Production of P-wave quarkonia in pp collisions at 7 and 8 TeV at CMS

QWG 2014, CERN, November 2014

Valentin Knünz* *(HEPHY Vienna)*

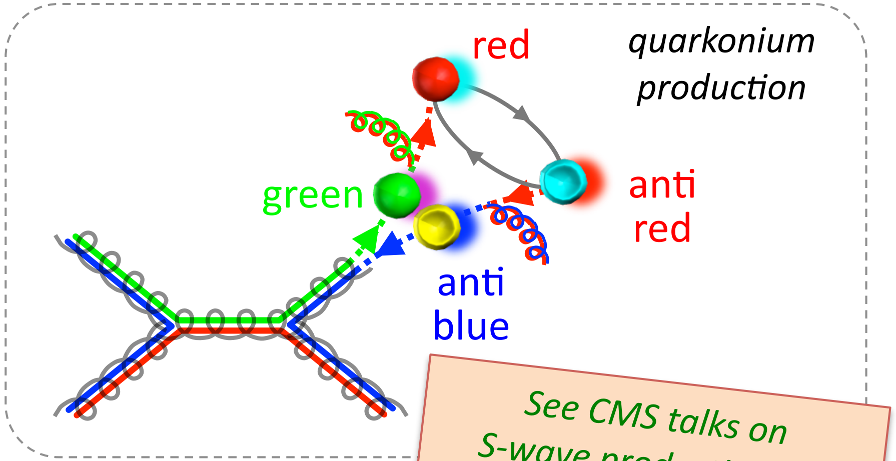
on behalf of the CMS collaboration

* Supported by FWF grant P 24167-N16

The big picture in a nutshell

Quarkonium production is an ideal probe to study hadron formation, part of the non-perturbative QCD sector → how do quarks combine into a bound state?

Properties of QCD can be probed through several quarkonium production measurements, including
→ Production cross sections
→ Polarizations



See CMS talks on S-wave production by:

Chris Ferraioli
Ilse Krätschmer

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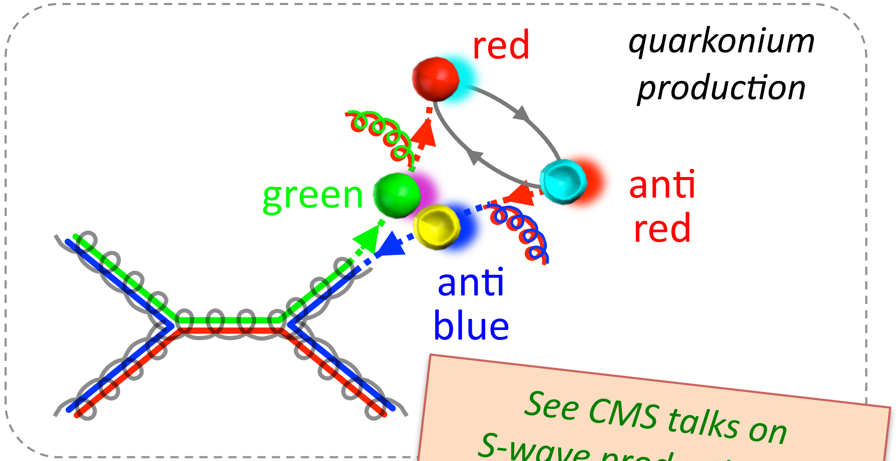
P-wave states should help understanding the relative importance of the singlet and several octet terms



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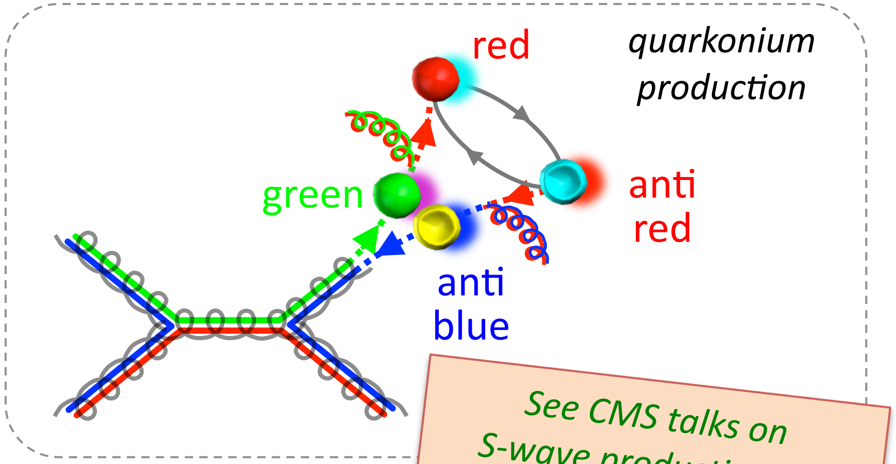
Puzzling χ_{c2} / χ_{c1} cross section ratio

CDF measures ≈ 0.75

Naive expectation (spin counting): 5/3

CMS is ideally suited to study P-wave quarkonia through their radiative decays to S-wave quarkonia



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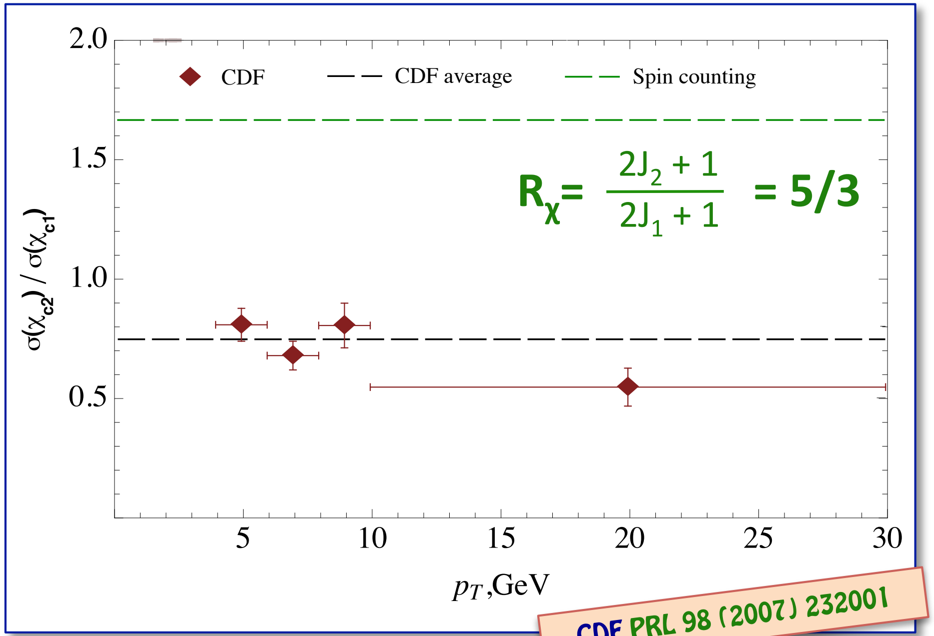
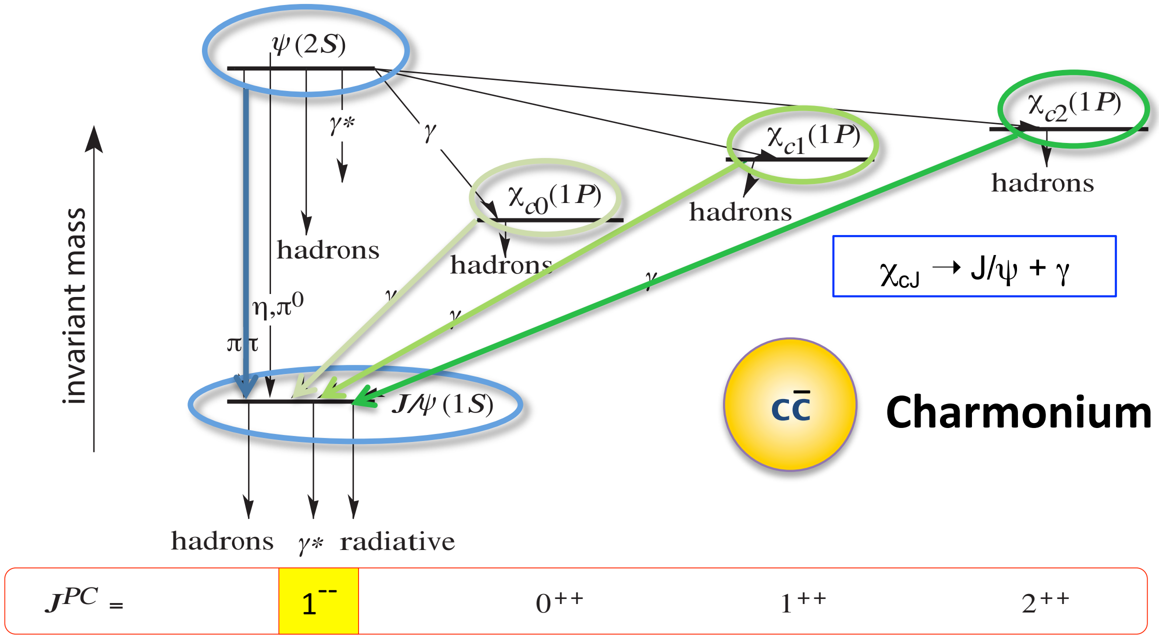


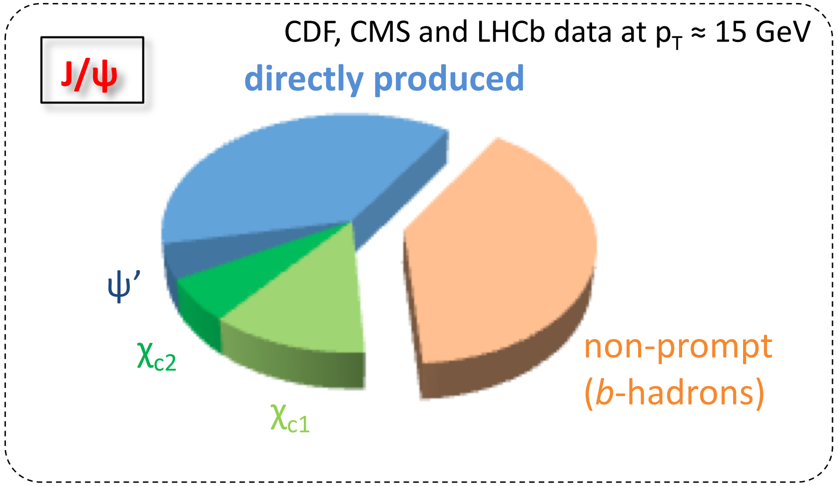
$$R_\chi = \frac{2J_2 + 1}{2J_1 + 1} = 5/3$$

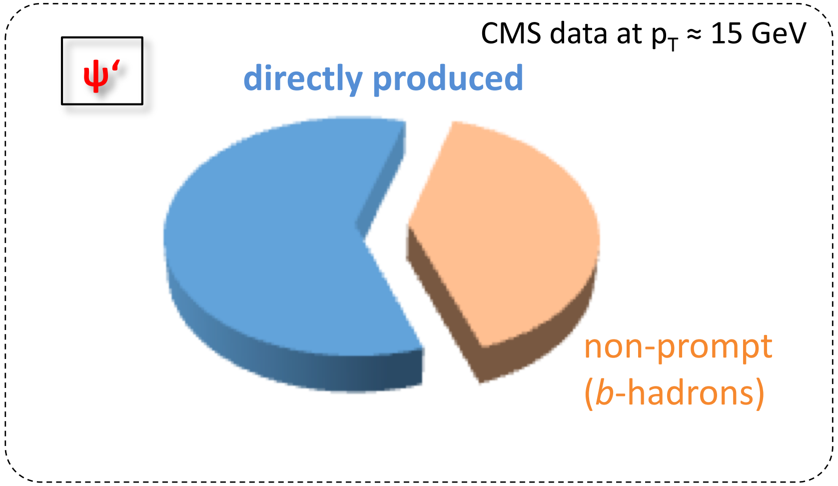
CDF PRL 98 (2007) 232001

Feed-down: Charmonium system



- **Prompt J/ψ production** consists of direct production and P-wave + ψ(2S) feed-down
- **Non-prompt** decays can be separated experimentally
- **Prompt ψ(2S)** gives access to direct production studies





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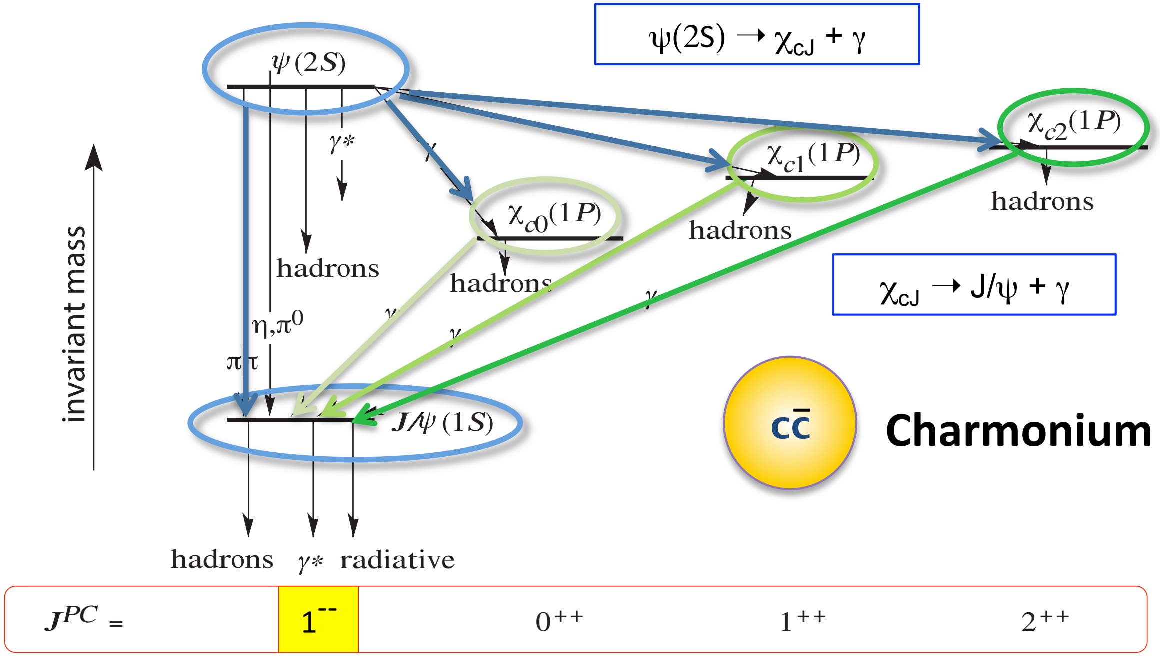

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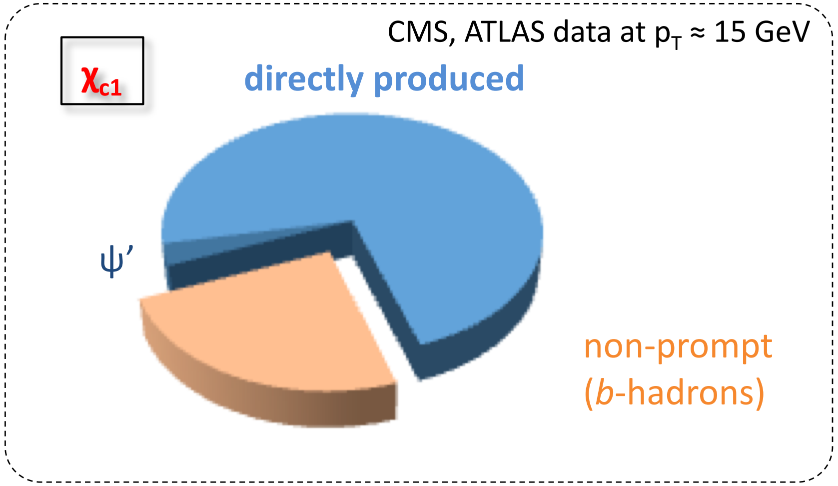
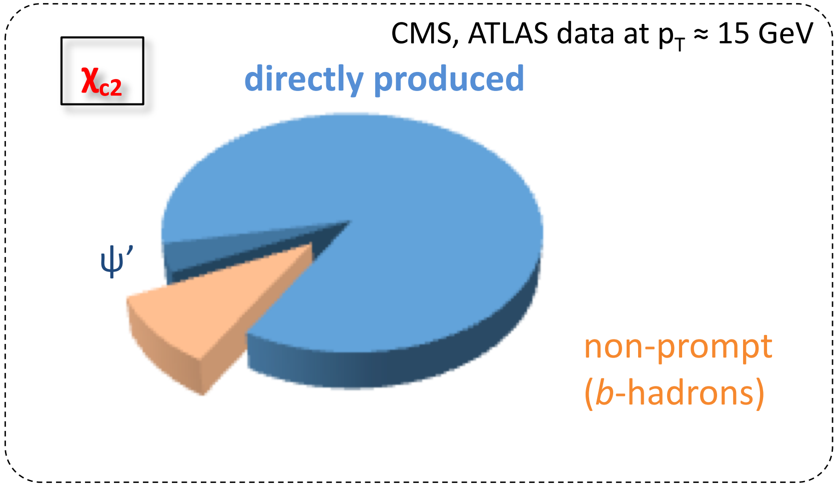
- Non-prompt decays can be separated experimentally
- Prompt ψ(2S) gives access to direct production studies
- Prompt χ_{cJ} states should be almost free of feed-down


