QCD measurements in the forward region with the LHCb experiment

Bundesministerium für Bildung und Forschung

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(on behalf of the LHCb collaboration)

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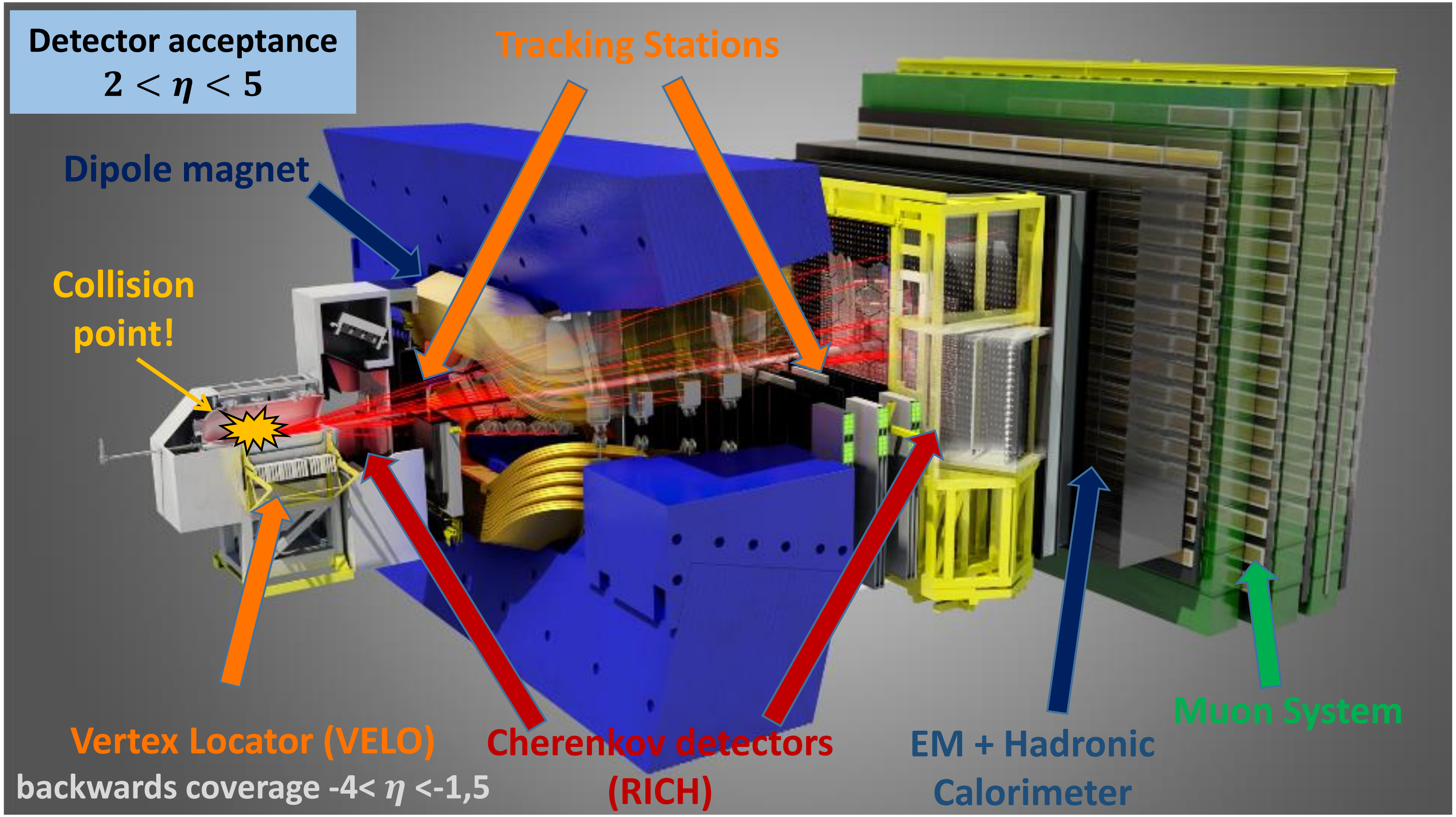
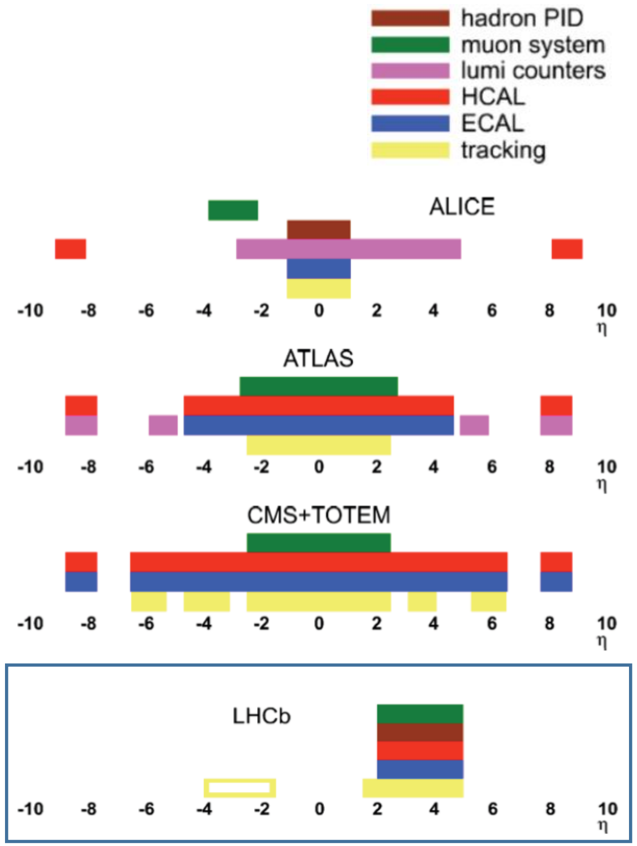
The LHCb detector



JINST 3 (2008) S08005



LHCb is fully equipped over the whole acceptance in the forward region ($2 < \eta < 5$) !

List of Soft-QCD/Charm publications

Global event properties:

- EPJC73(2012)1947 Measurement of charged particle multiplicities at $\sqrt{s} = 7\ TeV$
- EPJC73(2013)2124 Measurement of the forward energy flow at $\sqrt{s} = 7\ TeV$
- arXiV:1402.4430 Measurement of charged particle multiplicities and densities in pp collisions at $\sqrt{s} = 7\ TeV$ in the forward region

Light quarks & strangeness:

- PLB693(2010) 69 Prompt K_S^0 production in pp collisions at $\sqrt{s} = 0.9\ TeV$
- PLB703(2011) 267 Measurement of in the inclusive ϕ-cross-section $\sqrt{s} = 7\ TeV$
- JHEP08(2011) 034 Measurement of V^0 production ratios at $\sqrt{s} = 0.9$ and $7\ TeV$
- EPJC72(2012) 2168 Prompt hadron production ratios at $\sqrt{s} = 0.9$ and $7\ TeV$

Open charm and charmonium:

- EPJC71(2011) 1645 J/Ψ production in pp collisions at $\sqrt{s} = 7\ TeV$
- EPJC72(2012) 2100 Ψ(2S) meson production in pp collisions at $\sqrt{s} = 7\ TeV$
- NPB871(2013) 1 Prompt charm production at $\sqrt{s} = 7\ TeV$
- JHEP02(2013) 041 J/Ψ production in pp collisions at $\sqrt{s} = 2.76\ TeV$
- JHEP06(2013) 064 Production of J/Ψ and Υ mesons in pp collisions at $\sqrt{s} = 8\ TeV$
- JPG40(2013)045001 Exclusive J/Ψ and Ψ(2S) production at $\sqrt{s} = 7\ TeV$

