CMS results on quarkonium cross sections at 13 TeV

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With photos by the author

Outline

New CMS paper on the measurement of the production cross sections of J/ψ, ψ(2S), and Υ(1,2,3S) in pp collisions at 13 TeV arxiv:1710.11002 .

- Introduction
- The CMS detector at LHC
- Measurement strategy
  - Yields
  - Acceptance and efficiency
  - Systematic uncertainties
- Results
- Discussion

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CERN-EP-2017-267
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CMS-BPH-15-005

Measurement of quarkonium production cross sections in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

Differential production cross sections of J/ψ and ψ(2S) charmonium and Υ(nS) (n = 1, 2, 3) bottomonium states are measured in proton-proton collisions at $\sqrt{s} = 13$ TeV, with data collected by the CMS detector at the LHC, corresponding to an integrated luminosity of 2.3 fb^{-1} for the J/ψ and 2.7 fb^{-1} for the other mesons. The five quarkonium states are reconstructed in the dimuon decay channel, for dimuon rapidity $|y| < 1.2$. The double-differential cross sections for each state are measured as a function of y and transverse momentum, and compared to theoretical expectations. In addition, ratios are presented of cross sections for prompt ψ(2S) to J/ψ, Υ(2S) to Υ(1S), and Υ(3S) to Υ(1S) production.

Submitted to Physics Letters B

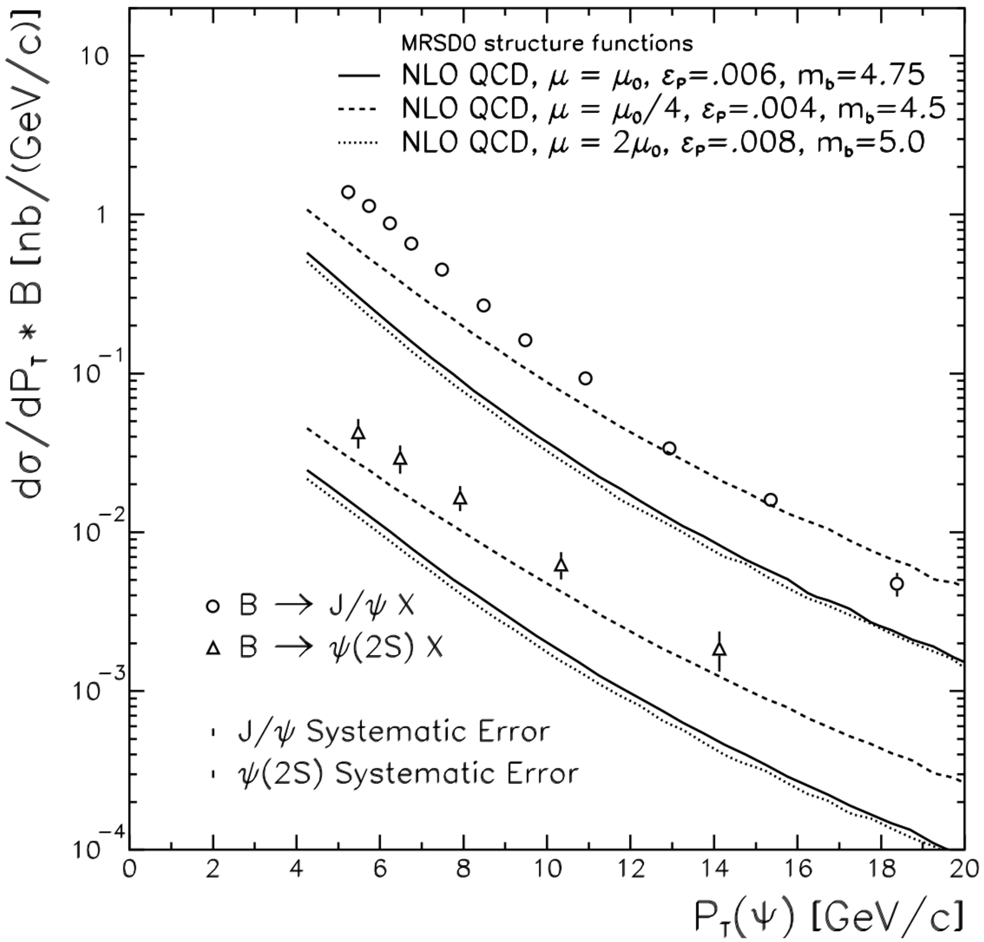
arXiv:1710.11002v1 [hep-ex] 30 Oct 2017

Background

The mechanisms underlying quarkonium production is subject of intense research and discussion since the J/ψ, ψ(2S) “anomalies” found at Tevatron Run I.

The modern silicon tracker of CDF made the distinction between prompt and B-decay J/ψ, ψ(2S) possible

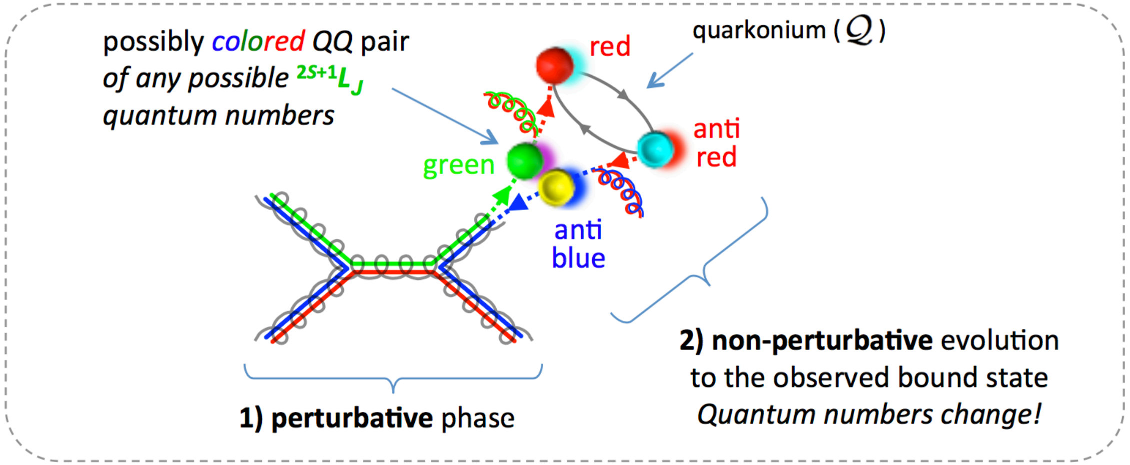
Prompt production predictions based on the “color singlet” (CS) model were found low by a factor 50. Very striking especially for the ψ(2S).



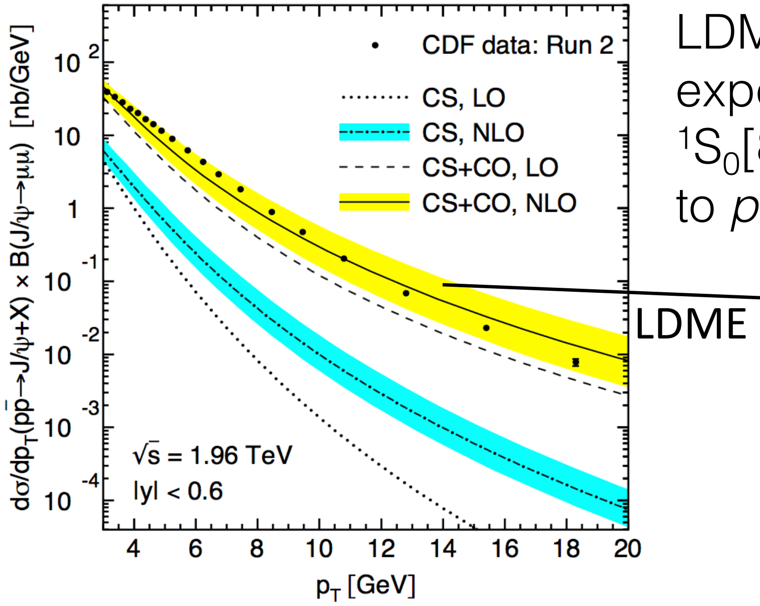
Phys. Rev. Lett. **79**, 572

NRQCD

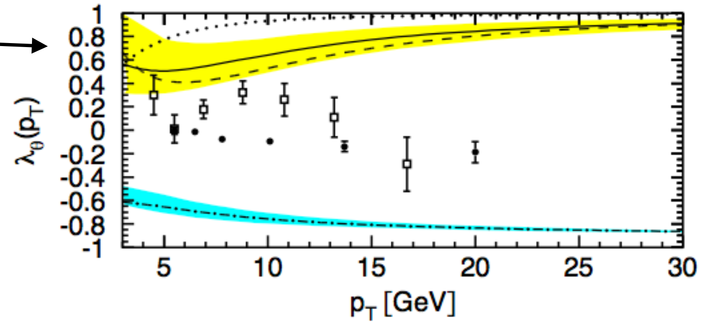
Today one of the most accredited theories is **NRQCD***, an effective theory that factorizes the production mechanism into a perturbative (Short Distance Coefficients) and non-perturbative (Long Distance Matrix Elements). The "missing" contribution is thought to derive from qqbar pairs created in a color-octet state, that "evolve" into a color-singlet physical state by soft gluon radiation.



