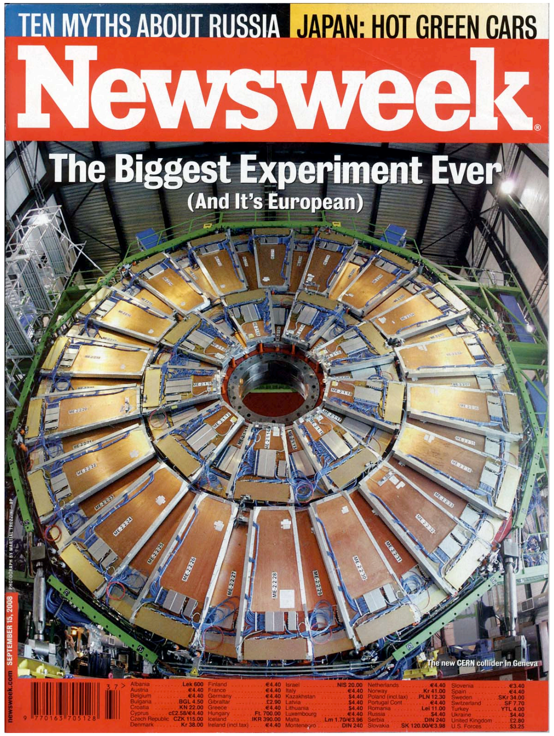
# Quarkonium production in pp collisions at $\sqrt{s}$ = 7 TeV with the CMS experiment





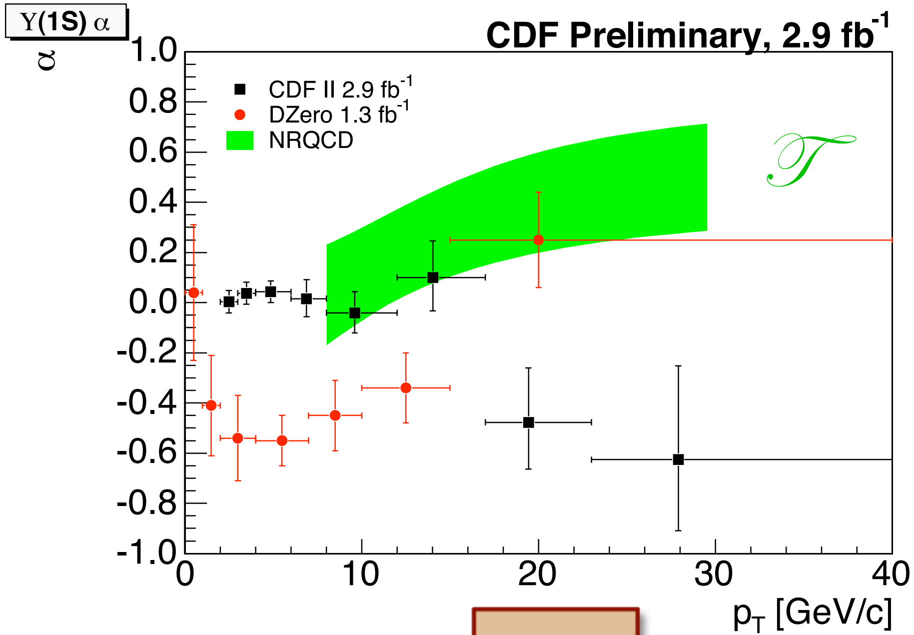
Bora Akgün
(Carnegie Mellon University)
on behalf of CMS Collaboration

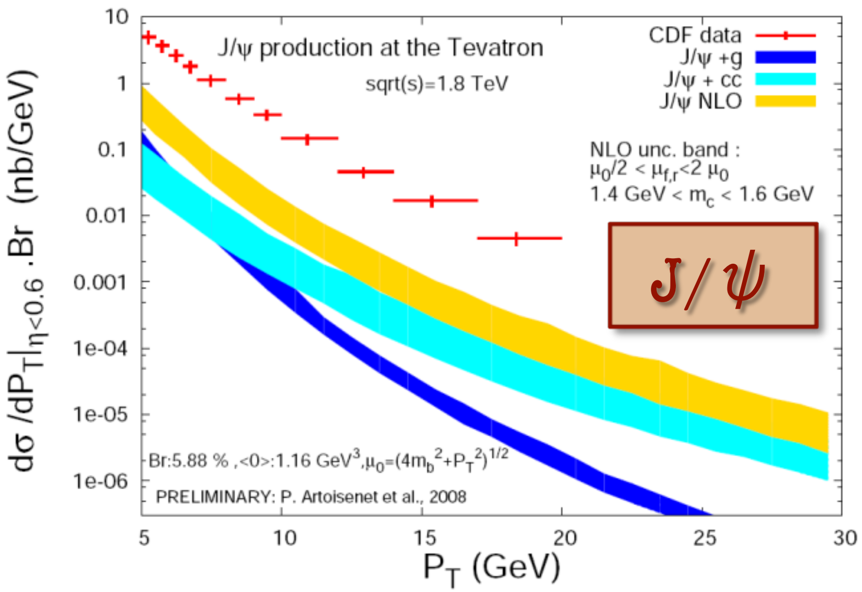

Hadron 2011

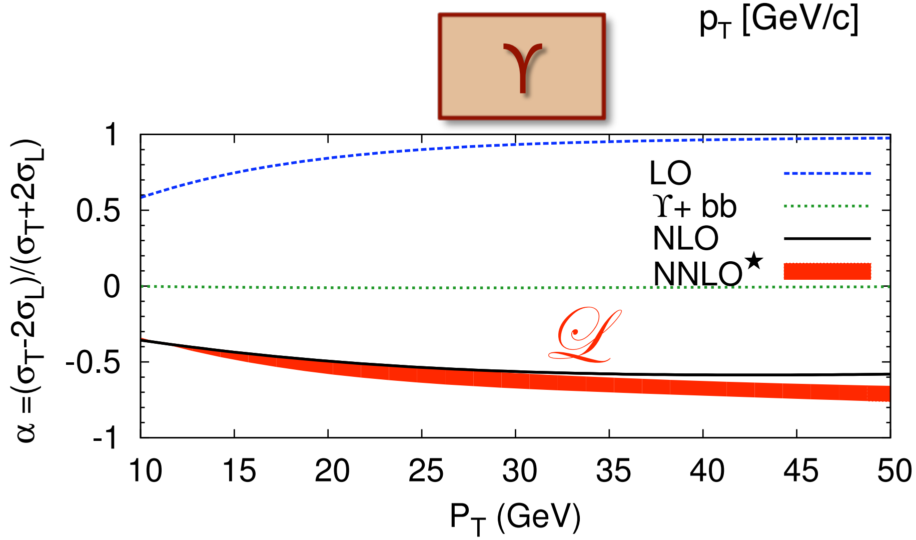
Munich, June 14, 2011

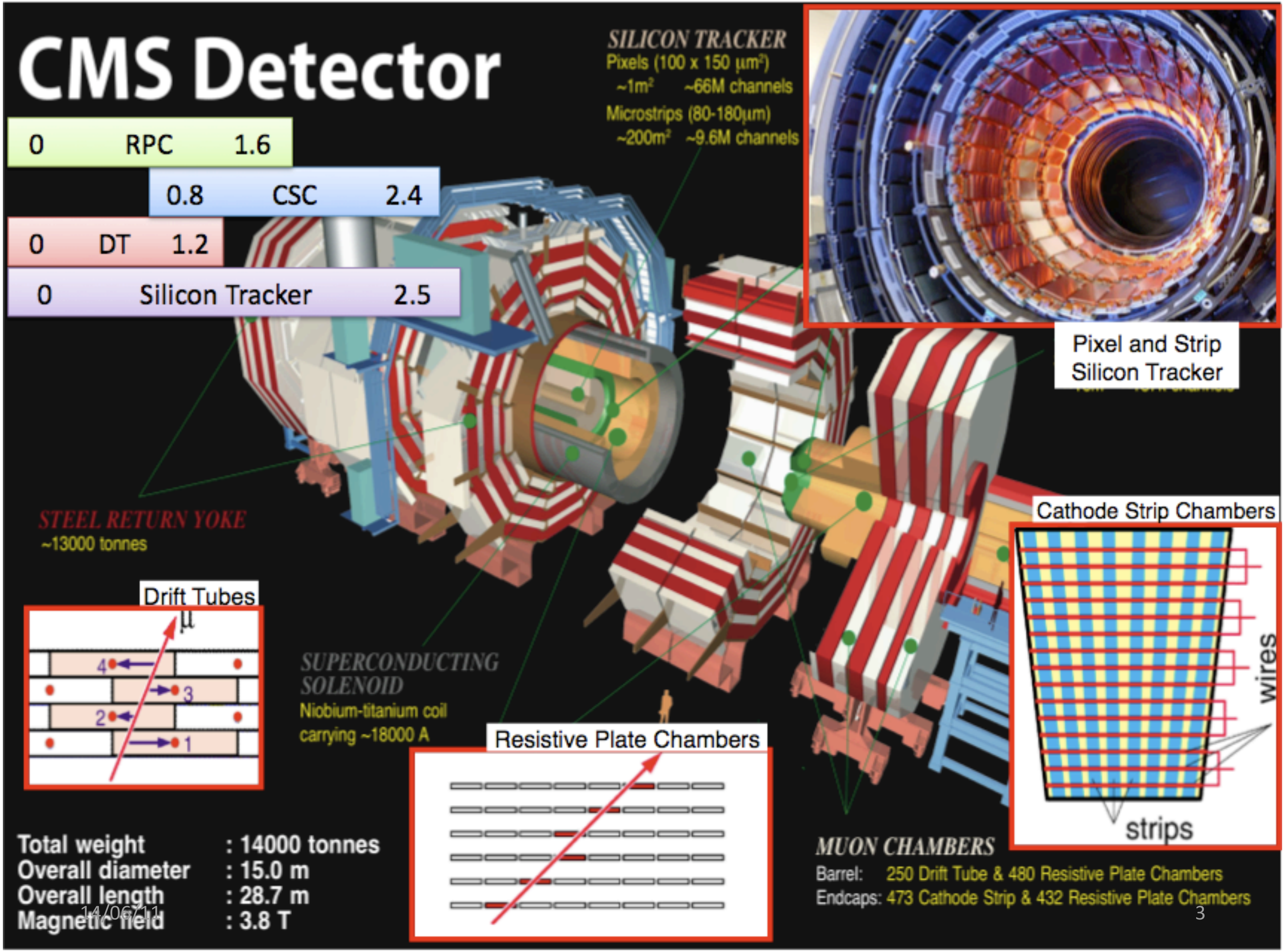
# Quarkonium production puzzle

- Hadroproduction of quarkonia is not fully understood
- No theory has simultaneously explained the experimental measurements of both cross section and polarization
- Opportunity at LHC to provide valuable input for understanding quarkonium production including reach to higher $p_T$

