Quarkonia and Vector Boson production in CMS

Mihee Jo
Korea University

for the CMS collaboration

Outline

- Quarkonia
  - Introduction
  - J/ψ and ϒ production at pp $\sqrt{s}$ = 7 TeV
  - J/ψ and ϒ production at PbPb $\sqrt{s_{NN}}$ = 2.76 TeV

- Vector Boson
  - Introduction
  - Z production at pp $\sqrt{s}$ = 7 TeV
  - $Z \rightarrow \mu^+\mu^-$ production at PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
  - $W^{\pm}$ and $Z \rightarrow e^+e^-$ production

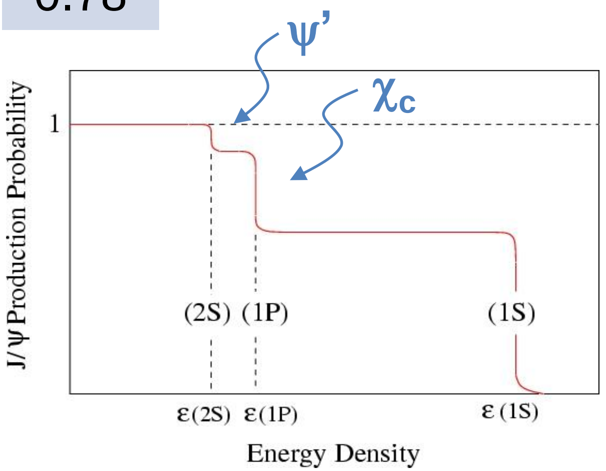
Quarkonia production

Quarkonia in heavy ion collisions

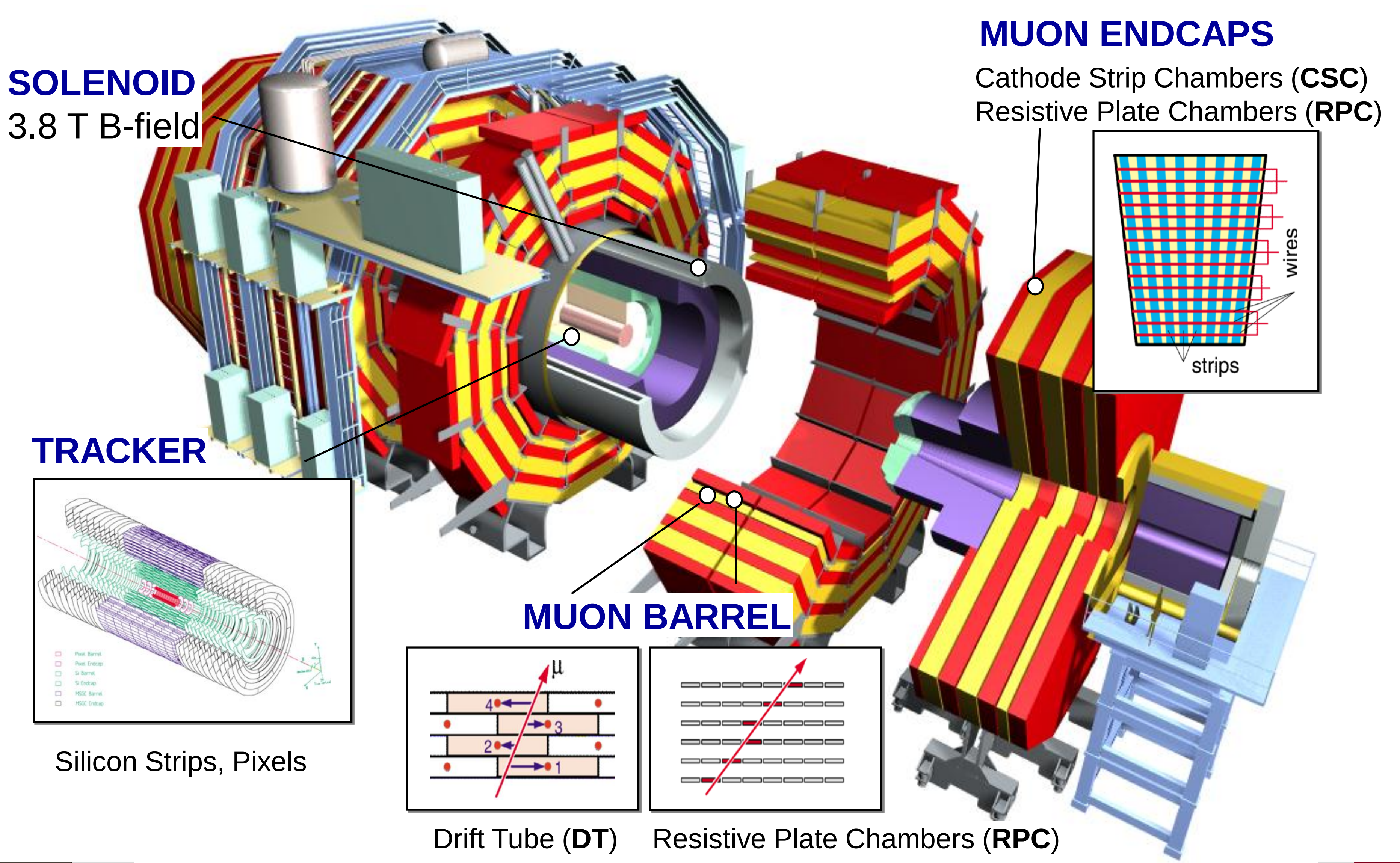
- Good candidates to probe the QGP in heavy ion collisions
  - Large masses and dominantly produced at the early stage of the collision by hard-scattering of gluons
  - Characterized by its binding energy and radius

	J/ψ	χ_c	ψ (2s)	ϒ (1s)	ϒ (2s)	ϒ (3s)
M (GeV/c^2)	3.10	3.53	3.69	9.46	10.0	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.54	0.20
r_0 (fm)	0.25	0.36	0.45	0.28	0.56	0.78

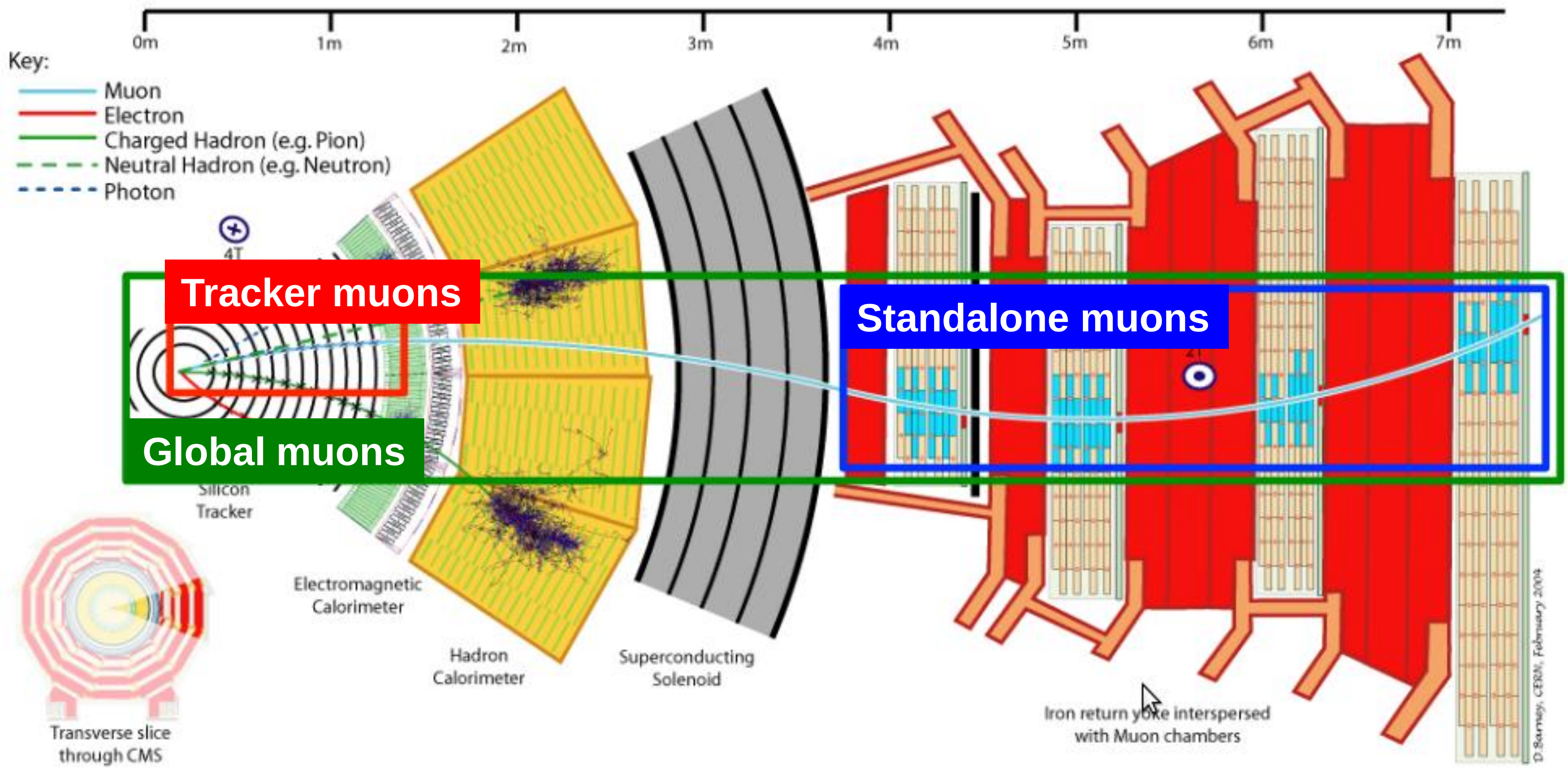
  - Debye screening radius decreases with increasing temperature → sequential melting
  - Thermometer for the temperature reaches in the HI collisions



