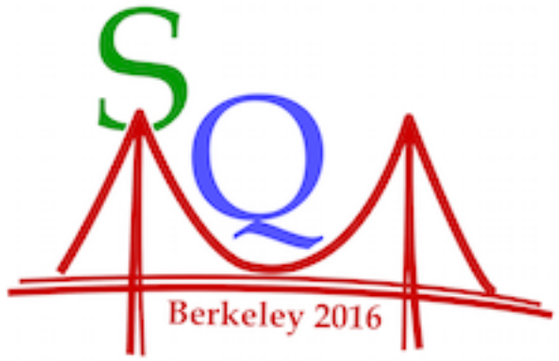
# Charmonium Production in pp, pPb and PbPb with CMS

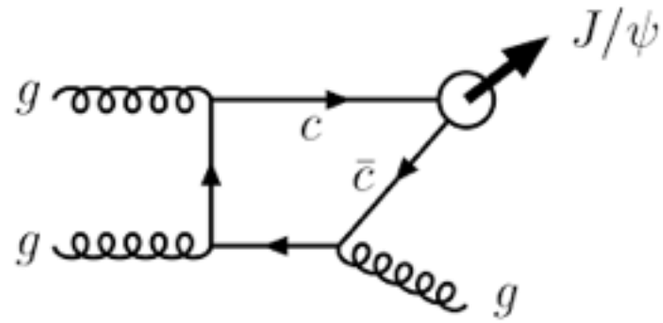
Songkyo Lee (Korea Univ.)
on behalf of the CMS Collaboration




SQM2016
UC Berkeley, Berkeley, CA, United States
28th June 2016

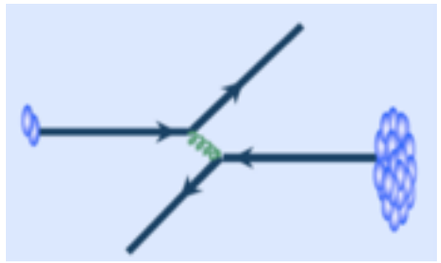
# Motivation

- Quarkonia - important probes in Heavy Ion collisions
  - Produced by gluon-gluon hard scattering in the early stage of collisions
  - Sensitive to gluon Parton Distribution Functions
  - Experience the full evolution of the medium



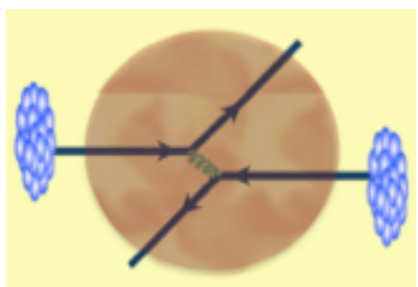

- Cold Nuclear Matter effects (CNM)

  e.g.)
  - Modification of PDFs
  - Initial state energy loss
  - Nuclear absorption



- Hot and Dense Medium effects (QGP)

  e.g.)
  - Debye screening - suppression
  - Recombination - enhancement



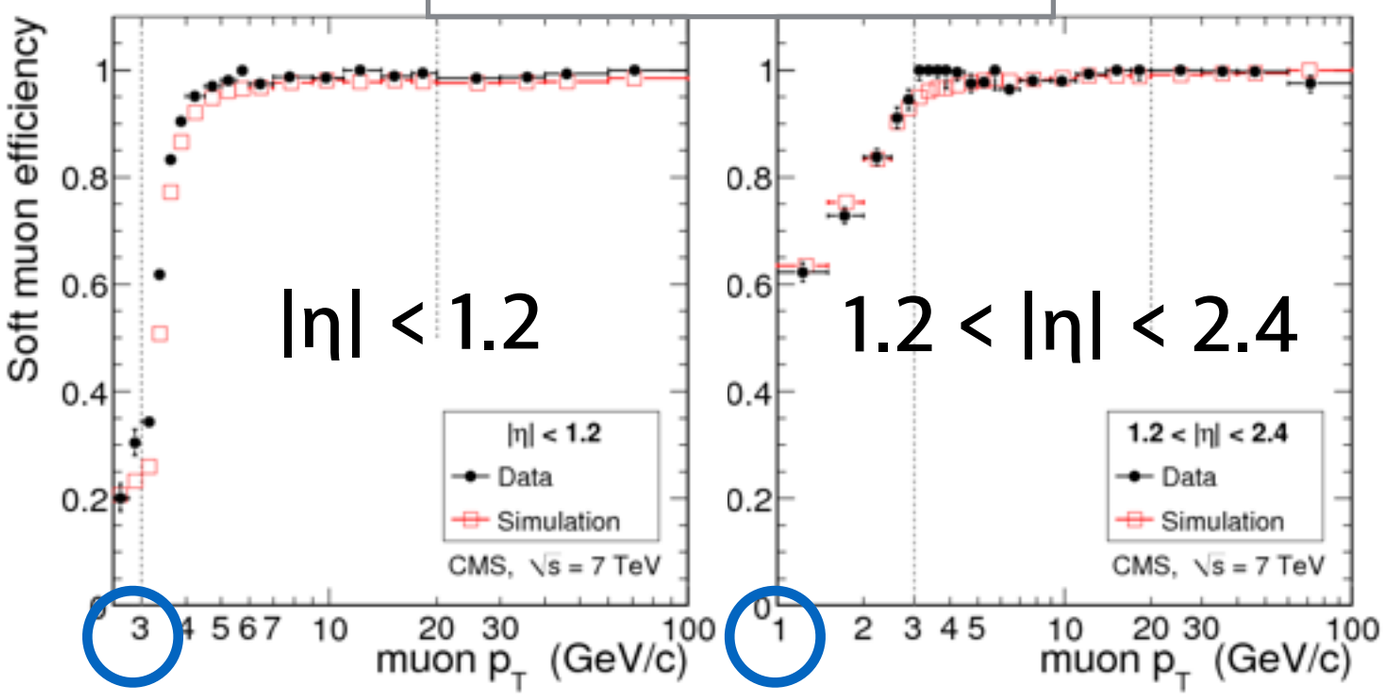
# CMS Acceptance for Charmonia

- Charmonia reconstructed via $\mu^+\mu^-$ decay channel
  - Easy to detect with excellent momentum resolution
- Kinematic coverage of CMS
  - $|y| < 2.4$
  - $p_T$ down to 0 GeV/c at forward ($1.6 < |y| < 2.4$)
  - $p_T > 6.5$ GeV/c at mid-rapidity due to B field

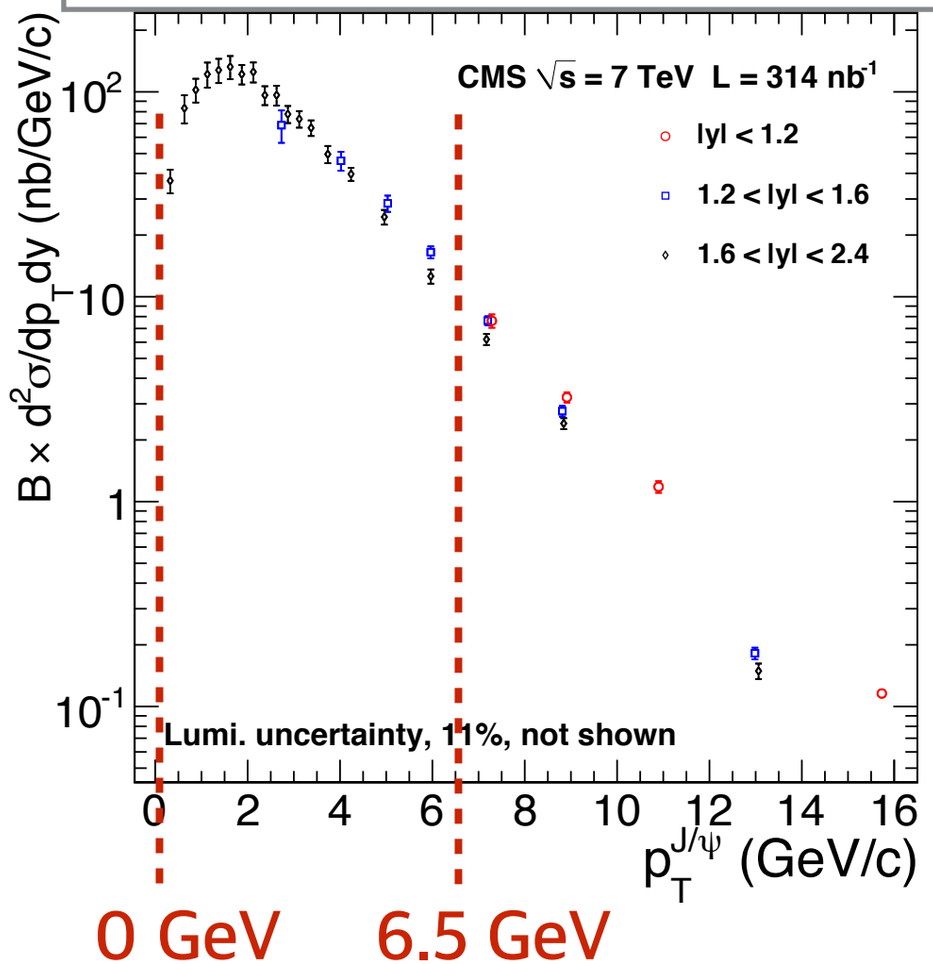
EPJC 71 (2011) 1575

JINST 7 (2012) P10002

## muon efficiency



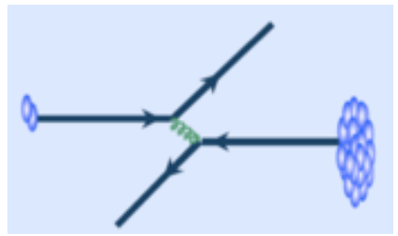

## J/ψ cross sections in pp



# Outline

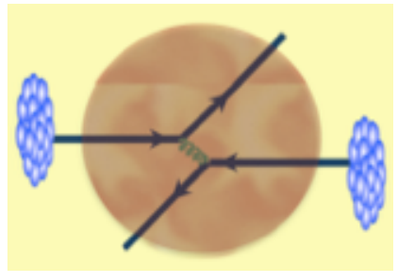
## Probe CNM effects

- J/ψ in Ultra Peripheral PbPb Collisions — arXiv:1605.06966, submitted to PLB
- J/ψ in pPb Collisions — CMS-PAS HIN-14-009

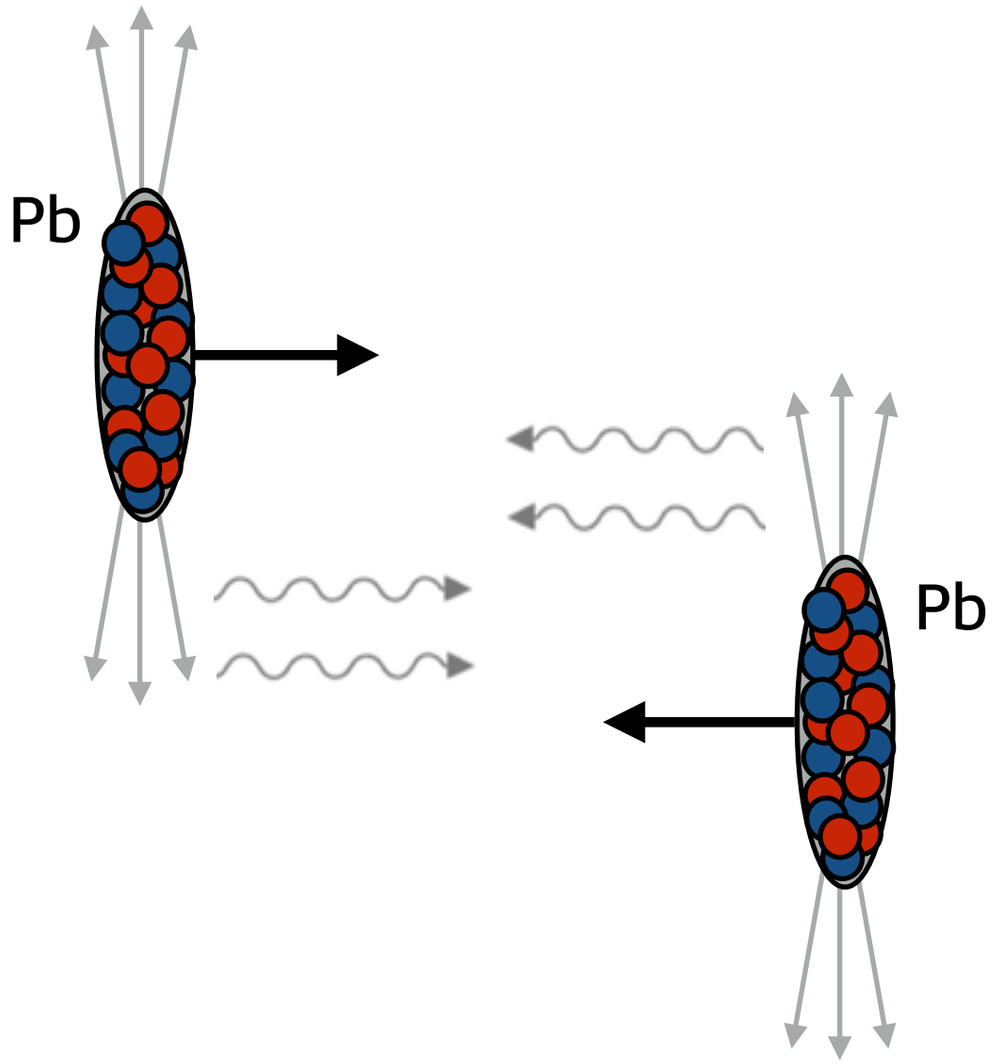


## Probe CNM + QGP effects

- J/ψ in PbPb Collisions — CMS-PAS HIN-12-014
- ψ(2S) in PbPb Collisions — PRL 113 (2014) 262301



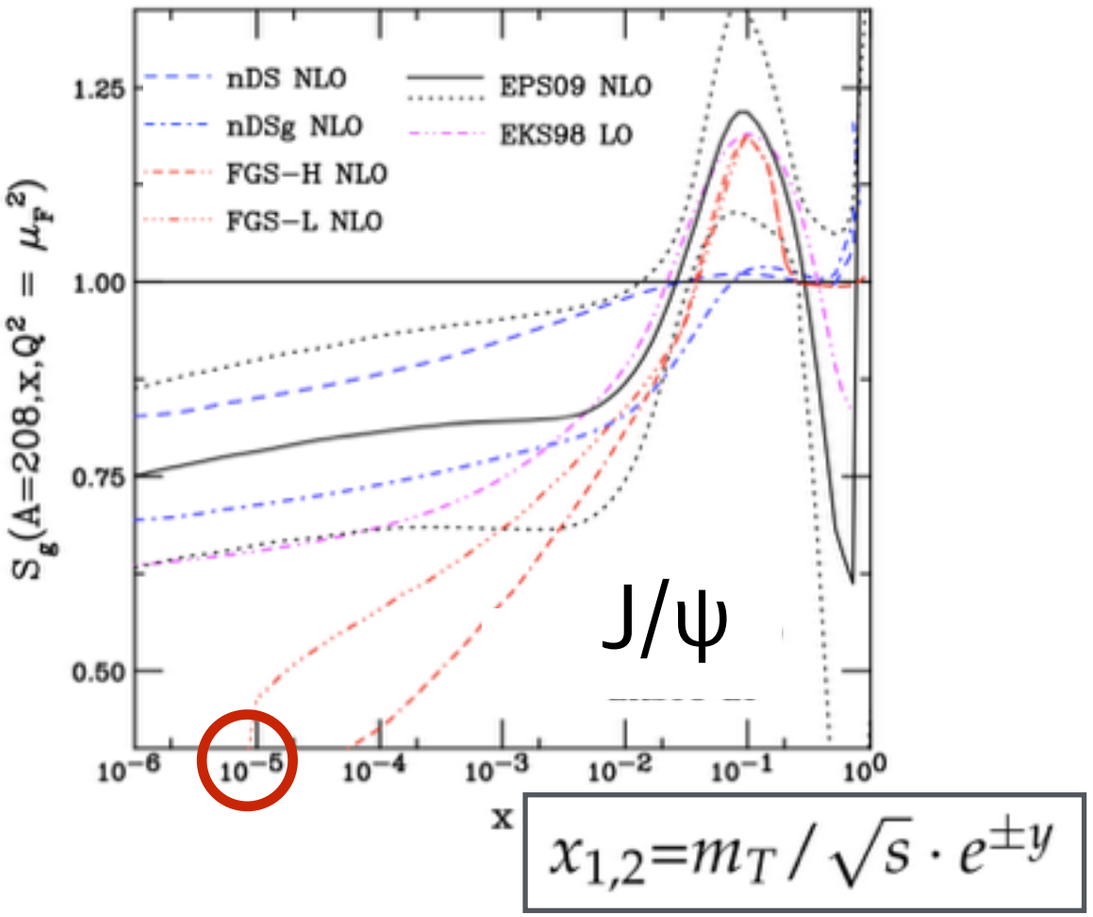
# Ultra Peripheral PbPb @ 2.76 TeV

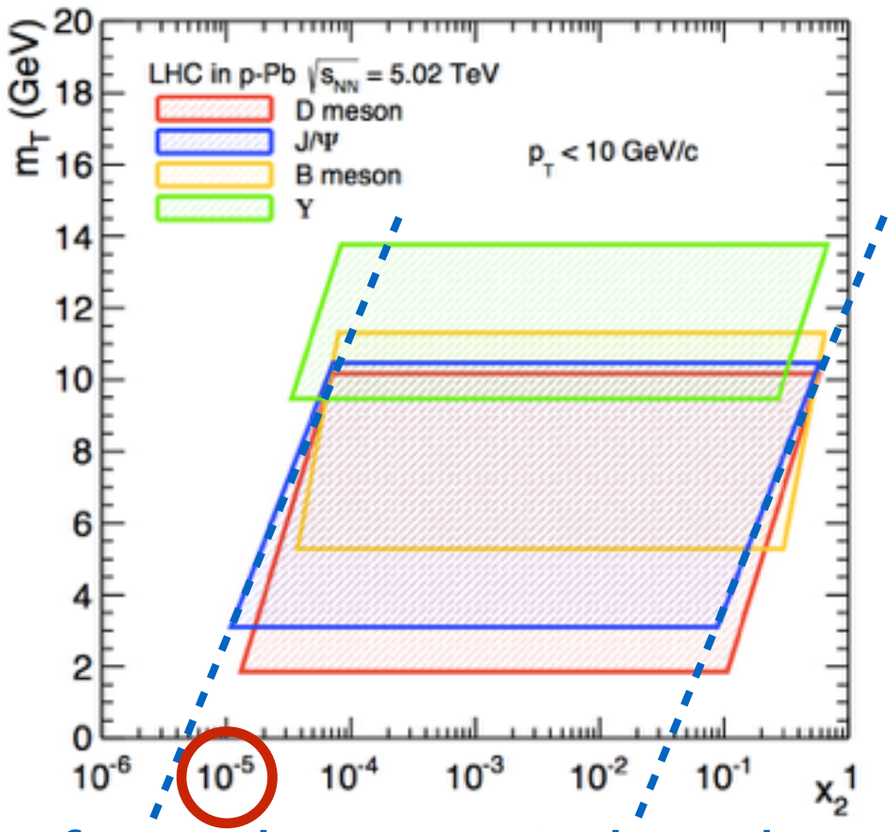


# CNM physics

- nuclear PDFs : $R_i^A(x,Q^2) = \dfrac{f_i^{p/A}(x,Q^2)}{f_i^p(x,Q^2)}$ ← proton PDF inside nucleus ← proton PDF

$R_g^{Pb}$



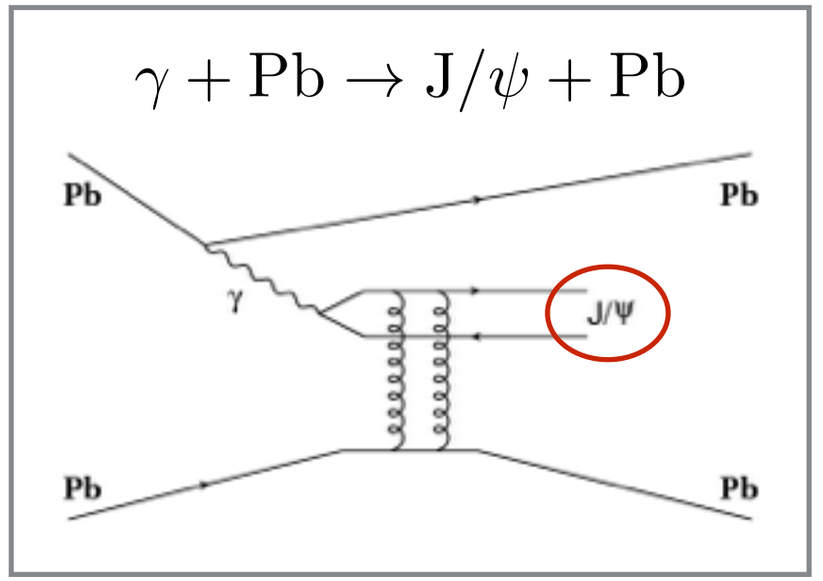




- CMS covers a broad range in Bjorken-x (gluon shadowing)
- Measurement in low x is crucial to understand the CNM effects and constrain various theoretical models

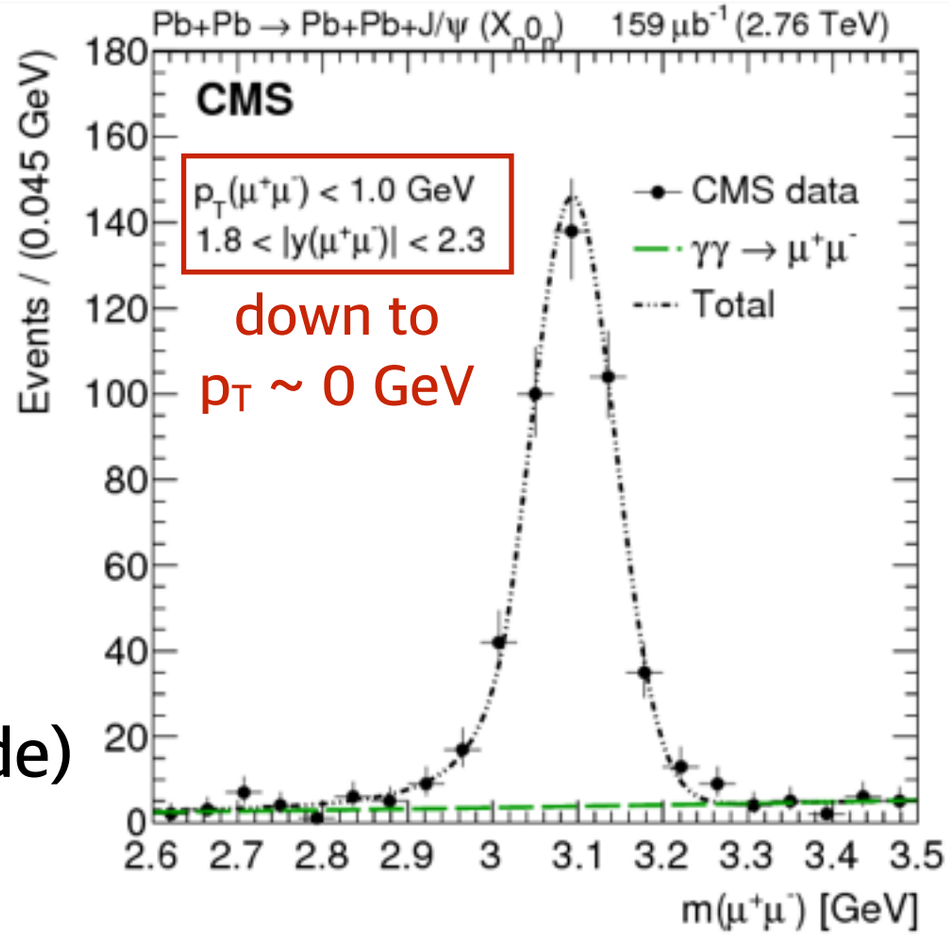
arXiv:1507.04418 arXiv:1506.03981

# J/ψ in Ultra Peripheral PbPb

- Photon-induced reactions
  - b (impact parameter) > 2R (nucleus radius)
  - Cross sections ∝ (gluon density)$^2$
  - Clean probes with low background for gluon PDFs ($10^{-5} < x < 10^{-2}$)




