Quarkonium cross sections in pp collisions with CMS

Quarkonium 2016, Richland

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on behalf of the CMS collaboration

HEPHY Vienna

June 06, 2016

*supported by
Austrian Science Fund (FWF): P28411-N36

Published or new CMS results since QWG 2014

- $\chi_{b2}(1P)/\chi_{b1}(1P)$ cross section ratios at 8 TeV — PLB **743** (2015) 383
- Prompt J/ψ and $\psi(2S)$ cross sections at 7 TeV — PRL **114** (2015) 191802
- $\Upsilon(nS)$ $(n = 1, 2, 3)$ cross sections at 7 TeV — PLB **749** (2015) 14
- S–wave quarkonium cross sections at 13 TeV — CMS PAS-BPH-15-005

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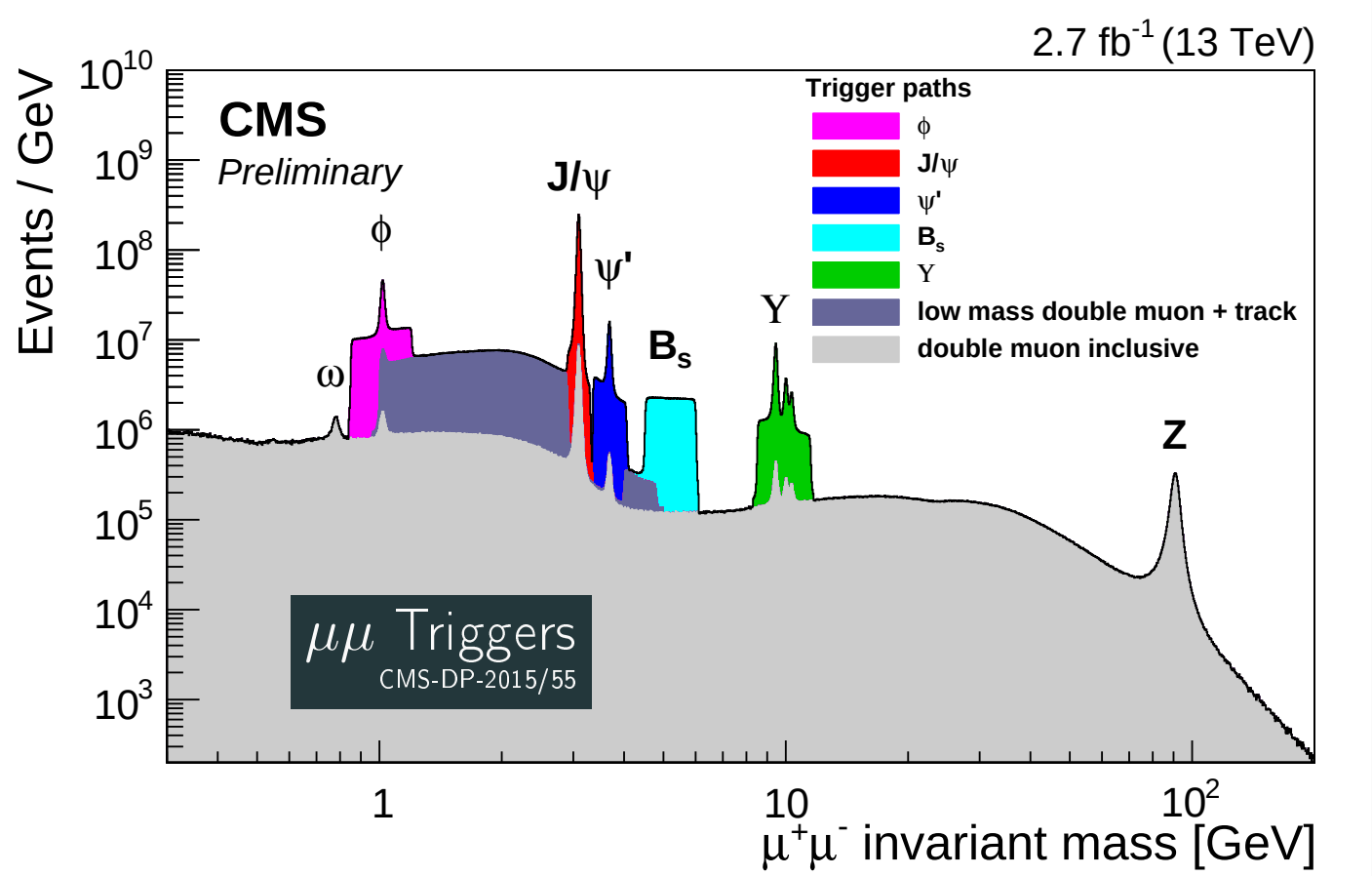
Focus on S–wave quarkonium states at 7 and 13 TeV in this talk

Quarkonium reconstruction with CMS

Dimuon spectrum and triggers at 13 TeV



Colored: Dedicated triggers with (e.g.) opposite charge, p_T and invariant mass region requirements

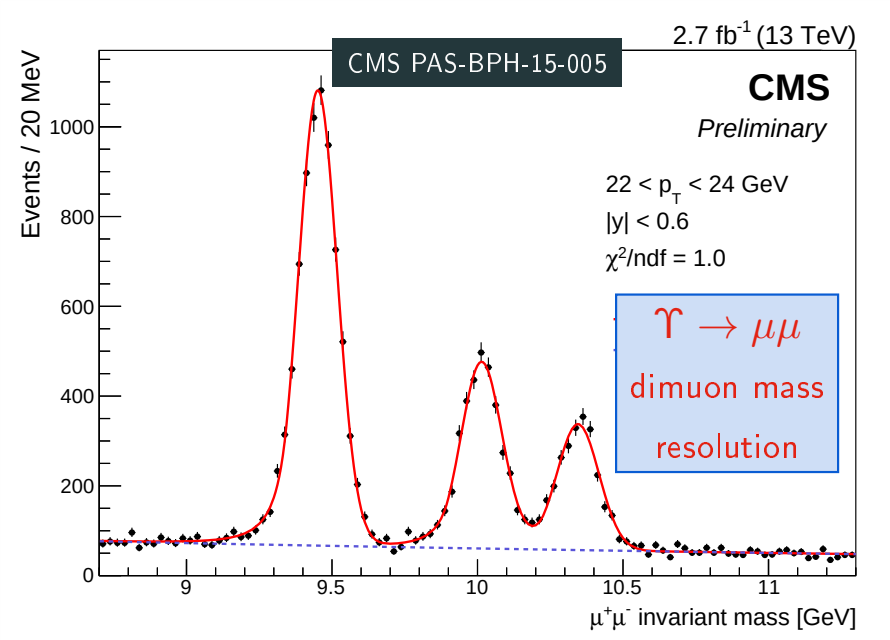
Dark gray: Low mass non-resonant double muons plus track

Light gray: Inclusive double muon triggers

Quarkonium reconstruction performance

- Flexible trigger
- Huge silicon tracker
- Very strong magnetic field
- High p_T–coverage

Quarkonium reconstruction performance



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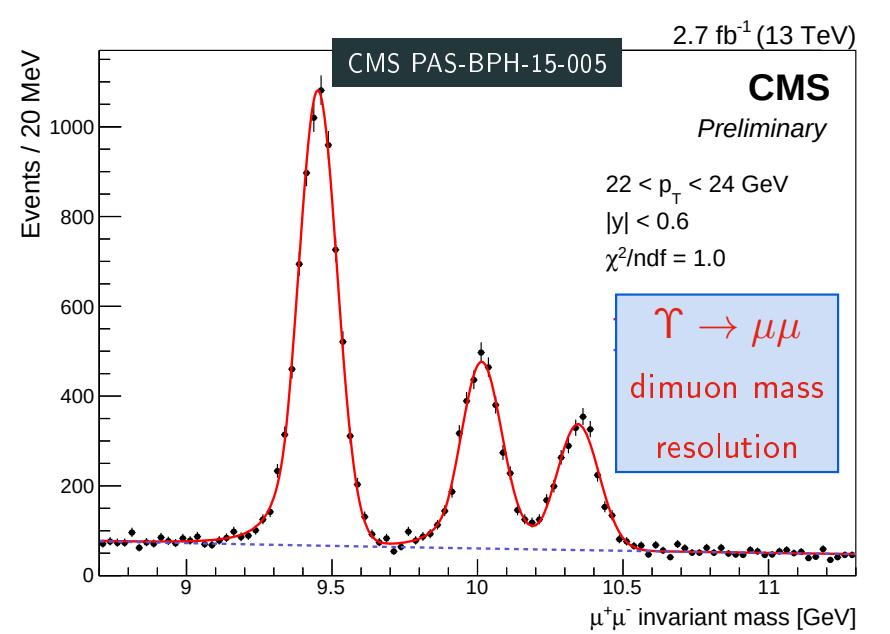

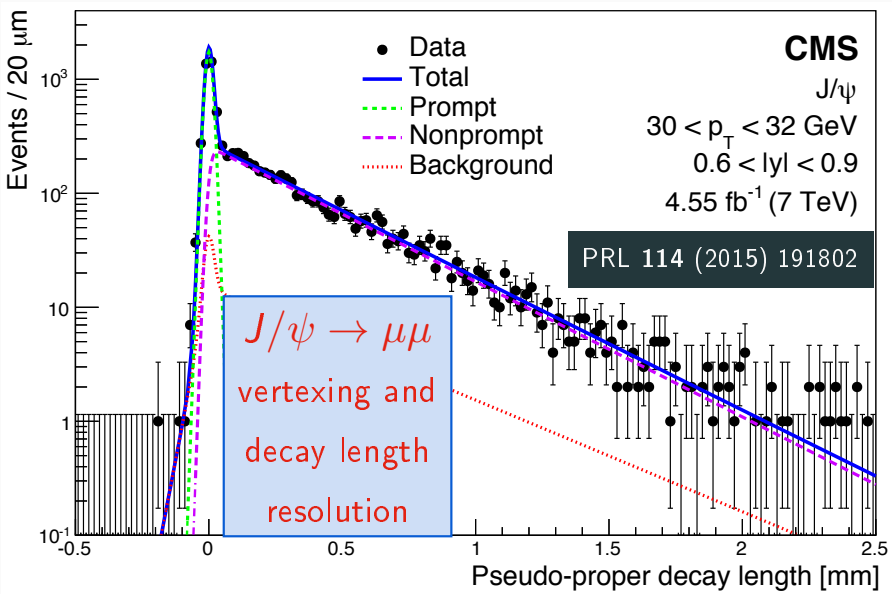

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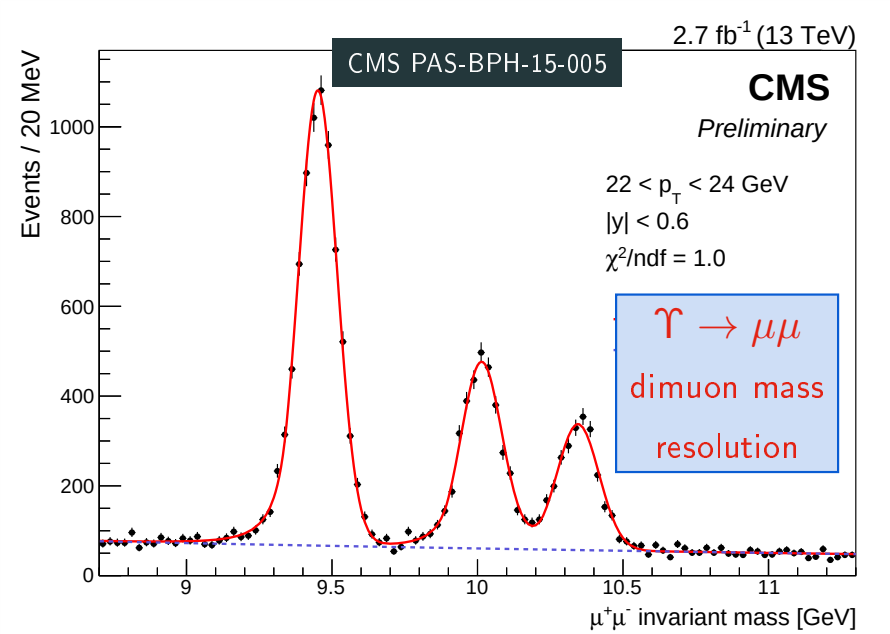

