Clues to a mysterious Universe exploring the interface of particle, gravity and quantum physics

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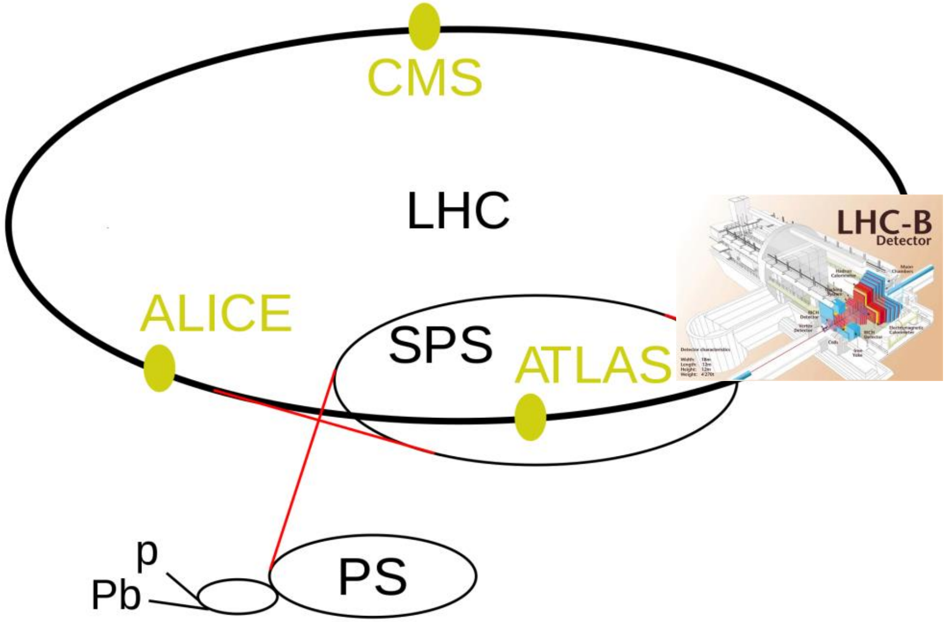
Outline

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

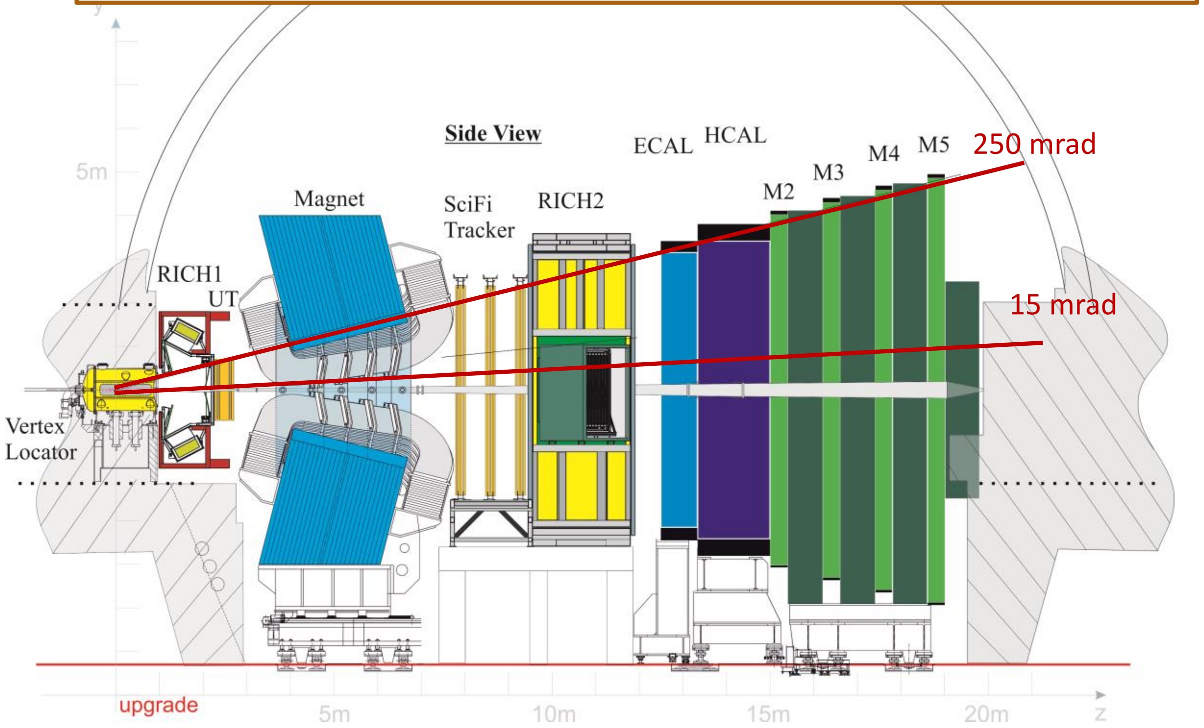
1. Proton-proton collisions at $\sqrt{s}$ =13 TeV
   a) charged particle multiplicities
   b) inelastic cross-section
2. Collisions of pPb and Pbp
3. Fixed target experiment
4. Prospects for Upgrade I and II



LHCb spectrometer for flavour physics and rare decays

- LHCb detector has a unique forward coverage in the pseudorapidity range $2 < \eta < 5$

The forward region is sensitive to low Bjorken-x QCD and low Q^2 dynamics and multiparton interaction so-far unexplored kinematic regions.



Excellent performance:

- 3 fb^{-1} accumulated in RUN 1, 6 fb^{-1} in Run 2;
- 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 $\mathcal{E}(\pi \to K) \sim 5\%$

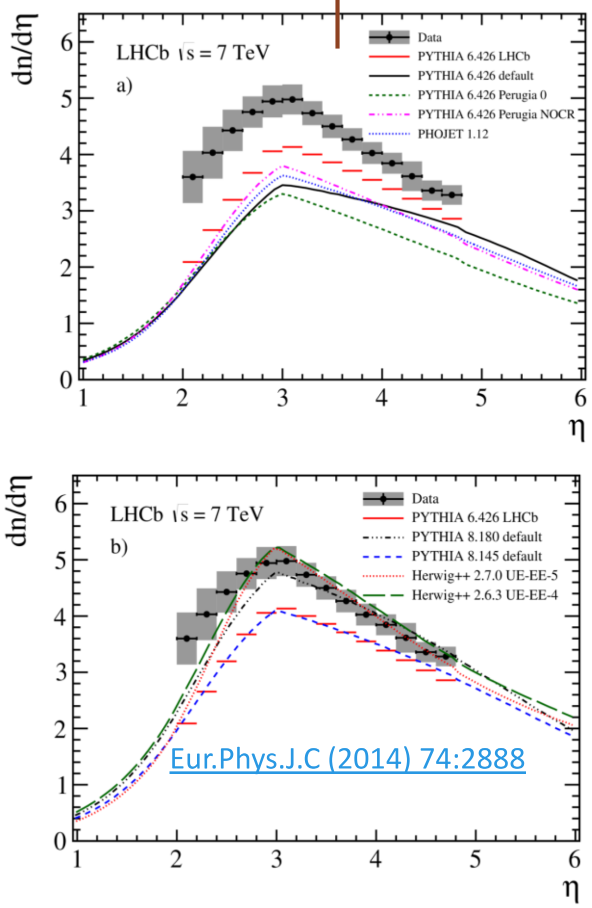
- Calorimeters ECAL, HCAL, $\Delta E/E = 1\% + 10\%/\sqrt{E[GeV]}$ for ECAL

2022 start of Run 3 with Upgrade I

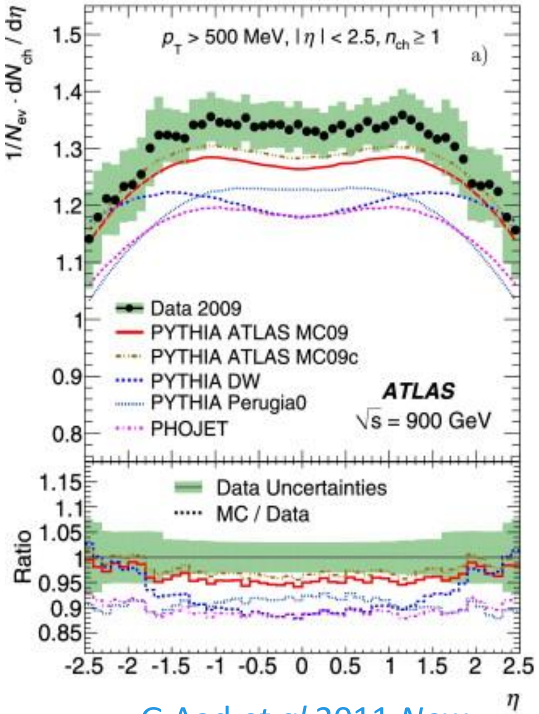
Run 3-4: 50 fb^{-1} with $\mathcal{L}_{max} = 2 \times 10^{33}$ $cm^{-2}s^{-1}$

LHCb unique role in soft QCD

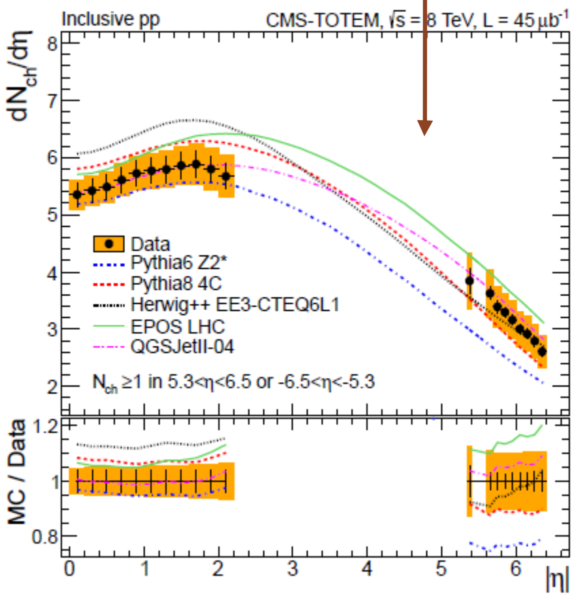
- LHCb is optimised (general) for beauty and charm decays with low-p_T threshold



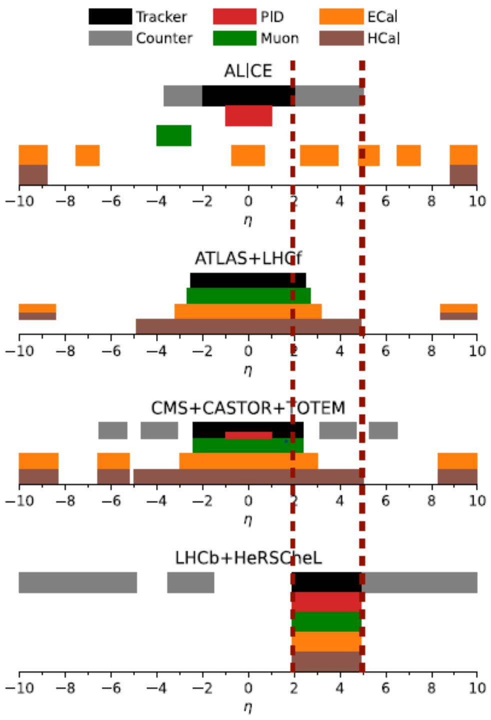
[Eur.Phys.J.C (2014) 74:2888]