CMS, ATLAS data at $p_T \approx 15$ GeV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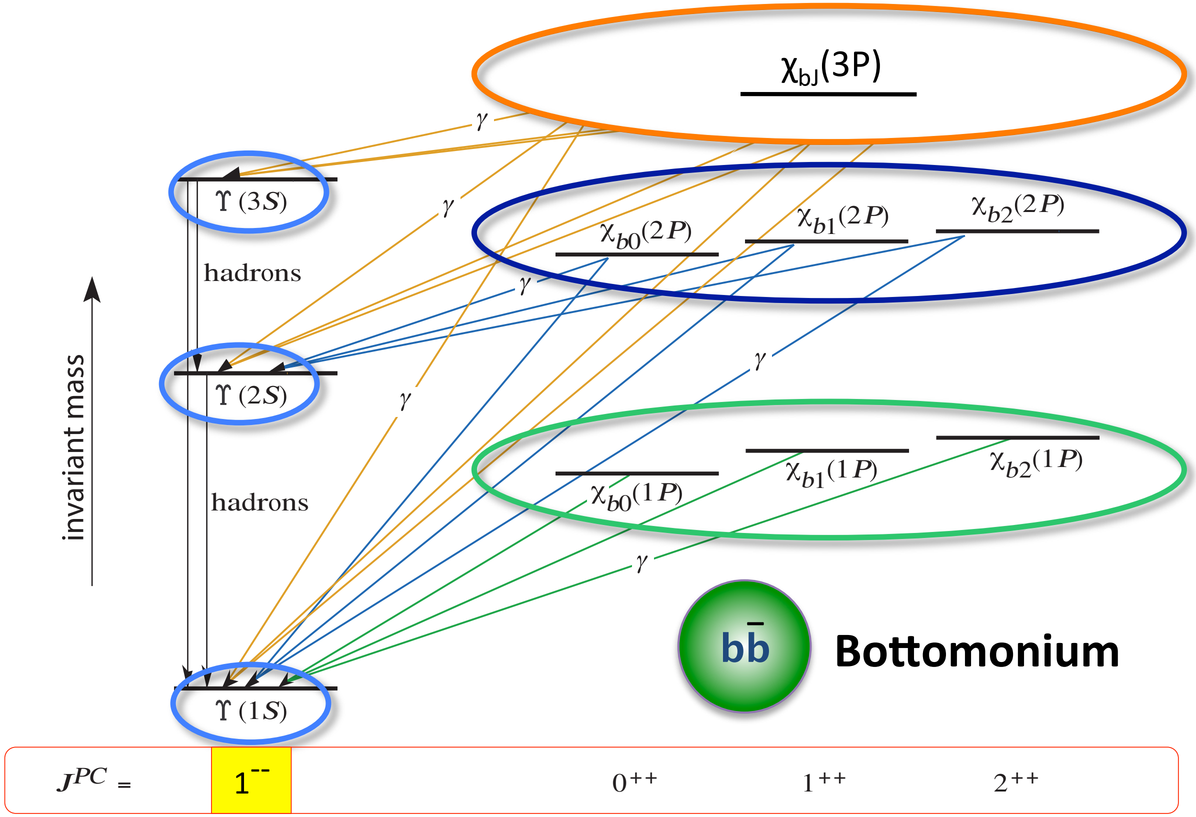
Feed-down: Bottomonium system

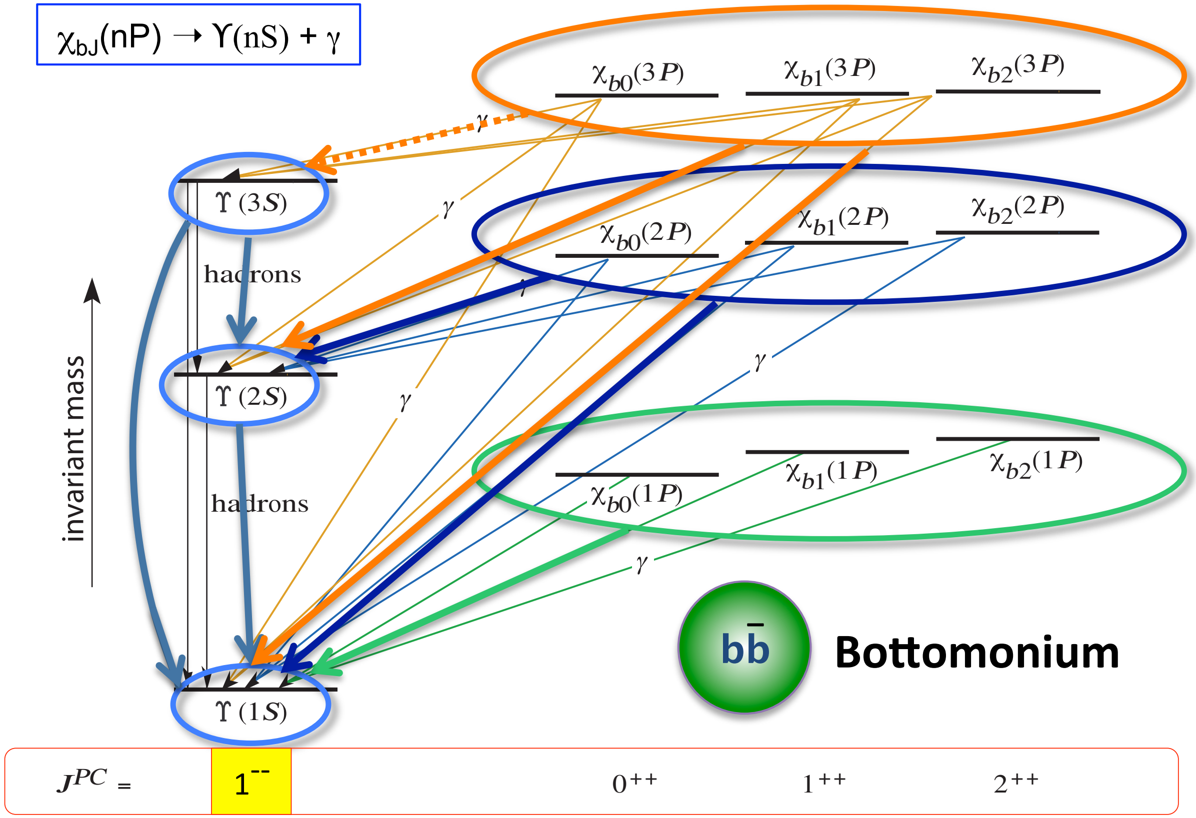


Bottomonium P-wave states:

- $\chi_{bJ}(3P)$ triplet structure not yet established

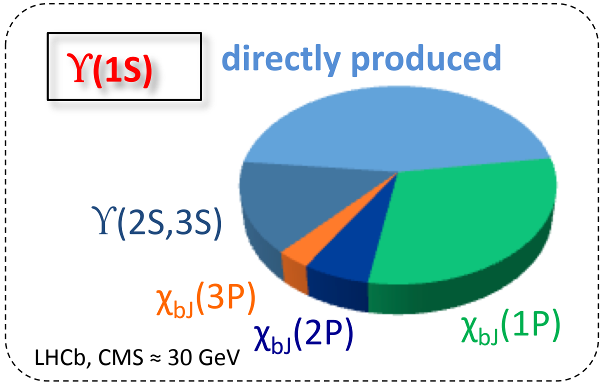
Feed-down: Bottomonium system

$\chi_{bJ}(nP) \rightarrow \Upsilon(nS) + \gamma$

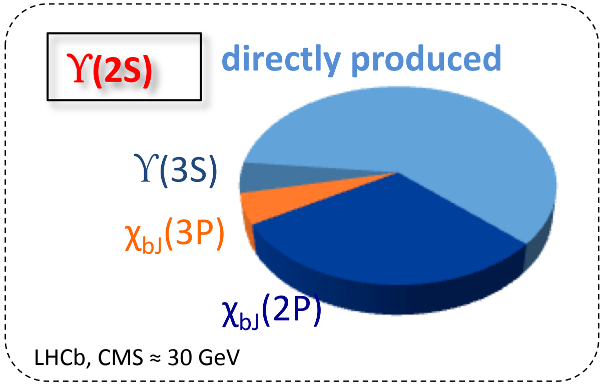


Bottomonium P-wave states:

- $\chi_{bJ}(3P)$ triplet structure not yet established
- More states contributing to feed-down structure



LHCb, CMS ≈ 30 GeV



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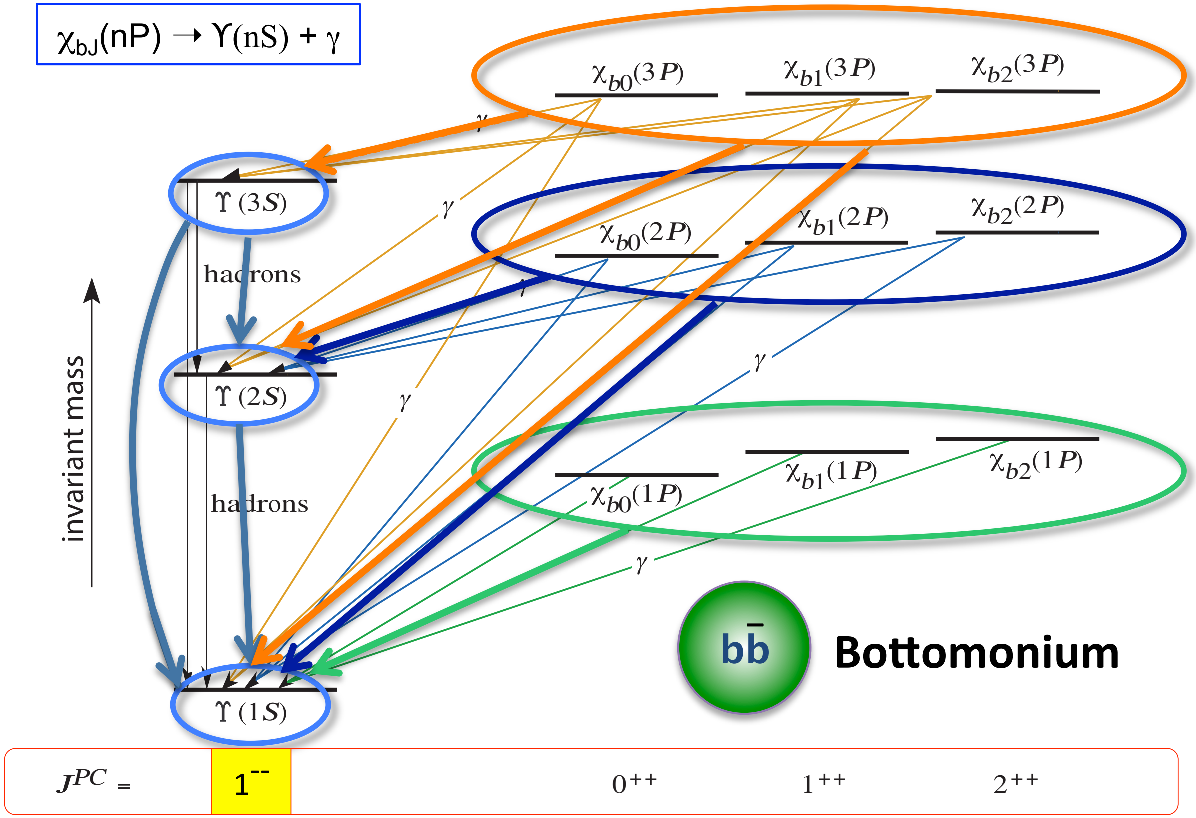

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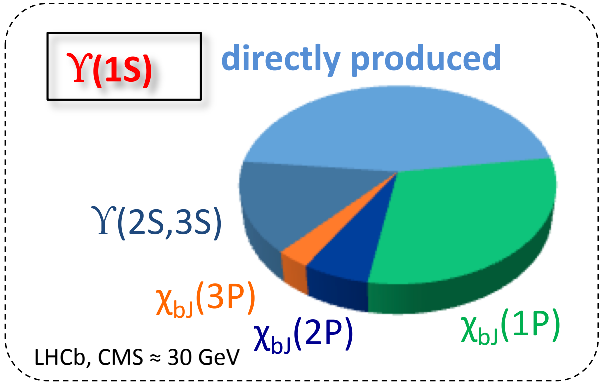
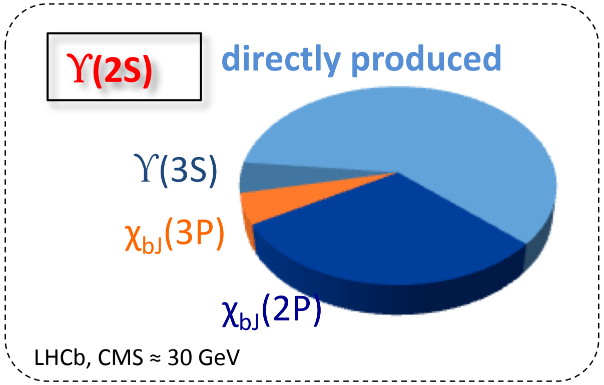
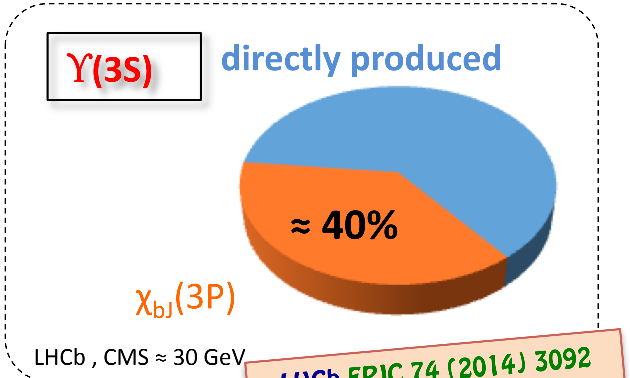
- $\Upsilon(3S)$ affected by large $\chi_{bJ}(3P)$ feed-down fraction







LHCb EPJC 74 (2014) 3092

The NRQCD factorization approach

NRQCD is an effective field theory that factorizes quarkonium production in two steps:

1) production of the initial quark-antiquark pair (perturbative QCD)
2) hadronization of the quark pair into a bound quarkonium state (non-perturbative QCD)

$$\sigma(\mathcal{Q}) = \sum_n \mathcal{S}[Q\bar{Q}(n)] \cdot \mathcal{O}^{\mathcal{Q}}(n)$$

$n = {}^{2S+1}L_J^{[C]}$, C = 1,8

Quantum numbers of the heavy quark pair
S, L, J = spin, orbital and total ang. momentum

Short-distance coefficients (SDCs)

- Cross section of partonic processes to form $Q\bar{Q}$ in state $n \otimes$ PDF
- Process-dependent functions of kinematics
- Can be calculated perturbatively (expansion in α_s)

Long-distance matrix elements (LDMEs)

- Probability of $Q\bar{Q}$ in state n to form quarkonium state $\mathcal{Q}$
- Universal constants (independent of kinematics)
- Determined from fits to experimental data

The LDMEs should follow a hierarchy in powers of *v*, the relative velocity of the quark pair in the quarkonium system → Non-relativistic approximation (v^2~0.3 for the ψ and ~0.1 for the ϒ):
→ Truncation of v-expansion, NRQCD includes only few terms (intermediate states)

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S-wave states:
CS term $^3S_1^{[1]}$ (same n as $\mathcal{Q}$)
CO terms: $^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_J^{[8]}$

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Faccioli et al.
PLB 736 (2014) 98

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CO terms: ${}^3S_1^{[8]}$ + ${}^1S_0^{[8]}$ + ${}^3P_J^{[8]}$ + ${}^1P_1^{[8]}$
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Faccioli et al. PLB 736 (2014) 98

Likhoded et al. PRD 90 (2014) 074021

The NRQCD factorization approach: P-wave production

Open questions in P-wave production:

1. What is the role of the color singlet component $^3P_J^{[1]}$, is it negligible as in S-wave production?

2. Is the $^3S_1^{[8]}$ color octet component dominant, as predicted by v-scaling? Or is it suppressed, as in S-wave production? Do the $^1S_0^{[8]}$, $^3P_J^{[8]}$ or $^1P_1^{[8]}$ terms play a role?

Faccioli et al.
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3. Are all χ states produced similarly?