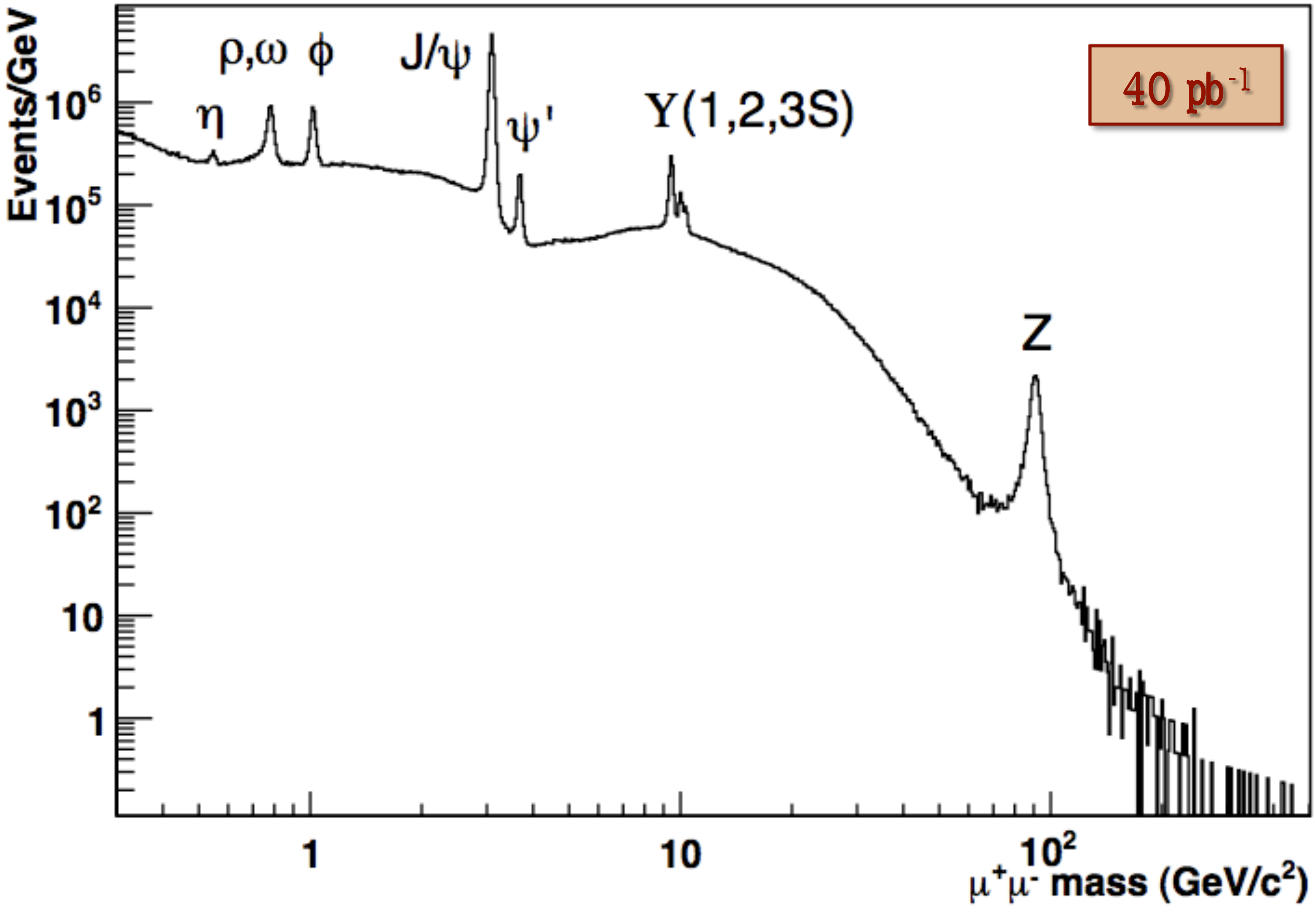


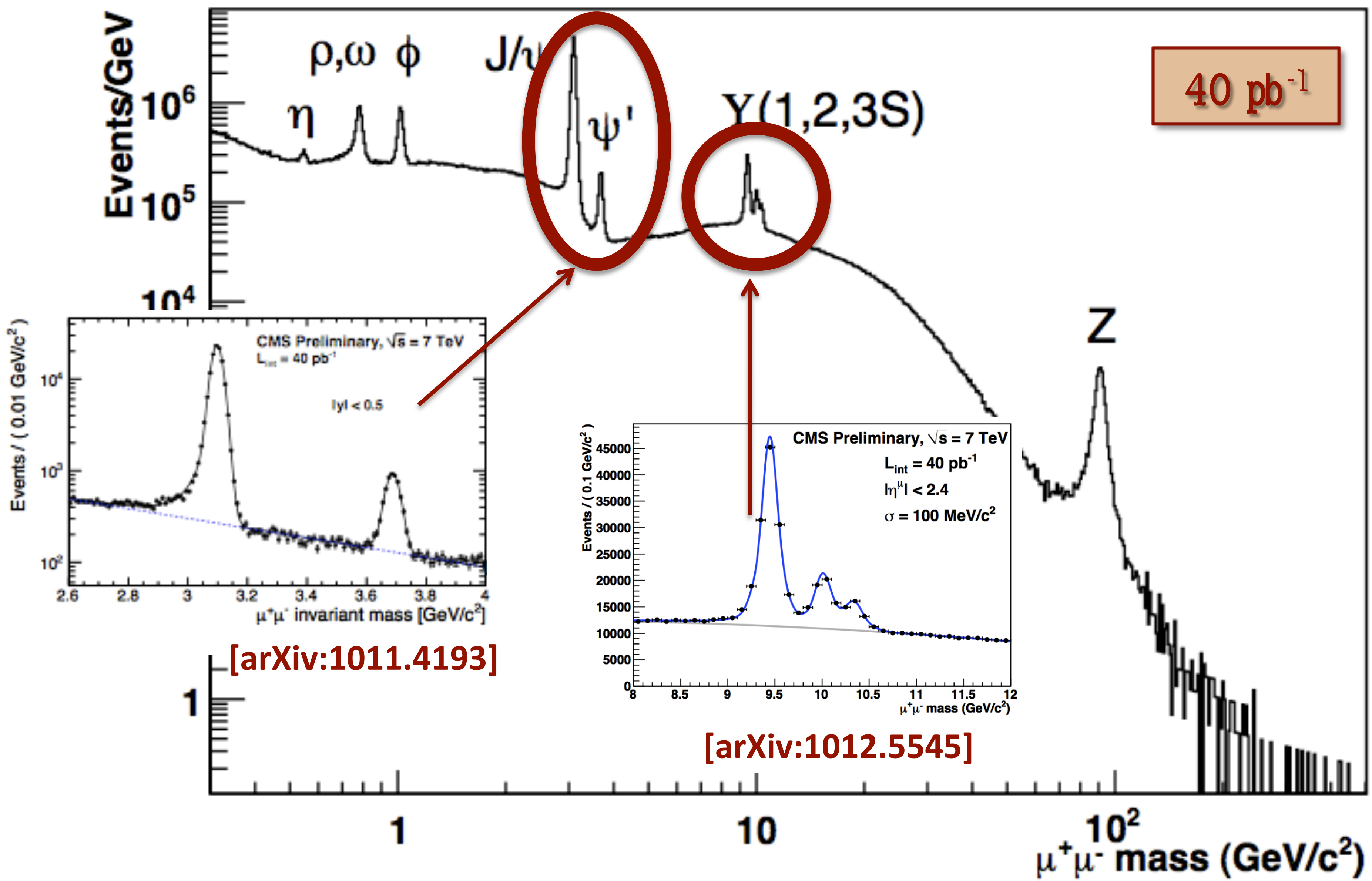




CMS Detector
0 RPC 1.6
0.8 CSC 2.4
0 DT 1.2
0 Silicon Tracker 2.5
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
Pixel and Strip
Silicon Tracker
STEEL RETURN YOKE
~13000 tonnes
Drift Tubes
μ
4
3
2
1
SUPERCONDUCTING
SOLENOID
Niobium-titanium coil
carrying ~18000 A
Resistive Plate Chambers
Cathode Strip Chambers
wires
strips
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

# CMS Di-muon Invariant Mass Spectrum



# CMS Di-muon Invariant Mass Spectrum



# Muon Triggers @ CMS

- Level 1 Trigger
  - Custom Hardware
  - Muon and Calorimeter System information only
- High Level Trigger (HLT)
  - Software, computing farm
  - Tracker included, fast (local) reconstruction

- Trigger requirements adapted to increasing luminosity
- Single-Muon Trigger Paths
  - $p_T > 3$ GeV/c threshold at LHC startup
  - Gradually increasing thresholds (e.g., $p_T > 7$ GeV/c at $\mathcal{L} \sim 10^{31}$ $cm^{-2}s^{-1}$)
  - Require additional objects, e.g., single-muon plus track
- Di-Muon Trigger Paths
  - No $p_T$ threshold, selection based on L1 only (for first 3 $pb^{-1}$)
  - At higher luminosities combination of L1 &HLT muon, track, mass cuts requirements
- Trigger used lower luminosities in 2010 for quarkonia studies
  - Demonstrated ability to trigger muons at low $p_T$

# Cross Section Overview

$$\frac{d^2\sigma}{dp_T dy} \cdot B(X \to \mu\mu) = \frac{N_{fit} \langle \frac{1}{A \cdot \varepsilon} \rangle}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y}$$

$N_{fit}$: Corrected signal yield from fit to weighted di-muon invariant mass distribution, with per-event acceptance and efficiency corrections

- A: Detector acceptance from simulation
- ε: Muon trigger and reconstruction efficiencies measured in data with tag-and-probe method
- $\mathcal{L}$: Integrated luminosity
- $\Delta p_T$, $\Delta y$: Transverse momentum and rapidity bin widths

