Heavy ions at LHCb and connections to EIC

Matt Durham
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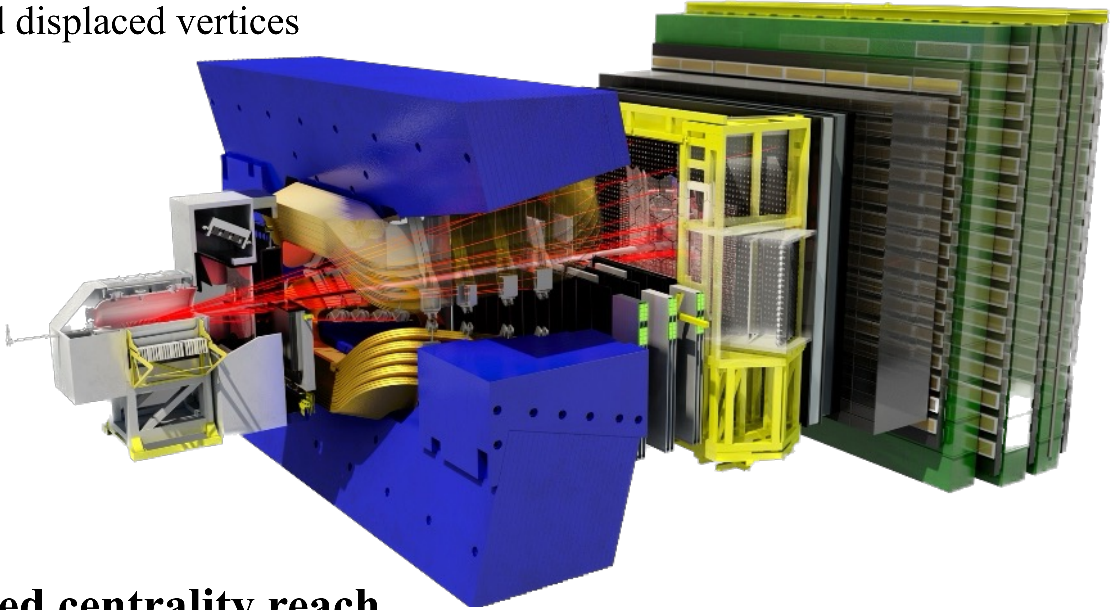
LHCb – unique capabilities for QCD

- **Unique forward rapidity coverage**
  - Unparalleled access to low- and high-x regions inside the nucleus
- **Large forward momentum boost**
  - Full PID, reconstruct resonances to $p_T = 0$
  - Clear separation between primary and displaced vertices
- **Fast DAQ and detectors**
  - Access to rare probes: b quarks, higher quarkonia, exotic states
- **Unique fixed-target system**
  - Explore p+gas and Pb+gas collisions at ~RHIC energies
  - Incredibly versatile physics program
- **Major upgrades in place – increased centrality reach**



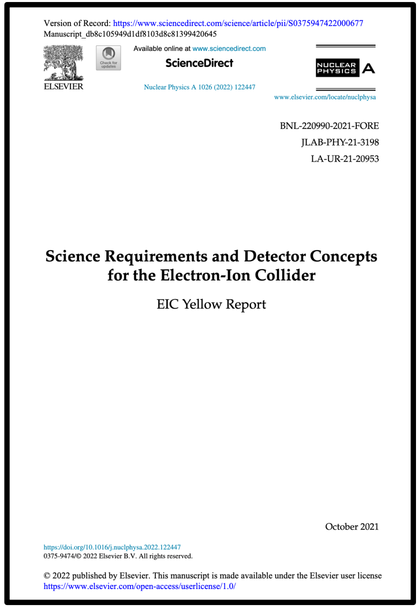
LHCb and EIC:
many overlapping physics topics

Partonic structure of nucleons

Photoproduction

Hadronization

Hadron spectroscopy



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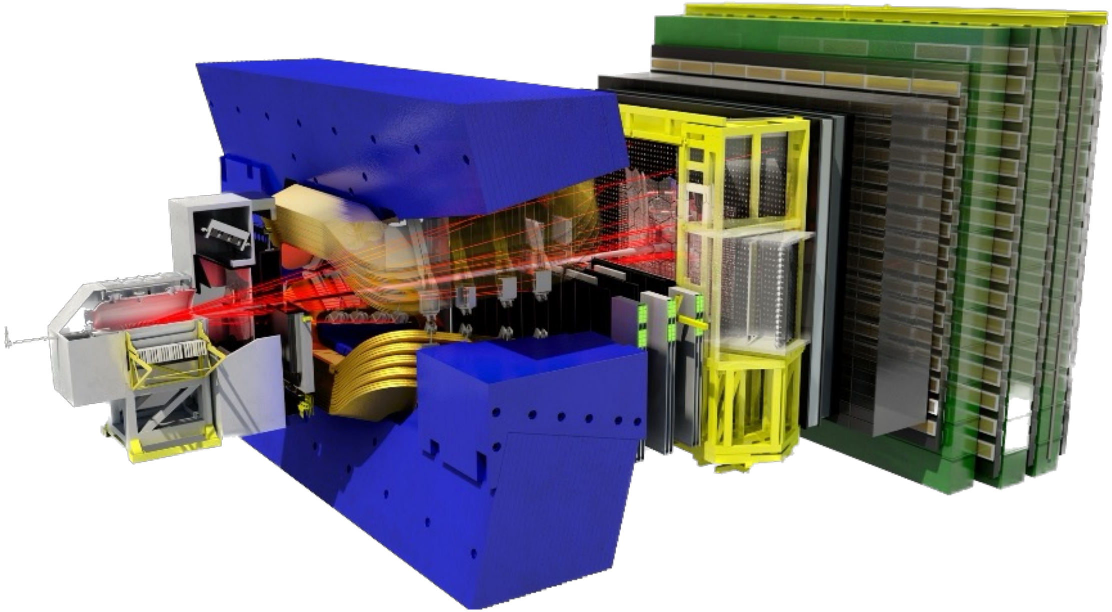

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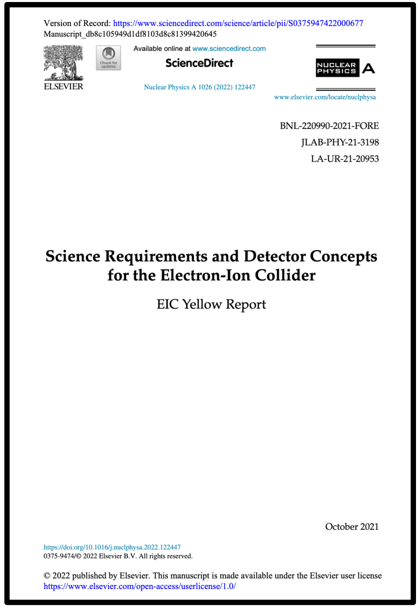

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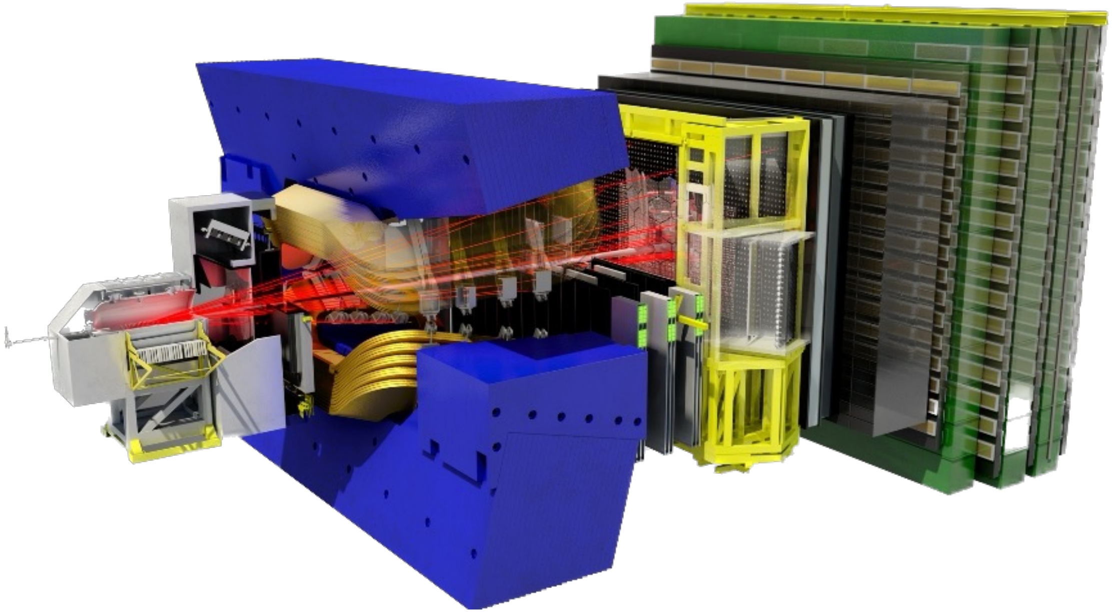
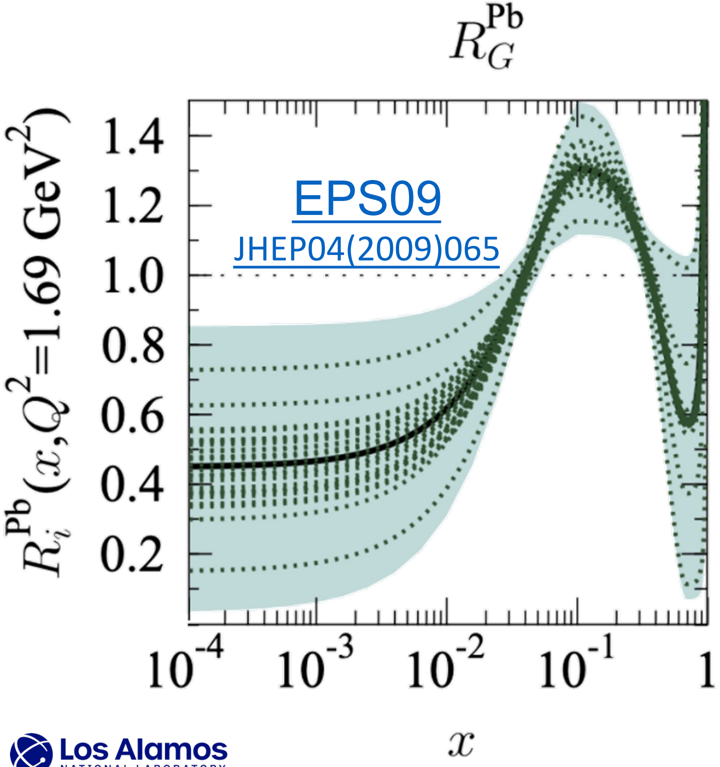


Low x

- Forward rapidity allows us to look deep into the nucleus:
  - Constrain structure of nucleons at low x values
  - Understand the physics of QCD at high gluon density → search for saturation



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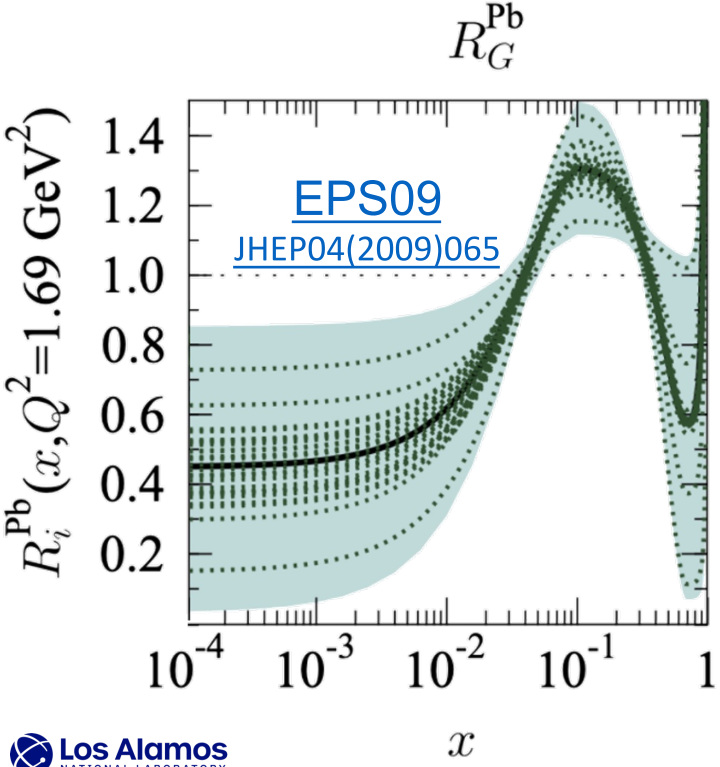

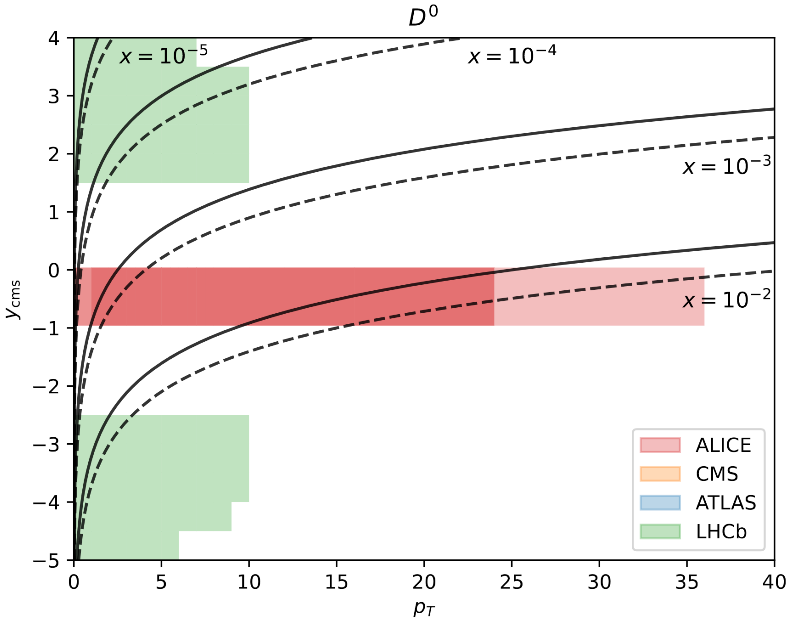

Plot from Pit Duwentaster's talk, Week 3

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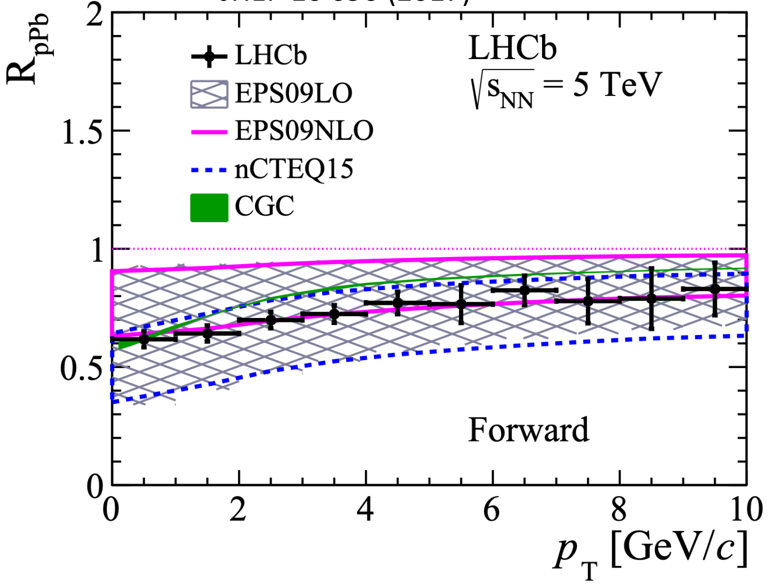
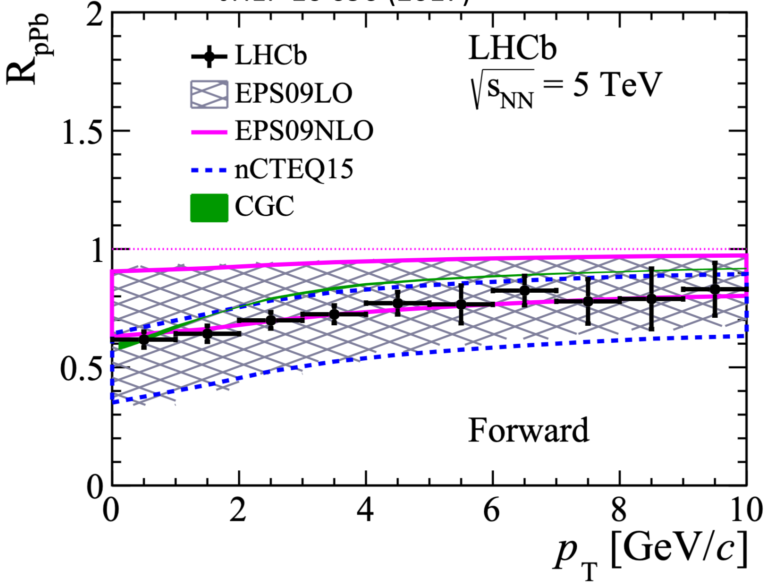
Forward charm – constraining nPDF

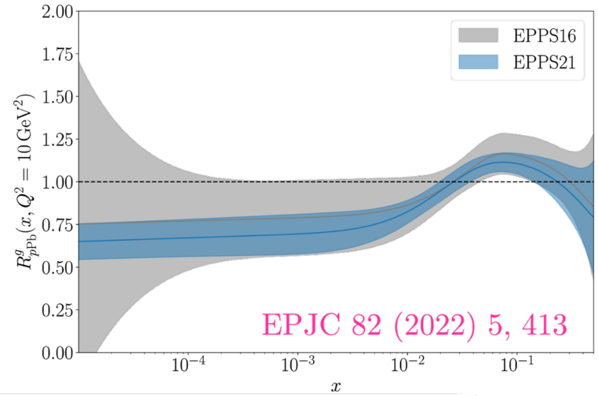
JHEP 10 090 (2017)

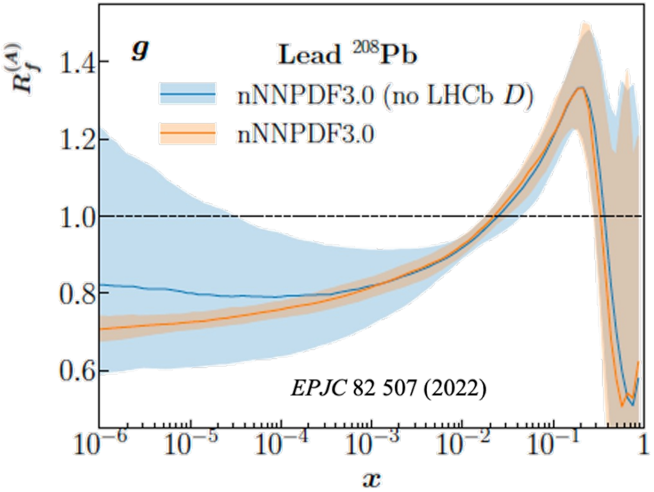


Forward charm – constraining nPDF

JHEP 10 090 (2017)



