

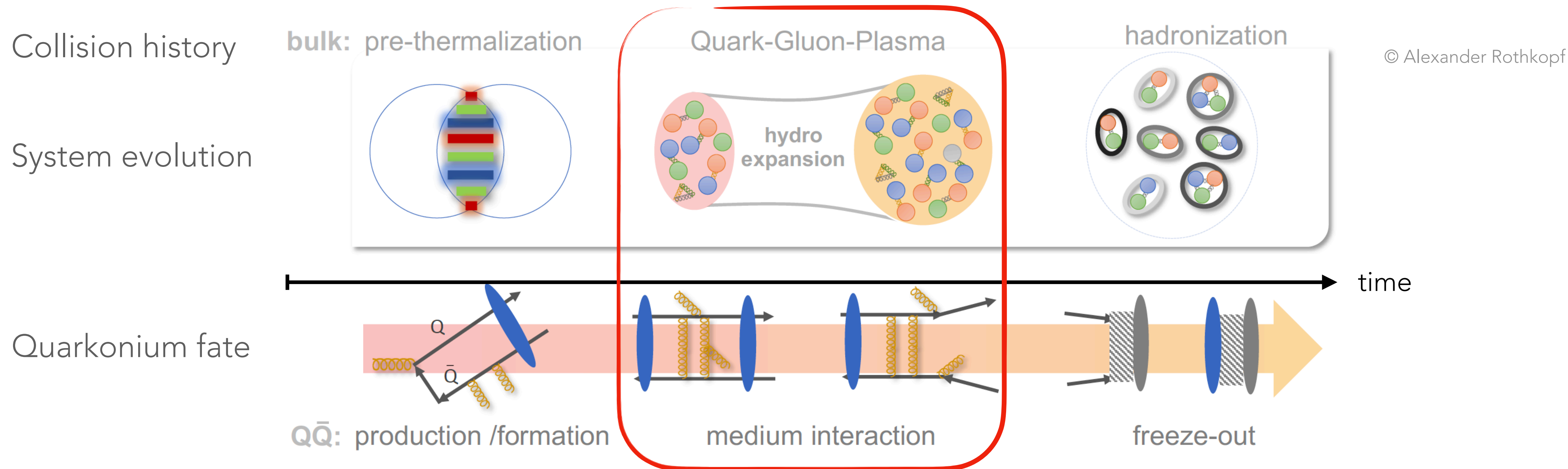
$X(3872)$ and B_c^+ production in PbPb collisions with CMS

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Laboratoire Leprince-Ringuet (École Polytechnique, France)

QWG workshop (GSI Darmstadt, Germany), 27 September 2022



Golden probes to characterize the quark-gluon plasma (QGP) properties



Interactions with the medium constituents

- ▶ suppression effects (energy loss mechanisms, dissociative processes for quarkonia)
- ▶ hadronization modified by (re)combination of quarks ➔ **enhancement of rare observables?!**

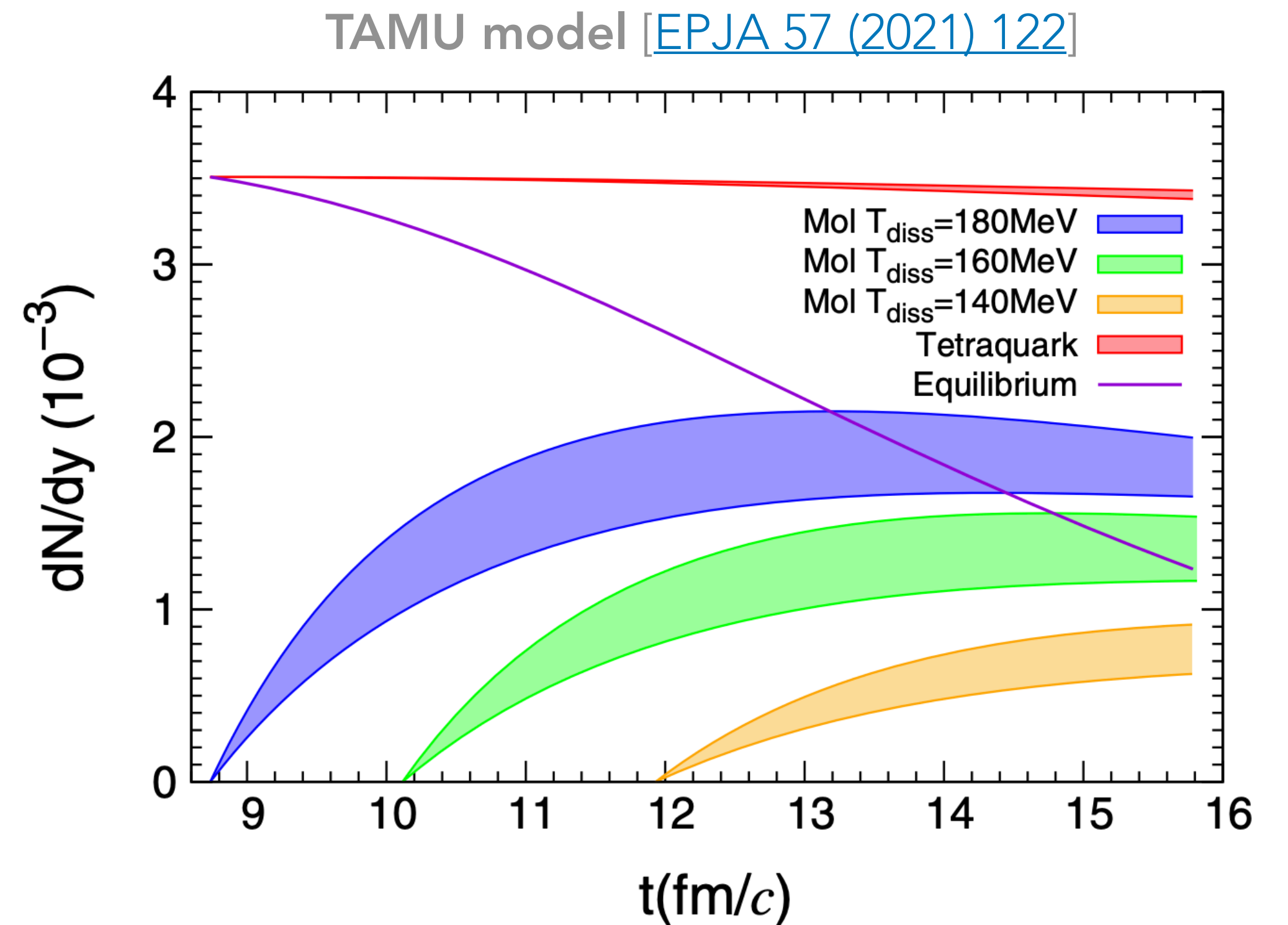
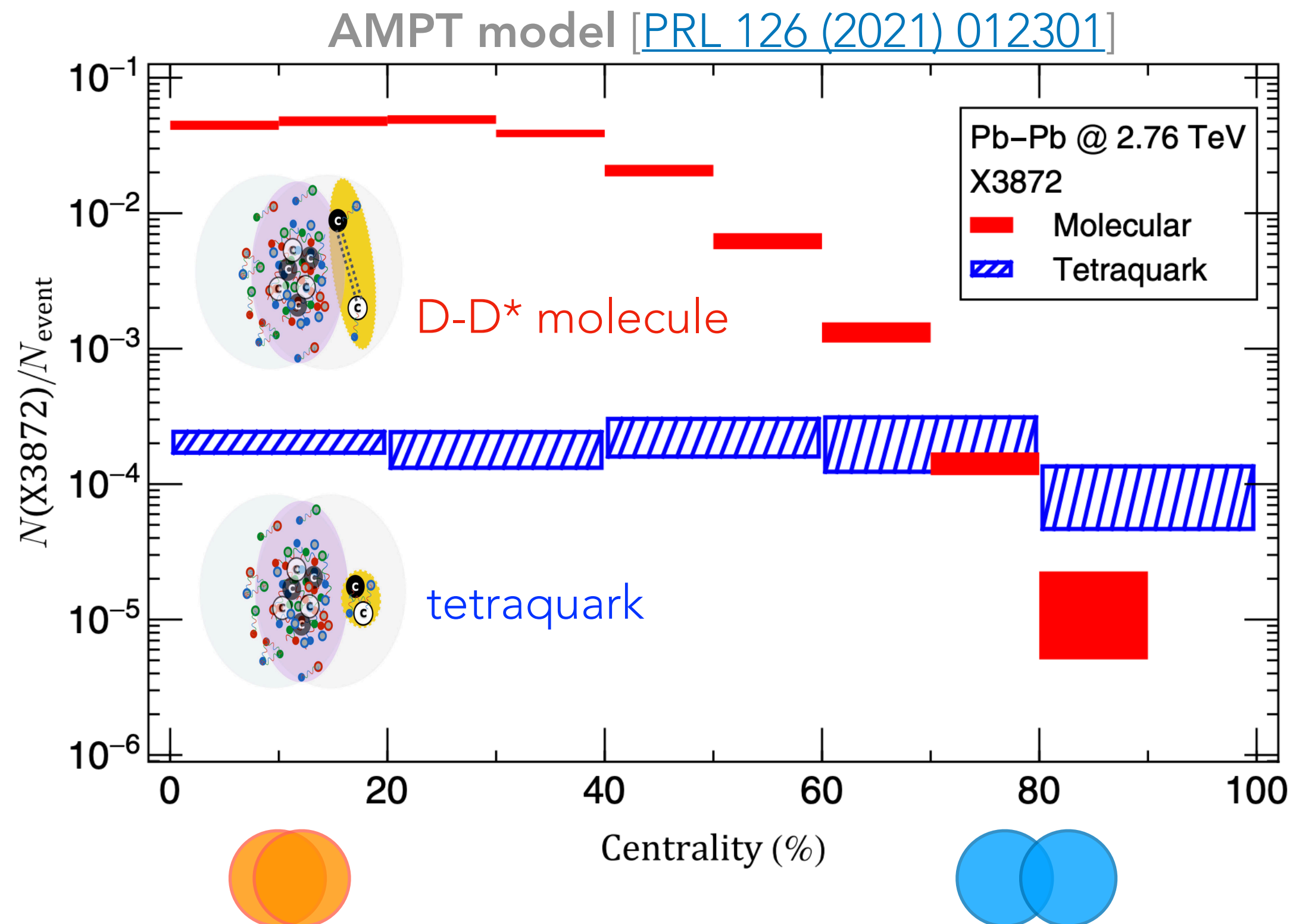
The measurement of its production in heavy ion collisions could reveal its structure!

Strong yield enhancement for molecular states?