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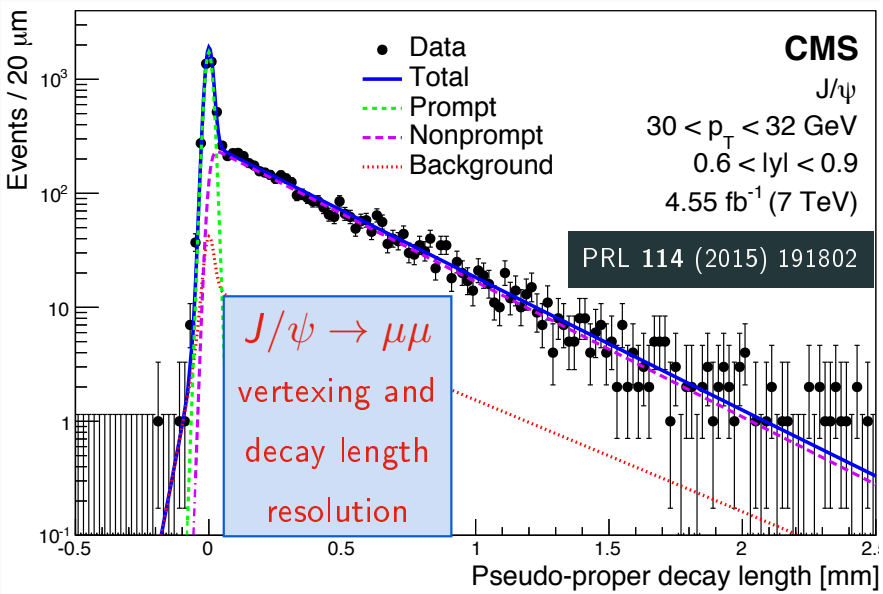
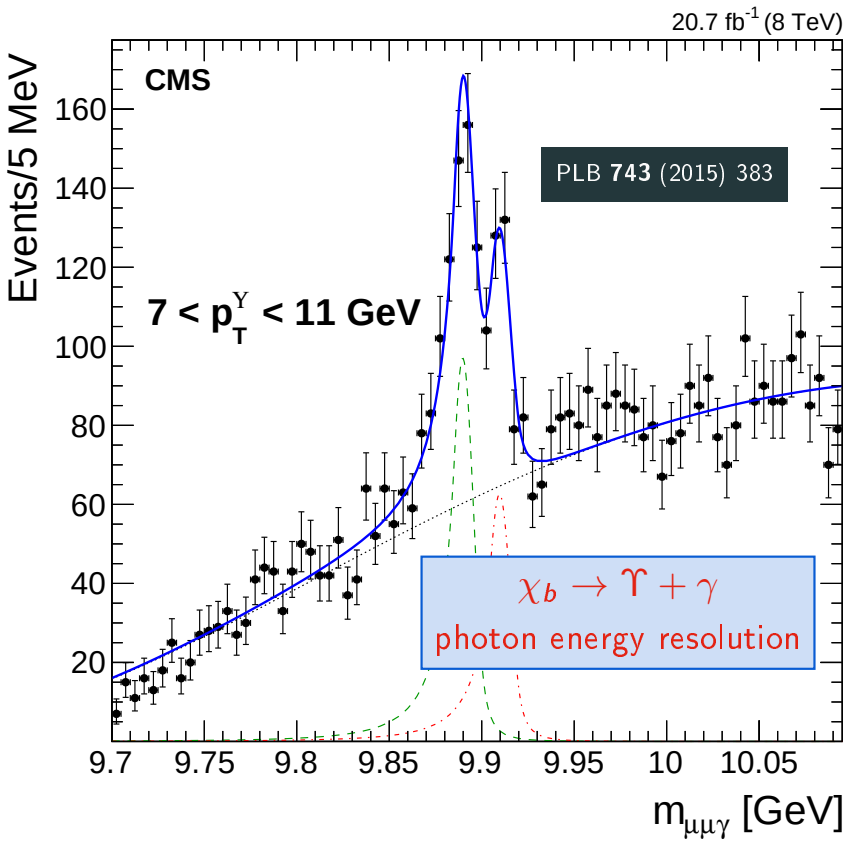




Cross section measurements

Quarkonium cross sections

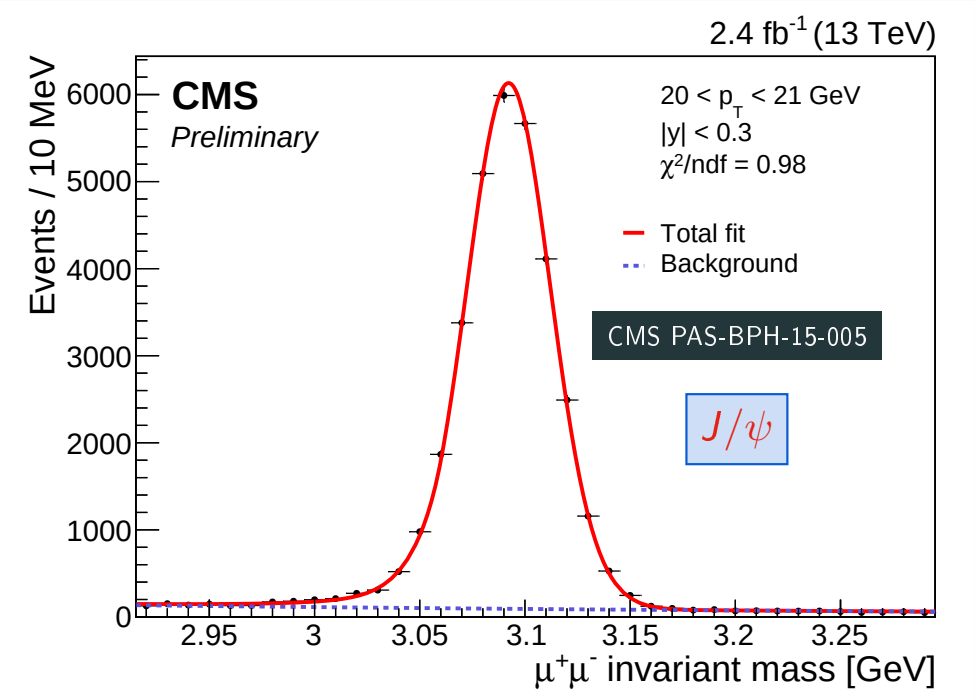
Double differential cross section times branching ratio

$$\frac{d^2\sigma(pp \to \mathcal{Q})}{dp_T dy} \times \mathcal{B}(\mathcal{Q} \to \mu^+\mu^-) = \frac{N(p_T, y)}{\mathcal{L}\Delta p_T \Delta y} \cdot \frac{1}{\epsilon(p_T, y)\mathcal{A}(p_T, y)}$$

- $\mathcal{B}(\mathcal{Q} \to \mu^+\mu^-)$ – branching ratio of quarkonium into two muons
- $N(p_T, y)$ – number of prompt signal events in (p_T, y) bin
- $\epsilon(p_T, y)\mathcal{A}(p_T, y)$ - efficiency and acceptance corrections
- $\mathcal{L}$ – integrated luminosity
- Δp_T, Δy – bin widths

Determination of prompt J/ψ and $\psi(2S)$ yields

Obtained from simultaneous fits to dimuon mass–decay length distributions



- Crystal Ball function for modeling mass signal
- Dimuon mass background modeled with exponential function