- Event selection
  - UPC requirement
    - low activity in Hadron Forward Calorimeter
  - J/ψ - exactly two muon tracks
  - Forward Neutron
    - detection in Zero Degree Calorimeter
    - ($X_n0_n$) break-up mode selected (neutrons on one side, nothing on the other side)

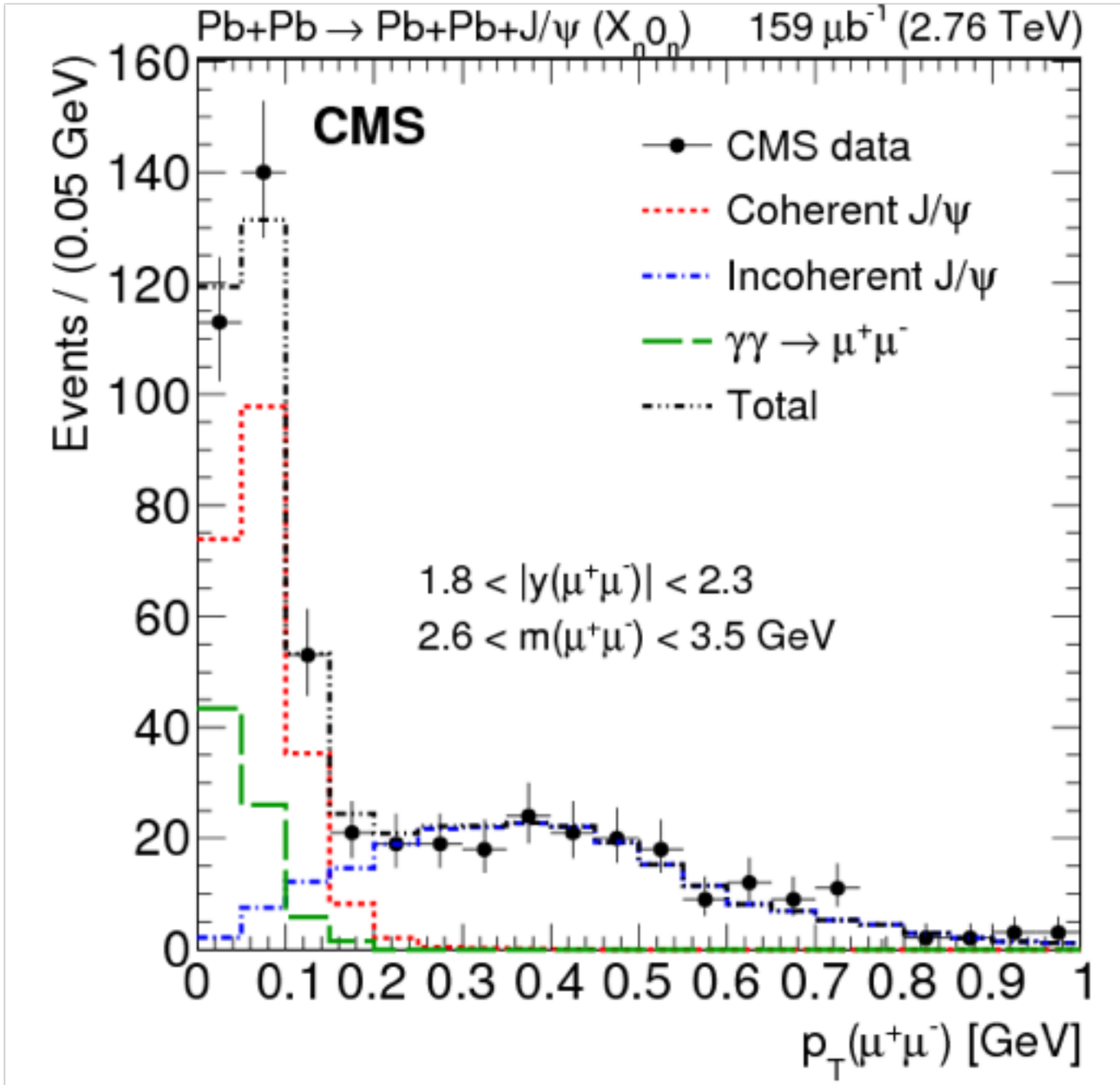



arXiv:1605.06996

# Different Interactions in UPC

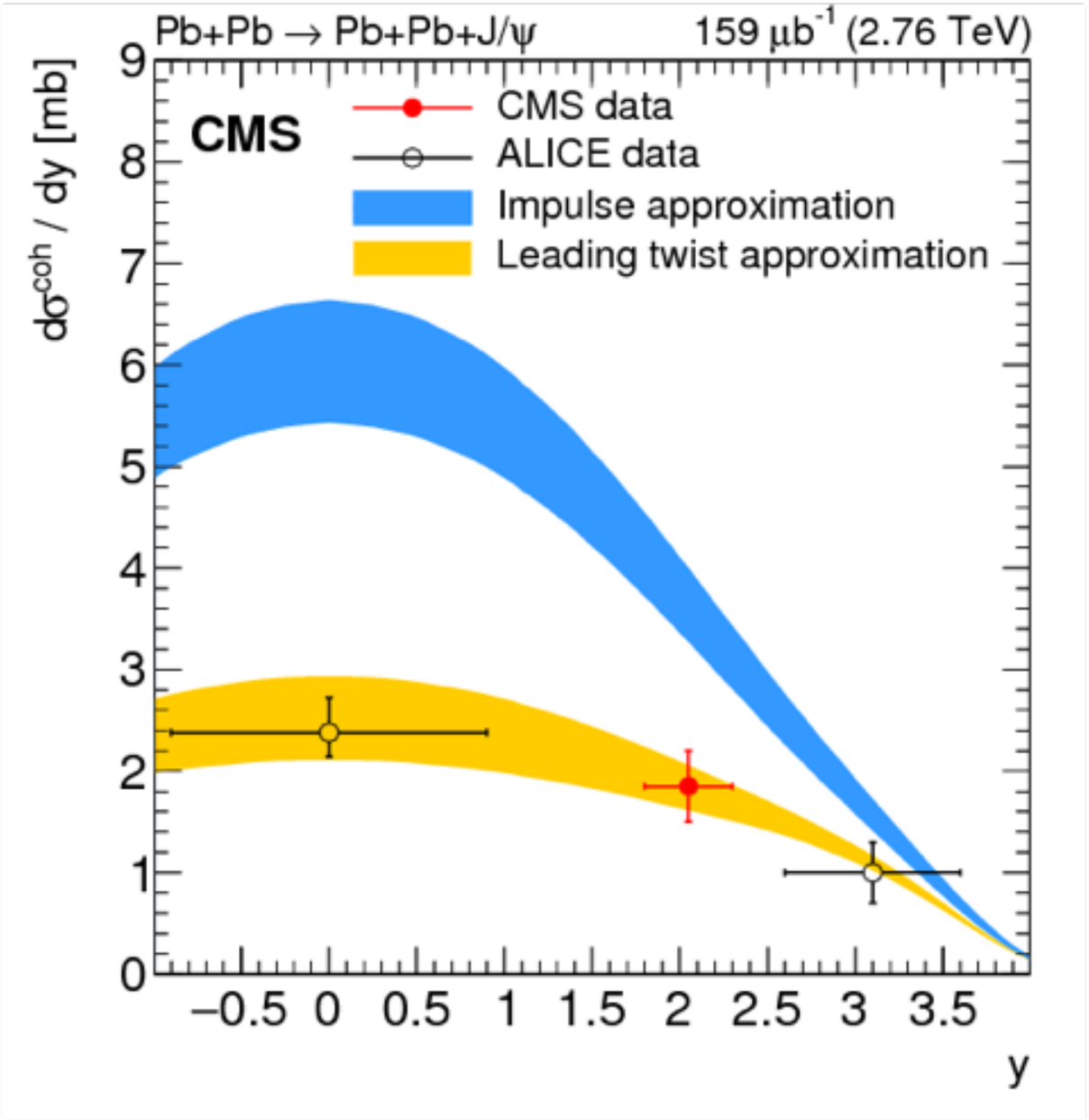
arXiv:1605.06996

- Coherent J/ψ
  - Photon couples to “a whole nucleus”
  - $p_T$ < 0.15 GeV/c
- Incoherent J/ψ
  - Photon couples to “a single nucleon”
  - 0.15 < $p_T$ < 1.05 GeV/c
- Two photon → Dimuon
  - QED Background




- MC(STARLIGHT) template fit to extract coherent contributions

# Coherent J/ψ cross sections



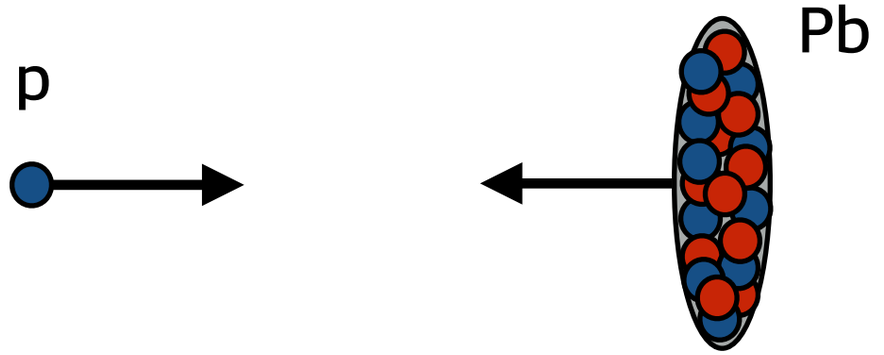

arXiv:1605.06996

Recently submitted to PLB

- Impulse approximation
  neglects all nuclear effects
- Leading twist approximation
  includes an effective gluon shadowing

- Results favor a model with shadowing effects
- Complementary to ALICE covering different rapidity range

# pPb @ 5.02 TeV

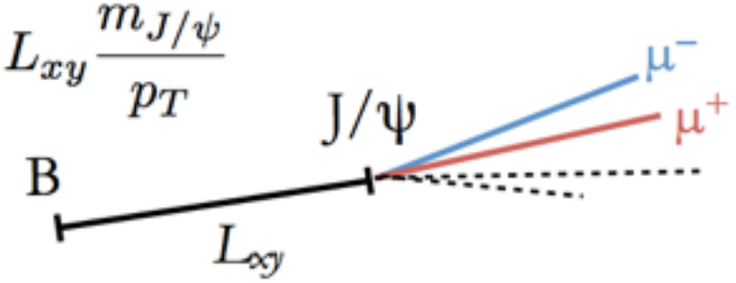


# Separation of prompt & non-prompt

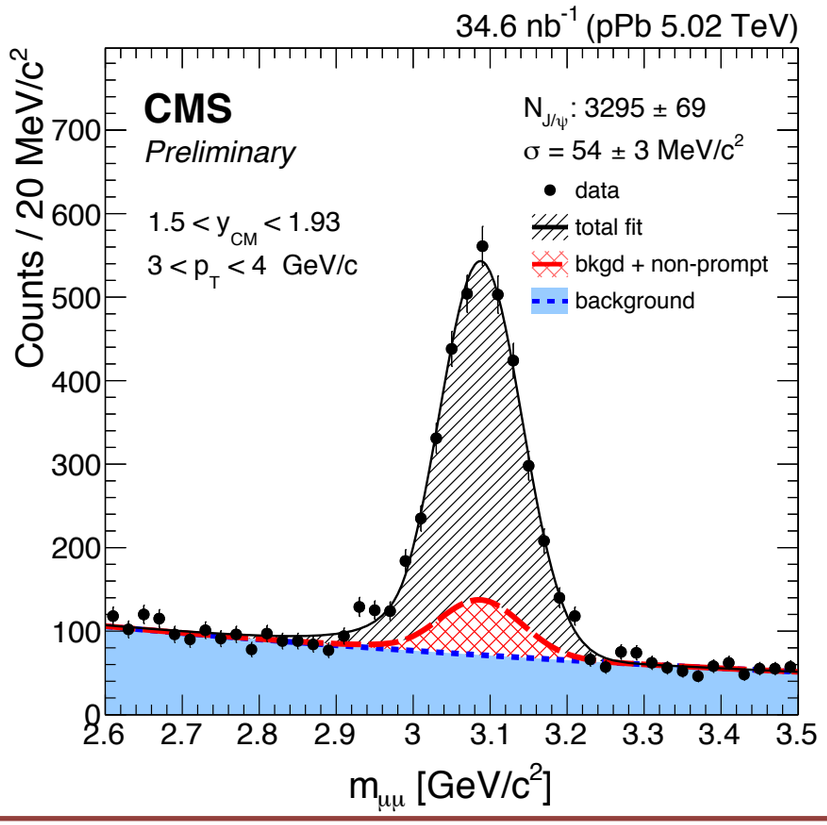
CMS-PAS HIN-14-009

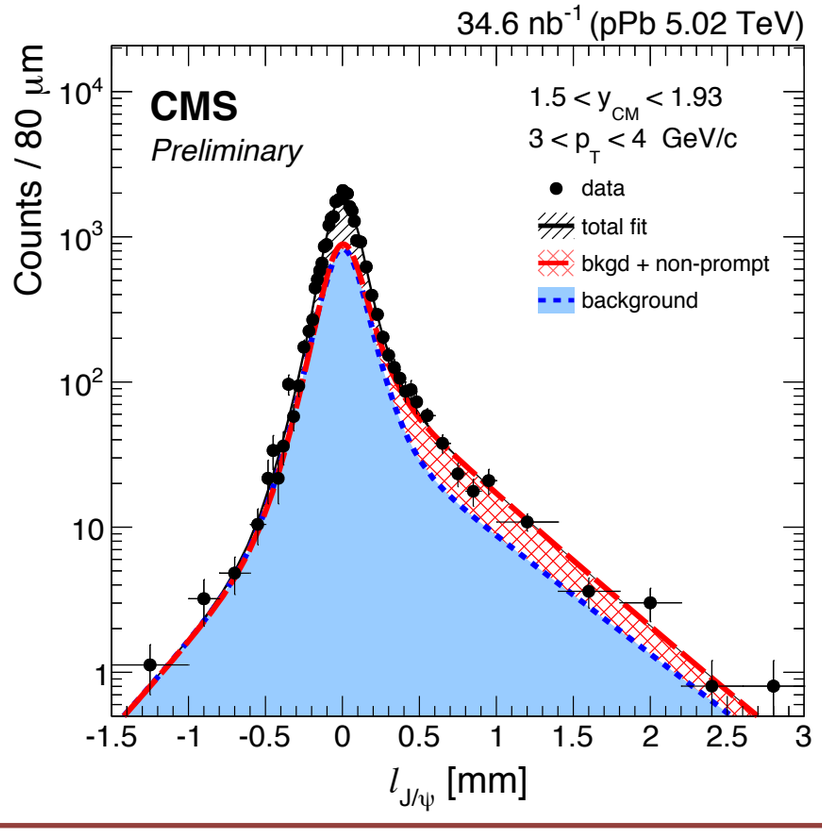
- 2D fit to “dimuon mass” and “decay length”
  - Prompt : direct J/ψ or feed down from ψ’ and $X_c$
  - Non-prompt : from B hadron decays

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




- Lifetime of B ~ O(500) μm/c
- IP resolution of CMS
  - transverse ~ 25-90 μm
  - longitudinal ~ 45-150 μm

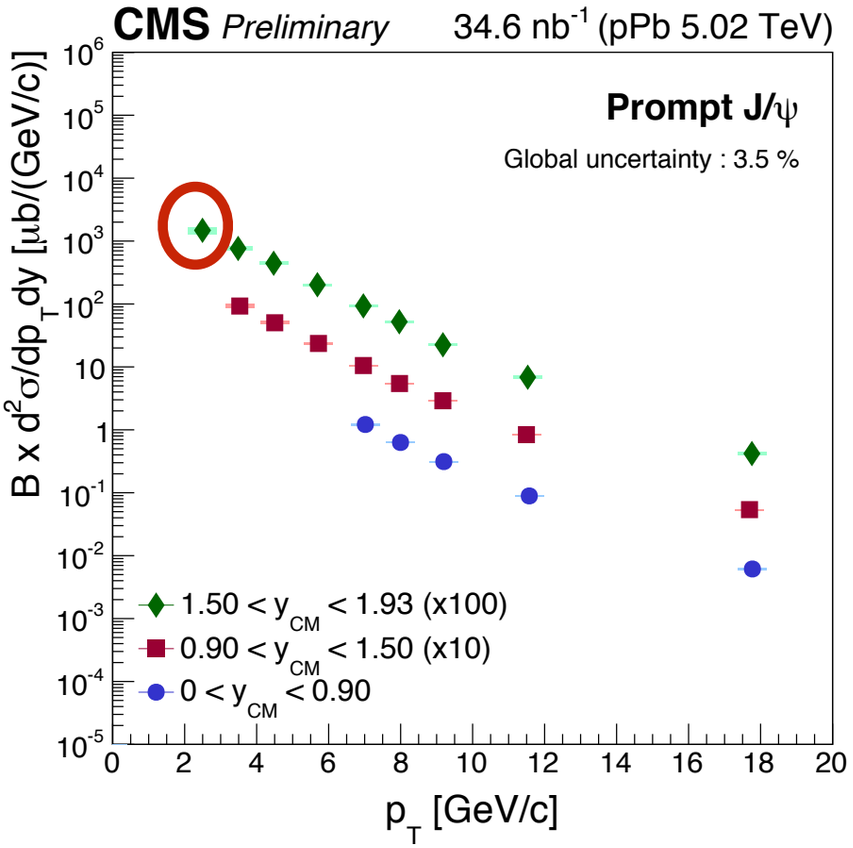


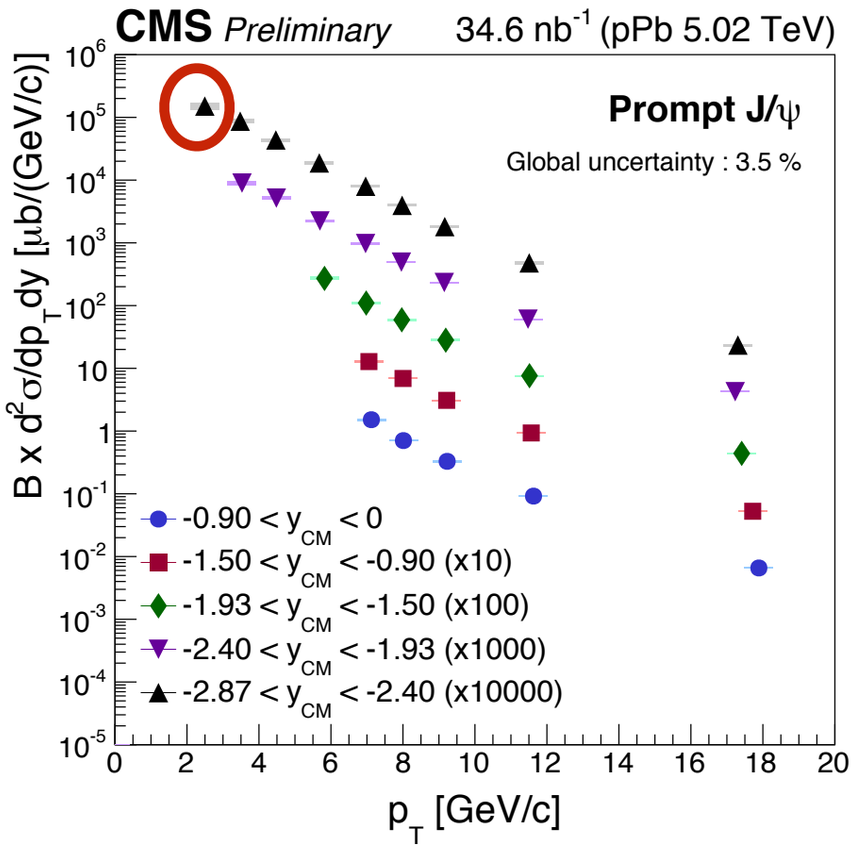
# J/ψ in pPb - cross section

CMS-PAS HIN-14-009

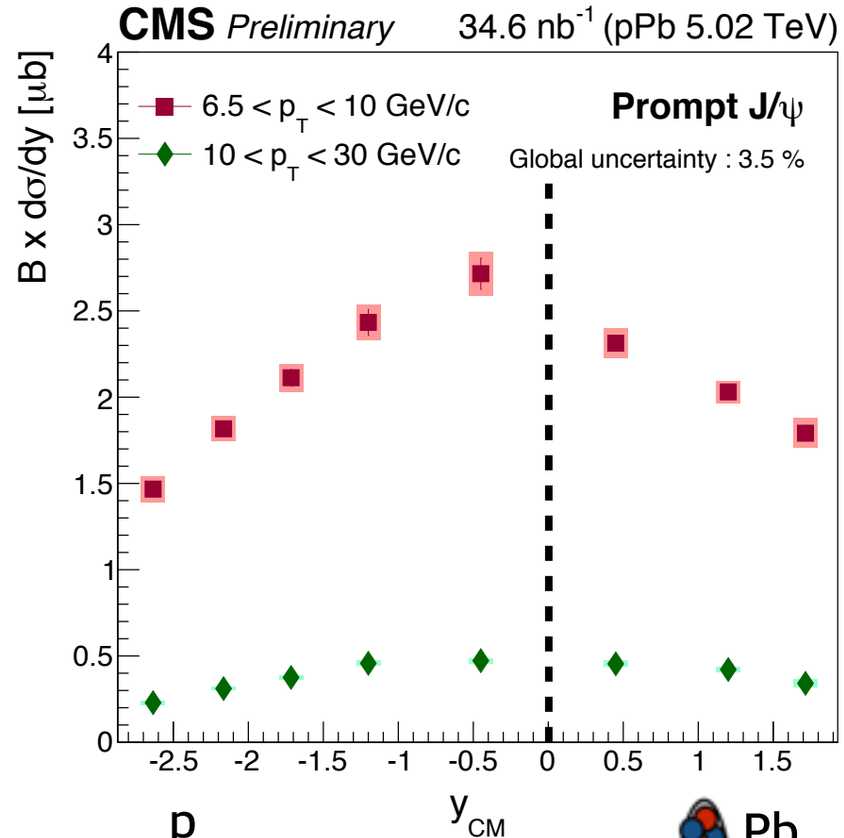
- Wide range in rapidity and $p_T$ bins
  - $-2.87 < y_{CM} < 1.93$ ($-2.4 < y_{lab} < 2.4$)
  - $2 < p_T < 30$ GeV/c (down to lower $p_T$ at most forward)