[G Aad *et al* 2011 *New J. Phys.* **13** 053033]



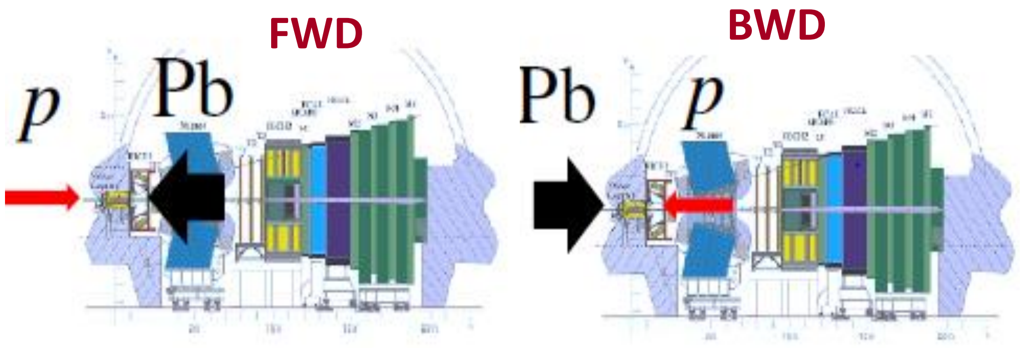
[EPJC 74 (2014) 2053]

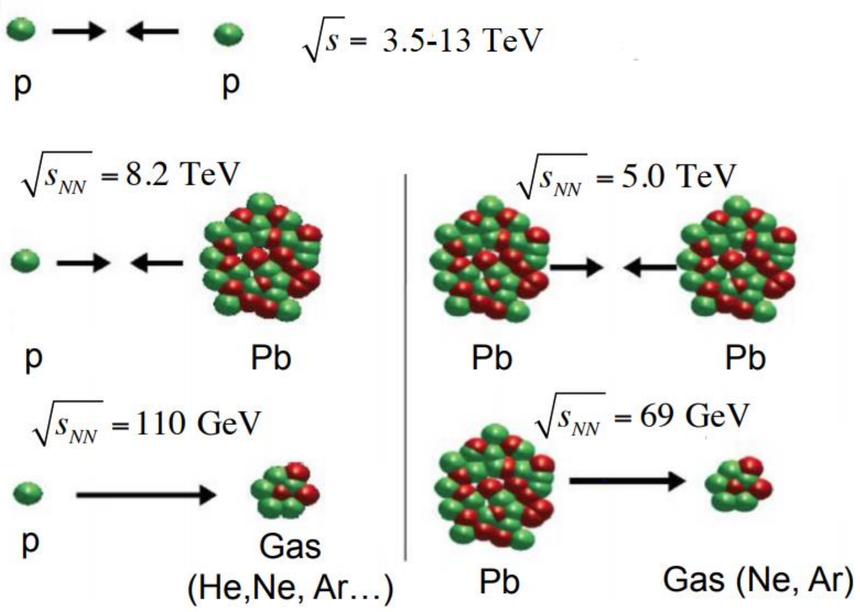


Experimental results with a vital impact on phenomenological models and generator tunes aimed to understand the soft component of the hadron-hadron collision.

LHCb insigns into hadrons

- 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:
    central and backward





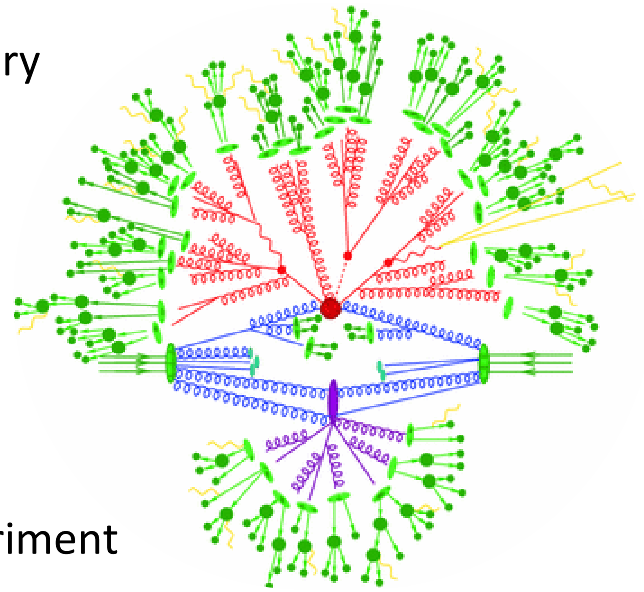
LHCb is the only detector at LHC fully instrumented in the forward region.

Multiplicity in proton-proton collisions

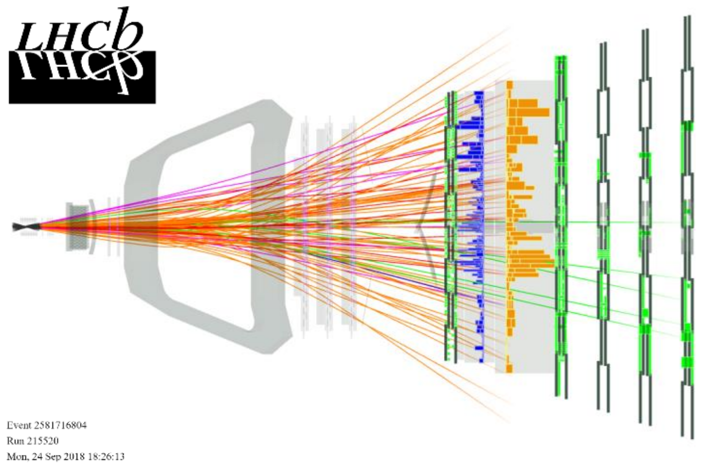
Motivation:

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.
4. Production of light hadrons at TeV scale in the forward region – crucial for air-shower models

theory

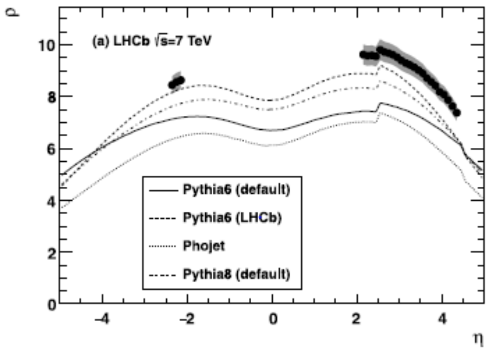


experiment



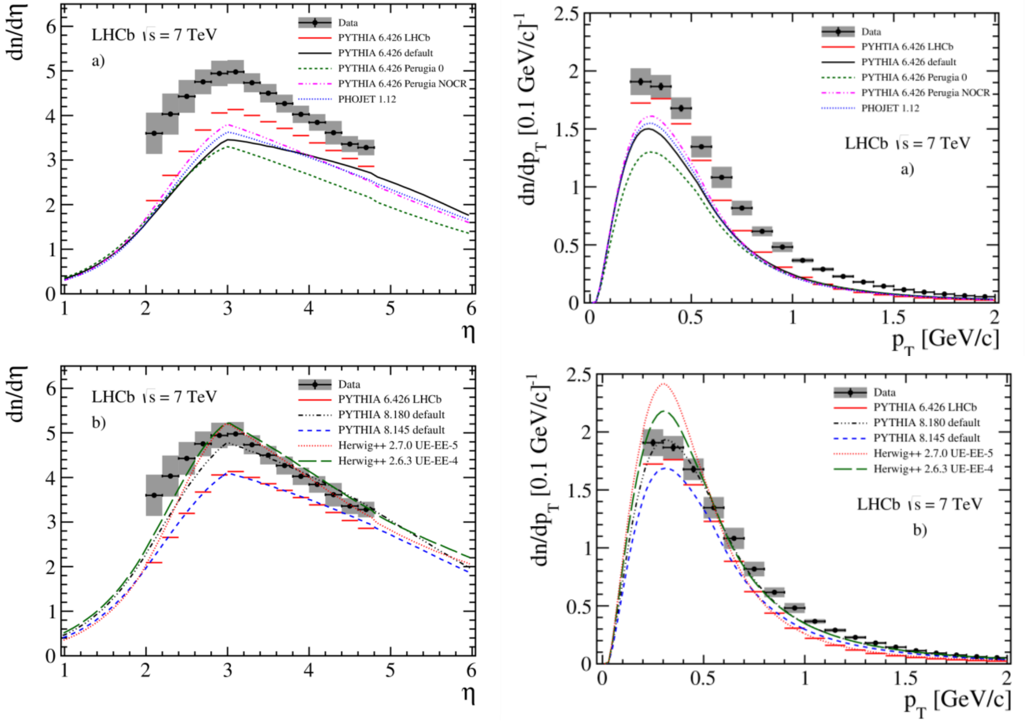
Prompt particle production in pp @ 7 TeV

<u>Eur. Phys. J. C (2012) 72:1947</u>



- tracks reconstructed in forward and backward: $2 < \eta < 4.8$ or $-2.5 < \eta < -2$,
- hard QCD sample $p_T > 1$ GeV/c

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



Selection:

- min bias trigger,
- 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 in Run 1 data.

Charged-particle multiplicity in pp @ 13 TeV

JHEP 01 (2022) 166

- 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;
  - about 350×10^6 events with both magnet polarities, 5.4 nb^{-1},
  - $\langle\mu\rangle \sim 0.9$
- Measurement of double-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, $\eta \in [2, 4.8]$
- Comparison with four hadronic-interaction models

