Evidence for X(3872) production in PbPb collisions at 5.02 TeV

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For the CMS Collaboration

The 19th International Conference on Strangeness in Quark Matter

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MIT HIG group's work was supported by US DOE-NP

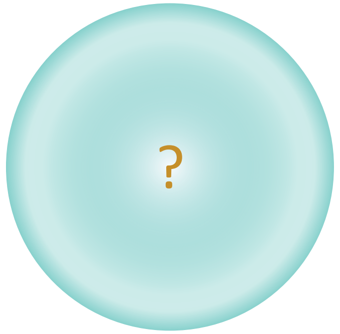
Introduction

X(3872): Observed by BELLE (2003), its internal structure is still under debate

- Also known as $\chi_{c1}(3872)$
- Quantum number determined by CDF and LHCb data: **J^{PC}=1^{++}**
- **Charmonium state**: **abandoned**, predict wrong mass with J^{PC}=1^{++}
- Remaining possibilities:
  - D-$\bar{D}^*$ hadron molecule: mass X(3872) ≈ D(1875)$\bar{D}^*$(2007), large & extended state
  - **Tetraquark:** a compact four quark state
  - **Hybrid**: mixed molecule-charmonium state

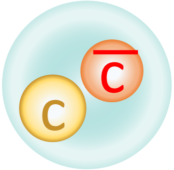
BELLE PRL 91, 262001 (2003)
CDF PRL 98, 132002 (2007)
LHCb PRL 110, 222001 (2013)

Hybrid



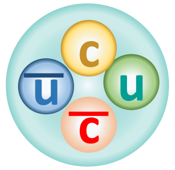
EPJA47 (2011) 101

Charmonium



PLB 590 209-215 (2004)

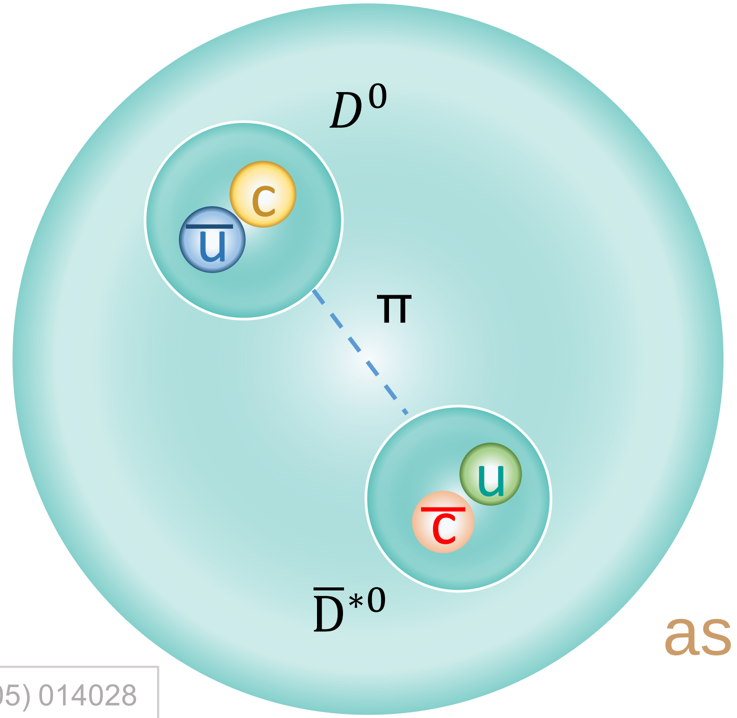
Tetraquark (4q)



$r_{4q} \approx r_{c\bar{c}}$
≈ 0.3 fm

PRD 71 (2005) 014028

$D^0 - \bar{D}^{*0}$ molecule



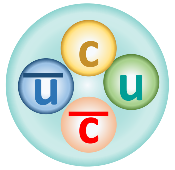
$r_{molecule}$
as large as 5 fm

PRD71 (2005) 014028

Probe the nature of X(3872)

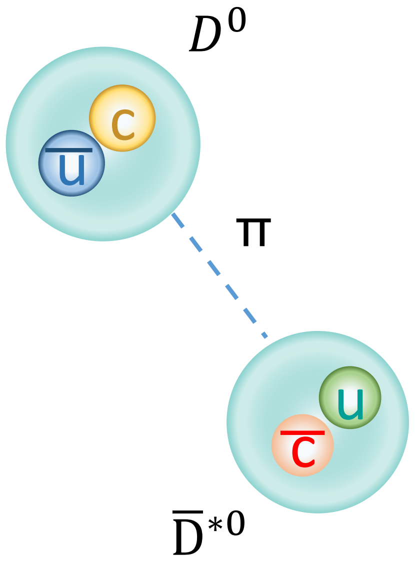
Tightly bound

Tetraquark (4q)



Loosely bound

$D^0 - \bar{D}^{*0}$ molecule

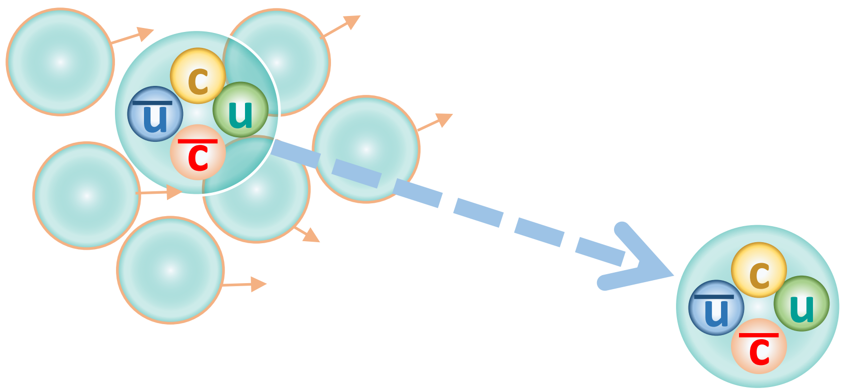


Esposito et al, arXiv: 2006.15044

Probe the nature of X(3872) with comoving particles

Tightly bound

Tetraquark (4q)

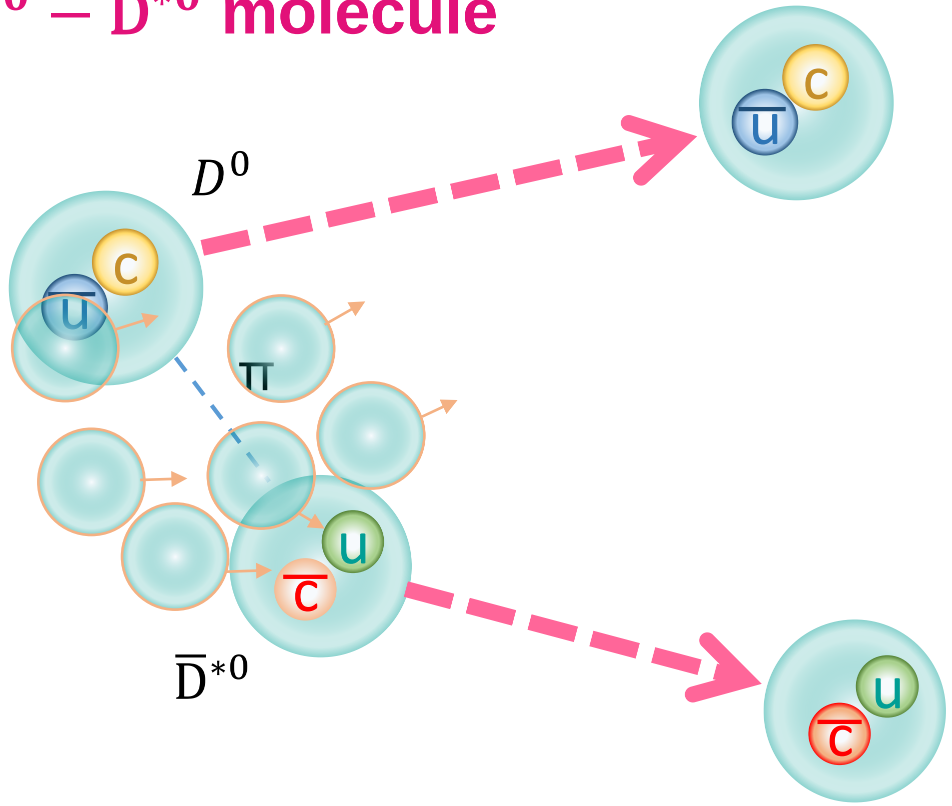


Comoving particles

Smaller dissociation probability

Loosely bound

$D^0 - \bar{D}^{*0}$ molecule

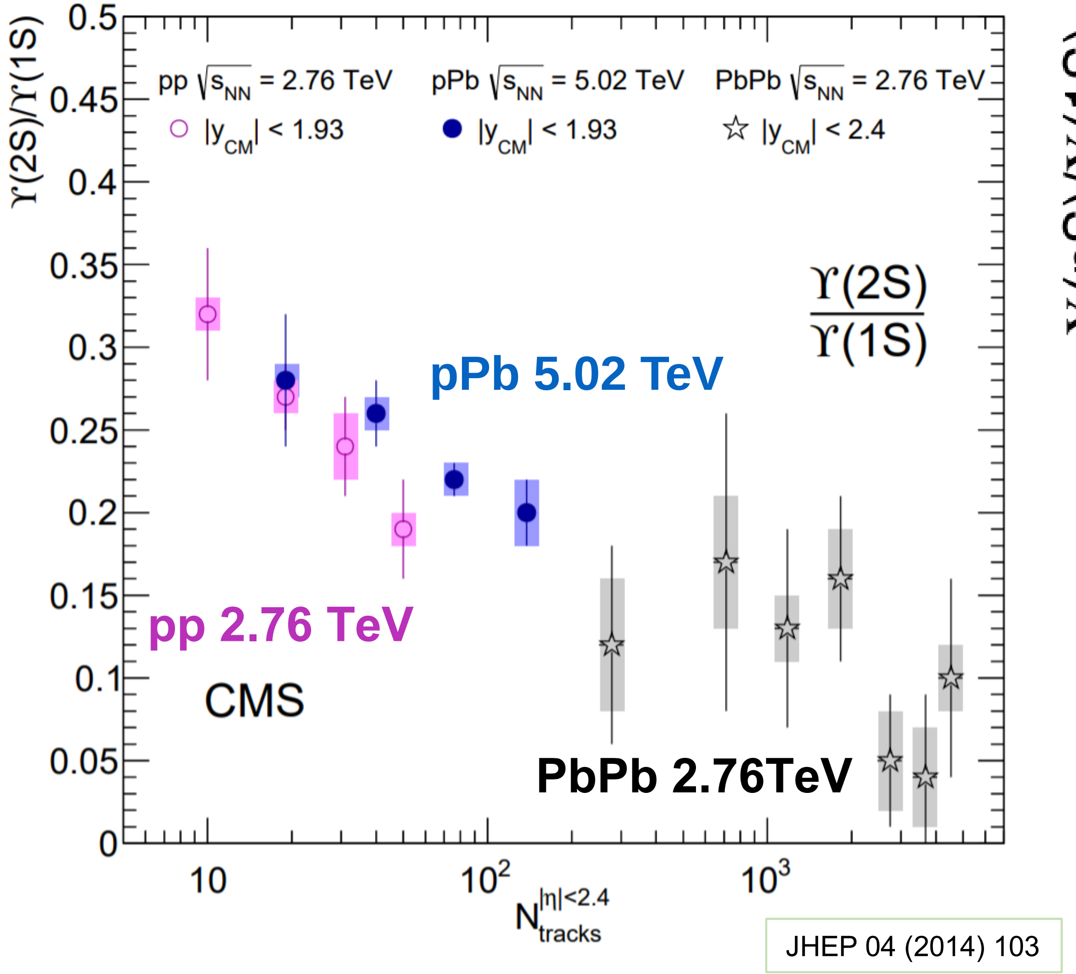


Larger dissociation probability

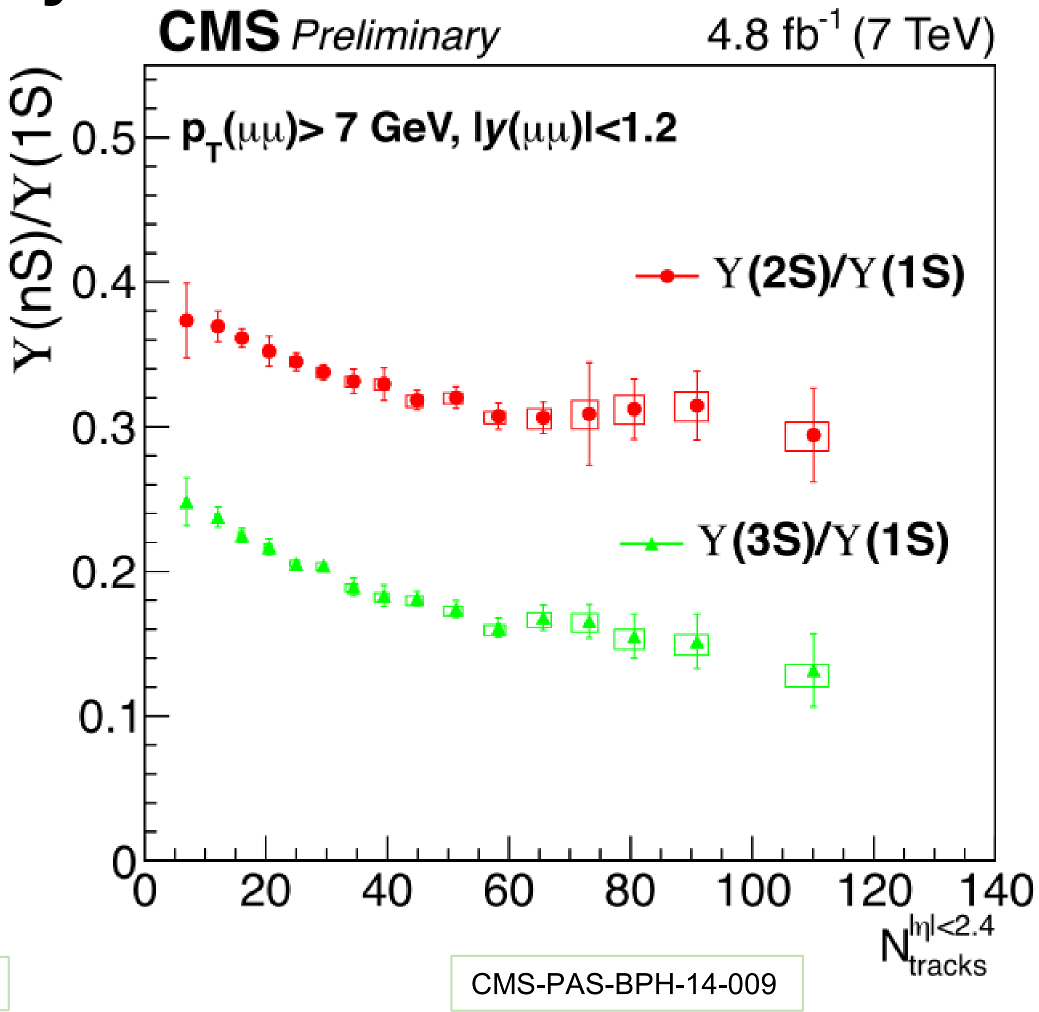
Esposito et al, arXiv: 2006.15044

Upsilon Suppression in High Multiplicity Events

Υ(2S)/Υ(1S) ratio vs. multiplicity



pp at 7 TeV



- Origin of the sequential suppression in high multiplicity pp events?