Compact Muon Solenoid

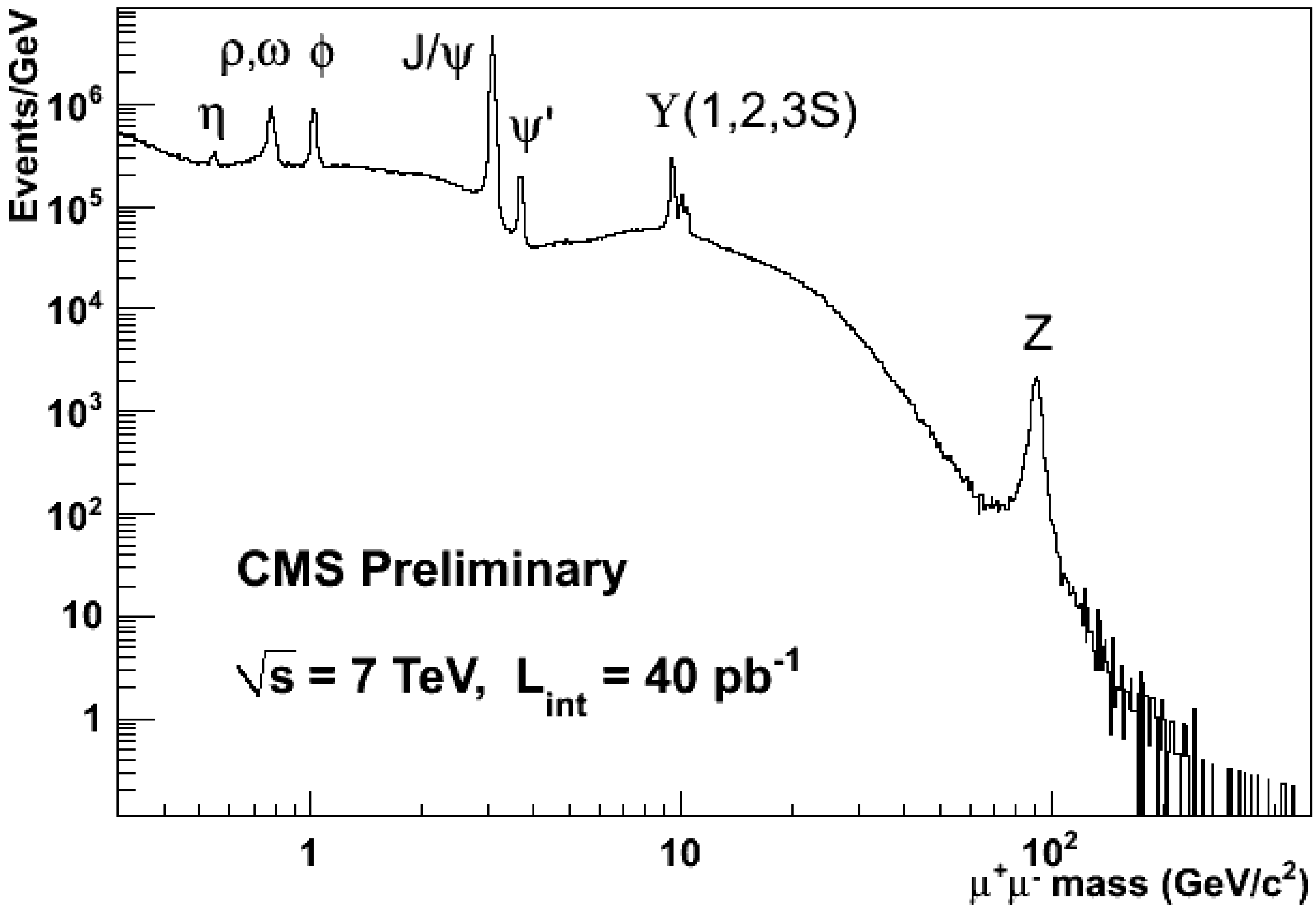


Muon reconstruction in CMS

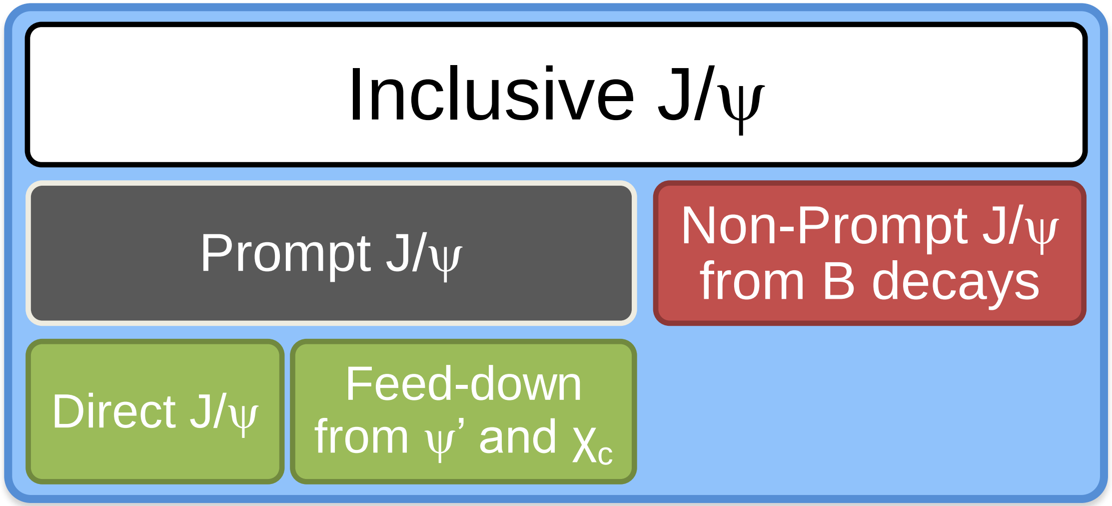


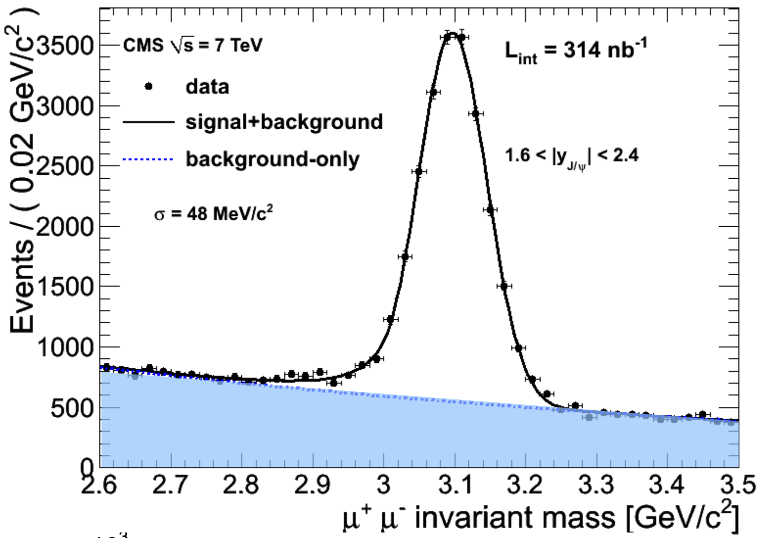
- Great muon identification & triggering (Muon system)
- High mass/momentum resolution (Tracker)

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



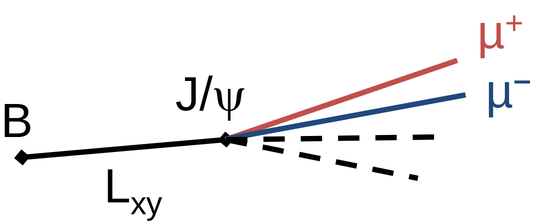
J/ψ in pp at $\sqrt{s}$ = 7 TeV

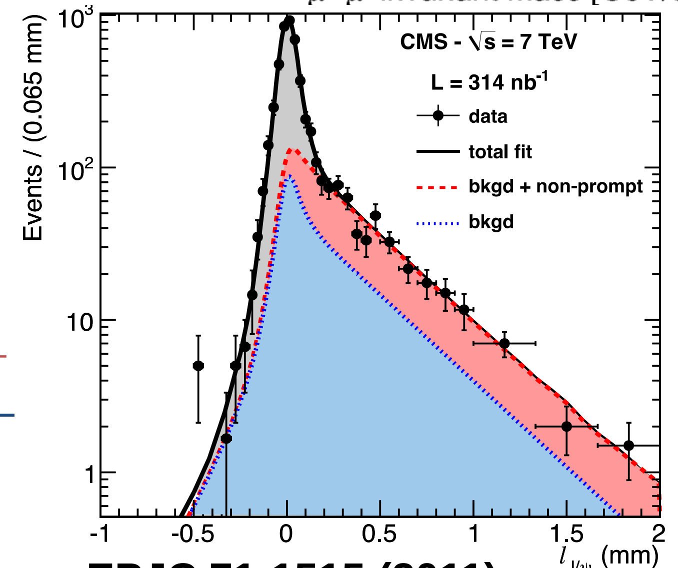




- Reconstruct $\mu^+\mu^-$ vertex
- Simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length

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

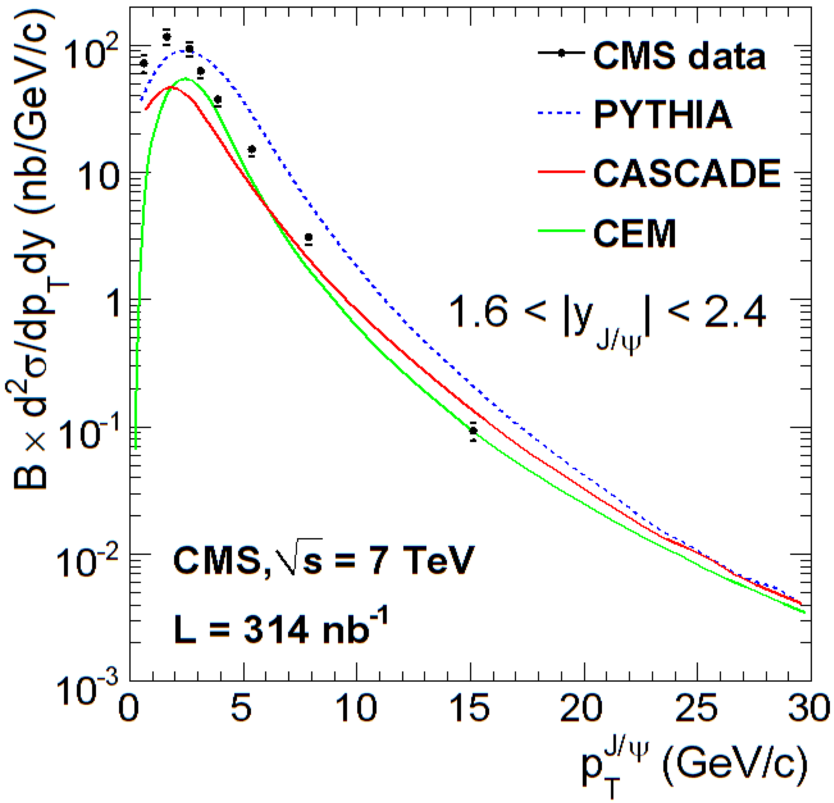




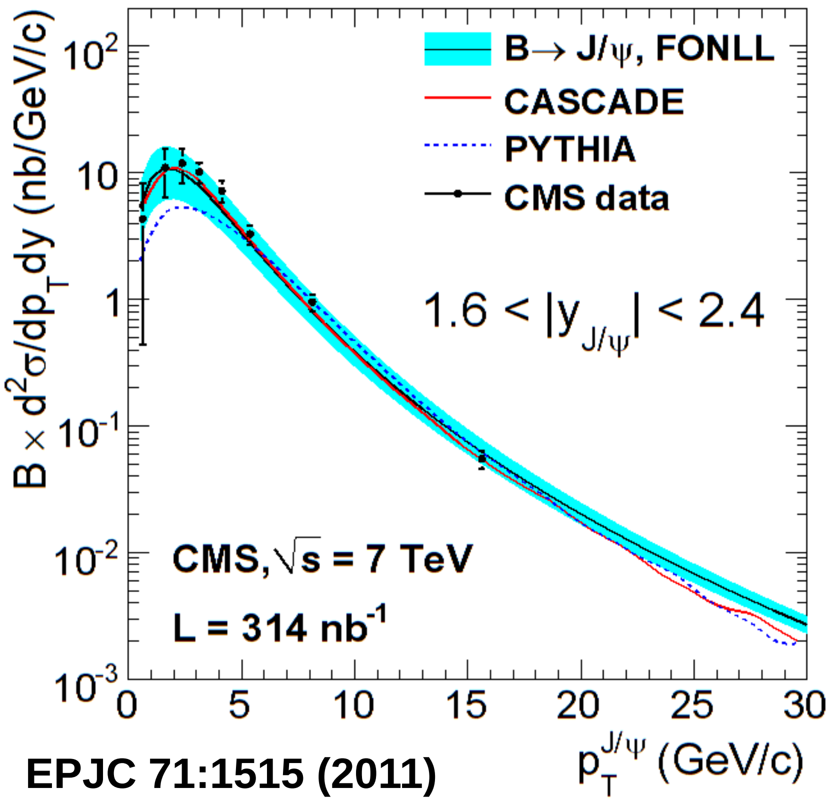
EPJC 71:1515 (2011)

J/ψ in pp at $\sqrt{s}$ = 7 TeV

PROMPT



NON PROMPT

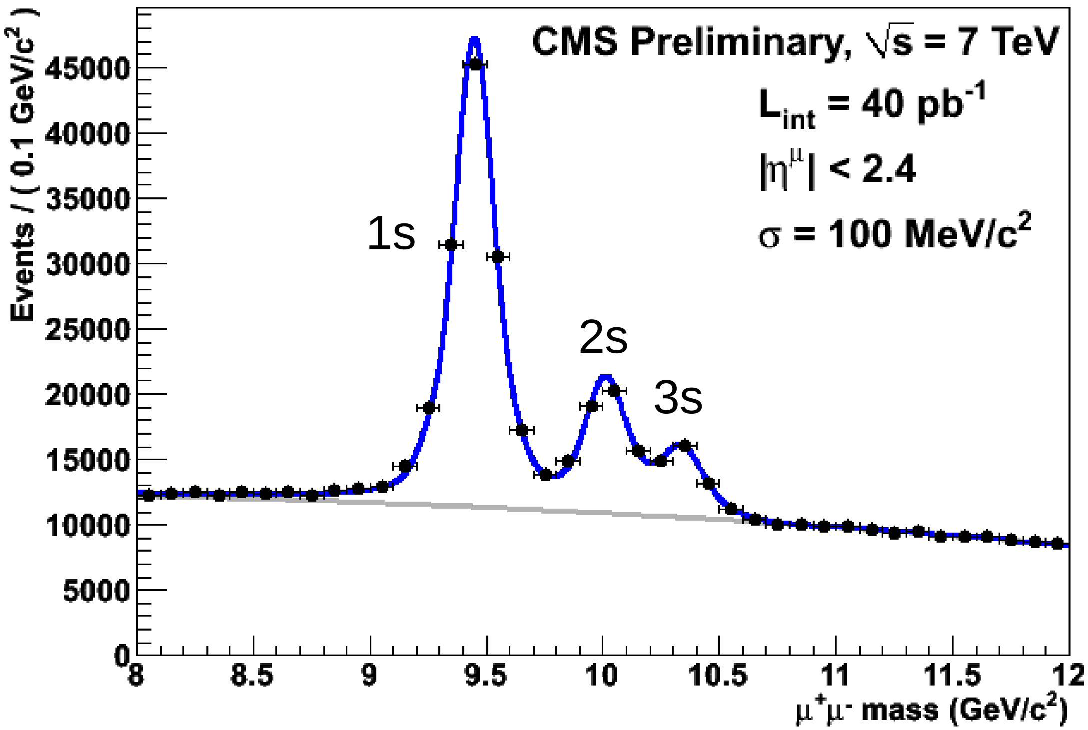


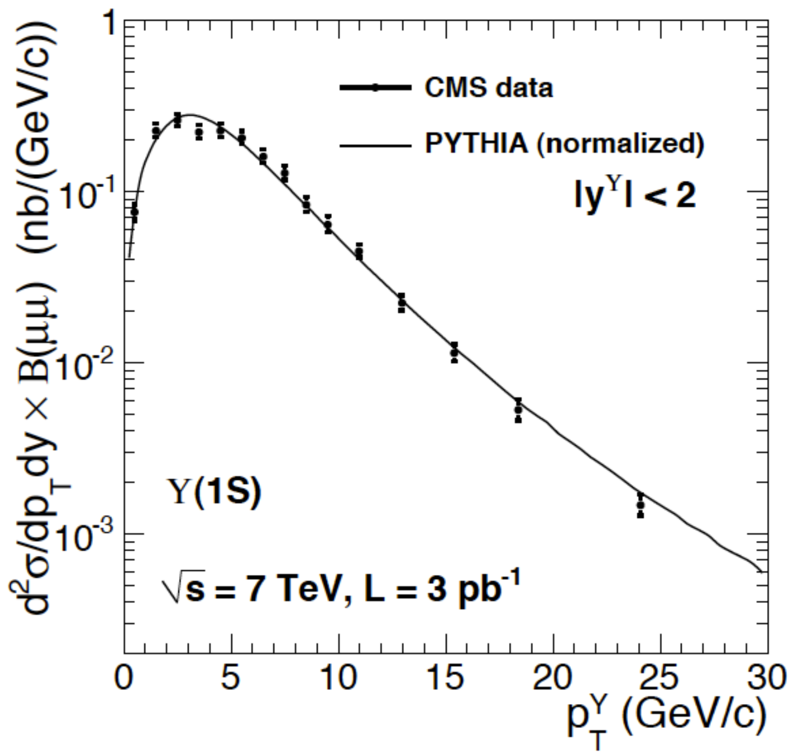
EPJC 71:1515 (2011)

- Prompt J/ψ production not well reproduced
- Models describe non-prompt J/ψ production better

