Quarkonium Physics at CMS

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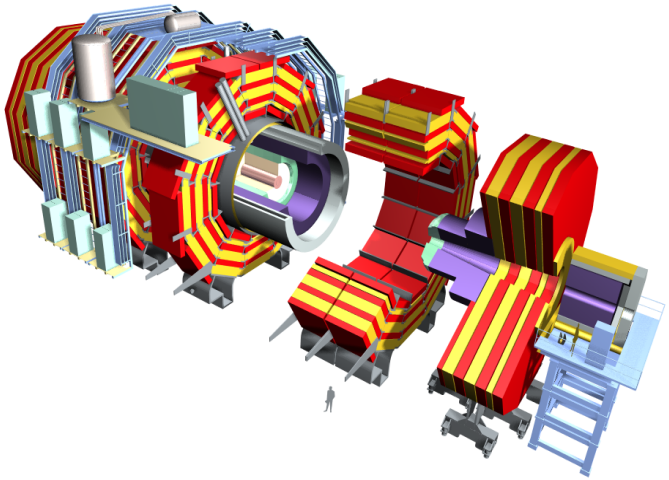
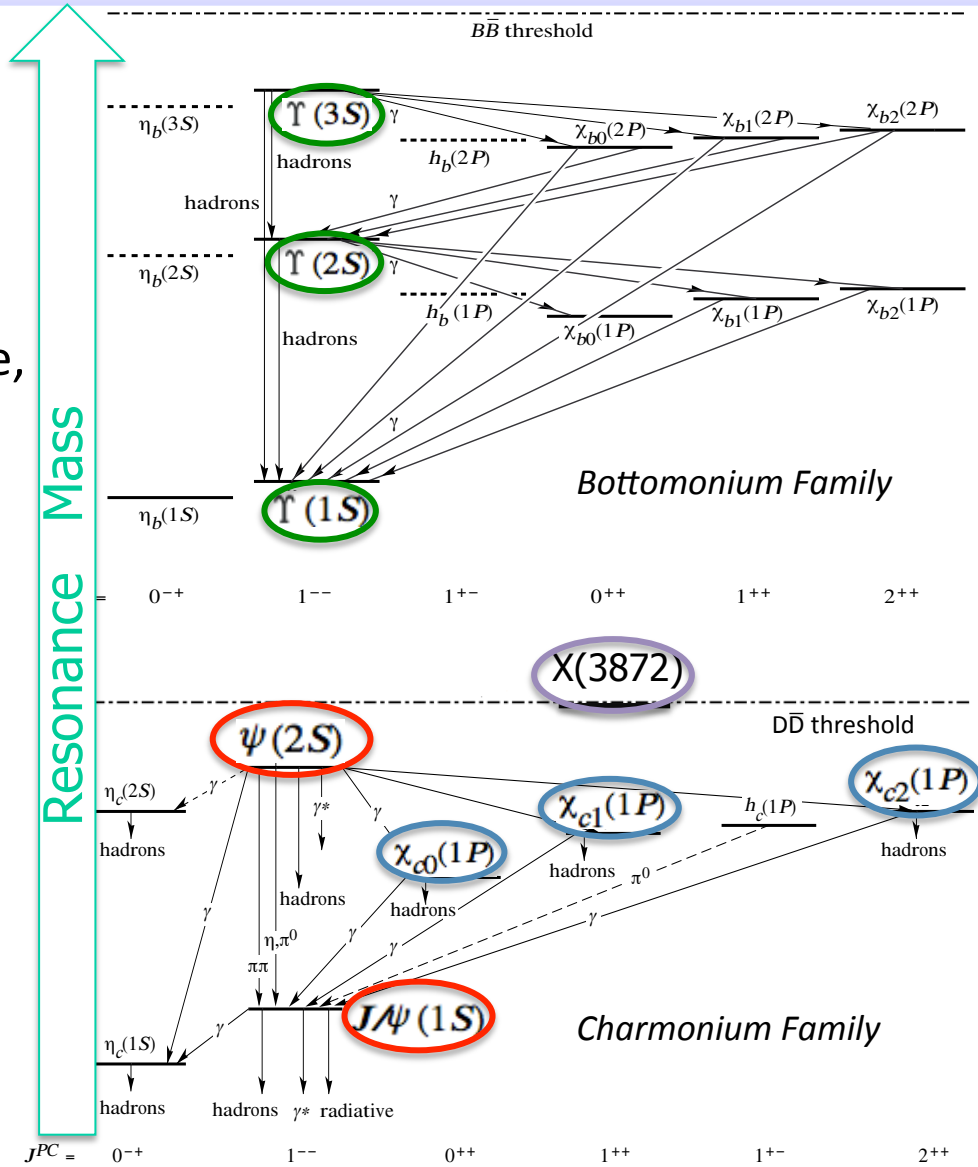
on Behalf of the CMS Collaboration



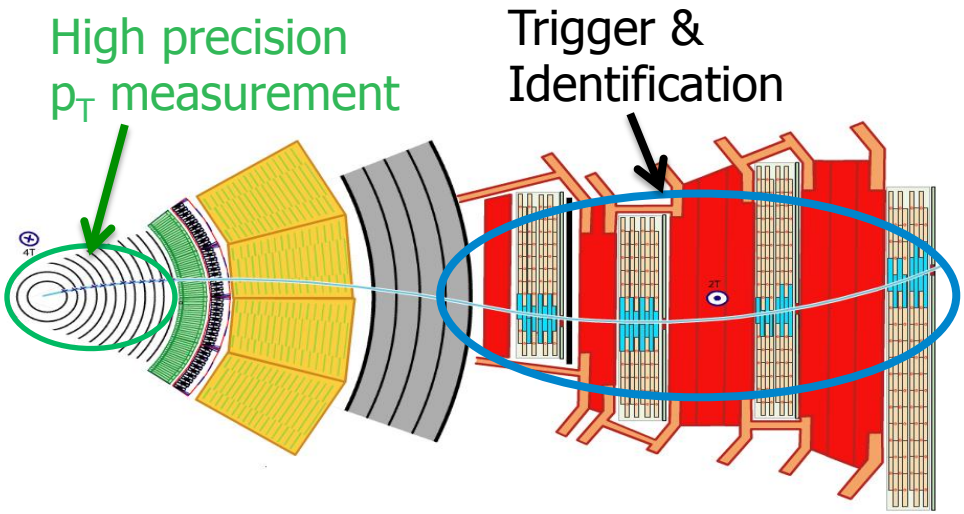
CMS Quarkonium Studies

- Heavy quarkonia are an excellent laboratory for understanding QCD
  - non-relativistic due to their high mass
  - nonperturbative effects can be simplified and constrained
- Definitive understanding still a challenge, several models competing for confirmation
- Renewed interest in quarkonium spectroscopy since the discovery of the XYZ exotic states:
  - search of new possible states
  - new measurements needed to understand their true nature
- CMS already studied many quarkonia with di-muons final states
  - production cross section for S-wave quarkonia
  - observation of χ_{cJ} states
  - study of the X(3872) exotic