Forward
(p-going)




Backward
(Pb-going)



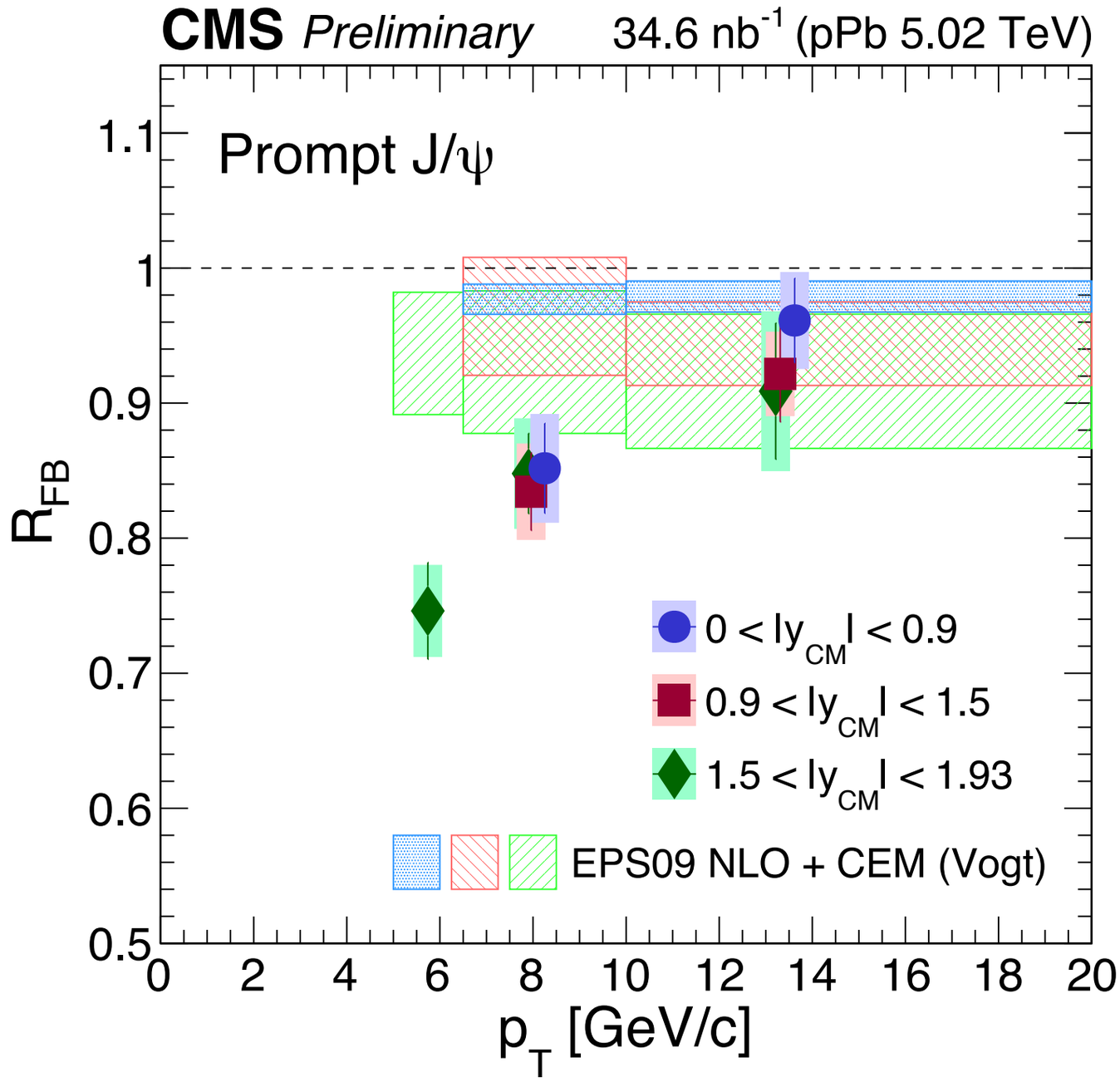
# J/ψ in pPb - $R_{FB}$

CMS-PAS HIN-14-009

- Forward-to-Backward Ratio :

$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y) = \frac{d^2\sigma(p_{\mathrm{T}}, y > 0)/dp_{\mathrm{T}}dy}{d^2\sigma(p_{\mathrm{T}}, y < 0)/dp_{\mathrm{T}}dy}$$

$$= \frac{\text{p-going (x}\sim10^{-4}\text{)}}{\text{Pb-going (x}\sim10^{-2}\text{)}}$$

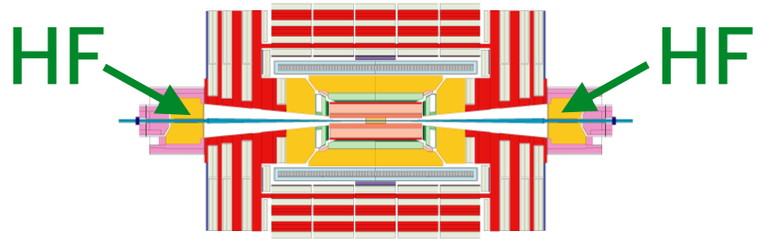


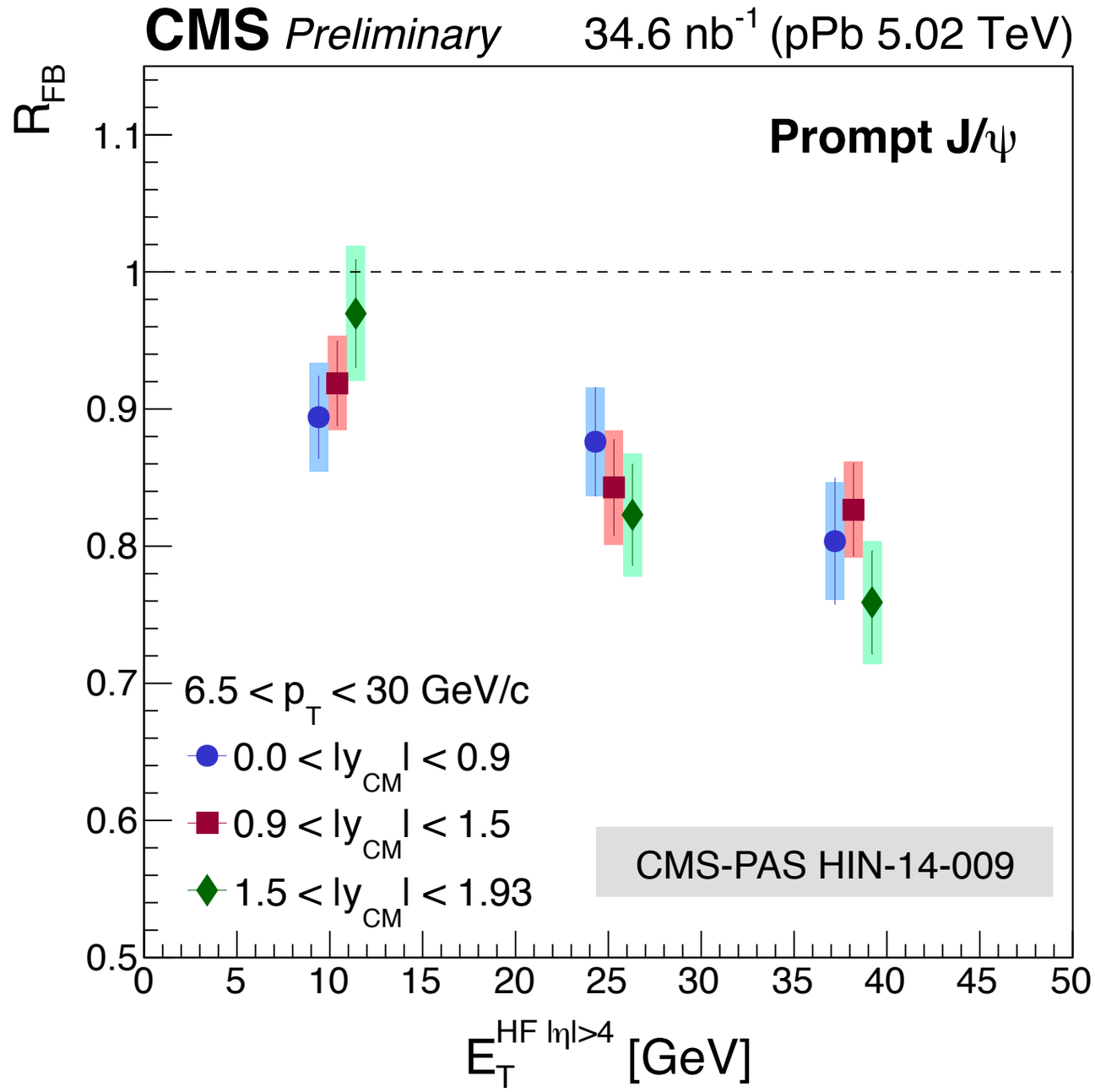

- $R_{FB} < 1$ at low $p_T$
- Clue for other effects beyond presented nPDF predictions?

# J/ψ in pPb - event activity

- Event activity characterized by $E_T^{HF|\eta|>4}$
  - Transverse energy deposited in Hadron Forward Calorimeter (HF) at $4 < |\eta| < 5.2$
  - Fraction of minimum bias events :

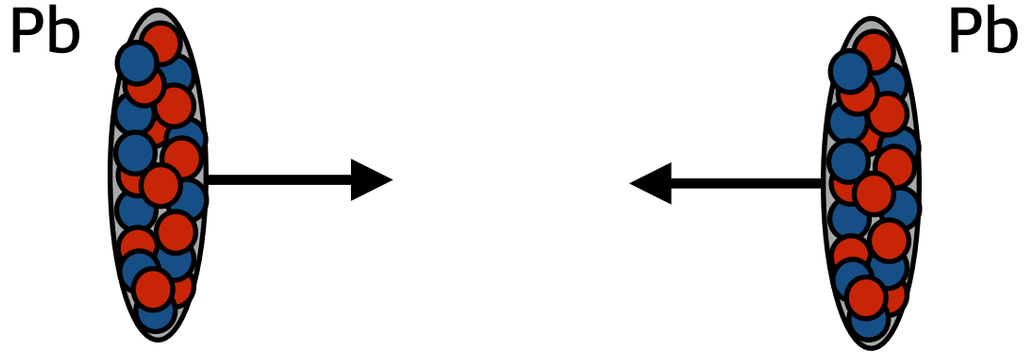
| | $[E_T^{HF\|\eta\|>4}]$ | $\langle E_T^{HF\|\eta\|>4} \rangle$ | Frac |
|---|---|---|---|
| pPb | 0–20 | 9.4 | 73% |
| min- | 20–30 | 24.3 | 18% |
| bias | 30–120 | 37.2 | 9% |




- $R_{FB}$ decreases with increasing event activity
- Stay Tuned! $R_{pPb}$ coming soon with 2015 pp at same $\sqrt{s_{NN}}$

# PbPb @ 2.76 TeV



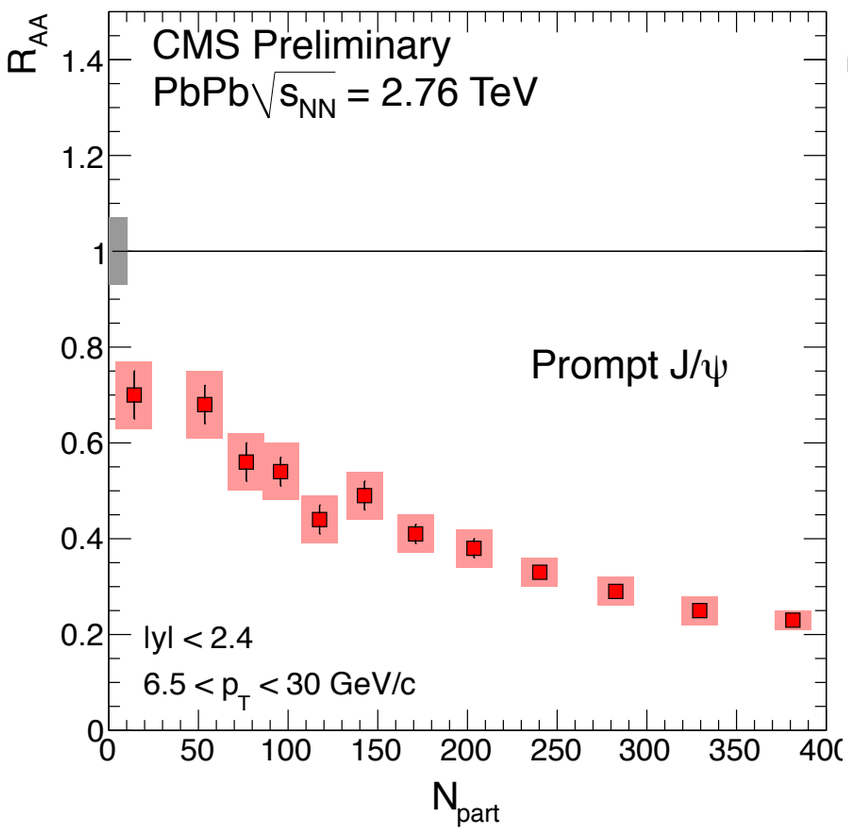
# J/ψ in PbPb

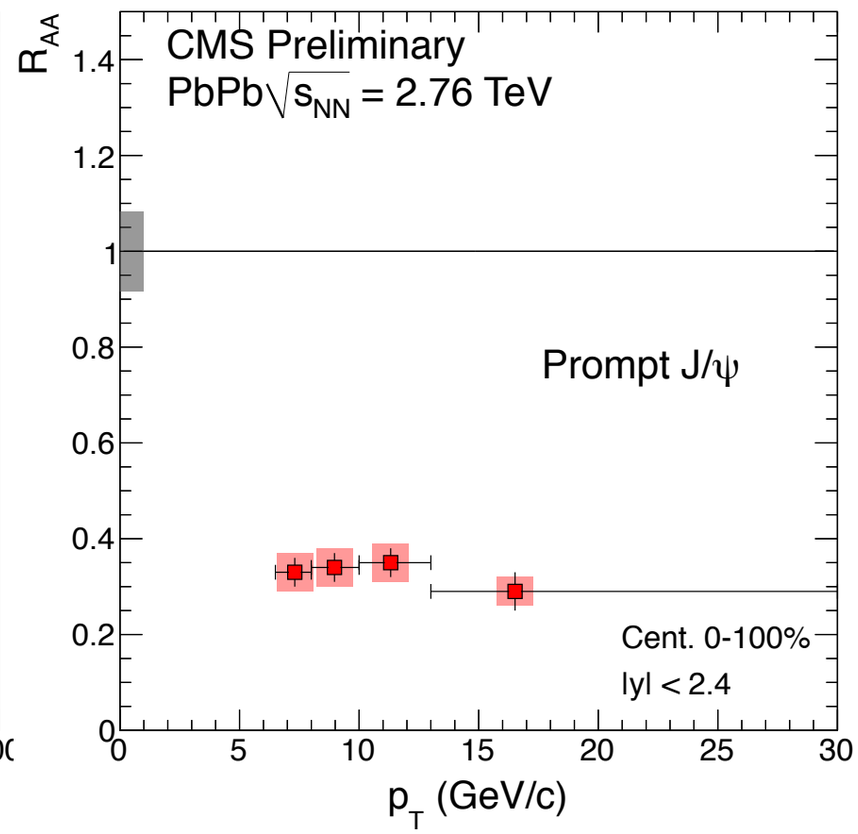
- Nuclear modification factor

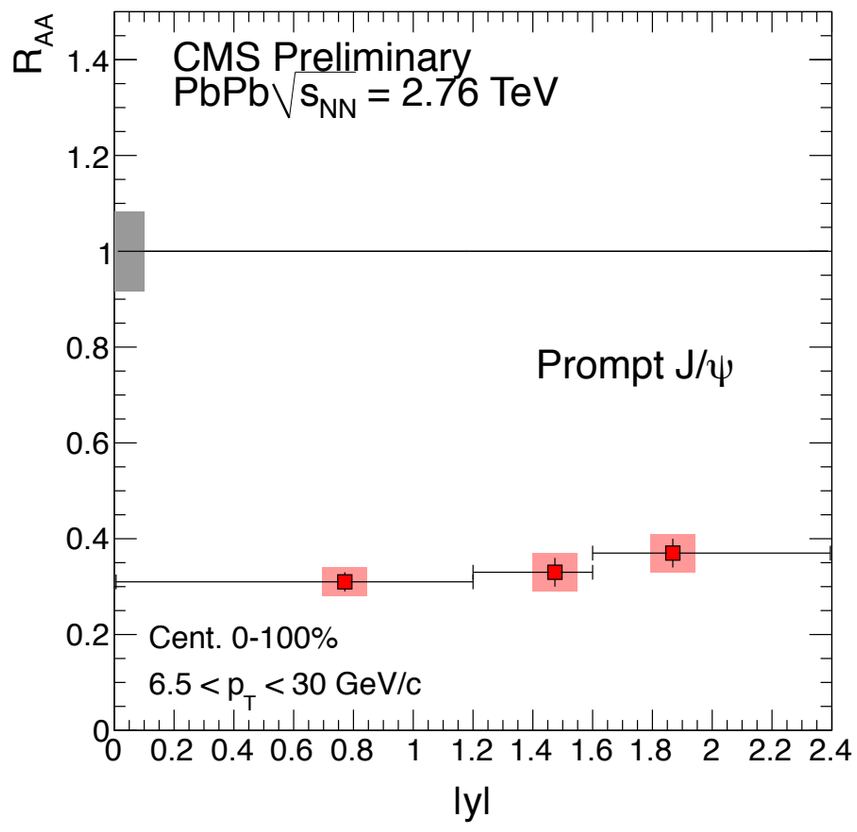
CMS-PAS HIN-12-014

$$R_{AA} = \frac{1}{T_{AA}} \cdot \frac{dN_{AA}}{d\sigma_{pp}} = \frac{L_{int}^{pp}}{T_{AA} N_{MB}} \cdot \frac{N_{J/\psi}^{PbPb}}{N_{J/\psi}^{pp}} \cdot \frac{\epsilon_{pp}}{\epsilon_{PbPb}}$$

- $R_{AA}$ < 1 : suppression
- $R_{AA}$ = 1 : no modification compared to pp
- $R_{AA}$ > 1: enhancement



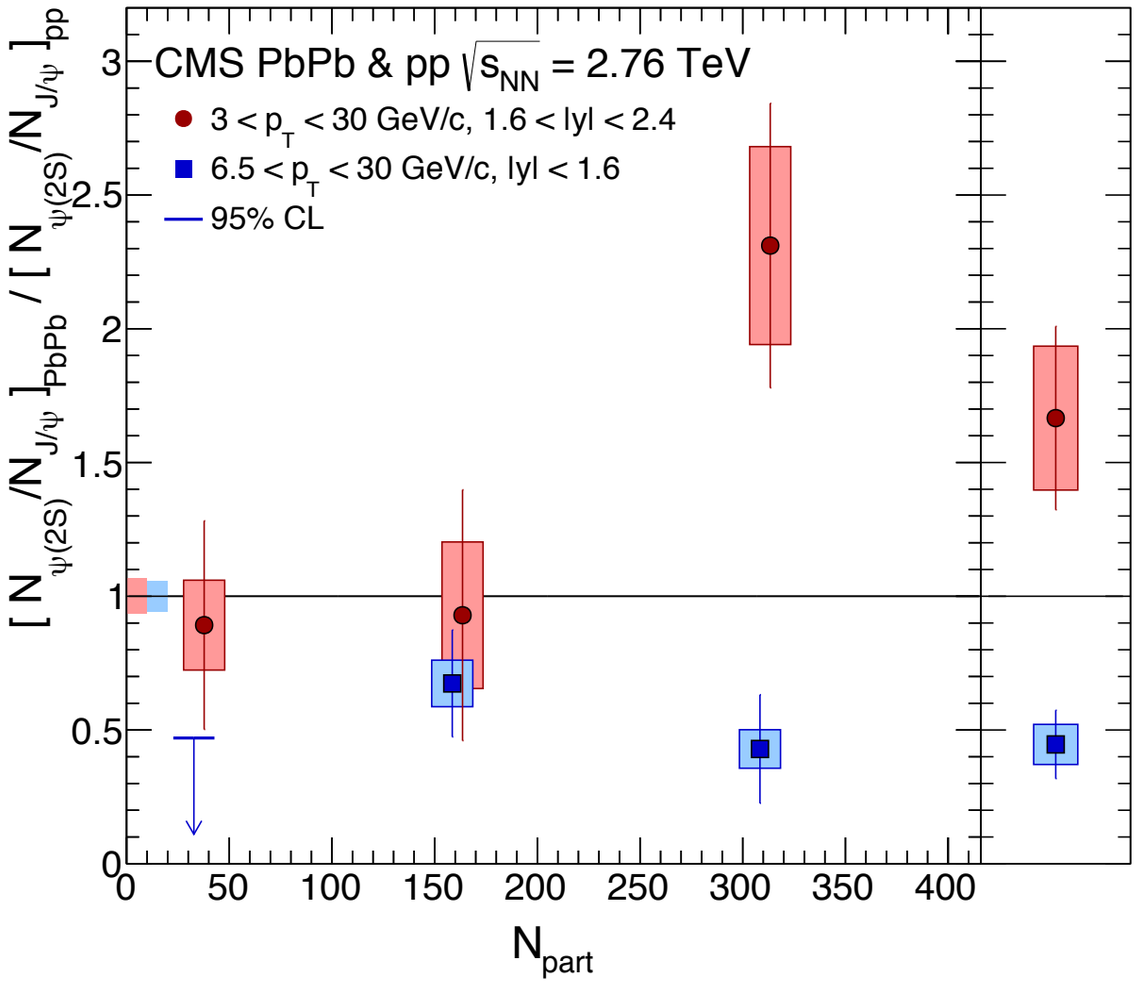




- More suppressed in more central collisions
- No significant $p_T$ and rapidity dependence

# ψ(2S) in PbPb

PRL 113 (2014) 262301

- Double Ratio : $\frac{[\frac{\psi(2S)}{J/\psi}]_{AA}}{[\frac{\psi(2S)}{J/\psi}]_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$




?

2015 PbPb @ 5.02 TeV

Stay Tuned!

- At high $p_T$ & mid-rapidity : consistent with sequential melting
- At low $p_T$ & forward : hint of recombination?

