Los Alamos NATIONAL LABORATORY

LHCb

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

Matt Durham
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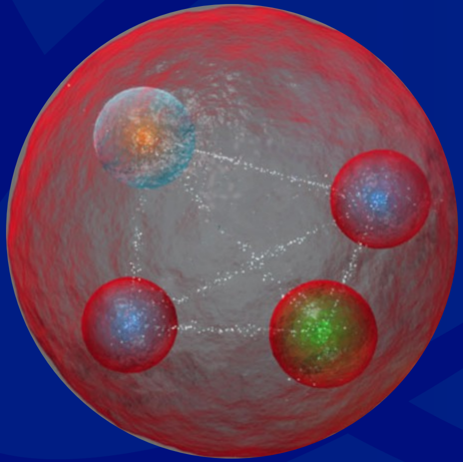
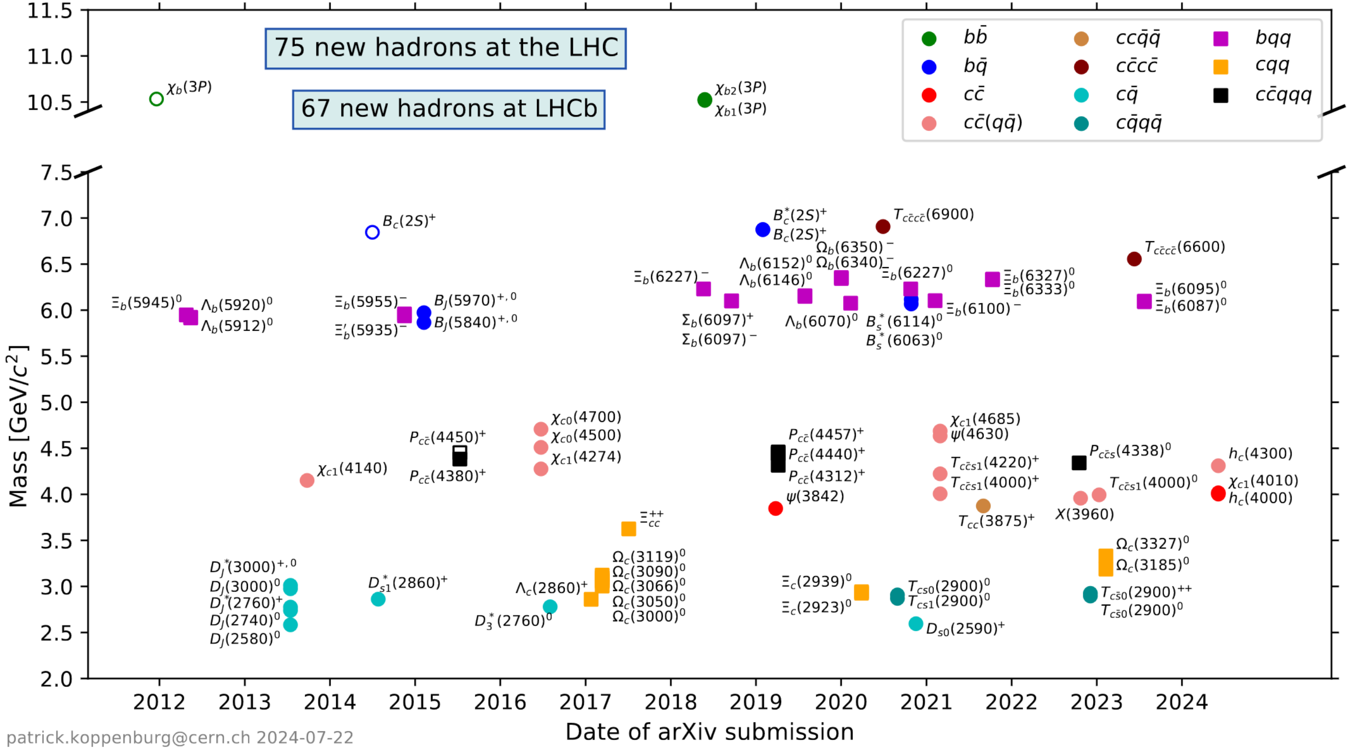
HP2024 NAGASAKI

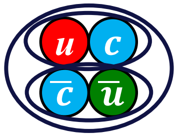
12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions



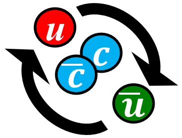
New hadrons discovered at the LHC



Compact tetraquark/pentaquark

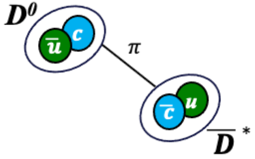


Diquark-diantiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



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

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

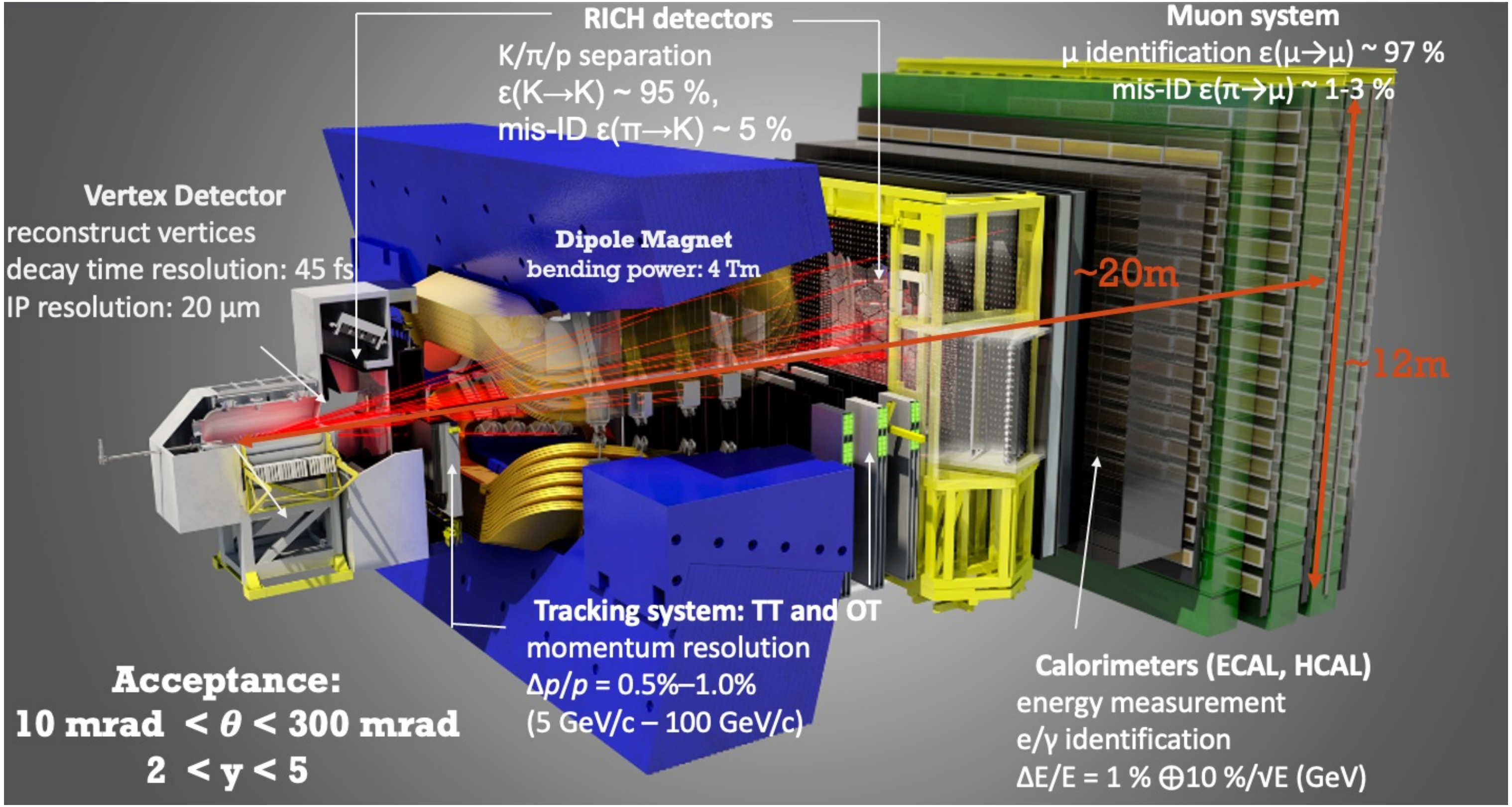
PLB 578 365 (2004)
PRD 96 074014 (2017)

~90% of the new particles were discovered by LHCb

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



Production of exotic hadrons

- Most common method of discovery: *b* hadron decays

- Photon induced interactions on protons/nuclei
  - Accessible via Central Exclusive Production (*pp*) and Ultra-Peripheral Collisions (PbPb)
  - First measurement of exotic hadrons in CEP: arXiv:2407.14301

- Prompt production in *pp*
  - First measurement of exotic hadrons in jets: LHCb-PAPER-2024-021

- Prompt production in heavy ion collisions
  - Exotic subject to effects of cold nuclear matter/QGP
  - First measurement of exotic hadron nuclear modification factor R_{pA}: PRL 132 242301 (2024)

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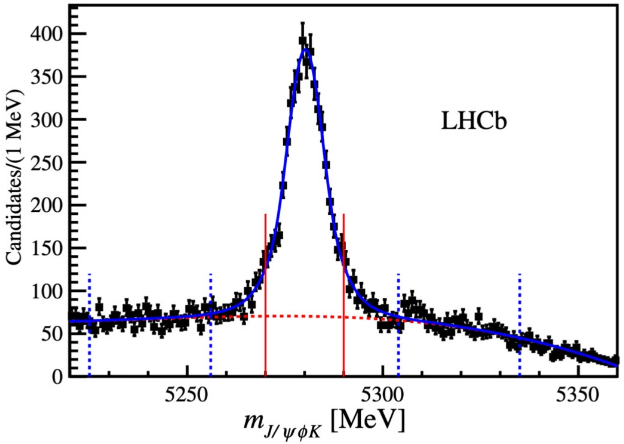
b hadron decays

