Nucleon Structure and Soft QCD from LHCb

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On behalf of LHCb Collaboration

Outline

Recent LHCb results with a vital impact on phenomenological models and generator tunes aimed to understand the soft component of the hadron-hadron collision.

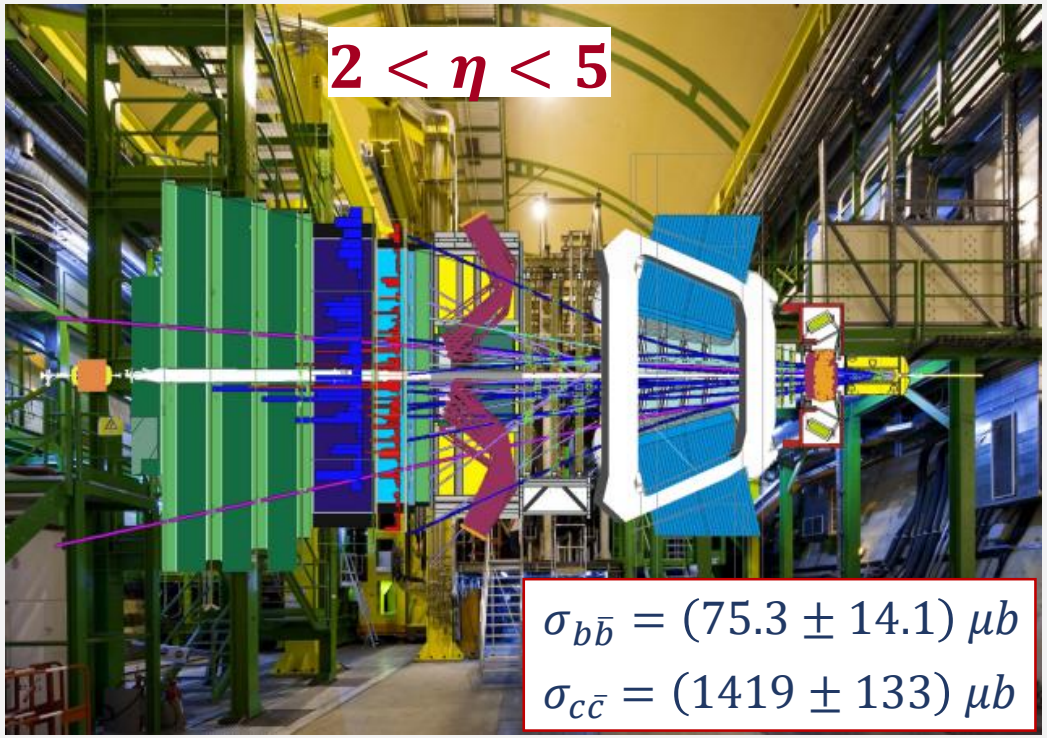
1. Measurement of charged-particle multiplicity production in pp collisions at $\sqrt{s} = 13$ TeV LHCb-PAPER-2021-010 (in preparation)
2. Measurement of the nuclear modification factor and prompt charged particle production in pPb and pp collisions at $\sqrt{s} = 5$ TeV LHCb-PAPER-2021-015
3. Observation of enhanced Double Parton Scattering in Proton-Lead Collisions at $\sqrt{s_{NN}}$ =8.16 TeV, Phys. Rev. Lett. **125**, 212001

LHCb spectrometer

LHCb JINST 3 (2008) S08005

Physics program:

- CP Violation and rare decays of beauty and charm meson
- …
- …
- QCD, electroweak, exotica …



Excellent performance:

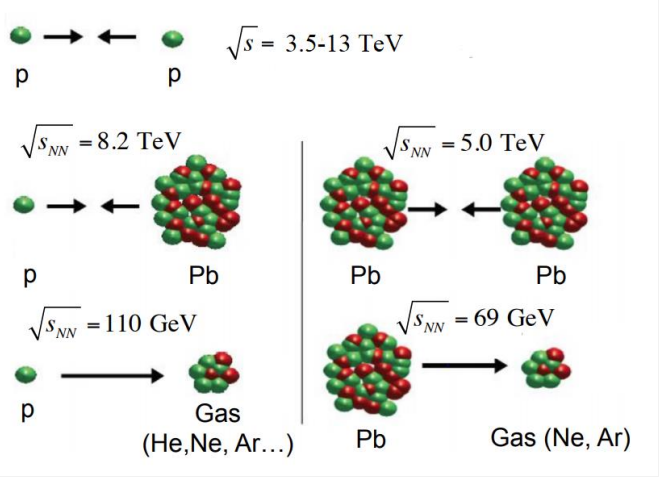
- 3 fb^{-1} accumulated in RUN I, 6 fb^{-1} in Run II;
- Tracking system with momentum resolution $\Delta p/p \sim 0.5 - 1\%$ (from 2 to 200 GeV);
- Excellent time (50 fs) resolution;
- Precise vertexing: $\sigma(IP) = (15 + 29/p_T[GeV])\ \mu m$
- Efficient hadronic identification (2-100 GeV/c):

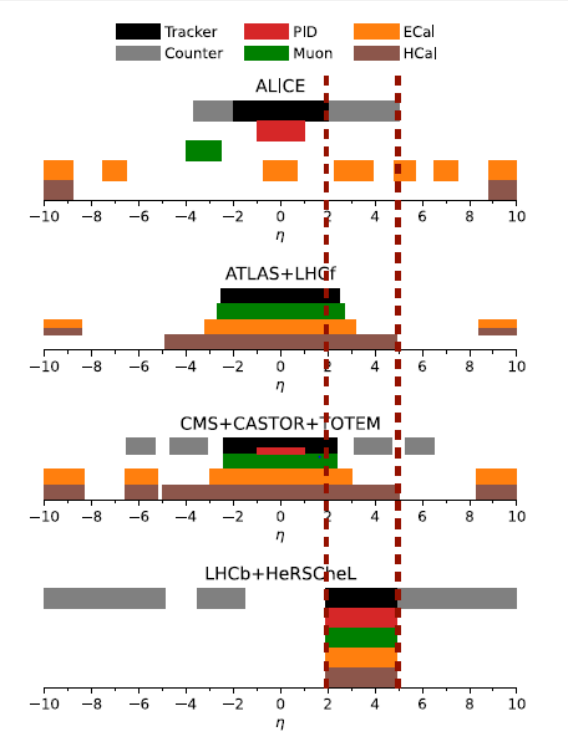
  $\mathcal{E}(K \to K) \sim 95\%$

  misID $\mathcal{E}(\pi \to K) \sim 5\%$
- Calorimeters ECAL, HCAL, $\Delta E/E = 1\% + 10\%/\sqrt{E[GeV]}$ for ECAL
- HeRSChel detector: scintillator counters covering high rapidity region to veto detector activity (for rapidity gap)

LHCb insights into hadrons

1. LHCb is the only detector at LHC fully instrumented in the forward region.
2. The forward region is sensitive to low Bjorken-x QCD dynamics and multiparton interaction.
3. LHCb can work in the collider and fixed target mode.

