Quarkonia Studies at CMS

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on behalf of the CMS collaboration

Outline

Why quarkonia @ CMS?

Quarkonia reconstruction in CMS

Measurements in pp collisions at $\sqrt{s}$=7TeV

Cross sections for ψ and ϒ states

X_c and X(3872)

Quarkonia in Pb-Pb collisions

Summary and outlook

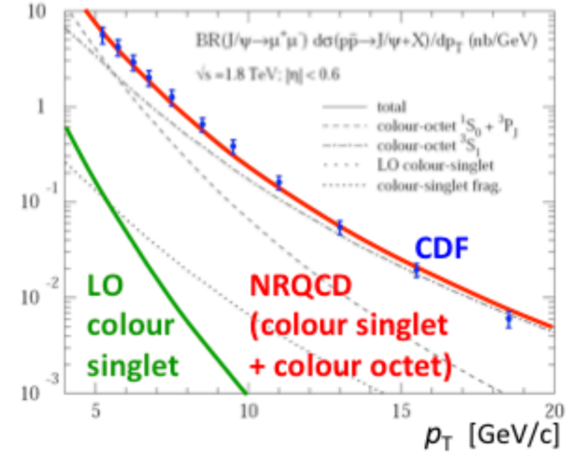
Why quarkonia @ CMS?

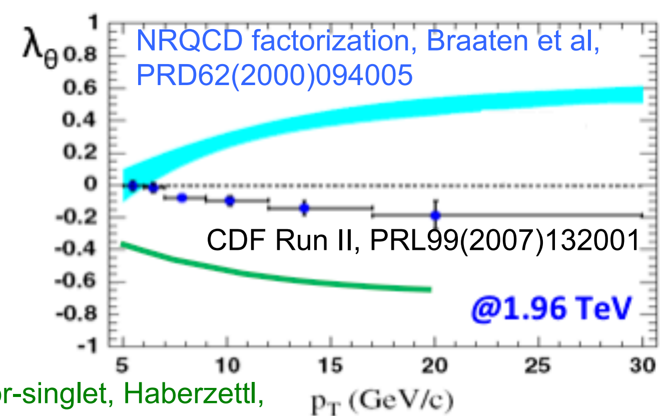
Many good reasons!

- They provide a unique laboratory for studying QCD
- They are abundantly produced at LHC
- They can be used to probe hot, dense matter

Some history …

- In the 90's CDF observed direct production rates for the J/ψ and ψ(2S) far beyond the prediction for LO color-singlet production
- Several theoretical approaches were developed
  - The inclusion of color-octet terms (NRQCD) could describe the increase using freely adjustable LDME terms
  - NLO color singlet models could also match the cross sections
  - None of the two approaches describes the polarization data



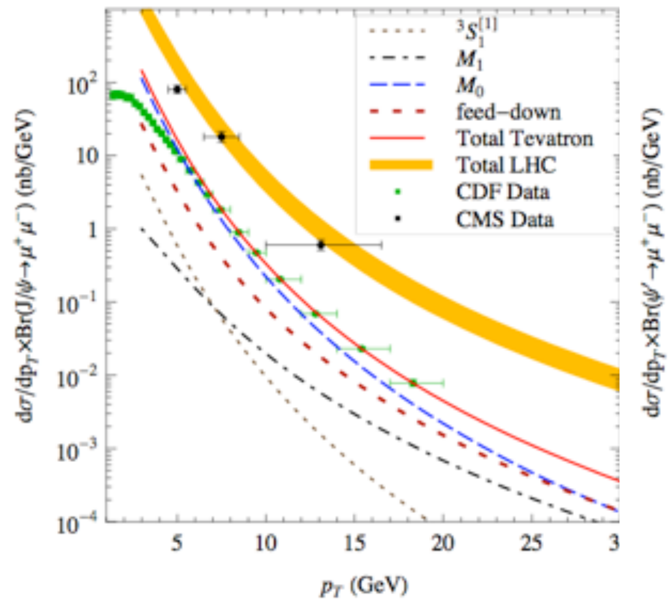


NLO color-singlet, Haberzettl, Lansberg, PRL100(2008)032006

Why quarkonia @ CMS?

