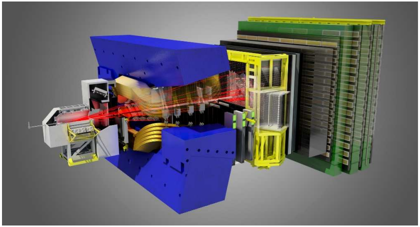
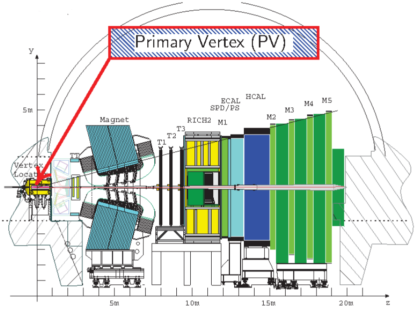
CERN Workshop: Results and prospects of forward physics at the LHC: Implications for the study of diffraction, cosmic ray interactions, and more

February 11th, 2013

LHCb Detector

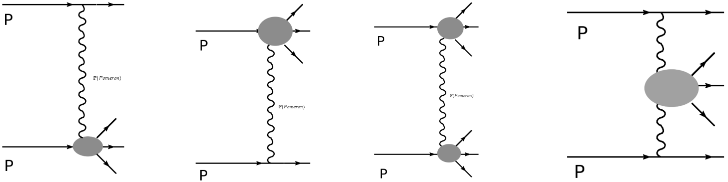




1. Single arm spectrometer.
2. Stations:
   - VErtex LOcator (VELO);
   - 4 tracker stations;
   - 4 Tm integrated field;
   - Calorimeters;
   - RICH detectors;
   - Muon system.
3. Precise measurements:
   - Impact parameter resolution $\approx 20\ \mu$m for high-p_T.
4. Exact Particle IDentification (PID) and tracking in a unique pseudorapidity range.

JINST 3 (2008) S08005

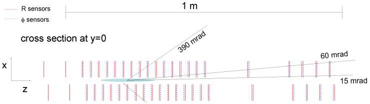
Diffractive Events, Rapidity Gap, Central Exclusive



D1 Single Dissociation 1 D2 Single Dissociation 2 D3 Double Dissociation D4 Central Exclusive Production (CEP)

For D4 See tomorrow's LHCb talk on "LHCb: Central Exclusive Production, results and prospects"

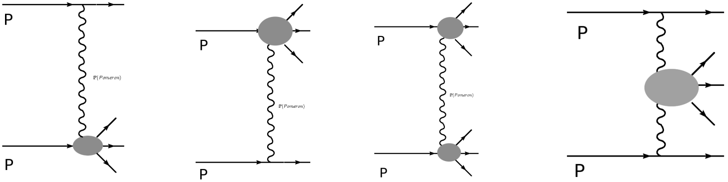
- Single Dissociation (SD) and Double Dissociation (DD) diffractive events considered in energy flow analysis, CEP as higher order effect is not.
- Diffraction in studied in context of softQCD at LHCb, with very small X_{Bj} and low Q^2.
- Given the colorless nature of the Pomeron exchange, the final state topology of a typical diffractive event displays: a Large Rapidity Gap as signature.



⋆ Collision vertex deep inside VELO;

⋆ VELO track sample split in backward - $\eta \in [-3.5, -1.5]$ - and forward tracks - $\eta \in [1.9, 4.9]$.

Diffractive Events, Rapidity Gap, Central Exclusive



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Backward VELO acceptance usefulness in context Large Rapidity Gap: Events without particle in pseudorapidity range of $[-3.5, -1.5]$ are predominantly diffractive $\approx 95\%$;

Energy Flow: Event Classes, MC Generators, Data Analysis

arXiv 1212.4755

- Energy flow is measured within the forward η-acceptance $[1.9, 4.9]$ where momentum is precisely determined.