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

$\boldsymbol{n}$- number of recorded tracks after corrections

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

Corrections to particle production

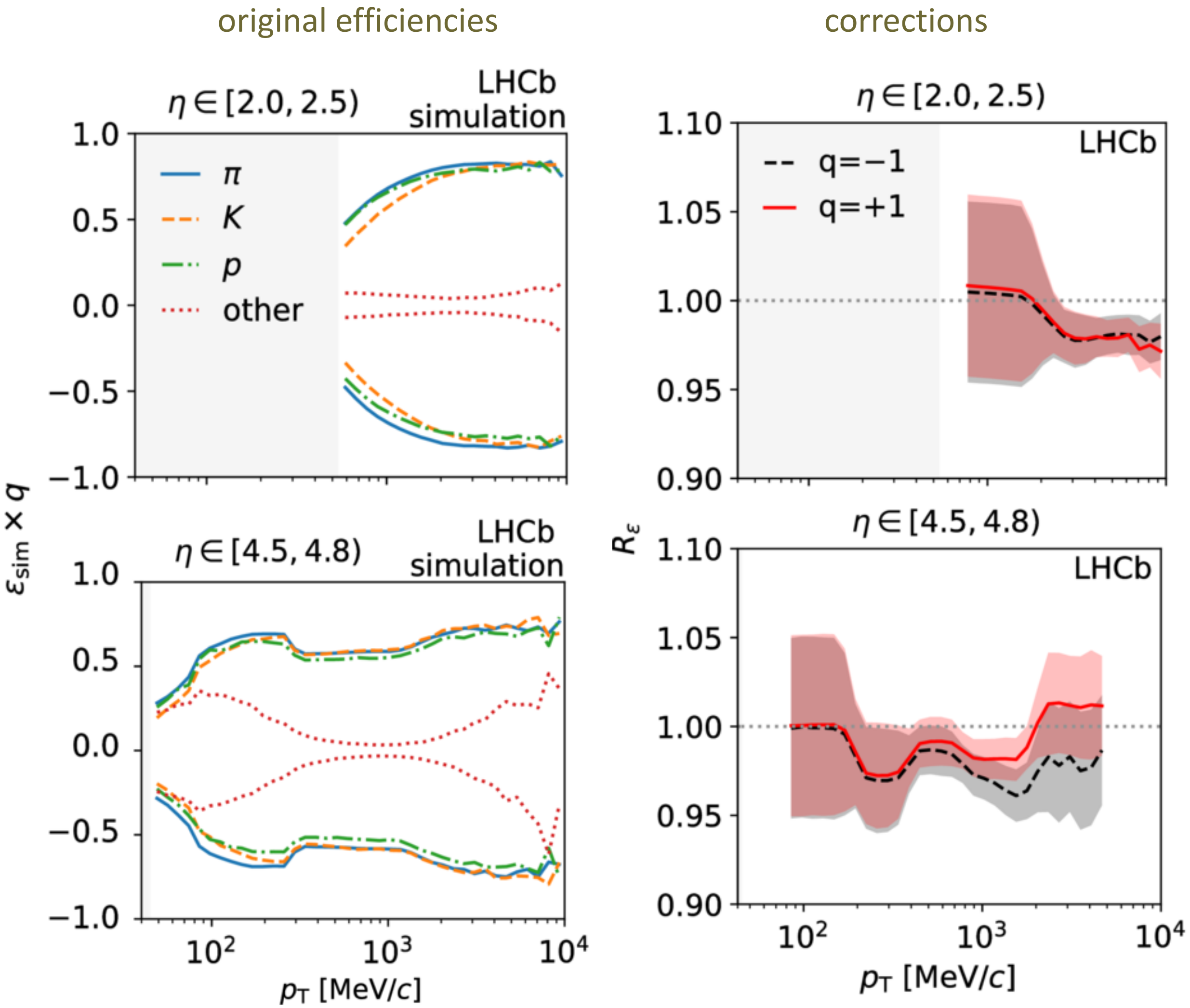
JHEP 01 (2022) 166

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)



Charged-particle multiplicity @ 13 TeV

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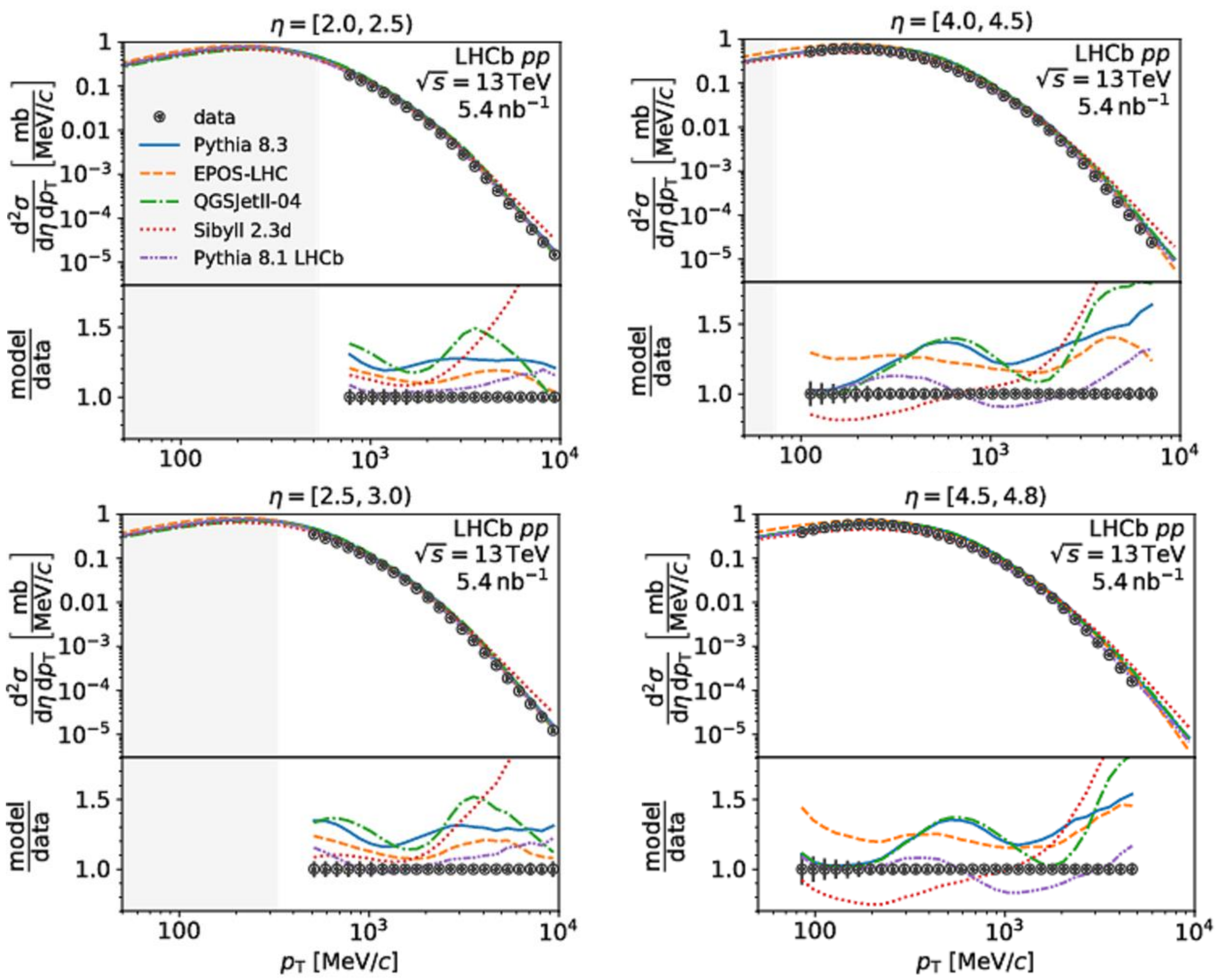
Results:

- Differential X-section of prompt production of charged long-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.



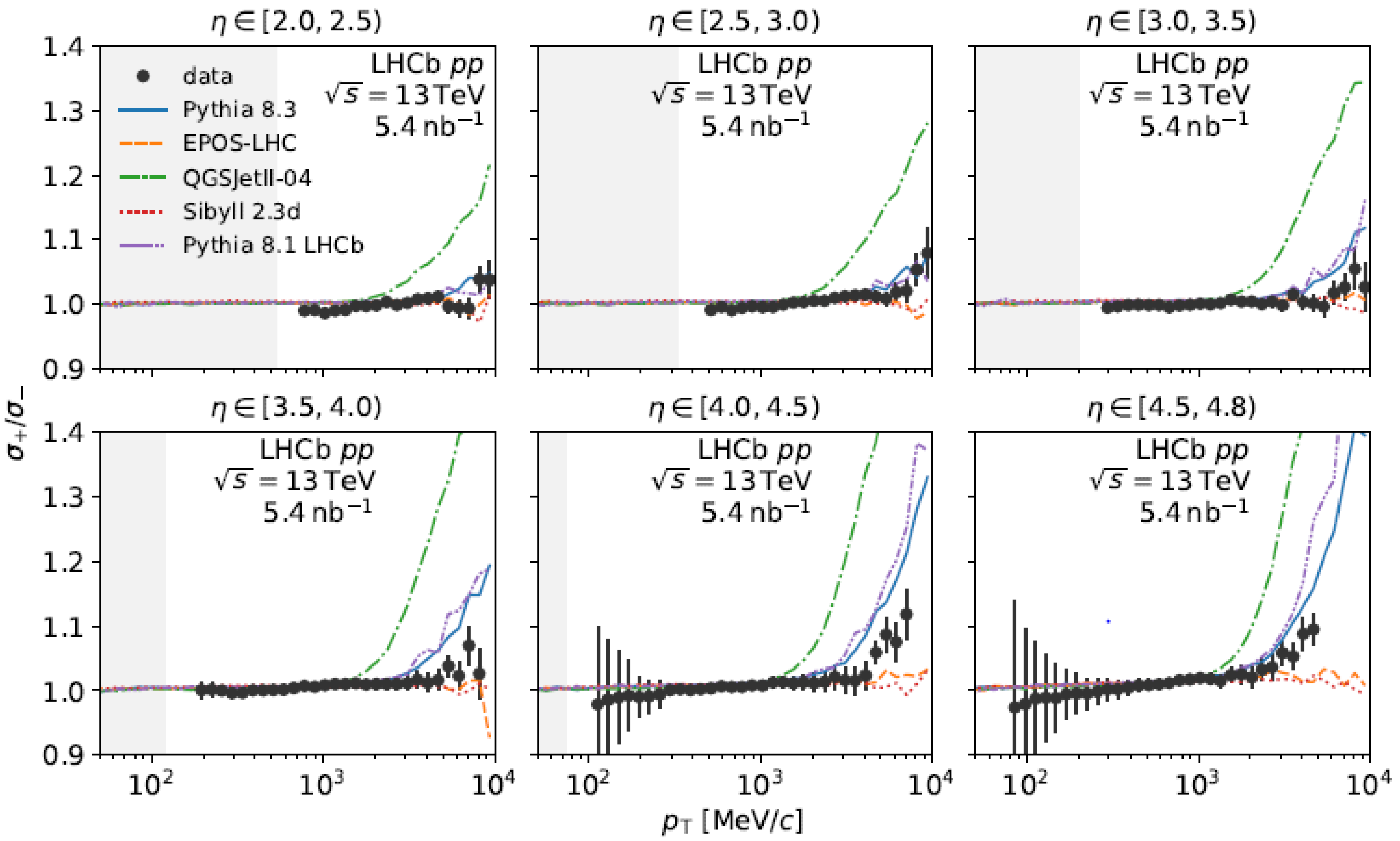
Cross-section mostly overestimated by recent hadronic-interaction models.