Υ in pp at $\sqrt{s}$ = 7 TeV

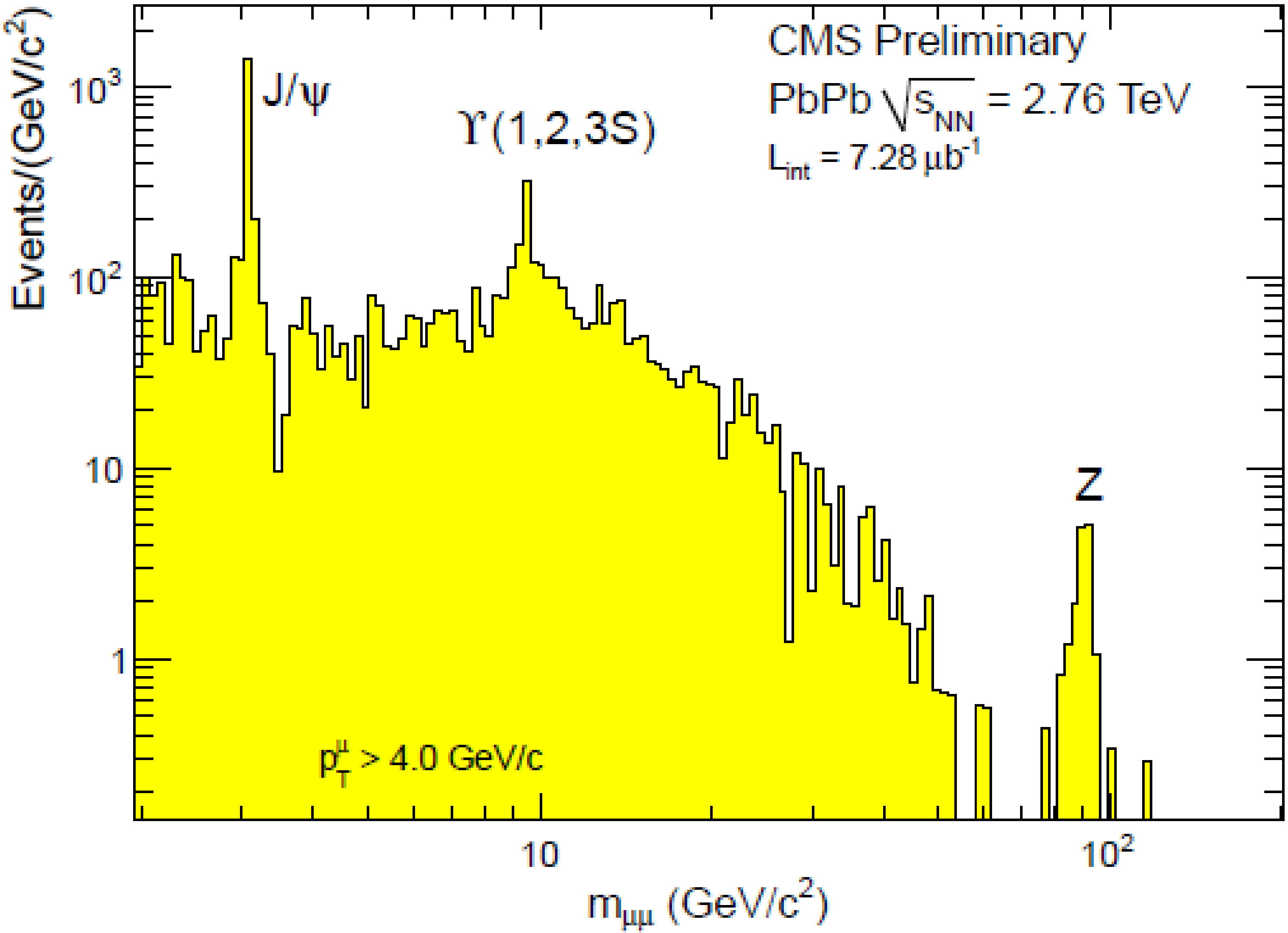
arXiv : 1012.5545





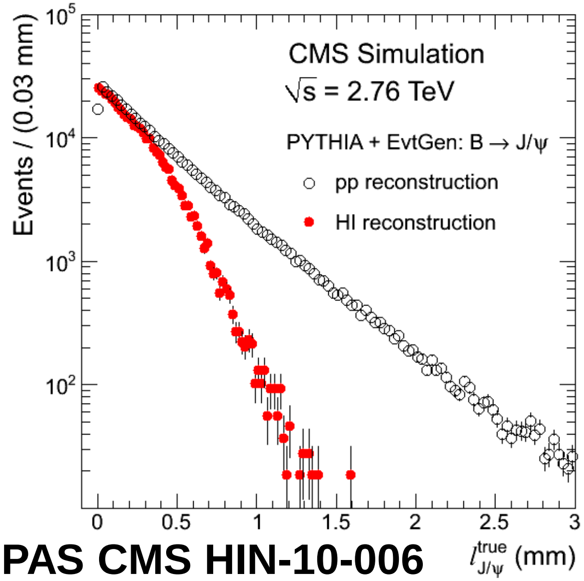
- Separation of the 3 Υ states with good mass resolution
- Pythia (LO/CSM+COM) agrees in shape, not in normalization
  - Overestimated by about a factor 2

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

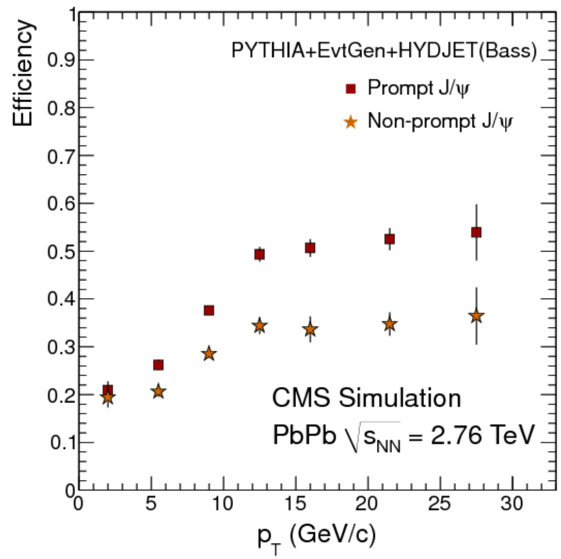


J/ψ in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

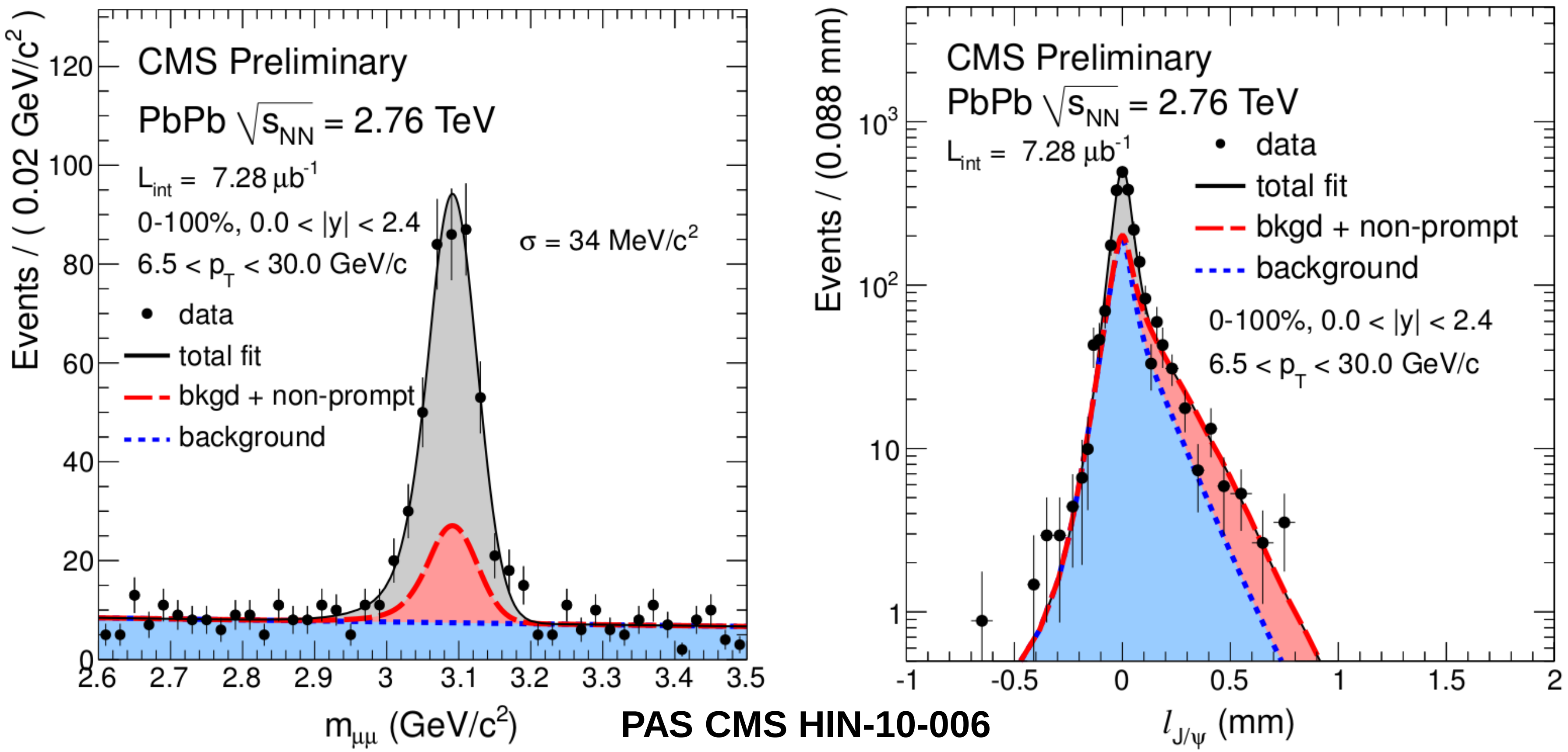
- Separate prompt & non-prompt J/ψ
- HI tracking algorithm uses vertex constraint
  - Smaller efficiency for non-prompt than for prompt J/ψ
  - Effect increases with p_T
- Efficiencies from Monte Carlo
  - Simulate signal with PYTHIA
  - Embed signal in min-bias event simulated with HYDJET
  - Validated MC by comparing efficiencies measured with “Tag & Probe” in MC and data



PAS CMS HIN-10-006



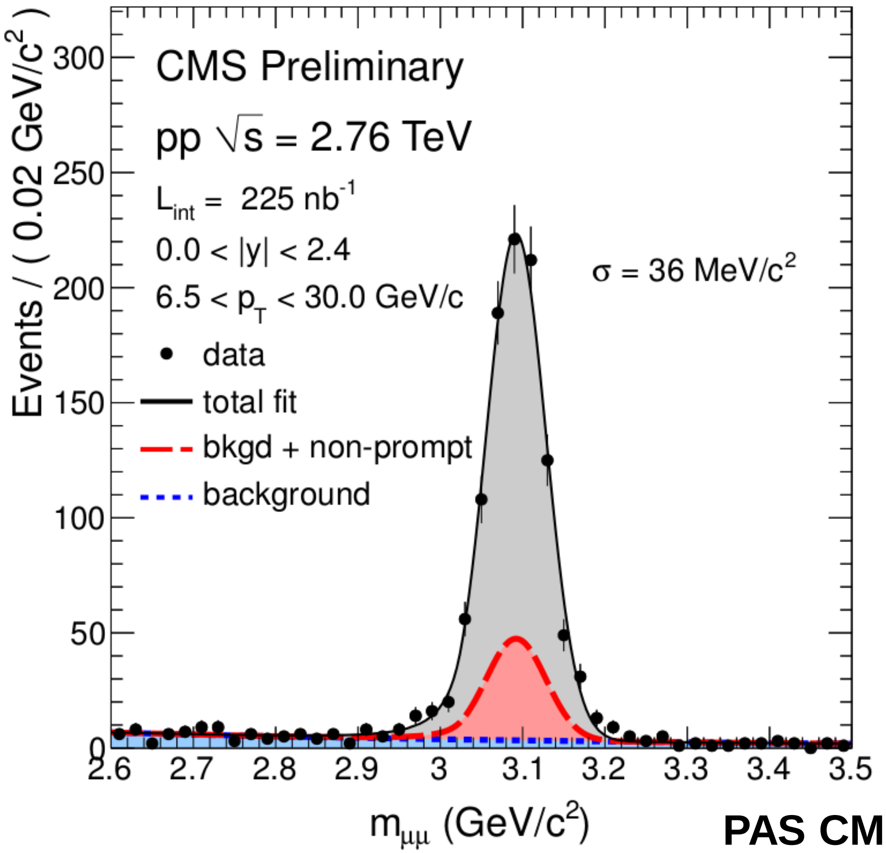
Prompt vs. non-prompt J/ψ in PbPb

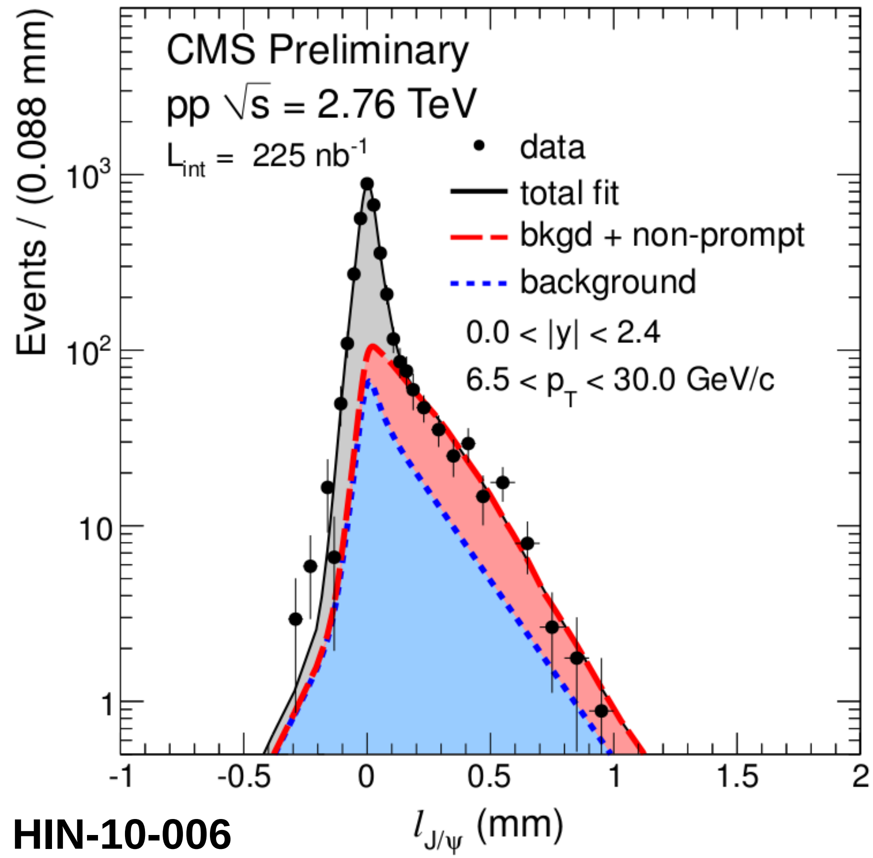


PAS CMS HIN-10-006

First time that prompt and non-prompt J/ψ have been separated in heavy ion collisions !