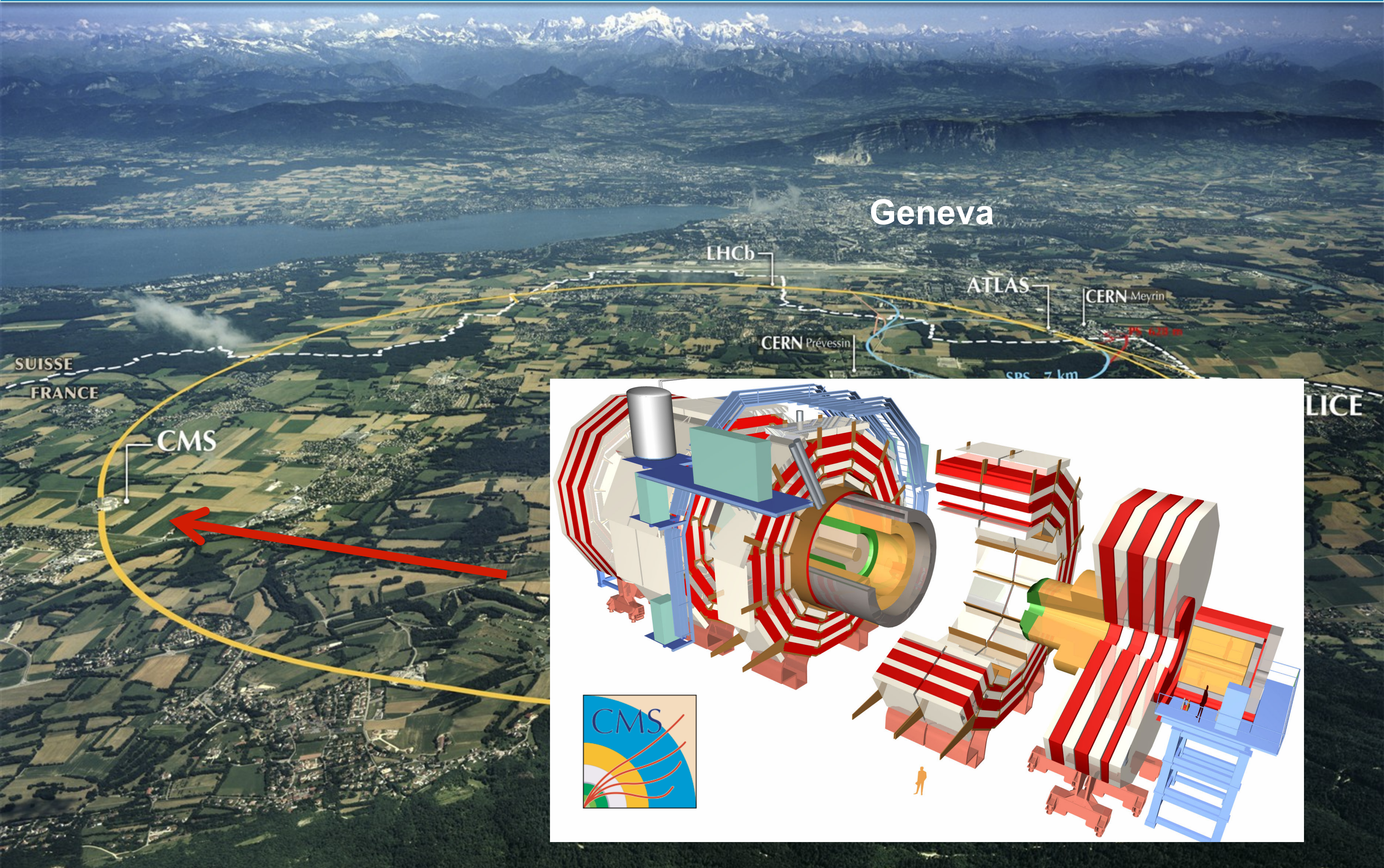
Recent progress on theory …

- New NRQCD calculations at NLO became available for charmonium (including color-singlet and color-octet contributions) at $O(\alpha_s^4 v^4)$.
- They agree well with cross sections measured at the Tevatron and first LHC results.
- There is a hint that one CO state ($^1S_0^{[8]}$) dominates J/ψ direct production
- Further comparisons with increasing precision on LHC cross section data and with polarization measurements are needed!



Ma et al, PRL106(2011)042002

Quarkonium reconstruction in CMS



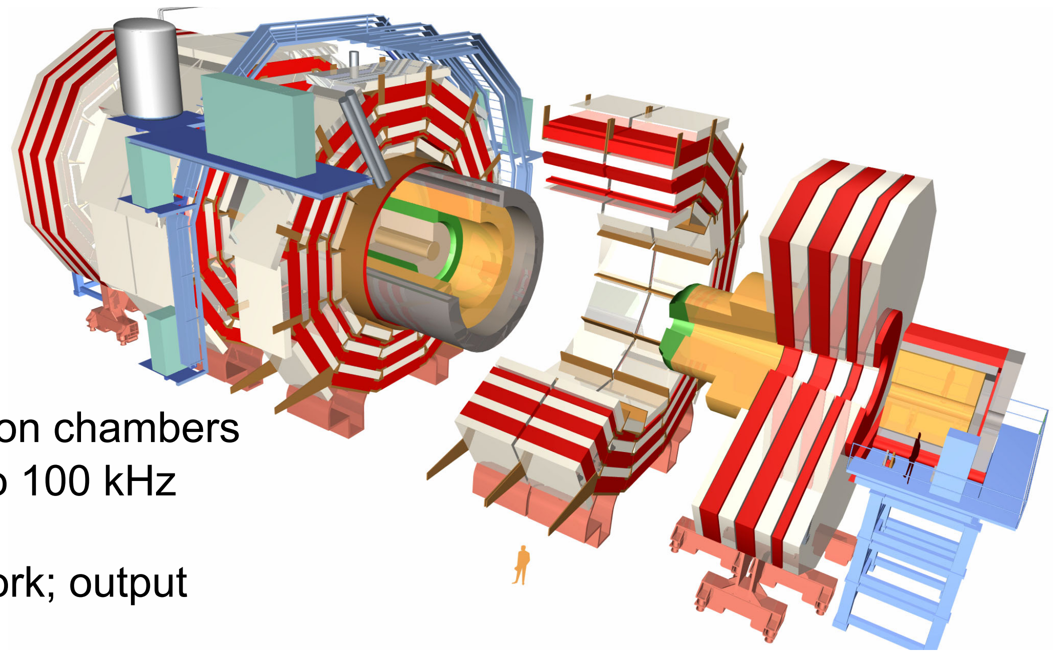
Quarkonium reconstruction in CMS

Silicon pixel & strip tracker
- 1440 pixel and 15k strip modules
- Track reconstruction in $|\eta|<2.5$
  extends to p_T below 100 MeV
- Typical resolutions (central region) at p_T=10 GeV
  $\sigma(p_T)/p_T$ < 1%, σ(dxy) ~ 20 μm

Muon chambers
- 3 different technologies
- Combined reconstruction with tracker
  Acceptance up to $|\eta|$=2.4
  p_T cutoff due to material & B-field
  typically 1 – 3 GeV
  Low-energy p_T resolution dominated by inner track measurement

Magnet
- Superconducting solenoid
  B = 3.8T

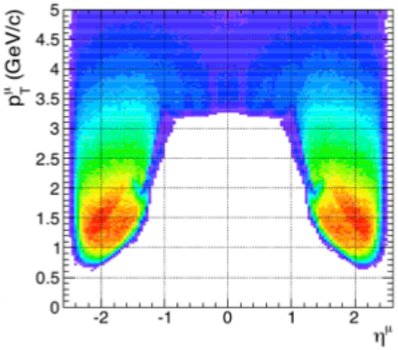
Two-Tier trigger system
- Input:
  up to 40 MHz bunch crossing rate
- L1 (hardware)
  (multi-)object conditions using muon chambers and calorimeters; output rate up to 100 kHz
- HLT (software)
  PC farm using offline SW framework; output rate up to a few 100 Hz



