Overview of Quarkonium at LHC

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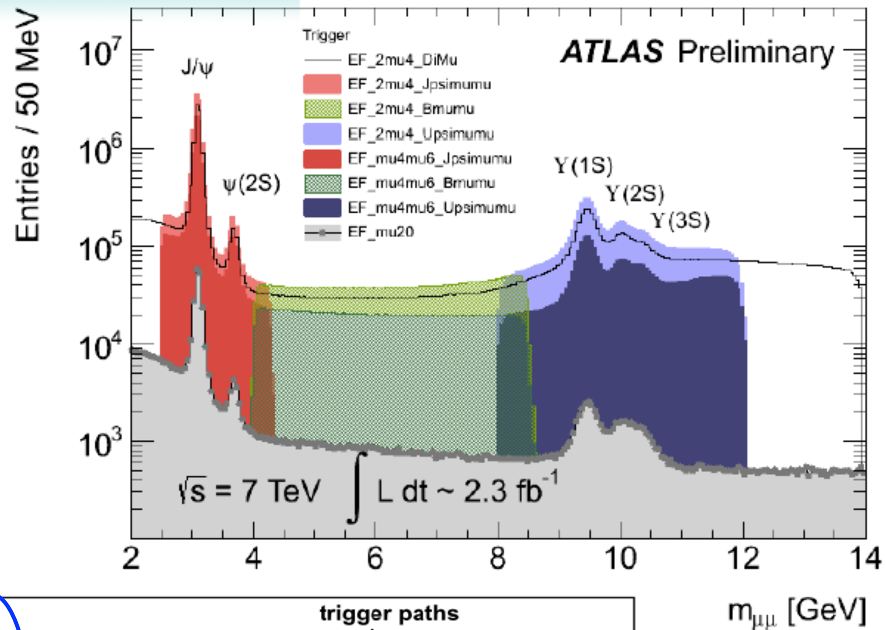
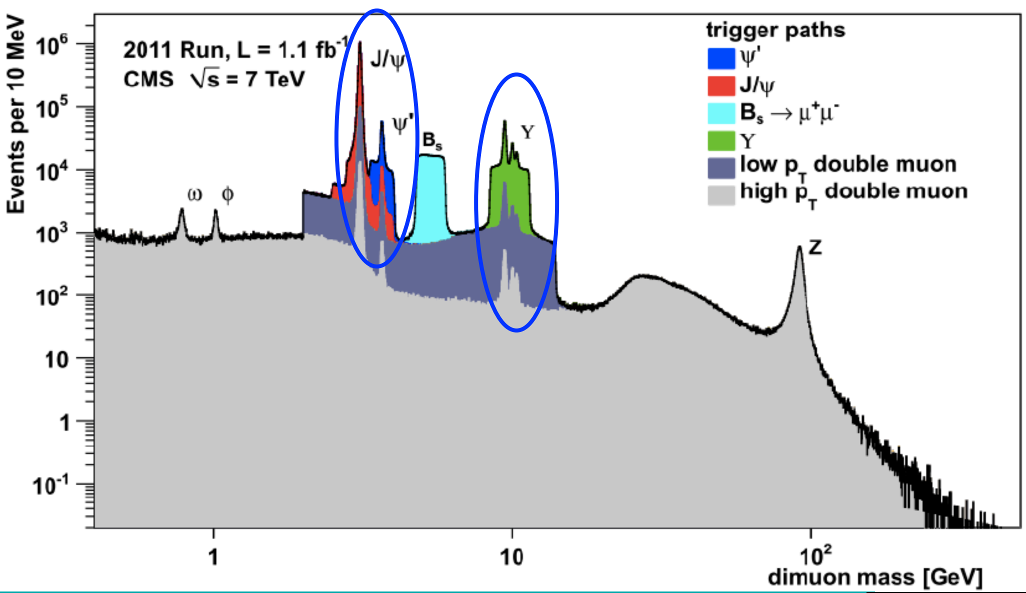
*on behalf of ATLAS, CMS and LHCb collaborations

Outline

- Quarkonium
- J/ψ, ψ(2S) and ϒ(nS) cross sections, ratios and polarization(*)
- P-wave Onia: χ_c and χ_b
- J/ψ and W associate production

(*) including ψ(2S) polarization

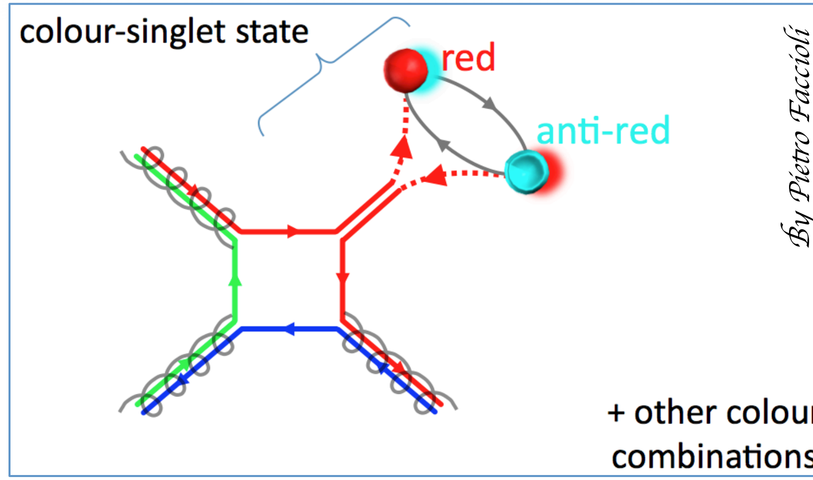


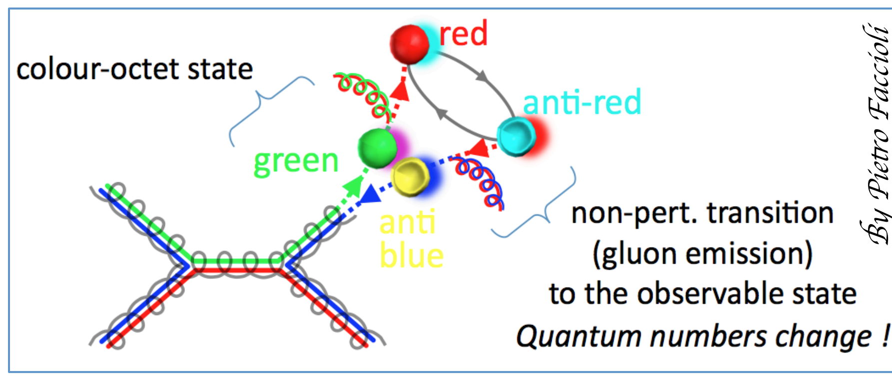


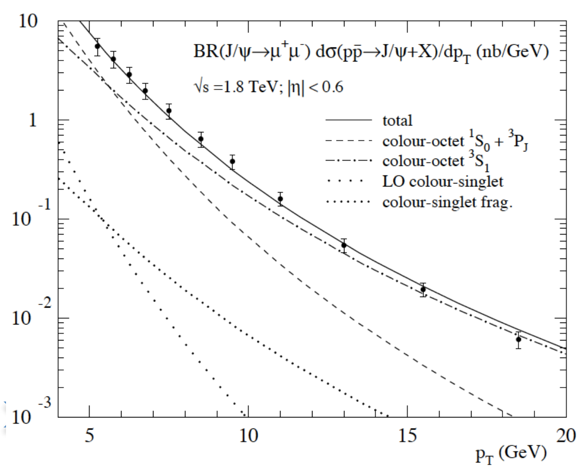
Why Quarkonium?

From a naïve point of view quarkonium is a simple state: a flavorless meson whose constituents are a quark and its own antiquark, in a bound state.

- Quarkonia production is not yet understood:
  ★ Production model for quarkonia may require a q-qbar state produced as color-singlet in the LO Feynman diagram (Color Singlet Model)
  ★ May ask a q-qbar pair being produced in any color, subsequently removed with soft gluon irradiation (Color Octet Model).
- Long history of disagreement between Theory and Experimental results





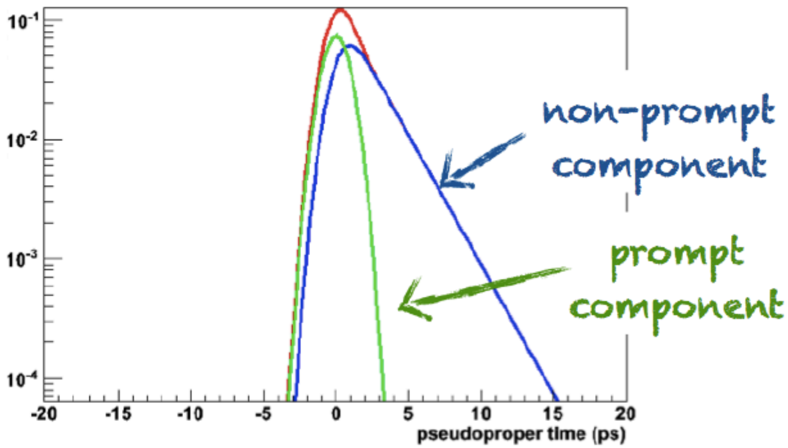


LHC provides luminosity, new energy scale and large p_T reach

Trigger and reconstruction of Quarkonium

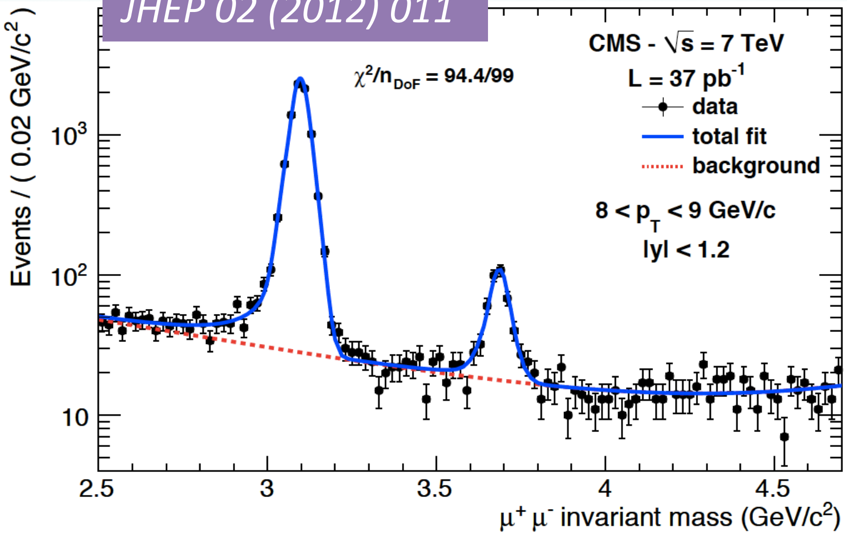
- Quarkonium is reconstructed through dimuons final states.
- Sophisticated triggers are applied to select signal and reduce data rate
- Over time triggers are tightened to balance rate with increasing luminosity, affecting quarkonia
  - ✓ High p_T only accessible in ATLAS/CMS
  - ✓ Low p_T threshold single muon trigger
  - ✓ Low p_T dimuon trigger (high priority in LHCb, while must be kept at reasonable rate in ATLAS/CMS)
  - ✓ J/ψ, Υ, $B_S(\mu\mu)$ dedicated triggers

- Rapidity coverage
  - ATLAS/CMS $|\eta|<2.4$
  - LHCb $2.0<|\eta|<5.0$
- Pseudo-proper time measured with precision tracking

