Latest results from the expanding heavy-ion and fixed-target program at LHCb

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on behalf of the LHCb collaboration

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CERN Seminar
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QCD at high-density: heavy-ion collisions

- Study QCD matter through the evolution of a nucleus-nucleus (AA) collision:
  1. Initial state and hard scattering
  2. QGP formation and hydrodynamic expansion
  3. Hadronization and freeze-out

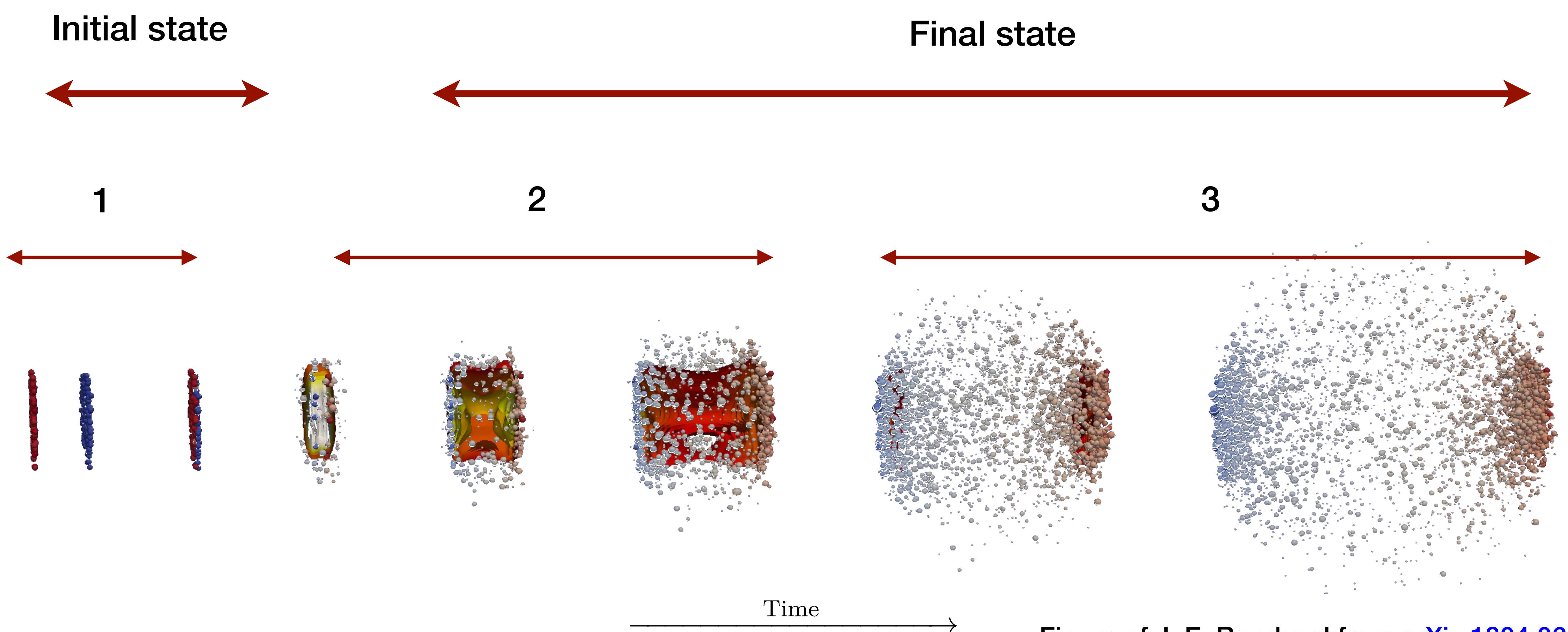
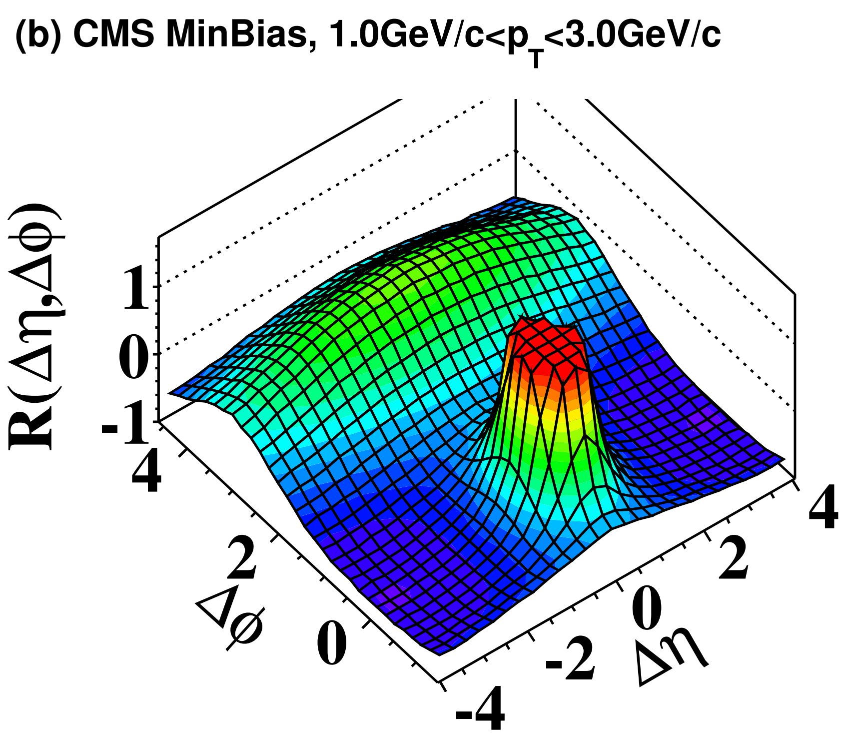


Figure of J. E. Bernhard from [arXiv:1804.06469]

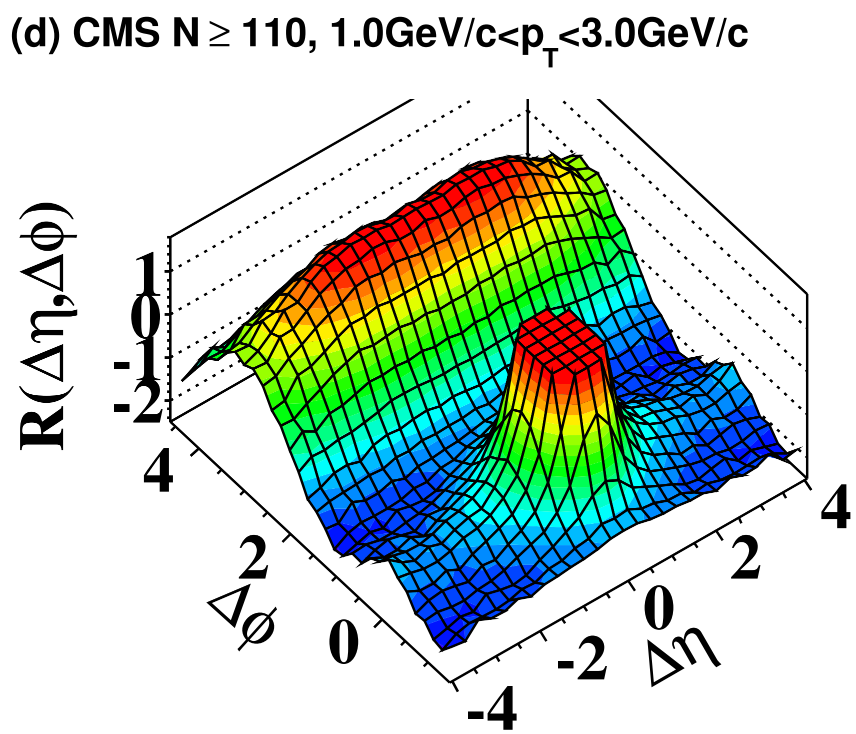
QCD at not-so-high-density: small systems

- pA, pp, … → lower energy density
- **Many QGP-like signatures observed in high-multiplicity collisions!** →
  - Collectivity
  - Quarkonia breakup in medium
  - Strangeness enhancement
  - Baryon/meson enhancement
- Open questions:
  - How can QGP-like signatures be explained in small systems?
  - How to describe the transition from a dilute to a high-density QCD system?

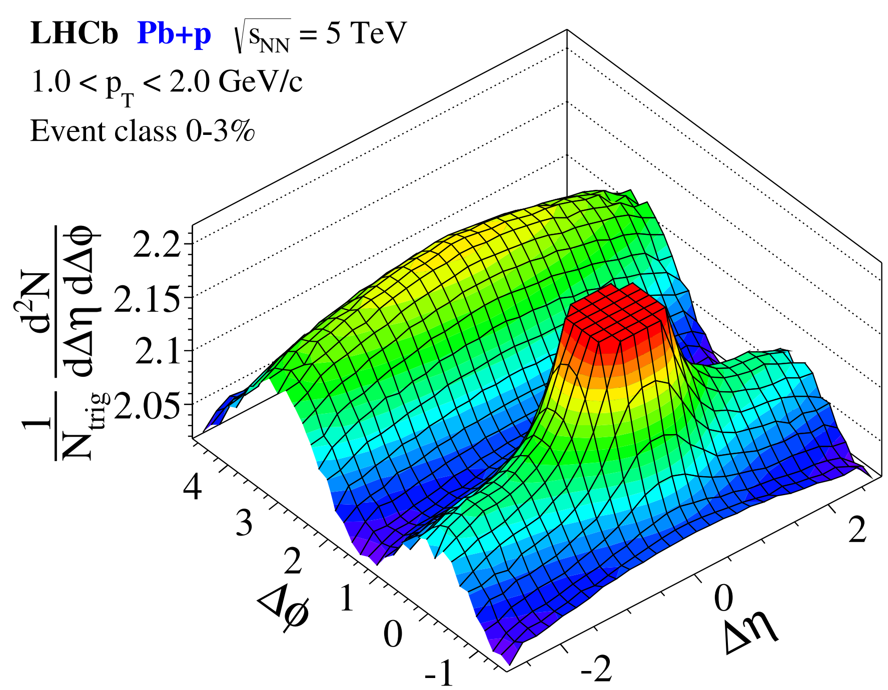
pp: minimum bias



pp: high multiplicity



pPb: high multiplicity



JHEP 09 (2010) 091

Phys. Lett. B762 (2016) 473

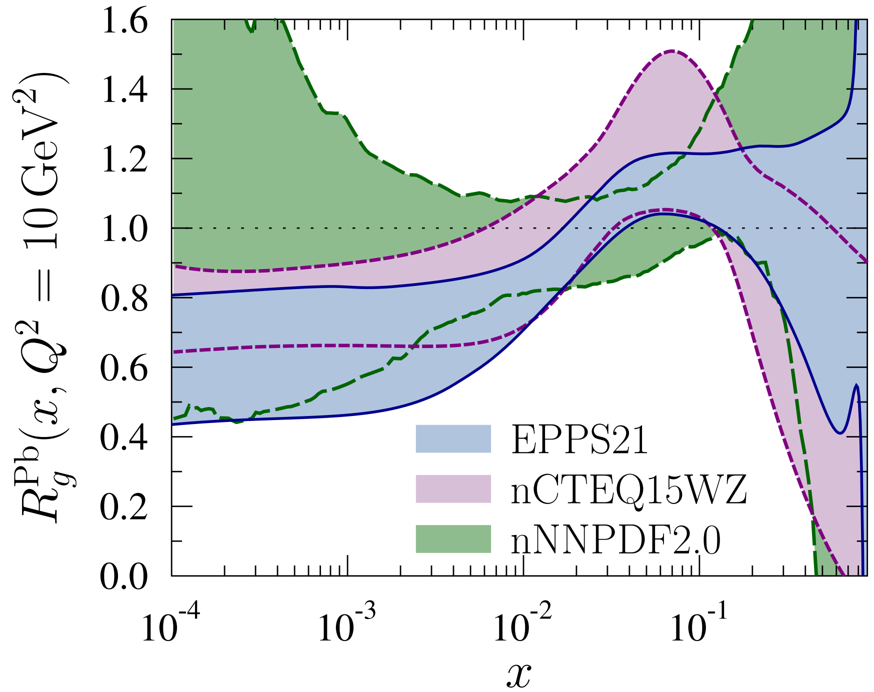
Initial state and hard scattering

- Describing parton structure inside a nucleus:

$$d\sigma^{h_1+h_2\to k+X}(\mu^2,Q^2)=\sum_{i,j,X'} f_{i/h_1}(x_1,Q^2)\otimes f_{i/h_2}(x_2,Q^2)\otimes d\hat{\sigma}^{ij\to k+X'}(\mu^2,Q^2)$$

Nuclear Parton Distribution Functions

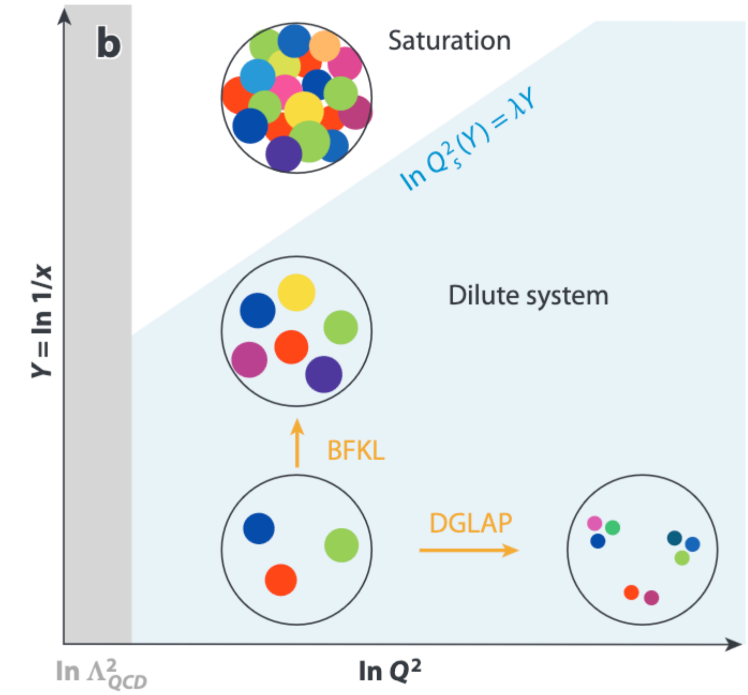
EPJC 82 (2022) 5, 413



- Non-perturbative objects → rely on **experimental data**
- **nPDFs flavour and** (x, Q^2, A) dependent → **dataset variety**
- At LHC, studied in $p\mathrm{A}$, but also $\gamma\mathrm{A}$ collision systems (UPC)

(ultra-peripheral collisions)

- Many open questions to be understood :
  - QCD at very high densities, large nuclei → gluon saturation
  - Are nPDF universal? (that is, process independent)
  - Is there an intrinsic charm contribution in the PDFs?
  - …

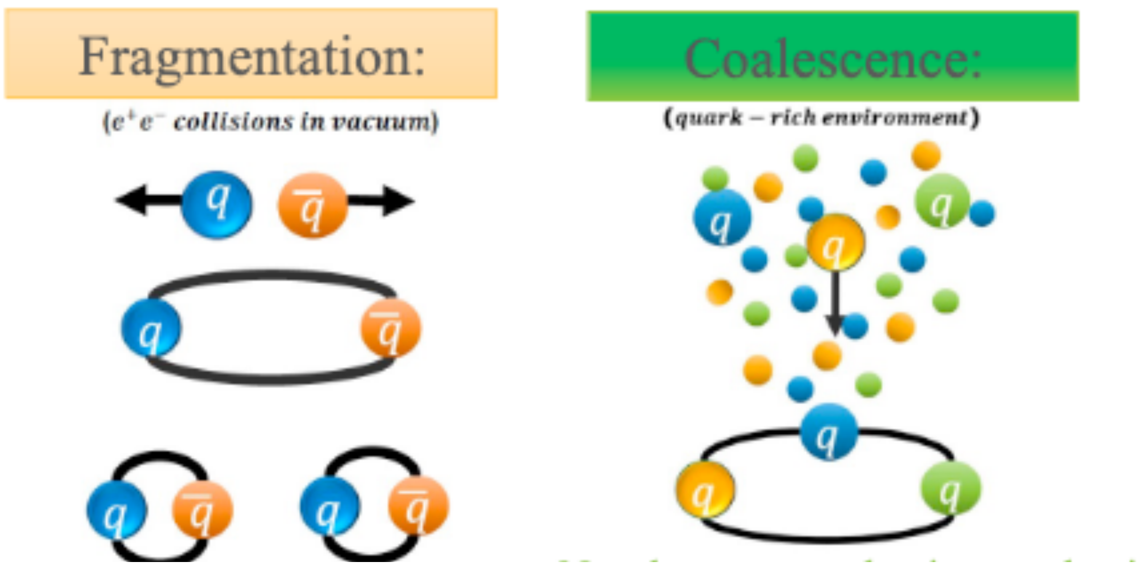


Ann.Rev.Nucl.Part.Sci. 60 (2010) 463-489

How does hadronization happen in a QCD medium?

- Hadronization remains **one of the key open topics of QCD**
  - Non-perturbative process hard to treat theoretically
  - **How "universal" hadronization is**? does it depend on the "environment" of quarks and gluons when they hadronize?
    - ✳ Differences between hadronization in e^+e^- collisions and hadronic collisions

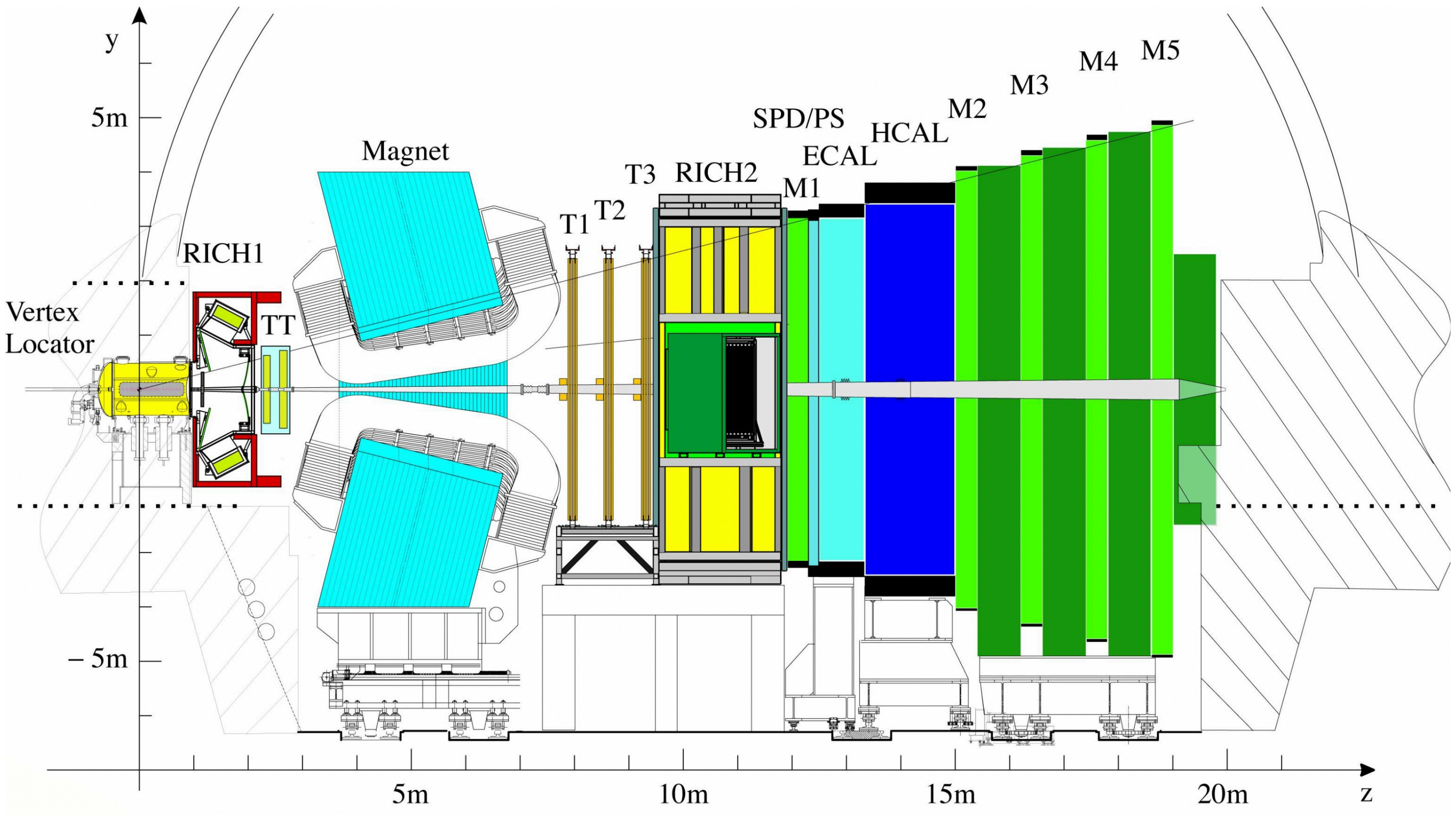
- Theoretical approaches:
  - **fragmentation**: hadronization happens as in vacuum (e^+e^- collisions)
  - **coalescence**: combination of quarks from QCD medium hadronize



- Experimentally:
  - Different hadrons probe different effects
  - Energy density scan: **system size** and **multiplicity**
  - Golden measurements are production ratio measurements:
    - ✳ Cancellation of other competing effects (i. e. initial state effects)

Our tool: LHCb

The LHCb experiment (Run1/Run2)



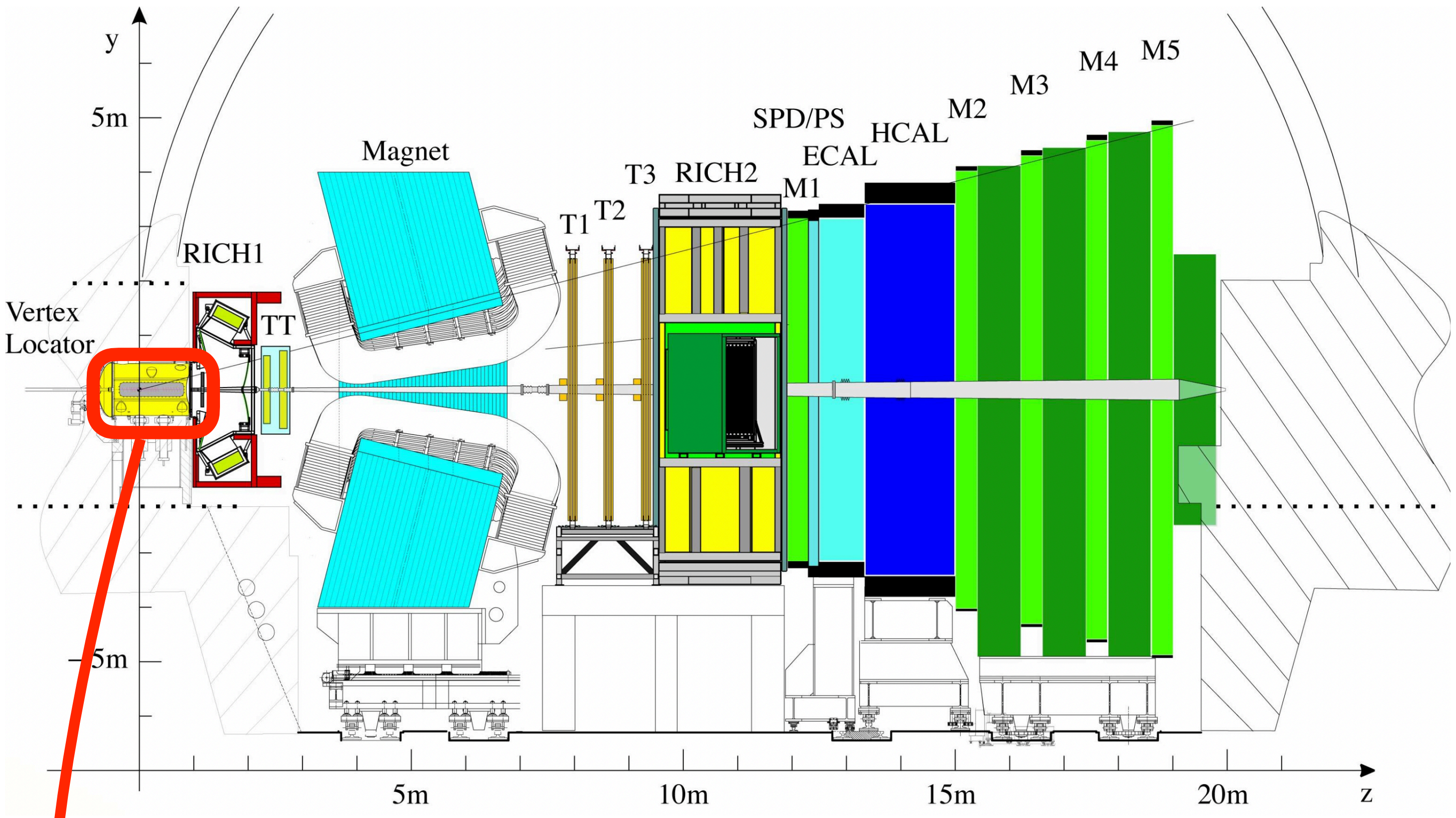
- One-arm spectrometer at LHC fully instrumented in $2 < \eta < 5$
  - Tracking system with excellent hadron and muon ID
  - Precise vertex reconstruction, for primary and decay vertices
  - Calorimeters ECAL, HCAL

Tailored capabilities to study heavy-flavour

LHCb JINST 3 (2008) S08005

LHCb performance IJMPA 30 (2015) 1530022

The LHCb experiment (Run1/Run2)



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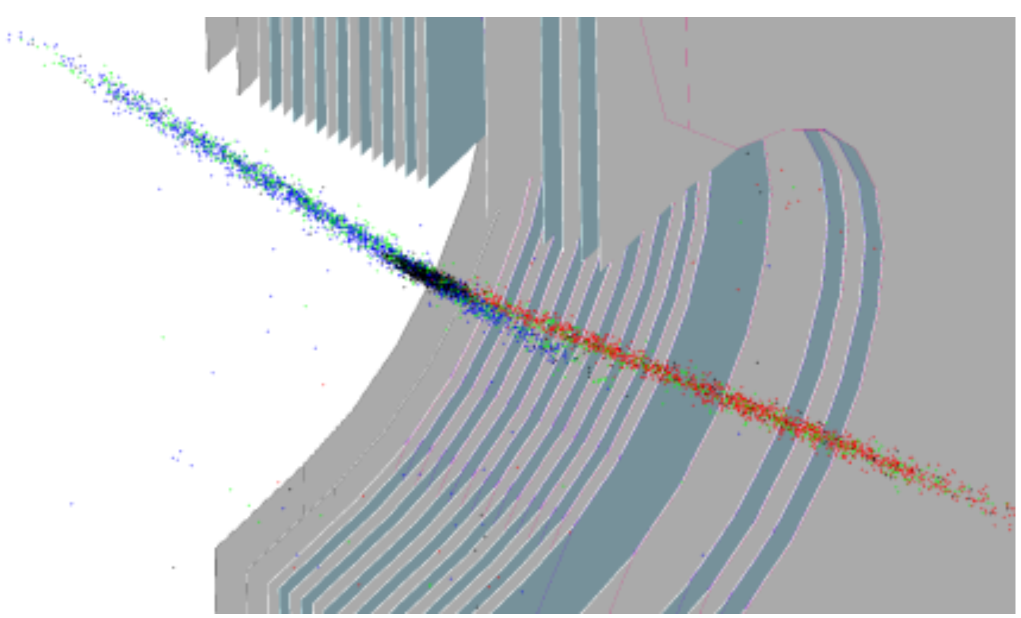
Tailored capabilities to study heavy-flavour

LHCb JINST 3 (2008) S08005

LHCb performance IJMPA 30 (2015) 1530022

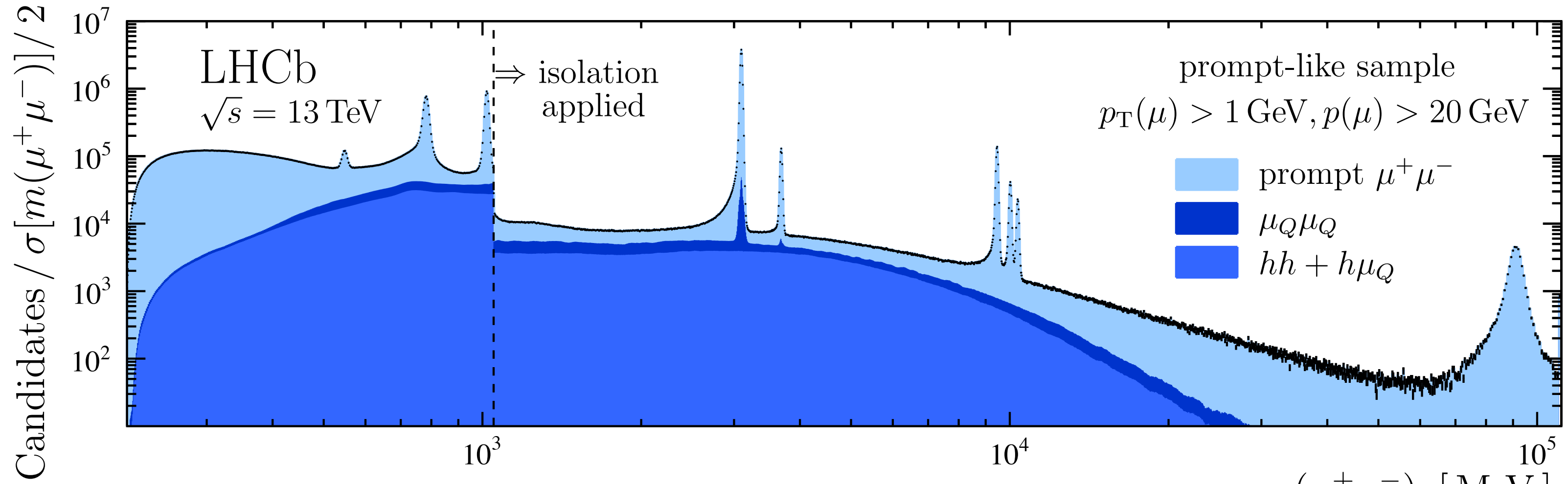
… and a unique fixed-target configuration at LHC using gas injection



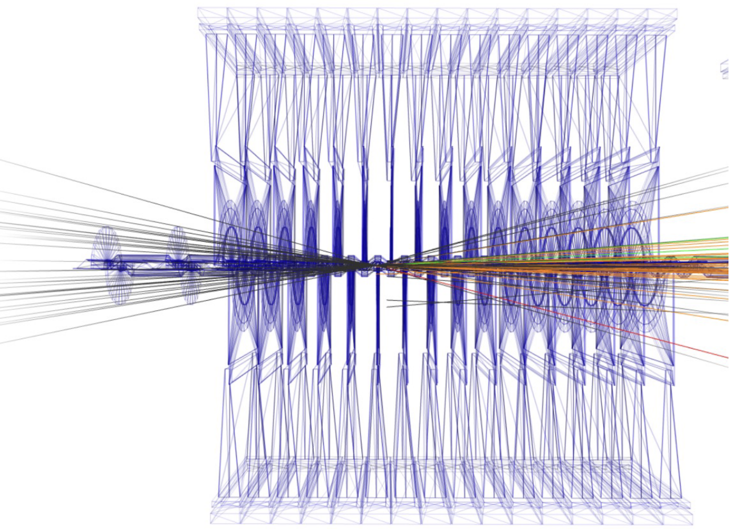
- **SMOG system**: in place originally for luminosity measurements JINST 9 (2014) 12, P12005
- Local increase LHC beam pipe pressure:
  - from $\approx 10^{-9}$ mbar to $\approx 10^{-7}$ mbar
- Use circulating LHC beams to produce $p\mathrm{A}$ or PbA collisions

Where does LHCb shine?