Butenschoen and Kniehl, 1212.2037



LDMEs, thought to be universal, have to be extracted from data, although expected to obey scaling rules. For the $^3S_1$ states, the relevant ones are $^3S_1[1]$, $^1S_0[8]$, $^3S_1[8]$, $^3P_J[8]$. The extraction of the LDMEs is a crucial point and can lead to *puzzling* results.



* Without forgetting the estimated audience exploring alternative approaches

State of the art

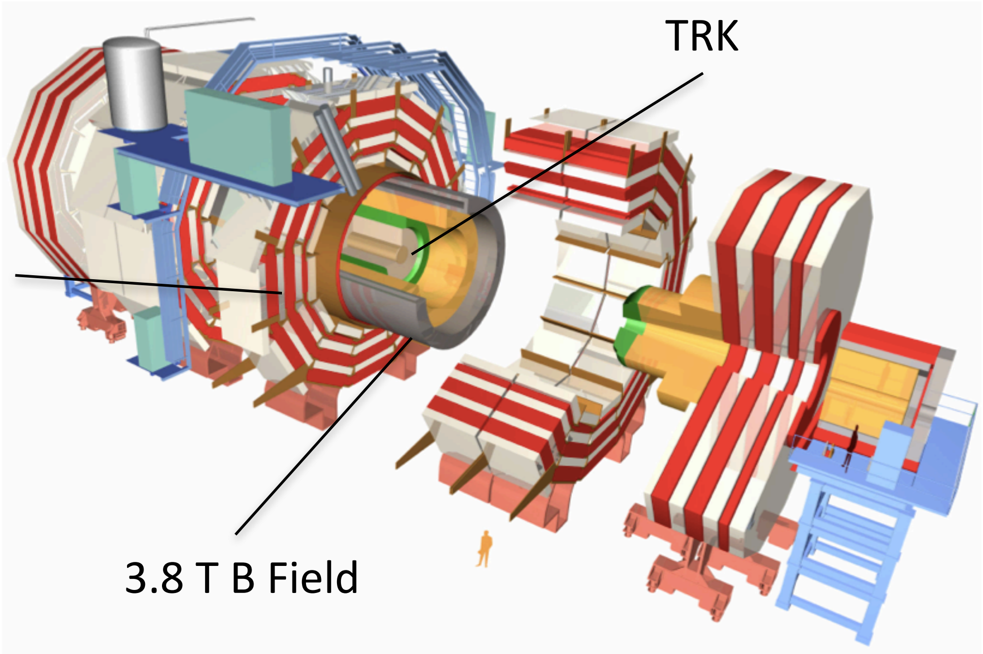
- The inclusion of polarization measurements in the global fit for the extraction of the LDMEs, and accounting for feed-down, results in good agreement of data and NLO NRQCD theory in both cross sections and polarization of the Y(nS) [B. Gong et al., PRL 112(2014)032001]. Also, the inclusion of feed-down from higher to lower states is crucial.

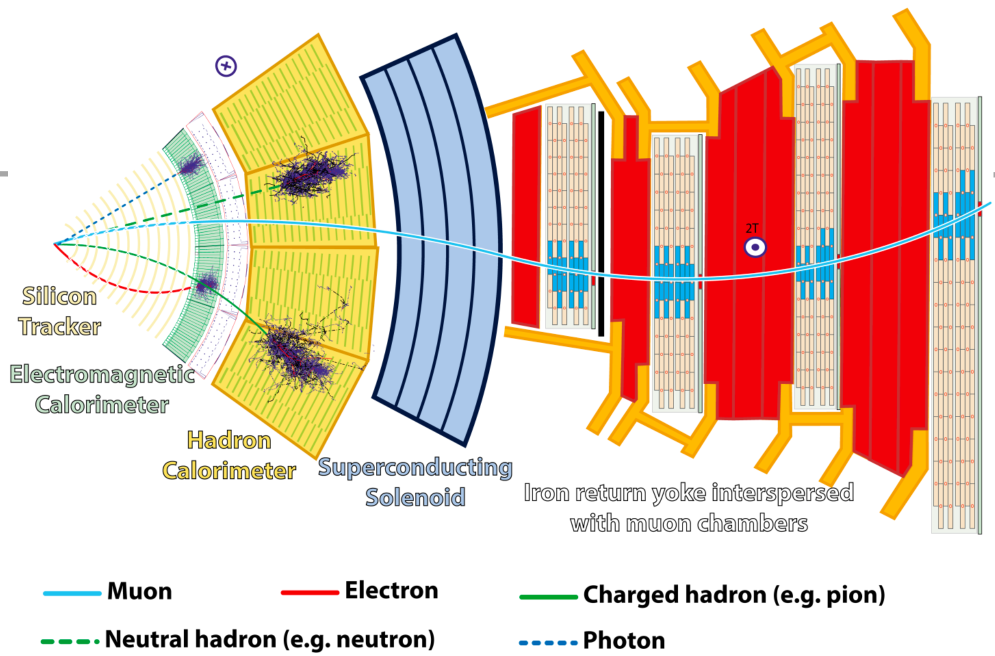
- The dominance of the $^1S_0[8]$ term is a possible explanation to the so-called ”quarkonium polarization puzzle” [Faccioli et al, 1403.3970]. See Pietro Faccioli’s talk for an updated overview.

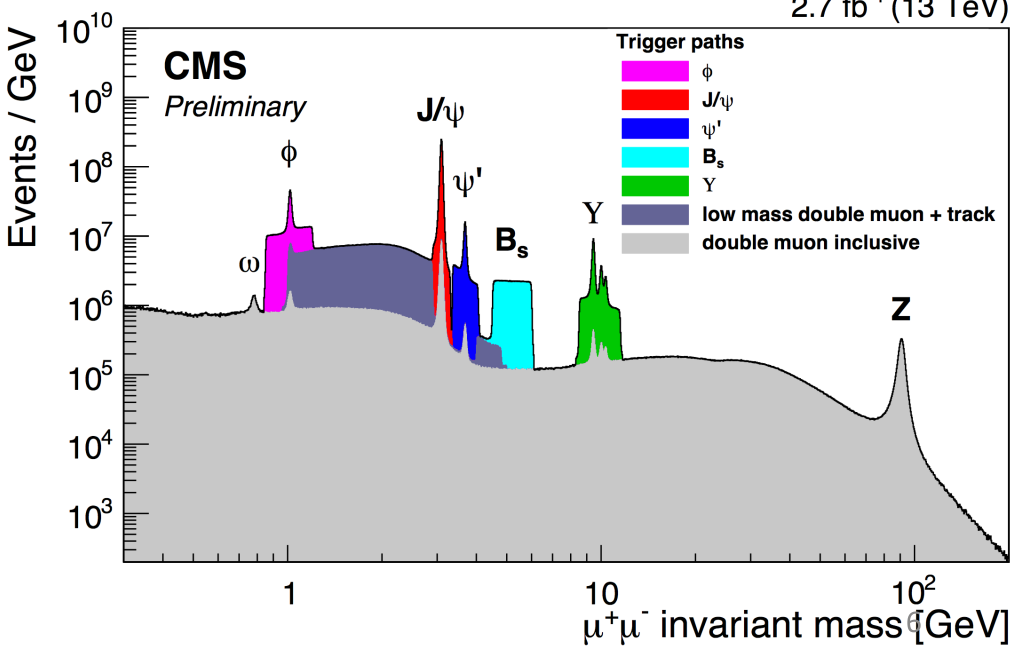
- However, the situation is far from settled. Moreover the study of the production of η_c at LHCb again shows tensions (LHCb arXiv:1409.3612, Butenschoen, He, Kniehl 10.1051/epjconf/201713706009)

- More data at high p_T are needed to consolidate the relative contribution of the LDMEs and test the underlying hypotheses of NRQCD.