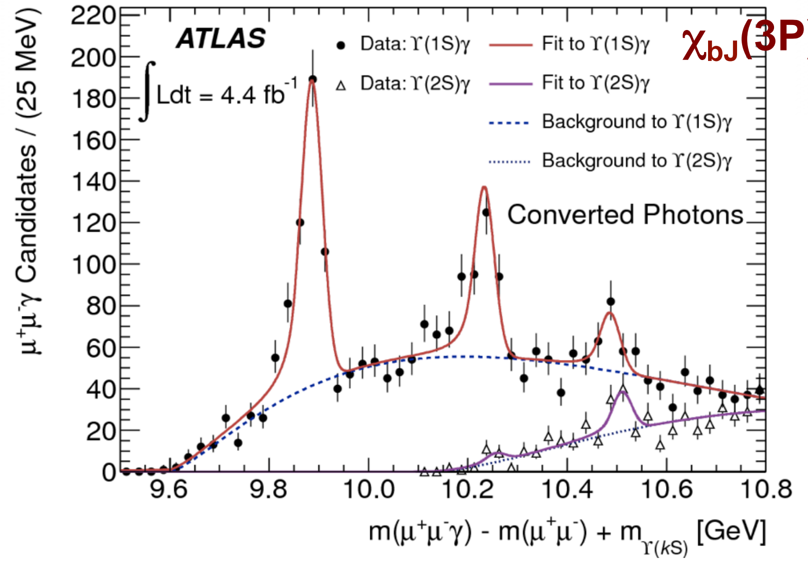


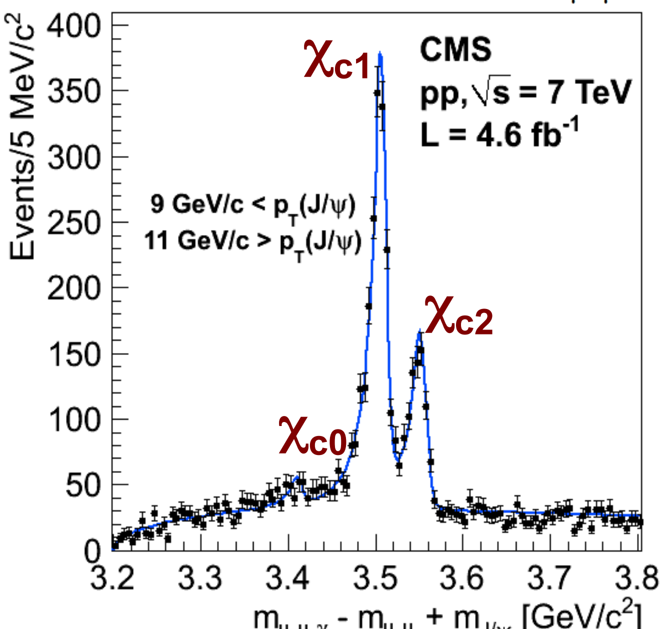
Mass Fits and Yields

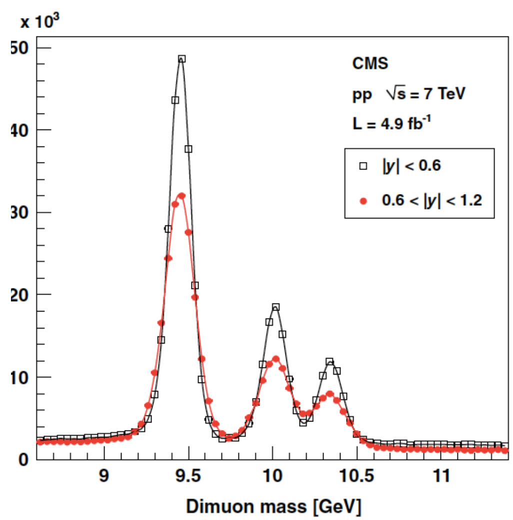
JHEP 02 (2012) 011

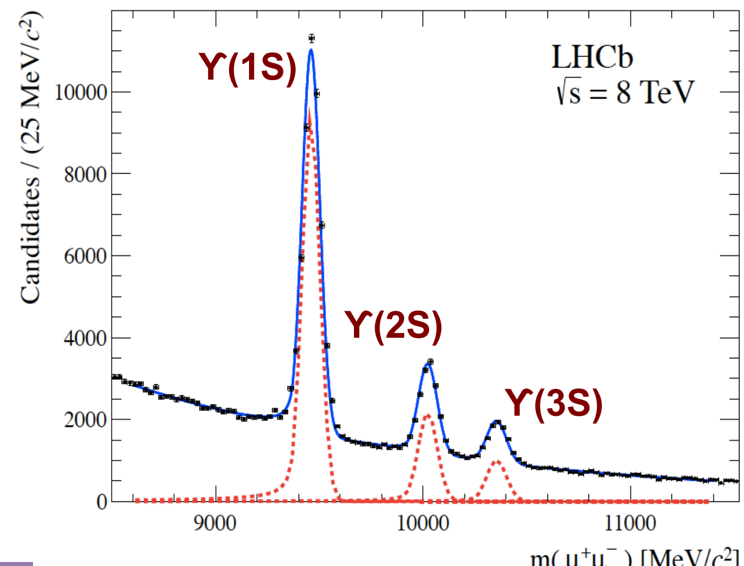


PRL 108 (2012) 152001







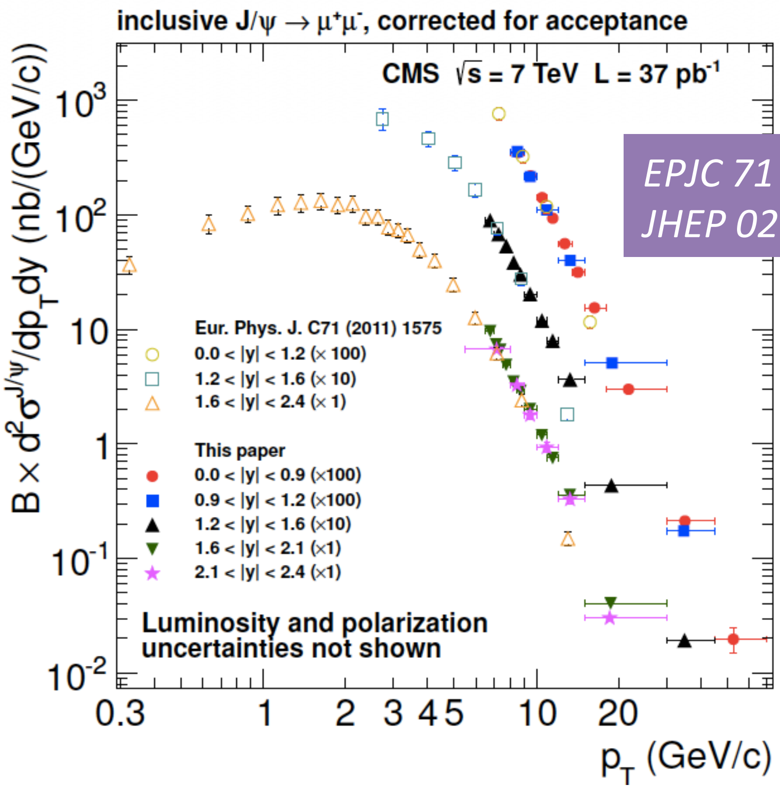


EPJC 72 (2012) 2251

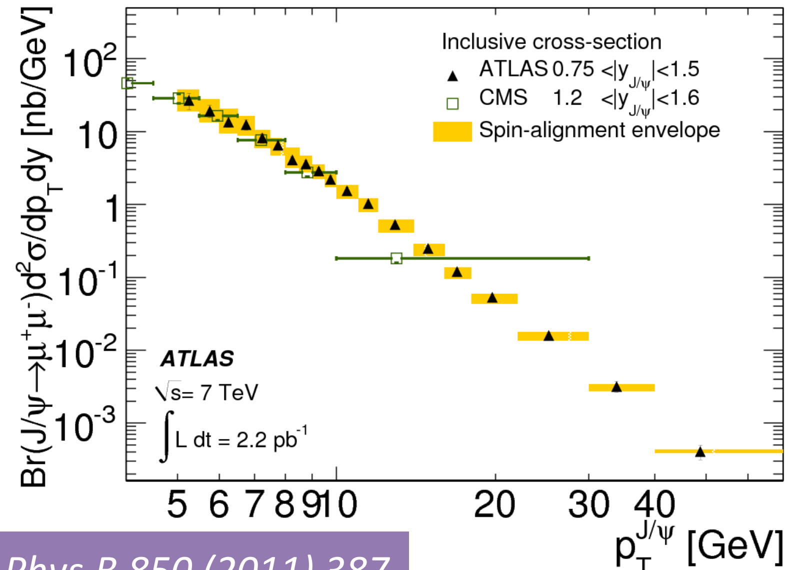
PRL 110 (2013) 081802

arXiv: 1304.6977

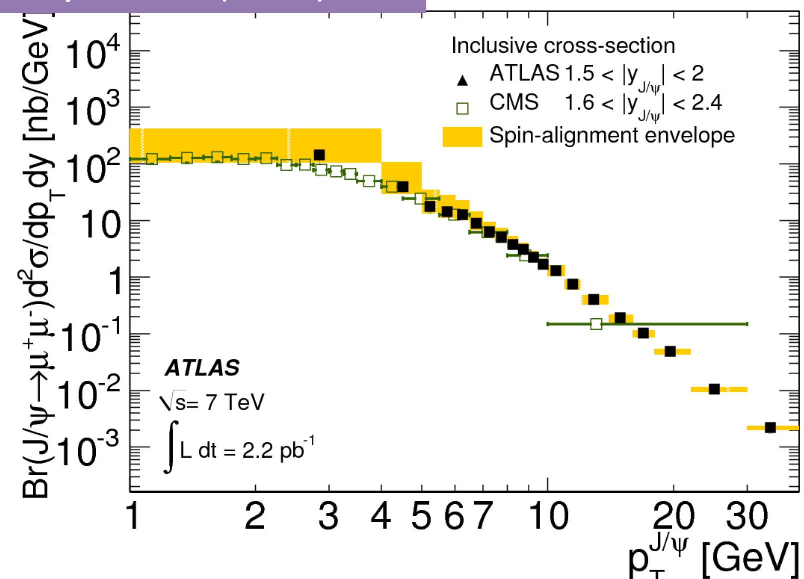
Inclusive J/ψ cross section



EPJC 71 (2011) 1575
JHEP 02 (2012) 011



Nucl.Phys.B 850 (2011) 387



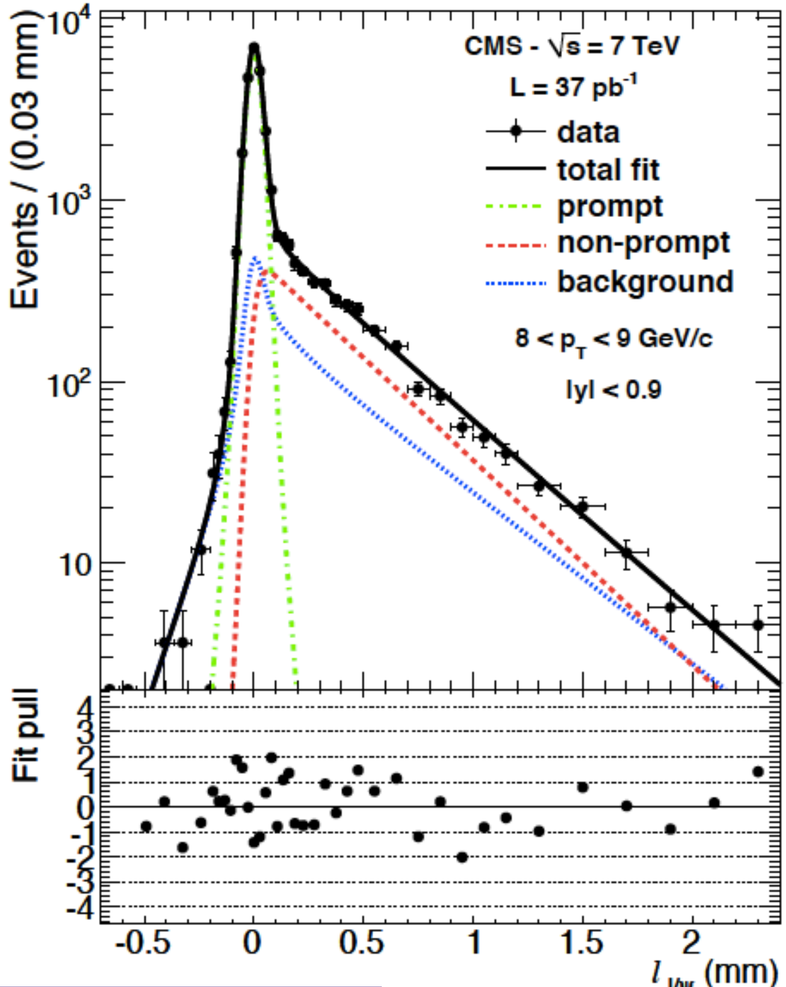
Precise measurements

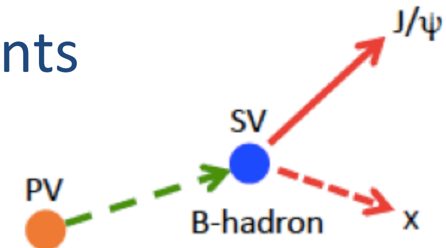
Reaching high p_T

Excellent agreement ATLAS *(black points)* & CMS *(green open points)*

Disentangling prompt and non-prompt J/ψ

Dimuon candidate events



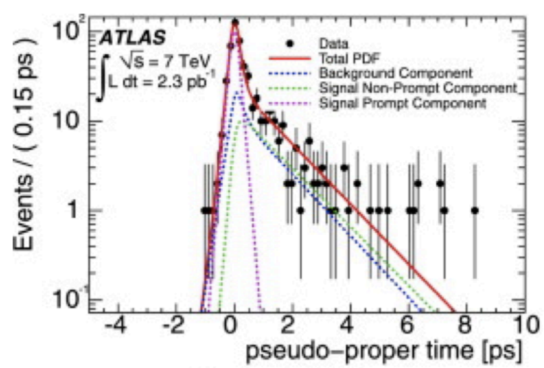


Pseudo-proper time: $\tau = \frac{L_{xy}\, m_{PDG}^{J/\psi}}{p_T^{J/\psi}}$

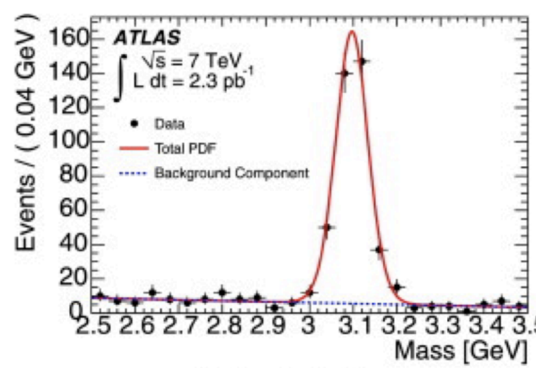
L_{xy}: the displacement of the J/ψ vertex in the transverse plane

L_z: the displacement of the J/ψ vertex in the z direction

$$t_z = [M_{J/\psi}(z_{J/\psi} - z_{PV})]/p_z$$



(a) $|y_{J/\psi}| < 0.75$



(b) $|y_{J/\psi}| < 0.75$

JHEP 02 (2012) 011

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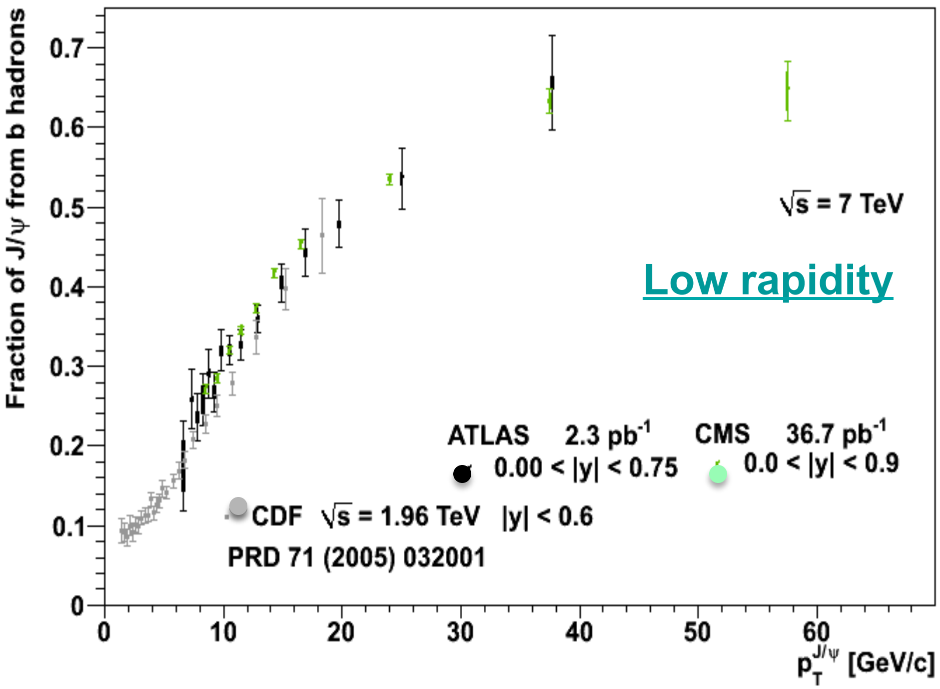
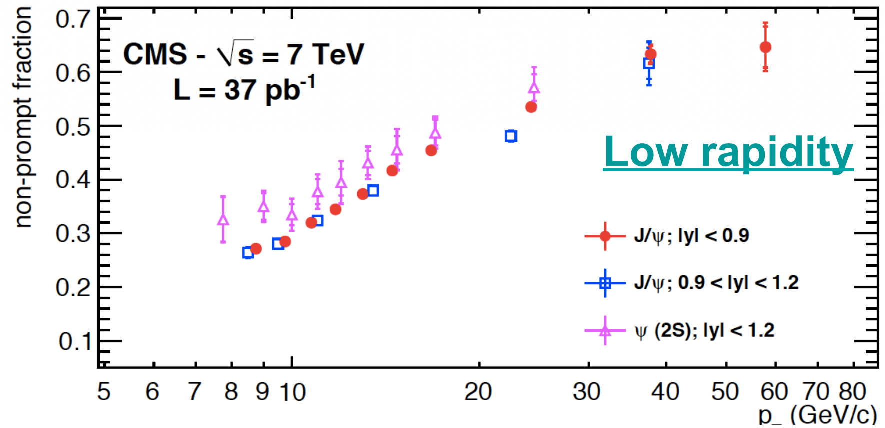
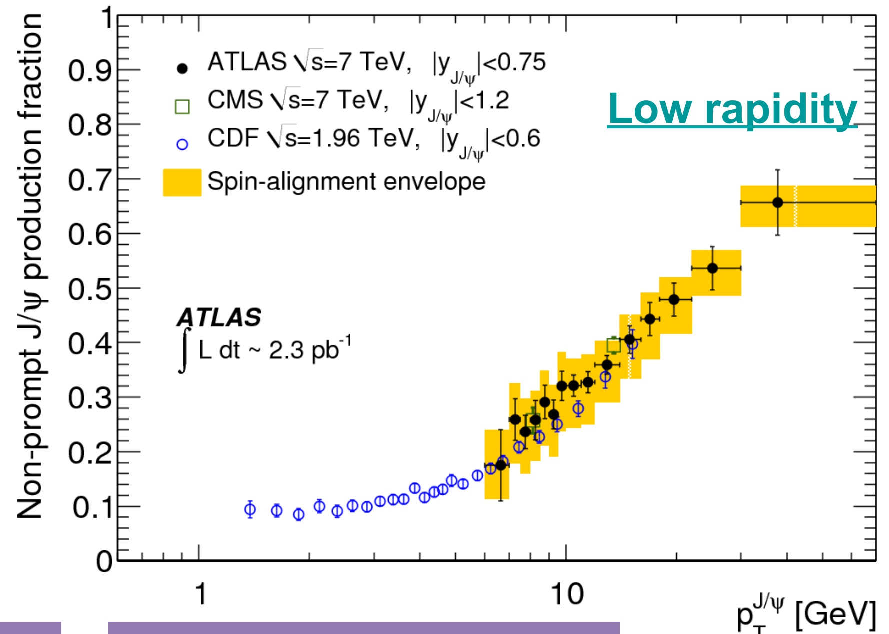
J/ψ & ψ(2S): fractions non-prompt to inclusive

Fraction of J/ψ from B decays







Above p_T = 20 GeV/c more than 50% of the J/ψ and ψ(2S) mesons result from B decays.