Reconstructed Event Classes

- Minimum Bias inclusive (MB) - 1 or more tracks in $[1.9, 4.9]$ and $p > 2$ GeV/c.
- Hard scattering - 1 or more tracks with $\eta \in [1.9, 4.9]$ and $p_T > 3$ GeV/c.
- Diffractive enriched - same as MB but no track with $\eta \in [-3.5, -1.5]$.
- non-Diffractive enriched - same as MB but with one or more backward tracks $\eta \in [-3.5, -1.5]$.
- Typically, diffractive enriched and non-diffractive MC samples have a purity of: $\approx$ 70 % and $\approx$90 %, respectively.
  $\star$ Mostly due to unreconstructed particles in the backward acceptance.

Energy Flow: Event Classes, MC Generators, Data Analysis

MC Generators and Samples

- PYTHIA 6 T.Sjöstrand, S. Mrenna, P. Skands, J. High Energ. Phys. 05, 026 (2006).
- PYTHIA8 T.Sjöstrand, S. Mrenna, P. Skands, Comput. Phys. Commun. 178 850 (2008).
- LHCb MC tuning of PYTHIA 6.4, I. Belyaev et al. IEEE Nucl. Sci. Symp. Conf. Rec. (2010), 1155. .
- Perugia0 and Perugia NOCR of PYTHIA 6, P. Z. Skands, Phys. Rev. D 82 (Oct, 2010) 074018
- Cosmic-Ray hadronic interaction models:
  - EPOS: T. Pierog and K. Werner, Nucl. Phys. Proc. Suppl. 196 (2009) 102; - QGSJET: S. Ostapchenko, Status of QGSJET, AIP Conf. Proc. 928 (2007) 118; - SYBILL: E.-J. Ahn et al., Phys. Rev. D80 (2009) 094003

1. Fully simulated and reconstructed MC samples:
   - PYTHIA6 LHCb, Perugia0, and Perugia NOCR - the Perugias have diffractive events suppressed at generator level - were selected to describe 3 events classes.
   - PYTHIA6 LHCb and PYTHIA8.130 - the latter with diffractive events only - to describe the diffractive enriched class.
2. Generator level only : PYTHIA8.135 and cosmic-ray generators.

Energy Flow: Event Classes, MC Generators, Data Analysis

1. Data sample used is Minimum Bias:
   $0.1\ \mathrm{nb}^{-1}$ 2010 run at 7 TeV - very low pile up $\approx 5\ \%$.
2. Charged component is directly measured and unfolded from reconstruction to generator level (see averages in next item).
3. Neutral component is obtained from simulation and scaled with data:
   - Averaged results from PYTHIA6 LHCb and Perugia0/NOCR used for MB, hard scattering, and non-diffractive classes;
   - For diffractive enriched sample: PYTHIA6 LHCb tune and PYTHIA8 results are averaged.
   - Subsequently, upper results are corrected with calorimeter measurements and constrained by the charged component estimates.

- Differential energy flow measured in LHCb:

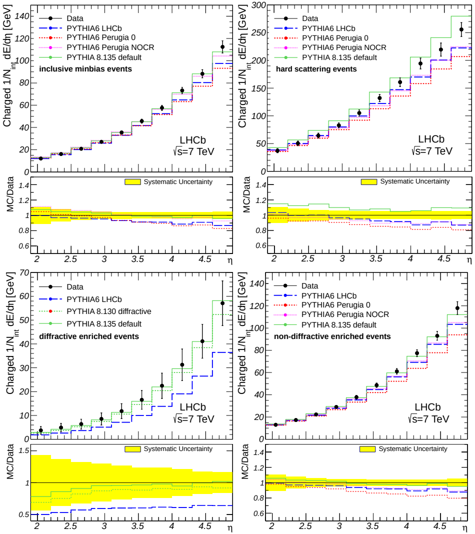
$$\frac{1}{N_{int}} \frac{dE_{total}}{d\eta} \Leftrightarrow \frac{1}{\Delta\eta} \left(\sum_{i=1}^{N_{part,\eta}} E_{i,\eta} \right), \quad \Delta\eta = 0.3 \text{ and } \eta \in [1.9, 4.9]$$