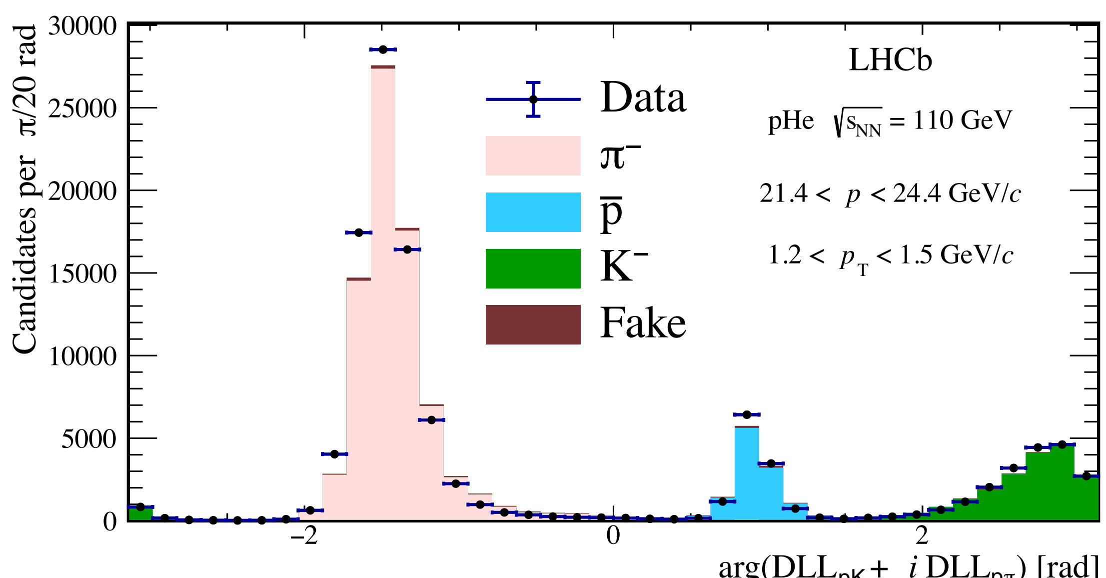
- **Excellent p_{T} resolution**
- **Excellent identification of (π, K, p), muons, electrons and photons**
- **Precise vertex reconstruction**



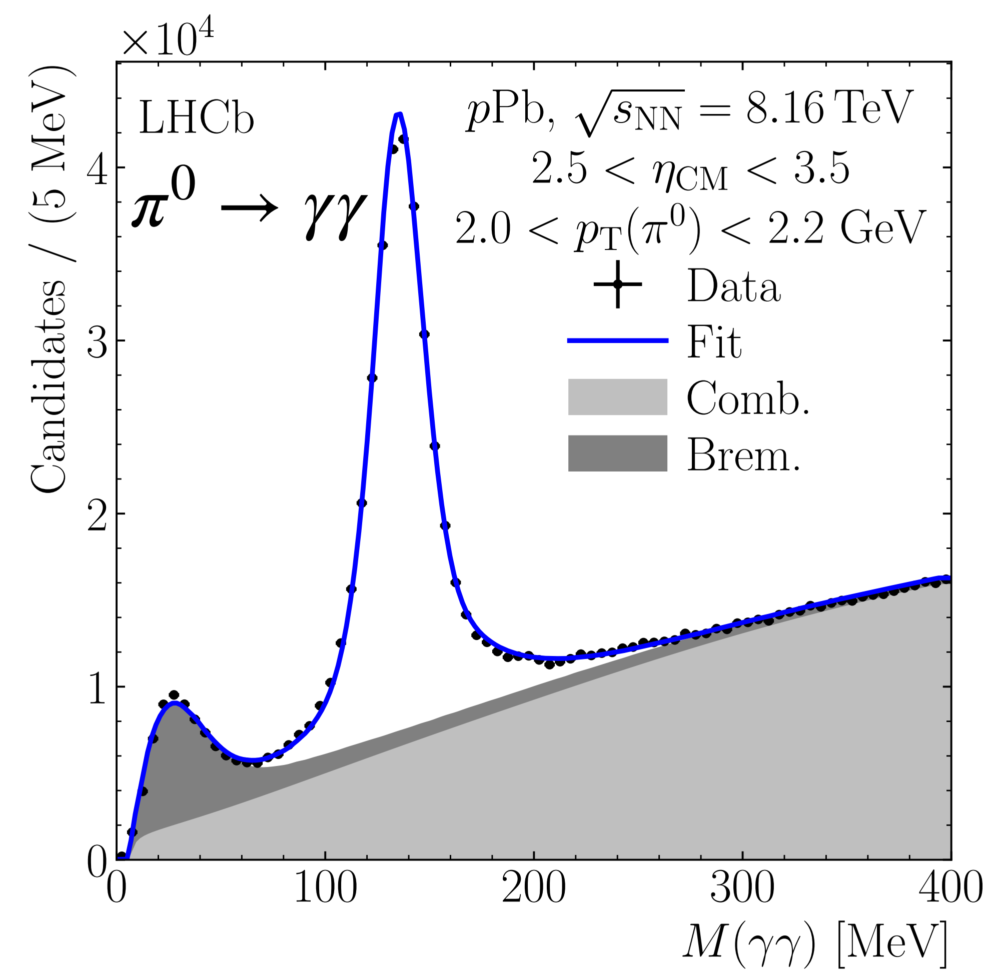
[Phys. Rev. Lett. 120 (2018) 061801]



Impact parameter resolution:
$(15 + 29/p_{\mathrm{T}}\,[\mathrm{GeV}])\,\mu\mathrm{m}$



[Phys. Rev. Lett. 121 (2018) 222001]

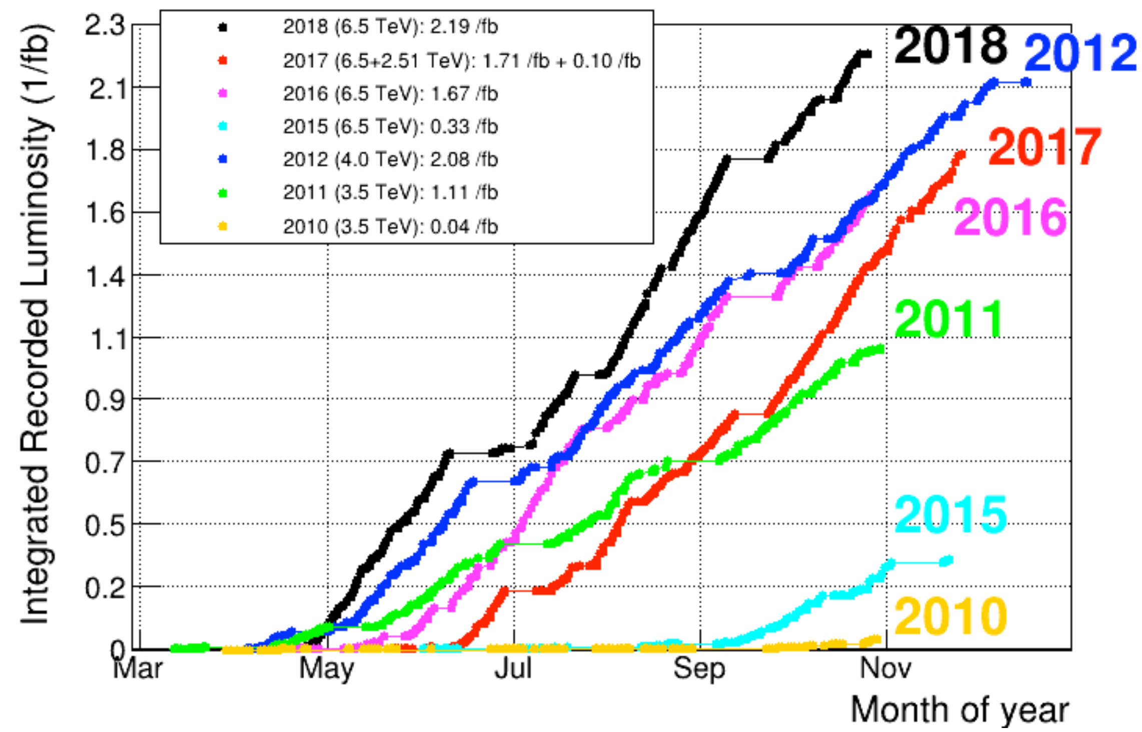


[Phys. Rev. Lett. 131 (2023) 042302]

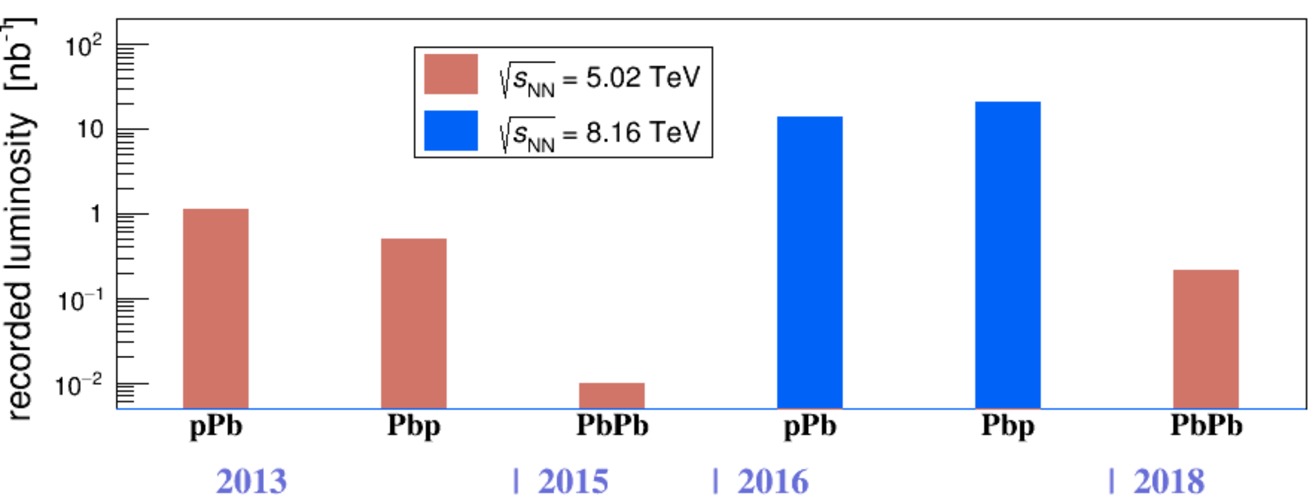
LHCb datasets from Run1/Run2

- **Huge variety of collision systems**: pp, pPb, PbPb, $p-$gas, Pb $-$ gas collisions (noble gases) and exclusive processes (γp, γPb and $\gamma\gamma$)
- Our main setbacks:
  - Limited statistics for fixed-target physics
  - Limited in PbPb $\approx 100-60\,\%$ centrality, due to saturation of vertex detector

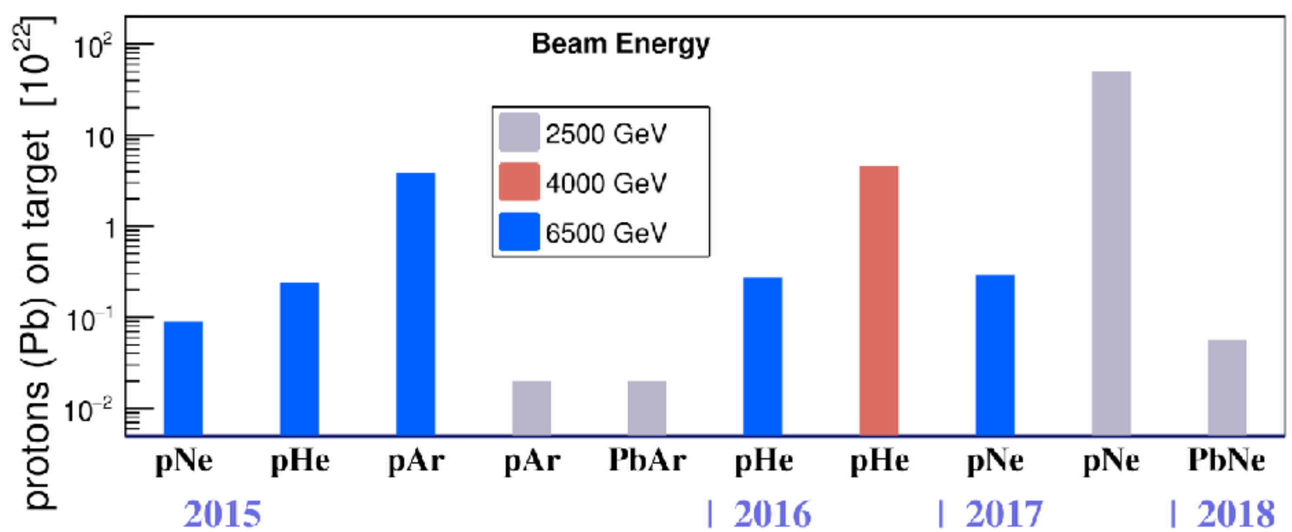
pp collisions



pPb and PbPb collisions

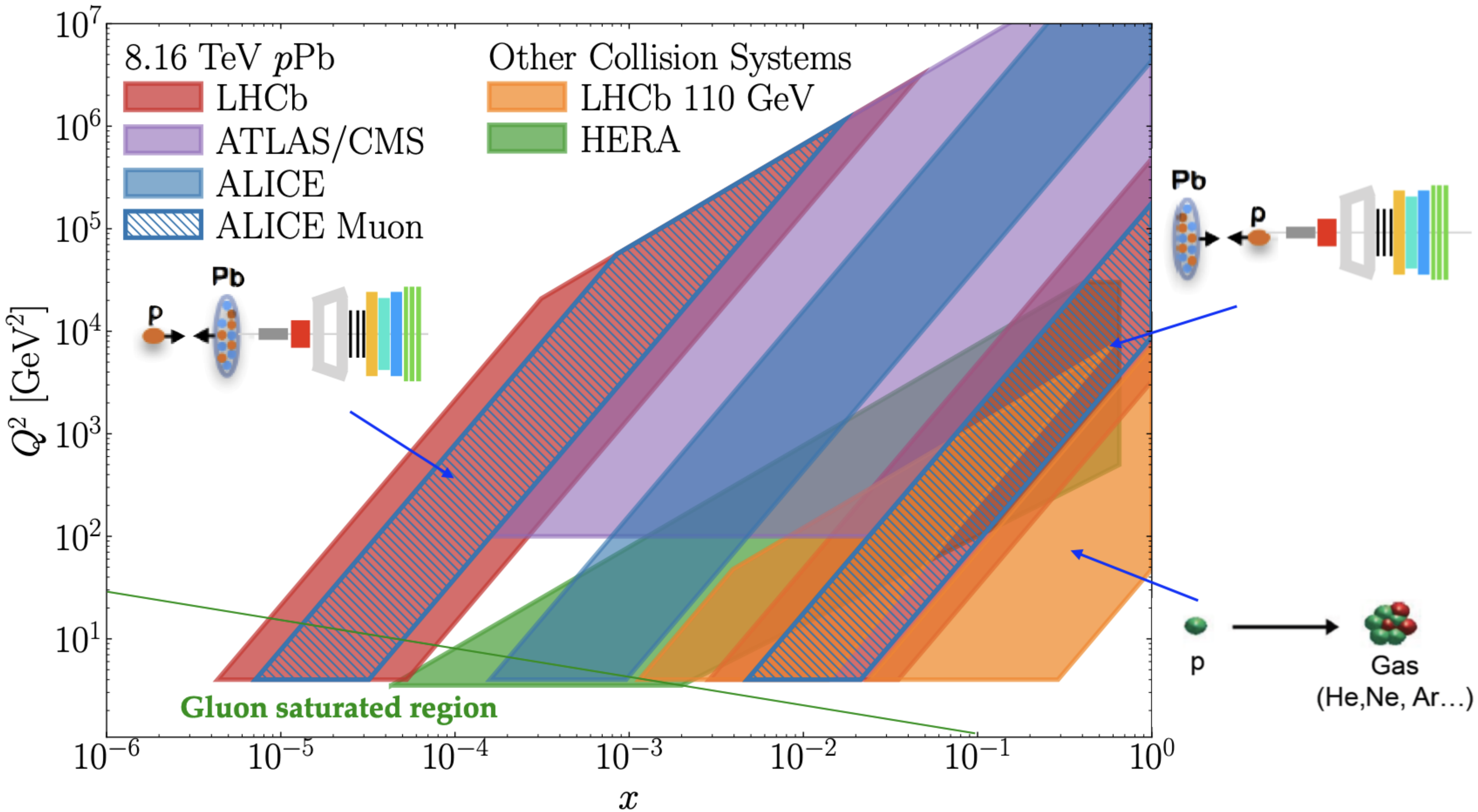


Fixed target collisions



$\mathscr{L}_{p\mathrm{Ne}} = 21.7 \pm 1.4\,\mathrm{nb}^{-1}$

Mapping the initial state with LHCb



Unique coverage of low-x (pPb), medium-x (Pbp) and large-x ($p -$ gas) regions

Results for today

1. Quarkonia

- $\psi(2S)$ in $p\mathrm{Pb}$, LHCb-PAPER-2023-024 *New!*
- $\chi_c(1P)$ in $p\mathrm{Pb}$, LHCb-PAPER-2023-028 *New!*
- J/ψ and D^0 in PbNe and $p\mathrm{Ne}$, EPJ C83 (2023) 658, EPJ C83 (2023) 625, EPJ C83 (2023) 541

2. Open heavy-flavour

- D^0 production in $p\mathrm{Pb}$, PRL 131 (2023) 102301
- D_s^+ and D^+ in $p\mathrm{Pb}$, LHCb-PAPER-2023-021 *New!*
- Λ_b/B with multiplicity in pp, LHCb-PAPER-2023-027 *New!*

3. Light flavour

- Charged hadron in $p\mathrm{Pb}$, PRL 128 (2022) 142004
- π^0 in $p\mathrm{Pb}$, PRL 131 (2023) 042302
- η and η' in $p\mathrm{Pb}$, LHCb-PAPER-2023-030 *New!*
- Charged hadron flow in PbPb, LHCb-PAPER-2023-031 *New!*

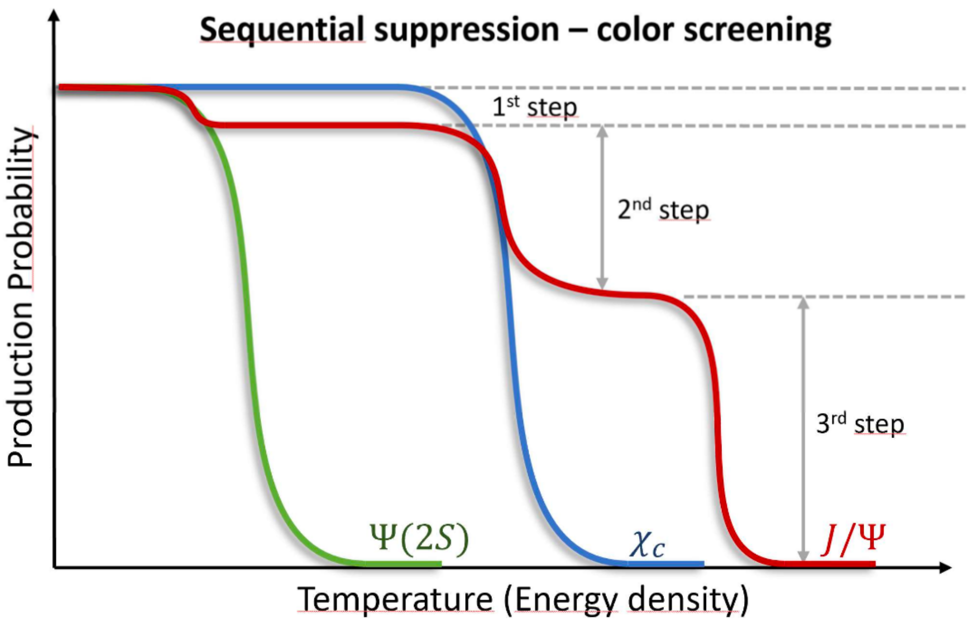
4. Light nuclei

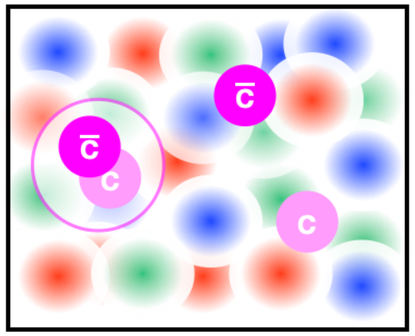
- Helium identification at LHCb, LHCb-DP-2023-002 *New!*
- Antihypertriton in pp, LHCb-CONF-2023-002 *New!*
- Antideuterium identification in $p\mathrm{He}$, LHCb-FIGURE-2023-017 *New!*

Quarkonia

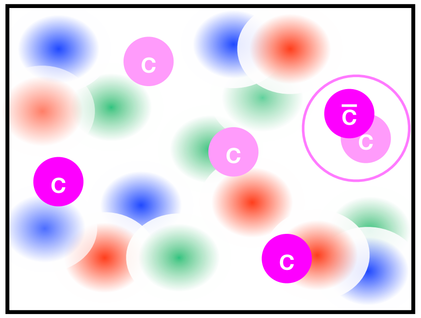
Quarkonium production in medium

- **Charmonia dissociation** in QGP due to color screening:
  - need to measure **full spectra of charmonia states** ($J/\psi \to \chi_c \to \psi(2S)$) to correlate with feed-down contributions
- **Charmonia recombination**: expected at LHC energies and at low p_{T}, competes with dissociation



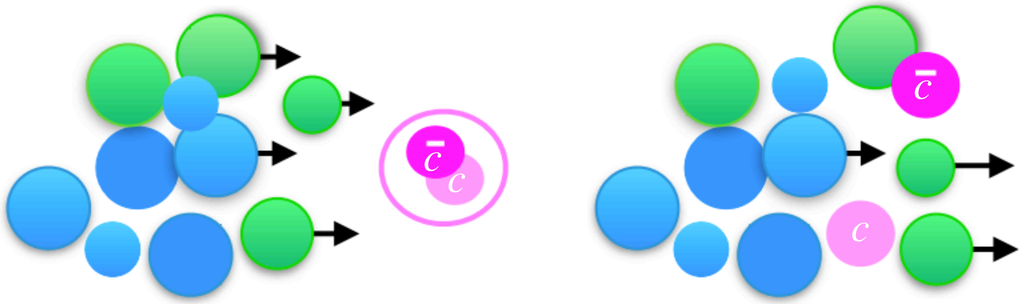


Dissociation in QGP



Recombination in QGP

- **Non-QGP nuclear effects also play a role**, also expected in small systems:
  - Excited-to-ground state suppression observed in medium size systems (pPb at LHC, dAu at RHIC)
  - Explanation possible in terms of final-state comover interaction, but also in terms of QGP

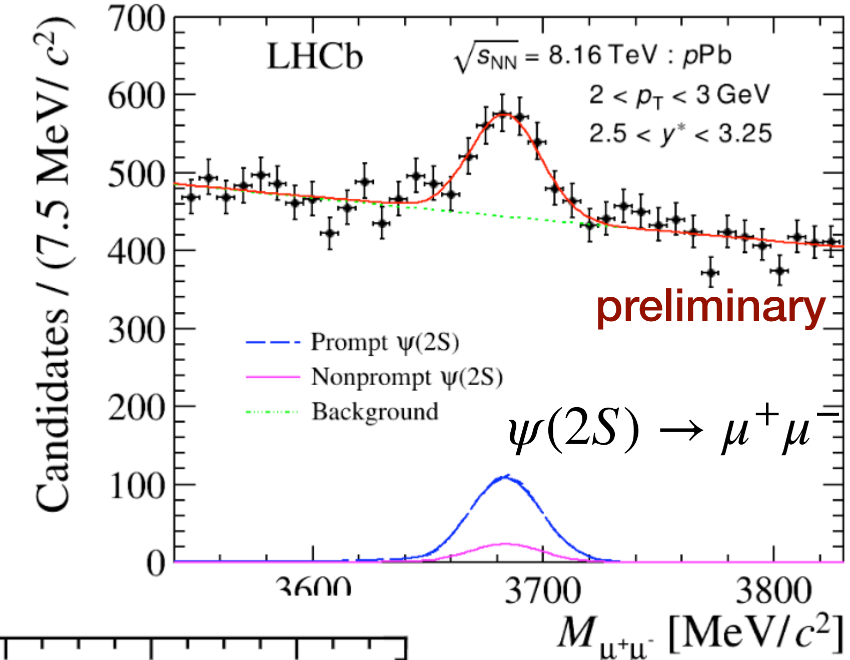


Breakup due to co-moving particles

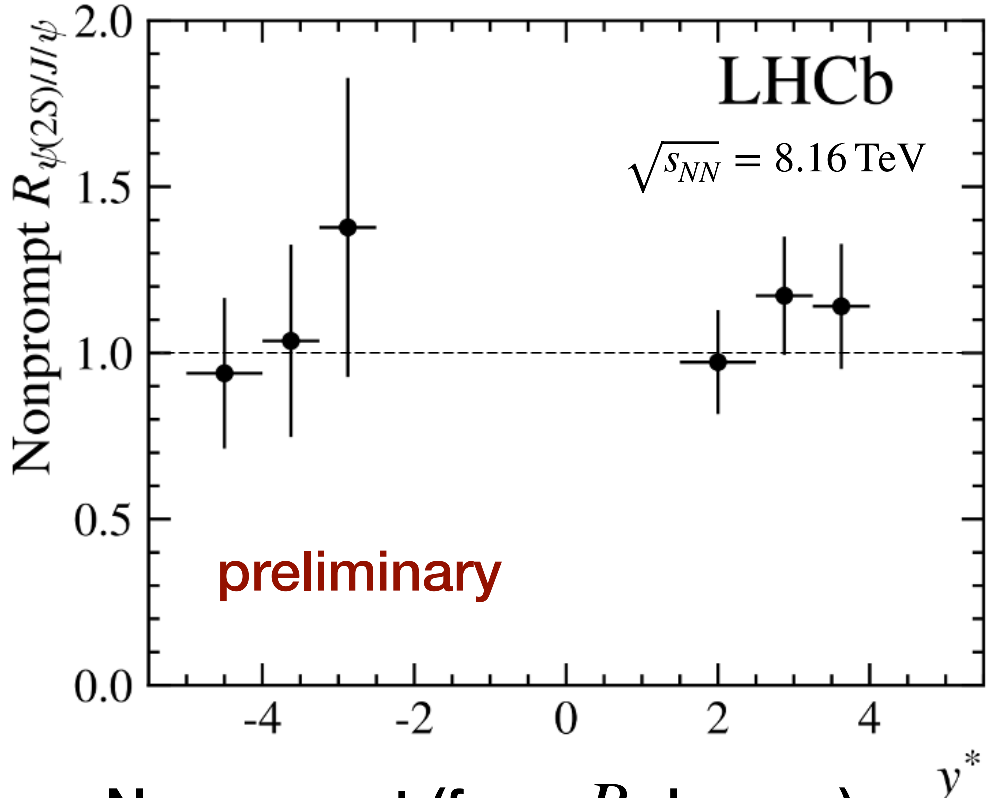
Final-state effects in small systems

Prompt and non-prompt $\psi(2S)$ production in pPb collisions **New!**

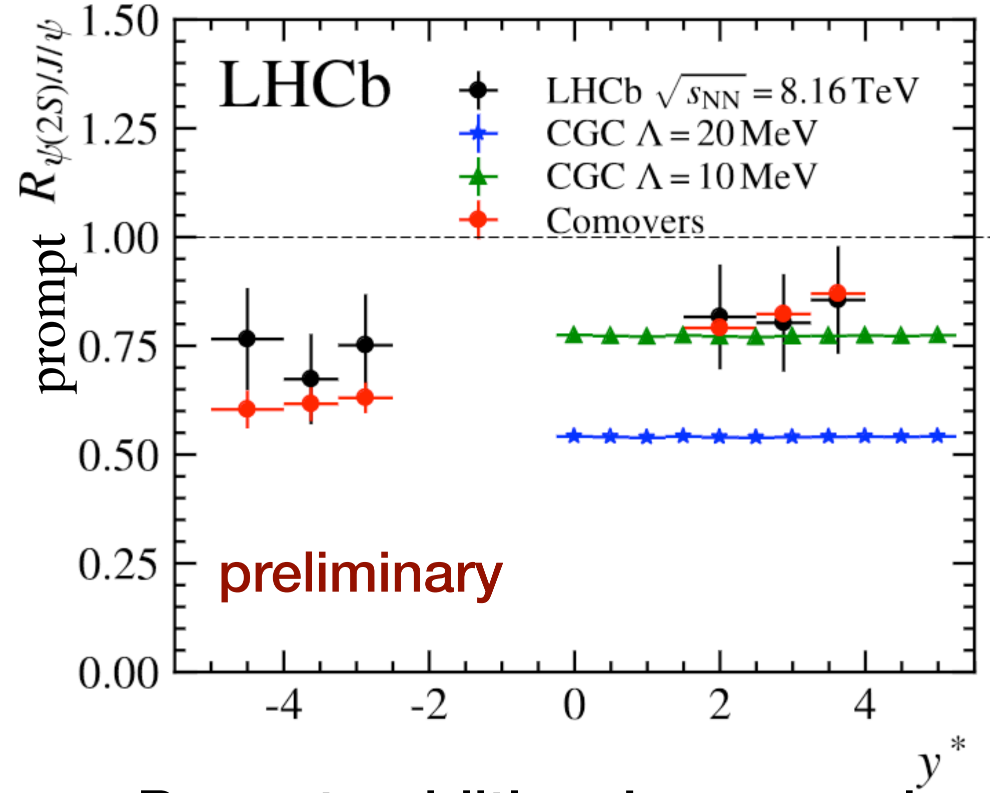
- New more precise result with $\times 20$ larger dataset than previous measurement with Run 1 (JHEP 03 (2016) 133)
  - compare with J/ψ (PLB 774 (2017) 159) in pPb, described by initial state effects



$$R_{\psi(2S)/J/\psi} = \frac{\sigma_{\psi(2S)}/\sigma_{J/\psi}|_{p\text{Pb}}}{\sigma_{\psi(2S)}/\sigma_{J/\psi}|_{pp}}$$ $\rightarrow$ probe of **final state effects**



Nonprompt (from B decays)
double ratio compatible with unity



CGC:
PRC 97, 014909 (2018)
Comovers:
PLB 749 (2015) 98-103

Prompt: additional suppression of $\psi(2S)$,
compatible with break-up for comovers