Determination of prompt J/ψ and $\psi(2S)$ yields

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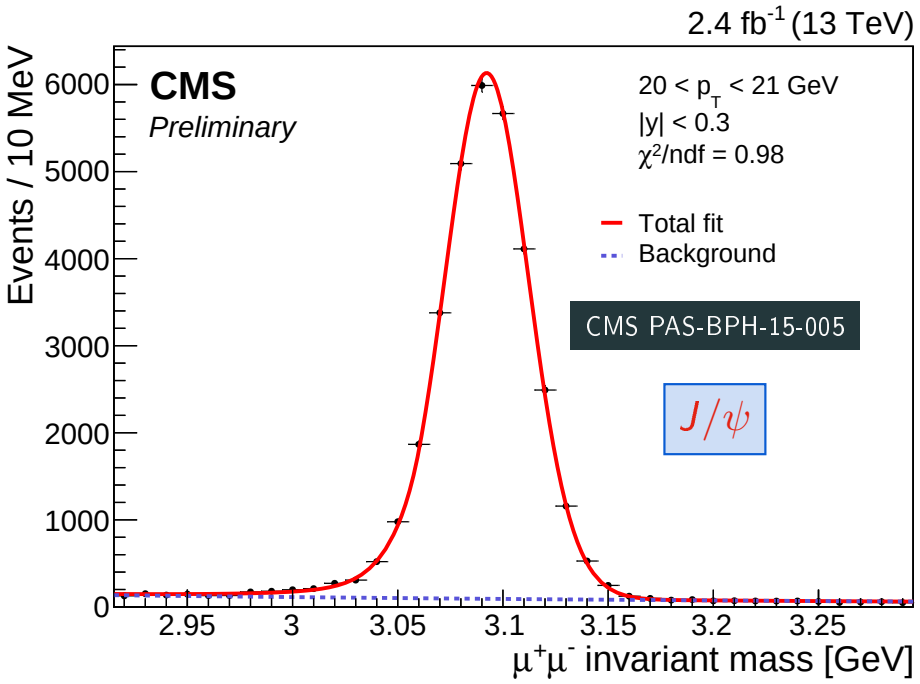
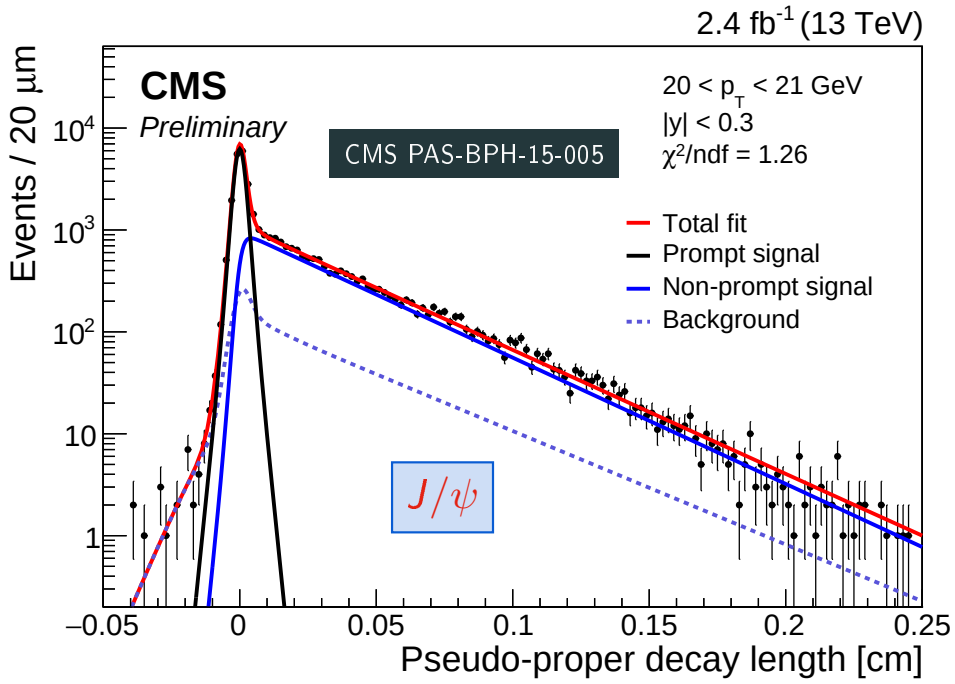
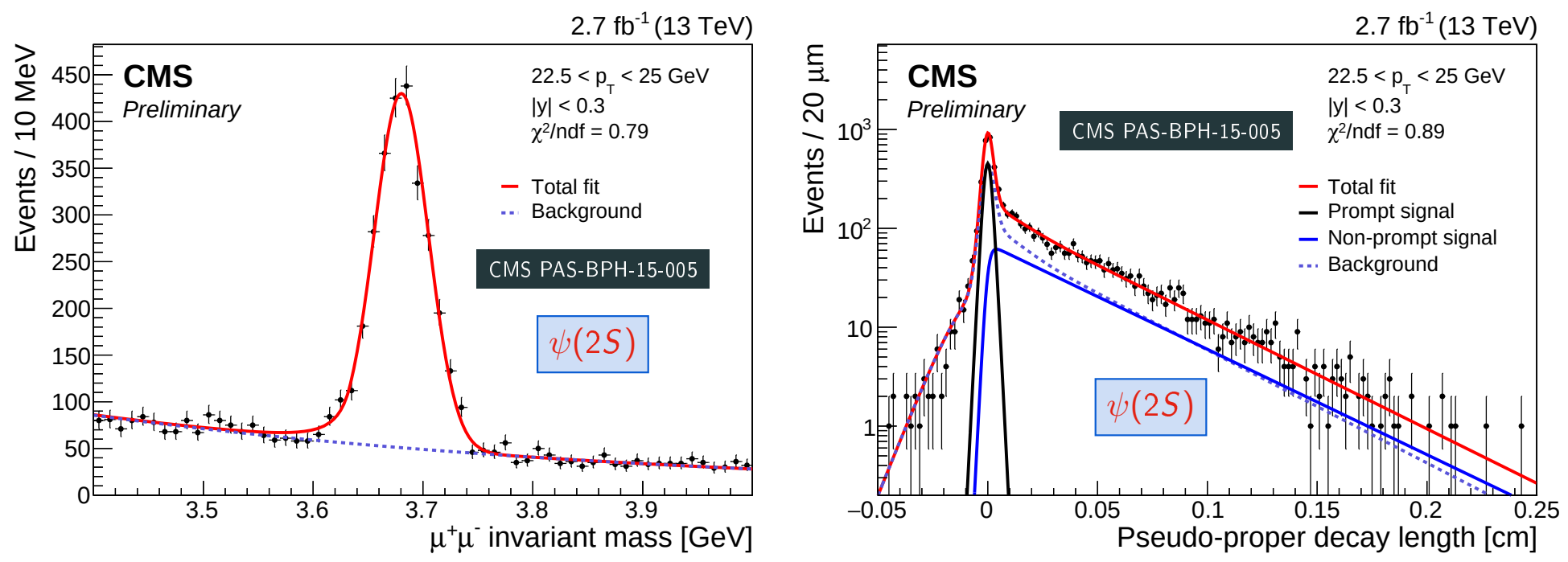




- Crystal Ball function for modeling mass signal
- Dimuon mass background modeled with exponential function
- Non-prompt component from b hadron decays separated using the pseudo-proper decay length $l = L_{xy} \cdot m_\psi / p_T$

Determination of prompt J/ψ and $\psi(2S)$ yields

Obtained from simultaneous fits to dimuon mass–decay length distributions



- Crystal Ball function for modeling mass signal
- Dimuon mass background modeled with exponential function
- Non-prompt component from b hadron decays separated using the pseudo-proper decay length $l = L_{xy} \cdot m_\psi / p_T$

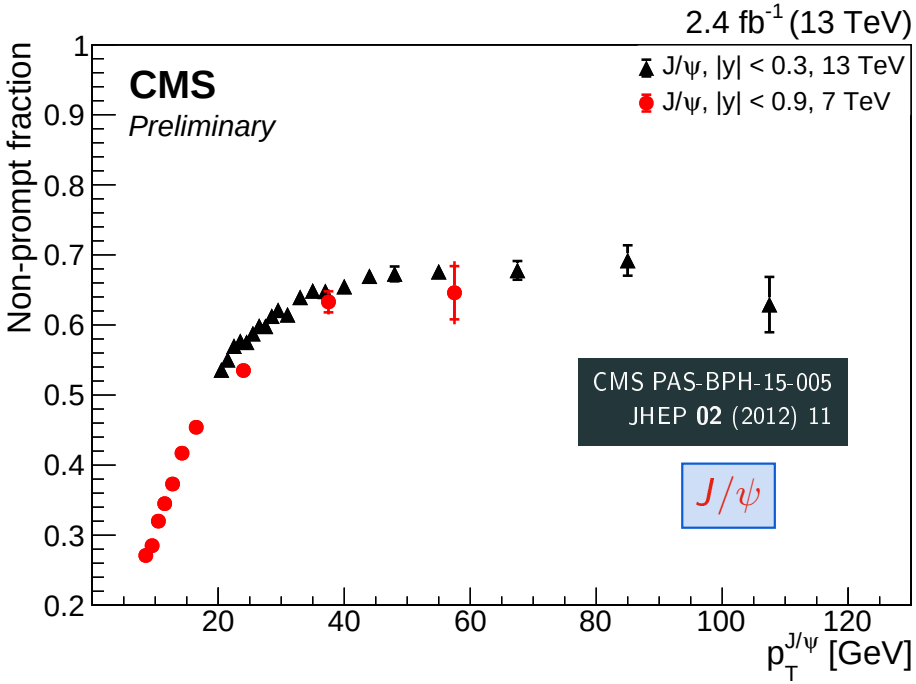
Non-prompt fractions

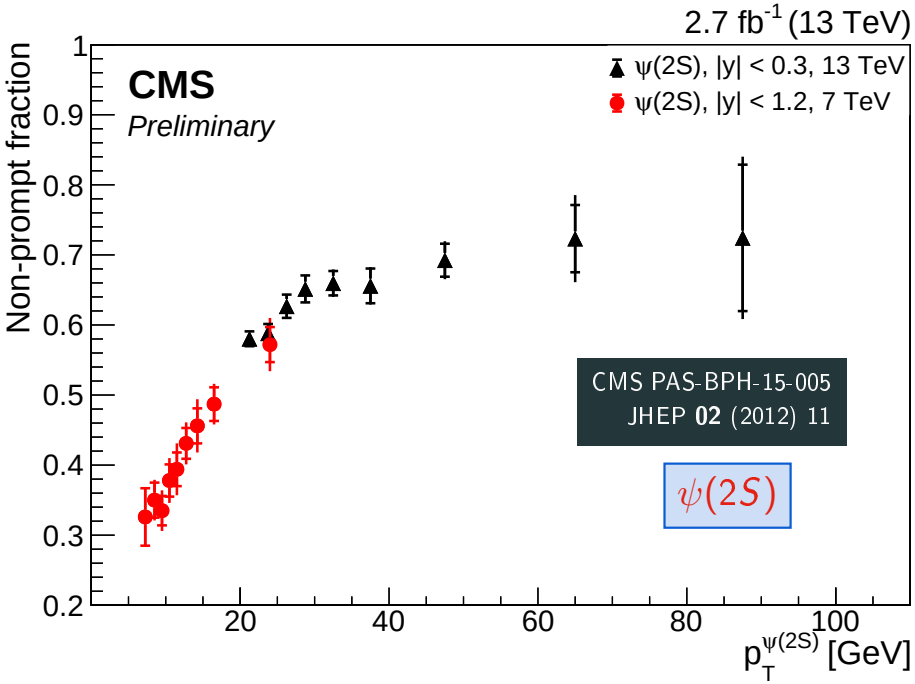
Prompt quarkonia:

- Direct production in pp collisions
- Indirect production via decays of heavier $\mathcal{Q}$ (e.g. χ_c) states

Non-prompt quarkonia:

- b hadron decays

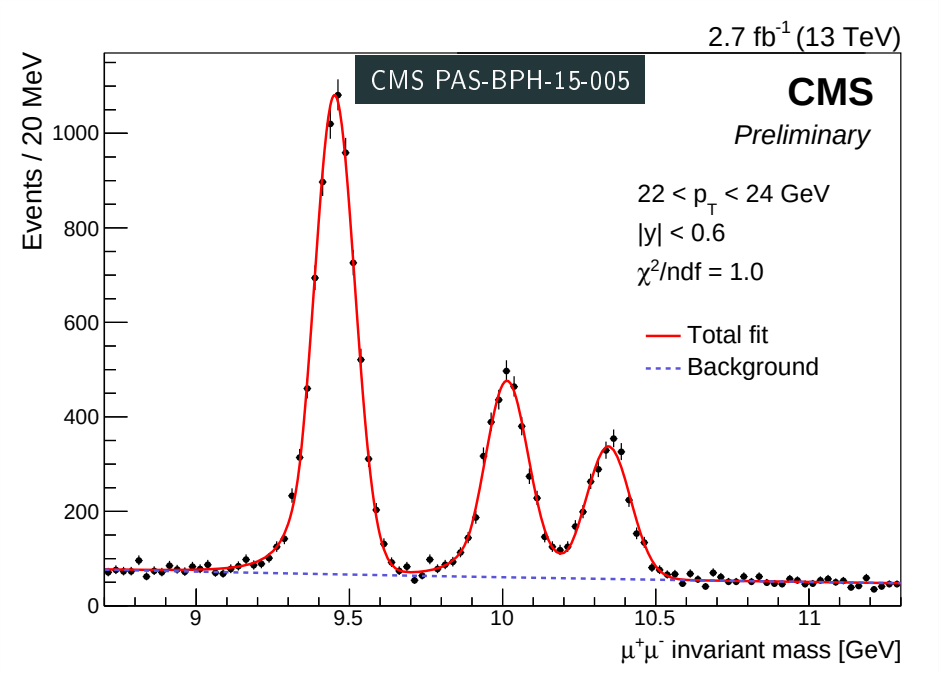




inner error bars: stat. only, total error bars: stat. $\oplus$ syst.

