Beauty and Exotica Production in Heavy Ion Collisions at the LHC

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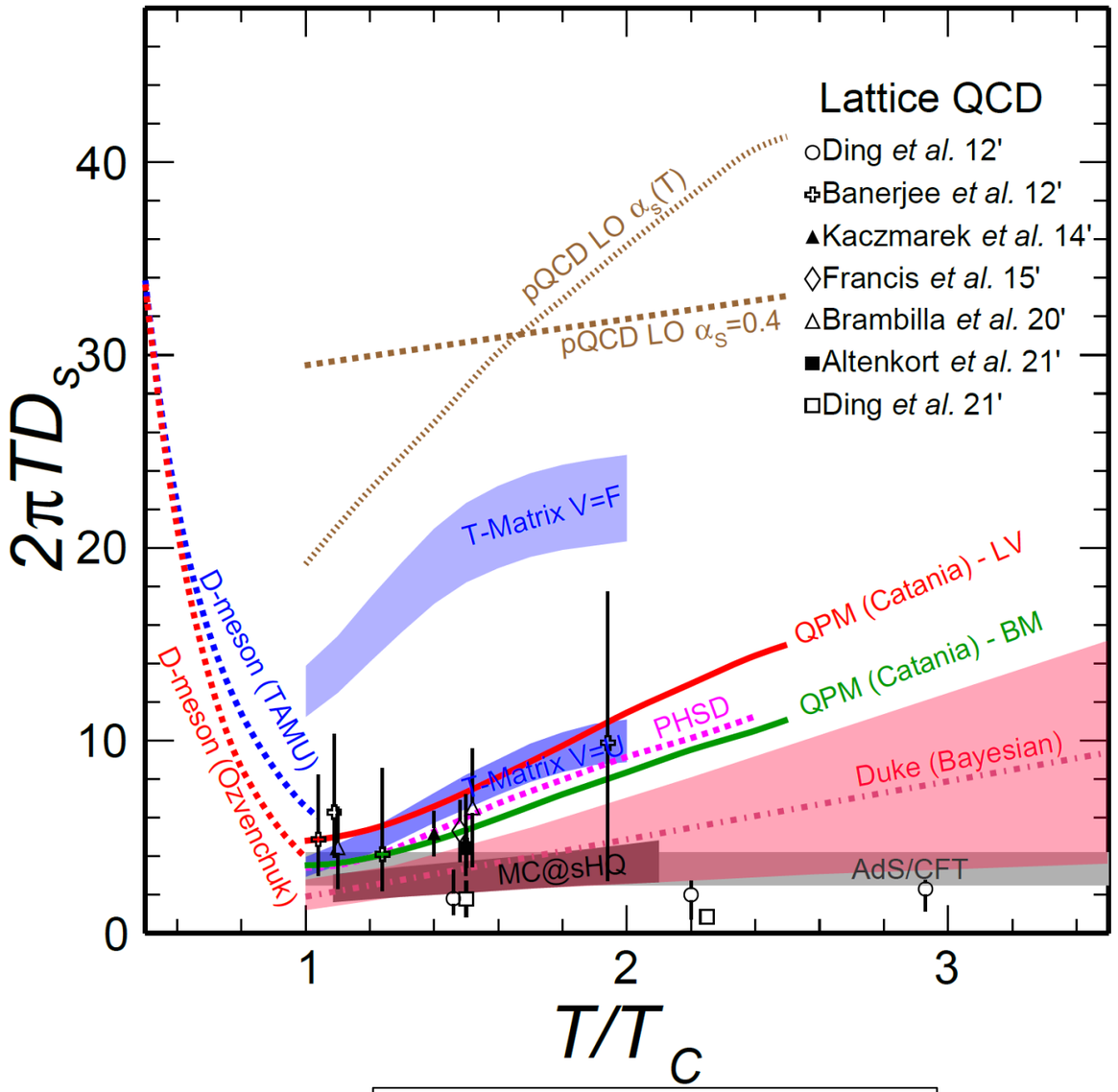
Heavy Quarks as Probes of QGP

- Produced **before** the QGP formation
- Heavy quark diffusion coefficient (D_s) provides a direct window on the in-medium QCD force
- **Hadronization** of heavy quarks could be modified in the presence of QGP, recombination of heavy (and light) quarks from independent hard parton-parton interactions
- Fast moving heavy quarks: **suppression of radiative energy loss** due to dead-cone effect compared to light quarks



Compilation from Xin Dong, Ralf Rapp, YJL
Review from Liliana Apolinário, Michael Winn, YJL in preparation

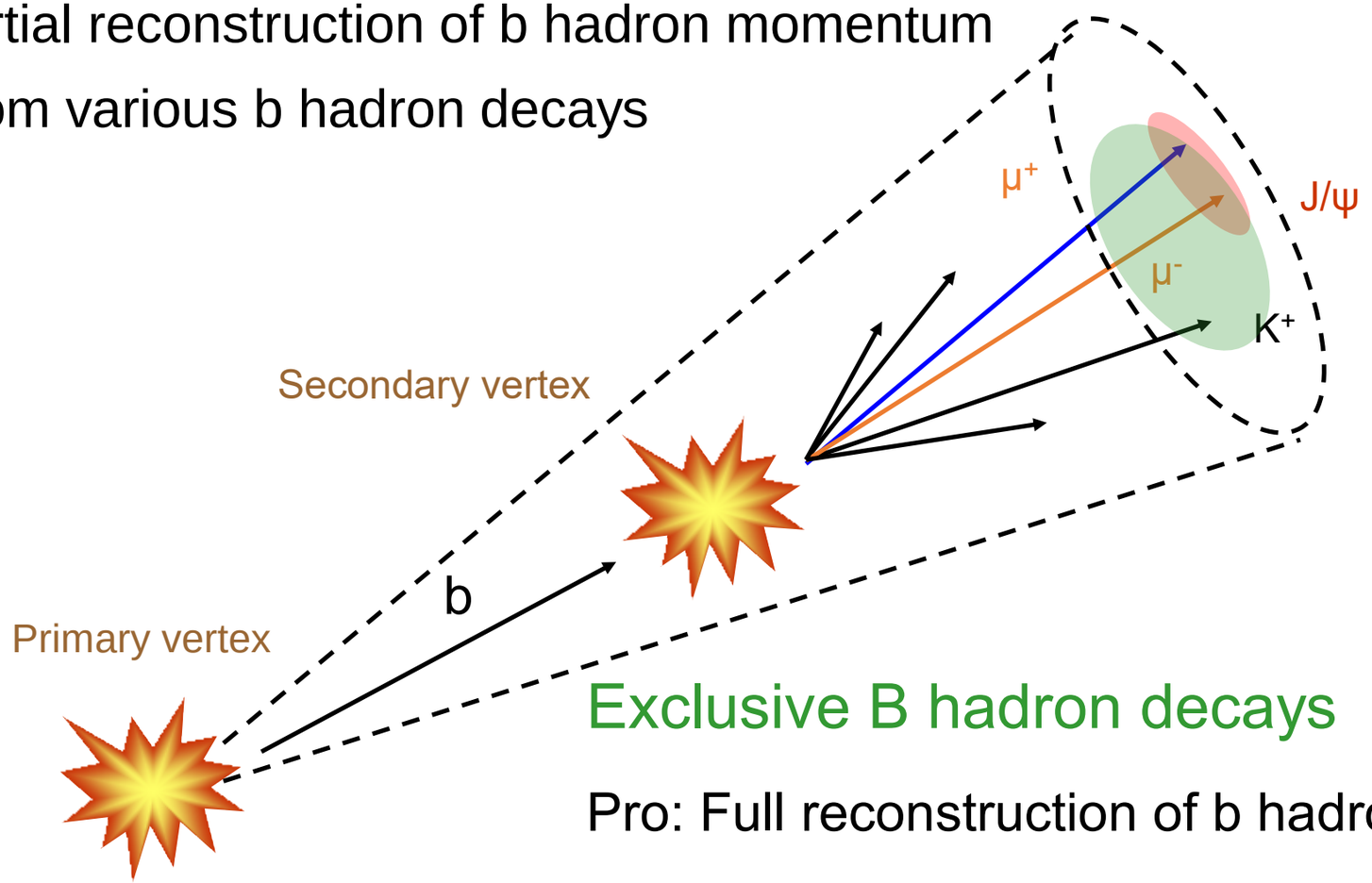
Study of Beauty Hadron

Non-prompt J/ψ (or D^0 or lepton):

Pro: Higher statistics than fully reconstructed b hadron

Con: Partial reconstruction of b hadron momentum

From various b hadron decays



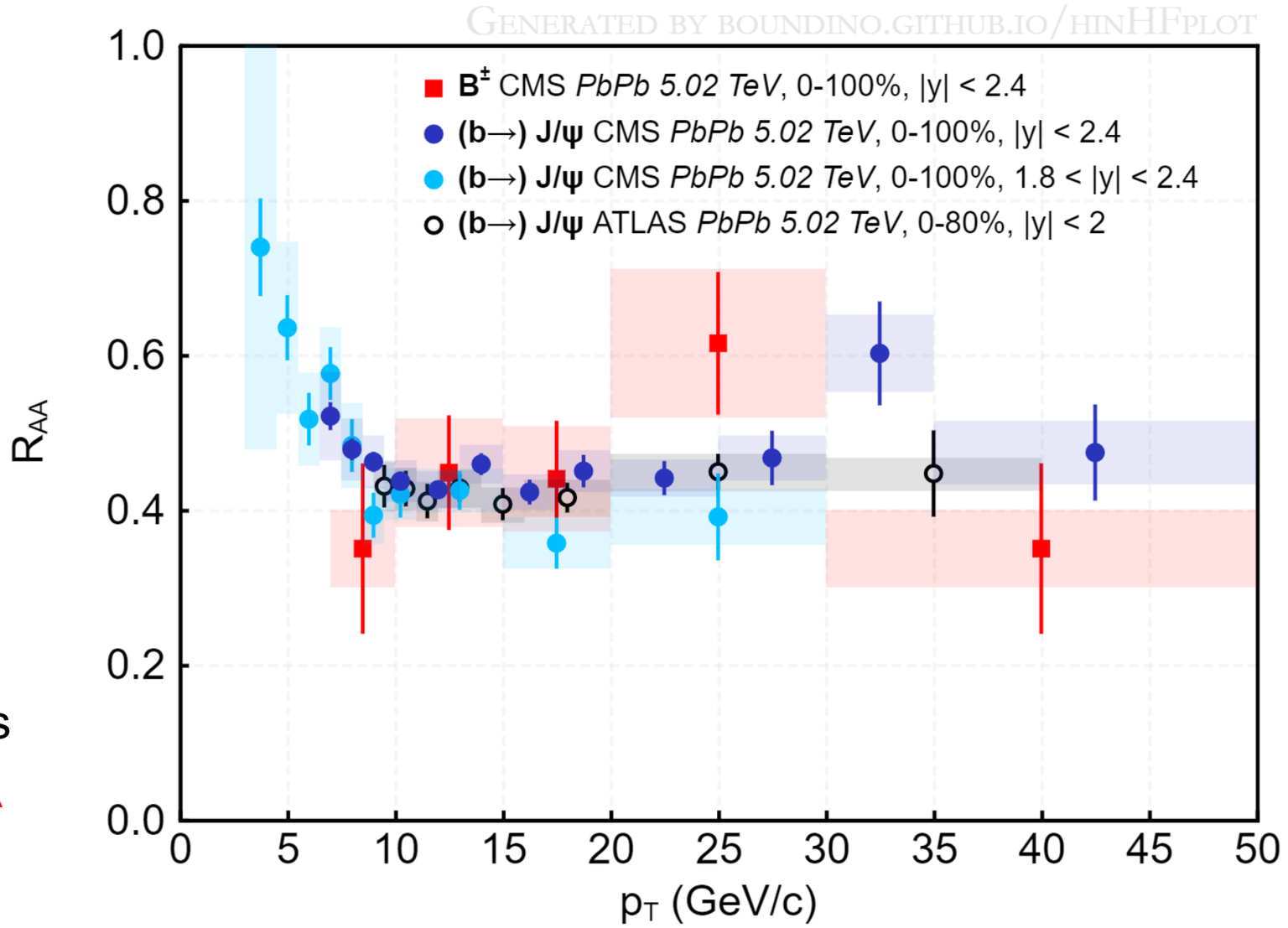
Exclusive B hadron decays

Pro: Full reconstruction of b hadron momentum and flavor

Con: low statistics

Non-prompt J/ψ R_{AA} in 0-100% PbPb at 5 TeV

- Precise measurement of beauty suppression from **non-prompt J/ψ** from b decay in PbPb
- In MinBias PbPb collisions, the results from **CMS** and ATLAS are consistent
- R_{AA} first decrease with p_T and then stay at around 0.4-0.5 at high p_T ($10<p_T<50$ GeV)
- **Non-prompt J/ψ R_{AA}** (from various beauty hadron decays) and **B^+ R_{AA}** are very close to each other



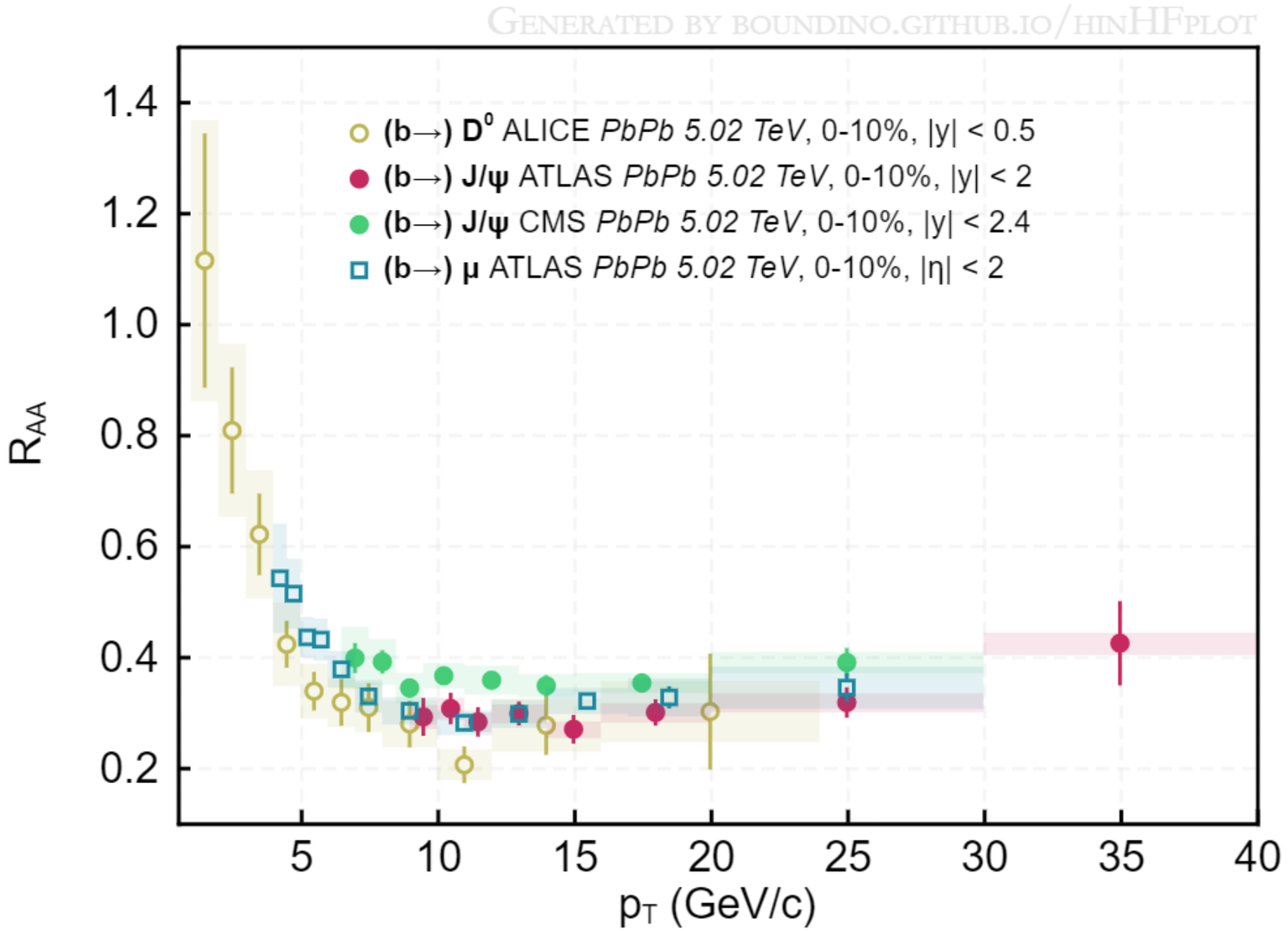
B^+ PRL 119 (2017) 152301
NP J/ψ CMS EPJC 78 (2018) 509

Beauty R_{AA} in 0-10% PbPb at 5 TeV

- Precise measurement of beauty suppression from **non-prompt J/ψ**, **D^0** and **μ** from b decay in **0-10% PbPb**

- R_{AA} results are close to each other at high p_T (although **J/ψ**, **D^0** and **μ** carry different fraction of beauty momentum)

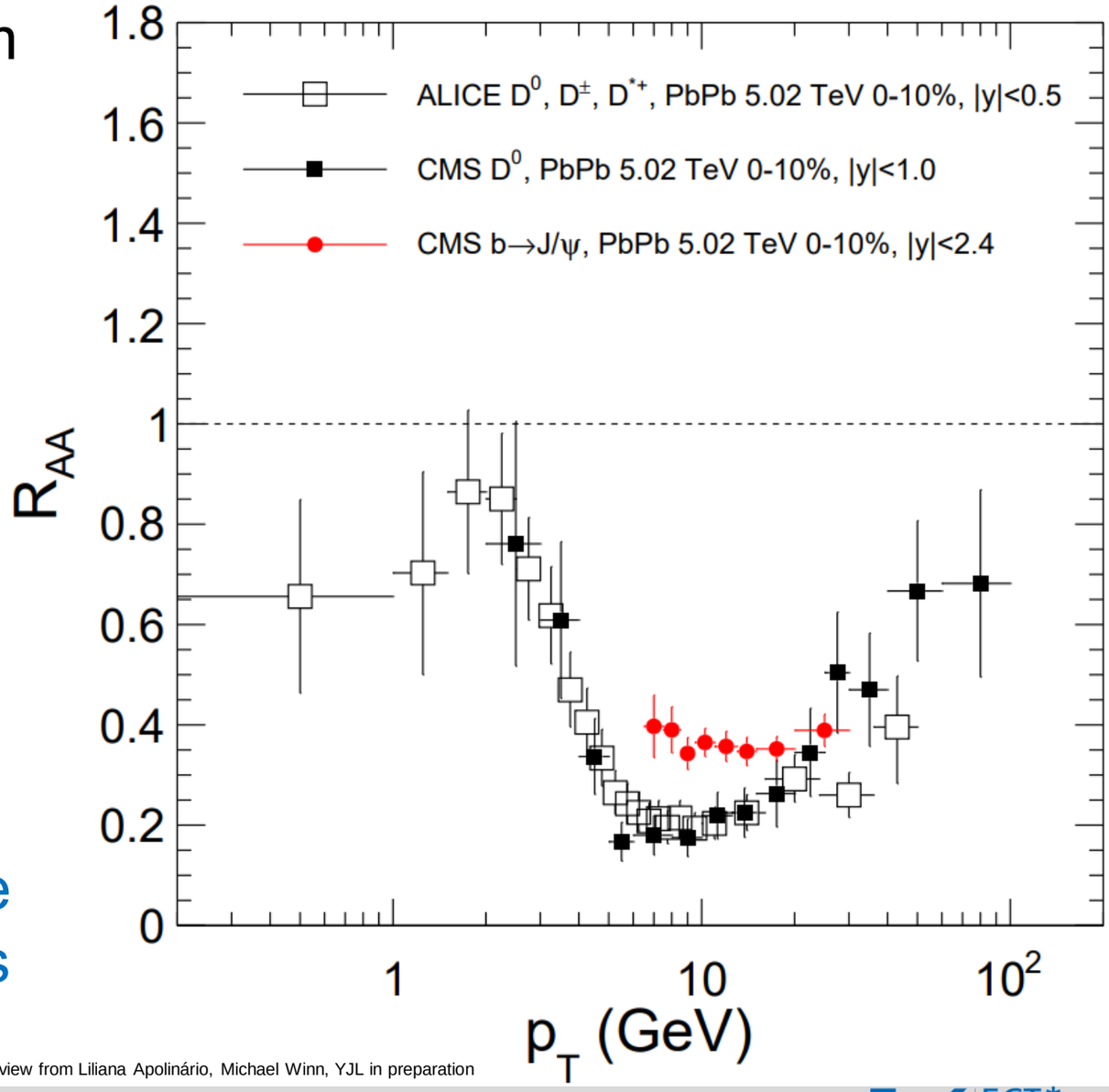
- Some difference between non-prompt J/ψ from **ATLAS** and **CMS**, to be followed up with Run 3+4 data



B⁺ PRL 119 (2017) 152301
NP J/ψ CMS EPJC 78 (2018) 509

Charm and Beauty Hadron R_{AA}

- Summary of the highest precision charm and beauty hadron measurements
- Very good agreement between ALICE D R_{AA} and **CMS D^0 R_{AA}**
- p_T<20 GeV: **non-prompt J/ψ** R_{AA} is significantly higher than **D** R_{AA}
- p_T>20 GeV: **non-prompt J/ψ** R_{AA} is close to **D** R_{AA}
- Consistent with the expectation from the mass dependence of parton energy loss

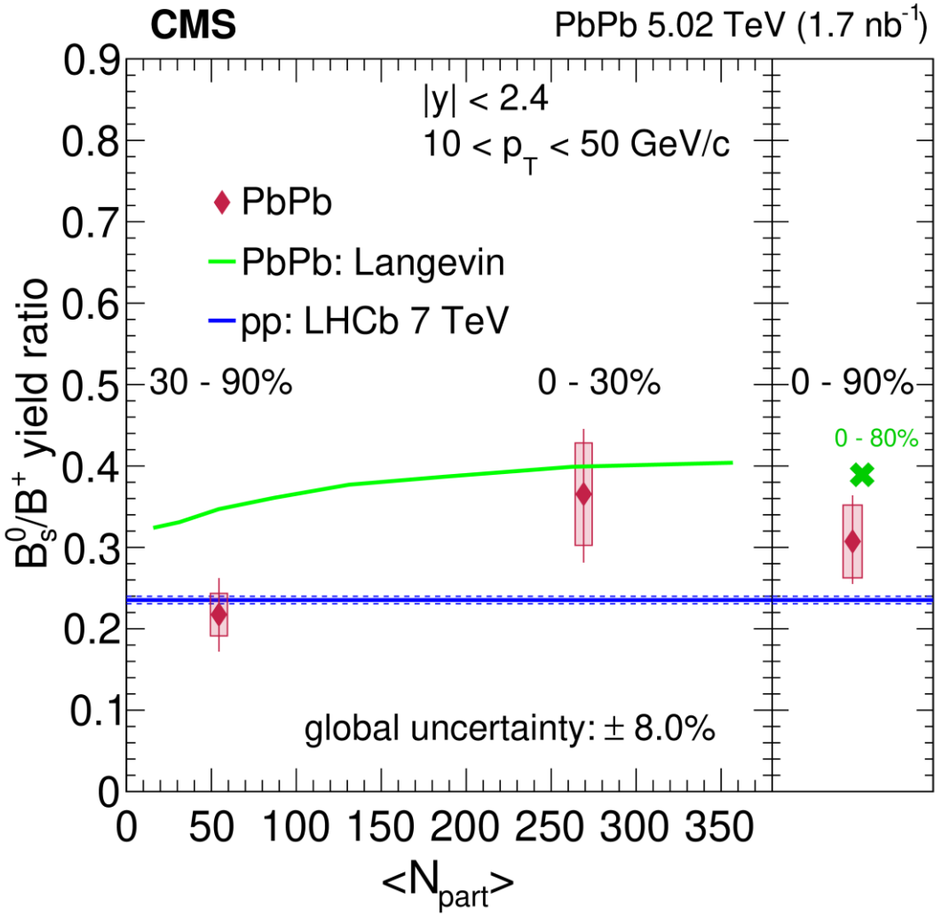


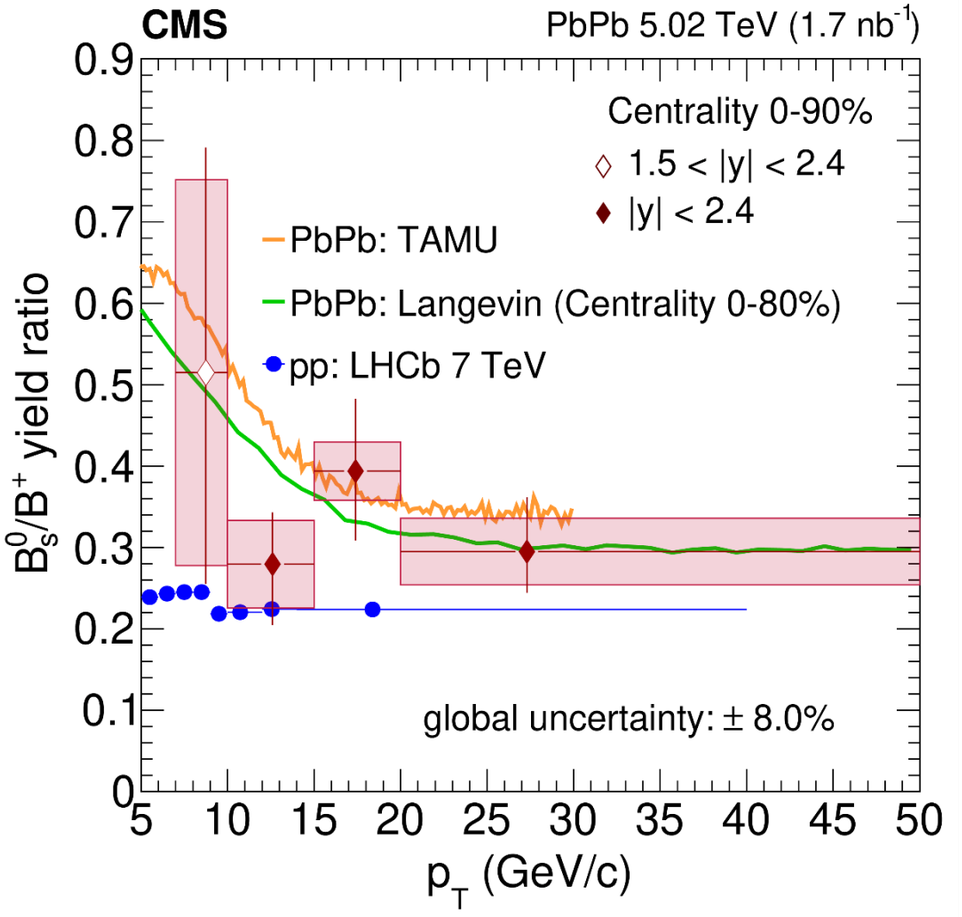
NP J/ψ CMS EPJC 78 (2018) 509
ALICE D 2110.09420

