CMS Results for Quarkonium Production in 7 TeV pp Collisions

James Russ for the CMS Collaboration

- Why Do These Measurements?
  – Issues in Hadroproduction

- New CMS results for P-wave charmonium production

- CMS results for Upsilon differential cross section in central-rapidity region

The Problem with Hadroproduction

- How to make a colorless hadron that contains two heavy quarks?
  -- many, many possibilities!

- current models: NRQCD, CSM, k_T Factorization

- Different predictions for polarization and excited-state production for charm and bottom

- NLO and NNLO corrections can be large and p_T dependent

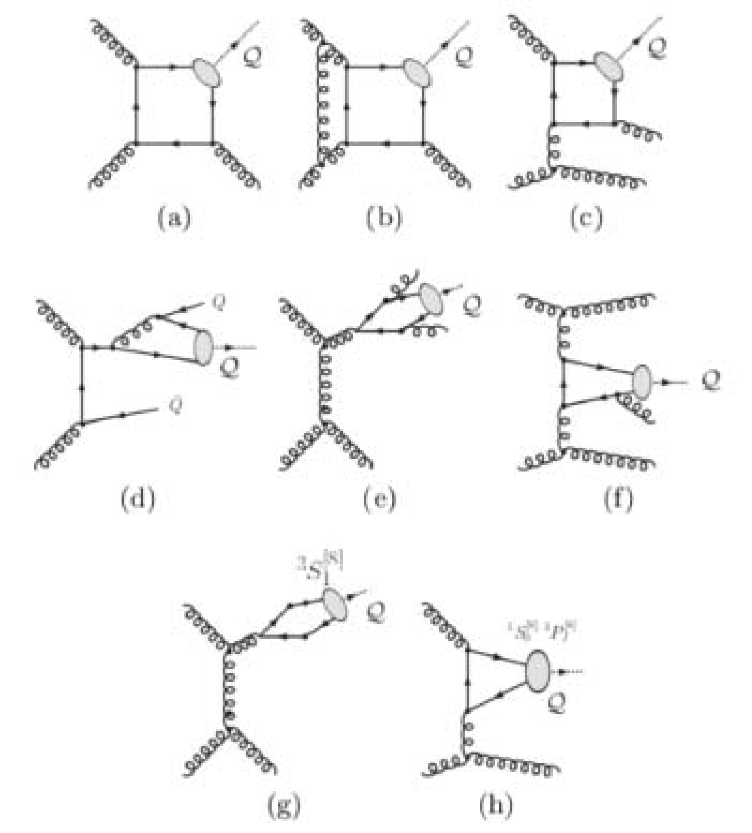


Figure from J-P Lansberg, EJP C60, 693 (2009)

Two New CMS Contributions

- Ratio of Production Cross Sections for χ_{c2} and χ_{c1} P-wave excited states of charmonium for $7 < p_T < 25$ GeV at $\sqrt{s} = 7$ TeV. (Eur.Phys.J. C72 (2012), 2251)

- Differential Cross Section Measurements for Prompt Production of Υ(1S), Υ(2S) and Υ(3S) states with $0 < p_T < 30$ GeV at $\sqrt{s} = 7$ TeV. (arXiv: 1303.5900)

Cross Section Measurements for P-wave states of Charmonium

χ_c states decay into many final states. In CMS we measure

$$\chi_c \rightarrow J/\psi + \gamma \rightarrow \mu^+ + \mu^- + \gamma$$

Experimental Challenges:

1) Rest-frame photon energies are 390 and 430 MeV for χ_{c1} , χ_{c2} . How can an energy-frontier detector measure such low-energy photons well enough to separate the two states?

Answer: use photon conversions in the silicon tracker to get very high precision photon energy and direction *because* the p_T boost in hadroproduction brings the photons into the GeV energy range, good for conversion

More Experimental Issues

- χ_c states are produced promptly or from b-decays
  - use J/ψ vertex position to select prompt fraction

- χ_{c0} decays into J/ψ + γ are strongly suppressed but not zero
  - include this state in mass spectrum

- χ_{c2} and χ_{c1} acceptance and mass resolution functions differ slightly and acceptances are low.
  - efficiencies are a simulation challenge.

- The conversion reconstruction efficiency is quite low compared to using the EM calorimeter
  - the LHC charm cross section is large and CMS is a superb high-rate detector, so we can use the high resolution of conversions for physics.

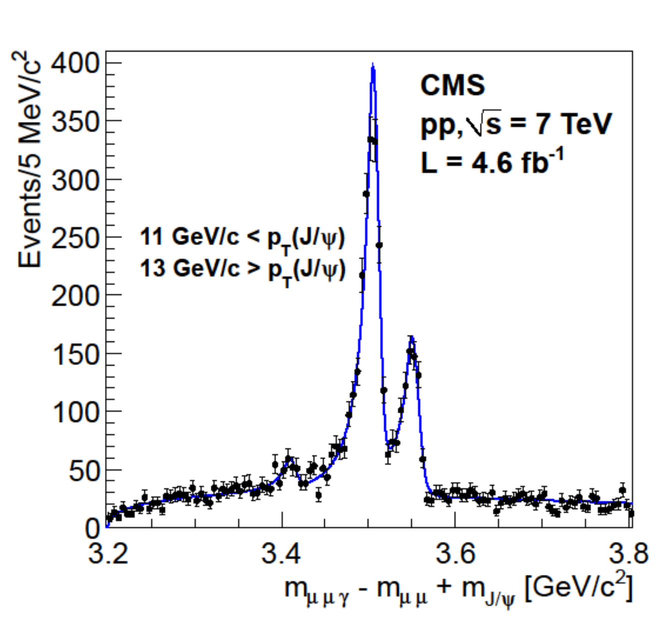
The Physics Goal:

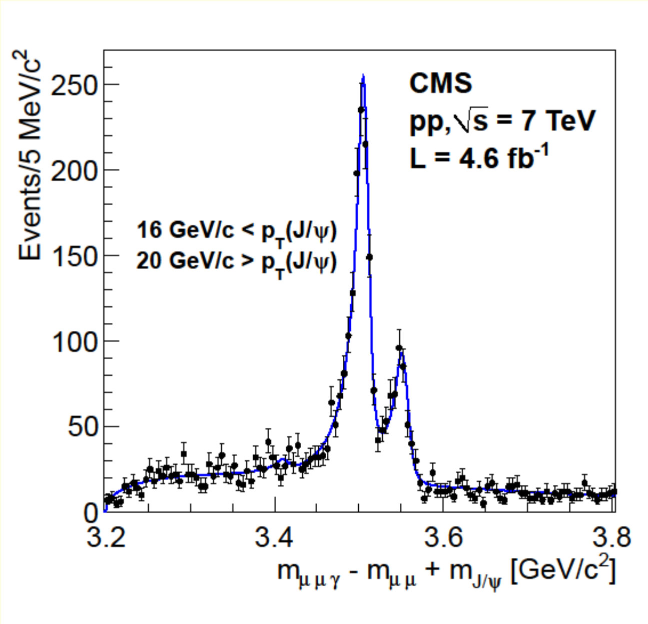
- Measure the prompt production cross section ratio for χ_{c2}/χ_{c1} to test theoretical predictions.

$$R_{\mathrm{p}} \equiv \frac{\sigma(\mathrm{pp} \to \chi_{c2} + X)\mathcal{B}(\chi_{c2} \to \mathrm{J}/\psi + \gamma)}{\sigma(\mathrm{pp} \to \chi_{c1} + X)\mathcal{B}(\chi_{c1} \to \mathrm{J}/\psi + \gamma)} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \cdot \frac{\varepsilon_1}{\varepsilon_2}$$

- We need four quantities. How to get them?

χ_c Mass Spectrum and Yields





$\mu\mu\gamma$ mass spectra for two bins of $p_T(J/\psi)$

Line shapes agree well with data in all p_T bins.

Mass PDFs determined from simulation. Only normalization comes from fit to data. Table gives yields and statistical uncertainty.

$p_T(J/\psi)$ [GeV/c]	$N_{\chi_{c1}}$	$N_{\chi_{c2}}$	$N_{\chi_{c2}}/N_{\chi_{c1}}$
7–9	618 ± 31	315 ± 24	0.510 ± 0.049
9–11	1680 ± 49	788 ± 37	0.469 ± 0.027
11–13	1819 ± 51	819 ± 38	0.451 ± 0.025
13–16	1767 ± 51	851 ± 39	0.482 ± 0.027
16–20	1269 ± 43	487 ± 30	0.384 ± 0.028
20–25	642 ± 31	236 ± 22	0.368 ± 0.040

Finding the Acceptance Ratio

Have two of the four numbers. Now we need the detection efficiency ratio $\varepsilon_2/\varepsilon_1$.

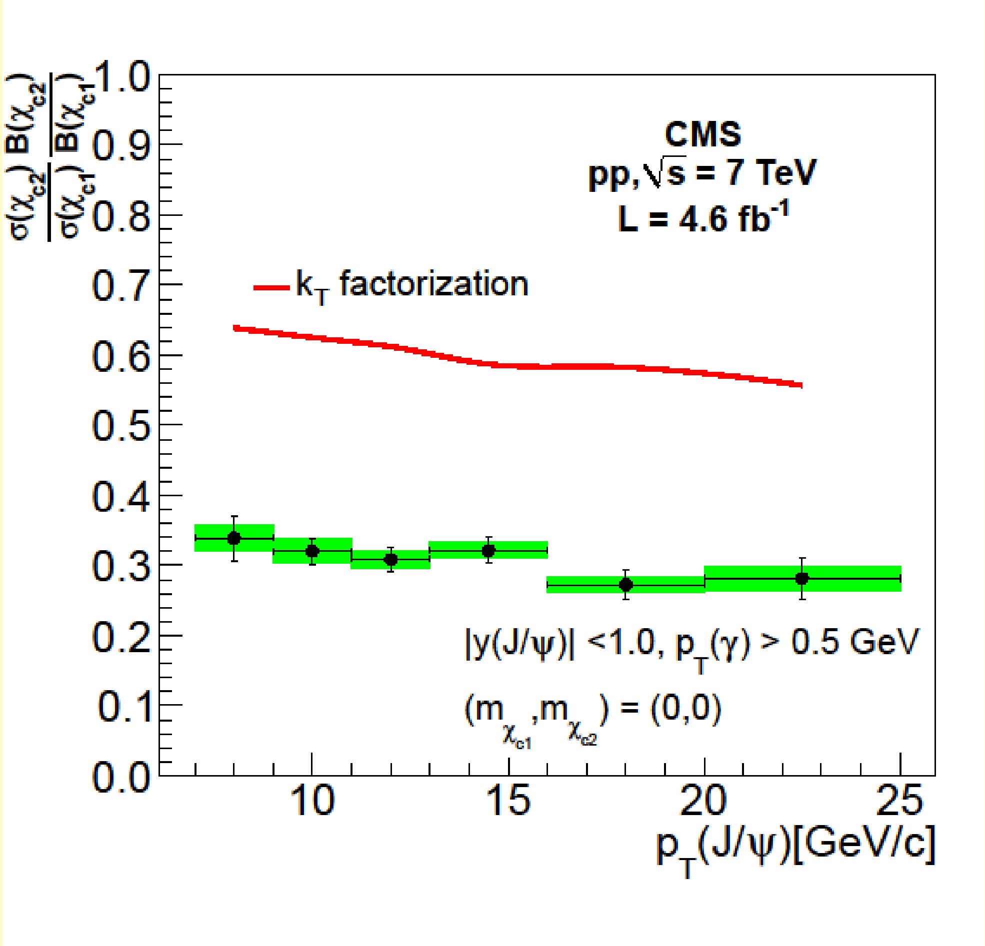
- Assume χ production has same p_T spectrum as $\psi(2S)$
- Use unpolarized decays in simulation to get $\varepsilon_2/\varepsilon_1(p_T(J/\psi))$
- Study range of acceptance corrections due to possible spin states for J = 2 and J = 1 χ states.
- Have to consider several polarization frames, since polarization in one frame may appear as zero polarization in another. Compare Collins-Soper (CS) and helicity (HX) frames.

