LHCb colliding-beam measurements for astroparticle physics

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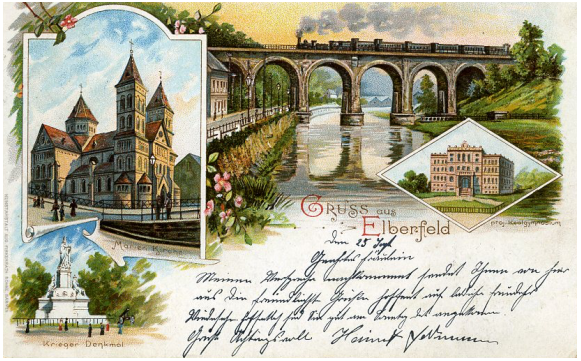
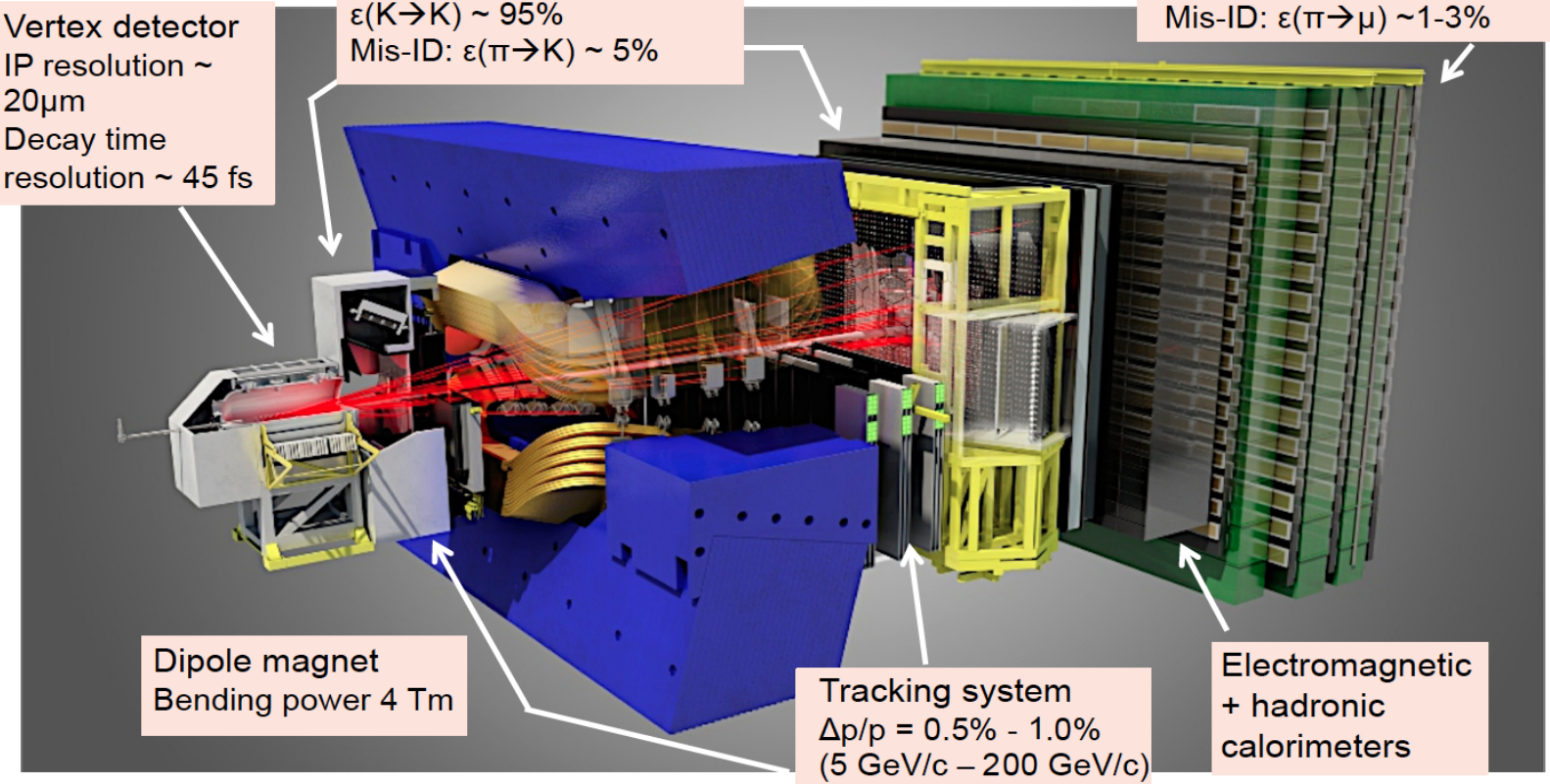
Outline

- The LHCb experiment
- Inelastic cross-sections
- Inclusive particle production and particle ratios
- Energy flow and multiplicities
- Strangeness and charm production
- Nuclear effects



SFB1491 Workshop on the tuning of hadronic interaction models

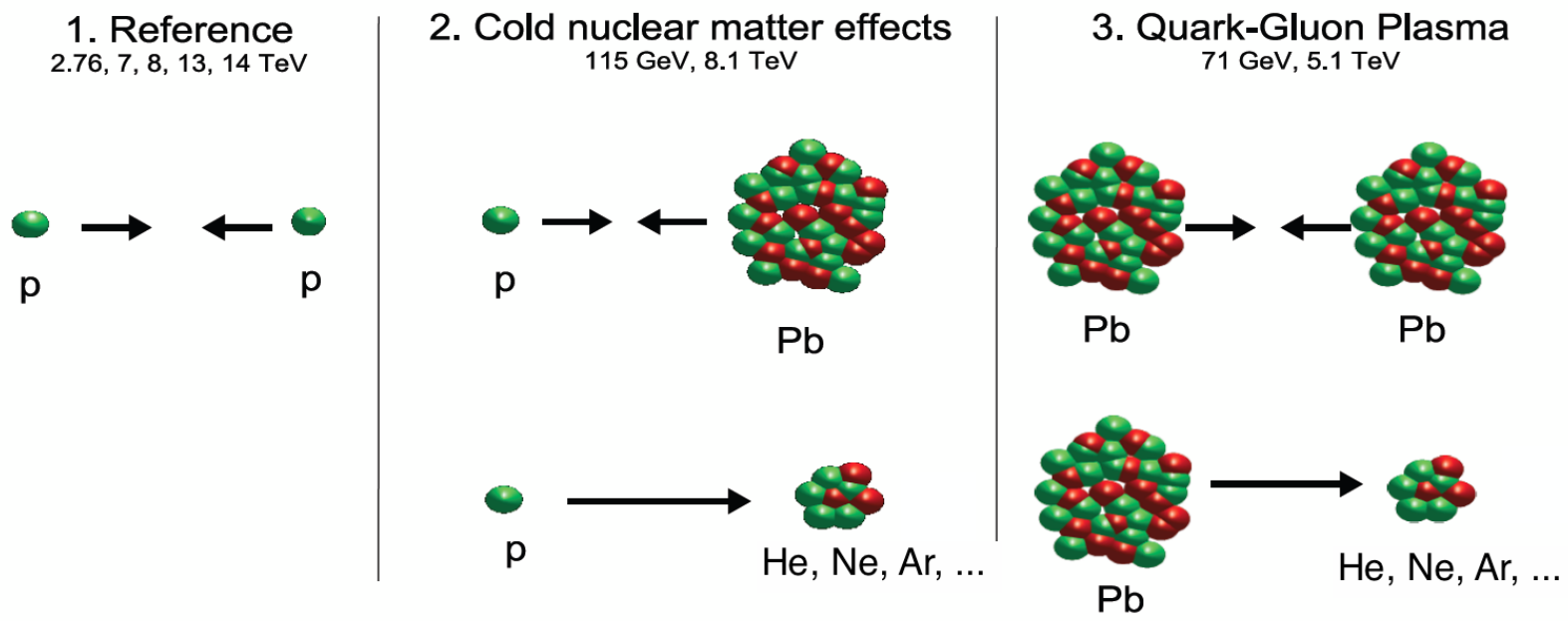
1 The LHCb experiment (Run 1&2)



JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

LHCb beam configurations

- possibility to study hadronic collisions. . .
  - as a function of the centre-of-mass energy
  - for different beam-target combinations



Colliding-beam versus fixed-target kinematics

❖ fixed-target beam energy

$$s_{NN} = (E_{\text{beam}} + m_N)^2 - E_{\text{beam}}^2 \approx 2 m_N E_{\text{beam}} \quad \text{and thus} \quad E_{\text{beam}} = \frac{s_{NN}}{2 m_N}$$

- LHC: $\sqrt{s_{NN}} = 13$ TeV and $E_{\text{beam}} = 9 \cdot 10^7$ GeV

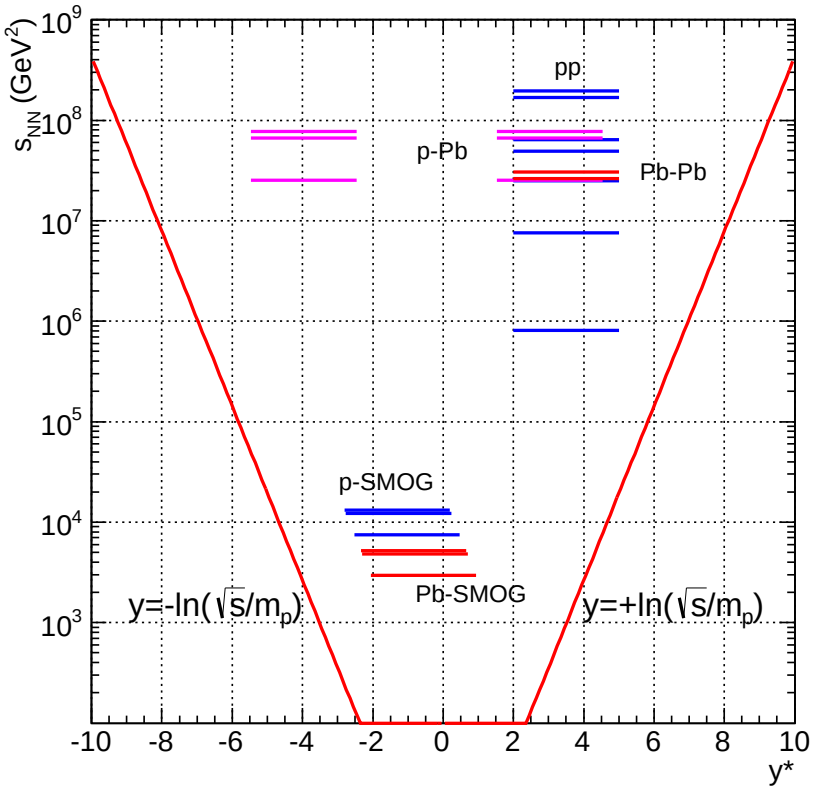
❖ Lorentz boost

$$y_{\text{boost}} = \frac{1}{2} \ln \frac{2 E_{\text{beam}}}{m_N} = \frac{1}{2} \ln \frac{s_{NN}}{m_N^2} = \ln \frac{\sqrt{s_{NN}}}{m_N}$$

- essentially the entire centre-of-mass final state is boosted forward
- rule of thumb at LHC energies:
  - rapidity range covered in centre-of-mass $O(-10 < y < 10)$
  - rapidity range covered in lab $O(0 < y < 20)$

Phase space coverage of LHCb

❖ kinematic acceptance for particle production measurements



❖ p_T range

$$p_T \sim 0.1 \ldots 10\,\mathrm{GeV}/c$$

❖ measurements

- total cross-sections
- inclusive particle production
- identified particles
- multiplicities
- energy flow

y^*: rapidity in NN-centre-of-mass system;
forward: (+ values) in proton/beam direction

Available data sets from Run 1&2

❖ beam target combinations and NN centre-of-mass energies $\sqrt{s_{NN}}$

E_{beam}(p)	pp	p-Gas	p-Pb/Pb-p	Pb-Gas	Pb-Pb	Xe-Xe
450 GeV	0.90 TeV					
1.38 TeV	2.76 TeV					
2.5 TeV	5 TeV	69 GeV				
3.5 TeV	7 TeV					
4.0 TeV	8 TeV	87 GeV	5 TeV	54 GeV		
6.5 TeV	13 TeV	110 GeV	8 TeV	69 GeV	5 TeV	5.4 TeV

- many measurements exists – some with RIVET plugin
- definitions of observables may vary

links to selected papers and plots of some key results ➜

2 Inelastic cross-sections

➤ JHEP 06 (2018) 100, arXiv:1803.10974

Measurement of the inelastic pp cross-section at a centre-of-mass energy of 13 TeV

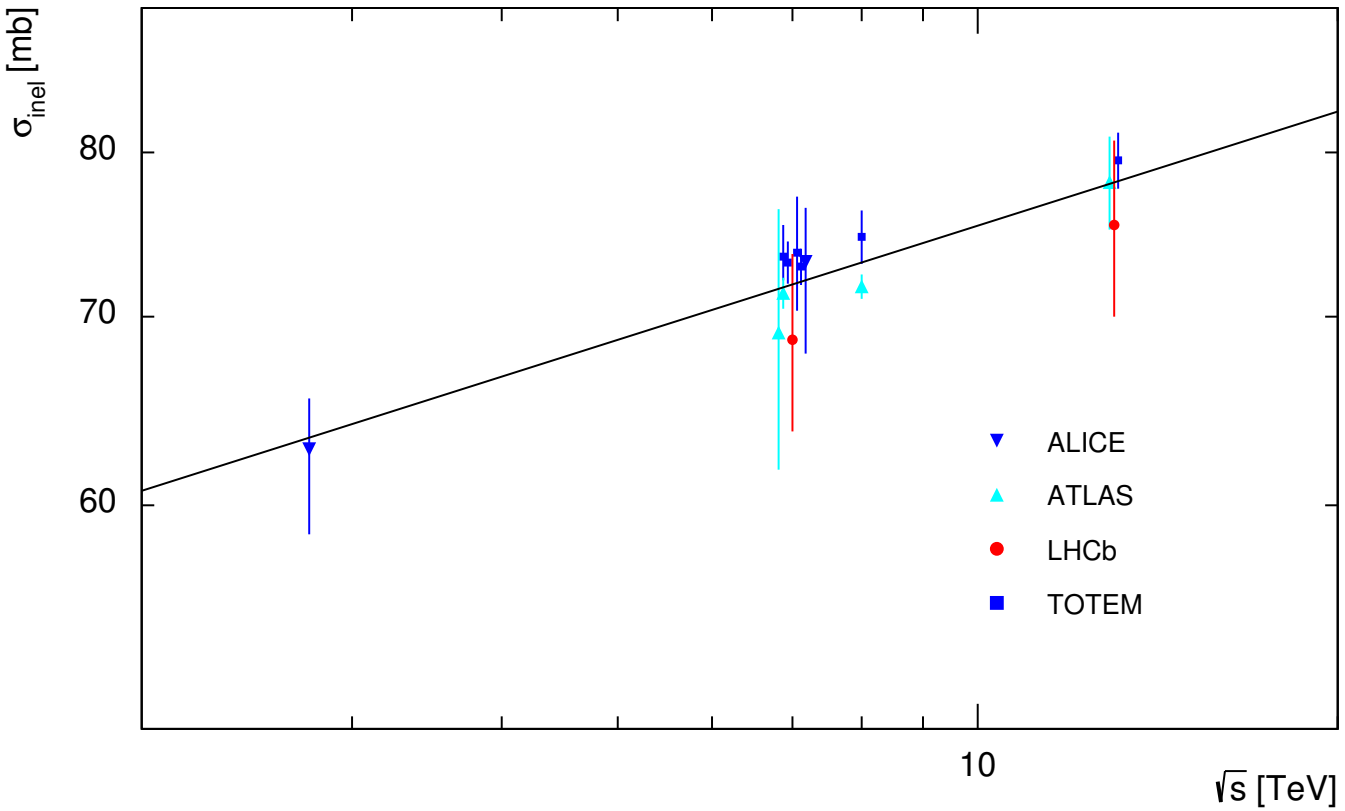
- $\geqslant 1$ long-lived prompt charged particle with $p > 2\,\text{GeV}$ and $2 < \eta < 5$
  - produced directly in the interaction or from decays of short-lived ancestors
  - "short-lived" defined as $\tau < 30\,\text{ps}$
- fiducial cross-section: $\sigma_{\text{acc}} = 62.2 \pm 0.2 \pm 2.5\,\text{mb}$
- extrapolation to full phase space: $\sigma_{\text{inel}} = 75.4 \pm 3.0 \pm 4.5\,\text{mb}$

