J/ψ and ϒ Physics at CMS

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on behalf of the CMS Collaboration

Implications of First LHC Data
MIT-Berkeley Workshop
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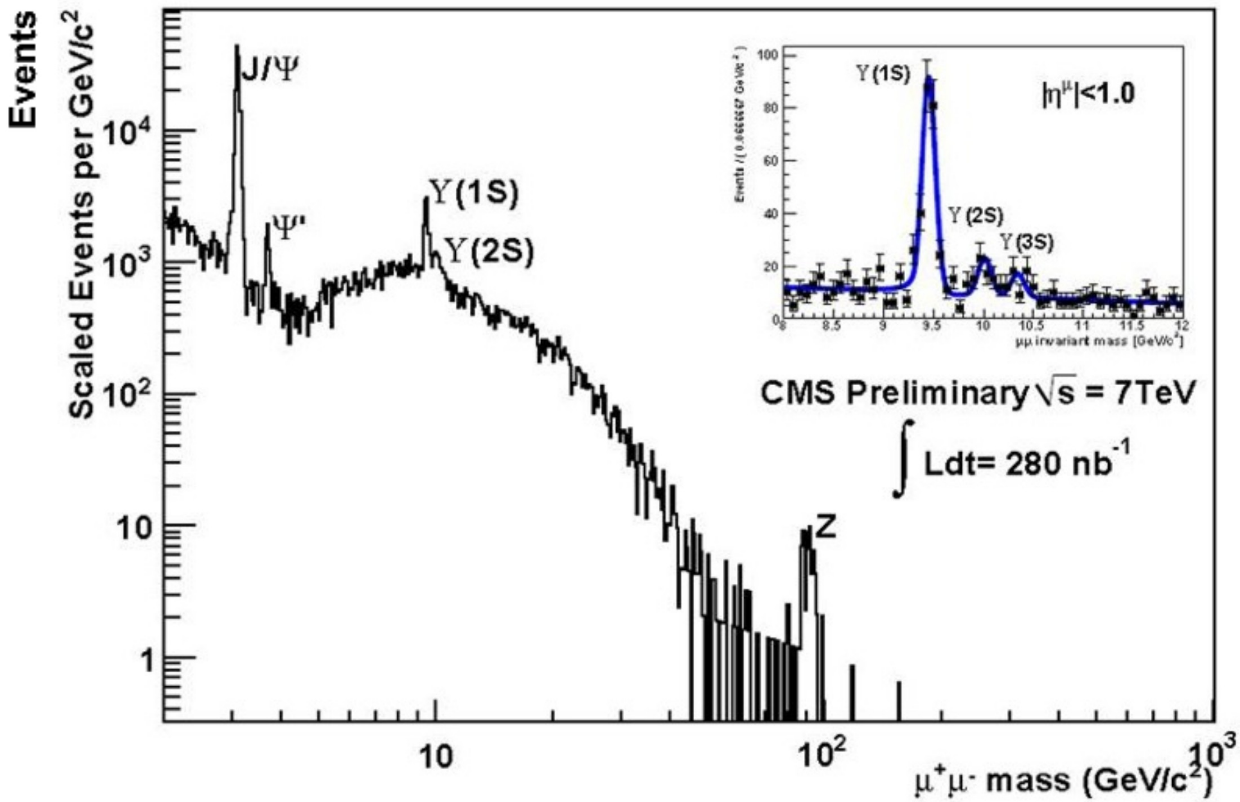
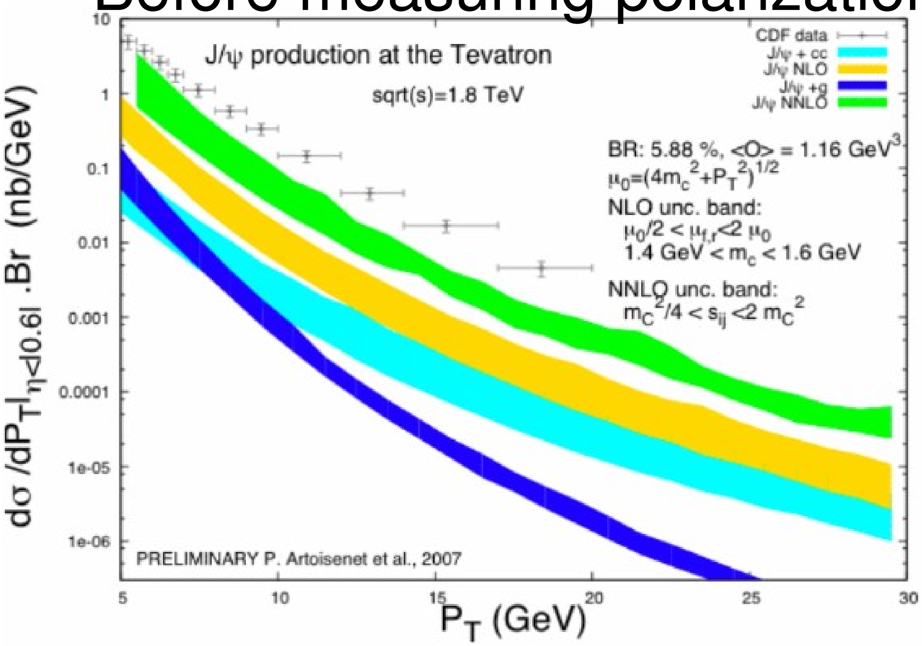
Outline

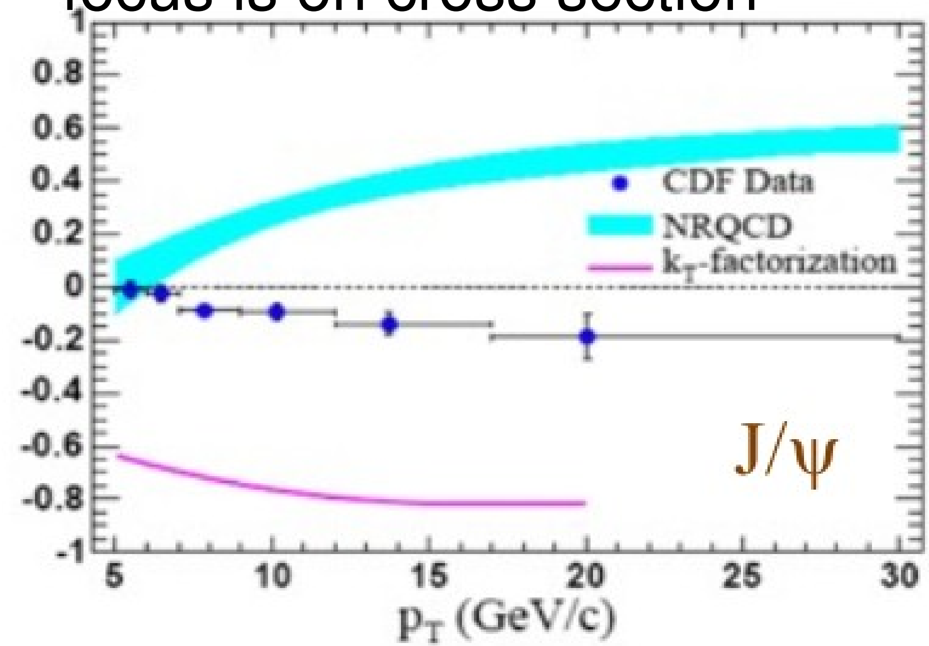
- Will present the first measurements at 7 TeV in CMS of J/ψ and ϒ production
- Inclusive differential J/ψ cross section and non-prompt fraction
- ϒ(1s) cross section and ϒ(2s+3s)/ϒ(1s) ratio
- Start of dimuon analyses!



