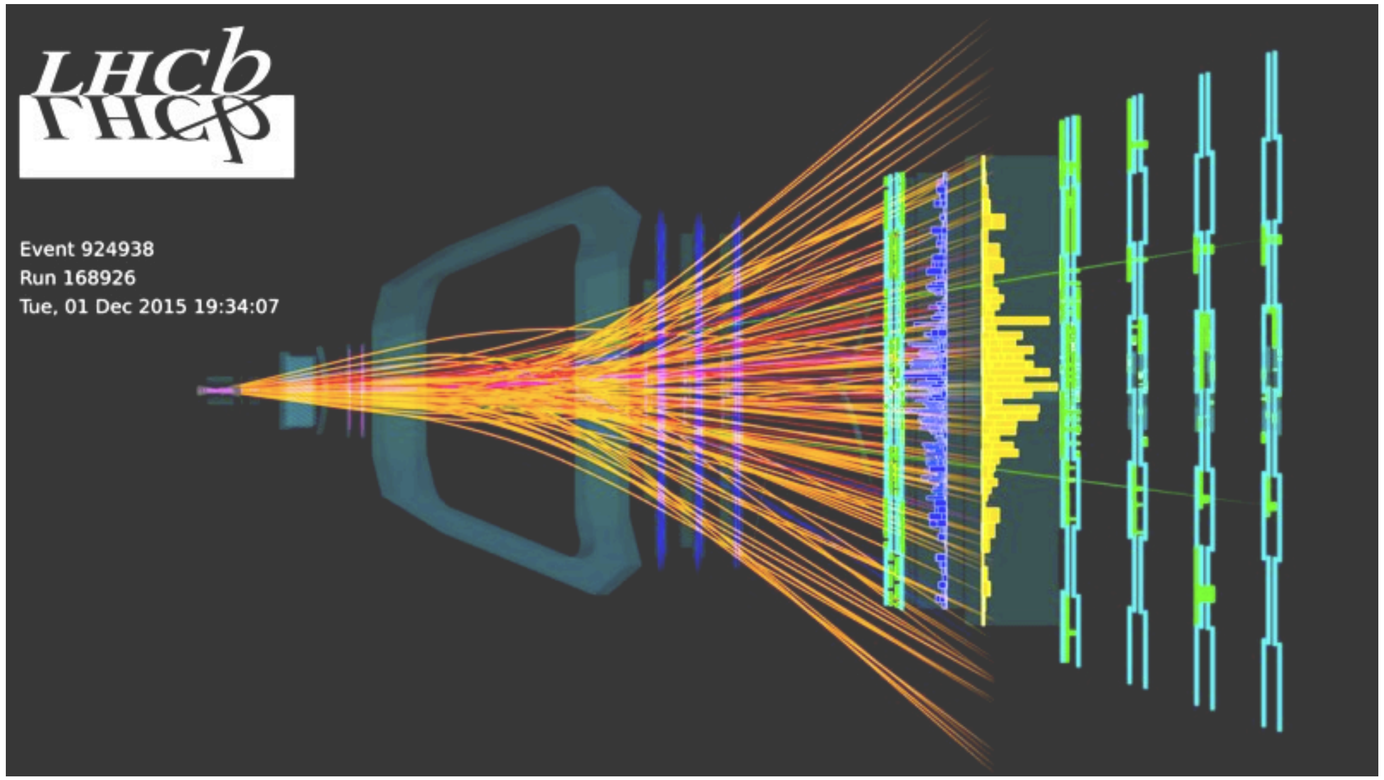


New heavy ion and fixed-target results at LHCb

Jiayin Sun
INFN Cagliari
on behalf of the LHCb collaboration

3rd May 2022

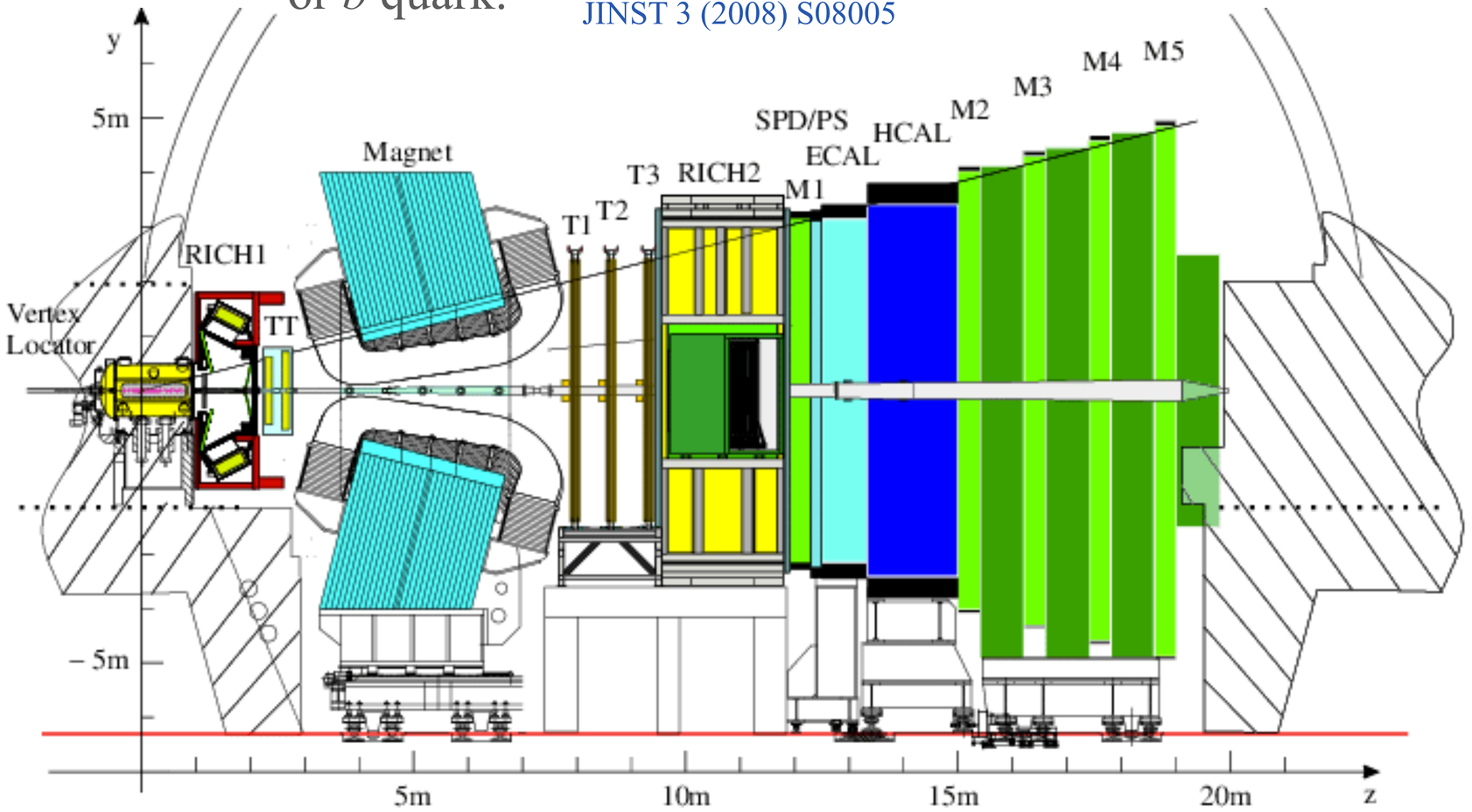
LHCb detector

- Acceptance: $2 < \eta < 5$
- Vertex detector (VELO)
  - IP resolution ~ $20\mu m$
- Tracking system
  - $\frac{\Delta p}{p} = 0.5 - 1\,\%$ (5-200 GeV/c)
- RICH
  - K/π/p seperation
- Electromagnetic + hadronic calorimeters
- Muon system
- Results presented in this talk are based on this configuration

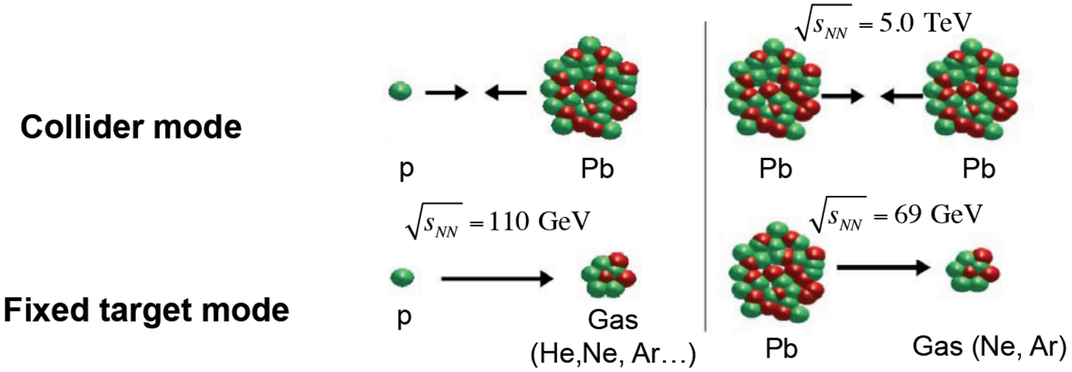
Already upgraded for Run3! more later

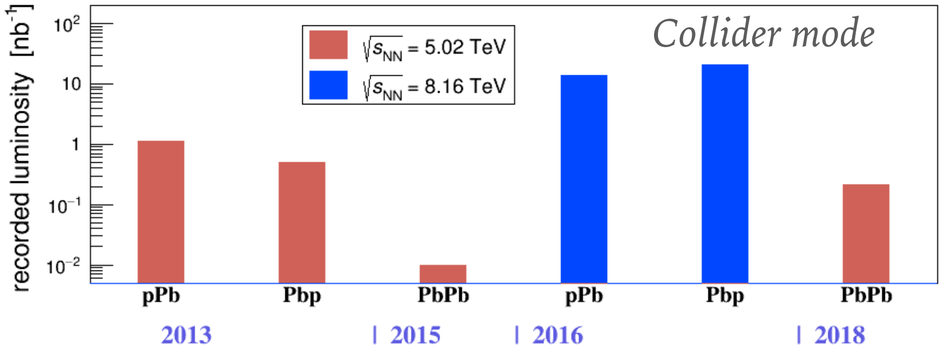
- A single arm spectrometer in forward rapidity, optimized in measuring particles containing c or b quark.

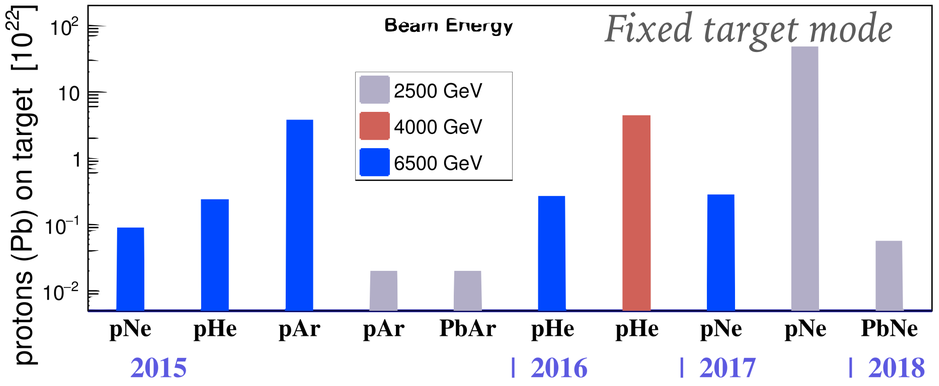
JINST 3 (2008) S08005



LHCb heavy ion collision modes and datasets



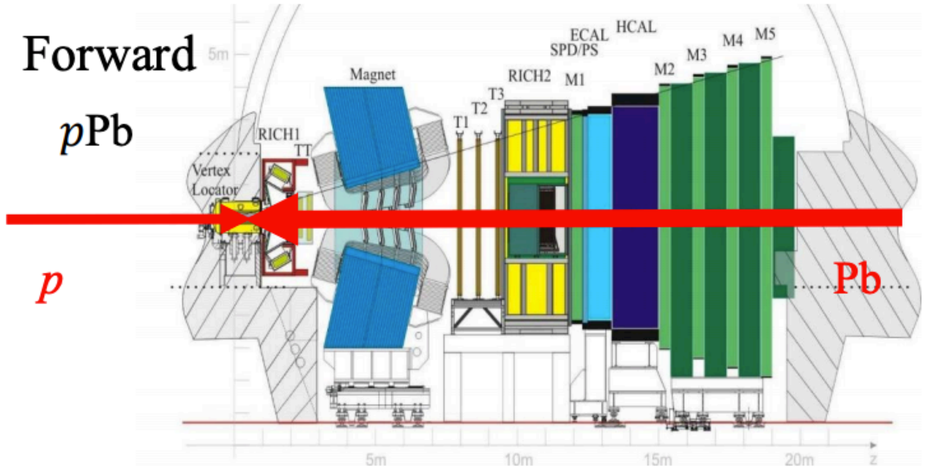




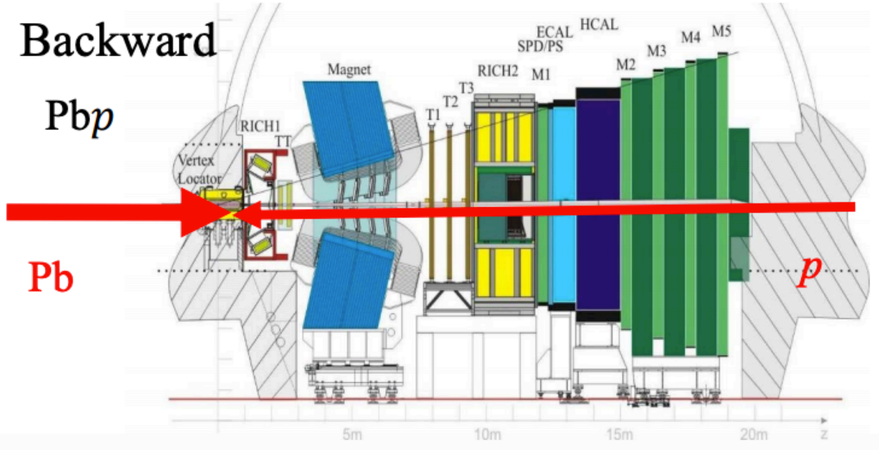
- **Collider mode**
  - *p*Pb/Pb*p*:
    - 5.02 TeV and 8.16TeV
  - PbPb:
    - 5 TeV
    - centrality-limited to 60%
- **Fixed-target mode (SMOG)**
  - *p*He, *p*Ne, *p*Ar: $\sqrt{s_{NN}}$~ 100 GeV
  - PbNe: $\sqrt{s_{NN}}$ ~ 68.6 GeV

➤ **Collider mode rapidity coverage**

- *y**: rapidity in nucleon-nucleon cms



*p*Pb (forward): $1.5 < y^* < 4.0$



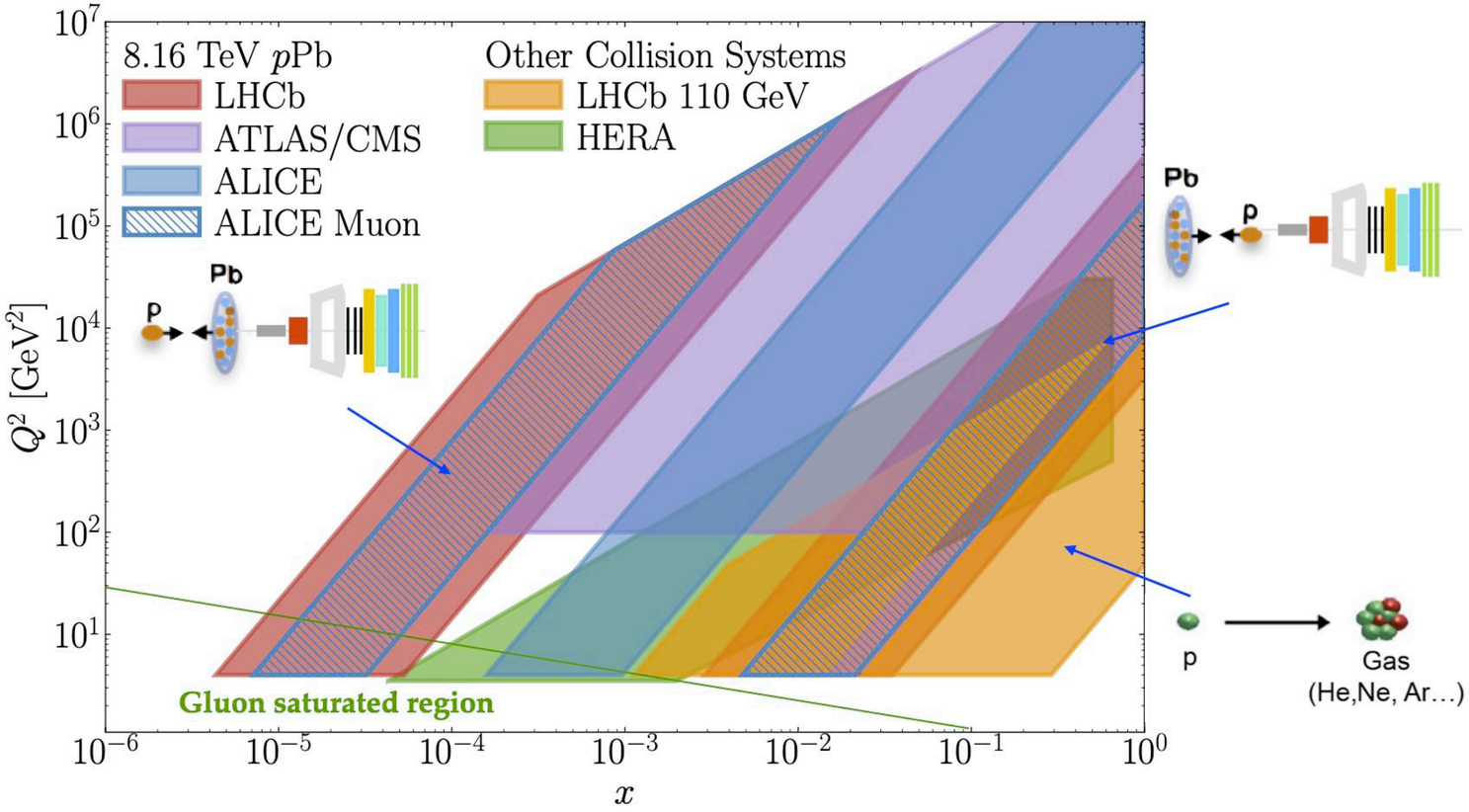
Pb*p* (backward): $-5.0 < y^* < -2.5$

LHCb in heavy ion physics

Collider mode centered

- Excellent for studying *pp*/*p*Pb collisions
  - Constrain nPDF at small and large Bjorken-*x*
  - Probe gluon saturation in low *x* and low Q^2 region
  - Test hadronization mechanisms in medium
  - Study final state effects in medium
  - Search for possible QGP droplet formation in small systems
- Promising at PbPb with the upgrade!

$Q^2 \sim m^2 + p_T^2$

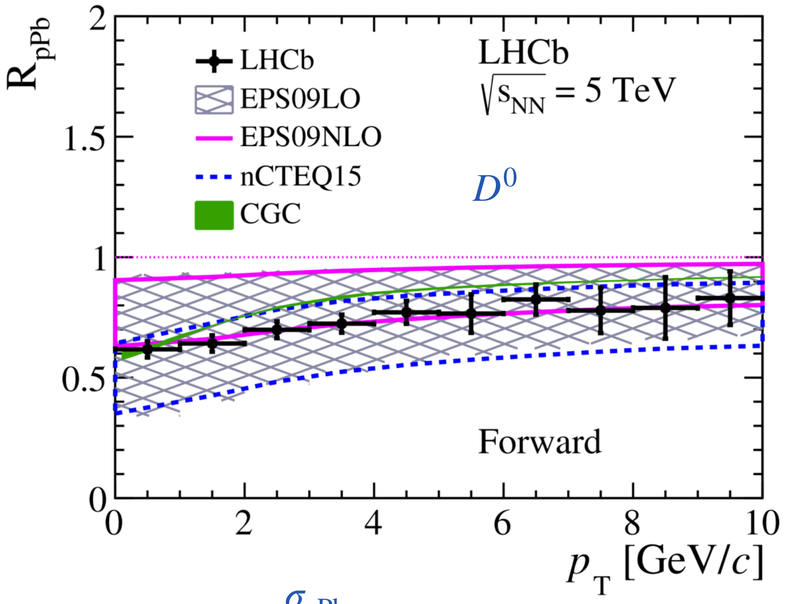


$x \sim \frac{Q}{\sqrt{s_{NN}}} e^{-\eta}$

Constrain nPDF with LHCb data

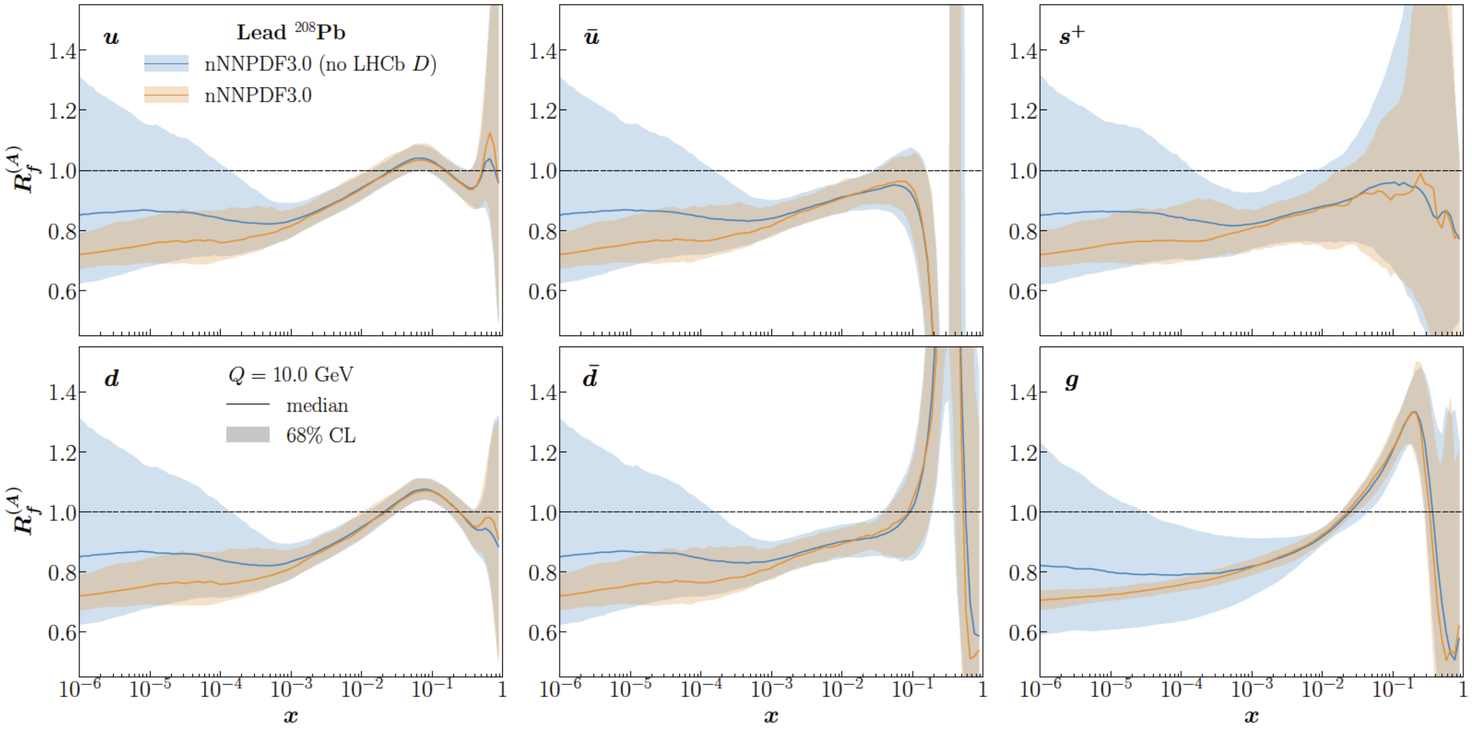
An example

JHEP 10 (2017) 090



$$R_{p\mathrm{Pb}} = \frac{\sigma_{p\mathrm{Pb}}}{208 \times \sigma_{pp}}$$

- nNNPDF3.0 arXiv:2201.12363
- LHCb measurement of prompt D^0 production in pPb collisions at 5TeV makes an impressive impact on reducing nPDF uncertainty down to $x \sim 10^{-6}$



New heavy ion results in this talk

Link to all publications (with references)

- ***pp*, *p*Pb results**
  - **Light flavor**:
    - charged hadron in *p*Pb 5TeV — PRL 128 (2022) 142004
    - π^0 production in *p*Pb 8.16 TeV — arXiv:2204.10608, submitted to PRL
  - **Open heavy flavor**:
    - prompt D^0 in *p*Pb 8.16TeV — LHCb-PAPER-2022-007, in preparation
    - *b*-hadrons in *pp* 13TeV — arXiv:2204.13042, submitted to PRL
  - **Z boson** in *p*Pb 8.16TeV — LHCb-PAPER-2022-009, in preparation
  - **Exotica**: $\chi_{c1}(3872)$ in *pp* 8TeV and *p*Pb 8.16TeV — LHCb-CONF-2022-001
- **PbPb results**
  - Λ_c^+/D^0 ratio in PbPb collisions — LHCb-PAPER-2021-046, in preparation
  - Quarkonia photoproduction in UPC collisions — LHCb-PAPER-2022-012, in preparation
- **Fixed-target (SMOG) results**
  - Antiproton in *p*He 110 GeV (detached) — LHCb-PAPER-2022-006, in preparation
  - Charm production in *p*Ne and PbNe at 68 GeV) — LHCb-PAPER-2022-011, in preparation; LHCb-PAPER-2022-014, in preparation

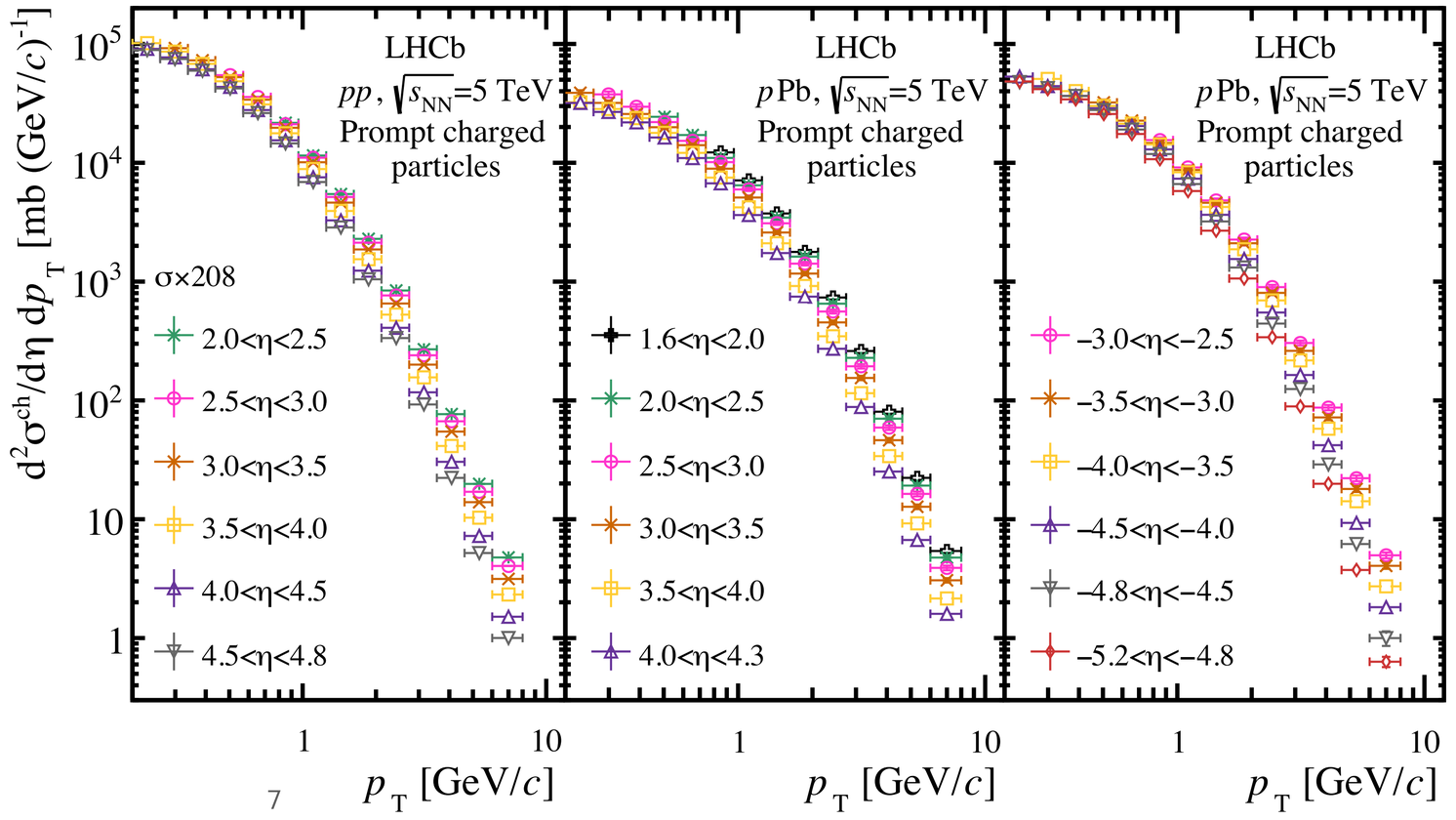
Prompt charged particles in *p*Pb and *pp* collisions at 5 TeV

Differential cross section

PhysRevLett. 128 (2022)142004

- Inclusive prompt charged particle spectra shed light on the initial state of the collision
- LHCb probes unprecedented Bjorken-x range with forward coverage:
  - Forward: $10^{-6} \leq x \leq 10^{-4}$
  - Backward: $10^{-3} \leq x \leq 10^{-1}$
- Prompt charged particle yields measured with tracking system
- Kinematic coverage:
  - $p > 2GeV/c$, $0.2 < p_{\mathrm{T}} < 8GeV/c$
  - pp: $2 < \eta < 4.8$
  - pPb: $1.6 < \eta < 4.3$
  - Pbp: $-5.2 < \eta < -2.5$
- Total uncertainty
  - Down to 2.8% in $d^2\sigma/d\eta dp_{\mathrm{T}}$
  - Down to 4.2% in $R_{p\mathrm{Pb}}$

Prompt charged particles: π, K, p, Ξ, Σ, Ω, e, μ…



Prompt charged particles in *p*Pb and *pp* collisions at 5 TeV

Nuclear modification factor $R_{p\mathrm{Pb}}$

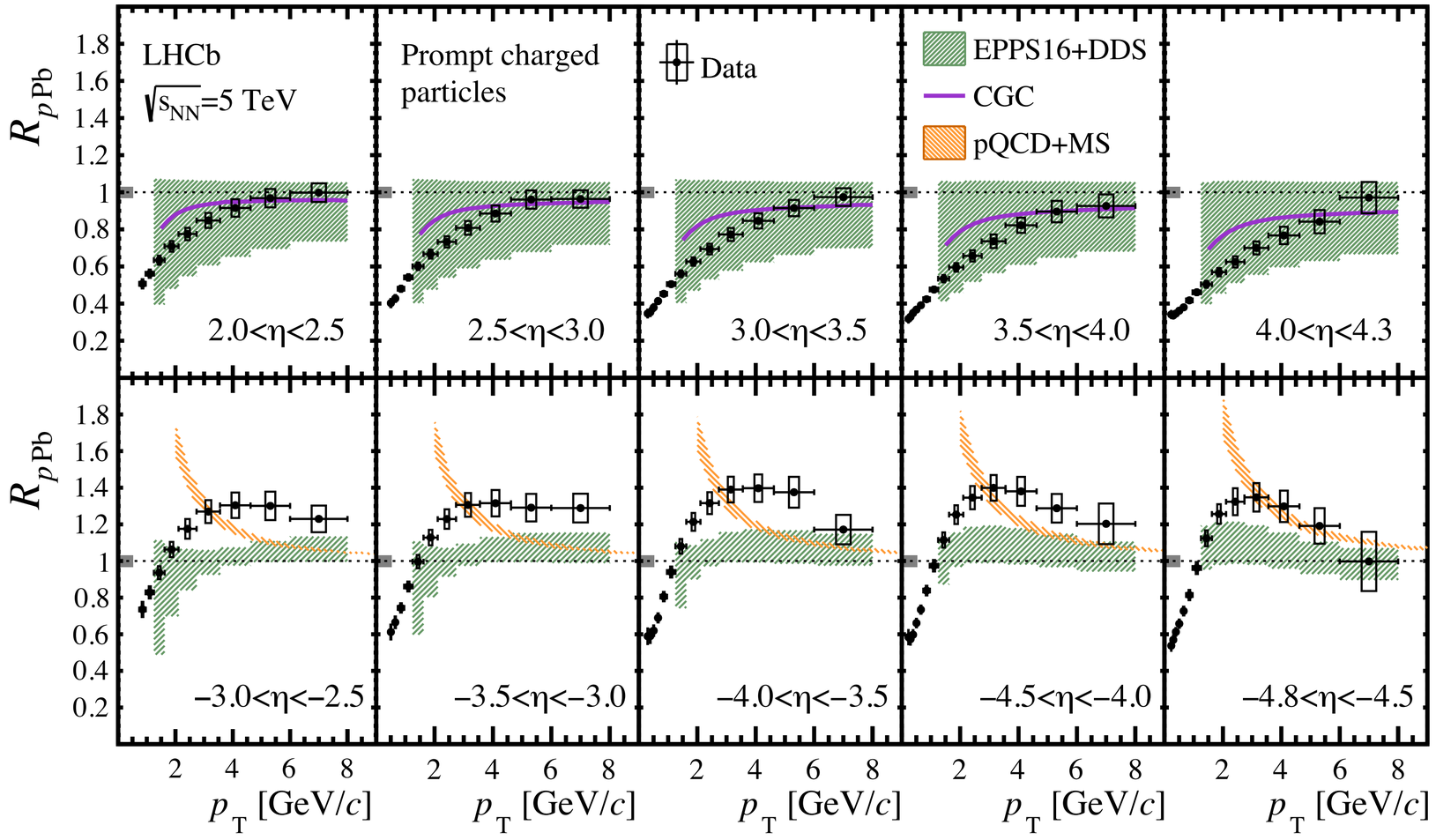
PhysRevLett. 128 (2022)142004

- Nuclear modification factor:

$$R_{p\mathrm{Pb}} = \frac{1}{A}\frac{d^2\sigma_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/d\eta dp_{\mathrm{T}}}{d^2\sigma_{pp}(\eta, p_{\mathrm{T}})/d\eta dp_{\mathrm{T}}}$$

$$A = 208$$

- Strong suppression at forward rapidity
- Enhancement at backward rapidity for $p_{\mathrm{T}} > 1.5\mathrm{GeV}/c$
- pQCD+Multiple Scattering model can describe PHENIX backward data, but is unable to reproduce backward data from this measurement
- **No model can successfully describe the data across the full rapidity range**