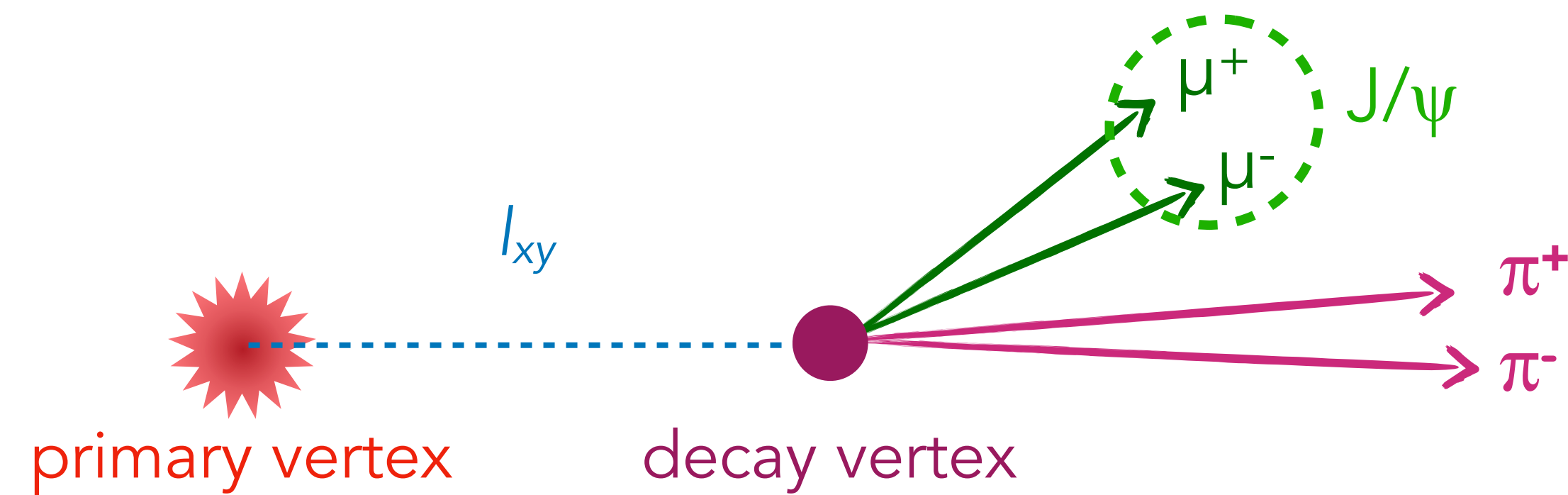
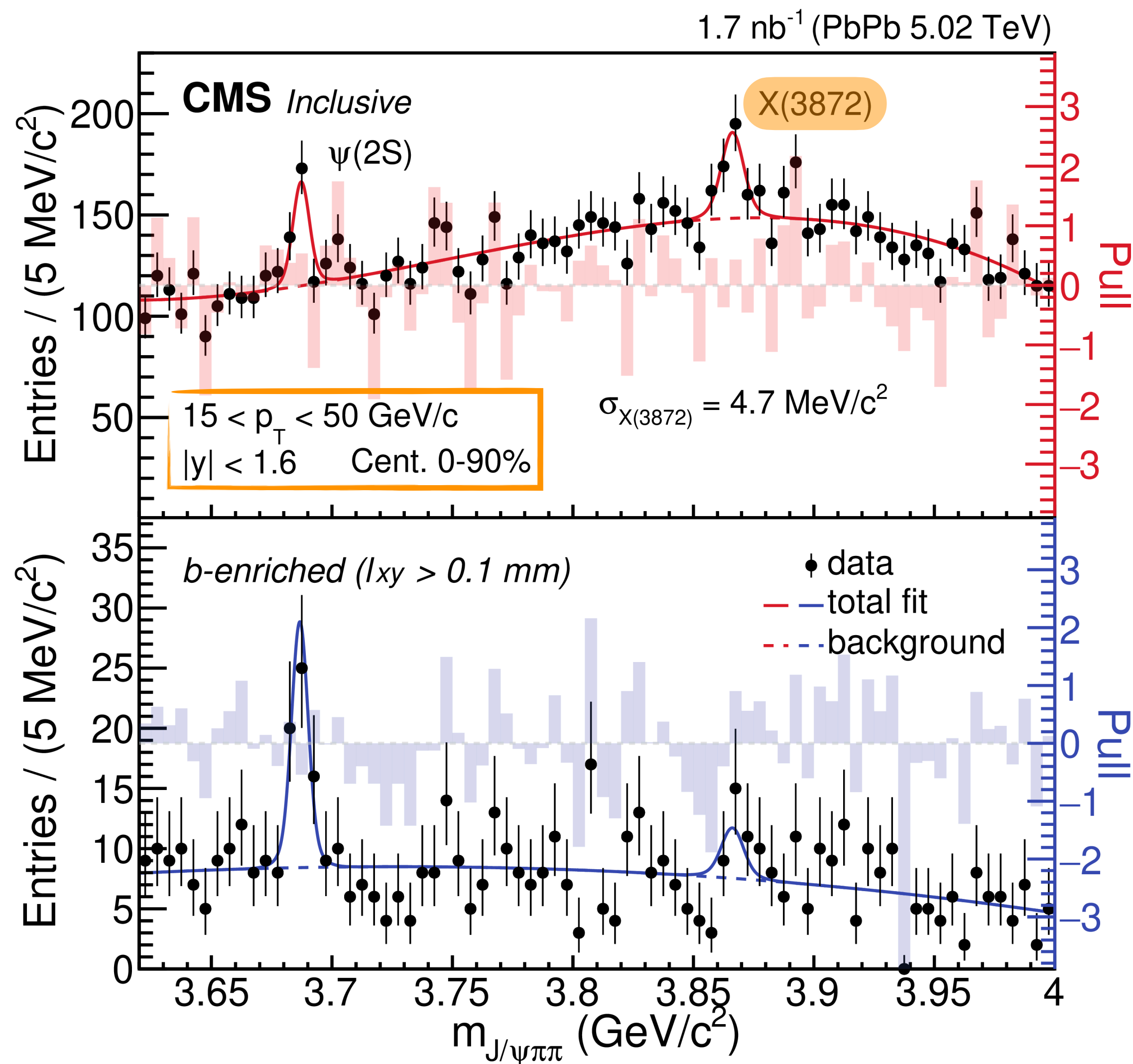
In-medium coalescence with a probability increasing with the fireball volume

Or solely produced at the hadronization stage?

Regeneration for loosely bound states delayed with respect to compact tetraquarks



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- ▶ selection of $J/\psi \pi \pi$ candidates optimized using a Boosted Decision Tree (BDT) algorithm
- ▶ **first evidence of inclusive X(3872) production in heavy ion collisions!** (statistical significance $\sim 4.2\sigma$)
- ▶ prompt fraction derived by **subtracting the b-hadron decay component** from **inclusive yields**

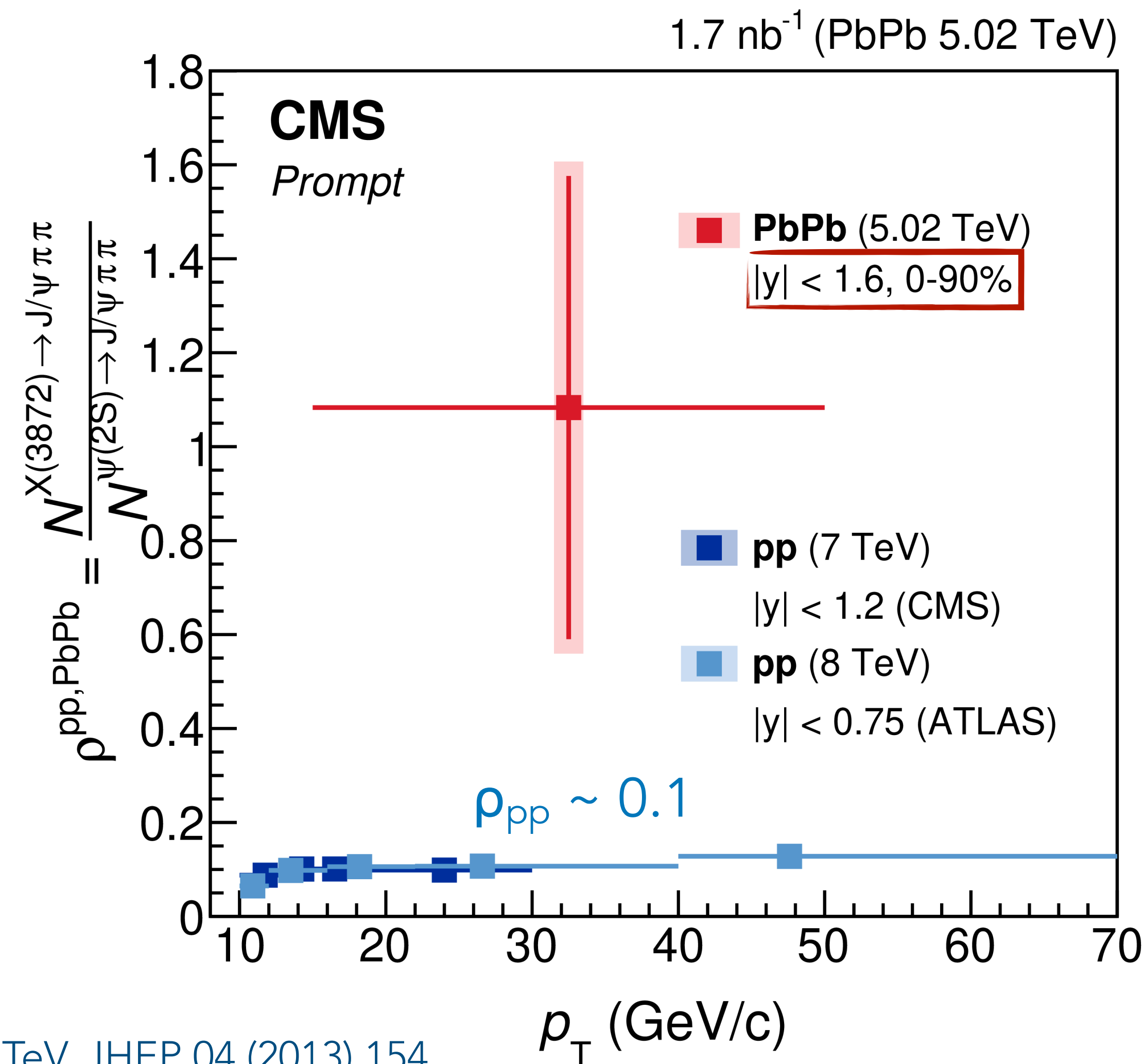
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$$\text{Yield ratio: } \rho \equiv \frac{N_{\text{corr}}^{X(3872) \rightarrow J/\psi \pi \pi}}{N_{\text{corr}}^{\psi(2S) \rightarrow J/\psi \pi \pi}}$$

$$\rho_{\text{PbPb}} = 1.08 \pm 0.49 \text{ (stat.)} \pm 0.52 \text{ (syst.)}$$

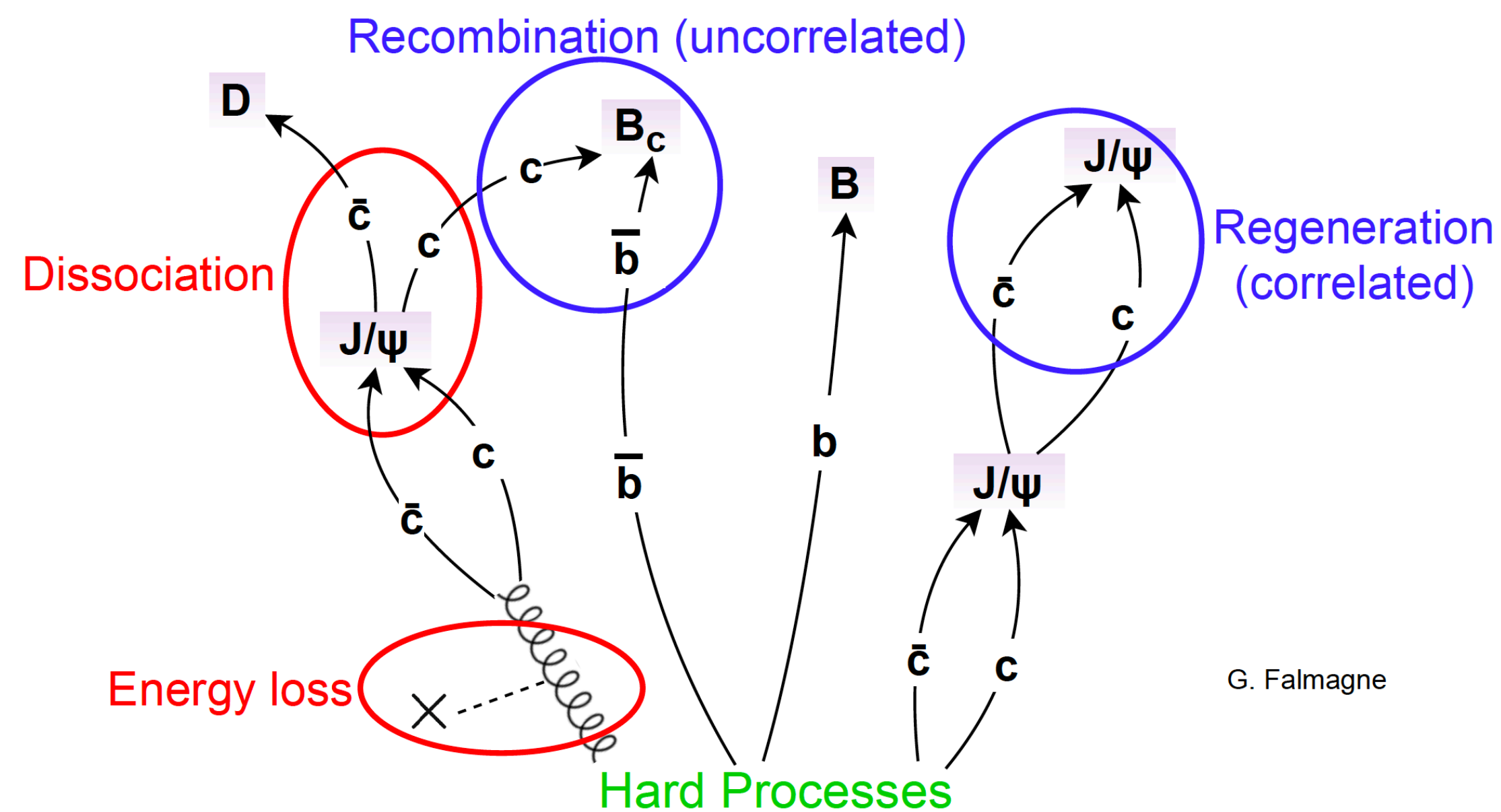
relative enhancement in **PbPb** with respect to **pp** collisions? or weaker suppression for X(3872) than for $\psi(2S)$?

better conclusion with future Run 3 and 4 data!



