LHCb soft-QCD measurements in the Forward Region

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LHCb workshop on quantum interference effects, QCD measurements and generator tuning

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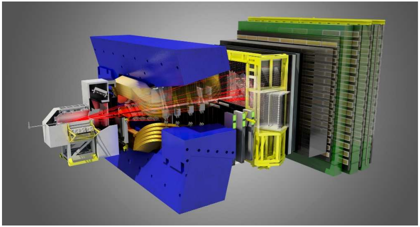
Outline

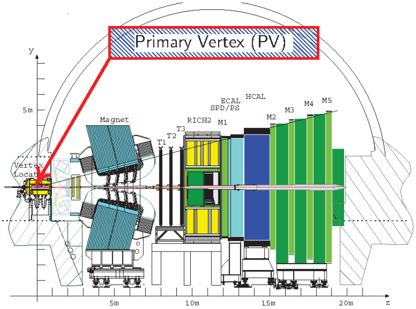
1. LHCb Detector

2. Soft-QCD measurement - the Energy Flow
   - Energy Flow Study: Data and Definitions
   - Energy Flow Study: Diffractive Events, Rapidity Gaps
   - Event Classes, MC Generators, Data Analysis
   - Results of Energy Flow Measurements - Eur. Phys. J. C 73 (2013) 2421
   - Charged Particle Multiplicities - Eur. Phys. J. C 72 (2012) 1947 and EPJ C

3. Summary and Conclusions

LHCb Detector





1. Single arm spectrometer, $\eta \in [2, 5]$.
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. Excellent Particle IDentification (PID) and tracking in a unique pseudorapidity range.

JINST 3 (2008) S08005

Energy Flow: Data and Definitions

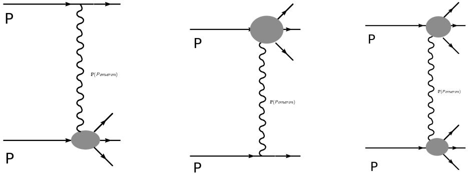
1. Data sample used is Minimum Bias:
   $0.1\ \mathrm{nb}^{-1}$ 2010 run at 7 TeV - very low pile up $\approx 5\ \%$.
2. Charged component is directly measured and unfolded from reconstruction to generator level.
   - Measured long lived charged particles.
   - Results from multiple generators and tunes used to extrapolate towards primary collision.
3. Differential energy flow measured in LHCb:

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

4. Adding the energy flow from the measured neutral long lived particles, does not change qualitatively the final results.
5. Underlying event essential in the forward energy flow studies.

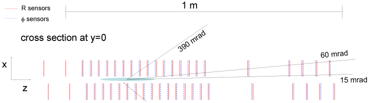
Energy Flow Study: Diffractive Events, Rapidity Gap

Eur. Phys. J. C 73 (2013) 2421



D1 Single Dissociation 1 D2 Single Dissociation 2 D3 Double Dissociation

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



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

Energy Flow Study: Diffractive Events, Rapidity Gap

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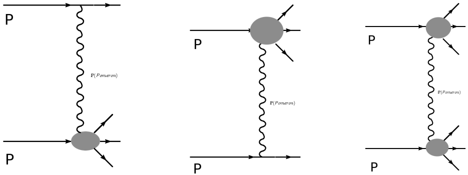

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Backward VELO acceptance usefulness in context Large Rapidity Gap: Events without particle in pseudorapidity range of $[-3.5, -1.5]$ are predominantly diffractive $\approx 95\%$;

Energy Flow: Event Classes, MC Generators, Data Analysis

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.
  - ⋆ 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: Results

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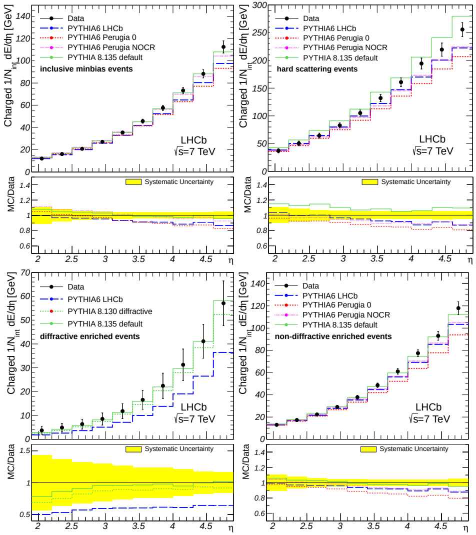
Charged Component of Energy Flow (EF)

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

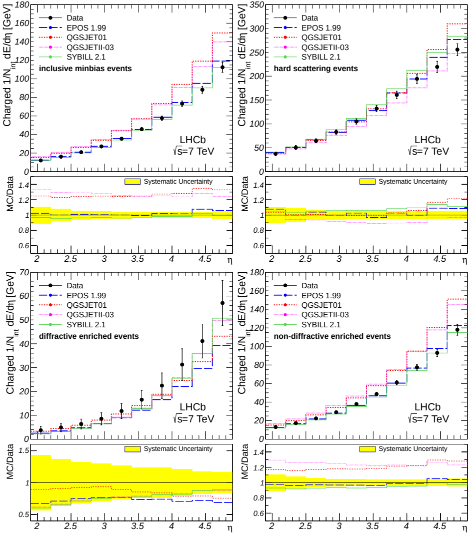


Energy Flow: Results

Eur. Phys. J. C 73 (2013) 2421

Charged Component of EF

- Cosmic-Ray models results superimposed on same data;
- QGSJET models severely overestimates 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.



