Soft QCD Measurements at LHCb

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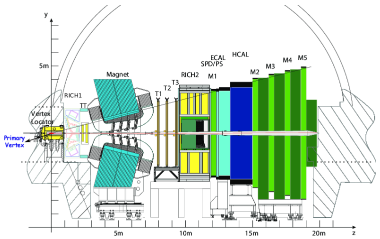
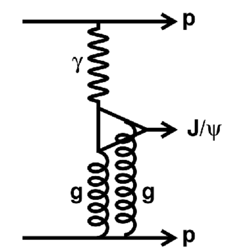
20th International Conference on Particles and Nuclei (PANIC 14)
Hamburg, Germany, 25^{th} – 29^{th} August 2014

Outline

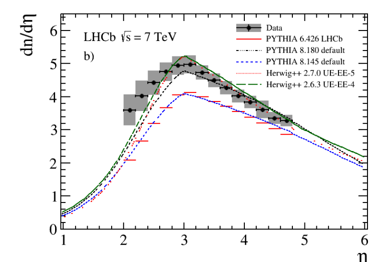
- The LHCb Detector at the LHC



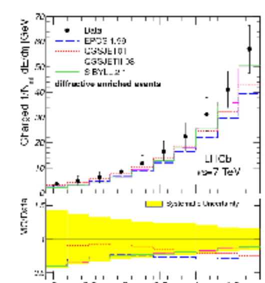
- J/ψ and ψ(2S) Central Exclusive Production (CEP) in Di-muon Channel at LHCb



- Charged Particle Multiplicity and Densities in *pp* Collisions at √s = 7 TeV in the Forward Region



- Forward Energy Flow (EF) in *pp* collisions at √s = 7 TeV



- Conclusions

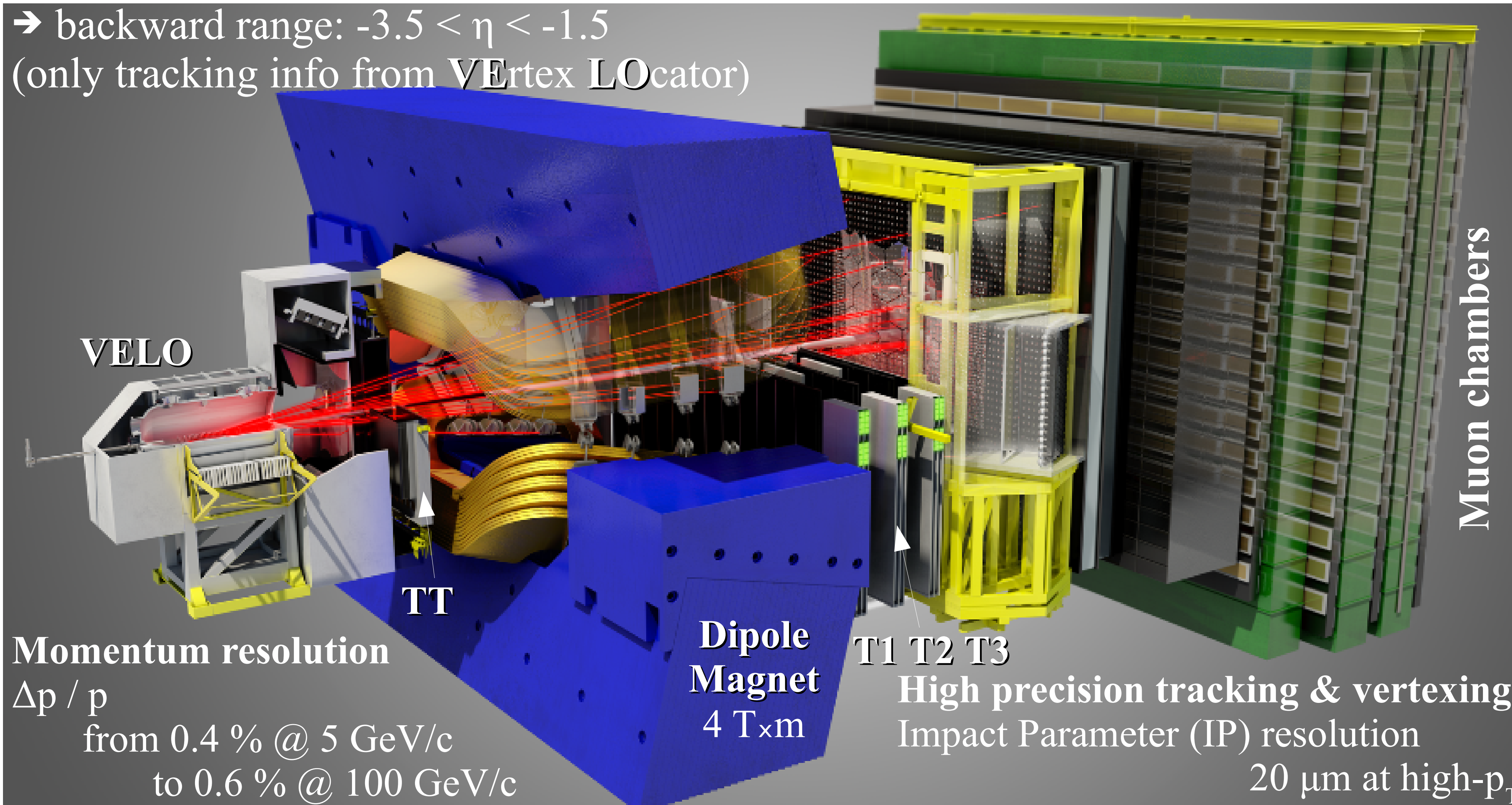
The LHCb detector at the LHC

JINST 3 (2008) S080005

Fully instrumented single-arm spectrometer. Unique pseudorapidity range:

➔ forward range: $1.9\ (2.0) < \eta < 4.9\ (5.0)$

➔ backward range: $-3.5 < \eta < -1.5$
(only tracking info from **VE**rtex **LO**cator)



Momentum resolution
$\Delta p / p$
from 0.4 % @ 5 GeV/c
to 0.6 % @ 100 GeV/c

High precision tracking & vertexing
Impact Parameter (IP) resolution
20 μm at high-p_T

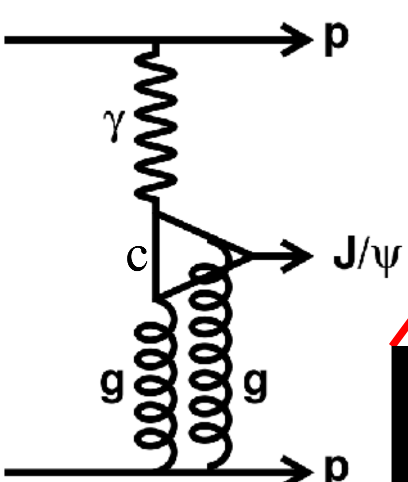
JPG 41 (2014) 055002

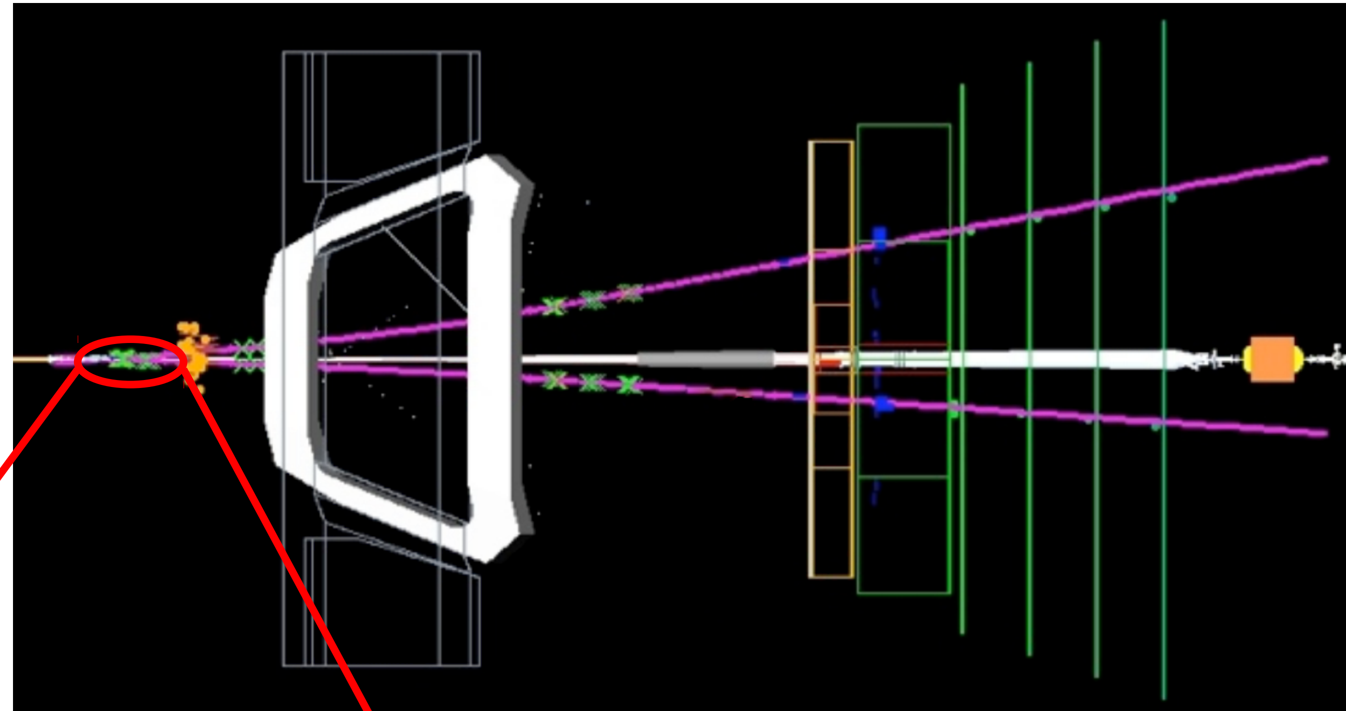
Central Exclusive Production at LHCb

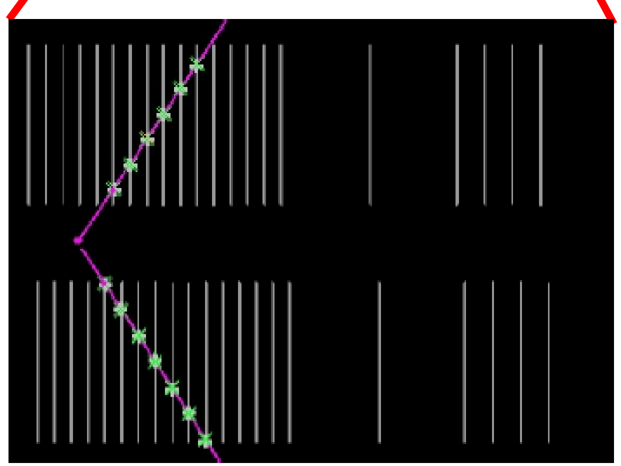
Exchange of colourless objects
γ, pomeron,...

$$J/\psi\ /\ \psi(2S) \rightarrow \mu^+\mu^-$$

protons undetected
rapidity gaps (signature)







Low *x*-Björken values ~ $5{\times}10^{-6}$

- soft pomeron exchange (Regge traject.)
- sensitive to parton saturation effects
- gluon parton density function (PDF)

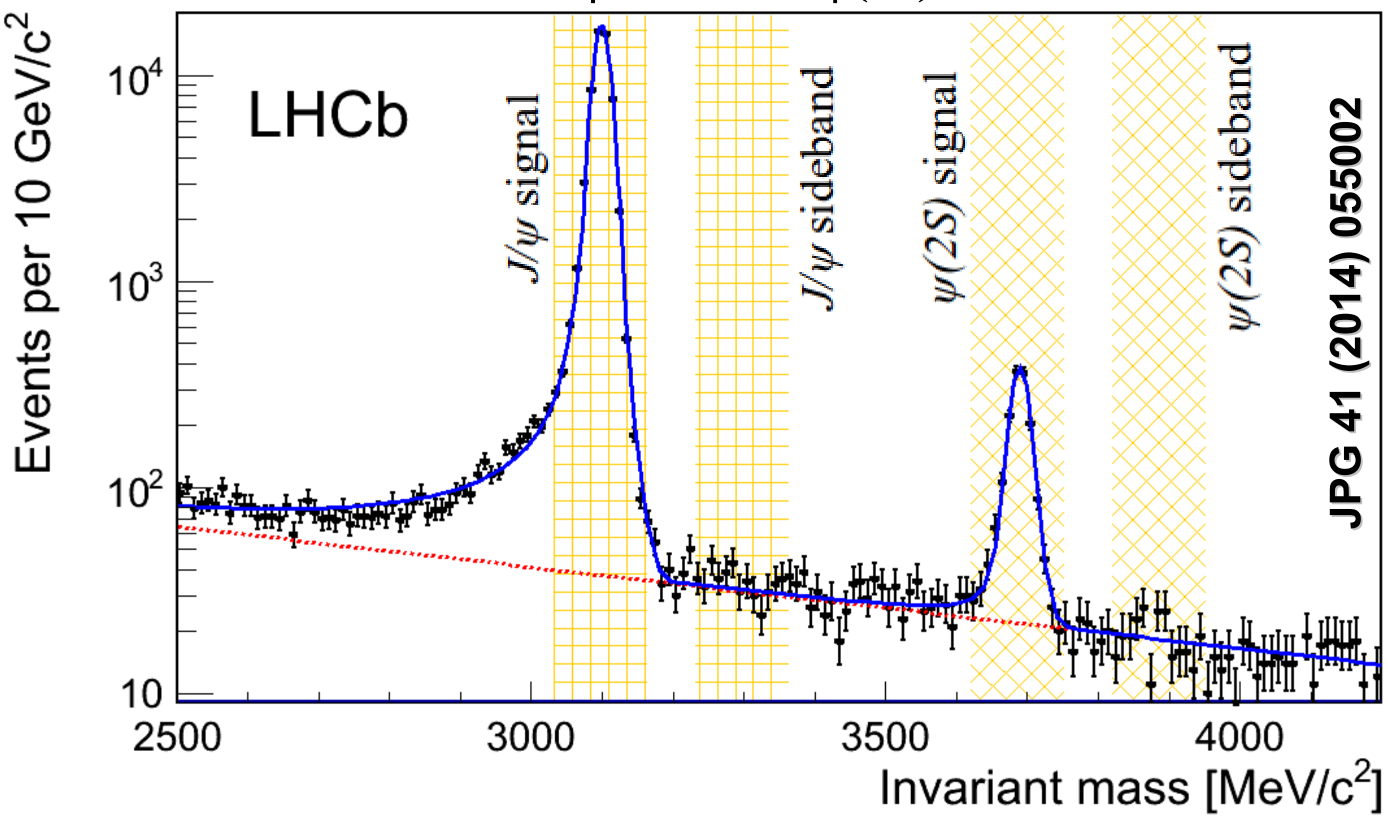
Central Exclusive Production at LHCb

- supersedes previous LHCb measurement [JPG **40** (2013) 045001]
- using 930 pb^{-1} (almost all) data sample collected in 2011 (at $\sqrt{s} = 7$ TeV)