CMS 7 TeV, [JHEP 04 \(2013\) 154](#)

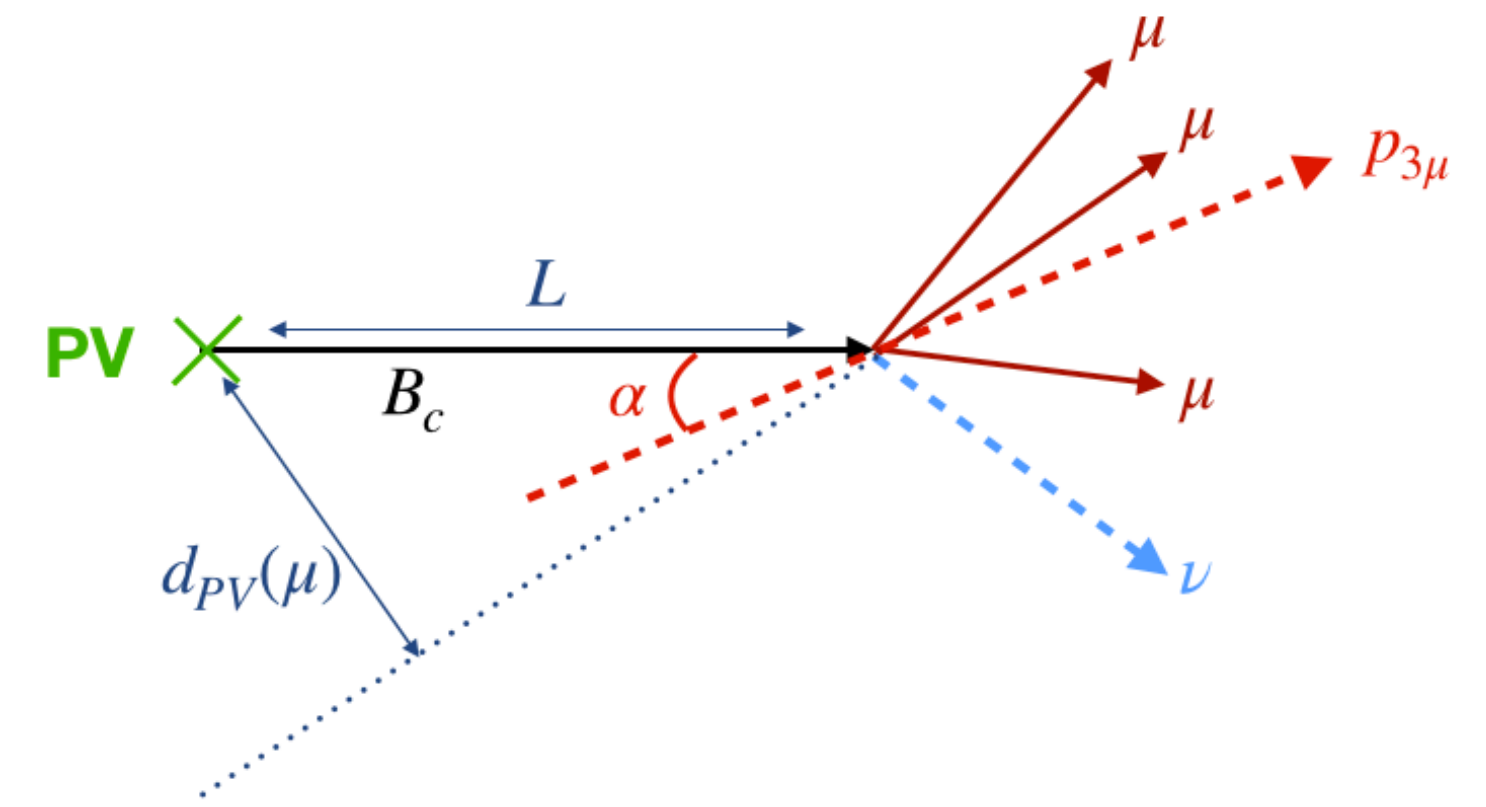
ATLAS 8 TeV, [JHEP 01 \(2017\) 117](#)



Hybrid quarkonium state

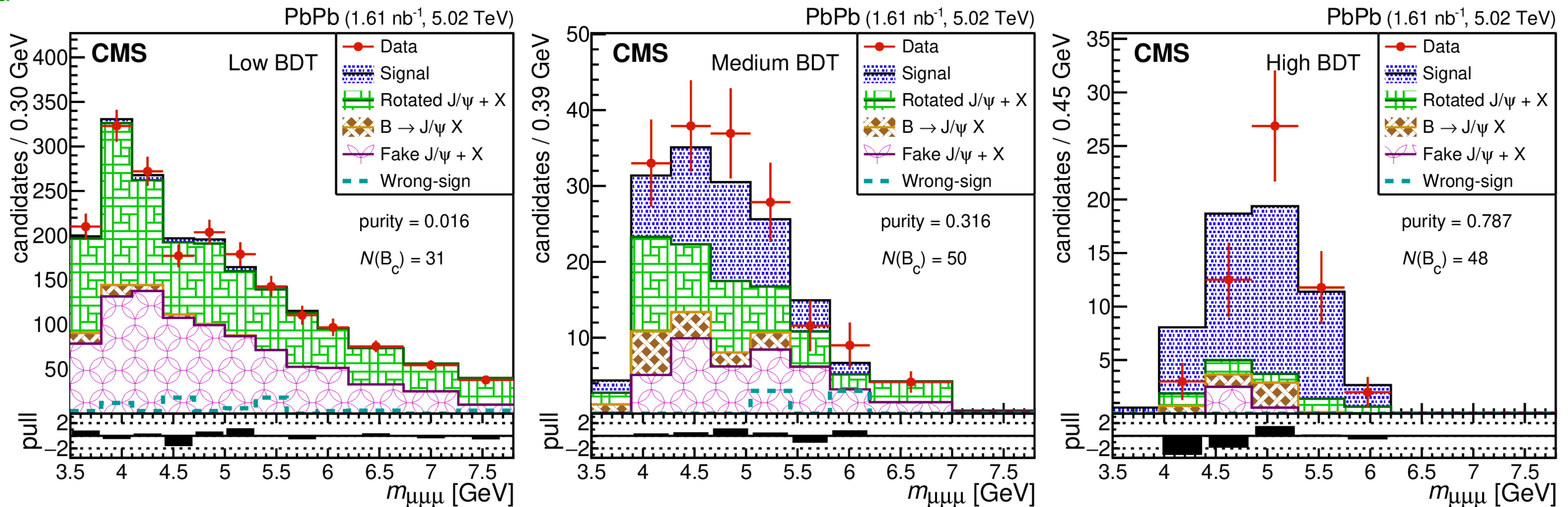
- ▶ mass and binding energy between J/ψ and $\Upsilon(1S)$
 - ➡ sensitive to **medium-induced dissociation**
- ▶ small production cross section in pp collisions
 - ➡ low- p_T enhancement via the **recombination** of beauty and charm quarks within the QGP
- ▶ probing the mass, flavor, and color charge dependence of **energy loss mechanisms** (high- p_T regime)

- ▶ reconstructed in the decay mode $B_c^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-) \mu^+ \nu_\mu$
- ▶ **template fit of the trimuon mass** performed simultaneously in three BDT intervals to maximize the significance
- ▶ background contributions estimated from data and MC samples



background enriched

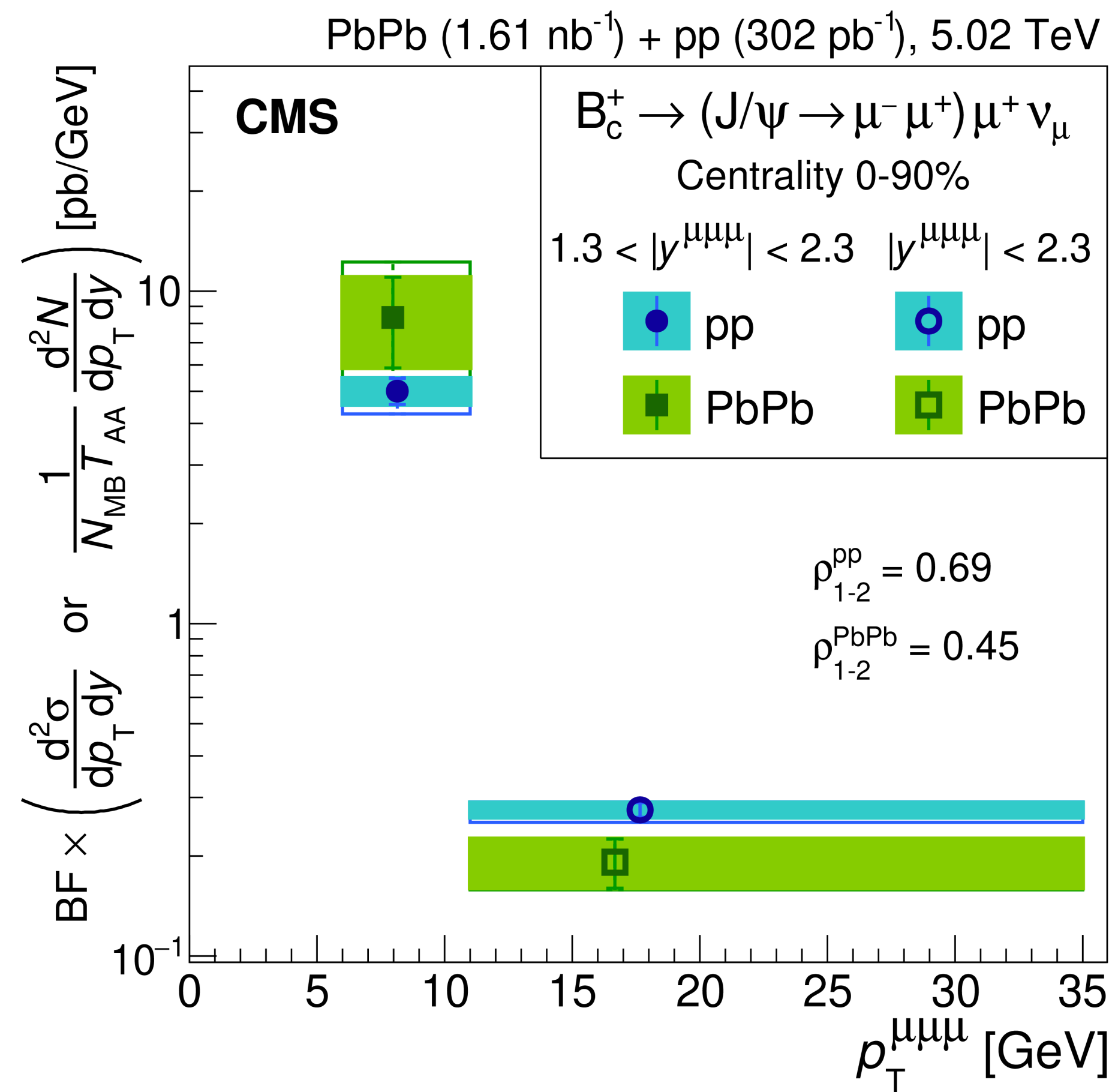
signal enriched



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Hint for a **softer** p_T spectrum in **PbPb** with respect to **pp** collisions

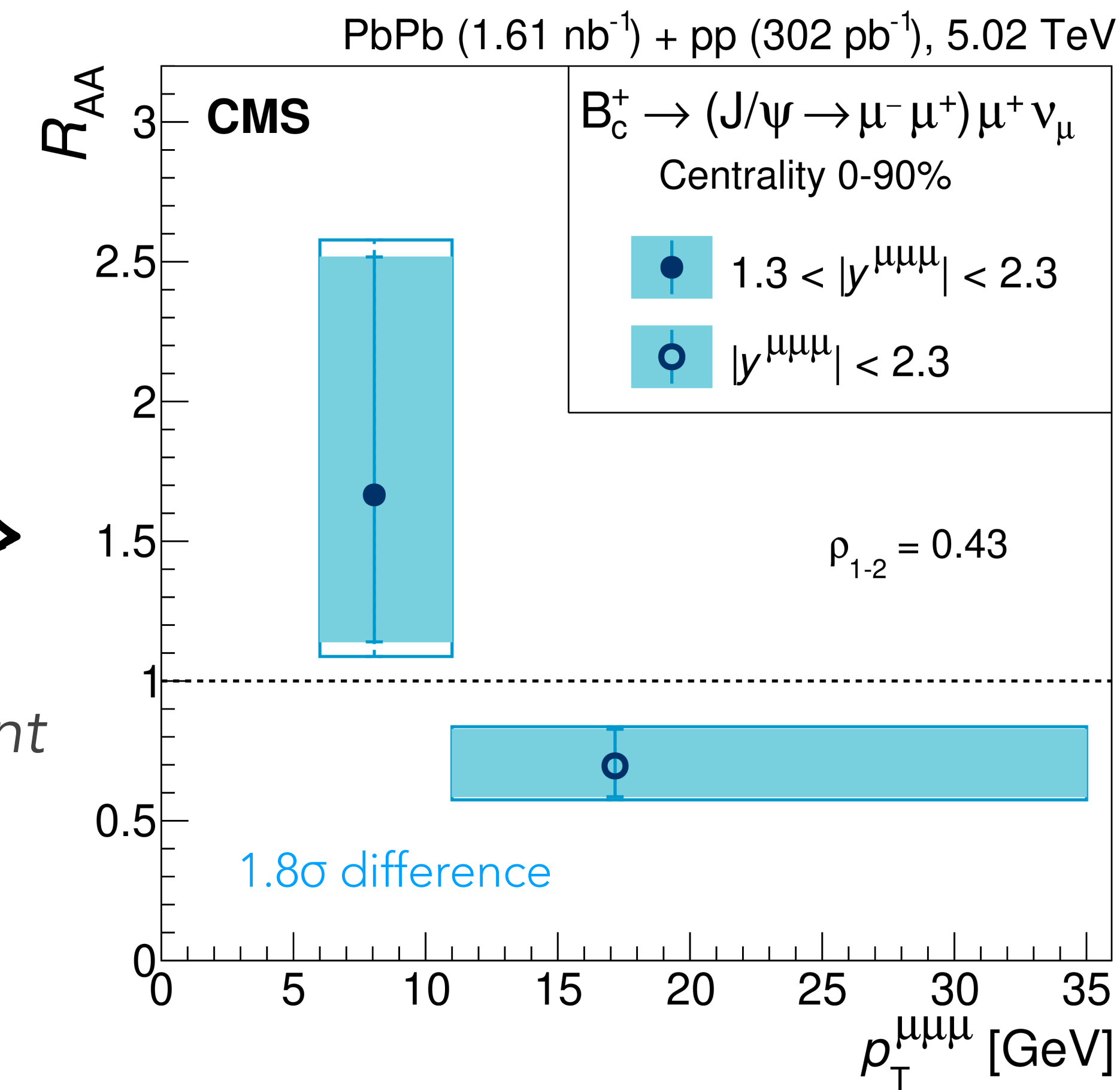
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$$R_{AA} \equiv \frac{dN_{AA} dp_T}{T_{AA} \times d\sigma_{pp} dp_T}$$



