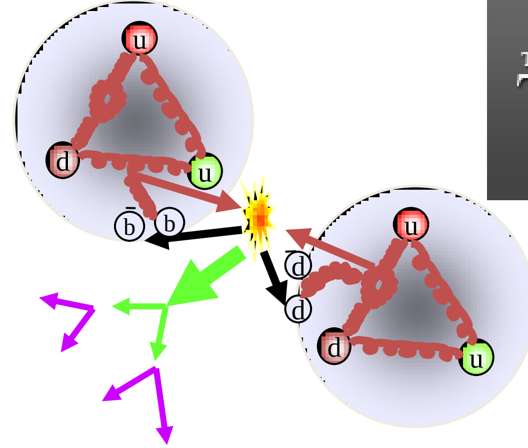
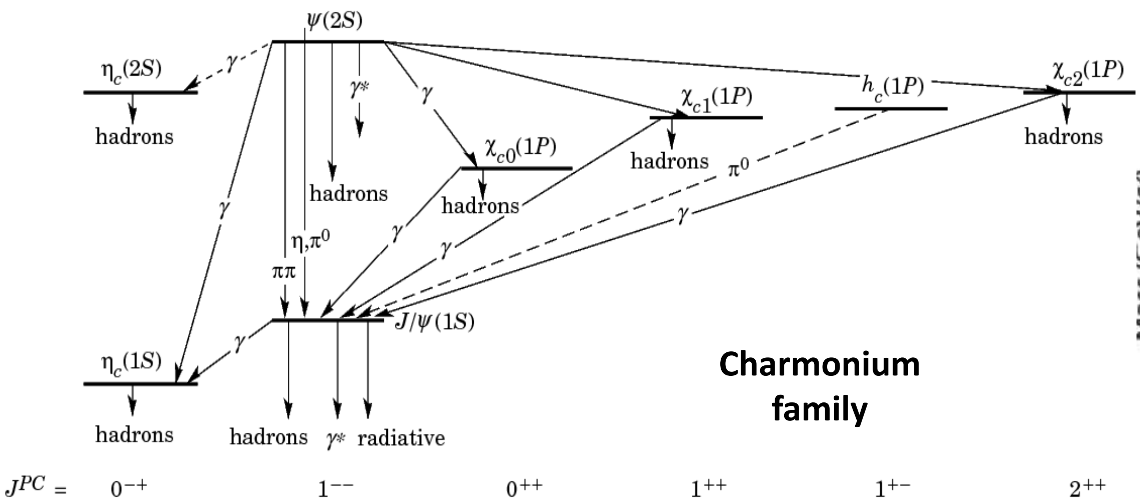
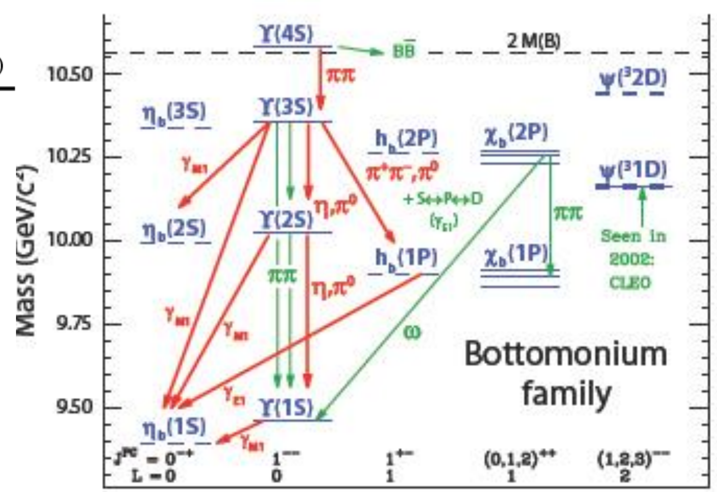


Measurement of Quarkonium Production with CMS in pp Collisions at √s = 7 TeV

Andrew York (University of Tennessee),
on behalf of the CMS Collaboration





Overview

- Motivations to study quarkonium production
- Overview of CMS detector and analysis techniques
- Production rates:
  - J/ψ and $\psi(2S)$ production
  - $\Upsilon(nS) \rightarrow \mu^{+}\mu^{-}$ production
  - Relative prompt production of χ_{c1} and χ_{c2}
- First observed decays in CMS:
  - Observation of $B_c^{\pm} \rightarrow J/\psi\ \pi^{\pm}$ and $B_c^{\pm} \rightarrow J/\psi\ \pi^{\pm}\ \pi^{\pm}\ \pi^{\mp}$
- Summary

Motivations to Study Quarkonium Production

<u>Motivation</u>: no theory has simultaneously explained measured production cross-sections and polarizations

NNLO

NLO

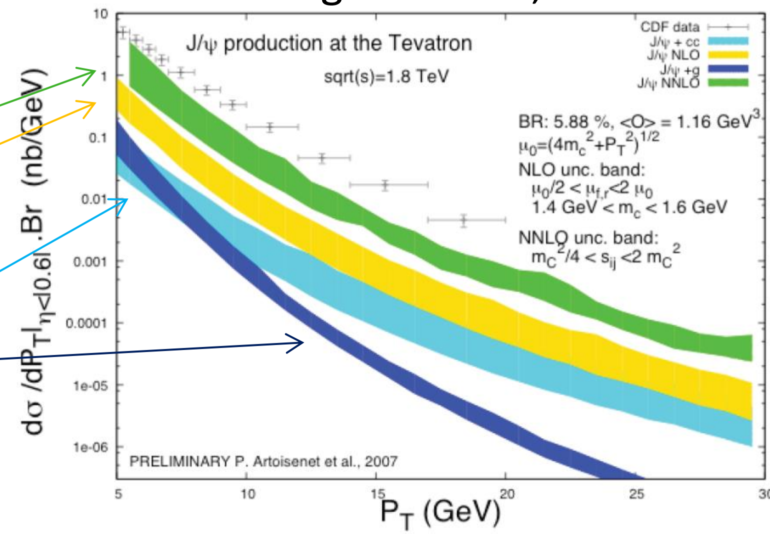
LO associate

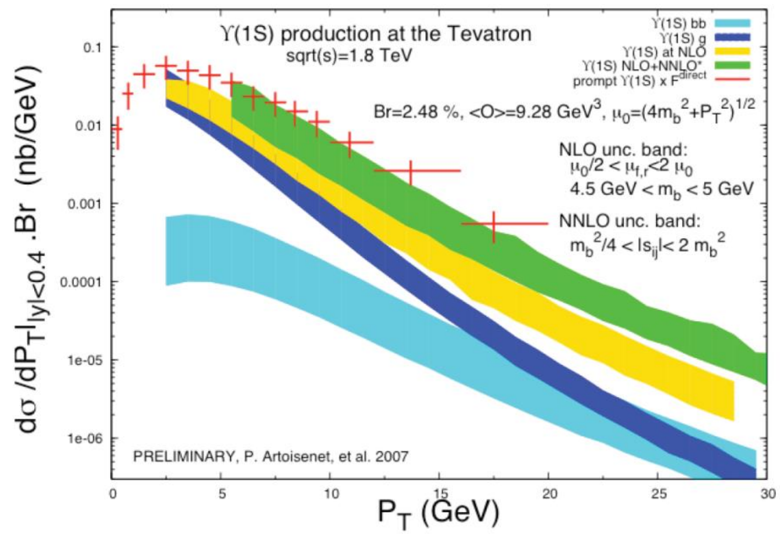
LO direct

<u>New experimental reach</u>:

- LHC extends the frontier for collisions
    - Increased energy and luminosity
    - gg fusion dominates production
- CMS provides:
    - Excellent dimuon mass resolution
    - Excellent photon resolution through $\gamma \to e^+e^-$ conversion

