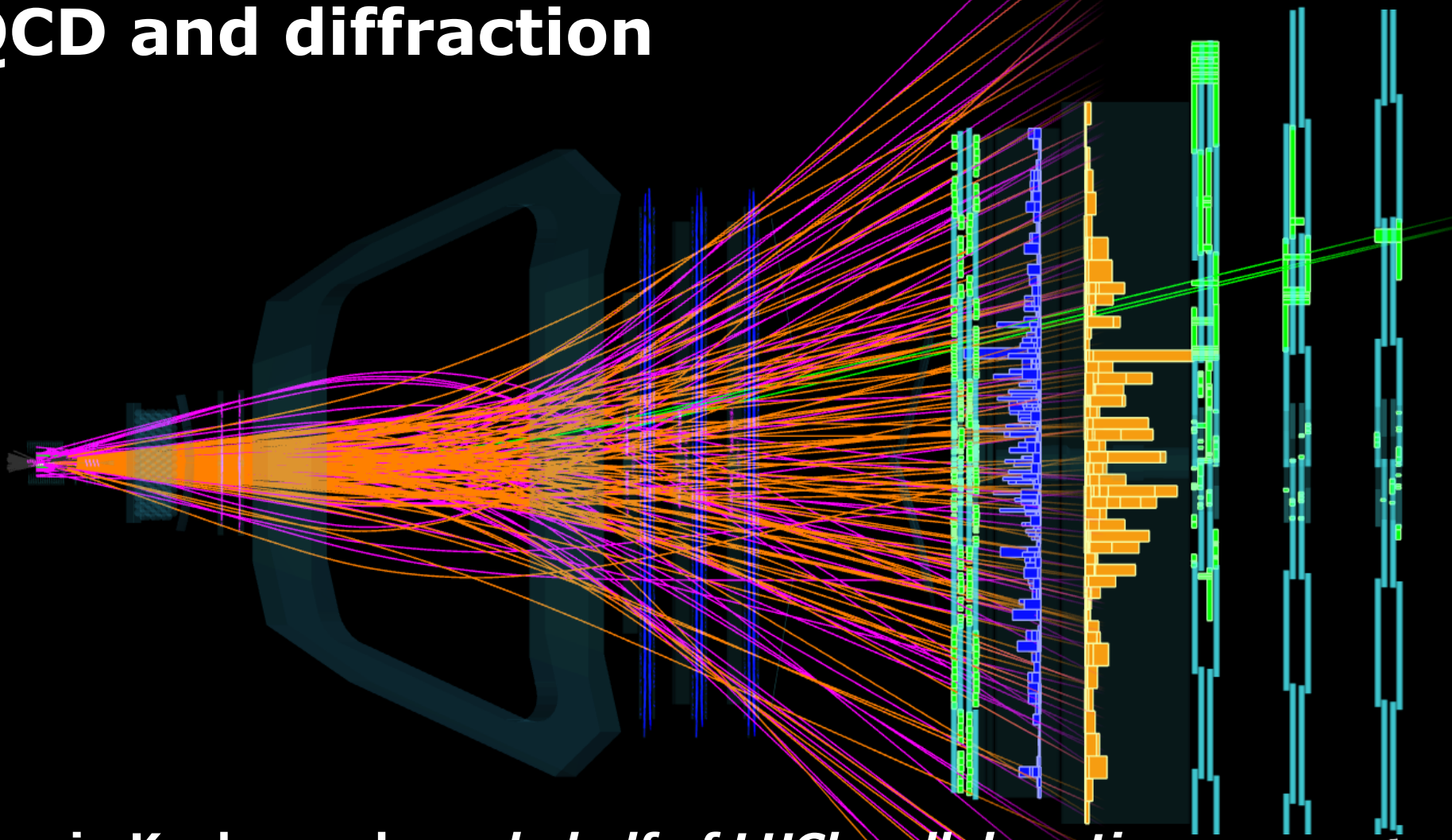
Review of LHCb results on MPI, soft QCD and diffraction



Marcin Kucharczyk *on behalf of LHCb collaboration*

HNI Krakow

EDS Blois 2015, Borgo (Corse), 30.06.2015

Outline

- LHCb - general purpose forward experiment
- Why soft QCD at LHCb
- Summary of LHCb QCD measurements
- Selected results:

  → charged particle multiplicities

  → forward energy flow

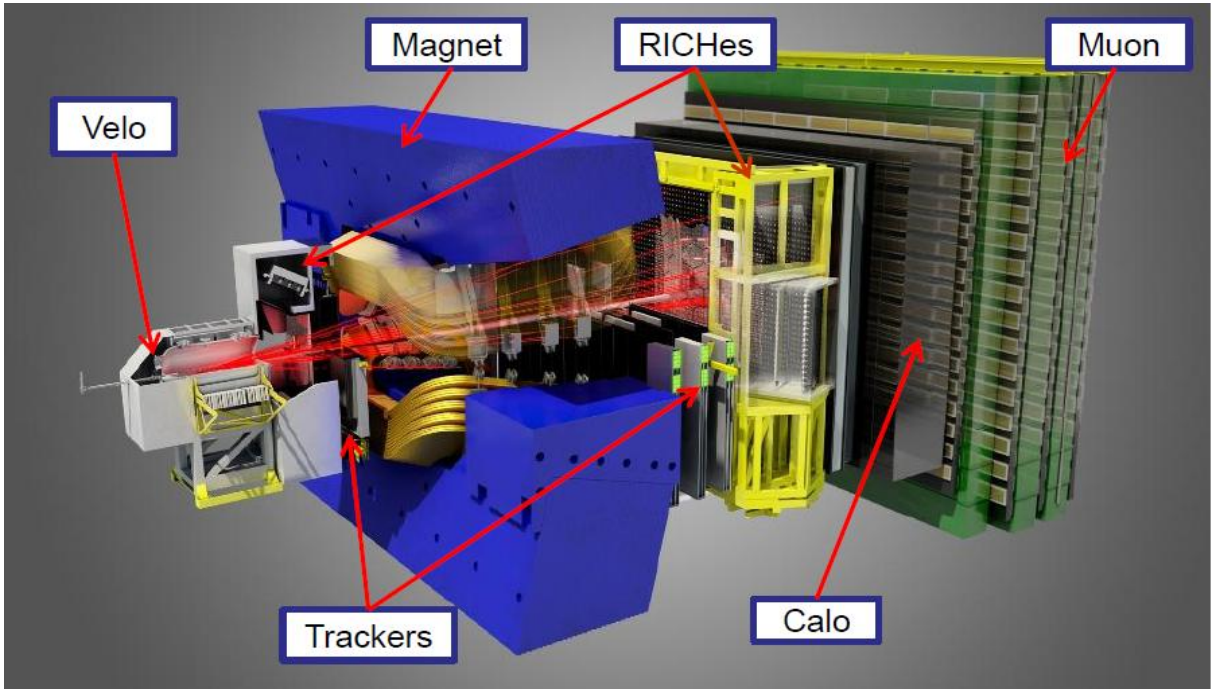
  → prompt charm production

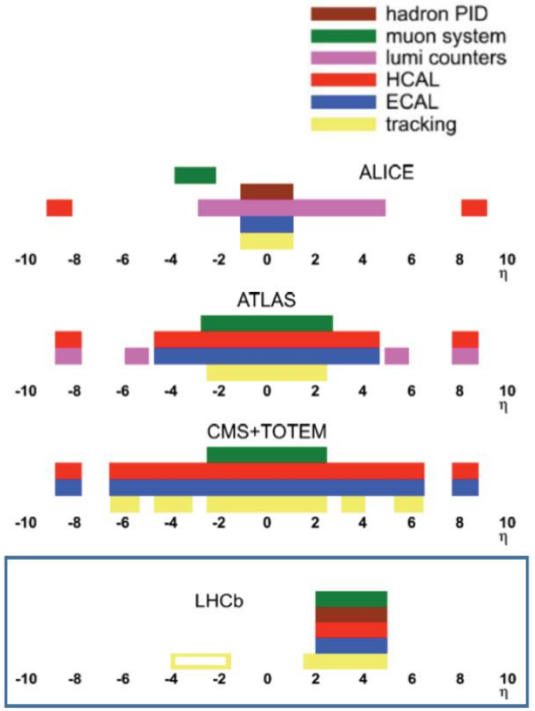
  → fixed-target physics at LHCb

LHCb experiment

[JINST 3 (2008) S08005]

- single arm spectrometer fully instrumented in forward region
- designed to study CP violation in B decays
- precision coverage unique for LHCb: $2.5 < \eta < 4.5$
- allows QCD studies complementary to ATLAS and CMS *(precision coverage: $|\eta| < 2.5$)*
- VELO also provides backward coverage: $-3.5 < \eta < -1.5$

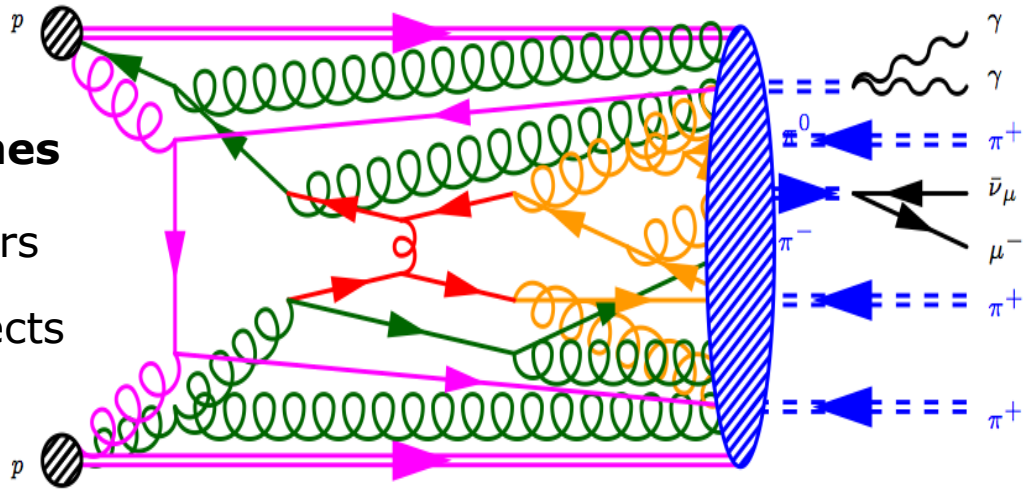




- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of 20 μm for high p_T tracks

2010 (7 TeV): 37.1 pb^{-1}
2011 (7 TeV): 1.0 fb^{-1}
2012 (8 TeV): 2.0 fb^{-1}

Soft QCD at LHCb



Test non-perturbative QCD regimes

- tune multi-purpose event generators
- refine existing models wrt new effects

Hadronization

- unique kinematic range: high η, p_T down to 50 MeV
  (current models have large uncertainties)
- charged particle density and multiplicity *(IR sensitive)*

Multi parton interactions

- explore activity and structure of underlying event *(UE)*
- energy flow *(IR safe)*

LHCb measurements

Chosen LHCb QCD results in pp collisions

→ Measurement of charged particle multiplicities and densities

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

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

[JHEP 1502 (2015) 129]

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

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

Measurement of V^0 production ratios in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV

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

Measurement of the inclusive φ cross section in pp collisions at $\sqrt{s}$ = 7 TeV

[Phys. Lett. B 703 (2011) 267]

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

[Nucl. Phys. B 871 (2013) 1-20]

Measurement of charged particle multiplicities in pp collisions at $\sqrt{s}$ = 7 TeV

[Eur. Phys. J. C 72 (2012) 1947]

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

[Phys. Lett. B 693 (2010) 69-80]

Charged particle multiplicities

Charged particle multiplicities and densities

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

Motivation

- Crucial to understand phenomenology of soft QCD processes
  - → non-perturbative soft-QCD *(e.g. light particle production)*
  - → different approach to fragmentation, hadronization, final state modelling in MC generators *(e.g. PYTHIA vs HERWIG)*
- Optimization of phenomenological models
  - → old models underestimate charged particle production
  - → can be tested and optimized with multiplicity measurements
- Complementary to previous LHCb analysis [Eur. Phys. J. C72 (2012) 1947]
  - → differential measurement in p_T and η *(access to momentum information)*
  - → uses overall LHCb tracking system
  - → different kinematic range
  - → particle multiplicities + particle densities

Charged particle multiplicities and densities

LHCb minimum bias data at 7 TeV *(~3M)*

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

- low multiplicity run
- low pile-up contribution *(< 4%)*
- VELO fiducial region of high track REC efficiency: $p_T \in (0.2 - 2.0)$, $\eta \in (2.0 - 4.5)$
- systematics: 1-10% (*inactive detector material*)

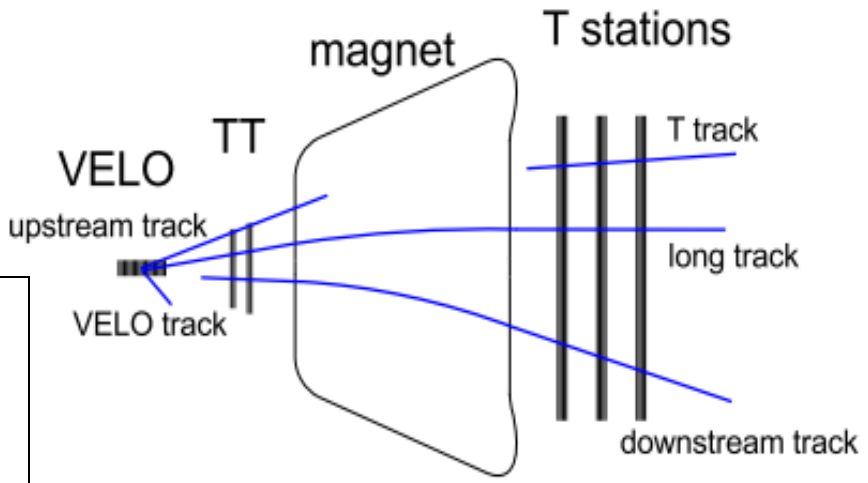
prompt charged particle defined as:
→ *originating directly from PV or decay chain with τ < 10 ps*