$R_{AA} > 1$: enhancement
 $R_{AA} < 1$: suppression



ρ_{1-2} : bin-to-bin correlation factor

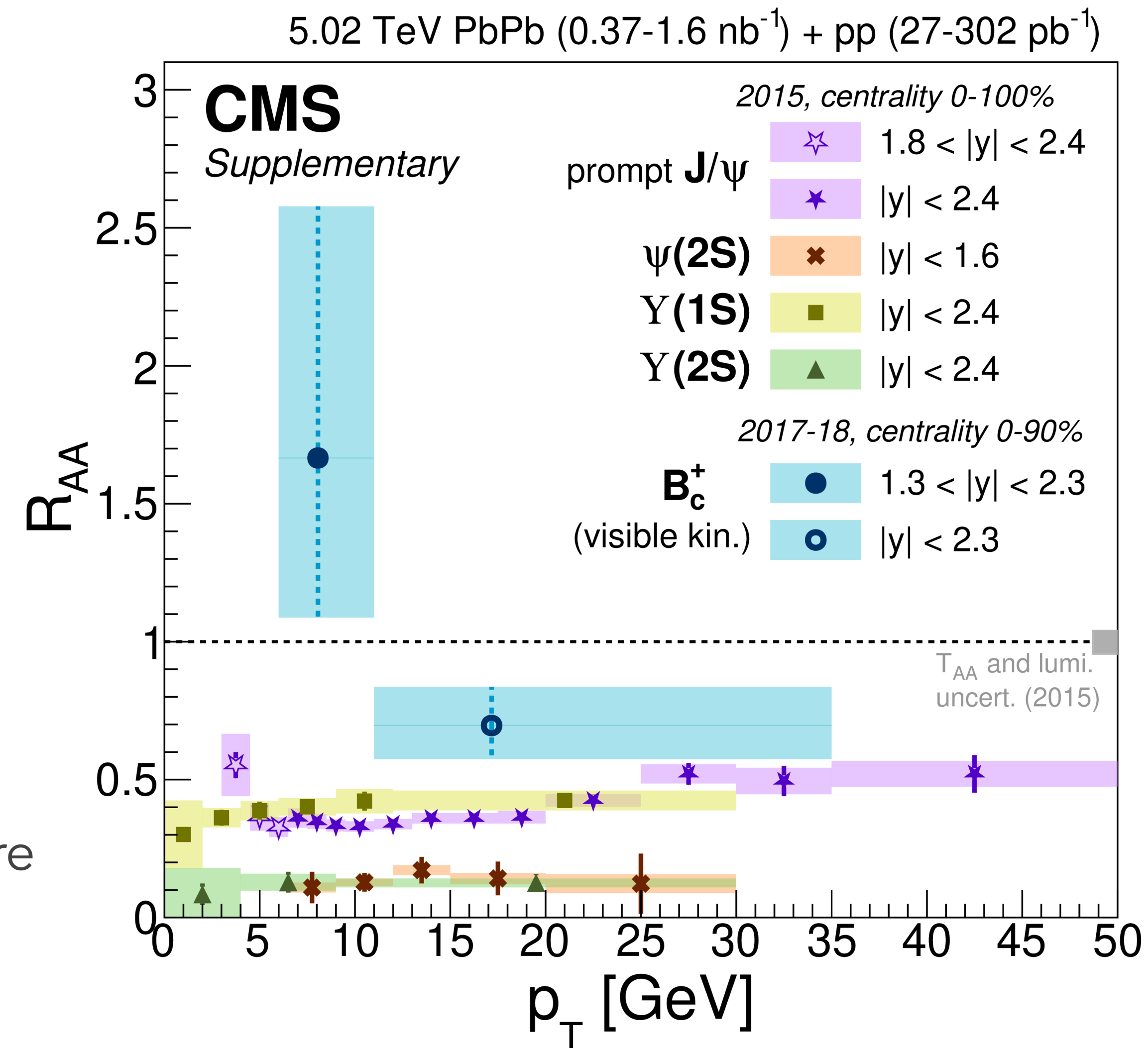
⚠ trimuon kinematics

Comparison with previous measurements:

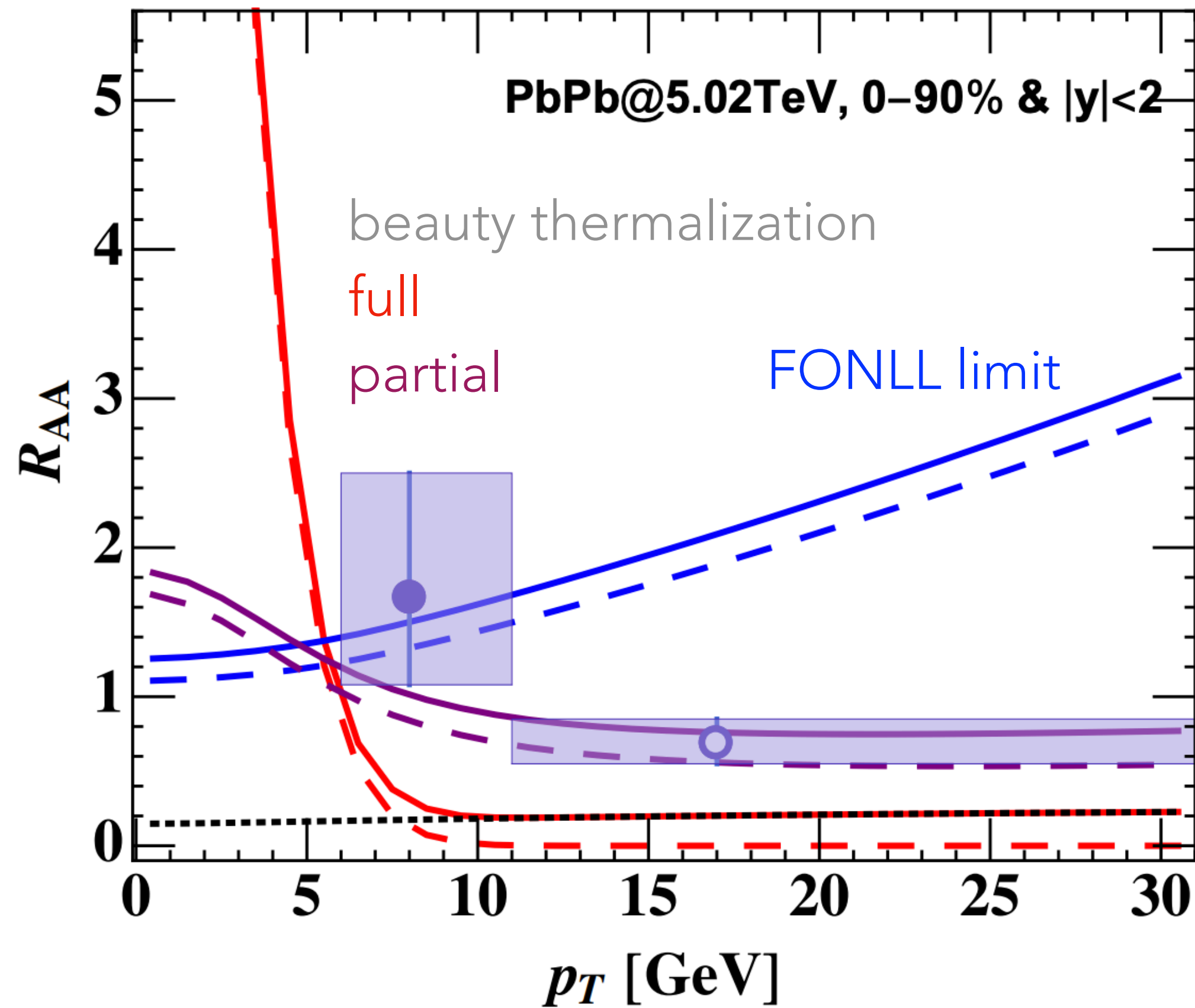
prompt J/ψ and $\psi(2S)$ [EPJC 78 (2018) 509]

$Y(1S)$ and $Y(2S)$ [PLB 790 (2019) 270]

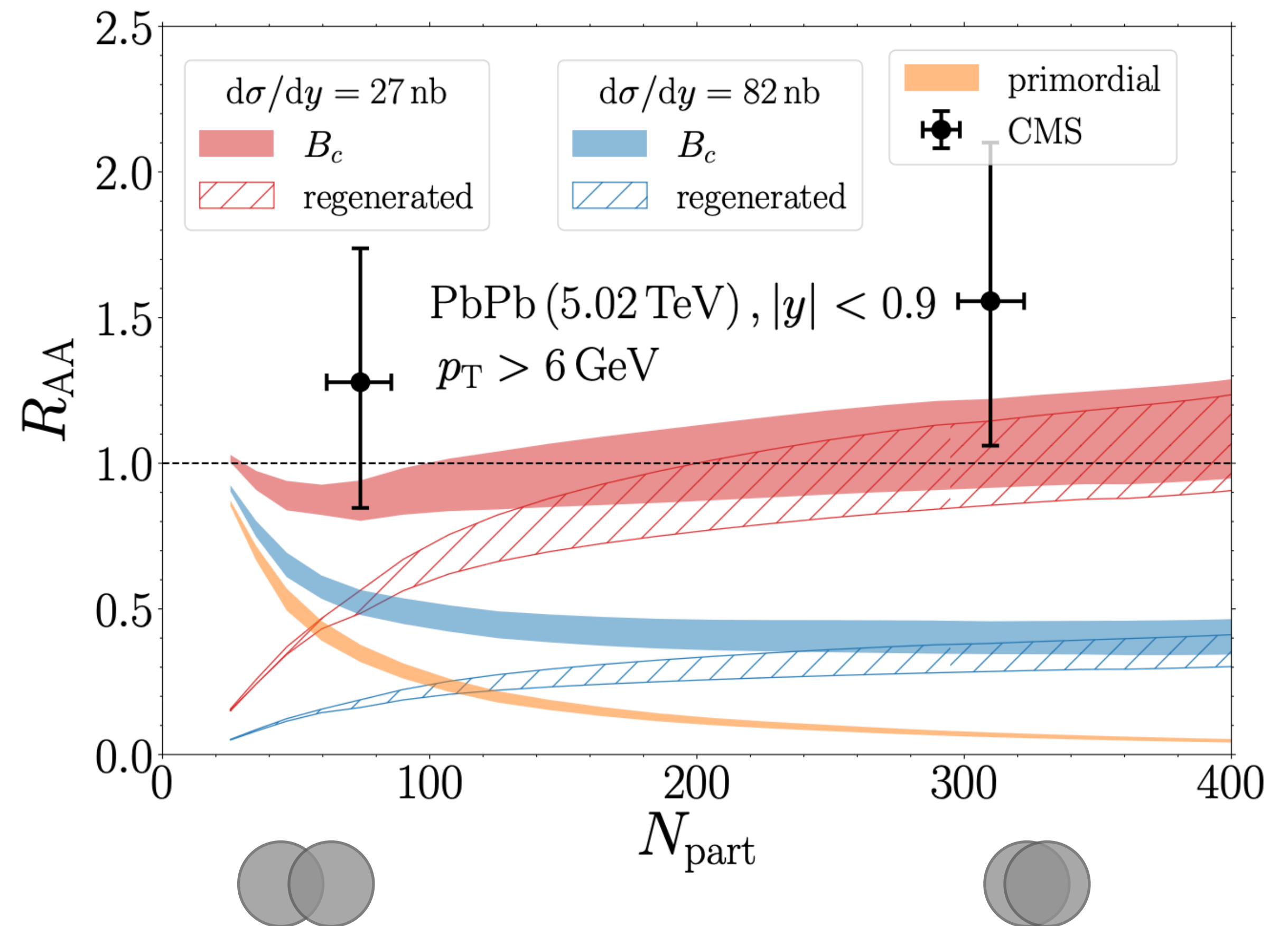
- ▶ B_c^+ less suppressed than other quarkonia despite a binding energy between J/ψ and $Y(1S)$
- ▶ importance of heavy-quark recombination?
- ▶ call for more-differential measurements in the future



Tsinghua model (J. Zhao @ HF-WINC 2022):
data do not support full thermalization for beauty quark



TAMU model (B. Wu @ HF-WINC 2022):
 B_c^+ production dominated by regeneration
 (strong suppression of the **primordial component**)