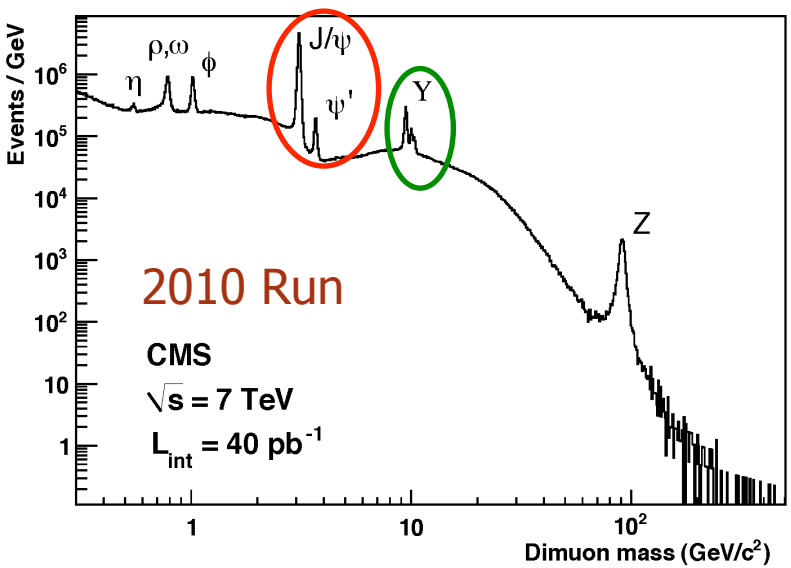


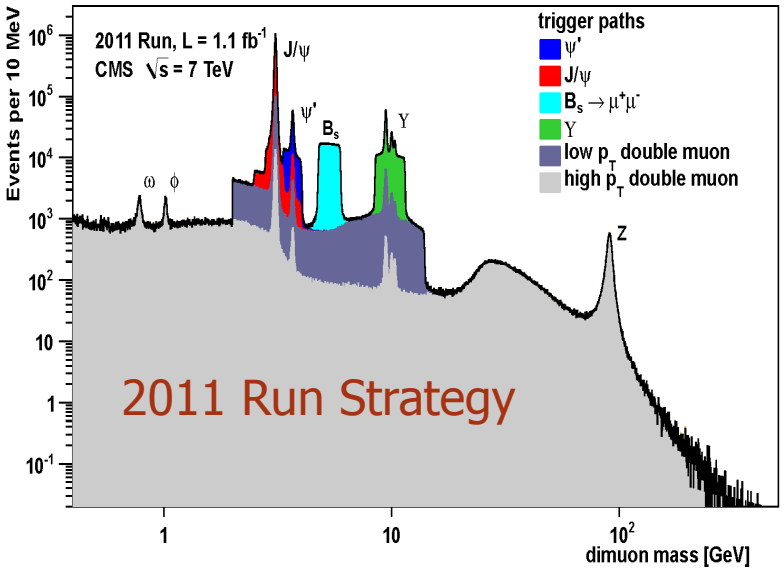
Muons in CMS

- Muon system information matched to an inner-tracker track for improved momentum resolution



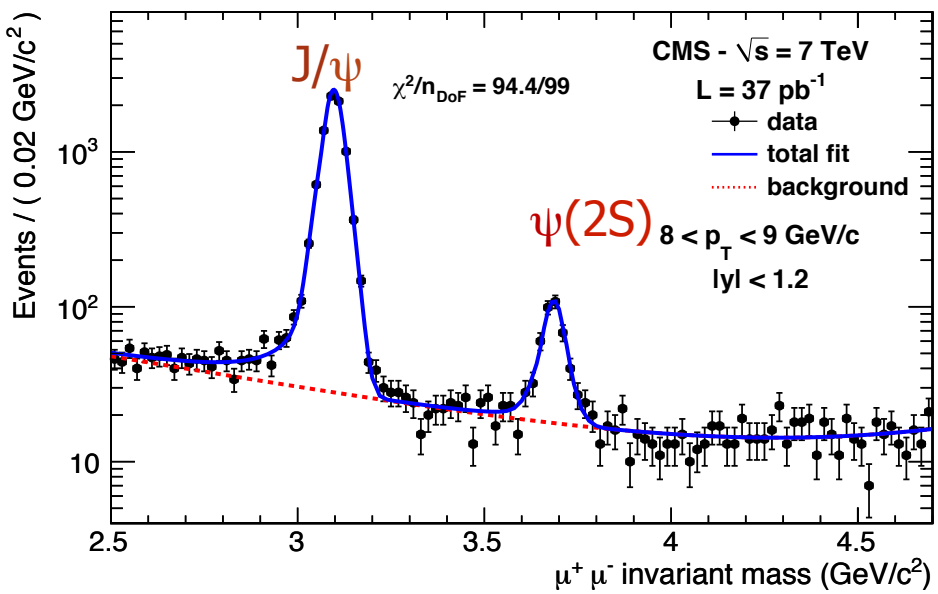
- Inner Tracker:
  - Silicon pixel and strip layers
- Muon System
  - 3 types of gaseous detectors
- Trigger choices of key importance for low energy studies
  - Physical objects reconstructed at trigger level to select high purity signals

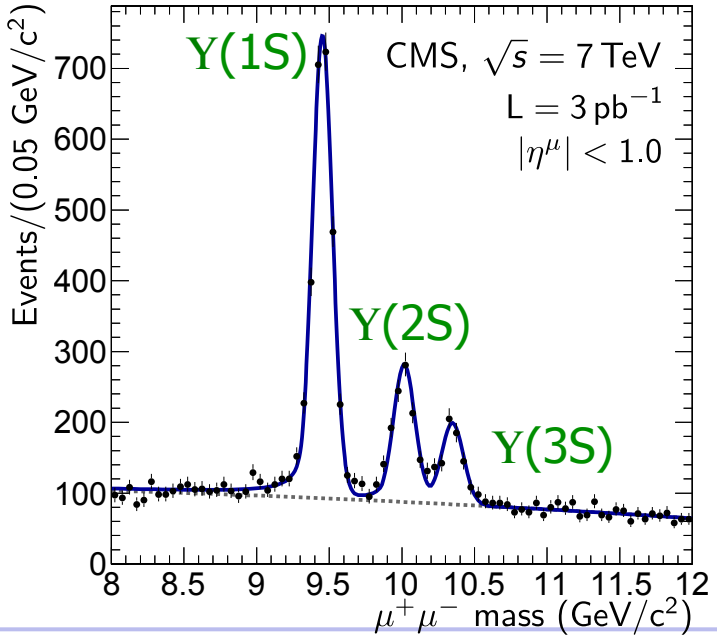




S-wave quarkonium states

- Unbinned Maximum Likelihood fit to $\mu^+\mu^-$ invariant mass distributions
- Signals modeled with Crystal Ball functions
- Mass differences are fixed from PDG, common resolution value (scaled by mass)
- Yields then corrected for Acceptance (from MC) and Efficiency (from data-driven methods)
  - ✓ muon acceptance is strongly dependent on production polarization





Inclusive J/ψ Production

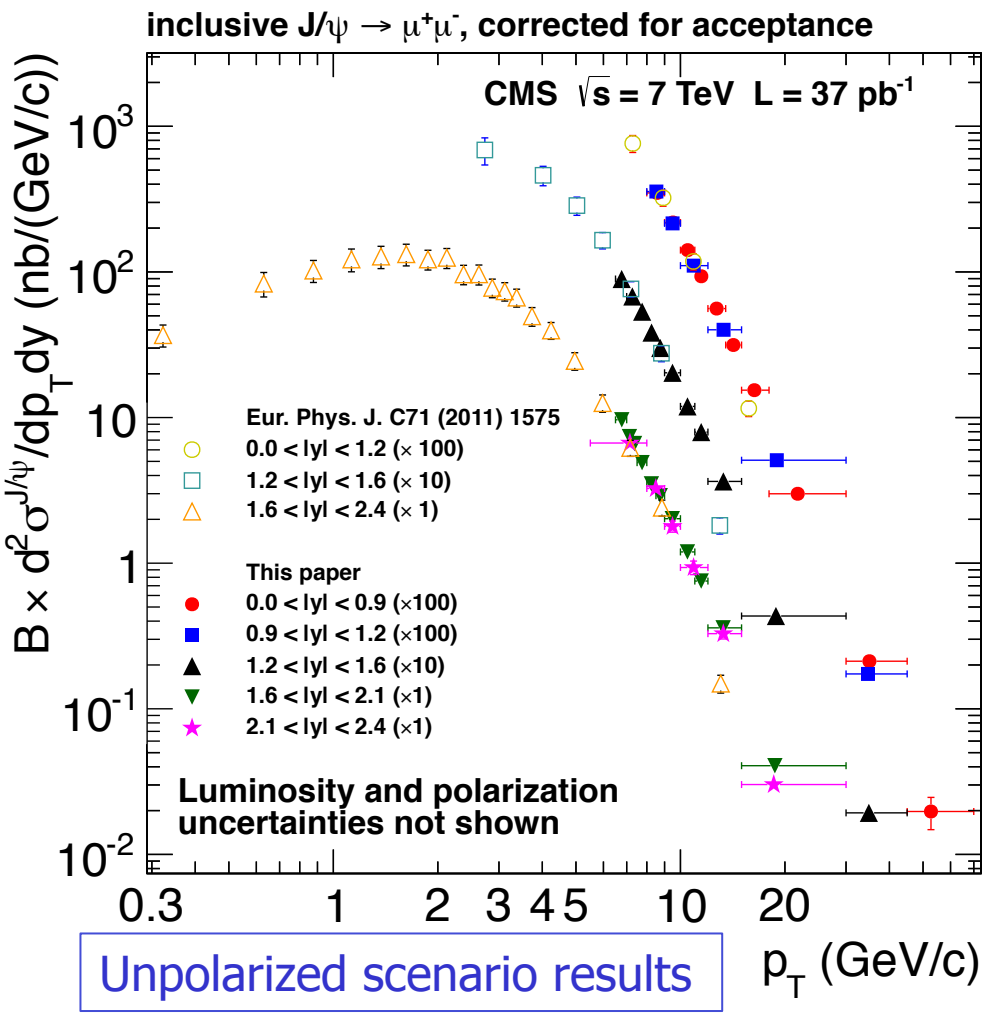
Eur.Phys. J C71, 1575 (2011)
JHEP 02, 011 (2012)

$$\frac{d^2\sigma}{dp_T dy}(J/\psi)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-) = \frac{N^{corr}_{J/\psi}(p_T,|y|)}{\int L\,dt\cdot\Delta p_T\cdot\Delta y}$$