Reference: J/ψ in pp at $\sqrt{s}$ = 2.76 TeV



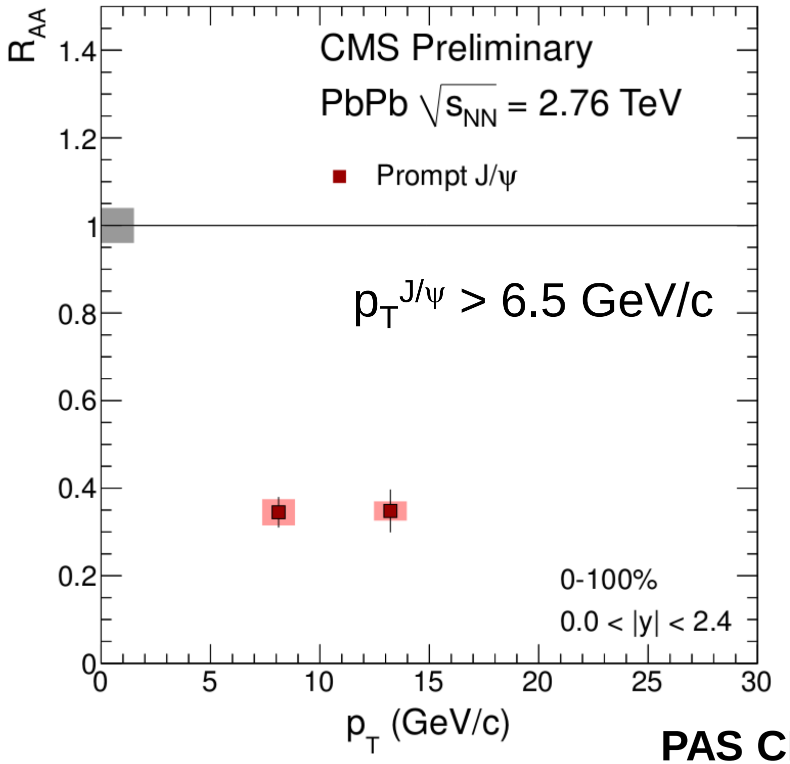


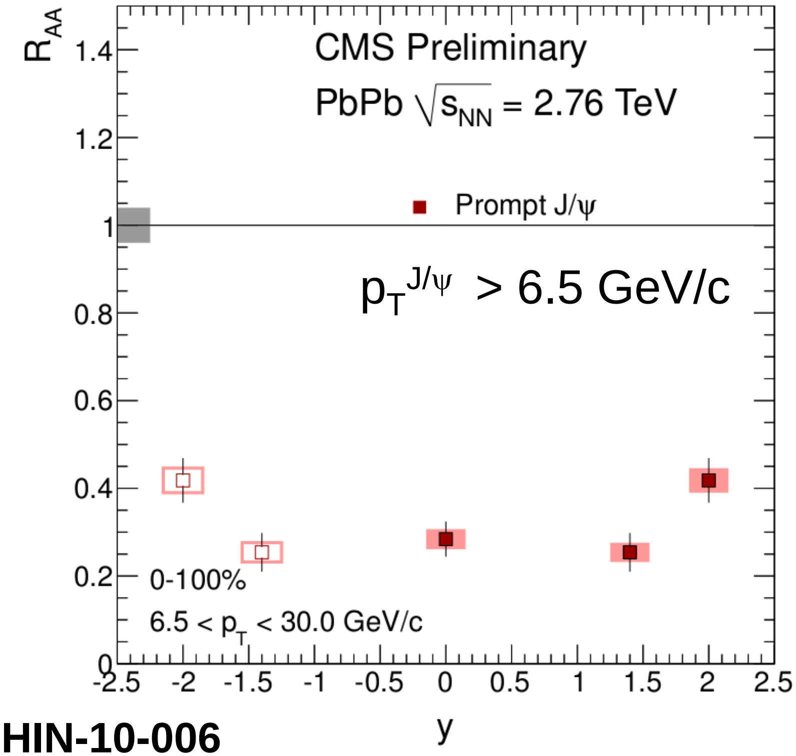
PAS CMS HIN-10-006

- 1 week long run at $\sqrt{s} = 2.76\,TeV$ in March 2011
- pp data reconstructed with heavy ion algorithm
- Identical cuts used as in heavy ion analysis

Prompt J/ψ R_{AA} vs. p_T and y

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

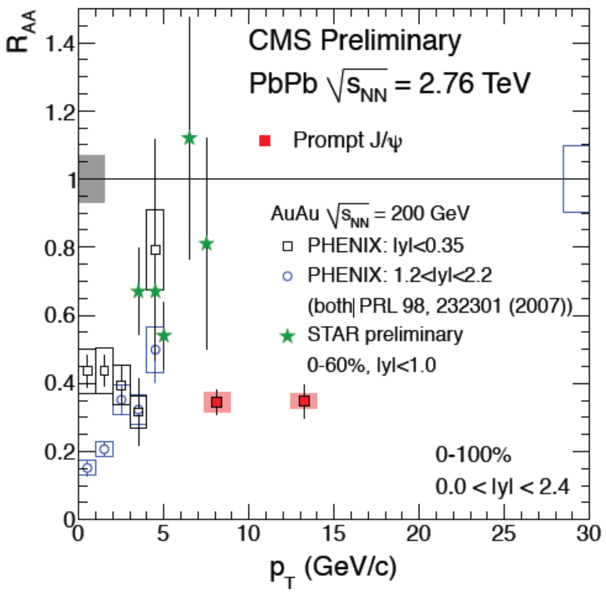


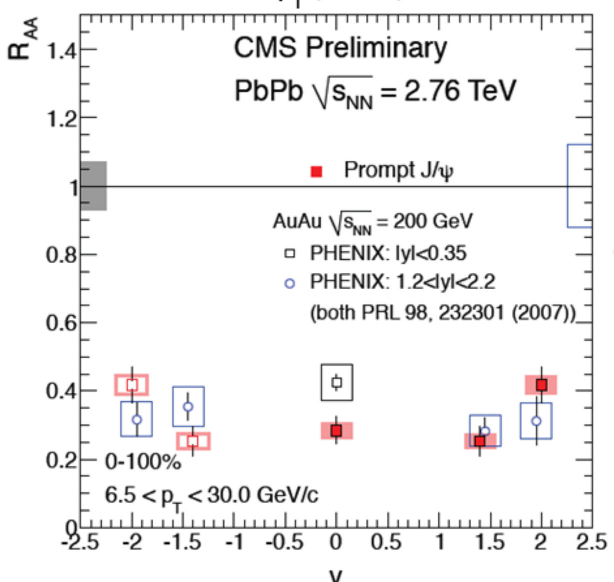


PAS CMS HIN-10-006

- Factor 3 suppression for p_T > 6.5 GeV/c and at y = 0
- Trend to less suppression at forward rapidity

Prompt J/ψ R_{AA} vs. p_T and y : Comparison





- **CMS** $p_T^{J/\psi}$ > 6.5 GeV/c
- **STAR** $p_T^{J/\psi}$ < 8 GeV/c
- **PHENIX** lower p_T

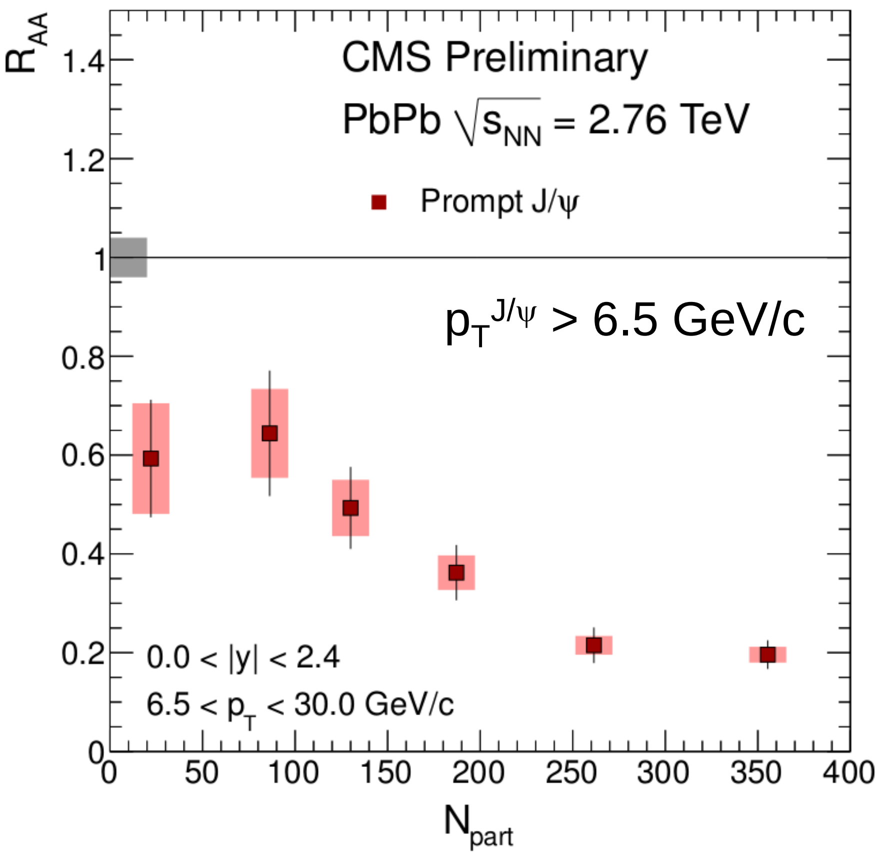
- High p_T J/ψ's tendency to survive at RHIC (and SPS) is not seen at the LHC
- CMS shows opposite trend than PHENIX but different p_T
- Increasing R_{AA} going towards ALICE y range
  - Watch out for anti-shadowing

CMS p_T > 3 GeV/c
R_{AA} = 0.39±0.06±0.03
p_T=10 up to x_1~0.02(x_2~5.10^{-4})

ALICE low $p_T^{J/\psi}$
R_{AA} = 0.49±0.03±0.11
p_T=0 up to x_1~0.06(x_2~2.10^{-5})

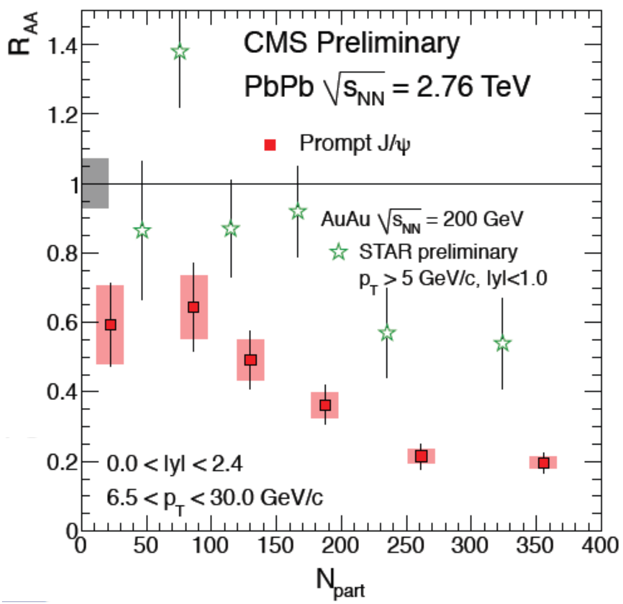
Prompt J/ψ R_{AA} vs. N_{part}

PAS CMS HIN-10-006



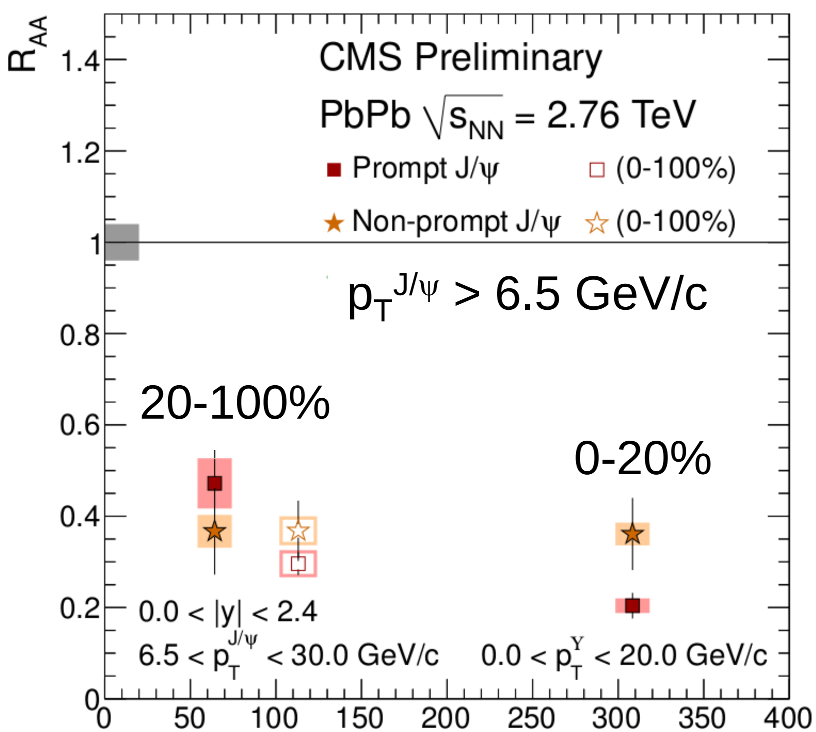
- 0-10% suppressed by factor 5
- 50-100% suppressed by factor ~1.6

