X(3872) in *pp* and *p*Pb collisions at LHCb

Matt Durham
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Outline

- Exotic hadrons at the Large Hadron Collider
  - A new understanding of the allowed configurations of quarks inside hadrons
- X(3872) production in *pp, p*Pb collisions
  - Comparison with conventional hadrons
- New environments for studying exotic hadrons:
  - First measurement of photoproduction of heavy exotic hadrons
  - First measurement of exotic hadrons in jets
- Outlook: many new nuclear systems to explore

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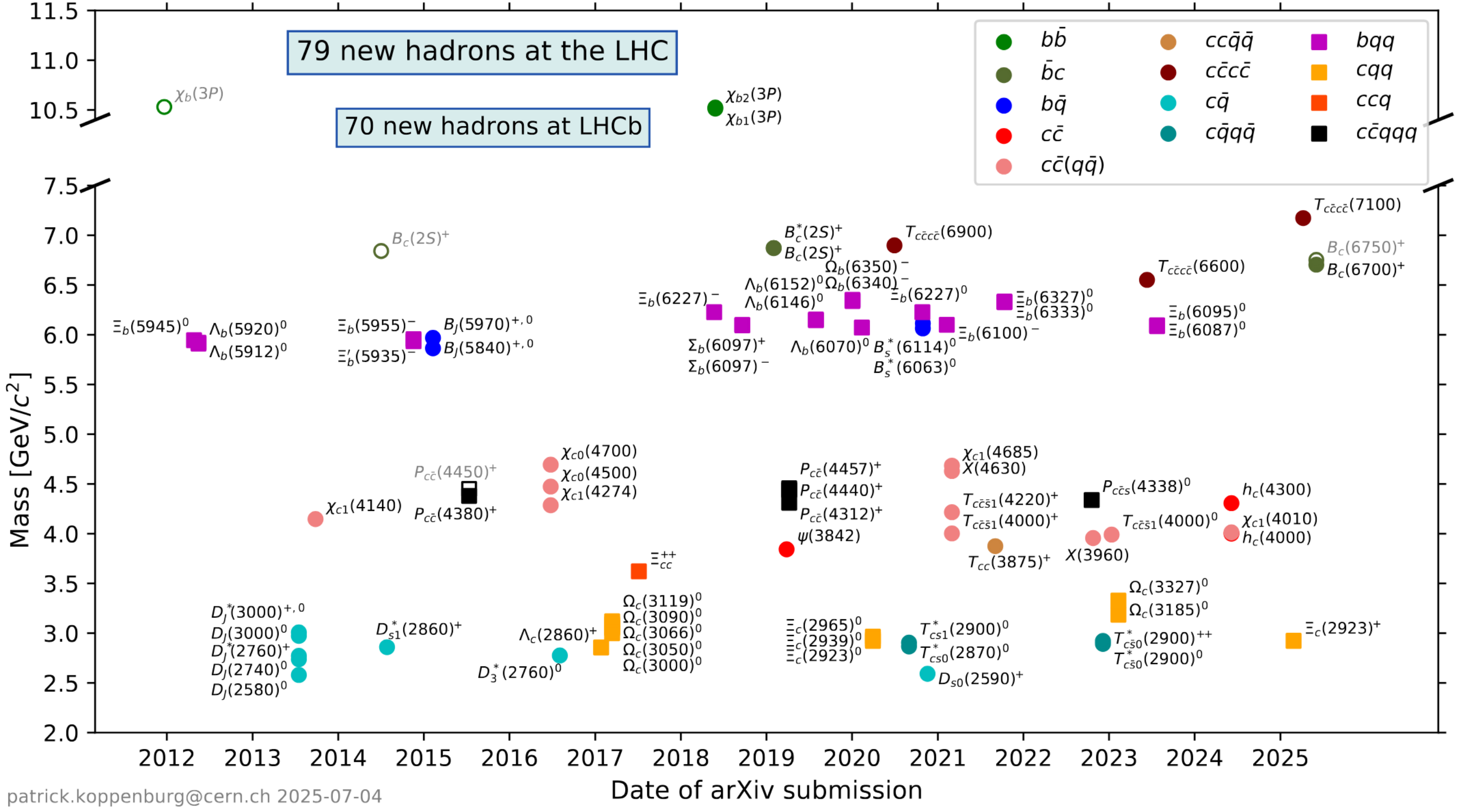
New hadrons discovered at LHC



The quark model is rapidly expanding:
study of exotics states largely driven by experiment

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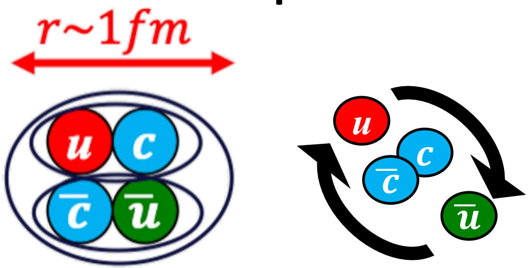
X(3872) – an enduring puzzle

- The first exotic hadron – discovered in $J/\psi\pi^{+}\pi^{-}$ mass spectrum from B decays by Belle, PRL 91 262001 (2003)
  - A new charmonium state? Eichten, Lane, Quigg PRD 69, 094019 (2004)
  - Charmonium hypothesis **disfavored** by measured mass and quantum numbers, LHCb PRL 110 222001 (2013)
  - Tetraquark state? Expected since Gell-Mann and Zweig proposed quark model but never conclusively observed.

Compact



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

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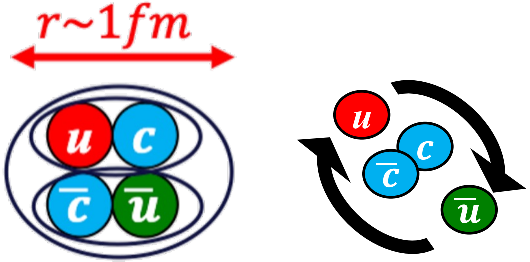
  - Tetraquark state? Expected since Gell-Mann and Zweig proposed quark model but never conclusively observed.
- Mass is consistent with mass of $D^0 + \bar{D}^{*0}$: $(M_{D^0} + M_{\bar{D}^{*0}}) - M_{\chi_{c1}(3872)} = 0.07 \pm 0.12 \text{ MeV}/c^2$ LHCb JHEP 08(2020)123
  - Hadronic molecule? Bound state of DD*?
  - Large prompt production fraction (~80%) – potentially inconsistent with D meson coalescence in pp PRD 81 114018 (2010)

Compact



Tightly bound via color exchange between diquarks
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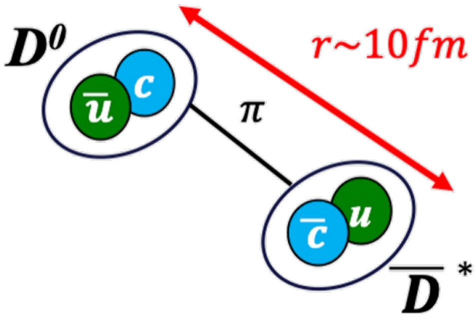
Molecule



***VERY* small binding energy**
***VERY* large radius, ~10fm**

Hundreds of theory papers exploring various possibilities, no broad consensus

Comparison with conventional charmonia $\psi(2S)$

Reconstruct the $\mu^+\mu^-\ \pi^+\pi^-$ final state from the decays:

$$X(3872) \to J/\psi(\to \mu^+\mu^-)\rho(\to \pi^+\pi^-)$$

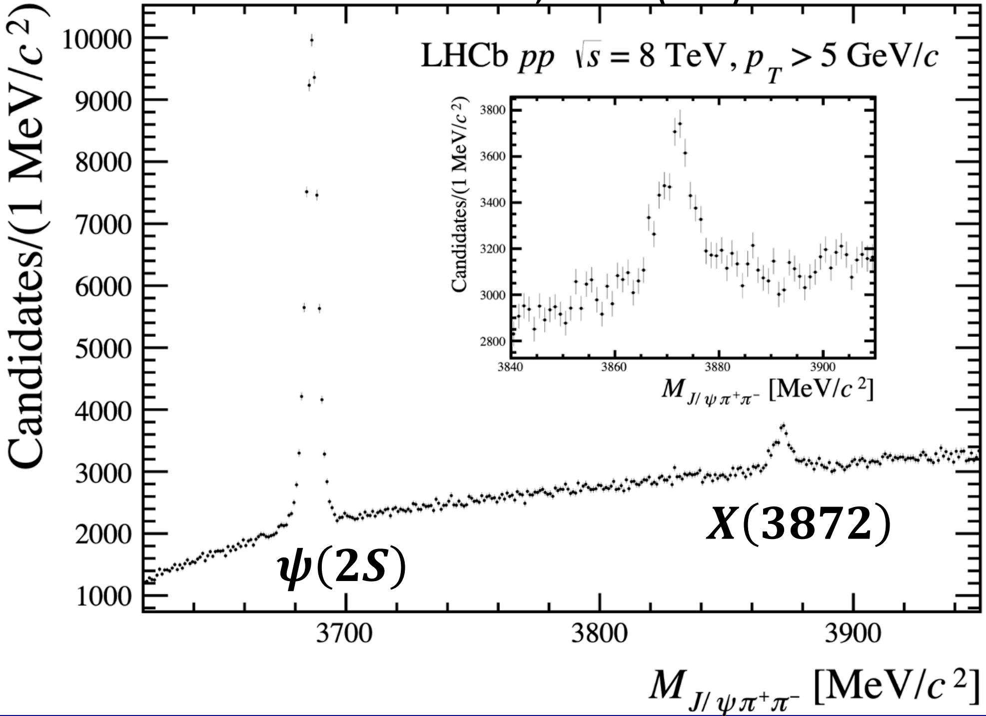
$$\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$$

Direct comparison between conventional charmonium $\psi(2S)$ and exotic $X(3872)$ via ratio of cross sections:

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]}$$

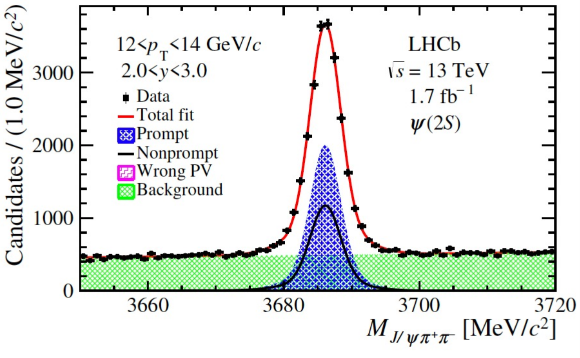
Events can be characterized by number of tracks reconstructed in LHCb vertex detector, N_{tracks}^{VELO}

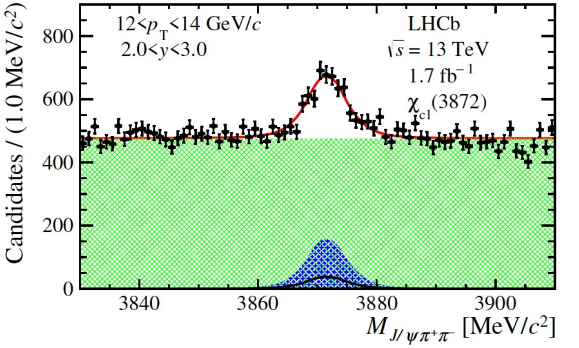
PRL 126, 092001 (2021)

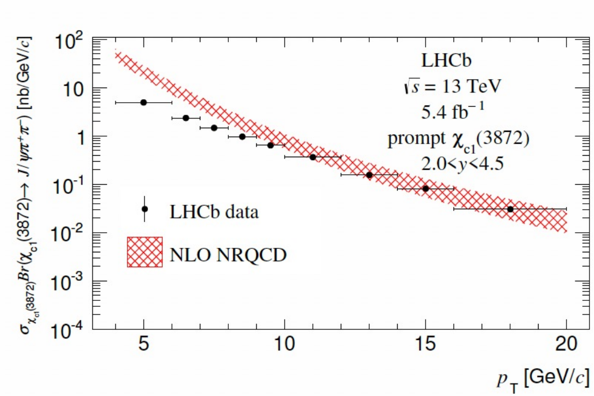


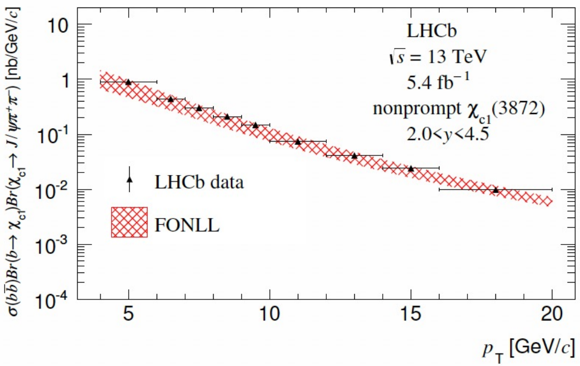
X(3872) production in *pp*

JHEP01 (2022) 131







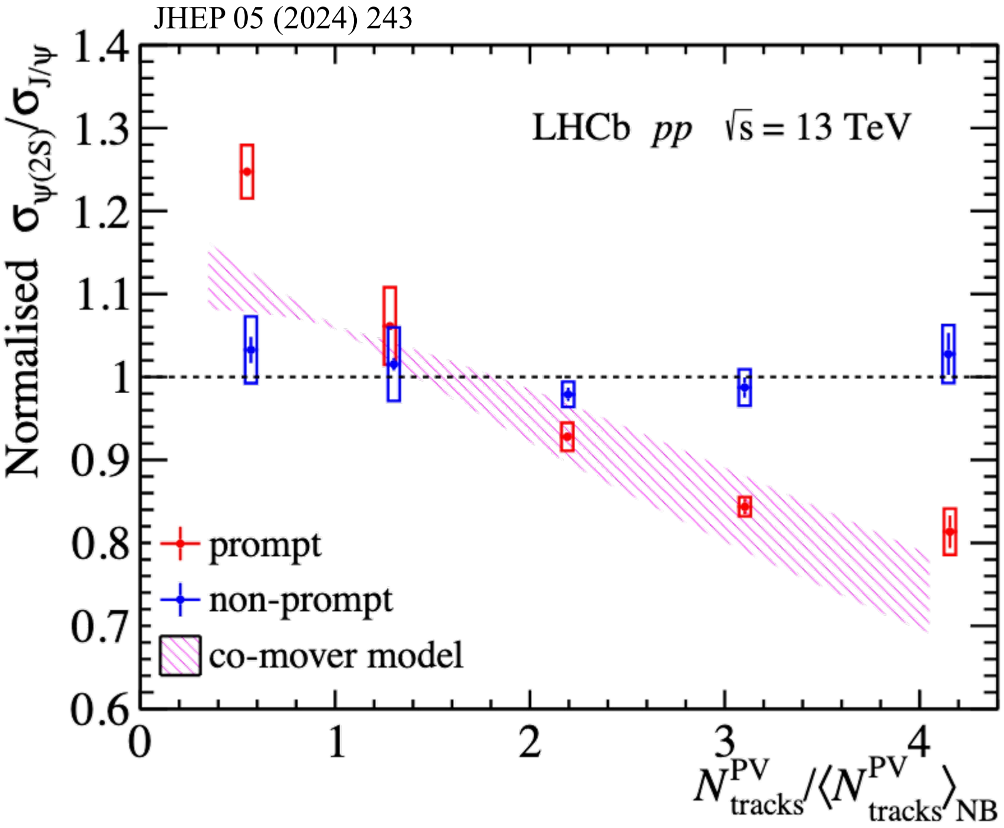


- NRQCD calculation matches high-p_T data well
- Overpredicts yield at lower p_T
- Room for additional effects?

