Soft QCD Measurements at LHCb

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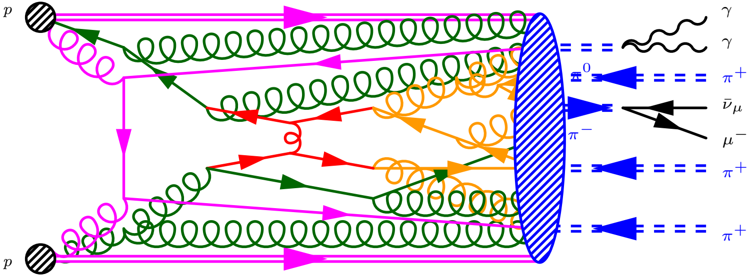
Overview

- test non-perturbative regimes of QCD
- tune multi purpose event generators
- look for new effects to refine models

- hadronization
  - partons to hadrons
  - IR sensitive: charge density and multiplicity
- multi parton interactions
  - underlying event
  - IR safe: energy flow

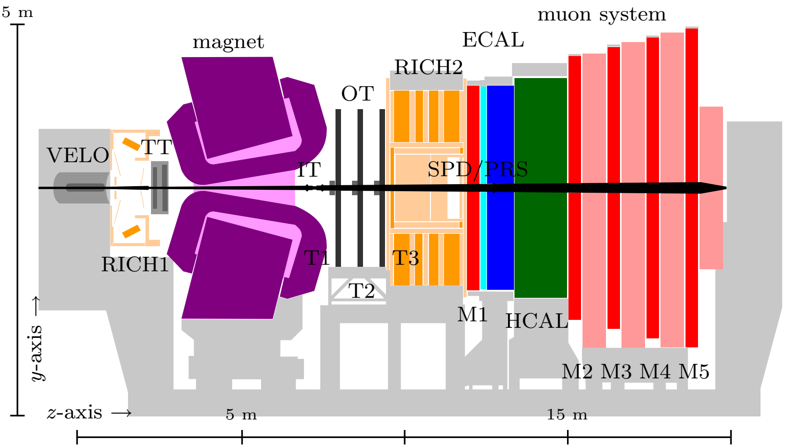


LHCb Measurements

title	Rivet plugin	reference
Measurement of charged particle multiplicities and densities	to be released	Eur. Phys. J. C 74 (2014) 2888
Prompt charm production in pp collisions at $\sqrt{s} = 7$ TeV	LHCB_2013_I1218996	Nucl. Phys. B 871 (2013) 1-20
Measurement of the forward energy flow in pp collisions at $\sqrt{s} = 7$ TeV	LHCB_2013_I1208105	Eur. Phys. J. C 73 (2013) 2421
Measurement of V^0 production ratios in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV	LHCB_2011_I917009	Eur. Phys. J. C 72 (2012) 2168
Measurement of the inclusive ϕ cross-section in pp collisions at $\sqrt{s} = 7$ TeV	LHCB_2011_I919315	Phys. Lett. B 703 (2011) 267-273
Measurement of charged particle multiplicities in pp collisions at $\sqrt{s} = 7$ TeV		Eur. Phys. J. C 72 (2012) 1947
Prompt K_S^0 production in pp collisions at $\sqrt{s} = 0.9$ TeV	LHCB_2010_S8758301	Phys. Lett. B 693 (2010) 69-80

LHCb Detector

[JINST 3 (2008) S08005]

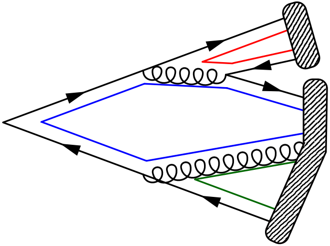


- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of 20 μm for high p_{T} tracks

Charge Multiplicity

Hadronization Models

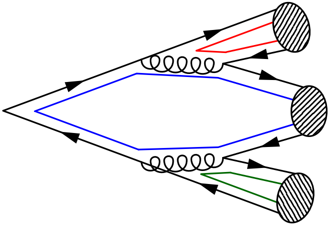
string model (PYTHIA)	cluster model (HERWIG)



- linear confinement

$$V \approx \kappa r - \frac{4\alpha_s}{3r}$$

- split strings into hadrons
- kinematics well modeled
- poor final state flavor description



- pre-confinement
  - clusters independent of hard process scale
  - dependent on QCD and shower scale
- decay clusters into hadrons
- kinematics not as well modeled
- better final state flavor description