Proton-Ion collisions:

- JHEP 02 (2014) 072 Study of J/Ψ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}} = 5\ TeV$

Charged particle multiplicities & densities

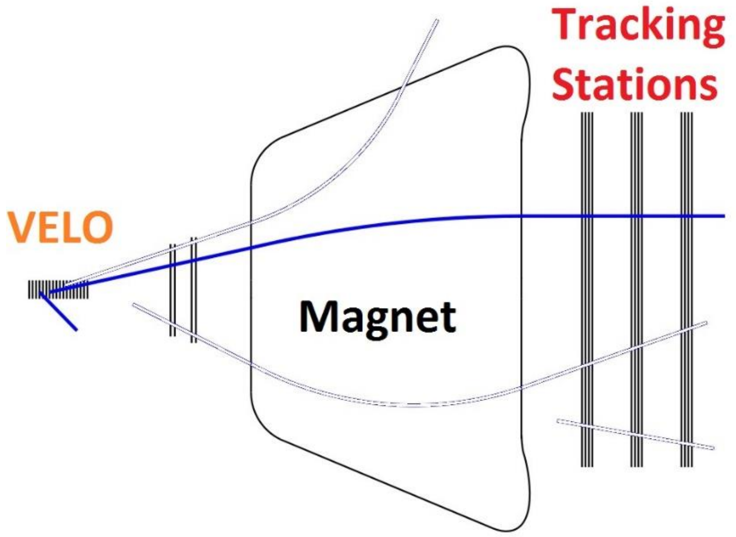
arXiv:1402.4430

(accepted for publication in EPJC)

new

- Second multiplicity measurement from LHCb (link to previous paper)

- This new analysis uses entire LHCb tracking system
  - ✓ Different kinematic range:
    $2.0 < \eta < 4.8$ and $\mathrm{p} > 2\mathrm{GeV}$ and $p_T > 200$ MeV
  - ✓ Gives access to momentum information
    -> differential measurement in p_T and η
  - ✓ measure particle multiplicities *P(n)*
    and particle densities *dn/dX*



- Used a minimum bias **data sample** of pp-collisions at $\sqrt{s} = 7$ TeV
  - ✓ 3M events (equal proportion of both magnetic field configurations)
  - ✓ low pile-up contribution of less than 4%

- Prompt charged particles are defined as:
  particles originating directly from the PV or from a decay chain with $\sum \tau_{PDG} < 10ps$.

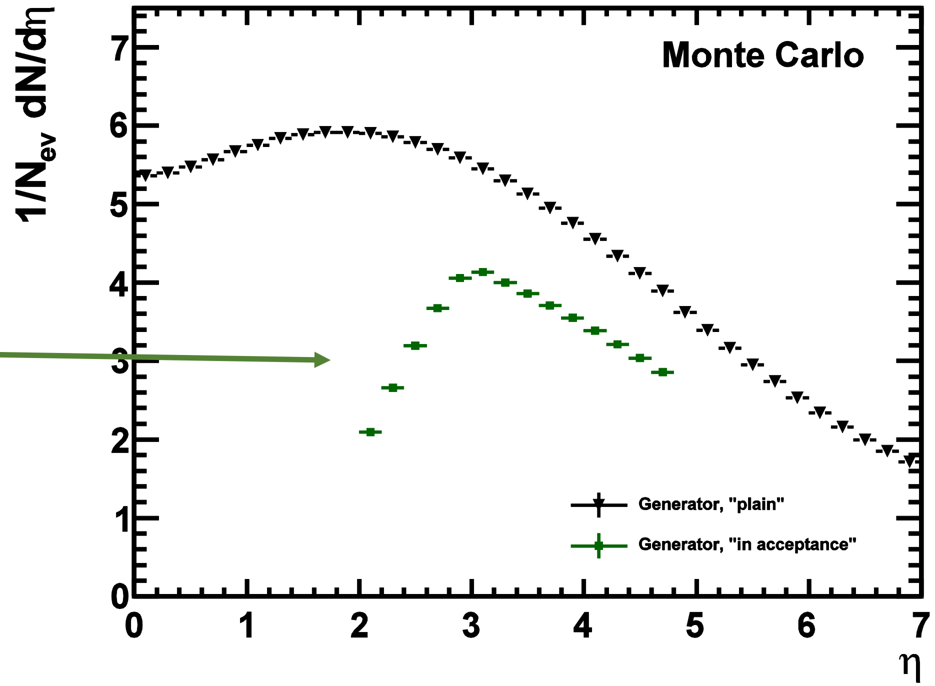
Charged particle multiplicities & densities

- Motivation:
  - Soft-QCD processes (e.g. light particle production) cannot be calculated perturbatively
  - Fragmentation, hadronisation and modelling of final states are treated differently in MC generators
  - Phenomenological models can be tested and optimized with multiplicity measurements.

- In order to compare the result directly to MC generator predictions the following definition is applied:

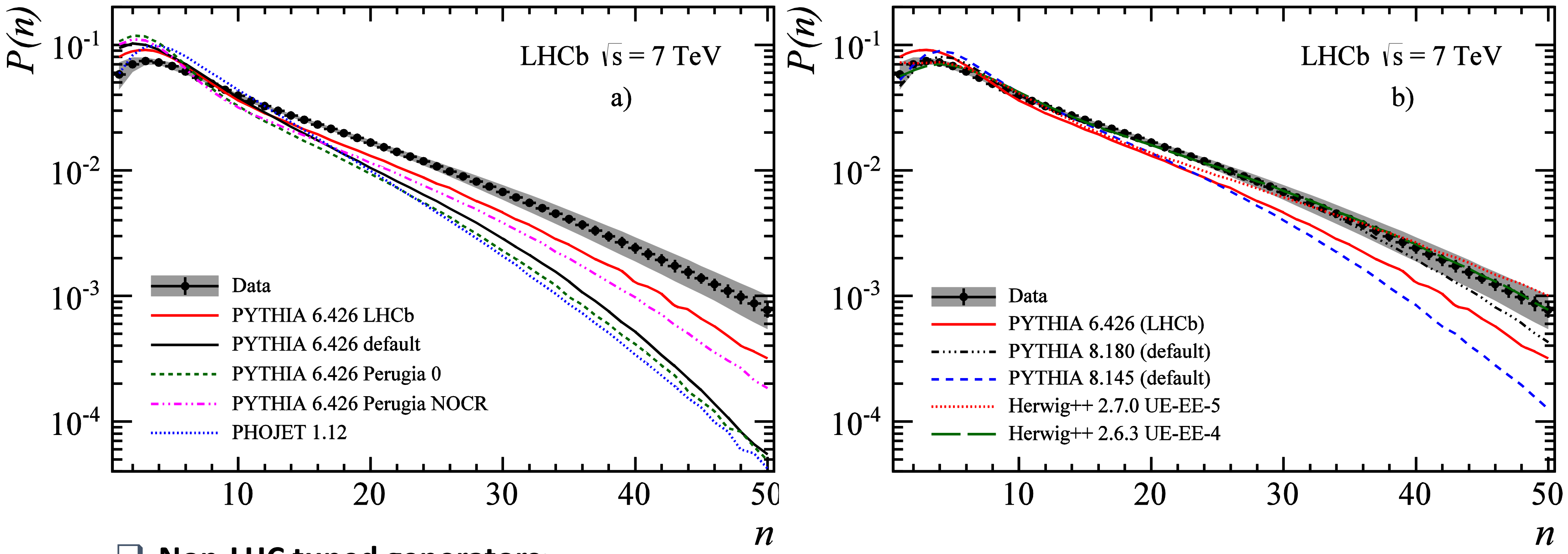
An **event is defined as visible,** if it contains at least one prompt charged particle within the kinematic range of the analysis:

- $2.0 < \eta < 4.8$
- $\mathrm{p} > 2\mathrm{GeV}$
- $p_T > 200\ \mathrm{MeV}$



typical momentum resolution: $\frac{\Delta p}{p} = 0.4 - 0.6\%$

Results – particle multiplicities



arXiv:1402.4430

Kinematic range:
- $2.0 < \eta < 4.8$
- $p_T > 200MeV$
- $p > 2GeV$

Multiplicities also measured in bins of η and p_T!

