Exotic Hadron Production in High Color Density Environment

Yen-Jie Lee

RF07: Opportunity in Hadron Spectroscopy

18 November, 2020

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

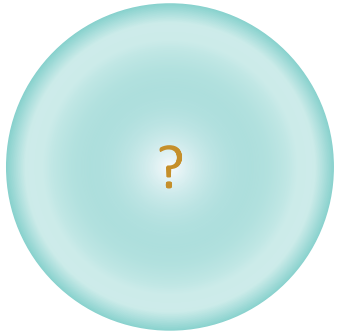
Introduction

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: $\mathbf{J^{PC}=1^{++}}$
- **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

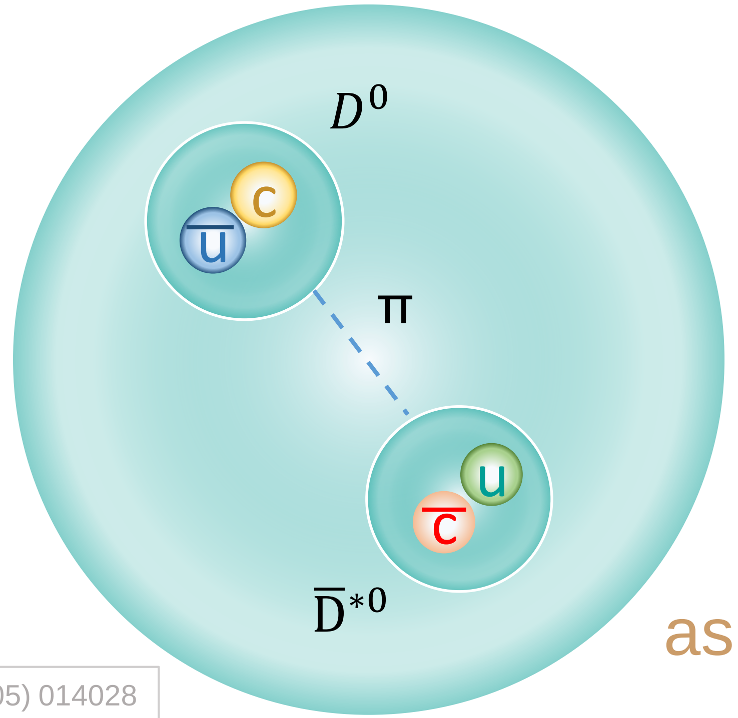
BELLE PRL 91, 262001 (2003)
CDF PRL 98, 132002 (2007)
LHCb PRL 110, 222001 (2013)

Hybrid



EPJA47 (2011) 101

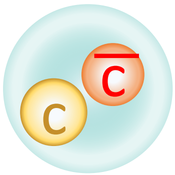
$D^0 - \bar{D}^{*0}$ molecule



$r_{molecule}$
as large as 5 fm

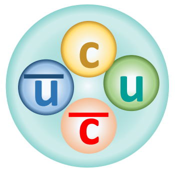
PRD71 (2005) 014028

Charmonium



PLB 590 209-215 (2004)

Tetraquark (4q)



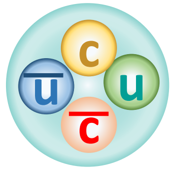
$r_{4q} \approx r_{c\bar{c}}$
≈ 0.3 fm

PRD 71 (2005) 014028

Probe the nature of X(3872)

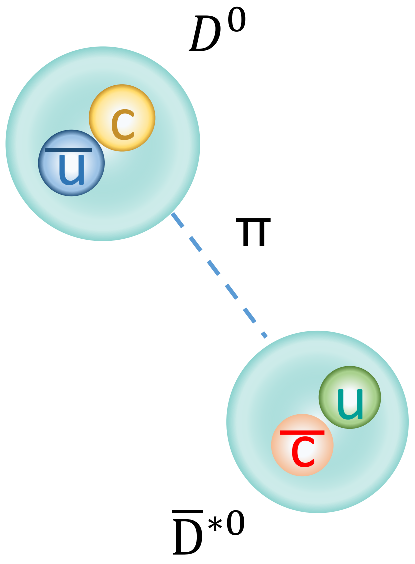
Tightly bound

Tetraquark (4q)



Loosely bound

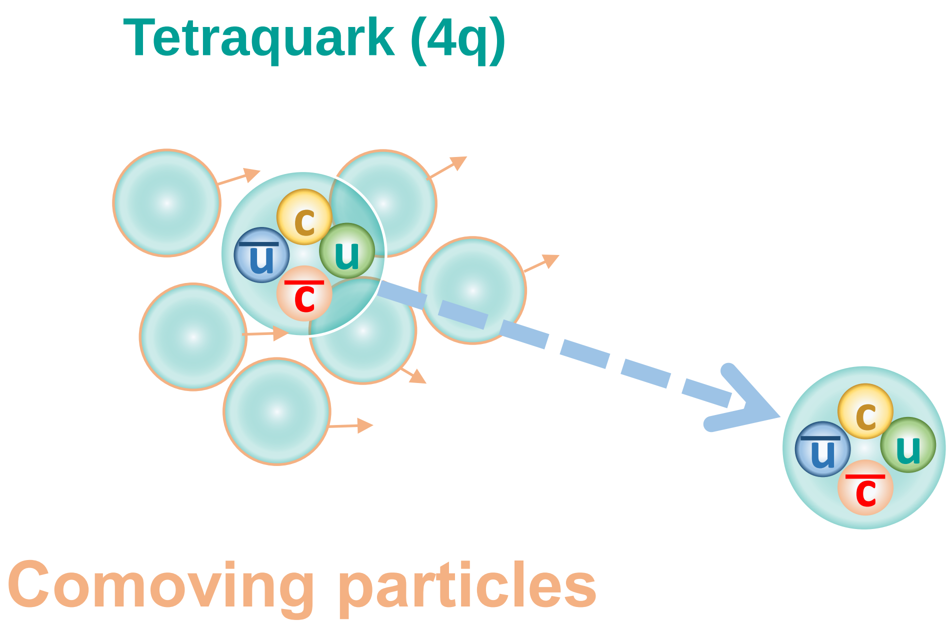
$D^0 - \bar{D}^{*0}$ molecule



Esposito et al, arXiv: 2006.15044

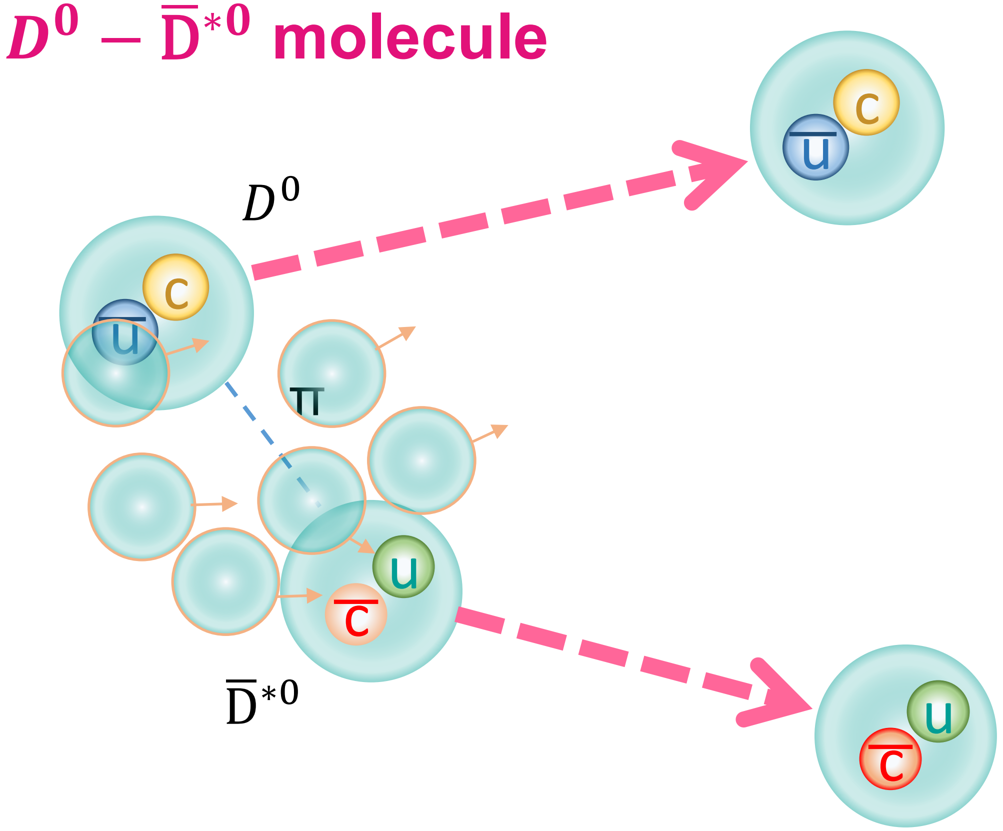
Probe the nature of X(3872) with comoving particles

Tightly bound



Smaller dissociation probability

Loosely bound

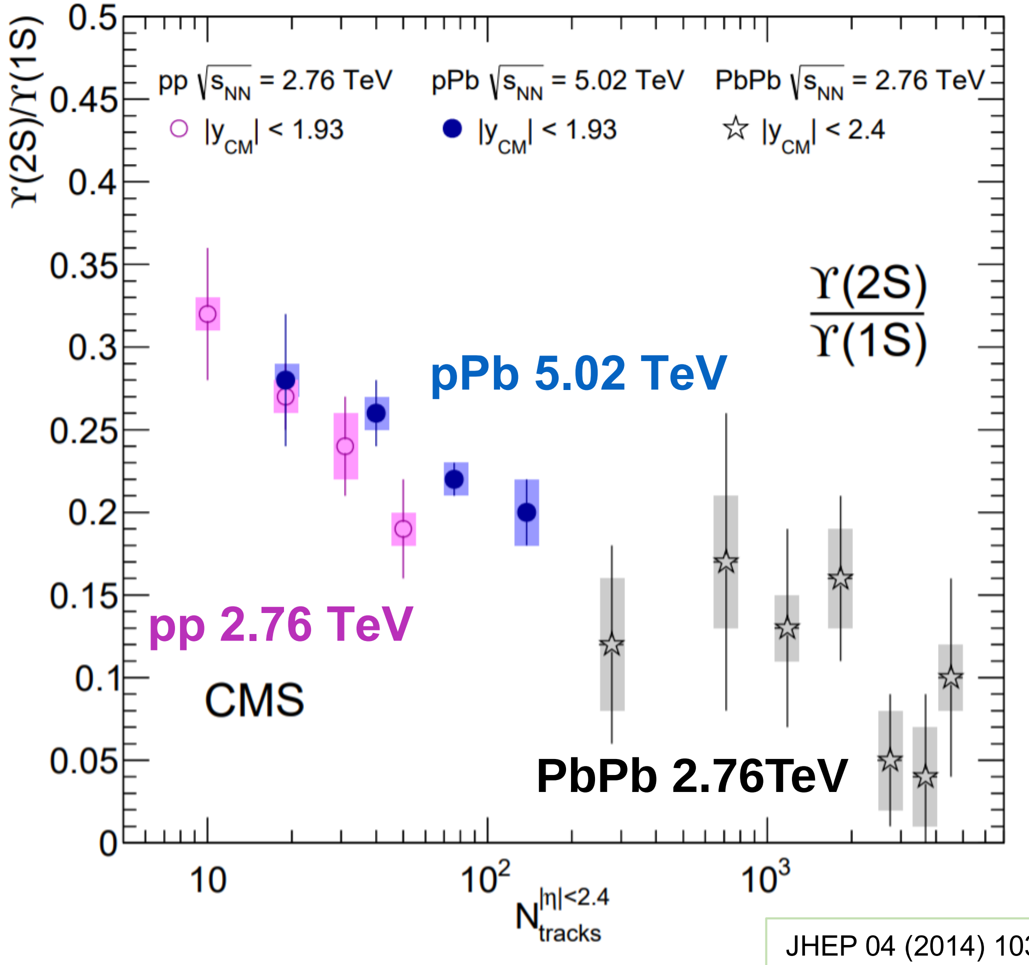


Larger dissociation probability

Esposito et al, arXiv: 2006.15044

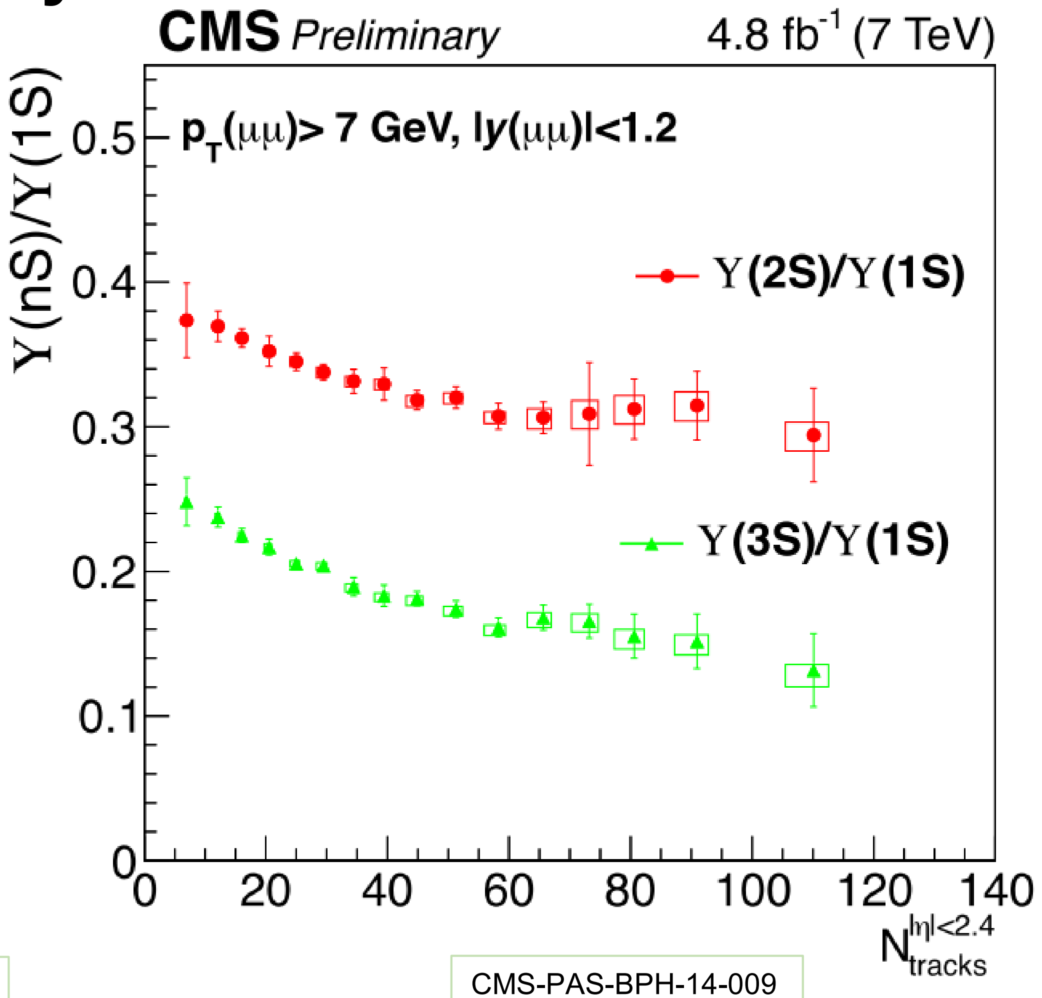
Upsilon Suppression in High Multiplicity Events