Quarkonia Modelling

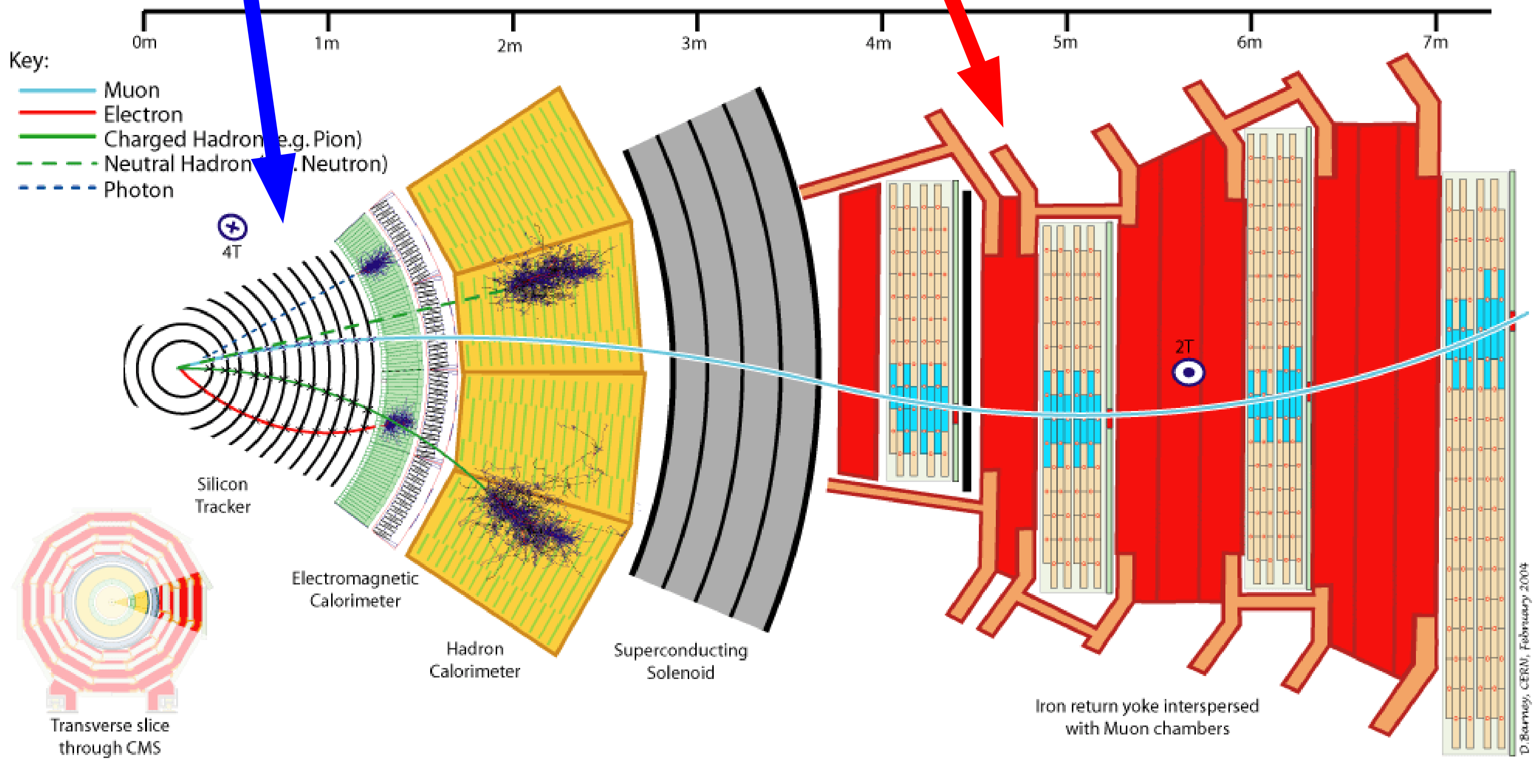
- Quarkonia production theoretically and experimentally puzzling
- No theory has simultaneously explained experimental measurements of both cross section and polarization
- Opportunity at LHC to provide valuable input to understanding of quarkonia production, including reach to higher p_T region
- Before measuring polarization – focus is on cross section





CMS Experiment

- For this analysis rely on muon chambers (DTs, CSCs, RPCs) for triggering and ID, and inner silicon pixel and strip tracker for momentum measurement



