Evidence of X(3872) and studies of its prompt production in PbPb collisions

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For the CMS Collaboration

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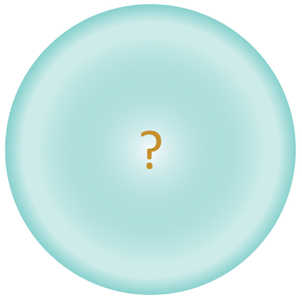
Introduction

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

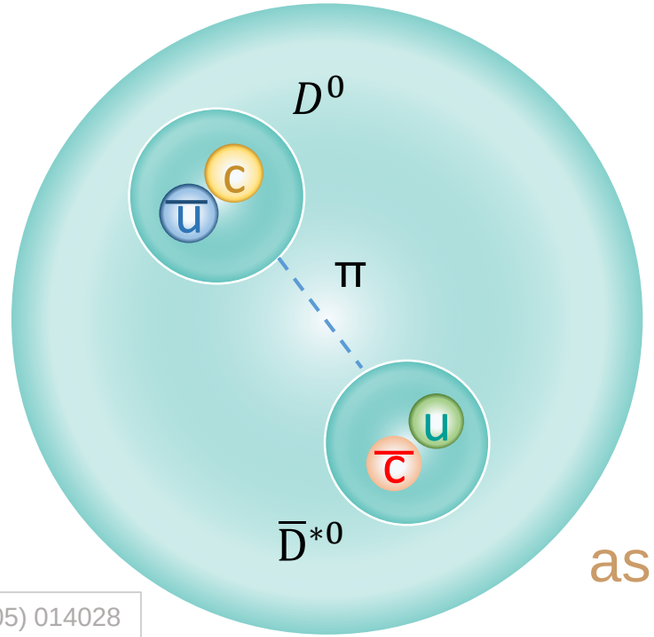
BELLE PRL 91, 262001 (2003)
CDF PRL 98, 132002 (2007)
LHCb PRL 110, 222001 (2013)

Hybrid



EPJA47 (2011) 101

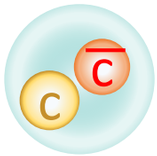
$D^0 - \bar{D}^{*0}$ molecule



$r_{molecule}$ as large as 5 fm

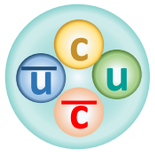
PRD71 (2005) 014028

Charmonium



PLB 590 209-215 (2004)

Tetraquark (4q)



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

PRD 71 (2005) 014028

X(3872) Production in Heavy Ion Collisions

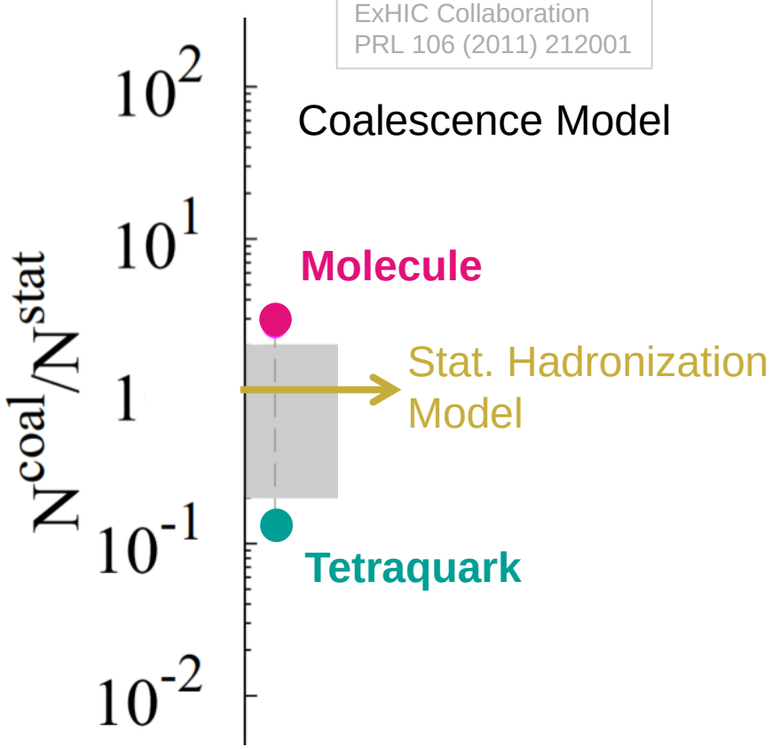
X(3872) production in Heavy Ion Collisions

- Production yield in QGP strongly reflects internal structure
- 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



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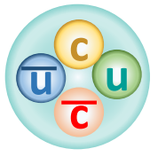

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PRD 71 (2005) 014028

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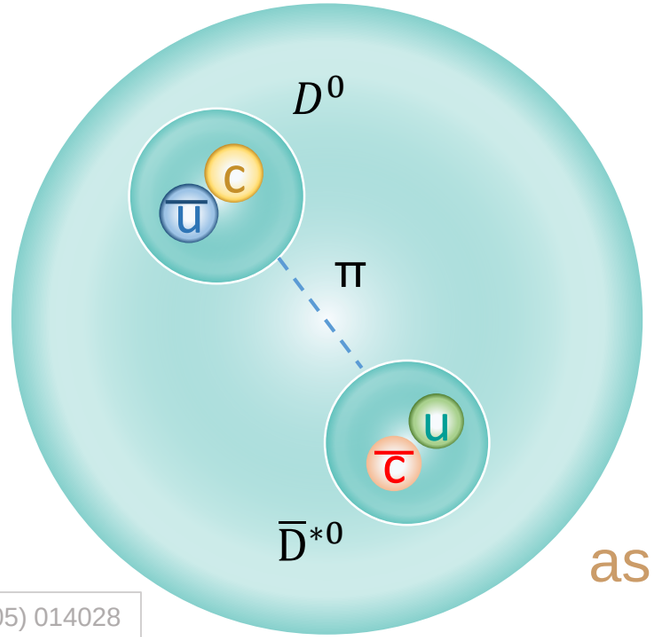
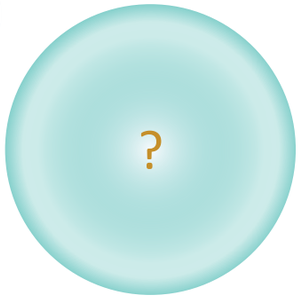


PRD71 (2005) 014028

Hybrid



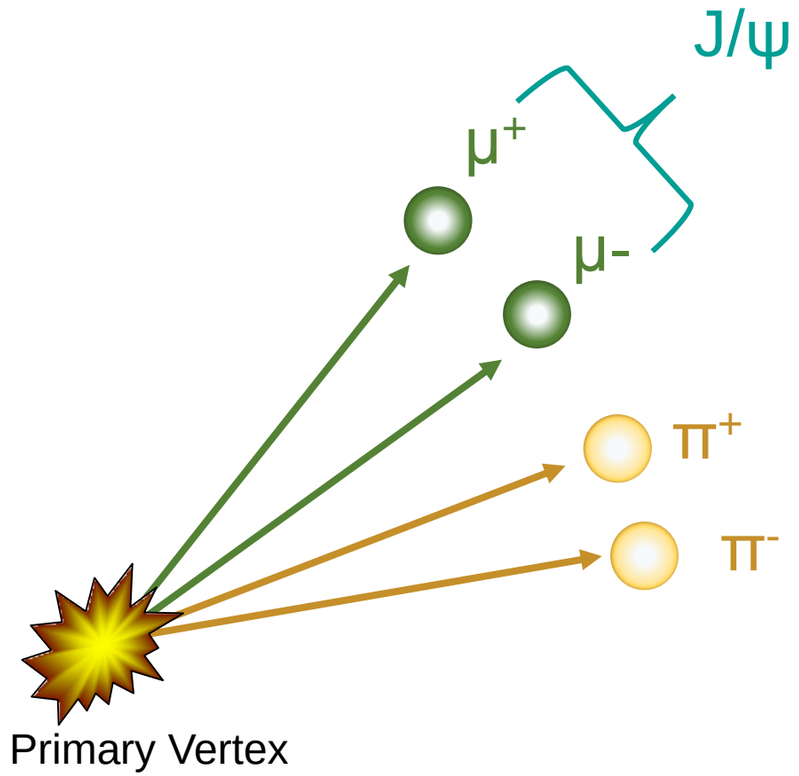
EPJA47 (2011) 101

$r_{molecule}$
as large as 5 fm

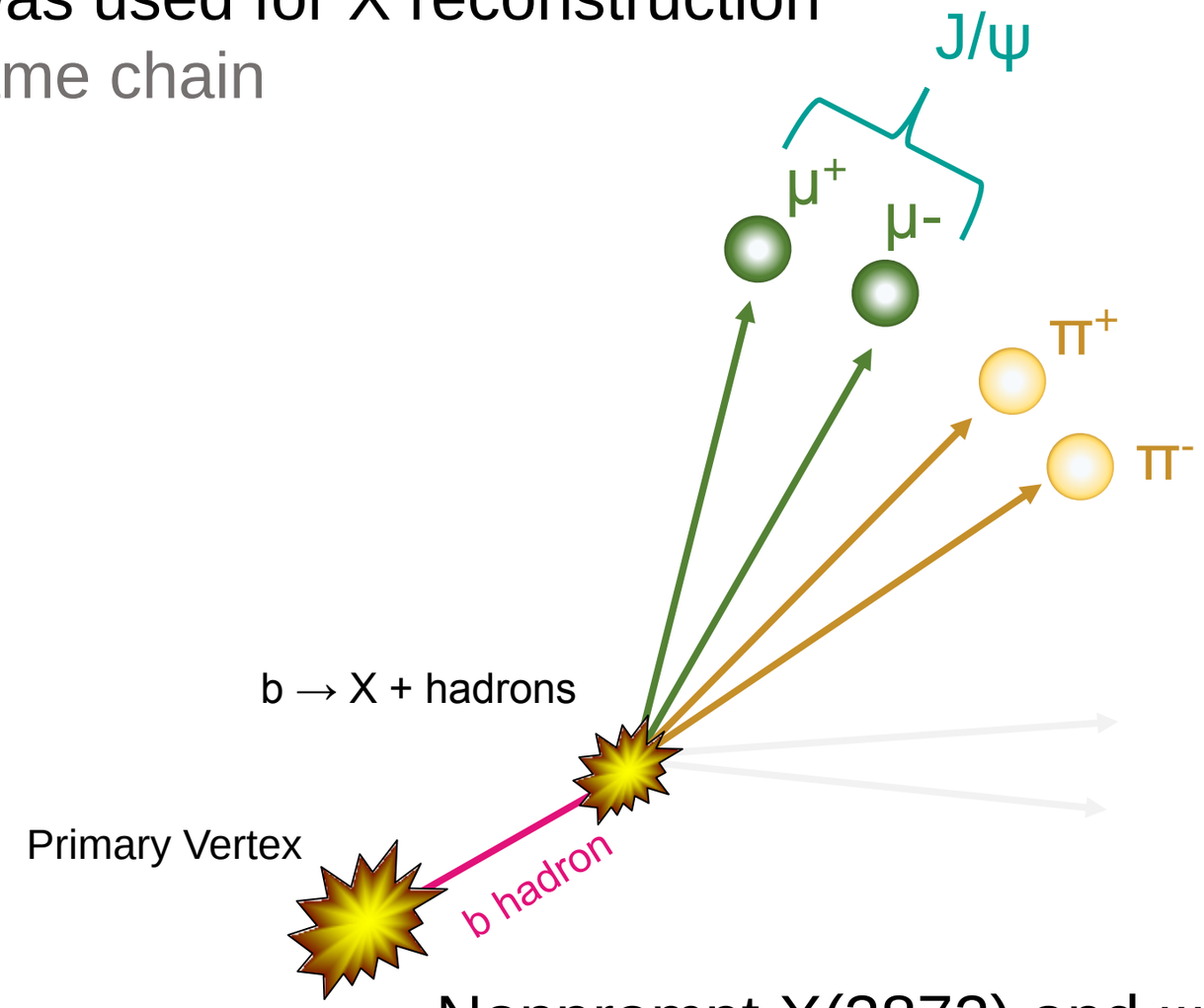
Reconstruction of X(3872) and ψ(2S)