Determination of $\Upsilon(nS)$ yields

Obtained from fits to dimuon mass distribution

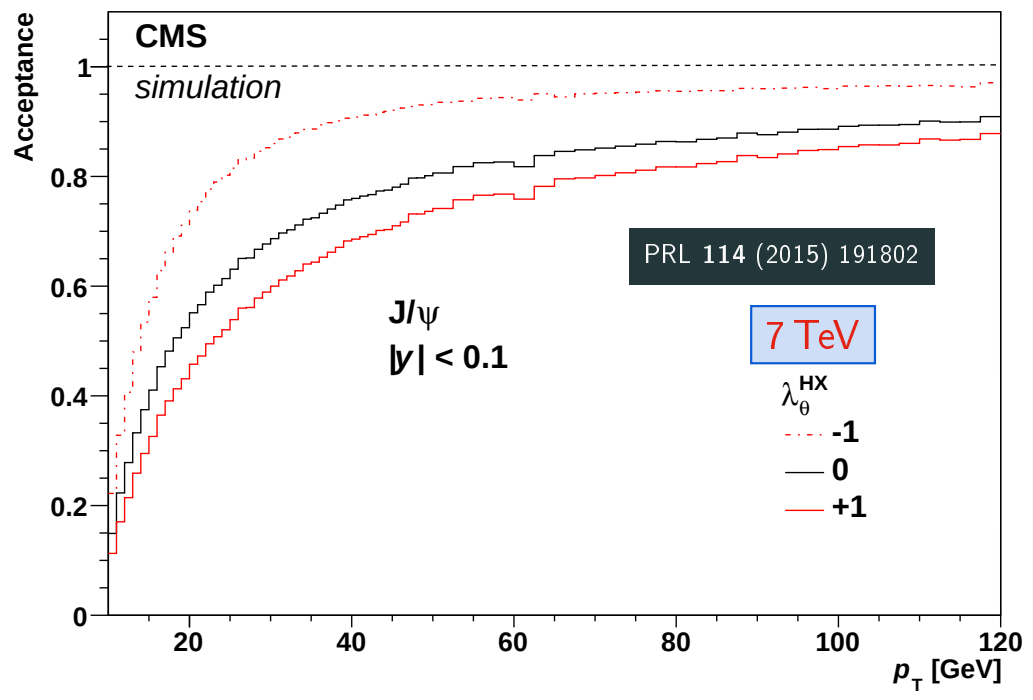


Signal peaks modeled with Crystal Ball functions

Mean values fixed to PDG values multiplied by common scale factor

Dimuon mass background modeled with exponential function

Acceptances



Acceptance

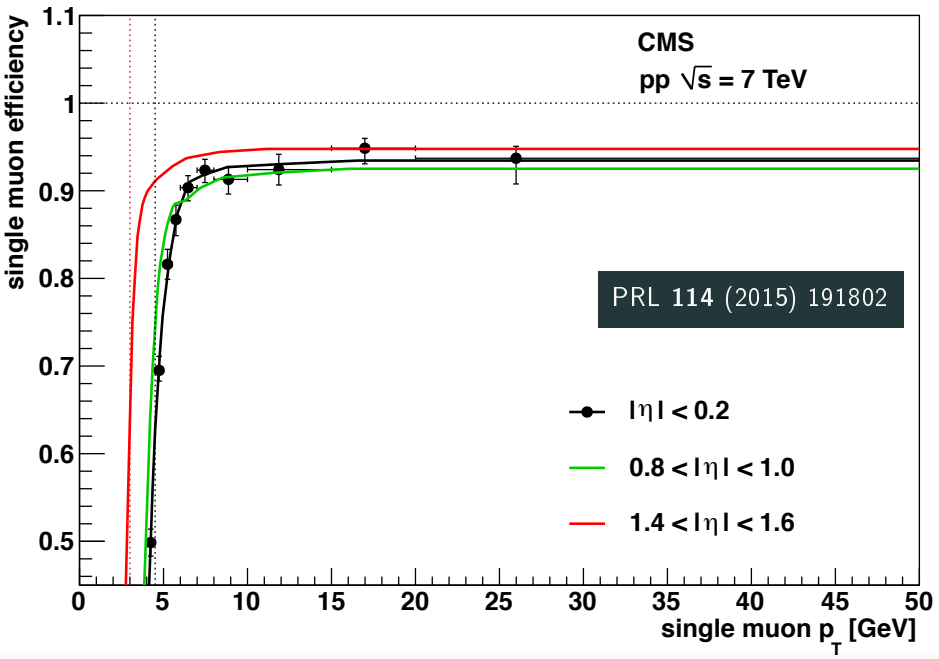
$$\mathcal{A} = \frac{N_{\text{kin}}^{\text{gen}}(p_T, y)}{N^{\text{gen}}(p_T, y)}$$

- $N_{\text{kin}}^{\text{gen}}(p_T, y)$ – generated events passing kinematic selection
- $N^{\text{gen}}(p_T, y)$ – total number of simulated events in (p_T, y) bin

- Obtained from MC simulations
- Dependent on polarization
- Similar acceptances for all $\mathcal{Q}$ states
- Rapidity dependence negligible

All results presented here assume unpolarized quarkonium states

Single muon and dimuon efficiencies

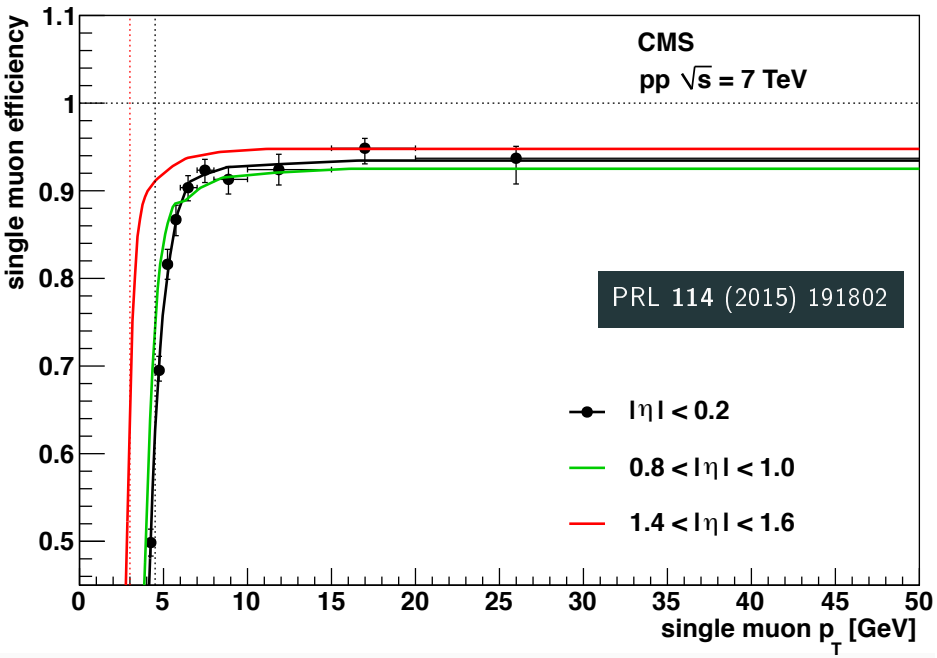


Dimuon efficiency

$$\epsilon_{\mu\mu} = \epsilon_{\mu 1} \cdot \epsilon_{\mu 2} \cdot \rho$$

$\leftarrow$ $\epsilon_{\mu i}$ – single muon efficiency from Tag & Probe

Single muon and dimuon efficiencies



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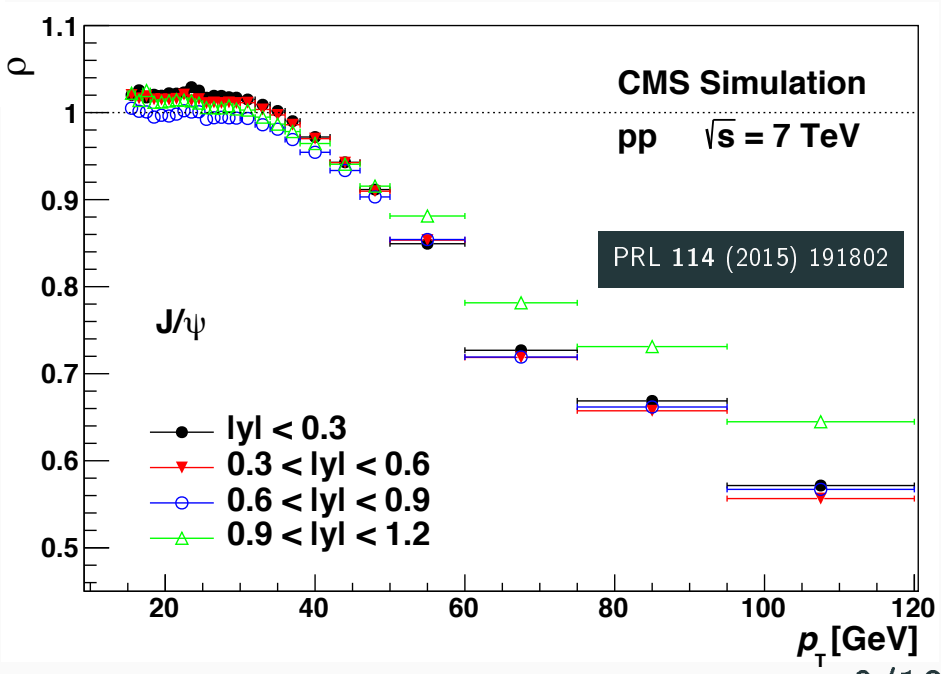

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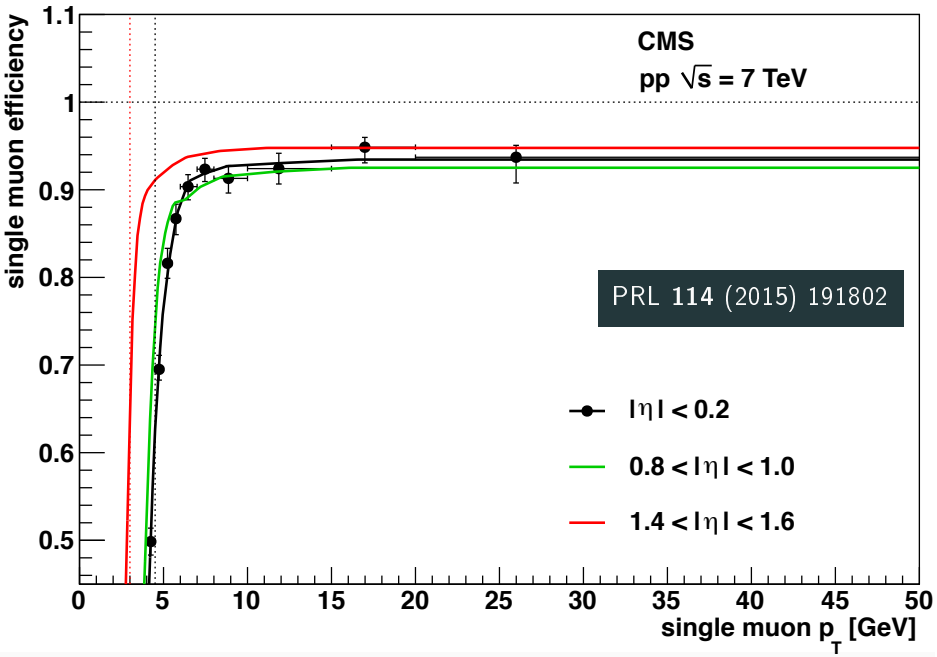