CMS D^0 PLB 782 (2018) 474

Review from Liliana Apolinário, Michael Winn, YJL in preparation

Beauty Quark Hadronization

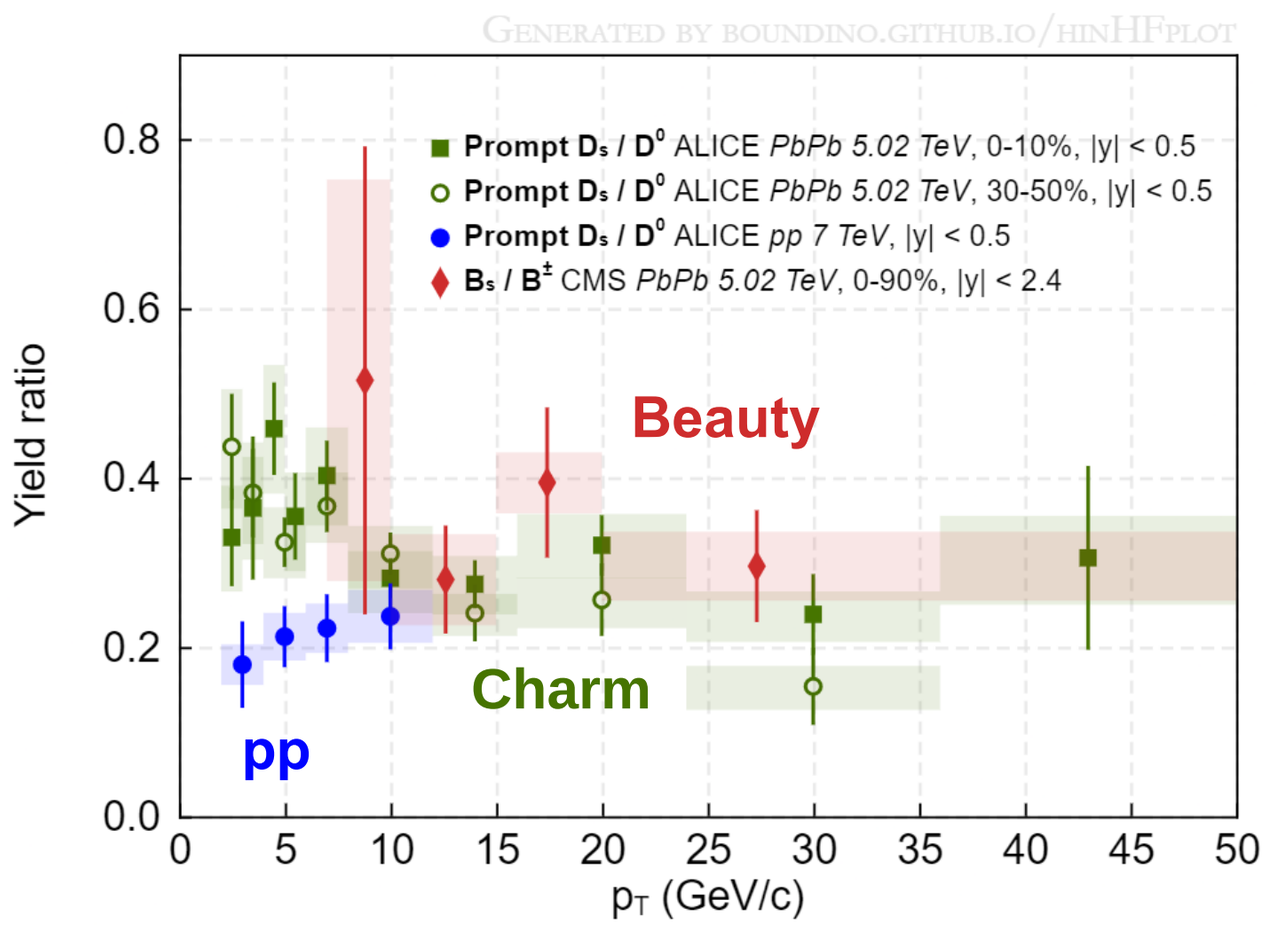


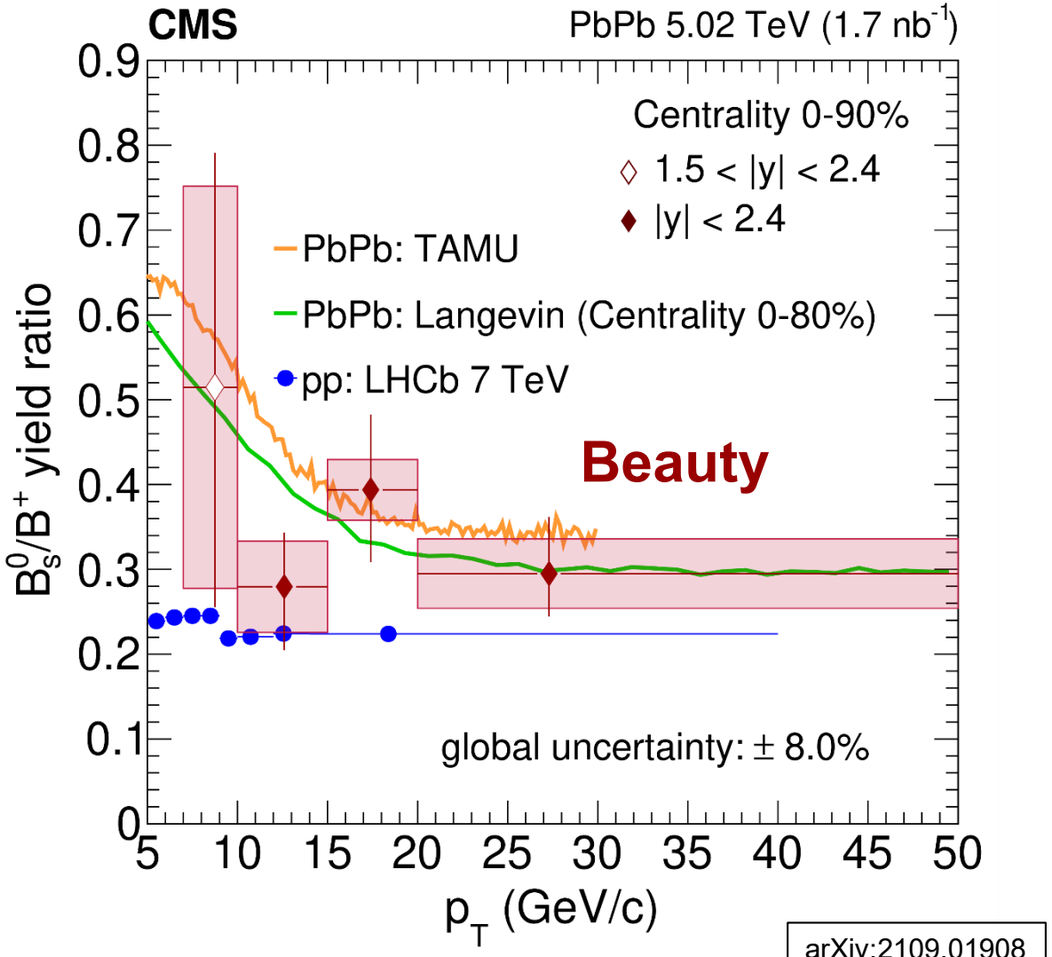


- Indication of larger B_s/B^+ ratios in PbPb compared to **pp reference**
- Data are consistent with expectation from theoretical models
- Indication of larger B_s/B^+ ratio in central event, to be followed up with Run 3+4 data

arXiv:2109.01908

Charm and Beauty Hadronization



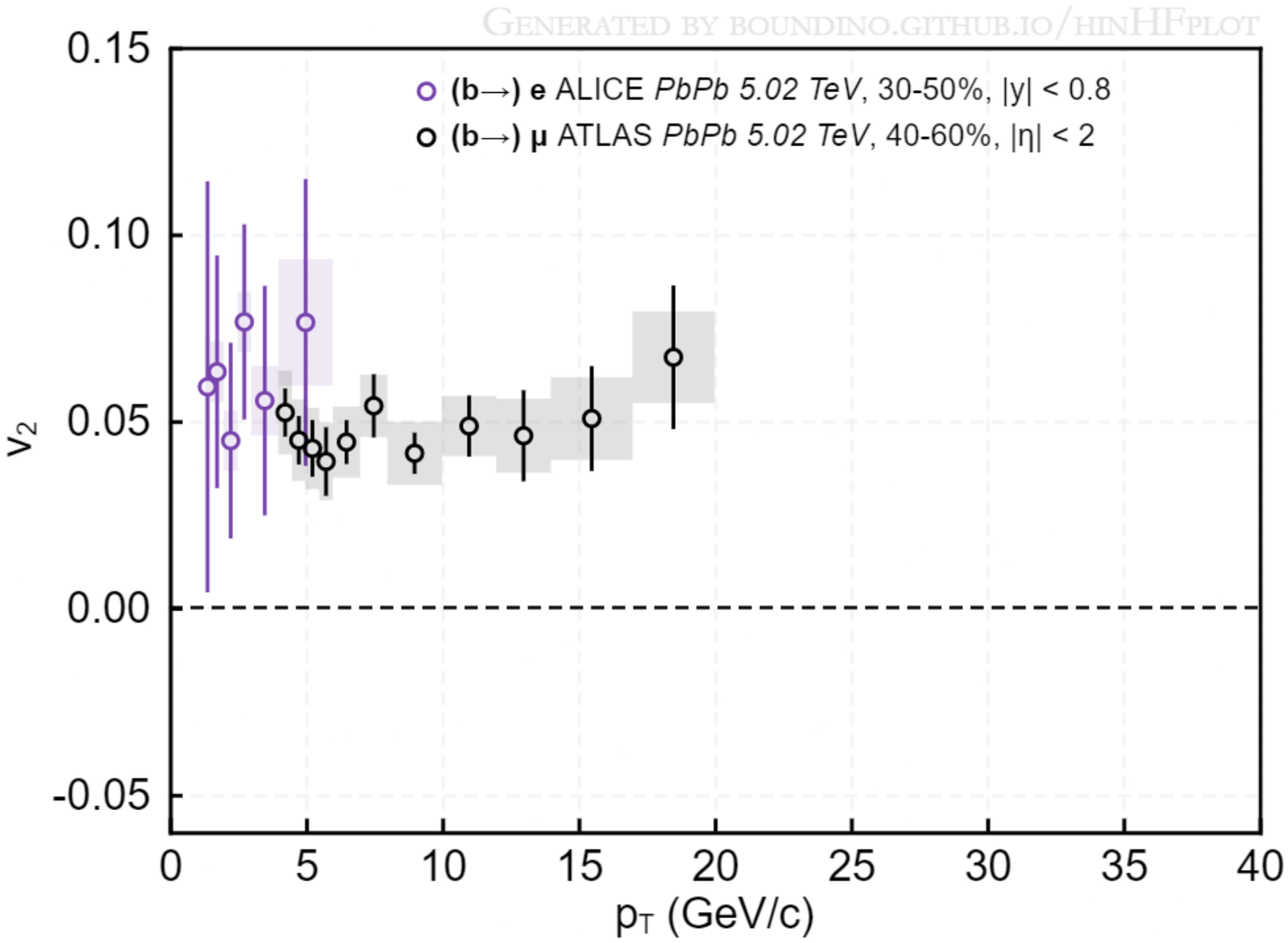


arXiv:2109.01908

- The magnitude of D_s/D^0 and B_s/B^+ are similar in **pp** and PbPb collisions
- Difference between PbPb data and **pp reference** decreases at high p_T

Beauty Azimuthal Anisotropy

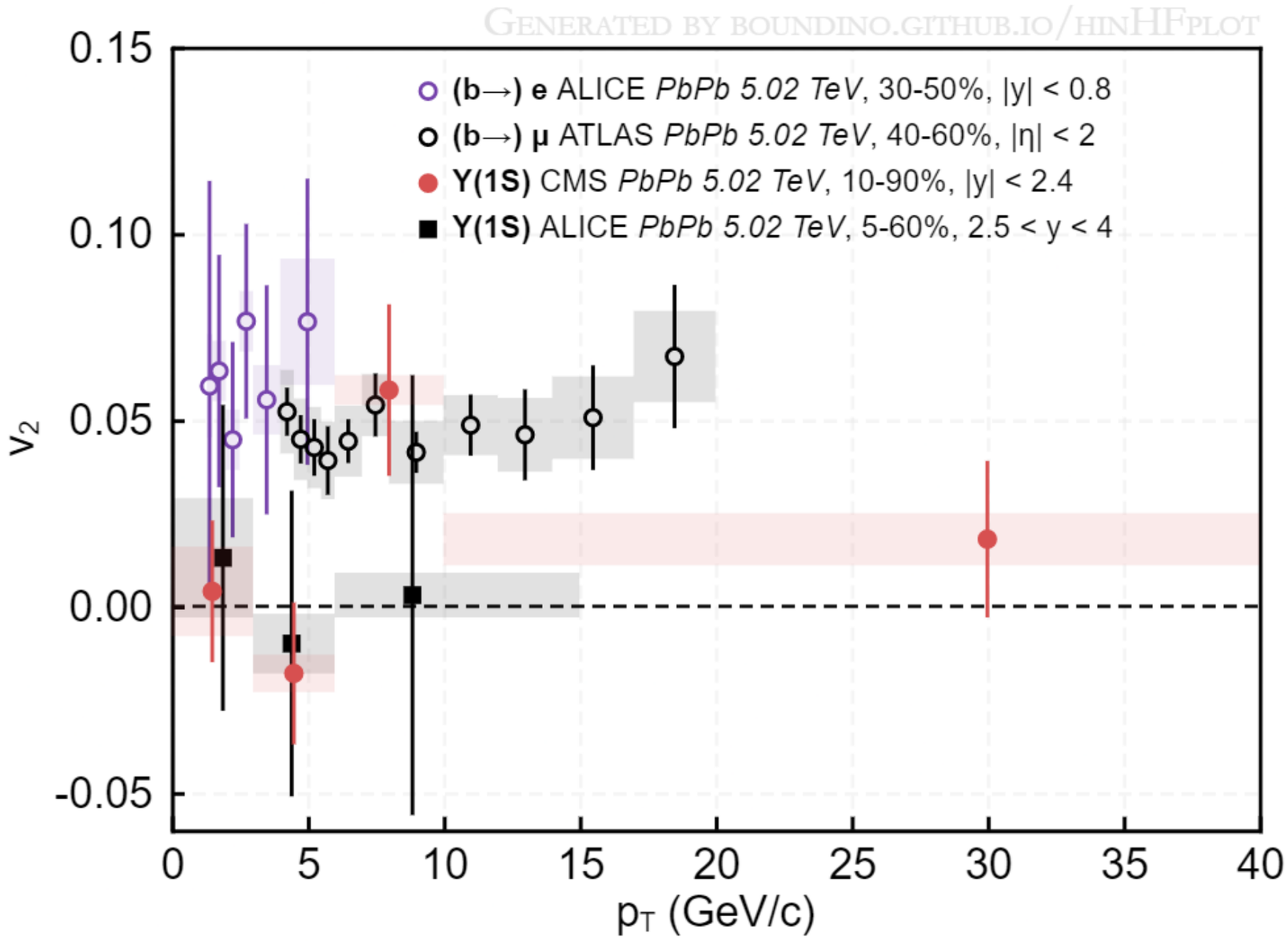
- Significant positive v_2 signals have been reported in beauty decay lepton measurements
- However, the correlation between **lepton** and **beauty** p_T (in particular, direction) is weaker at low p_T
- Lack of structure: the measured v_2 is not varying as a function of lepton p_T



2109.00411 ATLAS
ALICE preliminary

Beauty Azimuthal Anisotropy

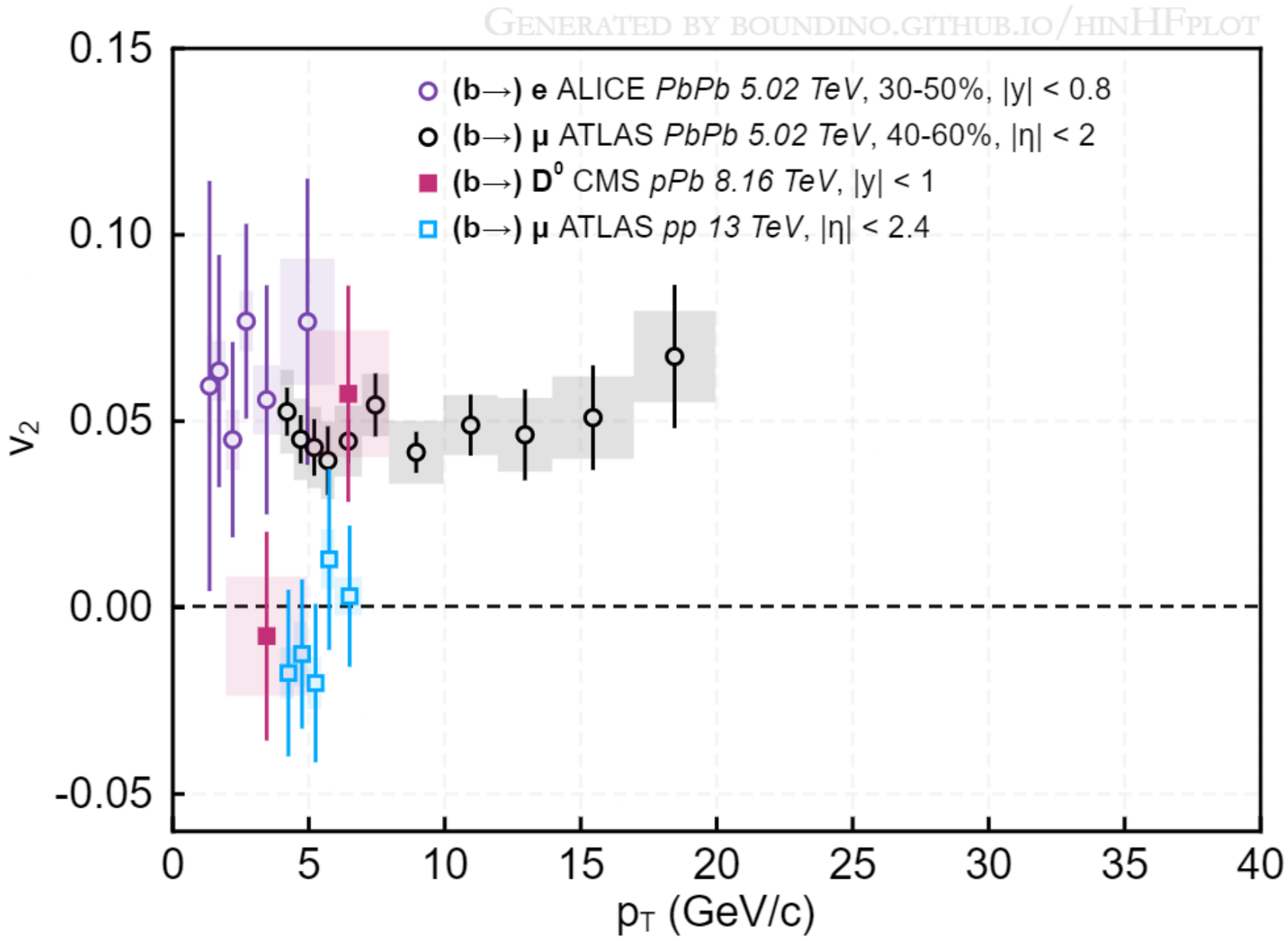
- Significant positive v_2 signals have been reported in beauty decay lepton measurements
- Indication of larger v_2 (from beauty decay leptons) compared to **Y(1S)**



2109.00411 ATLAS
ALICE preliminary
Y(1S) CMS PLB 819 (2021) 136385
Y(1S) ALICE PRL 123 (2019) 192301

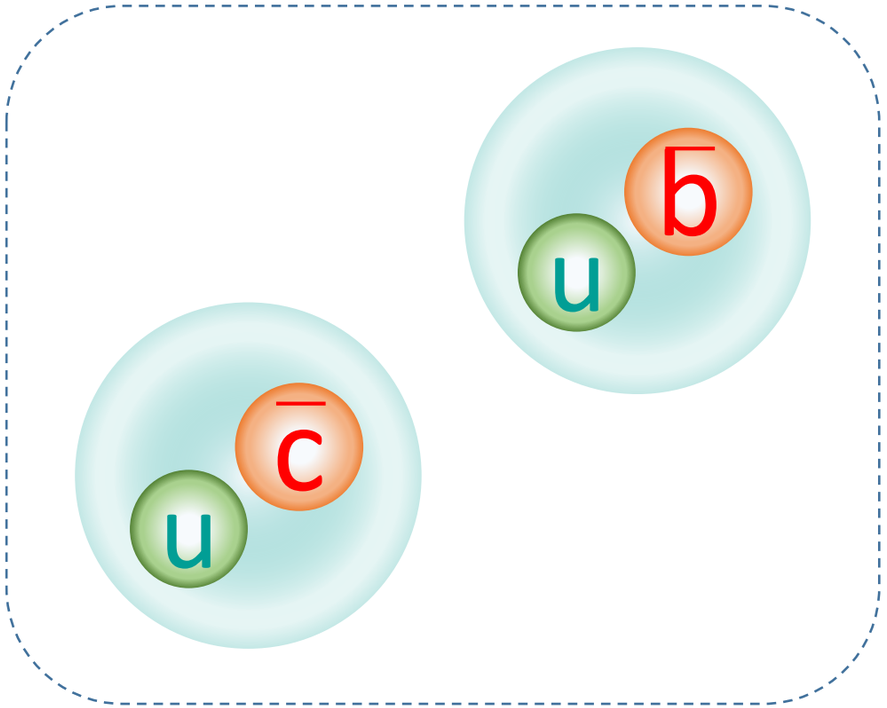
Beauty Azimuthal Anisotropy

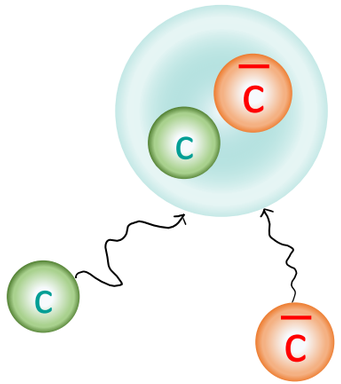
- Significant positive v_2 signals have been reported in beauty decay lepton measurements
- Indication of larger v_2 (from beauty decay leptons) compared to Y(1S)
- Indication of a smaller beauty v_2 signal in high multiplicity **pp** and **pPb** collisions