- Inclusive cross section comprises 3 production methods in hadron collisions:
  - Prompt:
    - ✓ Directly from pp collisions
    - ✓ "Feed-down" from heavier states as χ_c and $\psi(2S)$
  - Non Prompt
    - ✓ from b-hadron decays

- Very low p_T range covered using first 314 nb^{-1} of data

- With 37 pb^{-1} already covered a p_T range up to 70 GeV/c

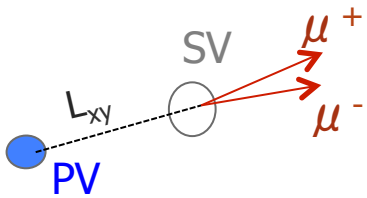


Unpolarized scenario results

Non prompt Fraction

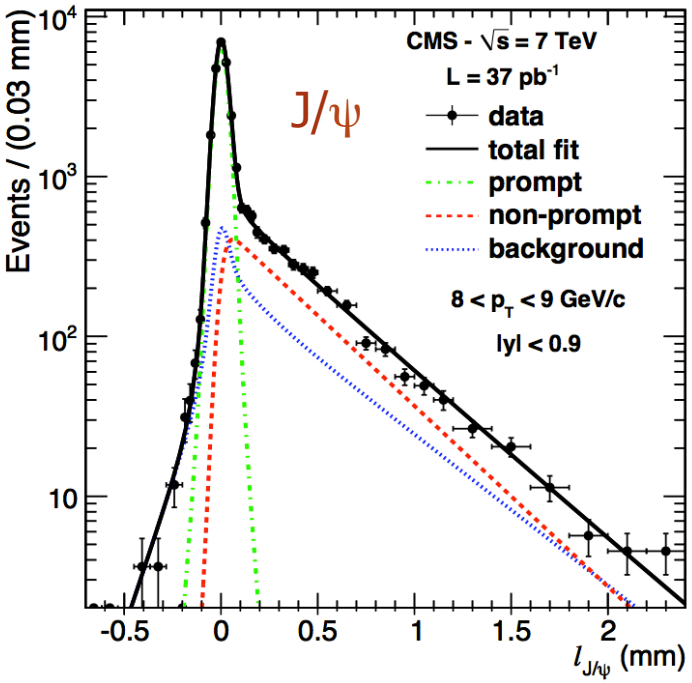
- Fraction coming from b-decay extracted with a 2-Dimensional fit of invariant mass and "pseudo-proper" decay length

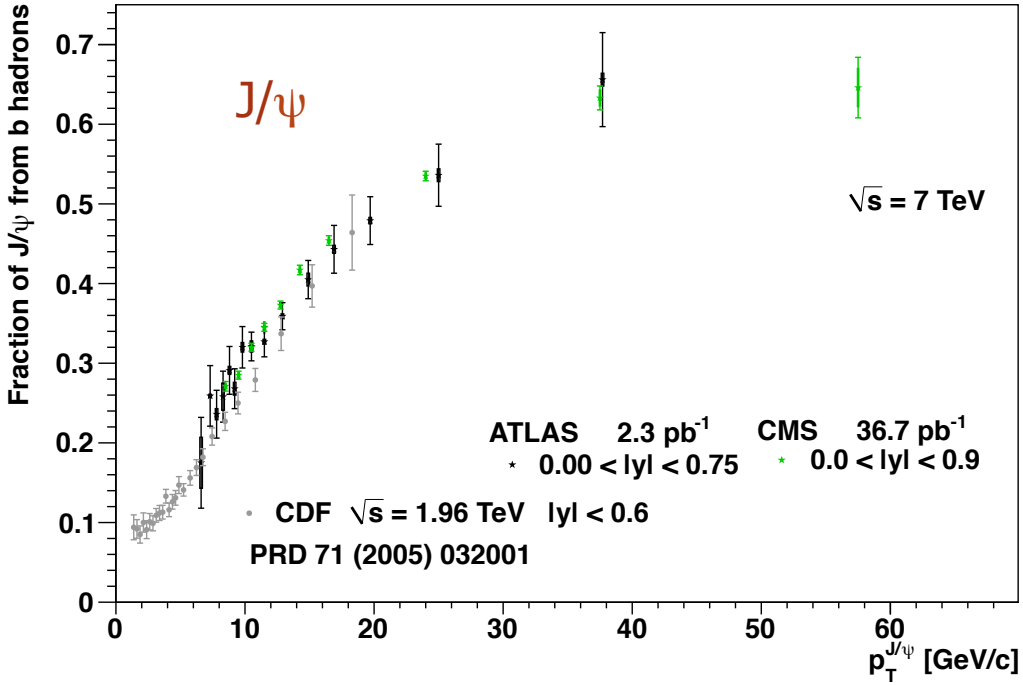
$$l_{J/\psi} = \frac{L_{xy} \cdot m_{J/\psi}}{p_T}$$



- $l_{J/\psi}$ distribution components:
  - prompt ➔ Resolution function
  - non prompt ➔ Resolution function convoluted with exponential
  - background ➔ Pre-fitted in mass sidebands

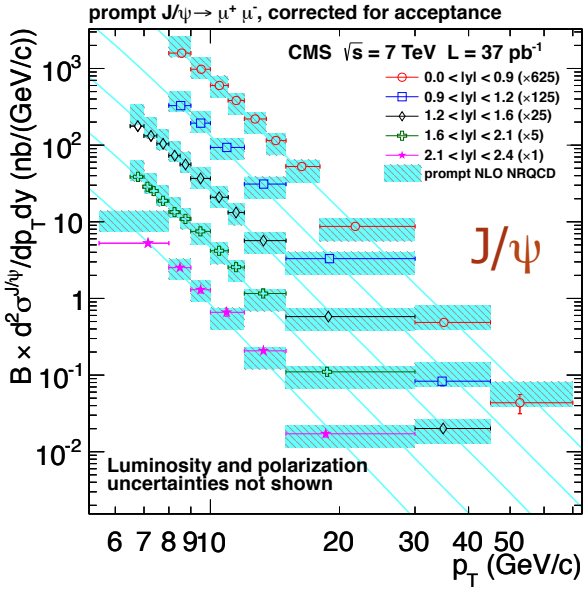
- Decay length resolution described by "per-event uncertainty" on $l_{J/\psi}$
- Results in agreement with ATLAS, higher fraction of J/ψ from B-decays at LHC energy w.r.t. CDF

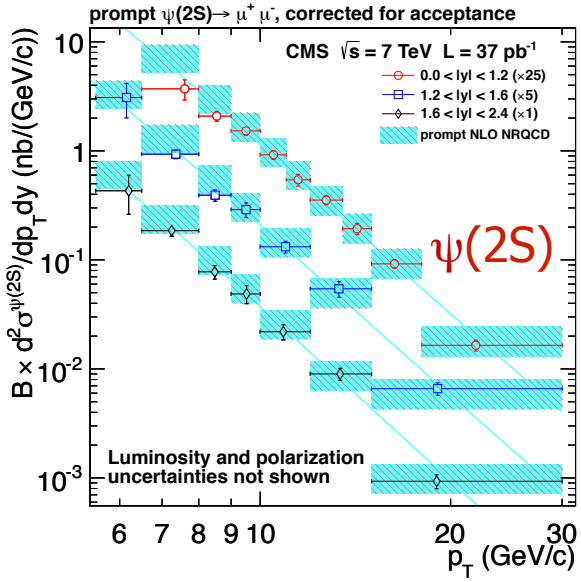




ψ(nS) cross sections

JHEP 02, 011 (2012)