The Results

$p_T(J/\psi)$ [GeV/c]	$\frac{\sigma(\chi_{c2})\mathcal{B}(\chi_{c2})}{\sigma(\chi_{c1})\mathcal{B}(\chi_{c1})}$	HX	CS
7–9	0.460 ± 0.044 (stat.) ± 0.025 (syst.)	$^{+0.136}_{-0.121}$	$^{+0.037}_{-0.023}$
9–11	0.439 ± 0.025 (stat.) ± 0.024 (syst.)	$^{+0.128}_{-0.119}$	$^{+0.052}_{-0.035}$
11–13	0.426 ± 0.024 (stat.) ± 0.017 (syst.)	$^{+0.125}_{-0.117}$	$^{+0.059}_{-0.042}$
13–16	0.442 ± 0.025 (stat.) ± 0.016 (syst.)	$^{+0.125}_{-0.121}$	$^{+0.065}_{-0.044}$
16–20	0.377 ± 0.028 (stat.) ± 0.015 (syst.)	$^{+0.106}_{-0.104}$	$^{+0.059}_{-0.042}$
20–25	0.379 ± 0.041 (stat.) ± 0.022 (syst.)	$^{+0.094}_{-0.097}$	$^{+0.055}_{-0.040}$

- Ratio decreases slowly as $p_T(J/\psi)$ increases, but the effect is not dramatic.
- Polarization uncertainties are important. No experimental constraints yet.
- Other systematics: background model; signal shape model; p_T spectrum, and limited Monte Carlo statistics.
- Interplay between various systematic contributions varies from bin to bin. No one source dominates.

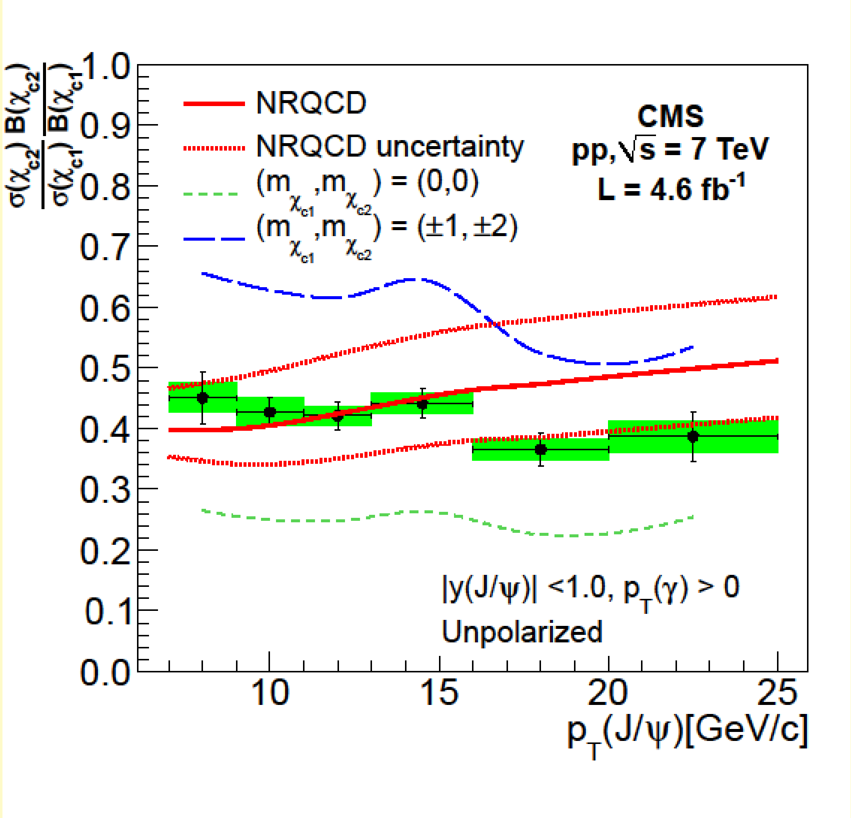
Comparison to k_T Factorization Model



- Model predicts zero helicity for χ_{c1} and χ_{c2}, so spin ambiguity systematic uncertainties are greatly reduced.

- Trend of data with p_T agrees with model prediction, *but* there is a factor of 2 difference in the magnitude.

Comparison to NRQCD Model



- normalization agrees, but p_T trend does not agree well with data

- No information from model about spin states for χ_{c1} and χ_{c2}, so all possibilities have to be considered.

- Treat data as unpolarized to match model. Green and blue dashed contours illustrate extreme ranges of spin effects in data.

- Red solid lines reflect color octet uncertainties in NRQCD calculation.

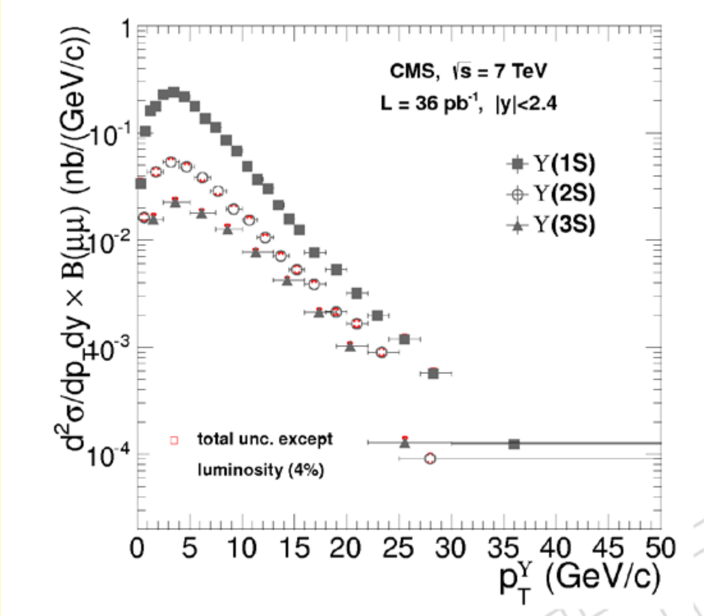
Summary of Charmonium Study

- Extending p_T range of ratio measurement illustrates relative strengths and weaknesses of two popular models

- First steps toward determining feed-down fraction from higher-lying states into χ_c channel are made. Biggest contribution expected from $\psi(2S)$. CMS cross section measurements $\Rightarrow$ <5% of χ_{c1} and χ_{c2} yield comes from feed-down from $\psi(2S)$ decays if the feed-down fraction is the same as CDF measured.