Data selection:

- events with exactly one primary interaction (no pile-up): 24% of total luminosity
- two identified muons in forward direction
- no backward tracks
- no photons
- $p_{\mu^\pm} > 6\ \mathrm{GeV}/c$
- $(p_T^{\mu\mu})^2 < 0.8\ \mathrm{GeV}^2/c^2$
- $M_{\mu\mu}$ within 65 MeV/c^2 of J/ψ / $\psi(2S)$ known mass
- $2.0 < \eta_{\mu^\pm} < 4.5$

55985 J/ψ and 1565 ψ(2S) candidates



JPG 41 (2014) 055002

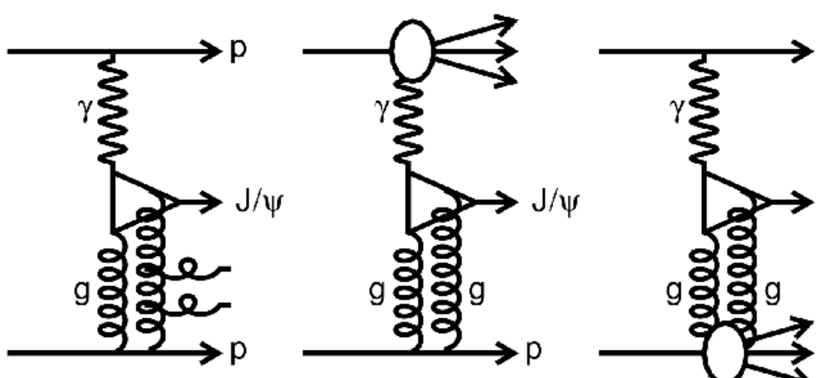
Central Exclusive Production at LHCb

Background:

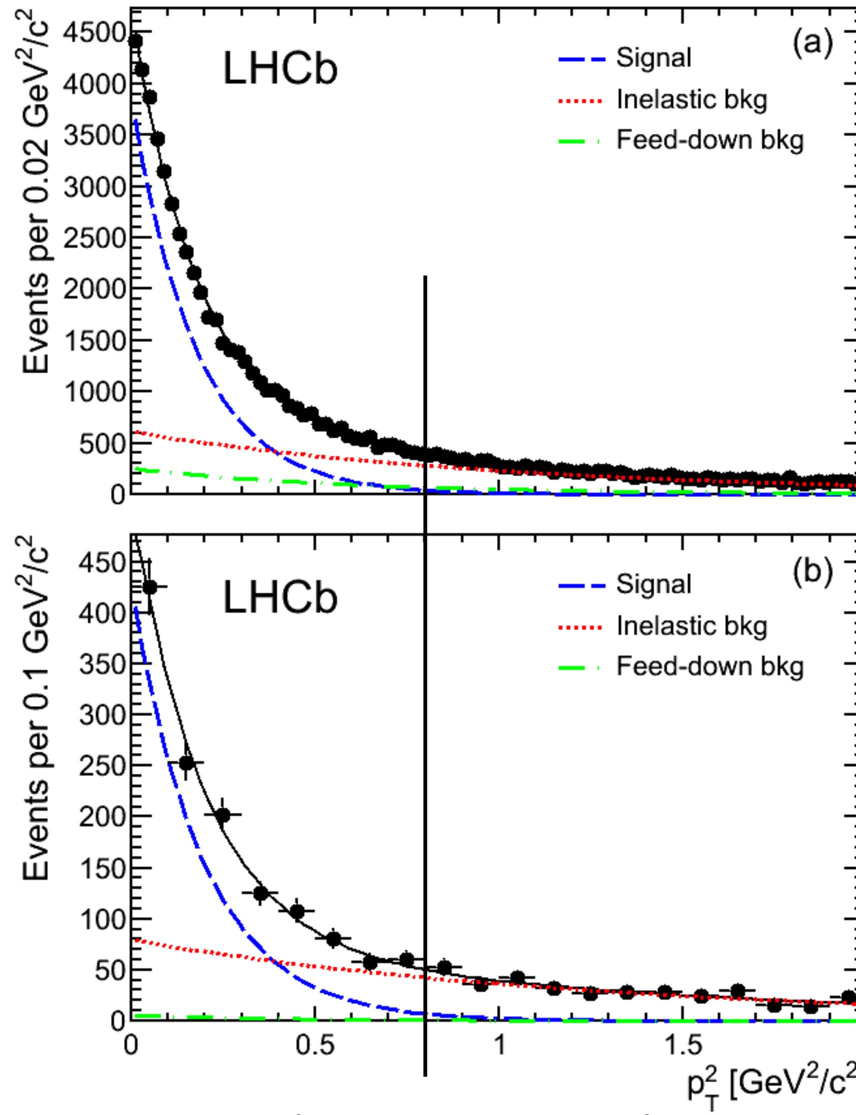
1. non-resonant: small – μ-pairs from QED process
→ estimated from sidebands
0.8±0.1 % for J/ψ and 17.0±0.3 % for ψ(2s)

2. feed-down:
J/ψ: 7.6±0.9 % from χ_c + 2.5±0.2 % from ψ(2S)
ψ(2S): 2.0±2.0 % from X(3872) and $\chi_c(2P)$
→ estimated from SUPERCHIC simulation with shape given by data $\chi_c \rightarrow J/\psi\gamma$ and $\psi(2S) \rightarrow J/\psi\pi\pi$

3. inelastic: dominant – extra particles produced out of LHCb acceptance or escaping down beam pipe (exp. shape – agreement with HERA expectations)



gluon radiation **proton dissociation**



JPG 41 (2014) 055002

Signal purity $p_T^2(\mu\mu) < 0.8$ GeV^2
0.59±0.01 for **J/ψ** and **0.52**±0.07 for **ψ(2S)**

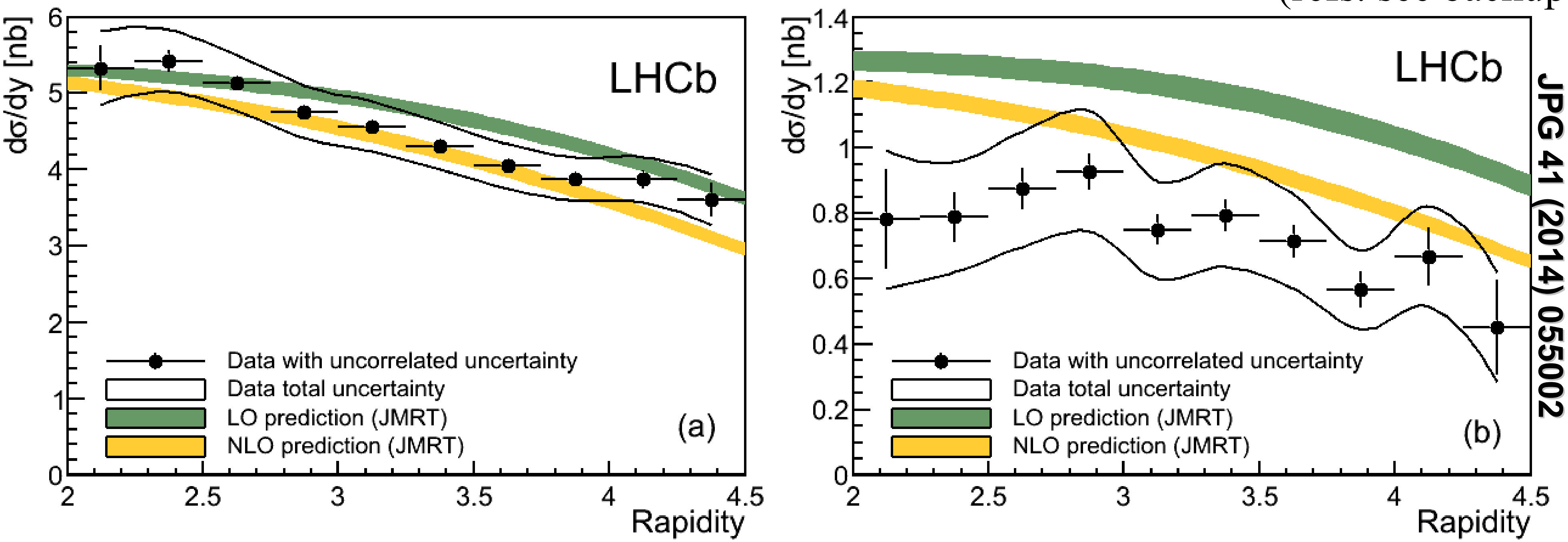
Central Exclusive Production at LHCb

Measured elastic cross-sections × BF to two muons – good agreement with models

G&M, JRMT, M&W, Ducati *et al.*, Sch&S, Starlight, Superchic (refs. see backups)

$$\sigma_{pp\to J/\psi\to\mu^+\mu^-}(2.0 < \eta_{\mu^\pm} < 4.5) = 291 \pm 7 \pm 19 \text{ pb}$$

$$\sigma_{pp\to\psi(2S)\to\mu^+\mu^-}(2.0 < \eta_{\mu^\pm} < 4.5) = 6.5 \pm 0.9 \pm 0.4 \text{ pb}$$



Differential cross-section for (a) *J/ψ* and (b) *ψ(2S)* compared to LO and NLO predictions obtained from Jones-Martin-Ryskin-Teubner (JHEP **11** (2013) 085) fit to **HERA** and LHCb data. Shape also well described by saturation models – arXiv:1305.4611 (2013), Phys. Rev. D **78** (2008) 014023 – see backups.

Comparison to HERA *γp* data (backups) – deviation from power-law – higher order terms and saturation effects.

EPJ C74 (2014) 2888

Charged Particle Multiplicity & Densities

- characterises hadronic final state, sensitive to underlying event activity
- together with previously reported measurements on (light hadron) production cross-sections and ratios (see backups) or total/charged energy flow fundamental input for tuning phenomenological models in the LHCb specific forward region

Data set and selection:

- low multiplicity, minimum-bias (MB) sample recorded at $\sqrt{s} = 7$ TeV
- contribution from bunch crossing with multiple *pp* collisions (pile-up) < 4%
- reconsider Eur. Phys. J. C **72** (2012) 1947: added measurement of momentum

- select tracks: $p_T > 0.2$ GeV/c, $p > 2$ GeV/c, $2.0 < \eta < 4.8$ – high reco. efficiency
- analysis kinematic range: $\boxed{0.2 < p_T < 2.0 \text{ GeV/c};\ 2.0 < \eta < 4.5}$

- systematic uncertainties (included in gray bands) up to 10% → dominated by uncertainty on the amount of detector material (non-prompt particles)

Charged Particle Multiplicity & Densities

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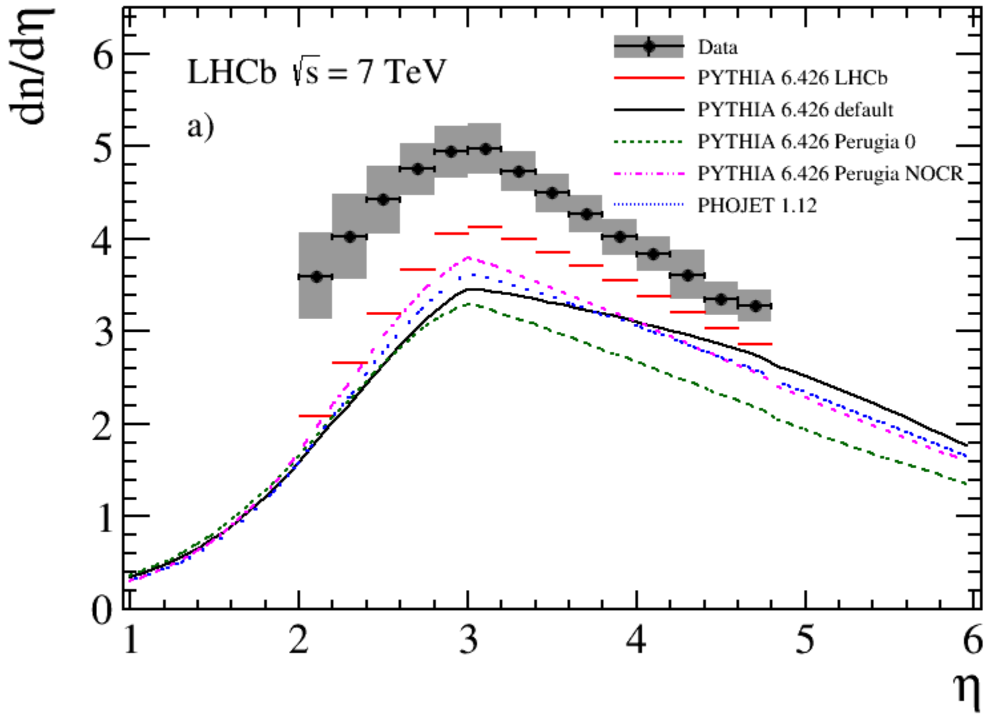