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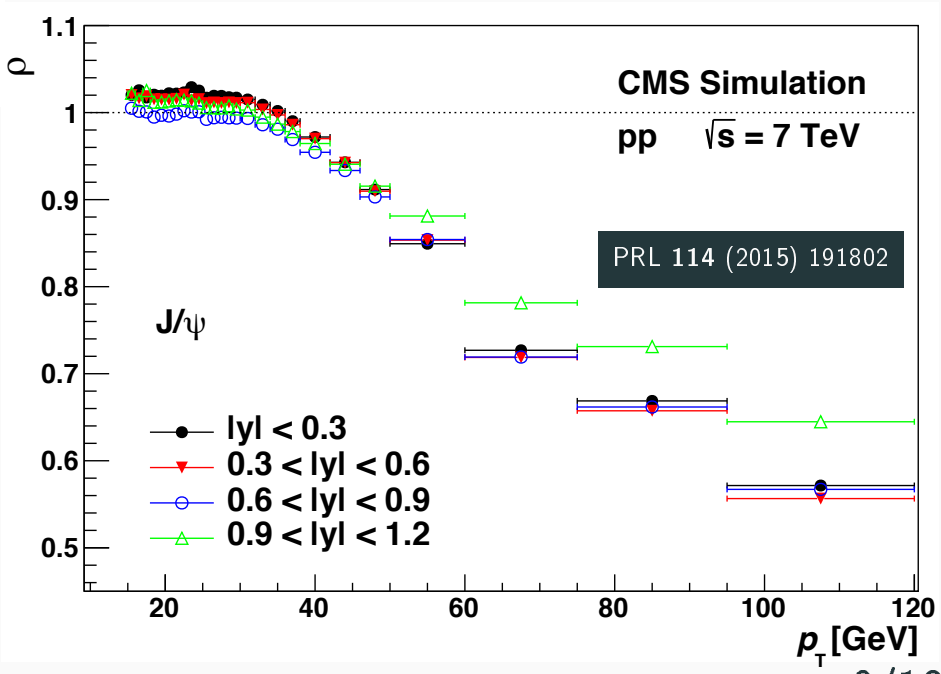


ϵ_μ and ρ are determined from data with specialized triggers or from simulation

Note: plots for 7 TeV

Similar behaviour at 13 TeV

Systematic uncertainties

Uncertainty on the luminosity measurement

→ 2.7 % ($\sqrt{s} = 13$ TeV) CMS PAS-LUM-15-001

→ 2.2 % ($\sqrt{s} = 7$ TeV) CMS PAS-SMP-12-008

→ NOT included in presented results

Uncertainties on the determination of the yields:

- Signal and background modeling

Uncertainties on the estimation the non-prompt fraction:

- Primary vertex assignment
- Signal and background modeling

Stated values for 13 TeV / 7 TeV results

Systematic uncertainties

Uncertainties on the acceptance and efficiency corrections:

- Acceptance calculation uncertainty dominated by statistical uncertainty of MC sample
- Uncertainties on single muon efficiencies
- Uncertainties on the dimuon efficiencies

Combined Systematic Uncertainties

excl. luminosity uncertainty, approx. values

→ $\approx 5 - 8$ % at low p_T (same for 7 TeV)

→ Between 10 and 30 % (10 and 20 %) at high p_T

CMS PAS-BPH-15-005
PRL **114** (2015) 191802
PLB **749** (2015) 14

Statistical and systematic uncertainties comparable for $\psi(nS)$

Statistical uncertainties dominate for $\Upsilon(nS)$

Stated values for 13 TeV / 7 TeV results

Results

Rapidity and p_T ranges at 7 and 13 TeV

Rapidity:

$\psi(nS)$	$\Upsilon(nS)$
$\lvert y\rvert < 1.2$	
4 bins	2 bins
$\Delta\lvert y\rvert = 0.3$	$\Delta\lvert y\rvert = 0.6$

p_T [GeV]:

$\sqrt{s}$ [TeV]	J/ψ	$\psi(2S)$	$\Upsilon(nS)$
7	15 - 95*	15 - 75†	10 - 100
13	20 - 120	20 - 100	
	variable bin widths		

* Up to 120 GeV

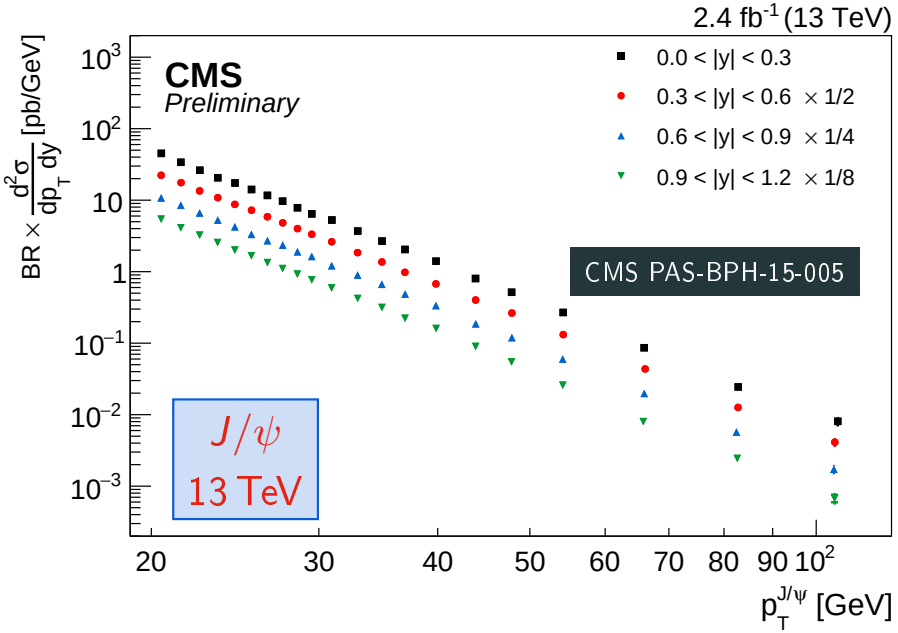
† Up to 100 GeV

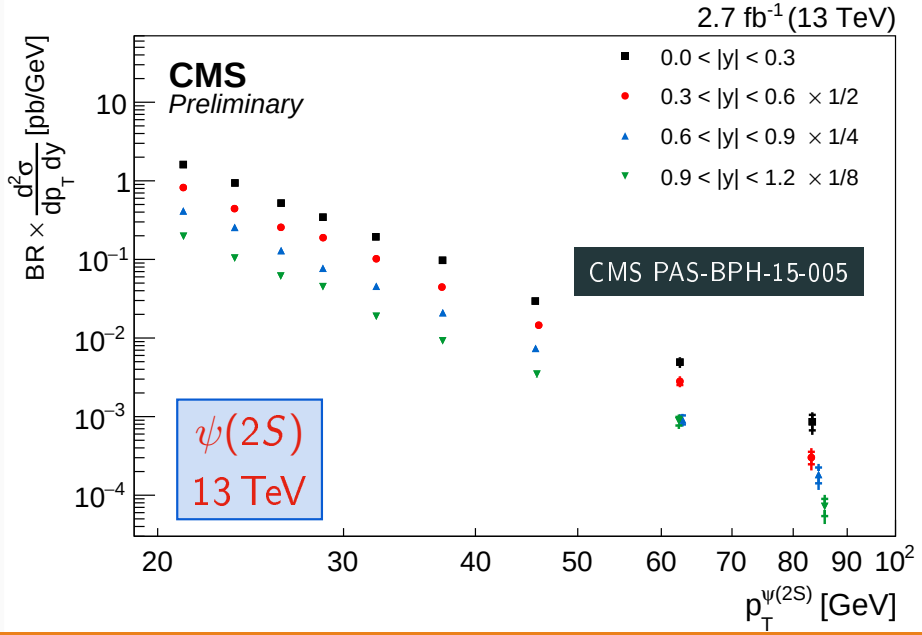
when integrated over rapidity

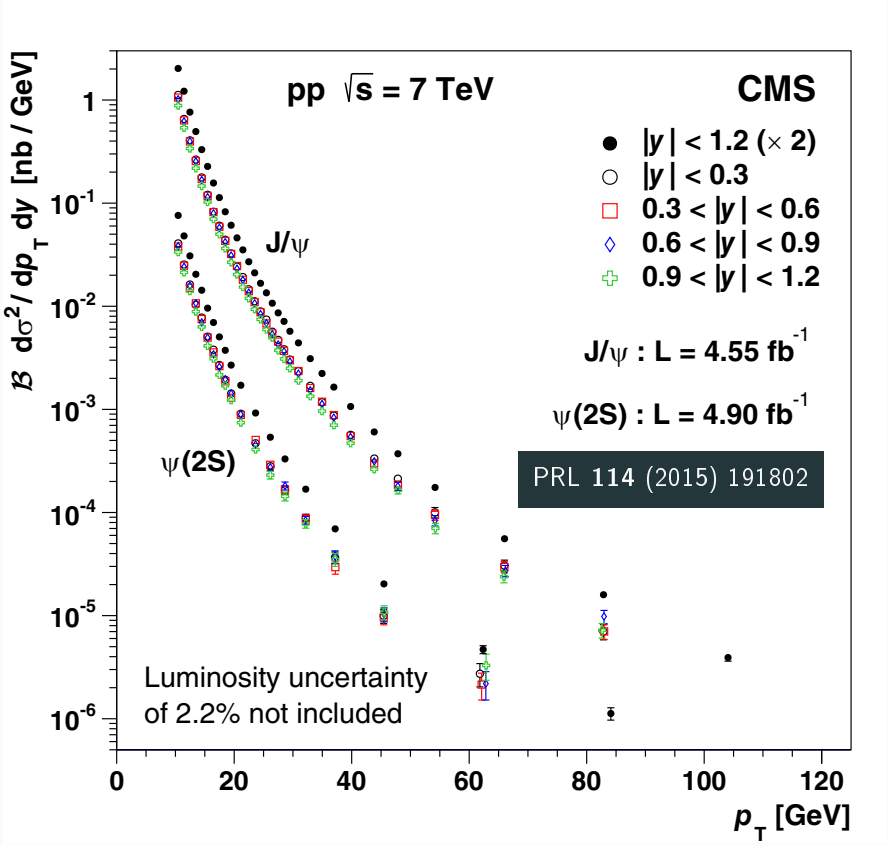
Integrated luminosity:

$\sqrt{s}$ [TeV]	J/ψ	$\psi(2S)$ & $\Upsilon(nS)$
7	4.55 fb^{-1}	4.9 fb^{-1}
13	2.4 fb^{-1}	2.7 fb^{-1}

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







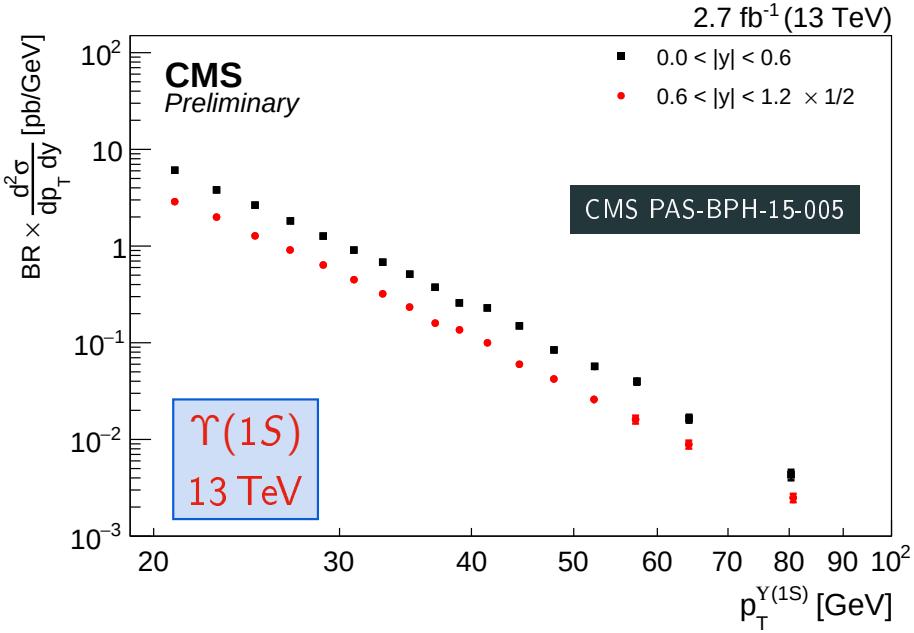
↑ 7 TeV

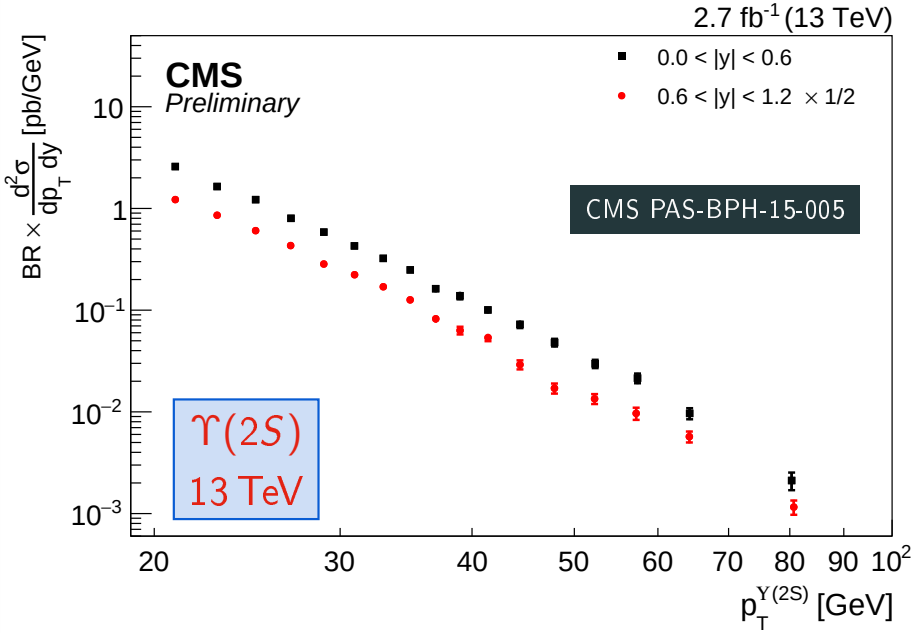
← 13 TeV

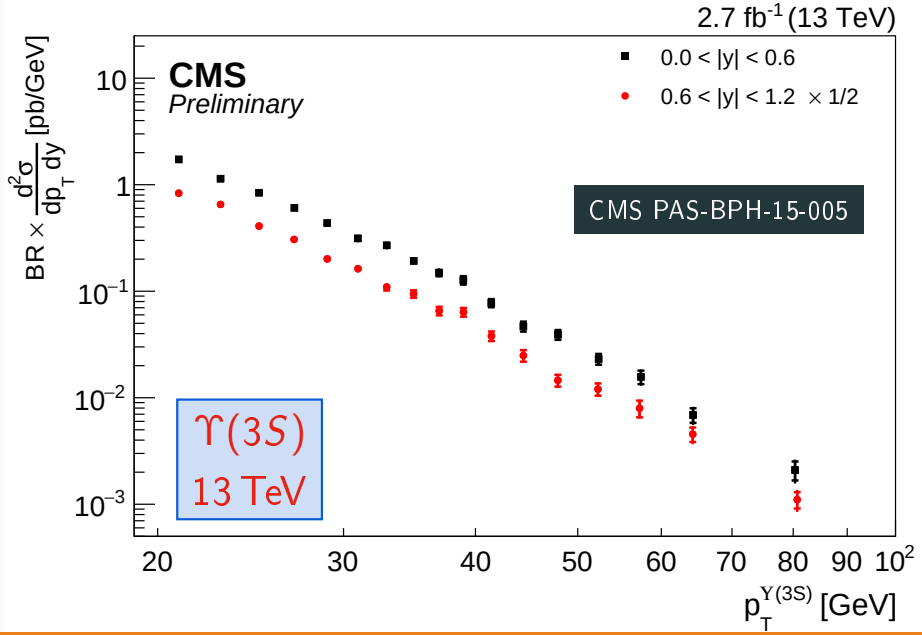
inner error bars: stat. only,

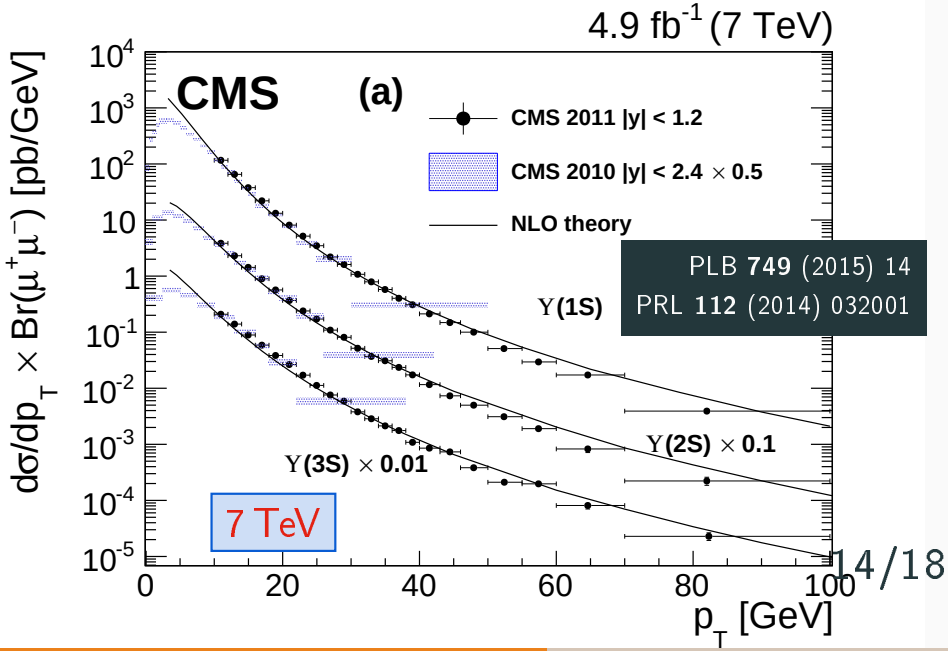
total error bars: stat. ⊕ syst.

$\Upsilon(nS)$ cross sections



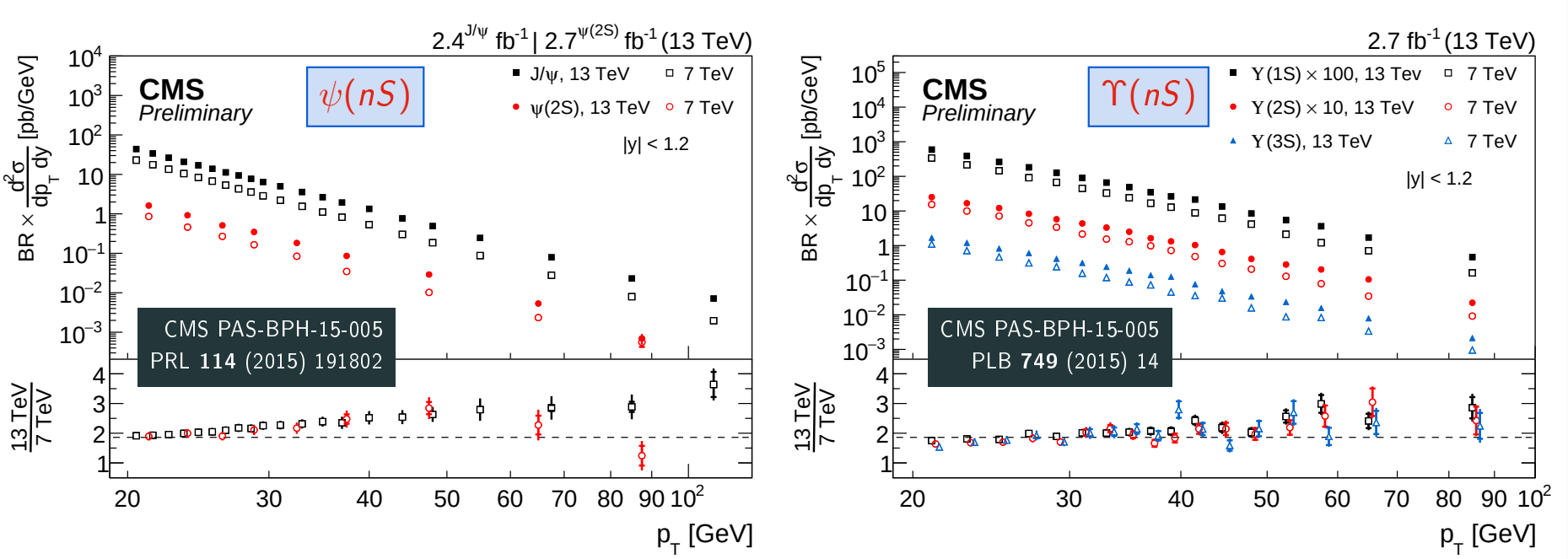






Comparison of 7 TeV and 13 TeV results

Cross sections integrated over $|y| < 1.2$



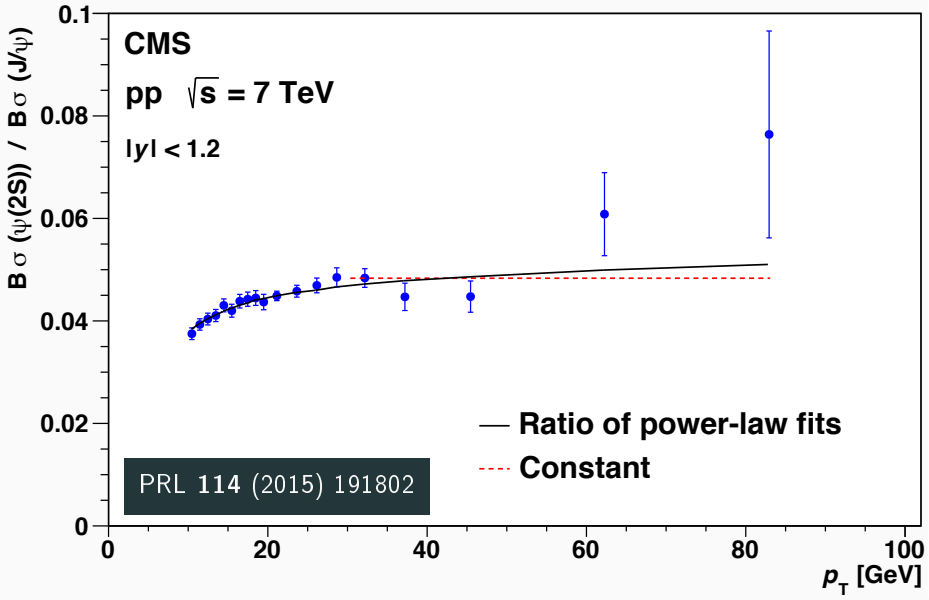
inner error bars: stat. only, total error bars: stat. $\oplus$ syst.

