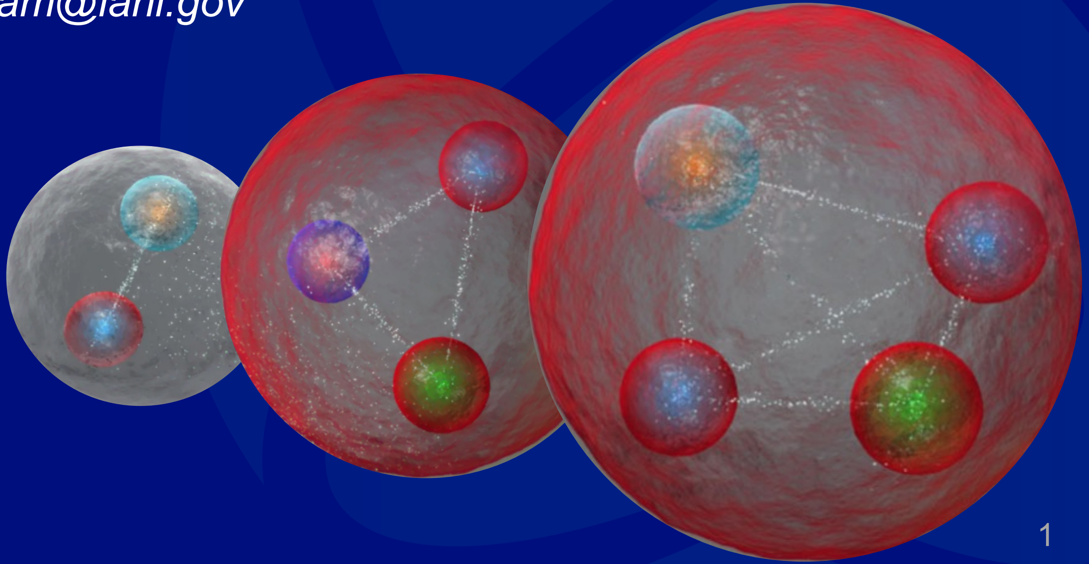
Los Alamos
NATIONAL LABORATORY

LHCb

# Heavy quark production at LHCb

Matt Durham
*durham@lanl.gov*



Cold Nuclear Matter Effects: from the LHC to the EIC

Jan 13 – 16, 2025

Center for Frontiers in Nuclear Science

# Heavy Quark Production

$$\sigma_{AA\to H+X} \propto f_1(x_1,Q^2)\otimes f_2(x_2,Q^2)\otimes\hat{\sigma}(Q^2,x_1,x_2)\otimes D_H(z)$$

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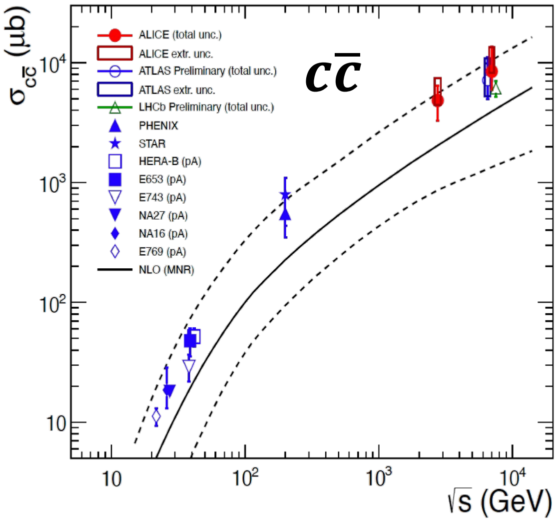
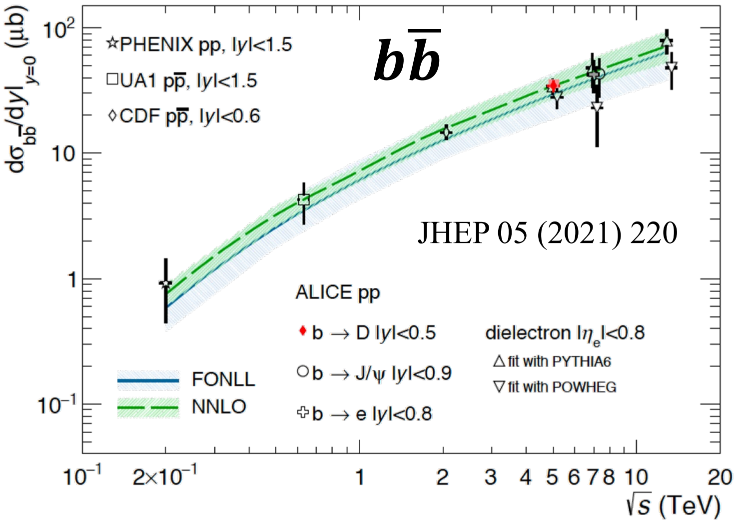
- **Hadron cross sections: measured at experiments**
- **Parton-parton cross sections: calculable by pQCD**

- ~No heavy quarks in beam projectiles
- Number of heavy quarks is essentially fixed in early stages of collisions



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**Must be constrained by data**

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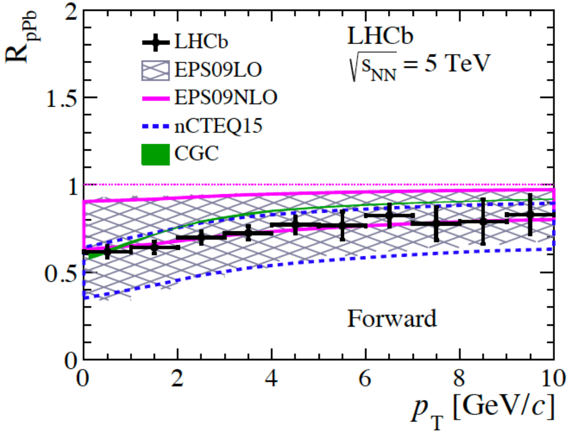
# Constraining nPDFs with D mesons

*JHEP* 1710 (2017)




- LHCb D meson data: significantly more precise than calculations from older nPDF sets
- Now included as constraint in updated nPDF sets

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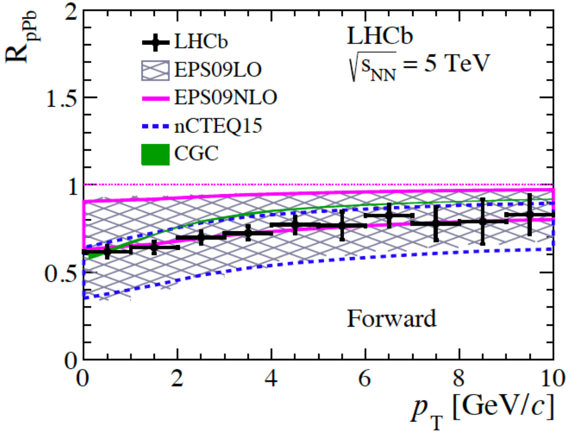


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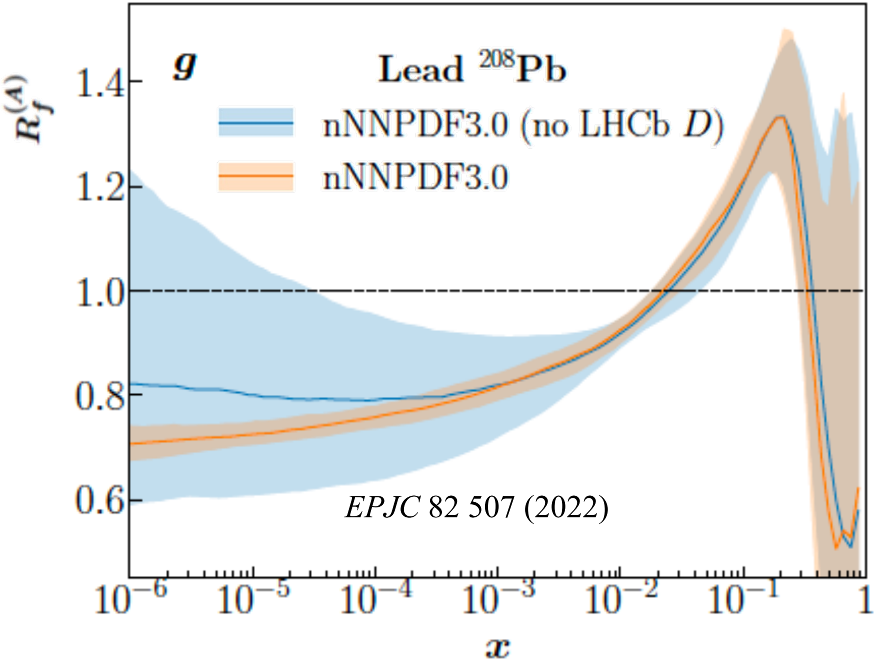
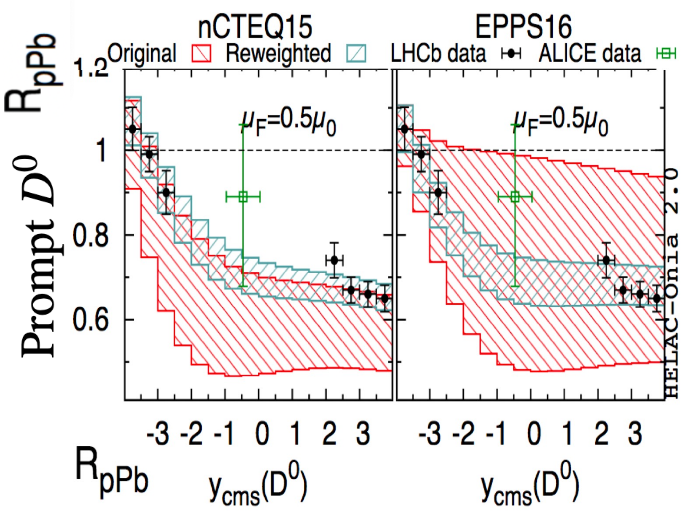



*EPJC* 82 507 (2022)

**LHCb data currently constrains nPDFs down to $x \sim 10^{-6}$**
**Places especially stringent bounds on gluon nPDF**

# Calculations with newly constrained nPDF

PRL 121 052004 (2018)




Updated calculations have dramatically reduced uncertainties

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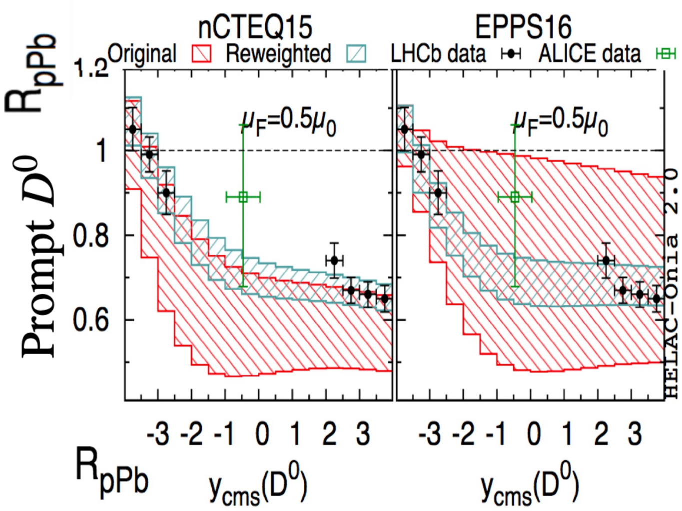
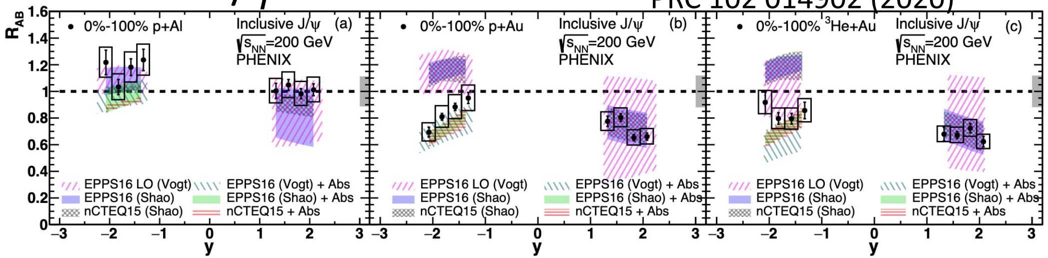



PHENIX J/$\psi$ data

PRC 102 014902 (2020)

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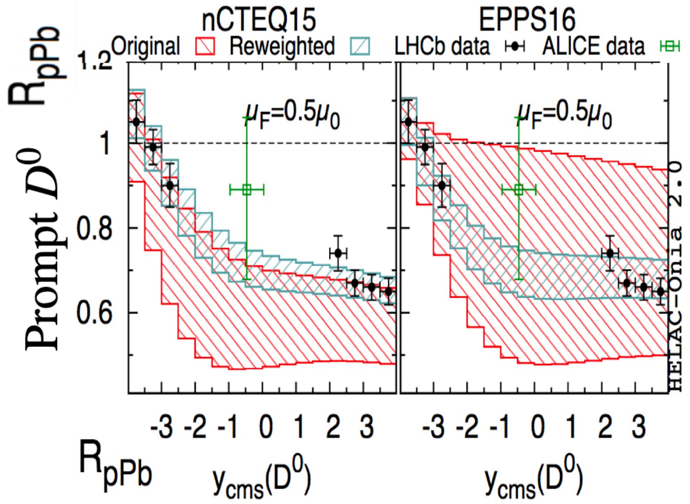


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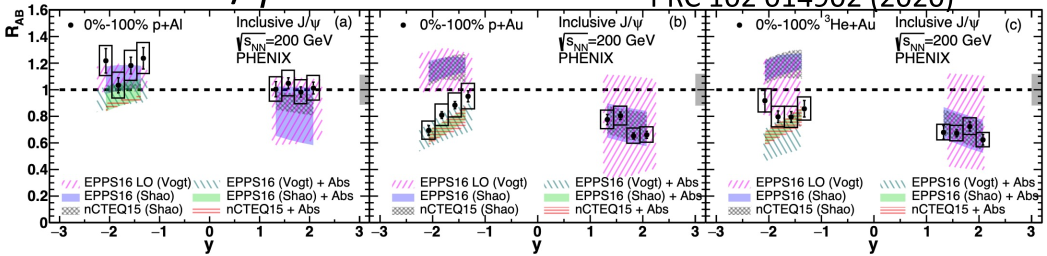
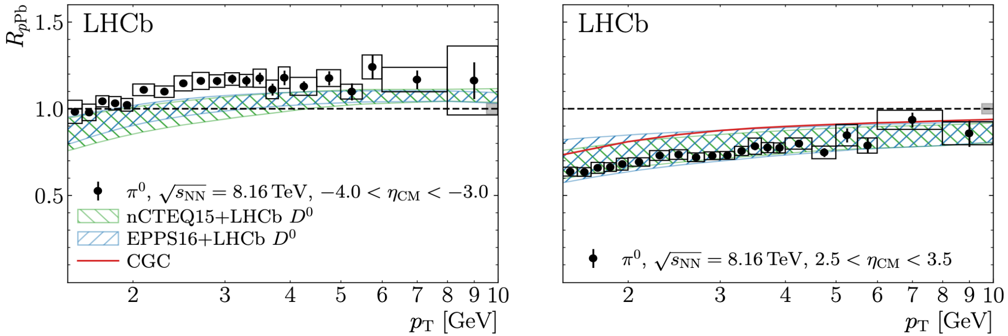



LHCb $\pi^0$ data

PRL 131 042302 (2023)




Updated calculations have dramatically reduced uncertainties

Forward light and heavy flavor well described bty precise nPDFs – Backwards required additional CNM effects