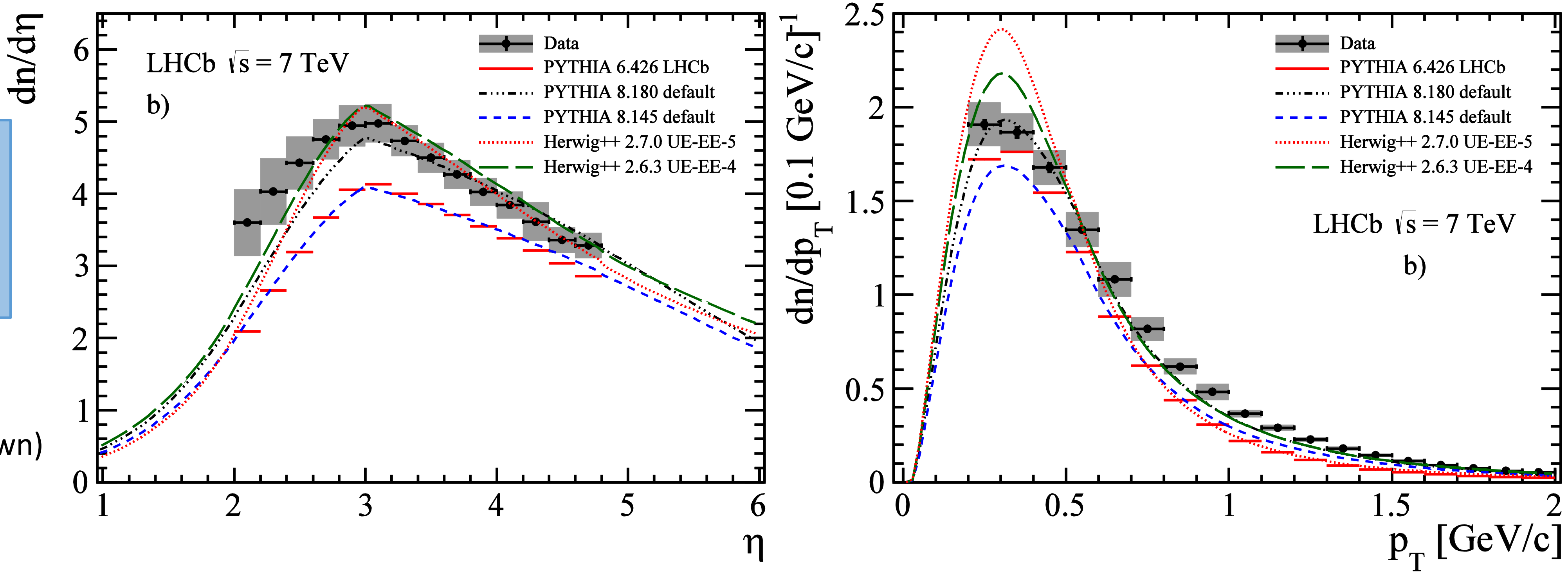
- **Non-LHC tuned generators**:
  - All PYTHIA 6 tunes, PHOJET and PYTHIA 8.145 underestimate charged particle production significantly!
  - LHCb tune of PYTHIA 6 is closest to data but still ~15% too small
- **Generators tuned to LHC data in central rapidity:**
  - PYTHIA 8.180 (Tune 4C) shows reasonable agreement
  - HERWIG++ tunes have good agreement, UE-EE-4 better than more recent UE-EE-5

Results – particle densities

arXiv:1402.4430

Kinematic range:
- $2.0 < \eta < 4.8$
- $p_T > 200MeV$
- $p > 2GeV$

(only comparison to recent generators shown)



Result compared to generators predictions, **tuned to LHC data** from the central rapidity region:

- PYTHIA 8.180 (Tune 4C) describes data significantly better than previous PYTHIA versions
- Also HERWIG++ gives a good description of the measurement, UE-EE-4 better than UE-EE-5
- The HERWIG++ tunes overestimate the density at small p_T and underestimate towards large p_T

➡ MC predictions are not yet optimal, still room for improvement

Energy flow

Energy Flow (EF): $$\frac{1}{N_{int}}\frac{dE_{total}}{d\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N_{int}}\sum_{i=1}^{N_{part,\eta}} E_{i,\eta}\right)$$

energy per particle

number of inelastic interactions

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

- Energy Flow at large pseudorapidity probes *multi-parton-interactions* (MPI) & *parton radiation*
- MPI is a predominant source of the *underlying event*
- Valuable input for generator tunings
  Comparison to *PYTHIA* and *cosmic-ray* event generators
- Analysis uses 0.1nb^{-1} of low pile-up pp-collision at $\sqrt{s}$ = 7 TeV

Energy Flow measured in 4 different event classes:

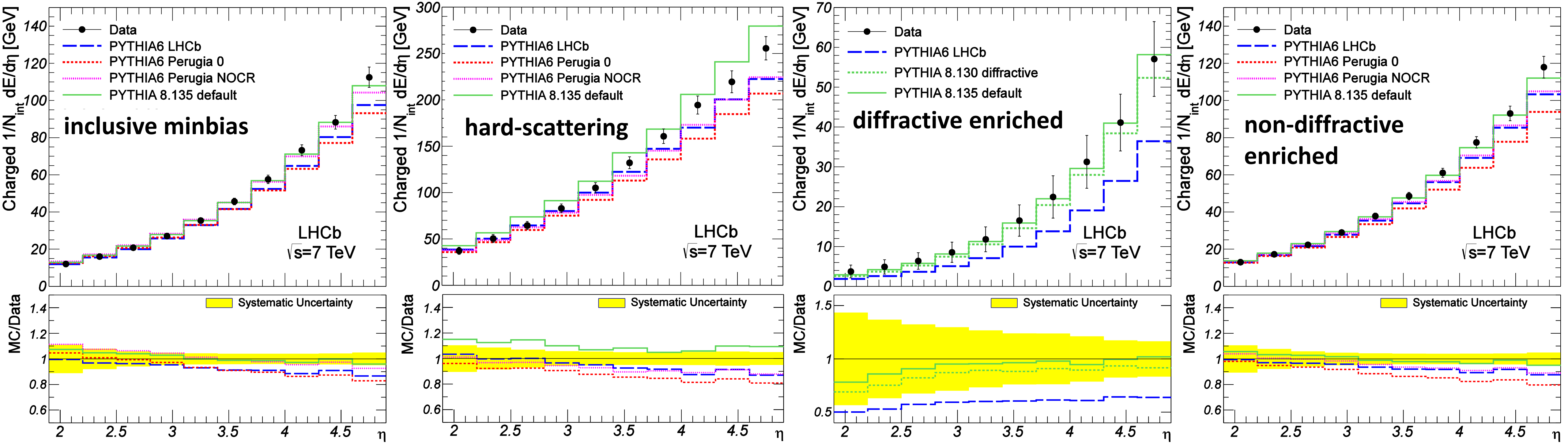
- Inclusive minimum-bias: at least 1 track in 1.9 < η < 4.9 and p > 2 GeV
- Hard- scattering: + p_T > 3 GeV
- Diffractive enriched: + no tracks in -3.5 < η < -1.5
- Non-diffractive enriched: + $\geq$ 1 track in -3.5 < η < -1.5