Y(2S)/Y(1S) ratio vs. multiplicity



JHEP 04 (2014) 103

pp at 7 TeV



CMS-PAS-BPH-14-009

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

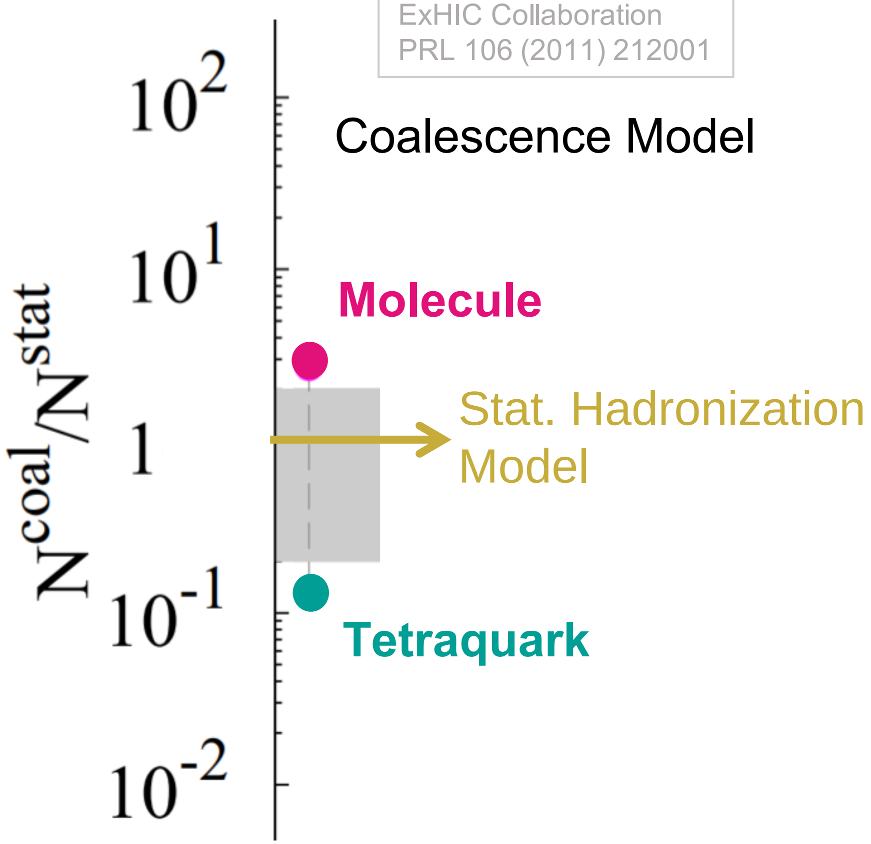
X(3872) Production in Heavy Ion Collisions

X(3872) production in Heavy Ion Collisions

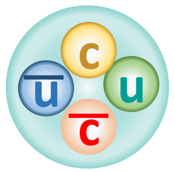
- Production yield in QGP strongly reflects internal structure in the coalescence model
- Hadron Gas Phase: Interact with other hadrons: production + absorption
  $\pi X \rightleftharpoons D\bar{D}, D\bar{D}^*$ & $\rho X \rightleftharpoons D\bar{D}, D\bar{D}^*, D^*\bar{D}^*$
- Radius $r_{4q} \ll r_{mol}$: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



$r_{4q} \approx r_{c\bar{c}}$
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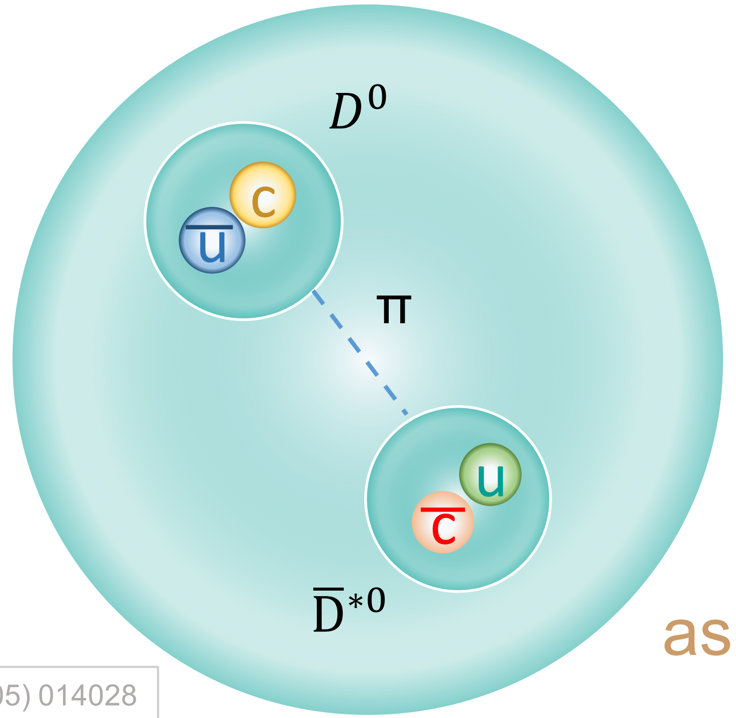
PRD 71 (2005) 014028