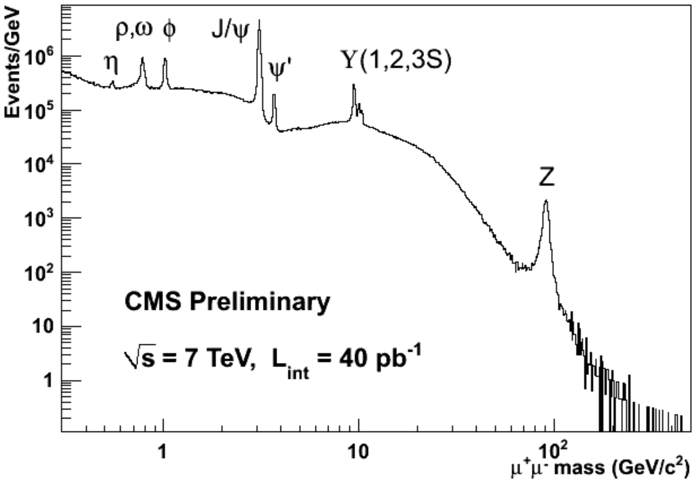
Quarkonium reconstruction in CMS

From collisions to tape …

- Quarkonia measurements are based on single and double muon triggers
  - Access to quarkonium $p_T \rightarrow 0$ and / or highly asymmetric decays requires low momentum thresholds for the muons



- "Golden" data taking period in 2010:
  - Double muon triggers without explicit p_T thresholds
  - Muon+track triggers for decays with a soft 2nd muon



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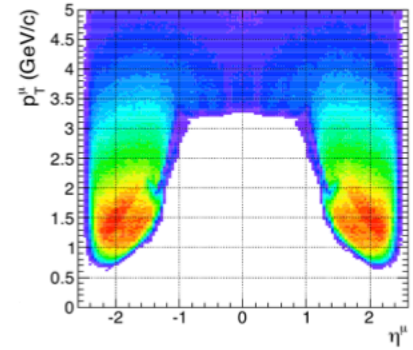

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  - Double muon triggers without explicit p_T thresholds
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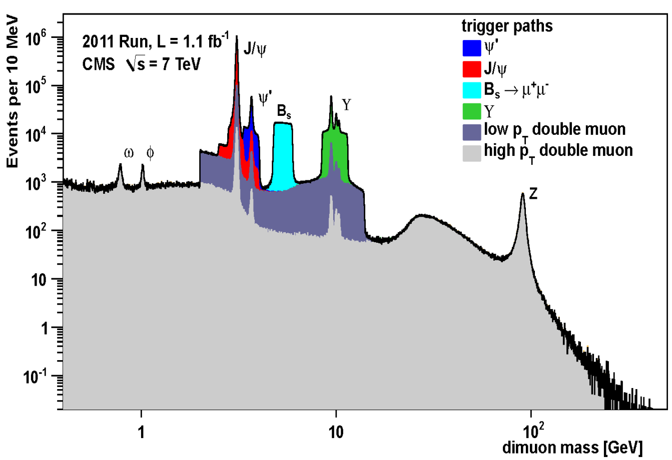
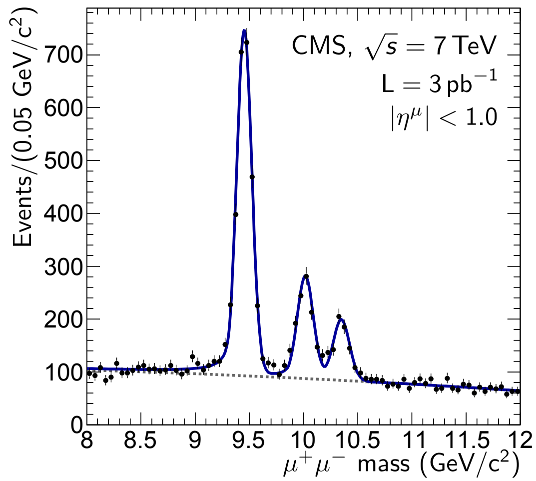
2011 data taking

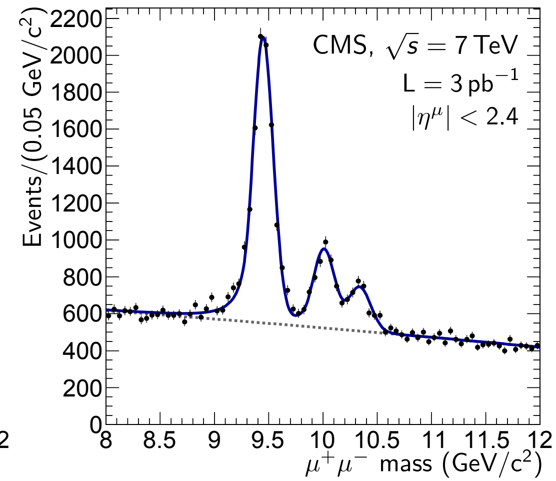
- have to compete with high priority analyses (searches, top physics, ..)
  - Specific trigger windows around each resonance (incl. sidebands)
  - Low rate control triggers for monitoring and measurement of the efficiency



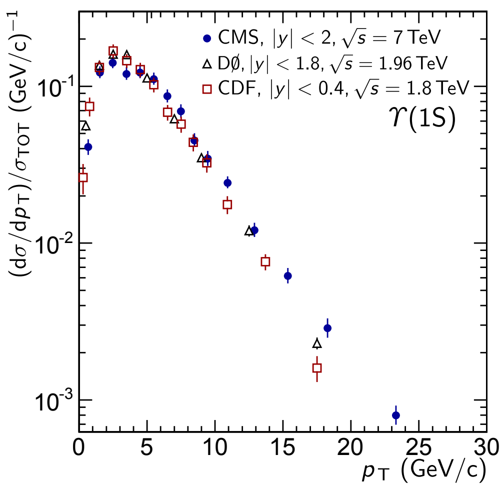
Upsilon

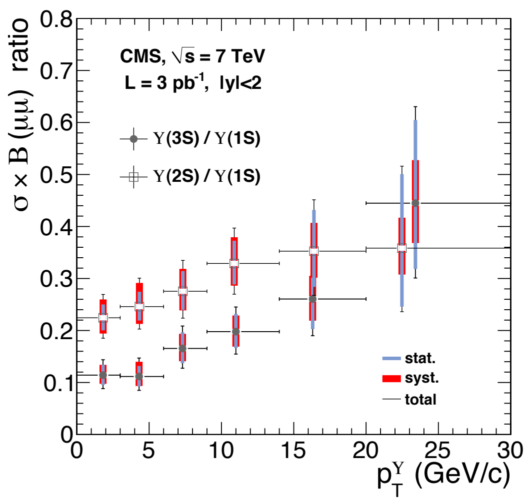
- Purely HW di-muon trigger
- Efficiencies measured from data on a 2D grid in $p_T \times |\eta_\mu|$
- Di-muon system:
  - Opposite charge, $8<M_{\mu\mu}/\text{GeV}<14$, $|y|<2$, good di-muon vertex
- Good separation of the states!





