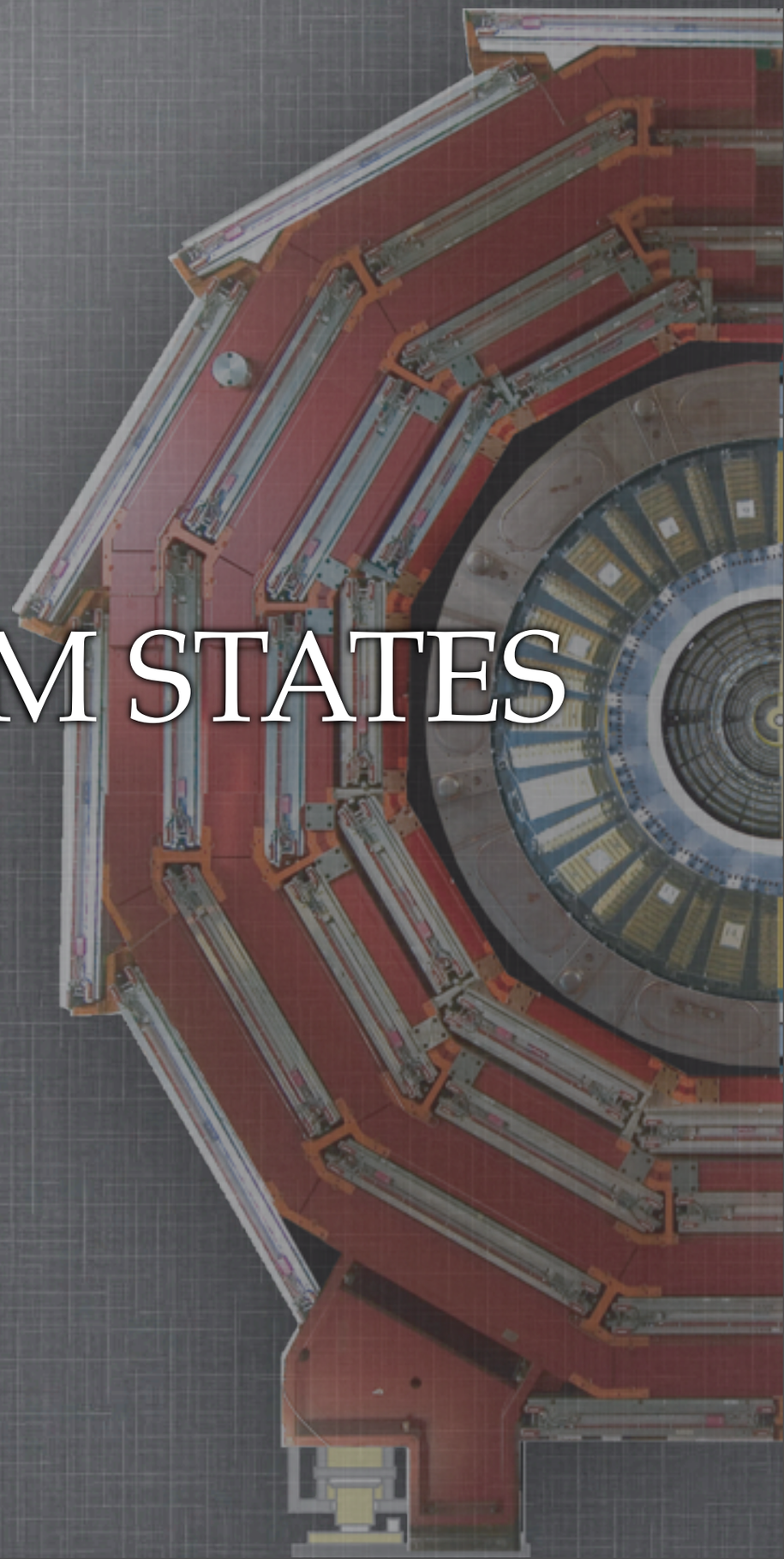
EXOTIC QUARKONIUM STATES IN CMS EXPERIMENT



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For the CMS Collaboration

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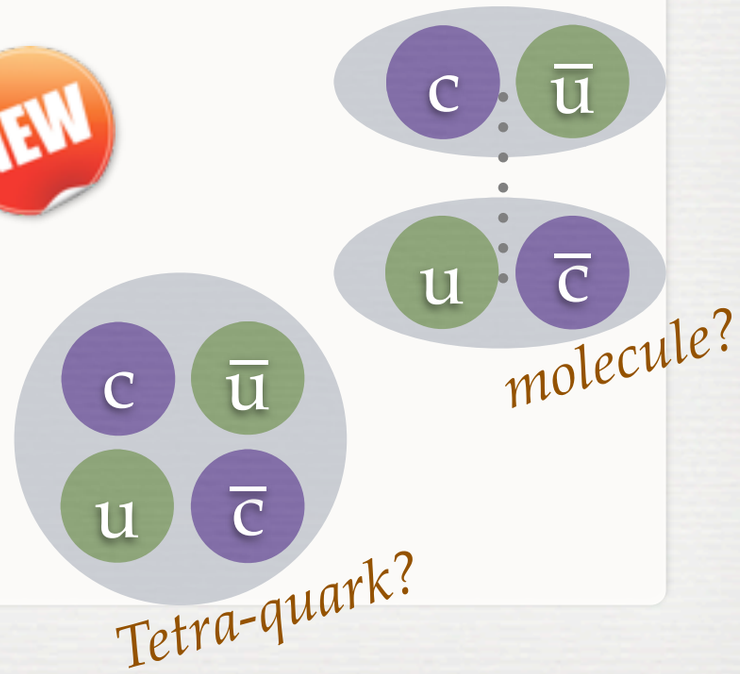
INTRODUCTION

- The discovery of the first exotic charmonium state X(3872) in 2003 has renewed the **(strong) interests** in the hadron spectroscopy.
  [*the first Belle X(3872) paper has been cited >800 times already!*]
- Several new states have been found at various places, however
  - The unconventional states are mostly seen in charmonium system; only few candidates in bottom/strange sector being probed.
  - Many theoretical models have been proposed, but the actual picture remains unclear still.
  - More experimental inputs, especially the ***property measurements*** and ***extended searches*** will help to clarify the nature of these states.

NEW

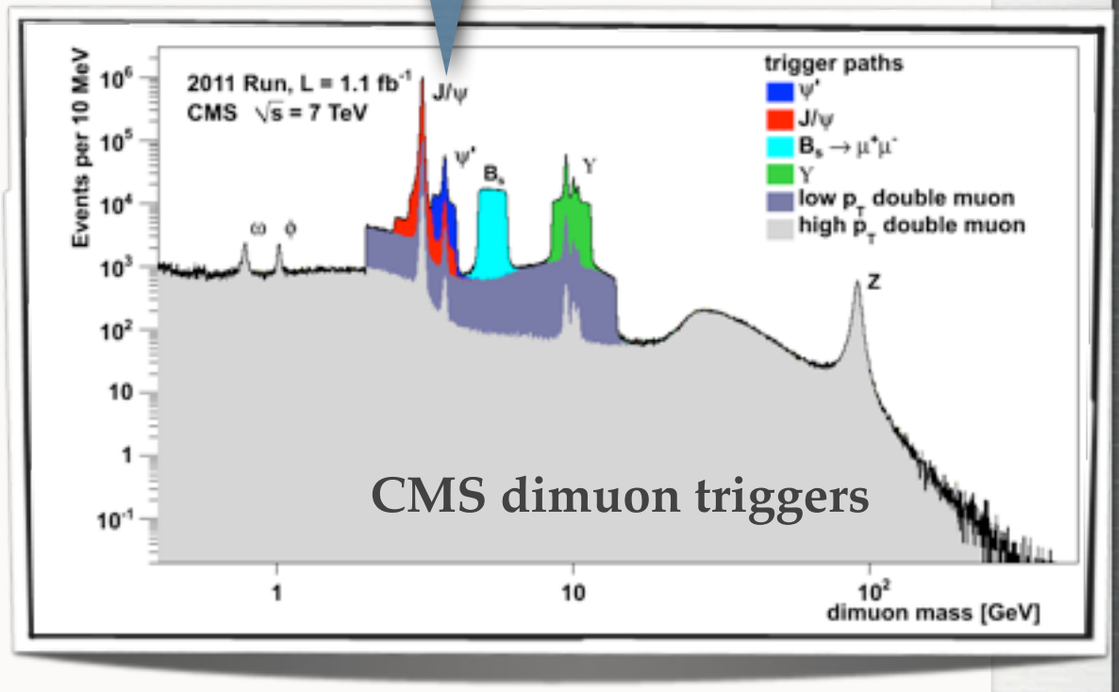


Beneficial from the large statistics provided by the LHC:
CMS selected >12000 X(3872) candidates!