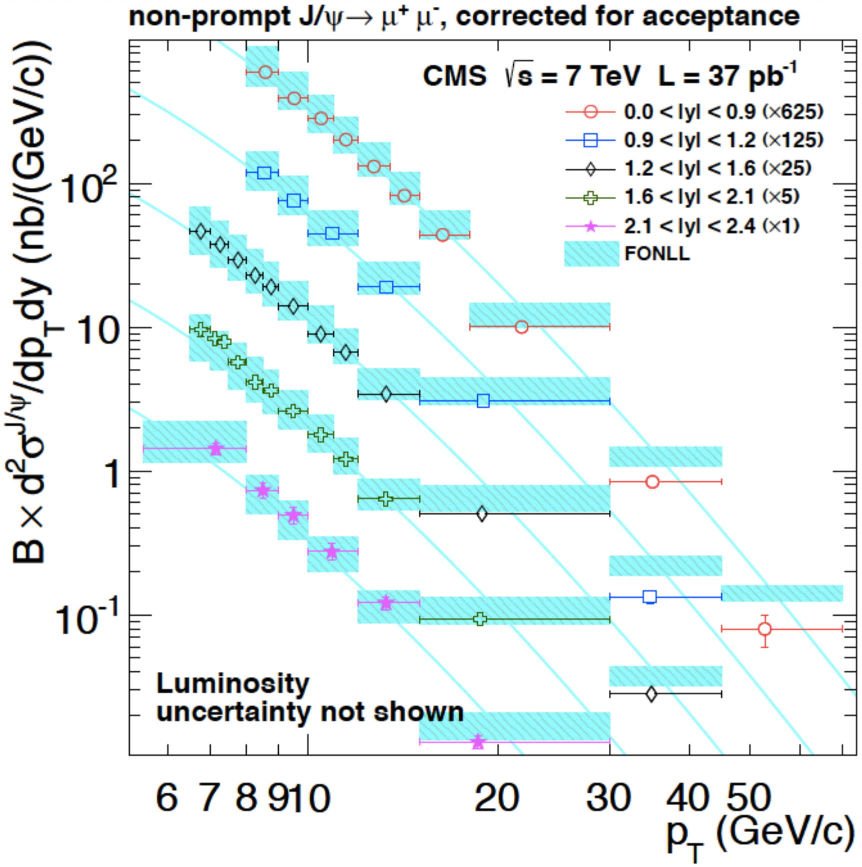
JHEP 02 (2012) 011

Nucl.Phys.B 850 (2011) 387

Non-prompt J/ψ) differential cross section

JHEP 02 (2012) 011

J/ψ



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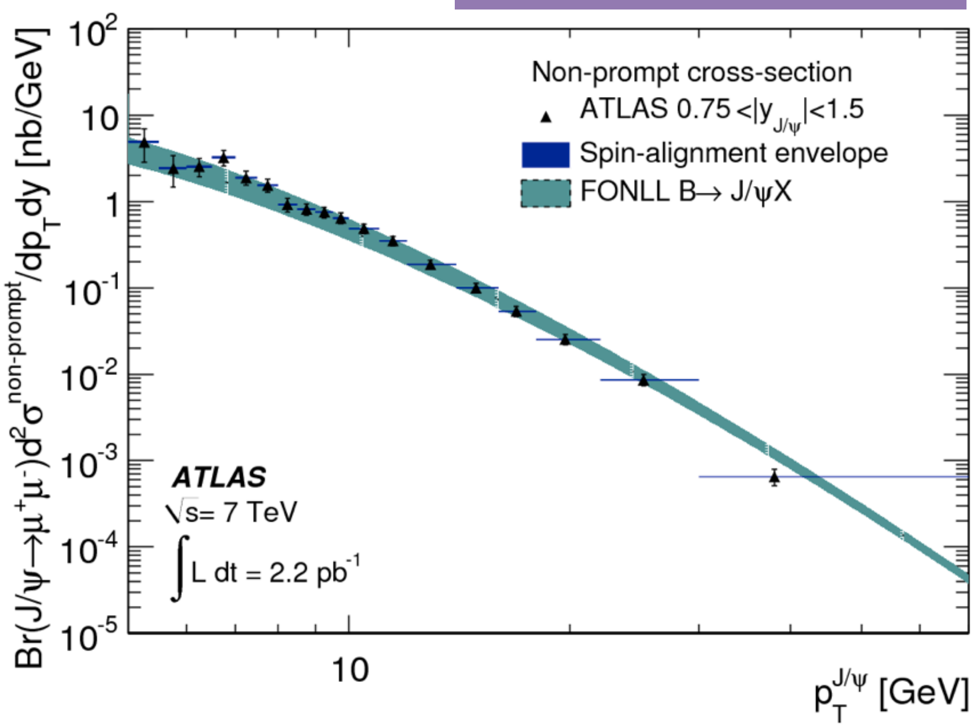

Comparison to FONLL predictions, in good agreement.

Prompt J/ψ differential cross section

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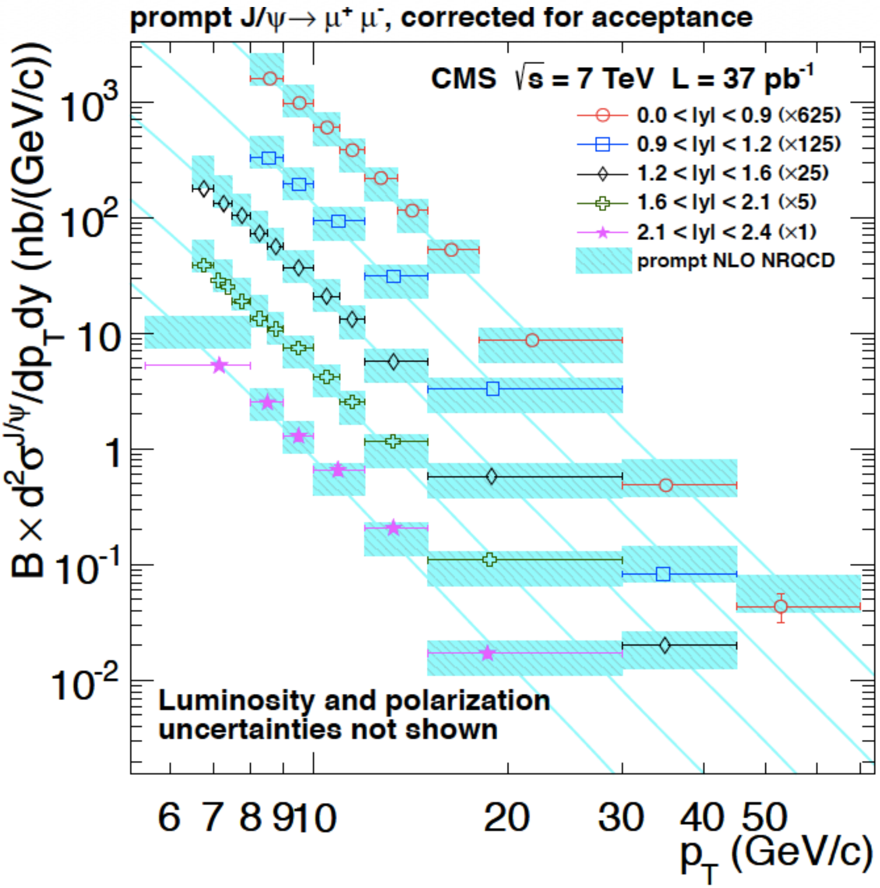
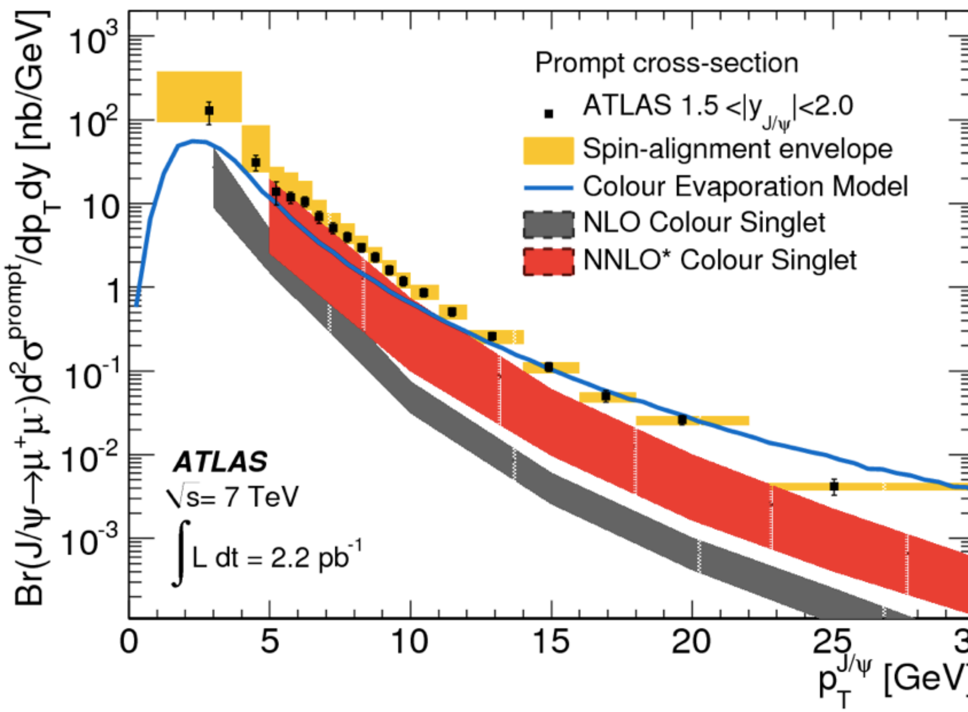
J/ψ

Nucl.Phys.B 850 (2011) 387



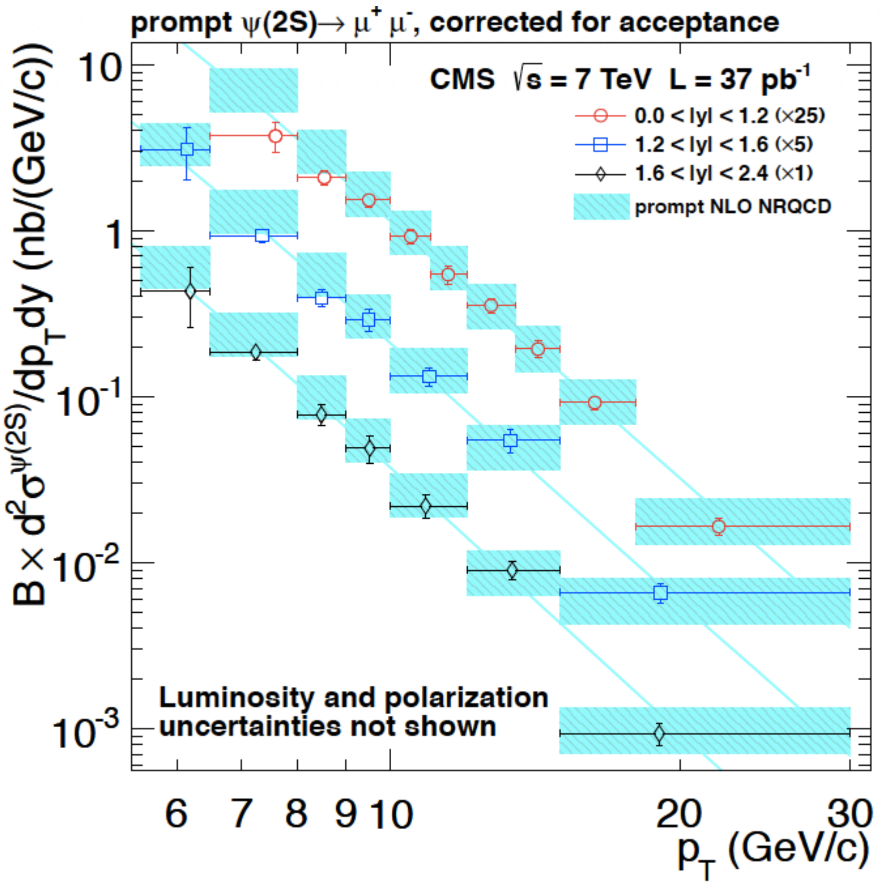


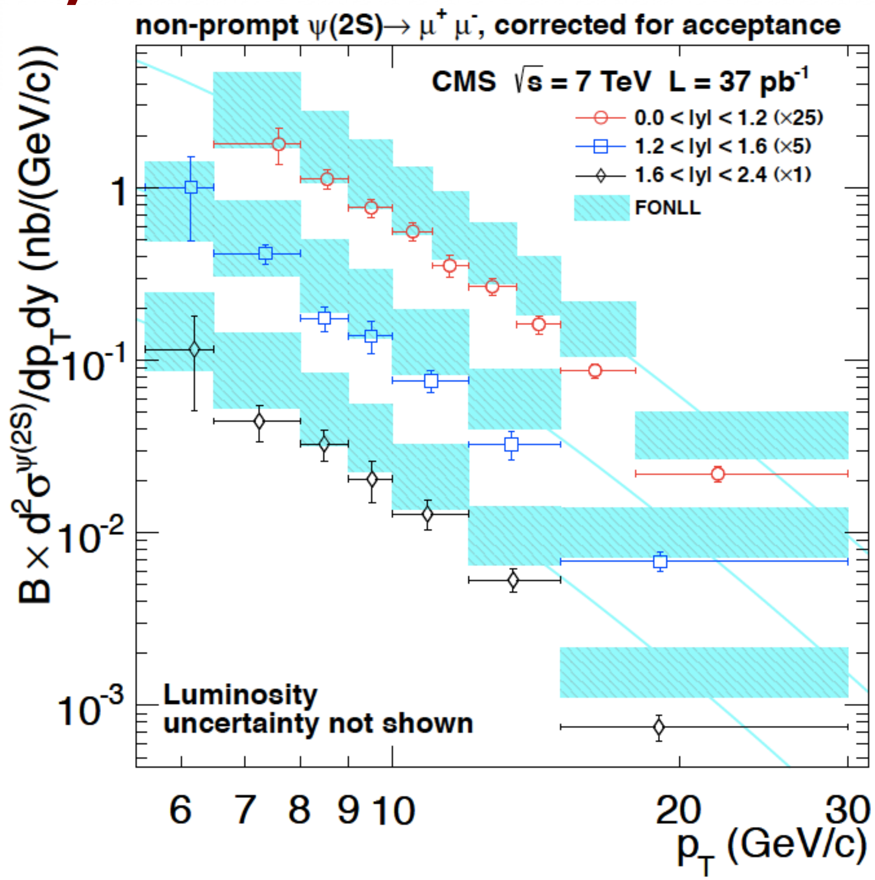
CMS in good agreement with NLO NRQCD with color octet contributions predictions.

Prompt and non-prompt ψ(2S) diff. cross section

JHEP 02 (2012) 011

ψ(2S)



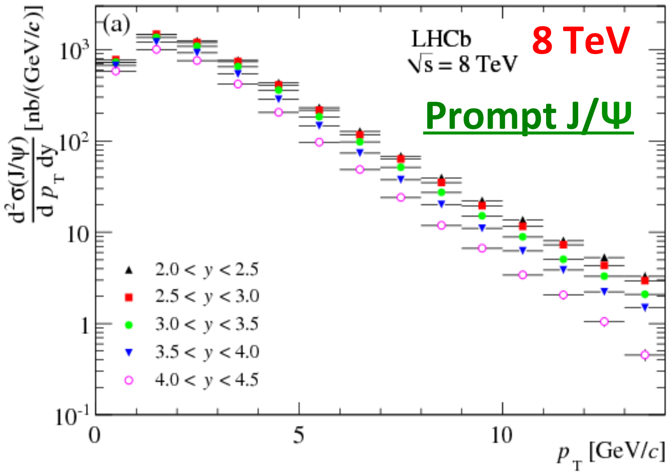


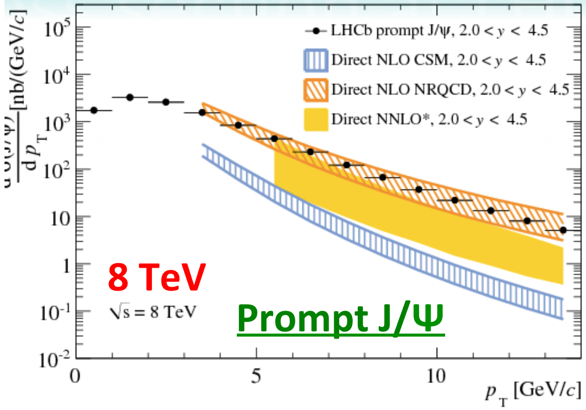
Excellent agreement with NLO NRQCD predictions

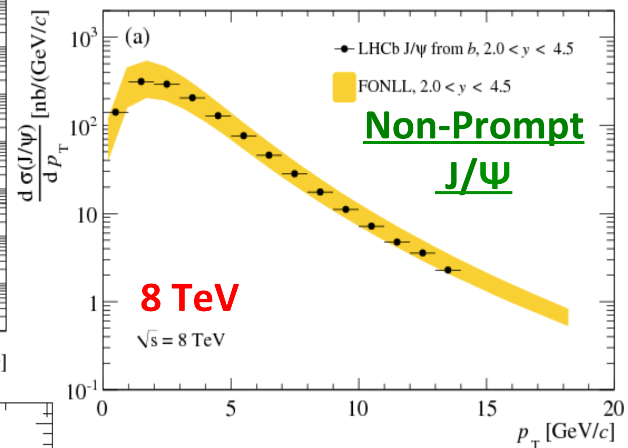
Comparison with FONLL predictions: overall shift

