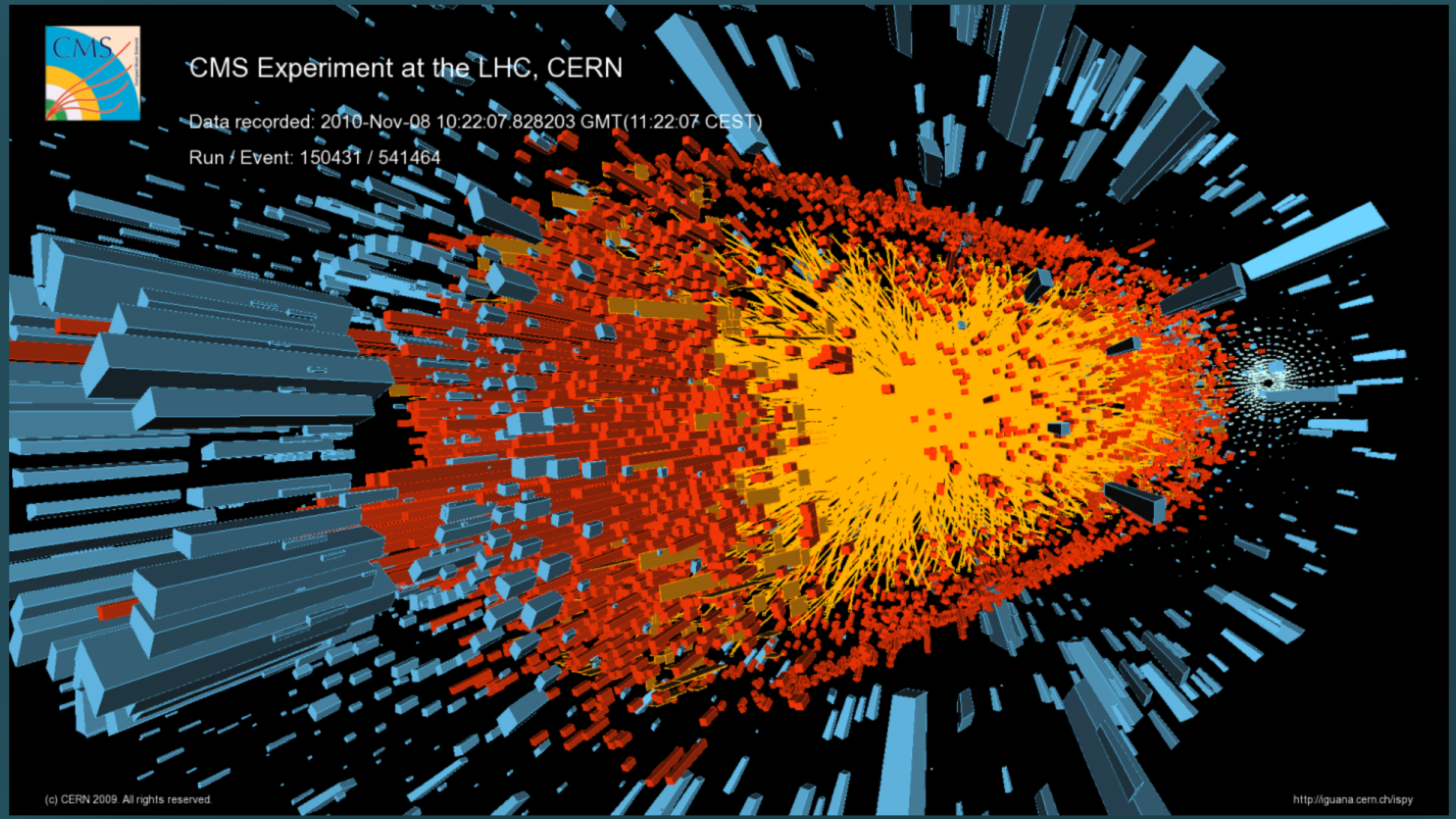
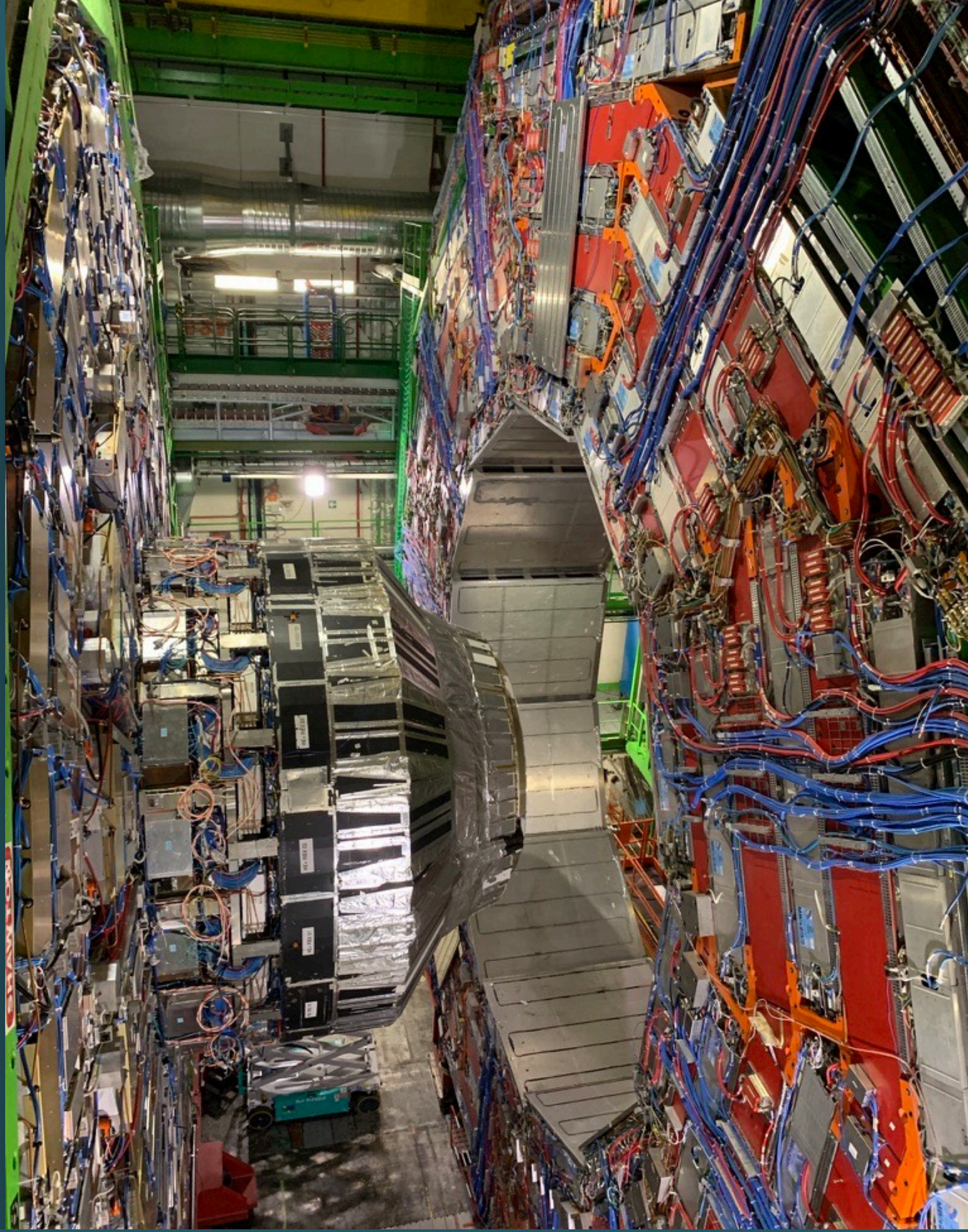
X(3872) in pp and Heavy Ions Data

Daniele Fasanella (CERN) on behalf of the **CMS** Collaboration

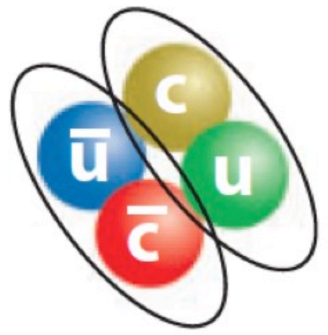




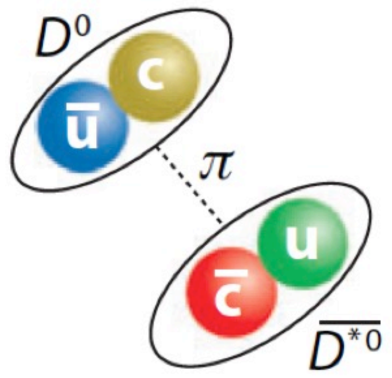
Beauty2020: 19th International Conference on B-Physics at Frontier Machines, 21-24 Sep 2020

The X(3872)

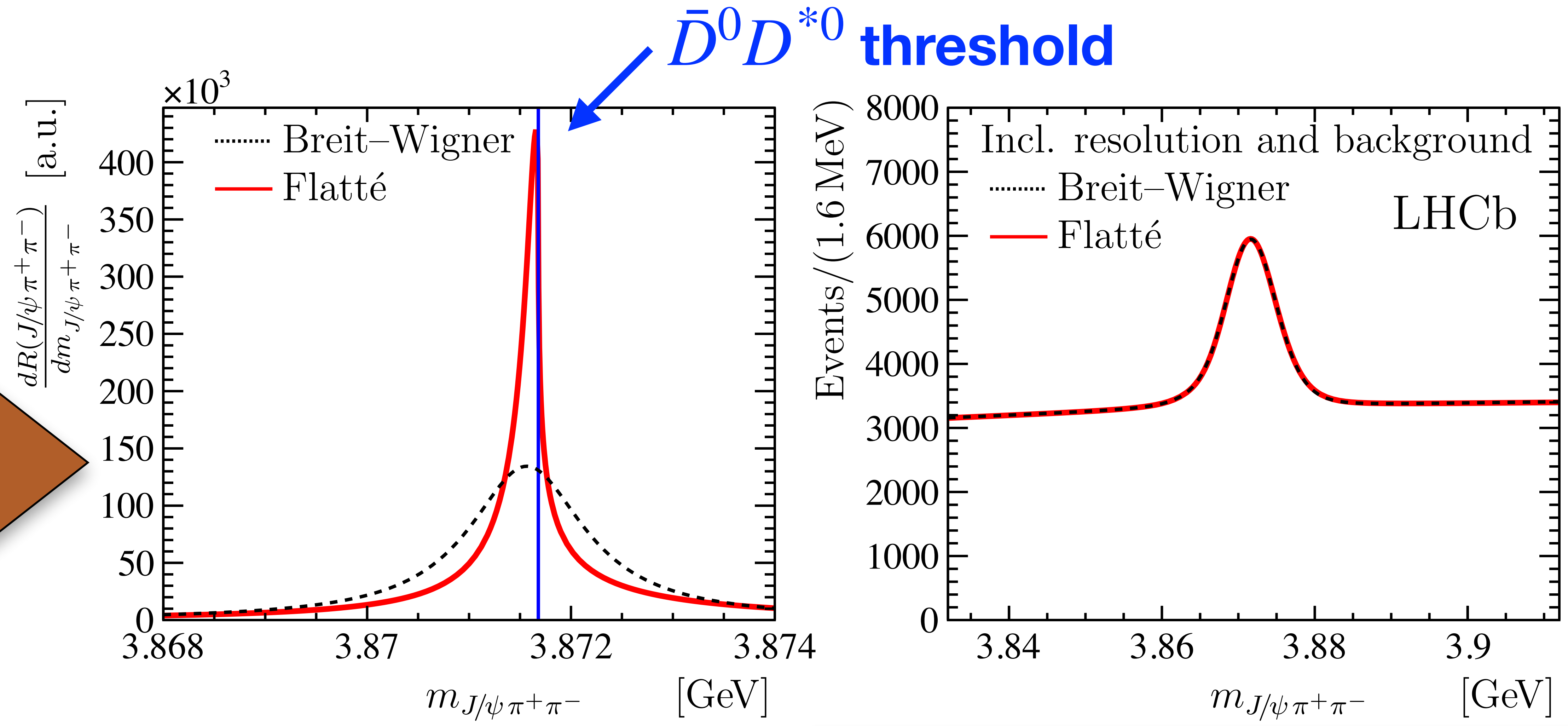
- Discovered by Belle (PRL 91, 262001 2003) in 2003 in the decay: $B \to K\,X(3872) \to K\left(J/\psi\pi^+\pi^-\right)$
- First **"exotic"** states: narrow peak with a mass strikingly on the $\bar{D}^0 D^{*0}$ threshold and incompatible with the standard charmonium expected value
- Quickly confirmed in protons collision at Tevatron and at LHC
- In 2013 LHCb measured the quantum numbers: $J^{PC} = 1^{++}$
- Nowadays open debated on X(3872) structure:
  - A compact (~1fm) diquark-anti-diquark 4q state



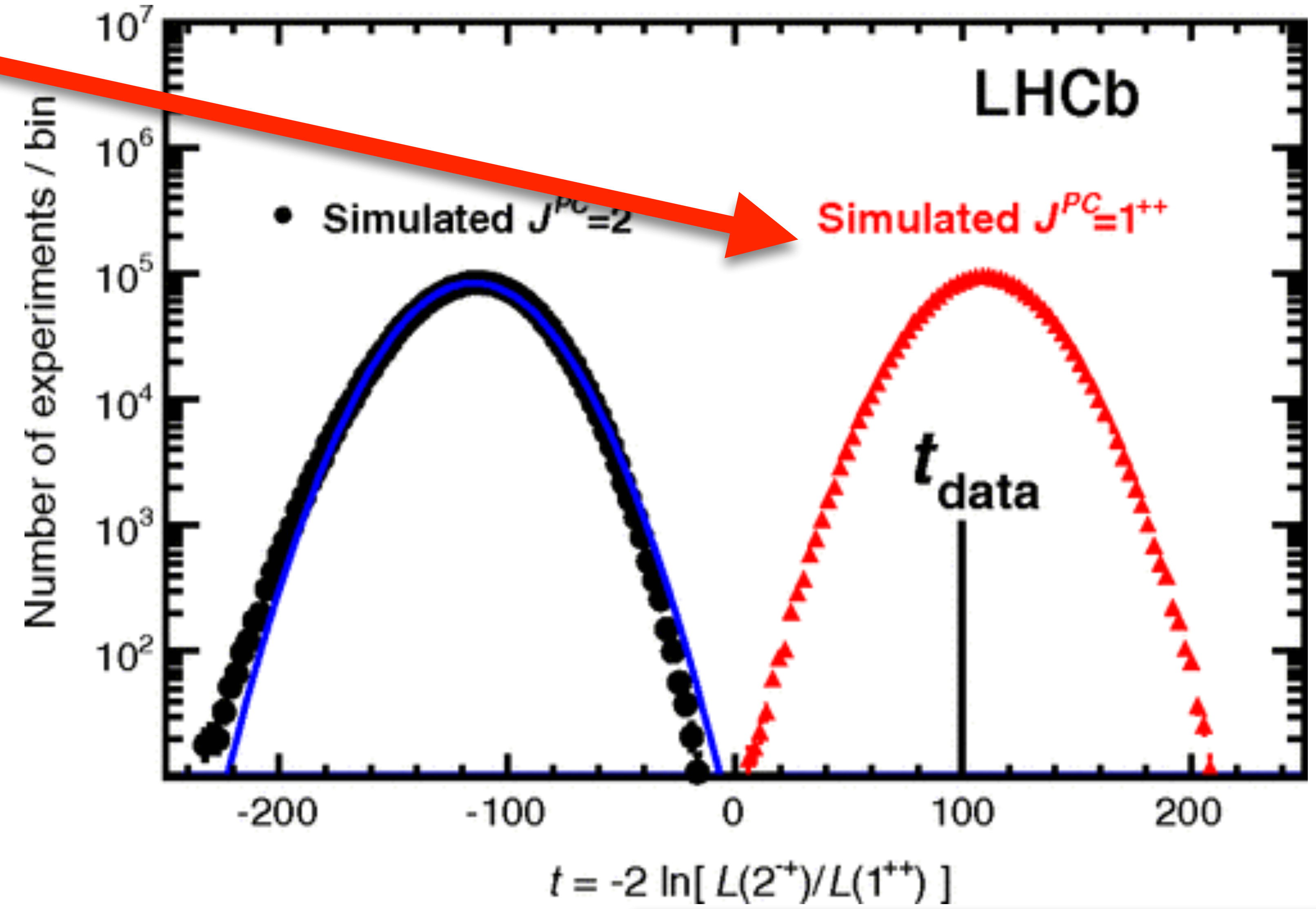
  - $\bar{D}^0 D^{*0}$ hadron molecule (loosely bound ~10 fm)



  - Quantum mixture of an hadron molecule and a charmonium state: $\bar{D}^0 D^{*0} + c\bar{c}[\chi_{c1}(2^3P_{1++})]$



LHCb: arXiv:2005.13419 (2020)