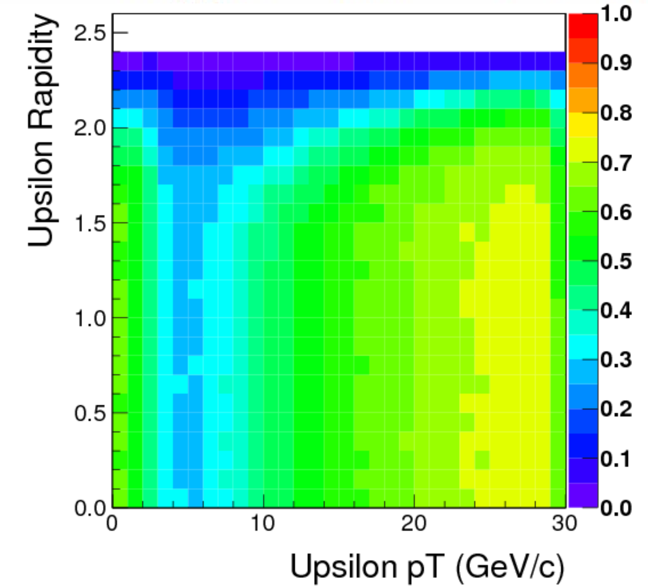
Triggering

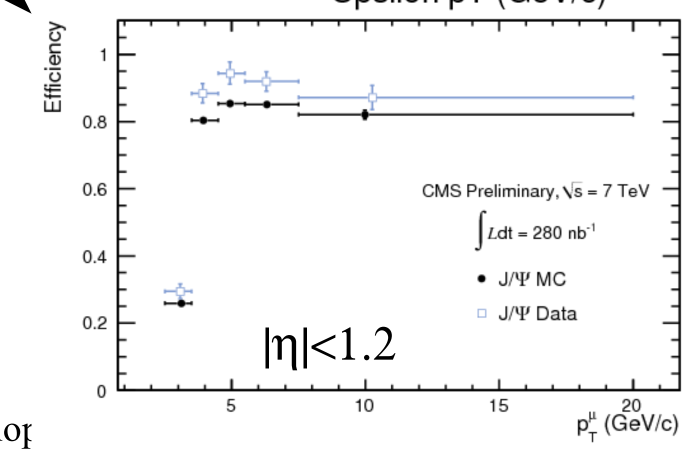
- Muon trigger important driver for quarkonia analysis
- Includes hardware (Level1) and software (HLT) parts
- Hardware works with all muon systems, HLT also includes fast inner tracking algorithm
- In early running trigger menus and prescales are still changing
- Presented analyses use:
  - L1 dimuon trigger – does not require an explicit p_T cut on the muons, and allows use of events with low p_T forward muons ($|\eta| < 2.4$)
  - HLT single muon trigger - requires $p_T > 3$ GeV for one muon

Cross Section

$$\frac{d^2\sigma}{dp_T dy}(pp \to Q\bar{Q}X) \times \mathcal{B}(Q\bar{Q} \to \mu^+\mu^-) = \frac{N_{Q\bar{Q}}}{\int L dt \cdot A \cdot \epsilon_{trigger} \cdot \epsilon_{reco} \cdot \Delta p_T \Delta y}$$

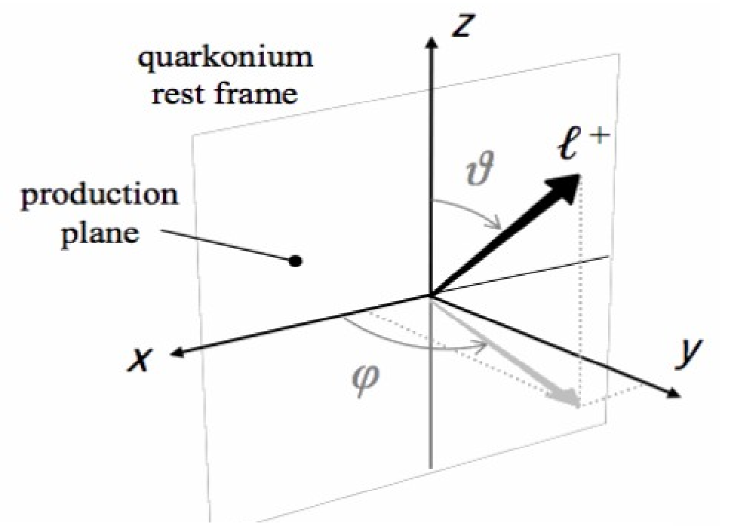
- A = acceptance from simulation
- ε's – trigger and reconstruction efficiency measured with J/ψ data using tag and probe method
- Measurement includes quarkonia from feeddown in cross section – only non-prompt J/ψ from b decays measured separately





Polarization Effects

- Production polarization is unknown
- Would be largest systematic uncertainty
- Different polarization parameters λ have large effect on acceptance



$$W(\cos\theta,\phi) = \frac{3}{2(3+\lambda_\theta)} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)$$

- Quote isotropic decay result as well as results for 4 other polarizations – LHC wide agreement to facilitate comparison
- Non-prompt J/ψ component modelled from theory and b-factory experimental results

Selection

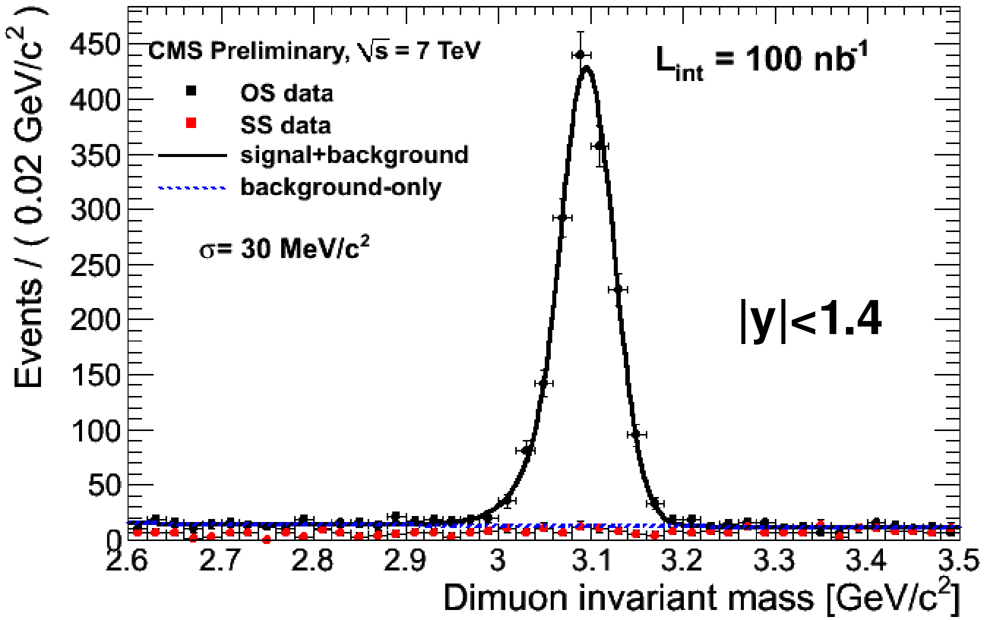
- J/ψ and ϒ feature similar selections:
  - Track and muon quality (number of hits, χ^2, impact parameters...)
  - Vertexing of opposite sign muons (require probability > 0.1%)
- Kinematic cuts on muons:

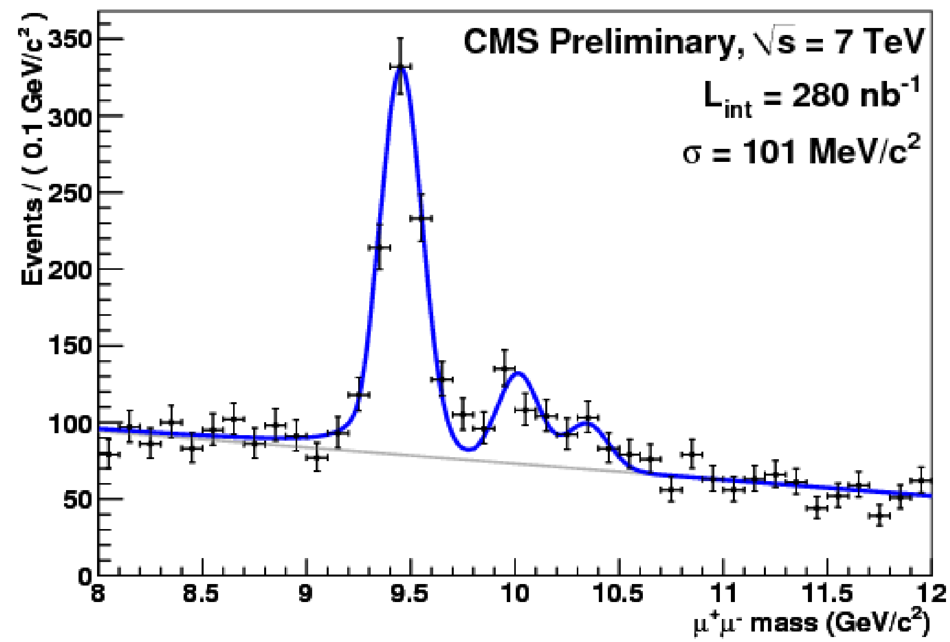
J/ψ		Υ	
$\lvert\eta\rvert < 1.3$	$p_T > 3.3$ GeV	$\lvert\eta\rvert < 1.6$	$p_T > 3.5$ GeV
$1.3 < \lvert\eta\rvert < 2.2$	$p > 2.9$ GeV	$1.6 < \lvert\eta\rvert < 2.4$	$p_T > 2.5$ GeV
$2.2 < \lvert\eta\rvert < 2.4$	$p_T > 0.8$ GeV		

- J/ψ kinematic cuts are more aggressive to include as much of signal as possible for low luminosity measurement

Yields

- Yields extracted with unbinned maximum likelihood fit
- J/ψ – Crystal Ball + exponential
- ϒ – Crystal Balls + linear
  - Common resolution for three peaks
  - ϒ(1s) mass floated, ΔM(2s-1s,3s-1s) fixed from PDG



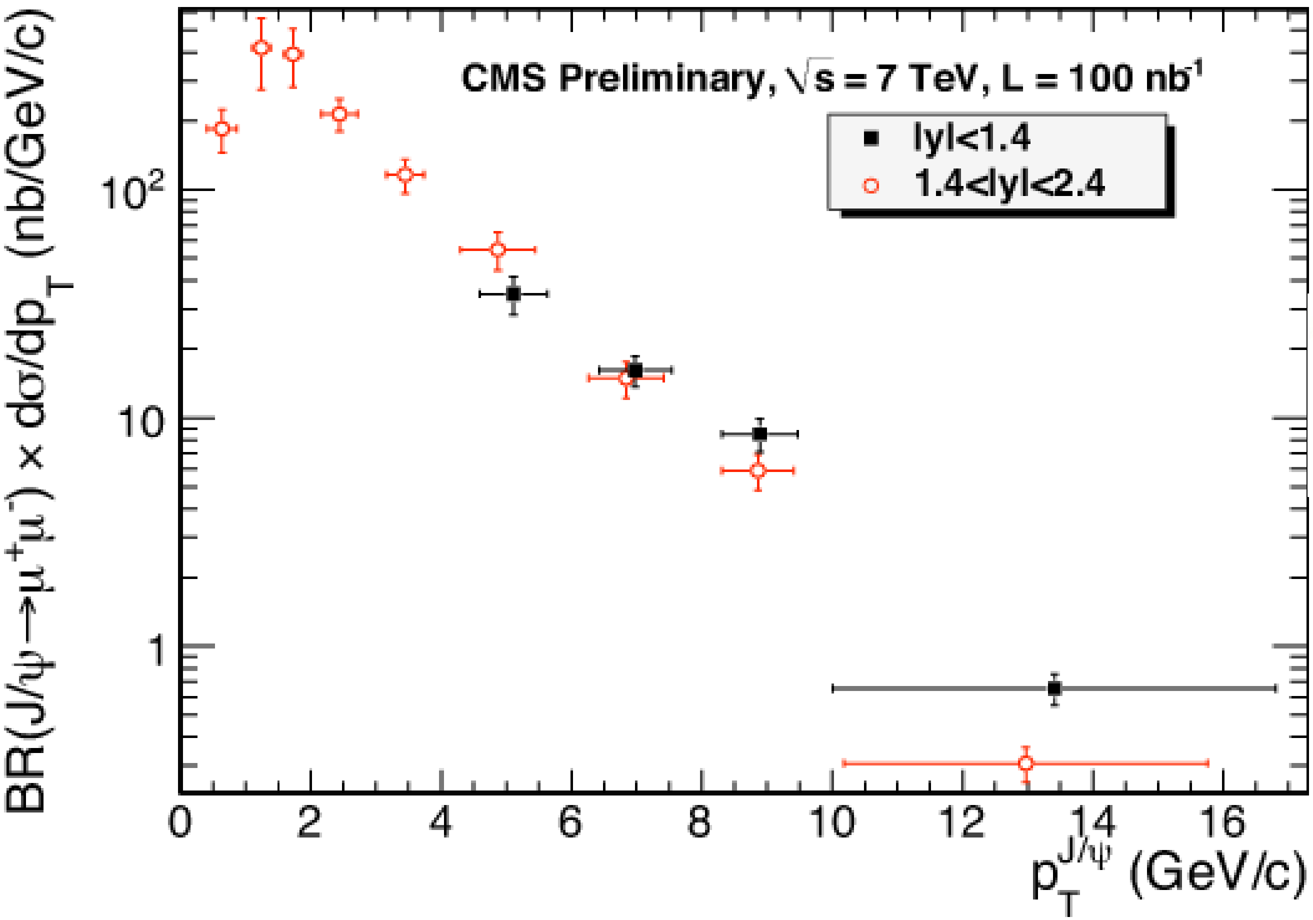


Systematic Uncertainties

- Many uncertainties in common between J/ψ and ϒ
- Polarization treated not as systematic uncertainty but different hypotheses used to provide separate results
- Efficiency – tag and probe uncertainty, factorization of efficiencies, binning effects
- Acceptance – FSR, p_T spectrum shape, momentum scale and resolution, b fraction, luminous region...
- Fit systematic uncertainties – yield and b fraction. Validated with MC
- Largest systematic uncertainty is muon efficiency from tag and probe uncertainties (~10%)

J/ψ Cross Section

- Differential cross section result with two rapidity bins for unpolarized scenario