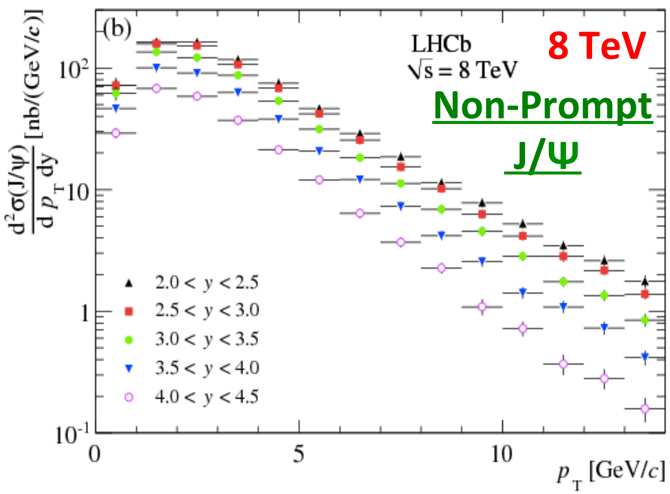
J/ψ and ψ (2S) cross section at LHCb

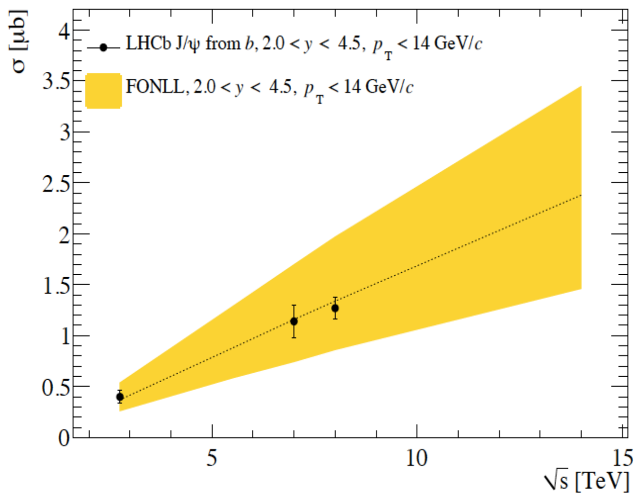
NEW

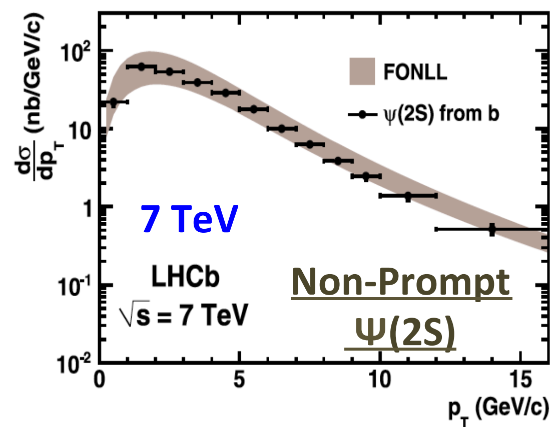












LHCb arXiv: 1304.6977

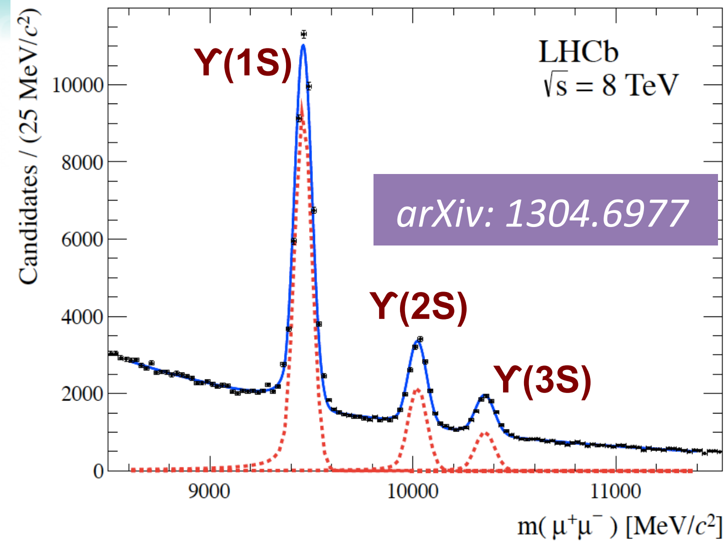
LHCb

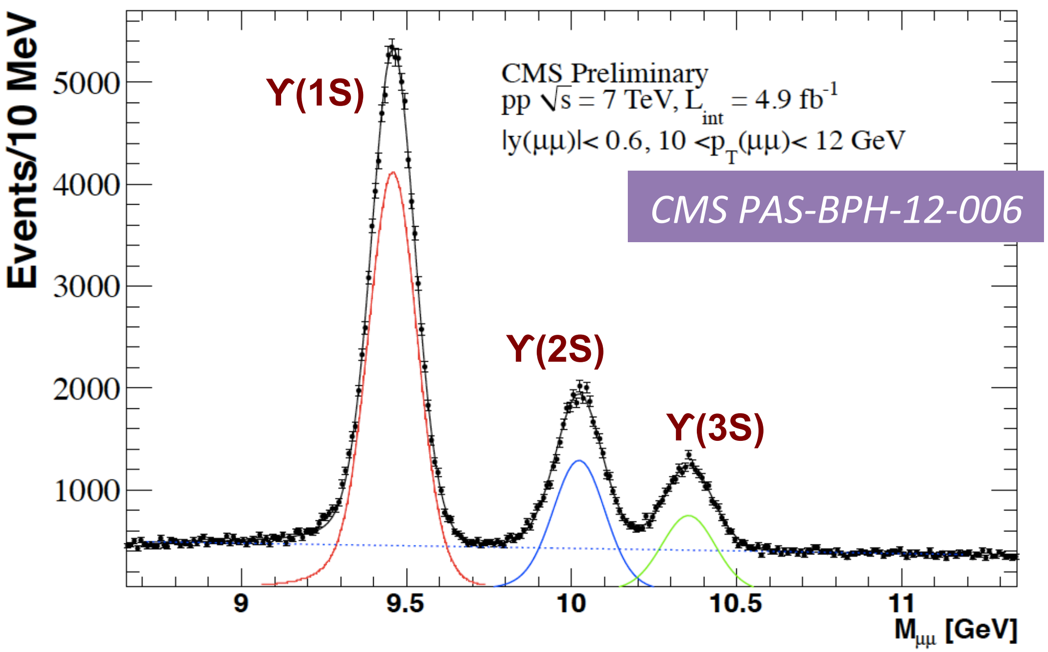
EPJ C 72 (2012) 2100

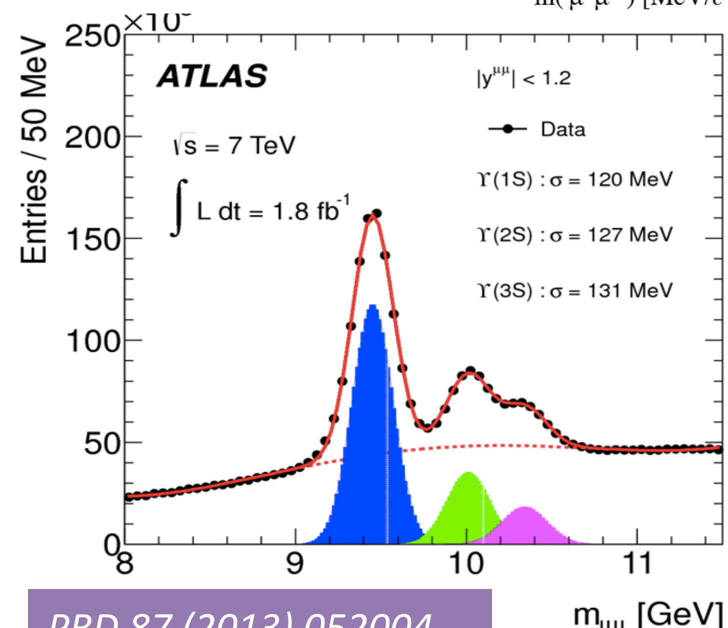
ϒ(nS) differential production cross section

ϒ(nS)→$\mu^+\mu^-$ decays

- Fiducial cross section → correcting only for reconstruction and trigger ε in a restricted phase-space
- Corrected cross section, correct also ϒ kinematic acceptance, full phase space
- Ratio $\sigma^{\Upsilon(2S)}/\sigma^{\Upsilon(1S)}$ and $\sigma^{\Upsilon(3S)}/\sigma^{\Upsilon(1S)}$



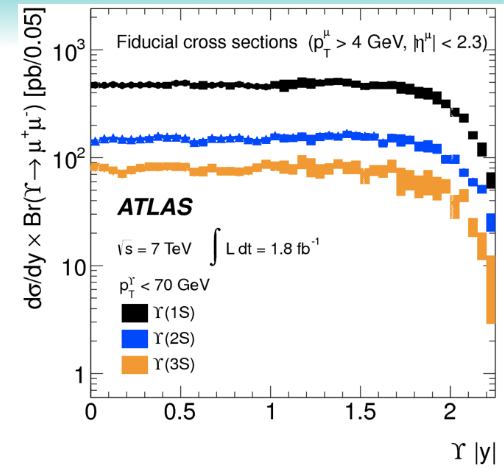


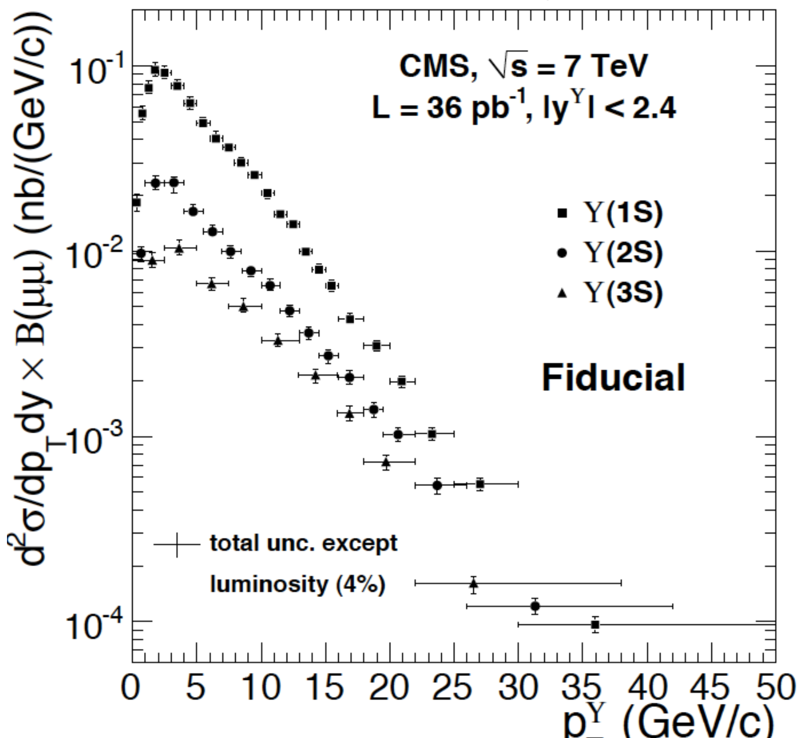


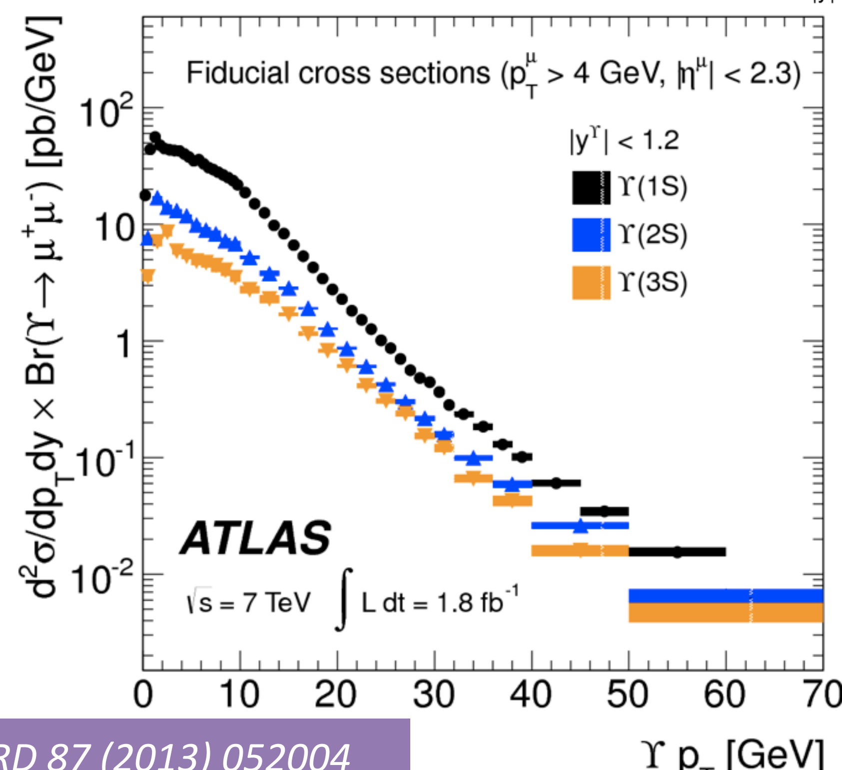
PRD 87 (2013) 052004

ϒ(nS) fiducial cross sections

- Precision measurement with largest p_T reach for quarkonia
- Free from theoretical uncertainties
- Useful for modeling of background, MC tuning; it can be used to allow polarization-independent theory comparisons.



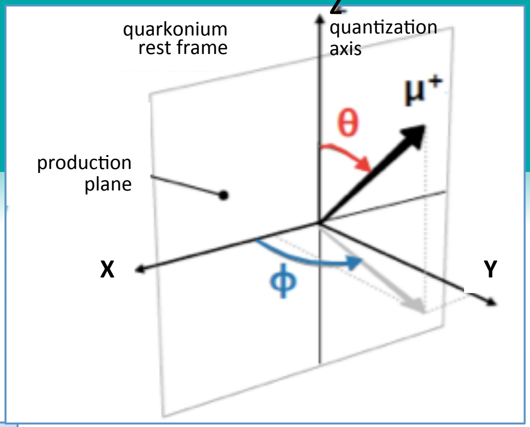




Acceptance corrections

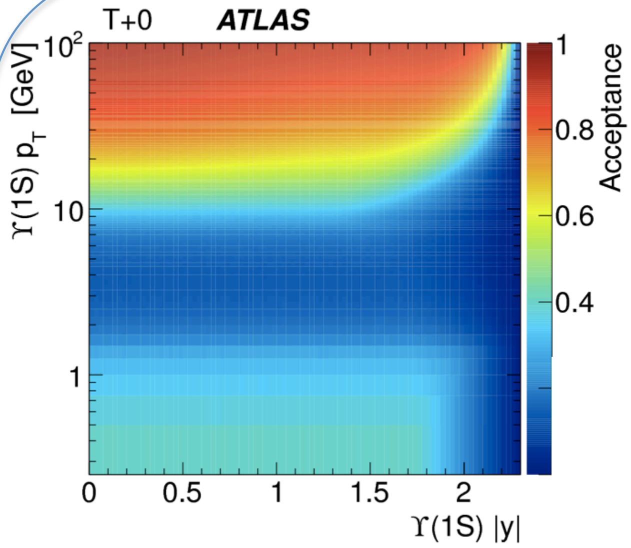
Acceptance corrections

- Acceptance depends on spin alignment/angular distribution of muons



$dN/d\Omega = dN/d\cos\theta\, d\phi = 1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\phi + \lambda_{\vartheta\phi} \sin 2\vartheta \cos\phi$

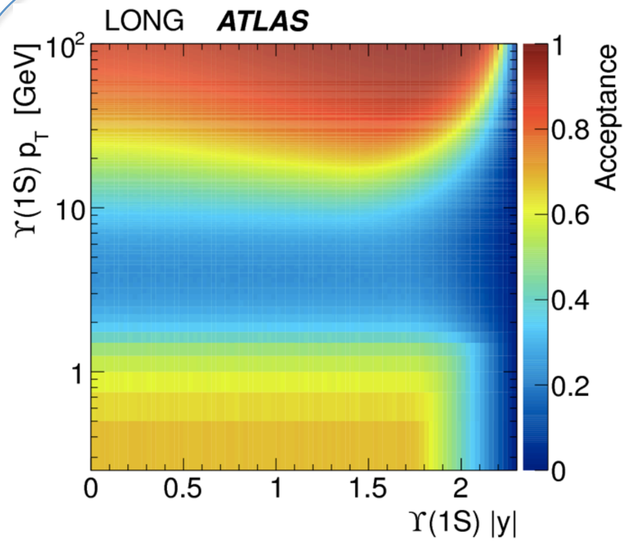
PRD 87 (2013) 052004



Transverse polarization
$J_z = \pm 1$

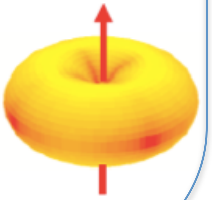
$\lambda_\theta = +1$
$\lambda_\phi = 0$
$\lambda_{\theta\phi} = 0$

$dN/d\Omega \approx 1 + \cos^2\vartheta$



Longitudinal polarization
$J_z = 0$

$\lambda_\theta = -1$
$\lambda_\phi = 0$
$\lambda_{\theta\phi} = 0$



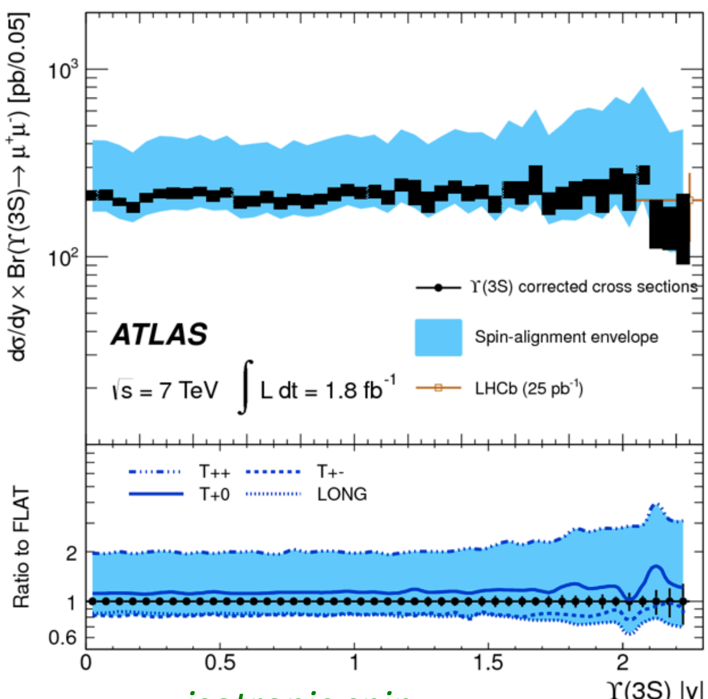
$dN/d\Omega \approx 1 - \cos^2\vartheta$

$\Upsilon(nS)$ corrected cross sections

PRD 87 (2013) 052004

CMS PAS-BPH-12-006

- Corrected for muon fiducial acceptance cuts
- Acceptance depends on spin alignment/angular distribution of muons
- Can be compared with theory
- Null polarization hypothesis: spin alignment envelop by far dominating systematic uncertainties.