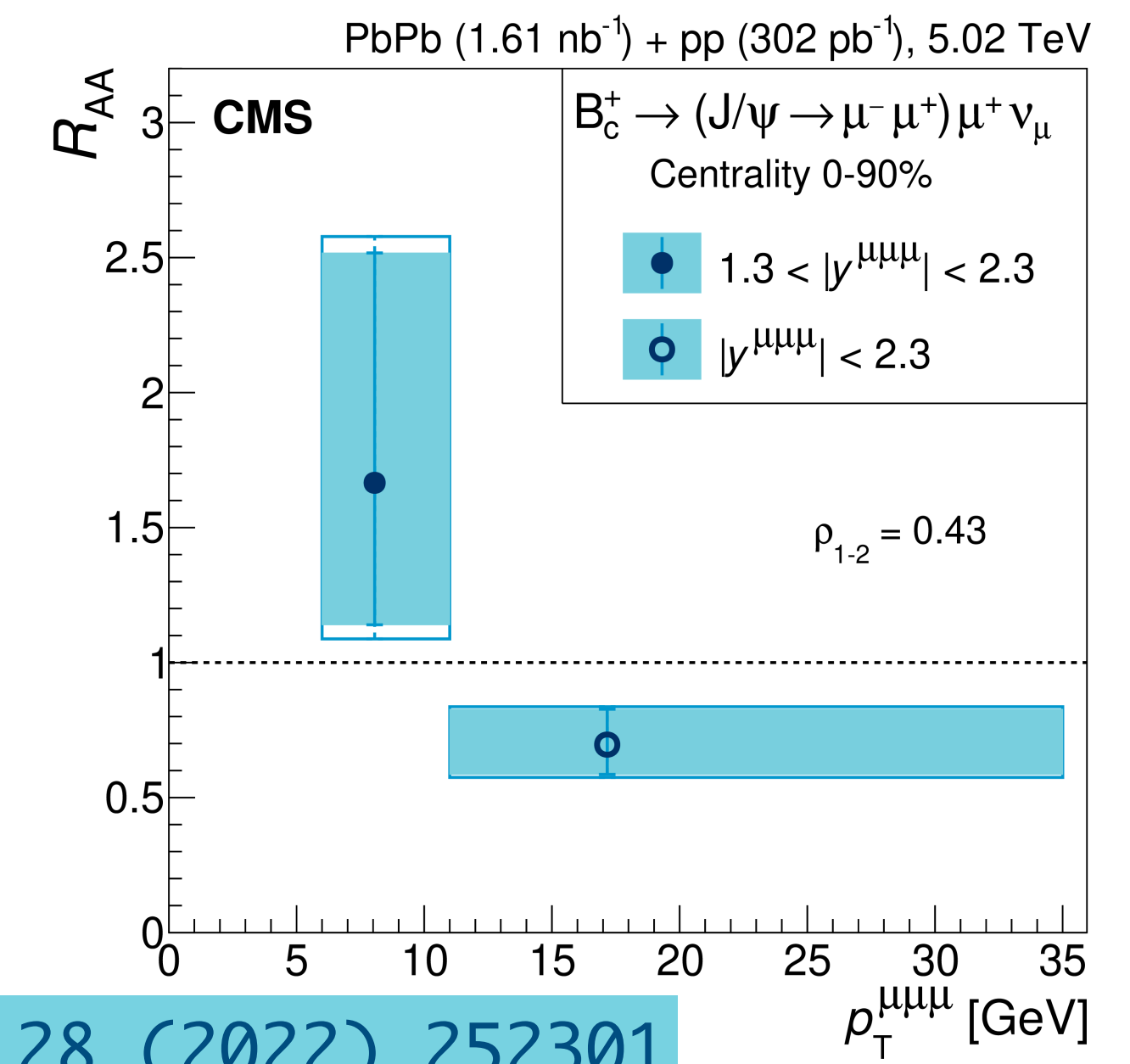
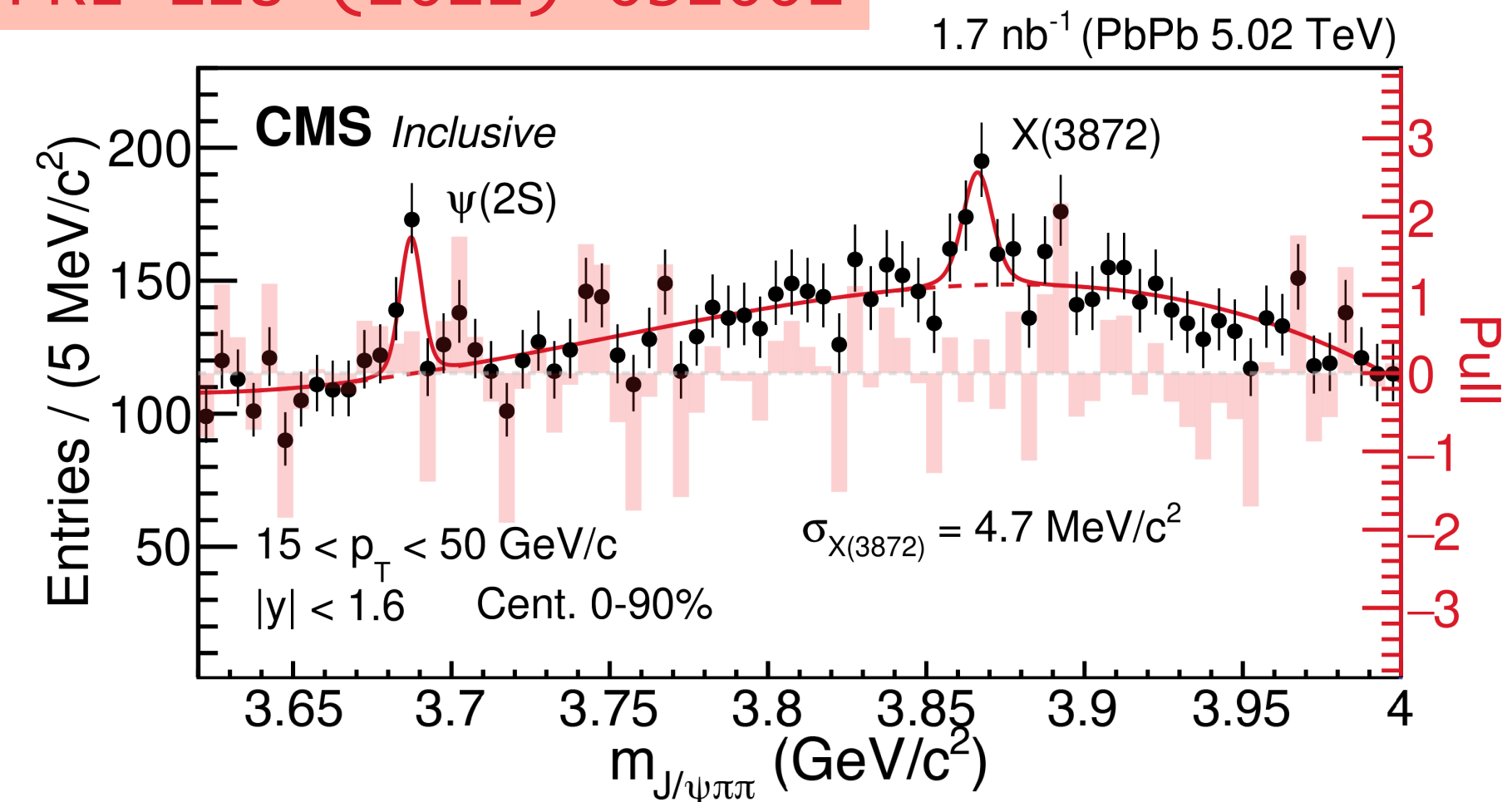


Novel observables for the study of heavy-quark interactions inside the quark-gluon plasma

- ▶ evidence for **X(3872) production in heavy ion collisions**
- ▶ observation of the **B_c⁺ in PbPb collisions**
 - ▶ hint for in-medium formation of charm and beauty quark bound states

First measurements dominated by statistical uncertainties, **to be continued in Run 3 and 4!**

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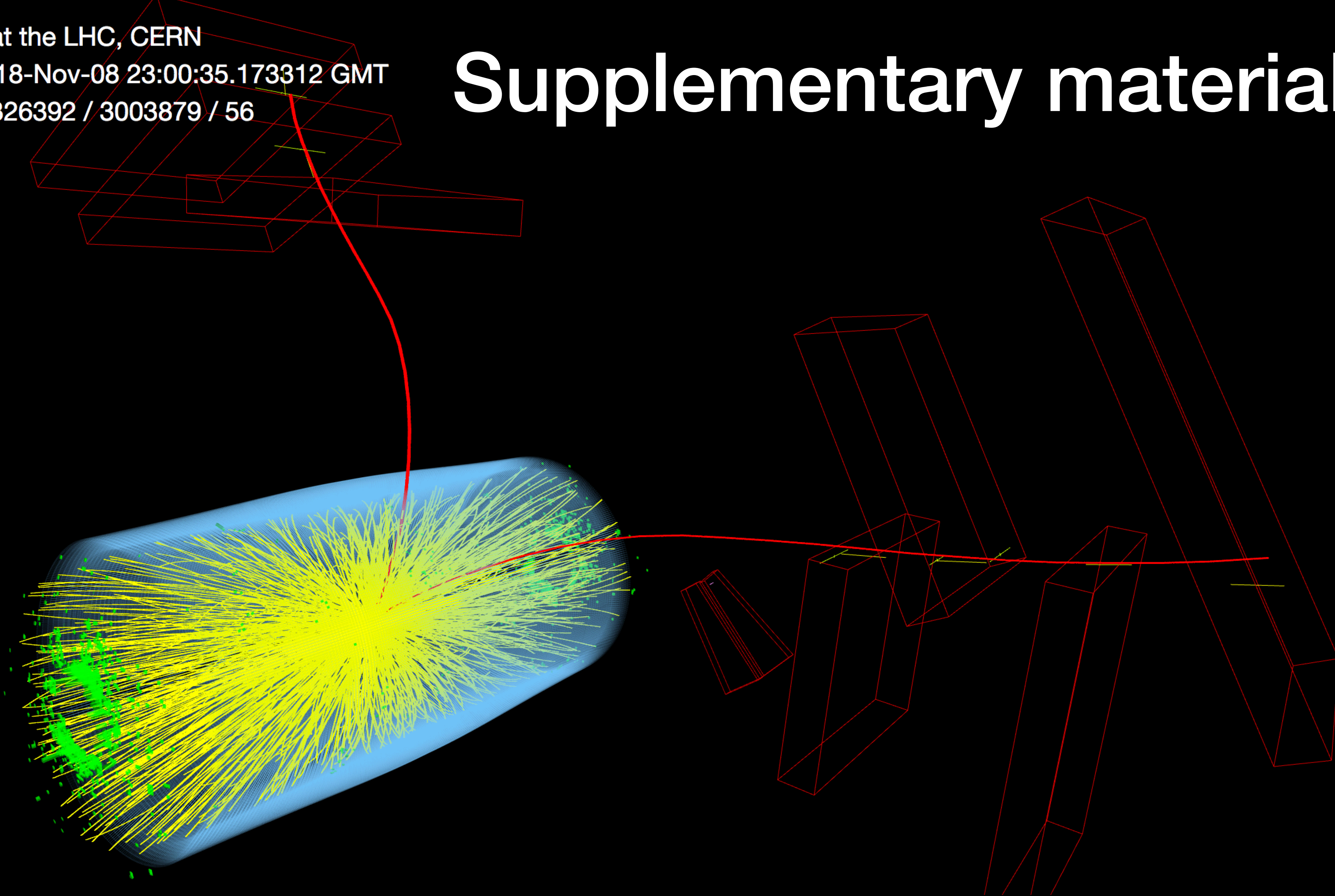