LHCb-PAPER-2023-024, in preparation

Exploring new charmonium states in pPb

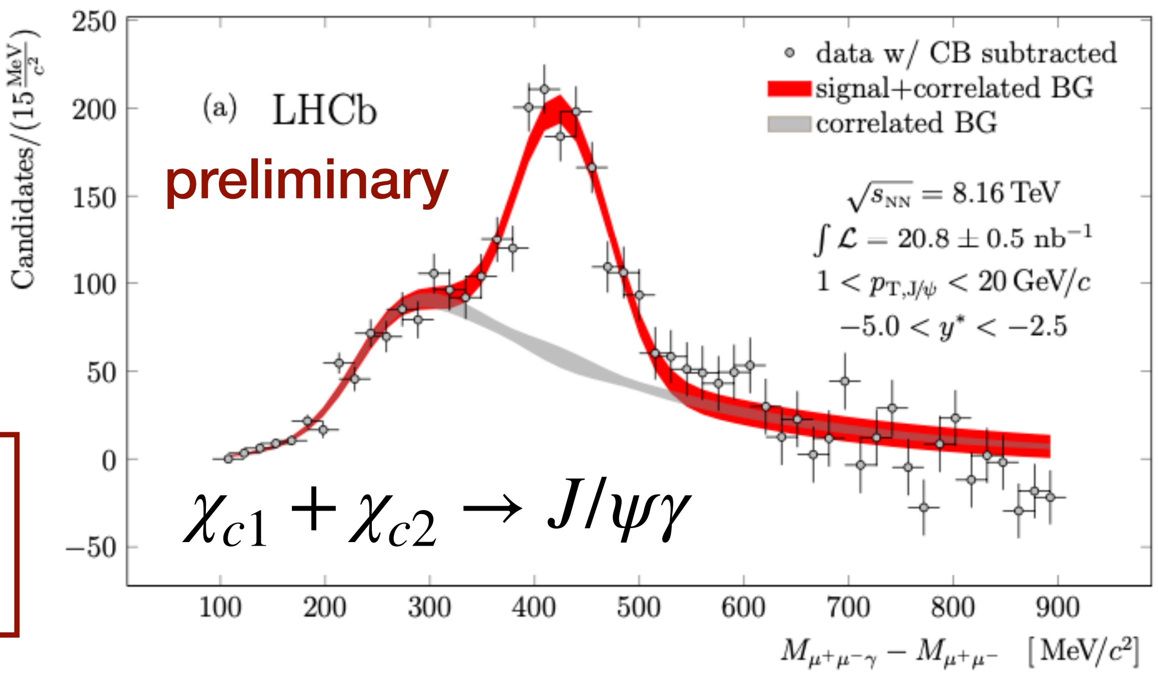
$\chi_c(1P)$ production in pPb at 8.16 TeV **New!**

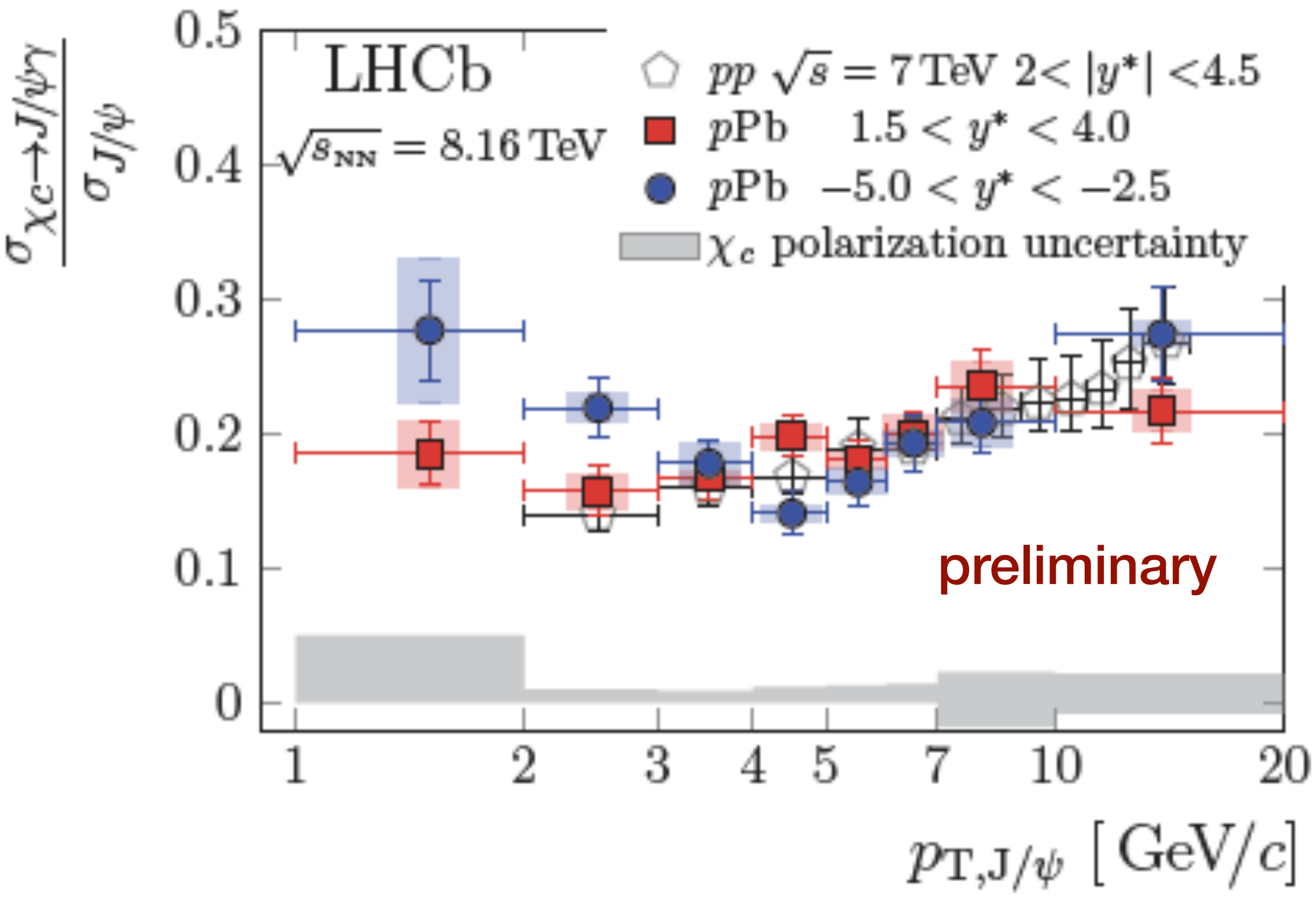
- **First measurement at LHC** of $\chi_{c1} + \chi_{c2} \to J/\psi\gamma$ feed-down to J/ψ in pPb collisions:

$$F_{\chi_c \to J/\psi} = \frac{\sigma_{\chi_c \to J/\psi\gamma}}{\sigma_{J/\psi}}$$

J/ψ from χ_c (numerator)

prompt J/ψ = direct J/ψ + J/ψ from χ_c and $\psi(2S)$ (denominator)



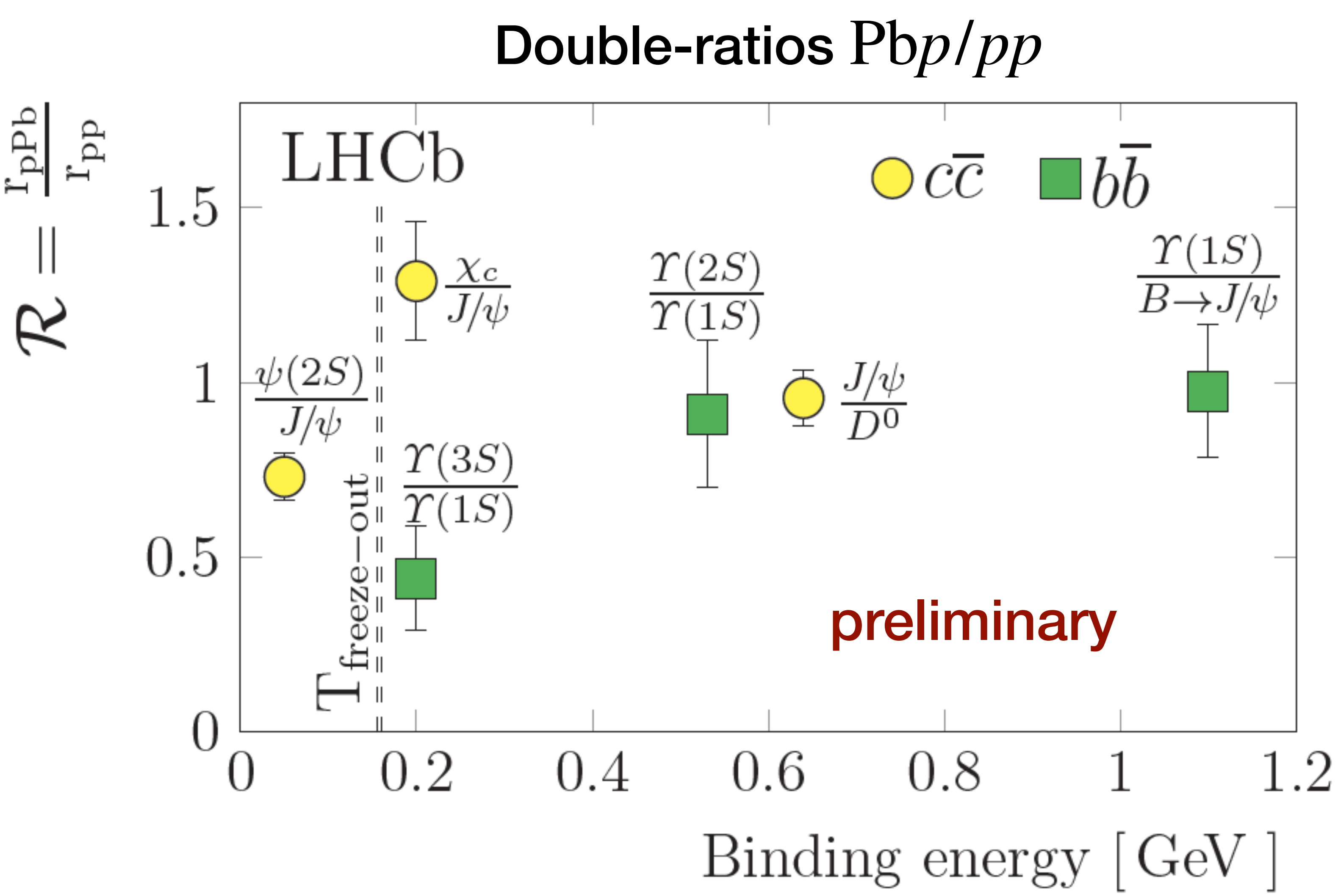


- $F_{\chi_c \to J/\psi}$ mostly affected by final-state interactions
- Data compatible with feed-down from pp at $\sqrt{s} = 7$ TeV (PLB 718 (2012) 431)
  - **No indication of comover break-up for χ_c**
- Intriguing increase of $F_{\chi_c \to J/\psi}$ in Pbp at low p_T

LHCb-PAPER-2023-028, in preparation

Quarkonium binding energy and suppression

$\chi_c(1P)$ production in pPb at $8.16\,\mathrm{TeV}$ New!



ΔE values from J. Phys. G32 (2006) R25
LHCb measurement references in backup

- Compare quarkonia **excited-to-ground state double-ratios**
- $\chi_{c1,c2}$ binding energy: $\Delta E \approx 0.20\,\mathrm{GeV}$
  - very close to QGP freeze-out temperature of $T_c \sim 0.16\,\mathrm{GeV}$

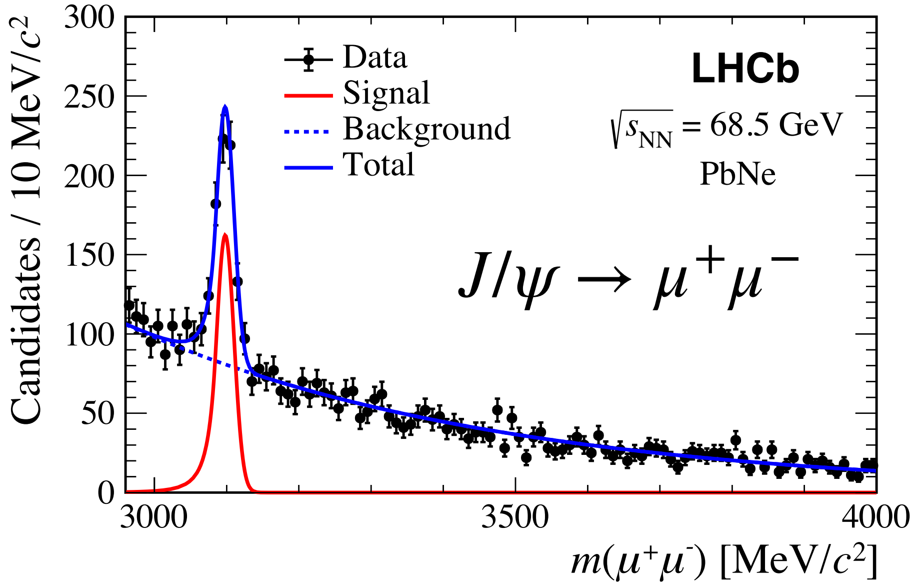
  PLB 795 (2019) 15, PRC 99 (2019) 4, 044914
  - **important constrain to QGP formation scenario in small systems**
- $\Upsilon(3S)$, with similar ΔE as χ_c, suppressed vs $\Upsilon(1S)$:
  - Larger mass of $\Upsilon(3S)$ vs χ_c?
  - S vs P state?

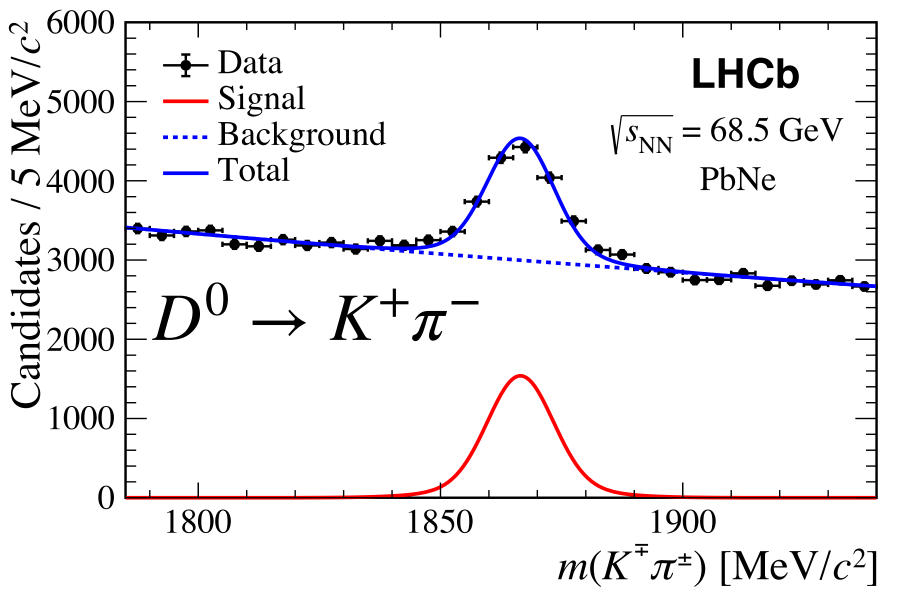
LHCb-PAPER-2023-028, in preparation

Dissociation at lower energies?

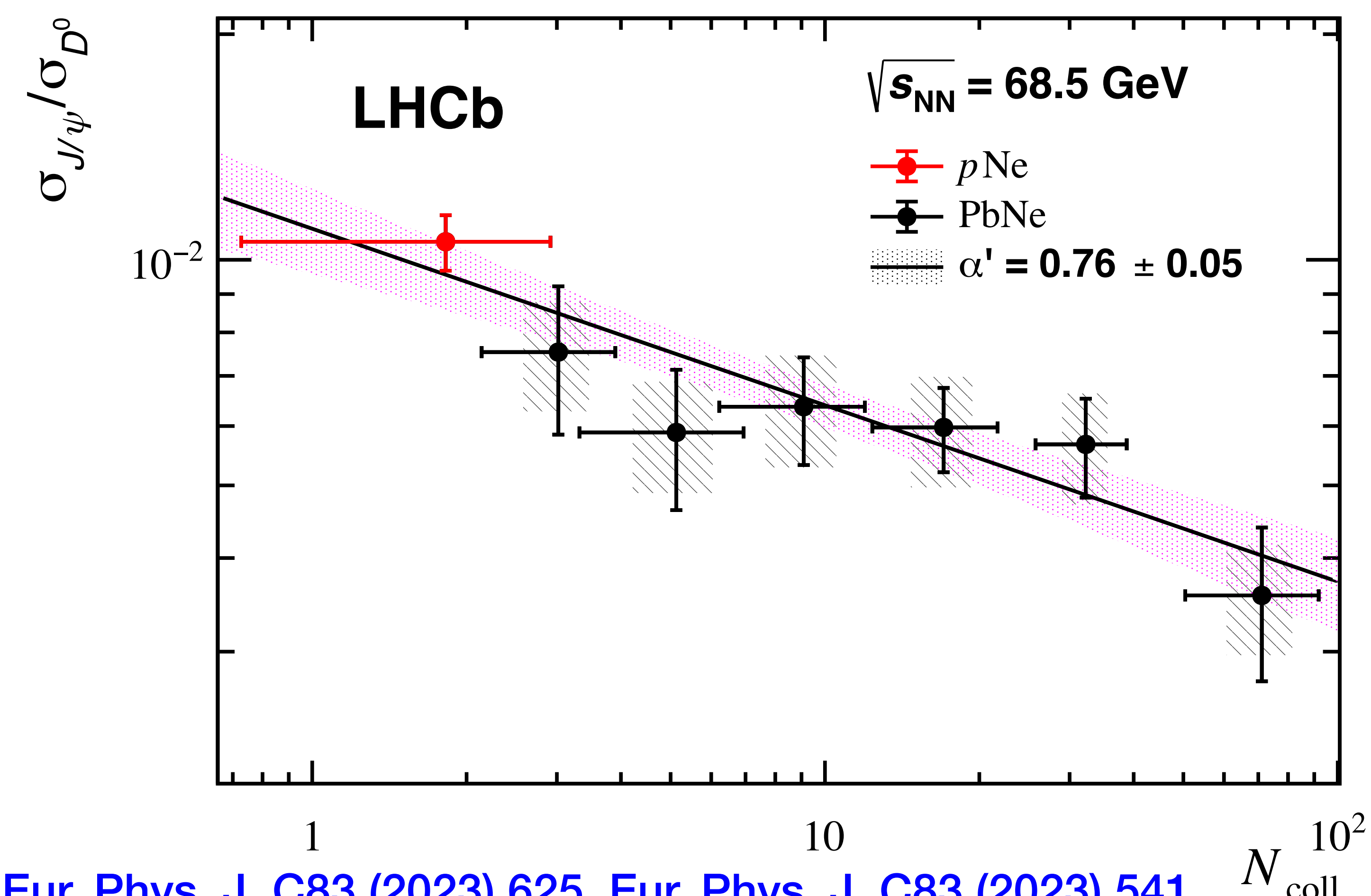
J/ψ and D^0 production in PbNe and pNe in fixed-target configuration

- Study PbNe sample at $\sqrt{s_{NN}} = 68.5\,\text{GeV}$, negligible charm recombination
  - **Cleaner environment to test sequential suppression**
- Studied J/ψ to D^0 production ratio, control cold nuclear effects with pNe





- Continuous suppression observed, compatible with no QGP scenario
  - Larger system size (PbAr) and precision reachable in Run 3



PbNe: Eur. Phys. J. C83 (2023) 658, pNe: Eur. Phys. J. C83 (2023) 625, Eur. Phys. J. C83 (2023) 541

Open heavy-flavour

Constraining nPDF with open charm

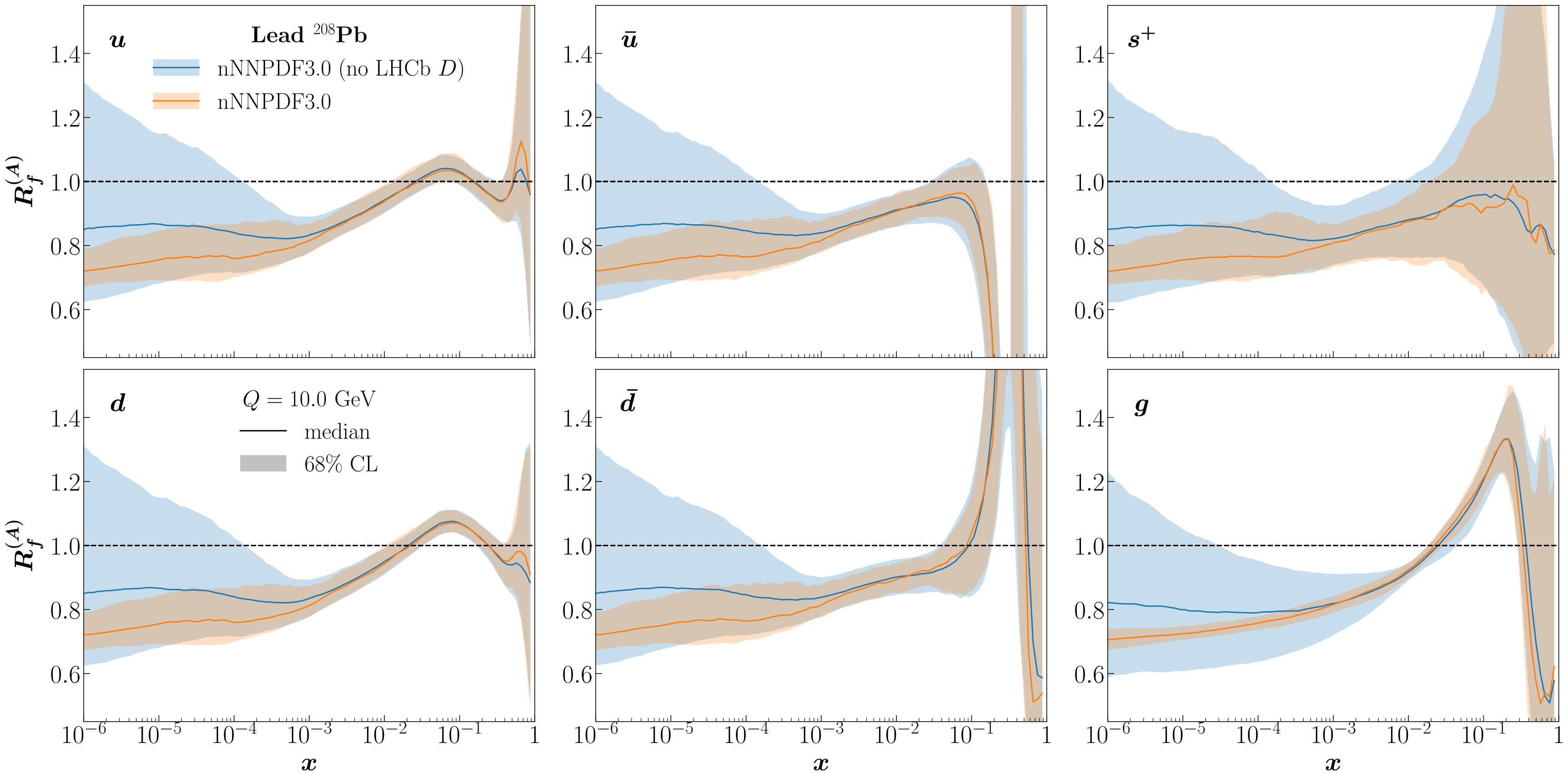
D^0 production in pPb collisions at $5\,\mathrm{TeV}$

- LHCb measured D^0 meson production with Run 1 data ($\mathscr{L}_{p\mathrm{Pb}} \sim 1.5\,\mathrm{nb}^{-1}$) in $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$ (JHEP 10 (2017) 090)
- Measure **nuclear modification factor**:

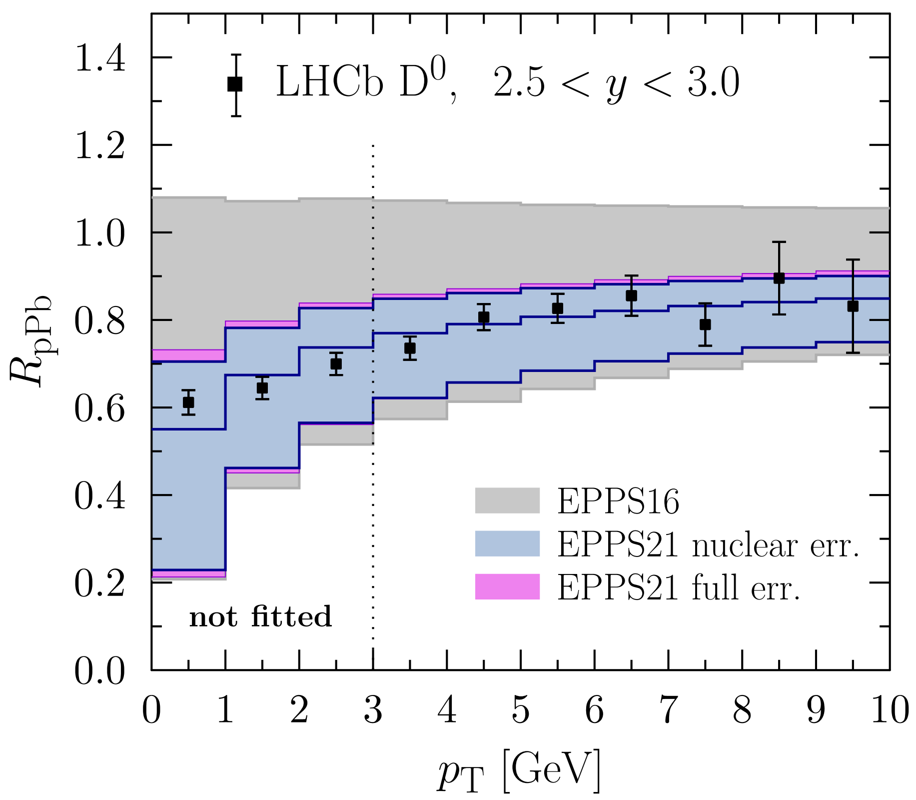
$$R_{p\mathrm{Pb}} = \frac{\sigma_{p\mathrm{Pb}}}{A\sigma_{pp}}$$

- Data included in EPPS21 (EPJ C82 (2022) 5, 413) and nNNPDF3.0 (EPJ C82 (2022) 6, 50)
  - **Drastic reduction of nPDF uncertainties** at low-x, specially in gluon nPDF

EPJ C82 (2022) 6, 50



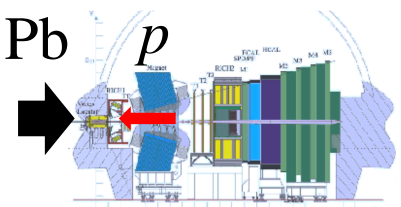
EPJ C82 (2022) 5, 413



Improving nPDF constrains with open charm

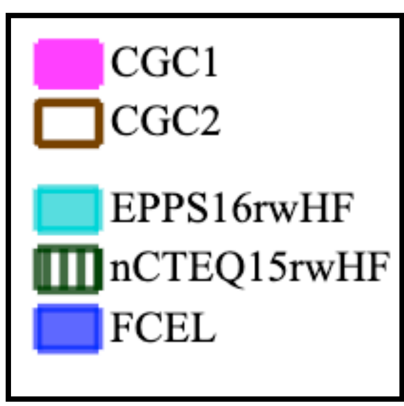
D^0, D^+ and D_s^+ production in pPb collisions at $8.16\,\text{TeV}$ **New!**

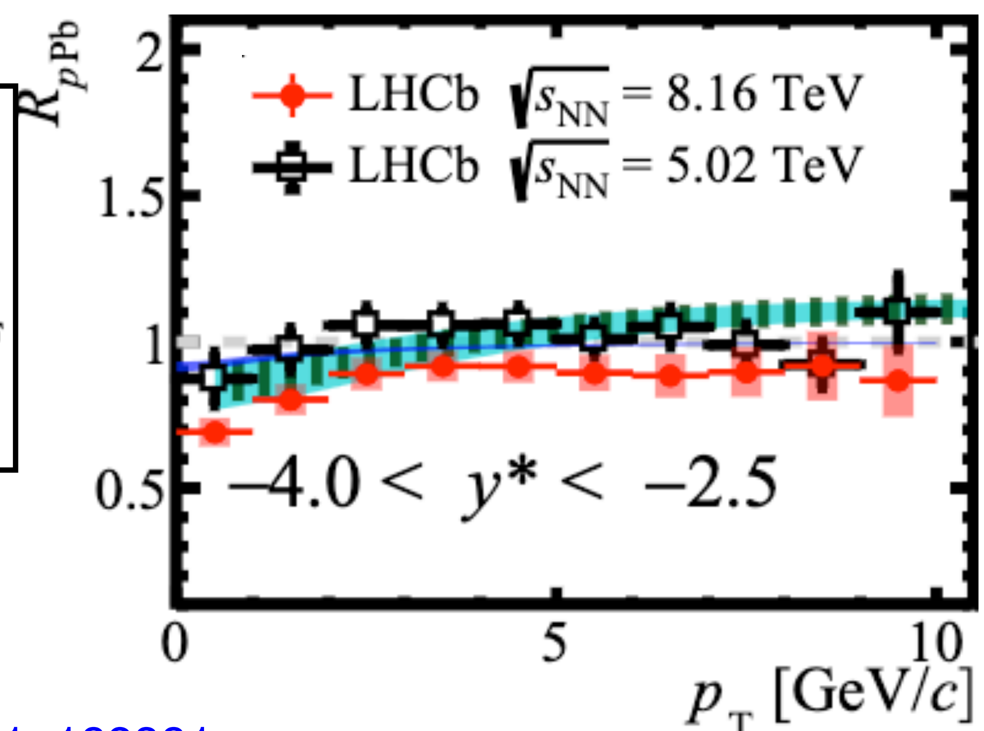
- Double-differential cross-sections with (p_T, y), down to very low p_T **with Run 2 dataset ($\times 20$ of Run 1)**
- Improve constrains on nPDFs over a wide x range:
  - consistent **tensions in the backward region** for all states