2109.00411 ATLAS
ALICE preliminary
CMS pPb PLB 813 (2021) 136036
ATLAS pp PRL 124 (2020) 082301

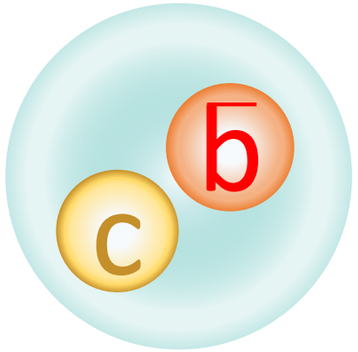
Beyond the Studies of Heavy Flavor Hadrons (I)

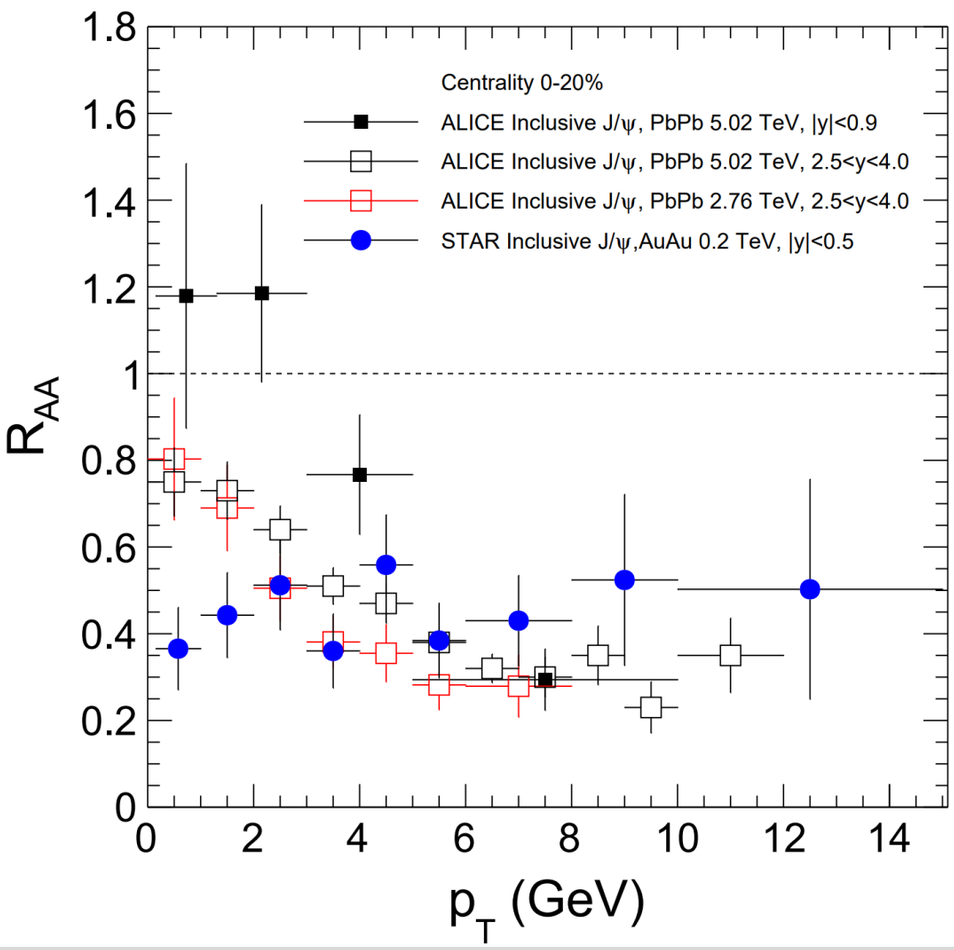




STAR PLB 797 (2019) 134917
ALICE JHEP 2002 (2020) 041
PLB 805 (2020) 135434
JHEP 05 (2016) 179

Charmed beauty hadron





Physics with B_c^+

- B_c^+ mass is below B+D mass threshold

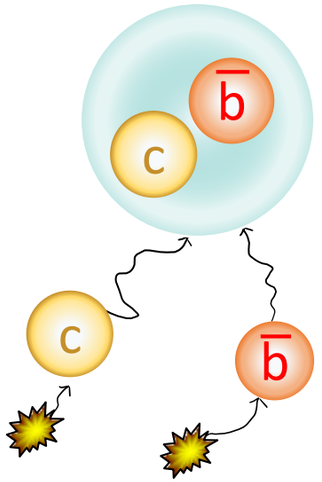
State	J/ψ	Ψ(2S)	B_c^+	Υ(1S)	Υ(2S)	Υ(3S)
Mass (GeV)	3.10	3.68	6.27	9.46	10.02	10.36
Δ E (GeV)	0.64	0.05	0.87	1.10	0.54	0.20

- Binding energy of B_c^+ is between J/ψ and Υ(1S):
  - Sensitive to medium induced dissociation

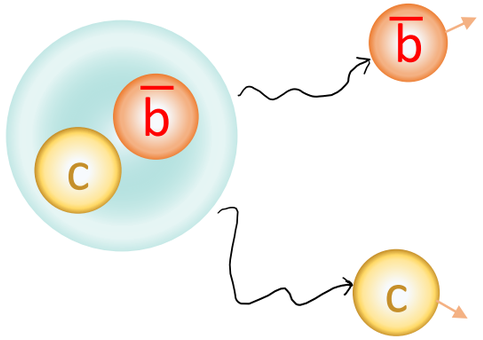
- Very small production cross-section in pp
  - Sensitive to medium effects such as recombination of beauty with an uncorrelated charm quark

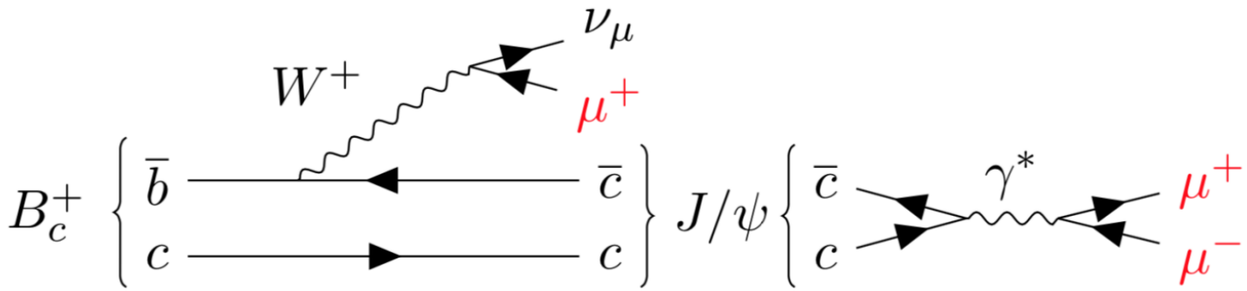
- Parton energy loss: interesting combination of beauty and charm quarks

Recombination



Dissociation





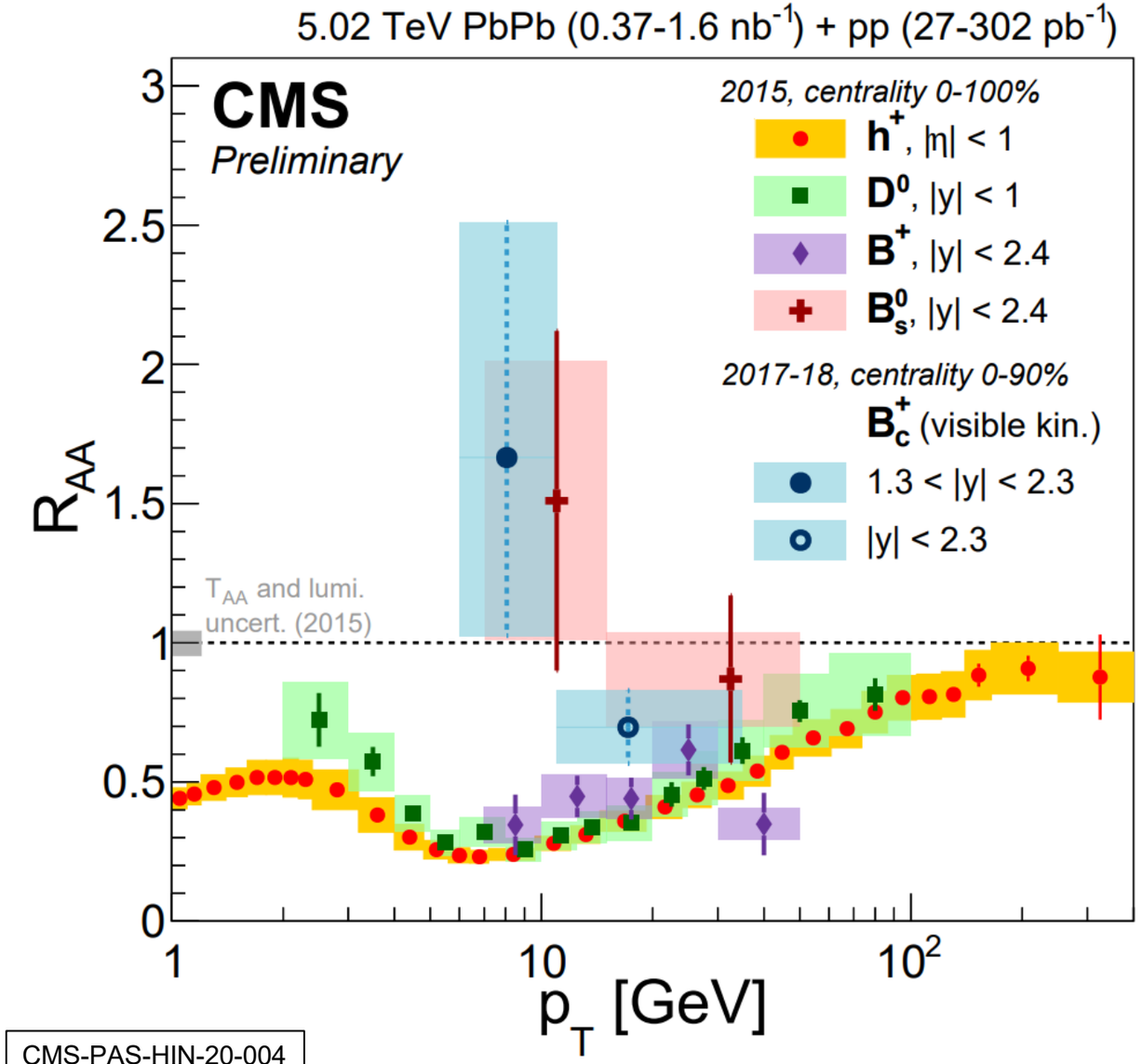
B_c^+ R_{AA} compared to charged hadron, D^0 and B

- Significance of B_c^+ signal is **well above 5σ**
  - **First observation of B_c^+ production in heavy ion collisions!**

- Similar suppression in B_s and B_c^+
  - B_c p_T is partially reconstructed (tri-muon)
  - Large experimental uncertainty to be improved with Run3+4 data.

- At low p_T: the B_c^+ R_{AA} central value is higher than charged hadron h^+, B^+ and D^0 R_{AA}

- At high p_T: similar suppression
  - Mass dependent medium modifications such as dead-cone and hadronization effects reduce at high p_T
  - R_{AA} of all flavor identified hadrons seem to converge above ~ 20-30 GeV



CMS-PAS-HIN-20-004

B_c^+ R_{AA} Compared to Quarkonia at CMS

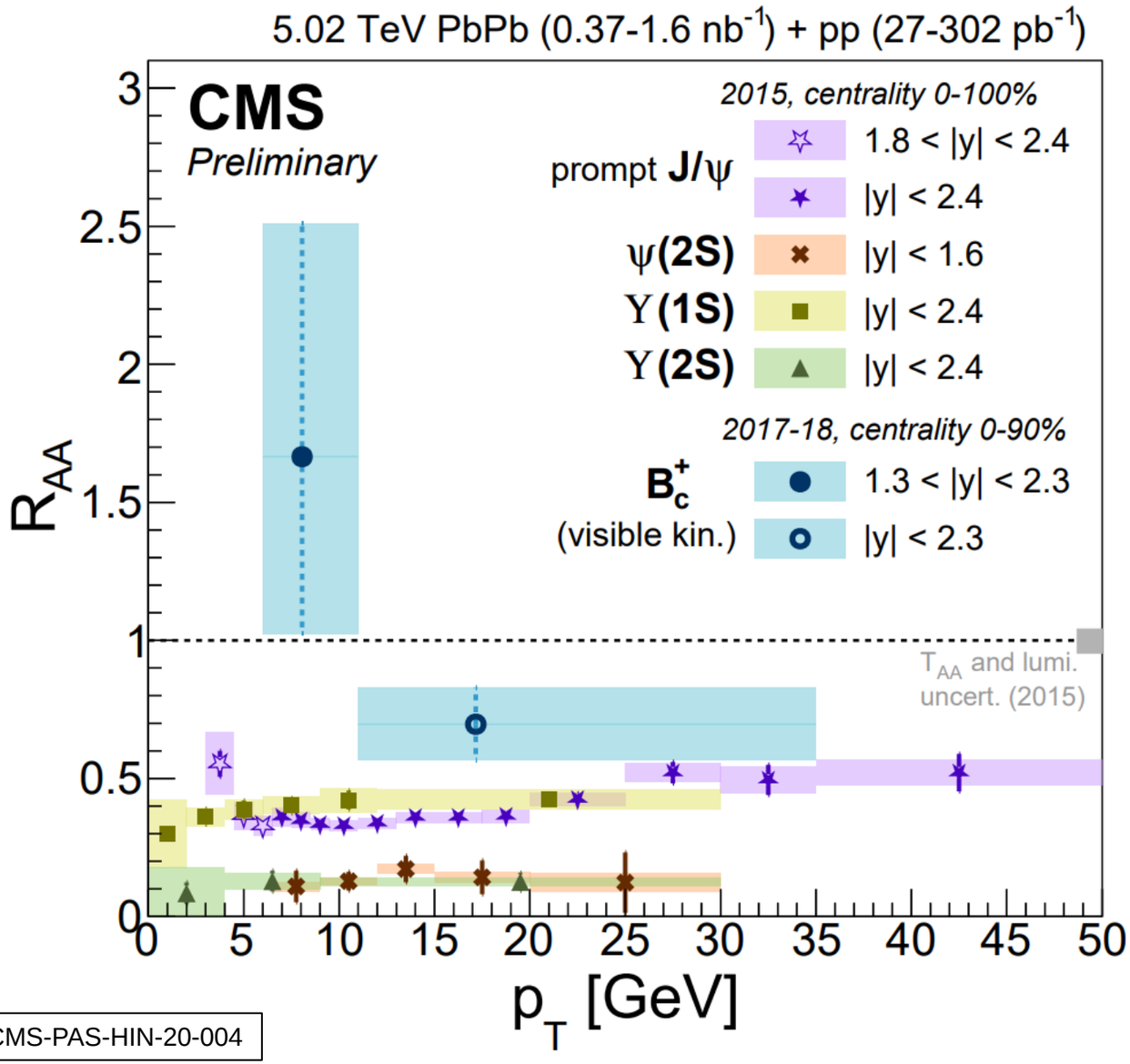
State	Ψ(2S)	Υ(2S)	J/ψ	B_c^+	Υ(1S)
Mass (GeV)	3.68	10.02	3.10	6.27	9.46
Δ E (GeV)	0.05	0.54	0.64	0.87	1.10

Small binding energy → Large binding energy

- B_c^+ R_{AA} is higher than Quarkonia
  - Binding energy between **J/ψ** and **Υ(1S)**
  - Large experimental uncertainties prevent a firm conclusion

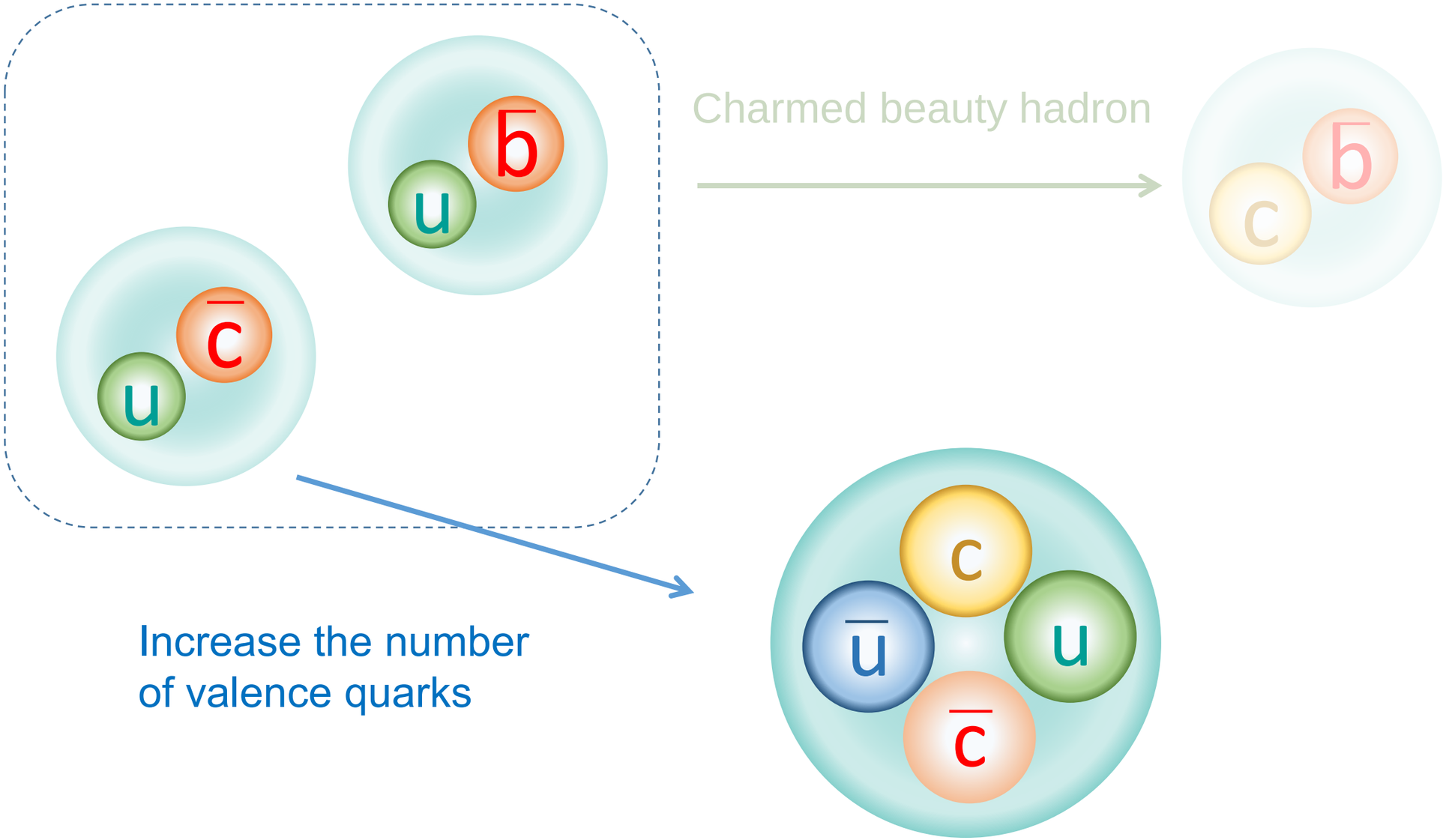
- Recombination of charm and beauty could increase the B_c^+ R_{AA}

- Would be interesting to go to low $p_T < 5$ GeV with future CMS and ALICE data in Run 3+4



CMS-PAS-HIN-20-004

Beyond the Studies of Heavy Flavor Hadrons (II)



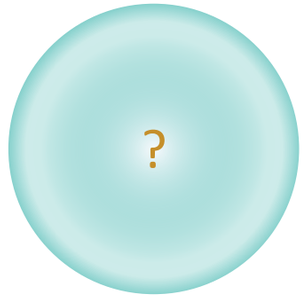
X(3872)

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

- Quantum number determined by CDF and LHCb data: $J^{PC}=1^{++}$
- **Charmonium** interpretation: **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

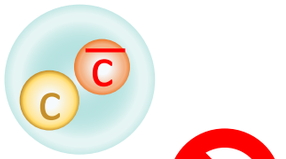
BELLE PRL 91, 262001 (2003)
CDF PRL 98, 132002 (2007)
LHCb PRL 110, 222001 (2013)

Hybrid



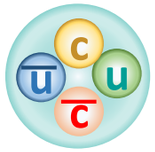
EPJA47 (2011) 101

Charmonium



PLB 590 209-215 (2004)

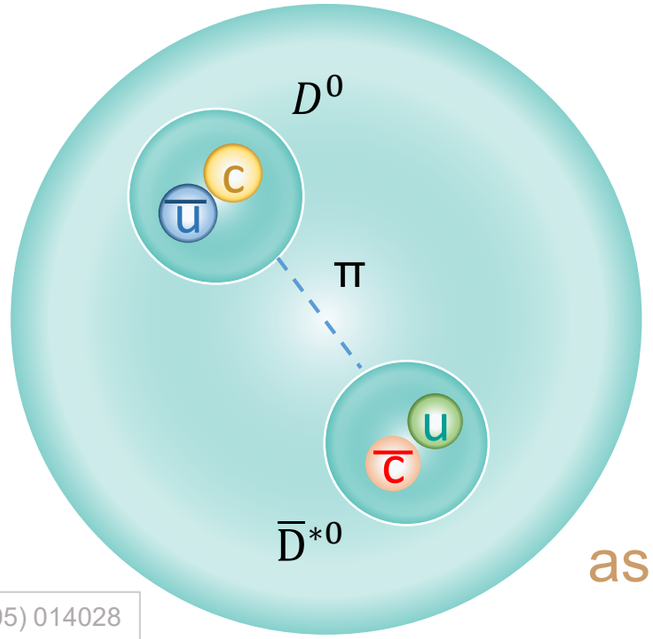
Tetraquark (4q)



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

PRD 71 (2005) 014028

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



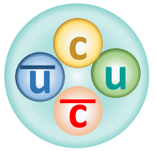
PRD71 (2005) 014028

$r_{molecule}$
as large as 5 fm

Probe the Nature of X(3872)

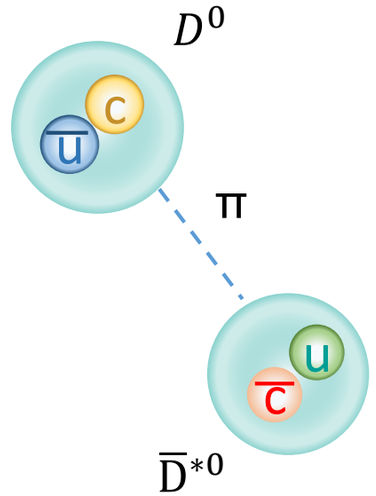
Tightly bound

Tetraquark (4q)



Loosely bound

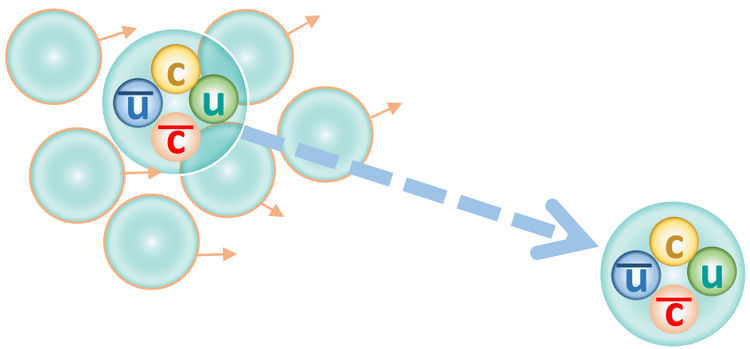
$D^0 - \bar{D}^{*0}$ molecule



Probe the Nature of X(3872) with Comoving Particles

Tightly bound

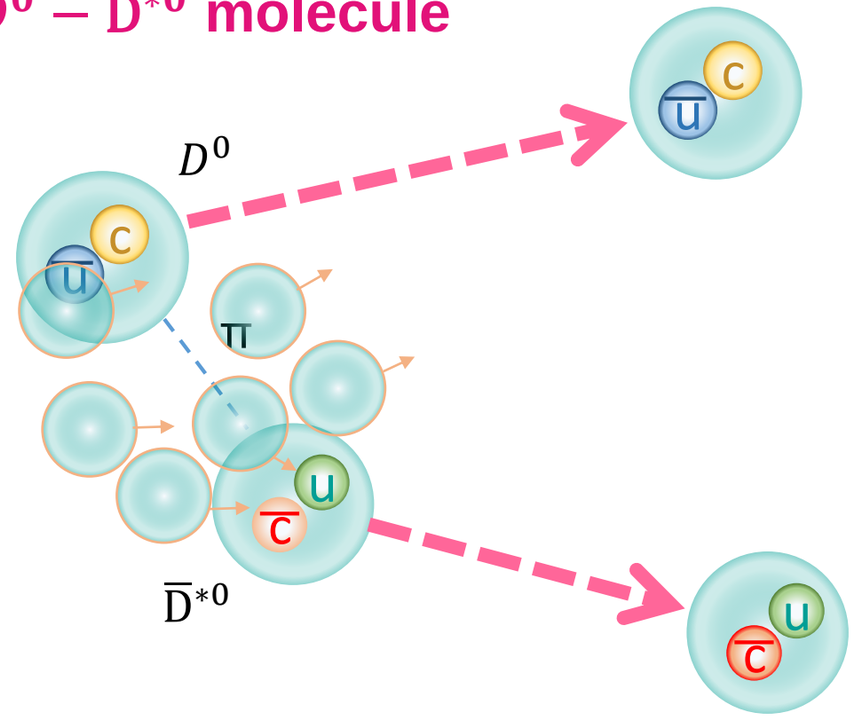
Tetraquark (4q)