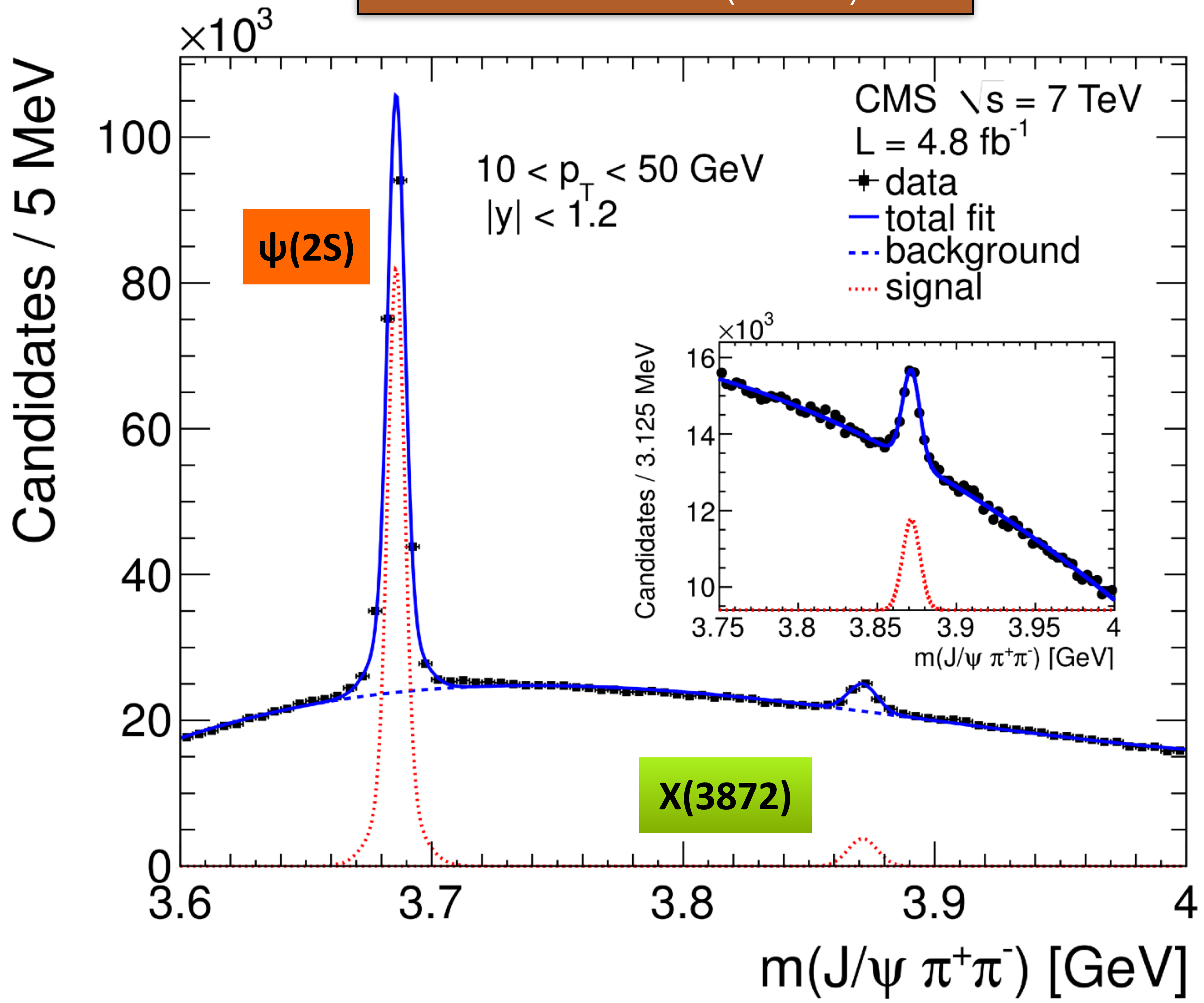


LHCb: PRL 110 (2013) 222001

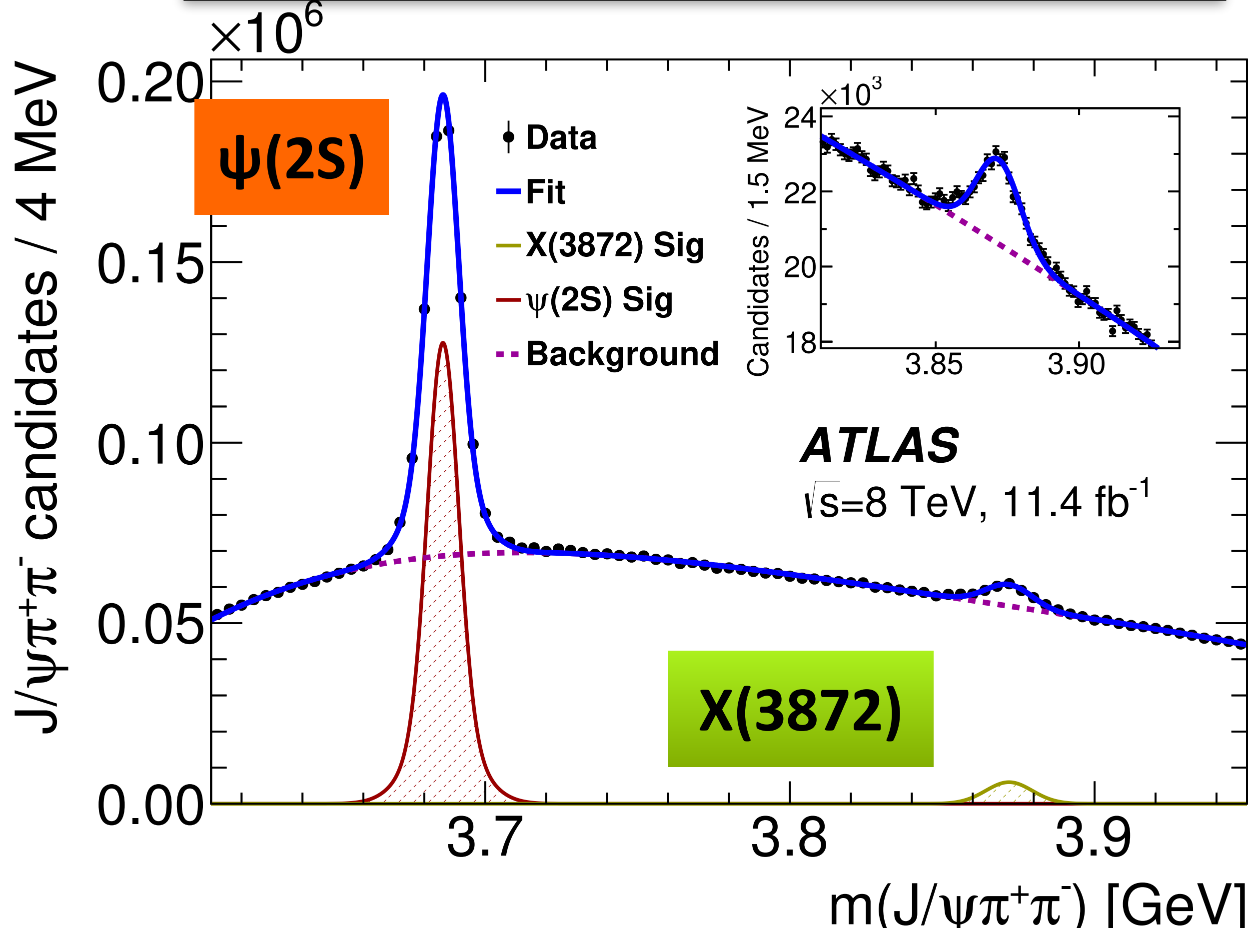
X(3872) at CMS

- CMS reconstructed ~**12.000** X(3872) in $J/\psi(\rightarrow\mu^+\mu^-)\pi^+\pi^-$ with 4.8 fb^{-1} of 7 TeV pp data collected in 2011
- Studied:
  - Non-prompt component vs p_T
  - Cross section ratio w.r.t. ψ(2S)
  - Prompt X(3872) cross section
  - Invariant mass distribution of the ππ system
- Results still relevant and compared to most recent publications from ATLAS and D0

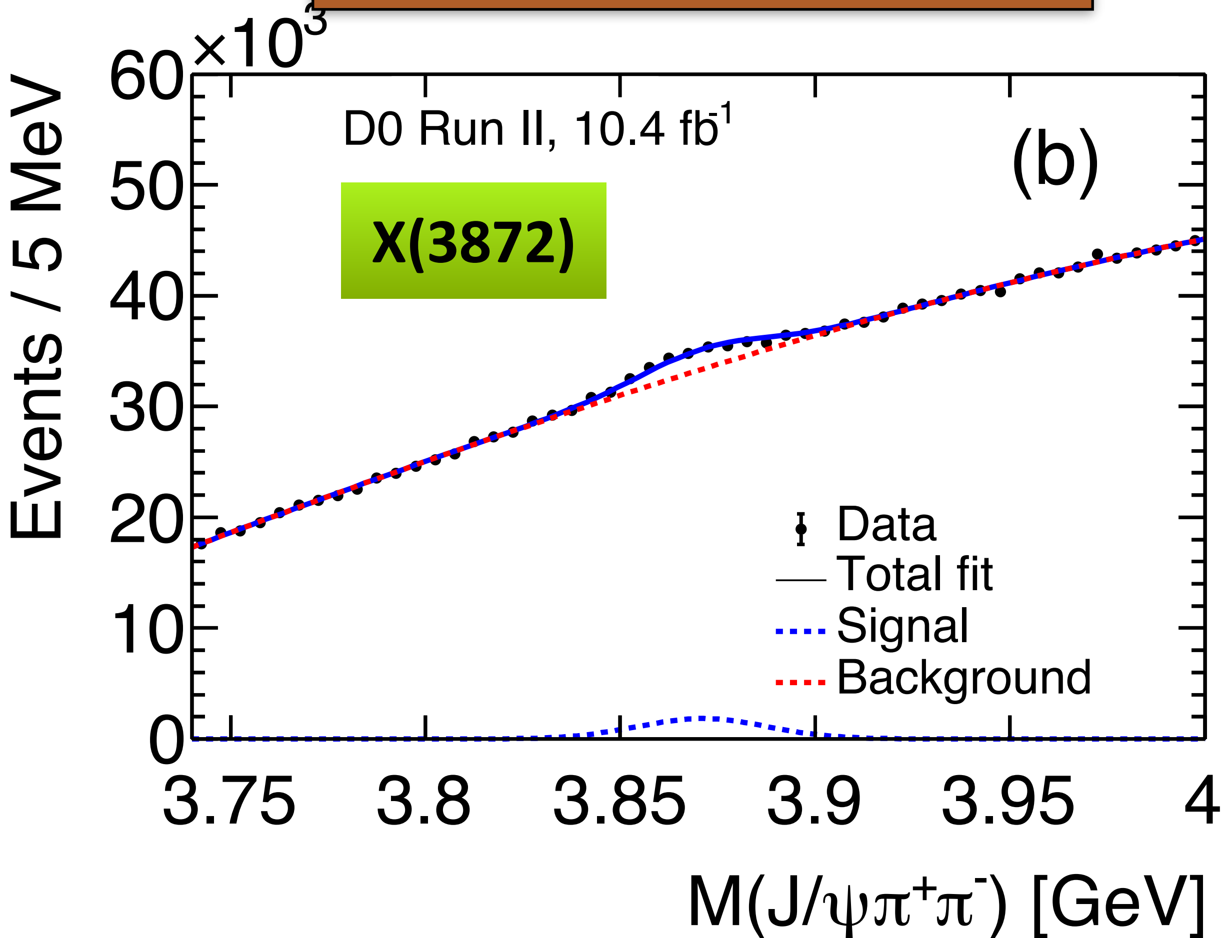
CMS: JHEP 04 (2013) 154



ATLAS: JHEP 01 (2017) 117



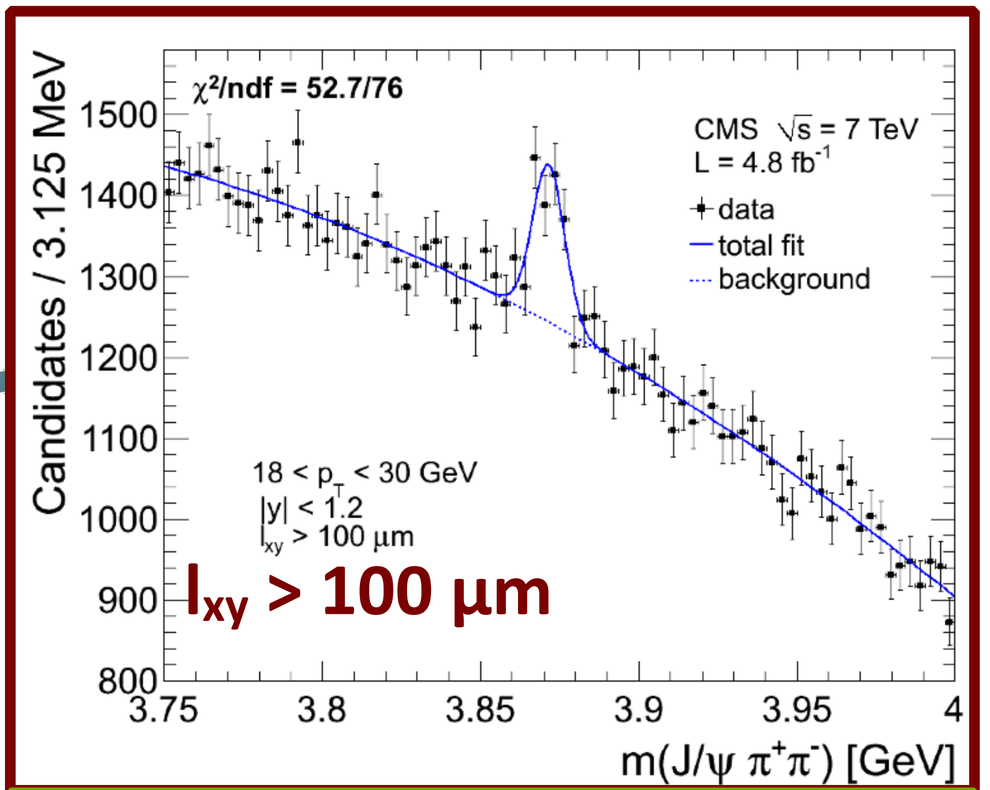
D0: arXiv:2007.13420

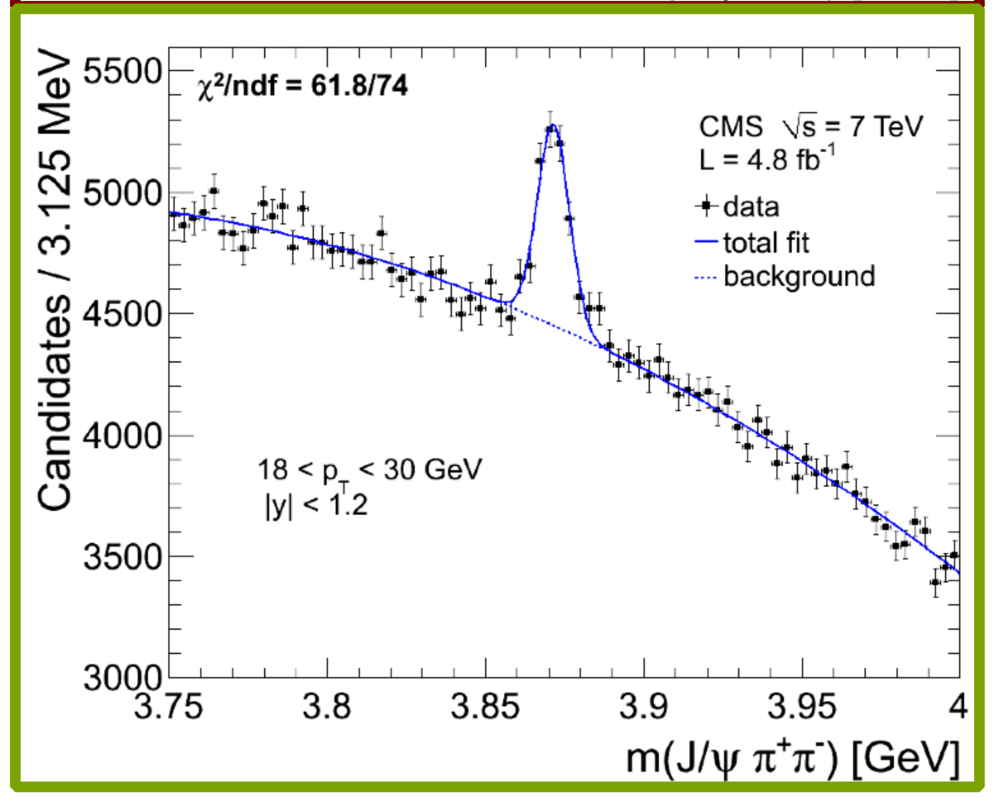


Signal reconstruction in CMS:

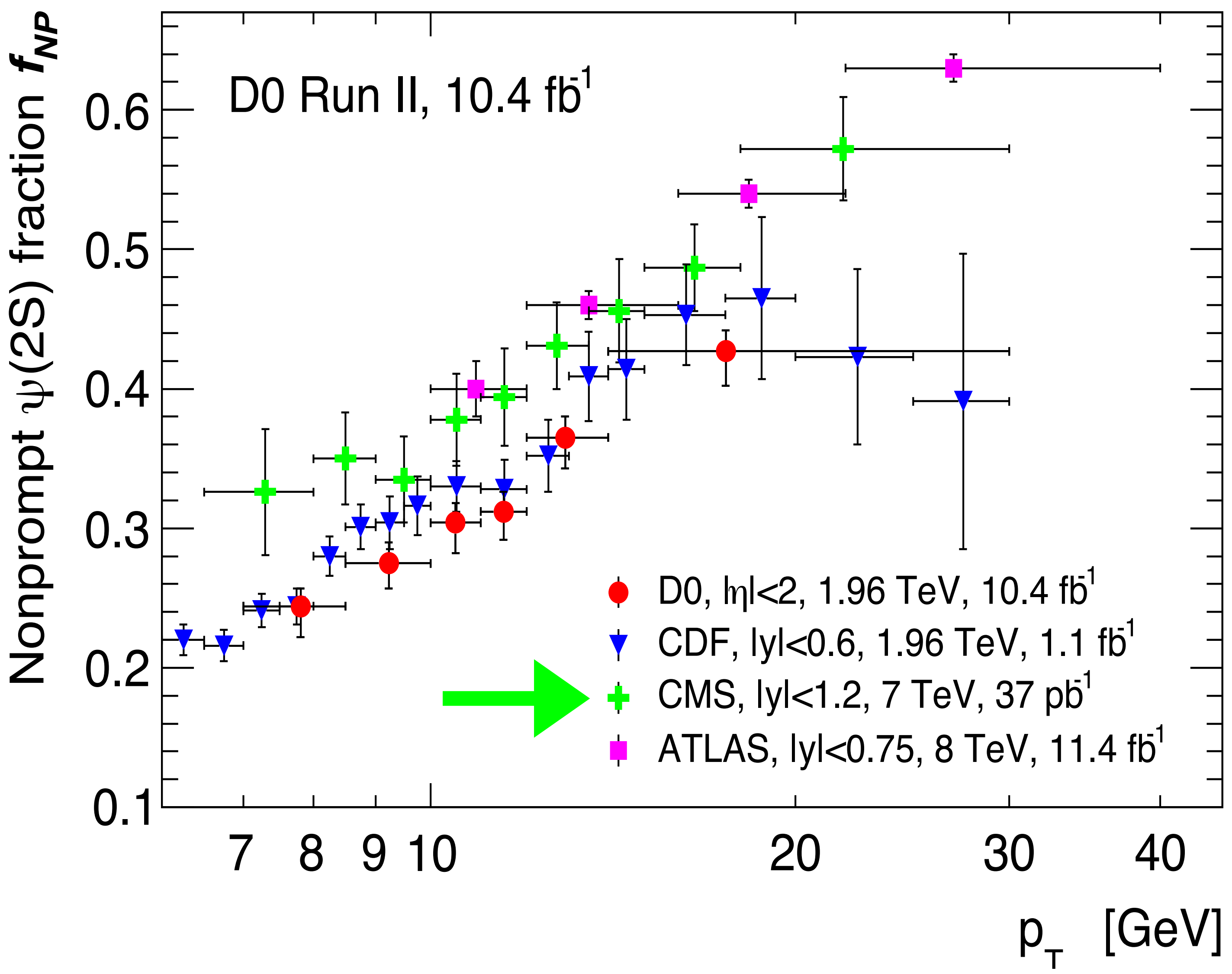
- 2 μ with p_T > 4GeV coming from J/ψ in the central region of the detector ($|y(\mu^+\mu^-)| < 1.25$).
- 2 tracks with opposite charge and p_T > 600 MeV
- combination of these four tracks with constraint on common vertex.
- selection on common vertex probability, angular distance between J/ψ and π, Q value [$M_{\pi\pi\mu\mu}-M_{J/\psi(PDG)}-M_{\pi\pi}$].