CMS ANALYSIS

- **A full-silicon tracker:**
  - Excellent track momentum resolution at low p_T.
  - Excellent vertex reconstruction and impact parameter resolution.
- **Muon system:**
  - High purity muon identification.
  - Good dimuon mass resolution
    ~0.6-1.5% (depending on $|y|$).
- **Triggers:**
  - Fast hardware trigger
  - Software trigger with full tracking & vertex reconstruction.
  - Specific triggers were developed for various analyses.

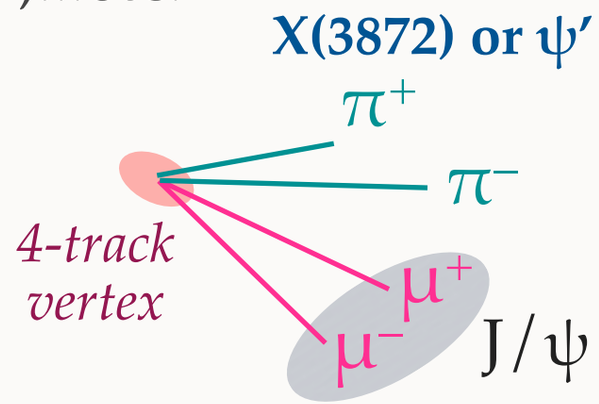
Specific quarkonium (J/ψ, ψ′ & ϒ) to dimuon triggers

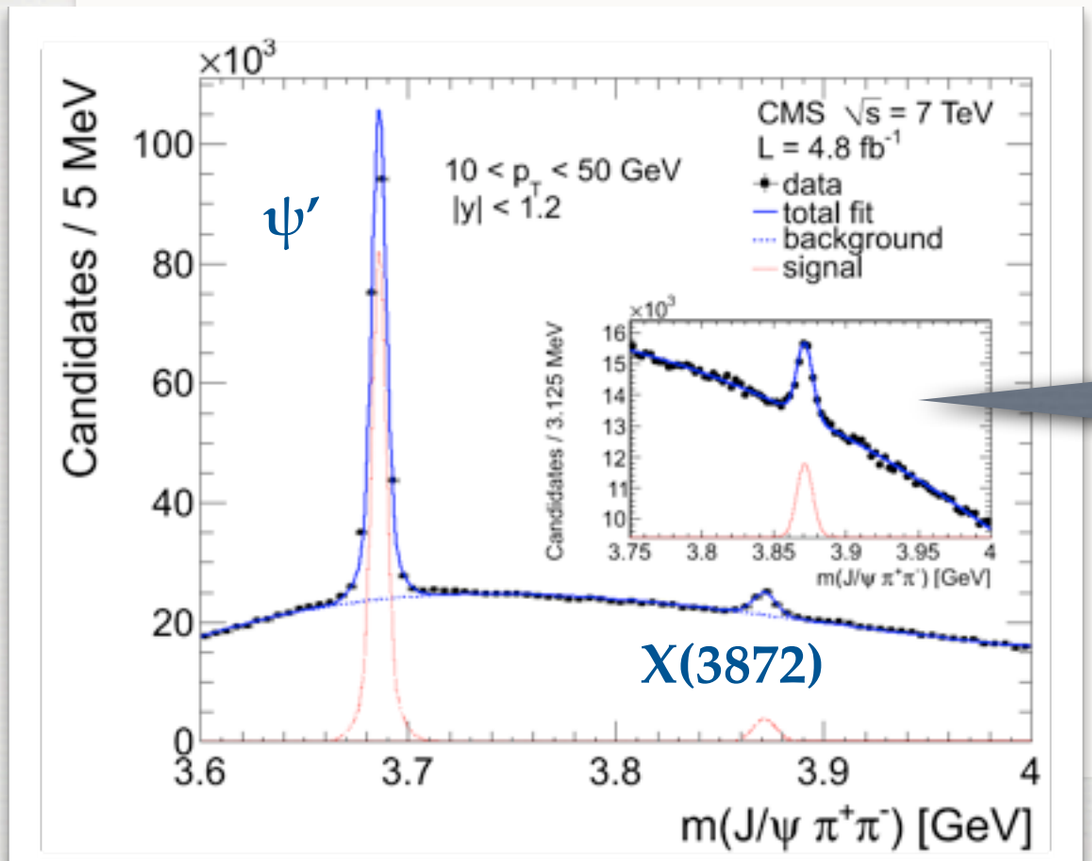


GREAT POTENTIAL FOR QUARKONIA STUDIES!

X(3872) PRODUCTION

- X(3872) has been found in various decays:
  - $J/\psi\,\pi^+\pi^-$(*most pronounced*), $J/\psi\gamma$, $\psi'\gamma$, $J/\psi\omega$, D*D,...etc.
  - Mass is just at D*D threshold.
  - The interpretation is not yet concluded: simply a charmonium, a molecule, or a possible 4-quark state, etc.





Based on CMS 4.8 fb^{-1} 7 TeV data
Published in JHEP 1304 (2013) 154

CMS ANALYSIS

Triggered by $J/\psi\to\mu^+\mu^-$

phase-space

$p_T(\mu)>4\,(3.3)$ GeV for $|\eta(\mu)|<1.2\,(1.2\text{–}2.4)$

$J/\psi\to\mu\mu$: $p_T>7$ GeV, $|y|<1.25$

$p_T(\pi^\pm)>0.6$ GeV, $\Delta R(J/\psi,\pi^\pm)<0.55$

4-track common vertex + J/ψ mass constraint

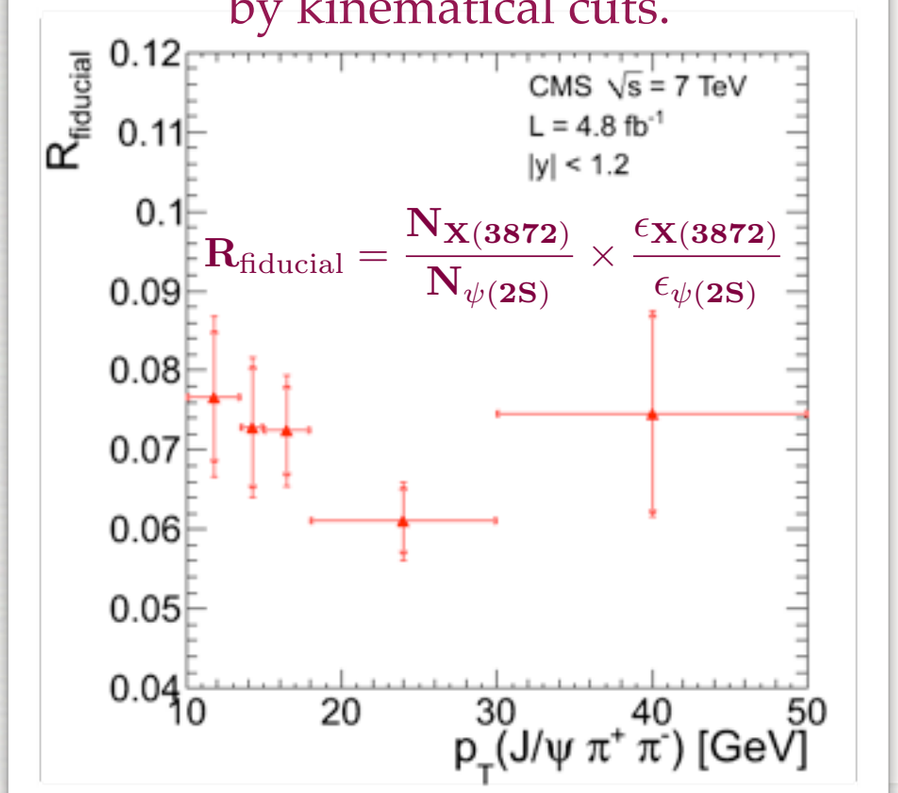
MEASUREMENT OF CROSS SECTION RATIO

Extracted from the fits to the $J/\psi\pi\pi$ mass spectrum.