# Heavy Quark Production

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- Hadron cross sections: measured at experiments
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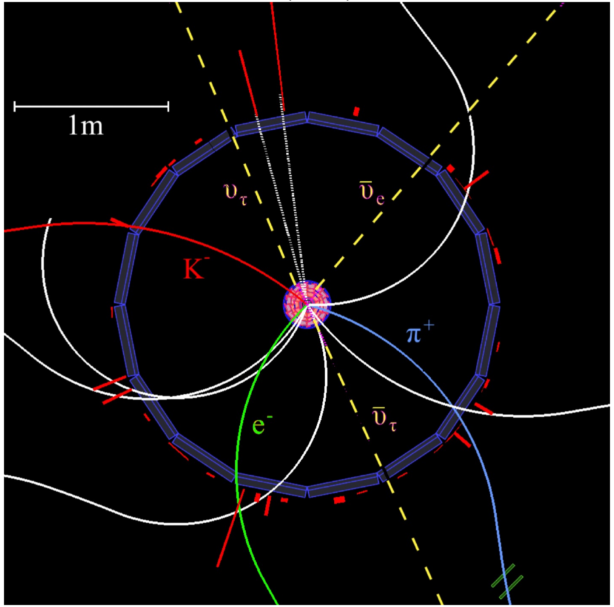
Fragmentation functions: parameterize hadronization process

# Fragmentation in vacuum

- The defining feature of QCD is **confinement**: quarks and gluons can never be observed as isolated particles
- Instead, they are found only as constituents of color-neutral hadrons

$e^+e^- \rightarrow \Upsilon(5S) \rightarrow b\bar{b}$ event




*b* factories:

$$e^+e^- \rightarrow \Upsilon(5S) \rightarrow b\bar{b}$$

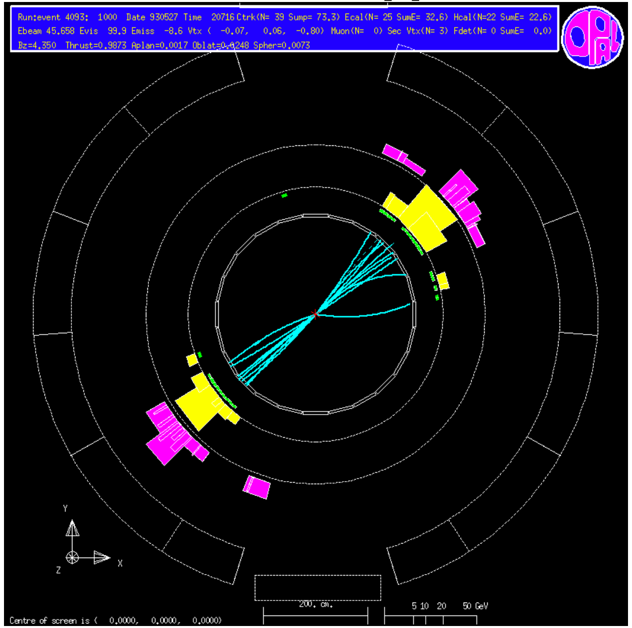
$$\boxed{B_s/_{B^0} = 0.26\,^{+0.05}_{-0.04}}$$

*LEP*

$$e^+e^- \rightarrow Z \rightarrow b\bar{b}$$

$$\boxed{B_s/_{B^0} = 0.25 \pm 0.02}$$

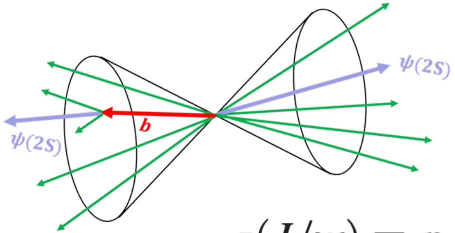
$e^+e^- \rightarrow Z \rightarrow q\bar{q}$ event



**Assumption**: hadronization is ***universal*** and ***factorizable*** from rest of collision

# $J/\psi$ in jets

- Long-standing challenge with description of production and polarization
- Charmonia in jets provides new way to examine production mechanisms




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

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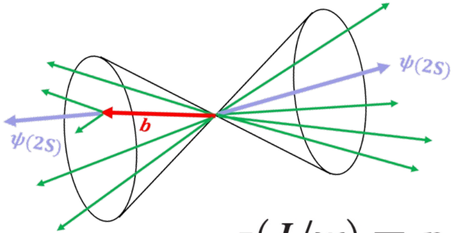


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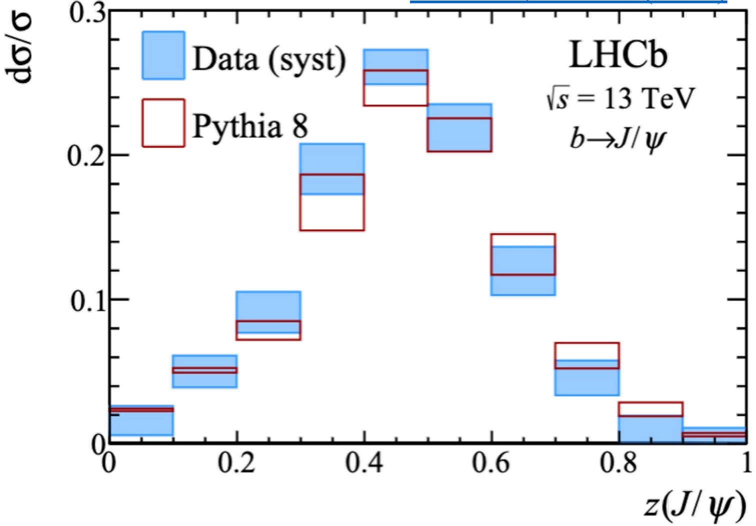
PRL 118, 192001 (2017)




Non-prompt: well described by PYTHIA

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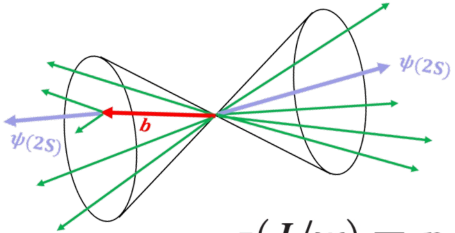


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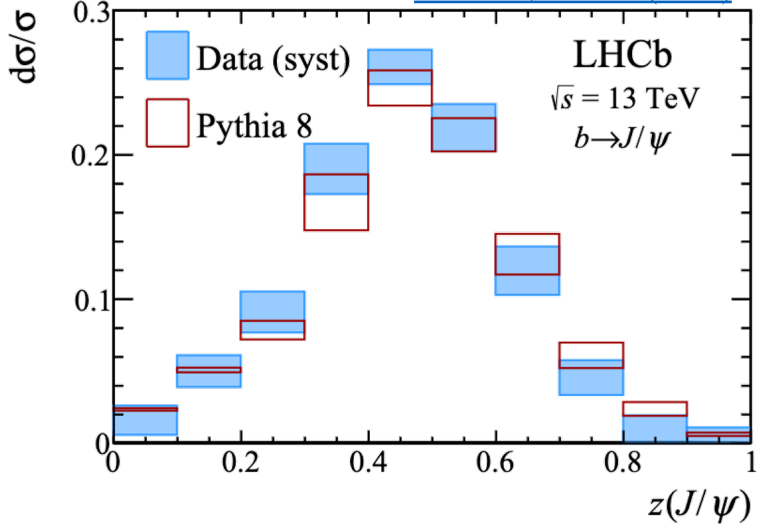


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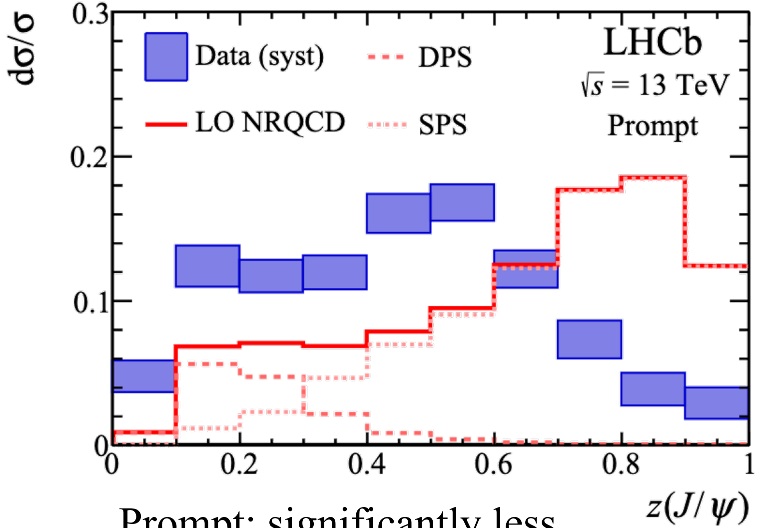
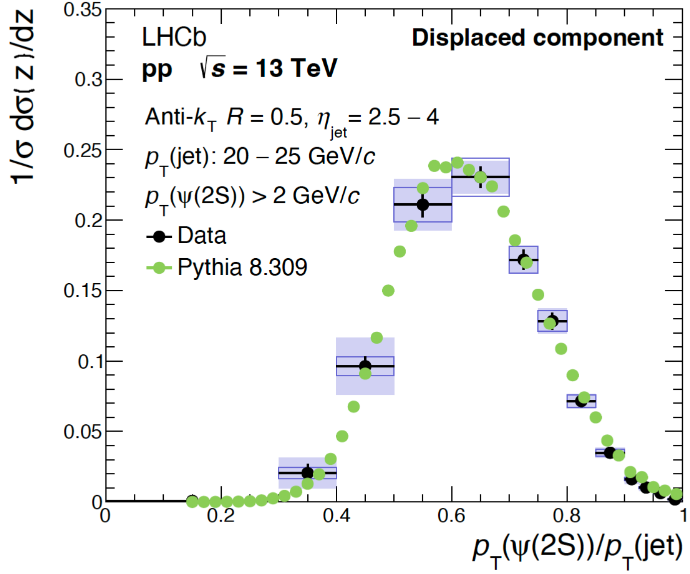


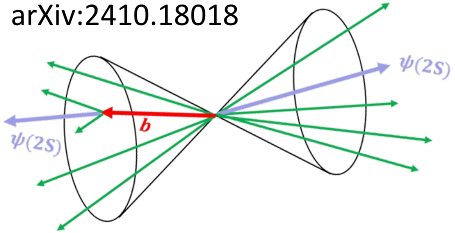

Prompt: significantly less isolated than NRQCD prediction

# $\psi(2S)$ in jets

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




arXiv:2410.18018

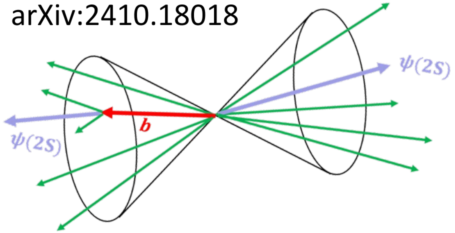


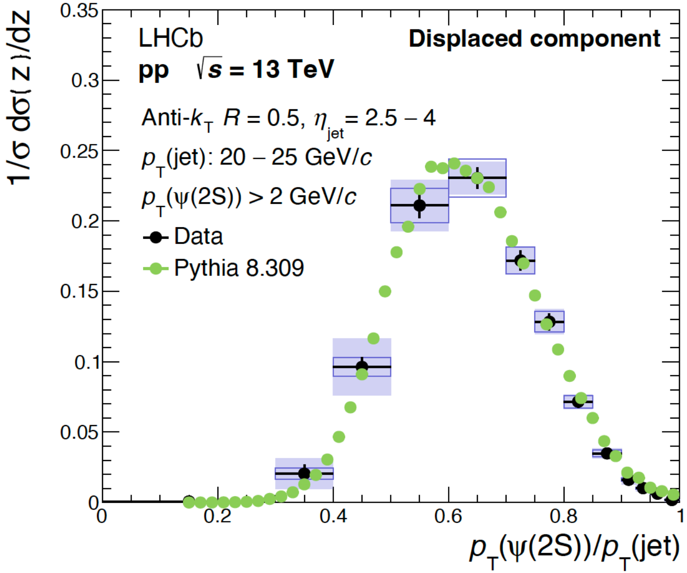

$b \rightarrow \psi(2S)$ : well described by PYTHIA
Very similar to $b \rightarrow J/\psi$

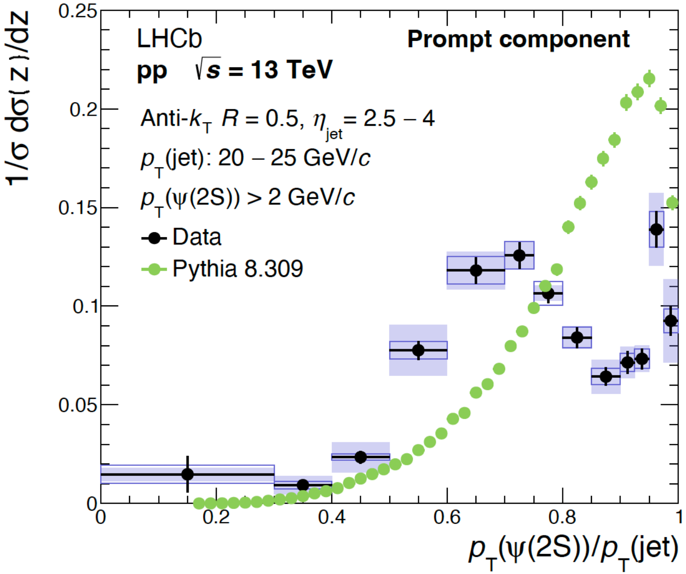
# $\psi$(2S) in jets

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

arXiv:2410.18018



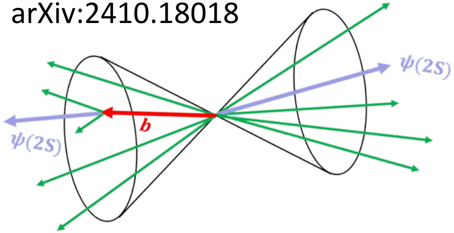



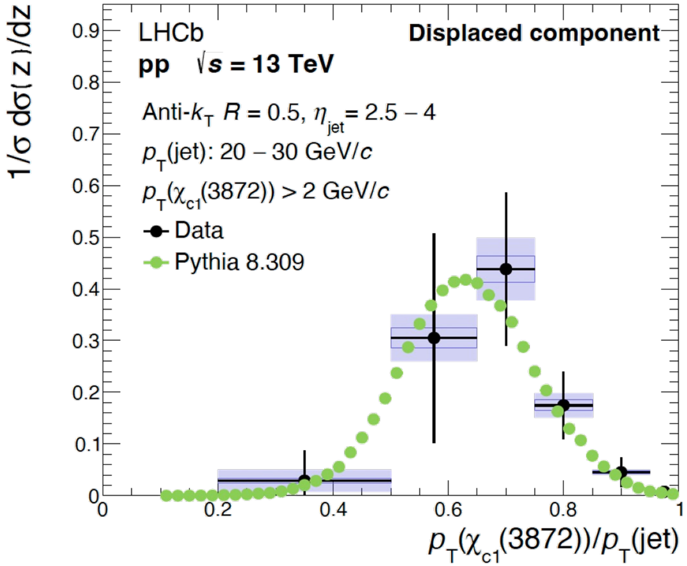

$\boldsymbol{b \rightarrow \psi}$(2S) : well described by PYTHIA
Very similar to $\boldsymbol{b \rightarrow J/\psi}$