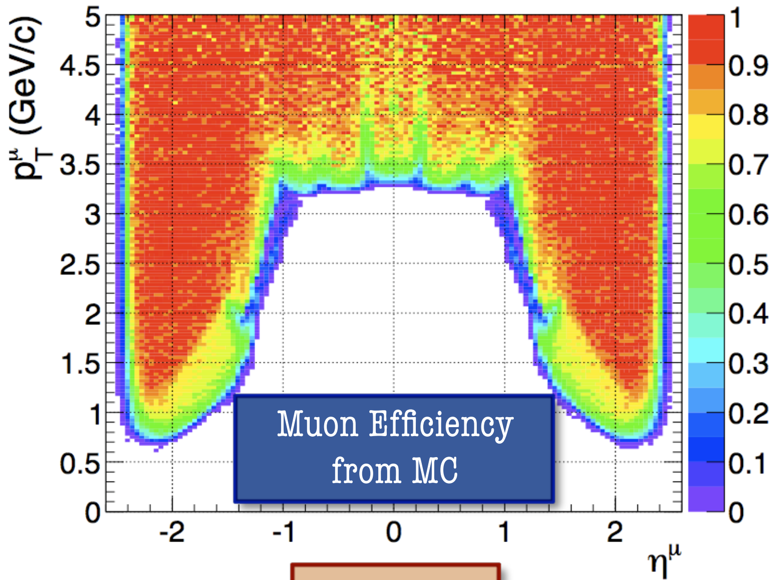
# Muon Kinematic Acceptance

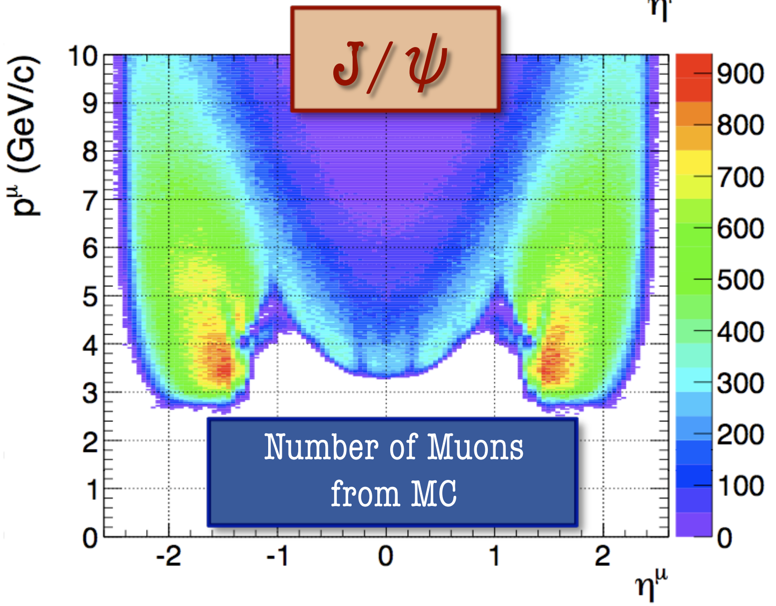
**J/ψ**

$p_T > 3.3$ GeV/c for $|\eta| < 1.3$
$p > 2.9$ GeV/c for $1.3 < |\eta| < 2.2$
$p_T > 0.8$ GeV/c for $2.2 < |\eta| < 2.4$

**ϒ**

$p_T > 3.5$ GeV/c for $|\eta| < 1.6$
$p_T > 2.5$ GeV/c for $1.6 < |\eta| < 2.4$

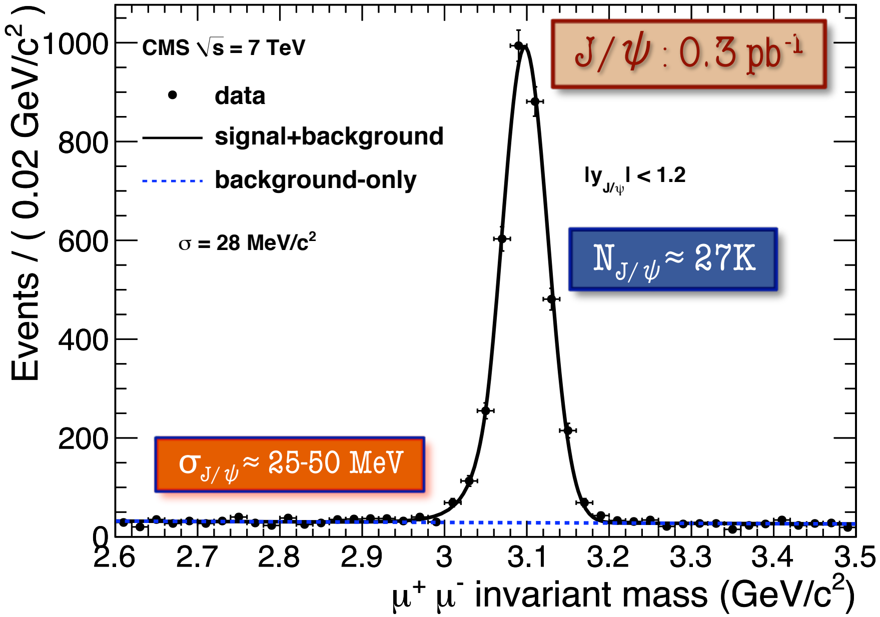


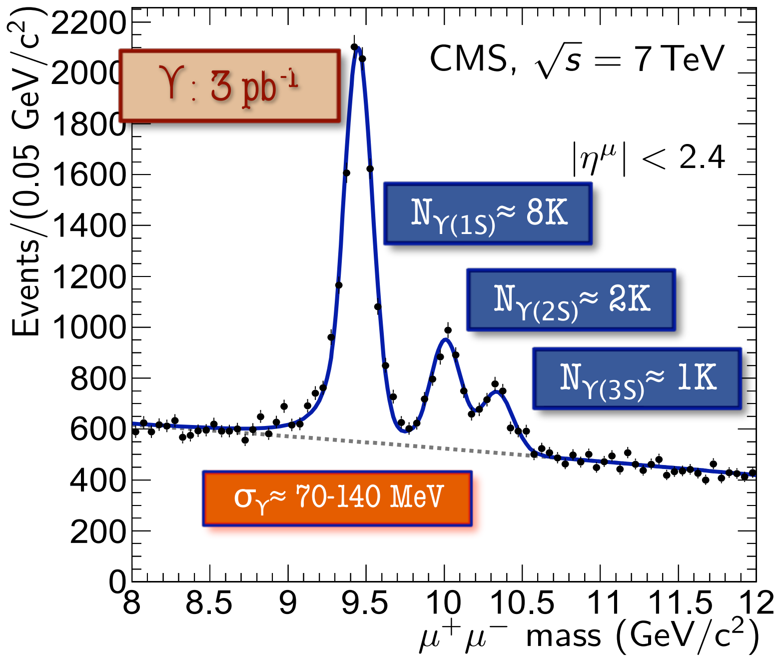




- Kinematical cuts for J/ψ analysis loose to study low $p_T$ J/ψ's
- Muons from Y have more uniform detector coverage

# Selection and Yields

- Similar selection criteria for both J/ψ and Υ
  - Trigger: di-muon at L1, without $p_T$ requirements
  - Two muons opposite sign, vertex probability > 0.1%, muon track quality cuts



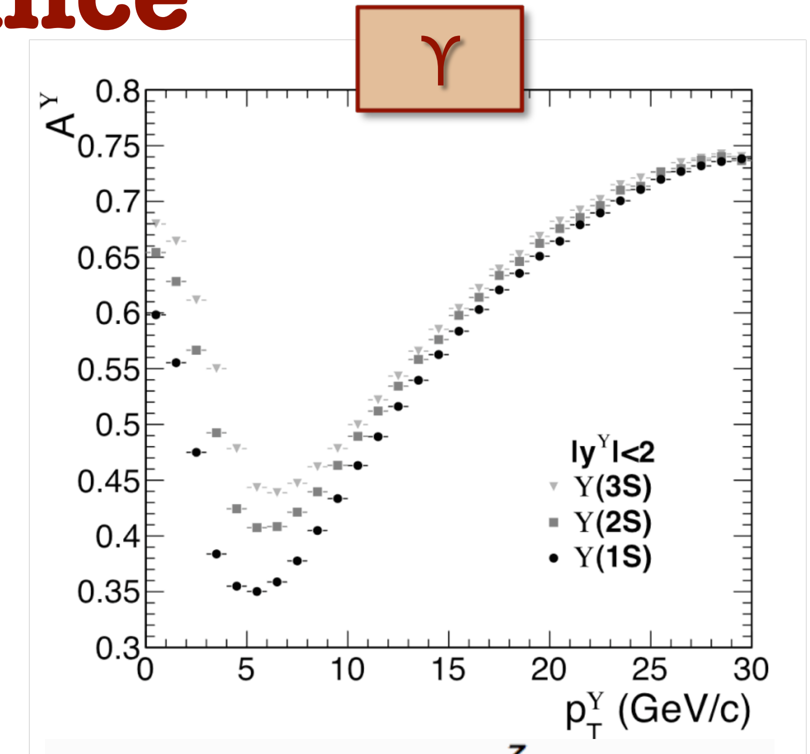

- Signal: Crystal Ball Function (Gauss + Exp FSR tail)
- Background: Exponential

- Signal: 3 Crystal Ball Functions, fixed mass peak differences and shared resolution
- Background: $2^{nd}$-order polynomial

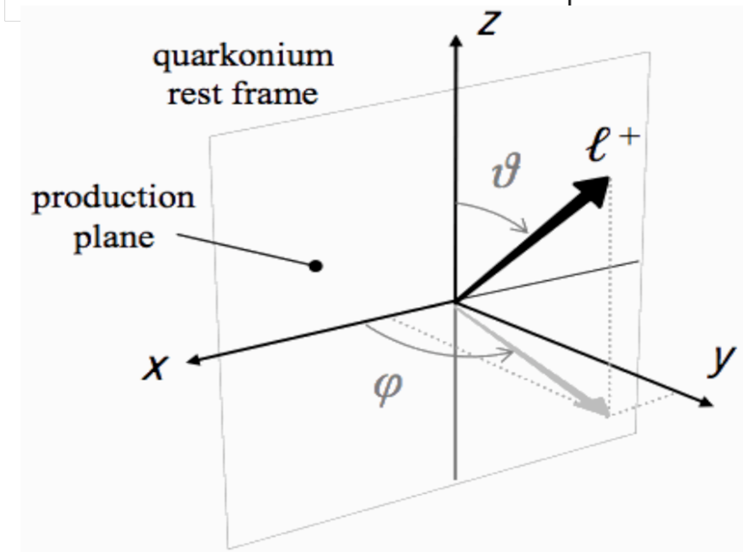
# Acceptance

$$A(p_T, y; \lambda_\theta) = \frac{N_{\det}(p_T, y; \lambda_\theta)}{N_{gen}(p_T, y; \lambda_\theta)}$$

- Evaluated from simulation
- Reconstructed Υ down to zero $p_T$
- Depends on Υ $p_T$, y and production polarization




- Upsilon production polarization is unknown
  - Acceptance changes by up to 20%
  - Quote results for 5 polarization scenarios: unpolarized, longitudinal and transverse in Collins-Soper and helicity frames