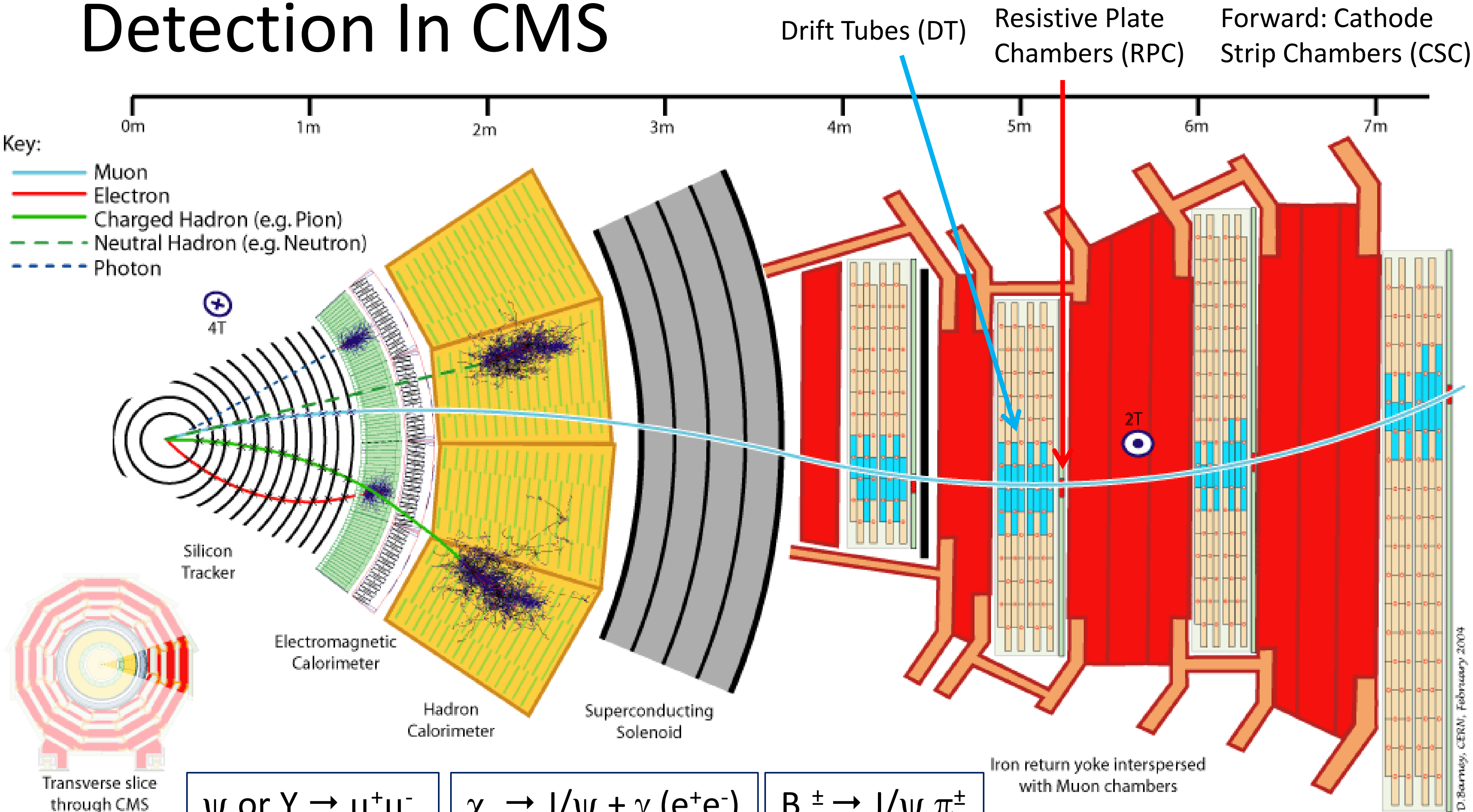
Color Singlet Model, Tevatron





P. Artoisenet, F. Maltoni et al, 2007

Detection In CMS



ψ or Y $\rightarrow \mu^+\mu^-$	$\chi_c \rightarrow J/\psi + \gamma\ (e^+e^-)$	$B_c^\pm \rightarrow J/\psi\ \pi^\pm$

- <u>Track building</u>: charge deposits in silicon pixel/strip tracker propagated from Pixel hit trajectories, $\sigma_{pT}/pT \sim 1\%$
- <u>Muon building</u>: charge deposits in DT/RPC layer merged into hits, propagated to beamspot to form segments. Tracks matched to muon segments.

Muon Efficiency in CMS

$$\epsilon_{\mu} = \epsilon_{trig} * \epsilon_{track} * \epsilon_{MuonID}$$

Muon efficiency measured in data using "tag and probe" technique

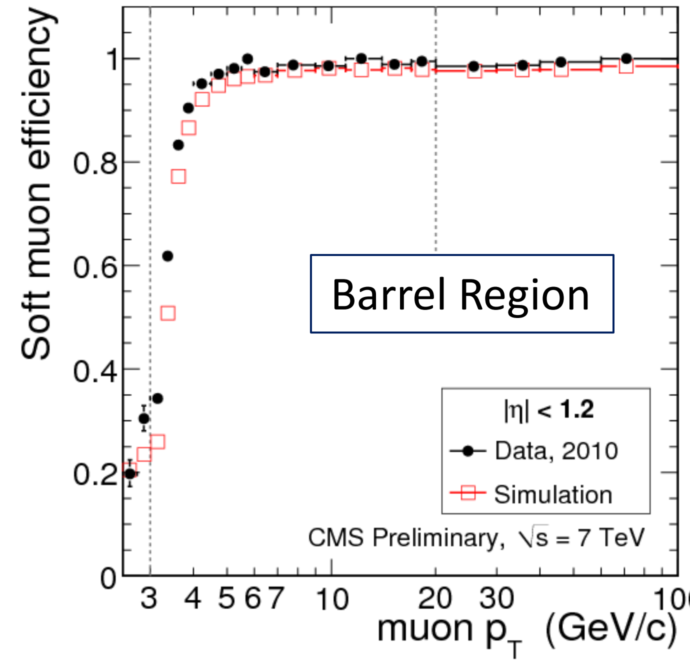
"tag" muon

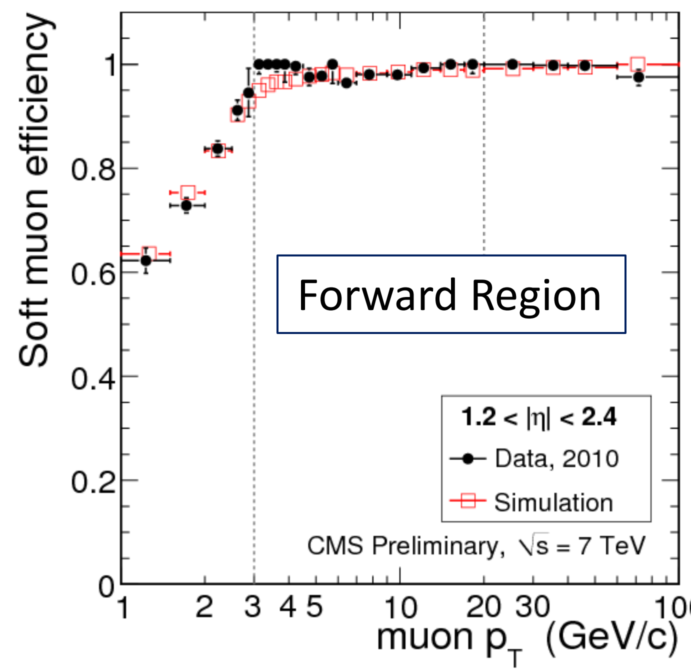
"probe" muon

J/ψ, Z decay

(simulation compatible with data)

