Quarkonia Production at 7 TeV with the CMS experiment

Yu Zheng

on behalf of the CMS collaboration

Purdue University

July 25, 2012

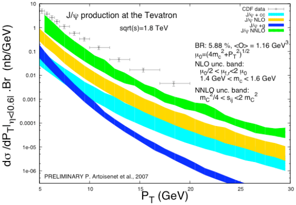
Outline

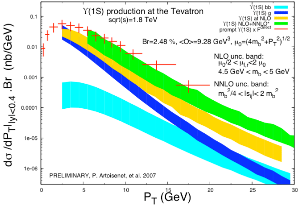
- Why study Quarkonia at the LHC?
- The CMS detector
- Quarkonia Cross Section Measurements
- χ_{c2}/χ_{c1} cross section ratio
- Summary

Motivation

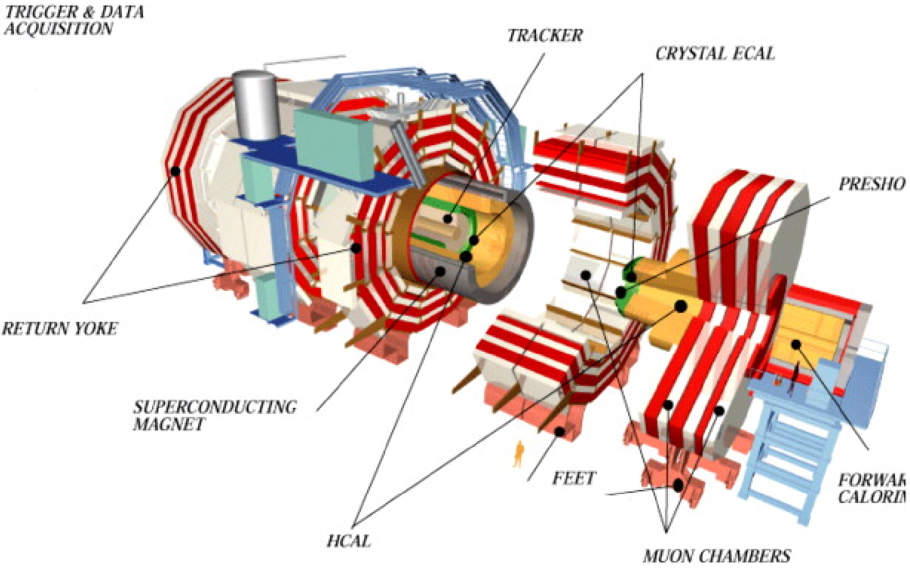
- Theoretical Motivation
  - no theory has simultaneously explained experimental measurements of both production cross section and polarization

- LHC provides:
  - New energy scale
  - Large p_T reach
- CMS provides:
  - excellent dimuon mass resolution
  - good photon reconstruction resolution, which allows to study P-wave quarkonia states through radiative decays

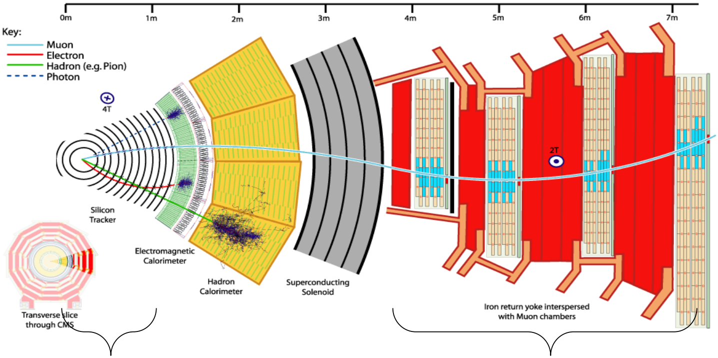




The CMS Detector



Muon Reconstruction



Tracker muons were developed to reconstruct muons down to very low momenta, where for identification purposes it is enough to traverse only 1 instrumented muon layer.

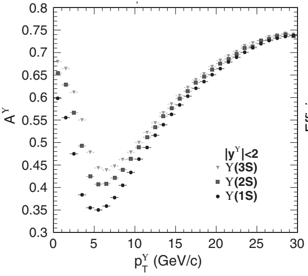
Low p_T muons might not traverse more than one instrumented muon layer because of the B-field (mid-rapidity) or material thickness (forward).

Quarkonium Production Cross Section Measurements

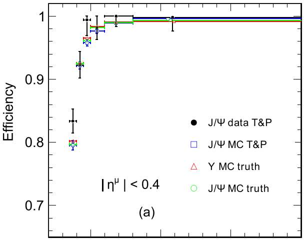
$$\frac{d^2\sigma(Q\overline{Q})}{dp_T dy}\mathcal{B}\left(Q\overline{Q}\to\mu^+\mu^-\right)=\frac{N_{fit}(Q\overline{Q})}{\mathcal{L}\ \cdot\mathcal{A}\cdot\epsilon\cdot\Delta p_T\cdot\Delta y},$$

- $\mathcal{A}$: Acceptance
- $\epsilon = \epsilon_{\mathrm{track}}\cdot\epsilon_{\mathrm{id}}\cdot\epsilon_{\mathrm{trig}}$
  - $\epsilon_{\mathrm{track}}$: Tracking efficiency
  - $\epsilon_{\mathrm{id}}, \epsilon_{\mathrm{trig}}$: Muon identification and trigger efficiency
- $N_{fit}(Q\overline{Q})$: The $Q\overline{Q}$ yields, extracted via an extended unbinned maximum likelihood fit
- $\mathcal{L}$: The integrated luminosity of the dataset