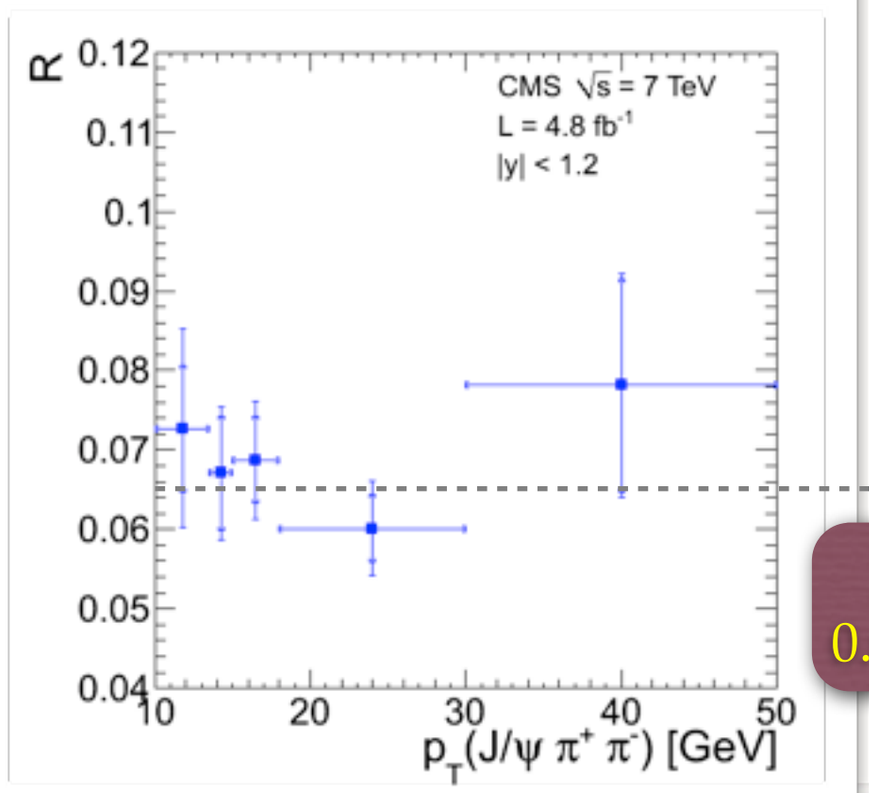
$$R = \frac{\sigma(pp \to X(3872)) \times \mathcal{B}(X(3872) \to J/\psi\pi\pi)}{\sigma(pp \to \psi(2S)) \times \mathcal{B}(\psi(2S) \to J/\psi\pi\pi)} = \frac{N_{X(3872)}}{N_{\psi(2S)}} \times \frac{\epsilon_{X(3872)}}{\epsilon_{\psi(2S)}} \times \frac{A_{X(3872)}}{A_{\psi(2S)}}$$

Determined from MC with unpolarized and $J^{PC} = 1^{++}$ for X(3872)

within the phase space window defined by kinematical cuts.



Acceptance correction applied.

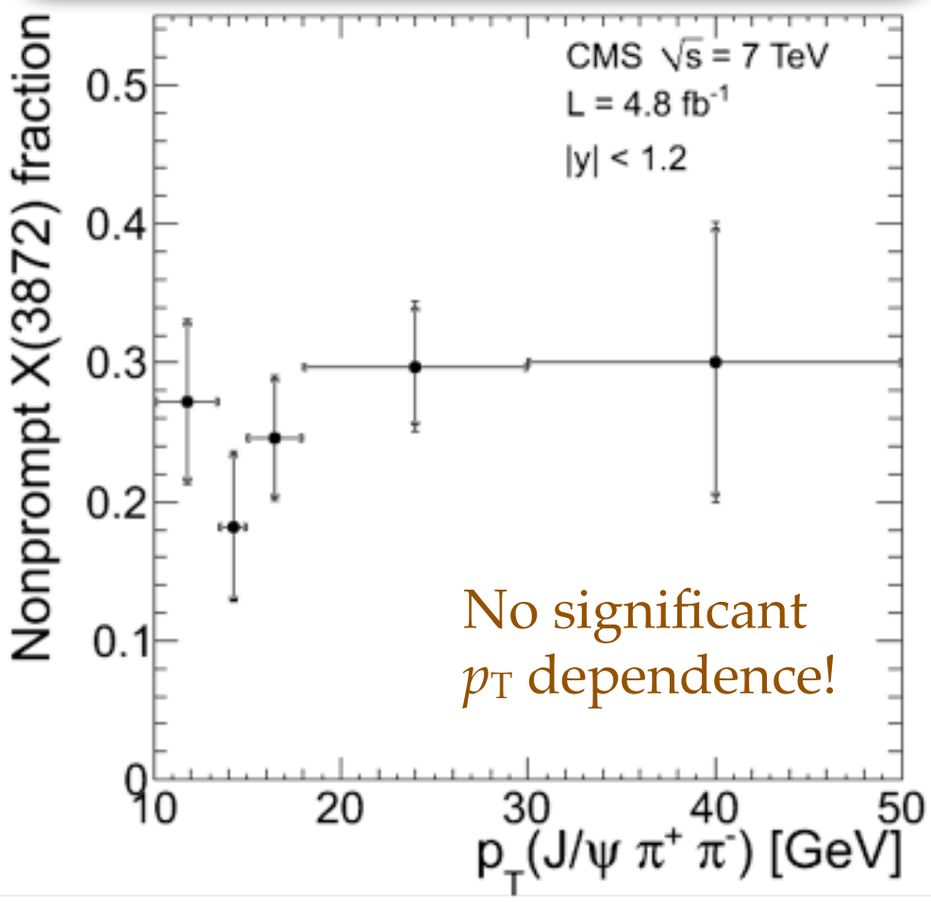


No significant p_T dependence!