➤ JHEP 02 (2015) 129, arXiv:1412.2500

Measurement of the inelastic pp cross-section at a centre-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$

- $\geqslant 1$ long-lived prompt charged particle with $p_T > 0.2\,\text{GeV}$ and $2.0 < \eta < 4.5$
  - long-lived particle with impact parameter $I < 0.2\,\text{mm}$ at primary vertex
- (updated) fiducial cross-section: $\sigma_{\text{acc}} = 56.5 \pm 1.7\,\text{mb}$
- extrapolation to full phase space: $\sigma_{\text{inel}} = 68.7 \pm 2.1 \pm 4.5\,\text{mb}$

LHC inelastic cross-section results



data with a power-law fit

3 Inclusive particle production and particle ratios

➤ JHEP 01 (2022) 166, arXiv:2107.10090

Measurement of prompt charged-particle production in pp collisions at $\sqrt{s} = 13$ TeV

- differential cross-section for prompt long-lived charged particles and charge ratios
  - produced directly in the interaction or from decays of short-lived ancestors
  - "short-lived" defined as $\tau < 30\,\text{ps}$
  - kinematic range: $p_T \in [80, 10000]$ MeV, $\eta \in [2.0, 4.8)$

➤ EPJC 72 (2012) 2168, arXiv:1206.5160

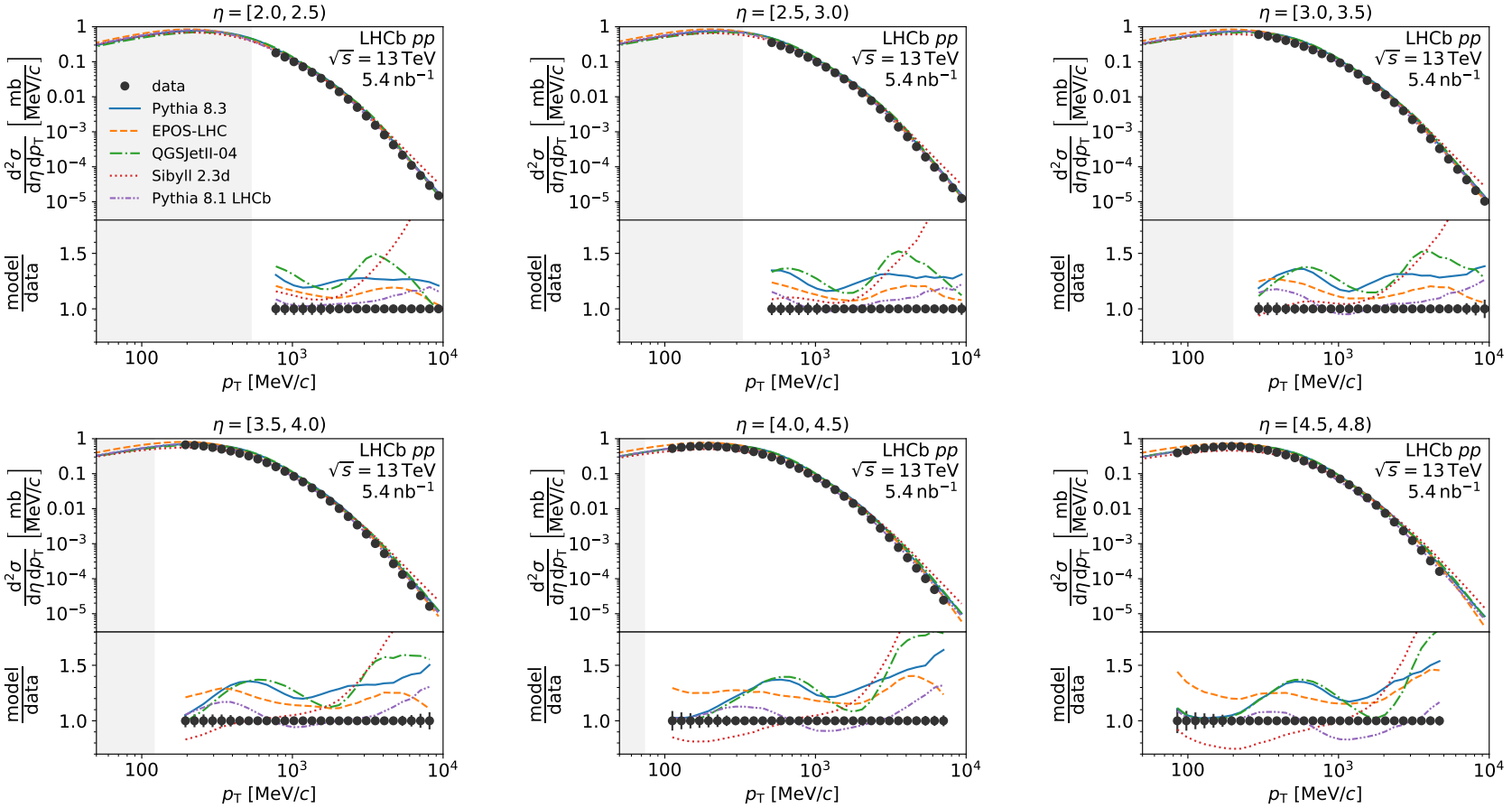
Measurement of prompt hadron production ratios in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV

- particle ratios

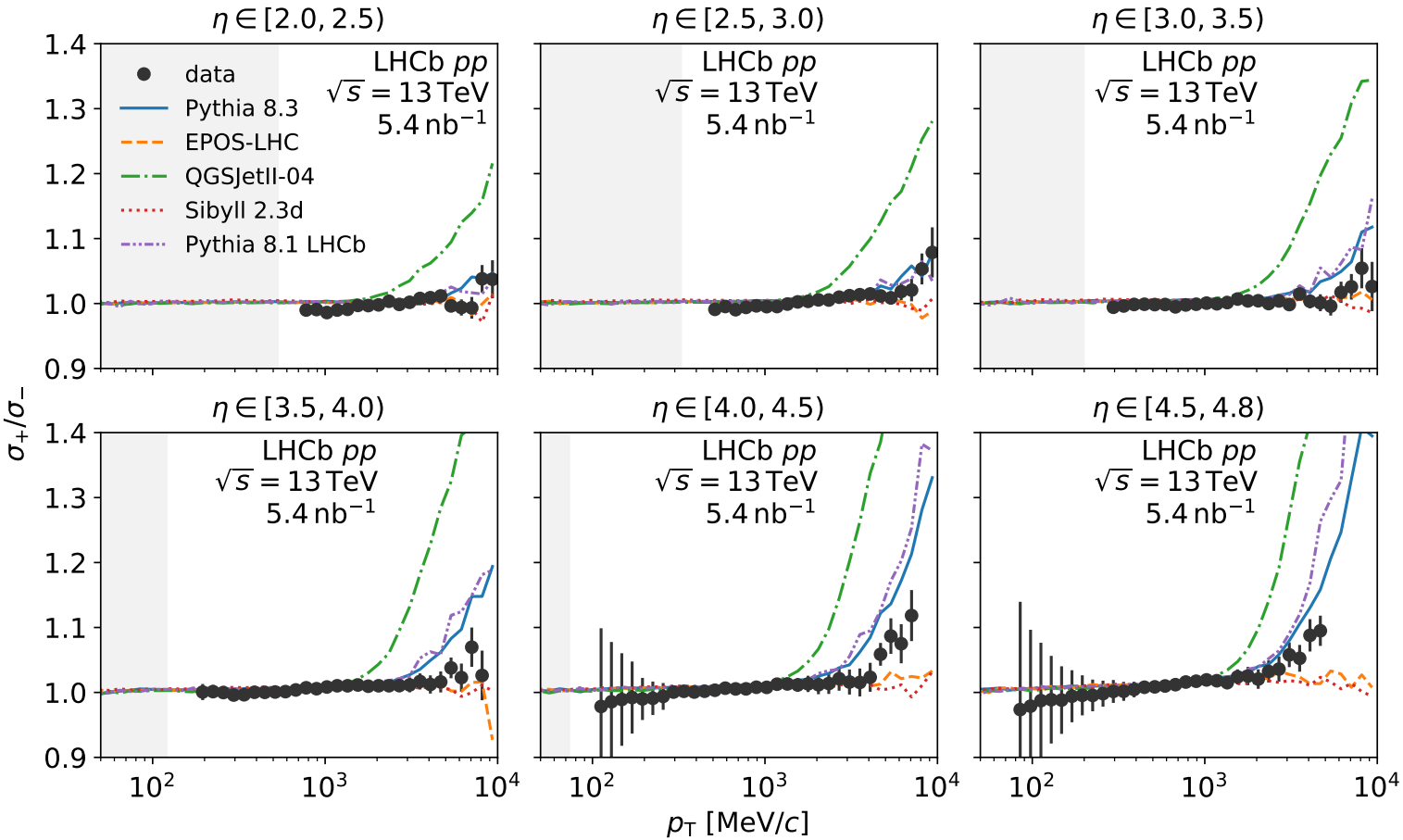
$$\frac{\pi^-}{\pi^+}\,,\ \frac{K^-}{K^+}\,,\ \frac{\bar{p}}{p}\,,\ \frac{\bar{\Lambda}}{\Lambda} \quad \text{and} \quad \frac{K^+ + K^-}{\pi^+ + \pi^-}\,,\ \frac{p + \bar{p}}{\pi^+ + \pi^-}\,,\ \frac{p + \bar{p}}{K^+ + K^-}\,,\ \frac{\bar{\Lambda}}{K^0_S}$$

  - lots of information about the hadronization process
  - e.g. strangeness and baryon suppression by kaon/pion and baryon/meson ratios