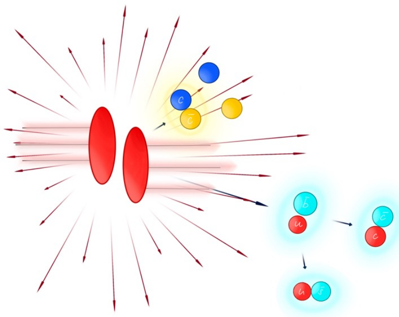
- FONLL describes non-prompt X(3872) production well (also at ATLAS and CMS)

Examine X(3872)/ψ(2S) ratio for direct comparison between exotic hadron and well-known conventional charmonium

What have we learned from conventional charmonia

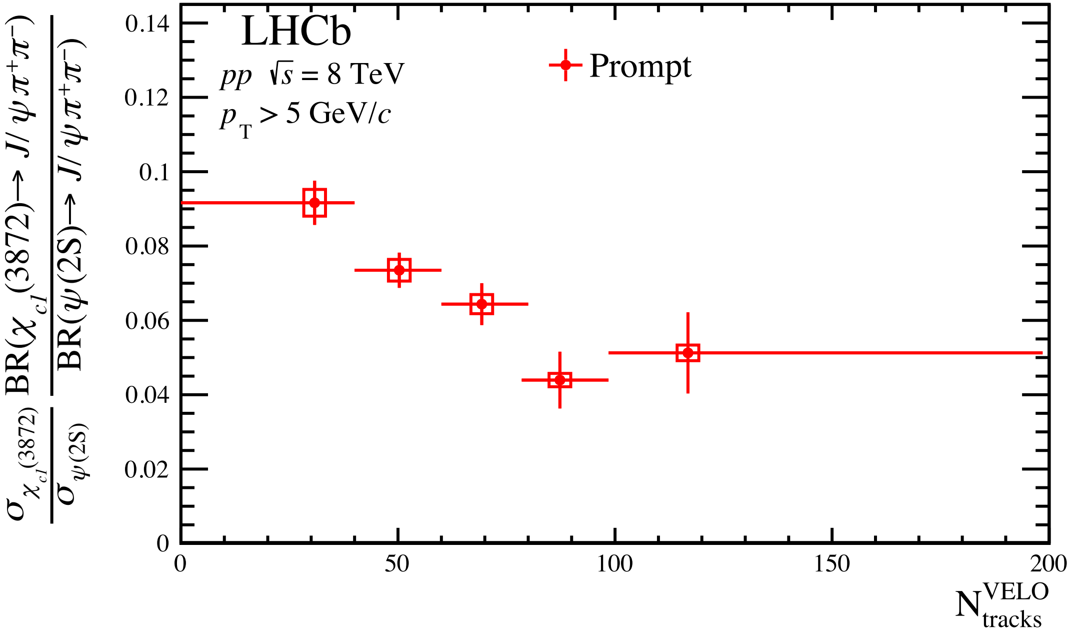


- Well established that $\psi(2S)$ is suppressed in high-multiplicity collisions (pp, pA, and AA)
- Co-mover model successfully describes the data: interactions with other particles produced in the event break up charmonia
- *b* component not affected



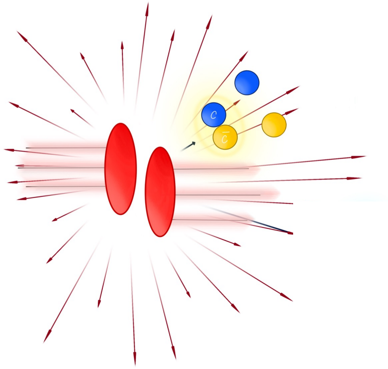
X(3872)/ψ(2S) vs multiplicity

PRL 126, 092001 (2021)



Prompt component:

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



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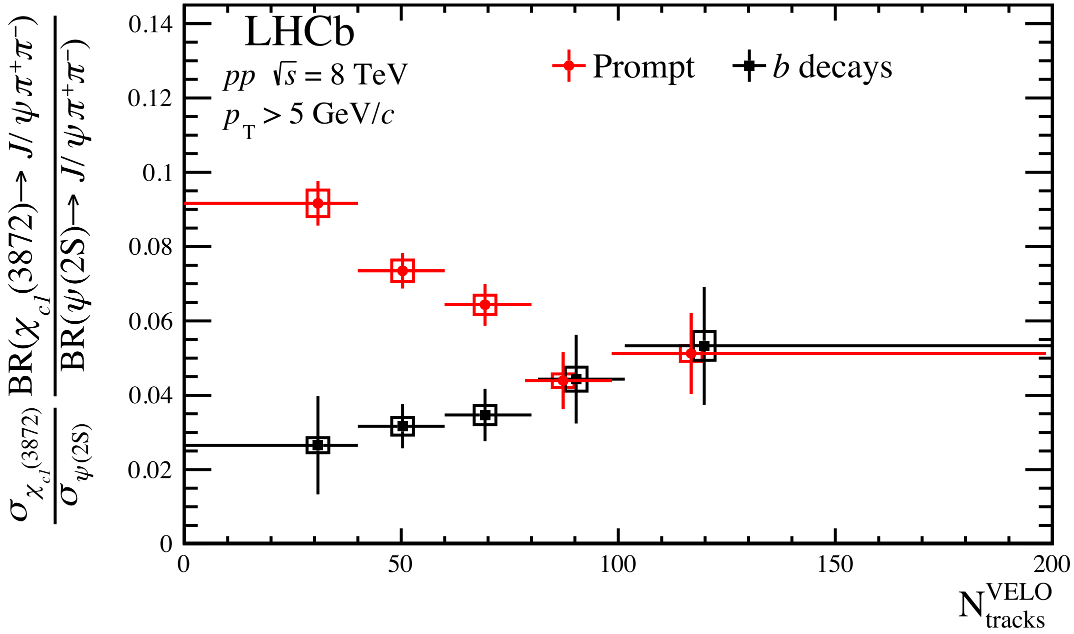

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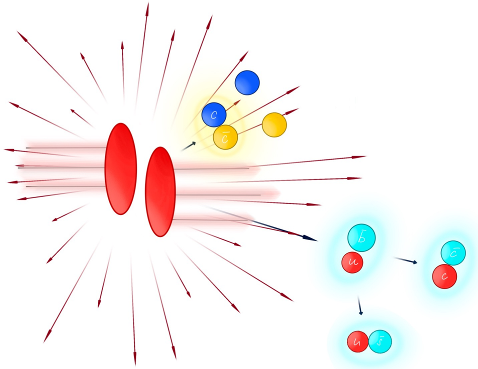
b-decay component:

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



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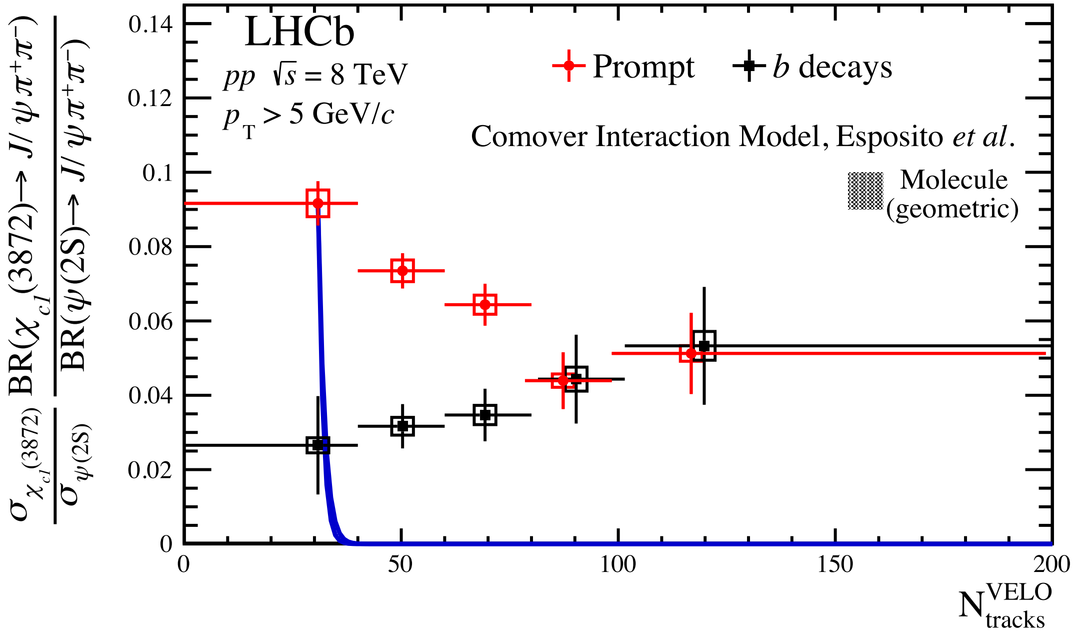
PRL 126, 092001 (2021)



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Calculations from EPJ C 81, 669 (2021)

Break-up cross section:

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

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

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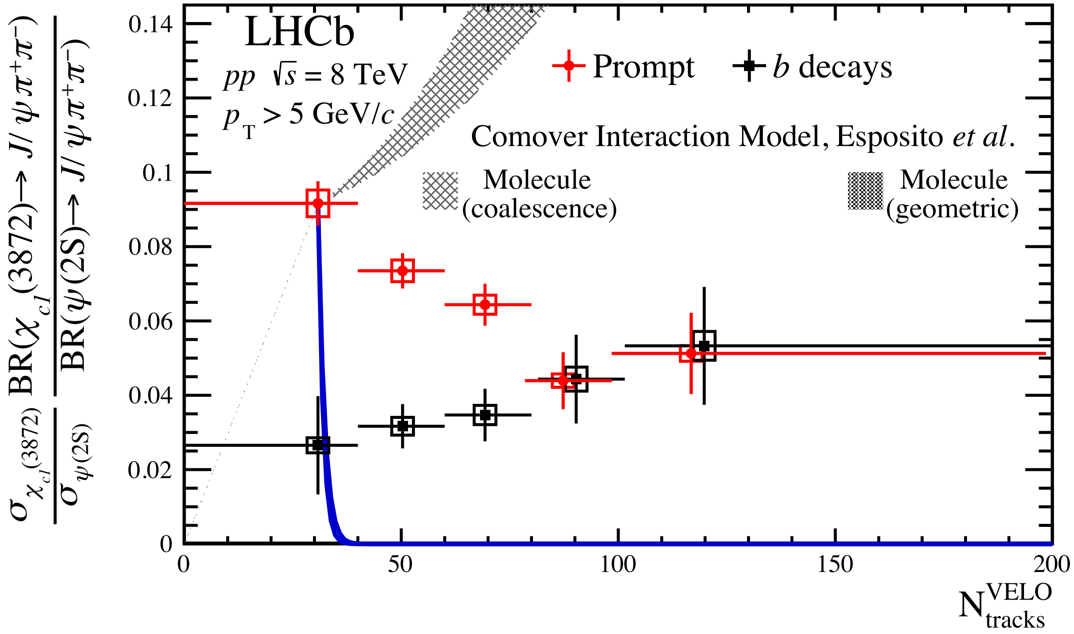

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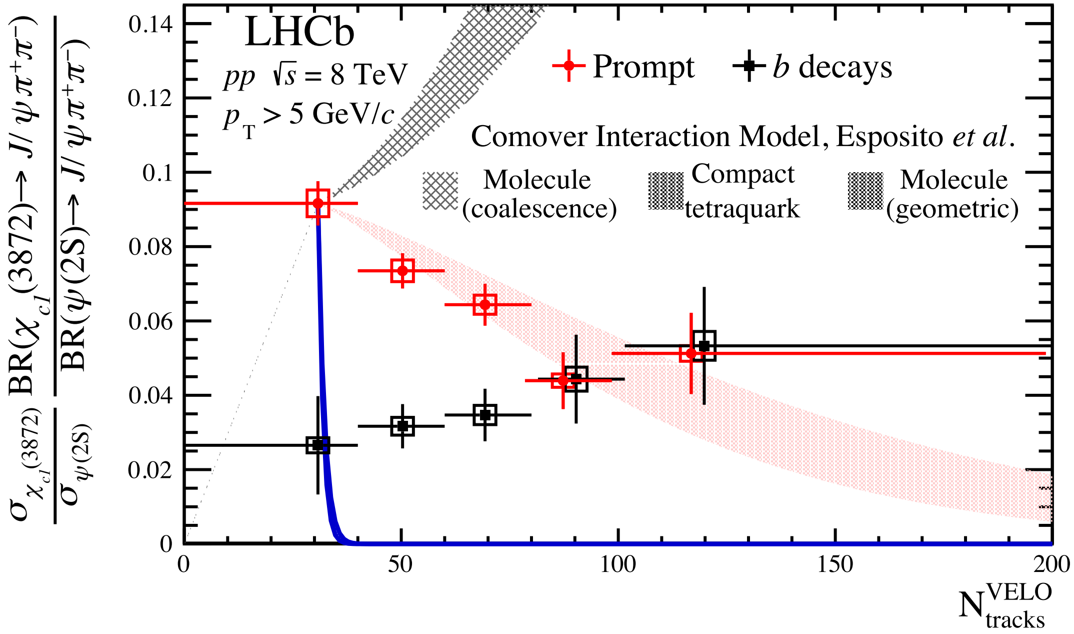

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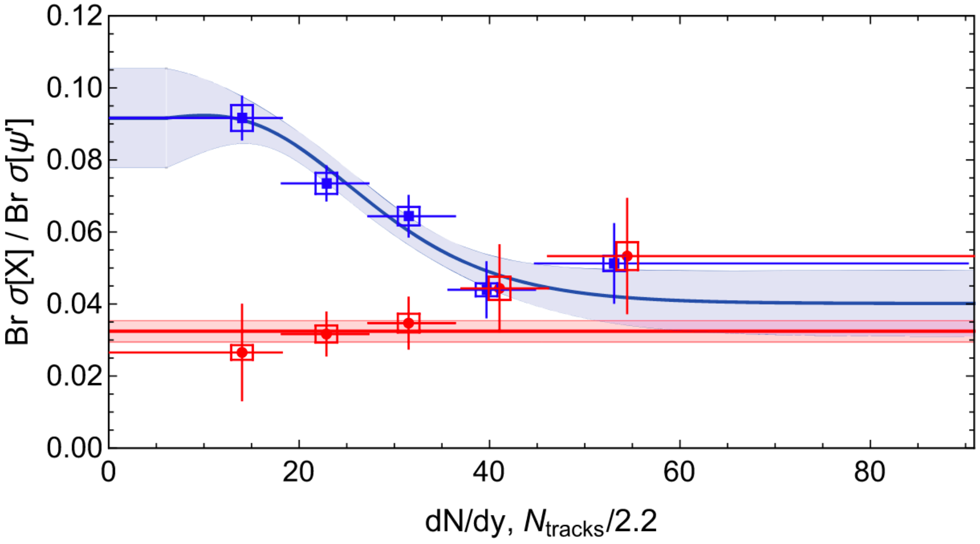
Compact tetraquark of size 1.3 fm gradually dissociated as multiplicity increases – consistent with data