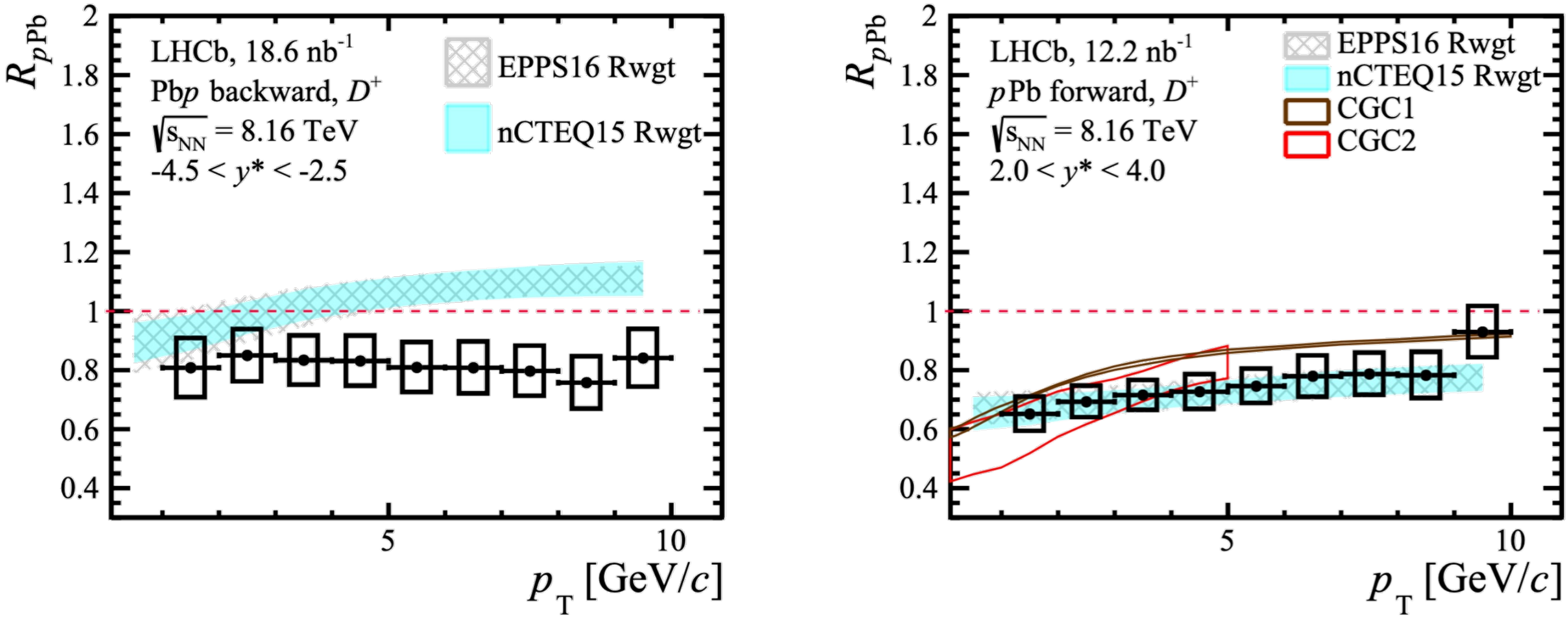




- Precise LHCb data on *D* mesons now the primary nPDF constraint at $x<10^{-3}$
- **Dramatic impact on gluon uncertainties down to $x\sim10^{-6}$ (nNNPDF3.0)**

Backward charm – challenging nPDF

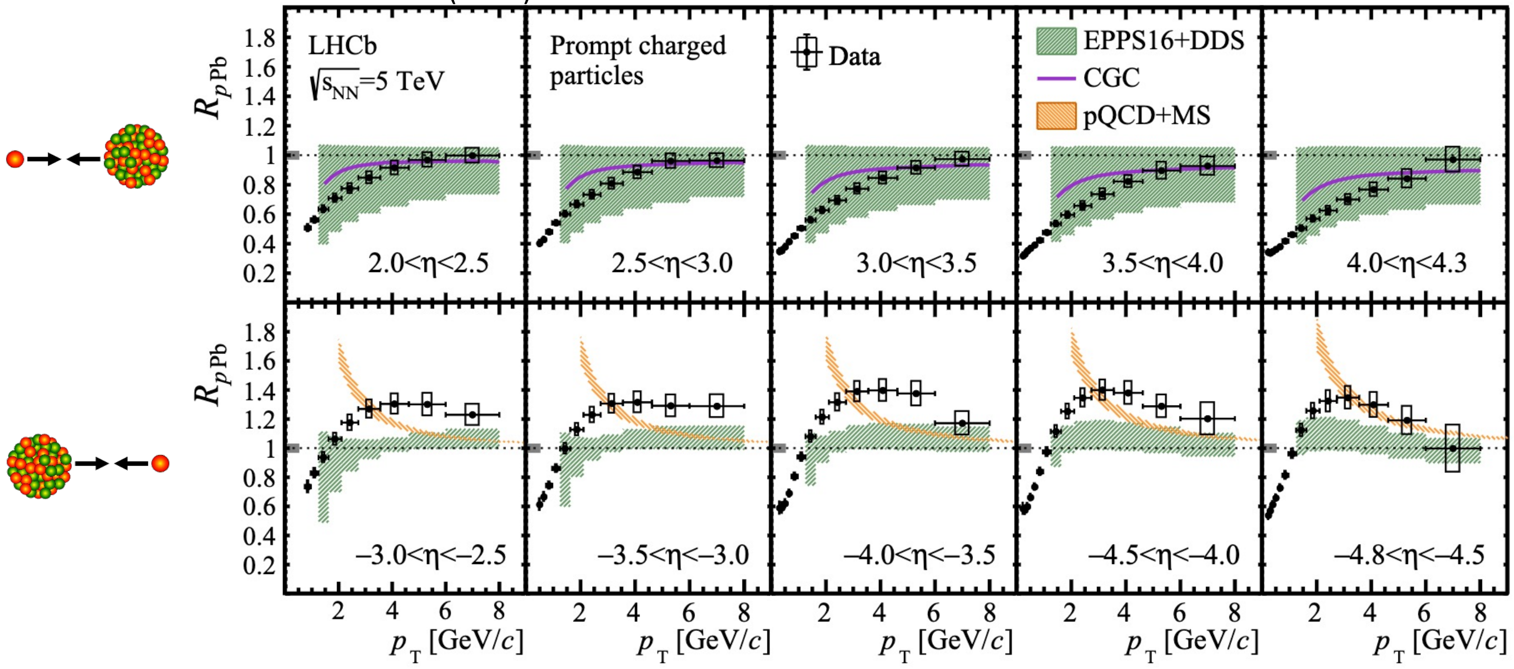
arXiv: 2311.08490



- Forward data well within uncertainties from updated nPDF calculation
- Backwards rapidity shows clear deviation from nPDF

Unidentified charged particles

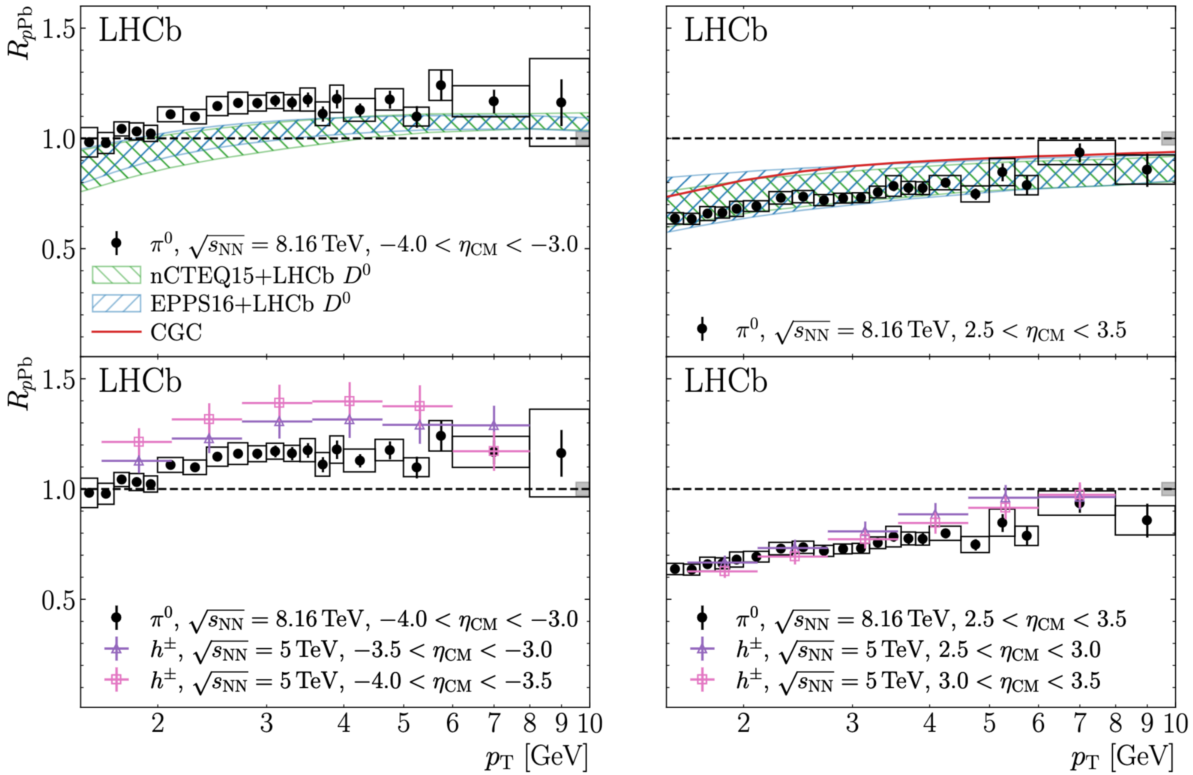
PRL 128 142004 (2022)



- Forward data well within uncertainties from EPPS16 nPDF calculation
- Backwards rapidity not described by nPDF or multiple scattering calculation
  - Additional effects from medium?

Identified light mesons - π^0

PRL 131 042302 (2023)

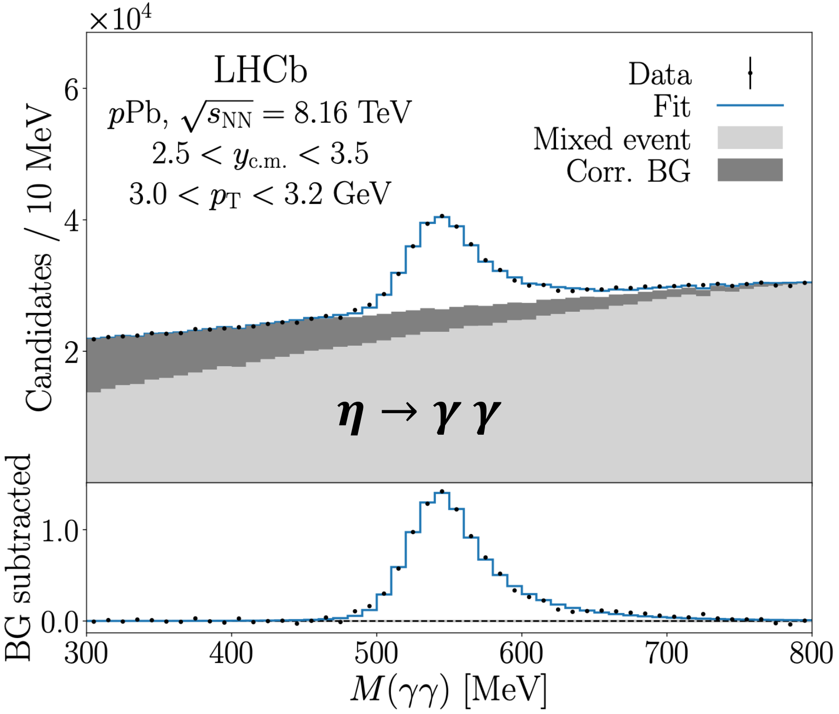


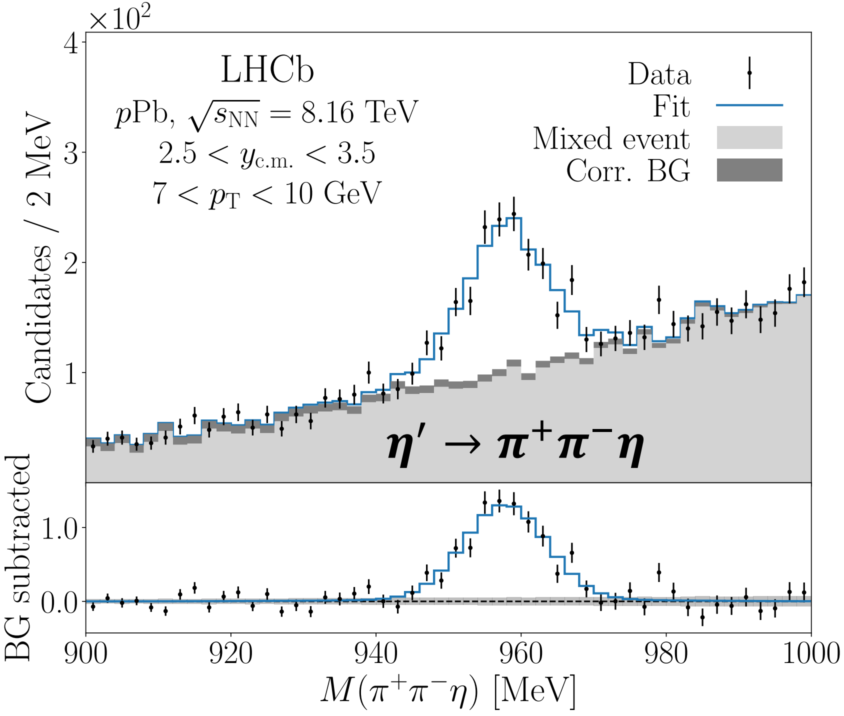
- Forward rapidity:
  - Excellent agreement with nPDF and charged particles
- Backward rapidity:
  - Slight excess over nPDF calculation
  - Deficit compared to charged particles
- Potential mechanisms:
  - Mass dependent radial flow affecting charged particles
  - Baryon enhancement at backwards rapidity

Identified light mesons - η and η'

PRC 109 024907 (2024)

- Nuclear modification of identified particles allows us to probe mass-dependent effects
- The η' is especially interesting: a meson with nearly the same mass as a proton





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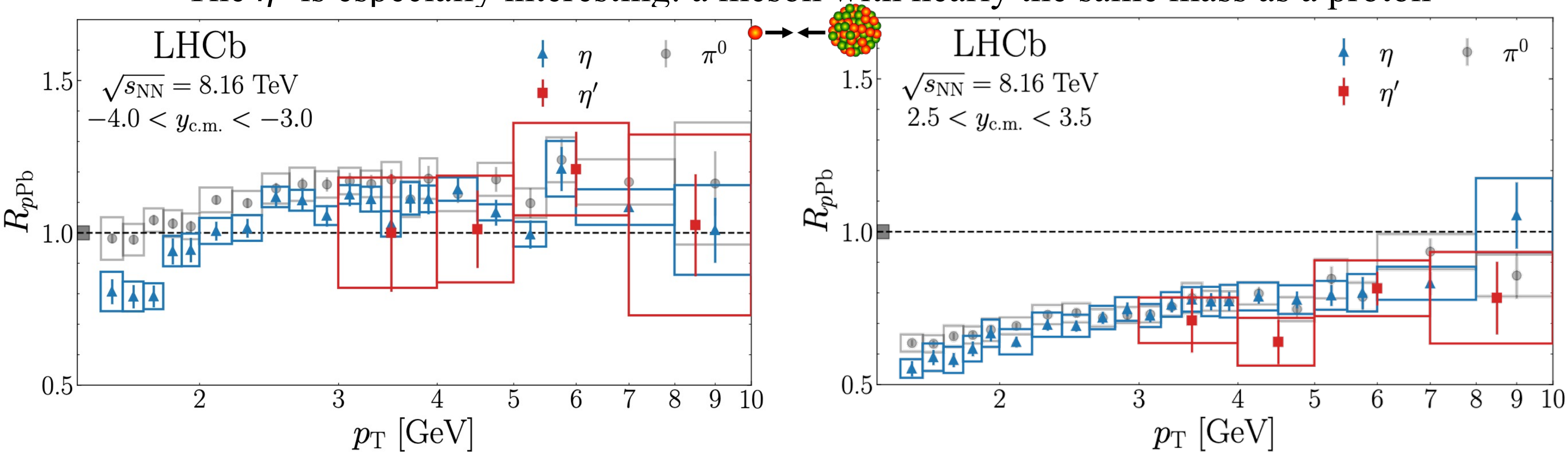

- Agreement between all light mesons - no evidence for mass dependence
- Potential baryon/meson effects under investigation with identified hadrons

LHCb and EIC: many overlapping physics topics

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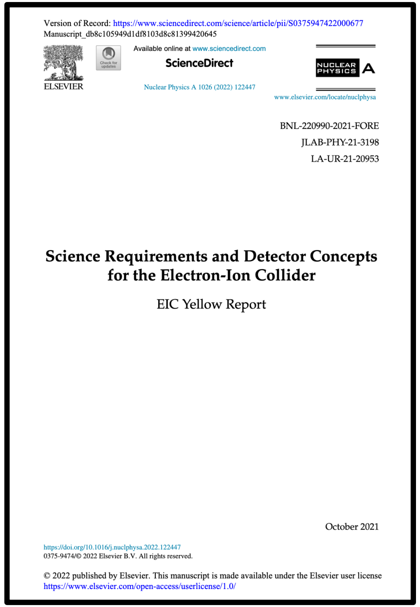
Hadronization