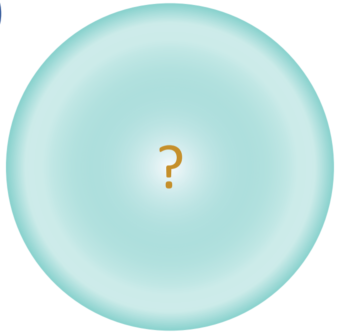
$D^0 - \bar{D}^{*0}$ molecule



PRD71 (2005) 014028

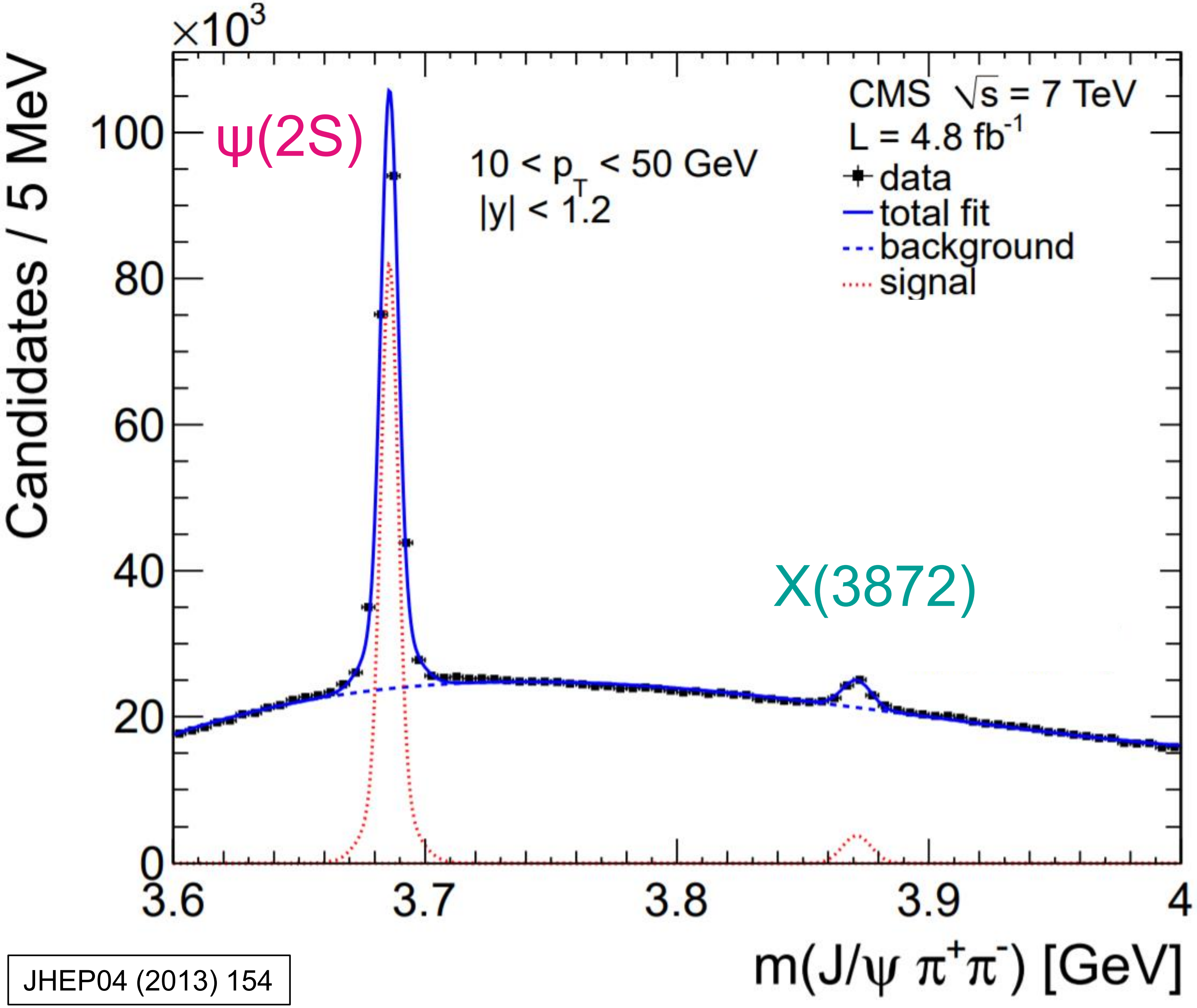
$r_{molecule}$
as large as 5 fm

Hybrid



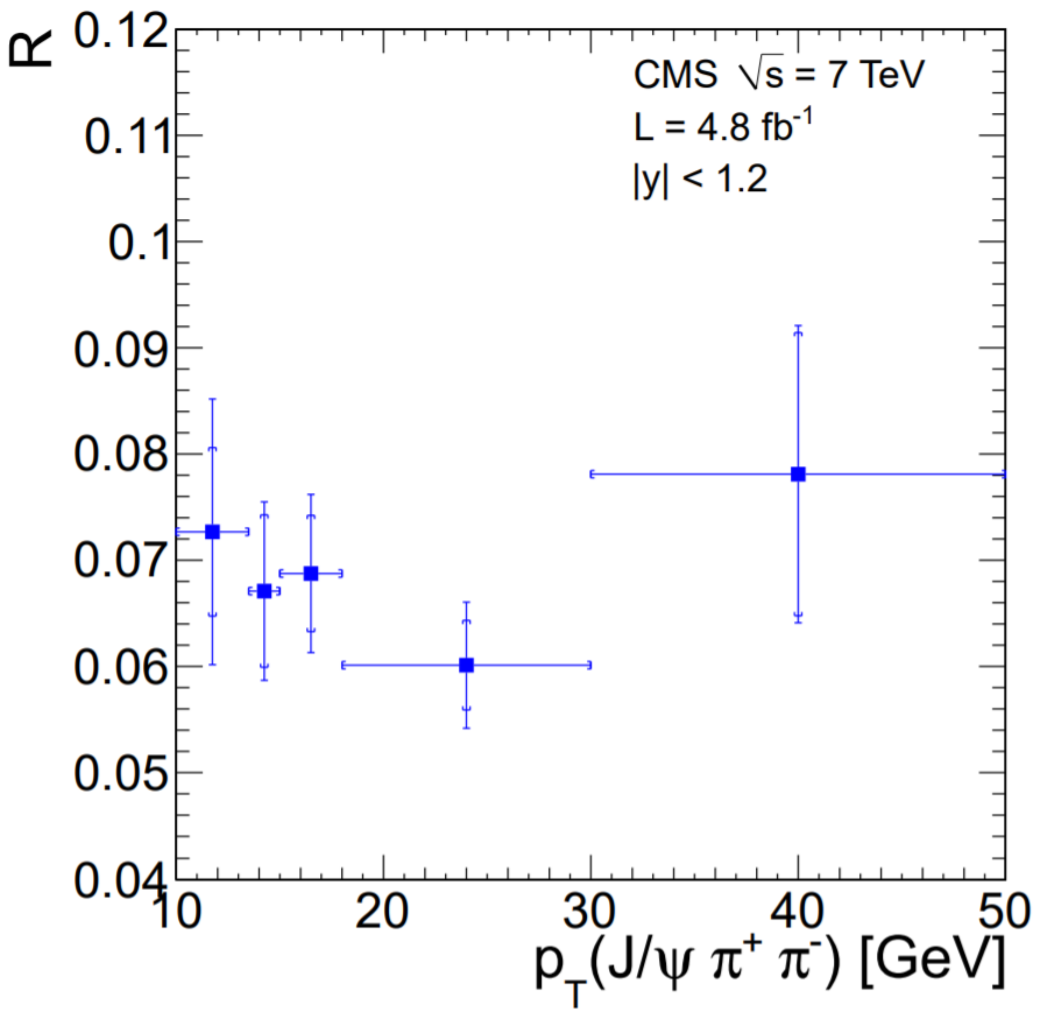
EPJA47 (2011) 101

Invariant Mass Spectra in pp Collisions at 7 TeV



JHEP04 (2013) 154

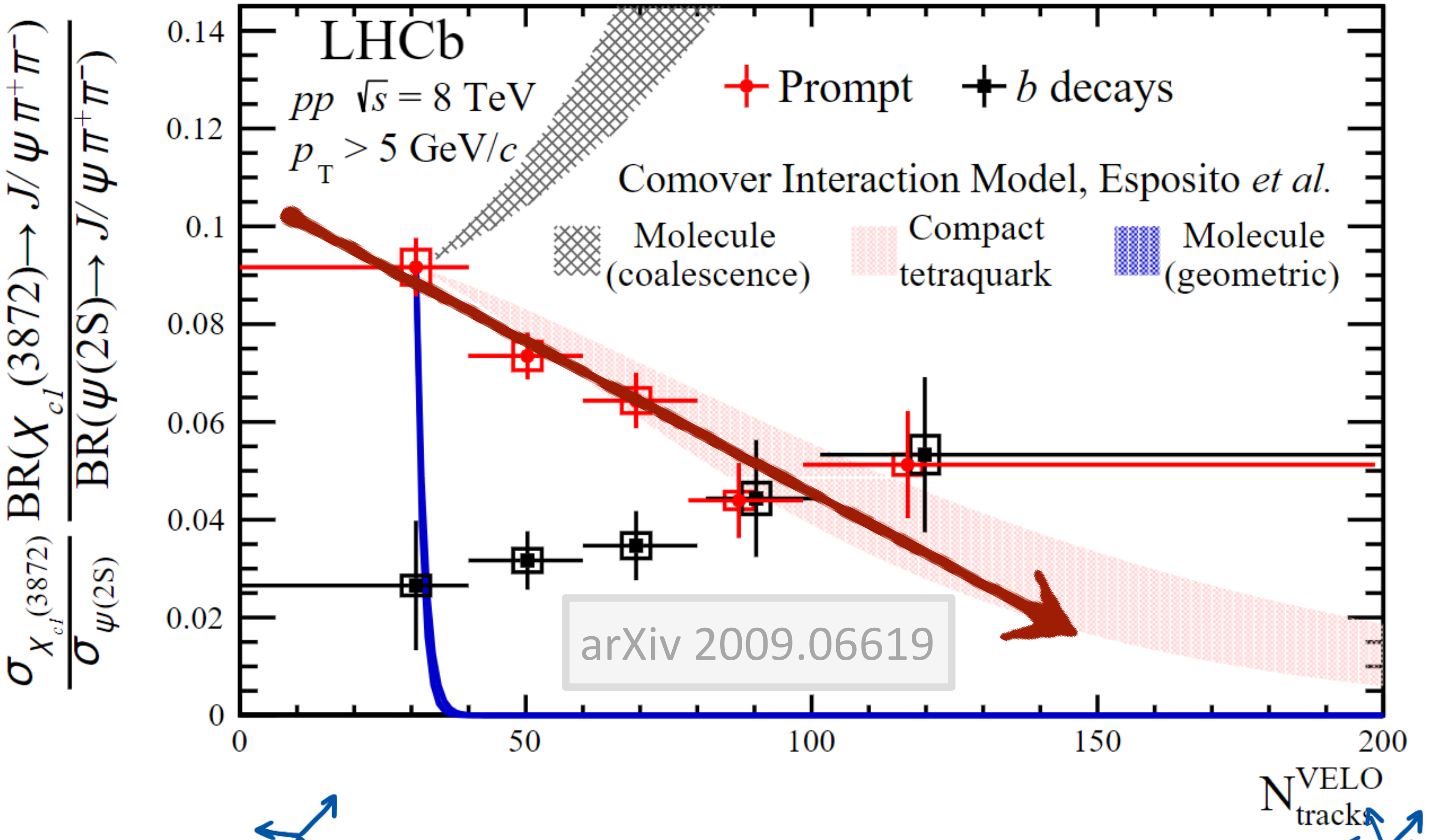
Inclusive X(3872) to ψ(2S) production ratio (include both prompt and nonprompt)



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

X(3872) in High Multiplicity pp from LHCb

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

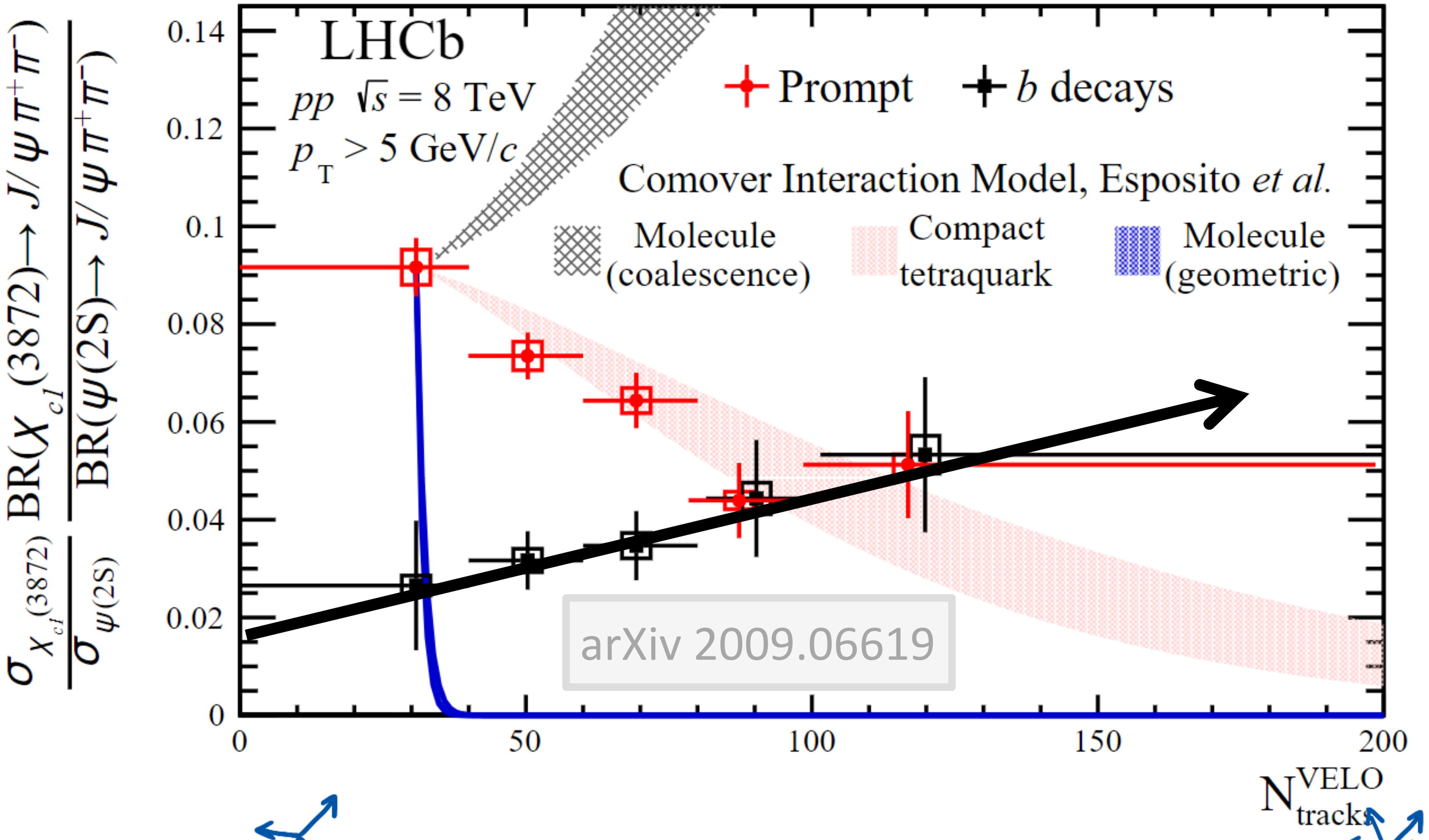


*** Slope significance: 5 σ**

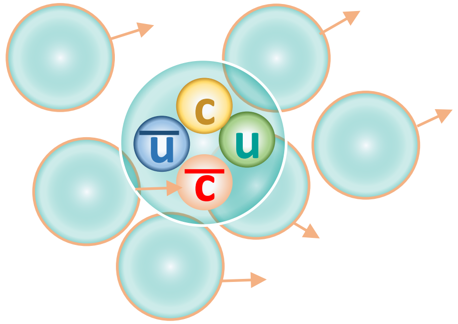
- Destroyed by interactions with other hadrons due to smaller binding energy?

Non-prompt X(3872) in pp from LHCb

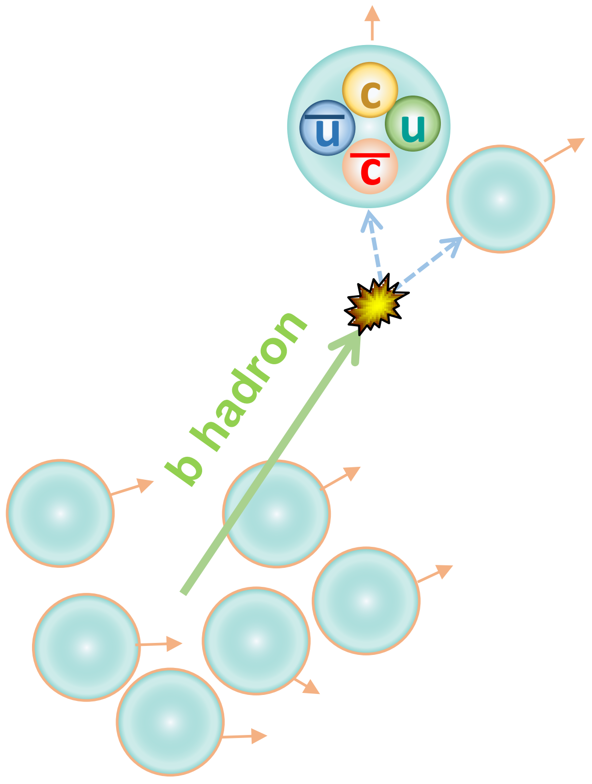
Prompt X(3872)/ψ(2S) vs. multiplicity in pp