Efficient over wide range of momentum and angular coverage

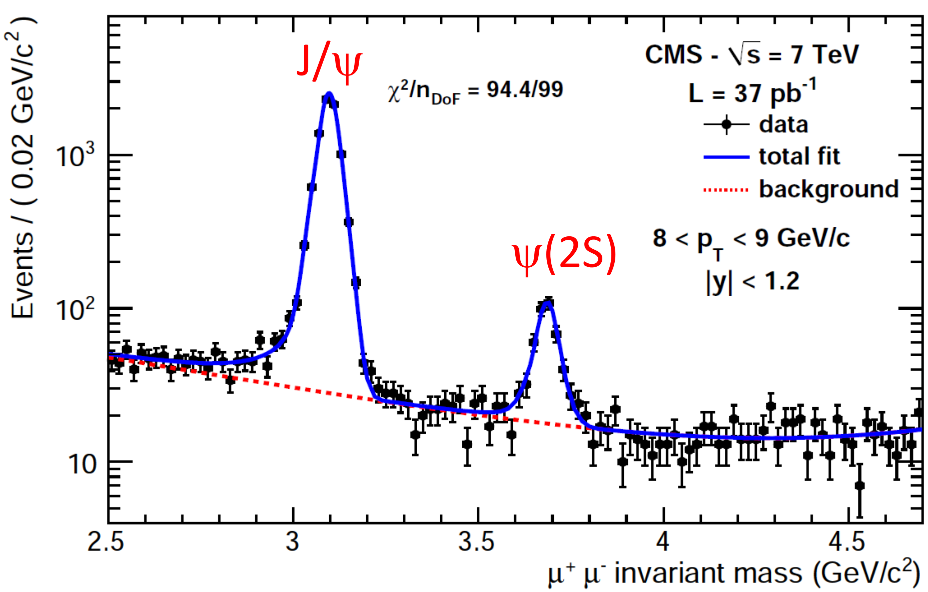




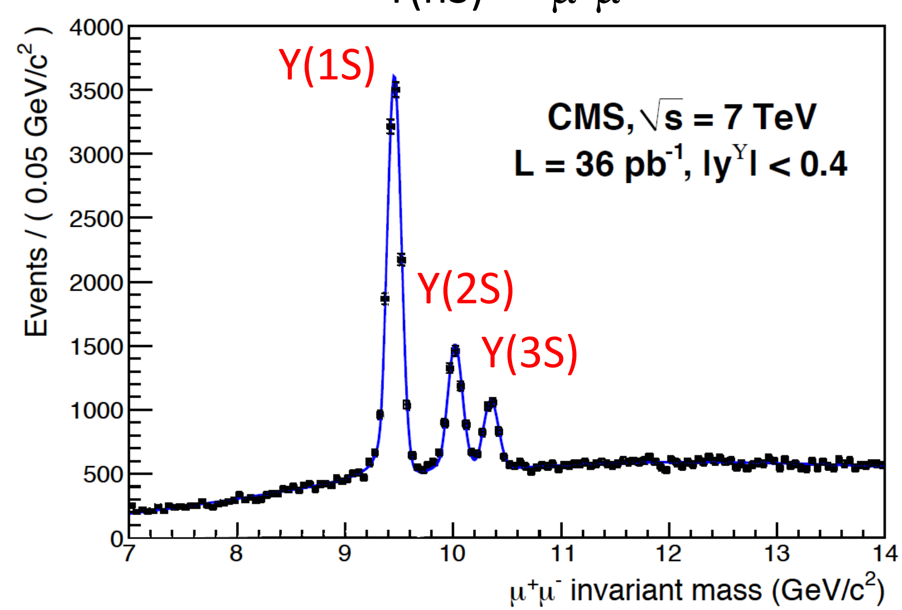
Signal Extraction

Discriminating variable: $\mu^+\mu^-$ Invariant Mass
Parameterization: Crystal Ball and/or Gaussian for signal, exponential or product of exponential and error function for background
Maximum Likelihood fit: with mass differences fixed to PDG values, common resolution value scaled by mass

$\psi(nS) \rightarrow \mu^+\mu^-$



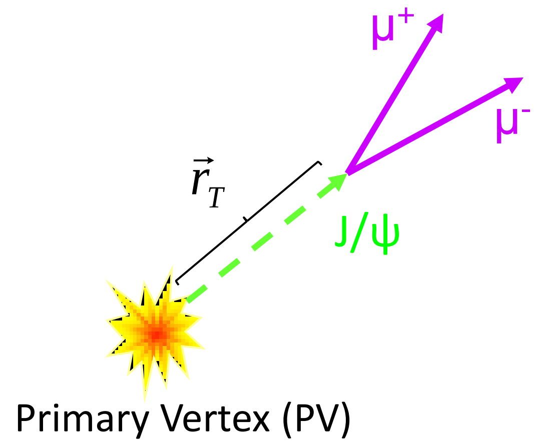
$\Upsilon(nS) \rightarrow \mu^+\mu^-$



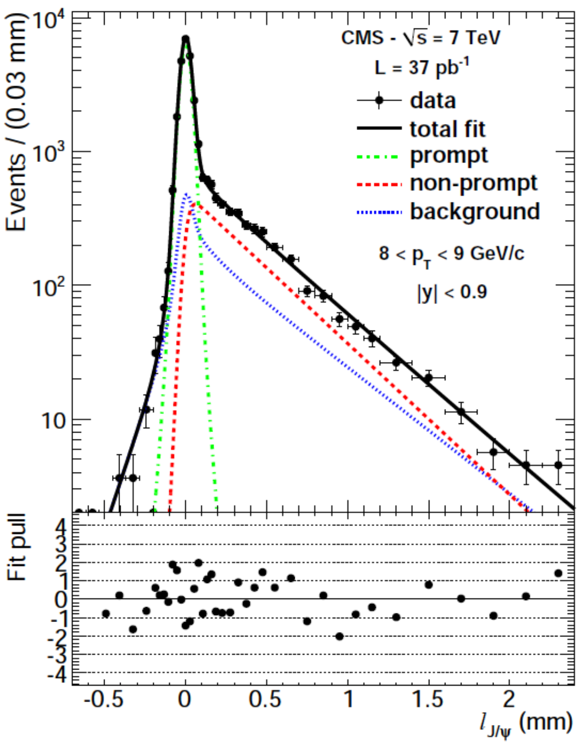
Separating Prompt and Non-prompt J/ψ

ML Fit as before, with addition of psuedo-proper decay length variable (ℓ_{xy})

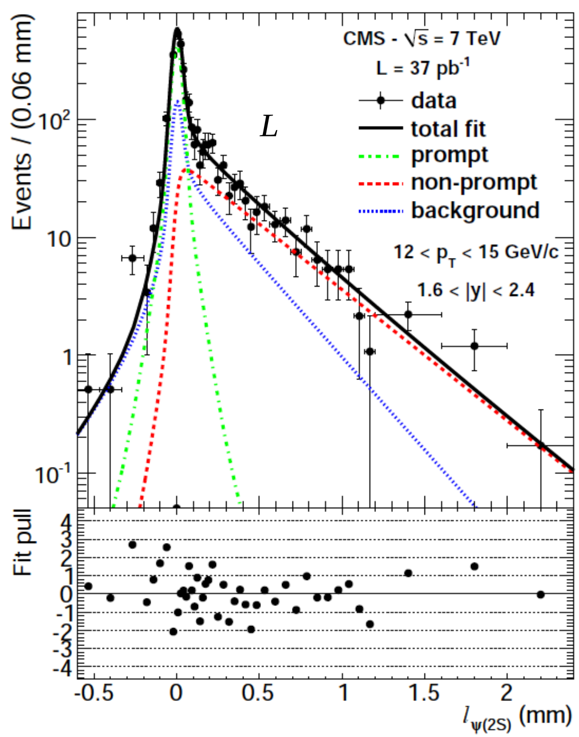
Parameterization: double Gaussian for resolution, times exponential decay for non-prompt