Backward

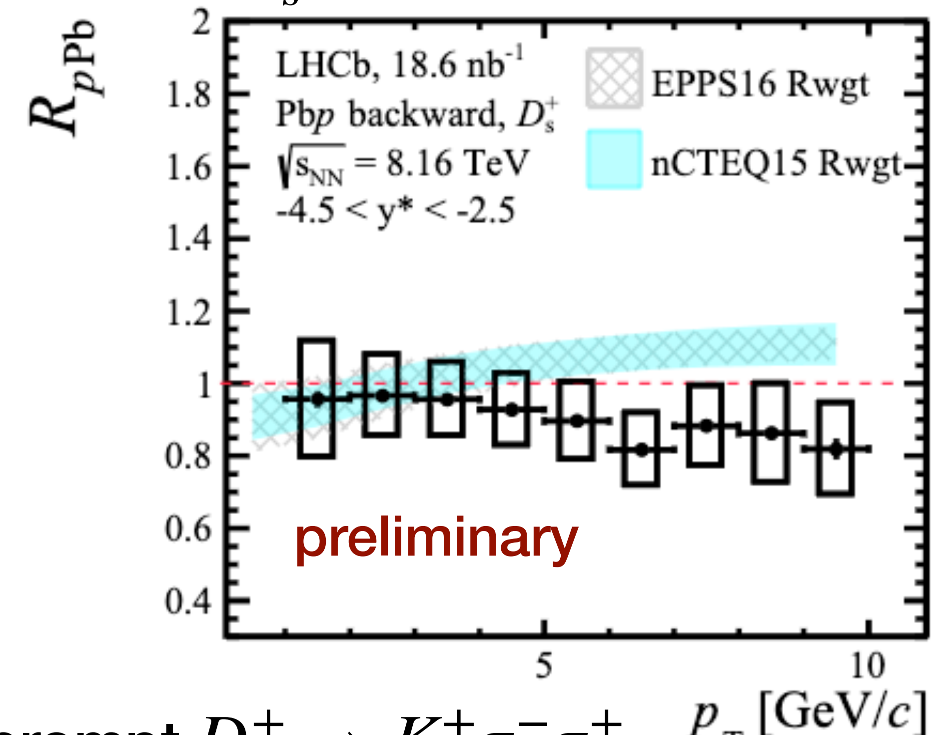
prompt $D^0 \to K^+\pi^-$



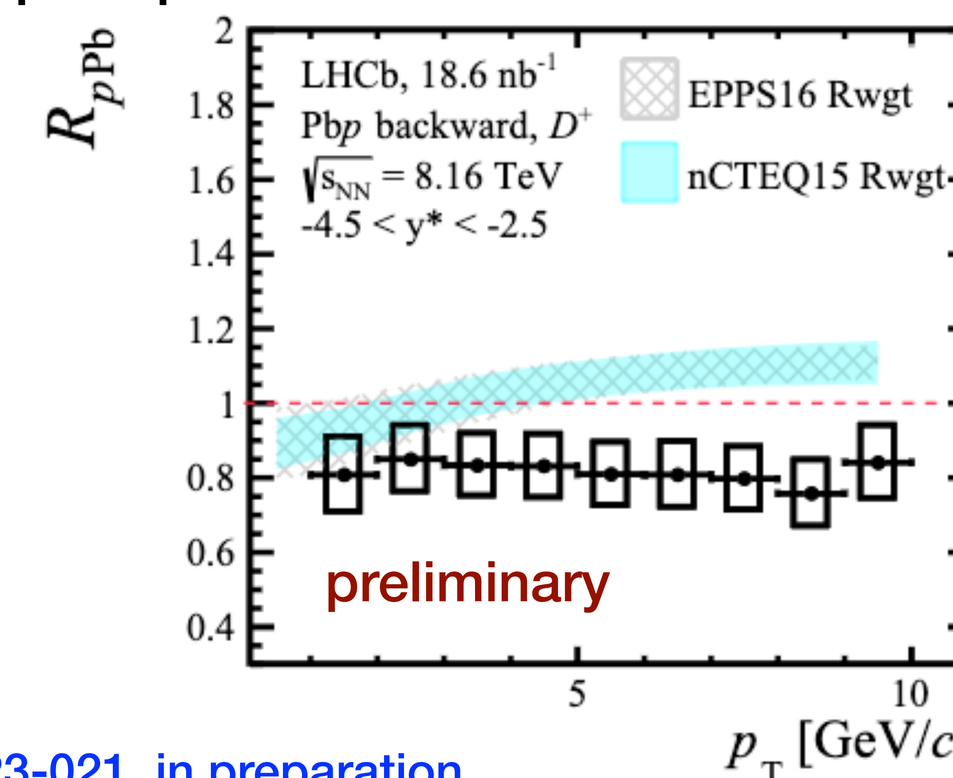


predictions for $\sqrt{s_\text{NN}} = 8.16\,\text{TeV}$

prompt $D_s^+ \to K^+K^-\pi^+$



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

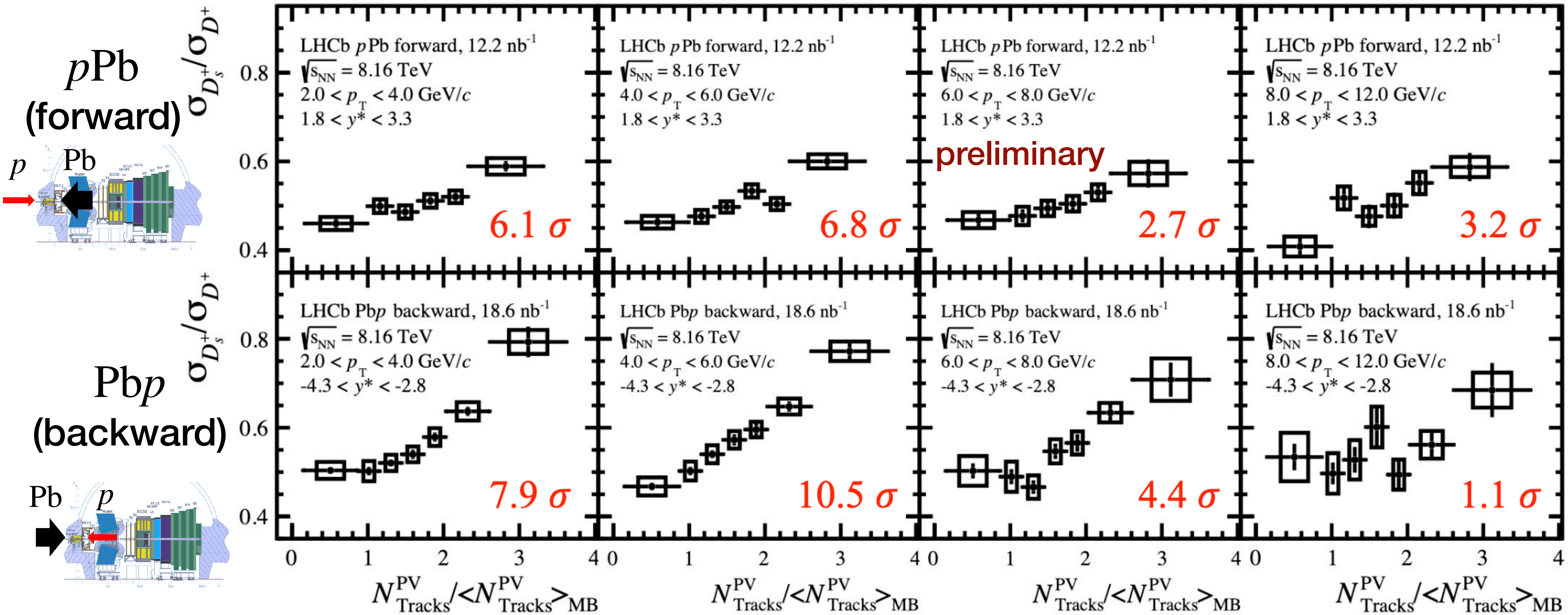


Phys. Rev. Lett. 131, 102301

LHCb-PAPER-2023-021, in preparation

Charm quark hadronization in pPb

D_s^+/D^+ production ratio with multiplicity in pPb collisions at 8.16 TeV **New!**



low p_T → high p_T

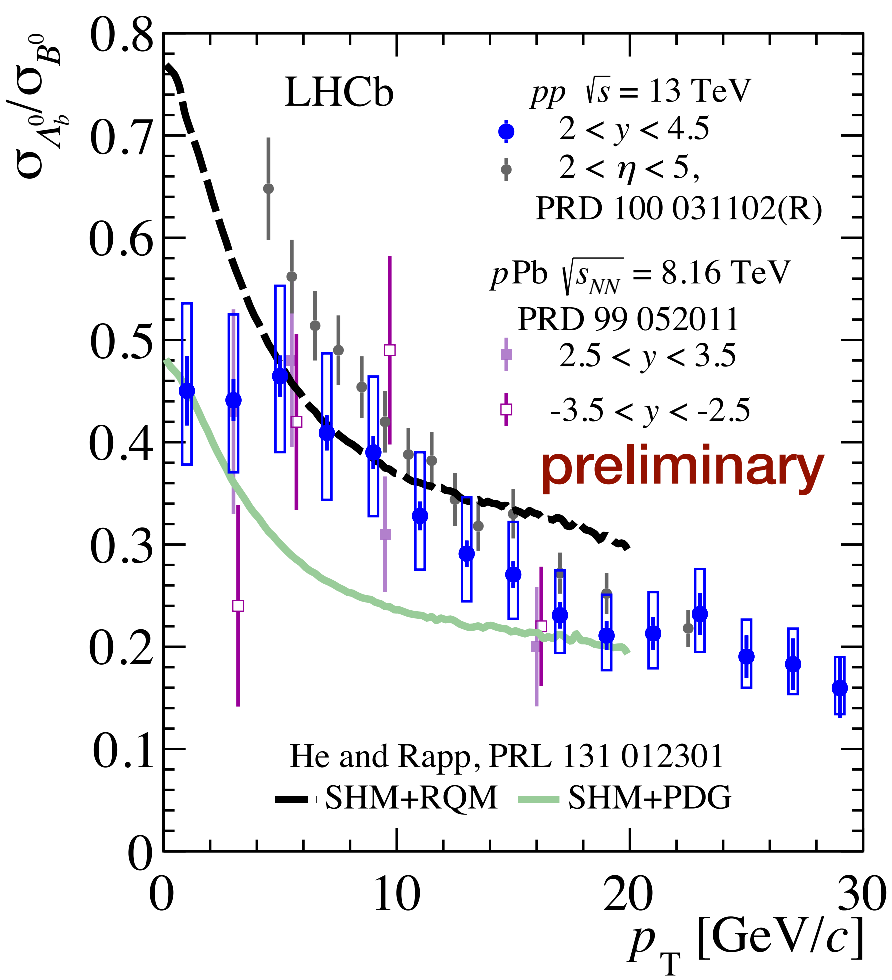
- **Measured multiplicity dependence of D_s^+/D^+ in p_T and y bins**
- Observation of an increase of D_s^+/D^+ with multiplicity → **strangeness enhancement**
- Charm quark hadronization is modified in high multiplicity pPb
  - qualitatively consistent with a coalescence picture; feed-down contributions still need to be studied

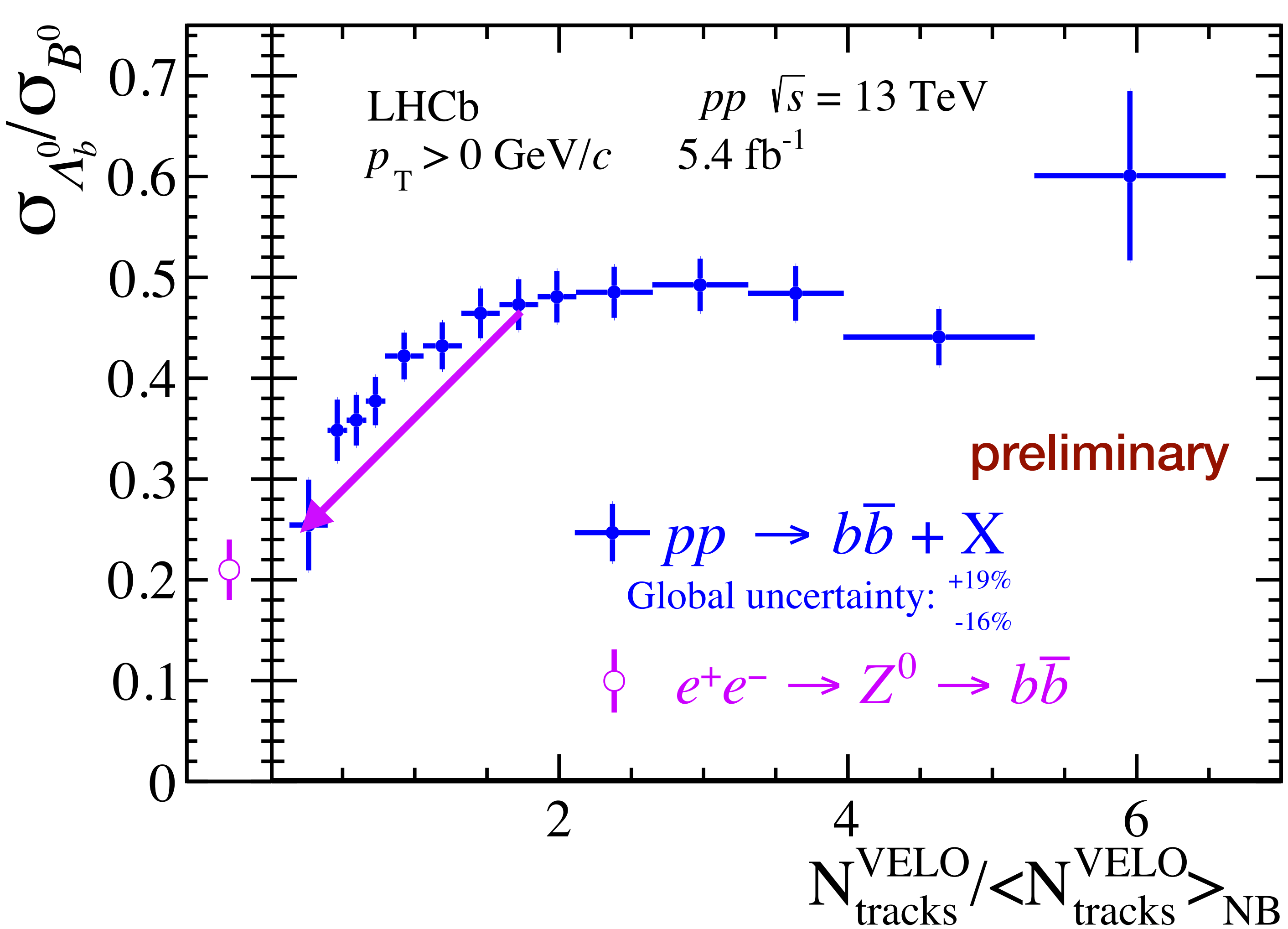
LHCb-PAPER-2023-021, in preparation

b quark hadronization in high-multiplicity pp

Λ_b^0/B^0 production ratio with multiplicity in pp collisions at 13 TeV **New!**

- Baryon-to-meson ratio measured down to zero p_T with $\Lambda_b^0 \rightarrow J/\psi pK$ and $B^0 \rightarrow J/\psi \pi K$





- p_T trend compatible with measurement with semileptonic channel and pPb

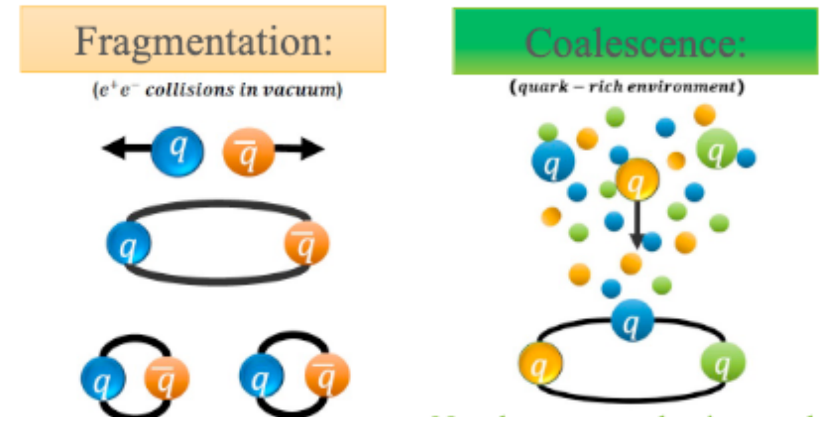
- We observe a **strong baryon enhancement with multiplicity**
- Ratio recovers e^+e^- value (QCD-vacuum) at low multiplicity

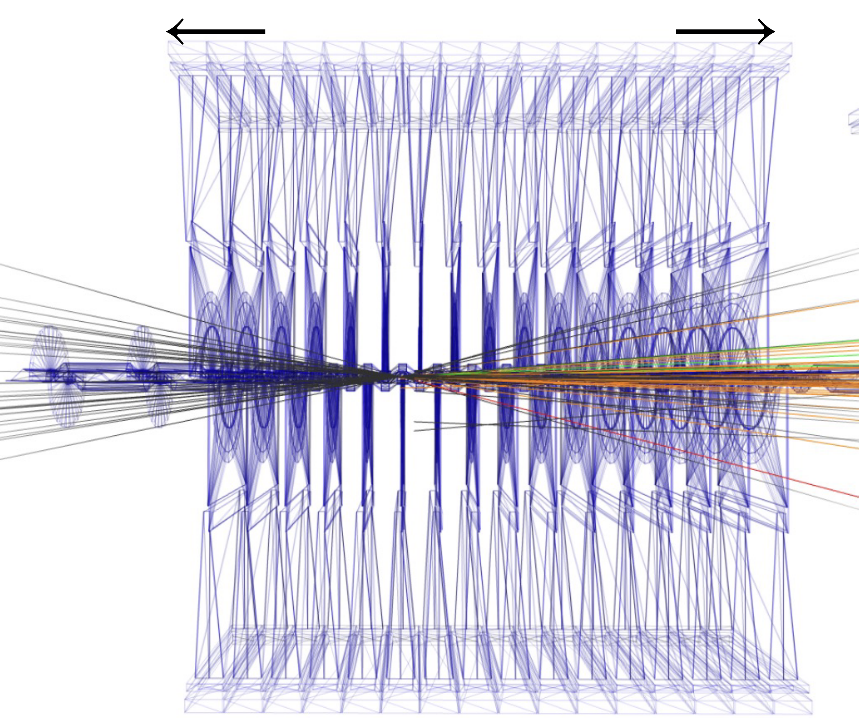
LHCb-PAPER-2023-027, in preparation

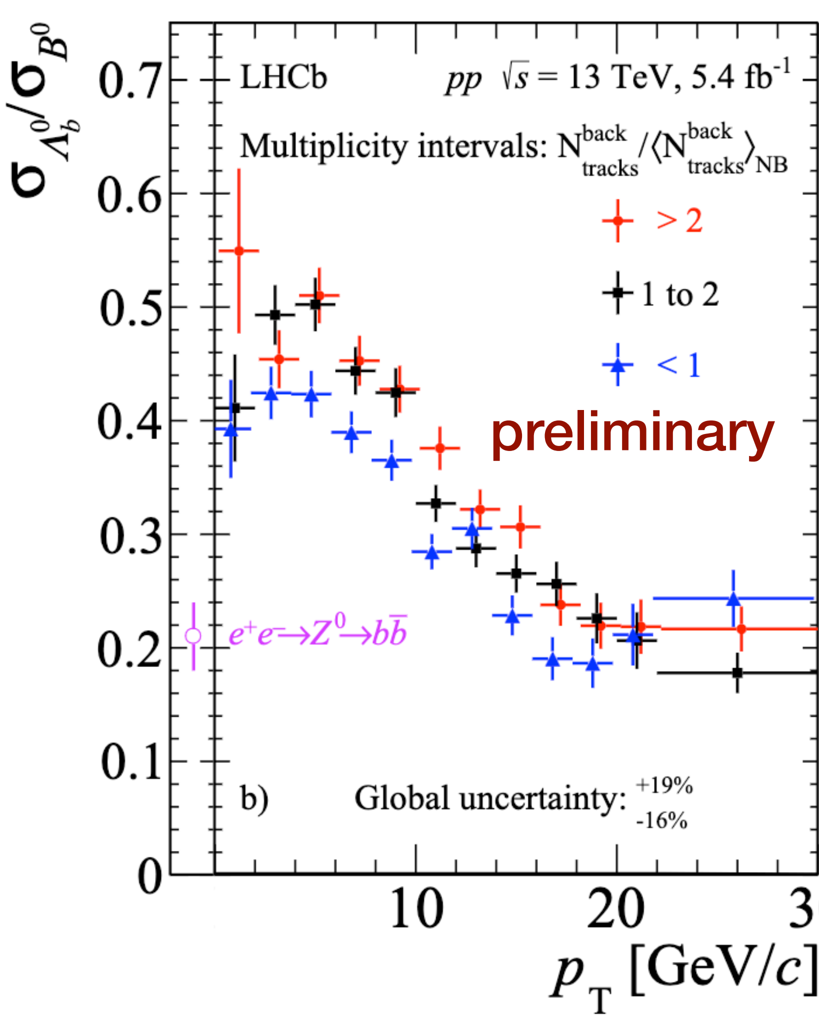
b quark hadronization in high-multiplicity pp

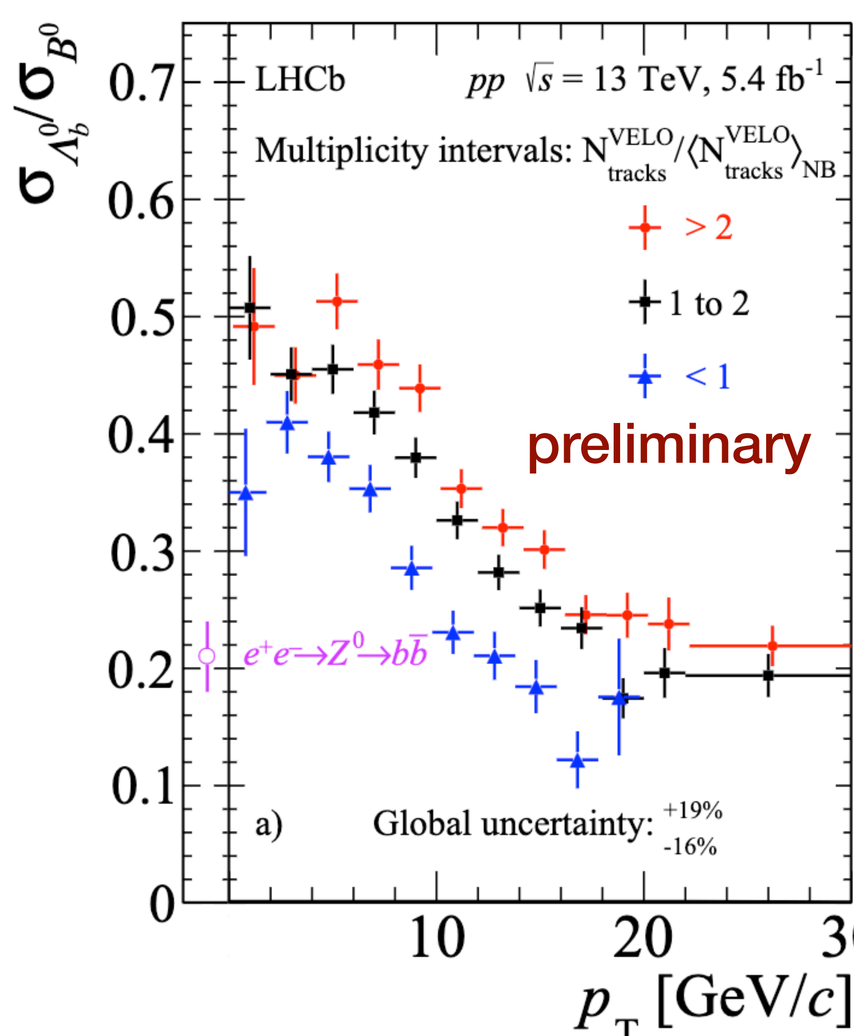
Λ_b^0/B^0 production ratio with multiplicity in pp collisions at $13\,\text{TeV}$ **New!**

- Compare p_T trend at low multiplicity and high multiplicity
- Λ_b^0/B^0 ratio consistent with e^+e^- at high p_T:
  - compatible with the coalescence picture being dominant at low p_T







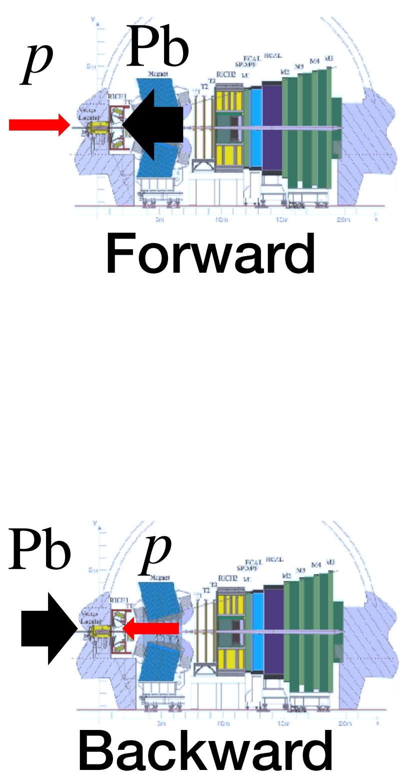


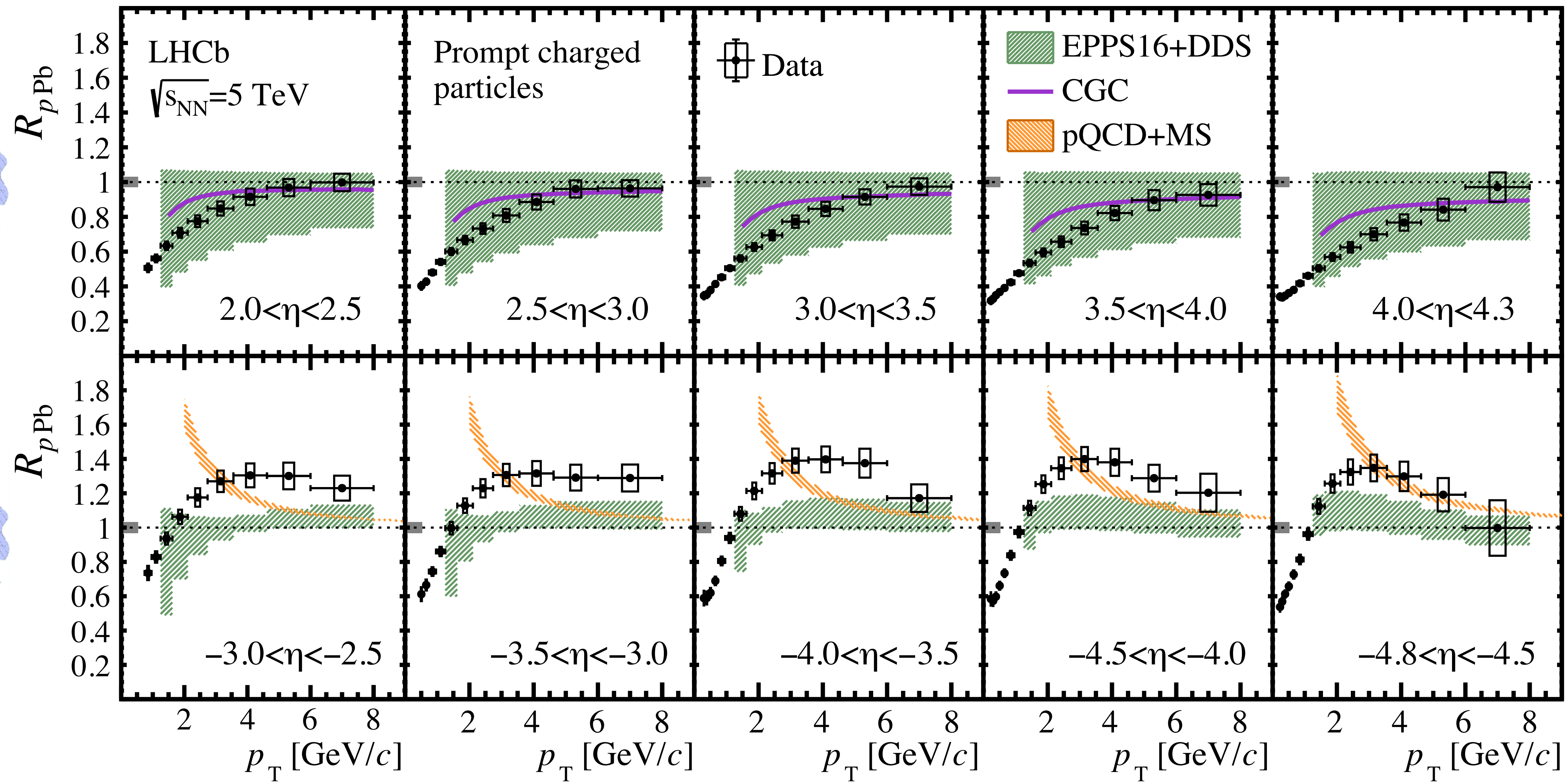
LHCb-PAPER-2023-027, in preparation

Light flavour

Charged hadron production in $p\mathrm{Pb}$ and pp

- Inclusive prompt long-lived charged hadrons: $\pi^{\pm}, K^{\pm}, \overset{(-)}{p}$, ...
- Forward: **strong suppression**, well reproduced by nPDFs and latest NLO CGC calculations (PRL 128 (2022) 20, 202302)
- Backward: **enhancement** for $p_{\mathrm{T}} > 1.5\,\mathrm{GeV}/c$ with η dependence, as observed by PHENIX in $p\mathrm{Au}$ (PRC101 (2020) 3, 034910). Not reproduced by nPDF or other calculations