* **Slope significance: 1.6 σ**



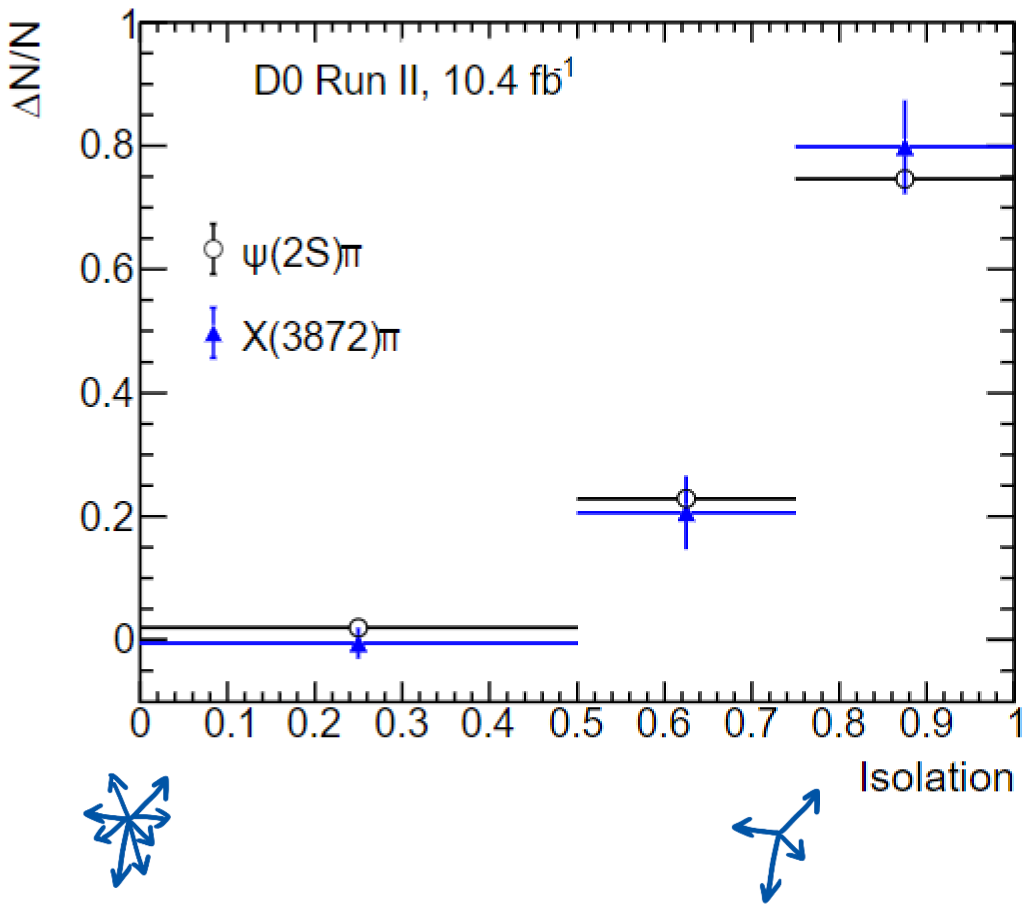
Prompt X

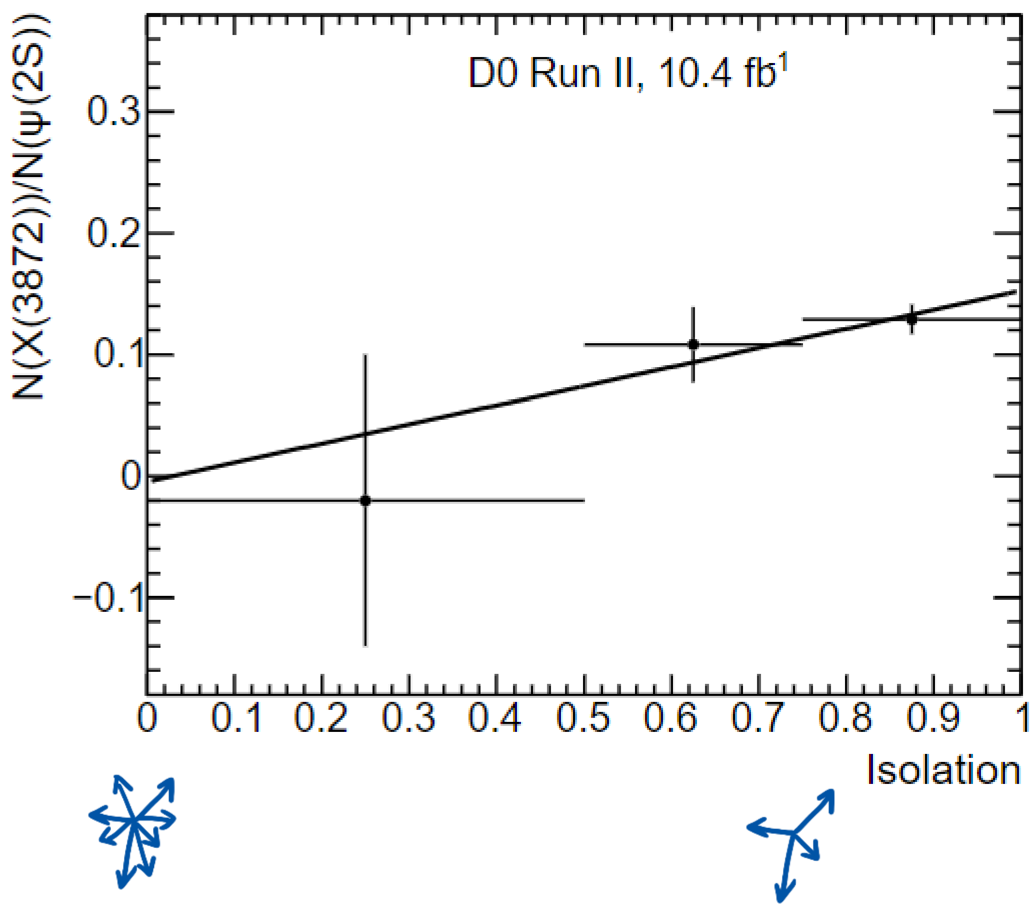


b hadron → X + hadrons

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

DZero measurement in pp





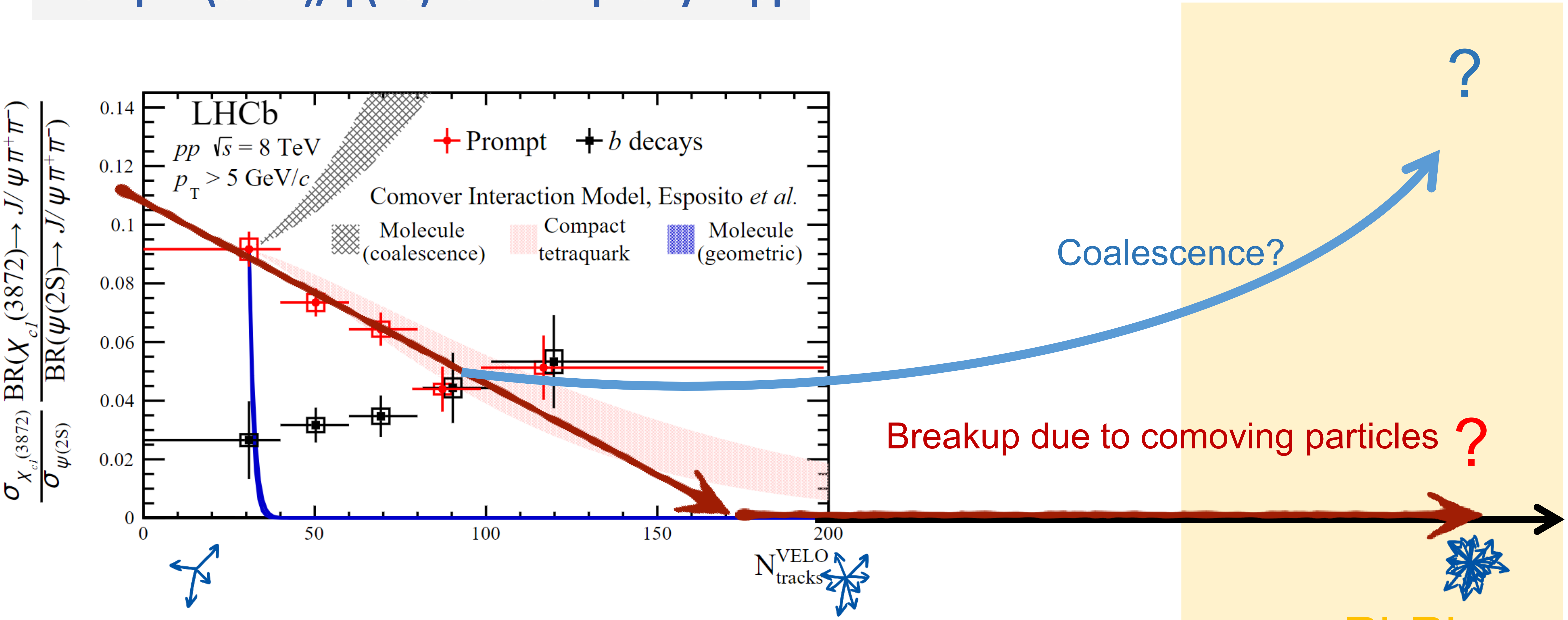
*** Slope significance: 1.2 σ**

- 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

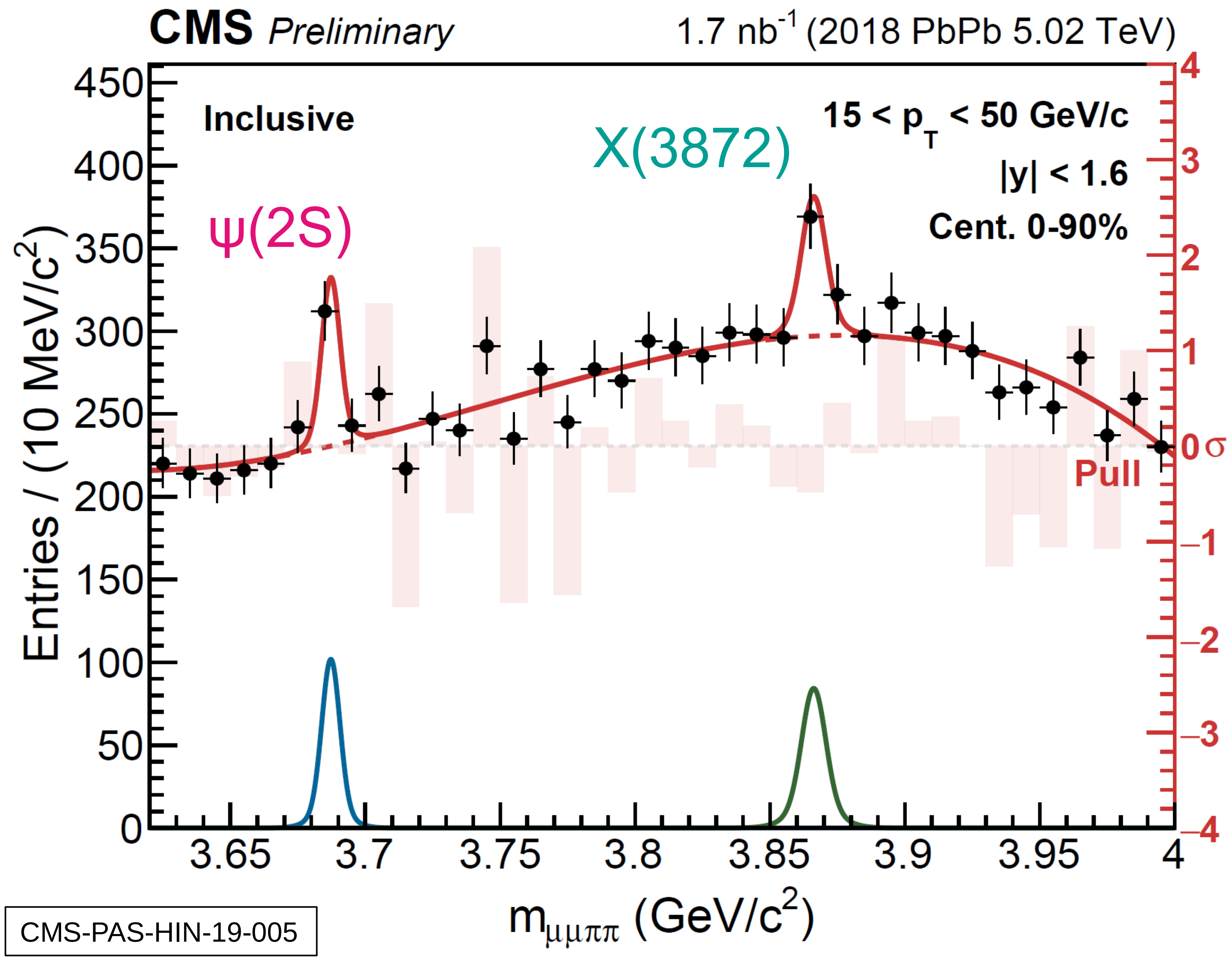
PRD 102, 072005 (2020)

X(3872) in PbPb?

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



Invariant Mass Spectra in PbPb Collisions at 5 TeV



CMS-PAS-HIN-19-005

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

  (statistical significance > **3σ**)

- 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

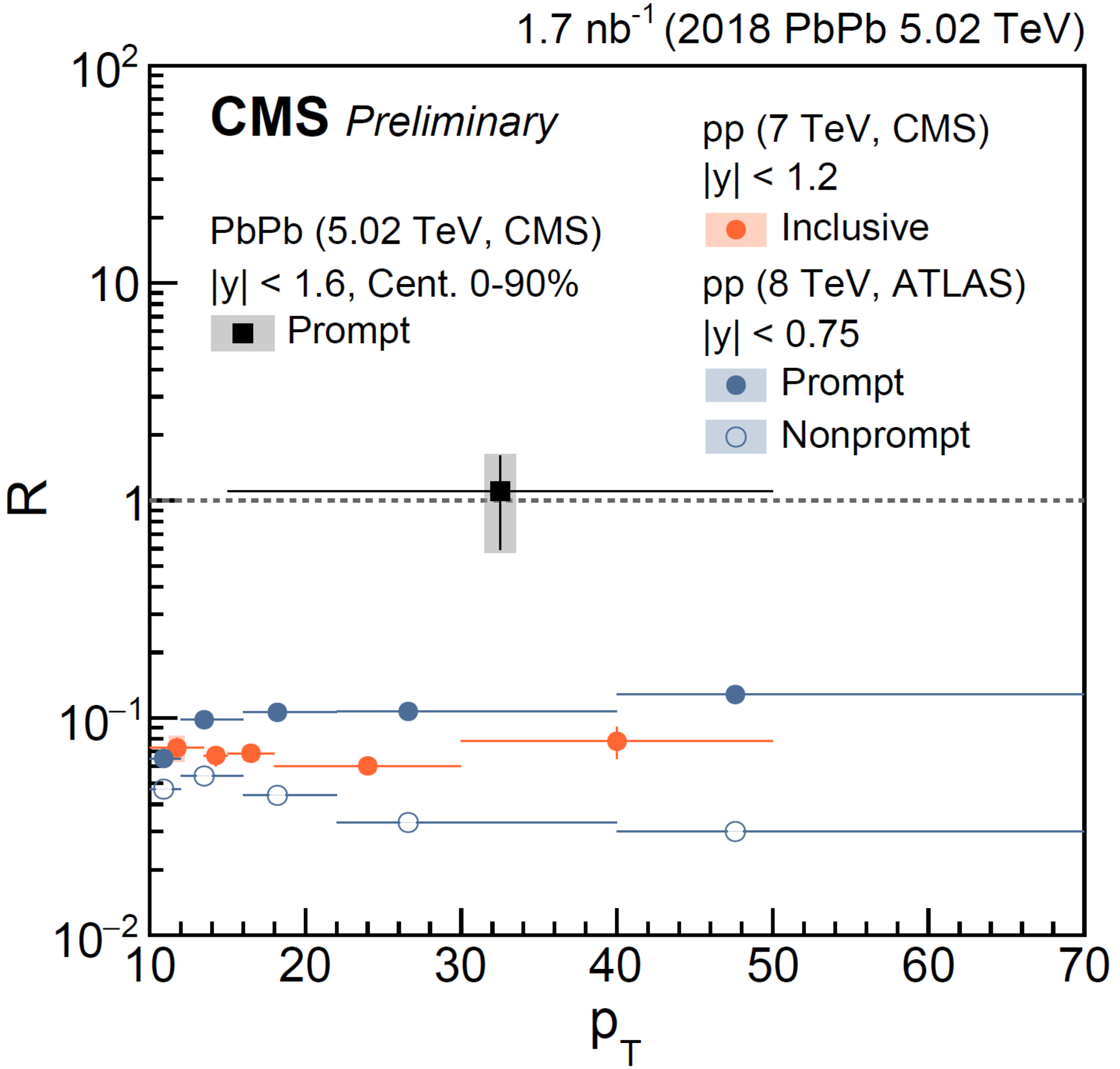
Ratio of X(3872) to ψ(2S) Yields in pp and PbPb

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

In PbPb collisions:

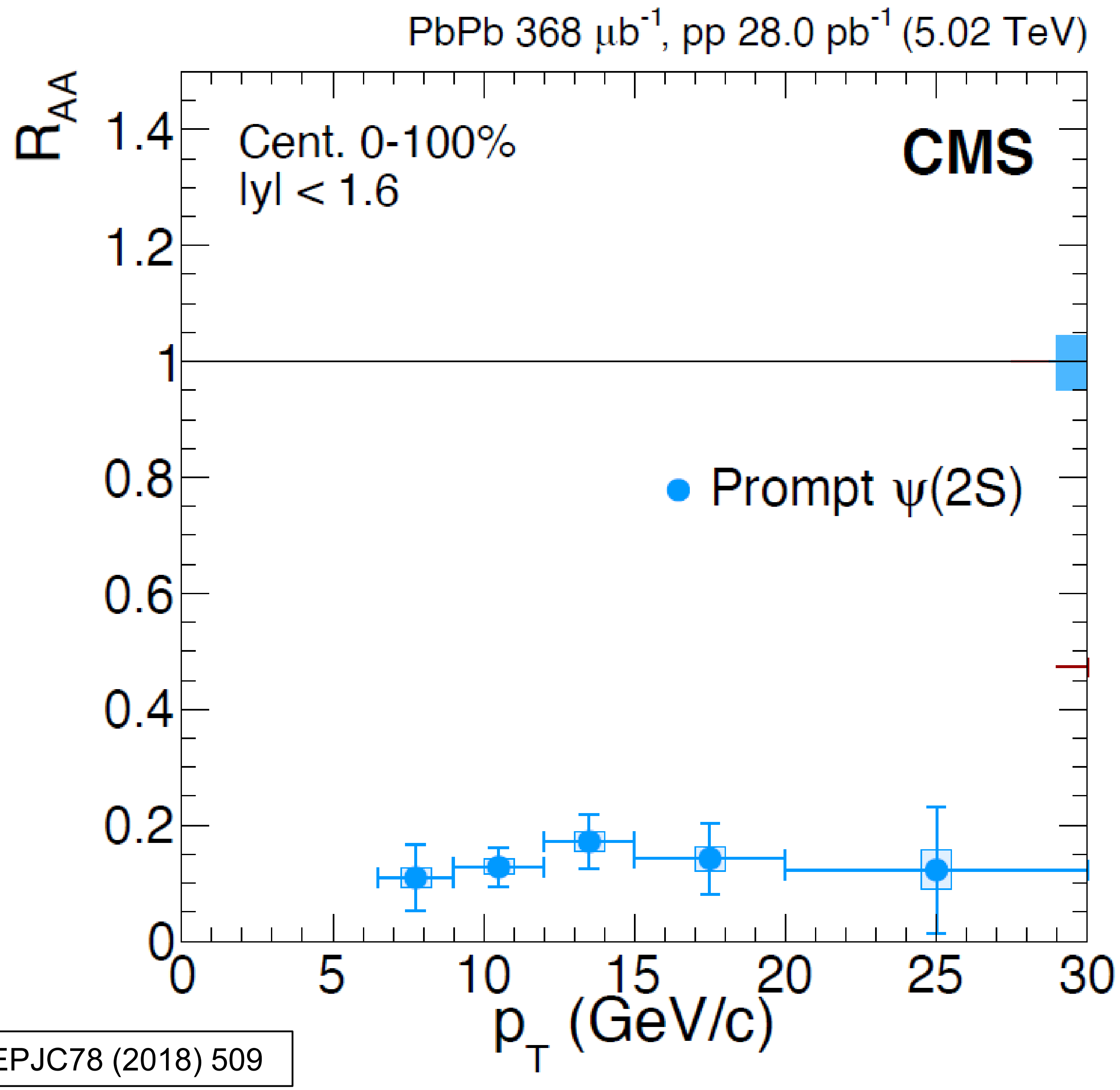
$$R = 1.10 \pm 0.51\ (\mathrm{stat.})\ \pm 0.53\ (\mathrm{syst.})$$