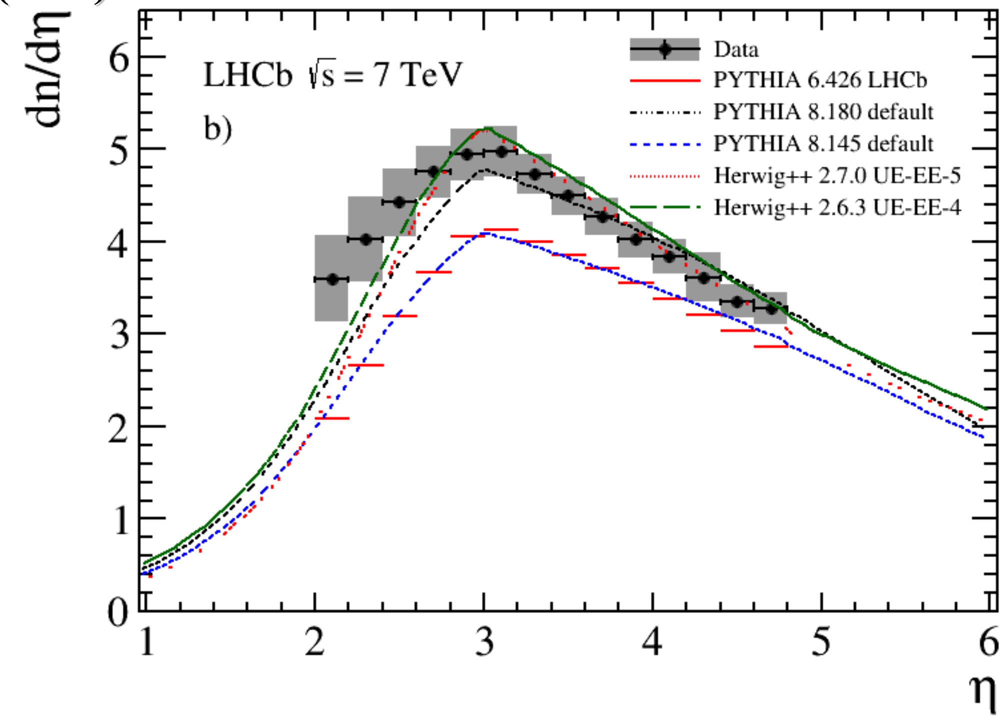

Charged particle density as function of η.

- Shapes well described qualitatively (even falling edge below 3 – momentum cut)
- PYTHIA6 and PHOJET underestimate the data (density and multiplicity)
- PYTHIA6 LHCb tune used as additional reference in plots
- PYTHIA 8.180 and Herwig++ (tuned to LHC data) – best description

Charged Particle Multiplicity & Densities

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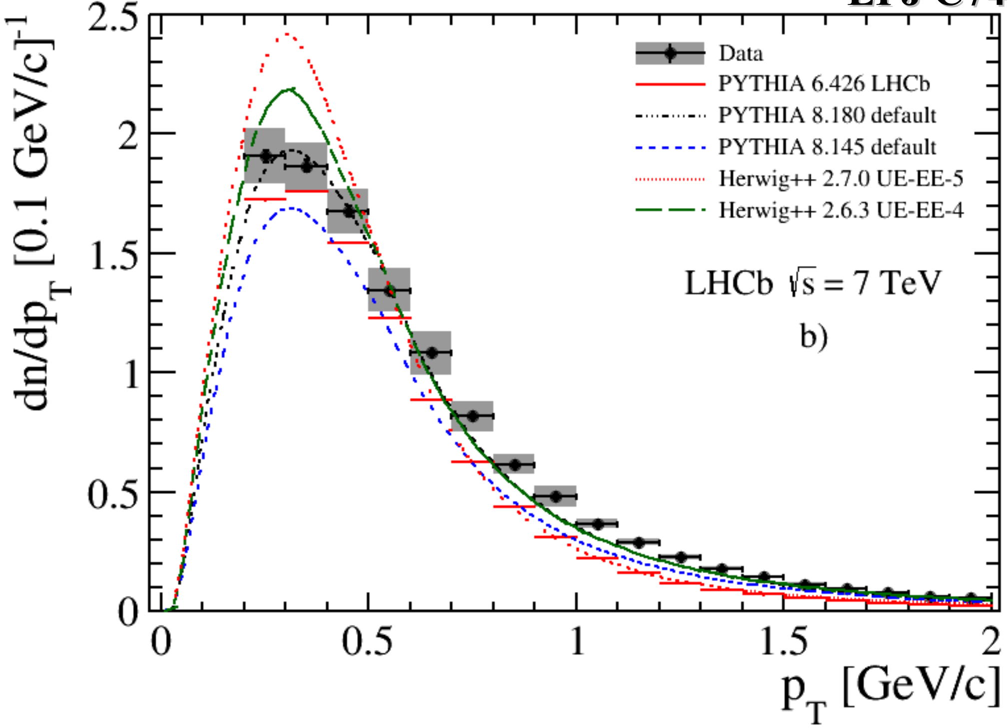
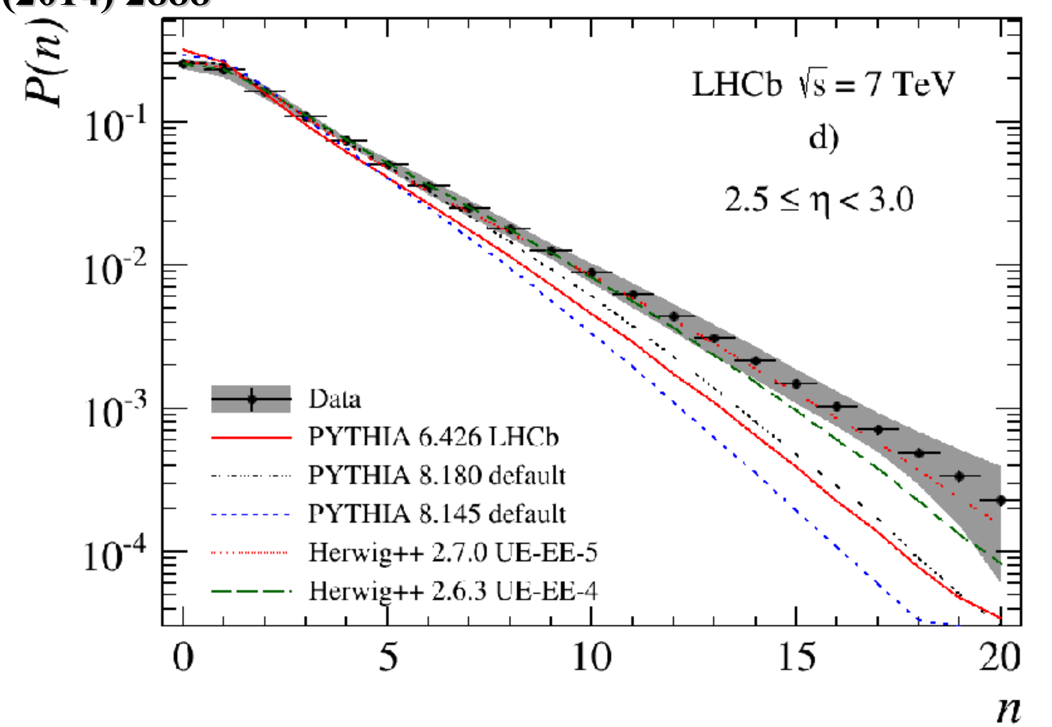




Charge particle density as function of p_T

- PYTHIA8.180 – best description, tends to underestimate at high p_T
- Herwig++ – shape not good: over-(under-)estimate at low(high) p_T

Particle multiplicity distributions

- in η and p_T (backups)
- overall model prediction below data at higher multiplicities
- PYTHIA8.180 and Herwig++ give a better description

None of the models describes all aspects of data – valuable input for tuning.

EPJ C73 (2013) 2421

Forward Energy Flow in *pp* collisions at √s = 7 TeV

- Energy Flow (EF) measurements at high η
  - valuable input for parton radiation estimation and MPI models
  - test or improve constraints on ultra high energy cosmic-ray interaction models
- EF is total energy of stable particles in a η bin *i* normalised to the number of non-elastic *pp* interactions (N_{nei})

$$EF_i = \frac{1}{N_{nei}} \frac{\mathrm{d}E_{\mathrm{total}}}{\mathrm{d}\eta}$$

- LHCb measurement:

$$EF_i = \frac{1}{\Delta\eta} \left(\frac{1}{N_{nei}} \sum_{i=1}^{N_{\mathrm{part},\eta}} E_{i,\eta} \right), \quad \Delta\eta = 0.3,\ \eta \in [1.9, 4.9]$$

$N_{\mathrm{part},\eta}$, $E_{i,\eta}$ – total nb. and individual energy of stable particles

  - **Data**: 0.1/nb, 2010 runs at √s = 7 TeV, low pile-up, micro-/no- bias
  - First time measured at a hadron collider by LHC experiments; extends CMS measurement CMS Collab., JHEP **11** (2011) 148

EPJ C73 (2013) 2421

Forward Energy Flow

Charged energy flow – only tracking information (no PID; $E \approx p$).

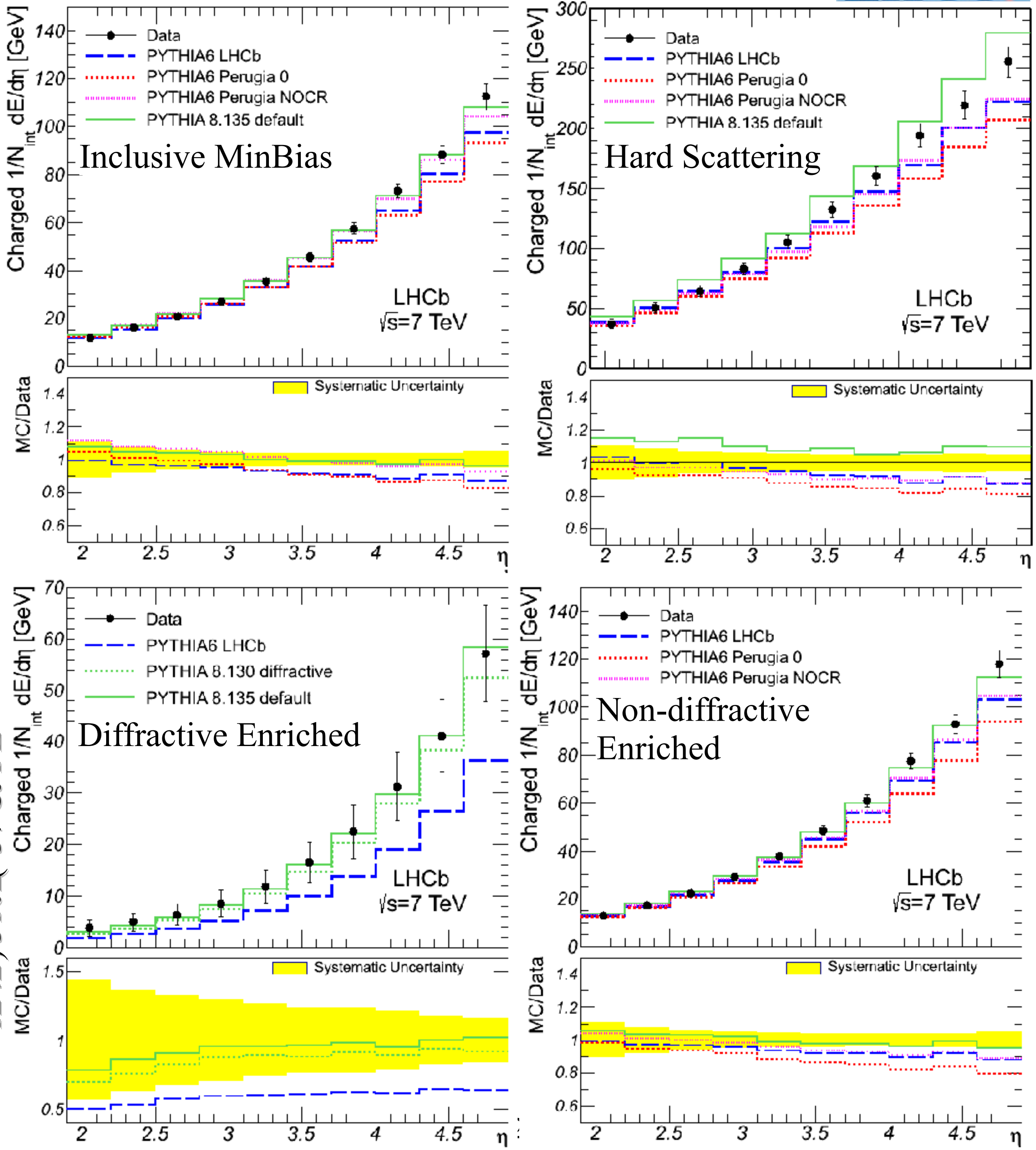
Total energy flow – data-constrained MC estimate of neutral component (ECAL info.)