CMS Coll., PRD83(2011)112004





Results

- For $p_T<30$ and $|y|<2$ and assuming unpolarized ϒ

$$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 7.37 \pm 0.13(\text{stat.})(\text{syst.}) \pm 0.81(\text{lumi.})\ \text{nb},$$

$$\sigma(pp \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 1.90 \pm 0.08(\text{stat.})(\text{syst.}) \pm 0.21(\text{lumi.})\ \text{nb},$$

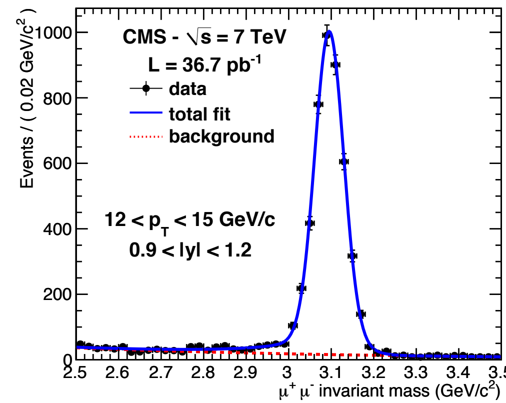
$$\sigma(pp \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 1.02 \pm 0.07(\text{stat.})(\text{syst.}) \pm 0.11(\text{lumi.})\ \text{nb}.$$

Υ(2S)/Υ(1S) = 0.26±0.02±0.04
Υ(3S)/Υ(1S) = 0.14±0.01±0.02

J/ψ

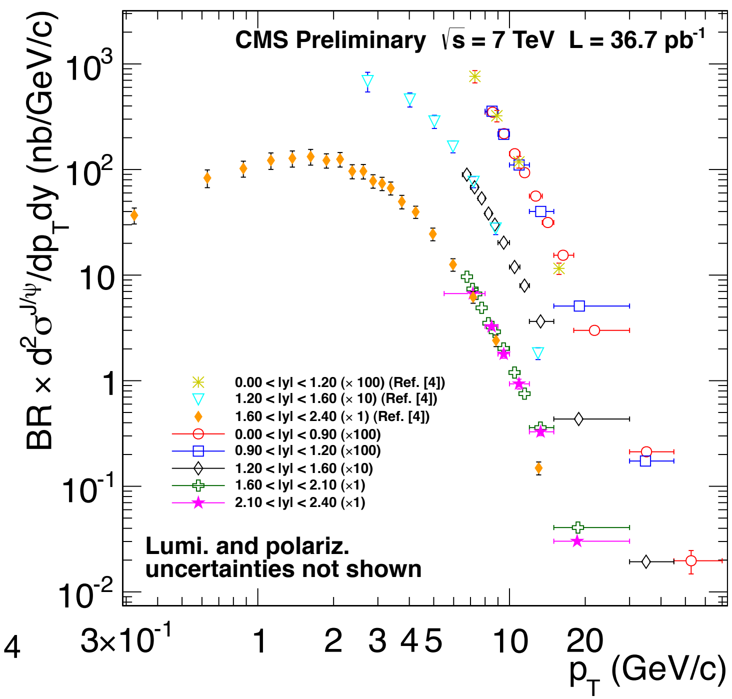
Charmonia

- More experimental challenges: contributions from feed down from heavier charmonia **AND** from b-hadron decays (for 1S)
- Combination of several triggers
- Selection of opposite-charge pairs with $2.5 < M_{\mu\mu}/\mathrm{GeV} < 4.7$ and a good common vertex
- Efficiency calculated as $\varepsilon(\mu_1)\times\varepsilon(\mu_2)\times\varepsilon_{vertex}\times\rho$
  - (single muon, vertex fit and correlation)
- Yield extraction from a fit to the mass spectrum



Results (inclusive)

- Cross section measurement up to p_T=70GeV
- Good agreement with first low-p_T analyses (different triggers and analysis methods)
- Errors in the range 2-9% (stat) and mostly <1% (syst) but dependence on polarization scenario (here: unpolarized)



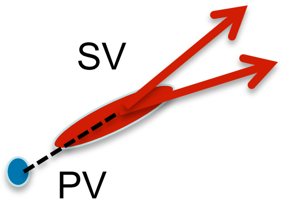
CMS-PAS-BPH-10-014

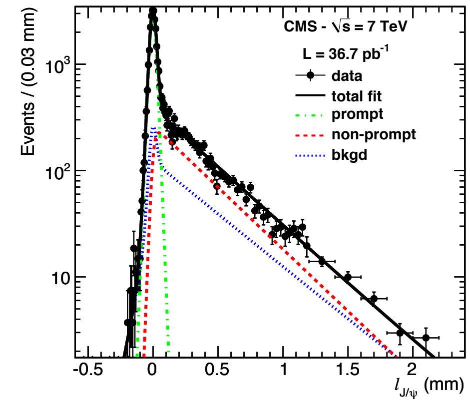
J/ψ

Separation of prompt and non-prompt components

- Using proper decay time associated with di-muon vertex

$$\ell_{J/\psi} = \frac{\mathbf{u}^T \mathbf{s}^{-1} \mathbf{x}}{\mathbf{u}^T \mathbf{s}^{-1} \mathbf{u}} m_{J/\psi} / |p_T| \qquad \mathbf{x} = (\mathbf{SV} - \mathbf{PV})_{xy} \qquad u = \mathbf{p_T} / |p_T|$$

