Measurement of quarkonium production in PbPb collisions at $\sqrt{s_{NN}}$ =2.76 TeV with CMS

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for the CMS collaboration

Outline

- Introduction
- J/ψ production at PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
  - Prompt and non-prompt J/ψ separation
  - Prompt and non-prompt J/ψ R_{AA}
- ϒ production at PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
  - ϒ(2S+3S) suppression
  - ϒ(1S) R_{AA}

Quarkonia in heavy ion collisions

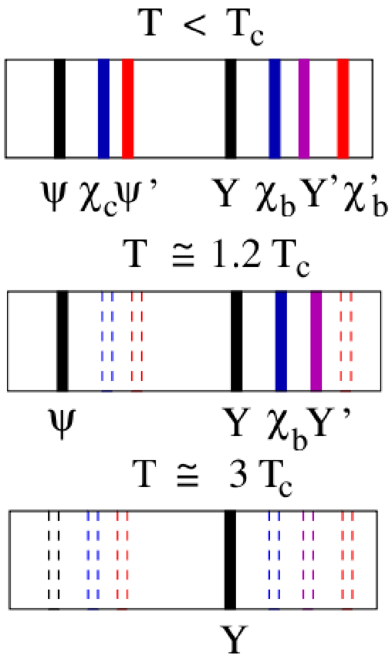
- Good candidates to probe the QGP in heavy ion collisions
  - Large masses and dominantly produced at the early stage of the collision by hard-scattering of gluons
  - Characterized by its binding energy and radius

H. Satz / Nucl. Phys. A 783 (2007) 249c–260c

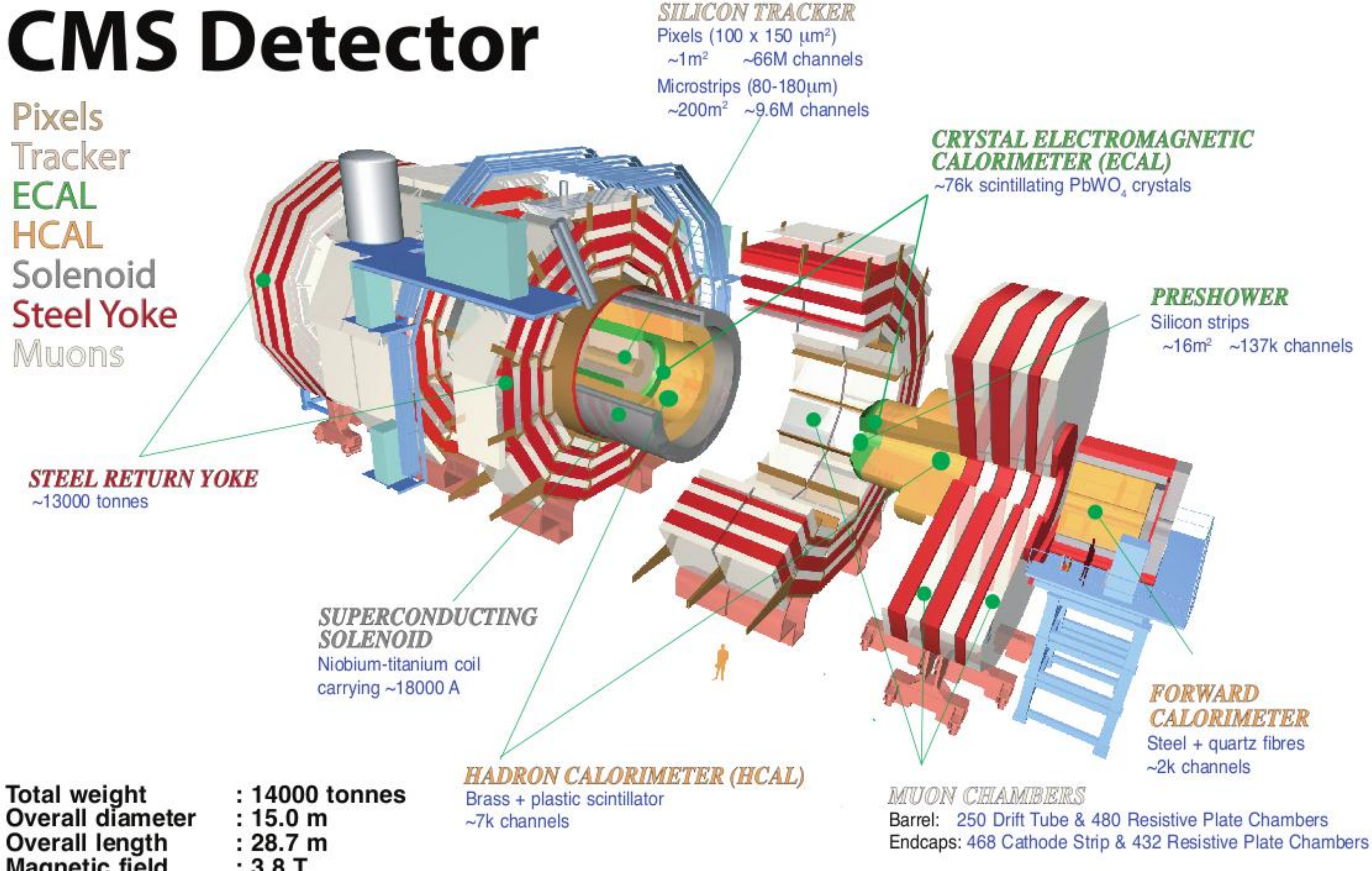
	J/ψ	χ_c	ψ (2s)	Υ (1s)	Υ (2s)	Υ (3s)
M (GeV/c^2)	3.10	3.53	3.68	9.46	10.02	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.54	0.20
r_0 (fm)	0.50	0.72	0.90	0.28	0.56	0.78

  - Debye screening radius decreases with increasing temperature $\rightarrow$ Sequential melting
  - Thermometer for the temperature reached in the HI collisions

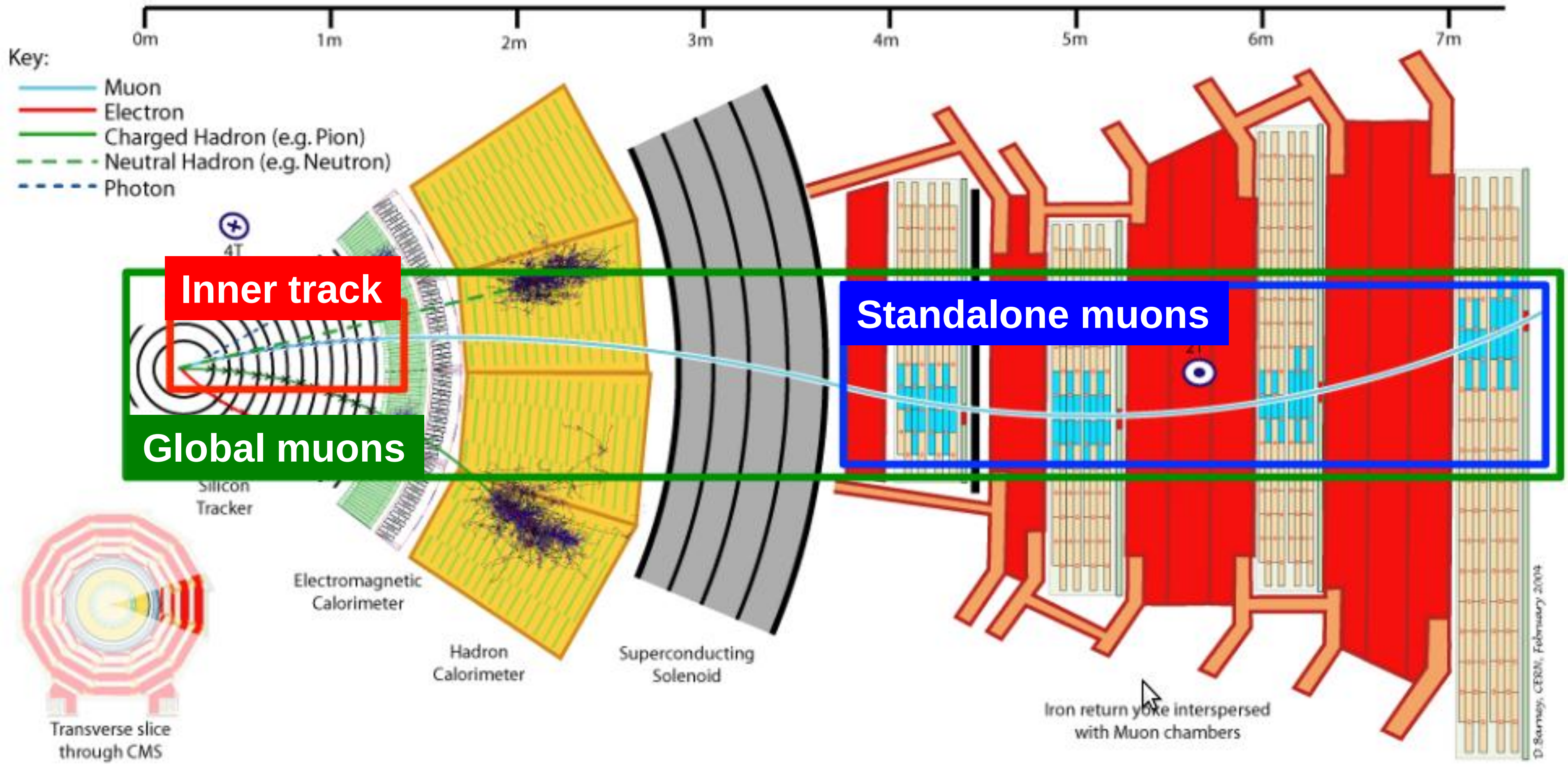
Quarkonium spectral lines as thermometer