- Next step is to measure the fraction of χ_c decays included in prompt J/ψ sample. While photon conversion efficiencies largely cancel in the χ_{c1}/χ_{c2} ratio, they pose a big challenge for this project.

Upsilon Production at Large p_T

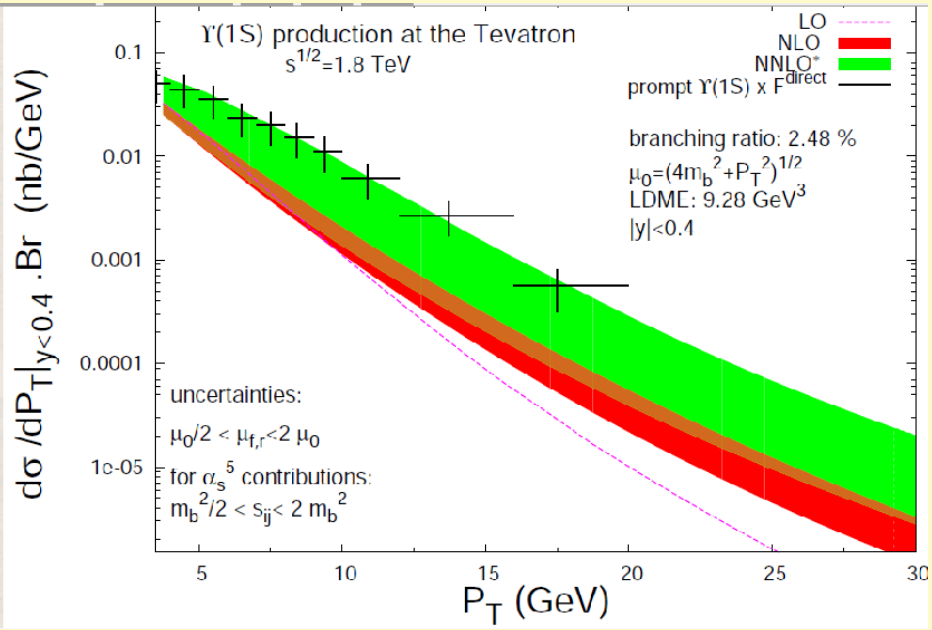


CMS 2010 Results
arXiv: 1303.5900

- Like all hadroproduction, Upsilon production cross section peaks near M/2, then falls roughly exponentially.

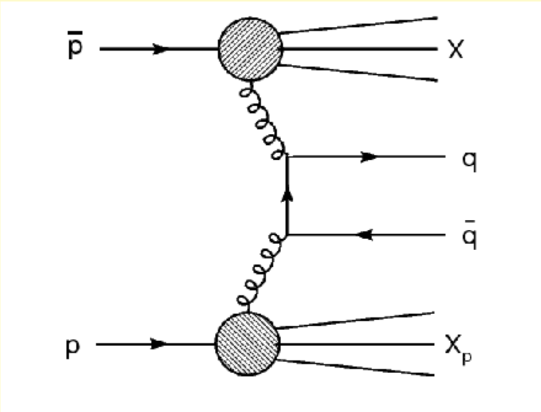
- Are there different production mechanisms mixed through this region?

Models Tell Various Stories



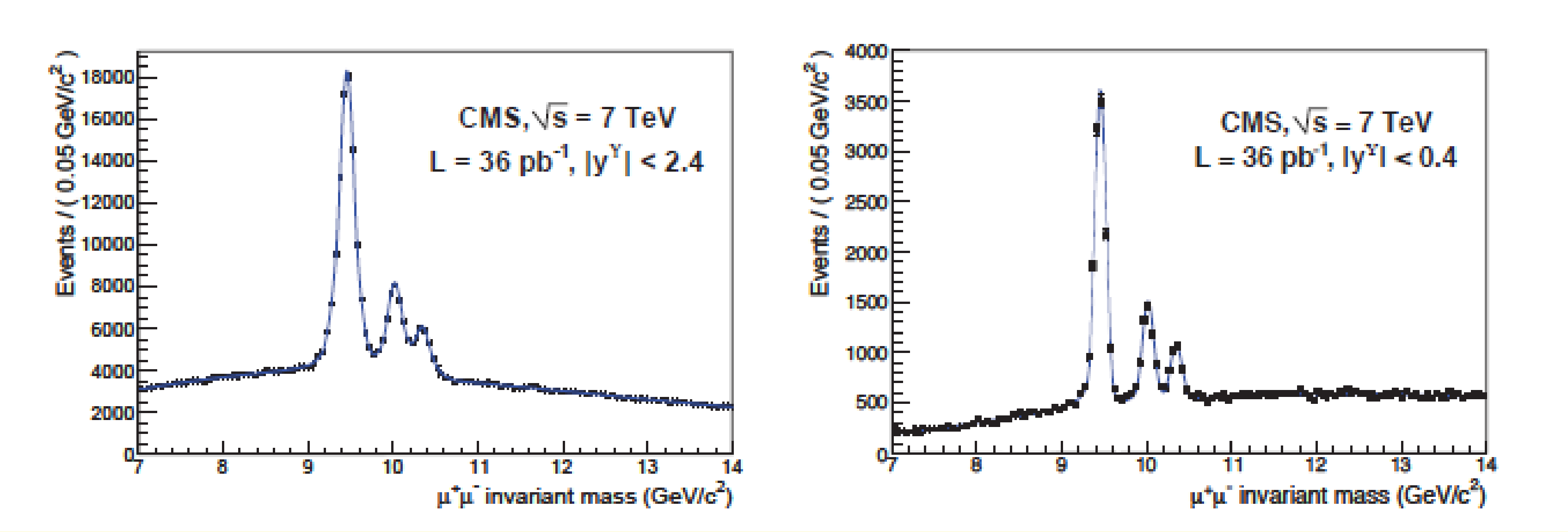
- NRQCD (not shown) with adjustable parameters fits Y(1S) cross section for LHC and Tevatron for $p_T < 30$ GeV/c.