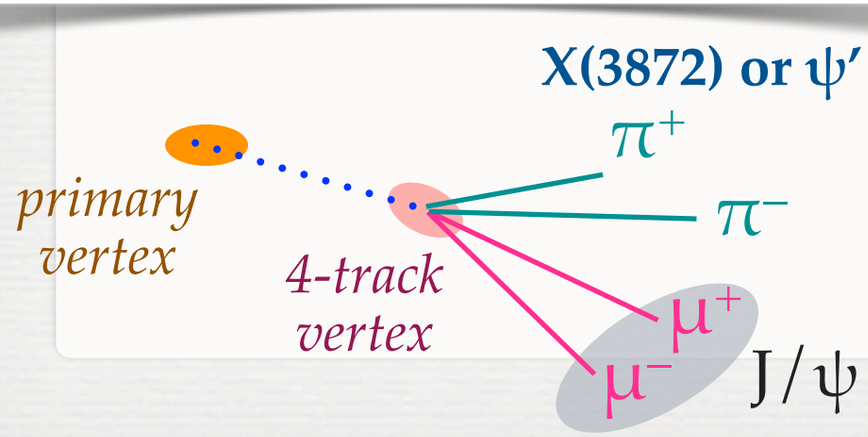
AVERAGE:
$0.0656 \pm 0.0029 \pm 0.0065$

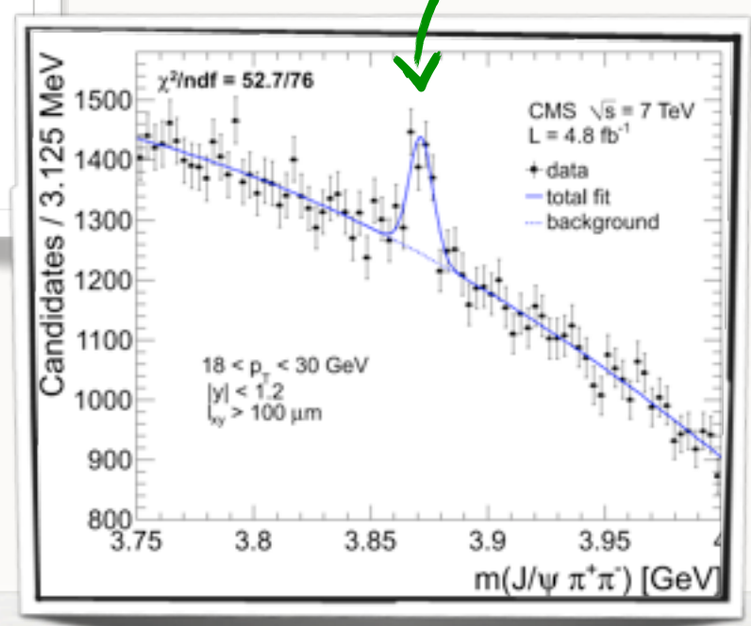
NON-PROMPT FRACTION

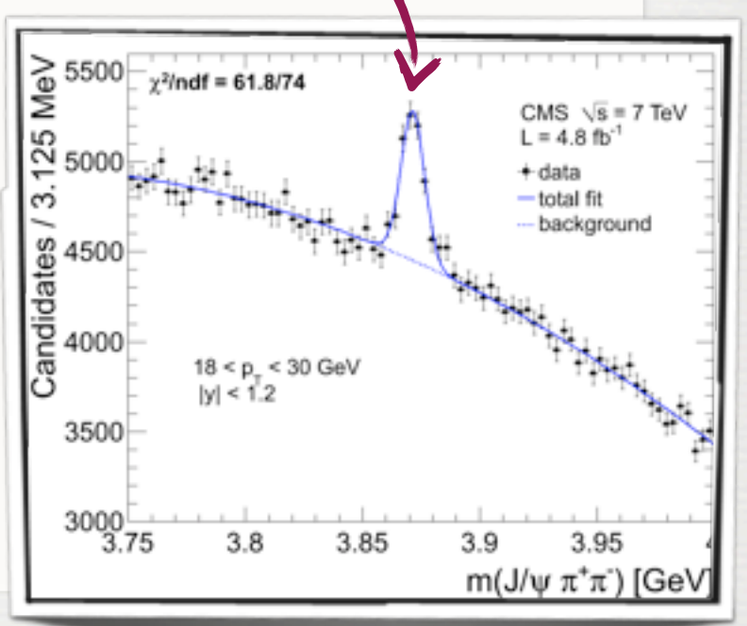
In 10 GeV < p_T < 50 GeV, |y|<1.2:
0.263 ± 0.023 (stat) ± 0.016 (syst)



- Non-prompt X(3872) events are from the decays of B hadrons.
- B-enriched events are selected with sizable proper decay length, $l_{xy} > 100$ μm
  [*fraction of prompt X(3872) is below 1%*].
- **non-prompt fraction =**
  $N_{X(3872)}$ [B-enriched] / $N_{X(3872)}$ [full sample]







PROMPT PRODUCTION CROSS SECTION

$$\sigma^{\text{prompt}}_{X(3872)} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) =$$

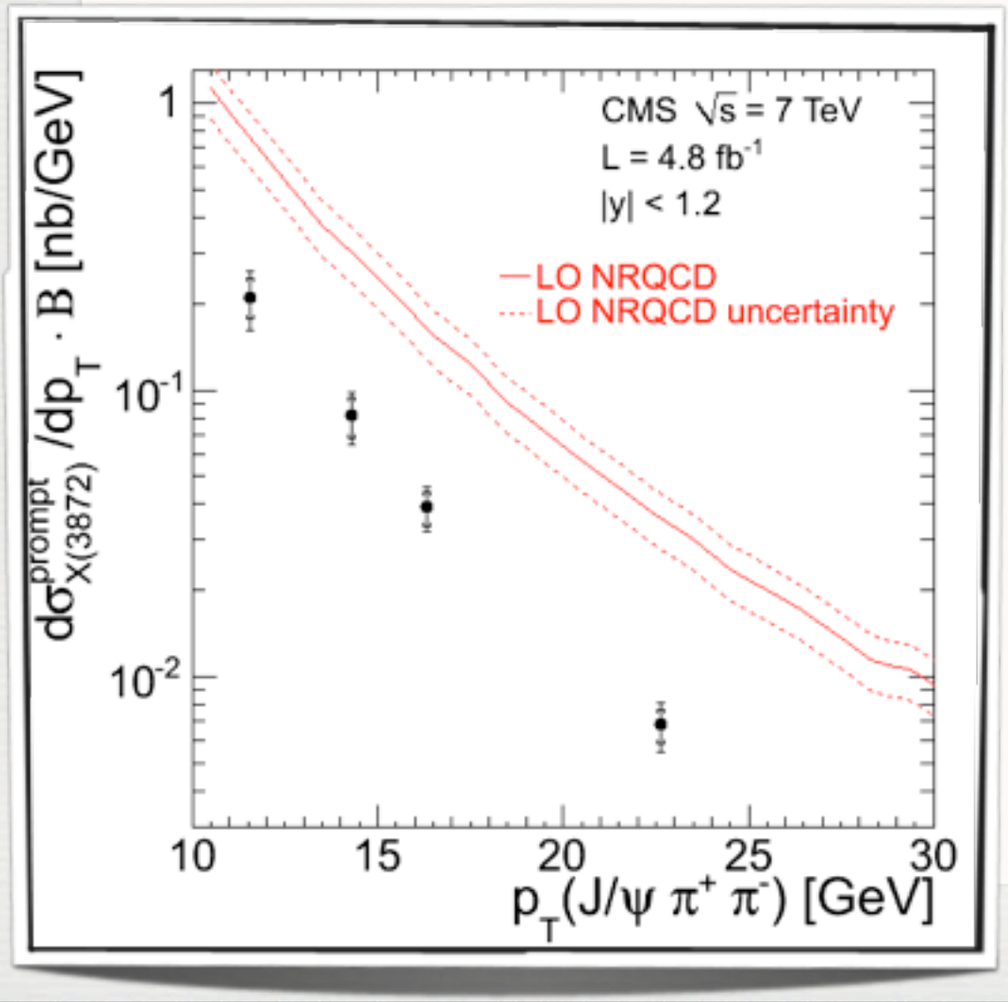
$$\frac{1 - f^B_{X(3872)}}{1 - f^B_{\psi(2S)}} \times R \times \sigma^{\text{prompt}}_{\psi(2S)} \times \mathcal{B}(\psi(2S) \to \mu^+\mu^-) \times \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$$

Prompt fraction

Cross section ratio

From CMS measurement
Ref. JHEP 02 (2012) 011

From PDG



- Cross section times branching ratio is measured differentially in p_T!
- Prediction is calculated using the NRQCD factorization formalism.
  [Ref. PRD 81 (2010) 114018]

Integrated prompt cross sections times branching fraction:
1.06 ± 0.11 (stat) ± 0.15 (syst) nb