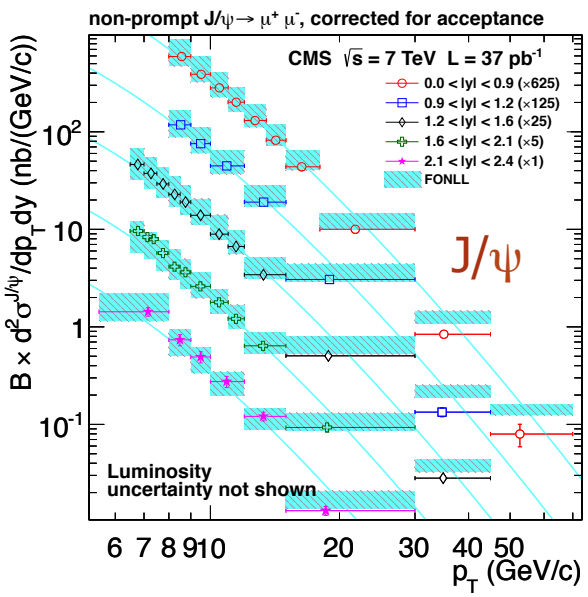


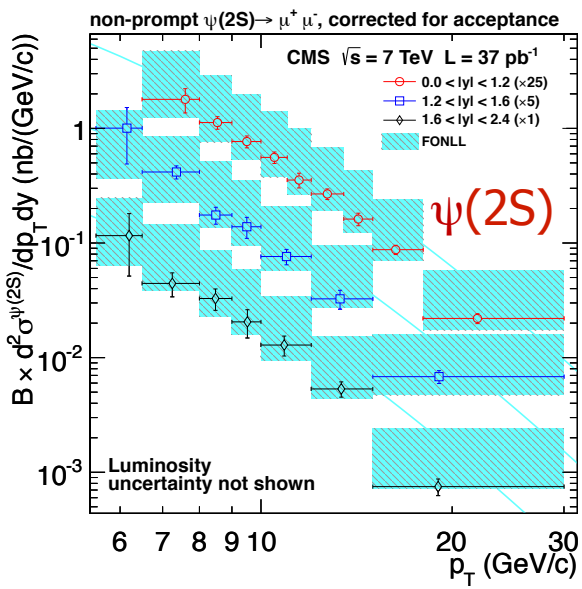


PROMPT

Excellent agreement with NRQCD predictions

- for J/ψ, feed down effect included in theory
- reduced theoretical uncertainties for ψ (2S) in absence of feed-down





NON-PROMPT

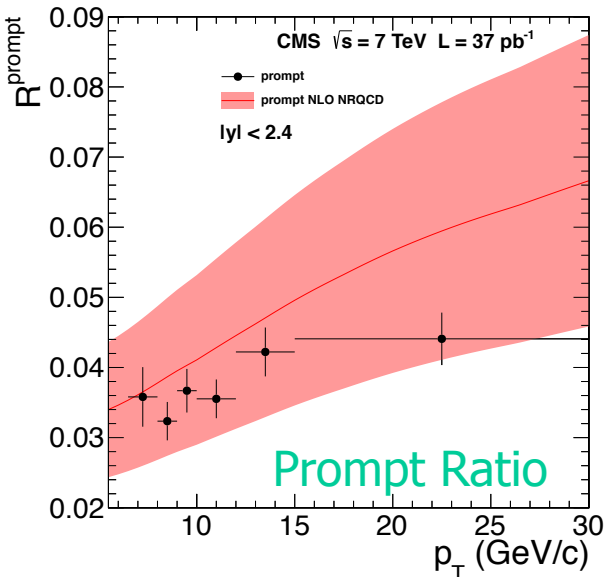
Comparison with FONLL predictions:

- For J/ψ:
  - agreement below 30 GeV
  - above 30 GeV FONLL overestimate data
- For ψ (2S):
  - agreement in the measurement region

ψ(2S) to J/ψ cross-sections ratios

JHEP 02, 011 (2012)

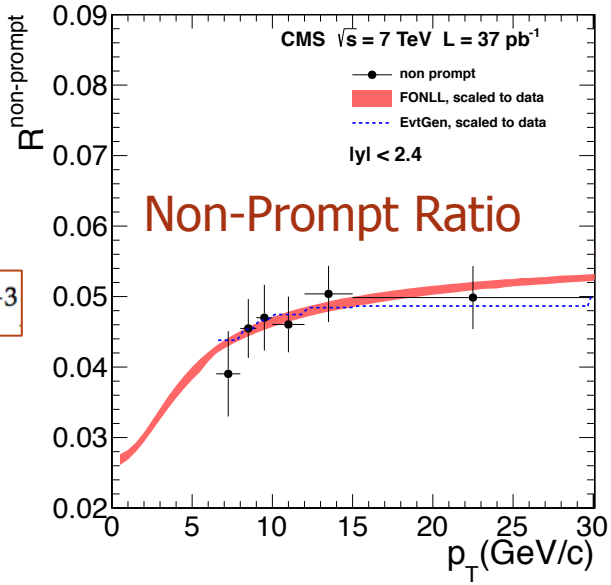
- **Cross Section Ratio calculation:**
  - Systematic uncertainties largely cancel (Luminosity, Single Muon Efficiencies…)
  - Direct production with same polarization
    - ✓ Residual polarization effect from J/ψ coming from feed-down
  - No |y| dependence seen, results as function of p_T



- **B → ψ(2S) X Branching Fraction**
  - measured fitting the non-prompt cross-section ratio with FONLL or EvtGen curves

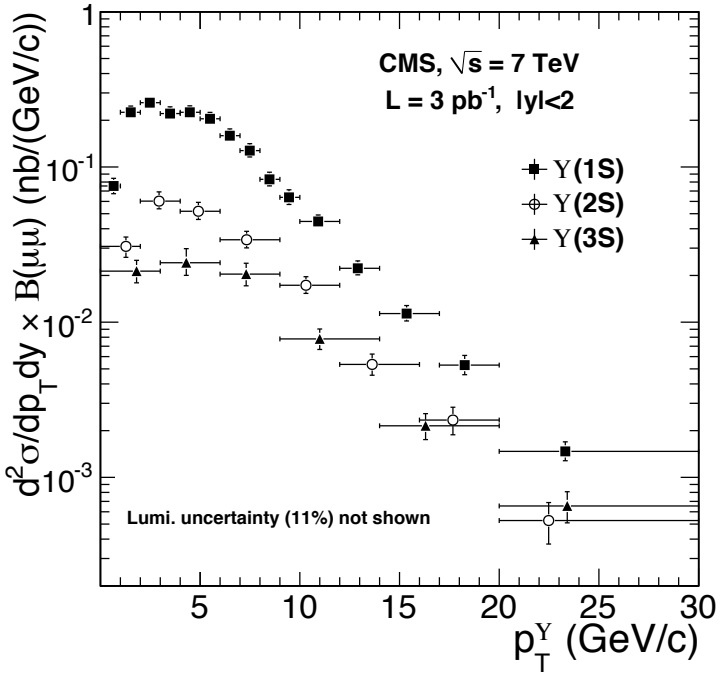
$$\mathcal{B}(\mathrm{B} \to \psi(2S)X) = (3.08 \pm 0.12(\text{stat.+syst.}) \pm 0.13(\text{theor.}) \pm 0.42(\mathcal{B}_{\mathrm{PDG}})) \cdot 10^{-3}$$

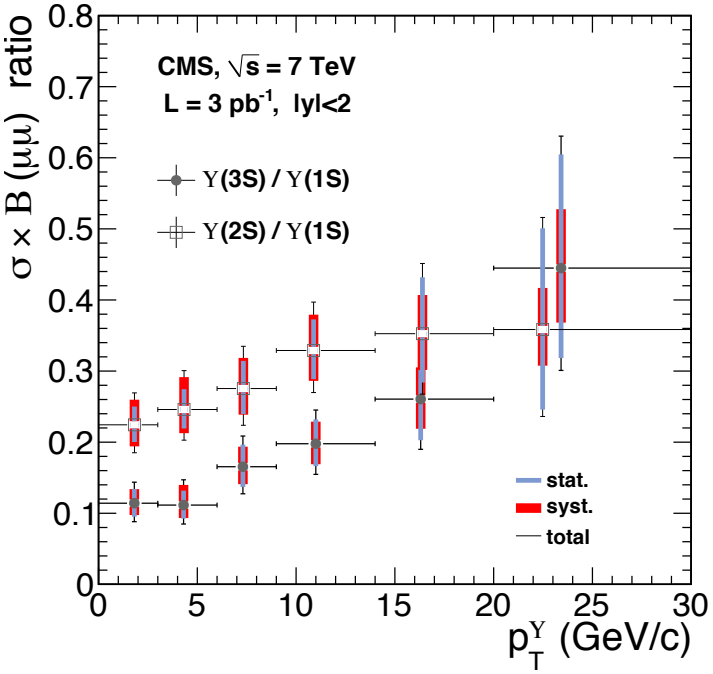
  - In agreement with world average $(4.8 \pm 2.4) \cdot 10^{-3}$
    - ✓ improving relative uncertainty by factor 3
    - ✓ main uncertainties from other PDG BRs