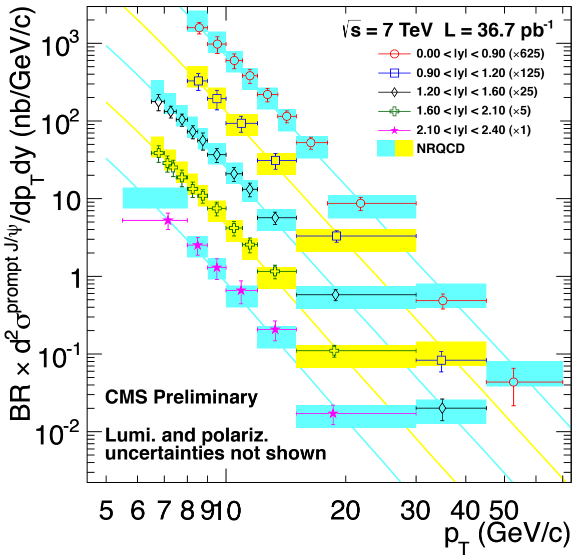


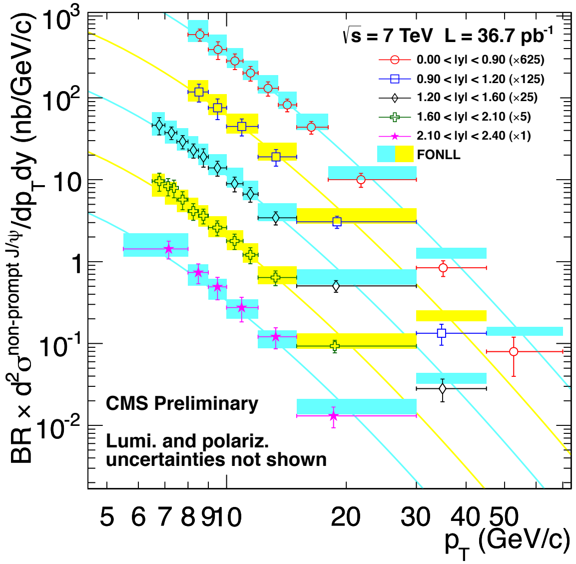


- Fit takes into account
  - Event-by-event estimates of the resolution
  - δ-function (prompt) and effective exponential (non-prompt)
  - Background shape from mass-sidebands

Results

- Excellent agreement with theoretical predictions:
  - NRQCD (prompt): Chao et al., PRL106:042002, 2011
  - FONLL (non-prompt): Cacciari et al., JHEP 0103 (2001) 006

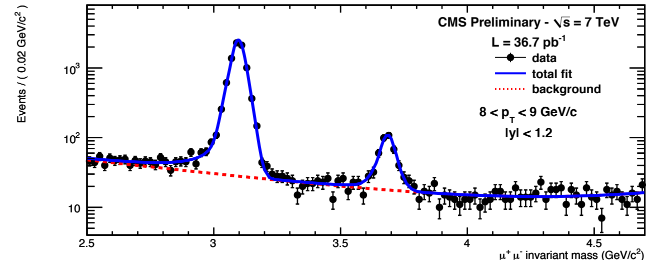


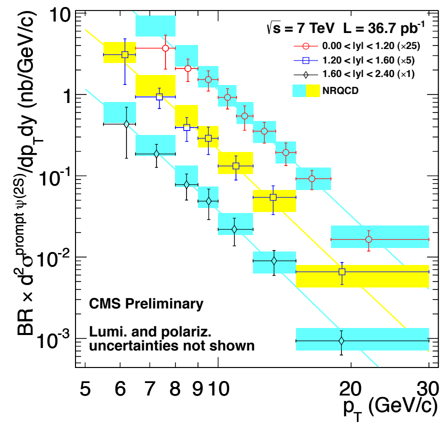


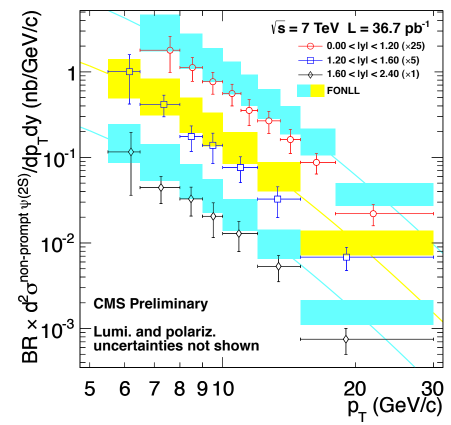
ψ (2S)

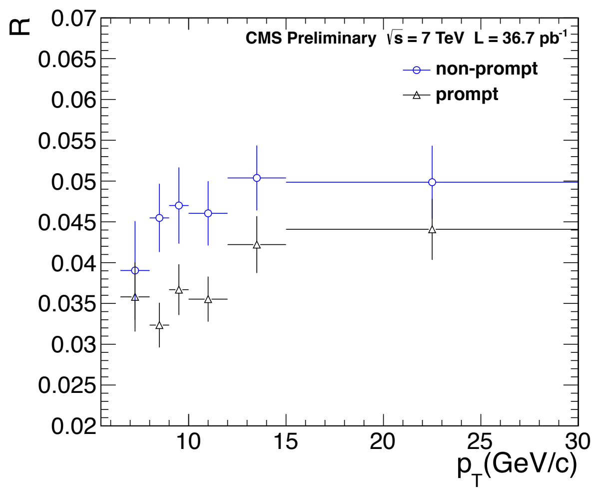
Same experimental approach as for J/ψ

- But some adjustments to lower statistics: mass difference M_{2S}-M_{1S} fixed to PDG values and Crystal Ball function parameters (resolution, tail) common with 1S
- Typical resolutions (both states):
  - ~20MeV (barrel) / ~50MeV (endcaps)
- Again, good agreement with predictions but measured ψ(2S) non-prompt spectrum falls steeper with increasing p_T









- Lower systematics on cross section ratio:
  - ~ 10% without polarization effects
  - Polarization: 12 – 20%
  - Stat. error ~ 3 – 5%

X(3872)

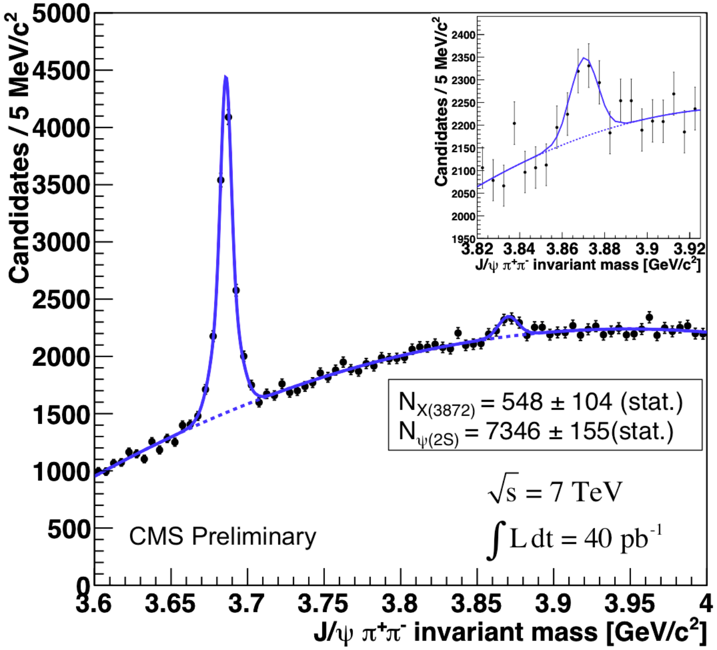
First “exotic” state measured at CMS

- Observed in the X(3872) → J/ψ $\pi^+\pi^-$ channel and measured relative to ψ(2S)
- Reconstruction using a 4-track vertex fit, imposing the J/ψ mass on the opposite-charge muon pair
- Cross section ratio for p_T > 8 GeV and |y| < 2.2

