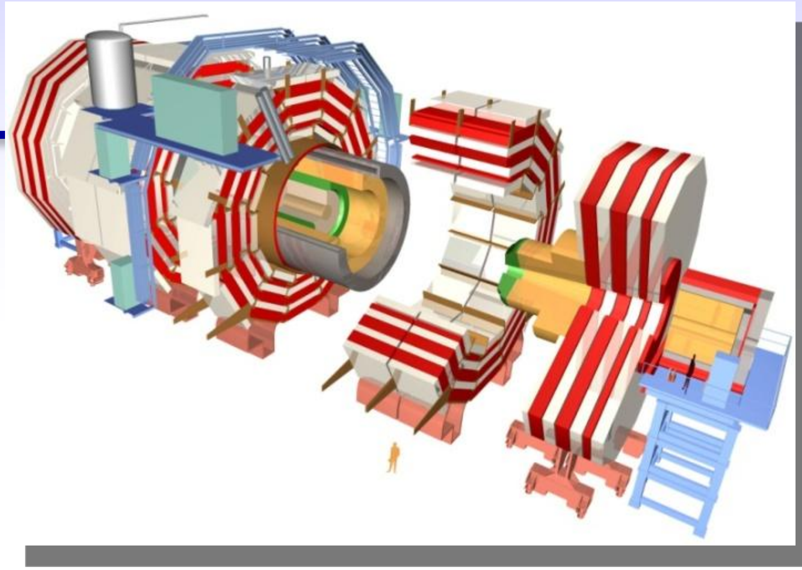
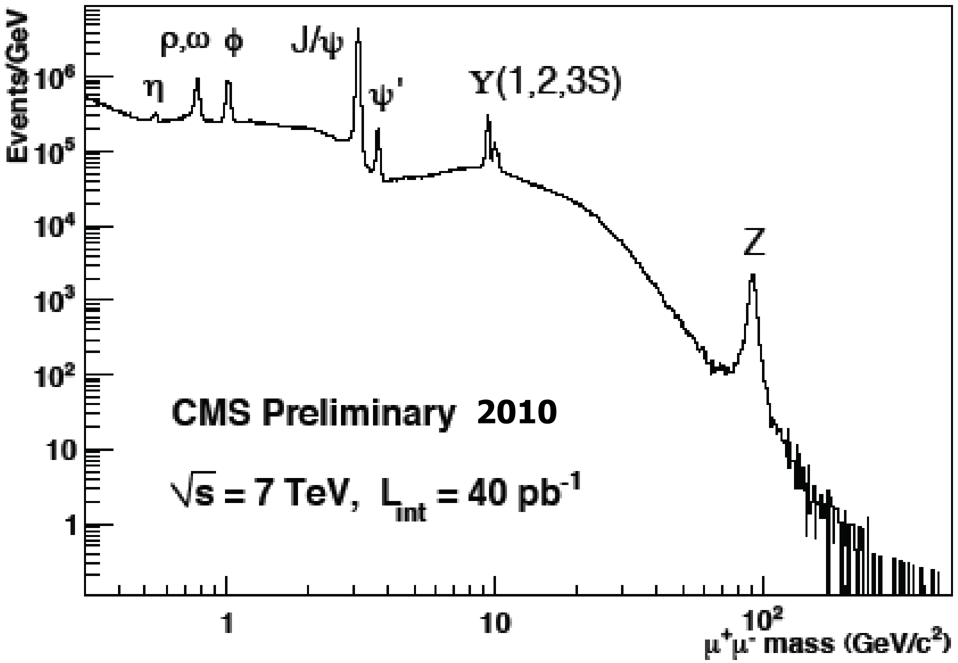
Charmonium production in pp collisions at 7 TeV with the CMS experiment



- Outline
  - J/ψ and ψ' ; X(3872) ; χ_{c1} and χ_{c2}



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on behalf of the CMS Collaboration

QWG2011
Int. Workshop on Heavy Quarkonium
GSI, Germany, 4-7 October 2011

Motivations

- Production of charmonium states still constitutes a challenge for QCD calculations
  - NLO calculation (color singlet) for hadroproduction only became available in 2007 *(Maltoni et al.)*. In recent NLO calculations, color octet components have been included(*) (**)
  - χ_{cJ} production and the ratio $\sigma(\chi_{c2}) / \sigma(\chi_{c2})$ provide further tests for NRQCD and heavy quarkonium production mechanisms (***)
- A number of unexpected (X,Y,Z) states have been discovered
  - One of the first and most prominent states, the X(3872), has been studied in detail but, as of now, its nature still remains unclear
  - LHC allows studies in a new energy regime where NRQCD predictions exist for the X(3872) cross section (****)

(*) K.T. Chao et al., Phys. Rev. Lett. 106: 042002, 2011

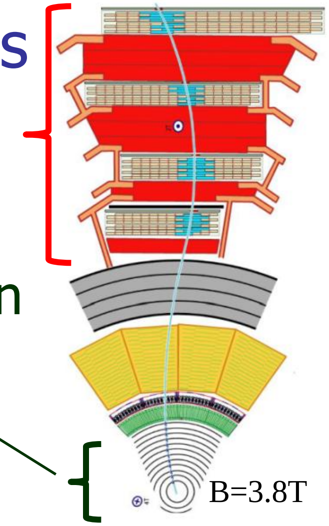
(**) M. Butenschon and B. Kniehl, Phys. Lett. 106:022003, 2011

(***) Y.Q. Ma, K. Wang, K.T. Chao, Phys. Rev. D83:111503, 2011

(****) P. Artoisenet and E. Braaten, Phys. Rev. D81:114018, 2010

CMS Detector and Muon Trigger

- CMS detector key ingredients for charmonium analysis
  - Muon detectors for trigger and high purity muon identification
  - Silicon Tracker detector for excellent track momentum resolution and vertices position



- Low p_T di-muon triggers in 2010 optimized for J/ψ, adapting to rapidly evolving instantaneous luminosity
  - At LHC startup the trigger requirements allowed us to go down to zero quarkonium p_T in the forward region
    - used for the fist CMS paper (*) based on $\int Ldt = 314\ nb^{-1}$
  - Data collected at higher luminosity
    - used to extend the results based on $\int Ldt = 36.7\ pb^{-1}$