Multiplicity Analysis

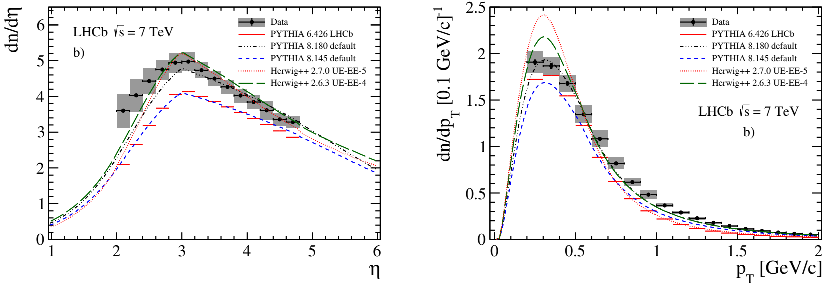
[Eur. Phys. J. C 74 (2014) 2888]

- visible event
  - at least one charged particle
  - $2.0 < \eta < 4.8$
  - $p_{\mathrm{T}} > 0.2$ GeV
  - $p > 2$ GeV
  - $\tau < 10$ ps
- reconstructed event
  - at least one track
  - must traverse all tracking stations
  - pass within 2 mm of beamline
  - originate from luminous region

1. correct for sample impurity
   - $\approx 6.5\%$ fakes, $\approx 1\%$ duplicates, $\approx 4.5\%$ non-prompt
2. account for visible events with no reconstructed tracks
3. unfold distribution for pile-up effects
4. apply reconstruction efficiencies

Density Results

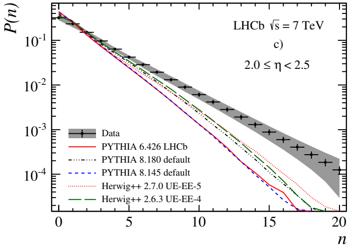
[Eur. Phys. J. C 74 (2014) 2888]

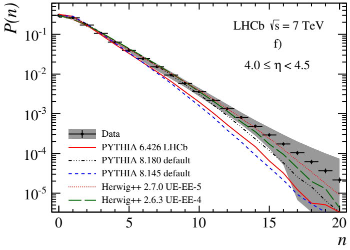


- the p requirement causes the falling distribution at low η
- neither Pythia 6 nor Pythia 8.145 were tuned with LHC data
    - these significantly under-estimate the data
- Pythia 8.180 describes the data well
- Herwig++ does as well, except for $0.2 < p_T < 0.5$

Multiplicity Results

[Eur. Phys. J. C 74 (2014) 2888]





- distributions for $2.0 < \eta < 2.5$ and $4.0 < \eta < 4.5$
  - inclusive, differential p_T, and differential η distributions in appendix
- at low and high η all tunes under-estimate for high multiplicity
  - LHC tunes do slightly better
  - non-LHC tunes typically over-estimate low multiplicity
- inclusively PYTHIA 8.180 describes data well, but under-estimates for high multiplicity
- HERWIG++ 2.6.3 consistently describes inclusive data well
- HERWIG++ 2.7.0 does not model the range $15 < n < 25$ well

Energy Flow

Multi Parton Interaction Models

hard → soft model (HEP)	soft → hard model (air-shower)

hard → soft model (HEP)

- begin with t-channel $2 \to 2$ QCD

$$\mathrm{d}\hat{\sigma}_{2\to 2} \propto \mathrm{d}p_{\mathrm{T}}^2 \frac{\alpha_s^2(p_{\mathrm{T}}^2)}{p_{\mathrm{T}}^4}$$

- divergent in p_{T}, cut-off or damp

$$\frac{\alpha_s^2({p_{\mathrm{T}}}_0^2 + p_{\mathrm{T}}^2)}{\alpha_s^2(p_{\mathrm{T}}^2)} \frac{p_{\mathrm{T}}^4}{({p_{\mathrm{T}}}_0^2 + p_{\mathrm{T}}^2)^2}$$

- models color screening and saturation effects
- number of interactions also depends on impact parameter

$$f(x, b) = f(x)g(b)$$

soft → hard model (air-shower)

- begin with Regge effective field theory

$$\mathrm{d}\sigma \propto \frac{\mathrm{d}M^2}{M^2}$$

- M is mass of the diffractive system
- exchange of color-singlet pomeron between hadrons
  - leading structure is $f\bar{f}$ or gg
  - at high energy primarily gg
- include hard structure by resolving pomeron constituents
- requires some smooth transition between the two regimes

Energy Flow Analysis

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

- measure charged energy flow
  - veto events with more than 1 primary vertex
  - use tracks with VELO and IT or OT hits
  - $2 < p < 1000$ GeV

$$\frac{1}{N}\frac{\mathrm{d}E}{\mathrm{d}\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N}\sum_{i=1}^{n(\Delta\eta)} E_i\right)$$