Prompt charged particles in *p*Pb and *pp* collisions at 5 TeV

PhysRevLett. 128 (2022)142004

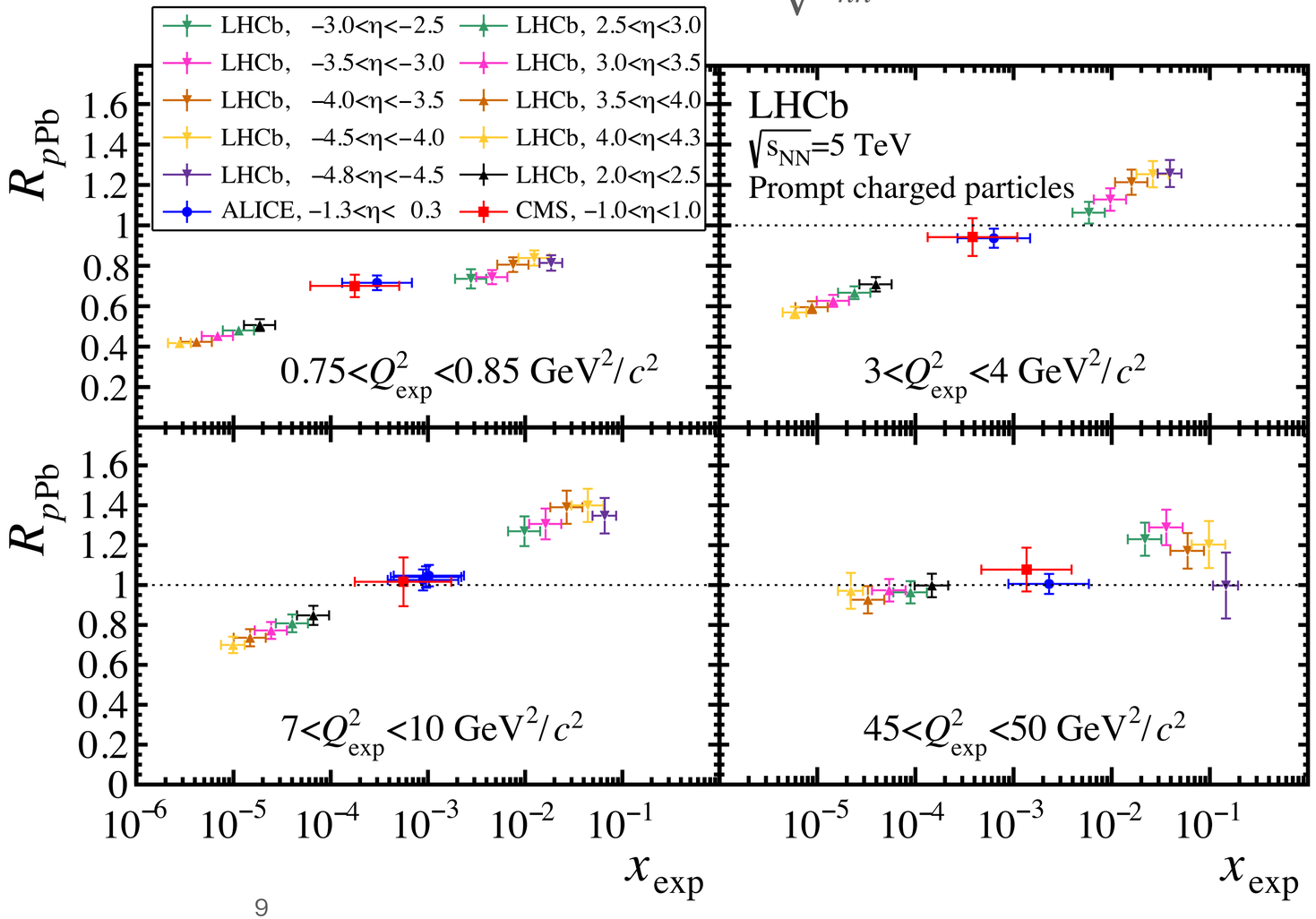
$R_{p\mathrm{Pb}}$ vs. x_{exp}

$$Q^2_{exp} \equiv m^2 + p_{\mathrm{T}}^2 \qquad x_{exp} \equiv \frac{Q_{exp}}{\sqrt{s_{nn}}} e^{-\eta}$$

ALICE: JHEP1811(2018)013

CMS: JHEP 04(2017)039

- Auxiliary variables x_{exp} and Q^2_{exp}
  - η and p_{T} the center of each bin
  - $m = 256\ GeV/c^2$
  - Indirect study of the evolution of $R_{p\mathrm{Pb}}$ with x and Q^2
- Continuous trend of $R_{p\mathrm{Pb}}$ with x_{exp} at different Q^2_{exp} across forward, middle and backward rapidity regions.

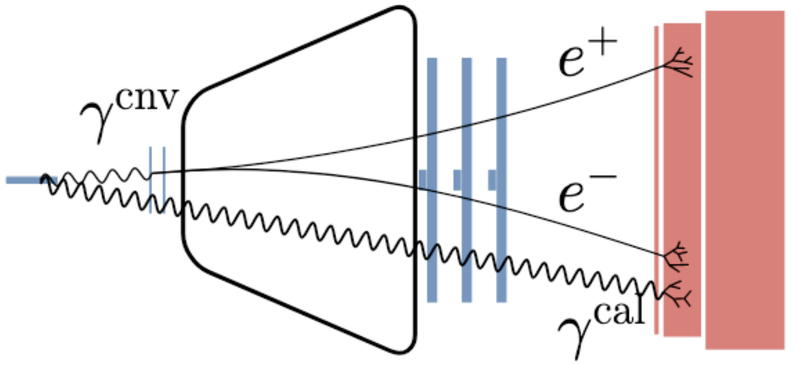


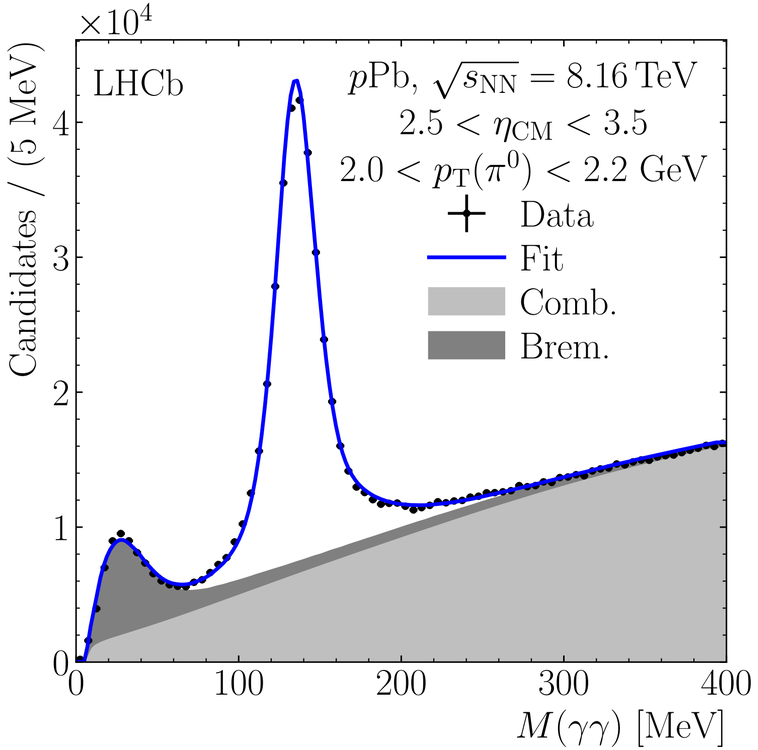
π^0 production in pPb collisions at 8.16TeV

arXiv:2204.10608
submitted to PRL

- First π^0 result in forward rapidity at LHC.
- π^0 production in pPb sensitive to nPDF at low and high x
- By constraining nPDFs, study nuclear effects beyond nPDFs
- Charged hadron in pPb: large enhancement at backward rapidities
- Disentangle effects from different hadrons, help differentiate between contributions from nPDFs, initial state multiple scattering and final-state effects
- Gateway to direct photon production measurement

- Construct $\pi^0 \to \gamma^{cnv}\gamma^{cal}$
- $1.5 < p_{\mathrm{T}} < 10.0$ GeV/c
- pPb: $2.5 < \eta_{CM} < 3.5$; Pbp: $-4.0 < \eta_{CM} < -3.0$





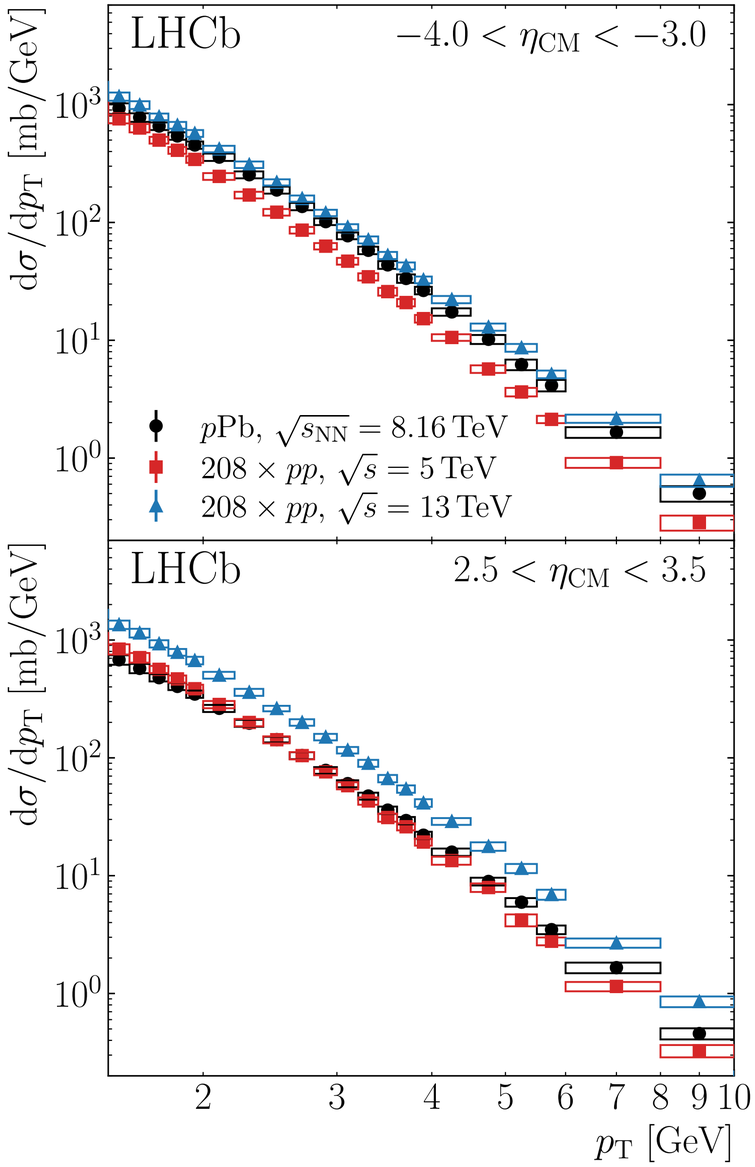
π^0 production in pPb collisions at 8.16TeV

π^0 differential cross-sections

arXiv:2204.10608
submitted to PRL

- pp reference for $R_{p\mathrm{Pb}}$: interpolation between 5 and 13TeV

$$R_{p\mathrm{Pb}} = \frac{\sigma_{p\mathrm{Pb}}}{208 \times \sigma_{pp}}$$



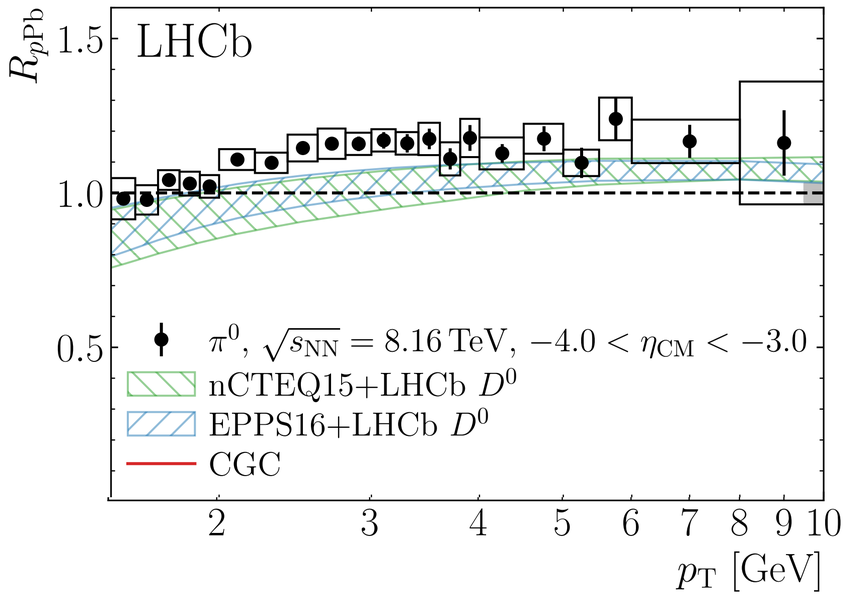
π^0 production in pPb collisions at 8.16TeV

Nuclear modification factor $R_{p\mathrm{Pb}}$

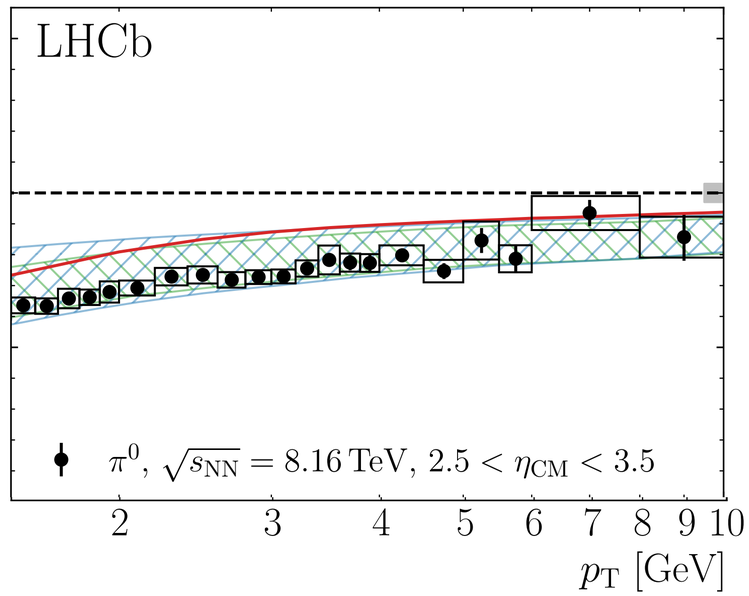
arXiv:2204.10608
submitted to PRL

- *pp* reference: interpolation between 5 and 13TeV
- Forward (*p*Pb):
  - Strong suppression
  - Data smaller uncertainties than the nPDF uncertainties
  - Lower than CGC calculation
- Backward (Pb*p*):
  - Cronin-like enhancement
  - Larger than nPDF calculations, similar to the charged hadron result

Backward rapidity



Forward rapidity



$$R_{p\mathrm{Pb}} = \frac{\sigma_{p\mathrm{Pb}}}{208 \times \sigma_{pp}}$$

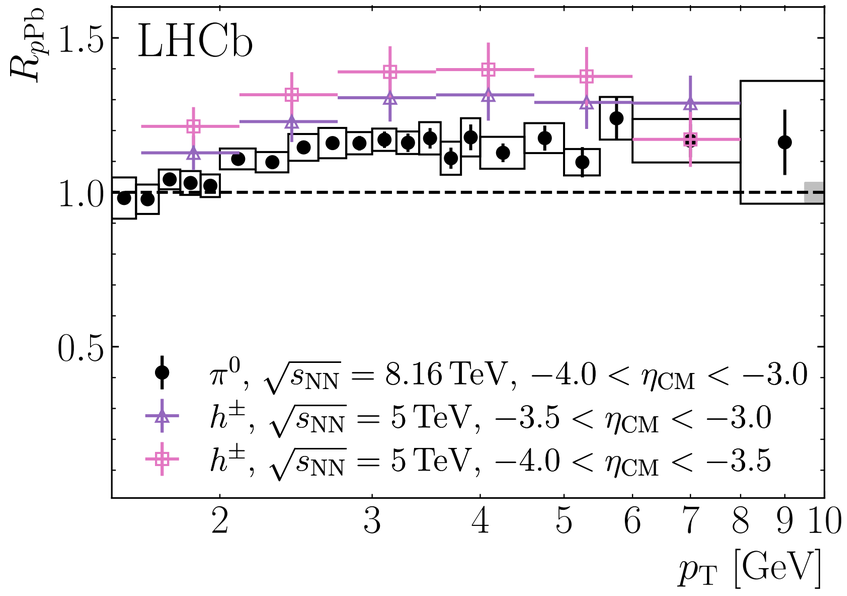
π^0 production in pPb collisions at 8.16TeV

Nuclear modification factor $R_{p\mathrm{Pb}}$

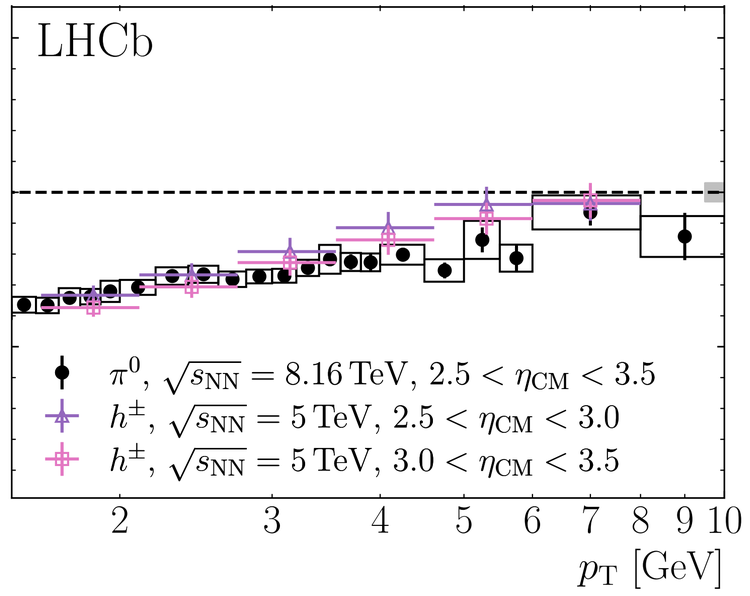
arXiv:2204.10608
submitted to PRL

- pp reference: interpolation between 5 and 13TeV
- Forward (pPb):
  - Consistent with charged hadron result
- Backward (Pbp):
  - Enhancement less pronounced than charged hadrons
  - Indicating a mass-ordering effect

Backward rapidity



Forward rapidity

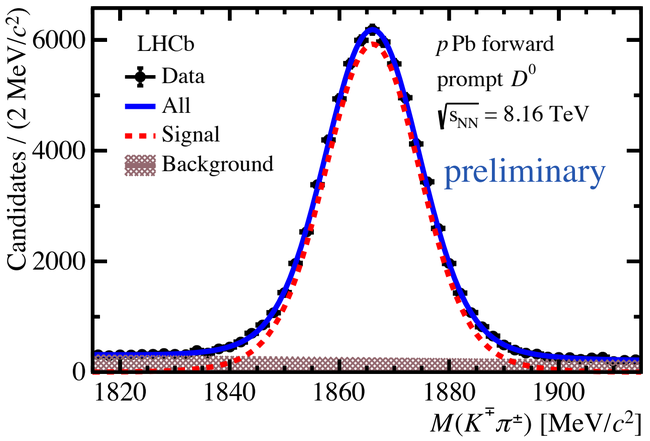


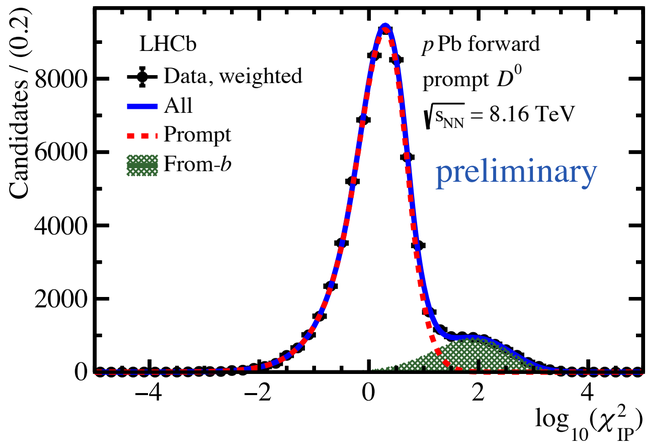
$$R_{p\mathrm{Pb}} = \frac{\sigma_{p\mathrm{Pb}}}{208 \times \sigma_{pp}}$$

Prompt D^0 production in pPb collisions at 8.16TeV

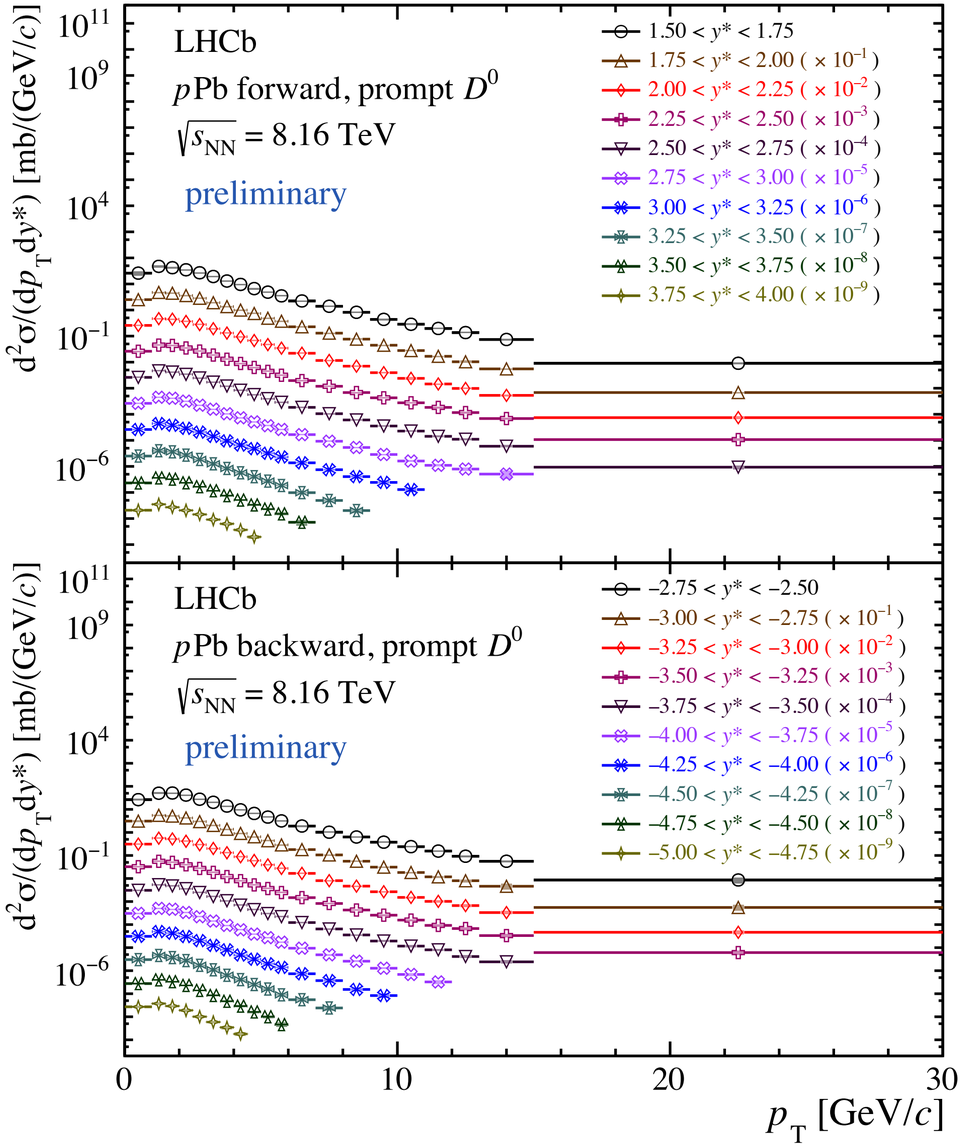
signals and differential cross-section

LHCb-PAPER-2022-007, in preparation





- Precise measurement of prompt D^0 production in pPb collisions
- 20 times larger statistics than previous LHCb D^0 result at 5TeV
- $D^0 \to K^-\pi^+$
- Use impact parameter to separate the prompt and b-decay components
- $0 < p_T < 30$ GeV/c
- pPb: $1.5 < y < 4.0$; Pbp: $-5.0 < y < -2.5$

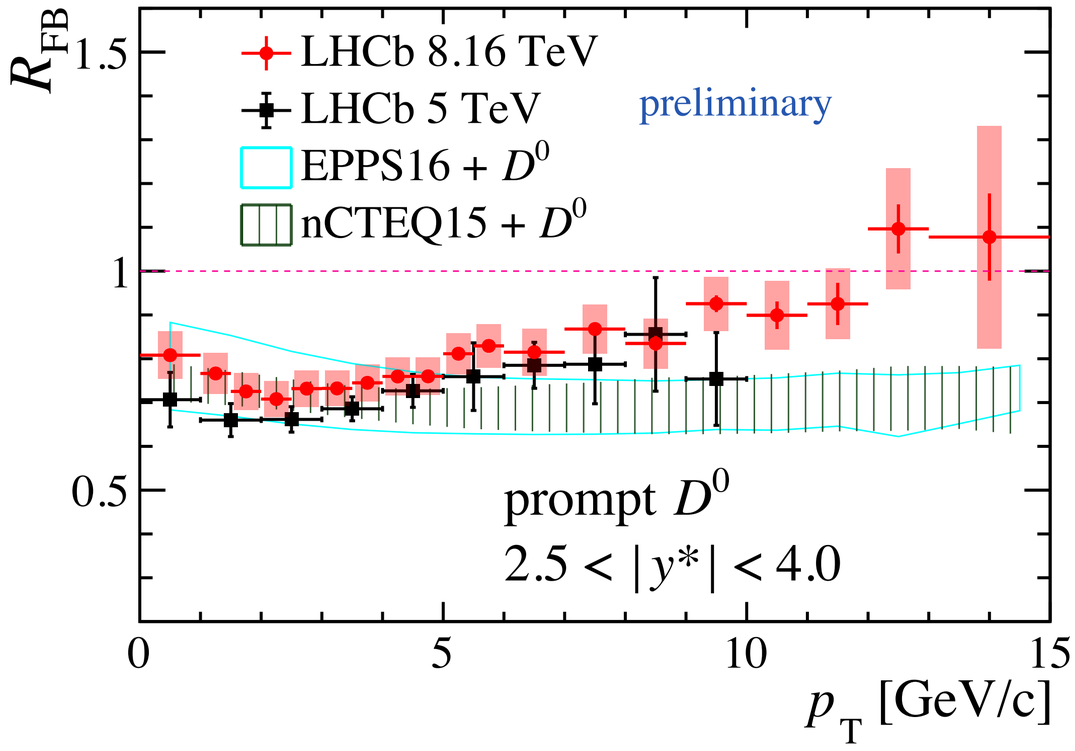


Prompt D^0 production in pPb collisions at 8.16TeV

R_{FB} and differential cross-section

LHCb-PAPER-2022-007, in preparation

$$R_{\mathrm{FB}} = \frac{\sigma_{p\mathrm{Pb}}}{\sigma_{\mathrm{Pb}p}}$$

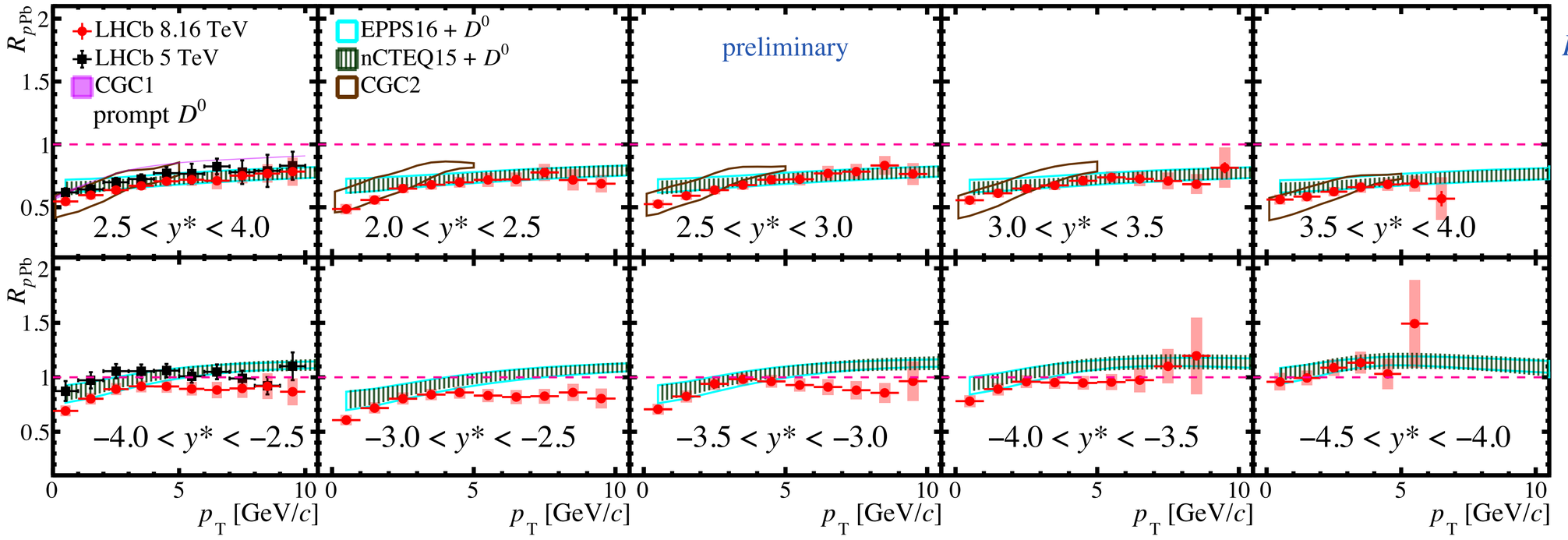


- Forward-backward production ratio R_{FB}
  - Low p_{T}: **consistent with nPDF expectations**
  - High p_{T}: **data > nPDF**

Prompt D^0 production in pPb collisions at 8.16TeV

Nuclear modification factor

LHCb-PAPER-2022-007, in preparation



Forward →

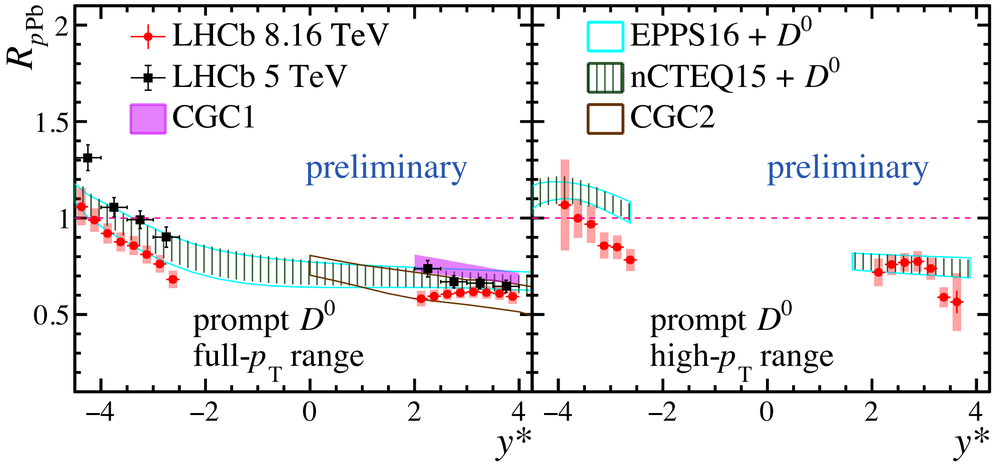
Backward →

$$R_{p\mathrm{Pb}} = \frac{\sigma_{p\mathrm{Pb}}}{208 \times \sigma_{pp}}$$

pp reference from interpolation between 5&13 TeV data

JHEP 06 (2017) 147
JHEP 05 (2017) 074

- Forward:
  - Suppression consistent with 5TeV D^0 result
  - Consistent with nPDF and CGC
- Backward:
  - Data lower than nPDF at high p_{T}
  - Room for additional effects in the backward rapidity
  - **nPDF calculations do not describe data for $h^{\pm}$, π^0 and D^0**