X(3872) →J/ψ $\pi^+\pi^-$ → $\mu^+\mu^-\pi^+\pi^-$ was used for X reconstruction

ψ(2S) also decays through the same chain

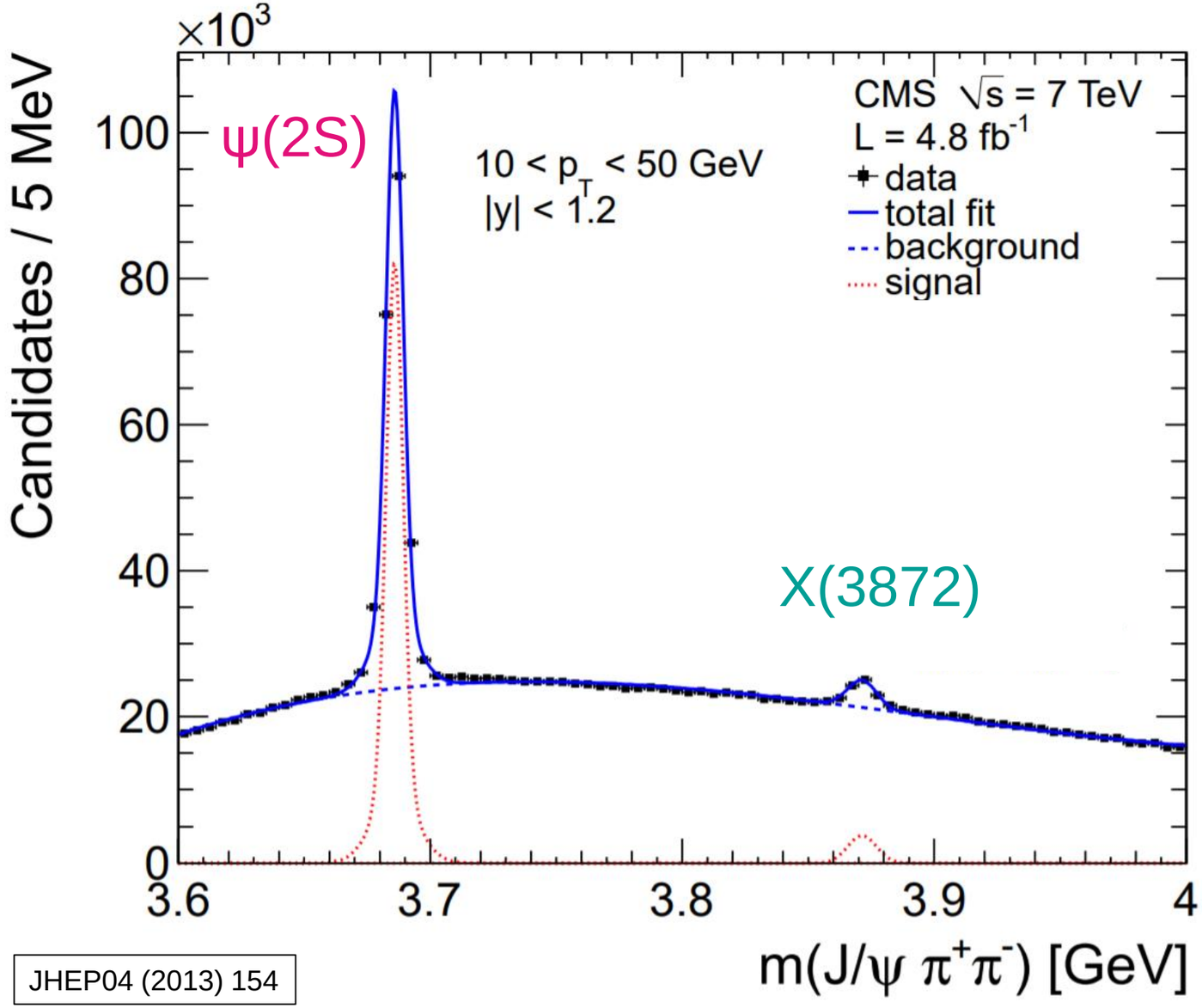


Prompt X(3872) and ψ(2S)



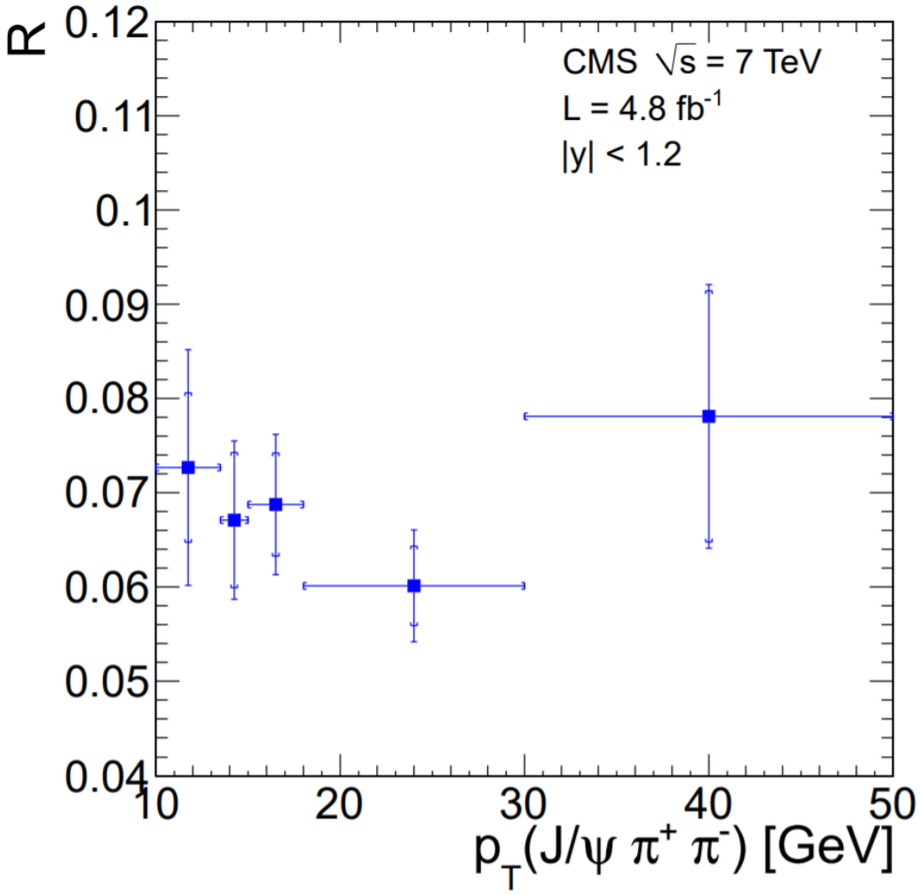
Nonprompt X(3872) and ψ(2S) from b hadron decays

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)



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

Combinatorial Background Suppression in PbPb

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

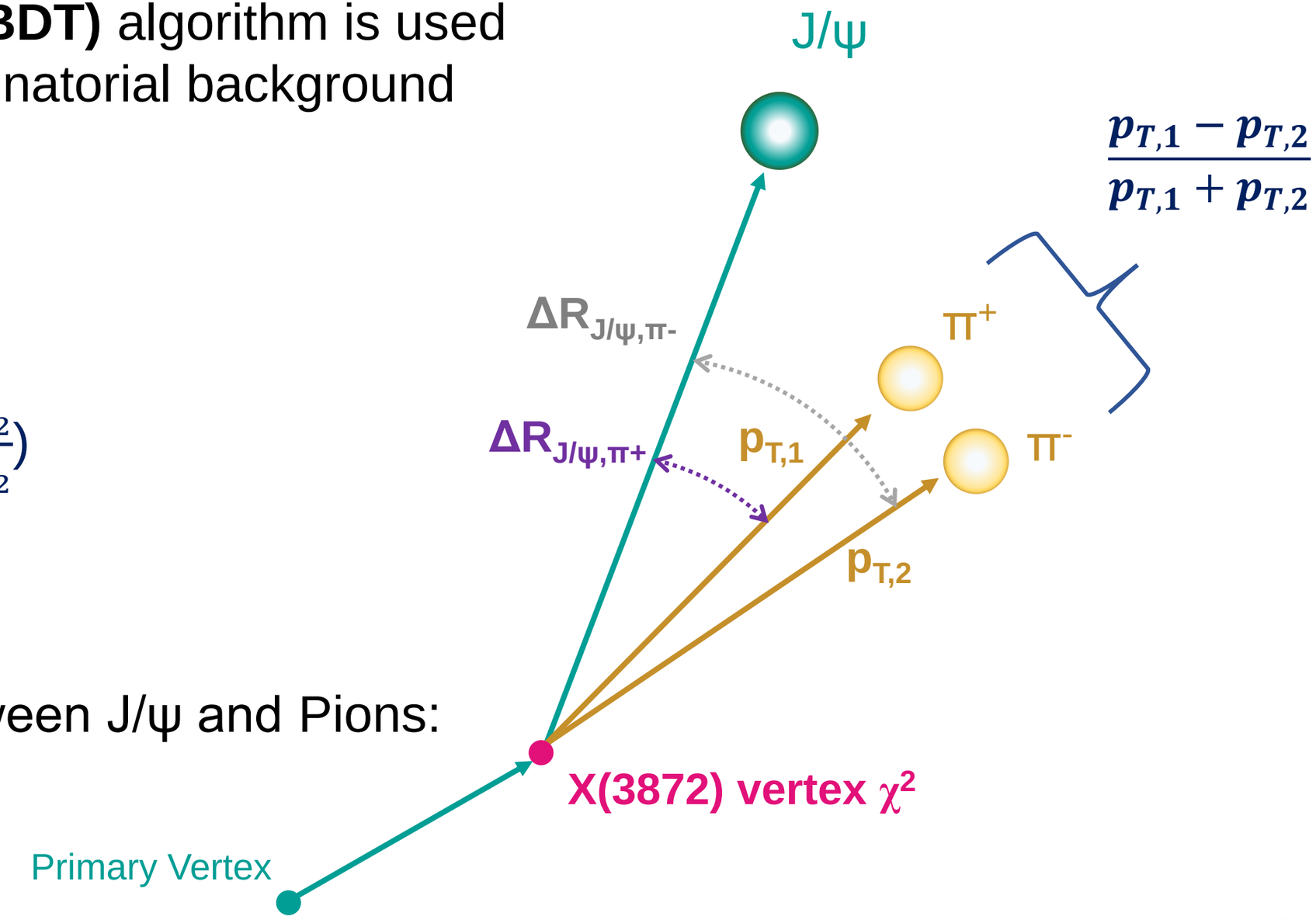
5 Input BDT observables:

(1) X(3872) vertex χ^2

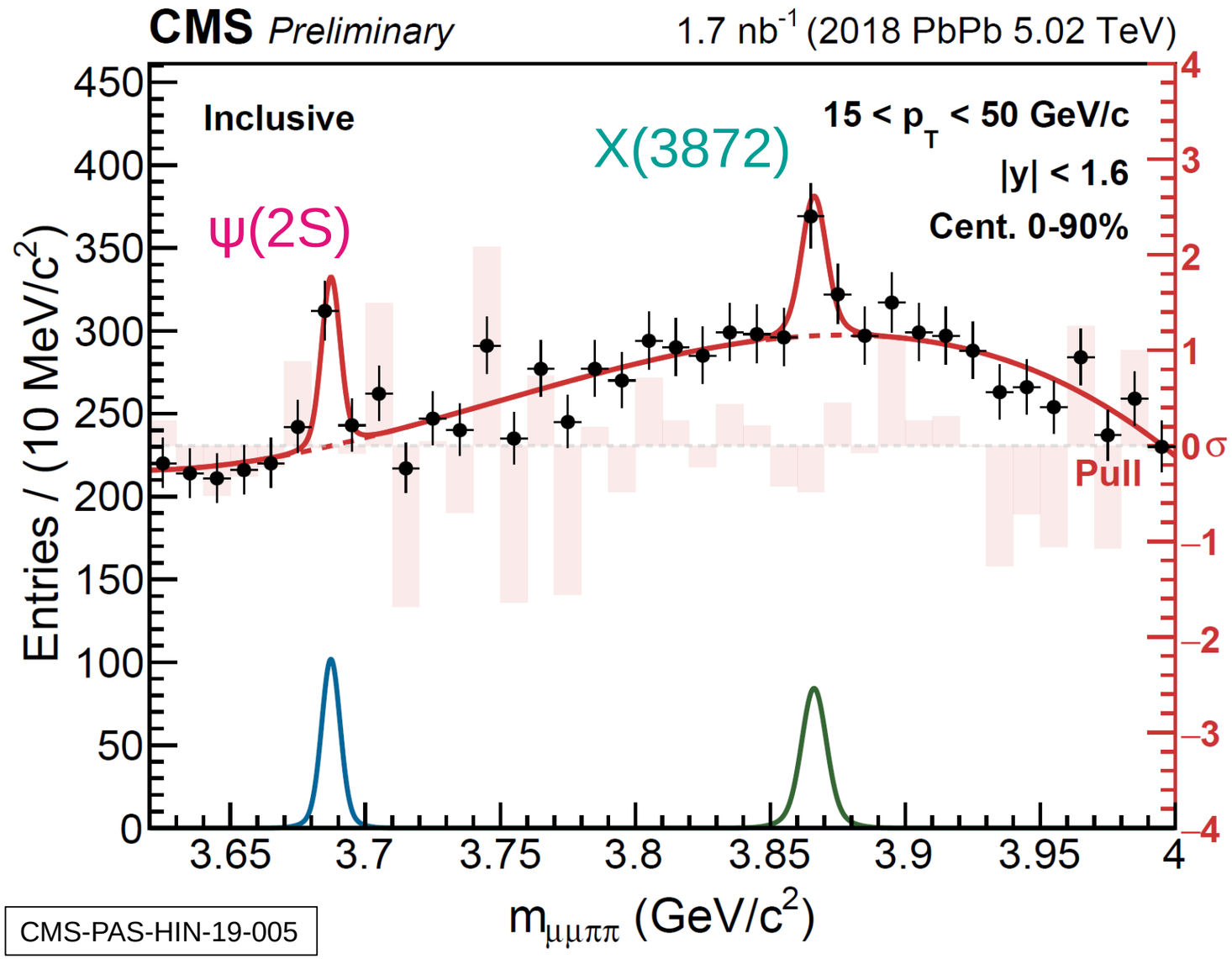
(2) Pion p_T balance $\left(\frac{p_{T,1}-p_{T,2}}{p_{T,1}+p_{T,2}}\right)$

(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



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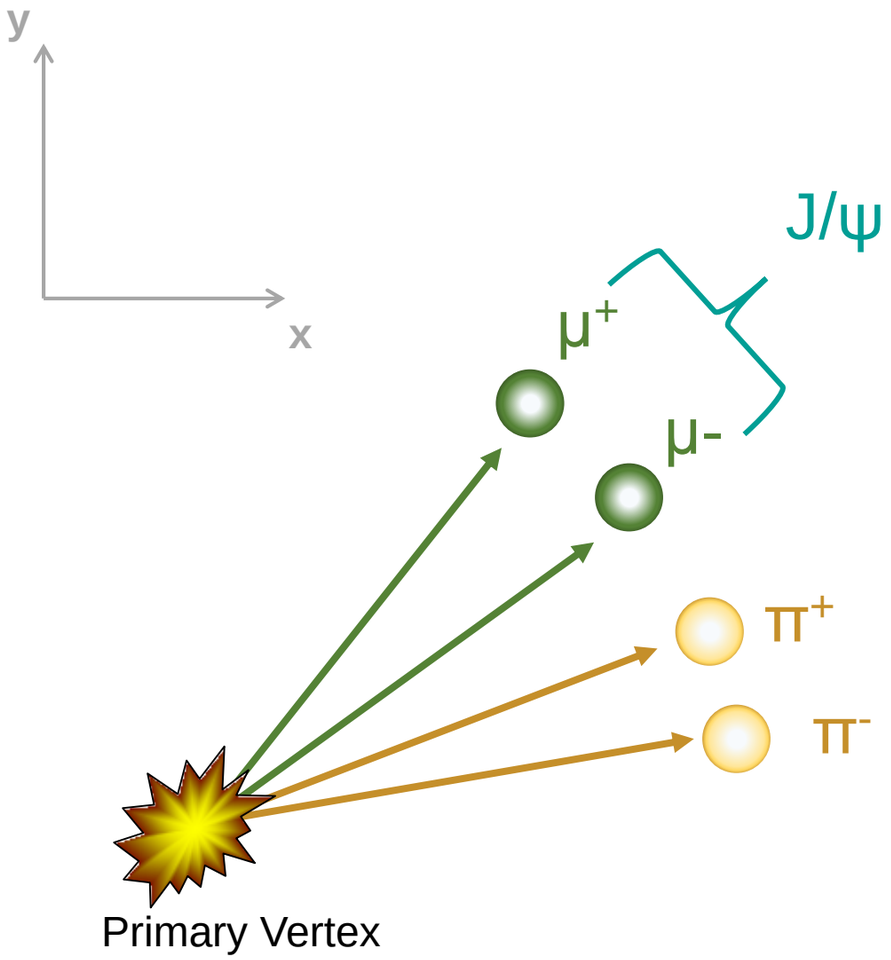
- First evidence of inclusive **X(3872)** production in heavy ion collisions!

  (statistical significance > **3 σ**)

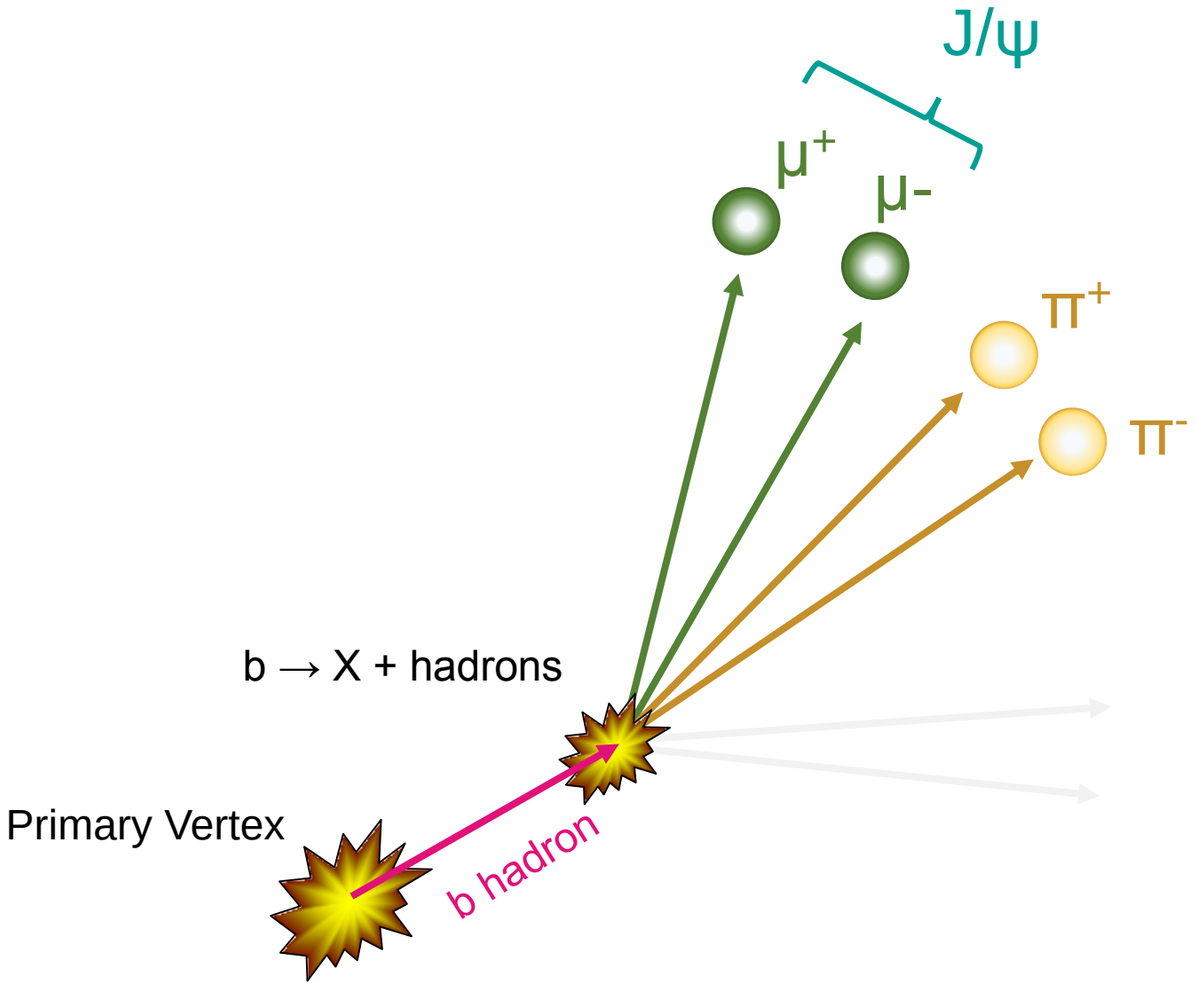
- A clear **ψ(2S)** signal to the same final state is also observed