# Υ(nS) Cross Section Results

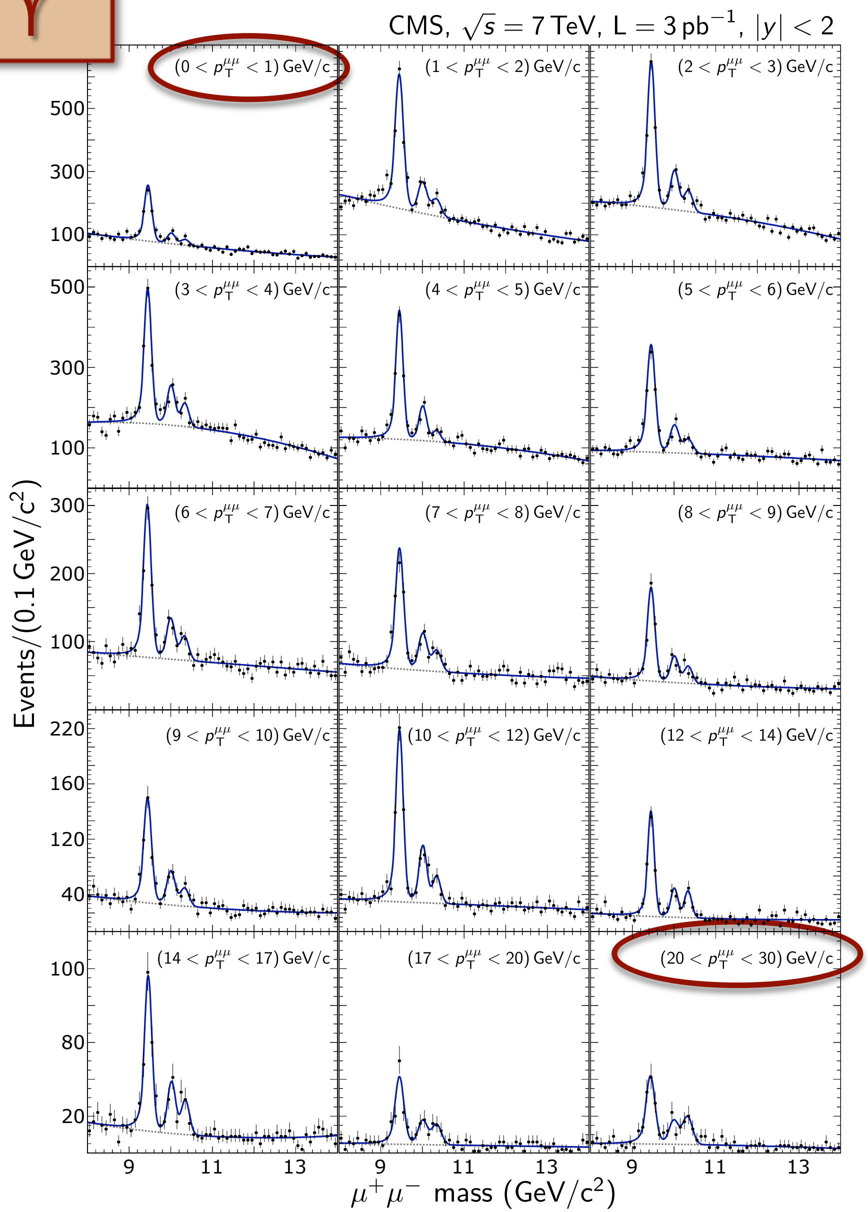
- Measured cross sections for |y|<2:

$$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 7.37 \pm 0.13(\text{stat.})^{+0.61}_{-0.42}(\text{syst.}) \pm 0.81(\text{lumi.})\text{ nb}$$
$$\sigma(pp \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 1.90 \pm 0.09(\text{stat.})^{+0.20}_{-0.14}(\text{syst.}) \pm 0.24(\text{lumi.})\text{ nb}$$
$$\sigma(pp \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 1.02 \pm 0.07(\text{stat.})^{+0.11}_{-0.08}(\text{syst.}) \pm 0.11(\text{lumi.})\text{ nb}$$

- Values shown for unpolarized assumption
  - Extreme scenarios yield variations by 20%
- Dominant systematic uncertainties
  - Muon reconstruction/trigger efficiency from T&P (~8%)
  - Luminosity normalization (11%)

# Differential Cross Section

Υ

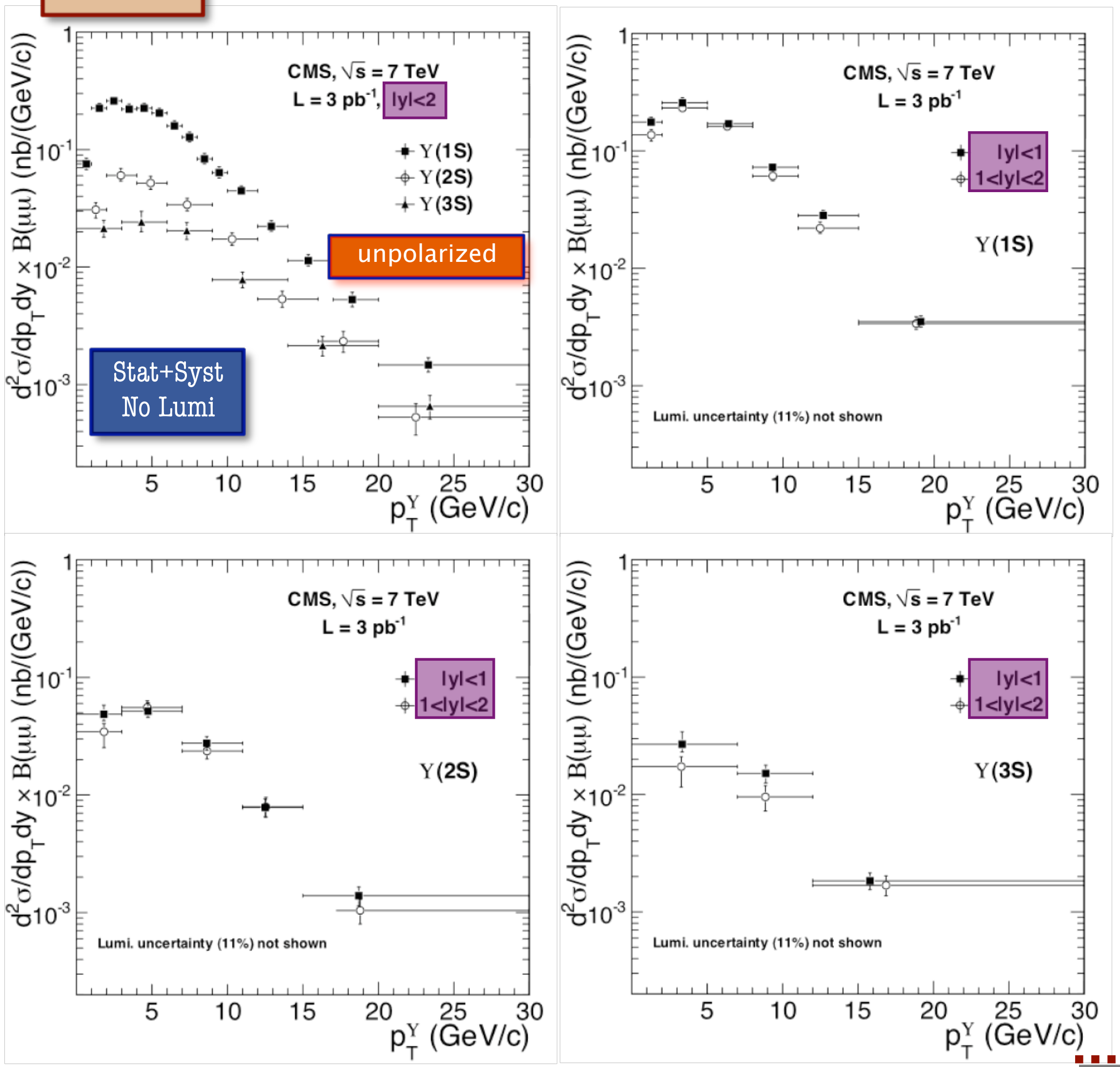



Polarization var. ≈ 20%

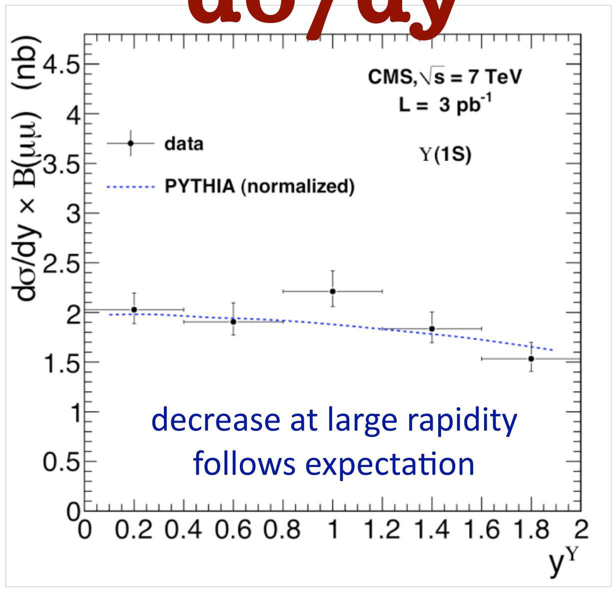
| $p_T$ (GeV/c) | $\sigma \cdot \mathcal{B}$ (nb) | stat. (%) | $\sum_{syst.}$ (%) | $\Delta\sigma$ (%) | HX-T | HX-L | CS-T | CS-L |
|---|---|---|---|---|---|---|---|---|
| Υ(1S) | | | | $|y| < 2$ | | | | |
| 0–30 | 7.37 | 1.8 | 8 (6) | 14 (13) | +16 | -22 | +13 | -16 |
| 0–1 | 0.30 | 8 | 10 (7) | 17 (15) | +16 | -22 | +17 | -23 |
| 1–2 | 0.90 | 5 | 9 (6) | 15 (14) | +16 | -20 | +19 | -24 |
| 2–3 | 1.04 | 5 | 8 (6) | 14 (13) | +15 | -20 | +19 | -24 |
| 3–4 | 0.88 | 6 | 9 (7) | 15 (14) | +18 | -23 | +18 | -23 |
| 4–5 | 0.90 | 6 | 8 (6) | 15 (14) | +18 | -23 | +16 | -21 |
| 5–6 | 0.82 | 6 | 8 (6) | 15 (14) | +17 | -23 | +13 | -19 |
| 6–7 | 0.64 | 7 | 8 (5) | 15 (14) | +17 | -22 | +11 | -16 |
| 7–8 | 0.51 | 7 | 8 (6) | 15 (14) | +16 | -22 | +7 | -10 |
| 8–9 | 0.33 | 8 | 8 (6) | 16 (14) | +16 | -22 | +4 | -5 |
| 9–10 | 0.25 | 8 | 9 (6) | 16 (15) | +15 | -21 | +2 | -1 |
| 10–12 | 0.36 | 6 | 8 (5) | 15 (14) | +15 | -21 | -1 | +3 |
| 12–14 | 0.18 | 8 | 9 (5) | 16 (14) | +15 | -20 | -3 | +7 |
| 14–17 | 0.14 | 9 | 10 (6) | 17 (15) | +14 | -19 | -4 | +9 |
| 17–20 | 0.06 | 12 | 10 (6) | 19 (17) | +13 | -18 | -4 | +10 |
| 20–30 | 0.06 | 12 | 10 (6) | 19 (17) | +12 | -17 | -4 | +10 |
| Υ(2S) | | | | $|y| < 2$ | | | | |
| 0–30 | 1.90 | 4.2 | 9 (6) | 15 (13) | +14 | -19 | +12 | -15 |
| 0–2 | 0.25 | 12 | 11 (9) | 20 (19) | +14 | -19 | +17 | -22 |
| 2–4 | 0.48 | 8 | 12 (10) | 18 (17) | +12 | -17 | +18 | -23 |
| 4–6 | 0.41 | 10 | 10 (8) | 18 (17) | +16 | -22 | +15 | -20 |
| 6–9 | 0.41 | 9 | 10 (7) | 17 (16) | +15 | -21 | +9 | -13 |
| 9–12 | 0.21 | 10 | 9 (6) | 17 (16) | +14 | -20 | +1 | -0 |
| 12–16 | 0.09 | 13 | 10 (7) | 20 (19) | +14 | -19 | -2 | +6 |
| 16–20 | 0.04 | 18 | 11 (8) | 24 (23) | +12 | -18 | -4 | +9 |
| 20–30 | 0.02 | 23 | 20 (18) | 32 (32) | +12 | -17 | -5 | +11 |
| Υ(3S) | | | | $|y| < 2$ | | | | |
| 0–30 | 1.02 | 6.7 | 11 (8) | 17 (15) | +14 | -19 | +10 | -13 |
| 0–3 | 0.26 | 14 | 10 (8) | 21 (19) | +13 | -18 | +16 | -22 |
| 3–6 | 0.29 | 14 | 18 (17) | 26 (25) | +13 | -18 | +16 | -21 |
| 6–9 | 0.24 | 14 | 11 (8) | 21 (19) | +15 | -20 | +10 | -13 |
| 9–14 | 0.16 | 12 | 10 (8) | 19 (18) | +15 | -20 | -1 | +2 |
| 14–20 | 0.05 | 17 | 11 (8) | 23 (22) | +13 | -18 | -4 | +9 |
| 20–30 | 0.03 | 20 | 12 (9) | 26 (25) | +11 | -16 | -4 | +9 |