Inclusive production cross-sections



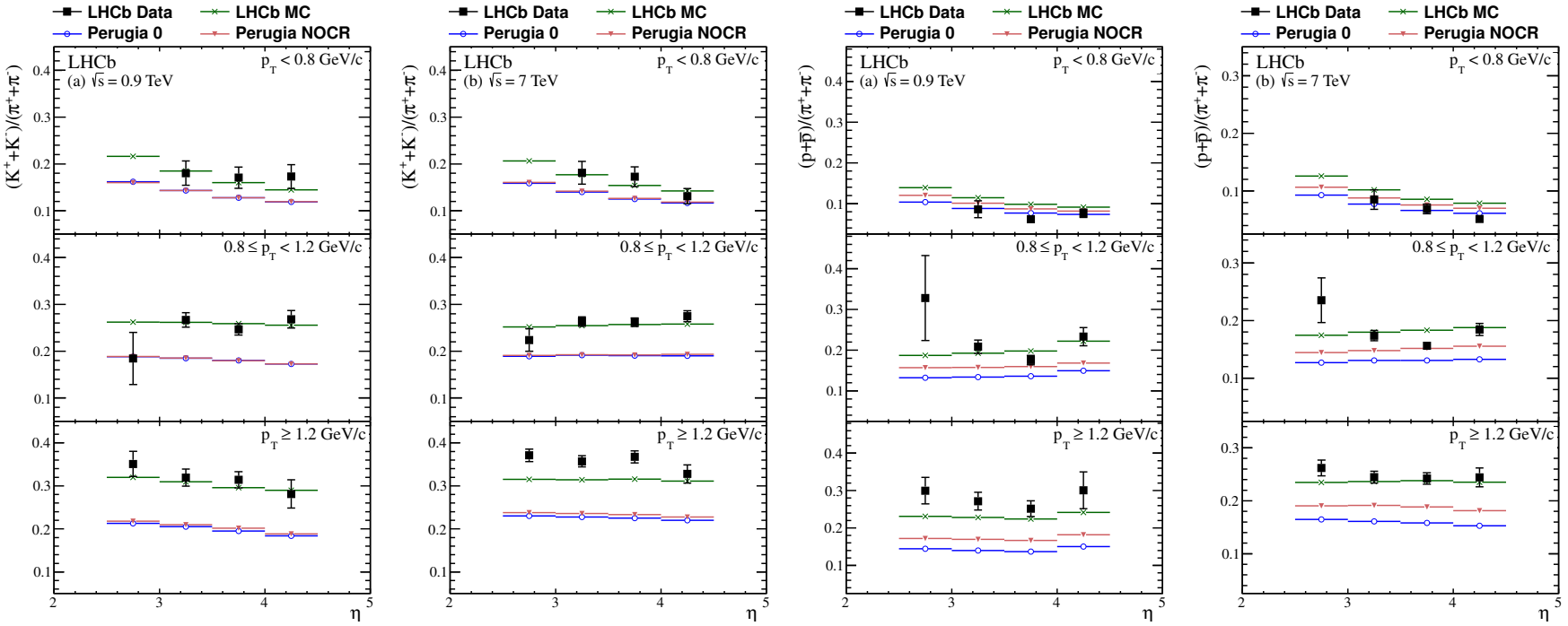
Charge ratios



Strangeness and baryon suppression

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

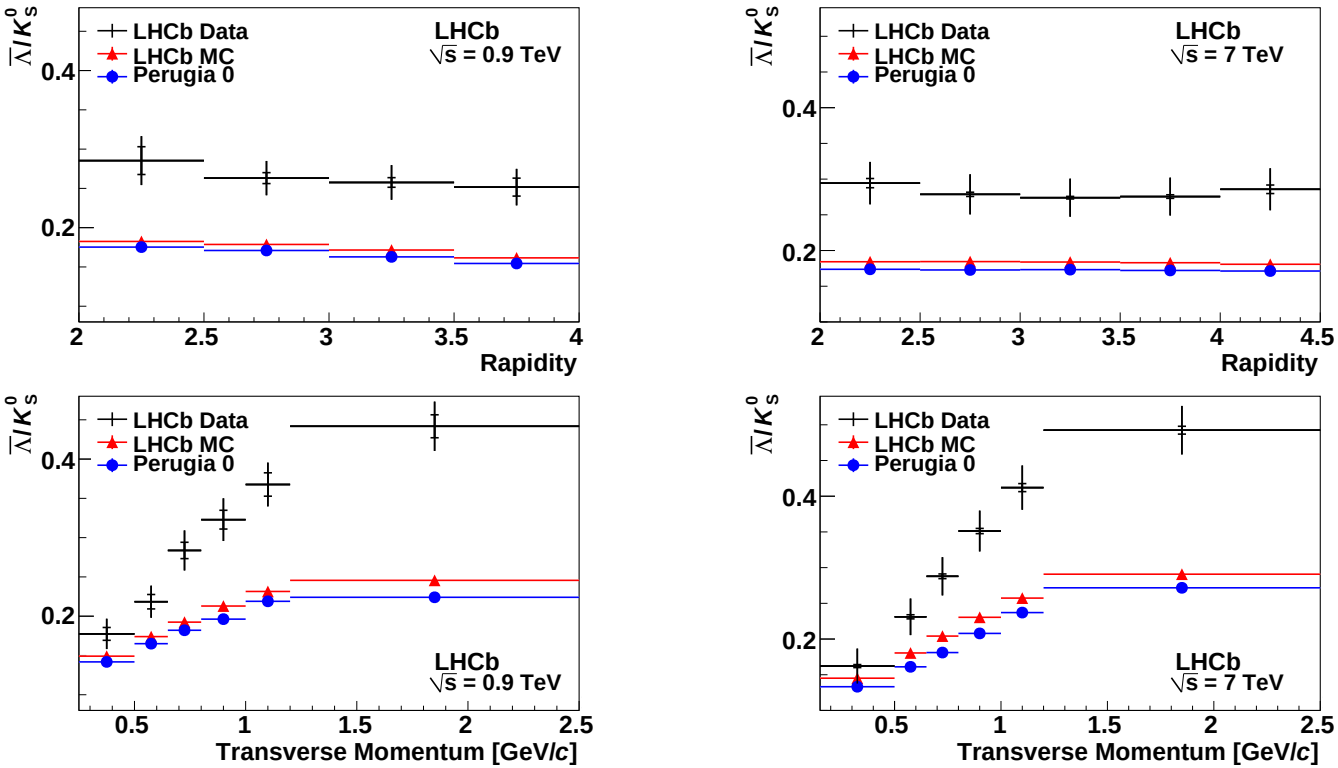
$\sqrt{s} = 0.9\,\text{TeV}$ $\sqrt{s} = 7\,\text{TeV}$ $\sqrt{s} = 0.9\,\text{TeV}$ $\sqrt{s} = 7\,\text{TeV}$



➜ here the LHCb MC based on Pythia 6 works best

Strange-baryon suppression

$\sqrt{s} = 0.9\,\text{TeV}$ $\sqrt{s} = 7\,\text{TeV}$



➜ all considered PYTHIA 6 tunes fail to describe the strangeness-data

4 Energy flow and multiplicities

➤ EPJC 73 (2013) 2421, arXiv:1212.4755

Measurement of the forward energy flow in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

- event classes for measurement of $1/N_{\text{int}}\, dE/d\eta$
  - inclusive minimum bias: $\geqslant 1$ tracks with $\eta \in [1.9, 4.9]$ and $p > 2\,\text{GeV}/c$
  - hard scattering: inclusive && $\geqslant 1$ tracks with $p_T > 3\,\text{GeV}/c$
  - diffractive enriched: inclusive && 0 tracks with $\eta \in [-3.5, -1.5]$
  - non-diffractive enriched: inclusive && $\geqslant 1$ tracks with $\eta \in [-3.5, -1.5]$

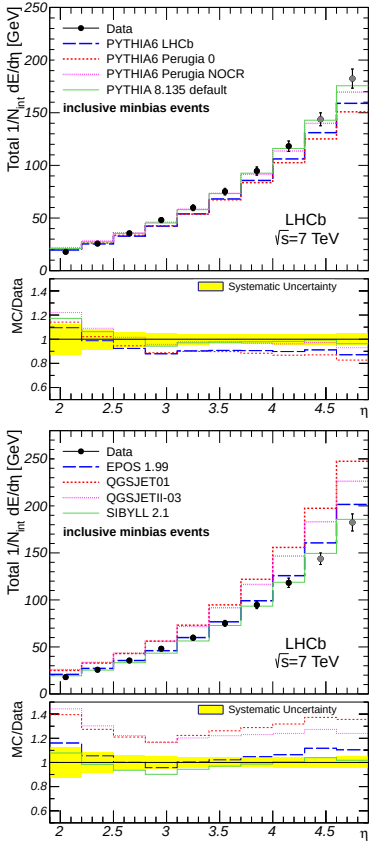
➤ EPJC 74 (2014) 2888, arXiv:1402.4430

Measurement of charged particle multiplicities and densities in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ in the forward region

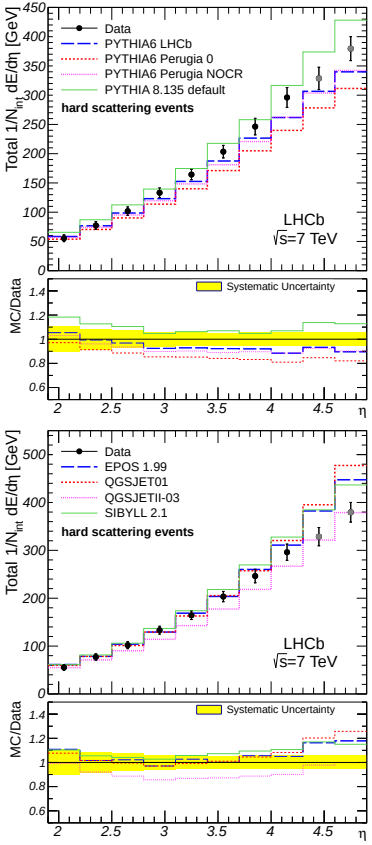
- charged particles with $p_T > 0.2\,\text{GeV}$, $p > 2\,\text{GeV}$, $2.0 < \eta < 4.8$
- produced directly of from decays of ancestors with $\sum \tau < 10$,ps