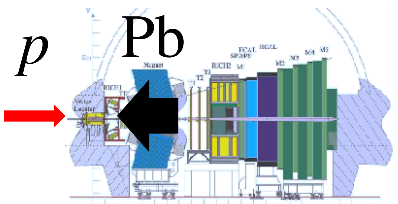


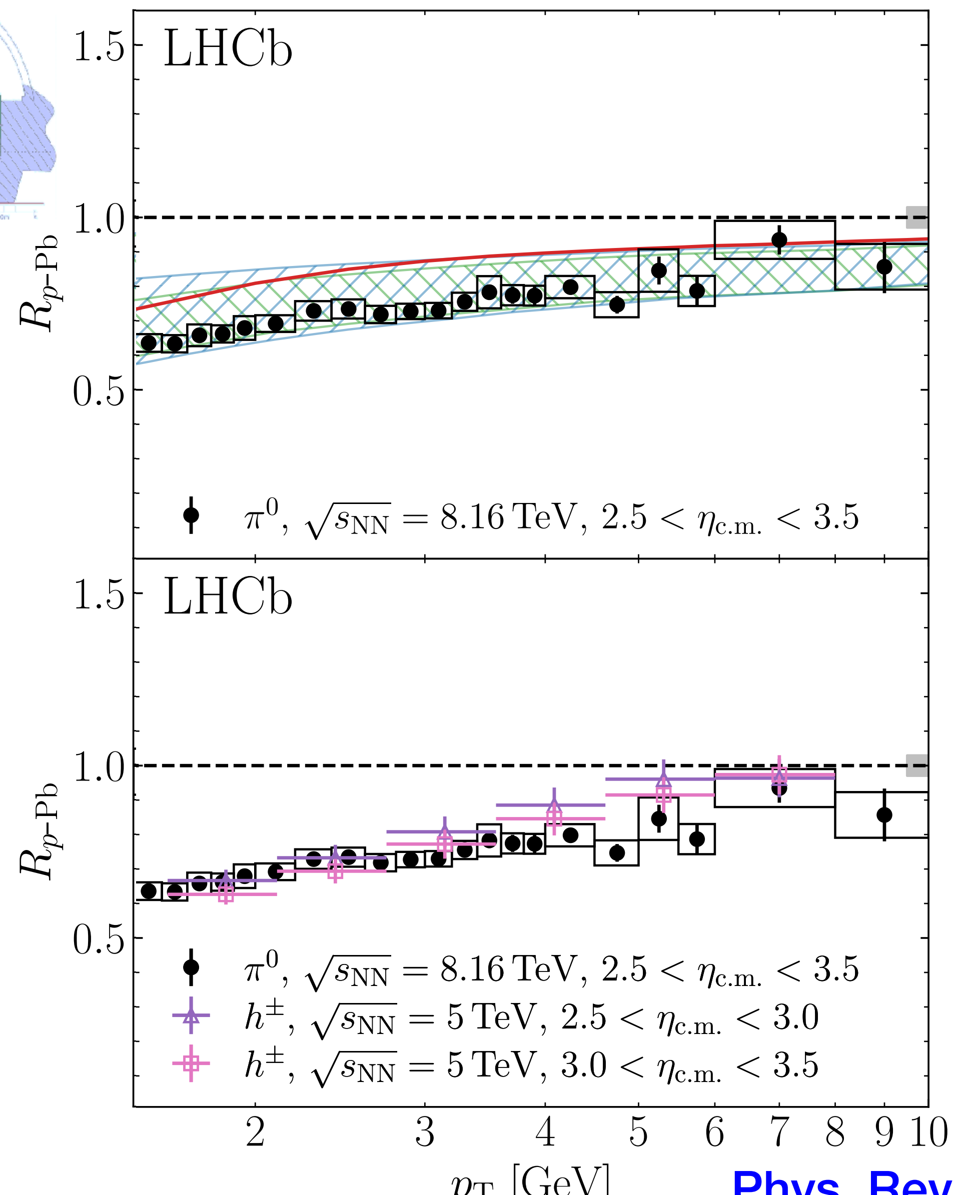


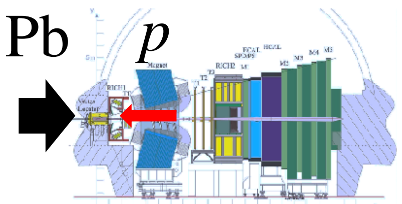
Phys. Rev. Lett. 128 (2022) 142004

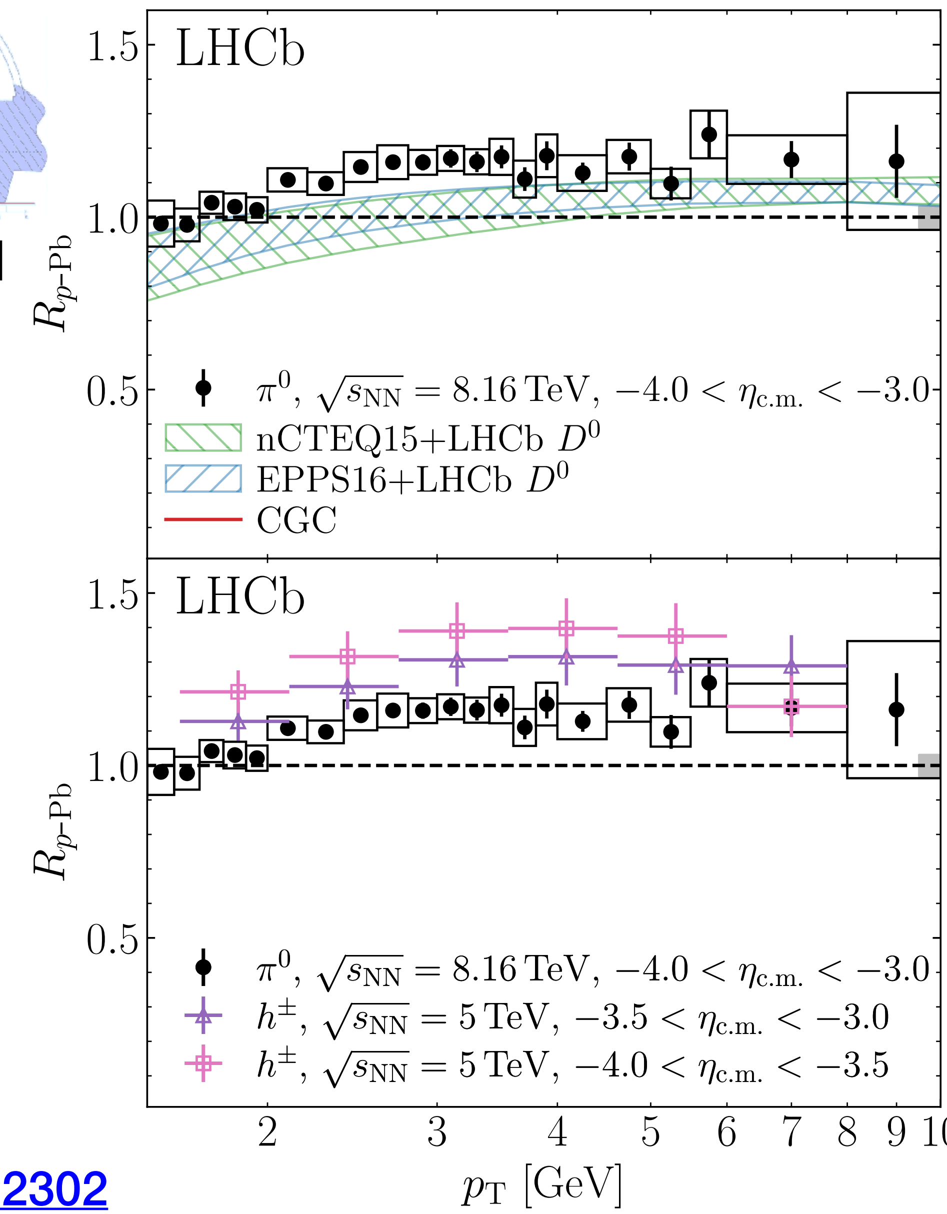
π^0 production in pPb and pp

- Measure π^0 with $\pi^0 \to \gamma\gamma$
- **Forward**: agreement with nPDF predictions and charged hadron data
- **Backward**: enhancement below that of charged hadrons
  - Potential explanations:
    - Radial flow leading to mass-dependent enhancement
    - Quark coalescence causing baryon enhancement







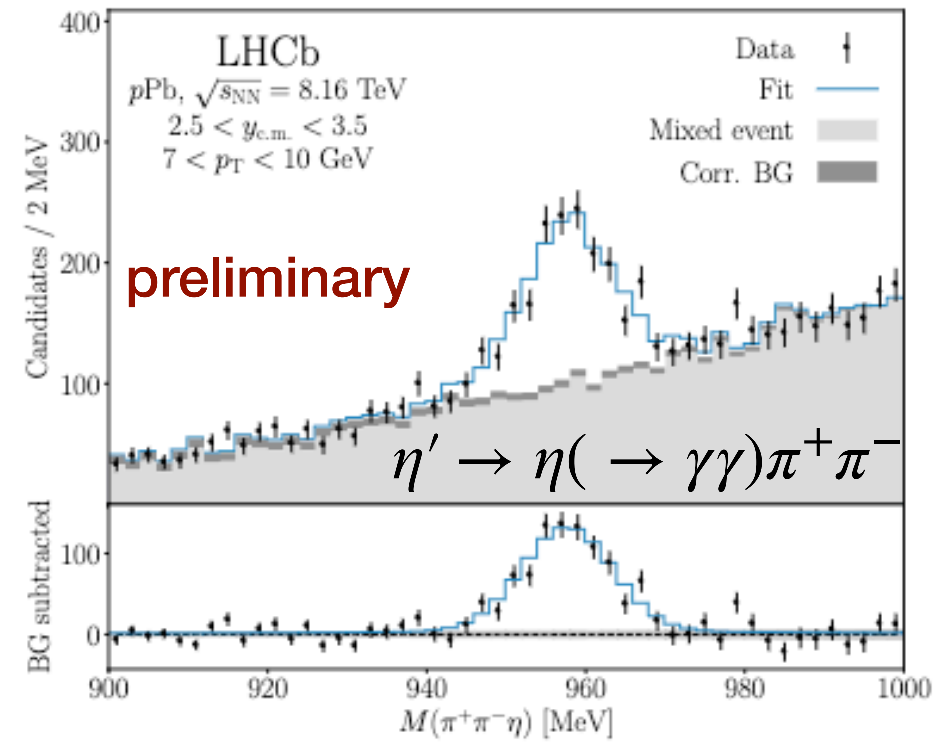


Phys. Rev. Lett. 131 (2023) 042302

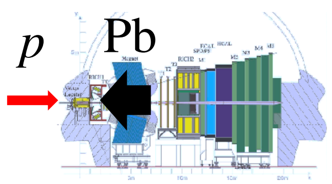
η and η' production in pPb and pp

New!

- $\eta(548)$ and $\eta'(958)$: almost identical properties, but different mass
  - study mass-dependent effects in pPb
- New measurement of $\eta \rightarrow \gamma\gamma$ and $\eta' \rightarrow \gamma\gamma\pi^+\pi^-$ in pPb and pp collisions
  - **First η' production measurement at LHC**
- Agreement of $R_{p\mathrm{Pb}}$ of π^0, η and η':
  - **No indication of mass-dependent effects**



Forward



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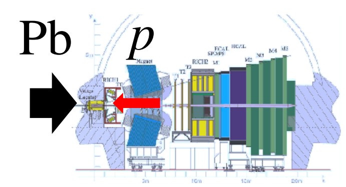
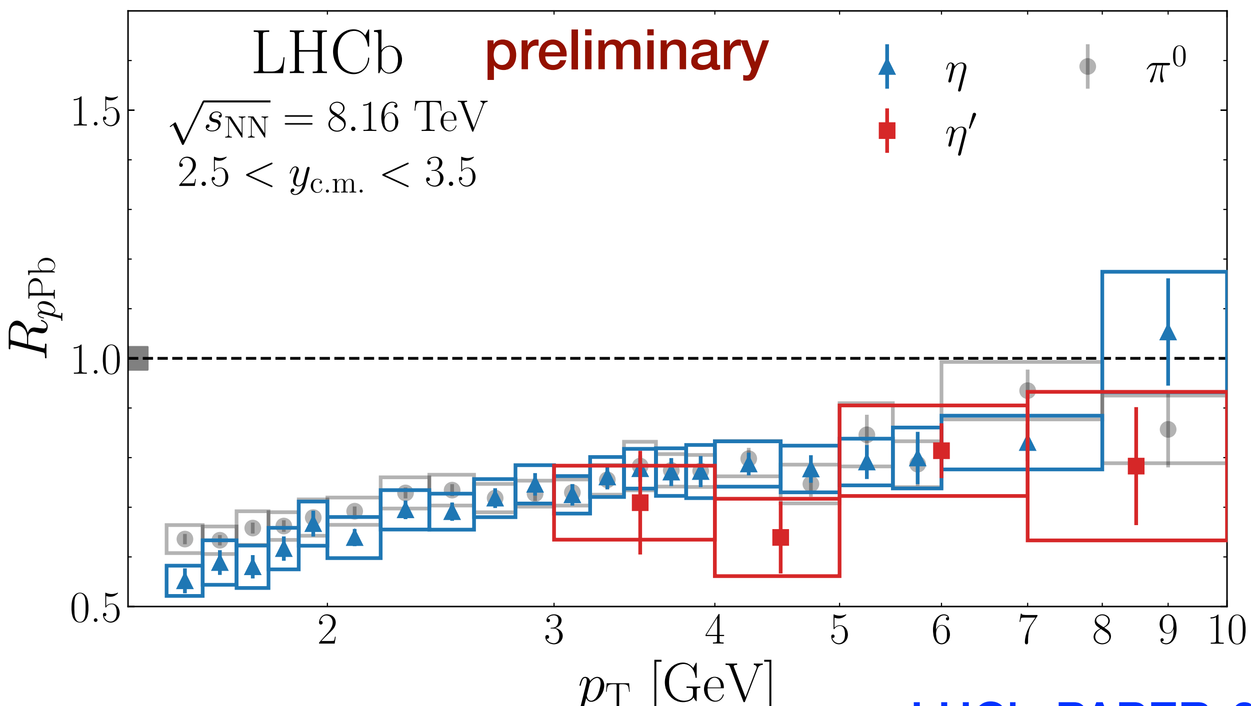
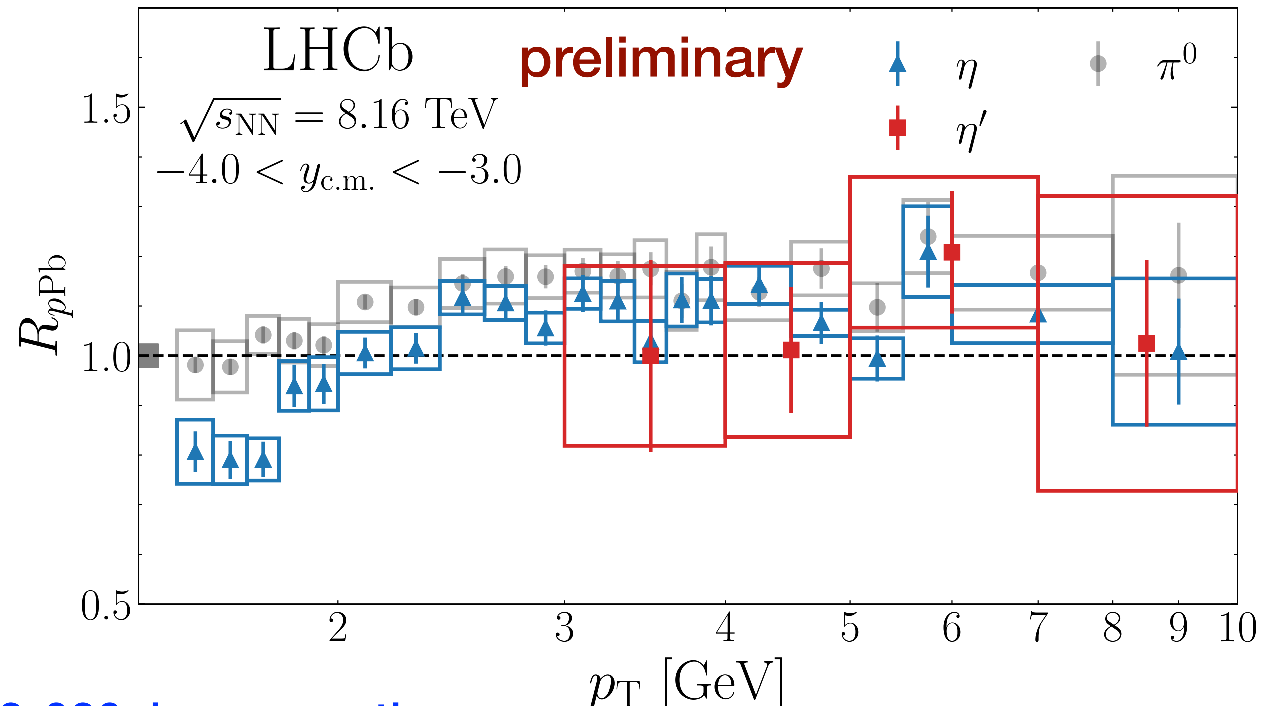


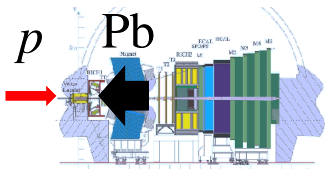


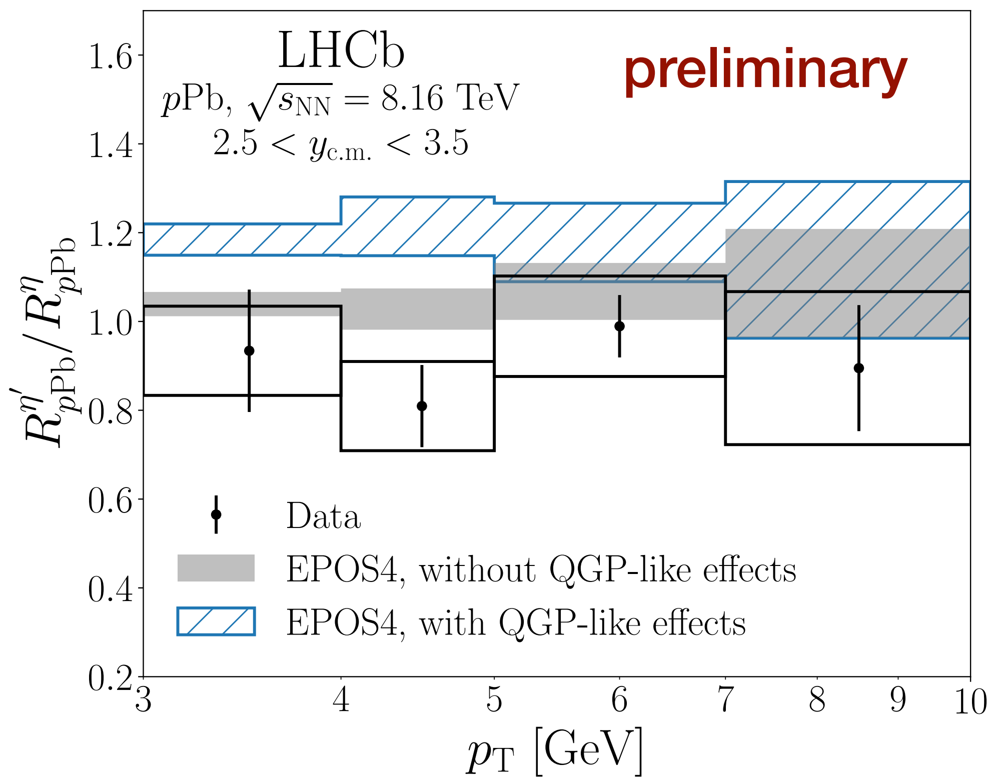


LHCb-PAPER-2023-030, in preparation

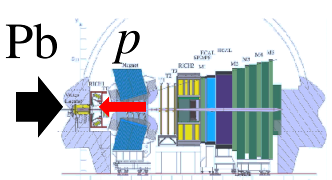
η and η' production in pPb and pp New!

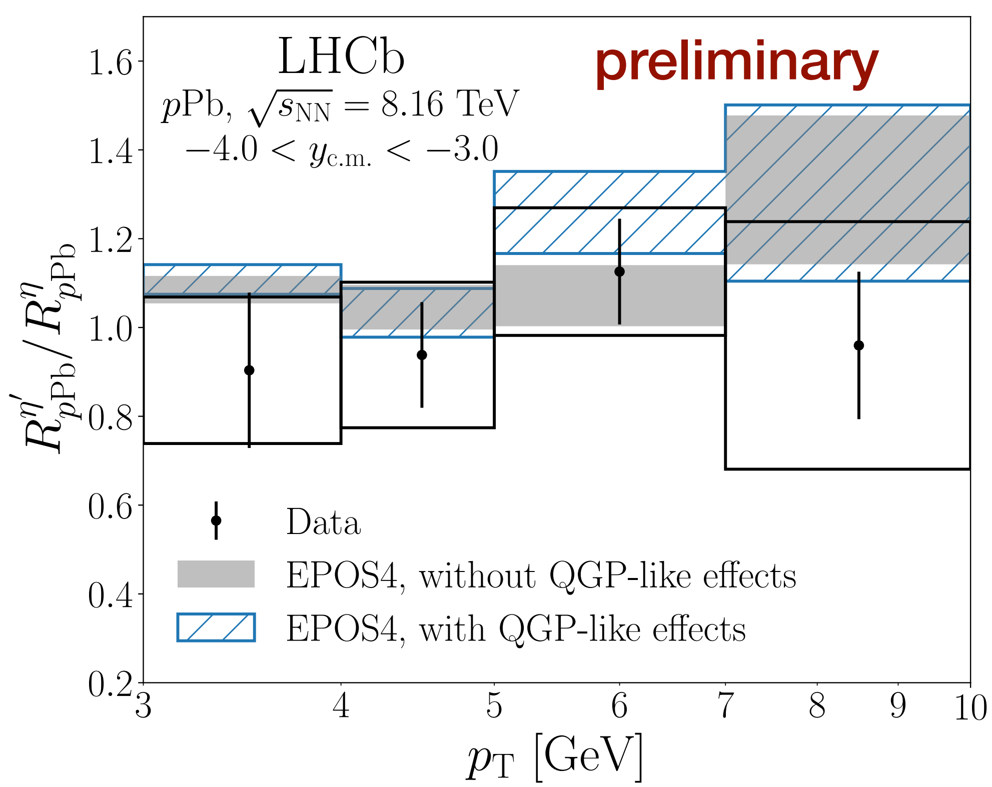
Forward





Backward





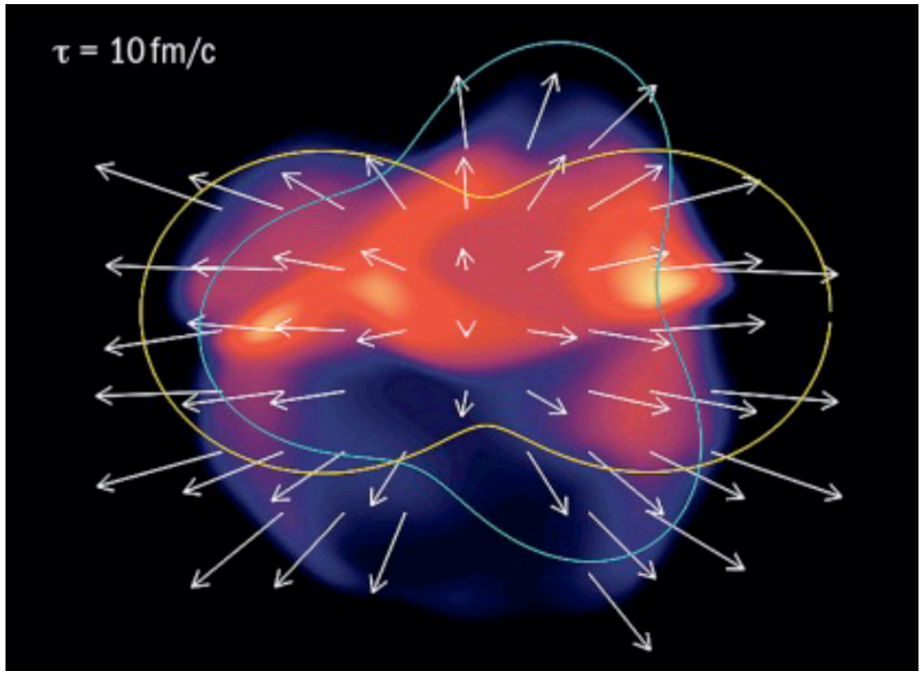
- Ratio η'/η can also help to understand QGP-like effects in small systems
  - EPOS4 predicts sensitivity to these effects in forward region (arXiv:2301.12517)
  - **Data favours the no QGP-like effects scenario**
- Measurements of η and π^0 production are also a needed input for a **direct photon measurement** in pPb

LHCb-PAPER-2023-030, in preparation

Charged-hadron flow harmonics in PbPb

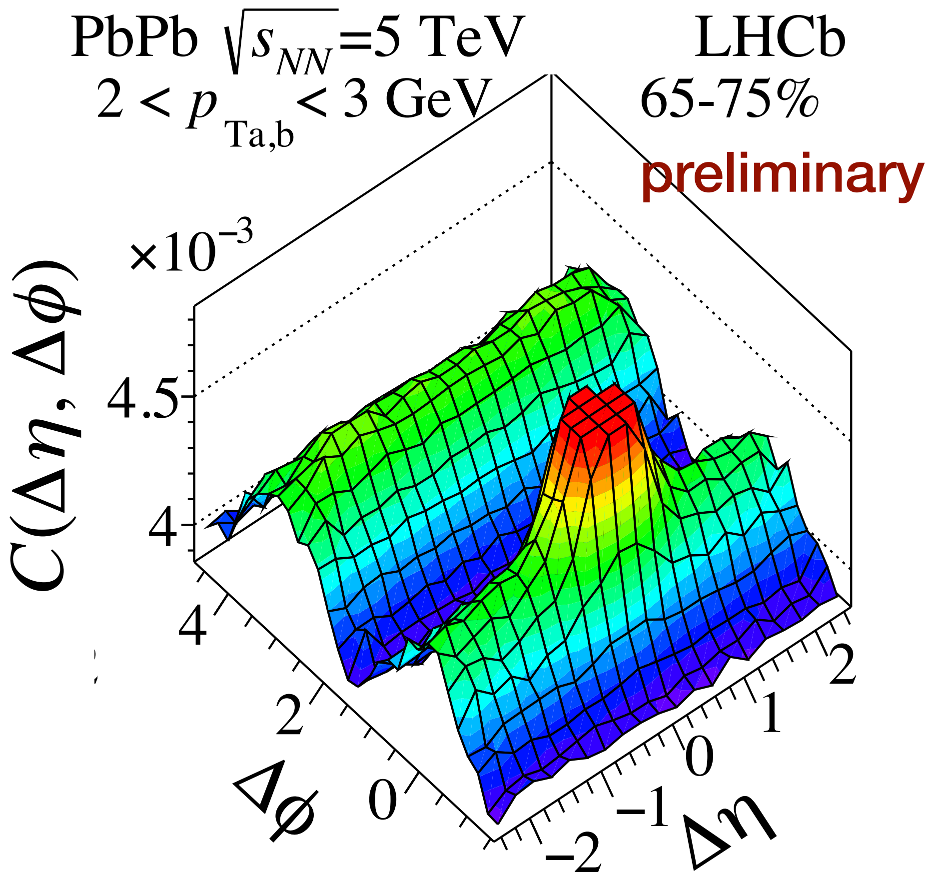
New!

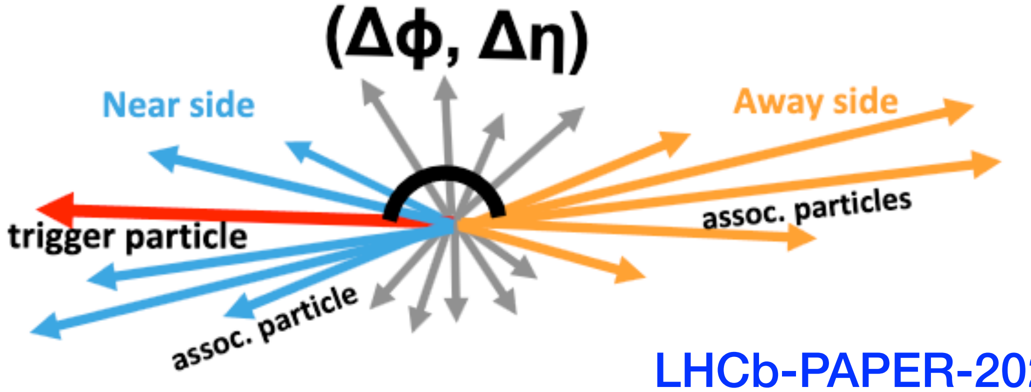
- Particle correlations: study QGP **hydrodynamics and transport properties**
  - Sensitive to the initial system configuration
- **First flow harmonics measurement at LHCb!**
  - Peripheral PbPb collisions in $2 < \eta < 4.9$
  - 2-particle correlations, use mixed-event technique to extract $C(\Delta\eta, \Delta\phi)$
  - Select particle combinations with $\Delta\eta > 1$ and extract flow by fitting $C(\Delta\phi)$



$$C(\Delta\phi) = A\left[1 + 2\sum_{n=1}^{3} V_n(p_{Ta}, p_{Tb}\cos(n\cdot\Delta\phi)\right]$$

$$V_n(p_{T,a}, p_{T,b}) = v_n^a(p_{Ta})\cdot v_n^b(p_{Tb})$$



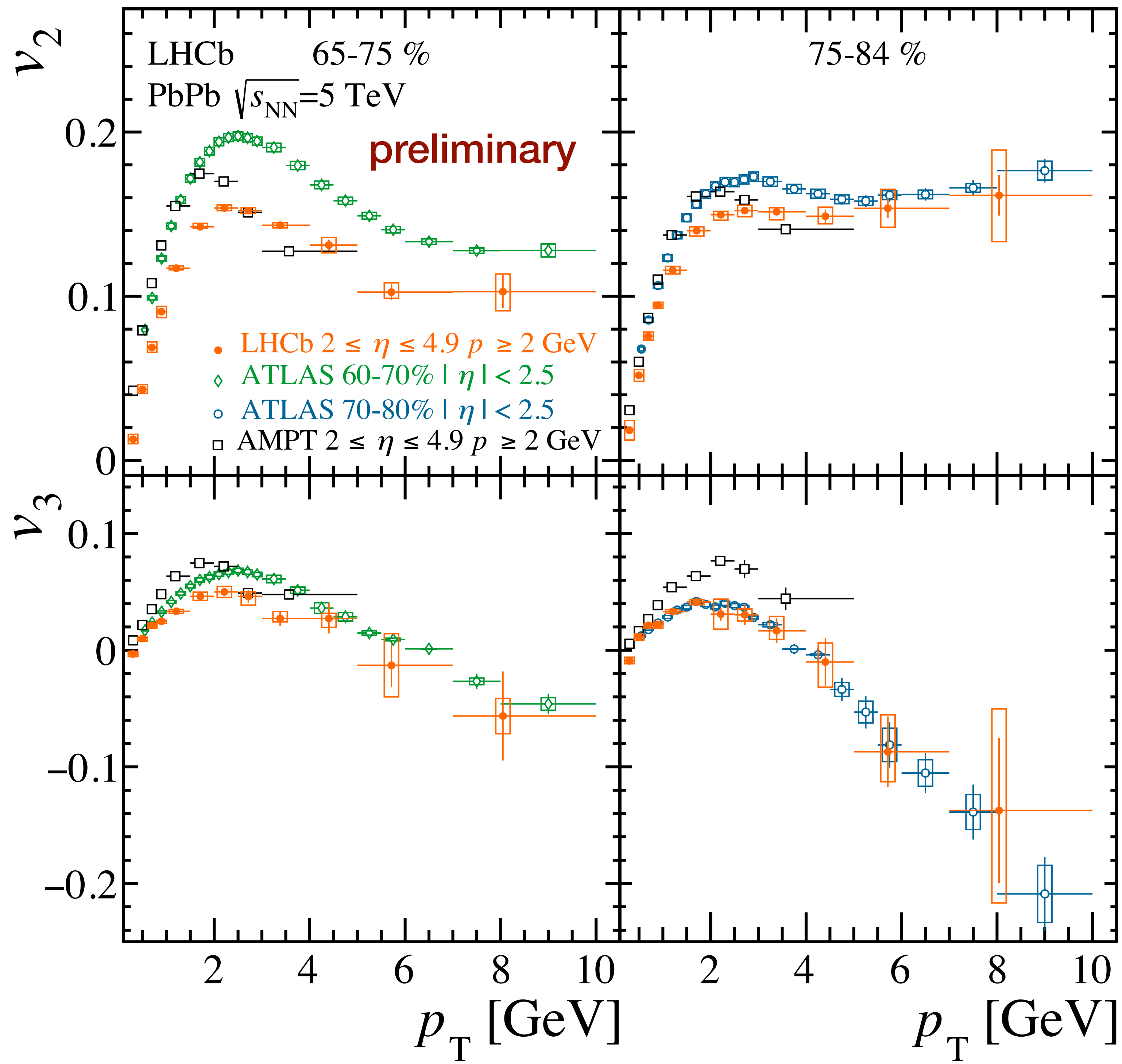


LHCb-PAPER-2023-031, in preparation

Charged-hadron flow harmonics in PbPb

New!