- Event Classes/Data Selection:
  - *Inclusive MB* – at least one track with p > 2 GeV/c
  - *Hard Scattering* – at least one track with $p_T > 3$ GeV/c
  - *Diffractive Enriched Interactions*
    - inclusive MB with no backward tracks ($-3.5 < \eta < -1.5$)
    - rapidity gap signature
  - *Non-Diffractive Enriched Interactions*
    - inclusive MB with at least one backward track
- Correction for detector effects in each η bin using simulation.
- Systematic uncertainties:
  - Tracking efficiency
  - Pile-up effect – multiple primary interactions in ~5% of events
  - Influence of simulation models (main contribution)

Charged Forward Energy Flow vs. PYTHIA Tunes

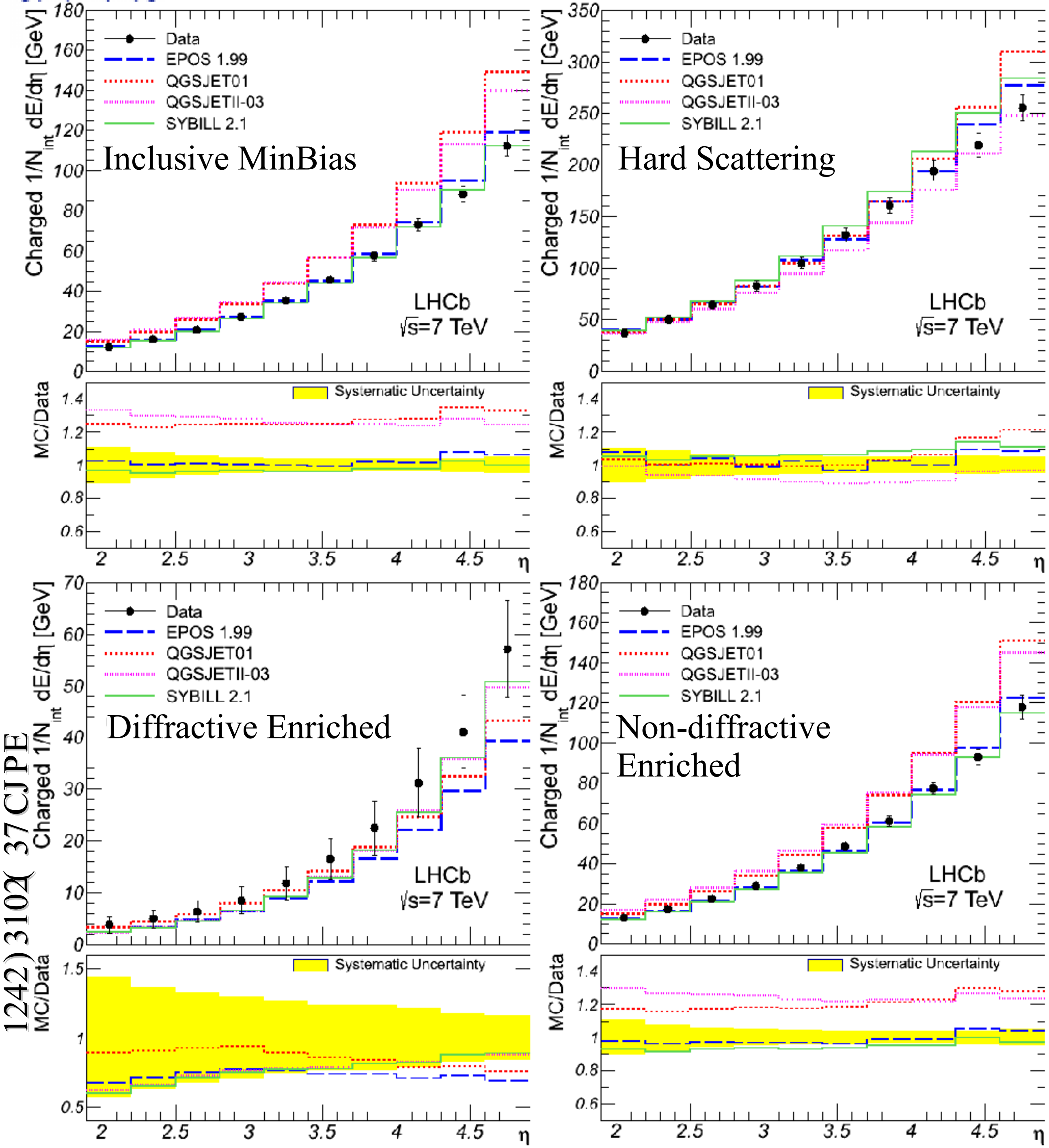
- PYTHIA6 underestimates charged EF for all event categories studied at higher η
- PYTHIA8 – best agreement for diffractive enriched events, yet it overestimates EF in hard scattering ones
- Same conclusions apply for the total EF (backups)

Low uncertainties in forward region – large divergencies between models
→ tune against data



EPJC 73 (2013) 2421

Charged Forward Energy Flow vs. Cosmic-Ray Models



- Cosmic-ray interaction models tend to overestimate the EF
- SYBILL and EPOS give the best description for MB inclusive events
- SYBILL:
  - good agreement in all 4 LHCb event classes except at high η for hard scattering events
  - competitive results with respect to PYTHIA8 for diffractive events
- QGSJETII-03 reliable in describing hard scattering events
- Corrected total energy flow distributions given in backups

Conclusions

• The large LHC collision energy allows LHCb to measure in a previously out of the reach phase space region with very low-x_{Bj}.

• LHCb CEP measurements are in good agreement with theoretical predictions contributing to better understanding the pomeron exchange process in the forward region.

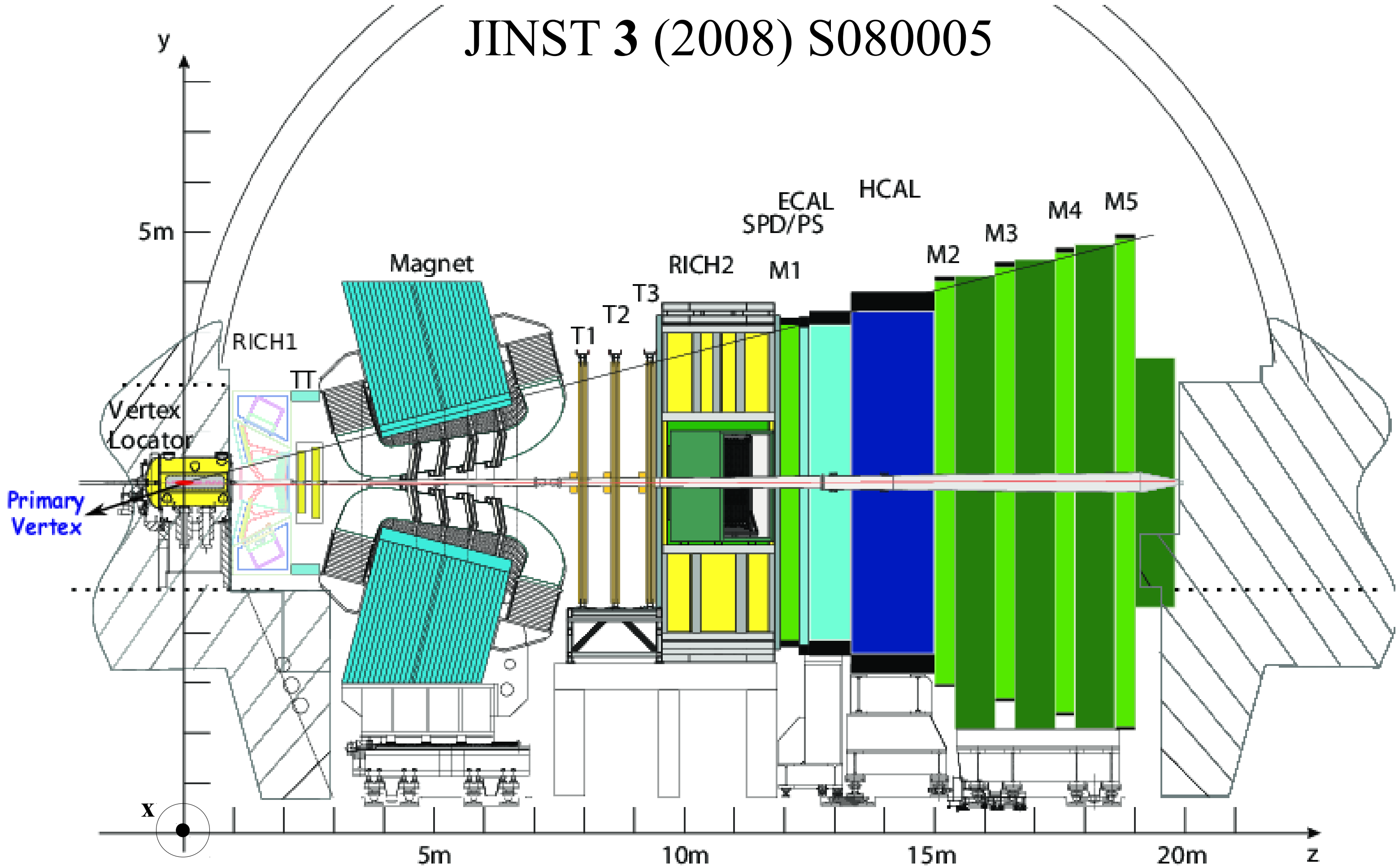
• Charged particle production, and multiplicity and density distributions in the forward region are valuable input for tuning parameters of the phenomenological models implemented in various MC event generators to describe underlying event activity.

• LHCb charged and total energy flow measurements constrain initial and final state parton radiation and multi-parton interaction models, from high energy physics and astrophysics generators, in the forward region.

Thank you!

BACKUPS

“*The LHCb Detector at the LHC*”
JINST **3** (2008) S080005



Particle IDentification:

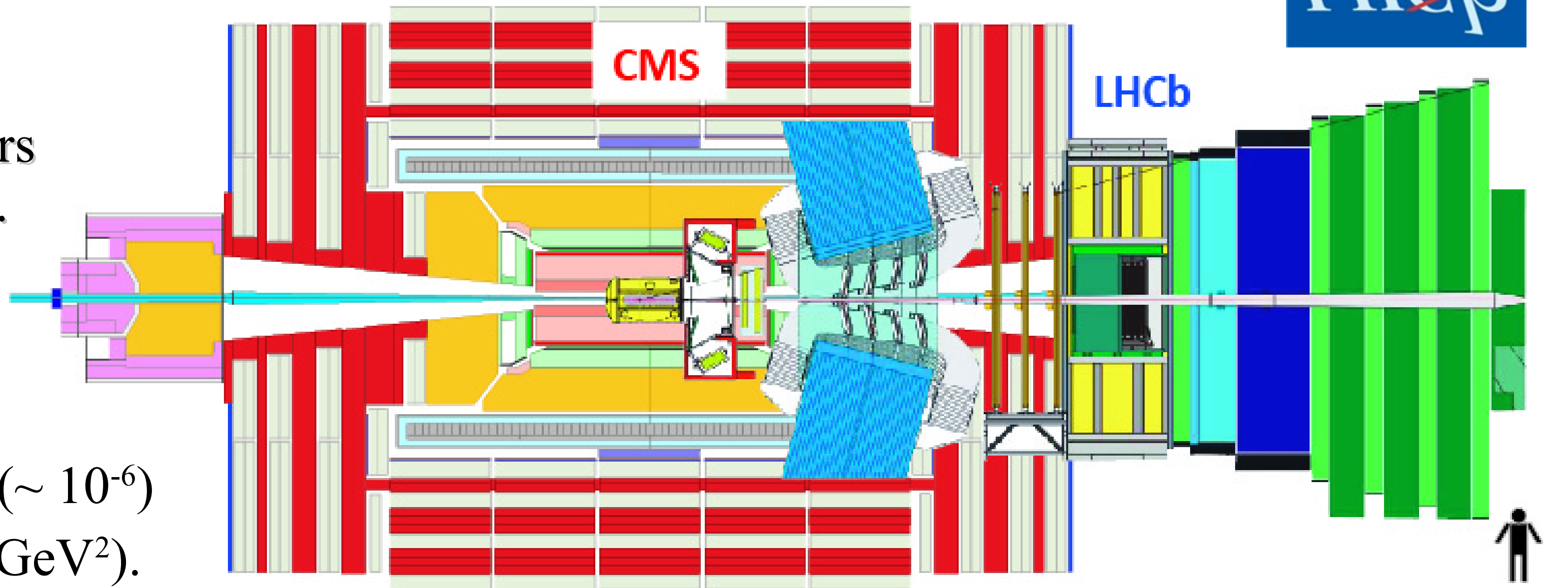
2 Ring Imaging Cherenkov (RICH) detectors: excellent π, p, K identification (2-100 GeV/c)

γ, e, μ separation in Hadronic, Electromagnetic CALorimeters & Muon chamber system

$$\sigma_{ECAL}(E)/E = 1\% + 10\% / \sqrt{E[GeV]}$$

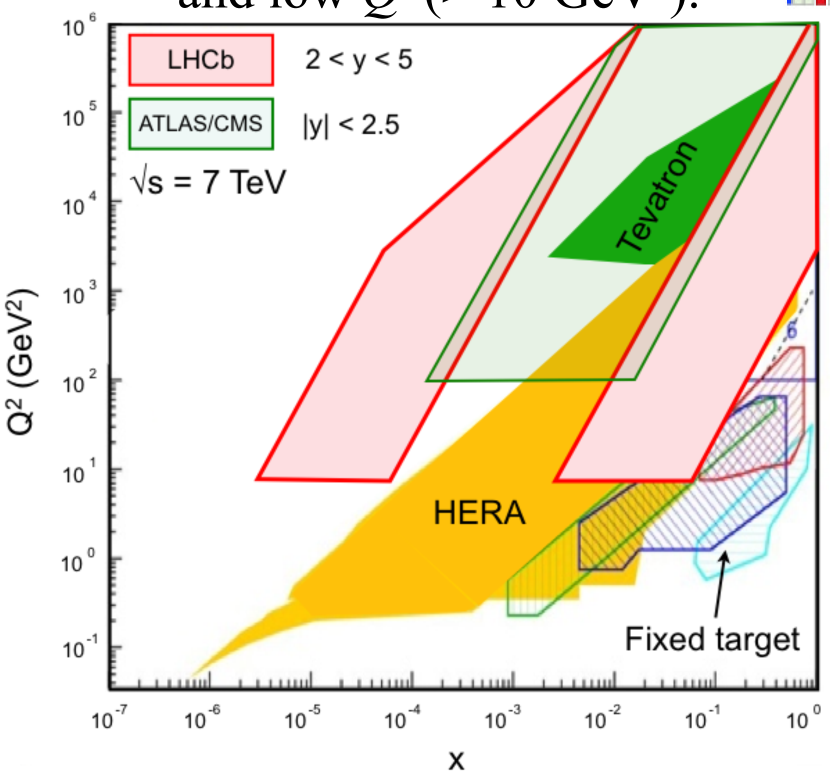
Multi-stage trigger: first level is hardware; next two levels implemented in software.