[isotropic spin-alignment scenario]

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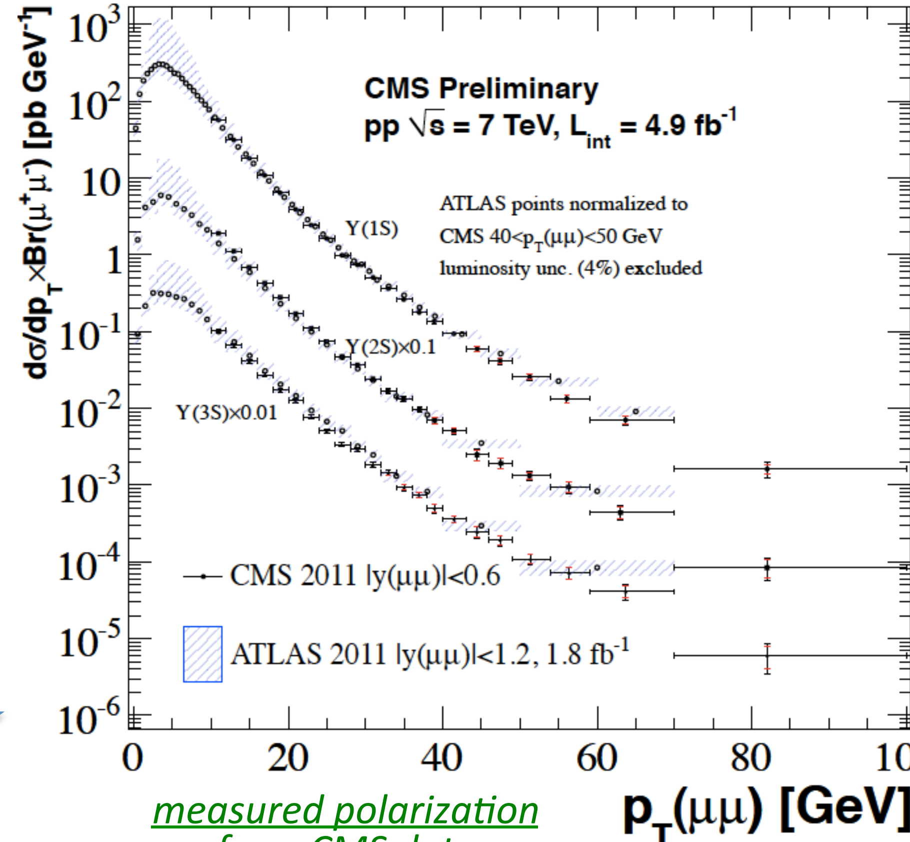
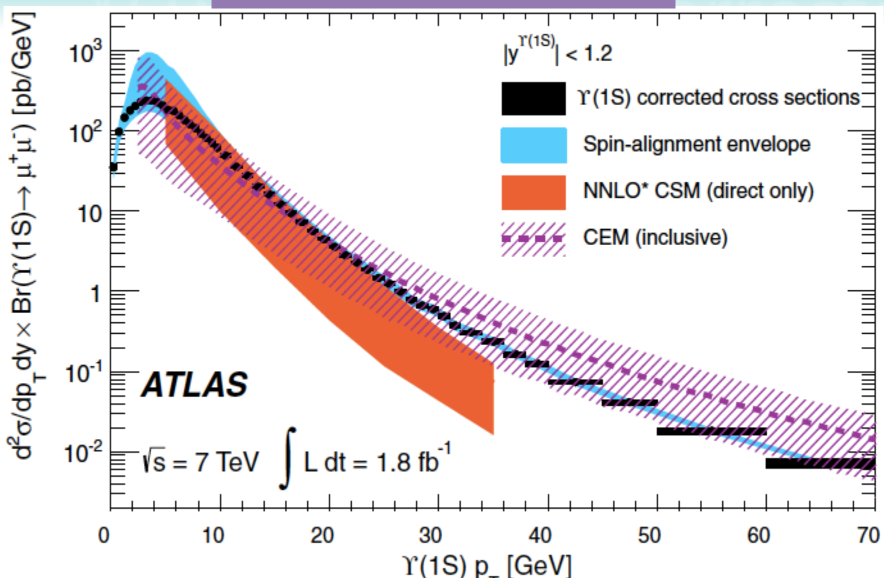


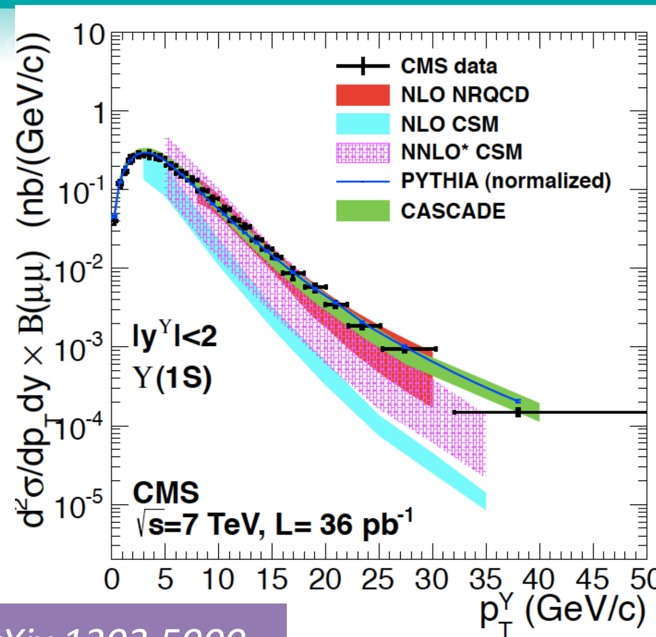
[measured polarization from CMS data]

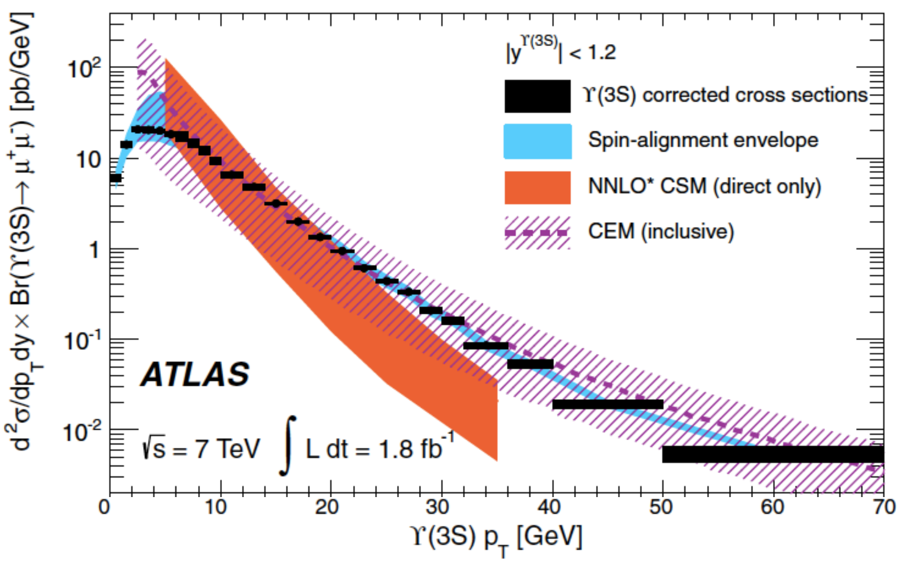
ϒ(1S) and ϒ(3S) corrected cross sections

NEW

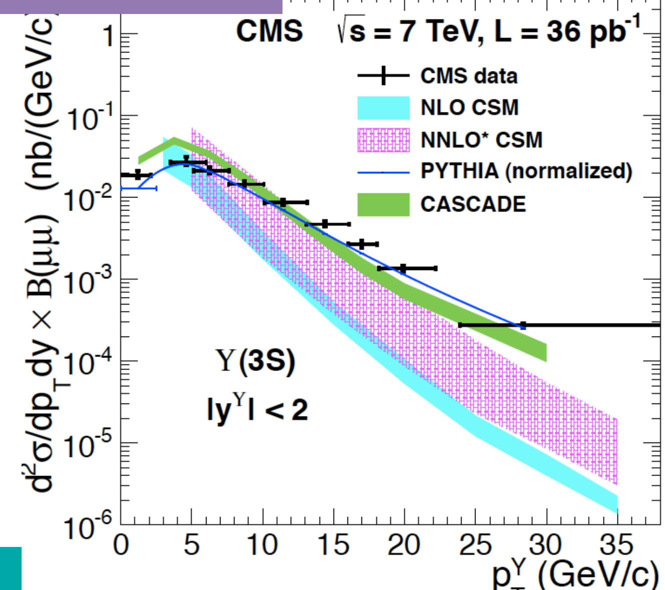
PRD 87 (2013) 052004





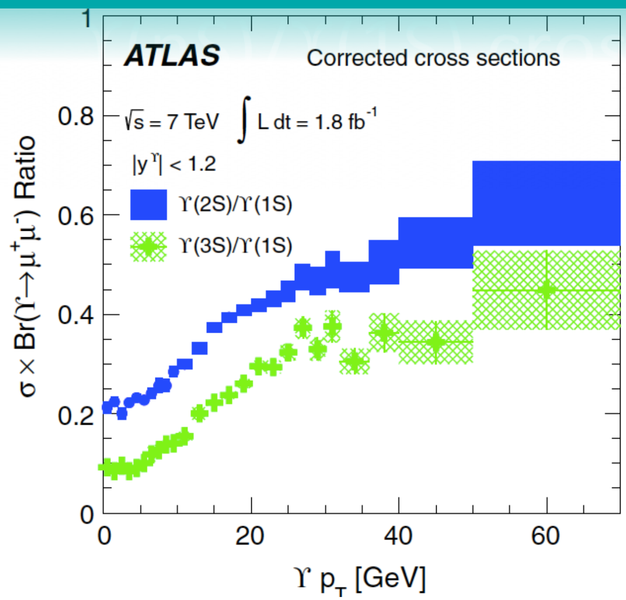


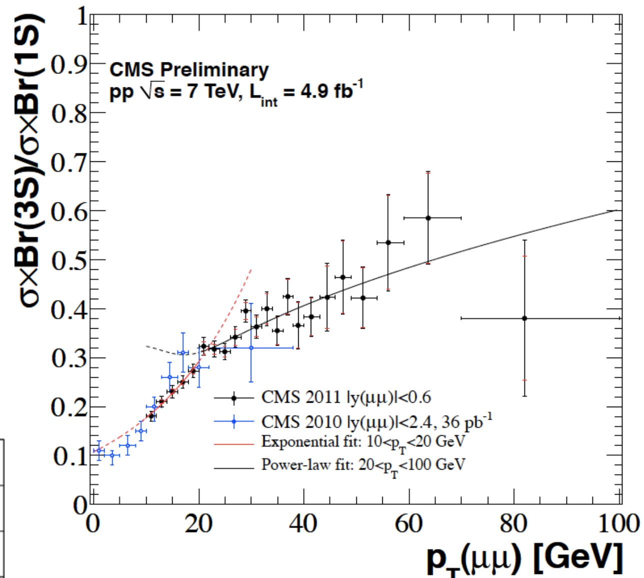
CMS: arXiv 1303.5900



Υ(nS)/Υ(1S) cross section ratios

Systematic uncertainties cancel in the ratio
→ precise measurement





- Strong dependence from p_T , increasing with p_T but seems to flatten at high p_T

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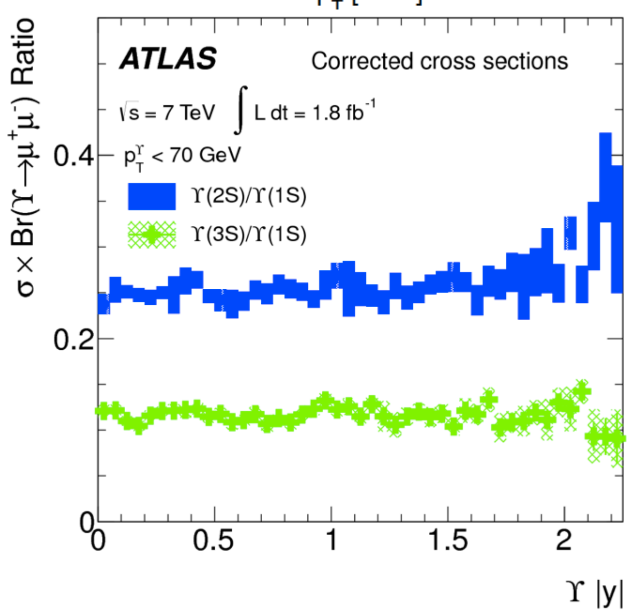
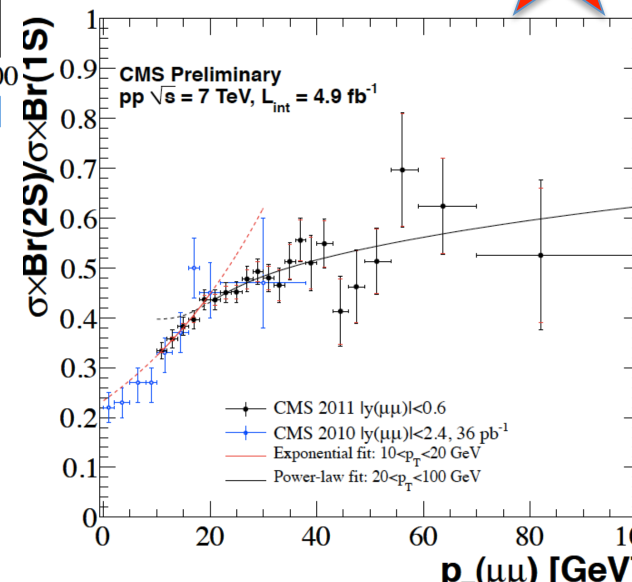


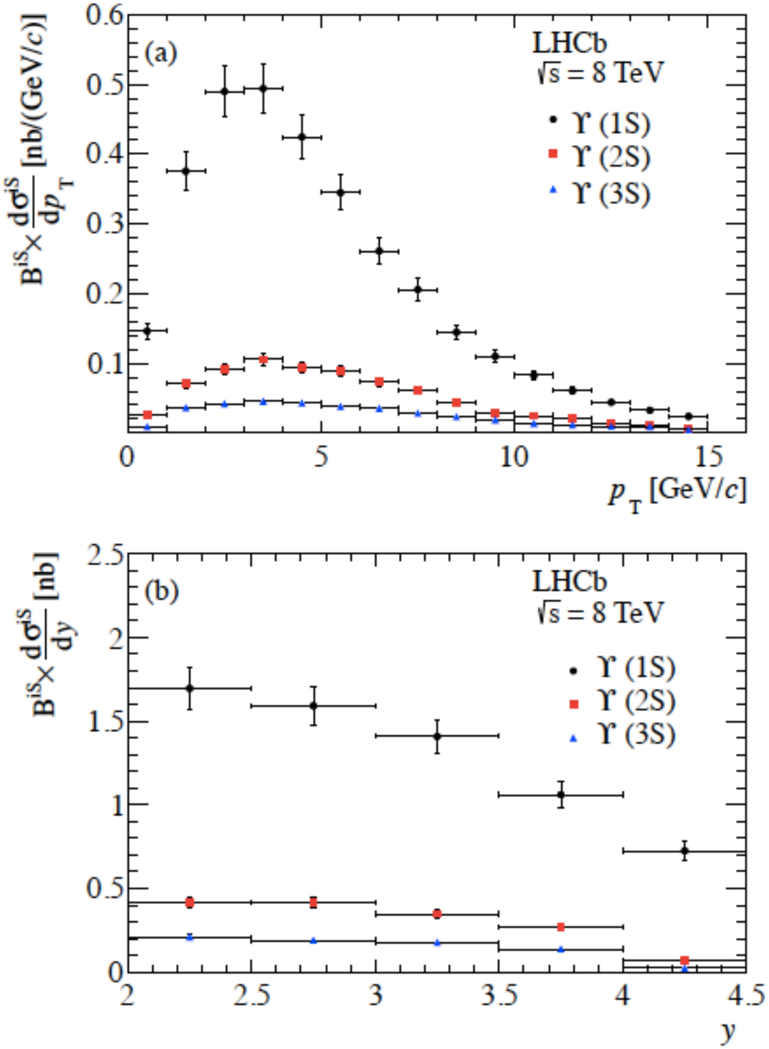
- Instead production vs. rapidity is quite flat