- CSM including NNLO diagrams fits Y(1S) cross section (Artoisenet, et al., Phys. Rev. Lett. 101, 152001 (2008)). Different orders have different p_T dependence.



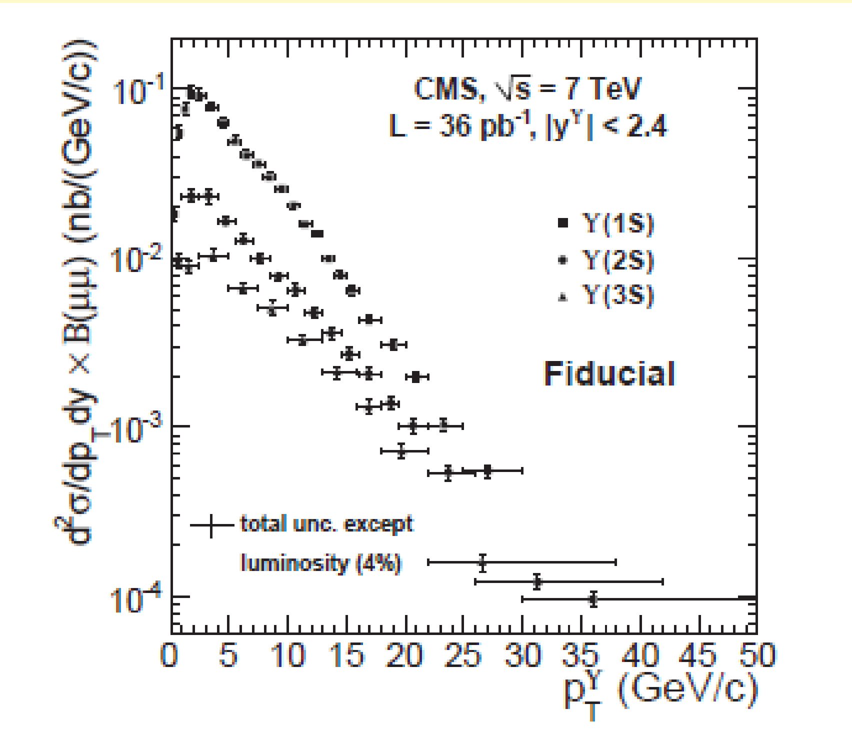
Baranov expects transition to power law behavior at large p_T for k_T factorization model (S. Baranov, Phys. Rev. D **86**, 054015 (2012))

A Look at the CMS 2010 Data



Precision tracking from CMS detector gives good separation of the Y(nS) peaks over wide $|y^{Y}|$ range (0-2.4) with best resolution in central rapidity region

Fiducial Cross Section in p_T



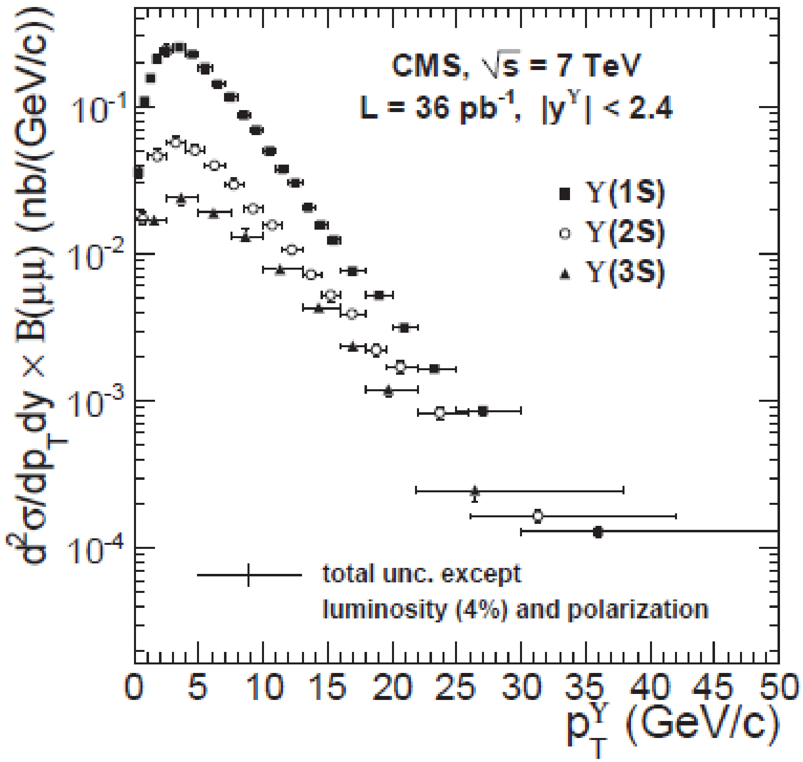
- The fiducial cross section assumes unit acceptance. It displays the efficiency-corrected yields for muons that satisfy the event selection criteria:

$$p_T^\mu > 3.75\,\mathrm{GeV}/c \quad \text{if} \quad |\eta^\mu| < 0.8,$$
$$p_T^\mu > 3.5\,\mathrm{GeV}/c \quad \text{if} \quad 0.8 < |\eta^\mu| < 1.6,$$
$$p_T^\mu > 3.0\,\mathrm{GeV}/c \quad \text{if} \quad 1.6 < |\eta^\mu| < 2.4.$$

Data show that relative production of Υ(nS) states changes rather significantly with p_T , perhaps due to feed-down from higher excitations into the Υ(1S) and less so into the Υ(2S).