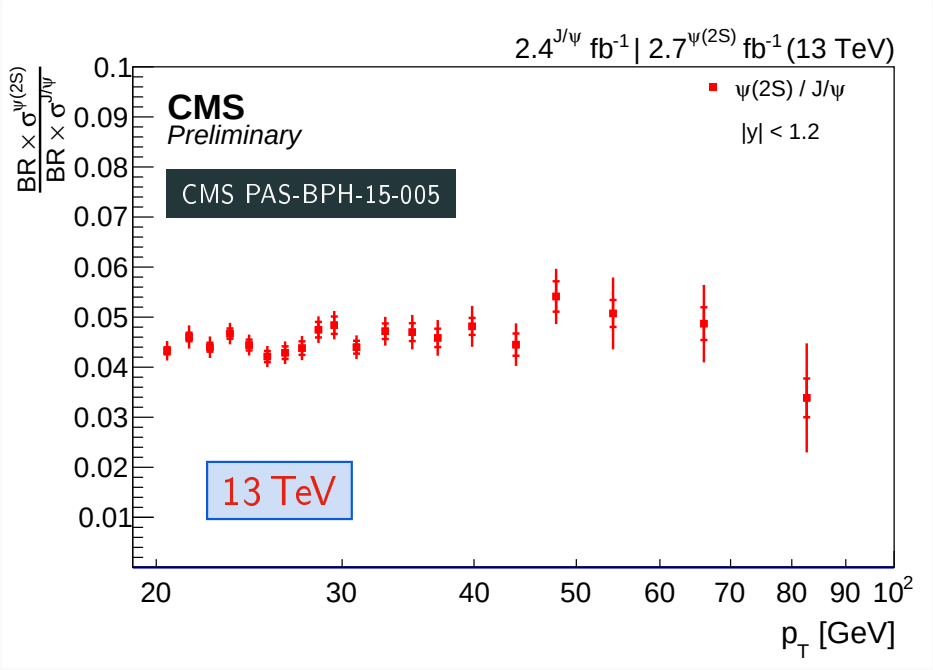
- Weighted average of individual $|y|$ ranges for 13 TeV
- Factor of 2–3 between 7 and 13 TeV cross sections
  - Slow changes with dimuon p_T

Double differential cross section ratios for $\psi(nS)$

Ratio of $\psi(2S)$ over J/ψ differential cross section times branching fraction

$$\frac{\mathcal{B}\sigma(\psi(2S))}{\mathcal{B}\sigma(J/\psi)}$$





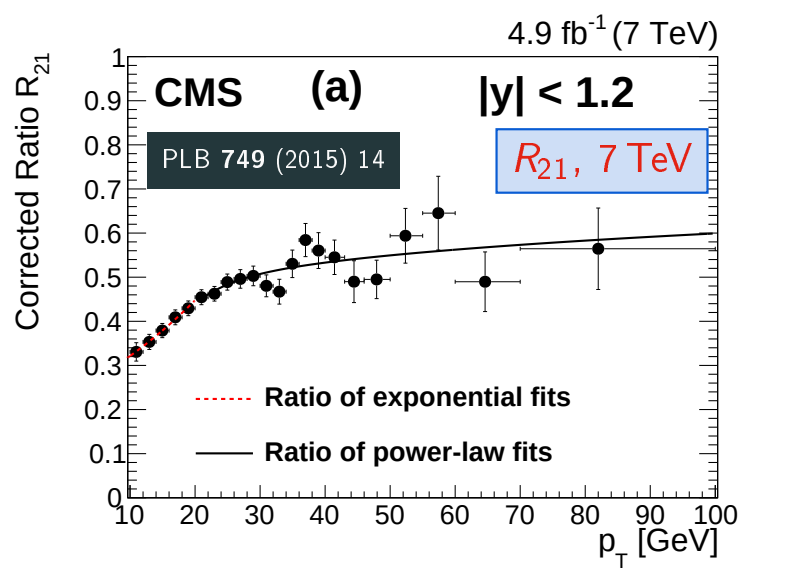
error bars: stat $\oplus$ syst.

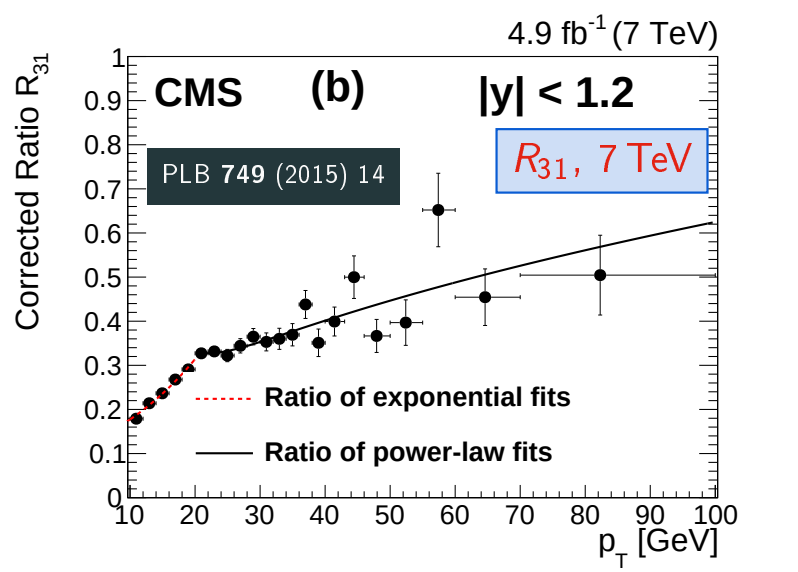
inner error bars: stat. only

total error bars: stat. $\oplus$ syst.

Cancellation of several systematic uncertainties

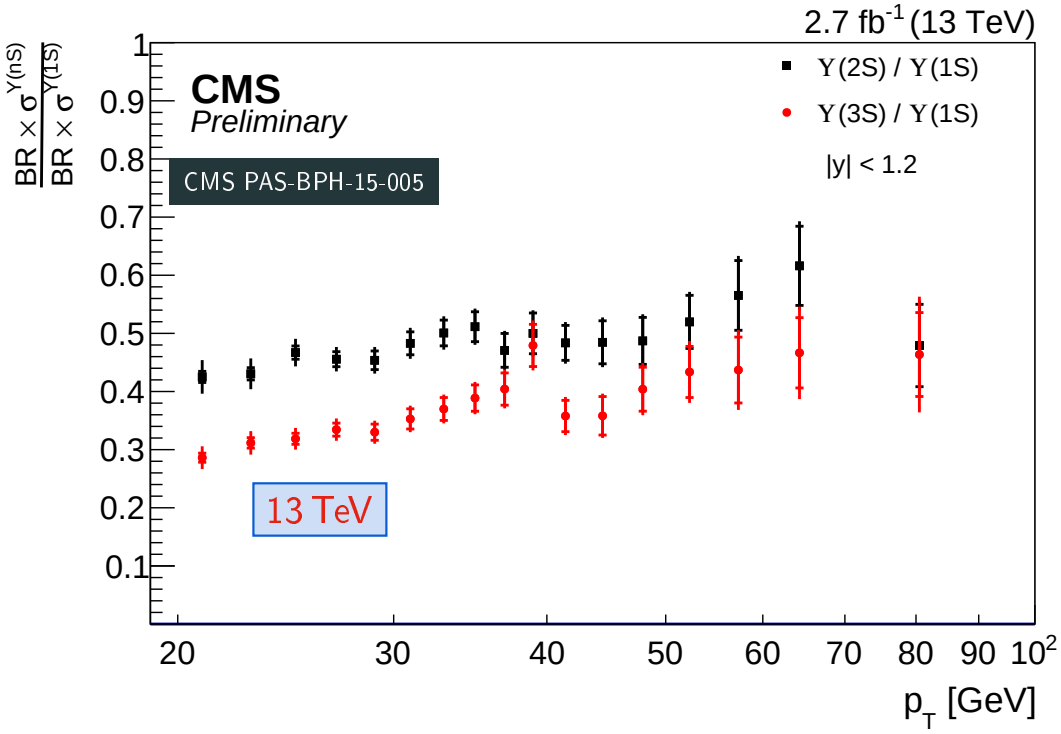
Double differential cross section ratios for $\Upsilon(nS)$





Ratio of $\Upsilon(3S)$ over $\Upsilon(1S)$ and $\Upsilon(2S)$ over $\Upsilon(1S)$ differential cross sections times branching fraction

$$R_{21} = \frac{\mathcal{B}\sigma(\Upsilon(2S))}{\mathcal{B}\sigma(\Upsilon(1S))} \qquad R_{31} = \frac{\mathcal{B}\sigma(\Upsilon(3S))}{\mathcal{B}\sigma(\Upsilon(1S))}$$