Energy Flow: Results

arXiv 1212.4755, submitted to EPJ C

Charged Component of Energy Flow

- Charged component for all 4 event classes;
- LHCb data extrapolated to generator level vs PYTHIA tunes results ;
- Error estimate for data are mostly systematic, with statistic errors much smaller;
  ⋆ A dominating effect is the model dependence, especially for diffractive sample;
- PYTHIA8 agrees with diffractive events;
- PYTHIA8 overestimates the hard scattering;
- PYTHIA6 tunes underestimate the energy flow for high η in all samples;

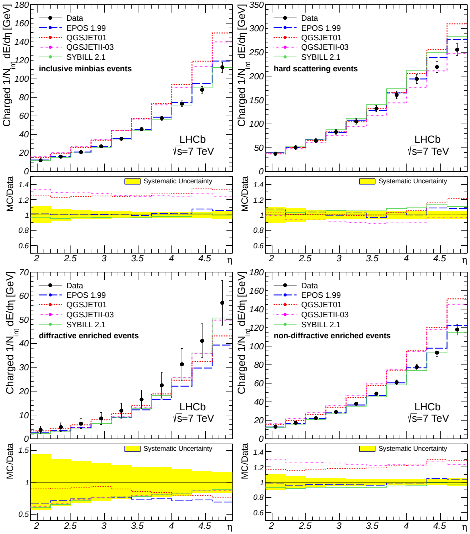


Energy Flow: Results

arXiv 1212.4755

Charged Component of Energy Flow

- Cosmic-Ray models results superimposed on same data;
- QGSJET models overestimate the soft-p_T component in MB inclusive and non-diffractive;
- All models tend to underestimate the diffractive component;
- SYBILL reproduces the best all 4 cases, though overall there is a visible disagreement with diffraction result.



Energy Flow: Results

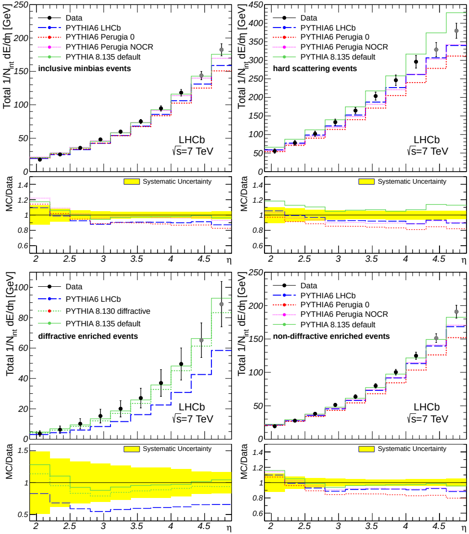
arXiv 1212.4755

Total Energy Flow

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

Conclusions regarding PYTHIA tunes

- Among those tried, there was no PYTHIA tune which describes all 4 components;
- PYTHIA8 give best agreement in general;
- Extra tuning needed, and higher order corrections as CEP contributions might account for the seen differences.



Energy Flow: Results

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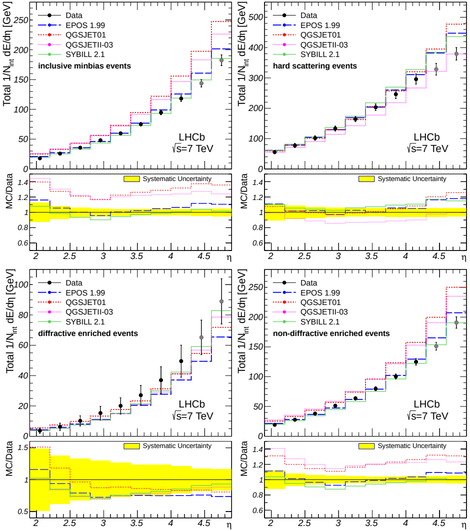
Total Energy Flow

- Total energy flow for all 4 event classes;
- 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-η bins for the hard component.

Conclusions for Cosmic-Ray Generators

- EPOS and especially SYBILL agree in general with LHCb data;
- Yet, not all cases agree with SYBILL over all LHCb η range [1.9, 4.9].
- As for PYTHIA, the Cosmic-ray models might have to consider higher order effects to be fully in agreement with LHCb data for softQCD region - low-X_{Bj} and low-Q^2.