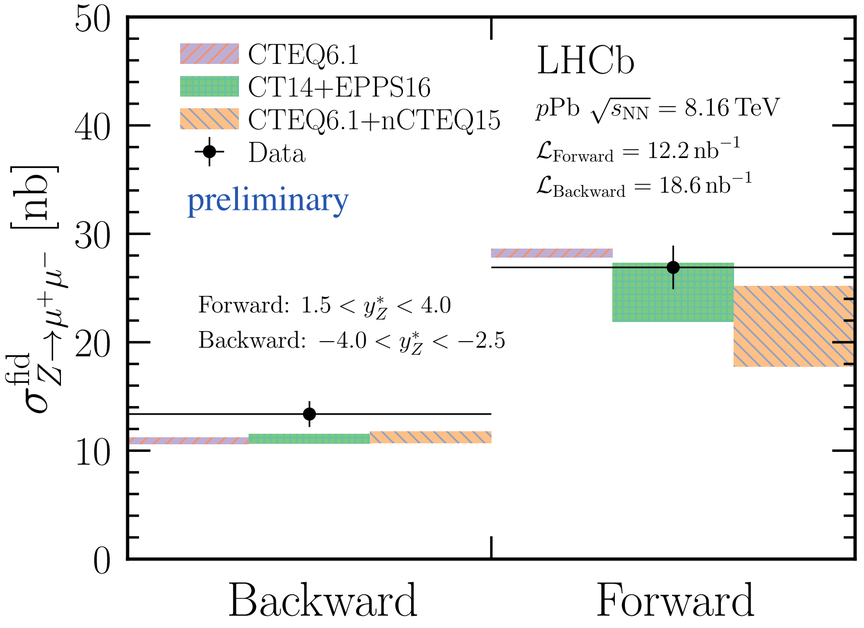


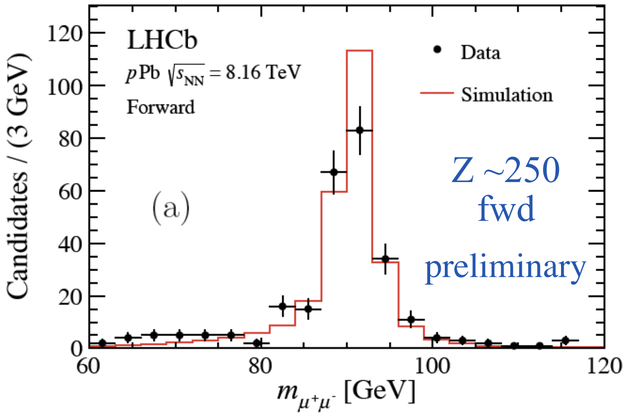
Z^0 boson production in *p*Pb collisions at 8.16 TeV

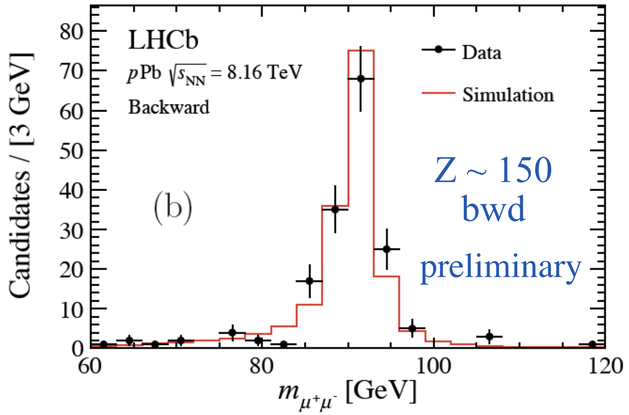
Z boson differential cross section

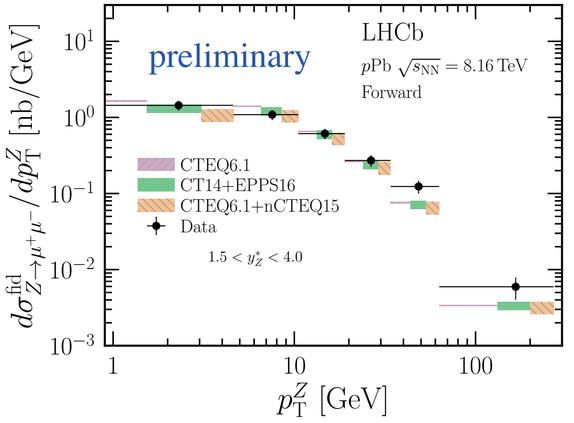
LHCb-PAPER-2022-009, in preparation

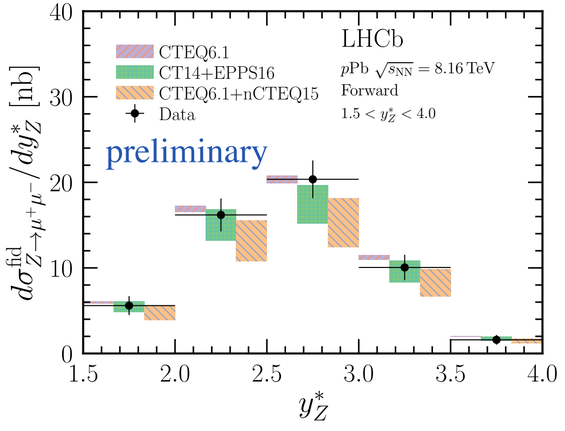
- Z boson negligible interaction with the nuclear medium
  - Sensitive only to initial-state with a well constrained final-state
- Clean probes of nuclear matter effects on the initial state.
- **Compatible with nPDFs EPPS16 and nCTEQ15**











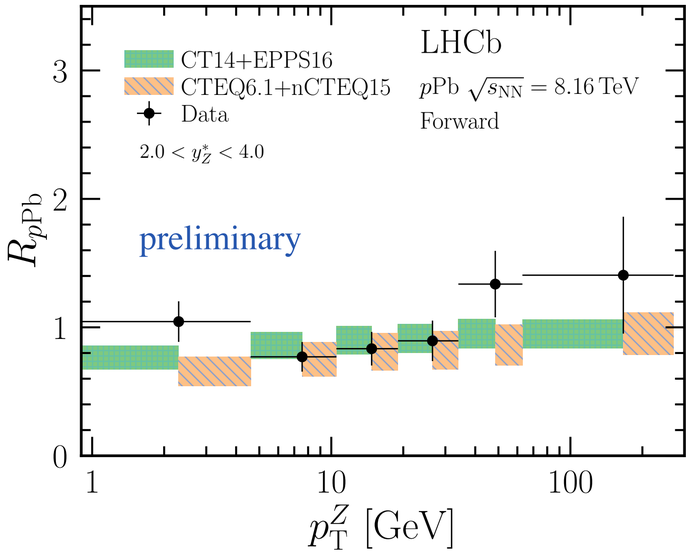
Z^0 boson production in pPb collisions at 8.16 TeV

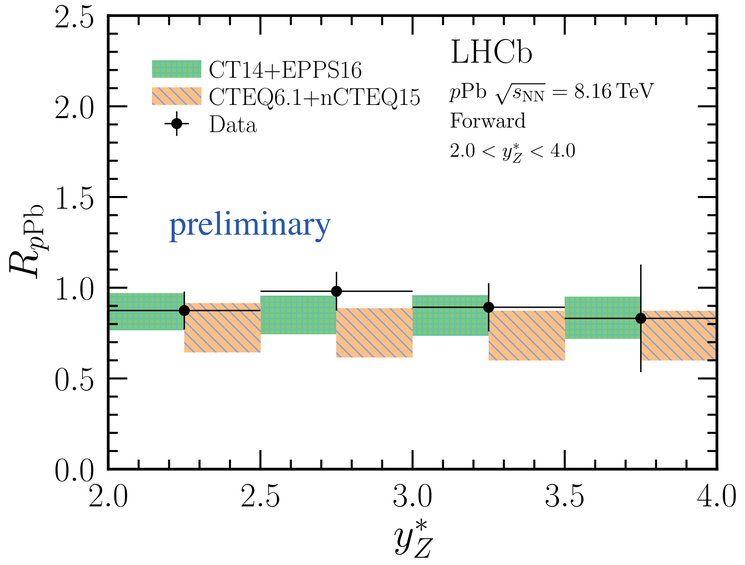
Nuclear modification factor $R_{p\mathrm{Pb}}$

LHCb-PAPER-2022-009, in preparation

- **General good agreement between data and nPDFs EPPS16 and nCTEQ15**

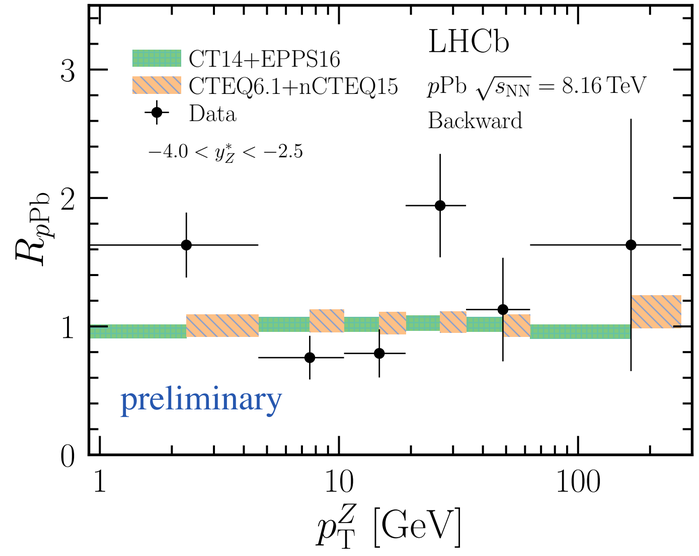
Forward →

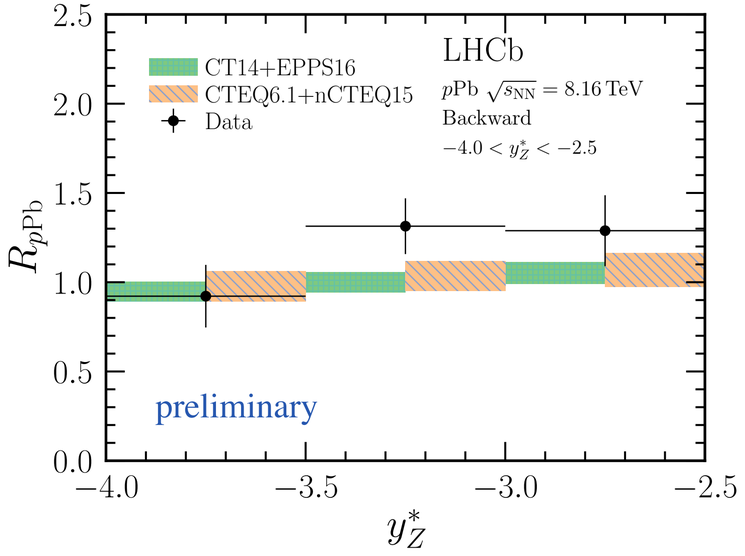




$$R_{p\mathrm{Pb}} = \frac{\sigma_{p\mathrm{Pb}}}{208 \times \sigma_{pp}}$$

Backward →



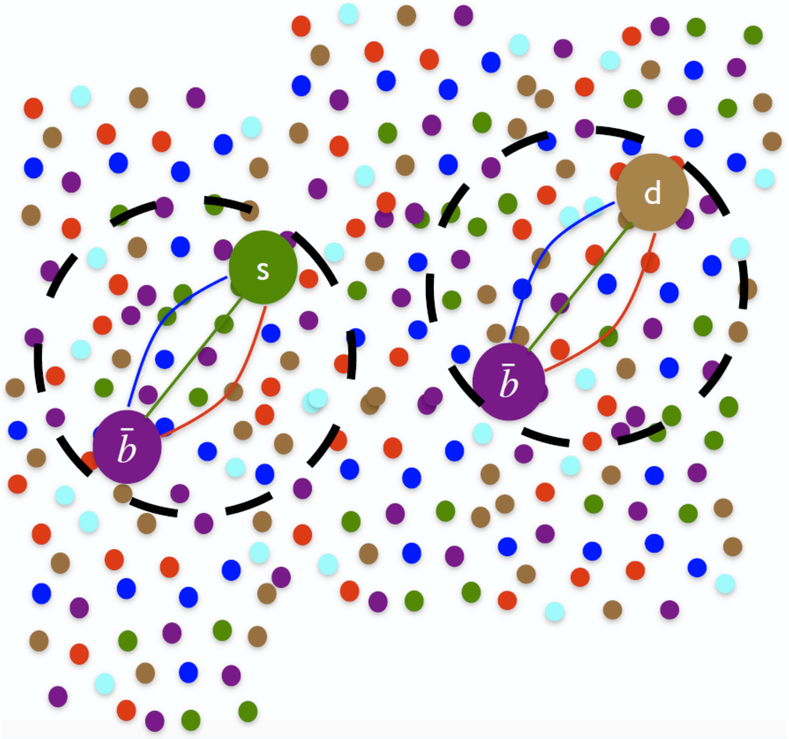


b hadronization in high multiplicity *pp* collisions at 13 TeV

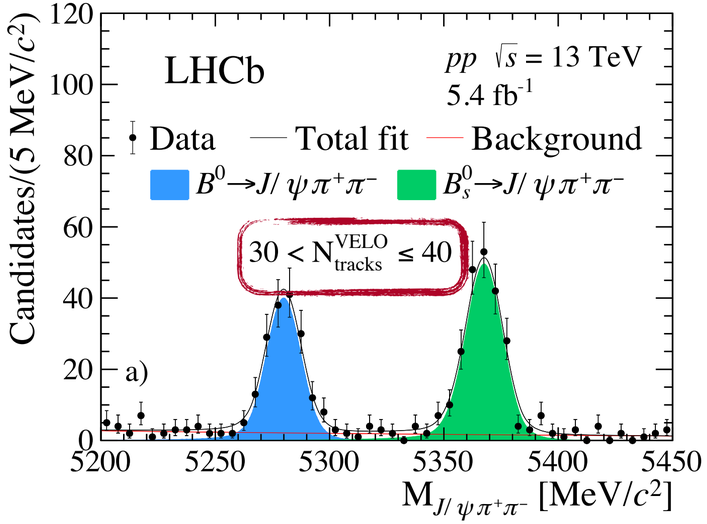
B_s^0/B^0

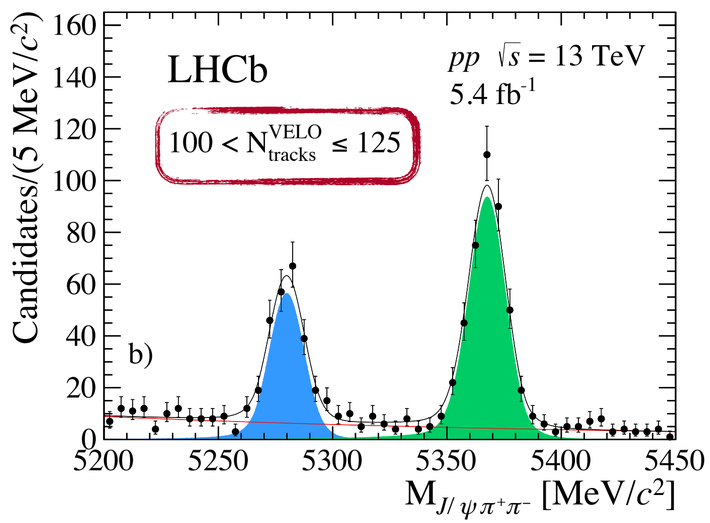
arXiv:2204.13042
submitted to PRL

- Production of $b\bar{b}$ pairs at hadron colliders dominated by hard parton-parton interactions in the initial stages, well described by pQCD calculations
- Enhanced strangeness production in light-quark baryons and mesons observed by ALICE Nature Phys. 13 (2017) 535
- **Possible quark coalescence → enhanced B_s^0/B^0 ratio with increasing particle multiplicity, especially at low p_T**



$B^0_{(s)} \to (J/\psi \to \mu^+\mu^-)\pi^+\pi^-$

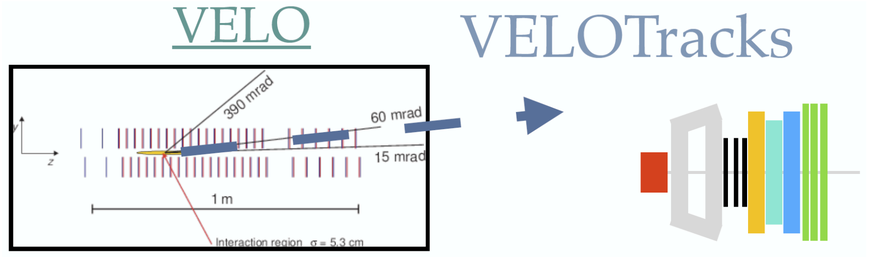




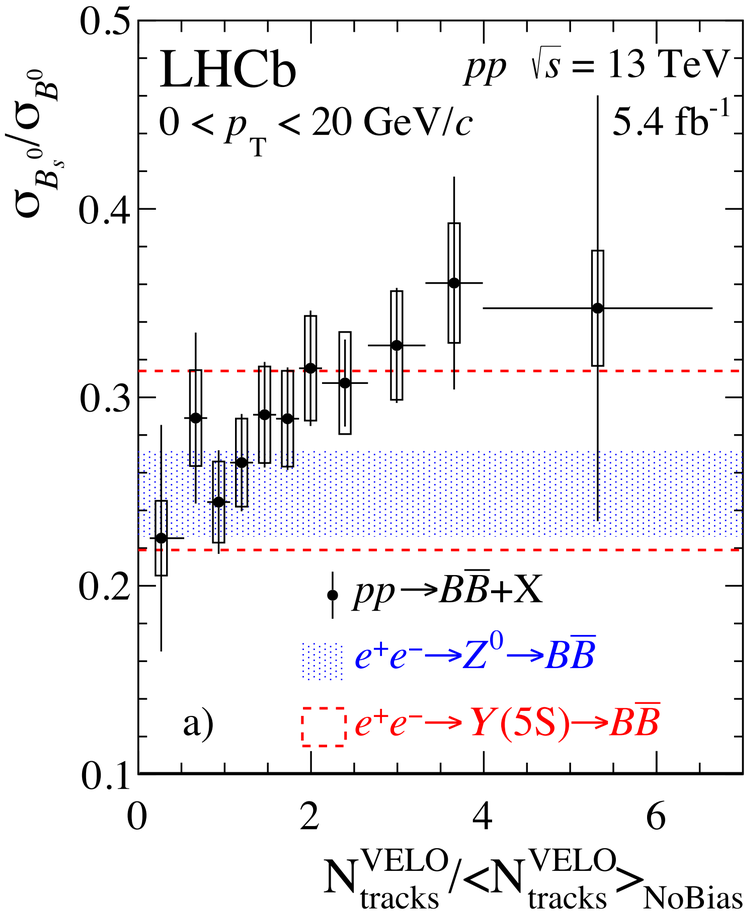
b hadronization in high multiplicity *pp* collisions at 13 TeV

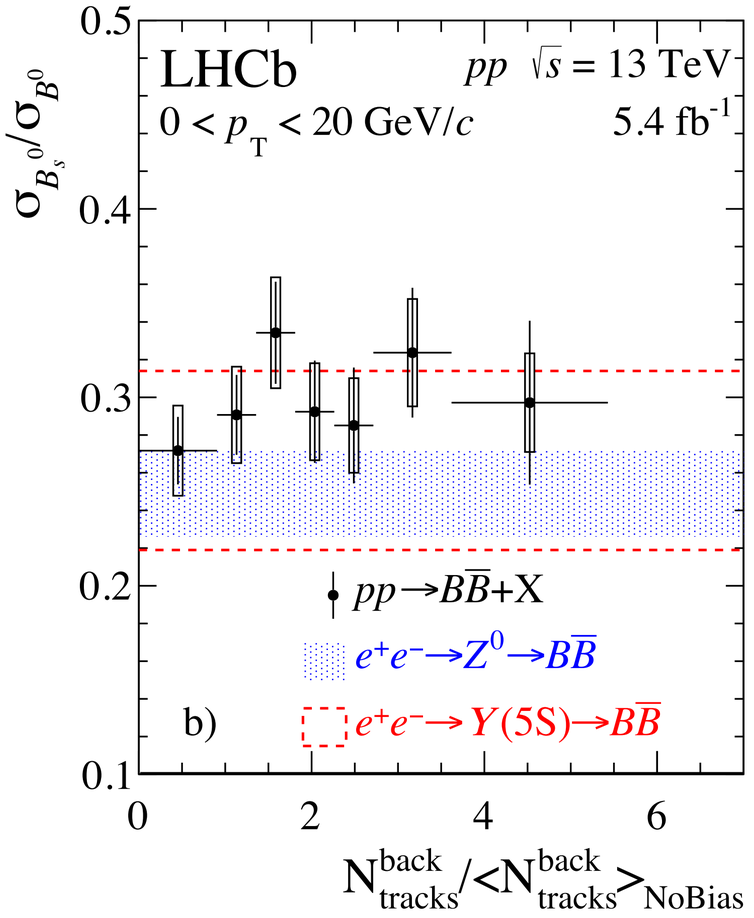
B_s^0/B^0 in different multiplicity metrics

arXiv:2204.13042
submitted to PRL



- Total VELO multiplicity:
  - Increasing trend
- Multiplicity measured in backward region:
  - No significant dependence
- Indicates B_s^0/B^0 increase related to the local particle density around the B mesons
- Compatible with expectations of coalescence

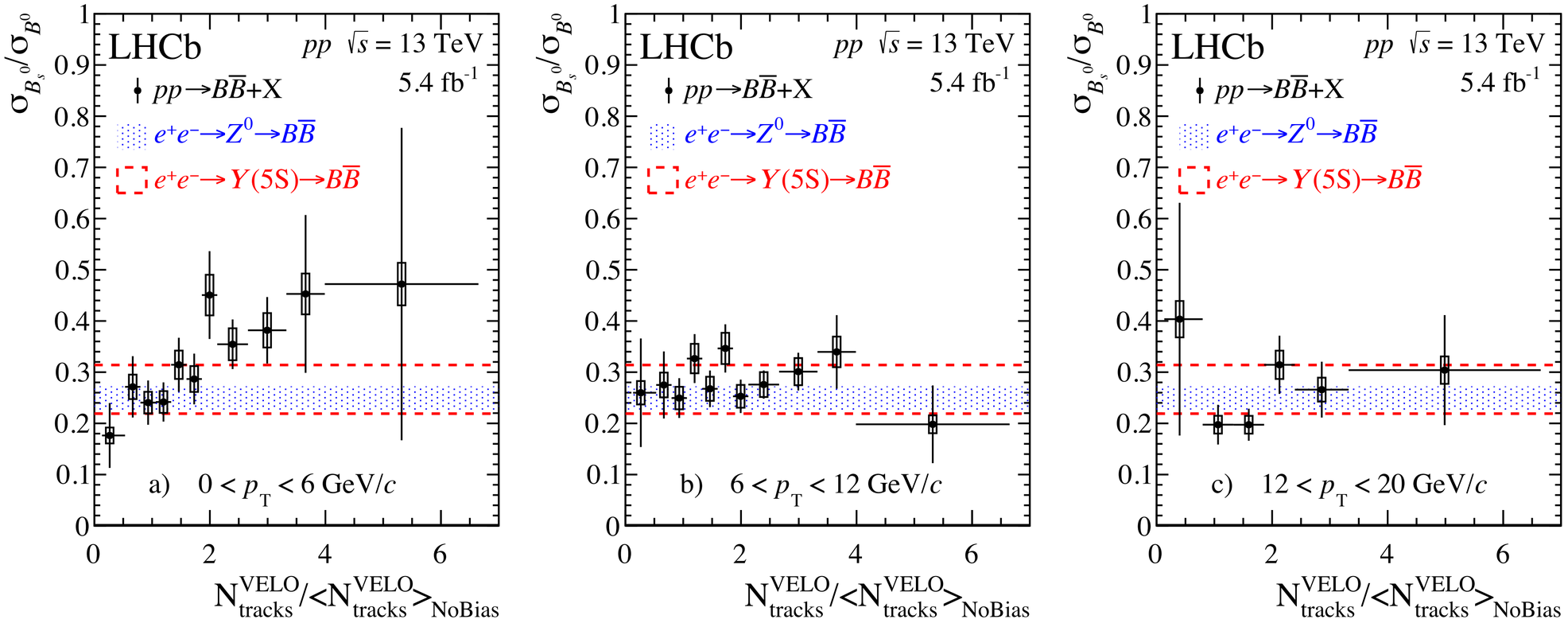




b hadronization in high multiplicity *pp* collisions at 13 TeV

B_s^0/B^0 vs. multiplicity in p_T intervals

arXiv:2204.13042
submitted to PRL

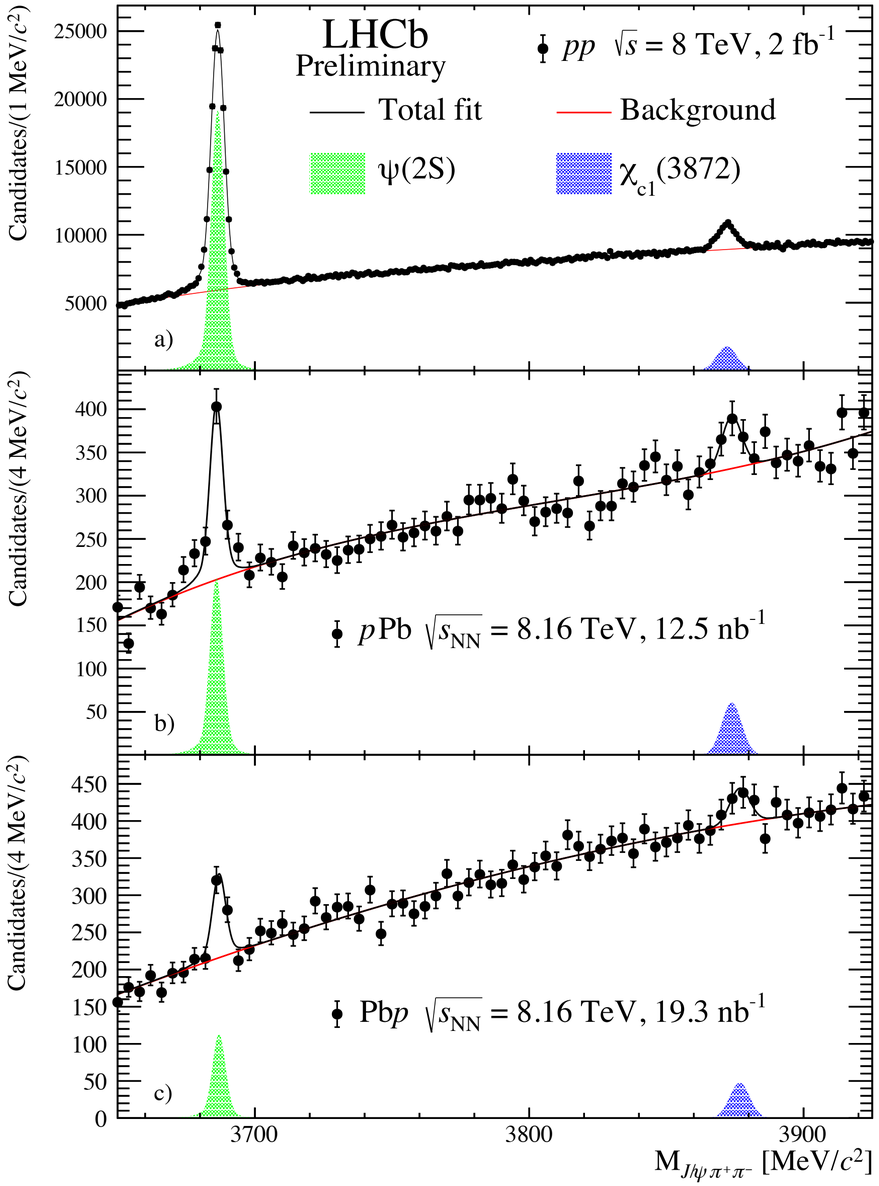


- Low multiplicity: consistent with values in e^+e^- collisions
- $0 < p_T < 6$: increases with increasing multiplicity, slope 3.4σ deviations from constant
- Higher p_T intervals: no significant dependence, consistent with e^+e^- data
- **Qualitatively consistent with expectations of coalescence**

Exotic hadron production in *p*Pb and *pp* collisions

$\chi_{c1}(3872)/\psi(2S)$

LHCb-CONF-2022-001



- First $\chi_{c1}(3872)$ result in *p*Pb collisions
- Testing $\chi_{c1}(3872)$ breaking up in higher multiplicity environment → probe inner structure
- Testing coalescence with 4 valence quarks with increasing particle multiplicity
- Prompt $\chi_{c1}(3872)$ and $\psi(2S)$ reconstructed via $J/\psi\pi^+\pi^-$ decay channel in *pp*, *p*Pb and Pb*p* collisions
- $p_T > 5$ GeV/c

Exotic hadron production in *p*Pb and *pp* collisions

$\chi_{c1}(3872)/\psi(2S)$

LHCb-CONF-2022-001

- $\chi_{c1}(3872)/\psi(2S)$ ratio increases with system size
- nPDF effects largely cancel in the ratio, final state effects dominant
- $\chi_{c1}(3872)$ behaves differently than $\psi(2S)$: coalescence dominates over break-up in *p*Pb?
- $\psi(2S)$ suppressed in *p*Pb system → necessary to study $R_{p\mathrm{Pb}}(\chi_{c1}(3872))$

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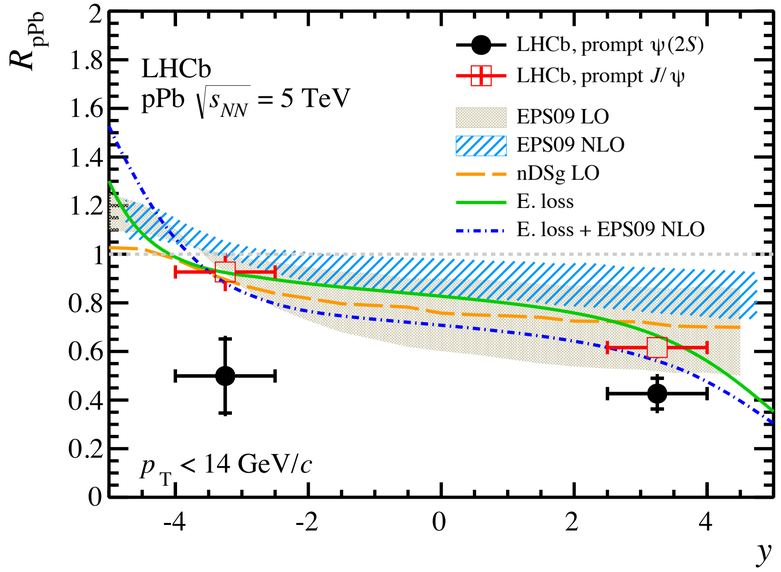
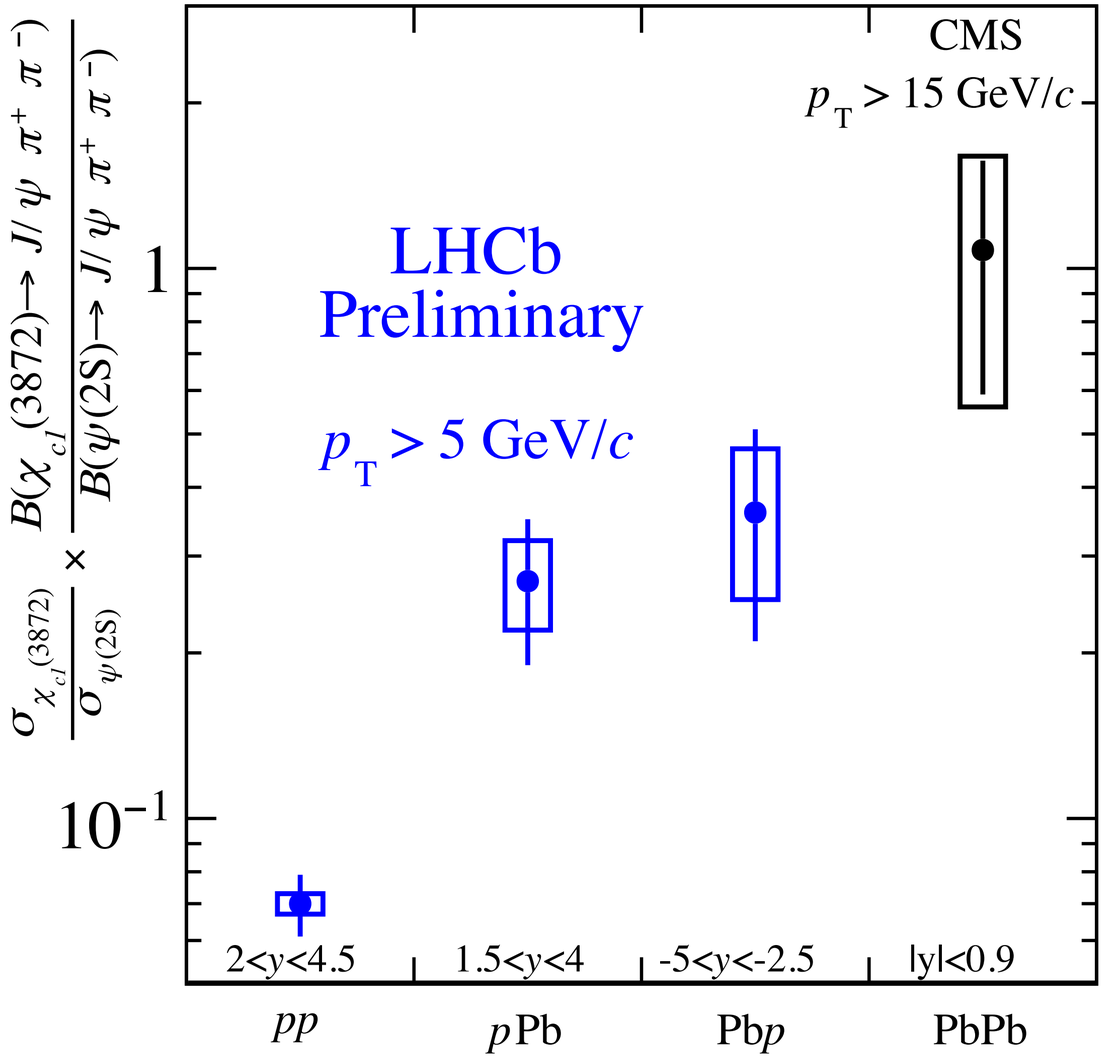
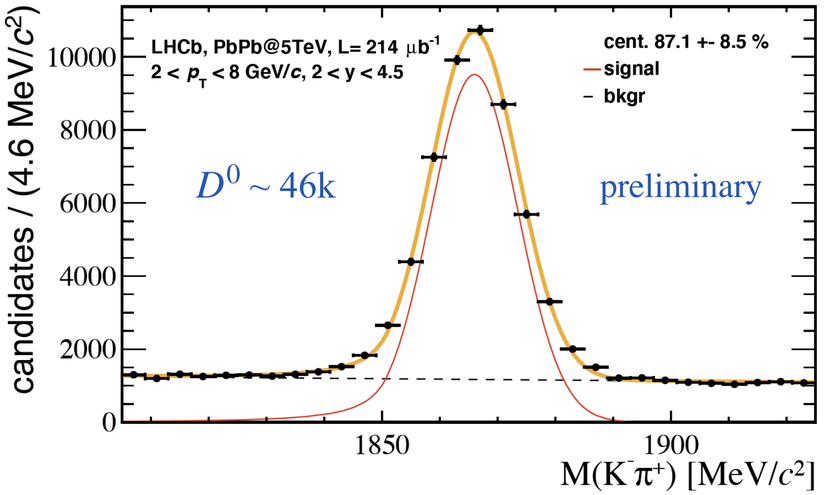