Υ

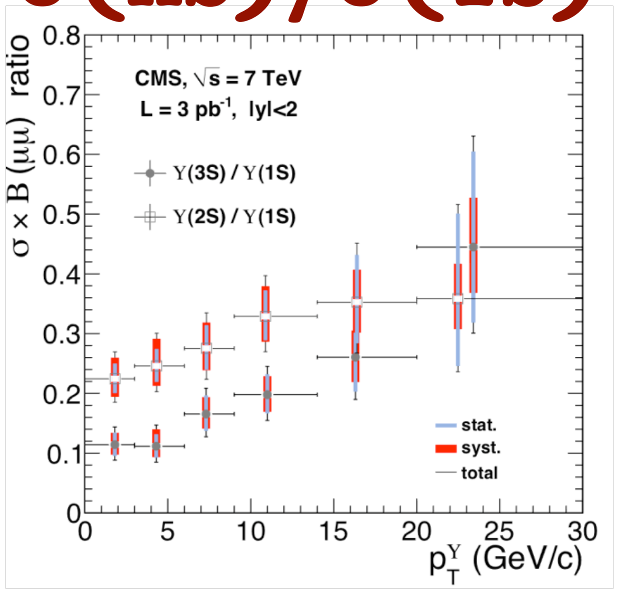
# dσ/dp$_T$




# dσ/dy



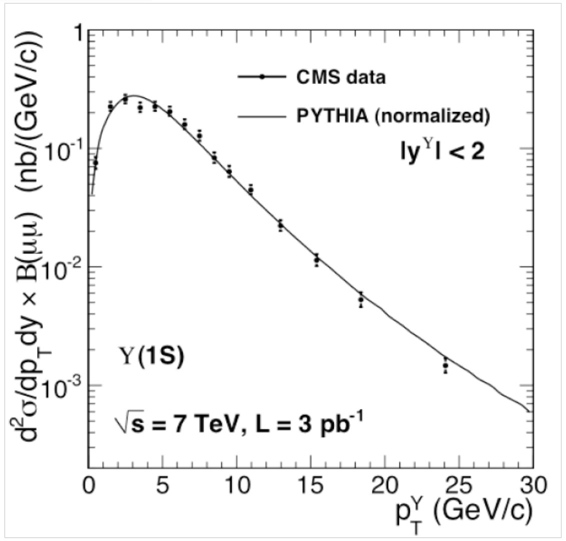

# σ(nS)/σ(1S)

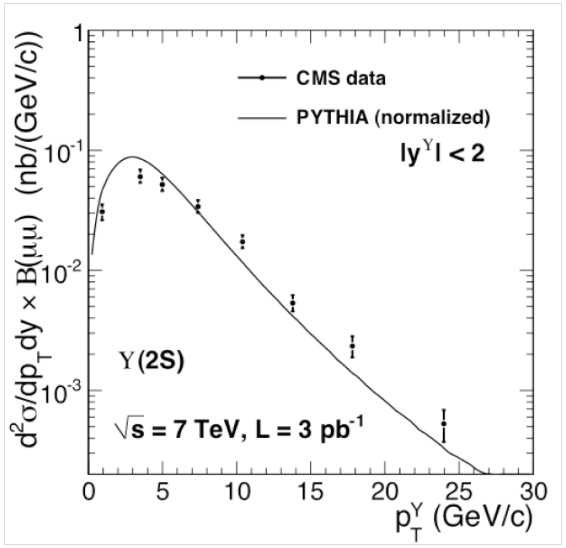


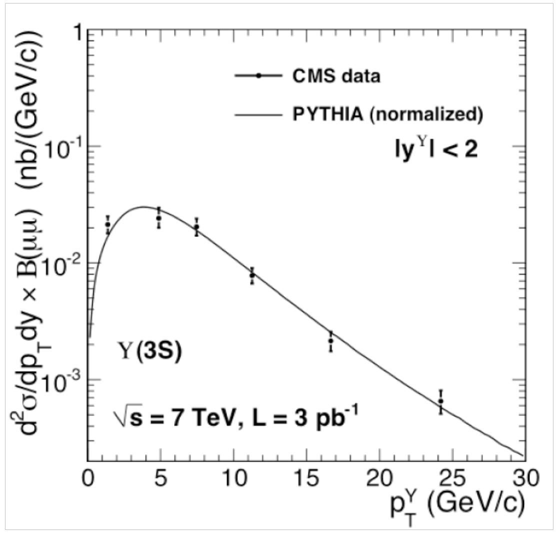

| $p_T$ (GeV/$c$) | Υ(3S) / Υ(1S) | Υ(2S) / Υ(1S) |
|---|---|---|
| 0–30 | $0.14 \pm 0.01 \pm 0.02$ | $0.26 \pm 0.02 \pm 0.04$ |