Energy flow compared to Pythia and cosmic ray models

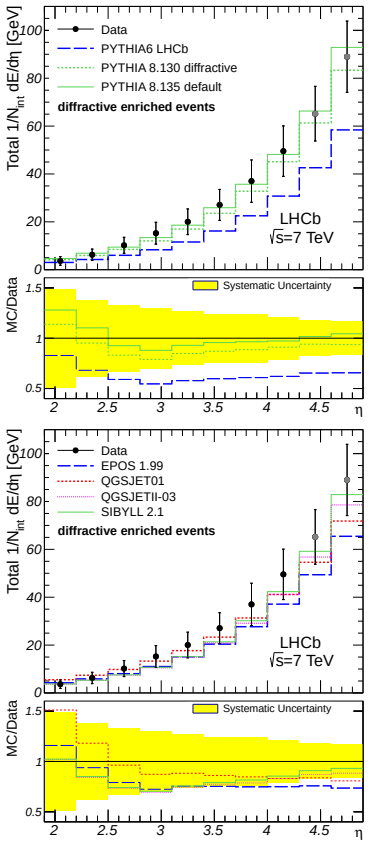
inclusive minimum bias



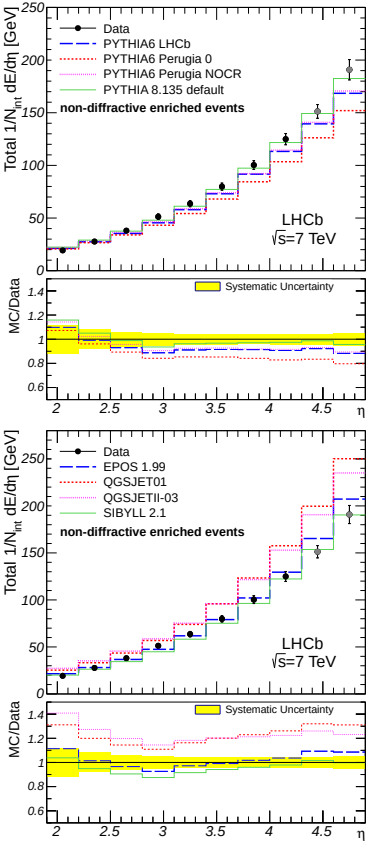
hard scattering



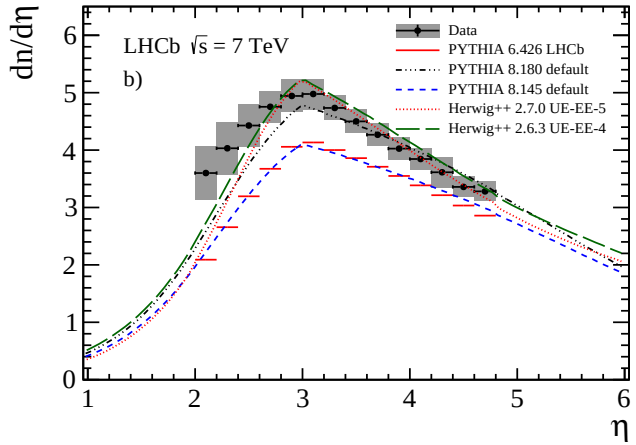
diffractively enriched

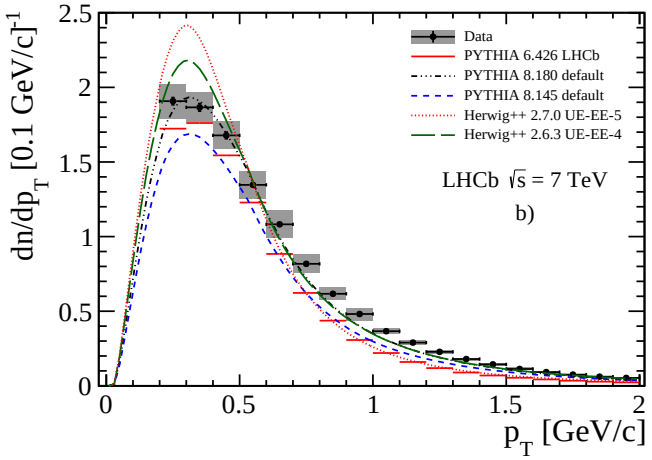


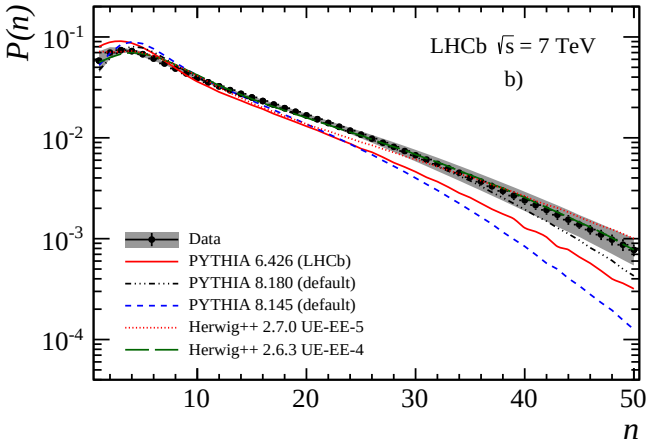
non-diffractive enriched



Particle densities and multiplicity distribution at 7 TeV







- none of the models is perfect
- satisfactory modelling by PYTHIA8 and Herwig++

5 Strangeness and charm production

➤ PLB 693(2010) 69, arXiv:1008.3105

Prompt K^0_S production in pp collisions at $\sqrt{s} = 0.9$ TeV

- prompt K^0_S mesons measure strangeness production

➤ JHEP 06 (2017) 147, arXiv:1610.02230

Measurements of prompt charm production cross-sections in pp collision at $\sqrt{s} = 5$ TeV

- prompt D mesons measure charm production; with fragmentation fractions:
  $\sigma(pp \to c\bar{c}X)|_{p_T<8\text{GeV},2.0<y<4.5} = 1193 \pm 3 \pm 67 \pm 58\,\mu\text{b}$

