CMS results on Quarkonium production

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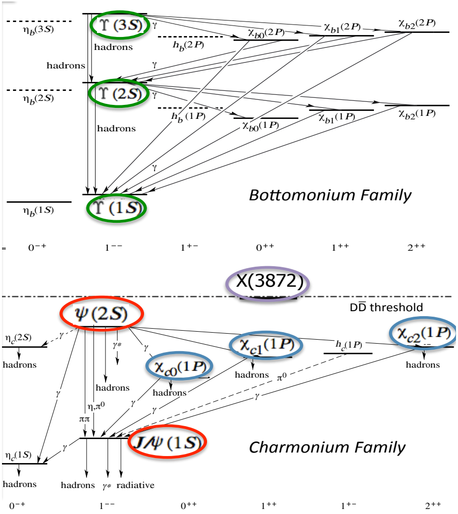
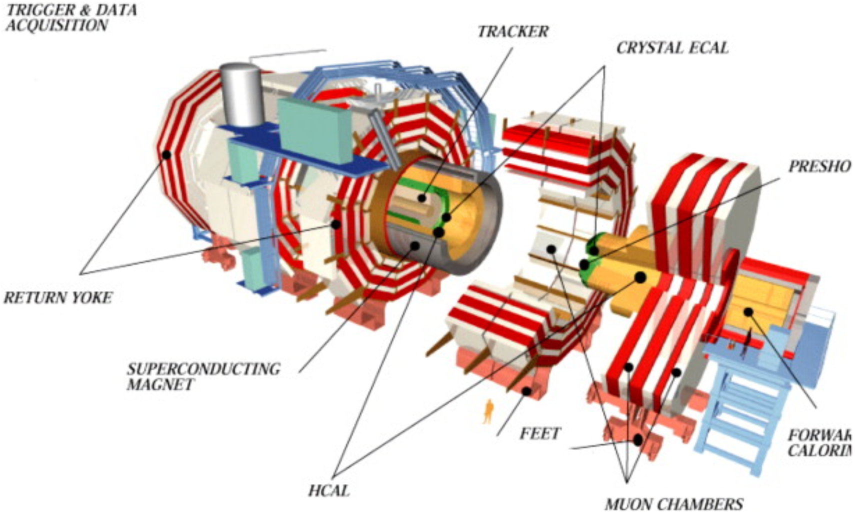


Motivation

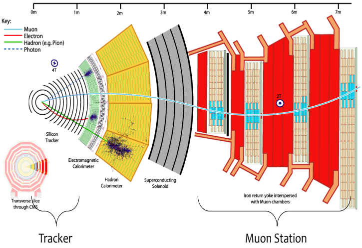
- Observation of quarkonium states challenges QCD calculations
  - ✓ Cross section and polarization measurements of quarkonium states J/ψ[1], $\psi(2S)$[1,2] and double J/ψ[3] can test the prediction of NLO QCD and NRQCD calculation, especially for color singlet and color octet models.
  - ✓ Measurements of P states χ_{cJ} provide effective tests of heavy quarkonum production mechanisms[4] based on NRQCD in which nonperturbative effects can be simplified safely.
- Exotic states (X,Y,Z) poses a serious challenge to the convetional quark model
  - ✓ X(3872) differential cross section measurements test NRQCD prediction[5] in a new energy range and a large pt reach.
  - ✓ need to understand their true nature such as hybrid, tetraquark state or molecular state.
- CMS provide good change to observe quarkonia
  - ✓ good dimuon mass resolution and p_T measurement
  - ✓ good photon momentum resolution
  - ✓ excellent trigger path for dimuon or multiple-muon events

