XX International Workshop on Deep-Inelastic Scattering and Related Subjects

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Measurements of Quarkonium production at CMS

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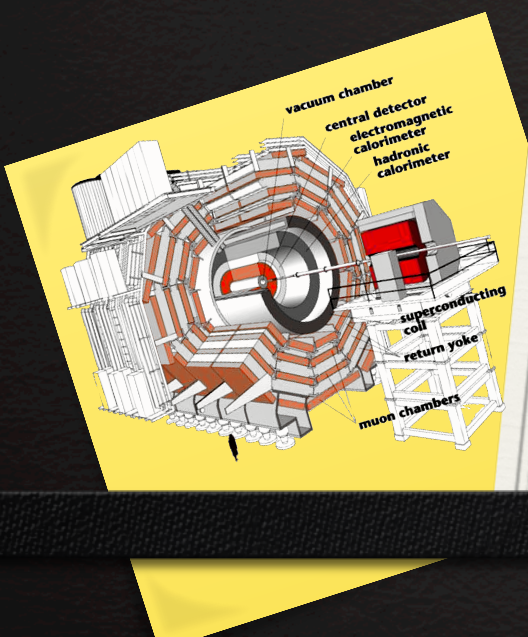
on Behalf of the CMS Collaboration



Motivations

- Heavy quarkonia are an excellent laboratory for understanding QCD
  - non-relativistic due to their high mass
  - nonperturbative effects can be simplified and constrained
- In the last decade, significant progress for production mechanisms
  - new experimental results
  - improved theoretical descriptions
- 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 Quarkonium Studies

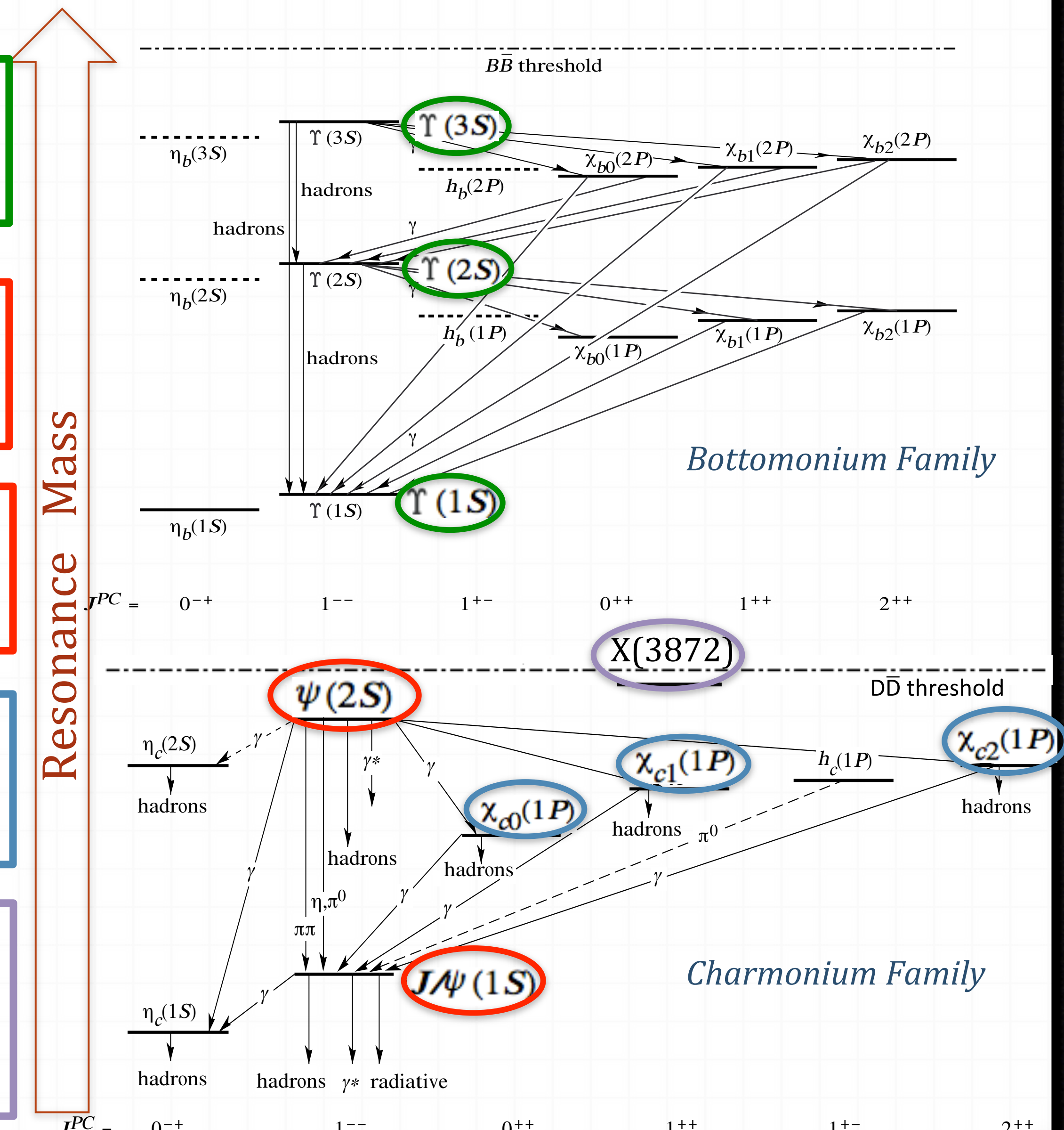
ϒ production cross section
$L_{int} = 3\ pb^{-1}$
Phys. Rev. D 83, 112004 (2011)

Prompt and non-prompt J/ψ production
$L_{int} = 314\ nb^{-1}$
Eur.Phys. J C71, 1575 (2011)

J/ψ and ψ(2S) production
$L_{int} = 37\ pb^{-1}$
JHEP 02, 011 (2012)

Observation of the χ_c states
$L_{int} = 1.1\ fb^{-1}$
CERN-CMS-DP-2011-011

Measurement of the production cross section ratio of X(3872) and ψ(2S)
$L_{int} = 40\ pb^{-1}$
CMS-PAS-BPH-10-018



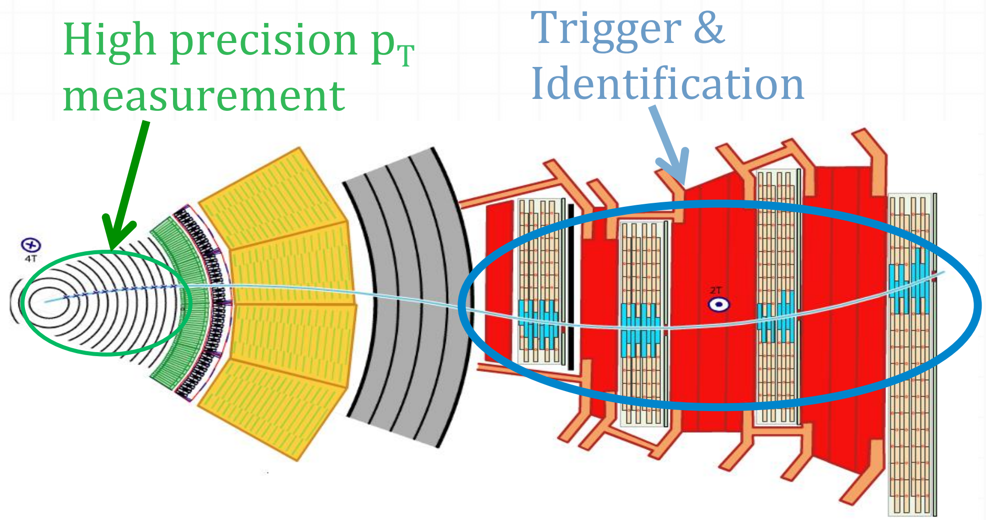
Muons in CMS

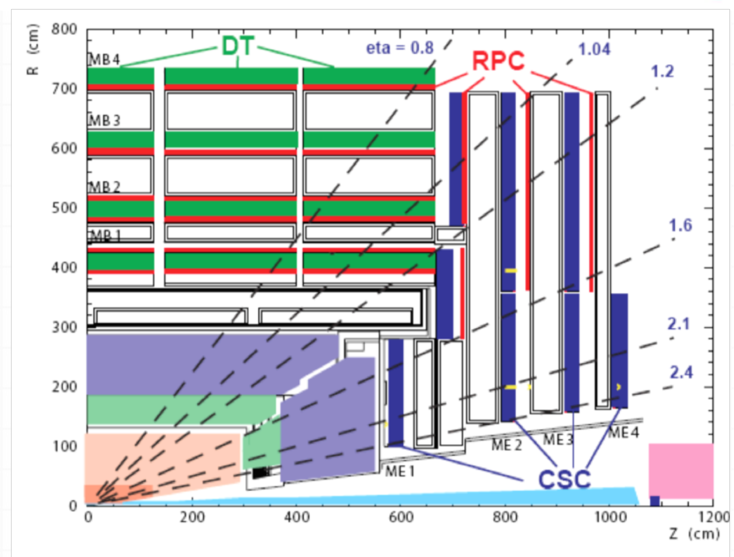
- Quarkonium states identified in final states with di-muons

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

- Inner Tracker:
  - Silicon pixel and strip layers
  - High p_T resolution ~1%
  - Excellent vertex reconstruction and impact parameter resolution