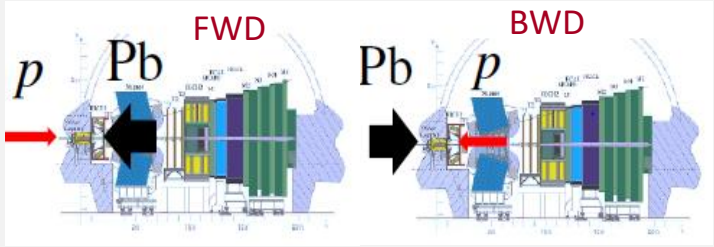


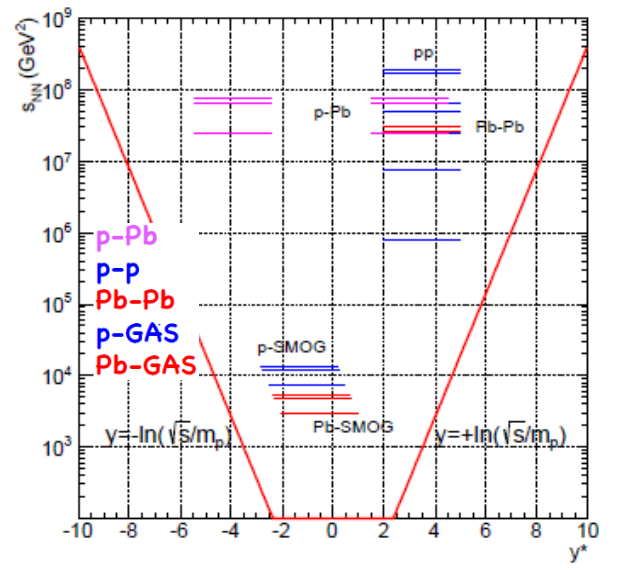


- proton-proton colliding mode: $2 < \eta < 5$
- ion colliding mode:

  forward and backward region
- fixed target (SMOG):

  central and backward



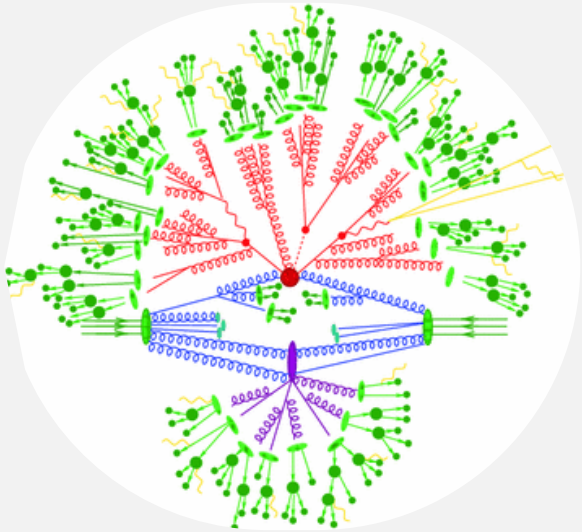


$y^* = y \pm 0.465$

(nucleon-nucleon CMS)

Charged-particle multiplicity @ 13 TeV

Measurement of prompt charged-particle multiplicity production in pp collisions at $\sqrt{s}$= 13 TeV (LHCb-PAPER-2021-010, to be submitted to JHEP).

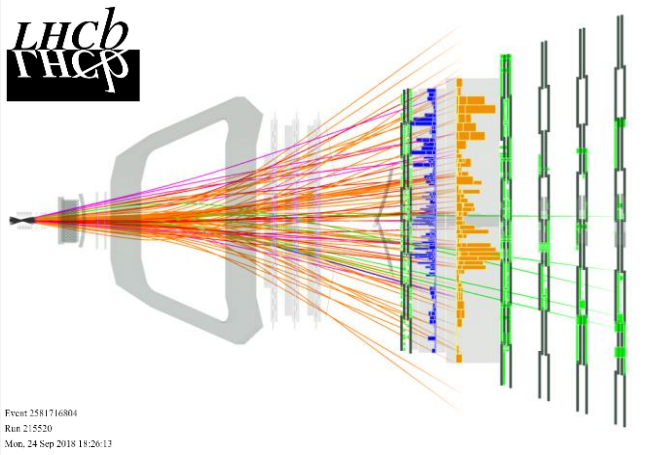


Motivation:

1. Light mesons constitute > 95% of the final state hadrons.
2. Prediction of multiple parton interaction based of effective models with parameters tuned to experimental results.
3. Searches of physics BSM requires good understanding of soft particle production.

- Unbiased data sample $\mathcal{L} = 5.4$ nb^{-1} (2015, two magnet polarities).
  - only tracks reconstructed in the entire tracking system, low fake-track probability;
- Measurement of differential cross-section of prompt production of long-lived charged particles*, separately for positively and negatively charged particles in bins: $p_T \in [0.08, 10]$ GeV/c, $\eta \in [2, 4.8]$

$$\frac{d^2\sigma}{d\eta\, dp_T} \equiv \frac{\boldsymbol{n}}{\mathcal{L}\, \Delta\eta\, \Delta p_T}$$



*charged long-lived particles: pions, kaons, protons, electrons, muons, Σ, Ξ, Ω

Corrections to particle production

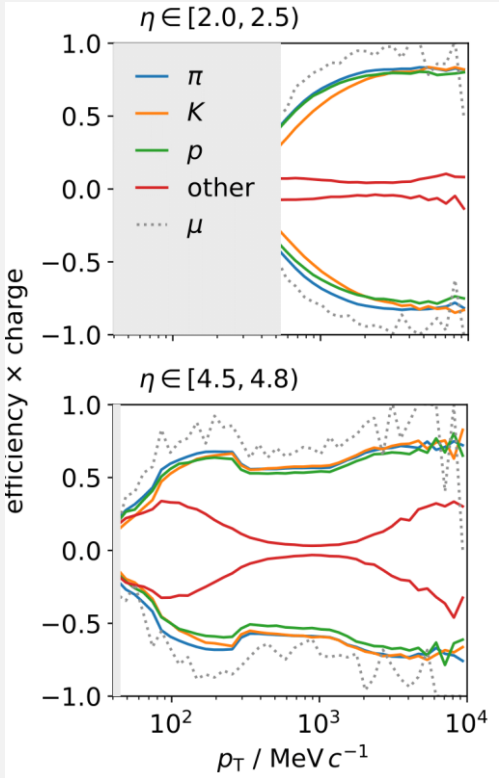
LHCb-PAPER-2021-010

1. Comparison of data with simulation of background and $\mathcal{E}$:

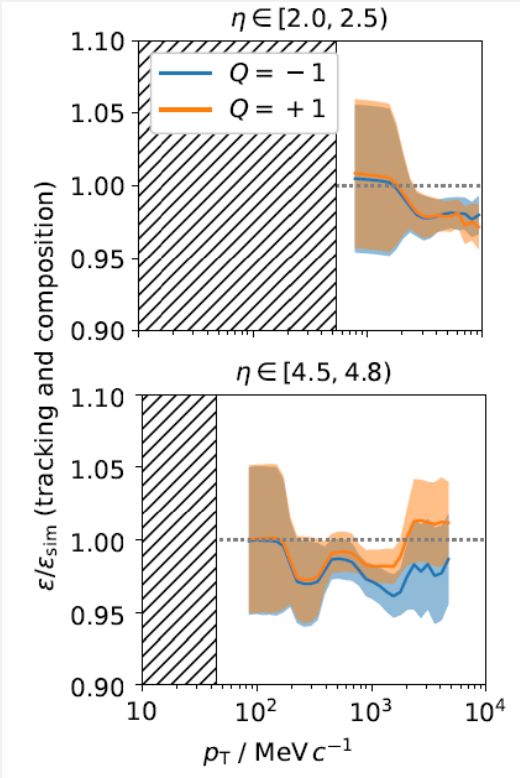
   $n_{cand} = \mathcal{E}\boldsymbol{n} + \sum_i n_{i,bkg}$, $\boldsymbol{n}$ - signal particles