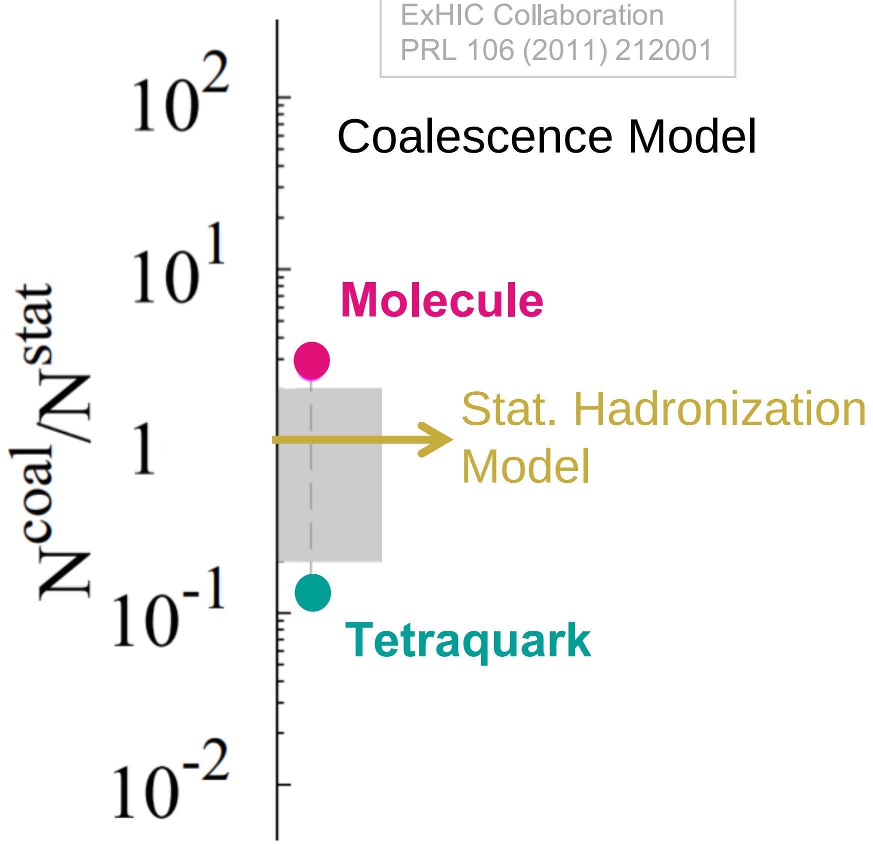
X(3872) Production in Heavy Ion Collisions

X(3872) production in Heavy Ion Collisions

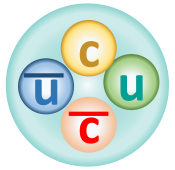
- Production yield in QGP strongly reflects internal structure in the coalescence model
- Hadron Gas Phase: Interact with other hadrons: production + absorption
  $\pi X \rightleftharpoons D\bar{D}, D\bar{D}^*$ & $\rho X \rightleftharpoons D\bar{D}, D\bar{D}^*, D^*\bar{D}^*$
- Radius $r_{4q} \ll r_{mol}$: Molecule easier to be produced and destroyed than tetraquark

⇒ Production in heavy ion collisions: Reveal the inner structure of X(3872)

ExHIC Collaboration
PRL 106 (2011) 212001



Tetraquark (4q)



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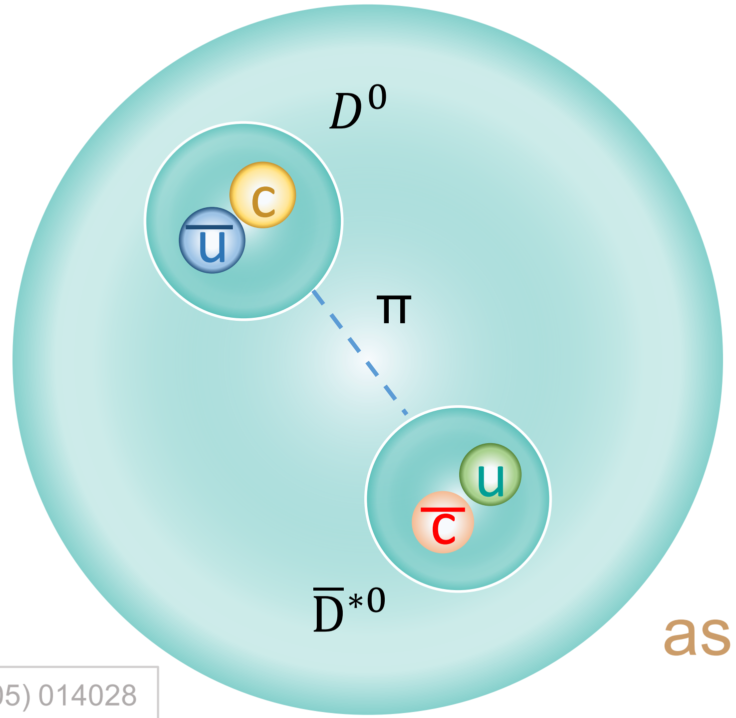
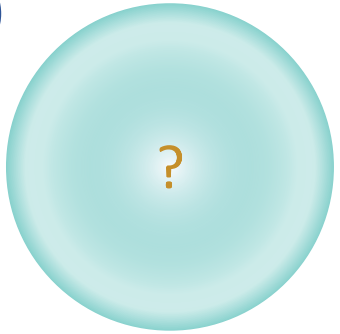