χ_c vs. χ_b → χ_0 vs. χ_1 vs. χ_2 → $\chi_b(1P)$ vs. $\chi_b(2P)$ vs. $\chi_b(3P)$

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Experimental effort to answer these questions:

- Measurements of χ cross section ratios
  - → Theoretical uncertainties cancel
- Measurements of “absolute” χ cross sections
  - → Relative importance of CO states
- Measurement of χ polarization: ultimate discriminant for $^3S_1^{[8]}$ vs. $^1S_0^{[8]}$

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Faccioli et al.
PLB 736 (2014) 98

χ_{c1}: λ_ϑ=+1/5

χ_{c2}: λ_ϑ=+21/73

λ_ϑ=0

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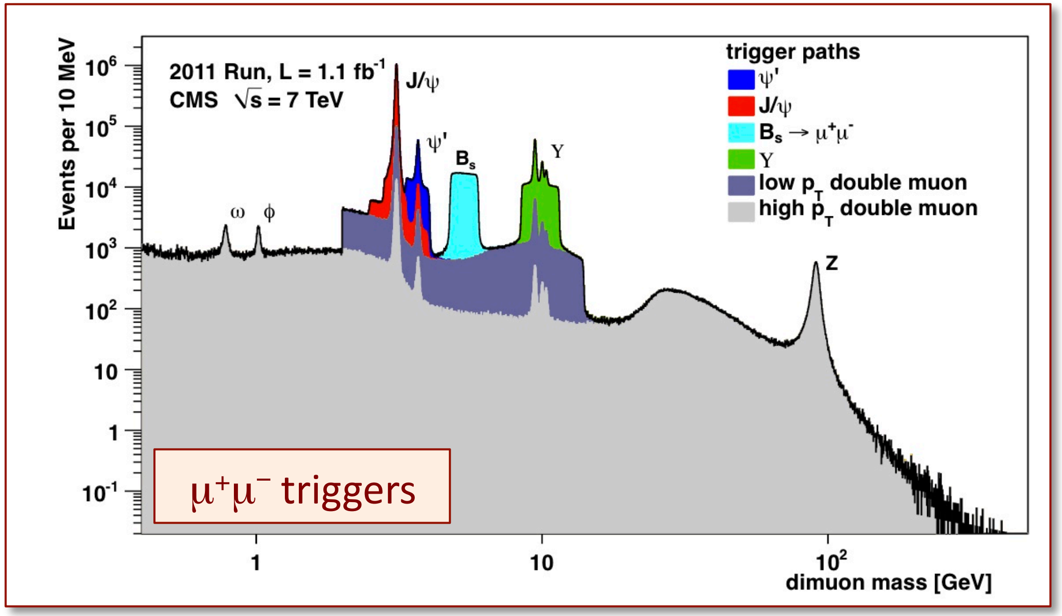
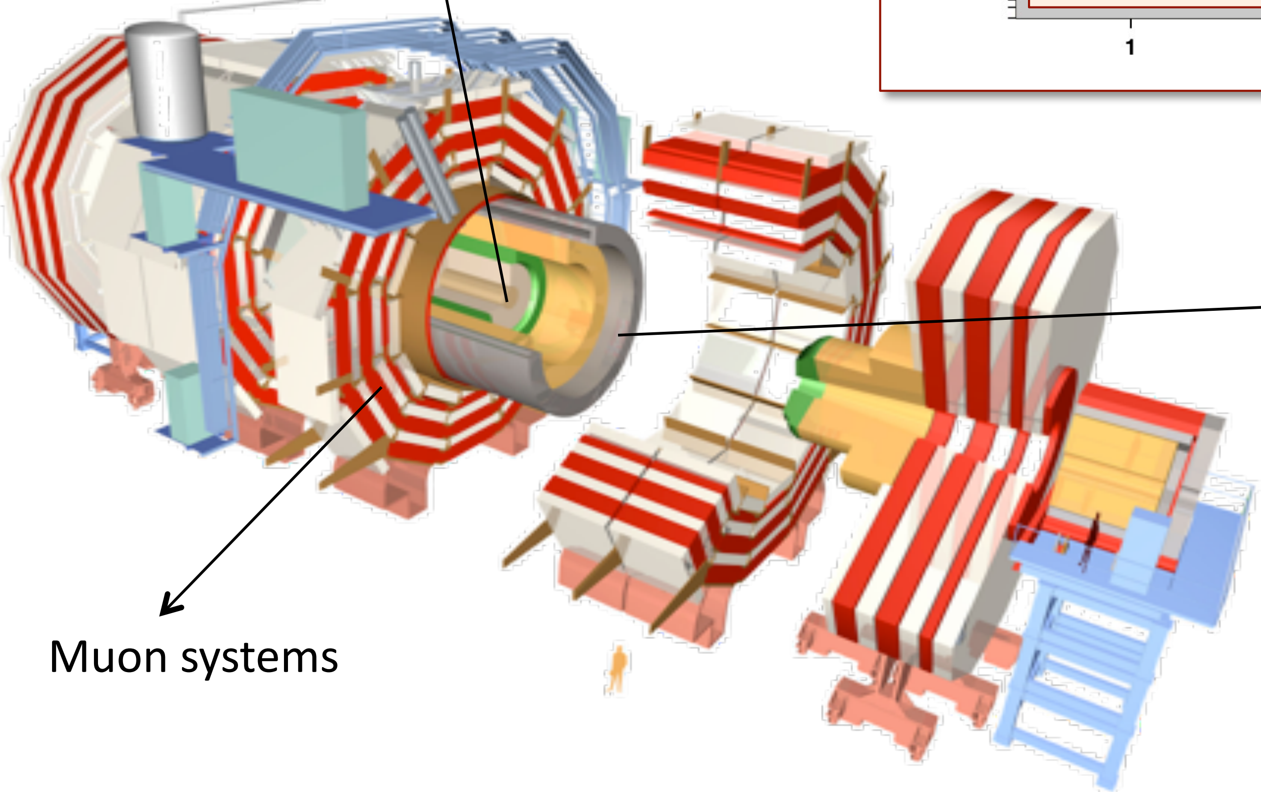
CMS: quarkonium detection performance





Inner tracker

3.8 T magnet

Muon systems

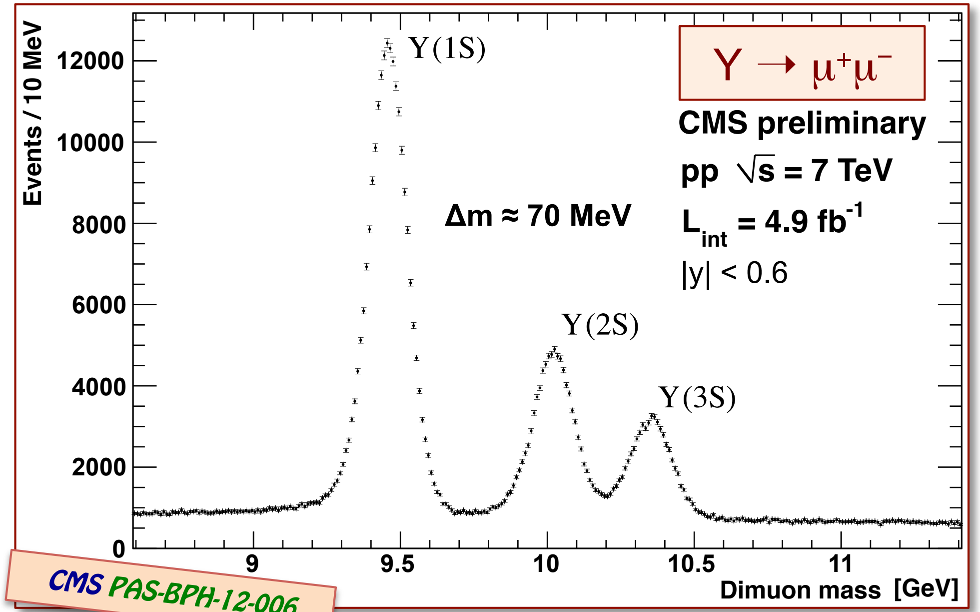
Flexible trigger

Large silicon tracker

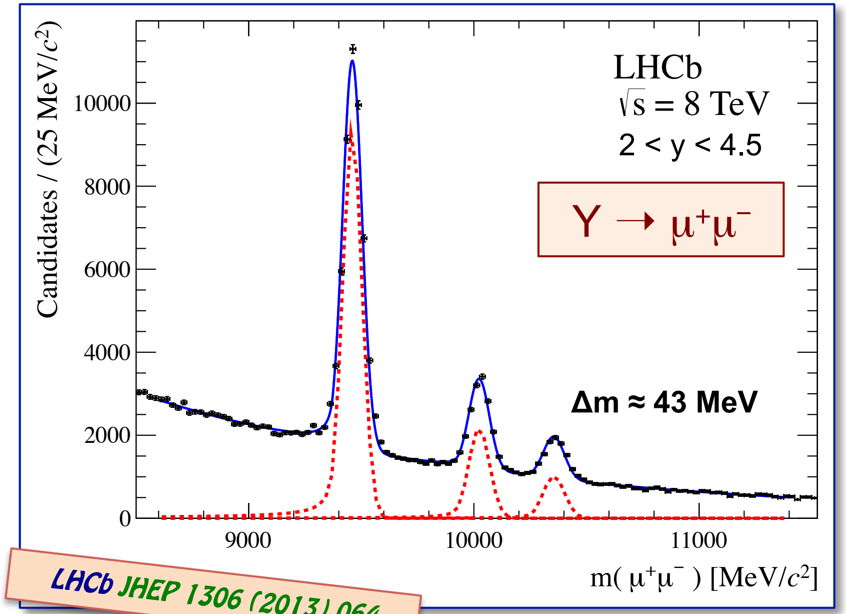
Strong magnetic field

Broad acceptance

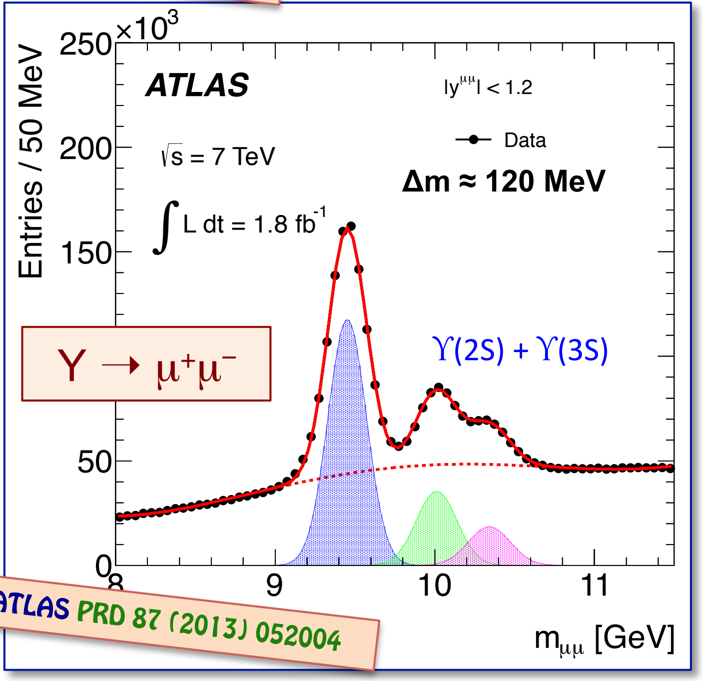
CMS: quarkonium detection performance vs. ATLAS/LHCb



CMS PAS-BPH-12-006



LHCb JHEP 1306 (2013) 064



ATLAS PRD 87 (2013) 052004

Quarkonium reconstruction performance in dimuon decay:

Excellent dimuon mass resolution

High p_T coverage

Excellent decay length resolution

S-wave → $\mu^+\mu^-$

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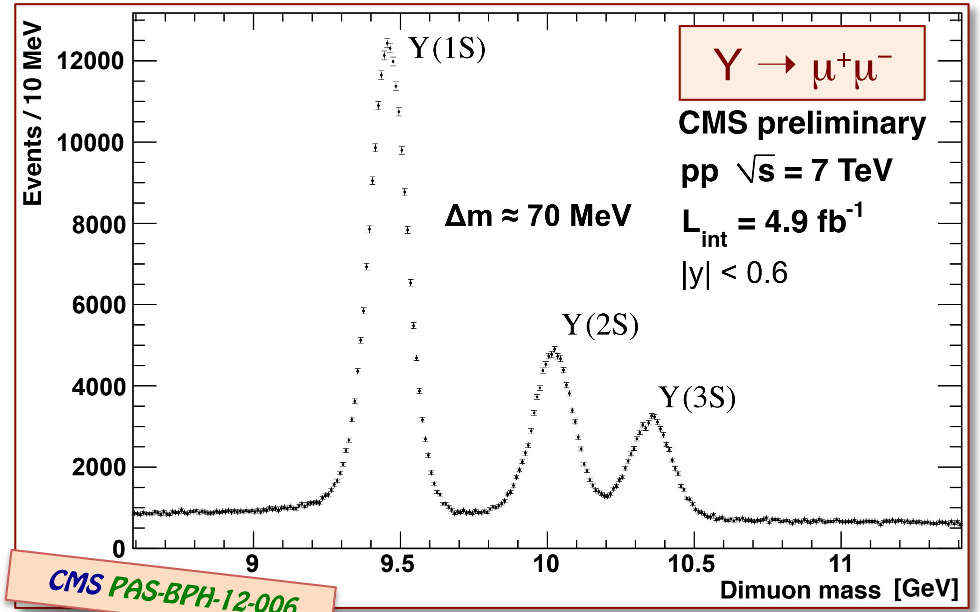


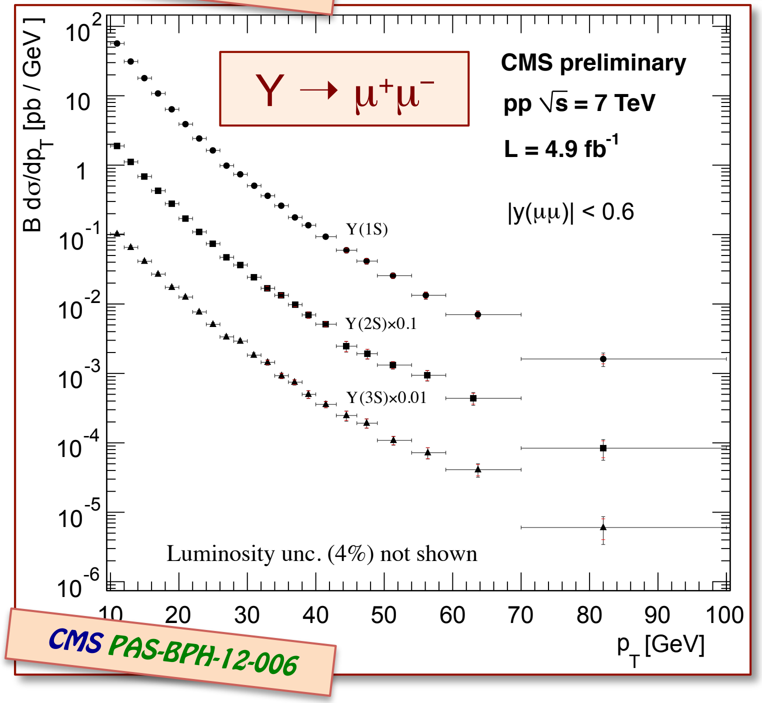
CMS PAS-BPH-12-006

High-p_T reach, Υ(nS) cross sections:

CMS: p_T up to 85 GeV

ATLAS: p_T up to 65 GeV

LHCb: p_T up to 14 GeV



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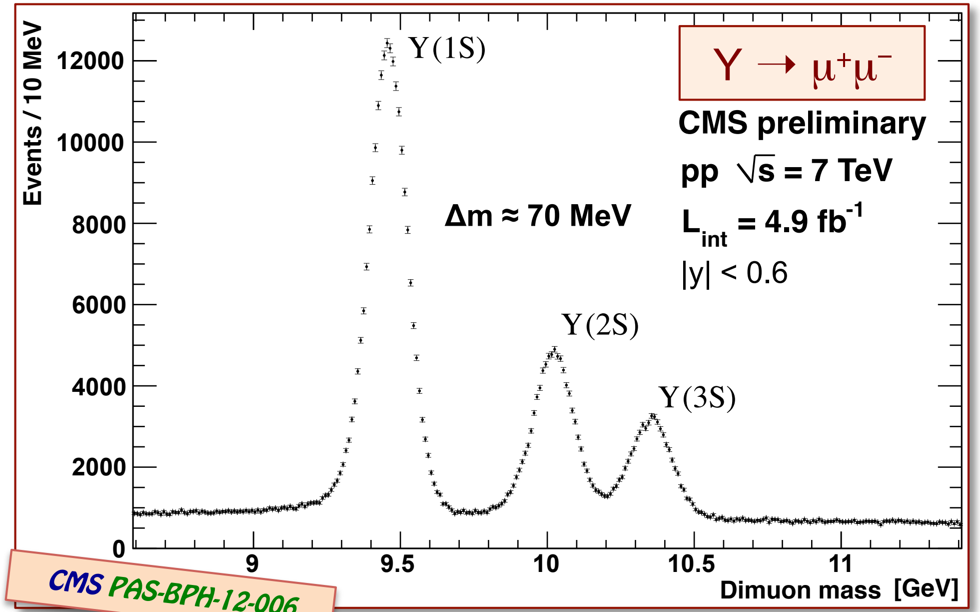