Charged-particle multiplicity @ 13 TeV

JHEP 01 (2022) 166

Results:

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



At high η and high p_T, the production of positively charged particles increases +2 initial state)

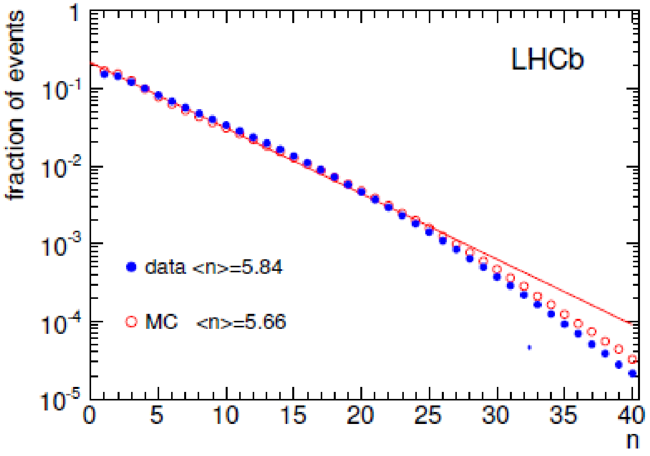
Inelastic pp cross-section @ 7 TeV

JHEP 02 (2015) 129

$$\sigma_{inel}^{acc} = \frac{N_{vis}}{\epsilon L}$$

N_{vis} selection:

- prompt long-lived particles, at least one reconstructed track,
- $p_T > 0.2$ GeV/c and $2 < \eta < 4.5$,



Efficiency ϵ: full simulation

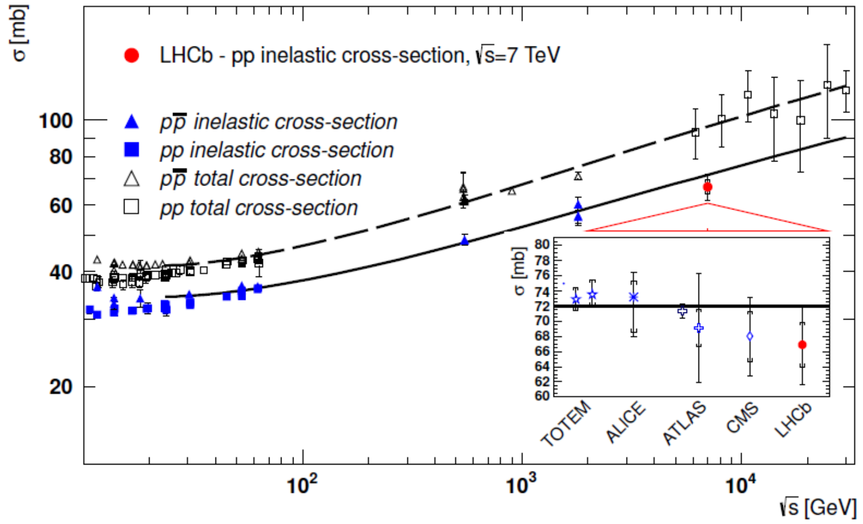
$$\sigma_{inel}^{inacc} = 55.0 \pm 2.4(\text{exp.})\ \text{mb}$$

Extrapolation to full phase space: model dependent (Pythia 6)

$$\sigma_{inel} = s_{extr}\ \sigma_{inel}^{inacc}$$

$$s_{extr} = 1.2168 \pm 0.0001$$

$$\sigma_{inel} = 66.9 \pm 2.9\ (exp.) \pm 4.4(extr.)\ \text{mb}$$



Inelastic pp cross-section @ 13 TeV

JHEP 06 (2018) 100

N_{vis} selection:

- prompt long-lived particles, at least one reconstructed track
- $p_T > 2$ GeV/c and $2 < \eta < 4.5$,

Efficiency ϵ: full simulation

$$\sigma_{inel}^{inacc} = 62.237 \pm 0.002(\text{stat}) \pm 2.55)\text{syst})\ \text{mb}$$

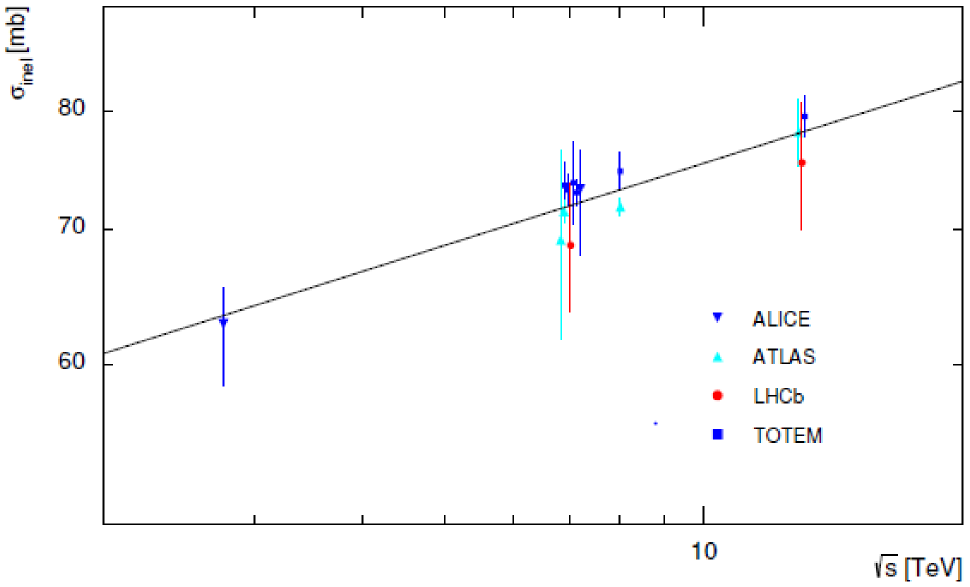
Extrapolation to full phase space: $\sigma_{inel} = F_T\, \sigma_{inel}^{inacc}$

- model dependent (Pythia 8.230 with current tunes)

$$F_T = \frac{\sum \sigma_i}{\sum \sigma_i v_i}$$

$i = ND, SD, DD$

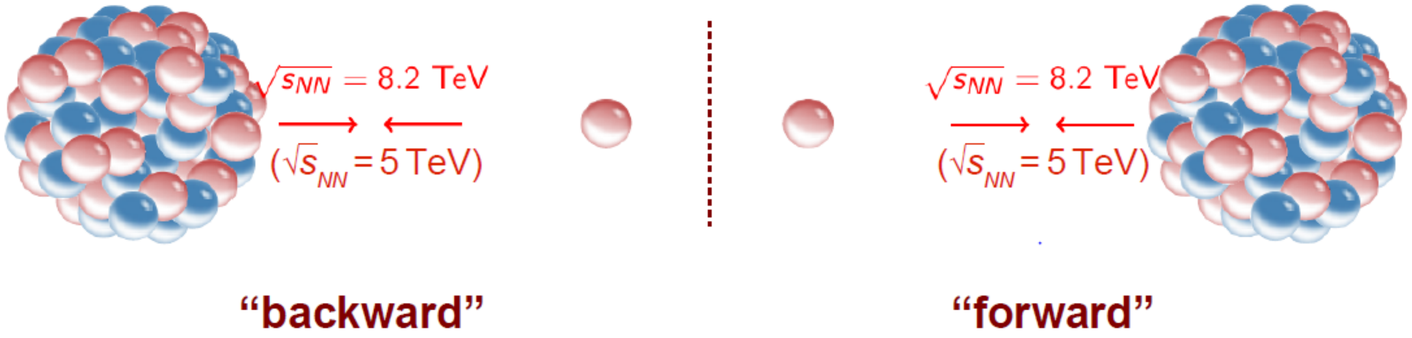
v_i - fractions of visible interactions

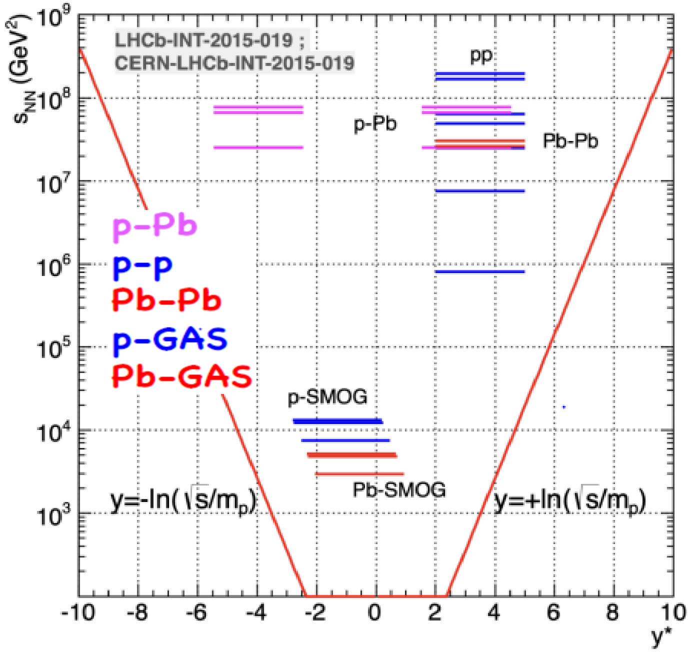


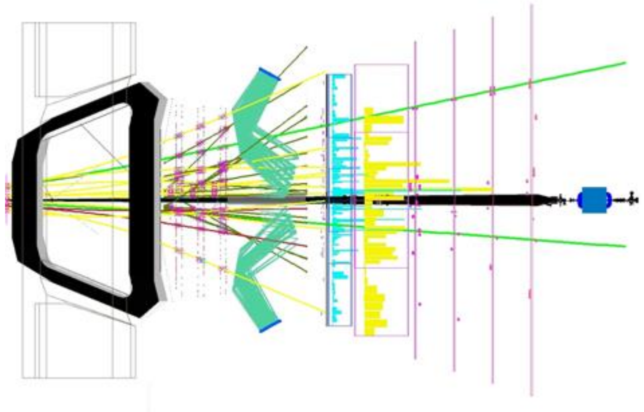
$$\sigma_{inel}(\sqrt{s} = 13\ \text{TeV}) = 74.5 \pm 3.0\ (exp.) \pm 4.5(extr.)\ \text{mb}$$

$$\sigma_{inel}(\sqrt{s} = 7\ \text{TeV}) = 68.7 \pm 2.1\ (exp.) \pm 4.5(extr.)\ \text{mb}$$

Proton – lead collision



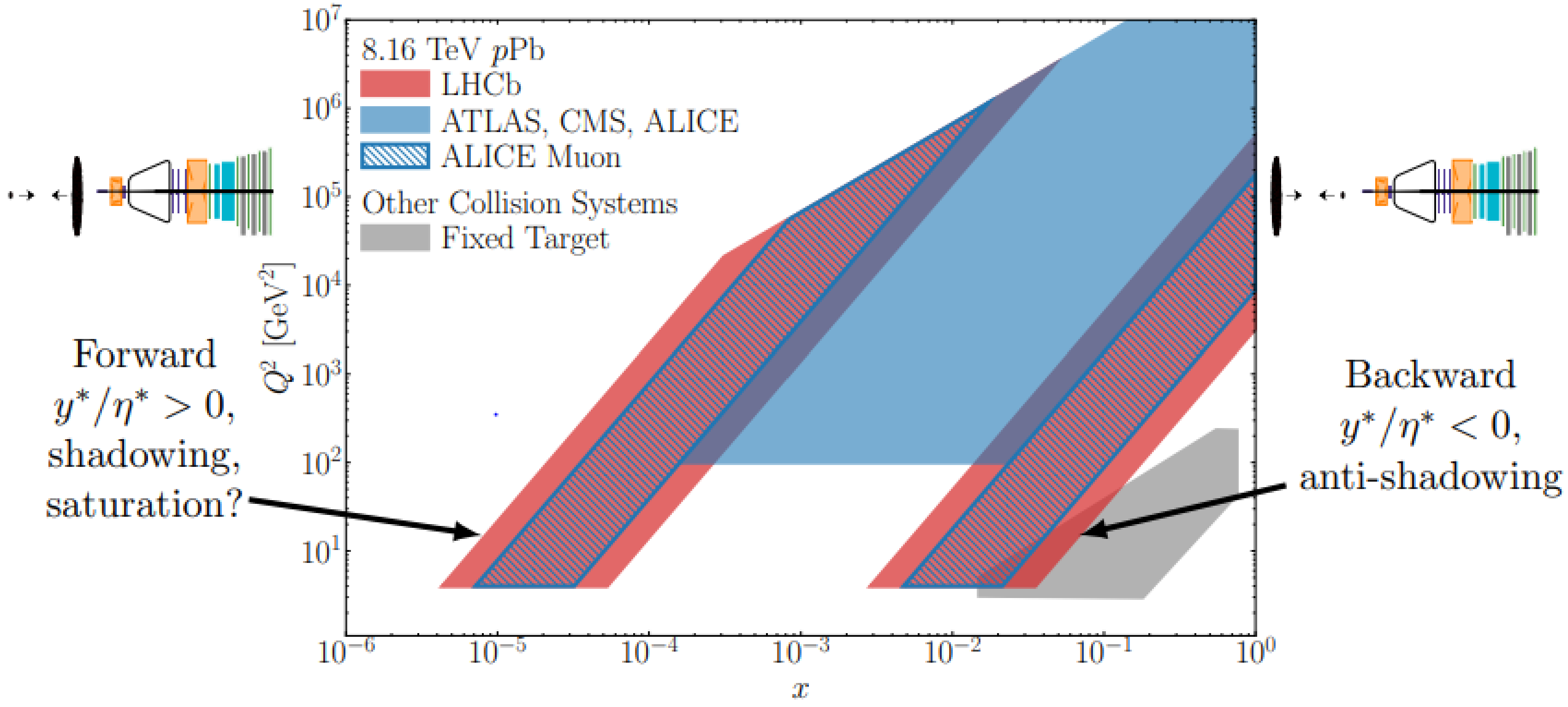




LHCb detector for pPb collisions

Phys. Rev. Lett. 128 (2022) 142004

Production of light hadrons is an important probe of Cold Nuclear Matter.
CNM effects are described in nuclear PDF (nPDF).
LHCb offers access to low-x and low Q – saturation region?