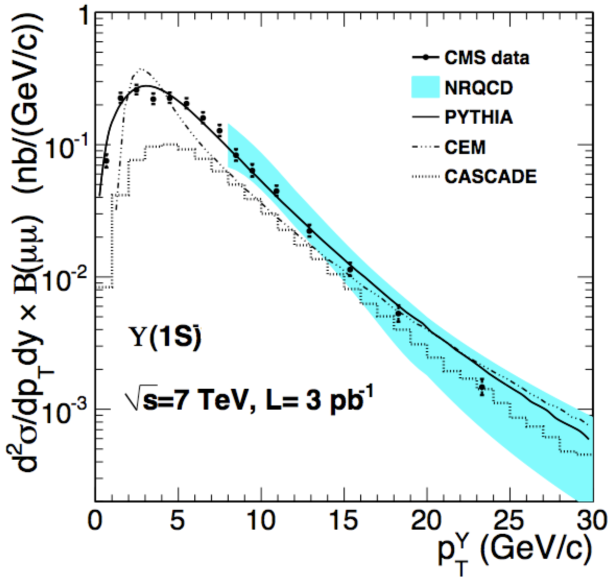
Υ

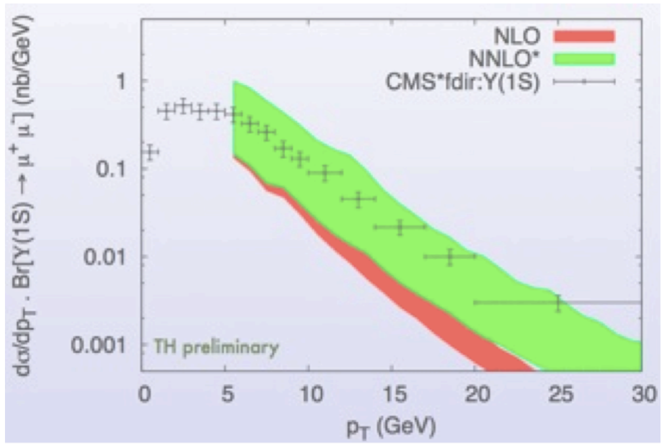
# Comparison to Theory



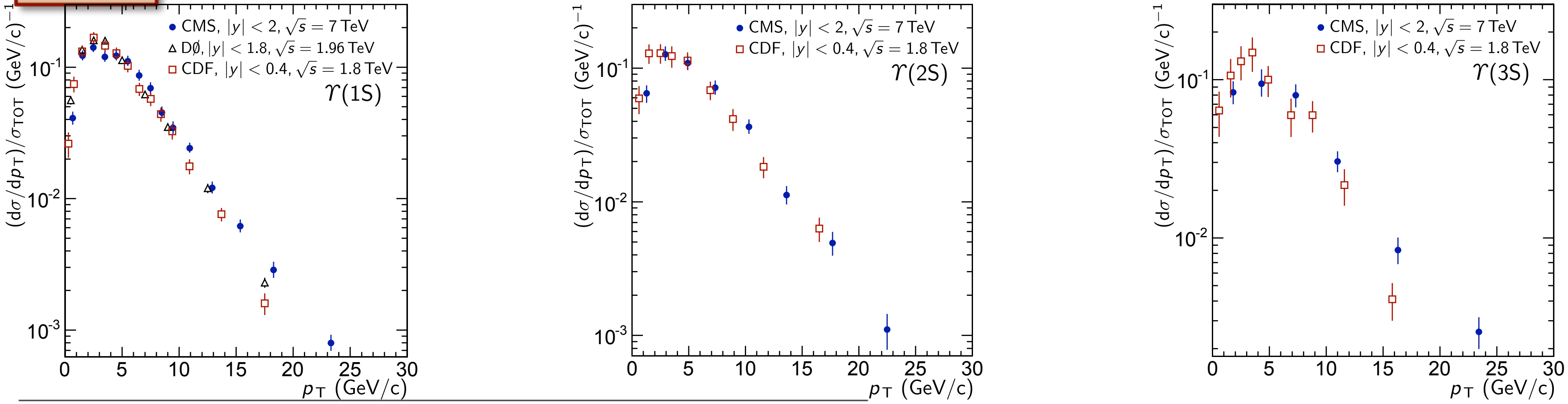



Υ

# Comparison to Tevatron

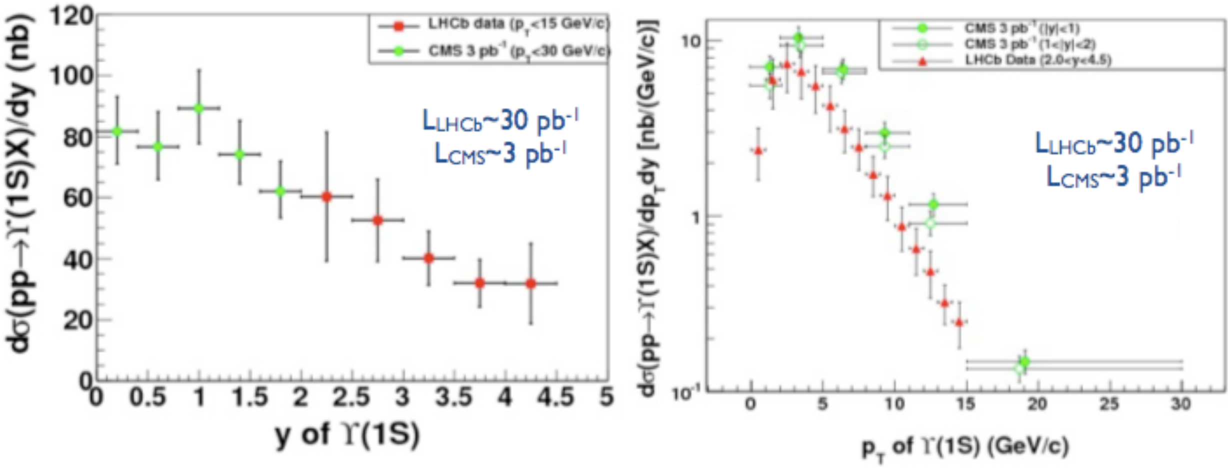



| Exp. | $\sqrt{s}$ (TeV) | $\frac{d\sigma}{dy}(p\bar{p} \to \Upsilon(1S)X) \cdot B(\Upsilon \to \mu\mu)$ | rapidity range |
|---|---|---|---|
| CDF | 1.8 | $0.680 \pm 0.015 \pm 0.018 \pm 0.026$ nb [4] | $\lvert y\rvert < 0.4$ |
| DØ | 1.96 | $0.628 \pm 0.016 \pm 0.065 \pm 0.038$ nb [5] | $\lvert y\rvert < 0.6$ |
| CMS | 7.0 | $2.02 \pm 0.03^{+0.16}_{-0.12} \pm 0.22$ nb (this work) | $\lvert y\rvert < 1.0$ |

CDF source: PRL 88 161802(2002)

D0 source: PRL 100 049902(2008)

# Comparison to LHCb




- Complementary rapidity regions probed by the two experiments
- Results are in good agreement

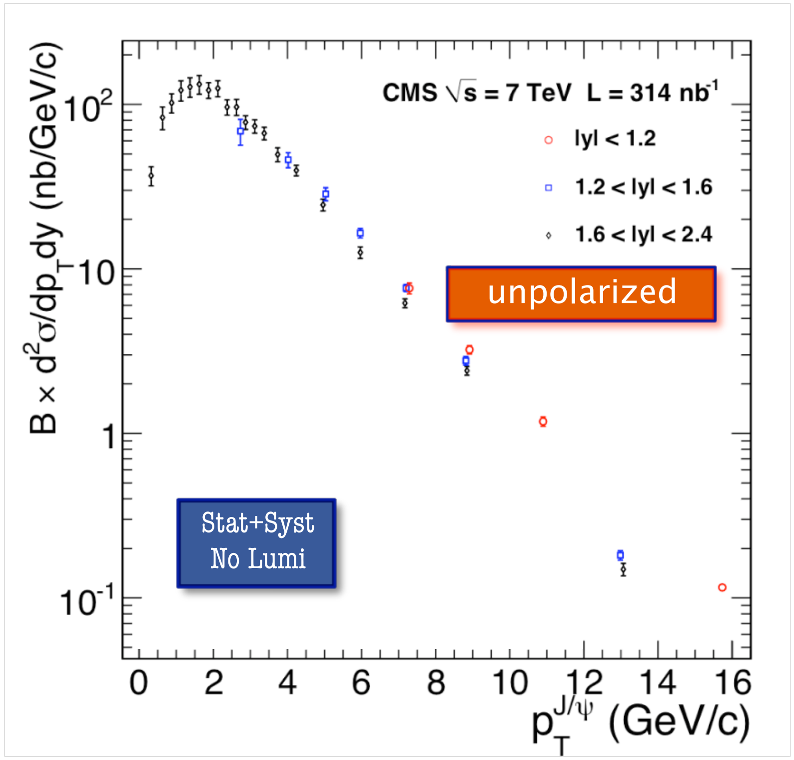
LHCb source: LHCb-CONF-2011-016

# J/ψ Inclusive Measurement

- Total inclusive J/ψ cross section in range $6.5 < p_T < 30$ GeV/c and $|y| < 2.4$

$$\sigma(pp \to J/\psi + X) \cdot \mathrm{BR}(J/\psi \to \mu^+\mu^-) =$$
$$97.5 \pm 1.5(\mathrm{stat}) \pm 3.4(\mathrm{syst}) \pm 10.7(\mathrm{luminosity})\ \mathrm{nb}.$$

- Polarization induces up to 20% variations
- Dominant Systematic Uncertainties
  - Luminosity
  - Muon efficiencies from data
  - Fit function

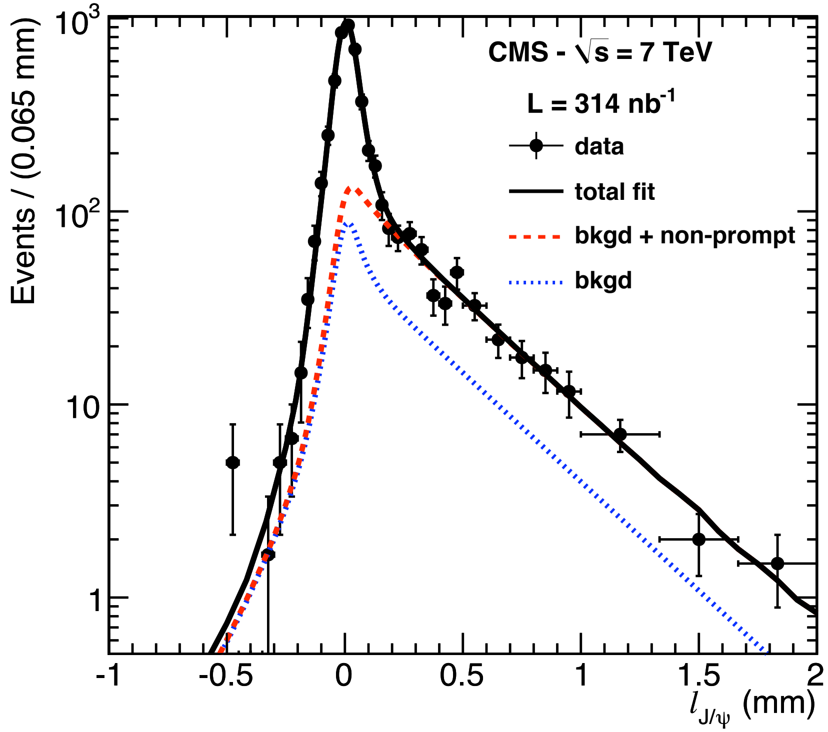



| Affected quantity | Source | Relative error (%) | | |
|---|---|---|---|---|
| | | $\|y\| < 1.2$ | $1.2 < \|y\| < 1.6$ | $1.6 < \|y\| < 2.4$ |
| Acceptance | FSR | 0.8 – 2.5 | 0.3 – 1.6 | 0.0 – 0.9 |
| | $p_T$ calibration and resolution | 1.0 – 2.5 | 0.8 – 1.2 | 0.1 – 1.0 |
| | Kinematical distributions | 0.3 – 0.8 | 0.6 – 2.6 | 0.9 – 3.1 |
| | b-hadron fraction and polarization | 1.9 – 3.1 | 0.5 – 1.2 | 0.2 – 3.0 |
| Efficiency | Muon efficiency | 1.9 – 5.1 | 2.3 – 12.2 | 2.7 – 9.2 |
| | $\rho$ factor | 0.5 – 0.9 | 0.6 – 8.1 | 0.2 – 7.1 |
| Yields | Fit function | 0.6 – 1.1 | 0.4 – 5.3 | 0.3 – 8.8 |