The CMS experiment at LHC



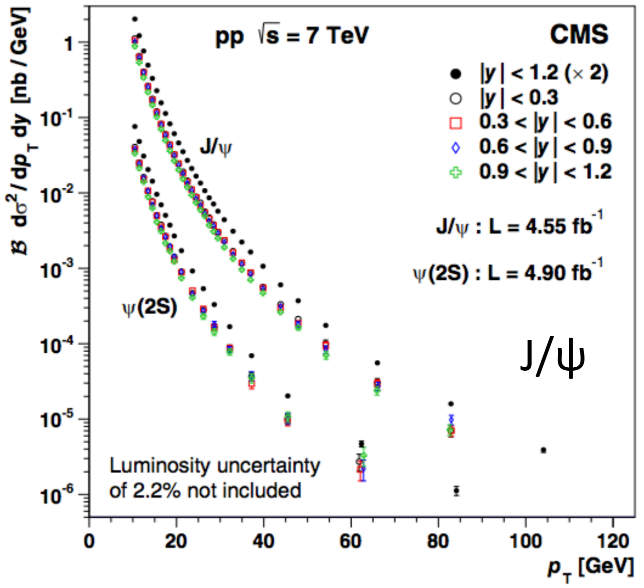




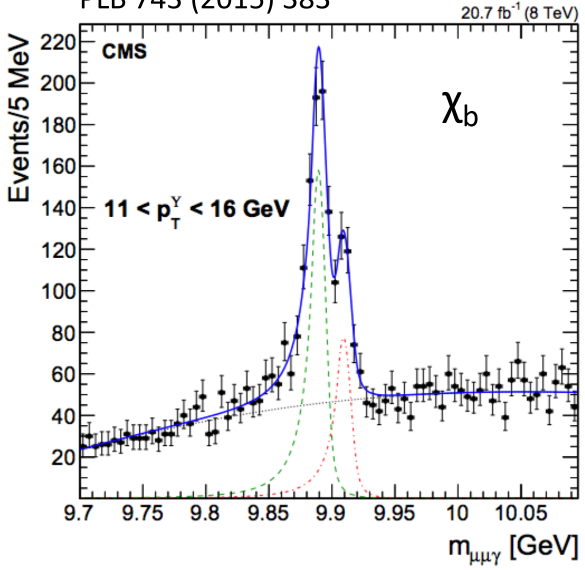
- The Muon system, the Silicon Tracker and the Magnetic Field system allow the measurement of muon pairs over a wide range of η and p_T.
- A flexible trigger system accommodates Higgs physics, SUSY searches, and even quarkonium

CMS and quarkonia, a success story

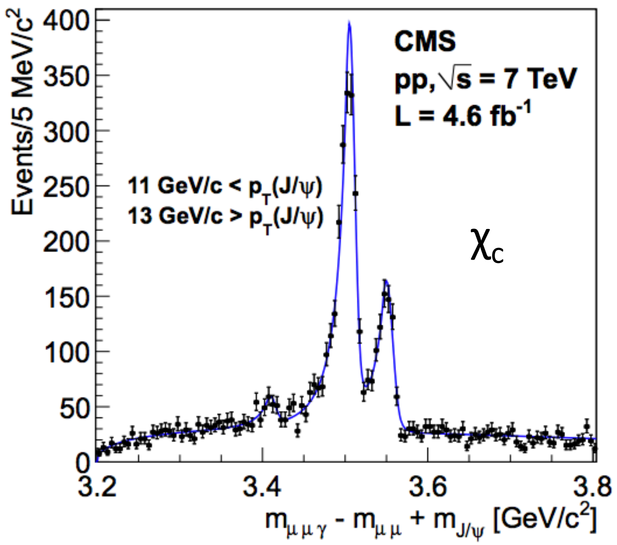
PRL 114 (2015) 191802



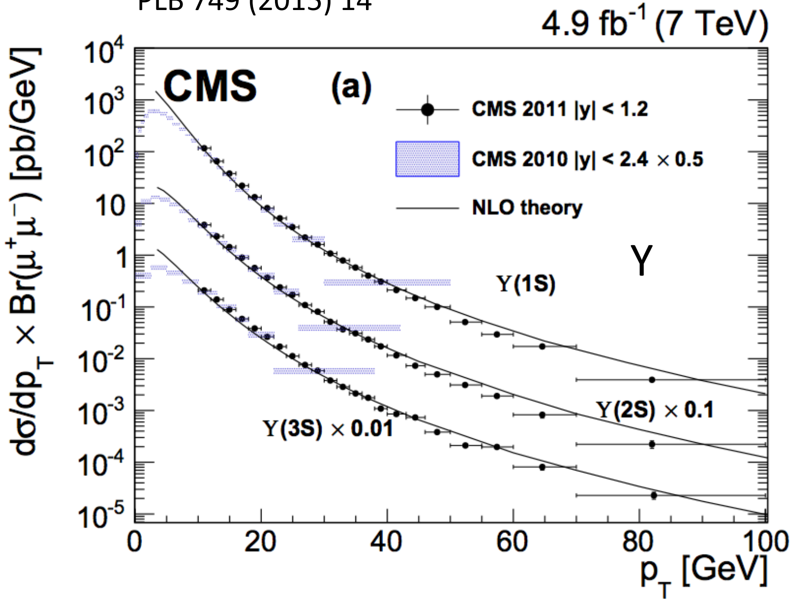
PLB 743 (2015) 383



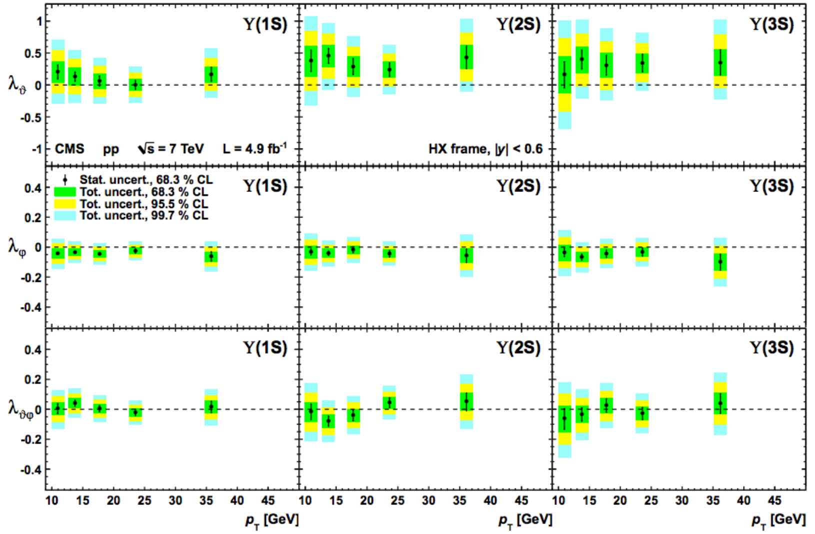
EPJC 72 (2012) 2251



PLB 749 (2015) 14



A dimuon mass resolution of 18-40 MeV (depending on rapidity), a secondary vertex resolution of 25 µm, and high muon detection and identification capabilities made this possible. Over 15 onia-related publications.



PLB 727 (2013) 381
PRL 110 (2013) 081802

Υ, J/ψ polarization

Xsec@13TeV: Measurement strategy

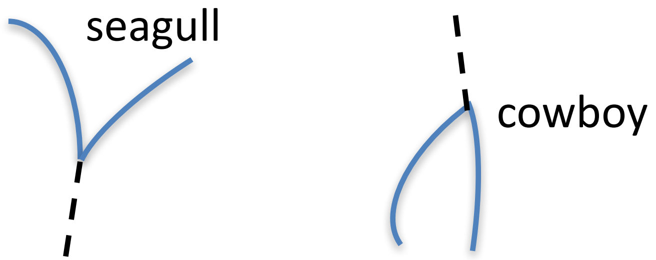
$$\mathcal{B}(\mathcal{Q} \to \mu^+\mu^-)\,\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y} = \frac{N(p_\mathrm{T},y)}{\mathcal{L}\Delta y \Delta p_\mathrm{T}} \left\langle \frac{1}{\epsilon(p_\mathrm{T},y)\mathcal{A}(p_\mathrm{T},y)} \right\rangle$$

- Δp_T, Δy: width of the transverse momentum and rapidity bin
- $N(p_T,y)$: yield of prompt J/ψ, ψ(2S) or Υ(nS) candidates from unbinned maximum likelihood fit to dimuon invariant mass spectrum.
- $\mathcal{L}$: integrated luminosity
- $\mathcal{A}$: geometrical acceptance, from simulation
- ε : efficiency, from data and simulation
- <> average over (rapidity, tranverse momentum) bin