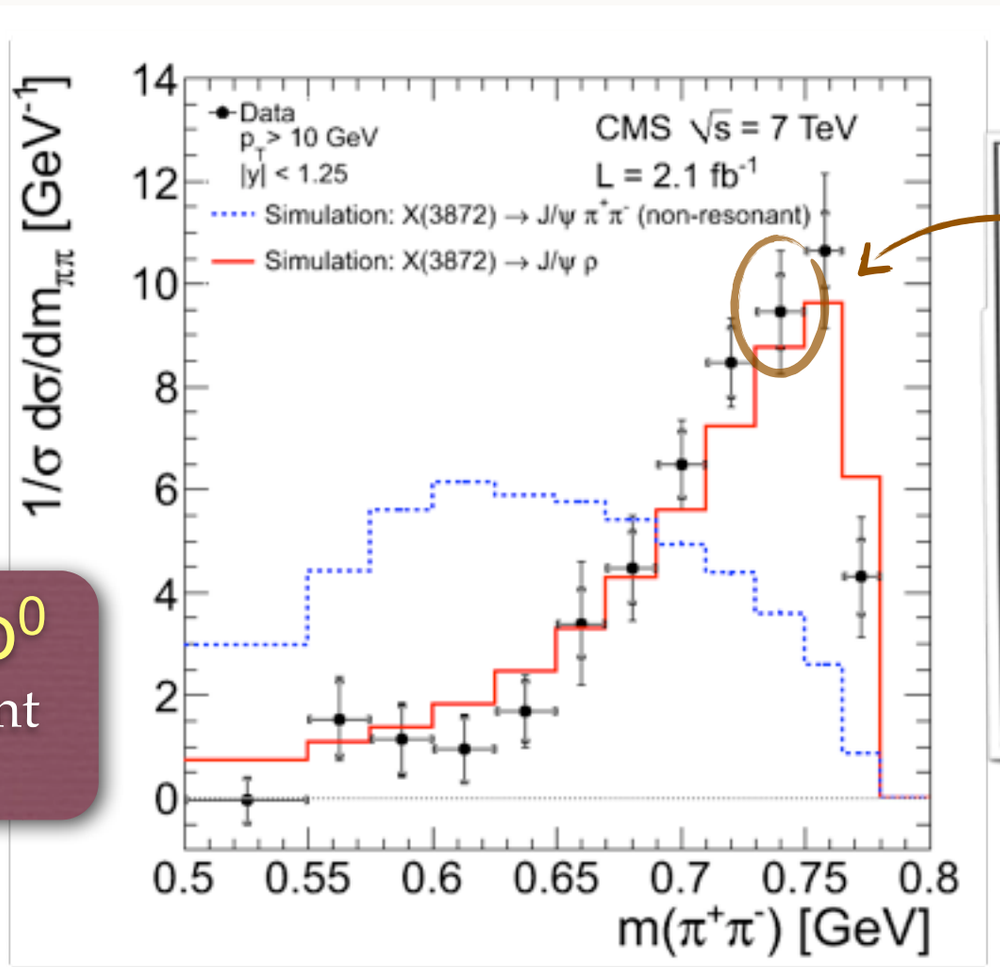
Significantly lower than the prediction: **4.01 ± 0.88 nb**

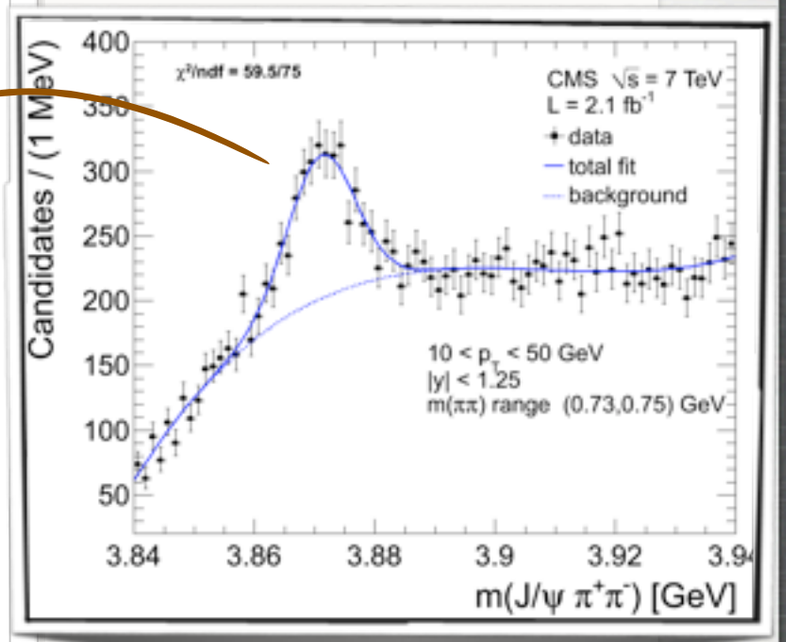
DIPION INVARIANT MASS DISTRIBUTION

- Events are divided into 12 M($\pi^+\pi^-$) bins.
- The $\pi^+\pi^-$ invariant mass spectrum of X(3872) is extracted from the likelihood **fits to the J/$\psi\pi^+\pi^-$ invariant mass spectrum**.
- Yields are corrected for the detector acceptance and efficiency.

$$X(3872) \to J/\psi\rho^0$$
$$\to \mu^+\mu^-\pi^+\pi^-$$

Including an intermediate ρ^0 decay gives better agreement with the data!