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

Separation of Nonprompt Component

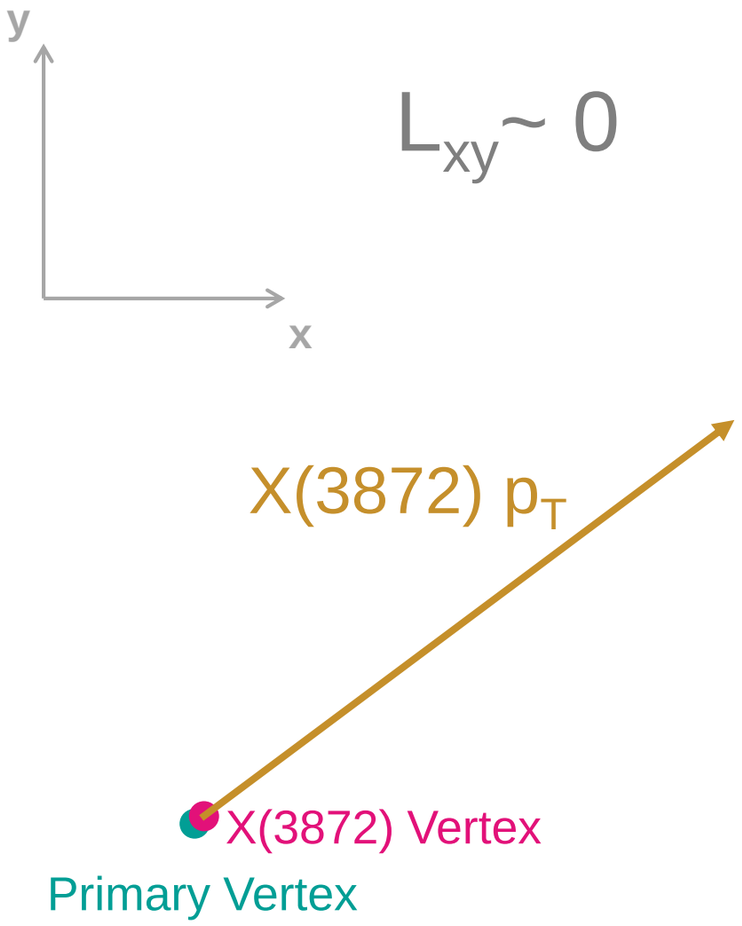


Prompt X(3872) or ψ(2S)

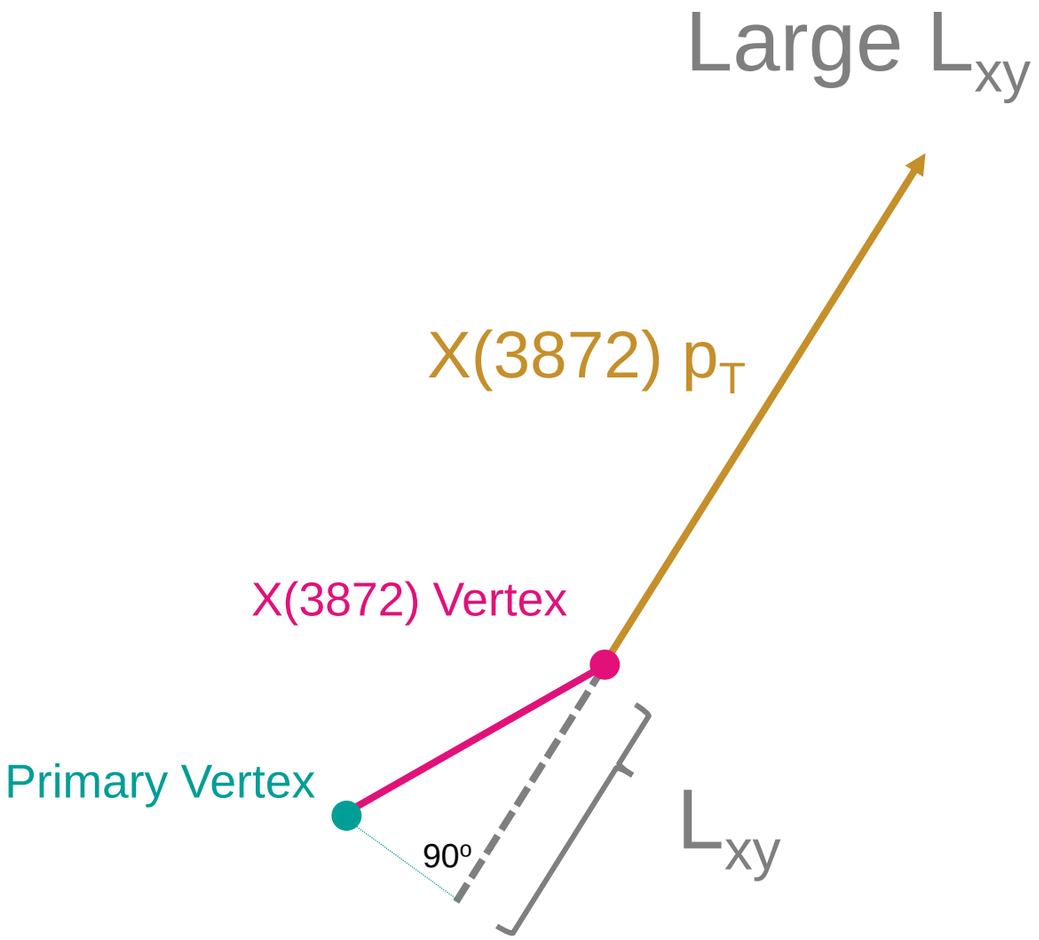


Nonprompt X(3872) or ψ(2S) from b hadron decays

Separation of Nonprompt Component (from b Decay)

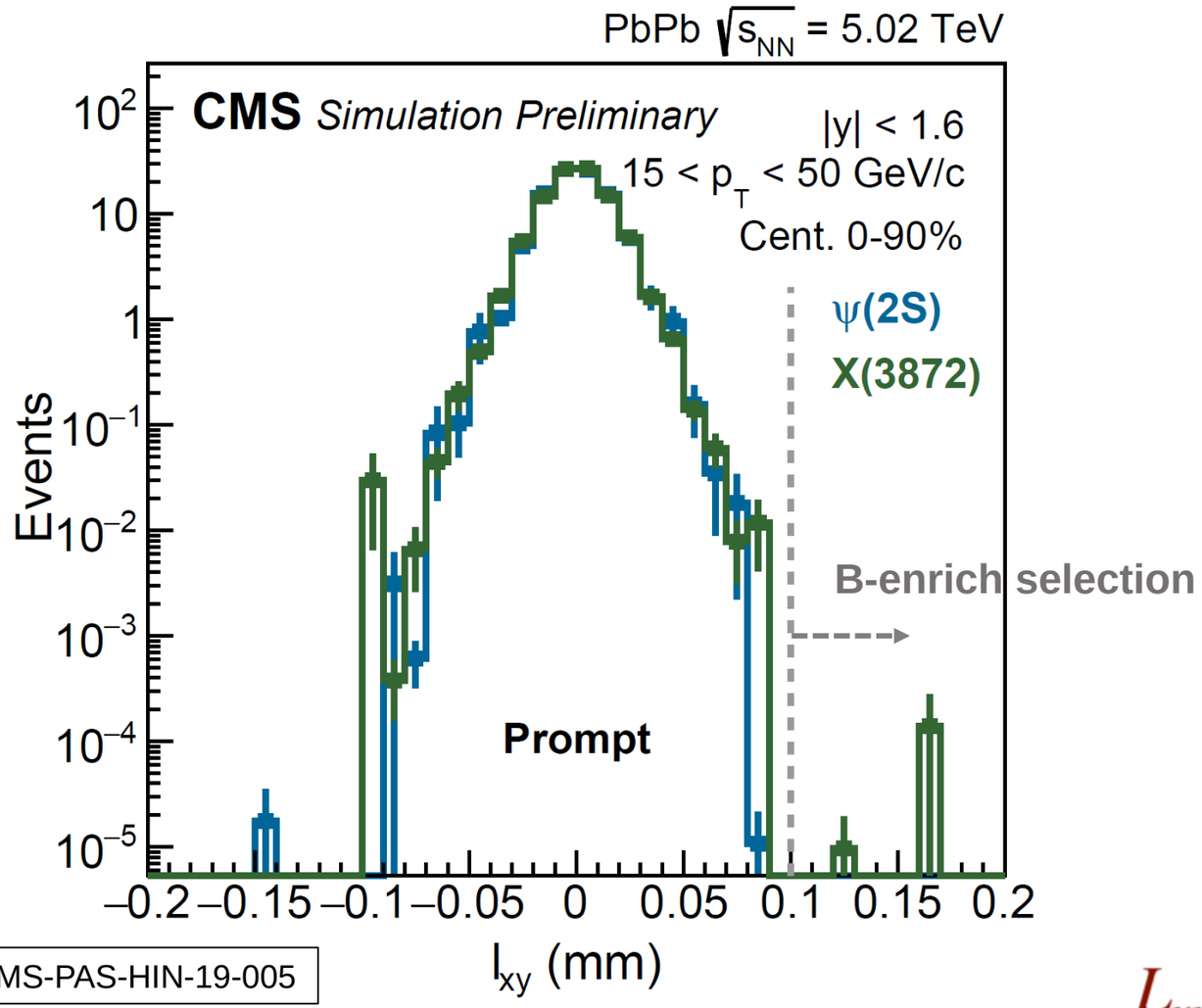


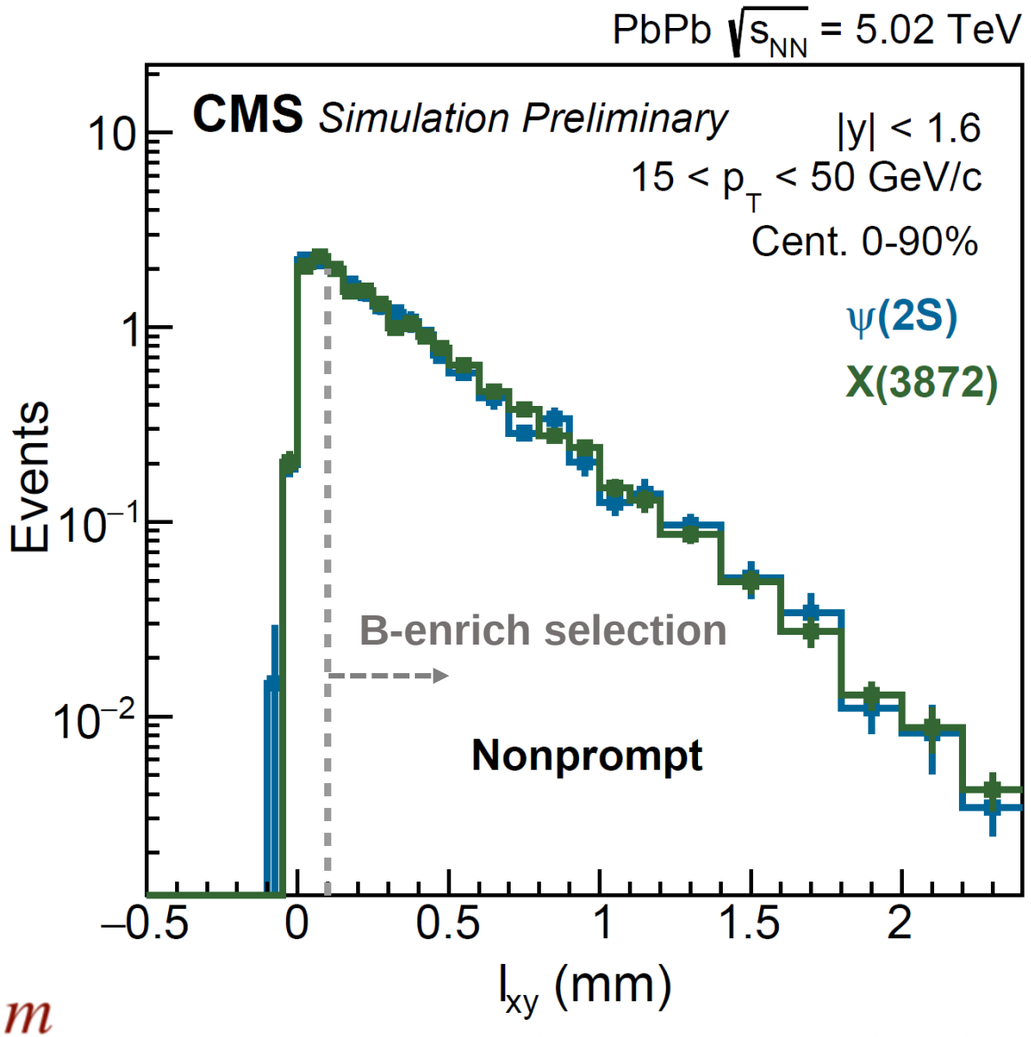
Prompt X(3872) or ψ(2S)