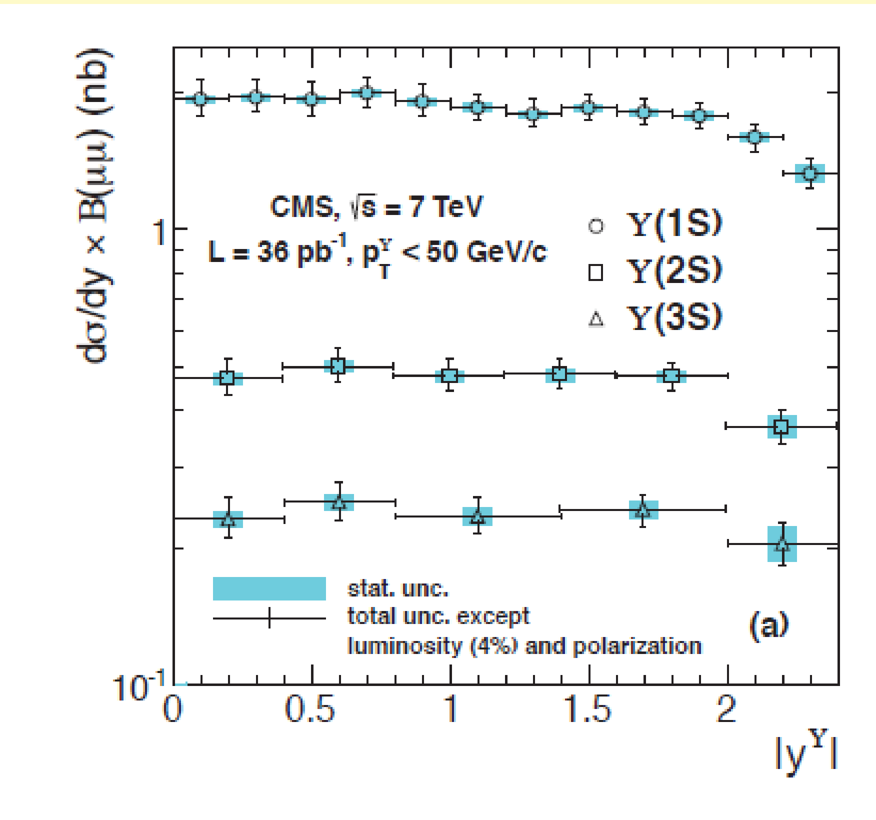
- single muon efficiency $\varepsilon(\eta,p_T)$ determined from data using Tag and Probe method

Acceptance-Corrected $d\sigma/dp_T$



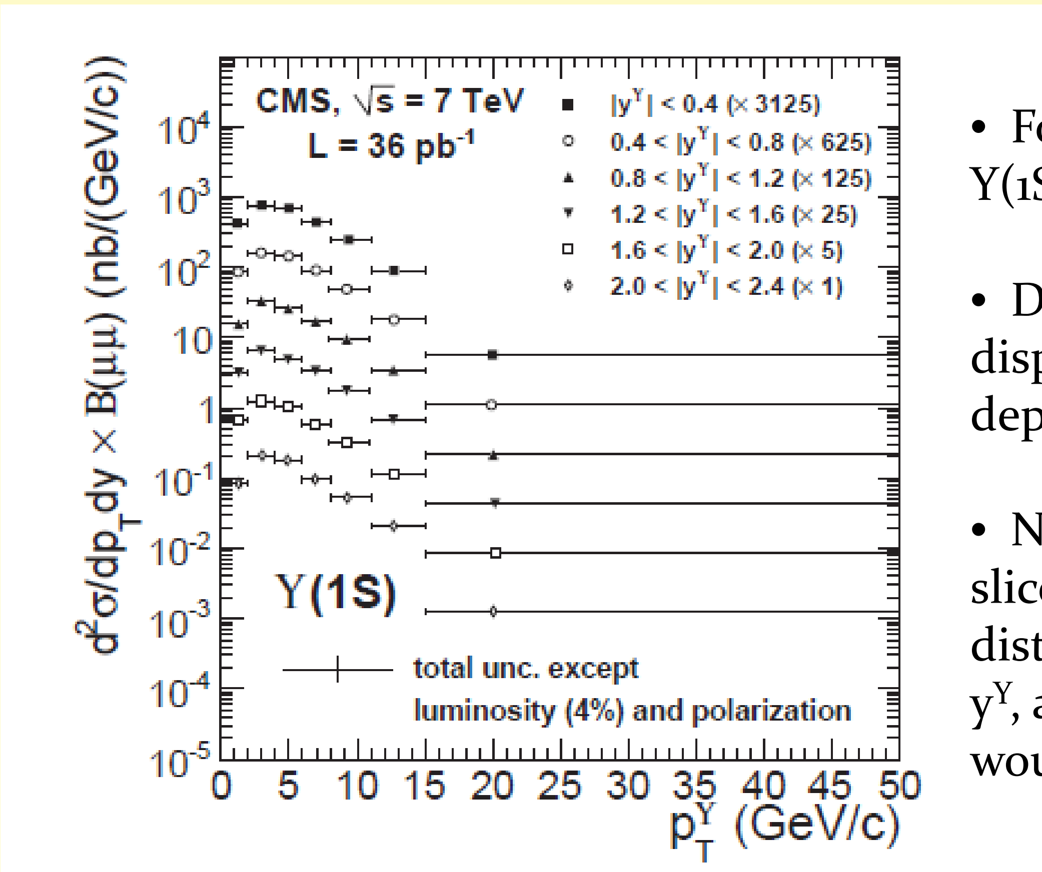
- Evidence from CMS polarization measurements is that polarization is small.
- Correct fiducial cross sections for acceptance assuming *zero* polarization
- All three states peak at $p_T \sim 4$ GeV/c and still show different slopes as p_T increases.