ϒ(nS) Cross Sections

Phys. Rev. D 83, 112004 (2011)

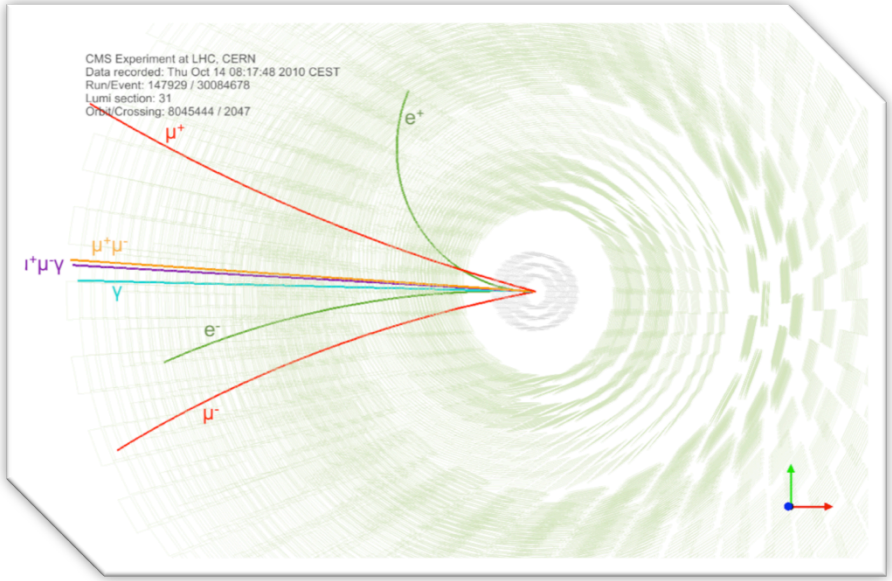


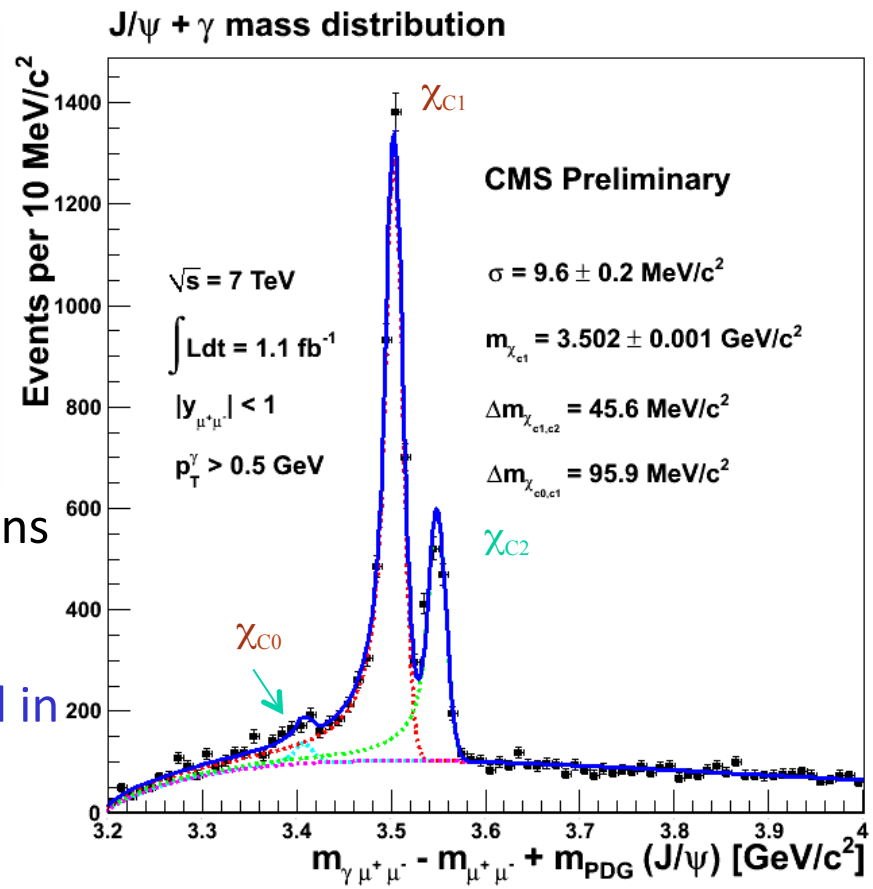


- Unpolarized ϒ(nS) assumption
- ϒ(1S) and ϒ(2S) include feed-down from higher-mass states
- Results compared to D0 and CDF measurements
  - Assuming cross section uniform in rapidity an increase by a factor 3 is observed at √s = 7 TeV
- Consistent shape to PYTHIA both as function of p_T and |y|
  - integrated cross section overestimated by a factor 2

$\chi_{cJ} \rightarrow J/\psi\ \gamma$ mass distribution

CERN-CMS-DP-2011-011





- Excellent resolution (< 10 MeV) for photons converted in the tracker volume
- χ_{c1} and χ_{c2} ($\Delta m \sim 45$ MeV) peaks resolved in the $J/\psi\ \gamma$ spectrum
- Studies on χ_{cJ} states
  - discriminate between different theoretical production models
  - evaluate the feed-down corrections to prompt J/ψ production

The X(3872) state

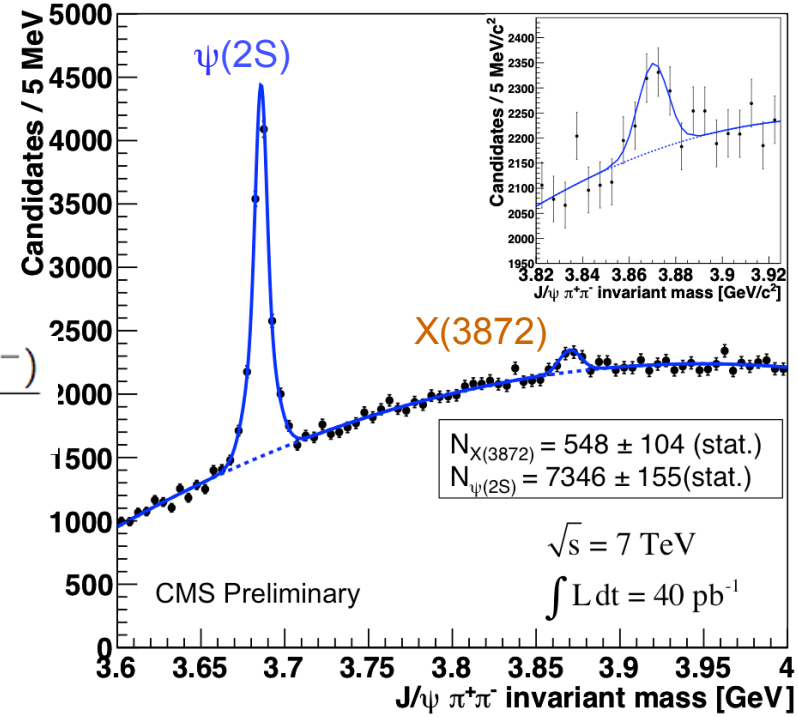
CMS-PAS-BPH-10-018

- Discovered in 2003 by Belle → its nature still unclear
- A clear signal is established in 2010 in the $J/\psi\ \pi^+\pi^-$ decay channel
- A pair of compatible good quality opposite-charged tracks associated to a reconstructed J/ψ
  - 4-track vertex fit with J/ψ mass fixed to the PDG value
- Measured the quantity

$$R = \frac{\sigma(pp \to X(3872) + anything)BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + anything)BR(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

in the kinematical region

$p_T(X) > 8$ GeV and $|y(X)| < 2.2$



- Acceptance and efficiency correction from simulation applied on the mass spectrum yields
  - Pythia 6 with mass of χ_{c1} ($J^{PC}=1^{++}$) set to 3.872 GeV
  - Null polarization assumed
  - 30% non-prompt fraction assumed
- Ratio results

R = 0.087 ± 0.017 (stat.) ± 0.009 (syst.)