CMS Experiment at the LHC, CERN

Data recorded: 2018-Nov-08 23:00:35.173312 GMT

Run / Event / LS: 326392 / 3003879 / 56

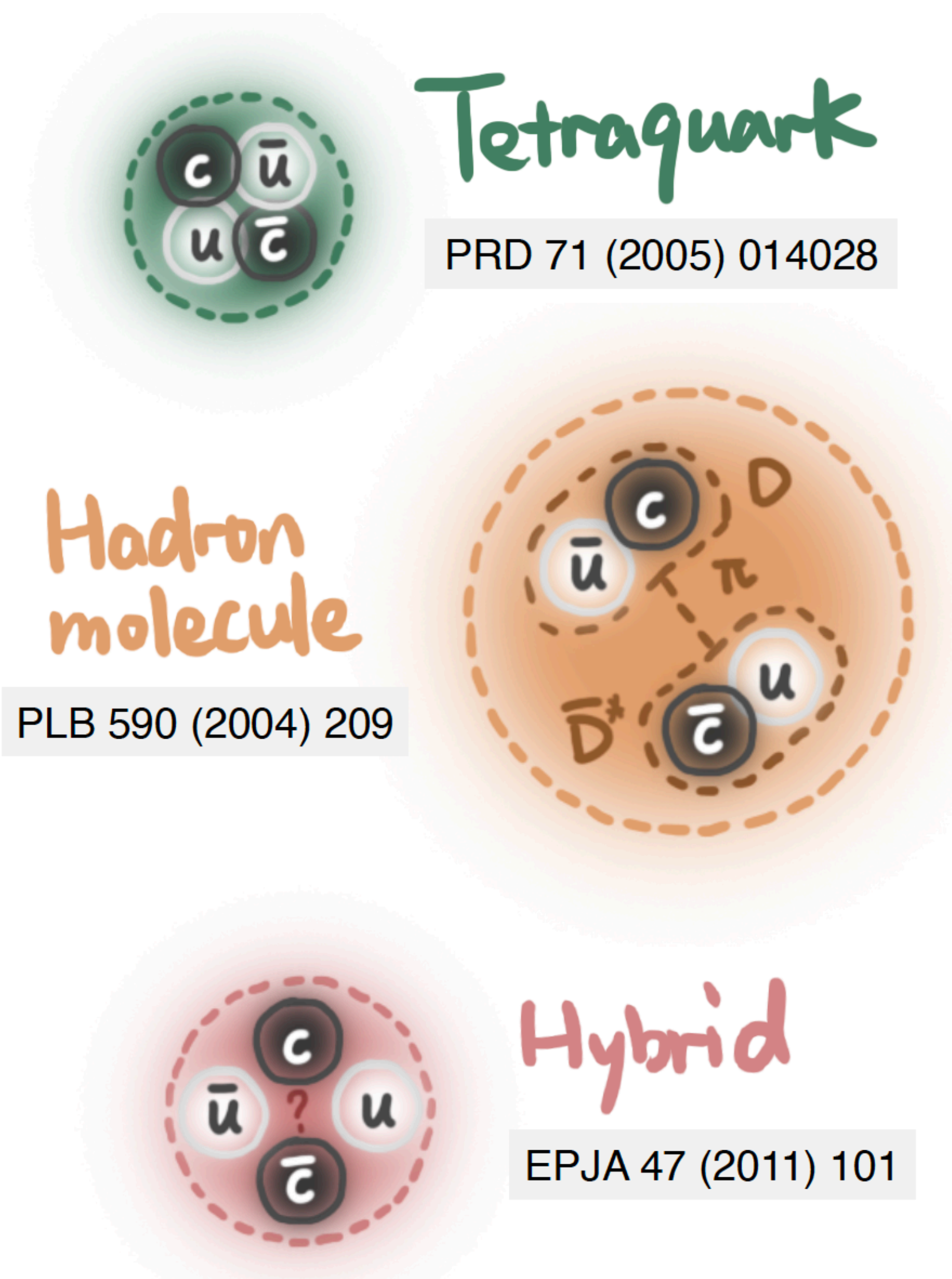
Supplementary material



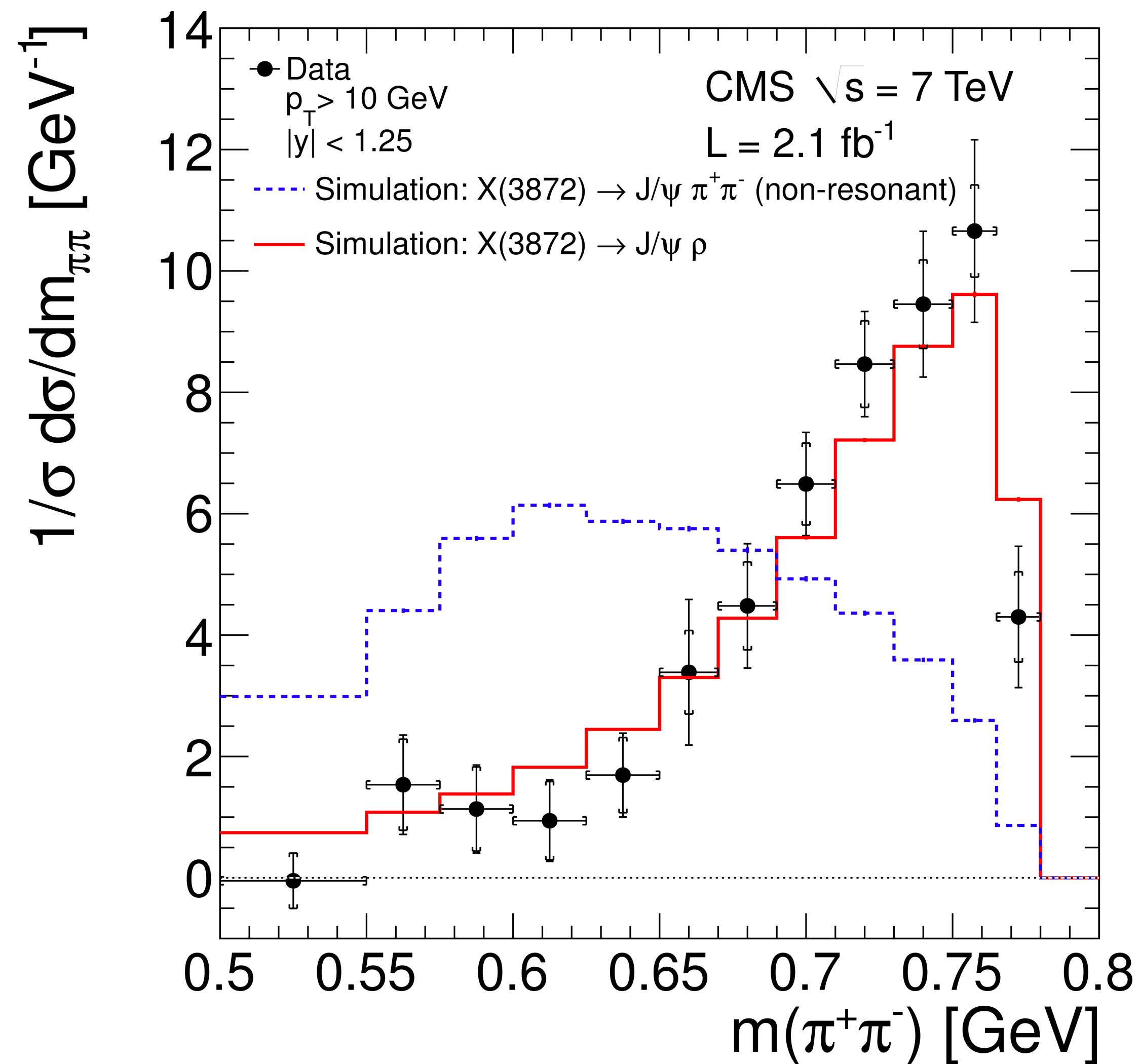
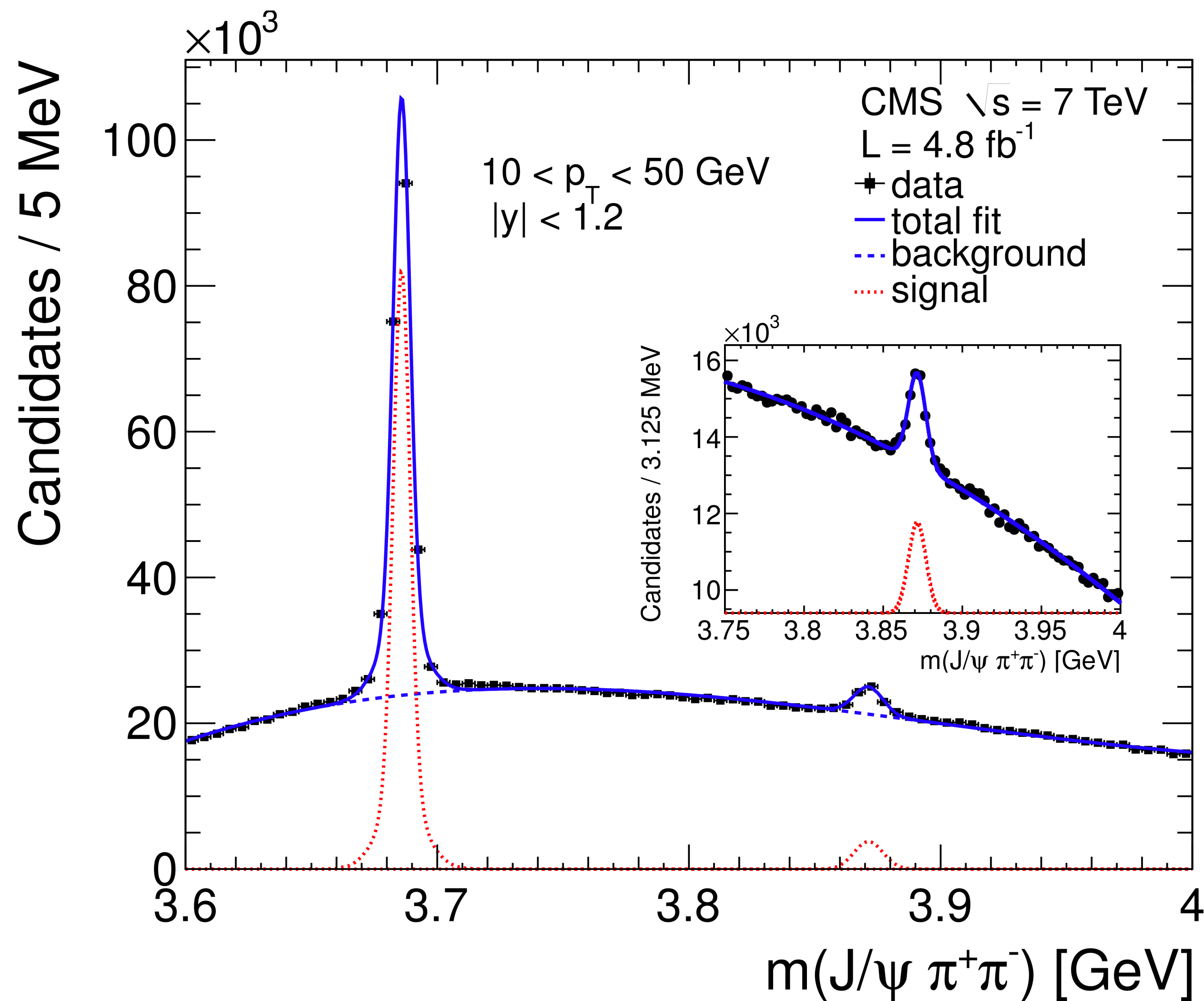
Event display of a $J/\psi \rightarrow \mu\mu$ candidate in 2018 PbPb collisions

slide from [Jing Wang's talk @ Quark Matter 2022](#)

- 2003: X(3872), aka $\chi_{c1}(3872)$, discovered by Belle
 - Today: Internal structure is still under debate
- Possible **interpretations**:
- ➔ **Tetraquark**: Compact four quark state
 - ➔ **D- \bar{D}^* hadron molecule**: $X(3872) \approx D(1875)\bar{D}^*(2007)$
 - ➔ **Hybrid**: mixed molecule-charmonium state
- All interpretations can explain measured mass/decay width
- ⇒ **Any way to distinguish these models?**

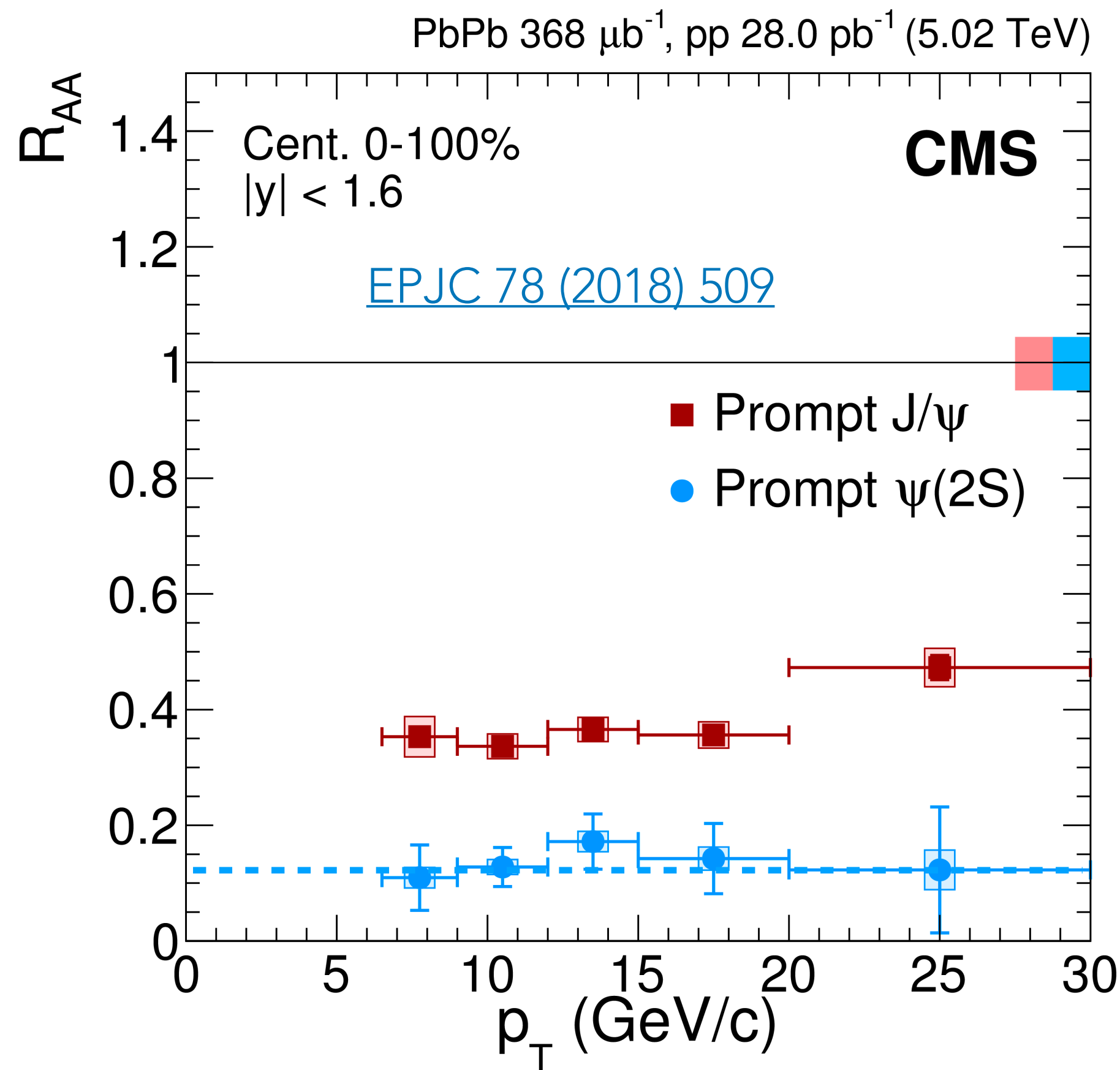


Measurement in pp collisions at 7 TeV [[JHEP 04 \(2013\) 154](#)]