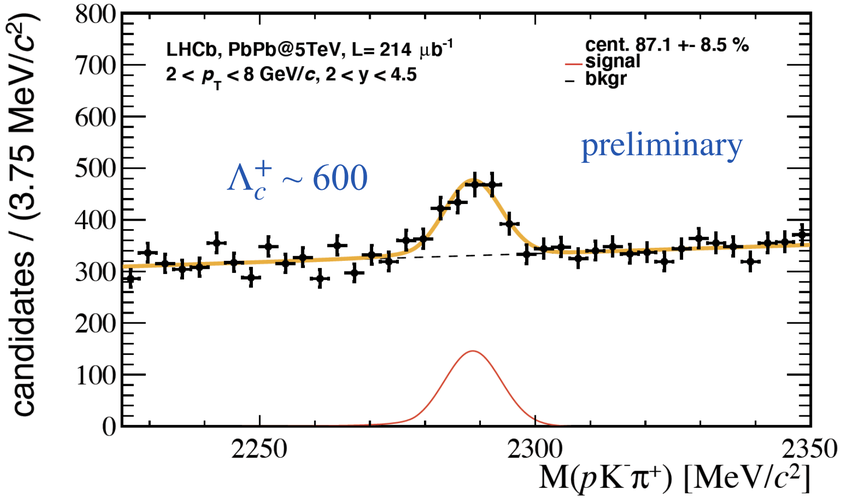


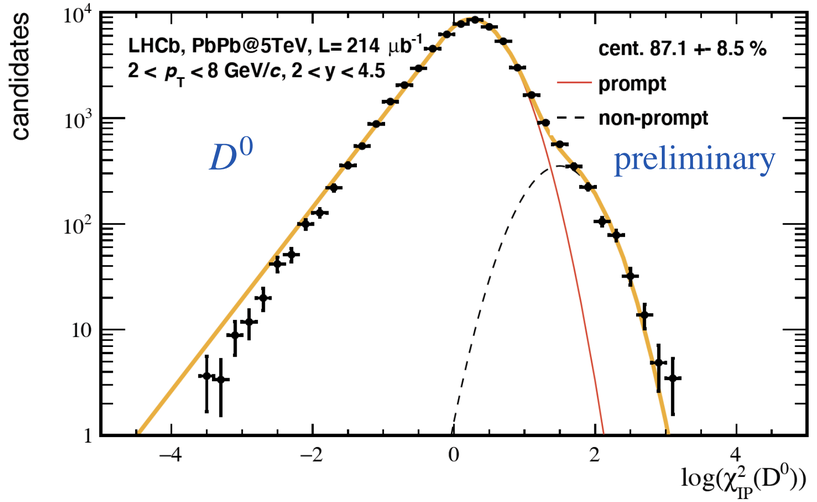
Λ_c^+/D^0 production ratio in peripheral PbPb collisions at 5 TeV

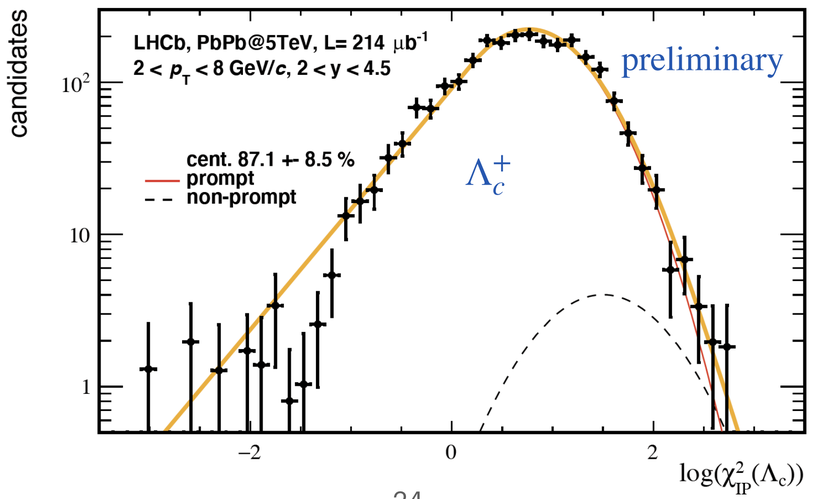
Signals

LHCb-PAPER-2021-046, in preparation

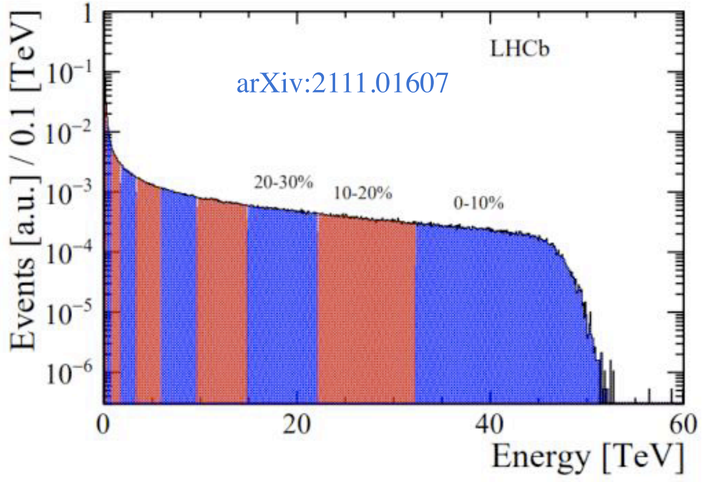






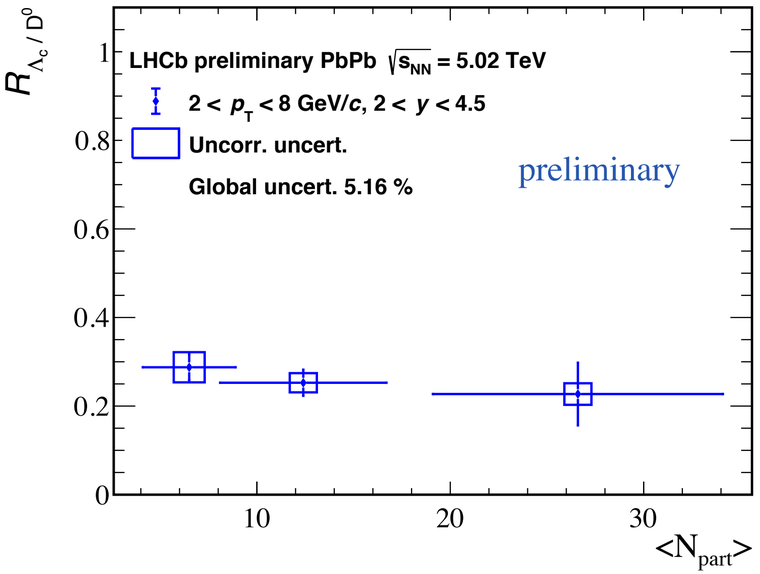


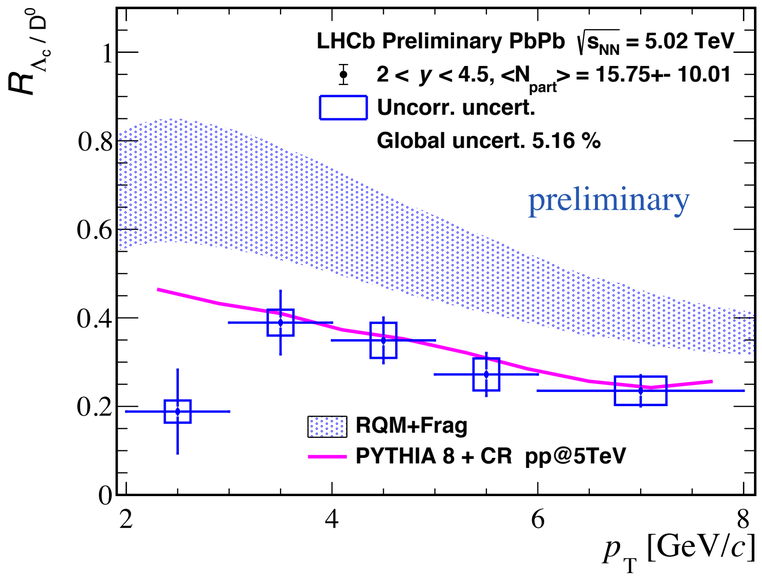
- **One of the first LHCb PbPb results in hadronic collisions**
- PbPb data collected in 2018
- Centrality determined by energy in Ecal
- Up to 60% centrality in hadronic collisions
- Separation of the prompt and *b*-decay components by impact parameter

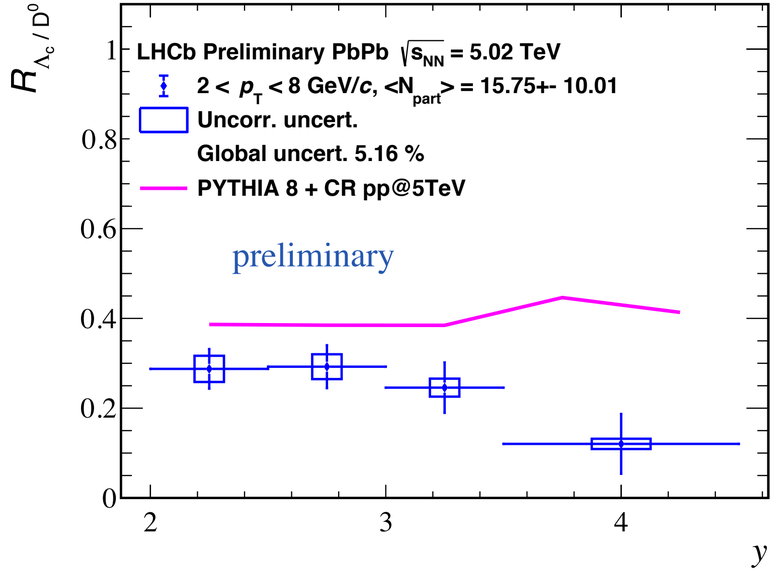


Λ_c^+/D^0 production ratio in peripheral PbPb collisions at 5 TeV

LHCb-PAPER-2021-046, in preparation







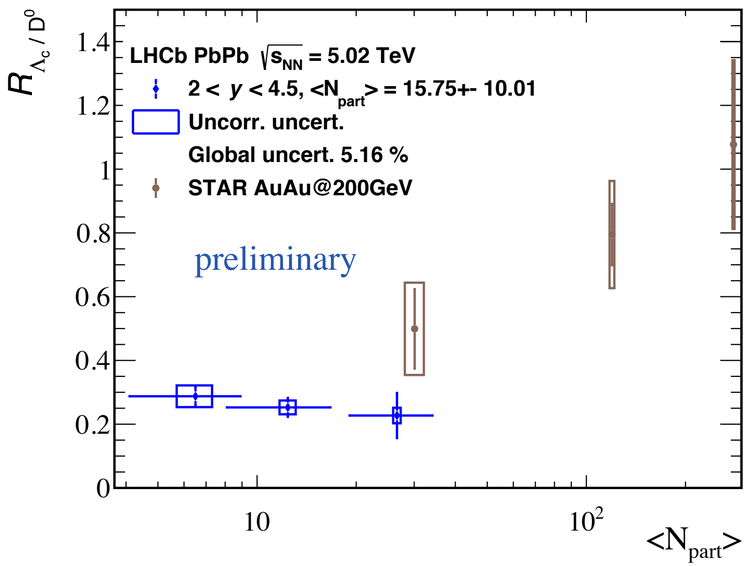
- Flat dependence vs. $\langle N_{part} \rangle$
- Enhancement at intermediate p_T
- Compatible with flat dependence vs. rapidity

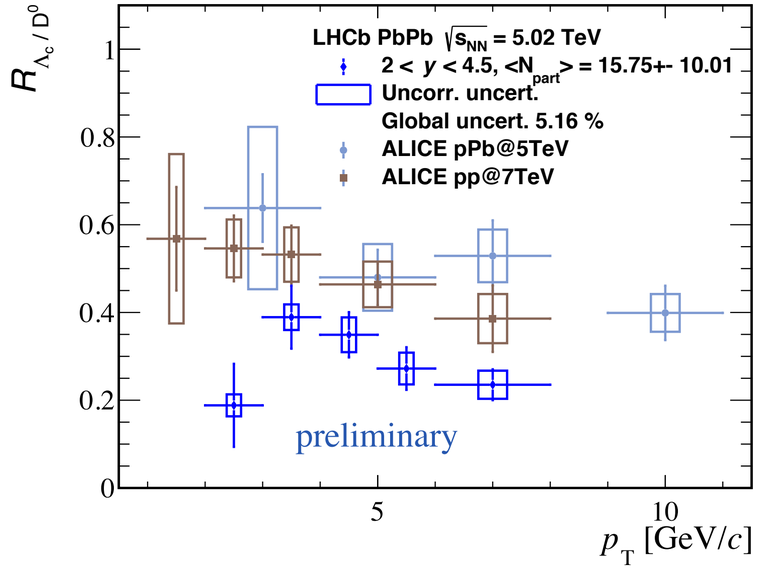
  - $\langle \Lambda_c^+/D^0 \rangle \sim 0.27$
  - PYTHIA8 + Color Reconnection: compatible with data within 3σ
  - Standard Hadronization Model is above the data
  - Needs better understanding of charm hadronization

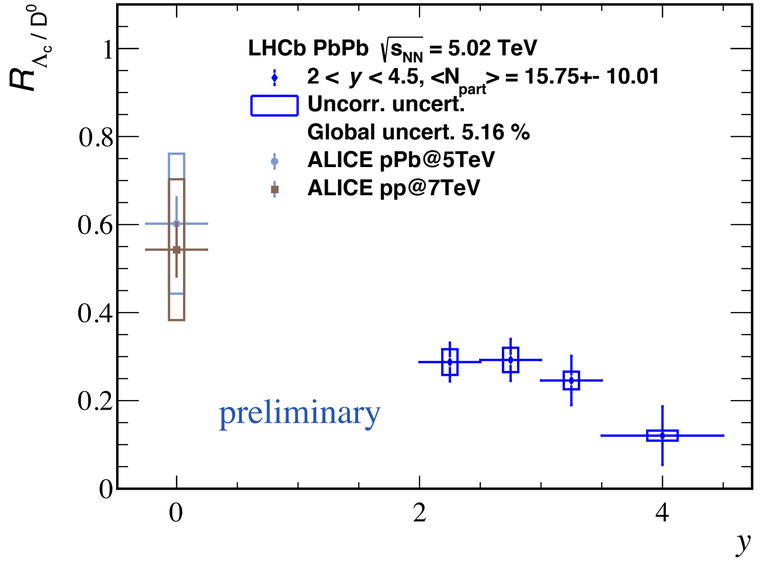
Λ_c^+/D^0 production ratio in peripheral PbPb collisions at 5 TeV

Comparison to other experiments

LHCb-PAPER-2021-046, in preparation







- Compatible with STAR at overlapping $\langle N_{part} \rangle$ values
- Similar decreasing trend at $p_T > 4$ GeV/c
- Lower values than ALICE in midrapidity

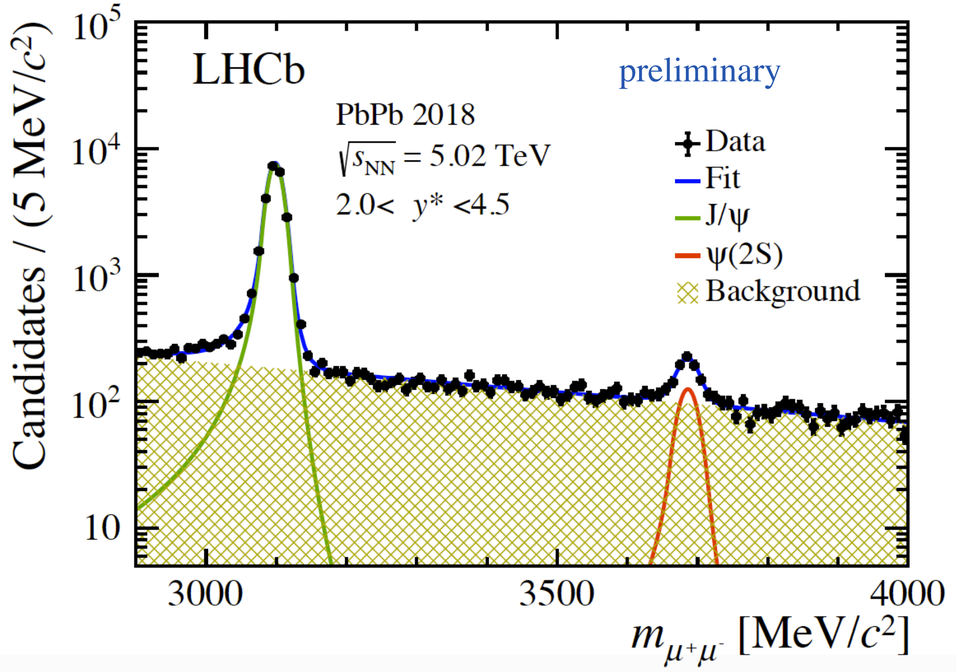
- Λ_c^+/D^0 ratio systematically lower than ALICE measurements in midrapidity
- Λ_c^+/D^0 ratio dependence on rapidity?

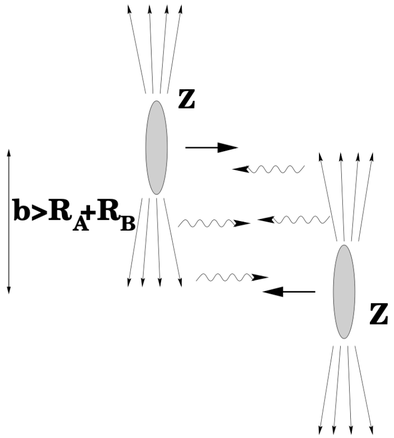
J/ψ photoproduction in ultra peripheral PbPb collisions at 5TeV

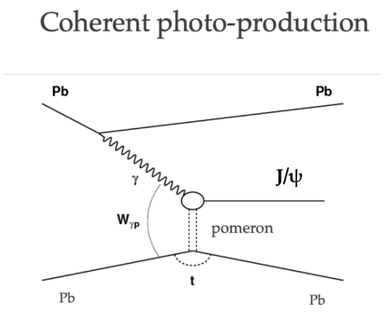
New measurement using PbPb data taken in 2018

LHCb-PAPER-2022-012, in preparation

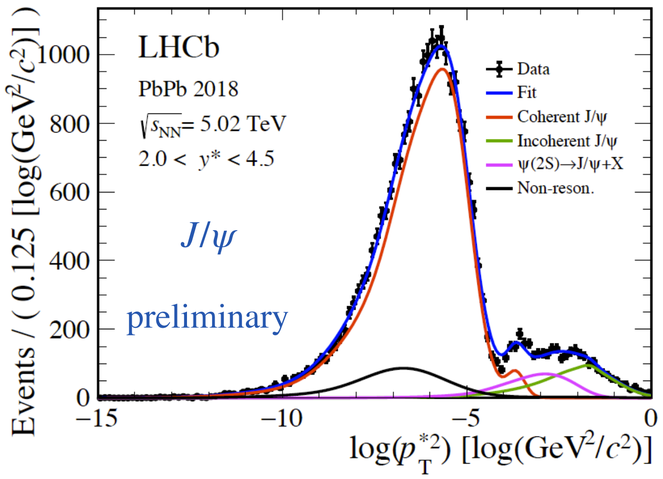
- Impact parameter $b > R_1 + R_2$
- No actual hadronic collisions
- Interaction through the quasi real-photon cloud from one or both nuclei
- Photon flux $\propto Z^2 \rightarrow$ reaction rate $\propto Z^4$
- Vector meson produced with the interaction between a photon and a pomeron
- Probe the nuclear gluon distribution functions at a hard scale $Q^2 \approx m^2/4$

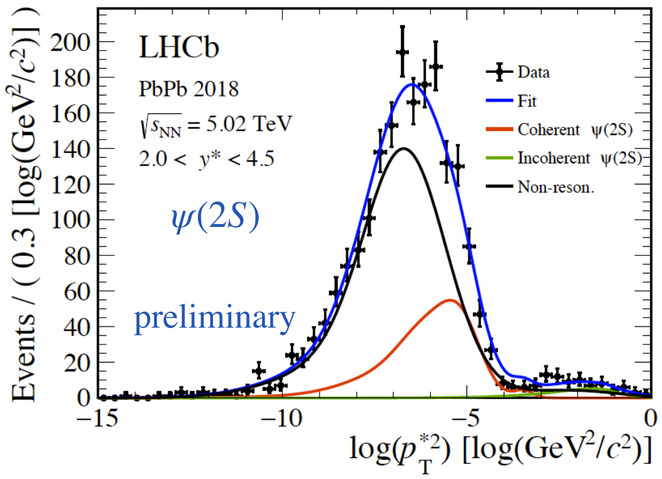






$\gamma(pomeron) \rightarrow J/\psi$

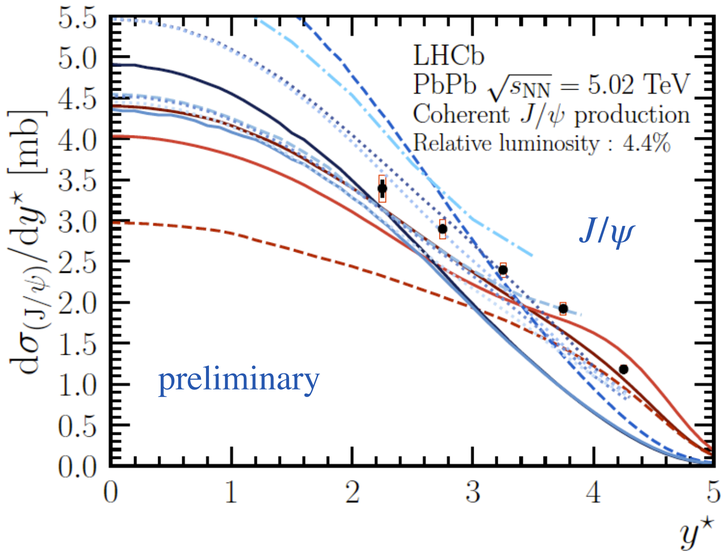


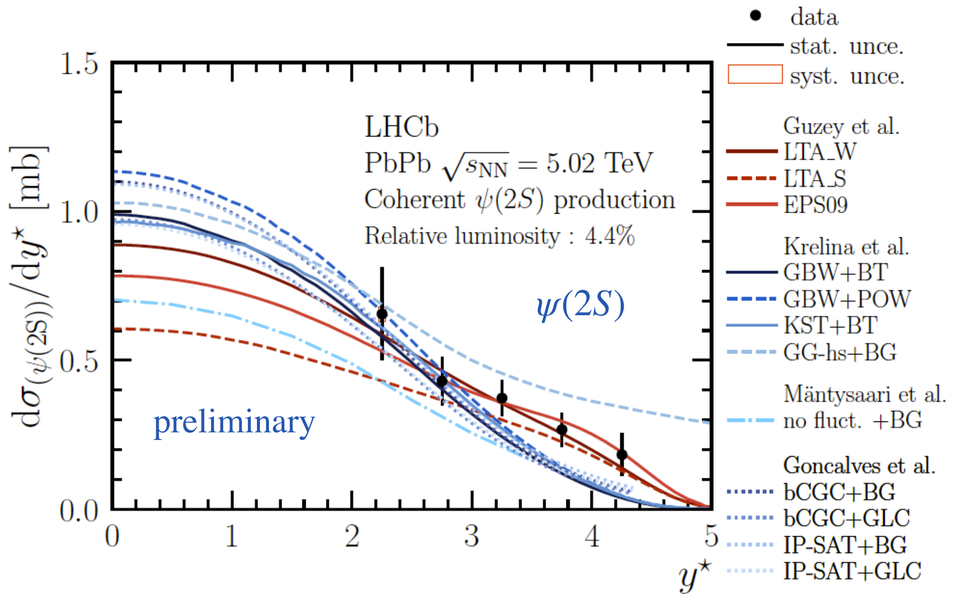


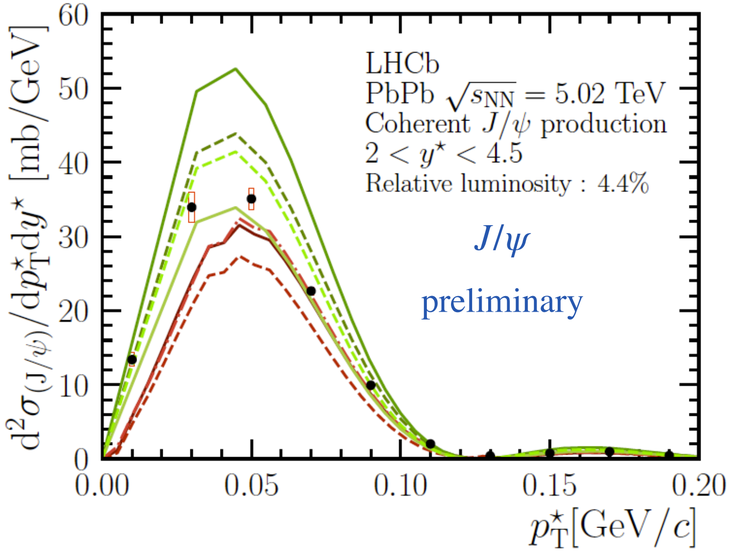
J/ψ photoproduction in ultra peripheral PbPb collisions at 5TeV

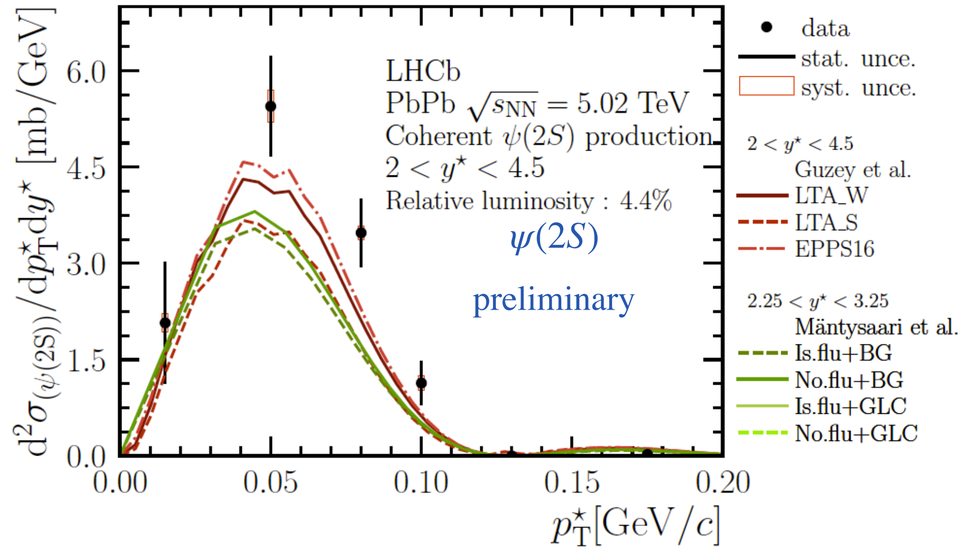
Differential cross-section

LHCb-PAPER-2022-012, in preparation







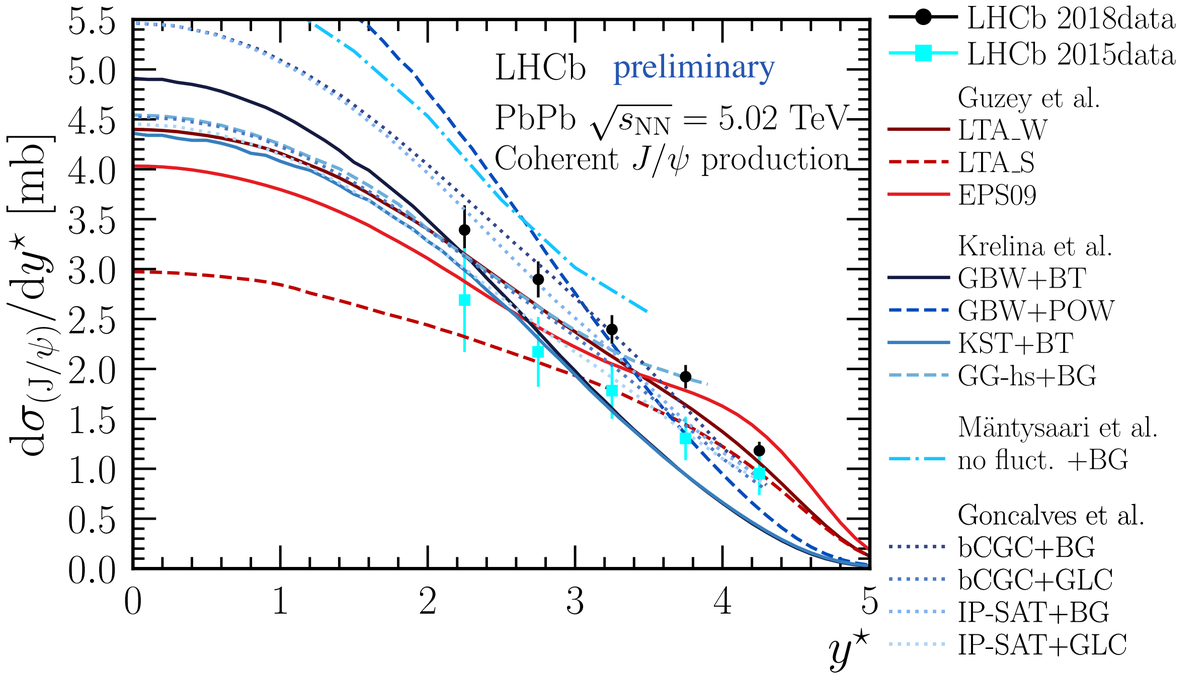


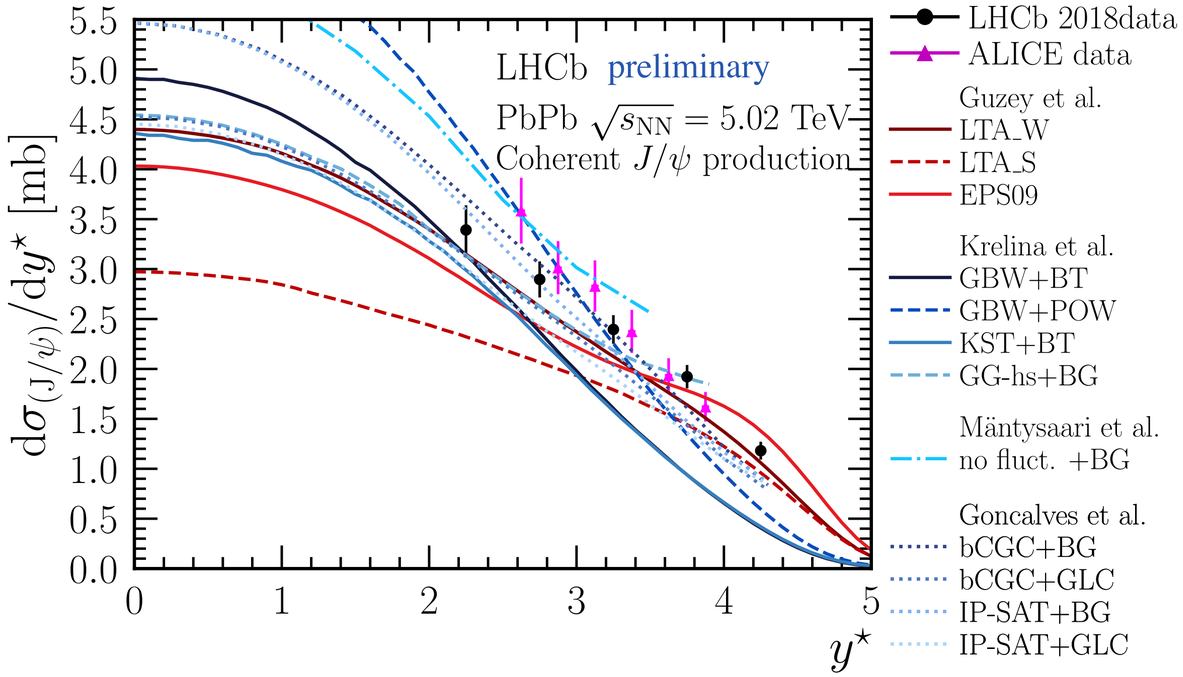
- First coherent $\psi(2S)$ measurement in forward rapidities at the LHC
- First measurement of coherent charmonia cross-section vs. p_T in PbPb UPC
- **Reasonable description of data by models based on nPDF/CGC.**