Conclusions

CMS has issued several studies on heavy quarkonia with the first LHC data:

- Differential cross-sections in p_T and $|y|$ of J/ψ and $\psi(2S)$ mesons
  - prompt and non-prompt contributions separated
  - general good compatibility with NRQCD and FONLL predictions
  - consistent results with other LHC experiments

- Differential cross-sections in p_T for $\Upsilon(nS)$ states
  - shape compatible to PYTHIA and results at Tevatron

- χ_{cJ} peaks resolved in their radiative decay to J/ψ, using converted photons

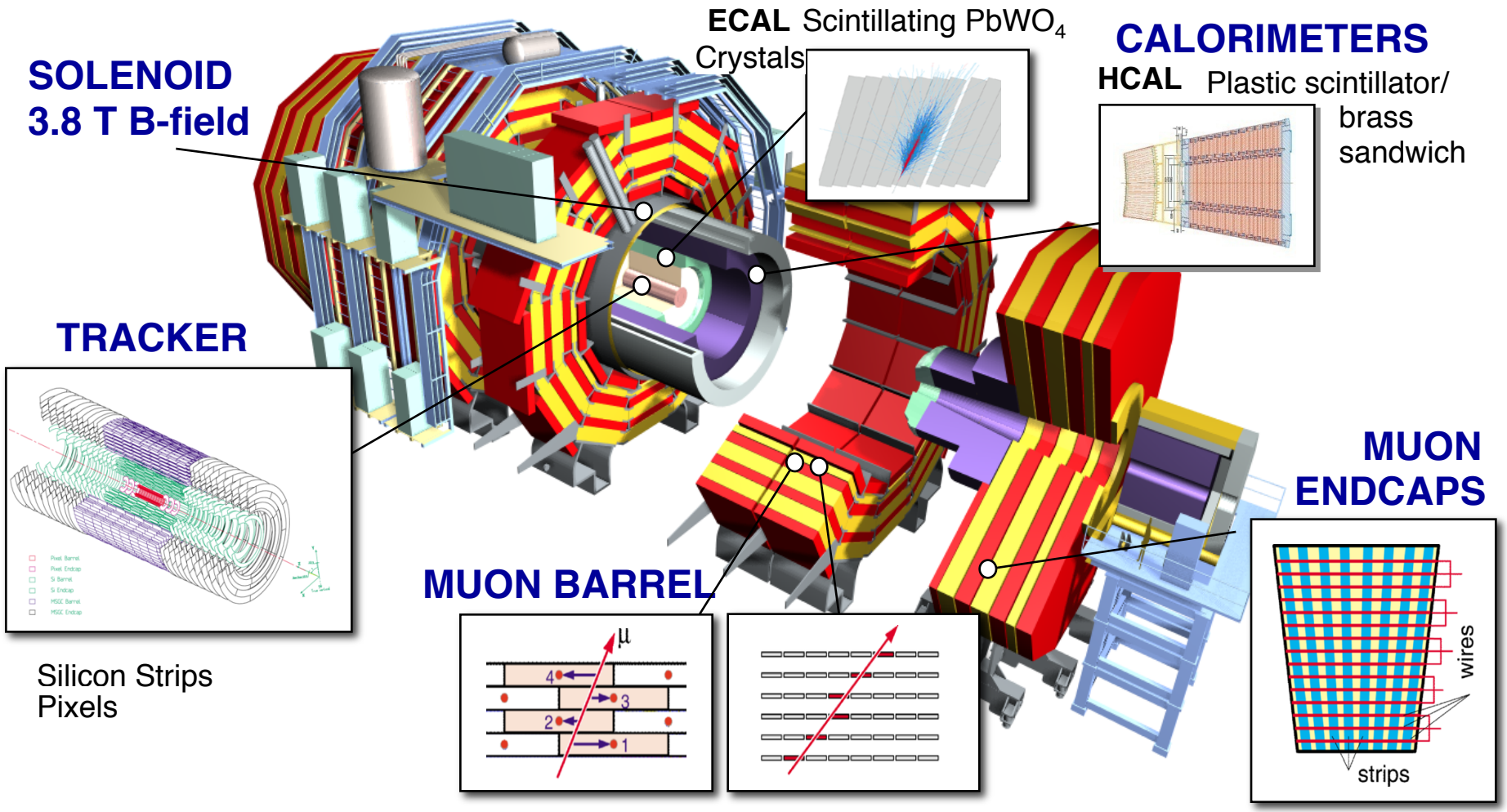
- Measurement for the X(3872) to $\psi(2S)$ cross section ratio

Bibliography

- " J/ψ prompt and non-prompt cross sections in pp collisions at √s = 7 TeV ", Eur.Phys. J C71, 1575 (2011)
- " J/ψ and ψ(2S) production in pp collisions at √s = 7 TeV ", JHEP 02, 011 (2012)
- " ϒ production cross section in pp collisions at √s = 7 TeV ", Phys. Rev. D 83, 112004 (2011)
- " Observation of the χ_c states with 1.1fb^{-1} ", CERN-CMS-DP-2011-011
- " Measurement of the production cross section ratio of X(3872) and ψ(2S) ", *CMS-PAS-BPH-10-018*