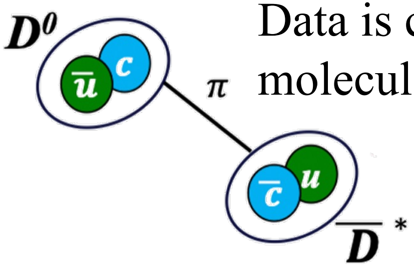
Comover model: constituent interaction

Different method of calculating breakup cross section:
Braaten, He Ingles, Jiang Phys. Rev. D 103, 071901 (2021)



Breakup cross section approximated as sum of cross section for molecule constituents:

$$\sigma^{\text{incl}}[\pi X] \approx \frac{1}{2}\left(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}]\right)$$



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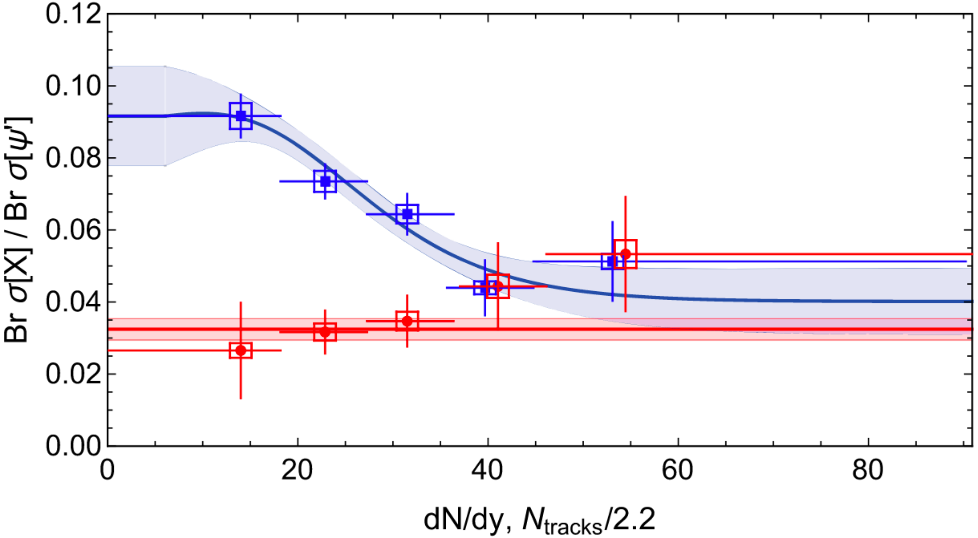

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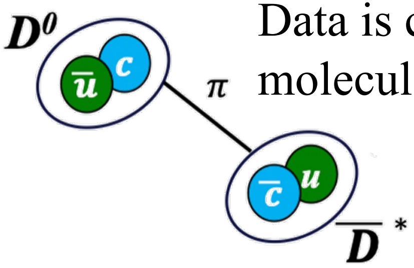

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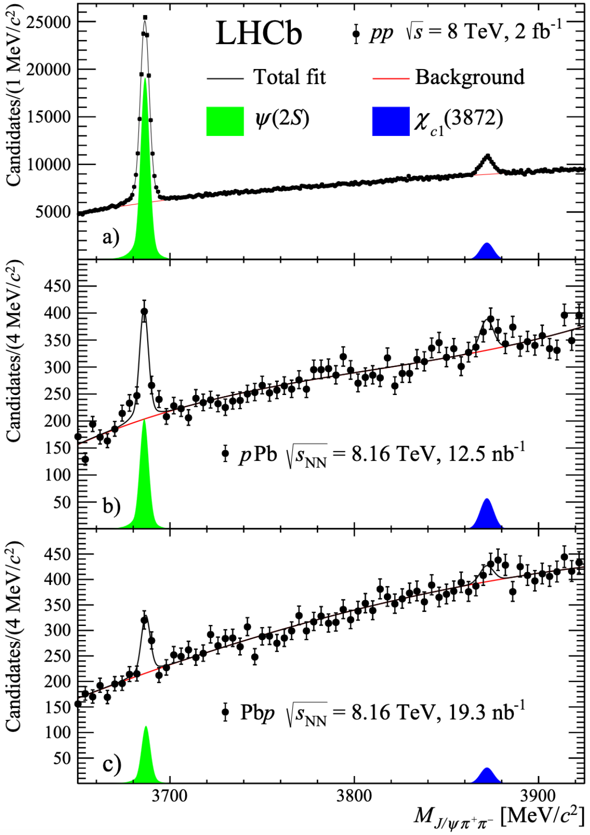
If breakup is due to scattering of individual constituents, would all $c\bar{c}$ have equal suppression?
Not observed in charmonium or bottomonium systems.

X(3872) in *p*Pb

PRL 132 (2024) 242301



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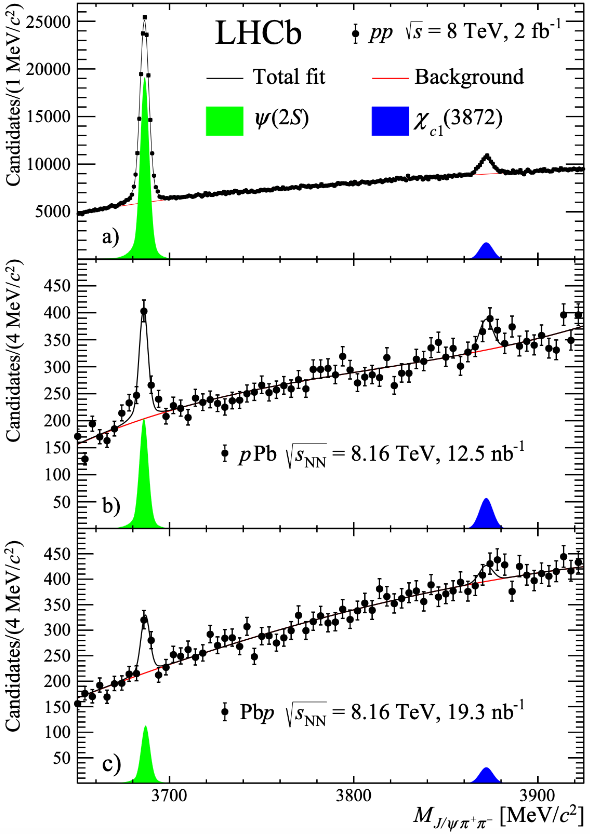
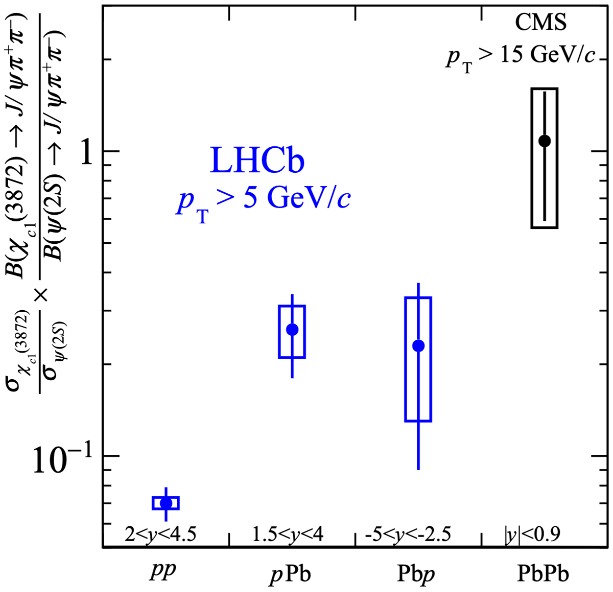
PRL 132 (2024) 242301





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?

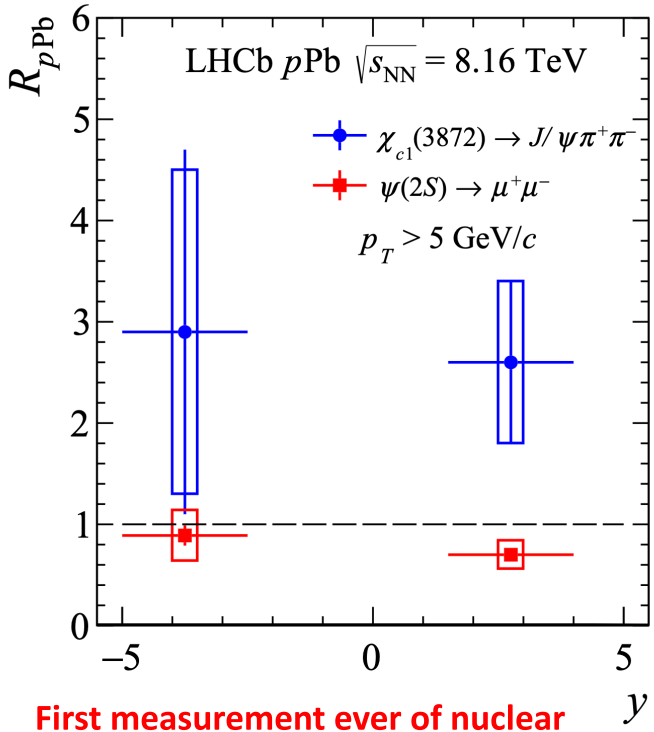
- arXiv:2302.03828

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 pPb

PRL 132 (2024) 242301



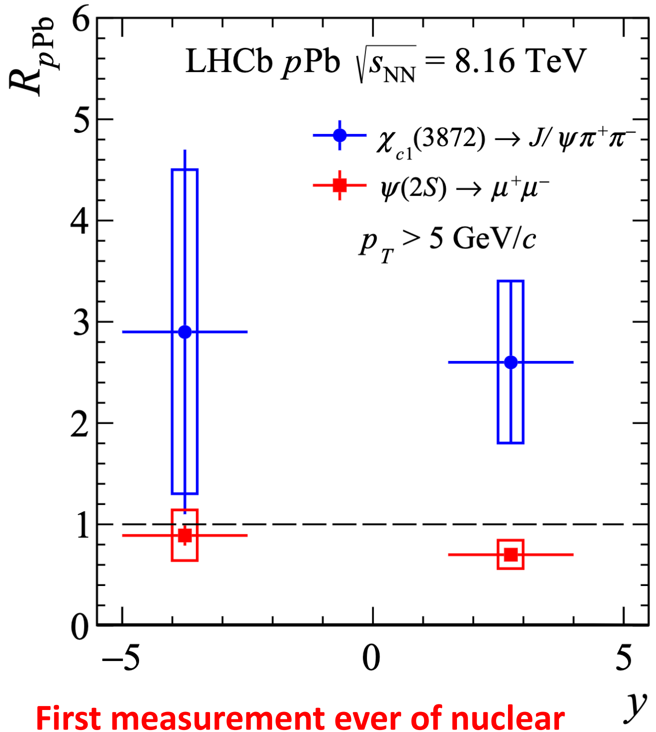
First measurement ever of nuclear modification factor of a tetraquark!

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 *p*Pb

PRL 132 (2024) 242301



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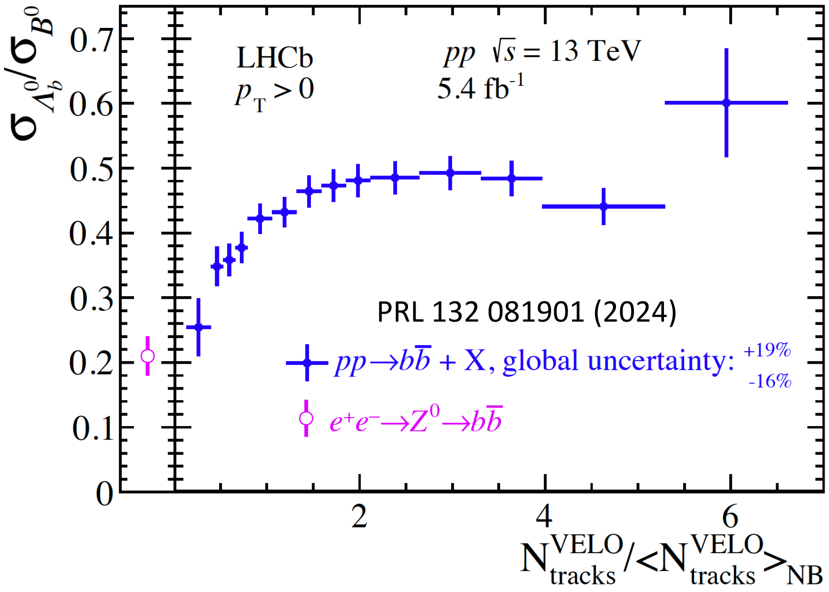
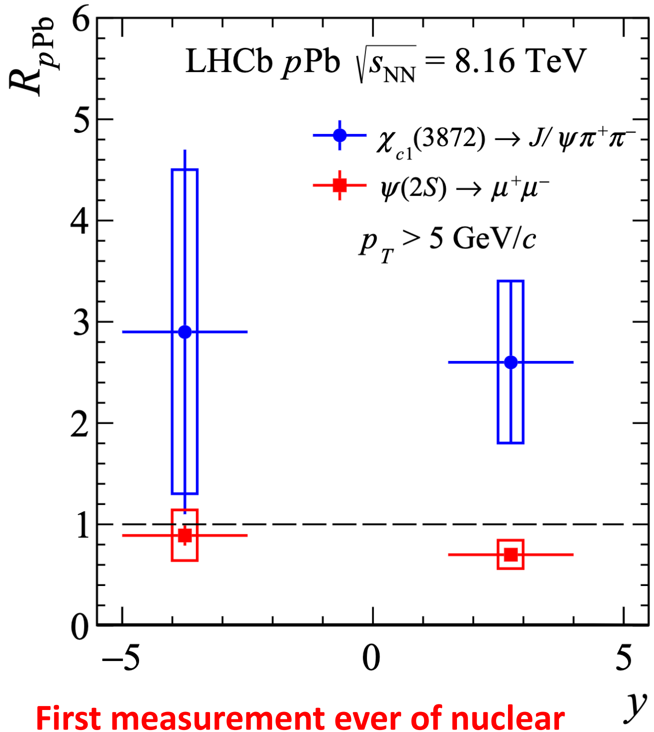
Heavy baryon production increases with multiplicity:



X(3872) in *p*Pb

PRL 132 (2024) 242301



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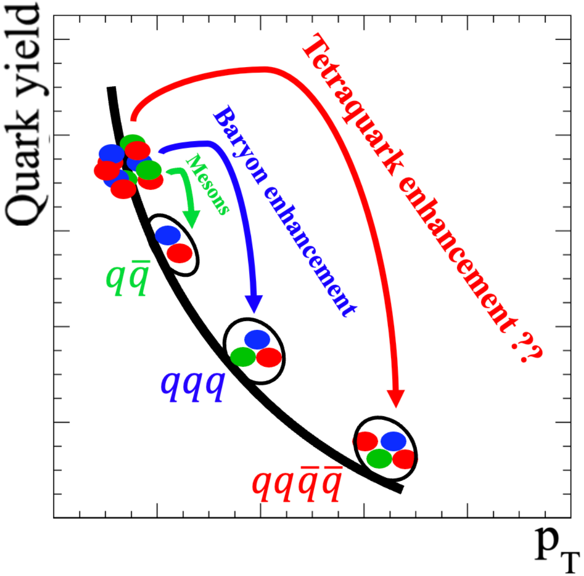
Evidence for enhancement of X(3872) in *p*Pb: Coalescence dominating over breakup?