- $N \equiv$ number of inelastic pp interactions
- $n \equiv$ number of tracks within bin of $\Delta\eta$

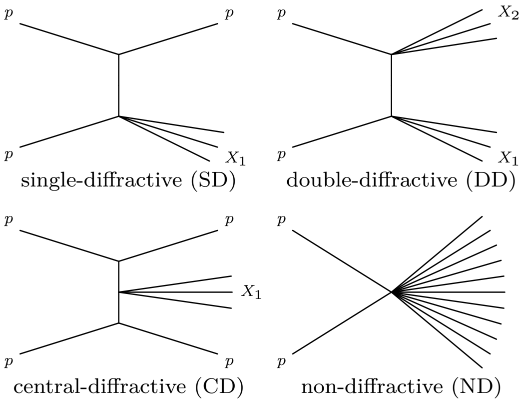
1. unfold detector effects with bin-to-bin corrections
   - estimate systematic uncertainty from model bias using various PYTHIA configurations
2. calculate total energy flow using neutral to charged ratio, R

$$F_{\text{total}} = F_{\text{charged}}(1 + R_{\text{gen}})\left(\frac{1 + R_{\text{data}}}{1 + R_{\text{MC}}}\right)$$

Event Classification

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

$$\sigma_{\text{inelastic}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}$$



hard

- $p_T > 3$ GeV
- $1.9 < \eta < 4.9$

diffractive

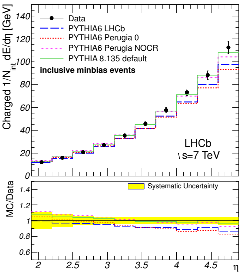
- no track with $-3.5 < \eta < -1.5$
- $\approx 70\%$ purity with Pythia 6

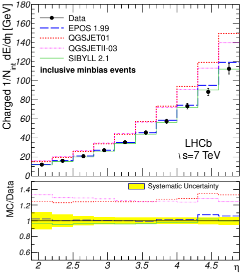
non-diffractive

- track with $-3.5 < \eta < -1.5$
- $\approx 90\%$ purity with Pythia 6

Inclusive Results

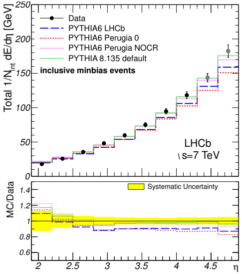
[Eur. Phys. J. C 73 (2013) 2421]

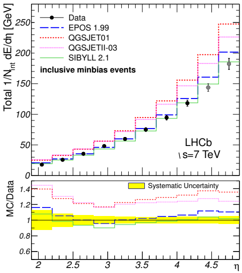




charged

- PYTHIA 8 and 6 with no CR model data well
- PYTHIA 6 under-estimates for large η
- EPOS and SIBYLL model data well
- QGSJET uniformly over-estimates



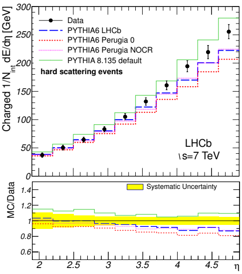


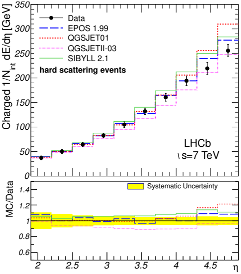
total

- similar behavior to charged energy flow

Hard Scatter Results

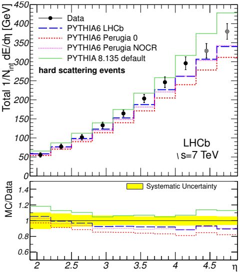
[Eur. Phys. J. C 73 (2013) 2421]

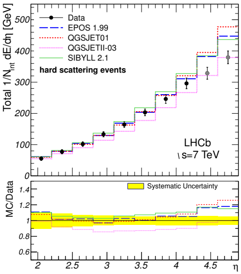




charged

- PYTHIA 8 uniformly over-estimates
- PYTHIA 6 under-estimates for large η
- EPOS, QGSJET01, and SIBYLL over-estimate for large η
- QGSJETII-03 under-estimates at middle η