- Reconstruct the decay $B^+ \to J/\psi\phi K^+$



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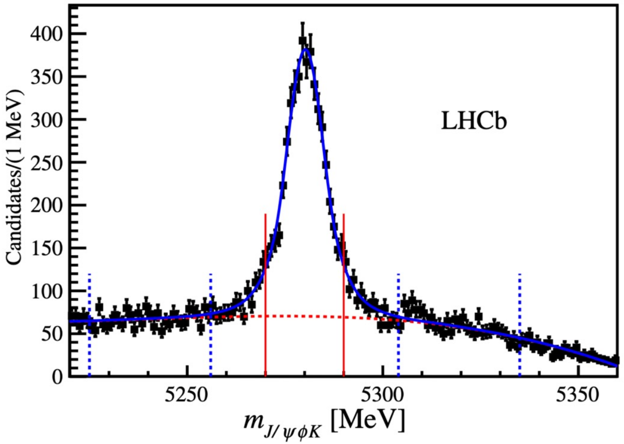
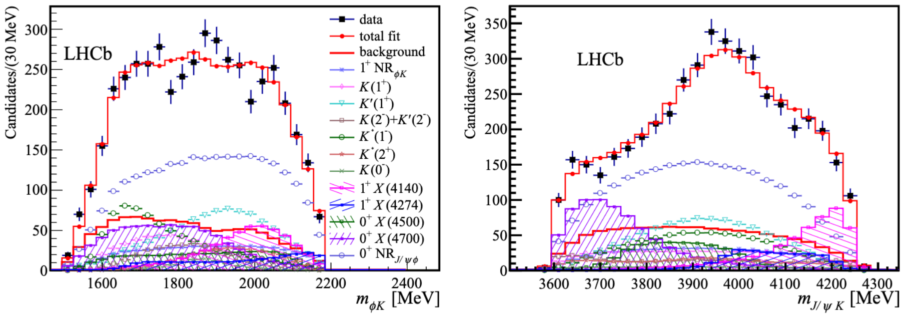
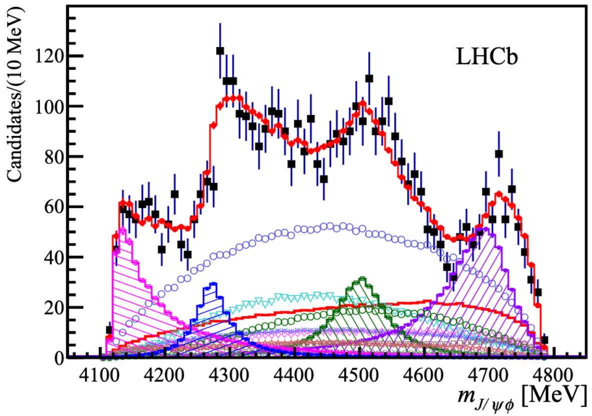


- Inspect combinations of daughter products for intermediate states

PRL 118, 022003 (2017), PRD 95 012002 (2017), PRL 127, 082001 (2021)





b hadron decays

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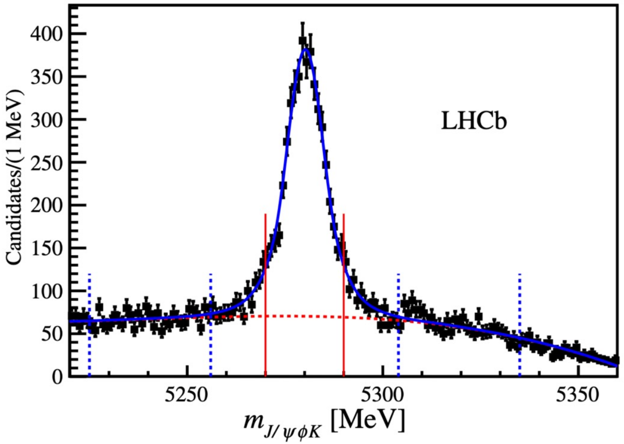
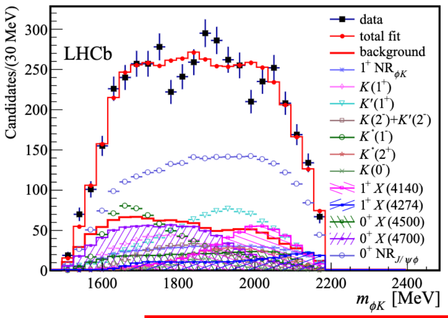
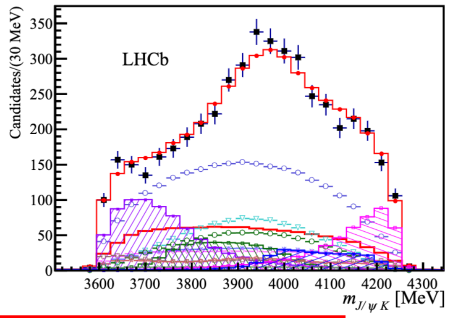


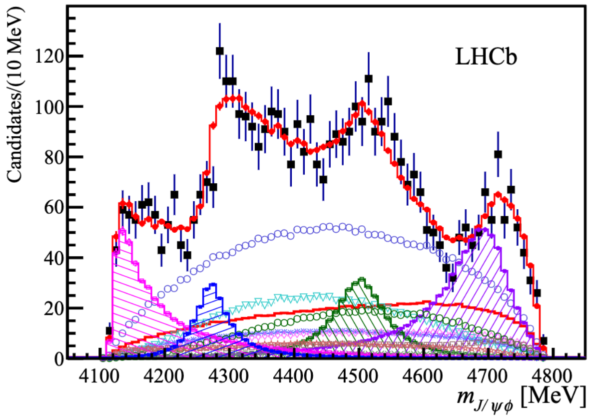
- Inspect combinations of daughter products for intermediate states

- Amplitude analysis requires four new $J/\psi\phi$ resonances to describe data.

[PRL 118, 022003 (2017)](), [PRD 95 012002 (2017)](), [PRL 127, 082001 (2021)]()

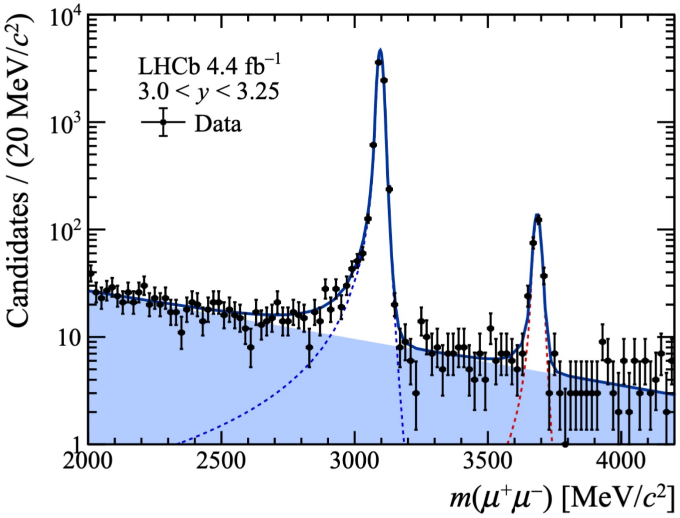


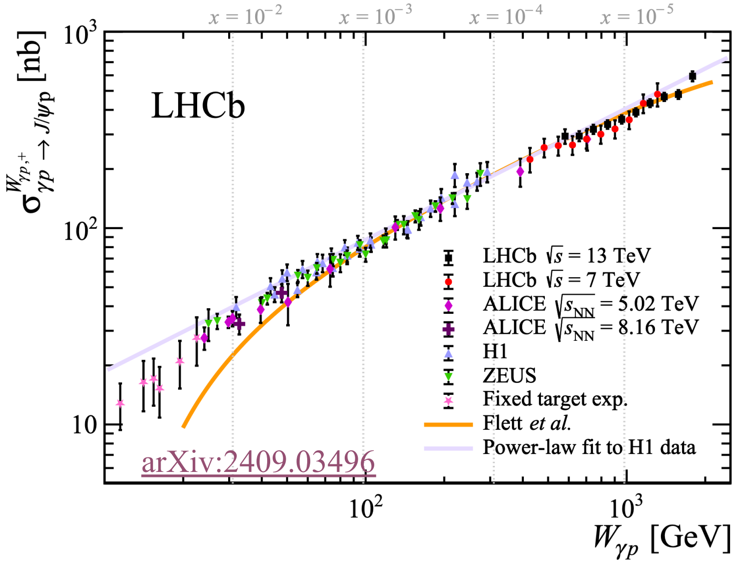


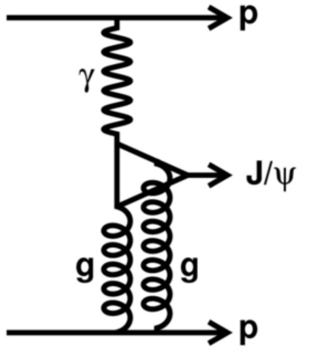


Central Exclusive Production/Ultra-Peripheral Collisions

Conventional charmonia states $J/\psi, \psi(2S)$ have been studied extensively in CEP/UPC







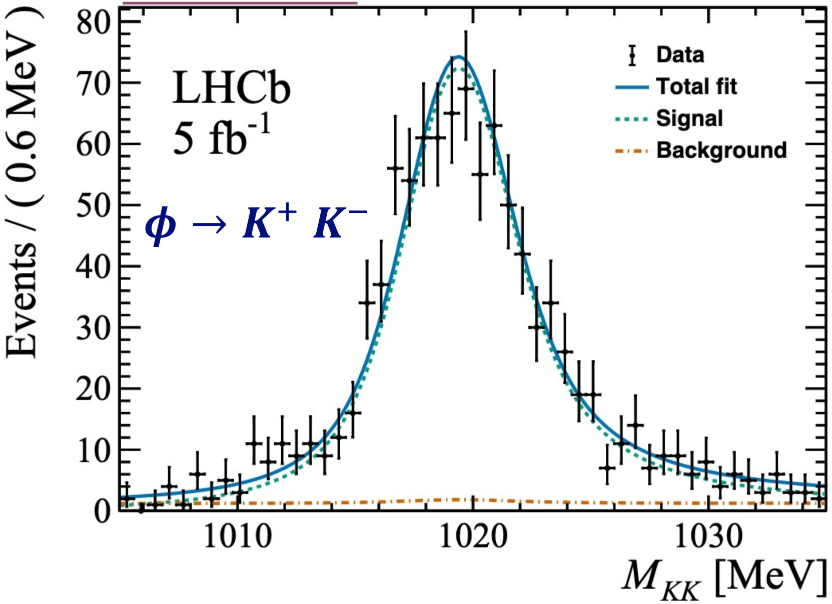
Amanda Donohoe, Wednesday 9:20

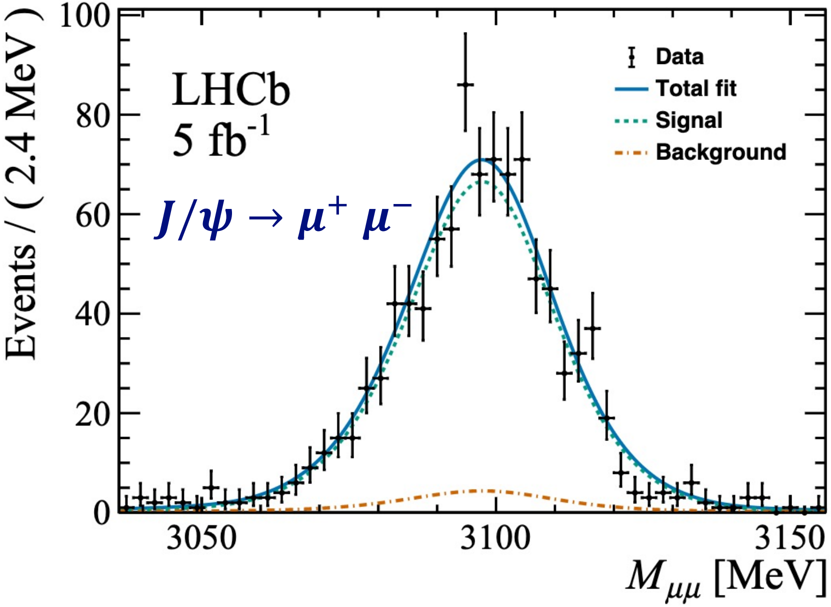
- There is HUGE interest in the production of exotic hadrons in these events:

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 $J/\psi\phi$

arXiv:2407.14301





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

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

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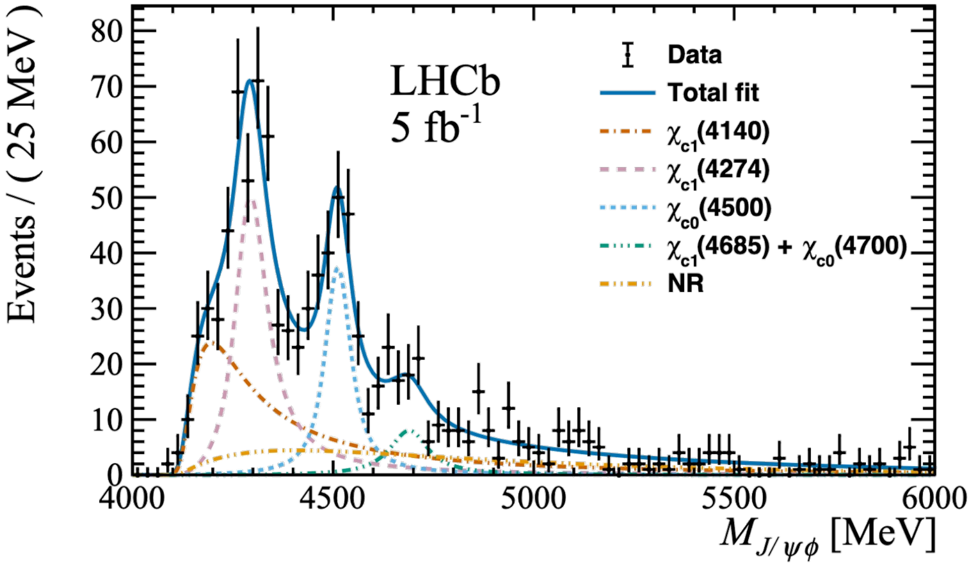

- Structures apparent in CEP data (exactly 4 tracks)

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

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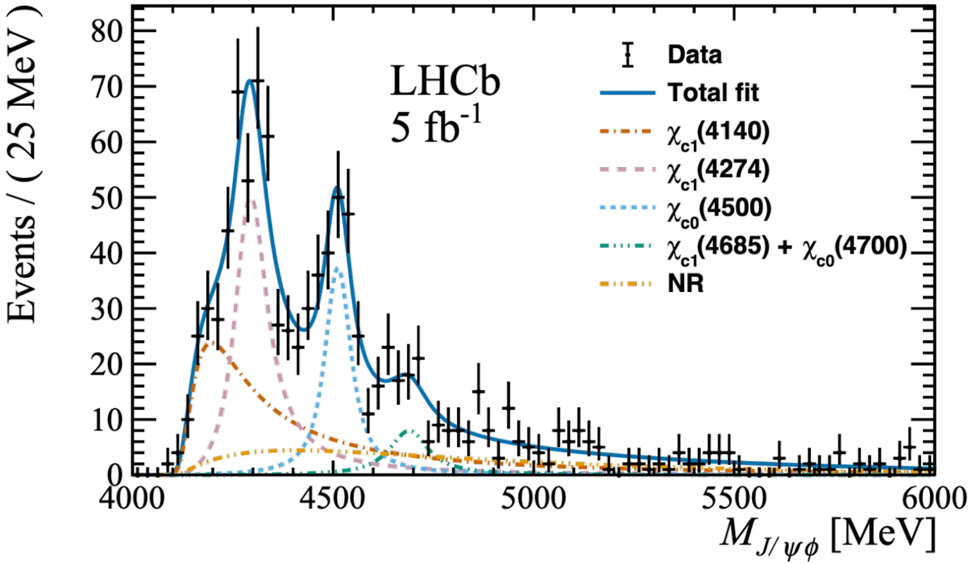
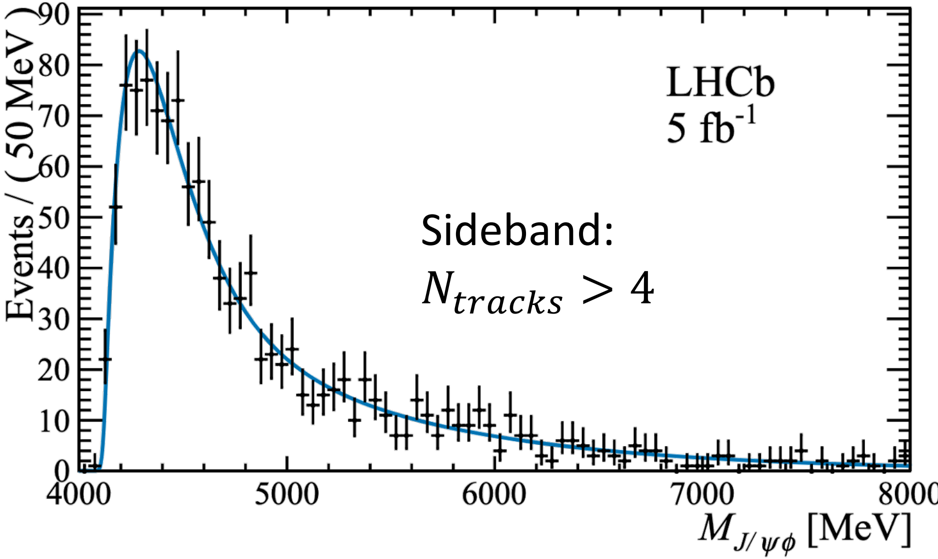
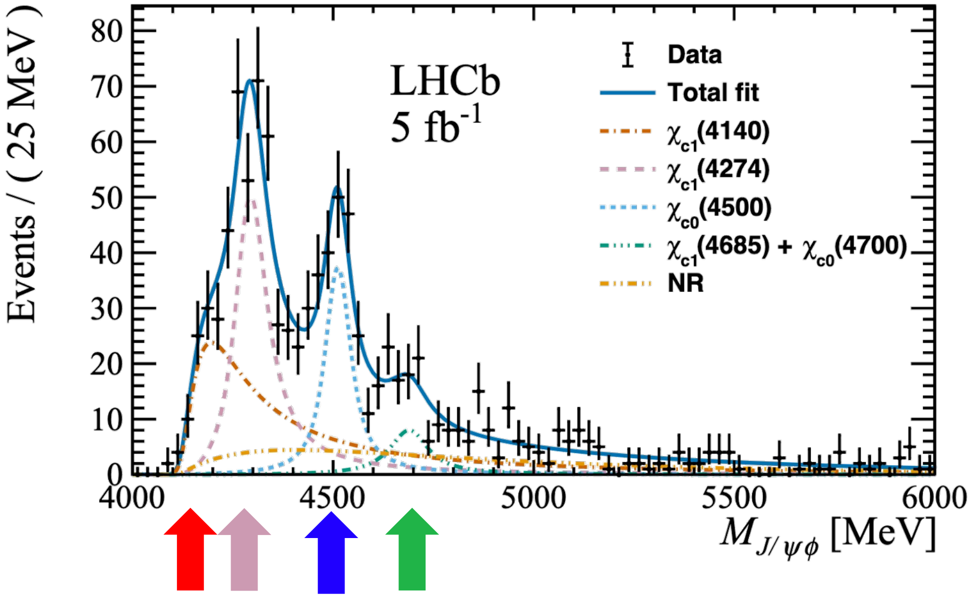




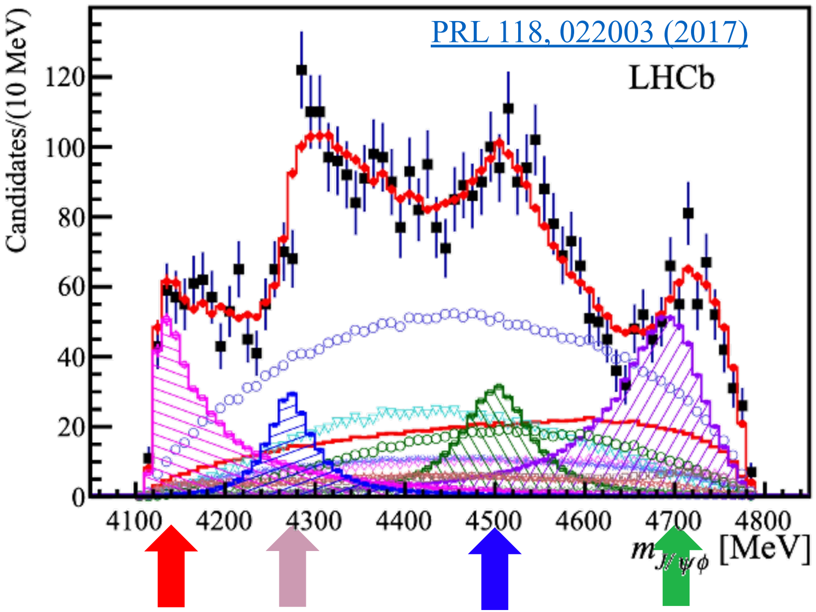
- Structures apparent in CEP data (exactly 4 tracks)
- Gone when looking at “sideband” of events with more activity

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

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- Prompt production in *pp*
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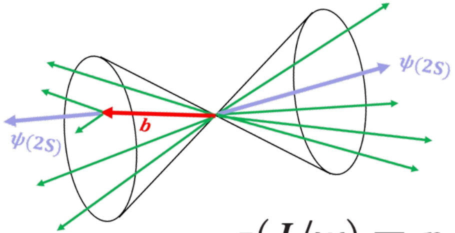
J/ψ in jets

- 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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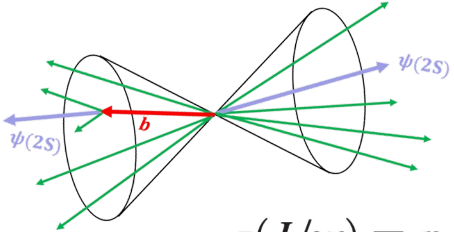