CMS-PAS-BPH-10-018

$$\frac{\sigma(pp \to X(3872) + anything) \times BR(X(3872) \to J/\psi\ \pi^+\pi^-)}{\sigma(pp \to \psi(2S) + anything) \times BR(\psi(2S) \to J/\psi\ \pi^+\pi^-)} = 0.087 \pm 0.017(stat) \pm 0.009(syst)$$

- Most systematic effects cancel



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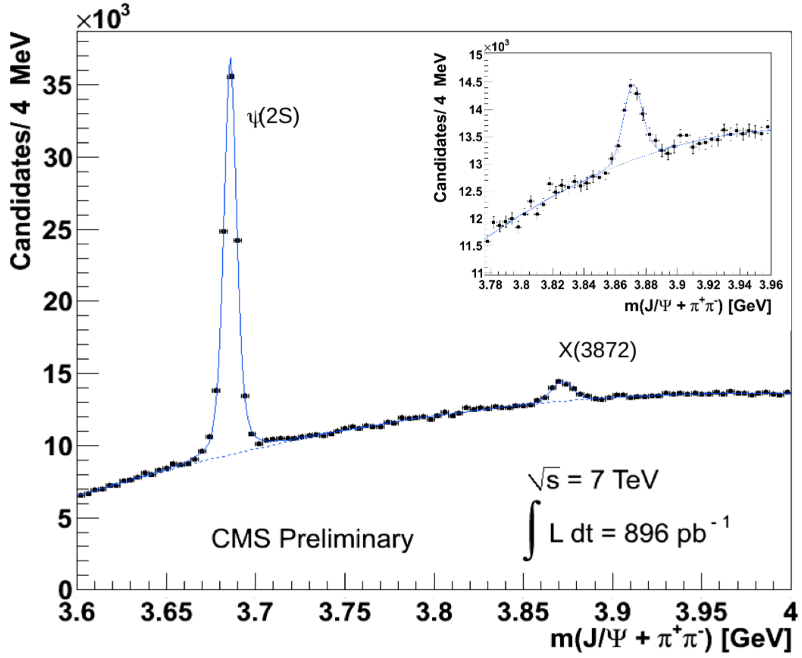
Update with 0.9 fb^{-1}

- Estimated yield
  - N(X(3872)) = 5304 ± 341

CMS-DP-2011-009

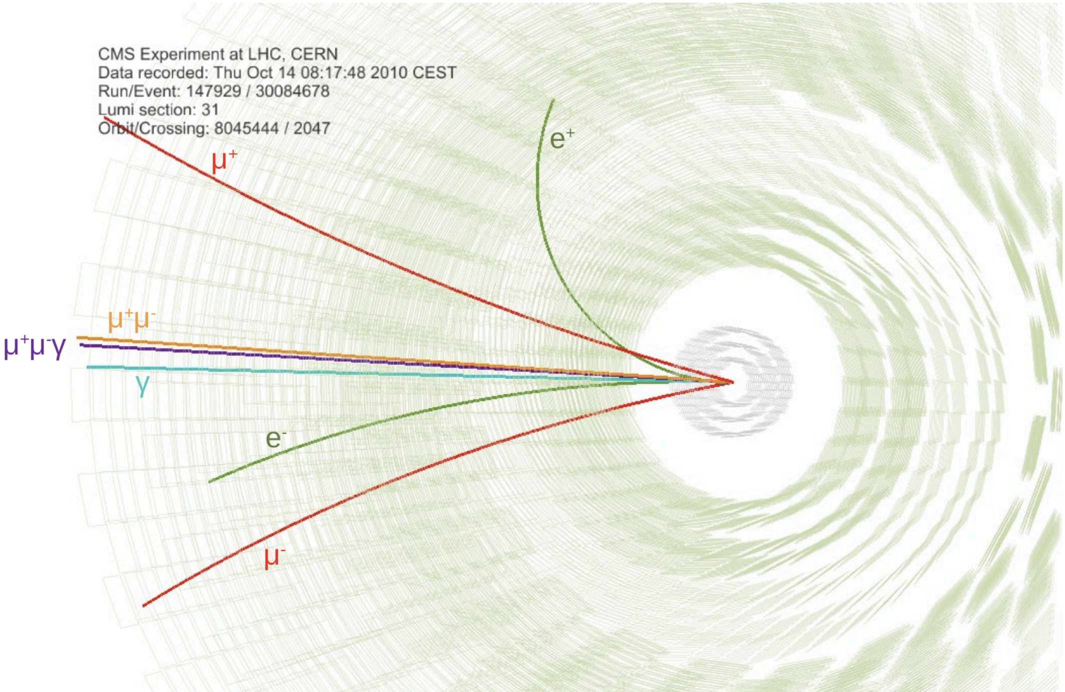


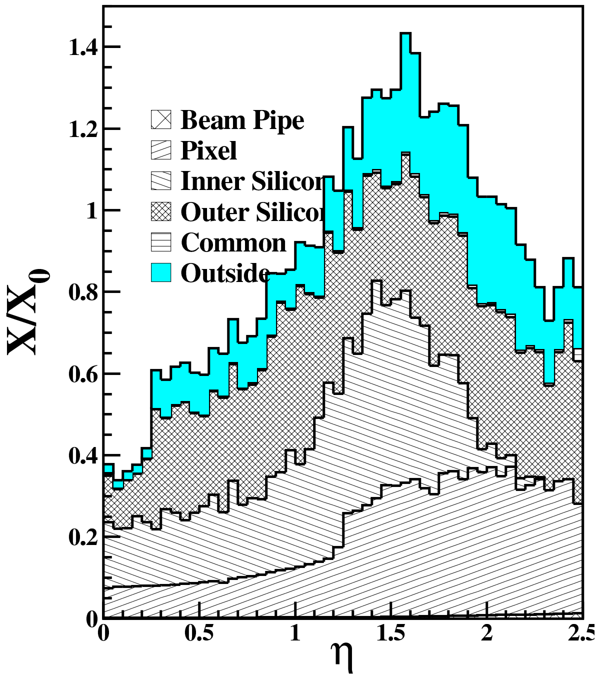
Radiative χ_c decays

Observation of χ_{c1} and χ_{c2} in their decays to $J/\psi\ \gamma$

- Small mass differences:
  $\Delta M(\chi_{c2},\chi_{c1})$=45.6MeV and $\Delta M(\chi_{c1},\chi_{c0})$=95.9 MeV
- Challenging measurement for a high-p_T detector like CMS !