To compare directly to MC generators

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

→ *sample impurity taken into account*
→ *correct for visible events with no rec. tracks*
→ *distributions unfolded wrt pile-up*
→ *reconstruction efficiencies applied*

LHCb tracking system

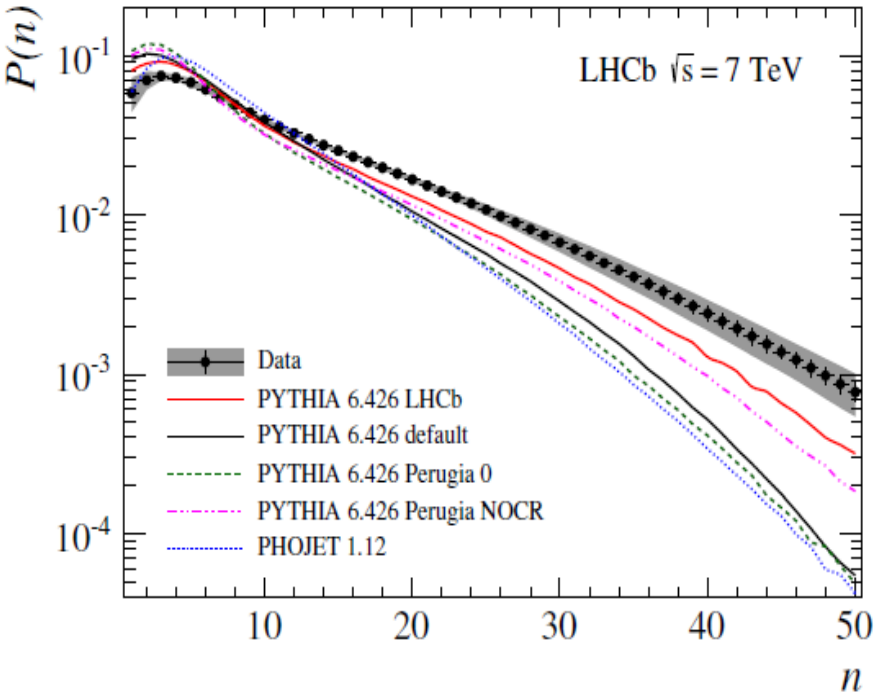


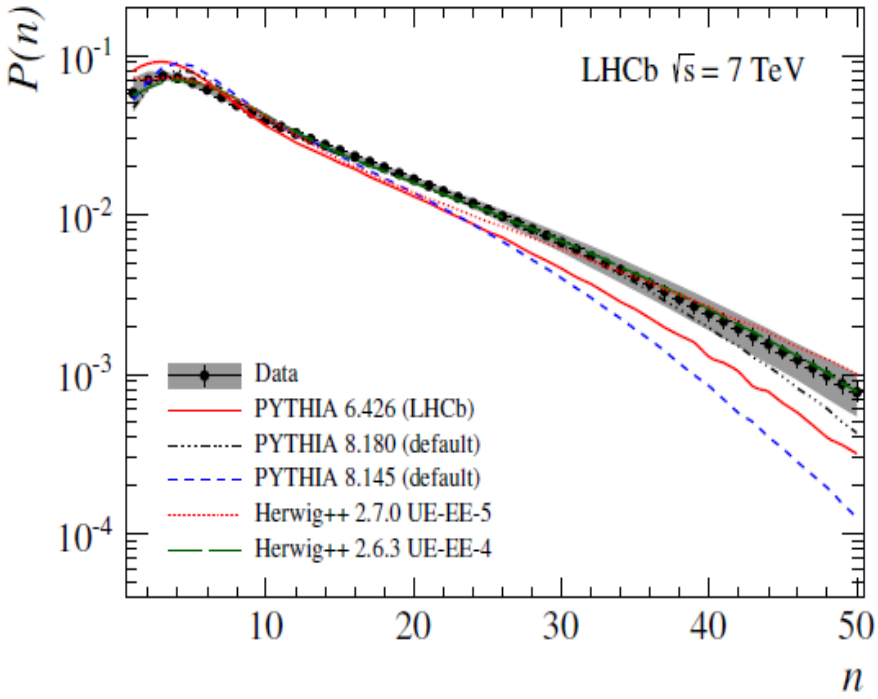
[JINST 10 (2015) P02007]