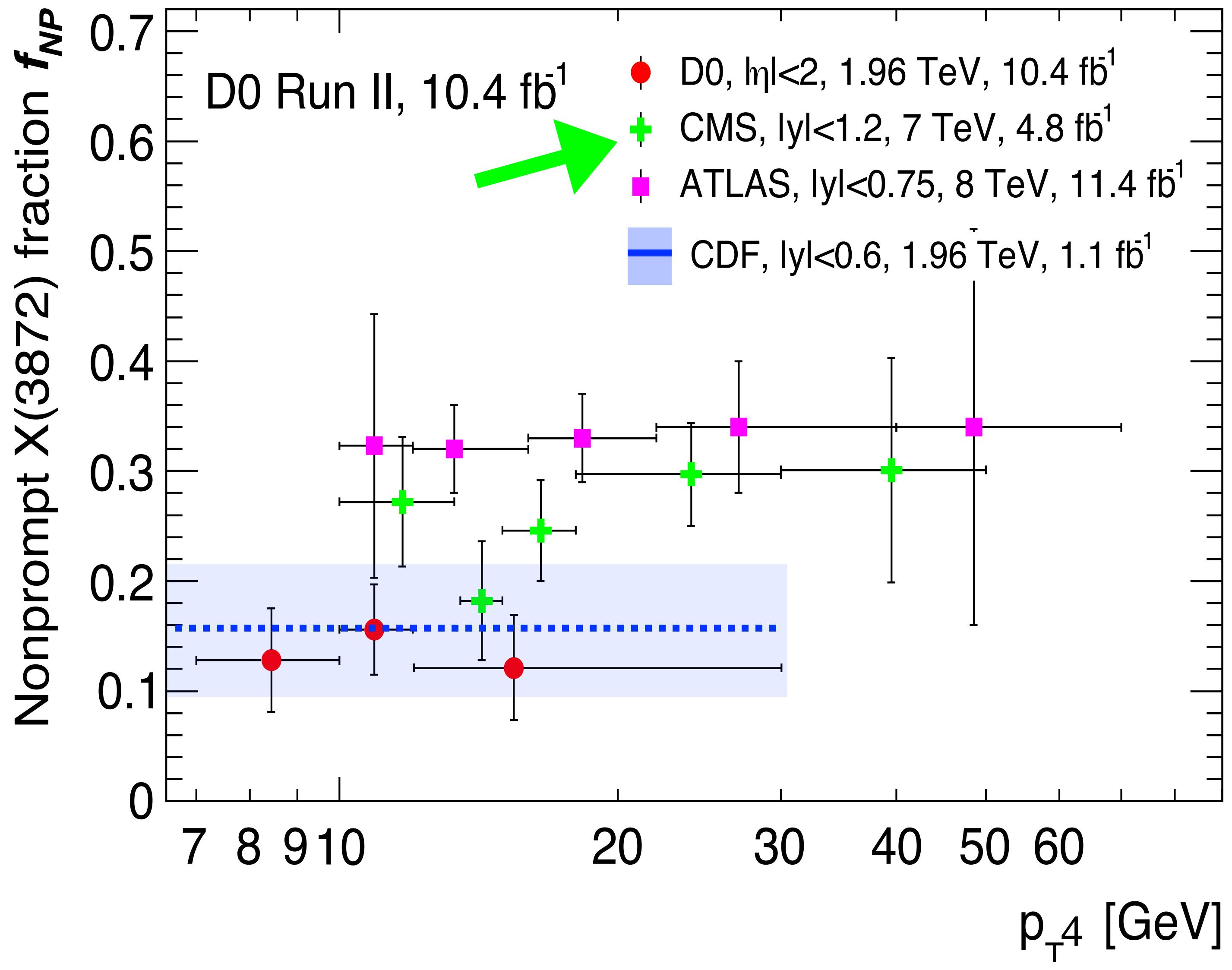
Non prompt fraction (f_{NP})





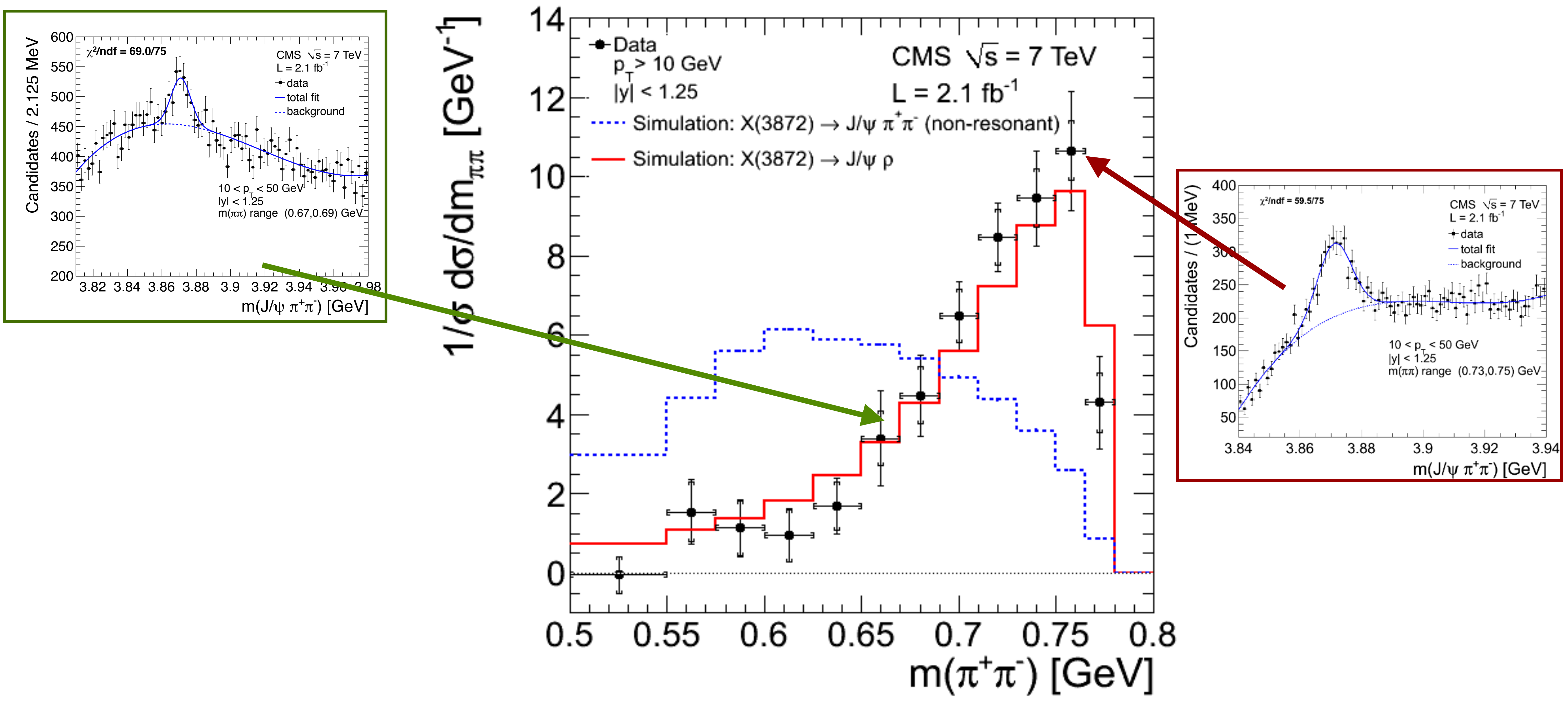
- Non prompt X(3872) comes from decays of B hadrons in a secondary vertex related to the **decay length (l_{xy})** of the B meson.
- Events with X(3872) from B decays are selected by requiring **l_{xy} > 100 µm**
  - X(3872) prompt fraction with l_{xy} > 100 µm is negligible (<0.1%)
  - **First study of the p_T dependence of f_{NP}**
- Measurement dominated by statistics: ~20% stat., 6-10% syst. for each p_T interval
- Same study performed by ATLAS and D0 with a full fit of the l_{xy} distribution
- Compatible results:
  - For ψ(2S) f_{NP} increases as a function of p_T whereas those for X(3872) are consistent with being independent of p_T
  - f_{NP} for X(3872) seems more dependent on the collision energy than for ψ(2S)



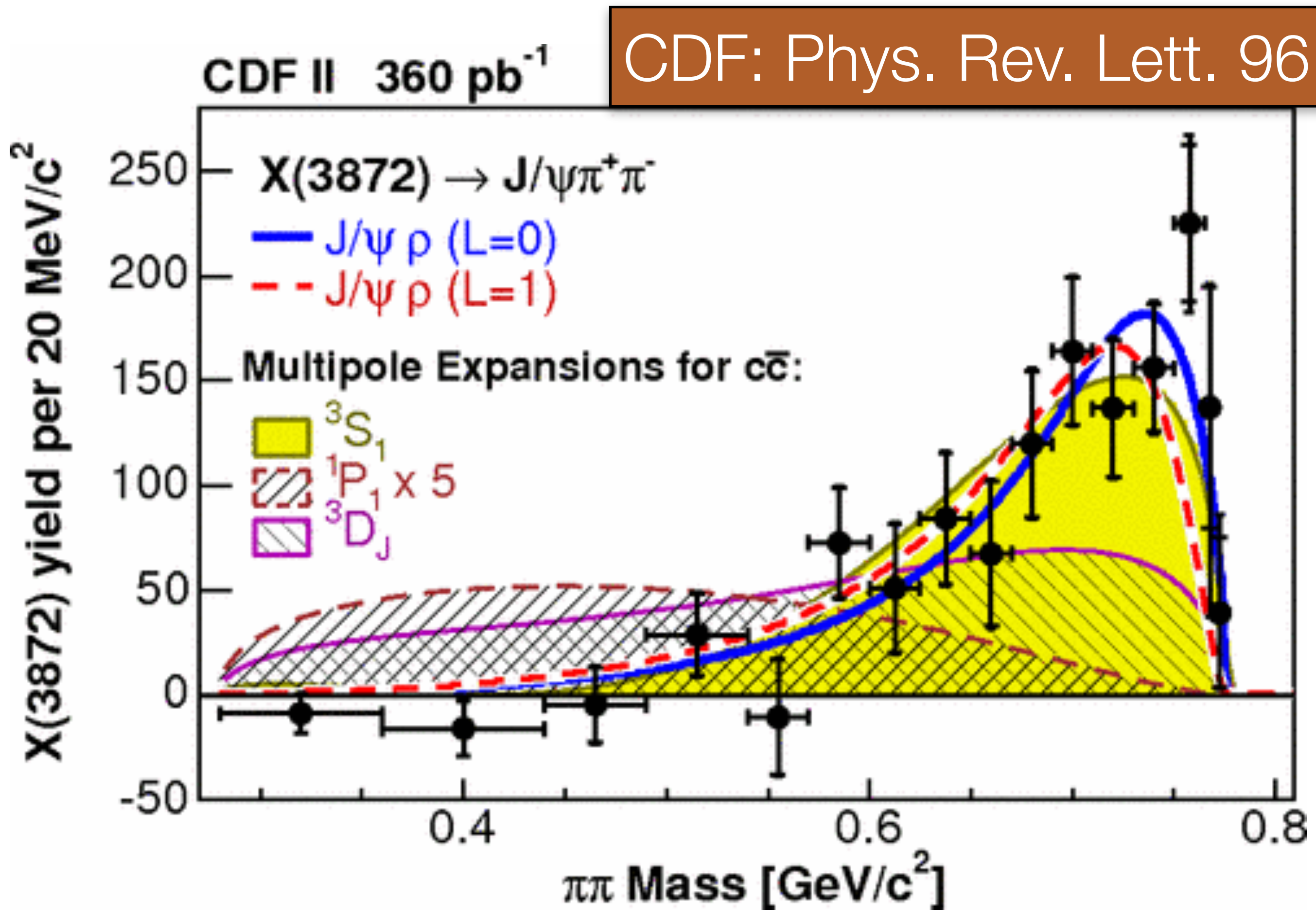


Invariant mass distribution of the ππ system

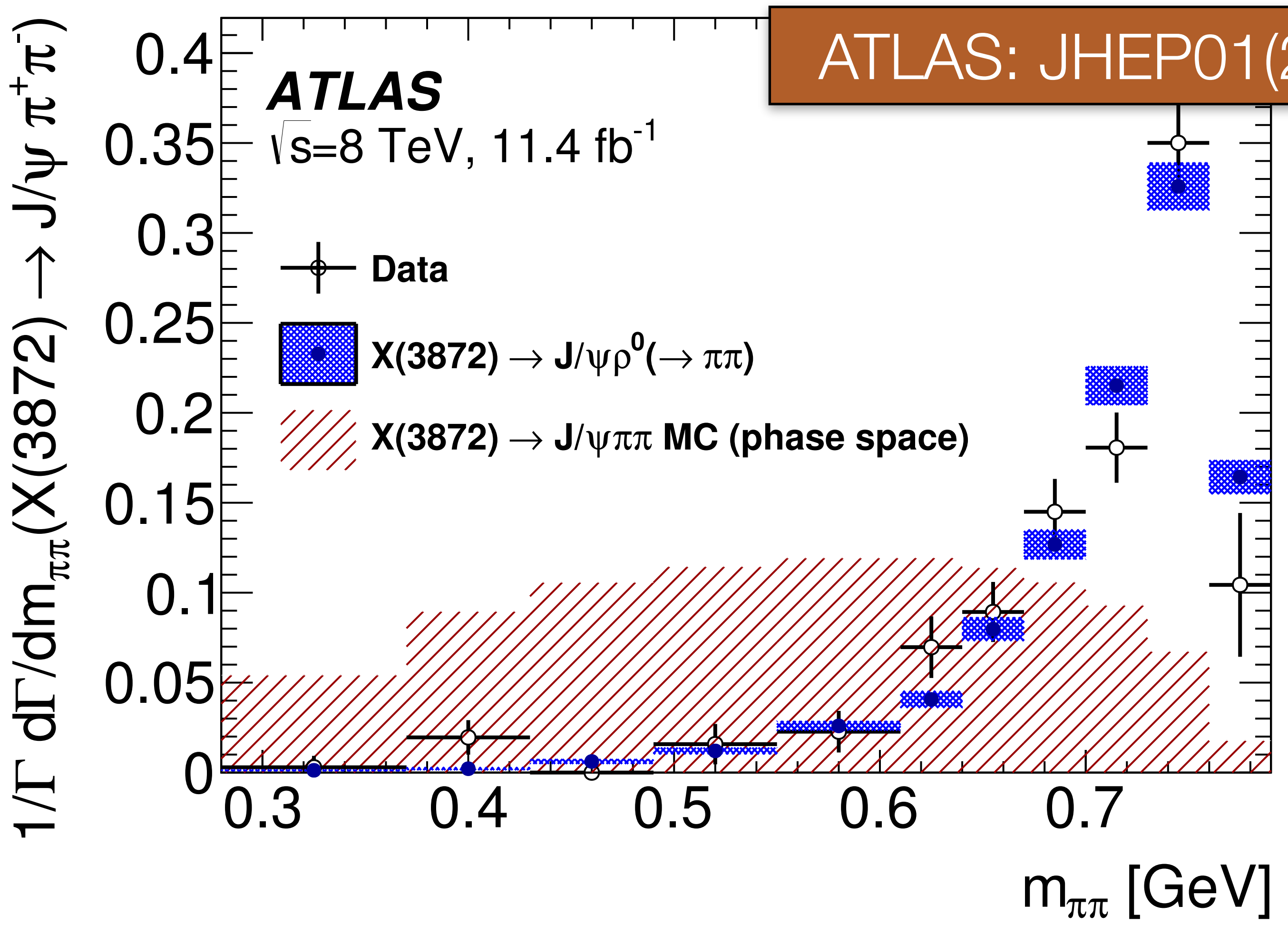
- Studies at CDF and Belle suggested that X(3872) decays in J/ψ and ρ^0
- CMS Event sample divided into **$m(\pi^+\pi^-)$** intervals and X(3872) yields extracted from fits to **$m(J/\psi\ \pi^+\pi^-)$**
- **The spectrum obtained from data is compared to simulations with and without an intermediate ρ**



CDF: Phys. Rev. Lett. 96, 102002 (2006)



ATLAS: JHEP01(2017)117



- **The assumption with the ρ^0 gives better agreement with the data.**
  - **Confirmation of CDF result**
  - **Same agreement found by ATLAS**