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

# $X(3872)$ in jets

arXiv:2410.18018



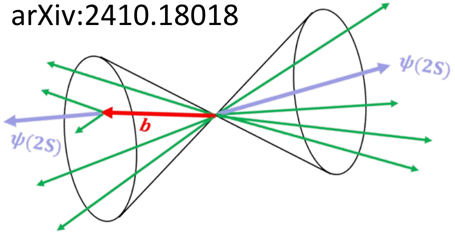



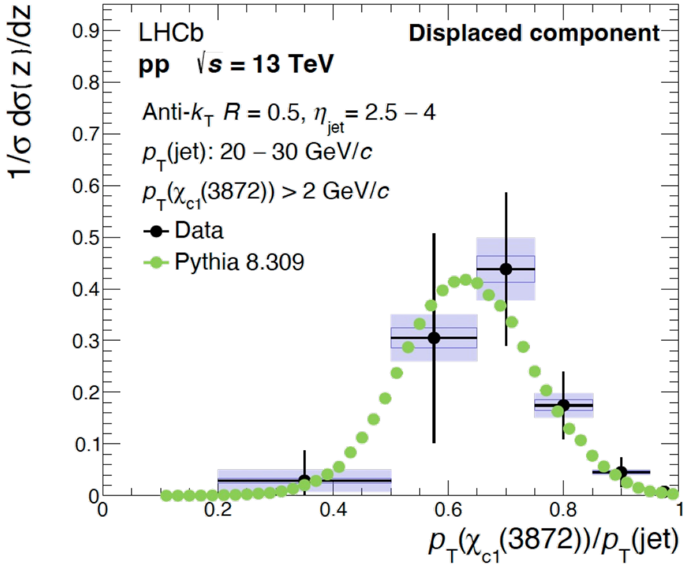

$b \rightarrow X(3872)$ : well described by PYTHIA

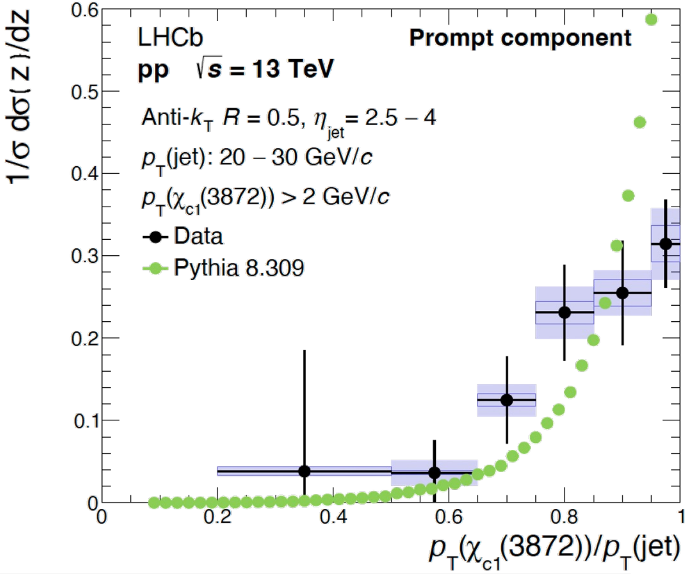
Very similar to $b \rightarrow J/\psi$, $\psi(2S)$

# $X(3872)$ in jets

arXiv:2410.18018



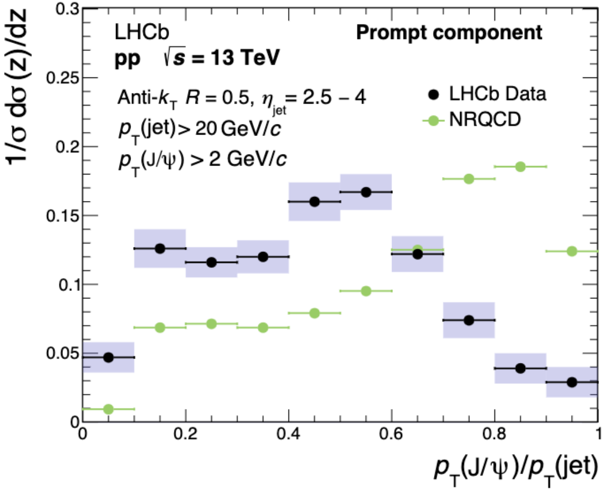



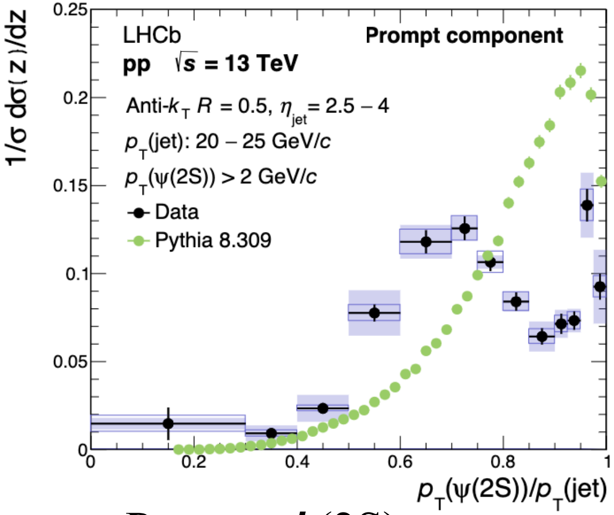

$\boldsymbol{b \to X(3872)}$ : well described by PYTHIA
Very similar to $\boldsymbol{b \to J/\psi}$, $\boldsymbol{\psi}$(2S)

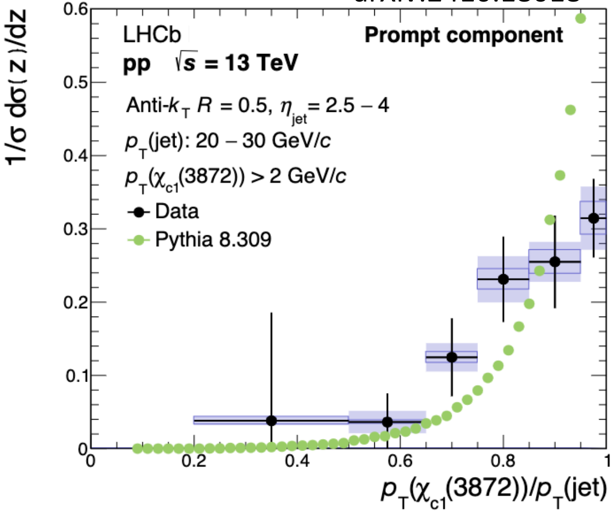
Prompt: Rises towards isolation, very different from conventional $c\bar{c}$ state $\boldsymbol{\psi}$(2S)

# Compare: prompt $J/\psi$ , $\psi(2S)$, X(3872)

arXiv:2410.18018




Prompt $J/\psi$: less isolated than expected

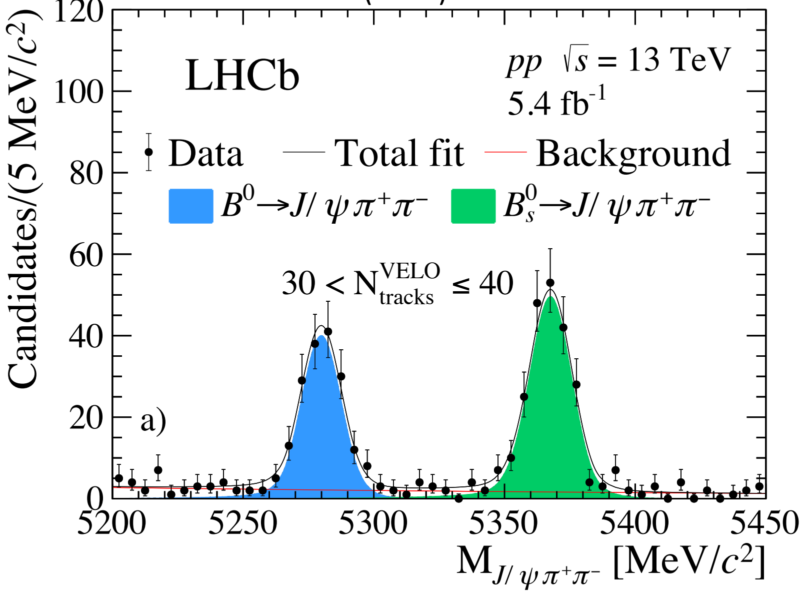
Prompt $\psi(2S)$:
Two component structure:
Different production mechanisms?

Prompt $X(3872)$:
More isolated than conventional charmonia

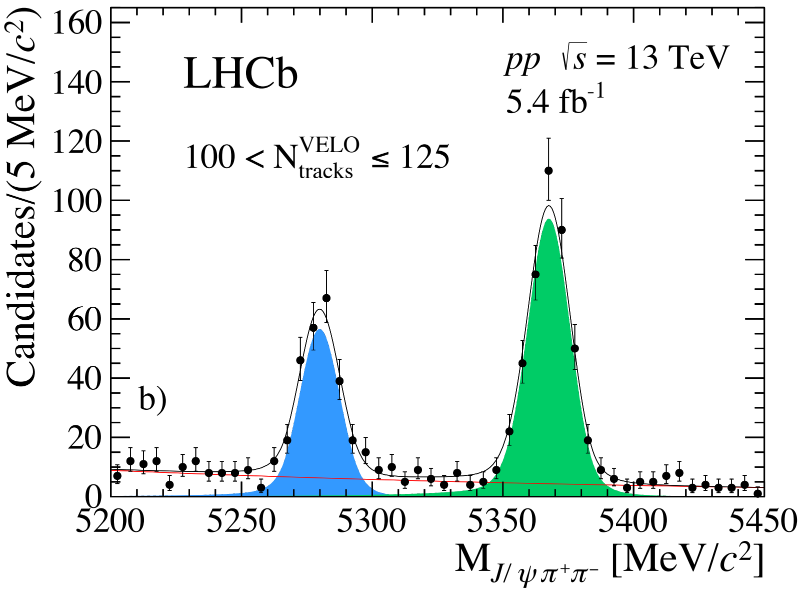
# Modification of *b* hadronization – strange B mesons

- Heavy *b* hadrons are ideal for examining fragmentation
- Hadron ratios as a function of event activity can show how underlying event effects hadronization

PRL 131 061901 (2023)




Low multiplicity – few tracks

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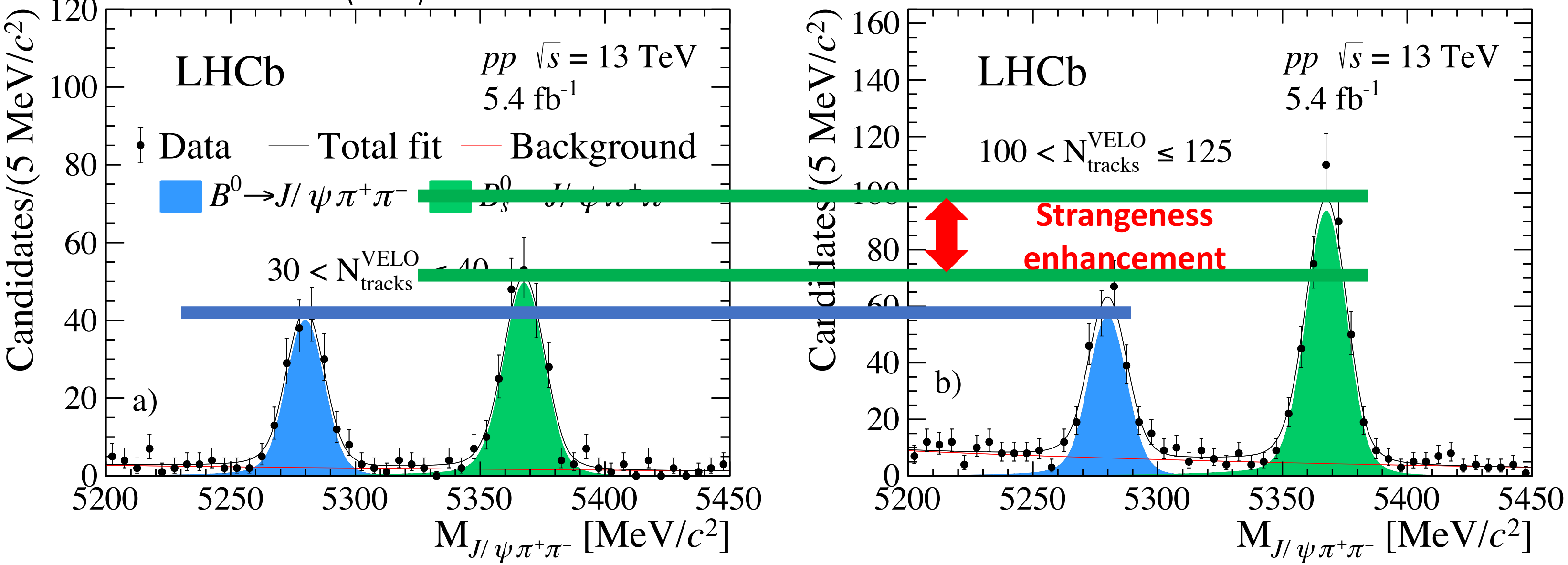


Low multiplicity – few tracks

High multiplicity – many tracks

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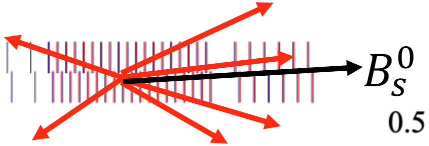
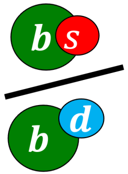
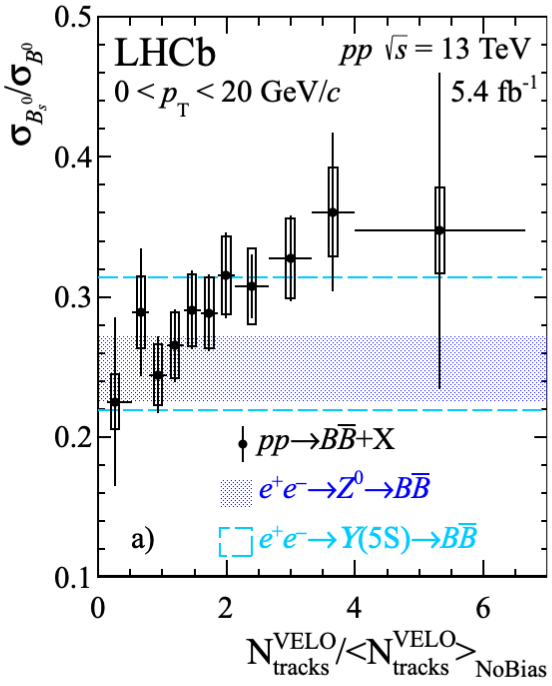



PRL 131 061901 (2023)

$N_{tracks}^{VELO}$

Total VELO multiplicity, dominated by forward tracks



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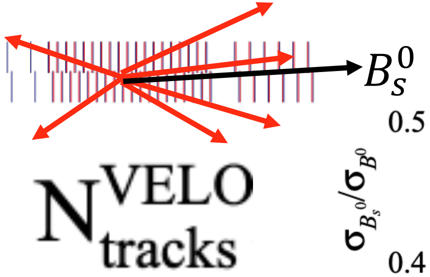