J/ψ photoproduction in ultra peripheral PbPb collisions at 5TeV

Comparison to 2015 measurement

LHCb-PAPER-2022-012, in preparation
arXiv:2107.03223

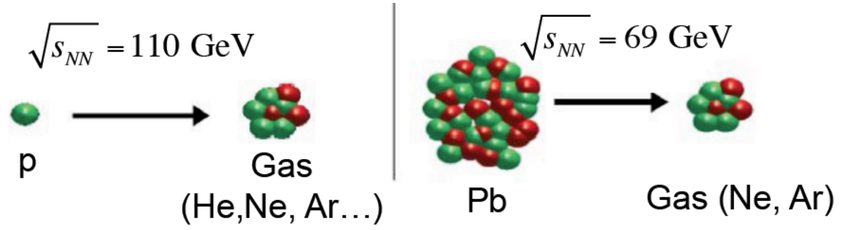


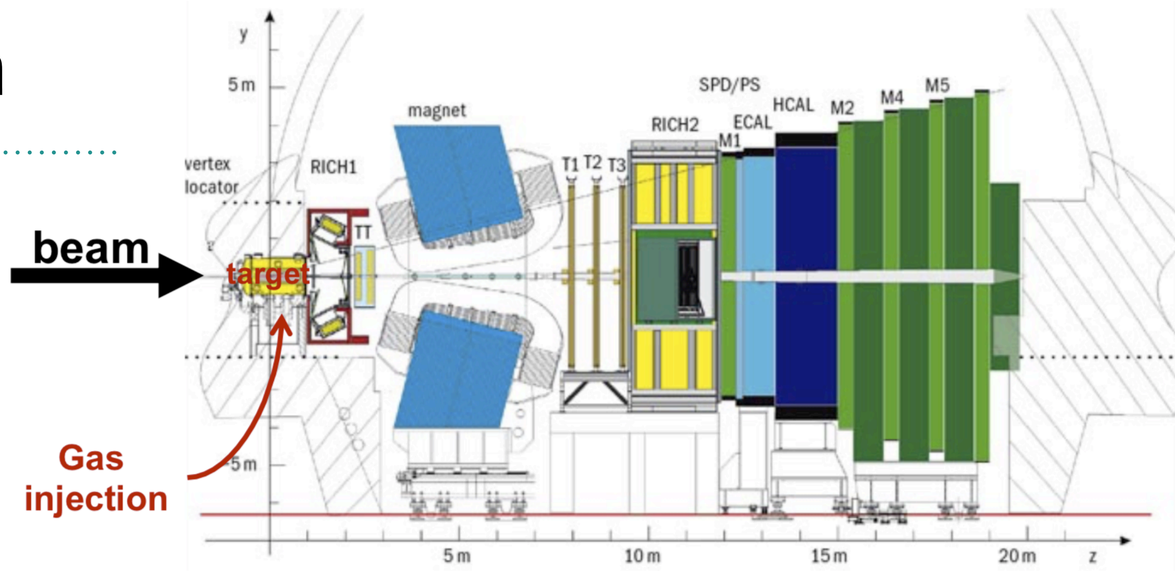


- New results is above the older 2015 measurement by 2.0σ
- Compatible with ALICE data

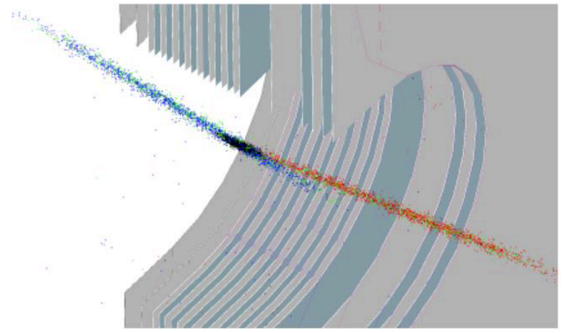
SMOG: fixed-target program

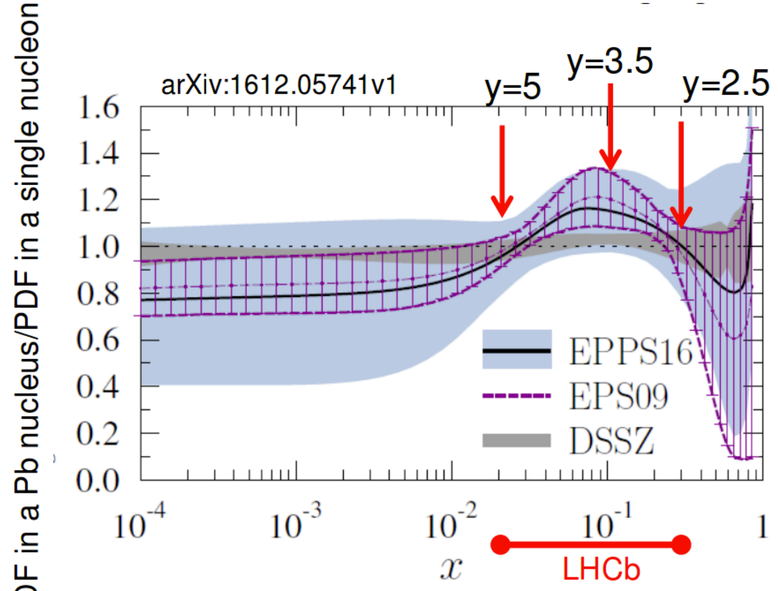
Fixed target mode

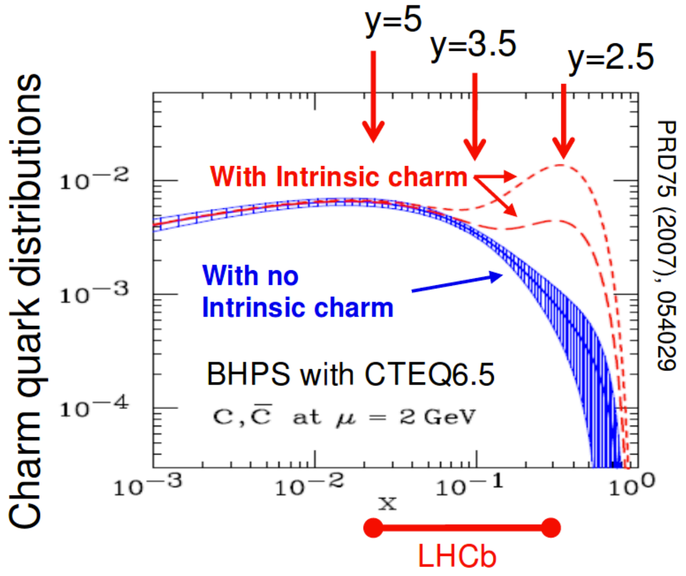




- SMOG: System for Measuring Overlap with Gas
- A noble gas (He, Ne, Ar) at ~2×10^{-7} mbar pressure injected into the LHC vacuum around the LHCb interaction region
- Originally used to determine luminosity, since 2015 started to collect fixed-target collision data







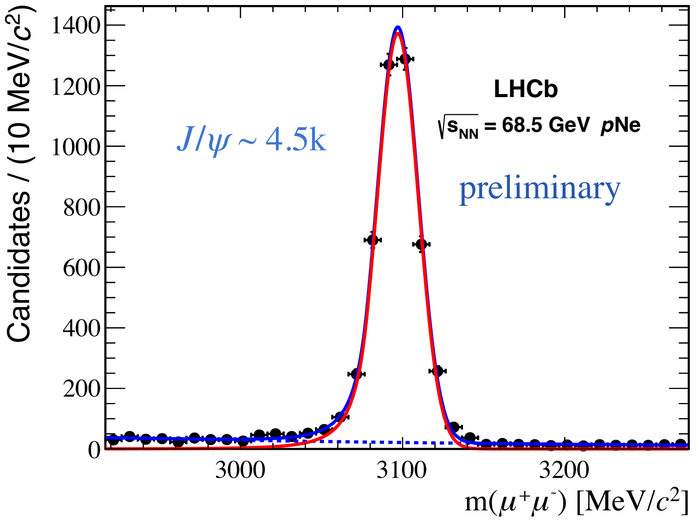
- $\sqrt{s_{\mathrm{NN}}}$ = 69-110 GeV between SPS & RHIC
- $-3.0 < y^* < 0$
- Access nPDF anti-shadowing region
- Probe intrinsic charm content in the nucleon
- **Inputs to astrophysics**

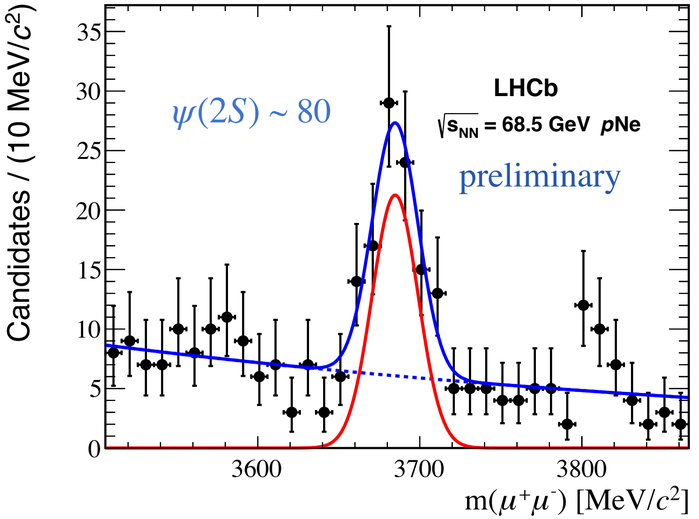
Charmonia in *p*Ne collisions at 68.5 GeV

LHCb-PAPER-2022-014
In preparation

- Charmonium production modified by initial and final state effects in proton-nucleus collisions
  - Modification of PDFs inside nuclei, CGC
  - Nuclear absorption, multiple scattering, energy loss
  - Comovers

- Dataset: collisions of 2.5 TeV protons and neon nuclei at rest ==> $\sqrt{s_{\mathrm{NN}}} = 68.5$ GeV
- Luminosity $21.7 \pm 1.4\ nb^{-1}$
- Center-of-mass rapidity coverage: $-2.3 < y^{*} < 0$

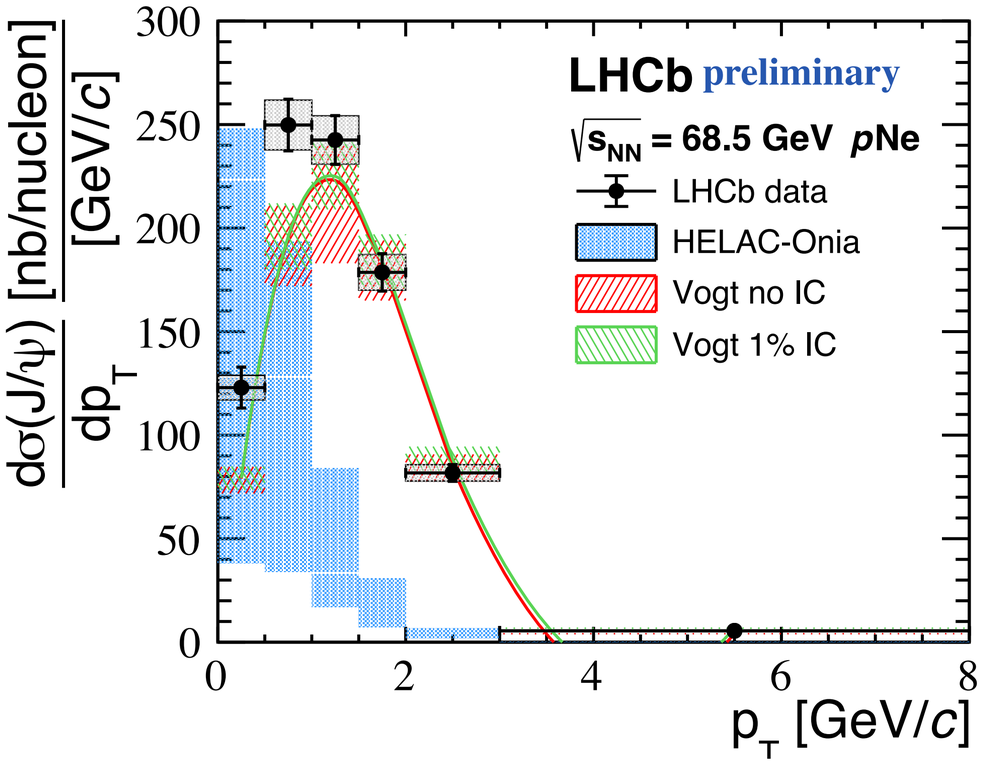


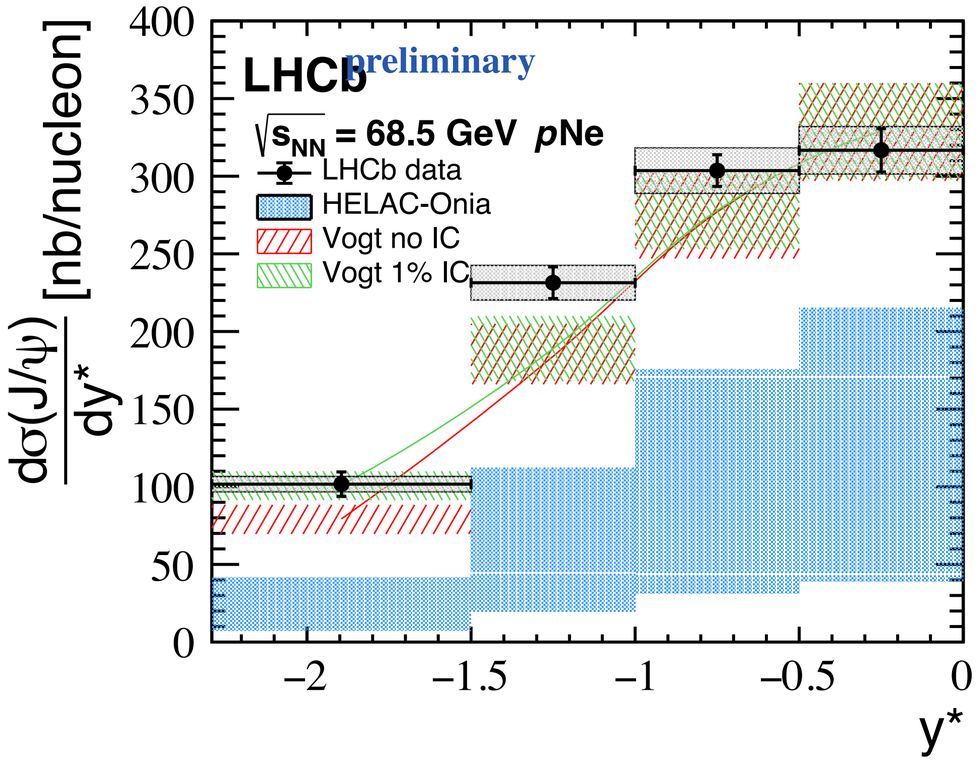


Charmonia in *p*Ne collisions at 68.5 GeV

LHCb-PAPER-2022-014
In preparation

Differential J/ψ production cross-section

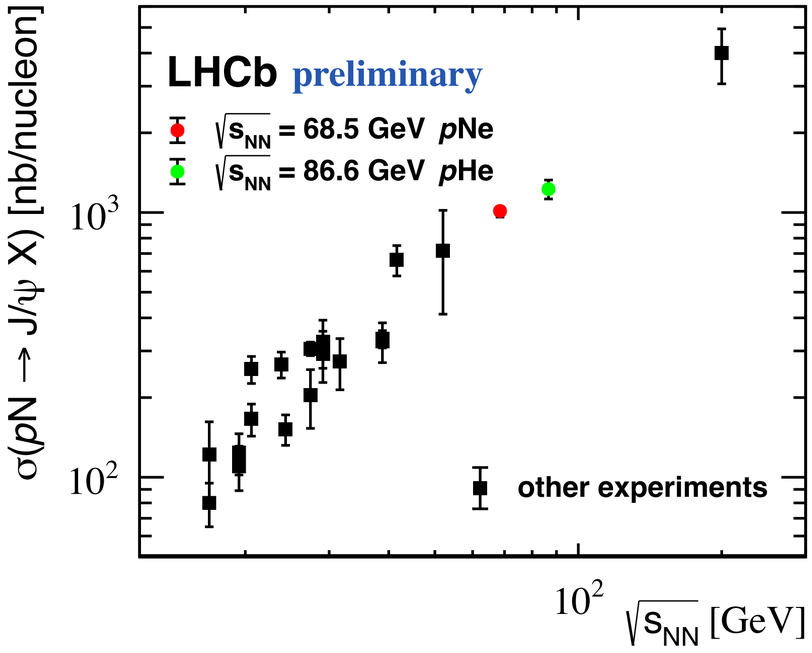


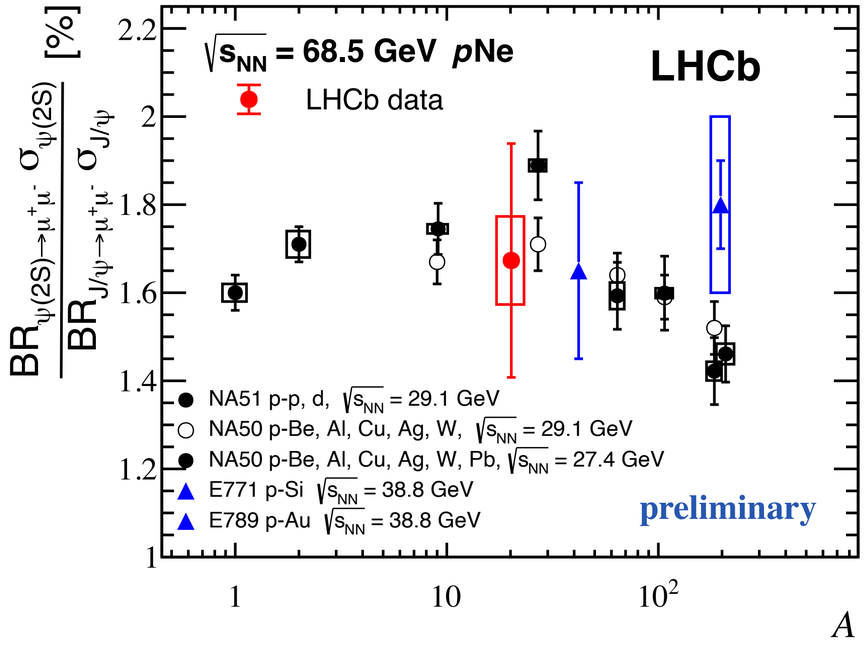


- HELAC-ONIA using CT14NLO and nCTEQ15 under predicts the data
- **Good agreement with predictions with (1%) and without an Intrinsic Charm contribution** [PRC103 (2021) 035204]

Charmonia in *p*Ne collisions at 68.5 GeV

LHCb-PAPER-2022-014
In preparation



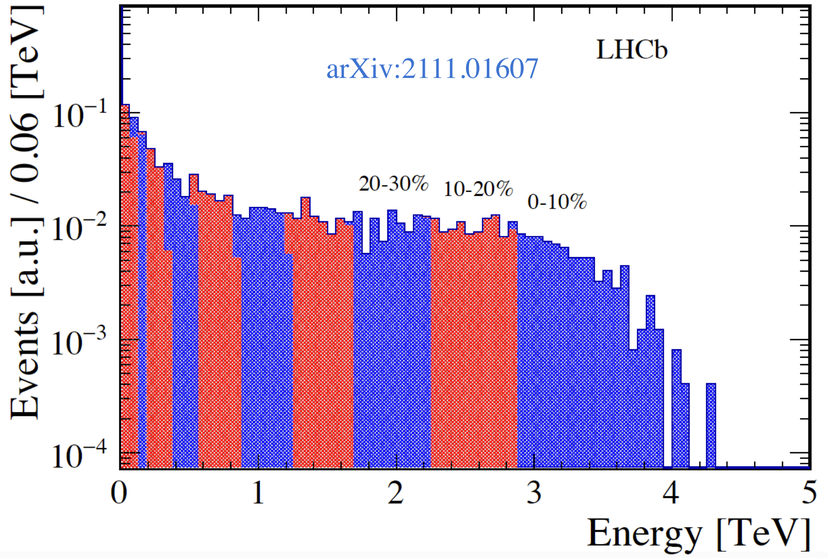


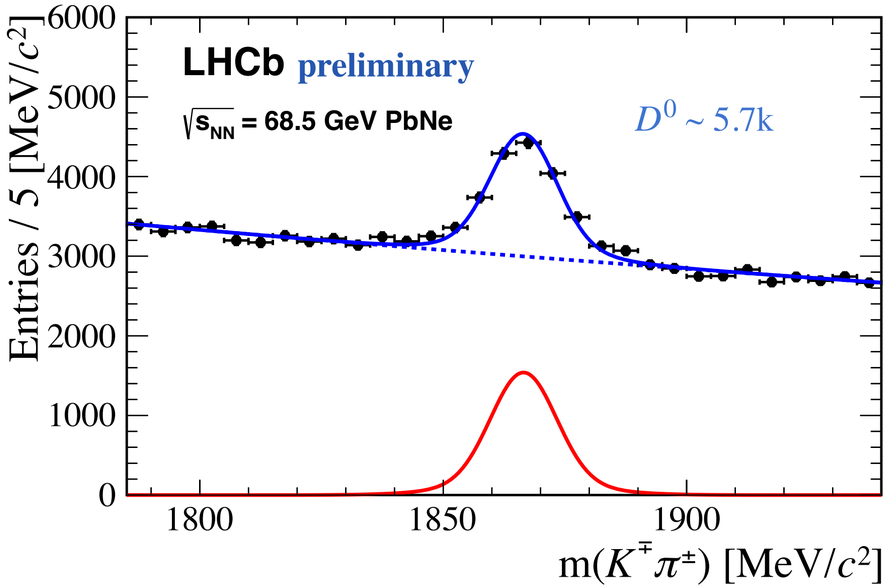
- Total J/ψ cross-section: extrapolation to full phase space using Pythia8+CT09MCS PDF, assuming forward-backward symmetry.
  - shows a power-law dependency with the center-of-mass energy $\sqrt{s_{NN}}$
- $\psi(2S)$ to J/ψ production ratio in good agreement with other proton-nucleus measurements at small values of target atomic mass number, A.
- **The first measurement of $\psi(2S)$ to J/ψ production ratio with SMOG**

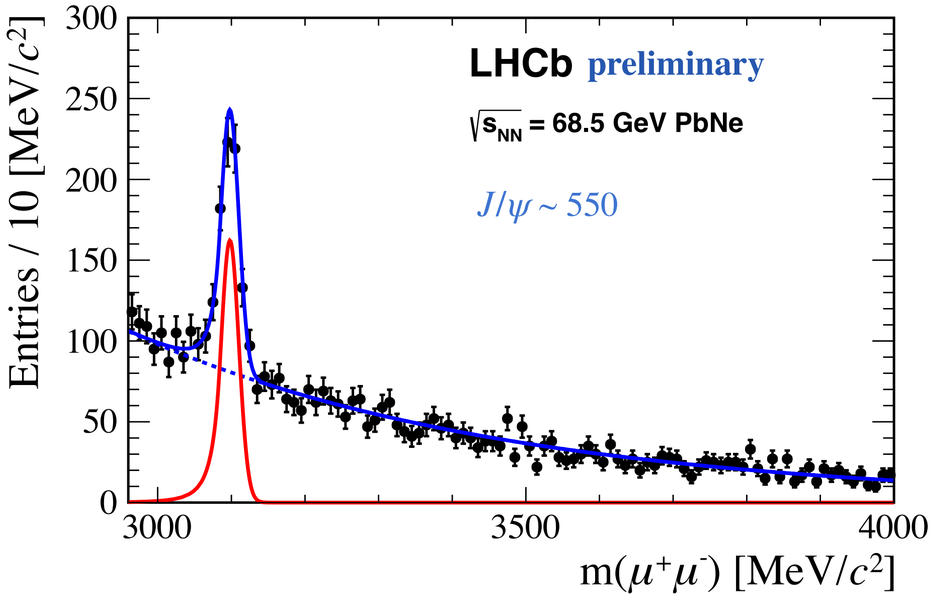
D^0 and J/ψ in PbNe collisions at 68.5 GeV

LHCb-PAPER-2022-011, in preparation

- **The first measurement in fixed-target nucleus-nucleus collisions at the LHC, a milestone for the SMOG program**
- Search for the potential formation of quark-gluon plasma. Look for the onset of the transition from ordinary hadronic matter to the QGP.
- Suppression of charmonium $c\bar{c}$ bound states due to presence of the hot and dense medium
- Dataset: 2.5 TeV lead ions incident on neon nuclei ==> $\sqrt{s_{\mathrm{NN}}} = 68.5$ GeV
- PbNe centrality determined by energy in ECal



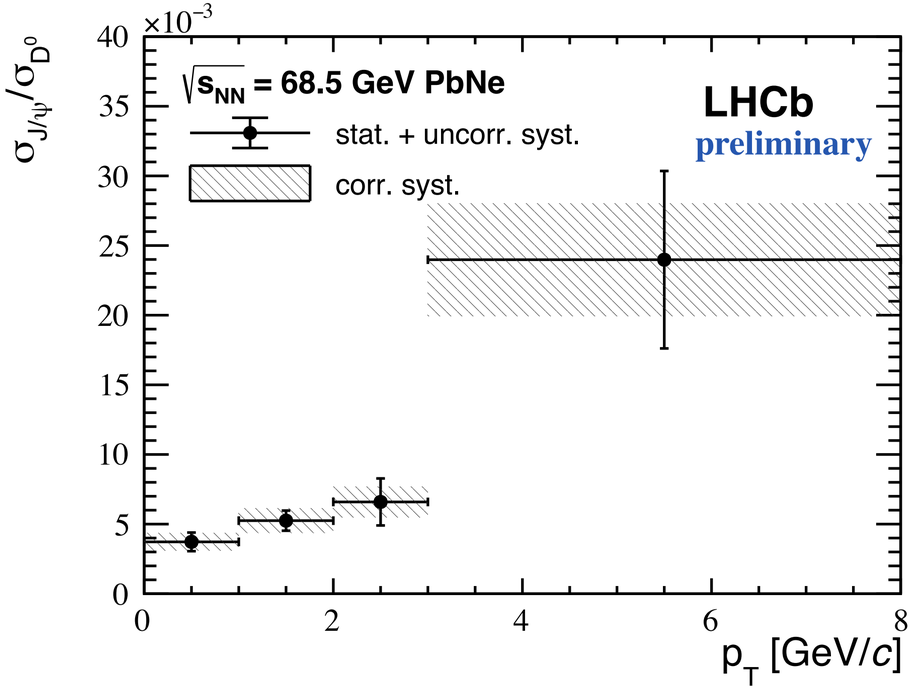




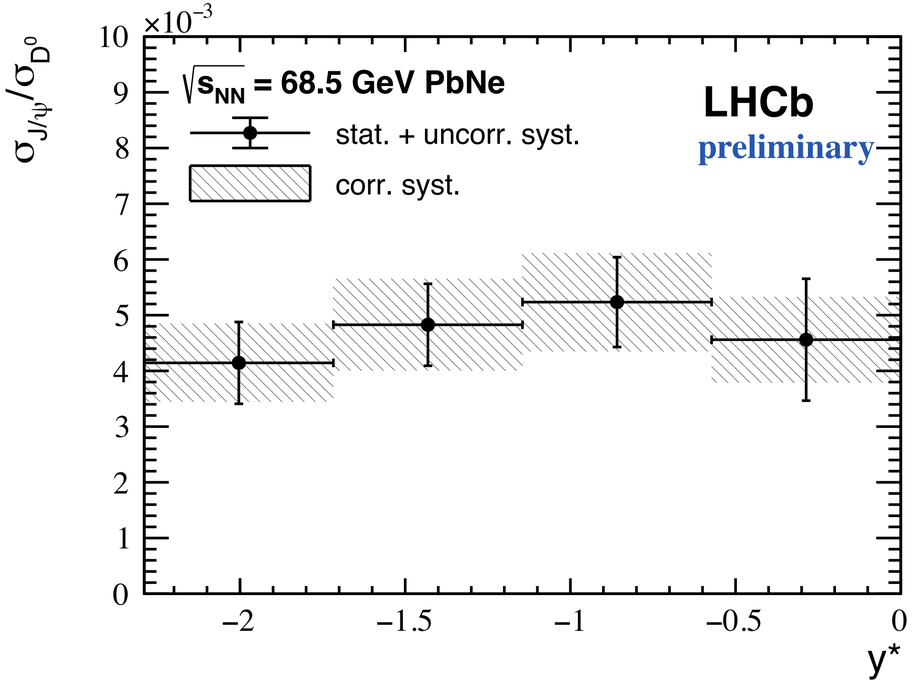
D^0 and J/ψ in PbNe collisions at 68.5 GeV

LHCb-PAPER-2022-011
In preparation

Production ratio J/ψ / D^0 vs. p_T and y*



- Depends strongly on p_T



- Compatible with no dependence on rapidity

- Suppression of $c\bar{c}$ bound states: measure charmonium together with the overall charm quark production
- The production of D^0 mesons reflects a large fraction of the overall charm quark production
- D^0 acts as a reference for studying quarkonium modification inside nuclear medium

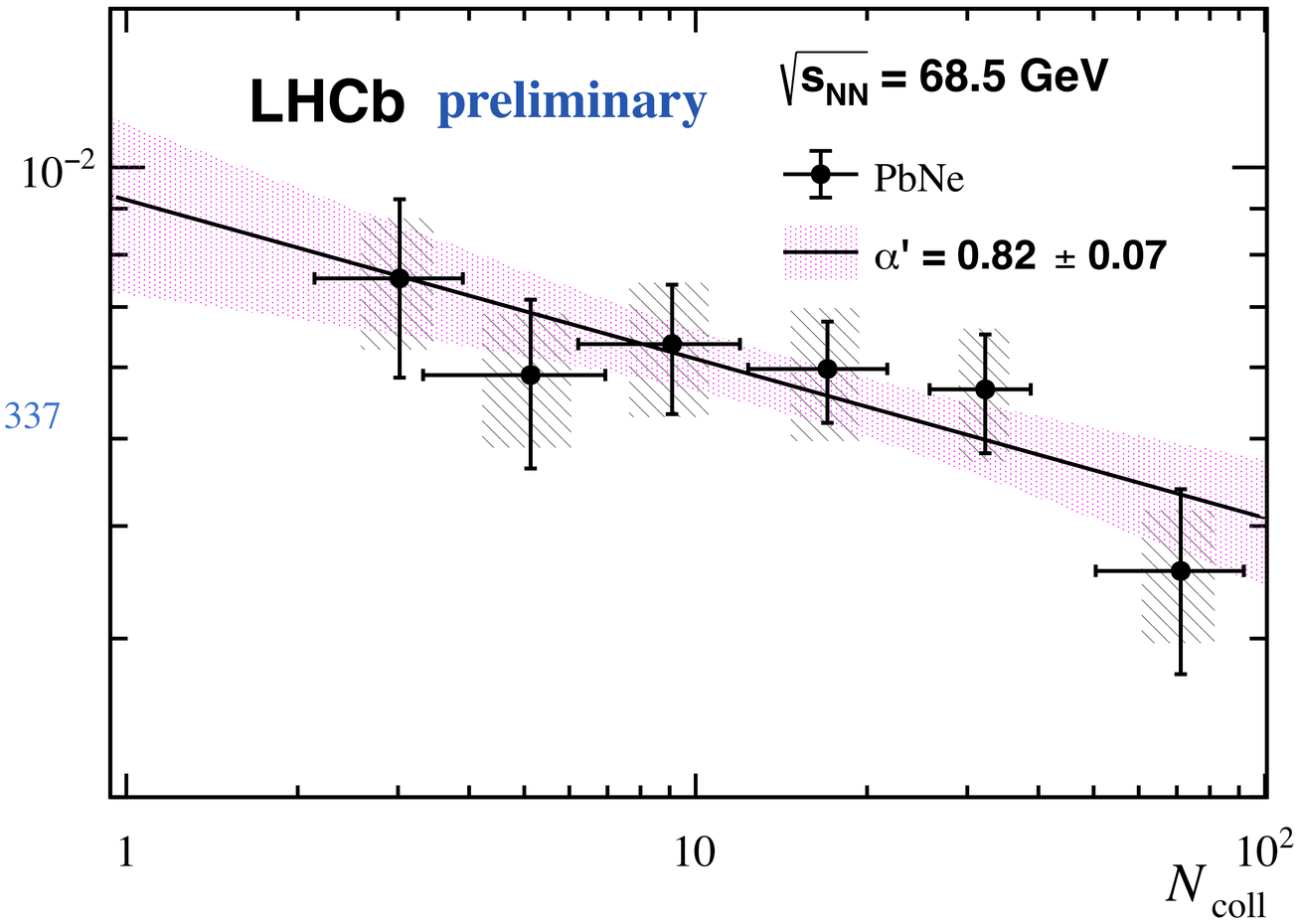
D^0 and J/ψ in PbNe collisions at 68.5 GeV

LHCb-PAPER-2022-011
In preparation

J/ψ / D^0 ratio as a function of N_{coll}

- Assuming $\sigma_{J/\psi} \propto \langle N_{coll} \rangle^{\alpha'}$ and $\sigma_{D^0} \propto \langle N_{coll} \rangle$

  ==> $\sigma_{J/\psi}/\sigma_{D^0} \propto \langle N_{coll} \rangle^{\alpha'-1}$
- $\alpha' = 0.82 \pm 0.07$
- Agree with measurements from proton-nucleus collisions by NA50 Phys. Lett. B 410 (1997) 337
- J/ψ production affected by additional nuclear effects compared to D^0
- **No anomalous J/ψ suppression is observed that could indicate the formation of QGP**



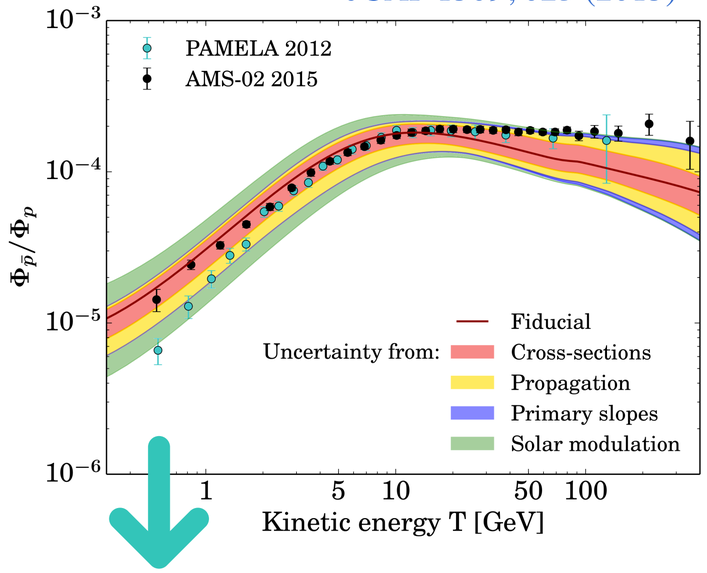
Detached antiproton in *p*He collisions at 110 GeV