# Summary

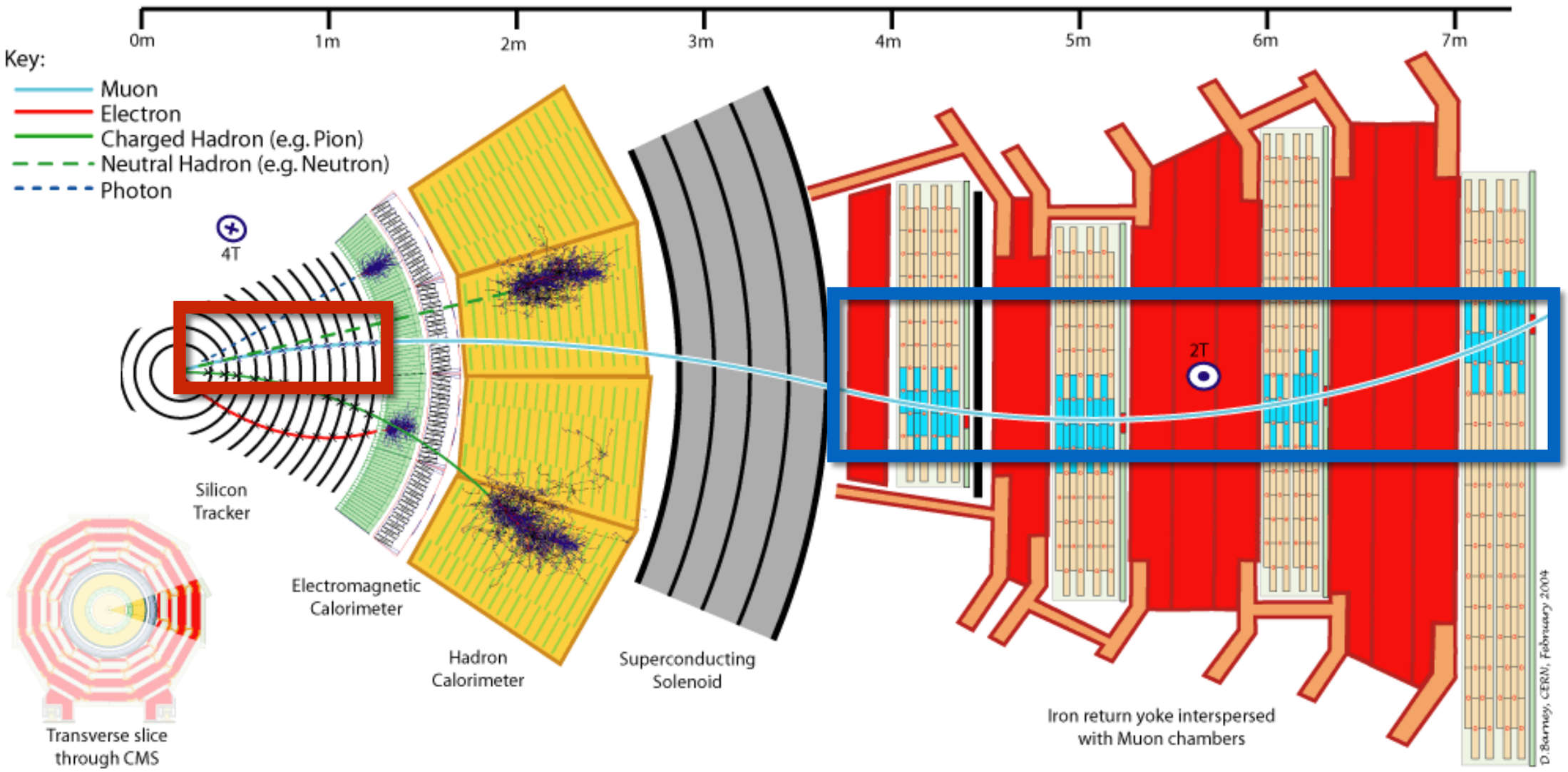
- CNM effects probed by J/ψ in pPb
  - $R_{FB} < 1$ especially at low $p_T$
  - $R_{FB}$ decreases with increasing event activity

- Coherent J/ψ photo-production in UPC PbPb
  - Evidence for gluon shadowing at low x region (at low $Q^2$)

- Suppression of J/ψ and ψ(2S) in PbPb
  - J/ψ is more suppressed in more central collisions
  - ψ(2S) is more suppressed than J/ψ at higher $p_T$ & mid-y, and less suppressed at lower $p_T$ & forward y

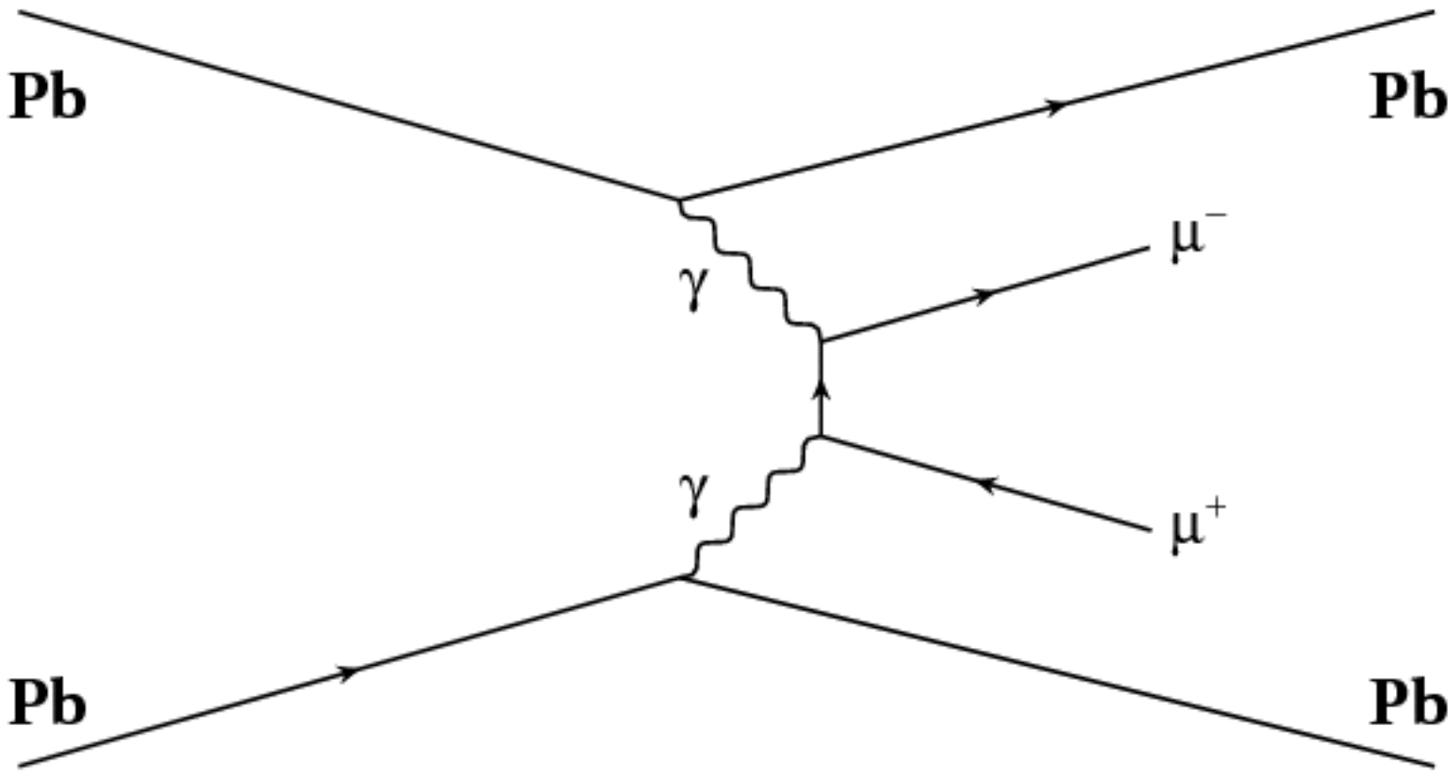
# Backup

# CMS Detector



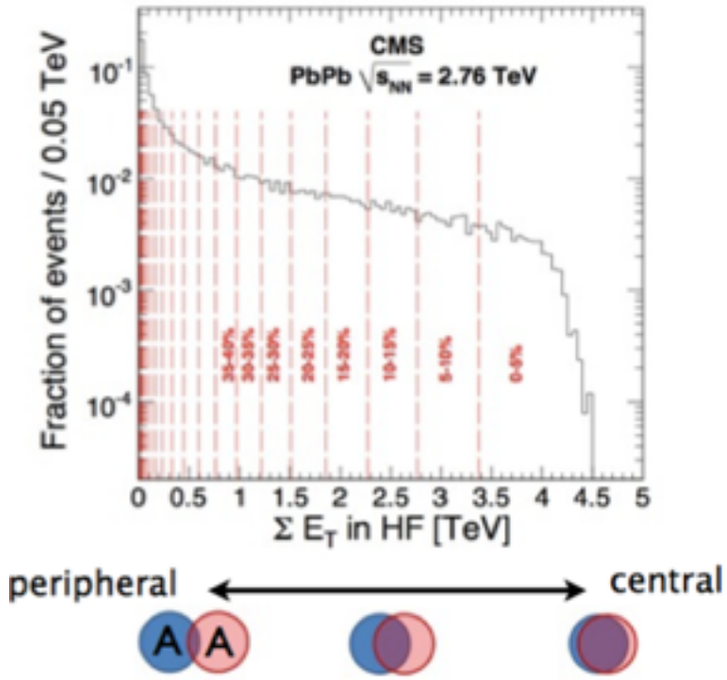

- Large coverage (muon & tracker $|\eta| < 2.4$)
- Highly selective trigger & muon ID in the muon system
- Excellent momentum and vertex resolution of the tracking system

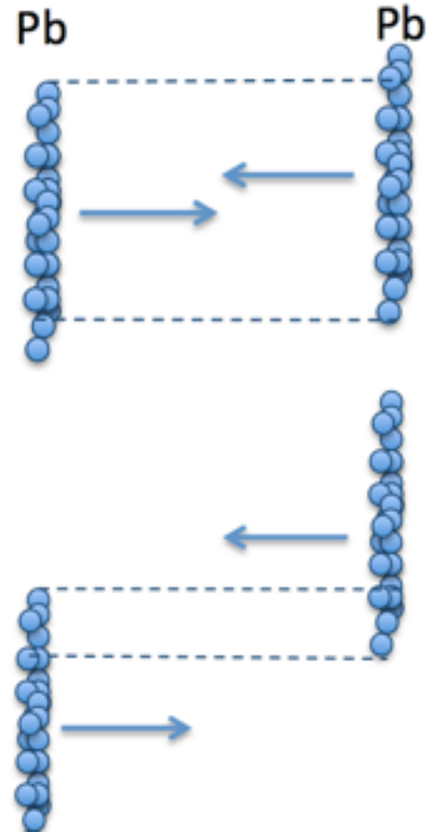
# two photon interaction



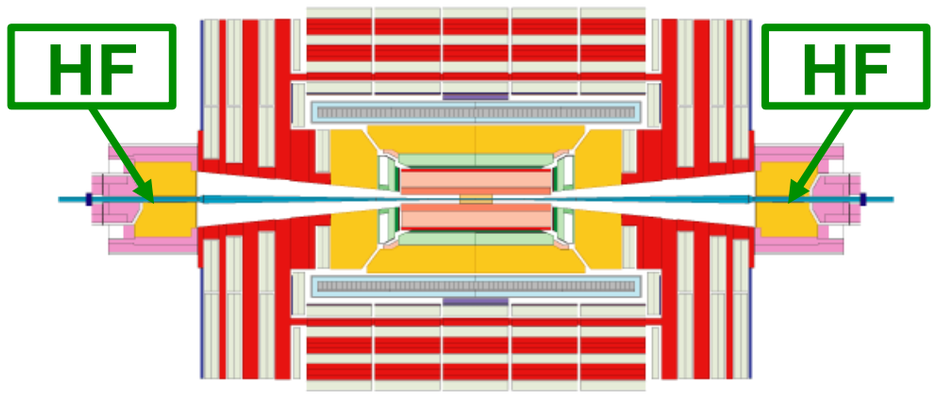
# Centrality? Event activity?

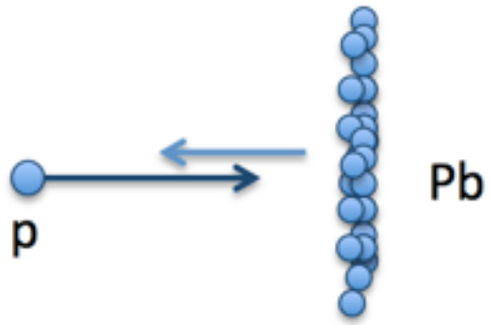
- Centrality in PbPb
  - Related to the overlap fraction of the geometrical cross sections




- Event-activity variables in pPb
  - $E_T^{HF}$ : raw transverse energy deposited in forward region HF (4<|η|<5.2)



# Centrality? Event activity?

- In pPb, the correlation between the centrality variable and $N_{coll}$ is very loose

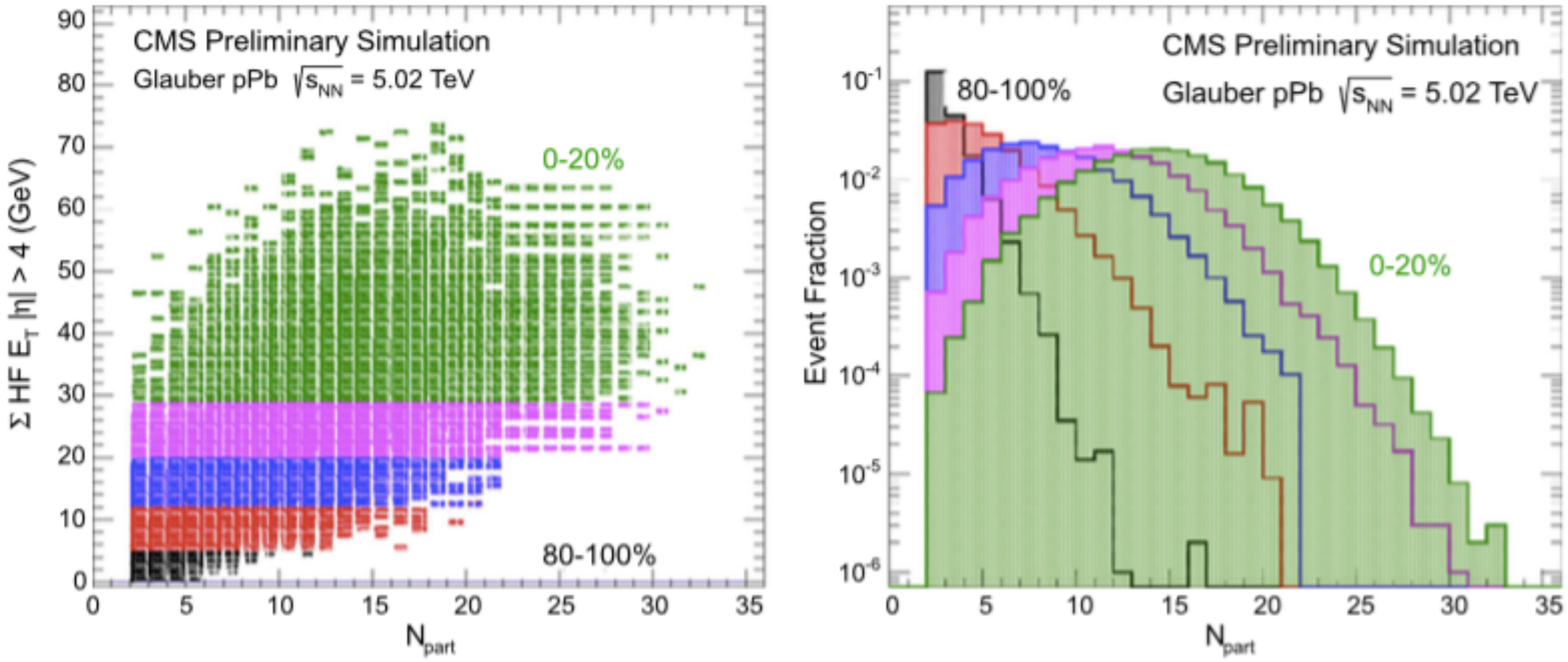
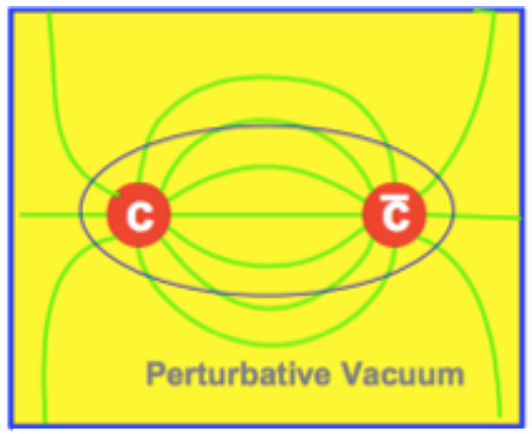



Fig. 4. Left: $\sum E_T$ vs. $N_{part}$ from Glauber + Smearing. Right: $N_{part}$ distribution for each centrality bin.

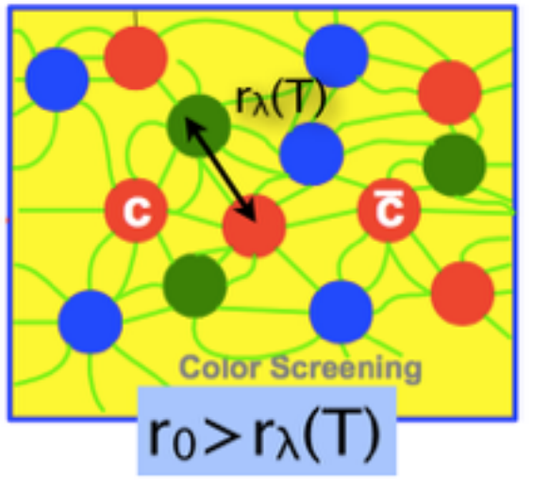
*Nuclear Physics A 926 (2014) 258–263*

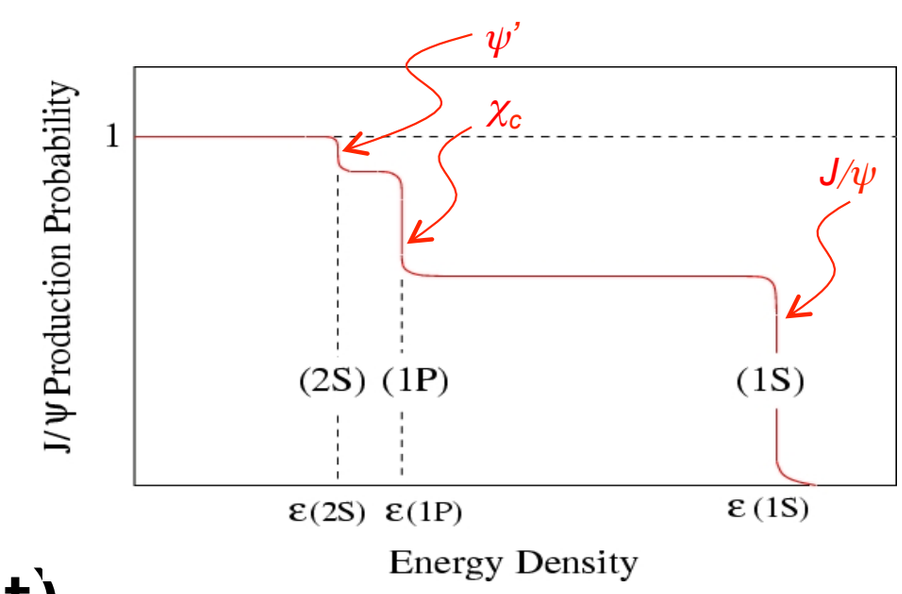
# QGP physics

- Debye screening (suppression)
  - Loosely bound states (with smaller binding energies) melt at lower temperature
  - Sequential melting of the quarkonia ⇒ Thermometer of QGP




| Resonance | J/ψ | Ψ' | ϒ(1S) | ϒ(2S) | ϒ(3S) |
|---|---|---|---|---|---|
| Mass [GeV] | 3.10 | 3.68 | 9.46 | 10.02 | 10.36 |
| ΔE [GeV] | 0.64 | 0.05 | 1.10 | 0.54 | 0.20 |
| Radius [fm] | 0.25 | 0.45 | 0.14 | 0.28 | 0.39 |




- Recombination (enhancement)
  - combination of quarks and antiquarks which are initially produced in "different" nucleon-nucleon collisions

PLB 178 (1986) 416

PLB 490 (2000) 196

PRC 63 (2001) 054905

# Non-prompt J/ψ in pPb - $R_{FB}$

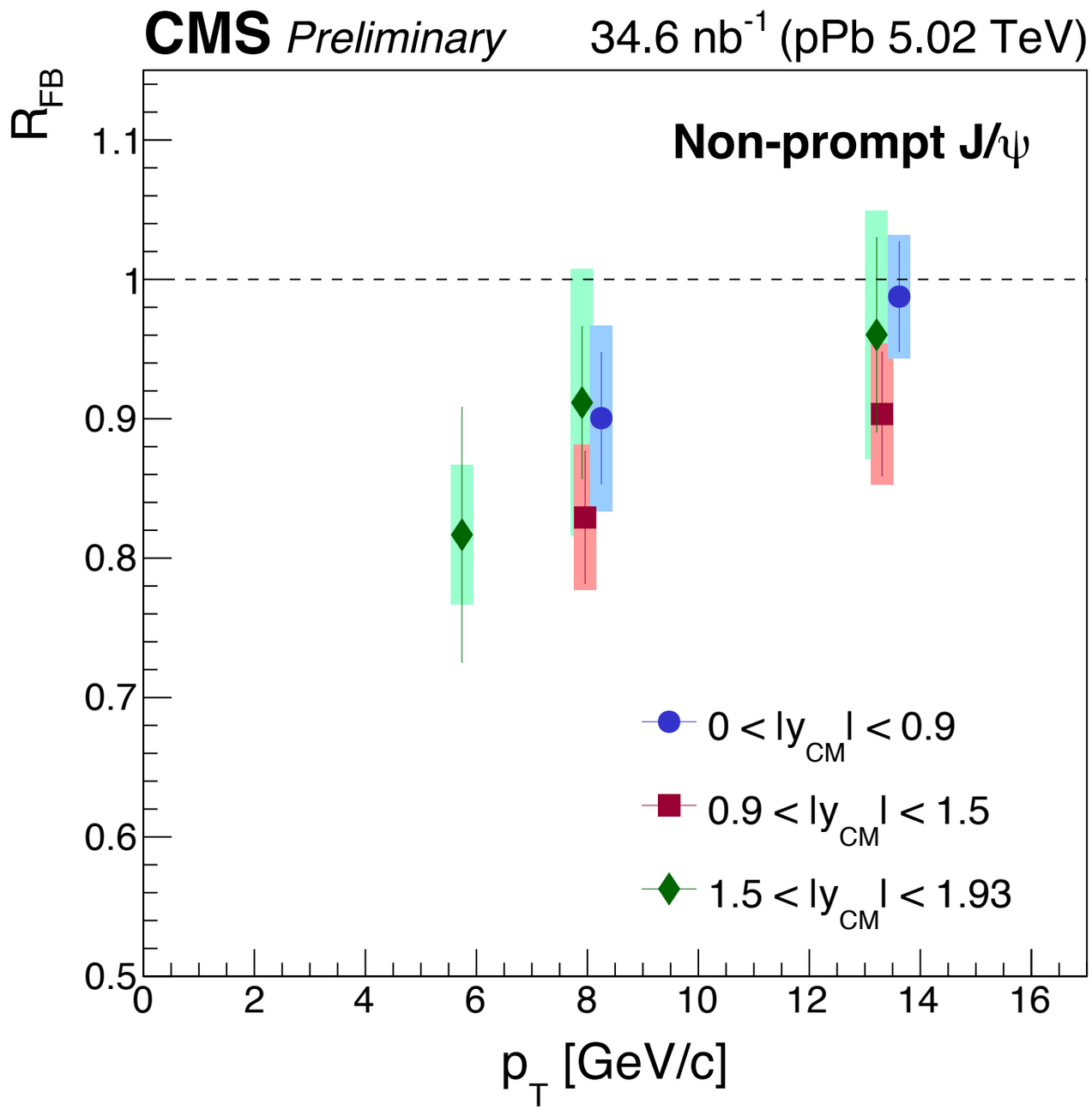
CMS-PAS HIN-14-009

- Forward-to-Backward Ratio :

$$R_{FB}(p_T, y) = \frac{d^2\sigma(p_T, y > 0)/dp_T dy}{d^2\sigma(p_T, y < 0)/dp_T dy}$$