Hadron spectroscopy



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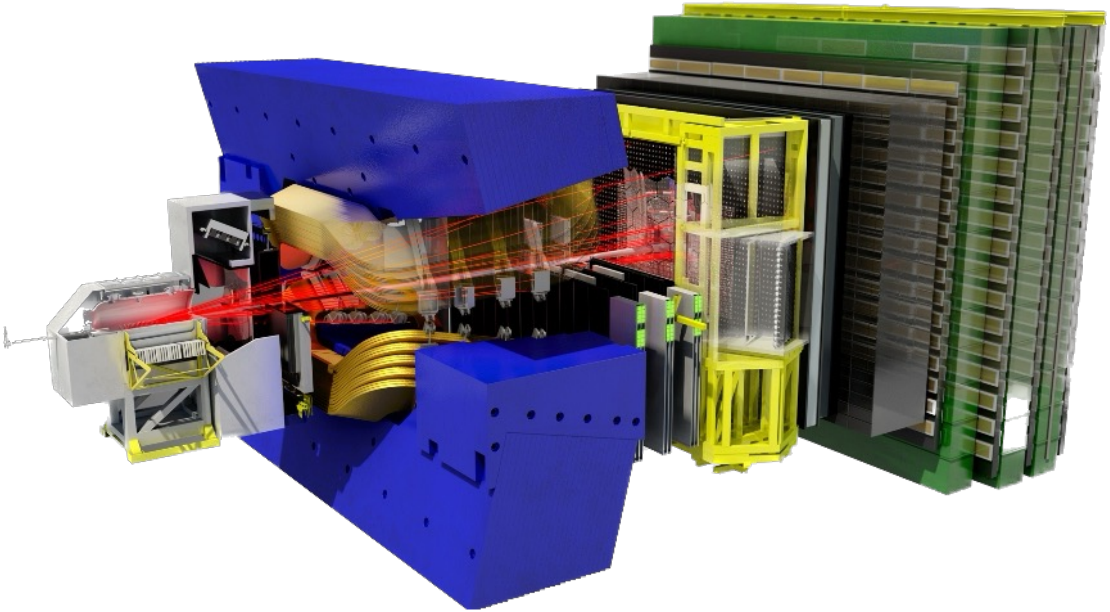
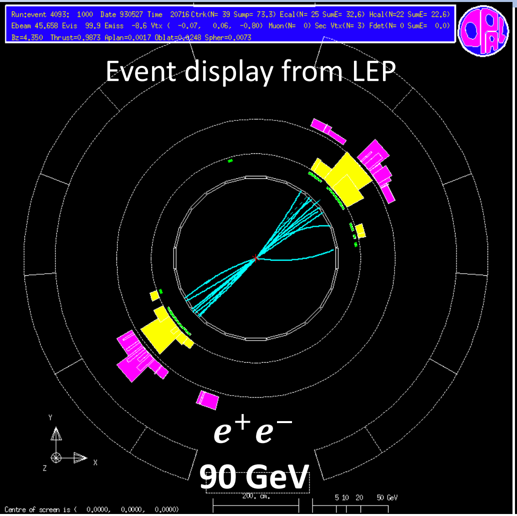
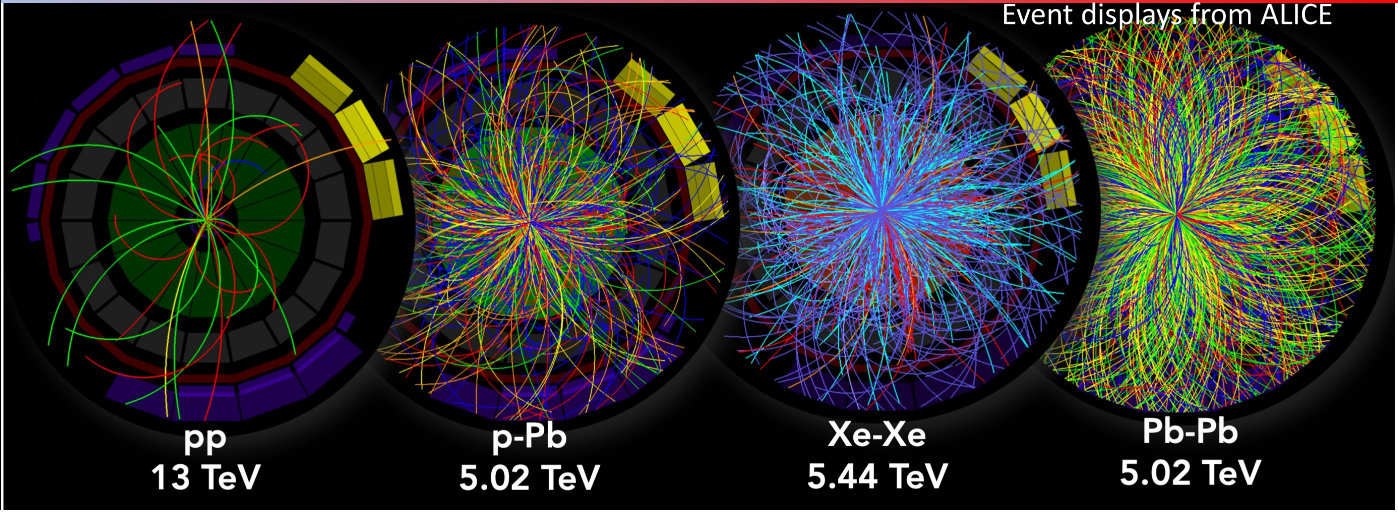


From vacuum to the QCD medium – quark coalescence

Vacuum (e^+e^-)   Diffuse medium (pp,pA)   Increasing T, $N_{charged}$ → Dense medium (pA, AA)





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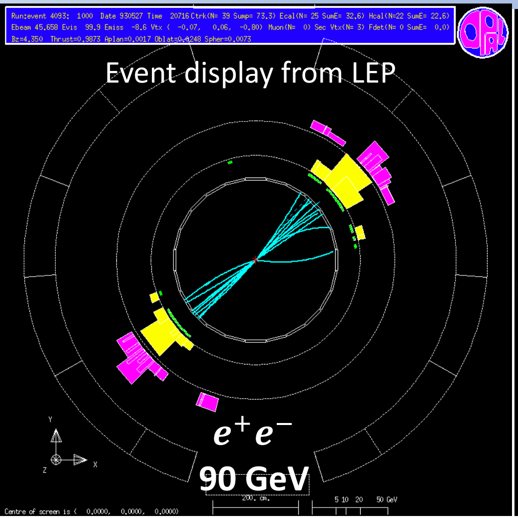

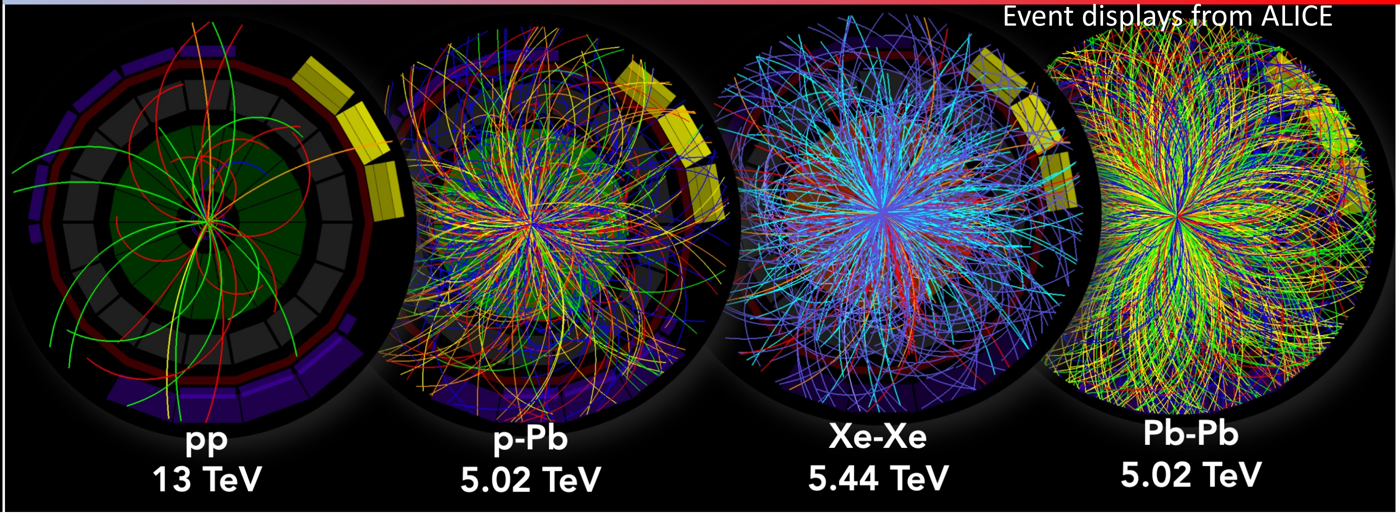

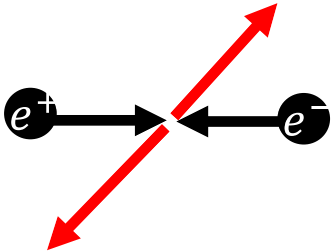

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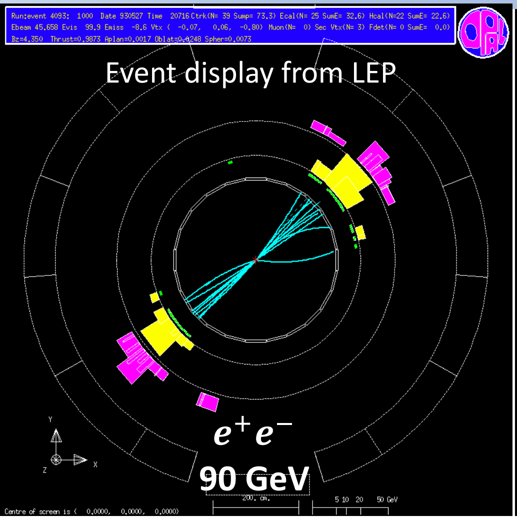
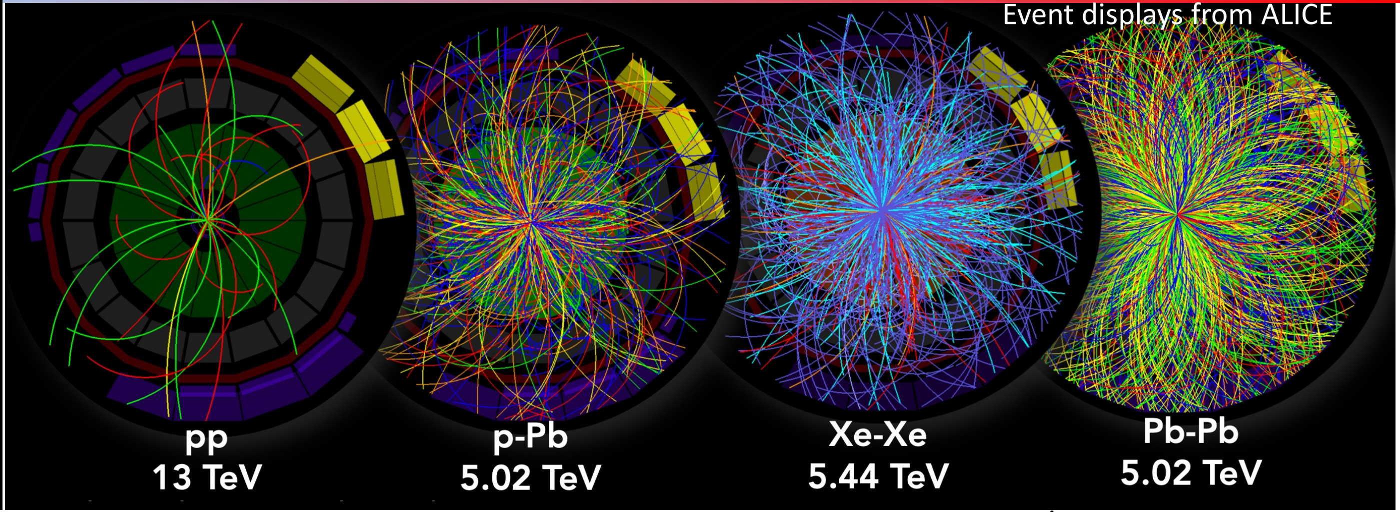
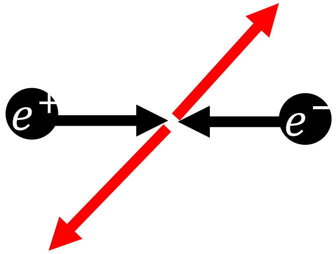
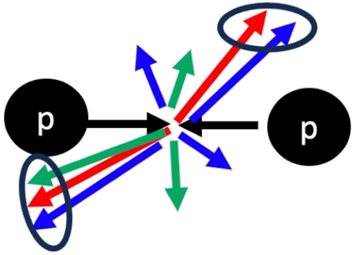






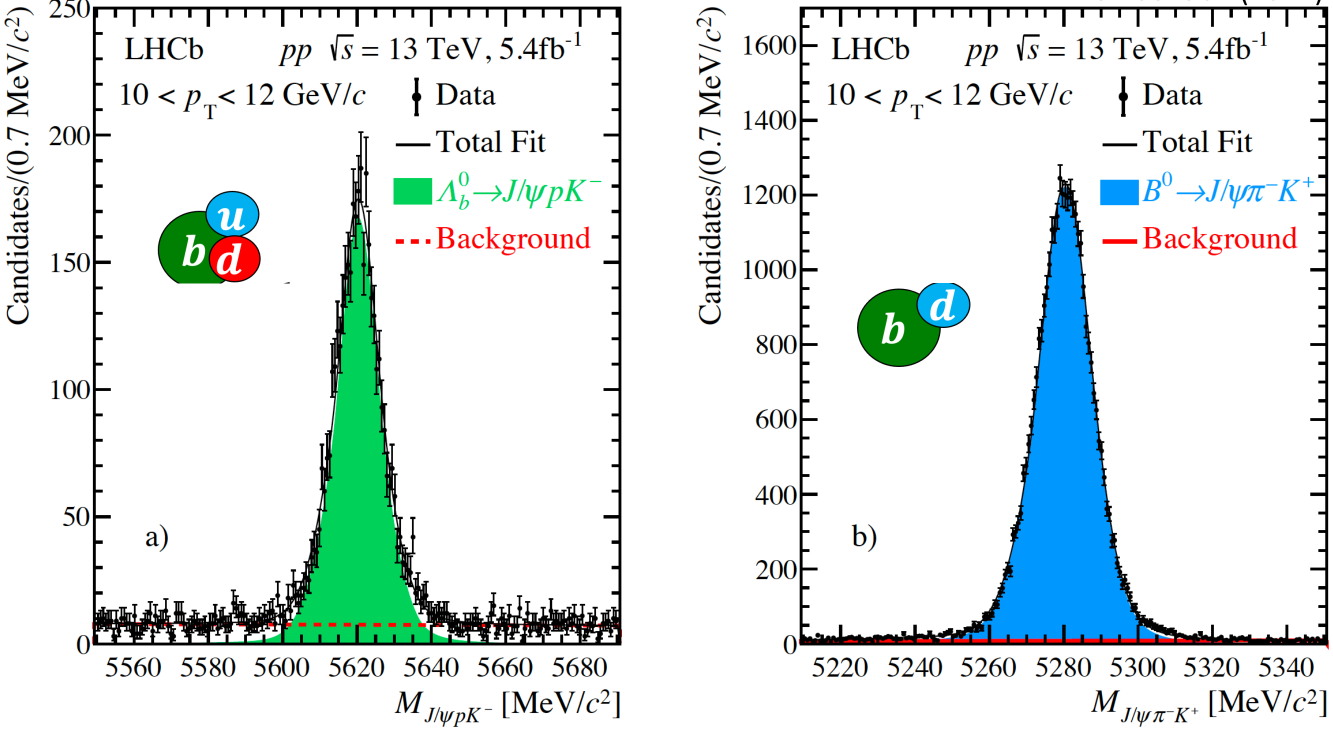


- Quarks that overlap in position/velocity space can coalesce to make color neutral hadrons
- At high density, expect increased production of **hadrons with strange quarks** and enhanced production of **3-quark baryons**
- Expect pure fragmentation at low density

Modification of b hadronization – B baryons

- Coalescence provides a new mechanism for baryon formation - 3 quarks wavefunctions overlap
- Baryon enhancement is therefore a signature of coalescence

PRL 132 081901 (2024)



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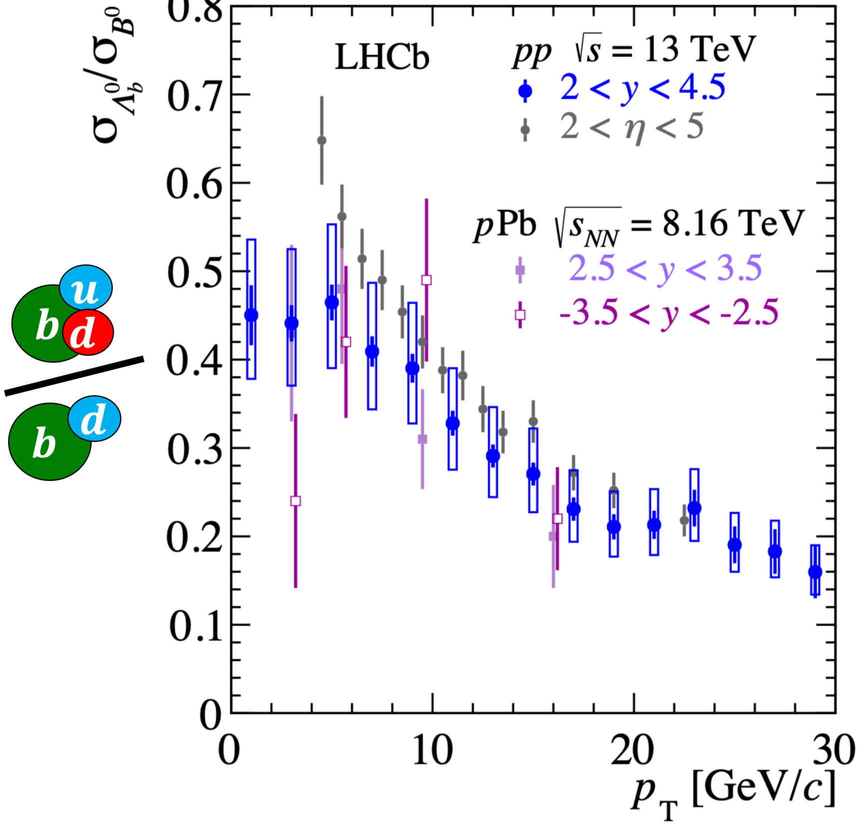
Modification of *b* hadronization – B baryons

PRL 132 081901 (2024) Featured in Physics



Baryon/meson ratio shows significant p_T dependence

Consistent with previous results (semileptonic decays)

Consistent with pPb results, within large uncertainties

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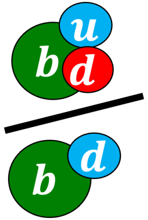

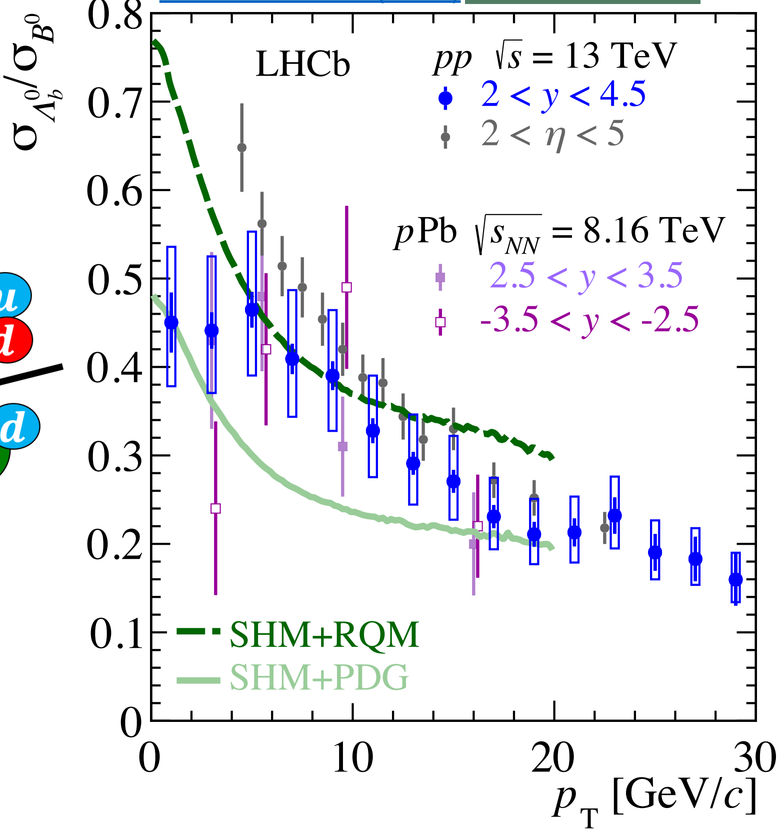

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- Expanded set of baryons predicted by the Relativistic Quark Model