PRD71 (2005) 014028

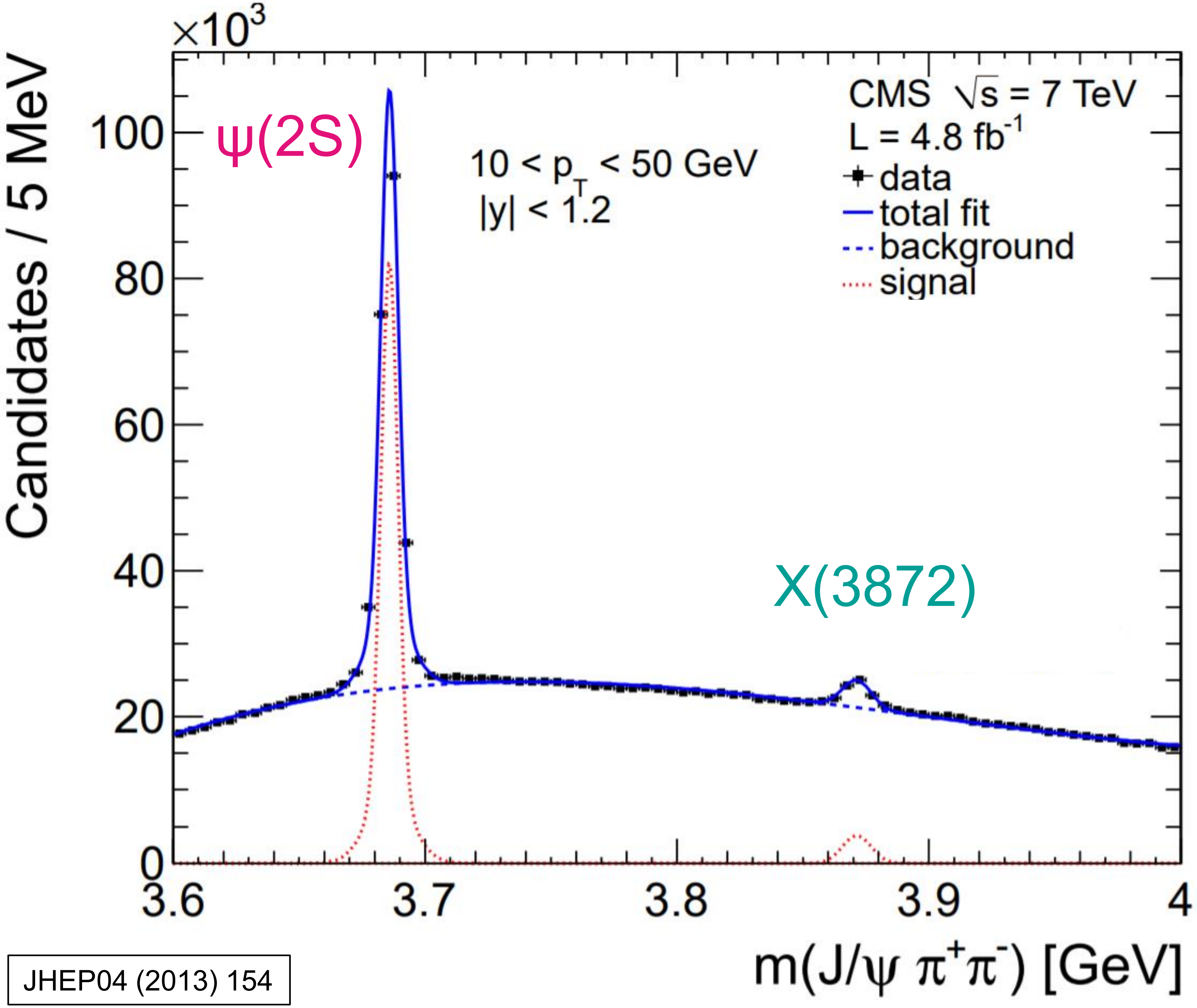
$r_{molecule}$
as large as 5 fm

Hybrid



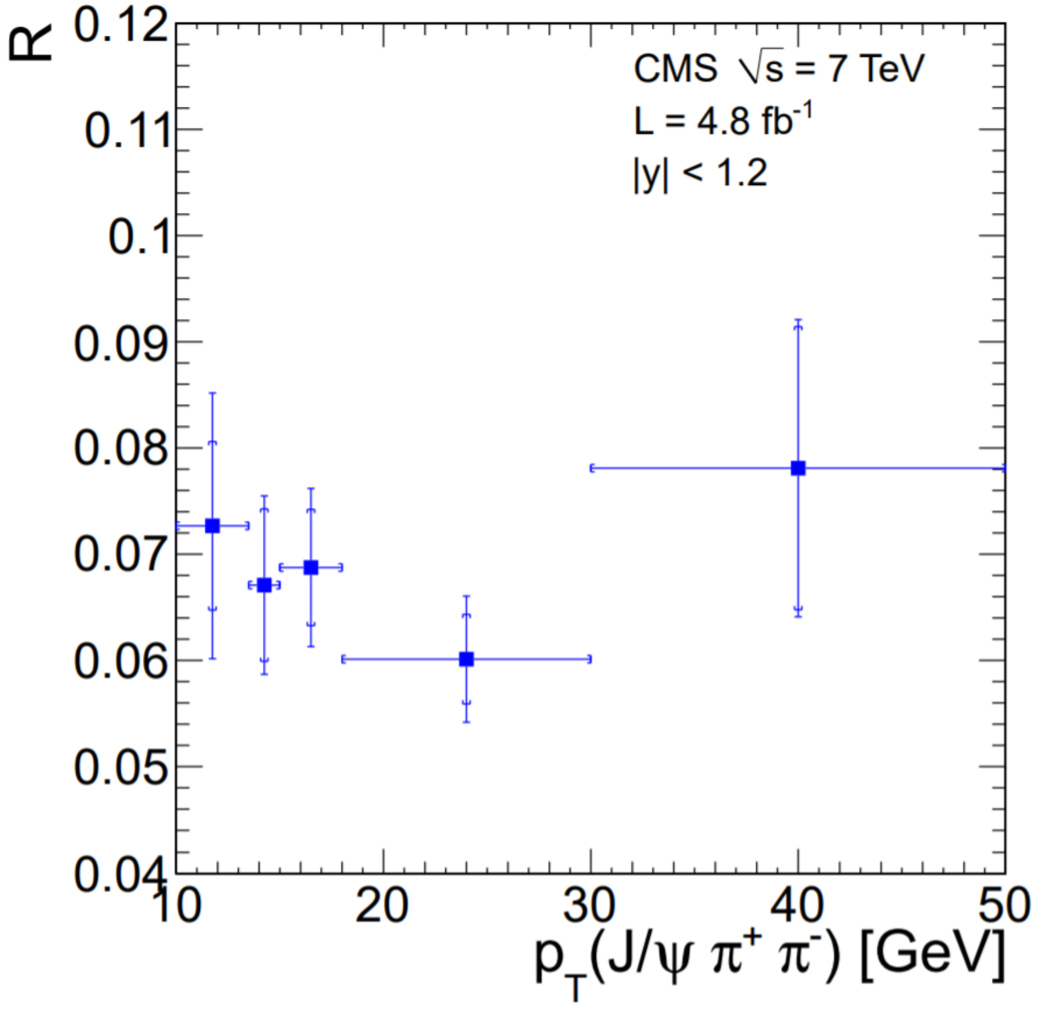
EPJA47 (2011) 101

Invariant Mass Spectra in pp Collisions at 7 TeV



JHEP04 (2013) 154

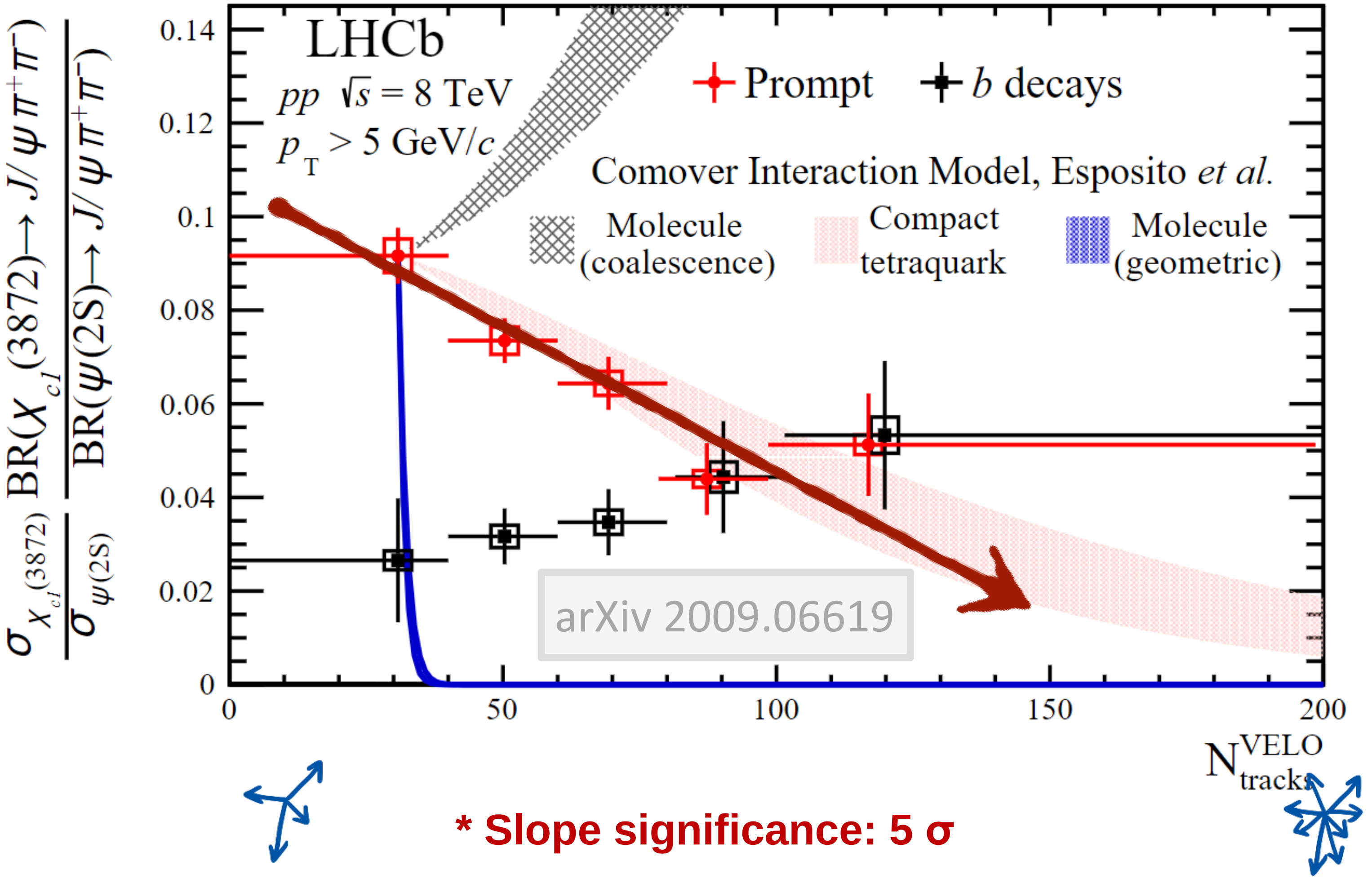
Inclusive X(3872) to ψ(2S) production ratio (include both prompt and nonprompt)



$$R = N^{(Corr)}_{X(3872)} / N^{(Corr)}_{\psi(2S)}$$

X(3872) in High Multiplicity pp from LHCb

Prompt X(3872)/ψ(2S) vs. multiplicity in pp

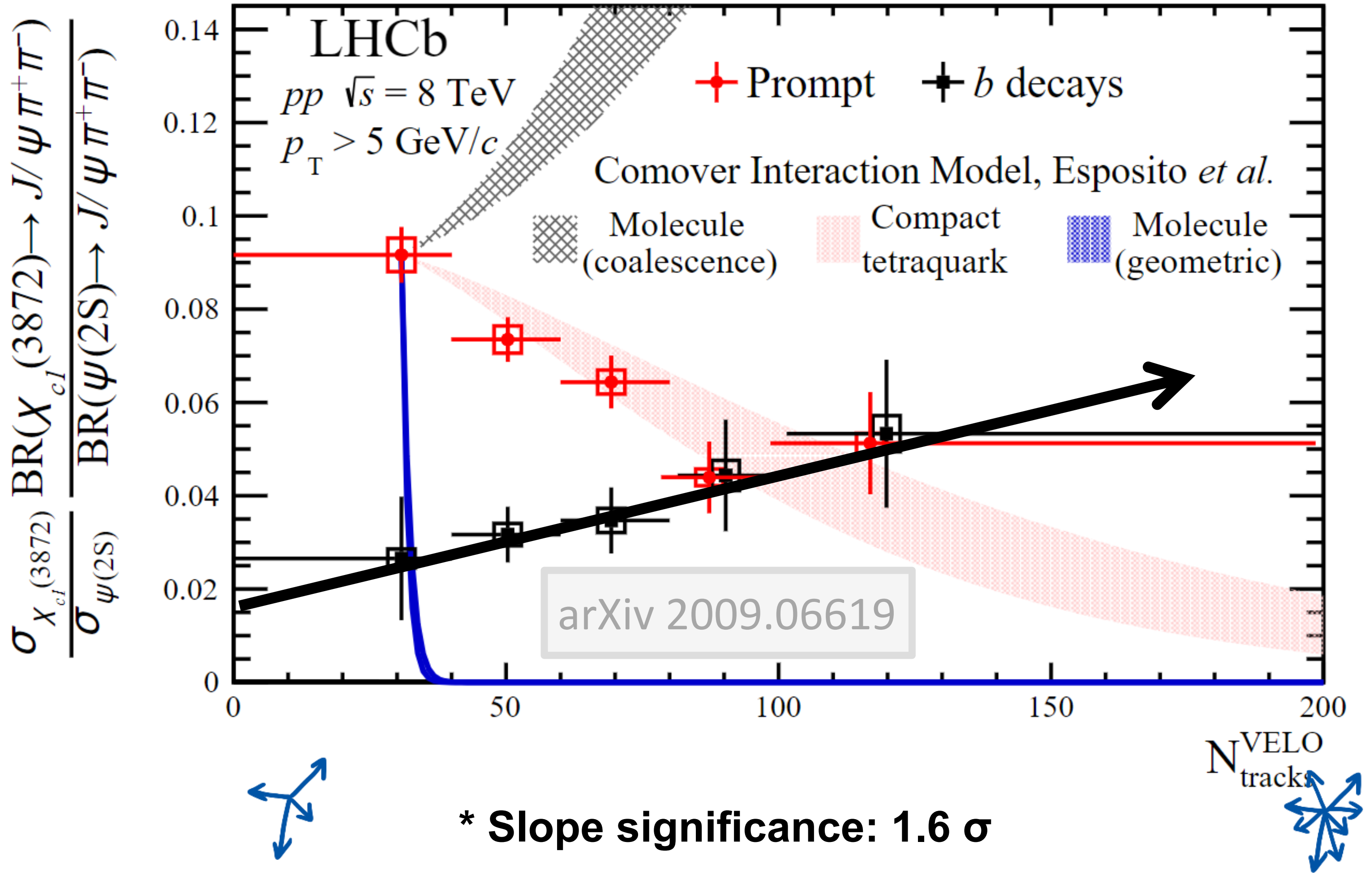


*** Slope significance: 5 σ**

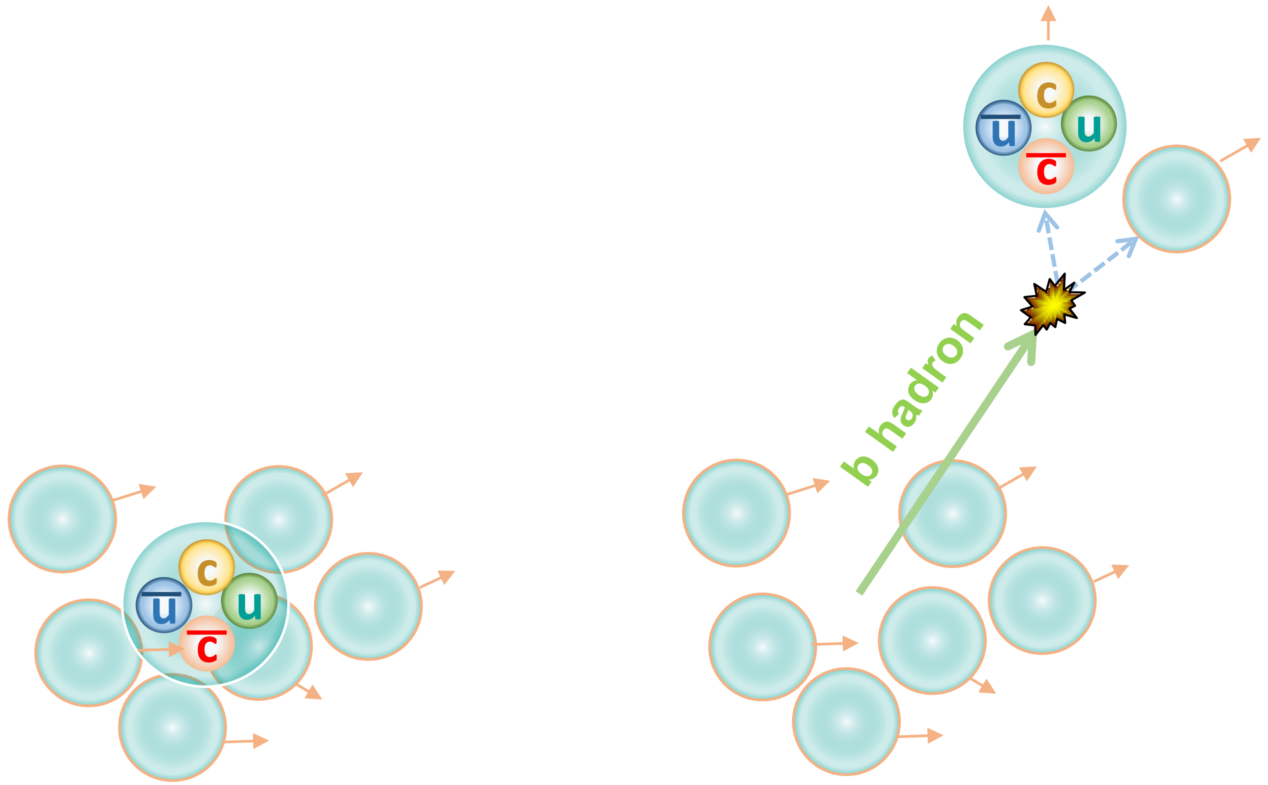
- Destroyed by interactions with other hadrons due to smaller binding energy?

Non-prompt X(3872) in pp from LHCb

Prompt X(3872)/ψ(2S) vs. multiplicity in pp



* **Slope significance: 1.6 σ**



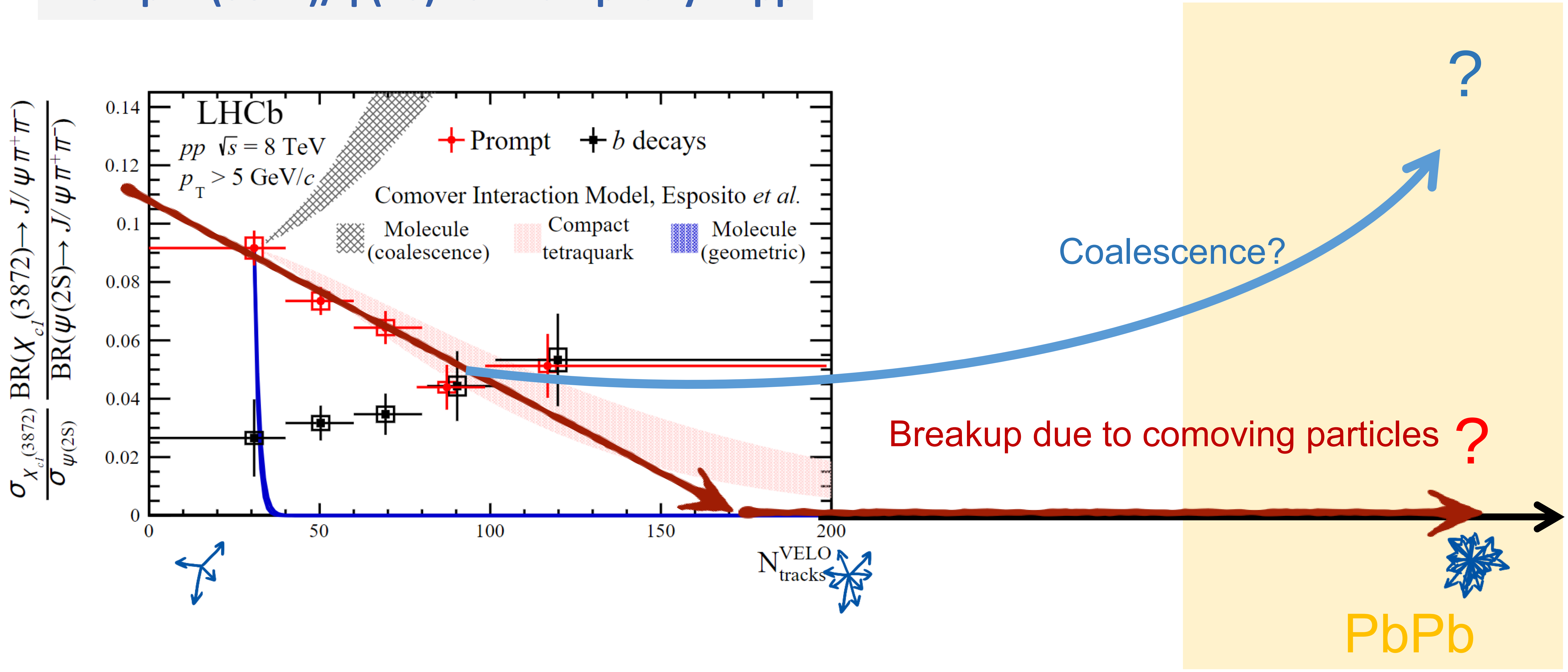
Prompt X

b hadron → X + hadrons

- X(3872) from b decays seems to follow a different trend
- Look forward to the future high multiplicity data from pA collisions

X(3872) in PbPb?