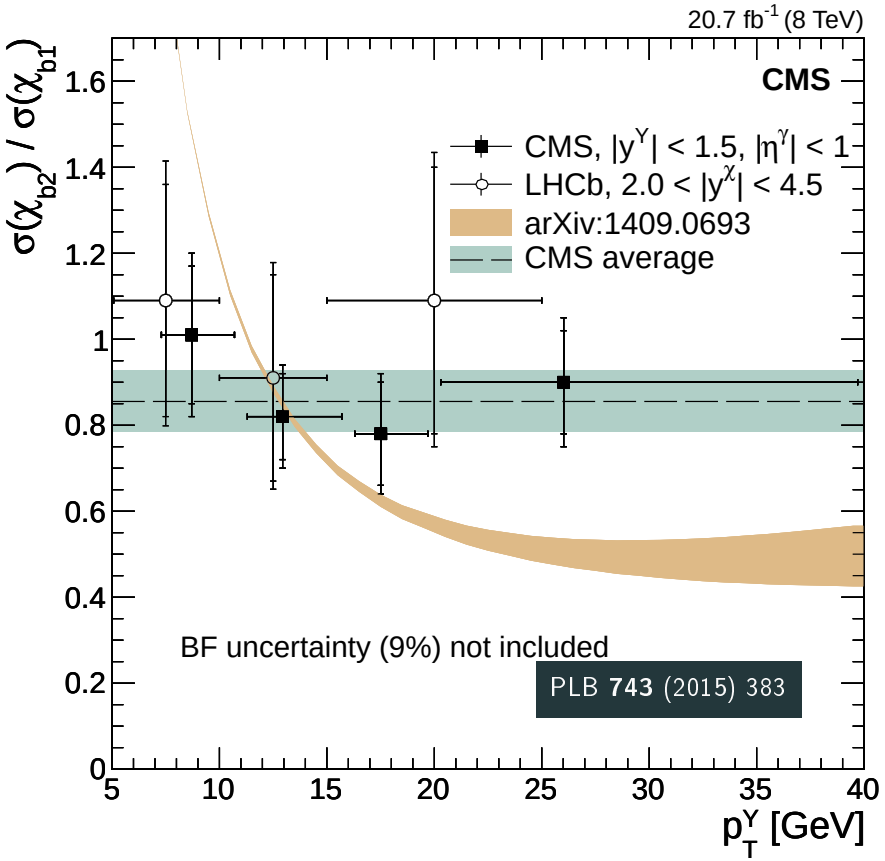


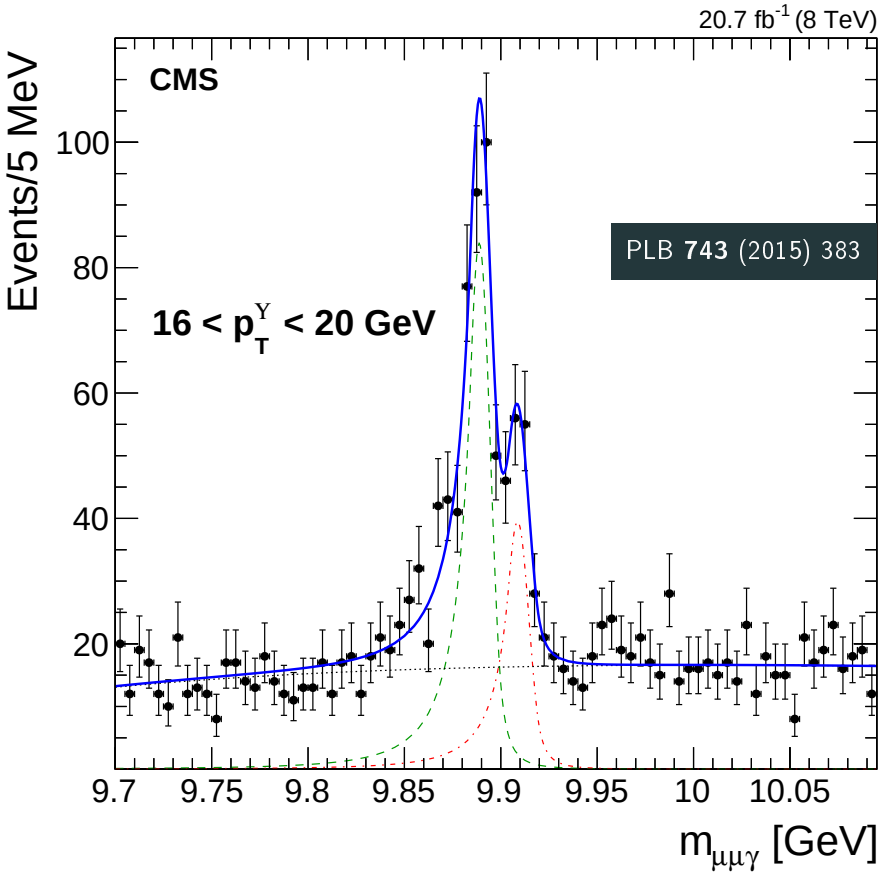
Summary

- Differential cross sections of S–wave quarkonia measured at 7 and 13 TeV up to $p_T = 100\,(120\,\text{for}\,J/\psi)$ GeV and $|y| < 1.2$
- Cross sections at 13 TeV larger by factor 2–3 compared to 7 TeV for all states
- Extended measurement of non-prompt fraction up to $p_T = 100\,(120)$ GeV for $\psi(2S)\,(J/\psi)$
- Differential cross section ratios measured at 7 and 13 TeV for prompt J/ψ to $\psi(2S)$ and for $\Upsilon(2S)$ and $\Upsilon(3S)$ to $\Upsilon(1S)$

Backup

$\chi_{b2}(1P)/\chi_{b1}(1P)$ cross section ratio at 8 TeV

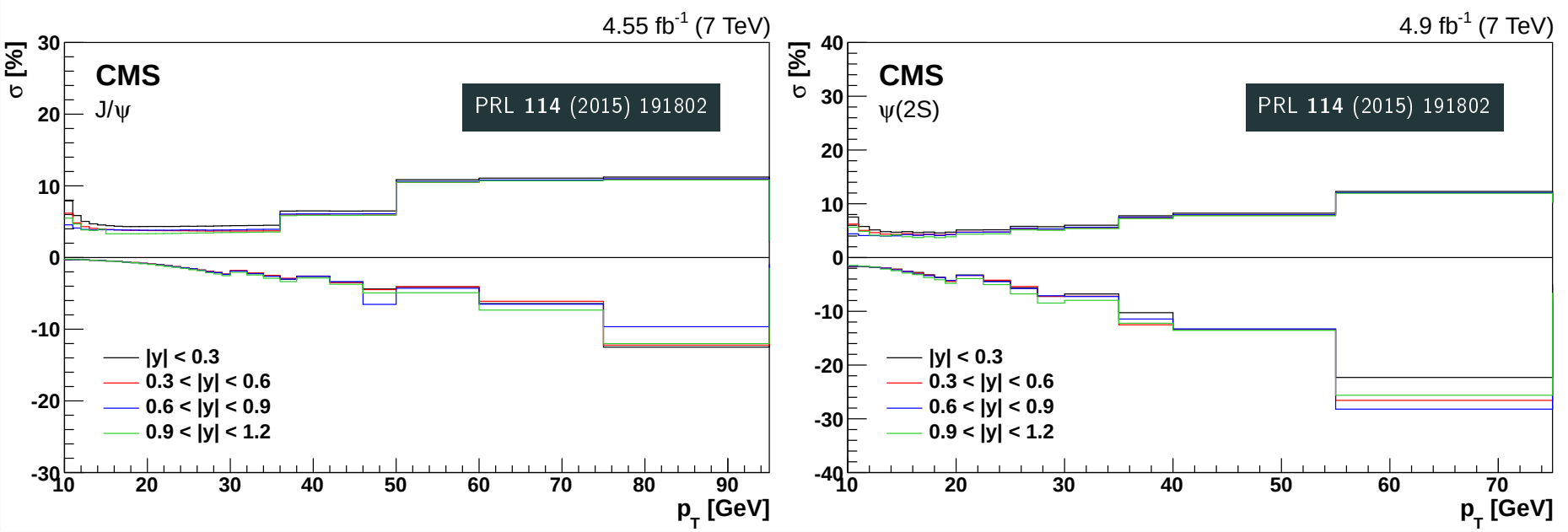




$$\mathcal{R} = \frac{\sigma(pp \to \chi_{b2} + X)}{\sigma(pp \to \chi_{b1} + X)} = \frac{N_{\chi_{b2}}}{N_{\chi_{b1}}} \cdot \frac{\epsilon_{\chi_{b1}}}{\epsilon_{\chi_{b2}}} \cdot \frac{\mathcal{B}(\chi_{b1} \to \Upsilon(1S) + \gamma)}{\mathcal{B}(\chi_{b2} \to \Upsilon(1S) + \gamma)}$$

- $N_{\chi_{b1,2}}$ – yields obtained from ML fit to $\mu\mu\gamma$ mass spectrum
- $\epsilon_{\chi_{b1}}/\epsilon_{\chi_{b2}}$ – efficiency and acceptance ratio from MC simulation

Systematic uncertainties for J/ψ and $\psi(2S)$ at 7 TeV

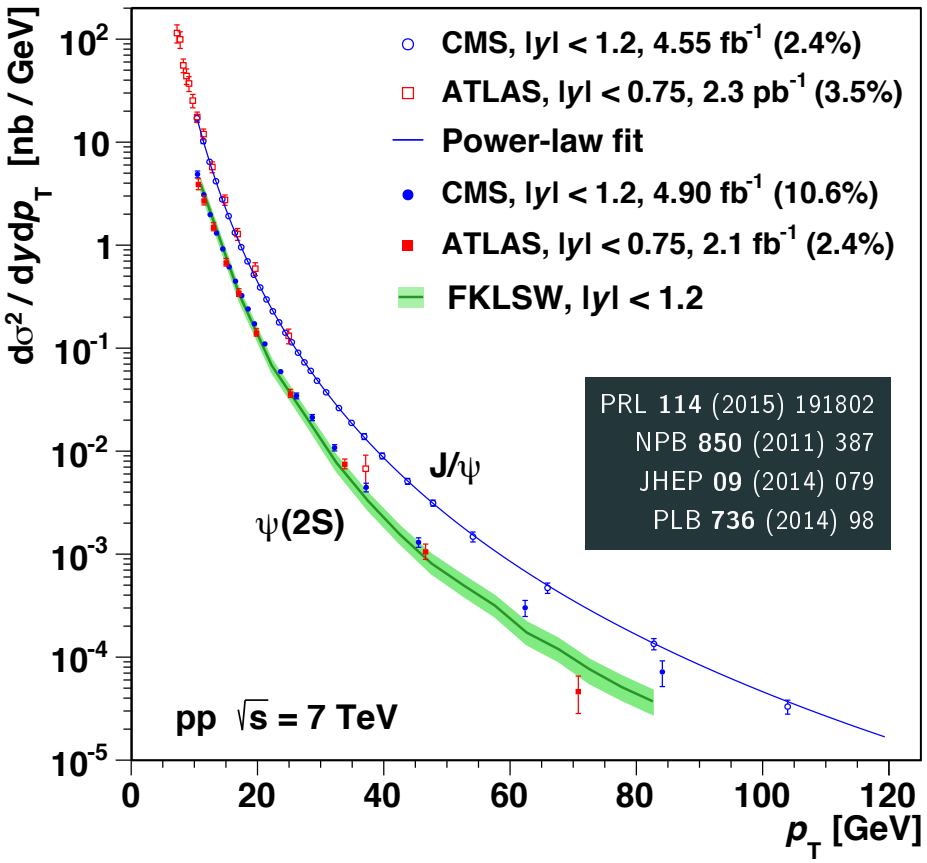


Quadratically added systematic uncertainties on positive side,

Statistical uncertainty on negative side

Prompt J/ψ and $\psi(2S)$ cross sections at 7 TeV

Comparison to ATLAS and theory



FKLSW band: global fit to $\psi(2S)$ cross sections from CMS and LHCb using SDCs at NLO extended to higher p_T