Total for 4 GeV < p_T < 30 GeV, |y|<2.4:

$$BR(J/\psi \rightarrow \mu^+\mu^-)\cdot\sigma(pp\rightarrow J/\psi + X) =$$

$$(289.1 \pm 16.7(\mathrm{stat}) \pm 60.1(\mathrm{syst}))\ \mathrm{nb}$$

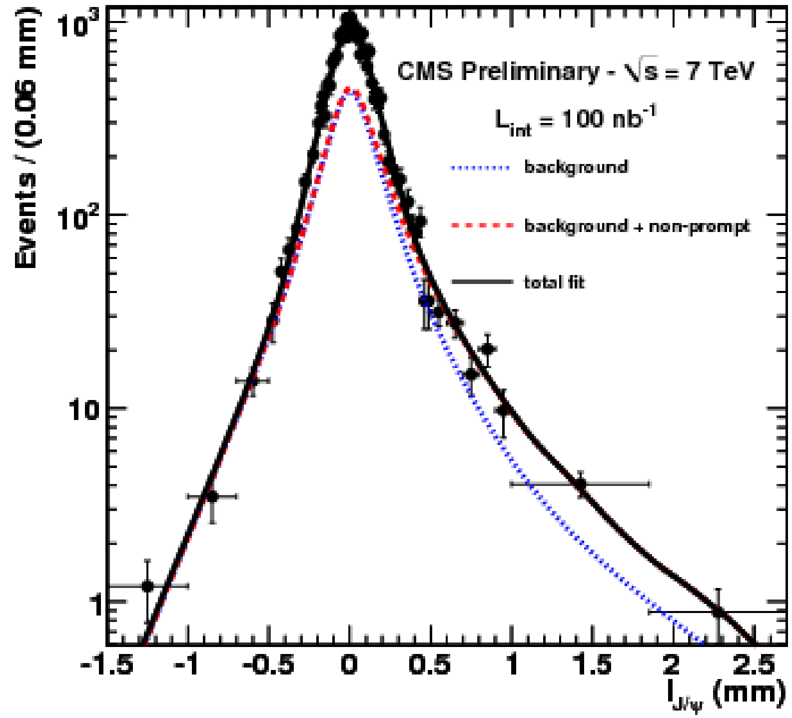
Polarizations change result by 20-30%

Prompt and Non-prompt

- Measure the contribution of prompt and non-prompt components of J/ψ with 2D unbinned likelihood fit to mass and pseudo-proper decay length

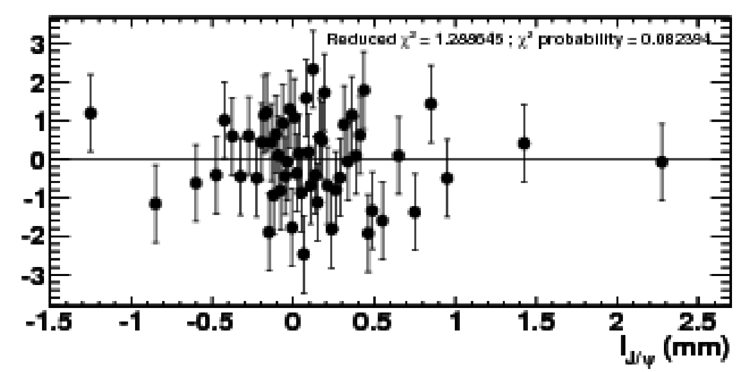
$$l_{J/\psi} = \frac{L_{xy}^{J/\psi} * M^{J/\psi}}{p_T^{J/\psi}}$$

- Three gaussian resolution alone for prompt part, convolution with exponential for non-prompt part