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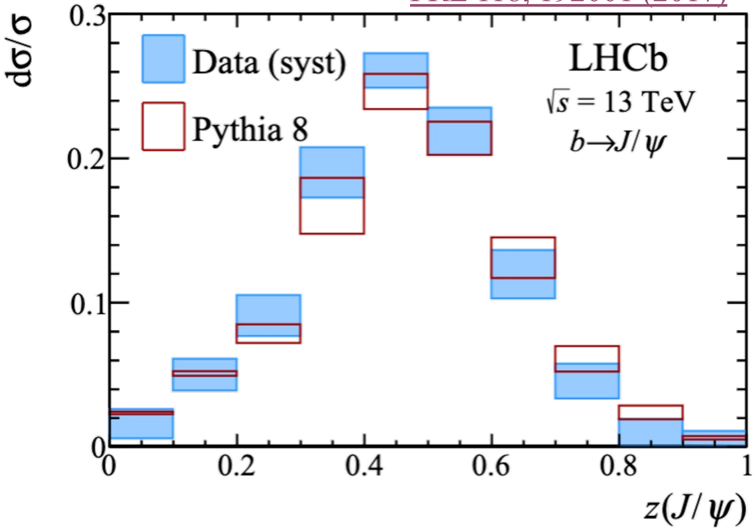
PRL 118, 192001 (2017)



Non-prompt: well described by PYTHIA

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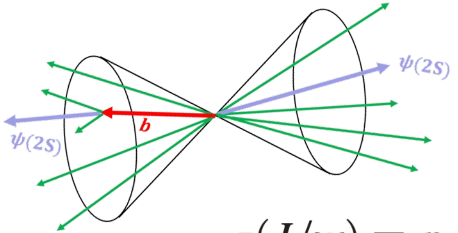

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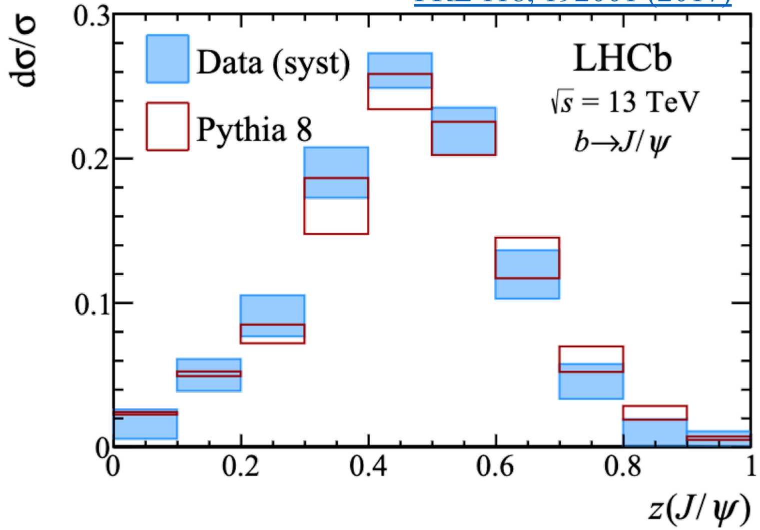

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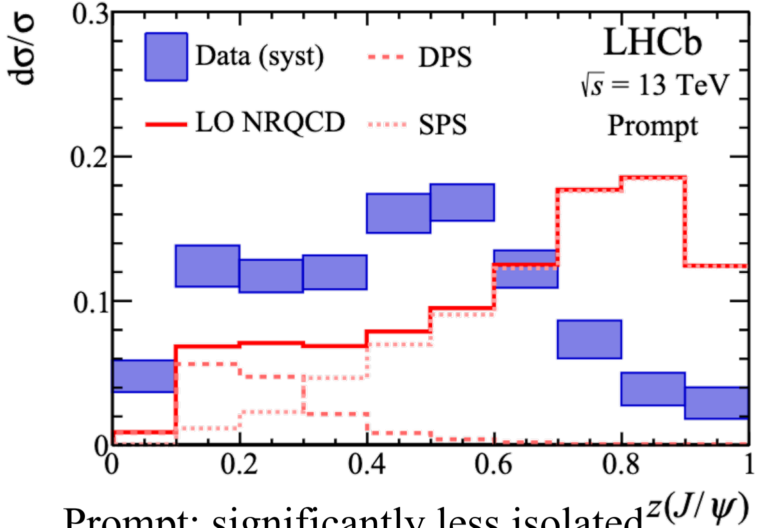
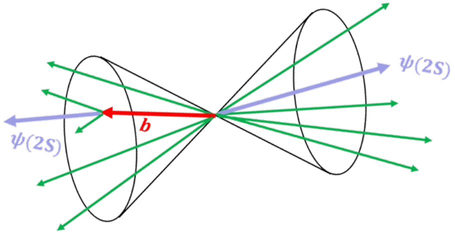
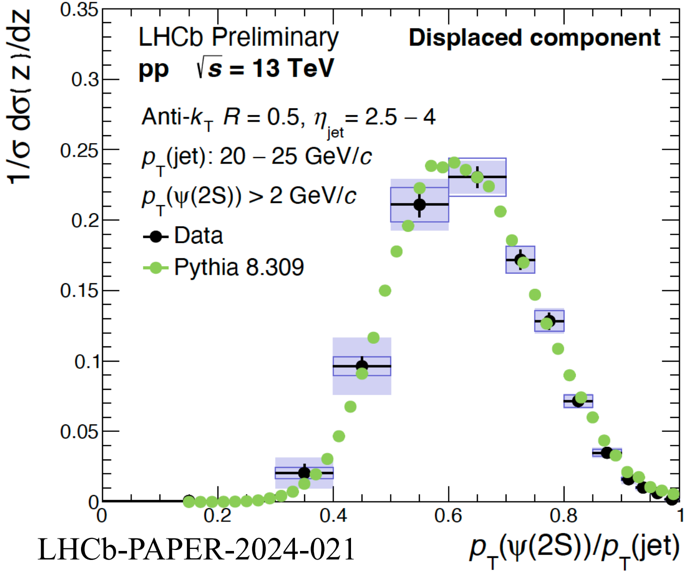


Prompt: significantly less isolated than NRQCD prediction

ψ(2S) in jets



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

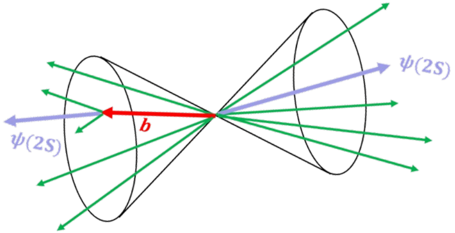


LHCb-PAPER-2024-021

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

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

$\psi(2S)$ in jets



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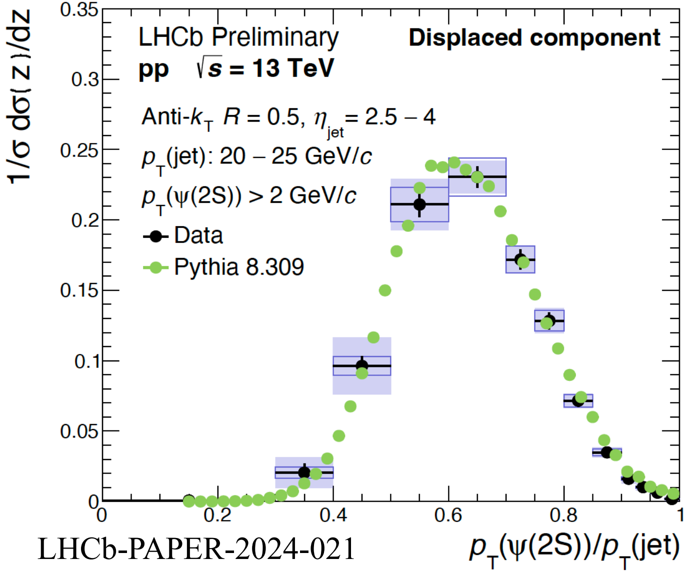
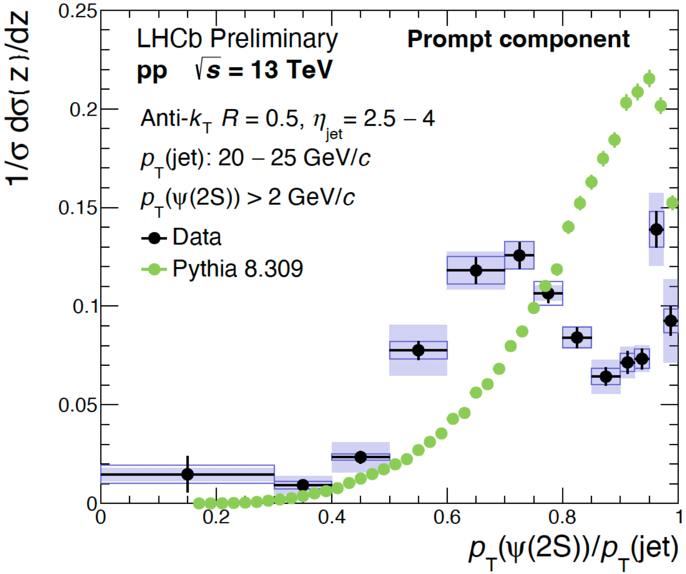


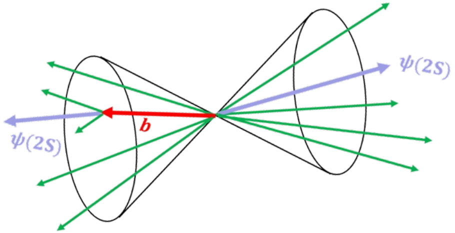
LHCb-PAPER-2024-021

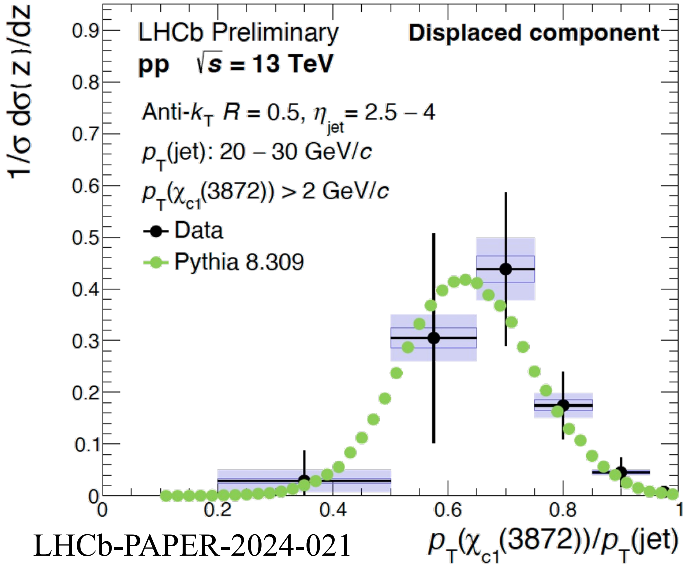


$\boldsymbol{b} \rightarrow \boldsymbol{\psi}(2S)$: well described by PYTHIA
Very similar to $\boldsymbol{b} \rightarrow \boldsymbol{J/\psi}$