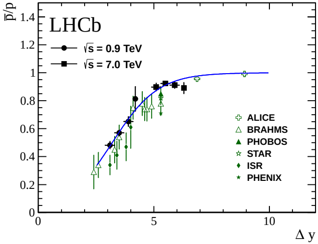
SoftQCD: Prompt hadron production ratios

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

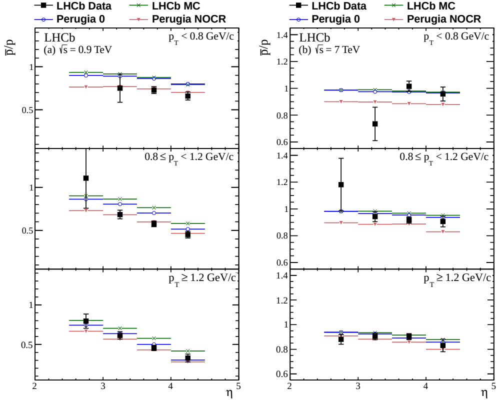
rapidity loss $\Delta y = y_{beam} - y_{particle}$
$y_{beam} = 8.9(6.9)$ at 7 (0.9) TeV.

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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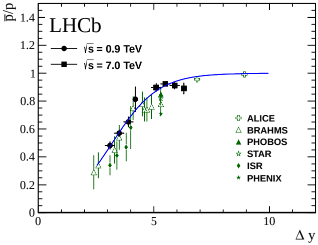
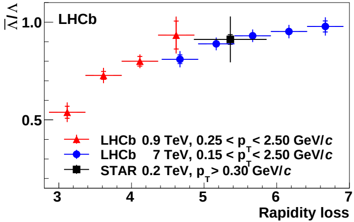


J. High Energy Phys. 08 (2011) 034

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

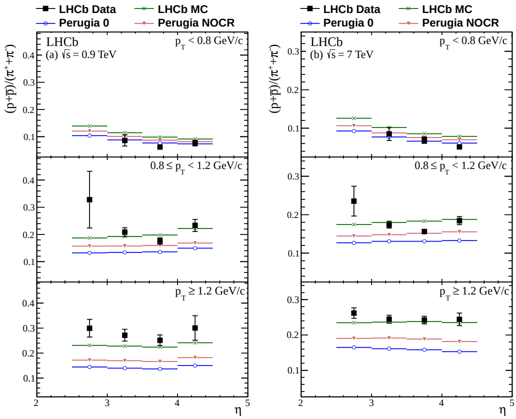
⋆ Qualitatively no difference, the two ratios close.

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;

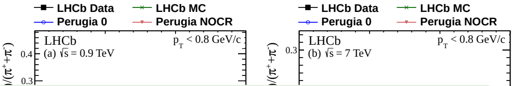
⋆ MC generators tend to overestimate baryon suppression.

⋆ 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

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



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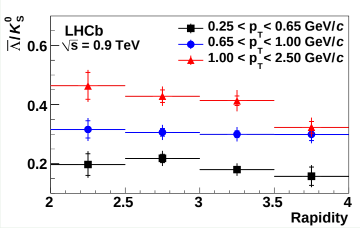

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SoftQCD: Charged Particle Multiplicities

Eur. Phys. J. C 72 (2012) 1947, EPJ C74 (2014) 2888

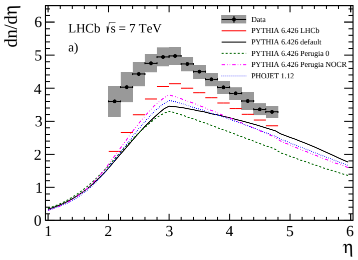
- LHCb data on charge track multiplicities.
  - ⋆ LHCb Minimum Bias data at 7 TeV low pile-up,
- VELO fiducial region with high track reconstruction efficiency spanned by η:
  $p_T \in [0.2, 2]$ and $\eta \in [2, 4.5]$

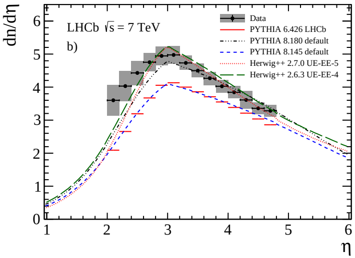
- Error on data dominated by systematic effects;
  - ⋆ track efficiency uncertainty in VELO.
- ρ represents the charged particle density over η bin.