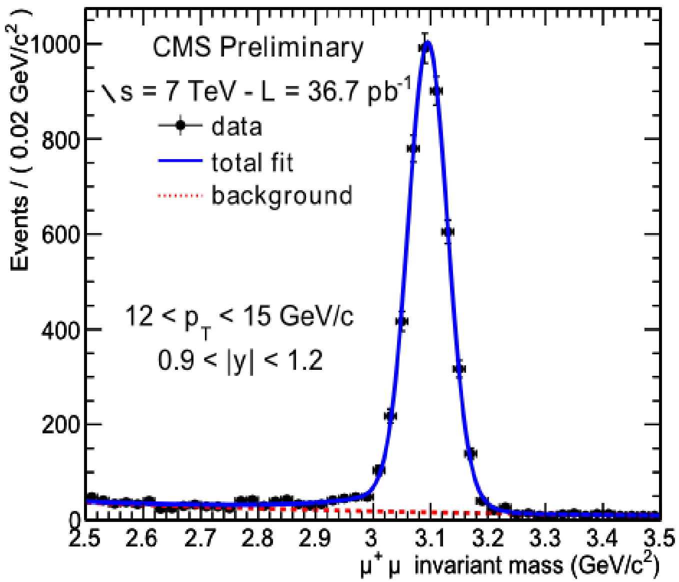
(*) Eur. Phys. J. C71 (2011) 1575

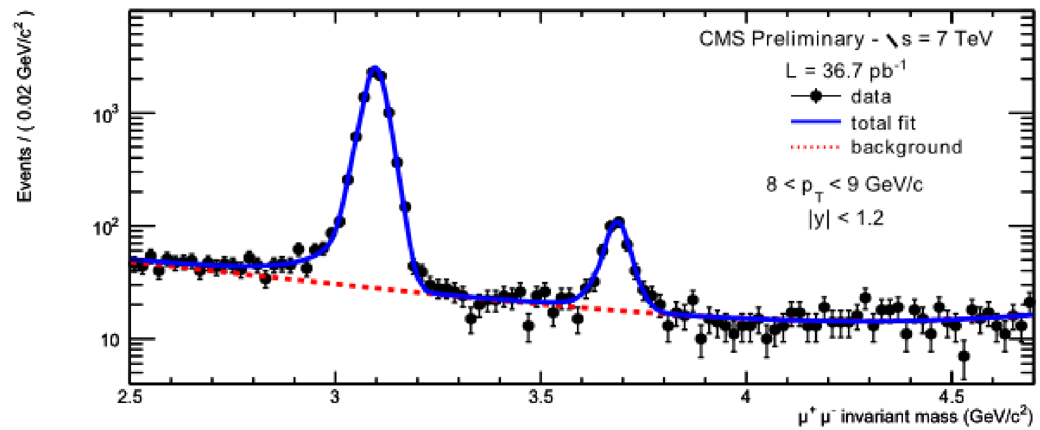
J/ψ and ψ(2S) yields extraction

- Unbinned Maximum Likelihood fit to invariant mass distributions

- J/ψ: 6-70 GeV in five rapidity bins
  - Crystal-Ball + Gaussian signal
  - exponential background

- ψ(2S): 5.5-30 GeV in three rapidity bins
  - Fit to ψ′ and J/ψ + 2 exp. bkg.
    - CB tail parameters and resolution (scaled by mass) in common
    - Pole mass ratio fixed to PDG values



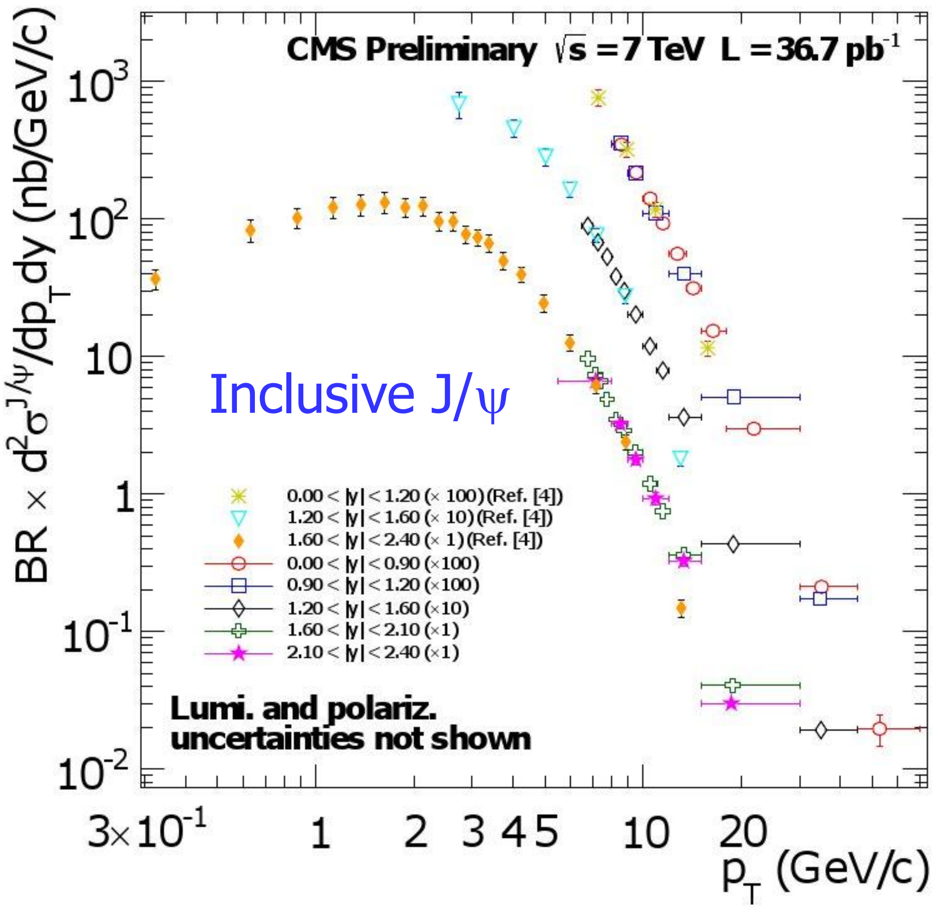


- Mass resolution ~20 MeV for |y|<0.5 , ~50 MeV for |y|>2.1

- Yields are corrected for di-muon efficiency and acceptance
  - acceptance is strongly dependent on production polarization

Inclusive J/ψ cross-section

- CMS J/ψ cross-section measurement from 0 to 70 GeV/c



Null polarization scenario

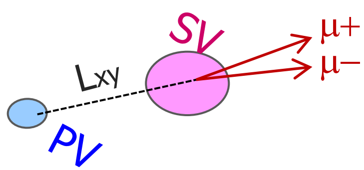
(Ref. [4]) Eur. Phys. J. C71 (2011) 1575

- Nice agreement among different triggers/methods
- Statistical errors 2 to 9%
- Systematics of few % (except polarization)
  - Largest systematics:
    - at the boundary of the acceptance (FSR)
    - at very high pT where the correlation between 2 muons is large

Non prompt J/ψ fraction

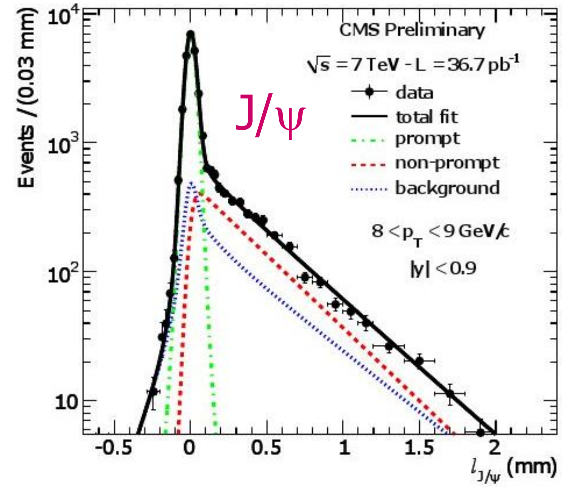
- 2D fit to mass and pseudo proper decay length