• In order to achieve best photon energy solution:
  - Use conversions in the CMS tracker!



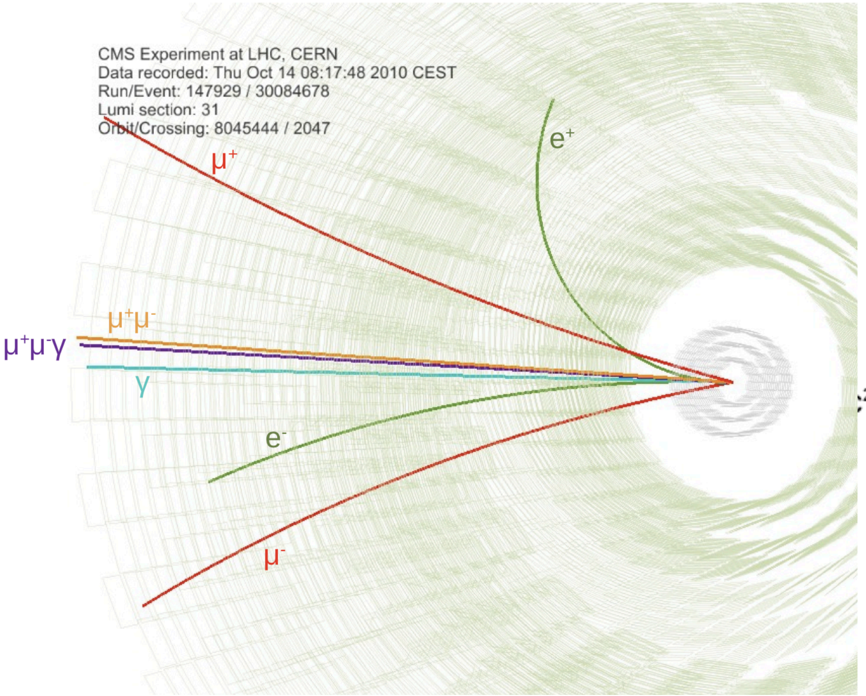


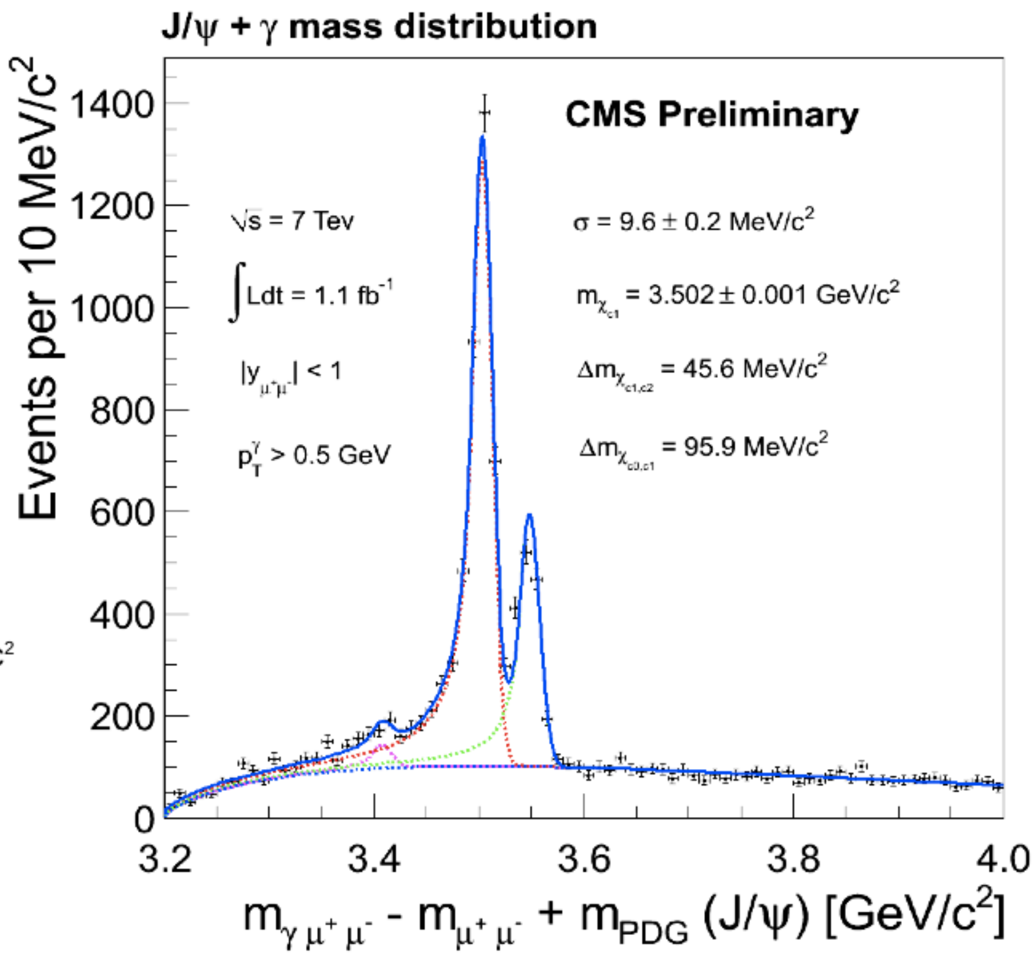
Radiative χ_c decays

Observation of χ_{c1} and χ_{c2} in their decays to J/ψ γ

- In order to achieve best photon energy solution:
  - Use conversions in the CMS tracker!
  - Can achieve ~10MeV resolution
    → χ_c states are well resolved!