Prompt X(3872)/ψ(2S) vs. multiplicity in pp



Combinatorial Background Suppression in PbPb

A **boosted decision tree (BDT)** algorithm is used to suppress the large combinatorial background

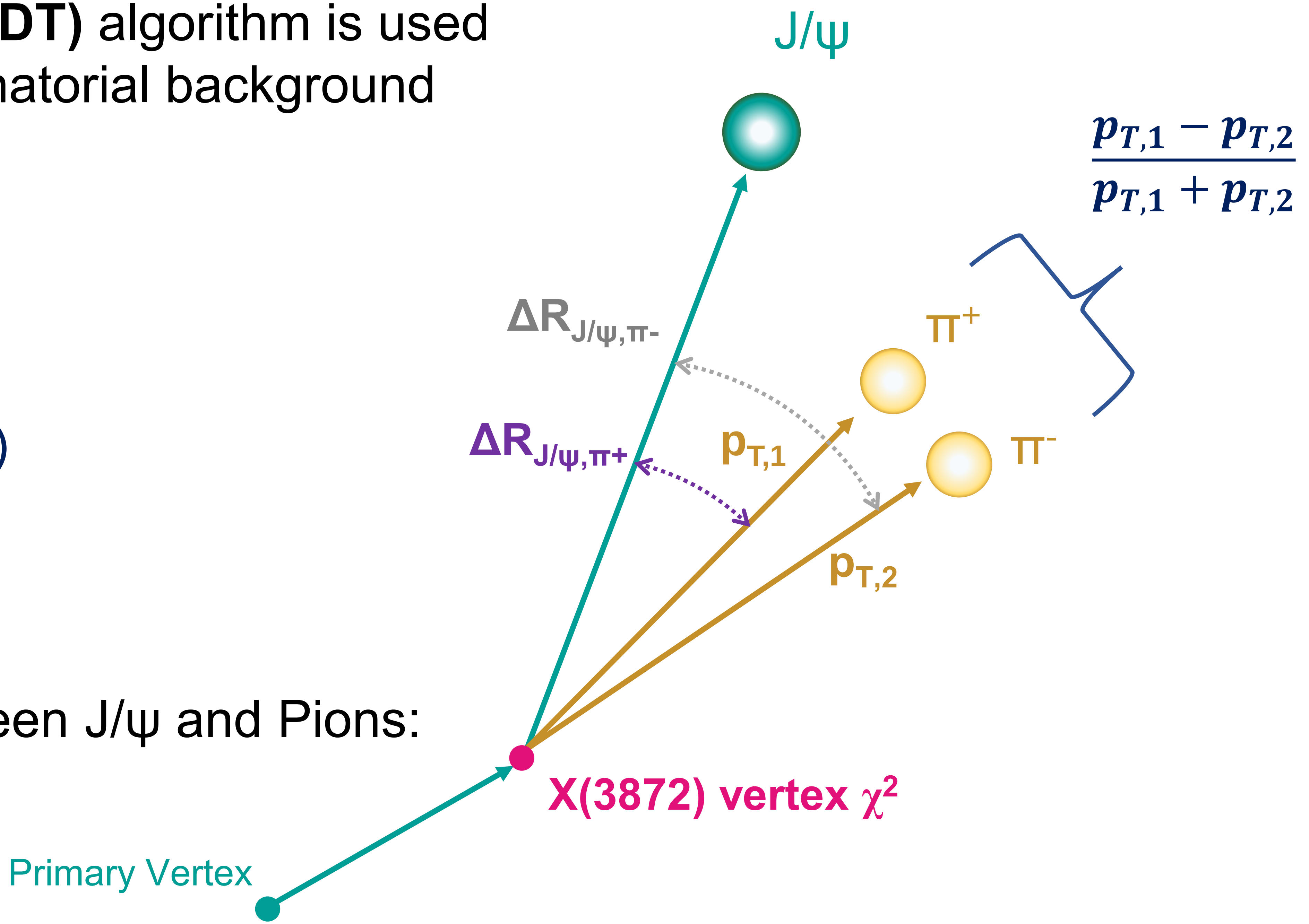
5 Input BDT observables:

(1) X(3872) vertex χ^2

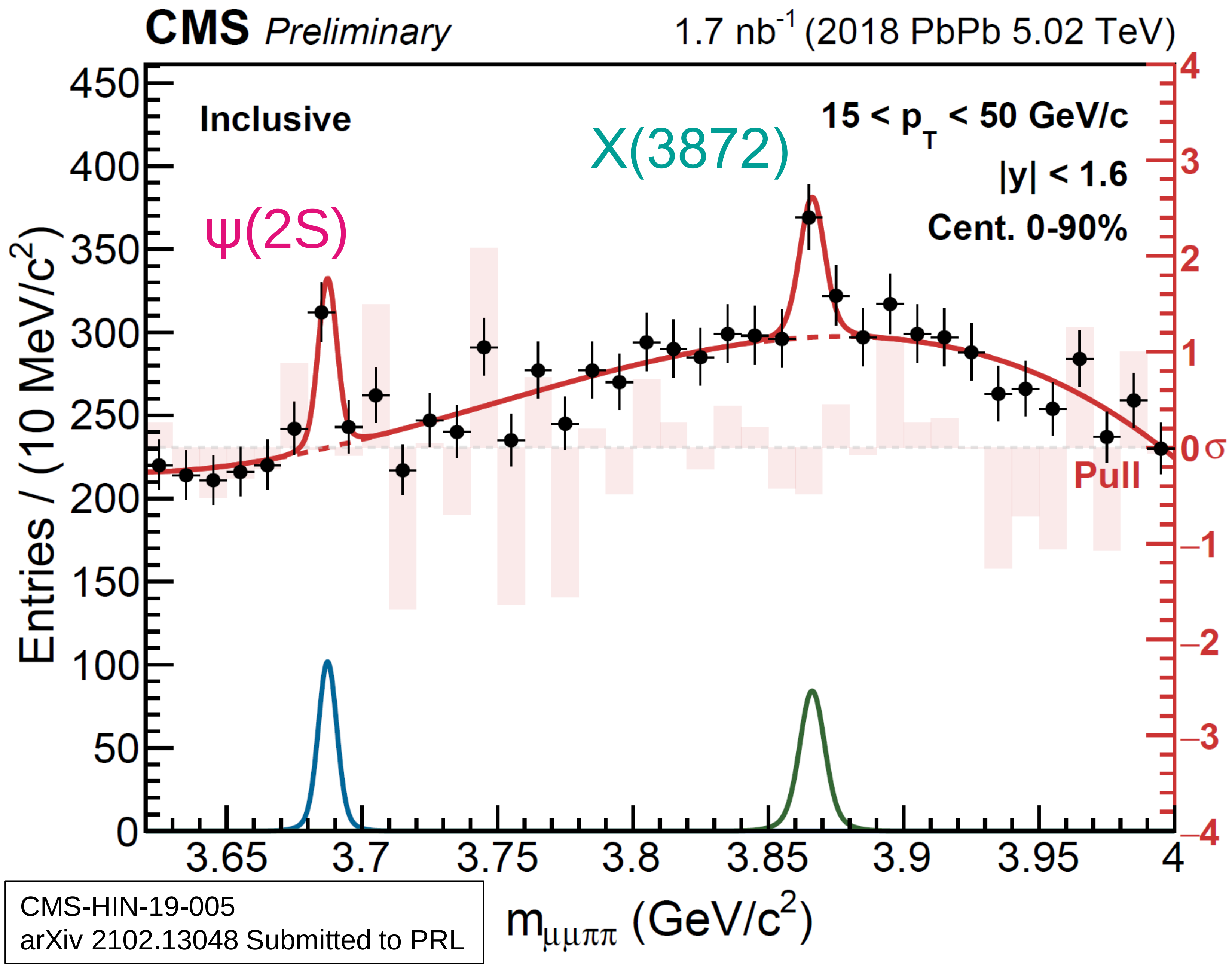
(2) Pion p_T balance $\left(\frac{p_{T,1}-p_{T,2}}{p_{T,1}+p_{T,2}}\right)$

(3) Slow Pion $p_{T,2}$

(4)&(5) Opening angle between J/ψ and Pions: $\Delta R_{J/\psi,\pi+}$ and $\Delta R_{J/\psi,\pi-}$



Invariant Mass Spectra in PbPb Collisions at 5 TeV



CMS-HIN-19-005
arXiv 2102.13048 Submitted to PRL

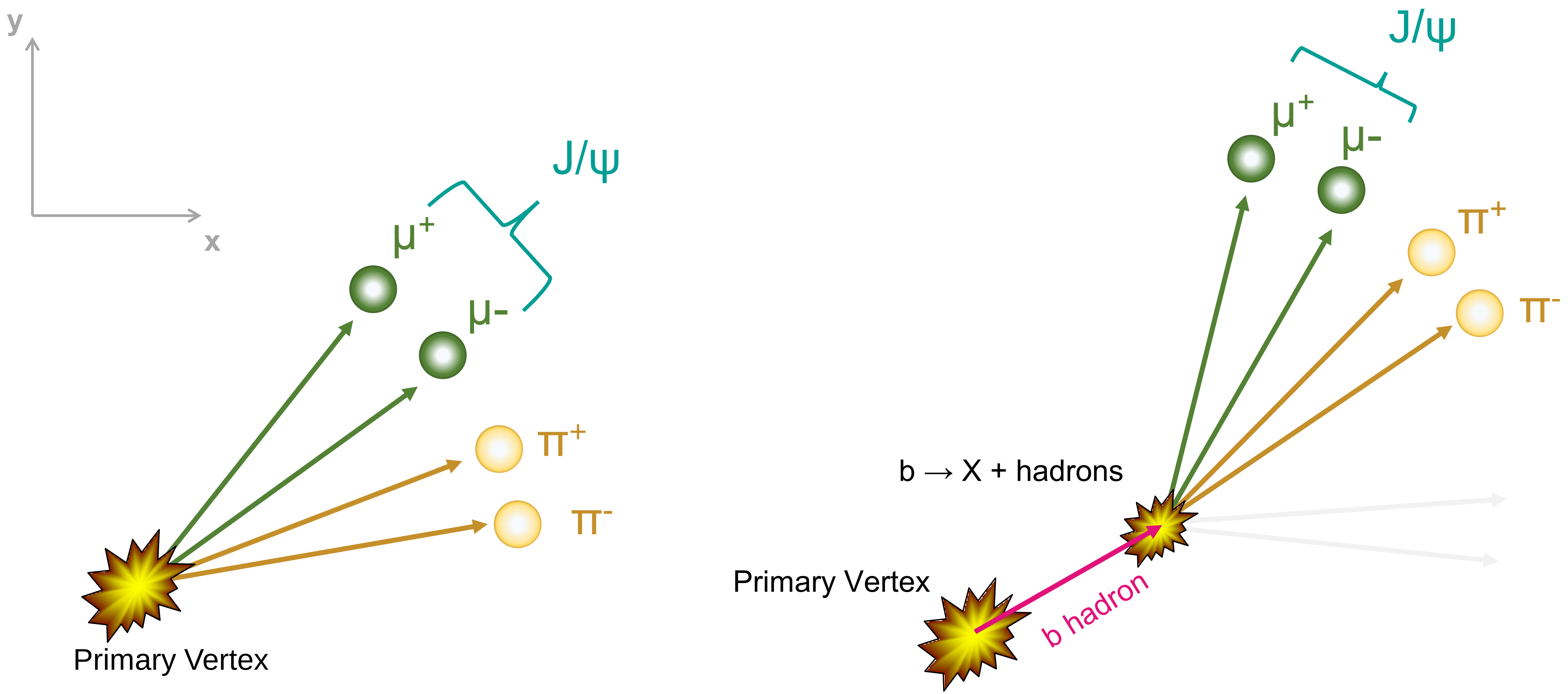
- First evidence of inclusive **X(3872)** production in heavy ion collisions!