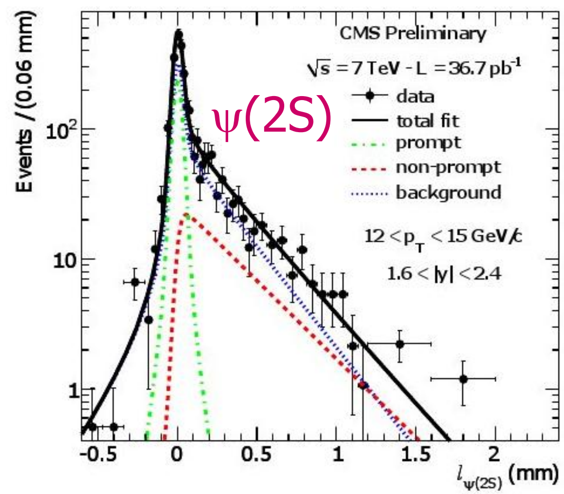
$$l_{J/\psi} = L_{xy} \,.\, m_{J/\psi}/p_T$$



- **Decay length parameterization:**
  - resolution function for prompt decays
  - convolution with exponential for non-prompt
  - different contributions from the side-bands for bkg

- **Fit techniques**
  - core resolution function given by one Gaussian using "per event error" σ_l
    - plus <1% of a second Gaussian for incorrect PV assignment



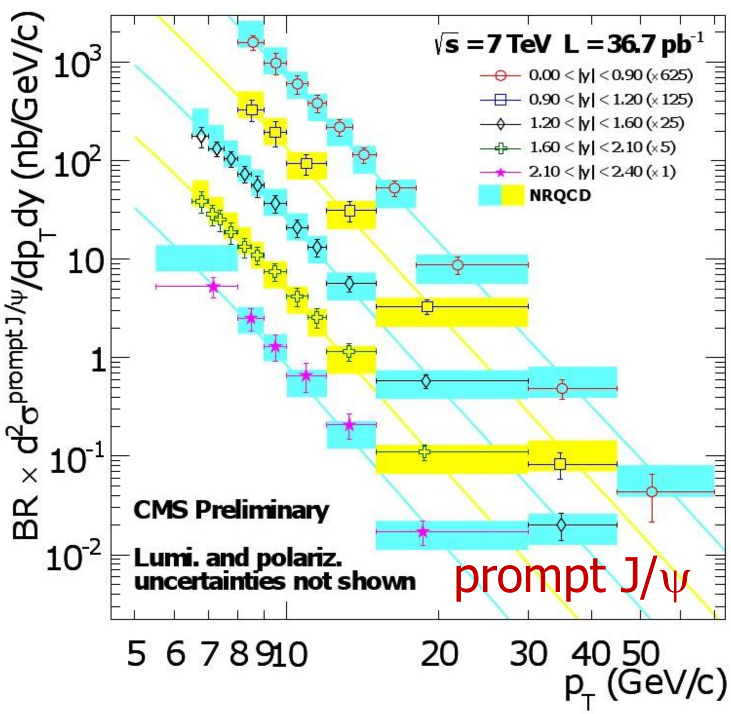


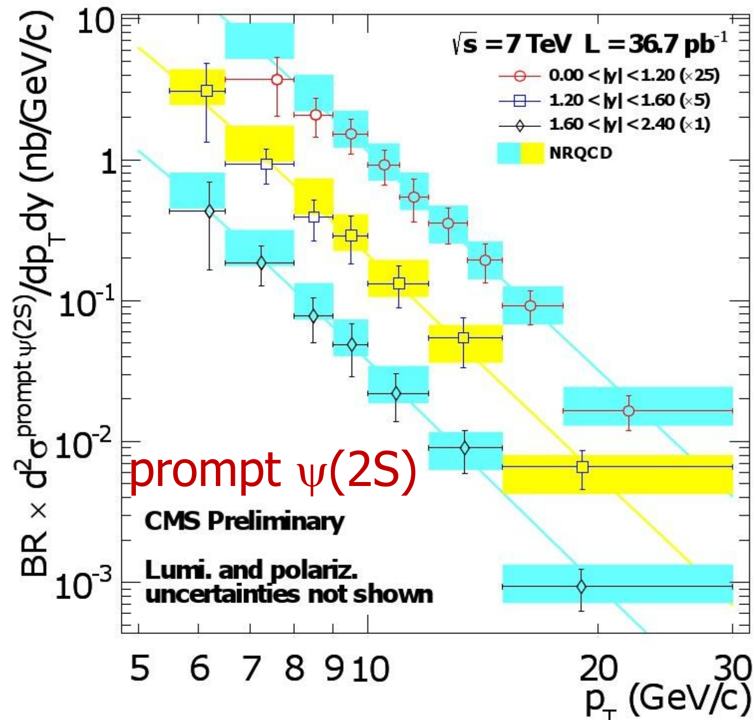
- In the ψ(2S) case: simultaneous fit together with the J/ψ, using some constraints (same resolution and mean, same effective background lifetimes)

Prompt cross-sections

- NRQCD *prompt* predictions (including feed-down for J/ψ) in excellent agreement with the data