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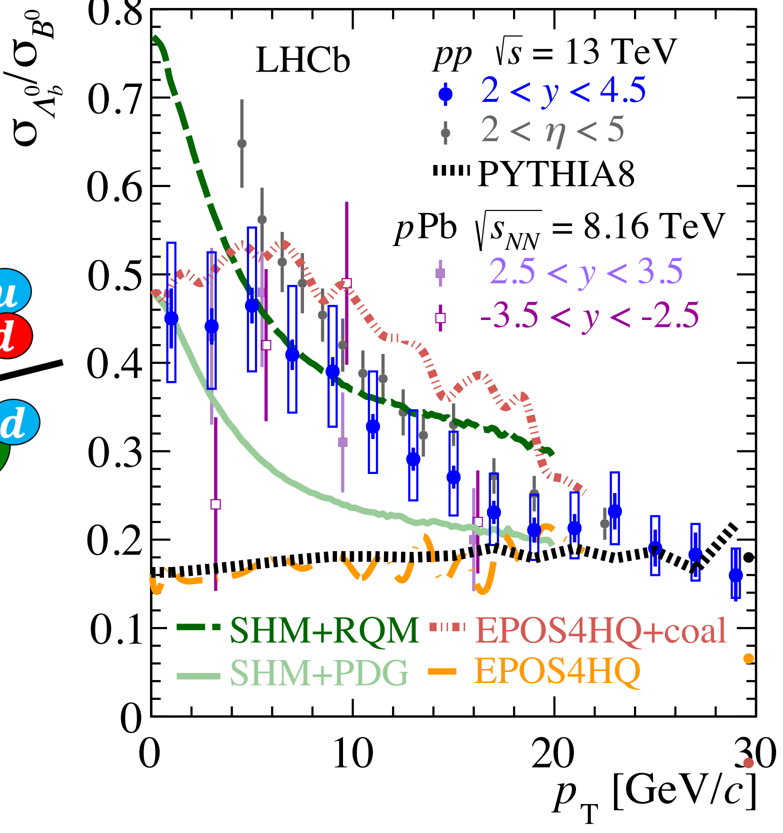

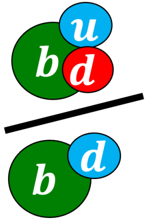

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PYTHIA8 fails to reproduce p_T dependence

EPOS4HQ with only fragmentation also fails

EPOS4HQ with fragmentation+quark coalescence does much better, slightly overpredicts ratio

Modification of *b* hadronization – B baryons

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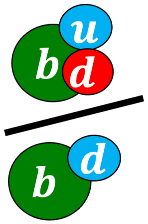
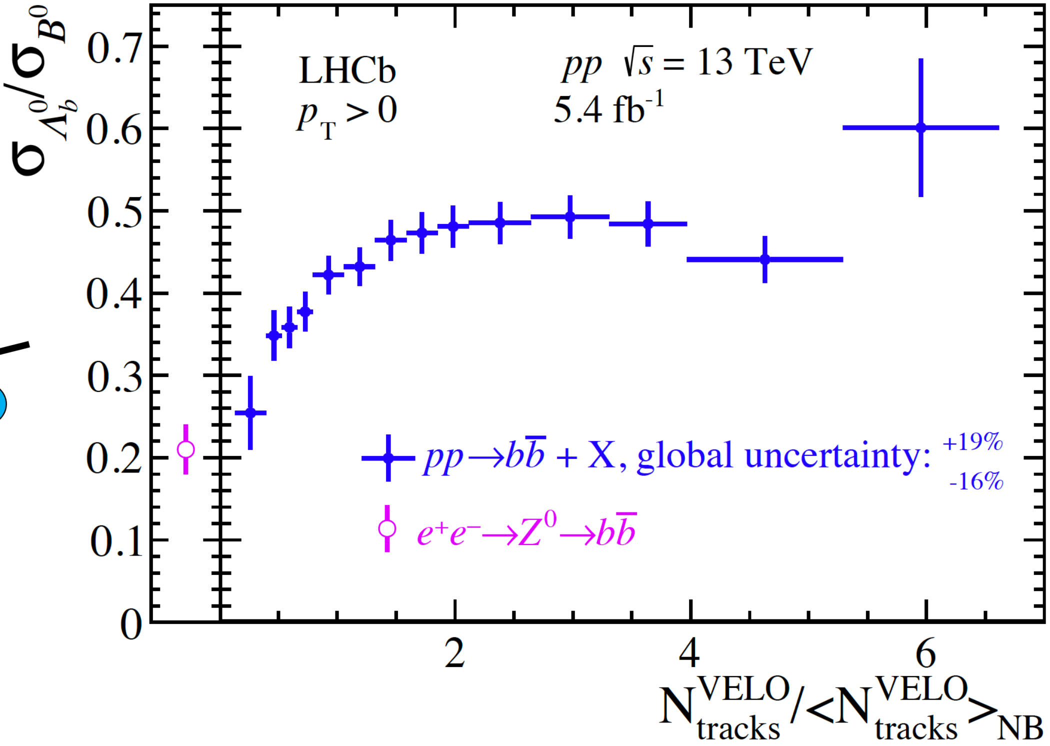
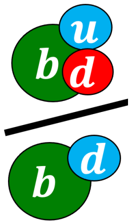


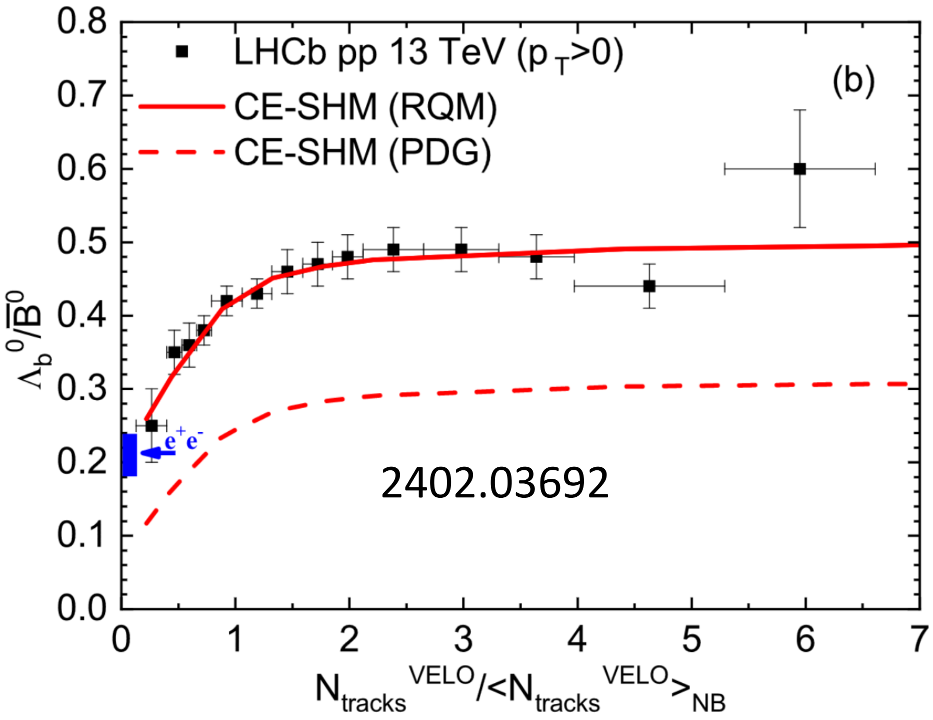


- Baryon/meson ratio shows significant multiplicity dependence
- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Reproduce e^+e^- result as multiplicity approaches zero

b quarks in low multiplicity collisions have nothing to coalesce with → fragment in vacuum

Modification of b hadronization – B baryons





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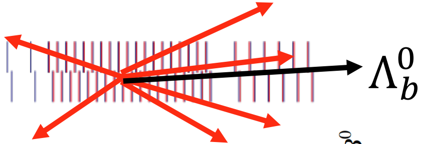
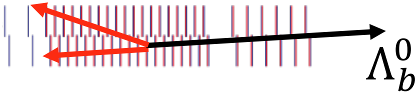
SHM reproduces trend with plateau – all possible baryon states populated at high multiplicity

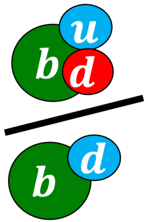
Modification of *b* hadronization – B baryons





N_{tracks}^{VELO}

N_{tracks}^{back}



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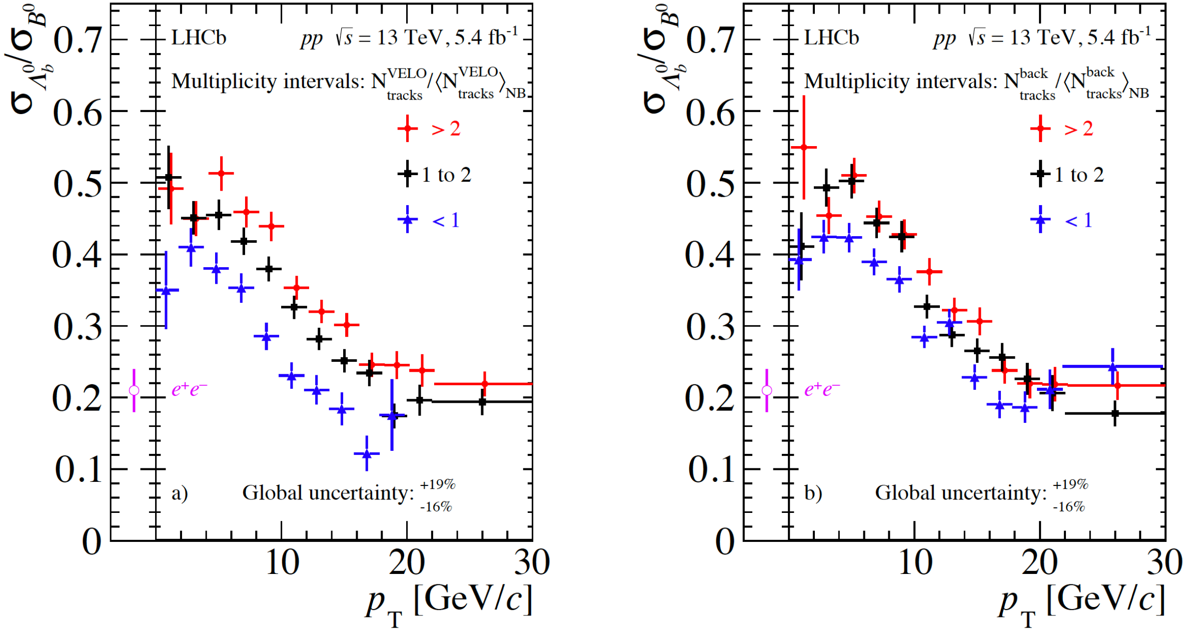
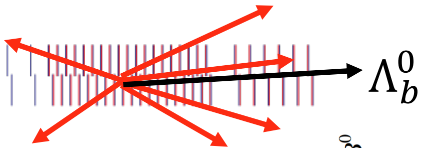
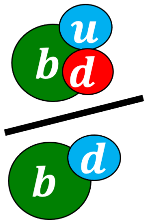


- Clear multiplicity dependence at relatively low p_T

Modification of *b* hadronization – B baryons



$N_{\text{tracks}}^{\text{VELO}}$



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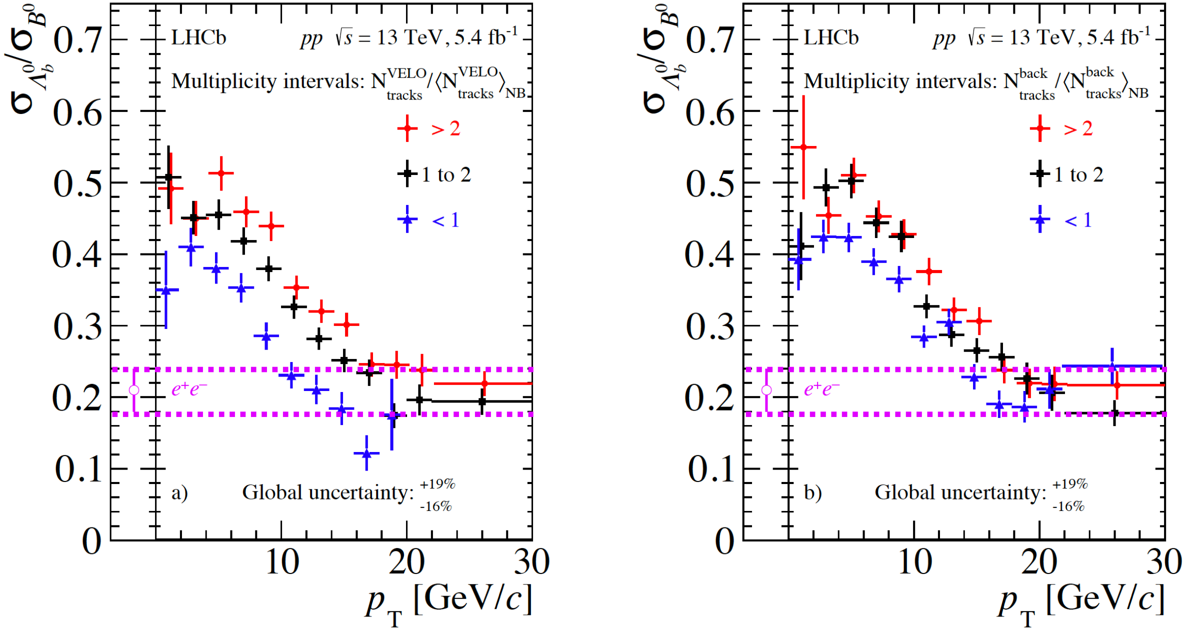
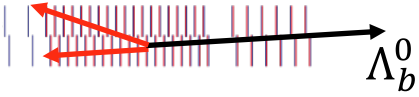


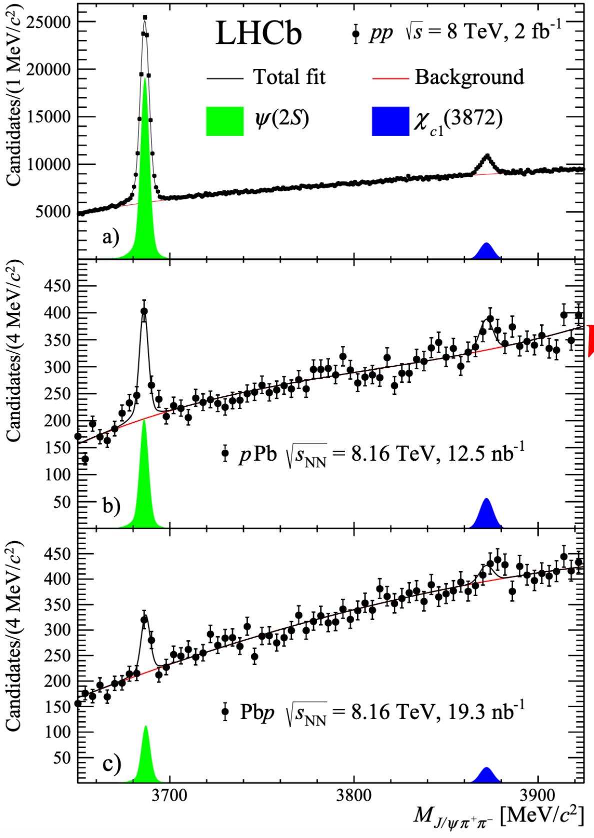


$N_{\text{tracks}}^{\text{back}}$

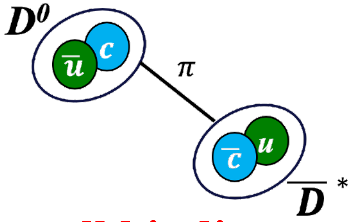
- Clear multiplicity dependence at relatively low p_T
- Reproduce e^+e^- result at high p_T where *b* quarks don't interact with bulk and just fragment
- Identical conclusions for strangeness enhancement in B mesons: Phys. Rev. Lett. 131, 061901

X(3872) in pPb

PRL 132 242301 (2024) Editors' Suggestion

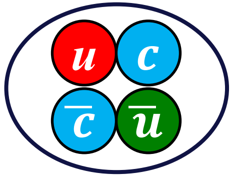


$D^0\overline{D}^*$ Molecule



VERY small binding energy
VERY large radius, ~10 fm

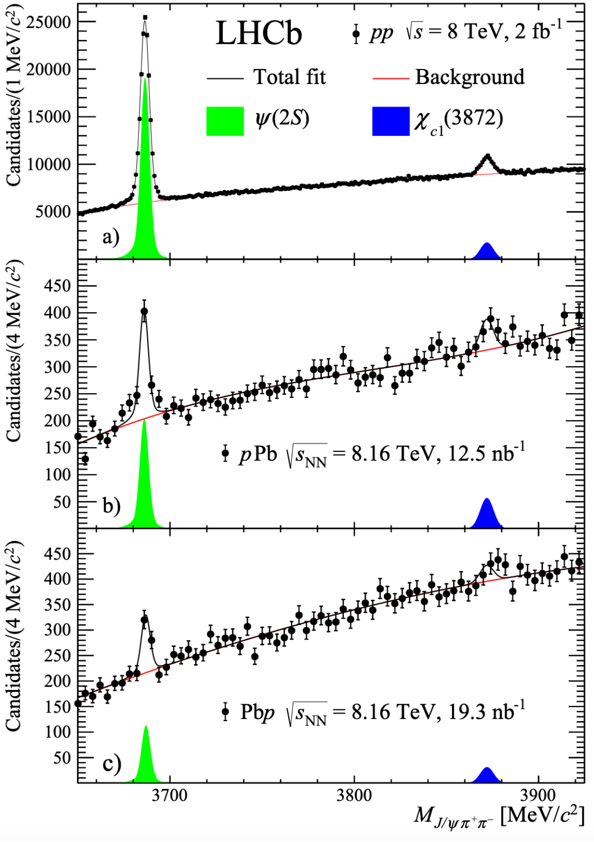
Compact tetraquark

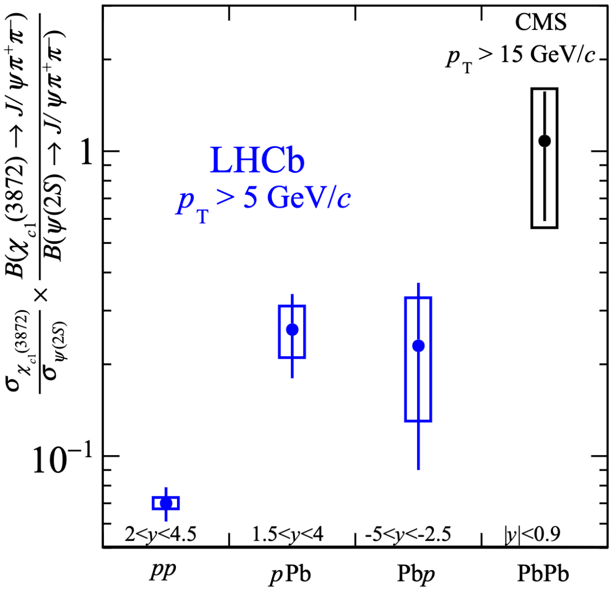


Tightly bound via color exchange between diquarks
Small radius, ~1 fm

X(3872) in *p*Pb

PRL 132 242301 (2024) Editors' Suggestion





Comparison between X(3872) and ψ(2S) suggests ***something different*** may be happening to exotic vs conventional hadrons in medium