   - background: fake tracks, photon conversions, charged-pion material interactions and strange decays;
   - $\mathcal{E}$ and $n_{i,bkg}$ are taken from simulation after data-driven correction for imperfect modelling,
2. In each bin of (η, p_T) efficiency is corrected for:
   - differences in $\mathcal{E}$ between data and simulation (muons from $J/\psi \to \mu^+\mu^-$);
   - simulated particle composition (π, K, p)

original efficiencies



corrections



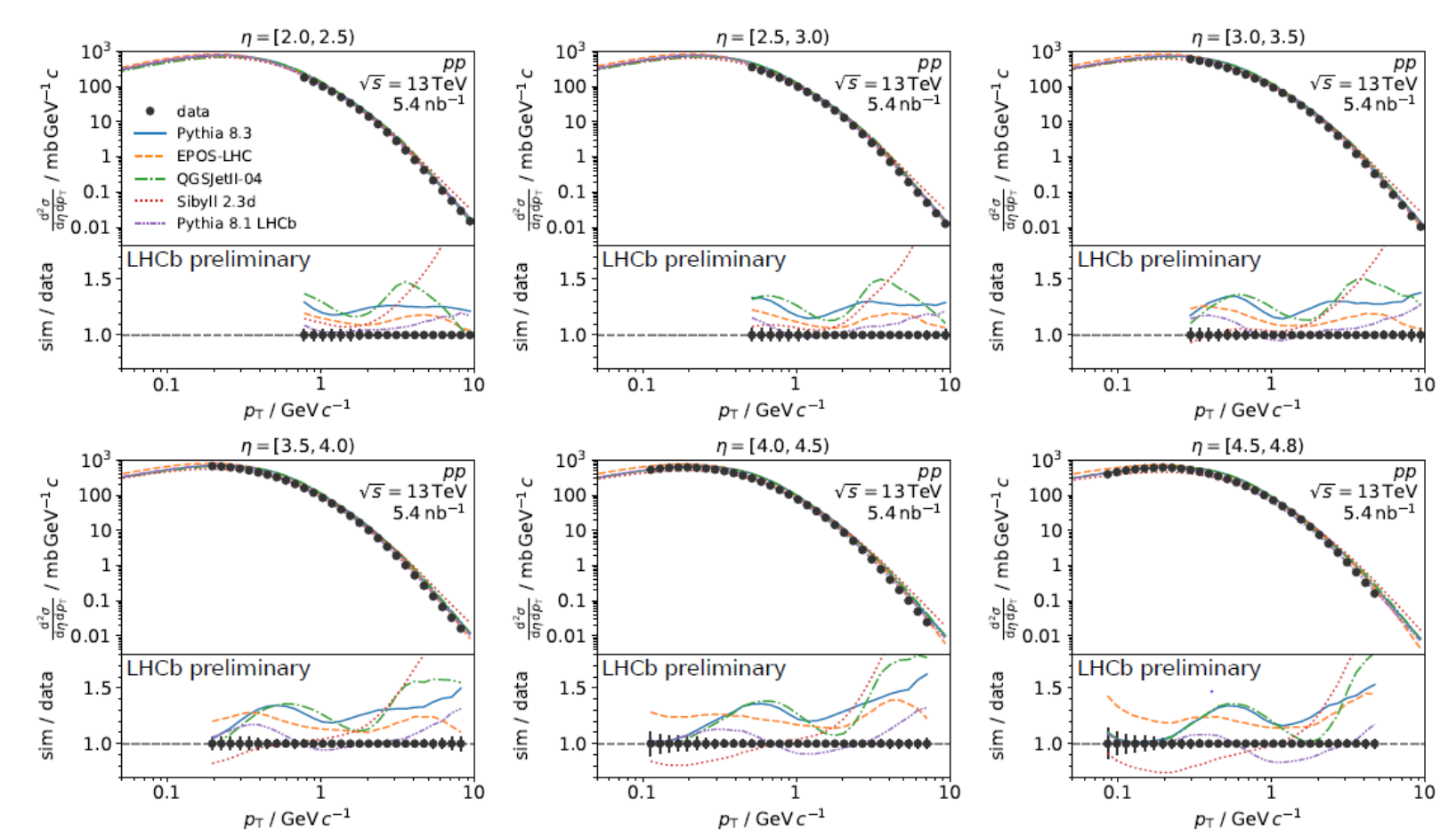
Charged-particle multiplicity @ 13 TeV

LHCb-PAPER-2021-010

Results:

- Differential X-section of prompt production of charged ling-lived particles;
- Dissimilarities wrt models are between -26% and +170%.
- Smallest discrepancies in EPOS-LHC.

Source	Relative uncertainty in %
Data-sample size	< 0.02
Simulated-sample size	< 3.0
Selection efficiency	0.9–5.1
Fake tracks	0.1–9.5
Material interactions	< 12
Strange-hadron decays	< 1.5
Beam-gas interactions	< 1.7
Other background contributions	< 1.1
Integrated luminosity	2.0



Total uncertainty is between 2.3% and 15% depending on the kinematic bin.

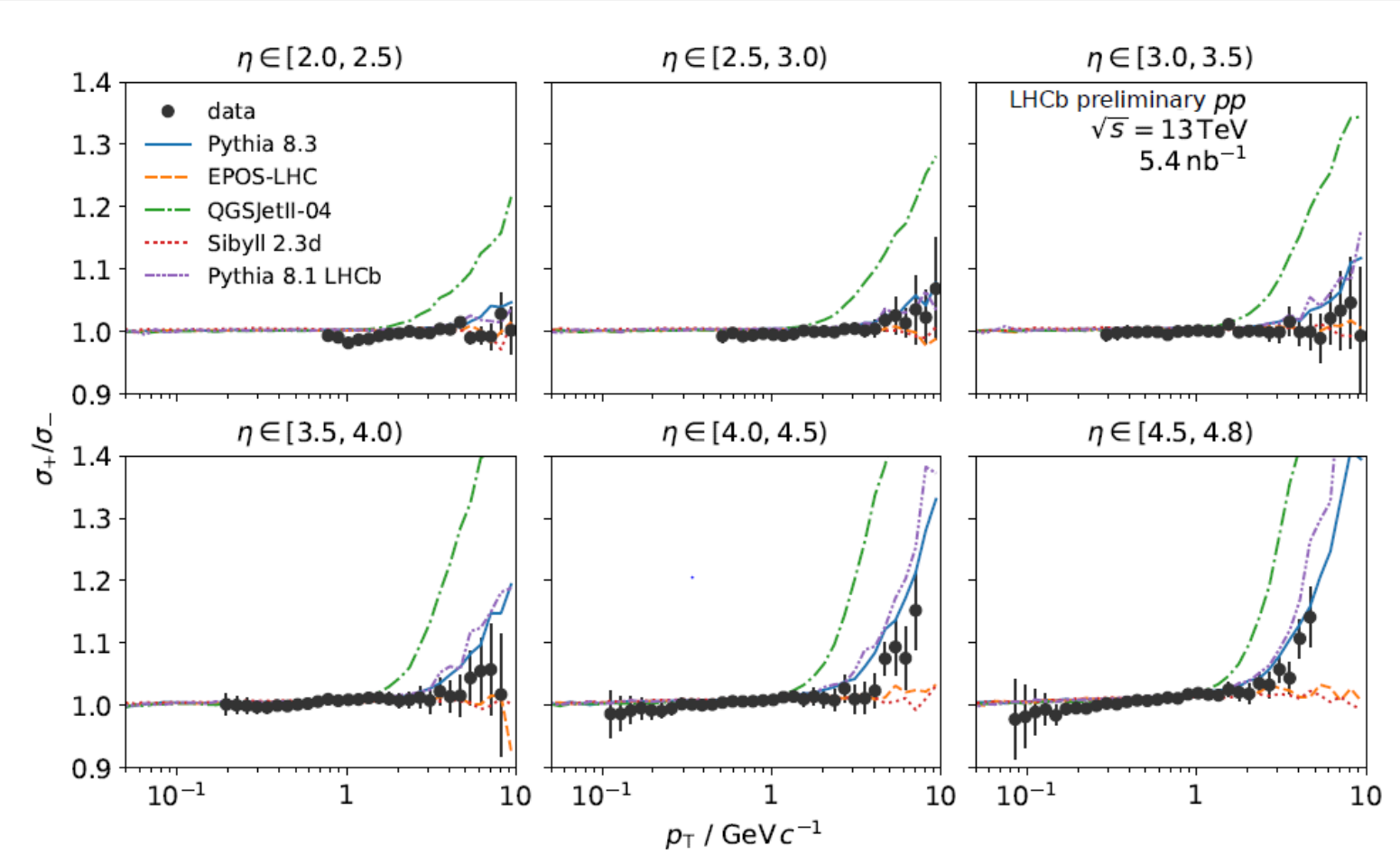
Cross-section mostly overestimated by recent hadronic-interaction models.