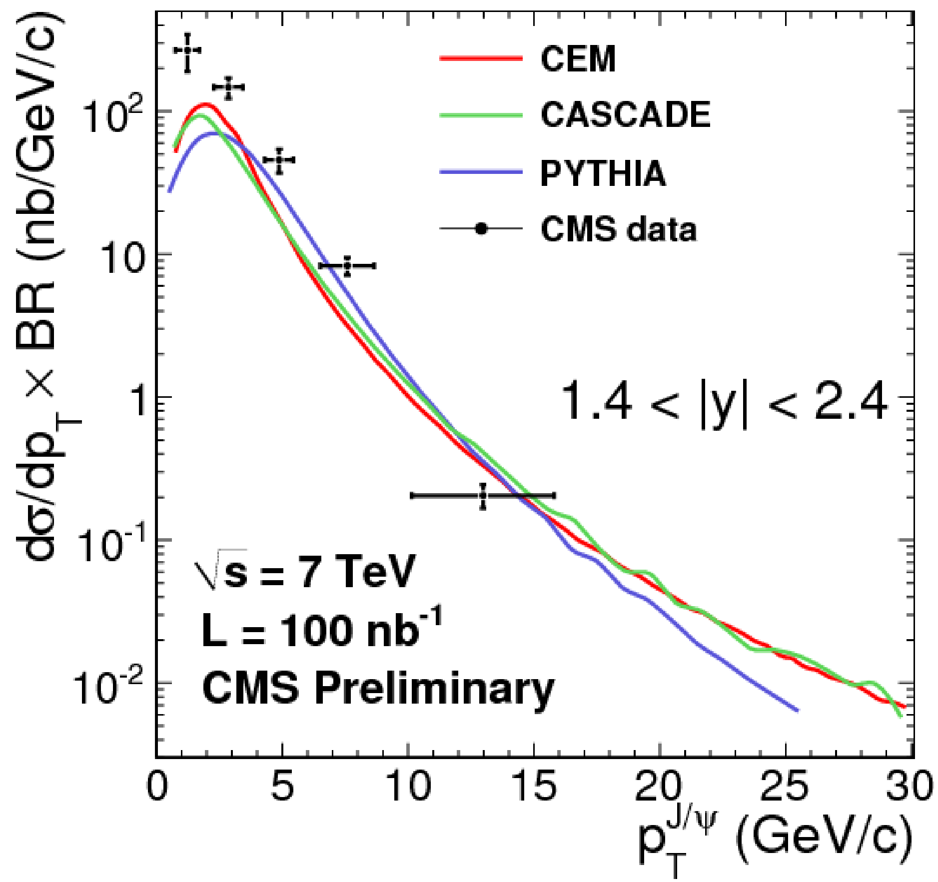
2 GeV < p_T < 4 GeV; 1.4 < |y| < 2.4

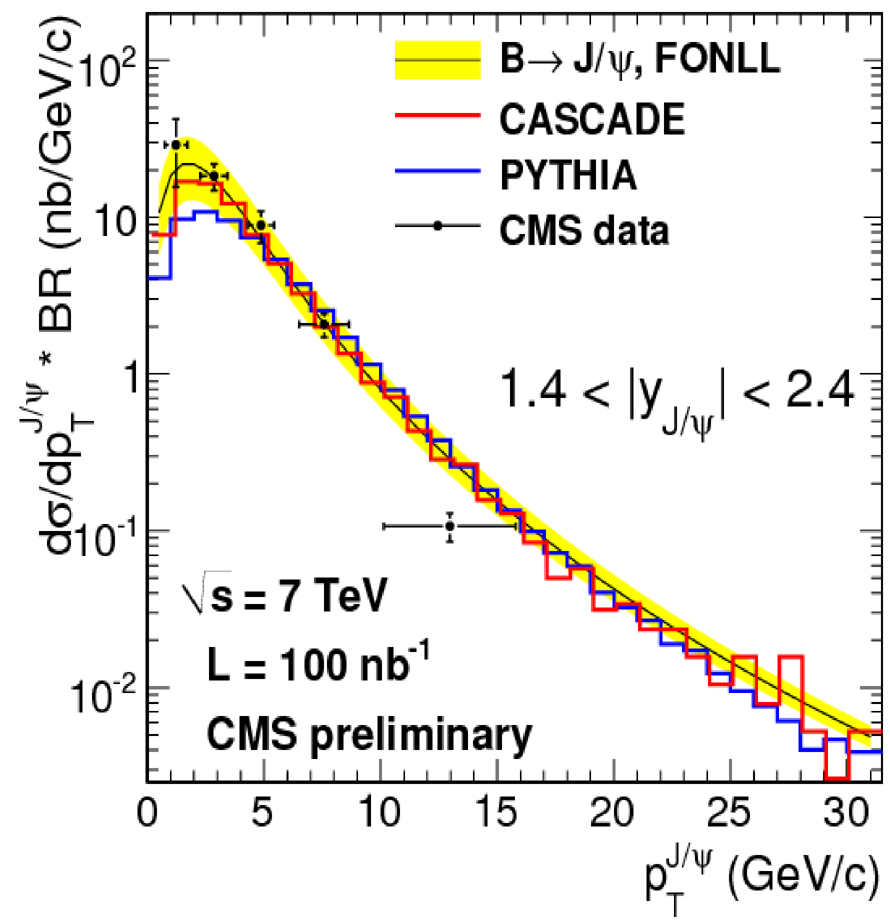
Pull



Prompt and Non-prompt

- Results for prompt (left) and non-prompt (right) J/ψ differential cross section compared to MC and theory curves
- Discrepancy for prompt component at low p_T





Υ Cross Section

- Differential result in p_T with single rapidity bin compared to MC and theory curves
- Total

$$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S)) \to \mu^+\mu^-) =$$

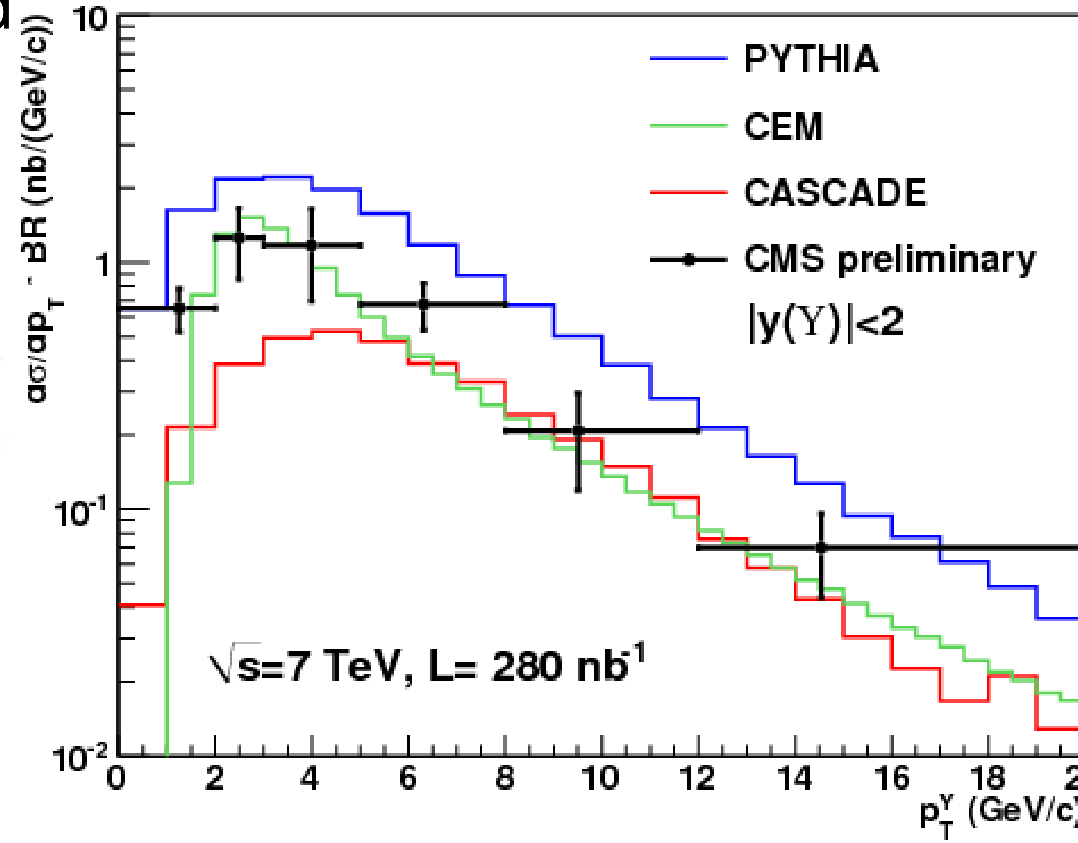
$$8.3 \pm (0.5)_{\text{stat.}} \pm (0.9)_{\text{lumi.}} \pm (1.0)_{\text{syst.}}\ \text{nb}$$

- Ratio

$\Upsilon(2S) + \Upsilon(3S)$ to $\Upsilon(1S)$ ratio

$$0.44 \pm 0.06 \pm 0.05$$

- Large discrepancy from Pythia and CASCADE, less from CEM



Polarizations change result by 20-30%

Conclusions

- First CMS quarkonia measurements at 7 TeV already showing good capability for comparisons with predictions
  - J/ψ and $\Upsilon(1s)$ differential cross sections
  - Non-prompt J/ψ fraction from b decay
  - $\Upsilon(2s+3s)/\Upsilon(1s)$ cross section ratio
- Shown excellent detector performance that demonstrates the good prospects for muon analyses in CMS
- To come:
  - Measurements limited by systematics but can improve both detector knowledge and analysis strategy
  - Polarization measurements essential for complete understanding