- **CMS** $p_T^{J/\psi}$ > 6.5 GeV/c
- **STAR** 5 < $p_T^{J/\psi}$ < 8 GeV/c

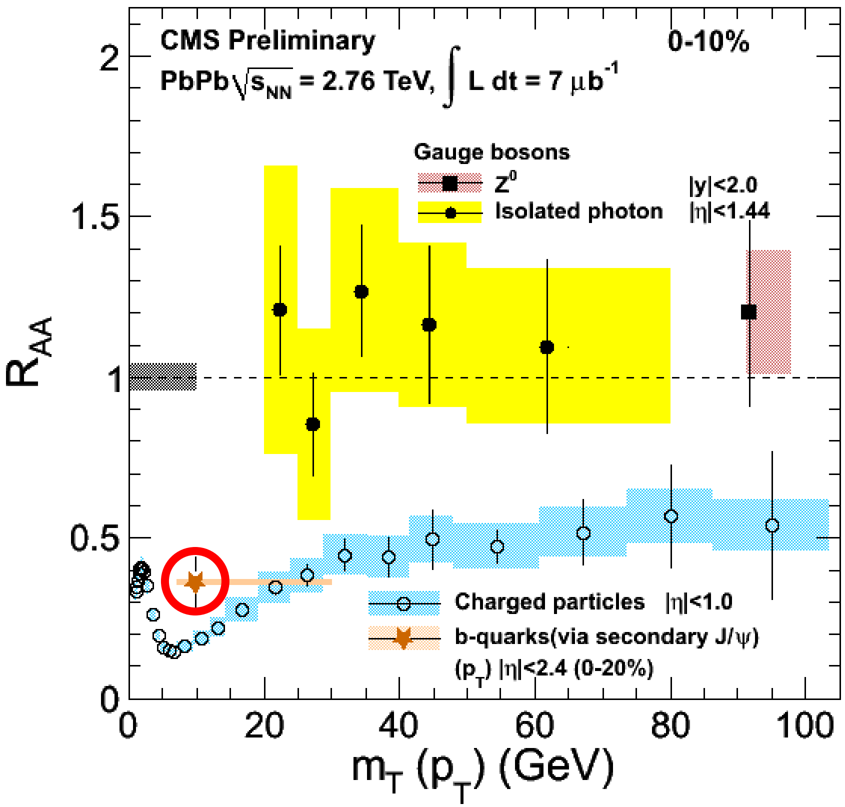


Stronger suppression seen in CMS than at STAR

Non-prompt J/ψ R_{AA}



PAS CMS HIN-10-006

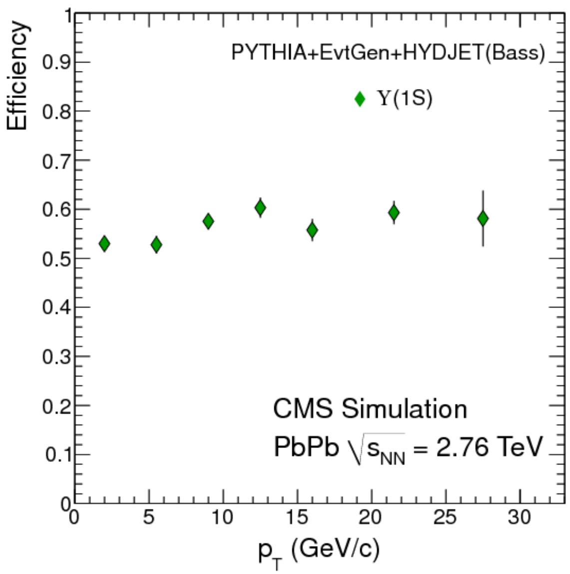


Suppression of non-prompt J/ψ observed in min-bias and central PbPb at $\sqrt{s_{NN}} = 2.76\,TeV$

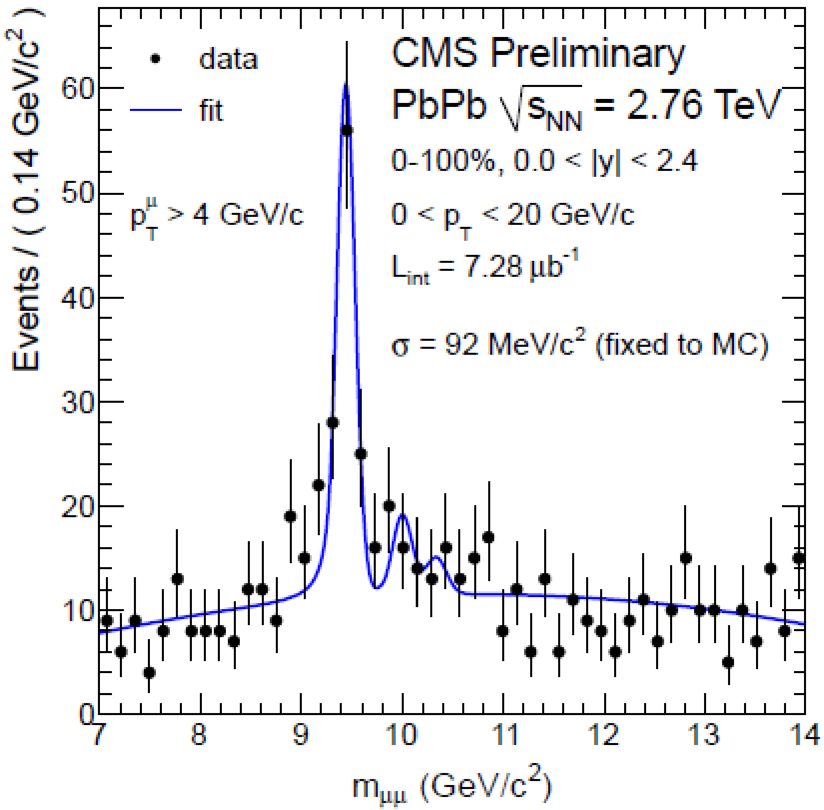
– First indications of high-p_T b-quark quenching !

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

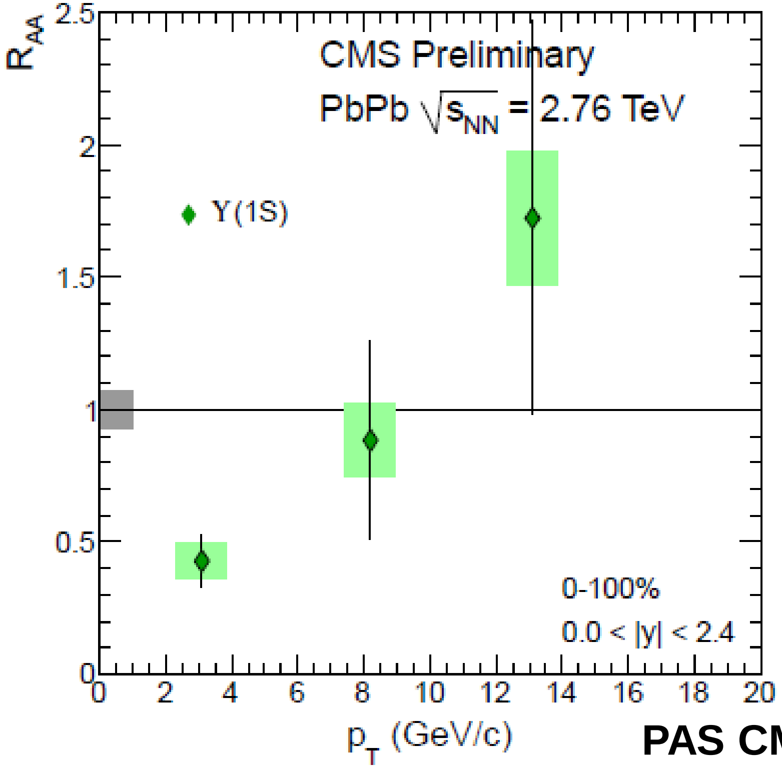
- Signal extraction
  - Resolution fixed from MC
  - Peak separation fixed to PDG
- Efficiencies from Monte Carlo
  - Same method and validation process as J/ψ



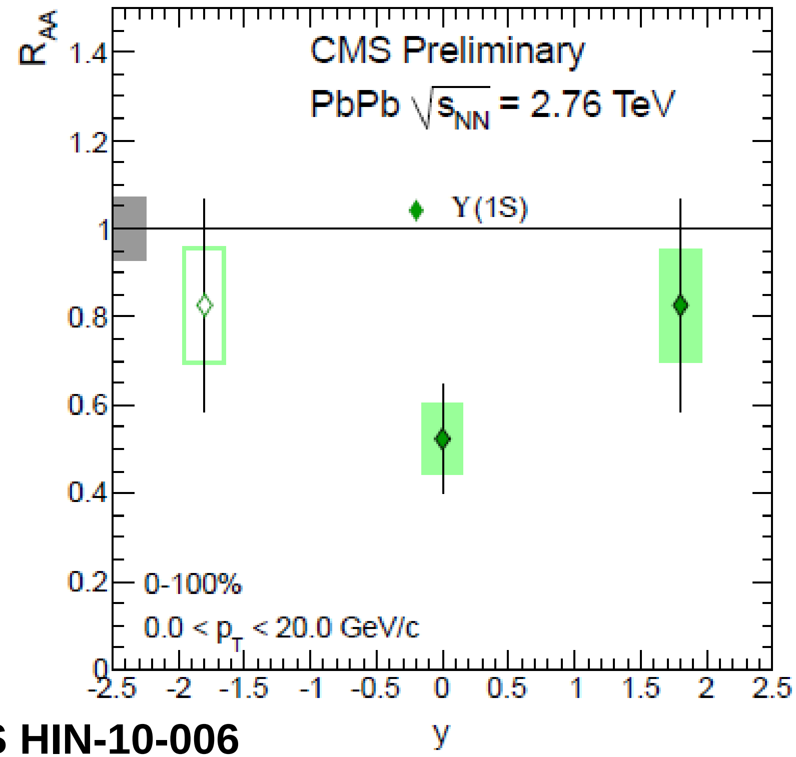
PAS CMS HIN-10-006



$\Upsilon(1S)$ R_{AA} vs. p_T and y



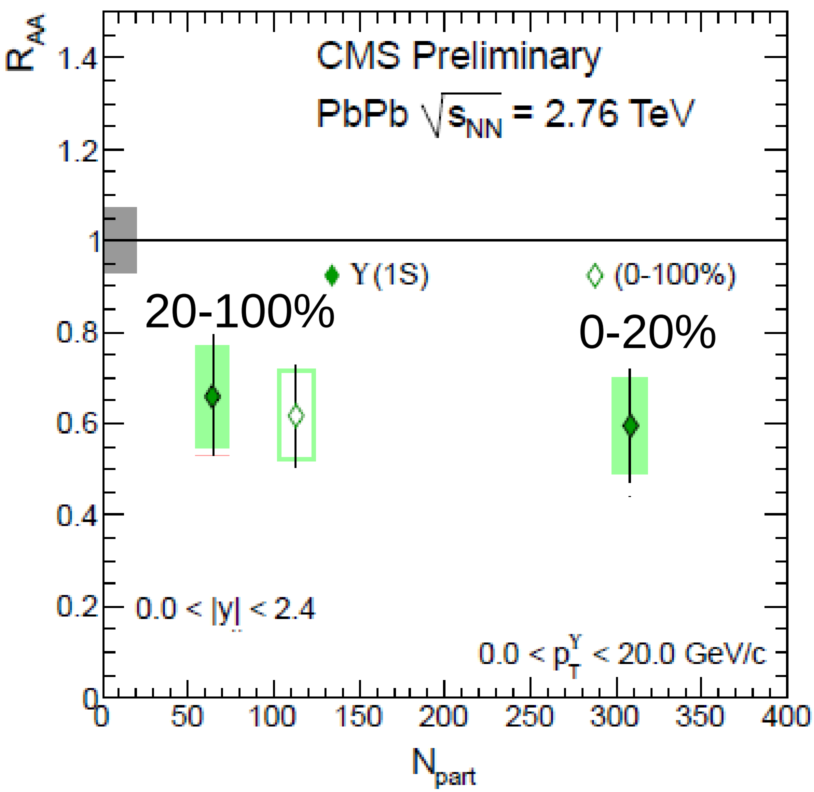
PAS CMS HIN-10-006

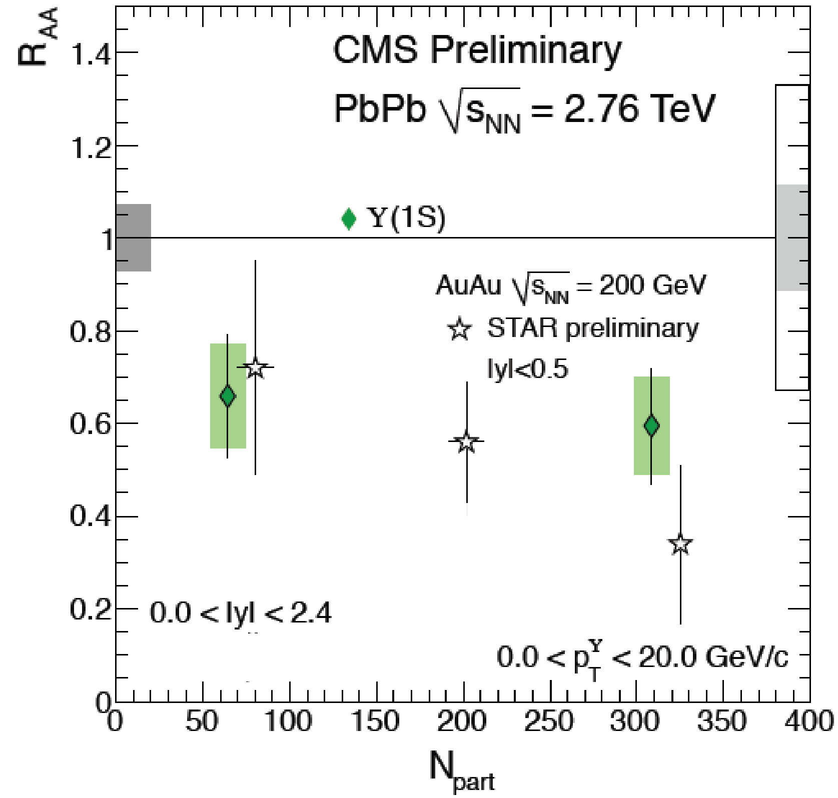


- Does high p_T not suppressed?
- No obvious y dependence
- Need more data next year

Υ(1S) R_{AA} vs. N_{part}

PAS CMS HIN-10-006





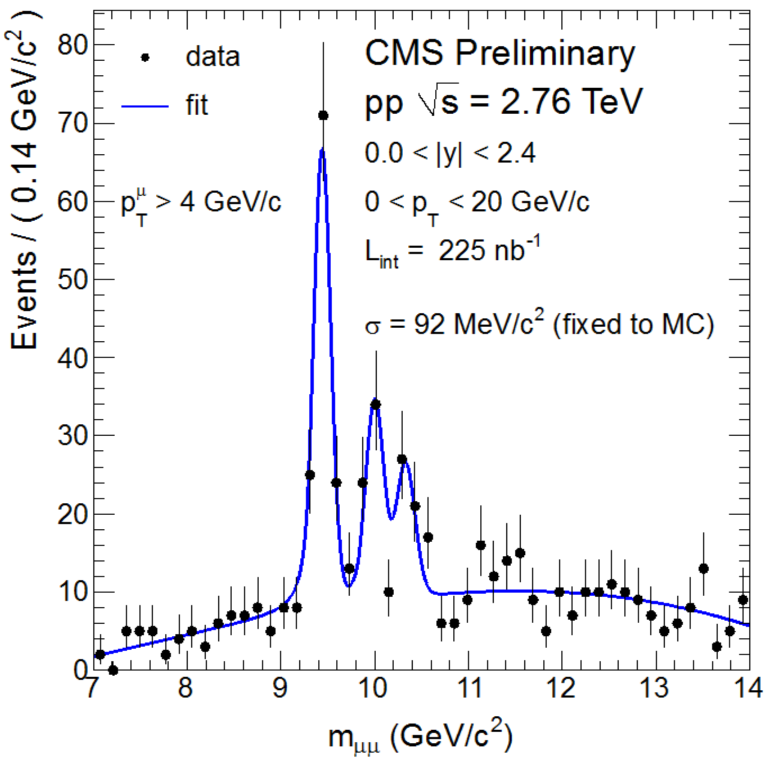
- STAR Υ(1S+2S+3S) but CMS Υ(1S)
- 0-20% suppressed by factor ~1.6