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

Proper Decay Length Distributions in Monte Carlo





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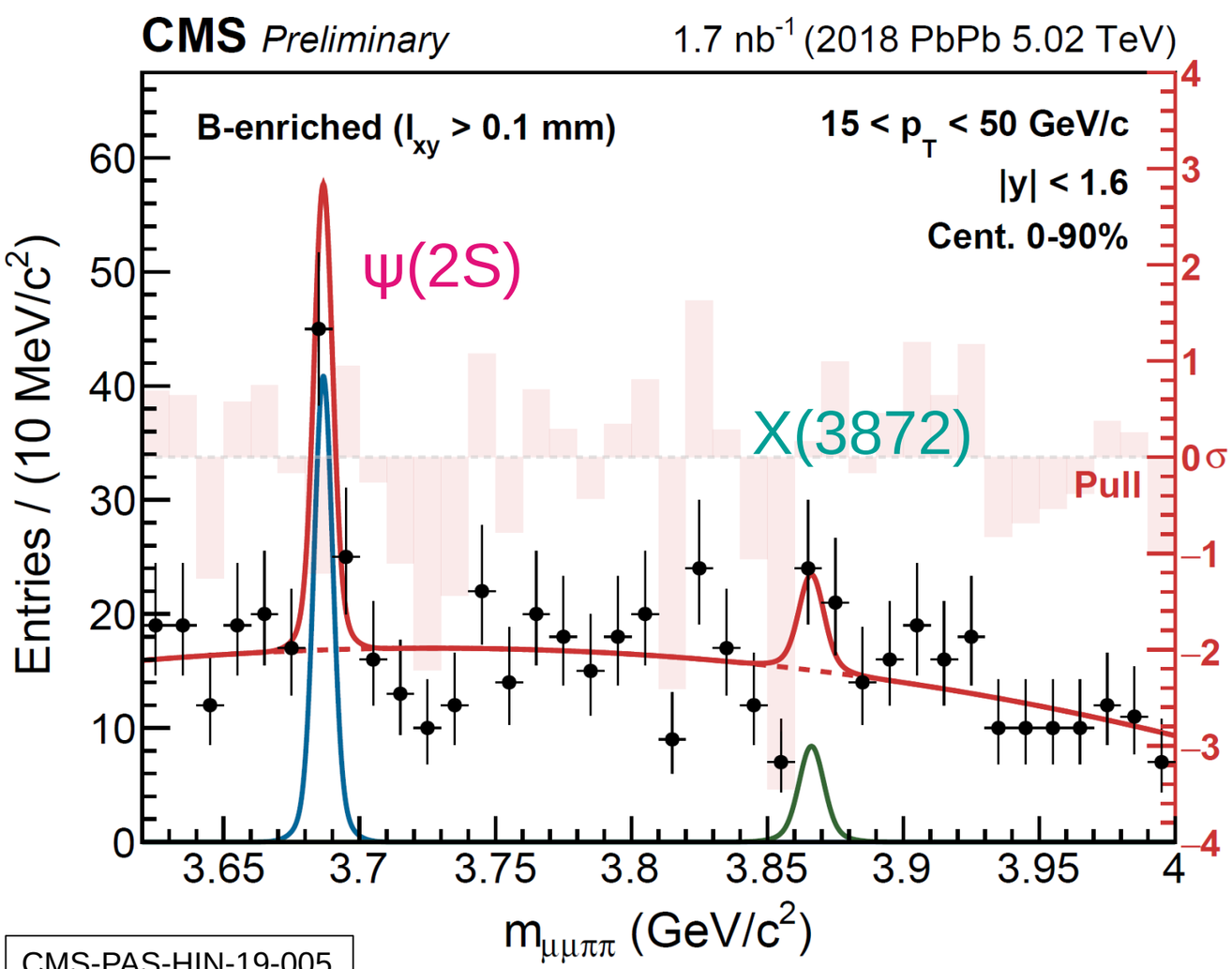
Prompt X(3872) or ψ(2S)

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

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

Invariant Mass Distribution of B-enriched Sample



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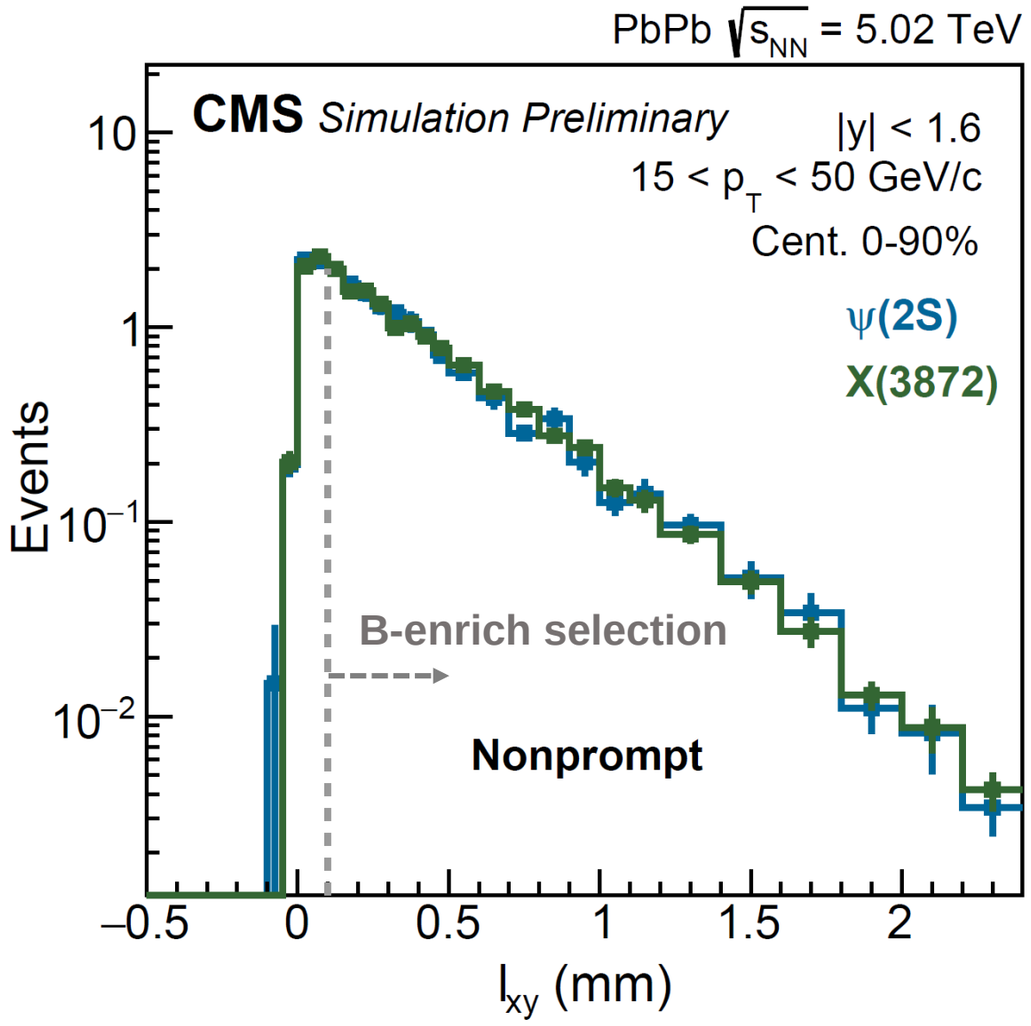
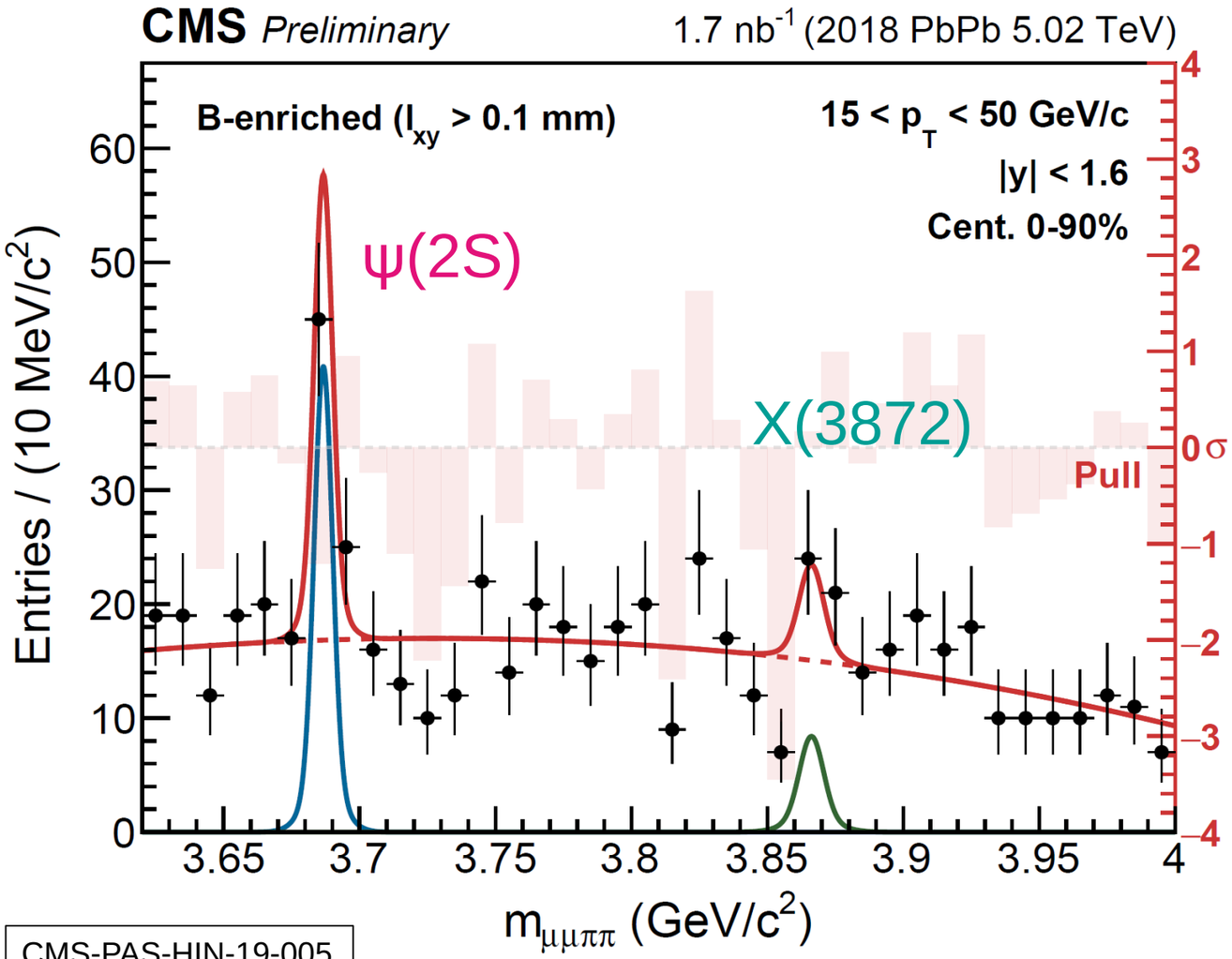
Nonprompt **ψ(2S)** clearly visible