Particle multiplicities

Inclusive multiplicity results

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



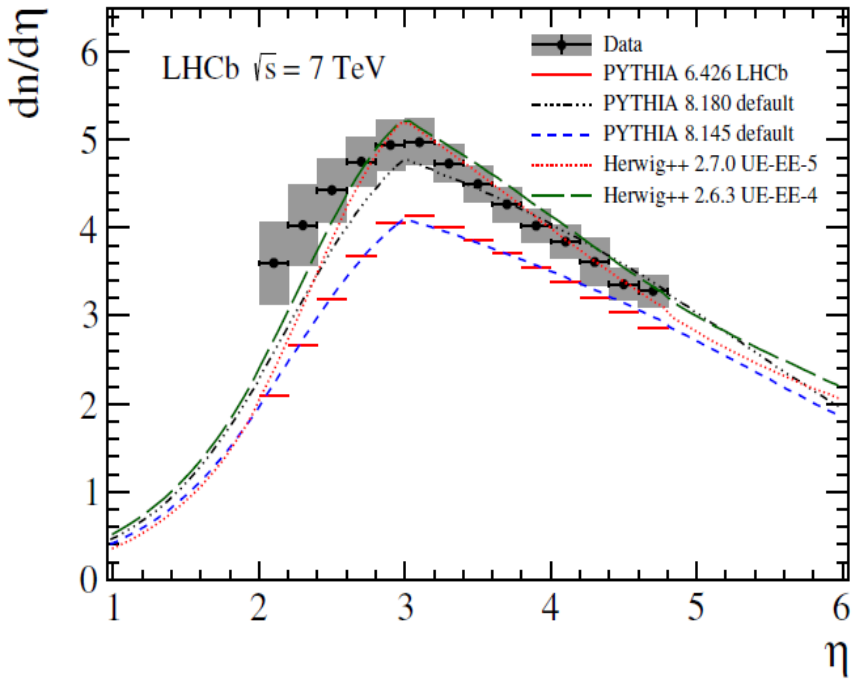


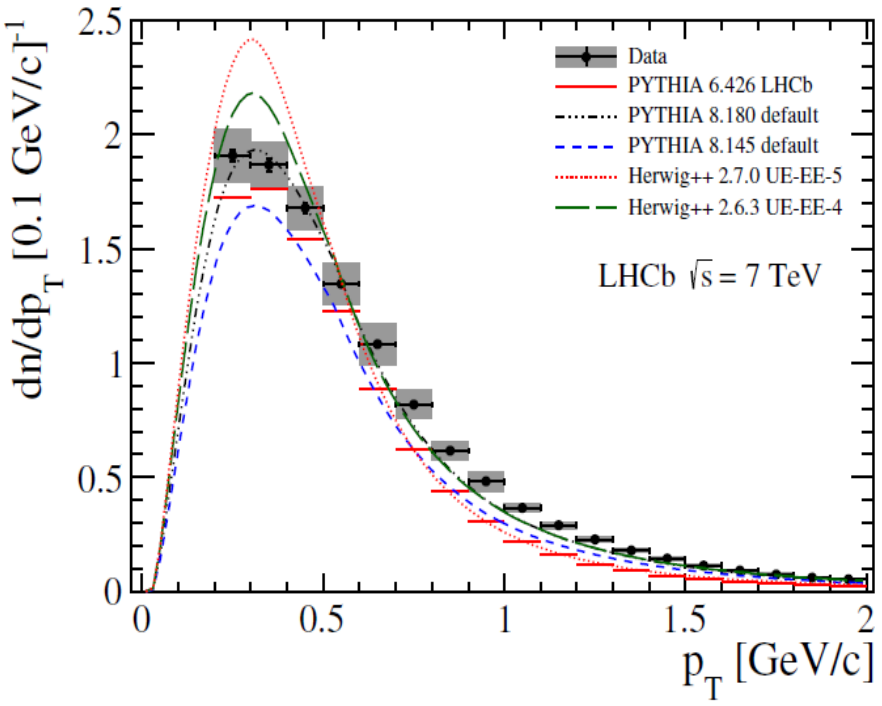
- all tunes underestimate at high multiplicity *(for both low and high η)*
- models tuned to central LHC data → better agreement ***(HERWIG++, PYTHIA 8.180)***
- non-LHC tunes overestimate low multiplicity ***(all other models)***
- PYTHIA 8.180 shows reasonable agreement *(underestimates for high n)*
- Herwig++ 2.6.3 consistently describes inclusive data well

Particle densities

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

Charged particle density as a function of η and p_T





- PYTHIA 6 *(not tuned to LHC)* underestimates particle density
- PYTHIA 8.180 *(tuned to central LHC data)* describes data significantly better
- HERWIG++ tunes overestimate at low p_T, underestimate at large p_T

Energy flow

Forward energy flow

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

Energy flow *(EF)* measurements at high *η*

- probes multi-parton-interactions (MPI) and parton radiation
  - → precise description of UE *(MPI is predominant source of UE)*
  - → study diffractive effects in various simulation models
  - → discrimination among MPI models
  - → strong constraints on ultra high energy cosmic-ray interaction models
- **EF**: average energy of stable particles emitted in *η* bin per inelastic pp interaction:

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

energy per particle

number of inelastic interactions

  - → LHCb measurement: charged and total EF
  - → comparison to PYTHIA and cosmic-ray event generators

Forward energy flow

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

minBias: 0.1 nb^{-1}, 2010 runs at $\sqrt{s}$ = 7 TeV

- low pile-up
- only events with 1 interaction per bunch crossing

LHCb data extrapolated to generator level vs PYTHIA tunes

→ unfold detector effects in each η bin

→ systematic error dominates:

- tracking efficiency
- pile-up *(~5%)*
- model dependence *(main contribution)*

Large rapidity gap for diffractive processes

Purity *(PYTHIA6 based)*: non-diffractive ~90%, diffractive ~70%

Event classification

Inclusive minBias

≥1 track with

- p > 2 GeV
- 1.9 < η < 4.9

Hard scattering

≥1 track with

- p_T > 3 GeV
- 1.9 < η < 4.9

Diffractive enriched

inclusive minBias

- no backward track in $-3.5 < \eta < -1.5$

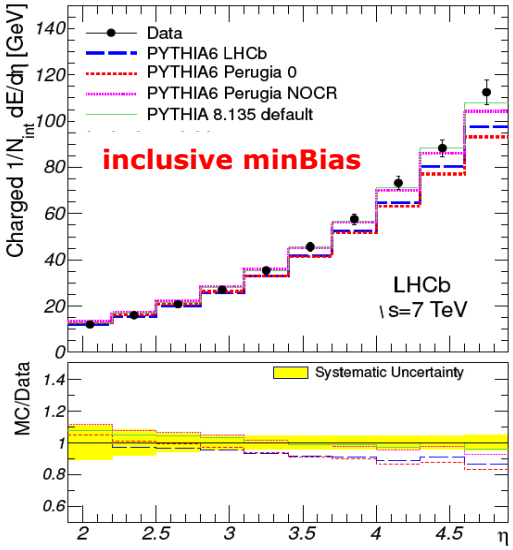
Non-diffractive enriched

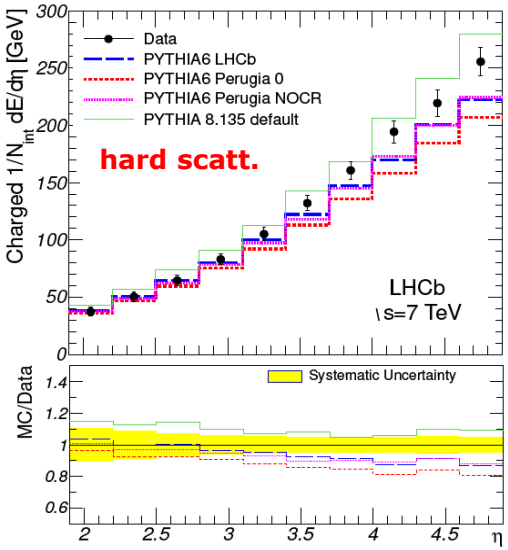
inclusive minBias

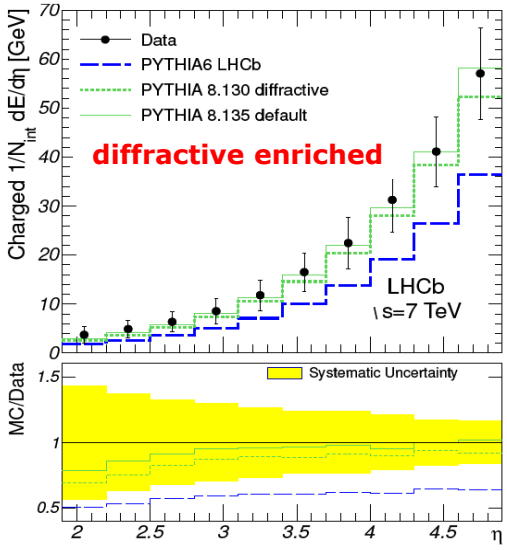
- ≥ 1 backward track with $-3.5 < \eta < -1.5$