- Weaker v_2 and v_3 in the forward region compared to ATLAS at midrapidity
- AMPT transport model overestimates v_2 and v_3:
  - Tuning in the forward region might be needed
- **This is only the beginning!**
  - Small-system flow: pPb and pp
  - Heavy-flavour flow to study initial state effects at low-x
  - Fixed target: access to smaller asymmetric systems (PbNe and PbAr)
    - ✶Study initial-state geometry



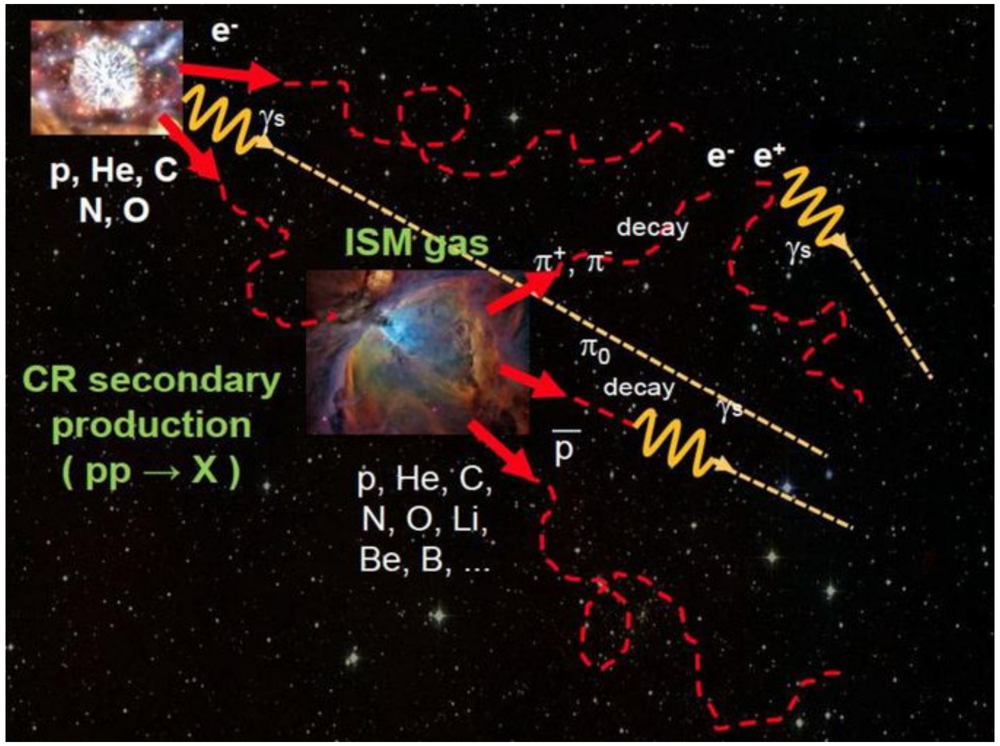
ATLAS: EPJC 78 (2018) 12 997
AMPT: Nucl.Sci.Tech. 32 (2021) 113

LHCb-PAPER-2023-031, in preparation

Nucleus identification at LHCb and astroparticle physics

Synergies with astroparticle physics

- Our gained knowledge about QCD has applications:
  - **Dark matter searches in extragalactic cosmic rays** through antimatter detection → need understanding of SM backgrounds ($\overline{p}$, $\overline{d}$, $\overline{\mathrm{He}}$...)
  - **Gamma astronomy** → γ production in cosmic rays
  - **Neutrino astronomy** → background from charm decays in cosmic atmospheric showers
  - **UHE CR from extensive showers in atmosphere** → hadron production and interactions in non-perturbative regime

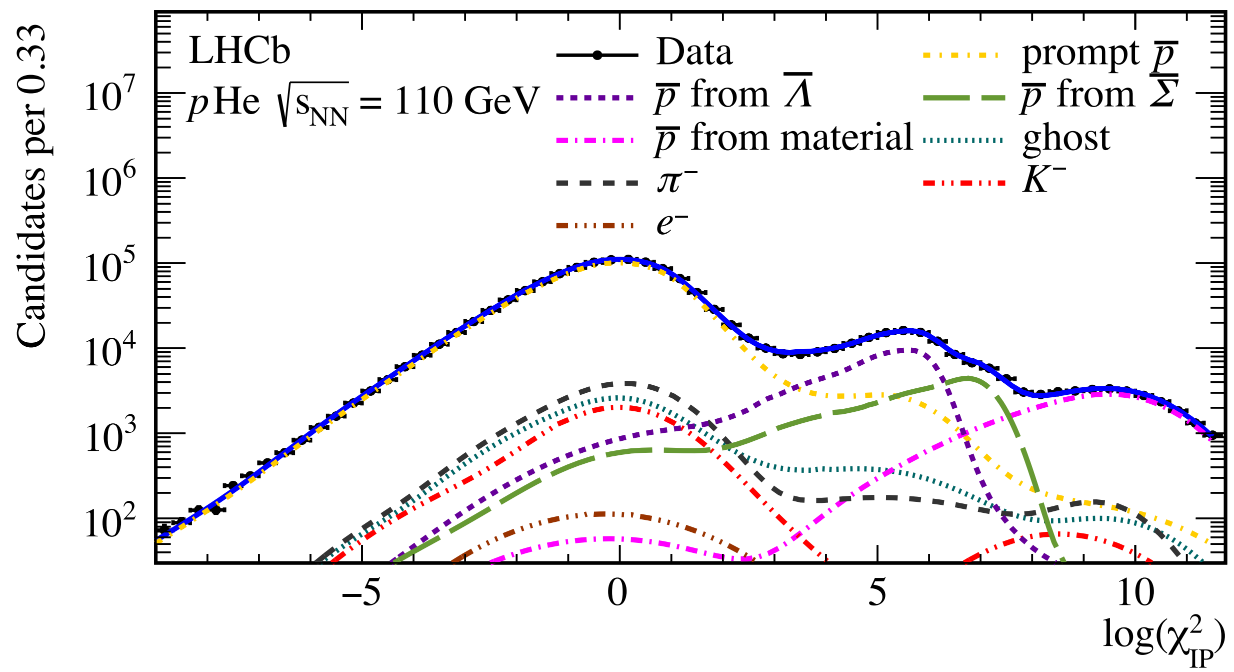


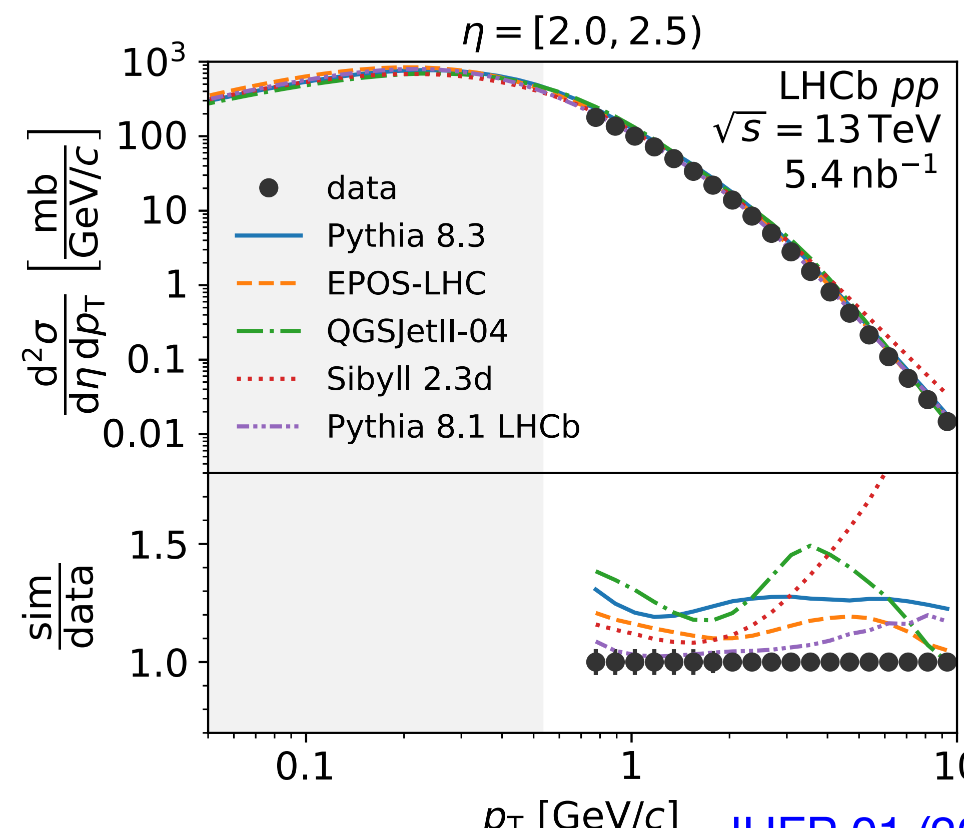
- LHCb has capabilities to make very unique and needed contributions:
  - Access to a unique $\sqrt{s}$ in the fixed-target configuration, between SPS and RHIC energies
  - Low p_{T} access → good coverage to extrapolate bulk production
  - Forward rapidity region is crucial in the description of UHE CR showers

Some examples…

EPJC 83, 543 (2023)

- Many of our measurements from the astrophysicist wish list:
  - Prompt (PRL 121 (2018) 222001) and detached (EPJC 83, 543 (2023)) antiproton production (pHe collisions at $\sqrt{s_{NN}} = 110\,\mathrm{GeV}$)
  - Charm production in fixed-target: ($p\mathrm{He}, p\mathrm{Ar}, p\mathrm{Ne}$: PRL 122 (2019) 132002, EPJC 83 (2023) 541)
  - Charged hadron production (pPb, pp: PRL 128 (2022) 142004, JHEP 01 (2022) 166)
  - π^0 production (pPb, pp: PRL 131 (2023) 042302)
- **Not yet everything that we could do, but more and more every year!**
- Still, one missing capability of LHCb is *light nucleus identification*





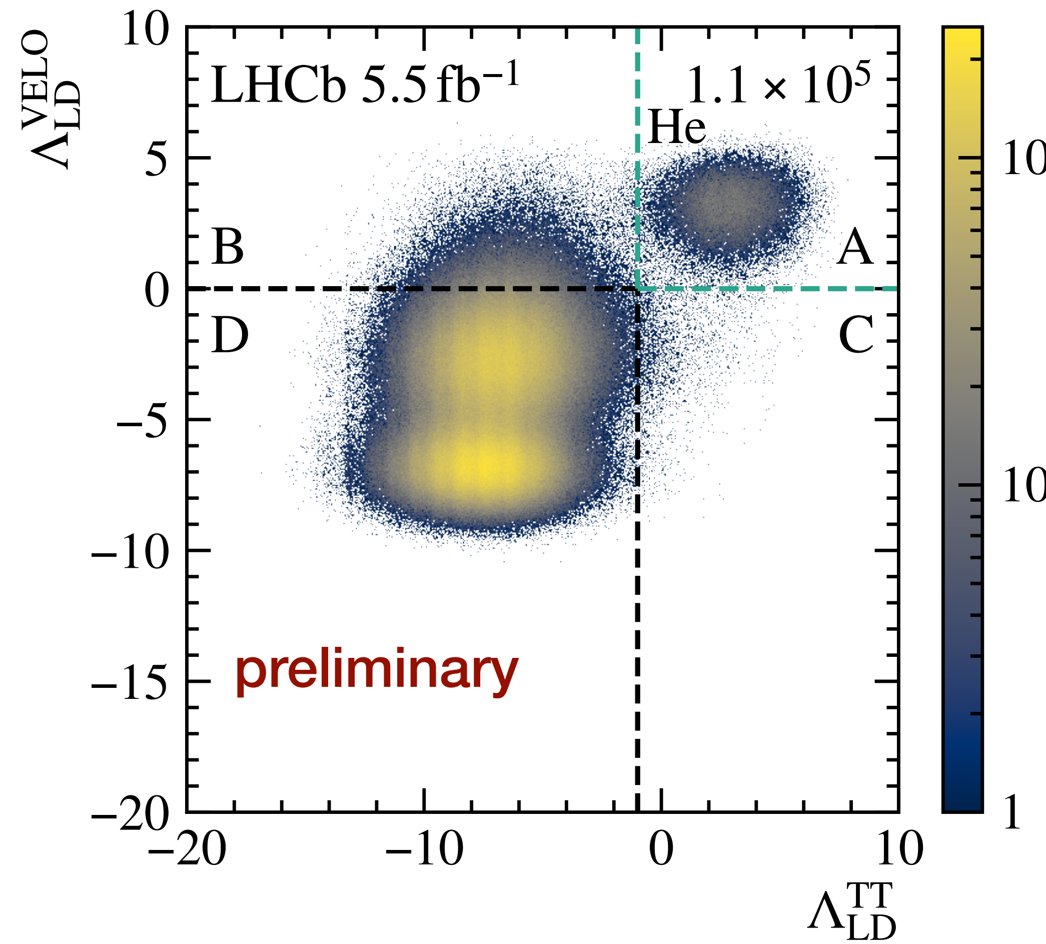
JHEP 01 (2022) 166

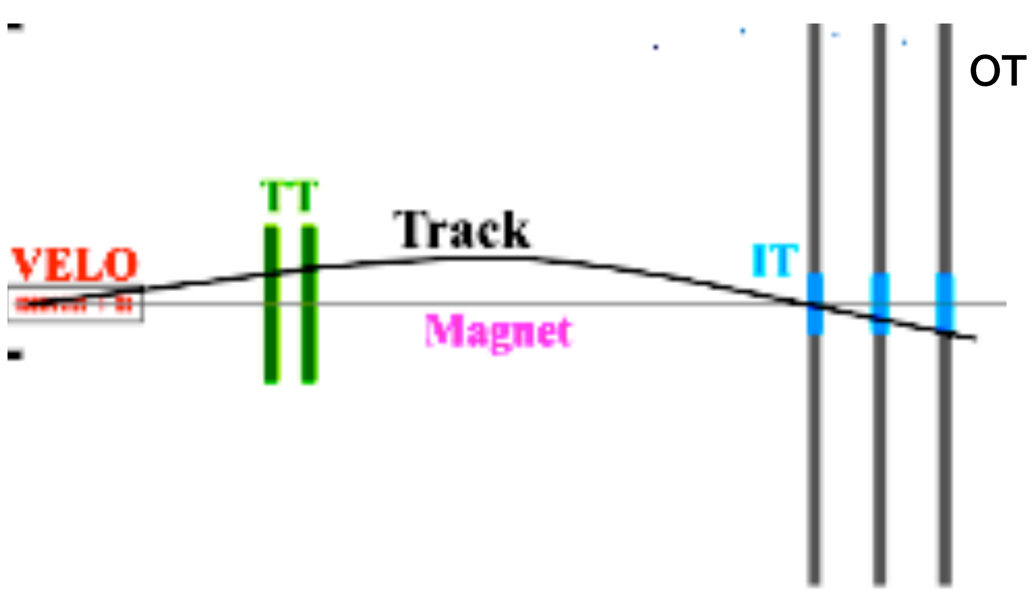
Helium identification at LHCb

- New technique to reconstruct He
- Tracking system of silicon microstrip detectors with ADC information
  - He^{++} induces higher ADC counts and wider clusters than particles with charge ± 1
- Combined likelihood for every silicon tracker (VELO, TT, IT):

$$\mathscr{L}^X = \left(\prod_{i=1}^{n} \mathrm{PPD}_i^X(\mathrm{CLS}, \mathrm{ADC}) \right)^{\frac{1}{n}}, \Lambda_{\mathrm{LD}} = \log \mathscr{L}^{\mathrm{He}} - \log \mathscr{L}$$

  - Tracks in OT acceptance selected with timing information
  - Rejection of photon conversions background using RICH
- **Sample of 10^5 He candidates**





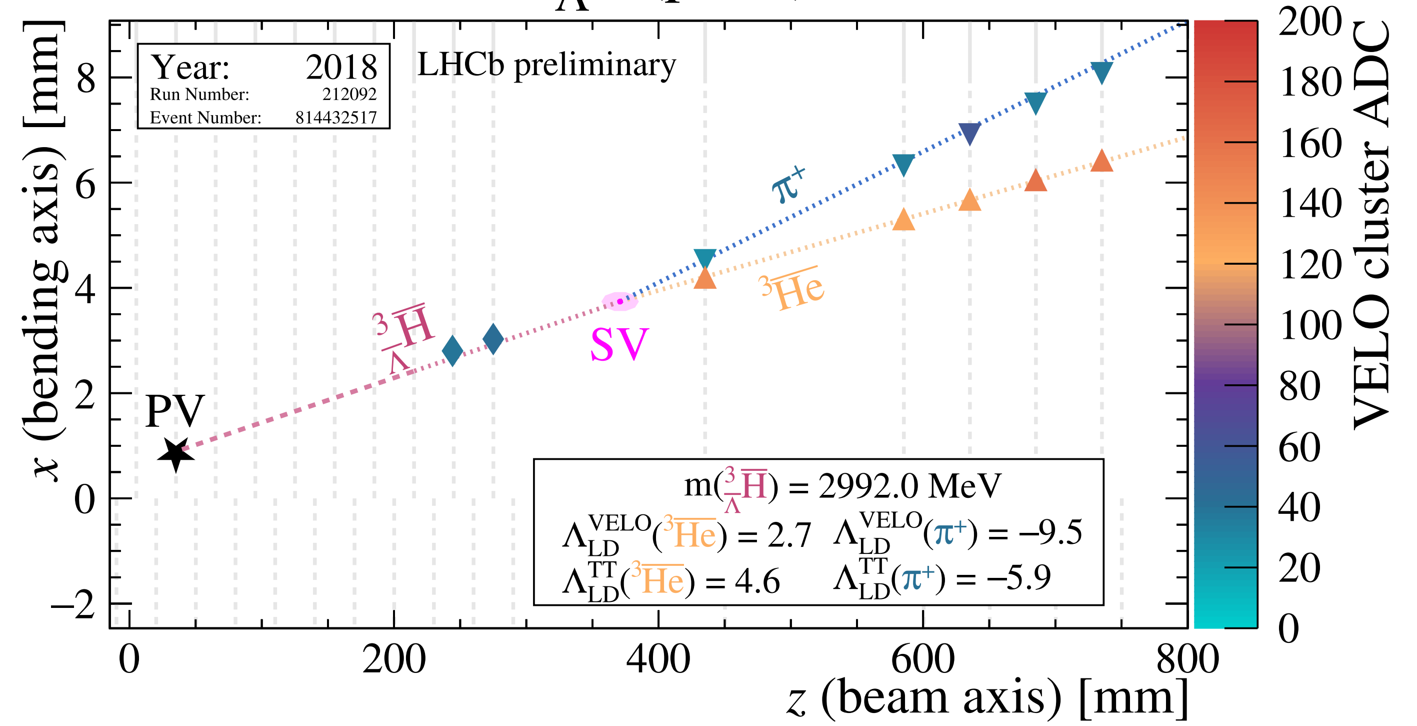
LHCb-DP-2023-002, in preparation

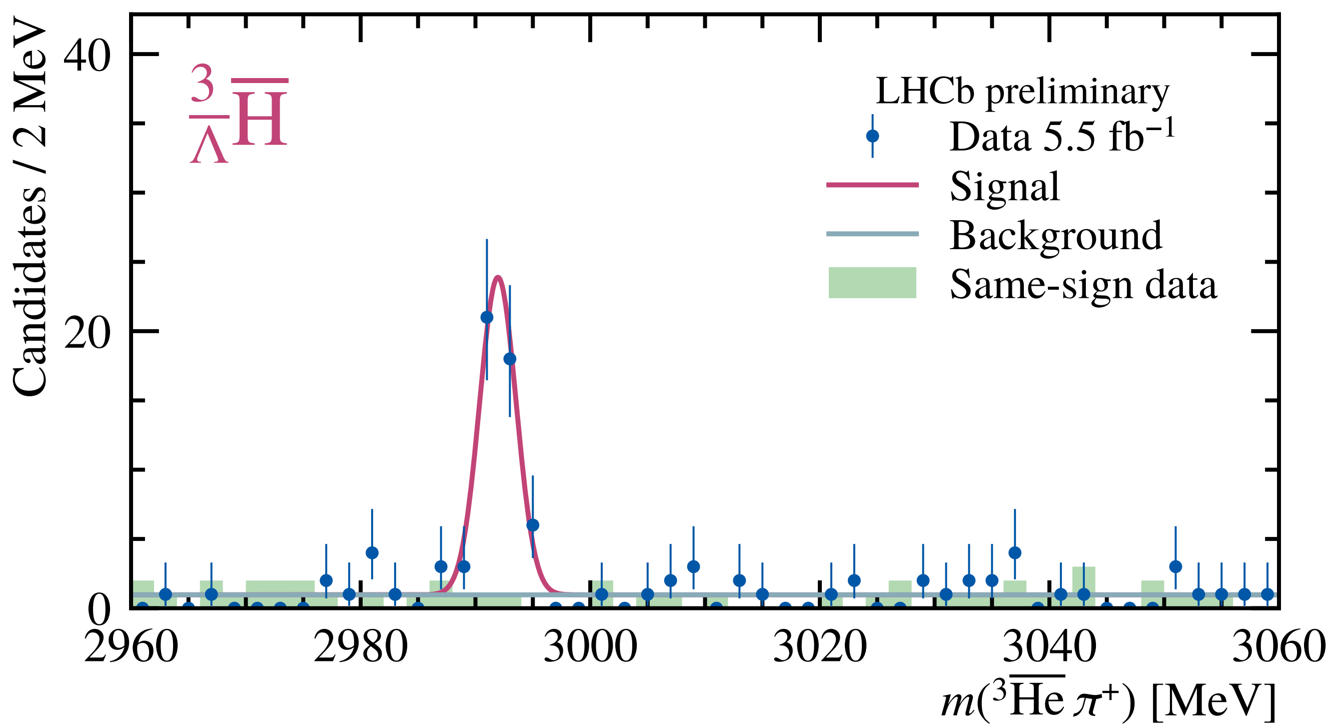
Search for antihypertriton in pp

New!

- Coalescence production of ${}^{3}_{\Lambda}\mathrm{H}(pn\Lambda)$ in pp collisions, lifetime and B_{Λ}:
  - Tension between ALICE and STAR measurements and astrophysical observations in neutron stars
- Exploit ${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^{-}$:
- **First observation of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\Lambda}\overline{\mathrm{H}}$ in pp at LHCb!**
  - Total 107 ± 11 candidates found, out of 46 ± 7 of ${}^{3}_{\Lambda}\overline{\mathrm{H}}$:
  - Under investigation: charged-sign dependent energy-loss, tracking and efficiency corrections
- Rich program ahead!
  - ${}^{3}_{\Lambda}\overline{\mathrm{H}}$ lifetime and B_{Λ} measurements
  - investigate larger systems: pPb and PbPb; also fixed-target

Reconstruction of a ${}^{3}_{\Lambda}\mathrm{H}(pn\Lambda)$ candidate:



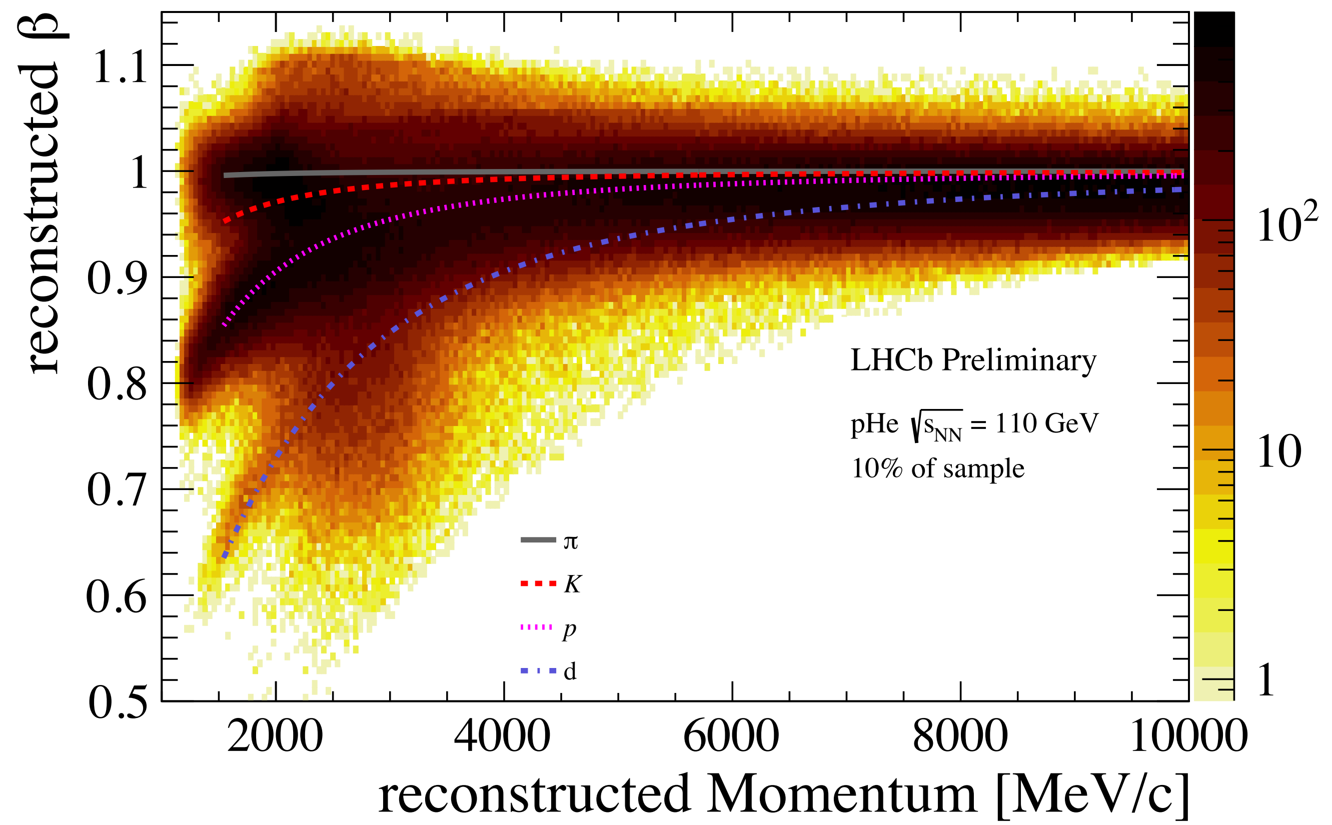


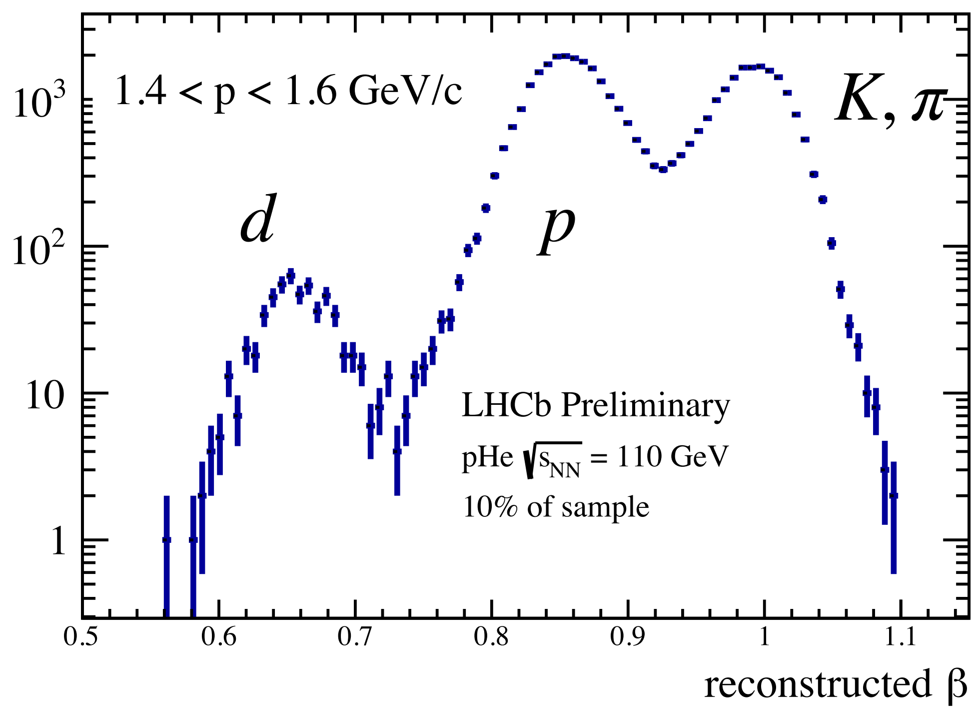
LHCb-CONF-2023-002

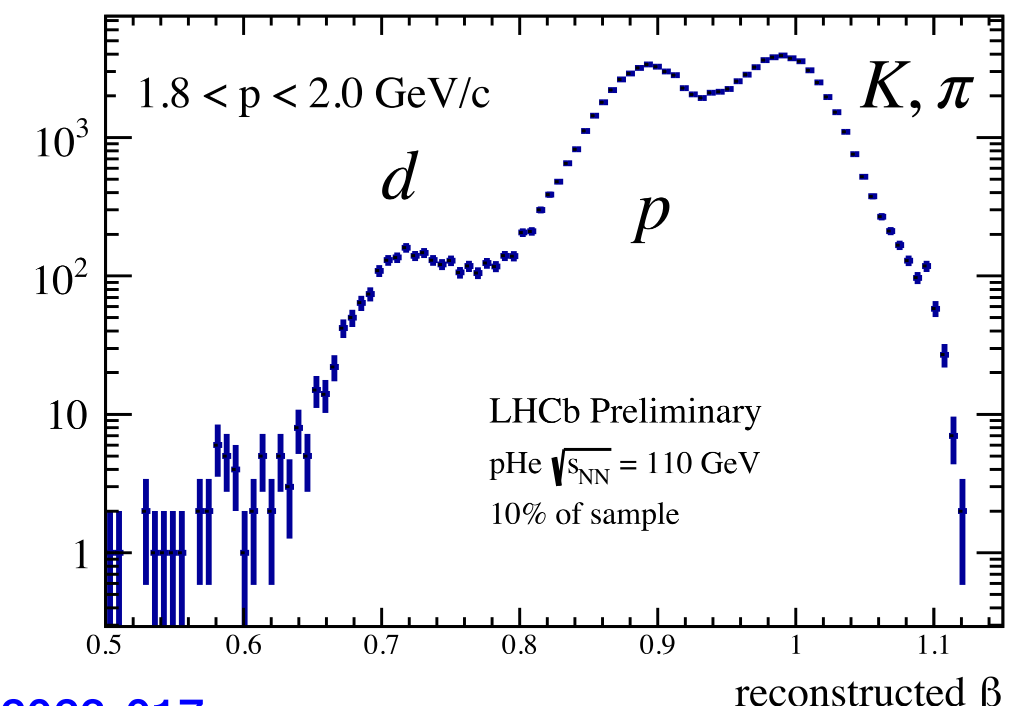
New deuterium identification technique

New!