X(3872) Cross Section Measurements

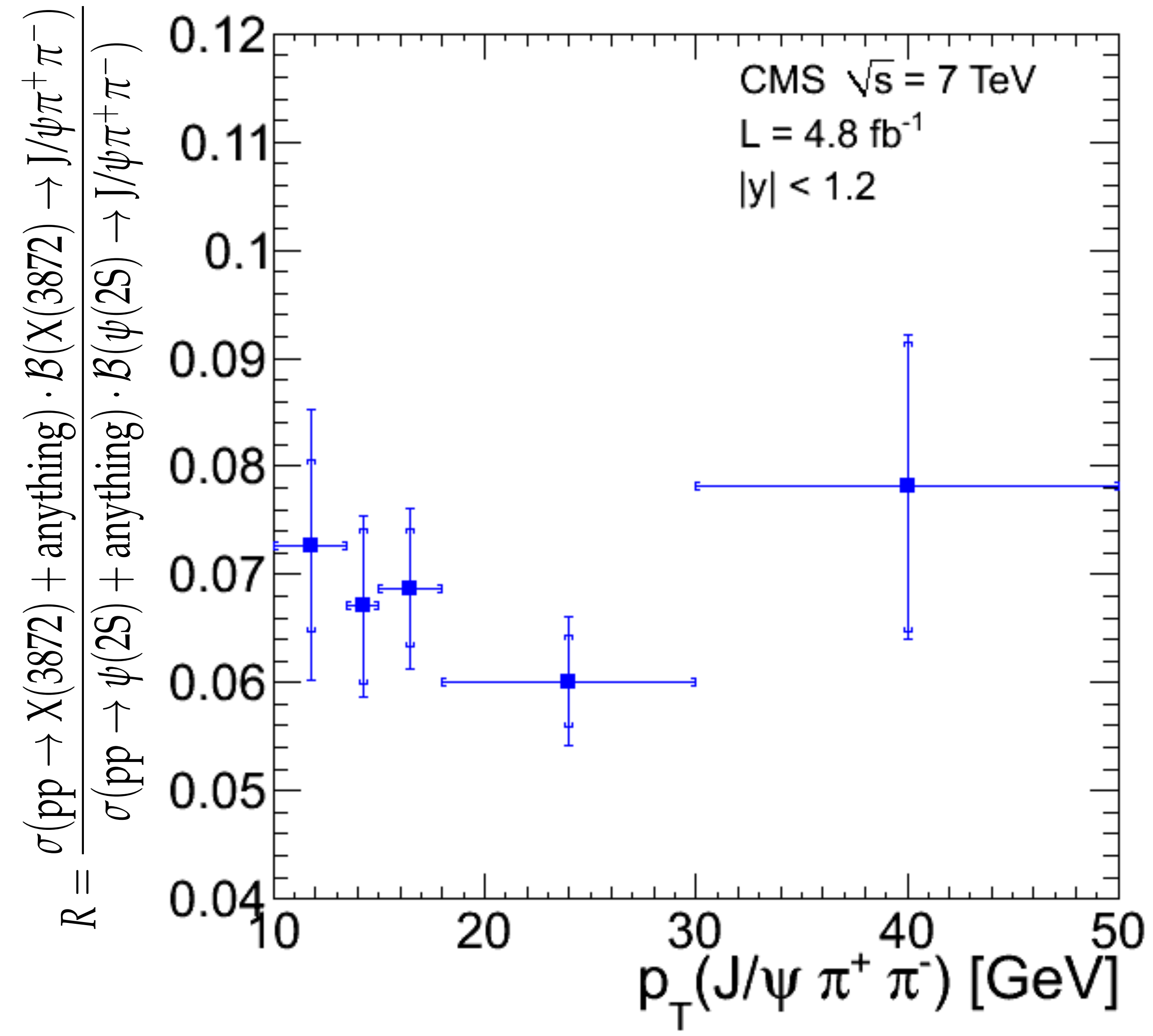
- CMS measured the cross section ratio to the ψ(2S) to cancel out many systematic sources
- The ratio showed **no significant dependence on the p_T** of the J/ψ $\pi^+\pi^-$ system
- Using the measured f_{NP} we gave also the prompt X(3872) cross section x BR:

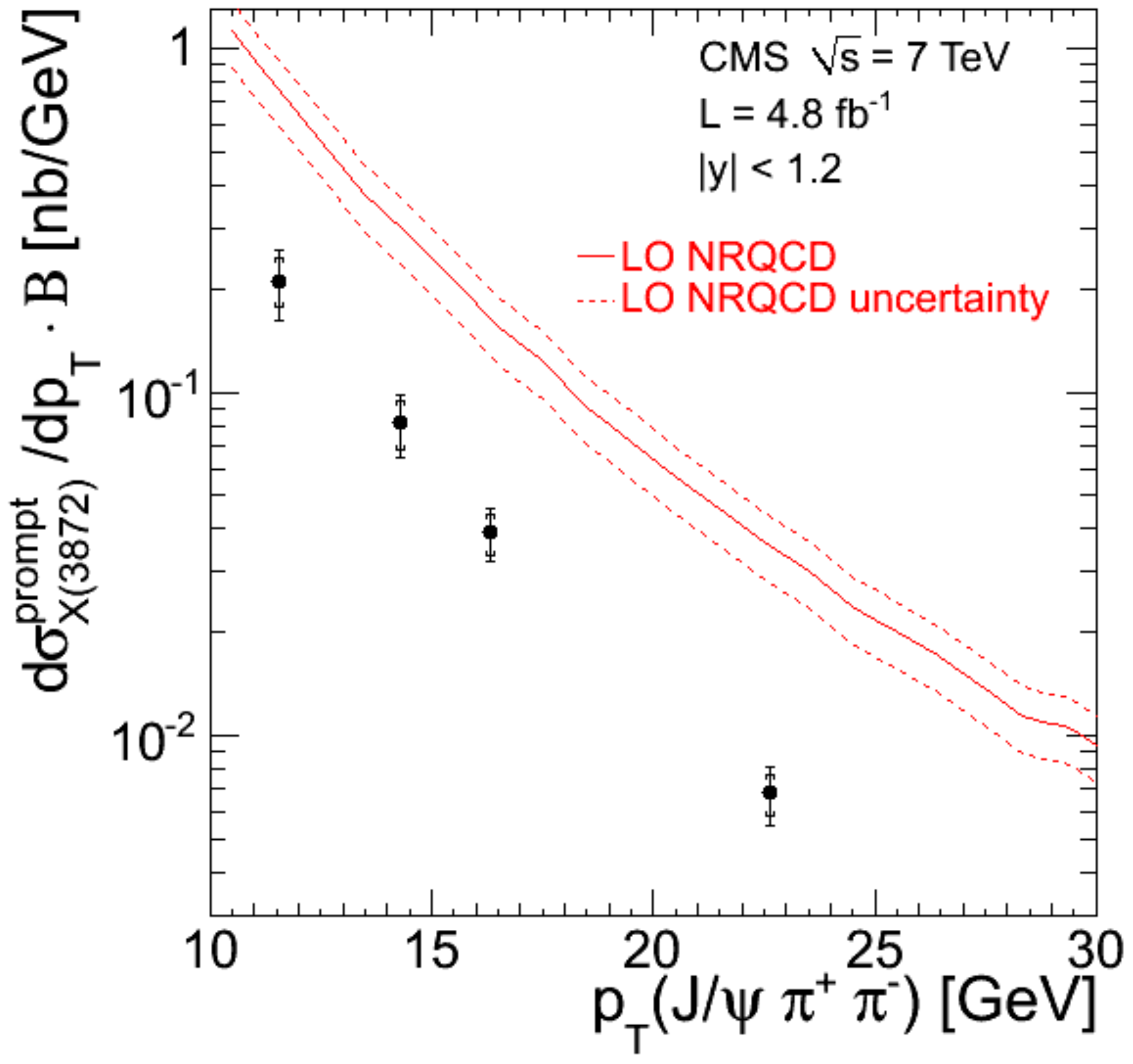
Non prompt fraction

Measured by CMS in JHEP 02 (2012) 011

From PDG
BR in muons = BR in electrons

$$\sigma^{\text{prompt}}_{X(3872)} \cdot \mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-) = \frac{1-f^B_{X(3872)}}{1-f^B_{\psi(2S)}} \cdot R \cdot \left(\sigma^{\text{prompt}}_{\psi(2S)}\cdot \mathcal{B}(\psi(2S)\to\mu^+\mu^-)\right)\cdot \frac{\mathcal{B}(\psi(2S)\to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S)\to\mu^+\mu^-)}$$

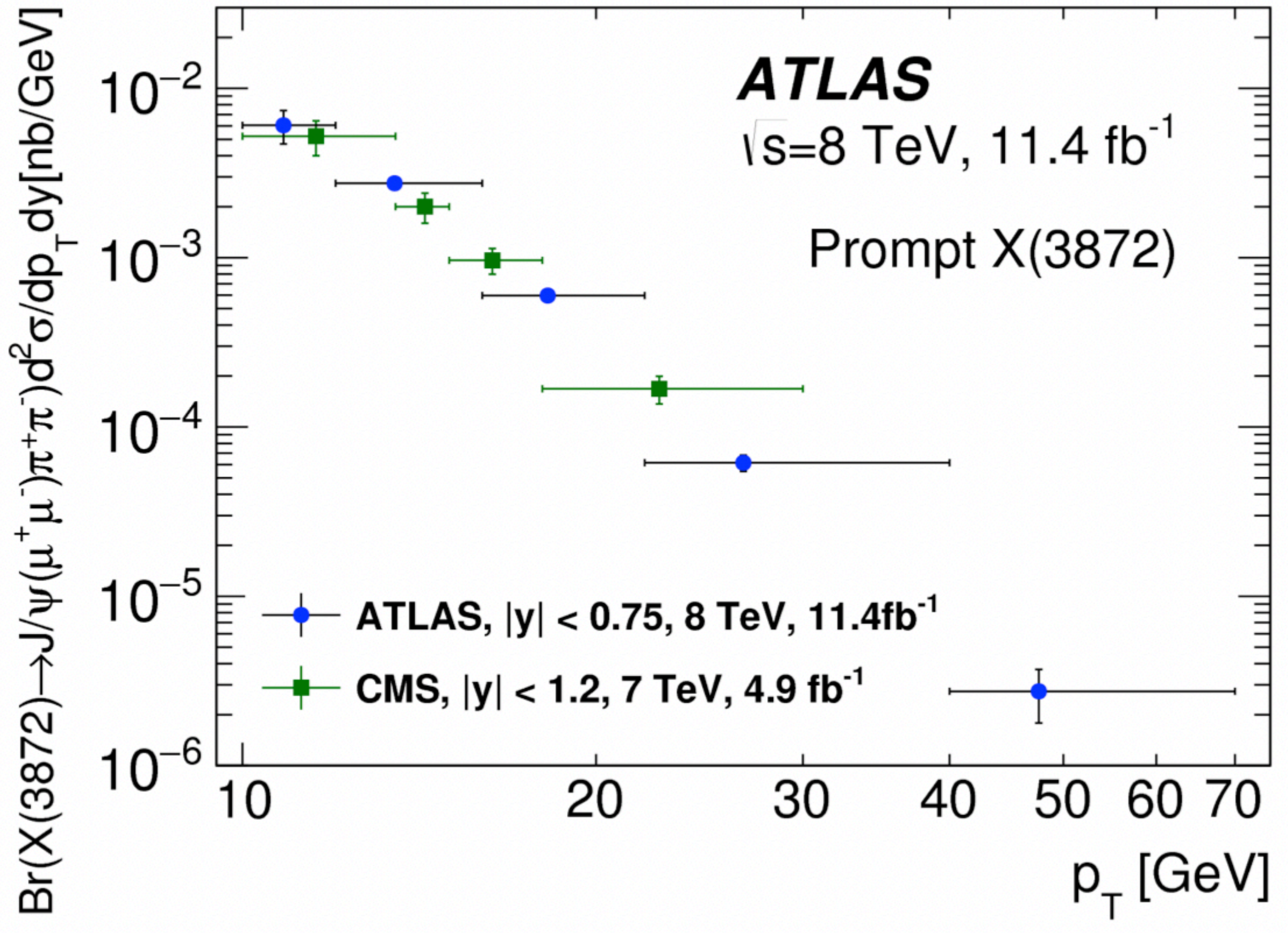




- This results are compared with a theoretical prediction, within an S-wave molecular model, by Artoisenet & Brateen **[PhysRevD.81.114018]** with calculations normalised using Tevatron results, modified by the authors to match the phase-space of the CMS measurement
- The shape is reasonably well described by the theory while the predicted cross-section is overestimated by over 3 σ
  - measurement is not supporting an S-wave molecular interpretation

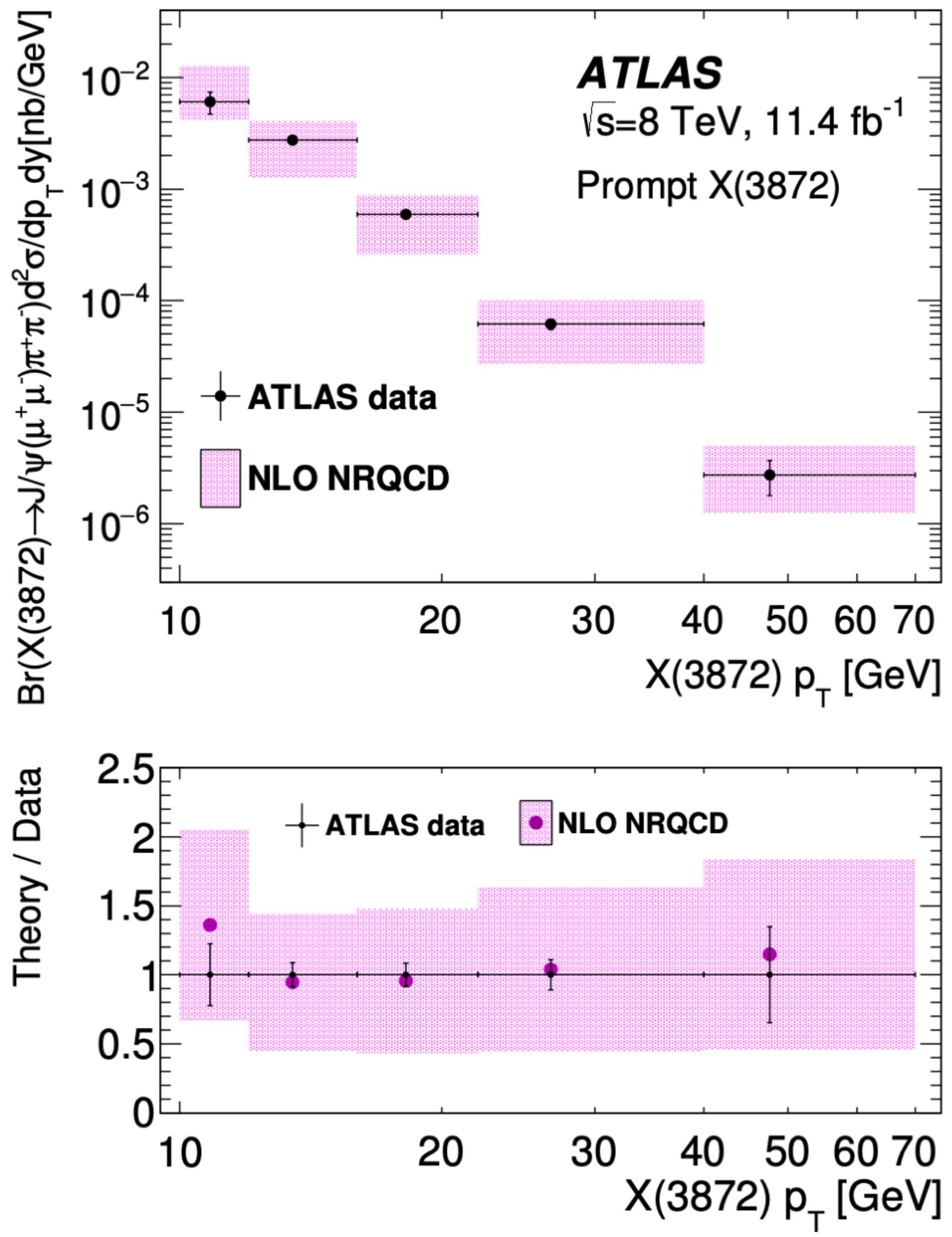
Prompt X(3872) Cross Section

- **CMS** measurement resulted consistent with **ATLAS**, considering that:
  - **ATLAS** points positioned at the mean p_T of the weighted signal events
  - **CMS** points positioned at the mean p_T of the theoretical predictions



ATLAS: JHEP01(2017)117

- **ATLAS** compared this distribution to NLO NRQCD predictions assuming the X(3872) modelled as a mixture of $\chi_{c1}(2P)$ and a $\bar{D}^0 D^{*0}$ molecular state by Meng et al. [PRD96 (2017) 074014].
  - $\chi_{c1}(2P)$ would play crucial role in the short-distance production
  - $\bar{D}^0 D^{*0}$ would be mainly in charge of the hadronic decays of X(3872) into DDπ, DDγ as well as J/ψρ and Jψω.
  - normalisation fixed through the fit to CMS data
  - **good agreement is found**