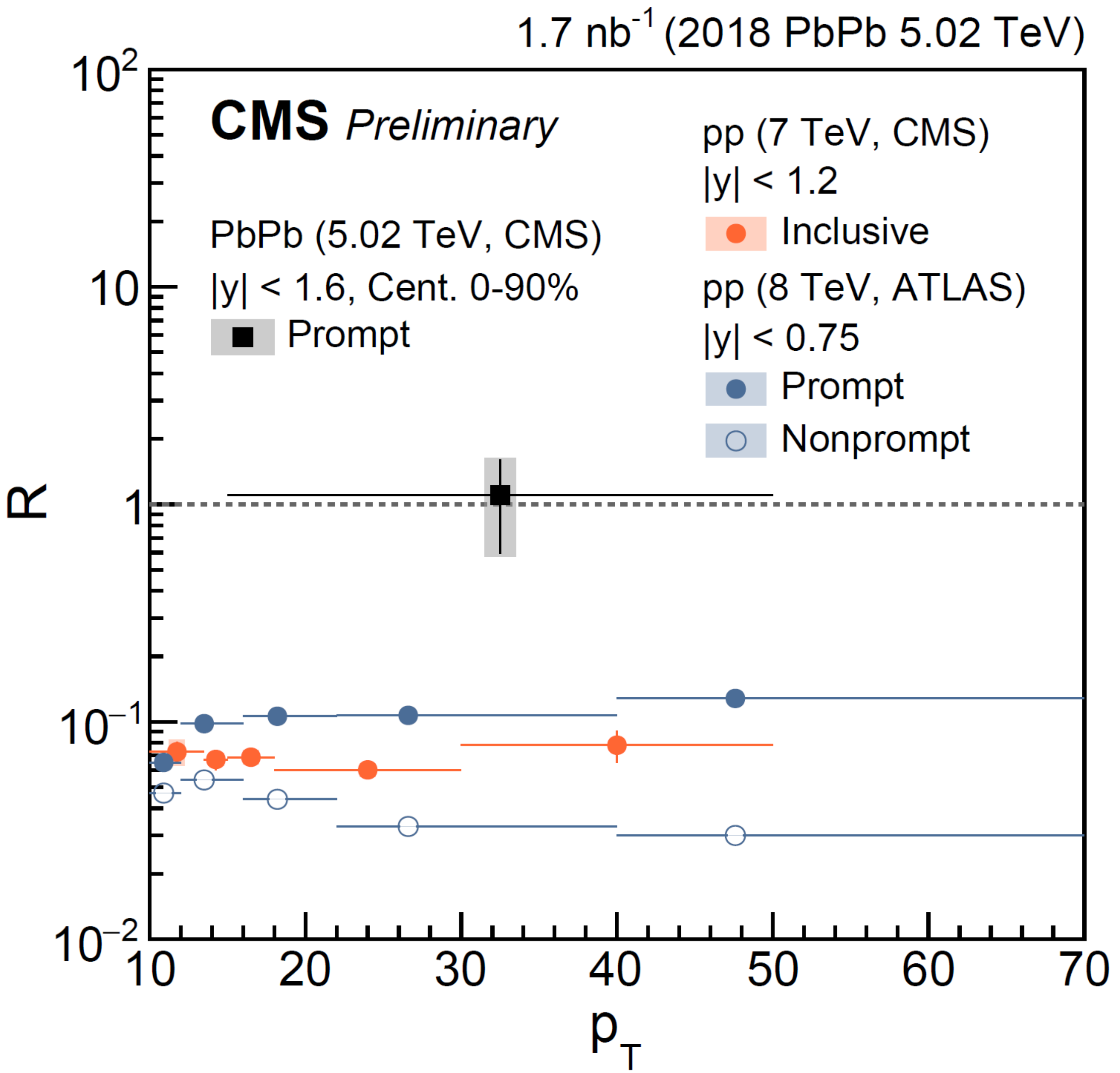
Indication of R enhancement in PbPb collisions with respect to pp at 7 and 8 TeV



CMS-PAS-HIN-19-005

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



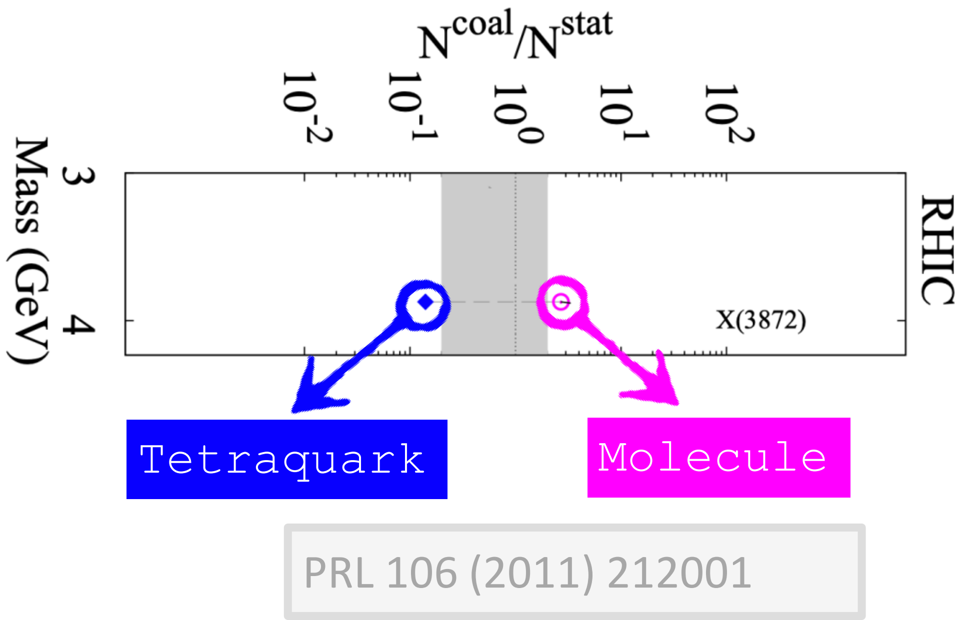


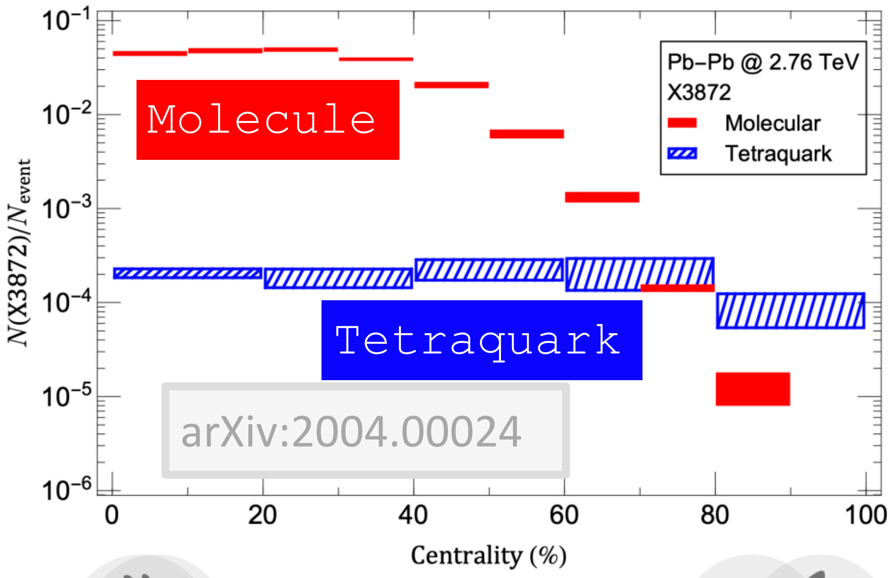
EPJC78 (2018) 509

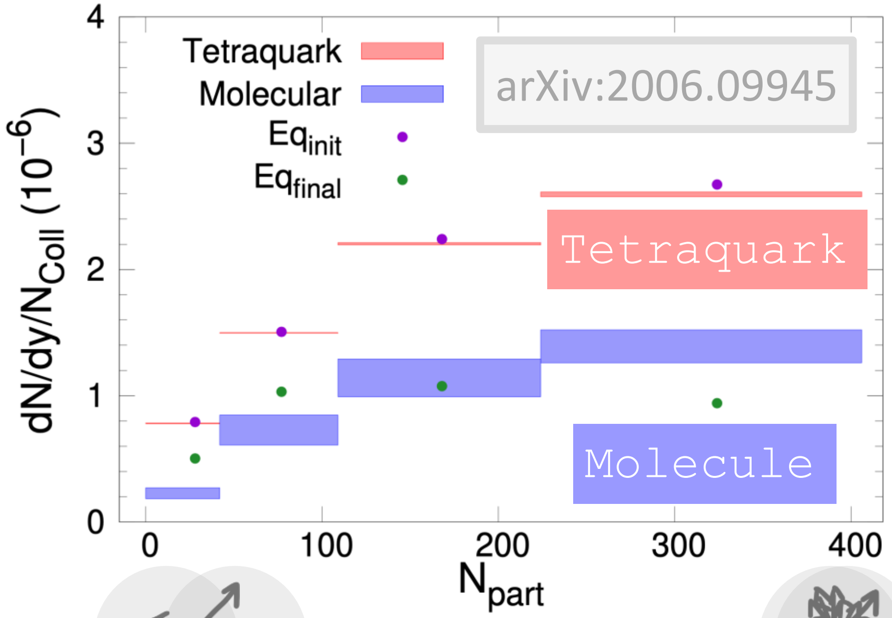
X(3872) Production

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

Coalescence model	AMPT transport model	TAMU transport model







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

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

- 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

LHC, RHIC and EIC Timeline

LHC — pO, OO, pPb — **HL-LHC**

PbPb 1.8 nb^{-1} | PbPb 7 nb^{-1} | PbPb 7 nb^{-1}

Run 2 | Long shutdown 2 | Run 3 | Long Shutdown 3 | Run 4

LHCb SMOG | LHCb SMOG2 (x100 higher rate)

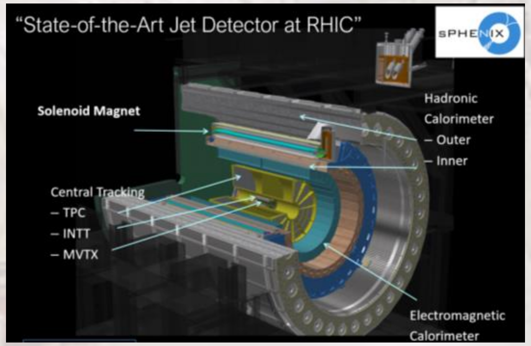
CMS/ATLAS Phase 1 Upgrade | CMS/ATLAS Phase 2 Upgrade

ALICE Upgrade (fast readout 50kHz) | ALICE LS3 Upgrade | New Detector? (Run5)

2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030

sPHENIX construction

sPHENIX Installation commissioning



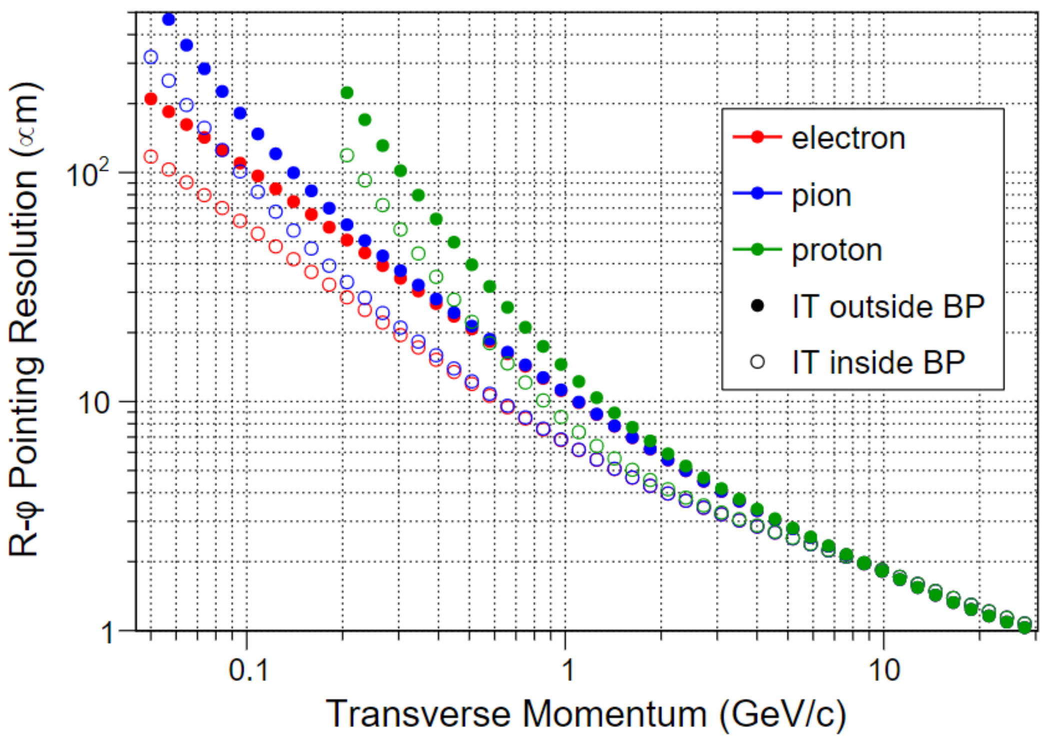
Run 1 | Run 2 ?