➤ NPB 718 (2013) 1, arXiv:1302.2864

Prompt charm production in pp collisions at $\sqrt{s} = 7$ TeV

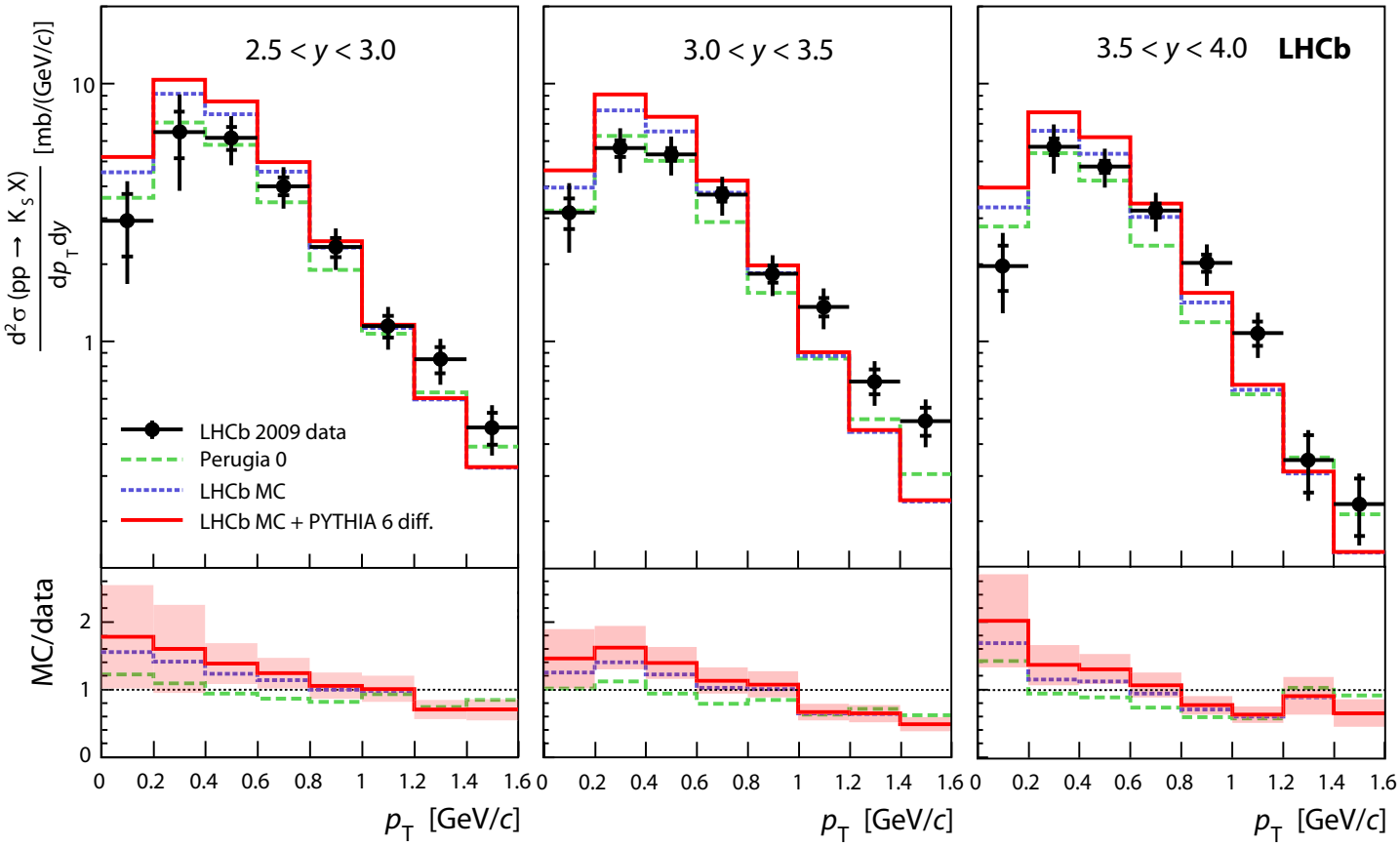
- $\sigma(pp \to c\bar{c}X)|_{p_T<8\text{GeV},2.0<y<4.5} = 1419 \pm 12 \pm 116 \pm 65\,\mu\text{b}$

➤ JHEP 05 (2017) 074, arXiv:1510.01707

Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV

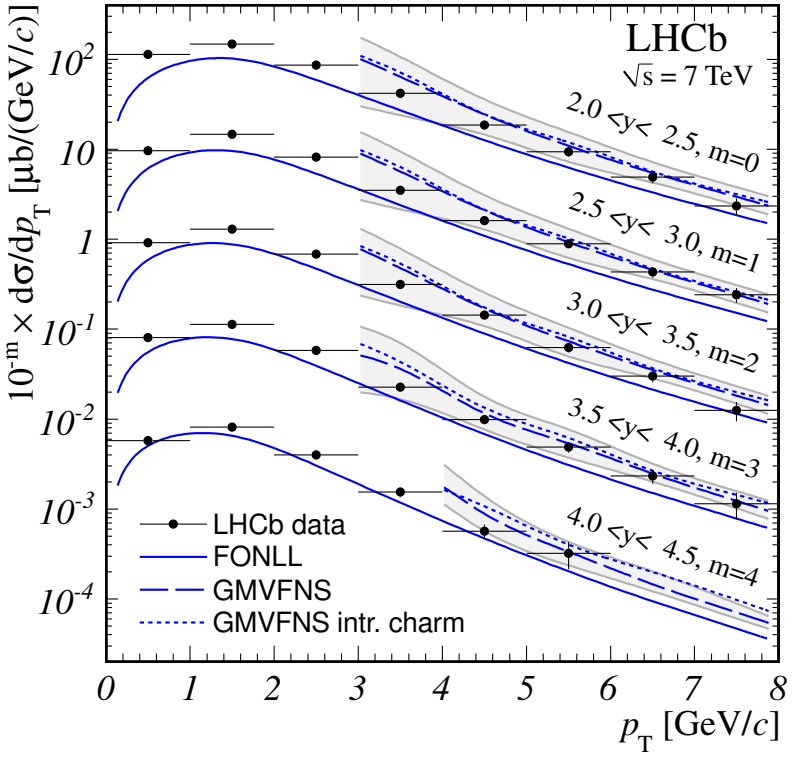
- $\sigma(pp \to c\bar{c}X)|_{p_T<8\text{GeV},2.0<y<4.5} = 2369 \pm 3 \pm 152 \pm 118\,\mu\text{b}$

Differential K^0_S production cross-sections

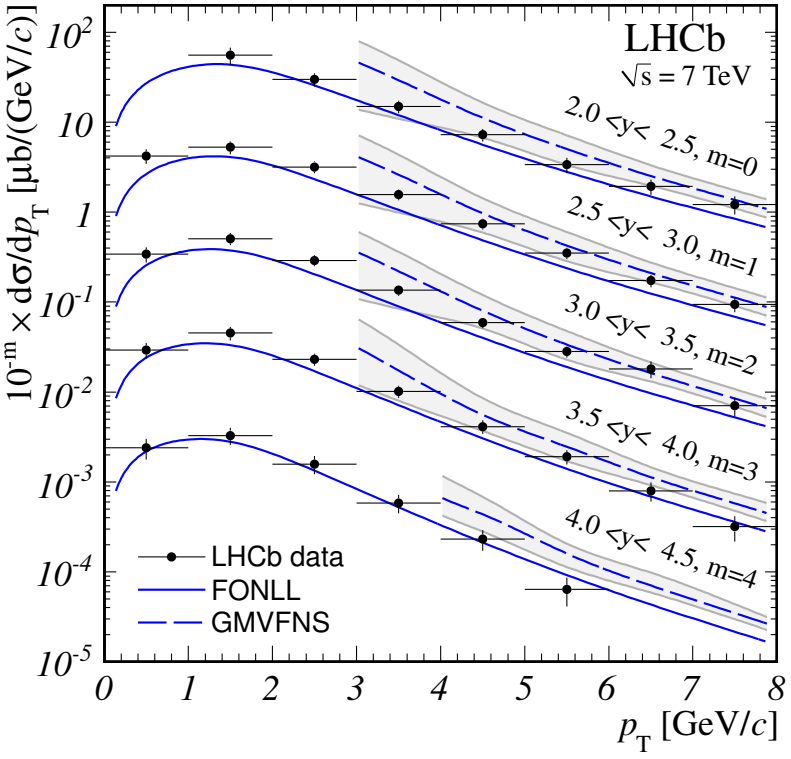


Differential D-meson production cross-sections

$D^0 + \overline{D^0}$



$D^+ + D^-$



6 Nuclear effects

➤ PRL 131 (2023) 042302, arXiv:2204.10608

Nuclear modification factor of neutral pions in the forward and backward regions in pPb collisions

➤ PRL 128 (2022) 142004, arXiv:2108.13115

Measurement of the nuclear modification factor and prompt charged particle production in pPb and pp collisions at $\sqrt{s_{NN}} = 5\,\text{TeV}$