Charged particle production in pPb

Phys. Rev. Lett. 128 (2022) 142004

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

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 pPb data from 2013 (81.84 μb^{-1}), pp – 2015 (3.49 nb^{-1}).

Prompt charged particle yields measured with tracking system.

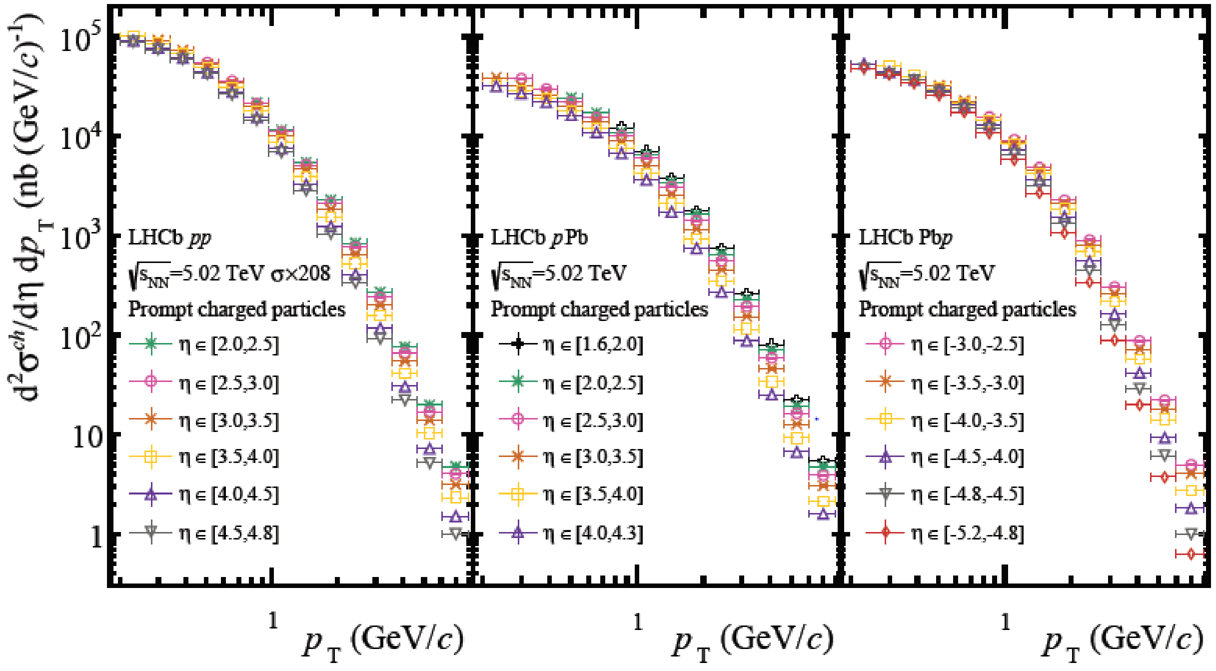
Selection with min bias trigger (one reconstructed track).

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): $-5.3 < \eta < -2.5$.

Raw yield corrected by:
reconstructed and selection efficiencies,
background from fake tracks and secondary particles.

Total uncertainty: 2.8% in $d^2\sigma$ and 4.2% in R_{pPb}



Nuclear modification factor

Phys. Rev. Lett. 128 (2022) 142004

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

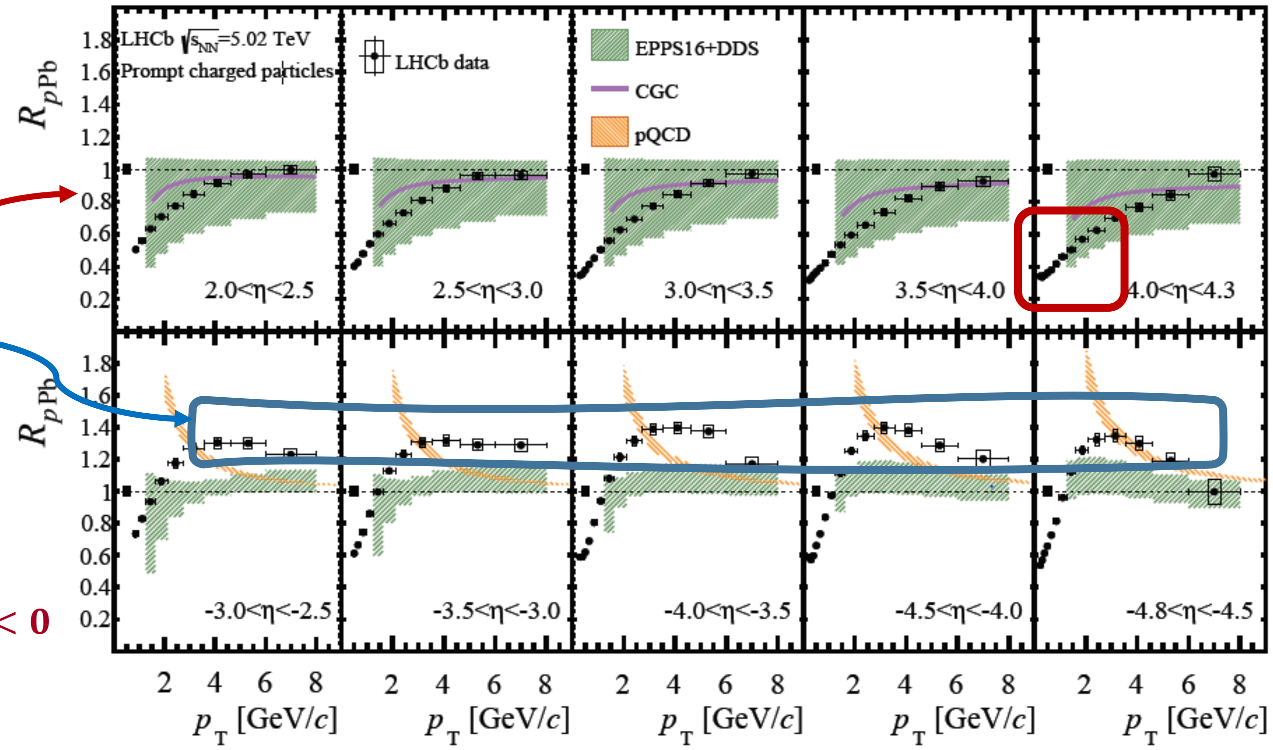
$$R_{pPb}(\eta, p_T) \equiv \frac{1}{A}\frac{d^2\sigma^{ch}_{pPb}(\eta, p_T)/d\eta\, dp_T}{d^2\sigma^{ch}_{pp}(\eta, p_T)/d\eta\, dp_T} \qquad A = 208$$

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 (interpreted as Cronin enhancement).
   Max $R_{pPb} \sim$ 1.3 is reached (depending on η).

FWD $\eta > 0$

BWD $\eta < 0$



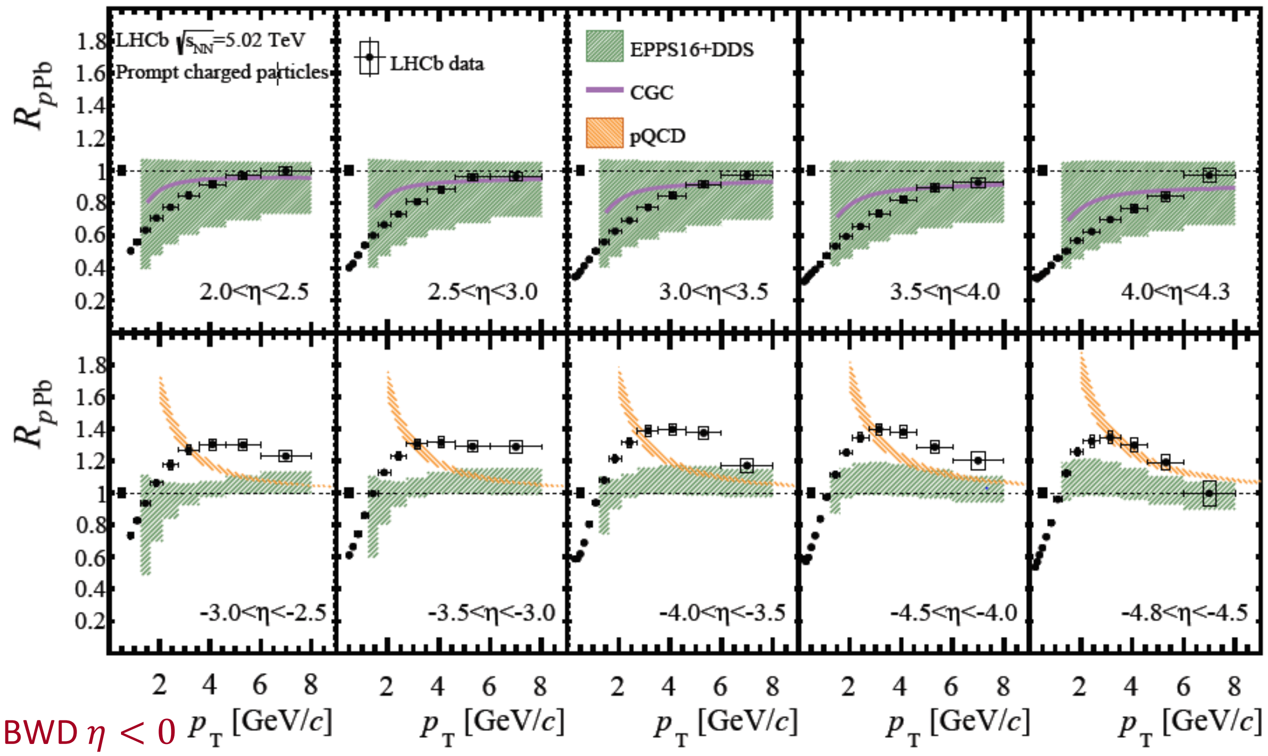
Nuclear modification factor – comparison with models

Phys. Rev. Lett. 128 (2022) 142004

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

- nPDF set EPPS16 and CT14 reproduces forward data (within uncertainties),
- CGC effective field theory 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.