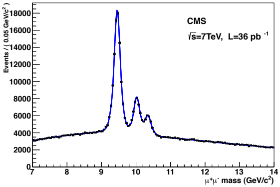
Acceptance ($\mathcal{A}$)



Efficiencies (ϵ)

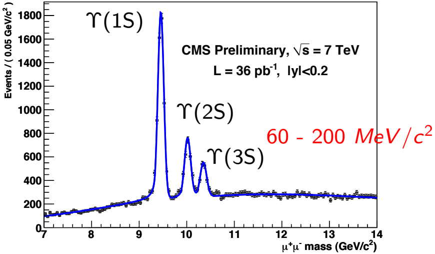


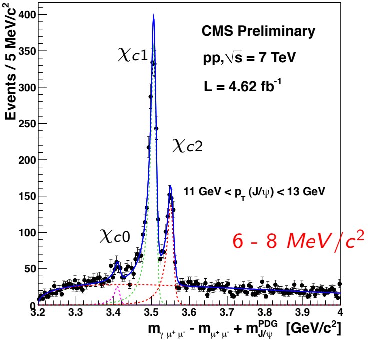
Mass Fit($N_{fit}(Q\overline{Q})$)

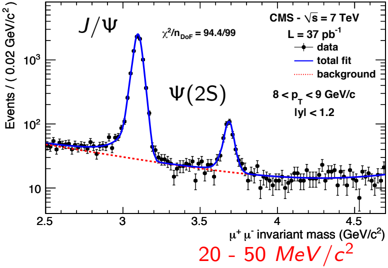


Mass Fits and Yields ($N_{Q\overline{Q}}$)

- Unbinned Maximum Likelihood fit
- signal: Crystal Ball, Background: Exponentials or exponential and error function product
- Mass differences fixed to PDG values, common resolution value scaled by mass



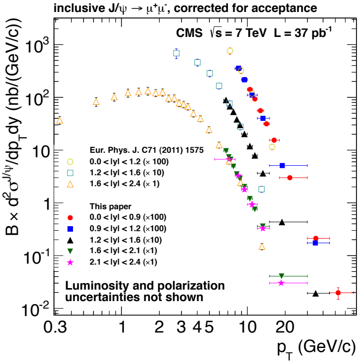




Inclusive J/Ψ Production

(Unpolarized)

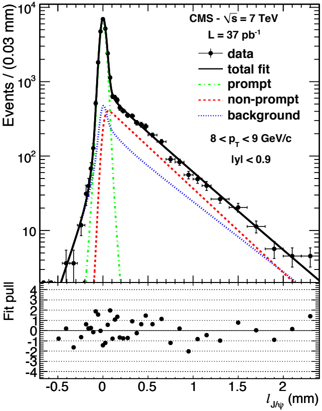
- Prompt:
  - Directly from pp collisions
  - "Feed-down" from heavier states, χ_c and $\Psi(2S)$
- Non-prompt: from B-hadron decays
- Large p_T coverage: down to 0 GeV/c, up to 70 GeV/c



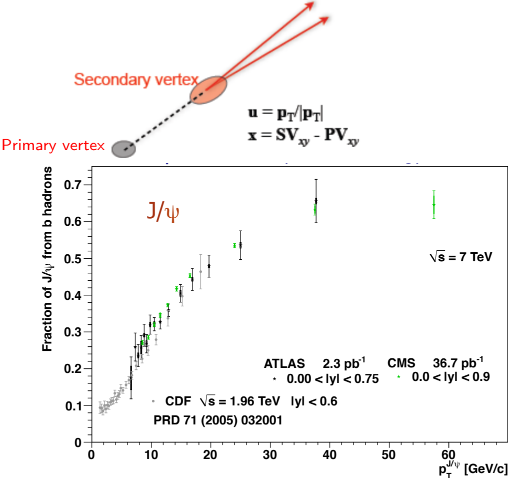
- Eur. Phys. J C71, 1575 (2011): 314 nb^{-1}
- JHEP 02,11(2012): 37 pb^{-1}

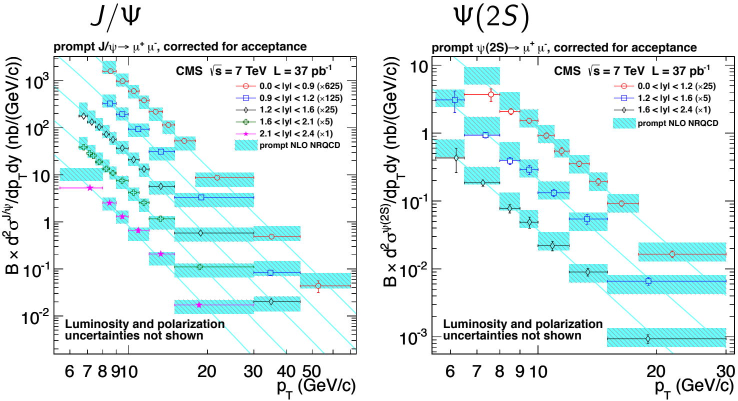
Disentangling Prompt and Non-prompt J/Ψ

- Based on pseudo-proper decay length $\ell_{xy} = \frac{L_{xy}^{J/\Psi} M_{J/\Psi}}{p_T^{J/\Psi}}$, $L_{xy}^{J/\Psi} = \frac{u^T \sigma^{-1} x}{u^T \sigma^{-1} u}$
- Prompt and non-prompt components determined from simultaneous likelihood fit to M and ℓ_{xy} in each p_T and $|y|$bin