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

$X(3872)$ in jets



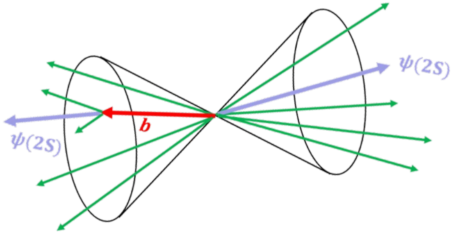


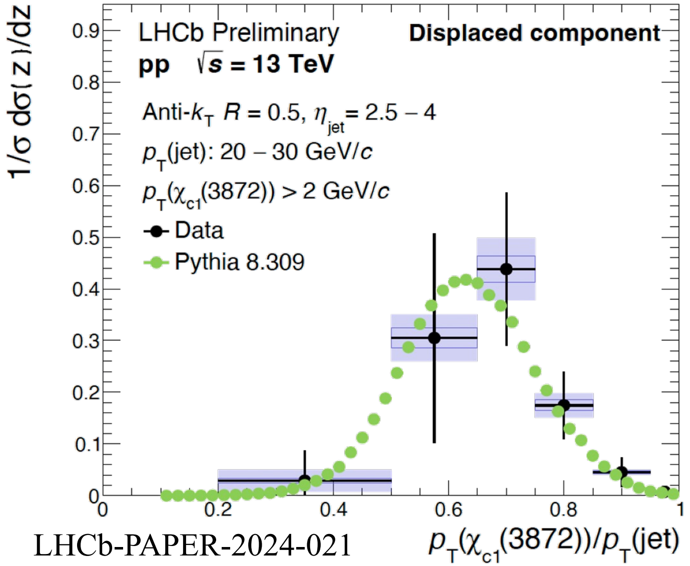
LHCb-PAPER-2024-021

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

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

$X(3872)$ in jets





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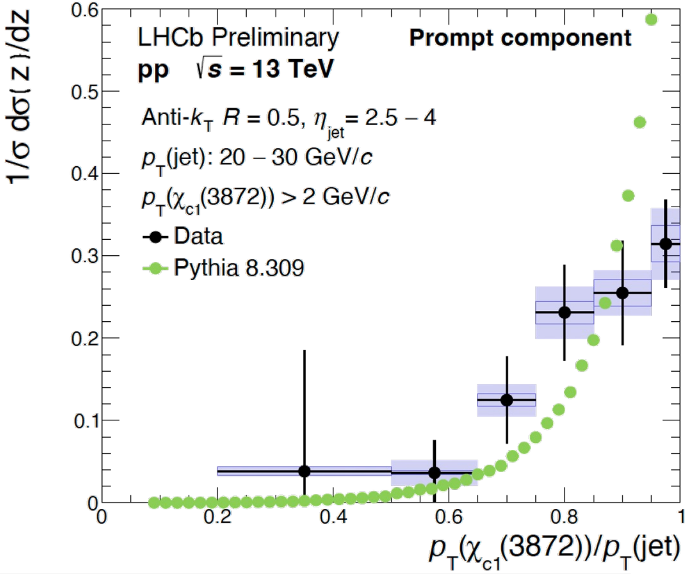
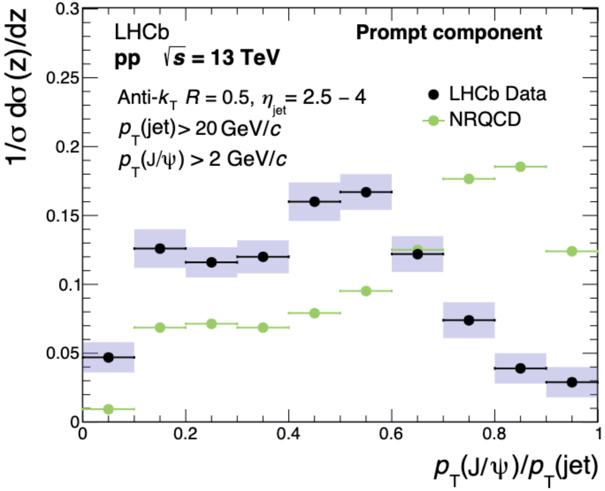


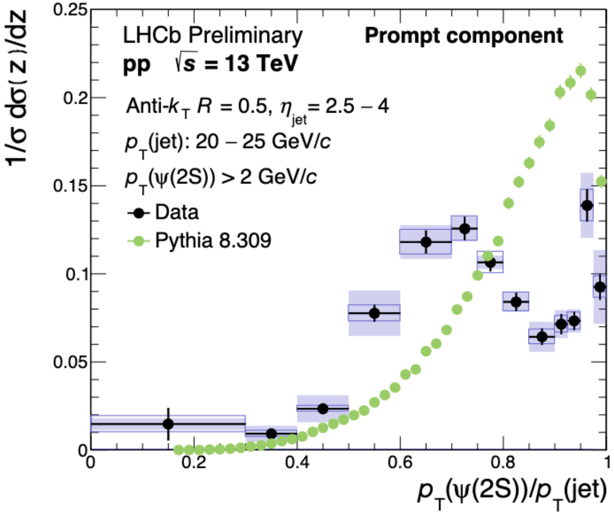
$\boldsymbol{b \rightarrow X(3872)}$: well described by PYTHIA
Very similar to $\boldsymbol{b \rightarrow J/\psi}$, $\boldsymbol{\psi}$(2S)

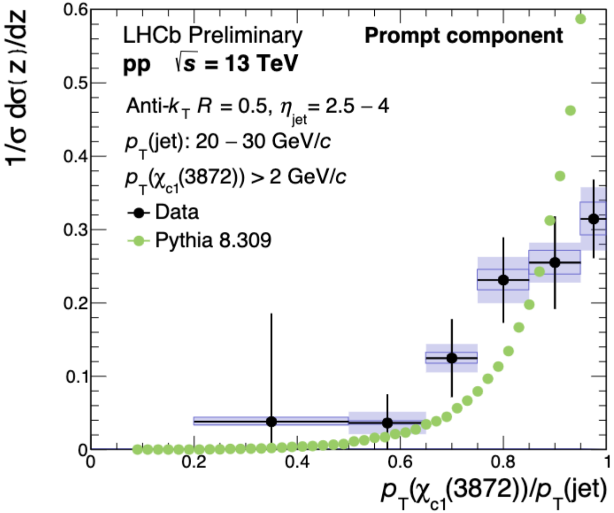
Prompt: Rises towards isolation, very different from conventional $c\bar{c}$ state $\boldsymbol{\psi}$(2S)

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

Ezra Lesser, Wednesday 11:30







Prompt J/ψ: less isolated than expected

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

Prompt X(3872):
More isolated than conventional charmonia

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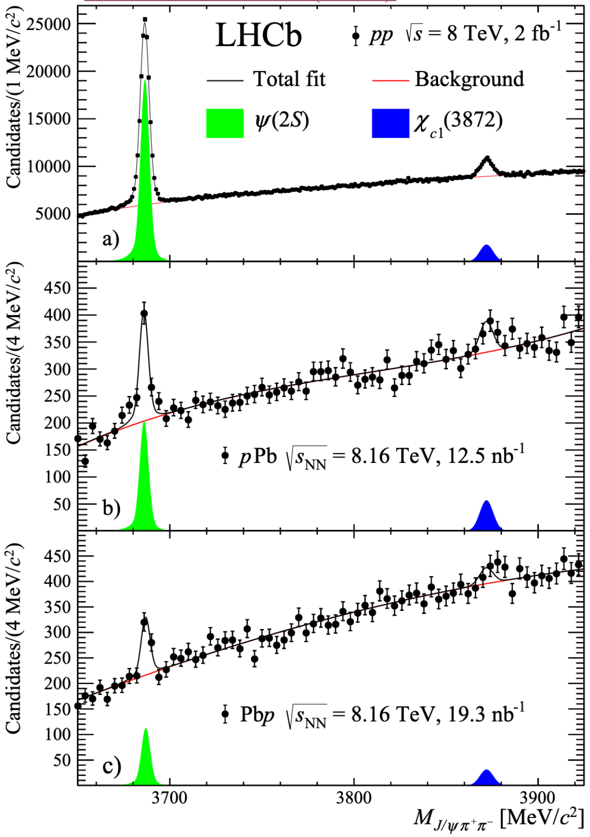
X(3872) in *p*Pb

PRL 132 242301 (2024)



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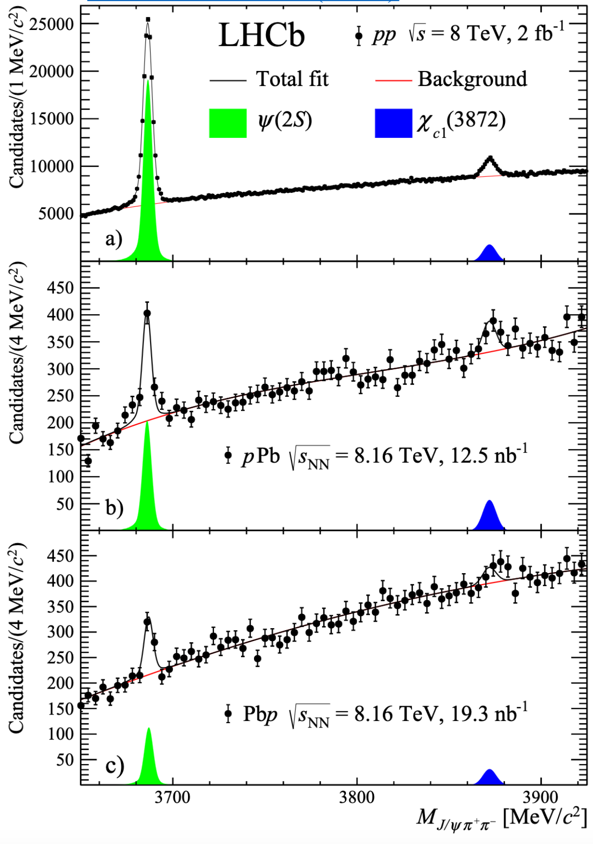
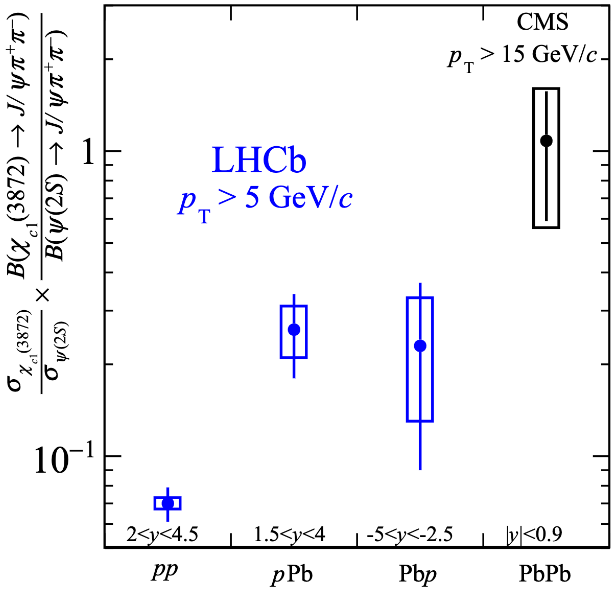
PRL 132 242301 (2024)