- Use time of flight in OT detector (outer tracker drift chambers)
  - Nucleus identification at low momentum
- Good separation in the low p region
- Applied to the $p\mathrm{He}$ sample at $\sqrt{s_{NN}} = 110\,\mathrm{GeV}$
  - promising for an antideuterium production measurement







LHCb-FIGURE-2023-017

Wrap-up of the new results

- **Quarkonia:**
  - Confirm final-state effects on $\psi(2S)$ in $p\mathrm{Pb}$ collisions…
  - … but χ_c production in $p\mathrm{Pb}$ is not suppressed with respect to pp
  - First constrains to QGP production in PbNe collisions at $\sqrt{s_{\mathrm{NN}}} = 68.5\,\mathrm{GeV}$
- **Open heavy flavour:**
  - Even stronger constrains to low-x nPDF with very precise D^0, D^+ and D_s^+ cross-sections
  - D_s^+/D^+ ratio in $p\mathrm{Pb}$ enhanced with multiplicity
  - Λ_b^0/B^0 ratio in pp enhanced with multiplicity

  } **Modification of the hadronization mechanism in small systems**
- **Light flavour:**
  - $R_{p\mathrm{Pb}}$ of η and η' show no indication of mass-dependent effects
  - First LHCb measurement of charged-hadron flow harmonics in PbPb collisions
- **Light nuclei:**
  - New technique for He identification
  - First observation of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\Lambda}\overline{\mathrm{H}}$ in pp at LHCb
  - New technique for d identification

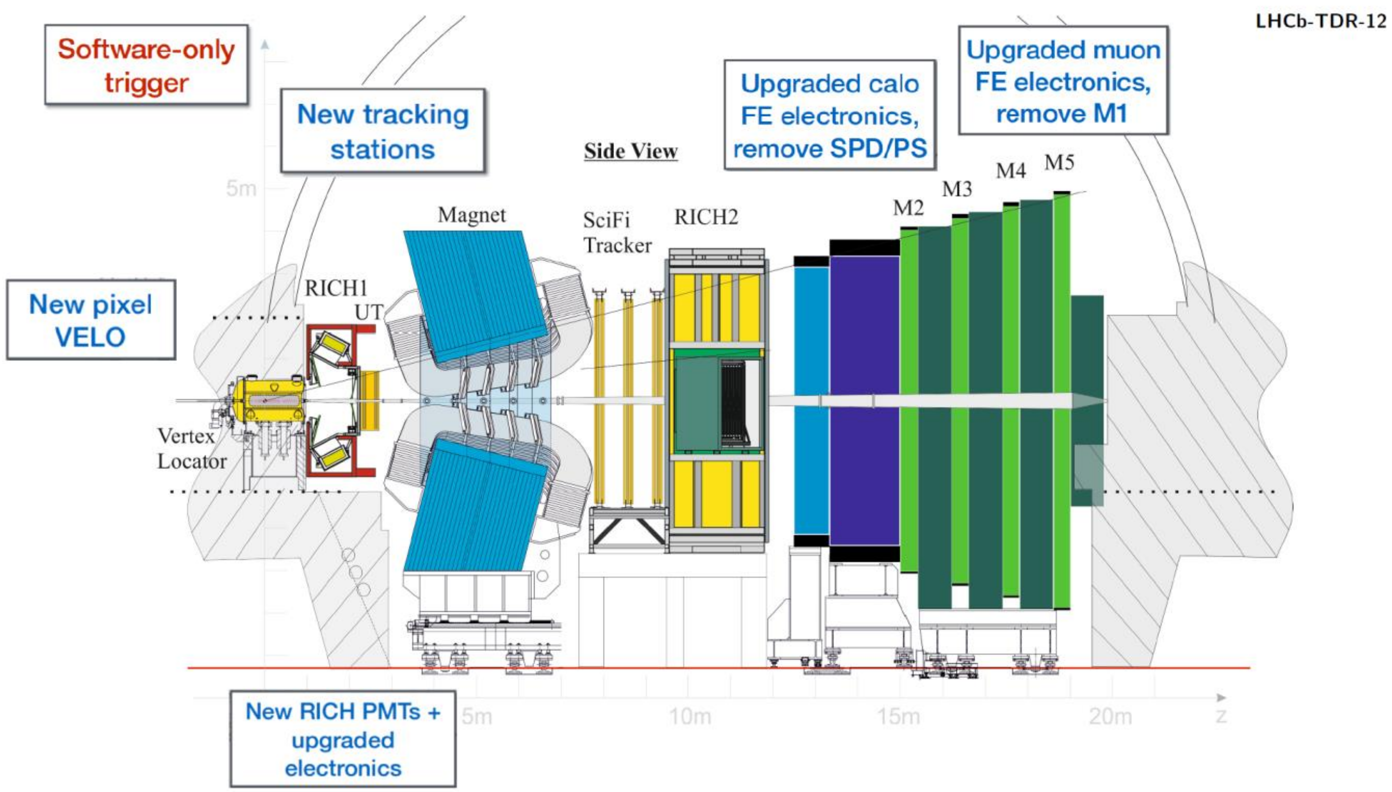
  } **Great expansion of LHCb physics reach**

The ~~future~~ present: Prospects in run 3

LHCb Upgrade I

- **Major upgrade:**
  - Replacement of full tracking and RICH1/2 detectors
  - Completely new readout electronics
  - New DAC & online system at $30\,\mathrm{MHz}$
    - based on flexible software trigger

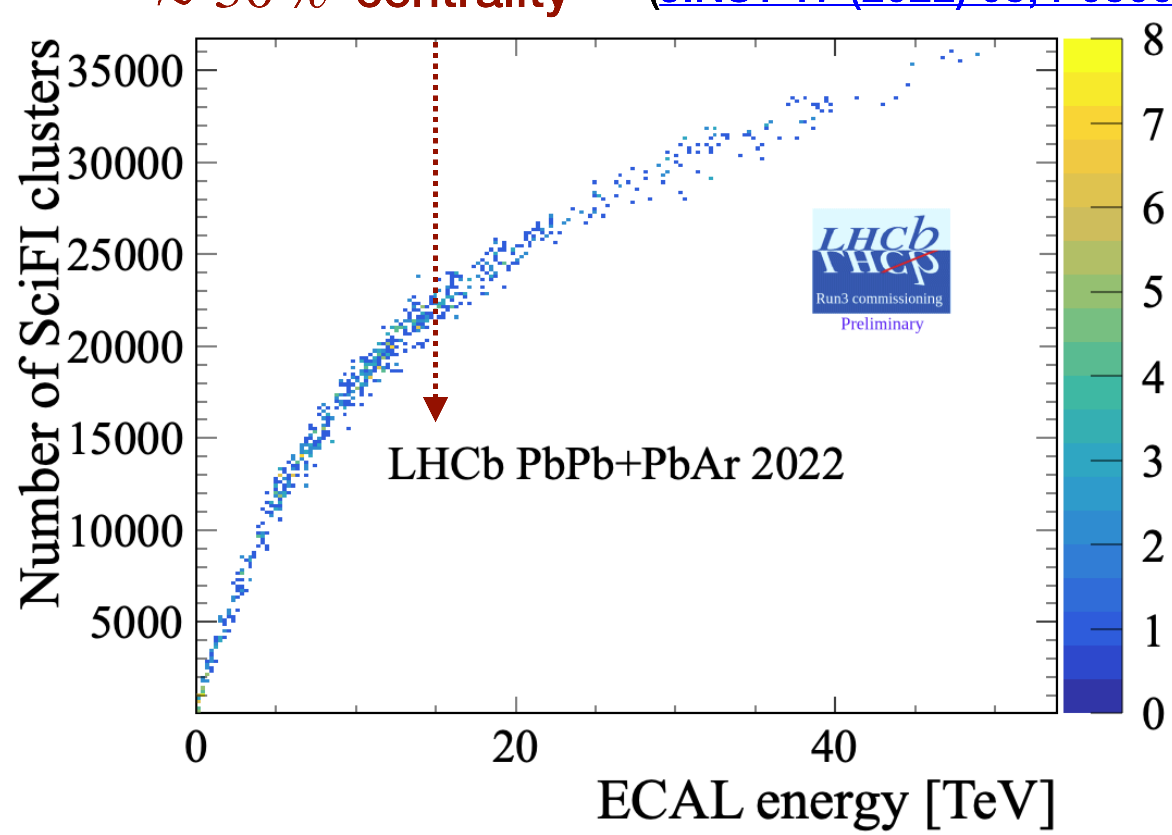
- **Major implications for heavy-ion physics:**
  - New SMOG2 system
  - New tracking system should reconstruct $\approx 100-30\,\%$ centrality in PbPb



arXiv:2305.10515

First data from $\mathrm{PbPb} + \mathrm{PbAr}$ collisions in 2022!

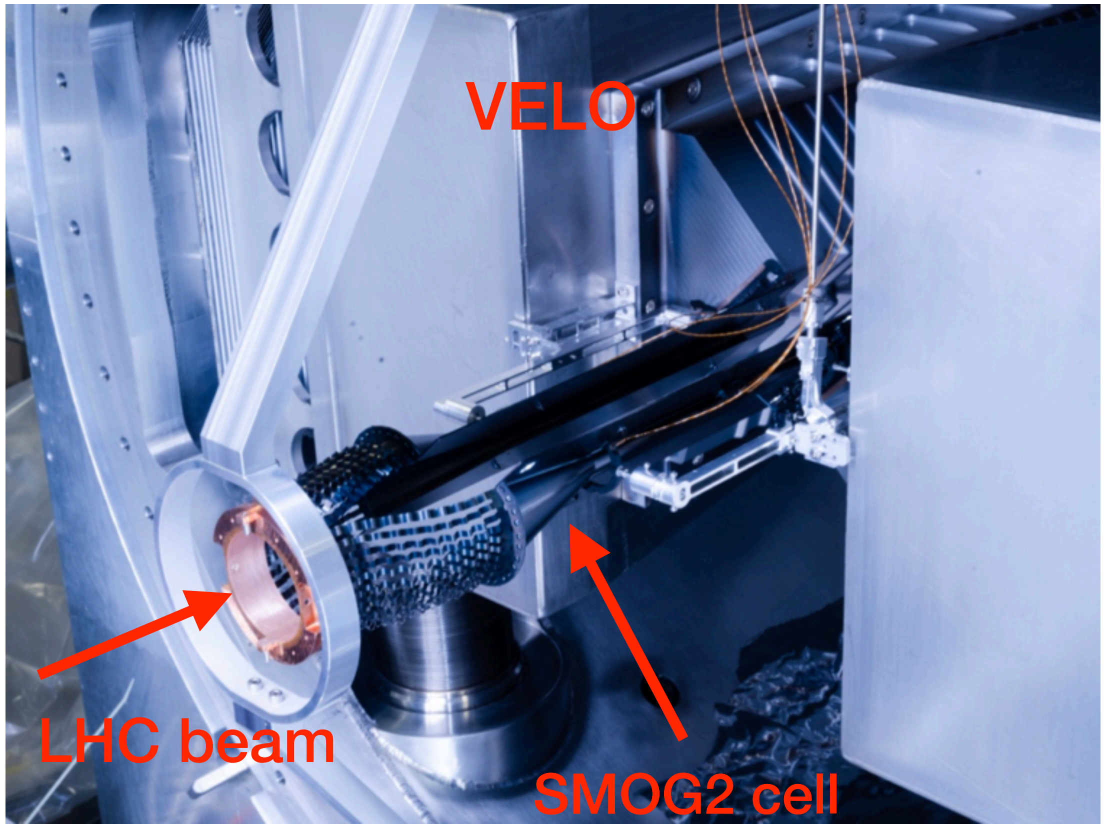
$\approx 30\,\%$ centrality (JINST 17 (2022) 05, P05009)



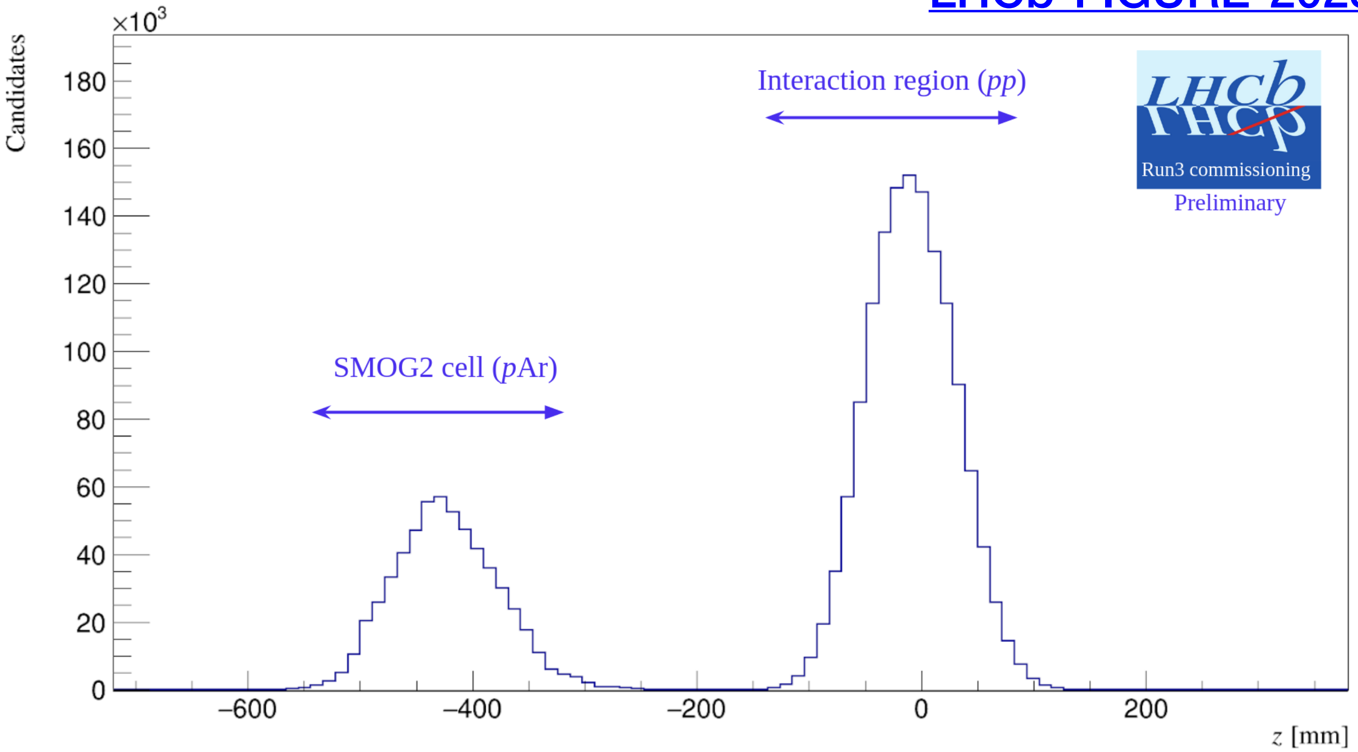
LHCb-FIGURE-2023-022

New gas storage cell: SMOG2

- New fixed-target device SMOG2:
  - storage cell, increase effective luminosity with the same gas flow
  - up to $\times 100$ **factor gain areal density**
- Possibility to inject new gases: H_2 (R_{AB} reference), D_2 (isospin violation), O_2 (important for astro) and large nuclei (Kr, Xe)
- Fast switch between gases possible during LHC operation → **LHCb has complete control**
- Independent interaction region from nominal pp:
  - **simultaneous data-taking with colliding beams**



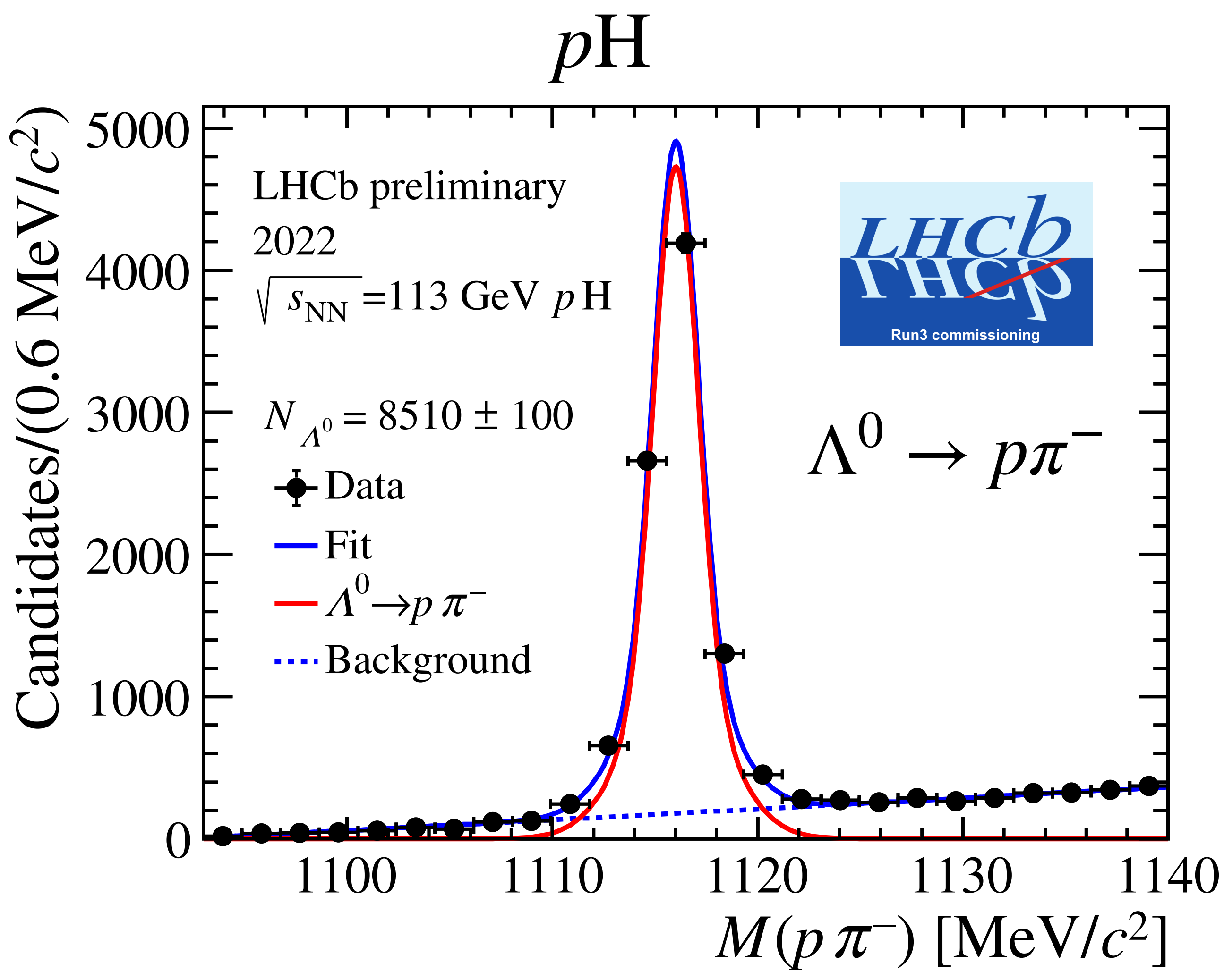
LHCb-FIGURE-2023-001

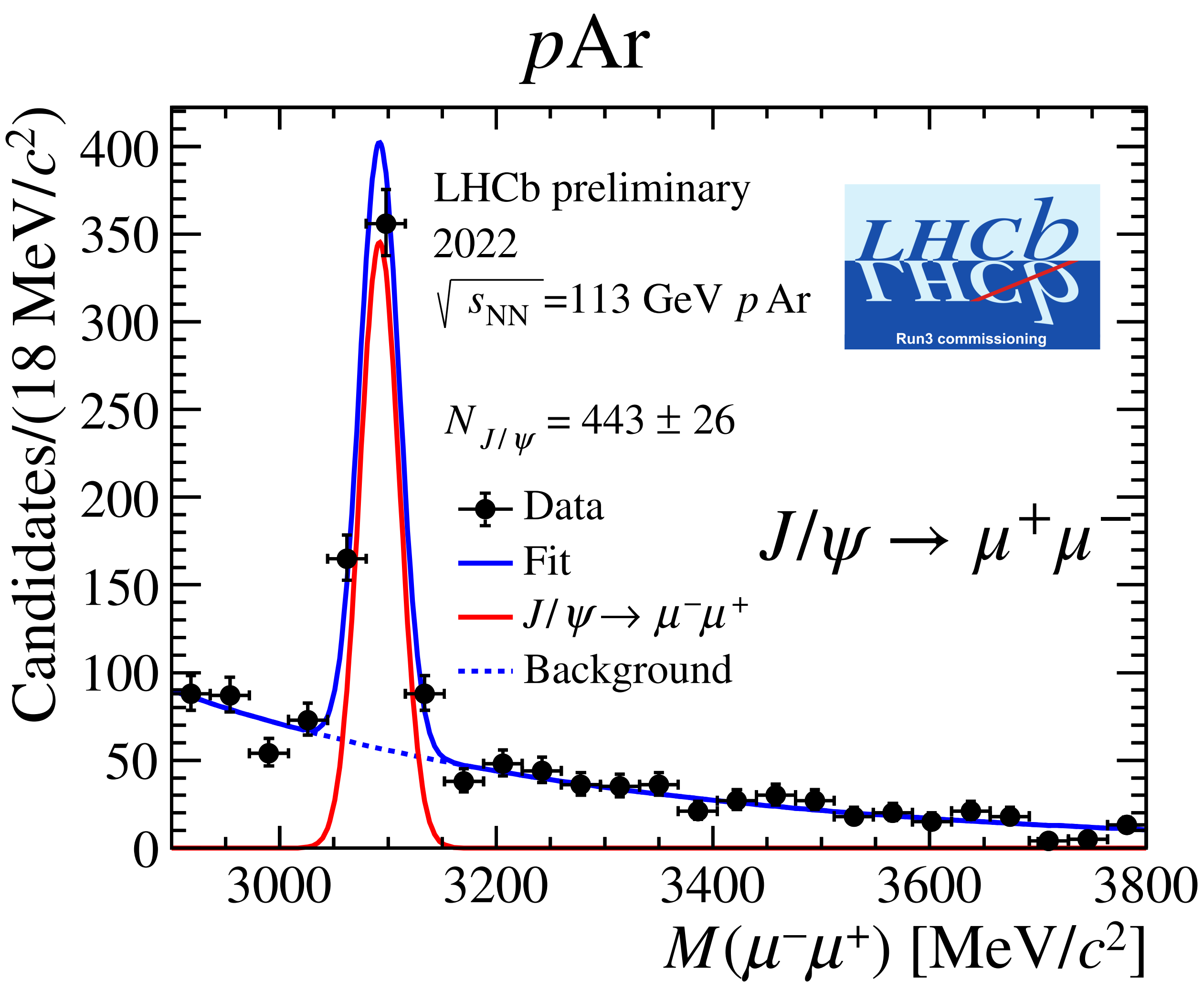


z distribution of primary vertices during simultaneous pp and pAr

SMOG2 commissioning: pH and pAr

- Successful commissioning campaign of SMOG2 in 2022 with short injections ($\sim 20\,\mathrm{min}$) of Ar and, for the first time, $\mathrm{H_2}$:
  - **First data taken in pH collisions at $\sqrt{s_{\mathrm{NN}}} = 113\,\mathrm{GeV}$!** → needed as pp reference
  - **Heavy-flavour samples obtained in only 18 minutes of data-taking of Ar injection of similar size of those collected in Run 2**





LHCb-FIGURE-2023-008

Conclusions

- LHCb has a very mature heavy-ion and fixed target program, which profits of the variety of datasets, forward coverage, high precision and a wide range of accessible physics probes

- A selection of recent LHCb Run1/2 results has been presented, many of which have an important impact in our understanding of high-density QCD

- **LHCb Upgrade I is ready** for Run 3:
  - Significant expansion of the LHCb heavy-ion program is foreseen for Run 3:
    - Increase centrality range in $\mathrm{PbPb} \rightarrow$ QGP physics!
    - Oxygen runs would be a great opportunity for LHCb: no centrality limitation in OO, possibility to have $\mathrm{O-gas}$ collisions with a variety of targets in SMOG2
  - SMOG2 has been successfully commissioned and preliminary yields very promising
    - High precision fixed-target physics with a large variety of collision systems

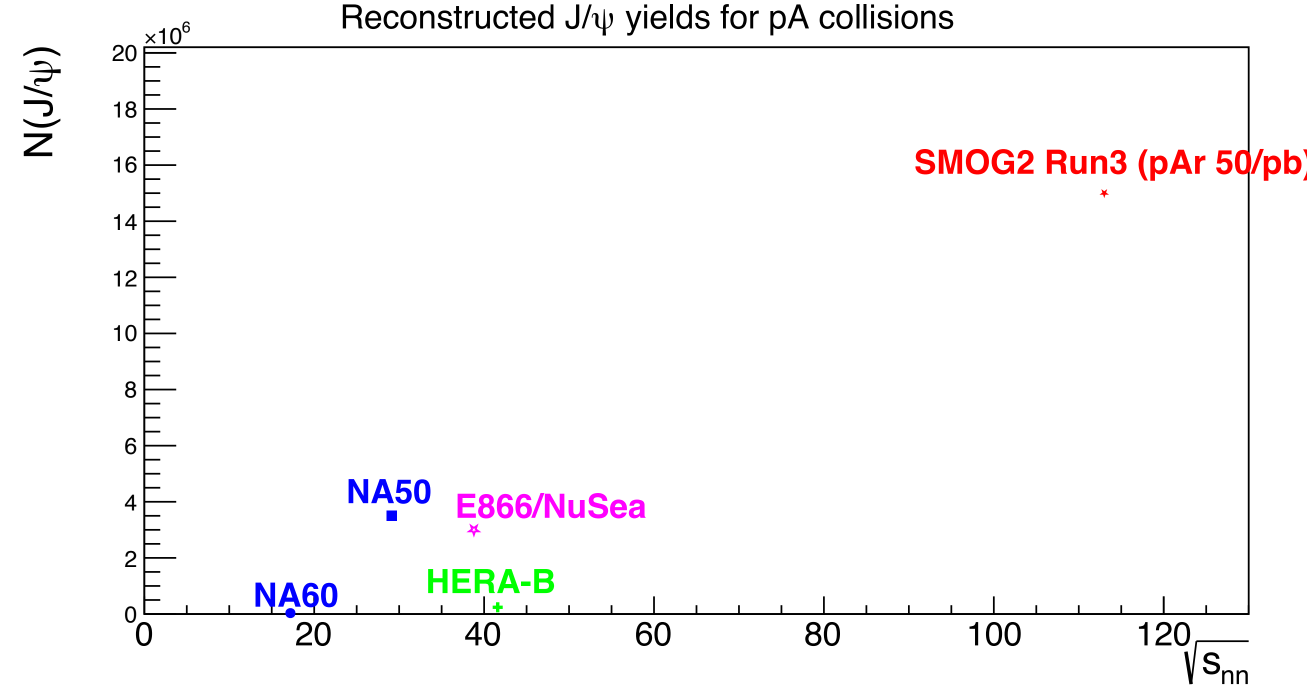
- For Run 5 and beyond → **LHCb Upgrade II**
  - Dream detector for heavy-ion physics, fully performant up to central PbPb collisions!

Backup

Bright prospects for Run 3 (and beyond)

- In 2024, aiming for simultaneous data taking $p$gas - pp about **half the pp beam time**
- **With this conditions, aiming for luminosities comparable (or better) than other fixed-target experiments**
- Fully profit of special runs of pO and/or OO and nominal ion runs (either pPb or PbPb)
  - Gas injection possible enabling **many collision systems at various $\sqrt{s_{\rm NN}}$**
  - Study QCD medium up to densities of $\approx 30\,\%$ **centrality in** PbPb

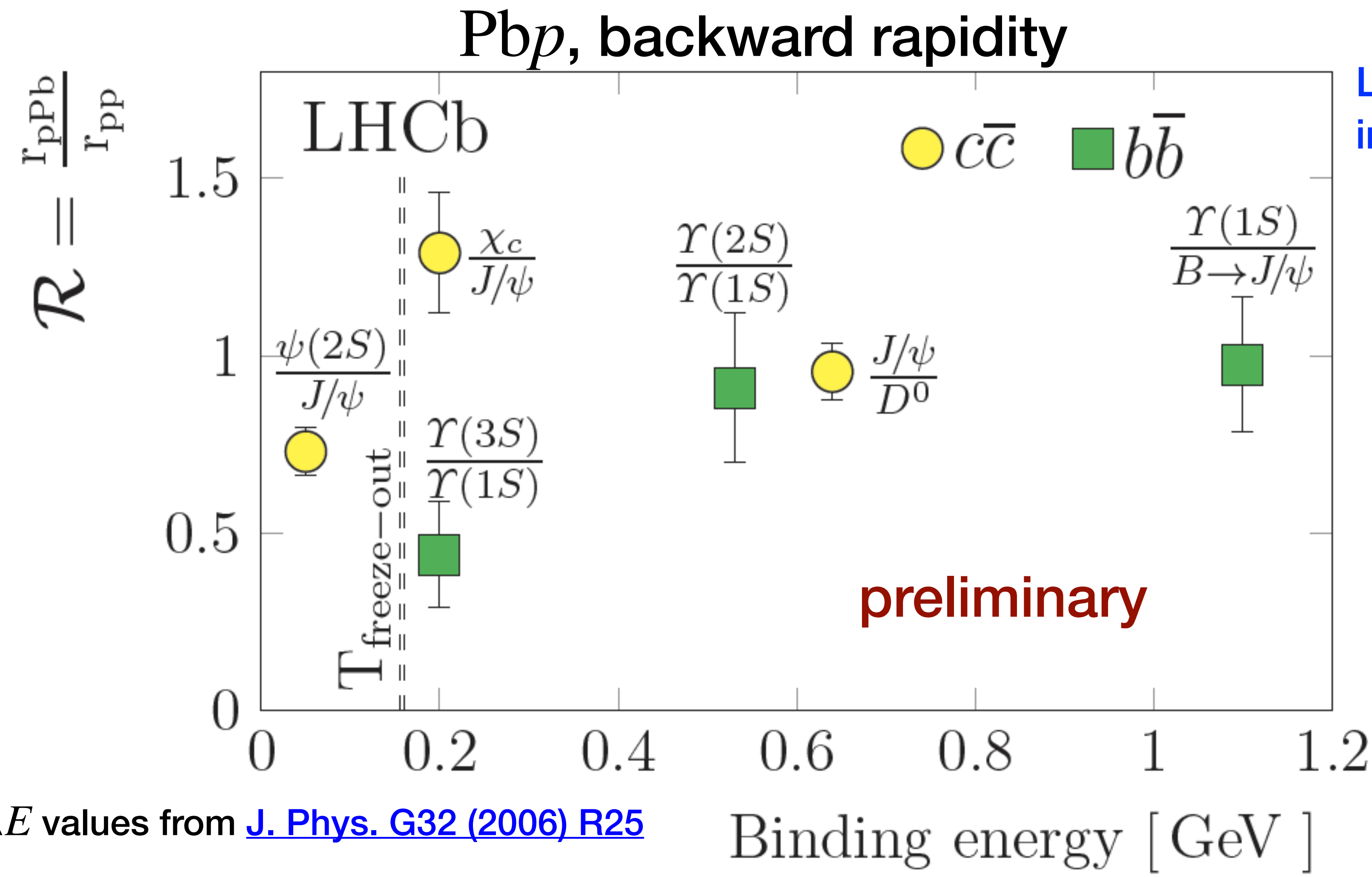
(figure from G. Graziani)



LHCb-PUB-2018-015

Quarkonium binding energy and suppression

$\chi_c(1P)$ production in pPb at 8.16 TeV   New!