Similar mechanism for baryon enhancement could also increase tetraquark production



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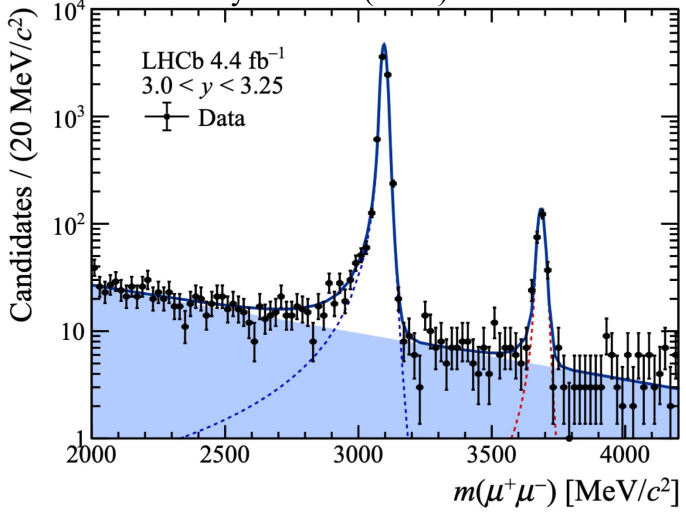
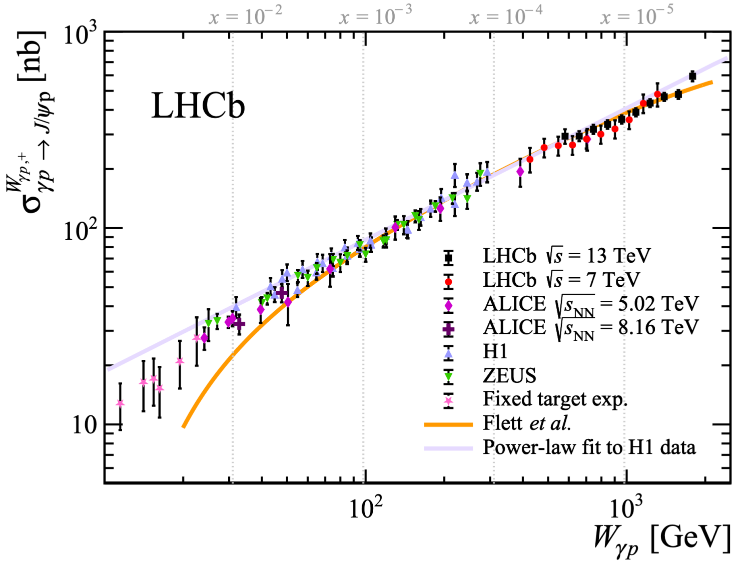
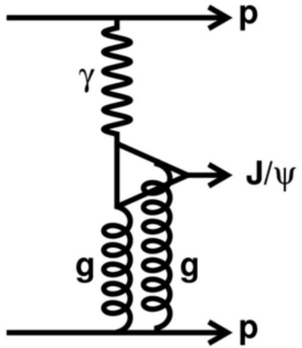
Central Exclusive Production/Ultra-Peripheral Collisions

- Detailed studies of conventional hadrons in CEP/UPC exist

SciPostPhys 18 071 (2025)



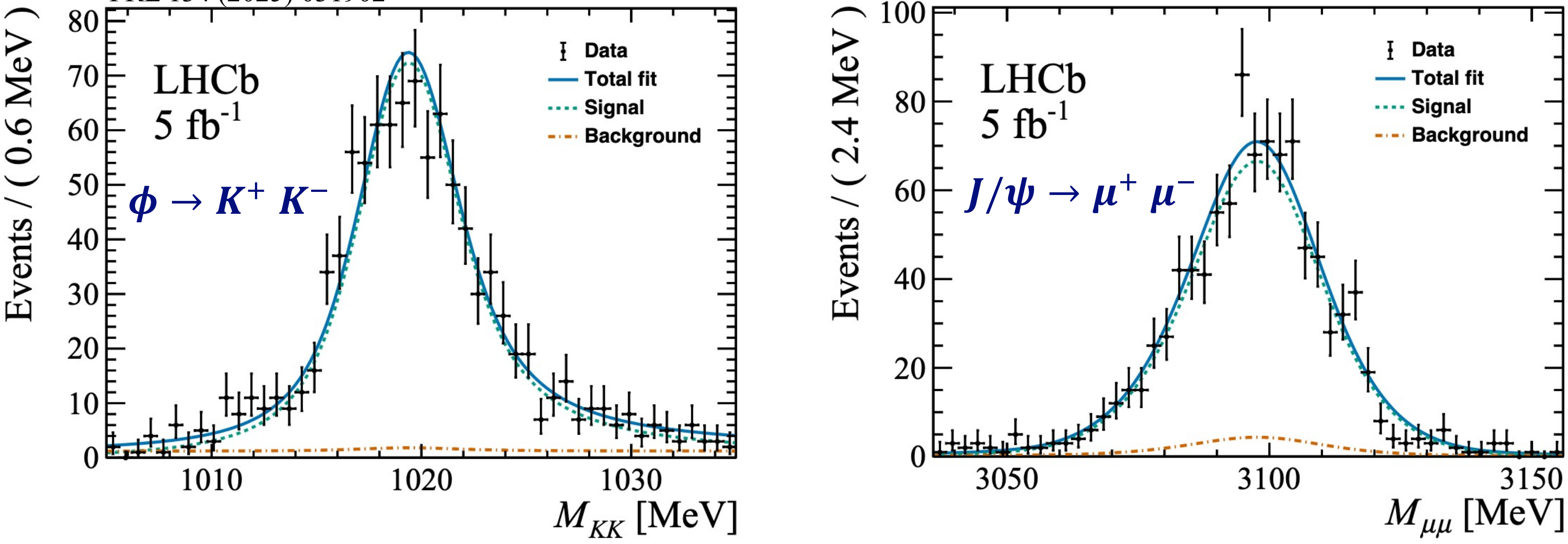




- There is increasing interest in the production of exotic hadrons in these events:
  PRD94, 094024 (2016), PRC100, 024620 (2019), PLB 805135447 (2020), PLB 810 136249 (2021), EPJC 81 710 (2021), PRD 104 114029 (2021), PRD 109 016007 (2024)

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

PRL 134 (2025) 031902



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

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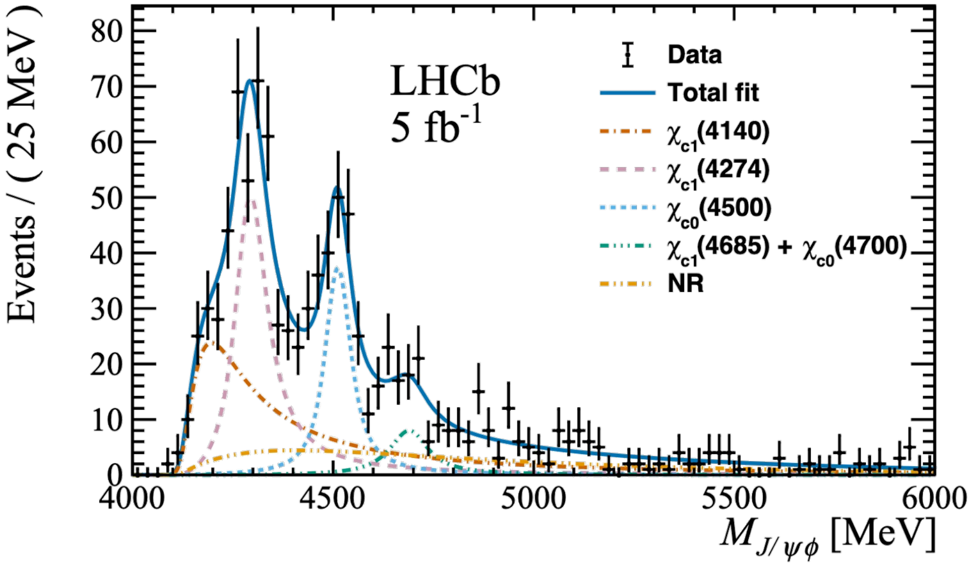
PRL 134 (2025) 031902



- Structures apparent in CEP data (exactly 4 tracks)

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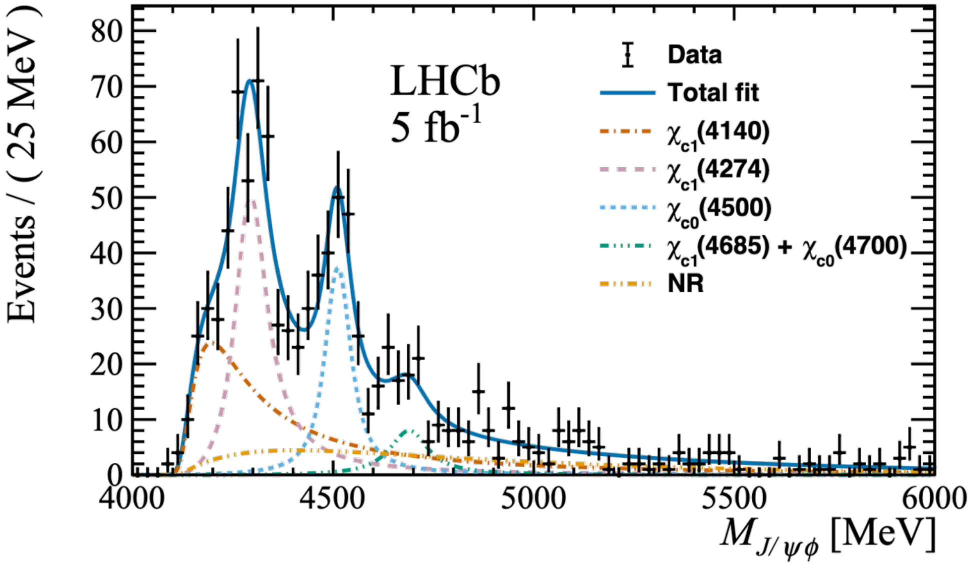

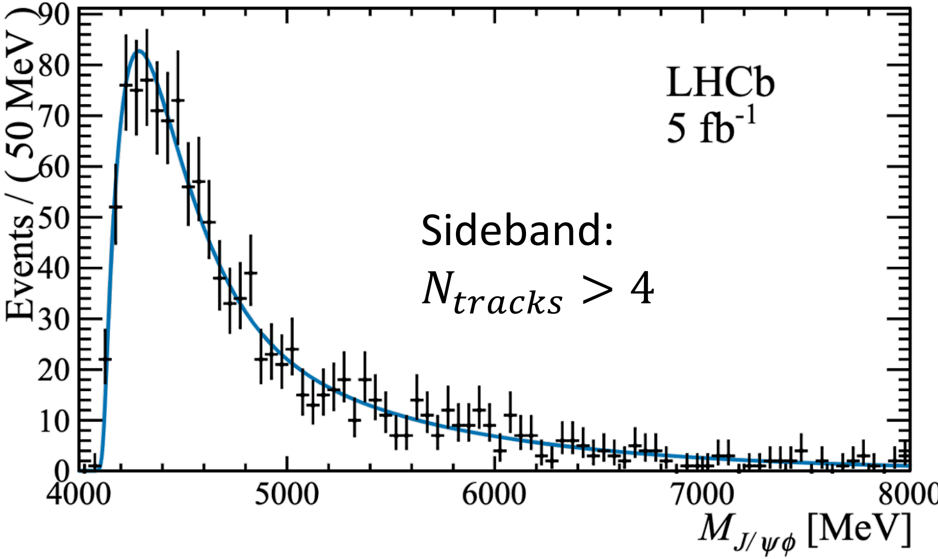

- Structures apparent in CEP data (exactly 4 tracks)
- Gone when looking at "sideband" of events with more activity

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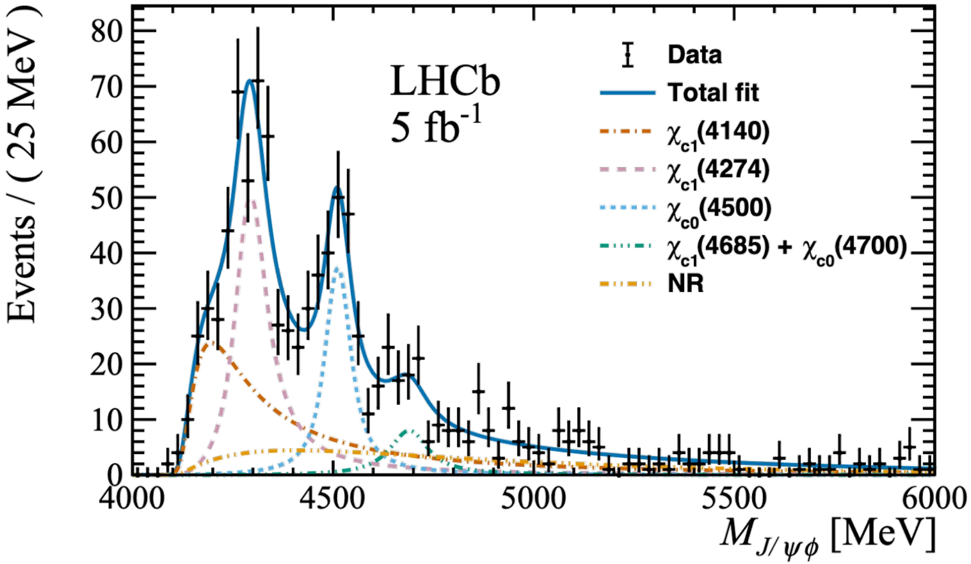
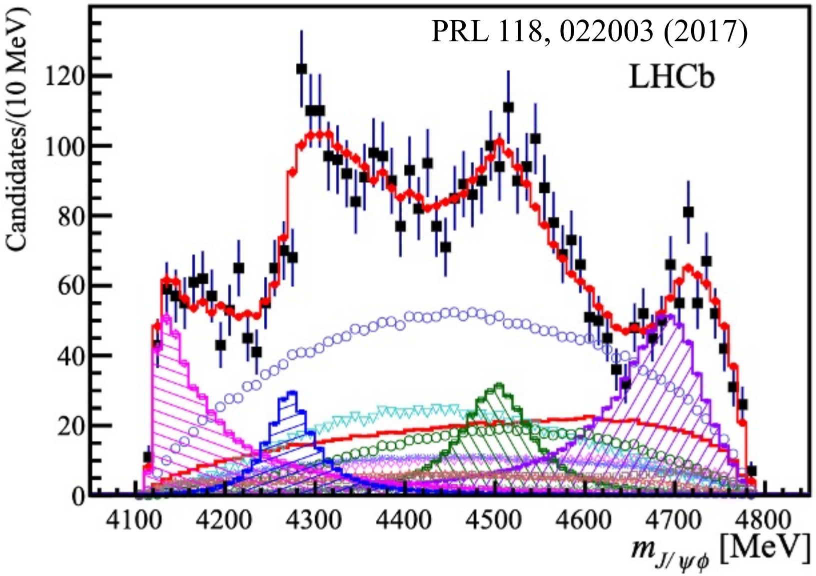
PRL 134 (2025) 031902



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

PRL 118, 022003 (2017)