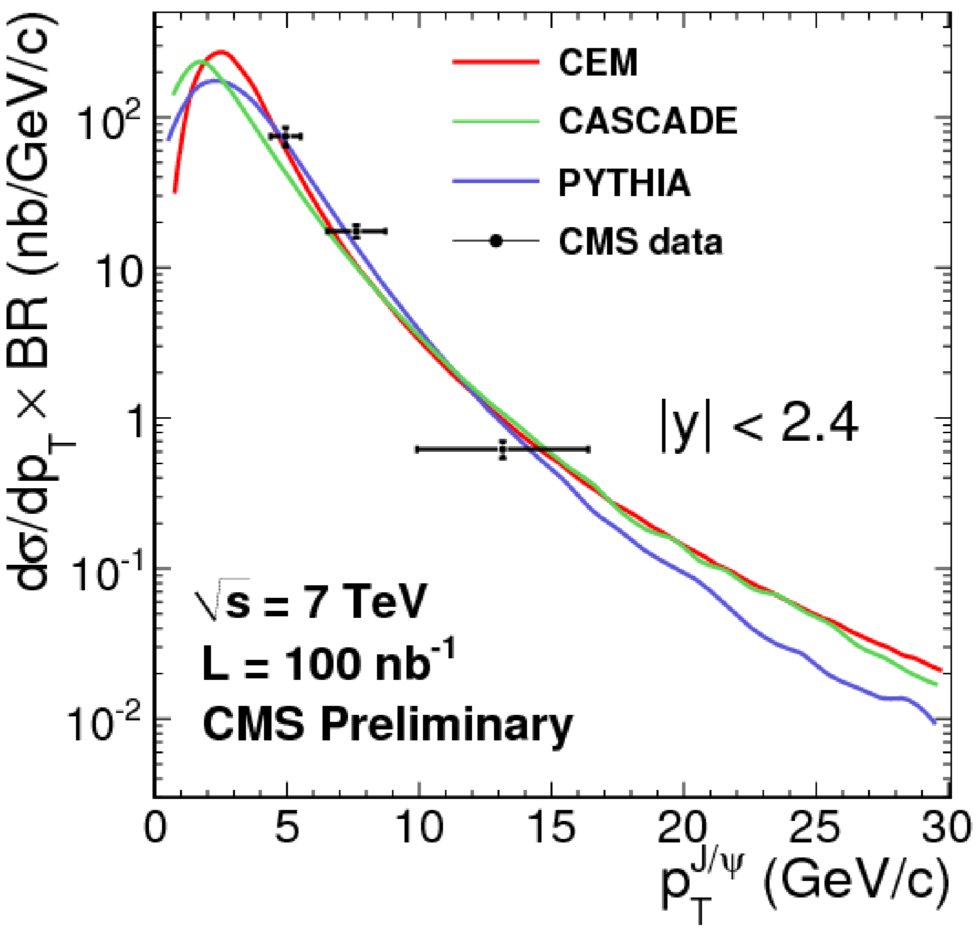
Backup

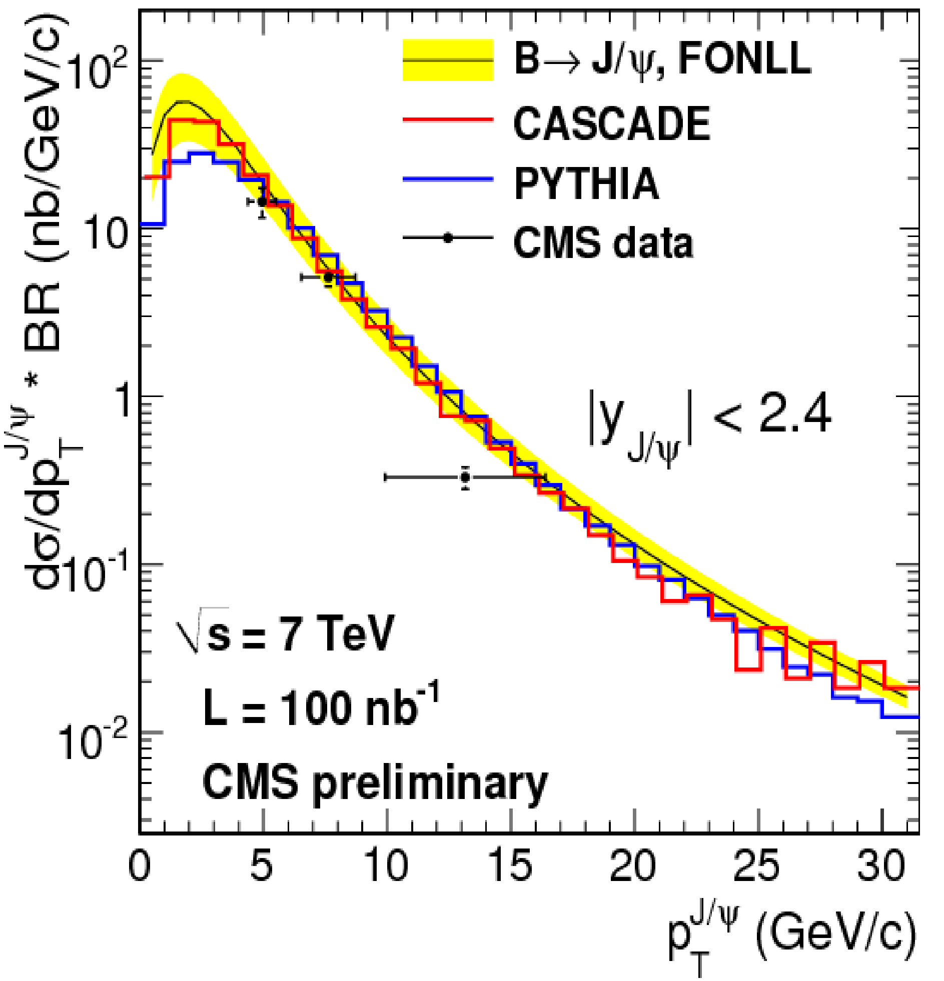
Documents

- Relevant public CMS physics analysis summaries:
  - BPH-PAS 10-002 *J/ψ prompt and non-prompt cross sections in pp collisions at* $\sqrt{s} = 7$ *TeV*
  - BPH-PAS 10-003 *Upsilon production cross section in pp collisions at* $\sqrt{s} = 7$ *TeV*
  - EWK-PAS 10-004 *Measurement of CMS luminosity*
  - MUO-PAS 10-002 *Performance of muon identification in pp collisions at* $\sqrt{s} = 7$ *TeV*
  - TRK-PAS 10-002 *Measurement of tracking efficiency*
  - TRK-PAS 10-004 *Measurement of momentum scale and resolution using low-mass resonances and cosmic-ray muons*

J/ψ Cross Sections

- Prompt and non-prompt in other rapidity bin





J/ψ Cross Sections

Table 3: Differential cross sections, and average p_T in the bin (in the data), for each prompt J/ψ polarization considered: the default null polarization, the polarization fully longitudinal ($\lambda_\theta = -1$) and fully transverse ($\lambda_\theta = +1$) in either the Collins-Soper (CS) or the Helicity (HX) frames (see Ref. [6]). Only for the null polarization case, the first error is statistical and the second is systematical; for the others the error is the total one.