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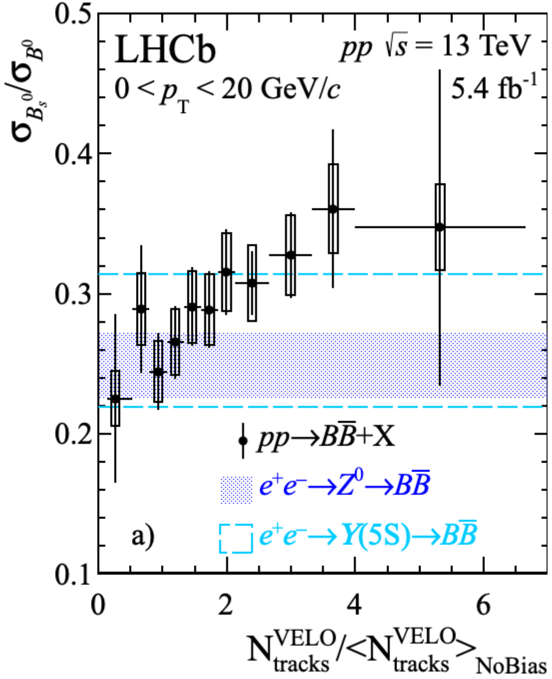
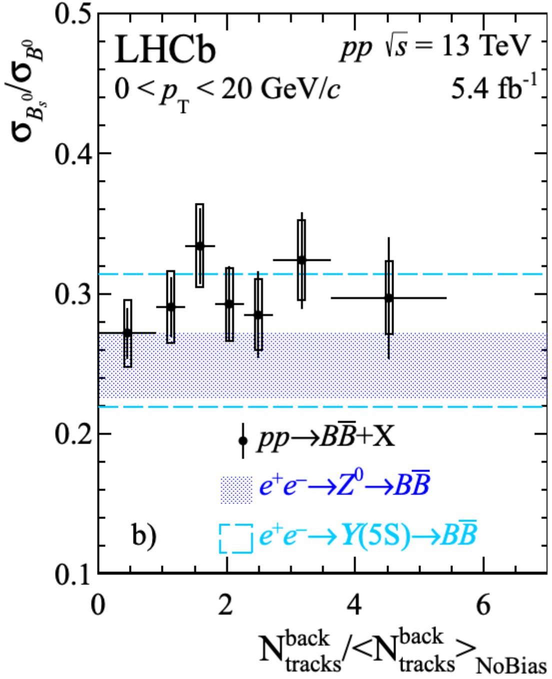
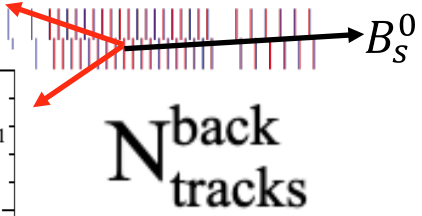
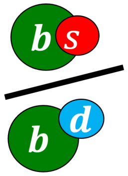


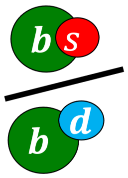

Total VELO multiplicity, dominated by forward tracks

Multiplicity in opposite hemisphere as B mesons

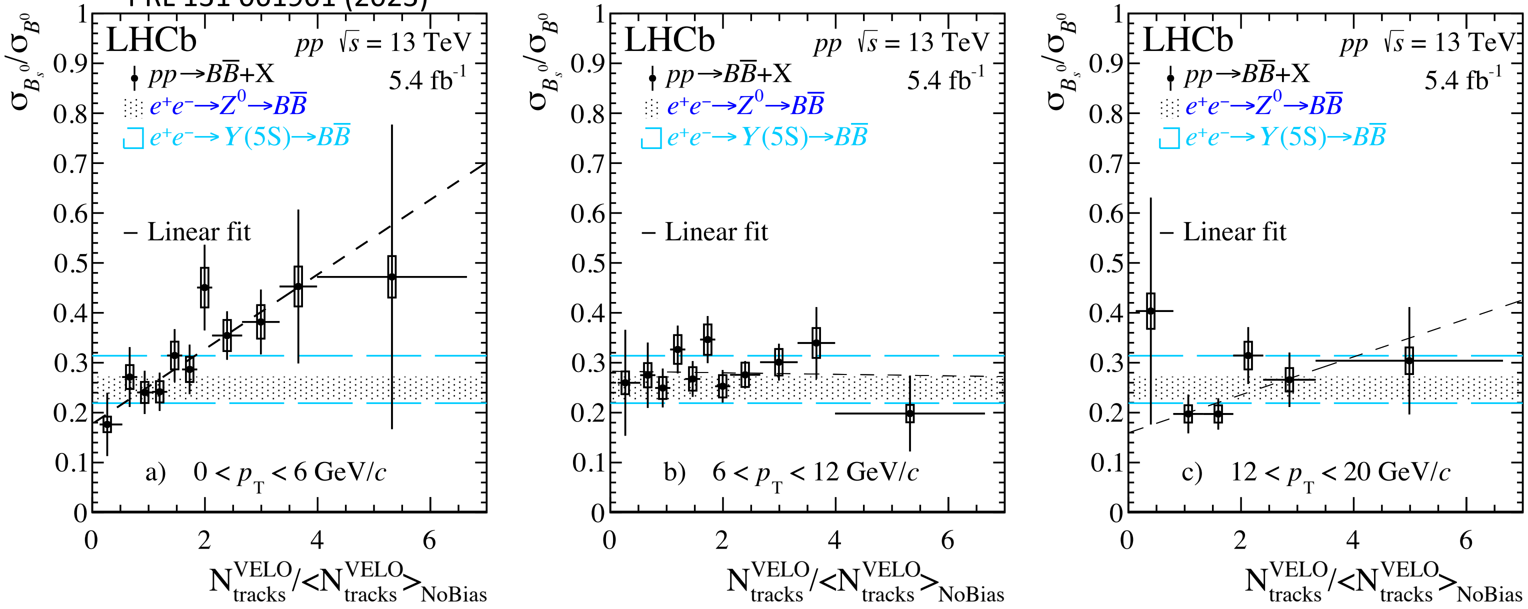



- Enhancement depends on *local* particle density around B mesons

# Modification of $b$ hadronization

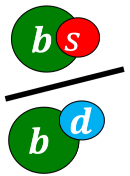



PRL 131 061901 (2023)

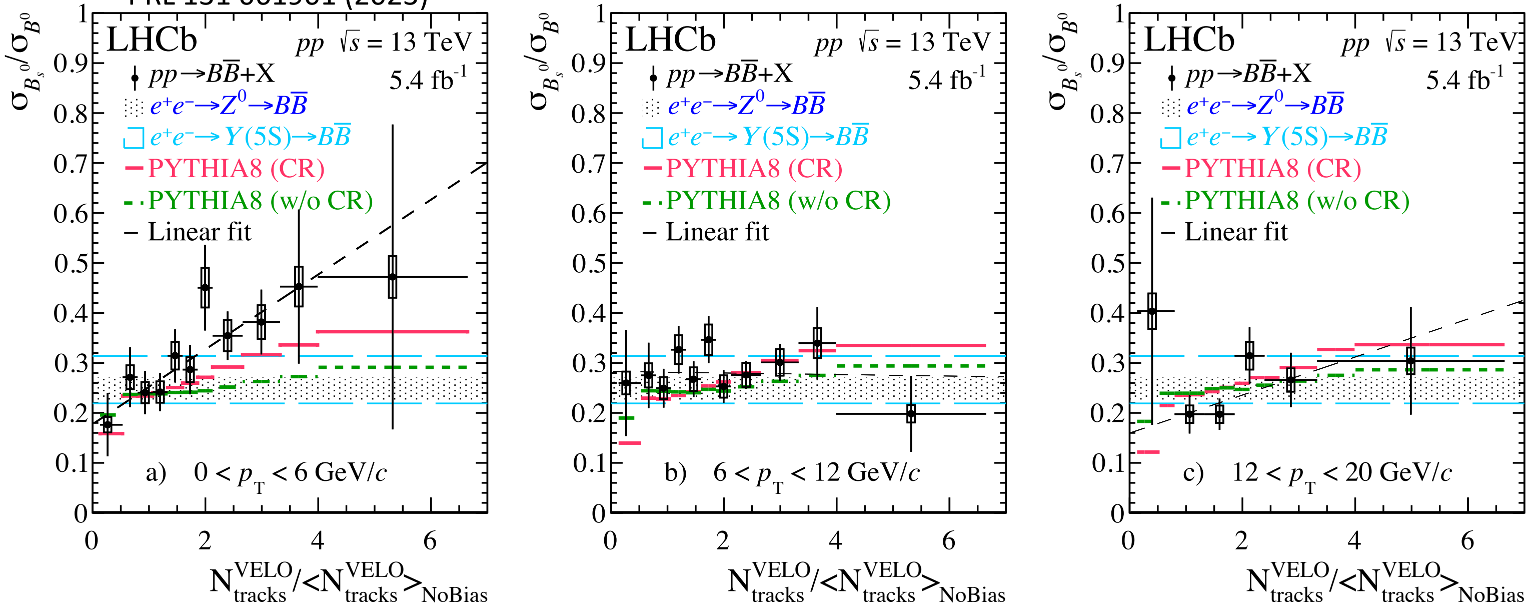



- Evidence for an increase of $B_s^0/B^0$ at low $p_T$
- Low multiplicity data consistent with fragmentation in vacuum measured in $e^+e^-$ collisions
- Higher $p_T$ B mesons show no enhancement

# Modification of *b* hadronization – PYTHIA8




PRL 131 061901 (2023)

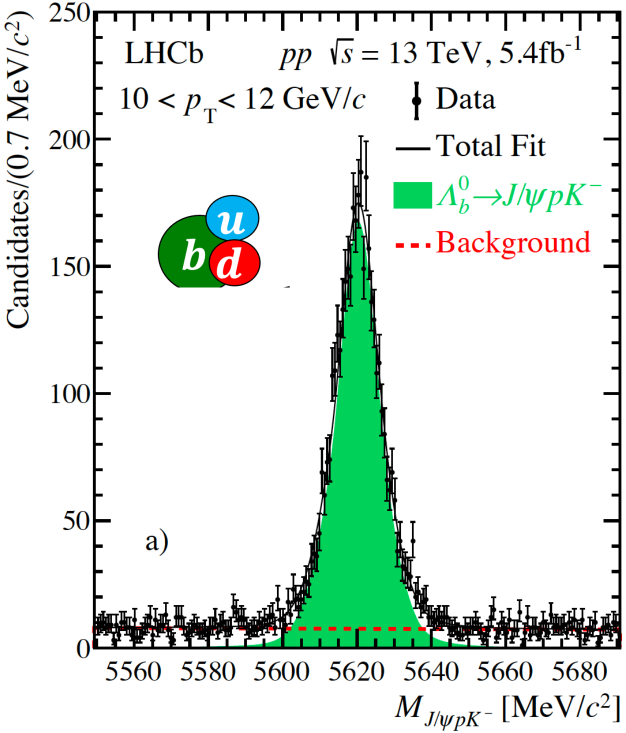


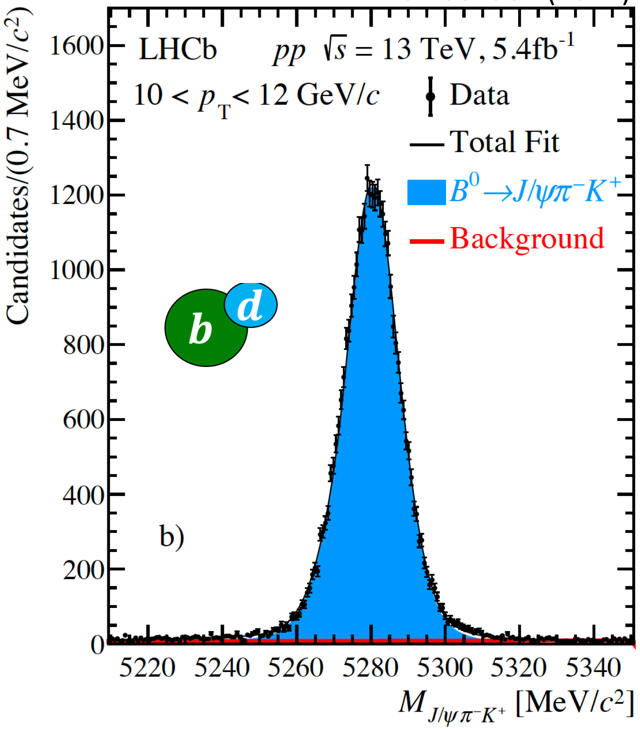

- Evidence for an increase of $B_s^0/B^0$ at low $p_T$
- Low multiplicity data consistent with fragmentation in vacuum measured in $e^+e^-$ collisions
- Higher $p_T$ B mesons show no enhancement
- PYTHIA8 w/color reconnection enabled describes high $p_T$ data, undershoots low $p_T$

# 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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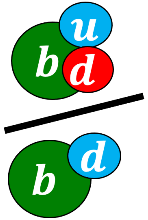
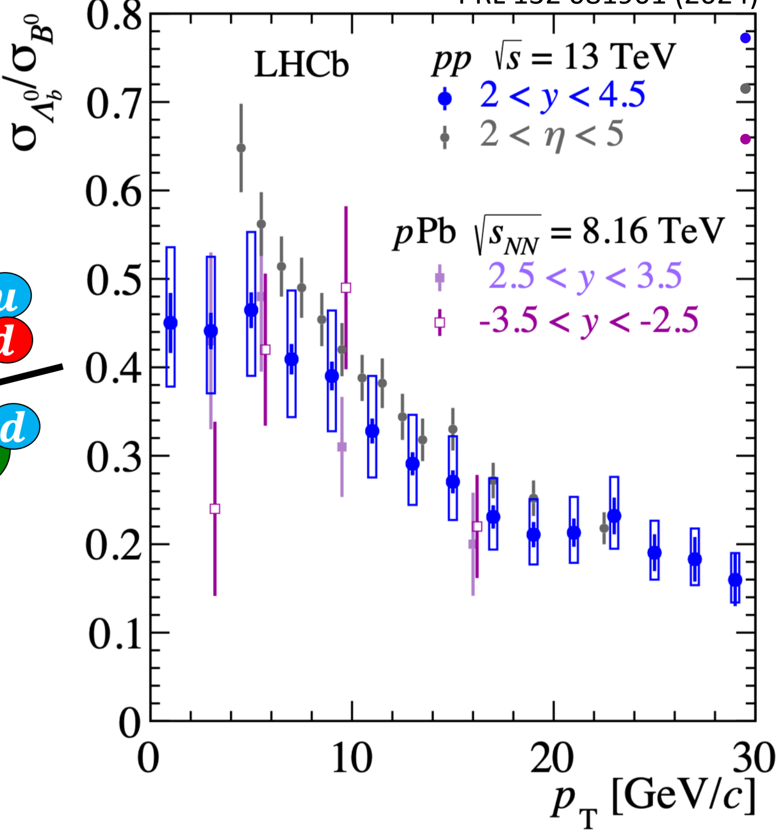
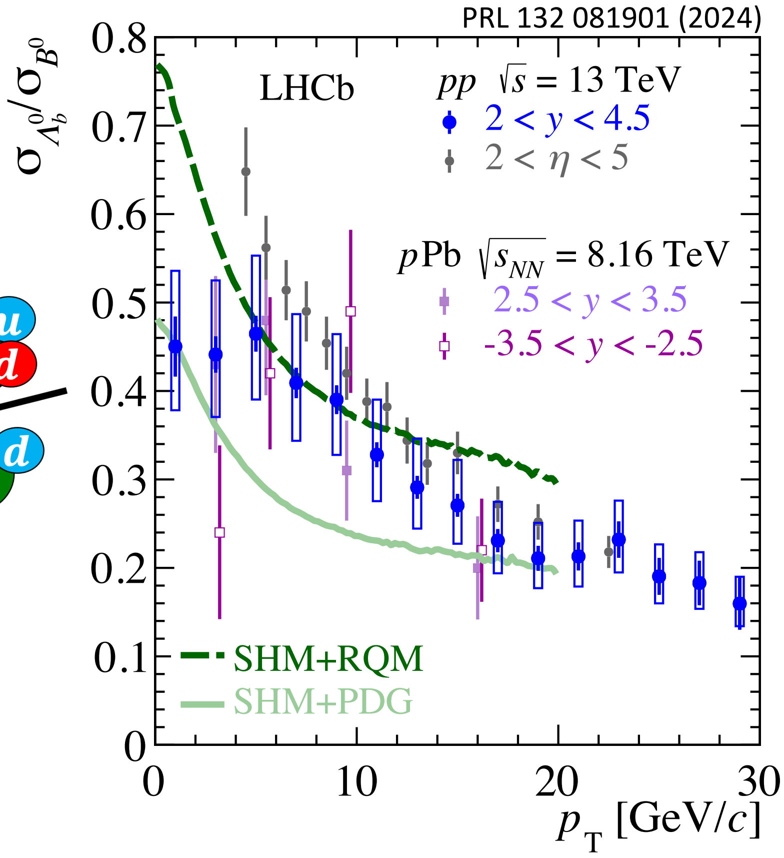