  - Forward (y>0) : proton-going

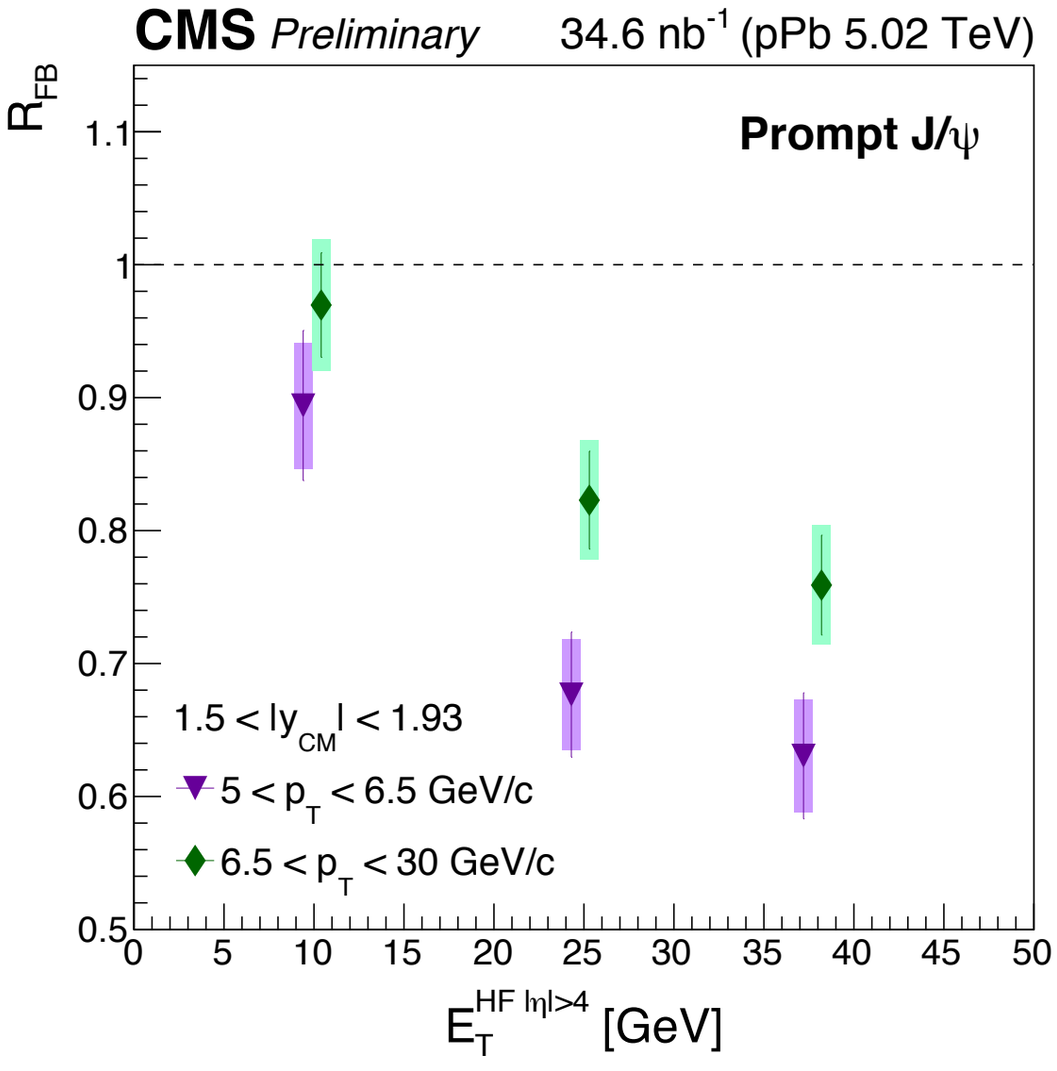
- $p_T$ dependence less significant compared to prompt J/ψ



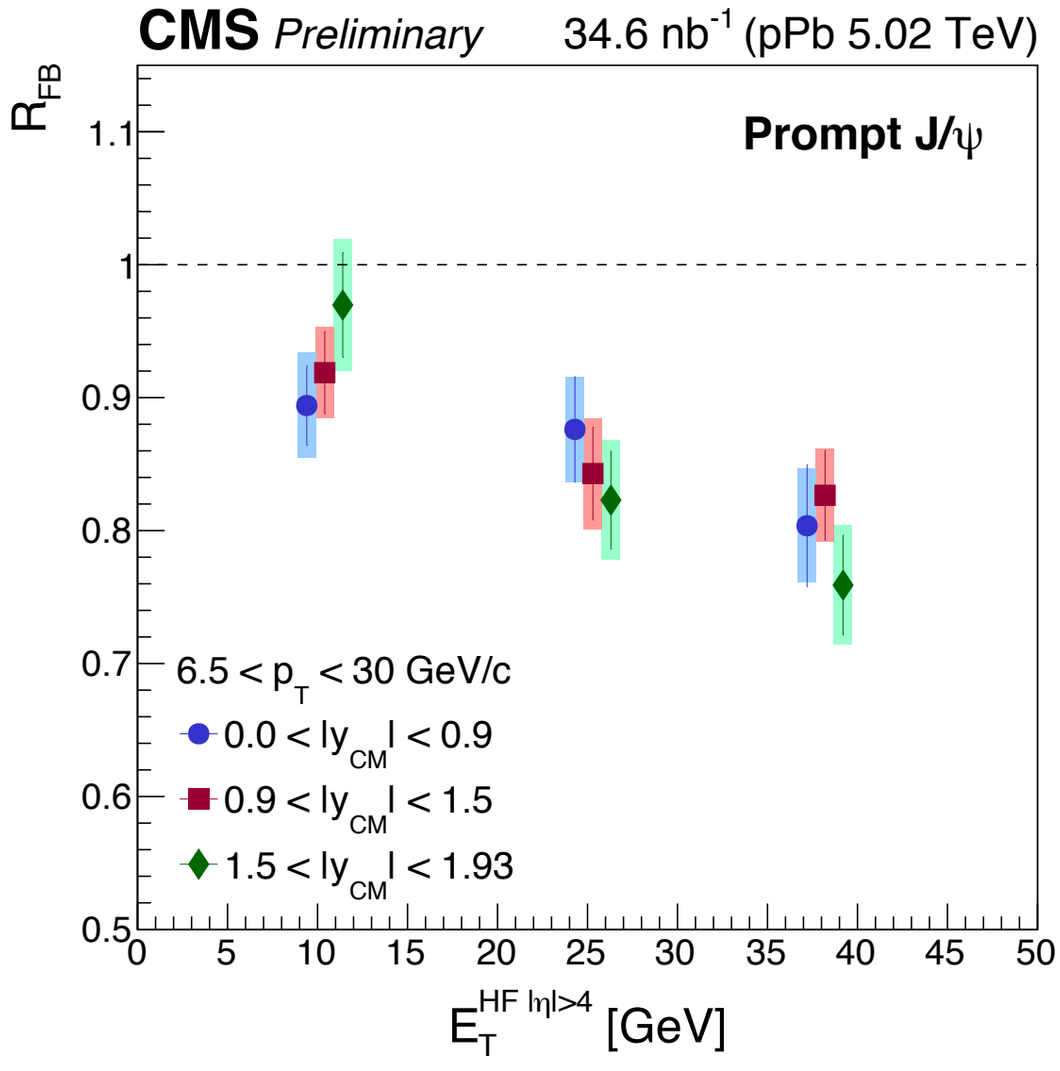
# J/ψ in pPb - event activity

CMS-PAS HIN-14-009

same $y_{CM}$
different $p_T$



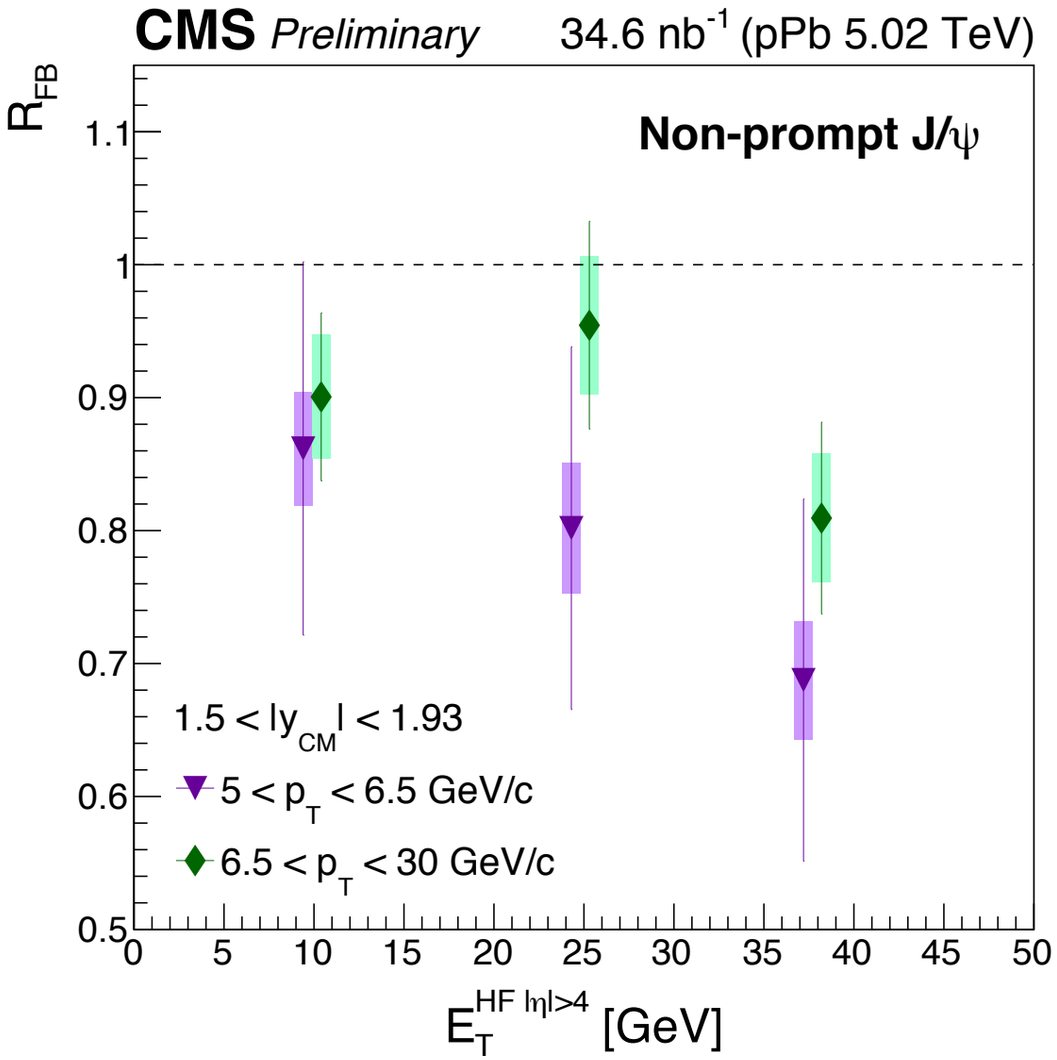

same $p_T$
different $y_{CM}$



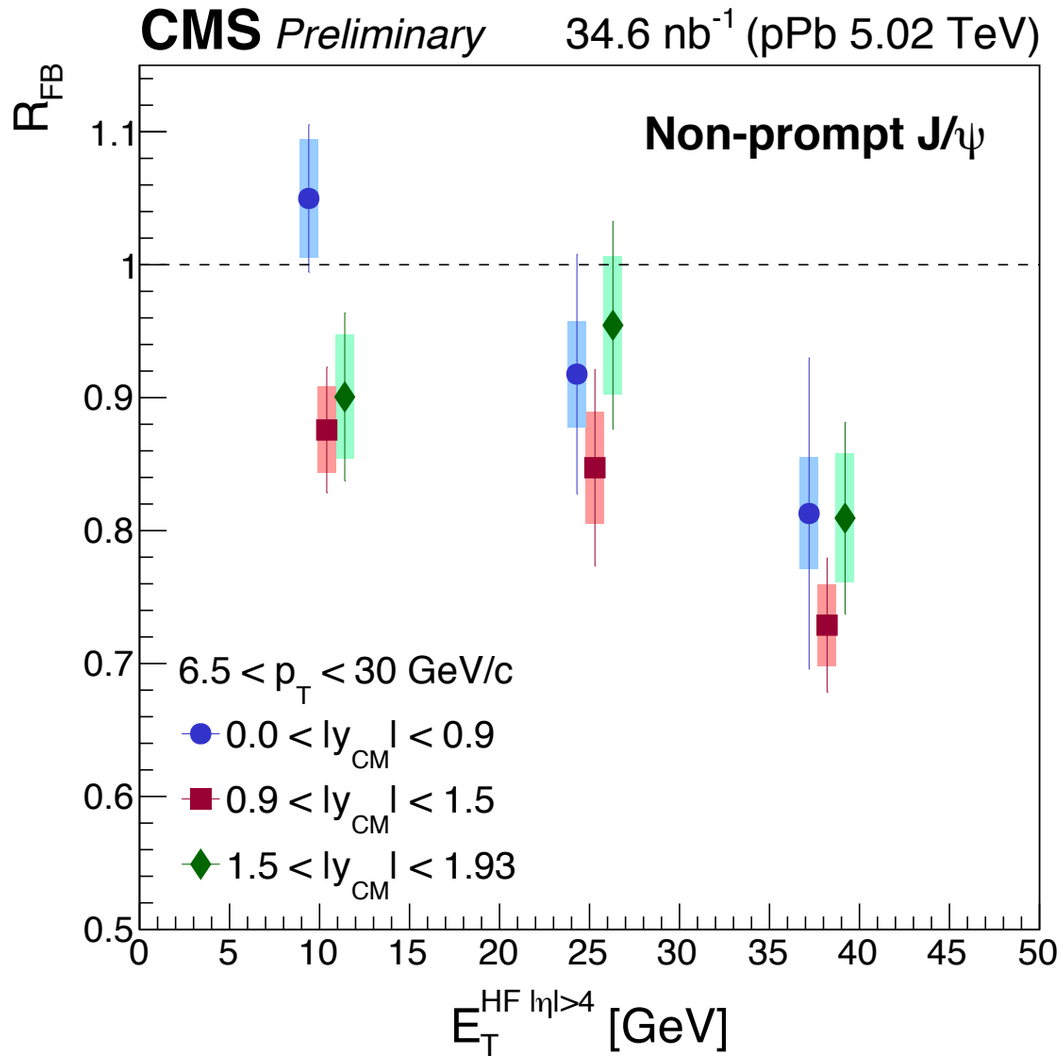
# J/ψ in pPb - event activity

CMS-PAS HIN-14-009

same $y_{CM}$
different $p_T$




same $p_T$
different $y_{CM}$

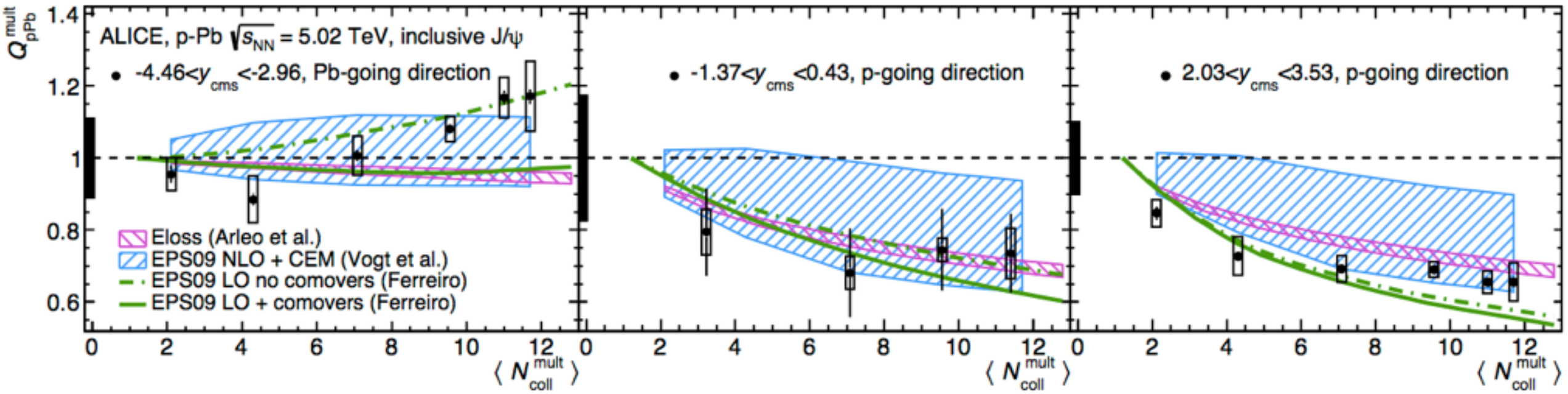


# $Q_{pPb}$ vs centrality (ALICE)

ALICE : JHEP 1511 (2015) 127

Backward

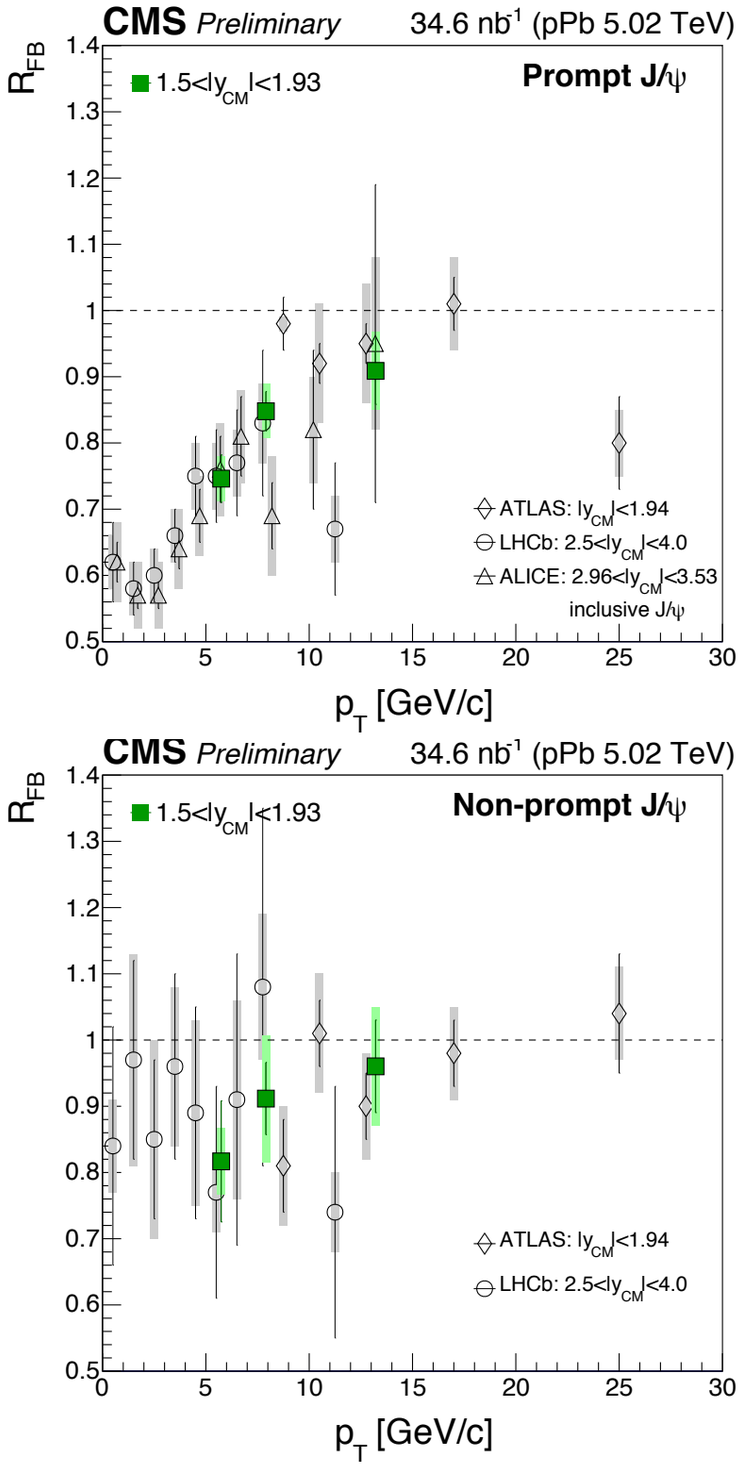
Forward

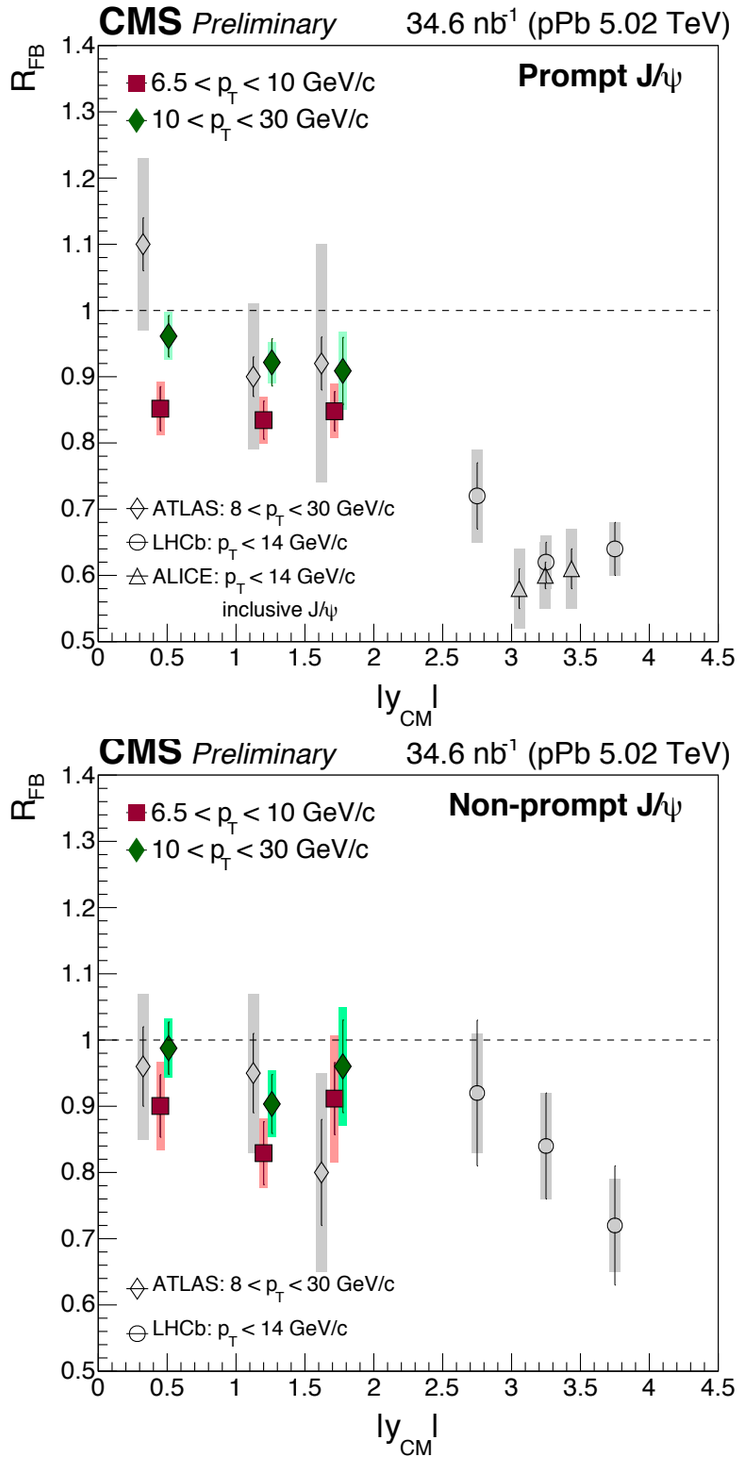



- $Q_{pPb}$ decreases with increasing centrality at forward
- $Q_{pPb}$ is rather flat or slightly increasing at backward
- Both in experimental data, and in CNM theoretical predictions