Υ(nS) production at LHCb

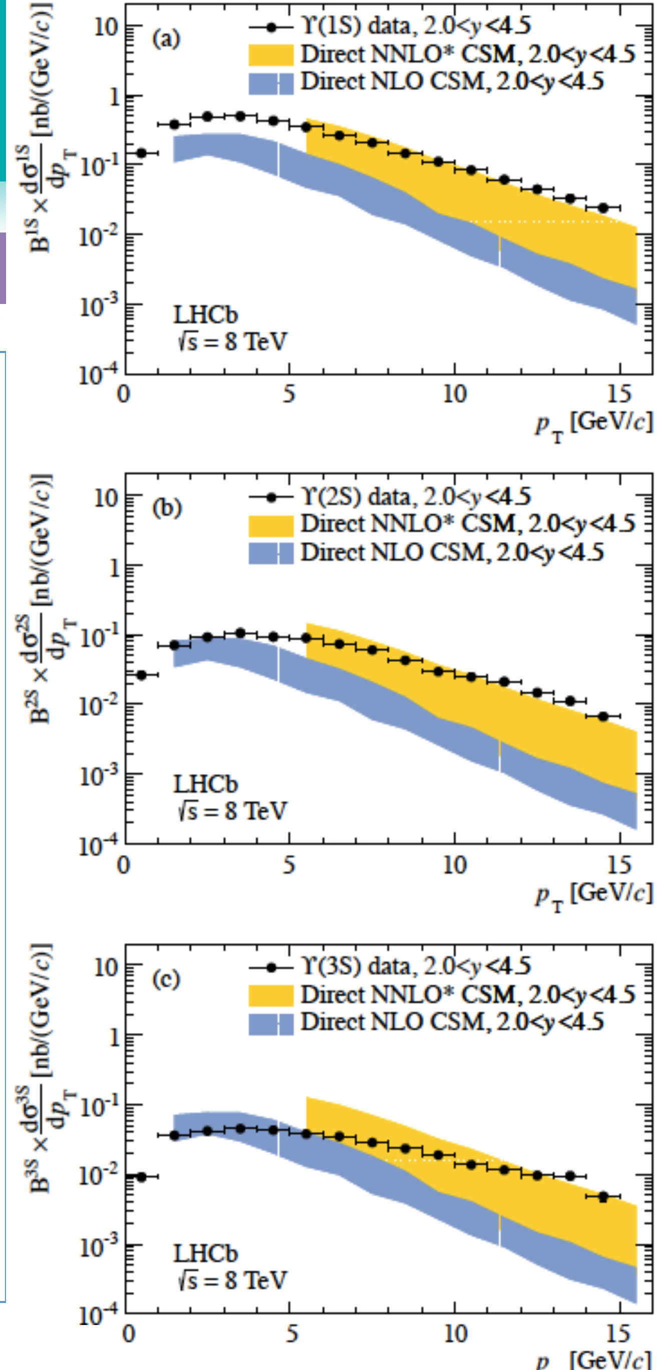
NEW

LHCb: arXiv 1304.6977

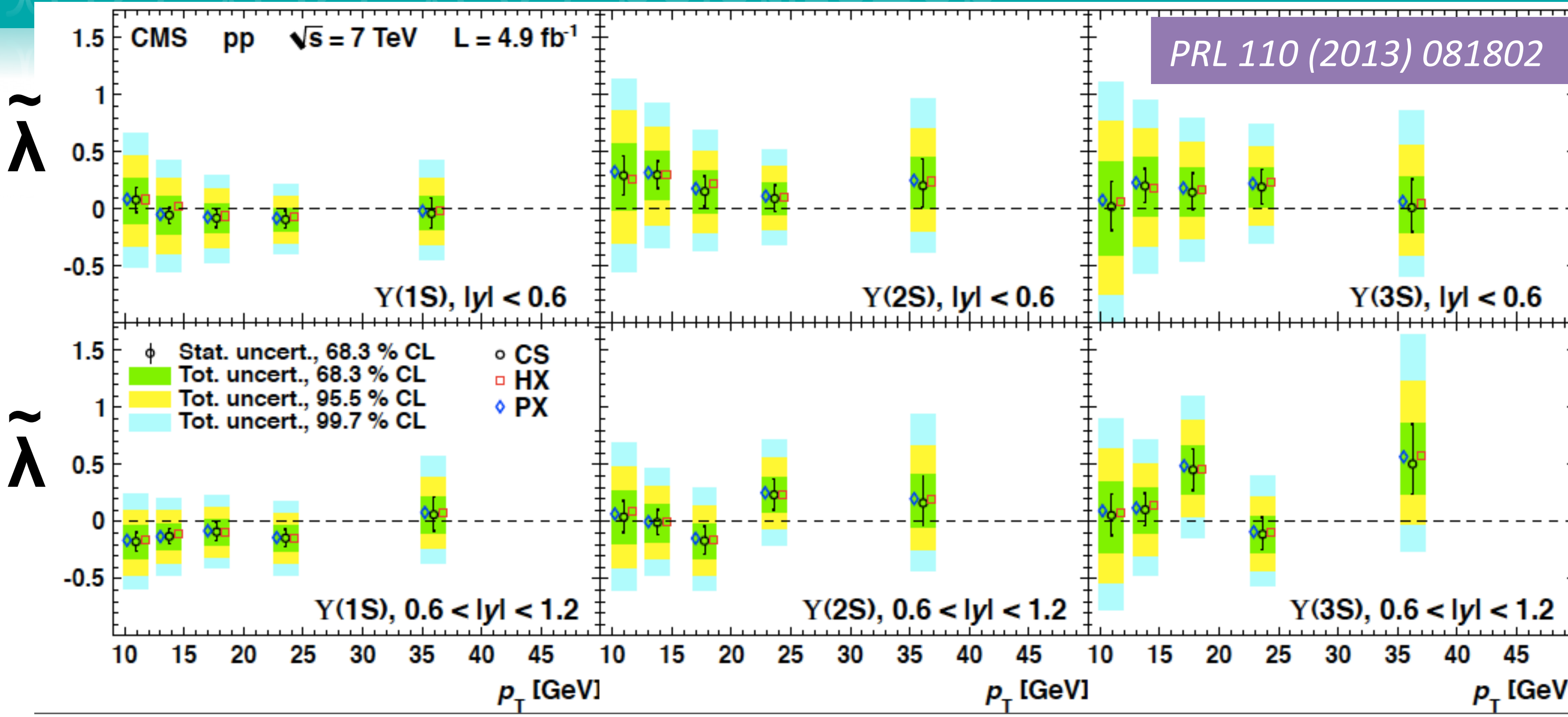


NNLO* CSM describe at first order the p_T shape and normalization

Feed down from P-wave and higher S-wave not included in calculations



Υ(1S), Υ(2S), Υ(3S) polarization

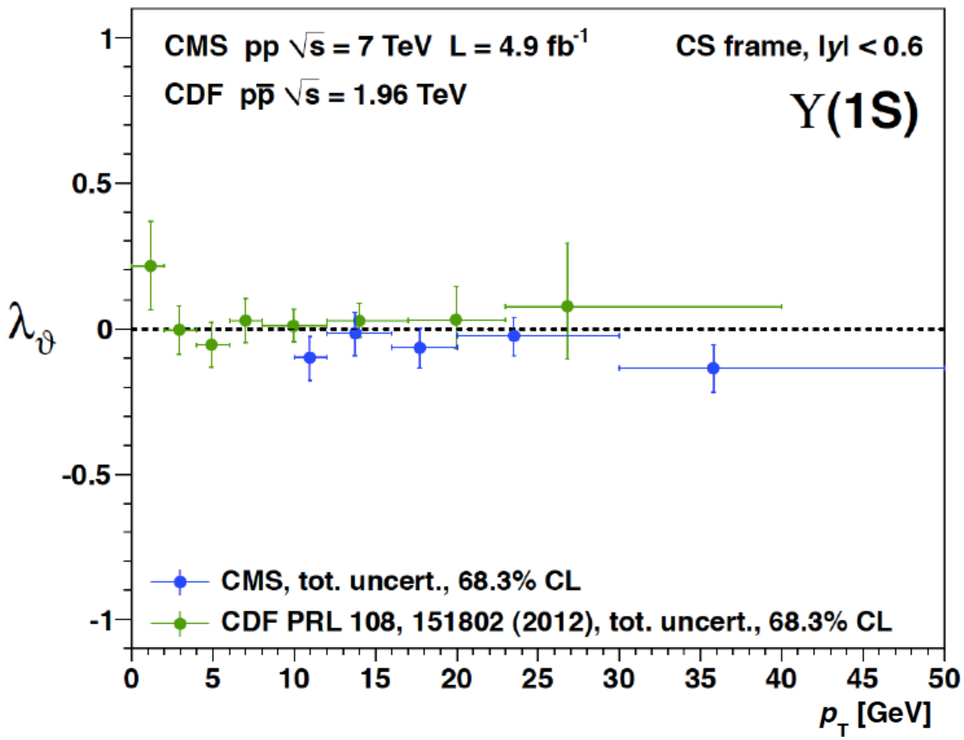


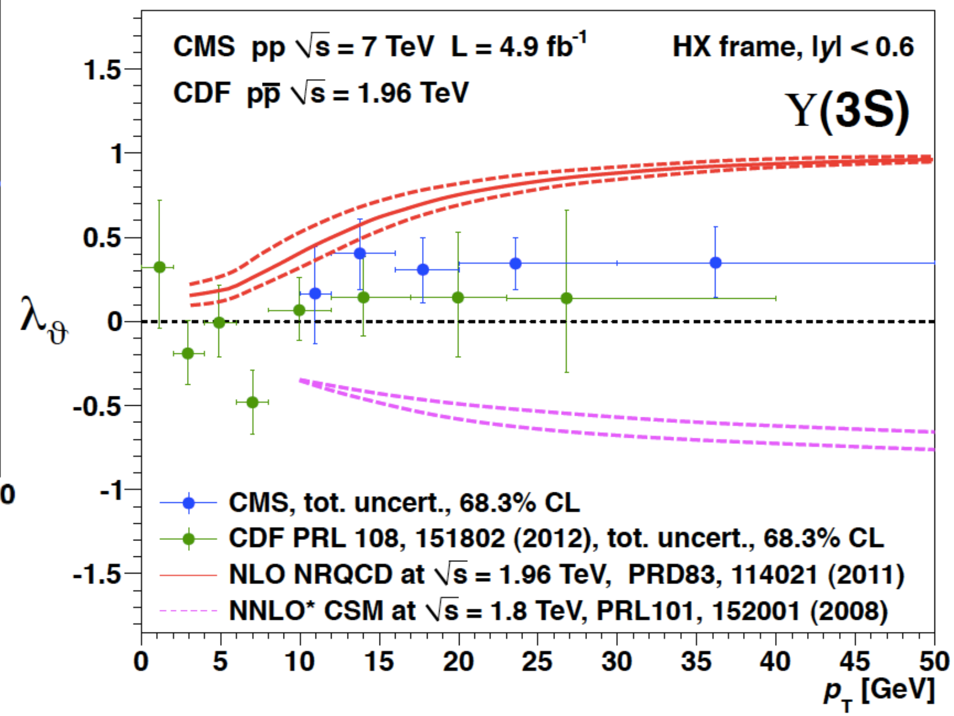
Data sample of **Υ(nS)→μ⁺μ⁻** decays: 8.5<M<11.5 and from a common vertex. The polarization parameters λ_ϑ, λ_ϕ, $\lambda_{\vartheta\phi}$ and the frame-invariant $\tilde{\lambda}=(\lambda_\vartheta + 3\lambda_\phi)/(1-\lambda_\phi)$ are measured for $p_{T\,Y(nS)}$=[10, 50 GeV], and in two rapidity regions (|y|<0.6 and 0.6<|y|<1.2). Angular distributions are analyzed in three different polarization frames: HX, CS, PX

No evidence of sizable transverse or longitudinal polarizations.

Measurement of Υ(1S), Υ(2S), Υ(3S) polarization

PRL 110 (2013) 081802





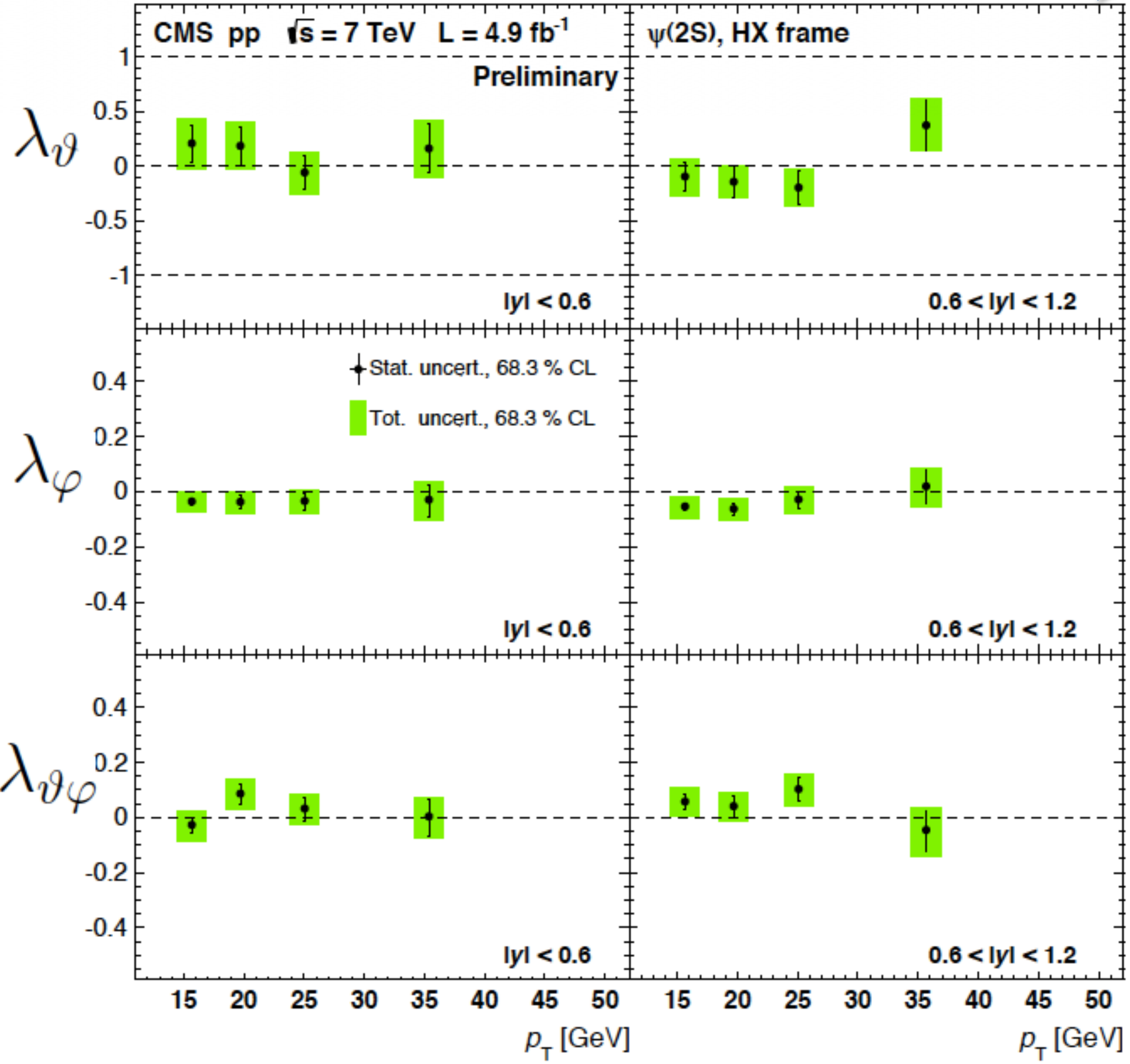
No evidence of significant transverse or longitudinal polarizations.