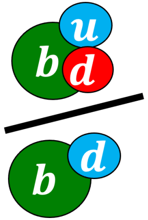

PRL 132 081901 (2024)




- Baryon/meson ratio shows significant $p_T$ dependence
- Consistent with previous results (semileptonic decays)
- Consistent with pPb results, within large uncertainties

# Modification of *b* hadronization – B baryons

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Compare to Statistical Hadronization Model that uses two sets of baryons as input:

- Known baryon states from PDG
- Expanded set of baryons predicted by the Relativistic Quark Model

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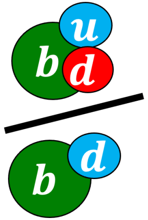
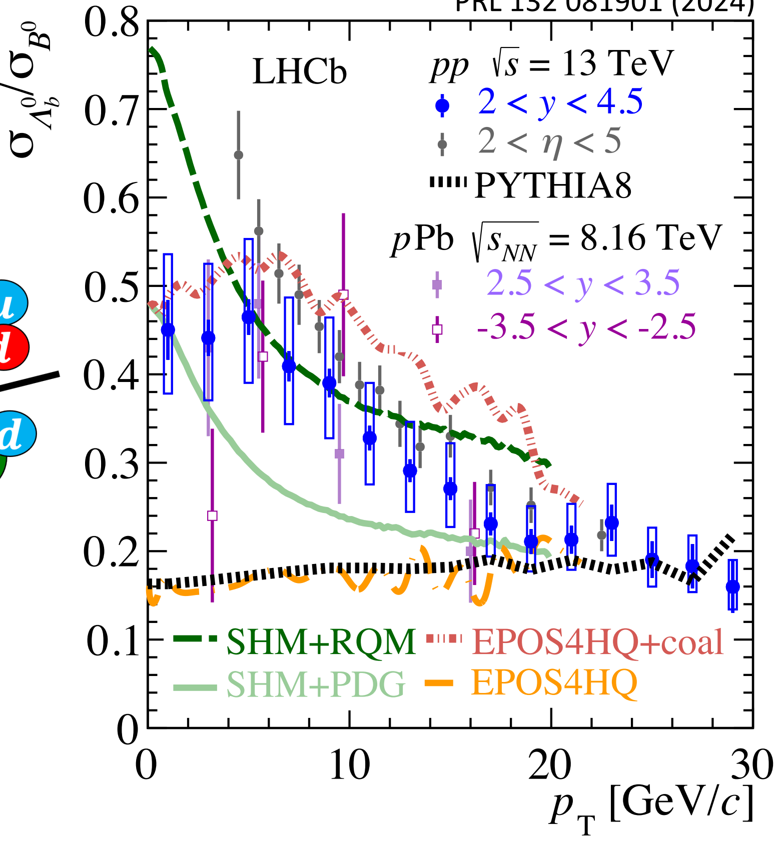
PRL 132 081901 (2024)



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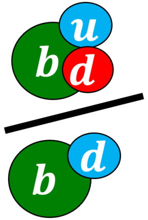
PYTHIA8 fails to reproduce $p_T$ dependence

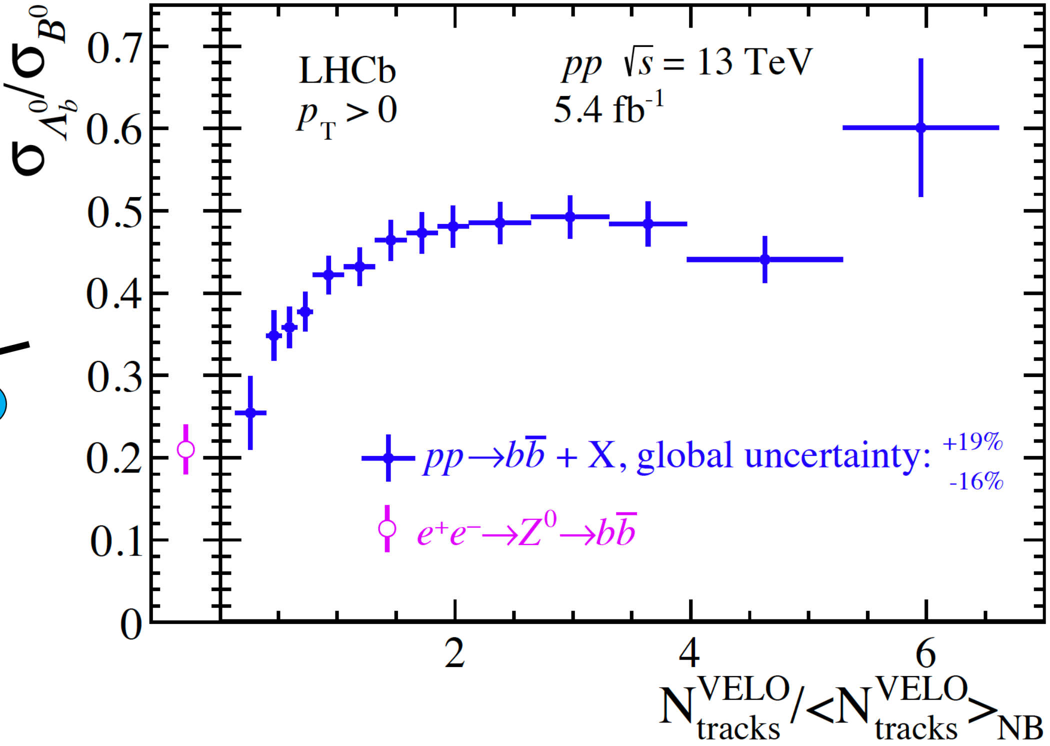
EPOS4HQ with only fragmentation also fails

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

# Modification of *b* hadronization – B baryons

PRL 132 081901 (2024)

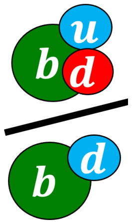


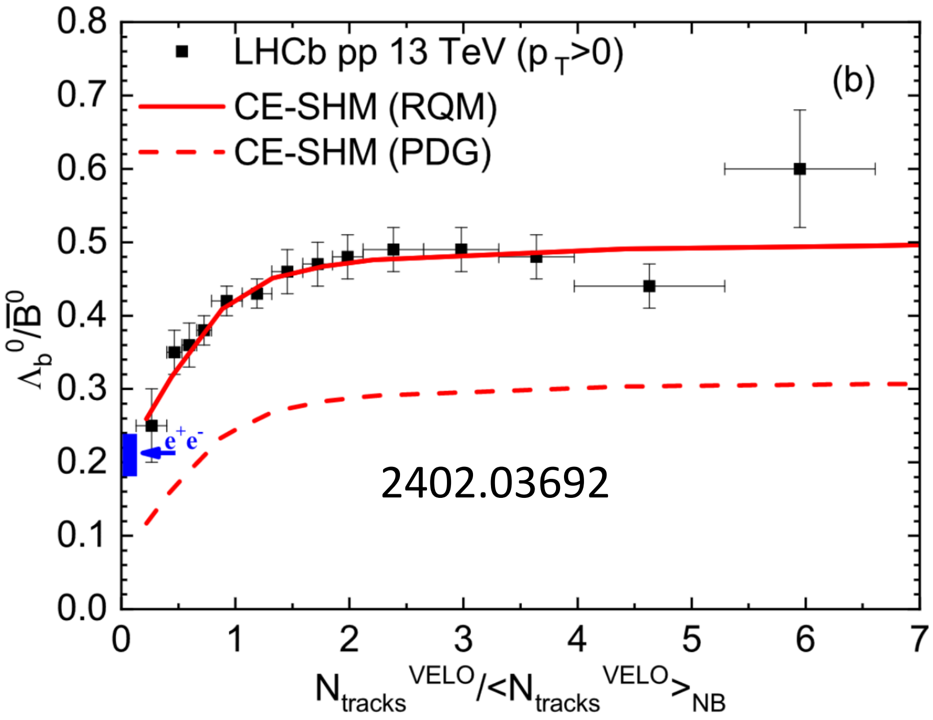




- Baryon/meson ratio shows significant multiplicity dependence
- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Reproduce $e^+e^-$ result as multiplicity approaches zero

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

# Modification of *b* hadronization – B baryons

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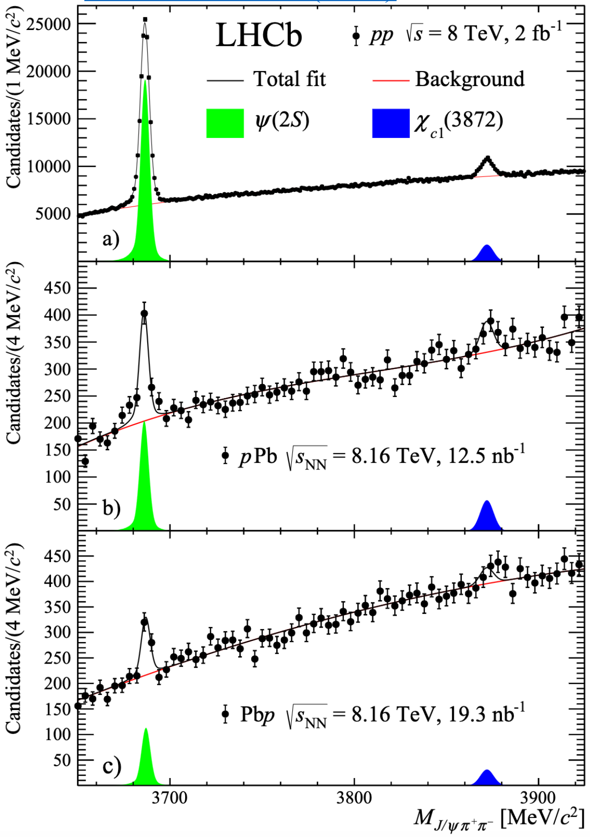
- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Reproduce $e^+e^-$ result as multiplicity approaches zero

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

# Exotic hadron X(3872) in *p*Pb

PRL 132 242301 (2024)



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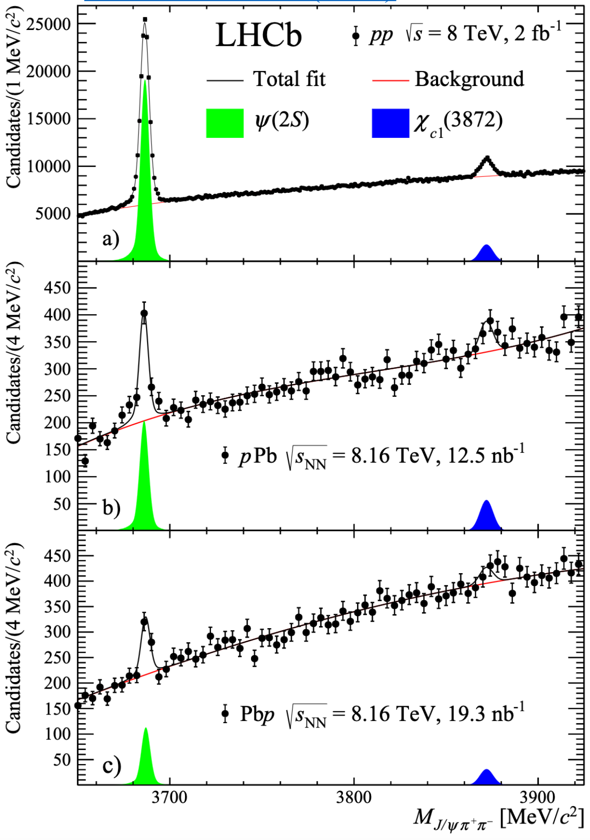
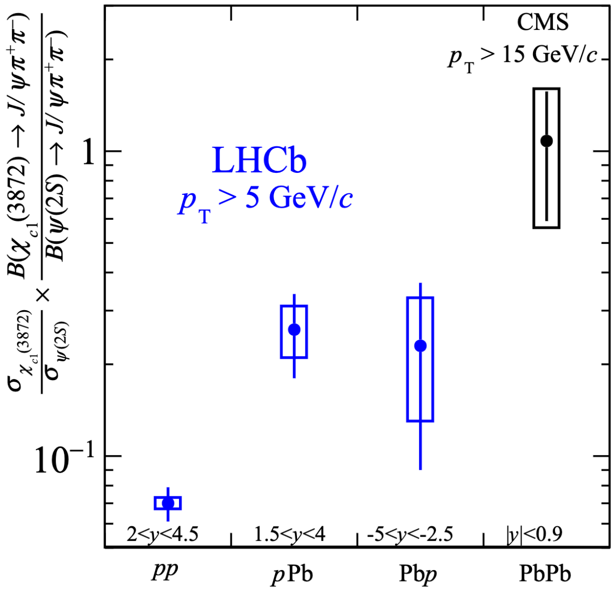
PRL 132 242301 (2024)




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

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

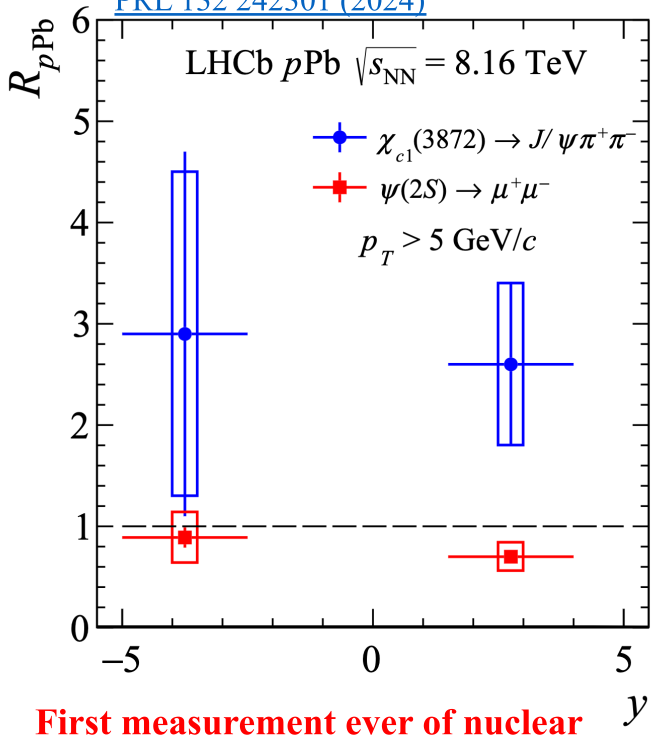
Enhancing effects start to out compete breakup?