Comoving particles

Loosely bound

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



Smaller dissociation probability

Larger dissociation probability

Esposito et al, arXiv: 2006.15044

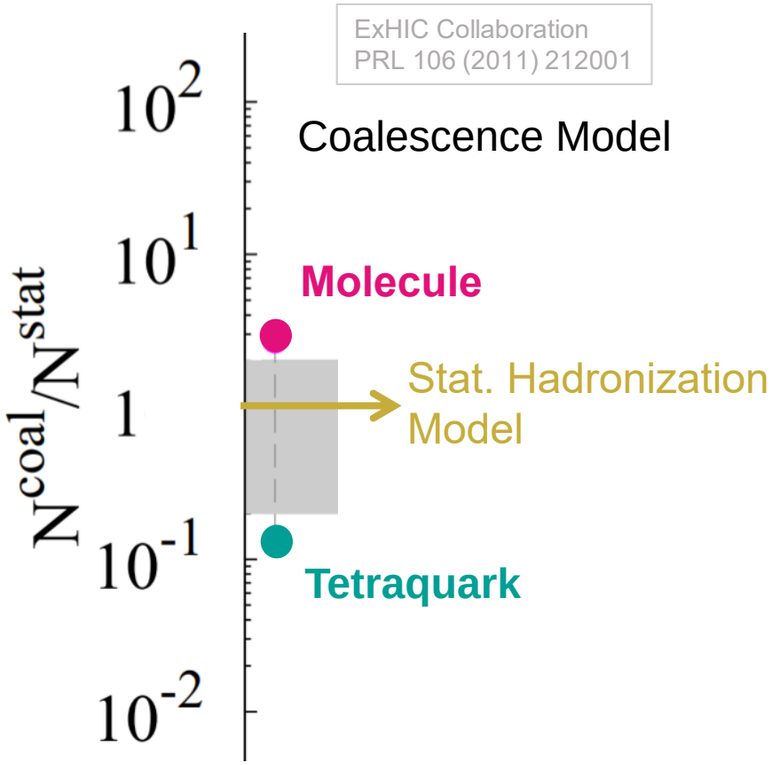
X(3872) Production in Heavy Ion Collisions

X(3872) production in Heavy Ion Collisions

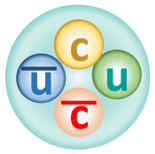
- Production yield in QGP strongly reflects internal structure in the coalescence model
- Hadron Gas Phase: Interact with other hadrons: production + absorption

  $\pi X \rightleftharpoons D\bar{D}, D\bar{D}^*$ & $\rho X \rightleftharpoons D\bar{D}, D\bar{D}^*, D^*\bar{D}^*$
- 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)



Tetraquark (4q)



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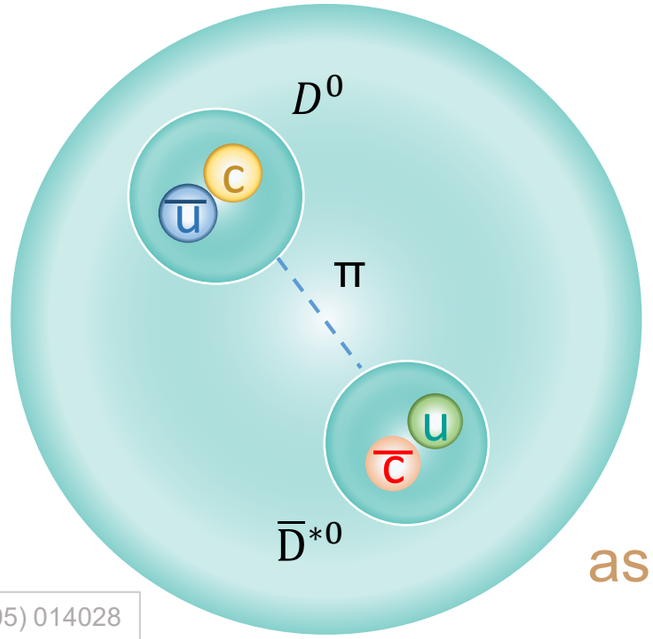
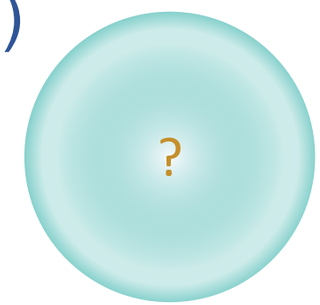
PRD 71 (2005) 014028

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



PRD71 (2005) 014028

Hybrid



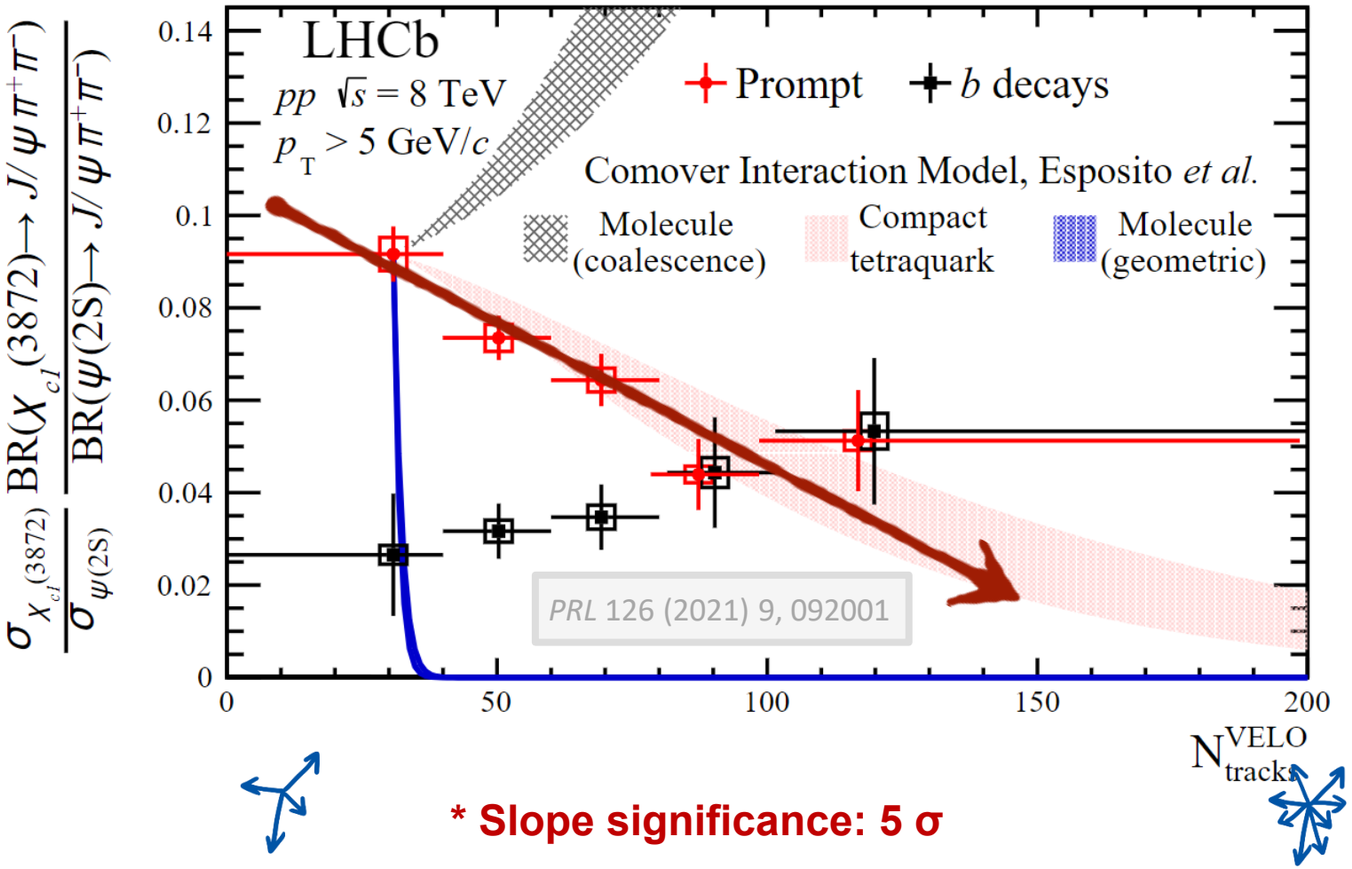
EPJA47 (2011) 101

$r_{molecule}$

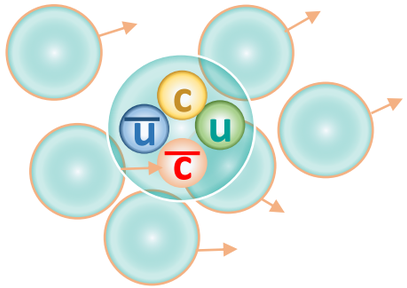
as large as 5 fm

X(3872) in High Multiplicity pp from LHCb

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



*** Slope significance: 5 σ**

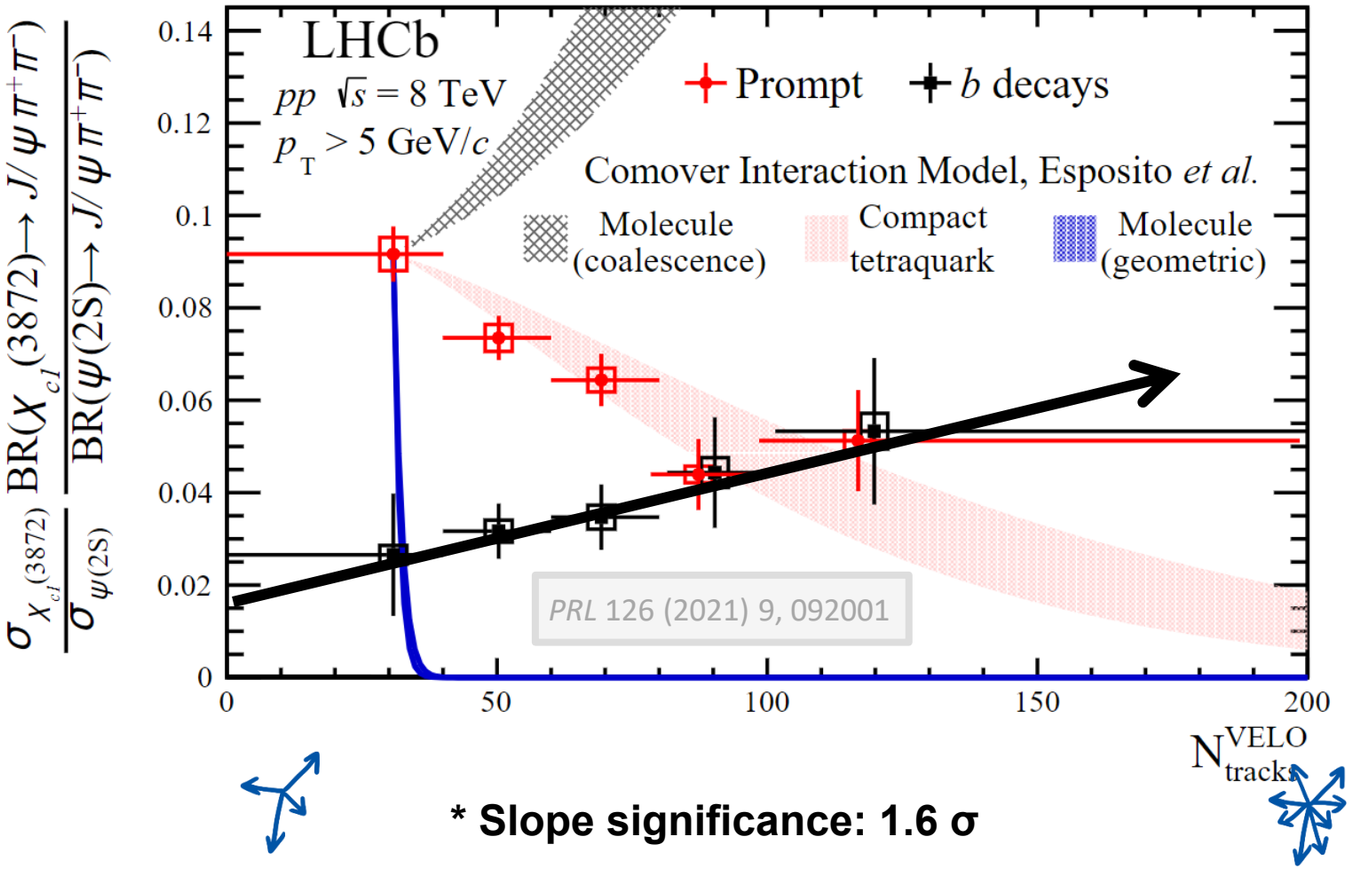


Prompt X

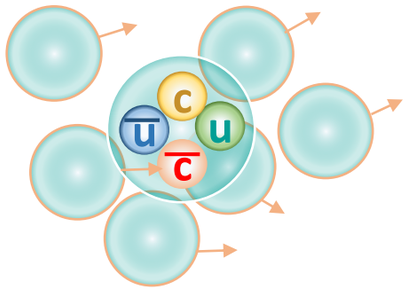
- Destroyed by interactions with other hadrons due to smaller binding energy?

Non-prompt X(3872) in pp from LHCb

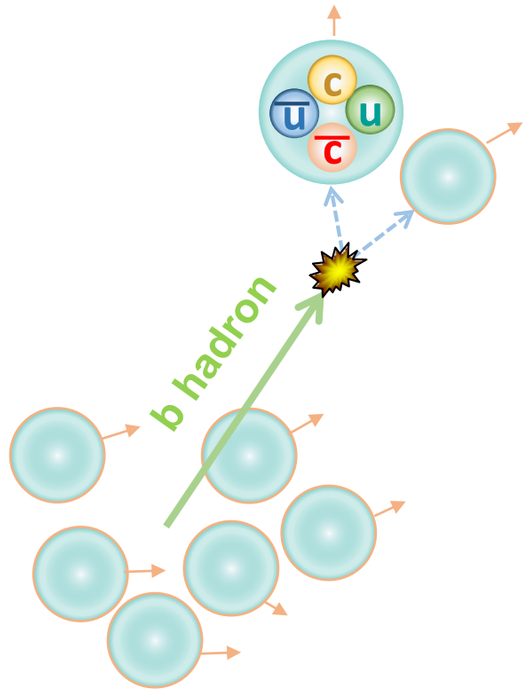
Prompt X(3872)/ψ(2S) vs. multiplicity in pp



*** Slope significance: 1.6 σ**



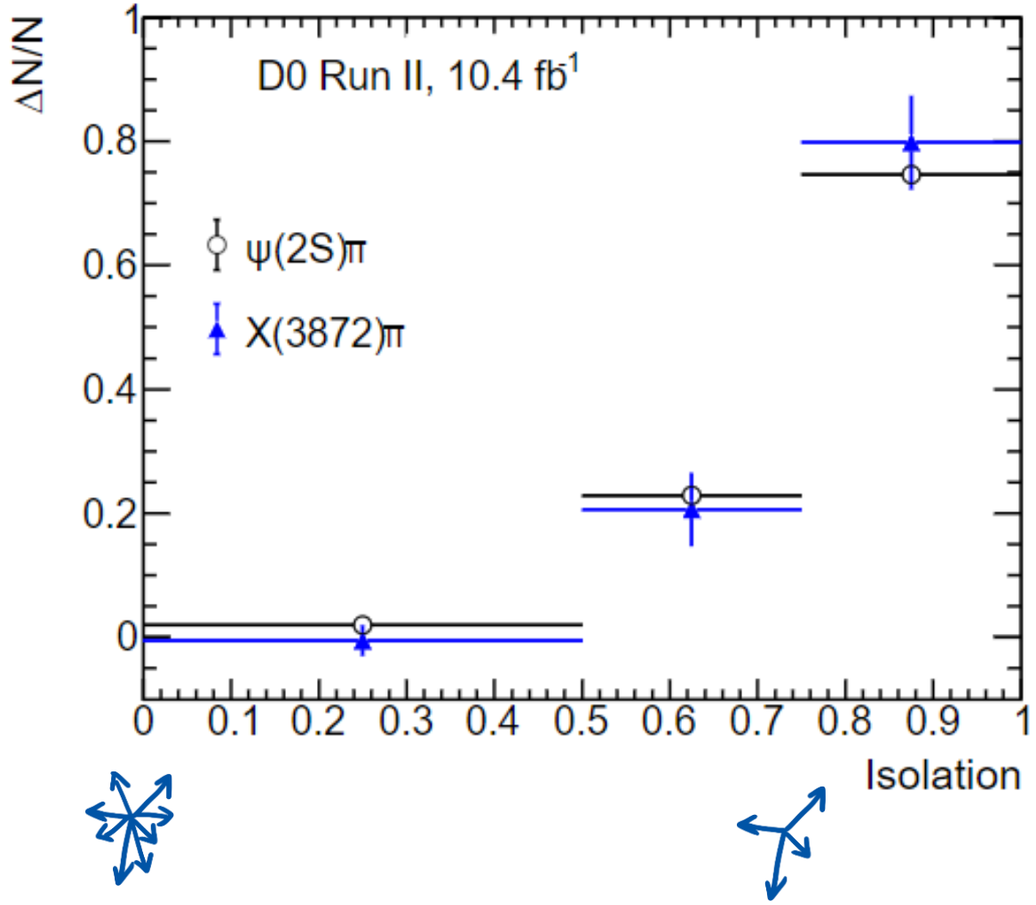
Prompt X

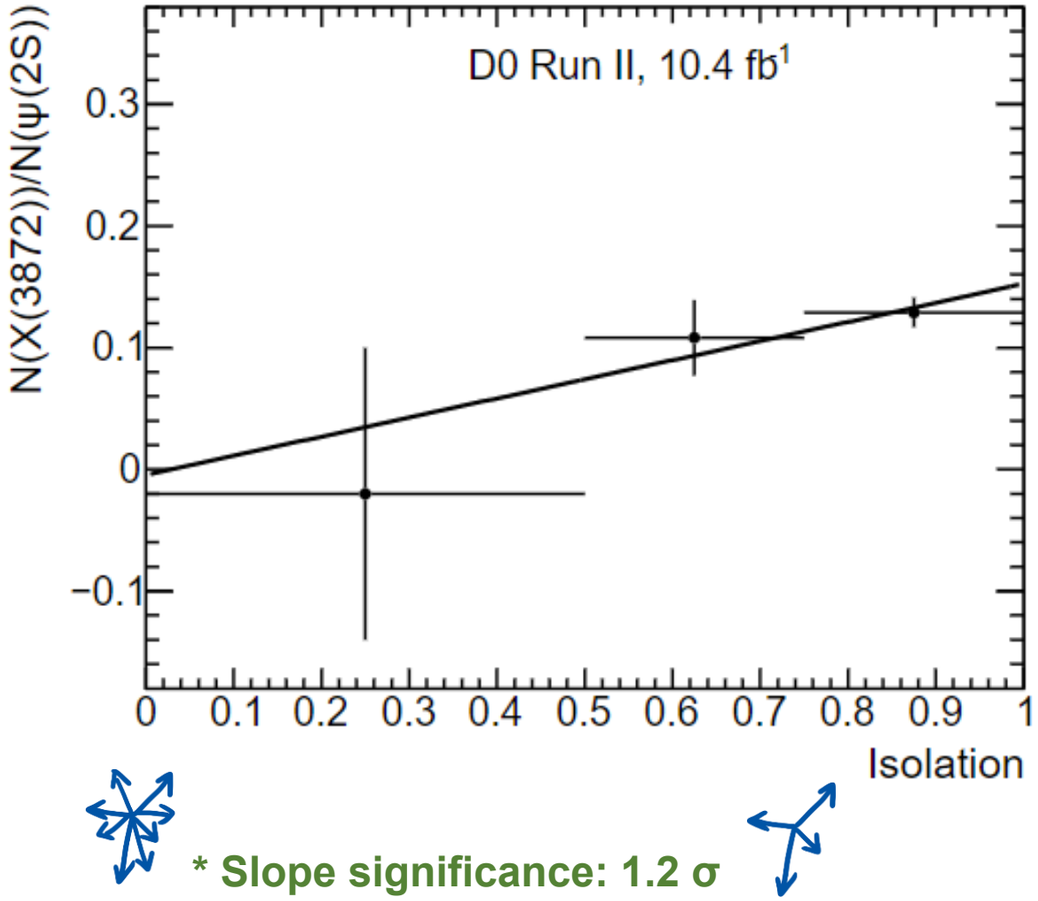


b hadron → X + hadrons

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

X(3872) and ψ(2S) in $p\bar{p}$ collisions at Tevatron





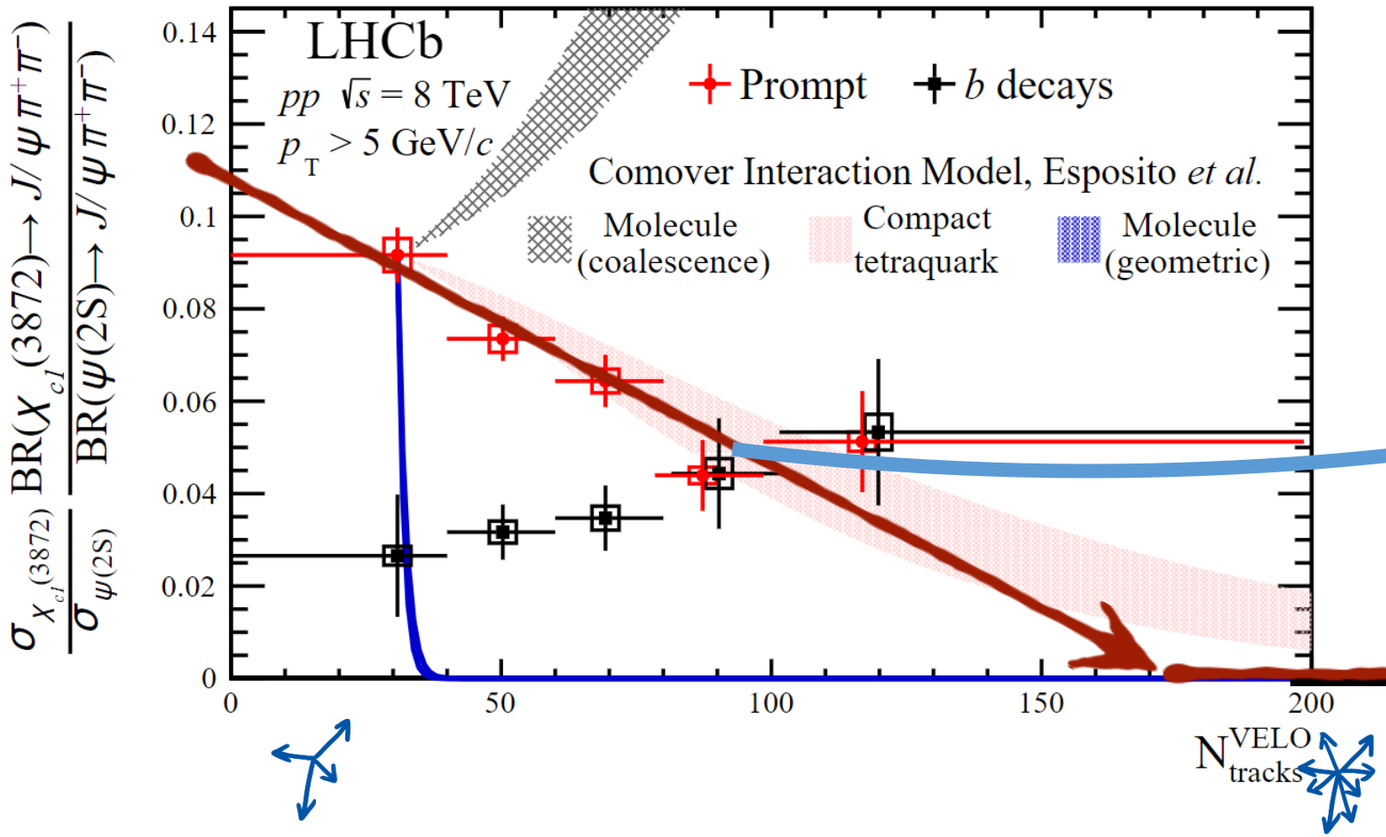
* Slope significance: 1.2 σ

- 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) suppresses its production

PRD 102, 072005 (2020)

X(3872) in PbPb?