  (statistical significance **4.2σ**)

- A clear **ψ(2S)** signal to the same final state is also observed

- To gain more insights: quantify the **prompt** X(3872) to ψ(2S) ratio

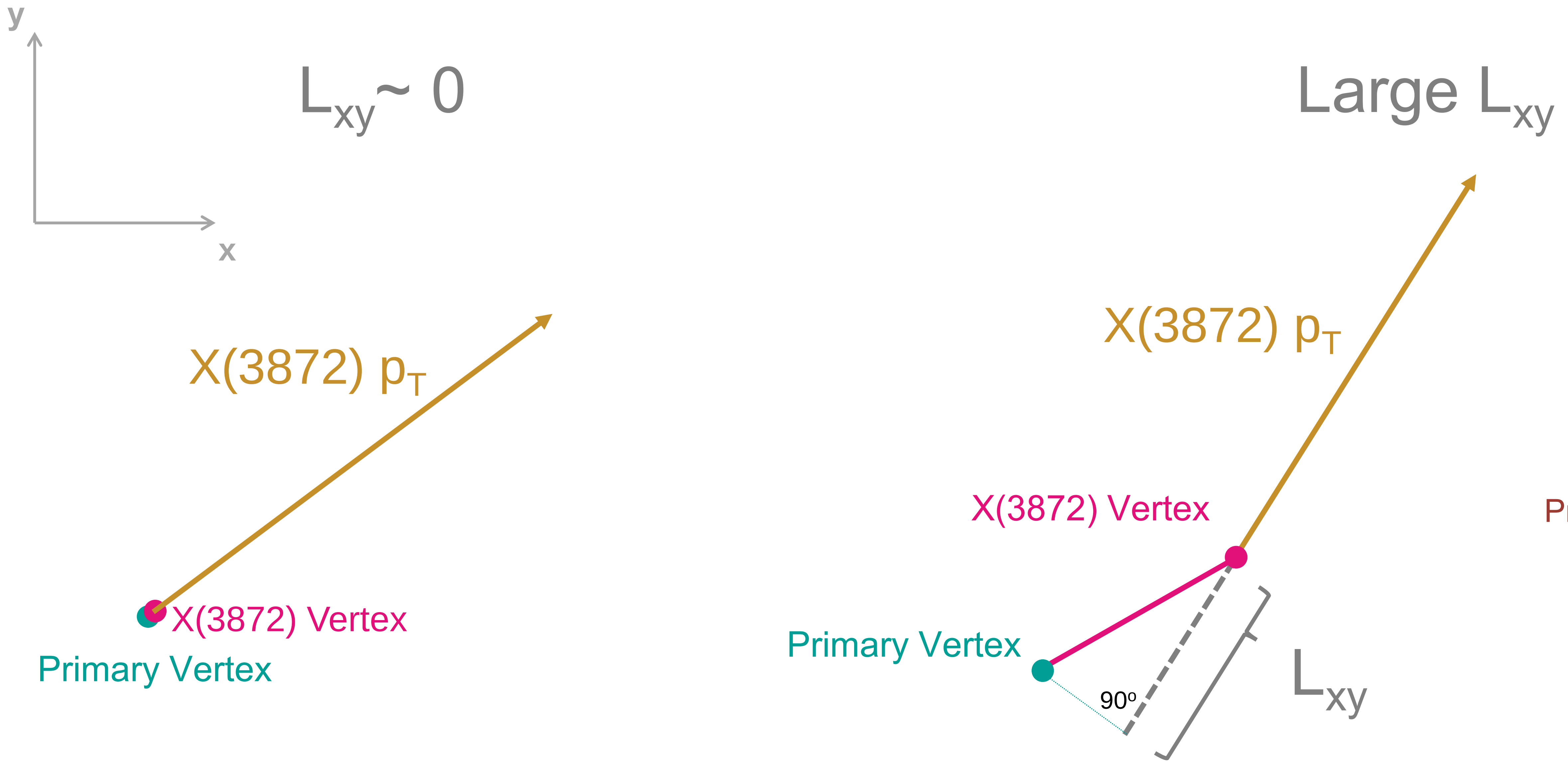
Separation of Nonprompt Component



Prompt X(3872) or ψ(2S)

Nonprompt X(3872) or ψ(2S) from b hadron decays

Separation of Nonprompt Component (from b Decay)



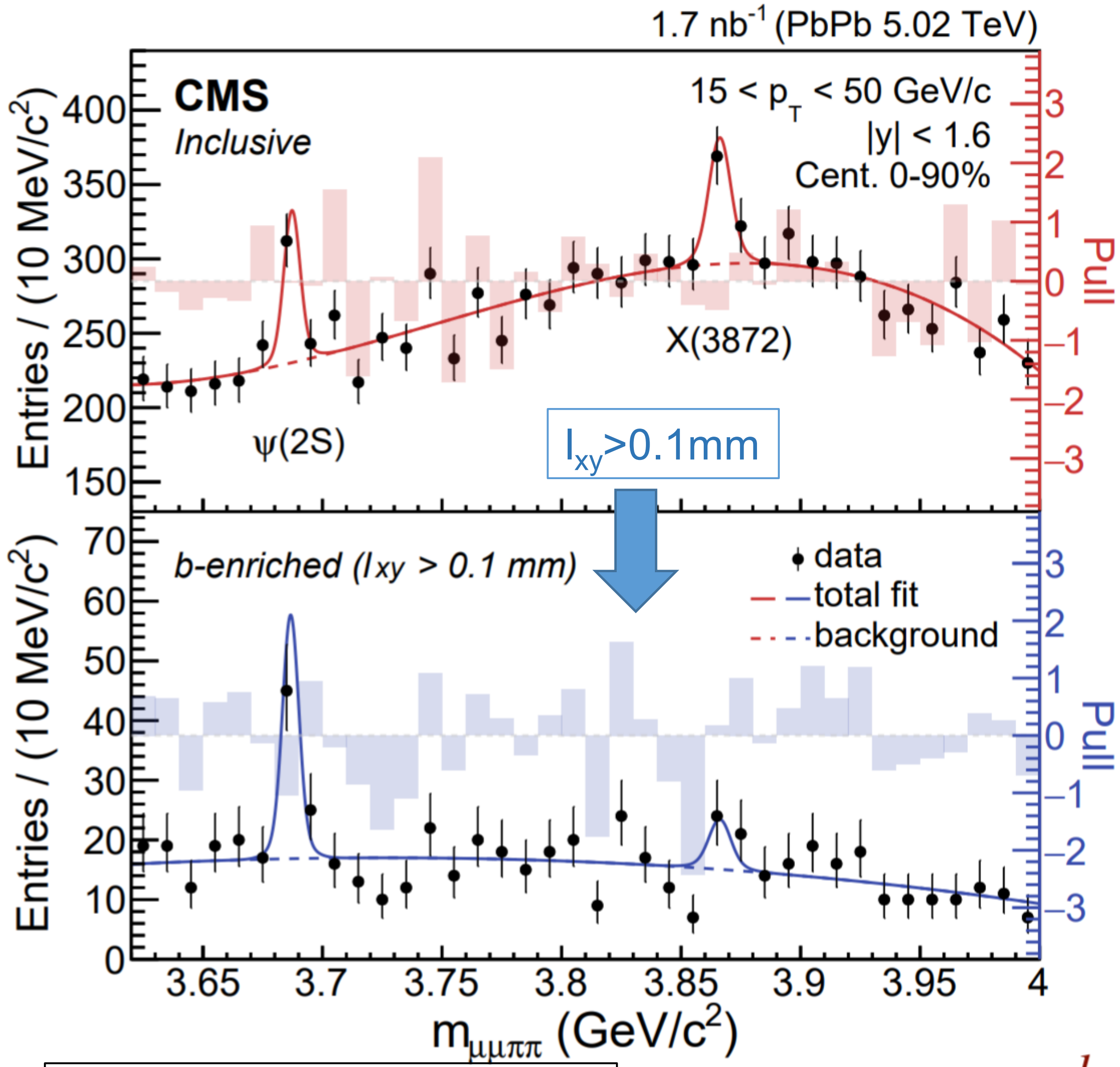
Proper 2D decay length

$$l_{xy} = \frac{L_{xy} \cdot m}{|\vec{p}_T|}$$

Prompt X(3872) or ψ(2S)

Nonprompt X(3872) or ψ(2S) from b hadron decays

Separation of Prompt and Non-prompt Component



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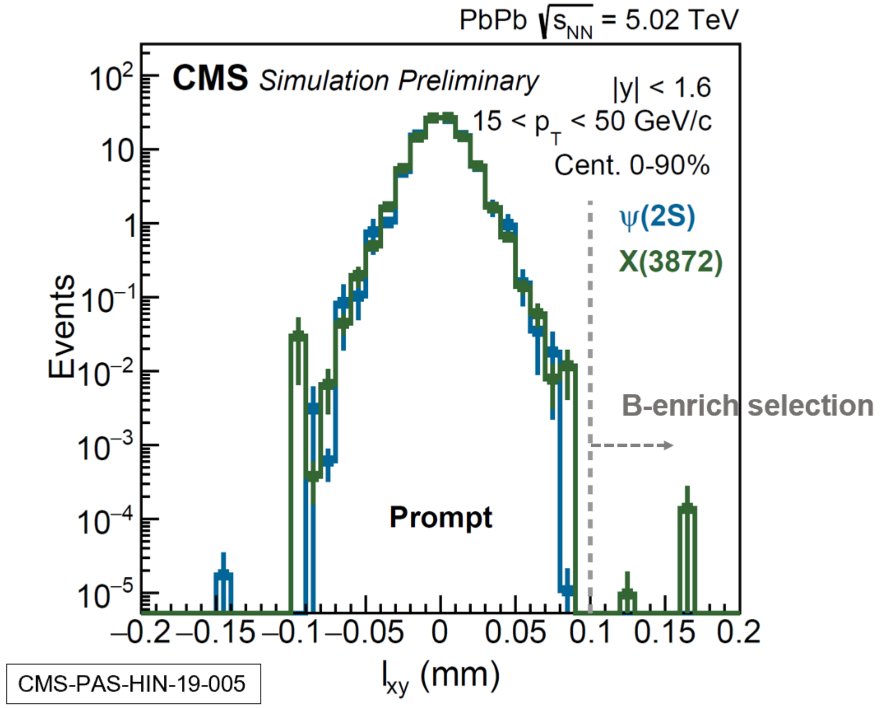
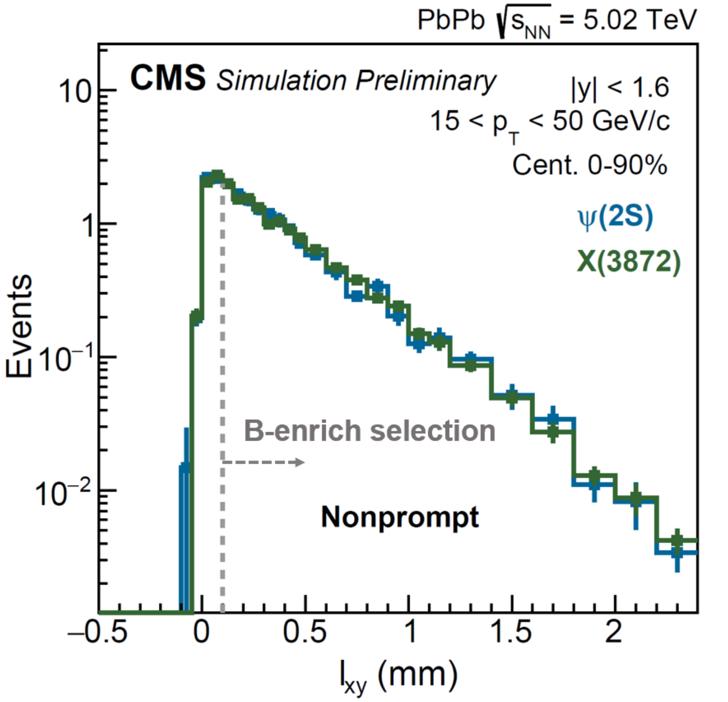


Prompt X(3872) or ψ(2S)



Nonprompt X(3872) or ψ(2S) from b hadron decays

Based on the 2D property decay length l_{xy}
One could select a b-enriched sample (l_{xy}>0.1mm)

$$l_{xy} = \frac{L_{xy} \cdot m}{|\overrightarrow{p}_T|}$$

$$f_{\text{prompt}} = 1 - \frac{N_{\text{b-enr}} / f^{\text{b-enr}}_{\text{nonprompt}}}{N_{\text{incl}}}$$

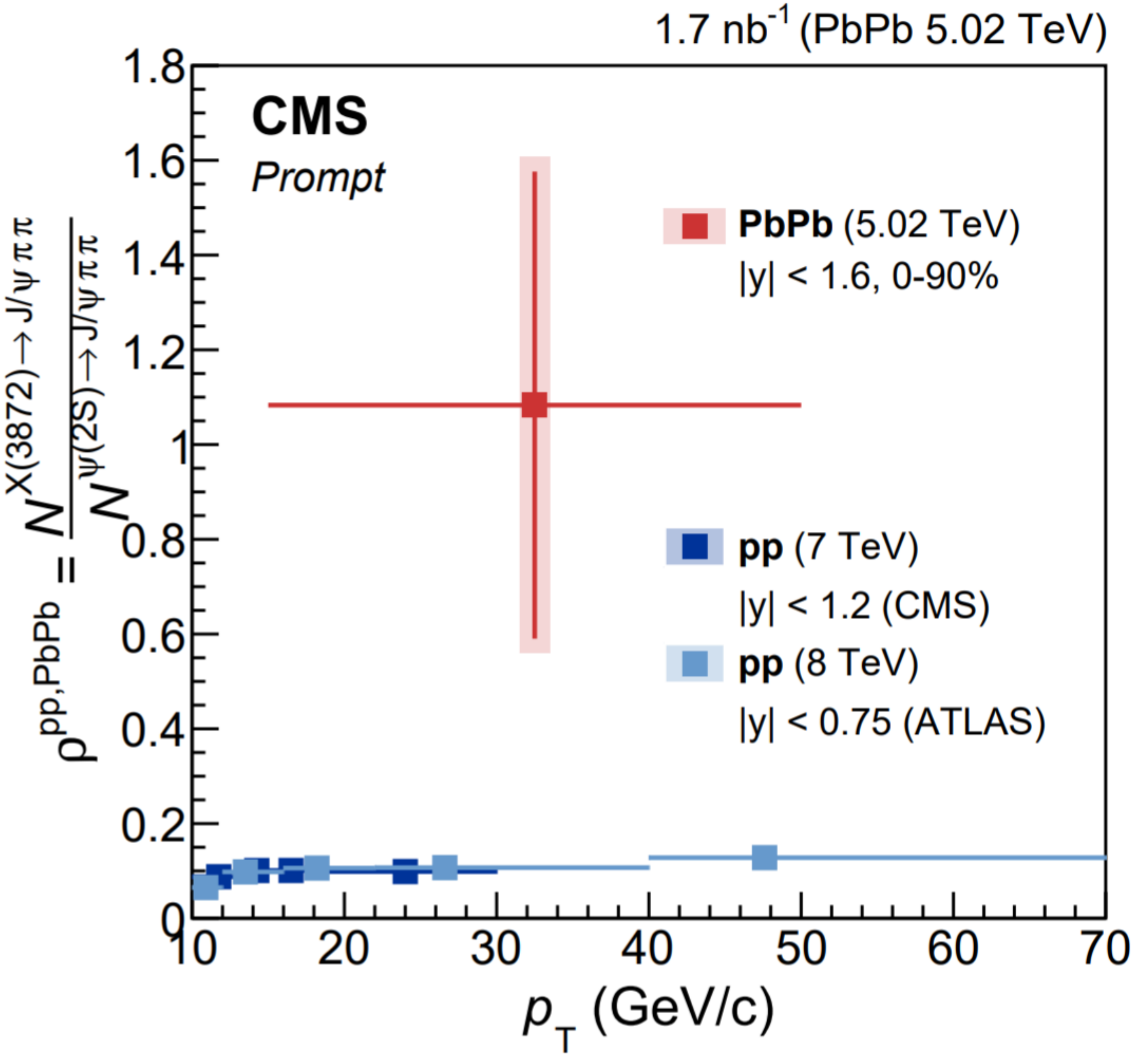
Ratio of X(3872) to ψ(2S) Yields in pp and PbPb