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

Corrected Prompt X(3872) and ψ(2S) Yields



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Nonprompt **ψ(2S)** clearly visible

Nonprompt X(3872) components are subtracted by a data-driven method:

$$N_{\text{Prompt}} = N_{\text{Inclusive}} - \frac{N_{\text{B-enrich}}^{\text{Nonprompt}}}{\epsilon_{\text{MC}}}$$

Prompt yields are corrected for efficiency and acceptance from a PYTHIA Monte Carlo embedded in HYDJET PbPb background

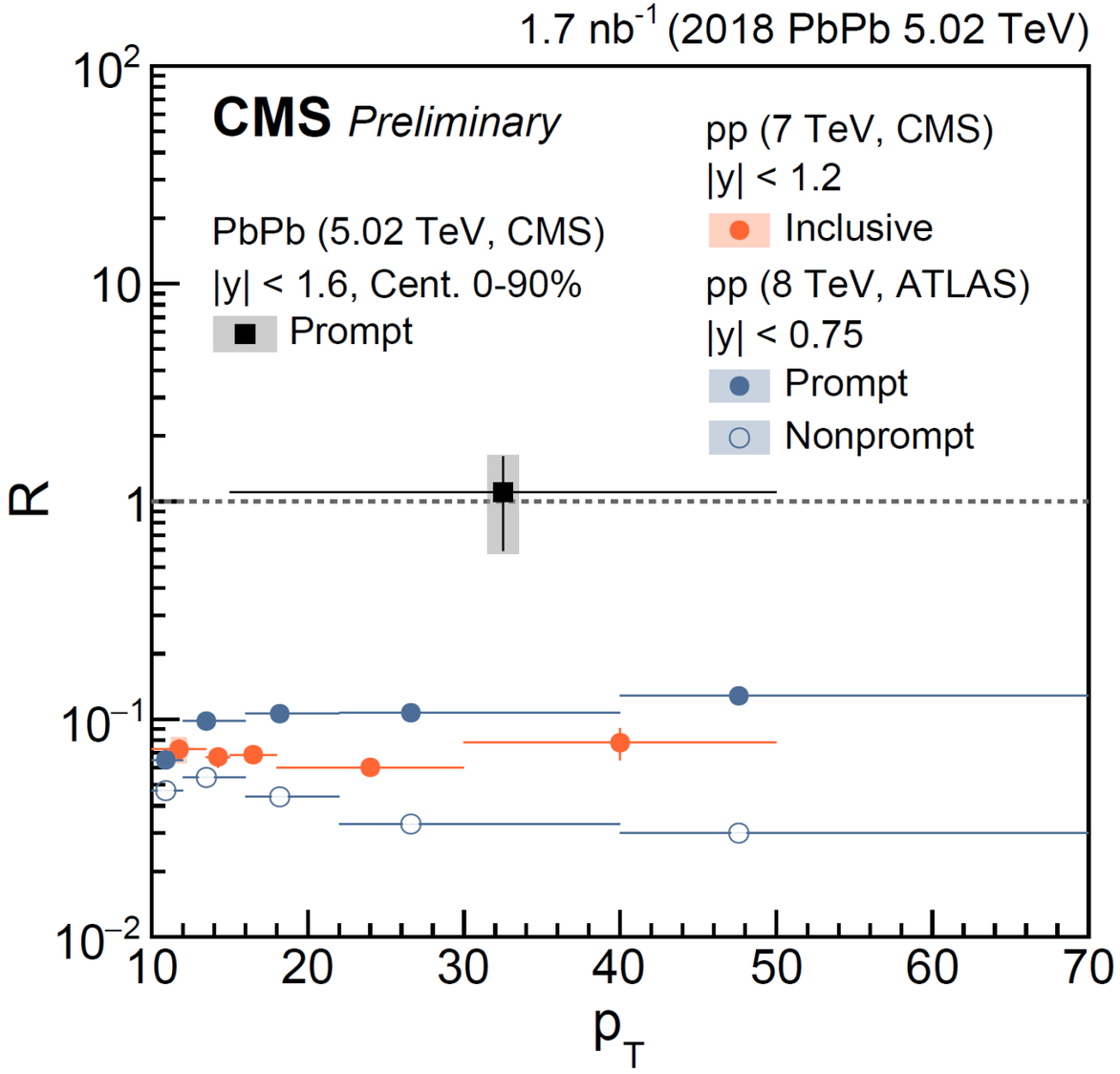
Ratio of X(3872) to ψ(2S) Yields in pp and PbPb

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

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



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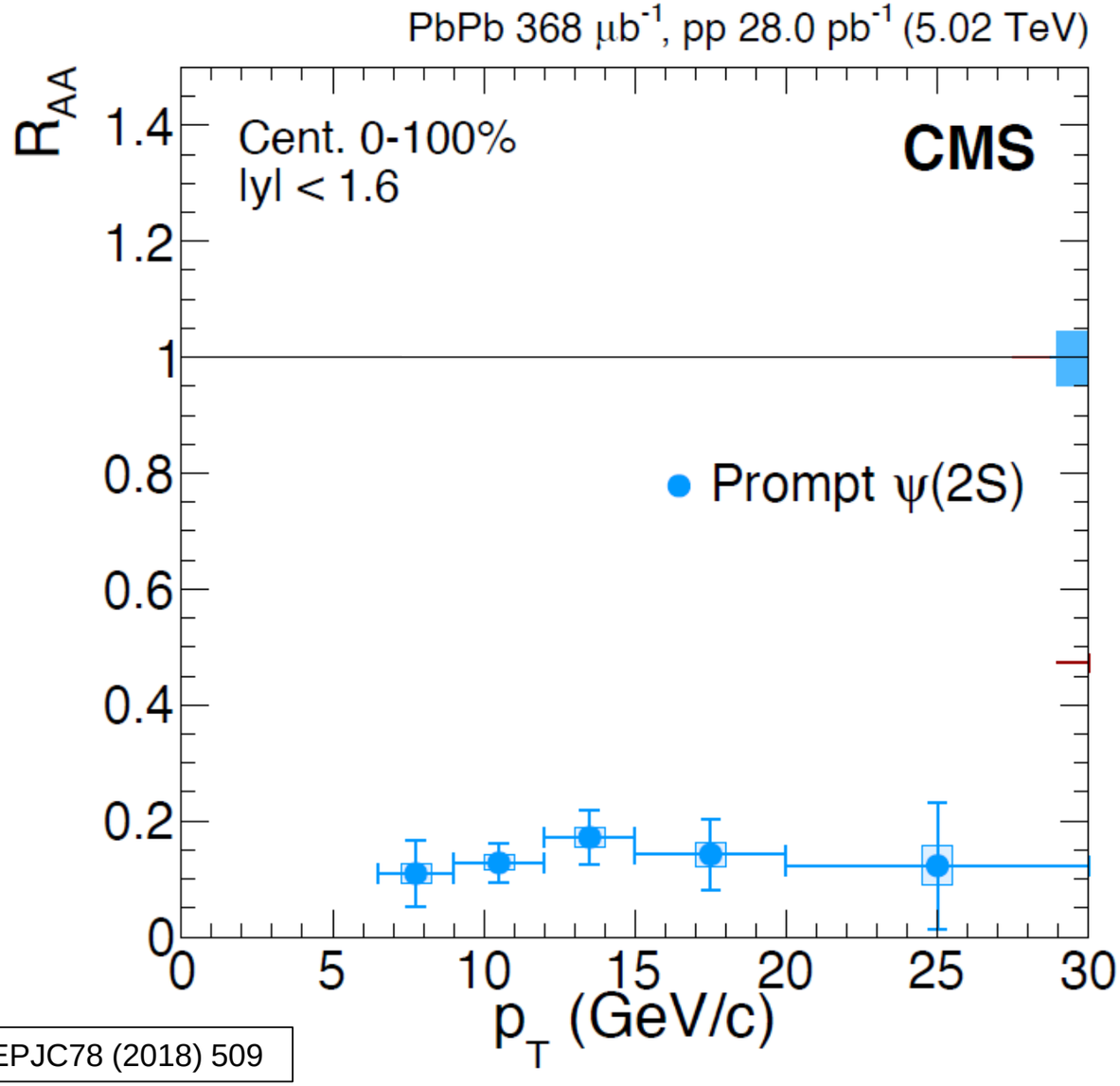
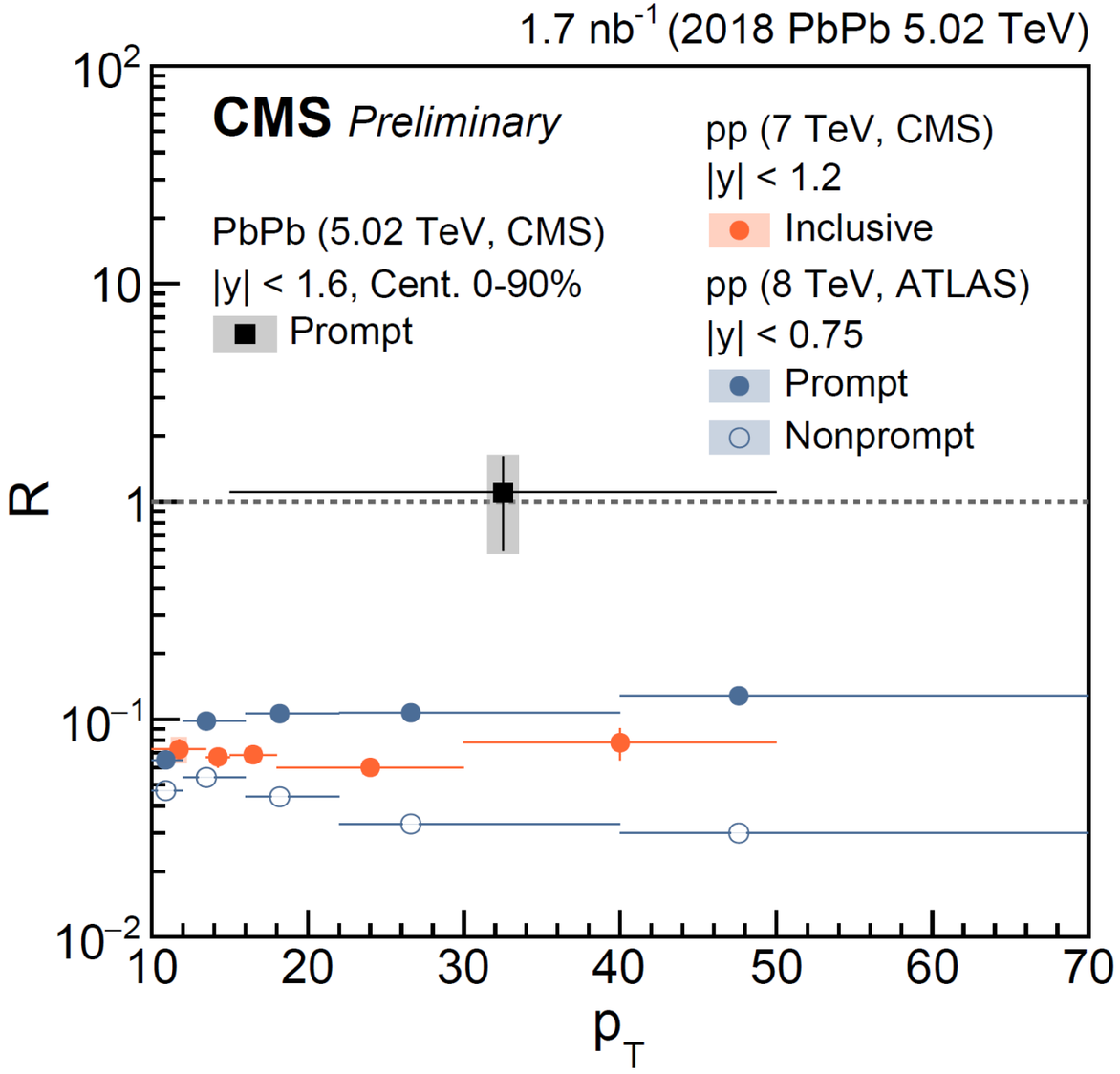
Ratio of X(3872) to ψ(2S) Yields in pp and PbPb