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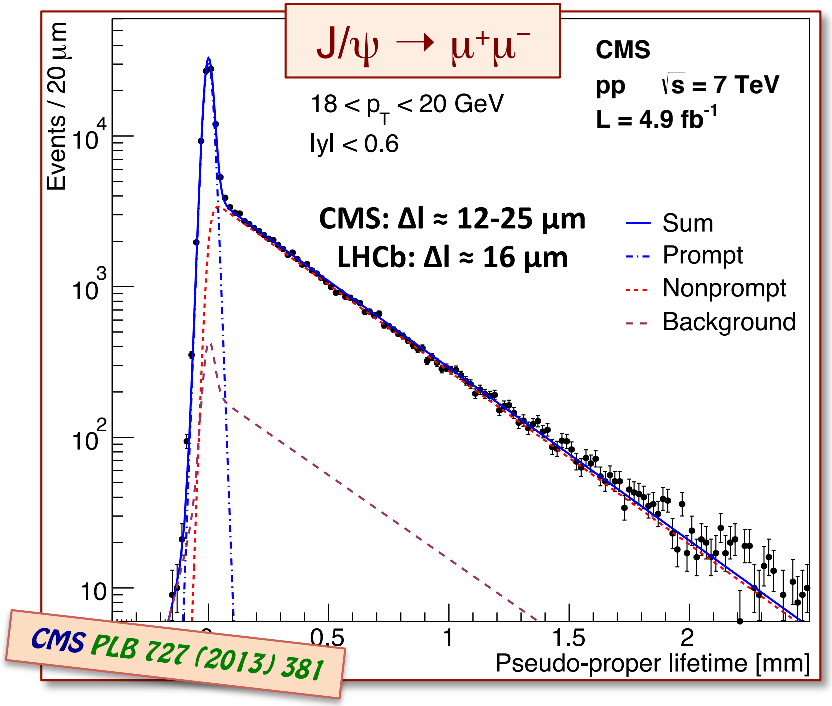
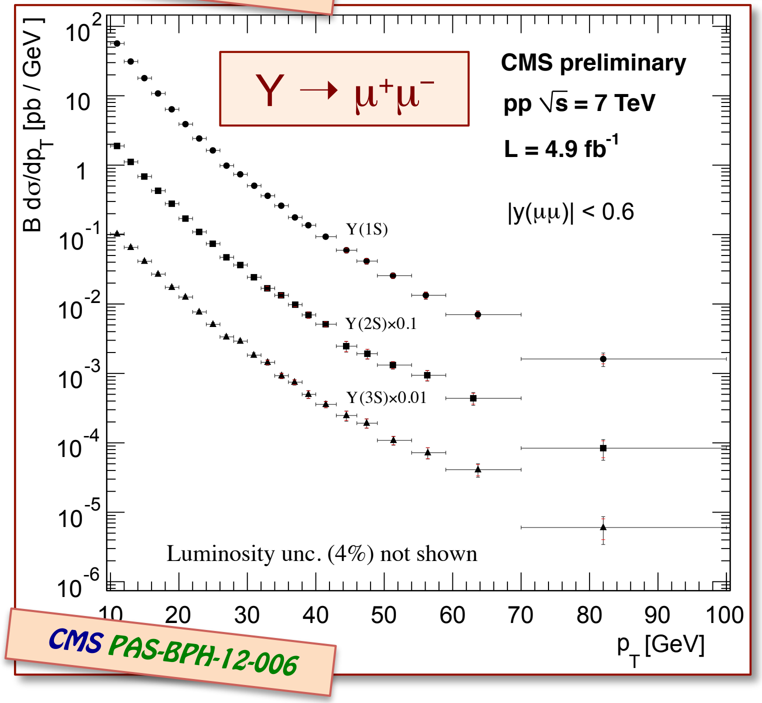


CMS PLB 727 (2013) 381



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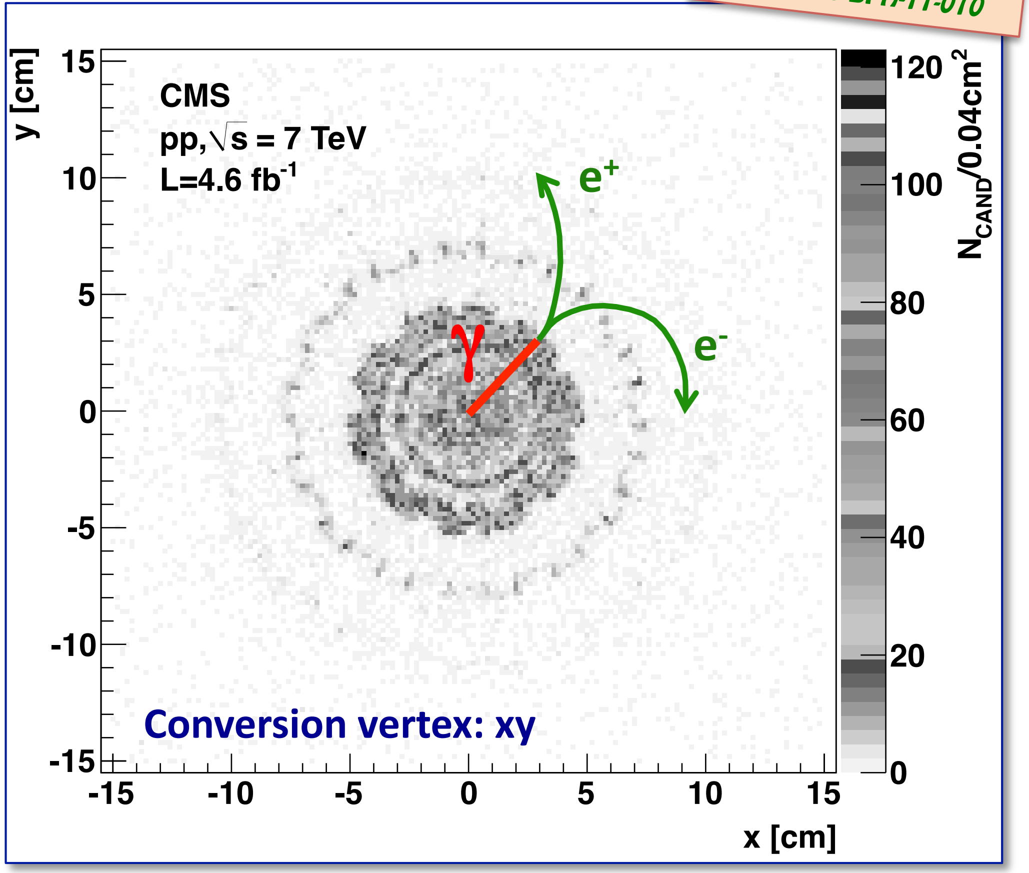
P-wave quarkonia are detected via their radiative decays

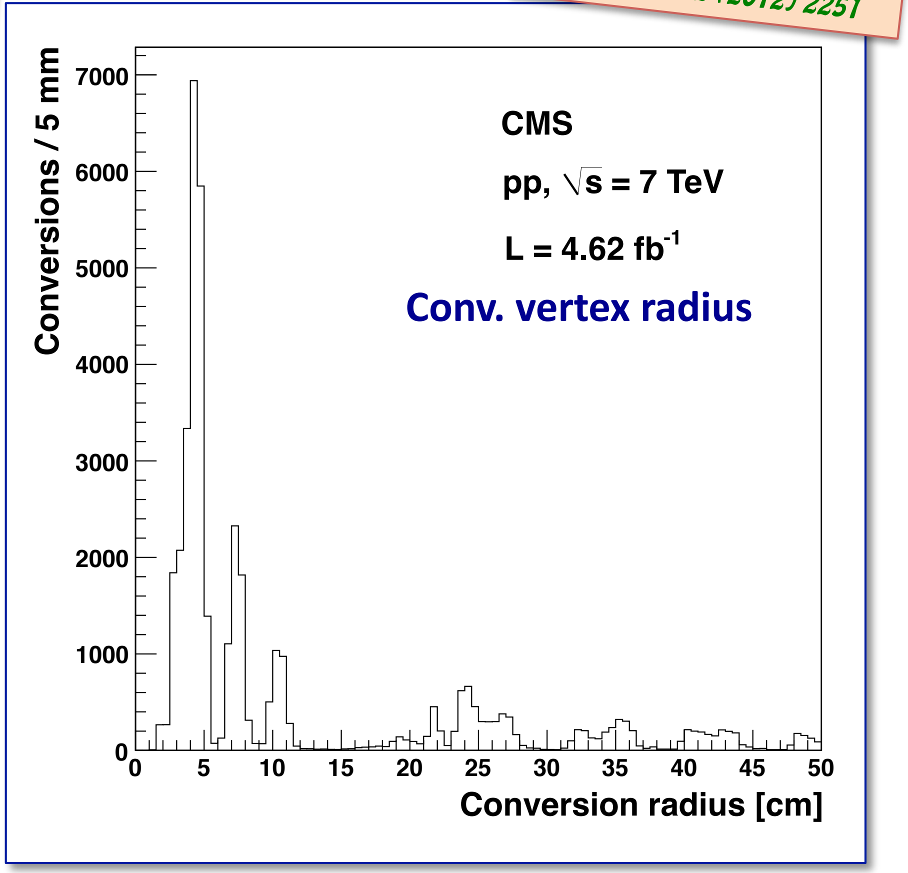
$$\chi_{cJ} \rightarrow J/\psi + \gamma \quad \text{and} \quad \chi_{bJ}(nP) \rightarrow \Upsilon(mS) + \gamma$$

Detection via photon conversion ($\gamma \rightarrow ee$) within the tracker volume (from a $\mu\mu$ triggered sample)
→ Excellent χ mass (≈6 MeV, $|y^{\mu\mu}|<1$ or $|\eta^{\gamma}|<1$) and conversion vertex resolutions

CMS PAS-BPH-11-010



CMS EPJC 72 (2012) 2251



CMS: P-wave quarkonium detection

P-wave quarkonia are detected via their radiative decays

$\chi_{cJ} \rightarrow J/\psi + \gamma$ and $\chi_{bJ}(nP) \rightarrow \Upsilon(mS) + \gamma$

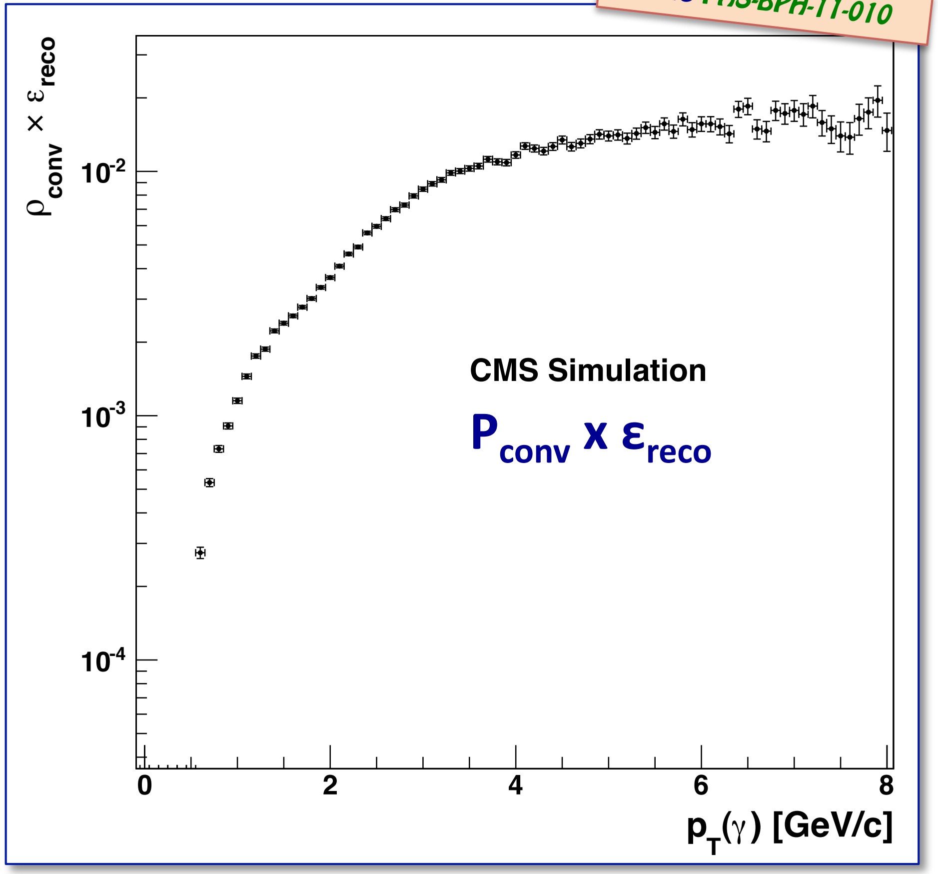
Detection via photon conversion ($\gamma \rightarrow ee$) within the tracker volume (from a $\mu\mu$ triggered sample)
→ Excellent χ mass (≈6 MeV, $|y^{\mu\mu}|<1$ or $|\eta^{\gamma}|<1$) and conversion vertex resolutions

Conversion probability $P_{conv} \approx 30\%$

Low detection efficiency ($\varepsilon_{reco} \approx 5\%$ in plateau) limits reach in p_T for P-wave states

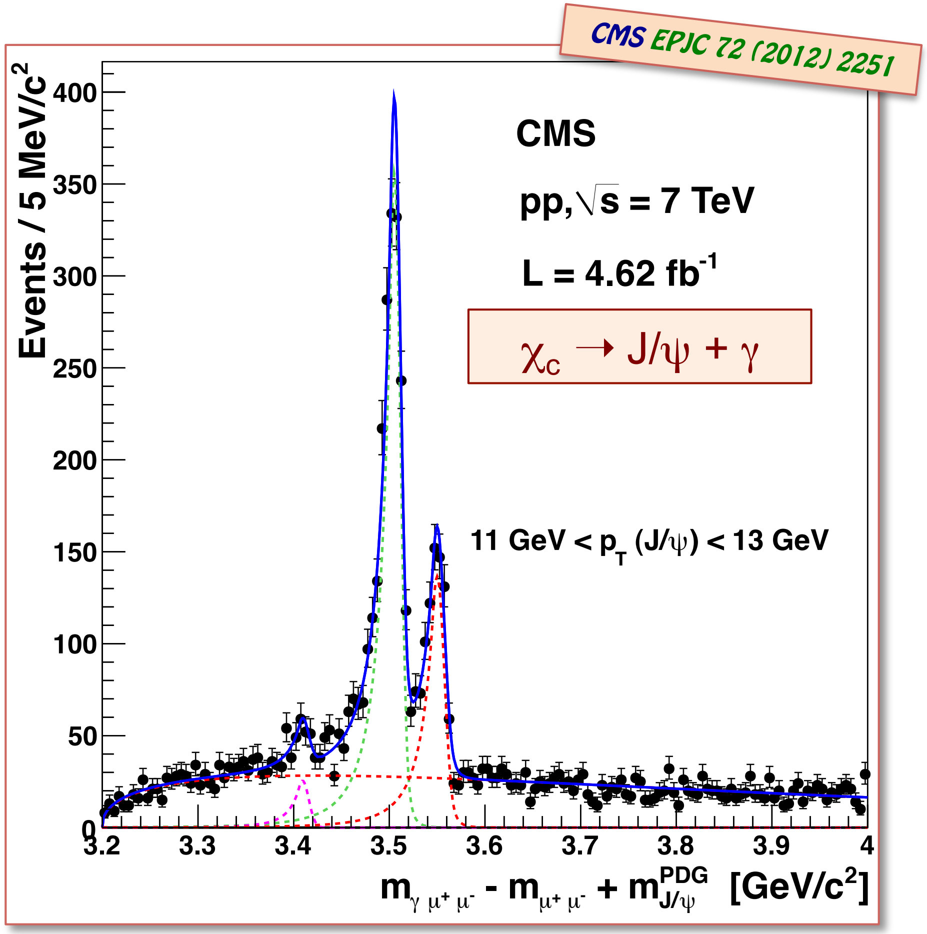
The photon (and electron) momentum is very low

The photon conversion efficiency cancels in cross section ratios
→ CMS currently presents ratios of cross sections