SoftQCD: Prompt Hadron Production Ratios

Eur. Phys. J. C 72 (2012) 2168

- LHCb has measured 6 ratios of distinct prompt hadrons:

$$\frac{\bar{p}}{p}, \frac{\pi^-}{\pi^+}, \frac{K^-}{K^+}, \frac{p+\bar{p}}{\pi^+ + \pi^-}, \frac{K^+ + K^-}{\pi^+ + \pi^-}, \frac{p+\bar{p}}{K^+ + K^-}$$

- $\frac{\bar{p}}{p}$ is essential in describing the Baryon Number Transport (BNT),
  - ⋆ Probe of hadronization in the forward region.
  - ⋆ Essential in tuning MC Generators.
- Data used have: $0.3\mathrm{nb}^{-1}$ at $\sqrt{s} = 900$ GeV and $1.8\mathrm{nb}^{-1}$ at 7 TeV.
- In LHCb, two RICH detectors allow separation of p/K/π extracting the PID.
- Main error on ratios is systematic and dominated by PID uncertainties.
  - due to size limitation on calibration samples in softQCD data

SoftQCD: Prompt hadron production ratios

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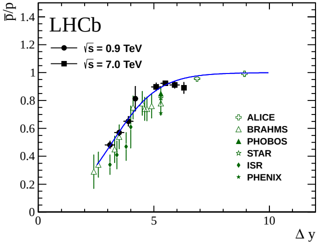
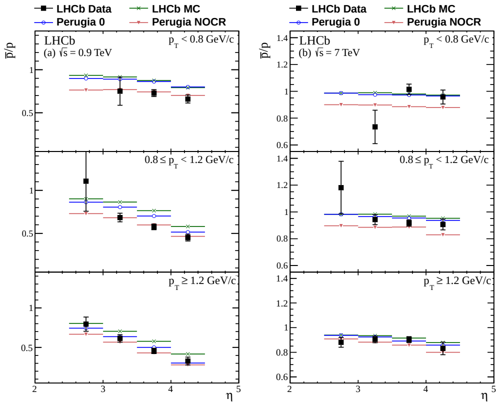
rapidity loss $\Delta y = y_{beam} - y_{particle}$
$y_{beam} = 8.9(6.9)$ at 7 (0.9) TeV.

LHCb data allow for a much better fit precision and are complementary to ALICE data.

First time measurement in this Δy range.



⋆ BNT at 0.9 and 7 TeV for 3 p_T ranges;
⋆ LHCb results are more in agreement with PYTHIA6 Perugia NOCR tune than PYTHIA6 LHCb and Perugia 0 tunes.



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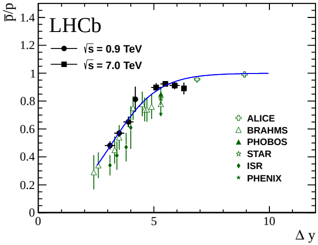
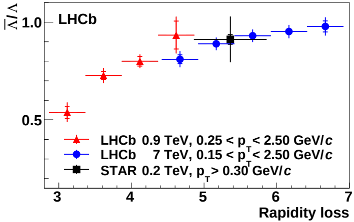


J. High Energy Phys. 08 (2011) 034

An older measurement of the baryon ratio $\frac{\bar{\Lambda}}{\Lambda}$ has similar dependence on rapidity loss variable like $\frac{\bar{p}}{p}$:

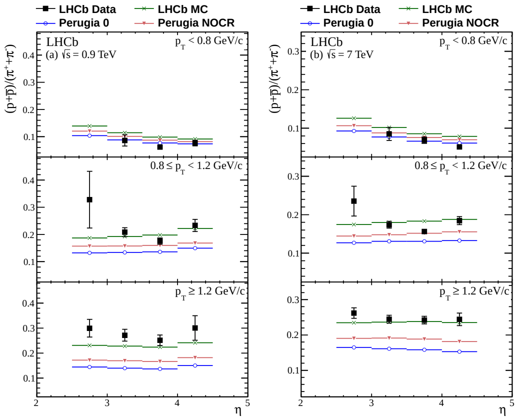
⋆ Qualitatively no difference, the two ratios close.

The two ratios are independent probes of the same baryon number transport process.