EPJC78 (2018) 509

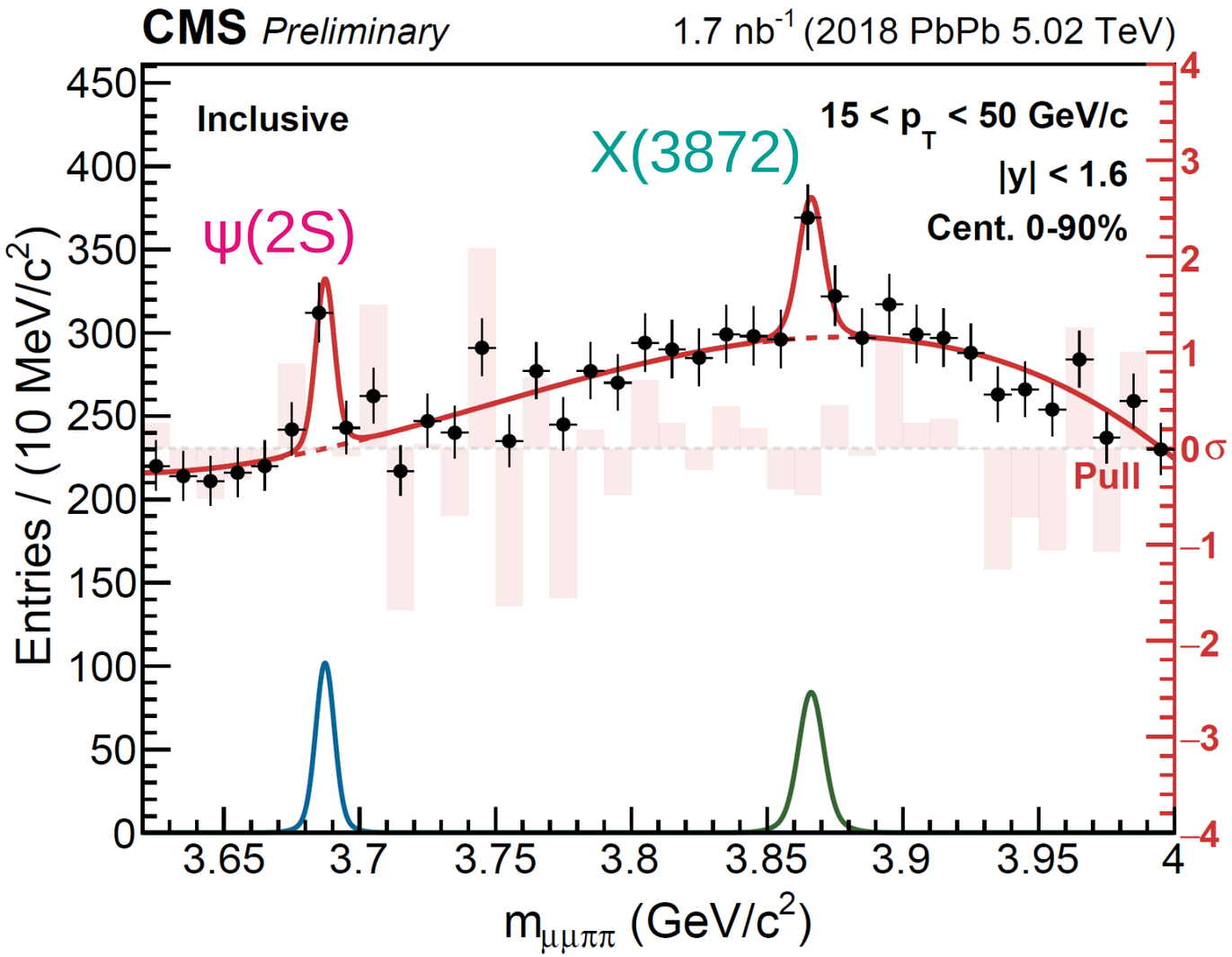
Summary

- First evidence of **X(3872)** production in heavy ion collisions!
- Indication of X(3872) to ψ(2S) ratio enhancement in PbPb:

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

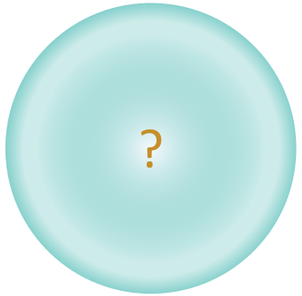
Compared to R ~ 0.04 – 0.1 in pp

- New constraints on coalescence recombination models and the inner structure of X(3872)

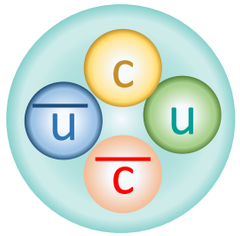


Thank You!

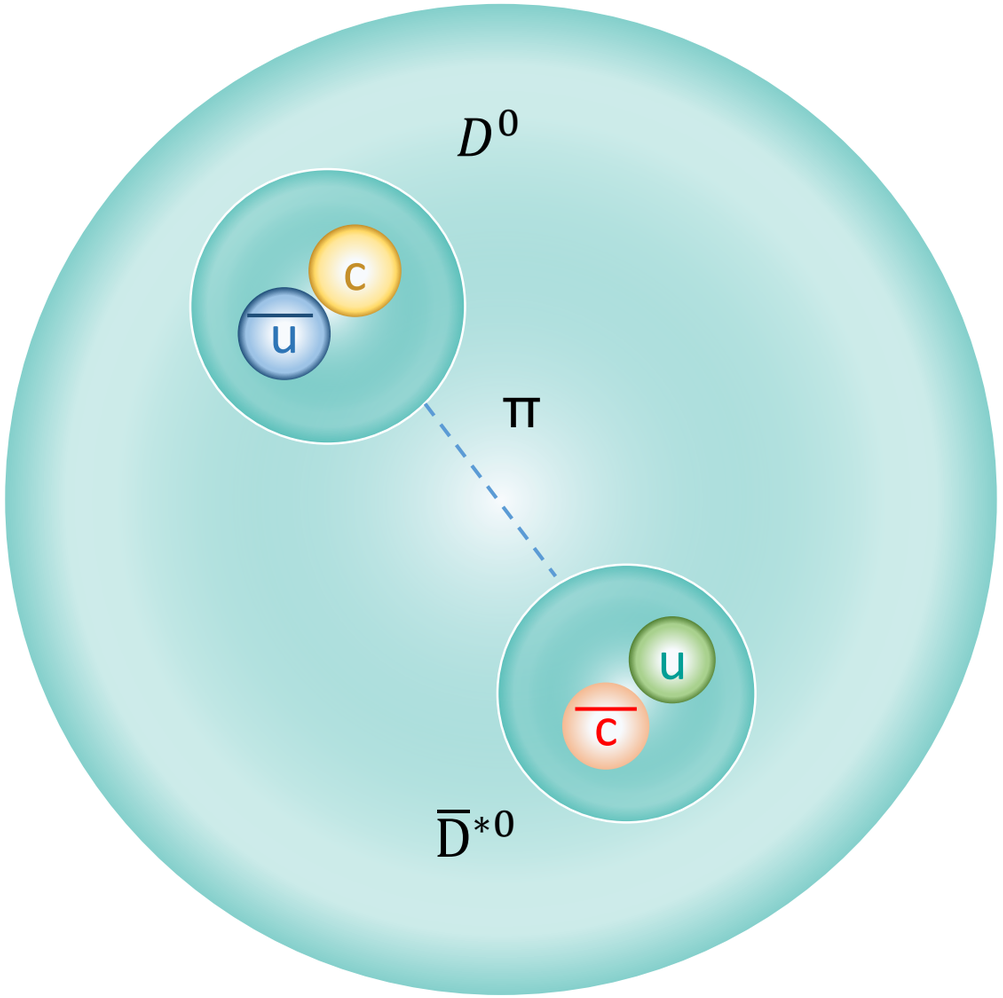
Hybrid



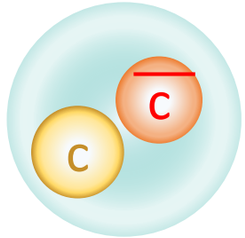
Tetraquark (4q)



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

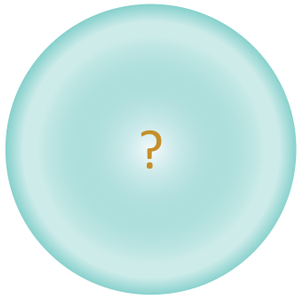


Charmonium



Backup Slides

Hybrid



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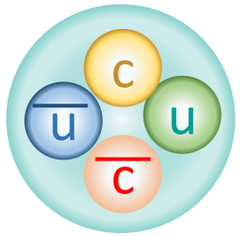