$$\rho^{PbPb} = N^{(Corr)}_{X(3872)} / N^{(Corr)}_{\psi(2S)}$$

In PbPb collisions:

$$\rho^{PbPb} = 1.08 \pm 0.49\,(\text{stat}) \pm 0.52\,(\text{syst})$$

Indication of R enhancement in PbPb collisions with respect to pp at 7 and 8 TeV



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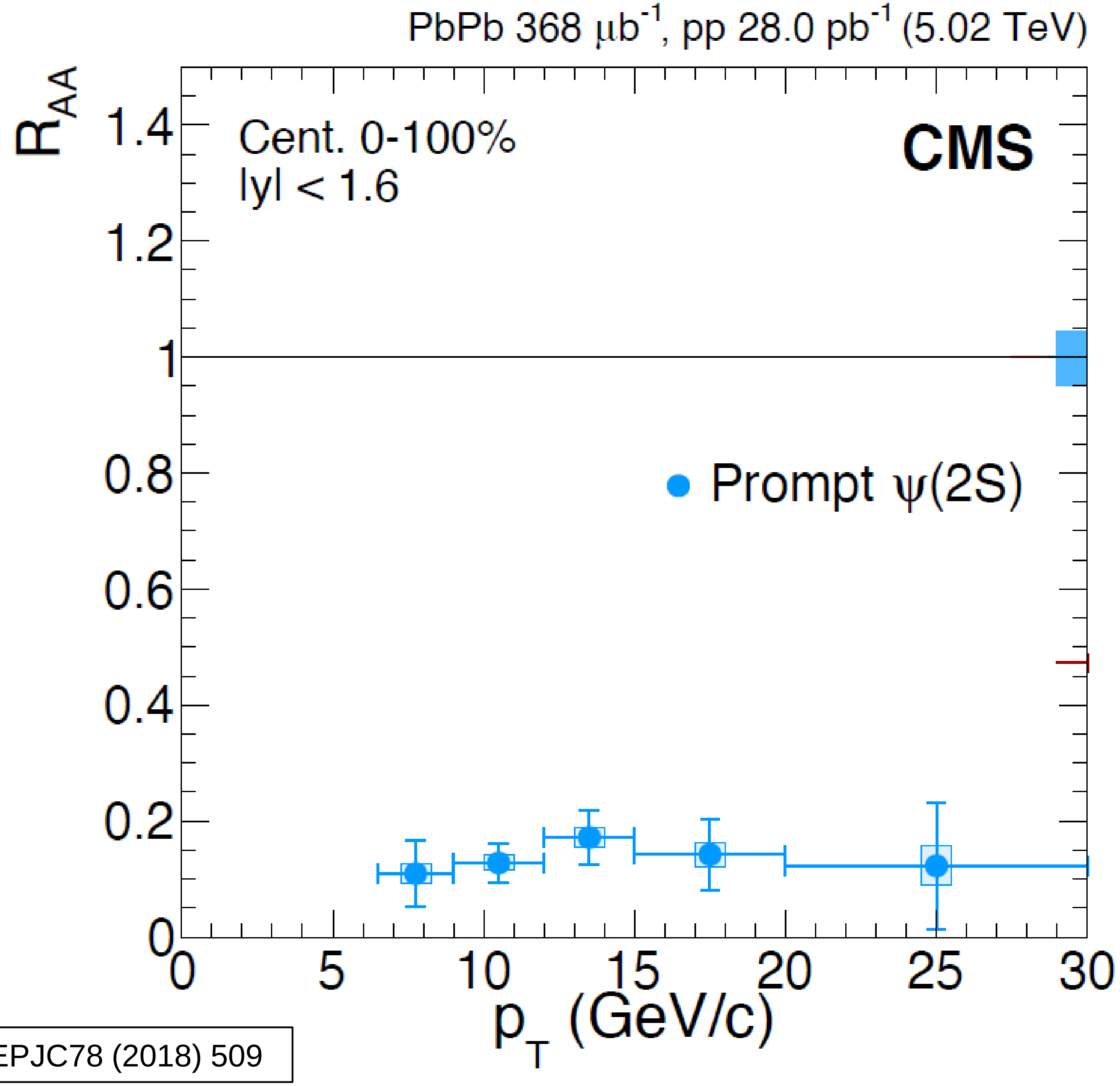
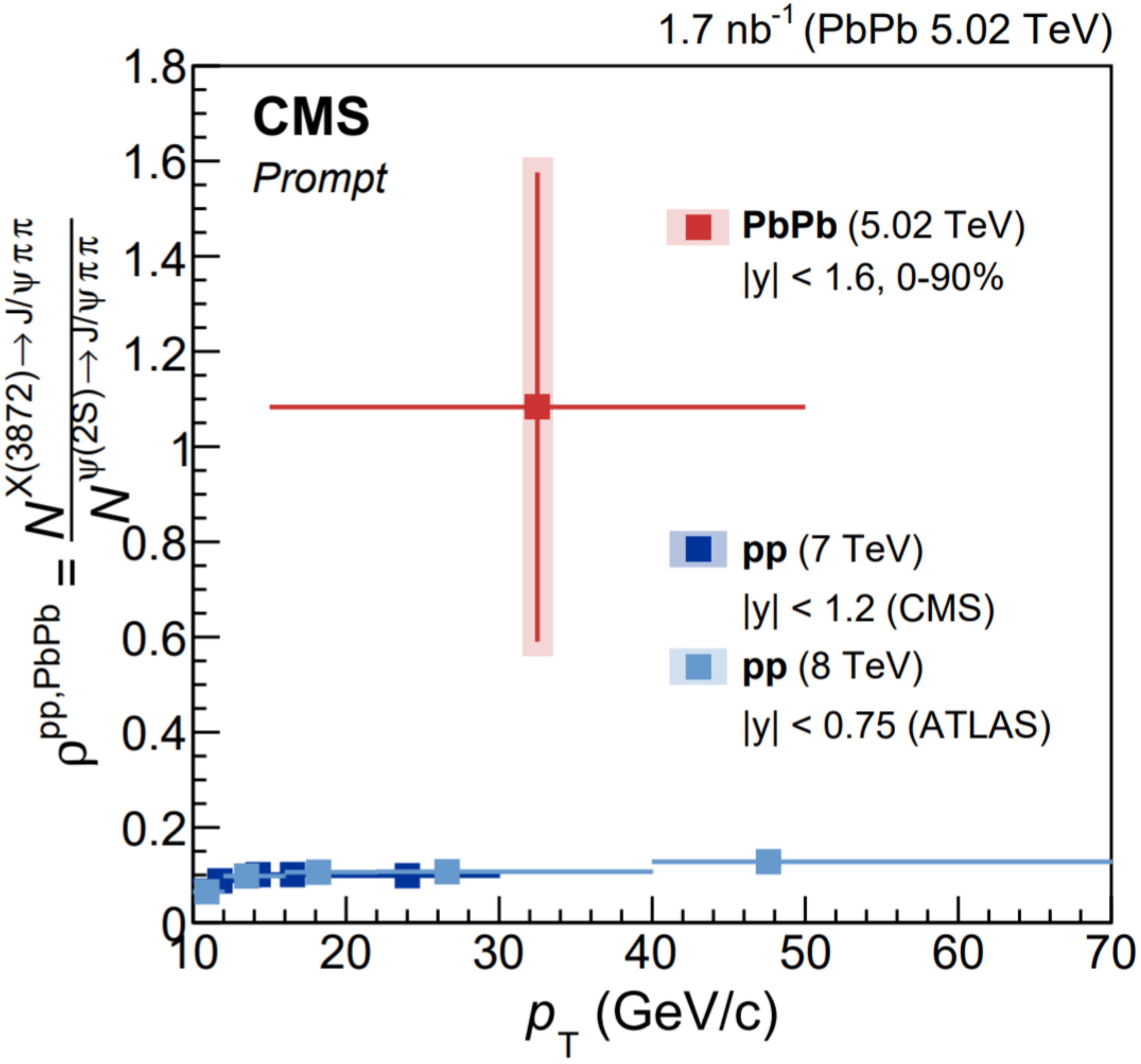
Ratio of X(3872) to ψ(2S) Yields in pp and PbPb



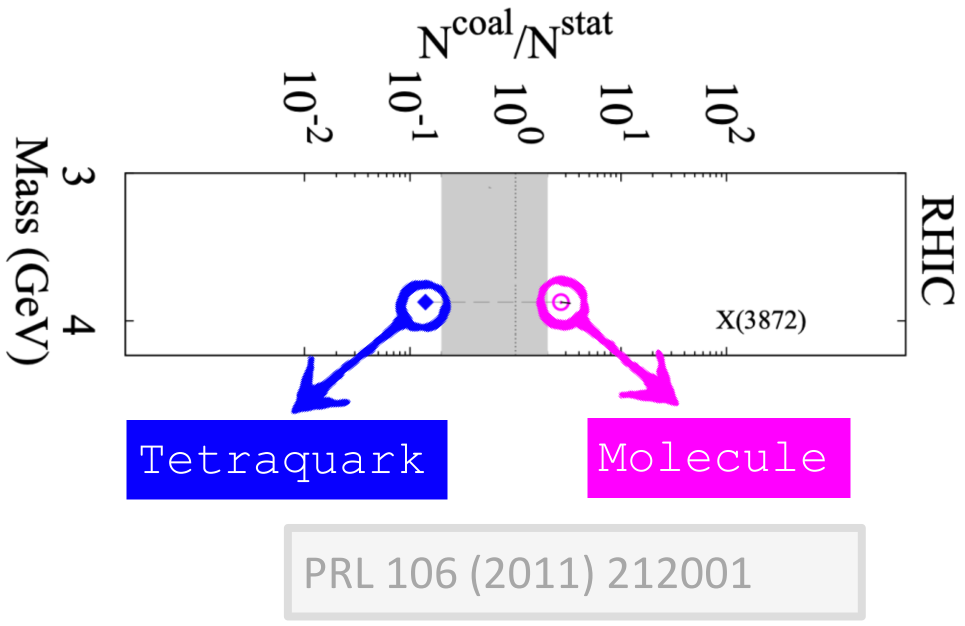


EPJC78 (2018) 509

X(3872) Production

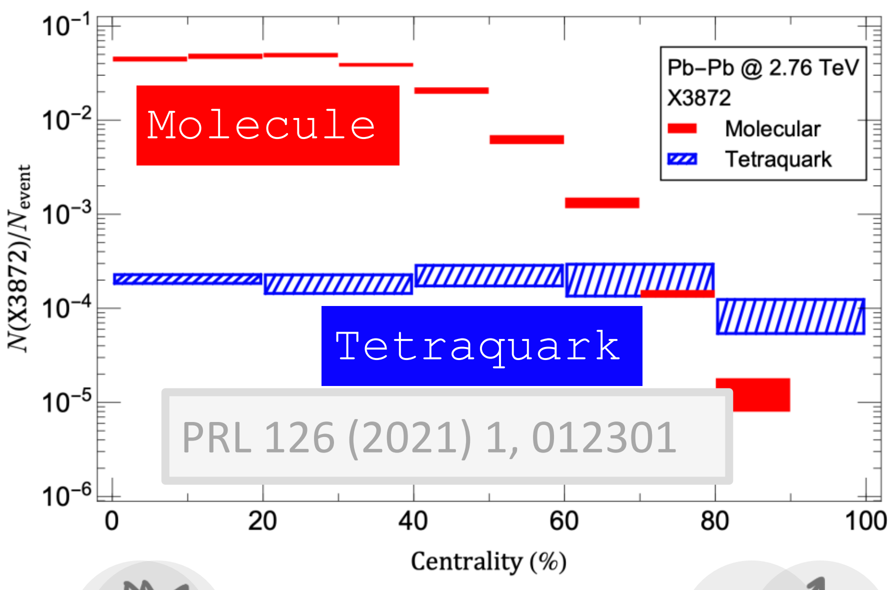
Status of current X(3872) theoretical calculations in heavy-ion collisions

Coalescence model



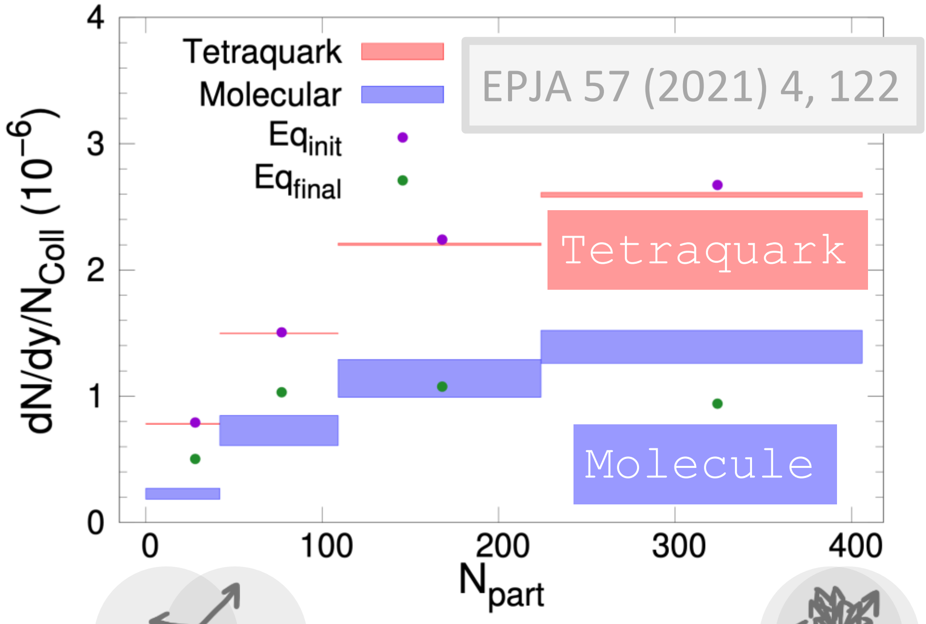
- Molecule easier to be produced w/ recombination of quarks in medium
- $N_{Molecule} > N_{Tetraquark}$

AMPT transport model



- Molecule production per event decreases from central to peripheral
- Tetraquark no centrality dependence
- $N_{Molecule} > N_{Tetraquark}$

TAMU transport model



- Molecule (more loosely bound) regenerated later in the evolution compared to tetraquark
- $N_{Molecule} < N_{Tetraquark}$

Compilation from Jing Wang (MIT)