# Comparison with other experiments

- Prompt J/ψ :




- Non-prompt J/ψ :







ALICE : JHEP 1402 (2014) 073

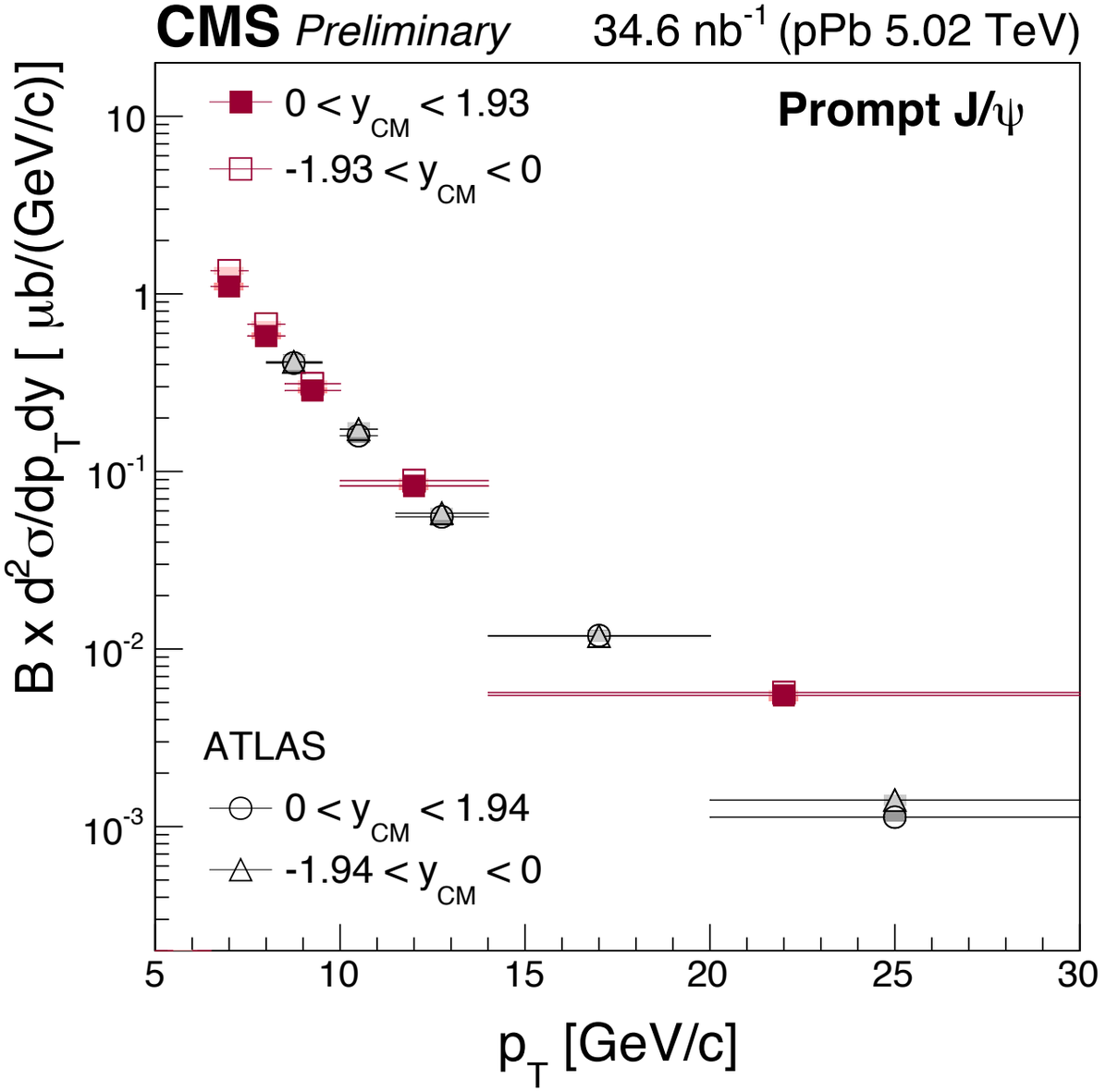
ATLAS : arXiv.1505.08141

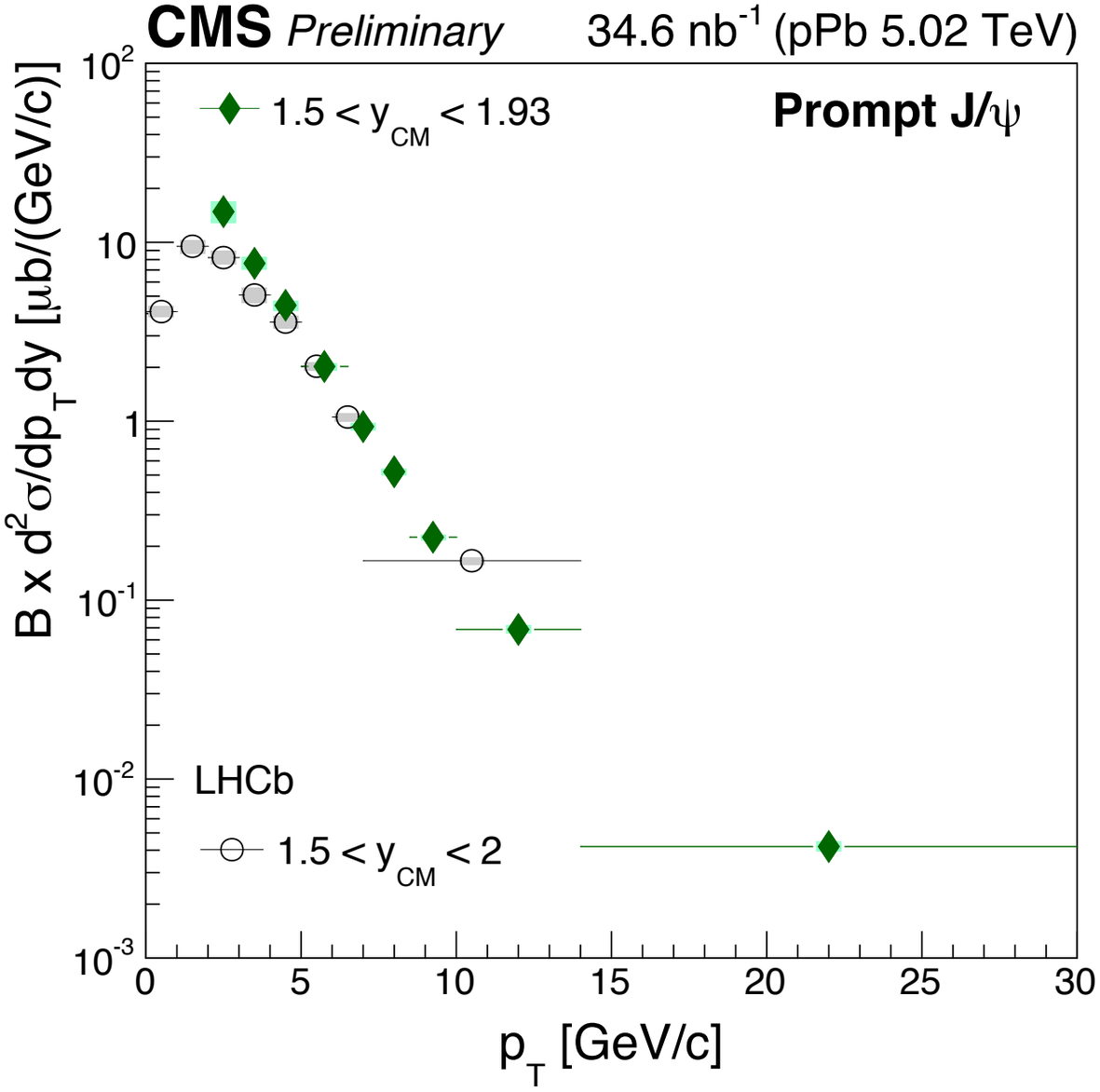
LHCb : JHEP 1402 (2014) 072

- Trends vs. $p_T$ and y are similar for all 4 experiments

# Comparison with other experiments

- Points are plotted in the middle of the bin



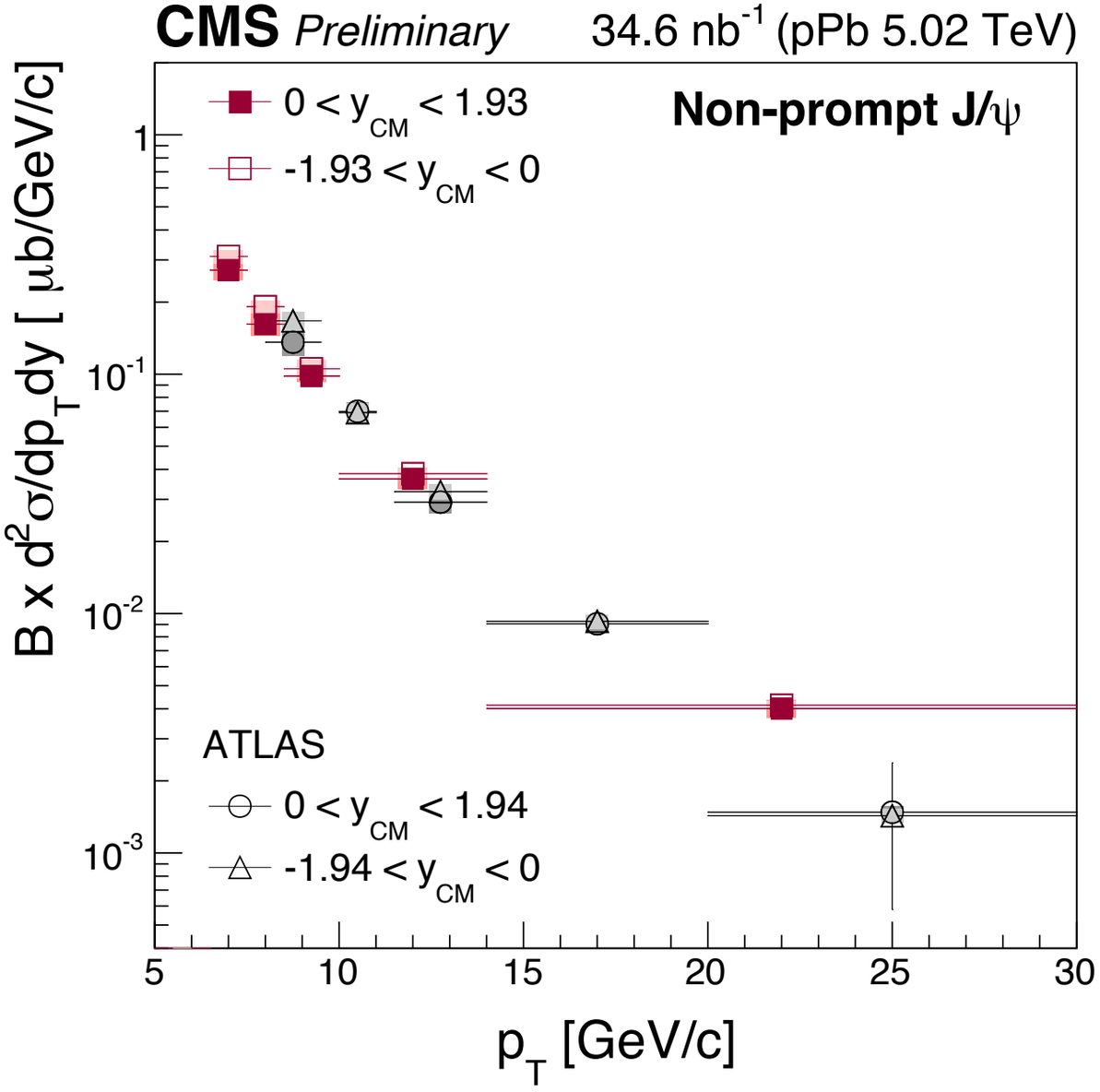



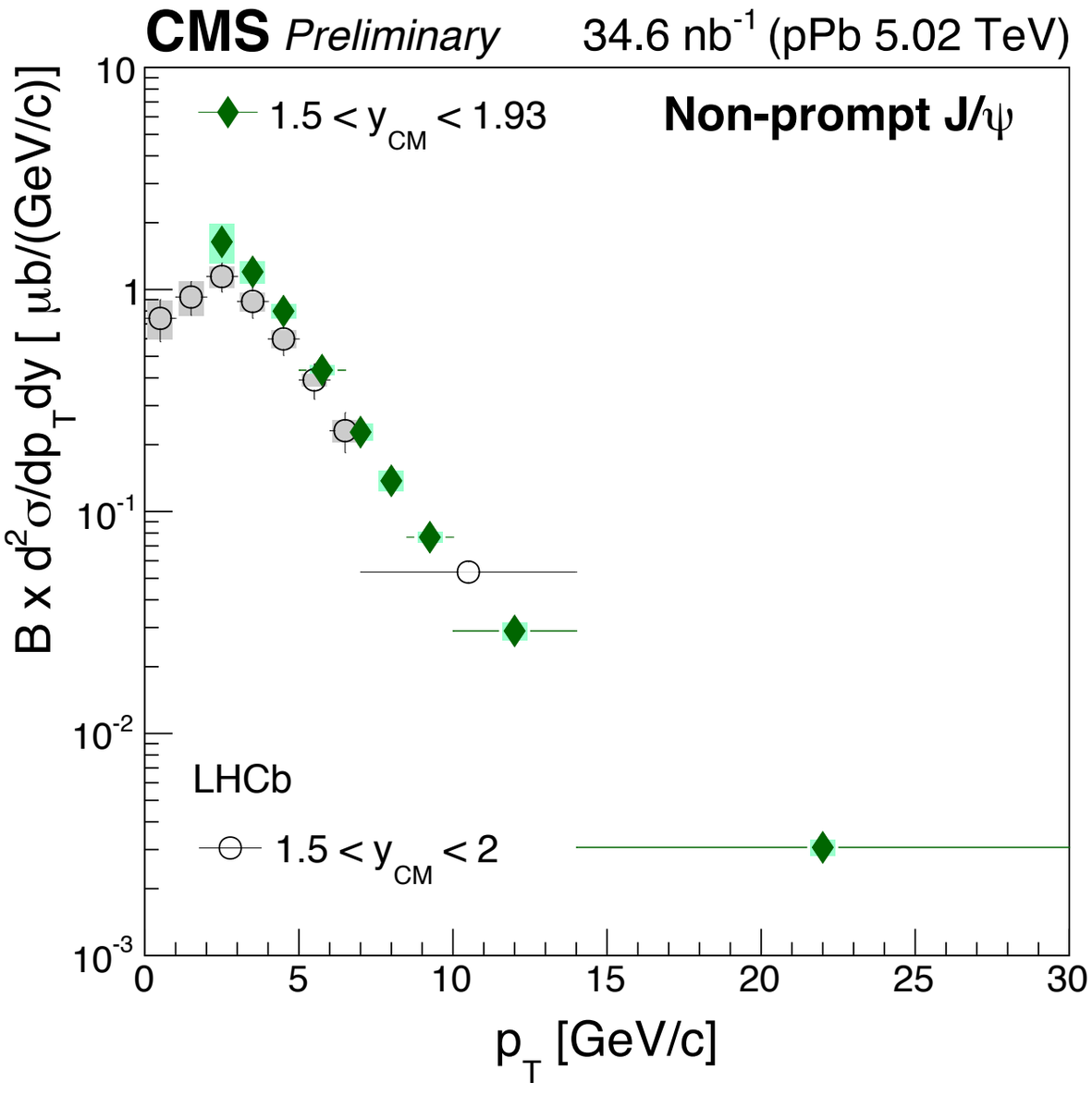

ATLAS : arXiv.1505.08141

LHCb : JHEP 1402 (2014) 072

# Comparison with other experiments

- Points are plotted in the middle of the bin




ATLAS : arXiv.1505.08141

LHCb : JHEP 1402 (2014) 072

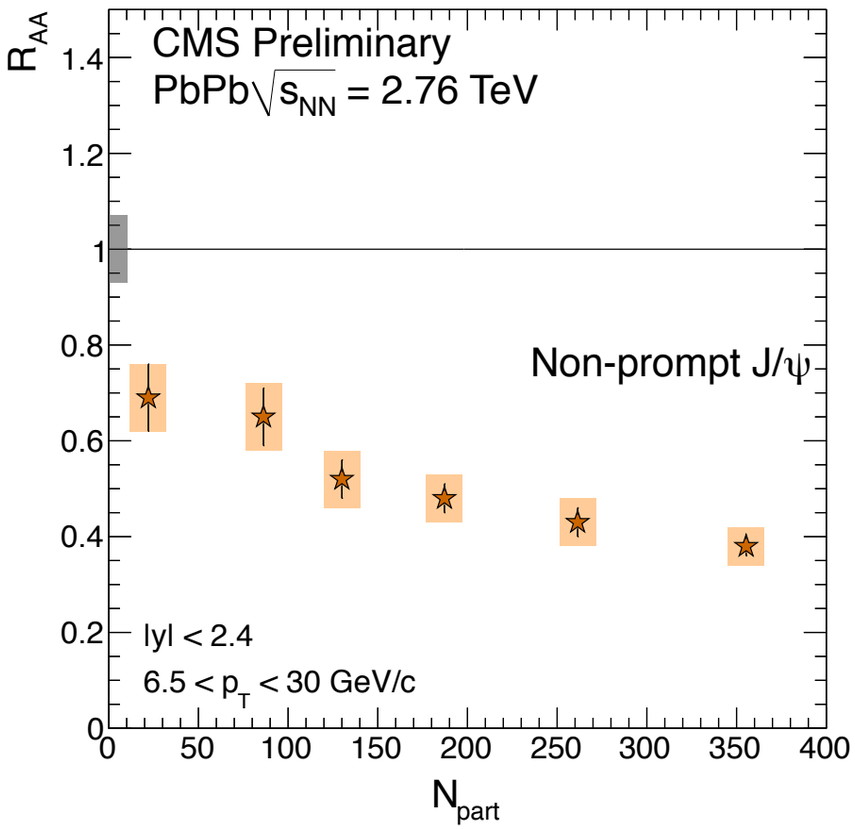
# Non-prompt J/ψ in PbPb

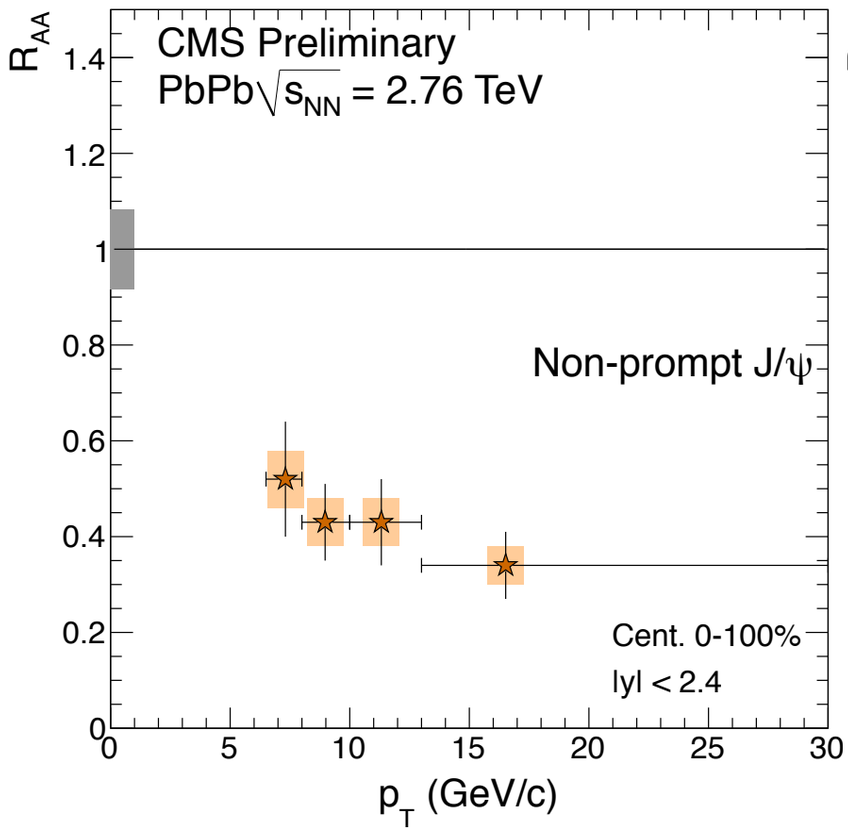
- Nuclear modification factor

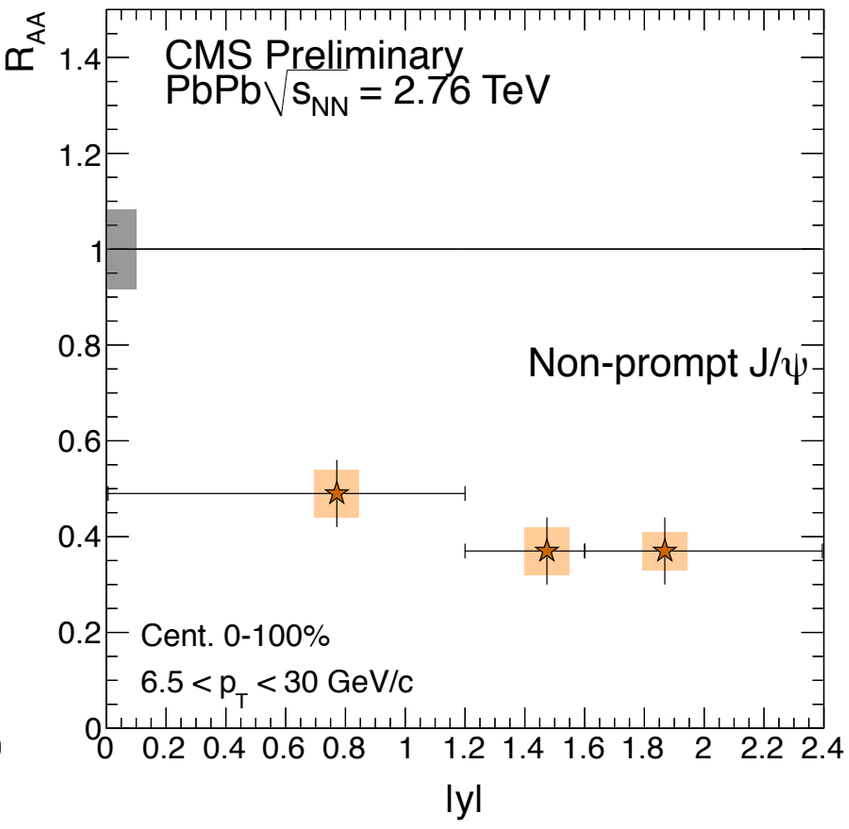
CMS-PAS HIN-12-014

$$R_{AA} = \frac{1}{T_{AA}} \cdot \frac{dN_{AA}}{d\sigma_{pp}} = \frac{L_{int}^{pp}}{T_{AA} N_{MB}} \cdot \frac{N_{J/\psi}^{PbPb}}{N_{J/\psi}^{pp}} \cdot \frac{\epsilon_{pp}}{\epsilon_{PbPb}}$$