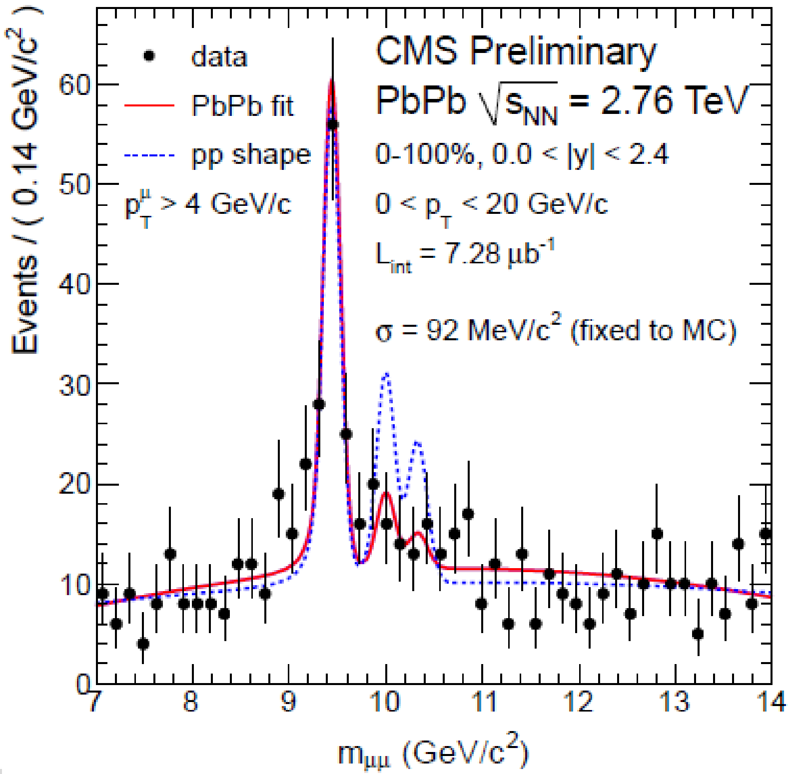
Υ(2S+3S) suppression

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

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

arXiv: 1105.4894
Submitted to PRL





Υ(2S+3S) suppression

arXiv: 1105.4894 ,Submitted to PRL

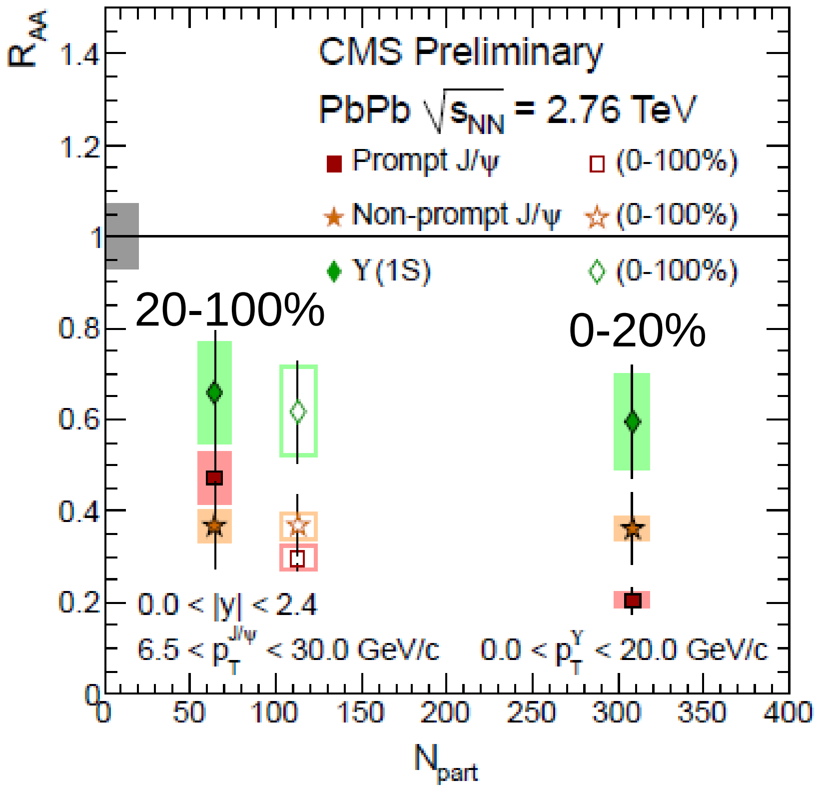
- Systematic uncertainty : 9.1%
- Statistical uncertainty : 55%
- Null hypothesis testing
  - p-value : 1%
  - Significance of suppression is 2.4σ

- Relative suppression of Υ(2S+3S) vs. Υ(1S)
  - Observation consistent with melting of the excited states only?
- What about cold nuclear matter effects?
  - Smaller σ_{abs} than at lower energy and for J/ψ **R. Vogt, arXiv : 1003.3497**
  - Shadowing cancelling in the Υ(2S+3S)/Υ(1S) ratio
    - pA run?

Quarkonia production summary

- Prompt J/ψ significantly suppressed
- First non-prompt J/ψ observation in heavy ion collision
  - b-quark energy loss
- ϒ(2S+3S) excited states suppressed
  - Consistent with ϒ(1S) suppression

arXiv: 1105.4894 ,Submitted to PRL
PAS CMS HIN-10-006



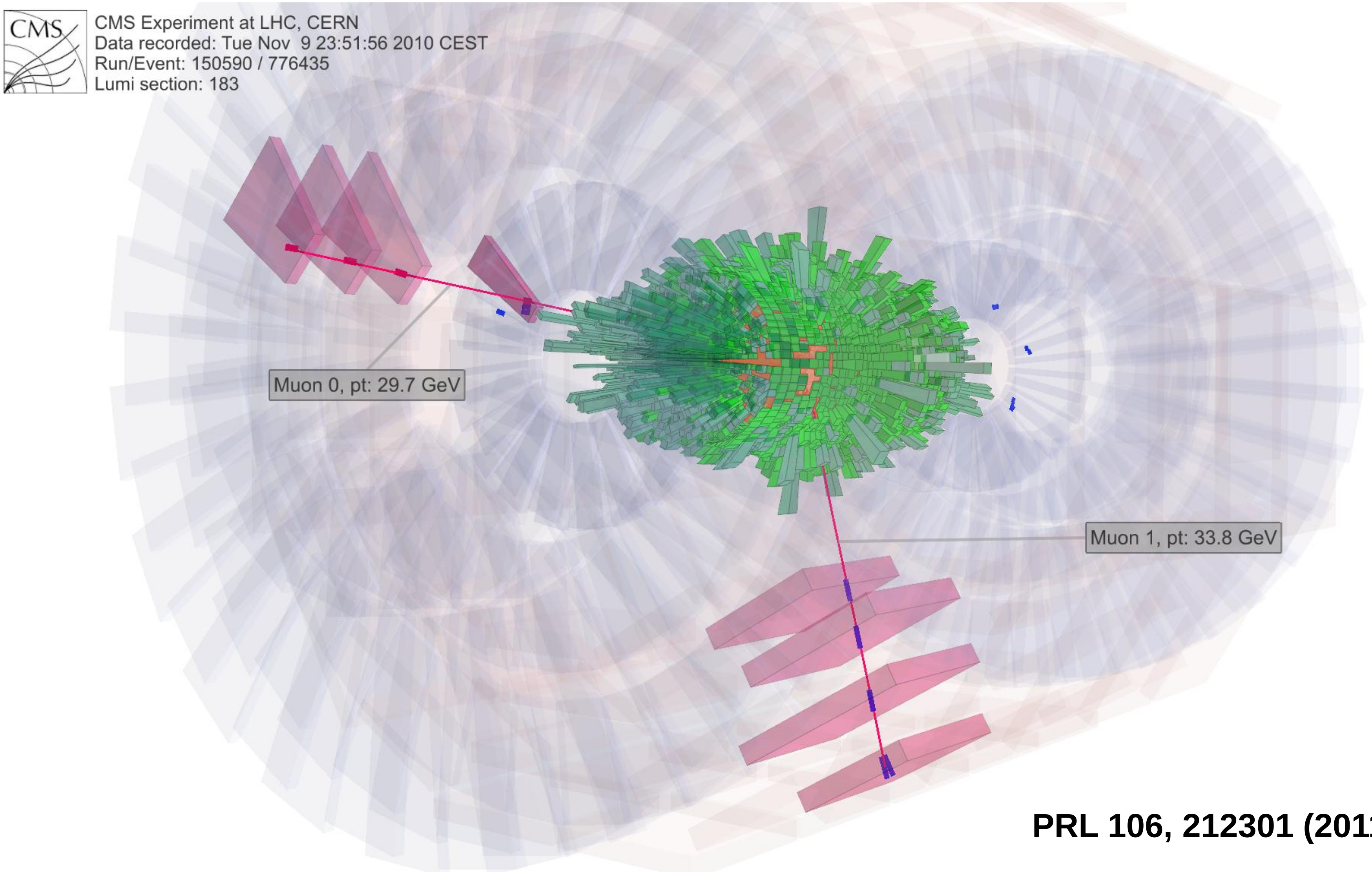
Sequential melting accessible with CMS resolution

Z, W boson production

Electro-weak probes in CMS

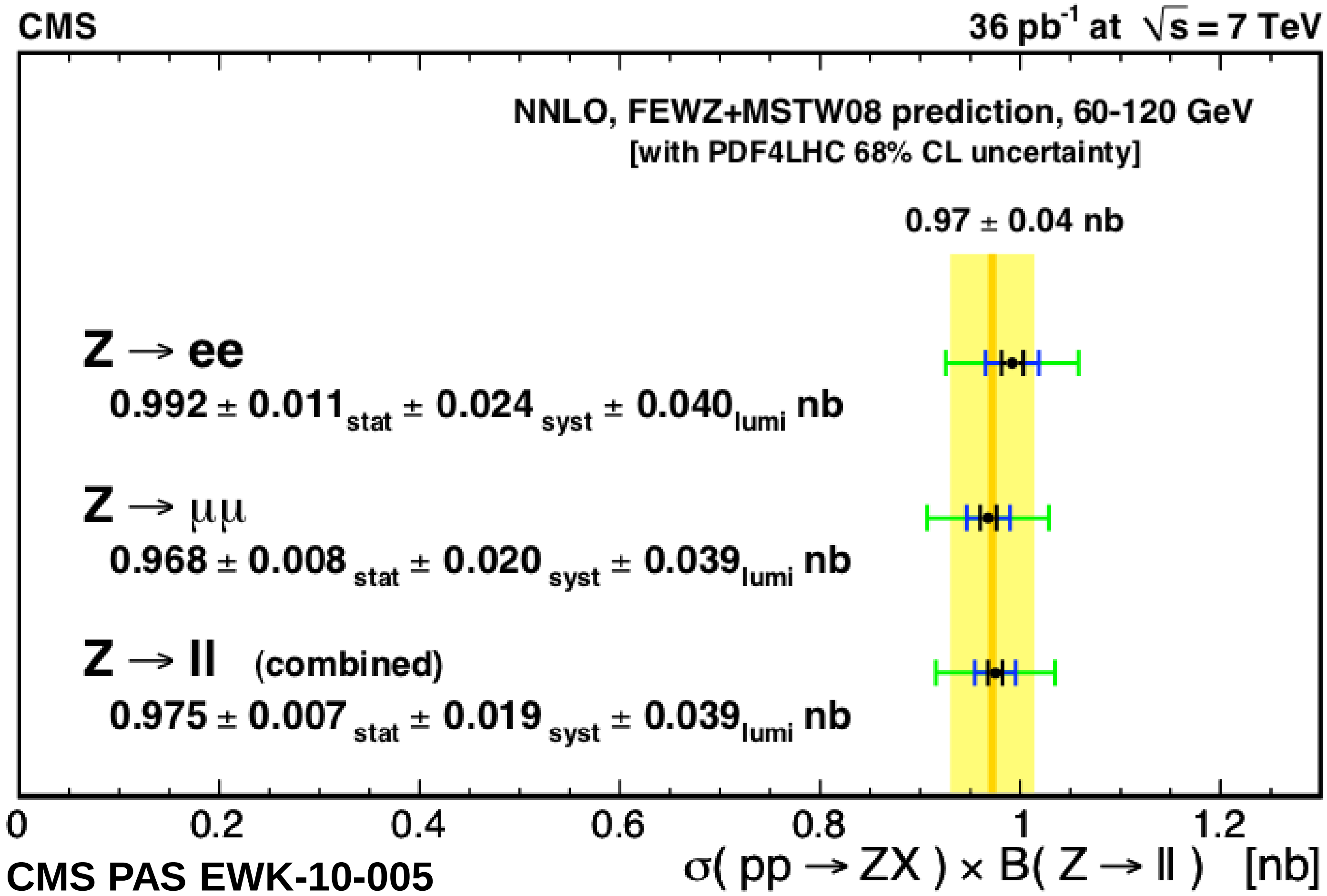
- Electro-weak probes accessible for the first time in heavy ion collisions
- Z and W bosons and leptons not affected by strongly interacting medium
- The Z to dilepton channel can be used as a standard candle
  - Precise measurement of Z production can help constrain cold nuclear effects
  - By exploiting the muon reconstruction capabilities of CMS the dimuon channel provides a clean measurement
- Z's can be used to calibrate parton traversing the medium via Z + jet events
  - Gives direct access to q^2 at tree-level

Z → $\mu^+\mu^-$ in CMS



PRL 106, 212301 (2011)