Compact Muon Solenoid

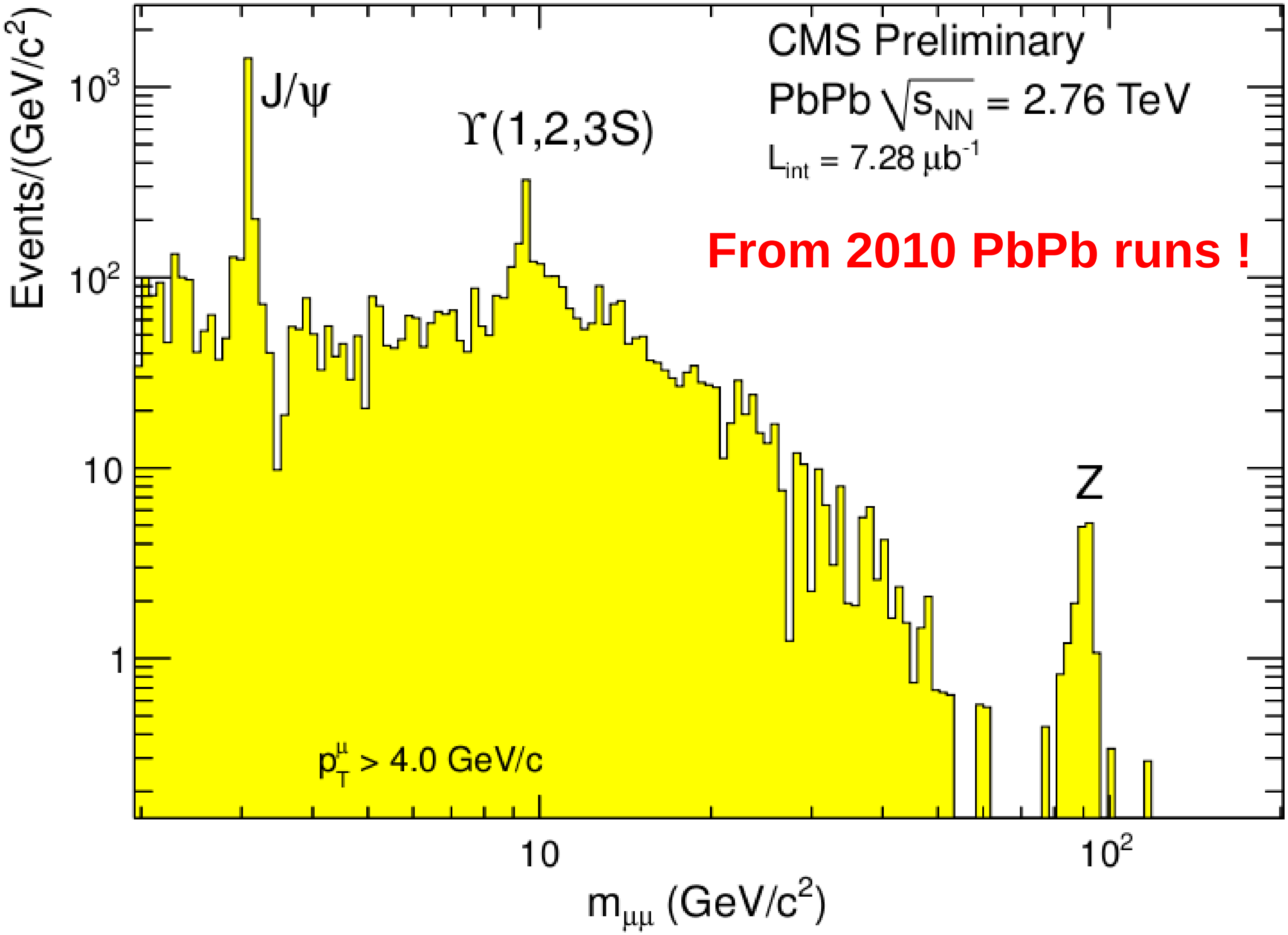


Muon reconstruction in CMS



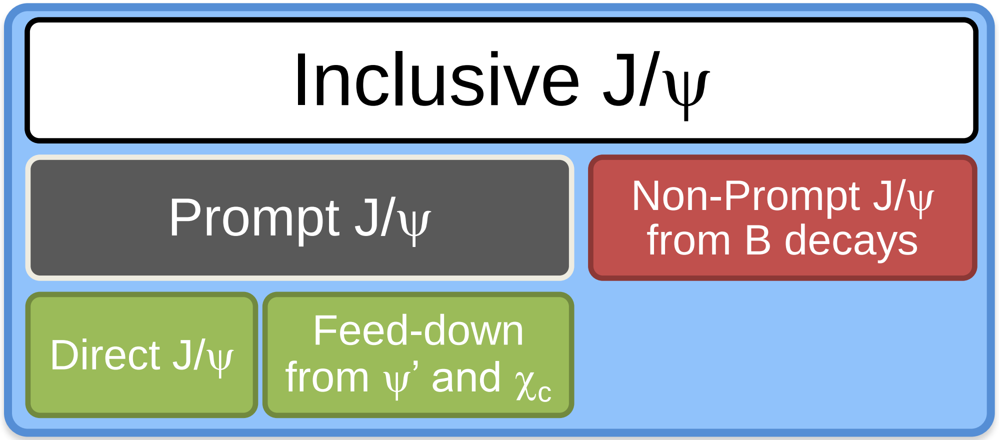
- Excellent muon identification & triggering (Muon system)
- High mass/momentum resolution (Tracker)

Dimuons in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV



From 2010 PbPb runs !

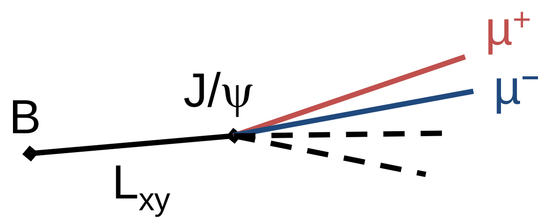
J/ψ in pp at $\sqrt{s}$ = 2.76 TeV

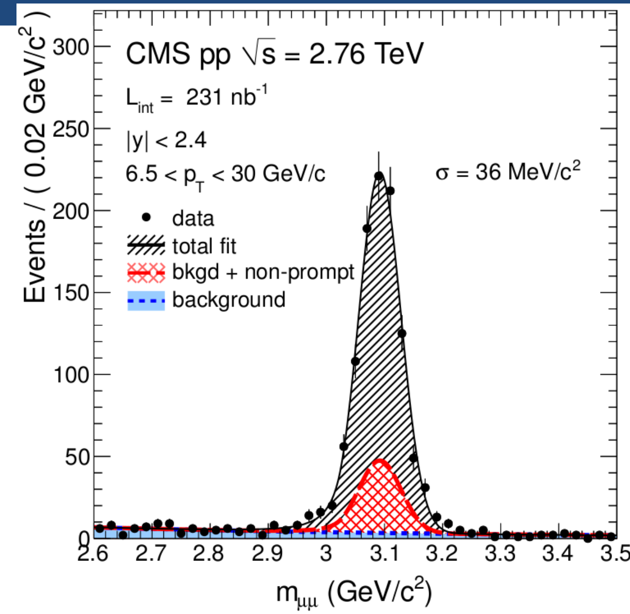


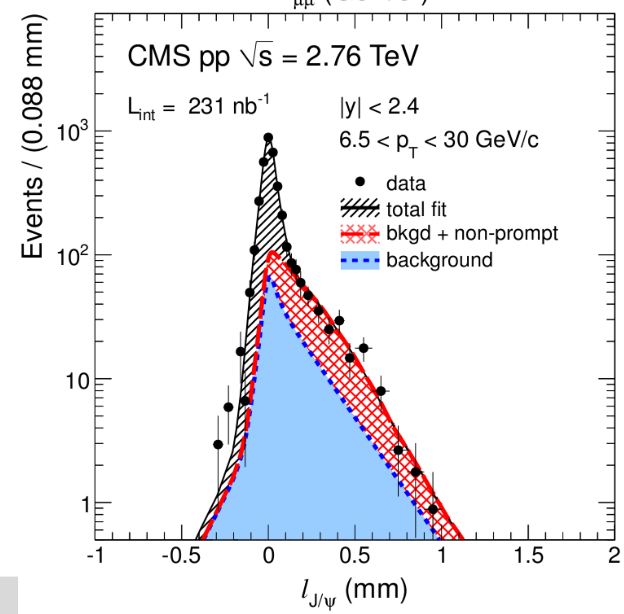
arXiv: 1201.5069
(submitted to JHEP)
CMS HIN-10-006

- Reconstruct $\mu^+\mu^-$ vertex
- 2-D unbinned maximum likelihood fit of $\mu^+\mu^-$ mass and pseudo-proper decay length ($l_{J/\psi}$)

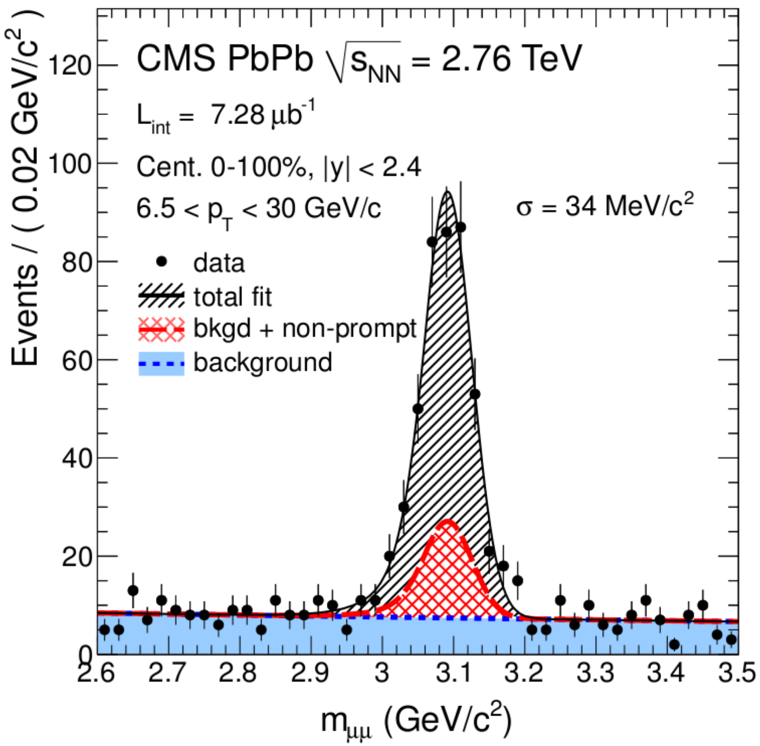
$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$

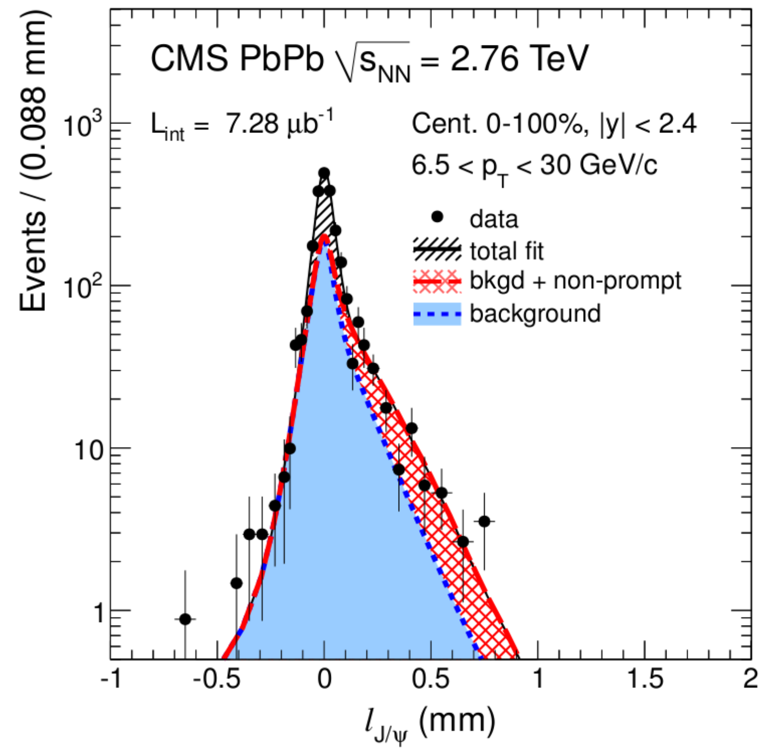






J/ψ in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV



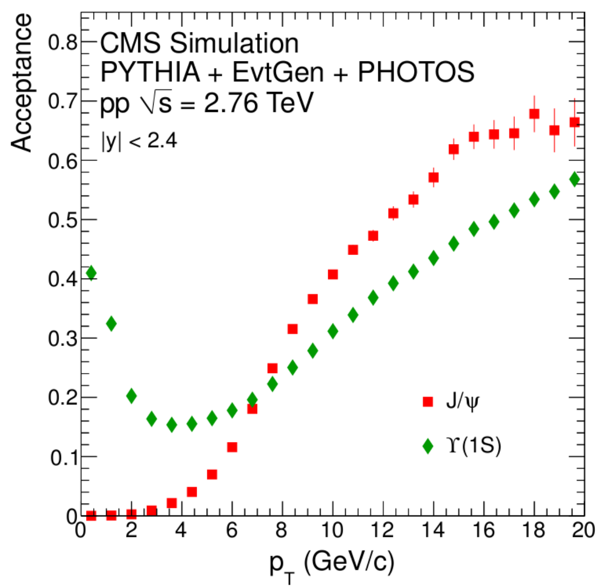


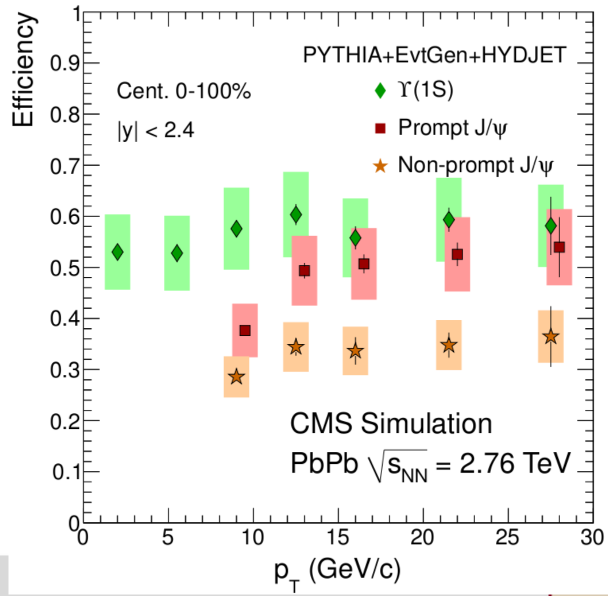
- Prompt and non-prompt J/ψ separation in PbPb
- Quarkonia in pp at $\sqrt{s_{NN}}$ = 2.76 TeV is used as a reference
  - Same HI reconstruction algorithm & analysis method has been used in PbPb and pp data