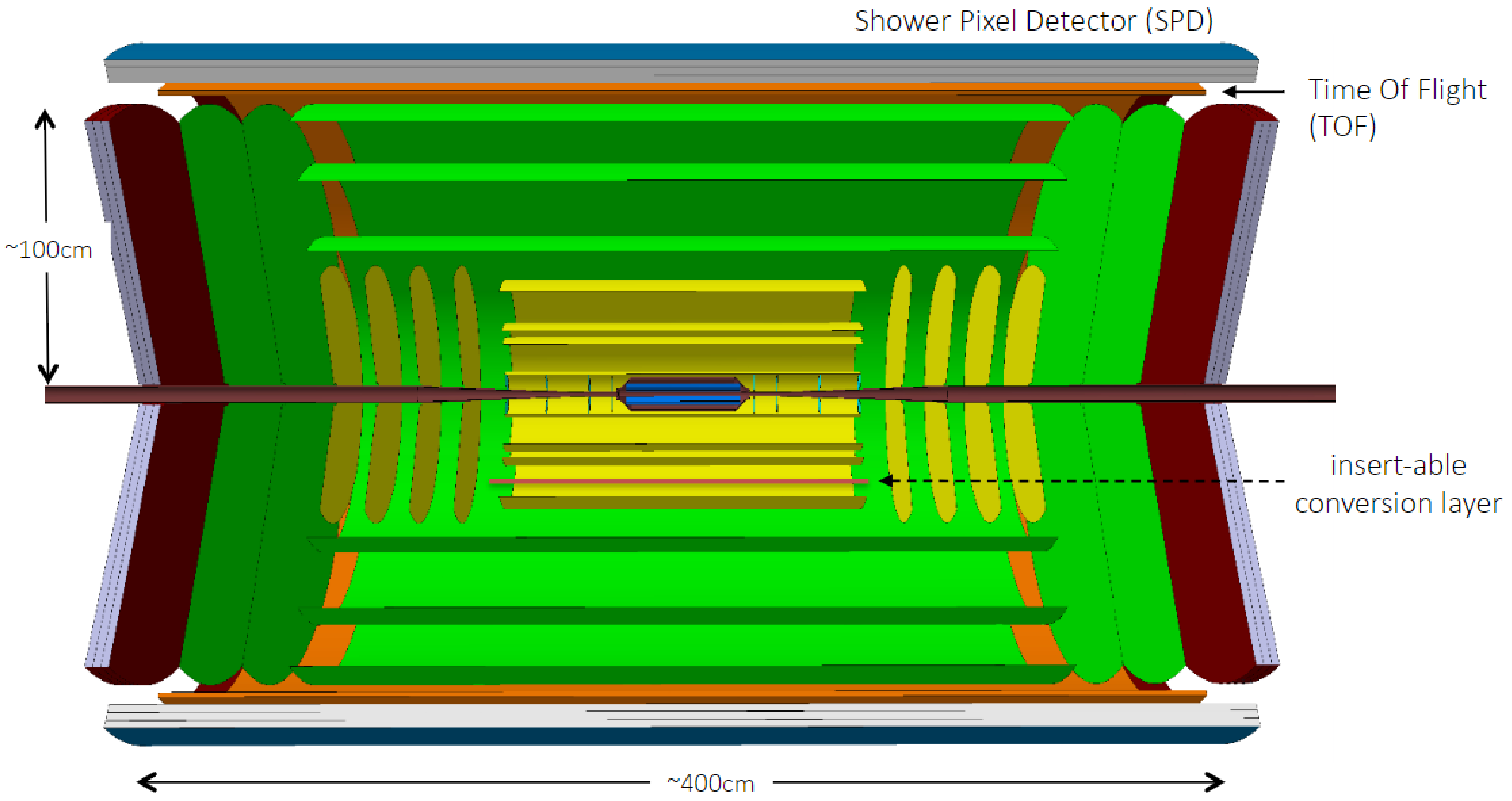
pp, pAu | pp, ArAr, OO

RHIC — **EIC**

AuAu 30 nb^{-1} | AuAu 30 nb^{-1}

A next-generation LHC heavy-ion experiment

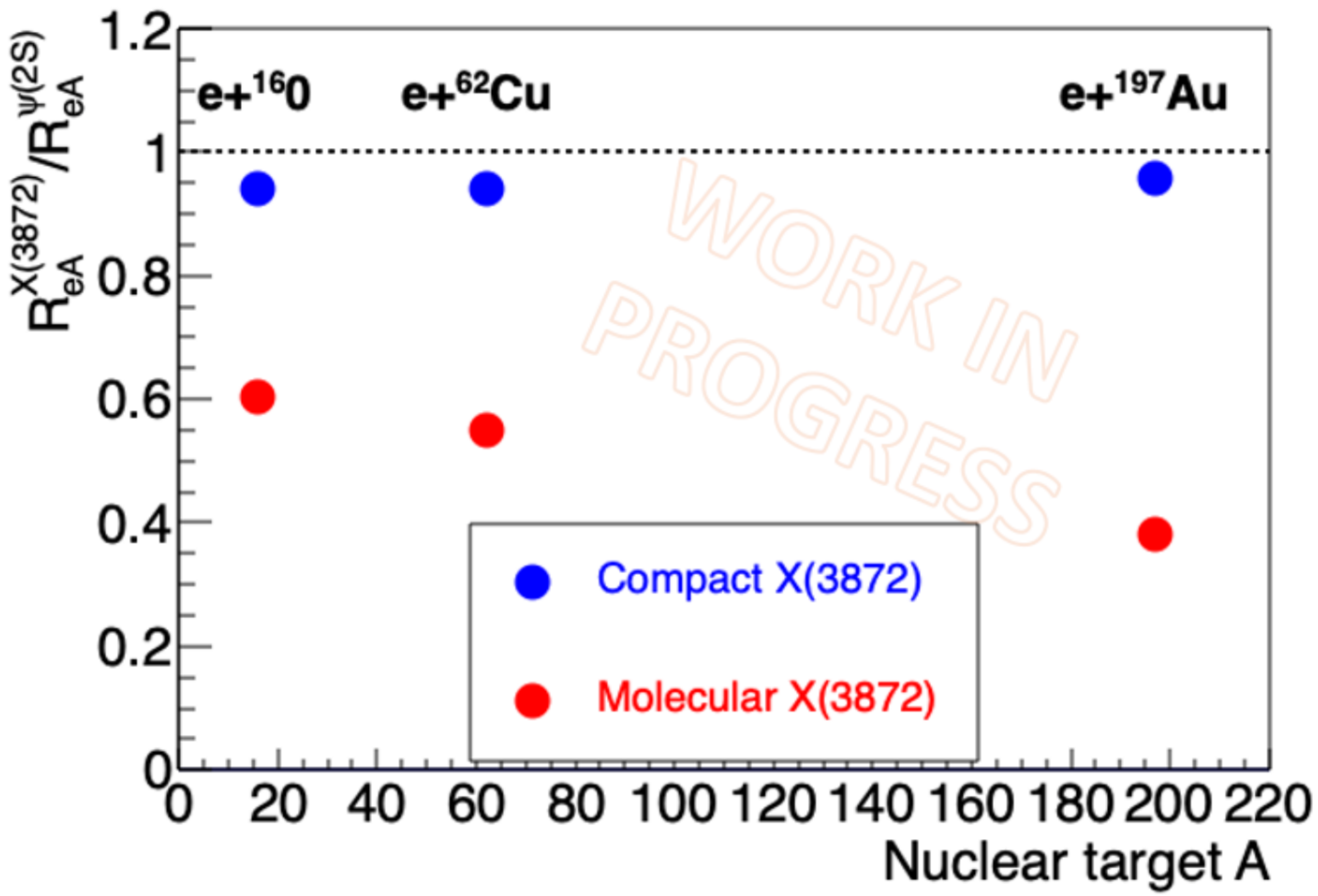




- Proposed after Run 5, optimized for heavy flavor meson and baryon reconstruction; detection of very low p_T charged particles
- Wide pseudorapidity coverage (up to 4 units), most likely equipped with forward tracking stations
- Could shed new light on the nature and structure of the X, Y, Z
- X(3872) yield is expected to be particularly enhanced at low transverse momenta (p_T<4 GeV/c)

See this documentation for details (Link)

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



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

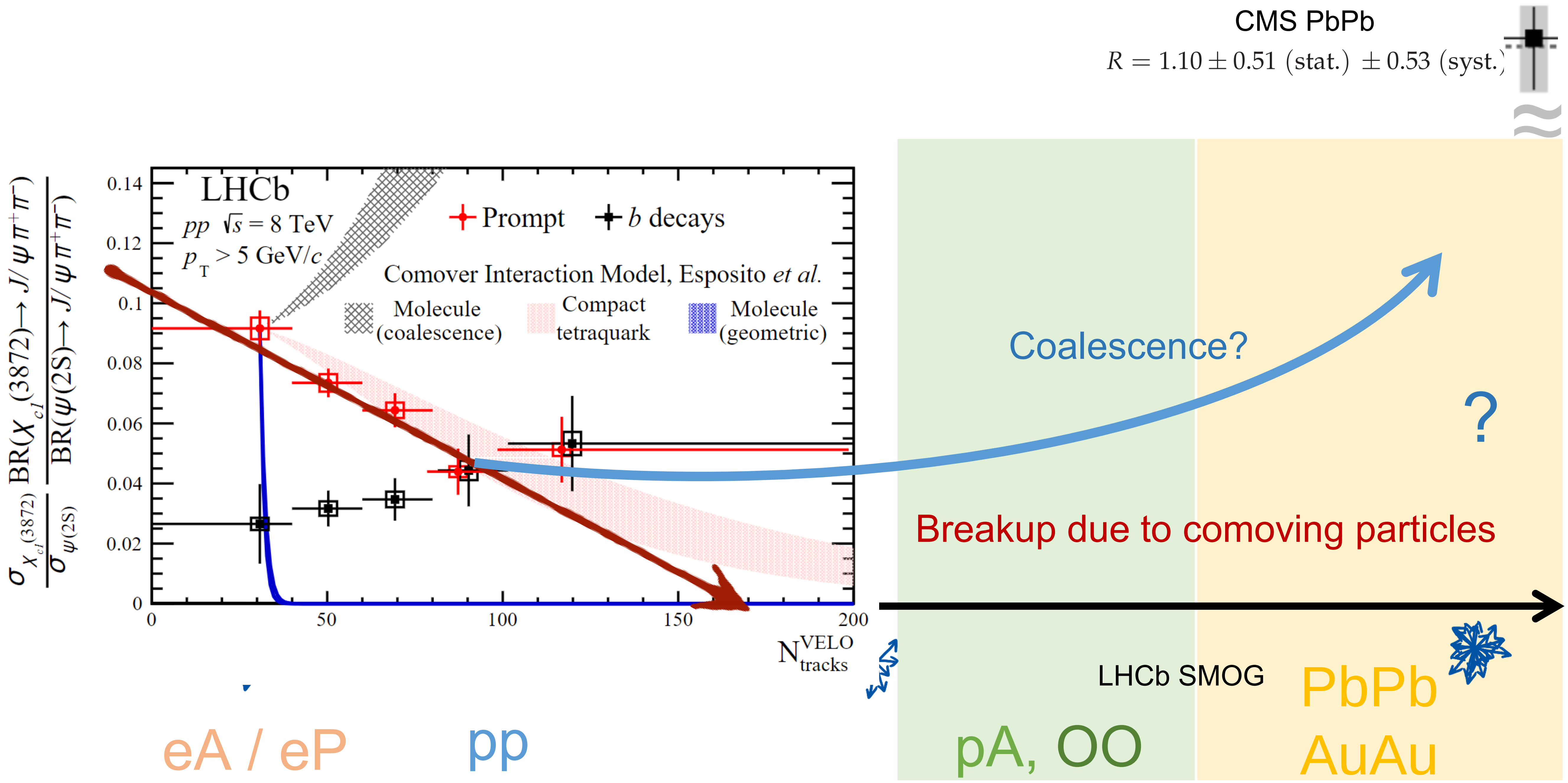
- Little difference in suppression between model of compact X(3872) and $\psi(2S)$, as expected.
- Large difference between model of molecular X(3872) and $\psi(2S)$.