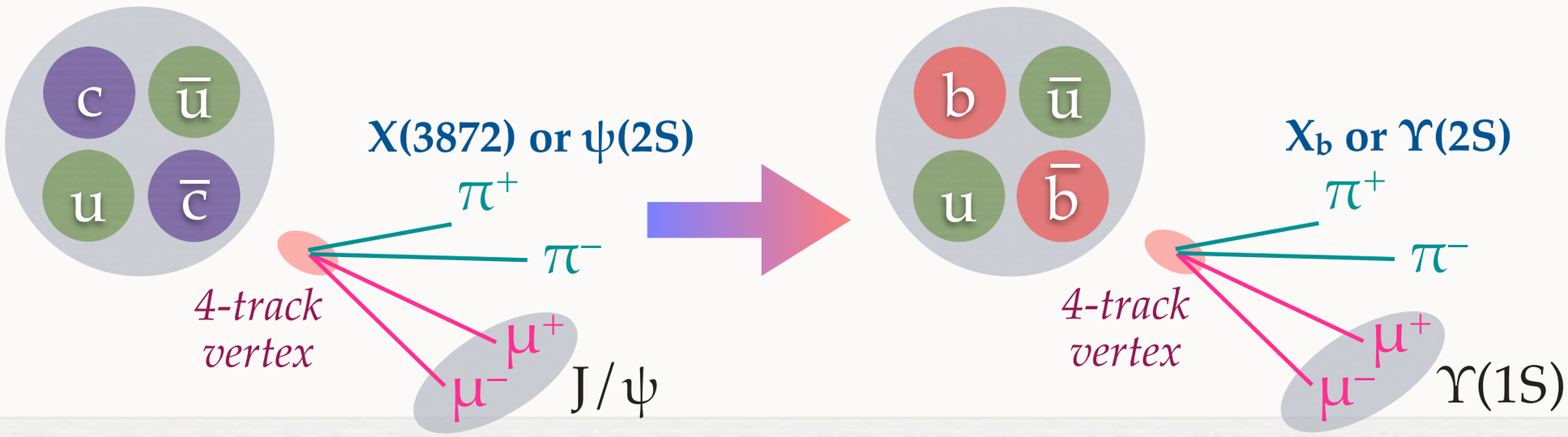


Fit to the J/$\psi\pi^+\pi^-$ mass for the events in the M($\pi^+\pi^-$) bins

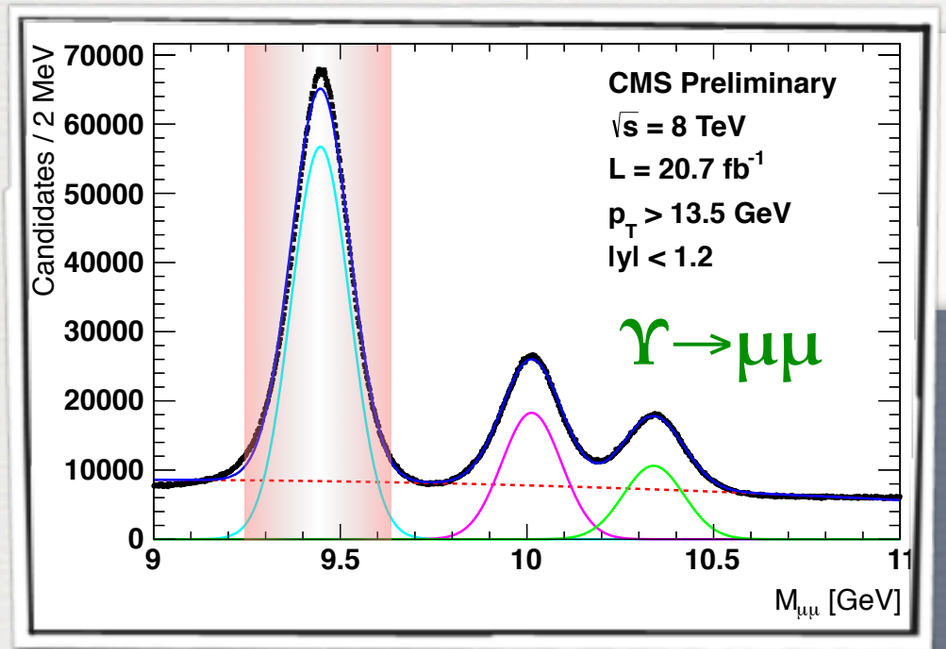
SEARCH FOR BOTTOMONIUM "X"

- A search for X_b – the bottom counterparts of X(3872) is performed based on full 8 TeV data of 20.7 fb^{-1} at CMS.
- Look for narrow resonance in $\Upsilon(1S)\pi^+\pi^-$ final state.
- Theoretical predictions of mass are highly dependent on the model, presumably in the range between 10 to 11 GeV.
- A possible scenario is right at the B*B threshold (10.562 GeV or 10.604 GeV).

Hints of exotic bottomonium have been seen by Belle:
$Y_b(10860) \to \Upsilon\pi^+\pi^-$,
$Z_b(10610), Z_b(10650) \to \Upsilon\pi^\pm$



$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ RECONSTRUCTION



Triggered: $\Upsilon \rightarrow \mu^+\mu^-$

$p_T(\pi^\pm) > 0.4$ GeV,

$\Delta R(\Upsilon, \pi^\pm) < 0.7$

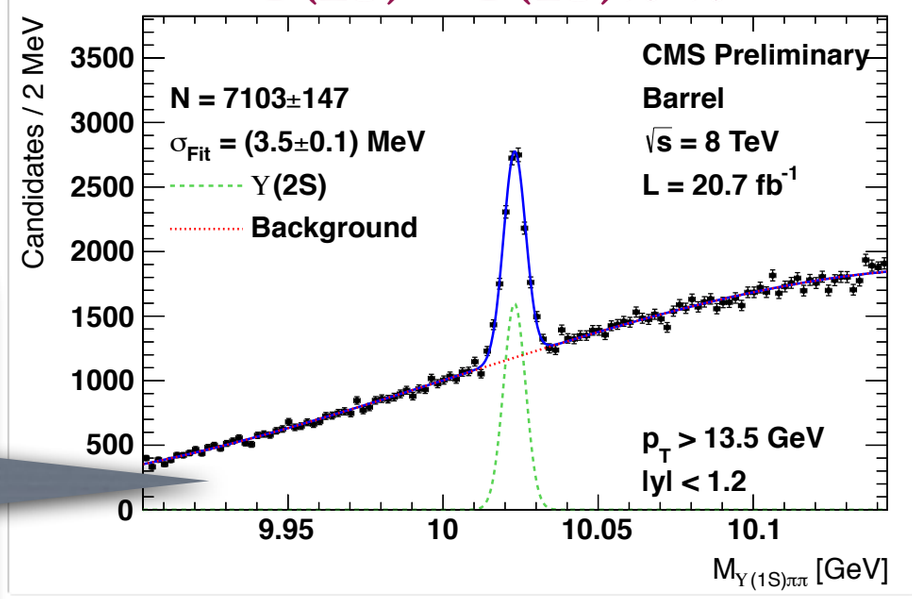
$|M_{\mu^+\mu^-} - M_\Upsilon| < 2.5\sigma$

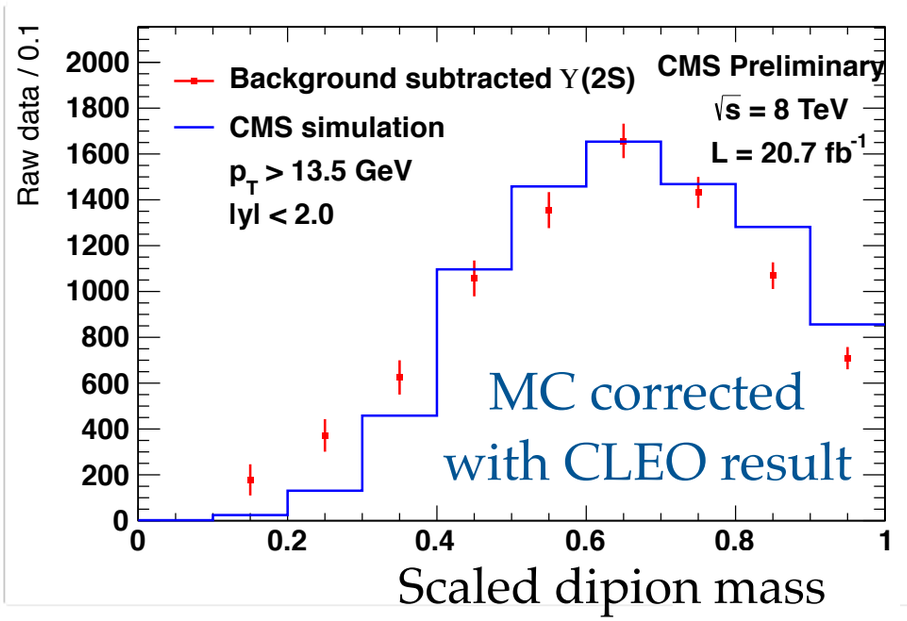
$\Upsilon\pi^+\pi^-$ candidate: $p_T > 13.5$ GeV, $|y| < 2.0$

4-track common vertex+ Υ mass constraint

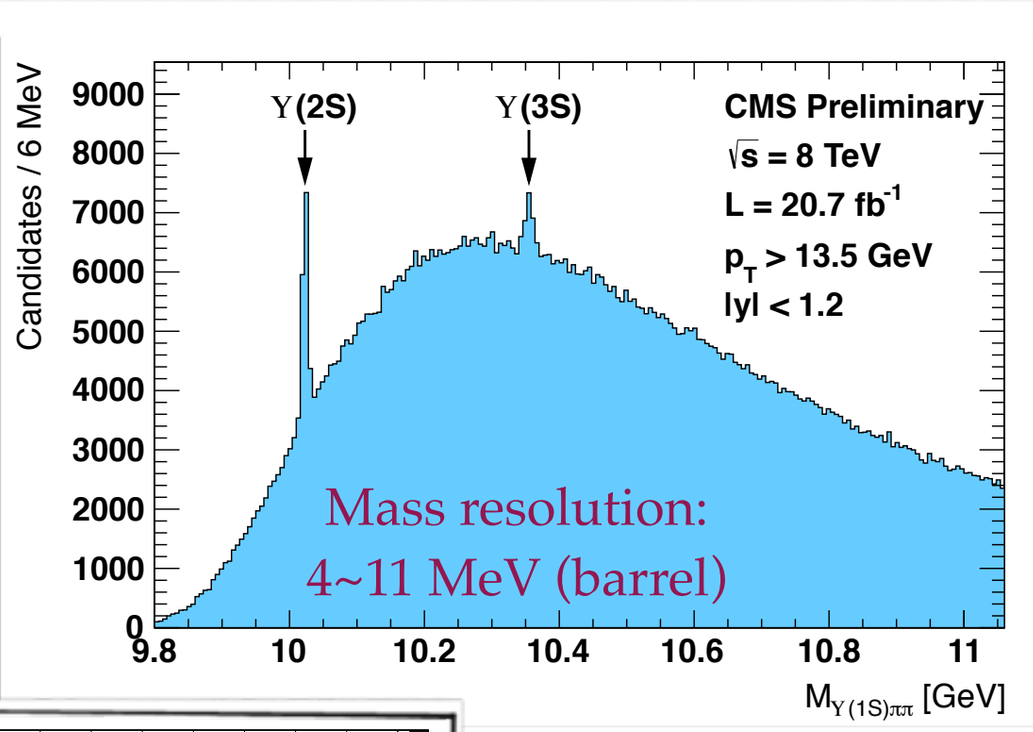
- Pairing $\Upsilon(\rightarrow\mu\mu)$ candidate with two pions.
- Plenty of **$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi\pi$** candidates are reconstructed. MC samples are validated.
- $\Upsilon(2S)$ as the normalization channel.