J/ψ



ψ(2S)



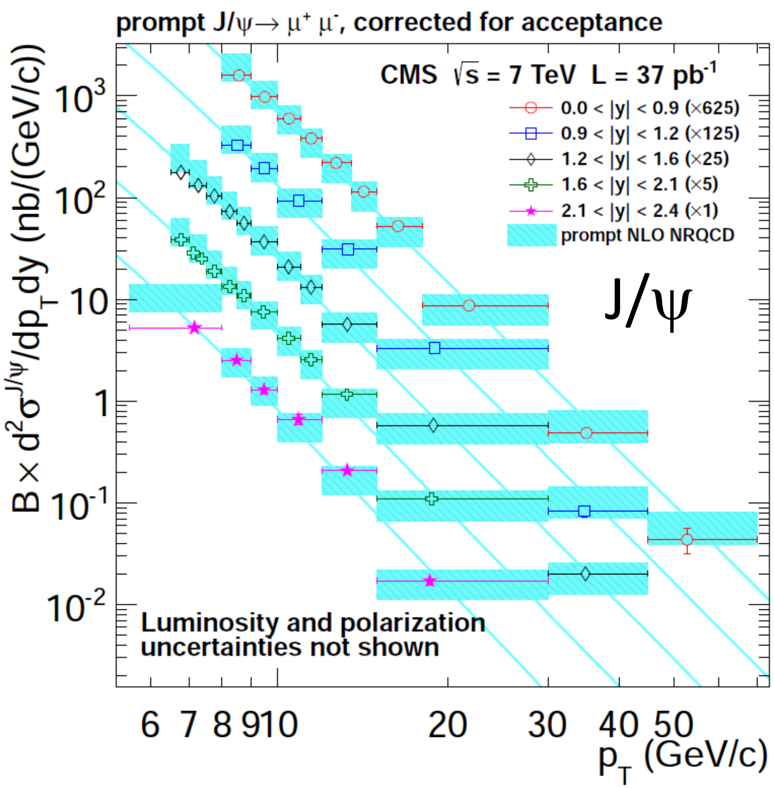
$$L_{xy}^{J/\psi} = \frac{\vec{\mathrm{r}}_\mathrm{T} \cdot \vec{\mathrm{p}}_\mathrm{T}^{J/\psi}}{|\mathrm{p}_\mathrm{T}^{J/\psi}|}$$

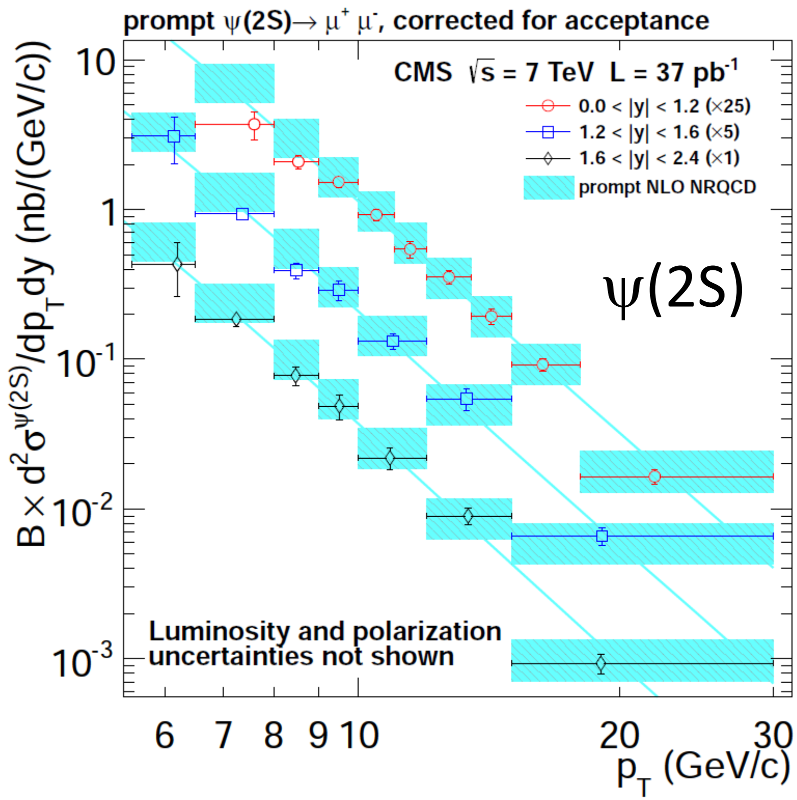
$$l_{xy} = \frac{M^{J/\psi}}{|\mathrm{p}_\mathrm{T}^{J/\psi}|} L_{xy}^{J/\psi}$$

J/ψ and ψ(2S) Production

JHEP 02 (2012), 011

Prompt cross-section results:





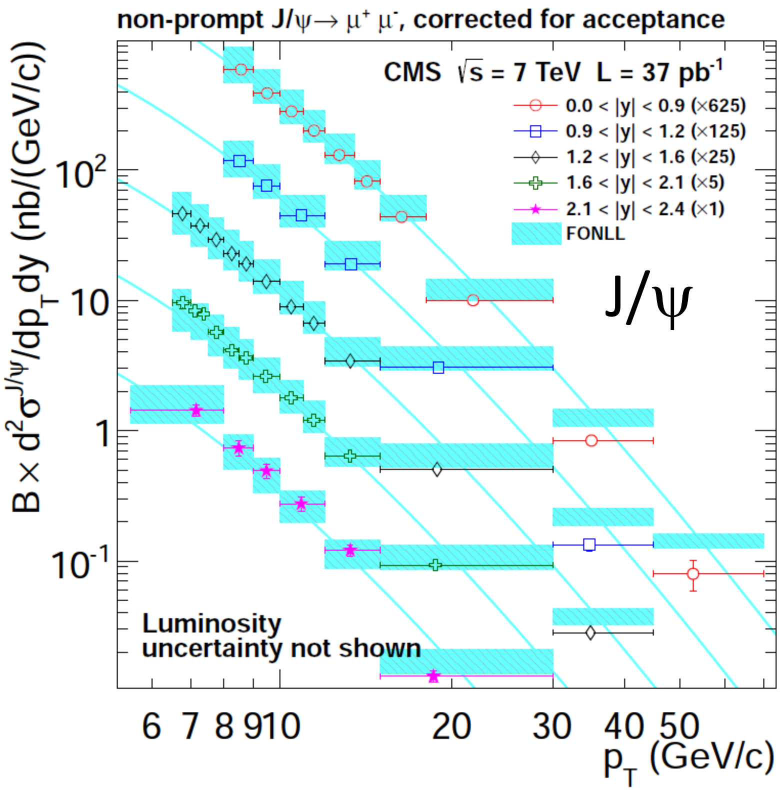
Agrees with NRQCD predictions

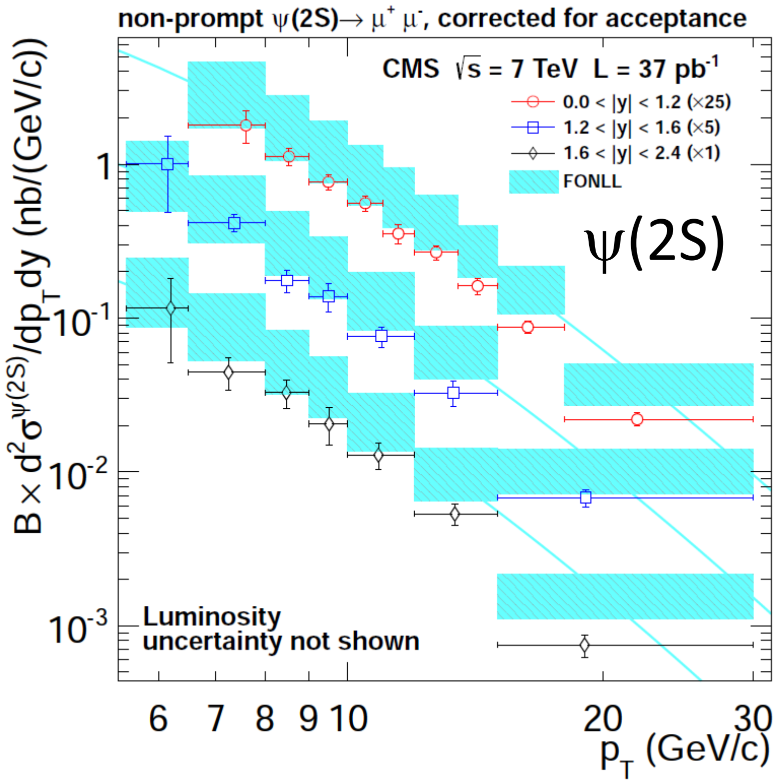
- Theory based on CS+CO model at NLO
- Feed-down effect included in theory