Initial state effects (eg shadowing) should largely cancel in ratio

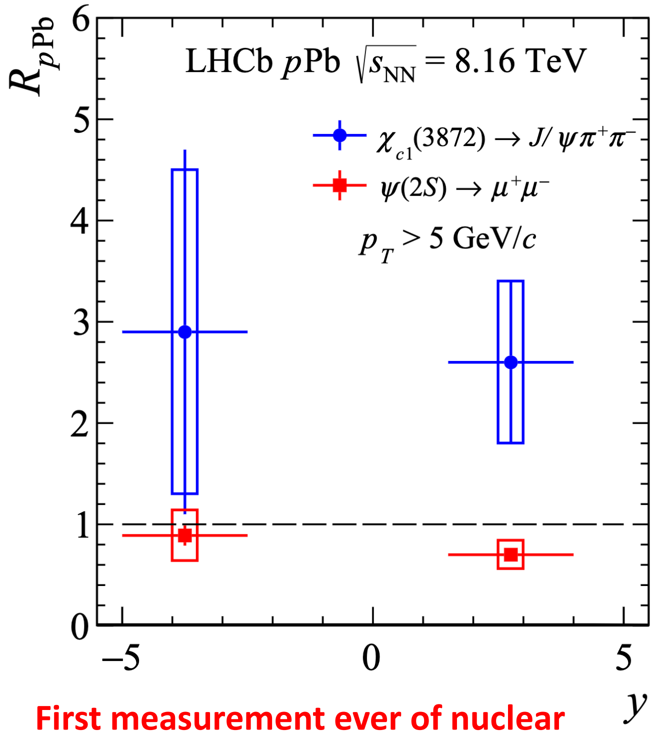
Enhancing effects start to out compete breakup?

- arXiv:2302.03828

Prompt X(3872)/ ψ(2S) = 0.26 ± 0.08 ± 0.05 in forward pPb
Prompt X(3872)/ ψ(2S) = 0.23 ± 0.15 ± 0.10 in backward pPb
Falls between pp (~0.1) and PbPb (~1.0)
AMBIGUITY between X(3872) enhancement and ψ(2S) suppression

X(3872) in *p*Pb

PRL 132 242301 (2024) **Editors' Suggestion**



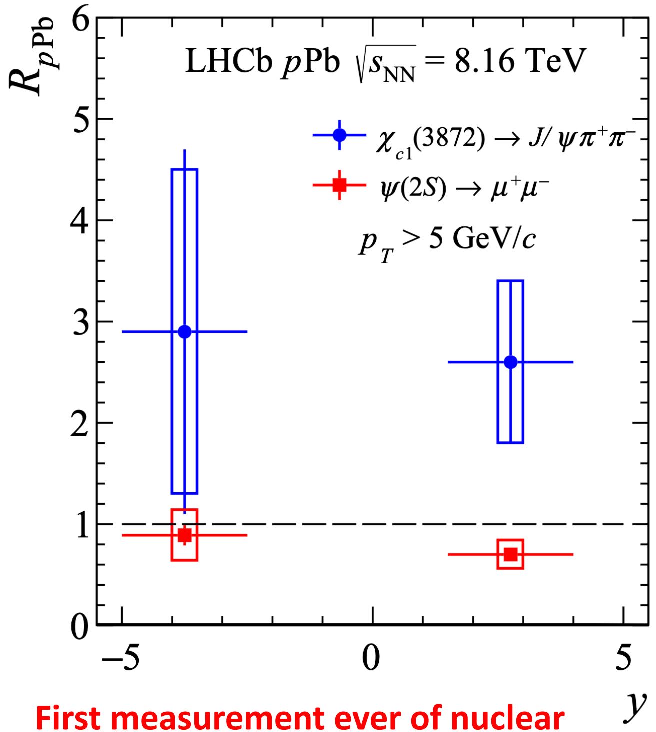
First measurement ever of nuclear modification factor of a tetraquark!

Ambiguity lifted by measuring nuclear modification factors:

$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208 \times \sigma_{pp}^{\chi_{c1}(3872)}}$$

X(3872) in pPb

PRL 132 242301 (2024) Editors' Suggestion



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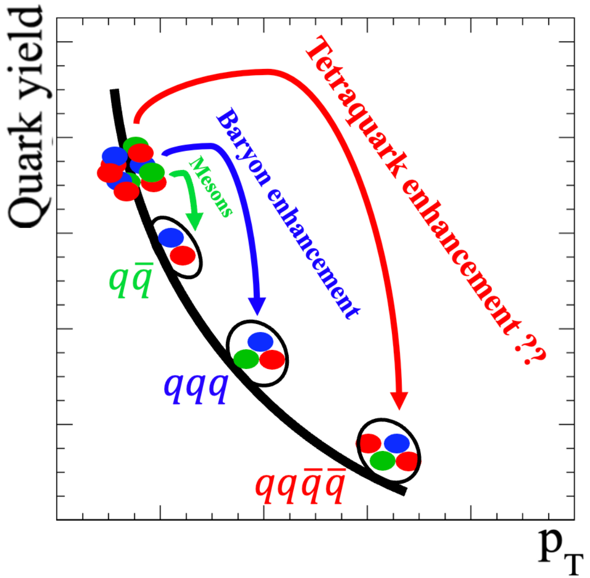
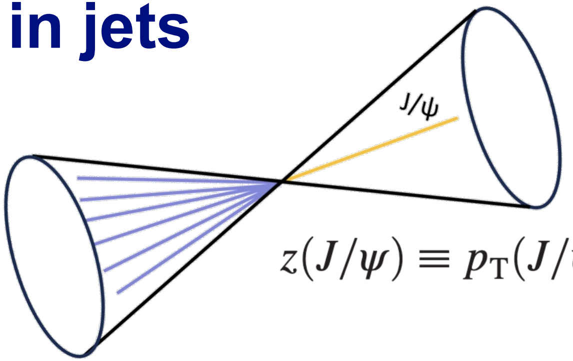
Evidence for enhancement of X(3872) in pPb: Coalescence dominating over breakup?

Similar mechanism for baryon enhancement could also increase tetraquark production



J/ψ in jets

- Charmonia provides a platform for testing perturbative and non-perturbative QCD
- Long-standing with description of charmonia production and polarization
- Charmonia in jets provides new way to examine production mechanisms



$$z(J/\psi) \equiv p_{\mathrm{T}}(J/\psi)/p_{\mathrm{T}}(\mathrm{jet})$$

J/ψ in jets

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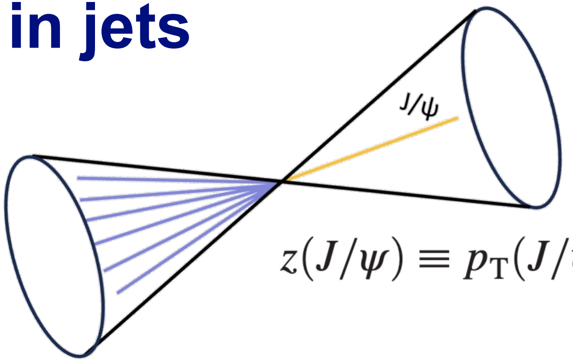

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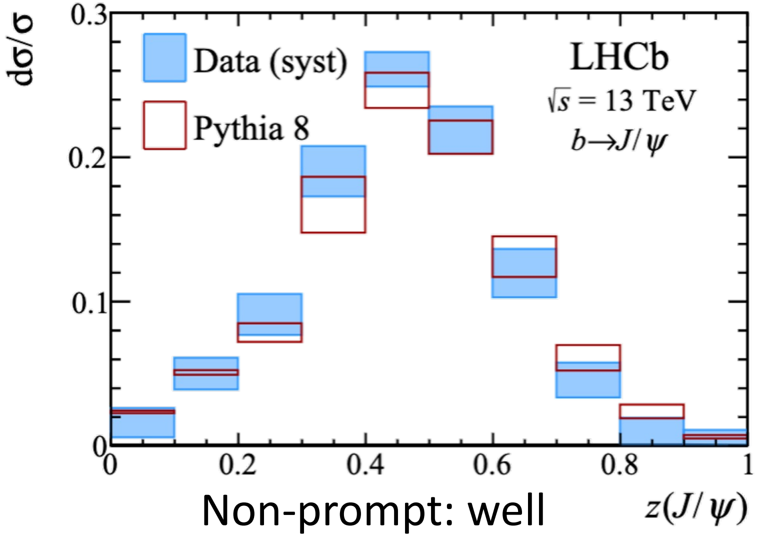

Non-prompt: well described by PYTHIA

J/ψ in jets

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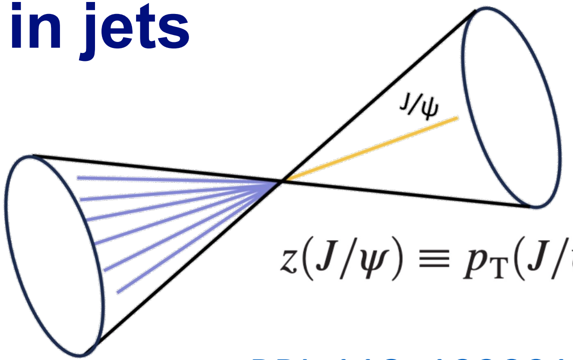

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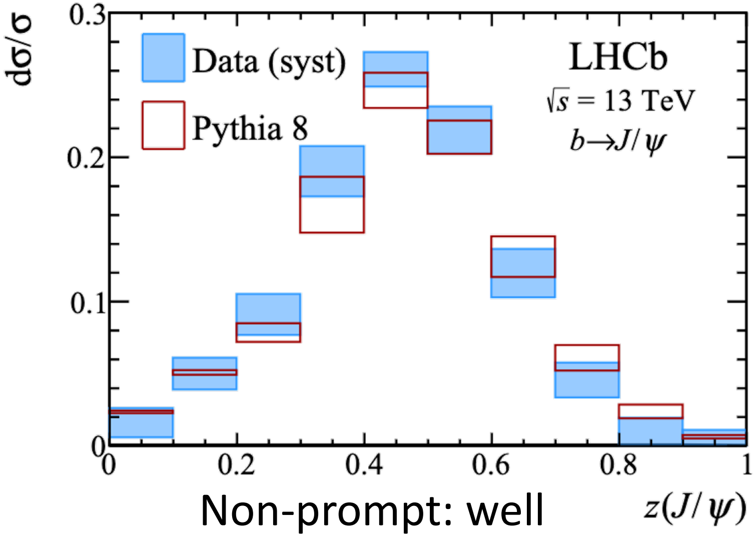
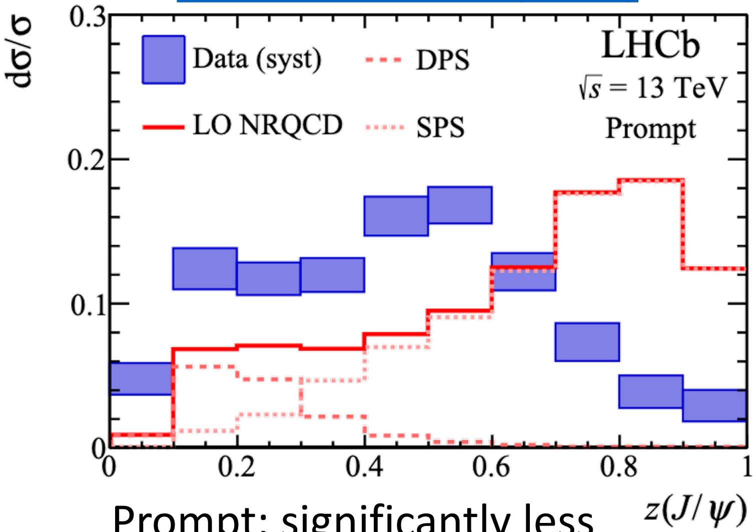
[PRL 118, 192001 (2017)]



Non-prompt: well described by PYTHIA

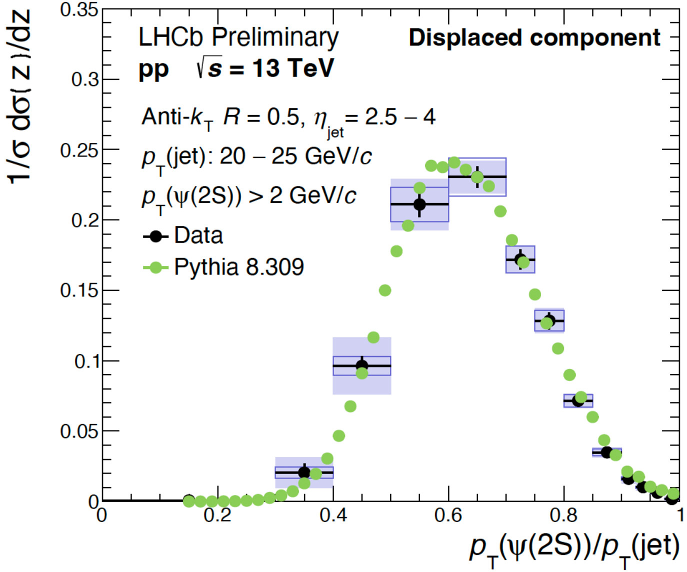


Prompt: significantly less isolated than NRQCD prediction

ψ(2S) in jets

- The same measurement can also be done with $\boldsymbol{\psi}$(2S)
  - Very little feeddown, unlike $\boldsymbol{J/\psi}$

LHCb-PAPER-2024-021



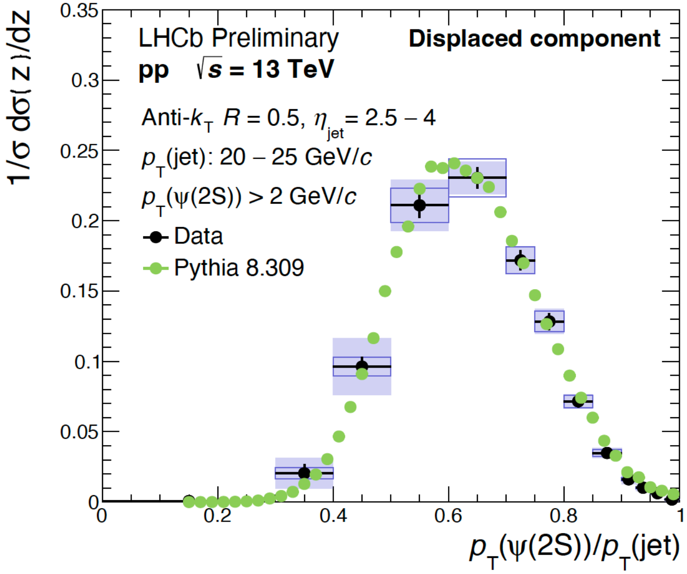
$\boldsymbol{b} \rightarrow \boldsymbol{\psi}$(2S) : well described by PYTHIA

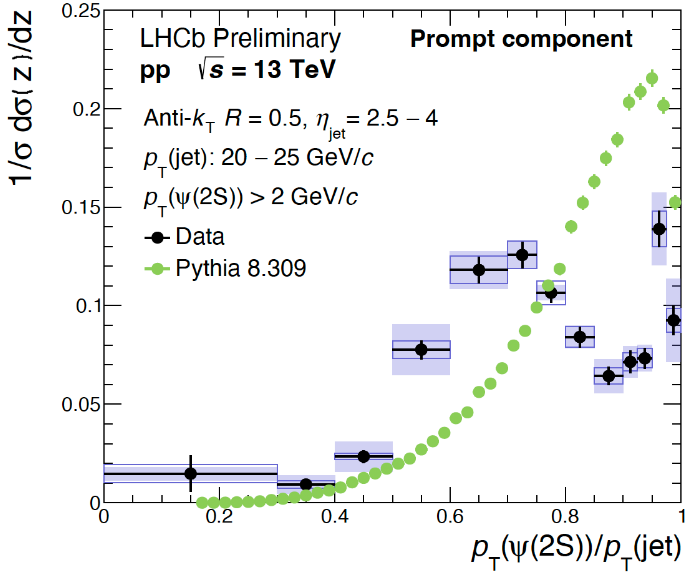
Very similar to $\boldsymbol{b} \rightarrow \boldsymbol{J/\psi}$

$\psi(2S)$ in jets

- The same measurement can also be done with $\psi(2S)$
  - Very little feeddown, unlike J/ψ

LHCb-PAPER-2024-021



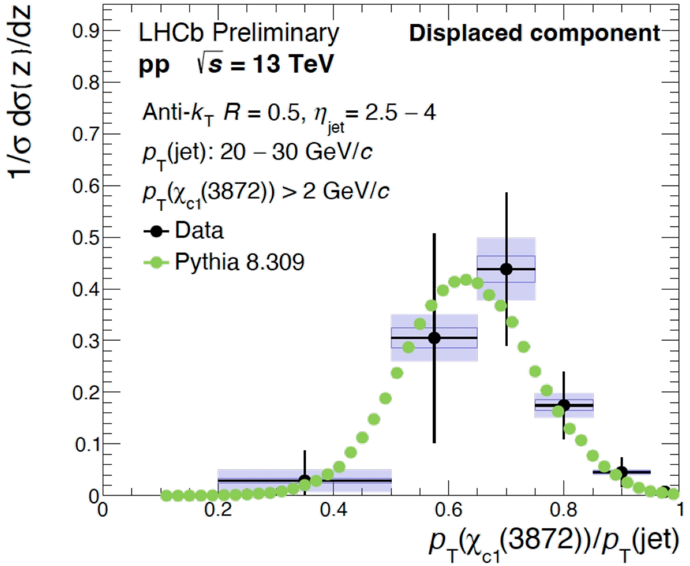


$b \to \psi(2S)$: well described by PYTHIA
Very similar to $b \to J/\psi$

Prompt: less isolated than NRQCD prediction
Two component structure: different production mechanisms?