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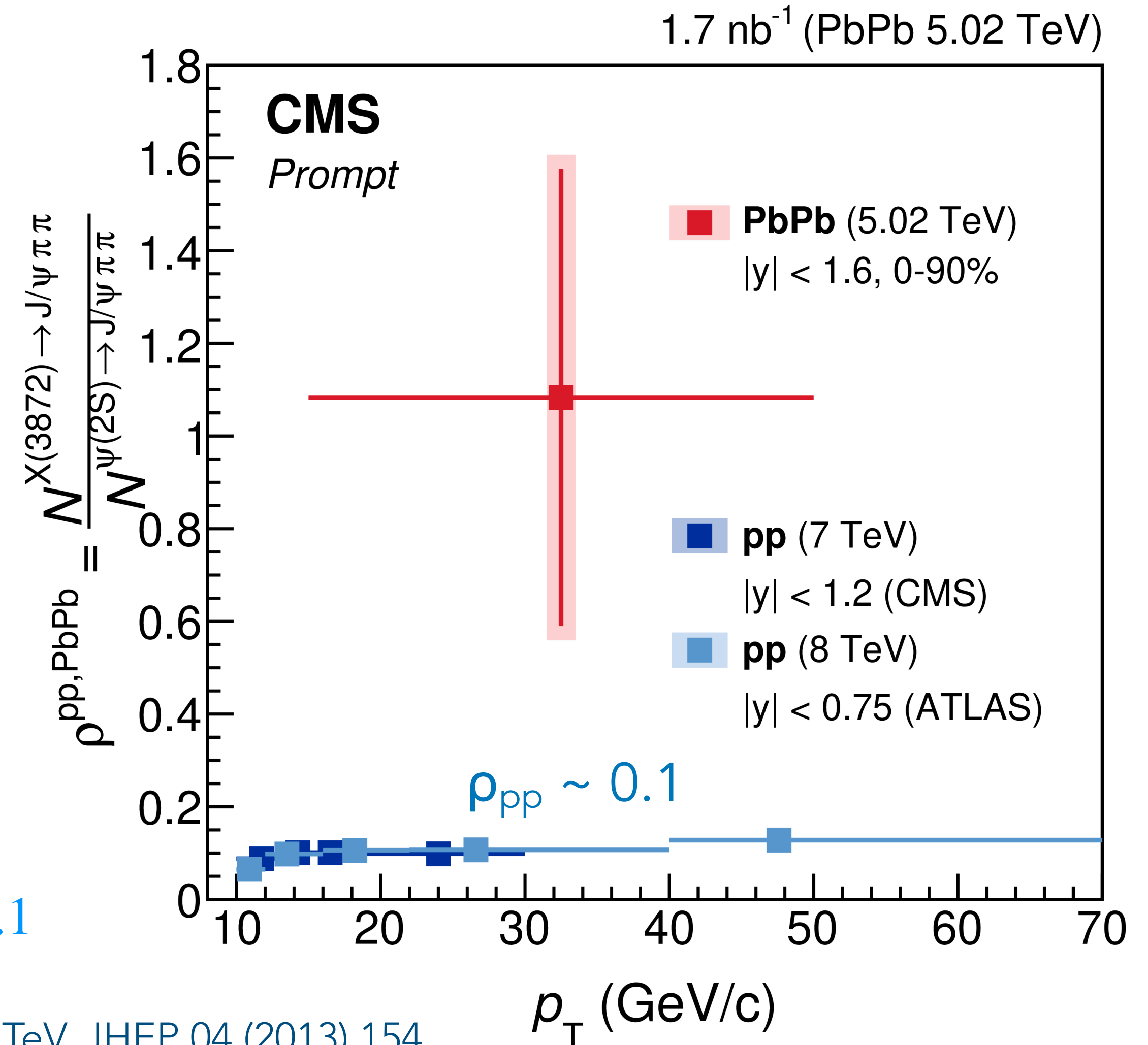
$$R_{AA}^{X(3872)} \equiv \frac{N_{PbPb}^{X(3872)}}{N_{coll} \times N_{pp}^{X(3872)}} = \frac{\rho_{PbPb}}{\rho_{pp}} \times R_{AA}^{\psi(2S)} \approx \rho_{PbPb}$$



$R_{AA}^{\psi(2S)} \approx 0.1$

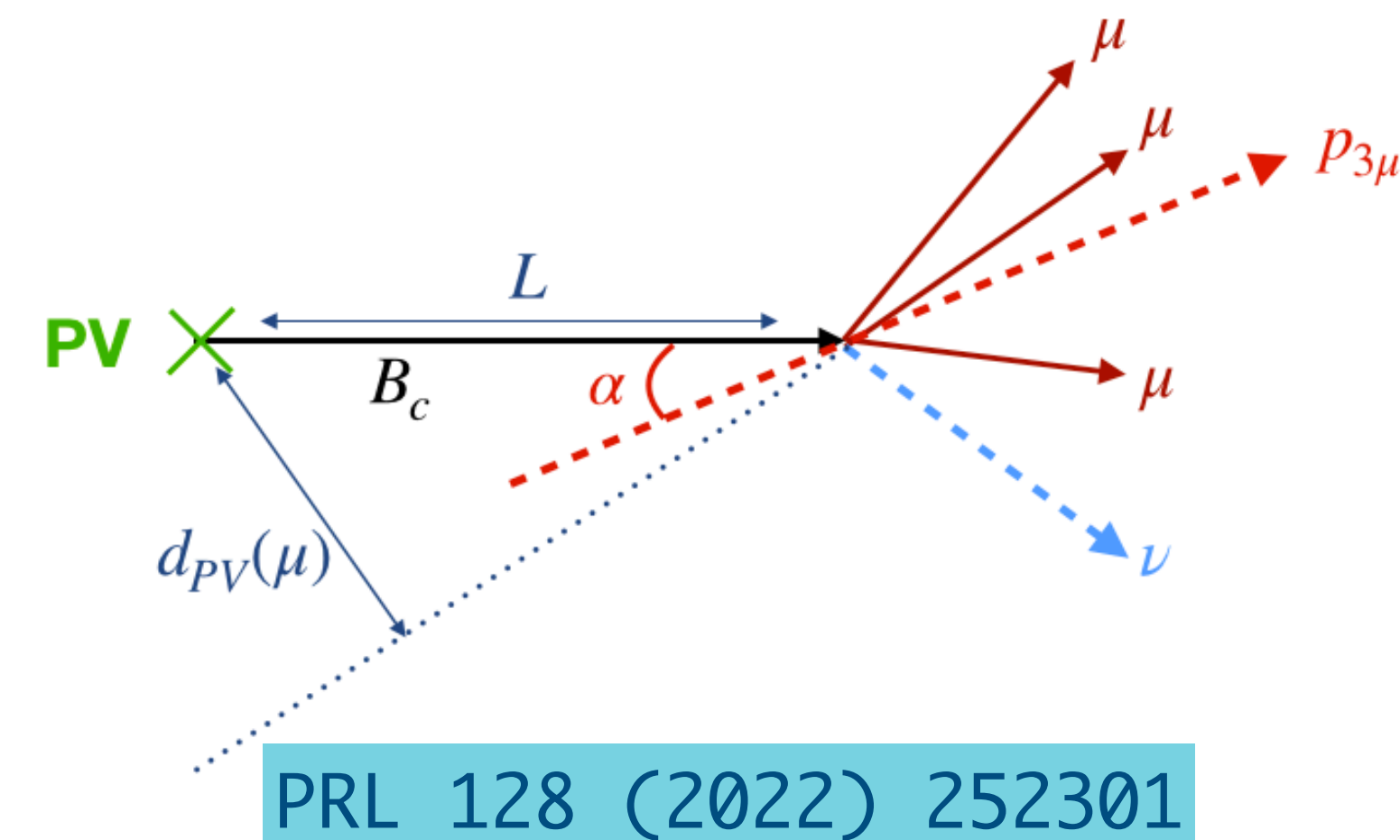
CMS 7 TeV, [JHEP 04 \(2013\) 154](#)

ATLAS 8 TeV, [JHEP 01 \(2017\) 117](#)



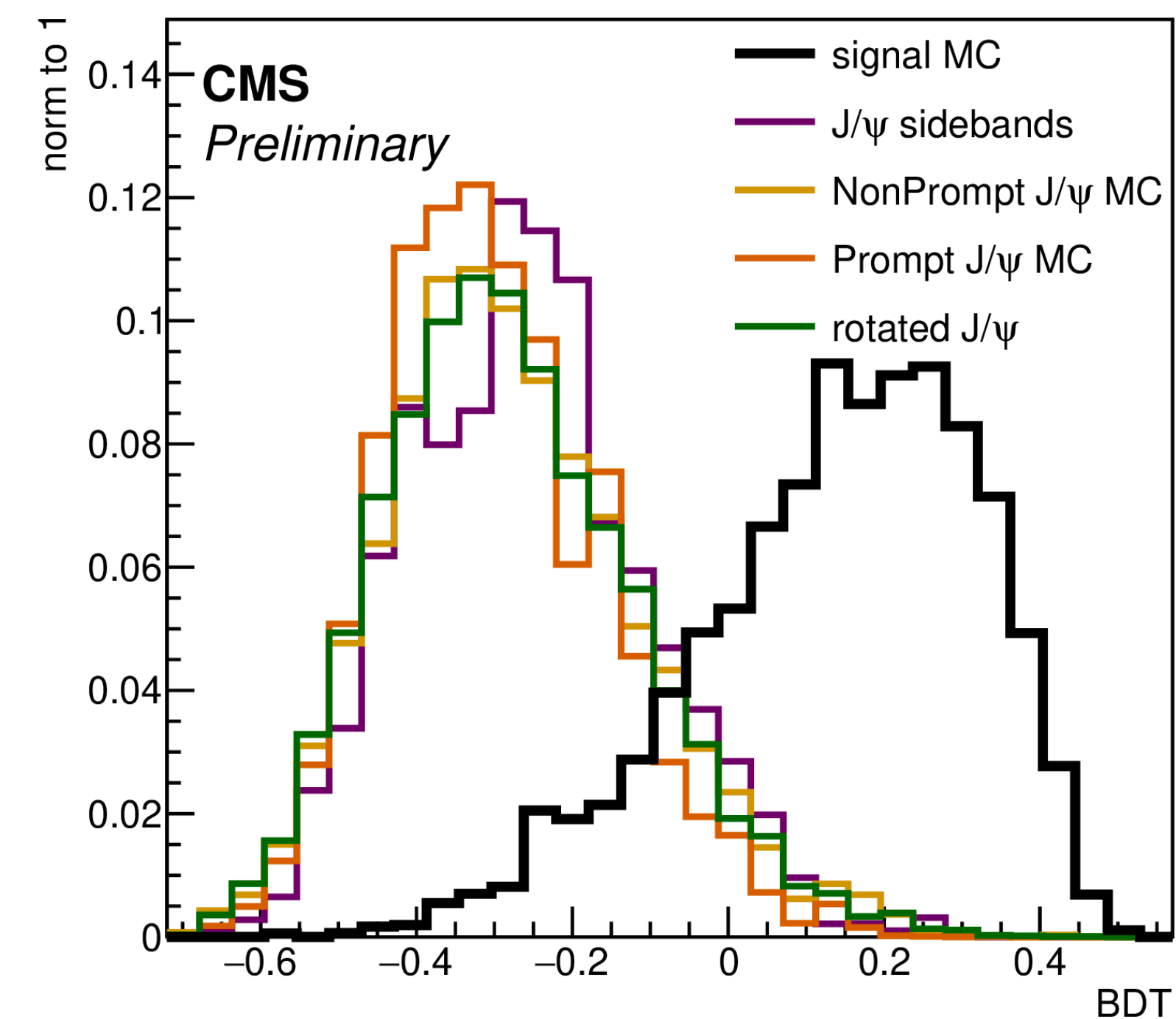
Reconstructed in the decay mode $B_c^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-) \mu^+ \nu_\mu$

- ▶ **three muons** from a same displaced vertex
- ▶ one opposite-sign pair consistent with the J/ψ mass
- ▶ trimuon kinematics + wide invariant mass distribution

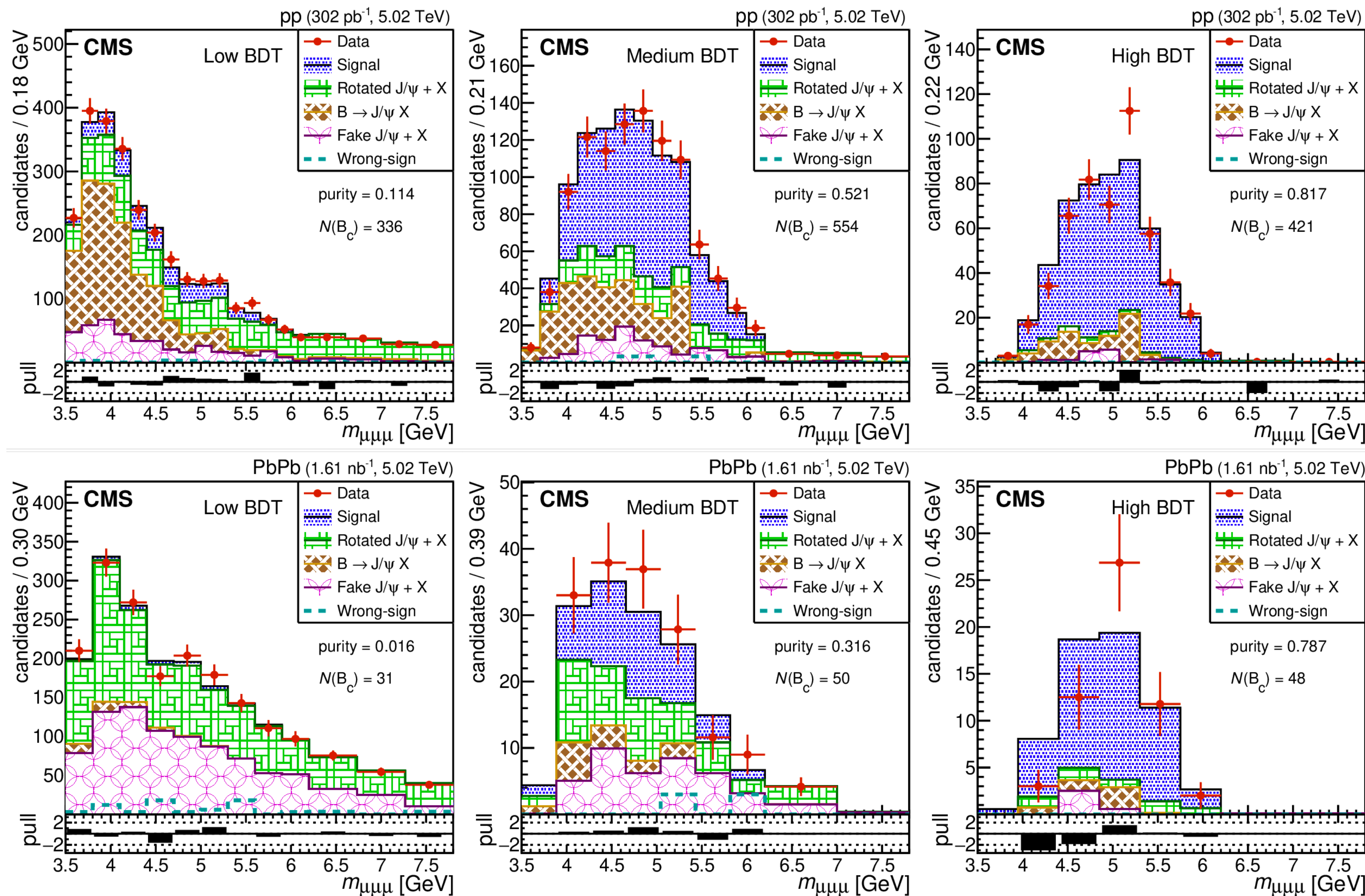


Signal topology similar to **three background categories**

- ▶ **Fake J/ψ** = accidental dimuon taken as the J/ψ
 - ▶ mass sidebands in data
- ▶ Association of a *true* J/ψ with a misidentified hadron
 - ▶ nonprompt J/ψ Monte Carlo ($B \rightarrow J/\psi + X$)
- ▶ Combination of a J/ψ and a muon from different vertices
 - ▶ decorrelation by rotating the J/ψ candidates around the primary vertex before association with muons (in data)