The LHCb Detector



Extends central detectors phase coverage at LHC.

Access to low x_{Bj} (~ 10^{-6}) and low Q^2 (> 10 GeV^2).



see also Katharina's talk about LHCb proton-Pb physics results earlier this afternoon...

Integrated luminosity LHC Run I (2010-2013)

2010: 37 pb^{-1} 2011: 1.0 fb^{-1} 2012: 2 fb^{-1}

Current measurements done on data sets collected at $\sqrt{s}$ = 7 TeV

Summary of LHCb results on soft QCD

CEP at LHCb

- *Exclusive J/ψ and $\psi(2S)$ production in pp collisions at $\sqrt{s} = 7$ TeV*, J. Phys. G **40** (2013) 045001 arXiv, DOI
- *Updated measurements of exclusive J/ψ and $\psi(2S)$ production cross-sections in pp collisions at $\sqrt{s} = 7$ TeV*, J. Phys. G **41** (2014) 055002. arXiv, DOI
- *Observation of charmonium pairs produced exclusively in pp collisions*, arXiv1407.5973 (Jul, 2014) 20pp link

Global Event Characteristics

- *Charged particle multiplicity at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C **72** (2012) 1947 arXiv, DOI
- *Measurement of the forward energy flow in pp collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C **73** (2013) 2421 arXiv, DOI
- *Measurement of charged particle multiplicities and densities in pp collisions at $\sqrt{s} = 7$ TeV in the forward region*, Eur. Phys. J. C **74** (2014) 2888 arXiv, DOI

Event Generator Tunes & Theoretical Models

- PYTHIA 6.4 T. Sjöstrand, S. Mrenna, P. Skands, JHEP **05** (2006) 026

  LHCb MC tune (GAUSS: PYTHIA6.4+EVTGEN+PHOTOS)

  I. Belyaev *et al.*, Nuclear Science Symposium Conference Record (NSS/MIC) (IEEE, New York 2010), p. 1155

  Perugia0, PerugiaNOCR, Perugia 2010 tunes

  P. Z. Skands, Phys. Rev. D **82** (Oct, 2010) 074018

- PYTHIA 8.1 T. Sjöstrand, S. Mrenna, P. Skands, Comput. Phys. Commun. **178** (2008) 850

- Cosmic-ray 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. D **80** (2009) 094003

- Other Monte Carlo Event Generators and Theoretical Models:

  PHOJET: R. Engel, Z. Phys. C **66** (1995) 203; doi

  HERWIG++: M. Bahr et al., Eur. Phys. J. C **58** (2008) 639-707; doi

  SUPERCHIC: L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, W.J. Stirling, Eur. Phys. J. C 65 (2010) 433

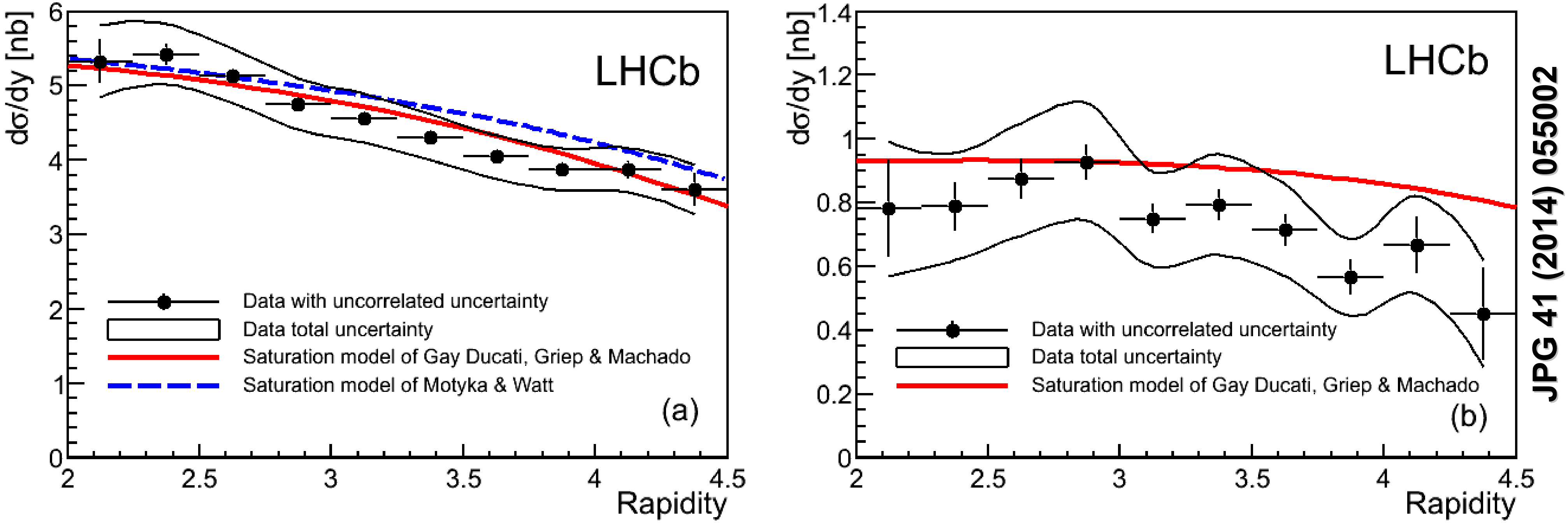
  STARLIGHT: S.R. Klein, J. Nystrand, Phys. Rev. Lett. **92** (2004) 142003

G&M model: V.P. Gonçalves and M.V.T. Machado, Phys. Rev. C **84** (2011) 011902; arXiv:1106.3036

Sch&S model: W. Schäfer and A. Szczurek, Phys. Rev. D **76** (2007) 094014; arXiv:0705:2887

JMRT model: Jones S., Martin A., Ryskin M. and Teubner T., JHEP **11** (2013) 085

Central Exclusive Production at LHCb



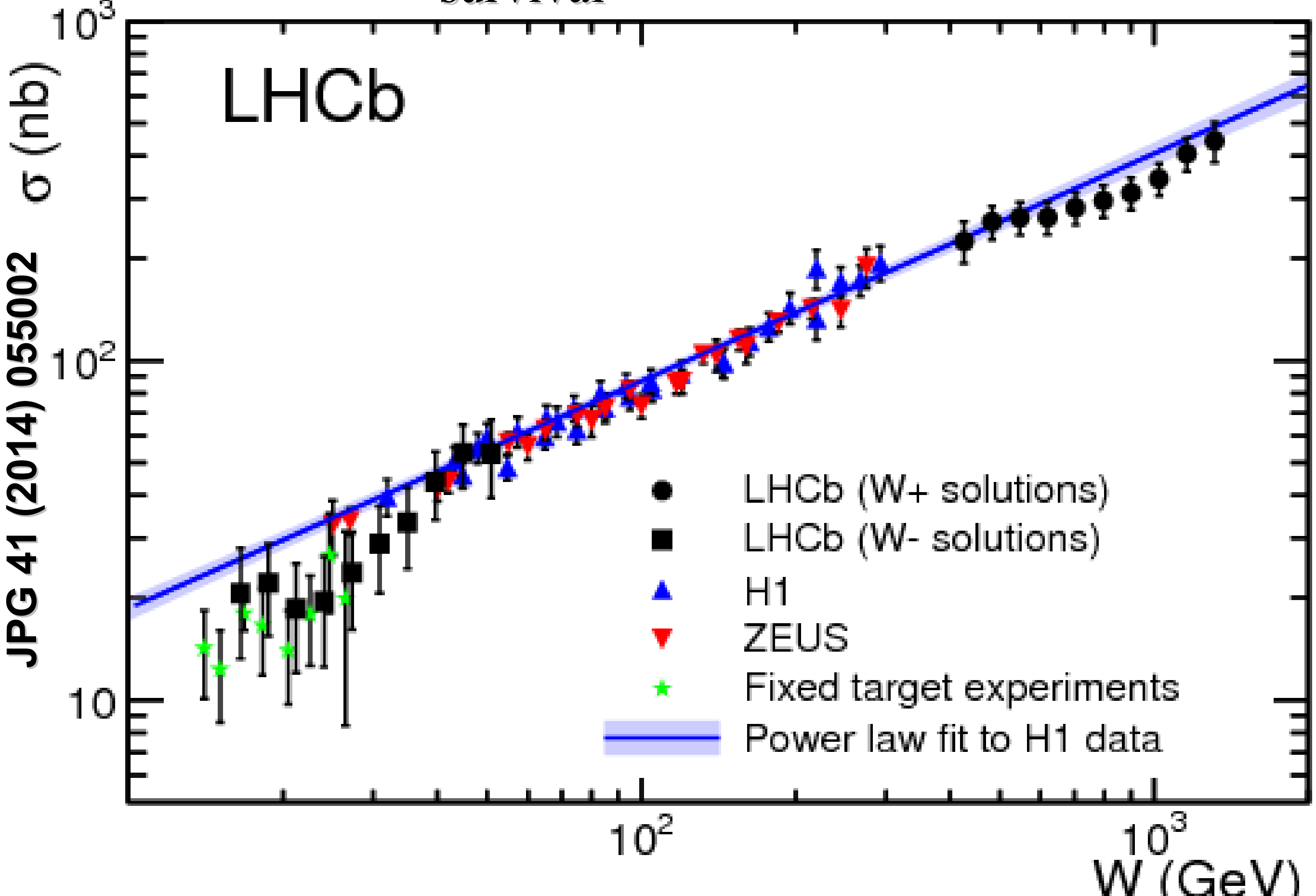
Differential cross-sections for (a) J/ψ and (b) $\psi(2S)$ compared to predictions of Gay Ducati *et al.* and Moytka and Watt which include saturation effects. Band indicates total uncertainty mostly correlated between bins.

M.B. Gay Ducati, M.T. Griep and M.V.T. Machado, arXiv:1305.4611 (2013)
L. Motyka and G. Watt, Phys. Rev. D **78** (2008) 014023

Central Exclusive Production at LHCb

Compare to HERA γp data using known photon flux for a given photon energy k

$$\underbrace{\frac{\mathrm{d}\,\sigma}{\mathrm{d}\,y}_{pp\to pVp}}_{\text{measured}} = \underbrace{r_+}_{\text{rapidity gap survival}} k_+ \frac{\mathrm{d}\,n}{\mathrm{d}\,k_+} \underbrace{\sigma_{\gamma p\to Vp}(W_+)}_{\text{extracted}} + r_- k_- \underbrace{\frac{\mathrm{d}\,n}{\mathrm{d}\,k_-}}_{\text{photon flux}} \underbrace{\sigma_{\gamma p\to Vp}(W_-)}_{\text{extracted}}$$



Correlated points for each measurement (W+,W-) in y

Deviation from power law:
- higher order interaction terms
- saturation effects

Some LHCb results for event generator tuning

Light Flavour Production Measurements

- *K^0_S production cross section at $\sqrt{s} = 0.9$ TeV*,
  Phys. Lett. B **693** (2010) 69-80 arXiv, DOI

- *Measurement of V^0 production ratios in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV* ,
  JHEP **08** (2011) 034 arXiv, DOI

- *Inclusive ϕ production cross section at $\sqrt{s} = 7$ TeV*,
  Phys. Lett. B **703** (2011) 267-273 arXiv, DOI

- *Measurement of prompt hadron production ratios in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV*,
  Eur. Phys. J. C **72** (2012) 2168 arXiv, DOI

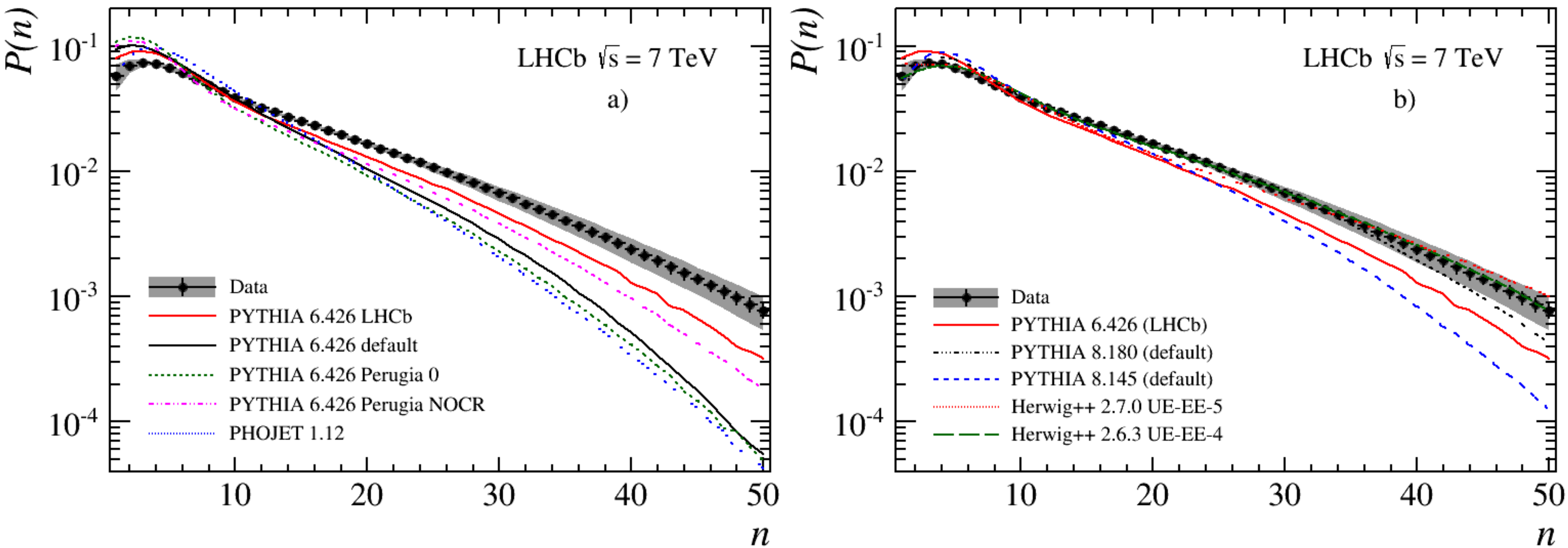
Some LHCb results for event generator tuning