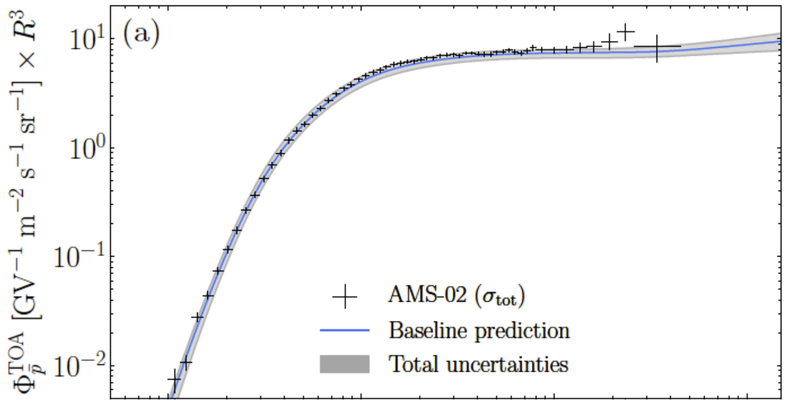
LHCb-PAPER-2022-006, in preparation

SMOG input to astrophysics

- **$\bar{p}/p$ in cosmic rays sensitive to a possible dark matter contribution**
- Precise $\bar{p}$ production cross-section in interstellar medium (H and He) necessary to interpretation data
- A first measurement of prompt $\bar{p}$ production in *p*He collisions at 110 GeV using SMOG PRL 121 (2018) 222001
- Extending the first measurement: antiproton from anti-hyperon decays (detached $\bar{p}$)

JCAP 1509, 023 (2015)





Phys. Rev. Research 2, 023022 (2020)

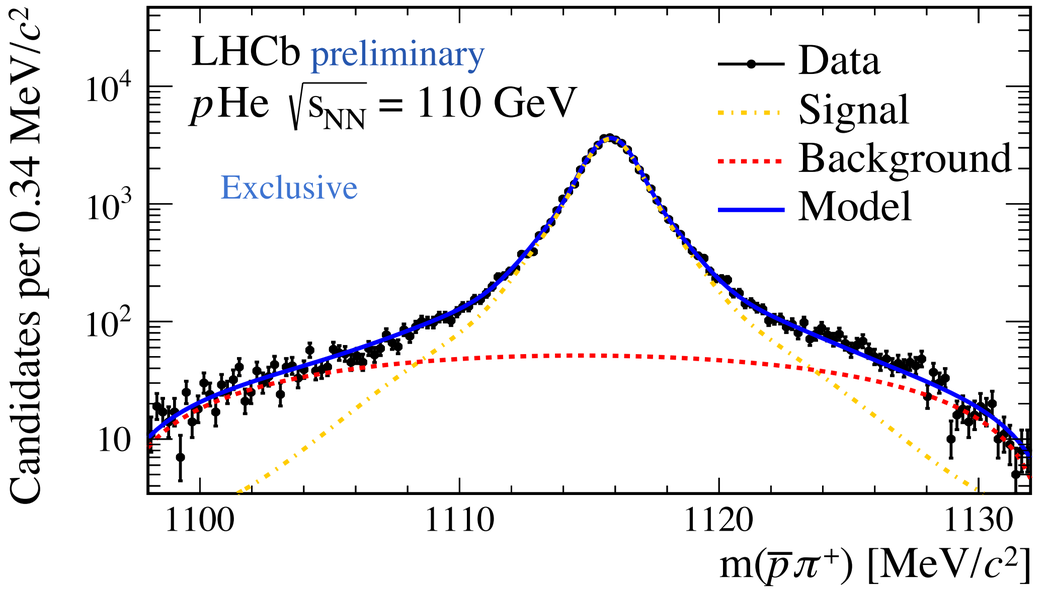
Detached antiproton in *p*He collisions at 110 GeV

LHCb-PAPER-2022-006, in preparation

Exclusive measurement (signal based):

- Dominant anti-hyperon contribution from $\overline{\Lambda}$ exclusively reconstructed
- $\overline{\Lambda} \to \bar{p}\pi^+$: $(50.7 \pm 0.3) \times 10^3$ candidates

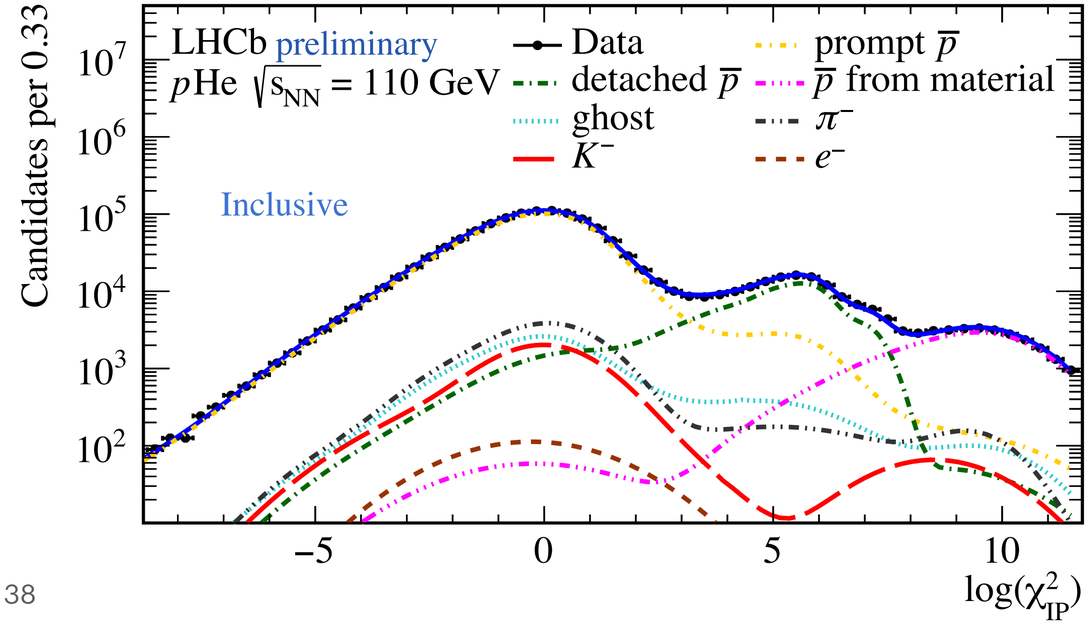
$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda} X \to \bar{p}\pi^+ X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}$$



Inclusive measurement (track based):

- Anti-hyperon $\overline{H} = \overline{\Lambda}, \overline{\Sigma}, \overline{\Xi}, \overline{\Omega}$
- template fit of $\bar{p}$ impact parameter:
  - Prompt, detached, secondary collisions from materials

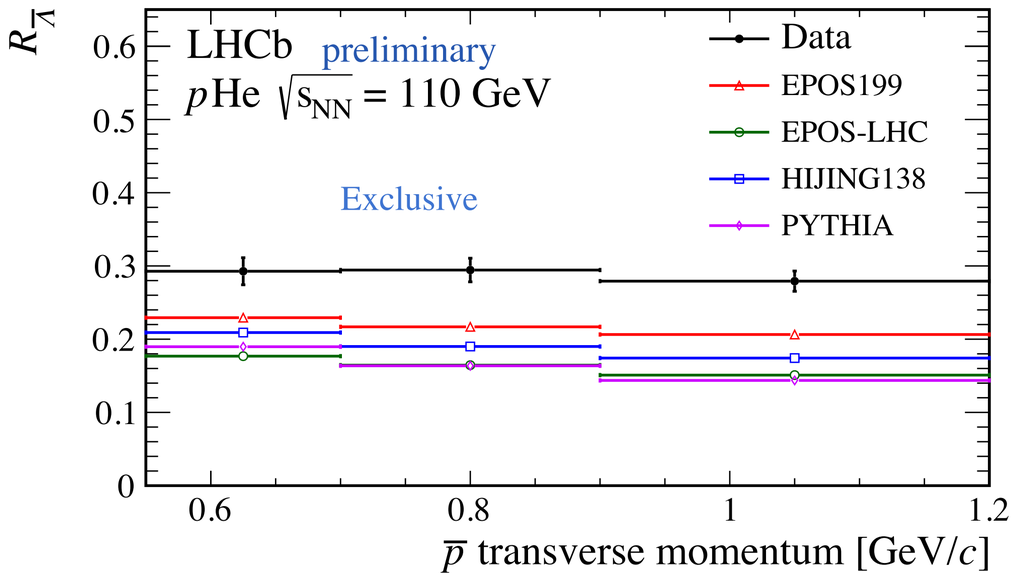
$$R_{\overline{H}} \equiv \frac{\sigma(p\mathrm{He} \to \overline{H} X \to \bar{p} X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}$$



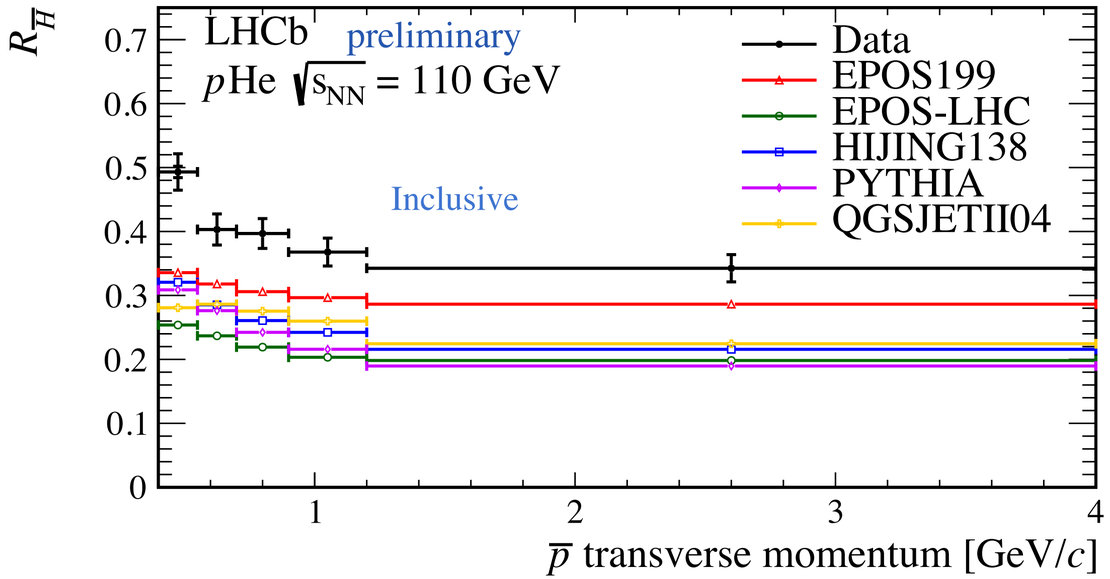
LHCb-PAPER-2022-006
In preparation

Detached antiproton in *p*He collisions at 110 GeV

$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda} X \to \bar{p}\pi^{+} X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}$$



$$R_{\bar{H}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{H} X \to \bar{p} X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}$$



- **Indicate a sizable underestimation of detached $\bar{p}$ contribution in most hadronic production models used in cosmic ray physics**

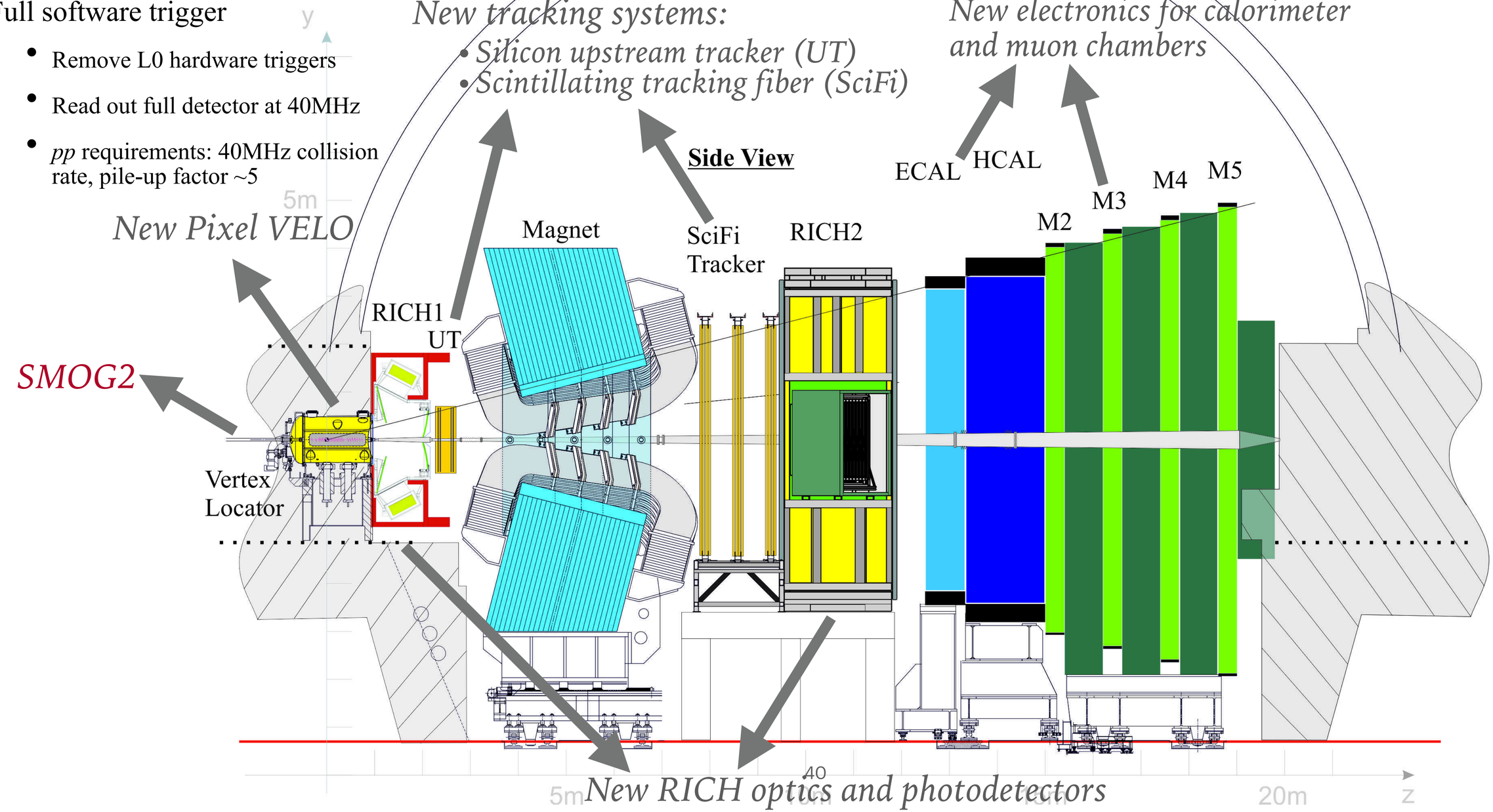
LHCb phase-I upgrade

Full software trigger

- Remove L0 hardware triggers
- Read out full detector at 40MHz
- *pp* requirements: 40MHz collision rate, pile-up factor ~5

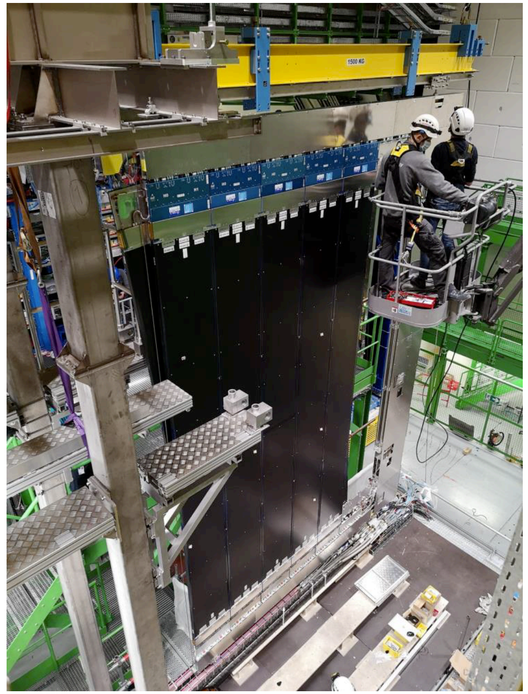
New tracking systems:
- *Silicon upstream tracker (UT)*
- *Scintillating tracking fiber (SciFi)*

New electronics for calorimeter and muon chambers

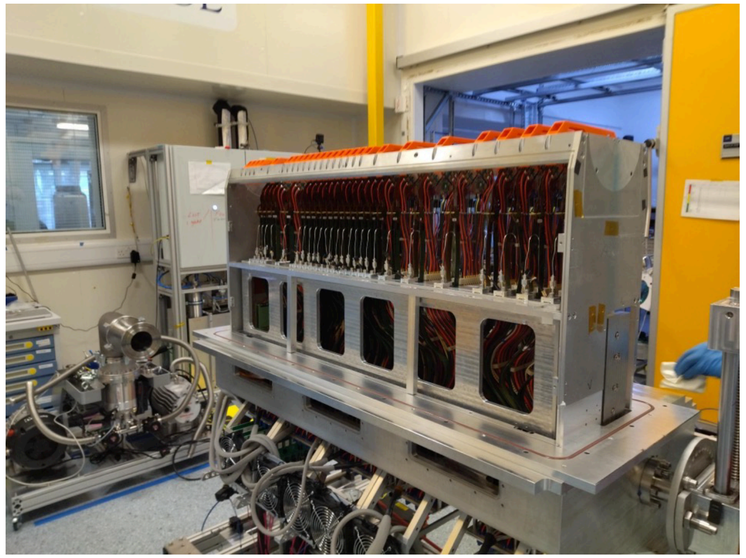


LHCb phase-I upgrade

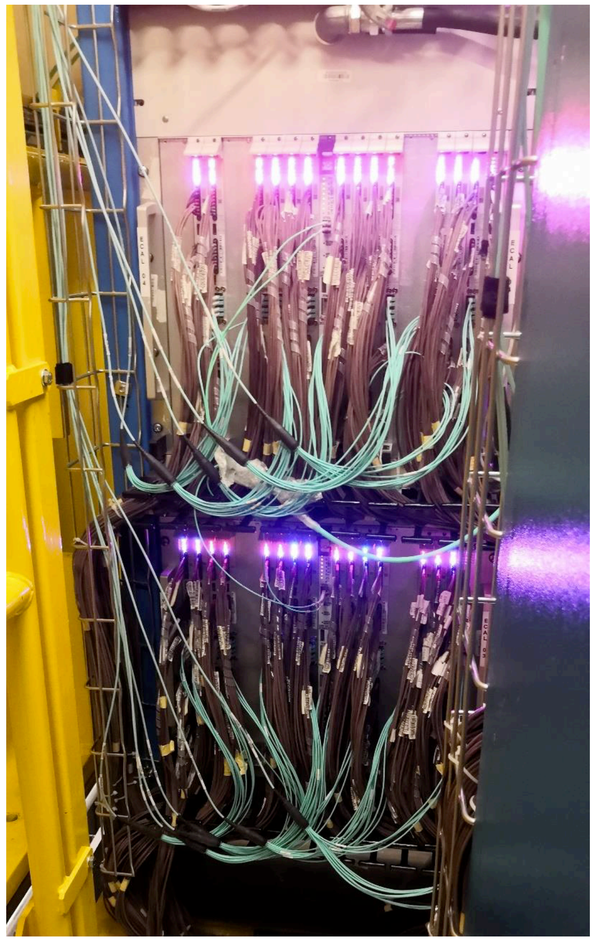
SciFi



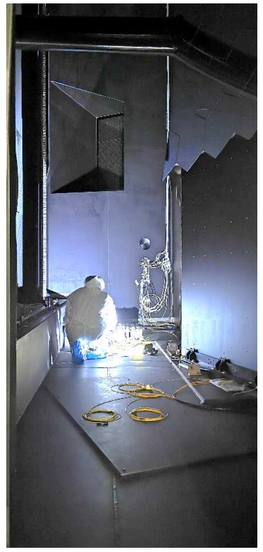
VELO

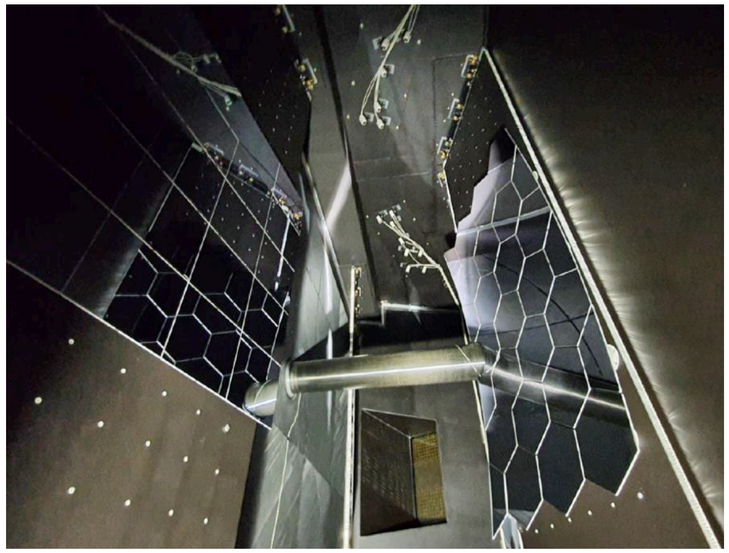


CALO

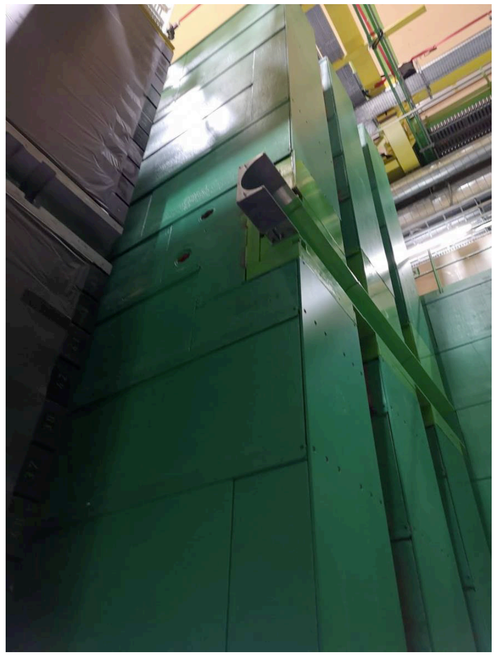


RICH

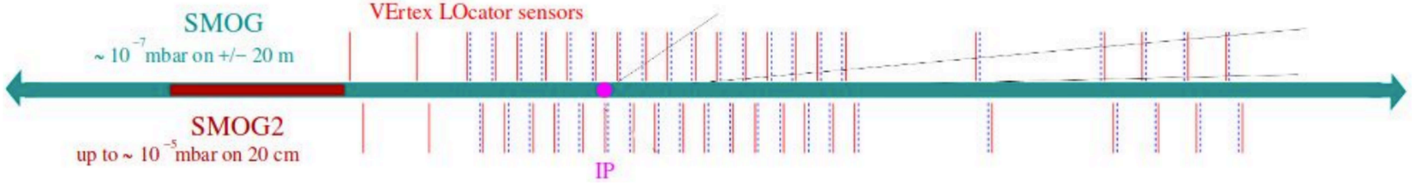




MUON



SMOG2

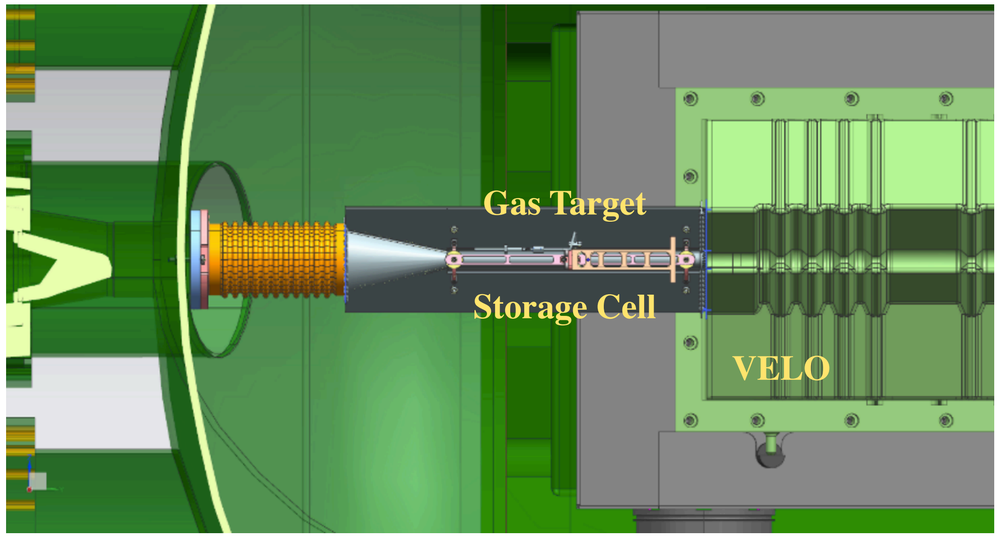


- SMOG2: Storage Cell for the gas upstream of the nominal IP (z in [-500, -300] mm) and precisely calibrated Gas Feed System.
  - Gas density increased by up to two orders of magnitude → much higher luminosity
  - More gas targets: H_2, D_2, He, N_2 , O_2, Ne, Ar, Kr, Xe
- beam-beam and beam-gas separate luminous regions:

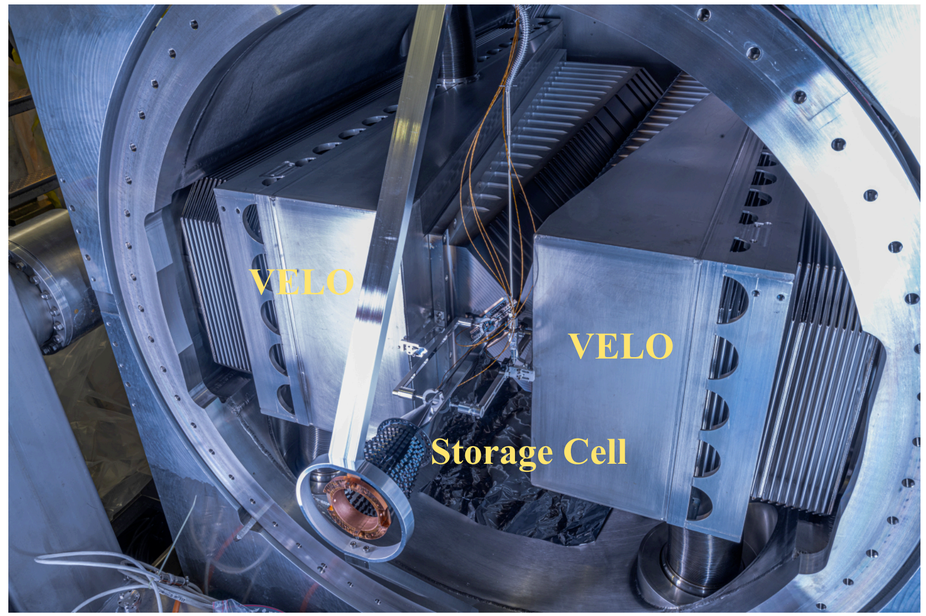
  → simultaneous *pp*-SMOG2 data-taking

  → large statistics
- Physics: LHCb-PUB-2018-015
  - Intrinsic heavy-quark
  - p-Gas collisions: nPDFs, gluon anti-shadowing at large x, cold nuclear matter effects
  - Pb-Gas collisions: QGP formation, rapidity scan at lower energy
  - Astrophysics

No centrality limitation!



LHCb-TDR-020



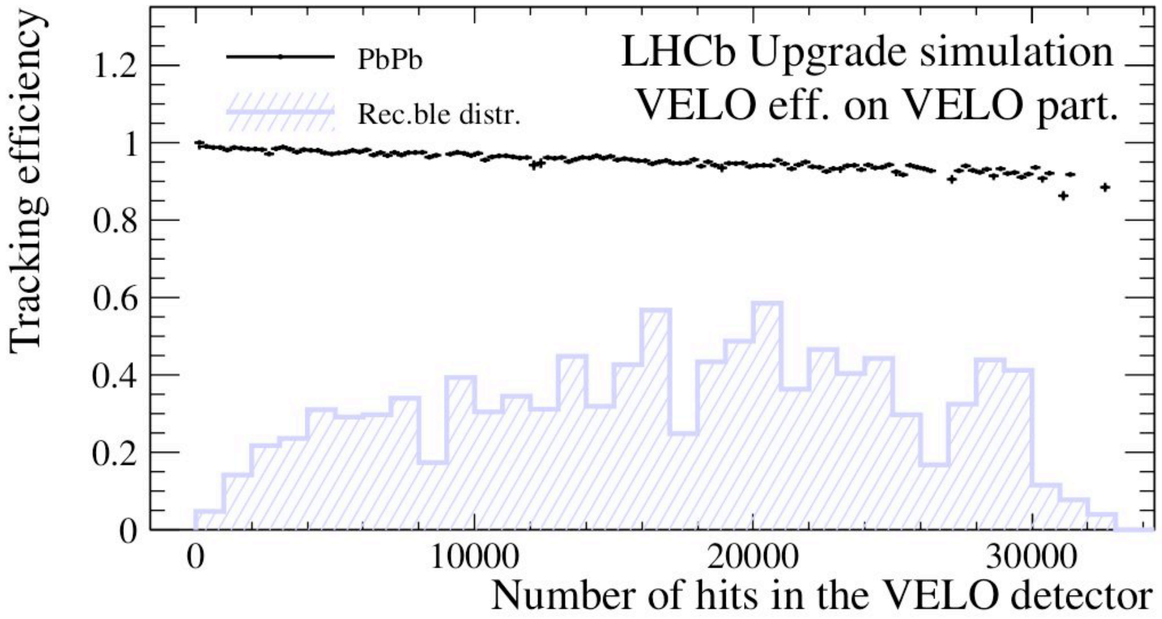
LHCb phase-I upgrade

Performance results

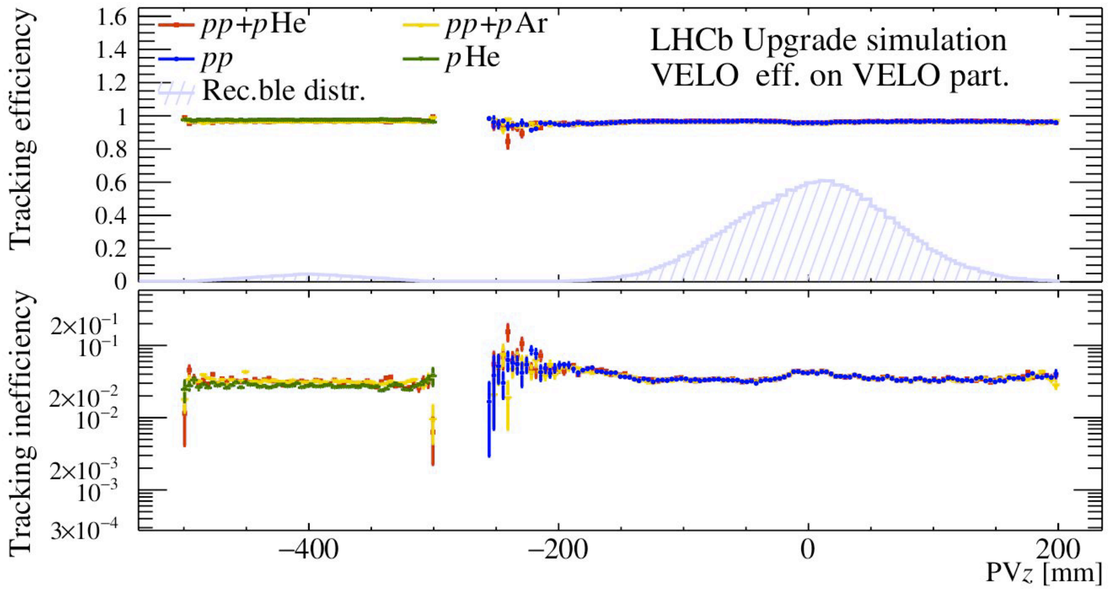
LHCb-FIGURE-2022-002

- PbPb: track reconstruction up to 30% centrality in PbPb collisions —> study QGP effects
- SMOG2: simulation studies of simultaneous beam-beam and SMOG2 data taking find no show stopper so far

PbPb



SMOG2



Conclusion

A few highlights

- Precision measurements of $h^{\pm}$, π^0 and D^0 production in pPb collisions
  - Forward rapidity: precisely pin down nPDF at small x
  - Backward rapidity: models cannot reproduce data, additional effects beyond nPDF
- Enhanced B_s^0/B^0 ratio in high multiplicity pp collisions
- First exotic $\chi_{c1}(3872)$ measurement in pPb
- Λ_c^+/D^0 ratio in PbPb
- First and precise measurement of coherent charmonia p_{T} spectra in UPC PbPb collisions
- First SMOG nucleus-nucleus result!

Conclusion

Thanks for your attention!

- LHCb has a rich heavy ion physics program, with excellent detector performance and unique kinematic coverage.