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}(J/\psi)}{N_{pp}(J/\psi)} \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb}}(\mathrm{cent})}$$

Efficiency and acceptance

- MC simulations with PYTHIA
  - Prompt J/ψ and $\Upsilon(1S)$
    - With the unpolarized scenario
  - Non-prompt J/ψ
    - Polarization as predicted by EvtGen
- Acceptance
  - No acceptance for J/ψ at mid-rapidity with $p_T < 6.5$ GeV/c
  - At forward rapidity, acceptance for J/ψ with $p_T > 3$ GeV/c
  - Acceptance for Υ with $p_T > 0$ GeV/c at all rapidities
- Efficiencies
  - Embedded signal in min-bias event simulated with HYDJET
  - Validated MC by comparing efficiencies measured with "Tag & Probe" in MC and data





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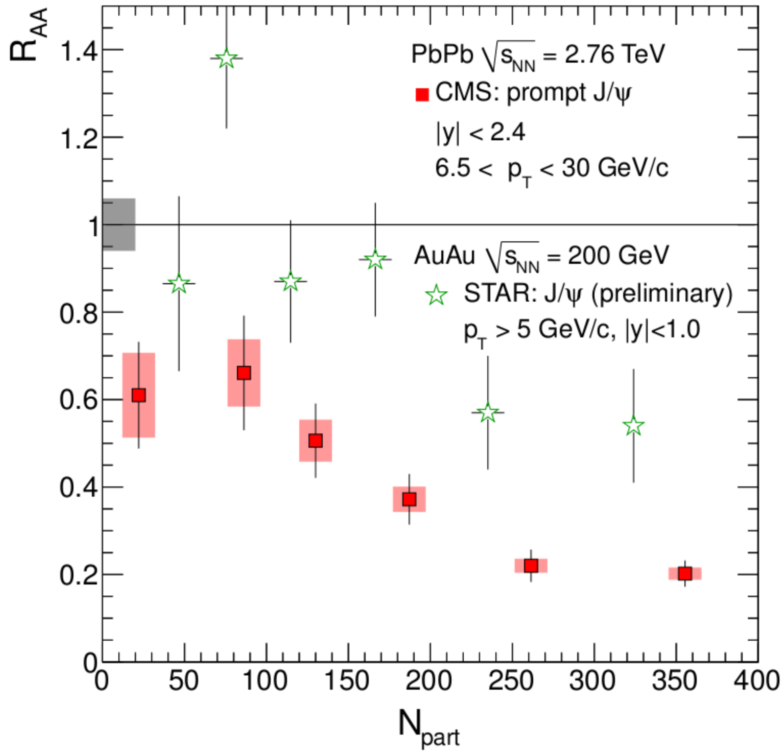
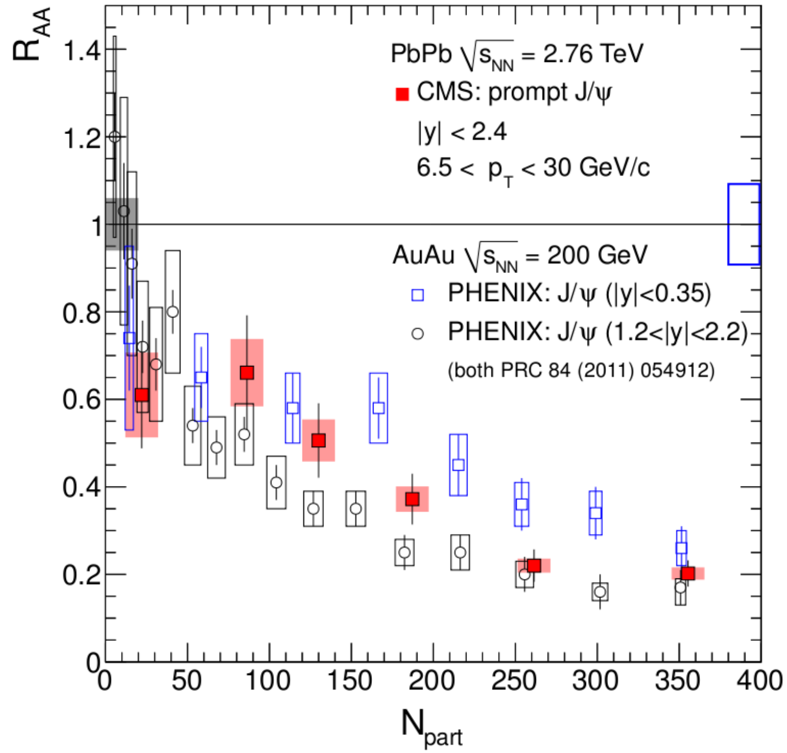
CMS HIN-10-006

Prompt J/ψ R_{AA} vs. N_{part}





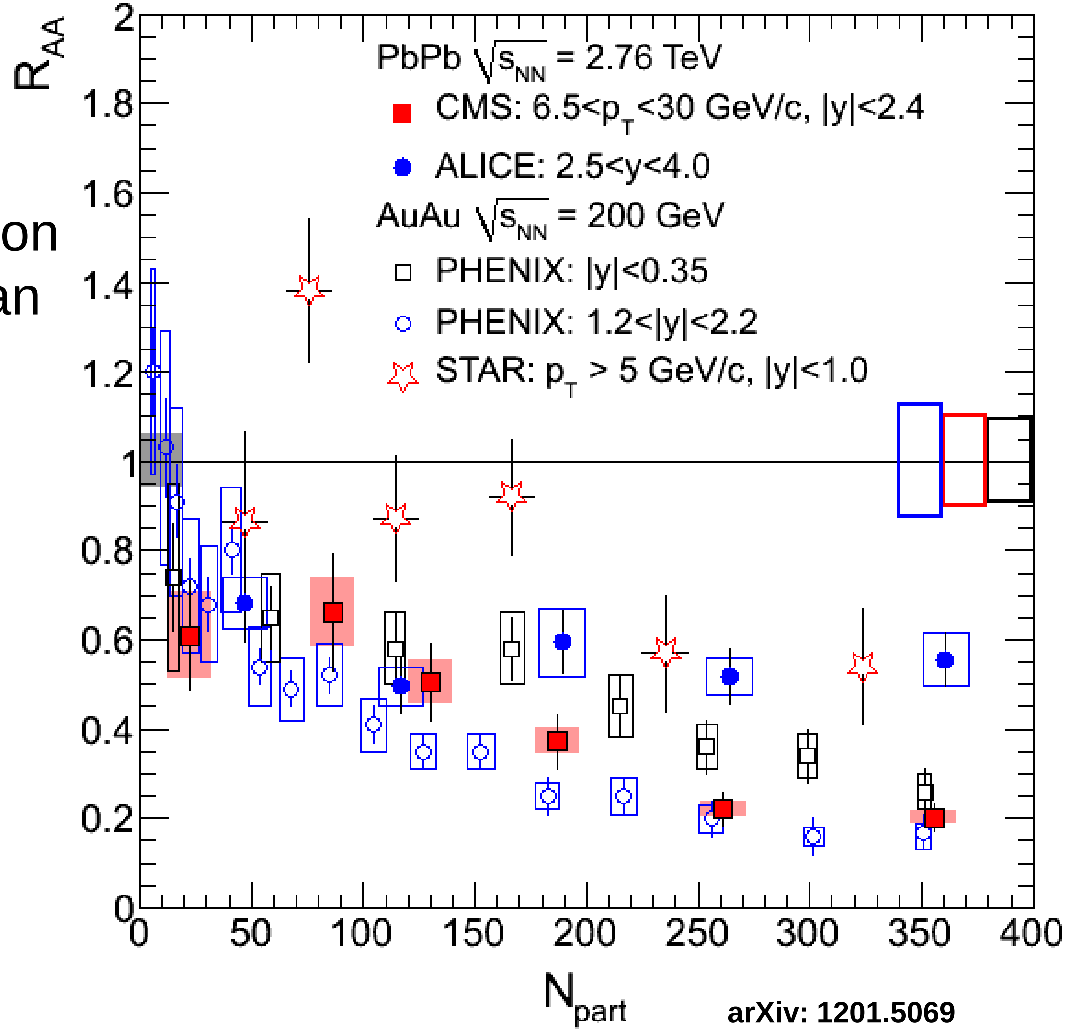
- 0-10% suppressed by factor 5
- 50-100% suppressed by factor ~1.6
- STAR measures less suppression at high p_T (> 5 GeV/c)
- Similar suppression seen in CMS and PHENIX
  (Despite of lower p_T range at lower energy)

arXiv: 1201.5069
(submitted to JHEP)
CMS HIN-10-006

Prompt J/ψ R_{AA} vs. N_{part}

arXiv:1202.1383

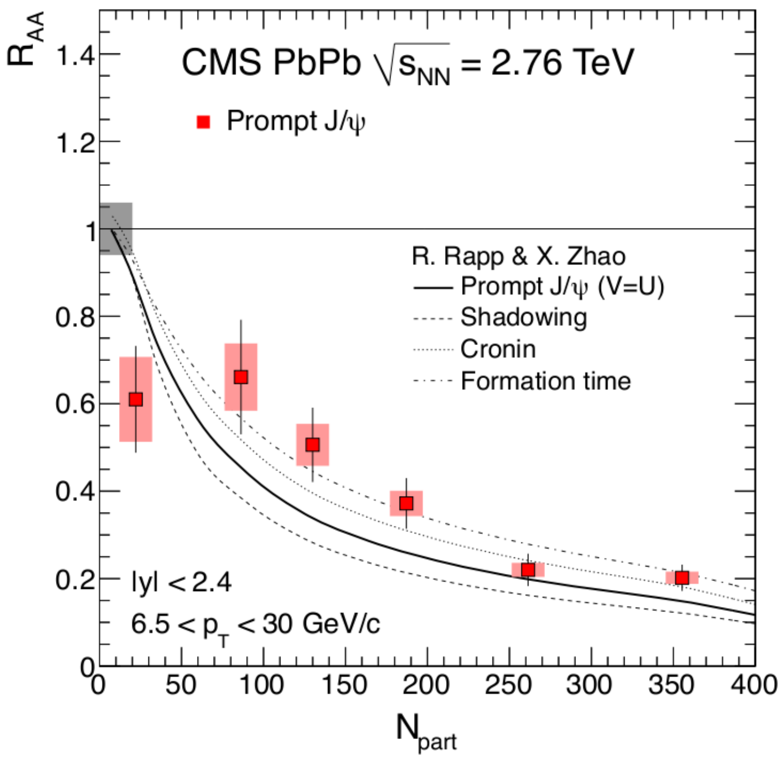
- ALICE measured less suppression & less centrality dependence than CMS
  - Lower p_T: Expect to be more sensitive to effects from recombination than CMS
  - More forward y region



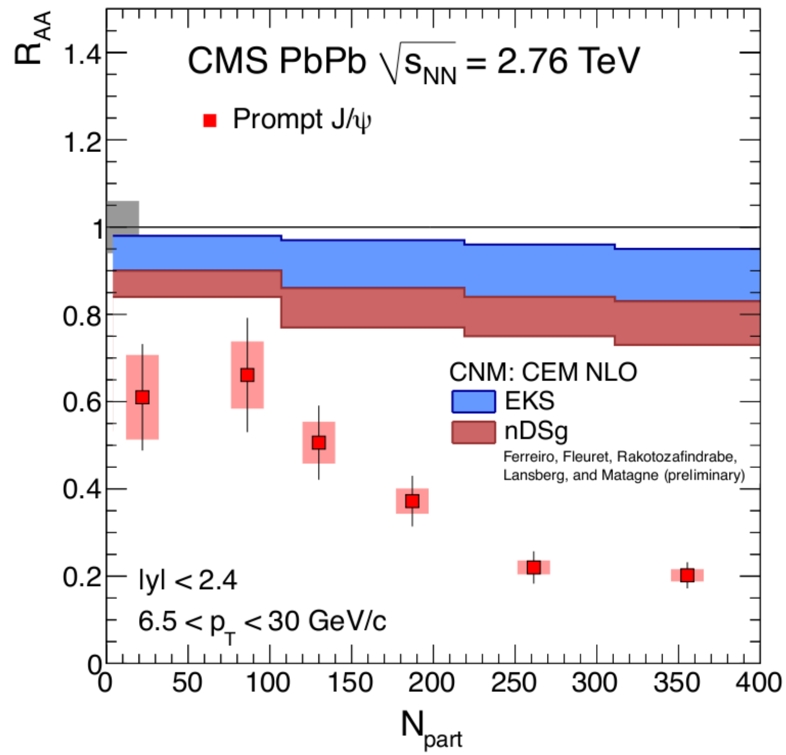
arXiv: 1201.5069
(submitted to JHEP)
CMS HIN-10-006