CMS PAS-BPH-11-010

CMS: P-wave quarkonium detection


CMS EPJC 72 (2012) 2251

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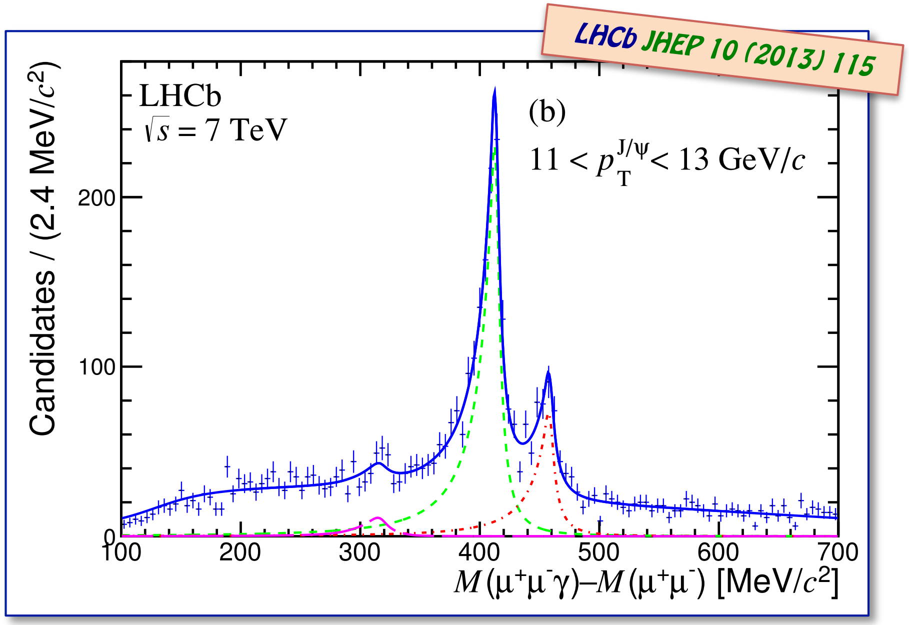
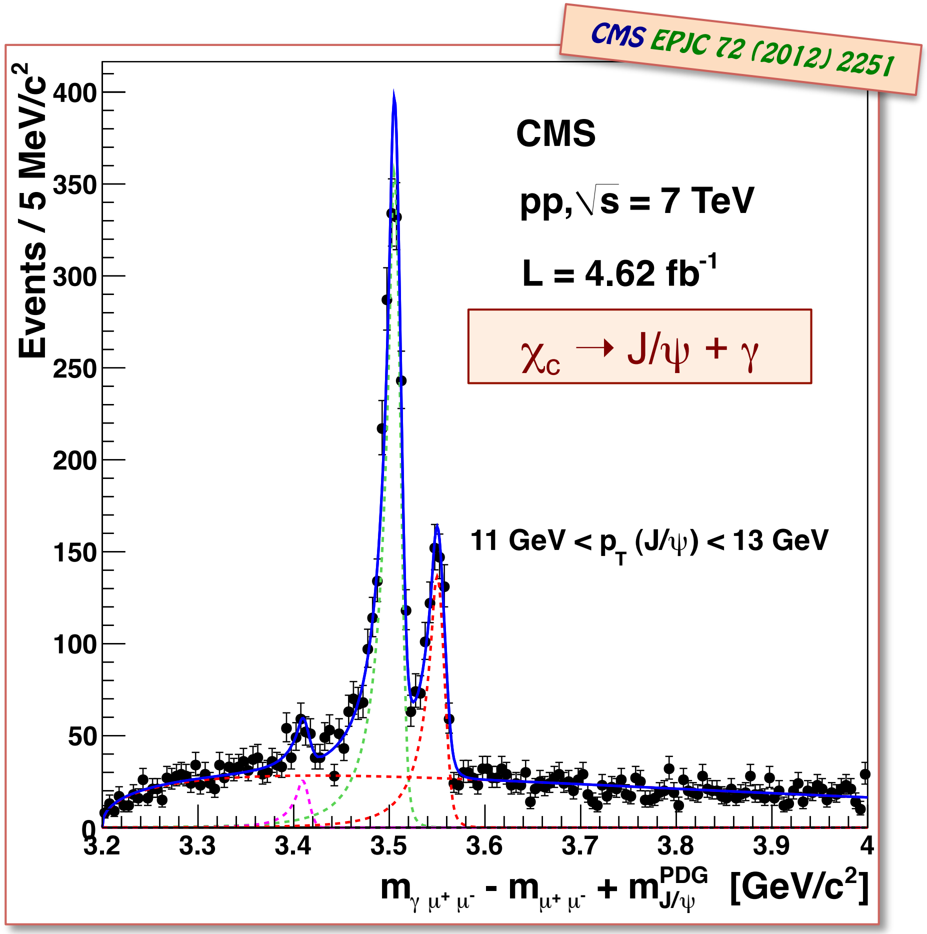


LHCb JHEP 10 (2013) 115

CMS vs. LHCb:

- LHCb: χ mass resolution and level of background similar to CMS



CMS EPJC 72 (2012) 2251

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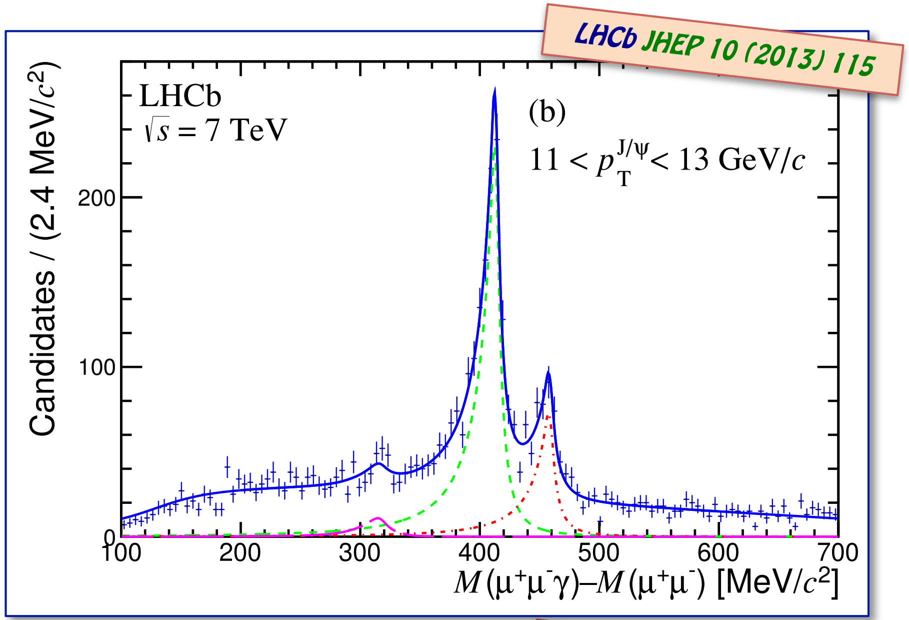
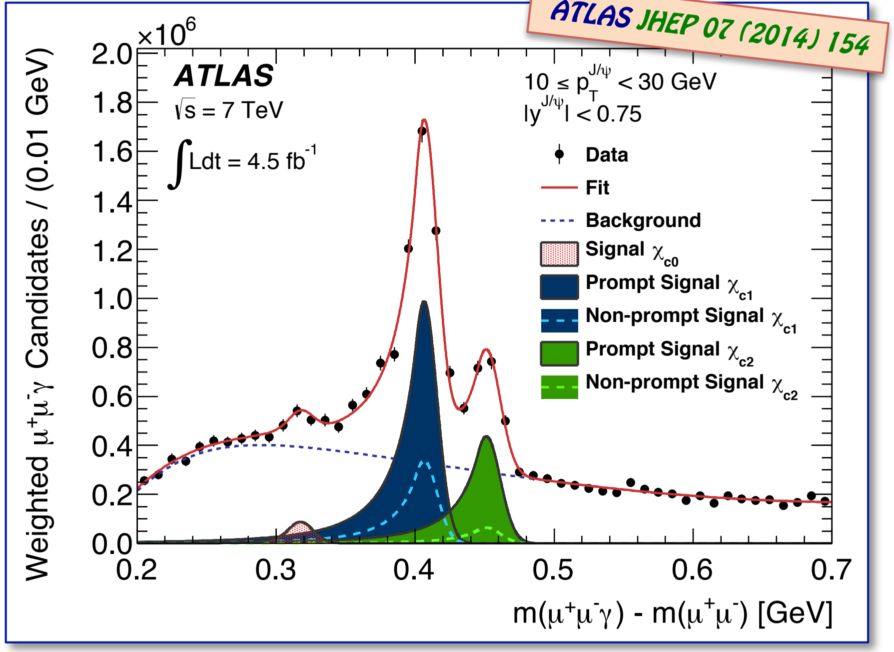


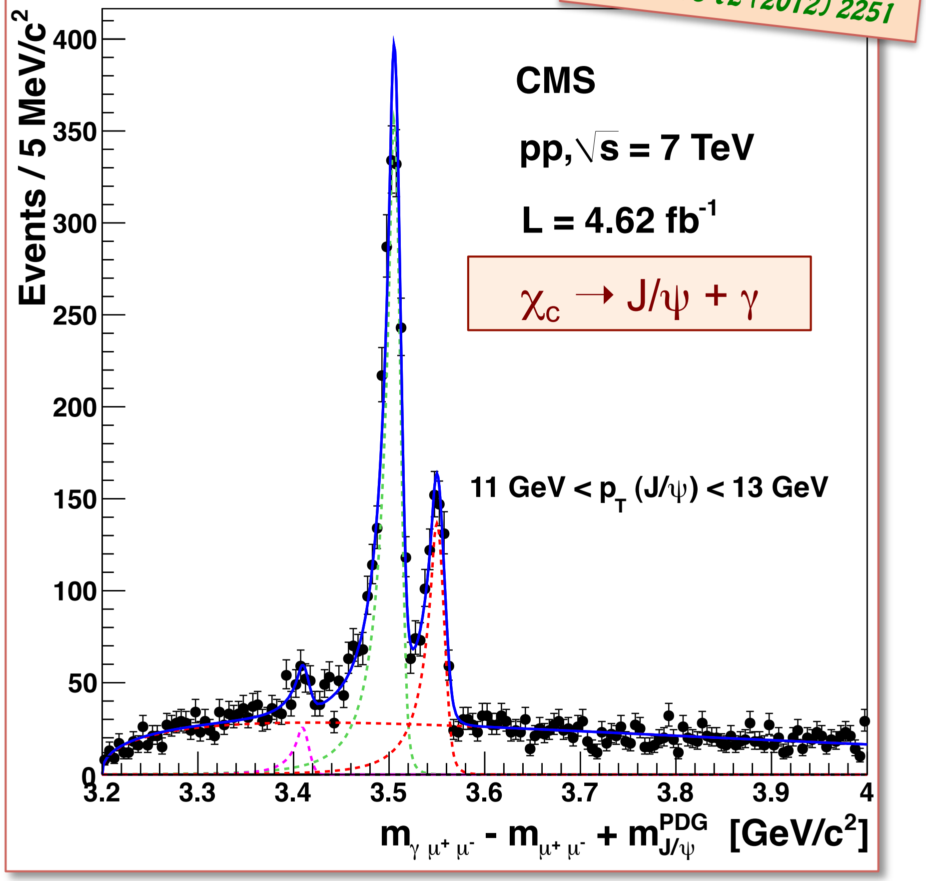
LHCb JHEP 10 (2013) 115



ATLAS JHEP 07 (2014) 154

CMS vs. LHCb and ATLAS:

- LHCb: χ mass resolution and level of background similar to CMS
- ATLAS: slightly worse χ mass resolution and background fraction; higher detection efficiency than CMS



CMS EPJC 72 (2012) 2251

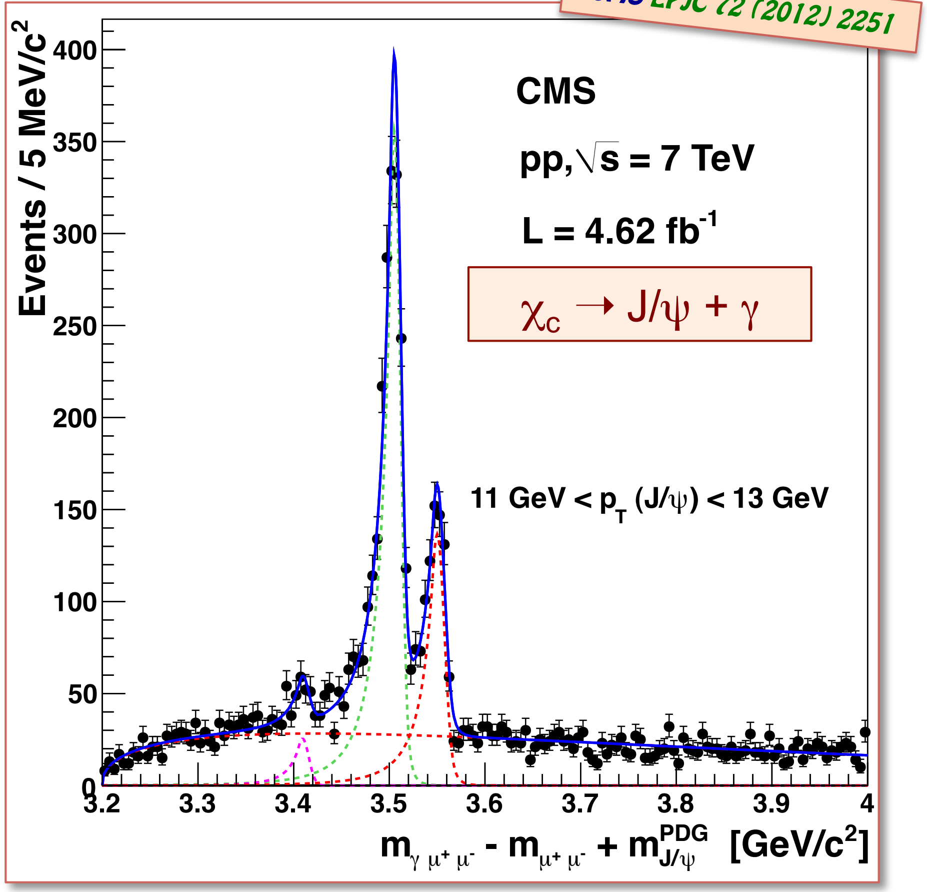
CMS: Prompt χ_{c2} / χ_{c1} cross section ratio at 7 TeV

Main variable $m_\chi = m_{\mu\mu\gamma} - m_{\mu\mu} + m_{J/\psi}^{PDG}$

→Mass resolution good enough to separate χ_{cJ} signals

$$R_p \equiv \frac{\sigma(pp \to \chi_{c2} + X)}{\sigma(pp \to \chi_{c1} + X)} \overset{\text{PDG}}{\boxed{\frac{\mathcal{B}(\chi_{c2} \to J/\psi + \gamma)}{\mathcal{B}(\chi_{c1} \to J/\psi + \gamma)}}} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \cdot \frac{\varepsilon_1}{\varepsilon_2}$$

CMS EPJC 72 (2012) 2251



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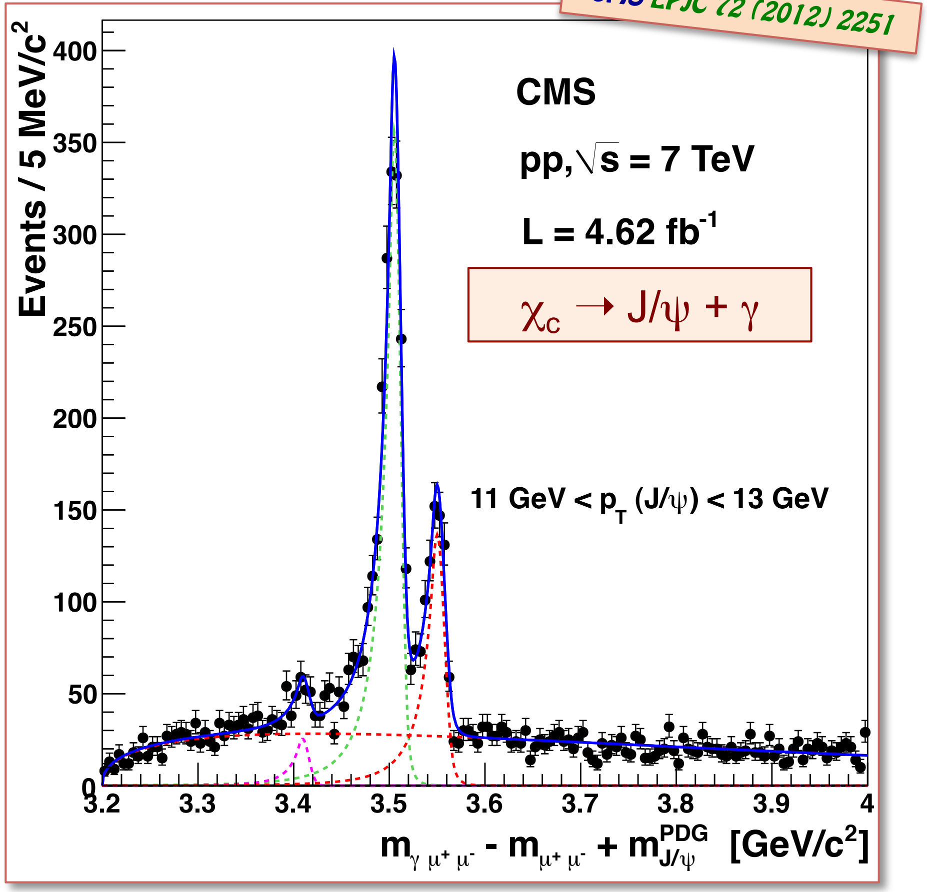
PDG FIT