(JHEP 02 (2012) 011)



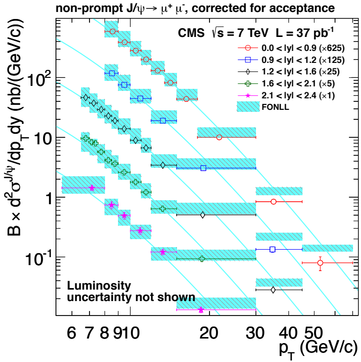


- Excellent agreement with NLO NRQCD predictions.
  - Prompt J/Ψ: feed-down effect included in theory
  - $\Psi(2S)$: feed-down not included in theory

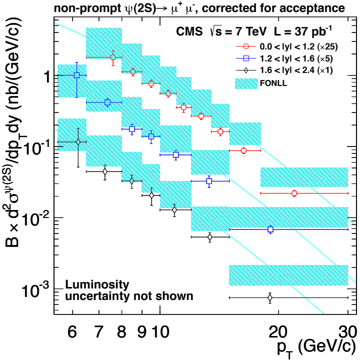
(JHEP 02 (2012) 011)

Results: Non-Prompt J/Ψ and $\Psi(2S)$ Differential X-section

J/Ψ



$\Psi(2S)$

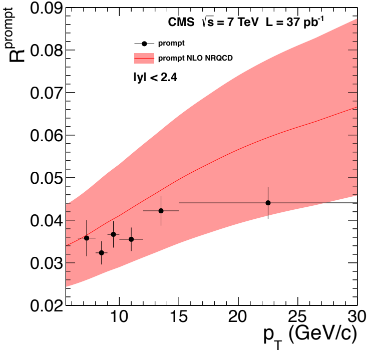


- Good agreement with FONLL predictions:
  - Overall shift in the $\Psi(2S)$ case
  - Spectra fall more rapidly than predictions at high p_T

(JHEP 02 (2012) 011)

Results: $\Psi(2S)$ to J/Ψ X-section Ratios

Prompt Ratio

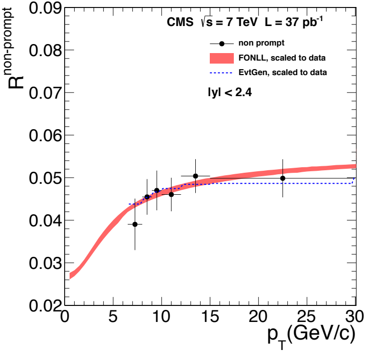


- No $|y|$ dependence observed

  Results as a function of p_T

(JHEP 02 (2012) 011)

Non-prompt Ratio



$\mathcal{B}(\mathrm{B} \to \Psi(2\mathrm{S})\mathrm{X}) = (3.08 \pm 0.12(\mathrm{stat.} + \mathrm{syst.}) \pm 0.13(\mathrm{theor.}) \pm 0.42(\mathcal{B}_{\mathrm{PDG}}))$

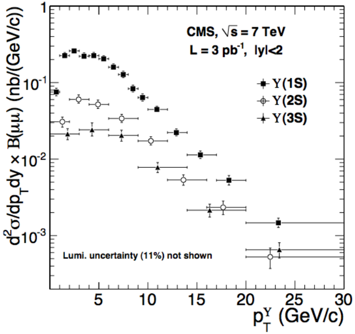
In agreement with world average $(4.8 \pm 2.4) \cdot 10^{-3}$

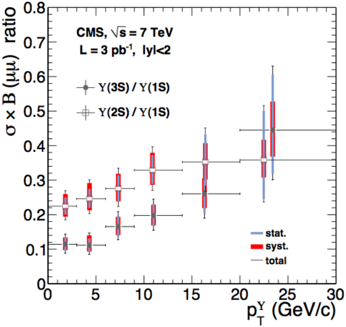
more precise by a factor of 2.5!

Υ Measurement at the CMS

- First Υ cross section measurement using 3 pb^{-1} data collected in 2010
- This was the first $\Upsilon(nS)$ measurement at the LHC. It was published in PRD in June 2011.

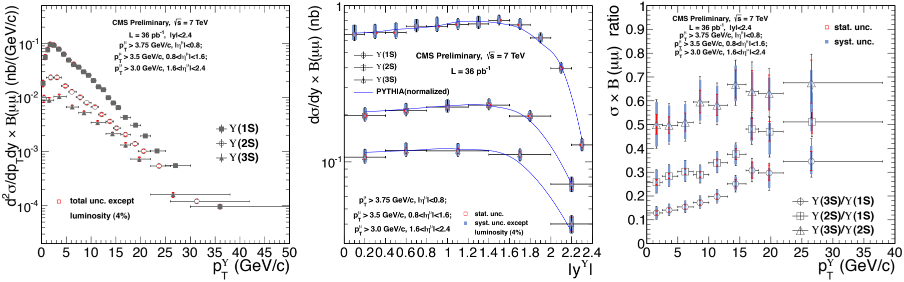
Phys. Rev. D 83, 112004 (2011)





7K $\Upsilon(1S)$

- Acceptance is a strong function of production polarization
- The fiducial cross section results are not corrected for acceptance.