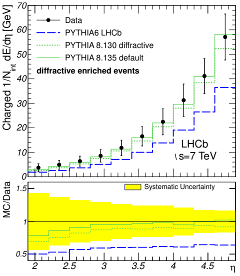


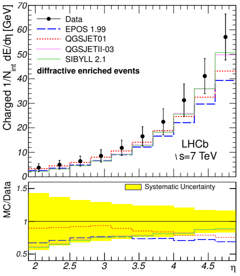
total

- similar behavior to charged energy flow

Diffractive Enriched Results

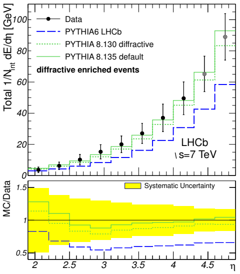
[Eur. Phys. J. C 73 (2013) 2421]

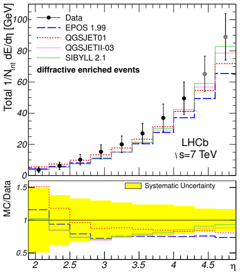




charged

- larger systematic from detector effects and magnet polarity
- PYTHIA 8 models data well
- PYTHIA 6 significantly under-estimates
- remaining generators under-estimate



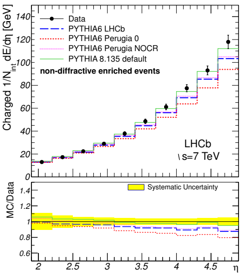


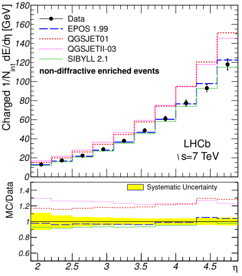
total

- similar behavior to charged energy flow for PYTHIA
- remaining generators more consistent with data
- EPOS and QGSJET01 under-estimate at high η

Non-diffractive Enriched Results

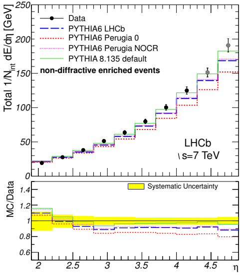
[Eur. Phys. J. C 73 (2013) 2421]

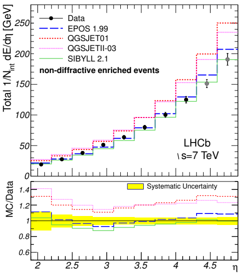




charged

- similar to inclusive results
- Pythia 8 models data well
- EPOS and Sibyll also model data well





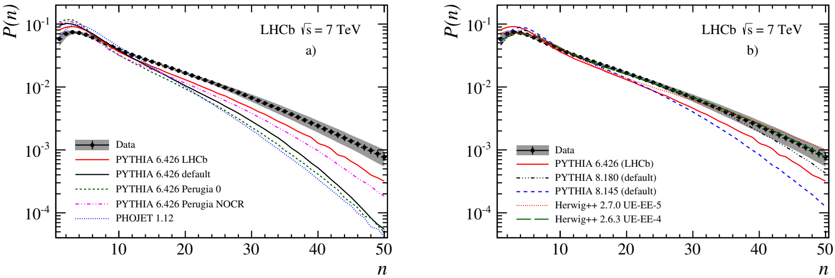
total

- similar behavior to charged energy flow

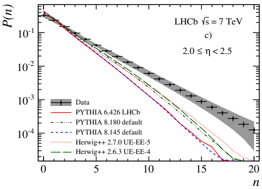
Conclusions

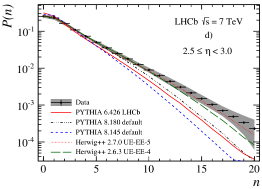
- LHCb provides complementary soft QCD measurements in the high η and low p_{T} regions to the other LHC detectors
- available (soon) as RIVET plugins for additional comparisons
- validates consistency of the MPI and hadronization models at LHC energies for forward production
- no unexpected behavior
  - no clear winners between hadronization and MPI models
- non-LHC tunes underestimate forward particle density
- default tune for Pythia 8.180 performs well
- UE-EE-4 tune for Herwig++ consistently out-performs UE-EE-5 tune for Herwig++
- looking forward to 13 TeV data!

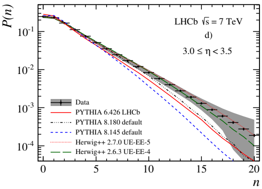
Inclusive Multiplicity Results

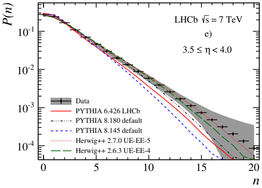


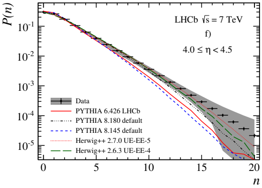
Differential Multiplicity Results (η)











Differential Multiplicity Results (p_T)