FWD $\eta > 0$



BWD $\eta < 0$

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 – Q^2 and x evolution

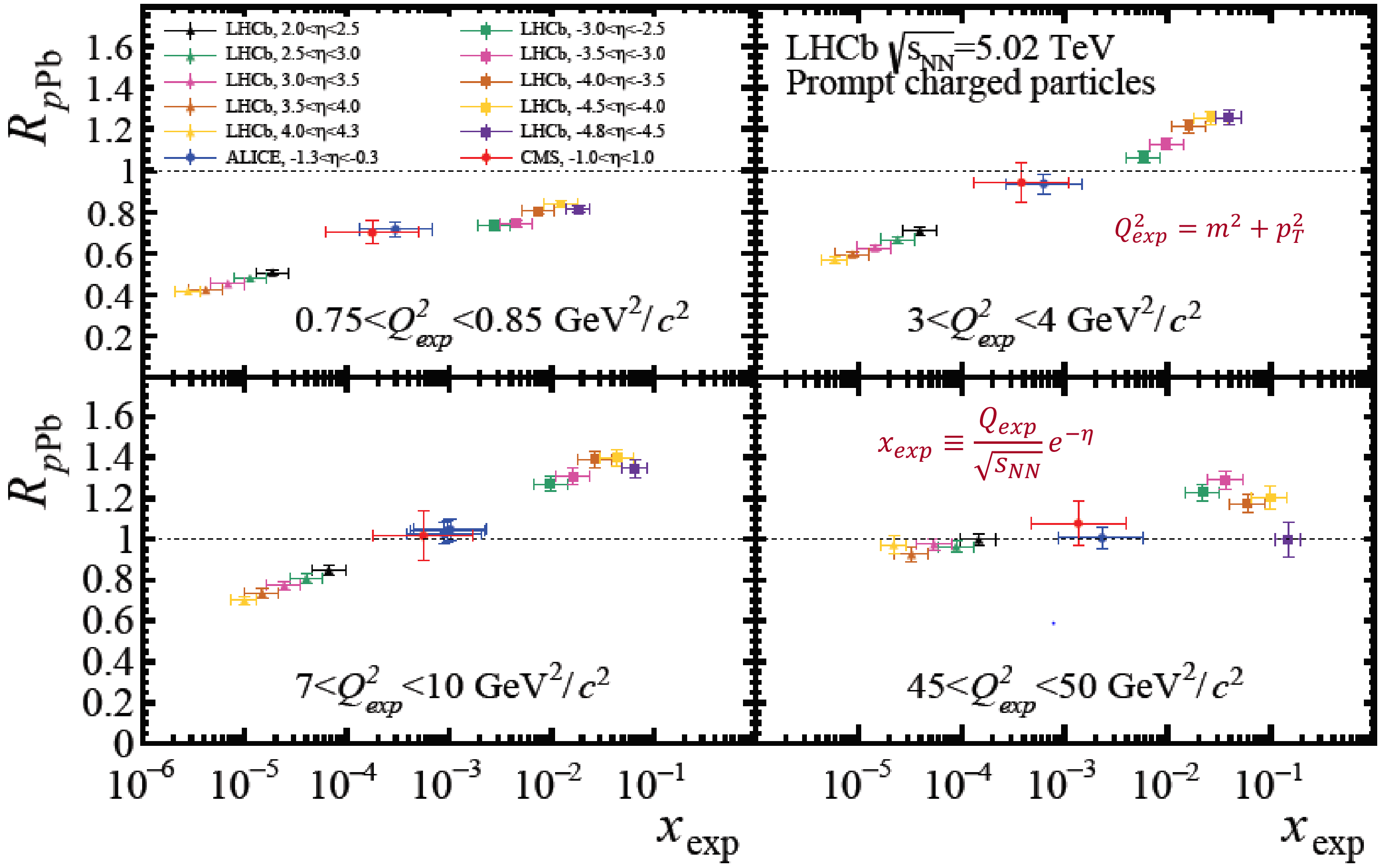
Phys. Rev. Lett. 128 (2022) 142004

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

$$Q^2_{exp} = m^2 + p_T^2, m = 256 \text{ MeV/c}^2,$$

$$x_{exp} \equiv \frac{Q_{exp}}{\sqrt{s_{NN}}} e^{-\eta}$$

- Agreement in bins of Q^2_{exp}.
- R_{pPb} depends on x_{exp} with start of decreasing at $x_{exp} > 0.1$

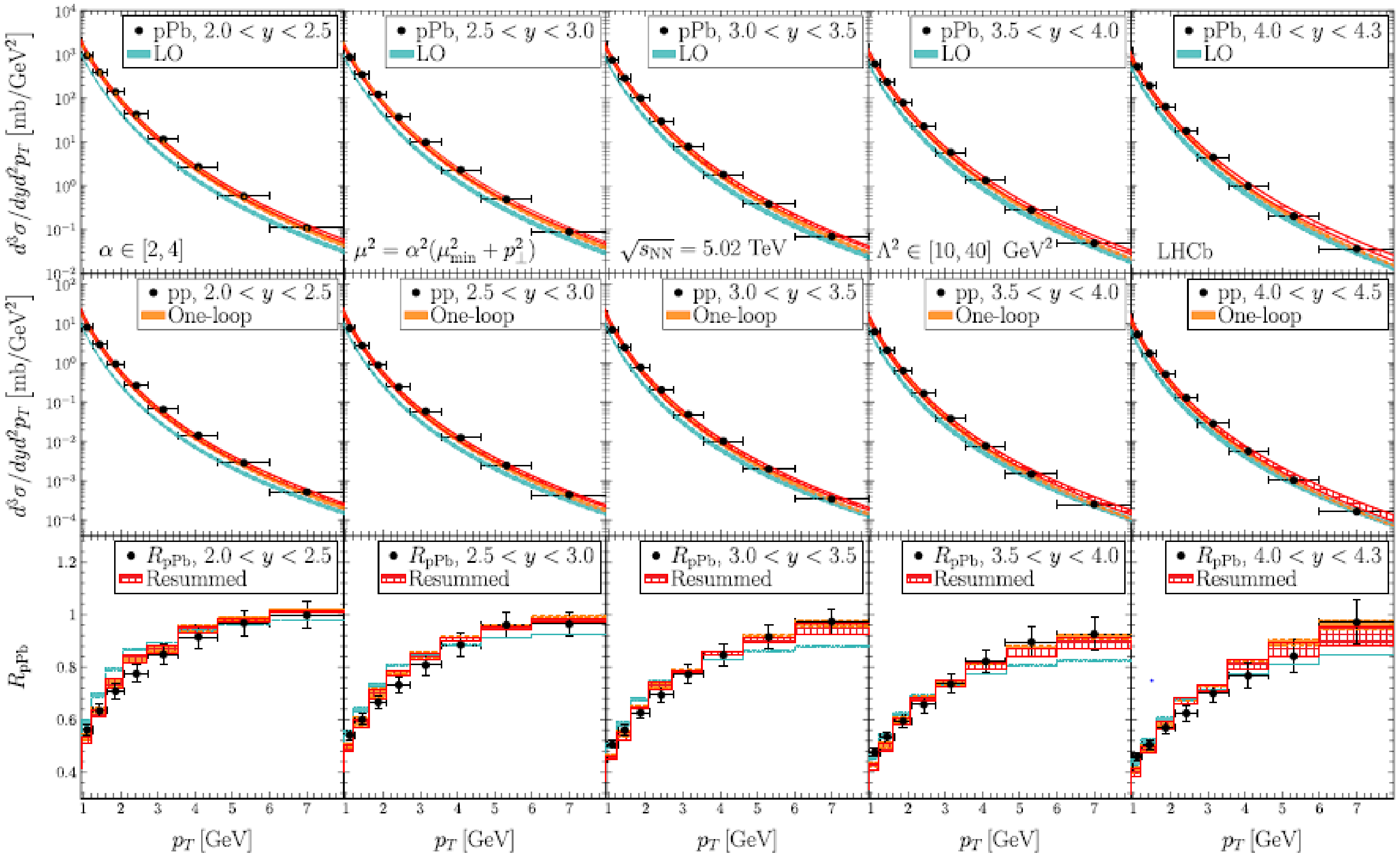


Nuclear modification factor – correction of model

[Phys. Rev. Lett. **128**, 202302](#)

Very recent comparison with CGC model shows better agreement with LHCb results in FWD region

Pursuing the Precision Study for Color Glass Condensate in Forward Hadron Productions
Yu Shi, Lei Wang, Shu-Yi Wei, and Bo-Wen Xiao
– Published 20 May 2022



Nuclear modification factor of π^0

CERN-EP-2022-050

ARXIV:2204.10608

R_{pA}:

BWD: Cronin-like enhancement

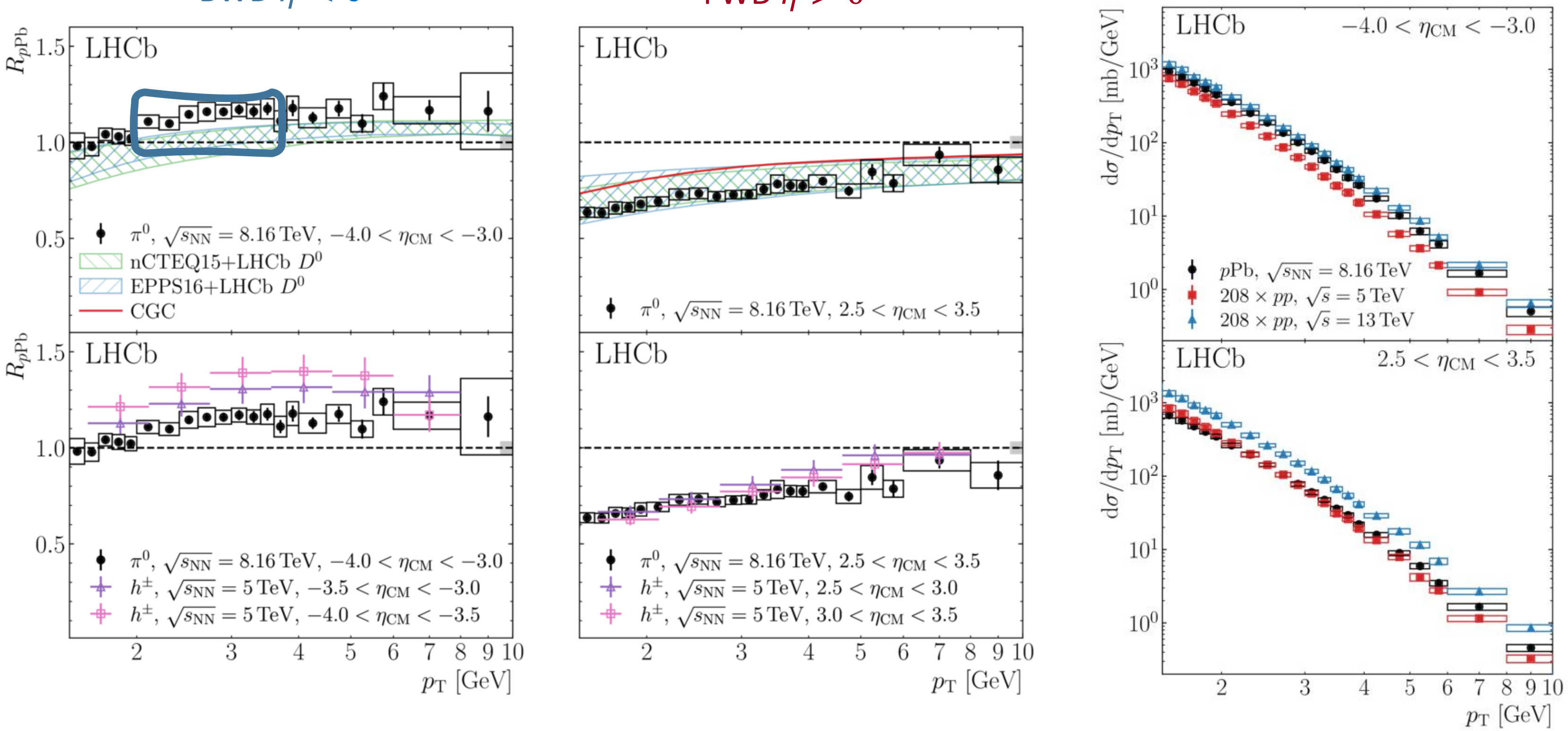
FWD: strong suppression

Comparison with models:

- FWD: small uncertainties – powerful constraints for nPDF at low x, tensions with CGC.
- BWD: above pQCD calculation in $p_T \in (2,4)$ GeV/c region

BWD $\eta < 0$

FWD $\eta > 0$



Agreement with charged-particle R_{pA} with $h^{\pm}$ slightly above π^0

Fixed target experiment at LHCb

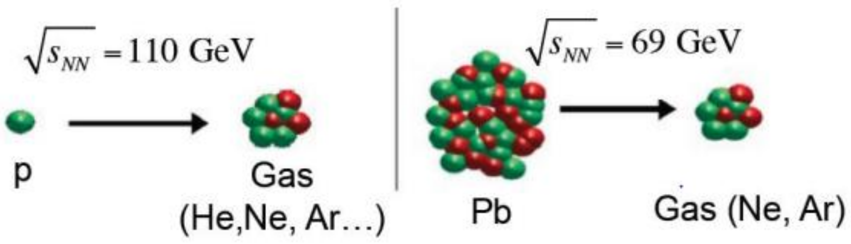
SMOG: **S**ystem for **M**easuring the **O**verlap with **G**as:

- inject small amounts of noble gas into LHC vacuum to pressure 10^{-7} mbar.

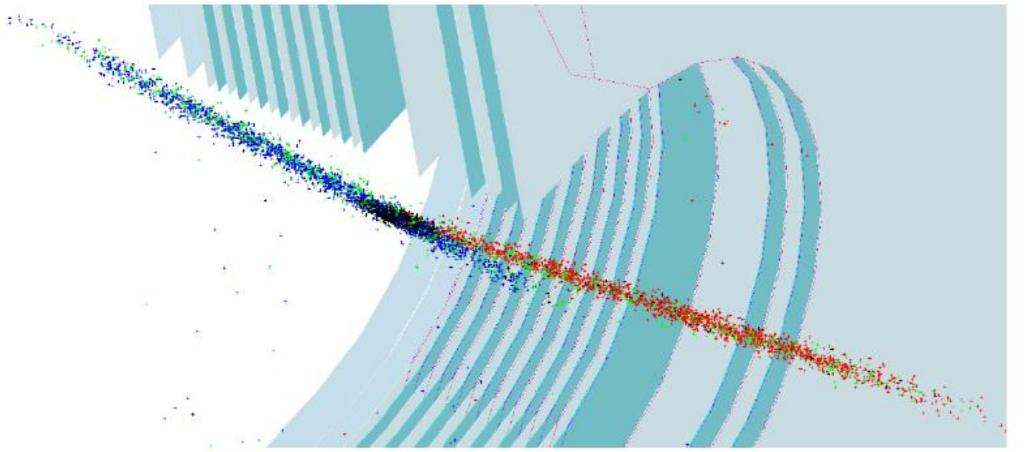
Main purpose: precise measurement of beam profiles for determination of instantaneous luminosity

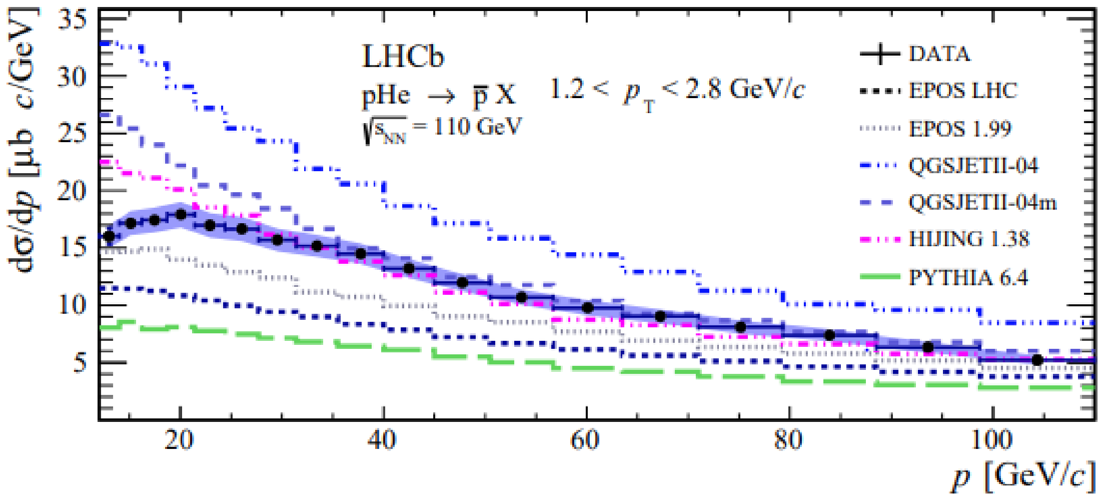
Allows to study fixed-target collisions of proton ion beam on gas atoms.

pHe collisions – cosmic ray interactions, pNe – atmospheric showers



PRL 121 (2018) 222001

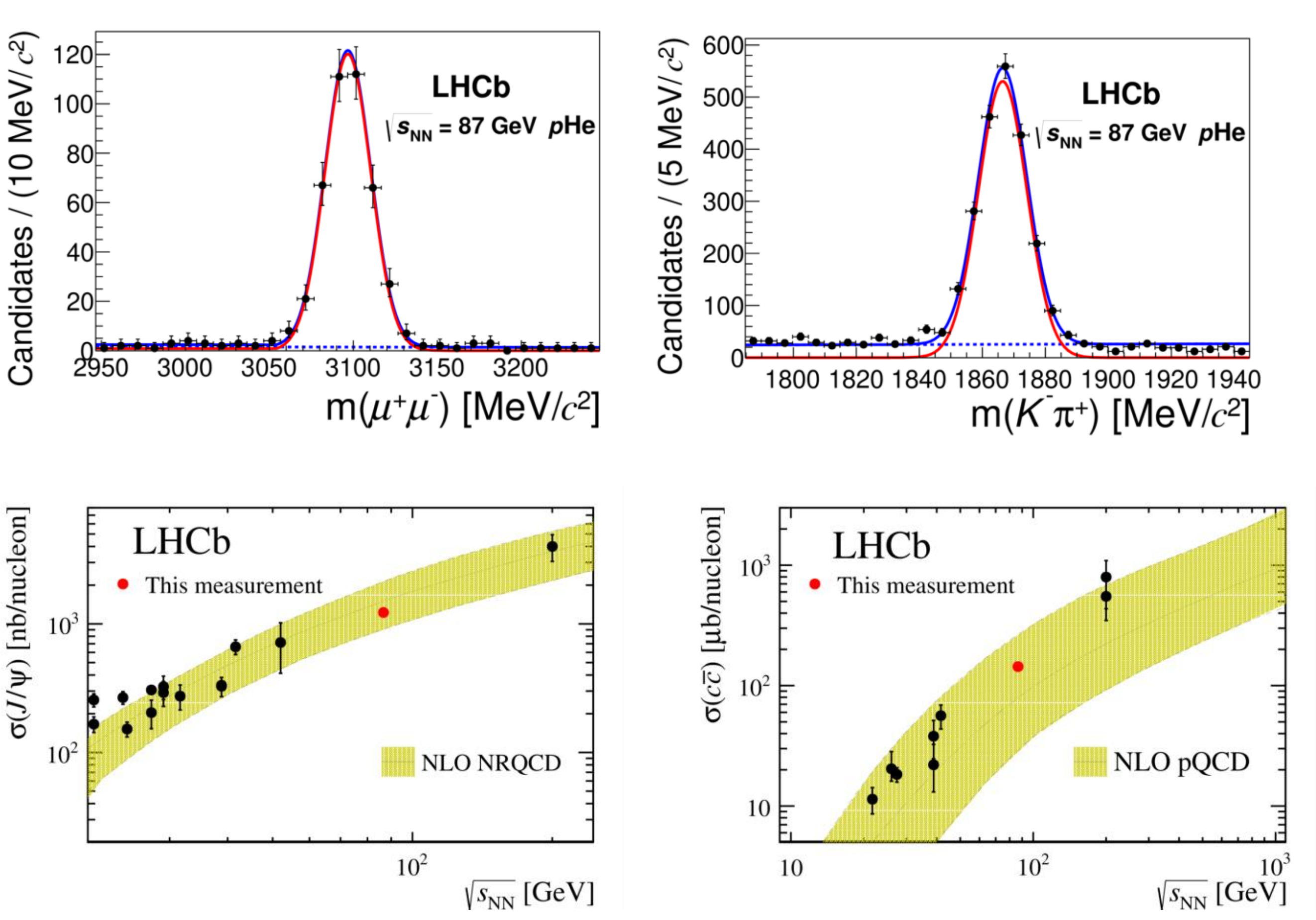




Prompt production of $\bar{p}$ - accuracy <10%, lower than spread among models

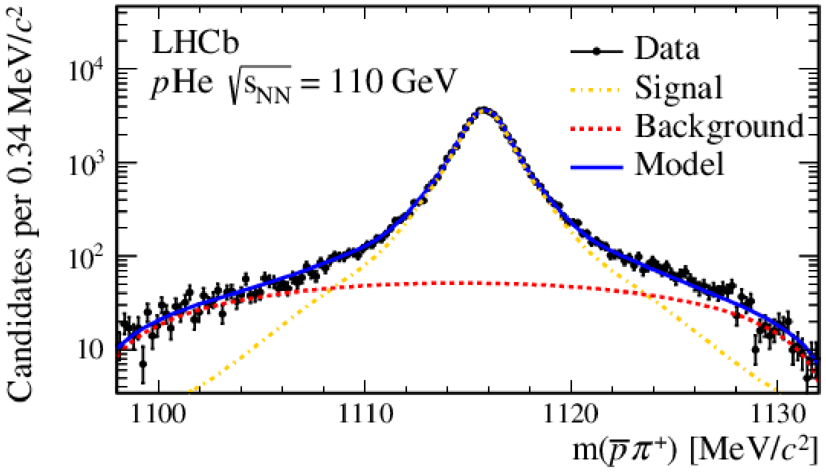
Fixed target experiment at LHCb

First Measurement of Charm Production in its Fixed-Target Configuration at the LHC [PHYS. REV. LETT. 122 (2019) 132002]



Measurement of antiproton production from antihyperon decays in pHe collisions at $\sqrt{s_{NN}}$= 110 GeV