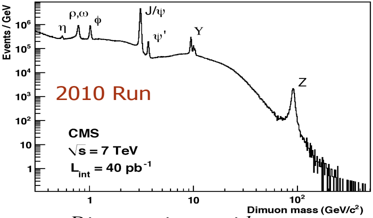
CMS detector



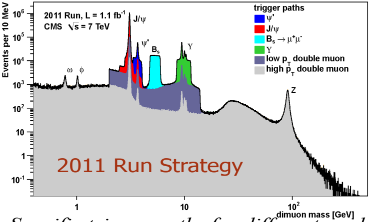
Muon system in CMS

- Muon Station provides trigger and muon identification to large pseudorapidity($|\eta| < 2.4$).
- Silicon Tracker provides improved momentum resolution.
- Mass resolution is $J/\psi \to \mu\mu$: 20-71, $\gamma \to ee$: 9.6 MeV
- Integrated Luminosity 2010: 40 pb^{-1}, 2011: 5.5 fb^{-1}





Dimuon trigger without p_t cut



Specific trigger paths for different analysis

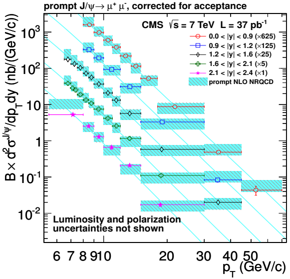
Prompt J/ψ and $\psi(2S)$ cross sections

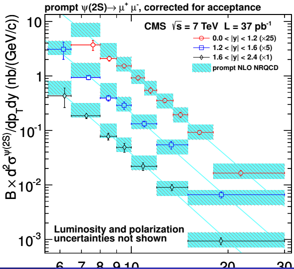
- Differential cross sections as functions of pt and y include feed down effect (JHEP 02 (2012) 011)
- Typical uncertainties: 5% for J/ψ, 20% for $\psi(2S)$
- largest uncertainties from unknown polarizations, which affects acceptance.

  ✓ helicity frame: 18-20% for

  ✓ collins-soper frame:6-15% for both

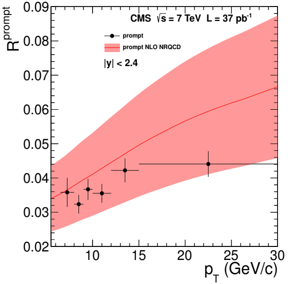
- Data in good agreement with NLO NRQCD calculation, J/ψ[1] theory includes color octet and feed down effect, $\psi(2S)$[2] theory includes only color octet beacuse of absense of feed down from heavier charmonium.





Ratio of prompt $\psi(2S)$ and J/ψ cross sections

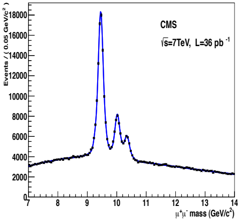
- Ratio of $\psi(2S)$ to J/ψ as a function of pt, no significant variation is over rapidity $\mid y \mid < 2.4$
- The branching fraction of the inclusive B to psi(2S) X decay is extracted from the ratio of the non-prompt cross sections to be: $Br(B \rightarrow \psi(2S)X) =$ $(3.08 \pm 0.12(stat. + syst.) \pm 0.13(thoer.) \pm 0.42(B_{\mathrm{PDG}})) \times 10^{-3}$.
- Advantage is that most of systematic uncertainties are cancelled (Luminosity, muon efficiencies, theory)
- statistical uncertainty is 3-5%, polarization uncertainty is 12-20% (referring to difference between J/ψ and χ_c), other systematic uncertainties is 10% (JHEP 02 (2012) 011)

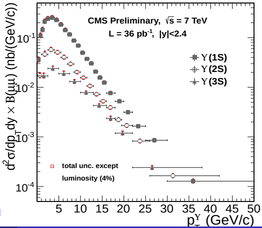


Υ(nS) differential cross sections

$$\sigma(pp \to Y(1S)X)B(Y(1S) \to \mu^+\mu^-) = (8.55 \pm 0.05^{+0.88}_{-0.78} \pm 0.34)\ \text{nb}$$
$$\sigma(pp \to Y(2S)X)B(Y(1S) \to \mu^+\mu^-) = (2.21 \pm 0.03^{+0.24}_{-0.21} \pm 0.09)\ \text{nb}$$
$$\sigma(pp \to Y(3S)X)B(Y(1S) \to \mu^+\mu^-) = (1.11 \pm 0.02^{+0.13}_{-0.12} \pm 0.04)\ \text{nb}$$