Prompt J/ψ R_{AA} & theory comparison

Rapp & Zhao, NPA 859 (2011) 114
+ private communication



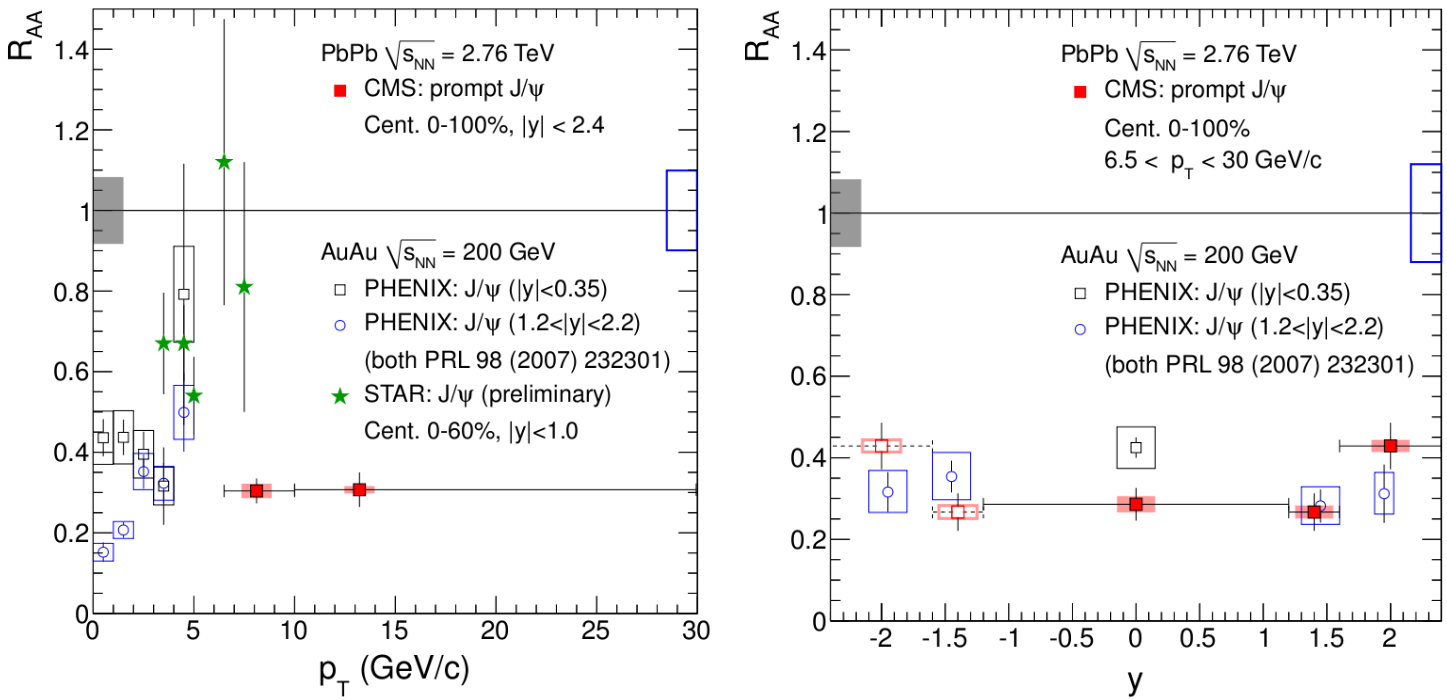
Ferreiro et al. (preliminary)



Recombination negligible for p_T > 6.5 GeV/c

Suppression by cold-nuclear-matter effect seems to be much smaller than observation

Prompt J/ψ R_{AA} vs. p_T and y



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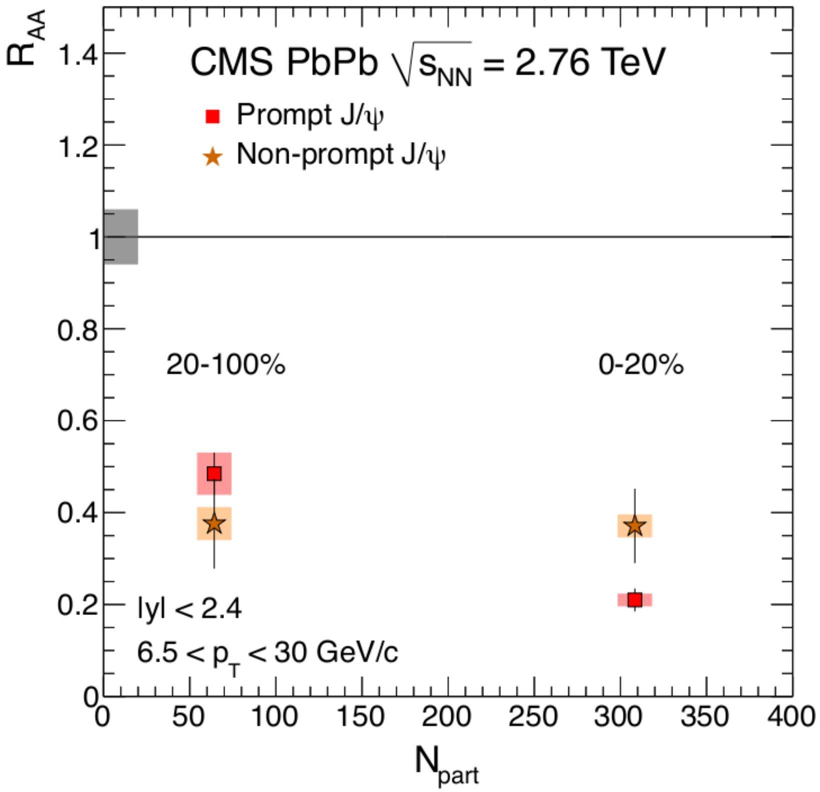
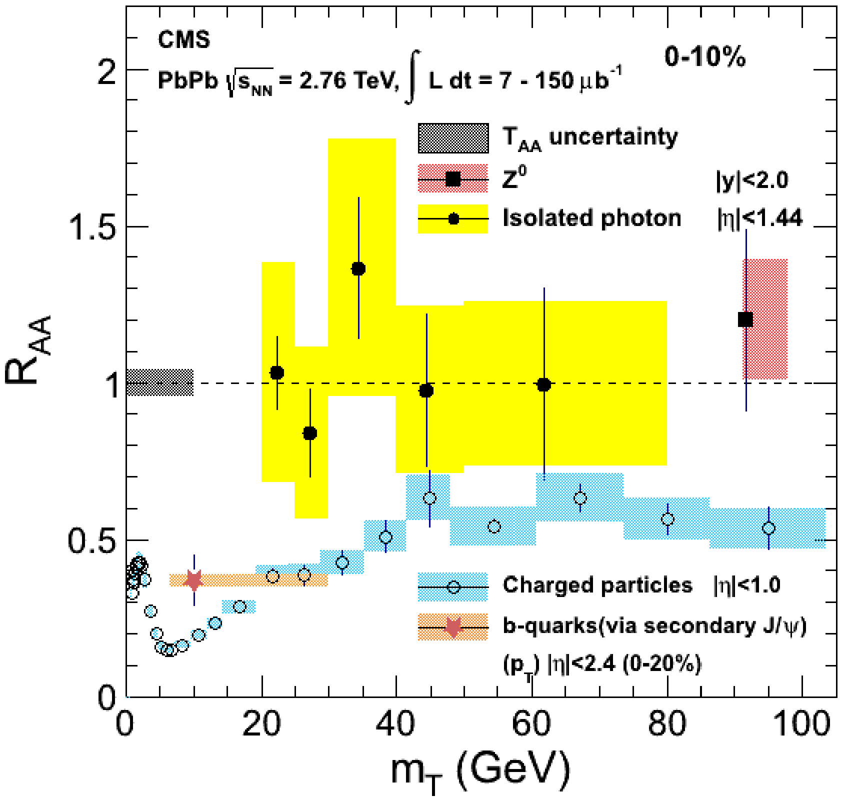
- High p_T J/ψ's tendency to survive at RHIC (and SPS) is not seen at the LHC
- CMS shows opposite trend vs. y than PHENIX but different p_T
- Increasing R_{AA} going towards ALICE y range
  - ALICE inclusive J/ψ R_{AA} = 0.545±0.032±0.84 (p_T > 0 GeV/c, 0-80%) **arXiv:1202.1383**
  - In pp at low p_T : ~10% b-fraction → Non-prompt J/ψ could shift R_{AA} by 11 %

Non-prompt J/ψ R_{AA}





Suppression of non-prompt J/ψ observed in min-bias and central PbPb at $\sqrt{s_{NN}} = 2.76\ TeV$

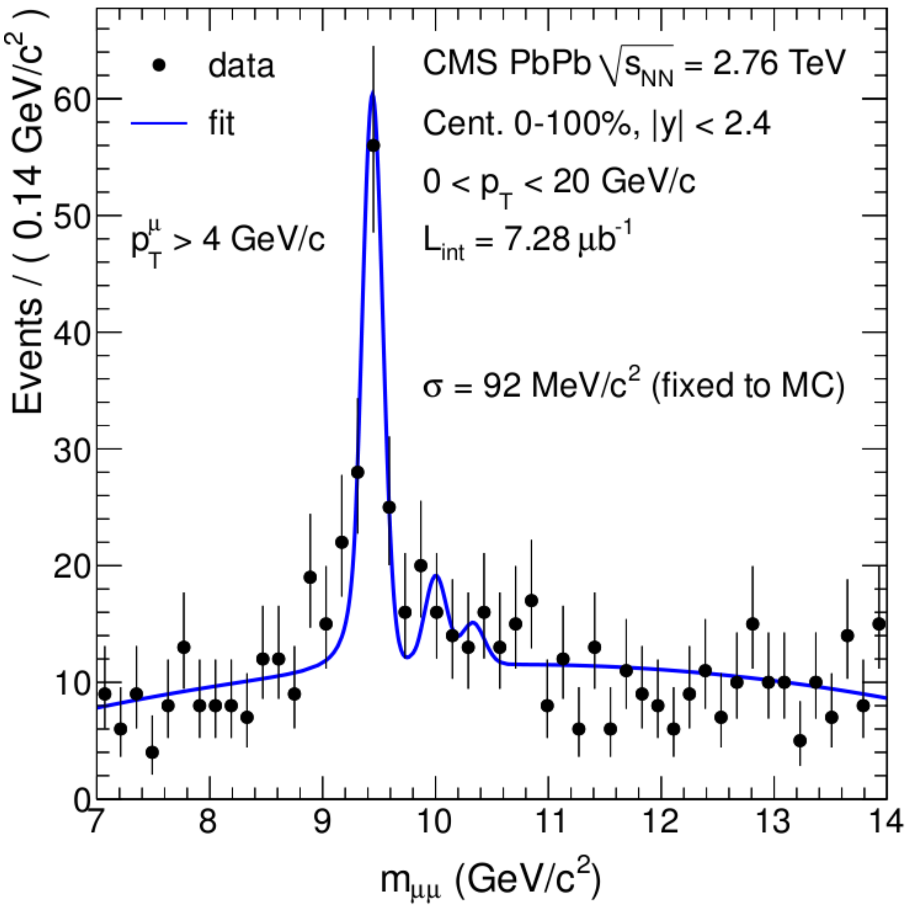
– First indications of high-p_T b-quark quenching !