78K $\Upsilon(1S)$

BPH-11-001,
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11001

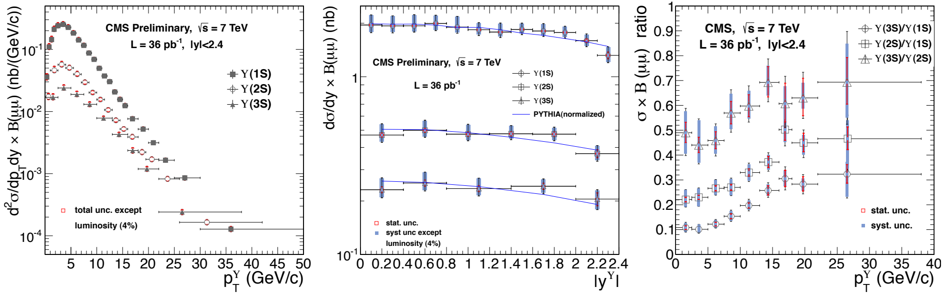
Differential $\Upsilon(nS)$ Cross Section of p_T and $|y|$ (36 pb^{-1})

BPH-11-001, https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11001

$$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = (8.55 \pm 0.05(\mathrm{stat.})^{+0.88}_{-0.78}(\mathrm{syst.}) \pm 0.34(\mathrm{lumi.}))\ \mathrm{nb}\,,$$

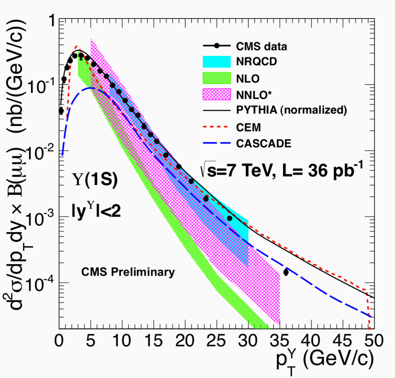
$$\sigma(pp \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = (2.21 \pm 0.03(\mathrm{stat.})^{+0.24}_{-0.21}(\mathrm{syst.}) \pm 0.09(\mathrm{lumi.}))\ \mathrm{nb}\,,$$

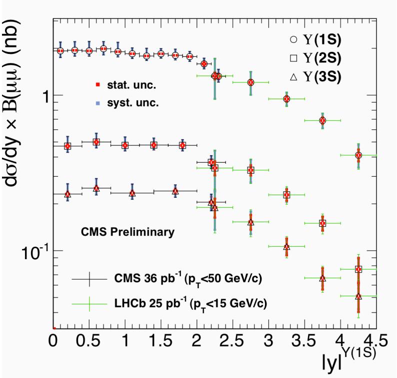
$$\sigma(pp \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = (1.11 \pm 0.01(\mathrm{stat.})^{+0.13}_{-0.12}(\mathrm{syst.}) \pm 0.04(\mathrm{lumi.}))\ \mathrm{nb}\,.$$



- Updated analysis using 36 pb^{-1} data, extending kinematic reach: $p_T <$ 30 GeV $\to 50 GeV$, $|y| < 2 \to 2.4$
- Acceptance corrections for unpolarized assumption, down to zero p_T
- The dominant systematic is from the calculation of the efficiencies.

Comparisons of Cross Section to Theory and Other Experiments





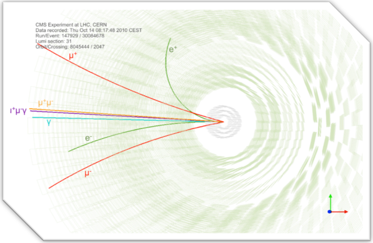
- NRQCD seems to give the best agreement

  BPH-11-001

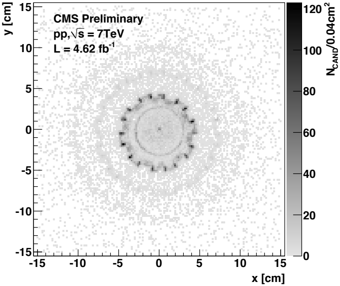
- Complementary to LHCb and consistent in the region of overlap

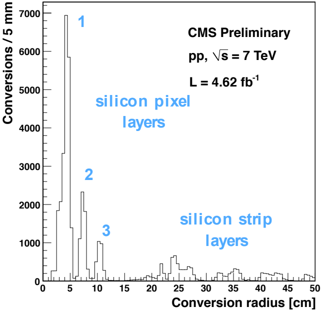
Measurement of the prompt χ_{c1}/χ_{c2} production cross-section ratio

- Excited quarkonium states (P-wave states) present complementary information to S-wave state production.
- Production of χ_c mesons studied via $\chi_c \to J/\Psi + \gamma$ decays, with tracker-only γ conversions to e^+e^-
- High purity γ Conversions



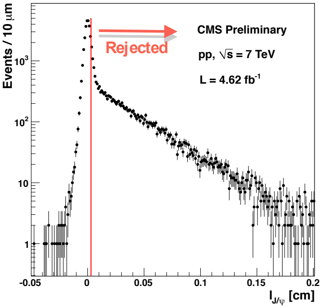
CMS-PAS-BPH-11-010





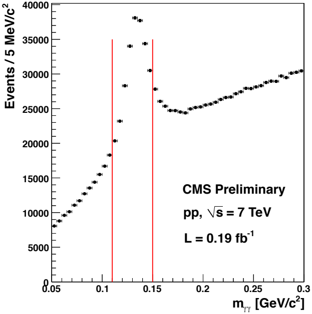
Background Rejection

- To study χ_c prompt production, we minimize feed-down from B decays by rejecting the displaced dimuons.