K.T.Chao et al. Phys. Rev. Lett. 106:042002,2011



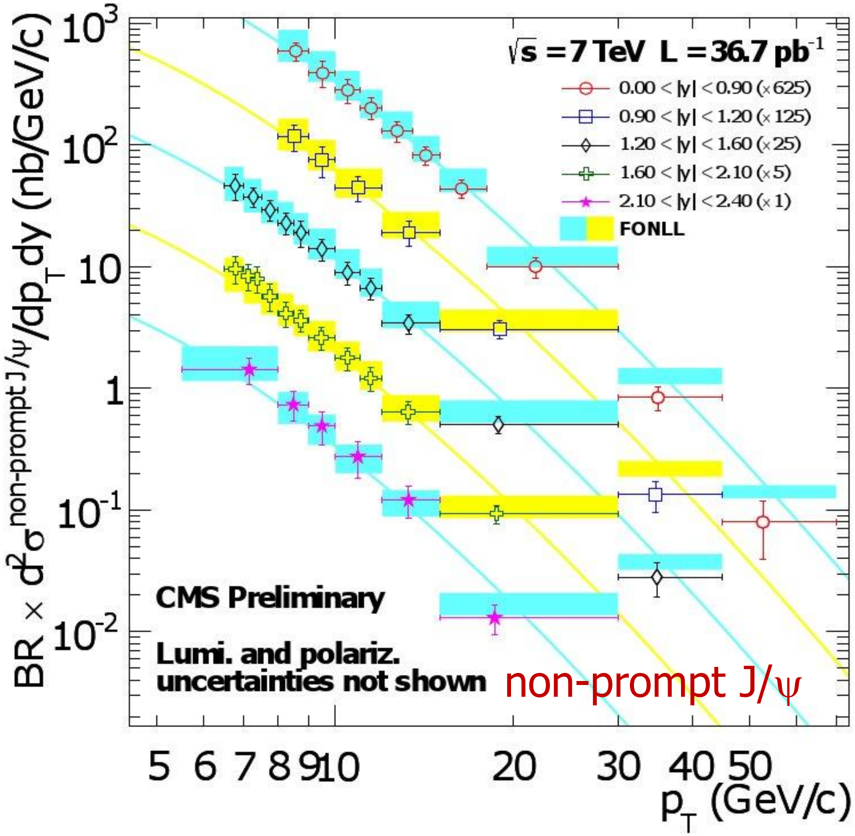


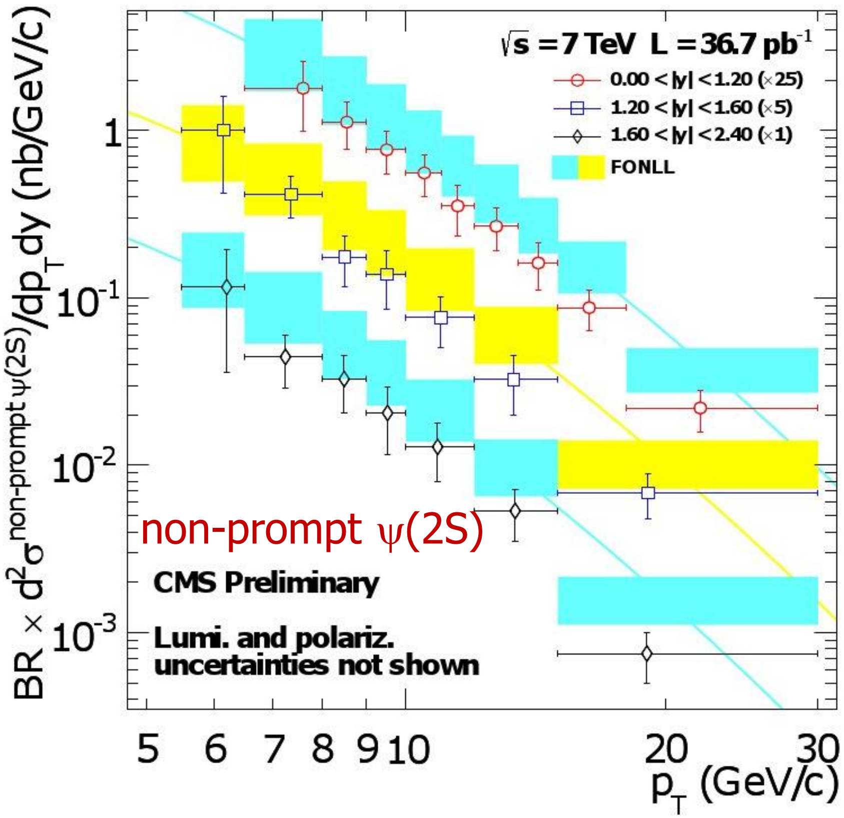
- Typical uncertainties ~5 [20]% on J/ψ [ψ(2S)] cross-sections
- Polarization uncertainty in 4 "extreme" scenarios:
  - Helicity frame (T-L): 18-20% for J/ψ and 25-28% for ψ(2S)
  - Collins-Soper frame (T-L) : 6-15% for both
- cross-sections not corrected for (MC-dep.) acceptance also available

Non-prompt cross-sections

- Good comparison with FONNL predictions for J/ψ
- Overall shift for ψ′ prediction
  - possibly due to BR(B→ψ′ X) big uncertainty

M.Cacciari et al. JHEP 0103 (2001) 006

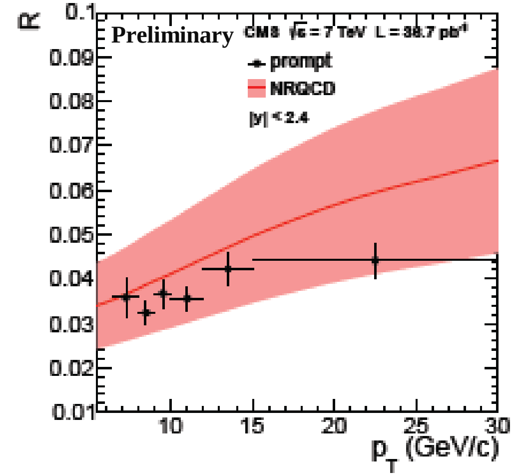




- Largest systematic from μ correlation
- Largest systematic from background lifetime
- At high pT, spectra of both states fall more rapidly than FONNL

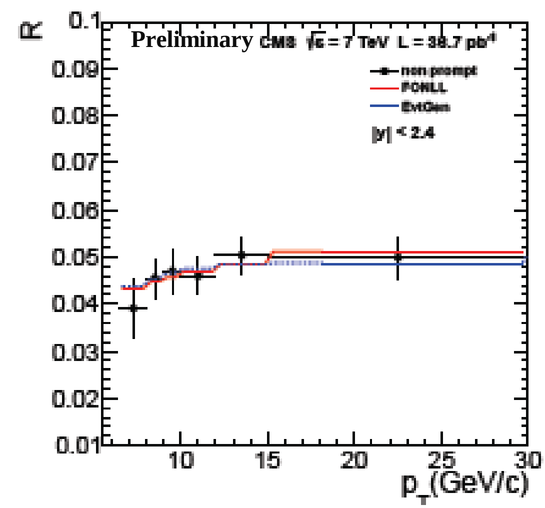
ψ' to J/ψ cross-sections ratio

- Cross-section ratio R: most of the systematics cancel



- ✸ No significant variation over rapidity: averaged within $|y|<2.4$
- ✸ Statistical errors ~3 to 5%, systematic uncertainty ~10% (acceptance dominated) - except polarization
- ✸ The polarization uncertainty on R ranges from 12% to 20%

- B→ ψ(2S) X Branching Fraction (Preliminary)



Measured from the non-prompt cross-section ratio fitting the data with FONLL or EvtGen curves:

$BR(B \to \psi' X) =$

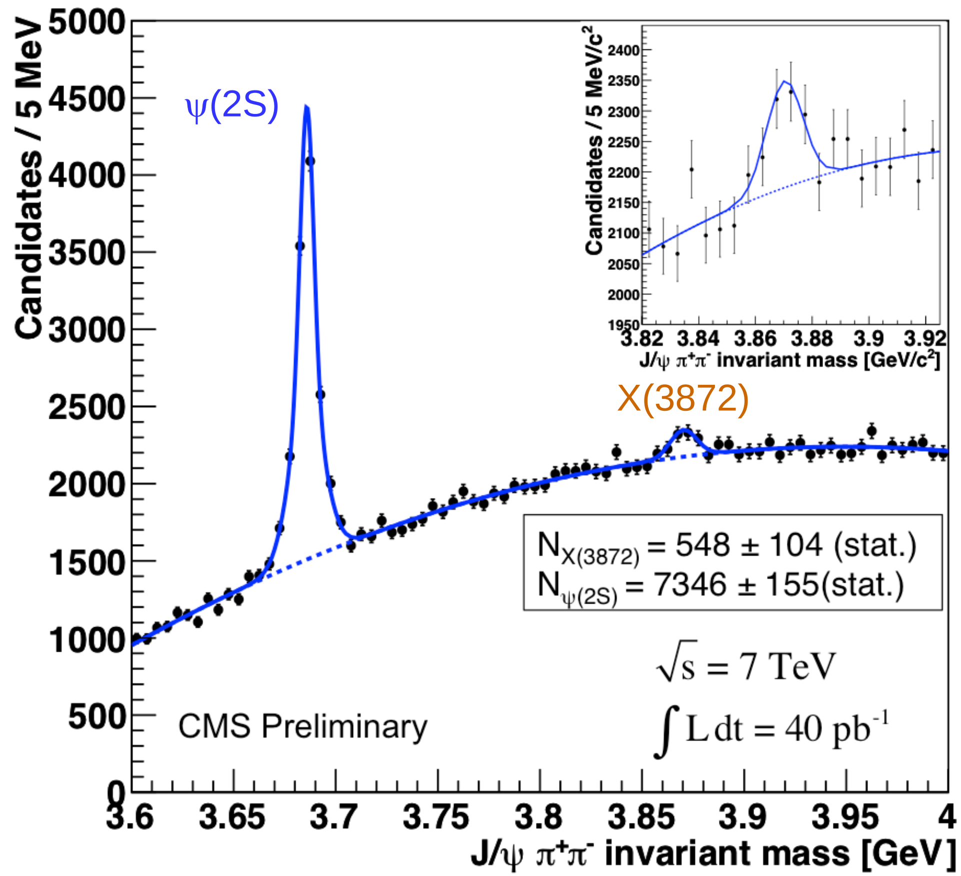
$[3.08 \pm 0.12\,(\text{stat,sys}) \pm 0.42\,(BR_{PDG}) \pm 0.06\,(\text{th.})] \times 10^{-3}$