PYTHIA6 and PYTHIA8 tunes, and Phojet;

Old models underestimate charged particle production. Herwic++ and new tunes of Pythia (LHC tunes) reproduce the data.

Inclusive MinBias sample





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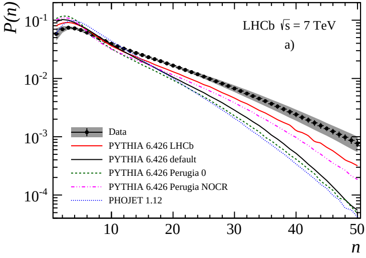

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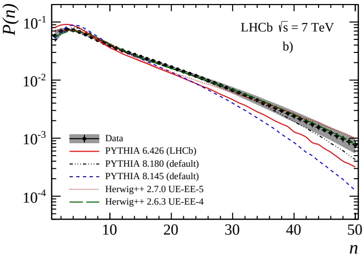
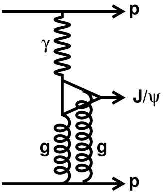
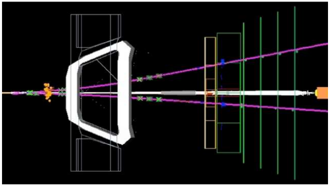
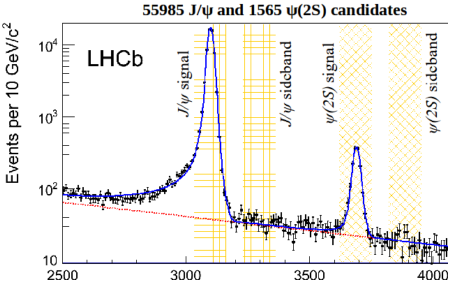


Soft-QCD: Central Exclusive Processes (CEP)

- $J/\psi\,(\psi(2s)) \rightarrow \mu\mu$ JPG 41 (2014) 055002
- pomeron and photon echange.







Summary and Conclusions

1. 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.
2. Besides Energy Flow, light hadron ratios, charged multiplicities, and central exclusive processes, we have also measured V0 ratios at 7 and 0.9 TeV and KS cross-section at 0.9 TeV.
3. All analyses except CEP have RIVET plugin and are to be used in LHCb MC tuning of PYTHIA8.

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.

Energy Flow: Results

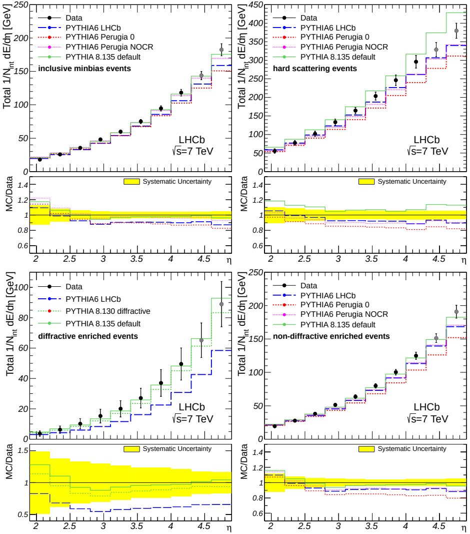
Eur. Phys. J. C 73 (2013) 2421

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.



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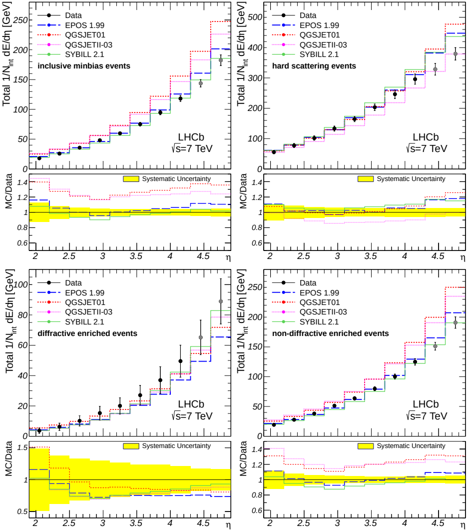
Total Energy Flow

- 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.



Energy Flow: Sources of Systematic Errors

Source of uncertainty	Inclusive minbias	Hard scattering	Diffractive enriched	Non-diffractive enriched
Model uncertainty on correction factors	0.6-9.2	0.7-4.1	16-43	0.7-8.6
Selection cuts	1.0-4.9	2.7-8.8	0.9-2.8	1.1-5.0
Tracking efficiency	3	3	3	3
Multiple tracks	1	1	1	1
Spurious tracks	0.3-1.2	0.4-1.7	0.2-0.7	0.3-1.2
Magnet polarity	-	-	2.6-7.7	-
Residual pile-up	1.7	1.7	1.7	1.7
Total on $F_{char,\eta}$	3.9-11	4.9-10	16-43	4.0-11