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



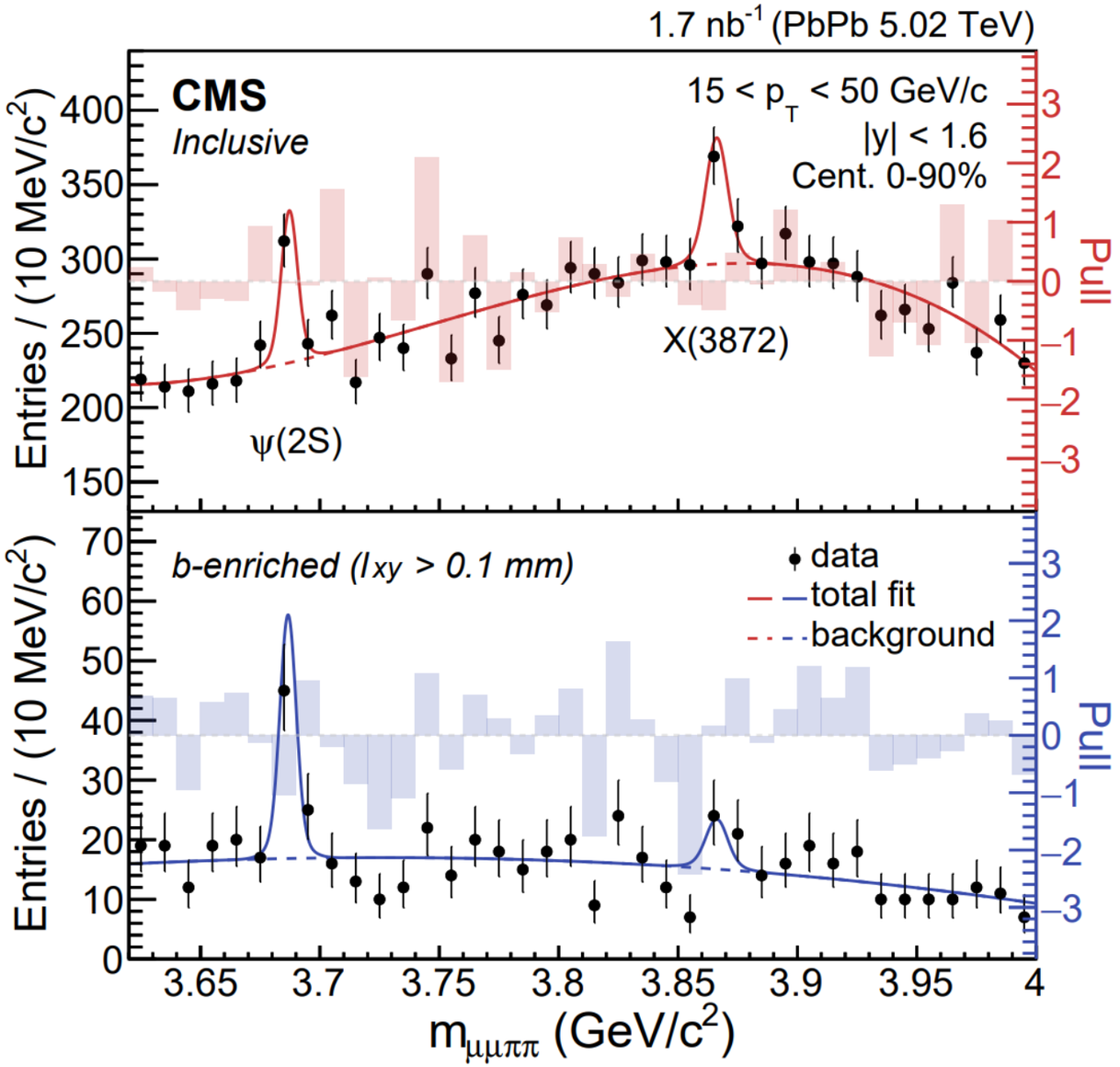
?

Coalescence?

Breakup due to comoving particles ?

PbPb

Invariant Mass Spectra in PbPb Collisions at 5 TeV



- First evidence of inclusive **X(3872)** production in heavy ion collisions!
  (statistical significance **4.2σ**)
- The fact that there is a X(3872) peak is already very interesting!
- A clear **ψ(2S)** signal to the same final state is also observed

arXiv:2102.13048
submitted to PRL

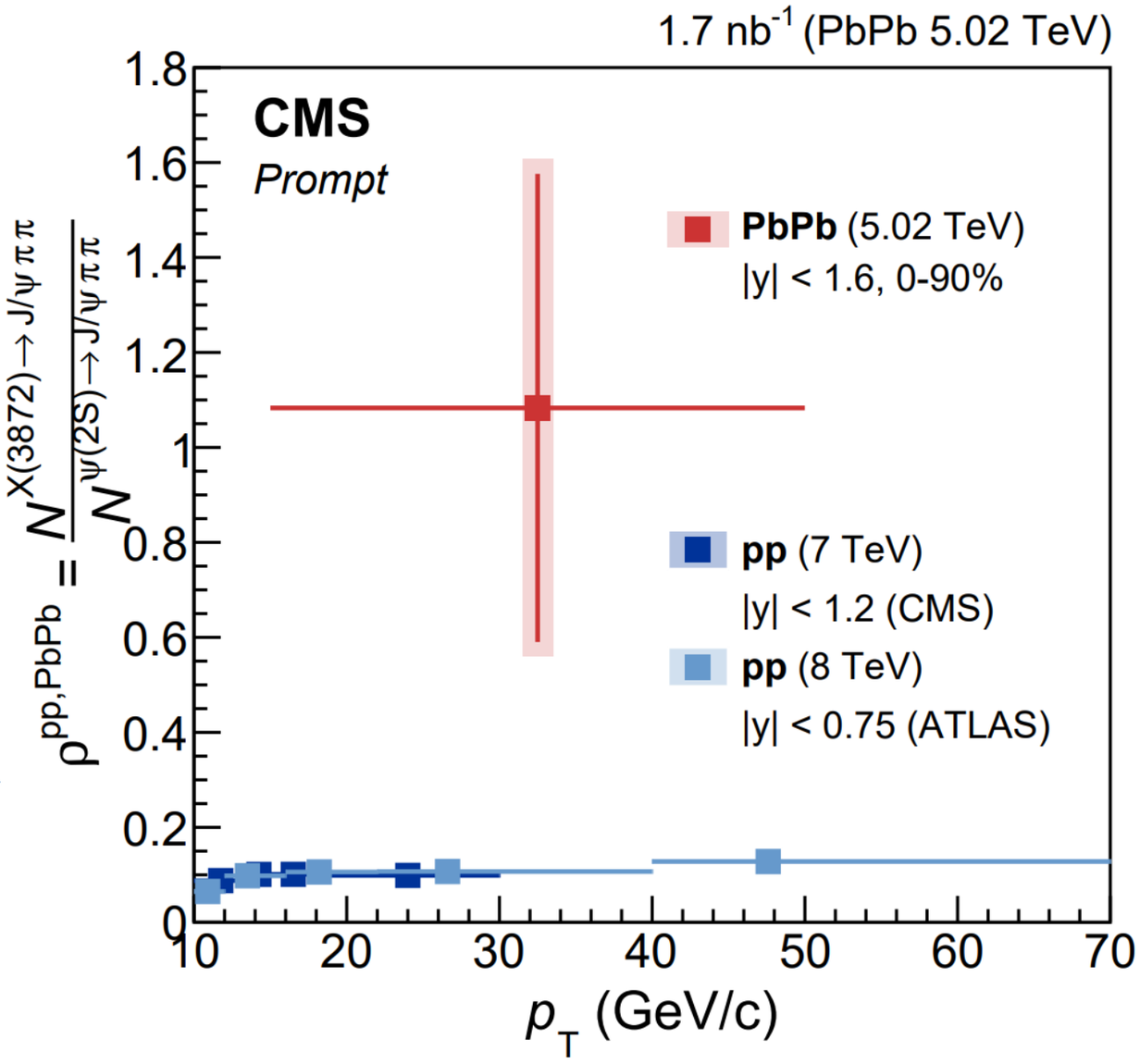
Ratio of X(3872) to ψ(2S) Yields in pp and PbPb

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

In PbPb collisions:

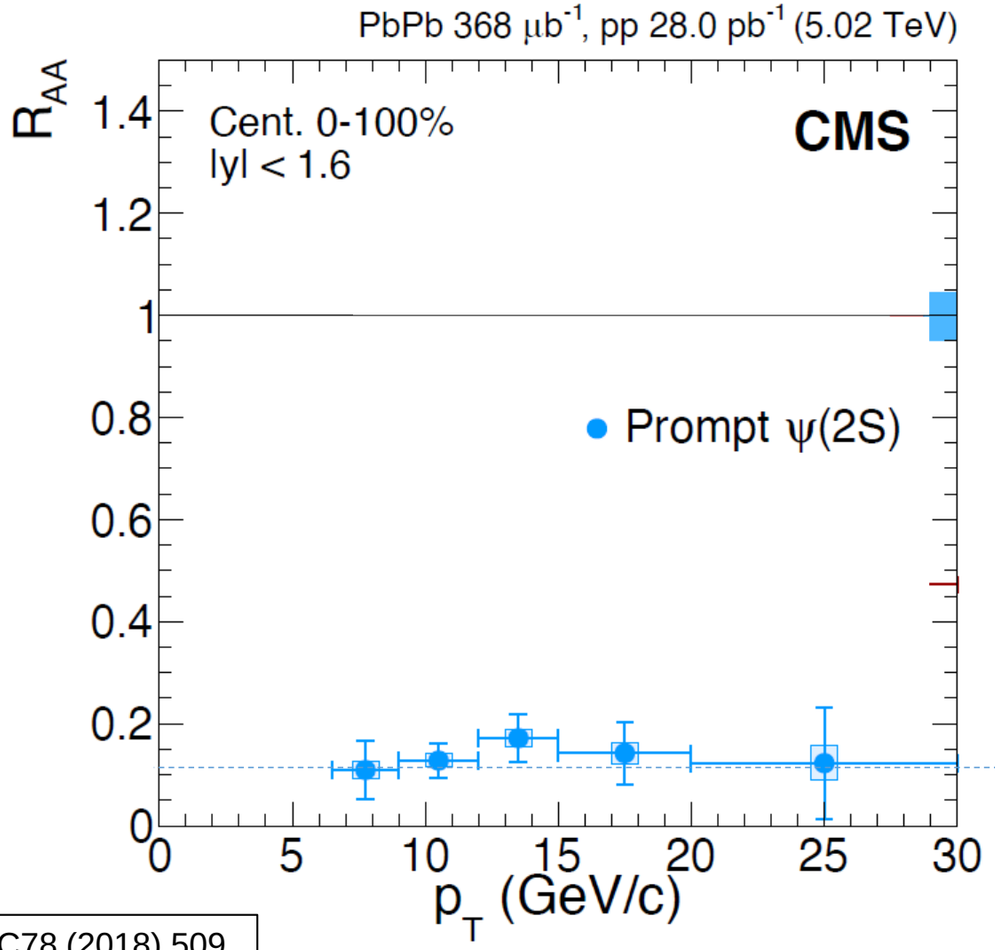
$$\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$$

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

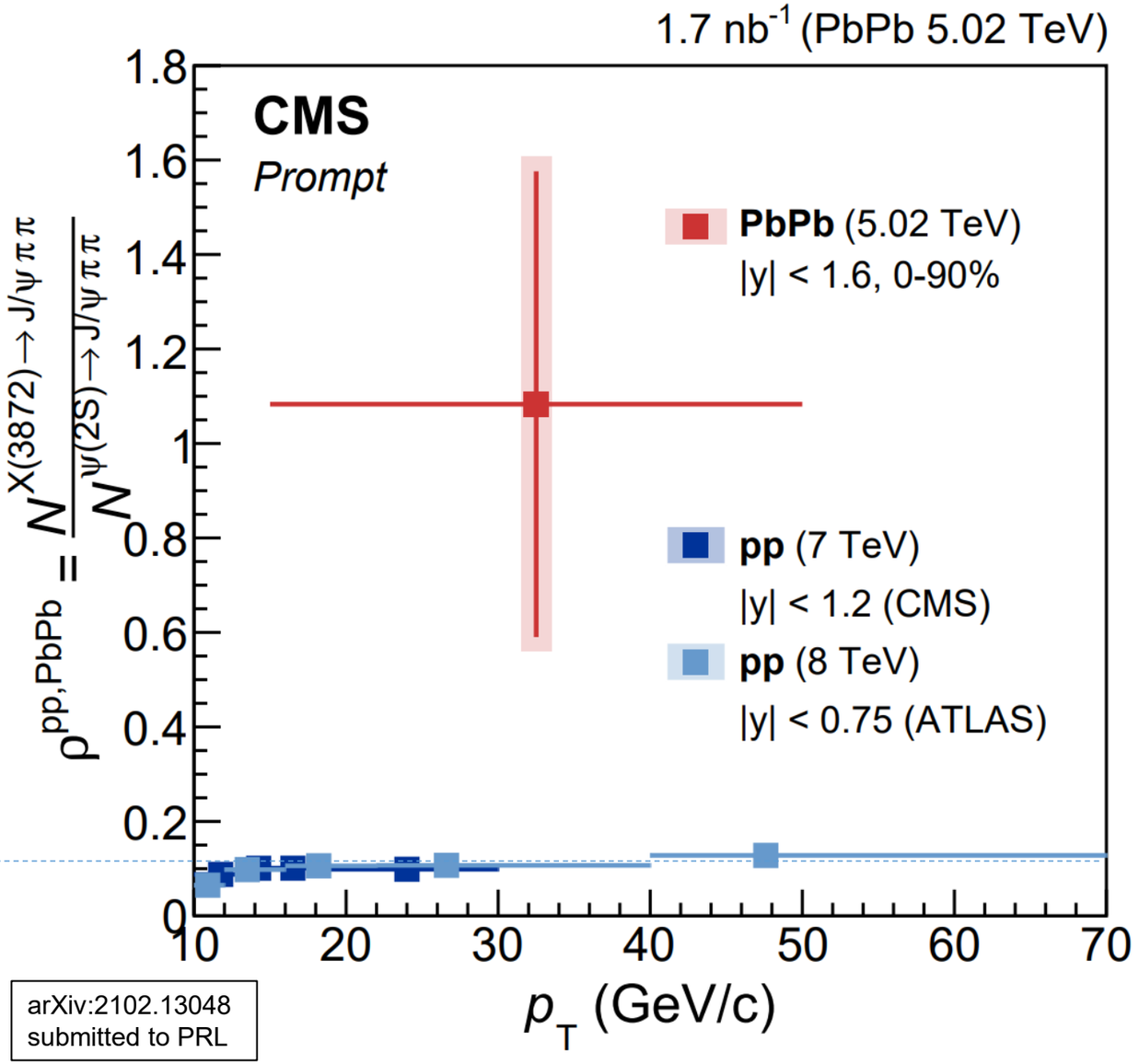


arXiv:2102.13048
submitted to PRL

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



EPJC78 (2018) 509

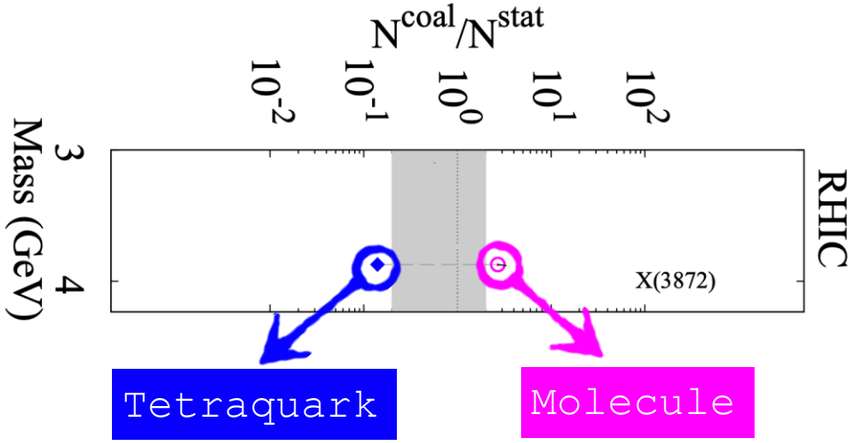


arXiv:2102.13048
submitted to PRL

X(3872) Production in Theoretical Calculations

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

Coalescence model

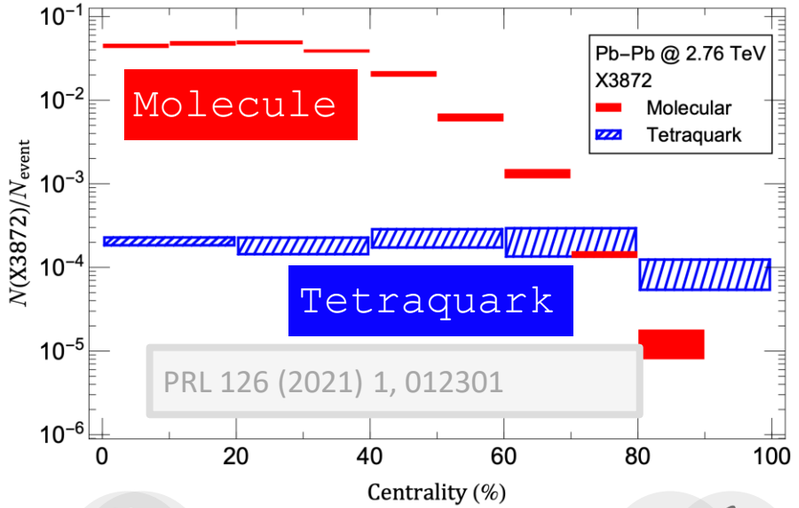


PRL 106 (2011) 212001

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

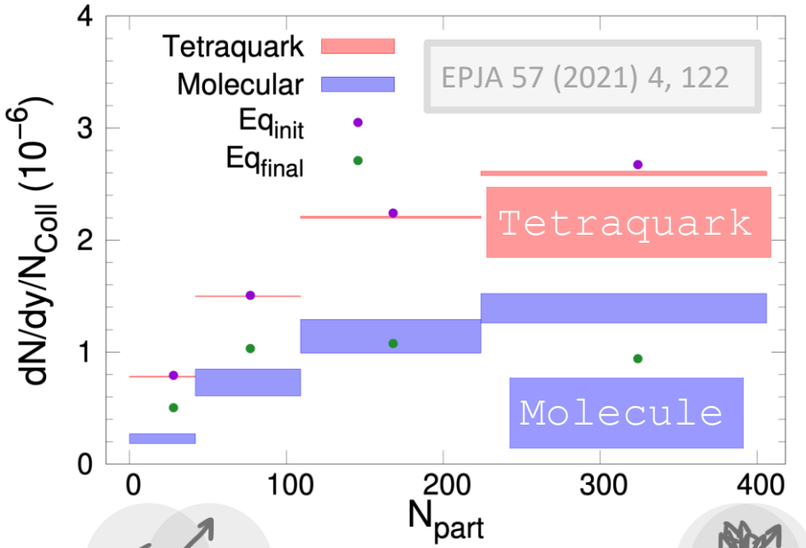
Compilation from Jing Wang (MIT)

AMPT transport model



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

TAMU transport model



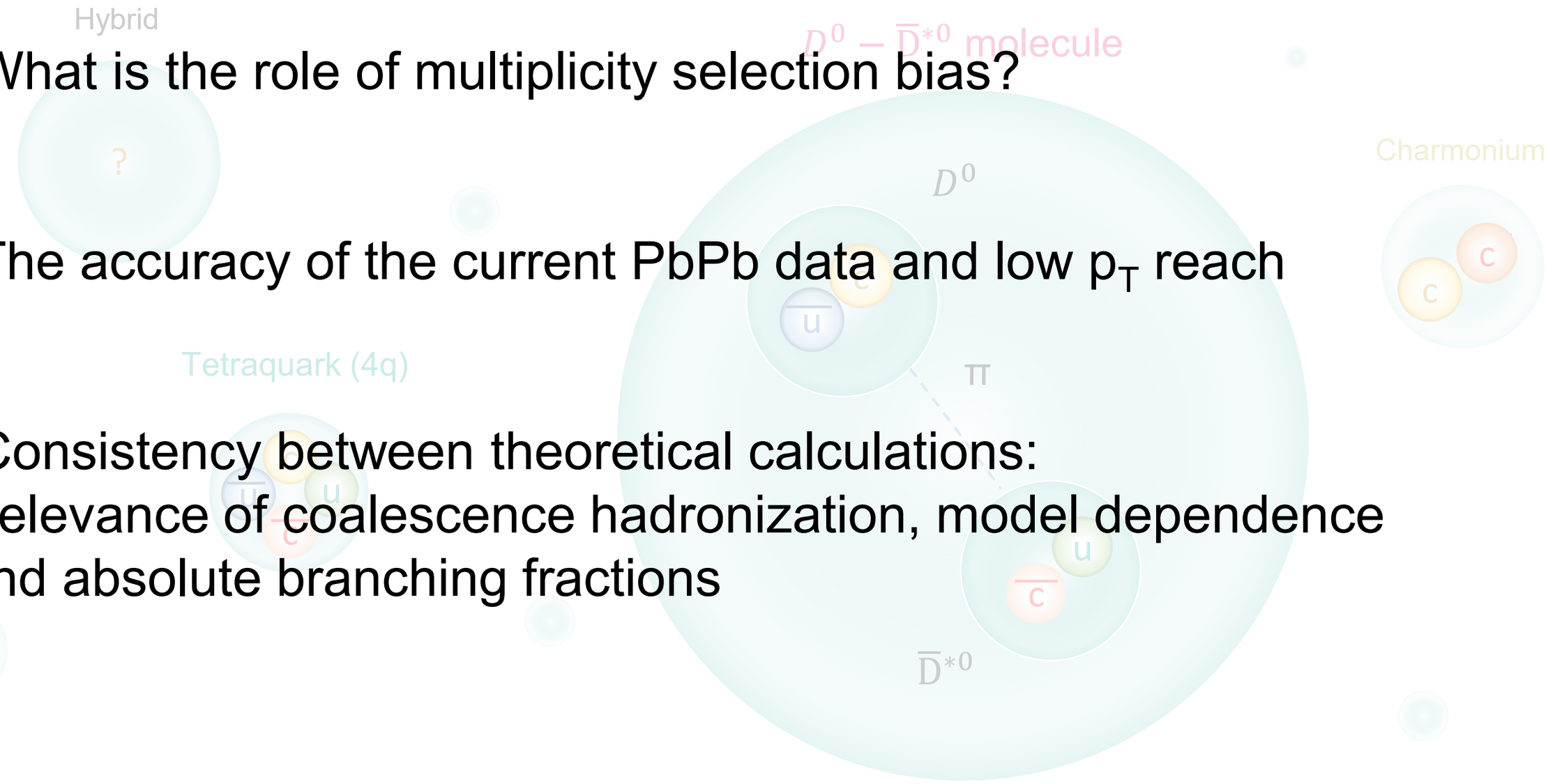
- Molecule (more loosely bound) regenerated later in the evolution compared to tetraquark
- $N_{Molecule} < N_{Tetraquark}$

Unresolved Issues for X(3872)

1. What is the role of multiplicity selection bias?

2. The accuracy of the current PbPb data and low p_T reach

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



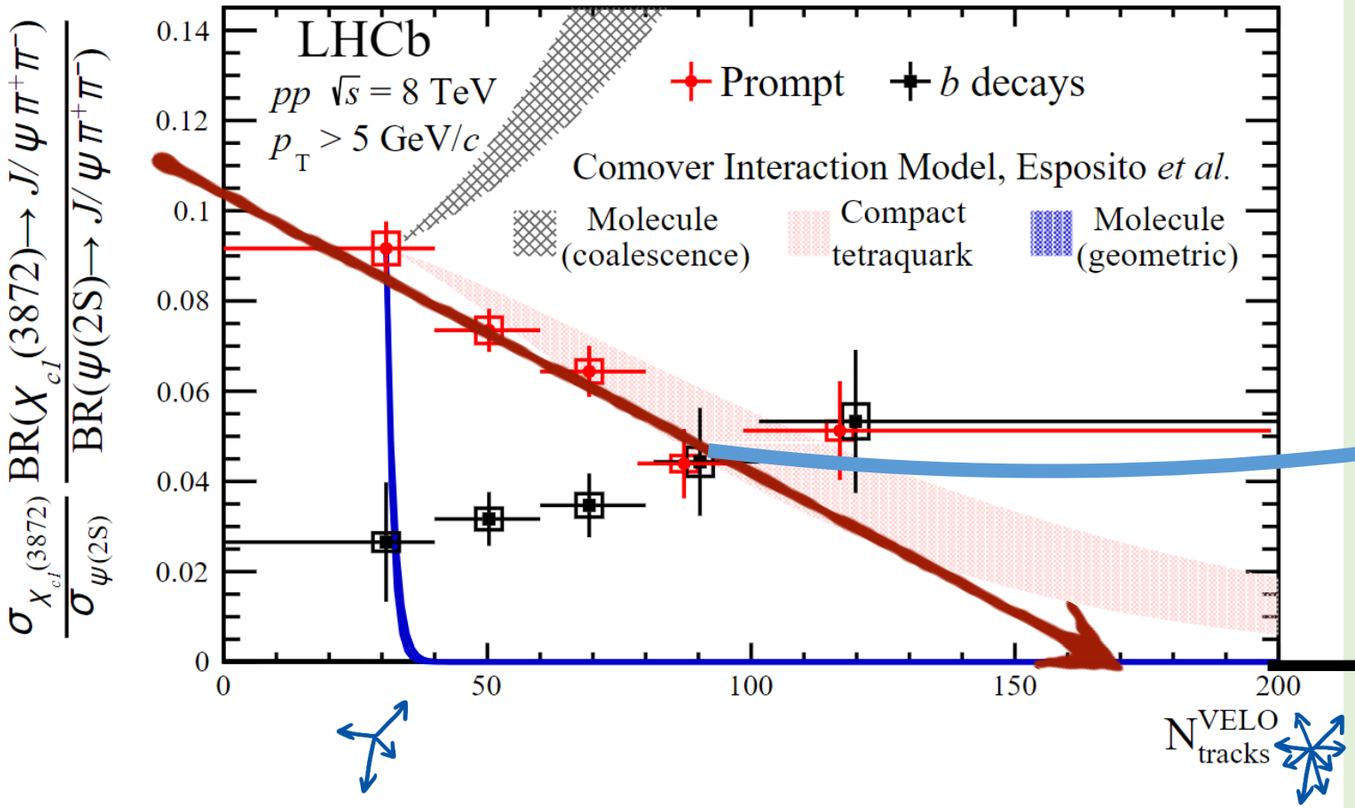
Unresolved Issues for X(3872)

1. What is the role of multiplicity selection bias?
   - Change the source of comoving particles using ep, eA, pp, pA collisions
2. The accuracy of the current PbPb data
   - Large dataset from Run 3 and Run 4 at the LHC; new detectors such as large acceptance CMS tracker in Run 4 and future ALICE 3.
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

Studies of X(3872) in HI and future EIC

CMS PbPb

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



Coalescence?