- $R_{AA}$ < 1 : suppression
- $R_{AA}$ = 1 : no modification compared to pp
- $R_{AA}$ > 1: enhancement

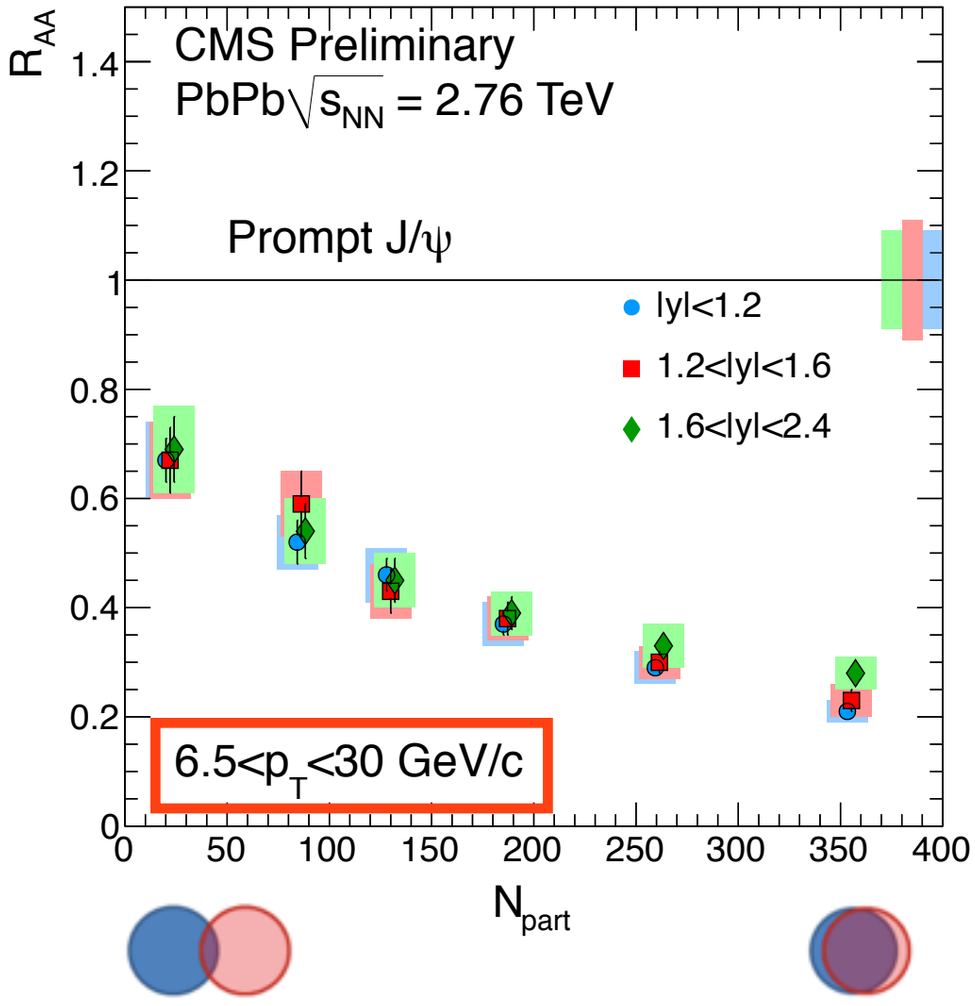


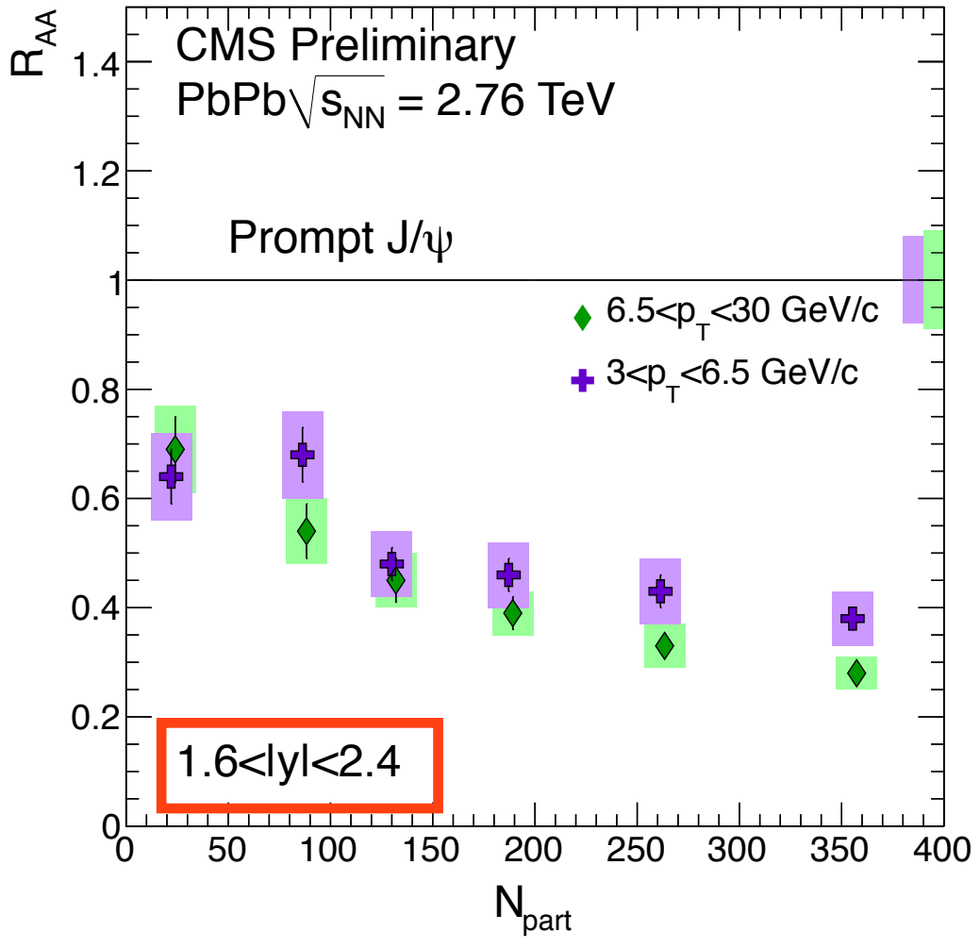




- More suppressed with increasing centrality (less than prompt)
- No significant $p_T$ and rapidity dependence

# prompt J/psi (differential)

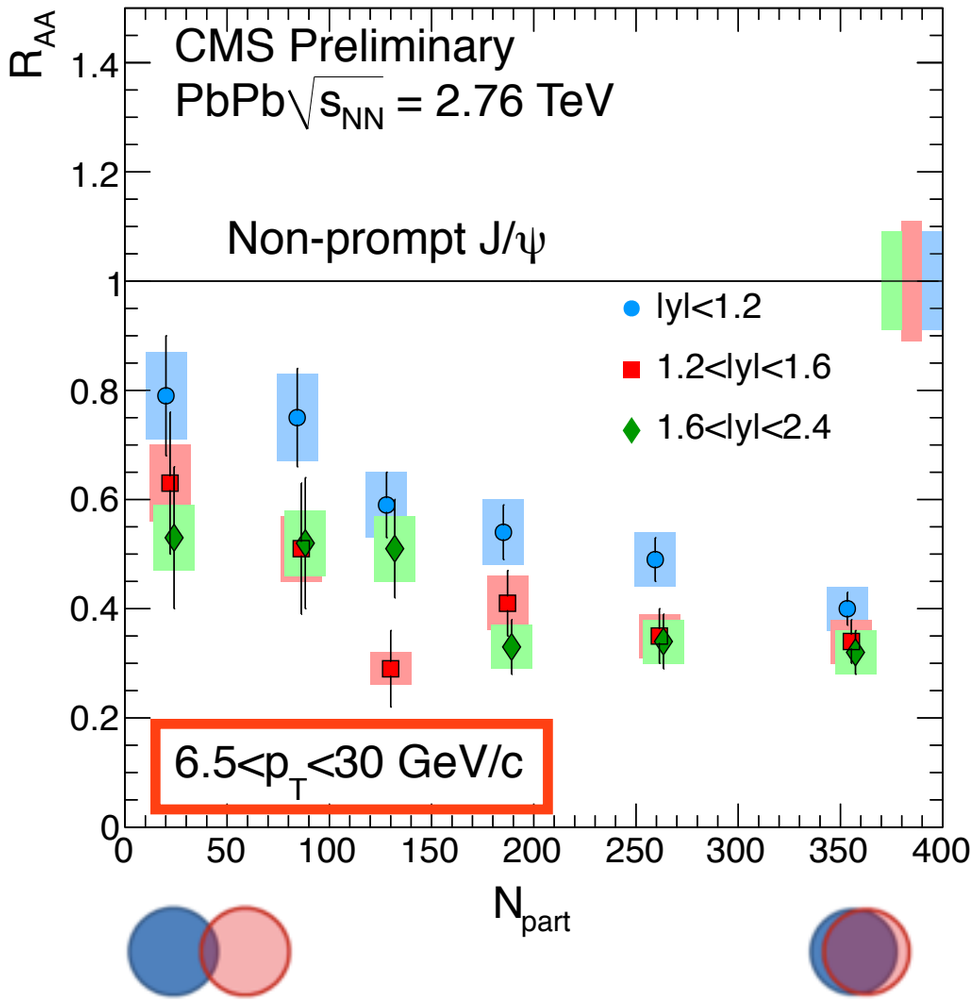


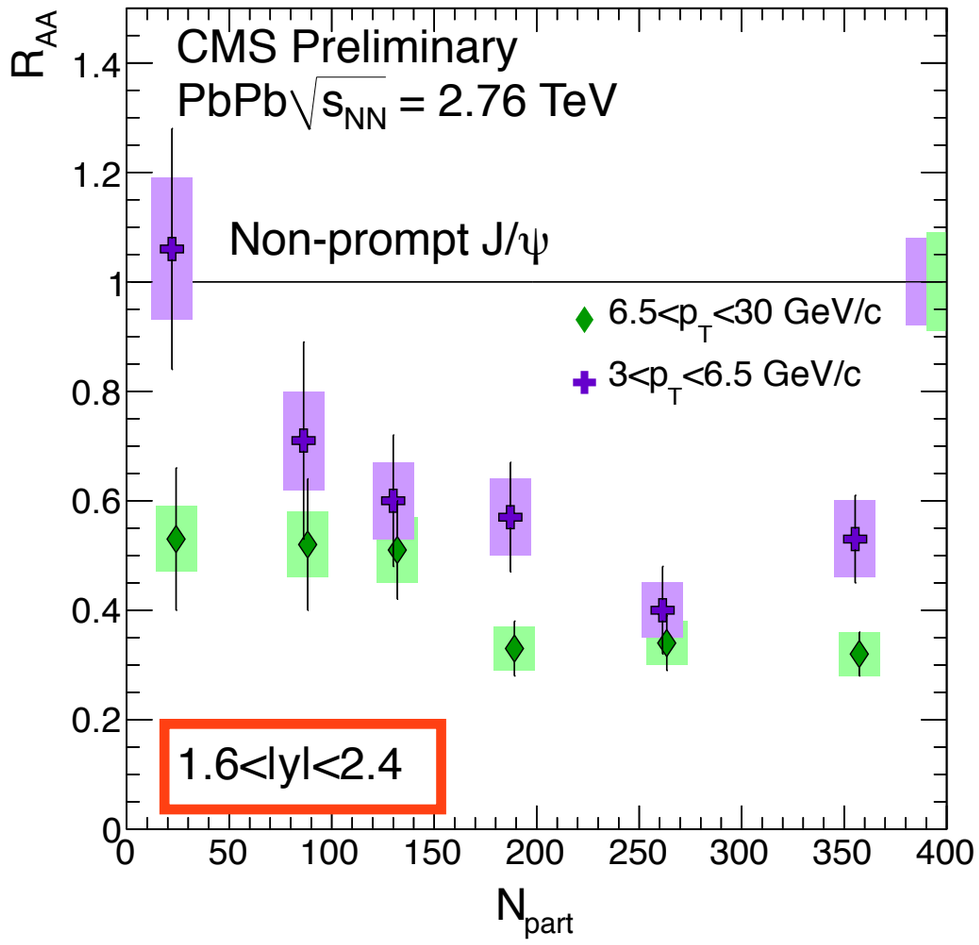

- No strong dependence on rapidity at high $p_T$
- At forward, lower $p_T$ J/ψ is slightly less suppressed in most central