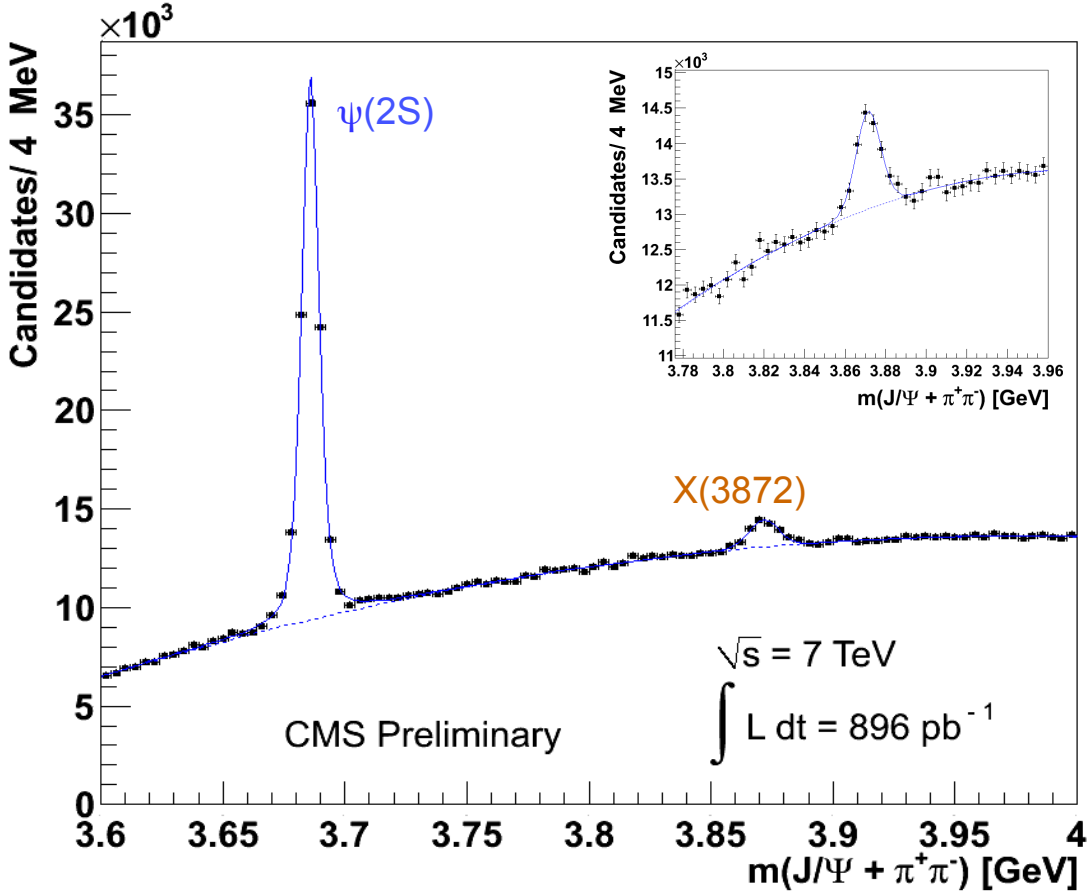
BACKUP

The CMS detector

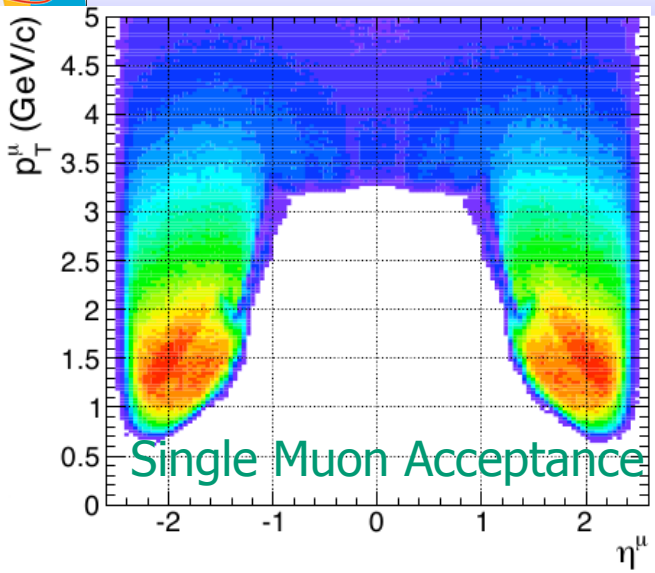


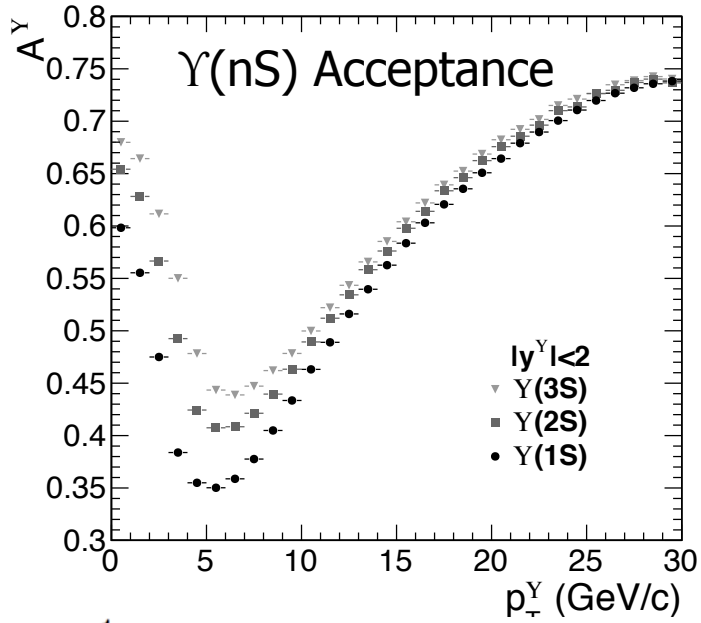
X(3872) with 2011 Data

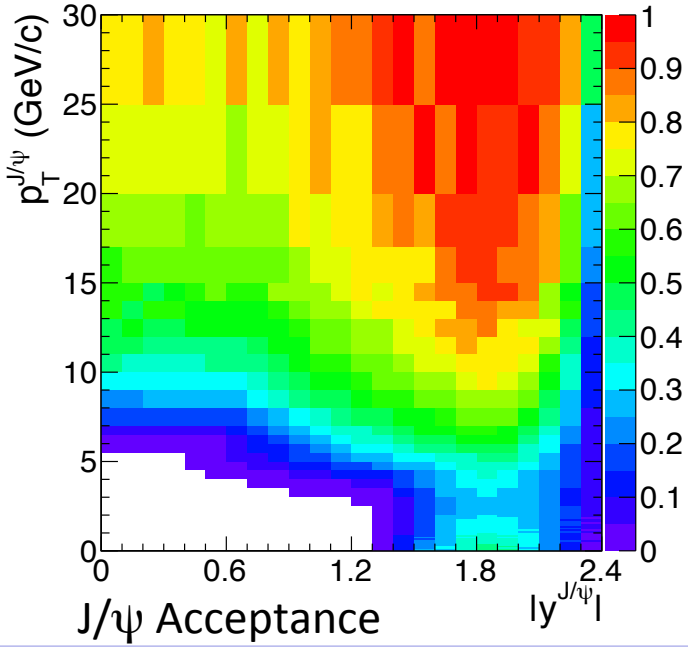
- In 2011 larger statistic collected with a J/ψ trigger restricted to the CMS barrel
- With first 896 pb^{-1}
  - $N_{\psi(2S)} = 72594 \pm 518$ (stat)
  - $N_{X(3872)} = 5303 \pm 341$ (stat)