?

Breakup due to comoving particles

LHCb SMOG

eA / eP

pp

pA, OO

PbPb

AuAu

Summary

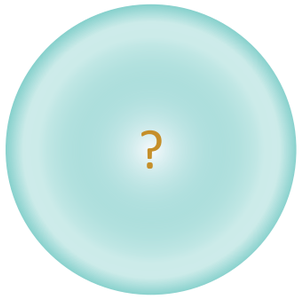
- Beauty Hadron:
  - Observation of mass dependence of parton energy loss
  - Indication of modified beauty hadronization via B_s/B^+ in PbPb
    - Similar to that was observed in D_s/D^0
  - Beauty hadron v_2 in PbPb via HF leptons
  - Interesting to follow up with fully reconstructed b mesons and baryons in Run 3+4

- B_c^+ Meson:
  - First observation in PbPb, larger R_{AA} than B^+ and quarkonia
  - Intriguing new R_{AA} results, sensitive to recombination effect (of beauty and charm)

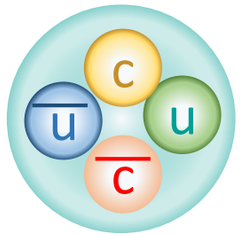
- X(3872) Hadron:
  - First evidence of X(3872) production in PbPb, **X(3872)/ψ(2S)** decrease with multiplicity in pp
  - Exciting new probe which is sensitive to comoving particles and recombination effects
  - X(3872) internal structure: inconclusive due to the current experimental accuracy and model dependence
  - Many interesting issues to be followed up with future large data in various collision systems

Thank You!

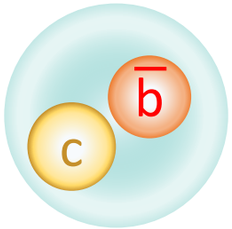
Hybrid



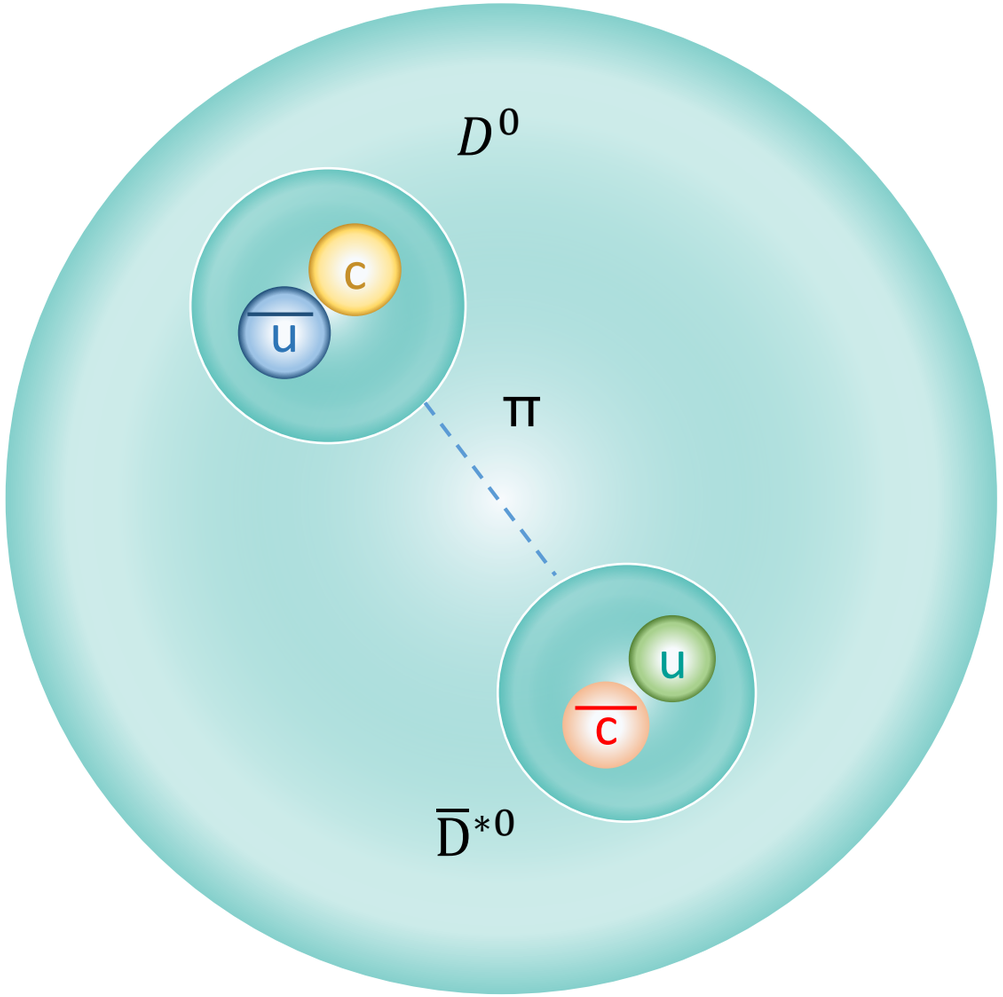
Tetraquark (4q)



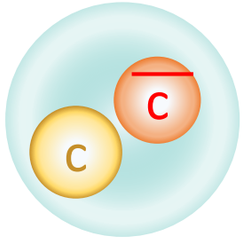
B_c



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

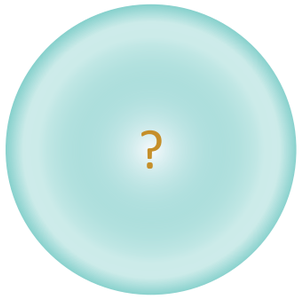


Charmonium

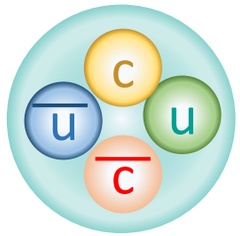


Backup Slides

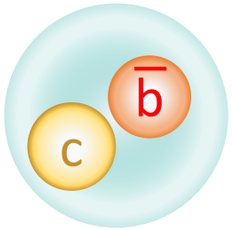
Hybrid



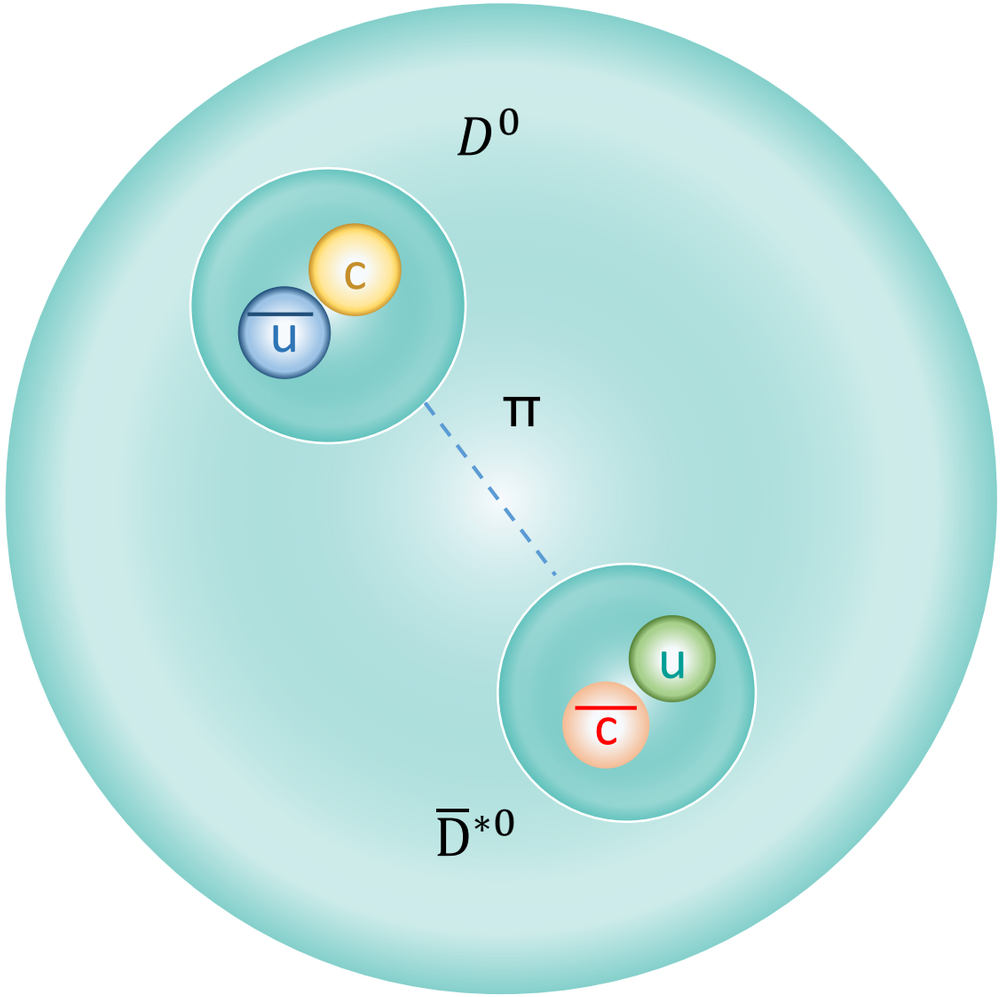
Tetraquark (4q)



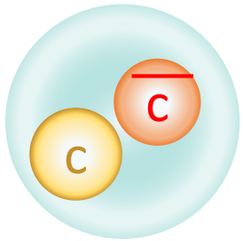
B_c



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

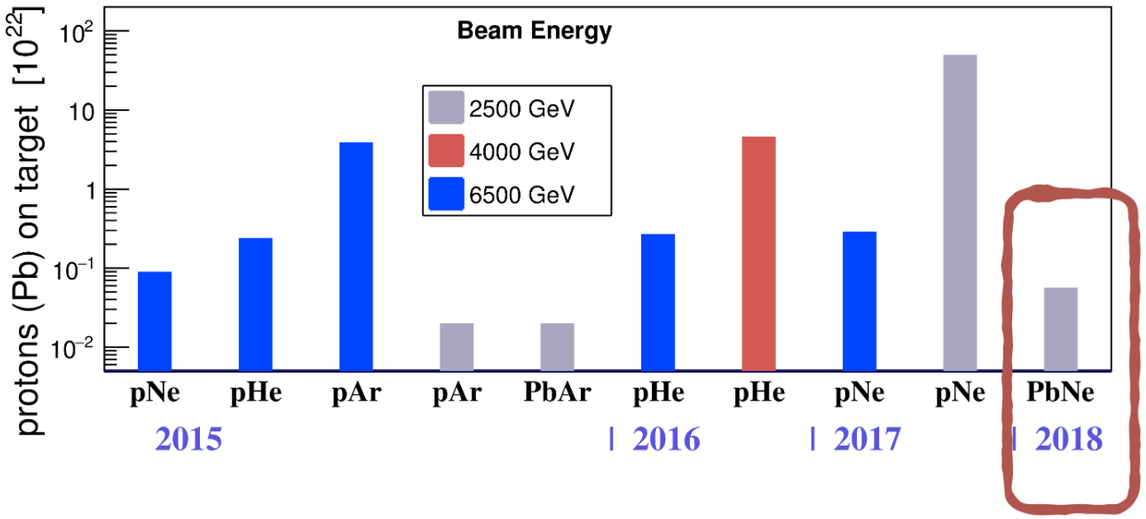


Charmonium

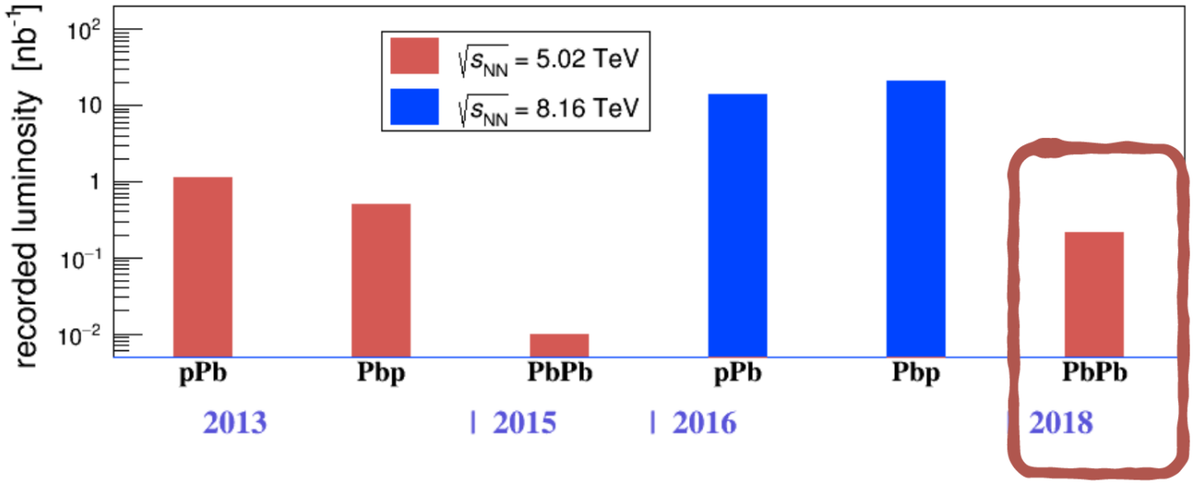


LHCb HI samples

Fixed-target mode samples



Collider mode samples

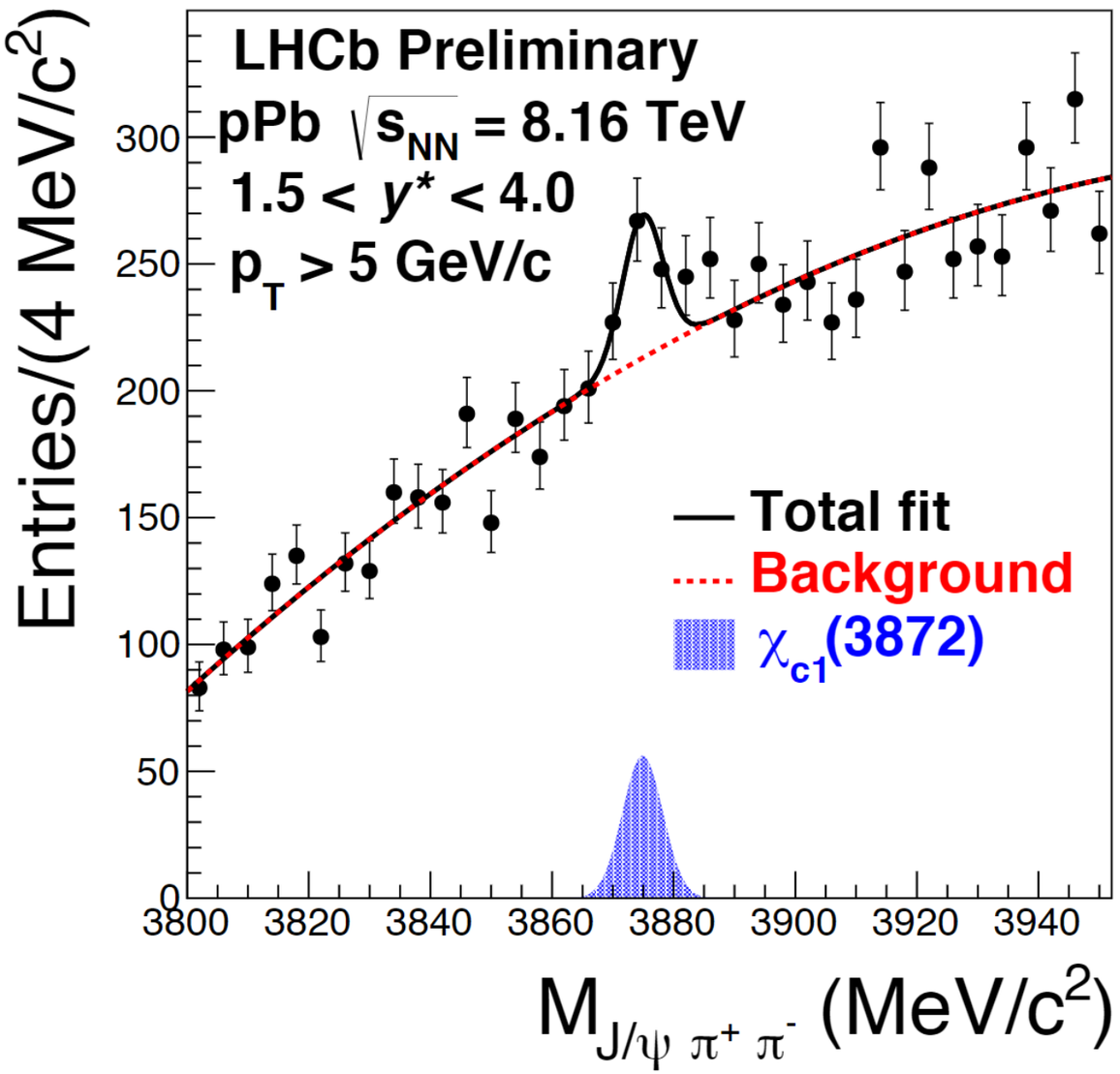


~ 20 times 2015 luminosity

- 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

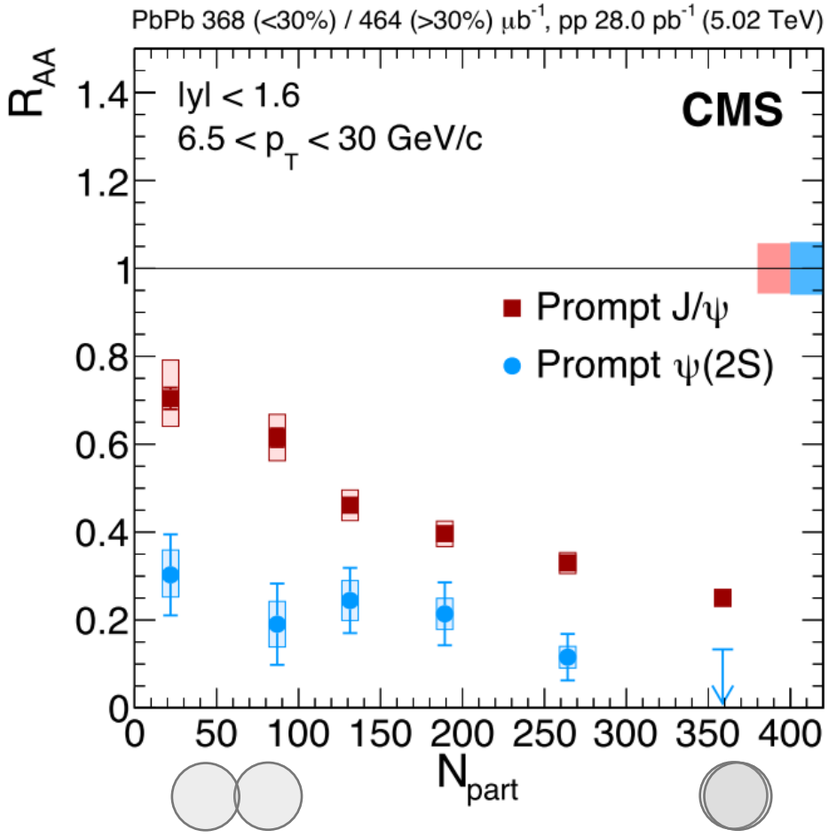
Benjamin Audurier (QM'19)