- ✸ uncertainty of 14.3%
  - PDG error is 50%: $BR(B \to \psi' X)_{PDG} = [4.8 \pm 2.4] \times 10^{-3}$
- ✸ main uncertainties from PDG BR

Established a clear X(3872) signal in the decay channel $J/\psi\ \pi^+\pi^-$ using the 2010 CMS data

- J/ψ reconstructed with 2 good quality μ
- pairs of good quality opposite-charge tracks with $\Delta R(\pi, J/\psi) < 0.7$
- 4-track vertex fit probability >1%
  - J/ψ mass fixed to the PDG value
- kinematic region:

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



- Unbinned maximum likelihood fit
  - $m_{\psi(2S)} = 3685.9 \pm 0.1$ MeV
  - $m_{X(3872)} = 3870.2 \pm 1.9$ MeV
  - $\sigma1_{\psi(2S)} = 8.1 \pm 0.6$ MeV
  - $\sigma2_{\psi(2S)} = 3.3 \pm 0.3$ MeV
  - $\sigma_{X(3872)} = 6.3 \pm 1.3$ MeV
- PDG values
  - $m_{\psi(2S)} = 3686.09 \pm 0.04$ MeV
  - $m_{X(3872)} = 3871.57 \pm 0.25$ MeV

X(3872) to ψ′ inclusive cross section ratio

- Extract the yields from J/ψ ππ mass fit

$$\mathbf{R} = \frac{N_{X(3872)}}{N_{\Psi(2S)}} / \mathbf{C}$$

- Extract the correction factor from MC studies

$$\mathbf{C} = \frac{Acc_{J/\Psi}(X) \cdot \varepsilon_{J/\Psi}(X) \cdot A_{\pi\pi}(X) \cdot \varepsilon_{\pi\pi}(X)}{Acc_{J/\Psi}(\Psi') \cdot \varepsilon_{J/\Psi}(\Psi') \cdot A_{\pi\pi}(\Psi') \cdot \varepsilon_{\pi\pi}(\Psi')}$$

  - Pythia 6 with mass of χ_{c1} ($J^{PC}=1^{++}$) set to 3.872 GeV
  - Null polarization assumed
  - 30% non-prompt fraction assumed

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

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

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

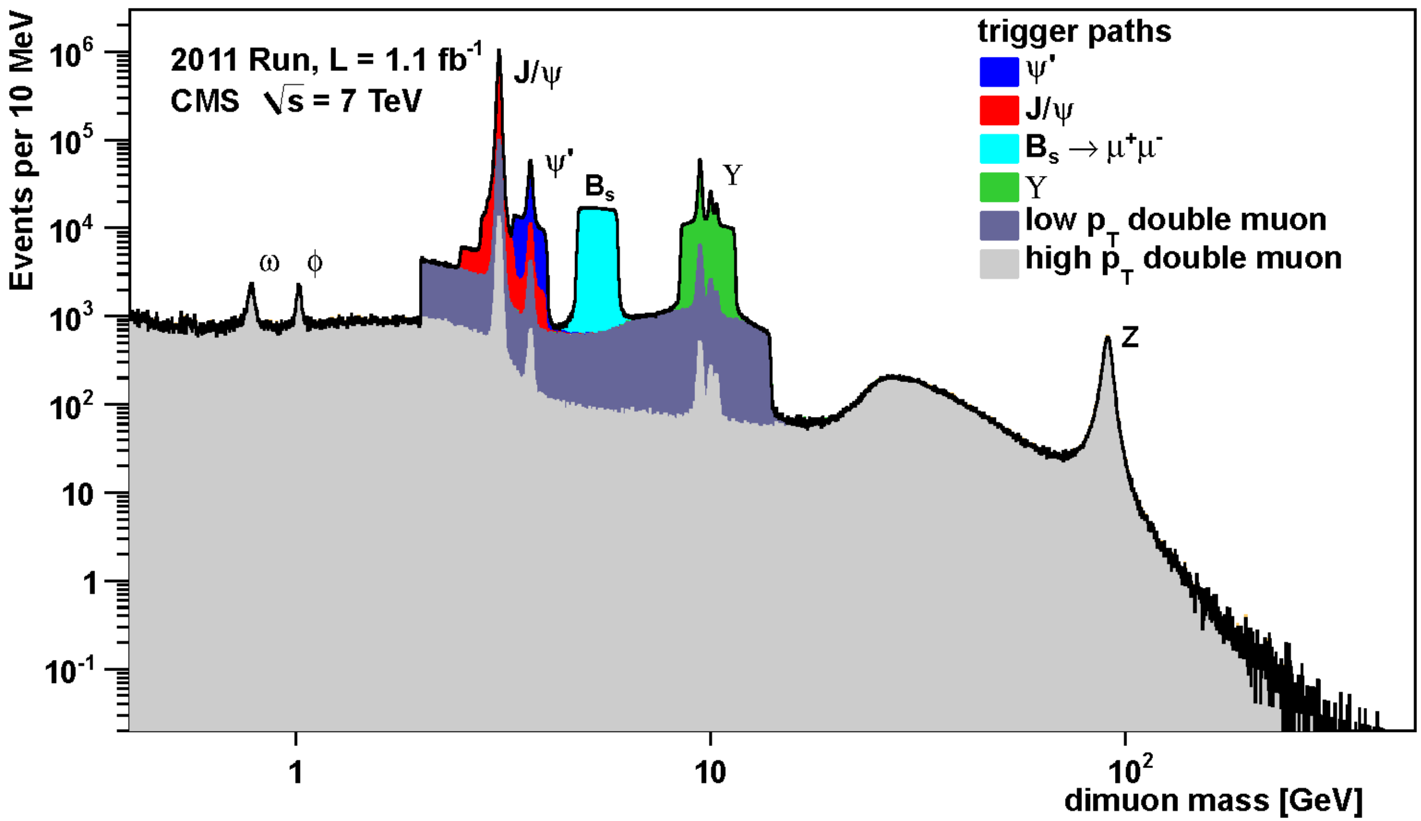
CMS-PAS-BPH-10-018 in CDS

uncertainty source	**Tot 10%**
Fit models	5.3%
Non-prompt fraction; changes 30 ± 20%	6.0%
Lack of knowledge of pT(X) shape	3.5%
Limited MC statistic	1.8%
Pion tracking efficiency Data driven check with $\psi' \to J/\psi\ \pi\pi$ and $\psi' \to \mu\mu$	4%