J/ψ and ψ(2S) Production

JHEP 02 (2012), 011

Non-prompt cross-section results:





Predictions based on Fixed Order plus Next to Leading Logs (FONLL)
- Fall at high p_T compared to theory, overall shift in ψ(2S) case

J/ψ and ψ(2S) Production

JHEP 02 (2012), 011

Improved branching fraction determination using

- from PDG: $\mathcal{B}(B \to J/\psi X)$, $\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$, $\mathcal{B}(J/\psi \to \mu^+\mu^-)$
- from measurement:

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

Determination made as:

$$\mathcal{B}(B \to \psi(2S)X) = \frac{R \cdot \sigma(J/\psi) \cdot \mathcal{B}(B \to J/\psi X) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)}{\sigma(\psi(2S)) \cdot \mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$$

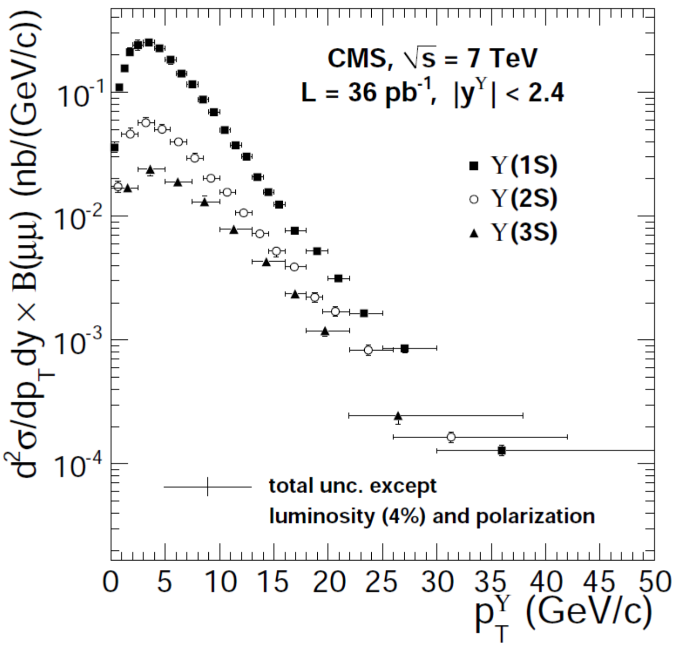
with result:

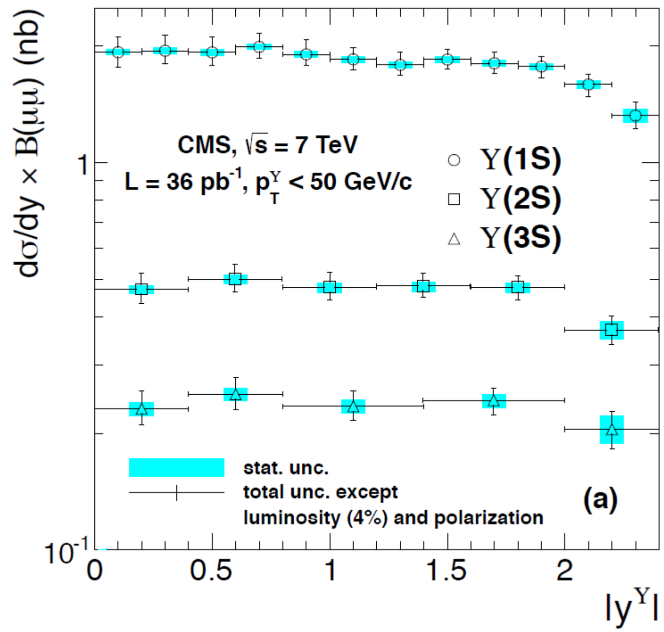
$$\mathcal{B}(B \to \psi(2S)X) = (3.08 \pm 0.12\,(\text{stat.+syst.}) \pm 0.13\,(\text{theor.}) \pm 0.42\,(\mathcal{B}_{PDG})) \times 10^{-3}$$

$\Upsilon(nS) \to \mu^+\mu^-$ Production

arXive:1303.5900

Production cross-section results:





$\Upsilon(nS)$ acceptance regime:

- $p_T < 50$ GeV/c
- $|y| < 2.4$

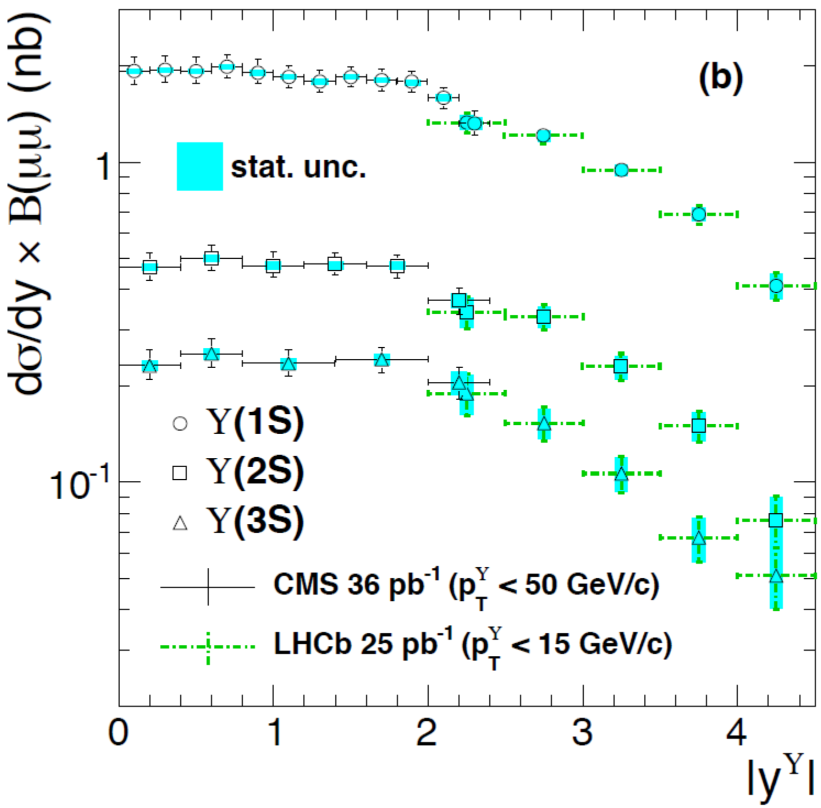
assumes unpolarized production

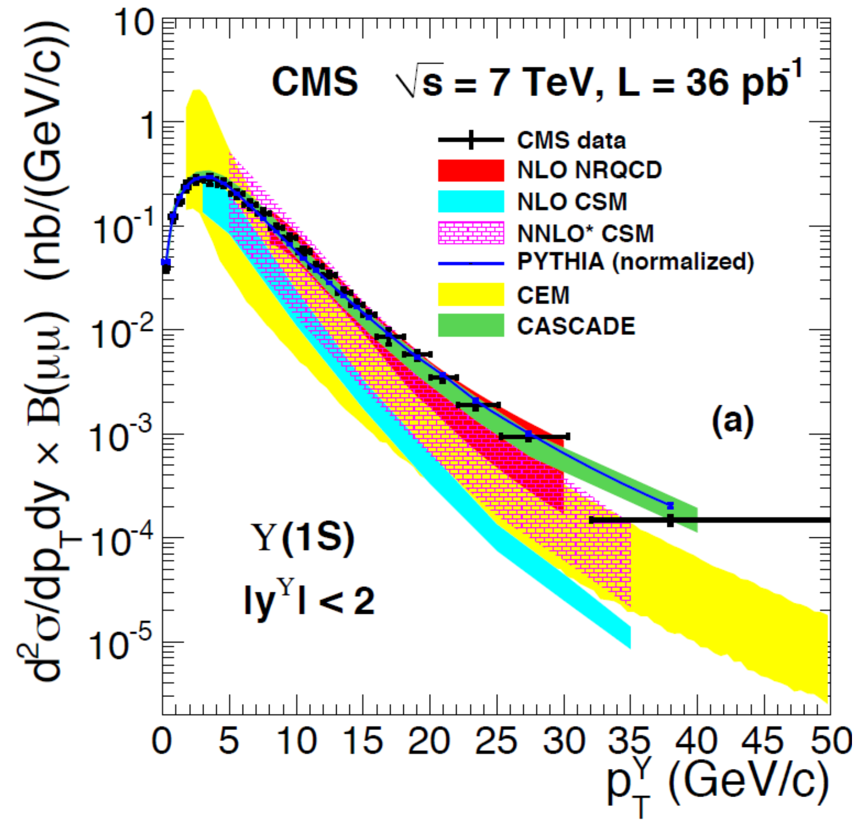
$$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = (8.55 \pm 0.05^{+0.56}_{-0.50} \pm 0.34)nb,$$
$$\sigma(pp \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = (2.21 \pm 0.03^{+0.16}_{-0.14} \pm 0.09)nb,$$
$$\sigma(pp \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = (1.11 \pm 0.02^{+0.10}_{-0.10} \pm 0.04)nb,$$

Υ(nS) → μ⁺μ⁻ Production

arXive:1303.5900

Comparison to LHCb and theory:



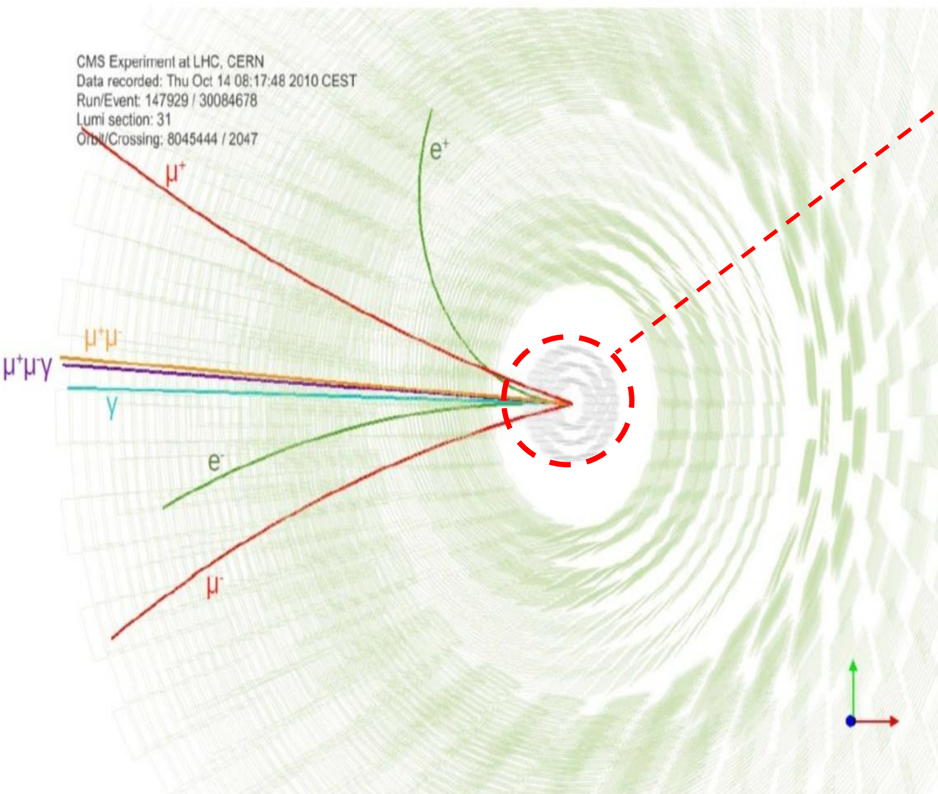


Complements LHCb and consistent in region of overlap

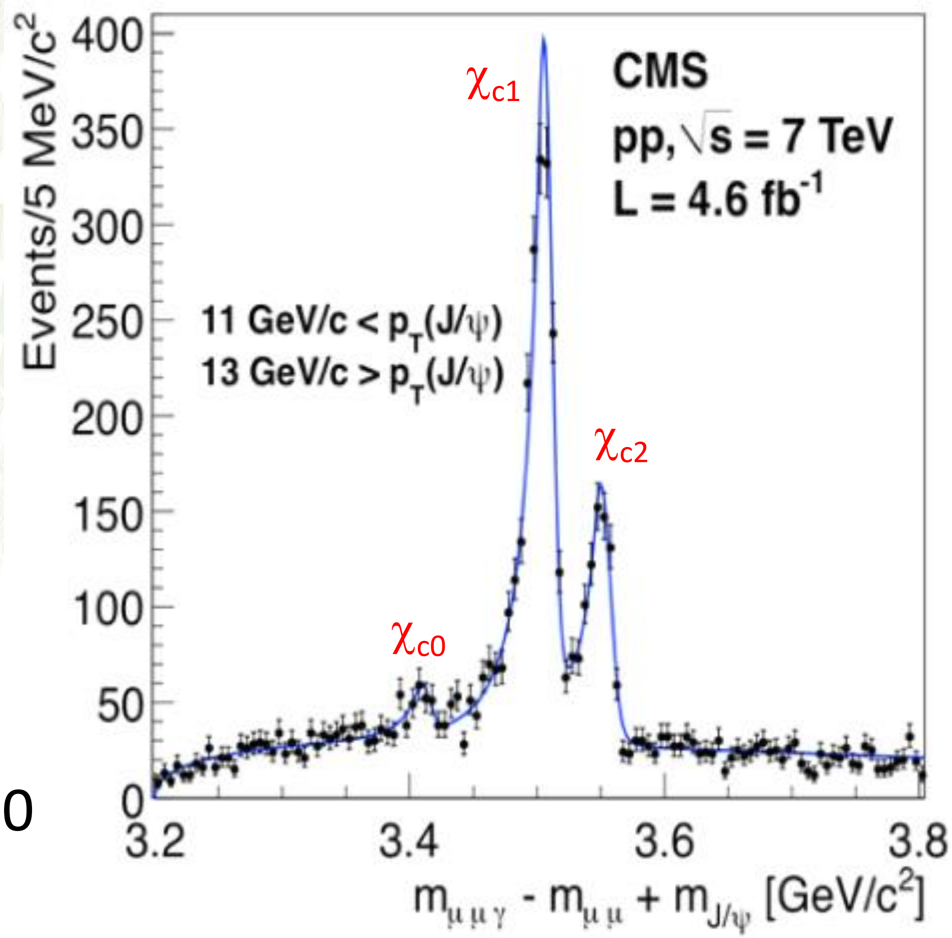
Best agreement with CASCADE and NRQCD (CS+CO at NLO)