Agreement with CDF PRL 108 (2012) 151802

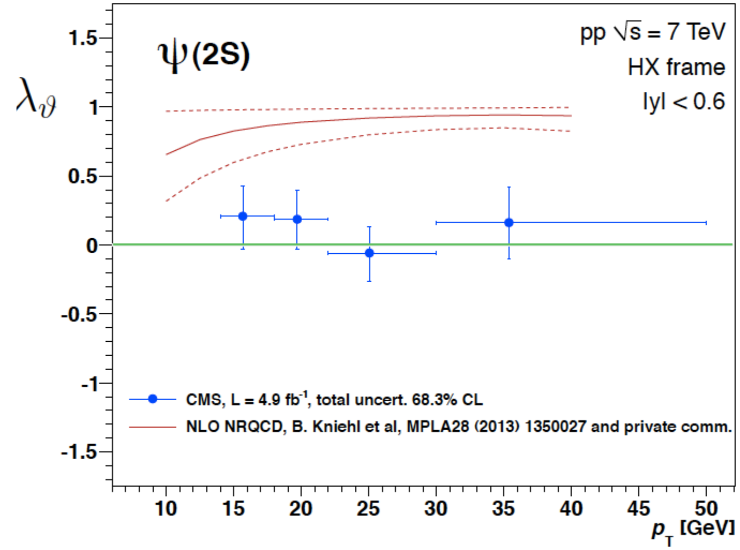
ψ(2S) polarization

NEW

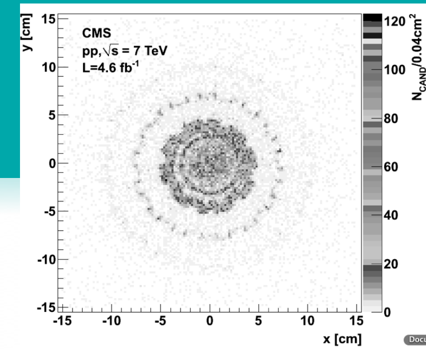
CMS-BPH-2013-003



No evidence of significant transverse or longitudinal polarizations and **in this case there is no feed-down from heavier quarkonia.**



P-wave Onia: $\chi_c(nP)$ and $\chi_b(nP)$

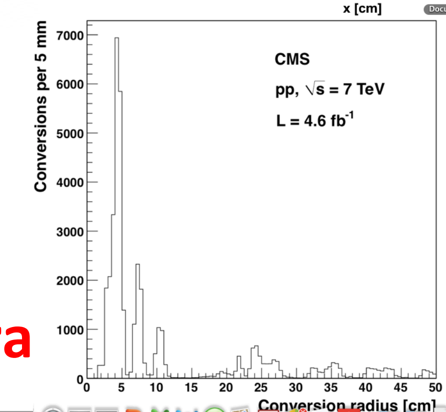


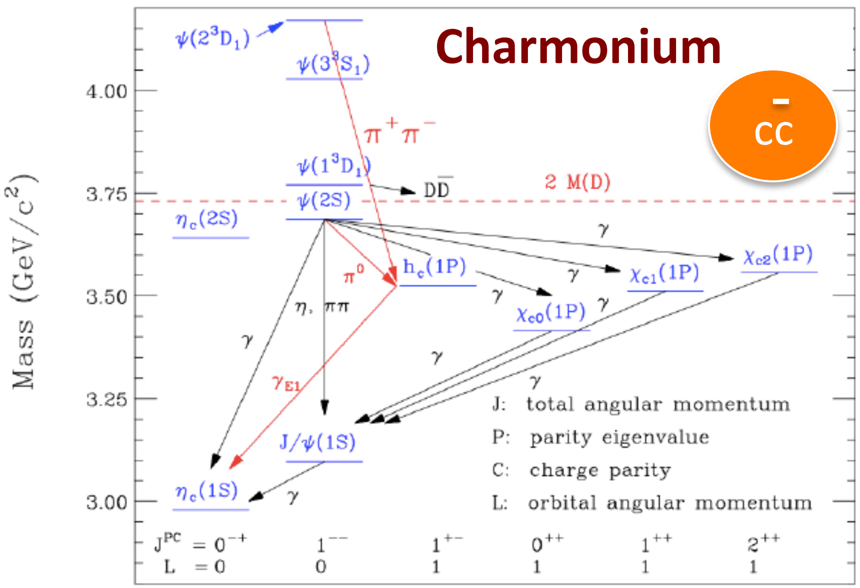
Provide tests of CS and CO production mechanism:

- measurement of ratios of $\chi_{c,bJ}$(J=0,1,2) spin states

Polarization measurements:

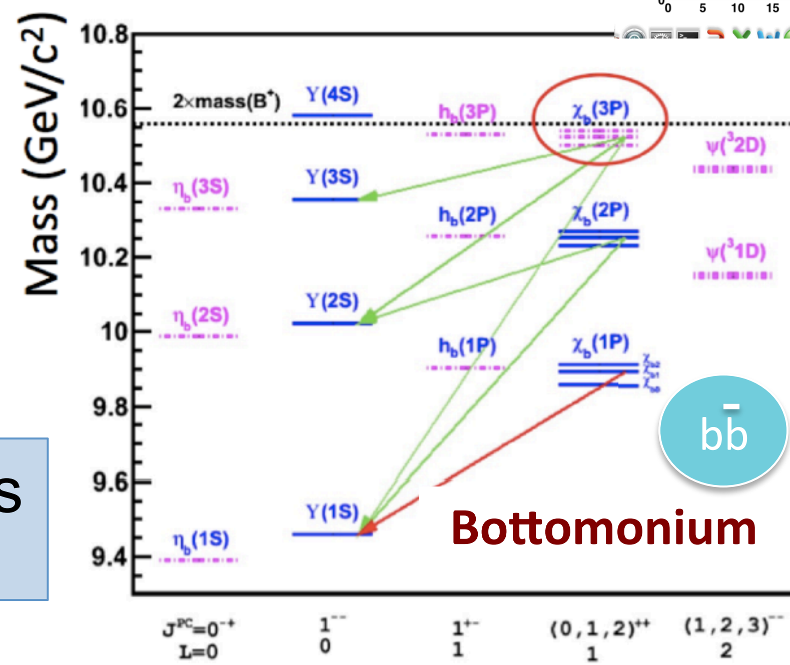
- feed-down fractions ($\chi_c \rightarrow J/\psi$; $\chi_b \rightarrow \Upsilon$)





EPJ C 72 (2012) 2251

Very simplified spectra

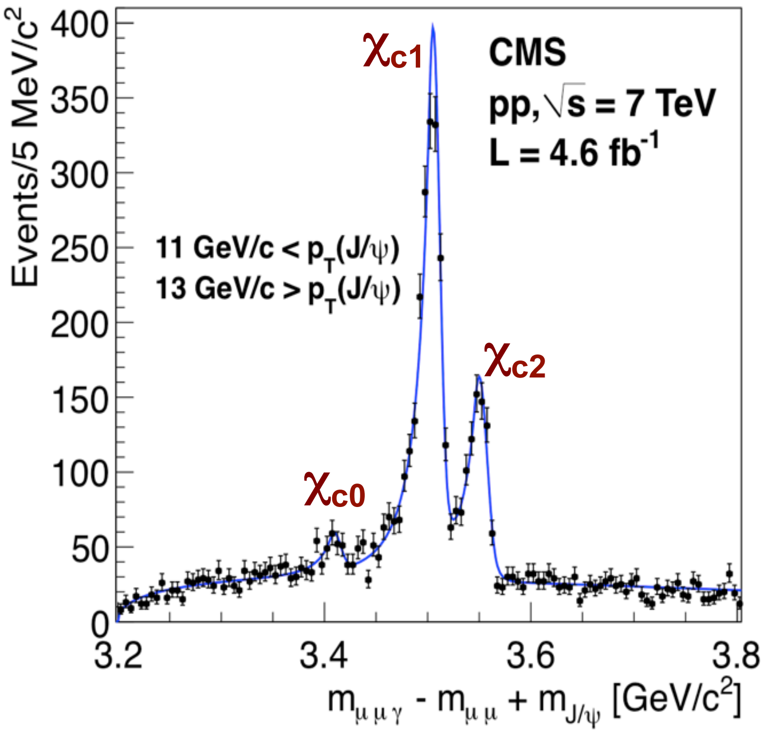


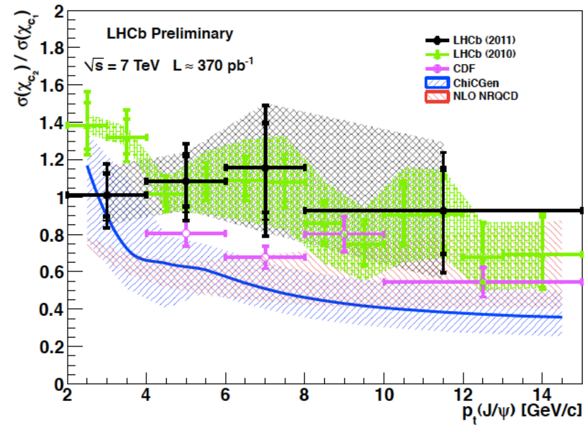
$\chi_c \rightarrow J/\psi\ \gamma$ and $\chi_b \rightarrow \Upsilon\gamma$ decays

γ converted to e^+e^-

χ_{cJ}(3P) charmonium states and prompt prod. ratio

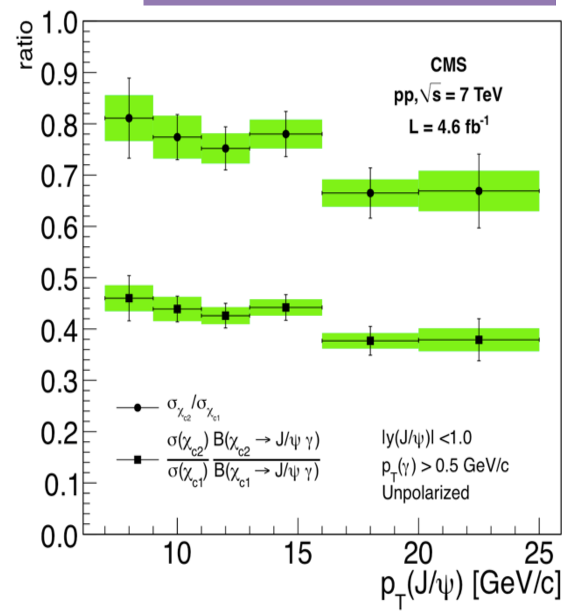
$\chi_c \rightarrow J/\psi(\mu^+\mu^-)\ \gamma$ (un/converted to e^+e^-)





LHCb-CONF-2011-062

EPJ C 72 (2012) 2251



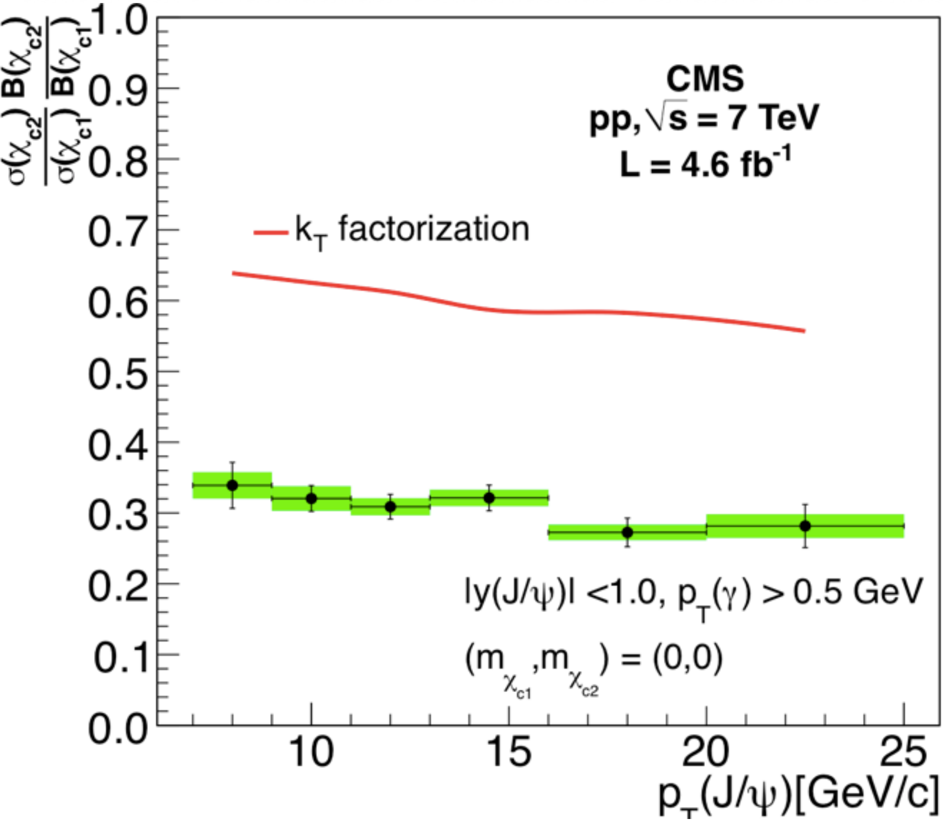
$$R_p = \frac{\sigma(pp \rightarrow \chi_{c2}+X)\ BR(\chi_{c2} \rightarrow J/\psi+\gamma)}{\sigma(pp \rightarrow \chi_{c1}+X)\ BR(\chi_{c1} \rightarrow J/\psi+\gamma)} = \frac{N_{\chi c2}}{N_{\chi c1}}\ \frac{\varepsilon_1}{\varepsilon_2}$$

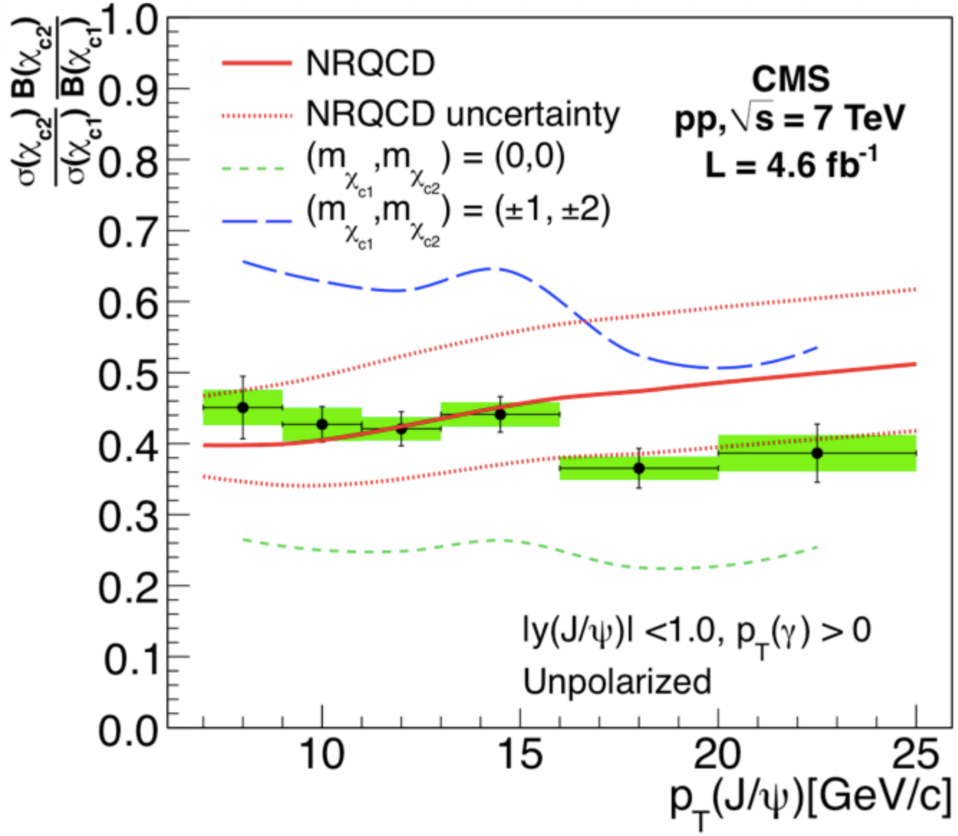
5.6% error from BR not included

Relative χ_{c2}/χ_{c1} prompt production ratio

Comparison to theories

EPJ C 72 (2012) 2251





Acceptance correction applied for 0 helicity hypothesis in k_T factorisation

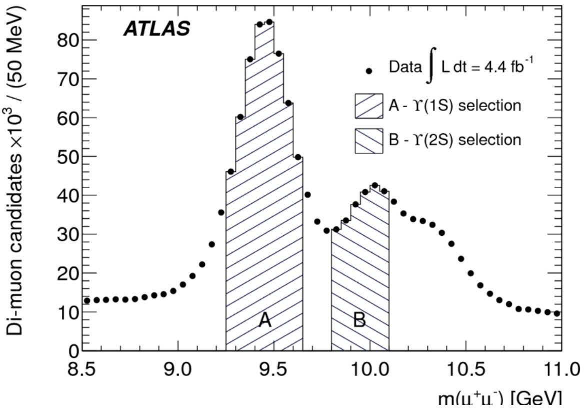
Acceptance correction to match calculation

kT fact: PRD 83 (2011) 034035

NRQCD: PRD 83 (2011) 111503

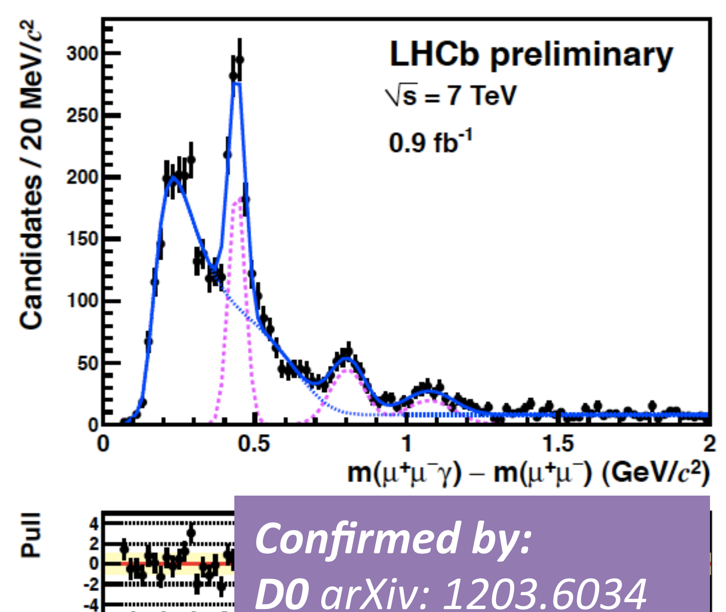
First observation of the χ_{bJ}(3P) bottomonium state

New state interpreted as χ_b(3P). Production through radiative transitions to ϒ(1S) and ϒ(2S) in two independent analysis channels.