# Non-prompt J/psi (differential)

## Rapidity dependence

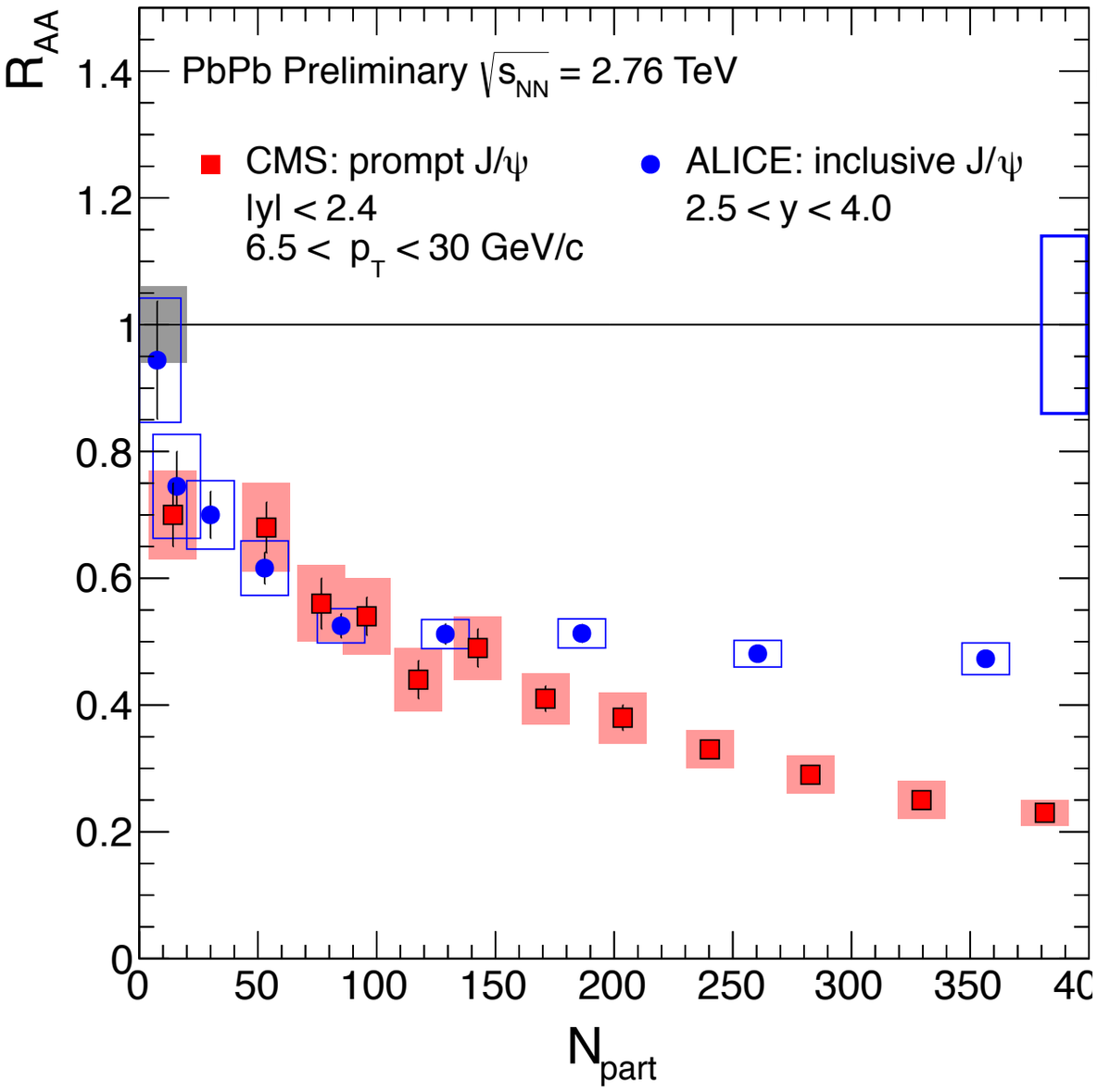


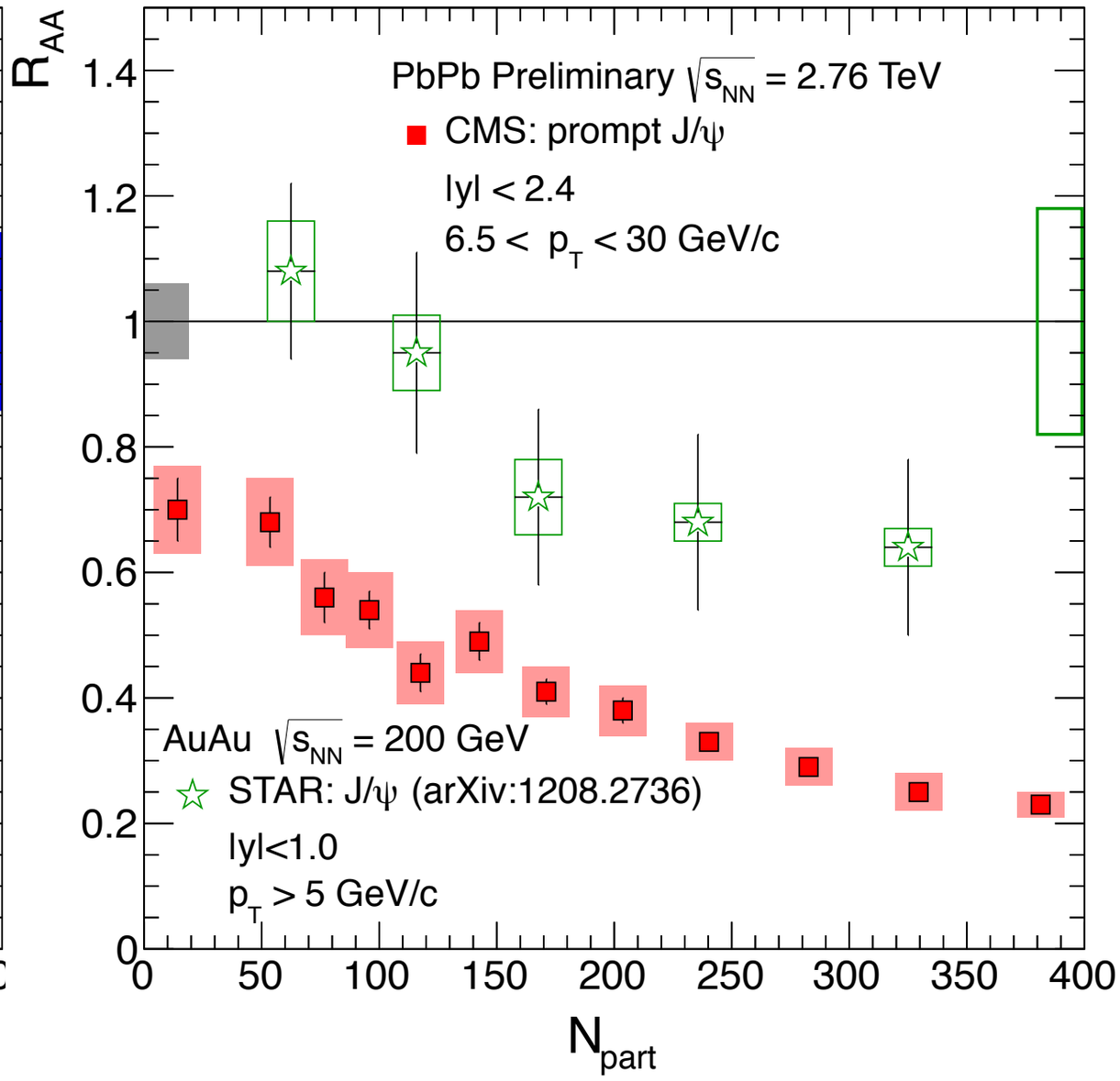

## $p_T$ dependence



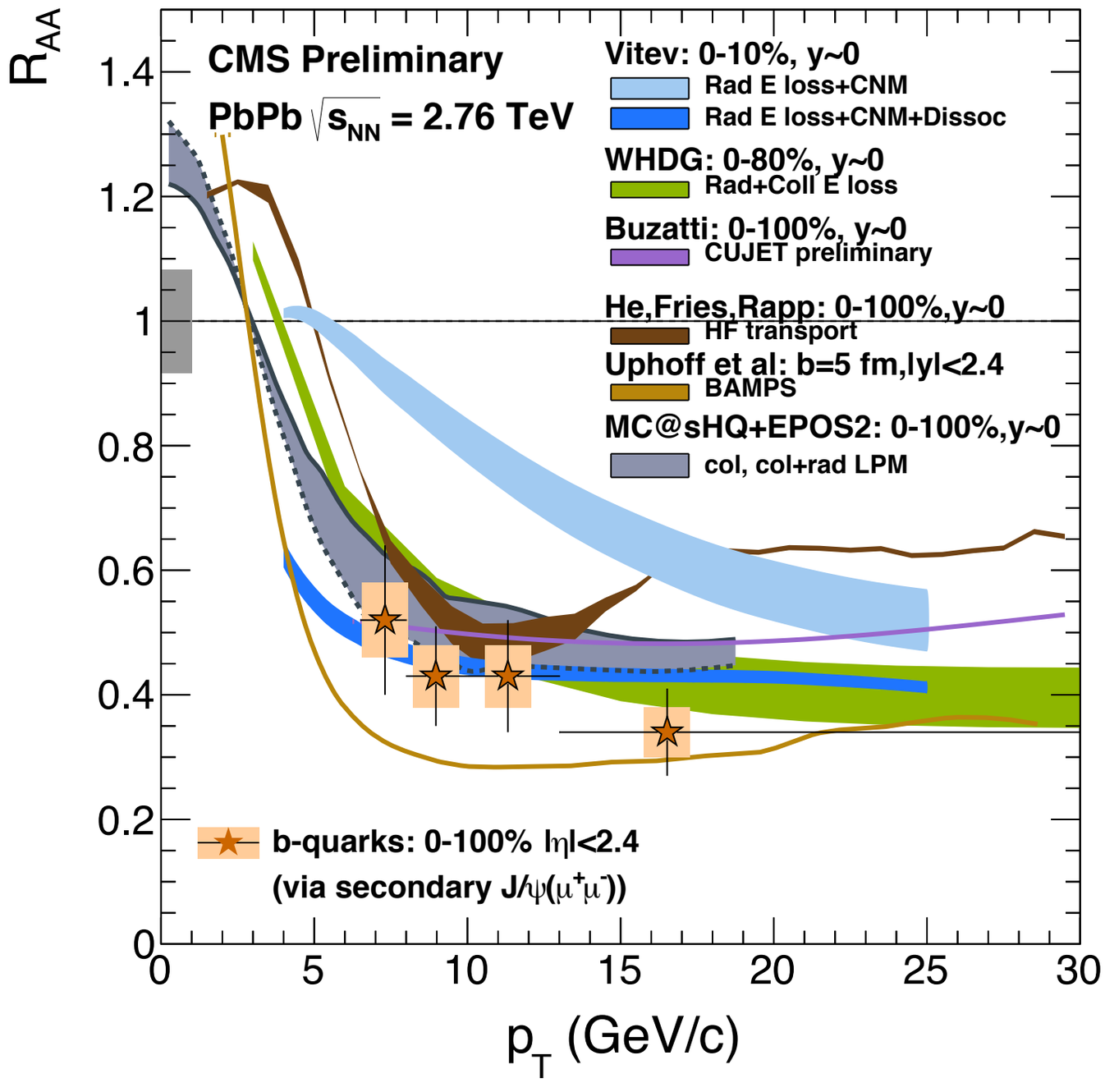

- No strong dependence on rapidity at high $p_T$
- At forward, lower $p_T$ J/ψ has strong dependence and less suppressed than higher pT J/ψ

# Comparison with other exp.



# Comparison with theory



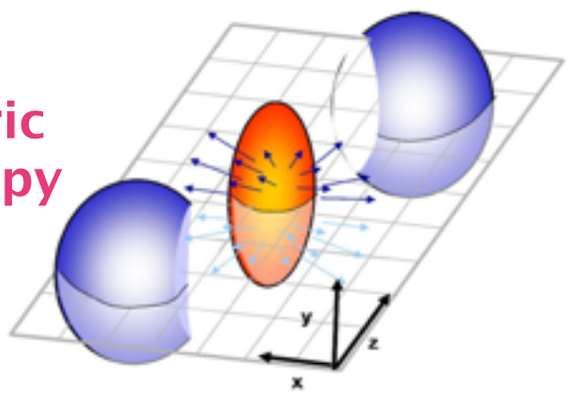
# J/ψ azimuthal anisotropy

CMS-PAS HIN-12-001

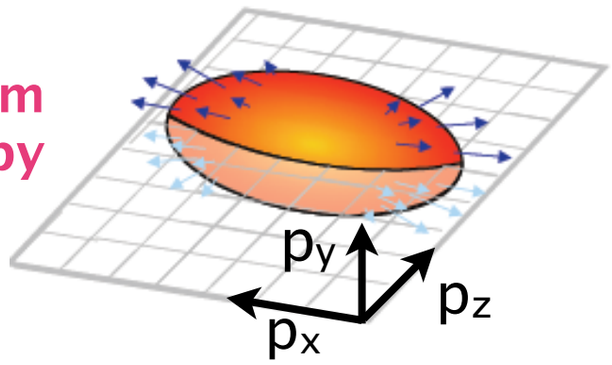
- **Elliptic flow ($v_2$)**
  - Important to understand the dynamics of heavy-ion collision

**In non-central collisions**

**Initial geometric anisotropy**



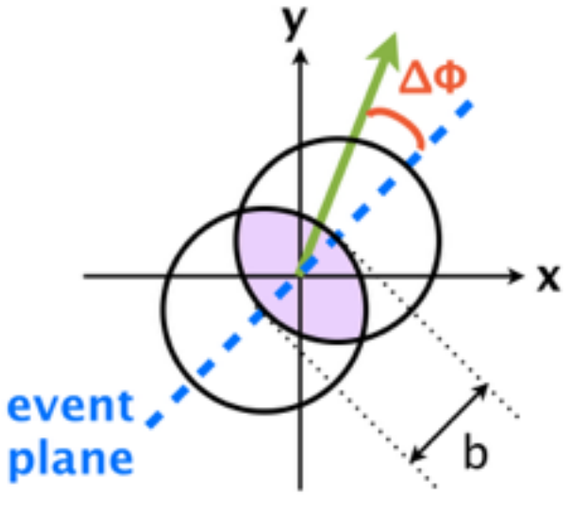

**Final momentum anisotropy**

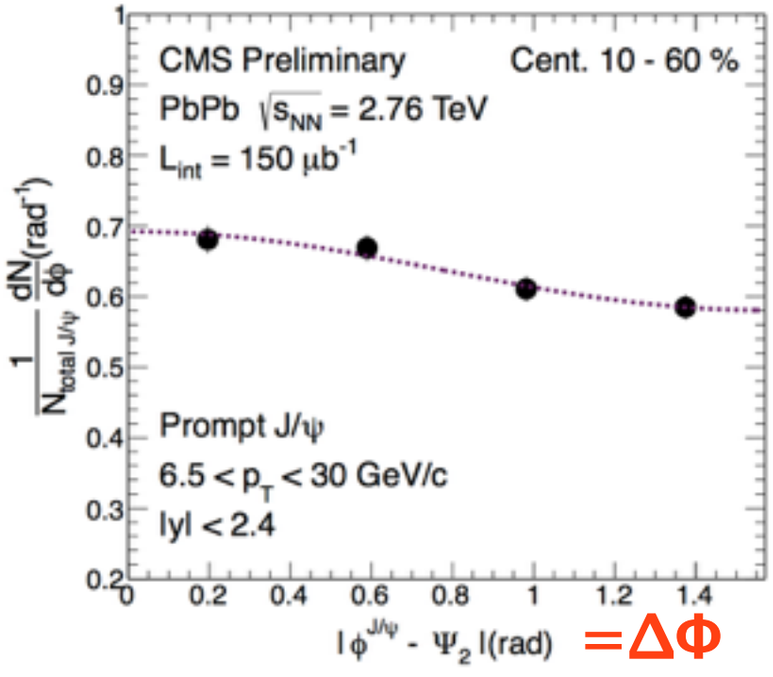



→ Asymmetry in the collective expansion

→ Path-length dependent absorption

- Reflected in the azimuthal distribution of particle yields

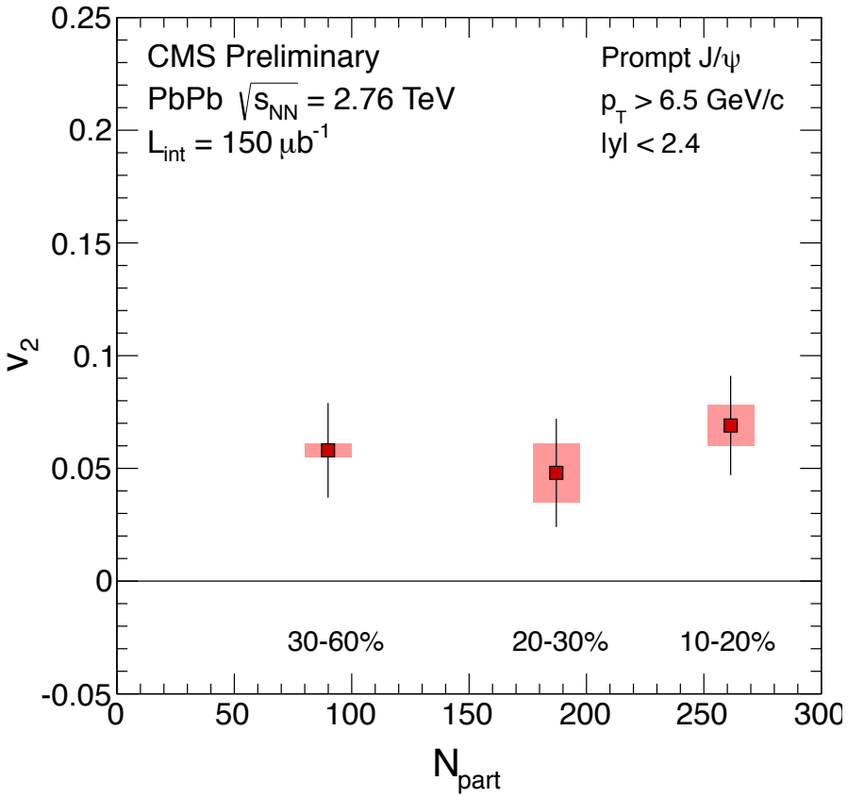


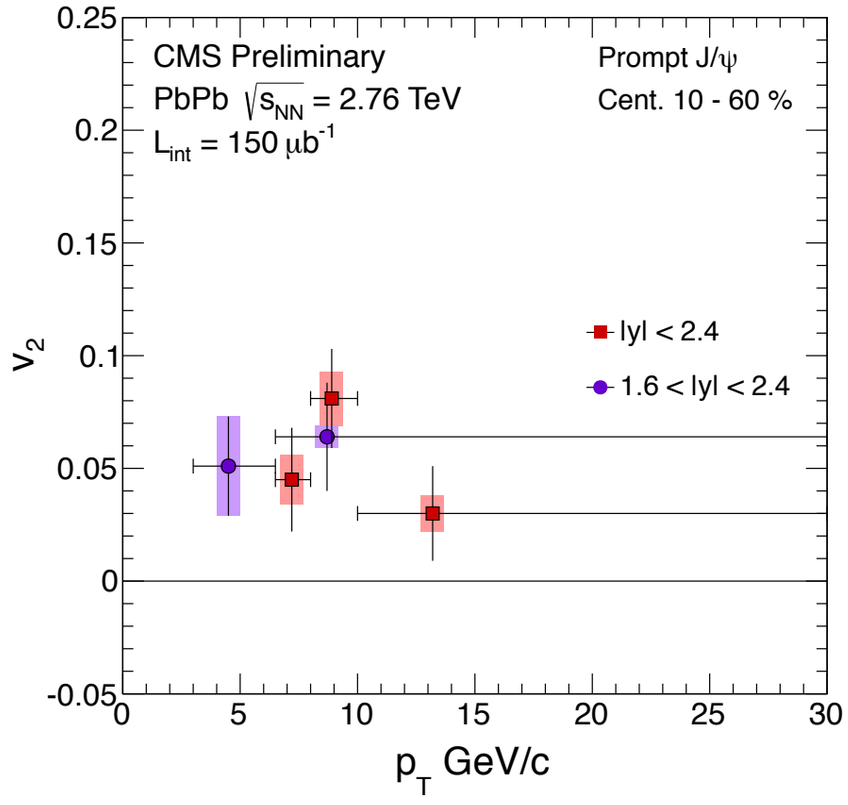



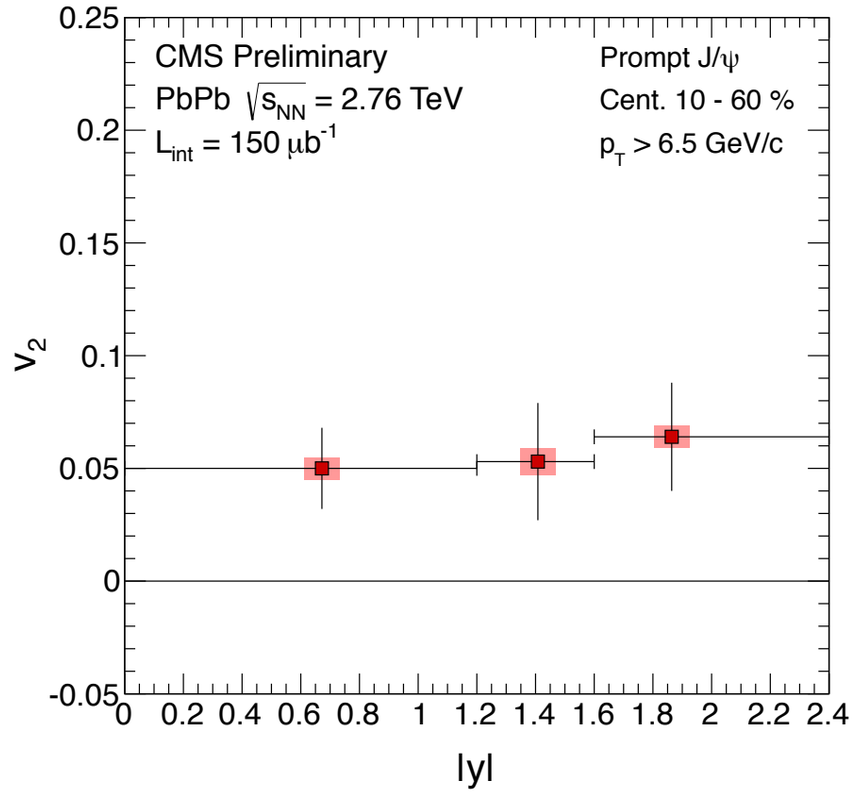

$$\frac{1}{N_{total}} \cdot \frac{d^2N}{d\phi} \propto 1 + 2v_2\cos(2\Delta\phi)$$

# J/ψ $v_2$ in PbPb

CMS-PAS HIN-12-001

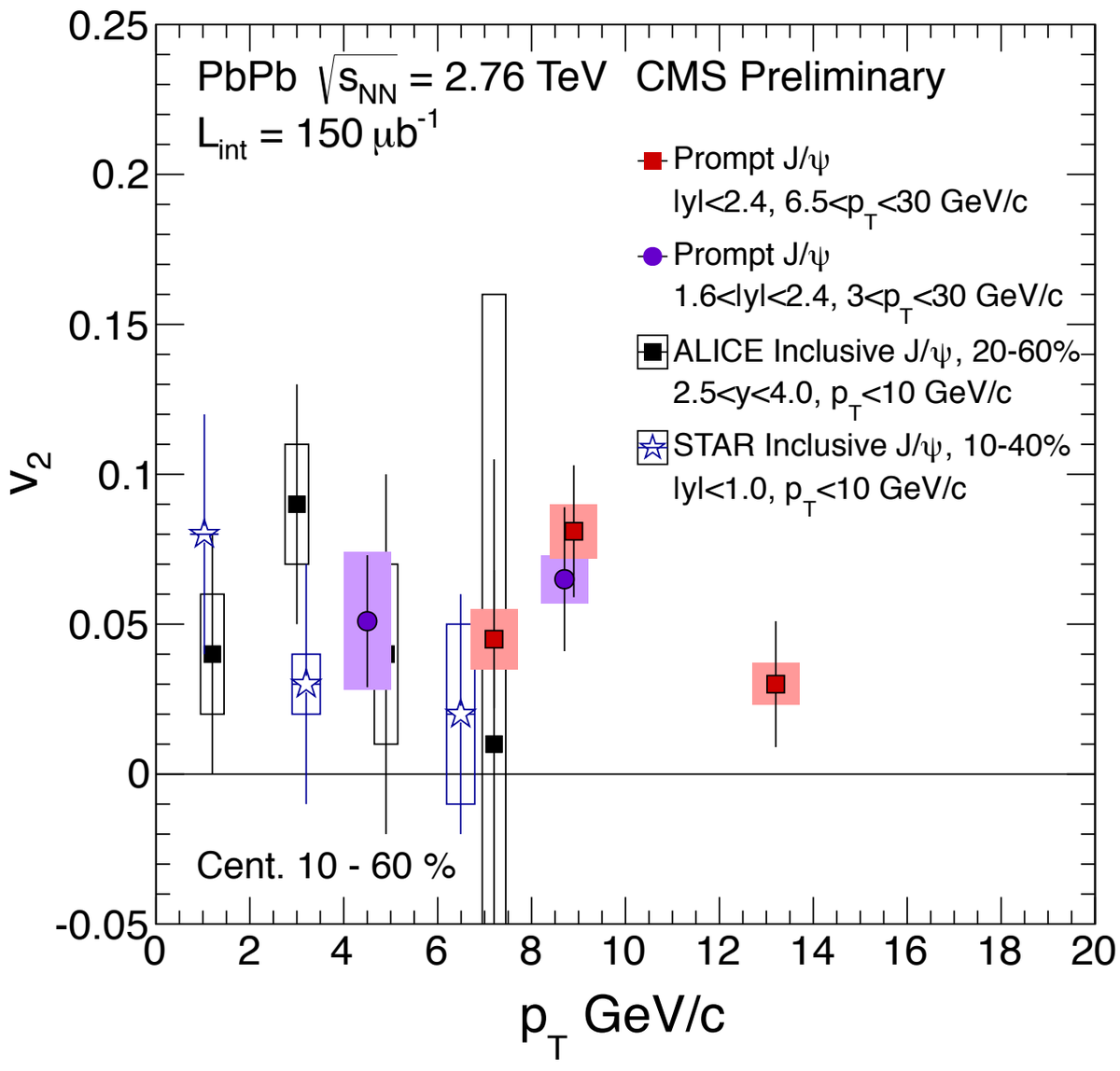



- J/ψ has a non-zero v2 : 0.054 ± 0.01(stat.) ± 0.006(syst.)
- No strong centrality, $p_T$ and rapidity dependence

# Non-prompt J/ψ in PbPb

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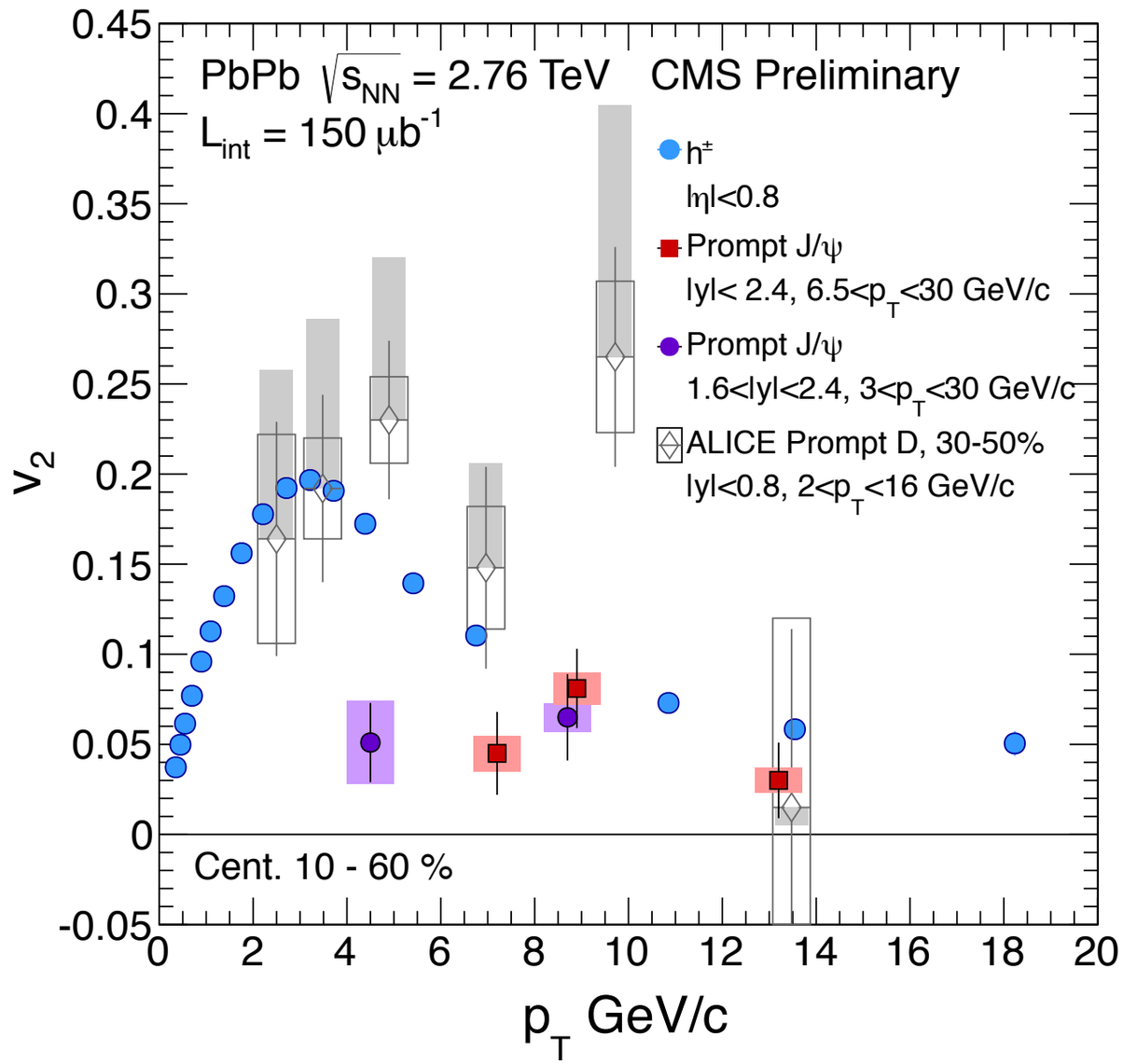
# Non-prompt J/ψ in PbPb




- J/ψ $v_2$ at low $p_T$ at is much smaller than hadron $v_2$ while higher pT shows similar $v_2$
- $D_0$ v2 has similar trend to hadron rather than J/ψ