(Diffractive / Non-diffractive enriched:) Large rapidity gap for diffractive processes

Purity of the samples (PYTHIA6 based):
non-diffractive sample: $\sim 90\%$
diffractive sample: $\sim 70\%$

Energy flow

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



Charged Energy Flow

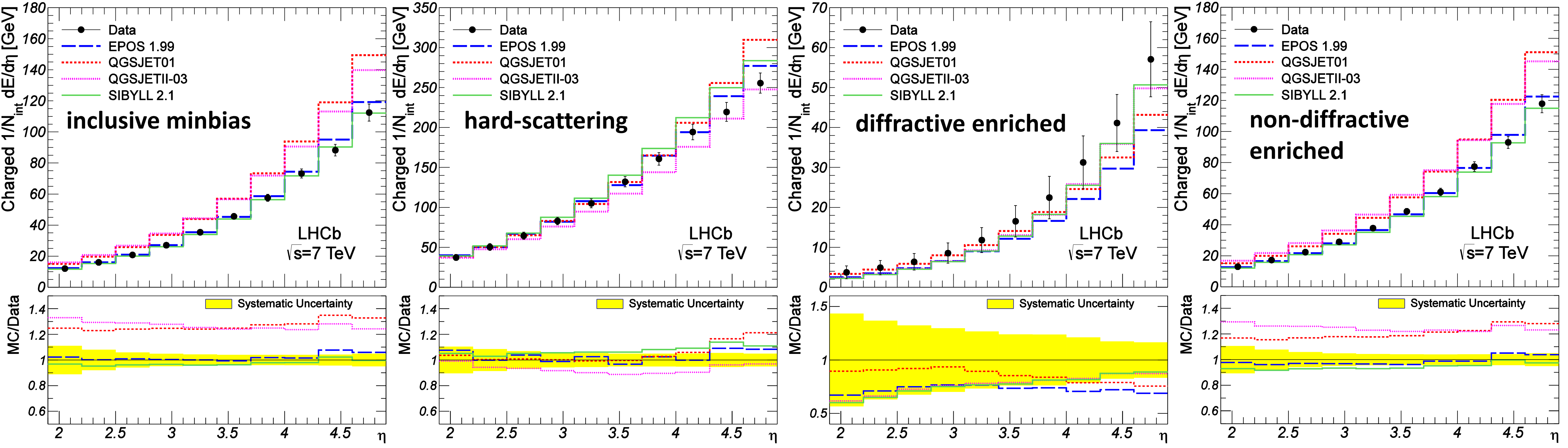
- Uncertainties decrease towards larger η
- EF increases with momentum transfer: $EF_{hard} > EF_{non-diff} > EF_{incl} > EF_{diff}$

➢ PYTHIA 6 tunes: in all samples EF is
-> overestimated at small η
-> underestimated at large η

➢ PYTHIA 8 tunes:
EF in all samples is well described at large η, except for hard scattering

Energy flow

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



Compared to **cosmic-ray** generators
(not tuned to LHC data!)

- Best description by SIBYLL
- All models underestimate EF in diffractive sample
  SIBYLL is good at large pseudorapidities

- EPOS & SIBYLL
  good description of minimum-bias and non-diffractive events
- QGSJET models
  overestimated EF in minimum-bias and non-diffractive events,
  but good description of hard scattering

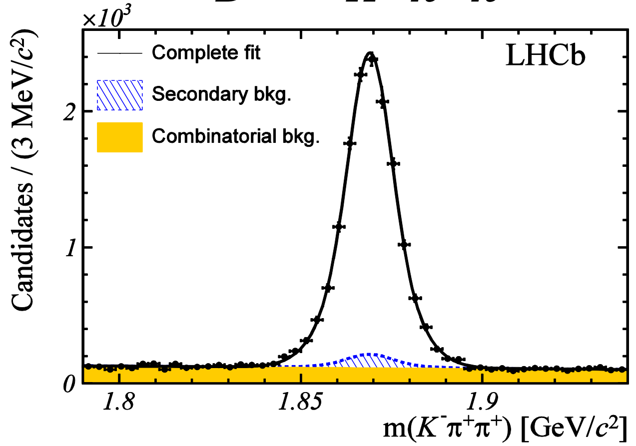
Prompt charm production

- Cross-section measurement tests QCD **fragmentation** and **hadronisation** models

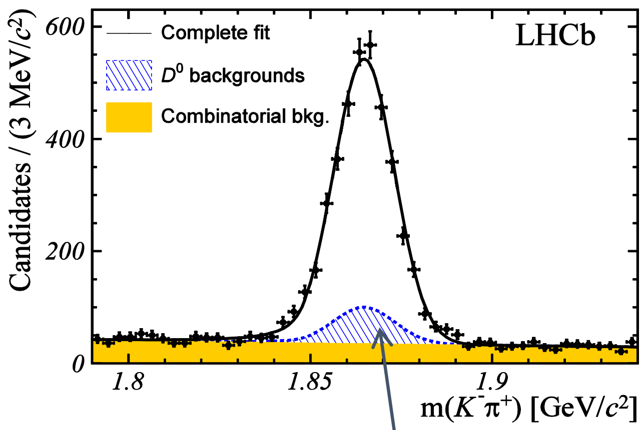
Nucl. Phys. B 871 (2013)

- $\sqrt{s}$ = 7TeV data set, $\mathcal{L}$=15nb^{-1}
- Fiducial region:
  2.0 < y < 4.5; 0 < p_T < 8 GeV
- Use fully reconstructed decays of prompt charm hadrons: $\boldsymbol{D^0}$, $\boldsymbol{D^+}$, $\boldsymbol{D^{*+}}$, $\boldsymbol{D_s^+}$ and $\boldsymbol{\Lambda_c^+}$
- PID efficiencies from data using K_S^0, ϕ and Λ decays
- Prompt signal yield gained from multidimensional extended maximum likelihood fit (mass + IP distribution)