- Lacking *BR(X(3872) → J/ψ π+π−)* to relate to theory calculations (different kinematic range):
  P. Artoisenet & E. Braaten Phys. Rev. D81:114018,2010

Triggers in 2011

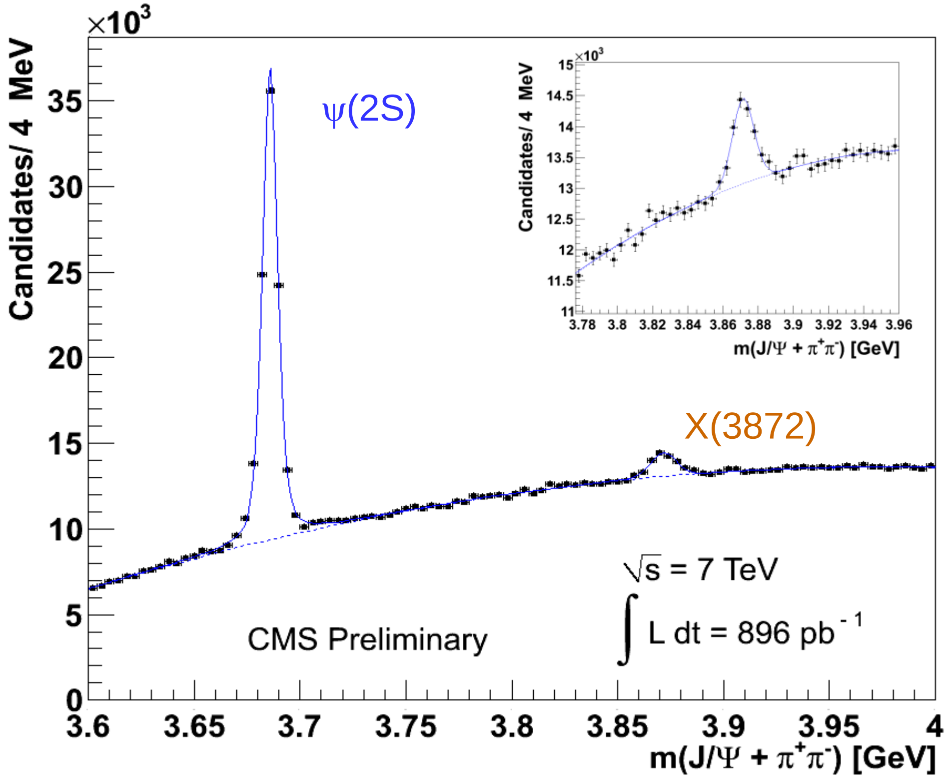
- Higher instantaneous luminosity in 2011 → limited bandwidth
- Big effort in CMS to define tighter triggers allowing a good B-physics program with the high statistics being collected



2011 J/ψ π+ π− mass distribution

J/ψ trigger in the barrel → New fiducial region:

$p_T(X) > 9$ GeV and $|y(X)| < 1.25$

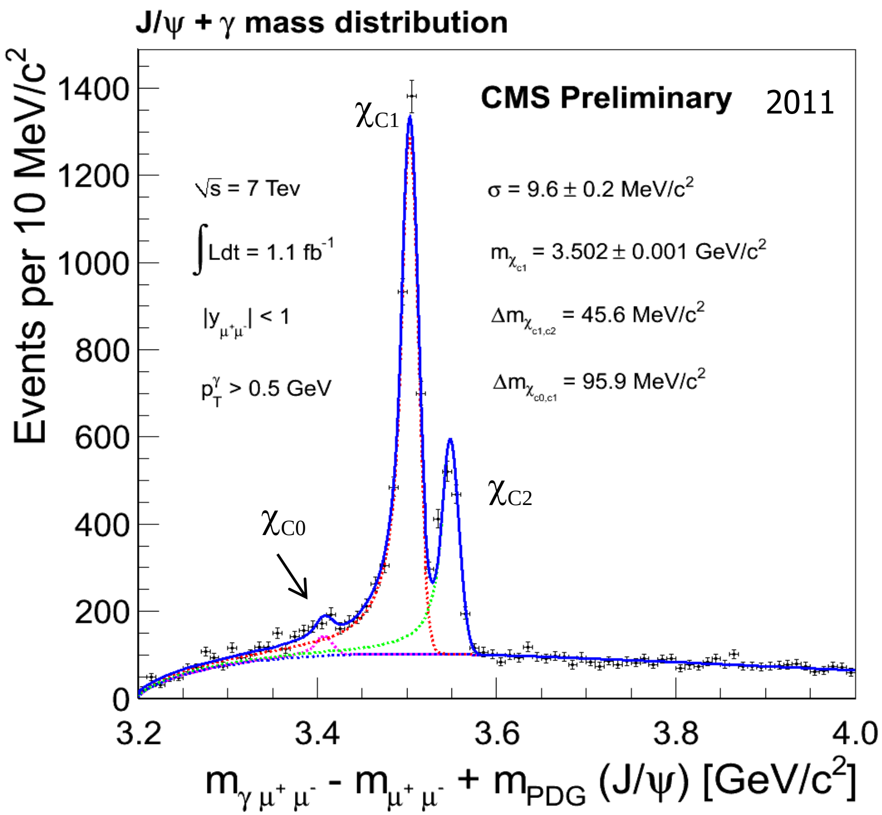


$N_{\psi(2S)} = 72594 \pm 518$ (stat)
$N_{X(3872)} = 5303 \pm 341$ (stat)

- In 2011 collected 10 times more X(3872) events improving the statistical uncertainty from 20% to 6%
- Cross-section ratio can be measured vs pT, together with the separation of the non-prompt fraction and the measurement of the X(3872) mass

$\chi_c \rightarrow J/\psi\ \gamma$ mass distribution

- Thanks to the CMS low pT track reconstruction, low energy photon conversions can be reconstructed with excellent resolution → resolve the χ_{c1} and χ_{c2} peaks



- The χ_{c1} and χ_{c2} ratio can be measured vs pT
- Main challenge: evaluation of the ratio of the γ reconstruction efficiencies

Conclusions

- Measurement of J/ψ cross section from 0 to 70 GeV/c with large rapidity coverage ($|y|<2.4$)
- Differential cross-sections in pT and $|y|$ of J/ψ and $\psi(2S)$ mesons plus ratio of cross sections
  - prompt and non-prompt contributions separated
  - measurements more precise than theory (except for polarization uncertainties)
- Results compared with NRQCD and FONNL predictions
  - good agreement for prompt case
  - at high pT steeper spectrum than prediction
- X(3872) to $\psi(2S)$ inclusive cross-sections ratio in $J/\psi\ \pi^+\pi^-$ channel → 2011 statistics allow further studies
  - pT differential cross-section ratio, non-prompt separation, mass
- Very good potential for χ_{cJ} production studies in CMS