Heavy Flavour Production Measurements

- *Production of J/ψ and Υ mesons in pp collisions at $\sqrt{s} = 8$ TeV,*
  J. High Energy Phys. **06** (2013) 064 arXiv, DOI
- *Prompt charm production in pp collisions at $\sqrt{s} = 7$ TeV,*
  Nucl. Phys. B **871** (2013) 1–20 arXiv, DOI
- *Measurement of J/ψ production in pp collisions at $\sqrt{s} = 2.76$ TeV,*
  J. High Energy Phys. **02** (2012) 041 arXiv, DOI
- *Measurement of Υ production in pp collisions at $\sqrt{s} = 2.76$ TeV,*
  Eur. Phys. J. C **74** (2014) 2835 arXiv, DOI
- *Measurement of $\psi(2S)$ meson production in pp collisions at $\sqrt{s}=7$ TeV,*
  Eur. Phys. J. C **72** (2012) 2100 arXiv, DOI

Charged Particle Multiplicity & Densities

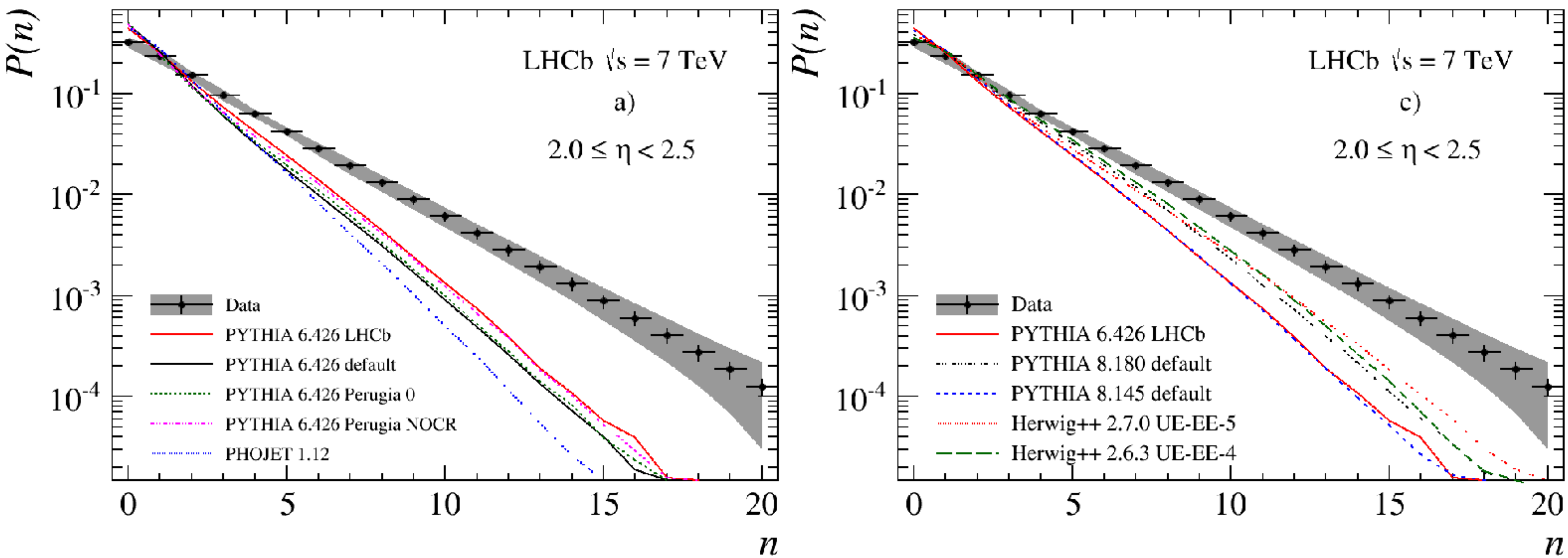
EPJ C74 (2014) 2888



Observed charged particle multiplicity distribution in the full kinematic range of the analysis. Event generator overestimate experimental distribution at low multiplicity and underestimate at high multiplicity. Shapes better described by Pythia6 LHCb tune, Pythia8.180 and Herwig++ tunes – overall poor description of shape, great divergences at high multiplicity. Consistent with previous LHCb measurements [EJP C**72**(2012)1947].

Charged Particle Multiplicity & Densities

EPJ C74 (2014) 2888



Charged particle multiplicity distributions towards central region. All considered generators and tunes fail to reproduce the shape of the experimental distributions and underestimate the values for high multiplicities.

Charged Particle Multiplicity & Densities

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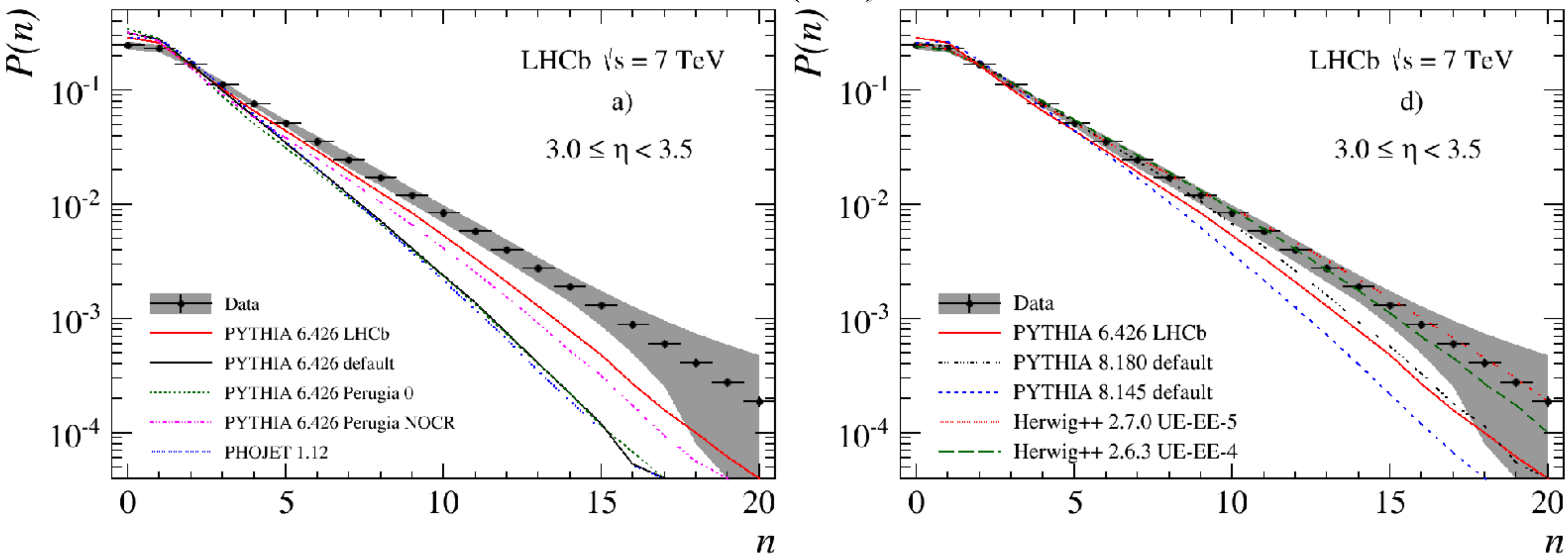

Charged particle multiplicity distributions for pseudorapidity range 3.0 < η < 3.5. PYTHIA6 and PHOJET still under-estimate the data points (best agreement for PYTHIA6 LHCb tune and PYTHIA8.180 – tuned on LHC data). Herwig++ tunes (UE-5!) fits better the data.

Charged Particle Multiplicity & Densities

~ dependency on η ~

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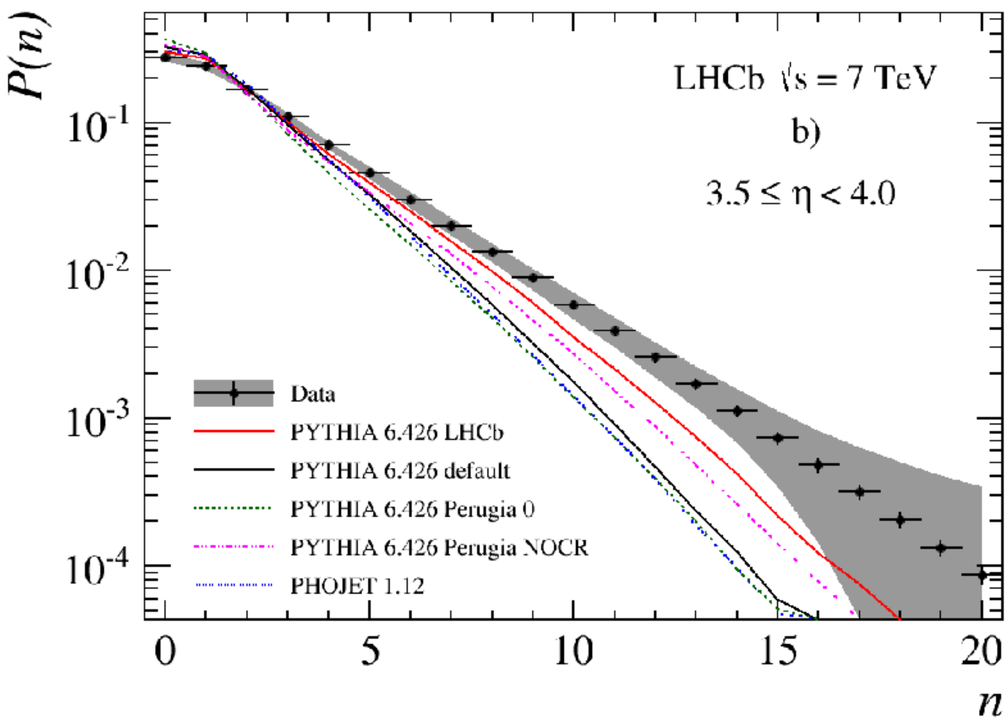

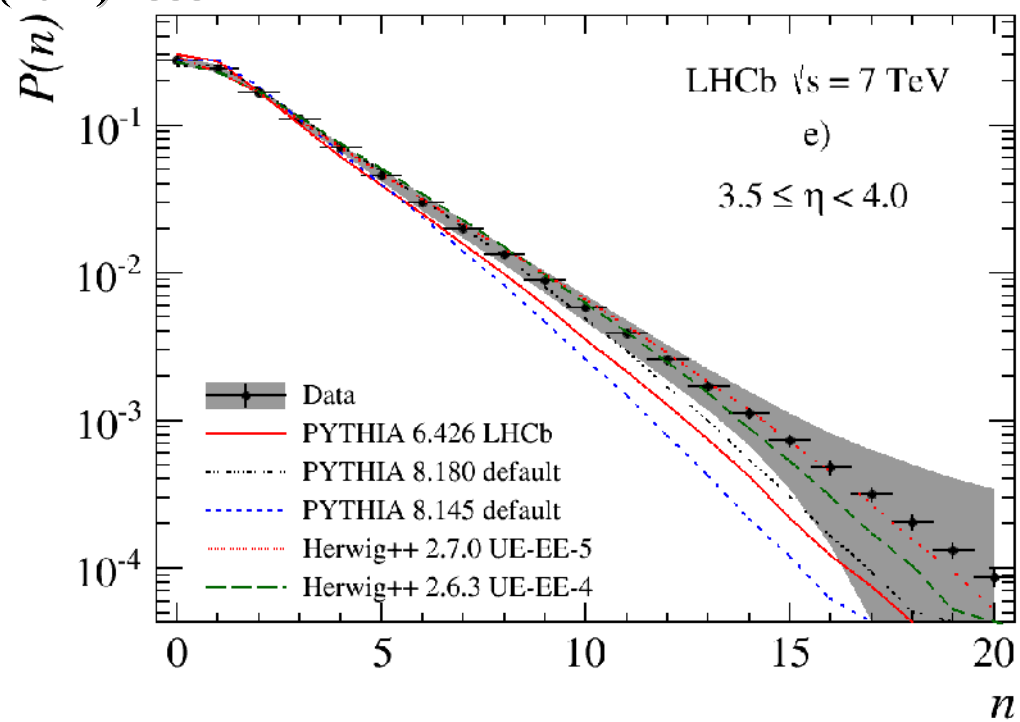

Charged multiplicity distribution in η bins.

- Herwig++ and Pythia8.180 tunes – better description of exp. distribution shape and values (in forward region).

- Pythia6 tunes and Phojet underestimate the data points.

- Pythia6 LHCb tune has best agreement with experimental data.