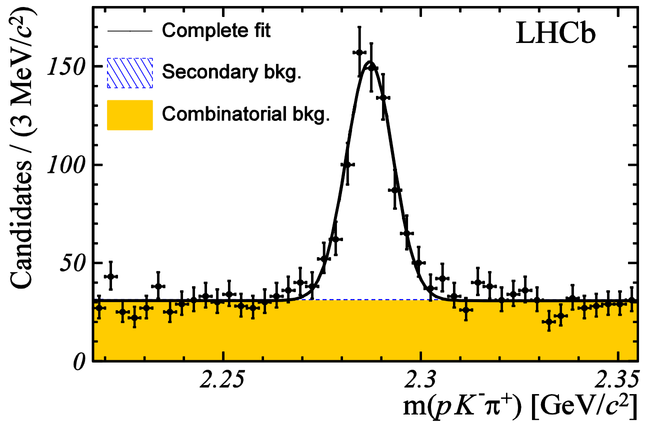
$\boldsymbol{D^+ \to K^- \pi^+ \pi^+}$



$\boldsymbol{D^{*+} \to D^0(K^-\pi^+)\pi^+}$



$\boldsymbol{\Lambda_c^+ \to p\, K^- \pi^+}$



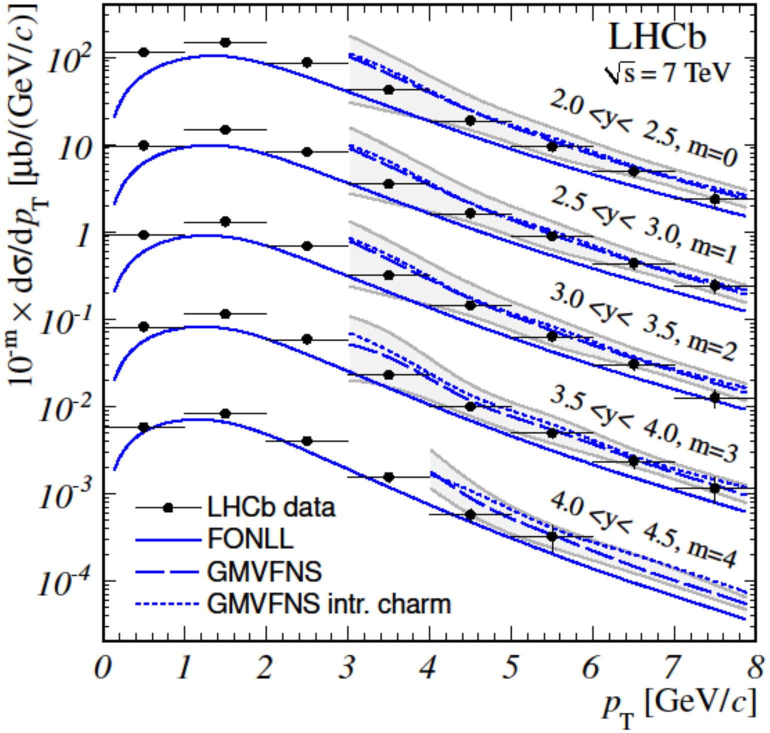
additional BG from prompt and secondary slow pions

Prompt charm production

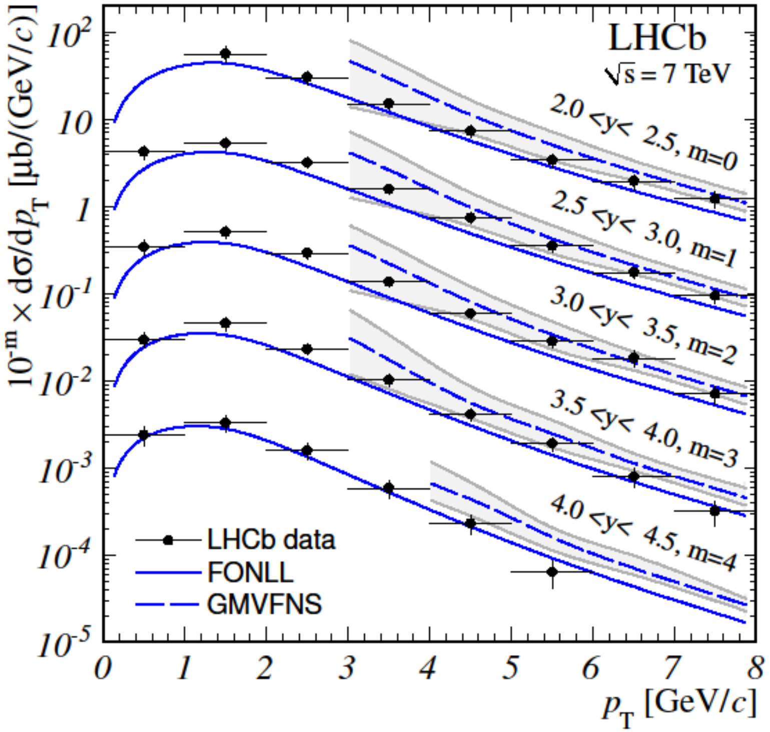
[Nucl. Phys. B 871 (2013)]

Differential cross-sections are compared to theoretical expectations, which reproduce Tevatron and ALICE measurements in the central rapidity region

D^0



D^+

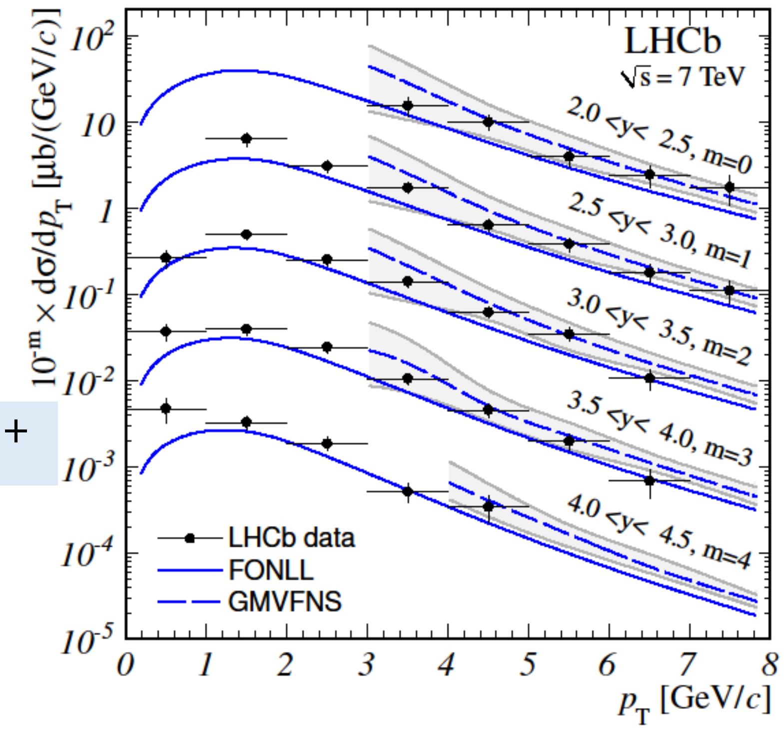


- Fixed order with next to leading-log resummation (**FONLL**) using CTEQ 6.6 (e.g. M.Cacciari et al. JHEP 1210 (2012) 137)
- NLO calculation in the *Generalized Mass Variable Flavour Number Scheme* (**GMVFNS**) using CTEQ 6.5 and CTEQ 6.5c2 (**intrinsic charm**), (e.g. B.Kniehl EPJ C72 (2012) 2082)
    - ➢ Predictions in good agreement with our measurement
    - ➢ Effect of intrinsic charm is predicted to be small in this phase space region

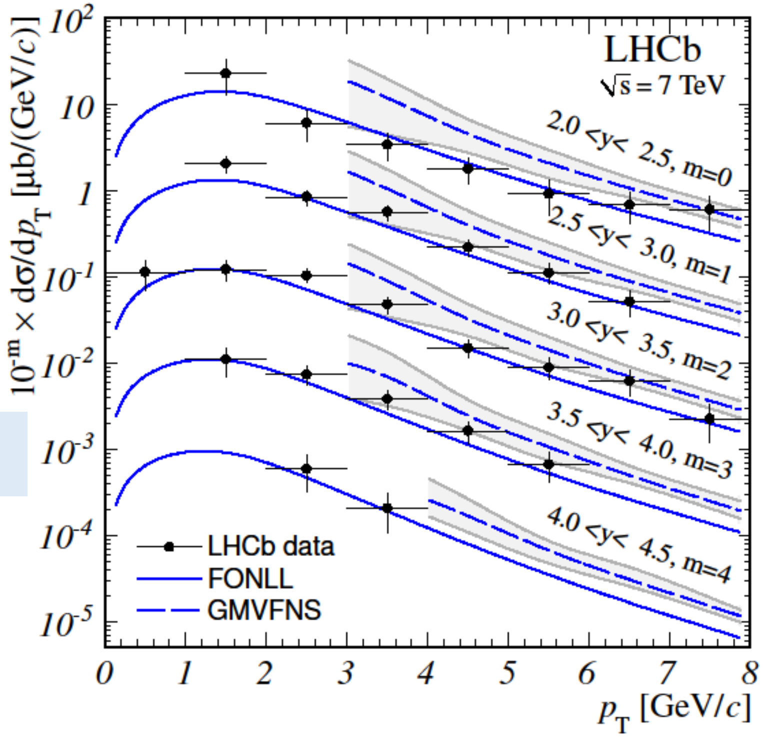
Prompt charm production

[Nucl. Phys. B 871 (2013)]