BACKUP

J/ψ systematics

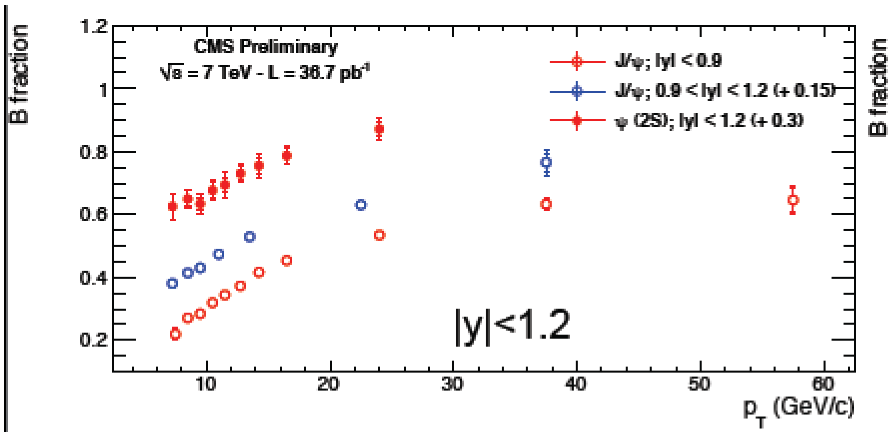
$\lvert y \rvert$ range		0 – 0.9	0.9 – 1.2	1.2 – 1.6	1.6 – 2.1	2.1 – 2.4
Quantity affected	Source	Relative uncertainty (in %)				
$m_{\mu\mu}$ fits	Statistical	1.2 – 8.9	1.5 – 7.1	1.6 – 8.4	1.2 – 3.2	2.3 – 3.9
$\ell_{J/\psi}$ fits	Statistical	1.0 – 5.9	1.4 – 4.7	1.4 – 7.6	2.1 – 8.3	4.4 – 7.1
Acceptance	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
	Kinematical 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
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	4	4	4	4
b-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

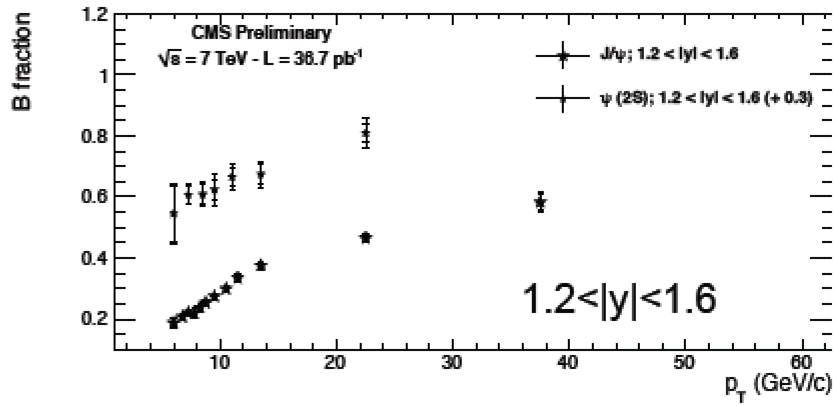
ψ' systematics

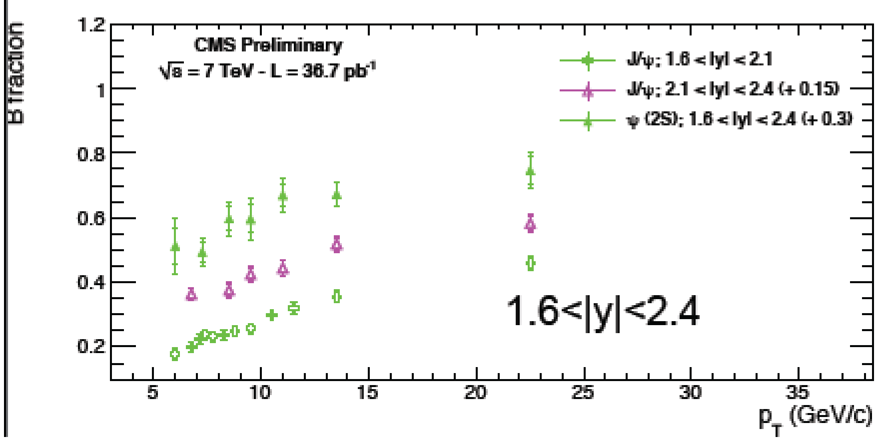
$\lvert y \rvert$ range		$0 - 1.2$	$1.2 - 1.6$	$1.6 - 2.4$
Quantity affected	Source	Relative uncertainty (in %)		
$m_{\mu\mu}$ fits	Statistical	5.6 – 14.8	7.5 – 31.7	7.3 – 24.1
$\ell_{\psi(2S)}$ fits	Statistical	4.3 – 12.7	5.9 – 38.0	9.1 – 26.4
Acceptance	FSR	0.0 – 3.9	0.5 – 3.4	0.3 – 4.1
	p_T calibration	0.2 – 0.5	0.3 – 0.5	0.3 – 0.5
	Kinematical 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
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	4	4
b-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