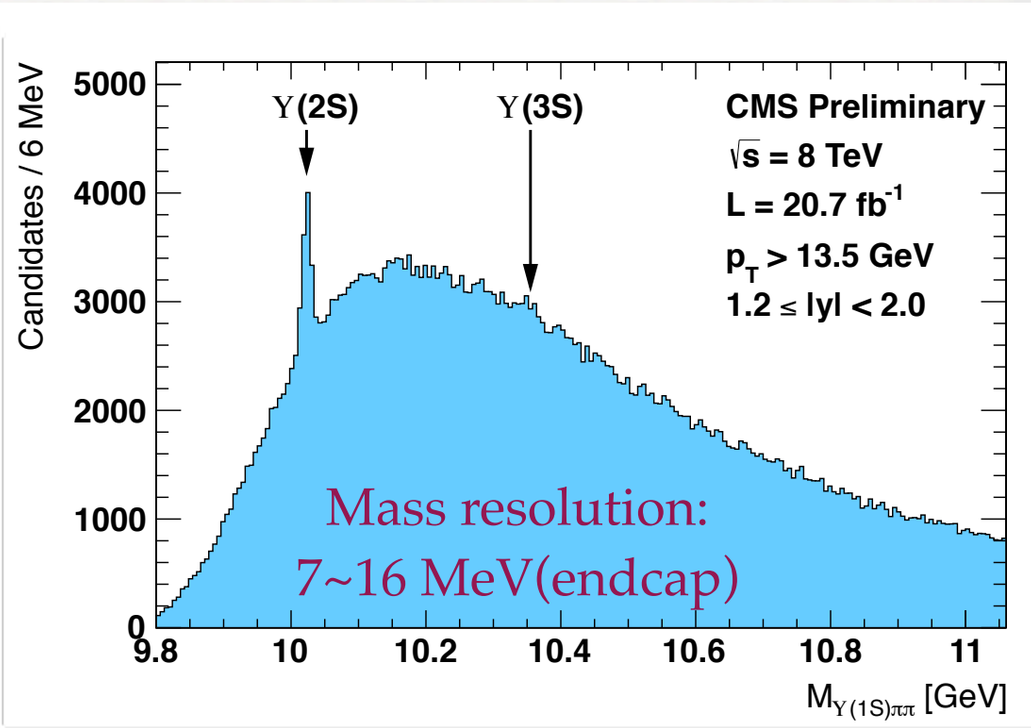
$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$