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**

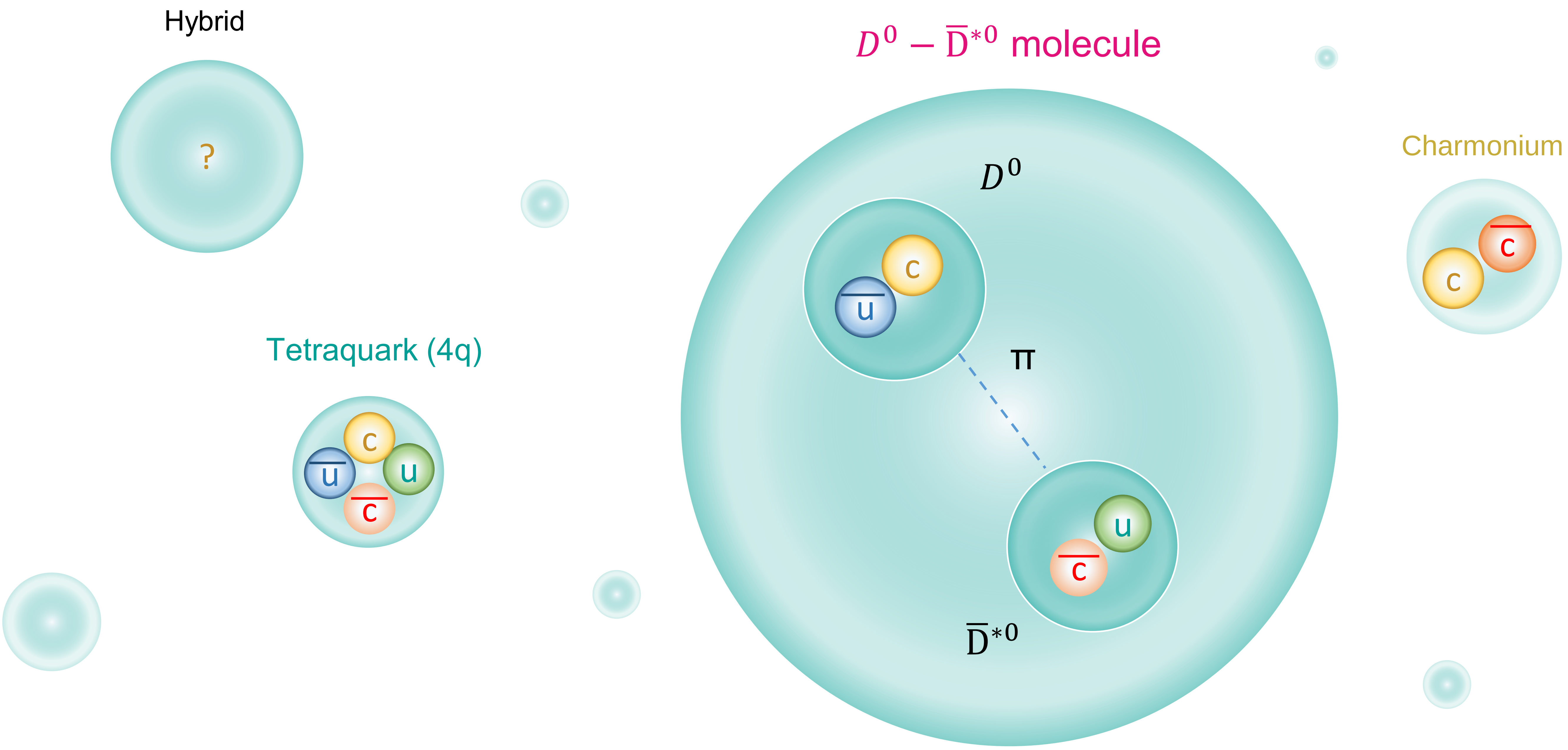
* See Matt Durham's presentation in EF06/07 meeting (Link)

Summary

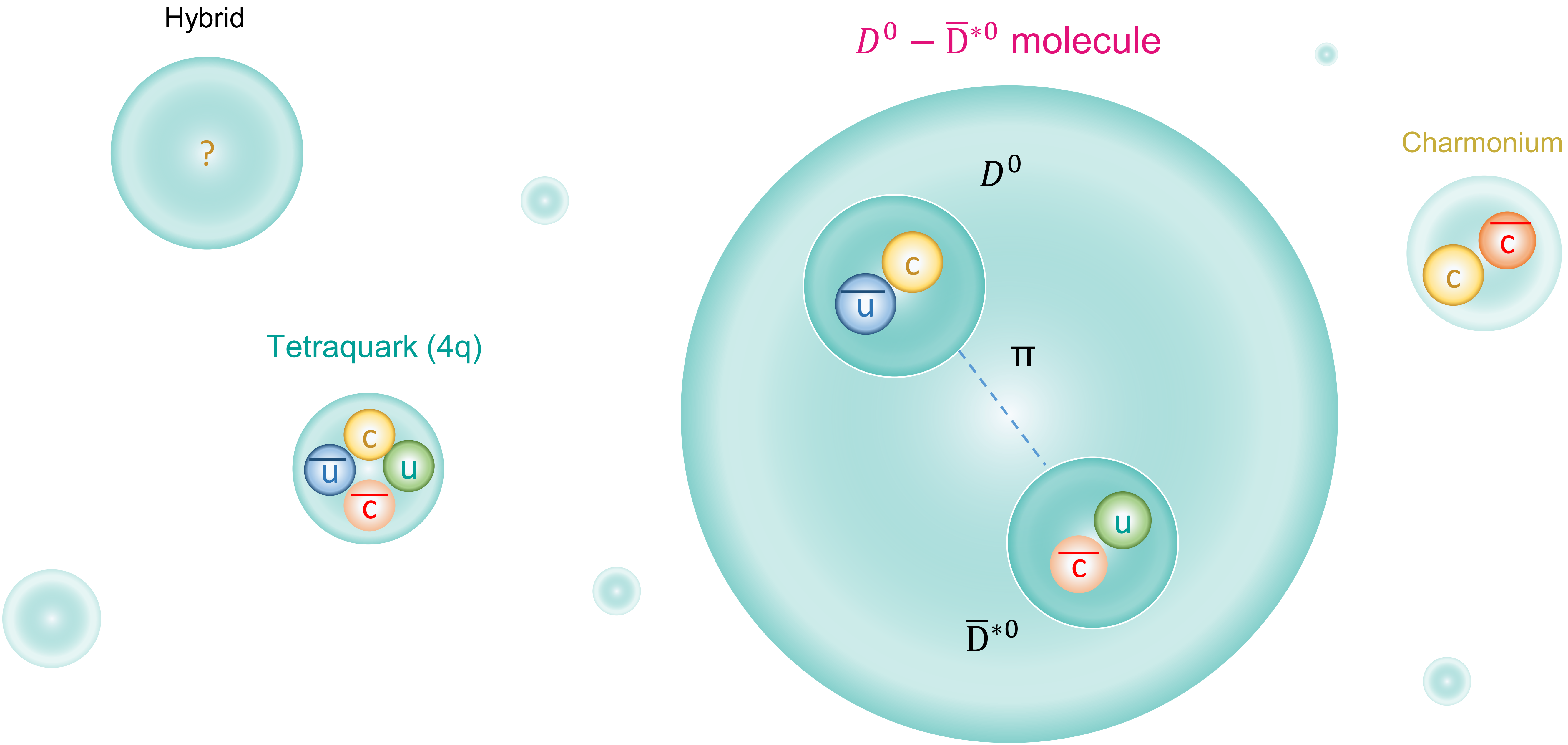


CMS PbPb
$R = 1.10 \pm 0.51$ (stat.) ± 0.53 (syst.)
LHCb
pp $\sqrt{s}$ = 8 TeV
p_T > 5 GeV/c
Prompt
b decays
Comover Interaction Model, Esposito et al.
Molecule (coalescence)
Compact tetraquark
Molecule (geometric)
$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \frac{BR(\chi_{c1}(3872)\to J/\psi\pi^+\pi^-)}{BR(\psi(2S)\to J/\psi\pi^+\pi^-)}$
N_{tracks}^{VELO}
Coalescence?
?
Breakup due to comoving particles
LHCb SMOG
eA / eP
pp
pA, OO
PbPb
AuAu

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



Proposed plan from sPHENIX

Table 8.2: Summary of Au+Au at 200 GeV running in the sPHENIX Beam Use Proposal. The recorded luminosity (Rec. Lum.) and first sampled luminosity (Samp. Lum.) values are for collisions with z-vertex $|z| < 10$ cm.

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $|z| <10$ cm	Samp. Lum. $|z| <10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

Table 8.3: Summary of p+p at 200 GeV running in the sPHENIX Beam Use Proposal. The recorded luminosity (Rec. Lum.) and sampled luminosity (Samp. Lum.) values are for collisions with z-vertex $|z| < 10$ cm.

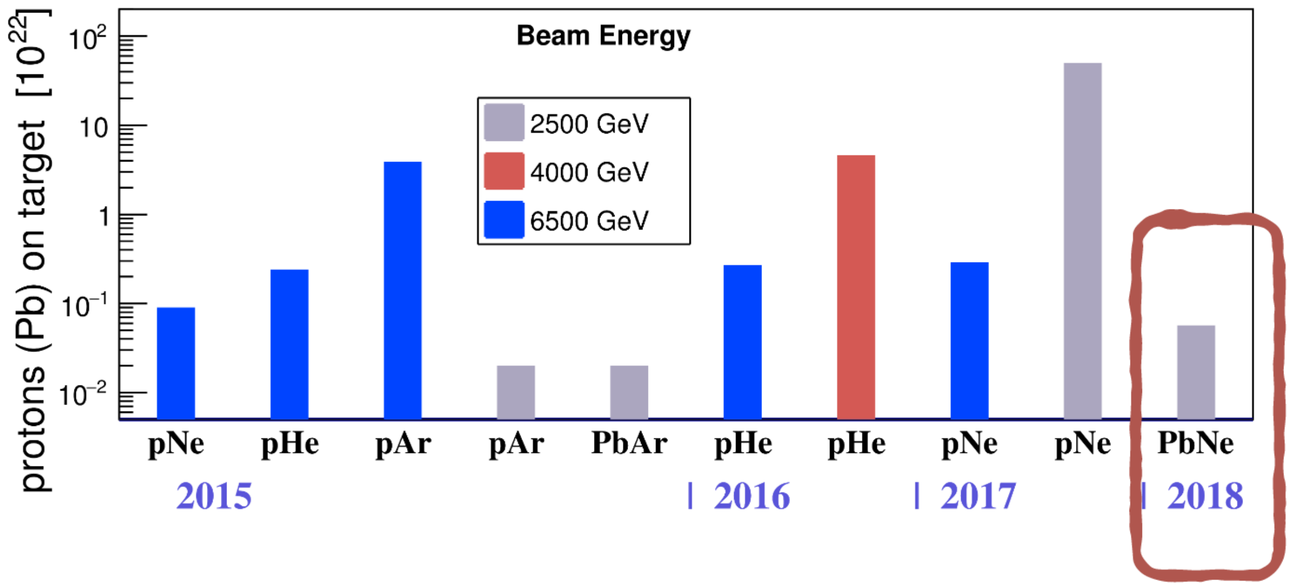
Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $|z| <10$ cm	Samp. Lum. $|z| <10$ cm
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-str]	45 (62) pb^{-1}

Optimistic scenario

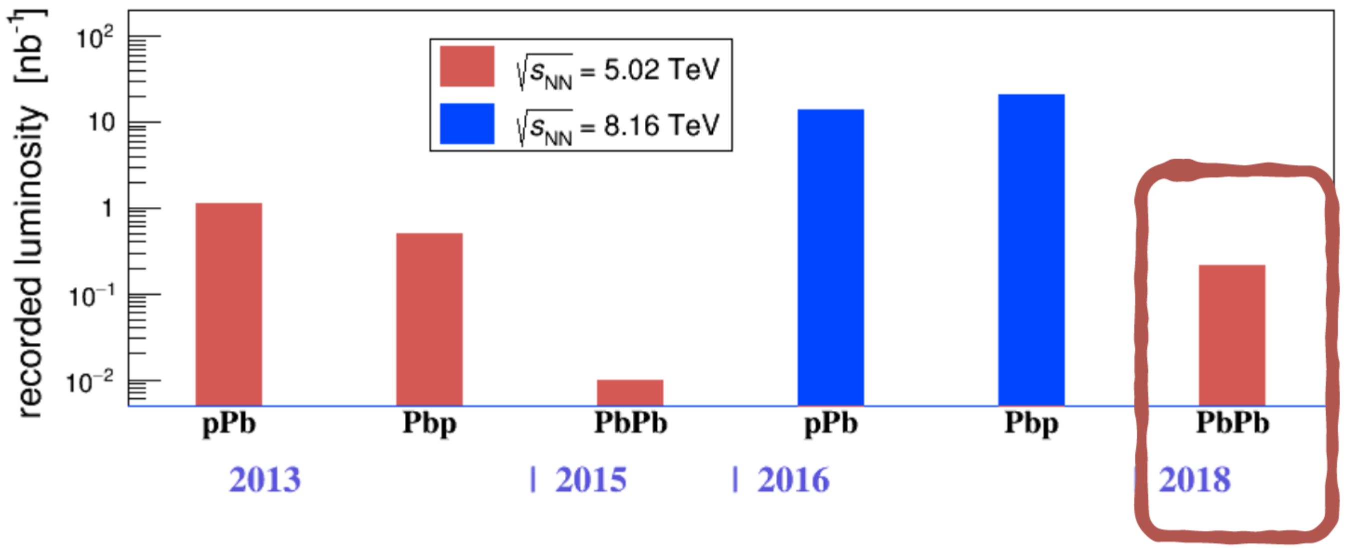
Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $|z| <10$ cm	Samp. Lum. $|z| <10$ cm
2026	$p^{\uparrow}p^{\uparrow}$	200	28	15.5	1.0 pb^{-1} [10 kHz] 80 pb^{-1} [100%-str]	80 pb^{-1}
–	O+O	200	–	2	18 nb^{-1} 37 nb^{-1} [100%-str]	37 nb^{-1}
–	Ar+Ar	200	–	2	6 nb^{-1} 12 nb^{-1} [100%-str]	12 nb^{-1}
2027	Au+Au	200	28	24.5	30 nb^{-1} [100%-str/DeMux]	30 nb^{-1}

LHCb HI samples

Fixed-target mode samples



Collider mode samples

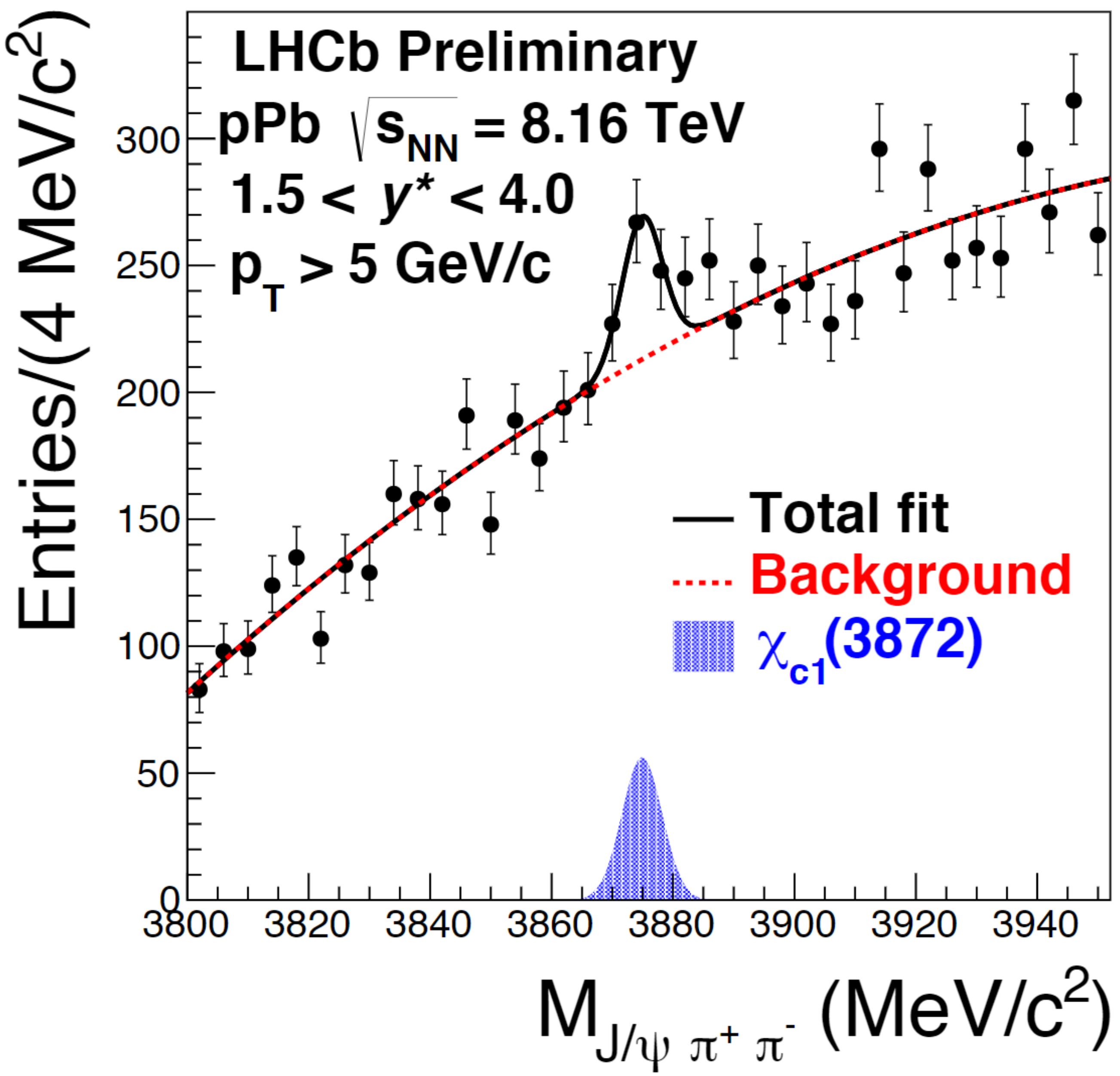


~ 20 times 2015 luminosity

- Large variety of samples to study !
- **Two new samples** : PbNe at $\sqrt{s_{NN}}$ = 68.6 GeV and PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV

Benjamin Audurier (QM'19)

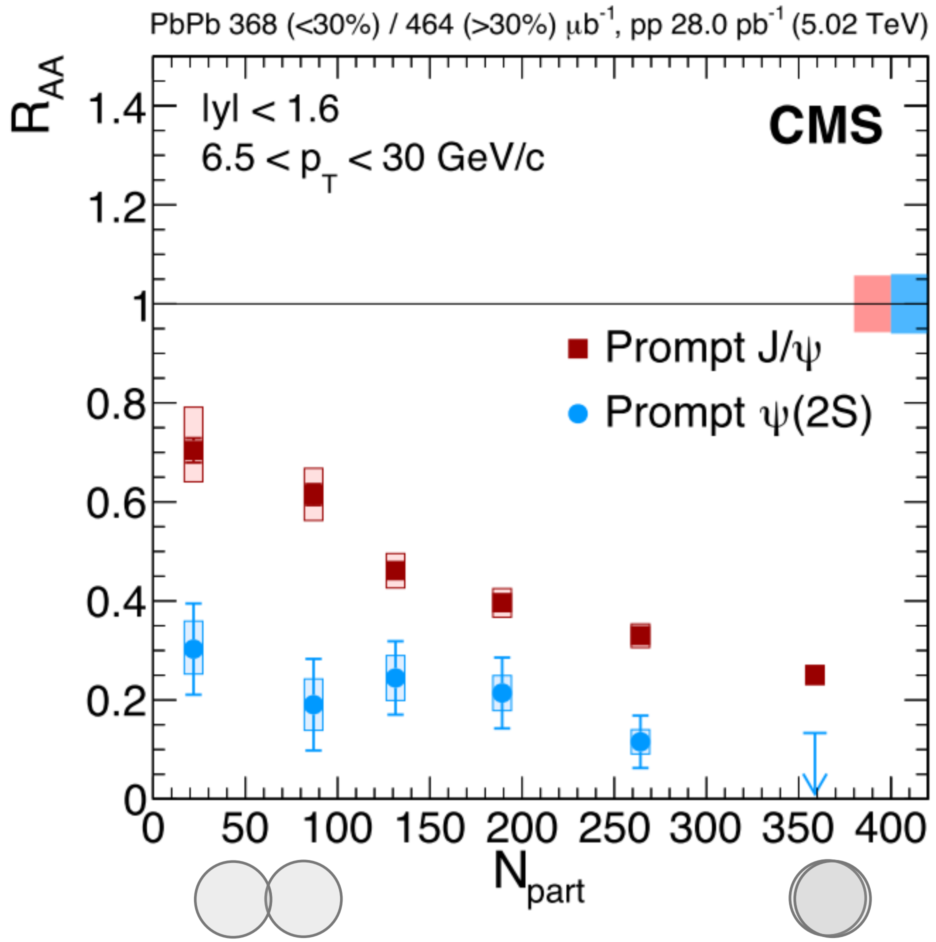
X(3872) peak in LHCb pPb sample



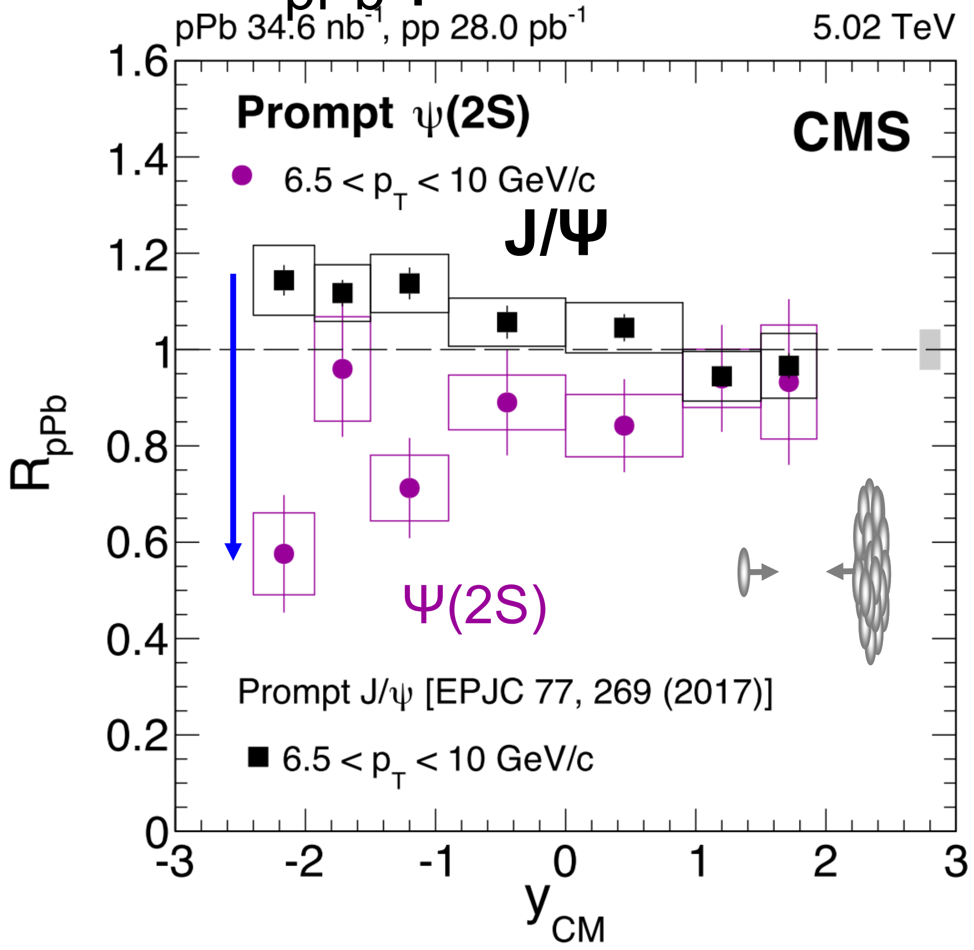
SnowMass2021

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

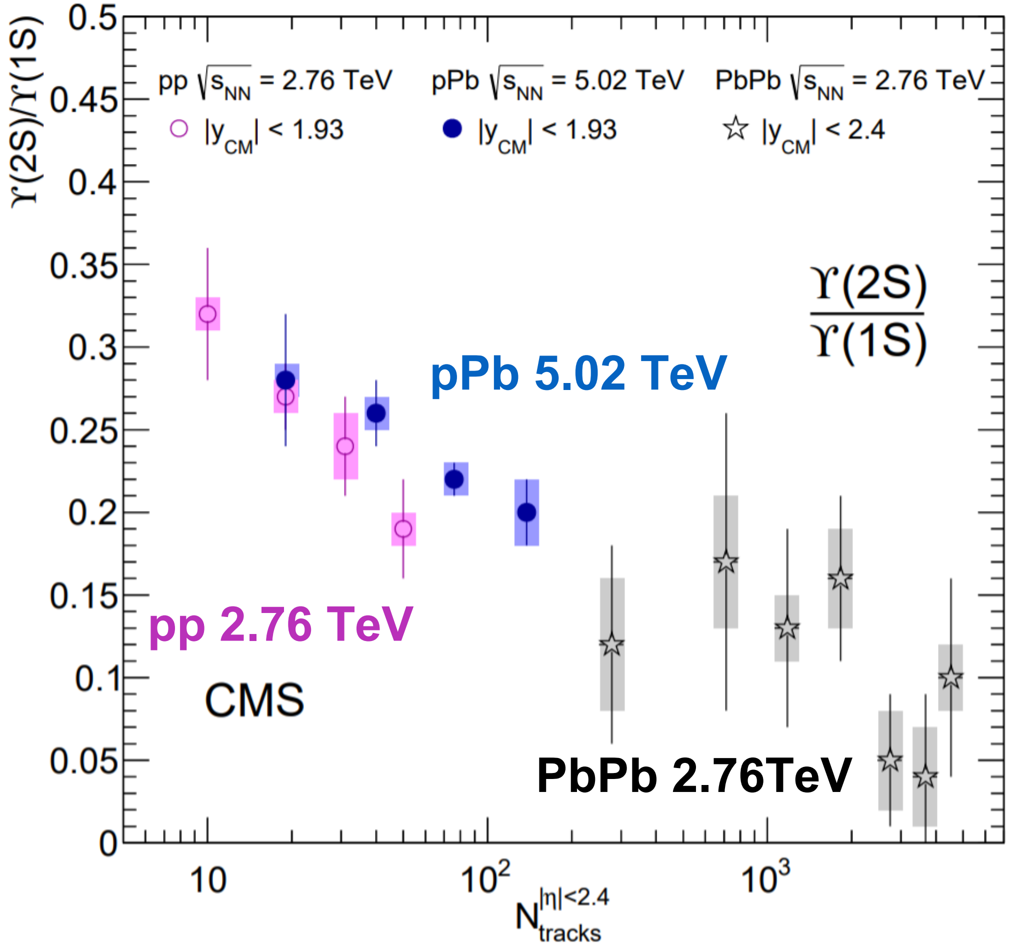
PbPb EPJC 78 (2018) 509

pPb arXiv:1805.02248

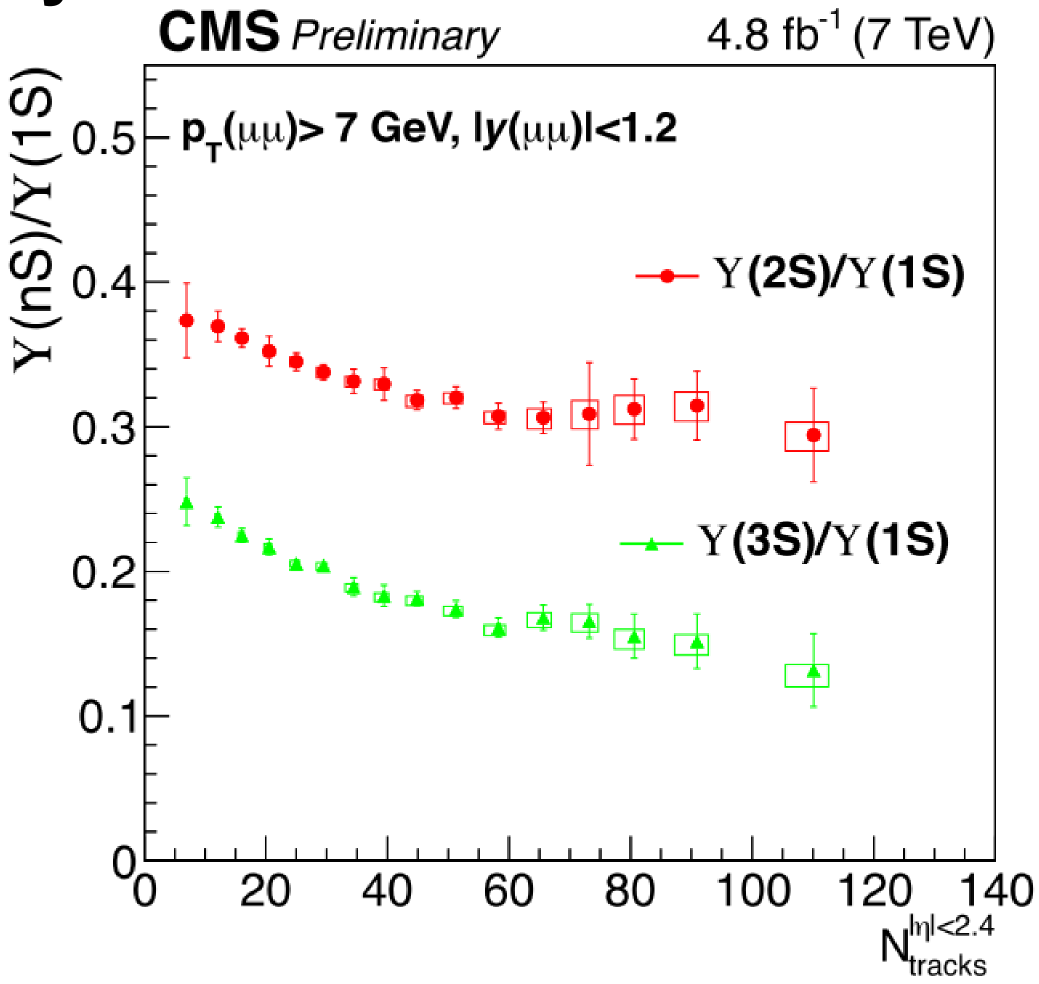
- **J/Ψ** and Ψ(2S) difference increases as we move to backward (lead-going) direction (higher dN_{ch}/dy)
- Can not be explained by nPDF or coherent energy loss model
- Final state effects from comoving (local) medium?

Upsilon suppression

Υ(2S)/Υ(1S) ratio vs. multiplicity



pp at 7 TeV



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