- arXiv:2302.03828

Prompt X(3872)/ $\psi$(2S) = 0.26 ± 0.08 ± 0.05 in forward pPb
Prompt X(3872)/ $\psi$(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 $\psi$(2S) suppression**

# Exotic hadron X(3872) in *p*Pb

PRL 132 242301 (2024)



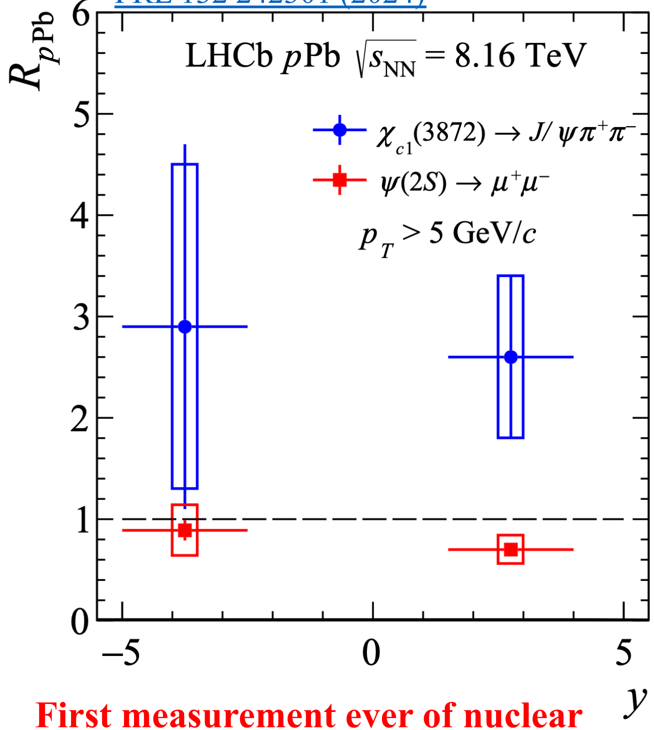

Ambiguity lifted by measuring nuclear modification factor:

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

**First measurement ever of nuclear modification factor of a tetraquark!**

# Exotic hadron X(3872) in $p$Pb

[PRL 132 242301 (2024)](PRL 132 242301 (2024))

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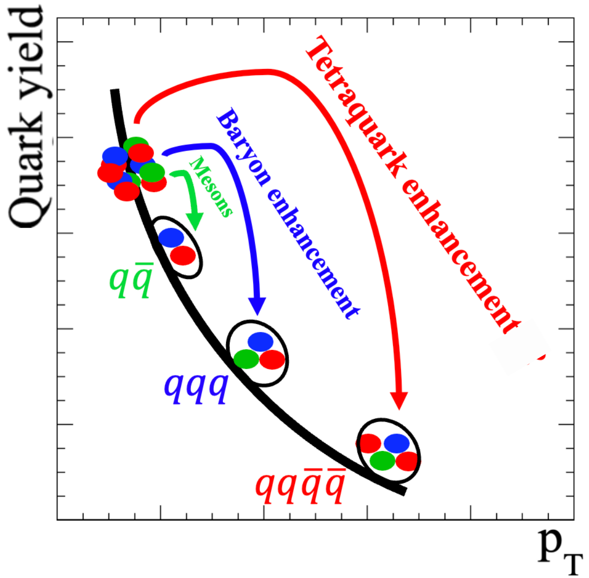
$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208 \times \sigma_{pp}^{\chi_{c1}(3872)}}$$

Evidence for enhancement of X(3872) in $p$Pb: Coalescence dominating over breakup?

We know heavy baryon production grows with multiplicity




**Similar mechanisms should also increase tetraquark production**

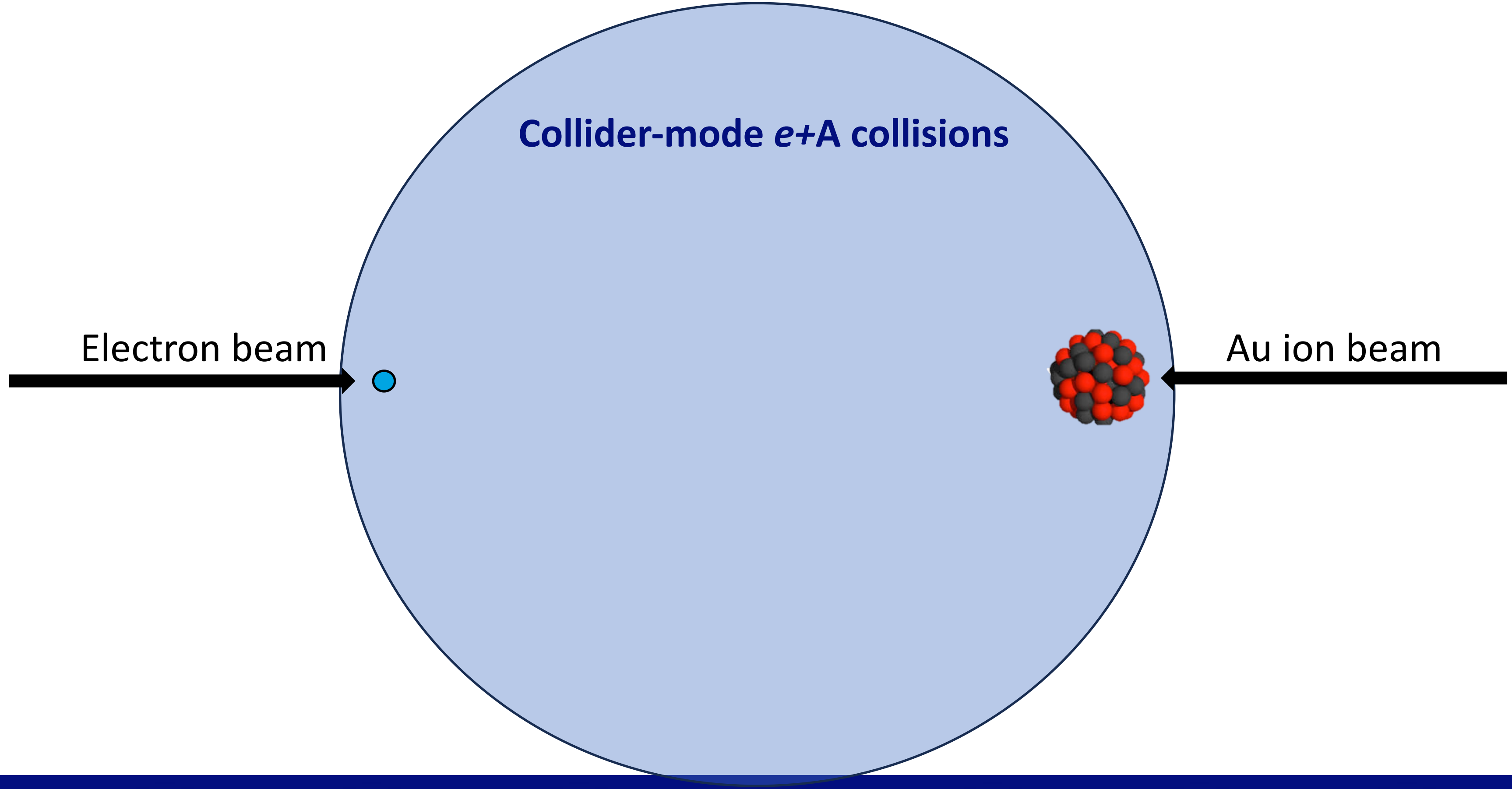
# Disentangling various effects

- Different CNM and HNM effects are expected to dominate in different collision species and energies, eg:
  - Fragmentation in vacuum: $e^+e^-$
  - Fragmentation + quark coalescence: *pp, p*A
  - Dominant coalescence: AA

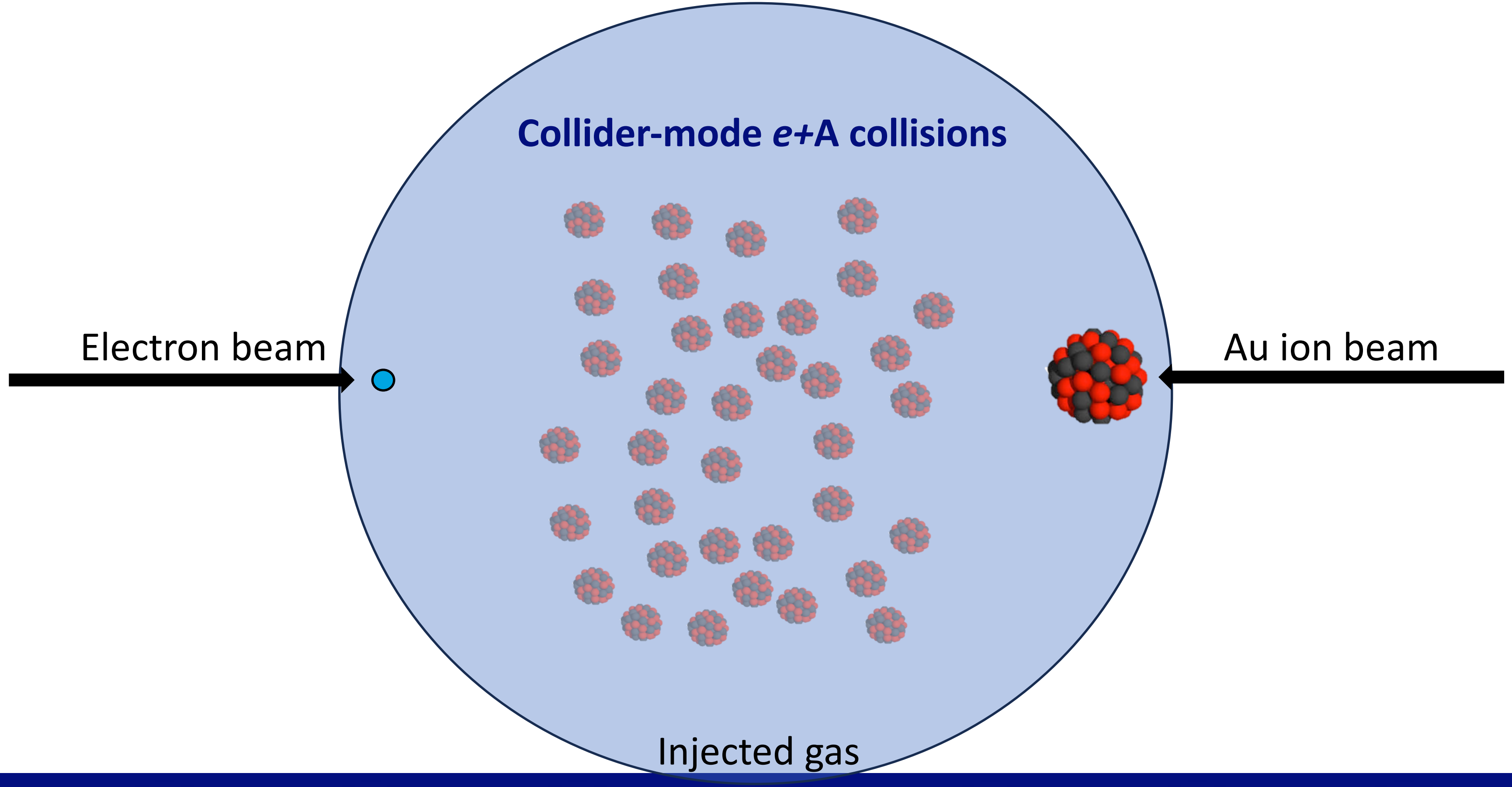
- Collider flexibility is crucial for studying the interplay of these effects

- Maximizing the EIC physics program is necessary for progress

# Fixed target at the EIC



# Fixed target at the EIC



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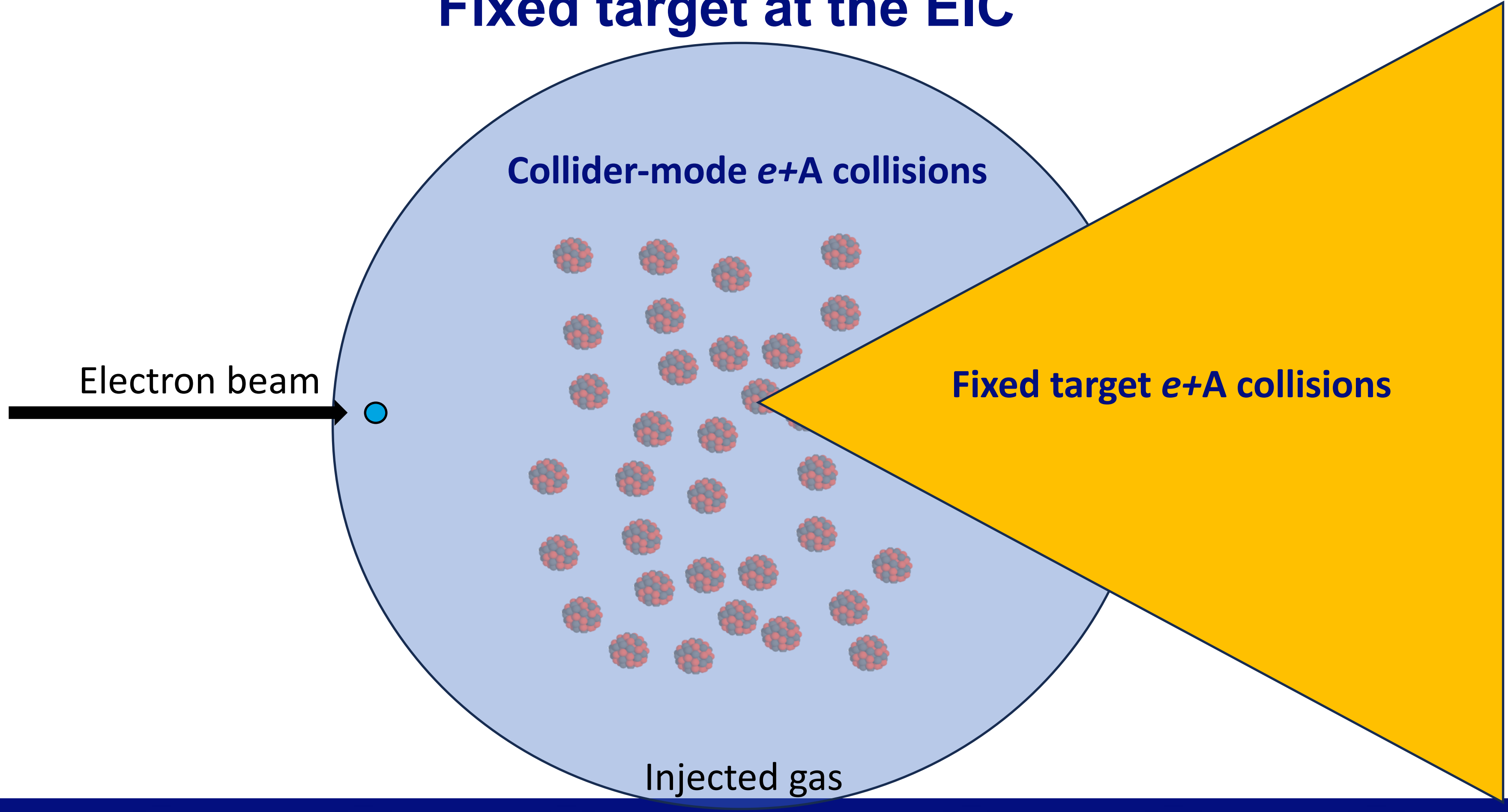