LHCb-PAPER-2023-028, in preparation

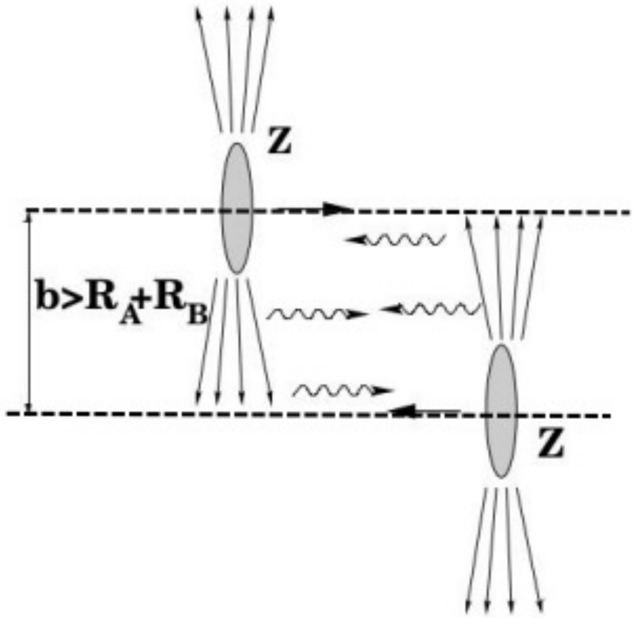
ΔE values from J. Phys. G32 (2006) R25

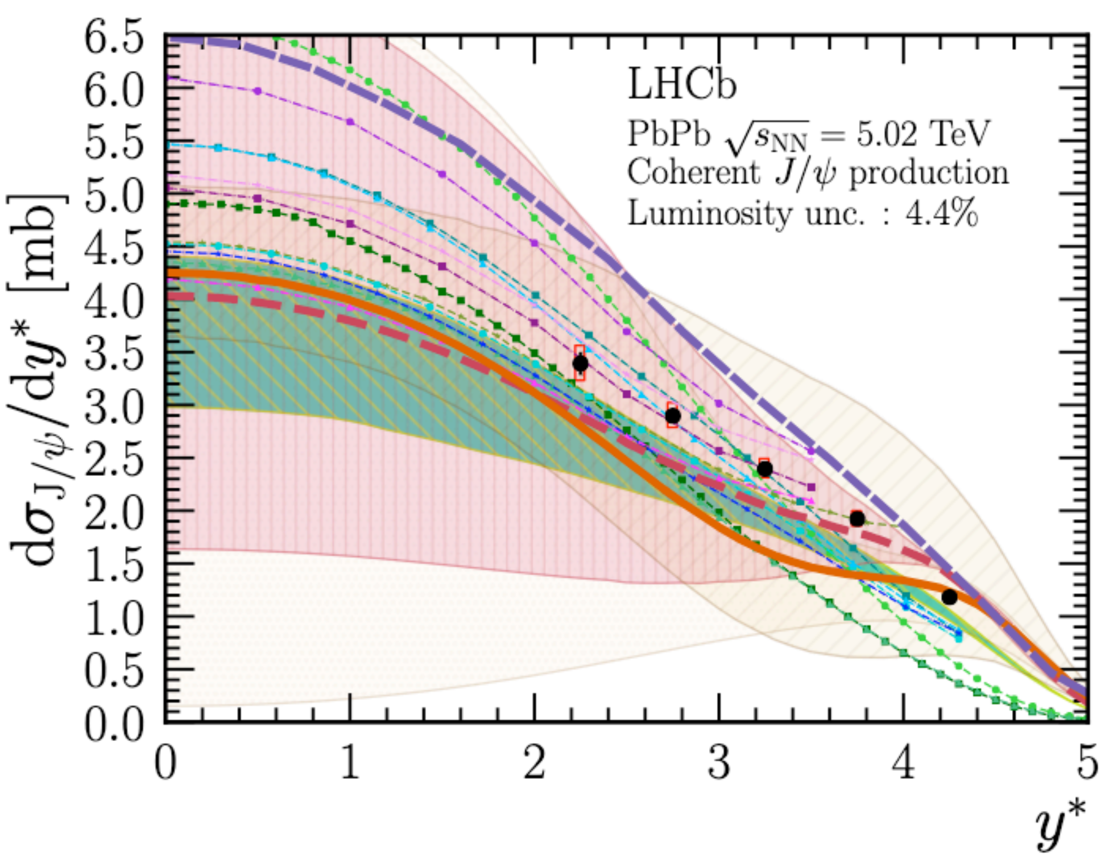
ratio	y^*	$\sqrt{s_{NN}}$	p_T	ref.
$\frac{\psi(2S)}{J/\psi}$	[-5.0,-2.5]	8.16 TeV	<14 GeV/c	LHCb-PAPER-2023-024
$\frac{\chi_c}{J/\psi}$	[-5.0,-2.5]	8.16 TeV	$2< p_{T,J/\psi} <20$ GeV/c	LHCb-PAPER-2023-028
$\frac{J/\psi}{D^0}$	[-4.0,-2.5]	5 TeV	<10 GeV/c	JHEP 10 (2017) 090
$\frac{\Upsilon(3S),\Upsilon(2S)}{\Upsilon(1S)}$	[-4.5,-2.5]	8.16 TeV	<25 GeV/c	JHEP 11 (2018) 194
$\frac{\Upsilon(1S)}{B\to J/\psi}$	[-4.5,-2.5]	8.16 TeV	<25 GeV/c	JHEP 11 (2018) 194

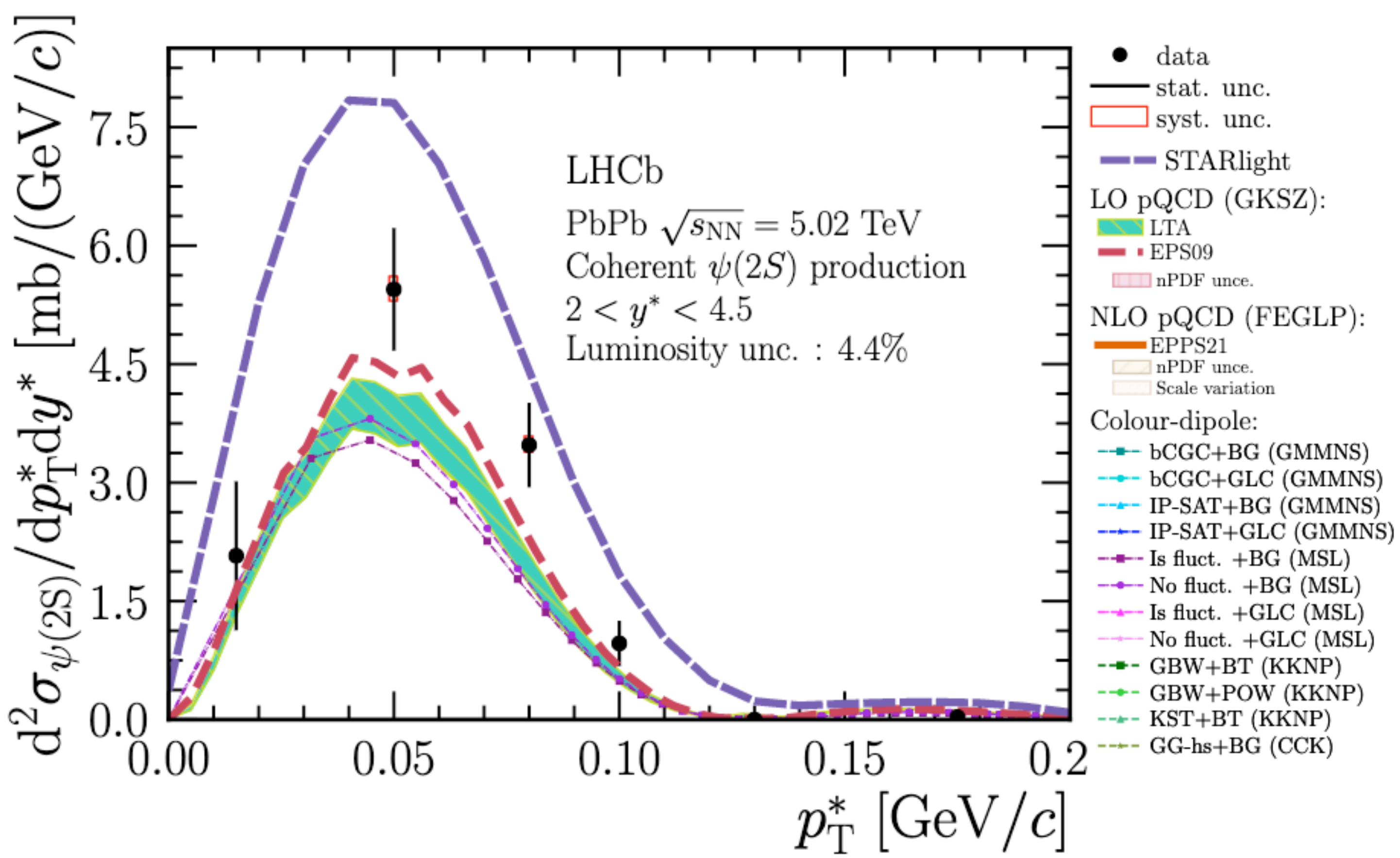
Charmonia in ultra-peripheral collisions

J/ψ and $\psi(2S)$ coherent production in UPC PbPb

- Measure very low p_T charmonia coherent production in UPC PbPb
  - most precise coherent J/ψ measurement in forward rapidity at LHC
  - **first $\psi(2S)$ production measurement** in forward rapidity at LHC
  - p_T **spectra determined for the first time** in UPC PbPb
  - set unprecedented constrains to saturation models







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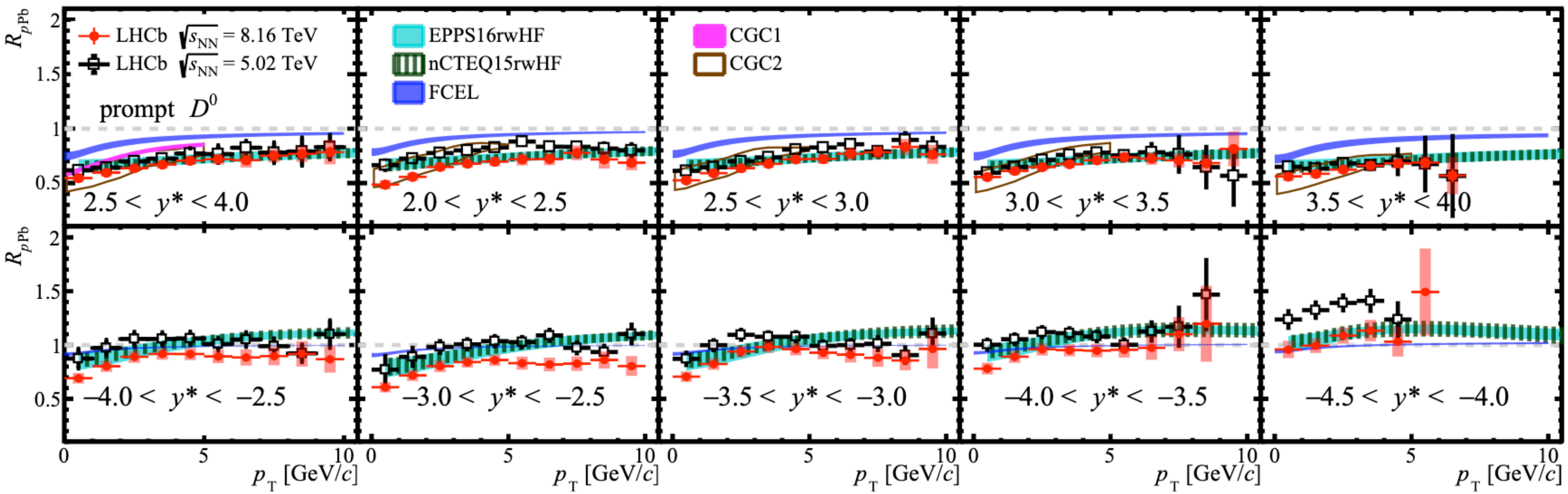
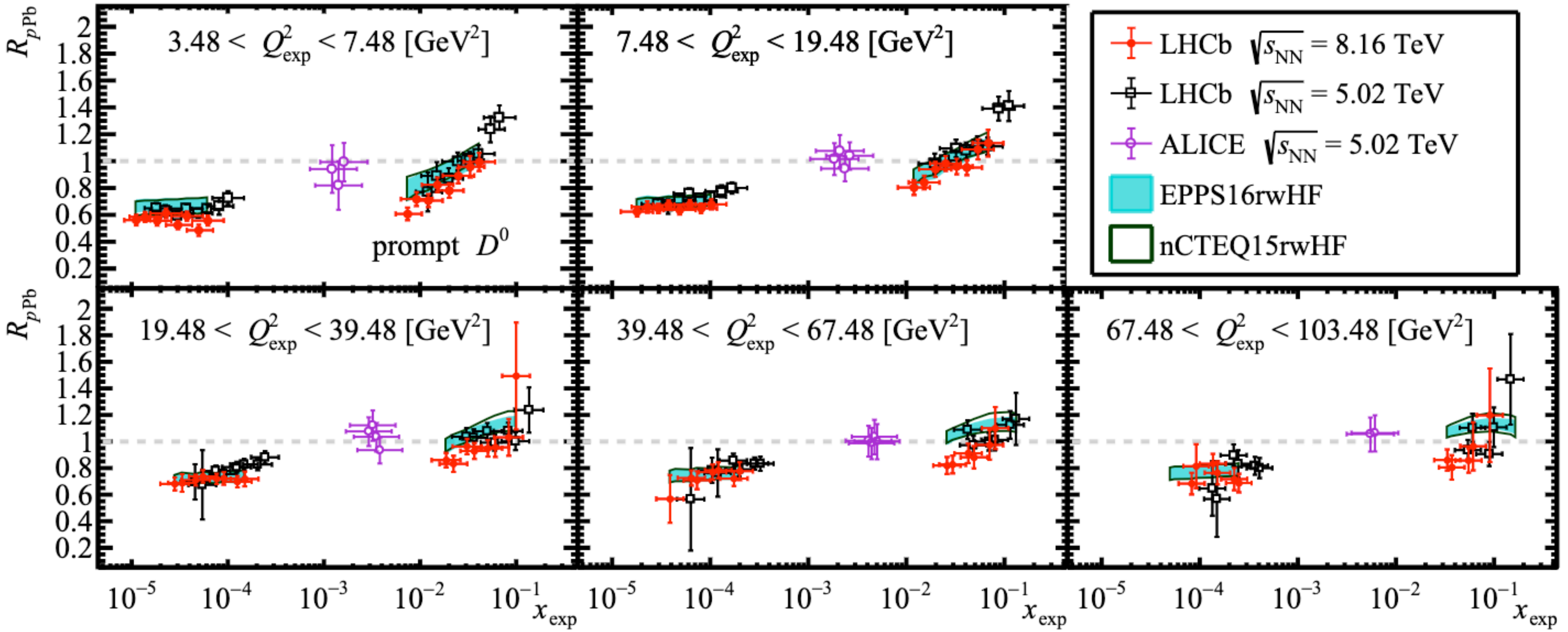
D^0 production

Phys. Rev. Lett. 131, 102301



$(x_{\rm exp}, Q^2_{\rm exp})$ dependence for D^0 meson in pPb

Phys. Rev. Lett. 131, 102301

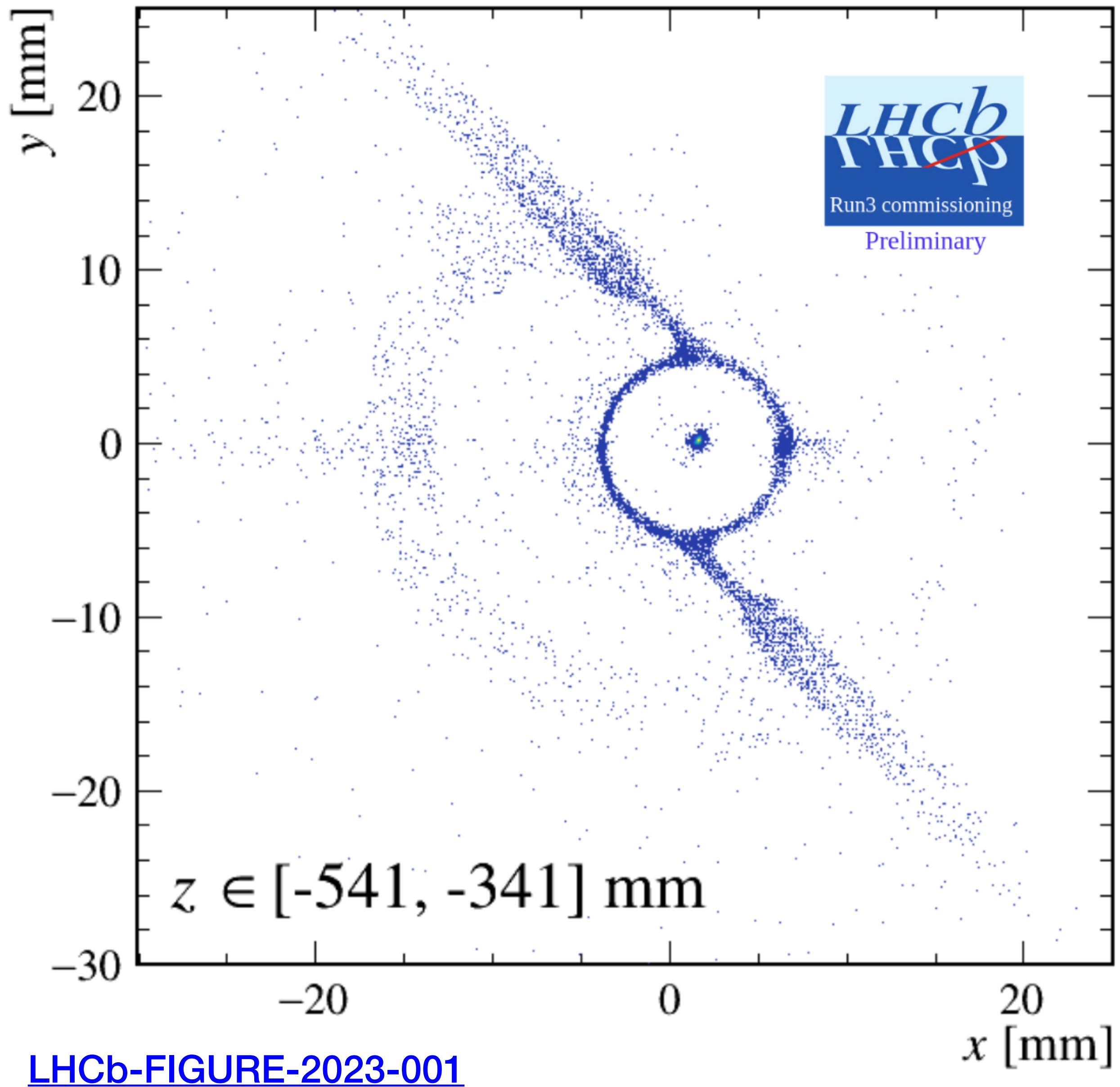


$$x_{\rm exp} \equiv 2\frac{\sqrt{p_{\rm T}^2(D^0) + M^2(D^0)}}{\sqrt{s_{\rm NN}}}e^{-y^*} \text{ and } Q^2_{\rm exp} \equiv p_{\rm T}^2(D^0) + M^2(D^0),$$

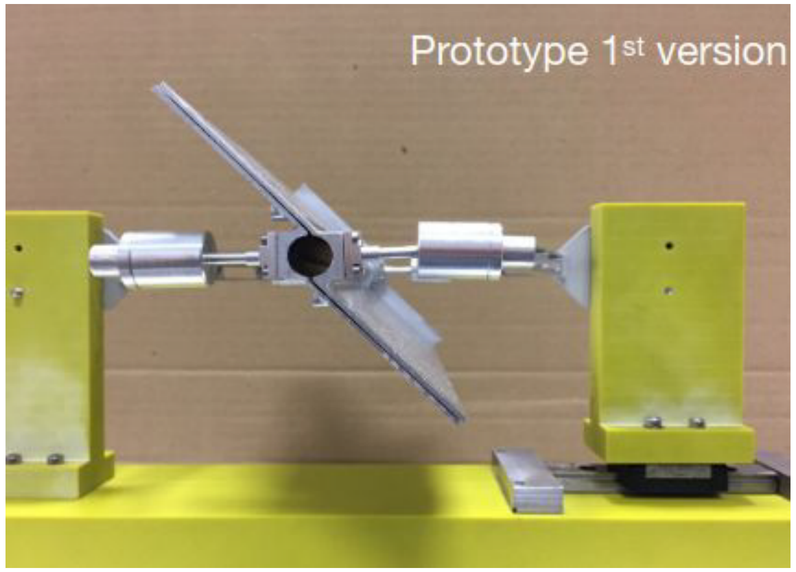
LHCb 5TeV: JHEP 10 (2017) 090
ALICE: JHEP 12 (2019) 092

SMOG2 cell mapping in real time

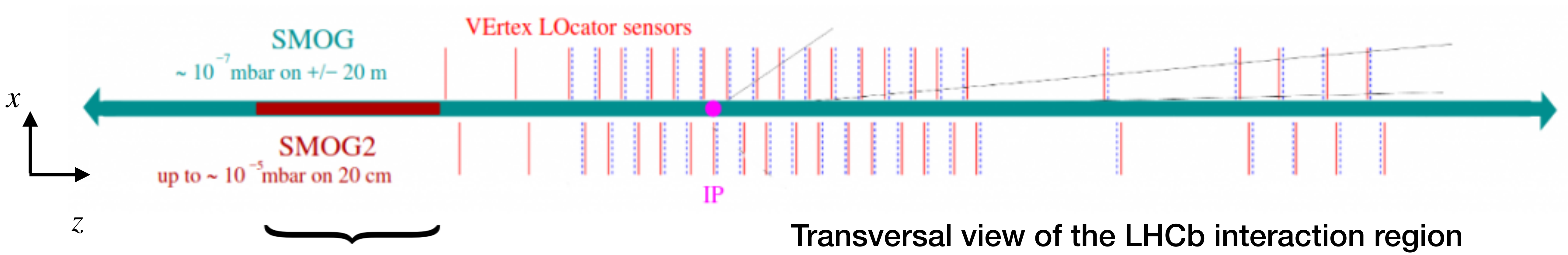
- Map of the SMOG2 material using VELO reconstructed vertices



LHCb-FIGURE-2023-001



The SMOG and SMOG2 systems



$PV_z \in [-541, -341]$ mm

Transversal view of the LHCb interaction region

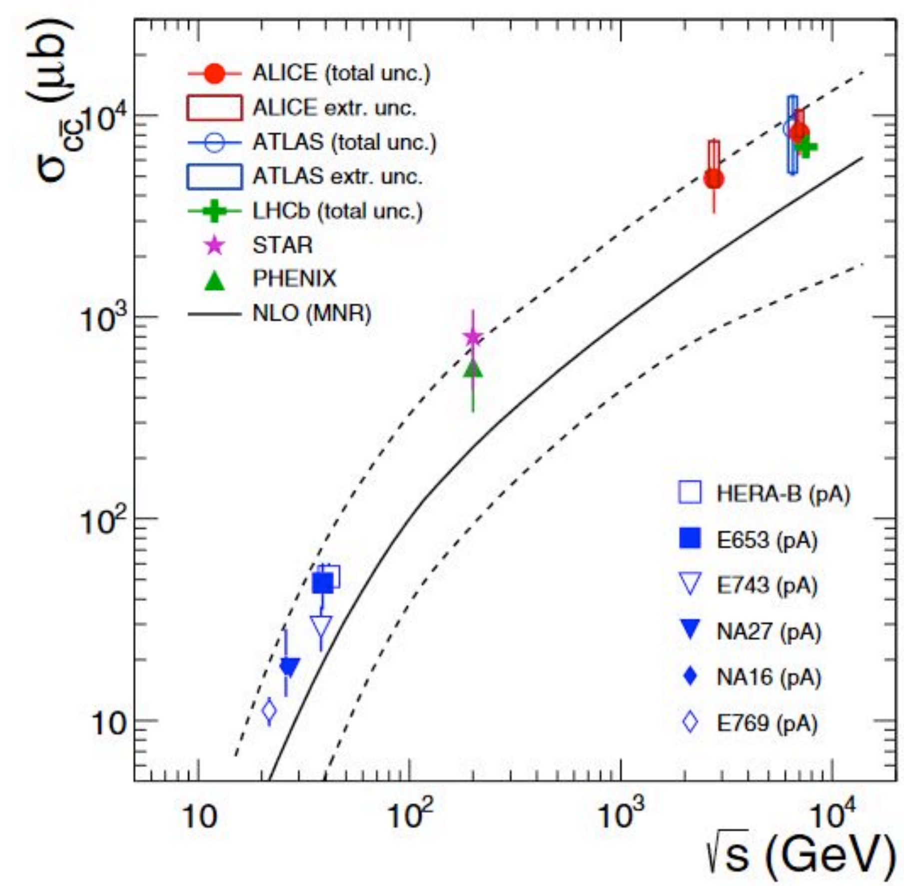
PV_z: z position of the Primary Vertex of the beam-gas collision

- **The SMOG system in Run 2**
  - interaction region is spread-out in PV_z
    - ✳ only non-colliding bunches can be used
    - ✳ ghost charge pollution (debunched pp collider interactions from protons)
  - luminosity determination: $p + e^-$ elastic scattering as a standard candle
    - ✳ $\approx 6\,\%$ systematic uncertainty

- **The new SMOG2 system:**
  - separate beam-beam and beam-gas interaction regions
    - ✳ both colliding and non-colliding bunches can be used
    - ✳ simultaneous data-taking with pp
  - precise luminosity determination: direct measurement of the pressure in storage cell
    - ✳ expecting $1-2\,\%$ systematic uncertainty

How many $c\bar{c}$ pairs are produced in PbA SMOG2 conditions?

- Charm cross-section across $\sqrt{s_{\mathrm{NN}}}$:
  - $\sigma_{c\bar{c}}^{5.5\ TeV} \sim 10 \times \sigma_{c\bar{c}}^{200\ GeV} \sim 100 \times \sigma_{c\bar{c}}^{70\ GeV} \sim 1000 \times \sigma_{c\bar{c}}^{20\ GeV}$
- Then, for $0-10\,\%$ centrality at RHIC:
  - $N_{c\bar{c}} = 597.10^{-3}\,\mathrm{mb} \times 22.8\,\mathrm{mb}^{-1} = 13$
- Therefore, we expect, on average:
  - $\sim 100\ c\bar{c}$ pairs produced at $5.5\,\mathrm{TeV}$
  - $\sim 10\ c\bar{c}$ pairs produced at $200\,\mathrm{GeV}$
  - $\sim 1\ c\bar{c}$ pairs produced at $70\,\mathrm{GeV}$
  - $\sim 0.1\ c\bar{c}$ pairs produced at $20\,\mathrm{GeV}$



PRC 94, 054908 (2016)

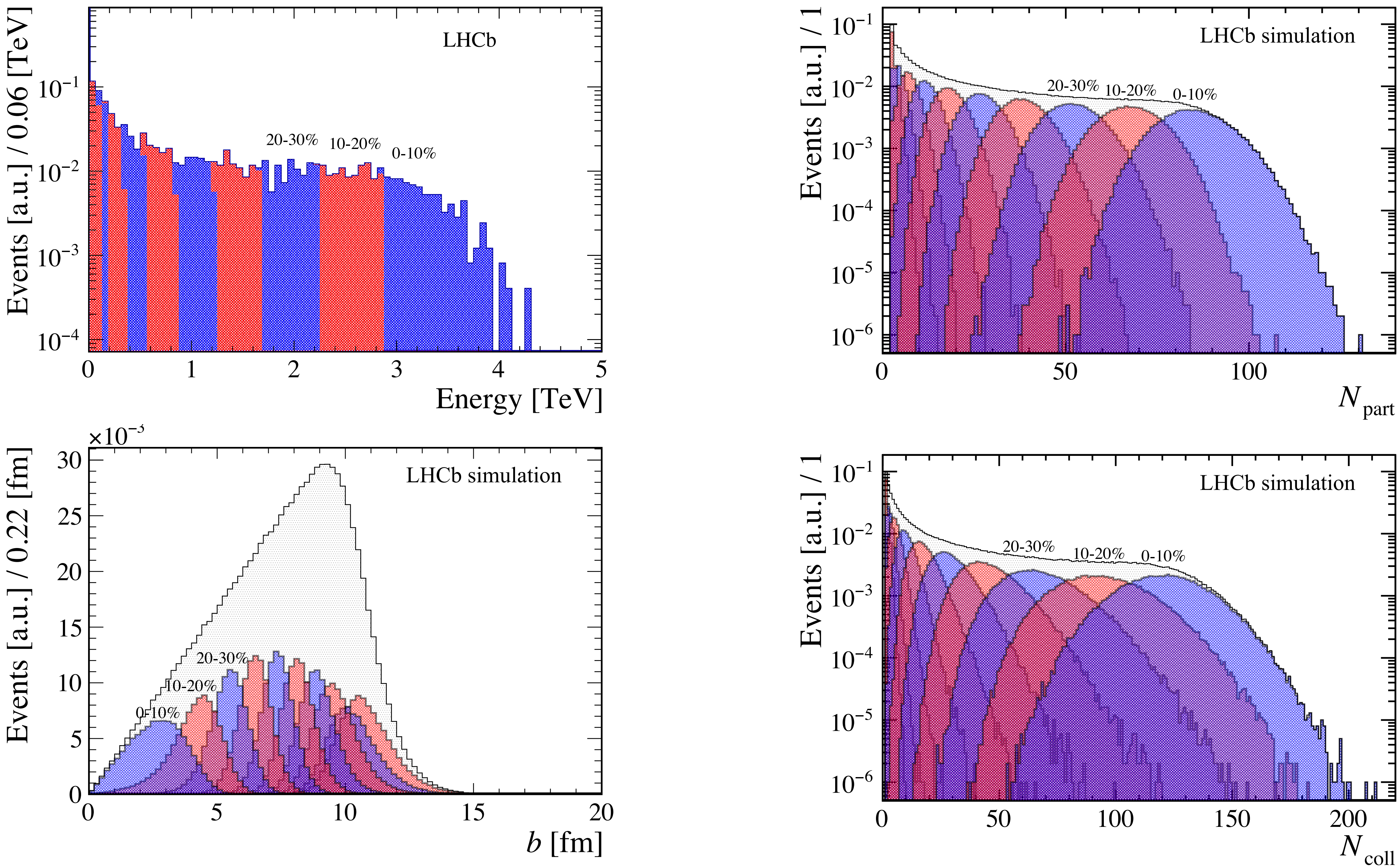
TABLE I. Centrality bin, number of NN collisions, nuclear overlap function, charm cross section per NN collision, and total charm multiplicity per NN collision, in $\sqrt{s_{NN}} = 200$ GeV Au + Au reactions.

Centrality (%)	N_{coll}	T_{AA} (mb^{-1})	$\frac{1}{T_{AA}}\frac{dN_{c\bar{c}}}{dy}\vert_{y=0}$ (μb)	$N_{c\bar{c}}/T_{AA}$ (μb)
Minimum bias	258 ± 25	6.14 ± 0.45	143 ± 13 ± 36	622 ± 57 ± 160
0–10	955 ± 94	22.8 ± 1.6	137 ± 21 ± 35	597 ± 93 ± 156
10–20	603 ± 59	14.4 ± 1.0	137 ± 26 ± 35	596 ± 115 ± 158
20–40	297 ± 31	7.07 ± 0.58	168 ± 27 ± 45	731 ± 117 ± 199
40–60	91 ± 12	2.16 ± 0.26	193 ± 47 ± 52	841 ± 205 ± 232
60–92	14.5 ± 4.0	0.35 ± 0.10	116 ± 87 ± 43	504 ± 378 ± 190

PRL 94, 082301 (2005)

Centrality determination in PbNe

JINST 17 (2022) 05, P05009



Centrality determination in PbPb