What About Rapidity Dependence?



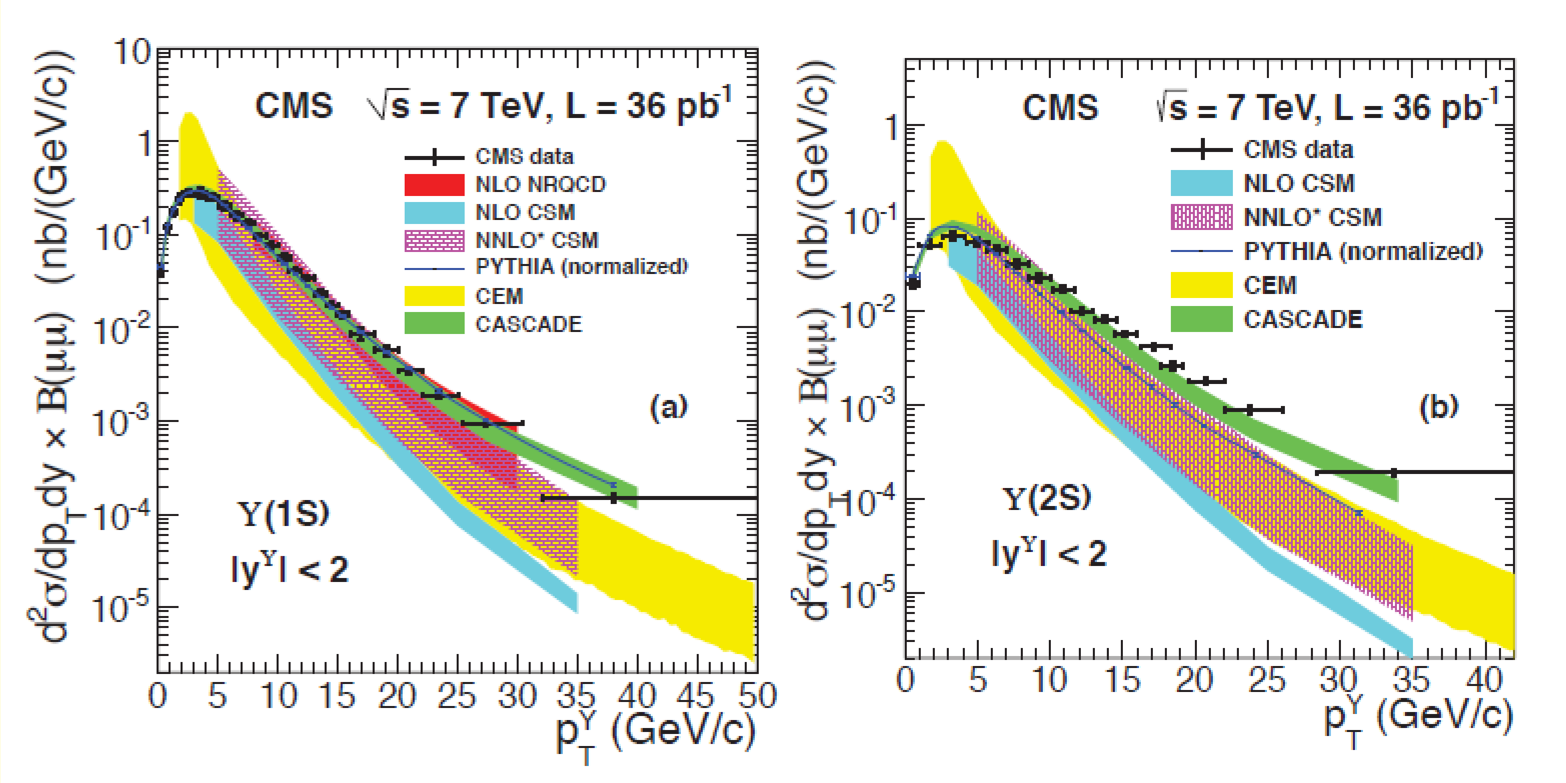
- For the acceptance-corrected data, integrated over pT, there is very little $|y^{\Upsilon}|$ dependence in any of the Υ(nS) data until $|y^{\Upsilon}| > 1.6$.
- At higher $|y^{\Upsilon}|$ the cross section falls, as reported by LHCb.
- Are the y^{Υ} and p_T variations independent?

Υ(1S) dσ/dp$_T$ in |y^Υ| Slices



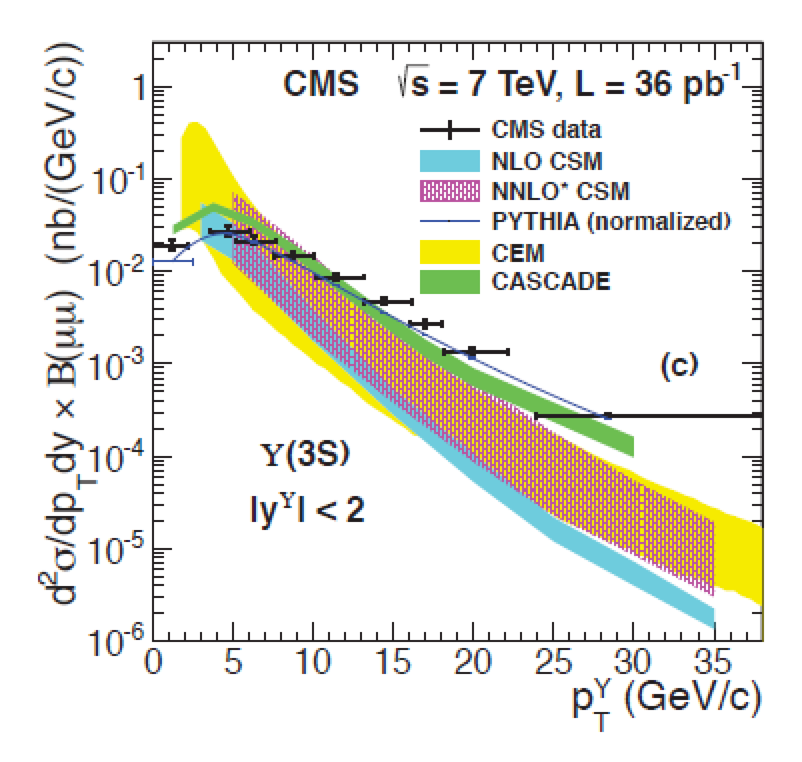
- Focus on highest-statistics sample: Υ(1S)
- Divide data into Δ|y^Υ| bins of 0.4 and display the acceptance-corrected p$_T$ dependence.
- Note scale factors used to offset each slice. The evidence is that the p$_T$ distributions are truly independent of y^Υ, as a factorized production model would expect.