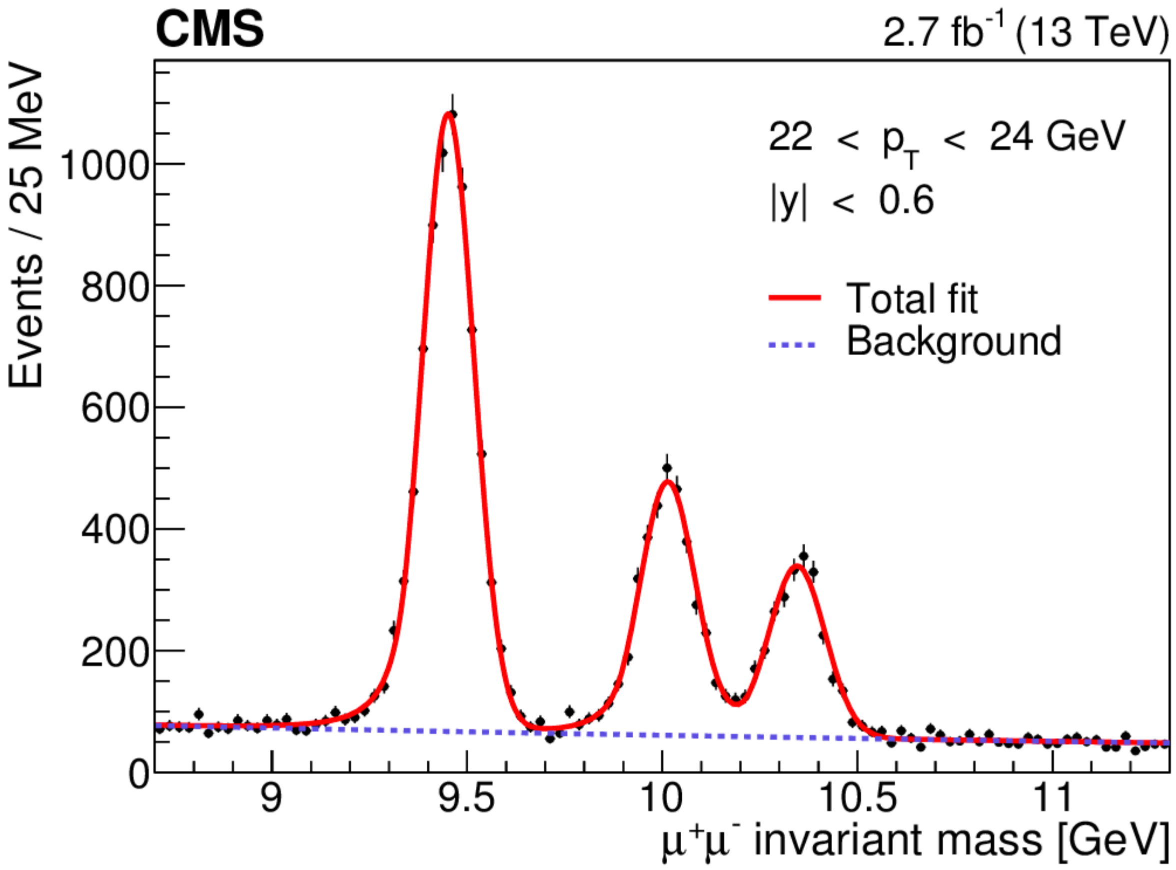
Trigger and Selection

- The analysis is performed using dedicated **dimuon triggers**
  - **L1** (hw): muon pairs identified and measured by the muon detector $|y|<1.6$
  - **L2** (sw): muons reconstructed combining tracker and muon system information
  - **L3** (sw): opposite-sign muons paired. Common-vertex compatibility >0.5%. Appropriate invariant mass window required.
- Using 2.4(2.7) fb^{-1} acquired in 2015 in pp collisions at LHC

- **Offline selection**:
  - Individual muons :
    - Acceptance $p_T > 4.5$ GeV for $|\eta| < 0.3$, $p_T > 4.0$ GeV for $0.3<|\eta|< 1.4$
    - High-quality tracks matching muon station
  - Vertex compatibility > 1%
  - Only pairs bending away from each other in the B field
  - Appropriate invariant mass requirements



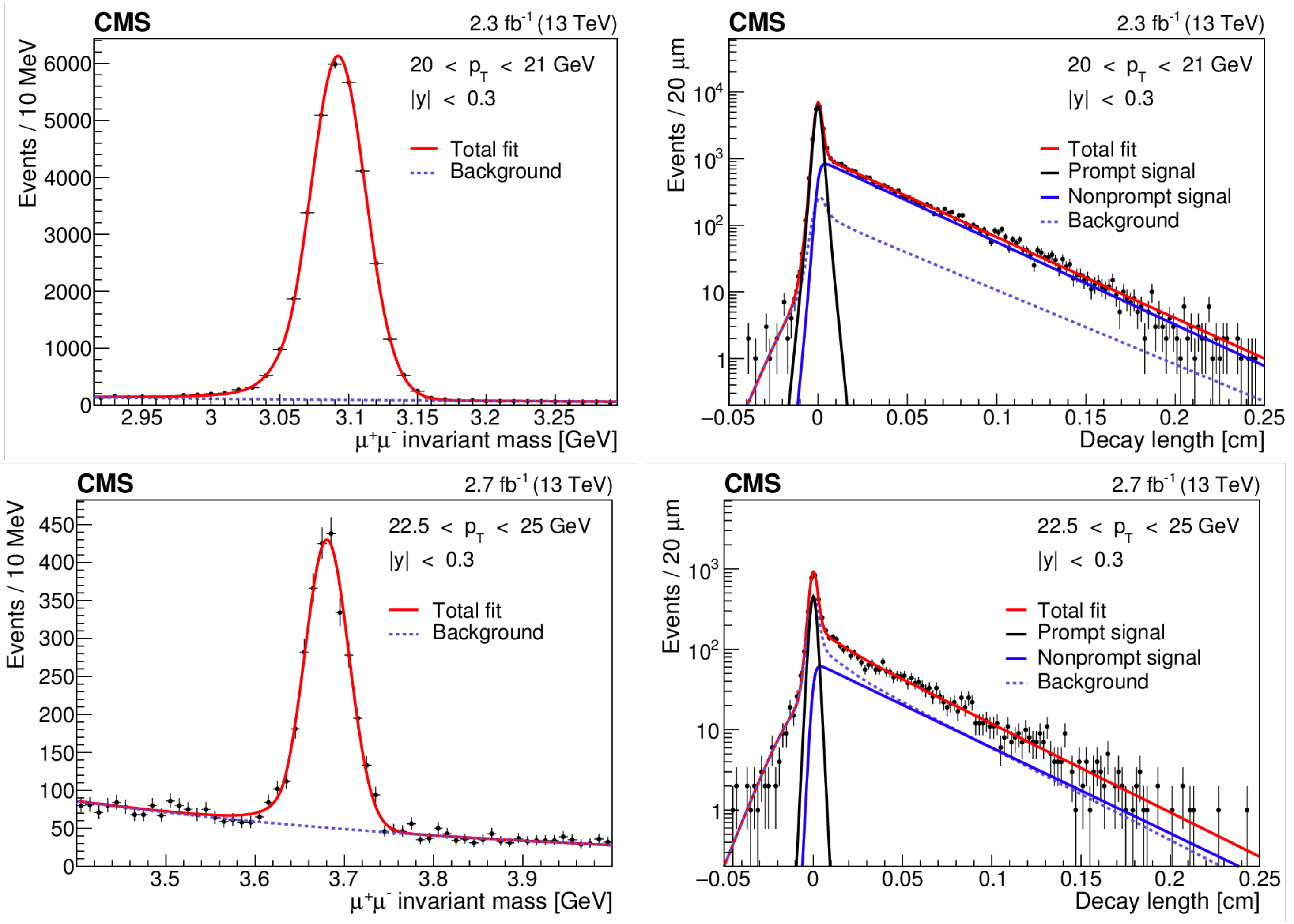
Υ(nS) yield



The signal is modeled using Crystal Ball functions. The backround PDF is an exponential function. The masses and widths of the Υ(nS) are constrained one another.

The yields are obtained using an unbinned Maximum Likelihood Fit to the dimuon invariant mass spectrum.

J/ψ, ψ(2S) yield



The mass signal is modeled by a CB plus gaussian function (CB only for the 2S). The background is exponential.