(see backups for details)

Charged Particle Multiplicity & Densities

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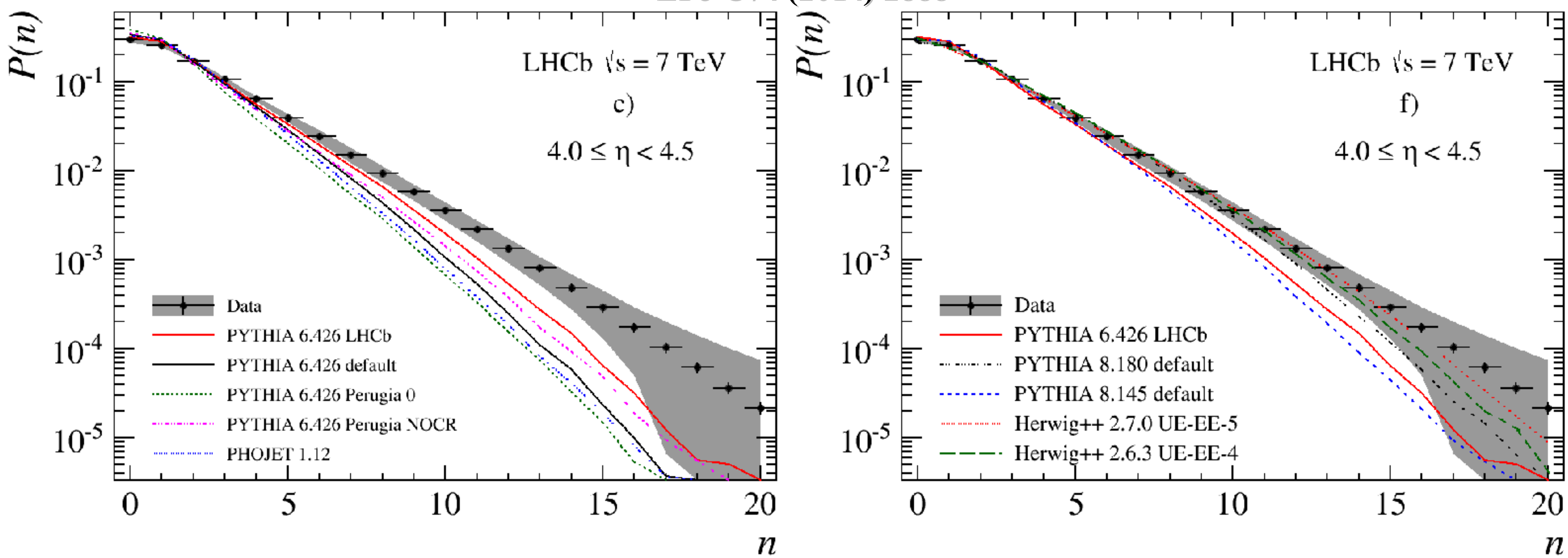

Charged particle multiplicity distributions at high pseudorapidity (in the forward region). Pythia6 LHCb tune gives best description of experimental data; all generator/tunes underestimate data points at high multiplicities. Best shape match by Herwig++ (UE-EE-5 tune), closely followed by Pythia 8.180

Charged Particle Multiplicity & Densities

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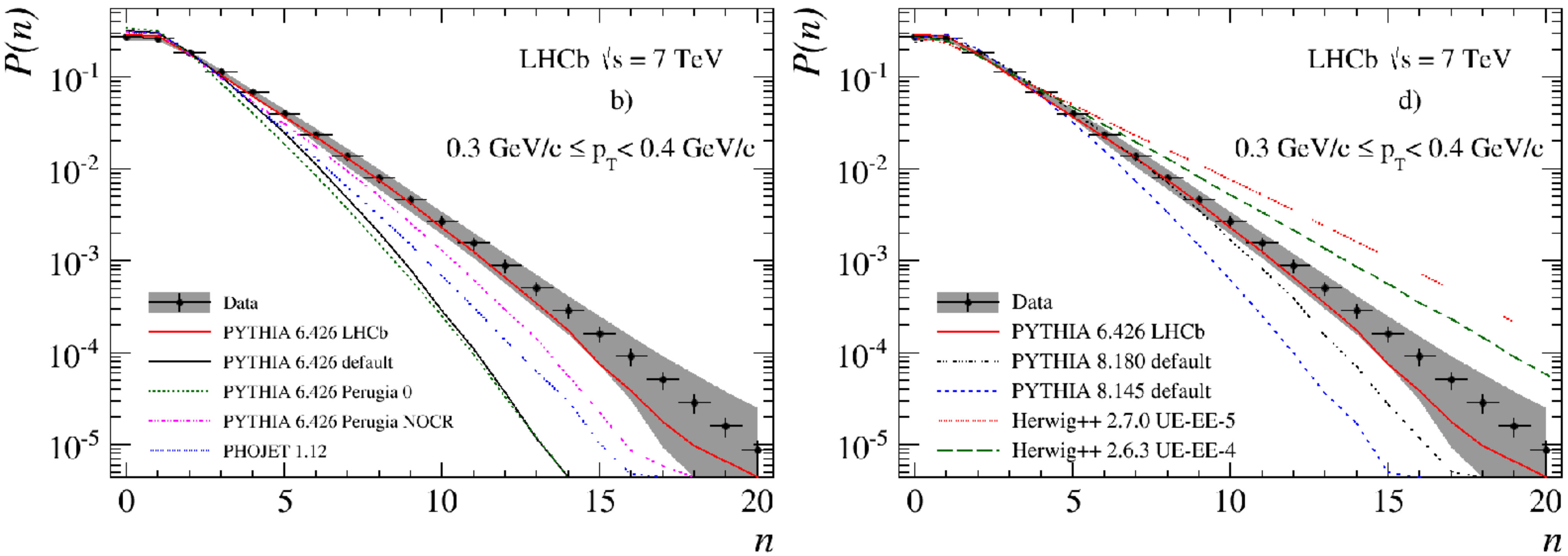

Observed charged particle multiplicity at low p_T.PYTHIA6 tunes and PHOJET tend to overestimate the data at low multiplicities and severly underestimate for high multiplicity events. PYTHIA6 LHCb tune gives the best agreement. PYTHIA8 tunes give lower predictions than experimental data (slightly better agreement for PYTHIA8.180). Herwig ++ overestimates the measured distributions at high multiplicity. Slopes at high multiplicity tails diverge from experimental distribution.

Charged Particle Multiplicity & Densities

~ dependency on p_T ~

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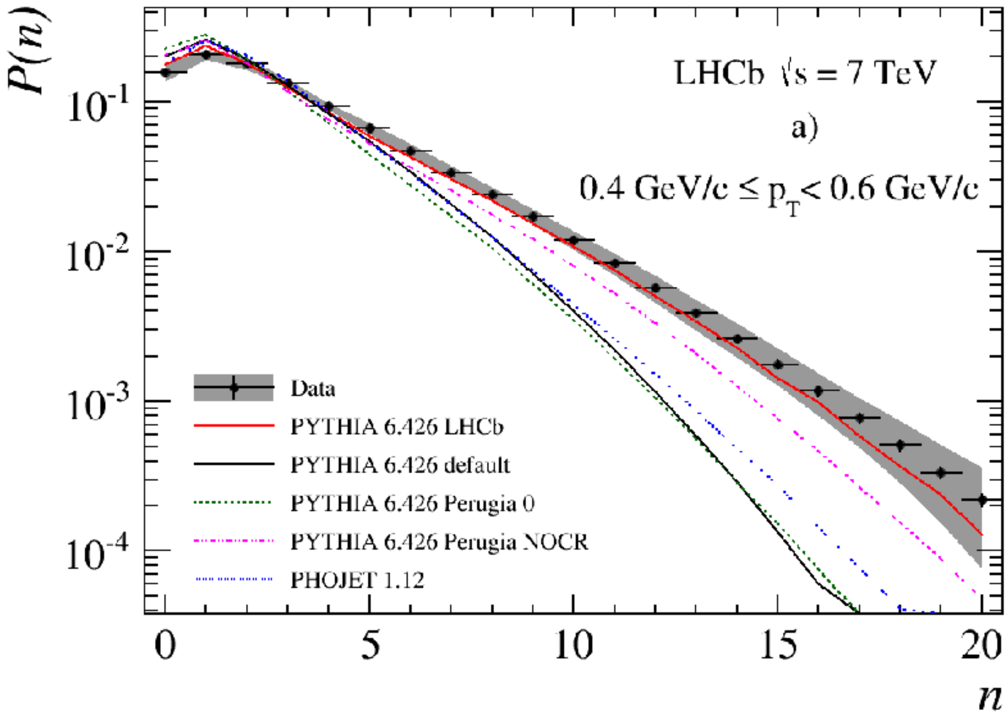

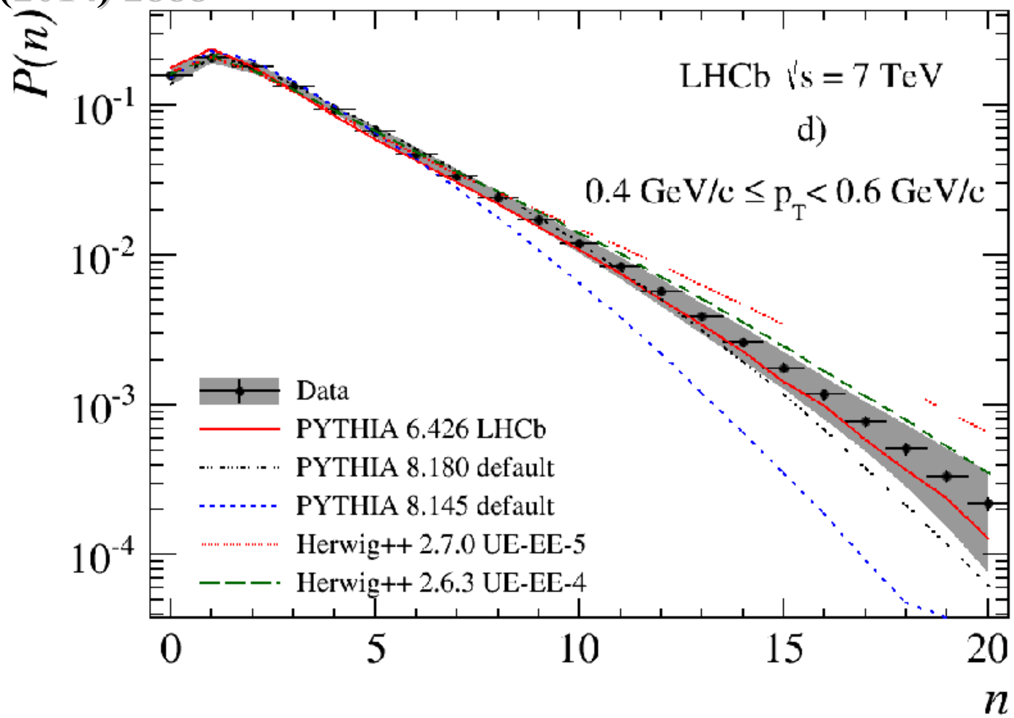

Charged multiplicity distribution in p_T bins.

- Herwig++ overestimates at high multiplicity for $p_T < 1$ GeV/c; reversed behaviour for $p_T > 1$ GeV/c. Pythia8 gives lower predictions overall. LHC data tuned Pythia8.180 in best agreement with data especially for $p_T > 1$ GeV/c. Pythia6, Phojet underestimate the data points over all p_T range at high multiplicities. Best agreement with experimental distribution: Pythia6 LHCb tune for $p_T < 1$ GeV/c; Pythia6 default tune at $p_T > 1$ GeV/c.
- experimental data shape poorly described by all generators/tunes at high multiplicity and p_T

Charged Particle Multiplicity & Densities

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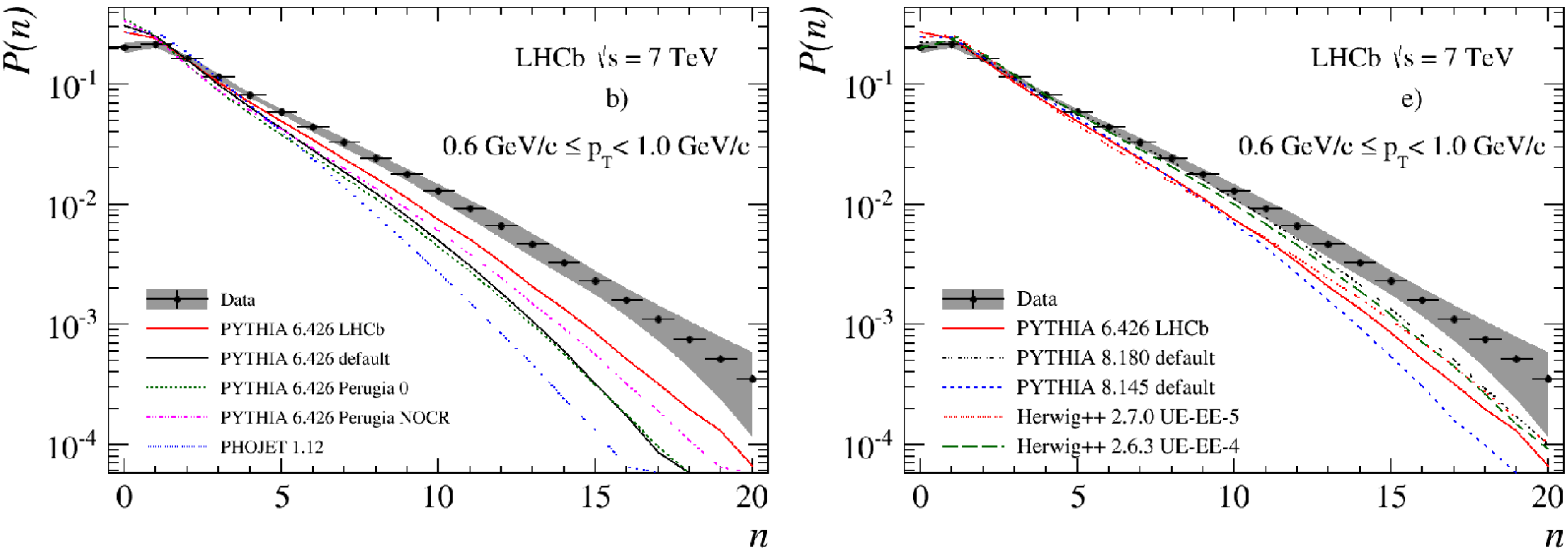

Observed charged particle multiplicity as function of p_T below 1.0 GeV/c. Models tend to overestimate at low multiplicity and underestimate data points at high multiplicities.