Unresolved Issues

1. What is the role of multiplicity selection bias?

2. Need to improve the accuracy of the current data

3. Consistency between theoretical calculations:
   Relevance of coalescence hadronization, model dependence and absolute branching fractions

Unresolved Issues

1. What is the role of multiplicity selection bias?
   - Change the source of comoving particles using ep, eA, pp, pA collisions

2. Need to improve the accuracy of the current data
   - Larger dataset from Run 3 and Run 4 at the LHC

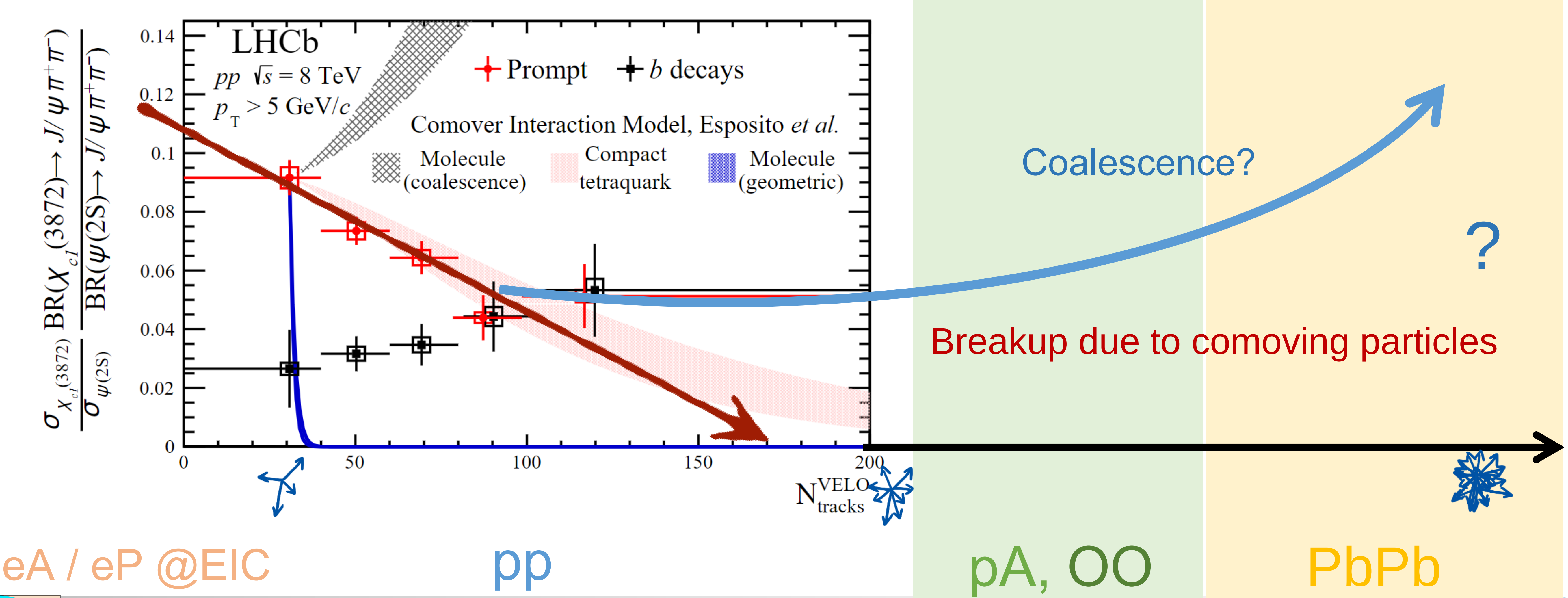
3. Consistency between theoretical calculations:
   Relevance of coalescence hadronization, model dependence and absolute branching fractions
   - Stress test with system size scan: from ep, eA, pp, pO, OO to PbPb
   - Centrality dependence

Summary

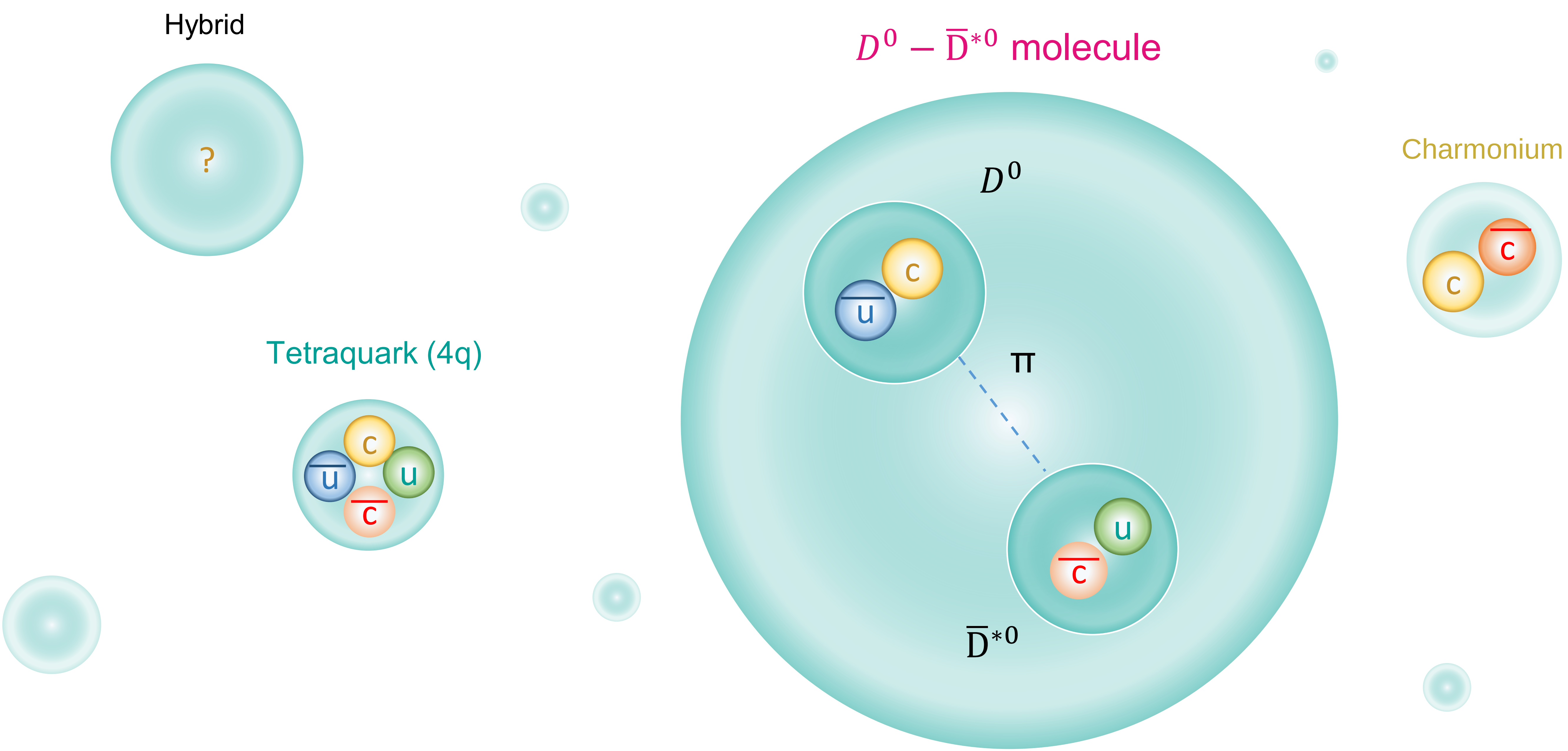
- The first evidence of X in PbPb collision!
  - Probe the X with QGP
- Look forward to high statistics analysis from the smallest to the largest collision systems!

CMS PbPb

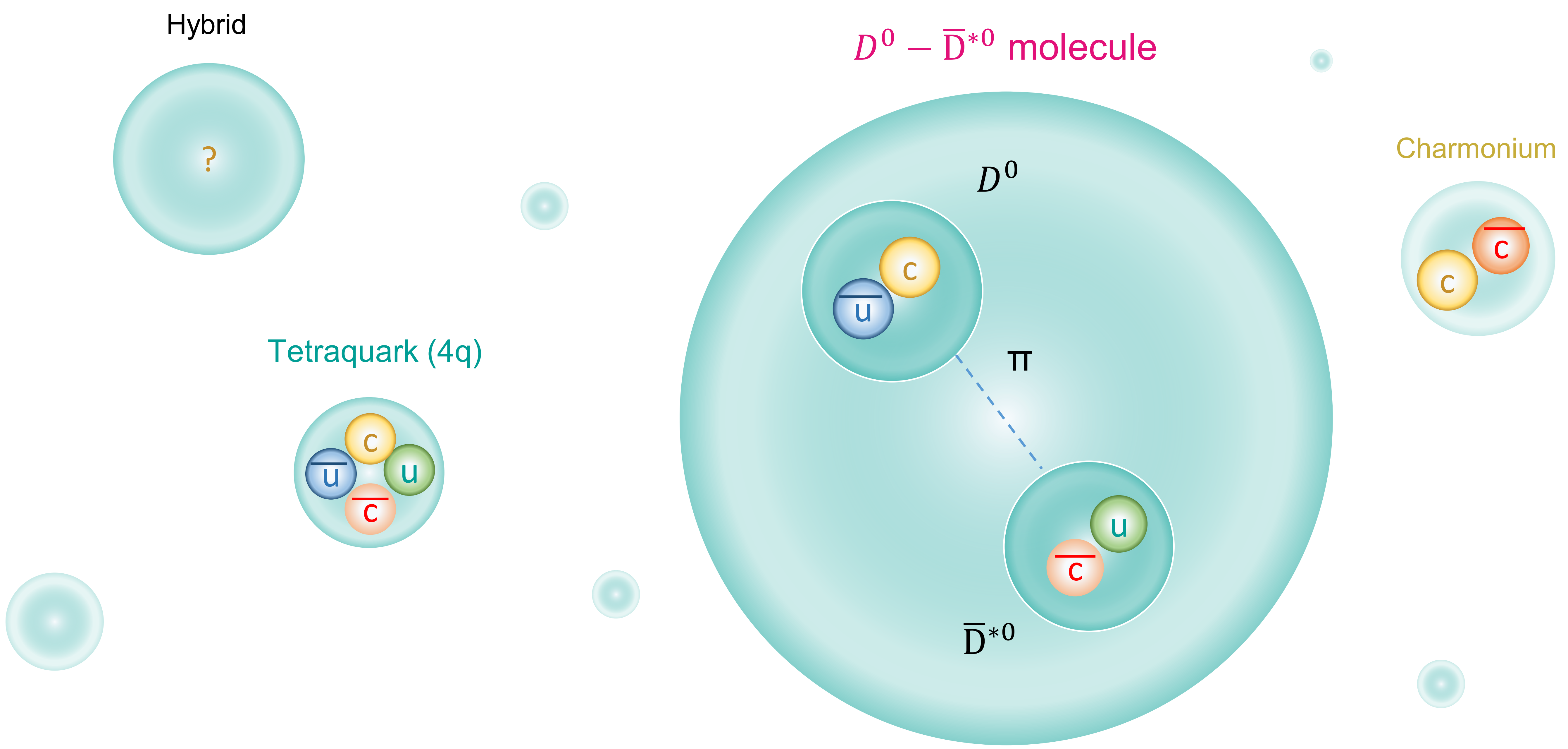
$$\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$$



Thank You!

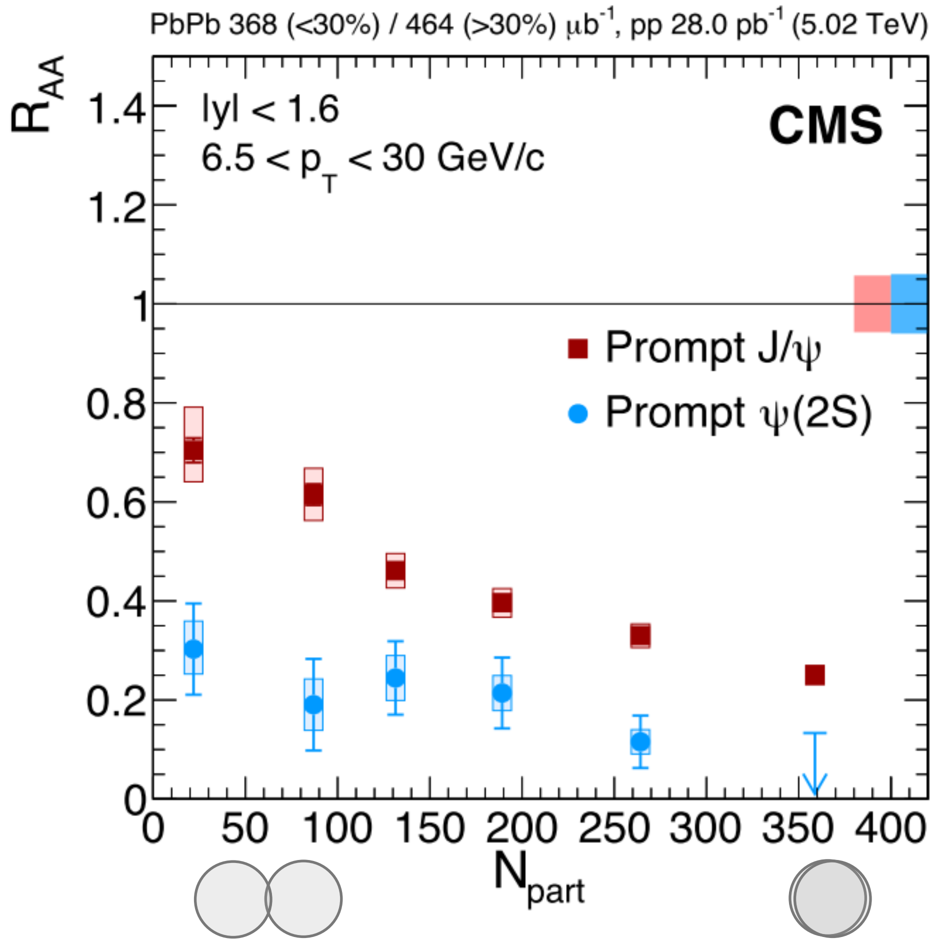

Hybrid
?
Tetraquark (4q)
c
u
u
c
$D^0 - \bar{D}^{*0}$ molecule
D^0
c
u
π
u
c
$\bar{D}^{*0}$
Charmonium
c
c