- No centrality dependence

arXiv: 1201.5069
(submitted to JHEP)
CMS HIN-10-006

Υ(nS) in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

- Signal extraction
  - A Crystal Ball for 1 resonance
  - Peak separation is fixed to PDG values
  - Mass resolution is forced to scale linearly with resonance mass
  - Fixed Υ(1S) resolution from simulation is consistent with not-fixed resolution



arXiv: 1201.5069
(submitted to JHEP)
CMS HIN-10-006

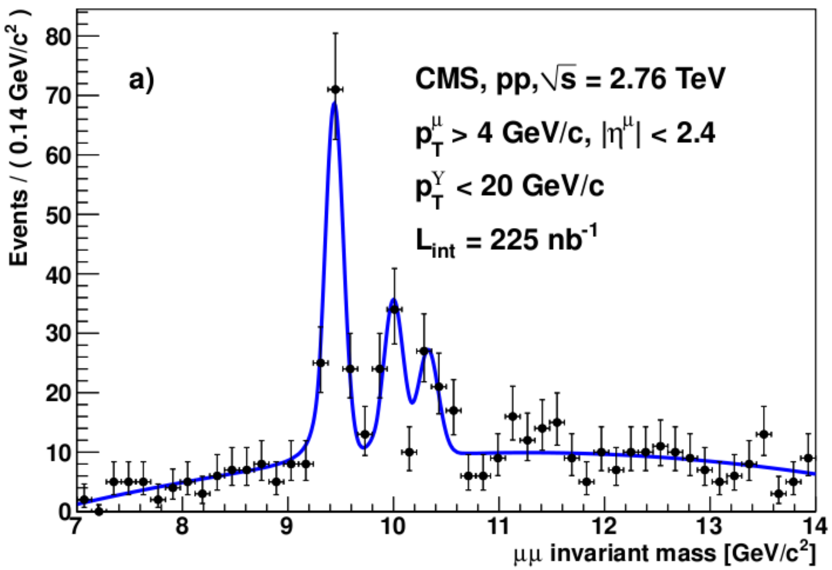
Υ(2S+3S) suppression

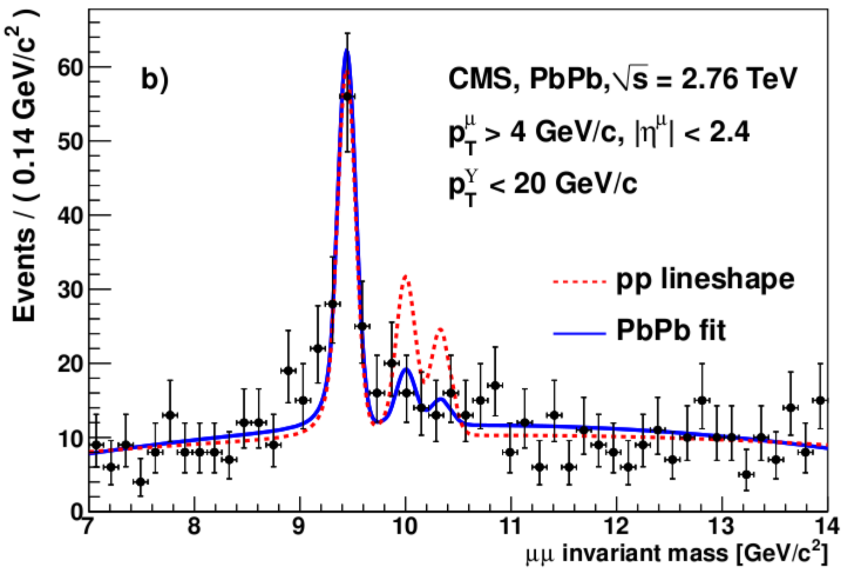
- Υ(2S+3S) production relative to Υ(1S) in pp and PbPb
- Simultaneous fit to PbPb and pp data at 2.76 TeV

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

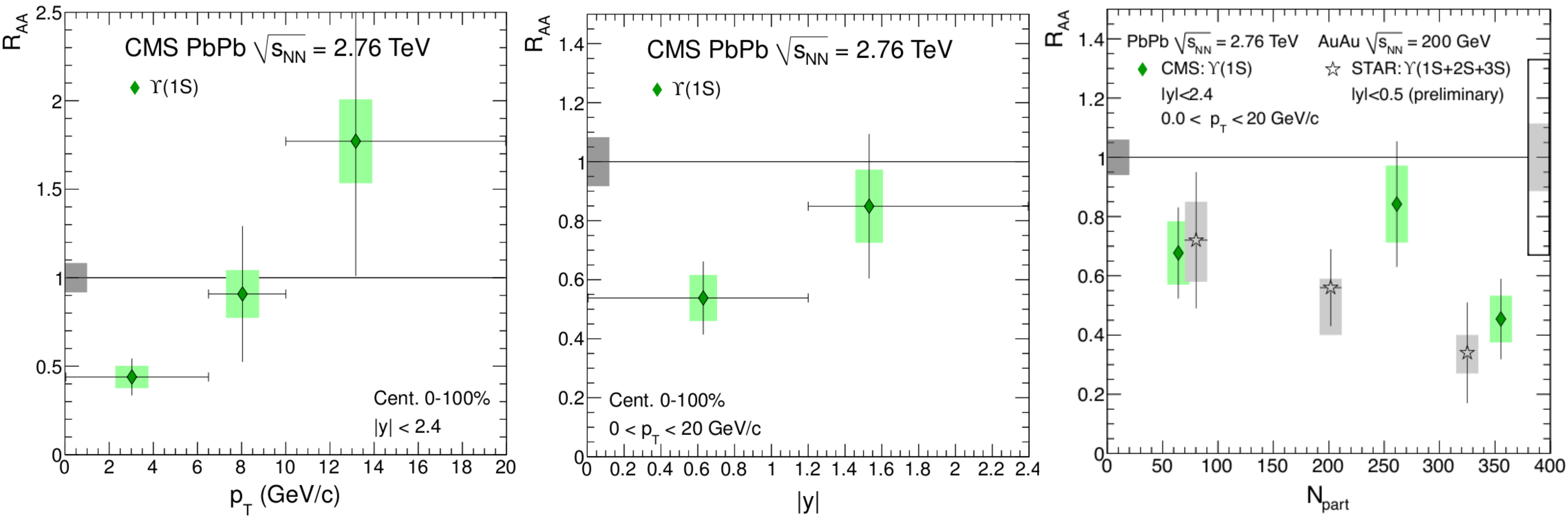
- Probability to obtain measured ratio (or lower) from background fluctuation is less than 1%

PRL 107 (2011) 052302





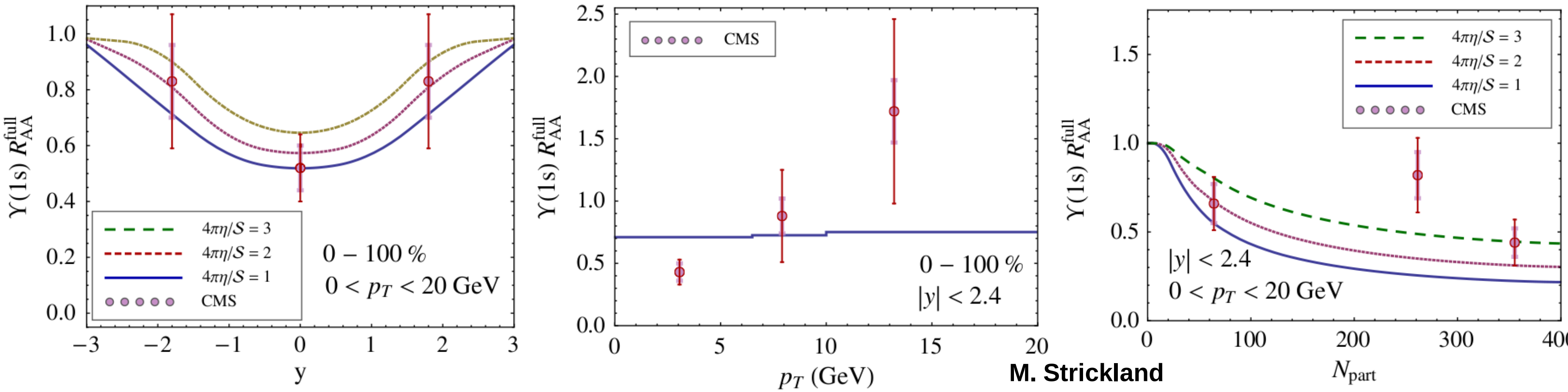
$\Upsilon(1S)$ R_{AA}



arXiv: 1201.5069
(submitted to JHEP)
CMS HIN-10-006

- $\Upsilon(1S)$ is suppressed at low p_T
- No obvious y dependence
- 0-10% suppressed by factor ~2.2
- Large feed down contribution from excited states (χ_b, $\Upsilon(2S)$, $\Upsilon(3S)$)
  - The $\Upsilon(2S+3S)$ suppression and $\Upsilon(1S)$ R_{AA} are consistent with the suppression of the excited Υ states only
- STAR $R_{AA}(\Upsilon(1S+2S+3S)) = 0.56 \pm 0.21^{+0.08}_{-0.16}$ (arXiv: 1109.3891)
  - CMS $R_{AA}(\Upsilon(1S+2S+3S)) = R_{AA}(\Upsilon(1S)) \times \frac{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.62 \times \frac{1+0.24}{1+0.78} \approx 0.43$

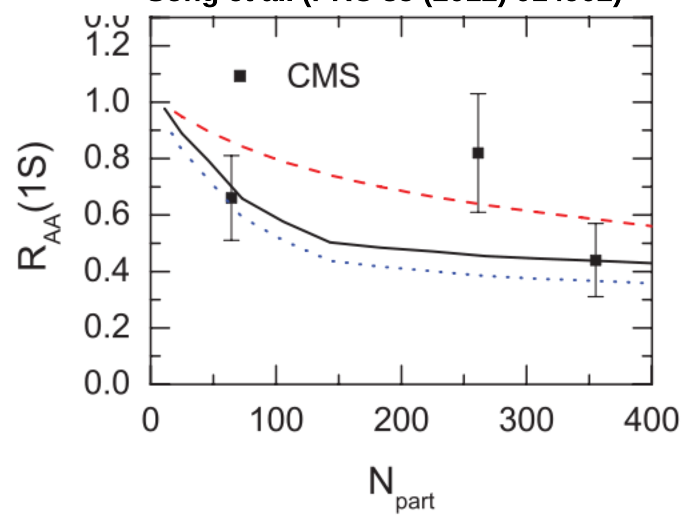
Υ(1S) R_{AA} & theory comparison



M. Strickland
PRL 107, 132301 (2011)

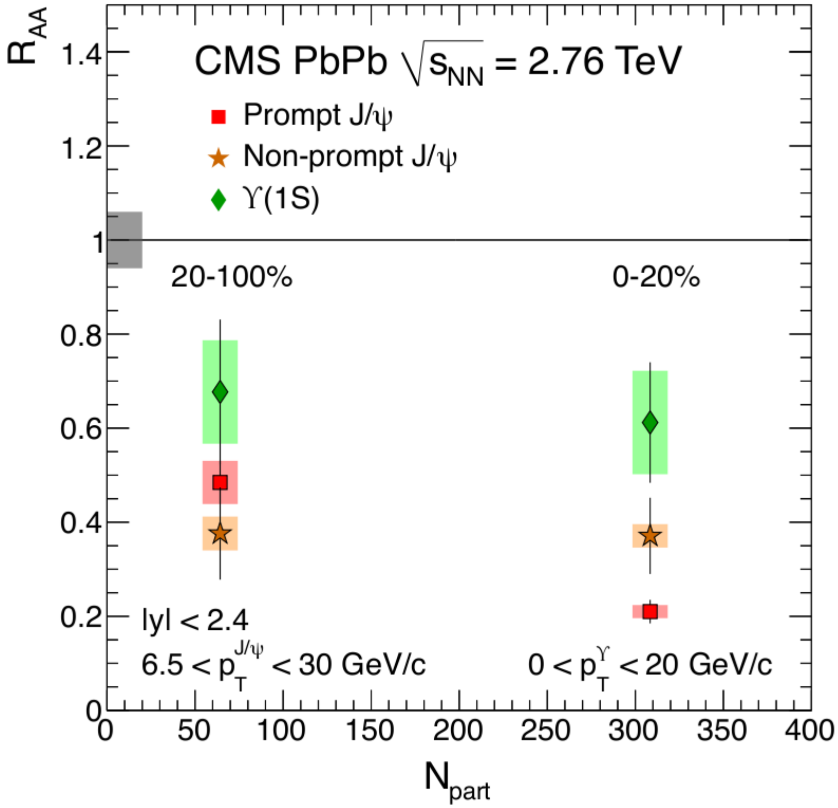
- Lots of activities on the theory side
  - Strickland (PRL 107 (2011) 132301)
  - Rapp et al. (arXiv:1111.6537)
  - Song et al. (PRC 85 (2012) 014902)
  - Brezinski et al. (PLB 707 (2012) 534)