The ct signal is the sum of a delta (P) and decay (NP) function, convolved with a gaussian resolution function. The ct background also has P and NP components

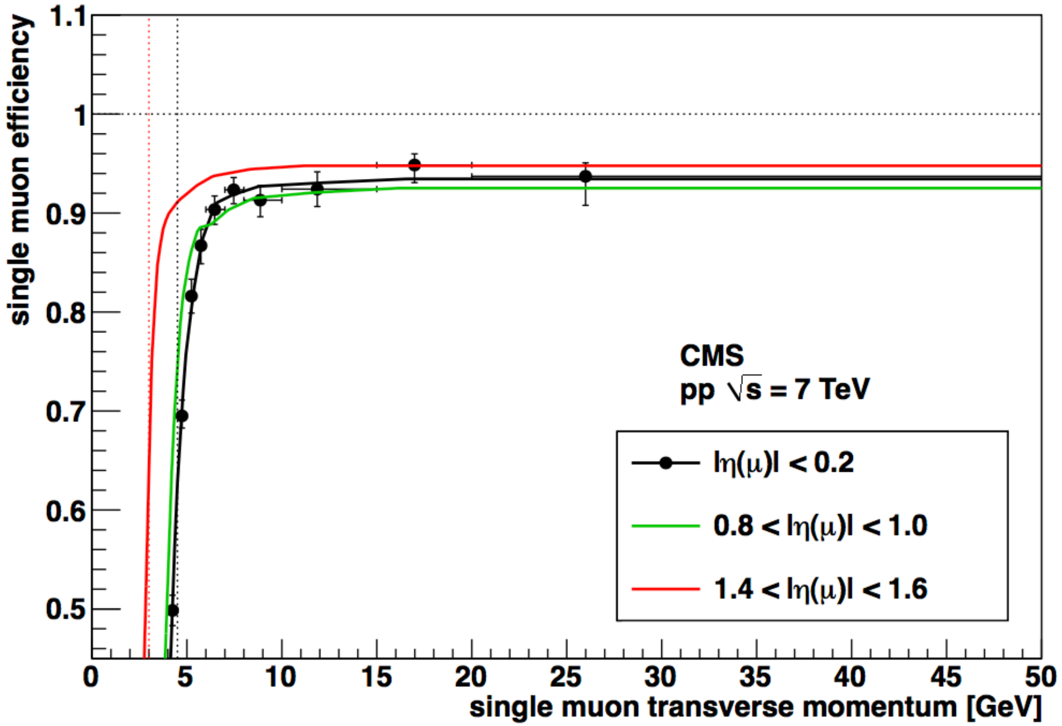
For J/ψ, ψ(2S) we perform a full 2D fit to invariant mass and decay length.

Acceptance and Efficiency

- Acceptance is calculated from simulation
- The total single-muon efficiency is the product of several factors: tracking, id, reconstruction, trigger (L1,L2,L3)
  - Measured from data using a Tag and Probe technique using J/ψ and Υ(1S) [L3 from sim]
- The dimuon efficiency is then calculated as :

$$\epsilon_{\mu\mu}(p_T, y) = \epsilon(p_{T1}, \eta_1) \cdot \epsilon(p_{T2}, \eta_2) \cdot \rho(p_T, y)$$

ρ is the correlation factor taking into account inefficiencies of the di-muon trigger and is measured from data

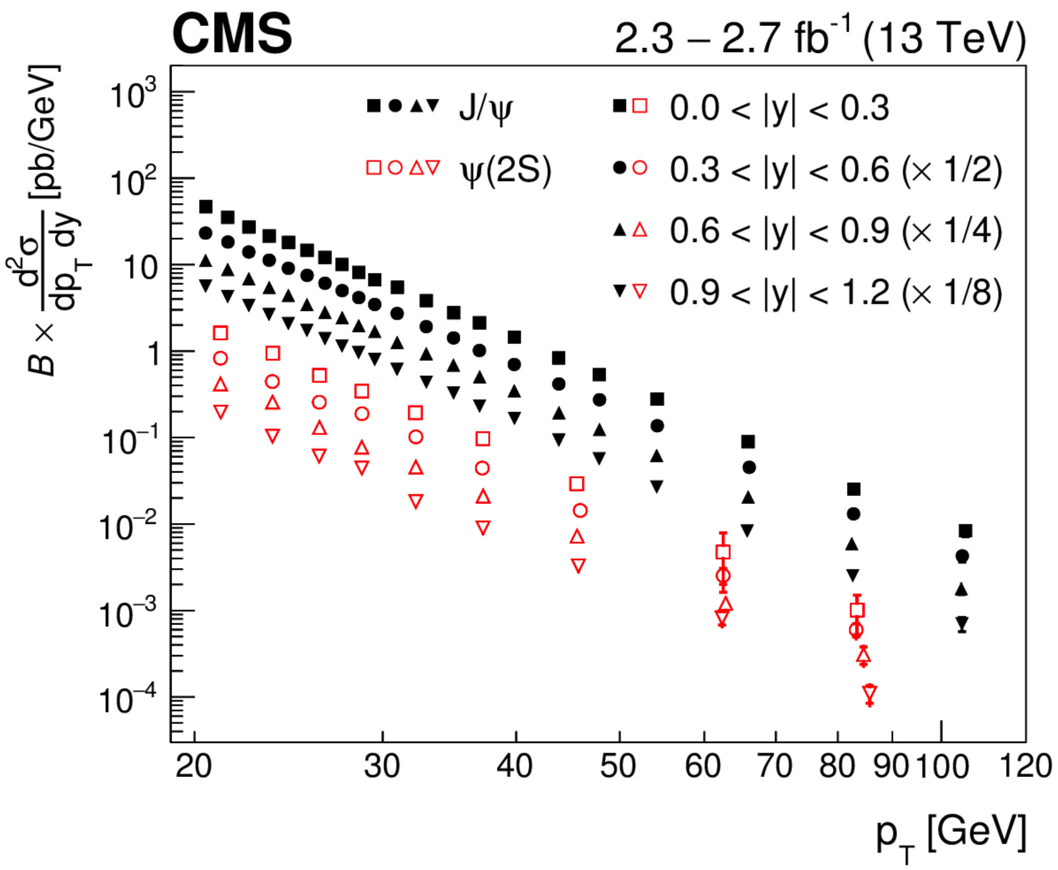


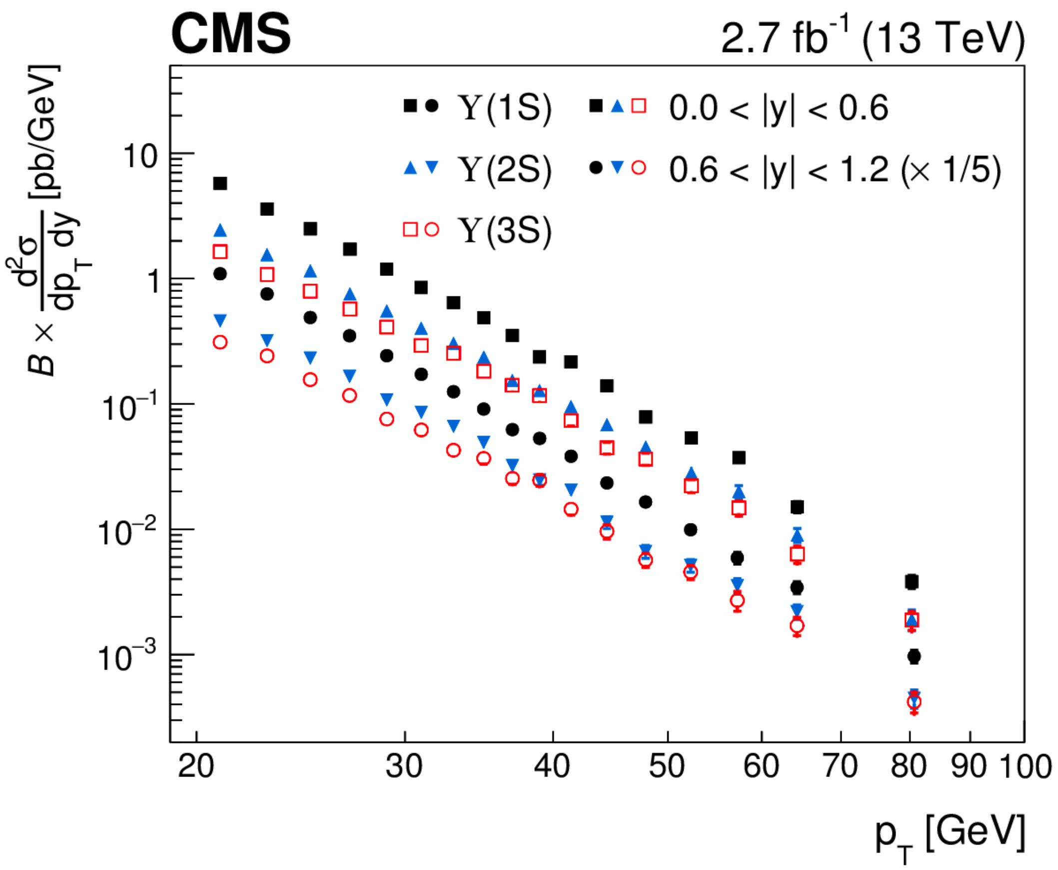
From the fine-grained acceptance and efficiency map, the average correction is calculated in each p_T,y bin of the analysis.