X(3872) peak in LHCb pPb sample



Charmonium R_{AA} in PbPb and pp

PbPb at 5 TeV

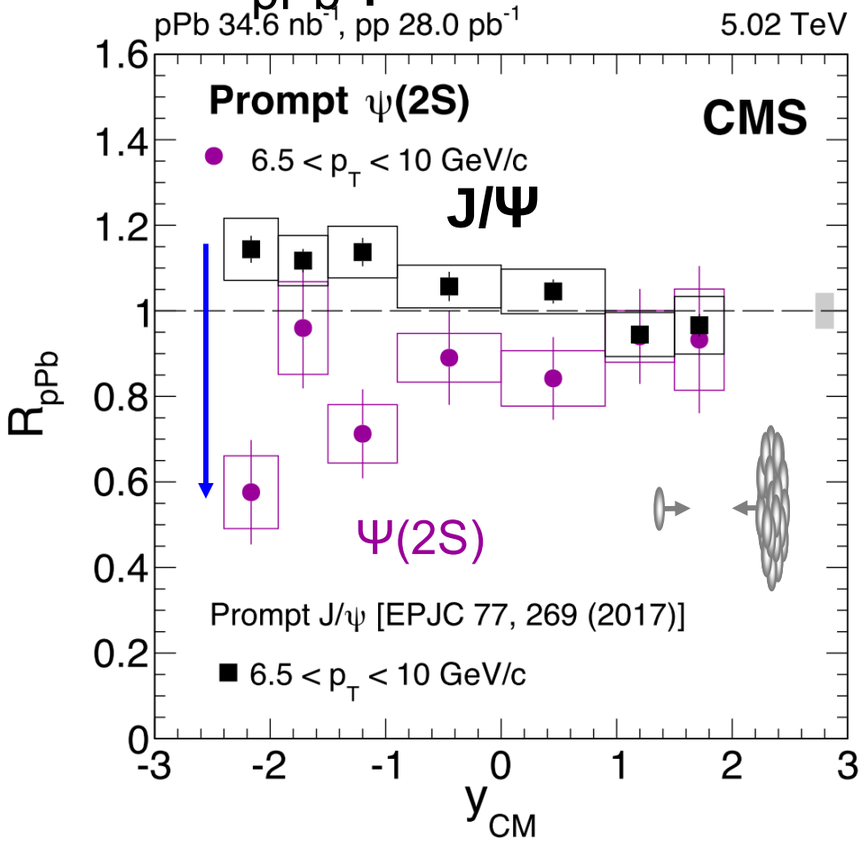


- Prompt Ψ(2S) R_{AA} < J/Ψ R_{AA} in PbPb at 5 TeV

PbPb EPJC 78 (2018) 509

pPb arXiv:1805.02248

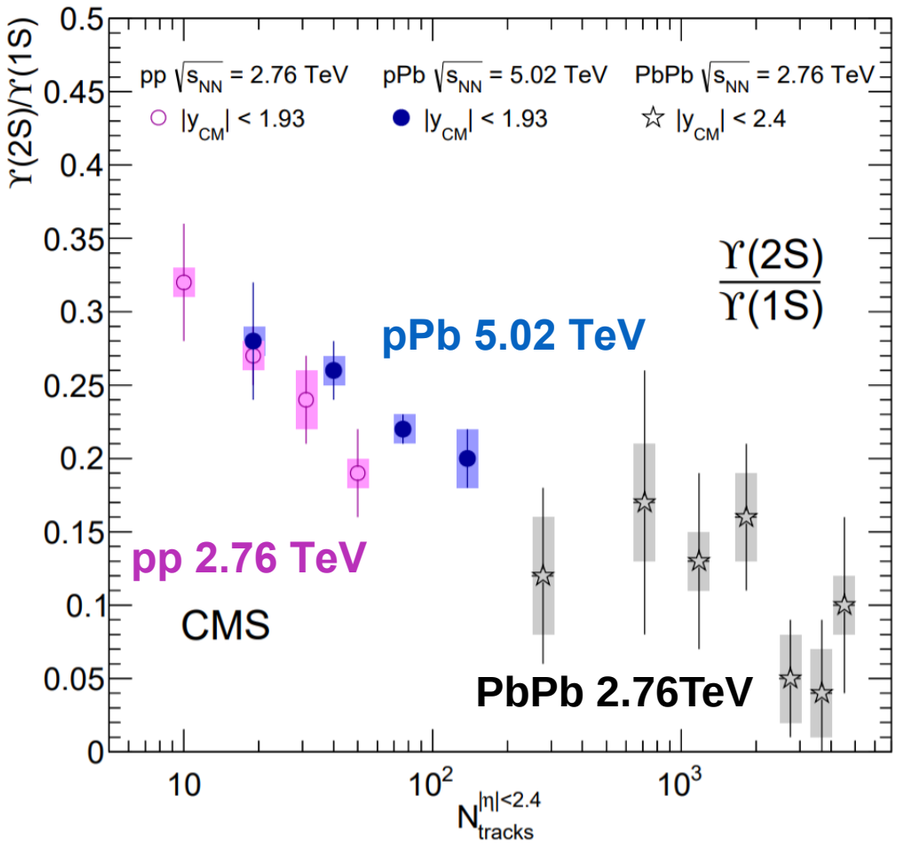
R_{pPb} pPb at 5 TeV



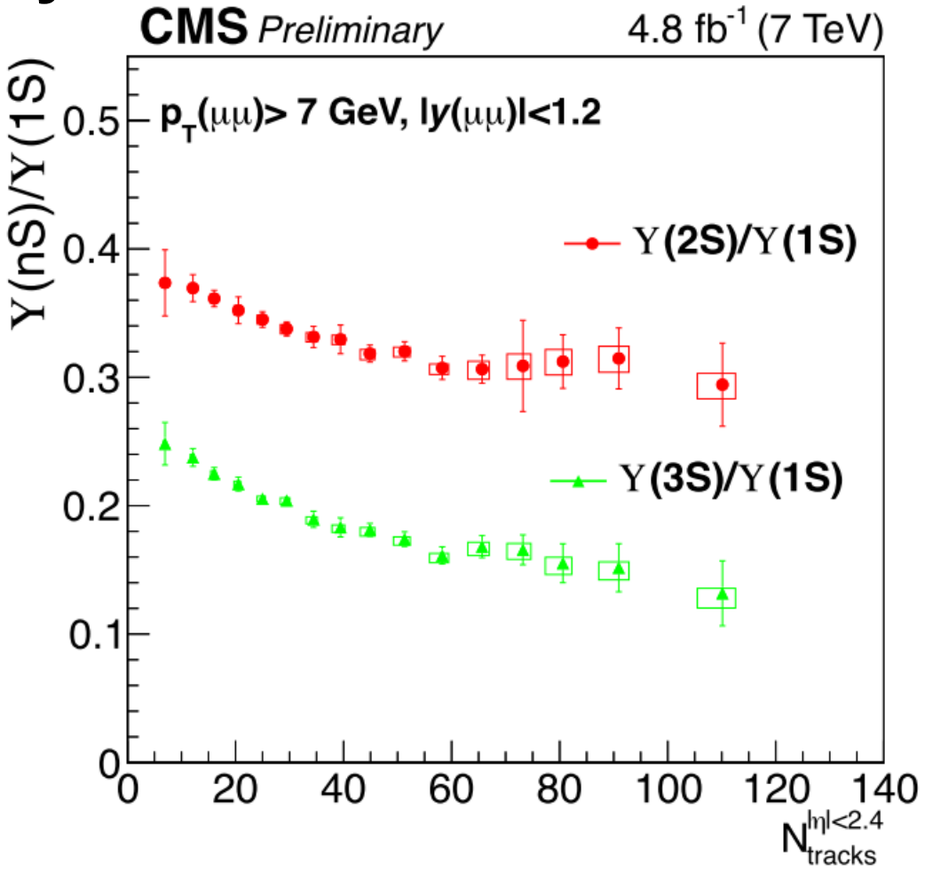
- **J/Ψ** and Ψ(2S) difference increases as we move to backward (lead-going) direction (higher dN_{ch}/dy)
- Can not be explained by nPDF or coherent energy loss model
- Final state effects from comoving (local) medium?

Upsilon suppression

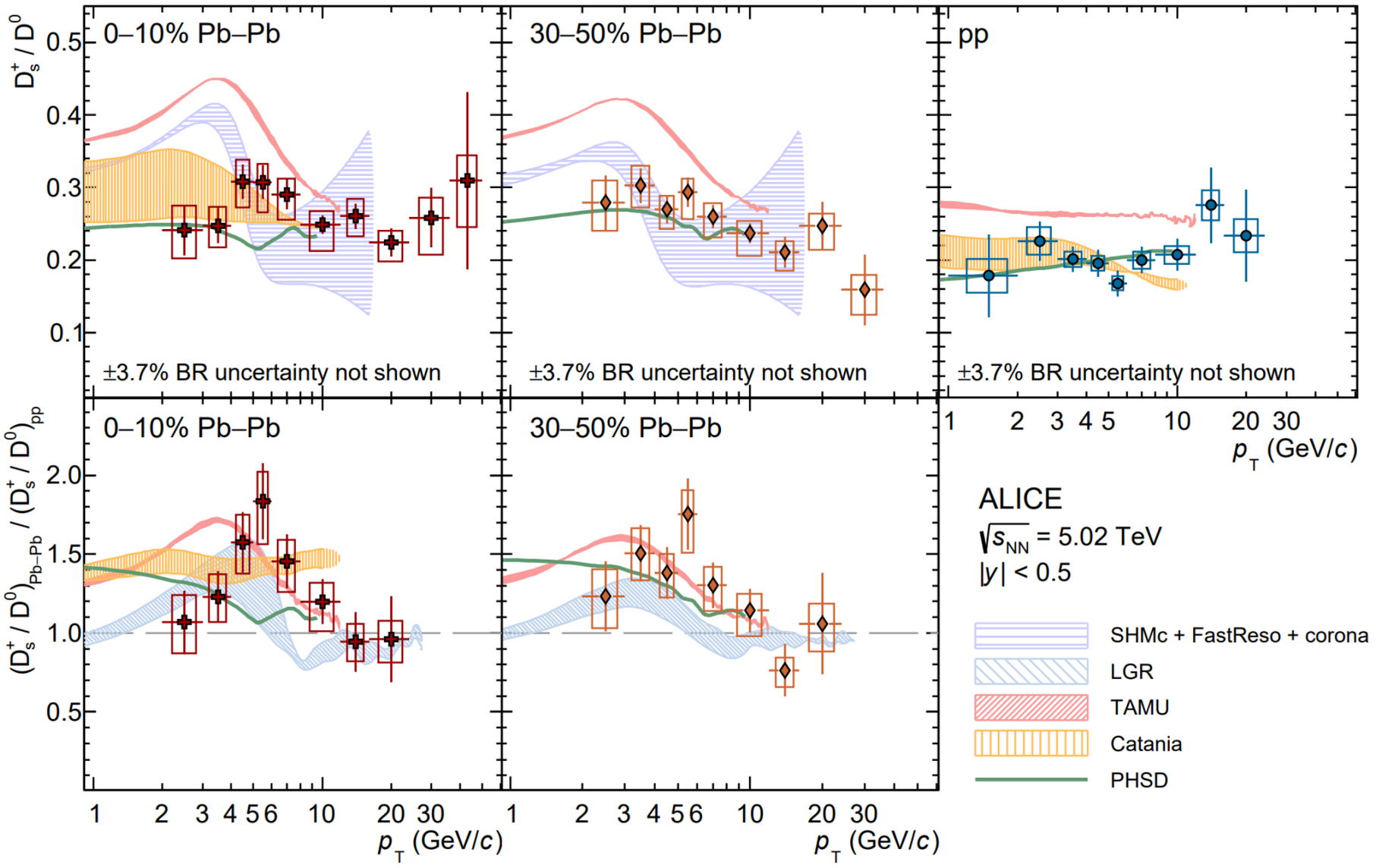
Y(2S)/Y(1S) ratio vs. multiplicity



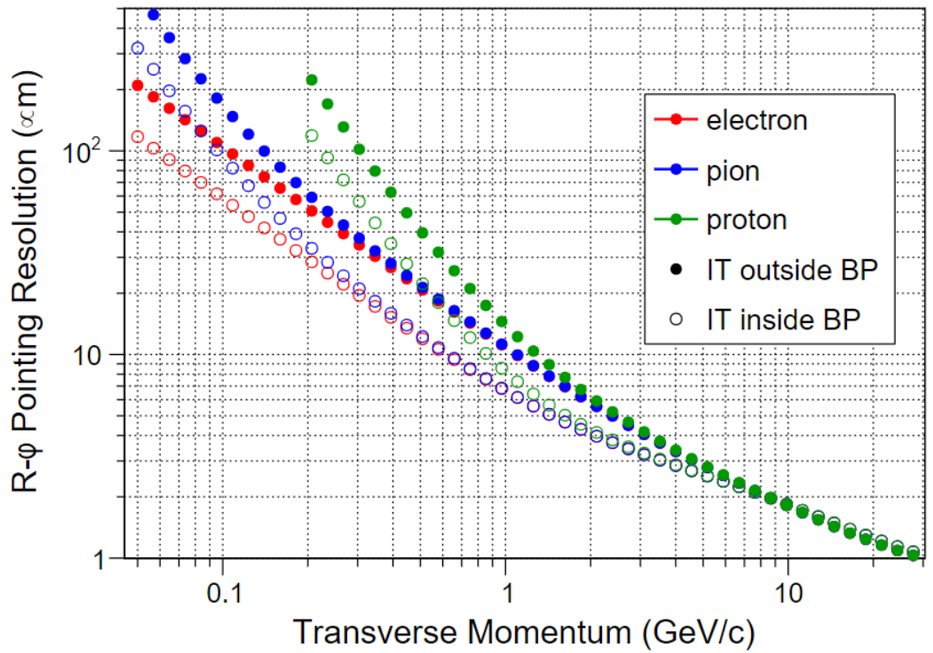
pp at 7 TeV

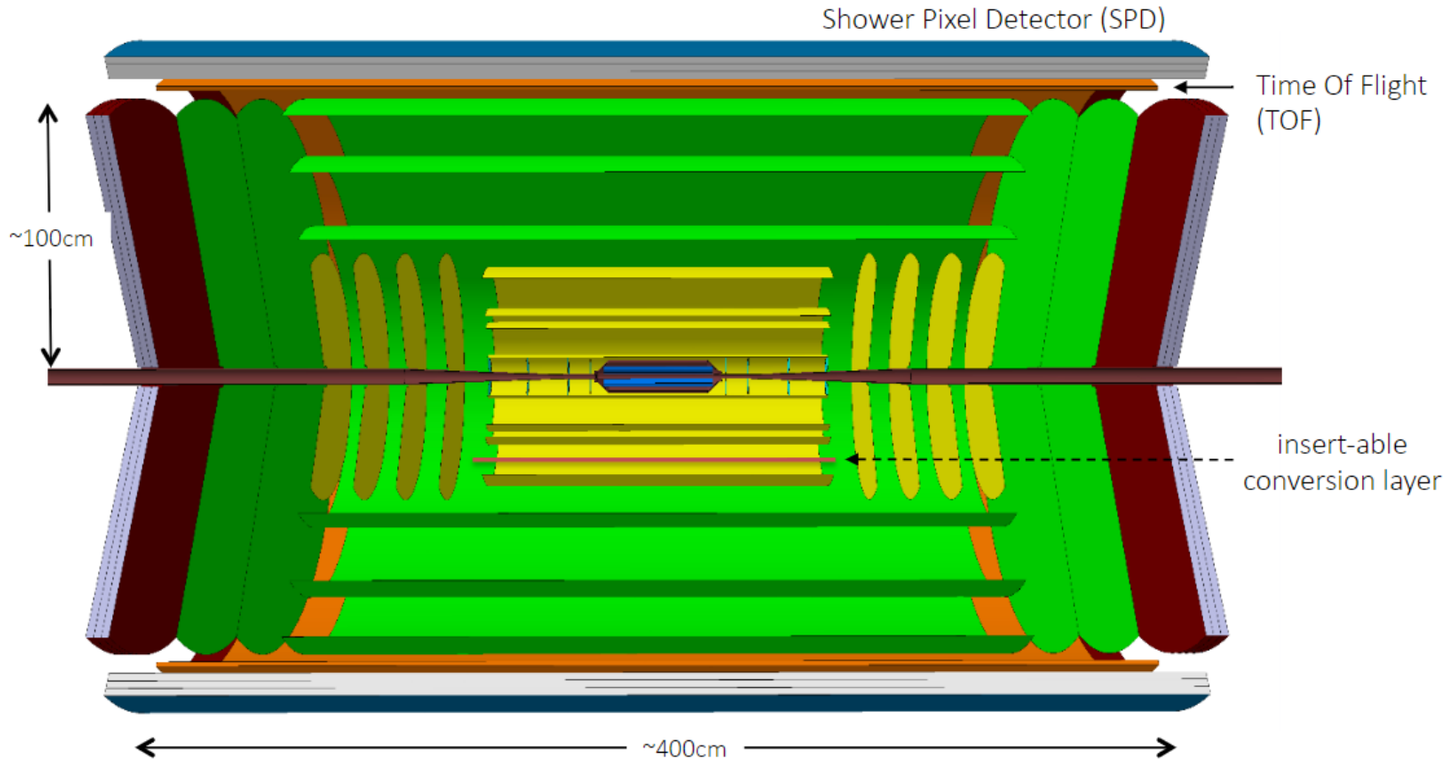


- Origin of the sequential suppression in high multiplicity pp events?


0–10% Pb–Pb
30–50% Pb–Pb
pp
D_s^+ / D^0
±3.7% BR uncertainty not shown
$(D_s^+ / D^0)_{Pb–Pb} / (D_s^+ / D^0)_{pp}$
p_T (GeV/c)
ALICE
$\sqrt{s_{NN}}$ = 5.02 TeV
$|y| < 0.5$
SHMc + FastReso + corona
LGR
TAMU
Catania
PHSD

A next-generation LHC heavy-ion experiment

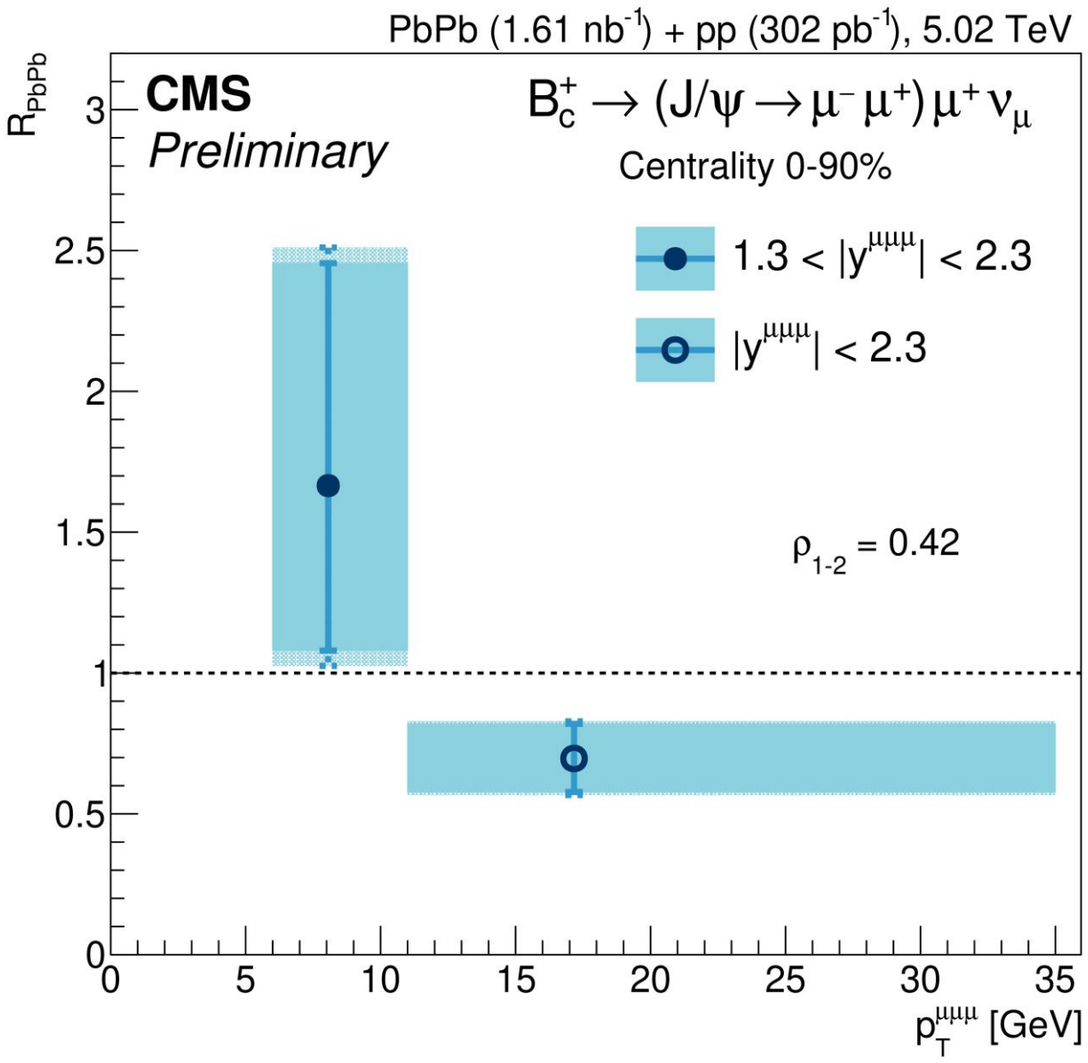


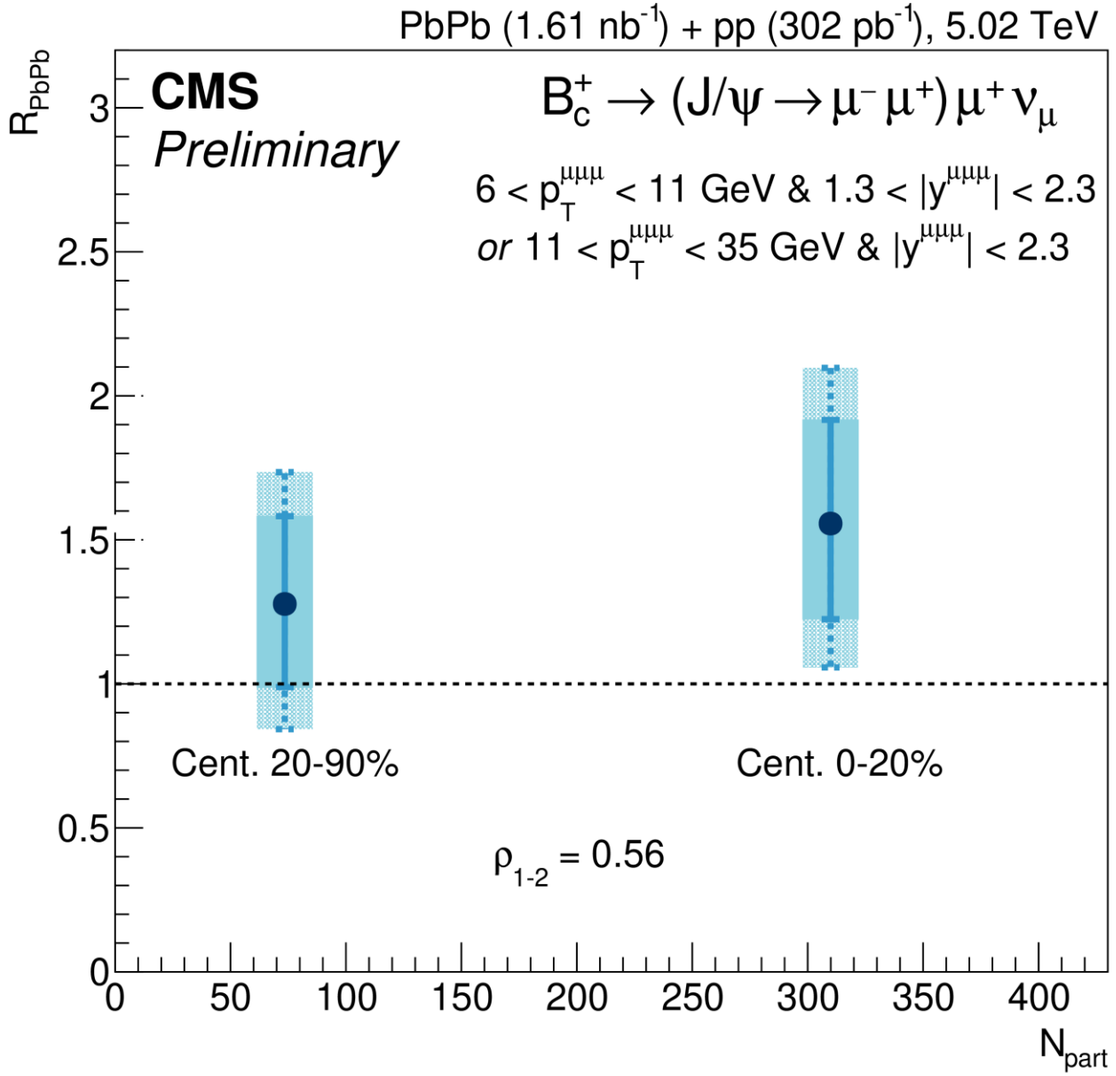


- Proposed after Run 5, optimized for heavy flavor meson and baryon reconstruction; detection of very low p_T charged particles
- Wide pseudorapidity coverage (up to 4 units), most likely equipped with forward tracking stations
- Could shed new light on the nature and structure of the X, Y, Z
- X(3872)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