Comparison to Models: Υ(1S), Υ(2S)



Comparing the unpolarized differential cross section data to model predictions, one sees that most of the models match the Υ(1S) dependence on p_T, but there is some tension for the Υ(2S).

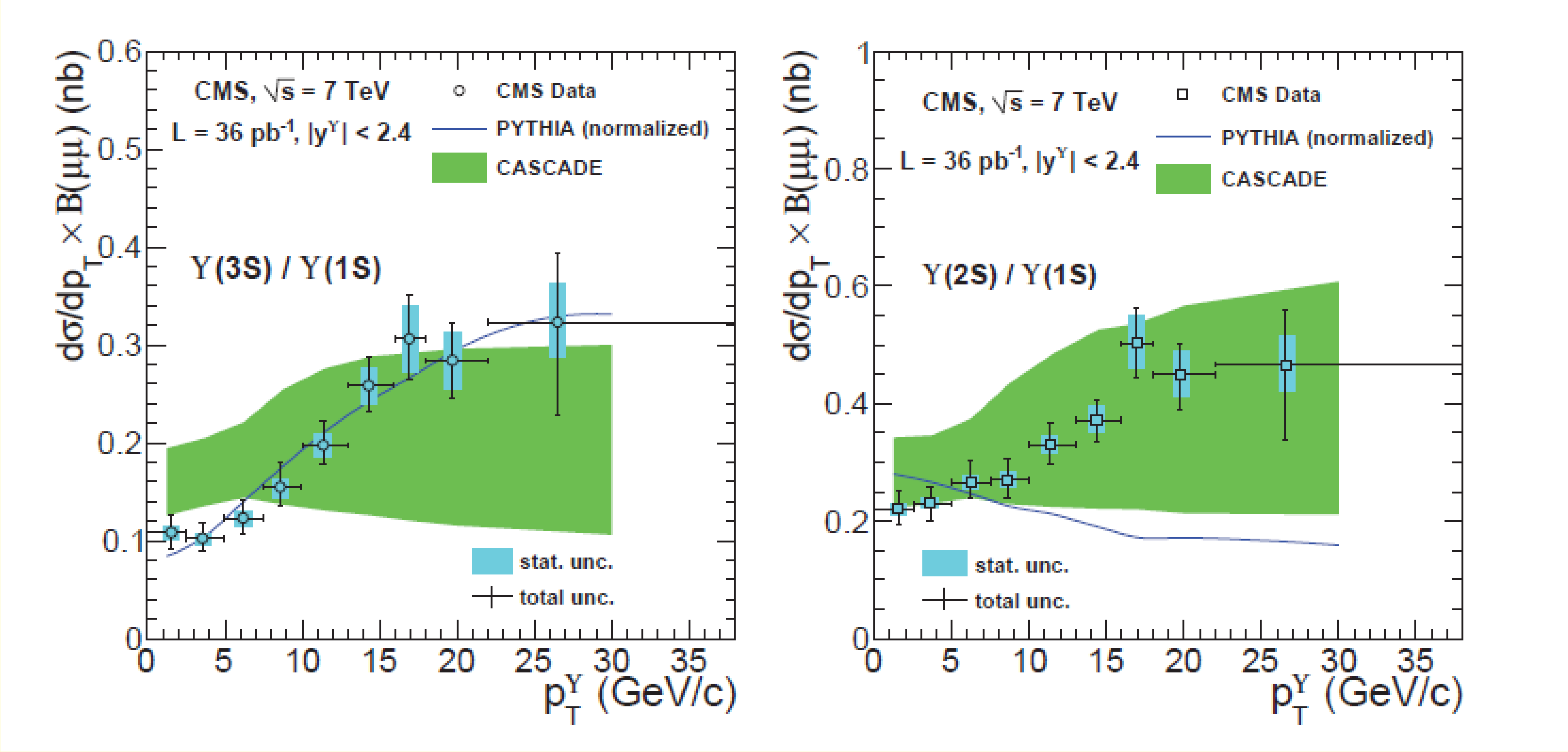
Is the Υ(3S) Different?



Even though we now know there are $\chi_b(3P)$ states that lie above the Υ(3S), the feed-down into the Υ(3S) is expected to be smaller than that to the Υ(1S) or Υ(2S).

These data do not suggest that the models do better for Υ(3S) than for Υ(2S) at large p_T.

What Do Production Ratios Say?



Ratios for Y(3S)/Y(1S) and Y(2S)/Y(1S) rise through the 5-20 GeV region. Then what happens? The data are suggestive but not definitive. There may be a break – or not. More data at higher p_T are needed to say.

Bottomonium Summary

- Detailed measurements of the p_T and y^{Υ} behavior of Υ(nS) production at 7 TeV show reasonable agreement with the popular models, e.g., CSM, NRQCD, and k_T-factorization.

- The production ratios of the acceptance-corrected $d\sigma/dp_T$ for Υ(2S)/Υ(1S) and Υ(3S)/Υ(1S) increase in the p_T interval 5 -20 GeV.

- At the largest p_T points for these data there is a suggestion of saturation of these ratios. Analysis of the 2011 data now underway at CMS will speak to the question of large p_T behavior.