Charged-particle multiplicity @ 13 TeV

LHCb-PAPER-2021-010

Results:

- Ratio of differential X-sections for positively and negatively charged particles.
- Best agreement with PYTHIA 8.303 Monash tune.

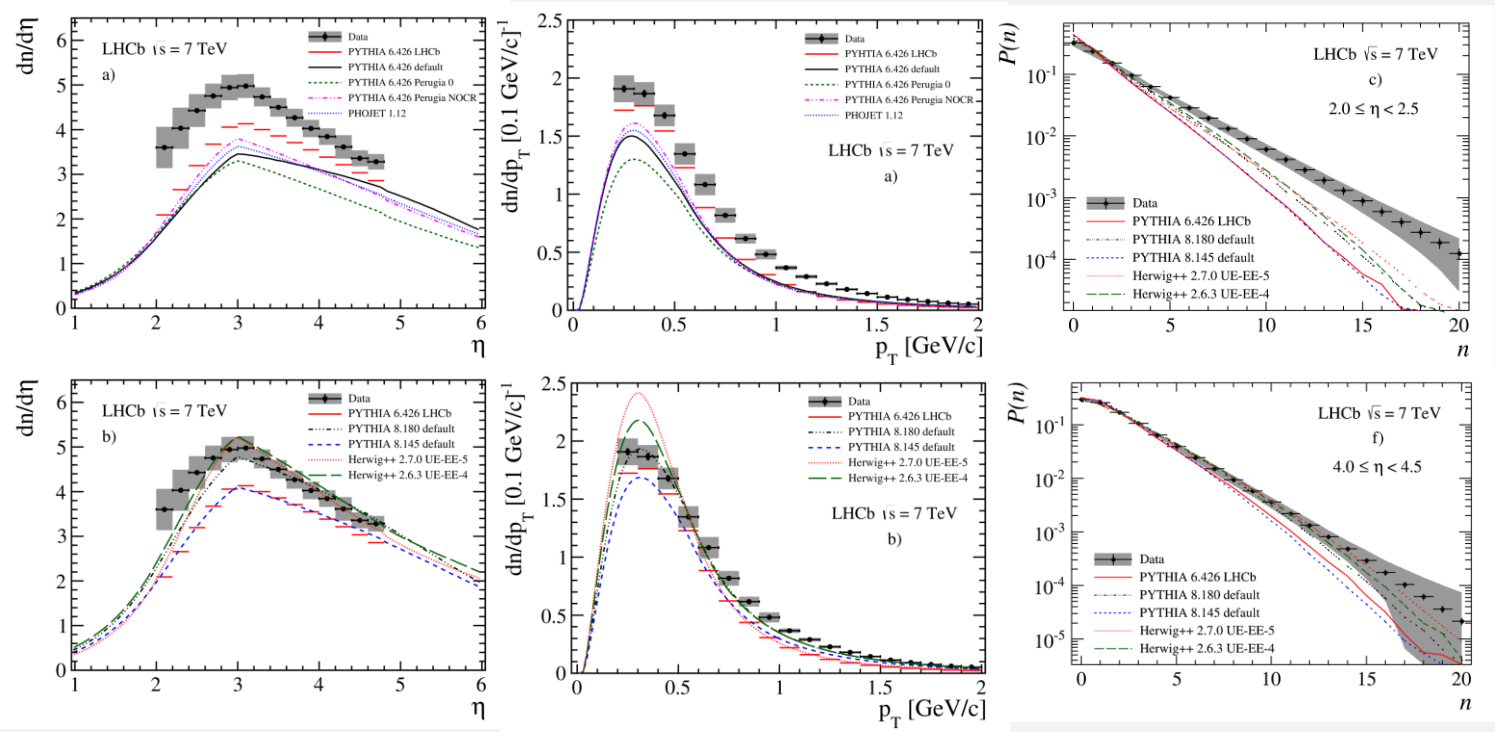


Cross-section mostly overestimated by recent hadronic-interaction models.

Particle production in pp @ 7 TeV

Measurement of charged-particle multiplicities in pp collisions at √s= 7 TeV in the forward region Eur. Phys. J. C (2012) 72:1947
Measurement of the forward energy flow in pp collisions at √s= 7 TeV Eur. Phys. J. C (2013) 73:2421

**Measurement of charged-particle multiplicities and densities in pp colisions at √s= 7 TeV in the forward region* Eur.Phys.J.C (2014) 74:2888



Eur.Phys.J.C (2014) 74:2888

* Selection:

- at least one reconstructed track in $2 < \eta < 4.8$,
- at least one particle with $p_T > 0.2$ GeV/c, $p > 2$ GeV/c,
- corrections for fake tracks and ghosts,
- data driven approach to correction for undetected events.

Results:

- none of the generators were able to fully describe the data,
- generator tuned to LHC measurements are in better agreement with data
- models underestimate charged particle production,

Charged particle production in pPb

Measurement of the nuclear modification factor and prompt charged particle production in pPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV LHCb-PAPER-2021-015, in preparation

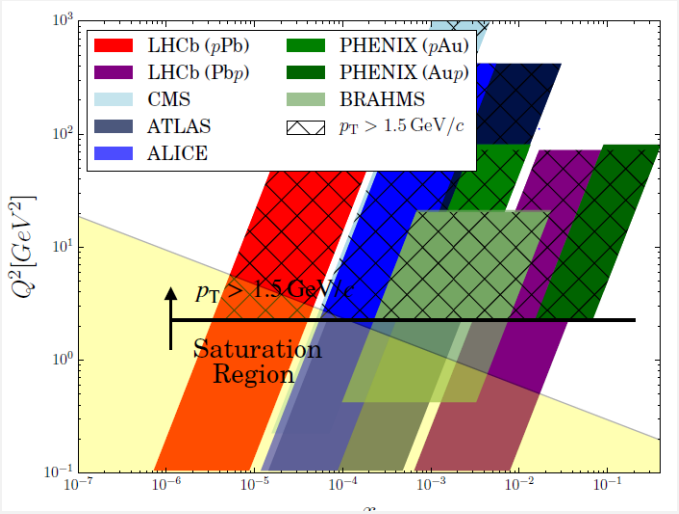
$$R_{pA} \equiv \frac{\sigma_{pA}}{A\sigma_{pp}}$$