Relative Prompt Production Rate of χ_{c1} and χ_{c2}

EPJC 72 (2012), 2251



most reconstructed photons converted in beampipe and Pixel layers

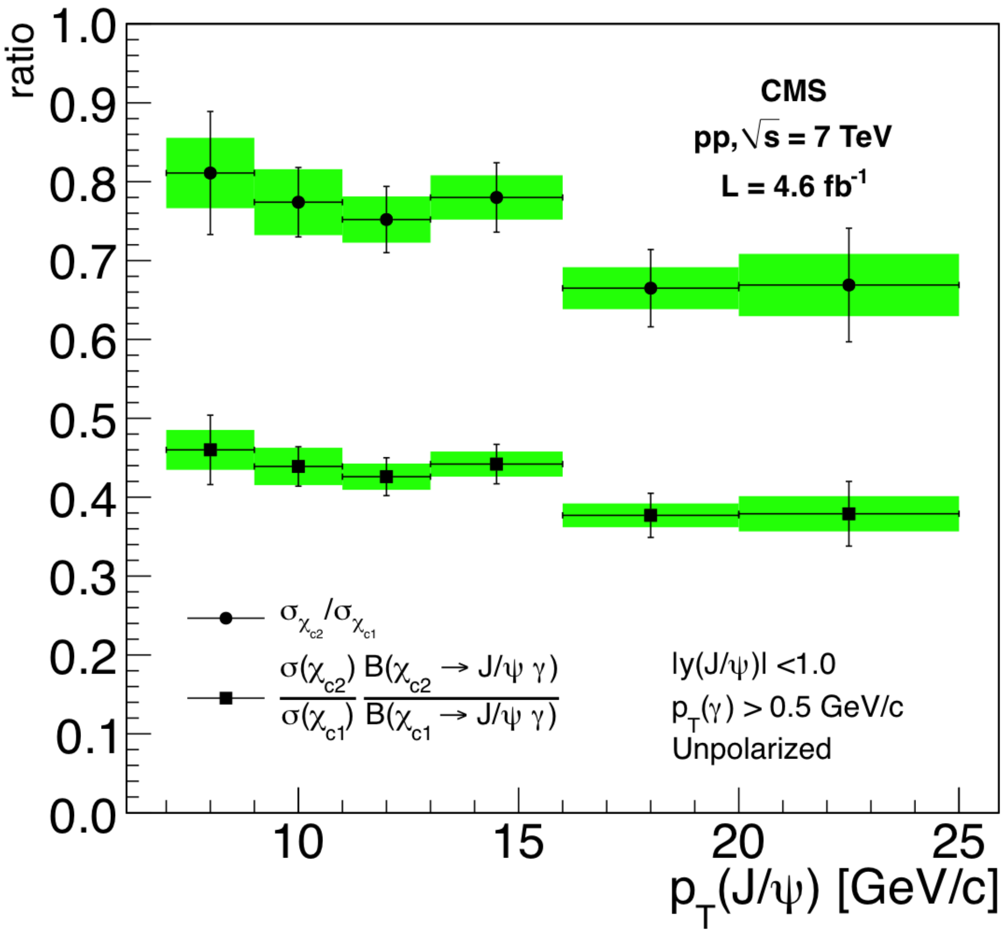


- Identified using radiative decay $\chi_c \rightarrow J/\psi + \gamma$ where $\gamma \rightarrow e^+e^-$
- With requirements: $|y(J/\psi)| < 1.0$ and $p_T(\gamma) > 0.5$ GeV/c

Relative Prompt Production Rate of χ_{c1} and χ_{c2}

EPJC 72 (2012), 2251

Results:



Cross-section ratio

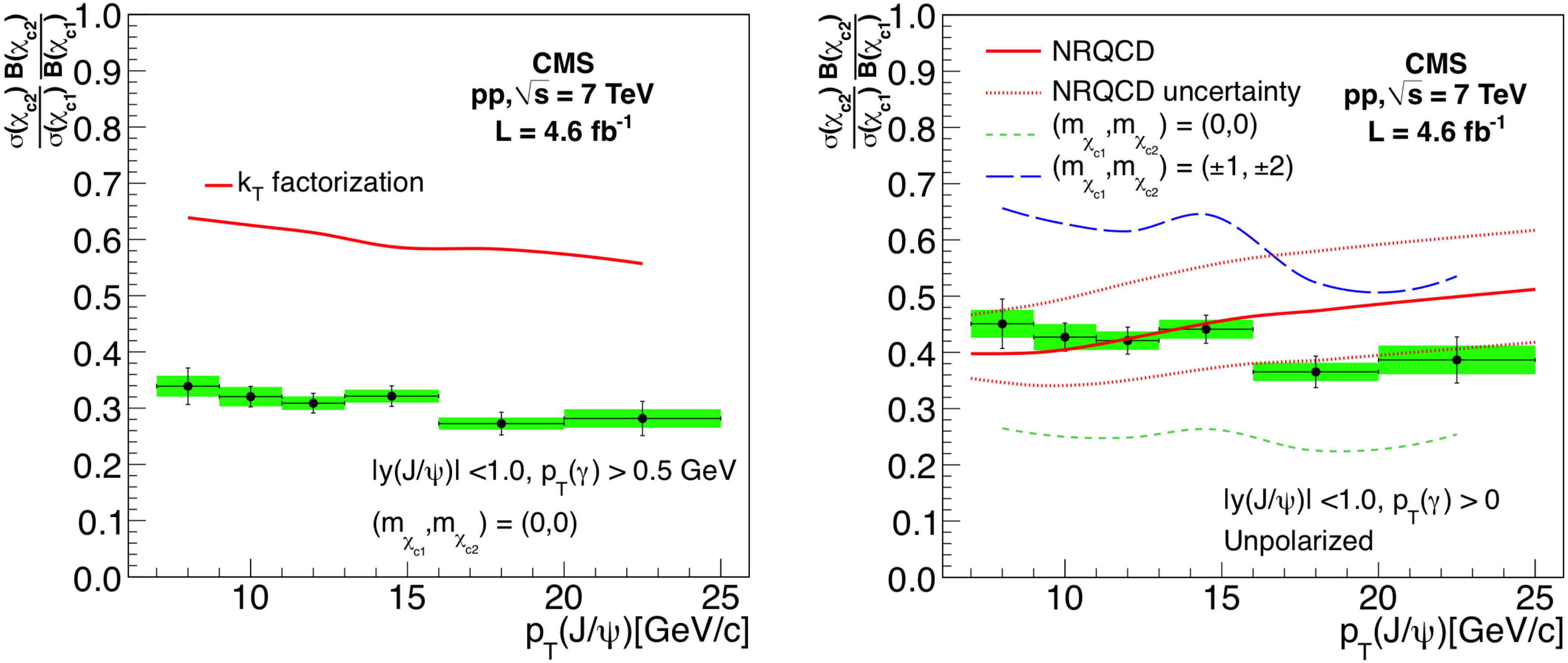
Cross-section*BF($\chi_c \to J/\psi + \gamma$) ratio

Unpolarized scenario

Relative Prompt Production Rate of χ_{c1} and χ_{c2}

EPJC 72 (2012), 2251

Comparison to theory:



- kT factorization describes shape, but not the level of χ_{c2}/χ_{c1} ratio
- NRQCD (CS+CO at NLO) provides agreement within uncertainty