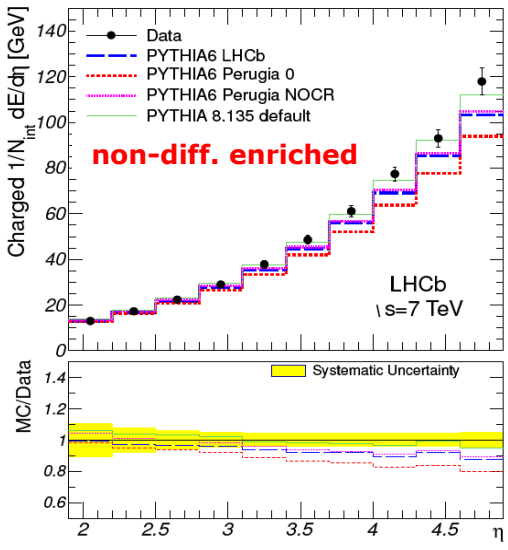
Charged forward EF: *PYTHIA tunes*

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









- systematic errors decrease towards higher η
- EF increases with momentum transfer:

  $EF_{hard} > EF_{non\text{-}diff} > EF_{incl} > EF_{diff}$

PYTHIA 6 tunes

→ overestimate EF for low η in all samples

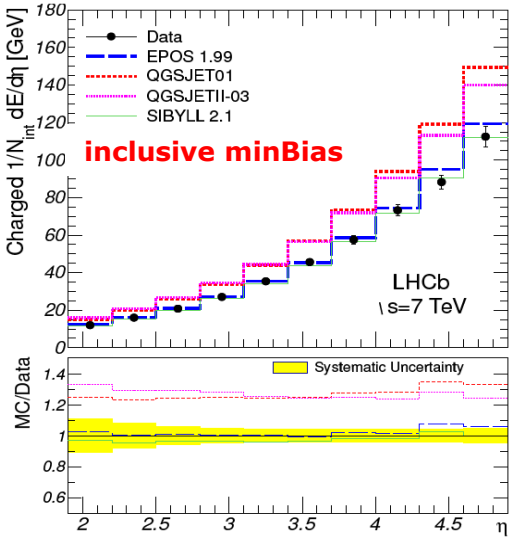
→ underestimate for high η

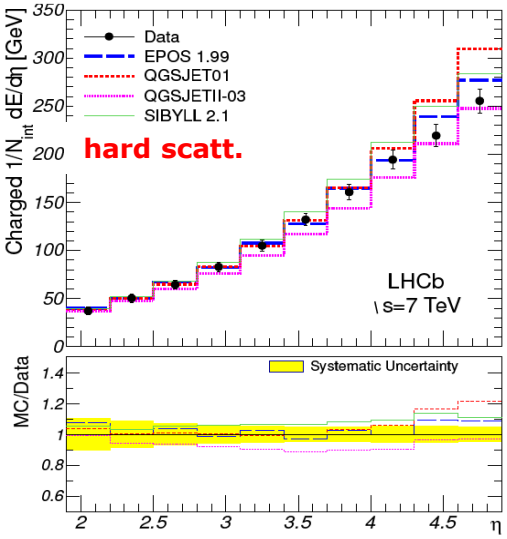
PYTHIA 8 tunes

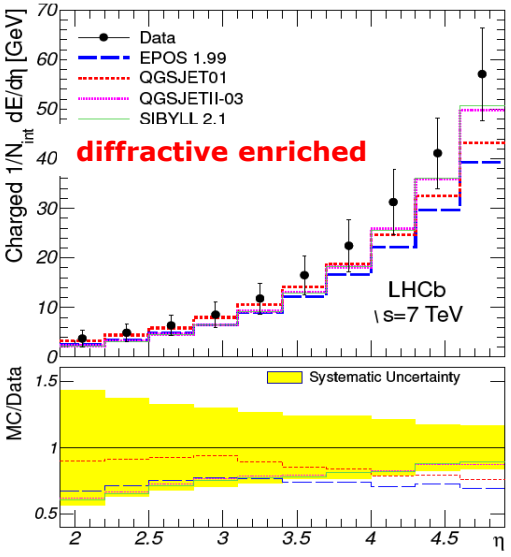
→ EF well described at high η, overestimated for hard scatt.

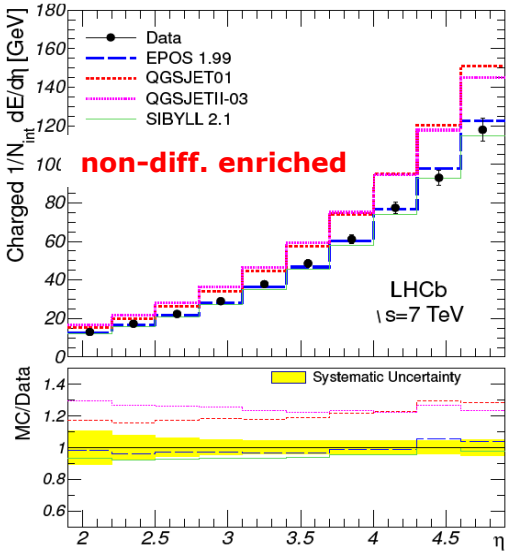
Same conclusion for total EF

Charged forward EF: *cosmic ray generators*









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

- compared with cosmic-ray interaction models

EPOS, SIBYLL, QGSJET, QGSJETII

- not tuned to LHC data

→ all models underestimate EF for diffractive sample

SYBILL *(best)*

→ good agreement for all classes

→ except hard scatt. at high η

EPOS

→ good description of minBias and non-diffractive events

QGSJET models

→ good description only for hard scattering

input for MPI/UE/cosmic-ray models

Prompt charm production

Prompt charm production

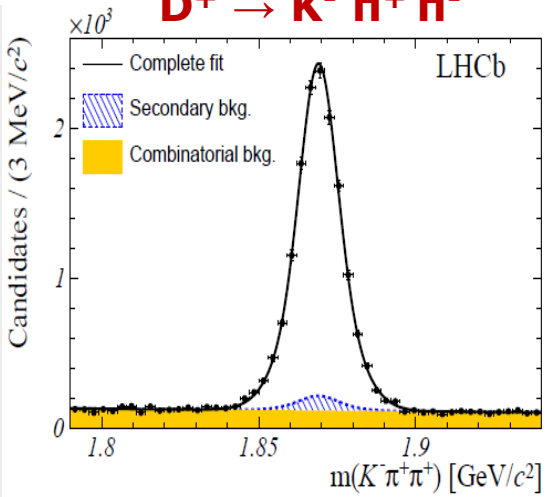
[Nucl. Phys. B 871 (2013)]