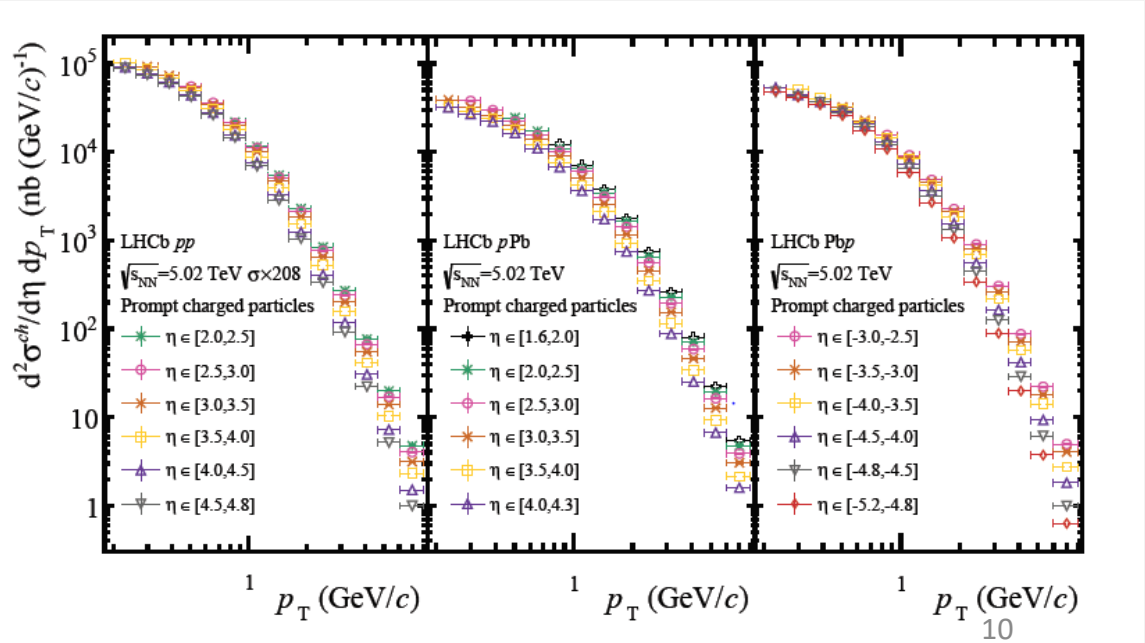
1. Colisions of pPb provide study of nuclear effects in initial and final state.
2. Dynamics of HI probed in context of Cold Nuclear Matter and saturation scale.
3. LHCb can explore the low-x and low Q^2 region, down to $p_T \to 0$.
   - forward mode: $10^{-6} \leq x \leq 10^{-4}$
   - backward mode: $10^{-3} \leq x \leq 10^{-1}$

   first results in soft-regime in pPb collisions
4. LHCb pPb data from 2013 (81.84 μb^{-1}), pp – 2015 (3.49 nb^{-1}).
5. Prompt charged particle yields measured with tracking system.
6. Selection with min bias trigger (one reconstructed track).
7. Kinematic coverage:
   - $p > 0.2$ GeV/c, $0.2 < p_T < 8$ GeV/c,
   - pp : $2 < \eta < 4.8$
   - pPb (FWD): $1.5 < \eta < 4.3$
   - pPb (BWD): $-5.3 < \eta < -2.5$.
7. Raw yield corrected by:
   - reconstructed and selection efficiencies,
   - background from fake tracks and secondary particles.
8. Total uncertainty: 2.8% in $d^2\sigma$ and 4.2% in R_{pPb}

Differential cross-section:

$$\frac{d^2\sigma^{ch}(\eta, p_T)}{d\eta\, dp_T} \equiv \frac{N^{ch}}{\mathcal{L}\, \Delta\eta\, \Delta p_T}$$



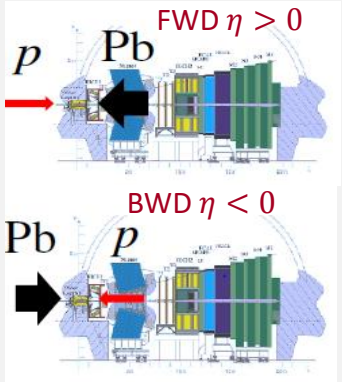


LHCb-PAPER-2021-015

Nuclear Modification Factor

$$R_{pPb}(\eta, p_T) \equiv \frac{1}{A}\frac{d^2\sigma^{ch}_{pPb}(\eta, p_T)/d\eta\, dp_T}{d^2\sigma^{ch}_{pp}(\eta, p_T)/d\eta\, dp_T}$$

$$A = 208$$



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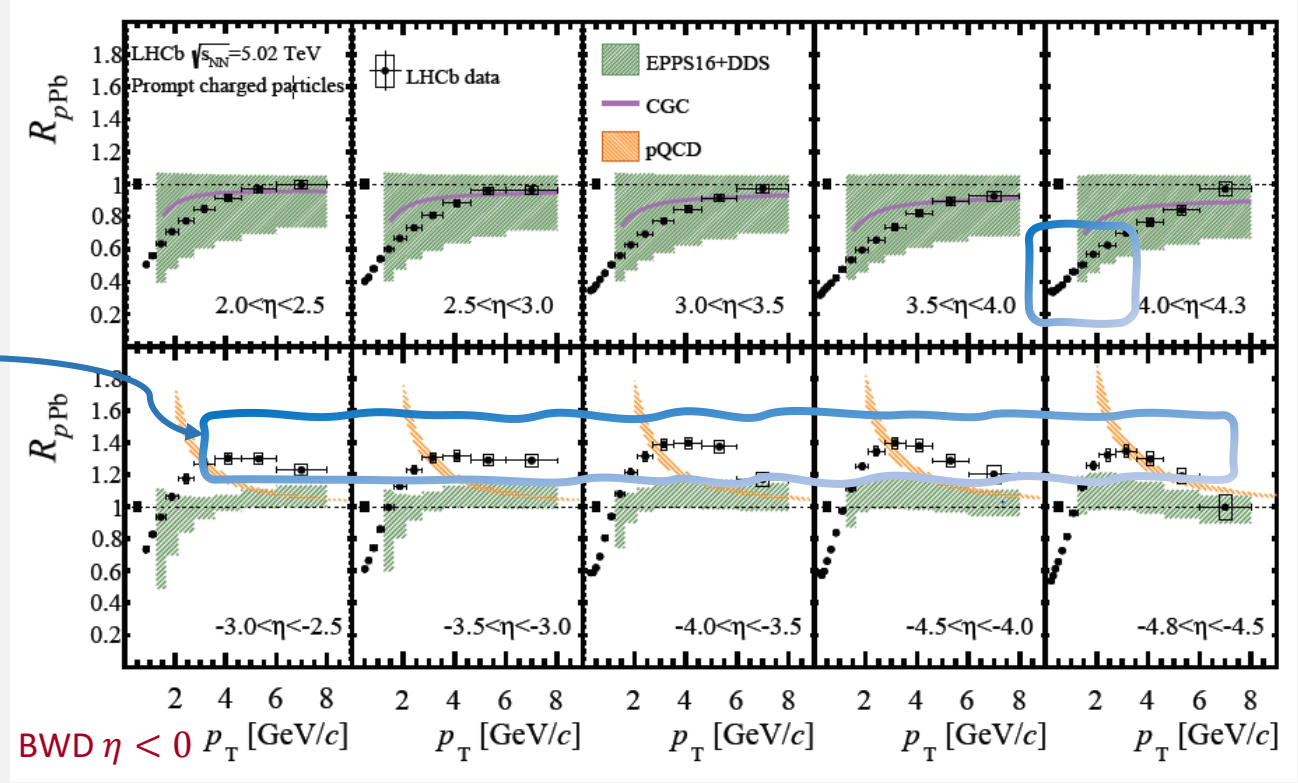
FWD $\eta > 0$



BWD $\eta < 0$

Results:

1. Suppression of charged particle production in pPb wrt pp at forward rapidity reaching $R_{pPb} = 0.3$ for low-p_T and high η.
2. Enhancement at backward rapidity for $p_T > 1.5$ GeV/c. Max $R_{pPb} \sim 1.3$ is reached (depending on η).