B fraction results

- Above pT ≈20 GeV, more than 50% of the J/ψ and ψ′ mesons result from B decays





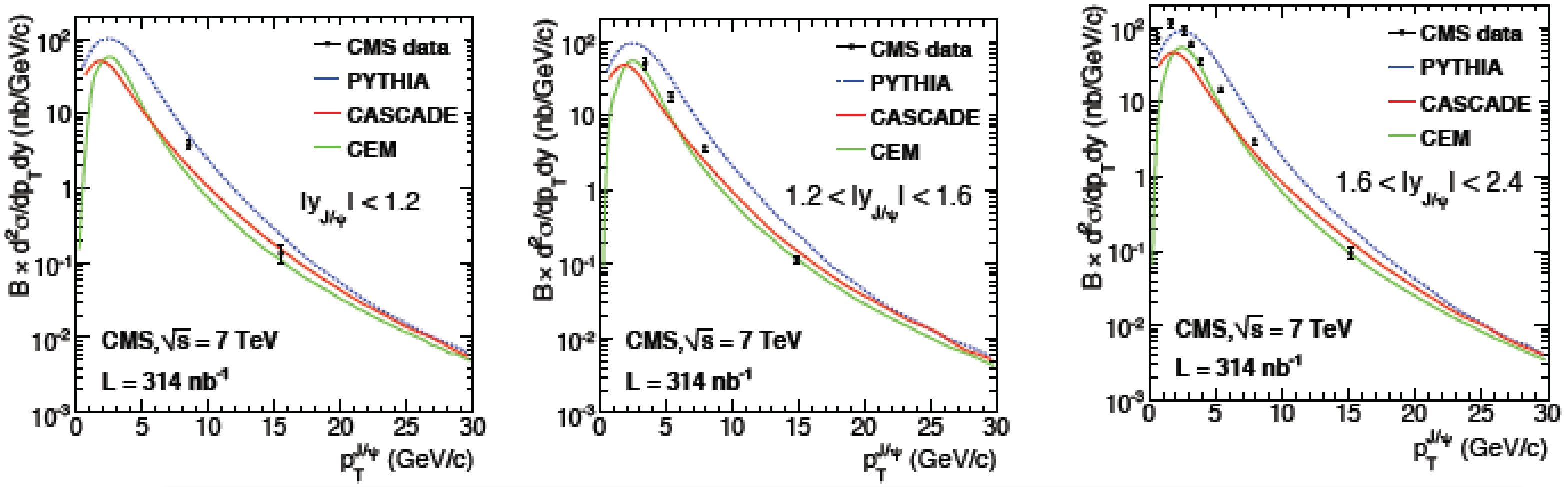


- Increasing monotonically with p_T

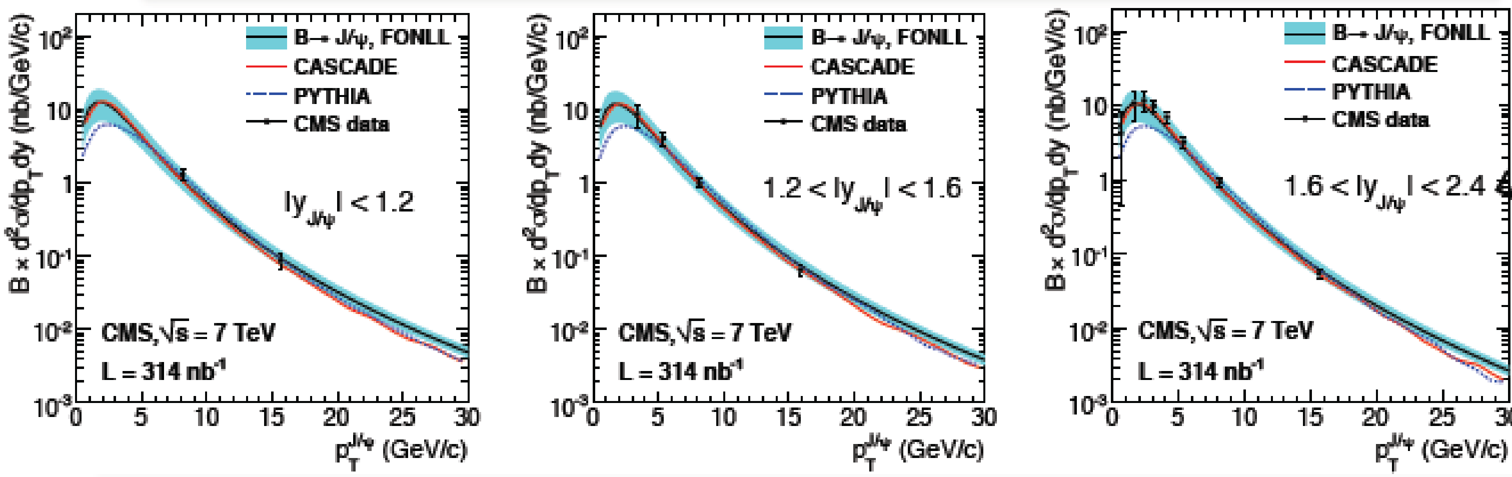
Systematics on B-fraction

- Tracker misalignment: data re-reconstructed in 3 "weak-mode" alignment scenarios and taking the maximum deviation as systematics
- B-lifetime model: "MC template" method used as alternative nonprompt PDF model
- Background fit: varying mass limits for the sideband fit which determines l_{qq} background parameters
- Pile-up: different choice criteria in case of multiple PVs
- Resolution model: double Gaussian → single Gaussian
- Different prompt/non-prompt efficiencies: evaluated from MC

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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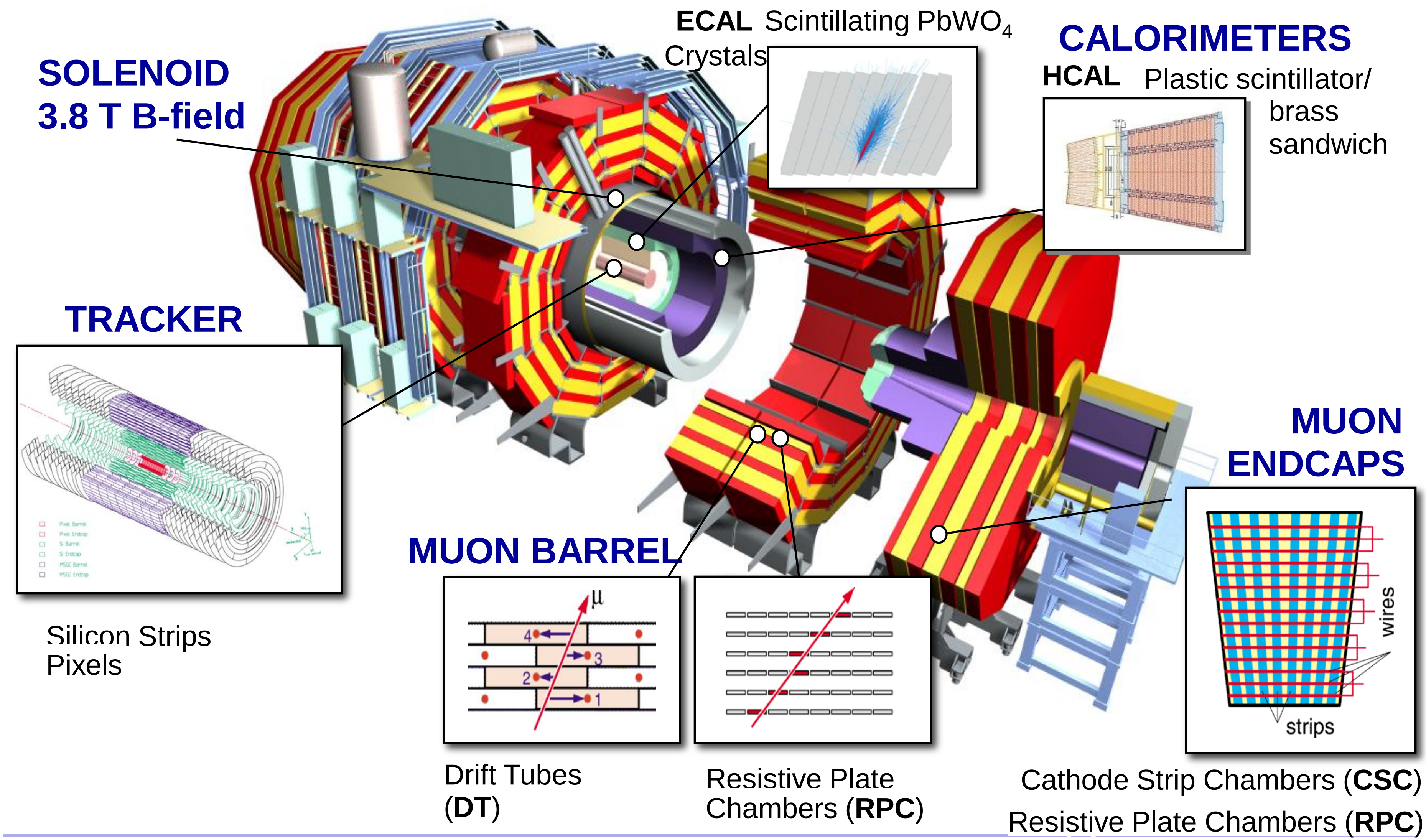
The CMS detector



Cross-section overview

$$\frac{d^2\sigma}{dp_T dy}(\psi)\times \mathrm{BR}(\psi\to\mu\mu)=\frac{N_{fit}(\psi)\left\langle \frac{1}{A\cdot\varepsilon}\right\rangle}{\int L dt\cdot\Delta p_T\cdot\Delta y}$$

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

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

A = geometrical and kinematical acceptance

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

- Strongly dependent on production polarization

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