- cross-section measurements
  → probes for hadronization and fragmentation
- LHCb → unique access to forward rapidity region
  → detector tailored for flavour physics

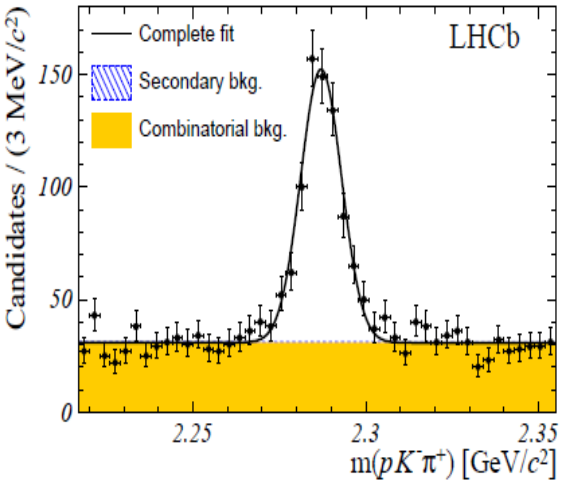
DATA: 15 nb^{-1} at $\sqrt{s}$ = 7 TeV

- fully rec. prompt charm decays
  D^0, D^+, D^{*+}, D_s^+, Λ_c^+
- fiducial region
  $2.0 < y < 4.5$, $p_T < 8$ GeV
- PID efficiencies from data
  decays of: K_s^0, φ, Λ
- **prompt signal yield**
  multidimensional extended maximum likelihood fit
  (to mass and IP)

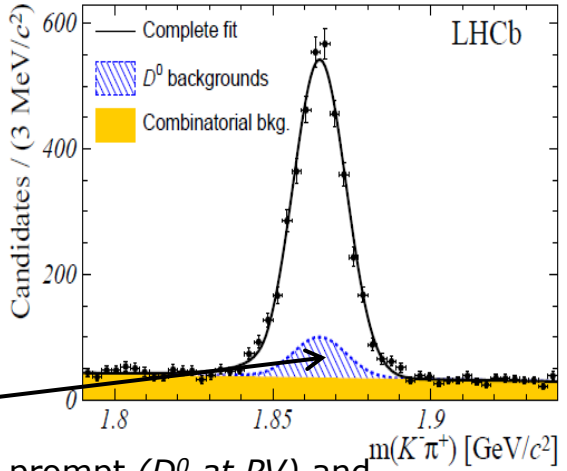
$D^+ \to K^- \pi^+ \pi^-$



$\Lambda_c^+ \to p K^- \pi^+$



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



D^0 backgrounds
additional components from prompt *(D^0 at PV)* and secondary *(D^0 from b-hadron)* slow pions

Prompt charm production

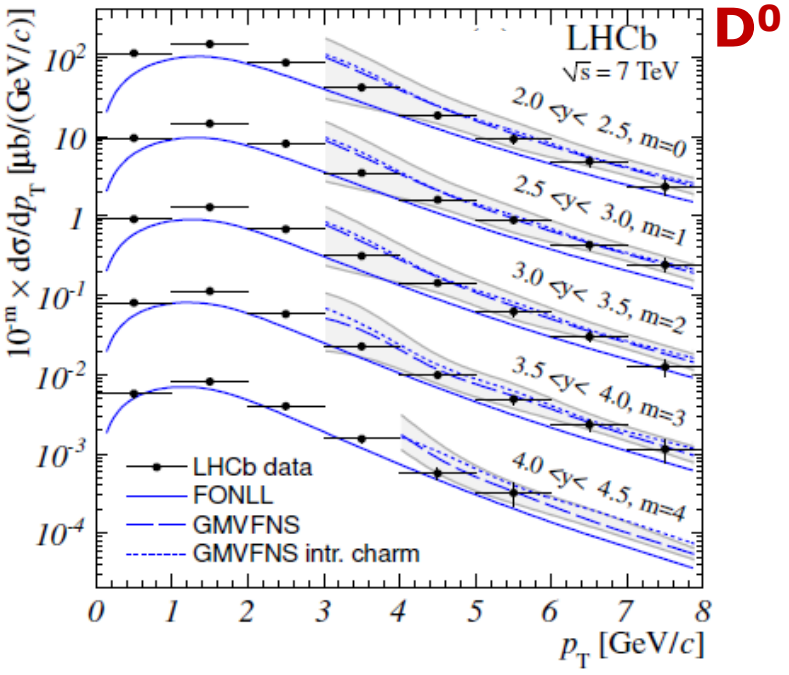
[Nucl. Phys. B 871 (2013)]

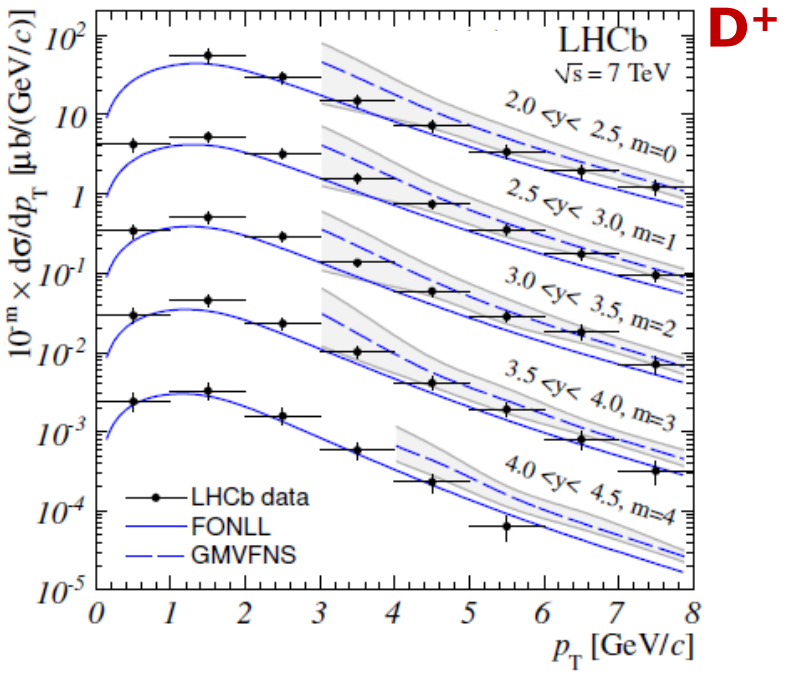
Differential cross-sections compared to perturbative calculations