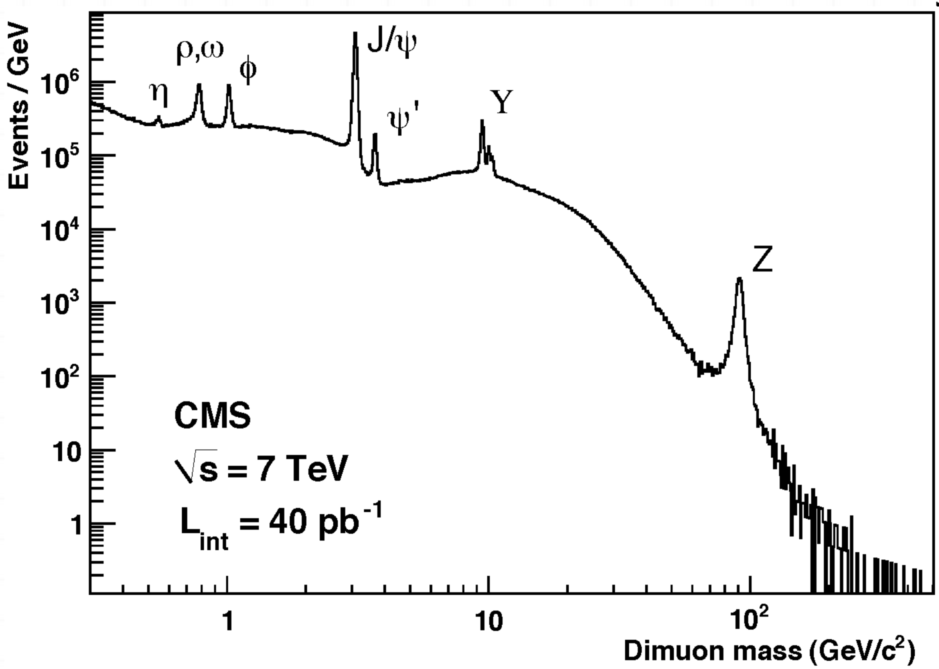
- Muon System
  - 3 types of gaseous detectors
  - Phase space coverage up to $|\eta| = 2.4$
  - Highly efficient muon trigger and identification
  - Resolution η dependent.



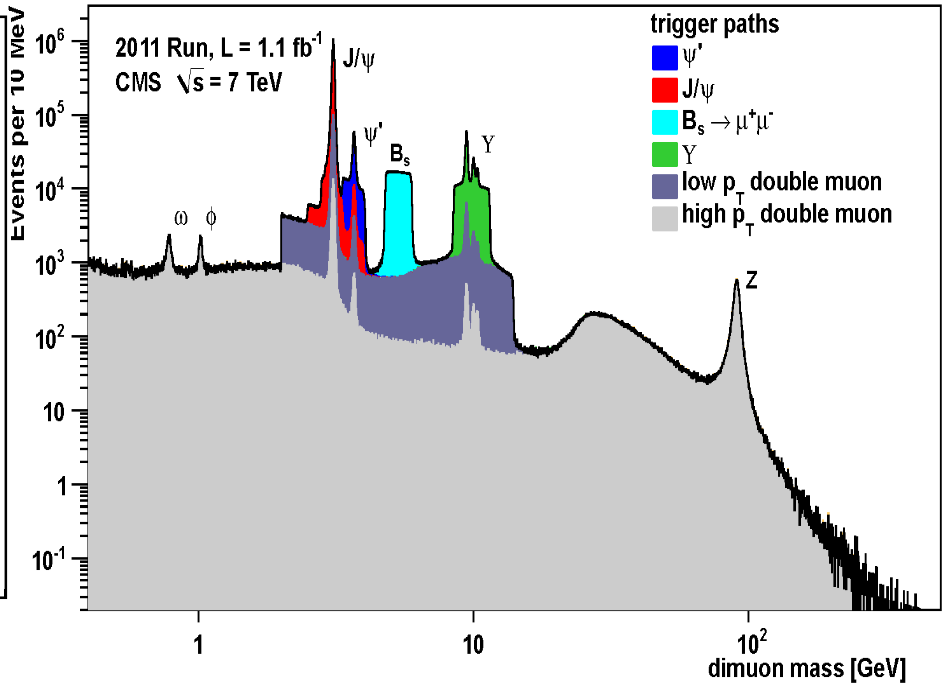


Muon Triggers

2010 Run



2011 Run Strategy



Low instantaneous luminosity in 2010:

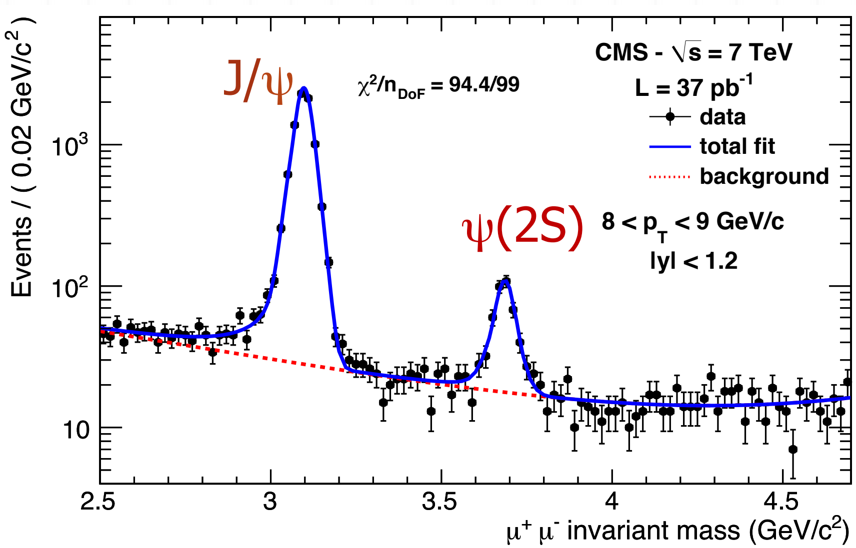
- Di-muon trigger without additional p_T requirements
- Special triggers to collect very low p_T muons in the first months

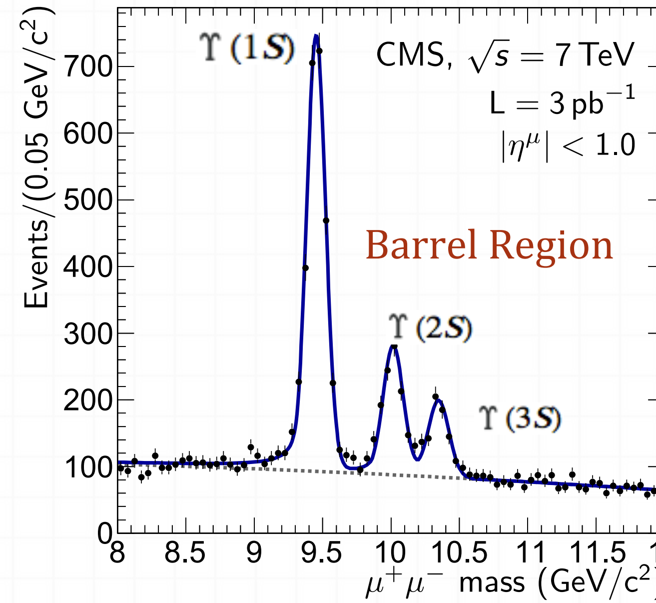
Higher instantaneous luminosity in 2011:

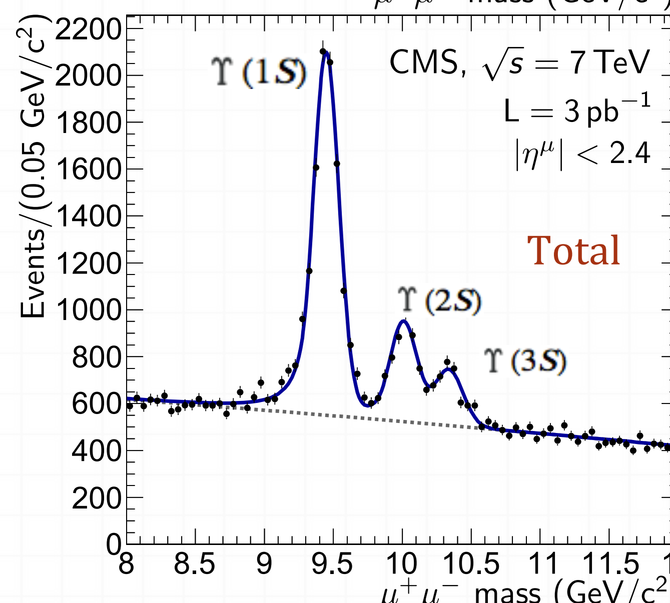
- Specific trigger paths developed for the different analyses
- High purity signal already at trigger level