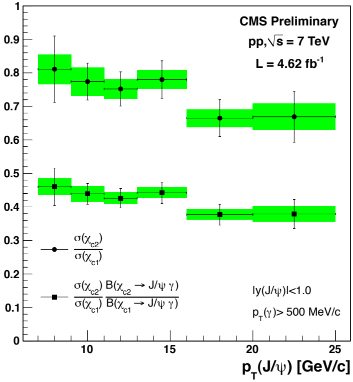
CMS-PAS-BPH-11-010

- To minimize the photon background from π^0 decays, we reject photons that, combined with other photons in the event, give the π^0 mass



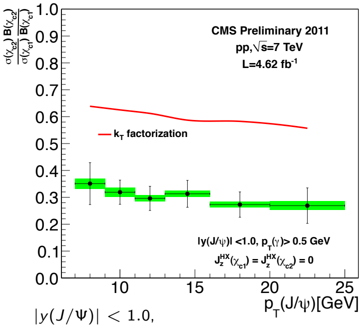
The Results

- The prompt χ_{c2}/χ_{c1} cross-section ratio has been measured vs. p_T
- Systematic uncertainties dominated by fit to mass distribution. Also include efficiencies statistical uncertainty.

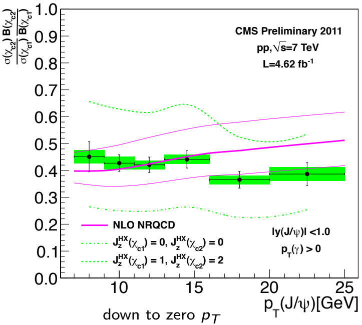


CMS-PAS-BPH-11-010

Comparisons to Theories



$|y(J/\Psi)| < 1.0$,
$p_T(\gamma) > 500 MeV/c$



down to zero p_T

- The k_T factorization model predicts the χ_{c1} and χ_{c2} states in a $J_z^{HX} = 0$ state. For a proper comparison, the acceptance was recalculated under this assumption.

- The NLO NRQCD predictions were made without a cut on the photon transverse momentum.
- Extrapolated down to zero photon p_T.
- The comparison requires the full polarization uncertainty, shown by the green envelope.

CMS-PAS-BPH-11-010

Summary

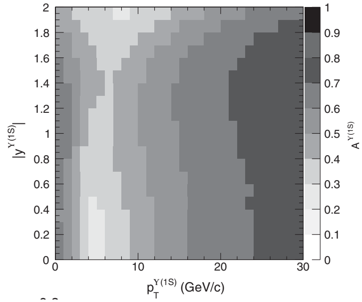
- J/Ψ, $\Psi(2S)$, $\Upsilon(nS)$ differential cross-sections measured with typical uncertainties (statistical + systematic) of 5%, 20%, 10%
  - p_T ranging from 0 to 70 GeV/c for the J/Ψ, 0 to 50 GeV/c for the Υs
  - For charmonium, prompt and non-prompt separation achieved using decay length information
  - Good agreement with NLO NRQCD predictions at 7 TeV
  - B$\rightarrow J/\Psi$, $\Psi(2S)$ in reasonable agreement with FONLL predictions, except for the very high p_T region and for the total $B \rightarrow \Psi(2S)$ rate
- $\chi_c \rightarrow J/\Psi + \gamma$ assessed through photon conversion
  - Excellent signal-to-background ratio, good separation of the three states: χ_{c0}, χ_{c1} and χ_{c2}
  - The χ_{c2}/χ_{c1} cross-section ratio measured up to unprecedented J/Ψ p_T
  - The most precise measurement currently!

Back Up

Acceptance ($\mathcal{A}$)

$$\mathcal{A}\left(p_T^{\Upsilon}, y^{\Upsilon}\right) = \frac{N^{\text{reco}}\left(p_T^{\Upsilon}, y^{\Upsilon} \middle| \text{SiTRK track pair satisfies fiducial cuts}\right)}{N^{\text{gen}}\left(p'^{\Upsilon}_T, y'^{\Upsilon}\right)}, \quad (1)$$

- Geometric and kinematic
- High-Statistics Υ(nS) Gun samples, generated flat in Υp_T
- Different acceptance maps for 1S, 2S and 3S



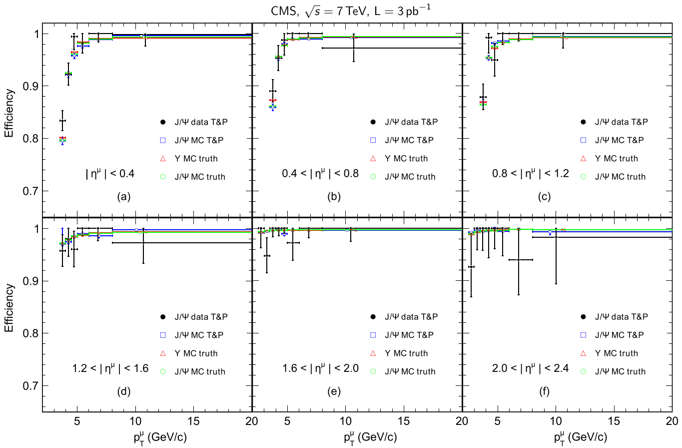
Phys. Rev. D 83, 112004 (2011)

Acceptance vs. Polarization

- Acceptance is a strong function of production polarization
- Acceptance is not used in fiducial cross section results
- For the acceptance-corrected production cross section results, quote five cross sections for discrete polarization values