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

Yield extraction:

- Unbinned maximum-likelihood fit
- Signal shape determined from simulation

CMS EPJC 72 (2012) 2251



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Yield extraction:

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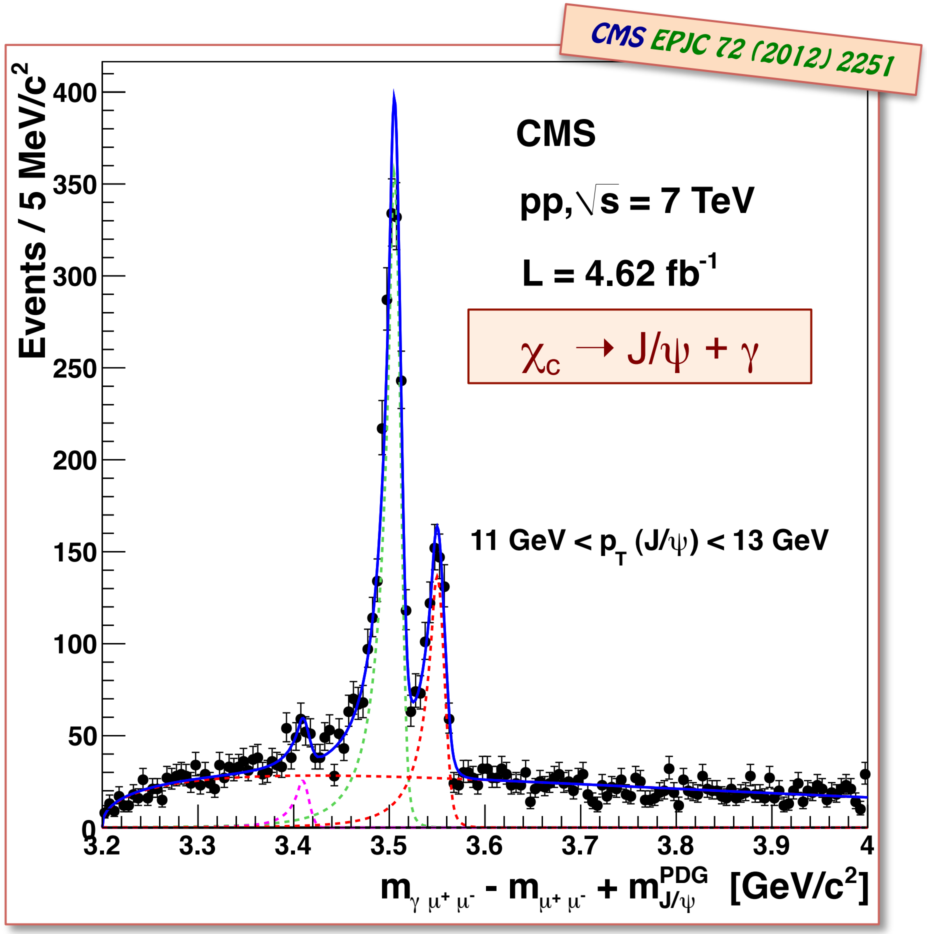
Efficiency ratio:

- Determined from simulation
- Close to unity
- Most uncertainties cancel in the ratio



CMS EPJC 72 (2012) 2251

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CMS EPJC 72 (2012) 2251

Yield extraction:

- Unbinned maximum-likelihood fit
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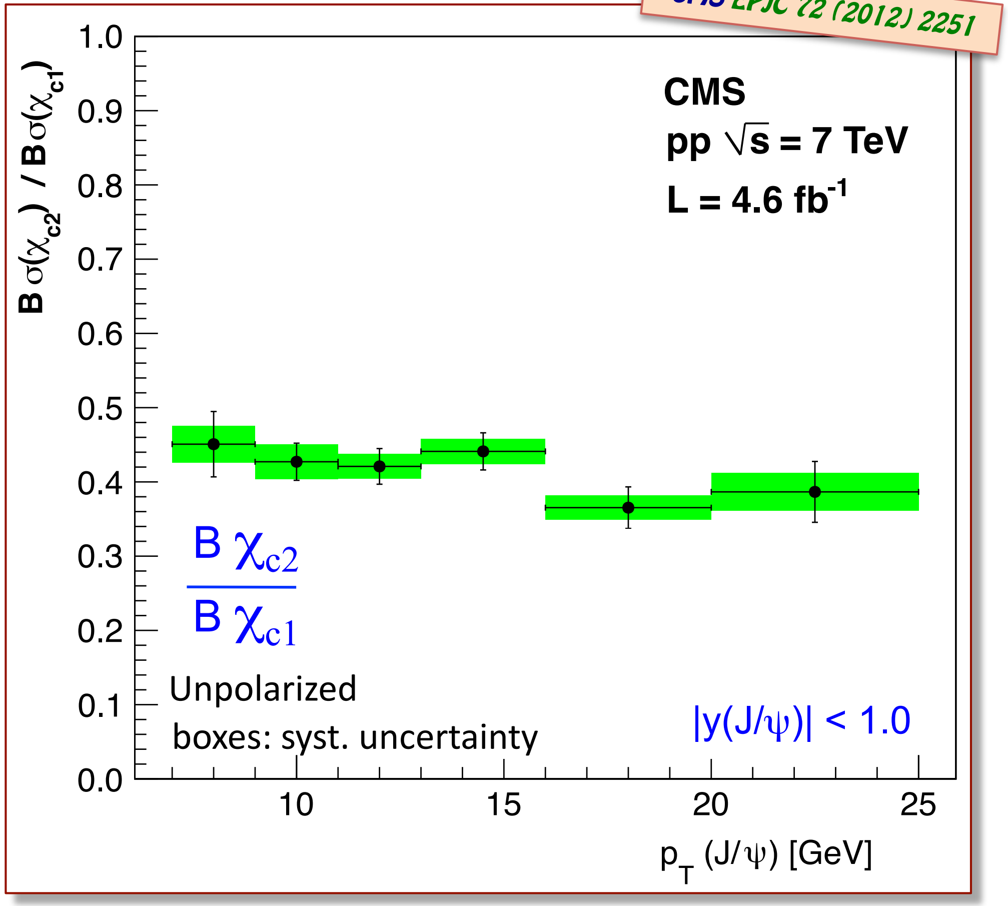
The χ_{c2} / χ_{c1} cross section ratio has been measured vs. p_T, up to much higher p_T and with smaller uncertainties than previous measurements

Cross section ratio seems to be rather flat with p_T



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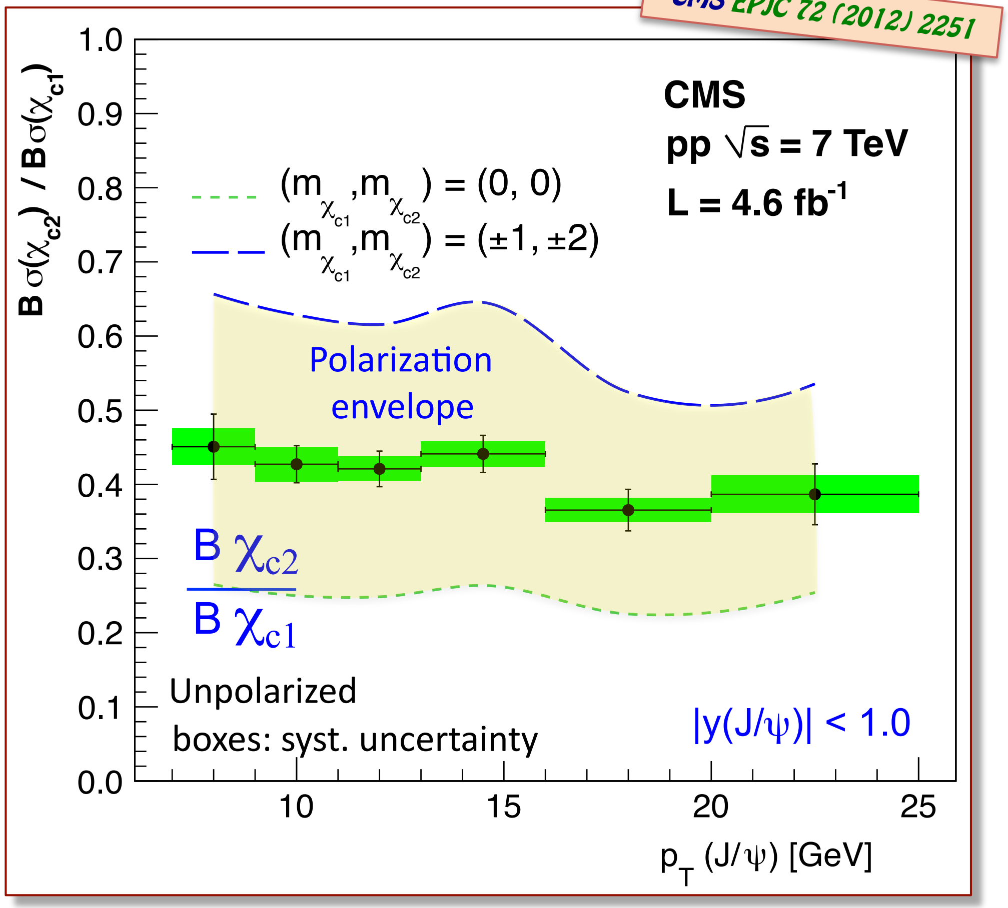
Care is needed regarding assumed polarizations that can significantly change the result



CMS EPJC 72 (2012) 2251

CMS: χ_{b2} / χ_{b1} cross section ratio at 8 TeV

Main variable m_χ from kinematic vertex fit → Mass resolution good enough to separate χ_{b1}(1P) and χ_{b2}(1P) signals, separated by only 19 MeV (as compared to around 46 MeV in the χ_c system)

$$\mathcal{R} \equiv \frac{\sigma(\mathrm{pp} \to \chi_{b2} + X)}{\sigma(\mathrm{pp} \to \chi_{b1} + X)} = \overset{\text{FIT}}{\boxed{\frac{N_{\chi_{b2}}}{N_{\chi_{b1}}}}} \cdot \overset{\text{MC}}{\boxed{\frac{\varepsilon_1}{\varepsilon_2}}} \cdot \overset{\text{PDG}}{\boxed{\frac{\mathcal{B}(\chi_{b1} \to \Upsilon(1S) + \gamma)}{\mathcal{B}(\chi_{b2} \to \Upsilon(1S) + \gamma)}}}$$

Yield extraction:
- Unbinned maximum-likelihood fit
- Signal shape determined from simulation

Efficiency ratio:
- Determined from simulation
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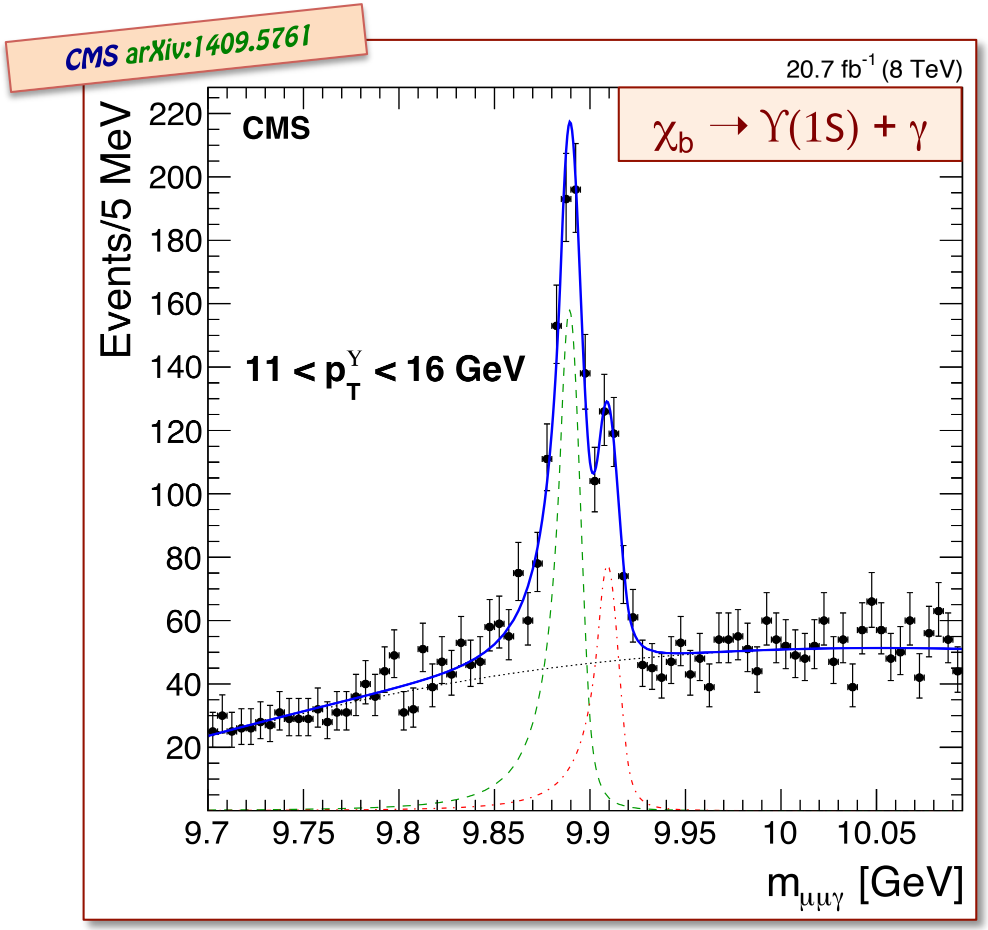
- Most uncertainties cancel in the ratio