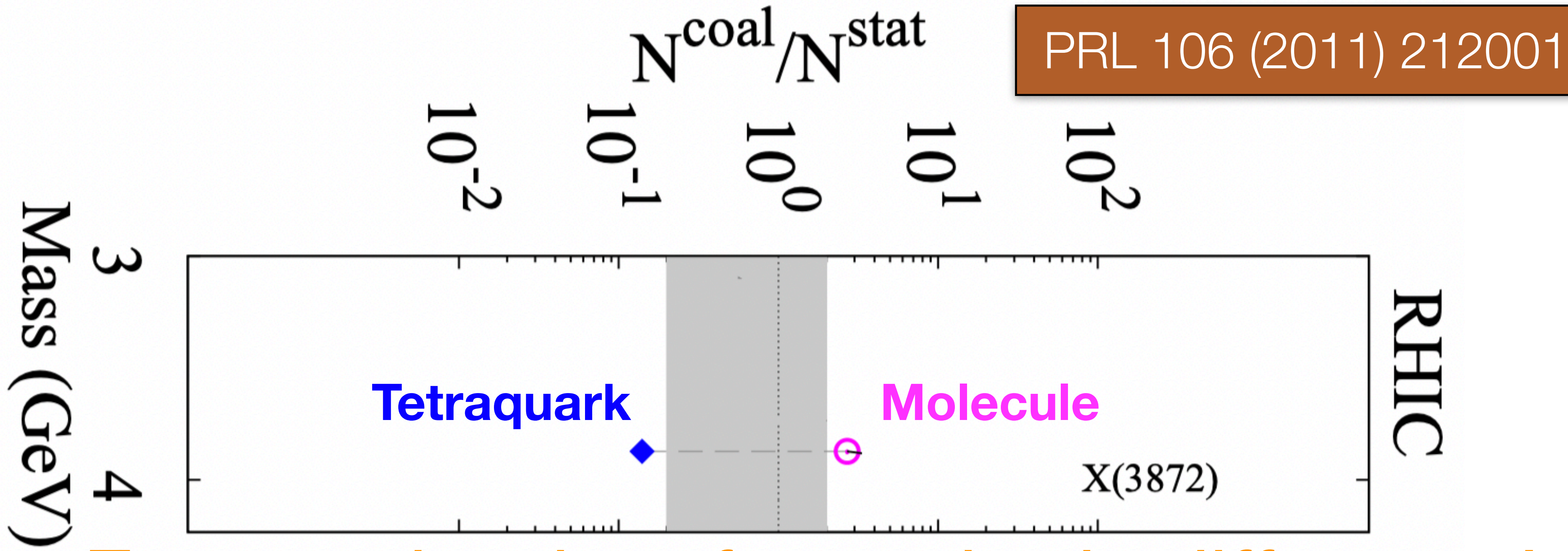


ATLAS: JHEP01(2017)117

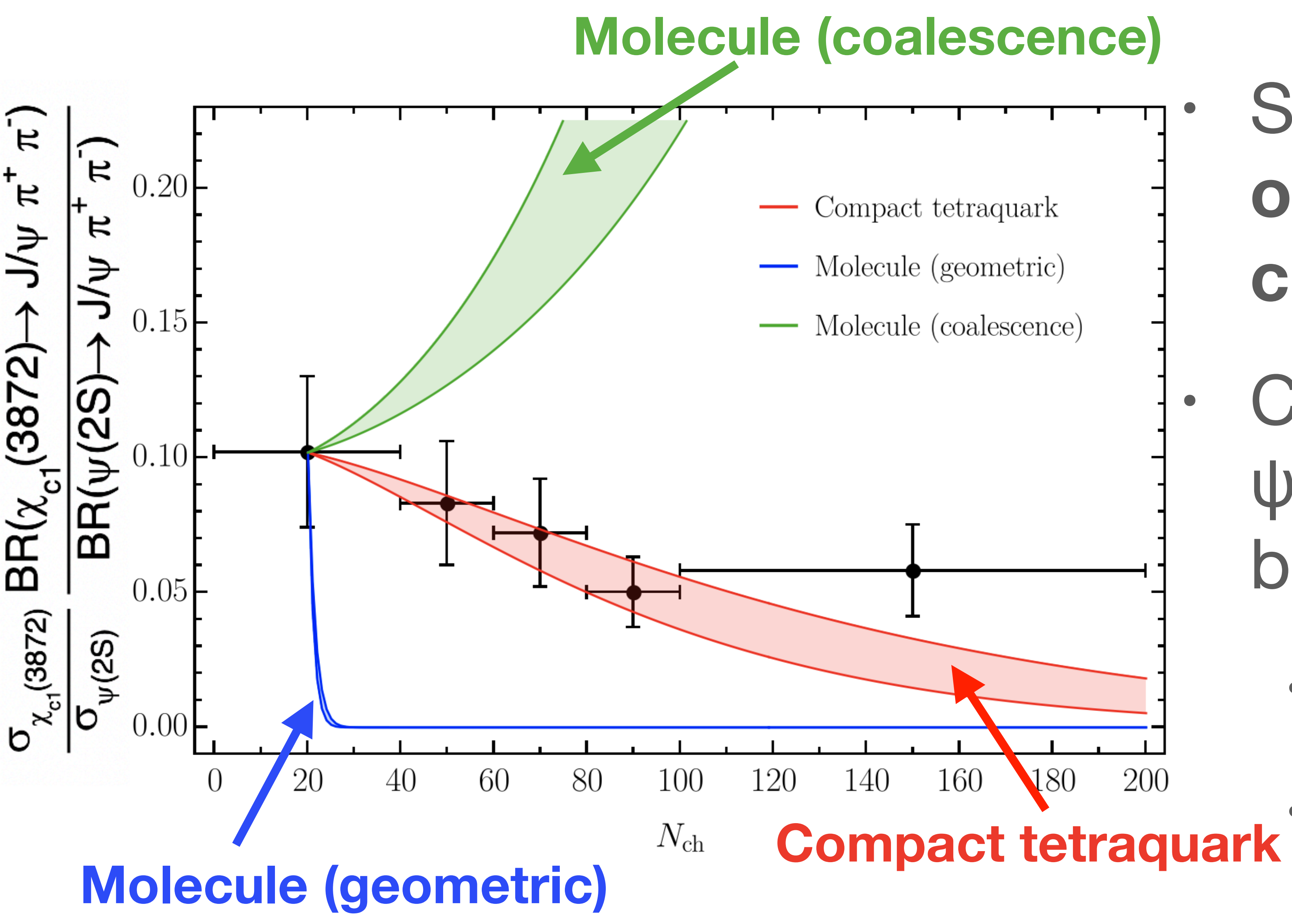
X(3872) in PbPb collisions

CMS-PAS-HIN-19-005

- X(3872) production yield in QGP can help to shred light on its internal structure
  - **Molecule are easier to be produced and destroyed than tetraquark**
- X(3872) production could be enhanced through the quark coalescence mechanism, which could depend on the spatial configuration (size) of this exotic state
- Relevant parameter is the ratio of hadron yields calculated in the coalescence model to those in the statistical hadronization model $\frac{N_{coal}}{N_{stat}}$

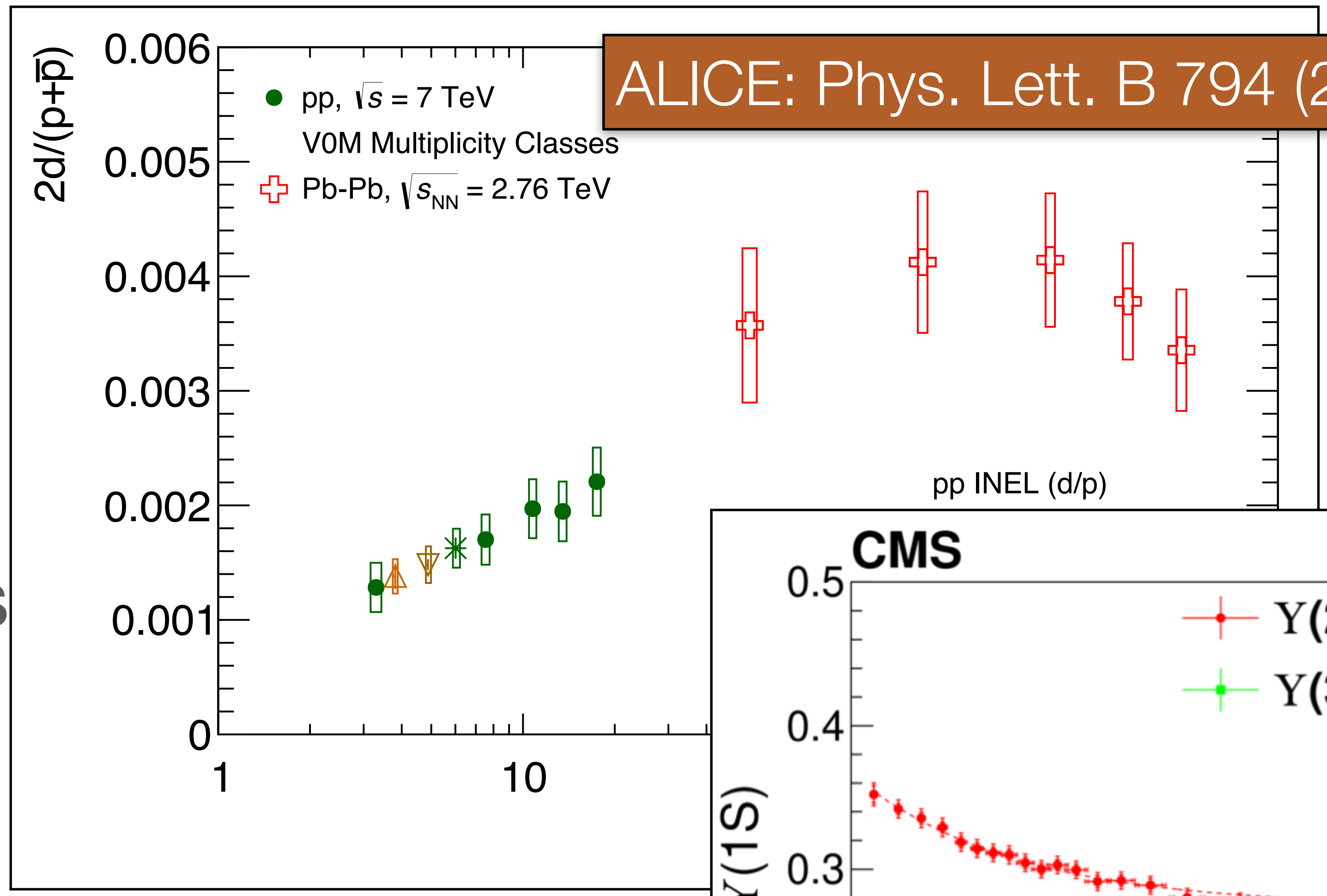


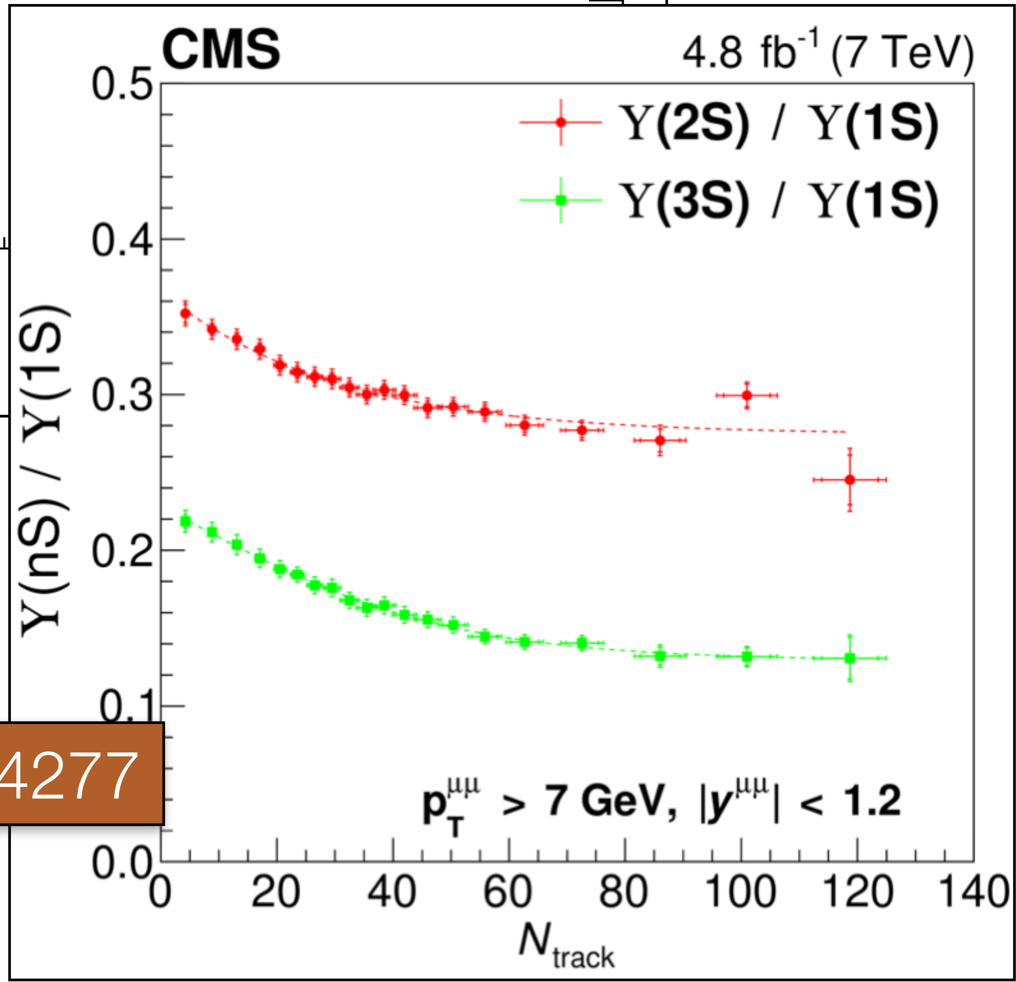
Expected order of magnitude difference!



arXiv:2006.15044v1 and LHCb: CONF-2019-005

- Some hints also coming from **LHCb study of X(3872) production vs Multiplicity in pp collision**
- Cross section decrease of prompt X(3872) vs ψ(2S) at higher multiplicity due to smaller binding energy?
  - ….but Deuteron/proton increases …
  - … while standards in standard quarkonium exited over ground states production decreases…

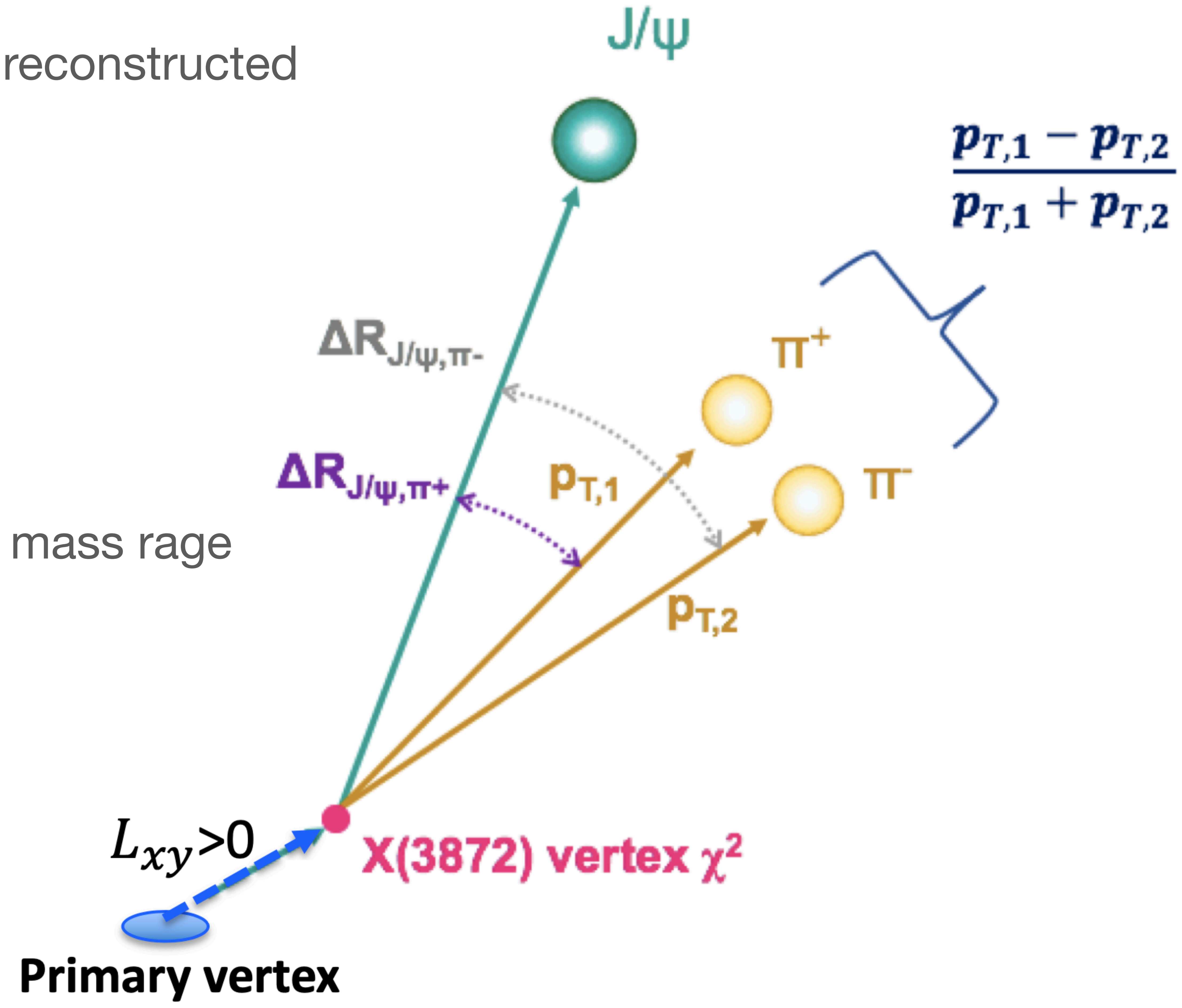




CMS: arXiv:2007.04277

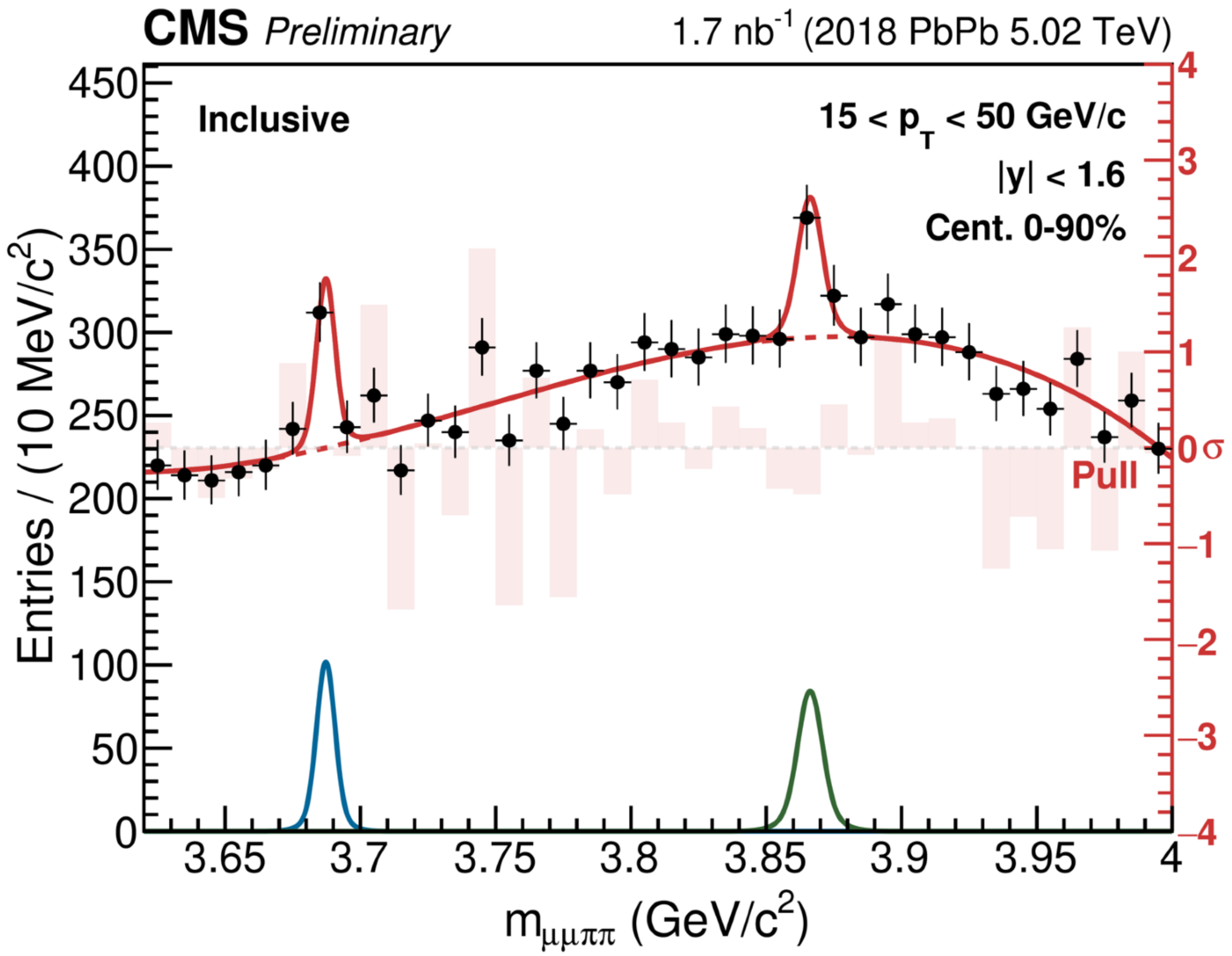
X(3872) in PbPb with CMS

- CMS analysed 1.7 nb^{-1} of PbPb collision at $\sqrt{s} = 5.02$ TeV
  - X(3872) and ψ(2S) with $15 < p_T^X < 50$ GeV and $|y^x| < 1.6$ fully reconstructed in same hadronic decay chain $J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$
  - kept only events with centrality >90%
  - **A boosted decision tree (BDT) algorithm used to suppress the combinatorial background**
    - signal samples are taken from simulation
    - background samples taken from data sidebands of the X(3872) mass rage
    - it uses 5 variables:
      - χ^2 of the 4-tracks vertex
      - p_T balance of the pions $\dfrac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$
      - p_{T2} balance of the slow pions
      - opening angle between J/ψ and p_{T1}
      - opening angle between J/ψ and p_{T2}