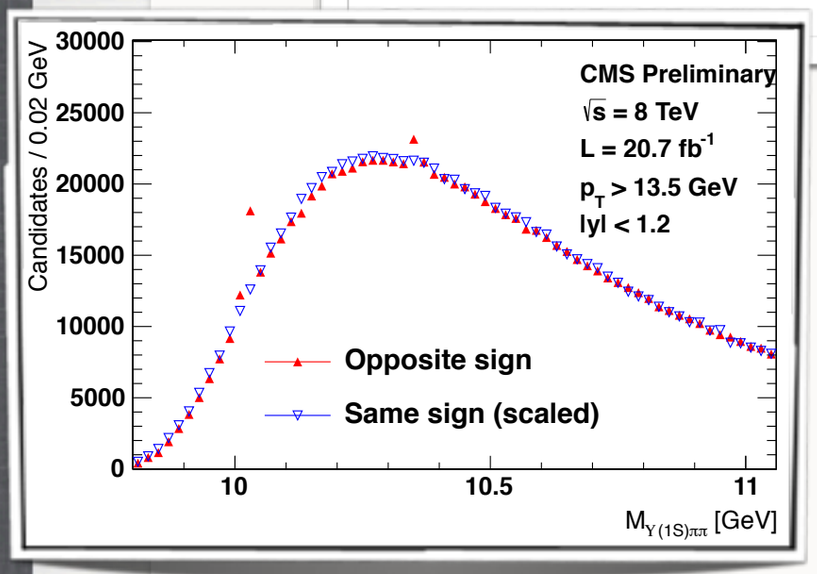




LOOK INTO THE FULL MASS WINDOW





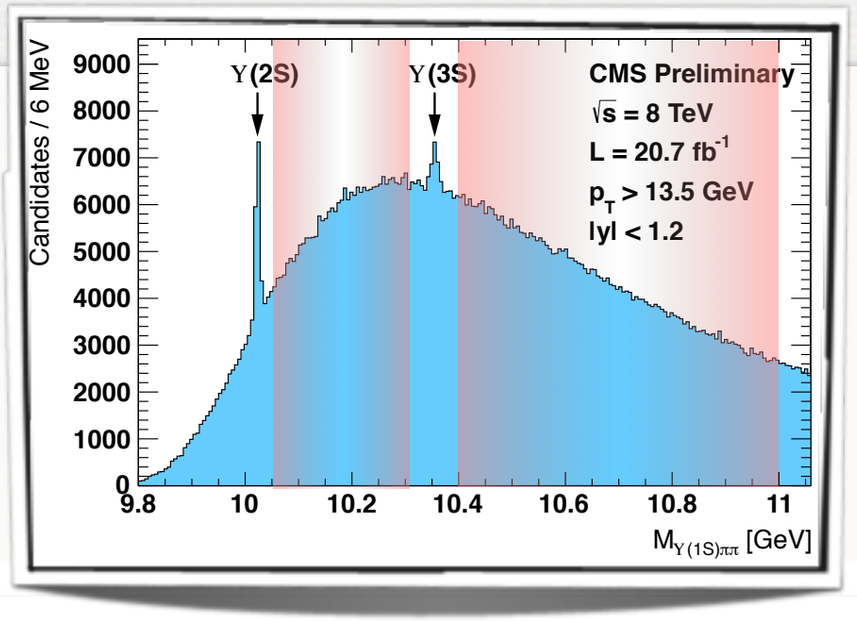


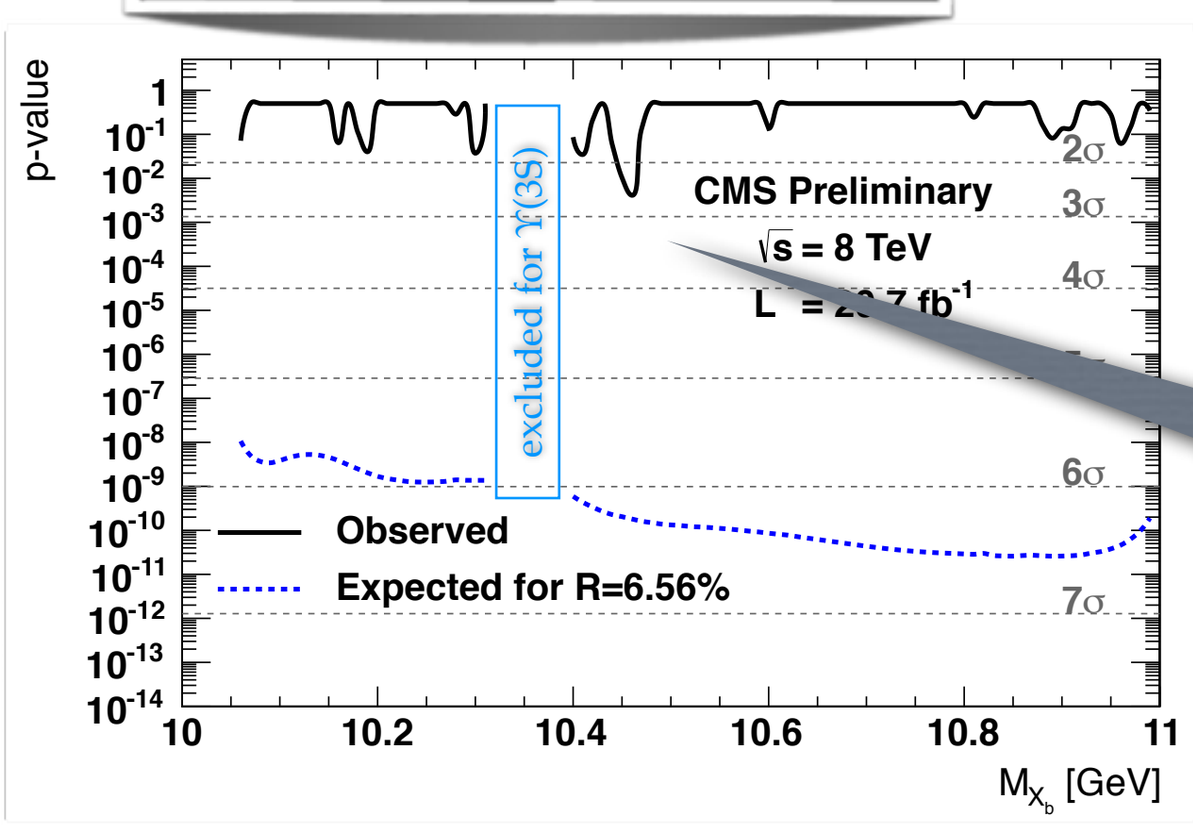
Good agreement between signal and same-sign dipion background.

- Separate the events into barrel ($|y|<1.2$) and endcap ($1.2\leq|y|<2.0$) channels due to their resolution difference.
- On the full mass spectrum, peaks corresponding to **Υ(2S)** and **Υ(3S)** are observed.

However, no obvious hint of new states...

STATISTICS: P-VALUES





- S+B unbinned maximum likelihood fits have been applied to two searching windows.
- The p-values are calculated for each hypothetical X_b mass, with 10 MeV as the interval.

$\Upsilon(2S)$ as the normalization channel:

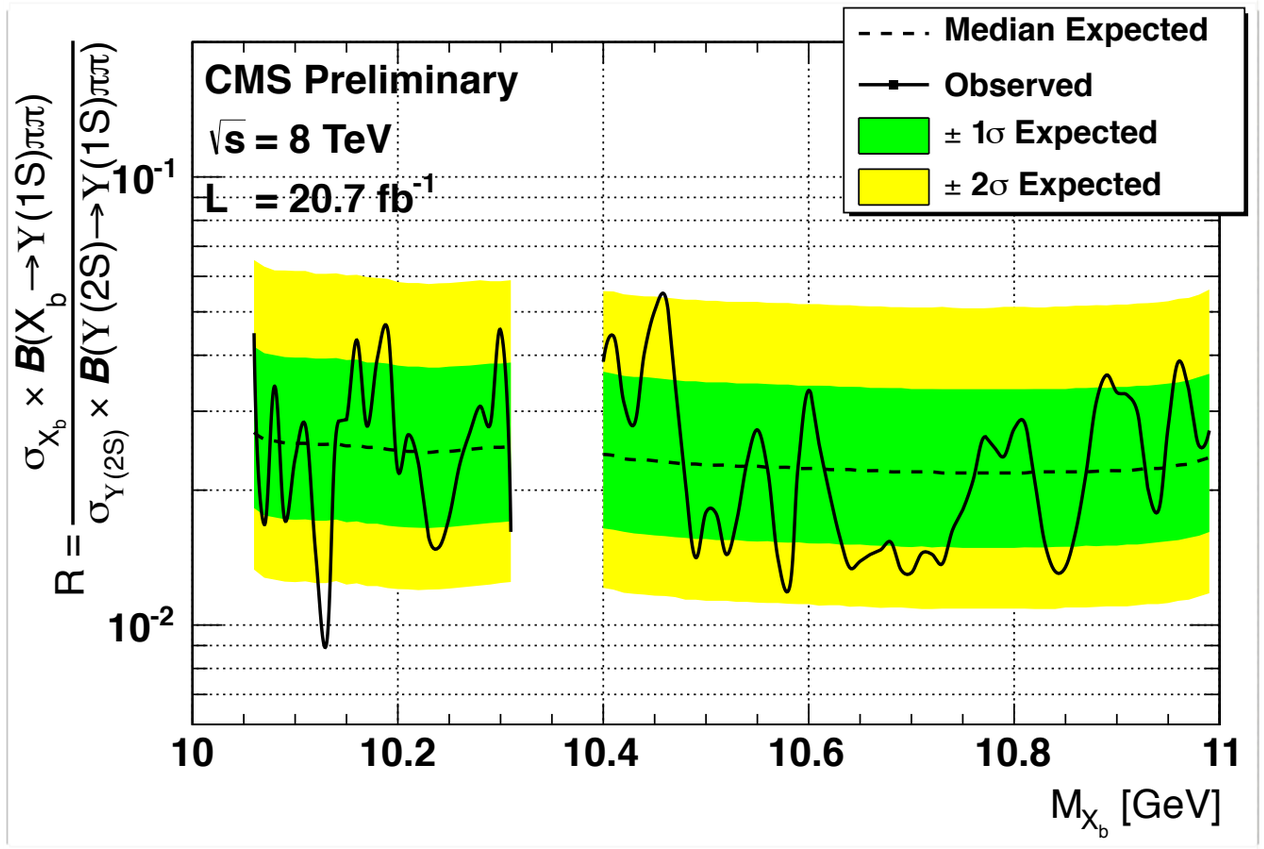
$$R = \frac{\sigma(pp \to X_b) \times \mathcal{B}(X_b \to \Upsilon\pi\pi)}{\sigma(pp \to \Upsilon(2S)) \times \mathcal{B}(\Upsilon(2S) \to \Upsilon\pi\pi)} = \frac{N_{X_b}}{N_{\Upsilon(2S)}} \times \frac{\epsilon_{\Upsilon(2S)}}{\epsilon_{X_b}}$$

If R is **6.56%** [the value of X(3872)], the expected significance should be well above **5σ**.

The highest local significance is **2.6σ** at 10.46 GeV, and it is reduced to **0.8σ** if the correction of LEE is included.

STATISTICS: LIMIT EVALUATION

- Based on the fits, the limit on R has been evaluated for each hypothetical mass of X_b.
- Systematics:
  - Physics: dipion mass distribution, polarization.
  - Signal modeling (resolution, lineshape, interpolation)
  - Background lineshape
- Perform a "Higgs-like" CL_S limit construction.



We have set an upper limit on the cross-section ratio to the Y(2S) as 0.9%~5.4%, depending on the possible mass of the X_b

Ref. https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11016

SUMMARY

- **Production of X(3872) has been studied at CMS:**
  - Ratio of cross section times branching fraction (R) respect to ψ' has been measured.
  - Disentangle the prompt and non-prompt productions.
  - No strong p_T dependence found.
  - The prompt production rate is found to be much smaller than the prediction; prompt cross section as a function of p_T has been measured for the first time.

NEW

Search of X_b in Υ system:

- Looking for peaks other than $\Upsilon(2S)$,$\Upsilon(3S)$ in the $\Upsilon(1S)\pi\pi$ mass spectrum.
- If the R [normalized by $\Upsilon(2S)$] is as large as 6.6%, we should be able to reach 5σ significance through out the whole searching window.
- No obvious hint found. A limit on R has been set to 0.9%~5.4% with full 2012 CMS data of 20.7 fb^{-1}.

CMS has a great potential in the field of exotic quarkonia studies. Stay tuned – more results to be expected!

See https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH for more!