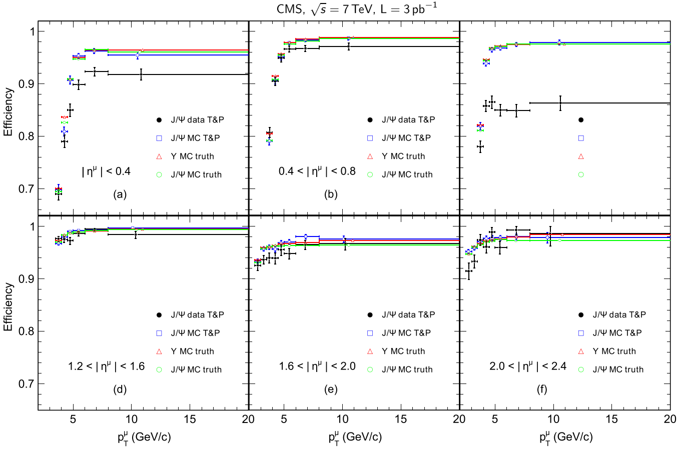
HXT: Helicity frame, transversely polarized
HXL: Helicity frame, longitudinally polarized
CST: Collins-Soper frame, longitudinally polarized
CSL: Collins-Soper frame, transversely polarized

MuonID Efficiencies (ϵ_{id})



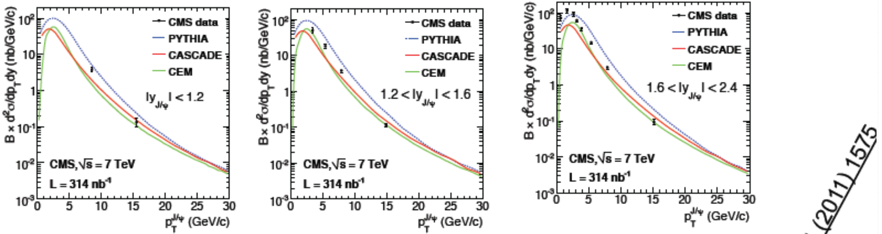
Phys. Rev. D 83, 112004 (2011)

Trigger Efficiencies (ϵ_{trig})

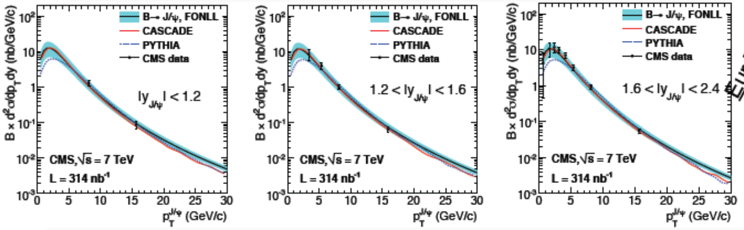


Phys. Rev. D 83, 112004 (2011)

First CMS paper on J/ψ



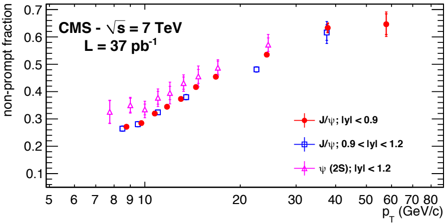
$$\sigma(pp \to J/\psi + X) \cdot BR(J/\psi \to \mu^+\mu^-) = 70.9 \pm 2.1(\text{stat}) \pm 3.0(\text{syst}) \pm 7.8(\text{luminosity})\ \text{nb}$$

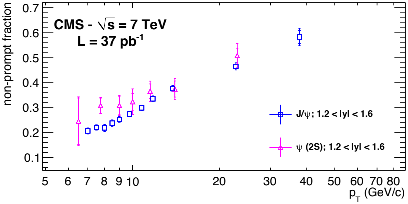


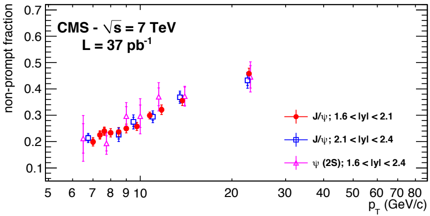
$$\sigma(pp \to bX \to J/\psi X) \cdot BR(J/\psi \to \mu^+\mu^-) = 26.0 \pm 1.4\ (\text{stat}) \pm 1.6\ (\text{syst}) \pm 2.9\ (\text{luminosity})\ \text{nb}$$