CMS arXiv:1409.5761

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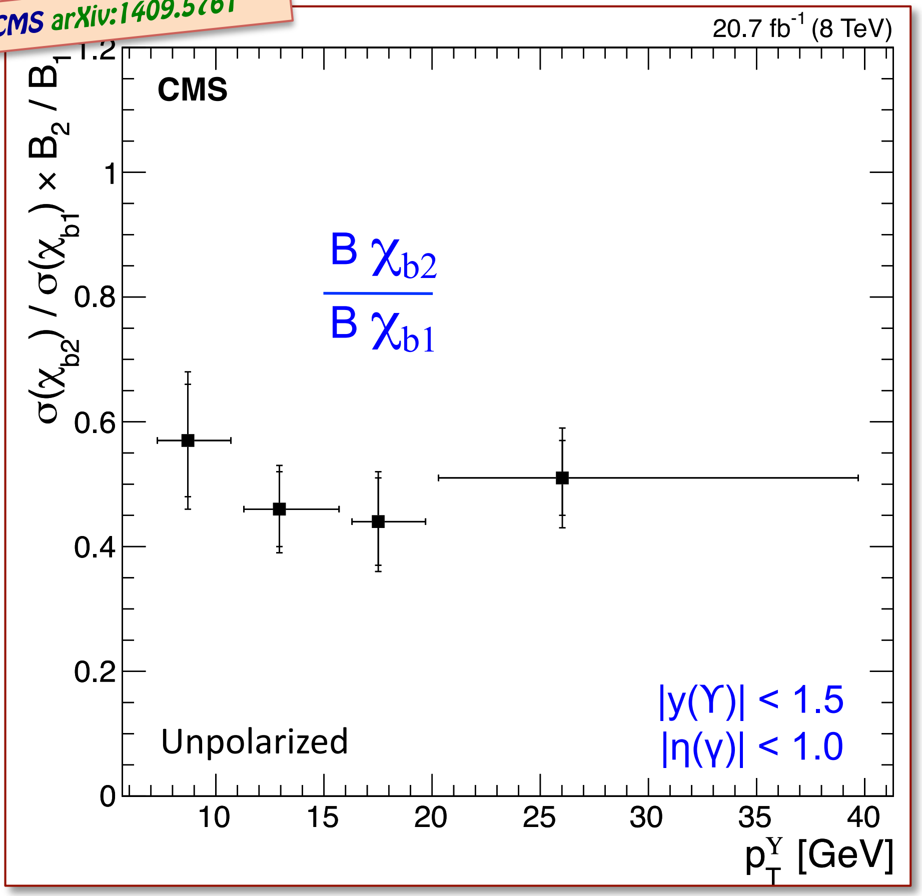
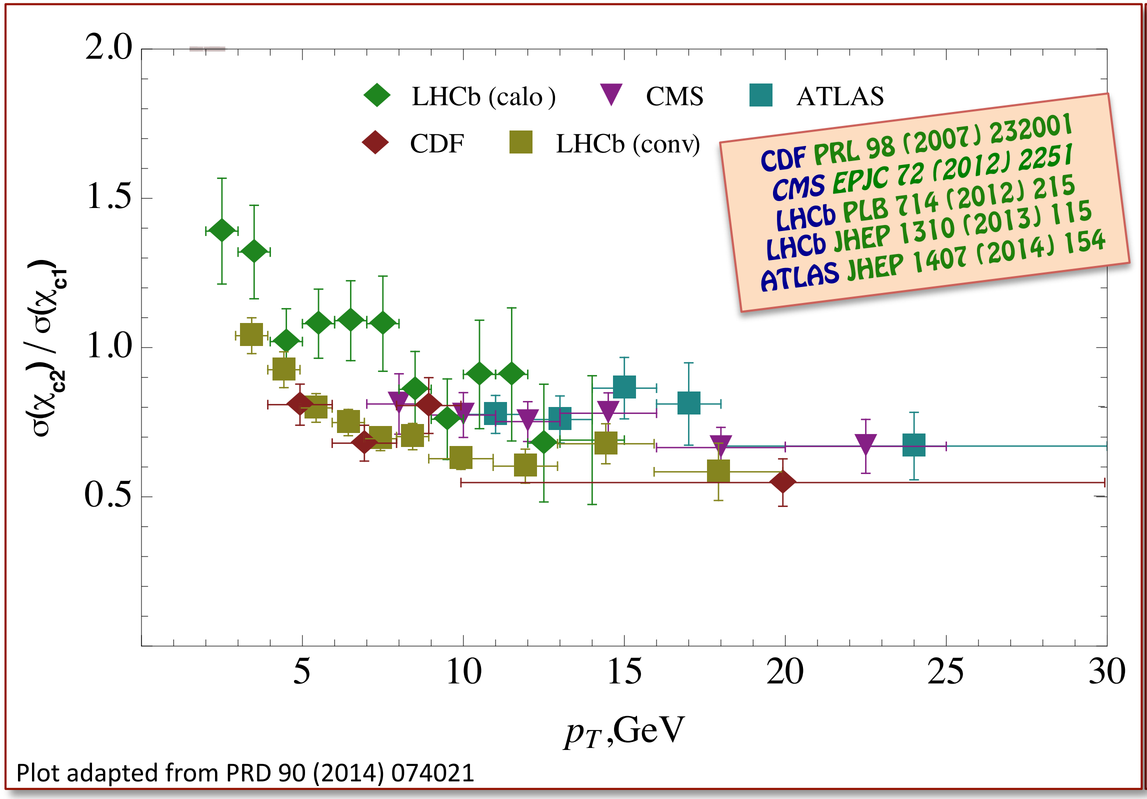
Cross section ratio seems to be rather flat with p_T

CMS arXiv:1409.5761



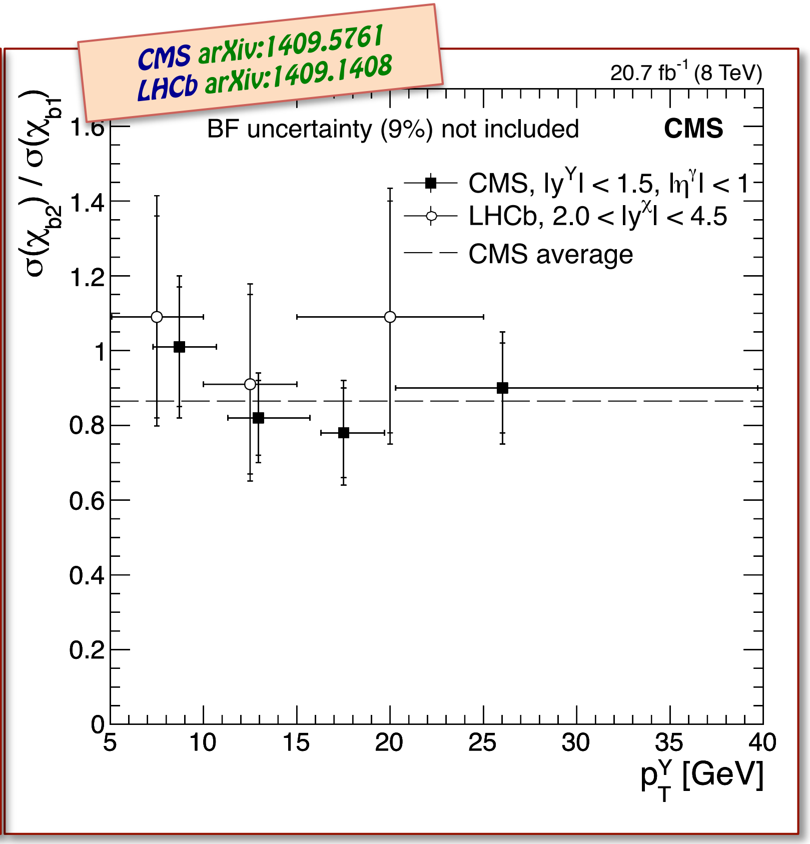
CMS: Comparison to data and theory calculations

Cross section ratio measurements compatible with other LHC results



CDF PRL 98 (2007) 232001
CMS EPJC 72 (2012) 2251
LHCb PLB 714 (2012) 215
LHCb JHEP 1310 (2013) 115
ATLAS JHEP 1407 (2014) 154

Plot adapted from PRD 90 (2014) 074021



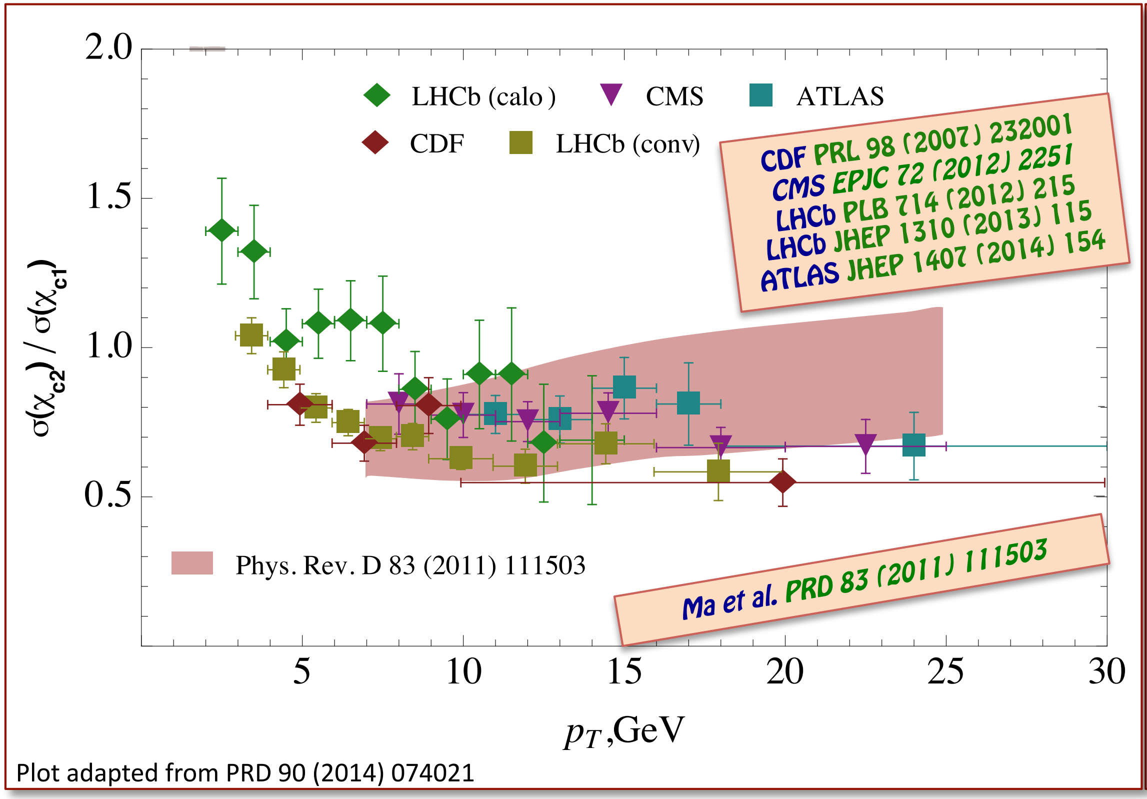
CMS arXiv:1409.5761
LHCb arXiv:1409.1408

CMS: Comparison to data and theory calculations

Cross section ratio measurements compatible with other LHC results (exception: LHCb calo vs. conv)

MWC (2011): NLO NRQCD calculations, including $^3P_J^{[1]}$ **CS (fixed norm.)** and $^3S_1^{[8]}$ **CO** components

Data: CDF χ_c ratio → CO contributions rather large and important



CDF PRL 98 (2007) 232001
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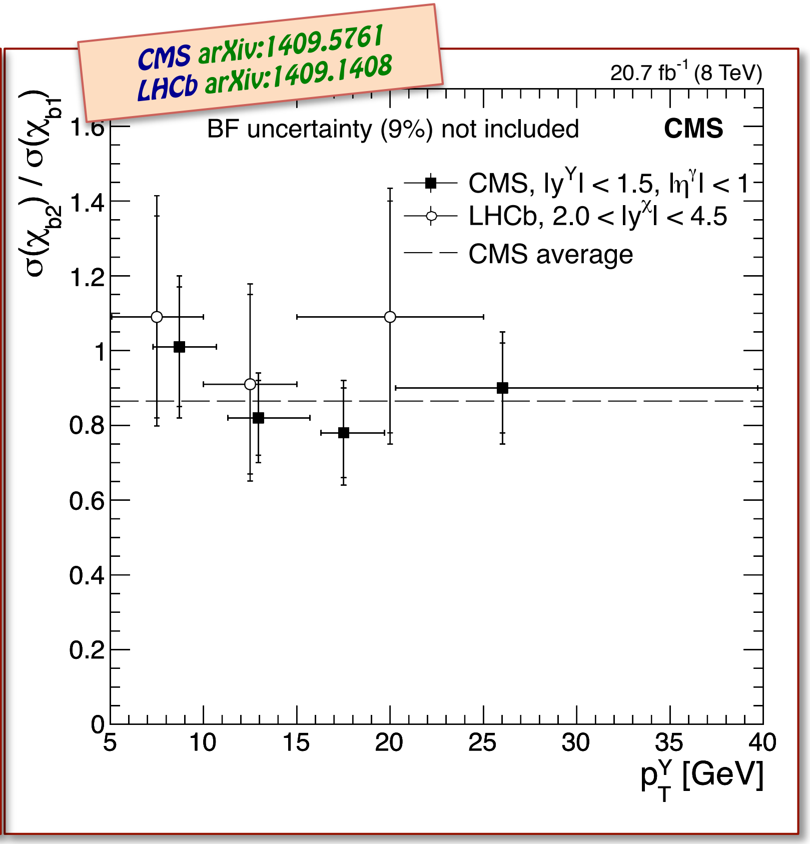
Ma et al. PRD 83 (2011) 111503

Plot adapted from PRD 90 (2014) 074021



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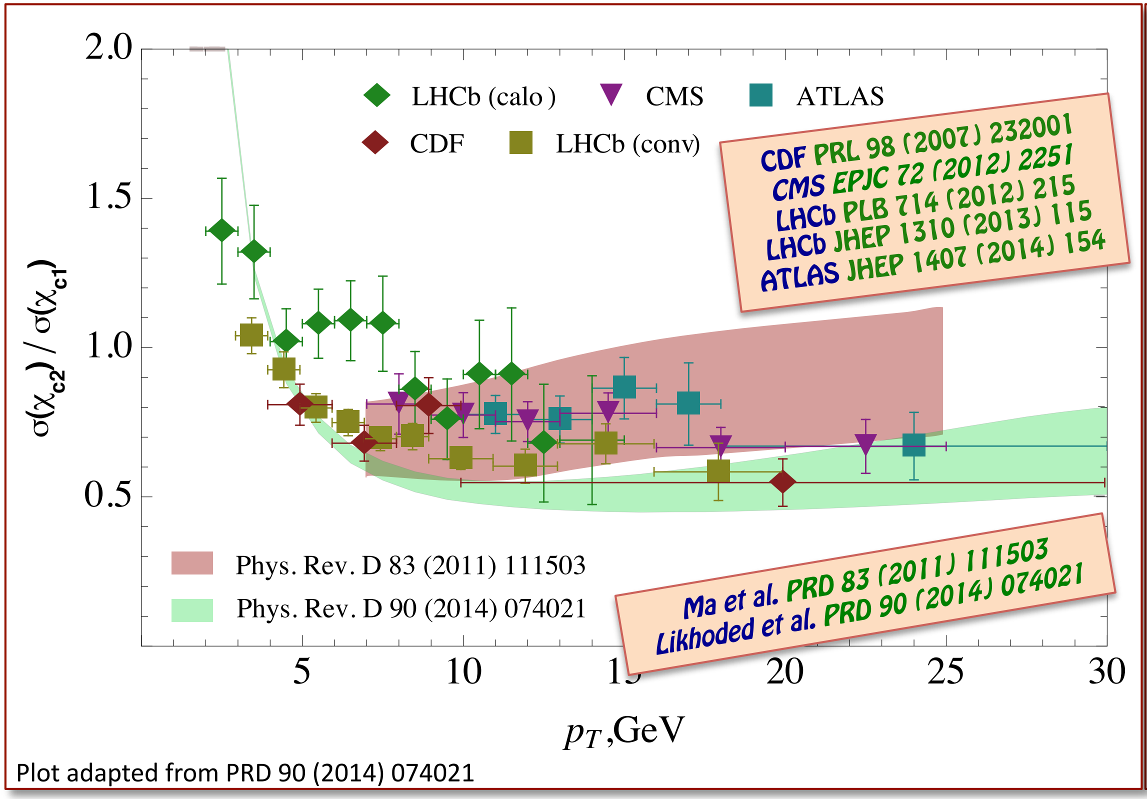
LLP (2014): NLO calculations, including $^3P_J^{[1]}$ **CS (free norm.)** and **$^3S_1^{[8]}$, $^3P_J^{[8]}$ + $^1P_1^{[8]}$ CO** components

Data: LHC+CDF χ_c ratios + CDF $\sigma(\chi_c)$ → CS contribution completely dominates χ_c and χ_b production

→ Predictions for χ_b ratio by applying NRQCD scaling rules



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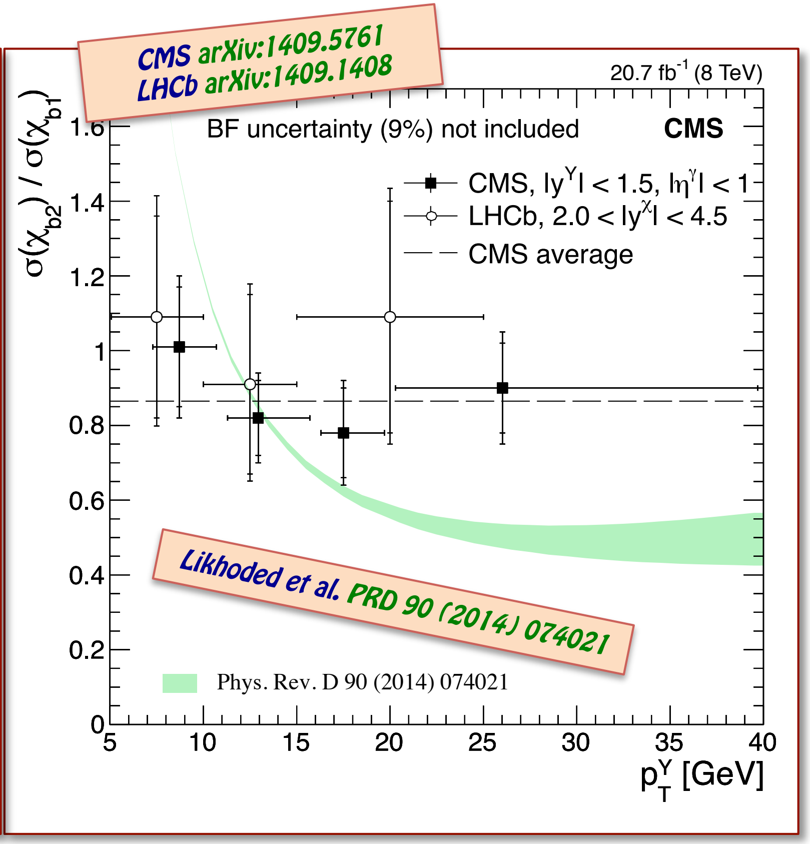