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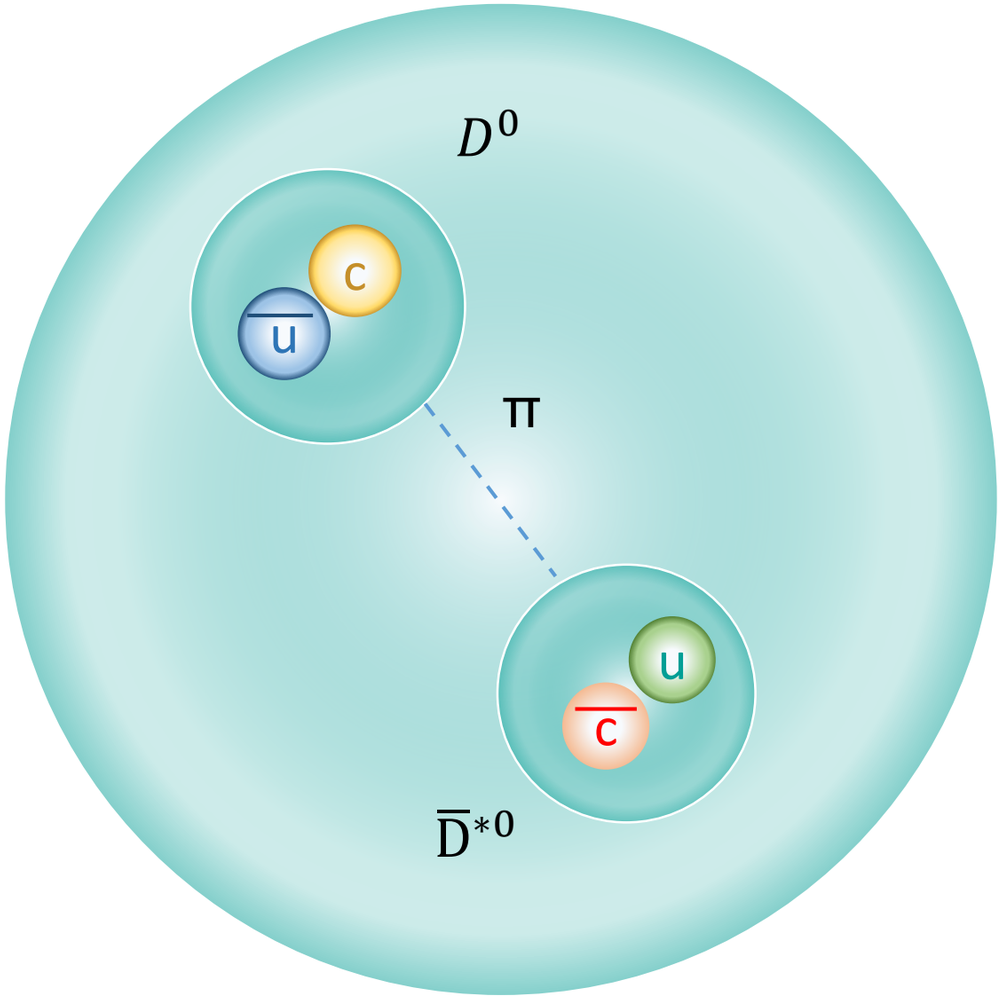
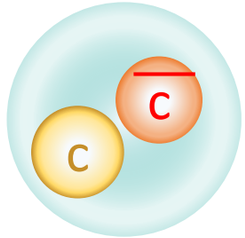


Charmonium



Systematical Uncertainties

	$N(\psi(2S))$	$N(\chi_{c1}(3872))$	$N(\chi_{c1}(3872))/N(\psi(2S))$
Yield Extraction	3.5%	4.3%	5.5%
Acceptance	1.8%	0.6%	1.9%
Efficiency	27.4%	43.1%	38.1%
p_T Shape	12.4%	2.9%	12.8%
TnP	+5.4%	+5.2%	+0.1%
	-5.0%	-4.8%	-0.2%
Prompt Fraction	22.4%	10.5%	15.4%
Total	+38.1%	+44.8%	+43.2%
	-38.0%	-44.8%	-43.2%

Monte Carlo, Muon and Charged Track Selection

- **MC** Signal samples:

  (Prompt / Nonprompt) X(3872)→J/ψ(μμ)ρ(ππ)

  (Prompt / Nonprompt) ψ(2S)→J/ψ(μμ)ππ

  PYTHIA8 (CP5) embedded in HYDJET (tune Drum5F)

  $\hat{P}_T$ > 5, 10, 15, 30, 50 GeV

- **Muon Selections**

  Muon ID: Hybrid-soft

  Muon acceptance selections

  Muon trigger matching

- **Track Selections**

  highPurity

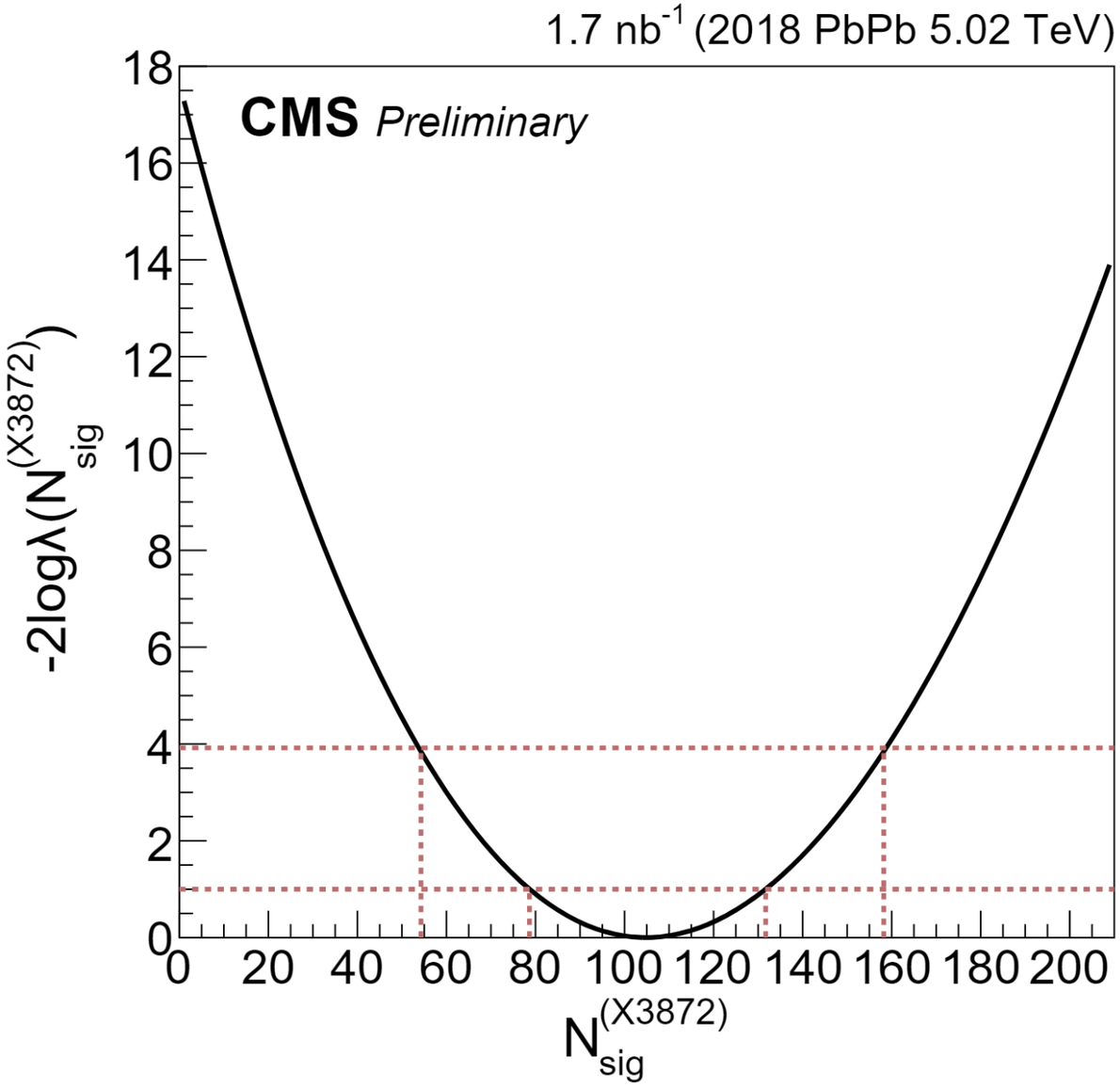
  p_T > 0.9 GeV/c → nHit ≥ 11

  |η| < 2.4

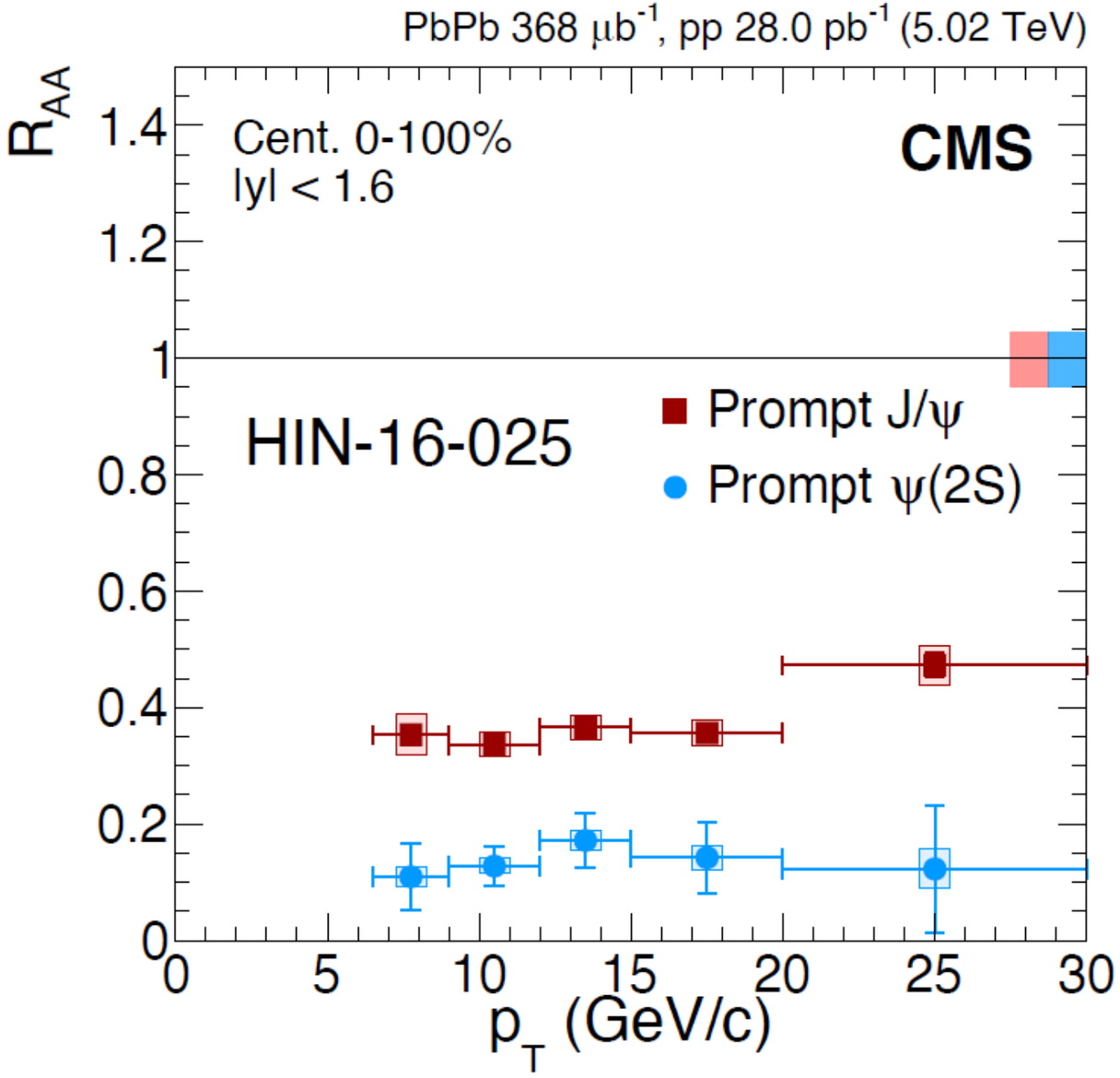
  $\sigma(p_T) / p_T < 0.1$

  χ^2/ndof/nLayers < 0.18

Likelihood vs. Number of X(3872) Signals



Charmonia Nuclear Modification Factors in PbPb



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