➤ PRL 131 (2023) 102301, arXiv:2205.03936

Measurement of the prompt D^0 nuclear modification factor in pPb collisions at $\sqrt{s_{NN}} = 8.16\,\text{TeV}$

- modification of (differential) particle production cross-section by nuclear environment

$$R_{pA} = \frac{1}{A}\,\frac{d\sigma(pA)}{d\sigma(pp)}$$

➤ PRL 125 (2020) 212001, arXiv:2007.06945

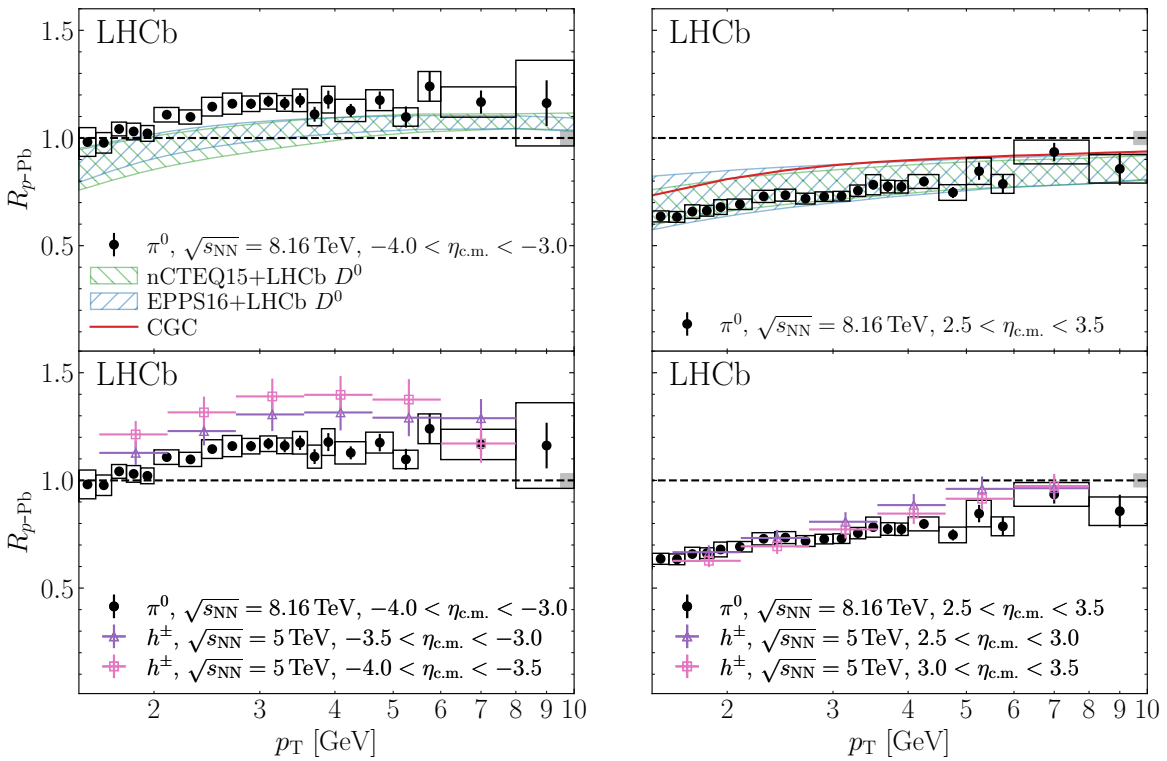
Observation of enhanced double-parton scattering in proton-lead collisions at $\sqrt{s_{NN}} = 8.16\,\text{TeV}$

- observed enhancement consistent with expectations

Nuclear modification factors for neural pions and charged hadrons

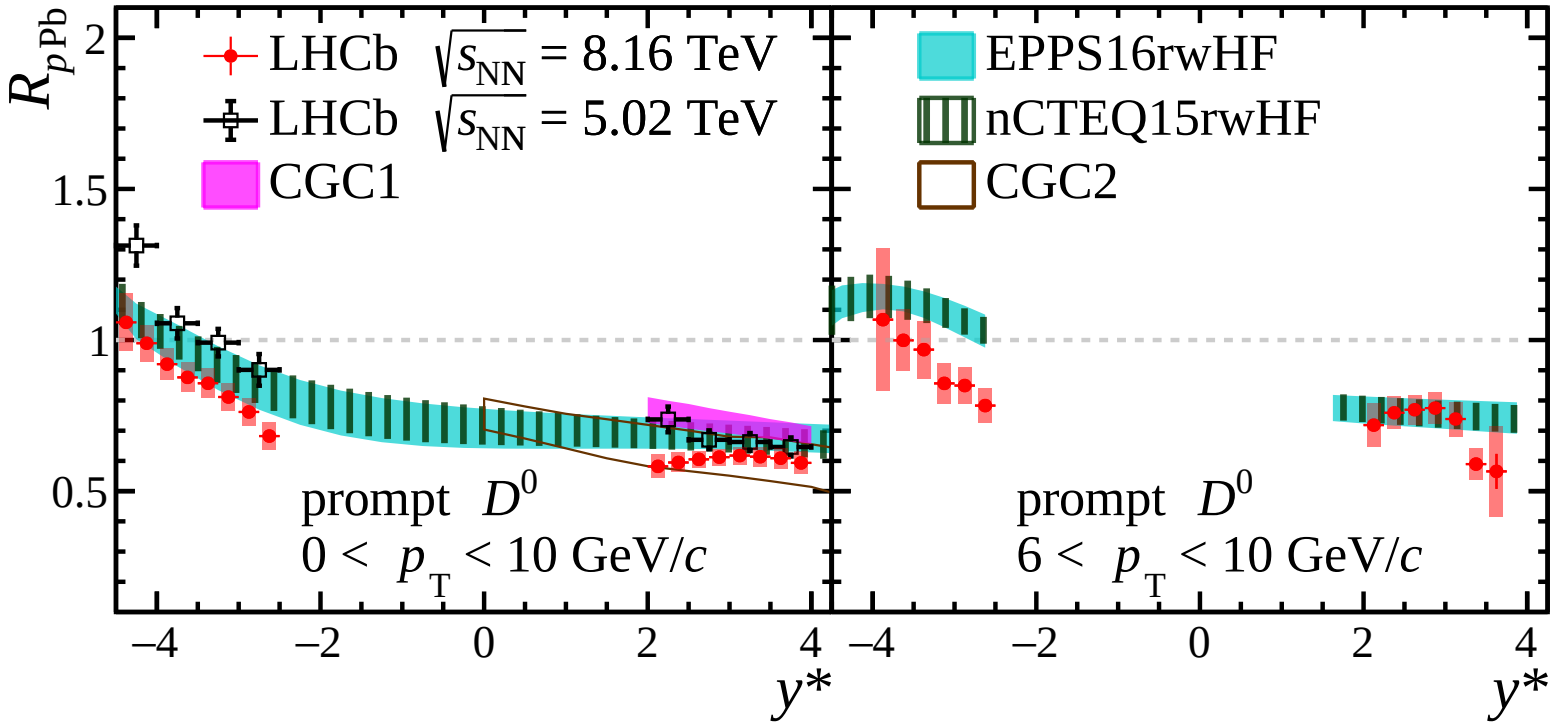
backward

forward



- forward suppression
- backward enhancement
- small energy dependence
- similar for all hadrons

Nuclear modification factors for charm mesons



➜ reasonable agreement with expectation from nuclear PDFs