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



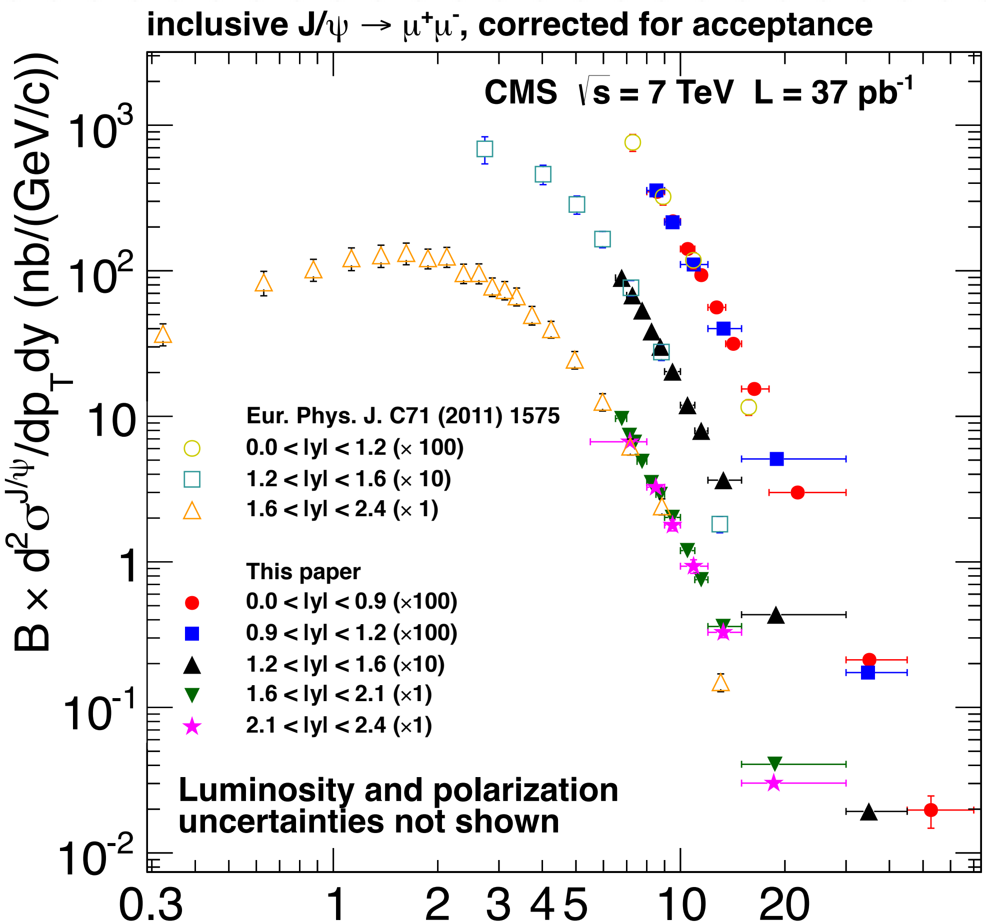




Inclusive J/ψ Production

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

- Inclusive cross section comprises 3 production methods in hadron collisions:
  - Prompt:
    - Directly from pp collisions
    - "Feed-down" from heavier states as χ_c and ψ(2S)
  - Non Prompt
    - from b-hadron decays
- Very low p_T range covered using first 314 nb^{-1} of data
- Statistical errors from 2 to 9%
- Systematical uncertainties of few % (except polarization)

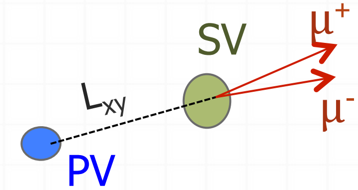


Unpolarized scenario results

Non prompt Fraction

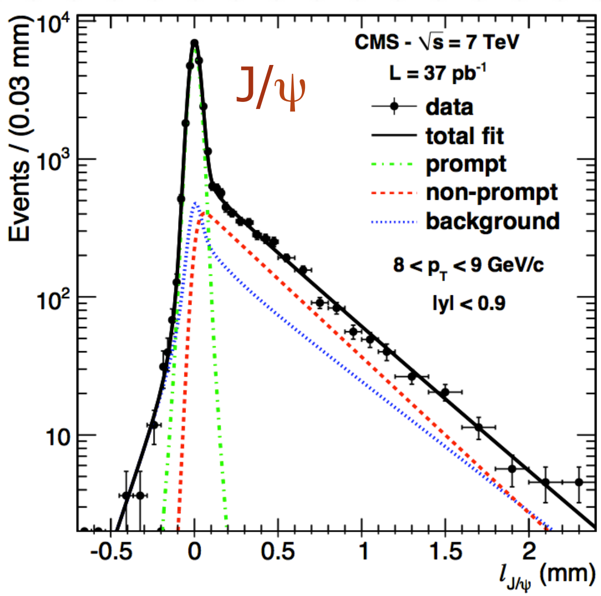
- Fraction coming from b-decay extracted with a 2-Dimensional fit of invariant mass and "pseudo-proper" decay length

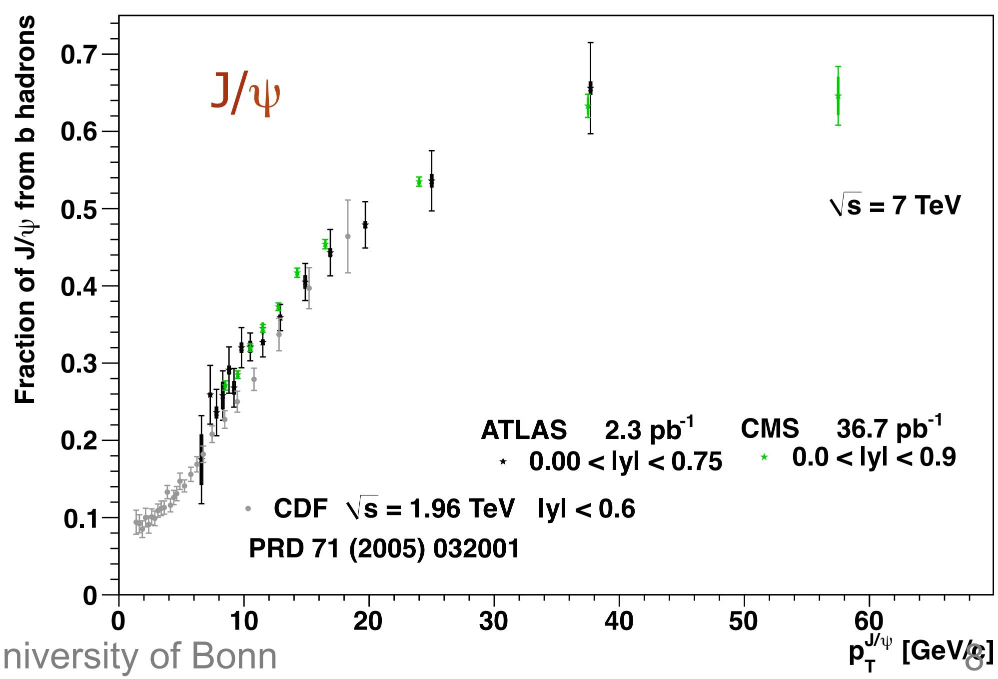
$$l_{J/\psi} = \frac{L_{xy} \cdot m_{J/\psi}}{p_T}$$



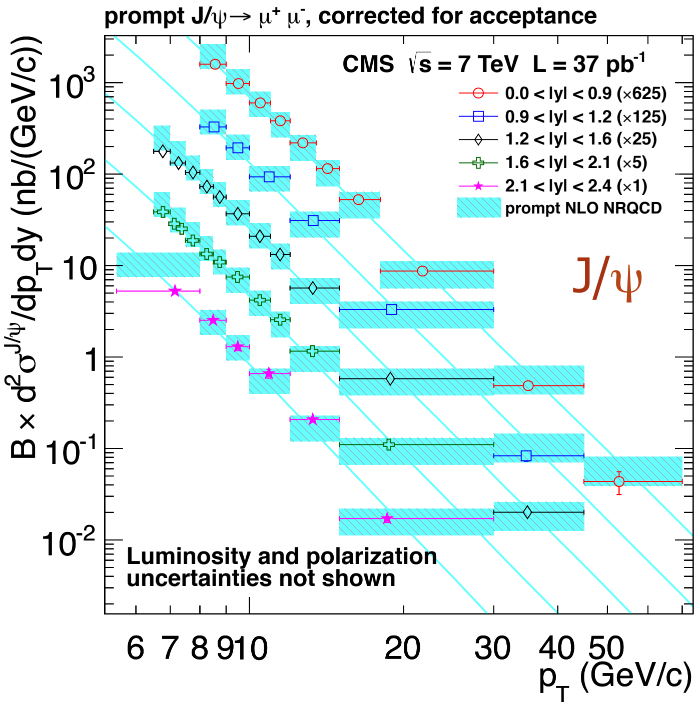
- $l_{J/\psi}$ distribution components:
  - prompt → Resolution function
  - non prompt → Resolution function convoluted with exponential
  - background → Pre-fitted in mass sidebands

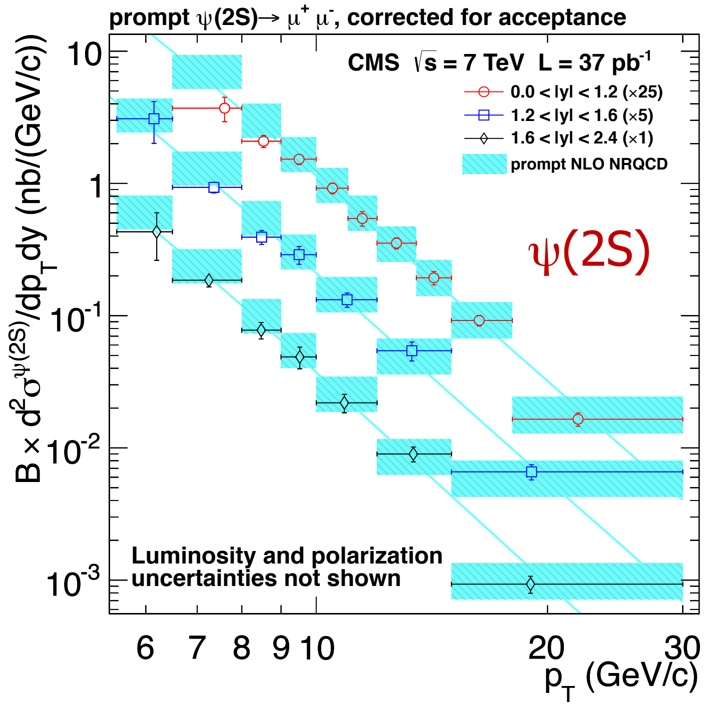
- Decay length resolution described by "per-event uncertainty" on $l_{J/\psi}$
- Results in agreement with CDF and ATLAS