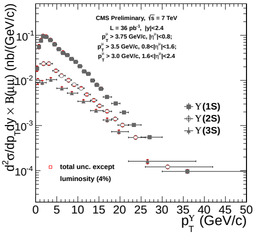
- The two approaches. The first is that a cross section is corrected for accaptance and efficienc as in this slide.
- kinematic region $0 < pt < 50$ GeV, $\mid y \mid < 2.4$
- unpolarized assumption for aceptance correction.
- feed down from higher states not corrected for.
- observation is in good agreement with NRQCD (BPH-11-001)

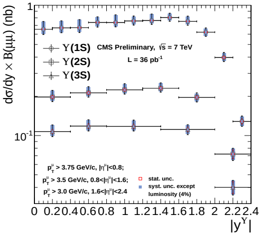


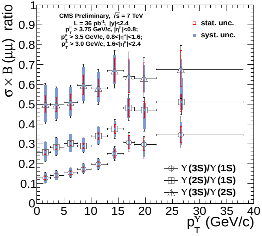


Υ(nS) fiducial differential cross sections

- The second approch is the fiducial cross section as a function of pt and y.
- a fiducial cross scetion is corrected for efficienies but not the acceptance, defined within a restricted muon kinematic range.
- The advantage of a fiducial cross section is that no polarization uncertainties are involved.
  (BPH-11-001)

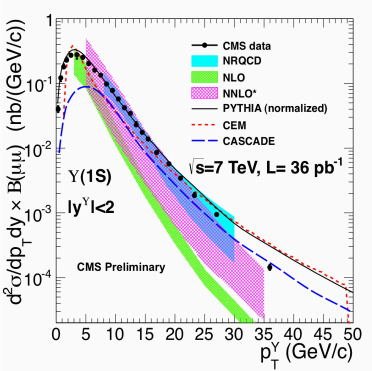






Comparison to theory and LHCb

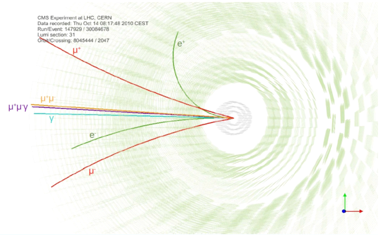
- Compared to PYTHIA, the Color Evaporation Model (CEM), nonrelativistic QCD (NRQCD) to next-to-leading order (NLO), the Color Singlet Model (CSM) to NLO and to next-to-next-to-leading order (NNLO*). pt shape is in favor of NRQCD.
- CMS and LHCb observation complementary in coverage and show good agreement in overlap

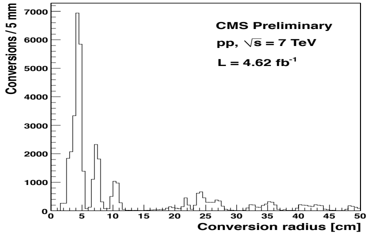


Ratio of χ_{c1} and χ_{c2} cross sections (I)

event display

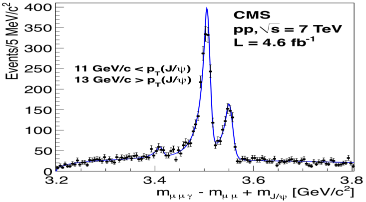
- The p wave states χ_{c1} and χ_{c2} are measured through the radiative decay $J/\psi + \gamma$ with $| y(J/\psi) | < 1.0$ and $p_T(\gamma) > 0.5$ GeV
- Photons are reconstructed using the photon conversion reconstruction technique.
- High photon conversion rate
- Excellent photon momentum resolution brings excellent mass resolution of 10 MeV to reslove the two states
- π^0 mass rejection