Song et al. (PRC 85 (2012) 014902)



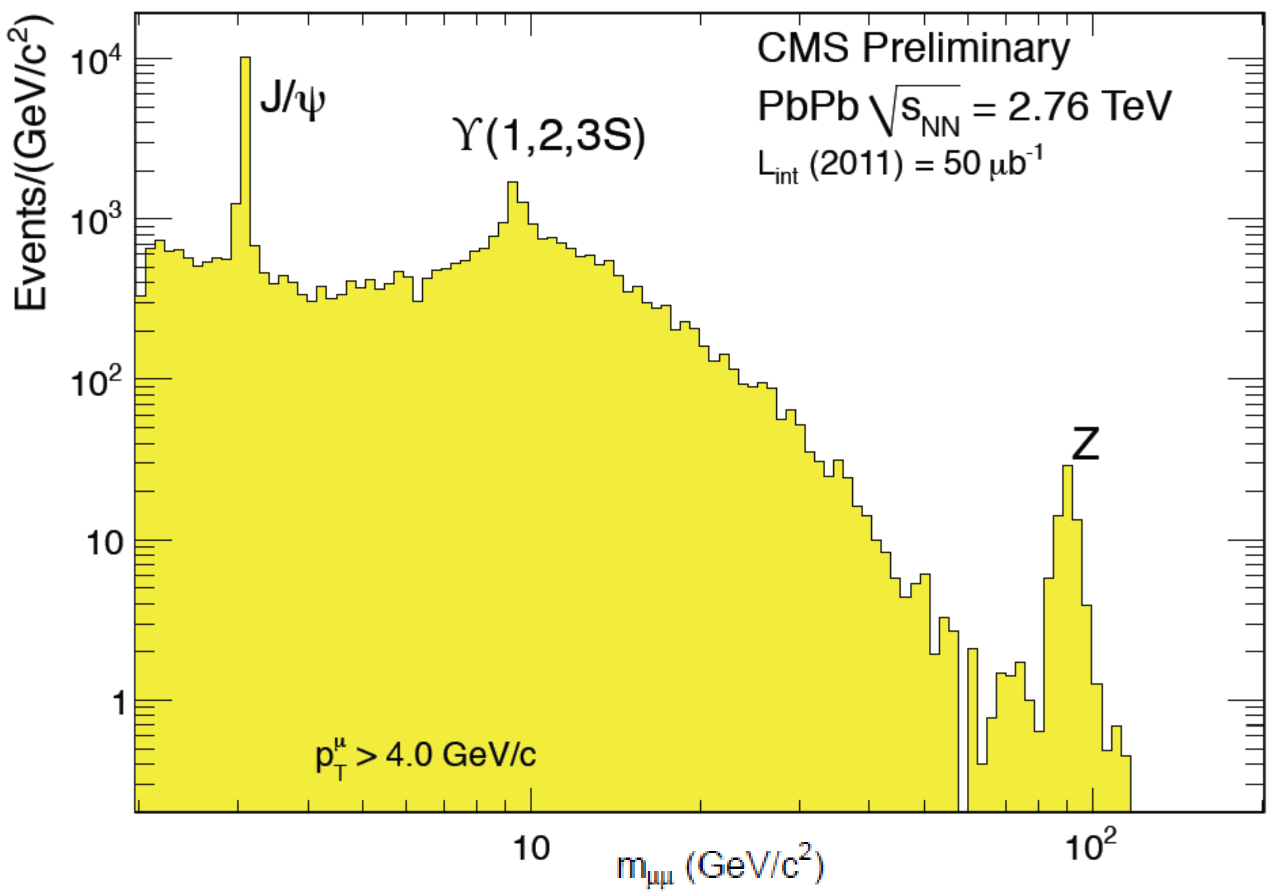
Summary

- Prompt J/ψ at high p_T significantly suppressed
- First non-prompt J/ψ observation in heavy ion collisions
  - b-quark energy loss
- Υ(2S+3S) excited states suppressed relative to Υ(1S)
  - This result, together with the Υ(1S) R_{AA}, is consistent with the suppression of the excited Υ states only



Sequential melting accessible with CMS mass resolution

Outlook



- In 2011 PbPb collisions, integrated luminosity is 150 μb^{-1}
  (Plot contains only 1/3 of total integrated luminosity)
- More detailed quarkonia studies are ongoing!

Back up

Systematic uncertainties

Table 2: Point-to-point systematic uncertainties on the prompt J/ψ, non-prompt J/ψ, and $\Upsilon(1S)$ yields measured in PbPb collisions.

	prompt J/ψ (%)	non-prompt J/ψ (%)	$\Upsilon(1S)$ (%)
Yield extraction	0.5–5.7	1.5–14.0	8.7–13.4
Efficiency	1.8–3.4	2.2–4.2	1.4–2.7
Acceptance	0.9–4.2	2.0–3.2	1.5–2.8
MC Validation	13.7	13.7	13.7
Stand-alone μ reco.	1.0	1.0	1.0
T_{AA}	4.3–15.0	4.6–8.6	4.3–8.6
Total	15–21	15–21	18–20

Table 3: Point-to-point systematic uncertainties on the prompt J/ψ, non-prompt J/ψ, and $\Upsilon(1S)$ yields measured in pp collisions.

	prompt J/ψ (%)	non-prompt J/ψ (%)	$\Upsilon(1S)$ (%)
Yield extraction	0.8–5.3	5.3–16.8	10.0
Efficiency	1.6–3.0	1.4–2.0	0.4–0.9
Acceptance	0.9–4.2	2.0–3.2	1.5–2.8
MC Validation	13.7	13.7	13.7
Stand-alone μ reco.	1.0	1.0	1.0
Total	14–16	15–22	17–18

A complex production

- J/ψ production in pp
  - Production of $q\bar{q}$ pair (perturbative)
  - Evolution of $q\bar{q}$ pair into a bound state (non perturbative)
- Different theoretical models of evolution
  - Color singlet model, color evaporation model, NRQCD, FONLL
- Production mechanism not completely understood

- Many effects altering production in nuclear reactions
  - In pA, cold nuclear matter (CNM) effects
    - Initial state: shadowing, parton energy loss
    - Final state: $c\bar{c}$ dissociation in the medium, final energy loss
  - In AA, hot and dense medium effects

Separating non-prompt J/ψ

- 2D $(l_{J/\psi}, m_{\mu\mu})$ unbinned maximum likelihood fit is done to separate J/ψ originating in B hadron decays.

$$\ln\mathcal{L} = \sum_{i=1}^{N} \ln F(l_{J/\psi}, m_{\mu\mu})$$

$$F(l_{J/\psi}, m_{\mu\mu}) = f_{sig} F_{sig}(l_{J/\psi}) M_{sig}(m_{\mu\mu}) + (1 - f_{sig}) F_{bkg}(l_{J/\psi}) M_{bkg}(m_{\mu\mu})$$

$$F_{sig}(l_{J/\psi}) = f_B F_B(l_{J/\psi}) + (1 - f_B) R(l_{J/\psi})$$

$$F_B(l_{J/\psi}) = R(l'_{J/\psi} - l_{J/\psi}) \otimes X_{MC}(l'_{J/\psi})$$

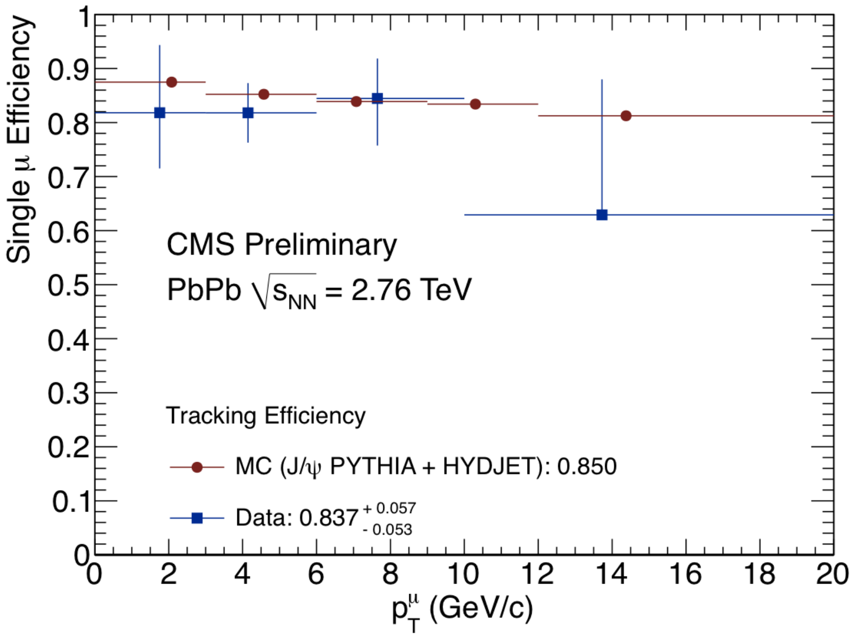
Resolution function $R(l_{J/\psi})$: Prompt J/ψ's $l_{J/\psi}$ distribution. Sum of 4 Gaussians

$F_{bkg}(l_{J/\psi})$: sum of 3 decay function (for long-lived components) convoluted with $X_{MC}(l_{J/\psi})$

B →J/ψ MC $l_{J/\psi}$ distribution

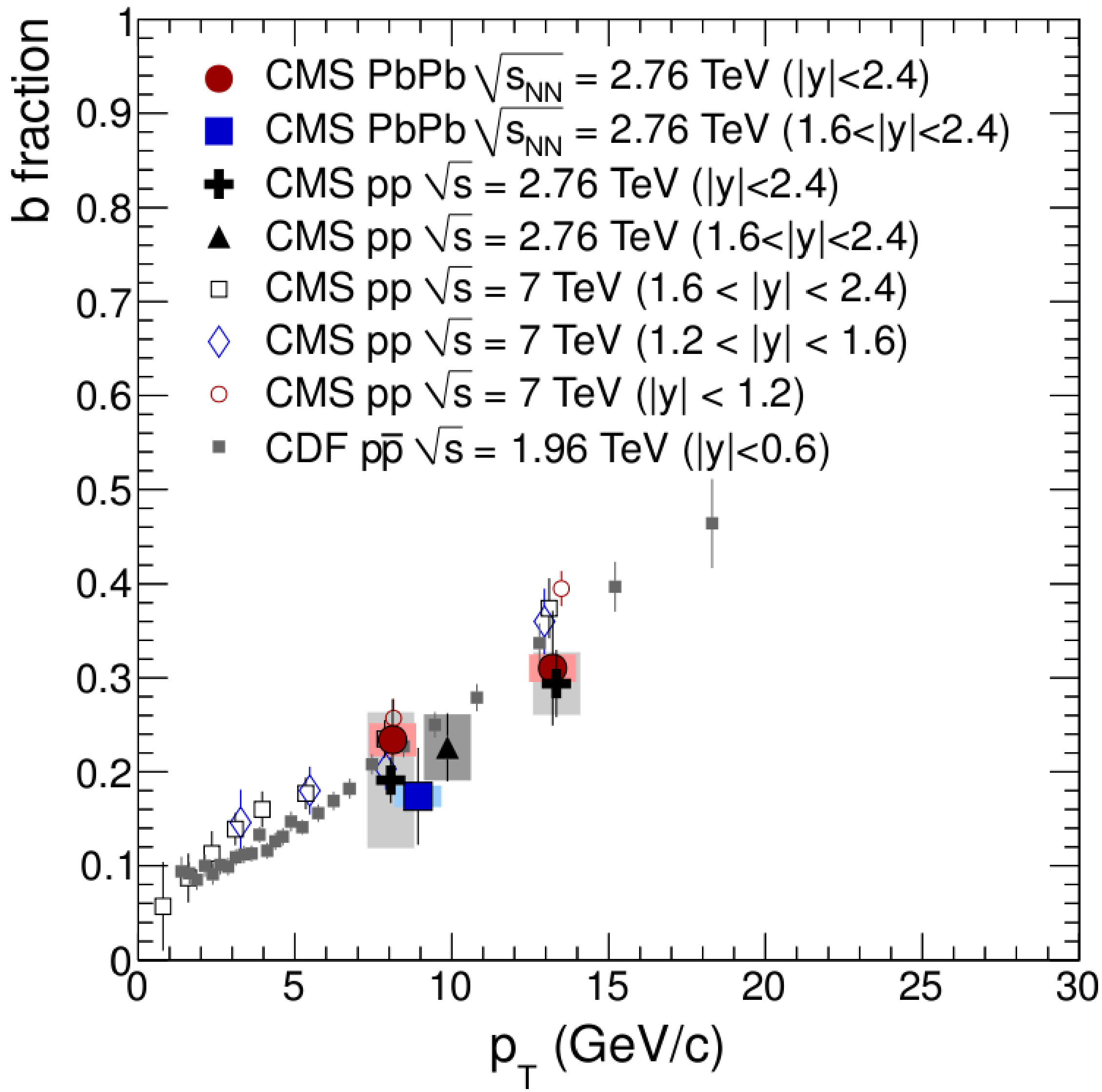
1) Fit to $m_{\mu\mu}$ to get inclusive J/ψ yield
2) Fit to $l_{J/\psi}$ in prompt J/ψ MC sample to get an initial estimation of each parameters of $R(l_{J/\psi})$
3) Fit to $l_{J/\psi}$ of sidebands of $m_{\mu\mu}$ with $F_{bkg}(l_{J/\psi})$
4) 2D simultaneous fit with $F(l_{J/\psi}, m_{\mu\mu})$