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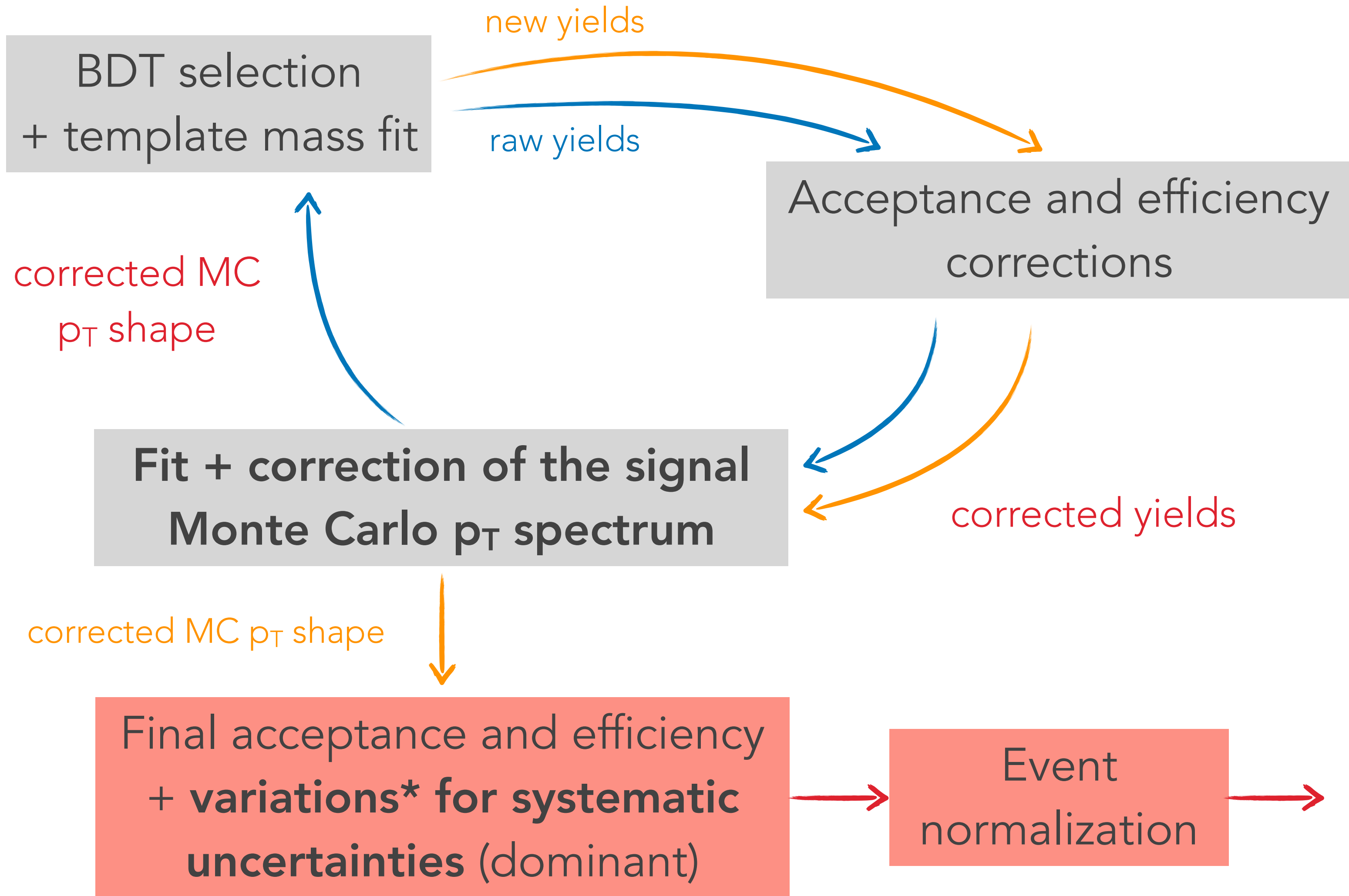


pp data

Background categories

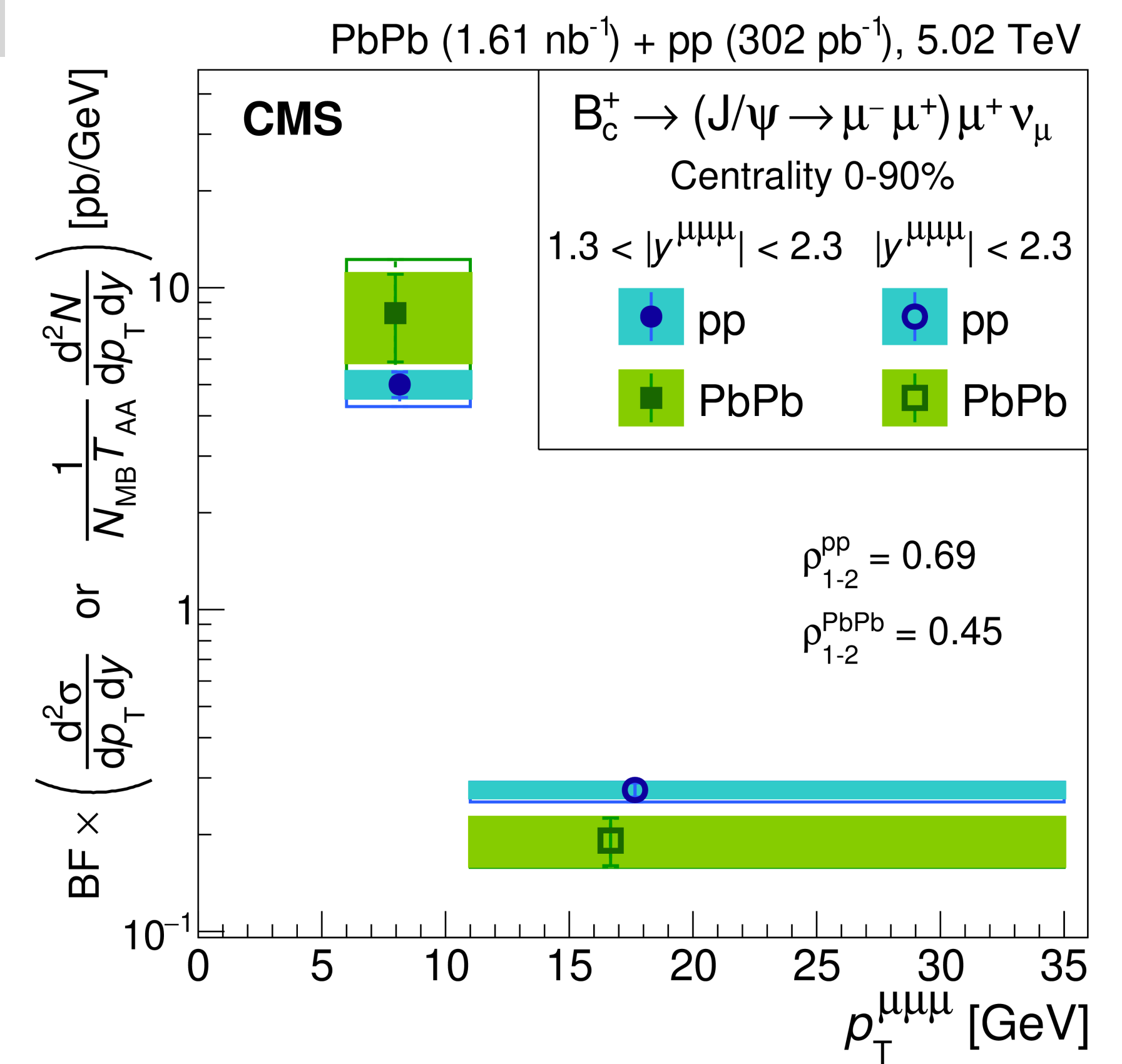
- ▶ rotated J/ψ data sample
- ▶ nonprompt J/ψ MC
- ▶ wrong J/ψ candidate (data dimuon sidebands)
- ▶ pure combinatorial background from three same-sign muons

PbPb data



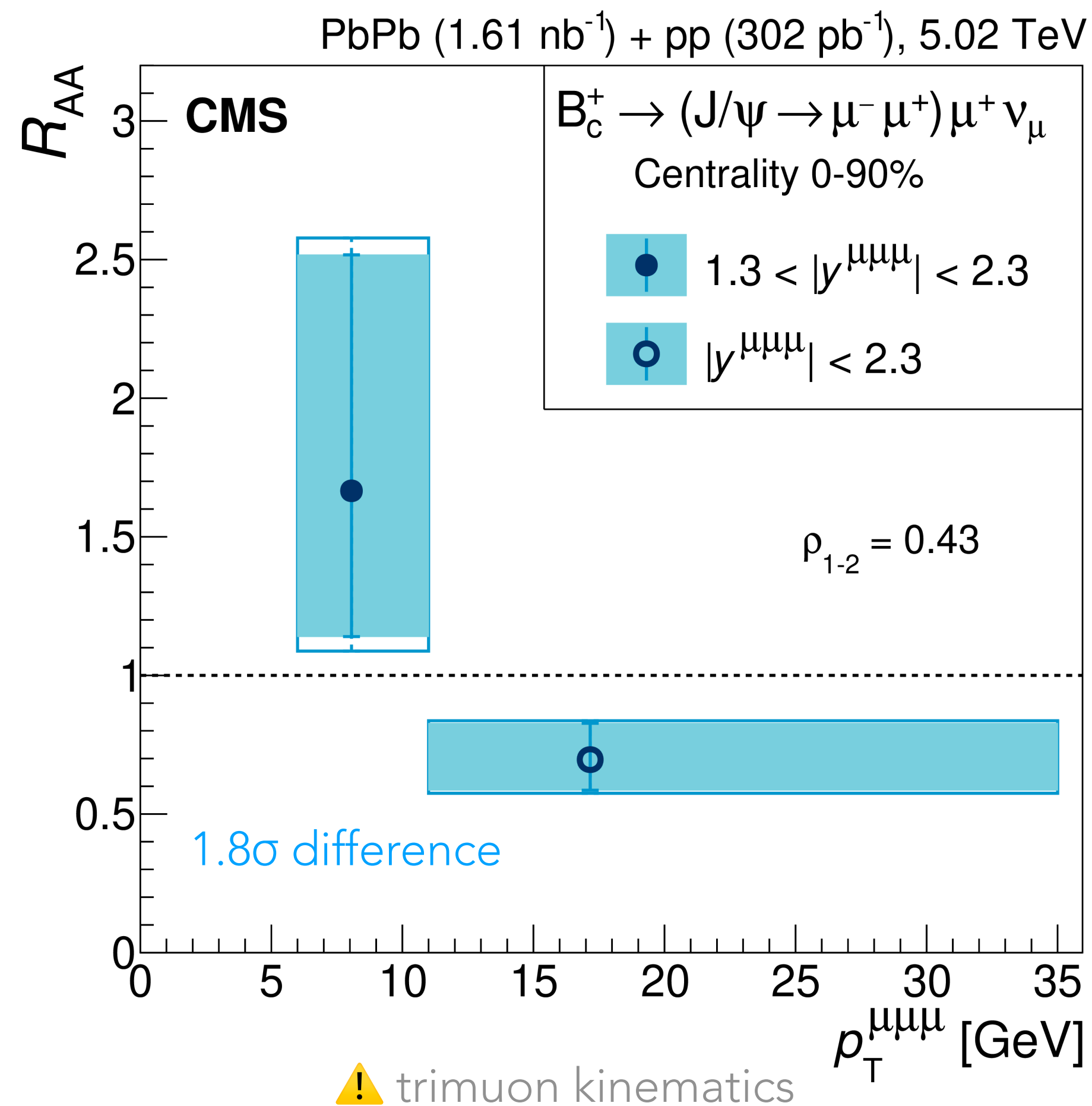
Analysis workflow
 first step
 second step
 output / result

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*account for correlations with other uncertainties (template fit shapes, ...)

Hint for a **softer p_T spectrum** in PbPb with respect to pp collisions



No significant variation with the centrality