- After the current upgrade:
- Unlock PbPb collisions up to mid-central events, enabling QGP studies at LHCb
- SMOG2:
  - rich program in unexplored energy and kinematic regions with varying system size
  - high statistics without centrality limitation

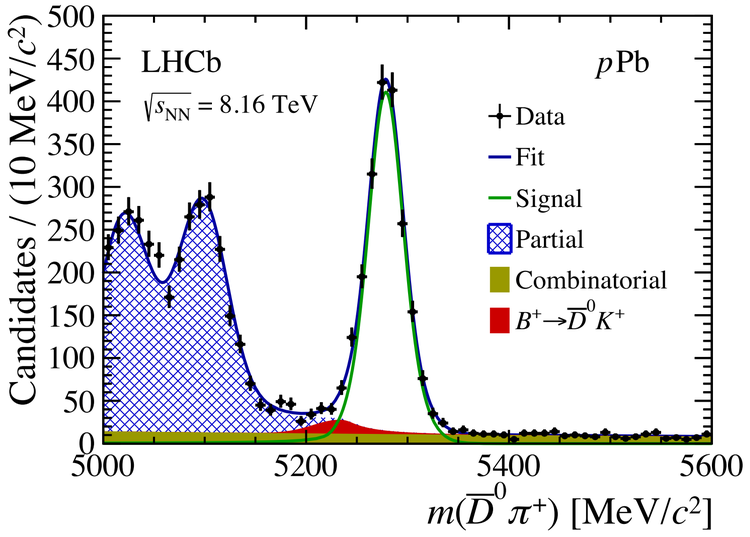
Backup

LHCb in heavy ion physics

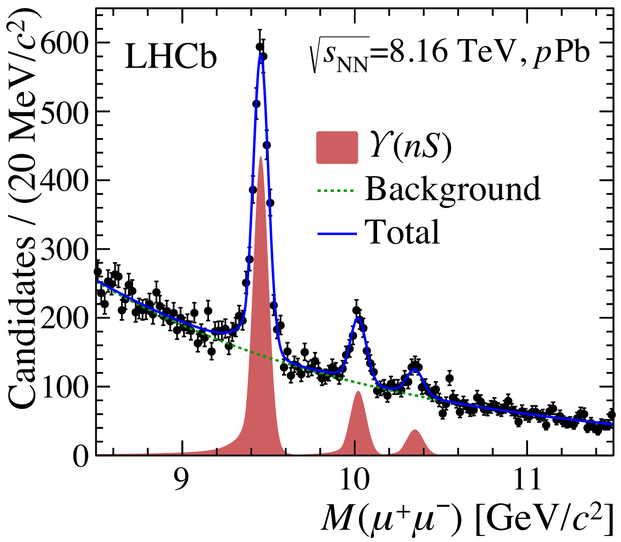
Collider mode centered

- Unique forward rapidity coverage
  - Complementary to experiments at midrapidity
- Precise vertexing, full particle identification, excellent tracking
  - Separation of hadrons originating from *c* and *b* quarks
  - Hadron reconstruction down to very low p_T
  - Heavy flavor is an LHCb specialty

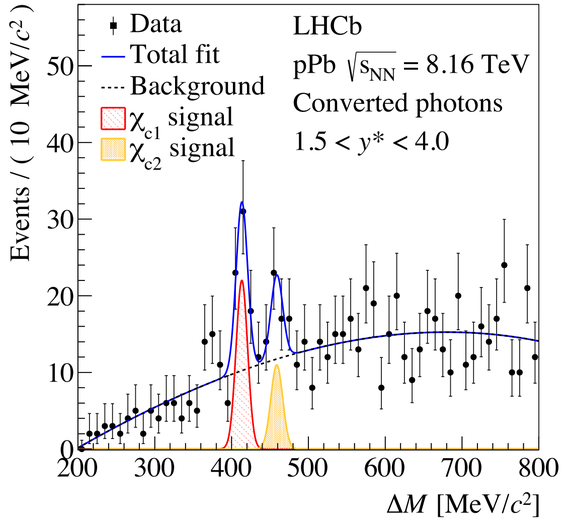
PHYS. REV. D99 052011 (2019)



JHEP 11 (2018) 194



PHYS. REV. C103 (2021) 064905



Overview of heavy ion results

Link to all publications (with references)

- ***pp*, *p*Pb results**
  - **Light flavor**: charged hadron, π^0 production in *p*Pb collisions at 5 and 8.16 TeV, ridge (*p*Pb 5TeV)
  - **Open heavy flavor**: prompt D^0 (*p*Pb 5TeV, 8.16TeV), Λ_c^+ (*p*Pb 5TeV), *b*-hadrons (*pp* 13TeV, *p*Pb 8.16TeV), double charm production (*p*Pb 8.16TeV)
  - **Quarkonia**: J/ψ (*p*Pb 5TeV, 8.16TeV), $\psi(2S)$ (*p*Pb 5TeV), Υ(*p*Pb 5TeV, 8.16TeV), χ_c (*p*Pb 8.16TeV)
  - **Z boson** (*p*Pb 5TeV, 8.16TeV)
  - **Exotica**: $\chi_{c1}(3872)$ (*pp* 8TeV, *p*Pb 8.16TeV)
- **PbPb results**
  - Λ_c^+/D^0 ratio in PbPb collisions
  - Quarkonia photoproduction in UPC and PC PbPb collisions
- **Fixed-target (SMOG) results**
  - Antiproton in *p*He 110 GeV (prompt, detached)
  - Charm production in *p*He, *p*Ne, *p*Ar and PbNe (68-110 GeV)

Prompt charged particles in *p*Pb and *pp* collisions at 5 TeV

$R_{p\mathrm{Pb}}$ vs. p_{T}

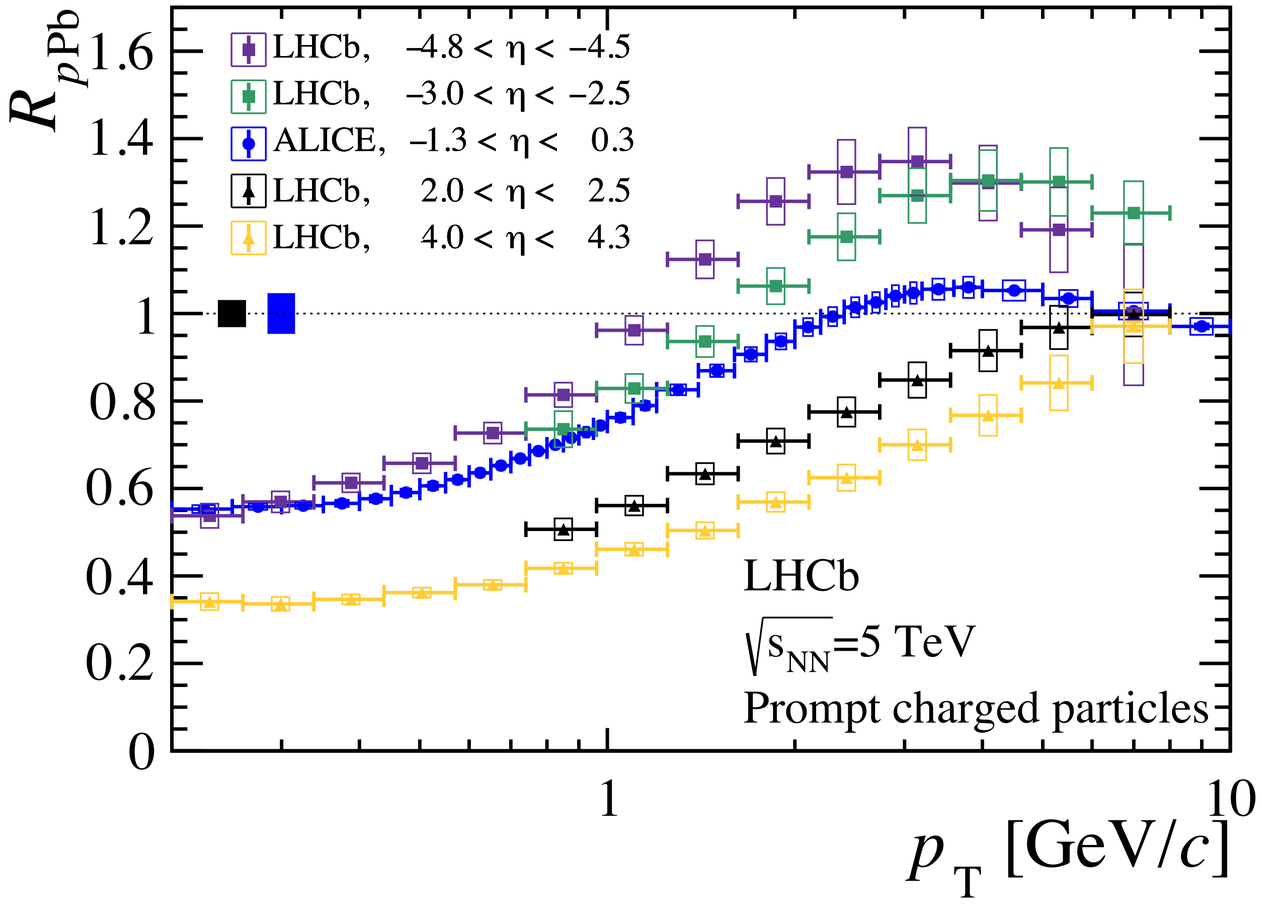
PhysRevLett. 128 (2022)142004

- Nuclear modification factor:

$$R_{p\mathrm{Pb}} = \frac{1}{A}\frac{d^2\sigma_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/d\eta dp_{\mathrm{T}}}{d^2\sigma_{pp}(\eta, p_{\mathrm{T}})/d\eta dp_{\mathrm{T}}}$$

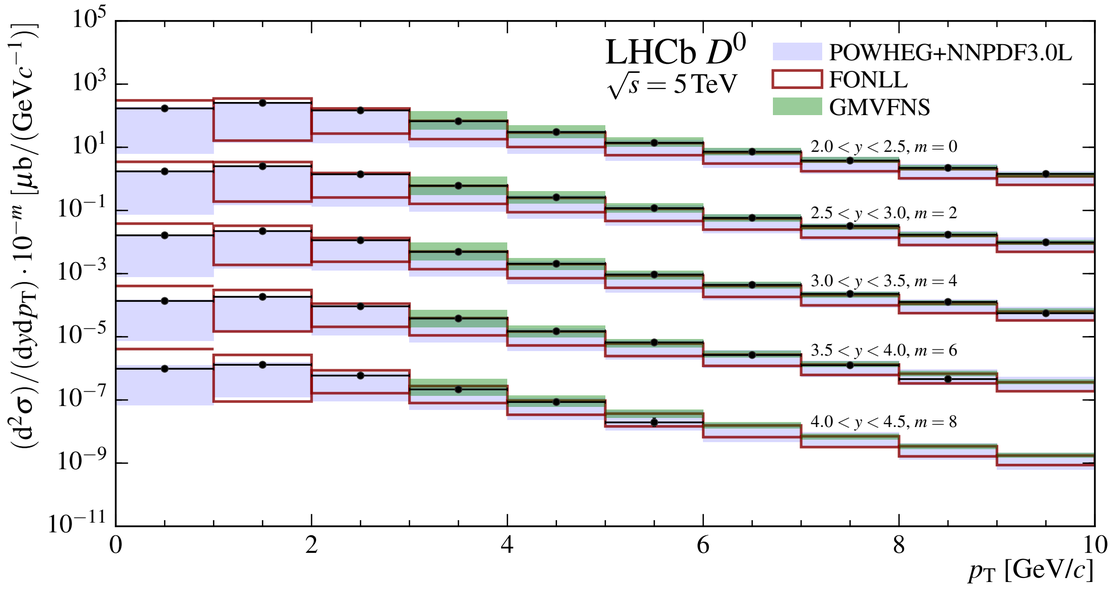
$$A = 208$$

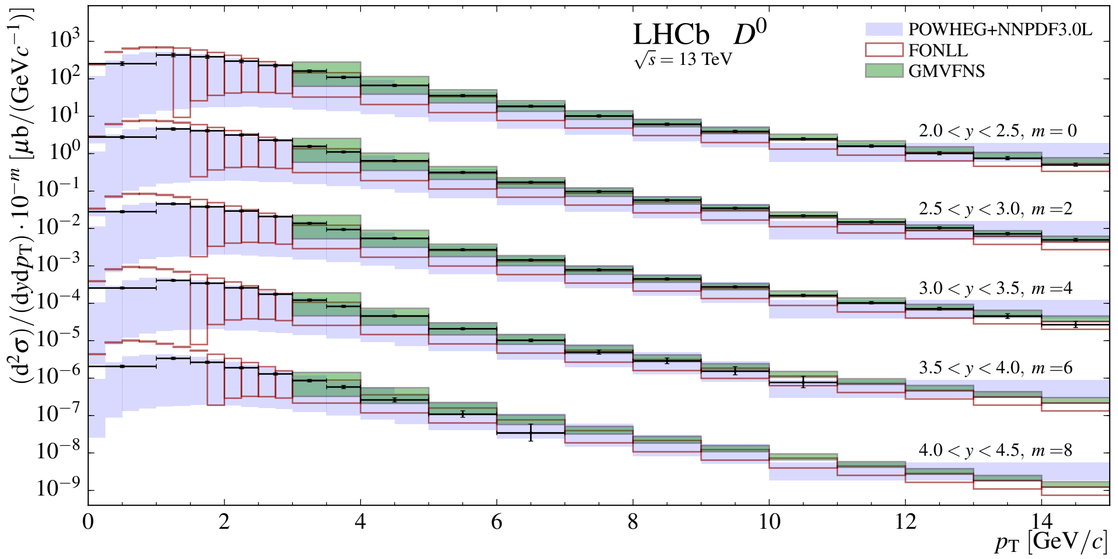
- Strong suppression at forward rapidity
- Enhancement at backward rapidity for $p_{\mathrm{T}} > 1.5\mathrm{GeV}/c$
- Continuous trend from forward to backward rapidity
- Enhancement in the backward region starts at lower p_{T} for higher $|\eta|$



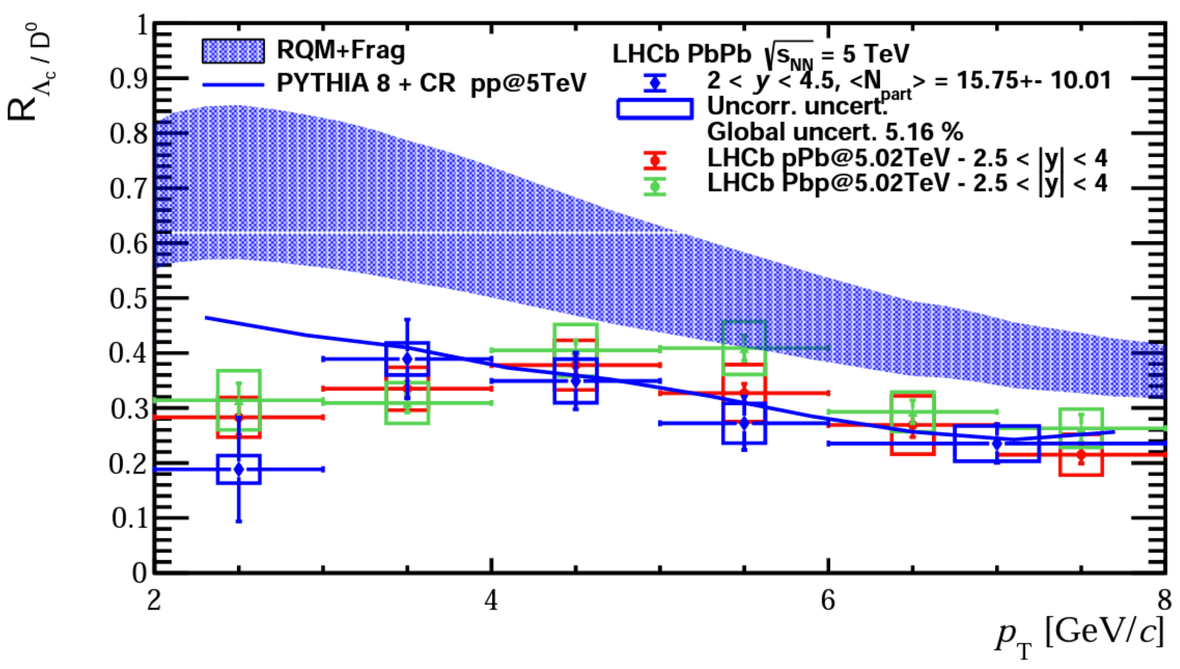
D^0 *pp* reference

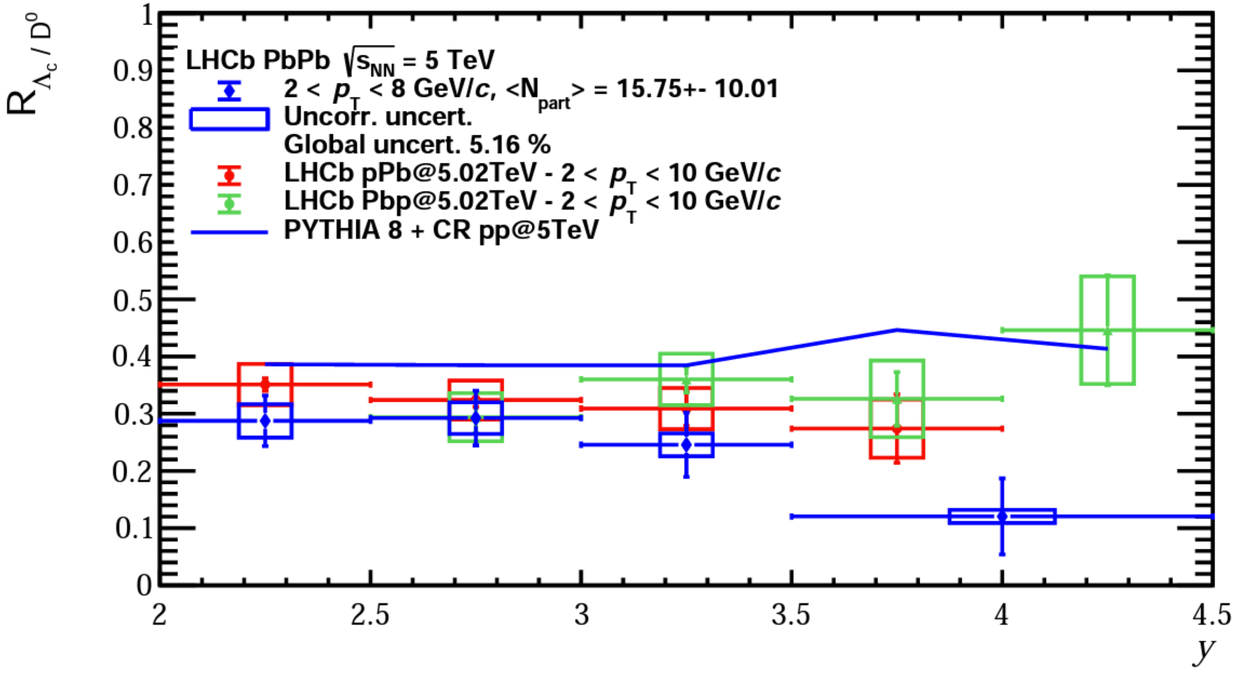
- Calculated with a power law function using 5&13 TeV *pp* data JHEP 06 (2017) 147 JHEP 05 (2017) 074





Λ_c^+/D^0 ratio in pPb and PbPb at 5TeV





SMOG2: statistics in 1 year data taking

simultaneous *pp*-SMOG2 data-taking

Storage cell assumptions	gas type	gas flow (s^{-1})	peak density (cm^{-3})	areal density (cm^{-2})	time per year (s)	int. lum. (pb^{-1})
SMOG2 SC	He	1.1×10^{16}	10^{12}	10^{13}	3×10^{3}	0.1
	Ne	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	Ar	2.4×10^{15}	10^{12}	10^{13}	2.5×10^{6}	80
	Kr	8.5×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	Xe	6.8×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	H_2	1.1×10^{16}	10^{12}	10^{13}	5×10^{6}	150
	D_2	7.8×10^{15}	10^{12}	10^{13}	3×10^{5}	10
	O_2	2.7×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	N_2	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1

No centrality limitation!

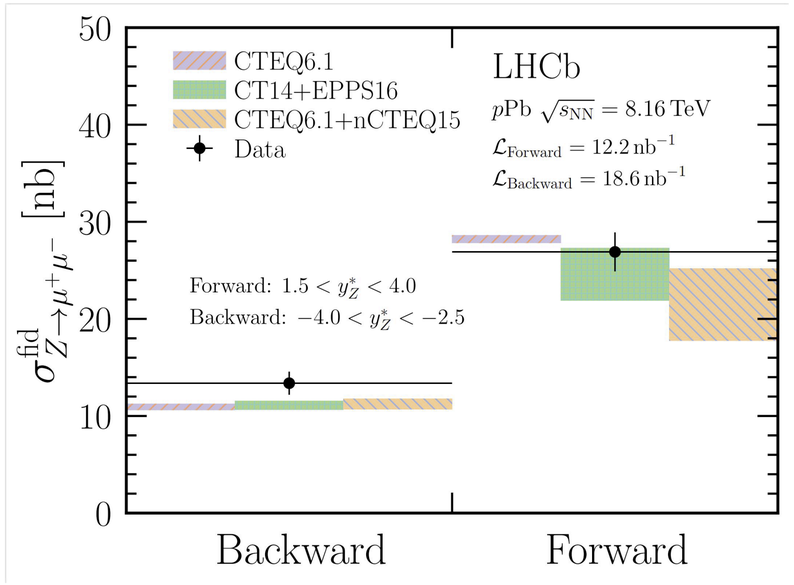
SMOG2 *p*Ar @ 115 GeV

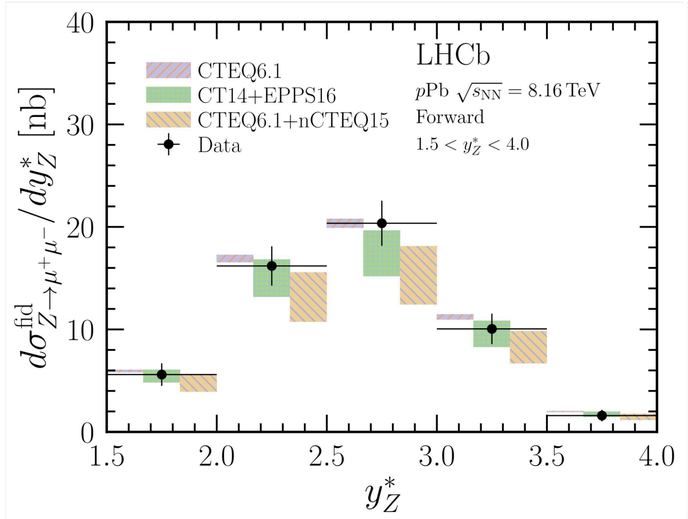
Int. Lumi.		80/pb
Sys.error of J/Ψ	xsection	~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

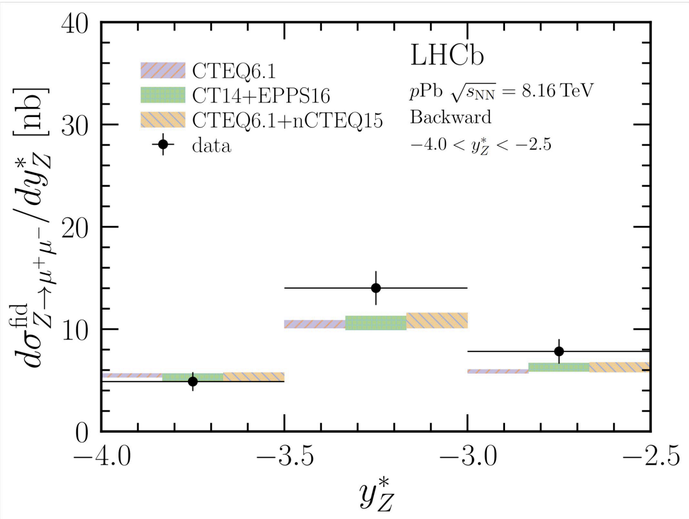
Z^0 boson production in pPb collisions at 8.16 TeV

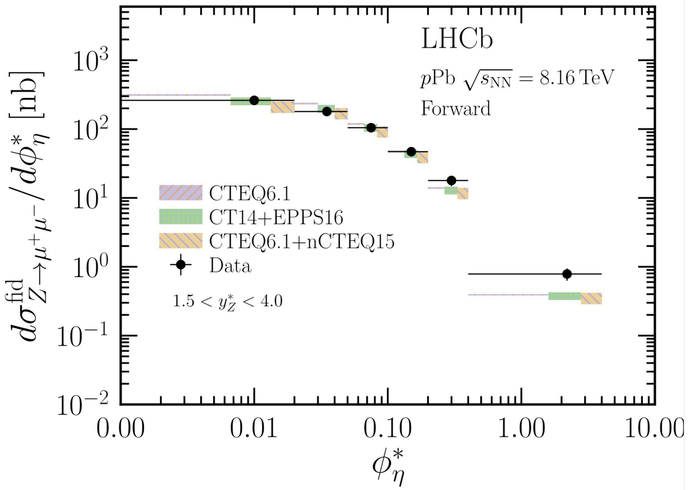
Z boson differential cross section

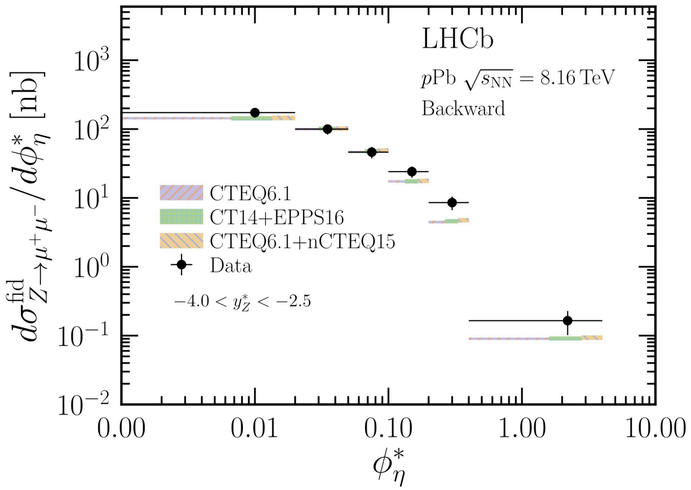
- Z boson negligible interaction with the nuclear medium
  - Sensitive only to initial-state with a well constrained final-state
- —> clean probes of nuclear matter effects on the initial state.
- $Z \to \mu^+\mu^-$





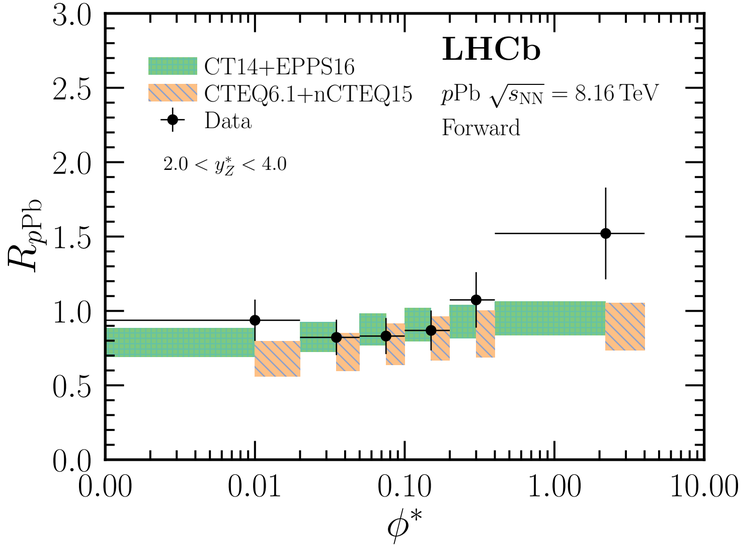


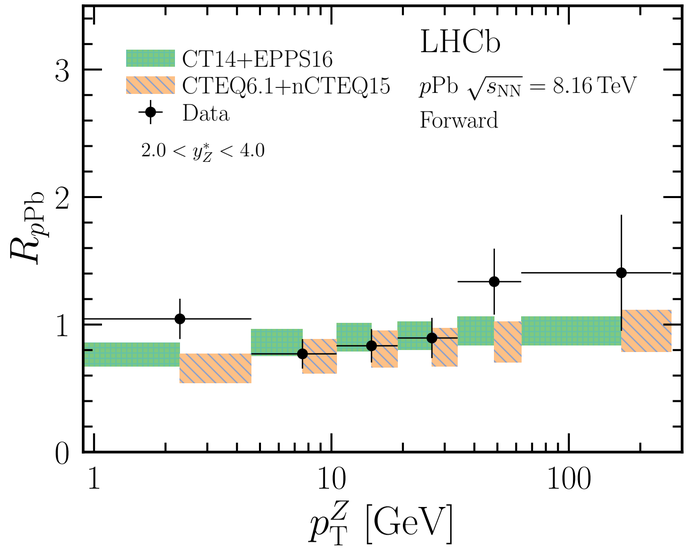


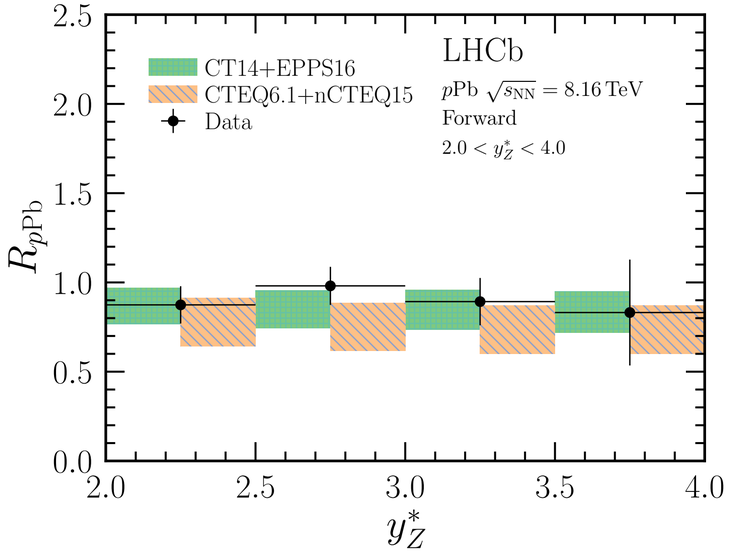


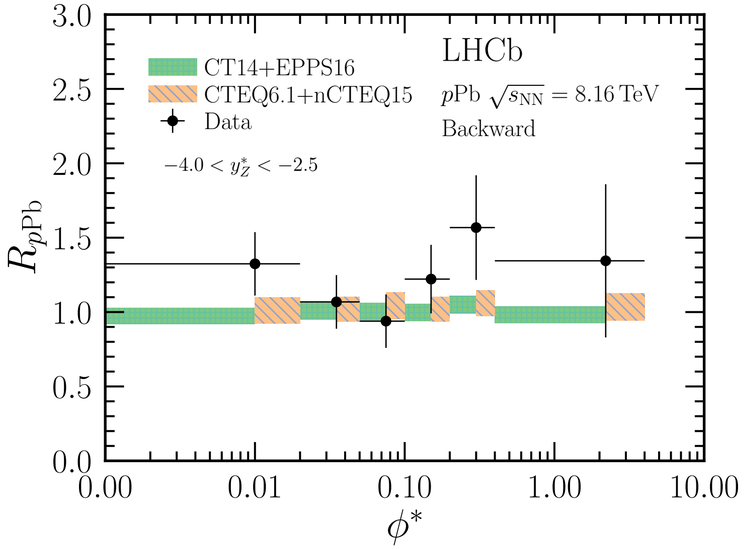
Z^0 boson production in pPb collisions at 8.16 TeV

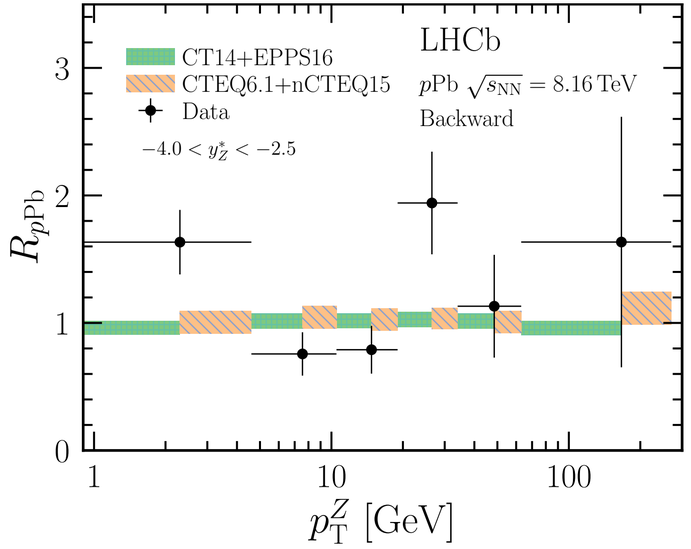
Nuclear modification factor $R_{p\mathrm{Pb}}$