Systematic Uncertainties

- Uncertainties in the **yields** ~3%
  - Evaluated by variations of the fits
- Uncertainties in the **acceptance** evaluation
  - Polarization does affect acceptance resulting in variations of up to ±20%. Our acceptance is calculated for isotropic decays.
  - We do not treat polarization as a syst. uncertainty, but provide corrections factors to reproduce several polarization scenarios.
- Uncertainties in **efficiencies**
  - Single-muon efficiencies (dominated by L3) (2-3%)
  - ρ correlation factor (3-15% p_T dependent)
- **Lumi**nosity measurement (2.3%)

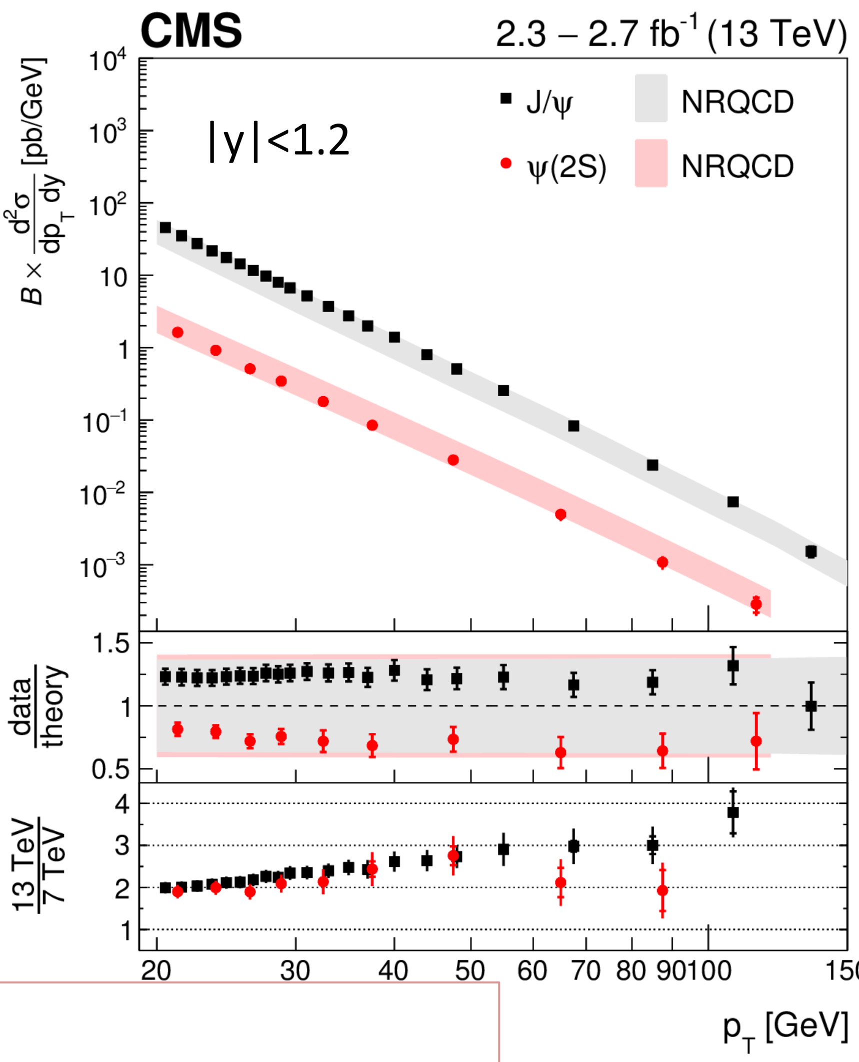
Results

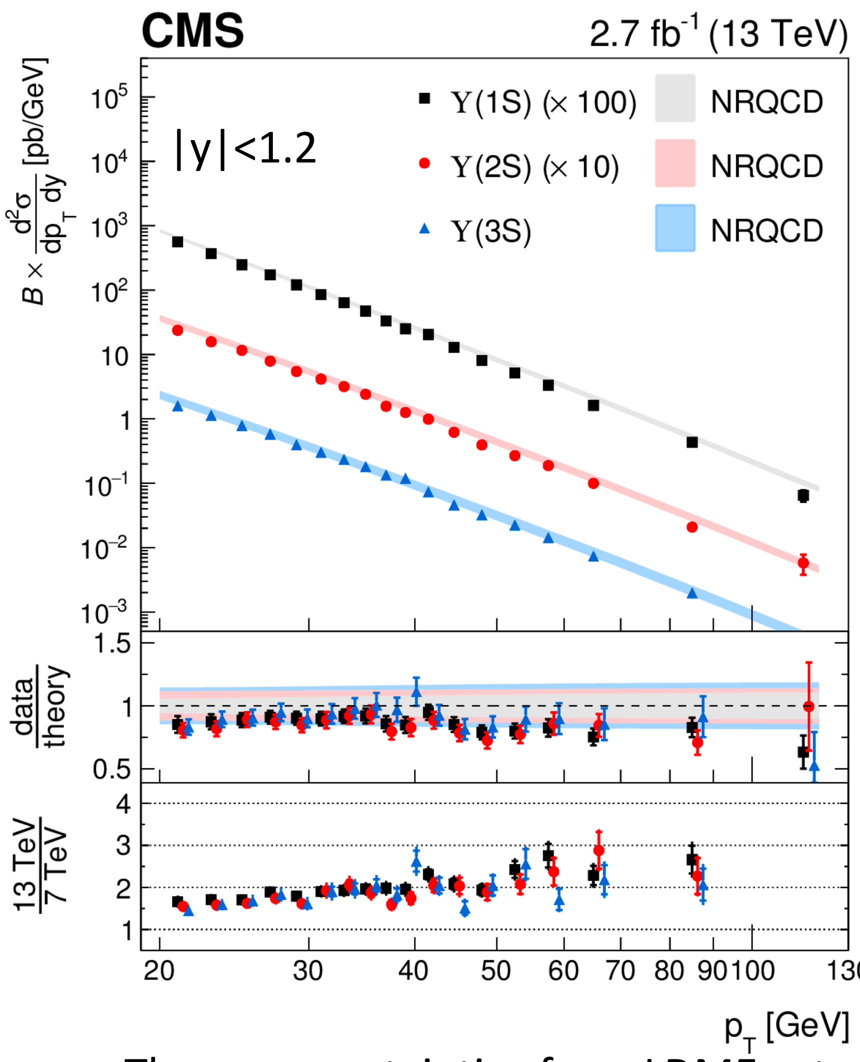




Differential cross section measurements for the five mesons in the four (two for the Y(nS)) rapidity ranges. Multiplication factors applied for clarity: the rapidity dependence is in fact rather weak in this y range.