$X(3872)$ in jets

LHCb-PAPER-2024-021

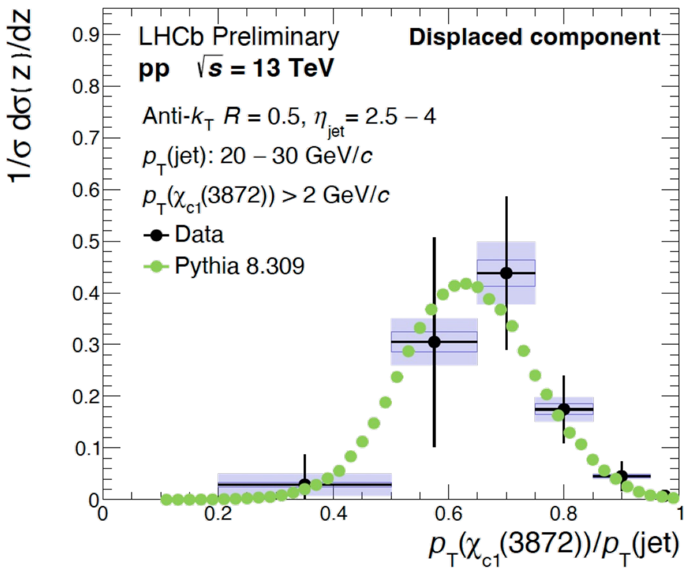


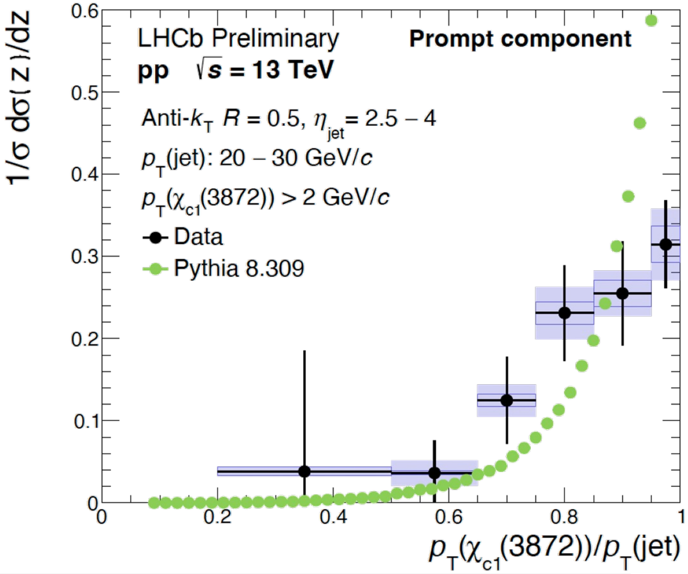
$b \rightarrow X(3872)$: well described by PYTHIA

Very similar to $b \rightarrow J/\psi$

$X(3872)$ in jets

LHCb-PAPER-2024-021

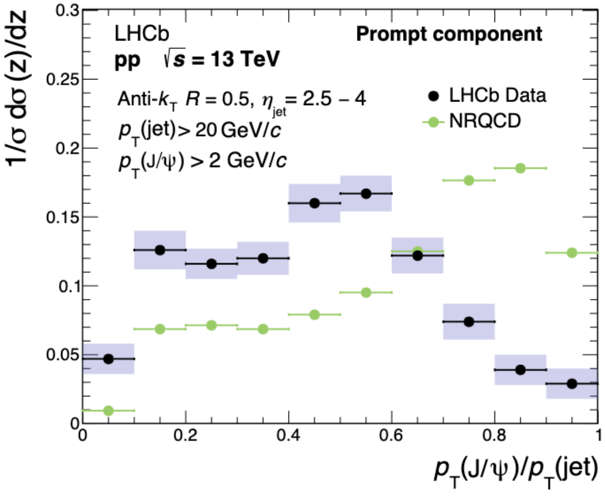


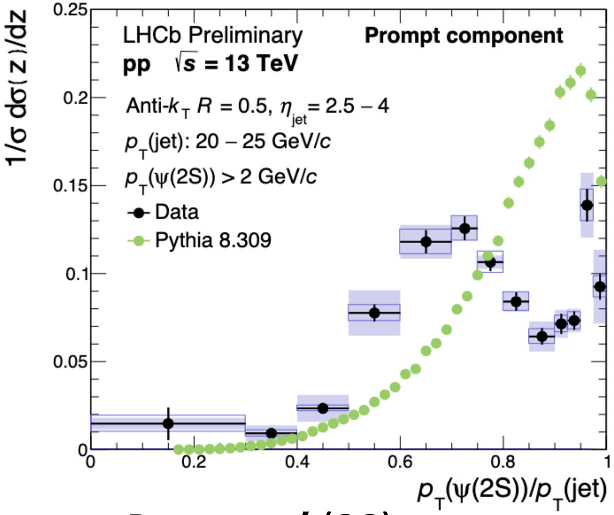


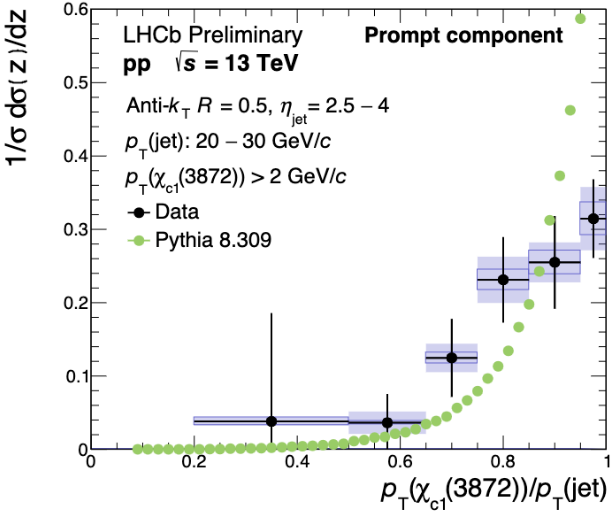
$b \rightarrow X(3872)$: well described by PYTHIA
Very similar to $b \rightarrow J/\psi$

Prompt: Rises towards isolation, very different from conventional $c\bar{c}$ state ψ(2S)

Compare: prompt J/ψ , ψ(2S), X(3872)







Prompt J/ψ: less isolated than expected

Prompt ψ(2S):
Two component structure:
Different production mechanisms?

Prompt X(3872):
More isolated than conventional charmonia

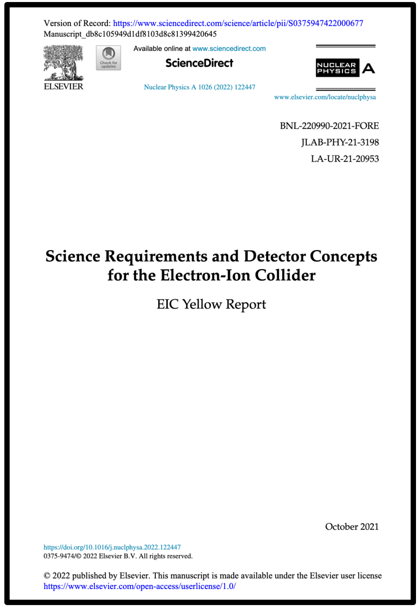
LHCb and EIC:
many overlapping physics topics

Partonic structure of nucleons

Hadronization

Photoproduction

Hadron spectroscopy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Science Requirements and Detector Concepts for the Electron-Ion Collider

EIC Yellow Report

October 2021

https://doi.org/10.1016/j.nuclphysa.2022.122447
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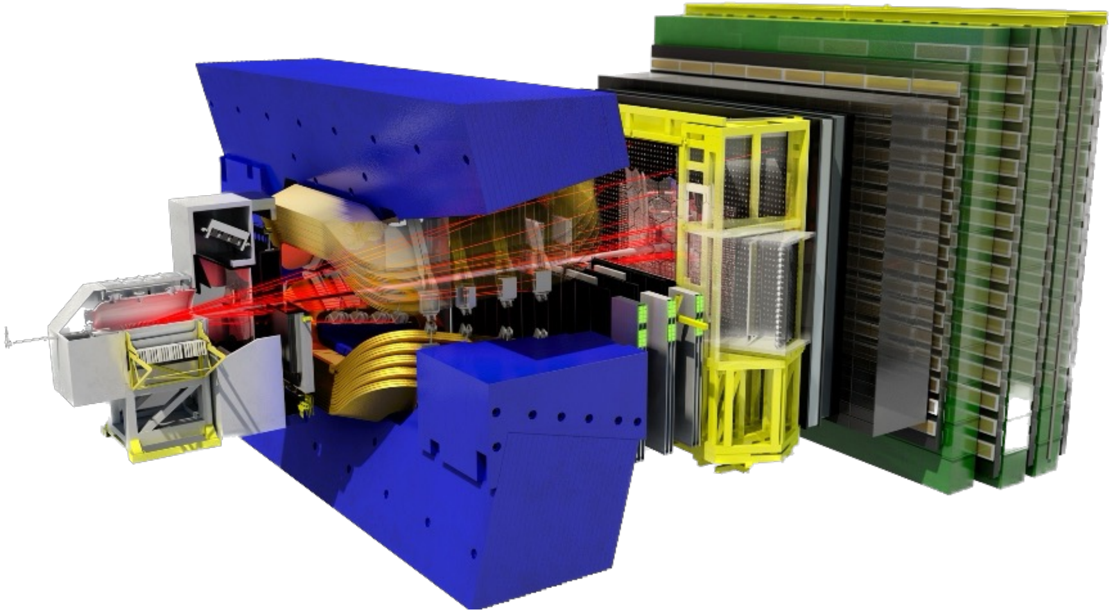
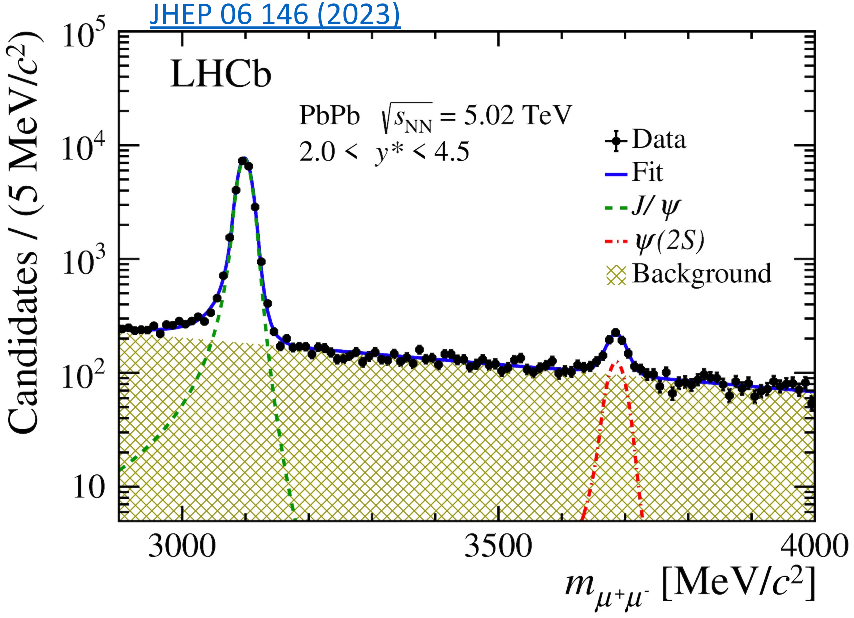
NPA 1026 122447(2022)

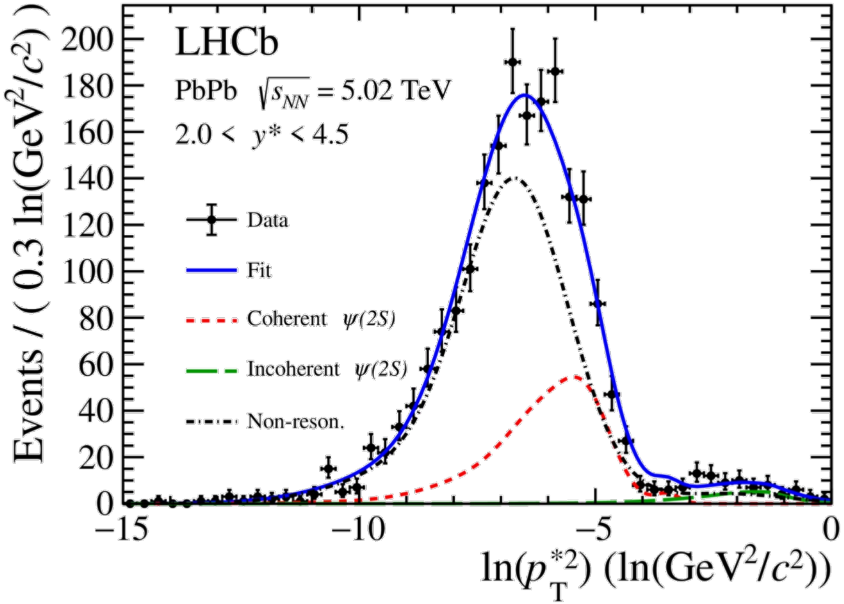


Different probes of the nucleus - UPC

- LHCb has full particle ID and collects large samples of UPC events
- Forward reach and high statistics provides new constraints on saturation models

JHEP 06 146 (2023)





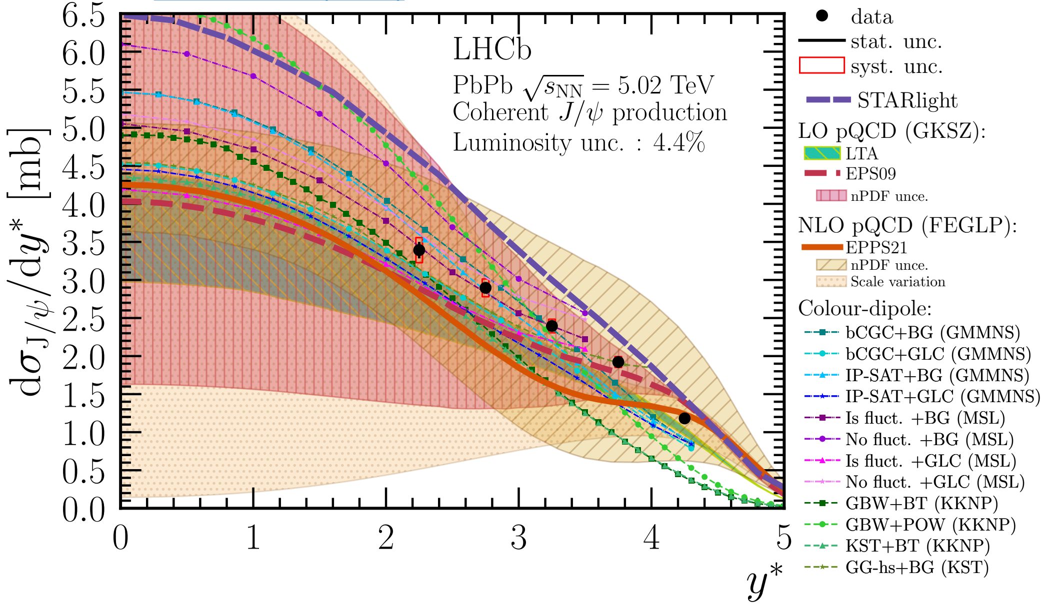
- LHCb is a nearly ideal detector for UPCs: fast DAQ, forward boost, full PID

Matt Durham

Different probes of the nucleus - UPC

- LHCb has full particle ID and collects large samples of UPC events
- Forward reach and high statistics provides new constraints on saturation models

JHEP 06 146 (2023)



- High precision access to very low p_T identified hadrons uniquely accessible at LHCb
- Multiple new UPC measurements underway

Different probes of the nucleus - UPC

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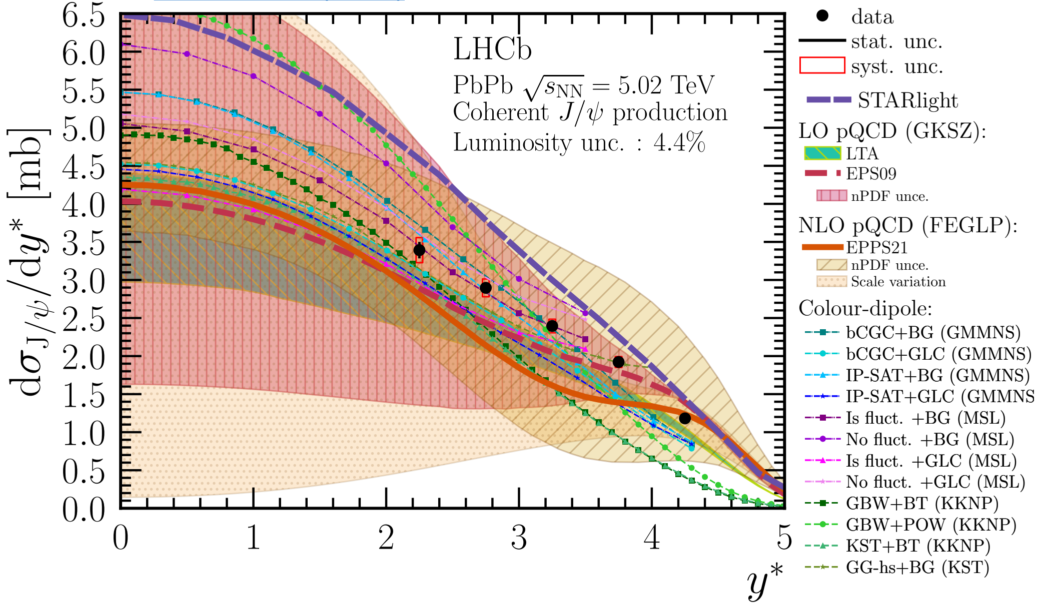
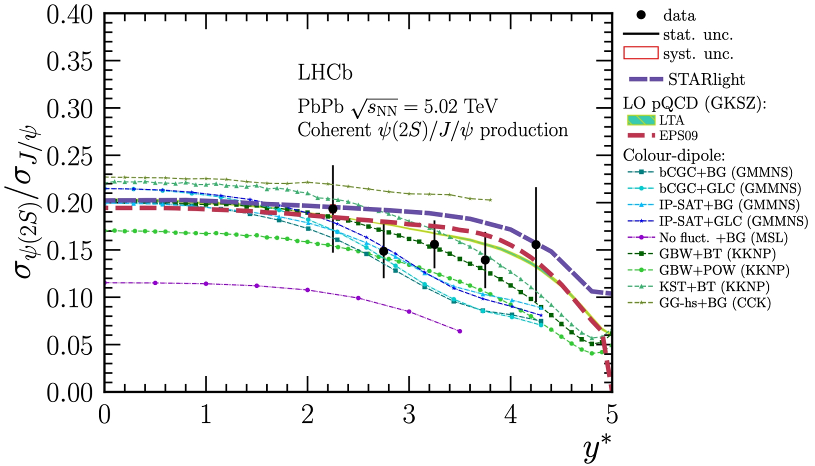
JHEP 06 146 (2023)