Comparison with models for $p_T > 1.5$ GeV/c:

- nPDF set EPPS16 and CT14 reproduces forward data (within uncertainties),
- CGC in the FWD (saturation region),
- pQCD+Multiple Scattering in the nucleus in agreement with the most backward data, but is unable to reproduce the other regions.

EPPS16: J. W. Cronin et al. Phys. Rev. D 11 (1975) 3105.
Helenius et al, JHEP 09 (2014) 138, arXiv:1406.1689
CGC: T. Lappi and H. Mantysaari, Phys. Rev. D 88 (2013) 114020
pQCD: Z.-B. Kang, I. Vitev, and H. Xing, Phys. Rev. D 88 (2013) 054010

Nuclear Modification Factor

LHCb-PAPER-2021-015

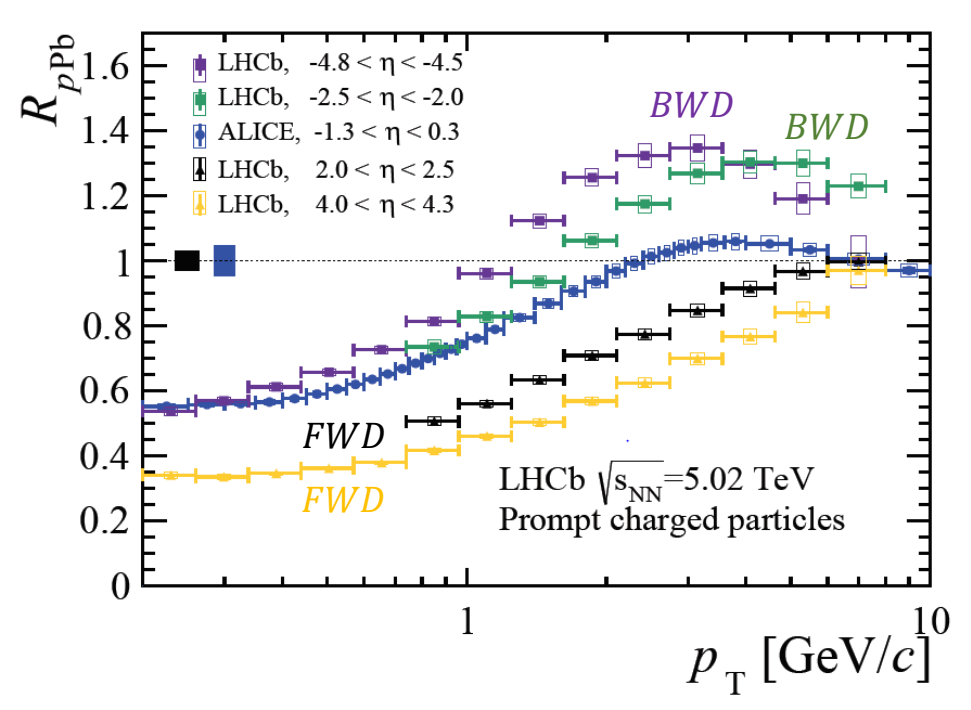
Comparison with other experiments:

- One of the most precise measurement of R_{pPb} to date with extended R_{pPb} coverage from very backward to very forward rapidity.
- ALICE result seems as transiton between FWD and BWD.

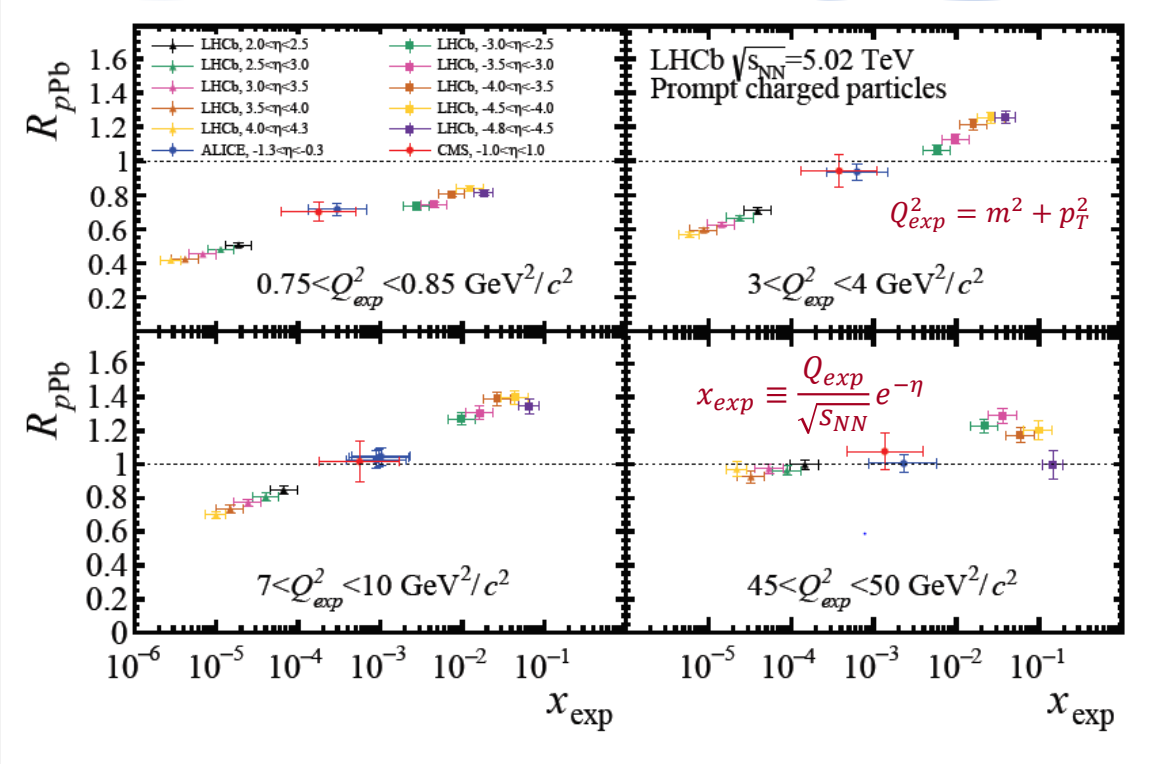
Evolution with x and Q^2 (crucial for Cold Nuclear Matter study):

$$Q^2_{exp} = m^2 + p_T^2,\ m = 256\ \text{MeV/c}^2,\ x_{exp} \equiv \frac{Q_{exp}}{\sqrt{s_{NN}}} e^{-\eta}$$

- R_{pPb} x_{exp} evolution is Q^2_{exp} dependent with start of decreasing at $x_{exp} > 0.1$



ALICE collaboration, JHEP 11 (2018) 013
CMS collaboration, JHEP 04 (2017) 039,



Double Parton Scattering in pPb

Observation of enhanced Double Parton Scattering in Proton-Lead Collisions at $\sqrt{s_{NN}}$ =8.16 TeV, Phys. Rev. Lett. **125**, 212001 (2020)

First measurement of charm pair production in pPb collision at $\sqrt{s_{NN}}$ =8.16 TeV.