Comparison to NLO NRQCD* and 7 TeV



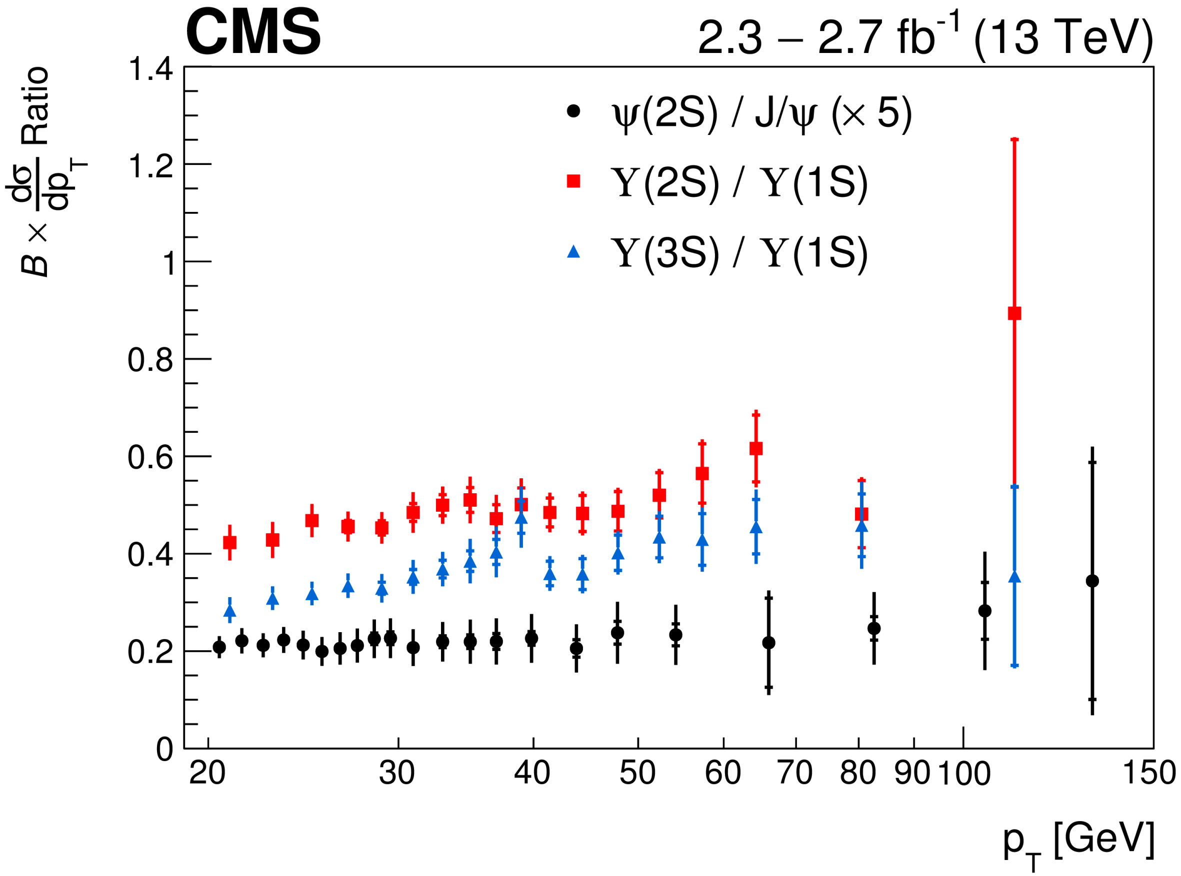


1009.3655
Ma, Wang, Chao
LDMEs from Tevatron (yields only)

*1410.8537
Han, Ma, Meng, Shao, Zhang, Chao
LDMEs from Tevatron and LHC 7 TeV yields

Theory uncertainties from LDME extraction, BR, quark masses, renormalization scale

Cross section ratios



Ratio of cross sections can be considered to cancel out systematic experimental as well as theoretical uncertainties. The error bars in this plot take into account correlations between the measurements.

Summary

- The **differential production cross section** of J/ψ, ψ(2S), and Υ(1,2,3S) at $\sqrt{s}$ = 13 TeV were measured at CMS with 2015 data (2.3 and 2.7 fb^{-1}). Two our knowledge, this the first time these **five S states** are measured in the same analysis.

- The results are presented in 4(2) rapidity bins and compared to NRQCD predictions, given LDMEs fitted from experimental data. Fair agreement is found.

- The paper is equipped with detailed cross section tables and polarization correction factors.

- We hope these measurements can be inserted in the global fit framework or in further NRQCD (or other approaches) tests, and help consolidate the knowledge of the processes at the base of QCD.

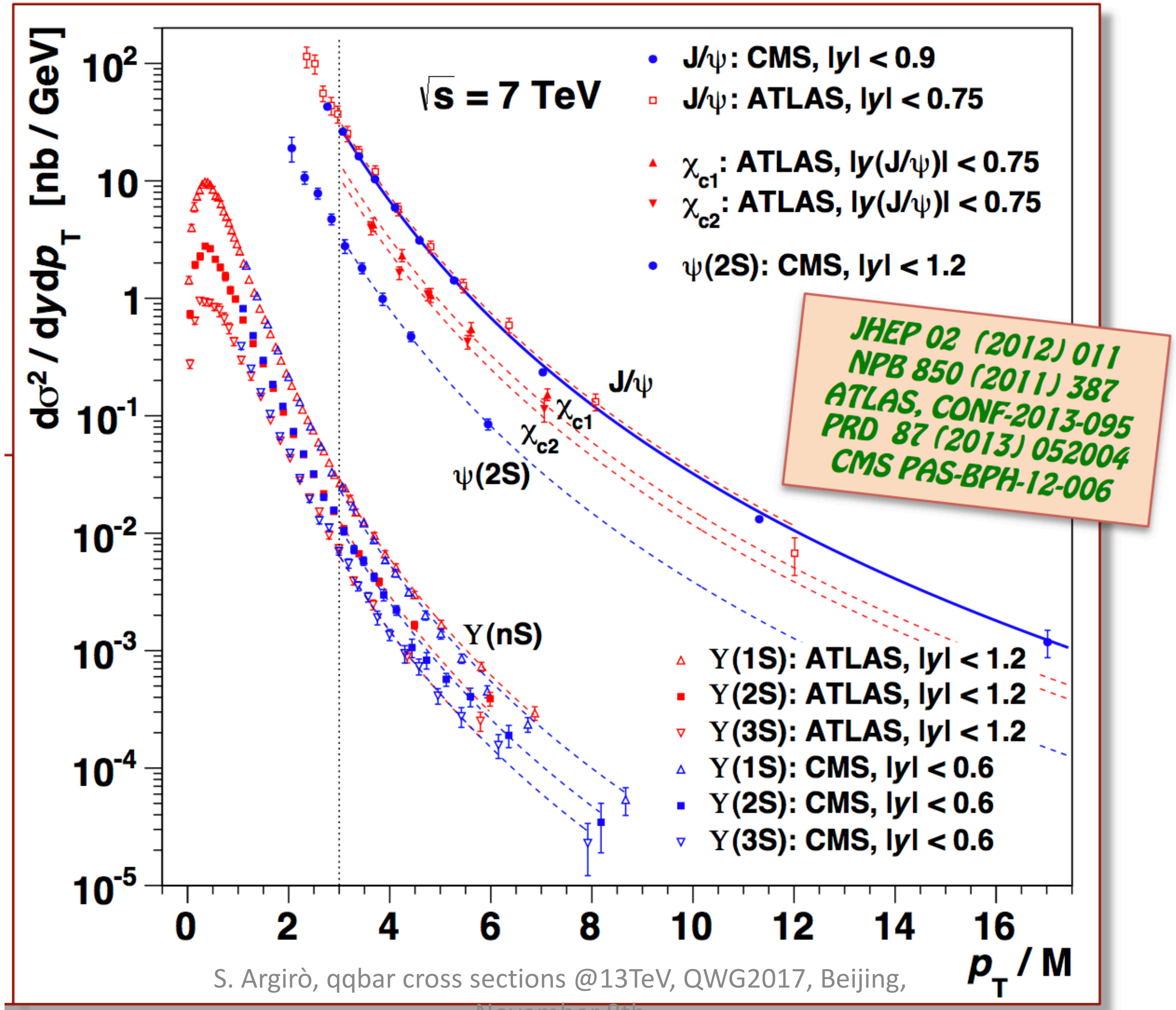
A compilation of CMS measurements

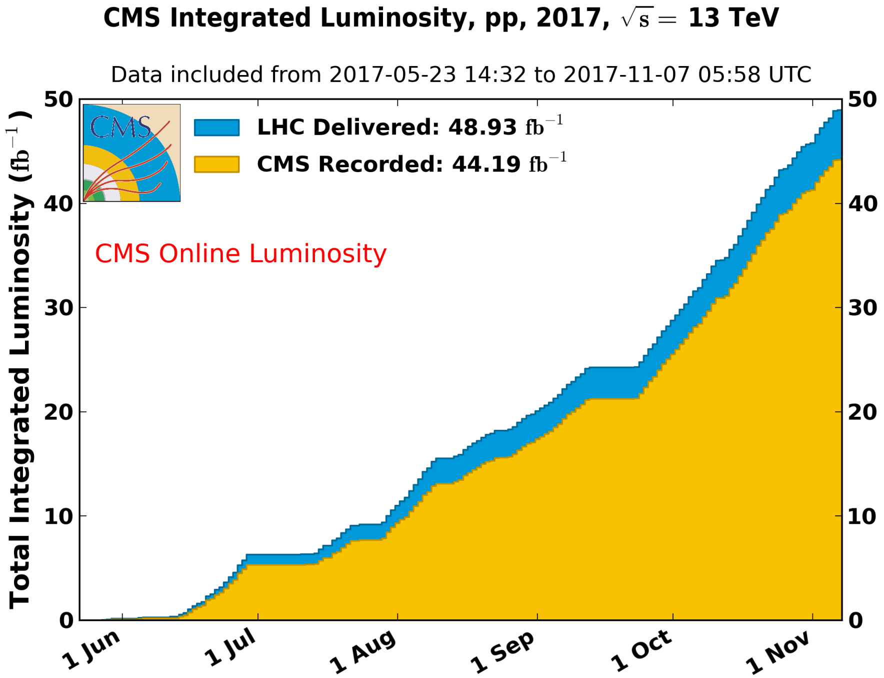
- Observation of Υ(1S) pair production at CMS arXiv:1610.07095
- Υ(nS) polarizations versus particle multiplicity in pp collisions at $\sqrt{s}$ = 7 TeV 1603.02913
- Prompt J/ψ and ψ(2S) double-differential production cross sections in pp collisions at 7 TeV 1502.04155
- Measurements of the Υ(1S), Υ(2S) and Υ(3S) differential cross sections in pp collisions at $\sqrt{s}$ = 7 TeV 1501.07750
- Measurement of the χ_{b2} and χ_{b1} cross section ratio in pp collisions at $\sqrt{s}$ = 8 TeV 1409.5761
- Measurement of prompt J/ψ pair production in pp collisions at = 7 TeV 1406.0484
- Search for a new bottomonium state decaying into $\Upsilon\pi\pi$ in pp collisions 1309.0250
- Prompt and non-prompt J/ψ and ψ(2S) polarizations in pp collisions at $\sqrt{s}$ = 7 TeV 1307.6070
- Measurement of the Upsilon(nS) production cross section 1303.5900
- Measurement of the X(3872) production cross section 1302.3968
- Measurement of the relative prompt production rate of χ_{c2} and χ_{c1} at $\sqrt{s}$ = 7 TeV 1210.0875
- Measurement of Υ(1S), Υ(2S), Υ(3S) polarizations at $\sqrt{s}$ = 7 TeV 1209.2922
- J/ψ and ψ(2S) production in pp collisions at $\sqrt{s}$ = 7 TeV 1111.1557
- Υ production cross section in pp collisions at $\sqrt{s}$ = 7 TeV 1012.5545
- J/ψ prompt and non-prompt cross sections in pp collisions at $\sqrt{s}$ = 7 TeV 1011.4193