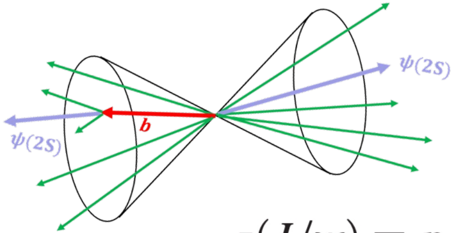


- Consistent with tetraquark candidates previously observed in $B^{\pm} \to J/\psi\phi K^{\pm}$ decays

Concept proven: CEP/UPCs provide totally new method to produce and study exotic hadrons

Charmonia 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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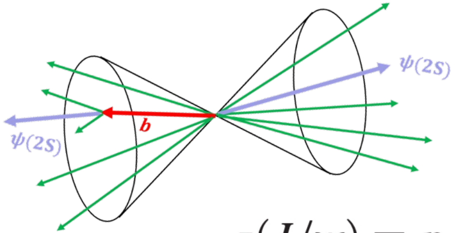

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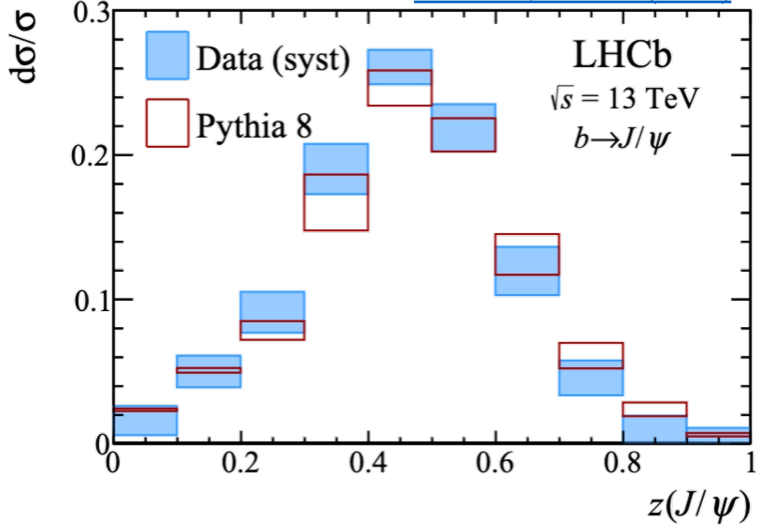
PRL 118, 192001 (2017)



Non-prompt: well described by PYTHIA

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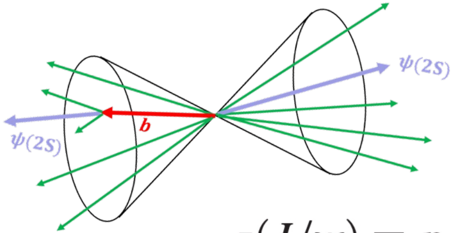
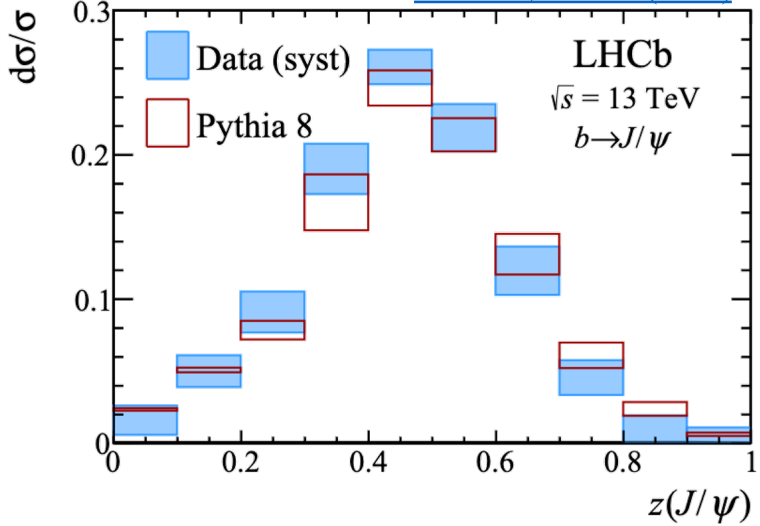
- Charmonia in jets provides new way to examine production mechanisms

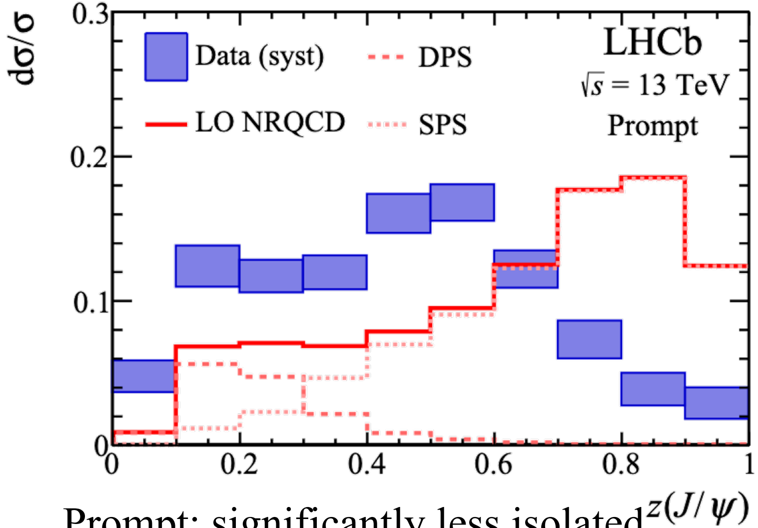


$$z(J/\psi) \equiv p_{\mathrm{T}}(J/\psi)/p_{\mathrm{T}}(\mathrm{jet})$$

PRL 118, 192001 (2017)

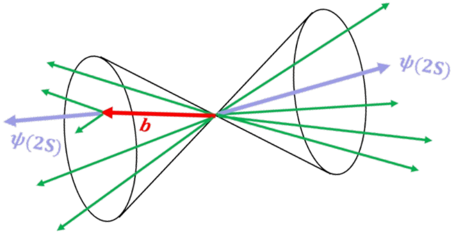


Non-prompt: well described by PYTHIA

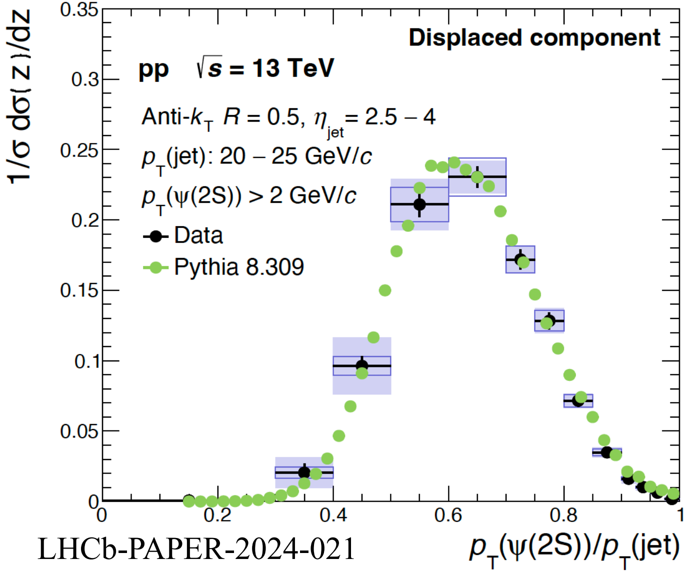


Prompt: significantly less isolated than NRQCD prediction

$\psi(2S)$ in jets



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



LHCb-PAPER-2024-021

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

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

$\psi(2S)$ in jets

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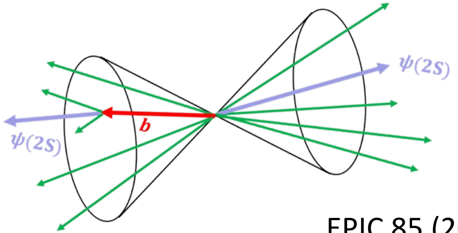
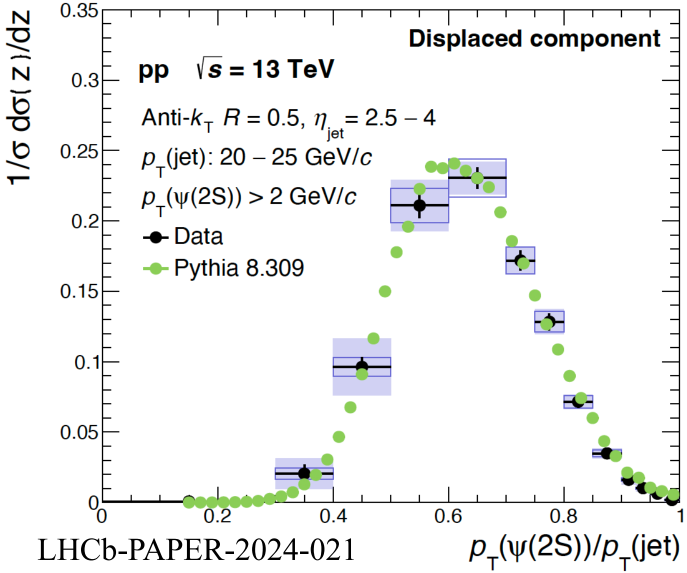
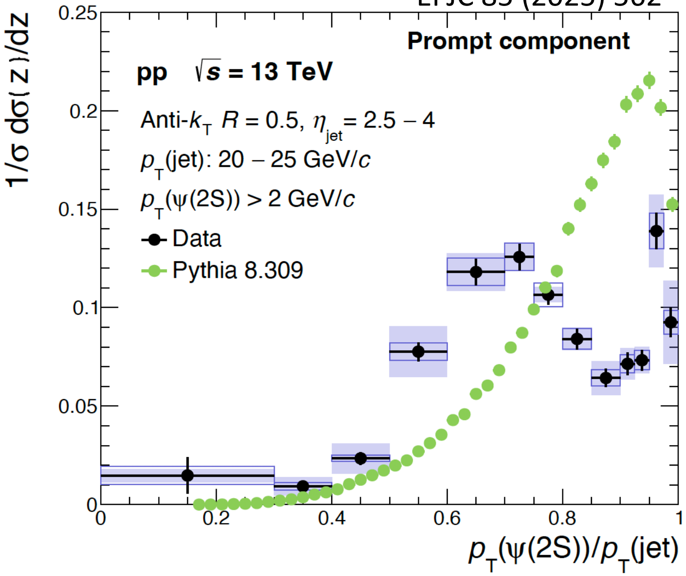


EPJC 85 (2025) 562



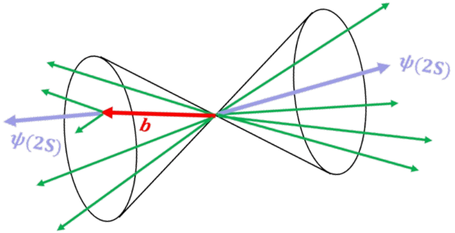
LHCb-PAPER-2024-021

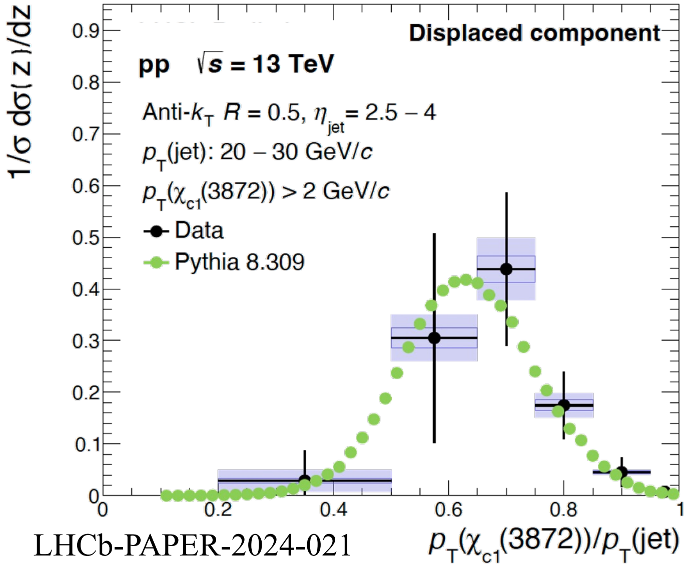


$b \rightarrow \psi(2S)$: well described by PYTHIA
Very similar to $b \rightarrow J/\psi$

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

$X(3872)$ in jets



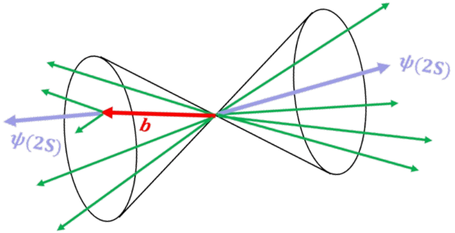


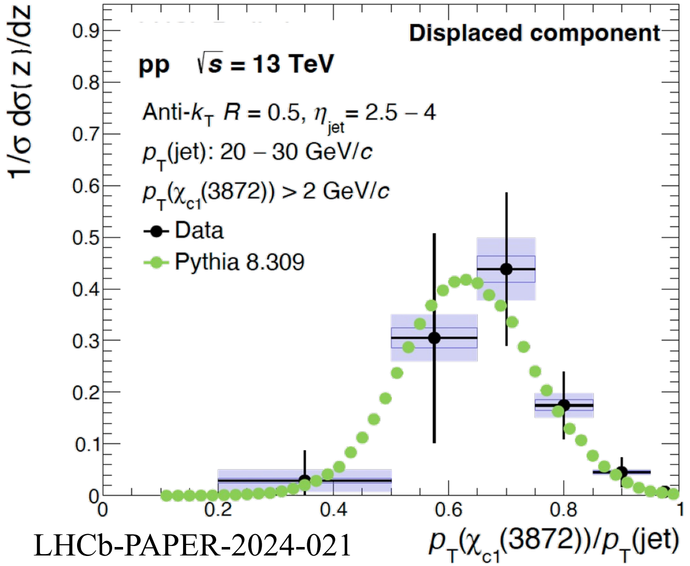
LHCb-PAPER-2024-021

$\boldsymbol{b \to X(3872)}$: well described by PYTHIA

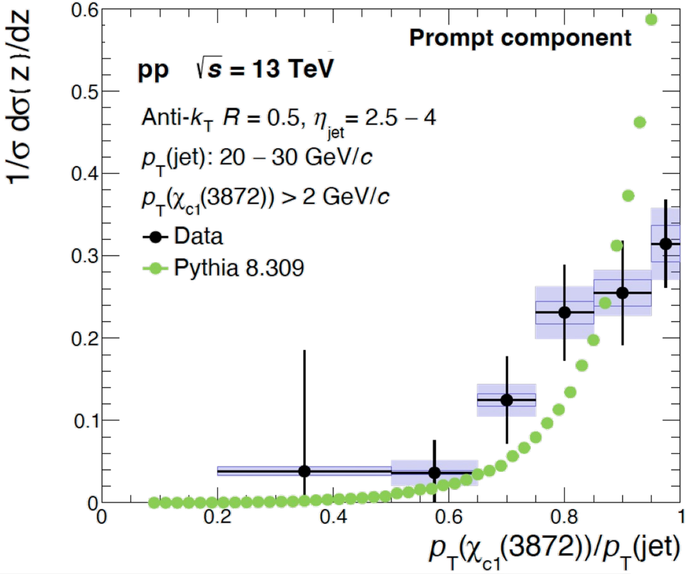
Very similar to $\boldsymbol{b \to J/\psi, \psi}$(2S)