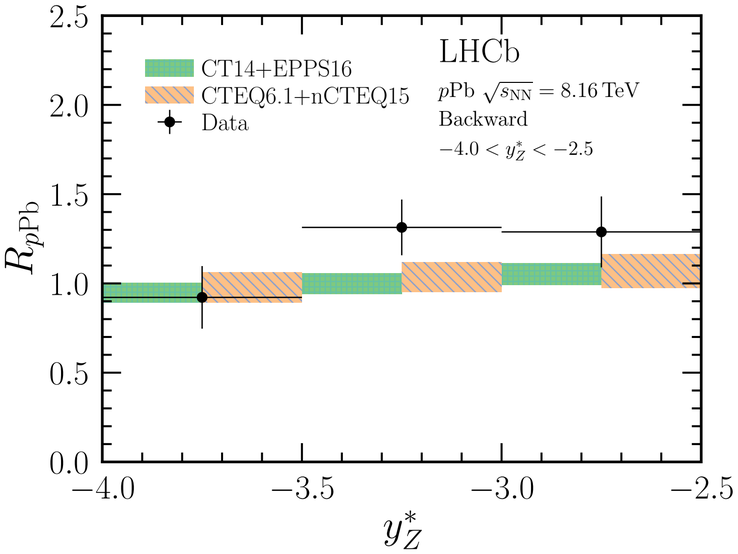






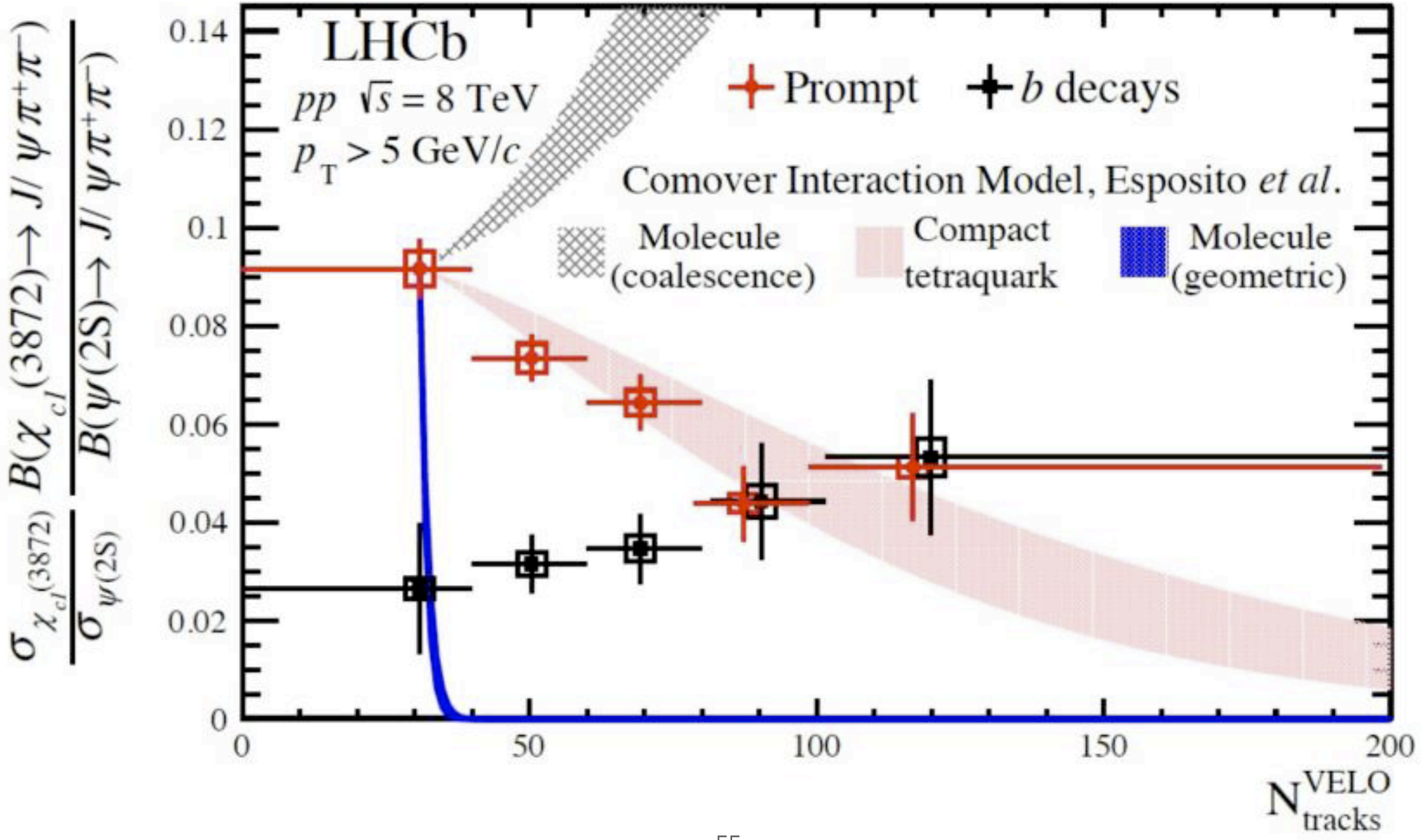






$\chi_{c1}(3872)/\psi(2S)$ ratio in pp collisions

Phys. Rev. Lett. 126 (2021) 092001

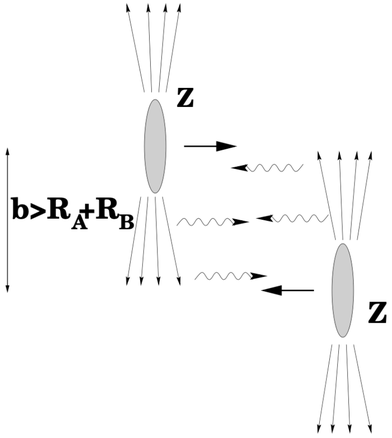


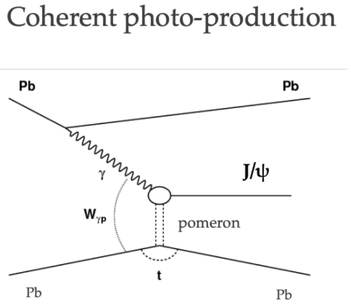
J/ψ photoproduction in ultra peripheral PbPb collisions at 5TeV

PbPb data collected in 2015

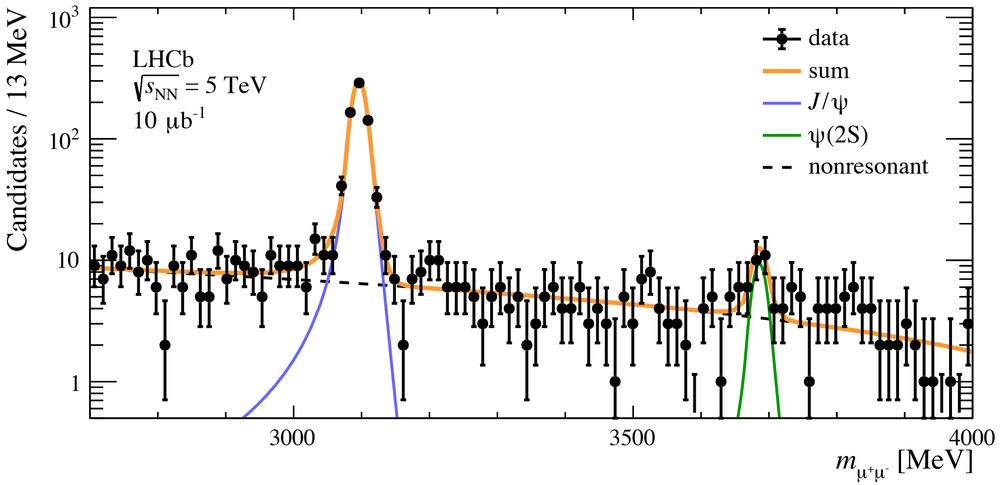
arXiv:2107.03223

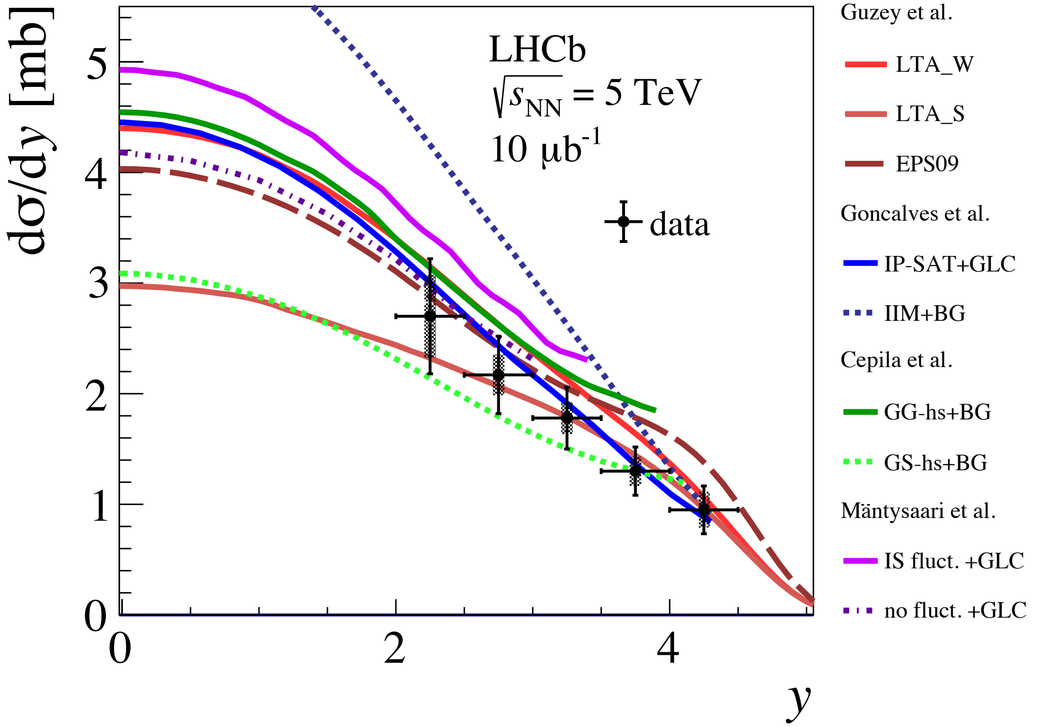
- Impact parameter $b > R_1 + R_2$,
- No actual hadronic collisions
- Interaction through the quasi real-photon cloud from one or both nuclei
- Photon flux $\propto Z^2$ —> reaction rate $\propto Z^4$
- Vector meson produced with the interaction between a photon and a pomeron
- Probe the nuclear gluon distribution functions at a hard scale $Q^2 \approx m^2/4$





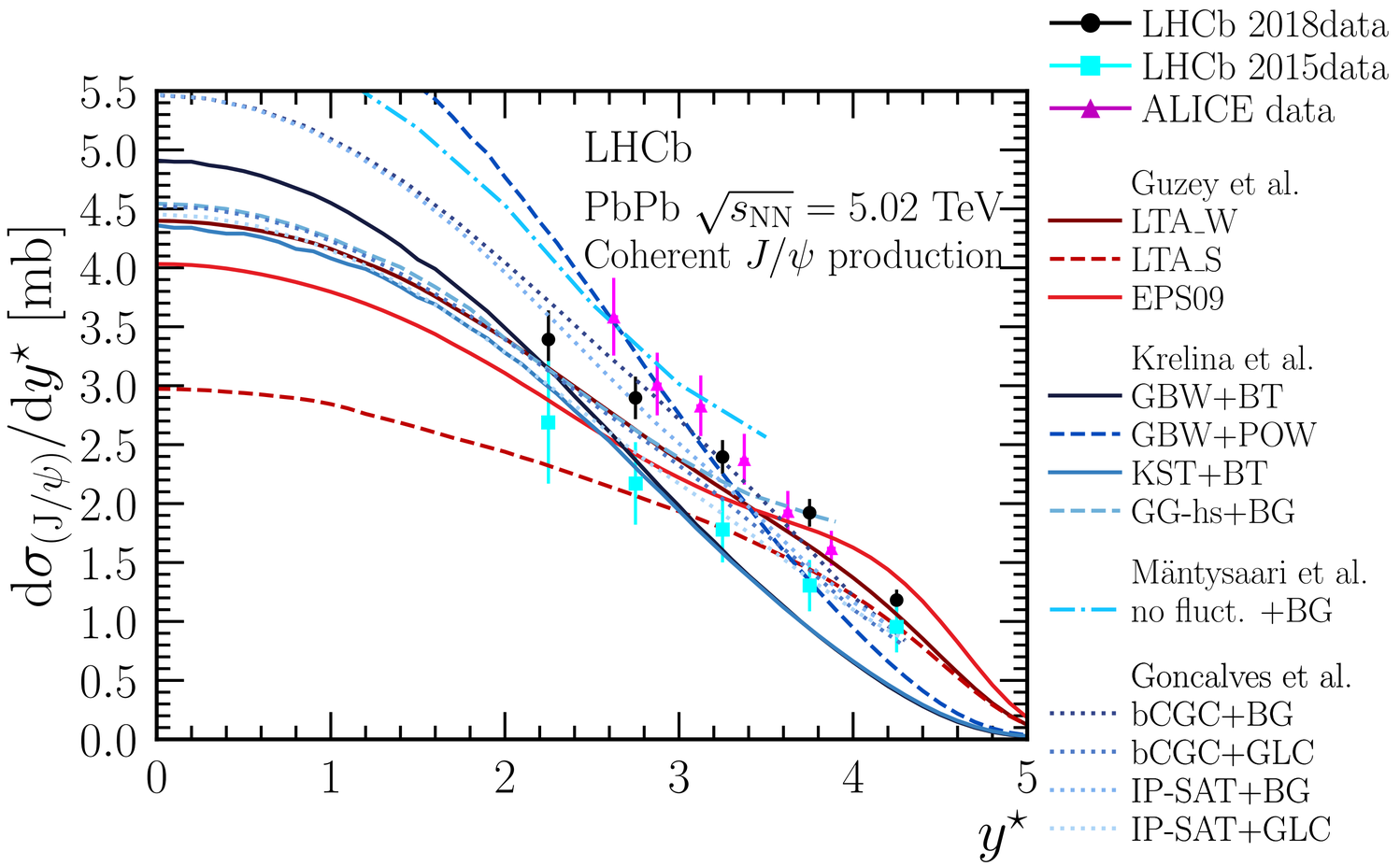
$\gamma(pomeron) \rightarrow J/\psi$





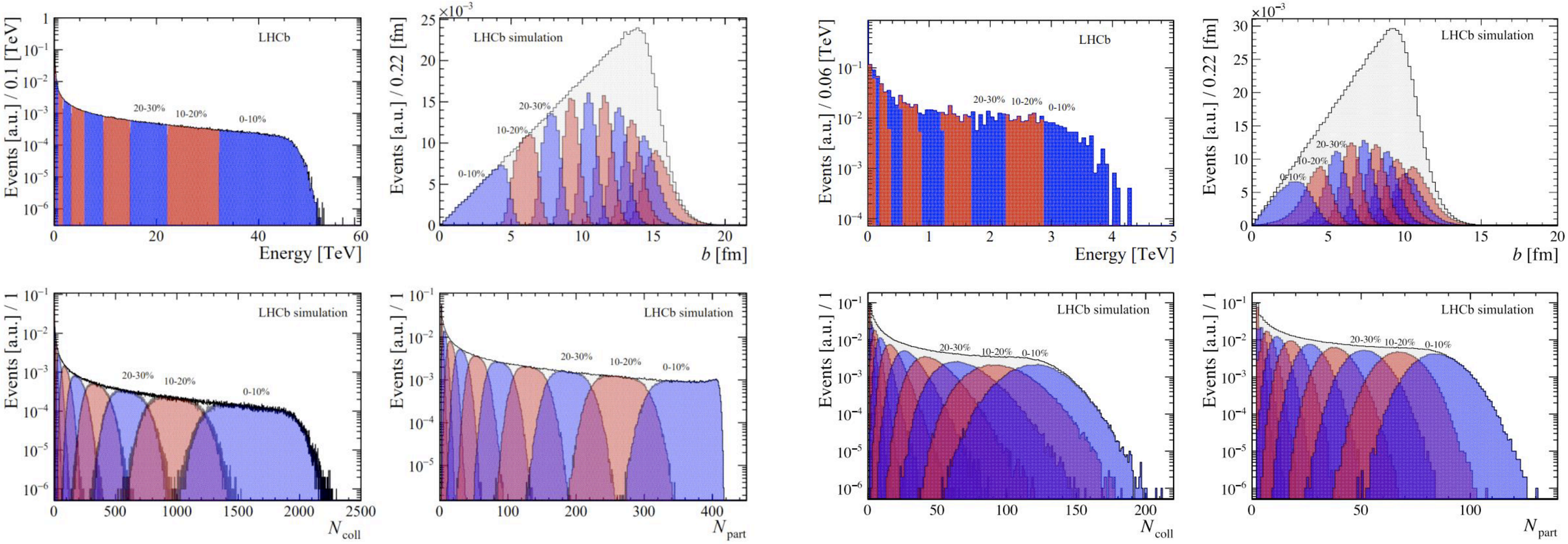
Coherence J/ψ in UPC PbPb at 5TeV

Comparison of results



PbPb PbNe centrality determination

- Centrality determined from Ecal energy using fits to Glauber model



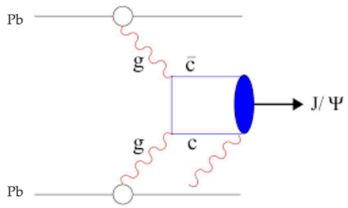
J/ψ photoproduction in peripheral PbPb collisions at 5TeV

coherent J/ψ signals

Phys. Rev. C 105, L032201

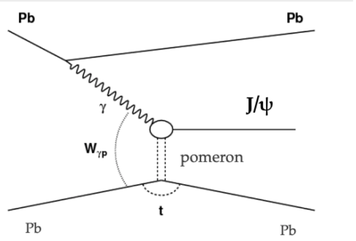
- **One of the first LHCb PbPb results in hadronic collisions**, using data collected in Nov-Dec 2018, with luminosity L~230 μb^{-1}
- Low p_T J/ψ excess observed by ALICE in PbPb and STAR in AuAu (PRL123, 132301, PRL116, 222301)
- Measure the photo-produced J/ψ yield in peripheral PbPb collisions (60-85%)
- The coherent and incoherent J/ψ production can be distinguished from their p_T shapes

Hadronic production



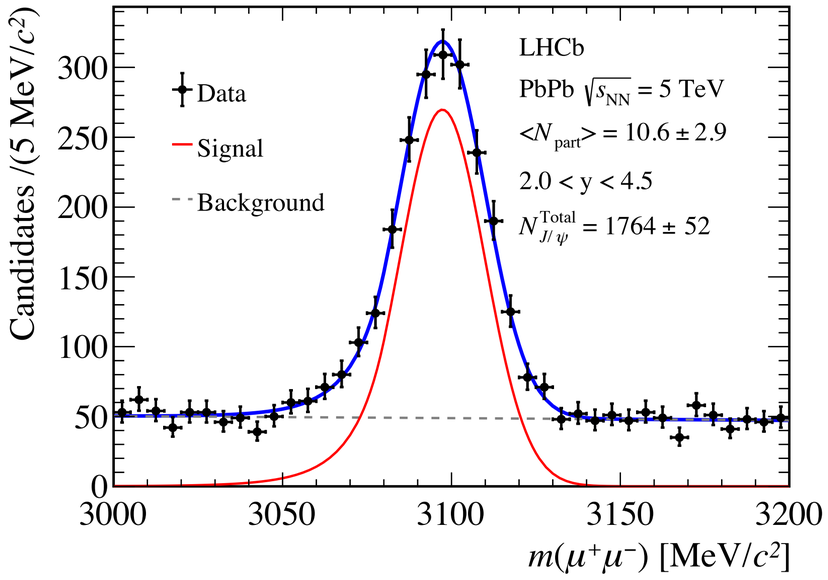
$gg \to J/\psi$

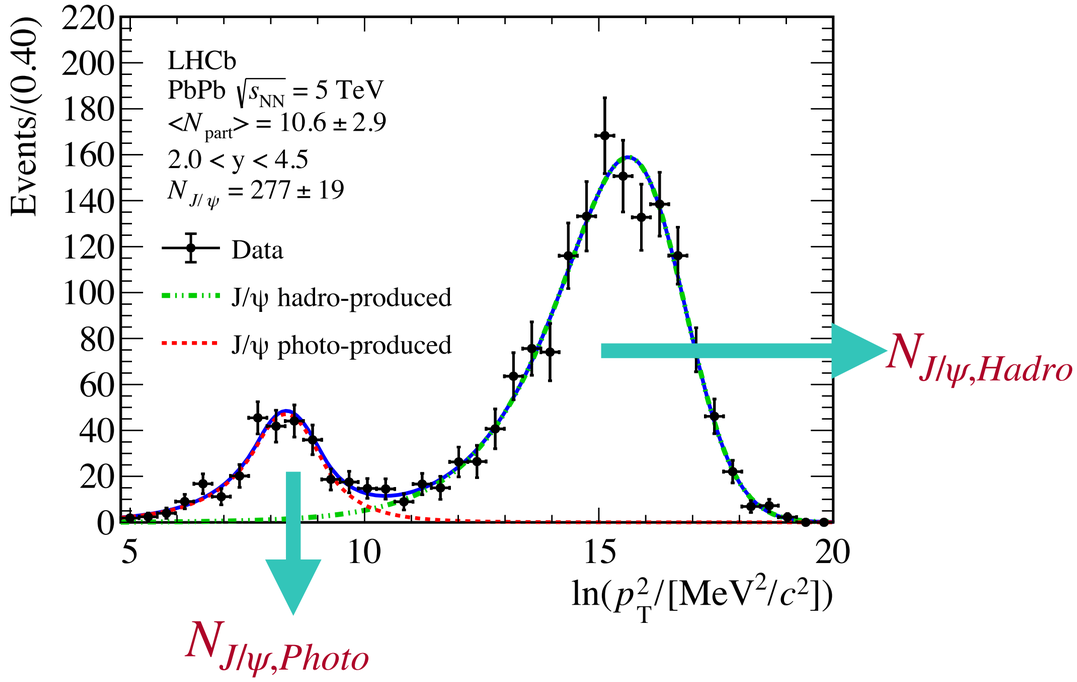
Coherent photo-production



$\gamma(pomeron) \to J/\psi$

- Non-prompt J/ψ removed with t_z selection.
- Centrality determined by energy deposited in ECAL and Glauber model

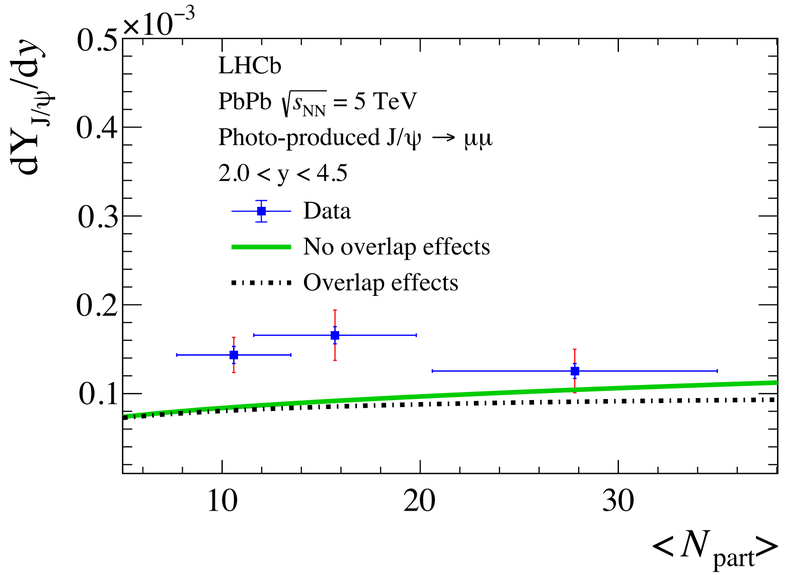


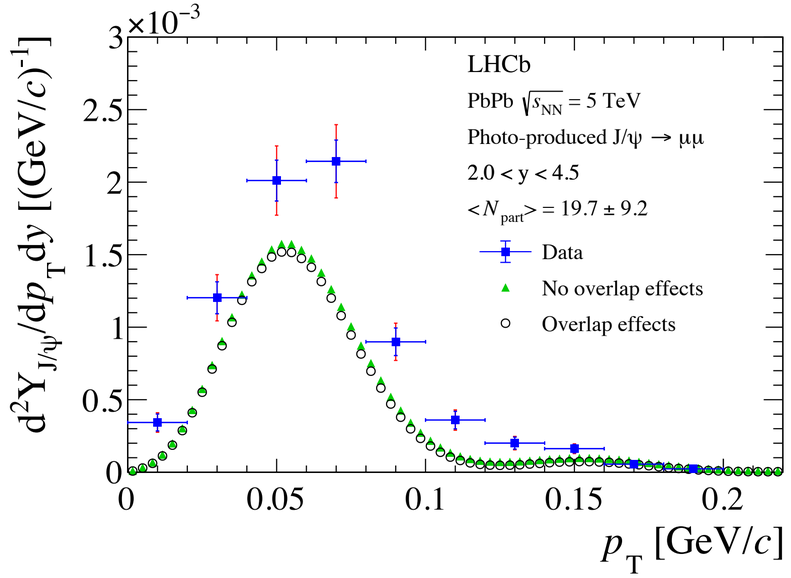


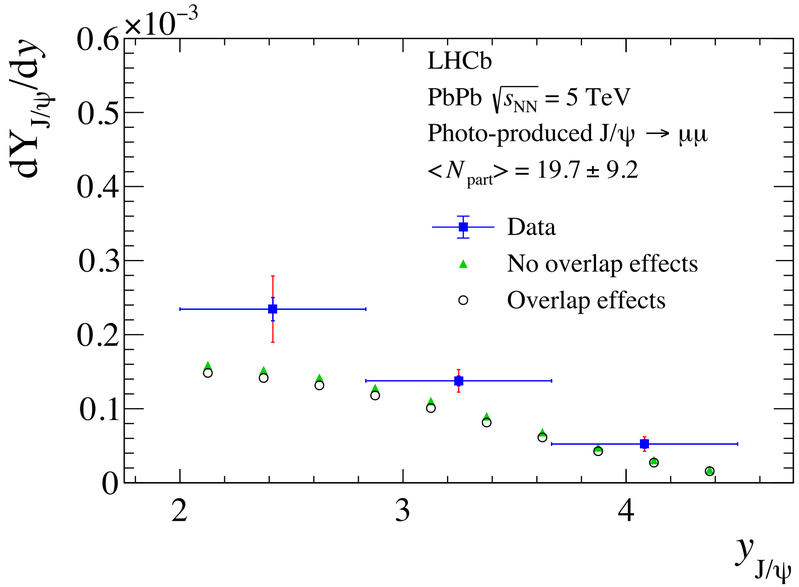
J/ψ photoproduction in peripheral PbPb collisions at 5TeV

invariant yields

Phys. Rev. C 105, L032201





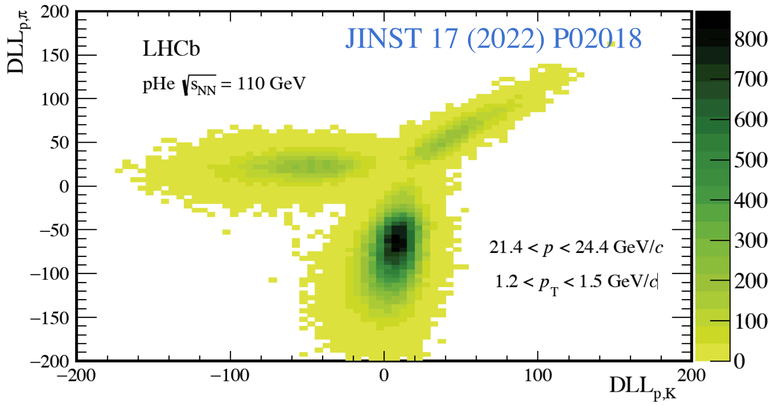


- Photo-produced J/ψ yields measured with high precision
  - Decreasing at larger rapidity
  - Consistent with constant with respect to $\langle N_{part} \rangle$
- The shape of coherent J/ψ transverse momentum distribution is measured for the first time at the LHC, very similar to the p_T shape seen in the UPC result!
- Data qualitatively well reproduced by models, with and without nuclear overlap effects

SMOG datasets and results

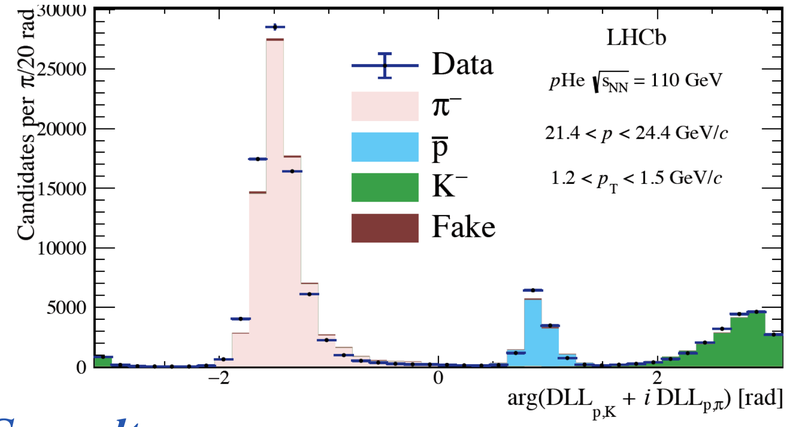
New results:

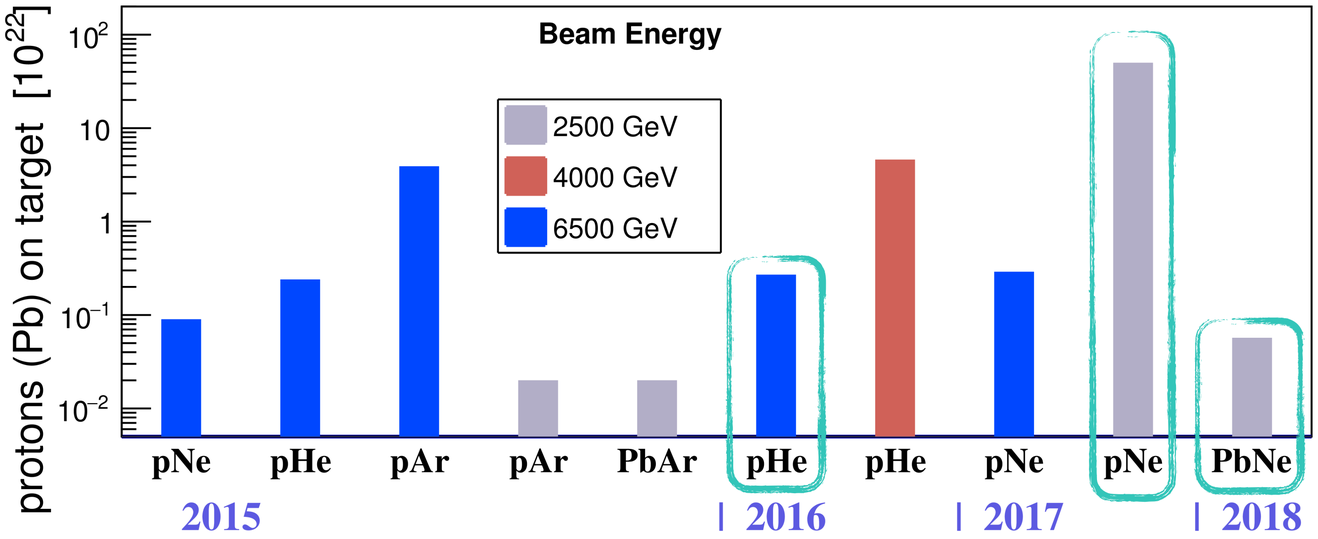
- Charmonia production in *p*Ne collisions at 68.5 GeV
- J/ψ and D^0 production in PbNe collisions at 68.5 GeV
- Detached antiproton production in *p*He collisions at 110 GeV



New technical publication:

- A Neural-Network-defined Gaussian Mixture Model for PID with SMOG data JINST 17 (2022) P02018
- Centrality determination in heavy-ion collisions with the LHCb detector arXiv:2111.01607





Previous SMOG results:

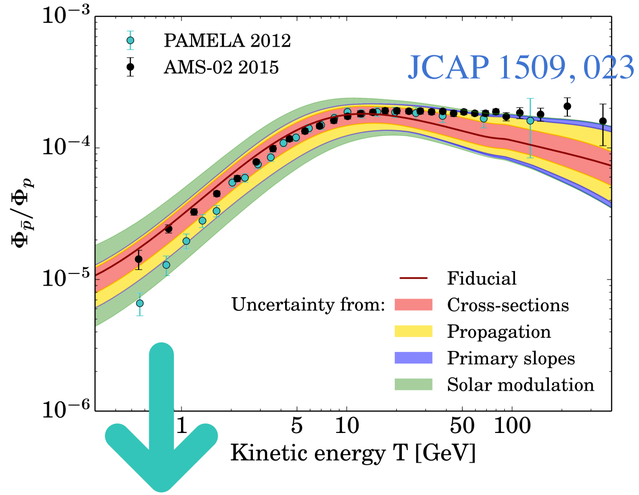
- Charm production in *p*Ar, *p*He collisions
  Phys. Rev. Lett. 122 (2019) 132002
- Prompt antiproton in *p*He collisions at 110 GeV
  Phys. Rev. Lett. 121 (2018) 222001

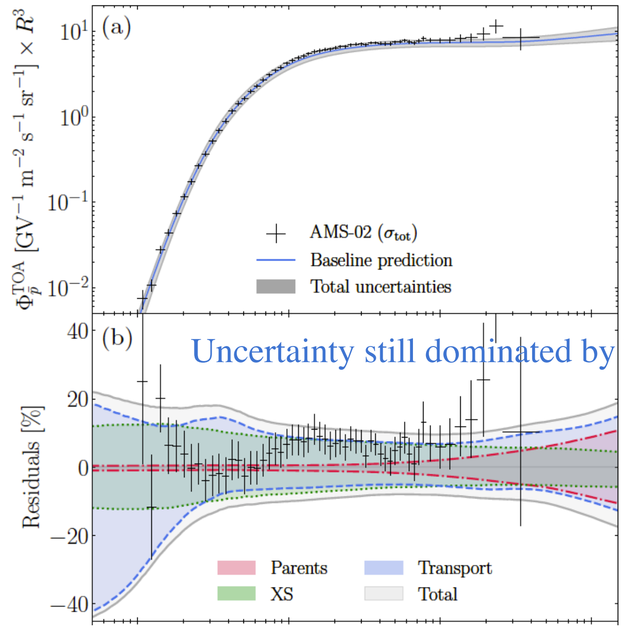
Detached antiproton in pHe collisions at 110 GeV

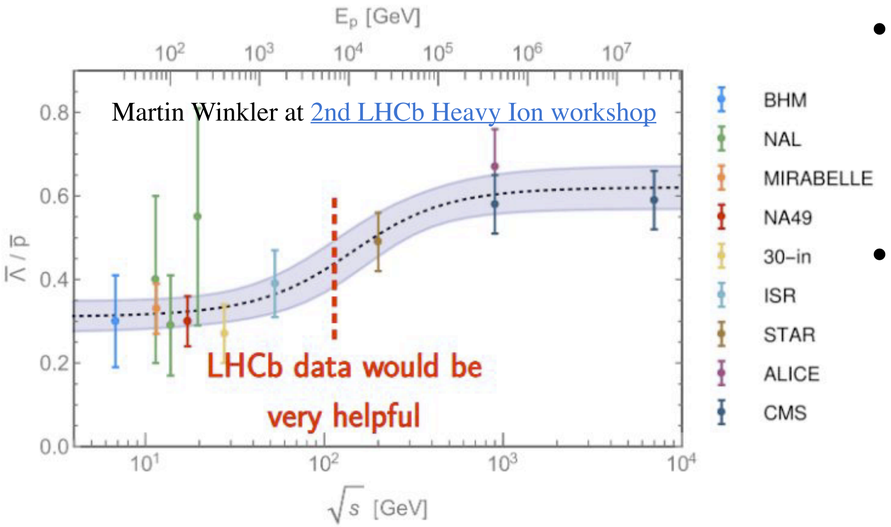
LHCb-PAPER-2022-006, in preparation

SMOG input to astrophysics

- PAMELA and AMS-02 measurements of $\bar{p}/p$ in cosmic rays sensitive to a possible dark matter contribution
- Interpretation of $\bar{p}/p$ measurements require precise $\bar{p}$ production cross-section in spallation of cosmic rays in the interstellar medium (H and He)
- A first measurement of prompt $\bar{p}$ production in pHe collisions at 110 GeV using SMOG PRL 121 (2018) 222001
- Extending the first measurement: antiproton from anti-hyperon decays (detached $\bar{p}$)







- Detached $\bar{p}$ can be distinguished from prompt $\bar{p}$ in LHCb by the separation of their original vertex and the primary pHe collision vertex.
- Study strangeness production enhancement at $\sqrt{s} \sim 100$GeV

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