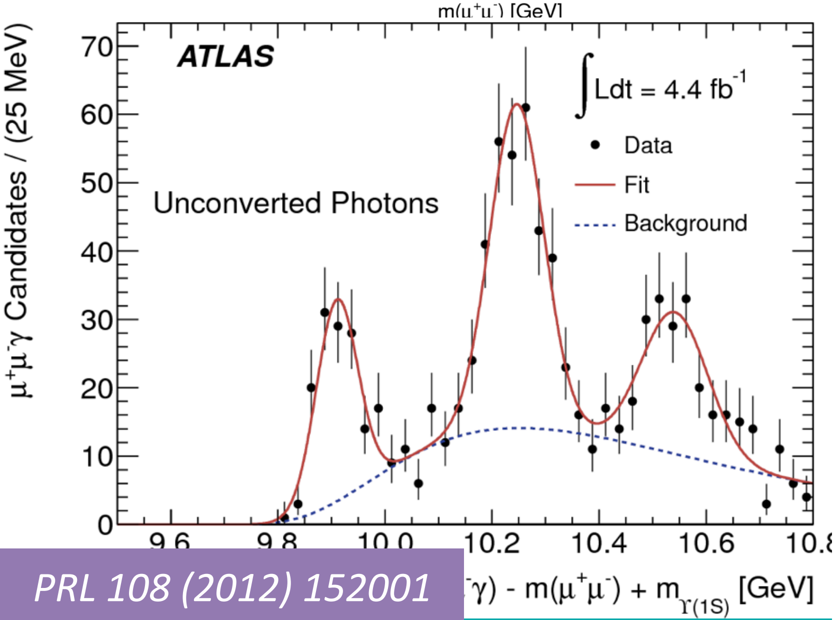


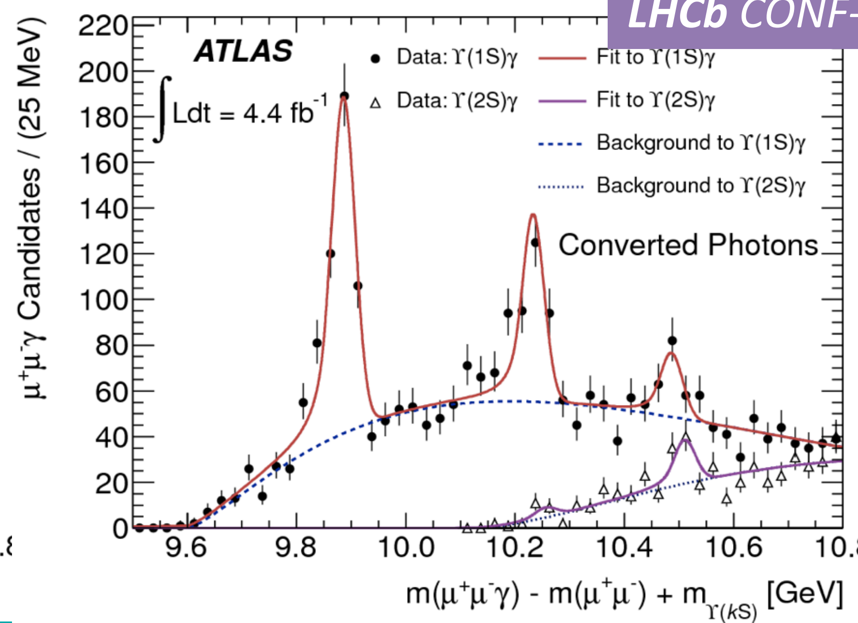
$M_{\chi b(3P)}$=10.530 ±0.005$_{stat}$ ±0.009$_{syst}$ GeV

mass is consistent with prediction from potential model (splitting ≈10-20 MeV



Confirmed by:
D0 arXiv: 1203.6034
LHCb CONF-2012-020



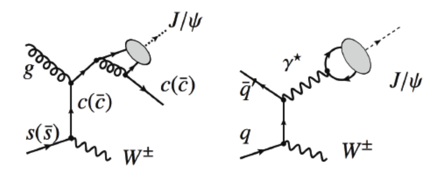


PRL 108 (2012) 152001

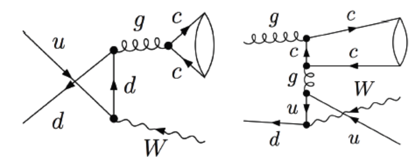
Prompt J/ψ + W associate production

Probes production modes, test theoretical predictions (and Color Octet vs Color Singlet Model)

In associated production J/ψ + W, the lowest order diagrams suggest that a better discrimination between the models may be possible.



LO CSM (SINGLET) arXiv:1303.5327



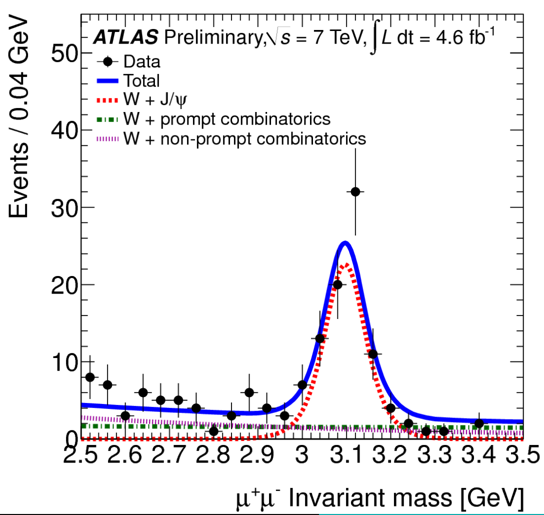
NLO COM (OCTET) arXiv:1304.4670

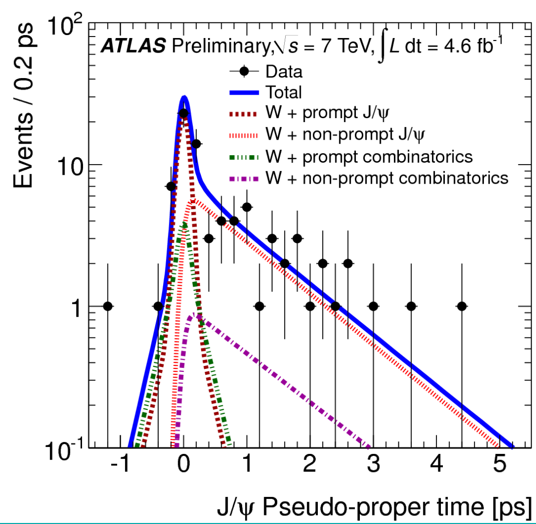
Favored diagram

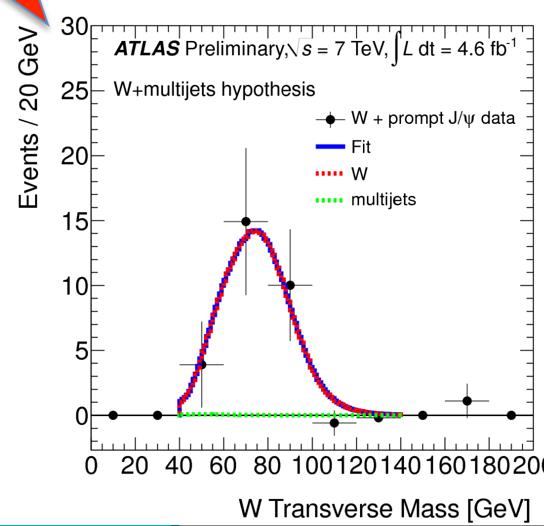
NEW

ATLAS-CONF-2013-042

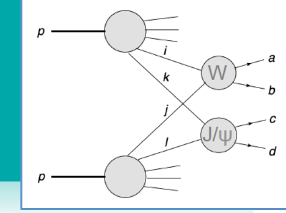
Unbinned max.likelihood fit to J/ψ mass and lifetime.
Background at 5.3 σ level.





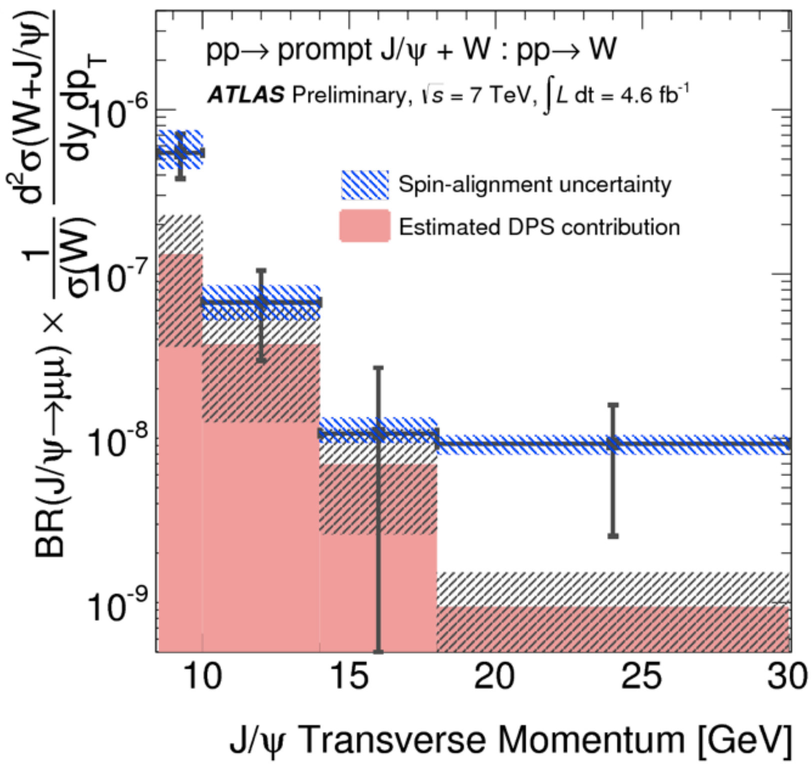


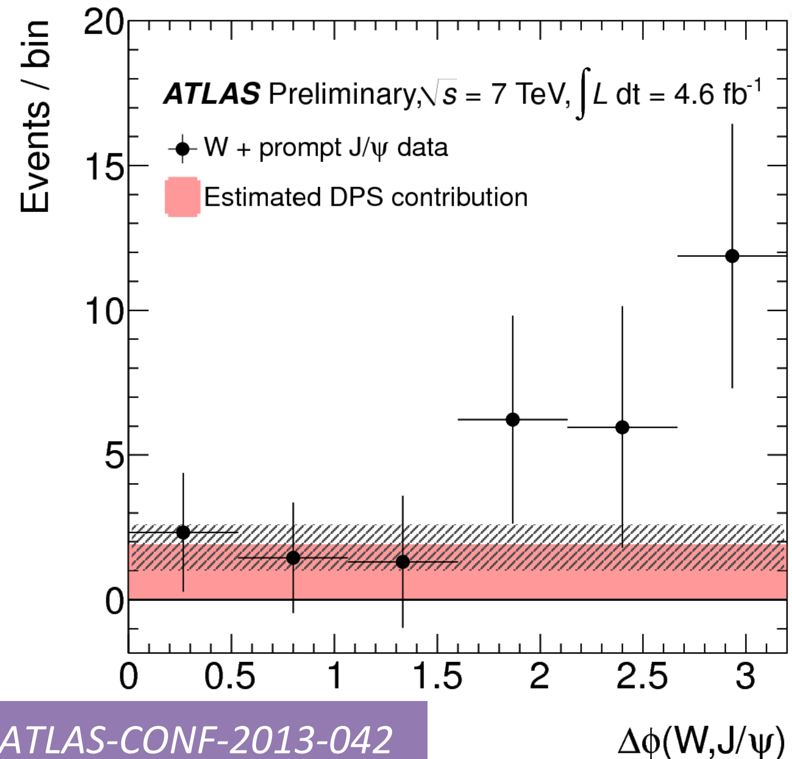
Prompt J/ψ + W associate production



Correct fiducial cross-section for muon acceptance from J/ψ decay to compare with theory (as for Upsilon analysis). Double Parton Scattering can contribute to signal.

NEW





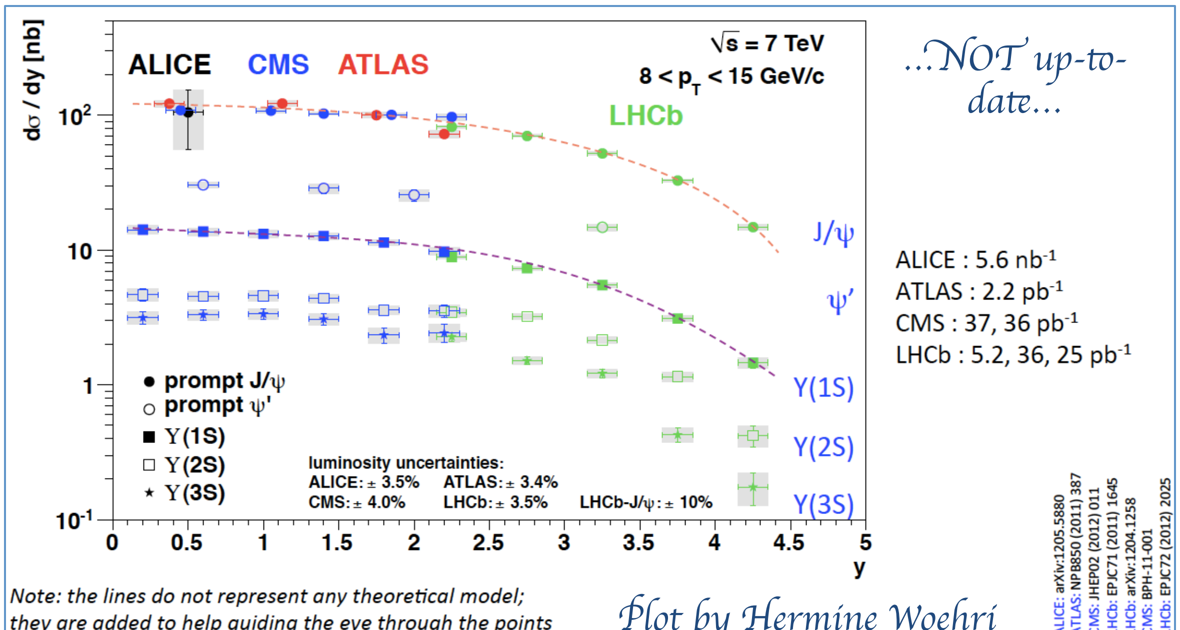
ATLAS-CONF-2013-042

J/ψ+W produced at relative rate of 10^{-5} of W production (w/o BR to $\mu^+\mu^-$), evidence >5 σ

Both single and double parton scattering components observed in the data (f_{DPS}~40%)

Conclusions

- NRQCD has problem in explaining both quarkonium production and polarization
- ϒ(3S) and ψ(2S) polarization measurements at high p_T and high p_T/m do not show the predicted strong transverse polarization of directly produced J=1 S-wave quarkonia.



Future:

- J/ψ polarization at 7 TeV up to large p_T
- 20/fb of data at 8TeV
- can try the challenging measurement of the χ_c and χ_b polarization

Thank you for your attention

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

http://lhcb.web.cern.ch/lhcb/Physics-Results/LHCB-Physics-Results.html