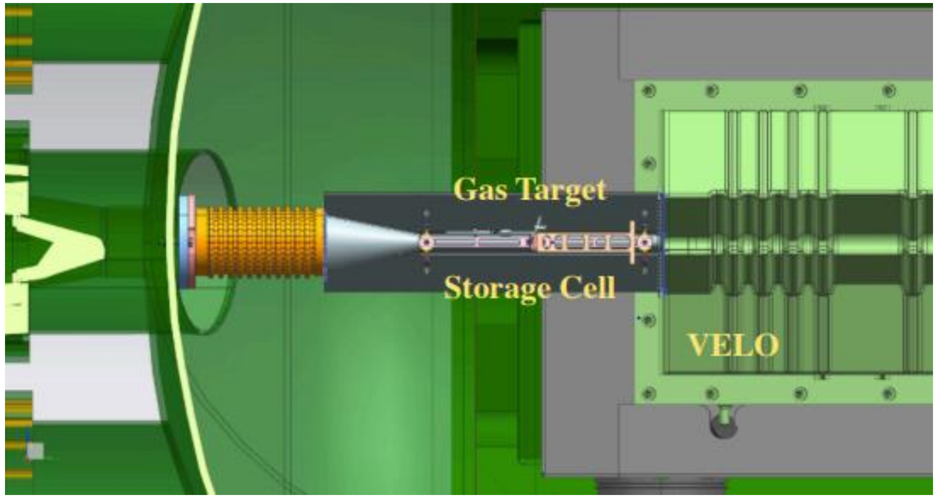
[arXiv:2205.09009] LHCb-PAPER-2022-006



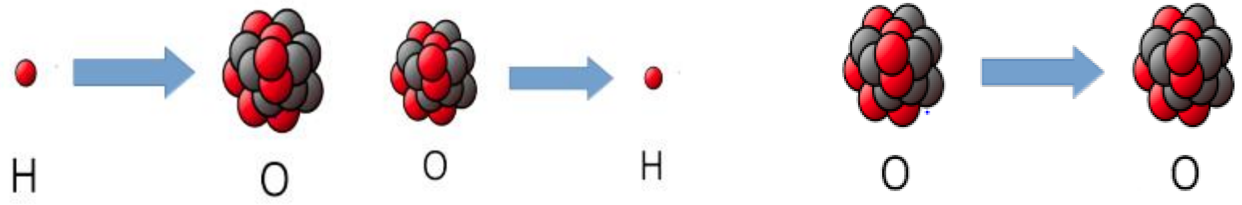
SMOG 2 prospects for Run 3

Currently growing physics programme: high-x and moderate Q^2 region in different collision systems

- New gas cell installed for Run 3 downstream of the LHCb nominal IP with possibility to inject Kr, Xe, H_2, O_2, D_2 gasses.
- Unique opportunities to extend heavy-ion, QCD and astrophysics studies! LHCb-PUB-2018-015



  - Charm production measurements
  - H and D targets – 3D structure functions
  - Possibility to complete cosmic antiproton study
  - Oxygen! Proton – Oxygen, Oxygen-Oxygen



We aim at acquiring beam-gas events simultaneously with beam-beam events, using all LHC bunches.

Gas does not affect pp physics program
Challenging online reconstruction.

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. Measurement of the inelastic pp cross-section – comparison with physics models.
3. 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.
4. Nuclear modification factor in π^0 production – new result for comparison with models.
5. LHCb is also a fixed-targed experiment!

This work was partially supported by the Polish NCN grants No. UMO-2019/35/O/ST2/00546

References

Measurement of charged-particle multiplicities in pp collisions at $\sqrt{s}$ *= 7 TeV in the forward region* Eur. Phys. J. C (2012) 72:1947

Measurement of the forward energy flow in pp collisions at $\sqrt{s}$ *= 7 TeV* Eur. Phys. J. C (2013) 73:2421

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

Measurement of the inelastic pp cross-section at a centre-of-mass energy of $\sqrt{s}$ *= 7 TeV* JHEP 02 (2015) 129

Measurement of the inelastic pp cross-section at a centre-of-mass energy of 13 TeV JHEP 06 (2018) 100

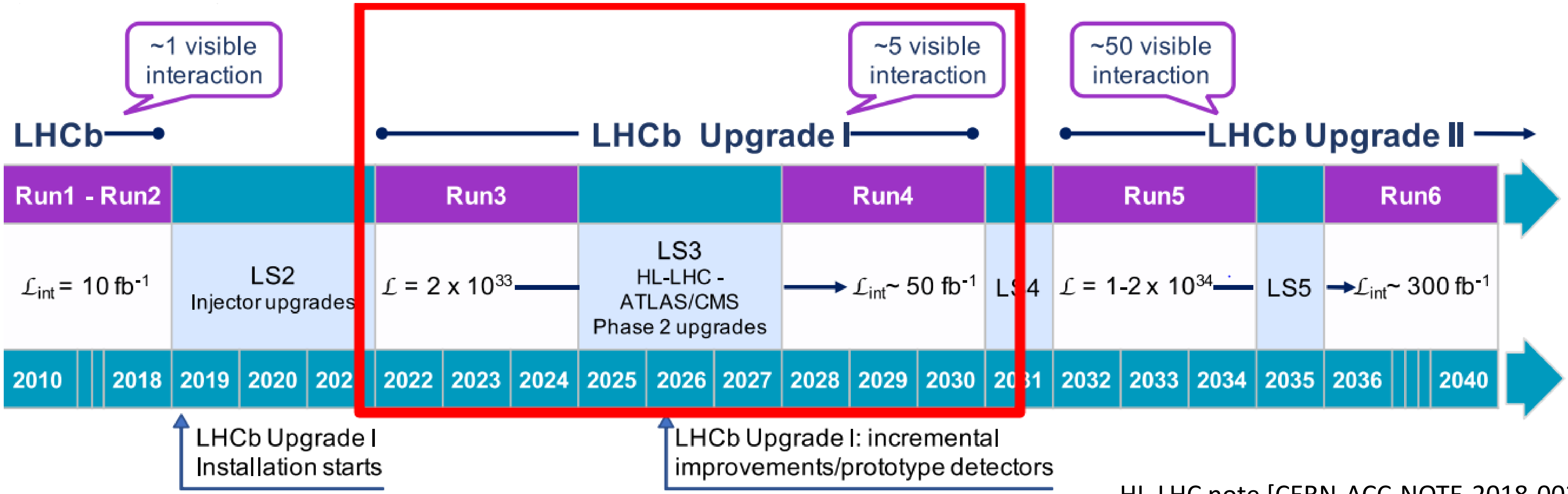
Measurement of prompt charged-particle production in pp collisions at $\sqrt{s} = 13$ *TeV* JHEP 01 (2022) 166

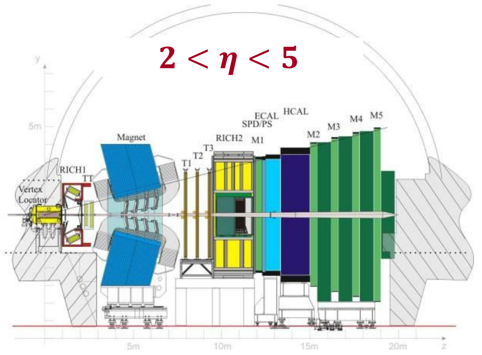
Measurement of the nuclear modification factor and prompt charged particle production in pPb and pp collisions at $\sqrt{s_{NN}} = 5$ *TeV* Phys. Rev. Lett. 128 (2022) 142004

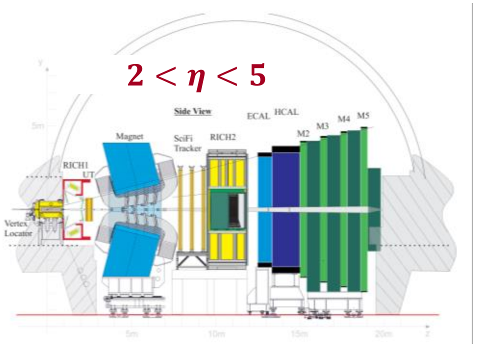
Nuclear modification factor of neutral pions in the forward and backward regions in pPb collisions arXiv:2204.10608, LHCb-PAPER-2021-053 Submitted to Phys. Rev. Lett. 2022

Backup

Timeline for the LHCb Upgrades







HL-LHC note [CERN-ACC-NOTE-2018-0038]

Feasibility of running of LHCb Upgrade II

LHCb response [LHCb-PUB-2019-001]

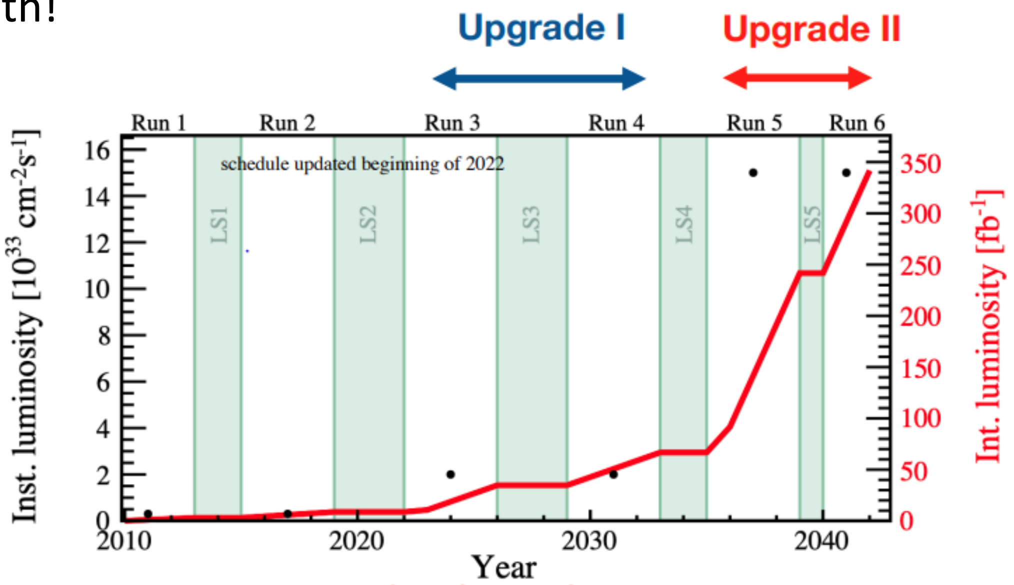
Considerations for the VELO detector at the LHCb Upgrade II

CERN-LHCb-PUB-2022-001

LHCb Upgrades

- LHCb physics programme in Run 1 – Run 3 and 4 is limited exclusively by the detector.
- LHCb **Upgrade I** has been completed this year, Run 3 starts next month!

Upgrade I:
- $\mathcal{L}_{max} = 2 \times 10^{33}$ cm^{-2}s^{-1}
- $\mathcal{L}_{int} = 50$ fb^{-1} (Run 3+4)



- LHCb Upgrade II starts after LS4 (major upgrade of ATLAS/CMS)

Upgrade II:
- $\mathcal{L}_{max} = 1.5 \times 10^{34}$ cm^{-2}s^{-1}
- $\mathcal{L}_{int} = 250\text{-}300$ fb^{-1} (Run 5+6)

Expresion of Interest LHCC-2017-003
Physics case LHCC-2018-027
Accelerator study CERN-ACC-2018-038