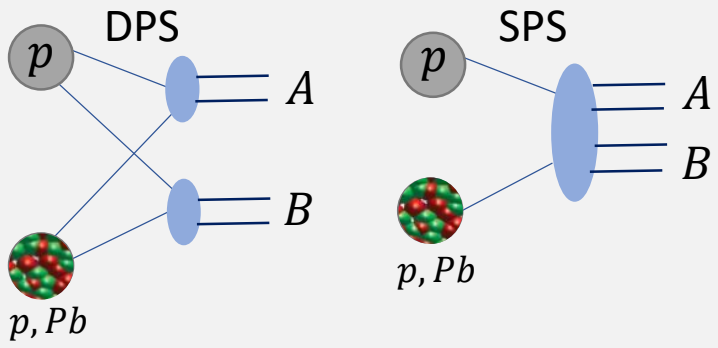
Motivation:

- Measurements of multiple parton scattering provide insight into the structure and long-range low-momentum scale interactions of the proton.
- MPI are the main factor that influence multiplicities.
- Ratio of DPS to SPS cross-section in pPb is expected to be about 3 times larger than in pp – heavy ion data are cleaner environment to study DPS.
- Test of PDF via comparison of single parton scattering (SPS) or multiple (double) parton scatterings (DPS).
- Production of open charm mesons:
  - LS (like-sign, cc), OS (opposite sign, $c\bar{c}$) pairs.
  - OS produced in SPS are correlated, correlation in pPb is modified wrt pp due to nuclear matter effects (nPDF).
  - LS pair in DPS are not correlated.
- Studies of LS pairs and a test of σ_{eff} universality.

$$pp(pPb) \rightarrow A + B + X$$

$$\sigma_{DPS}^{AB} = \frac{k}{2}\frac{\sigma^A \sigma^B}{\sigma_{eff}}$$

$$k = 1(2) \text{ for } A = B(\neq B)$$



$$A, B \equiv D = \{D^0, D^+, D_s^+\} \text{ and cc}$$

Double Parton Scattering in pPb

Phys. Rev. Lett. **125**, 212001

Selection:

- LHCb FWD and BWD pPb data (12.2±0.3 nb^{-1} and 18.6±0.5 nb^{-1})
- Pairs: $D^0D^{\pm}, D^0D_s^{\pm}, D^+D_s^{\pm}, J/\psi D^{0,\pm}$,
- Dominant source of systematic uncertainty originates from reconstruction efficiency: 5% per track in pPb, 10% in Pbp,

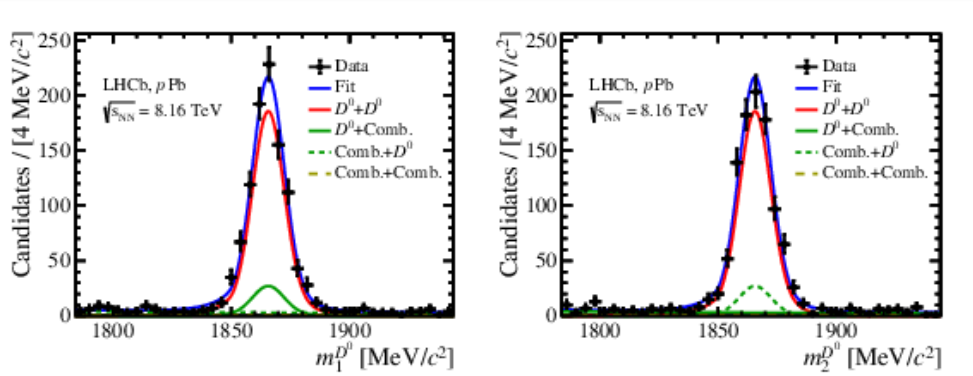
Results:

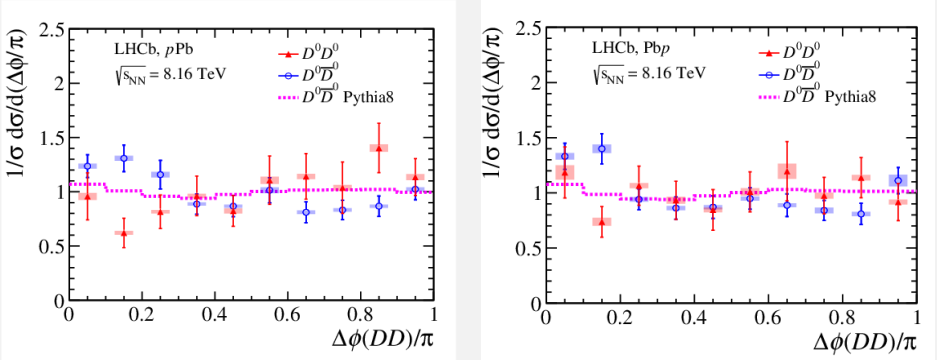
1. Study of azimuthal angle $\Delta\phi$ between mesons:

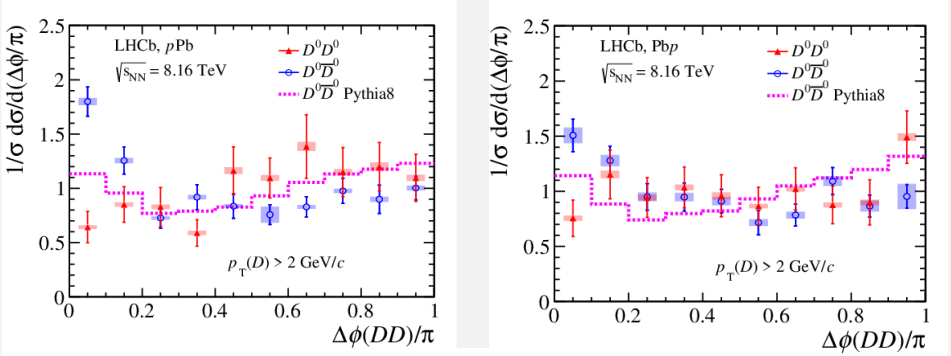
   no cut on D p_T: both LS and OS $\Delta\phi$ distributions are uniform, described by Pythia8;

   if $p_T(D^0)$ >2 GeV/c: D^0D^0 $\Delta\phi$ distribution is flat (LS in DPS are expected to be uncorrelated),

   $D^0\bar{D}^0$ favours $\Delta\phi \cong 0$, tensions with Pythia8.