ψ(nS) prompt cross sections

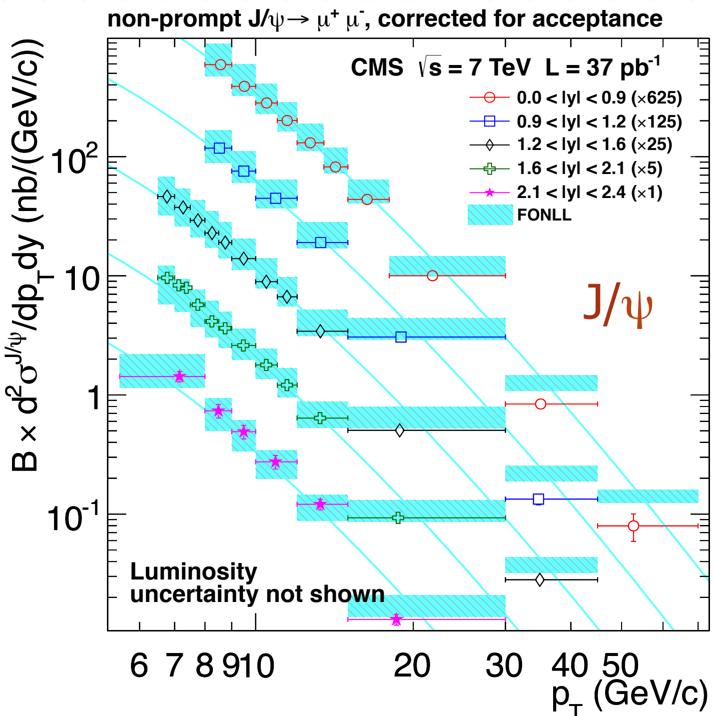


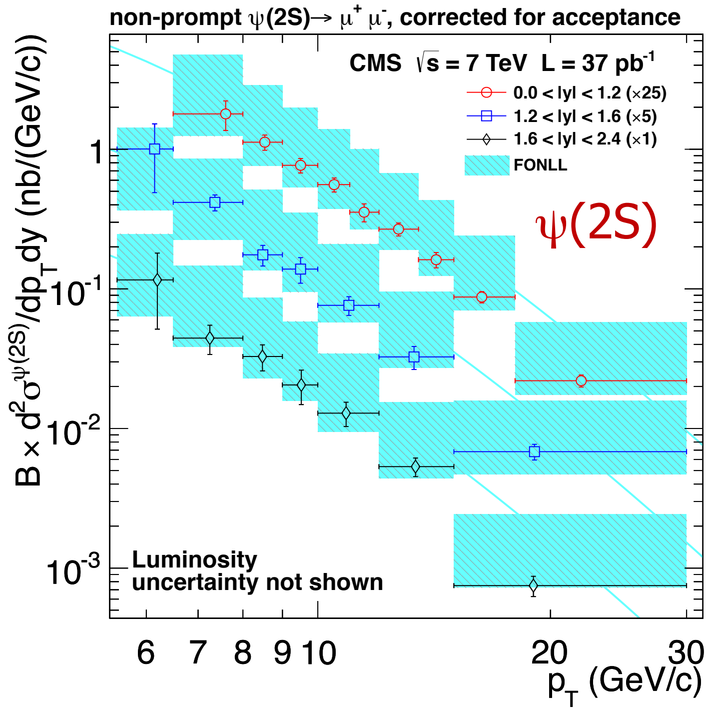


- Excellent agreement with NRQCD predictions
  - For prompt J/ψ, feed down effect included in theory
  - remarkable for ψ (2S) in absence of feed-down
- Typical uncertainties ~5 [20]% on J/ψ [ψ(2S)] cross-sections
- Polarization uncertainty studied in 4 "extreme" scenarios, effects up to 20[30]% for J/ψ [ψ(2S)]

B → ψ(nS)X cross sections

- Comparison with FONLL predictions:

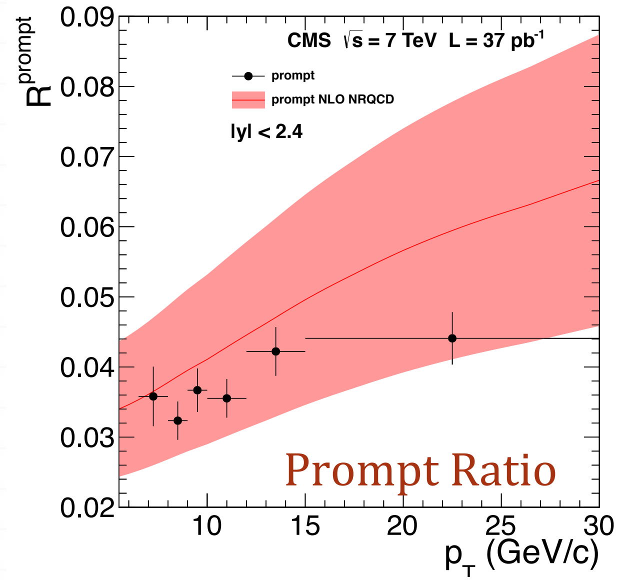




- For J/ψ:
  - agreement below 30 GeV
  - above 30 GeV FONLL overestimate data
- For ψ (2S):
  - Shape agreement in the measurement range
  - Uniform scale discrepancy found
    - improved determination of BR

ψ(2S) to J/ψ cross-sections ratios

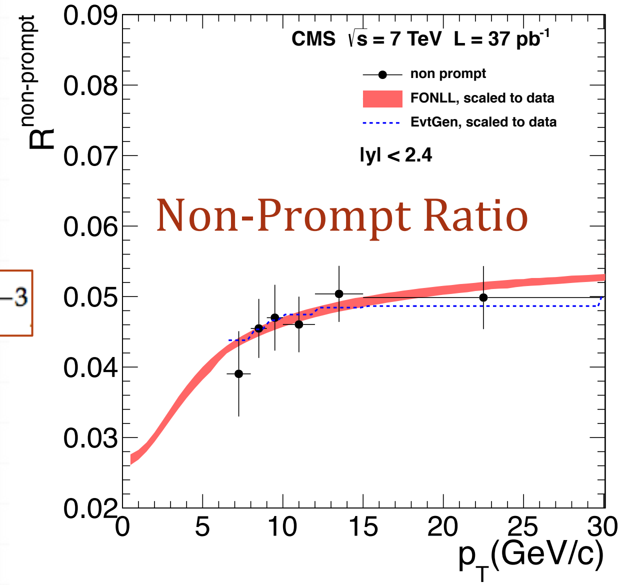
- **Cross Section Ratio calculation:**
  - Systematic uncertainties largely cancel (Luminosity, Single Muon Efficiencies…)
  - Direct production with same polarization
    - Residual polarization effect from J/ψ coming from feed-down
  - No |y| dependence seen, results as function of p_T



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

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

  - 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



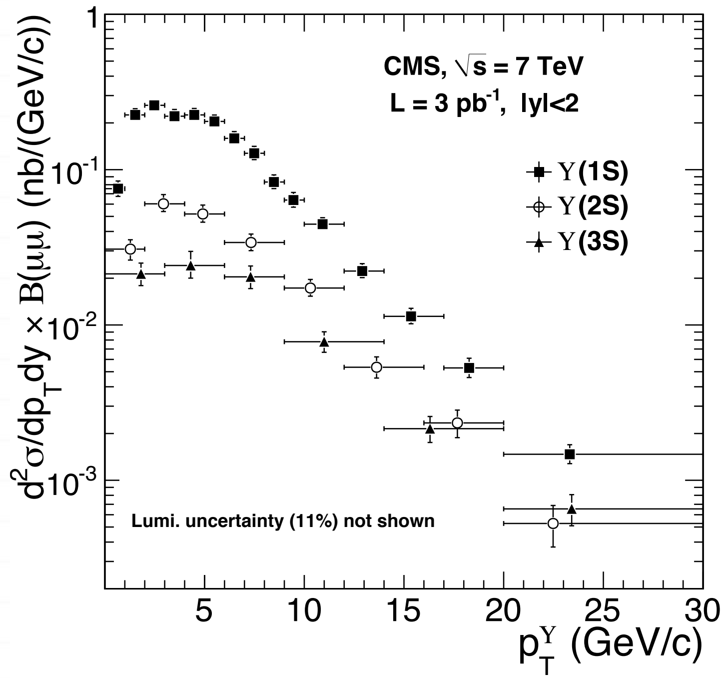
Υ(nS) Cross Sections

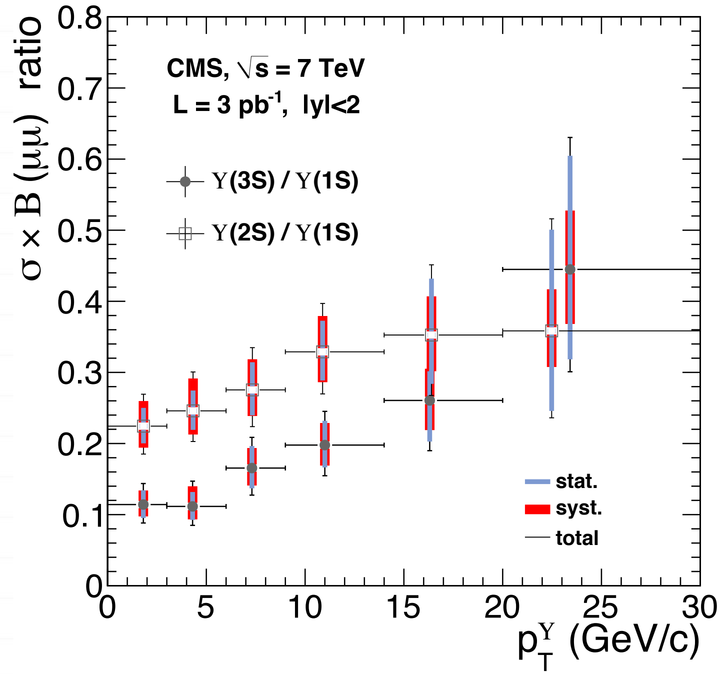
$$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 7.37 \pm 0.13(\text{stat.})^{+0.61}_{-0.42}(\text{syst.}) \pm 0.81(\text{lumi.})\ \text{nb}$$

$$\sigma(pp \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 1.90 \pm 0.09(\text{stat.})^{+0.20}_{-0.14}(\text{syst.}) \pm 0.24(\text{lumi.})\ \text{nb}$$