$X(3872)$ in jets





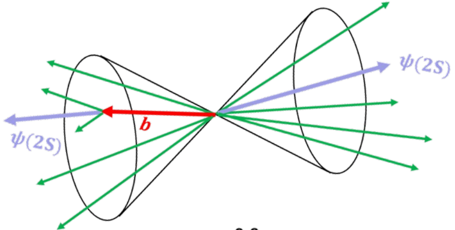
LHCb-PAPER-2024-021

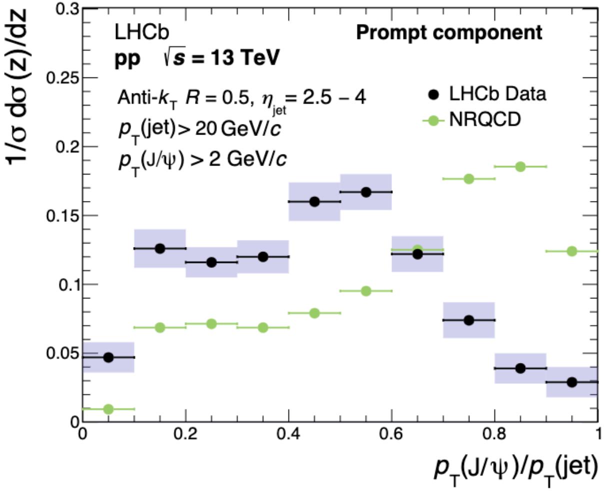


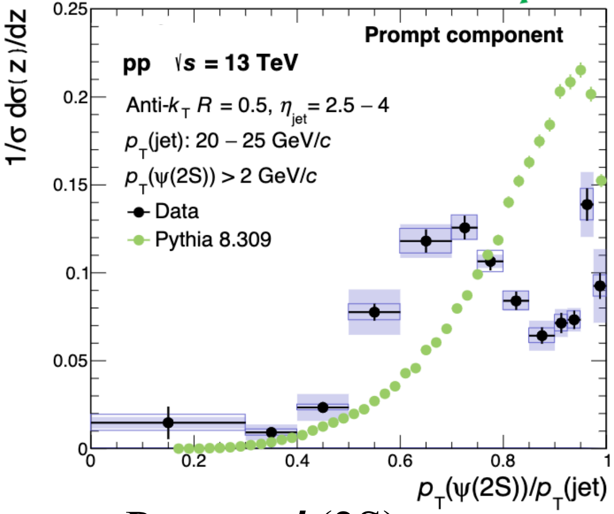
$\boldsymbol{b \to X(3872)}$: well described by PYTHIA
Very similar to $\boldsymbol{b \to J/\psi}$, $\boldsymbol{\psi}$(2S)

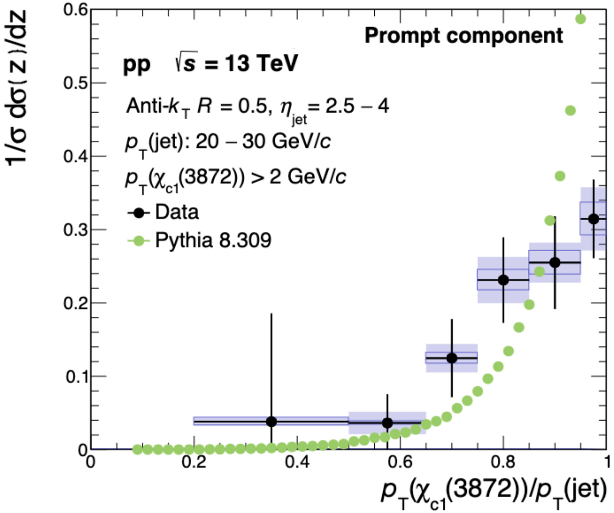
Prompt: Rises towards isolation, very different from conventional $c\bar{c}$ state $\boldsymbol{\psi}$(2S)

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









Prompt J/ψ: less isolated than expected

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

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

Outline

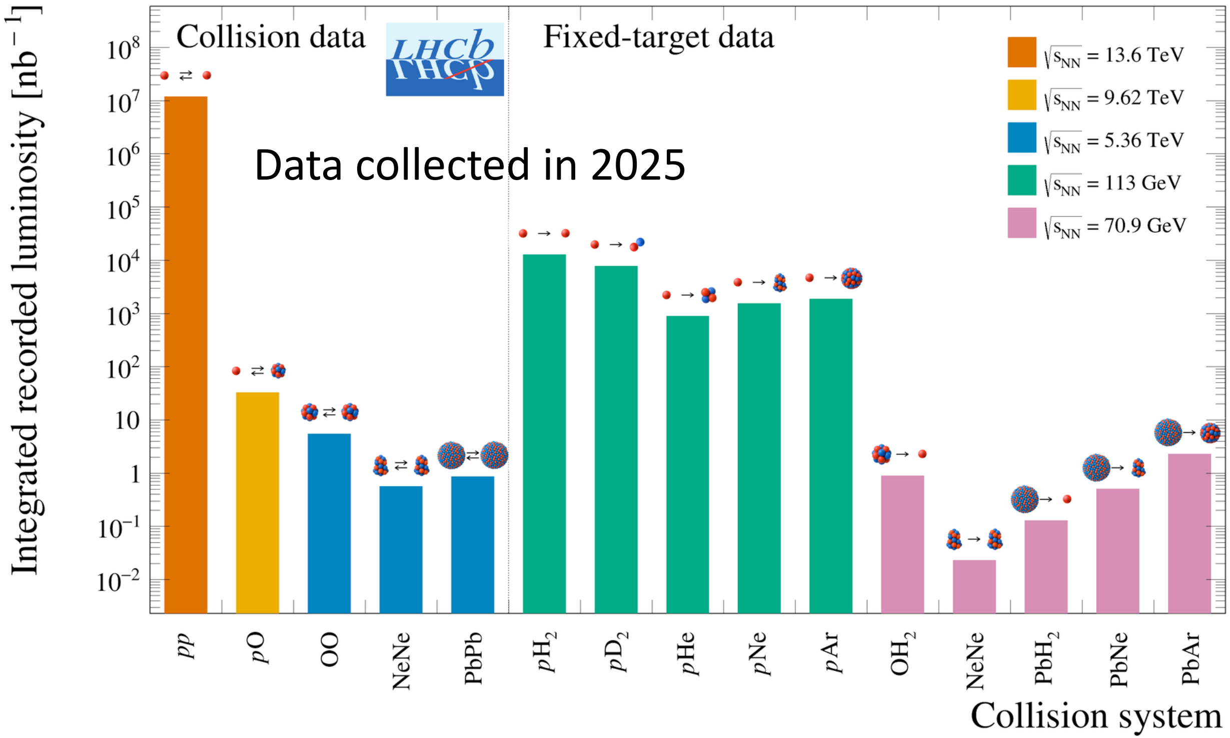
- Exotic hadrons at the Large Hadron Collider
  - A new understanding of the allowed configurations of quarks inside hadrons

- X(3872) production in *pp, p*Pb collisions
  - Comparison with conventional hadrons

- New environments for studying exotic hadrons:
  - First measurement of photoproduction of heavy exotic hadrons
  - First measurement of exotic hadrons in jets

- Outlook: many new nuclear systems to explore

Outlook: a treasure trove of data



- Many large datasets recently recorded by LHCb
- The most versatile heavy ion experiment ever fielded
- More collision systems than LHCb groups working on heavy ions

Many more results in progress

Summary

- Exotic hadrons are now measurable in heavy ion collisions
  - X(3872) studied in pp, pA, AA, and in jets
  - Photoproduction of heavy exotics now accessible

- Measurements providing new insight into fundamentally allowed bound states of quarks, and give new constraints on quark transport and hadronization

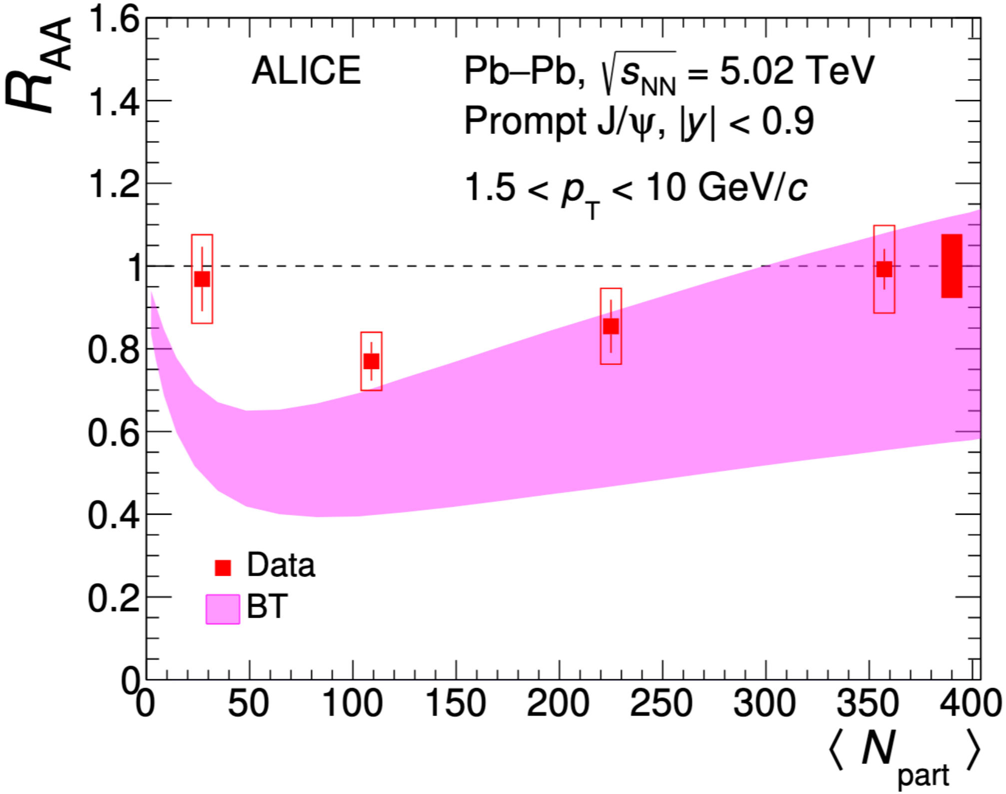
- Huge amounts of data are available for new studies, with more to come

Los Alamos National Laboratory is supported by the

US Dept. of Energy/Office of Science/Nuclear Physics

and DOE Early Career Awards

BACKUPS

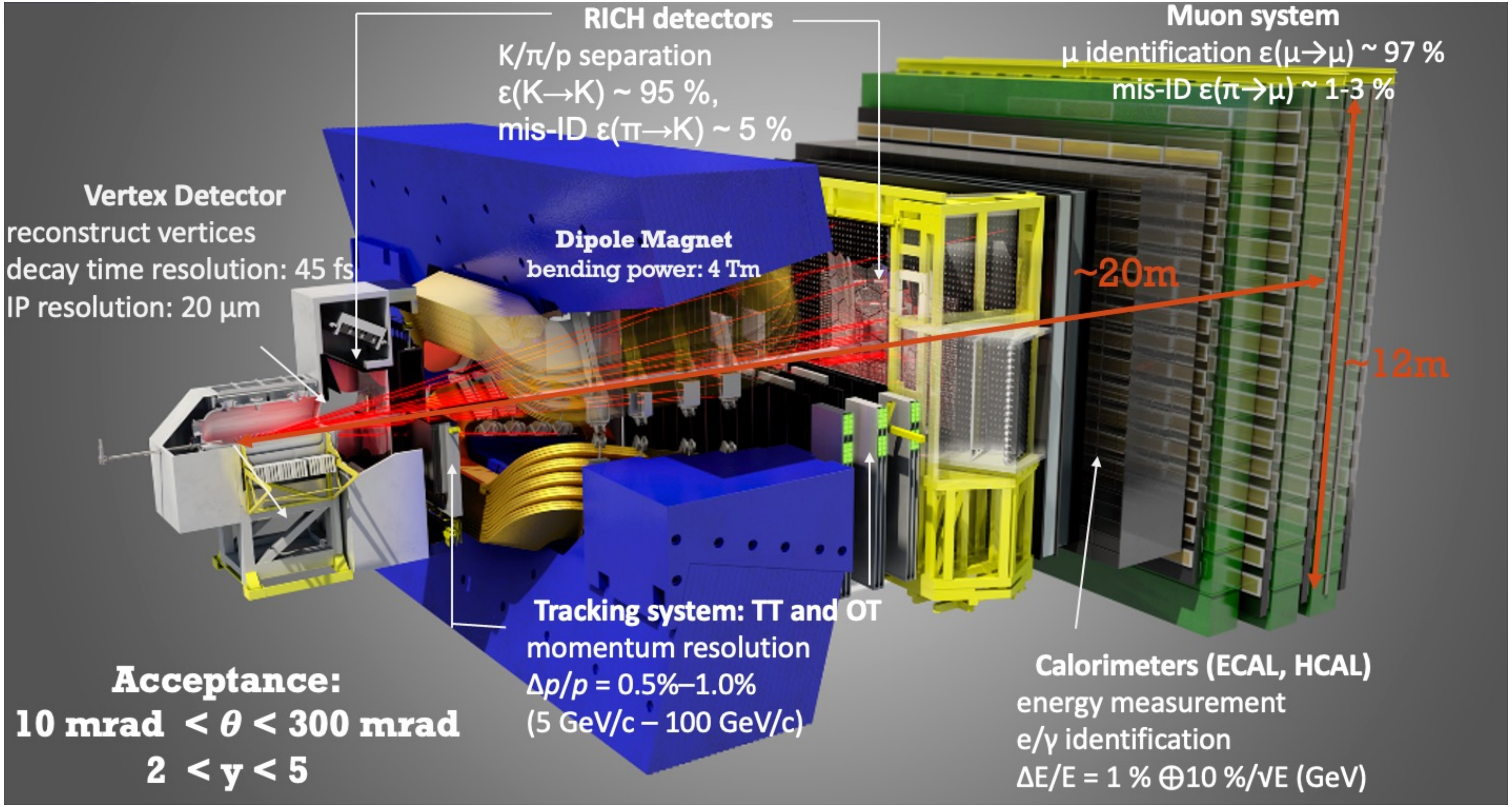


JHEP02(2024)066

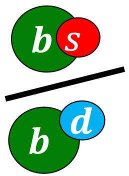
The LHCb detector

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

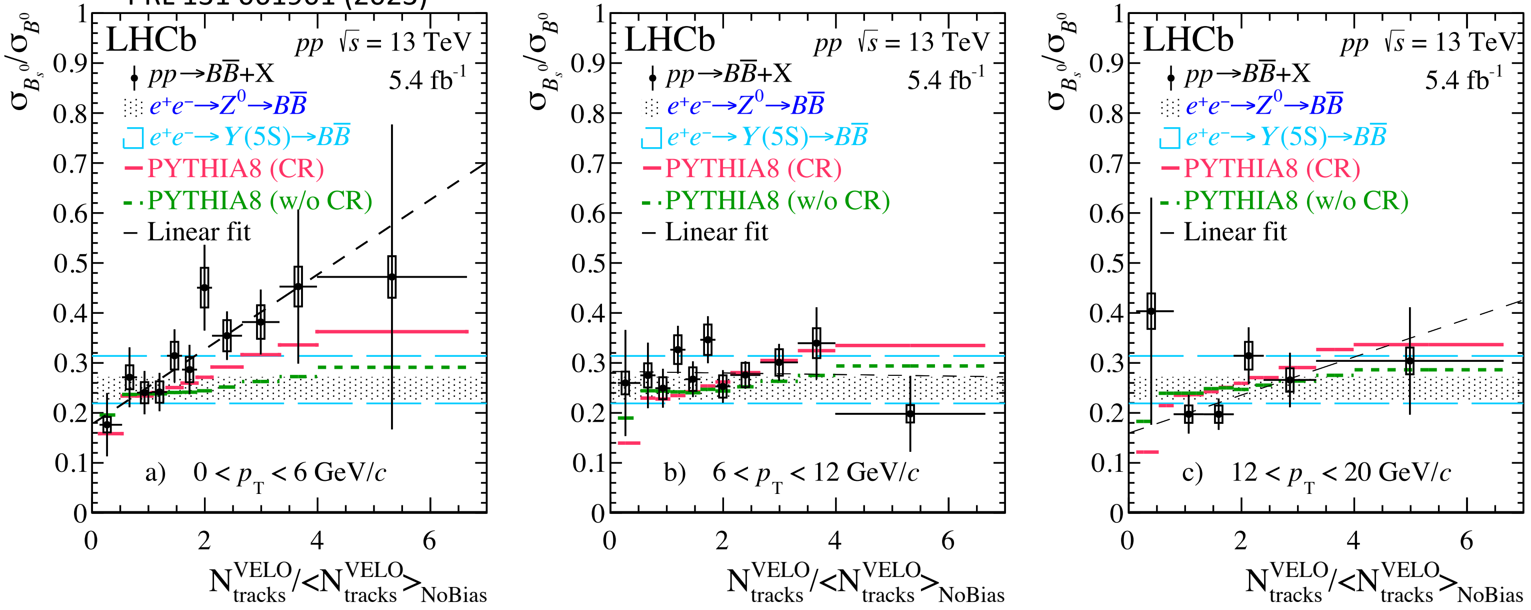
Unique forward rapidity coverage at the Large Hadron Collider in p+p, p+A, A+A, fixed target collisions