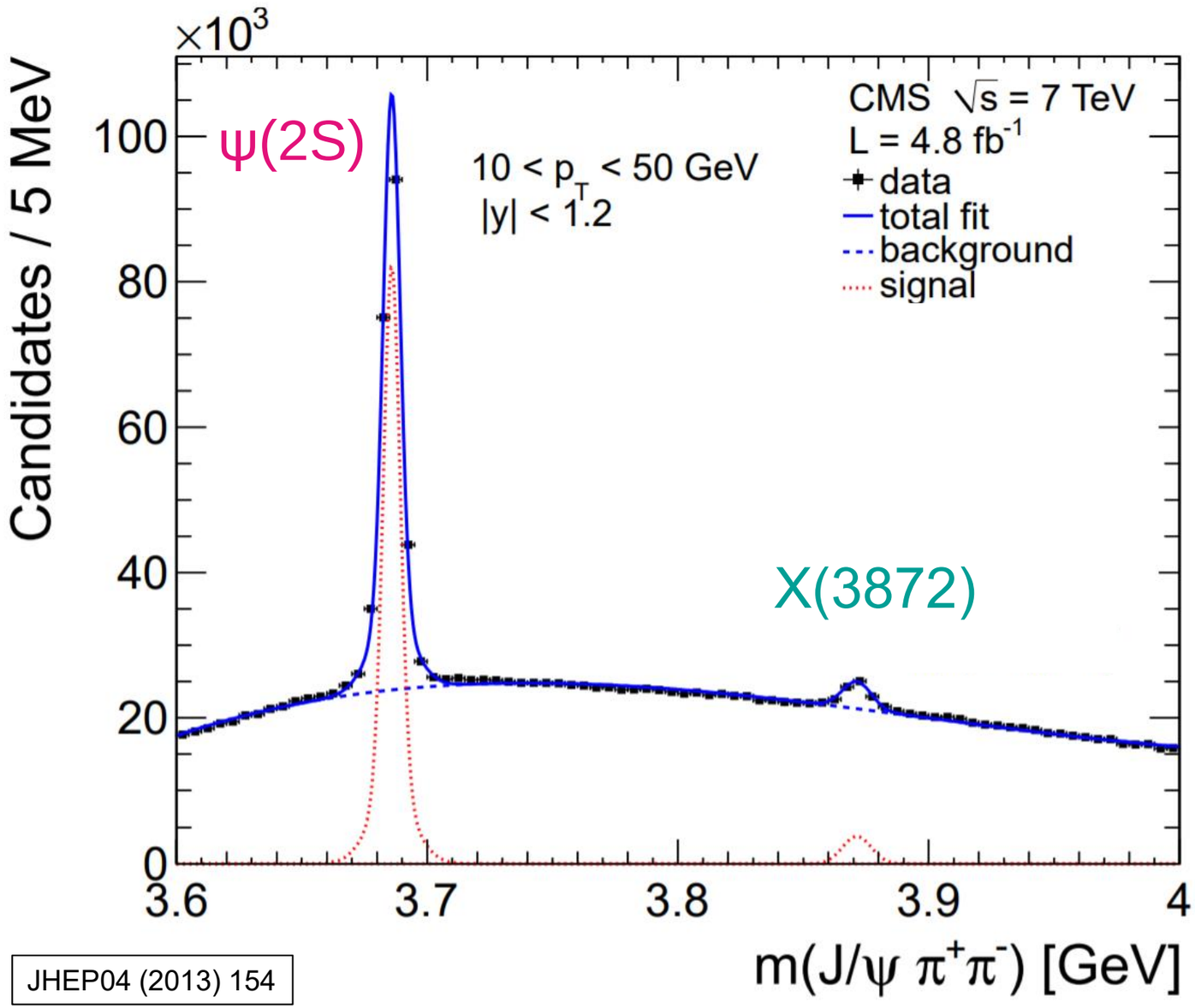
See this documentation for details (Link)

B_c R_{AA} in PbPb at 5.02 TeV



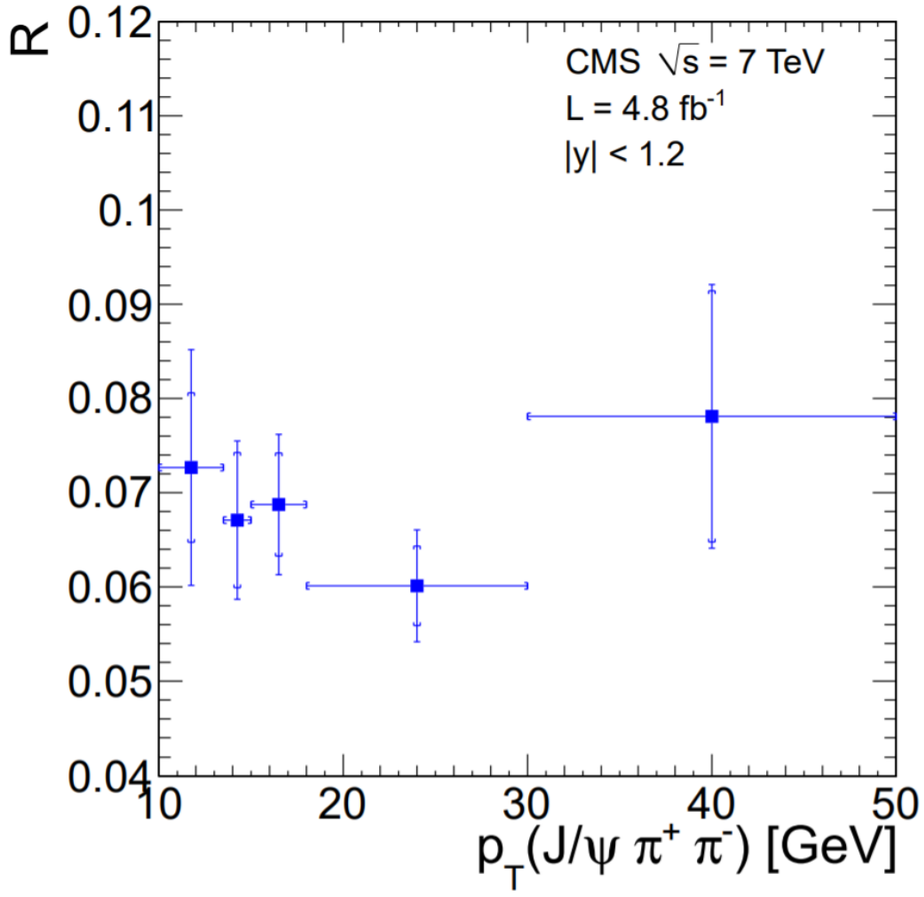


Invariant Mass Spectra in pp Collisions at 7 TeV



JHEP04 (2013) 154

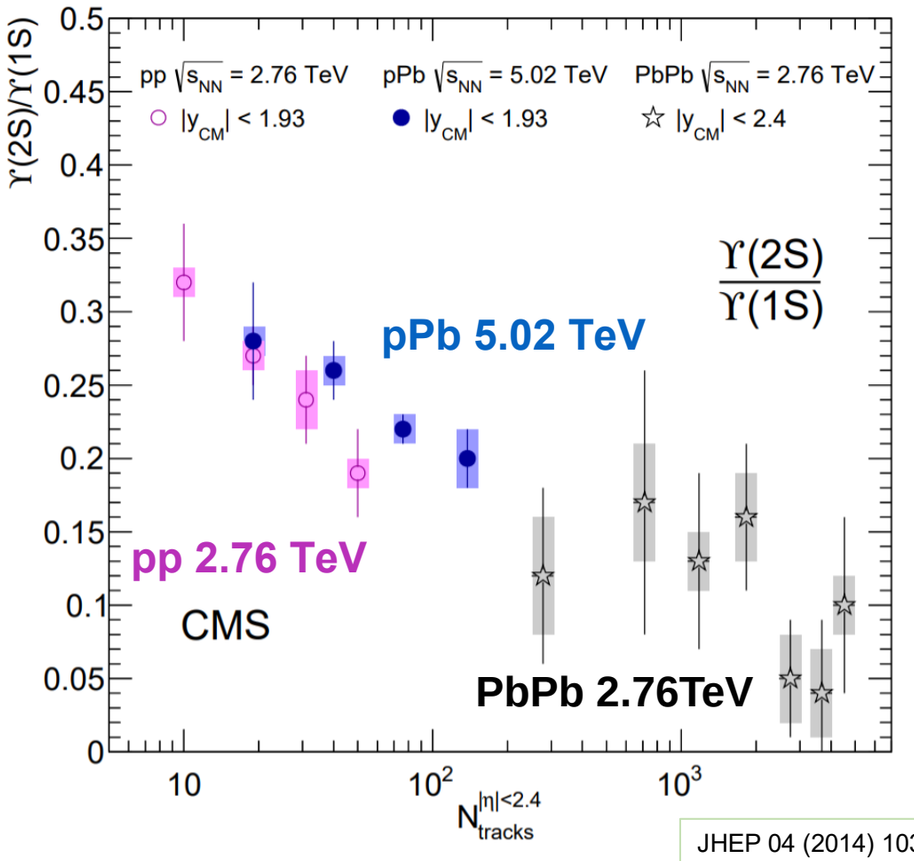
Inclusive X(3872) to ψ(2S) production ratio (include both prompt and nonprompt)



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

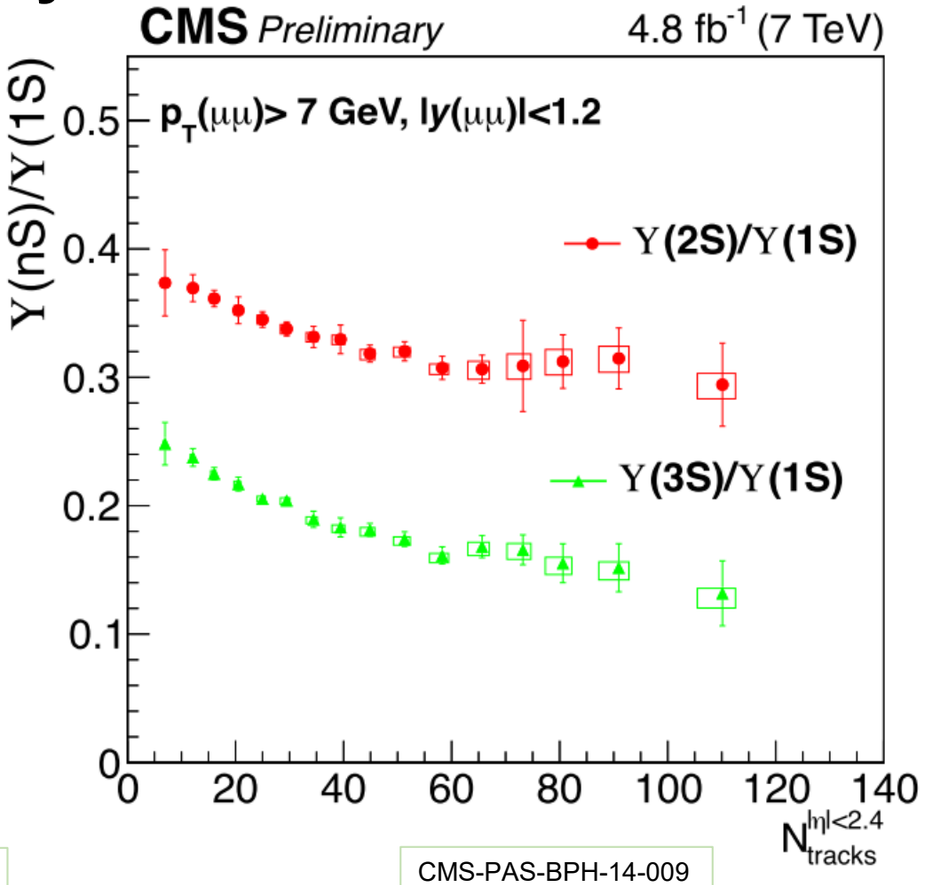
Upsilon Suppression in High Multiplicity Events

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



JHEP 04 (2014) 103

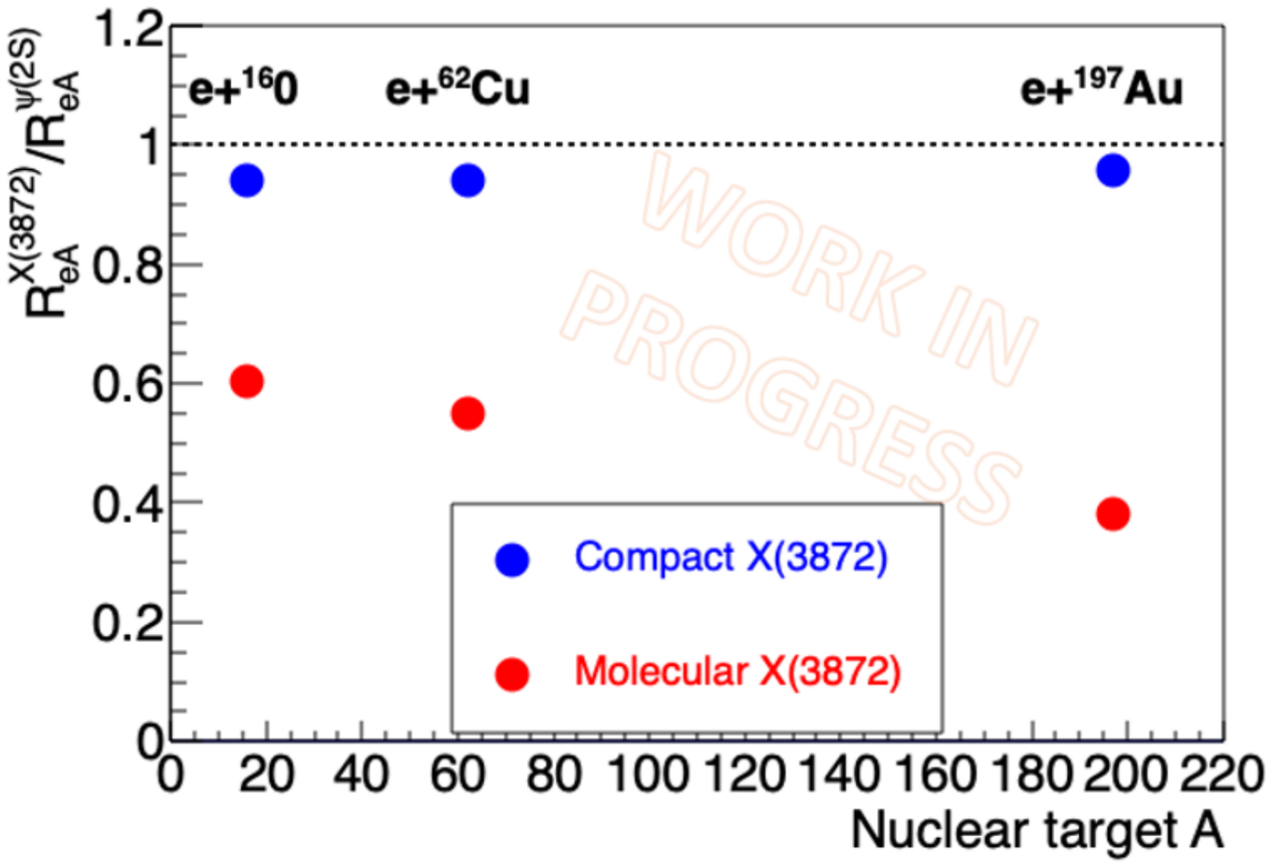
pp at 7 TeV



CMS-PAS-BPH-14-009

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

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



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

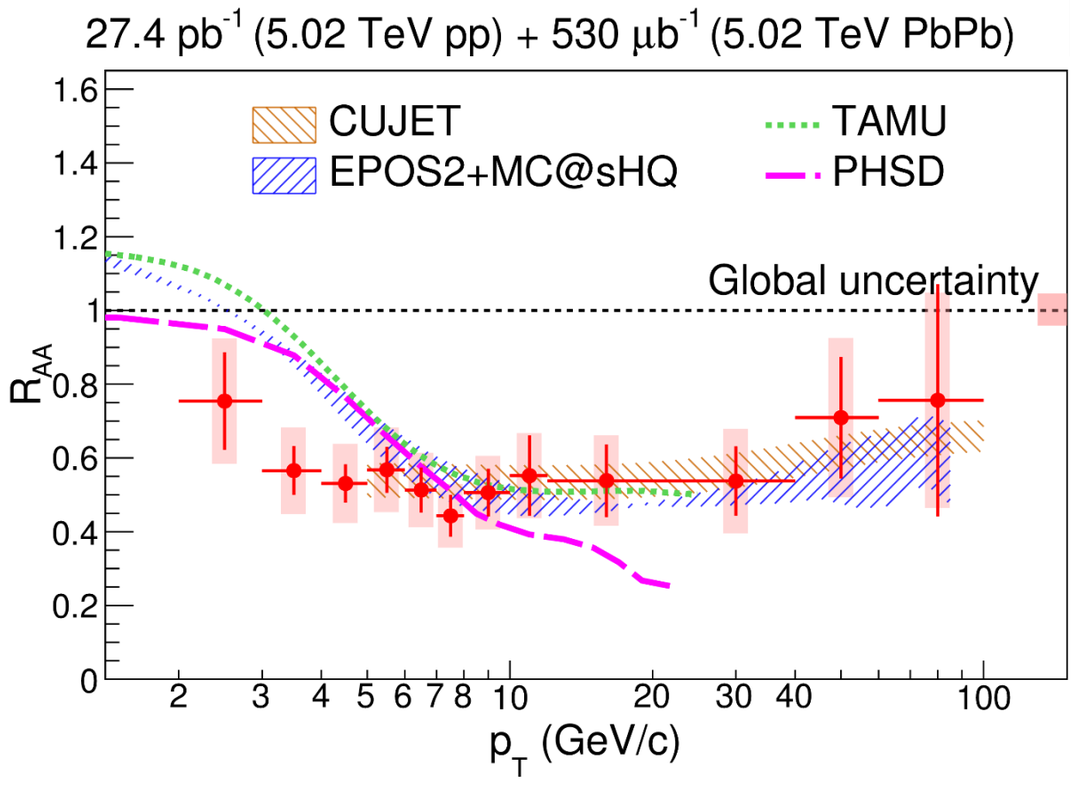
- Little difference in suppression between model of compact X(3872) and $\psi(2S)$, as expected.
- Large difference between model of molecular X(3872) and $\psi(2S)$.

Matt Durham (LANL)

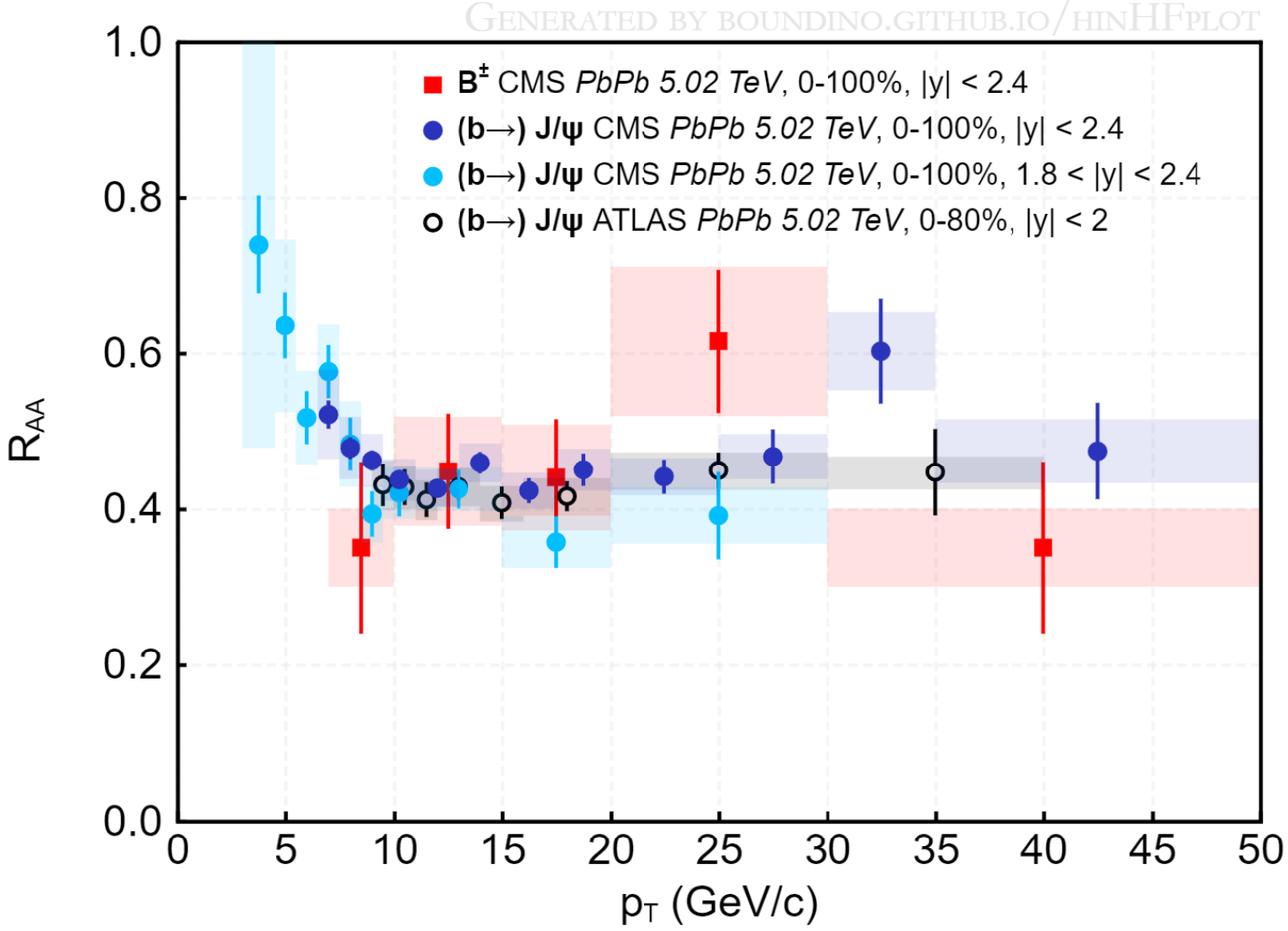
- **The EIC has the potential to provide decisive discrimination between exotic structure models.**
  - **X(3872) is only an example, technique can be applied to other exotics as well.**
    - **This work is supported by LANL Lab Directed R&D**

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

Non-prompt J/ψ R_{AA}

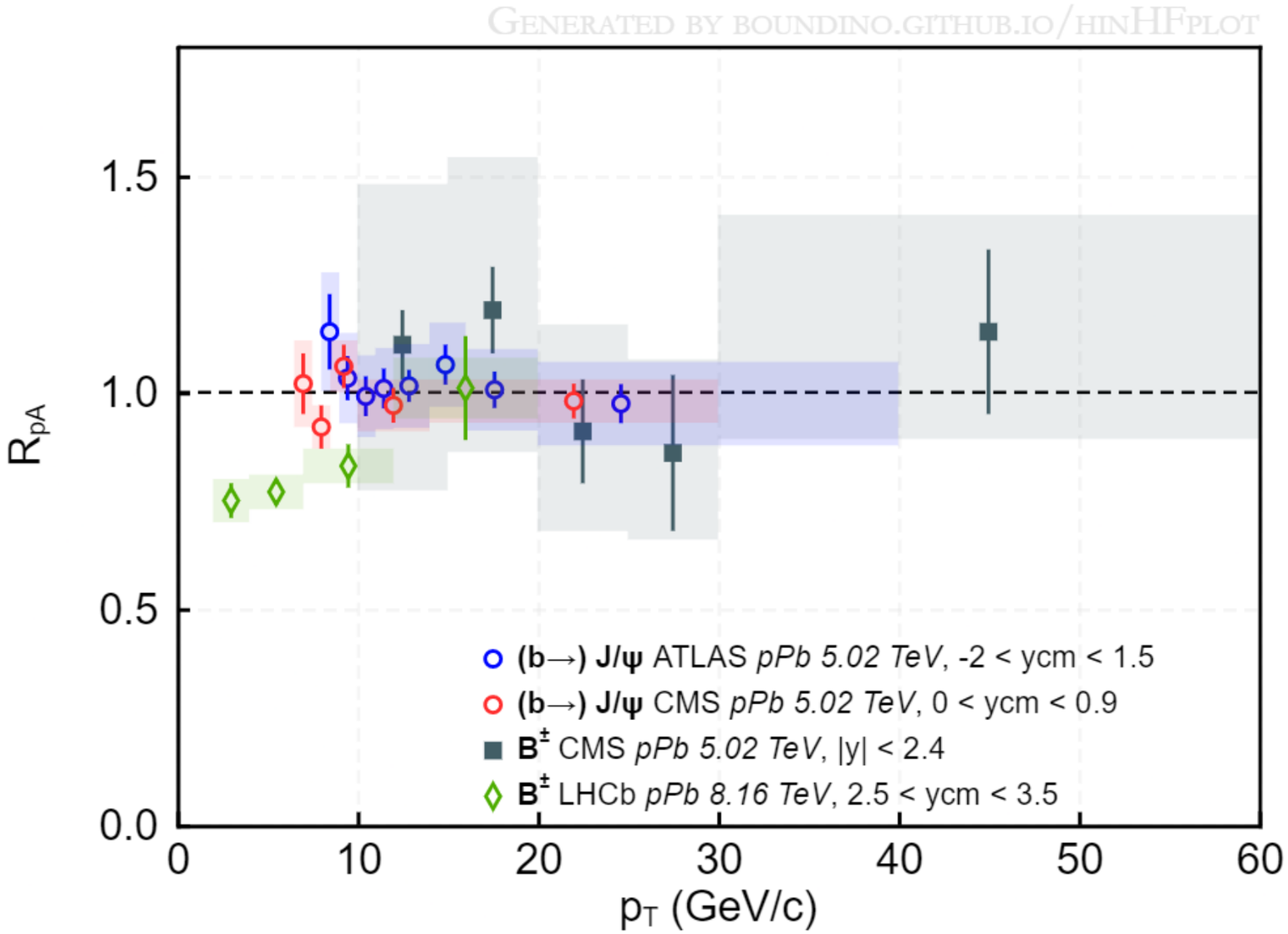


HIN-16-016



- PRL 119 (2017) 152301
- EPJC 78 (2018) 509
- EPJC 78 (2018) 762
- EPJC 78 (2018) 509

Beauty R_{pPb} at the LHC



B_c Signal in Tri-muon Mass Spectra

- Fit uncertainty 20%

centrality $0 - 20\%$ (p_T-integrated)