CMS-DP-2011-006

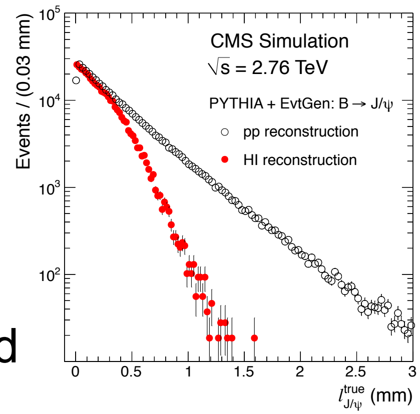


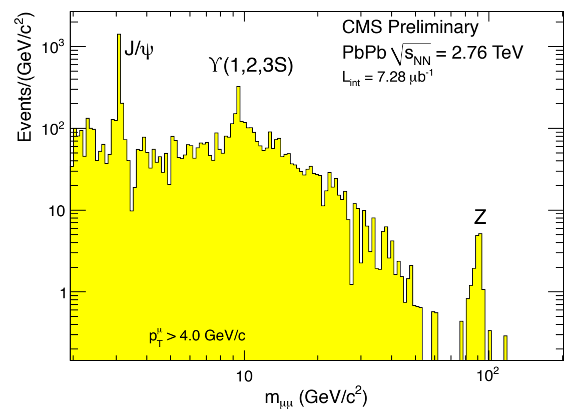


Quarkonia in Heavy Ion Collisions

Reconstruction of dimuon states in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76TeV

- Using similar algorithms as for pp, but optimized for the high track density in heavy ion collisions
  - Main difference: reconstructions is more focused on prompt muons





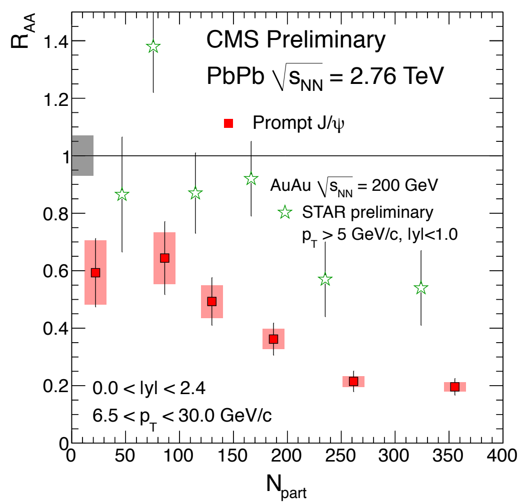
Suppression of quarkonia

- In deconfined matter quarkonia should dissolve into open charm and beauty
- Using pp-collisions at √s=2.76TeV as reference
  - Nuclear modification factor

$$R_{AA} = \frac{L_{pp}\sigma_{pp}}{N_{coll}N_{MB}} \frac{N_{HI}^{QQ}/\varepsilon_{HI}}{N_{pp}^{QQ}/\varepsilon_{pp}}$$

- For prompt J/ψ : R_{AA} = 0.20 ± 0.03 ± 0.01 (central)
  - At LHC B-decays to J/ψ becomes important
  - First measurement corrected for non-prompt component!

CMS-PAS-HIN-10-006



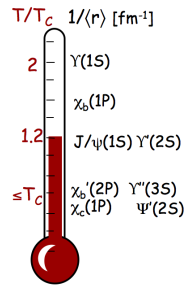
centrality →

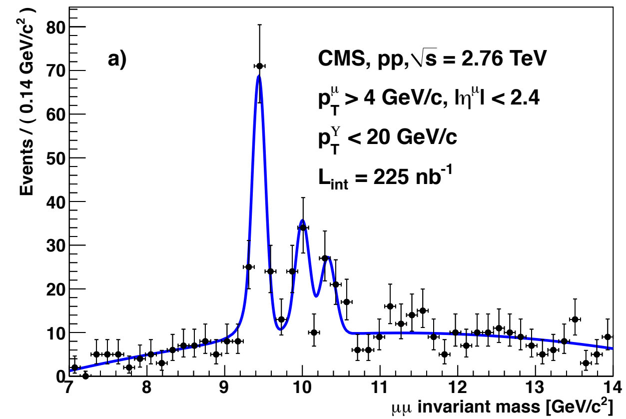
Suppression of Υ

- Expect successive "melting" according to the different binding energies:
  - establishes a "temperature" scale of the medium
  - strongest binding for Υ(1S)
- For the 0-20% most central PbPb collisions:

  $R_{AA}(\Upsilon(1S)) = 0.60 \pm 0.12 \pm 0.10$
  - Possibly due to high feed-down

  CMS-PAS-HIN-10-006



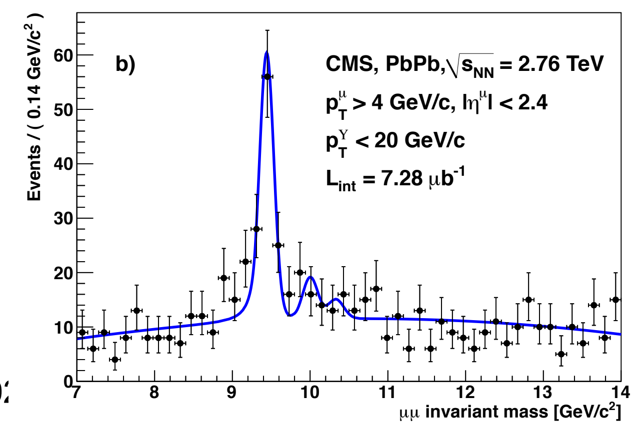


Suppression of higher Υ states

- Using double ratio to reduce experimental uncertainties

$$\frac{\Upsilon(2S+3S)_{HI}/\Upsilon(1S)_{HI}}{\Upsilon(2S+3S)_{pp}/\Upsilon(1S)_{pp}} = 0.31\ {}^{+0.19}_{-0.15} \pm 0.03$$

- For a true ratio of 1 the probability to measure this or a lower value is < 1%
- Future data samples will allow separate measurements for the 2S and 3S states



CMS Coll., PRL107(2011)05230:

Summary & Outlook

CMS shows an excellent performance in the reconstruction of low-mass dimuon states, both in pp and PbPb collisions

- Thanks to a flexible trigger system these events can be recorded even at high luminosity
- Quarkonia are reconstructed even at high track multiplicities

Differential production cross sections of ψ and Υ states have been measured, including the non-prompt component of the J/ψ

- In general a good agreement with the theoretical predictions is observed

The production of χ_c and X(3872) has been observed

- The cross section ratio of X(3872)/ψ(2S) has been measured

Production of quarkonia is suppressed in PbPb collisions

- In particular a strong indication for the suppression of excited Υ states has been found

The next important step in the comparison to QCD predictions will be the measurement of the Υ and J/ψ polarization