Modification of *b* hadronization – PYTHIA8

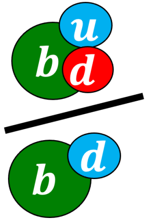


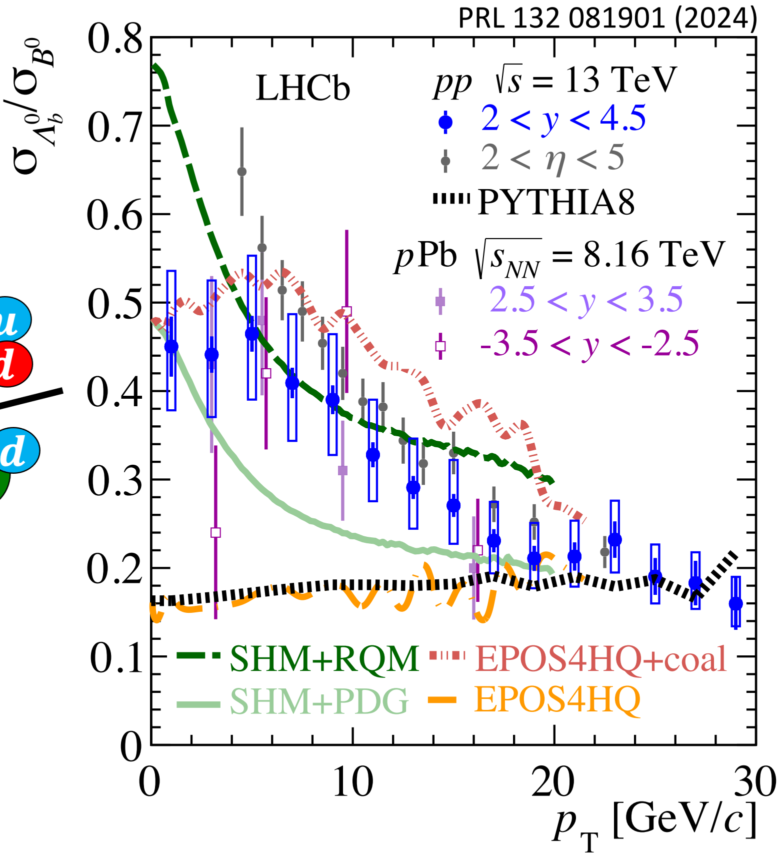
PRL 131 061901 (2023)



- 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





Baryon/meson ratio shows significant p_T dependence

Consistent with previous results (semileptonic decays)

Consistent with pPb results, within large uncertainties

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

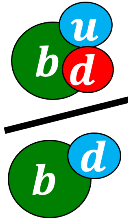
- Known baryon states from PDG
- Expanded set of baryons predicted by the Relativistic Quark Model

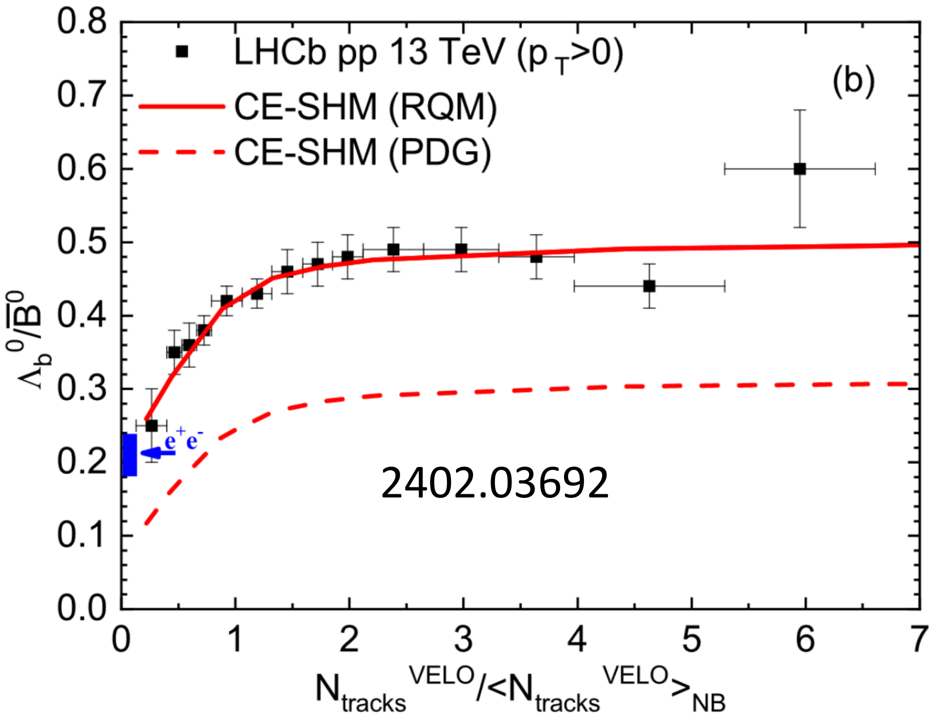
PYTHIA8 fails to reproduce p_T dependence

EPOS4HQ with only fragmentation also fails

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

Modification of *b* hadronization – B baryons



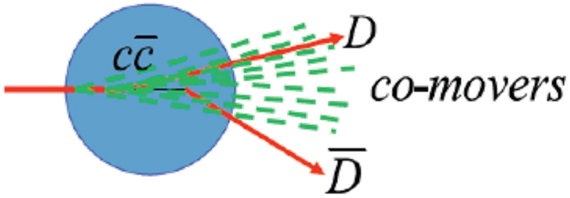


- Baryon/meson ratio shows significant multiplicity dependence
- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Reproduce e^+e^- result as multiplicity approaches zero

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

Quarkonia in the QCD medium

- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
  - Ratios of $\psi(2S)/_{J/\psi}$ and $\Upsilon(2S,3S)/_{\Upsilon(1S)}$



cf. PLB 749 98 (2015)

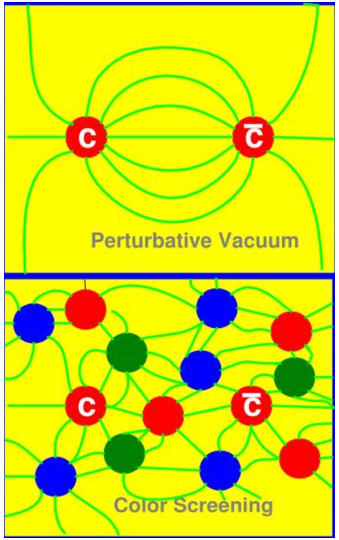
- In general, final state effects are required to explain difference in suppression between states
- Prevalent in regions with high particle multiplicity

- Weakly bound hadronic molecules may show similar effects.

$D\bar{D}^*$ Molecule

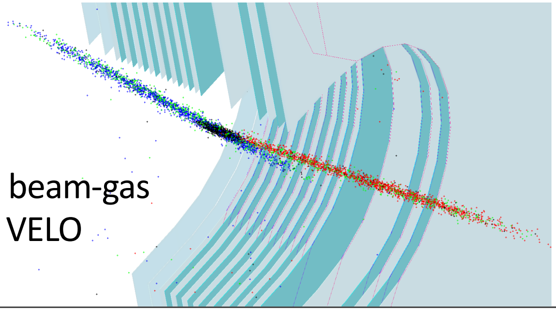
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027

Satz, J. Phys. G 32 (3) 2006

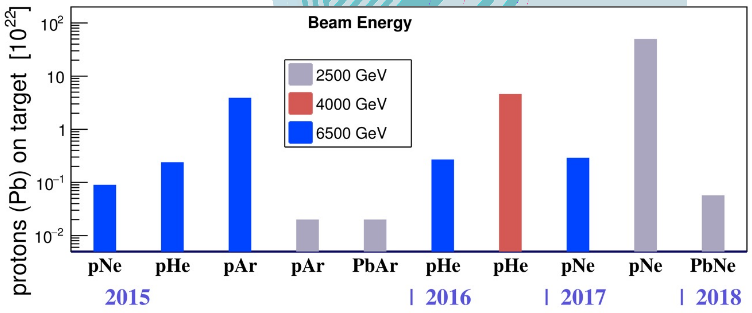


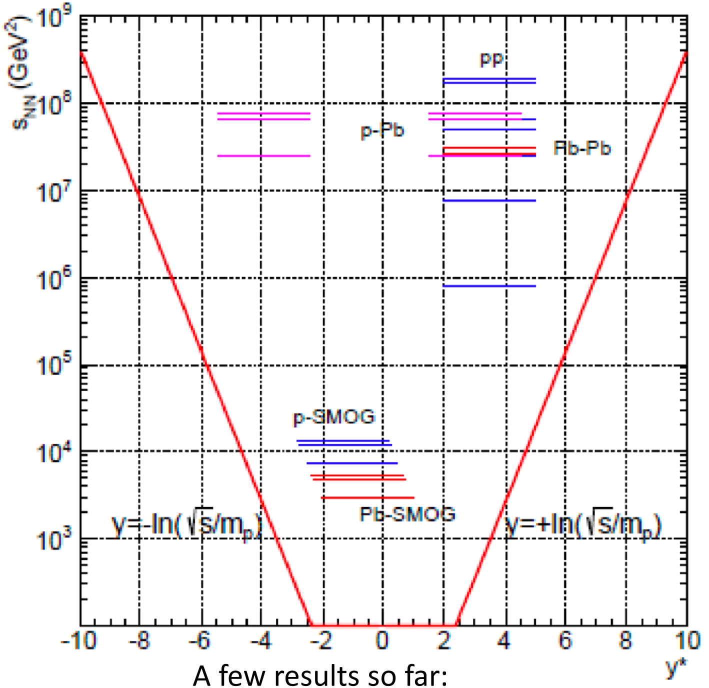
Fixed target configuration - SMOG

System for **M**easurement of **O**verlap with **G**as
A unique capability at LHCb: inject noble gas into beampipe
Originally intended for precise luminosity measurements:
JINST **9** P12005 (2014)



Reconstructed beam-gas vertices inside VELO

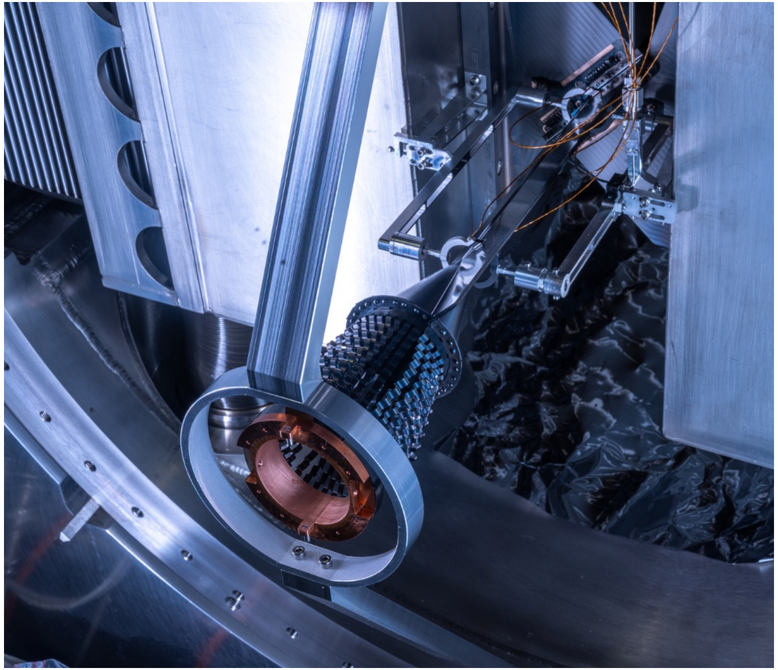


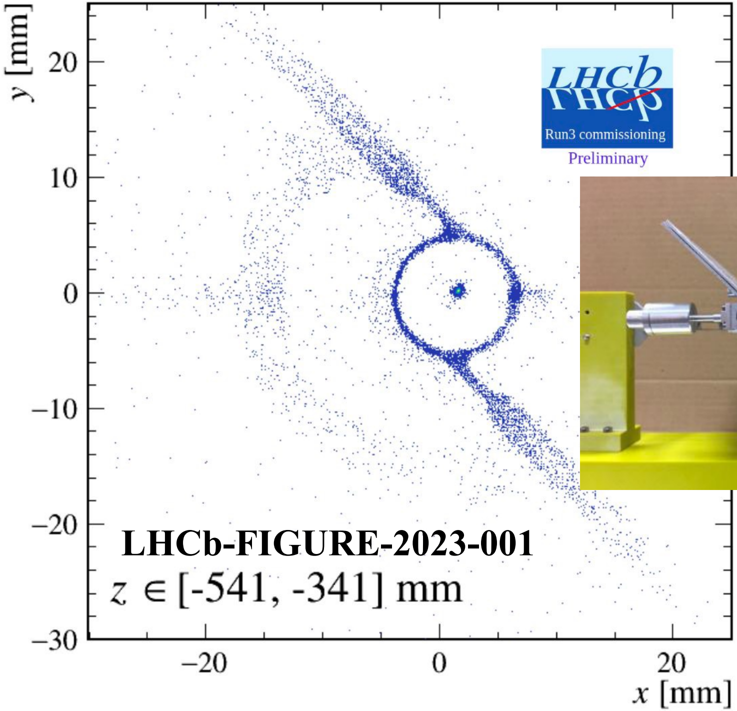


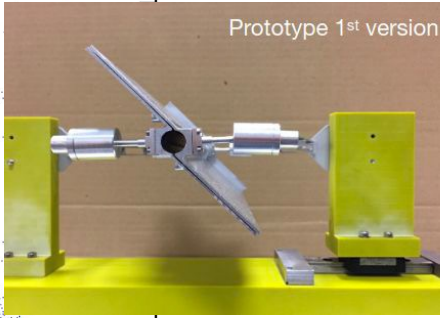
A few results so far:
D^0, J/ψ in PbNe: EPJC 83 658 (2023)
D^0, $J/\psi, \psi(2S)$ in pNe: EPJC 83 625, 541 (2023)
D^0, J/ψ in pHe, pAr: PRL 122 132002 (2019)
Antiproton production in pHe: PRL 121 222001 (2018)
Hyperons in pHe: EPJC 83 543 (2023)