B fraction results

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



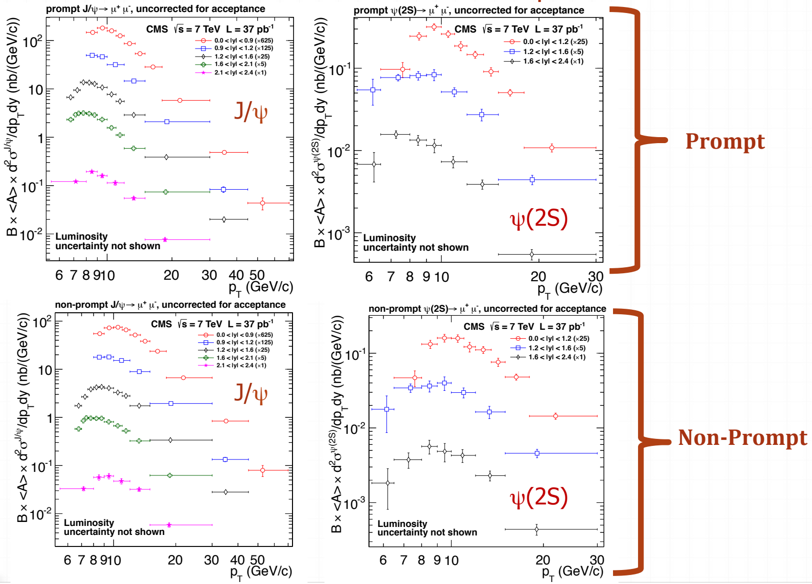




JHEP 02 (2012) 011

ψ(nS) Cross Sections

uncorrected for acceptance



JHEP 02 (2012) 011

J/Ψ Systematics

$\|y\|$ range		0 – 0.9	0.9 – 1.2	1.2 – 1.6	1.6 – 2.1	2.1 – 2.4
Quantity affected	Source	Relative uncertainty (in %)				
All cross sections						
$m_{\mu\mu}$ fits	Statistical	1.2 – 8.9	1.5 – 7.1	1.6 – 8.4	1.2 – 3.2	2.3 – 3.9
$\ell_{J/\psi}$ fits	Statistical	1.0 – 5.9	1.4 – 4.7	1.4 – 7.6	2.1 – 8.3	4.4 – 7.1
Efficiency	Single-muon efficiency	0.3 – 0.9	0.2 – 1.6	0.1 – 1.4	0.2 – 1.0	0.6 – 1.4
	ρ factor	1.9 – 23.2	1.2 – 7.6	0.7 – 5.7	0.8 – 5.4	3.7 – 6.8
Yields	Fit functions	0.6 – 3.4	0.4 – 2.8	0.5 – 2.8	0.8 – 2.2	1.0 – 4.2
Luminosity	Luminosity	4.0	4.0	4.0	4.0	4.0
Non-prompt fraction	Tracker misalignment	0.1 – 2.1	0.1 – 0.8	0.0 – 1.5	0.2 – 3.2	0.2 – 5.1
	b-lifetime model	0.1 – 3.0	0.1 – 3.4	0.1 – 3.7	0.2 – 2.6	0.2 – 6.6
	Vertex estimation	0.1 – 0.7	0.7 – 3.0	0.4 – 3.7	1.5 – 4.6	2.3 – 5.0
	Background fit	0.0 – 0.2	0.1 – 1.4	0.1 – 1.0	0.0 – 2.5	0.1 – 1.2
	Resolution model	0.2 – 3.5	0.0 – 4.2	0.8 – 3.5	1.1 – 5.0	1.1 – 4.4
	Efficiency	0.4 – 2.1	0.9 – 3.3	0.5 – 9.9	0.3 – 3.3	1.6 – 10.5
Only acceptance-corrected cross sections						
Acceptance	FSR	0.0 – 1.5	0.0 – 2.5	0.0 – 4.2	0.7 – 8.0	0.5 – 3.5
	p_T calibration	0.0 – 0.6	0.0 – 0.6	0.0 – 0.8	0.1 – 0.6	0.0 – 0.8
	Kinematic spectra	0.0 – 0.3	0.0 – 0.7	0.0 – 0.7	0.7 – 3.8	0.4 – 5.3
	B polarization	0.0 – 0.5	0.0 – 0.4	0.0 – 0.5	0.1 – 0.8	0.3 – 1.3

JHEP 02 (2012) 011

$\Psi(2S)$ Systematics

$\lvert y \rvert$ range		0 – 1.2	1.2 – 1.6	1.6 – 2.4
Quantity affected	Source	Relative uncertainty (in %)		
All cross sections				
$m_{\mu\mu}$ fits	Statistical	5.6 – 14.8	7.5 – 31.7	7.3 – 24.1
$\ell_{\psi(2S)}$ fits	Statistical	4.3 – 12.7	5.9 – 38.0	9.1 – 26.4
Efficiency	Single-muon efficiency	0.1 – 0.5	0.1 – 0.6	0.2 – 0.9
	ρ factor	0.7 – 13.1	2.1 – 6.6	2.3 – 9.8
Yields	Fit functions	1.2 – 3.7	0.6 – 12.1	3.1 – 10.0
Luminosity	Luminosity	4.0	4.0	4.0
Non-prompt fraction	Tracker misalignment	0.3 – 2.6	1.5 – 7.1	1.8 – 11.1
	b-lifetime model	0.0 – 2.5	0.4 – 7.6	0.0 – 2.9
	Vertex estimation	0.0 – 1.7	0.2 – 3.5	1.2 – 4.2
	Background fit	1.0 – 6.8	2.2 – 10.0	2.5 – 15.3
	Resolution model	0.5 – 3.5	0.1 – 4.6	0.9 – 24.9
	Efficiency	0.5 – 7.8	0.9 – 6.3	0.5 – 13.8
Only acceptance-corrected cross sections				
Acceptance	FSR	0.0 – 3.9	0.5 – 3.4	0.3 – 4.1
	p_{T} calibration	0.2 – 0.5	0.3 – 0.5	0.3 – 0.5
	Kinematic spectra	0.1 – 1.2	0.0 – 0.9	0.7 – 2.0
	B polarization	0.1 – 0.8	0.0 – 0.6	0.2 – 1.7