- Generalized Mass Variable Flavour Number Scheme *(GMVFNS)*
  → *NLO, CTEQ 6.5 and CTEQ 6.5c2 (intrinsic charm)*
- Fixed order with next to leading-log resummation *(FONLL)* *CTEQ 6.6*

Both reproduce Tevatron and ALICE measurements in central rapidity region

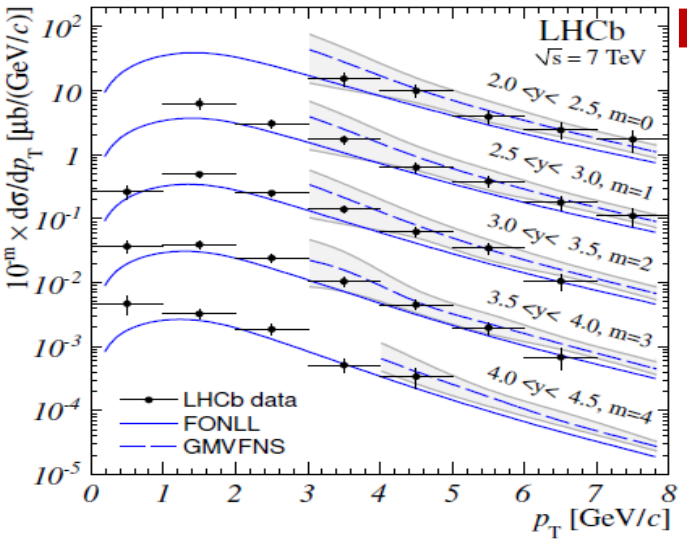
[arXiv:hep-ex/0307080, arXiv:1205.4007]

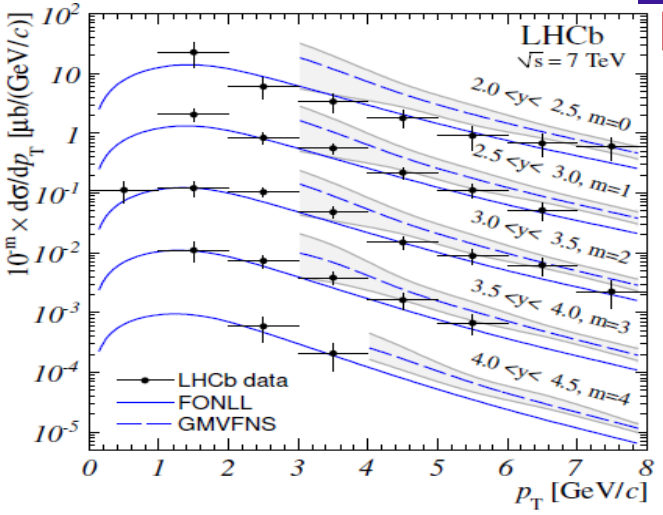


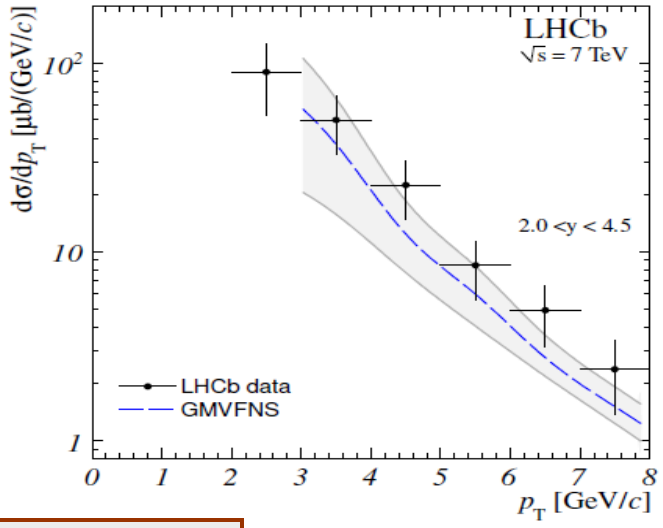


Prompt charm production

[Nucl. Phys. B 871 (2013)]







- good agreement with LHCb results
- effect of intrinsic charm small in analysed phase space

Total charm cross-section

- *y ϵ (2.0 - 4.5), p_T < 8 GeV*

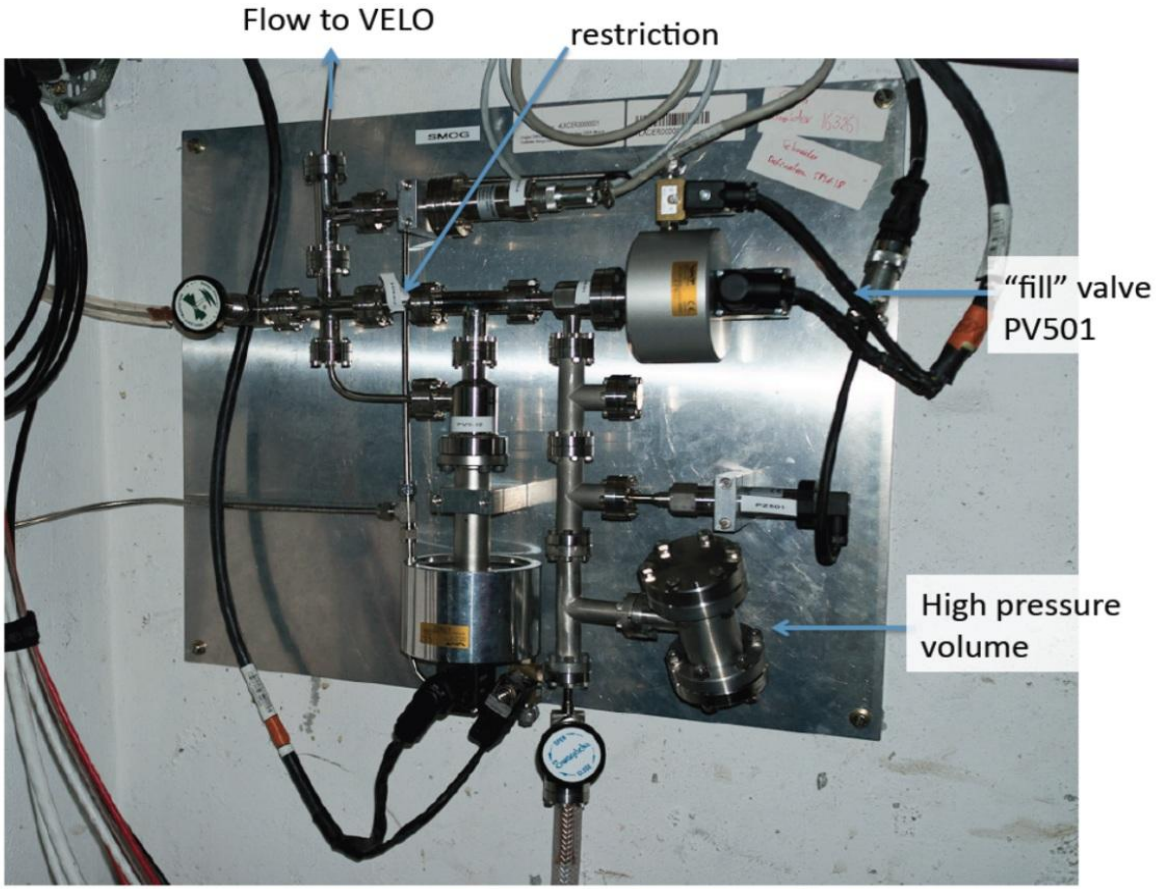
$\sigma(c\bar{c})$ = 1419 ± 12 (stat) ± 116 (syst) ± 65 (frag) μb