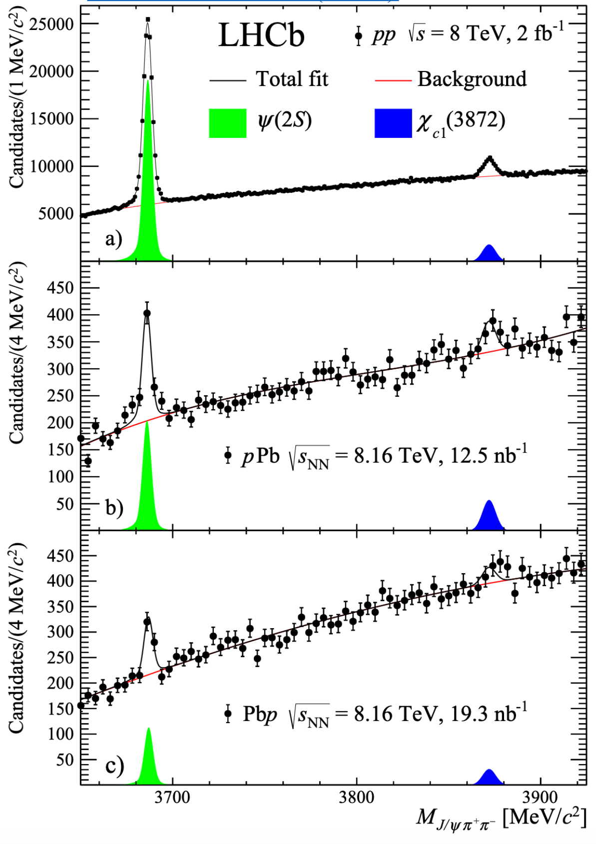


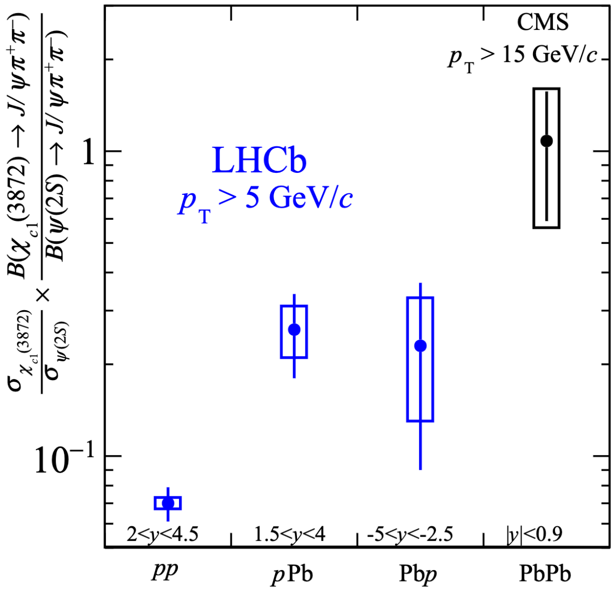
Comparison between X(3872) and $\psi(2S)$ suggests ***something different*** may be happening to exotic vs conventional hadrons in medium

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

X(3872) in pPb

PRL 132 242301 (2024)





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

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

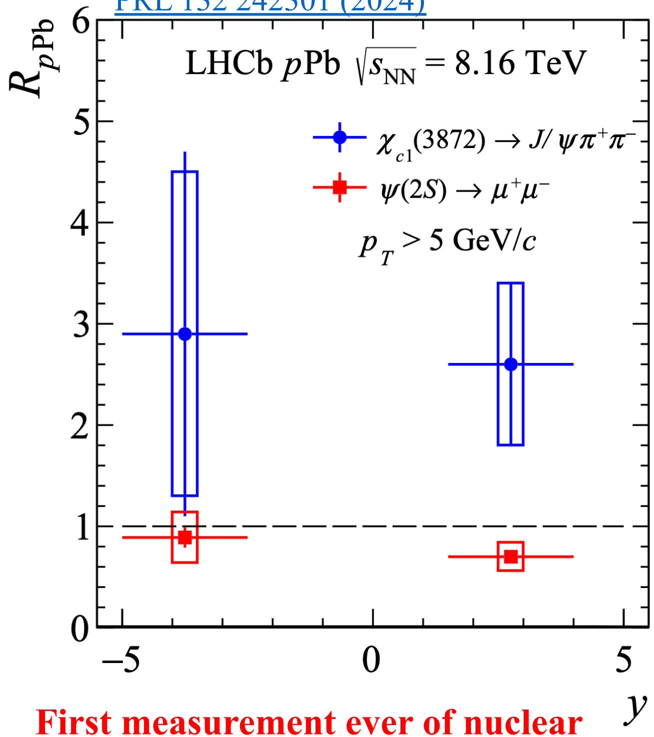
We know ψ(2S) is suppressed in pPb

Cesar da Silva, Tuesday 14:40

AMBIGUITY between X(3872) enhancement and ψ(2S) suppression

X(3872) in pPb

PRL 132 242301 (2024)



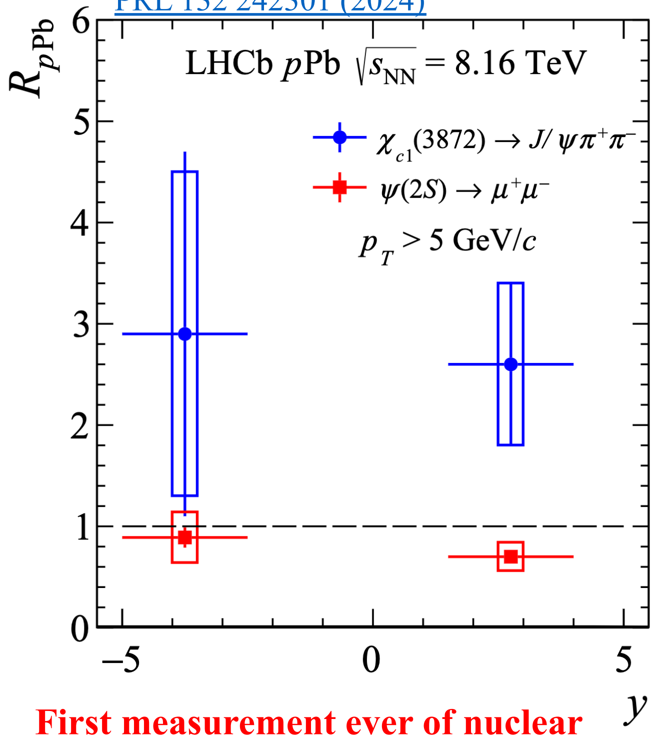
First measurement ever of nuclear modification factor of a tetraquark!

Ambiguity lifted by measuring nuclear modification factor:

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

X(3872) in pPb

[PRL 132 242301 (2024)](#)



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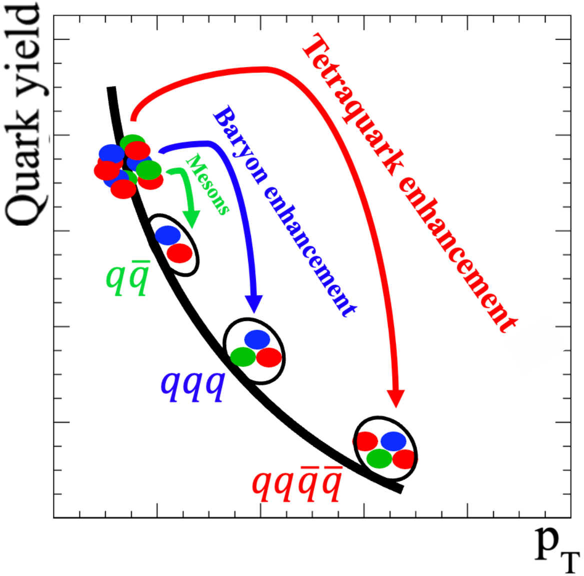
Evidence for enhancement of X(3872) in pPb: Coalescence dominating over breakup?

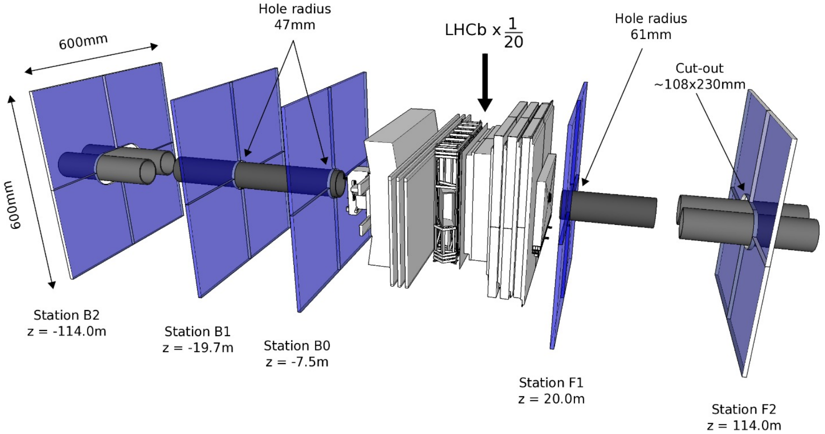
We know heavy baryon production grows with multiplicity:

Julie Napora, Monday 18:10

Similar mechanisms should also increase tetraquark production



LHCb upgrades – directly improving the HI physics program

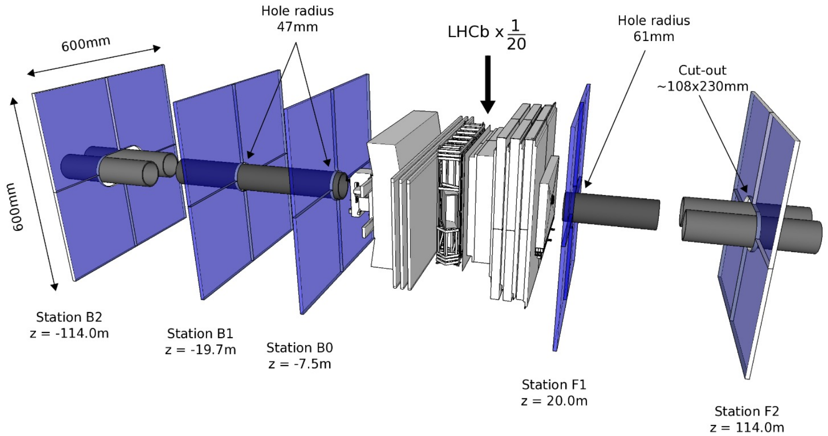


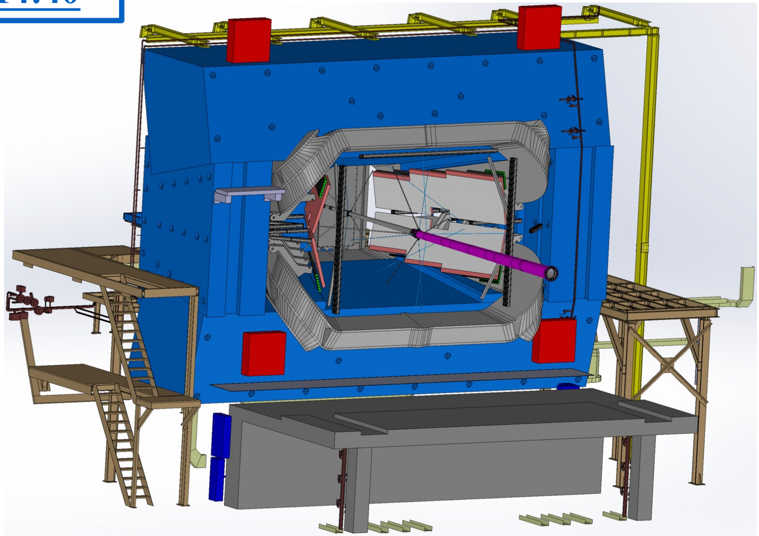
Herschel detector: used to characterized CEP/UPC events by measuring far forward/backward activity. Removed after Run 2 due to radiation damage.