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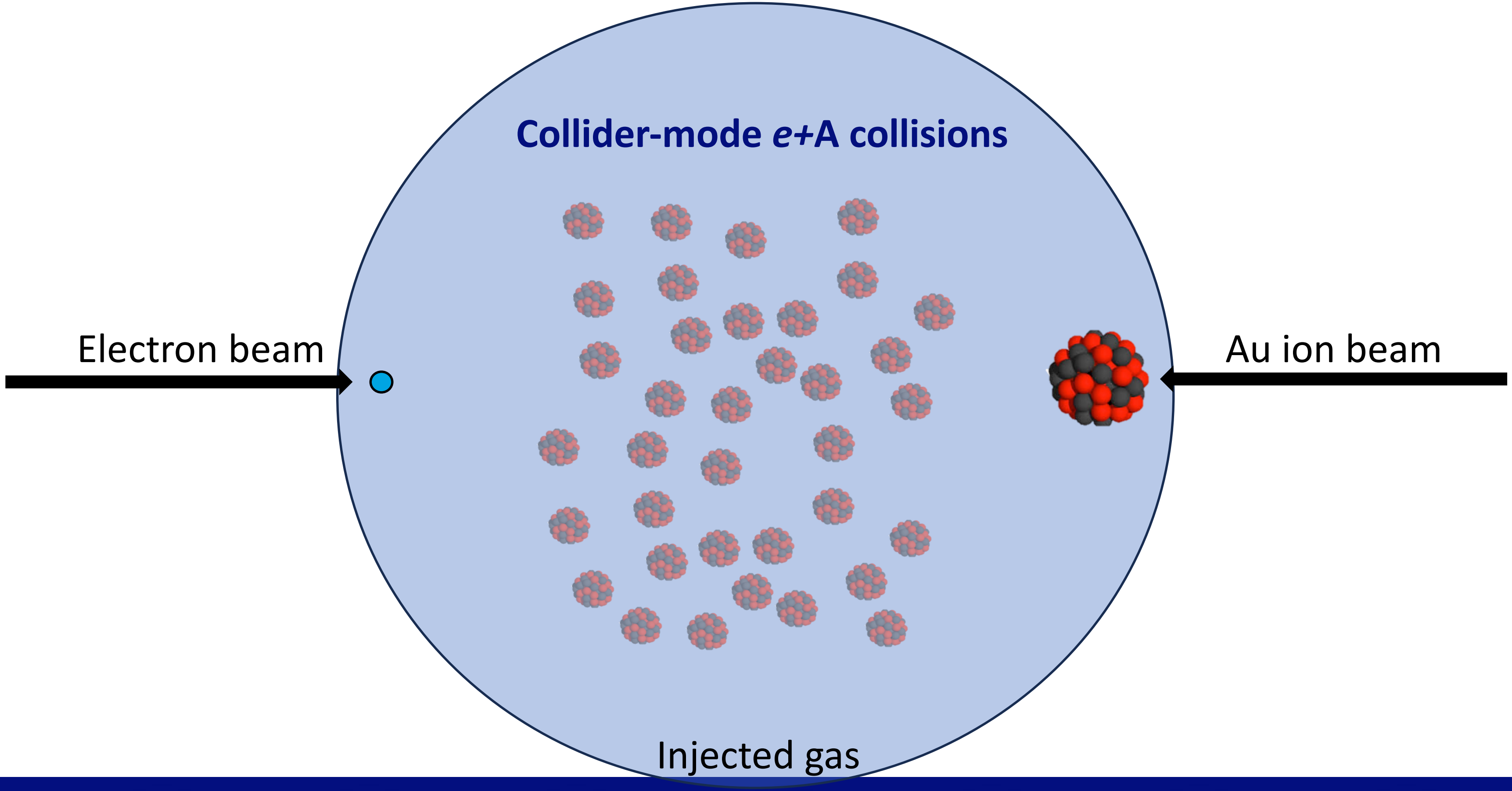

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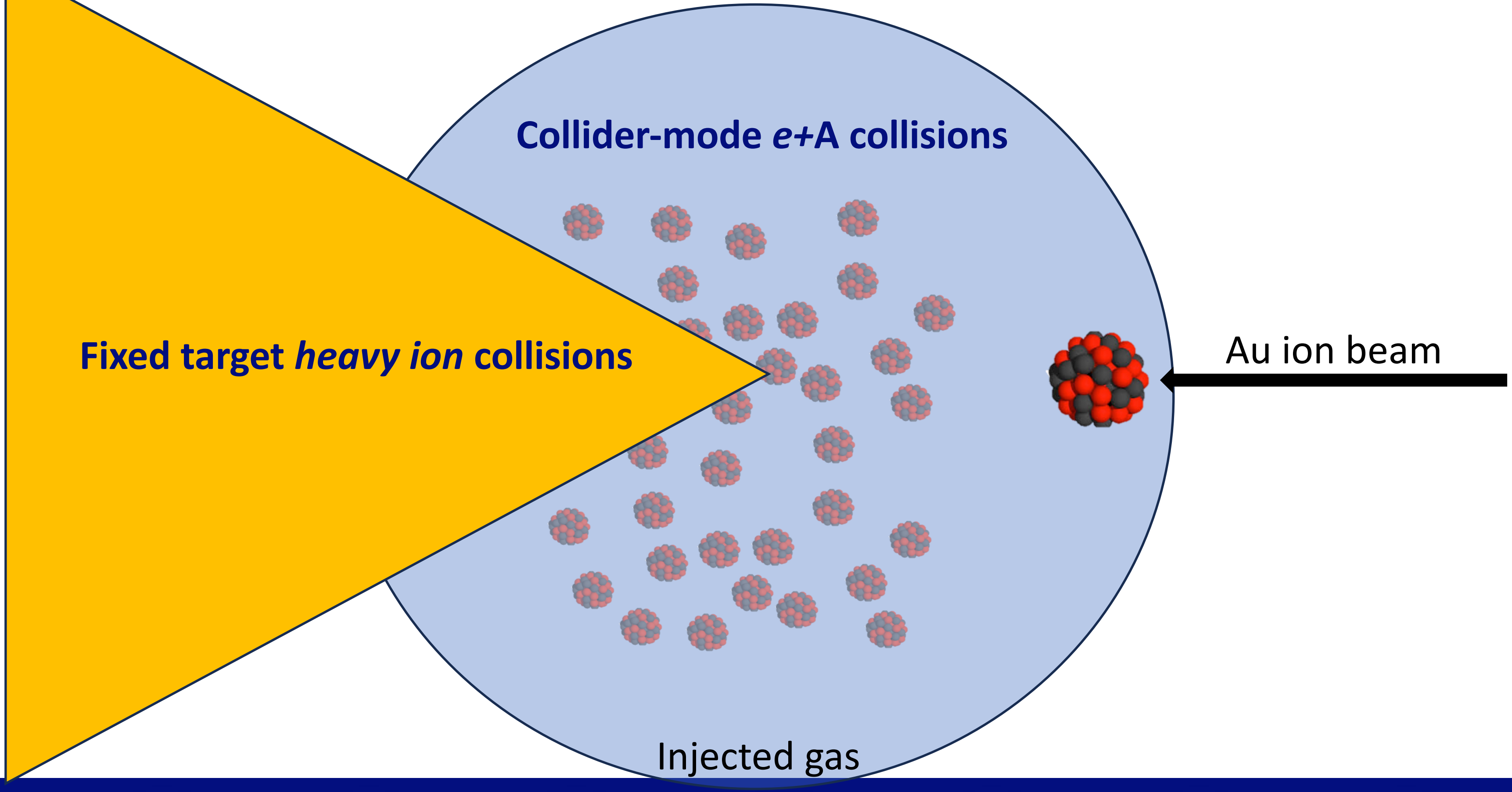

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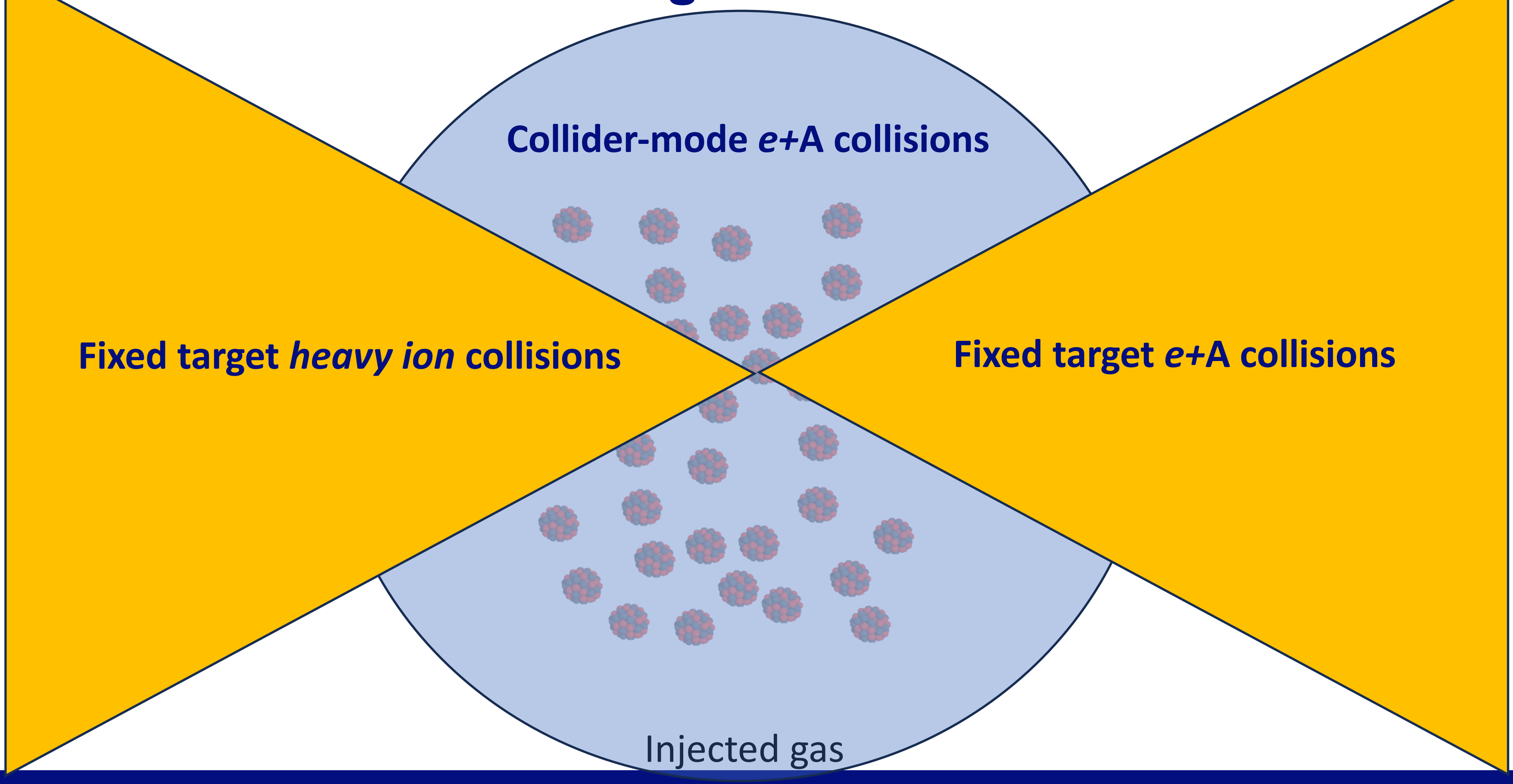


# Summary

- LHCb has unparalleled access to a wide range of heavy quark states
- Improved nPDF calculations describe forward rapidity *p*A data well, but additional effects are required to explain backwards rapidity
  - What are these effects? Do they all fit into our conventional picture of CNM?
- Clear differences in the hadronization process between collision species
  - Does strangeness/baryon enhancement necessarily imply deconfinement?
- Key to understanding the interplay of various effects is collider flexibility
  - Adding fixed-target capability greatly expands the EIC physics reach

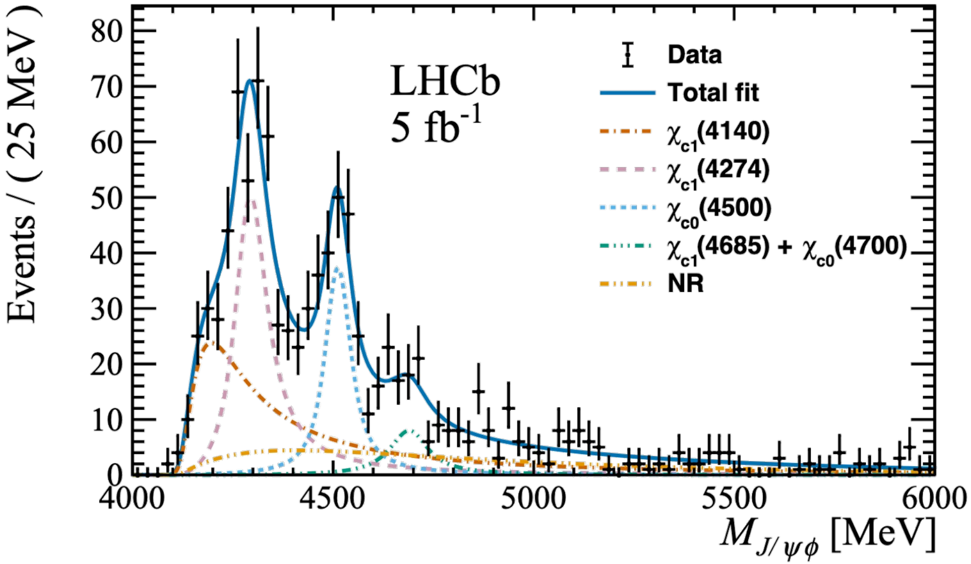
**Los Alamos is supported by the US Dept. of Energy/Office of Science/Office of Nuclear Physics**

**and DOE Early Career Awards program**

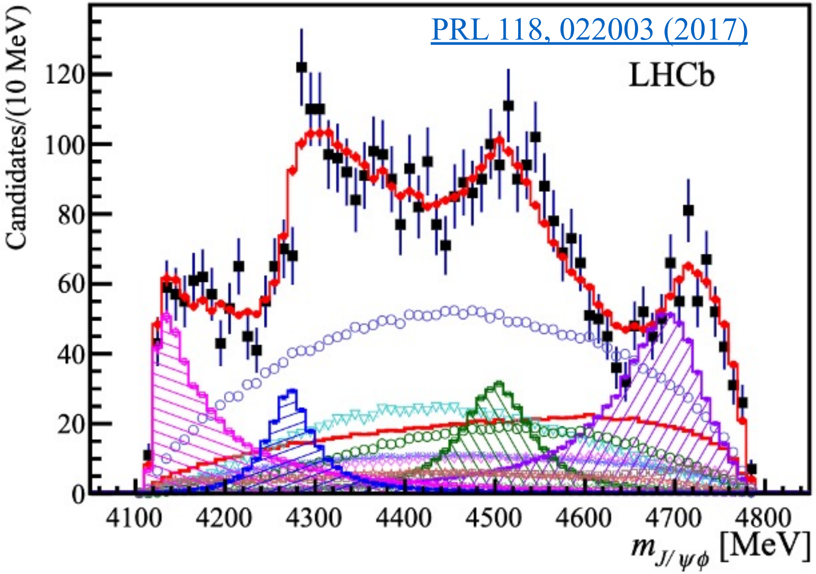
# BACKUPS

# Central exclusive production ($pp$) of $J/\psi\phi$

arXiv:2407.14301



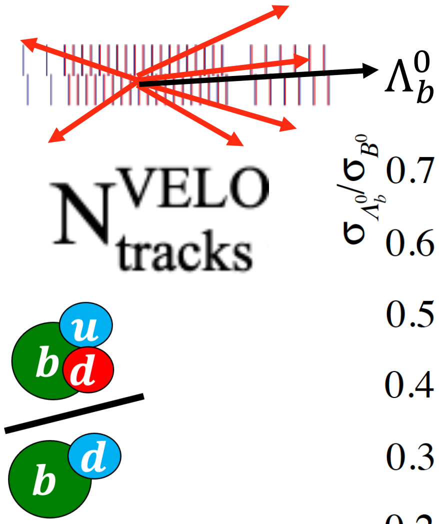

$B^{\pm} \to J/\psi\phi K^{\pm}$



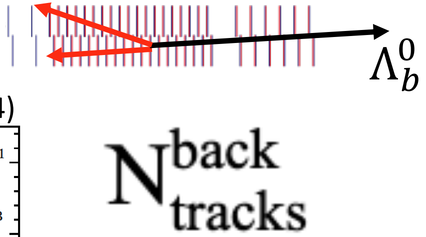

- Consistent with tetraquark candidates previously observed in $B^{\pm} \to J/\psi\phi K^{\pm}$ decays