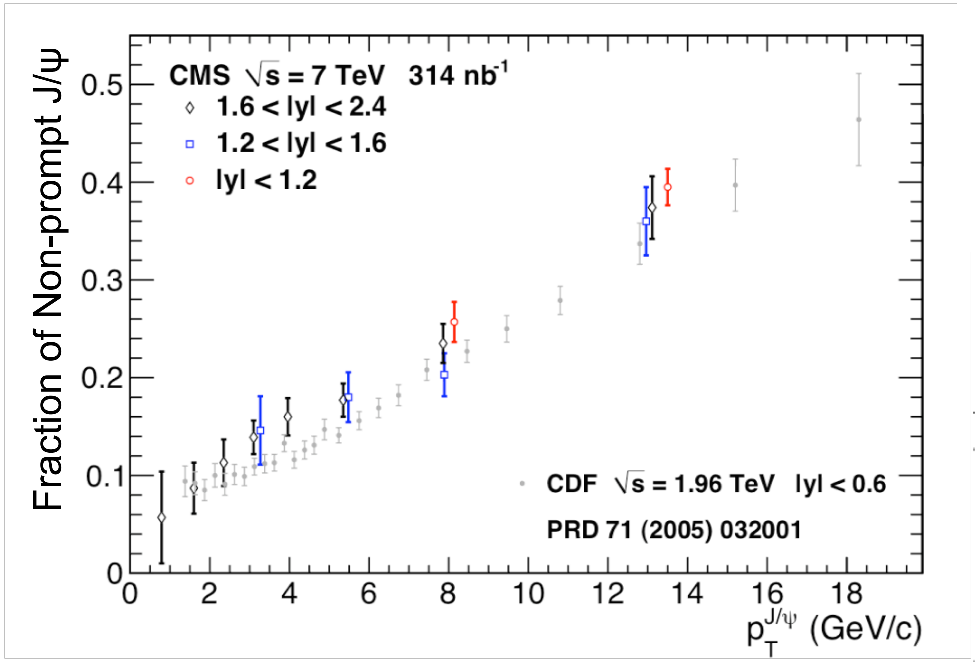
# Non-prompt J/ψ Fraction

- Simultaneous fit to J/ψ mass and pseudo-proper decay length

$$\ell_{J/\psi} = L_{xy} \cdot m_{J/\psi} / p_T$$




$6.5 < p_T < 10\,\mathrm{GeV}/c,\ 1.6 < |y| < 2.4$

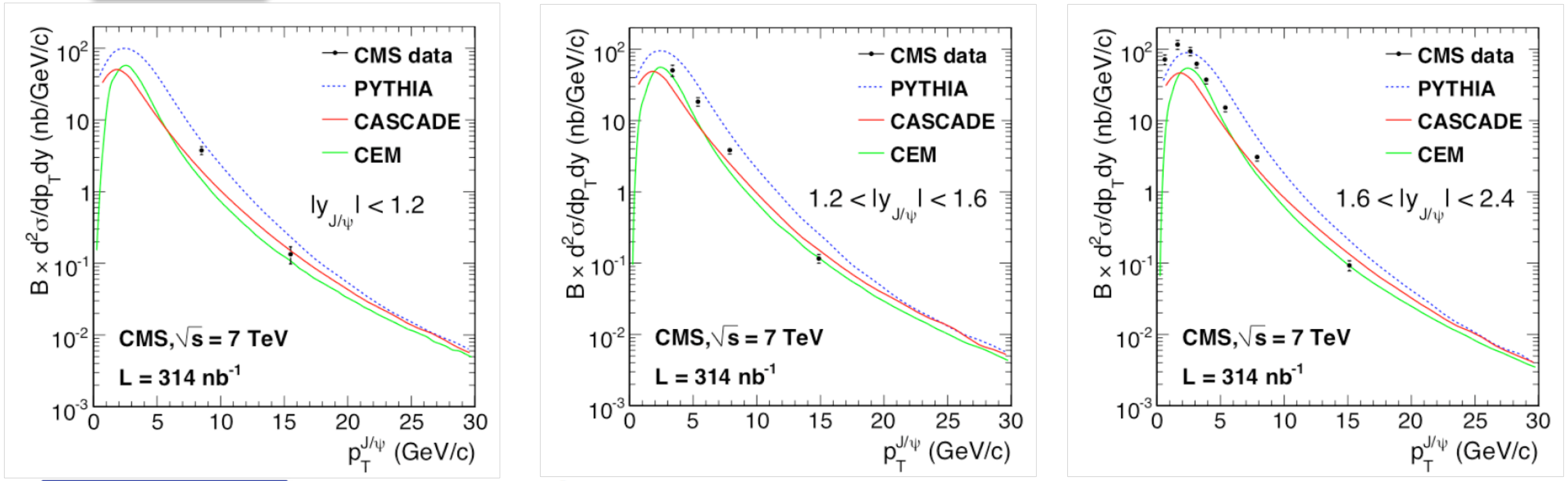



## Systematic Uncertainties:

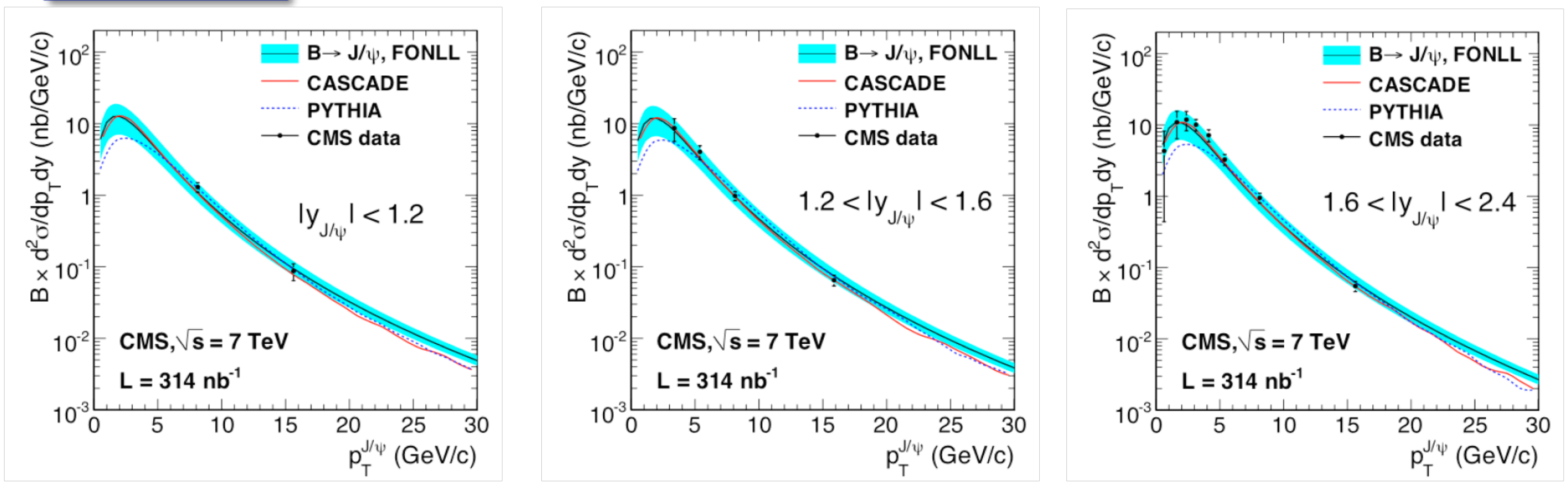
| | $\lvert y\rvert < 1.2$ | $1.2 < \lvert y\rvert < 1.6$ | $1.6 < \lvert y\rvert < 2.4$ |
|---|---|---|---|
| Tracker misalignment | 0.5 – 0.7 | 0.9 – 4.6 | 0.7 – 9.1 |
| b-lifetime model | 0.0 – 0.1 | 0.5 – 4.8 | 0.5 – 11.2 |
| Vertex estimation | 0.3 | 1.0 – 12.3 | 0.9 – 65.8 |
| Background fit | 0.1 – 4.7 | 0.5 – 9.5 | 0.2 – 14.8 |
| Resolution model | 0.8 – 2.8 | 1.3 – 13.0 | 0.4 – 30.2 |
| Efficiency | 0.1 – 1.1 | 0.3 – 1.3 | 0.2 – 2.4 |

# $J/\psi$ Comparison to Theory

**Prompt** $BR(J/\psi \to \mu^+\mu^-)\cdot\sigma(pp \to \text{prompt } J/\psi) = 70.9 \pm 2.1 \pm 3.0 \pm 7.8 \text{ nb}$




**Non-Prompt** $BR(J/\psi \to \mu^+\mu^-)\cdot\sigma(pp \to bX \to J/\psi X) = 26.0 \pm 1.4 \pm 1.6 \pm 2.9 \text{ nb}$



# ψ(2S) & X(3872) → J/ψ ππ

**Selection:**

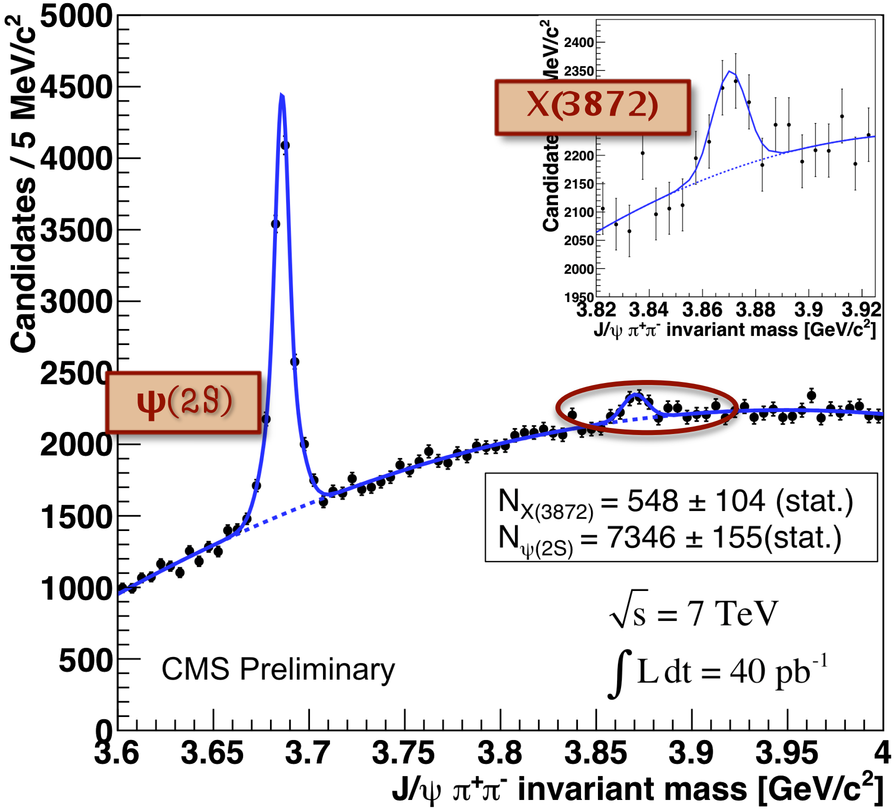
- J/ψ→μμ
  - Similar to J/ψ analysis
- X(3782),ψ(2S)→J/ψππ
  - $p_T(\pi)$>0.4GeV/c, $\Delta R_{J/\psi,\pi\pi}$<0.7, $p_T(\pi\pi)$>1.5GeV/c
  - 4-track vertex fit $\chi^2$ prob. >1%
  - $p_T$ > 8GeV/c, |y| < 2.2

**Fit Results:**

- $m_{\psi(2S)}$= 3685.9 ± 0.1 MeV
- $m_{X(3872)}$= 3870.2 ± 1.9 MeV

**PDG values:**

- $m_{\psi(2S)}$= 3686.09 ± 0.04 MeV
- $m_{X(3872)}$= 3871.56 ± 1.9 MeV




- First of a set of exotic states

# Ratio of σ.BR for X(3872) to ψ(2S)

- Extract the number of ψ(2S) and X(3872) from the invariant mass spectrum of J/ψ ππ
- Calculate the ratio