Large Area Scintillator Array for UPCs (LASARUS): Resurrect this capability at LHCb.

LHCb upgrades – directly improving the HI physics program

Sam Belin, Tuesday 14:40





Herschel detector: used to characterized CEP/UPC events by measuring far forward/backward activity. Removed after Run 2 due to radiation damage.

Large Area Scintillator Array for UPCs (LASARUS): Resurrect this capability at LHCb.

Magnet Station: tracks very soft particles that terminate in dipole.

Especially useful for UPC and complex hadronic decay channels of exotics

Summary

- QCD creates a rich spectrum of bound states - our knowledge of the allowed configuration of quarks inside hadrons is rapidly growing

- LHCb has unequalled capabilities to explore exotic hadrons with multiple production mechanisms across a wide range of hadronic environments

- Exploring exotic hadrons give us new ways to test some of our favorite models of heavy quark production, hadronization, and transport in nuclear collisions

- New capabilities from upgrades directly improve the heavy ion physics program

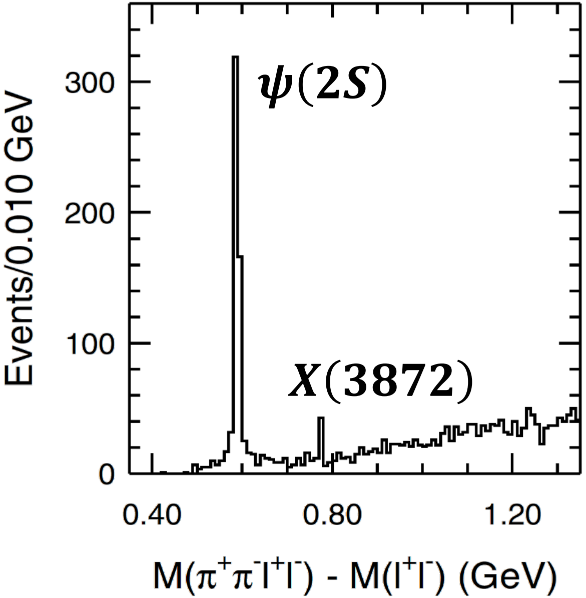
Los Alamos is supported by the US Dept. of Energy/Office of Science/Office of Nuclear Physics

and DOE Early Career Awards program

BACKUPS

An enduring puzzle: X(3872)

Belle Collaboration
PRL 91 262001 (2003)



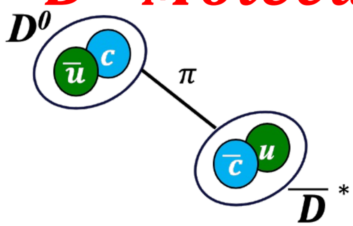
*Tension in theoretical literature:
c.f. Bignamini, Grinstein et al
PRL 103 162001 (2009)
Artoisenet, Braaten
PRD 81 114018 (2010)

- The first exotic hadron, discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle in 2003
- LHCb measured quantum numbers (PRL 110 222001 2013)
  - **Incompatible** with expected charmonium states
- Mass is consistent with sum of D^0 and $\overline{D}^{*0}$ masses:

$$\left(M_{D^0} + M_{\bar{D}^{*0}}\right) - M_{\chi_{c1}(3872)} = 0.07 \pm 0.12\ \mathrm{MeV}/c^2$$

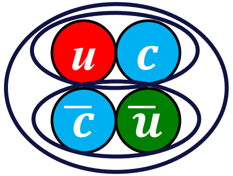
- Large prompt production fraction (~80%) – potentially inconsistent with D meson coalescence in pp*

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



VERY small binding energy
VERY large radius, ~10 fm

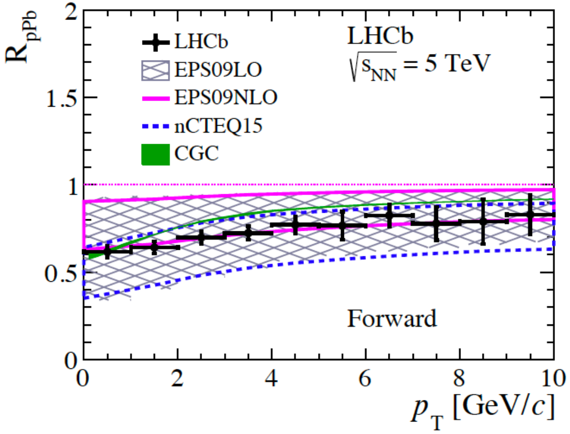
Compact tetraquark



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

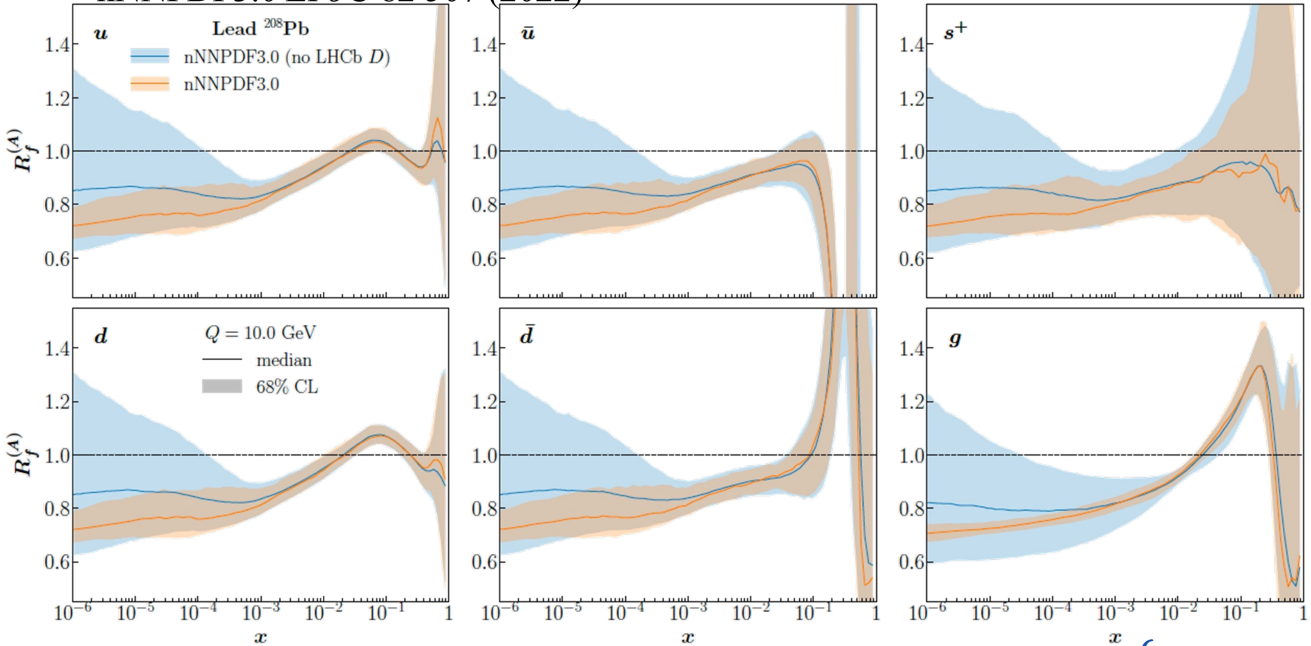
Constraining nPDFs with D mesons

JHEP 1710 (2017)



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

nNNPDF3.0 *EPJC* 82 507 (2022)

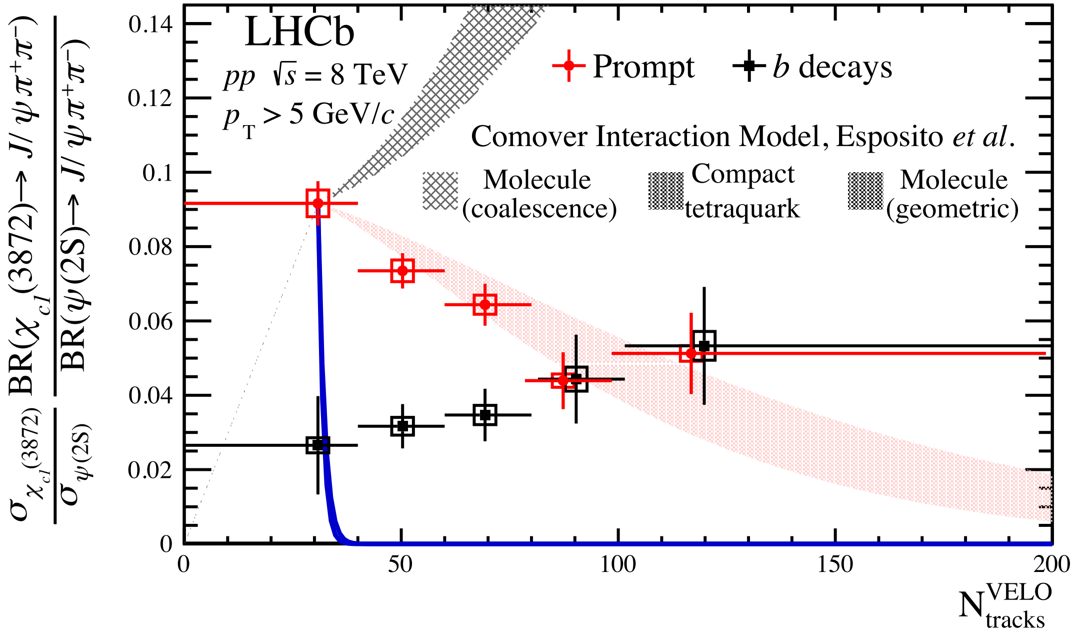


LHCb data currently constrains nPDFs down to x~10^{-6}

Places especially stringent bounds on gluon nPDF

X(3872)/ψ(2S)

PRL 126, 092001 (2021)



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:

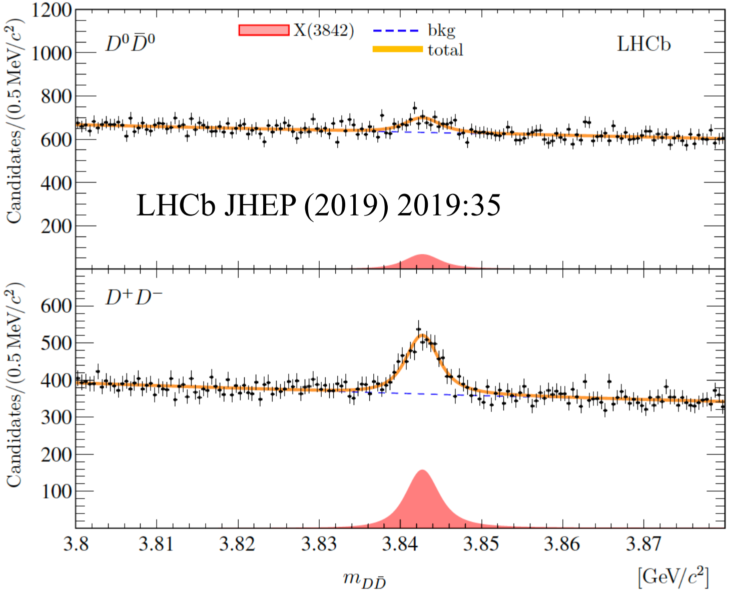
$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\rm geo}\left\langle\left(1-\frac{E_{\mathcal{Q}}^{\rm thr}}{E_c}\right)^n\right\rangle$$

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

Quarkonia – bound states of heavy quarks

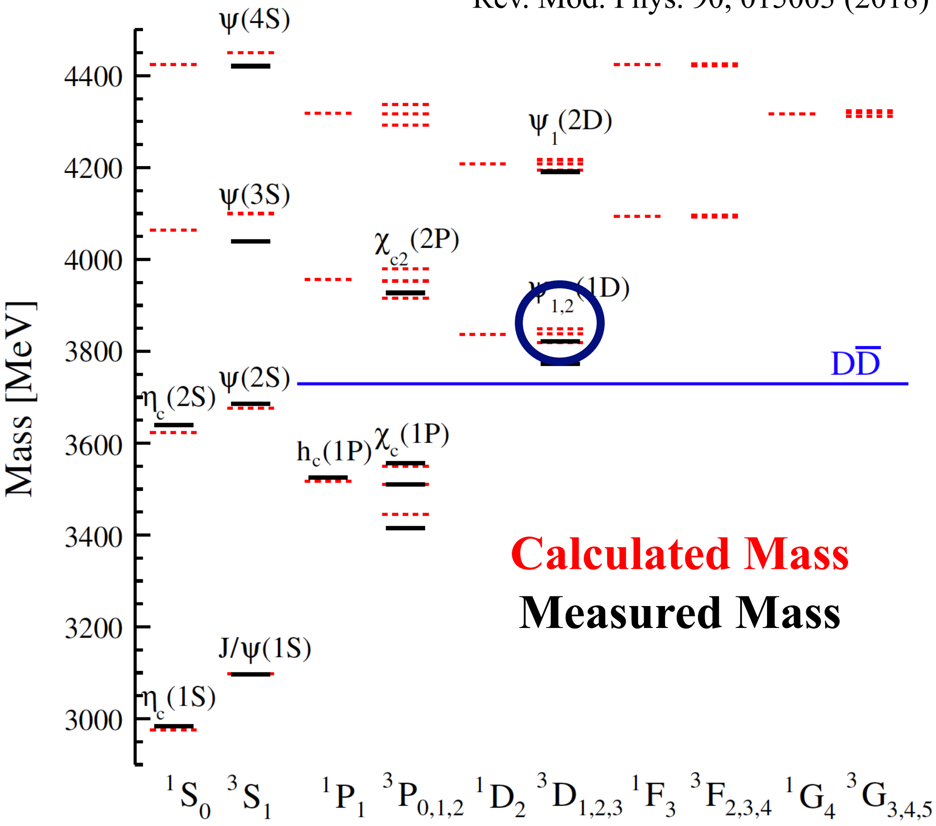


The most recently discovered charmonium state: $\psi_3(1^3D_3)$

Measured mass: 3842.71 ± 0.16 ± 0.12 MeV
Predicted mass: 3849 MeV

Incredibly rich structure, accessible theoretically and experimentally

Rev. Mod. Phys. 90, 015003 (2018)

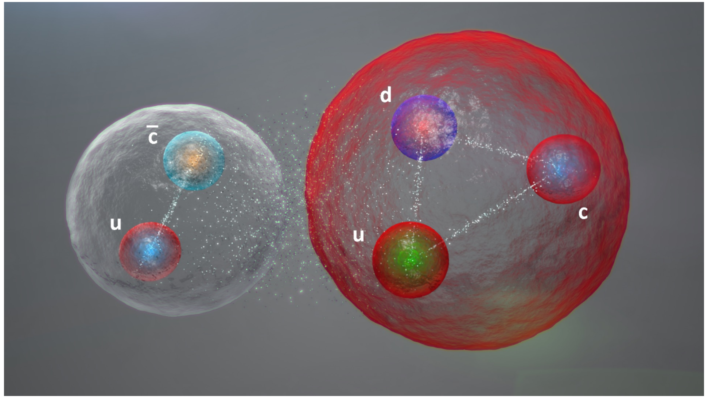


Example: $P_c^{\pm}$ pentaquarks

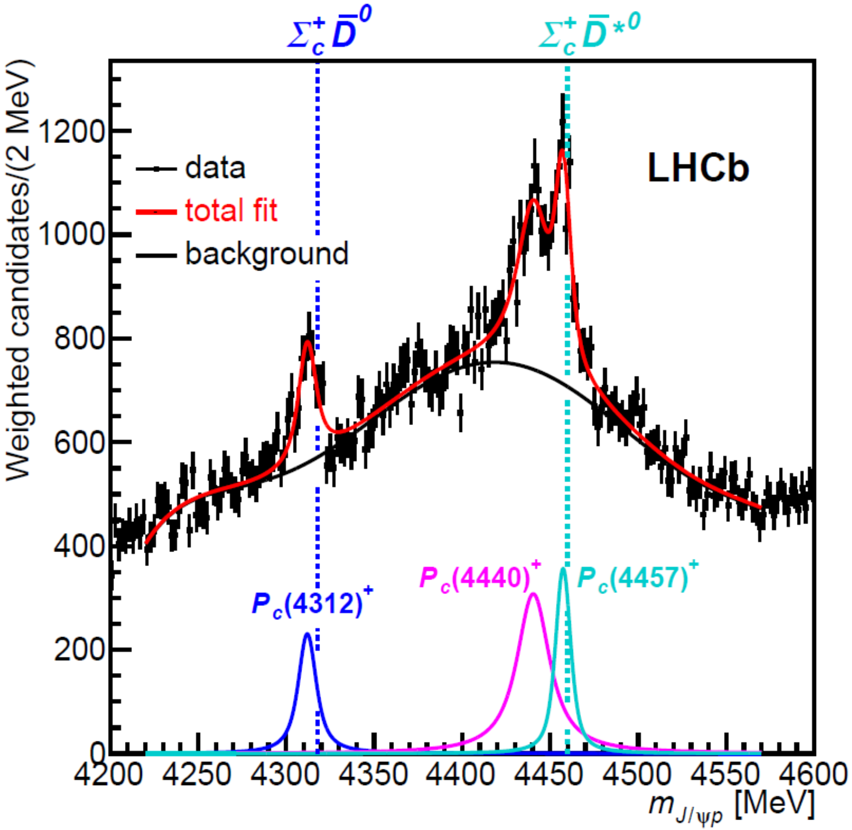
Select daughters from the decay

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

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

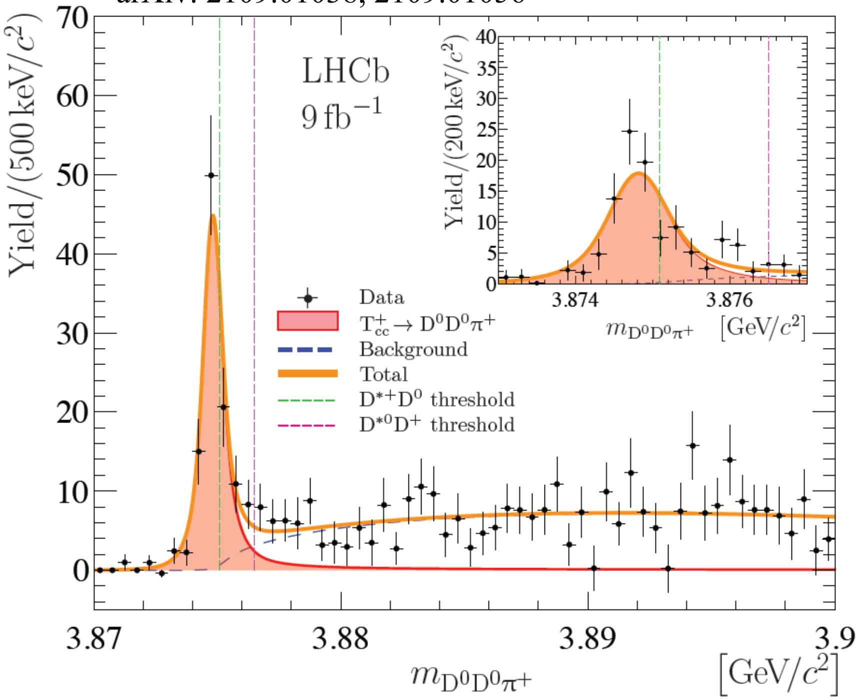


PRL 122 222001 (2019)



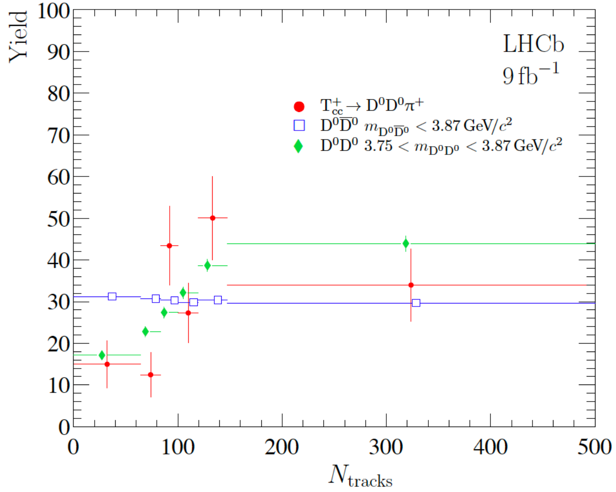
T_{cc}^{+}

arXiv: 2109.01038, 2109.01056



New state consistent with $cc\bar{u}\bar{d}$ tetraquark recently found:

Similar to X(3872), mass quite close to DD threshold
Big difference: contains cc or $\bar{c}\bar{c}$, rather than $c\bar{c}$



Yield favors higher multiplicity collisions, reminiscent of deuteron.
Evidence for hadronic molecule structure?