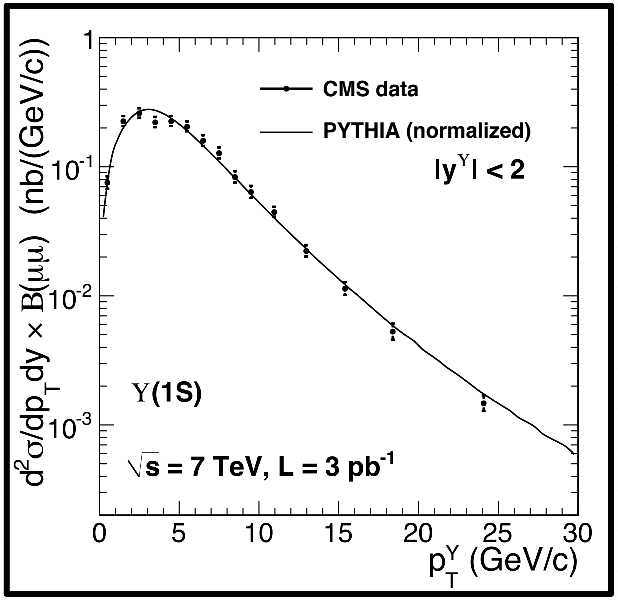
$$\sigma(pp \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 1.02 \pm 0.07(\text{stat.})^{+0.11}_{-0.08}(\text{syst.}) \pm 0.11(\text{lumi.})\ \text{nb}$$

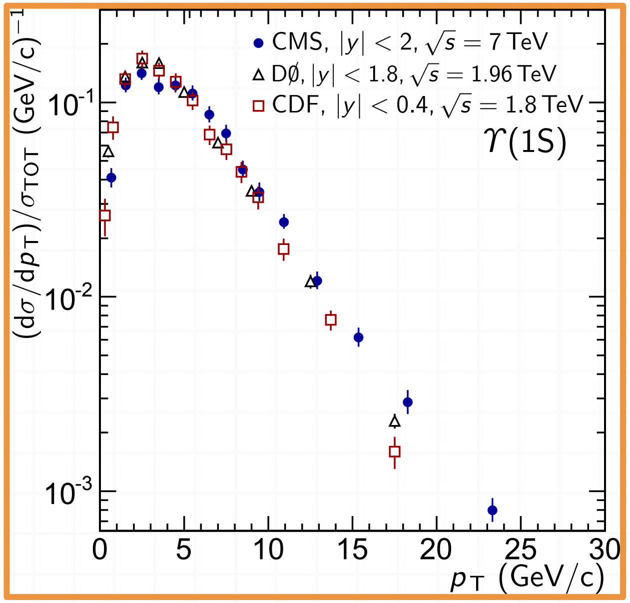
- Υ(1S) and Υ(2S) include feed-down from higher-mass states
- Unpolarized Υ(nS) assumption
  - Extreme polarization change cross sections by about 20%

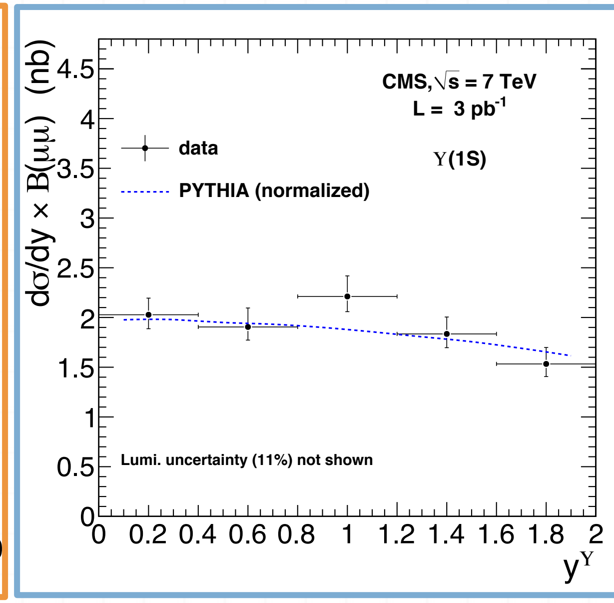




Υ(1S) Cross Section







Consistent shape to PYTHIA

- PYTHIA overestimates the integrated cross section by a factor 2

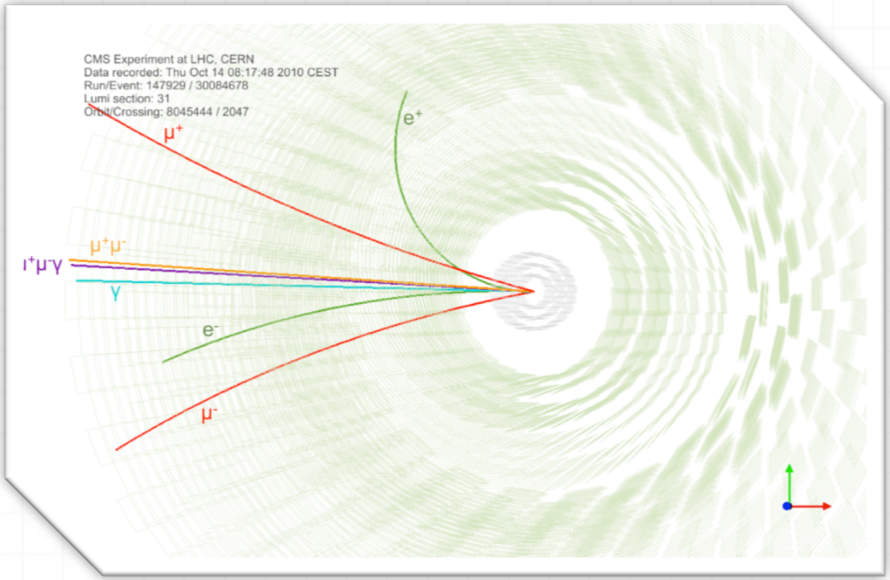
Results compared to D0 and CDF measurements

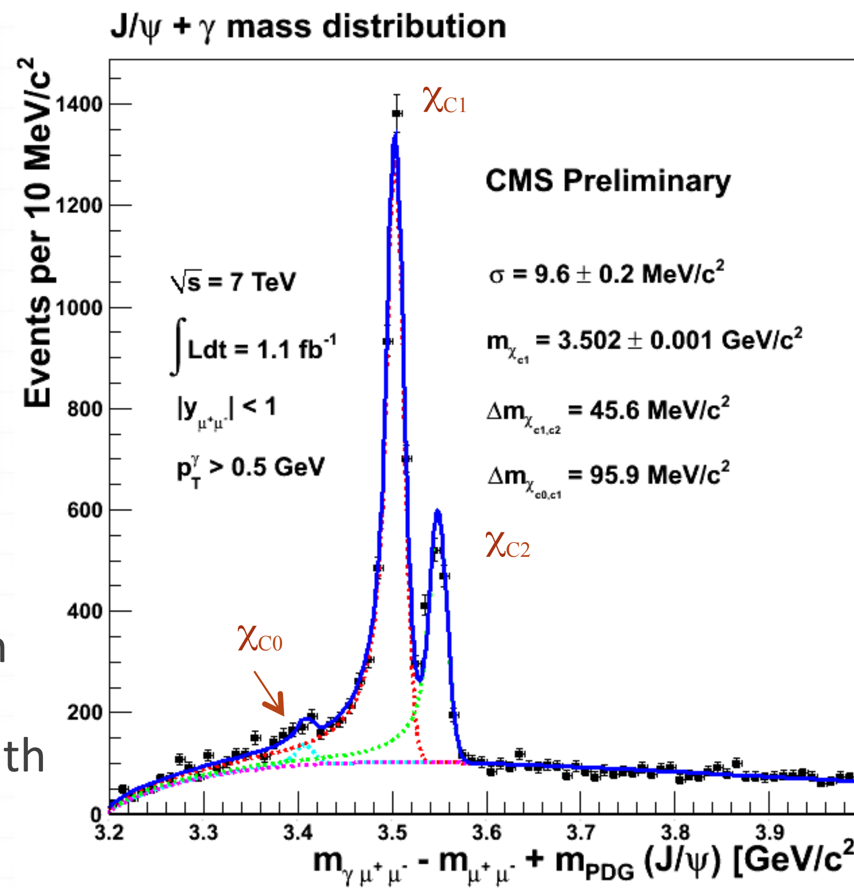
- Assuming cross section uniform in rapidity an increase by a factor 3 is observed at √s = 7 TeV

Differential cross-section vs rapidity:

- slight decrease towards |y|=2 consistent with PYTHIA

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



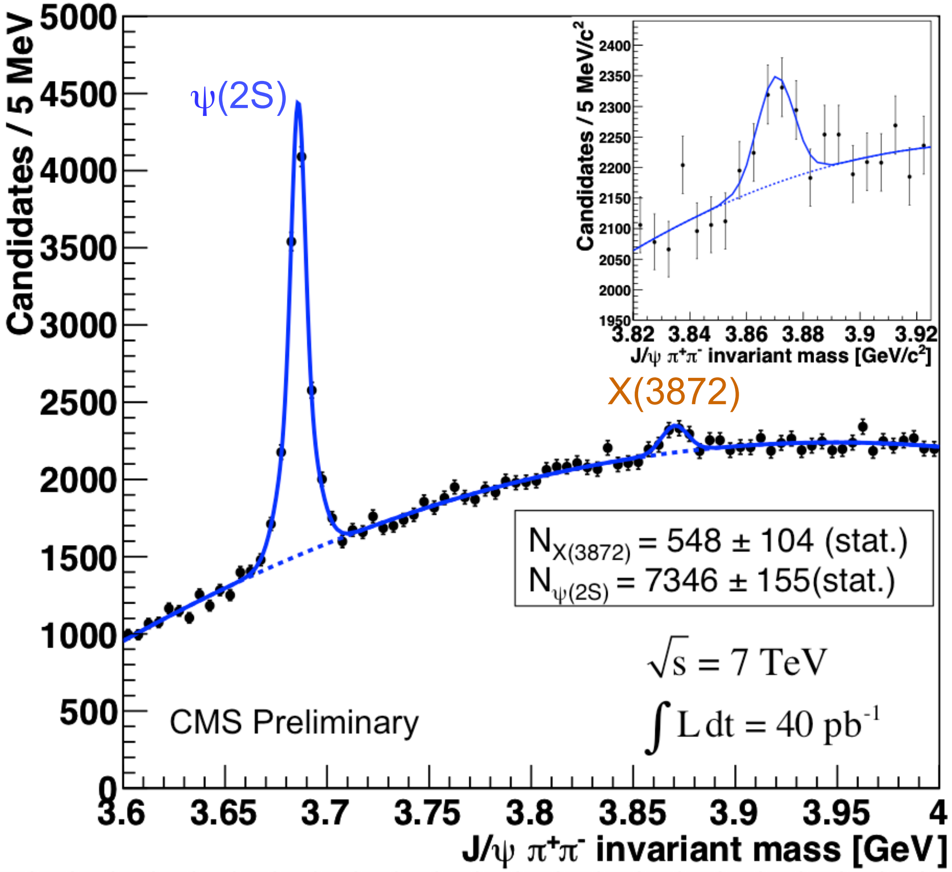


- Excellent resolution (< 10 MeV) for photons converted in the tracker volume
- χ_{c1} and χ_{c2} ($\Delta m \sim 45$ MeV) peaks resolved in the $J/\psi\ \gamma$ spectrum
- Signal modeled by 3 Crystal Ball functions with common parameters
- Studies on χ_{cJ} states
  - discriminate between different theoretical production models
  - evaluate the feed-down corrections to prompt J/ψ production

The X(3872) state

- Discovered in 2003 by Belle → its nature still unclear
- A clear signal is established in 2010 in the $J/\psi\ \pi^+\pi^-$ decay channel
- Starting from reconstructed J/ψ
  - Searched pair of compatible good quality opposite-charged tracks in $\Delta R(\pi, J/\psi)<0.7$
  - Performed 4-track vertex fit with J/ψ mass fixed to the PDG value
  - Kept good quality candidates in the kinematic region

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



- Unbinned maximum likelihood fit
  - $m_{\psi(2S)}$ = 3685.9 ± 0.1 (stat. only) MeV
  - $m_{X(3872)}$ = 3870.2 ± 1.9 (stat. only) MeV
  - $\sigma 1_{\psi(2S)}$ = 8.1 ± 0.6 MeV
  - $\sigma 2_{\psi(2S)}$ = 3.3 ± 0.3 MeV
  - $\sigma_{X(3872)}$ = 6.3 ± 1.3 MeV
- PDG values

  $m_{\psi(2S)}$ = 3686.09 ± 0.04 MeV
  $m_{X(3872)}$ = 3871.57 ± 0.25 MeV

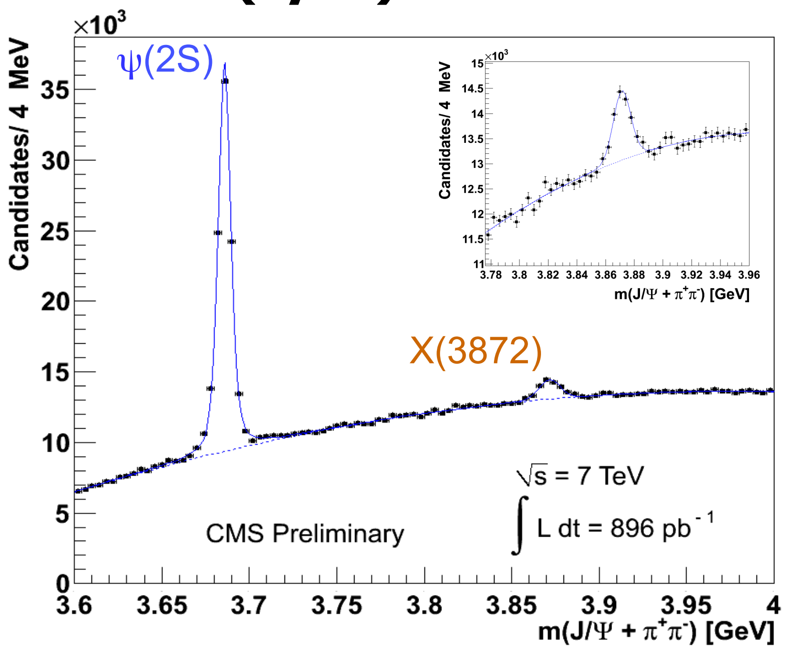
X(3872) to ψ(2S) inclusive cross section ratio

$$R = \frac{\sigma(pp \to X(3872) + \text{anything}) \cdot BR(X(3872) \to J/\psi\, \pi^+\pi^-)}{\sigma(pp \to \psi' + \text{anything}) \cdot BR(\psi' \to J/\psi\, \pi^+\pi^-)}$$

- Acceptance and efficiency correction from simulation are applied on the yields extracted from the mass spectrum
  - 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.)

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



Conclusions

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

- Measurement of J/ψ cross section from 0 to 70 GeV/c with large rapidity coverage ($|y|<2.4$)

- Differential cross-sections in p_T and $|y|$ of J/ψ and $\psi(2S)$ mesons
  - prompt and non-prompt contributions separated
  - compatible results to NRQCD prediction up to 30 GeV/c for prompt production
  - uniform scale discrepancy found and explained for non-prompt $\psi(2S)$ production w.r.t. FONLL
  - consistent results with other LHC experiments
  - improved relative uncertainty for BR(B->ψ(2S) X) of a factor 3

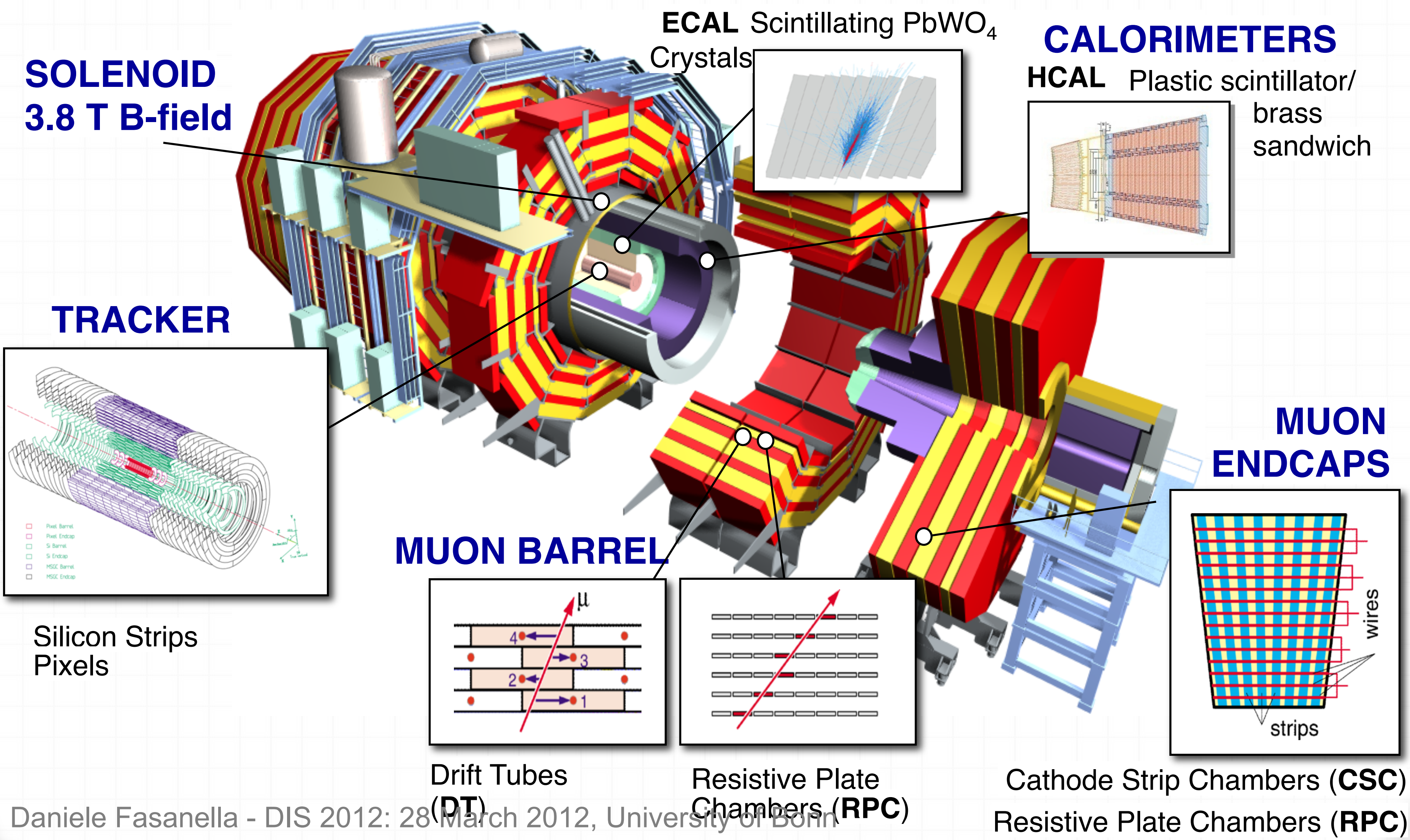
- Differential cross-sections in p_T for $\Upsilon(nS)$ states
  - shape compatible to PYTHIA and results at Tevatron