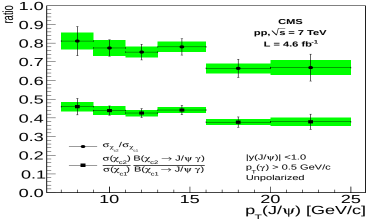




Ratio of χ_{c1} and χ_{c2} cross sections (II)

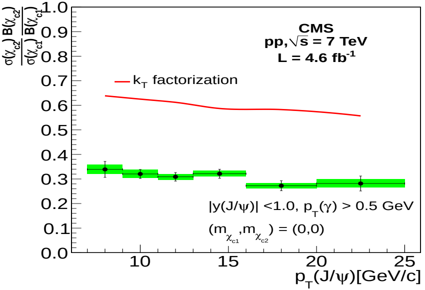
- Fit
  - ✓ Binned maximum likelihhod fit χ_{c1}&χ_{c2} pdfs: Crystal Balls
  - ✓ Free params: $m_{\chi_{c1}}$ σ n α
  - ✓ Fixed param: $\delta m(\chi_{c1}, \chi_{c2}) = 45.6$ MeV
  - ✓ Backgroundd pdf: $(m - m_0)^\lambda \cdot e^{(m - m_0)}$
- the prompt χ_{c2}/χ_{c1} cross section ratio vs pt has been measured

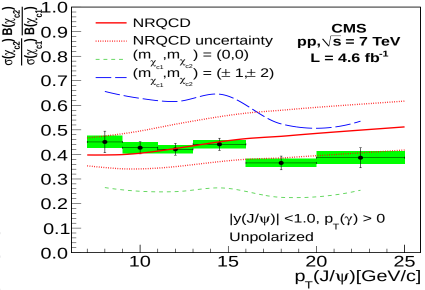




- systematic uncertainties are mainly from fit to mass distribution and polarization. χ_{c1} is either unpolarized or has helicity $m_{\chi_{c1}} = 0, \pm 1$ and the χ_{c2} is either unpolarized or has helicity $m_{\chi_{c2}} = 0, \pm 2$ in the helicity frame (CMS-PAS-BPH-11-010)

Ratio of χ_{c1} and χ_{c2} cross sections (III)



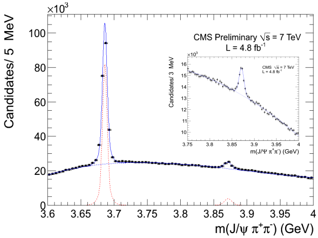


- kT-factorization prediction agrees well with the trend of Rp versus transverse momentum of the J/ψ
- A global normalization that is higher by about a factor two with respect to our measurement

- the NRQCD prediction is compatible with our data within the experimental and theoretical uncertainties.

Ratio of X(3872) and $\psi(2S)$ cross sections (I)

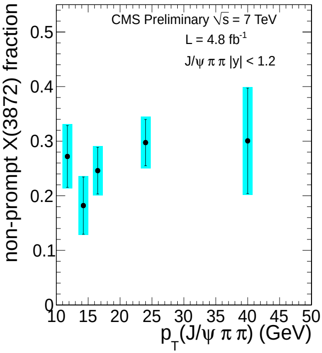
- discovered by Bell in 2003, confirmed by BaBar, CDF and D0
- interpreted as $c\bar{c}$ state, $D^*\overline{D}^0$ molecule, tetra-quark state



- J^{pc} is 1^{++} or 2^{-+}.
- both X(3872) and $\psi(2S)$ include promt and non-prompt components, the latter is from B.
- Measured quantity in $10 < pt(X) < 50$ GeV, $\mid y(X) \mid < 1.2$
  $$R = \frac{(pp \to X(3872)BR(X(3872) \to J/\psi\pi^+\pi^-)}{(pp \to \psi(2S))BR(\psi(2S) \to J/\psi\pi^+\pi^-)}$$
- MC sample is based on pythia 6 with χ_{c1} ($J^{pc} = 1^{++}$) mass set to 3.782 GeV and unploarization
- Result $R = 0.0662 \pm 0.0038 \pm 0.0064$