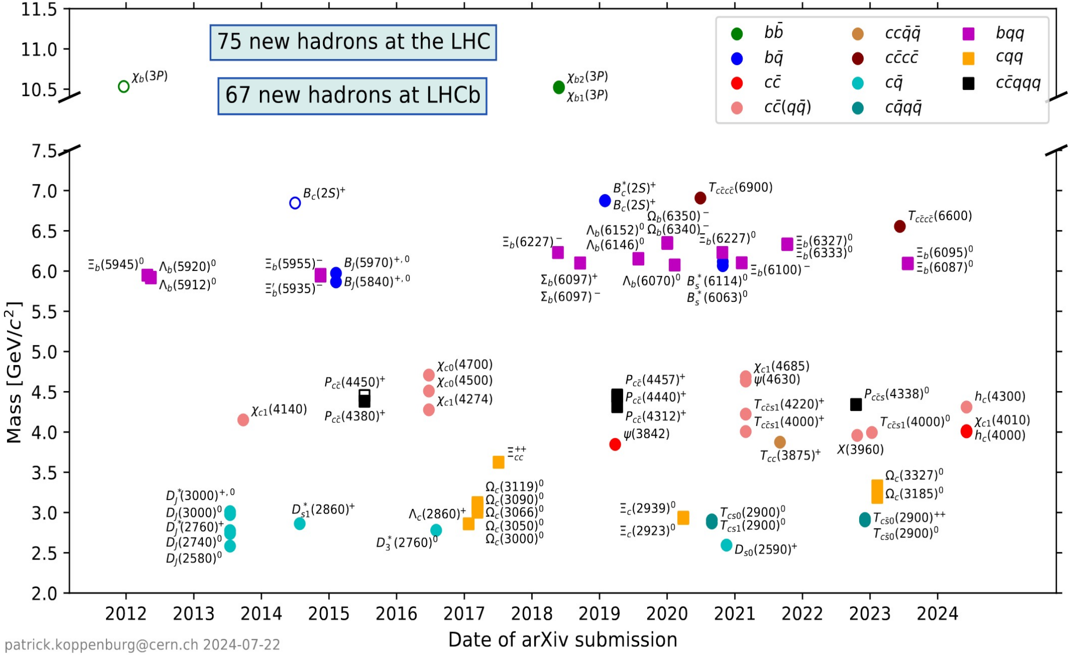




Some exp and theoretical uncertainties cancel in ratio

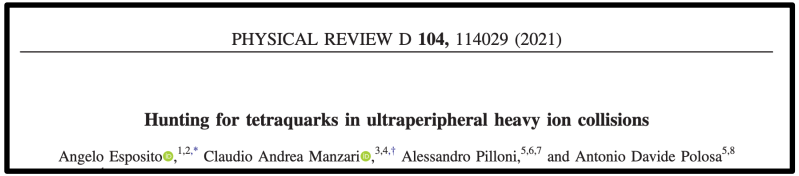
- High precision access to very low p_T identified hadrons uniquely accessible at LHCb
- Multiple new UPC measurements underway

New hadrons discovered at the LHC



LHCb is responsible for ~90% of the new particles discovered at the LHC

UPC and CEP are thought to be fertile grounds for producing exotic particles:



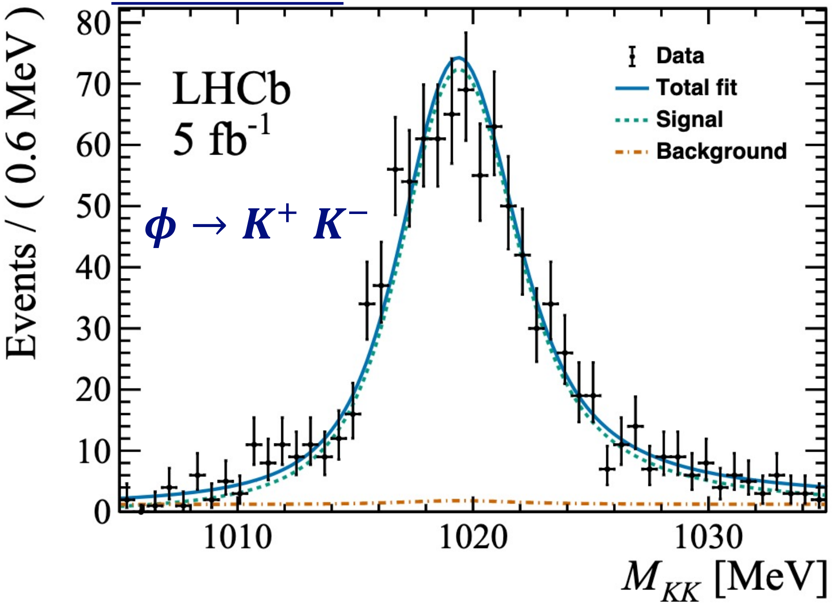
PHYSICAL REVIEW D **104,** 114029 (2021)

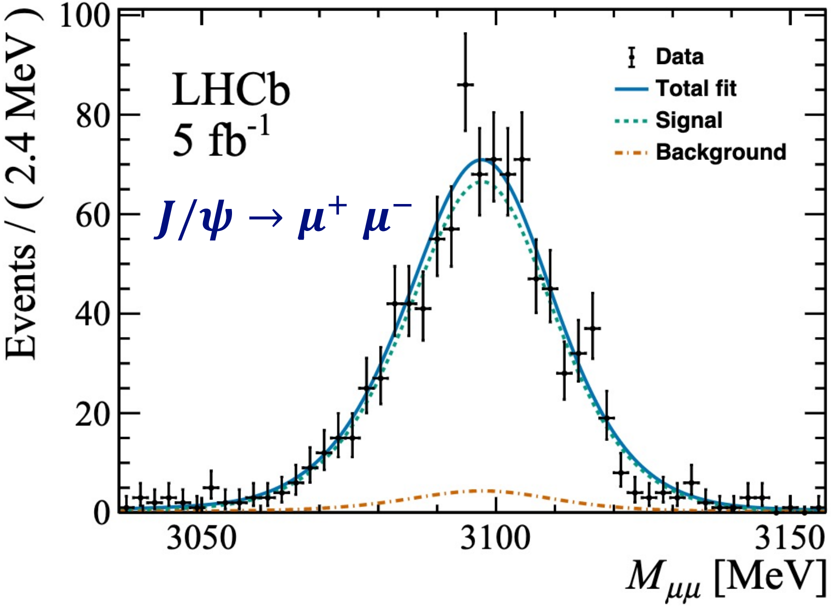
Hunting for tetraquarks in ultraperipheral heavy ion collisions

Angelo Esposito,[1,2,*] Claudio Andrea Manzari,[3,4,†] Alessandro Pilloni,[5,6,7] and Antonio Davide Polosa[5,8]

Central exclusive production of $J/\psi\phi$

2407.14301

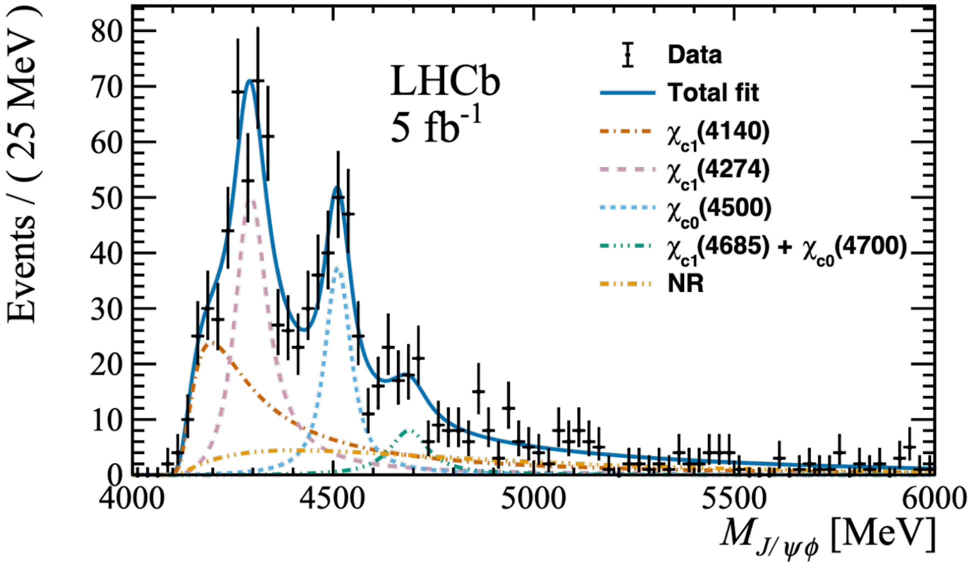


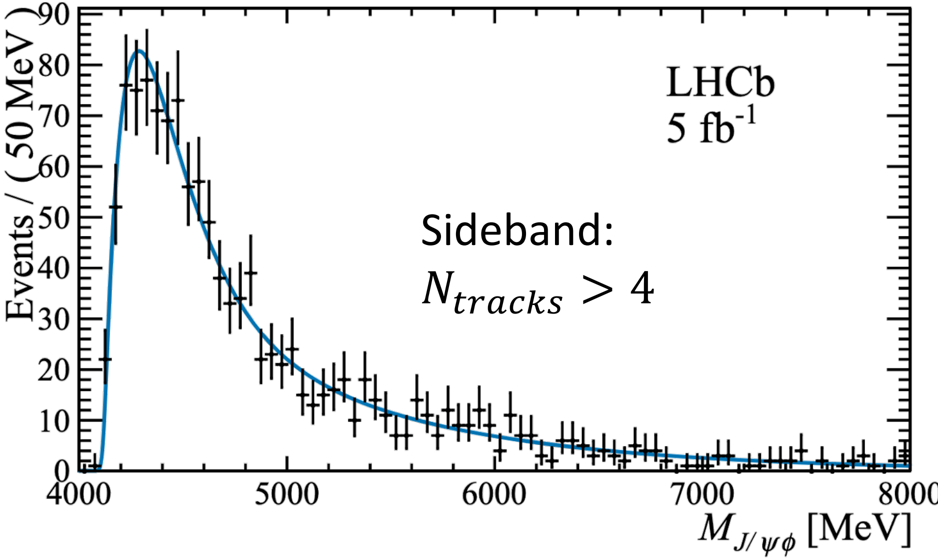


- Select events with exactly four tracks: two muons, two kaons
- Veto additional activity with HERSCHEL
- Clear signals for $\phi(1020)$ and J/ψ

Central exclusive production of $J/\psi\phi$

2407.14301



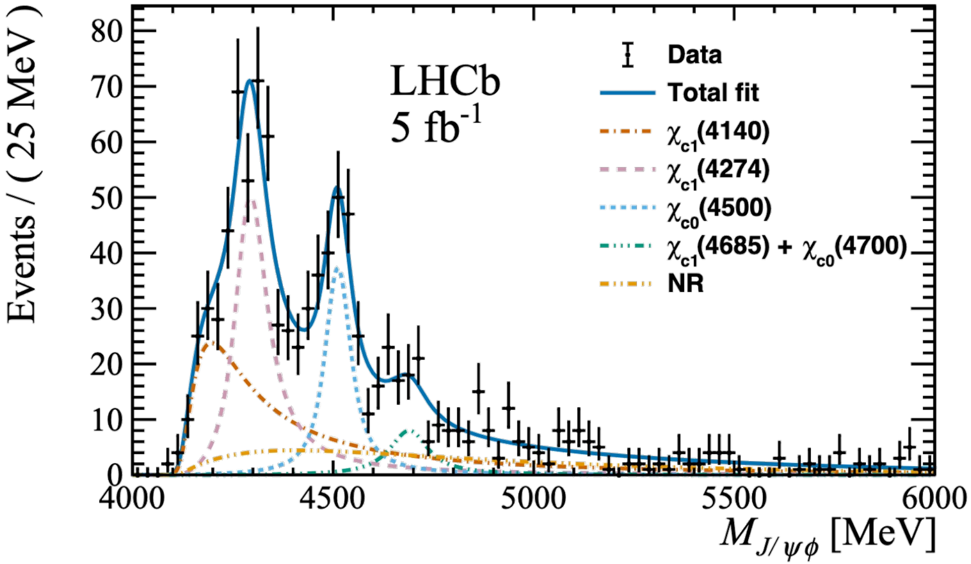


Sideband:
$N_{tracks} > 4$

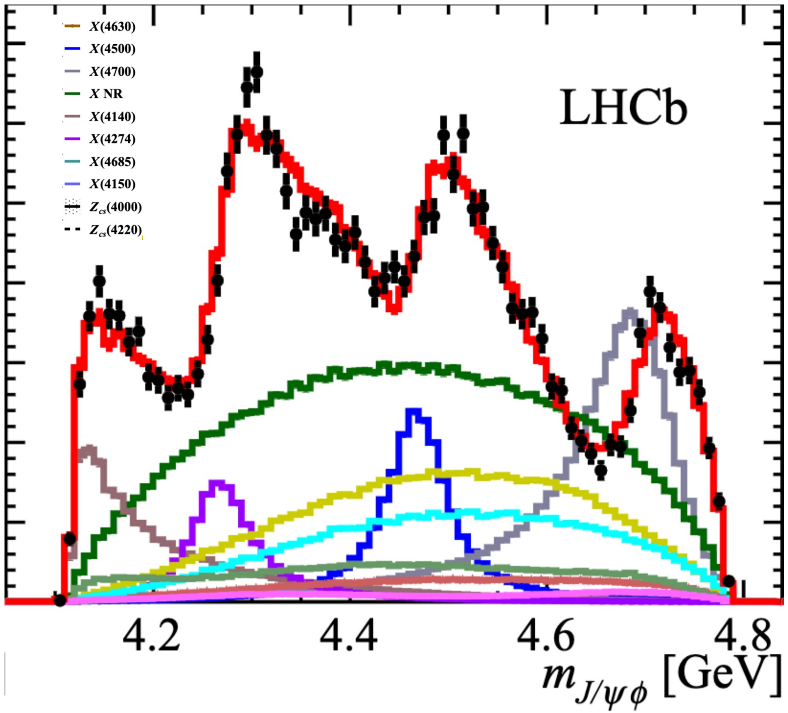
- Structures apparent when selecting only 4 tracks
- Gone when looking at “sideband” of events with more activity

Central exclusive production of $J/\psi\phi$

2407.14301



$B^{\pm} \rightarrow J/\psi\phi K^{\pm}$ PRL 127 082001 (2021)

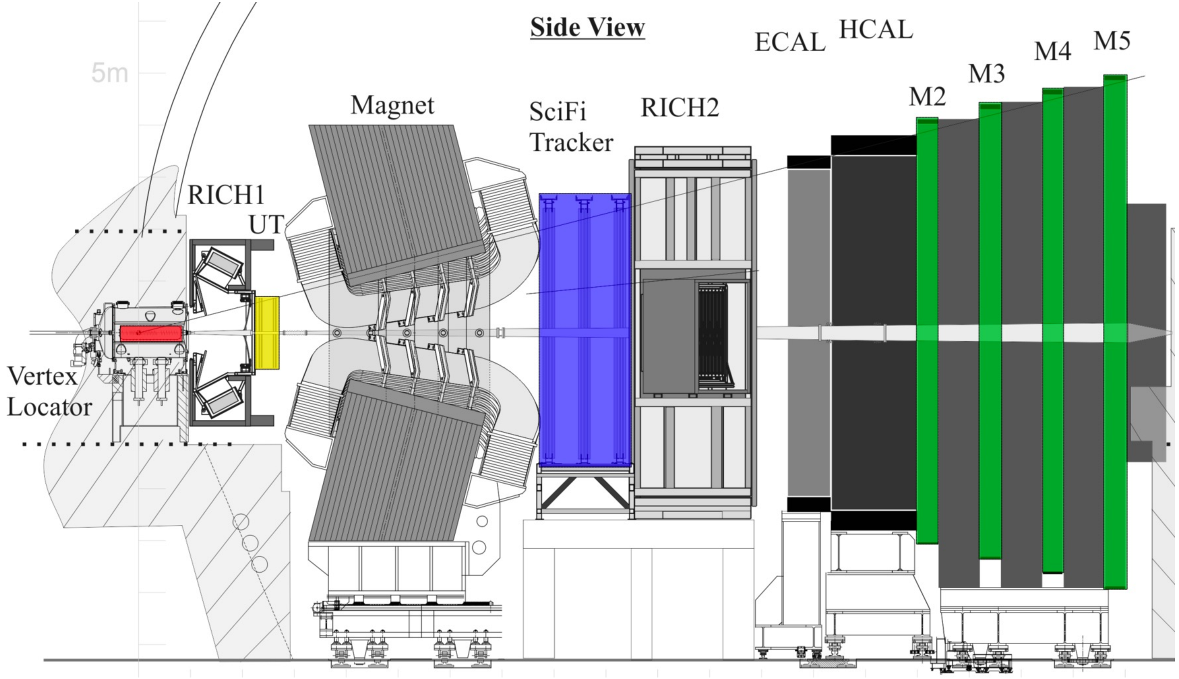


- Structure consistent with tetraquark candidates previously observed in $B^{\pm} \rightarrow J/\psi\phi K^{\pm}$ decays

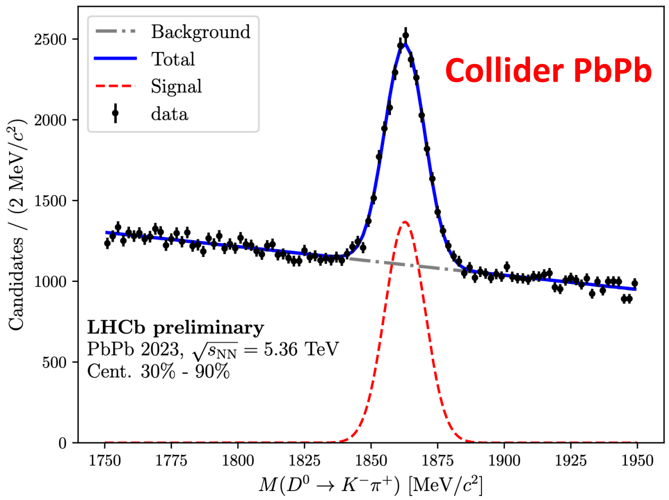
The beginning of a totally new hadron spectroscopy program

LHCb Upgrade 1(a) – Installed

- LHCb has **advanced the state of the art** with full streaming readout in *pp* at 40MHz
- All new tracking system allows reconstruction up to ~30% most central PbPb collisions