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

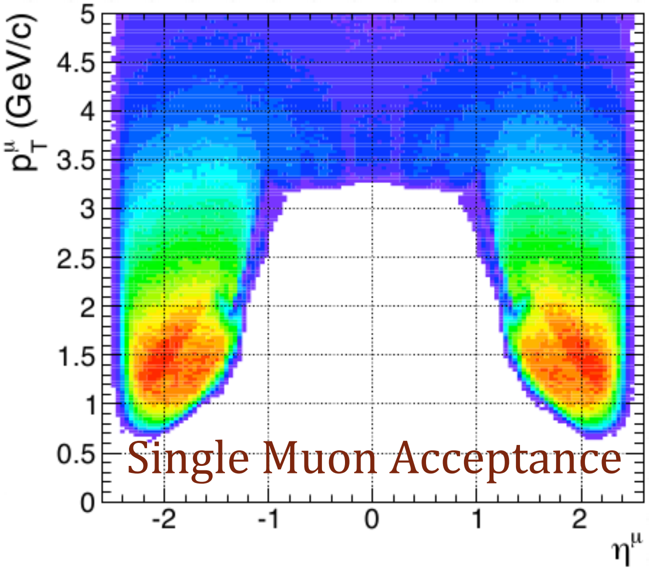
- χ_{cJ} peaks resolved in their radiative decay to J/ψ, using converted photons