Ratio of X(3872) and $\psi(2S)$ cross sections (II)

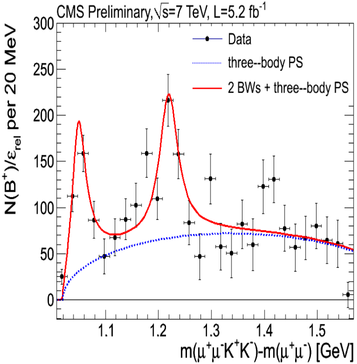
- measurment of the non-prompt X(3872) fraction
  - ✓ pseudo-proper decay length $\ell_{xy} > 100\ \mu m$ to enrich B hadron sample
  - ✓ no acceptance correction
  - ✓ correct for the efficiencies of the decay length selection criteria
- the fraction is ratio of the signal in the B sample and the signal in the whole sample
  fraction$=0.259 \pm 0.029 \pm 0.016$



Structures in the $J/\psi\phi$ spectrum

- evidence of Y(4140) was reported by CDF in 2009 in $J/\psi\phi$ mass in $B^+ \to J/\psi\phi K^+$ deacy.
- Y(4140) is a candidate of an exotic state
- it was not confirmed by Bell in 2010 and LHCb in 2011
- Y(4350) was reported by Bell in 2010 in the same decay channel
- CMS observed two structure

  in the $J/\psi\phi$ spectrum with masses of $4148.2 \pm 2.0 \pm 5.2$ MeV and $4316.7 \pm 3.0 \pm 10.0$ MeV, respectively.



Summary

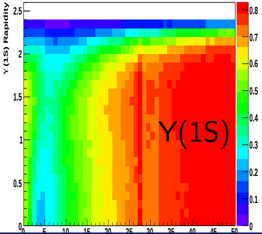
- The performance of the muon system in CMS is excellent: good muon pt resolution, gammar energy resolution and elaborate trigger paths for quarkonium observation. The Standard model was tested in quarkonium production and impressive agreement was obtained. The cross sections were measured up to unprecedented J/ψ pt.
- The cross sections for prompt J/ψ and $\psi(2S)$ and $Y(ns)$ were measured with high statistics and are good agreement with NLO NRQCD prediction at 7 TeV.
- χ_c was observed through photon conversion. The signal to background ratio was excellent and three states χ_{c0}, χ_{c1} and χ_{c2} were disentangled very well.
- The exotic state $X(3872)$ was observed at the new energy region with 2 times statistics as large as CDF.
- two structures were found in the $J/\psi\phi$ mass spectrum.

Backup: Analysis Strategy

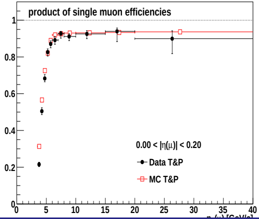
$$\frac{d^2\sigma(J/\psi)}{dp_t dy} B(J/\psi \to \mu^+\mu^-) = \frac{N_{fit}(J/\psi)}{\mathcal{L}\cdot\mathcal{A}\cdot\epsilon\cdot\Delta\mathrm{p_t}\cdot\Delta\mathrm{y}},$$

- $\mathcal{A}$: Acceptance to describe the geometry detecting ability of the detector
- $\epsilon = \epsilon_{trig}\epsilon_{id}\epsilon_{track}$: ϵ_{track}, ϵ_{id}, ϵ_{trig} are tracking, identification and trigger efficiency from T&P method.
  The minimal p_t for T&P is 2010: 0.8 GeV, 2011: 2.0 GeV.
- N_{fit}: the J/ψ yields from an unbinned maximum likelihood fit.
- $\mathcal{L}$: the integrated luminosity.

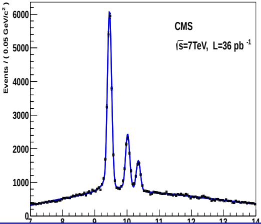
Acceptance $\mathcal{L}$



Efficiency (ϵ)



Likelihood fit (N_{fit})



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