$p_T(D^0)$ >2 GeV/c

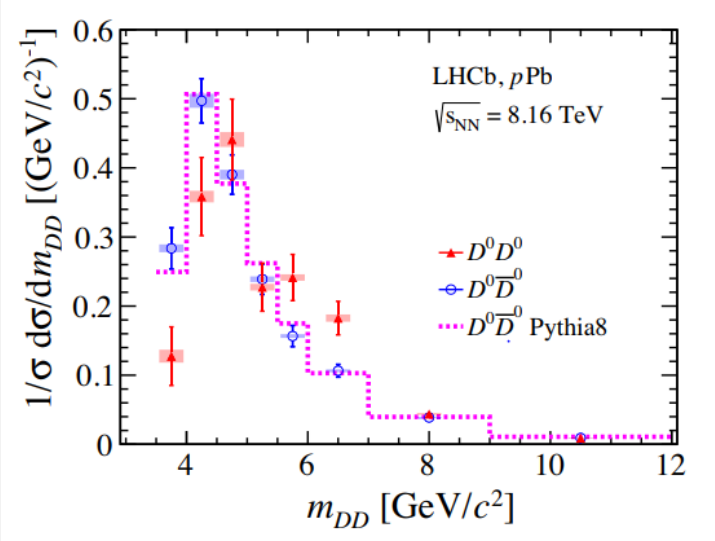
Double Parton Scattering in pPb

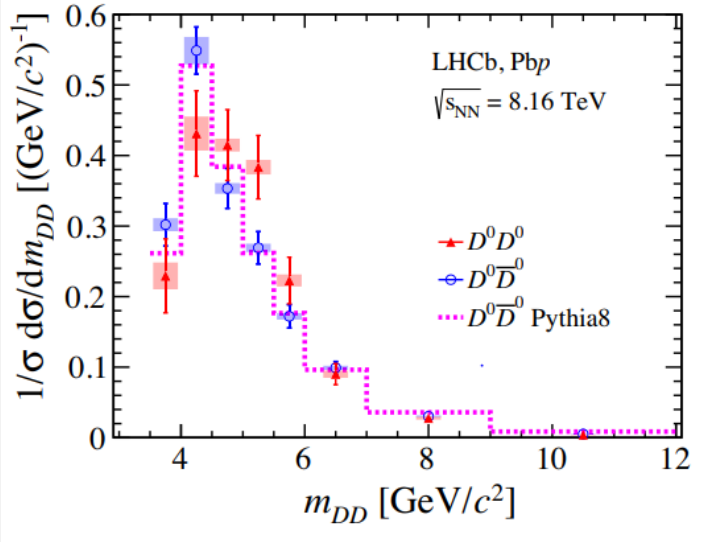
Phys. Rev. Lett. **125**, 212001

Results:

2. Cross-sections for all charm pairs: $\sigma = \frac{N_{corr}}{\mathcal{L}\,\mathcal{B}_1\mathcal{B}_2}$; N_{corr} is a signal yield after efficiency correction and subtraction of charm-from-b background.
   - LS Open Charm: good agreement with models for both SPS and DPS.
   - Prompt single charm X-section in pPb is smaller than in Pbp, explained by the modification of nPDF. In DPS this effect is stronger.
3. Forward-backward ratio R_{FB}: LS D^0D^0 can be interpreted as production via DPS.
   - $D^0\overline{D}^0$ well represented in Pythia8.

$$R_{FB} \equiv \frac{\sigma_{pPb}}{\sigma_{Pbp}} = \begin{cases} 0.40 \pm 0.05 \pm 0.10 \text{ (LS)} \\ 0.61 \pm 0.04 \pm 0.12 \text{ (OS)} \\ 0.16 \pm 0.06 \pm 0.04 \ (J/\psi D^0) \end{cases}$$





Double Parton Scattering in pPb

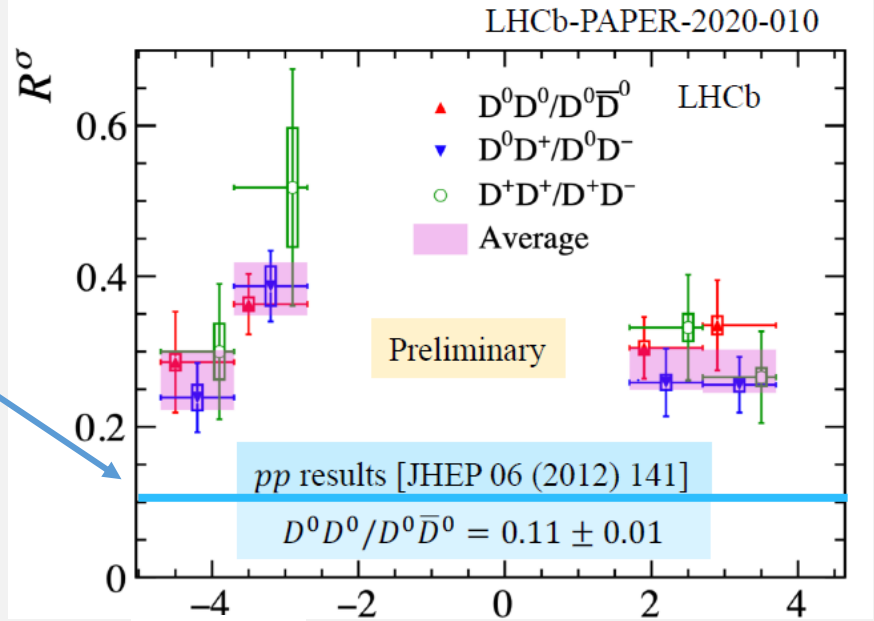
Phys. Rev. Lett. **125**, 212001

Results:

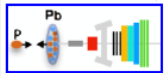
4. LS over OS X-section $R(D_1, D_2)$: 3 times enhancement of LS D^0D^0 pair production over OS $D^0\overline{D}^0$ from pp to pPb:

$$R(D_1, D_2) \equiv \frac{\sigma(D_1,D_2)}{\sigma(D_1,\overline{D_2})} = \begin{cases} 0.308 \pm 0.015 \pm 0.010 \text{ (pPb)} \\ 0.391 \pm 0.019 \pm 0.025 \text{ (Pbp)} \end{cases}$$

5. Effective X-section $\sigma_{eff,pPb}$ assuming DPS only, is ~1 b what confirms that DPS production in pPb is enhanced by a factor of three: $\sigma_{pPb}(DPS) \approx 3A\ \sigma_{pp}(DPS)$



x_{Pb}~0.01
x_p~0.00005



x_{Pb}~0.00005
x_p~0.01

$\sigma_{eff,pPb}$ [b]

Pairs	$-5 < y(H_c) < -2.5$	$1.5 < y(H_c) < 4$	pp extrapolation
D^0D^0	$0.99 \pm 0.09 \pm 0.09$	$1.41 \pm 0.11 \pm 0.10$	4.3 ± 0.5
$J/\psi D^0$	$0.64 \pm 0.10 \pm 0.06$	$0.92 \pm 0.22 \pm 0.06$	3.1 ± 0.3

3 times less than pp extrapolation with A=208 without modification of nPDF for DPS production

$$\sigma_{eff}(DD) = \frac{1}{2}\frac{\sigma_D\ \sigma_D}{\sigma_{DD}(DPS)}$$

$$\sigma_{eff}(\psi D) = \frac{\sigma_\psi\ \sigma_D}{\sigma_{\psi D}(DPS)}$$

$$R \equiv \frac{\sigma_{pPb}}{208\ \sigma_{pp}} = \begin{cases} 1.3 \pm 0.2\ (pPb\ D^0D^0) \\ 4.2 \pm 0.8\ (Pbp\ D^0D^0) \end{cases}$$

Different level of DPS enhancement in R

Summary

LHCb shows potential in the study of the insight of nucleon in proton-proton and proton-lead LHC runs with constraints to nuclear PDFs and saturation models down to very low x:

1. Measurement of differential cross-section of prompt production long-lived charged particles in pp collisions at $\sqrt{s}$= 13 TeV.
   - as a function of p_T and η, separately for positively and negatively charged particles
   - valuable input for generators, recent hadronic model overestimate data.
2. First and most precise measurement of differential cross-section of prompt charged particles in proton-lead at $\sqrt{s_{NN}}$=5.02 TeV and proton-proton collisions with the first determination of R_{pPb} for prompt charged particles in forward and backward regions at LHCb.
   - Nuclear modification factor in pPb indicate a nuclear suppression at forward rapidity compared to proton-proton.
3. Measurement of enhancement of Double Parton Scattering and two-parton correlations in Open Charm production in pPb.