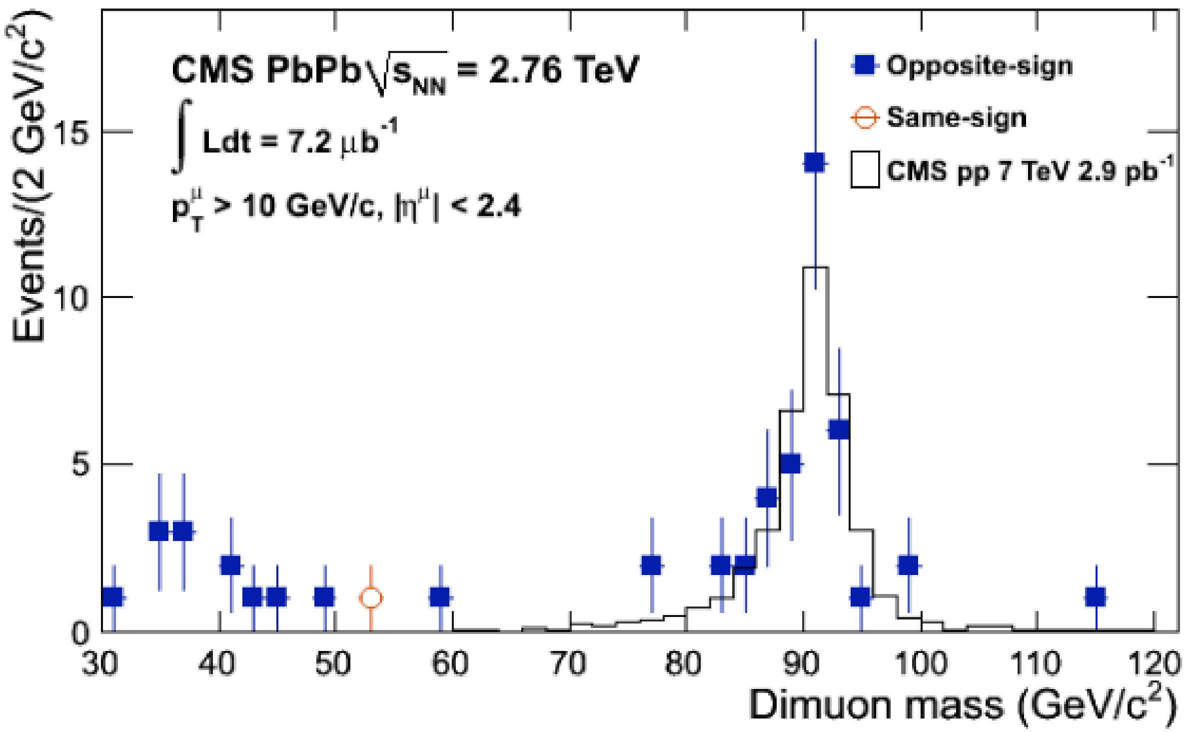
Z in pp at $\sqrt{s}$ = 7 TeV



Superb agreement of NNLO calculations with measurement of Z in dilepton channel

$Z \rightarrow \mu^+\mu^-$ in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

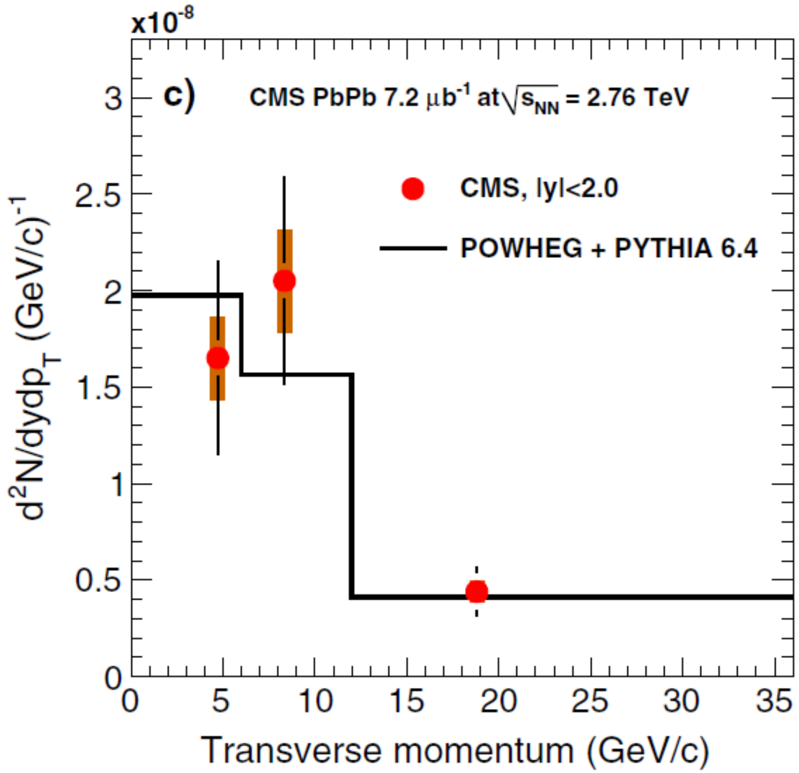
PRL 106, 212301 (2011)

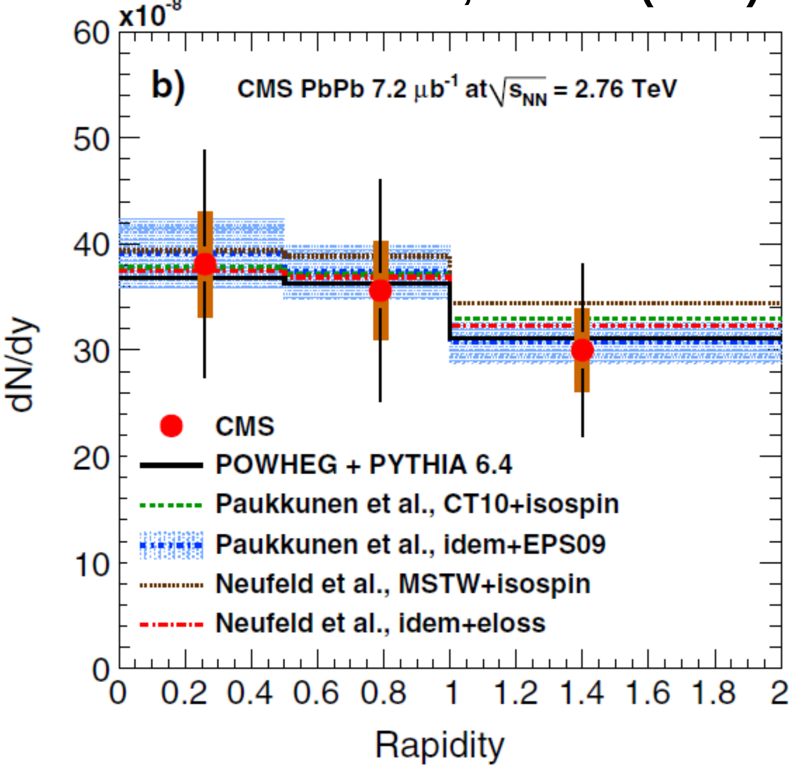


- The Z mass peak from PbPb : in agreement with pp data
- Very low background : only 1 like-sign pair

Z → $\mu^+\mu^-$ yield vs. p_T and y

PRL 106, 212301 (2011)





- Data and theoretical prediction agree within uncertainties
  - Theory curves scaled by nuclear geometry

$$T_{AB}(MinBias) = \frac{A^2}{\sigma_{PbPb}}$$

$Z \rightarrow \mu^+\mu^-$ normalized yield vs. N_{part}

- T_{AB} : Nuclear overlap function

  The number of elementary nucleon-nucleon binary collisions divided by the elementary NN cross section

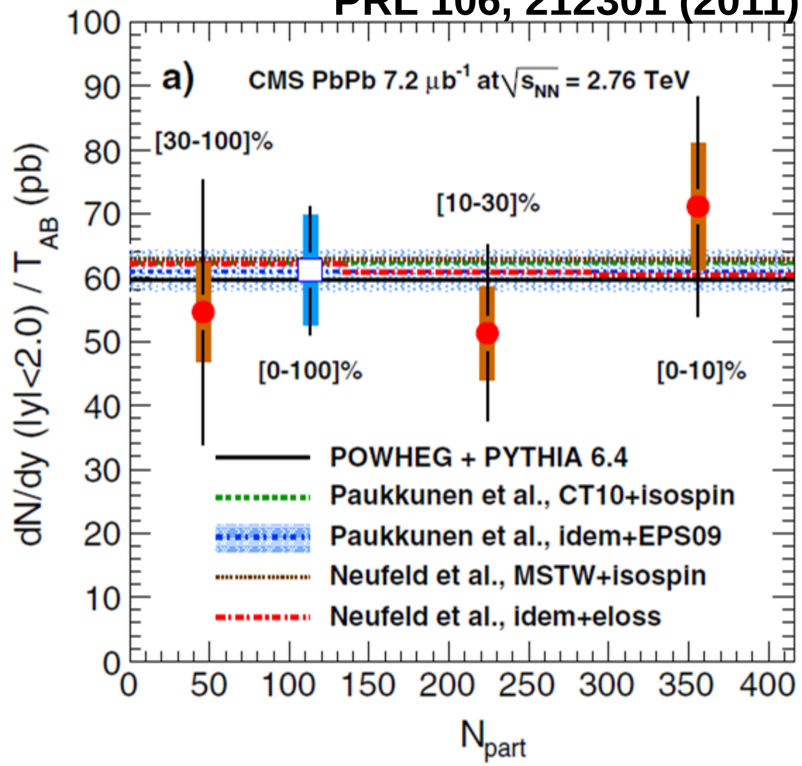
$$\frac{1}{T_{AB}}\frac{dN}{dy} = R_{AA}\frac{d\sigma_{pp}}{dy}$$

- Assuming $\frac{d\sigma_{pp}}{dy}$ = 59.6 pb (|y| <2)

$$R_{AA} = \frac{1}{T_{AB}}\frac{dN_{AA}}{\sigma_{pp}} = 1.00 \pm 0.16 \pm 0.14$$

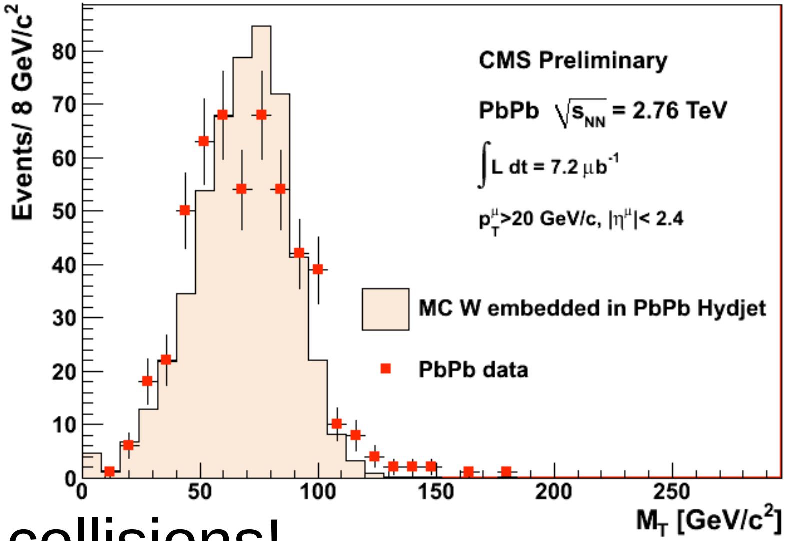
- Systematic uncertainty : 14%
- Statistical uncertainty : 16%
- Good agreement between NLO calculations and CMS results!

PRL 106, 212301 (2011)

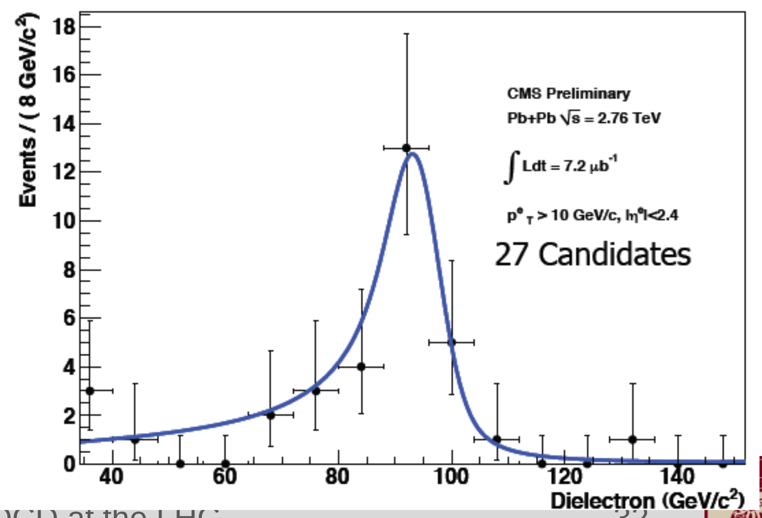


$W^{\pm} \rightarrow \mu^{\pm}\nu$ and $Z \rightarrow e^+e^-$

- First observation of W bosons in HI collisions!
- Signature for W candidates
  - High p_T isolated muon (> 20 GeV/c)
  - High p_T neutrino
- Missing transverse energy
  - Tracks p_T > 2 GeV/c



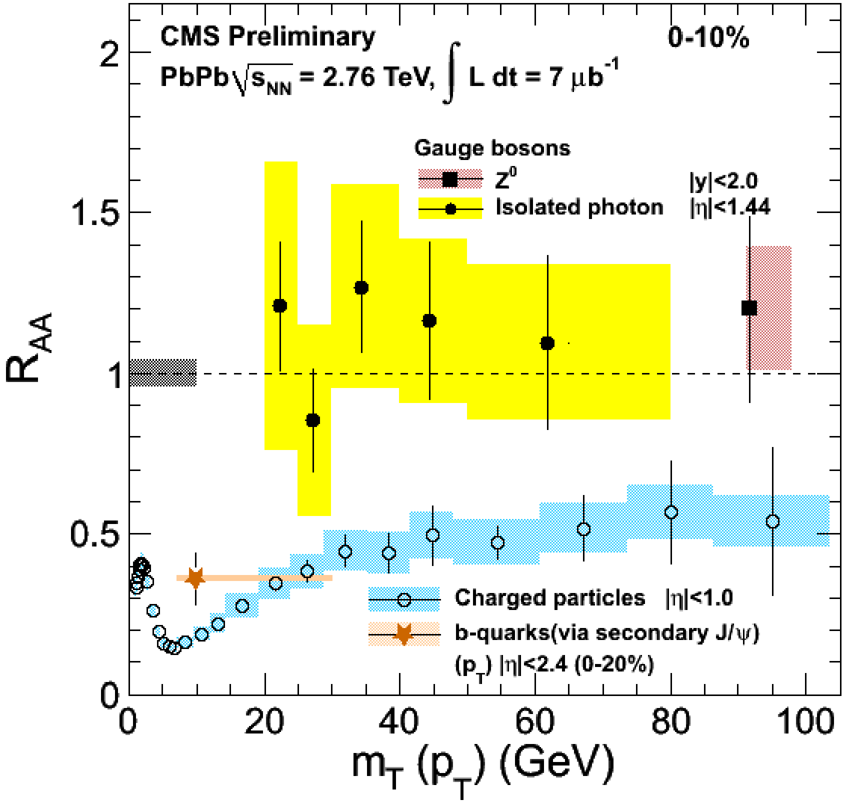
- First observation of $Z \rightarrow e^+e^-$ in HI collisions!
  - PbPb peak fitted with Breit-Weigner and exponential on one side