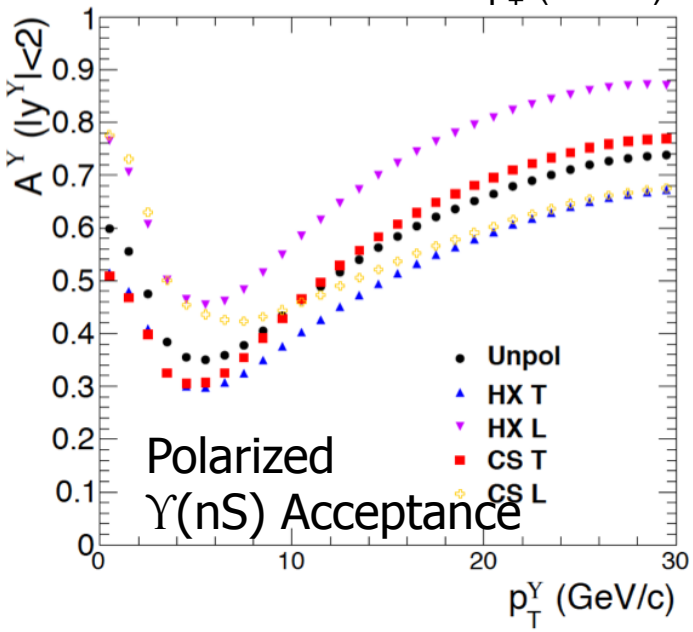


Acceptances

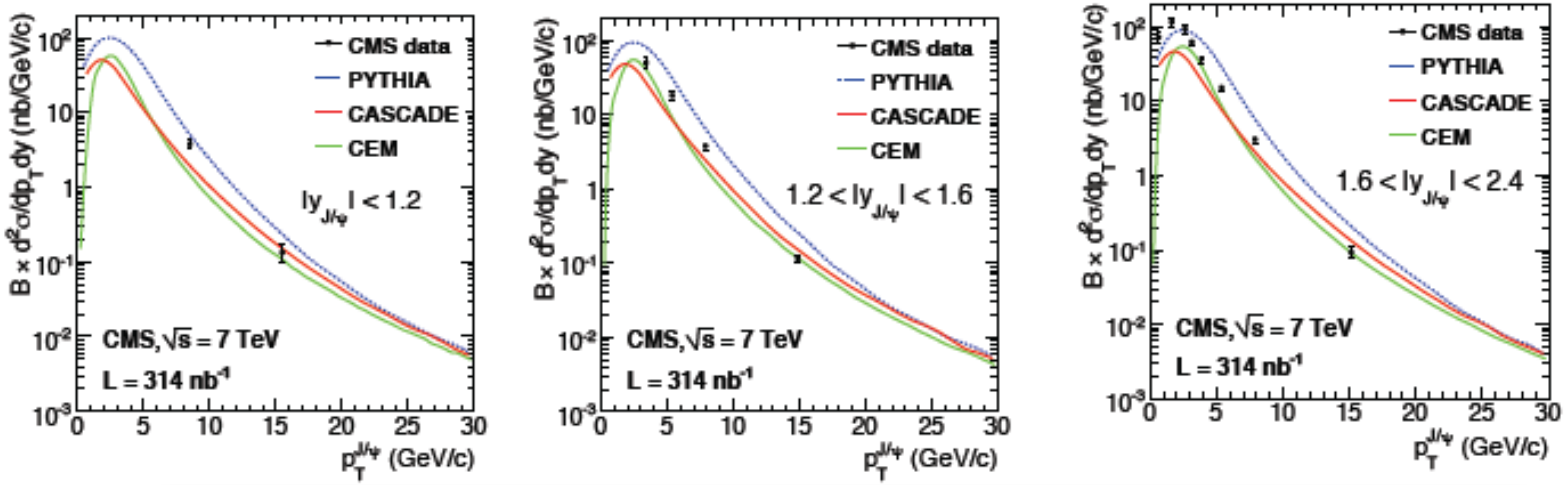




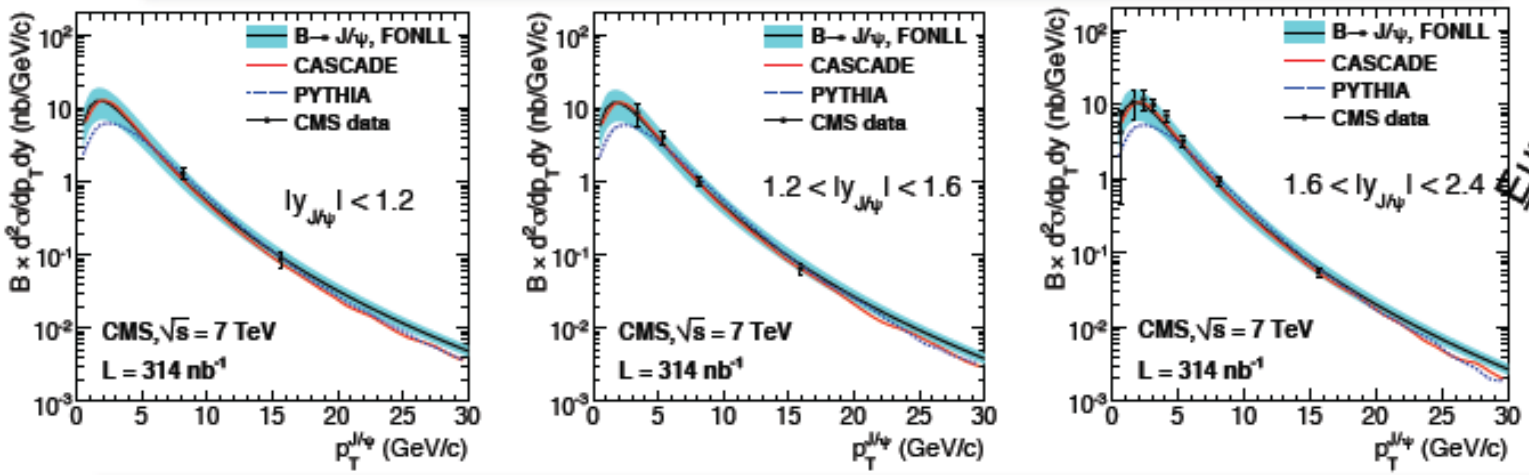




First CMS paper on J/ψ



$$\sigma(pp \to J/\psi + X) \cdot BR(J/\psi \to \mu^+\mu^-) = 70.9 \pm 2.1(\text{stat}) \pm 3.0(\text{syst}) \pm 7.8(\text{luminosity})\ \text{nb}$$



$$\sigma(pp \to bX \to J/\psi X) \cdot BR(J/\psi \to \mu^+\mu^-) = 26.0 \pm 1.4\ (\text{stat}) \pm 1.6\ (\text{syst}) \pm 2.9\ (\text{luminosity})\ \text{nb}$$

Eur.Phys.J. C71 (2011) 1575

ψ(nS) Cross-section overview

$$\frac{d^2\sigma}{dp_T dy}(J/\psi)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)=\frac{N^{corr}_{J/\psi}(p_T,|y|)}{\int L\,dt\cdot\Delta p_T\cdot\Delta y}$$

N_{fit} = signal yield from fit to $\mu\mu$ invariant mass

$\int$ Ldt = integrated luminosity (4% uncertainty)

A = geometrical and kinematical acceptance

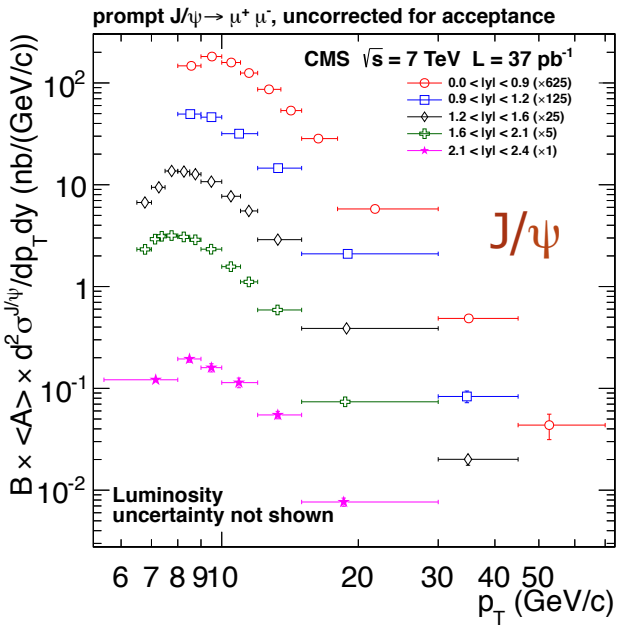
- Strongly dependent on production polarization

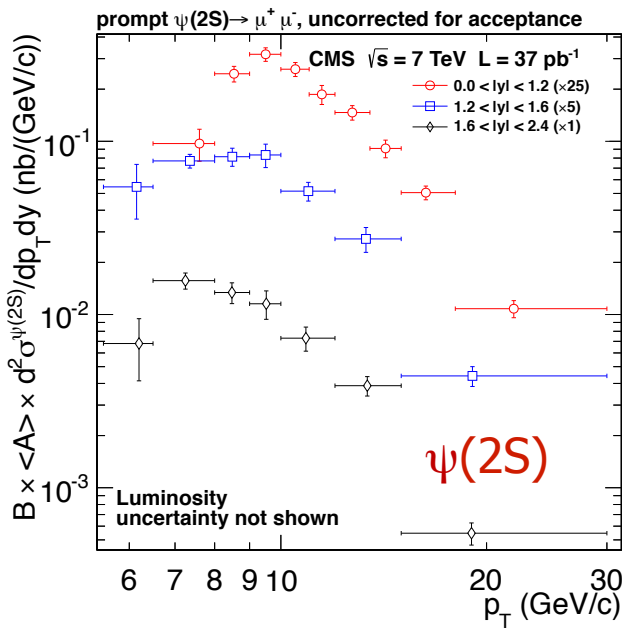
$$\begin{cases} |\eta^\mu|<1.2 & \rightarrow p_T>4\ \text{GeV/c} \\ 1.2<|\eta^\mu|<2.4 & \rightarrow p_T>3.3\ \text{GeV/c} \end{cases}$$

ε = dimuon efficiency = $\varepsilon(\mu^+)\,\varepsilon(\mu^-)\,\rho\,\varepsilon_{vertex}$

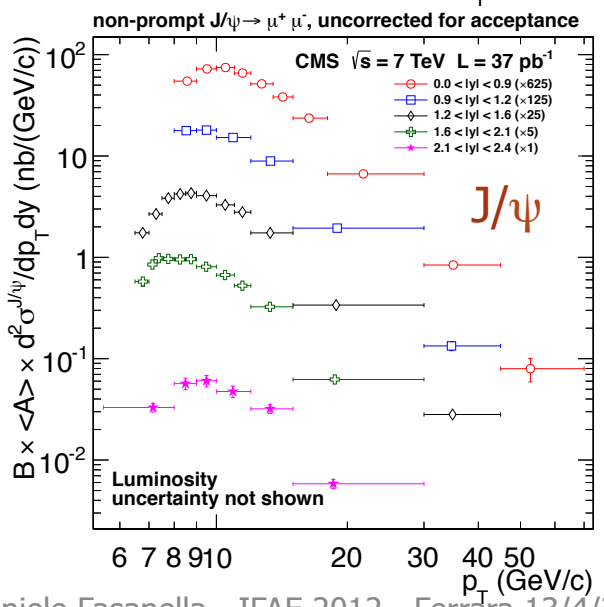
- single muon trigger and reconstruction $\varepsilon(\mu)$, data-driven via Tag & Probe
- vertexing of opposite sign dimuons (Prob>1%)
- selection based on high quality tracks associated to muon segments: cuts on n_{hits}, χ^2, $|d_{xy}|$, $|d_z|$
- ρ express the correlation between the two μ efficiencies
  - trigger settings remove too close μ (to reduce single μ faking double μ), inducing sizable correlations → Offline rejection of forward muons bending towards each other

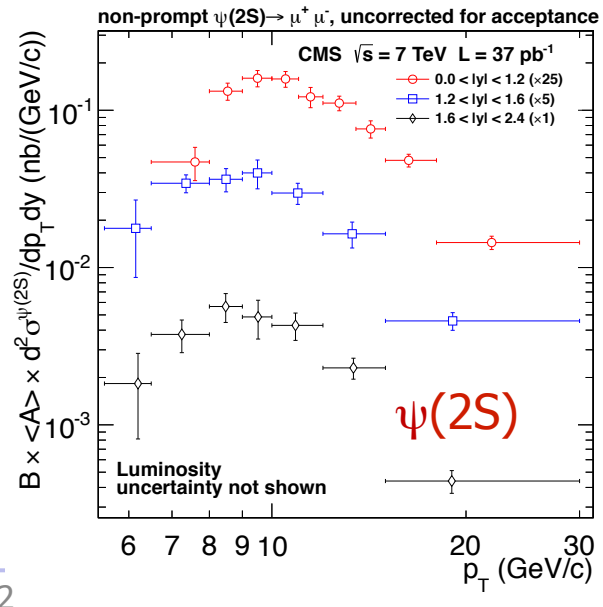
ψ(nS) Cross Sections
uncorrected for acceptance





Prompt





Non-Prompt

B fraction results

- Above $p_T \approx 20$ GeV, more than 50% of the J/ψ and ψ(2S) mesons result from B decays