Charged Particle Multiplicity & Densities

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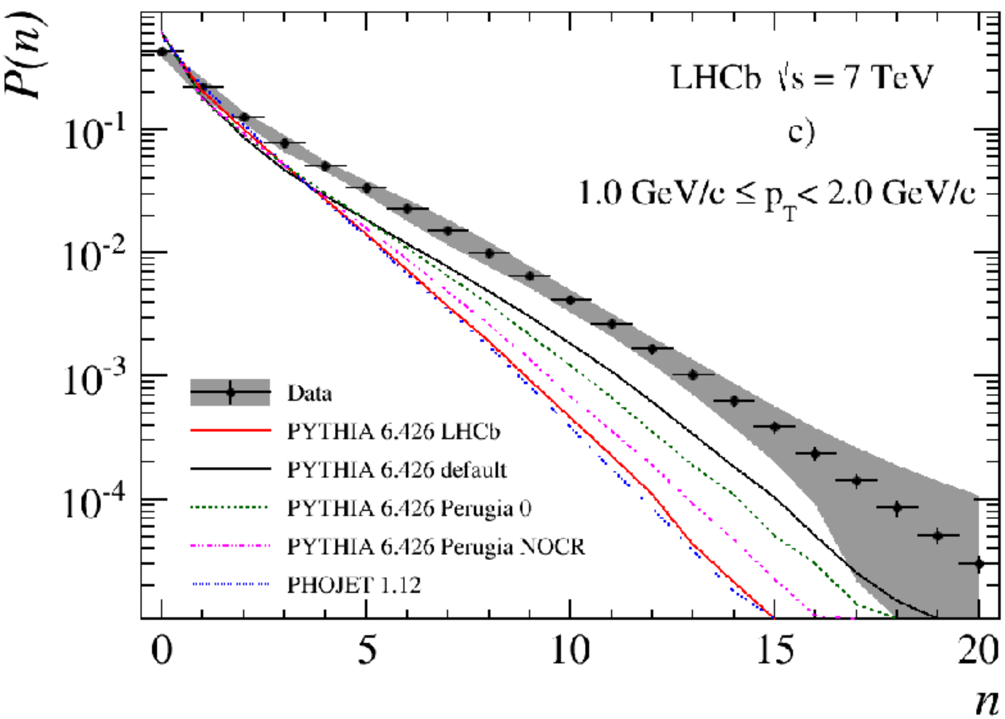
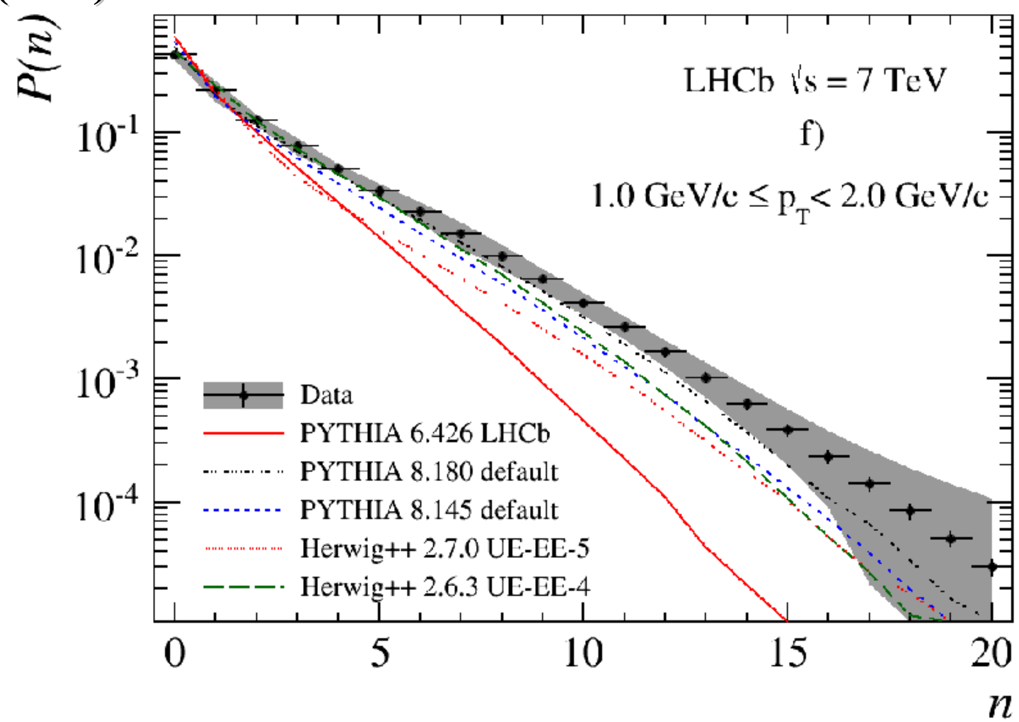




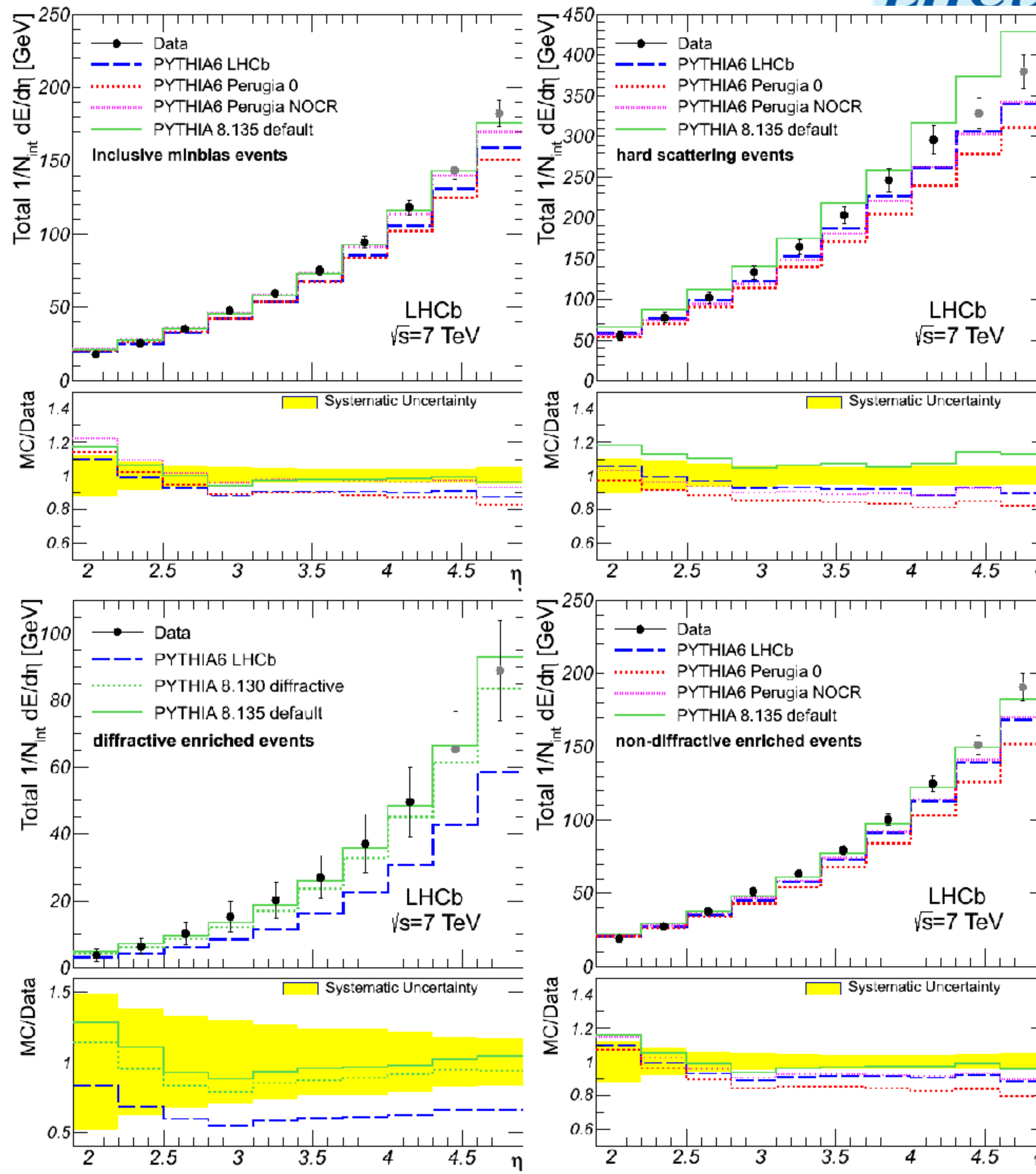
Charged particle multiplicity distribution in domain p_T > 1 GeV/c. With respect to shape, previous tendencies are enhanced. Best agreement with data from PYTHIA8.180 and PYTHIA6 default tune.

Total Forward Energy Flow vs. PYTHIA Tunes

- PYTHIA6 tunes – below total EF for all event categories at higher η

- PYTHIA8 – best agreement for diffractive enriched events, overestimates total EF in hard scattering events

- Same conclusions as for the charged energy flow



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Corrected Total Forward Energy Flow vs. Cosmic-Ray Models

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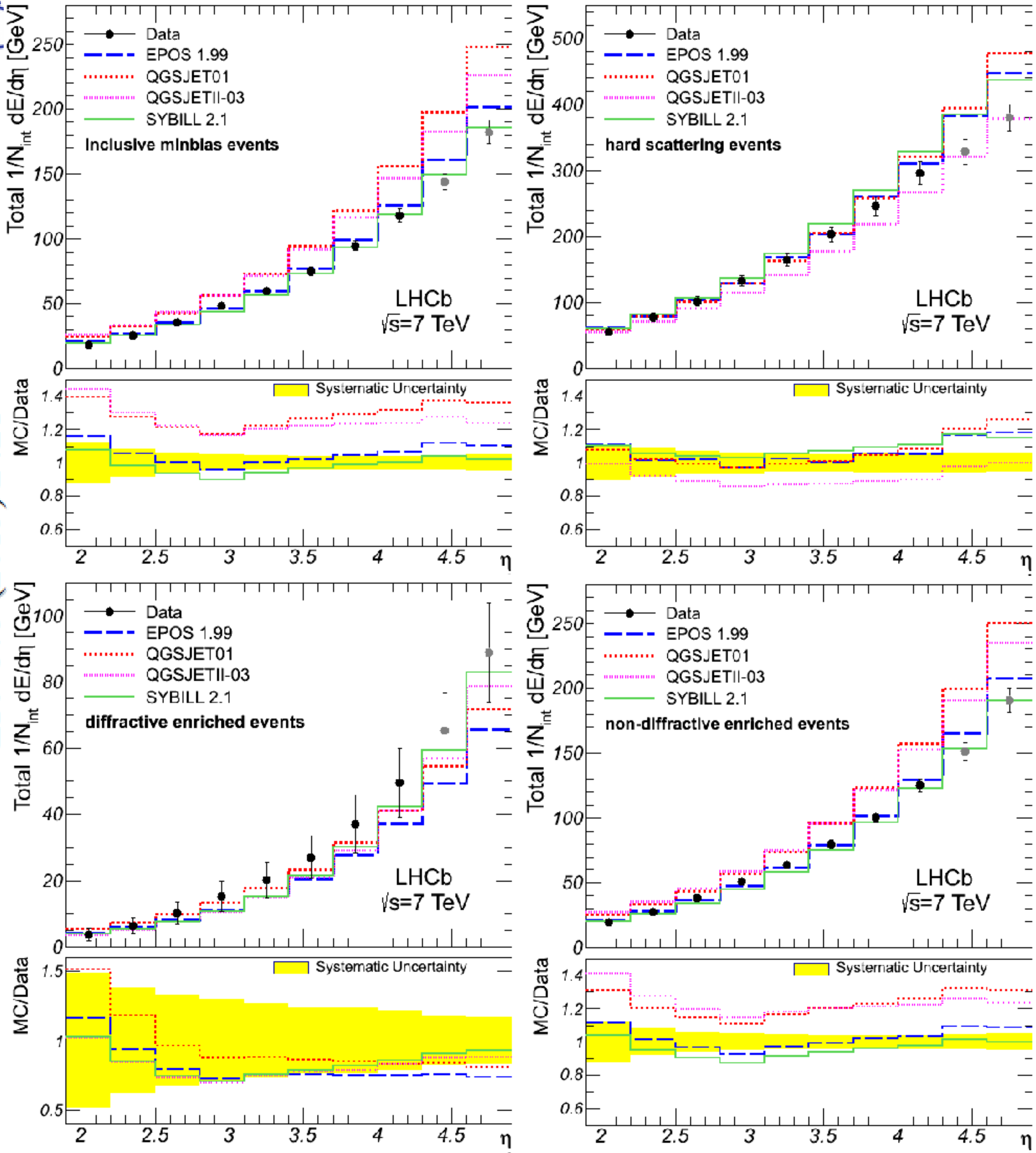

- Cosmic-ray interaction models tend to overestimate the total EF
- SYBILL and EPOS give the best description of the total EF for MB inclusive events
- SYBILL in particular has good agreement with LHCb events from all 4 classes considered except at high η for hard scattering events
- SYBILL interaction model seems to give competitive results with respect to PYTHIA8 for diffractive events
- QGSJETII-03 reliable in describing hard scattering events

Forward Energy Flow

Relative systematic uncertainties [%] on measurement of energy flow for all event classes. Total uncertainties obtained by summing in quadrature. Ranges correspond to the variation accros pseudorapidity domain.

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 charged EF	3.9 – 11	4.9 – 10	16 – 43	4.0 - 11
Variation of neutral EF estimation parameters	0.8 – 6.1	0.7 – 2.9	1.5 – 23	0.9 – 5.5
Photon efficiency	1.4 – 1.6	1.2 – 1.3	1.3 – 2.3	1.3 – 1.6
ECAL miscalibration	<1	<1	<1	<1
Total on total EF	4.3 – 13	5.4 – 11	17 – 49	4.4 – 12