Dedicated gas storage cell – SMOG2

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







LHCb Upgrade II (Run 5+)

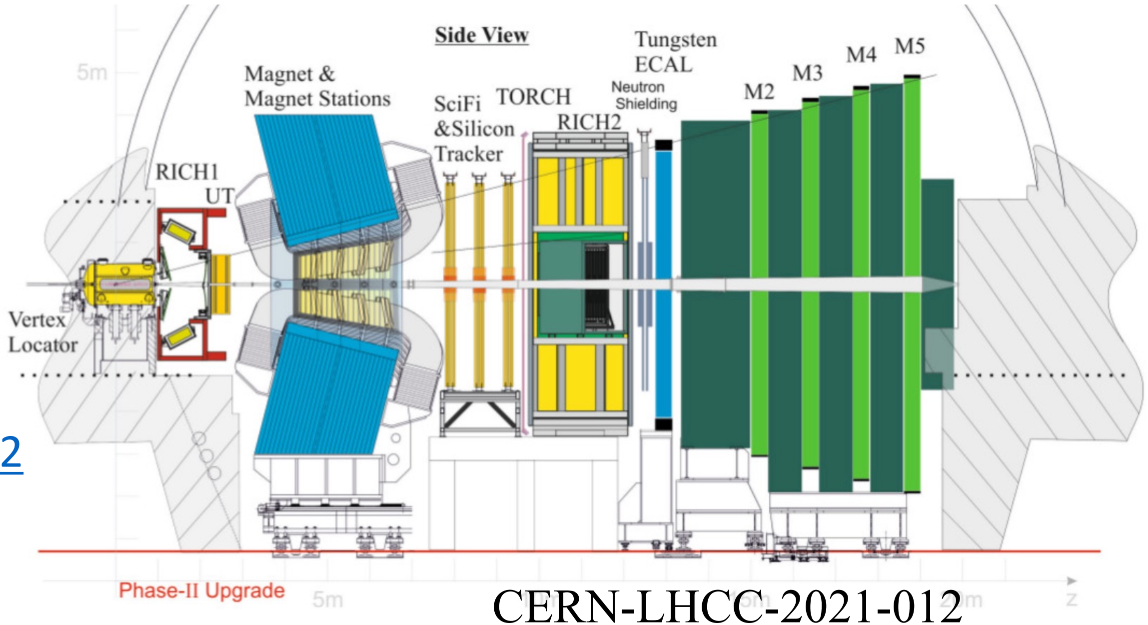
Further upgraded tracking to deal with high *pp* pileup and heavy ion collisions

- Access the full PbPb centrality range
- Precise measurements of B hadrons, exotic states, and more at low p_T in central collisions
- R&D well underway

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

LHCspin

arXiv:1901.08002



CERN-LHCC-2021-012

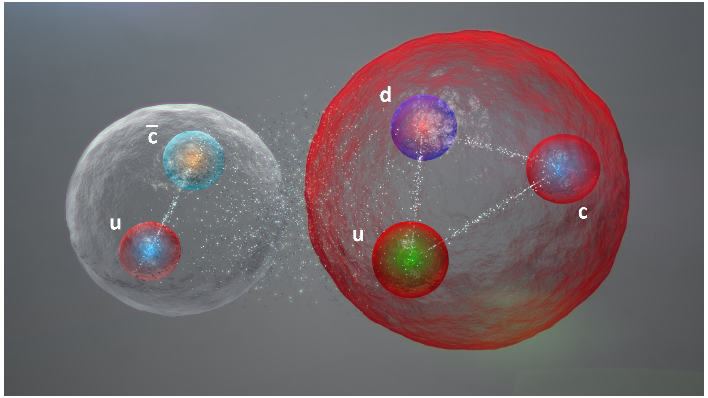
Example: $P_c^{\pm}$ pentaquarks

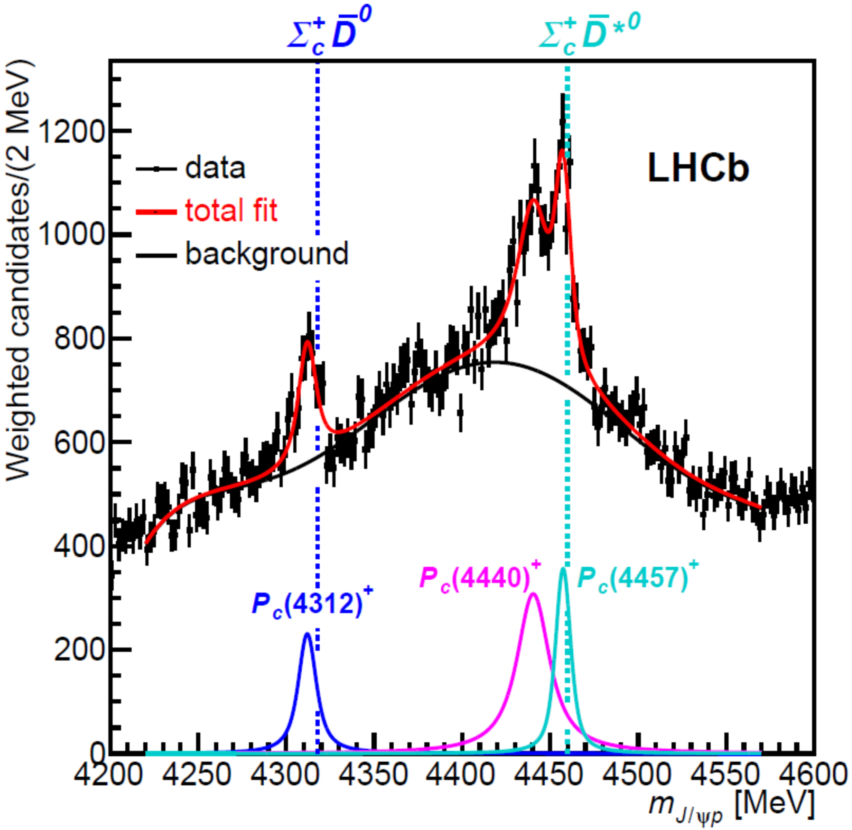
PRL 122 222001 (2019)

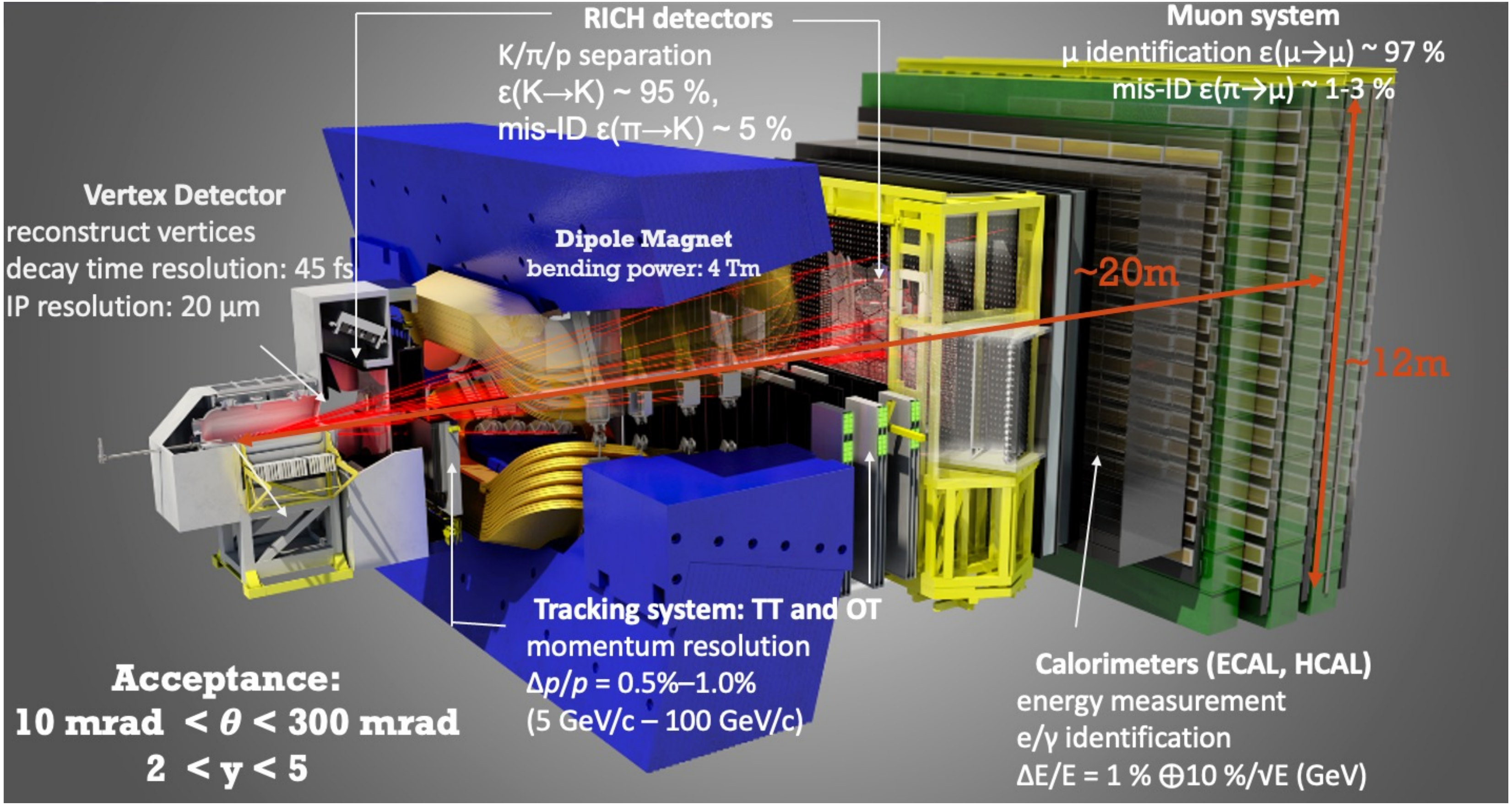
Select daughters from the decay

$$\Lambda_b^0 \rightarrow J/\psi\, p K^-$$

Masses are close to meson+baryon thresholds – candidate hadronic molecule






RICH detectors
K/π/p separation
ε(K→K) ~ 95 %,
mis-ID ε(π→K) ~ 5 %
Muon system
μ identification ε(μ→μ) ~ 97 %
mis-ID ε(π→μ) ~ 1-3 %
Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm
Dipole Magnet
bending power: 4 Tm
~20m
~12m
Tracking system: TT and OT
momentum resolution
Δp/p = 0.5%–1.0%
(5 GeV/c – 100 GeV/c)
Calorimeters (ECAL, HCAL)
energy measurement
e/γ identification
ΔE/E = 1 % ⊕10 %/√E (GeV)
Acceptance:
10 mrad < θ < 300 mrad
2 < y < 5

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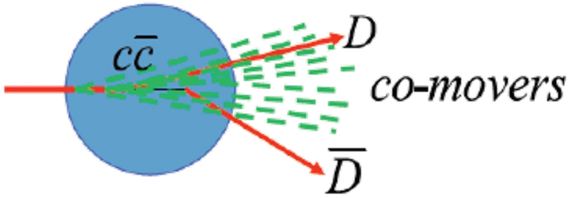
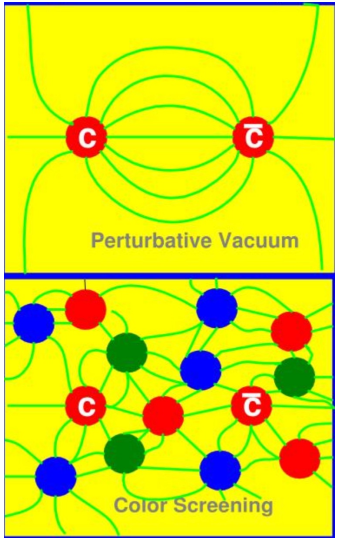


cf. PLB 749 98 (2015)



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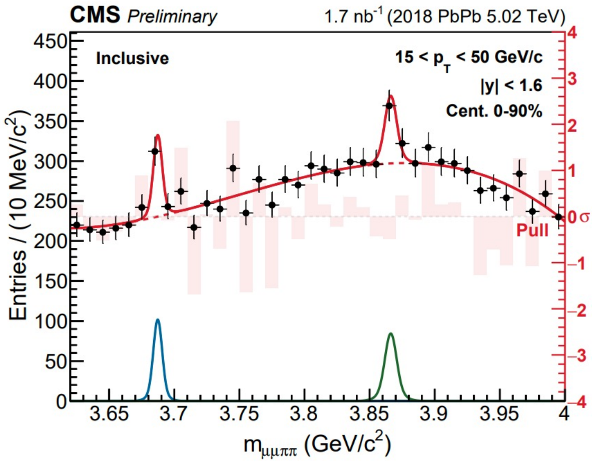
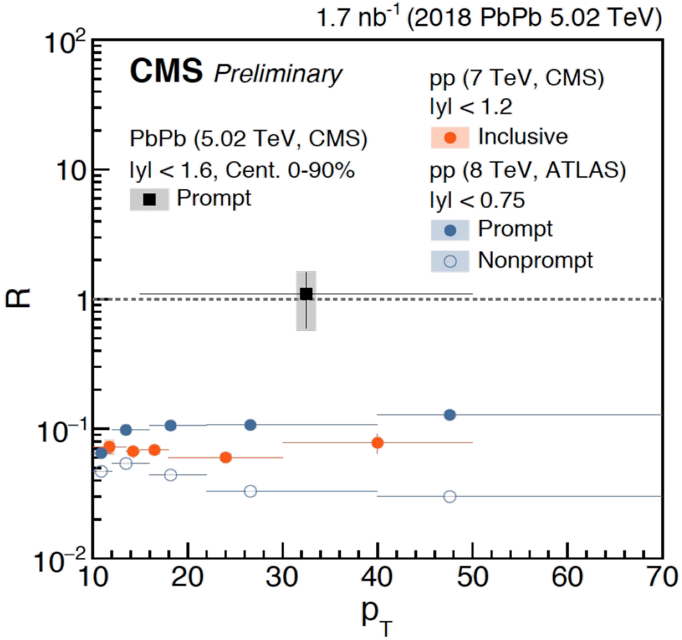
Satz, J. Phys. G 32 (3) 2006

Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005





Recombination of X(3872) at pT > 15 GeV?

Prompt X(3872)/ ψ(2S) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV

Prompt X(3872)/ ψ(2S) ≈ 0.1 in pp at 8 TeV