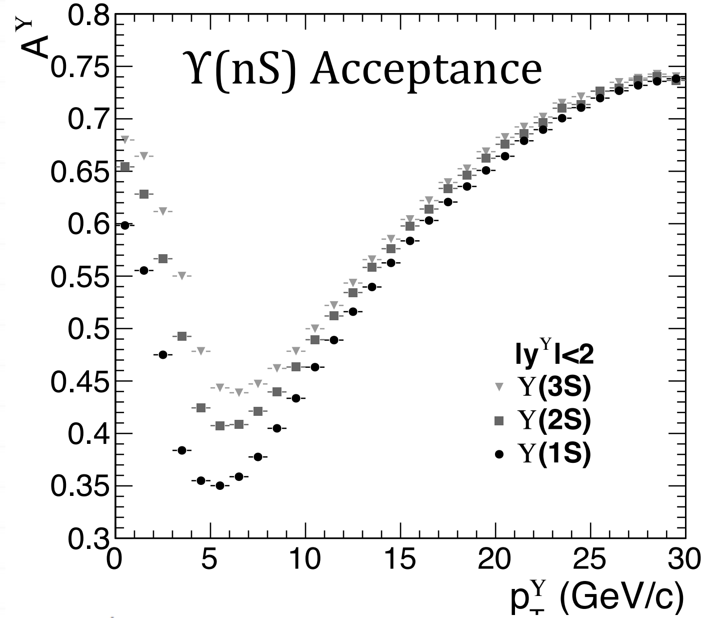
BACKUP

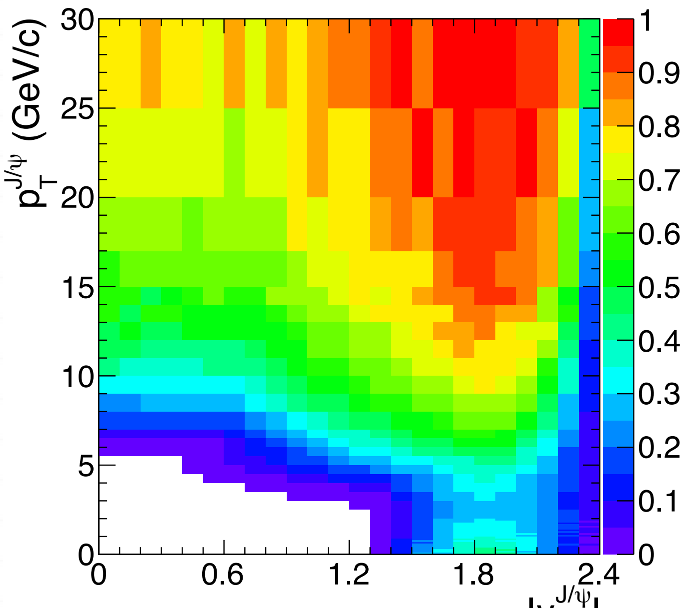
The CMS detector



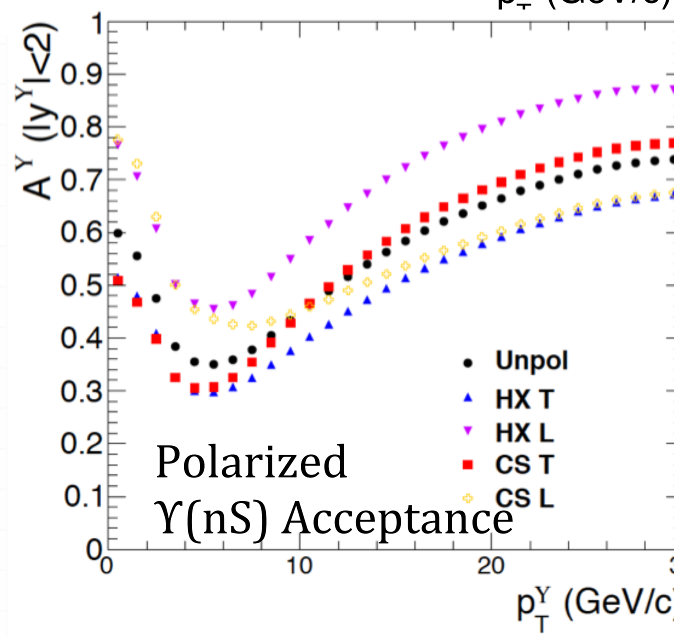
Acceptances



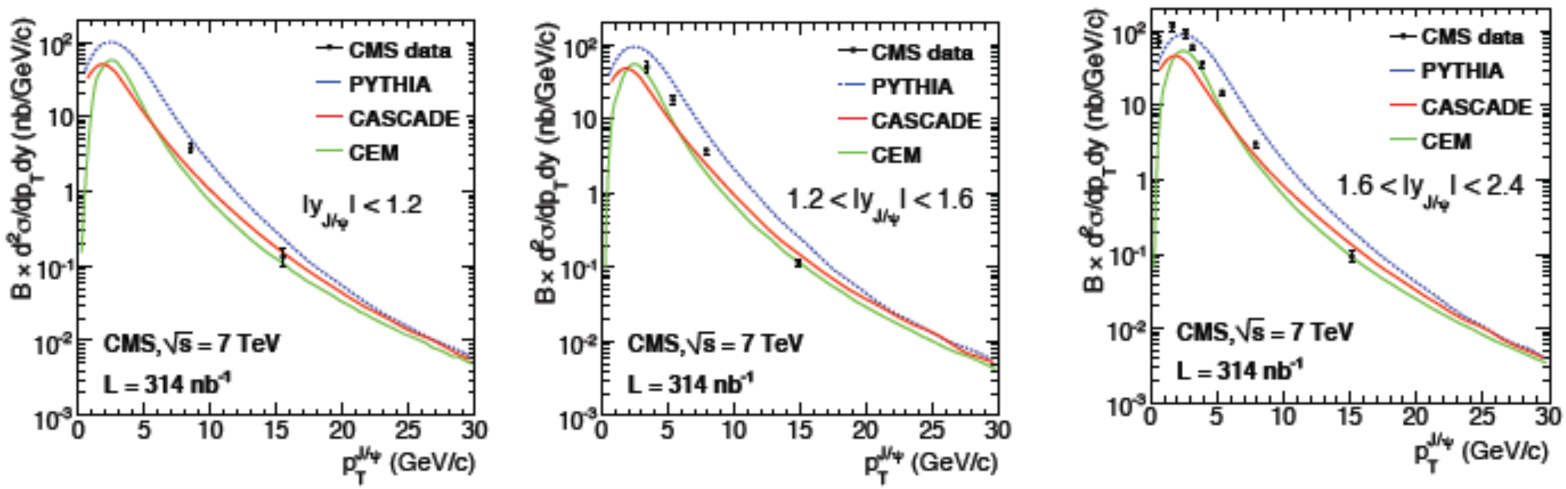




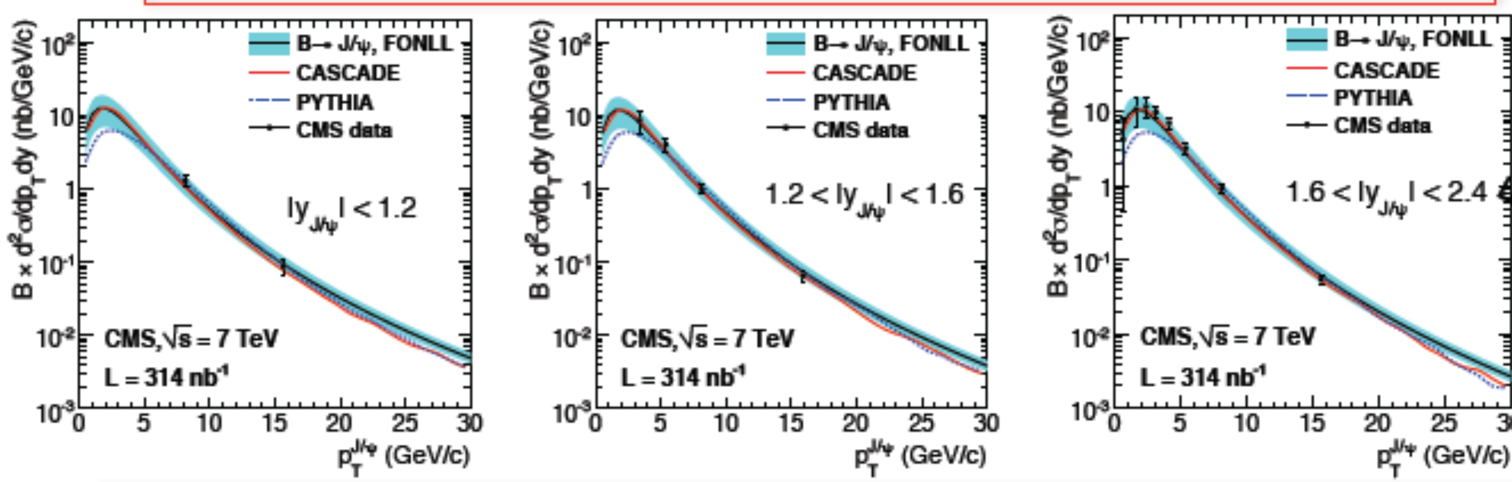
J/ψ Acceptance



First CMS paper on J/ψ



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



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

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$\psi(nS)$ 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)

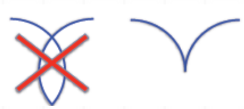
A = geometrical and kinematical acceptance

- Strongly dependent on production polarization

$|\eta^{\mu}|<1.2$ → p_T >4 GeV/c
$1.2<|\eta^{\mu}|<2.4$ → p_T >3.3 GeV/c

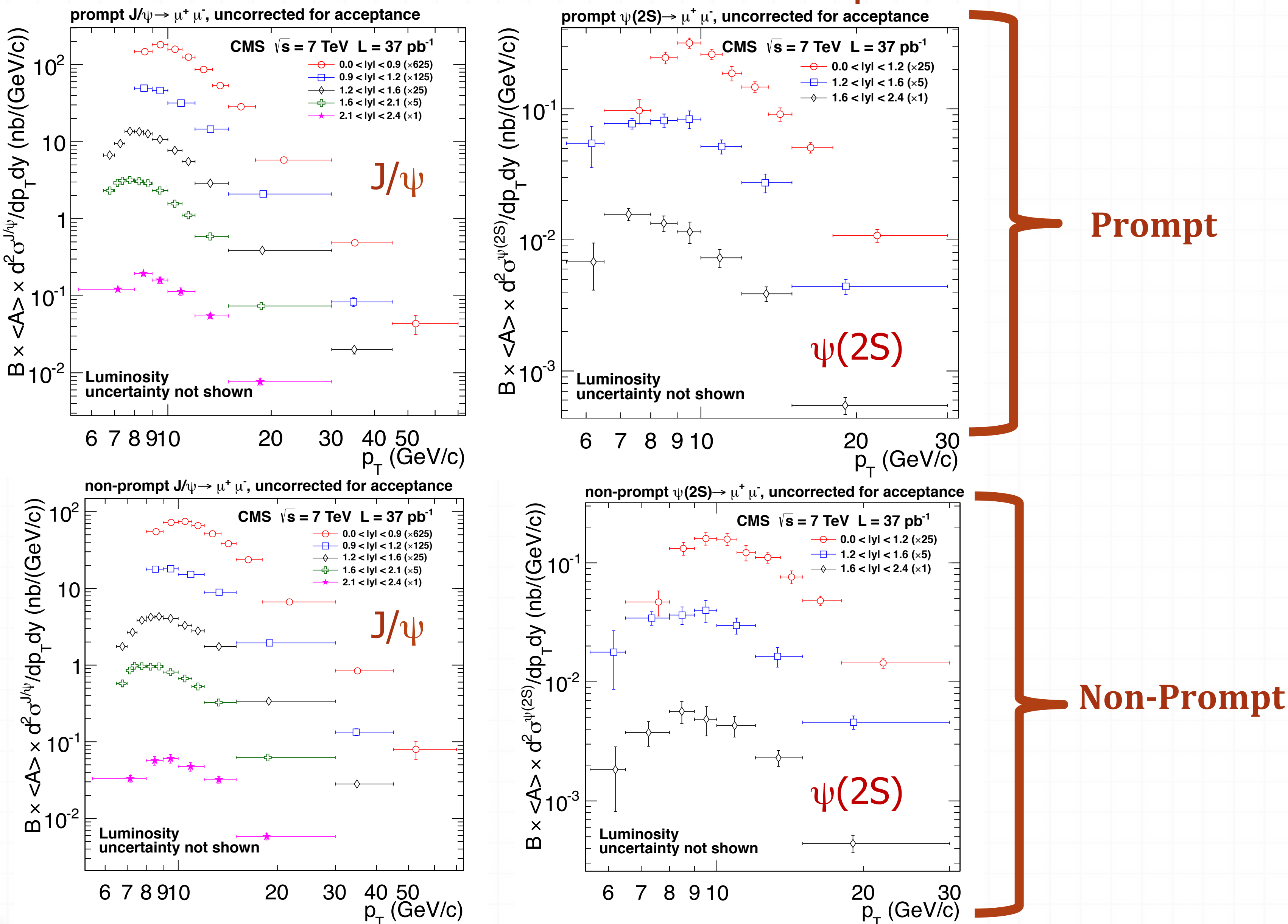
ε = dimuon efficiency = $\varepsilon(\mu^+)\,\varepsilon(\mu^-)\,\rho\,\varepsilon_{vertex}$

- 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



ψ(nS) Integrated Cross Sections

J/ψ

$8.0 < p_T < 70.0$ GeV/c for $|y| < 0.9$

$8.0 < p_T < 45.0$ GeV/c for $0.9 < |y| < 1.2$

$6.5 < p_T < 45.0$ GeV/c for $1.2 < |y| < 1.6$

$6.5 < p_T < 30.0$ GeV/c for $1.6 < |y| < 2.1$

$5.5 < p_T < 30.0$ GeV/c for $2.1 < |y| < 2.4$

ψ(2S)

$6.5 < p_T < 30.0$ GeV/c for $|y| < 1.2$

$5.5 < p_T < 30.0$ GeV/c for $1.2 < |y| < 2.4$

Corrected for acceptance:

$$\mathcal{B}(J/\psi \to \mu^+\mu^-) \cdot \sigma(\text{pp} \to \text{prompt } J/\psi) = 54.5 \pm 0.3 \pm 2.3 \pm 2.2 \text{ nb}$$

$$\mathcal{B}(J/\psi \to \mu^+\mu^-) \cdot \sigma(\text{pp} \to \text{b}X \to J/\psi X) = 20.2 \pm 0.2 \pm 0.8 \pm 0.8 \text{ nb}$$

$$\mathcal{B}(\psi(2\text{S}) \to \mu^+\mu^-) \cdot \sigma(\text{pp} \to \text{prompt } \psi(2\text{S})) = 3.53 \pm 0.26 \pm 0.32 \pm 0.14 \text{ nb}$$

$$\mathcal{B}(\psi(2\text{S}) \to \mu^+\mu^-) \cdot \sigma(\text{pp} \to \text{b}X \to \psi(2\text{S})X) = 1.47 \pm 0.12 \pm 0.13 \pm 0.06 \text{ nb}$$

Uncorrected for acceptance:

$$\mathcal{B}(J/\psi \to \mu^+\mu^-) \cdot \sigma(\text{pp} \to \text{prompt } J/\psi) = 9.83 \pm 0.03 \pm 0.38 \pm 0.39 \text{ nb}$$

$$\mathcal{B}(J/\psi \to \mu^+\mu^-) \cdot \sigma(\text{pp} \to \text{b}X \to J/\psi X) = 4.67 \pm 0.02 \pm 0.17 \pm 0.19 \text{ nb}$$

$$\mathcal{B}(\psi(2\text{S}) \to \mu^+\mu^-) \cdot \sigma(\text{pp} \to \text{prompt } \psi(2\text{S})) = 0.410 \pm 0.009 \pm 0.023 \pm 0.016 \text{ nb}$$

$$\mathcal{B}(\psi(2\text{S}) \to \mu^+\mu^-) \cdot \sigma(\text{pp} \to \text{b}X \to \psi(2\text{S})X) = 0.235 \pm 0.006 \pm 0.013 \pm 0.009 \text{ nb}$$

B fraction results

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