Tag & Probe



- Tag:
  - High quality muon
- Probe:
  - Track in the muon station
- Passing Probe:
  - Probe that is also reconstructed as global muon (i.e. with a track in the Si-tracker)
- Reconstruct J/ψ peak in passing probe-tag pairs and in failing probe-tag pairs
- Simultaneous fit to passing and failing probes allows us to measure the efficiency of the inner track reconstruction

B-fraction

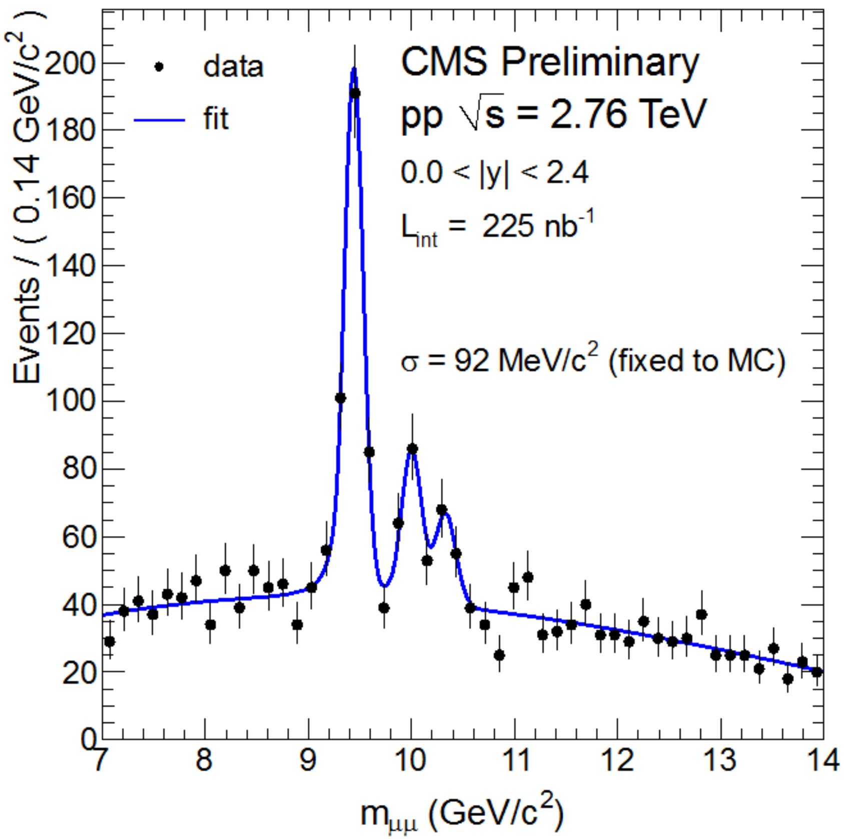


b fraction
CMS PbPb $\sqrt{s_{NN}}$ = 2.76 TeV (|y|<2.4)
CMS PbPb $\sqrt{s_{NN}}$ = 2.76 TeV (1.6<|y|<2.4)
CMS pp $\sqrt{s}$ = 2.76 TeV (|y|<2.4)
CMS pp $\sqrt{s}$ = 2.76 TeV (1.6<|y|<2.4)
CMS pp $\sqrt{s}$ = 7 TeV (1.6 < |y| < 2.4)
CMS pp $\sqrt{s}$ = 7 TeV (1.2 < |y| < 1.6)
CMS pp $\sqrt{s}$ = 7 TeV (|y| < 1.2)
CDF $p\bar{p}$ $\sqrt{s}$ = 1.96 TeV (|y|<0.6)
p_T (GeV/c)

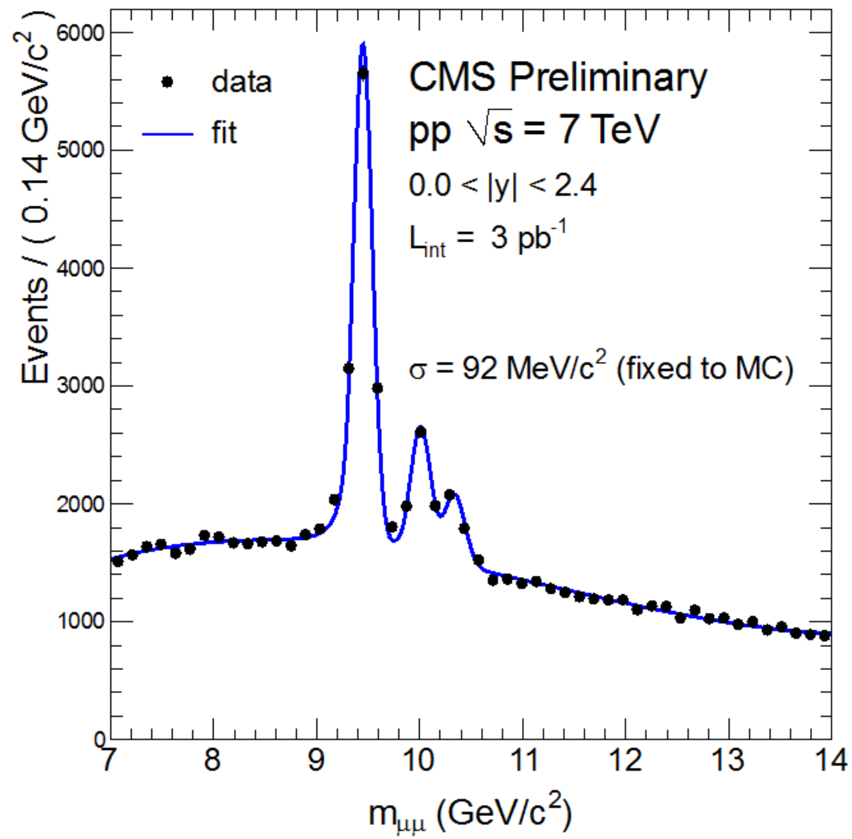
pp Comparison

Same pp reconstruction, including low p_T J/ψ
Agreement of the Υ(2S+3S)/ Υ(1S) ratio

- pp 2.76 TeV



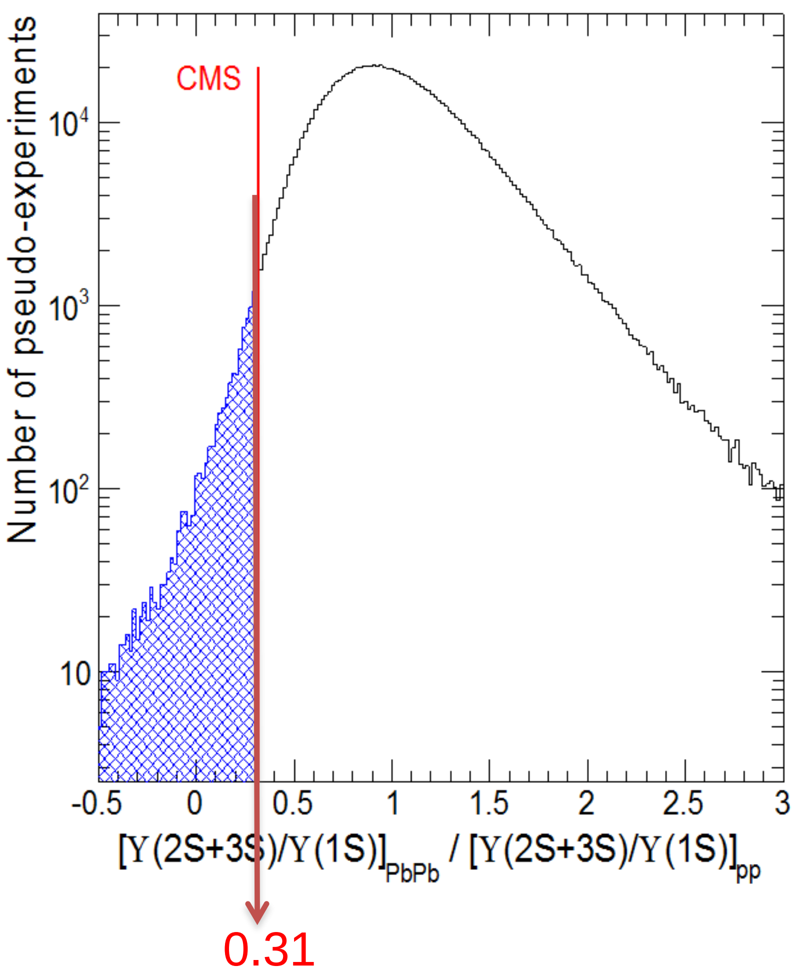
- pp 7 TeV



p-value

Could background fluctuation produce a result as extreme as observed in data?