First observation of X(3872) in PbPb Collisions

CMS-PAS-HIN-19-005



- **First evidence of X(3872) production in heavy ion collisions!**
  - ➡ **Statistical significance > 3σ**
- A clear ψ(2S) signal to the same final state is also visible
- Raw yields (N^{i}_{raw}) are extracted with a UML fits: 2 Gaussian (from signal MC) + 4th-polynomial

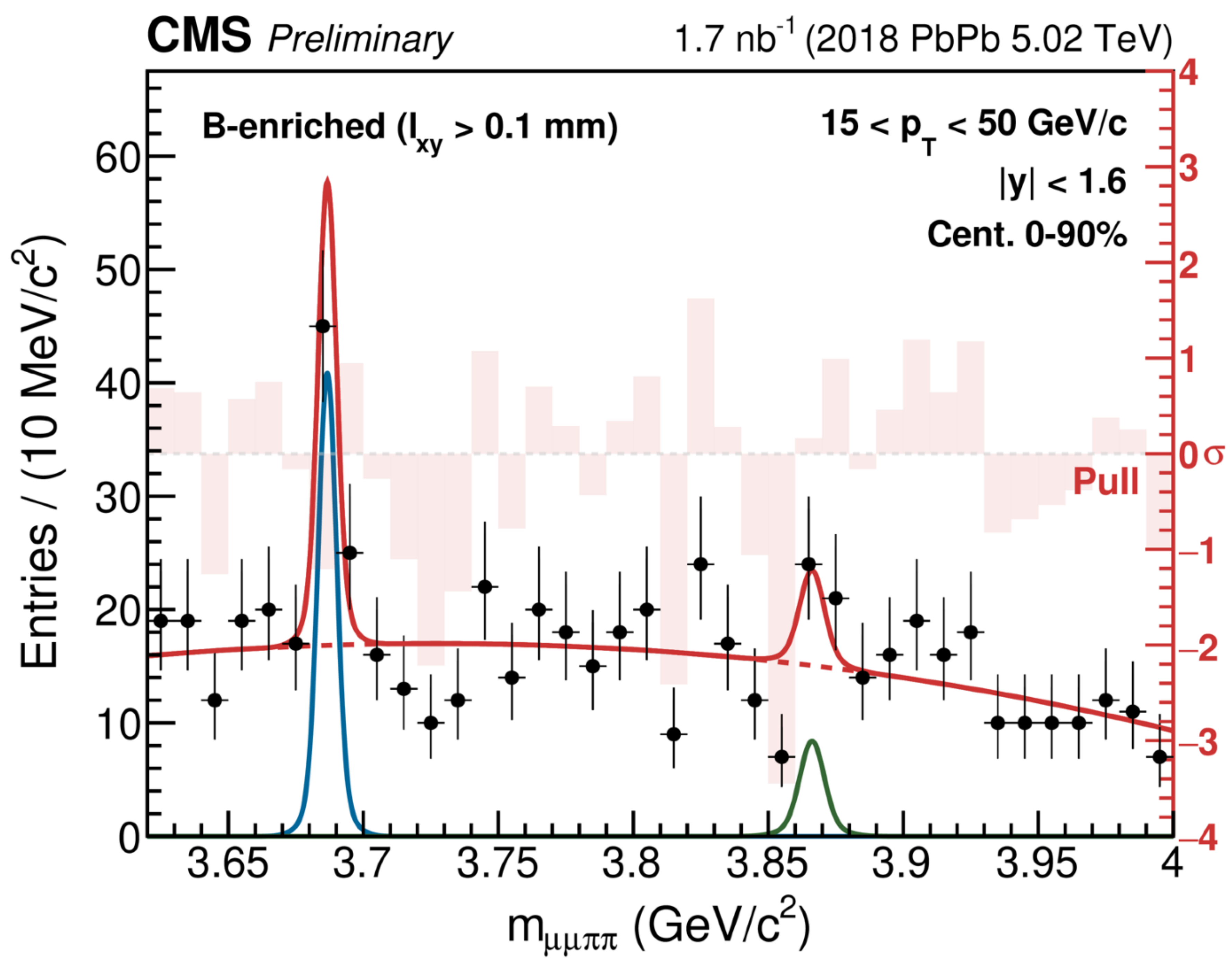
- This in an inclusive measurement:
  - the non-prompt part, coming from b-decays and produced outside of the QGP, it is related to the medium modification b-hadron production in HI collisions (such as beauty quark energy loss & modification of b-jet fragmentation)
  - we are interested in the **prompt part produced in QGP**:
    - measurement of the **l_{xy}** is used to disentangle the two components

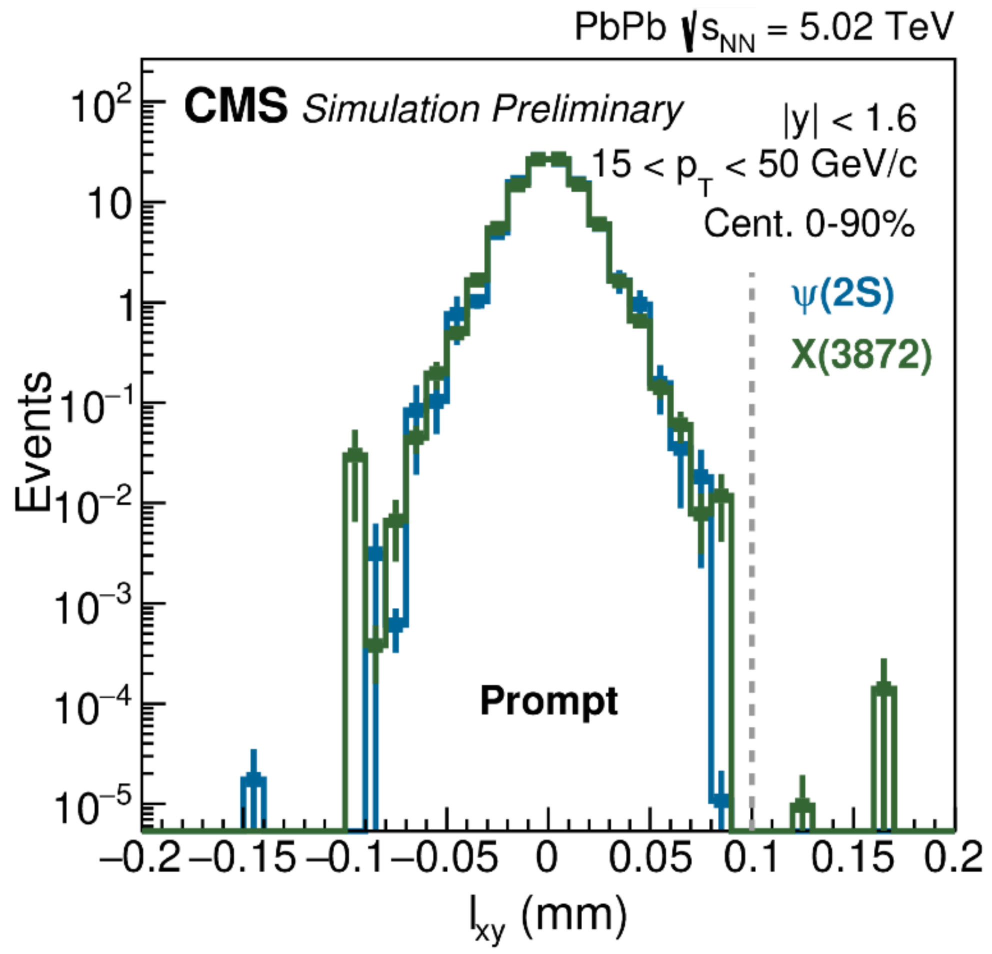
Corrected prompt X(3872) & ψ(2S) yields

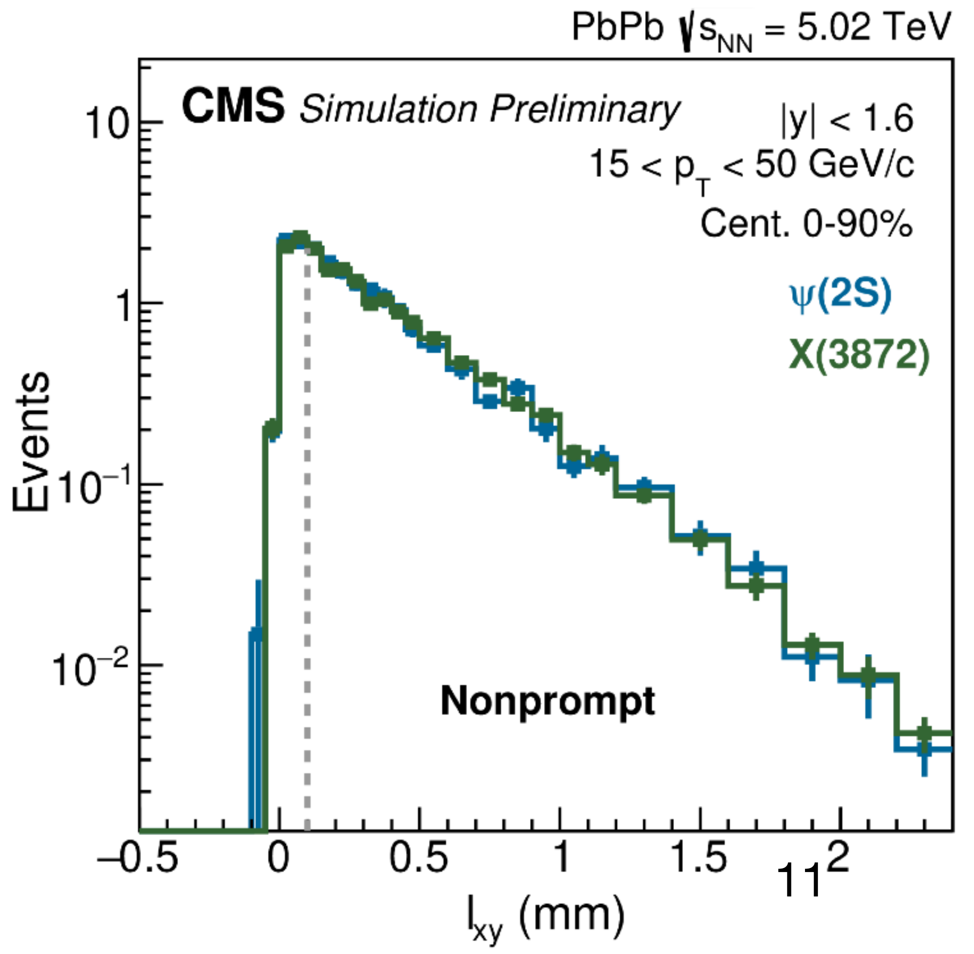
- As in the 7 TeV pp analysis a b-enriched sample is create imposing **l_{xy}>0.1 mm**
  - b-enriched yield obtained using the same fit
- Simulation are used to estimate the small prompt contamination in this sample

$$f_{prompt} = 1 - \frac{N^{data}_{B-enr} \cdot N^{NP\,MC}_{Inclusive}}{N^{NP\,MC}_{B-enr} \cdot N^{data}_{Inclusive}}$$

- Cross check performed with l_{xy} template fit method

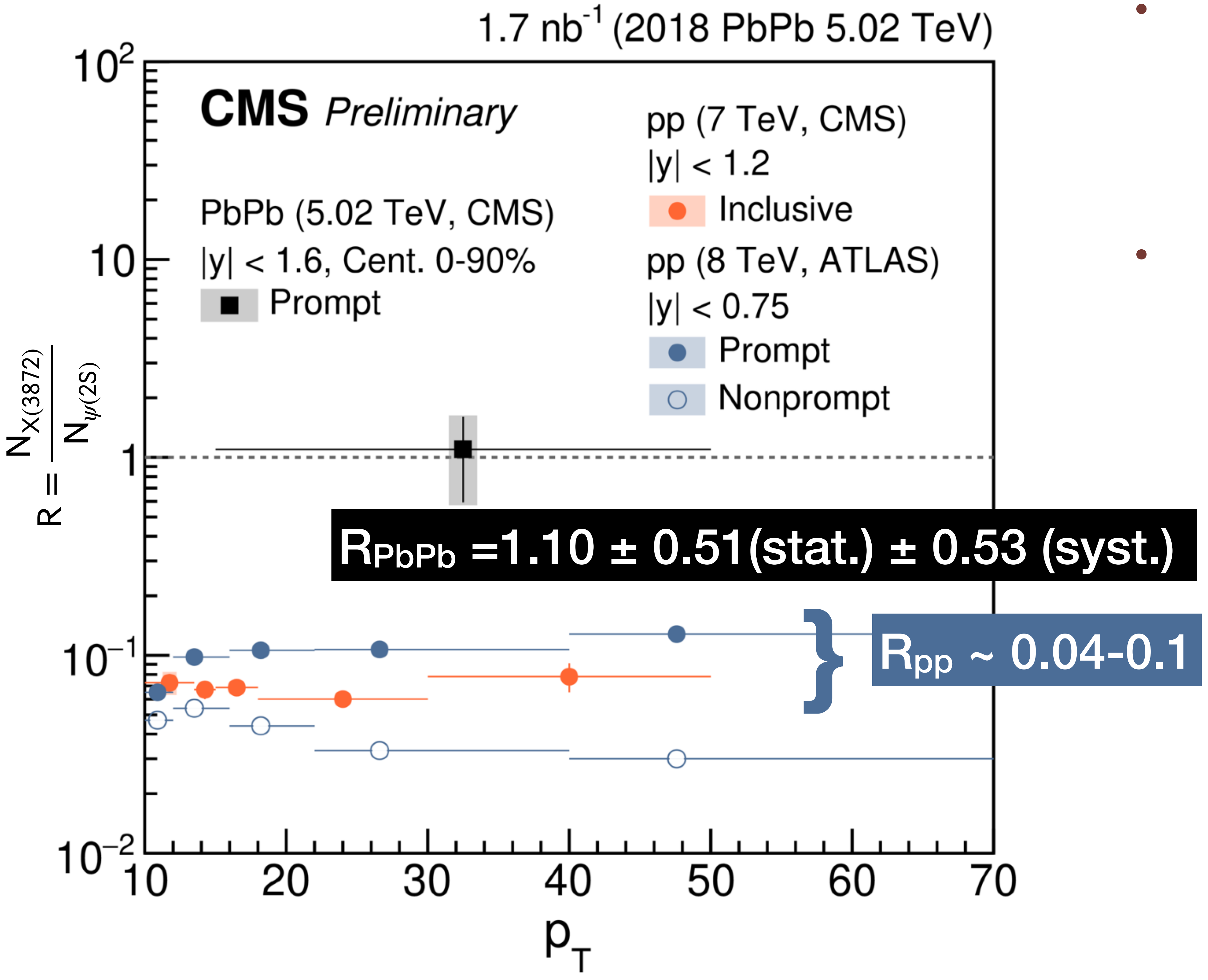




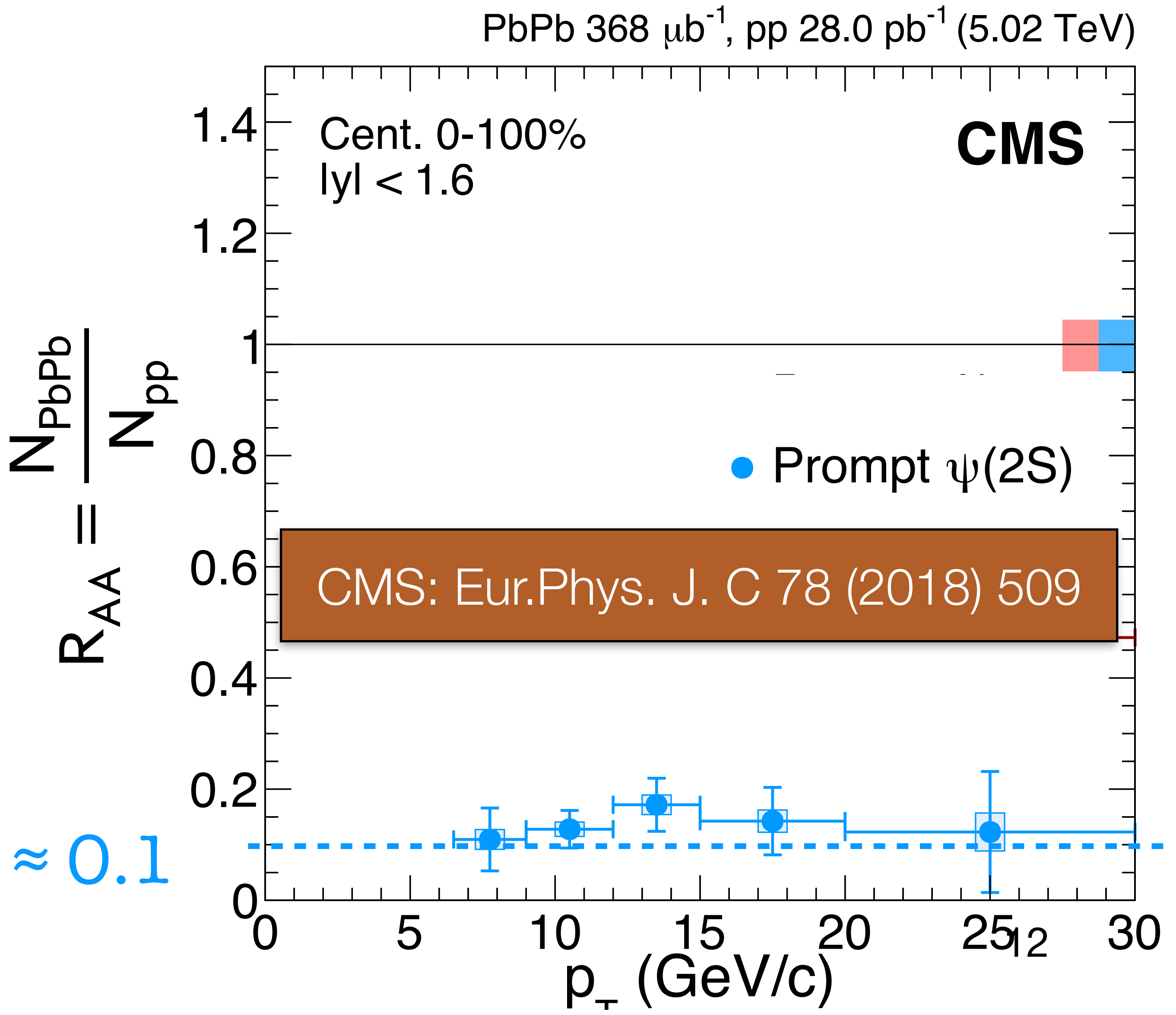


X(3872)/ψ(2S) Ratio in PbPb

- Ratio is defined as $R = \frac{N_{corr}^{X(3872)}}{N_{corr}^{\psi(2S)}}$, where $N_{corr}^{i} = \frac{N_{raw}^{i} \cdot f_{prompt}^{i}}{(\alpha \cdot \epsilon_{tot})^{i}}$
- Acceptance (α) and efficiency correction (ε_{tot}) are evaluated in PYTHIA MC embedded in HYDJET PbPb background