SoftQCD: Prompt Hadron Production Ratios

Baryon to Meson Ratio and Light Baryon Suppression at 0.9 and 7 TeV



Eur. Phys. J. C 72 (2012) 2168

$\frac{p+\bar{p}}{\pi^{+}+\pi^{-}}$ ratio at 0.9/7 TeV, 3 p_T ranges;

⋆ Baryon to meson ratio probes fragmentation.

⋆ LHCb MC more in agreement with data, and PYTHIA6 Perugia tunes have much lower estimates;

⋆ MC generators tend to overestimate baryon suppression.

⋆ Smaller baryons suppression than anticipated especially in hard-scattering - high p_T-biased sample;

⋆ $\frac{\bar{\Lambda}}{K_S}$ give the same qualitative image.

SoftQCD: Prompt Hadron Production Ratios

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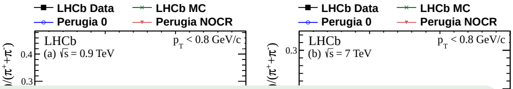

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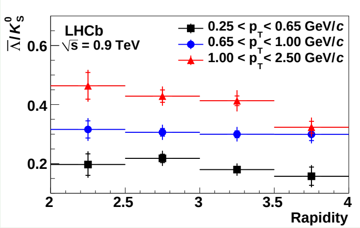

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SoftQCD: Charged Particle Multiplicities

Eur. Phys. J. C 72 (2012) 1947

- LHCb data on charge track multiplicities.
  ⋆ LHCb Minimum Bias data at 7 TeV low pile-up,
- VELO fiducial region with high track reconstruction efficiency spanned by η:
  $\eta \in [-2.5, -2]$ and $\eta \in [2, 4.5]$
- Two samples were selected:
  - a MinBias inclusive sample and its hard-p_T subsample.
  ⋆$p_T > 1$ GeV/c for at least 1 particle in the forward region.

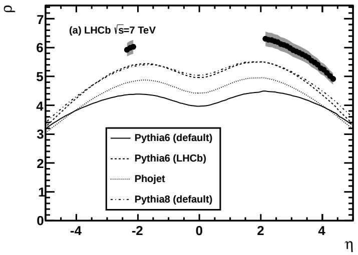
- Error on data dominated by systematic effects;
  ⋆ track efficiency uncertainty in VELO.
- ρ represents the charged particle density over η bin.

Inclusive sample is poorly described by PYTHIA6 and PYTHIA8 tunes, and Phojet;

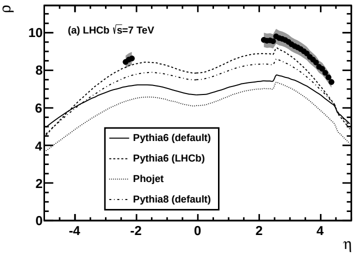
Hard scattering sample is better described, nevertheless generator results fail to reproduce the exact shape of PDF.

Models underestimate charged particle production.

Inclusive MinBias sample



Hard-p_T sample



Summary and Conclusions

1. The large LHC collision energy allows mapping in a previously out of the reach phase space region with very low-X_{Bj} and low-Q^2.
2. We were able to capitalize on the very high precision measurements and on the unique pseudorapidity range of LHCb to study in detail the softQCD processes.
   - Diffractive, hard scattering, and non-diffractive events were separated and the energy flow observable was measured.
   - Various prompt hadron ratios were measured, too.
   - Highlighted $\frac{\bar{p}}{p}$ - baryon number transport was obtained for the first time in the rapidity loss range of $[3.1, 6.3]$.
   - Prompt charge particle multiplicities distribution.
3. The generator results found to:
   ⋆ Underestimate the energy flow at high η.
   ⋆ Overestimate the baryon suppression, especially in the hard p_T ranges.
   ⋆ Underestimate particle multiplicities.
4. SoftQCD analyses at $\sqrt{s}$ =7 (0.9) TeV are expected to be supplemented soon by others at 8 TeV and 2.76 TeV, and a pA sample is prepared for analysis, too.

Backup Slides

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

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

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

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

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

Extra correction:

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

where

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

and

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

- $EF_{calorimeter,data}$ - 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.