Backup Slides

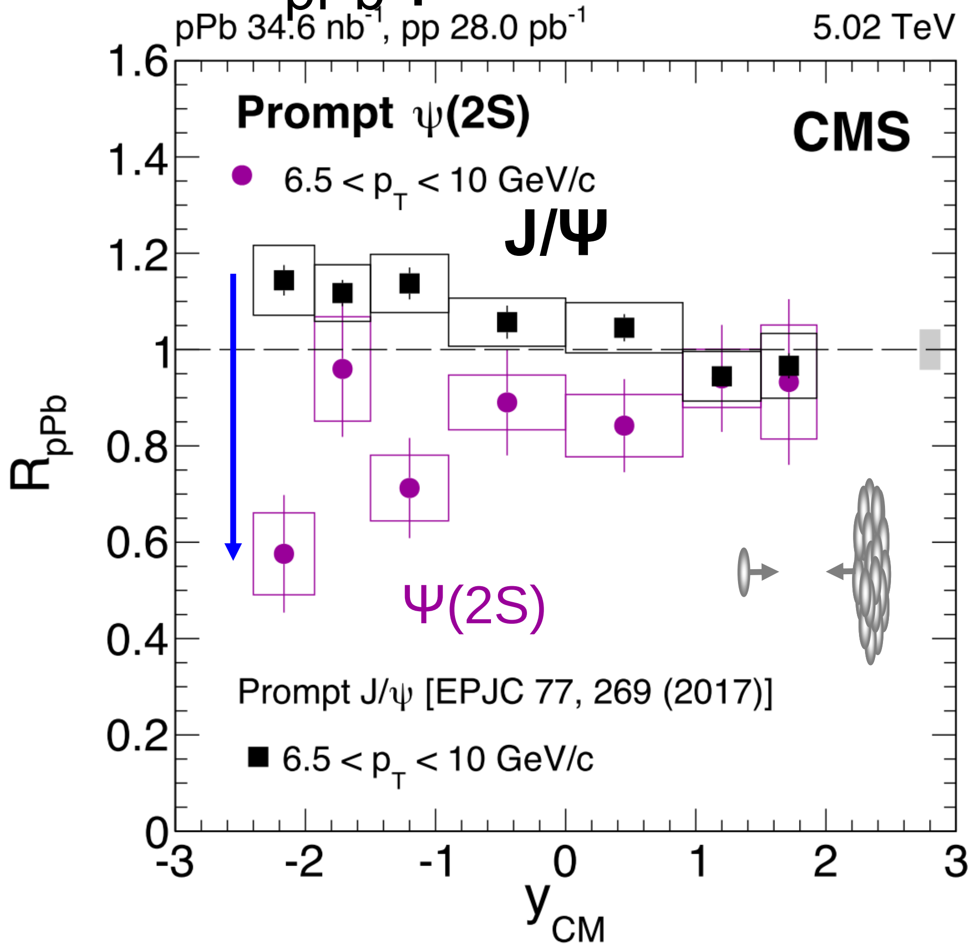


Charmonium R_{AA} in PbPb and pp

PbPb at 5 TeV



R_{pPb} pPb at 5 TeV



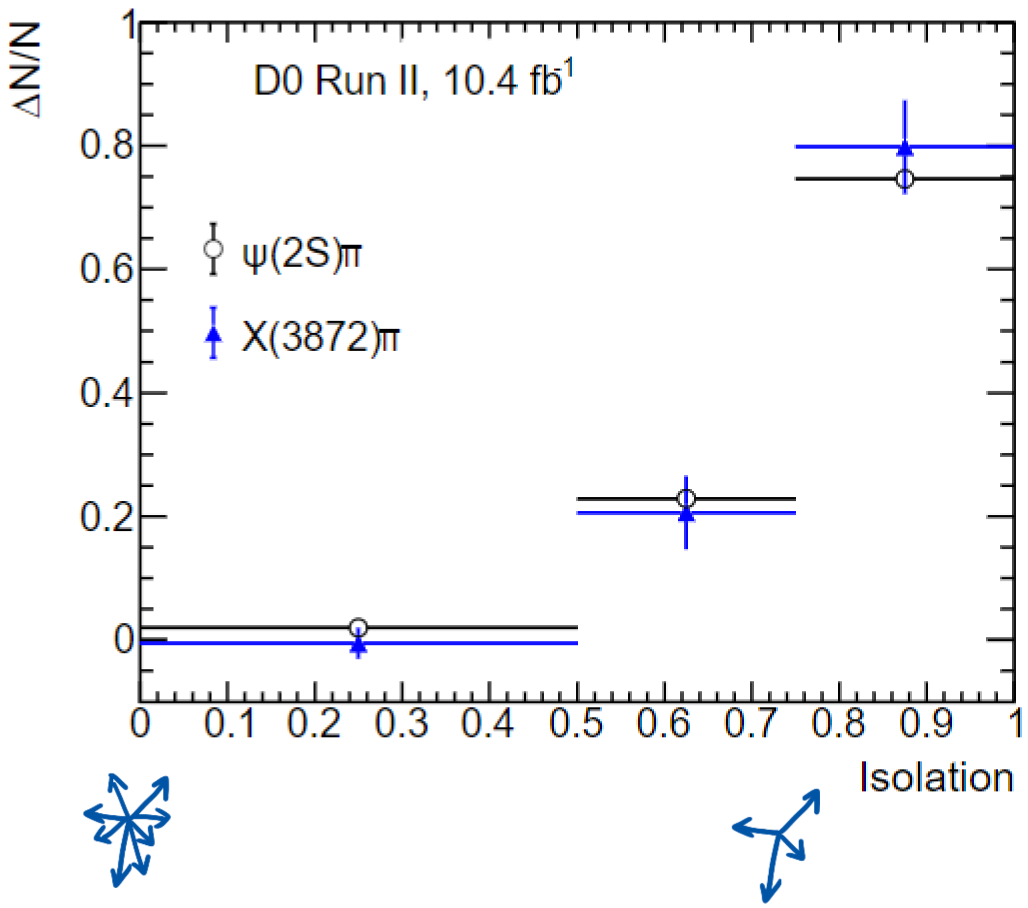
- Prompt Ψ(2S) R_{AA} < J/Ψ R_{AA} in PbPb at 5 TeV

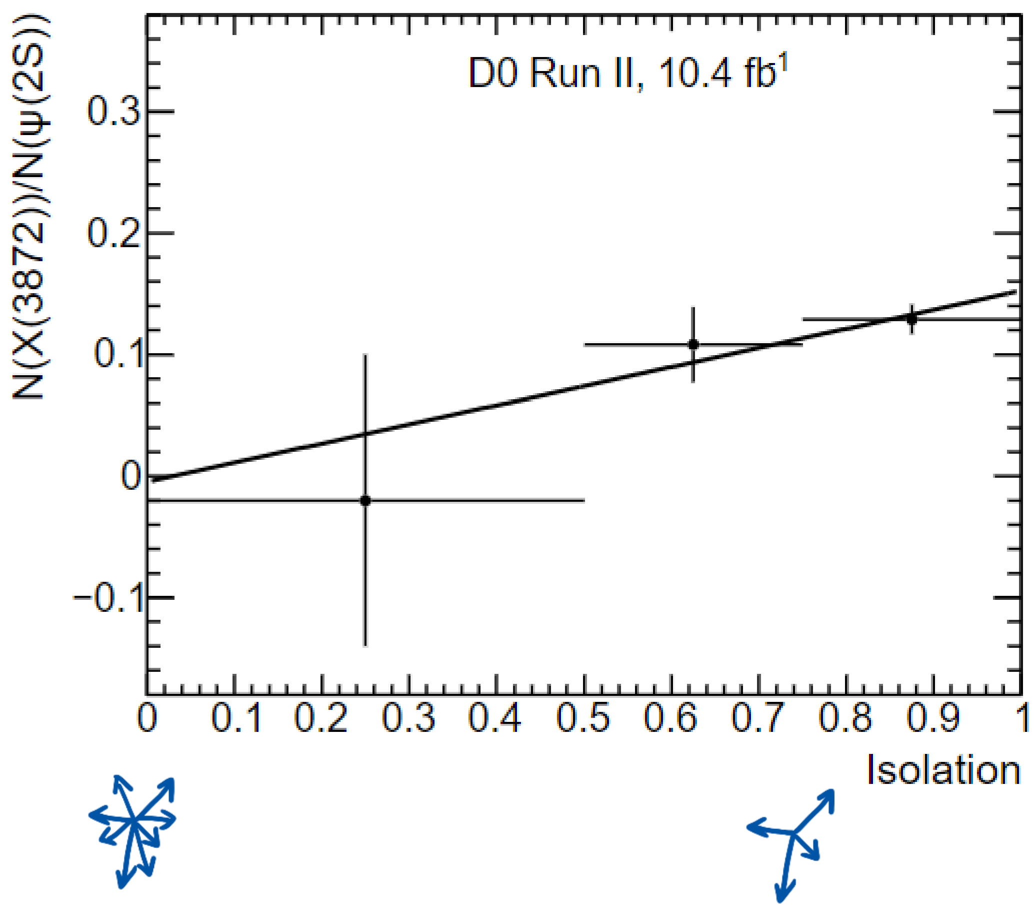
PbPb EPJC 78 (2018) 509

pPb arXiv:1805.02248

- **J/Ψ** and Ψ(2S) difference increases as we move to backward (lead-going) direction (higher dN_{ch}/dy)
- Can not be explained by nPDF or coherent energy loss model
- Final state effects from comoving (local) medium?

DZero measurement in pp



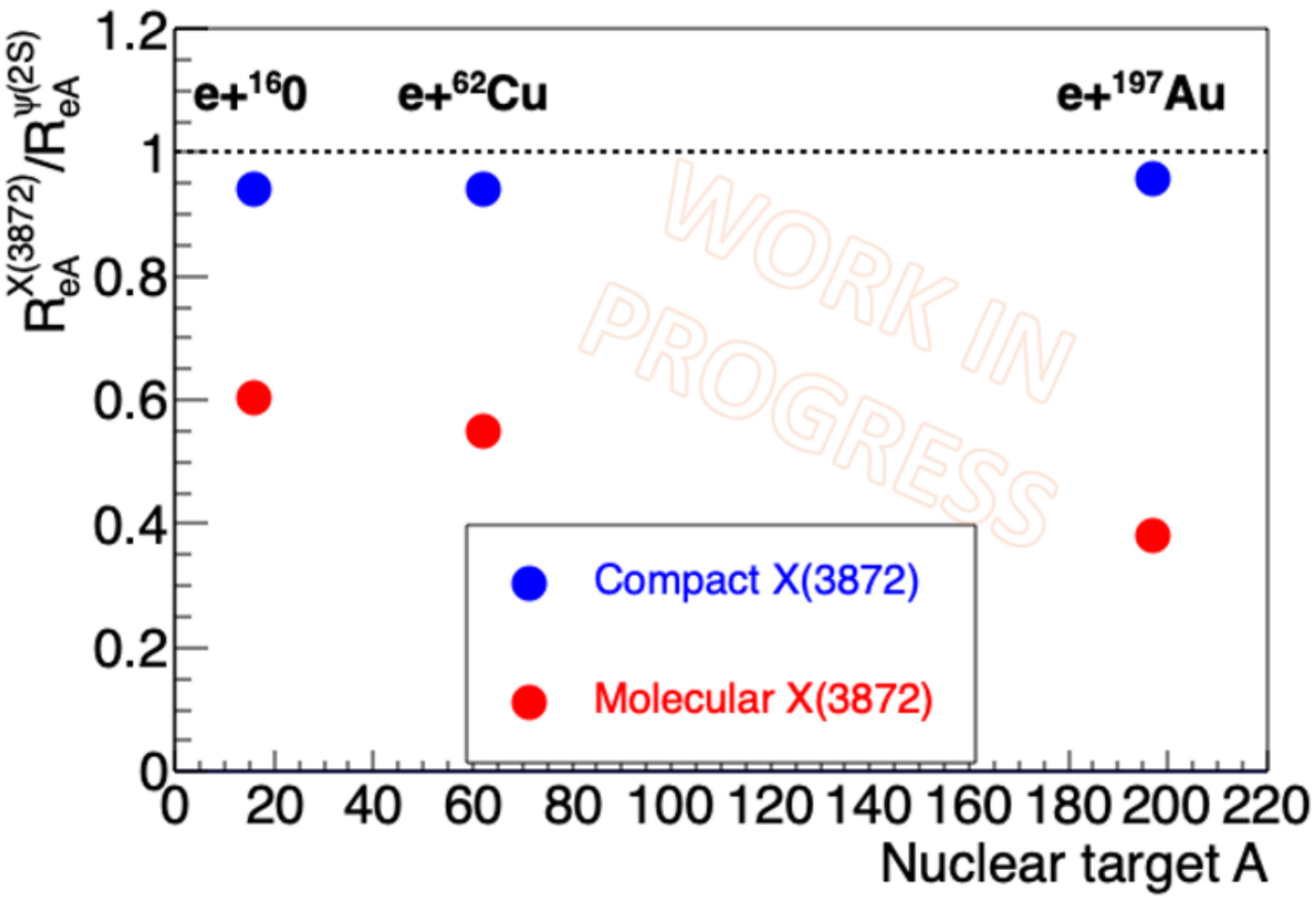


*** Slope significance: 1.2 σ**

- Normalized isolation distribution (1 = fully isolated, no other activities in a cone ΔR<1)
- Modest support for the hypothesis that increased hadronic activity near X(3872) depresses its production

PRD 102, 072005 (2020)

Relative Modification of X(3872) /ψ(2S) at EIC



$$\frac{R_{eA}^{X(3872)}}{R_{eA}^{\psi(2S)}} = \frac{\sigma_{eA}^{X}}{\sigma_{eA}^{\psi}} \Big/ \frac{\sigma_{ep}^{X}}{\sigma_{ep}^{\psi}}$$

- Little difference in suppression between model of compact X(3872) and $\psi(2S)$, as expected.
- Large difference between model of molecular X(3872) and $\psi(2S)$.

Matt Durham (LANL)

- **The EIC has the potential to provide decisive discrimination between exotic structure models.**
  - **X(3872) is only an example, technique can be applied to other exotics as well.**
    - **This work is supported by LANL Lab Directed R&D**

* See Matt Durham's presentation in EF06/07 meeting (Link)