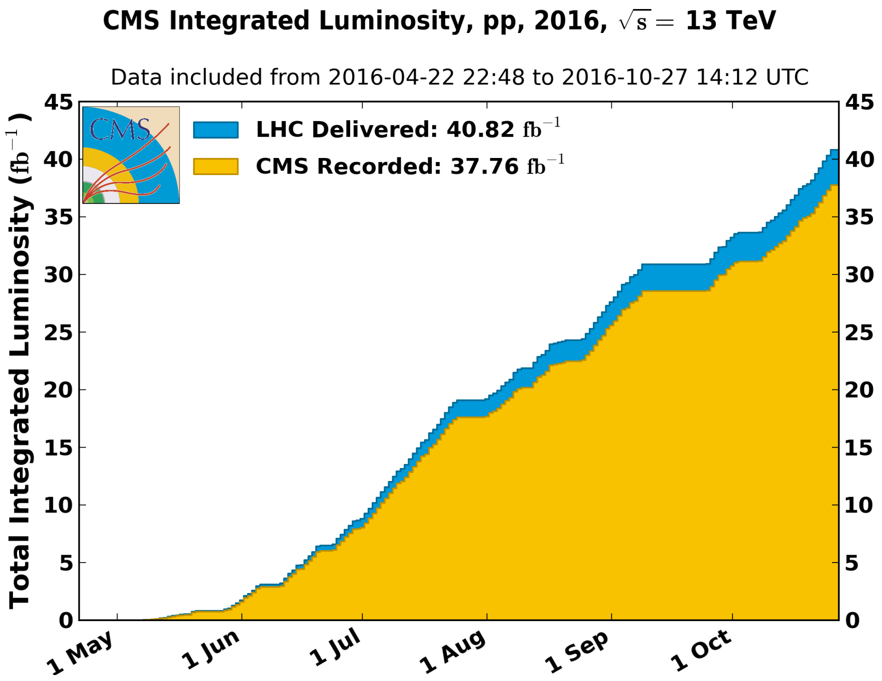
[Link to CMS B Physics public results](#)

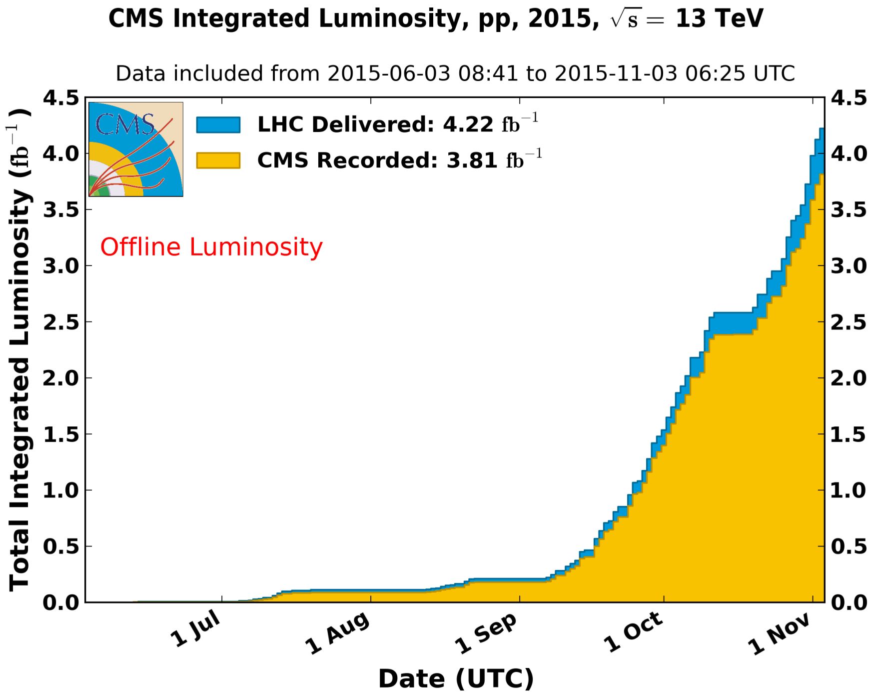
EXTRA

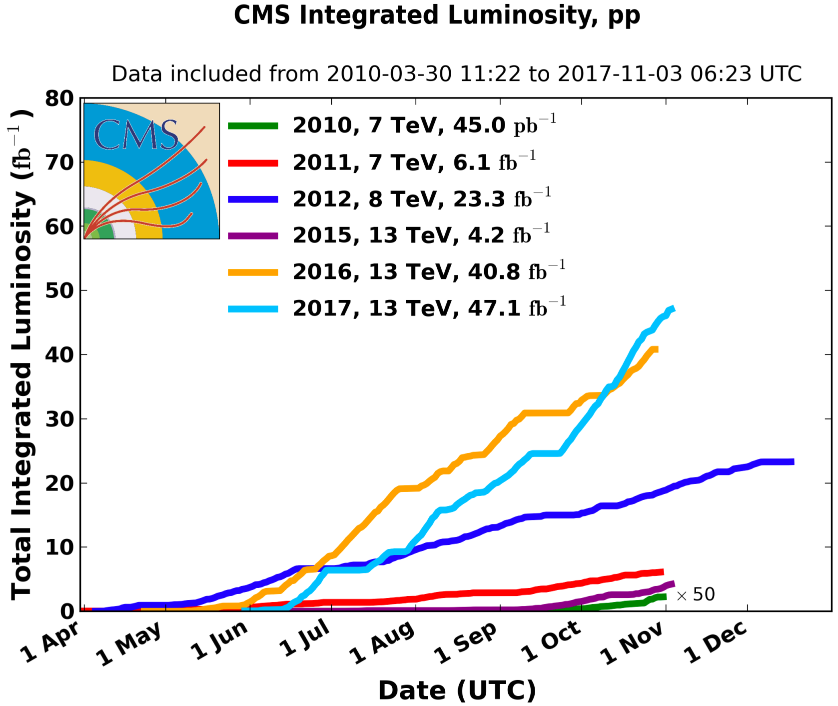
.. To be updated with this measurement…




CMS Integrated Luminosity, pp, 2017, √s = 13 TeV
Data included from 2017-05-23 14:32 to 2017-11-07 05:58 UTC
LHC Delivered: 48.93 fb⁻¹
CMS Recorded: 44.19 fb⁻¹
CMS Online Luminosity
Total Integrated Luminosity (fb⁻¹)
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov


CMS Integrated Luminosity, pp, 2016, √s = 13 TeV
Data included from 2016-04-22 22:48 to 2016-10-27 14:12 UTC
LHC Delivered: 40.82 fb⁻¹
CMS Recorded: 37.76 fb⁻¹
Total Integrated Luminosity (fb⁻¹)
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct


CMS Integrated Luminosity, pp, 2015, √s = 13 TeV
Data included from 2015-06-03 08:41 to 2015-11-03 06:25 UTC
LHC Delivered: 4.22 fb⁻¹
CMS Recorded: 3.81 fb⁻¹
Offline Luminosity
Total Integrated Luminosity (fb⁻¹)
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
Date (UTC)


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:22 to 2017-11-03 06:23 UTC
2010, 7 TeV, 45.0 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
2015, 13 TeV, 4.2 fb⁻¹
2016, 13 TeV, 40.8 fb⁻¹
2017, 13 TeV, 47.1 fb⁻¹
× 50
Total Integrated Luminosity (fb⁻¹)
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)