$p_T^{J/\psi}$ (GeV/c)	$\langle p_T^{J/\psi} \rangle$ (GeV/c)	$BR(J/\psi \to \mu^+\mu^-) \cdot \frac{d\sigma}{dp_T}$ (nb/ GeV/c) Prompt J/ψ polarization: null	$\lambda_\theta^{CS} = -1$	$\lambda_\theta^{CS} = +1$	$\lambda_\theta^{HX} = -1$	$\lambda_\theta^{HX} = +1$
		$\|y\| < 1.4$				
$4-6$	5.11	$34.9 \pm 2.5 \pm 6.0$	45.5 ± 14.6	32.2 ± 6.3	25.5 ± 10.3	42.9 ± 12.1
$6-8$	6.98	$16.18 \pm 0.84 \pm 2.33$	18.84 ± 4.04	15.15 ± 2.58	12.22 ± 4.58	19.30 ± 4.41
$8-10$	8.89	$8.49 \pm 0.45 \pm 1.35$	9.80 ± 1.64	7.97 ± 1.69	6.56 ± 2.84	9.98 ± 1.75
$10-30$	13.41	$0.653 \pm 0.031 \pm 0.097$	0.724 ± 0.099	0.622 ± 0.120	0.543 ± 0.184	0.728 ± 0.101
		$1.4 < \|y\| < 2.4$				
$0-1$	0.64	$185 \pm 12 \pm 38$	131 ± 67	234 ± 68	134 ± 65	229 ± 63
$1-1.5$	1.24	$419 \pm 40 \pm 138$	298 ± 172	524 ± 205	314 ± 162	501 ± 187
$1.5-2$	1.73	$393 \pm 24 \pm 110$	281 ± 150	490 ± 167	302 ± 136	464 ± 147
$2-3$	2.44	$214 \pm 9 \pm 33$	155 ± 71	265 ± 65	169 ± 58	248 ± 51
$3-4$	3.45	$116 \pm 5 \pm 19$	86 ± 36	141 ± 35	93 ± 30	133 ± 28
$4-6$	4.87	$54.6 \pm 3.0 \pm 10.$	44.0 ± 14.0	62.7 ± 14.6	44.5 ± 13.7	62.0 ± 14.1
$6-8$	6.84	$14.92 \pm 0.64 \pm 2.60$	13.74 ± 2.87	15.95 ± 3.00	12.74 ± 3.38	16.42 ± 3.24
$8-10$	8.86	$5.88 \pm 0.34 \pm 1.00$	5.80 ± 1.09	5.97 ± 1.03	5.18 ± 1.46	6.31 ± 1.01
$10-30$	12.97	$0.307 \pm 0.024 \pm 0.048$	0.309 ± 0.054	0.308 ± 0.054	0.281 ± 0.057	0.323 ± 0.058

J/ψ Systematics

Table 2: Relative uncertainties (in percent) on the corrected yield, in each p_T bin: statistical , final state radiation (FSR), p_T calibration, B-fraction, Non-prompt polarization, muon efficiency, ρ-factor, Fit functions

$p_T^{J/\psi}$ (GeV/c)	Statistics	FSR	p_T calibration	B-frac.	non-prompt polar.	Muon effic.	ρ	Fit function
				$\|y\| < 1.4$				
4 – 6	7.2	2.0	3.1	0.1	0.0	11.1	4.6	6.1
6 – 8	5.2	2.0	2.4	0.2	0.1	7.0	7.0	0.2
8 – 10	5.3	1.6	1.4	0.3	0.1	9.9	7.1	0.6
10 – 30	4.7	0.9	0.7	0.4	0.2	10.8	1.2	1.0
				$1.4 < \|y\| < 2.4$				
0 – 1	6.4	0.8	0.3	0.1	0.0	10.5	12.6	6.5
1 – 1.5	9.5	0.7	0.3	0.0	0.0	11.4	28.2	8.3
1.5 – 2	6.1	0.4	0.5	0.0	0.0	11.2	22.7	6.1
2 – 3	4.3	0.2	0.9	0.0	0.0	10.0	5.6	2.4
3 – 4	3.9	0.6	0.7	0.1	0.0	9.7	5.9	6.8
4 – 6	5.6	0.8	0.5	0.1	0.0	10.6	9.3	5.7
6 – 8	4.3	0.6	0.4	0.1	0.0	9.4	6.8	8.3
8 – 10	5.8	0.5	0.2	0.2	0.1	13.1	4.2	1.0
10 – 30	7.8	0.2	0.2	0.2	0.1	11.8	0.6	2.1

Υ Cross Section

Table 4: The product of the Υ(1S) integrated and differential production cross sections and the dimuon branching fraction, in nb, measured for various polarization scenarios (L= 100% longitudinal, T= 100% transverse) integrated over the rapidity range $|y| < 2.0$. Uncertainties are statistical only.

	$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$ [nb], $\lvert y \rvert < 2.0$				
Δp_T (GeV/c)		Collins-Soper		Helicity	
	unpolarized	L	T	L	T
0- 2	1.3 ± 0.2	1.0 ± 0.1	1.5 ± 0.2	1.0 ± 0.1	1.5 ± 0.2
2- 3	1.3 ± 0.2	0.9 ± 0.1	1.5 ± 0.2	1.0 ± 0.1	1.5 ± 0.2
3- 5	2.4 ± 0.3	1.8 ± 0.2	2.8 ± 0.3	1.8 ± 0.2	2.8 ± 0.3
5- 8	2.0 ± 0.3	1.7 ± 0.2	2.2 ± 0.3	1.6 ± 0.2	2.4 ± 0.3
8-12	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.7 ± 0.1	1.0 ± 0.2
12-20	0.6 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.45 ± 0.1	0.6 ± 0.1
0-20	8.3 ± 0.5	6.9 ± 0.4	9.3 ± 0.5	6.5 ± 0.4	9.6 ± 0.6

Υ Systematics

- Relative systematic uncertainties for Υ cross section

Δp_T	$\mathcal{A}^{\Upsilon}$	ε_{muid}	ε_{trig}	ε_{trk}	FSR	$S\ p_T$	T	$T\ J/\psi$	PDF	Σ
0-2	0.5	9.5	3.4	0.6	3.5	0.2	2.1	2.0	0.4	11.1
2-3	0.5	10.0	3.5	0.6	4.1	0.6	2.1	1.4	0.4	11.7
3-5	0.6	10.0	0.5	0.6	3.7	0.5	2.0	1.3	0.4	11.0
5-8	0.6	11.0	6.2	0.6	3.2	0.6	1.8	2.0	0.4	13.3
8-12	0.6	10.3	6.5	0.6	2.6	0.8	2.2	2.9	0.4	13.1
12-20	0.4	13.3	14.0	0.7	2.3	1.6	2.2	4.3	0.4	20.1
0-20	0.6	10.4	5.1	0.6	3.4	0.5	2.0	2.0	0.4	12.5