Electro-weak probes summary

- The Z boson has been observed in heavy ion collisions
  - **No modification**
  - The yield shows no centrality dependence

- Ongoing analysis
  - First observation of W bosons in heavy ion collisions
  - First observation of $Z \rightarrow e^+e^-$ in heavy ion collisions



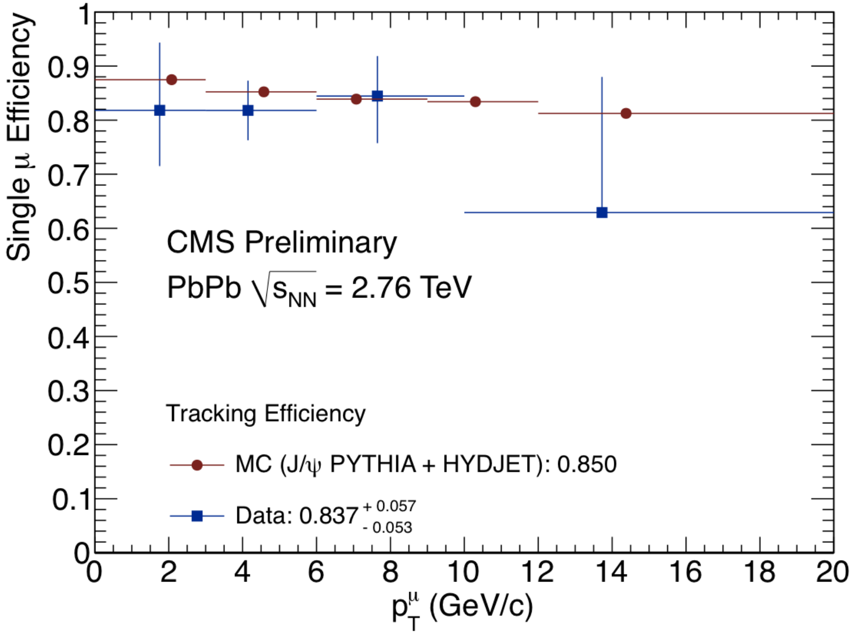
Back up

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

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/psi 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

Separating non-prompt J/ψ

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

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

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

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

$$F_B\left(l_{J/\psi}\right) = R\left(l'_{J/\psi} - l_{J/\psi}\right) \otimes \mathrm{X}_{MC}(l'_{J/\psi})$$

Resolution function $R\left(l_{J/\psi}\right)$: sum of 4 Gaussian

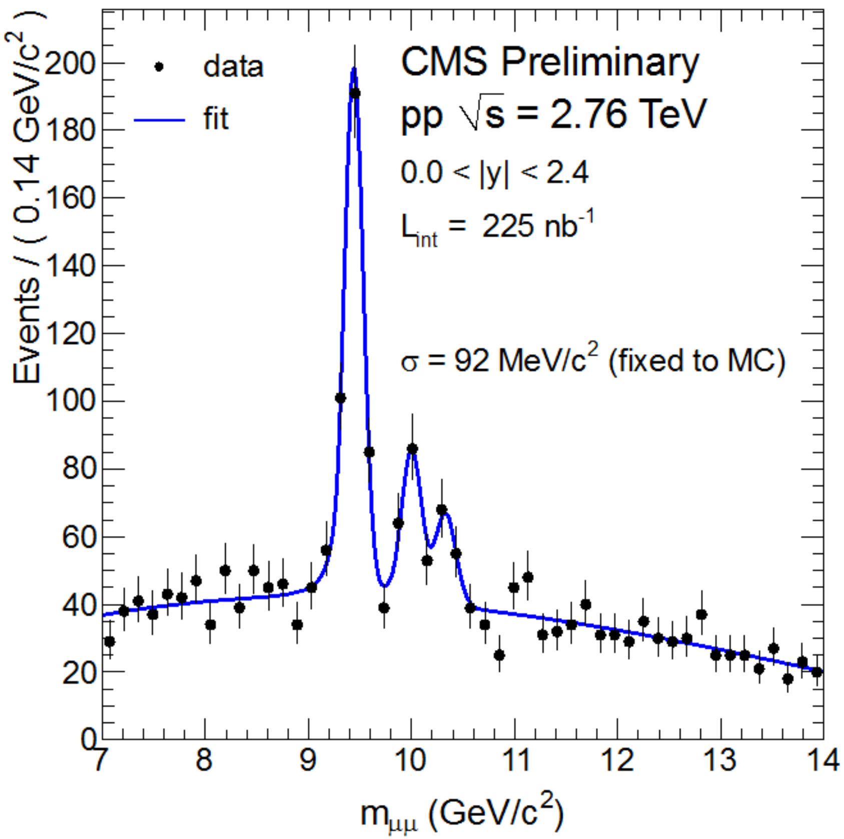
$F_{bkg}\left(l_{J/\psi}\right)$: sum of 3 decay function (for long-lived components) convoluted with $\mathrm{X}_{MC}(l_{J/\psi})$

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 $R\left(l_{J/\psi}\right)$
3) Fit to $l_{J/\psi}$ of sidebands of $m_{\mu\mu}$ with $F_{bkg}\left(l_{J/\psi}\right)$
4) 2D simultaneous fit with $F\left(l_{J/\psi}, m_{\mu\mu}\right)$

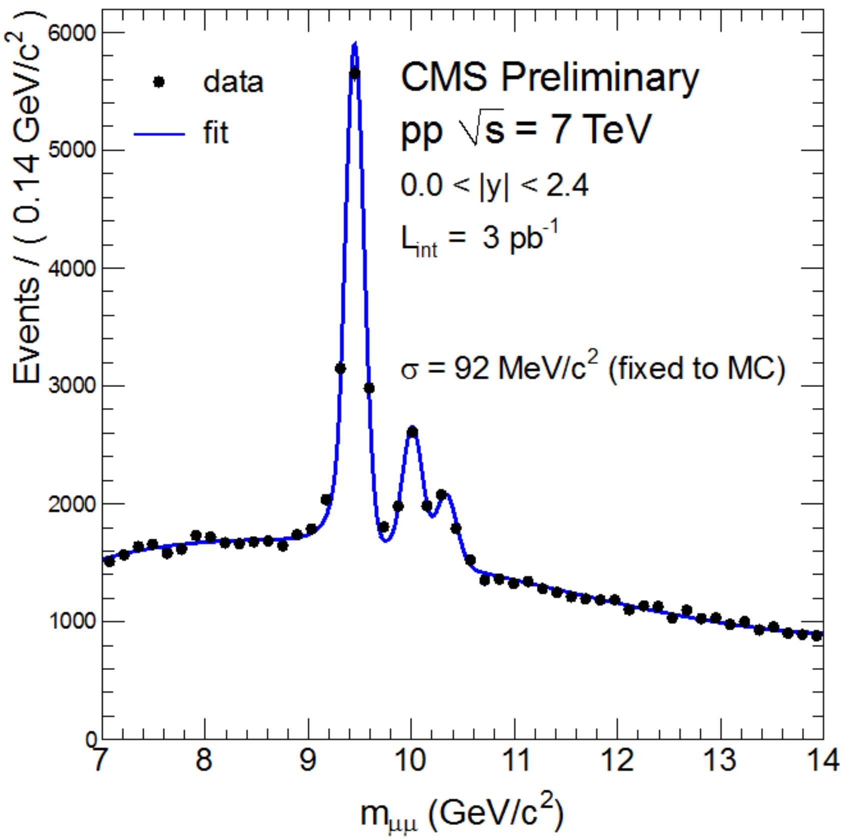
pp Comparison

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

- pp 2.76 TeV



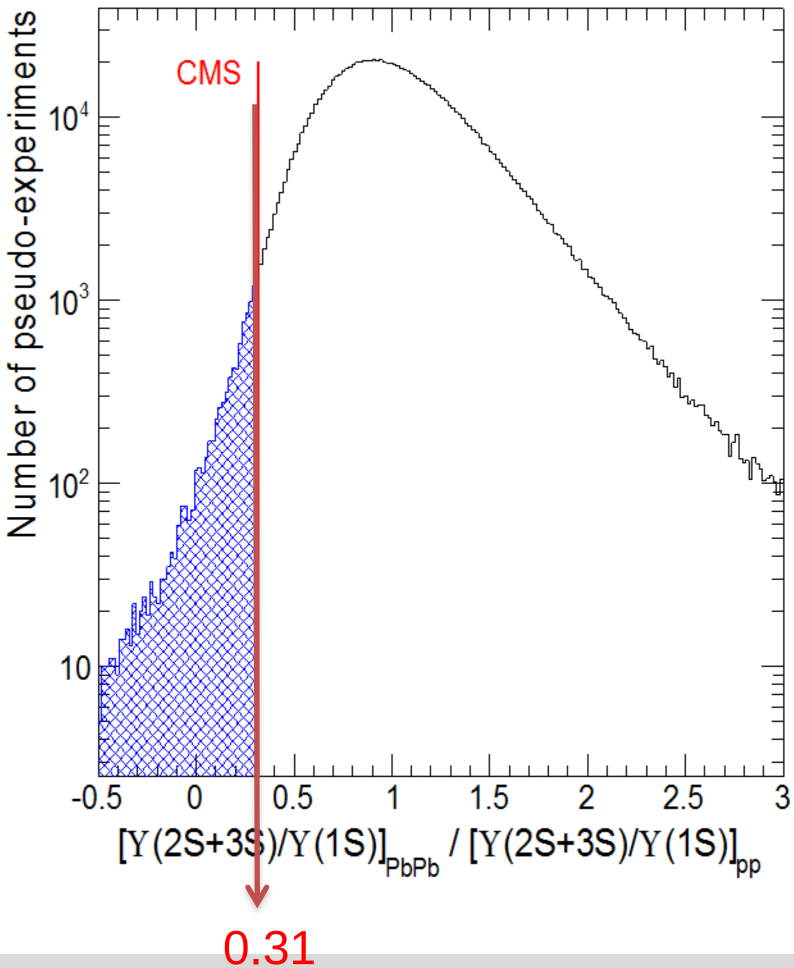
- pp 7 TeV



p-value

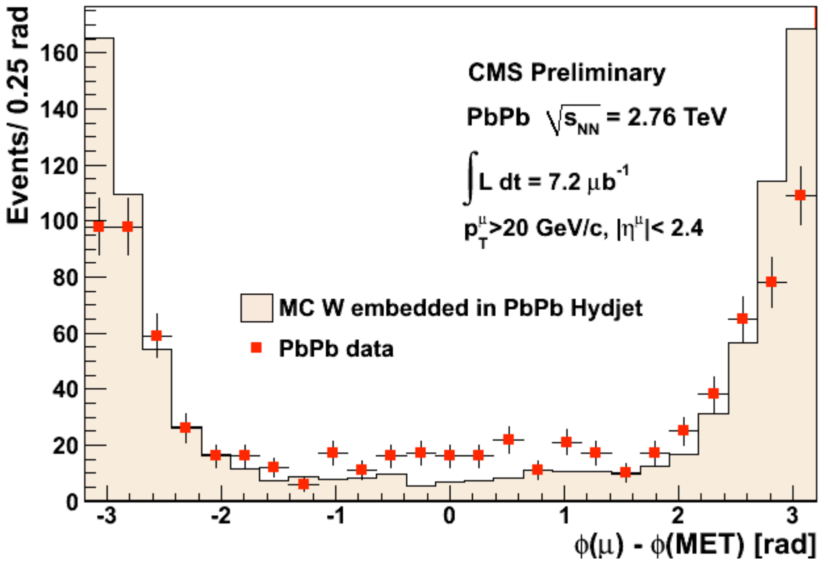
Could background fluctuation produce a result as extreme as observed in data?

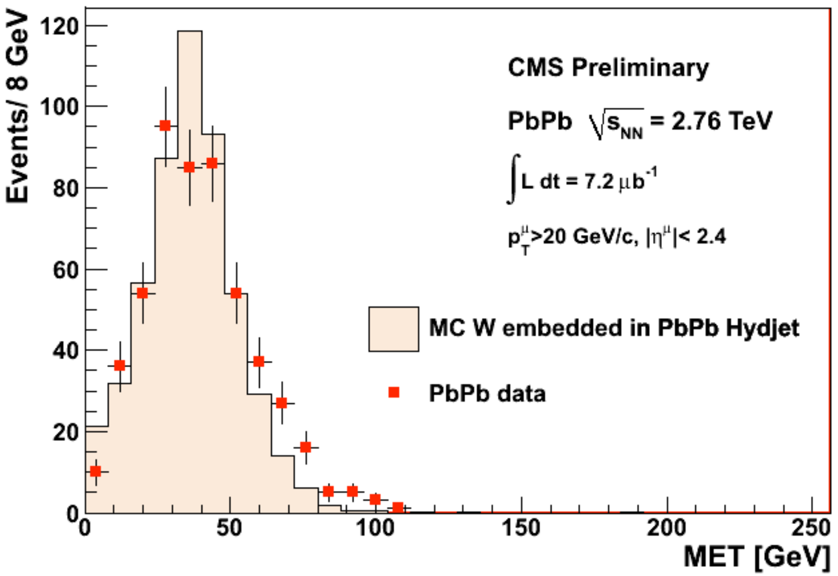
- Generate pseudo-experiments following the *null-hypothesis* (i.e. no suppression)
- Fit pseudo-data samples with nominal fit
- Count fraction of occurrences for which the ratio (taken as test statistic) is same or lower than observed:
  - p-value: 0.9%
  - 2.4σ (1-sided Gaussian test)



- Large fraction of Υ(1S) come from excited states
  - ~50% feed-down from χ_b for $p_T^{\Upsilon} > 8$ GeV/c **CDF: PRL84 (2000) 2094**

W bosons in PbPb and pp





CMS PAS EWK-10-005