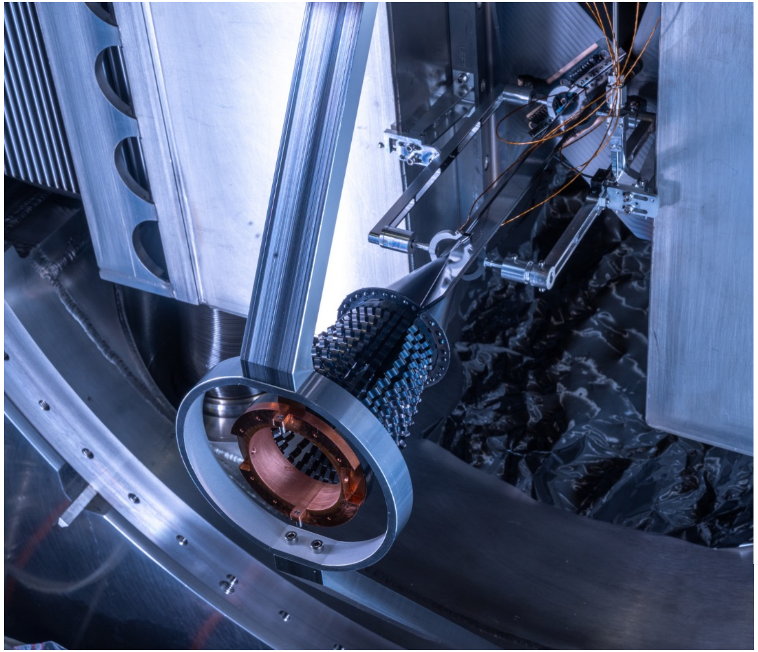


LHCb-FIGURE-2024-004

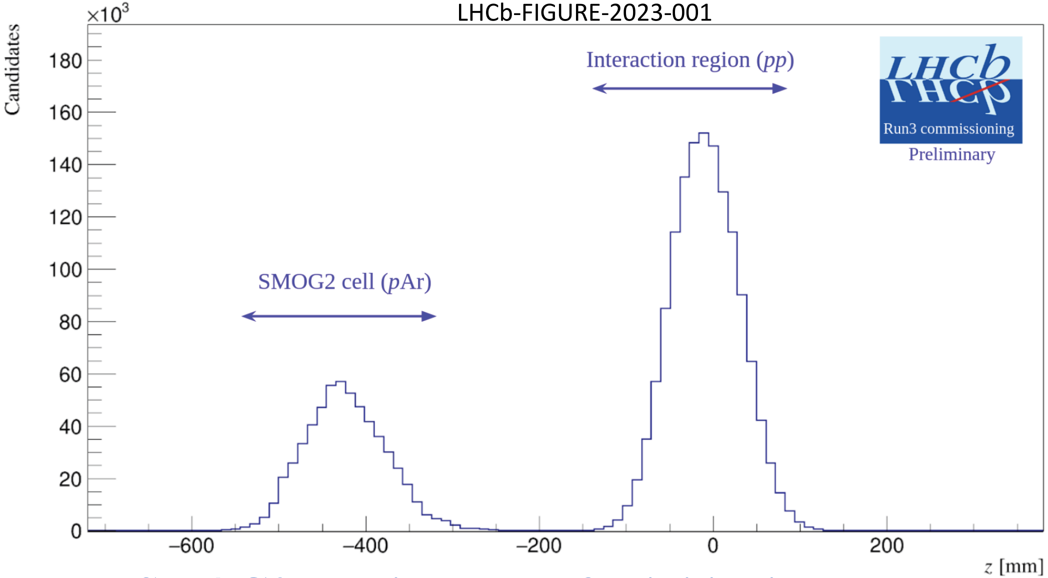


Fixed target upgrade – SMOG2

- Dedicated gas storage cell has been installed in front of LHCb VELO
- Allows greatly increased rates of beam+gas collisions



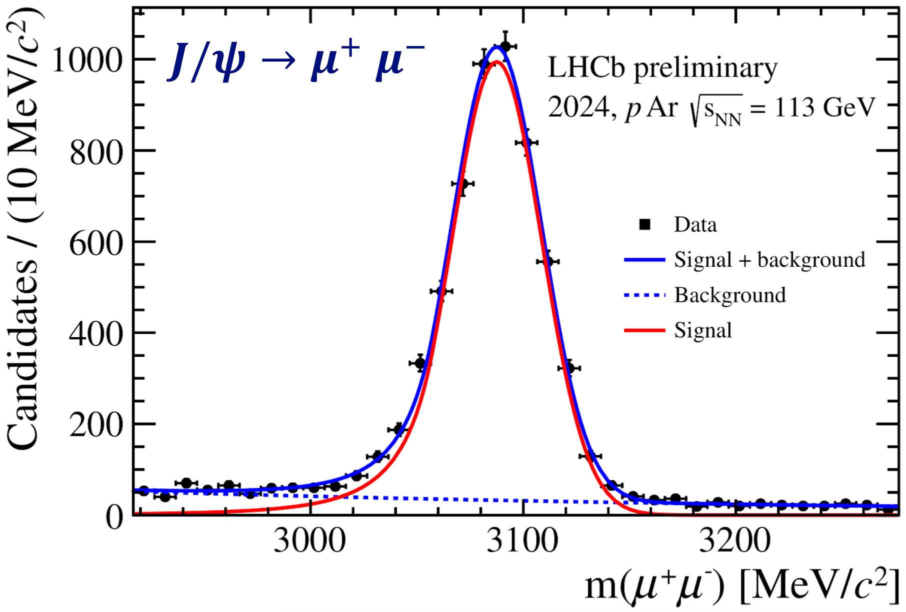
LHCb-FIGURE-2023-001



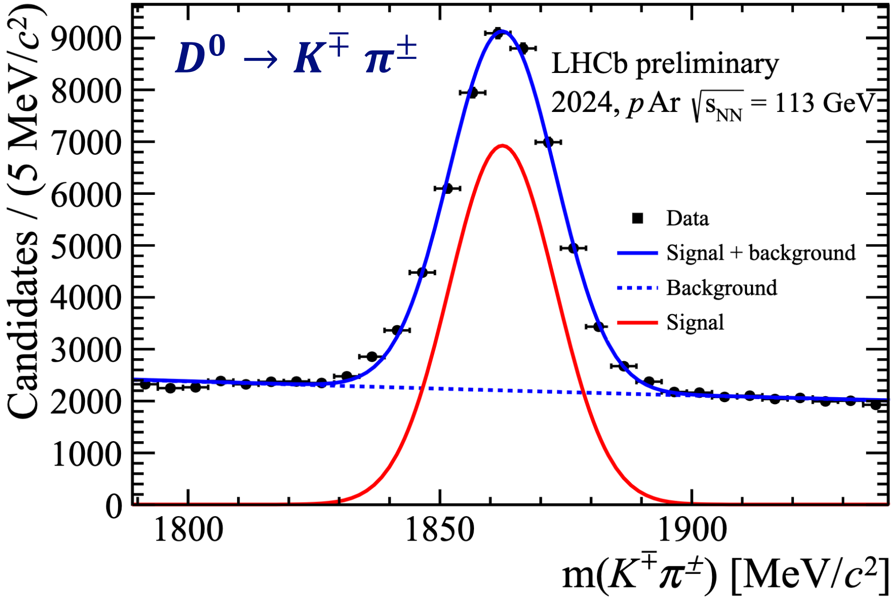
SMOG2 provides huge flexibility in targets:
e. g. run O+O at two collision energies simultaneously

Fixed target upgrade – SMOG2

- Concurrent running with *pp* data will provide HUGE data samples
- Reconstructions from 100 minutes of 2024 data
- Target species and luminosity priorities determined within LHCb
  - So far: *p*Ne, *p*Ar, *p*He, lots of pH_2, Pb+gas data coming

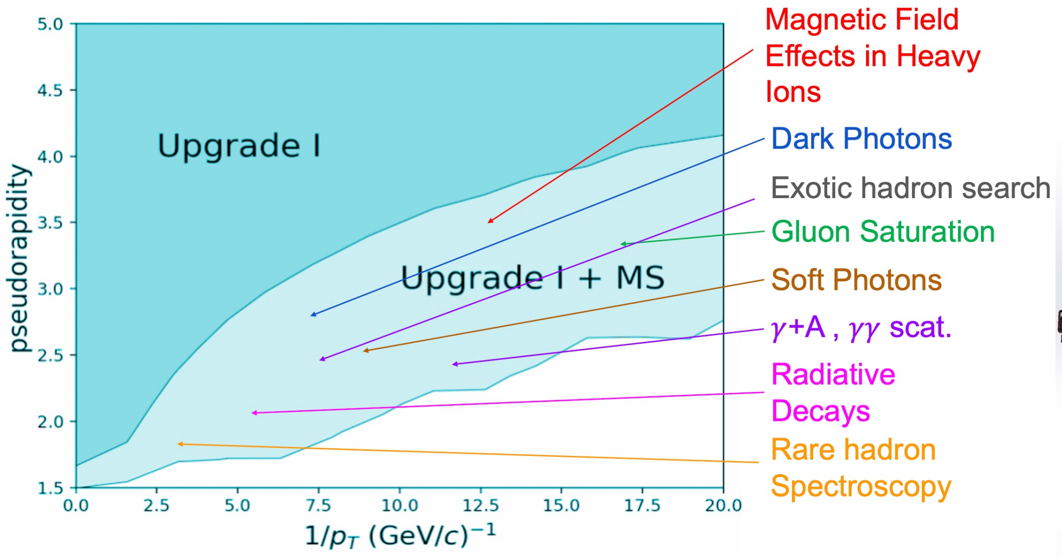


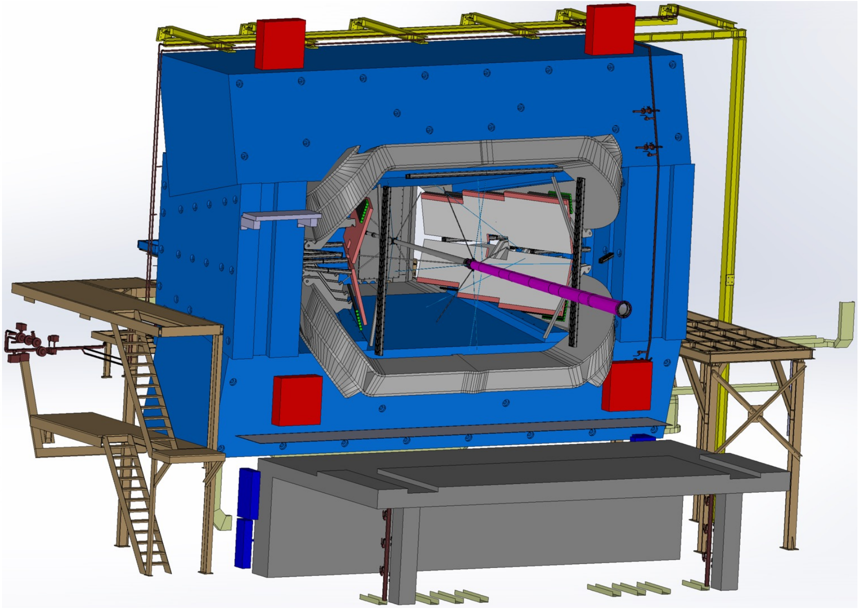
LHCb-FIGURE-2024-005



Tracking upgrade – Magnet Station (LS3)

- Scintillating bar tracker for very soft particles at LHCb, start installation LS3
- Expands soft physics channels previously unreachable at the LHC.
- Enahnced access to very low x, Q^2 region where gluon saturation may exist in nuclei.
- Access to very soft particles from UPCs





LHCb Upgrade II (Run 5+)

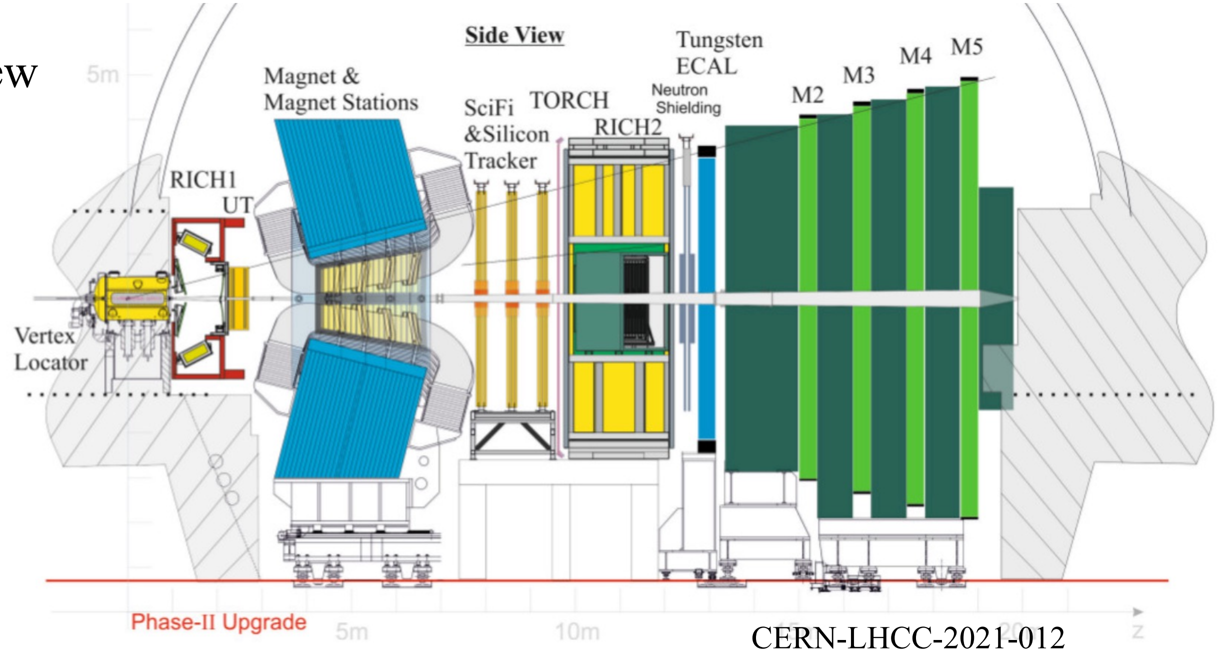
Further upgraded tracking to deal with high *pp* pileup and heavy ion collisions

- Access the full PbPb centrality range
- Precise measurements of *b* hadrons, exotic states, and more at low p_T in central collisions

Discussions beginning for a new era of fixed target physics: spin polarized target

arXiv:1901.08002

Huge complementarity with EIC



CERN-LHCC-2021-012

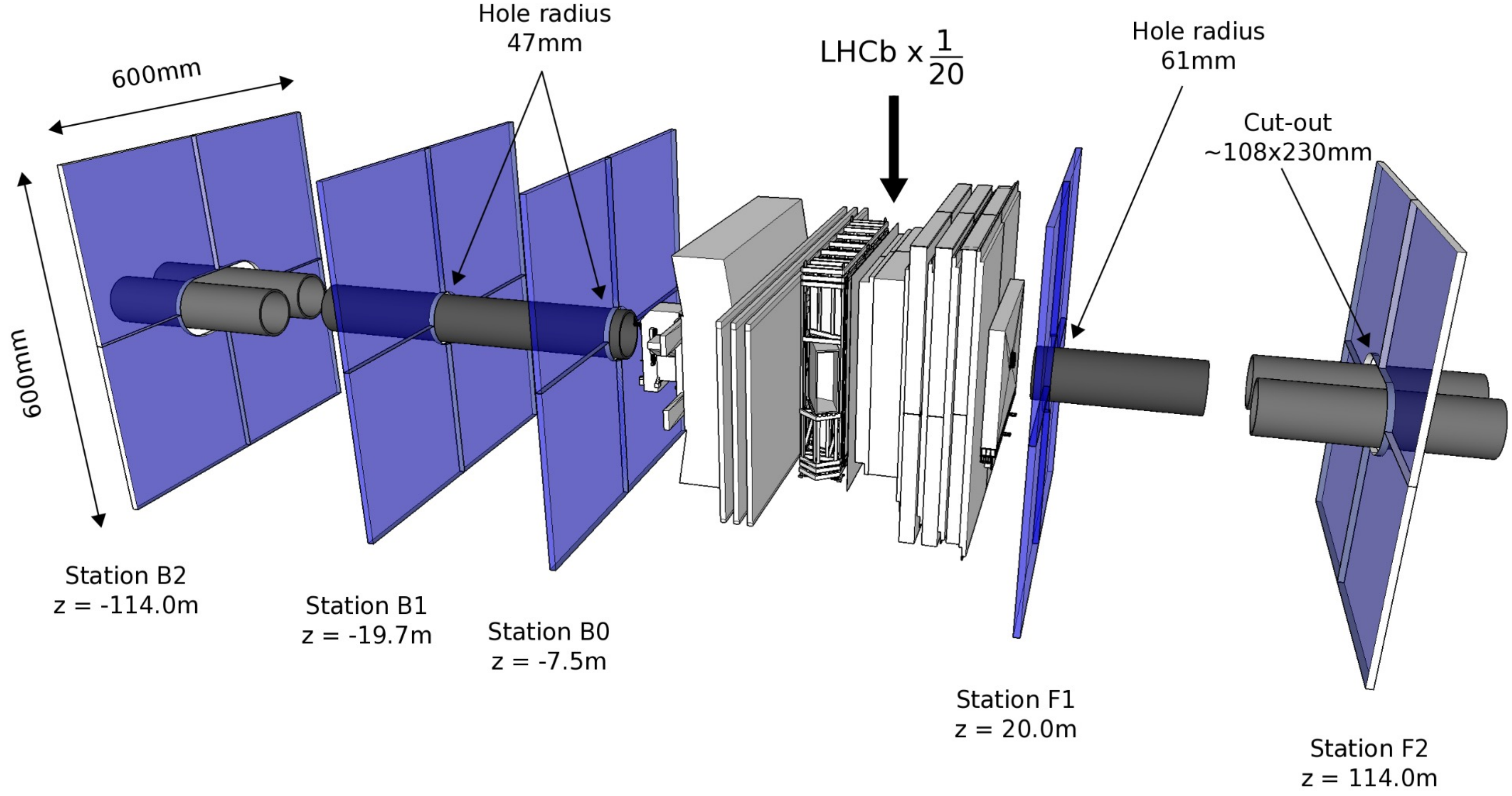
Summary

- LHCb plays a unique role in international heavy ion physics experiments
  - Widest range of x, Q^2 accessible in the laboratory
  - Unparalleled access to *b* quarks, higher charmonia, exotic hadrons, etc
  - Resonances reconstructed down to p_T=0
- The LHCb heavy ion group currently has a very high data/people ratio
  - With multiple SMOG2 species coming, soon we will have more data sets than groups involved in the heavy ion program
  - Severely under-utilized for UPC, flow, femtoscopy, jets, many other areas
- Ambitious upgrade plan with a direct impact on the heavy ion physics program is well underway.

Los Alamos National Laboratory is supported by

DOE/Office of Science/Nuclear Physics

backup


Hole radius
47mm
LHCb x $\frac{1}{20}$
Hole radius
61mm
600mm
Cut-out
~108x230mm
600mm
Station B2
z = -114.0m
Station B1
z = -19.7m
Station B0
z = -7.5m
Station F1
z = 20.0m
Station F2
z = 114.0m