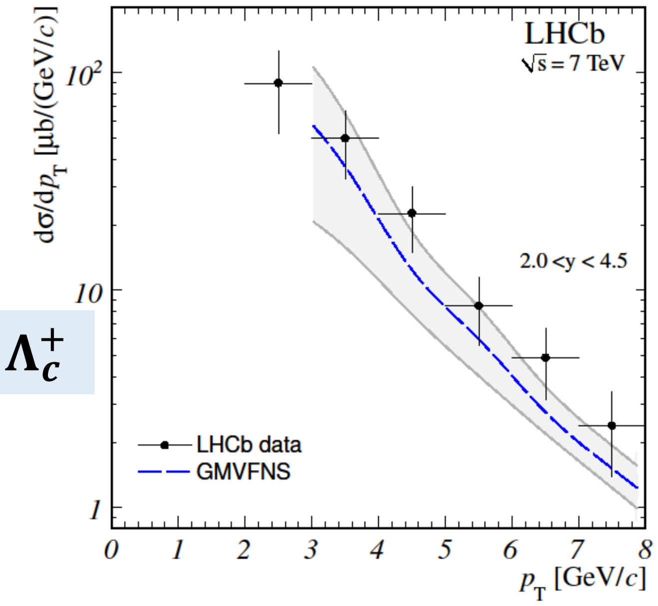
D^{*+}



D_s^+



Λ_c^+



- Good agreement in these modes as well
- Total charm cross-section* (p_T<8GeV, 2.0<y<4.5): $\sigma(c\bar{c})$ = 1419$\pm$12(stat) $\pm$ 116(syst) $\pm$ 65 (frag) μb

* Combination of bins where rel. precision < 50%, otherwise using extrapolation based on Pythia tunes (Perugia0, PerugiaNOCR, Perugia2010 & LHCb tune)

Summary

- LHCb performs QCD studies in unique kinematic range at the LHC

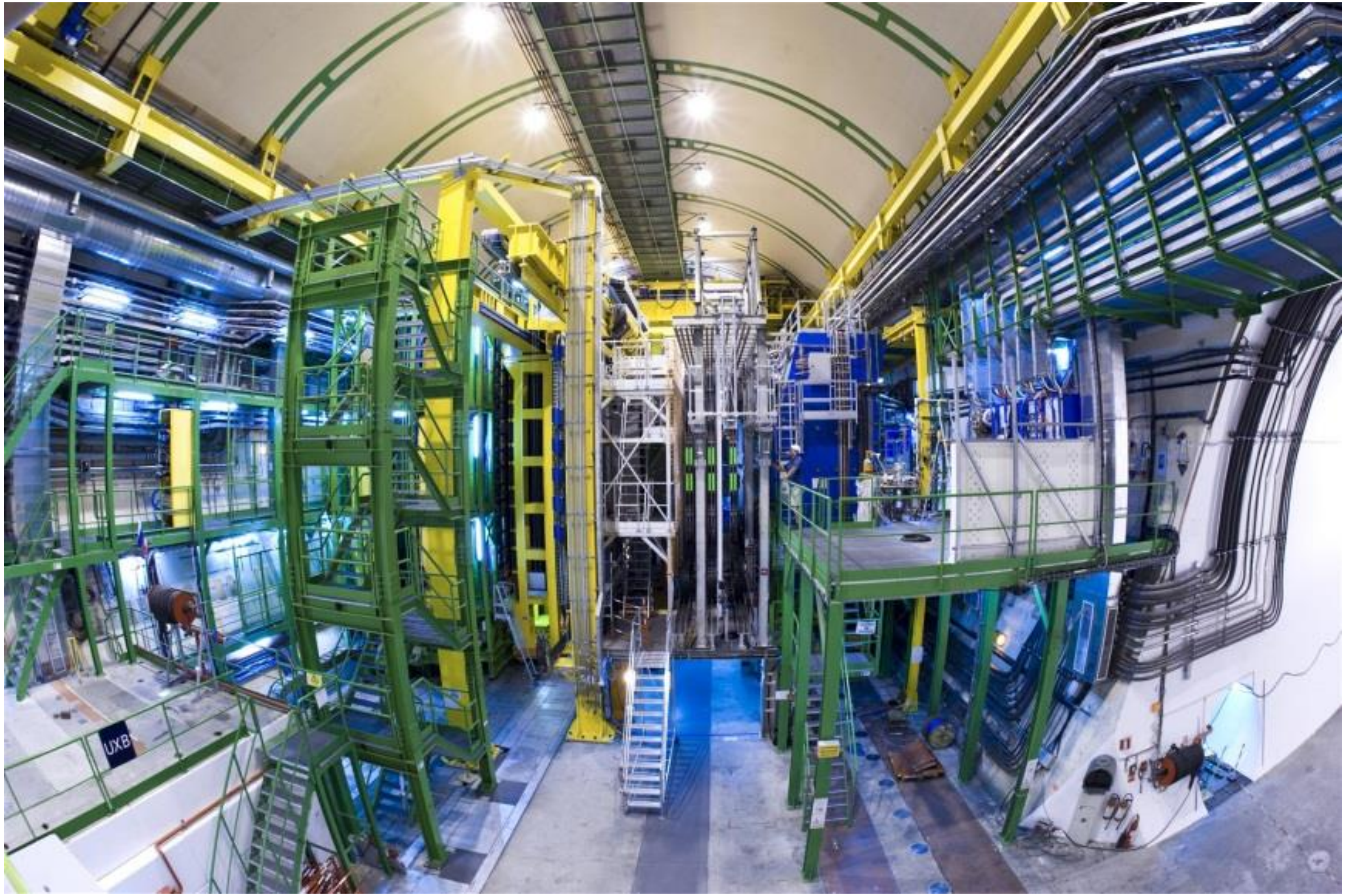
- Charged particle multiplicities & densities
  -> …underestimated by older MC generators
  -> recent generators (optimized to LHC data in central rapidity region) show reasonable agreement
  -> input for further optimization (RIVET plugin will be available)

- Energy Flow measured separately for inclusive, (non-)diffractive and hard scattering event classes
  -> PYTHIA 8 superior than PYTHIA 6
  -> Also cosmic-ray generators do a good job describing LHCb data