CMS arXiv:1409.5761
LHCb arXiv:1409.1408

Likhoded et al. PRD 90 (2014) 074021

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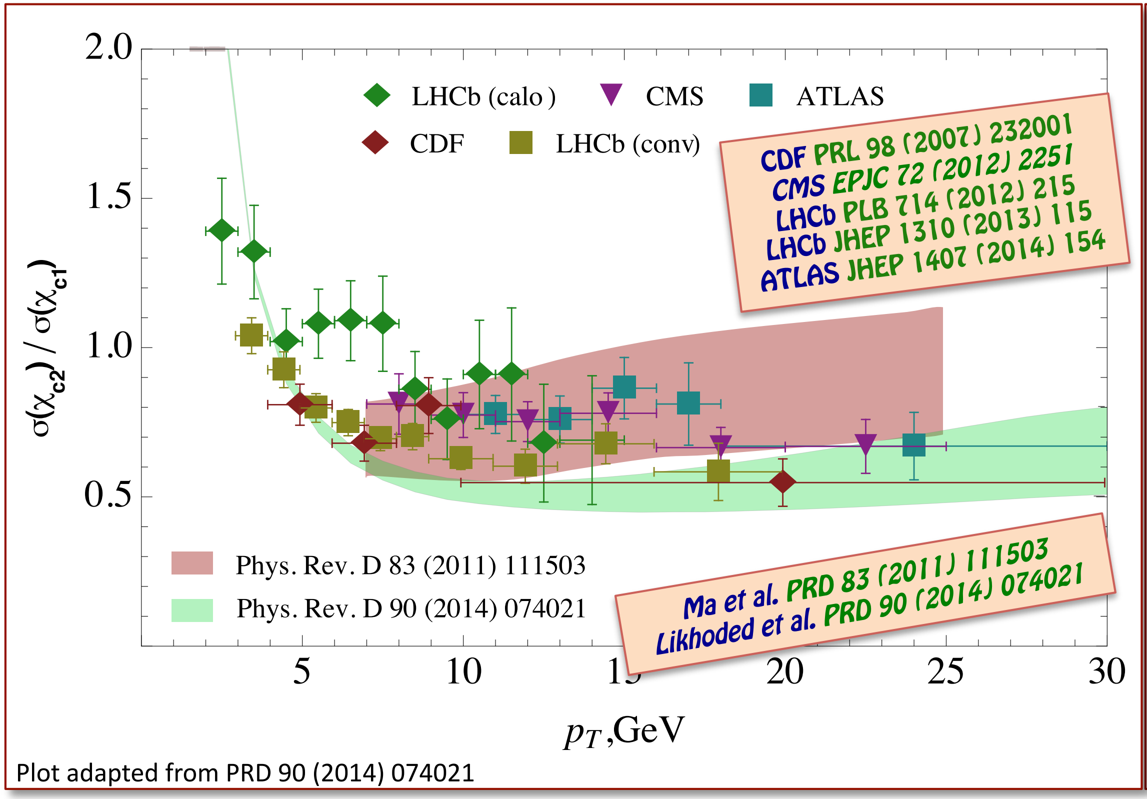
HMMSZC (2014): NLO NRQCD calculations, including $^3P_J^{[1]}$ **CS (fixed norm.)** and $^3S_1^{[8]}$ **CO** components

Data: LHC ϒ(nS) c.s. and polarizations + χ_b ratios → CO rather large and important



CDF PRL 98 (2007) 232001
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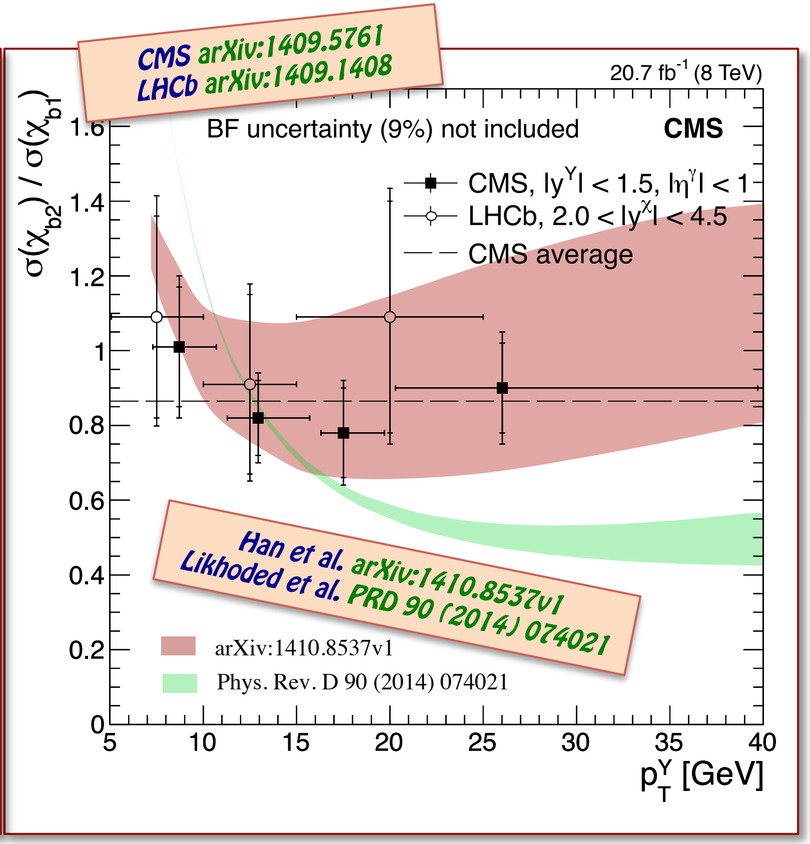
Ma et al. PRD 83 (2011) 111503
Likhoded et al. PRD 90 (2014) 074021

Plot adapted from PRD 90 (2014) 074021



CMS arXiv:1409.5761
LHCb arXiv:1409.1408

Han et al. arXiv:1410.8537v1
Likhoded et al. PRD 90 (2014) 074021

Conclusion

- P-wave measurements are crucial to understand quarkonium production
  - → Understand feed-down effects into S-wave states
  - → Constrain LDMEs of the χ_c and χ_b states

- Reconstruction of converted photons leads to an excellent χ mass resolution
  - → CMS has the potential to study all relevant decays

$\chi_{cJ} \rightarrow J/\psi+\gamma$, $\chi_{bJ}(1P) \rightarrow \Upsilon(1S)+\gamma$, $\chi_{bJ}(2P) \rightarrow \Upsilon(1,2S)+\gamma$, $\chi_{bJ}(3P) \rightarrow \Upsilon(1,2,3S)+\gamma$

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- CMS measured the cross section ratio in the χ_c and $\chi_b(1P)$ systems as function of p_T, with smaller uncertainties than competing analyses; CMS P-wave data is compatible with other LHC data

- The precision of the present CMS measurements is already sufficiently good to provide interesting comparisons with theoretical calculations

  ... and will become much better in time for the next QWG workshop!

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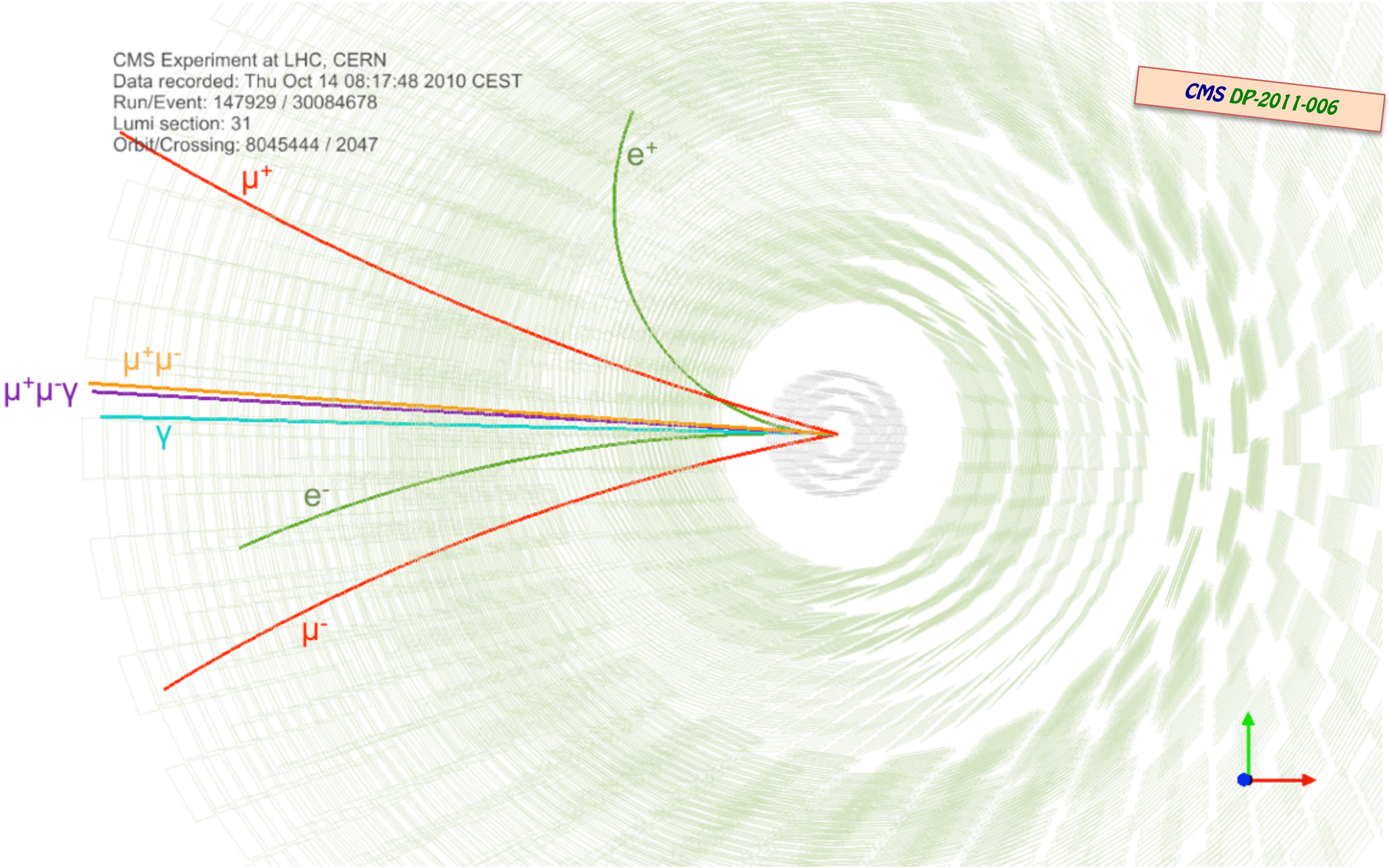
  ... and will become much better in time for the next QWG workshop!

- Further measurements in P-wave sector
  - → Absolute χ_c and χ_b cross sections
  - → Polarizations of prompt χ_{c1} and χ_{c2} states; Non-trivial but crucial measurement

- Present CMS P-wave measurements are conducted in the region $7 < p_T < 25$ GeV
- Higher p_T values reached once full LHC Run I data will be exploited (extend χ_c analysis up to 40 GeV)
- Run II data should further improve p_T reach and accuracy

Backup

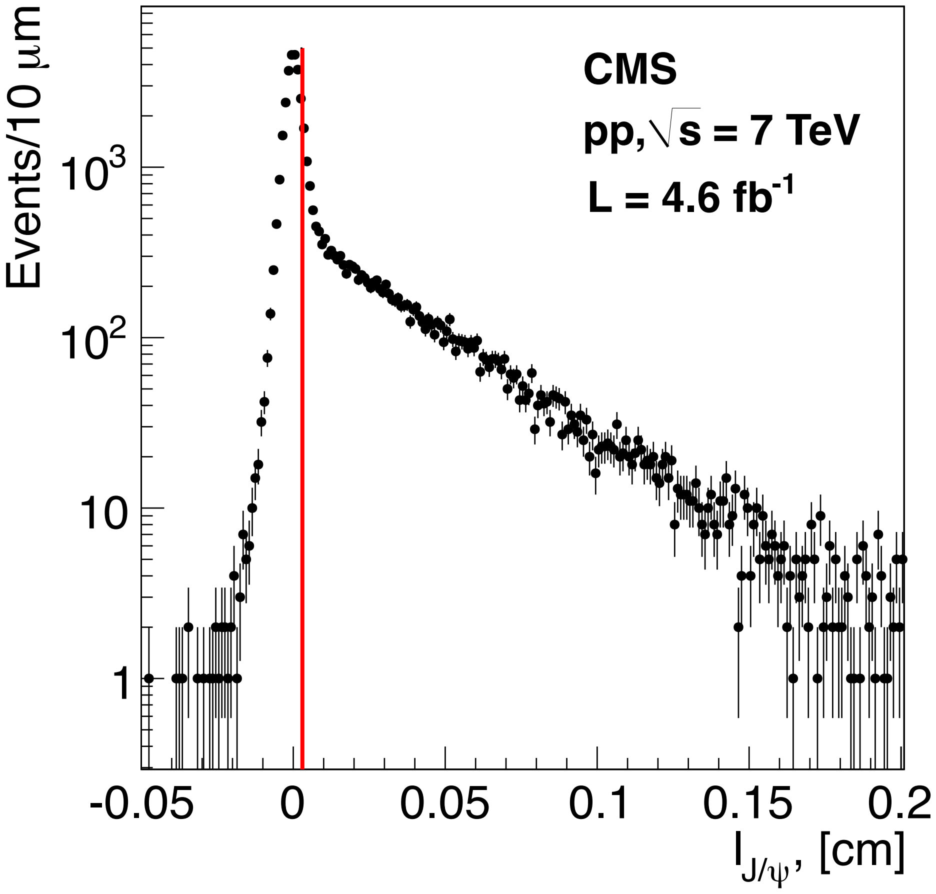
Event Display

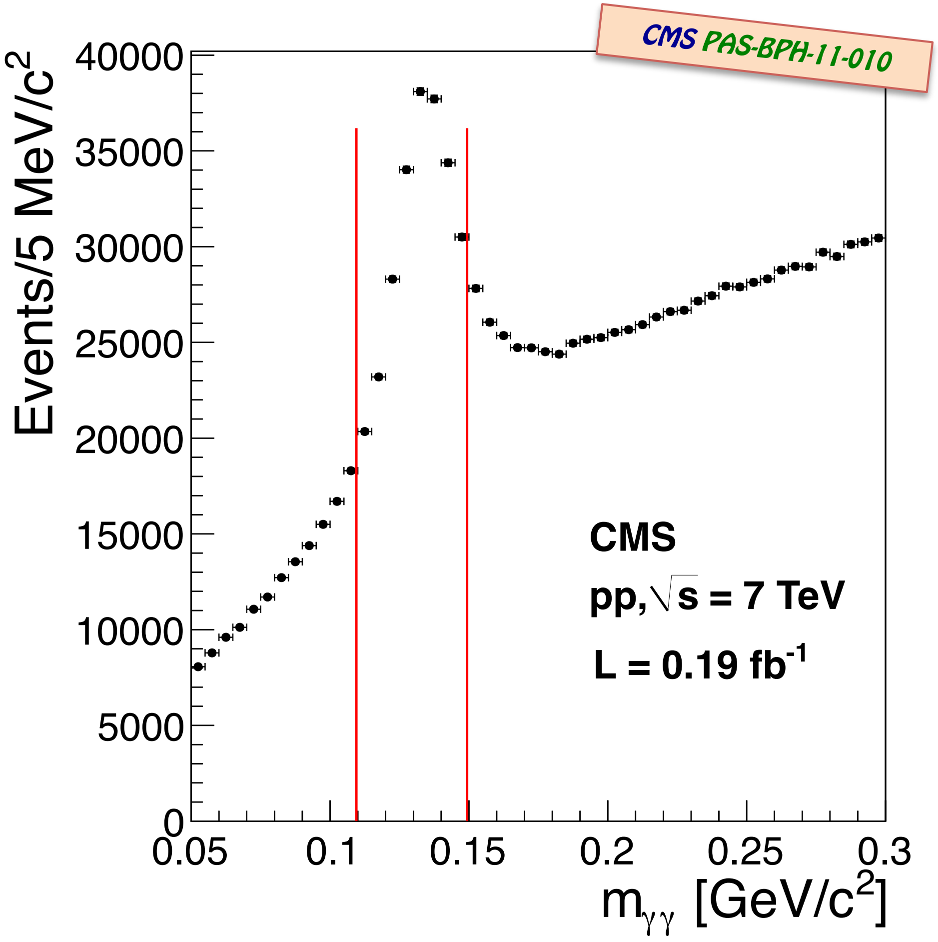


CMS Experiment at LHC, CERN
Data recorded: Thu Oct 14 08:17:48 2010 CEST
Run/Event: 147929 / 30084678
Lumi section: 31
Orbit/Crossing: 8045444 / 2047

CMS DP-2011-006

CMS: Prompt χ_{c2} / χ_{c1} cross section ratio at 7 TeV





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CMS EPJC 72 (2012) 2251