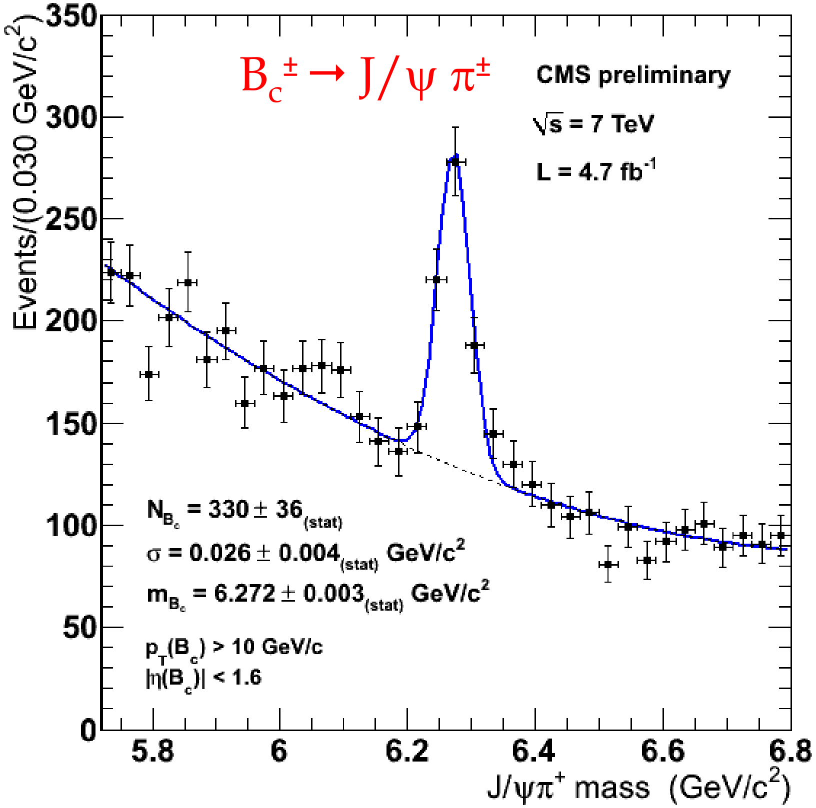
(data extrapolated back to $p_T(\gamma) > 0$ phase space for comparison)

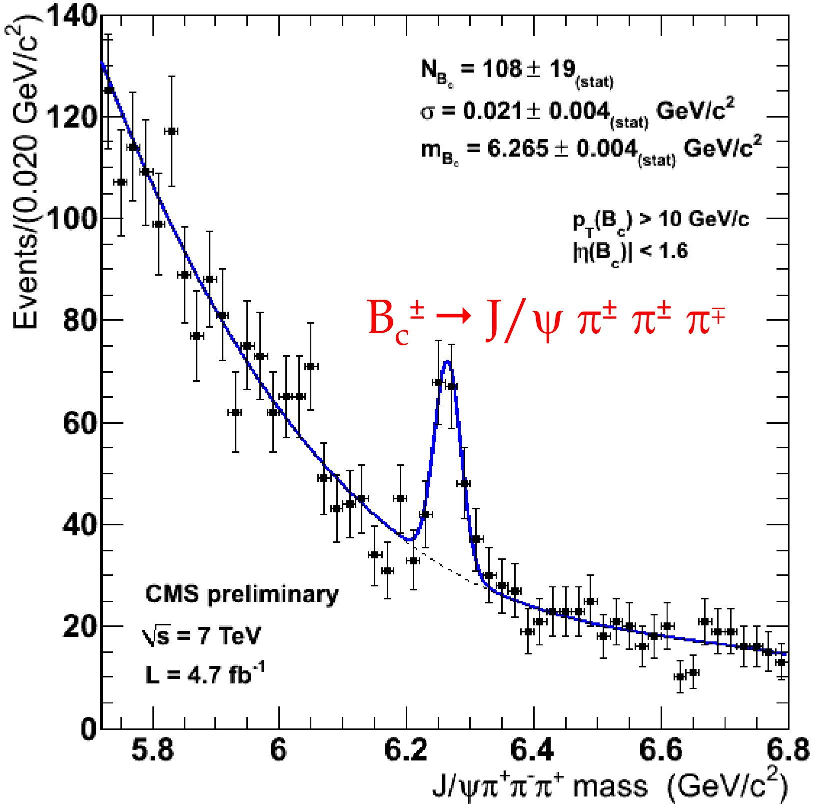
Observation of $B_c^{\pm} \rightarrow J/\psi\ \pi^{\pm}$ and $B_c^{\pm} \rightarrow J/\psi\ \pi^{\pm}\ \pi^{\pm}\ \pi^{\mp}$

CMS-PAS-BPH-11-003

$B_c^{\pm} \rightarrow J/\psi\ \pi^{\pm}$: $S/\sqrt{(S+B)} = 10.5$

$B_c^{\pm} \rightarrow J/\psi\ \pi^{\pm}\ \pi^{\pm}\ \pi^{\mp}$: $S/\sqrt{(S+B)} = 6.1$





Summary

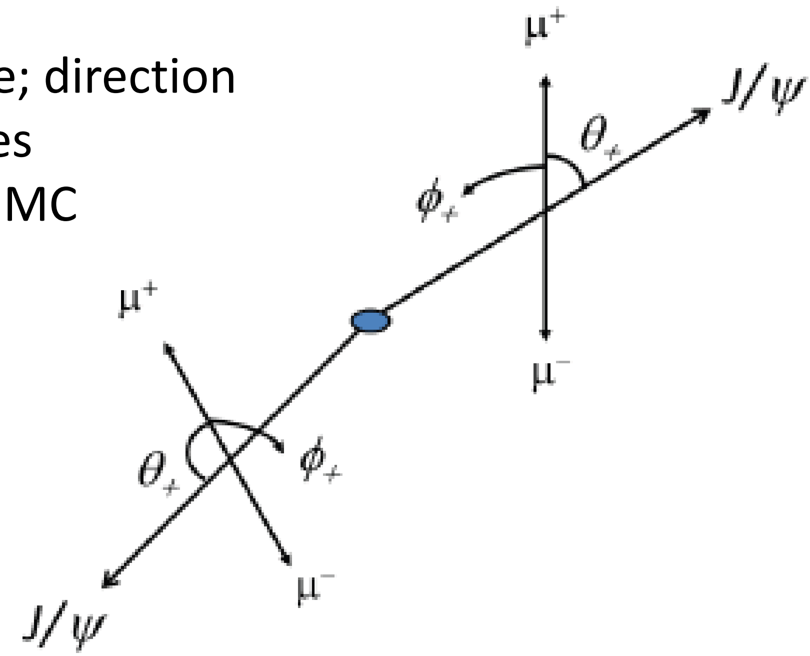
- J/ψ, $\psi(2S)$, and $\Upsilon(nS)$ differential cross-sections measured with uncertainties (statistical+systematic) of 20% or less
    - Complementary coverage to LHCb
    - Production rates agree with NRQCD predictions
    - Reduces relative uncertainty of $\mathcal{B}(B \to \psi(2S)\,X)$ agrees with world average value, improves relative uncertainty by factor of 3
- Production ratio χ_{c2}/χ_{c1} measured
    - Extends pT measurement beyond previous experiments
    - Most precise measurement to date!
- Observation of $B_c \to J/\psi\,\pi^{\pm}$ and $B_c \to J/\psi\,\pi^{\pm}\,\pi^{\pm}\,\pi^{\mp}$ decays provide first fully reconstructed observation of B_c decays in CMS (needed for lifetime measurement)

Backup

Acceptance and Polarization Uncertainty

Acceptance

Decay particles uniformly in their own rest frame; direction along flight path is reference axis for decay angles
 - Determine acceptance value per bin based on MC



Uncertainty

Instead of assuming muons are produced uniformly in J/ψ rest frame, assume distribution of:

$$\frac{dN}{d\cos\theta_+} \propto 1 + \lambda_\theta \cos^2\theta_+$$

→ Test acceptance limits by testing extremes of decay distribution, ie λ_θ = +1, -1

Photon Conversion Radii

CMS coll., EPJC 72 (2012), 2251