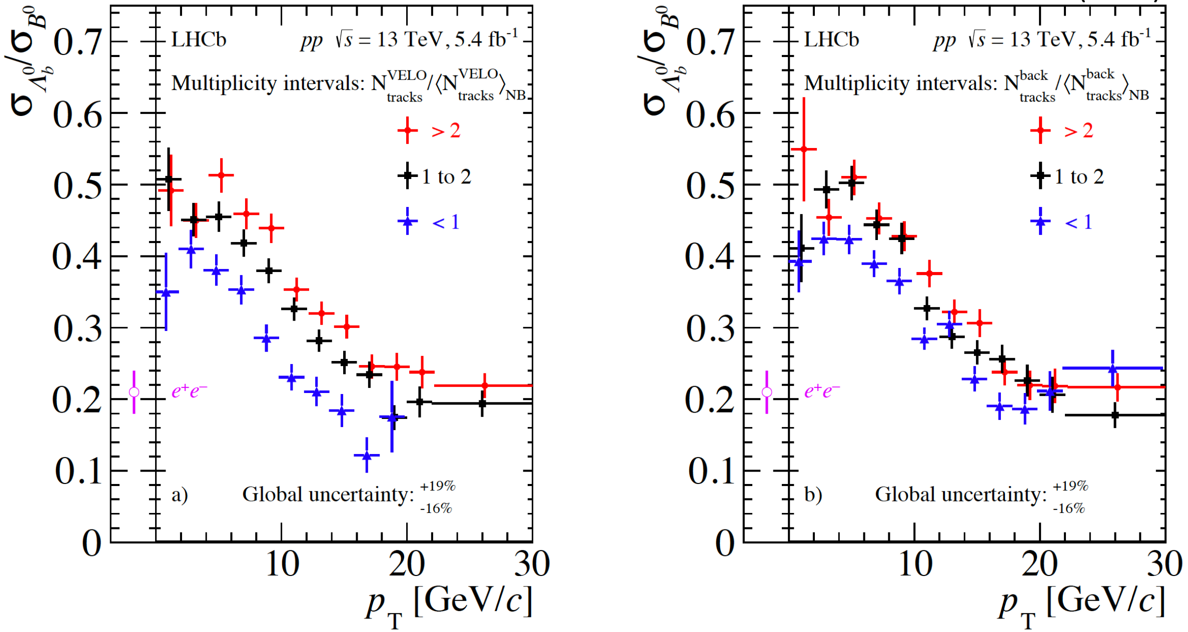
**CEP/UPCs provide totally new method to produce and study exotic hadrons**

# Modification of *b* hadronization – B baryons




PRL 132 081901 (2024)




- Clear multiplicity dependence at relatively low $p_T$

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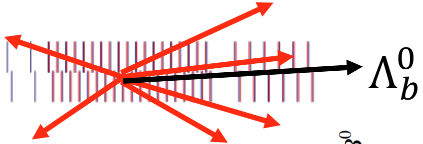
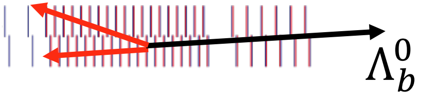
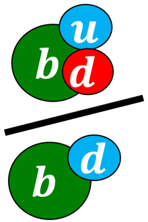


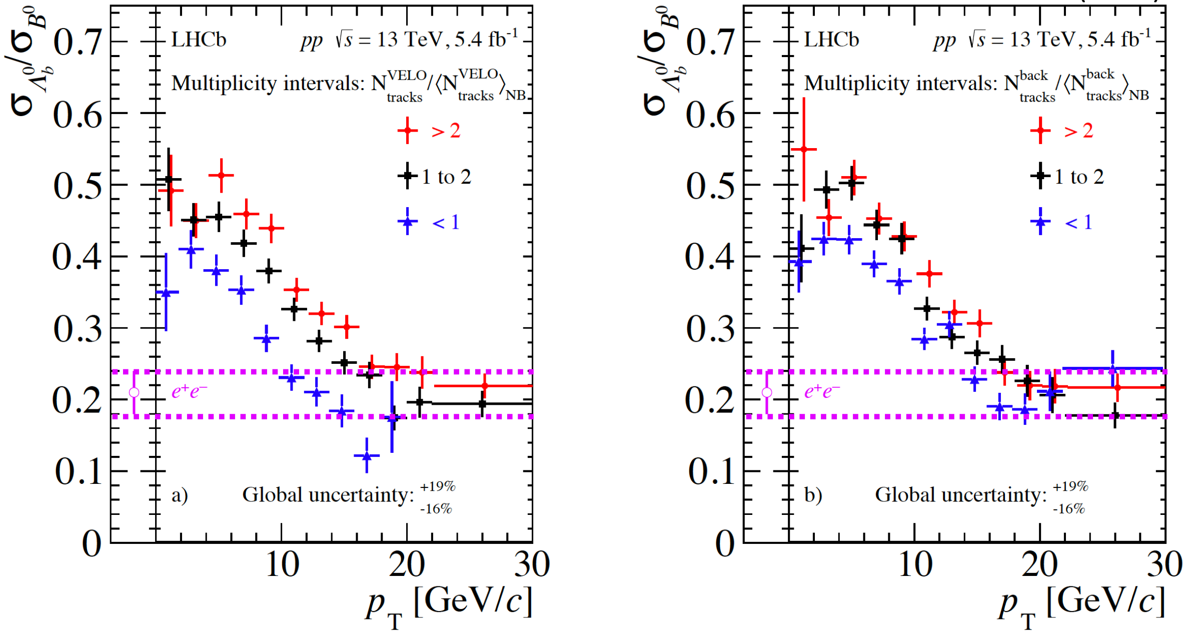

$N_{tracks}^{VELO}$




$N_{tracks}^{back}$




PRL 132 081901 (2024)

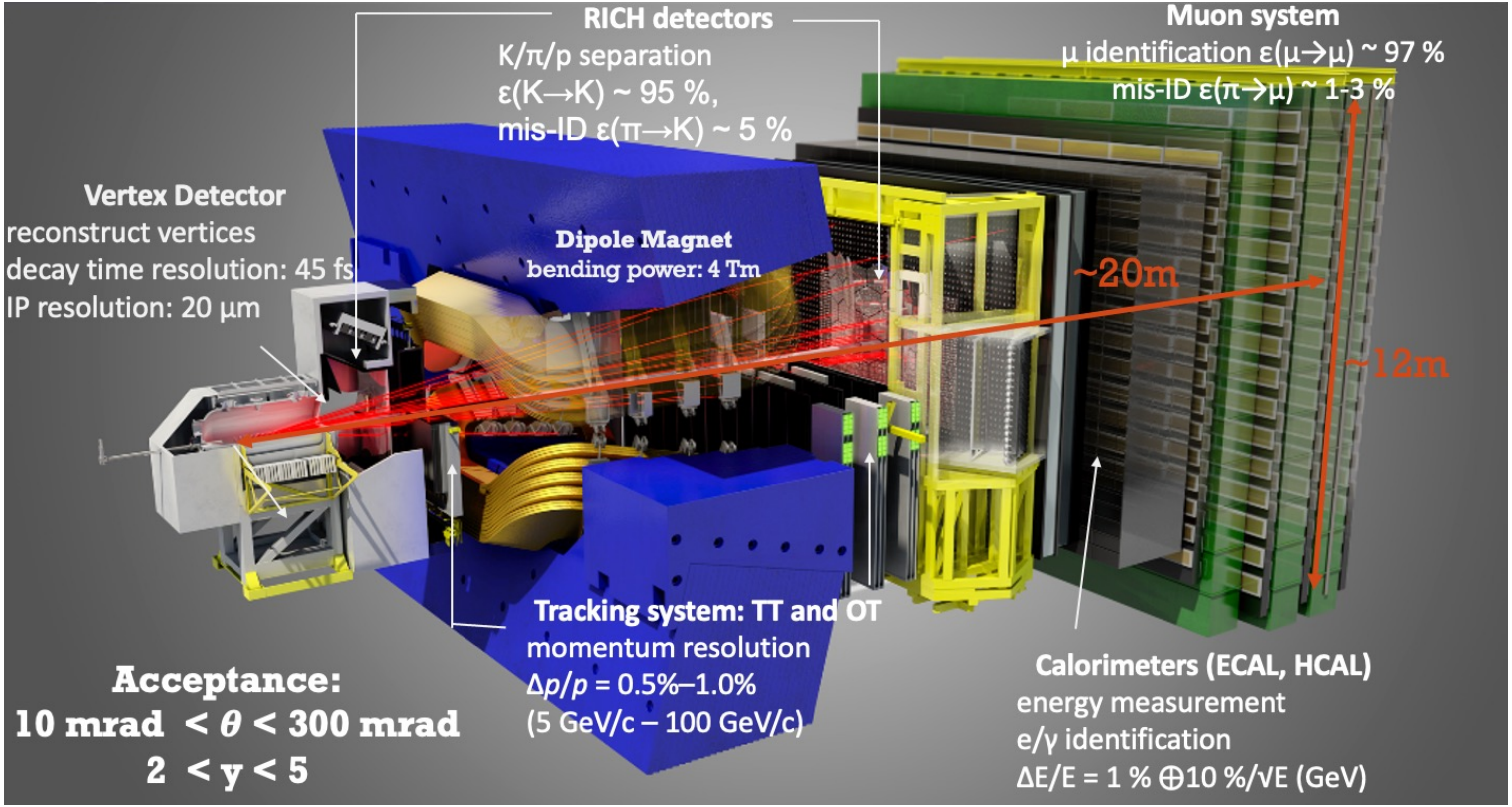



- Clear multiplicity dependence at relatively low $p_T$
- Reproduce $e^+e^-$ result at high $p_T$ where *b* quarks don't interact with bulk and just fragment

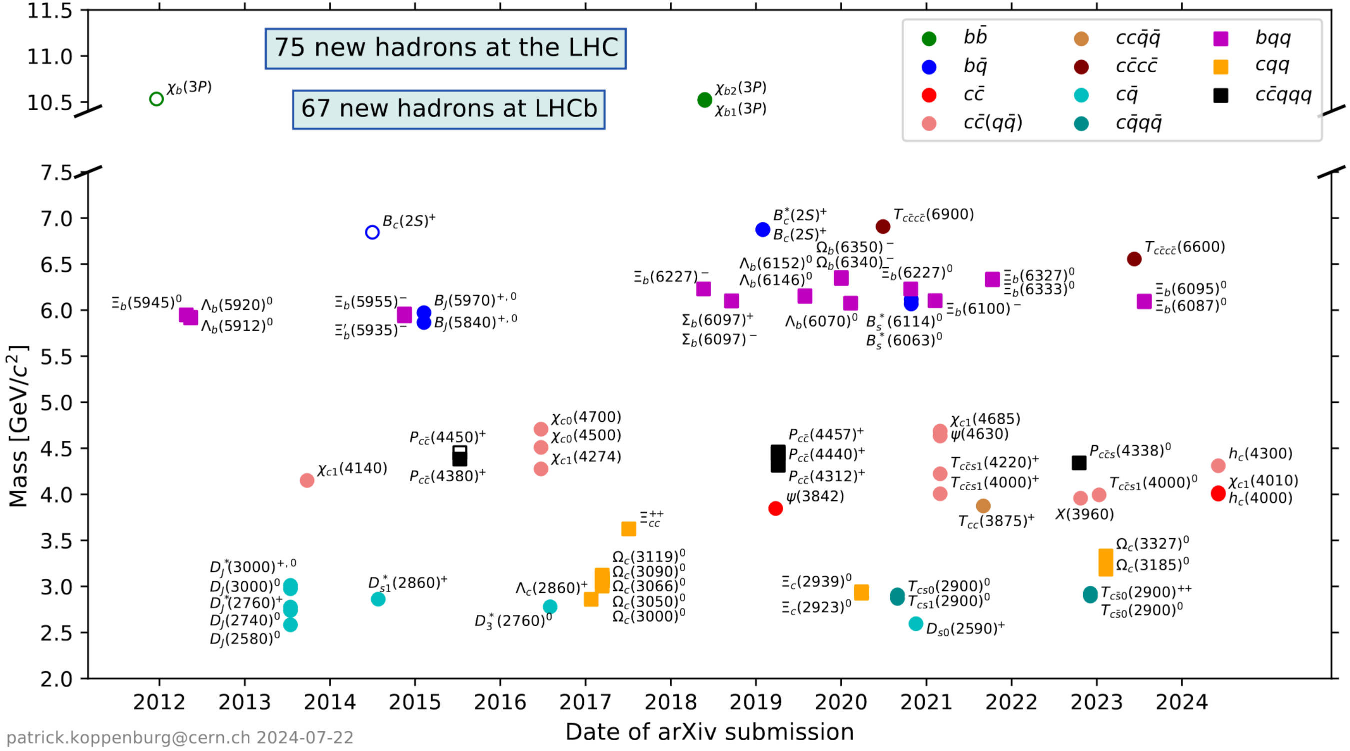
# The LHCb detector

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)

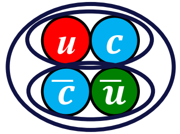
**Unique forward rapidity coverage at the Large Hadron Collider in p+p, p+A, A+A, fixed target collisions**



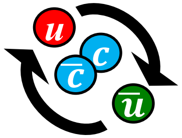
# New hadrons discovered at the LHC




## Compact tetraquark/pentaquark

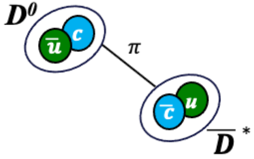



**Diquark-diantiquark**
*PRD 71, 014028 (2005)*
*PLB 662 424 (2008)*




**Hadrocharmonium/ adjoint charmonium**
*PLB 666 344 (2008)*
*PLB 671 82 (2009)*

## Hadronic Molecules




*PLB 590 209 (2004)*
*PRD 77 014029 (2008)*
*PRD 100 0115029(R) (2019)*

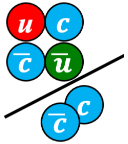
## Mixtures

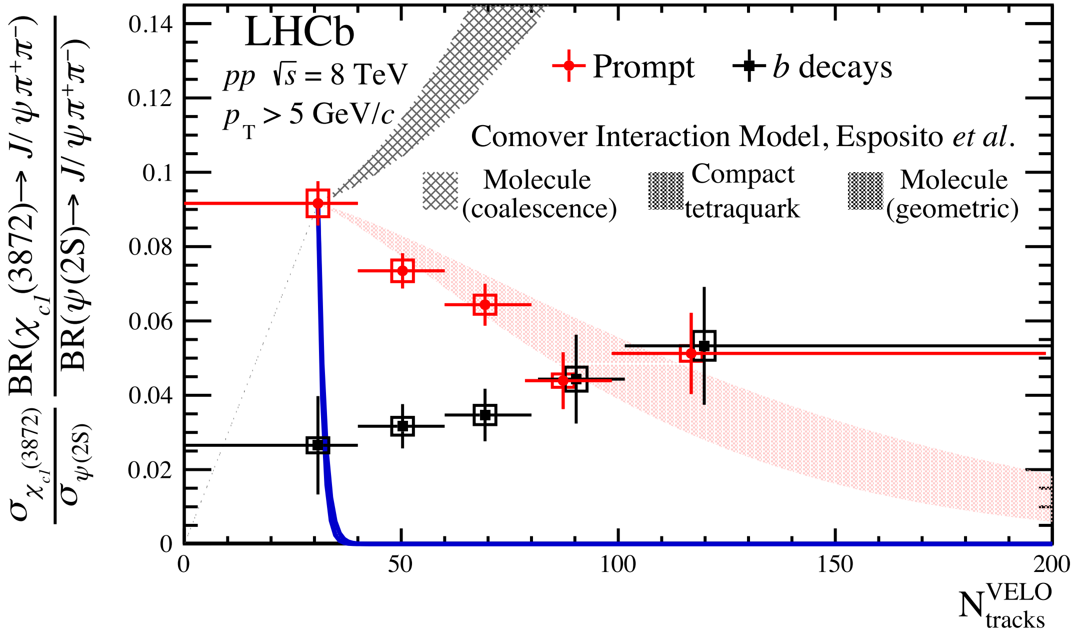
$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

*PLB 578 365 (2004)*
*PRD 96 074014 (2017)*

**~90% of the new particles were discovered by LHCb**

# X(3872)/ψ(2S)






**Prompt component:**

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

***b*-decay component:**

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.

Calculations from EPJ C 81, 669 (2021)

Break-up cross section:

$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\mathrm{geo}} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{\mathrm{thr}}}{E_c}\right)^n \right\rangle$$

**Molecular X(3872) with large radius and large comover breakup cross section is immediately dissociated**

**Coalescence of D mesons into molecular X(3872) increases ratio**

**Compact tetraquark of size 1.3 fm gradually dissociated as multiplicity increases – consistent with data**