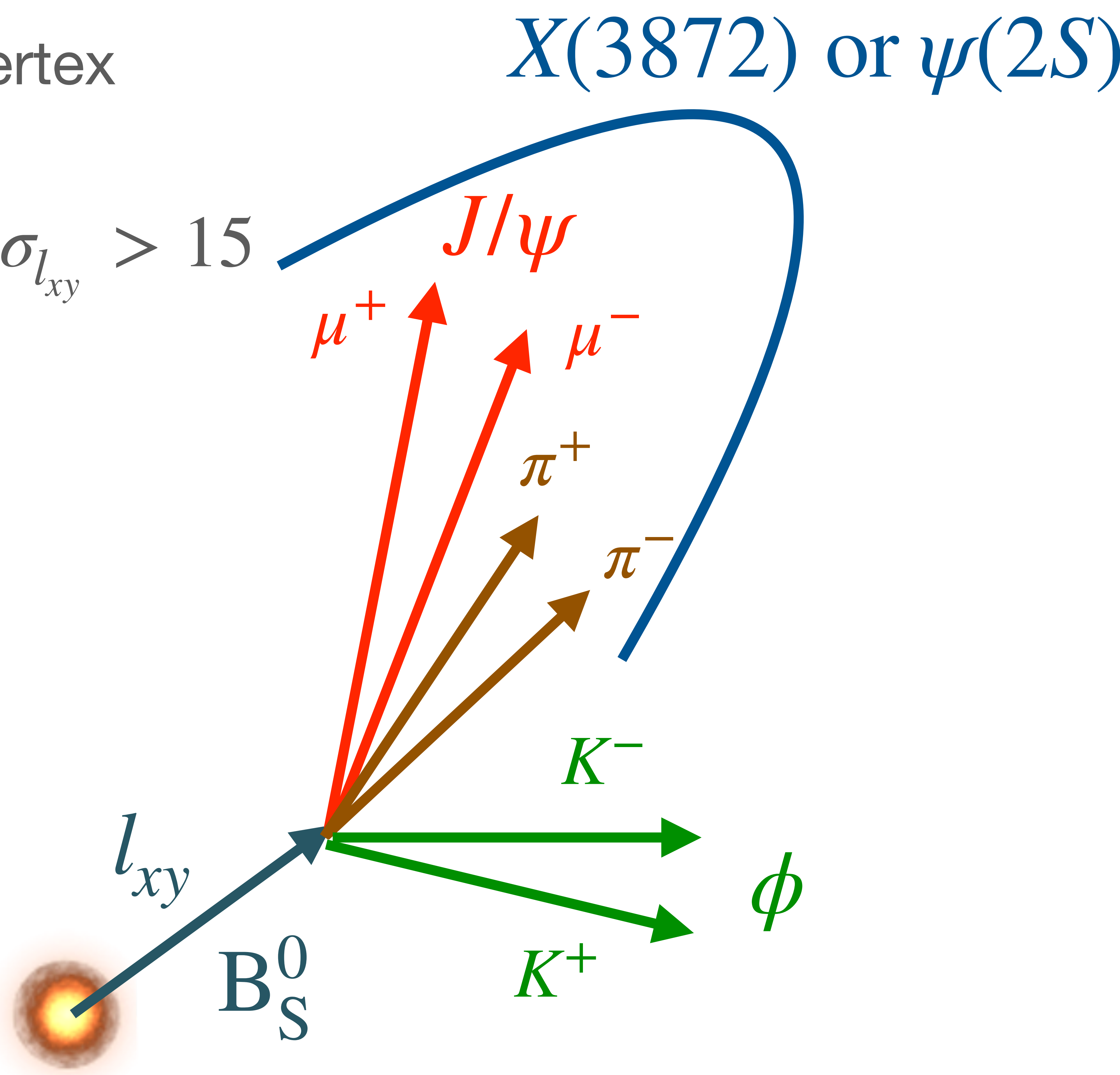
- **Indication of R enhancement in PbPb w.r.t. pp**
  - **Better precision and accuracy needed to draw conclusions**
- CMS also measured the **strong suppression of ψ(2S) in PbPb** collision
  - **X(3872) less suppressed than ψ(2S) in PbPb**
  - on the other side, LHCb measurement showed X(3872) more suppressed than ψ(2S) in high multiplicity pp collisions



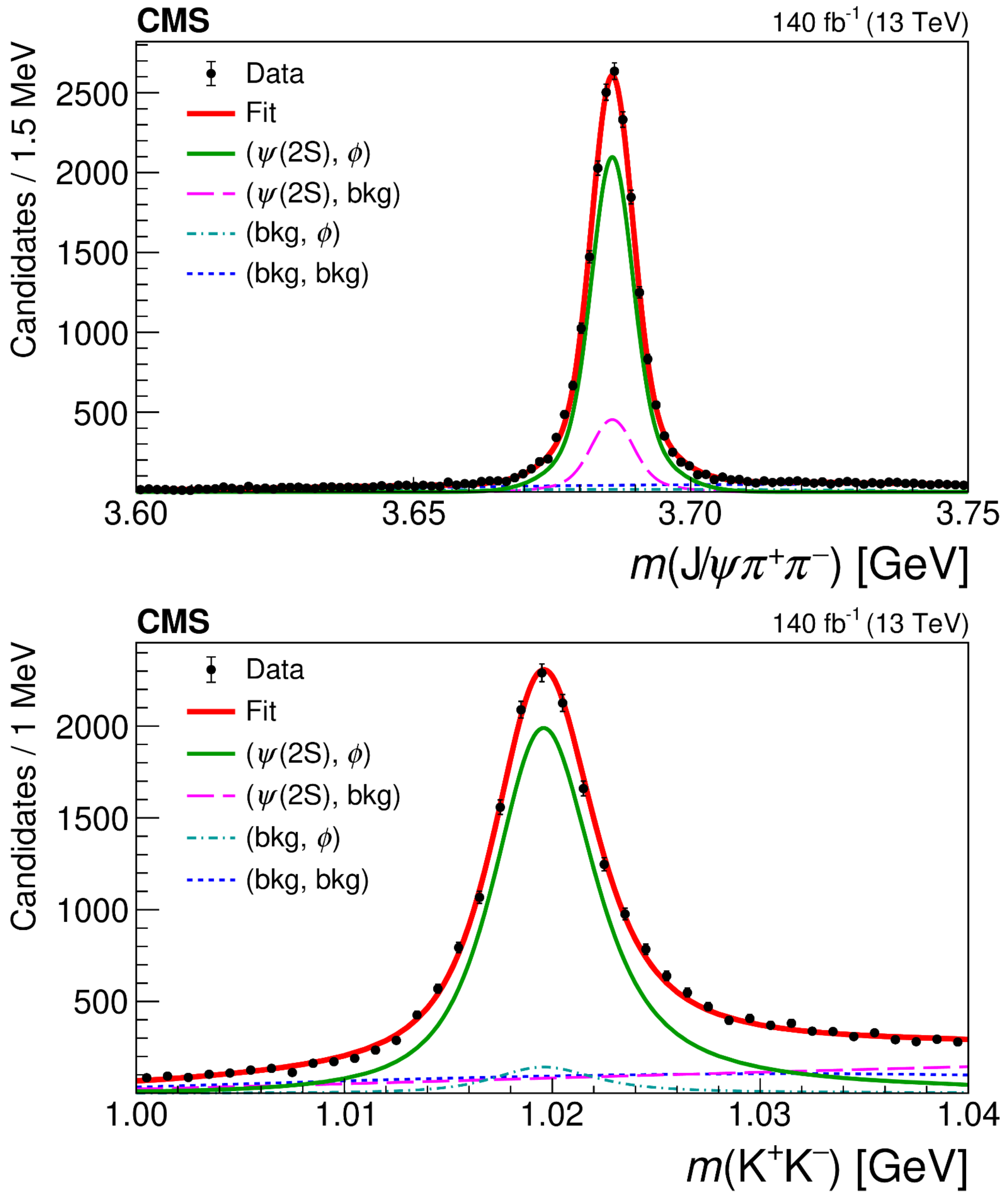
$B^0_S \to$ X(3872)ϕ Decay

CMS: arXiv:2005.04764
Accepted by PRL

- Additional measurements of **b hadron decays involving X(3872)** production can provide important inputs for understanding its internal structure and creation dynamics.
  - CMS looked for the decays $B^0_s \to X(3872)\phi$ and $B^0_s \to \psi(2S)\phi$ with 140 fb^{-1} at $\sqrt{s}$=13 TeV
- **Event Selection:**
  - HLT trigger of 2 muons compatible with J/ψ coming from a displaced vertex plus a track with $p_T > 1.2$ GeV
  - B^0_s: $5.32 < m(J/\psi K^+K^-\pi^+\pi^-) < 5.42$ GeV, $p_T(B^0_S) > 10$ GeV, $l_{xy}/\sigma_{l_{xy}} > 15$
  - Track assignment for the $B^0_S \to J/\psi\pi^+\pi^-K^+K^-$ candidates:
    - $3.60 < m(J/\psi\pi^+\pi^-) < 3.95$ GeV
    - $1.00 < m(K^+K^-) < 1.04$ GeV
    - $5.32 < m(B^0_S) < 5.42$ GeV
    - if more than one combination passes these selections, the candidate is discarded.
  - $p_T(K) > 1.5$ and 2.2 GeV
  - $p_T(\pi) > 0.7$ GeV

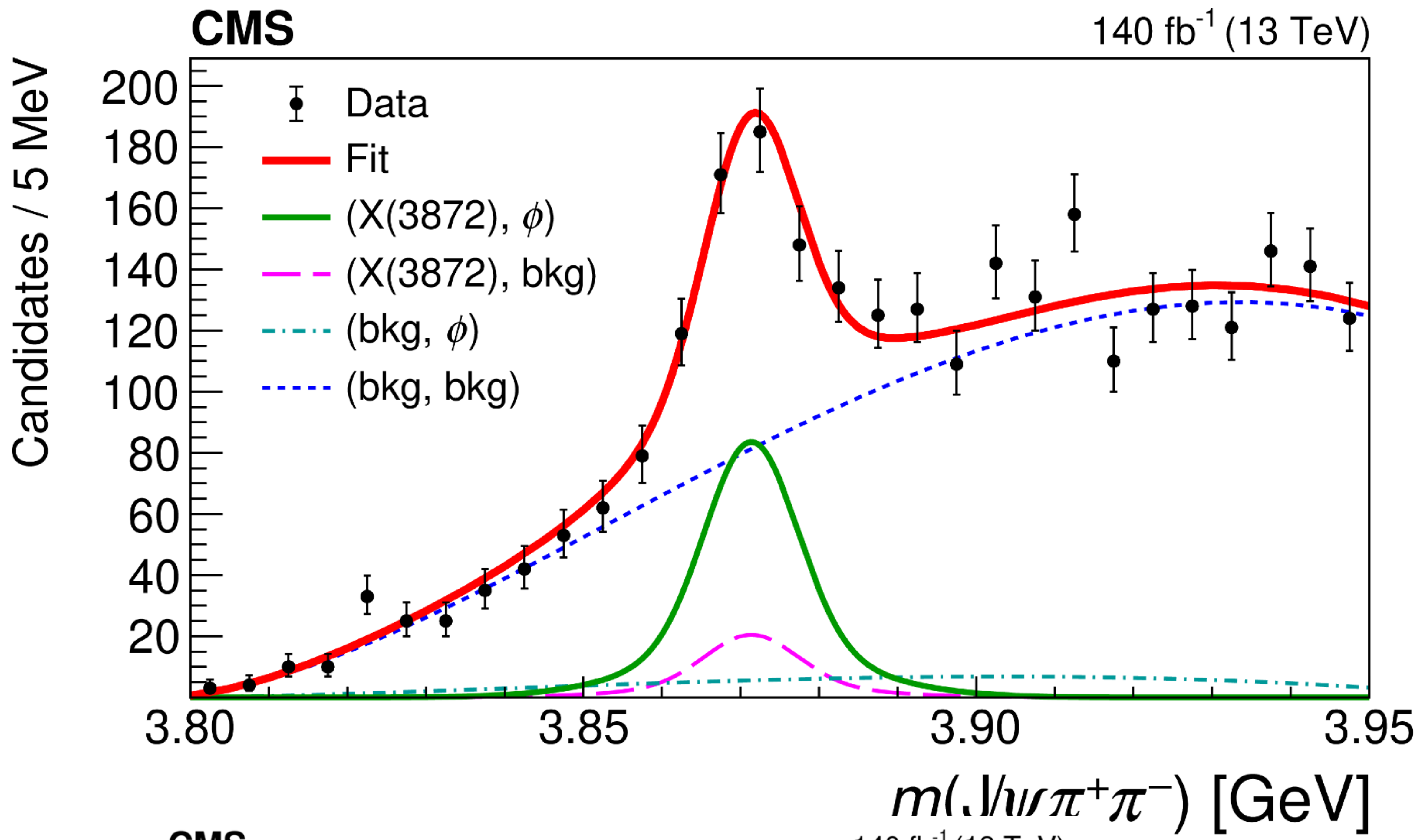


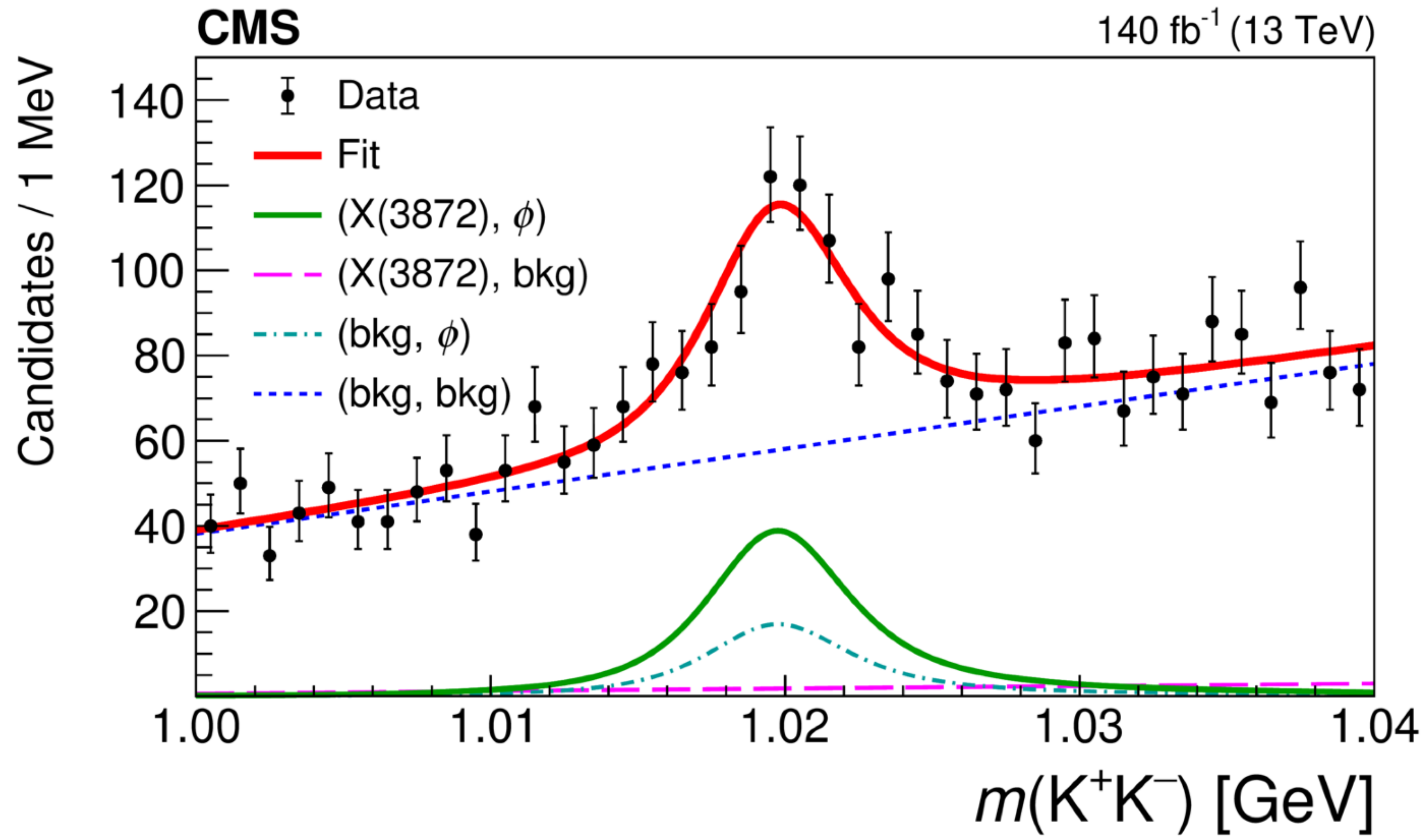
ψ(2S) signal



- The signal yields are extracted using a 2D maximum likelihood fit to the m(J/ψ π π) and m(K K) distributions of B^0_S with a 4-components model made of:
  - **ψ(2S) signal:** double Gaussian
  - **Φ signal:** Breit–Wigner function convolved with detector mass resolution
  - **background in m(KK):** threshold function multiplied by a 1st polynomial
  - **background in m(J/ψππ):** modified threshold function
- Fitted yield: 15 359 ± 171 ψ(2S)