Fixed target

Fixed target at LHCb

SMOG: System for Measuring Overlap with Gas

[LHCb-CONF-2012-034]



Samples: *p-Ne* and *Ne-Pb*

→ *p-Ne*:

- *p-A* pilot run
- $\sqrt{s_{NN}}$ = 87GeV
- boost $\Delta y \sim 4.5$

→ *Ne-Pb*

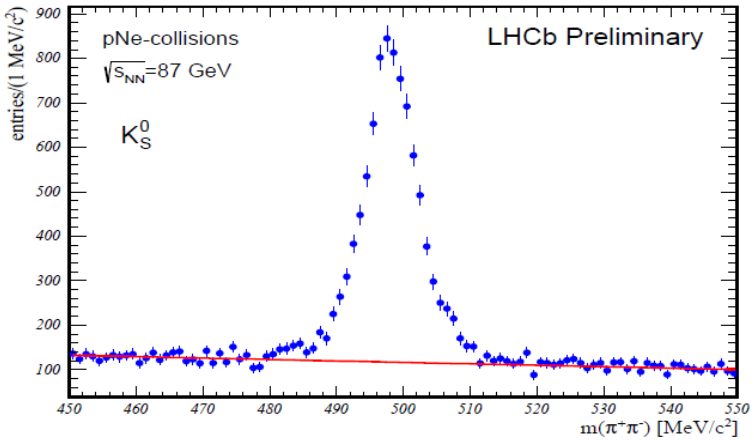
- $\sqrt{s_{NN}}$ = 87GeV
- low lumi collected *O(1/2h)*

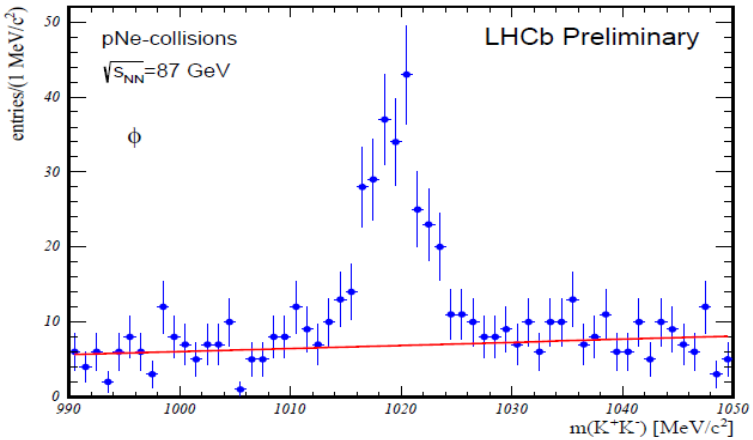
- injection of *Ne-gas* into collision region *(VELO)* with SMOG system
- designed to improve luminosity measurement with beam-gas imaging method
- LHCb: backward direction in nucleon-nucleon center-of-mass

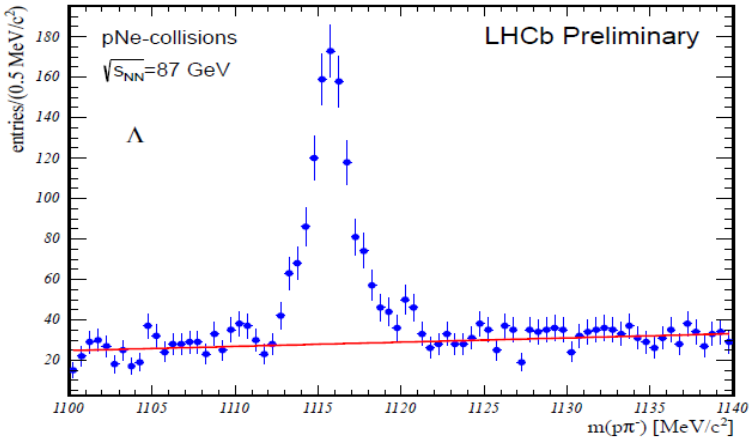
Fixed target at LHCb: *p-Ne*

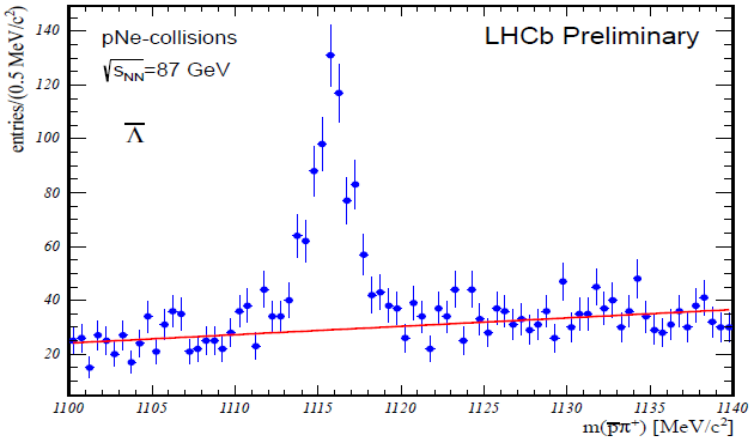
[LHCb-CONF-2012-034]

- rate of *p-Ne* sufficient to measure light quark and strangeness production
- ideal to test cosmic-ray interaction models *(ongoing)*
- possible to study nuclear PDFs at large *x* (*Ne-Pb)*









Conclusions

LHCb: general purpose forward experiment

- unique coverage in η and low p_T at LHC
- rich QCD/proton-nucleus physics program

Soft QCD measurements in LHCb acceptance

- charged particle multiplicities and densities
  → underestimated by older generators
  → generators tuned to LHC data in central rapidity show better agreement
  → input for further optimization *(RIVET)*
- forward energy flow
  → Pythia 8 gives the best description
  → also cosmic-ray generators close to describe LHCb data
  → none of the generators describe all measurements
- prompt charm production
  → good probe for hadronization and fragmentation models

First sets of event with fixed target pNe and PbNe collisions

High Rapidity Shower Counters are installed downstream and upstream from LHCb detector in Run II, and they are being tested…