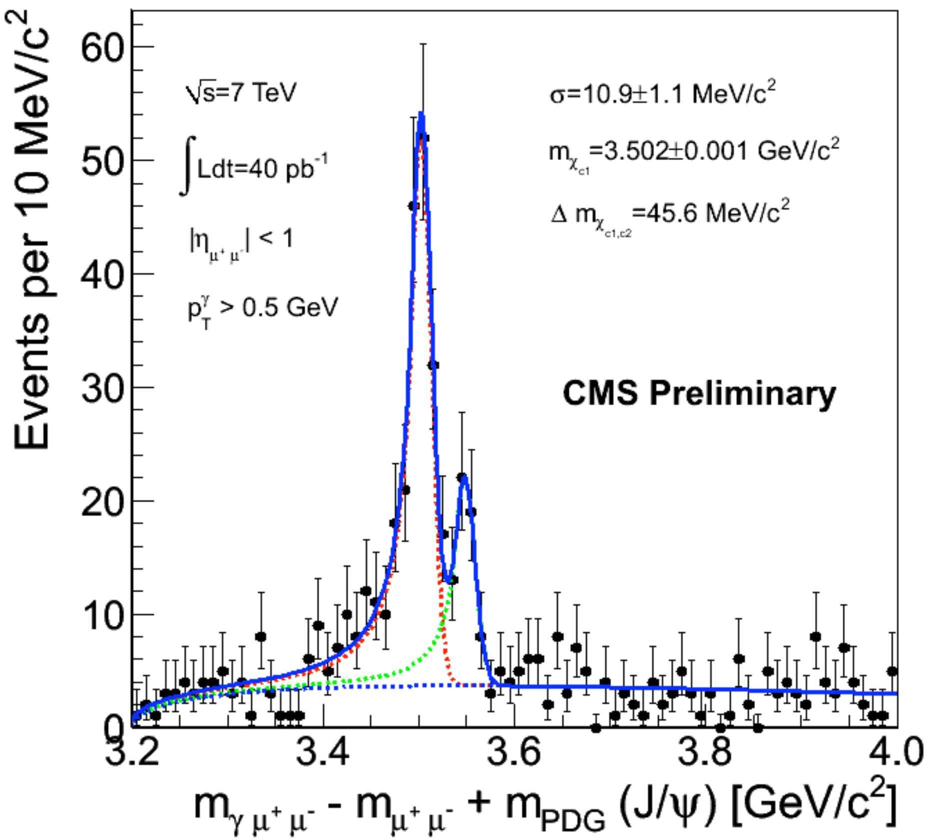
$$R = \frac{\sigma(pp \to X(3872) + anything) BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + anything) BR(\psi(2S) \to J/\psi\pi^+\pi^-)} = \frac{N_{X(3872)}}{N_{\psi(2S)}} \times C$$

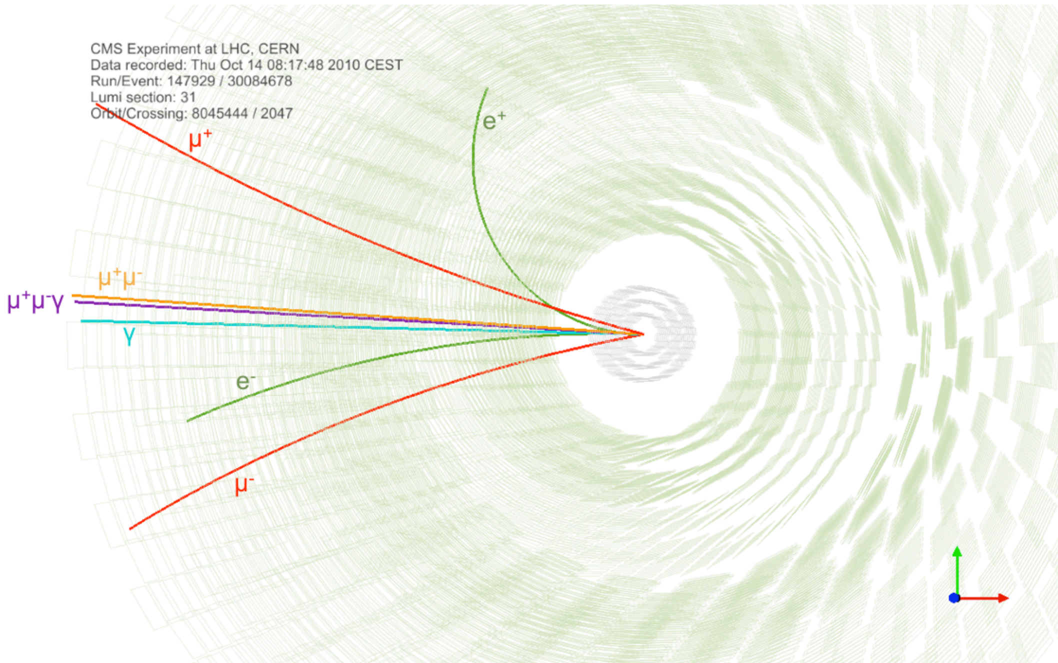
- Correction factor taking into account the kinematical differences of the decay products from Monte Carlo studies **C = 0.872 ± 0.015**
- Dominant Systematic Uncertainties
  - Variation of the the non-prompt fraction for X(3872) and ψ(2S)
  - Background parameterization and signal extraction

**R = 0.087 ± 0.017 (stat.) ± 0.009 (sys.)**

Available as CMS public document:
http://cms-physics.web.cern.ch/cms-physics/public/BPH-10-018-pas.pdf

# $\chi_c \rightarrow J/\psi + \gamma$



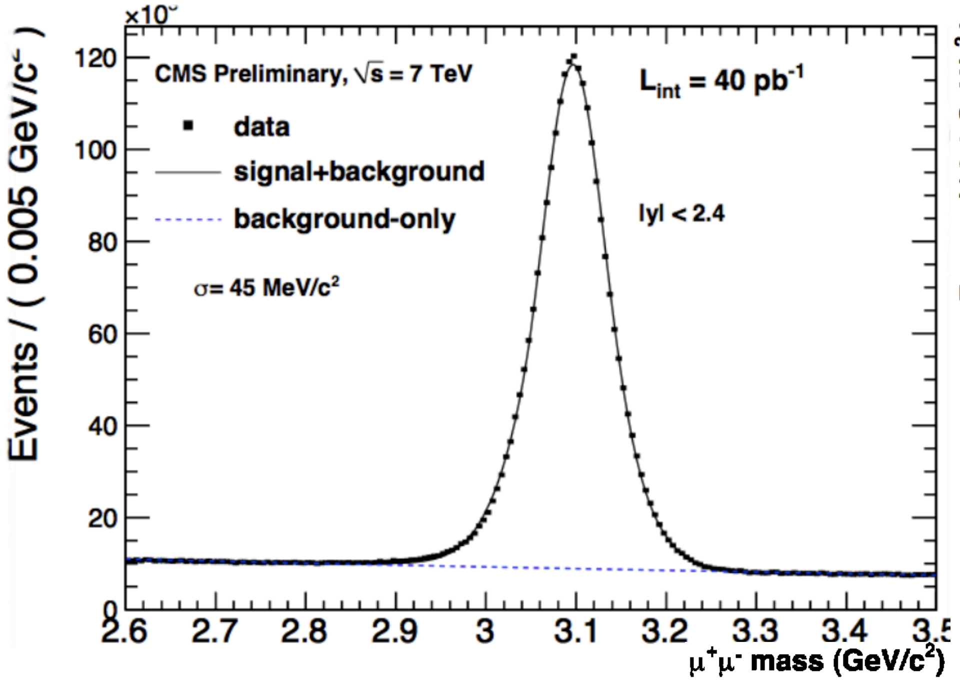

Binned maximum likelihood fit

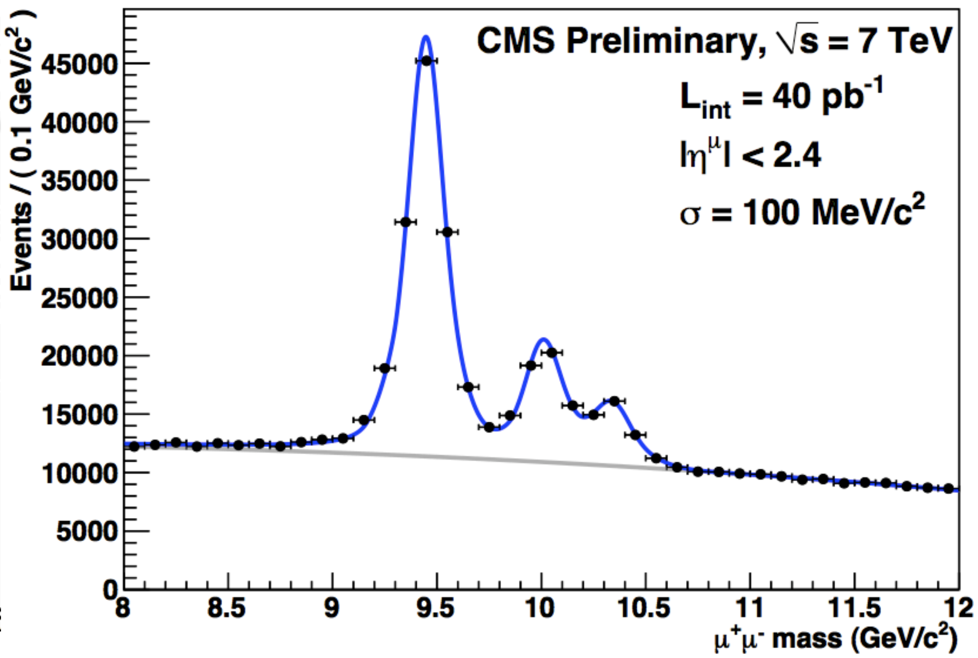
- Signal:
  - 2 Crystal Ball Functions with $\Delta m(\chi_{c1},\chi_{c2})$ fixed

- CMS has observed the $\chi_{c1}$ and $\chi_{c2}$ charmonium states through their radiative decay to $J/\Psi + \gamma$
- The photons are reconstructed using photon conversions in the inner tracker

# Conclusions

- First production cross-section measurements at 7 TeV pp collisions of J/ψ [arXiv:1011.4193] and ϒ(ns) [arXiv:1012.5545]
- CMS has now recorded more than $700pb^{-1}$ of pp data
  - Expect more precise cross section and polarization measurements
- Improved results are on the way!



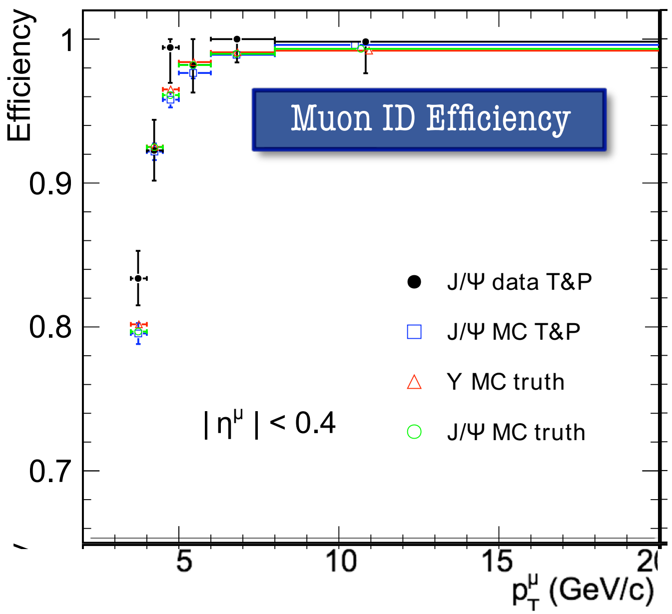



# Backup

# Efficiency

$$\varepsilon(\text{total}) = \varepsilon(\text{trig}|\text{id}) \cdot \varepsilon(\text{id}|\text{track}) \cdot \varepsilon(\text{track}|\text{accepted})$$

- Calculated from data, using tag-and-probe method on J/ψ sample
- T&P: unbinned maximum likelihood fit to passing and failing tag-probe mass distributions




J/ψ