X(3872) Signal





- **First observation of the decay $B^0_s \to X(3872)\phi$!**
  - **Significance > 6σ**
- Same fit function of the ψ(2S) with additional constrain:
  - X(3872) signal shape fixed to ψ(2S) one with a parameter for the resolution scaling
- X(3872) yield: 299 ± 39

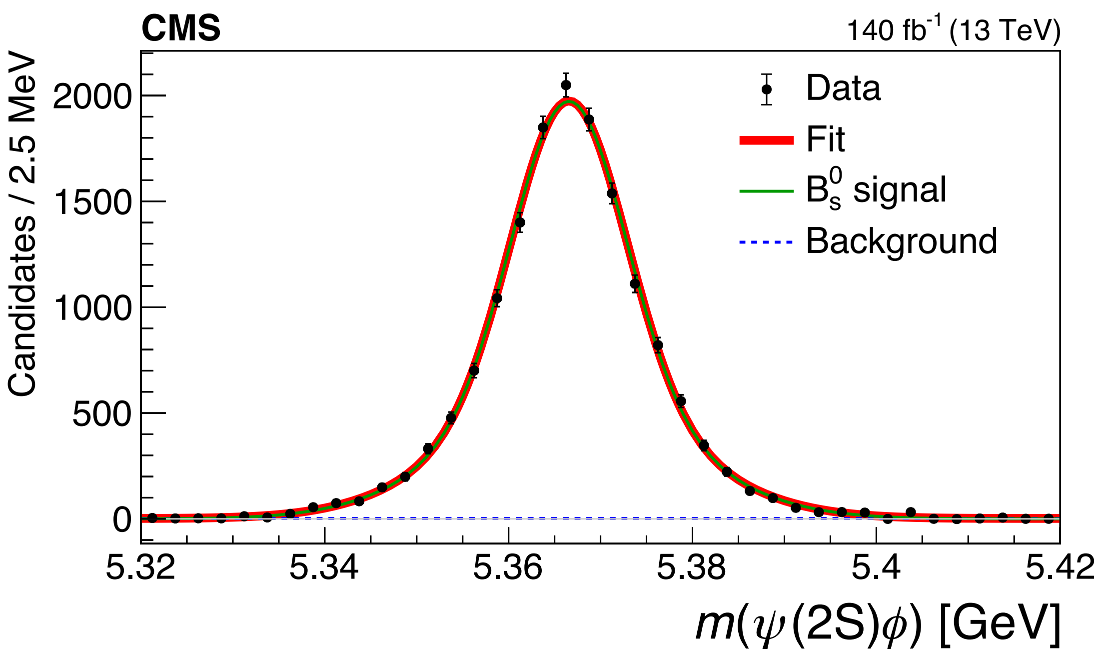
Production Ratios

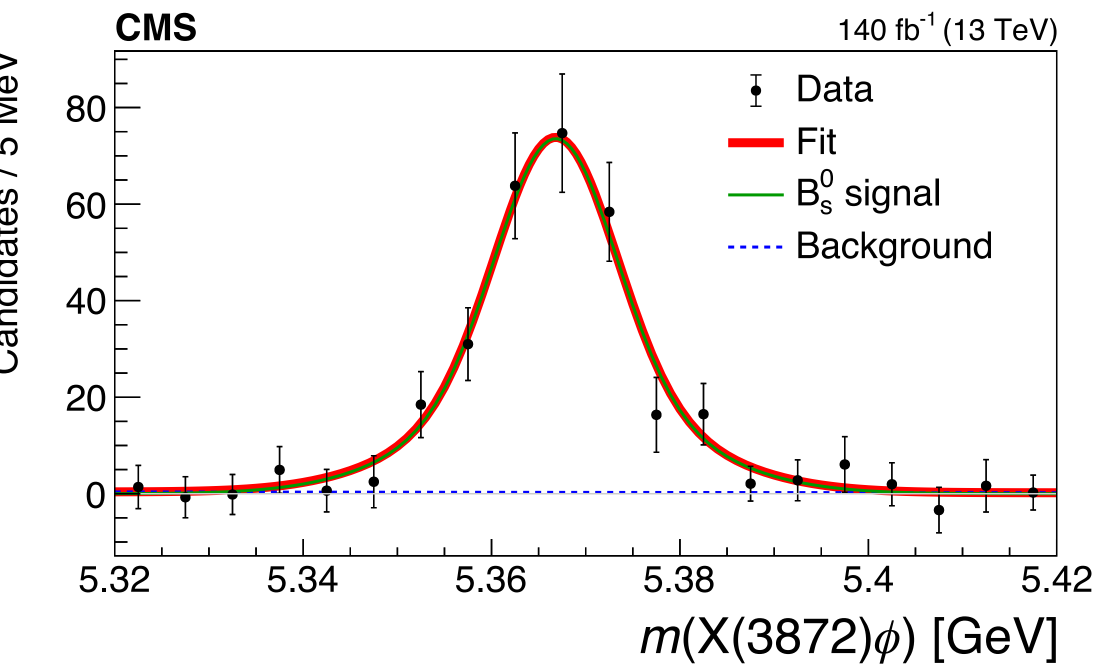
$$R \equiv \frac{\mathcal{B}(\mathrm{B_s^0} \to X(3872)\phi)\,\mathcal{B}(X(3872) \to \mathrm{J}/\psi\,\pi^+\pi^-)}{\mathcal{B}(\mathrm{B_s^0} \to \psi(2S)\phi)\,\mathcal{B}(\psi(2S) \to \mathrm{J}/\psi\,\pi^+\pi^-)} = \frac{N(\mathrm{B_s^0} \to X(3872)\phi)}{N(\mathrm{B_s^0} \to \psi(2S)\phi)} \frac{\epsilon_{\mathrm{B_s^0} \to \psi(2S)\phi}}{\epsilon_{\mathrm{B_s^0} \to X(3872)\phi}}$$

- Evaluated in Simulation
- Takes into account detector acceptance, trigger, and candidate reconstruction efficiencies
- Resulted:1.136 ± 0.026

Mass fit yields

$$R = (2.21 \pm 0.29\,(\mathrm{stat}) \pm 0.17\,(\mathrm{syst}))\%.$$





Background-subtracted mass distributions

Estimated using the *S*plot technique to subtract the contributions from non resonant K K and J/ψ π π combinations from the $m(B^0_s)$ distribution

Source	Uncertainty (%)
$m(\mathrm{K^+K^-})$ signal model	< 0.1
$m(\mathrm{K^+K^-})$ background model	2.5
$m(\mathrm{J}/\psi\pi^+\pi^-)$ signal model	5.3
$m(\mathrm{J}/\psi\pi^+\pi^-)$ background model	4.3
Non-$\mathrm{B_s^0}$ background	1.2
Simulated sample size	2.2
Total	7.7

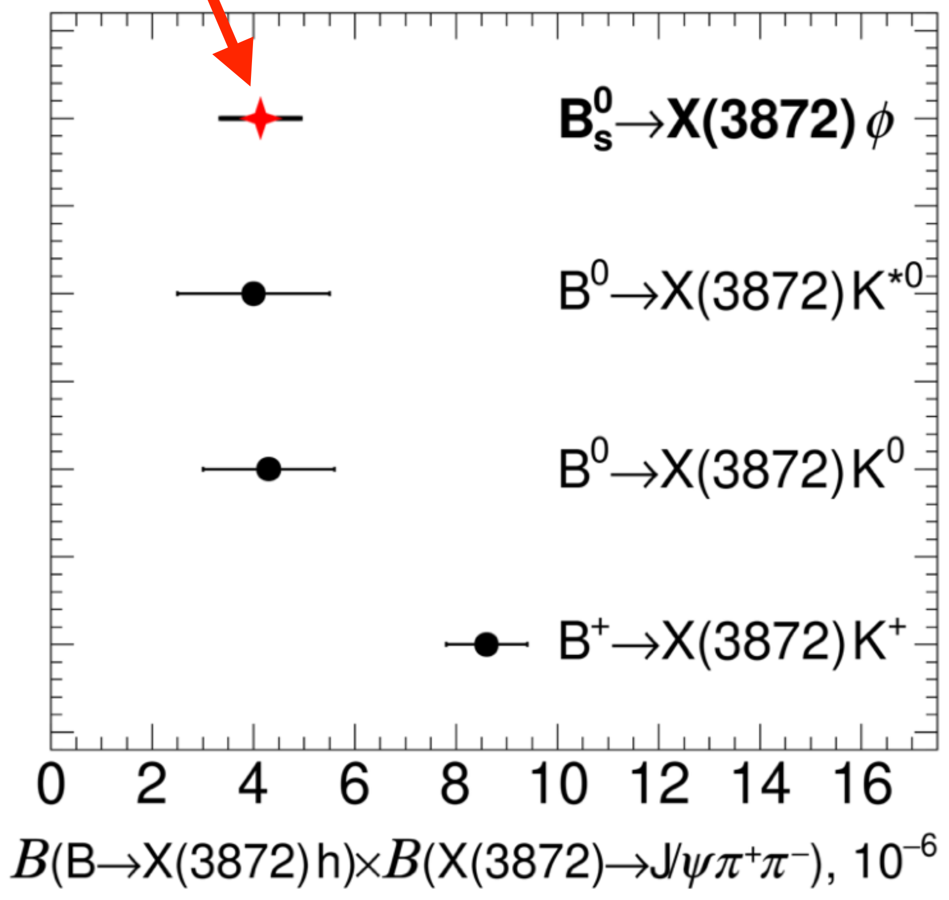
Estimated using several alternative fit functions

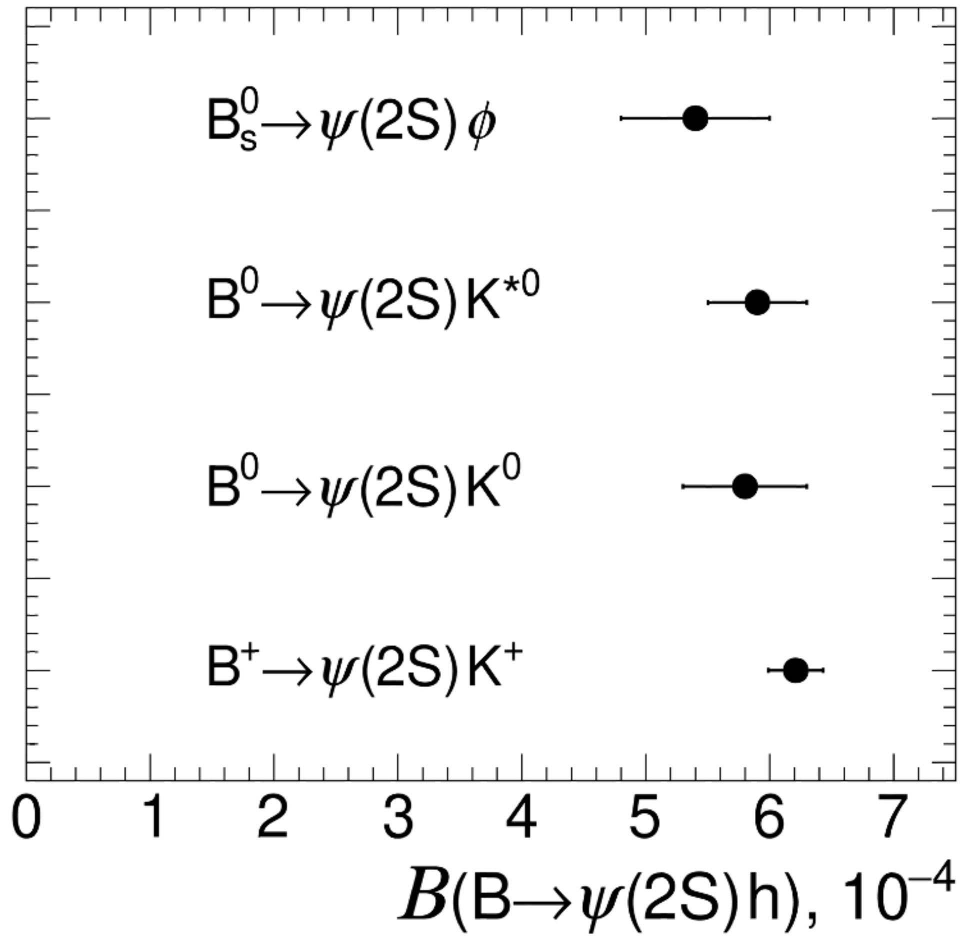
$\mathcal{B}(\mathrm{B_s^0} \to X(3872)\phi)\,\mathcal{B}(X(3872) \to \mathrm{J}/\psi\,\pi^+\pi^-)$

Multiplying R by the known BR ($\mathrm{B^0_s} \to \psi(2S)\phi$) and ($\psi(2S) \to J/\psi\pi\pi$):

$$\boxed{\mathcal{B}(\mathrm{B_s^0} \to X(3872)\phi)\,\mathcal{B}(X(3872) \to \mathrm{J}/\psi\,\pi^+\pi^-) = (4.14 \pm 0.54\,(\mathrm{stat}) \pm 0.32\,(\mathrm{syst}) \pm 0.46\,(\mathcal{B})) \times 10^{-6}}$$

Comparison of BRs indicates that the *X*(3872) formation in B meson decays is different from *ψ*(2S)



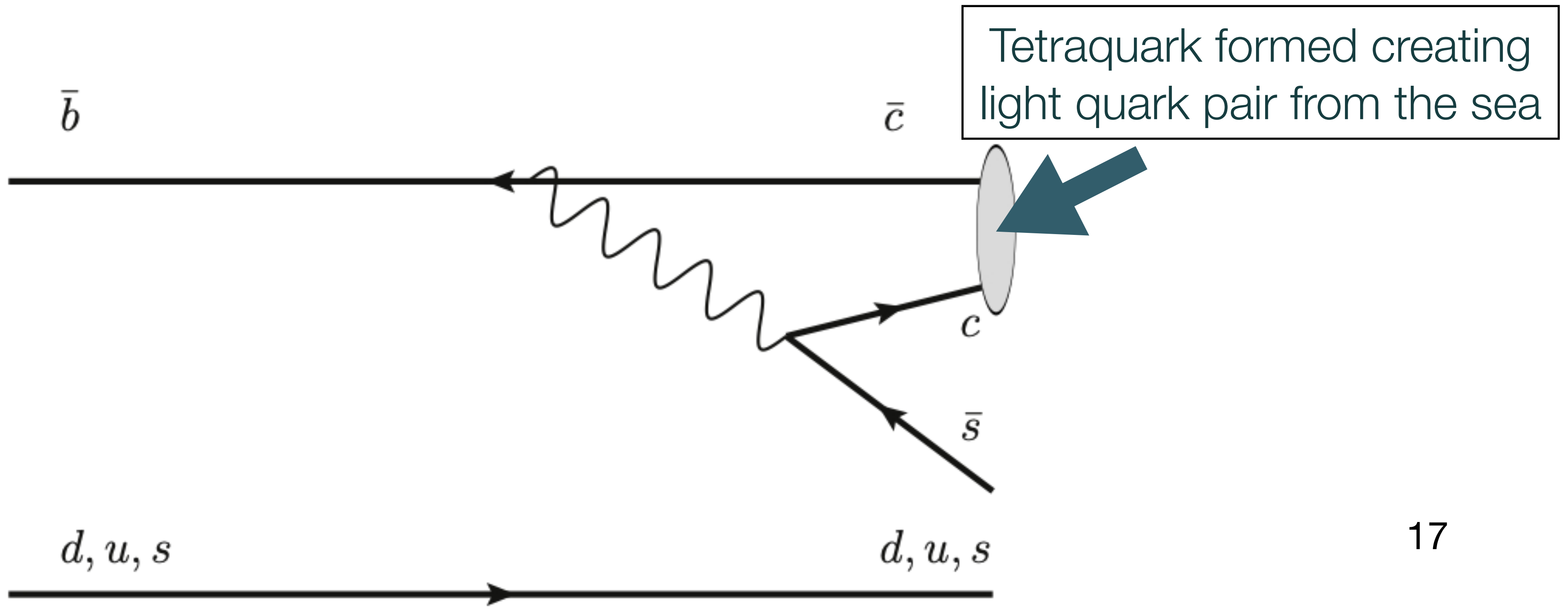


Additionally, the following pattern can be observed:

$$\boxed{\mathcal{B}(B_s^0 \to \phi X \to \phi\, J/\psi\,\pi^+\pi^-) \simeq \mathcal{B}(B^0 \to K^0 X \to K^0\, J/\psi\,\pi^+\pi^-) \simeq \frac{1}{2}\mathcal{B}(B^+ \to K^+ X \to K^+\, J/\psi\,\pi^+\pi^-)}$$

It has been shown in [Phys.Rev.D 102 (2020) 3, 034017] that this pattern can emerge from B decays in the compact tetraquark picture of the X(3872), where it belongs to a complex of four-quark bound states:

$X_u = [cu][\bar{c}\bar{u}]$, $X_d = [cd][\bar{c}\bar{d}]$ and $X^\pm = [cu][\bar{c}\bar{d}], [cd][\bar{c}\bar{u}]$



Summary

- After many years from its discovery the X(3872) remains “**exotic**”
  - it’s exact nature is still not univocally determined
  - many models are proposed and profit from the increasing number of experimental results
- **CMS has greatly contributed in this experimental effort**
  - First measurement of the non-prompt component dependence on p_T
  - NEW ! First evidence of the X(3872) in Heavy Ions collisions
  - NEW ! First observation of the decay $B^0_S \rightarrow X(3872)\phi$
- New CMS results will come from the large collected datasets and the new LHC runs ahead of us.