JHEP 02 (2012) 011

Υ Systematic Uncertainties

$|\mathbf{y}^{\Upsilon}| < \mathbf{2.4}$

Υ(1S)

p_T	A	S_p	A_{p_T}	A_{fsr}	$\varepsilon_{\text{trig,id}}$	ε_ρ	$\varepsilon_{\text{func}}$	ε_{trk}	PDF_{CB}	PDF_{bkgd}	M_{scale}
0.0 – 50.0	1.8 (1.7)	1.0 (1.0)	1.7	0.5	7.1 (5.4)	6.8	1.8	0.4 (0.3)	1.7	0.7	0.0 (0.0)
0.0 – 0.5	1.3 (1.2)	0.1 (0.1)	0.3	0.8	10.1 (7.9)	7.5	0.4	0.4 (0.3)	2.0	0.7	0.1 (0.1)
0.5 – 1.0	1.3 (1.3)	0.1 (0.1)	0.3	0.8	9.5 (7.6)	8.2	0.7	0.3 (0.4)	1.8	1.3	0.0 (0.4)
1.0 – 1.5	1.4 (1.3)	0.9 (0.9)	1.5	0.5	8.4 (6.8)	7.1	3.6	0.4 (0.4)	2.1	0.5	0.0 (0.0)
1.5 – 2.0	1.4 (1.4)	1.8 (1.8)	1.5	0.4	8.9 (7.0)	8.1	3.4	0.4 (0.4)	1.3	2.8	0.1 (0.0)
2.0 – 3.0	1.7 (1.6)	0.2 (0.0)	0.7	0.7	8.5 (6.6)	7.2	2.6	0.4 (0.3)	1.7	2.4	0.0 (0.0)
3.0 – 4.0	1.9 (1.9)	0.8 (0.8)	1.0	0.6	7.7 (5.6)	7.2	1.9	0.3 (0.4)	2.0	1.2	0.1 (0.1)
4.0 – 5.0	1.8 (1.9)	0.3 (0.3)	0.1	0.8	7.2 (5.3)	7.4	2.6	0.4 (0.6)	1.5	0.4	0.0 (0.2)
5.0 – 6.0	2.1 (2.1)	1.8 (1.8)	2.3	0.3	6.7 (5.0)	6.7	2.2	0.3 (0.4)	1.3	1.8	0.2 (0.2)
6.0 – 7.0	2.2 (1.9)	1.2 (1.2)	2.0	0.4	6.7 (4.7)	6.9	1.9	0.4 (0.2)	1.3	0.6	0.3 (0.3)
7.0 – 8.0	2.0 (1.9)	1.5 (1.5)	2.6	0.3	6.2 (4.6)	5.2	1.4	0.4 (0.4)	1.5	0.9	0.2 (0.2)
8.0 – 9.0	1.8 (1.8)	1.1 (1.1)	2.2	0.3	5.9 (4.3)	4.4	1.2	0.4 (0.4)	1.3	0.9	0.0 (0.0)
9.0 – 10.0	1.8 (1.7)	1.9 (1.9)	3.3	0.2	5.9 (4.4)	3.9	0.1	0.4 (0.4)	1.2	1.3	0.2 (0.1)
10.0 – 11.0	1.5 (1.5)	1.8 (1.8)	3.3	0.2	5.4 (4.1)	5.0	0.4	0.4 (0.3)	1.2	1.2	0.2 (0.0)
11.0 – 12.0	1.7 (1.6)	1.4 (1.4)	2.8	0.1	5.5 (4.2)	1.8	0.5	0.4 (0.4)	0.7	2.3	0.2 (0.2)
12.0 – 13.0	1.5 (1.4)	2.4 (2.4)	3.9	0.0	5.4 (4.2)	5.1	0.4	0.4 (0.4)	1.2	1.0	0.6 (0.6)
13.0 – 14.0	1.4 (1.4)	2.0 (2.0)	3.6	0.0	5.2 (4.0)	5.2	0.2	0.4 (0.3)	1.3	0.1	0.1 (1.0)
14.0 – 15.0	1.3 (1.3)	2.5 (2.5)	4.1	0.1	5.3 (4.2)	6.4	0.7	0.4 (0.3)	1.3	0.1	1.2 (0.4)
15.0 – 16.0	1.3 (1.2)	2.0 (2.0)	3.7	0.0	5.1 (4.1)	5.8	1.3	0.4 (0.3)	1.2	0.1	0.8 (0.1)
16.0 – 18.0	1.1 (1.1)	2.2 (2.2)	3.9	0.1	4.8 (3.9)	6.1	1.5	0.4 (0.4)	1.2	0.7	0.1 (0.4)
18.0 – 20.0	1.1 (1.1)	2.2 (2.2)	4.1	0.1	4.8 (3.8)	5.6	1.4	0.4 (0.4)	1.4	0.2	0.2 (0.2)
20.0 – 22.0	1.0 (1.0)	2.4 (2.4)	4.1	0.0	4.8 (3.9)	3.0	2.2	0.4 (0.3)	0.9	0.6	0.0 (0.0)
22.0 – 25.0	1.0 (1.0)	1.8 (1.8)	4.3	0.0	4.7 (3.9)	2.7	2.1	0.4 (0.4)	1.5	1.3	0.4 (0.4)
25.0 – 30.0	1.1 (1.1)	1.1 (1.1)	4.4	0.7	4.9 (4.2)	1.1	2.3	0.4 (0.4)	1.3	0.6	0.3 (0.2)
30.0 – 50.0	0.6 (0.6)	2.1 (2.1)	3.5	0.3	4.5 (3.8)	4.7	2.1	0.3 (0.3)	1.3	4.0	0.1 (1.0)

Phys. Rev. D 83, 112004 (2011)