- Generate pseudo-experiments following the *null-hypothesis* (i.e. no suppression)
- Fit pseudo-data samples with nominal fit
- Count fraction of occurrences for which the ratio (taken as test statistic) is same or lower than observed:
  - p-value: 0.9%
  - 2.4σ (1-sided Gaussian test)



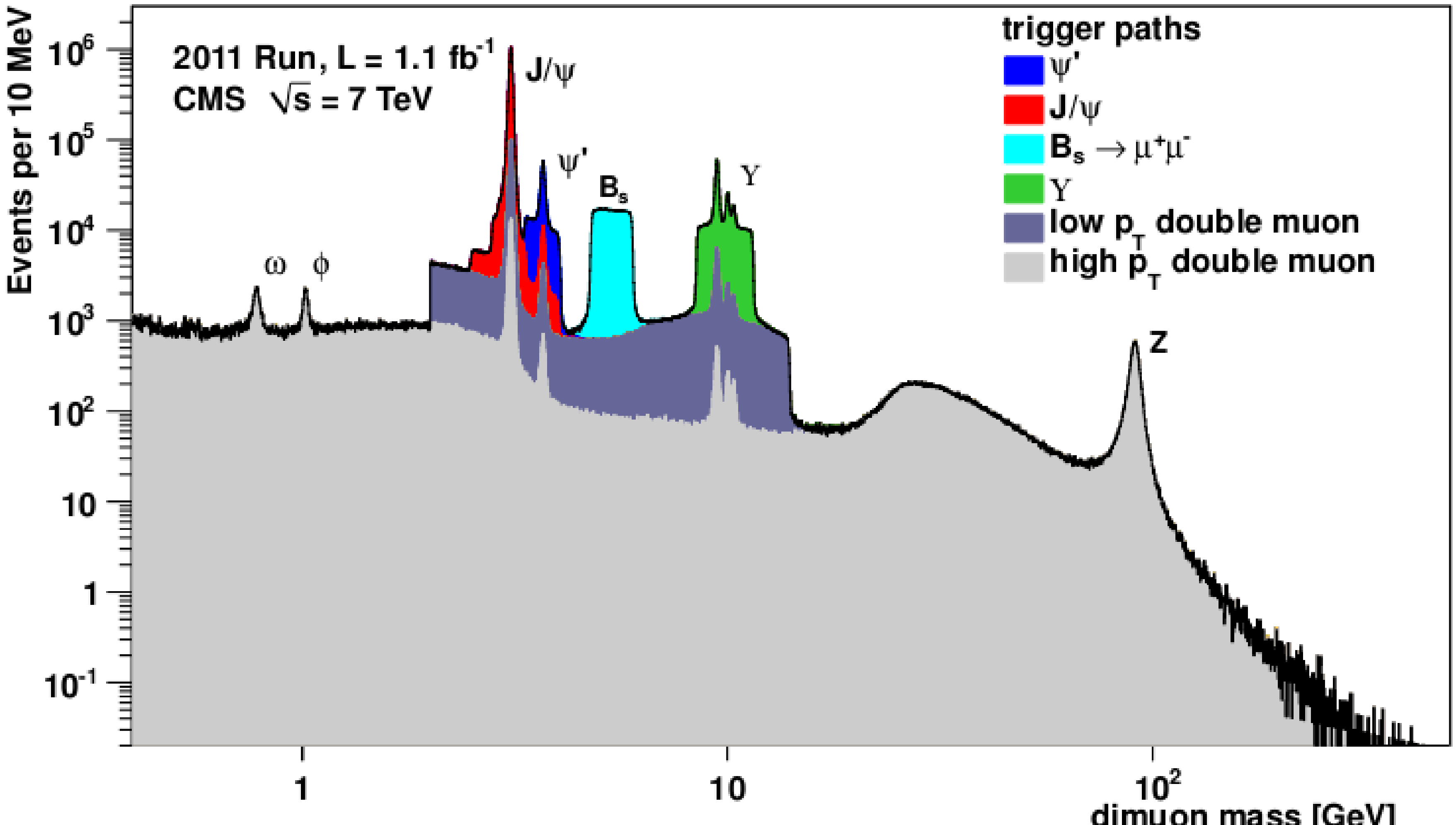
Υ(2S+3S), Υ(1S) suppression

- Systematic uncertainty : 9.1%
- Statistical uncertainty : 55%
- Null hypothesis testing
  - p-value : 1%
  - Significance of suppression is 2.4σ

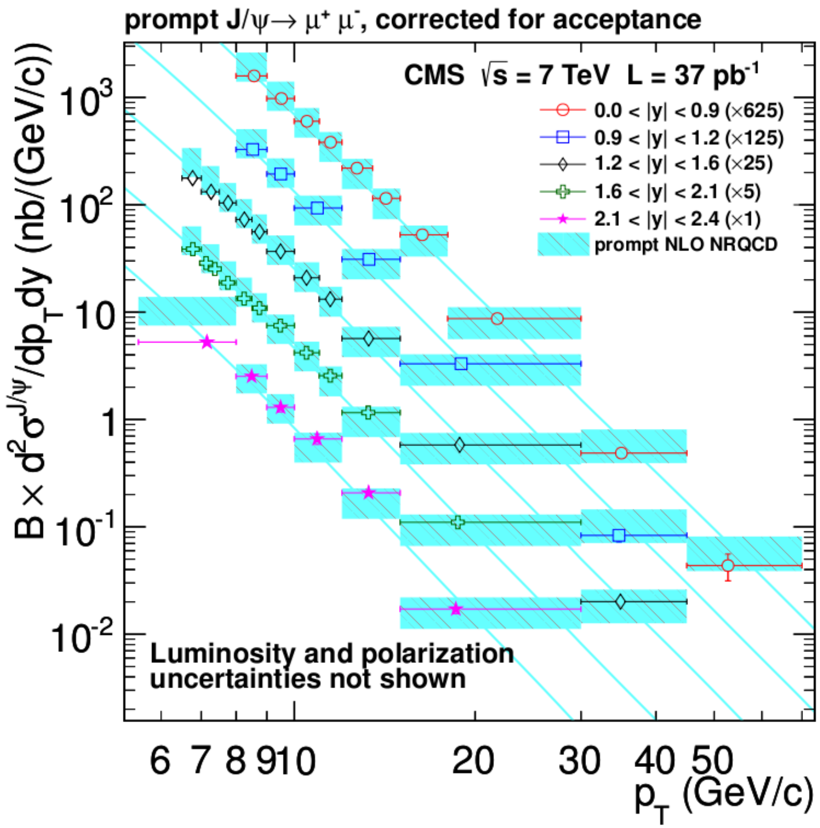
- Large fraction of Y(1S) come from excited states
  - ~50% feed-down from χ_b for p_T^Y > 8 GeV/c

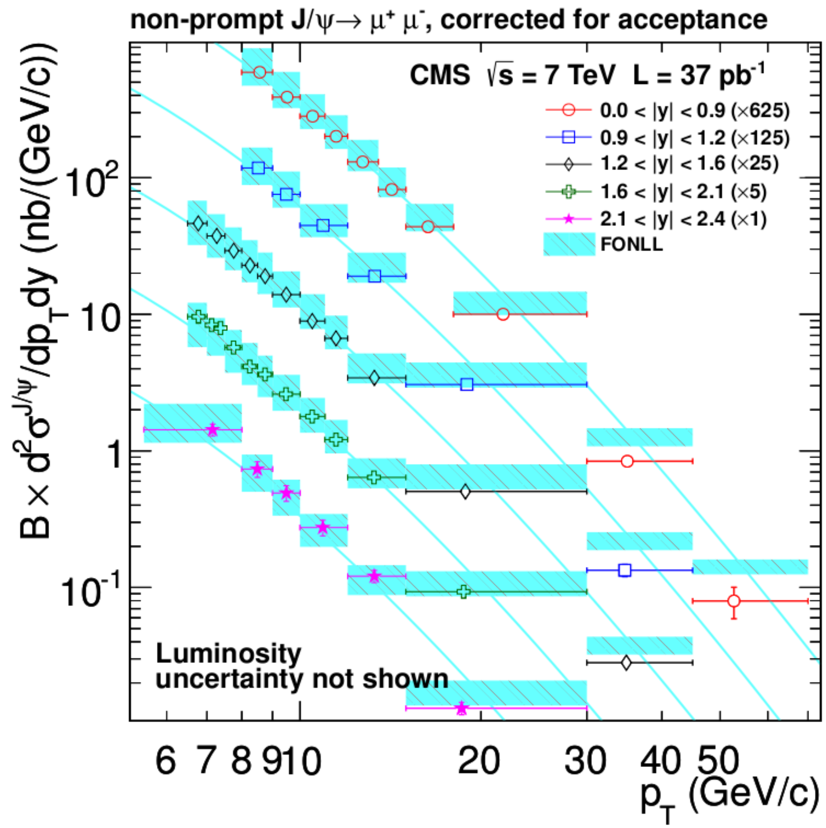
CDF: PRL84 (2000) 2094

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



J/ψ in pp at $\sqrt{s}$ = 7 TeV

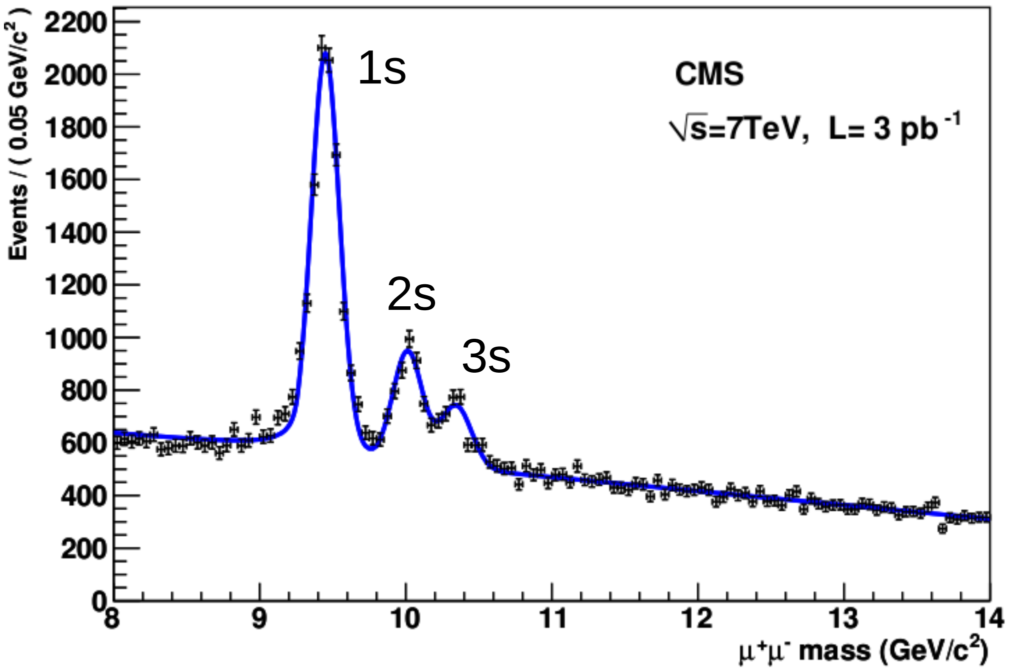


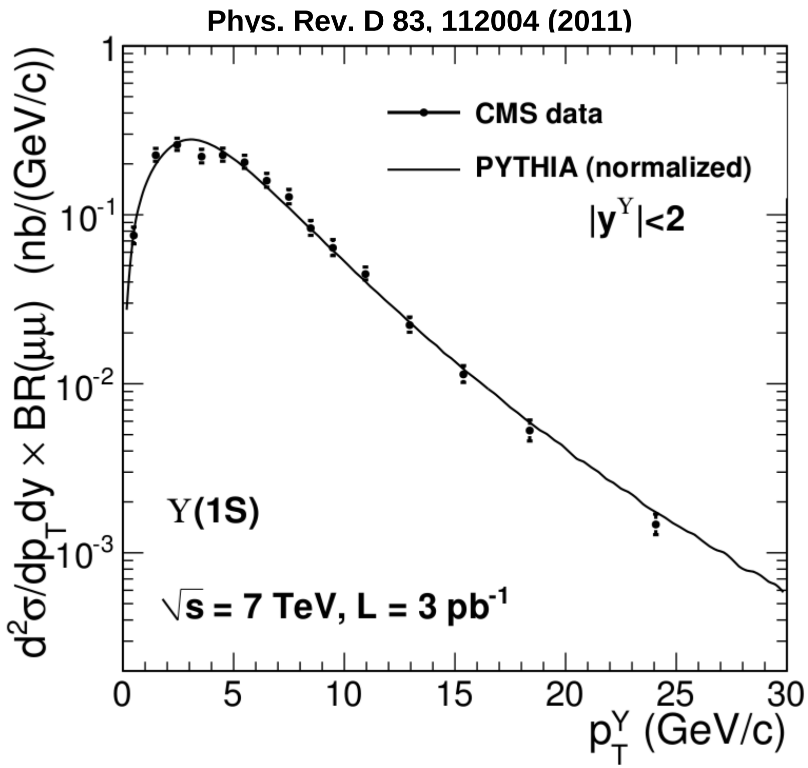


JHEP 02 (2012) 011

- Prompt J/ψ production well reproduced
  - NRQCD includes non-prompt production caused by feed-down decays from heavier charmonia
- Non-prompt J/ψ lie systematically below the FONLL predictions
  - Possibly because of the large uncertainty on the B→ψ(2S)X branching ratio

Υ in pp at $\sqrt{s}$ = 7 TeV





- Separation of the 3 Υ states with good mass resolution
- Pythia (LO/CSM+COM) agrees in shape, not in normalization
  - Overestimated by about a factor 2