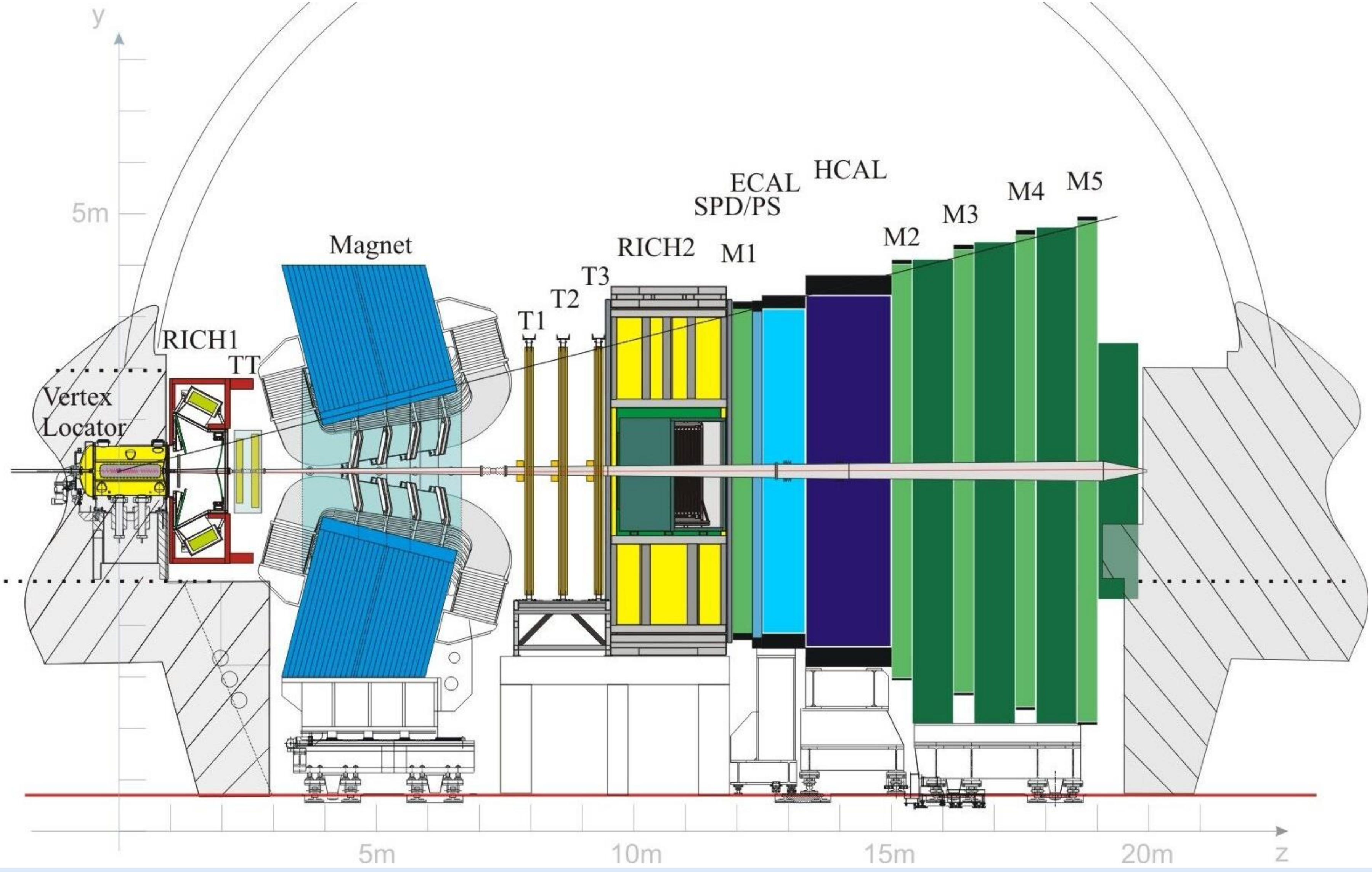
- Prompt Charm production, good probes for hadronisation and fragmentation models

- Results will be supplemented with further measurements
  -> pp data sets available at $\sqrt{s}$ = 0.9, 2.76, 7 and 8 TeV
  -> Also huge data sets of p-Pb & Pb-p collisions at $\sqrt{s_{NN}}$= 5 TeV

BACKUP



The LHCb detector

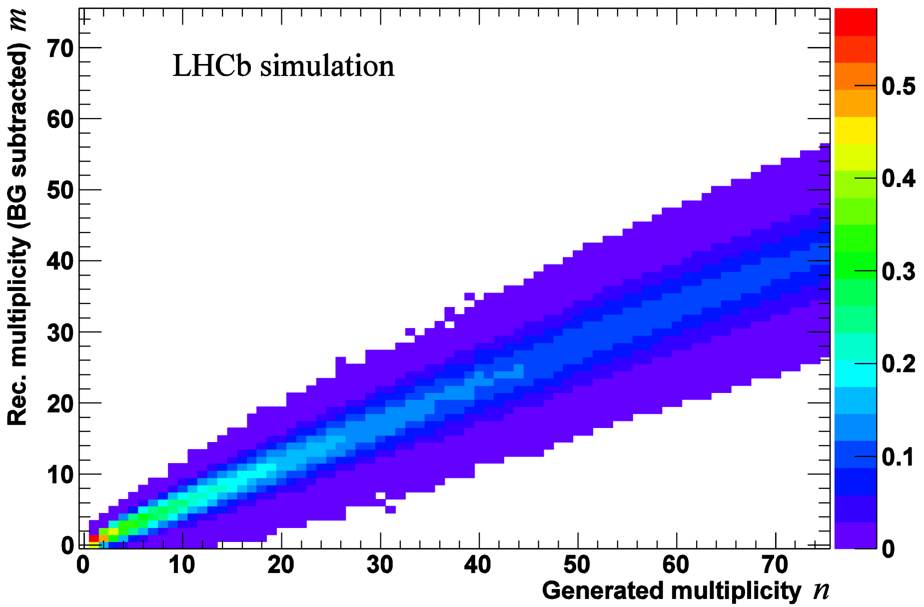


Charged particle multiplicities & densities

arXiv:1402.4430

Analysis strategy:

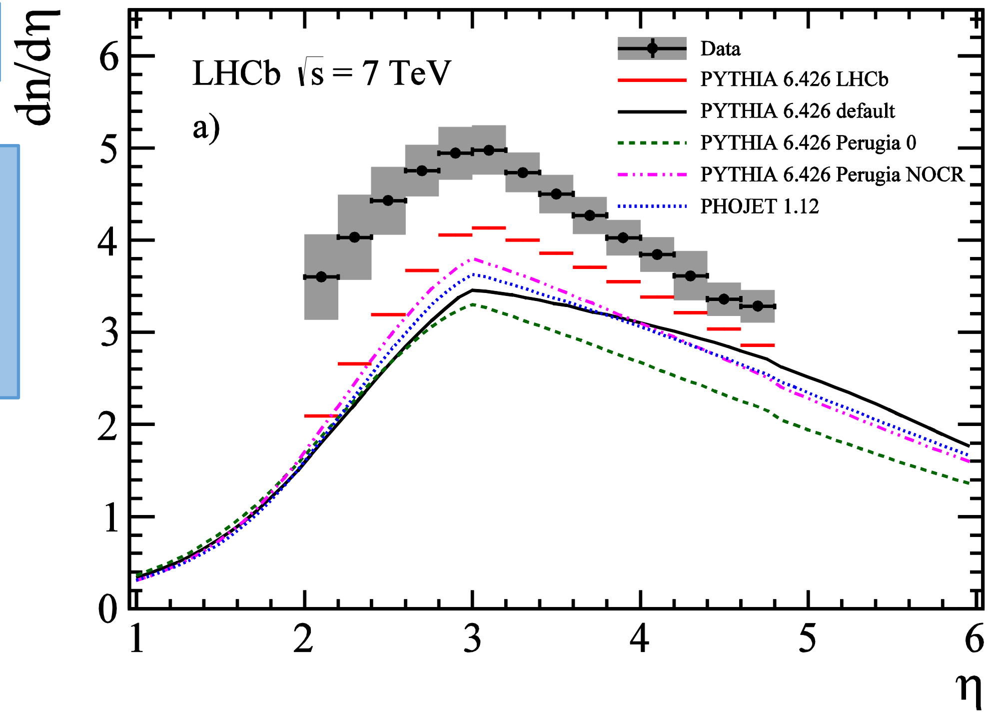
- Prompt charged particles are selected by
  - requiring tracks to originate from a "luminous region"
  - cut on distance to beam line
- Applied corrections to measured particle multiplicities & densities:
  1) Event-by-event correction for **reconstruction artefacts** (fake + duplicate tracks) & **non-prompt particles**
     -> weighting factor for each track according to purity of track
  2) Event sample is corrected for **undetected "visible" events**
  3) Subtraction of **pile-up** contamination
  4) **Detector acceptance** and **Tracking Efficiencies**
     -> particle densities:
     additional weighting factor $w = 1/\epsilon$
     -> particle multiplicities:
     unfold physical distribution by using a response matrix:

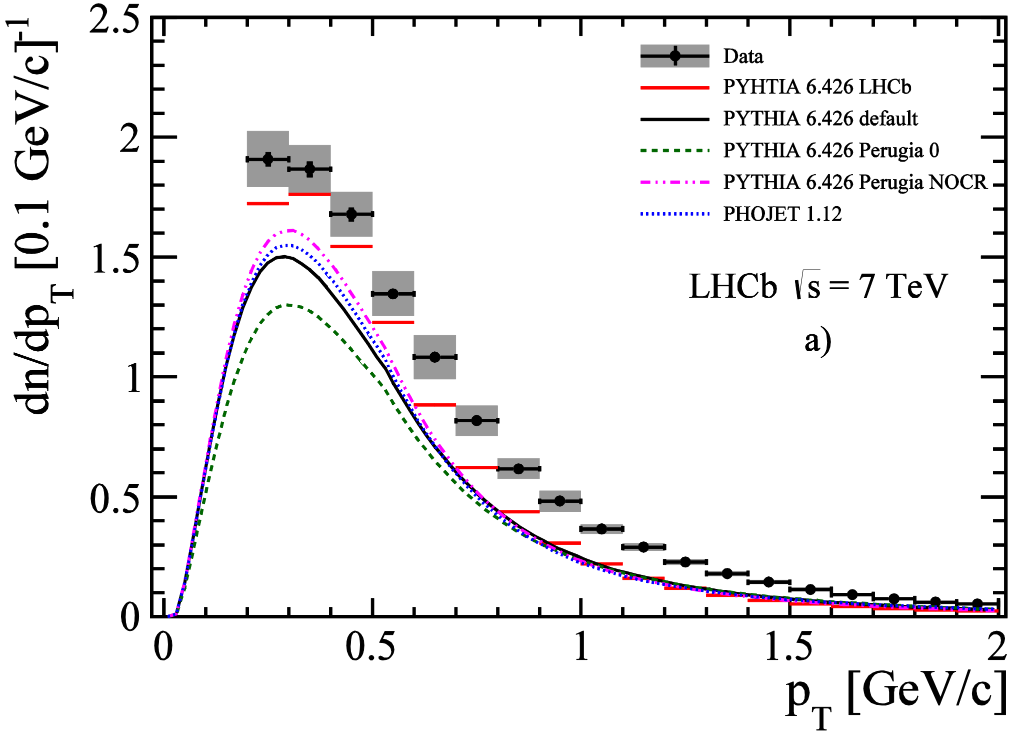


Results – particle densities (I)

arXiv:1402.4430

Kinematic range:
- $2.0 < \eta < 4.8$
- $p_T > 200MeV$
- $p > 2GeV$



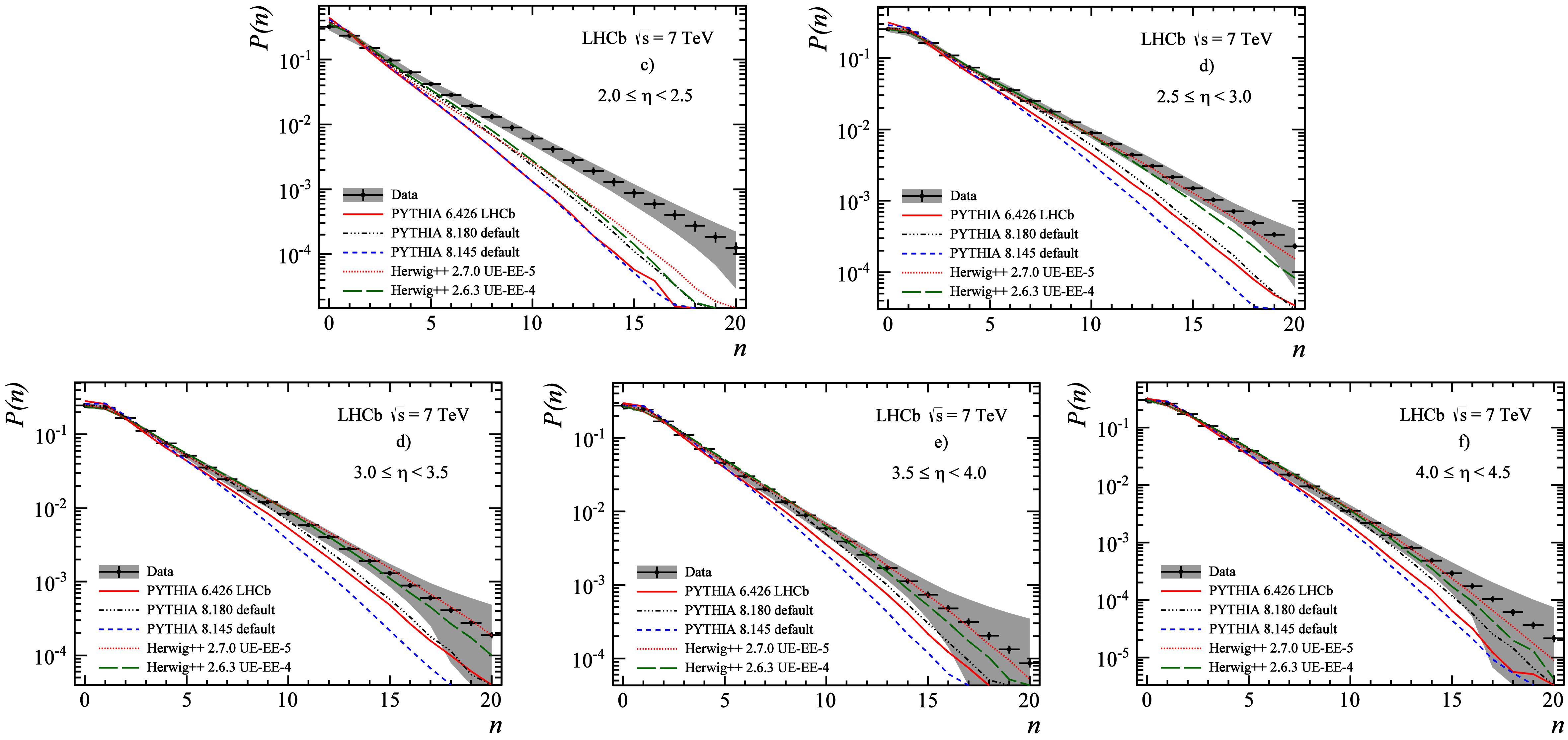


LHCb data are shown with black points, stat. error bars and combined uncertainty band (stat.+syst.)

Particle densities compared to MC generators prediction (**non-LHC tuned**):

- All PHYTHIA 6 tunes and PHOJET predict too small particle densities

Results –particle multiplicities (η)



Results –particle multiplicities (p_T)