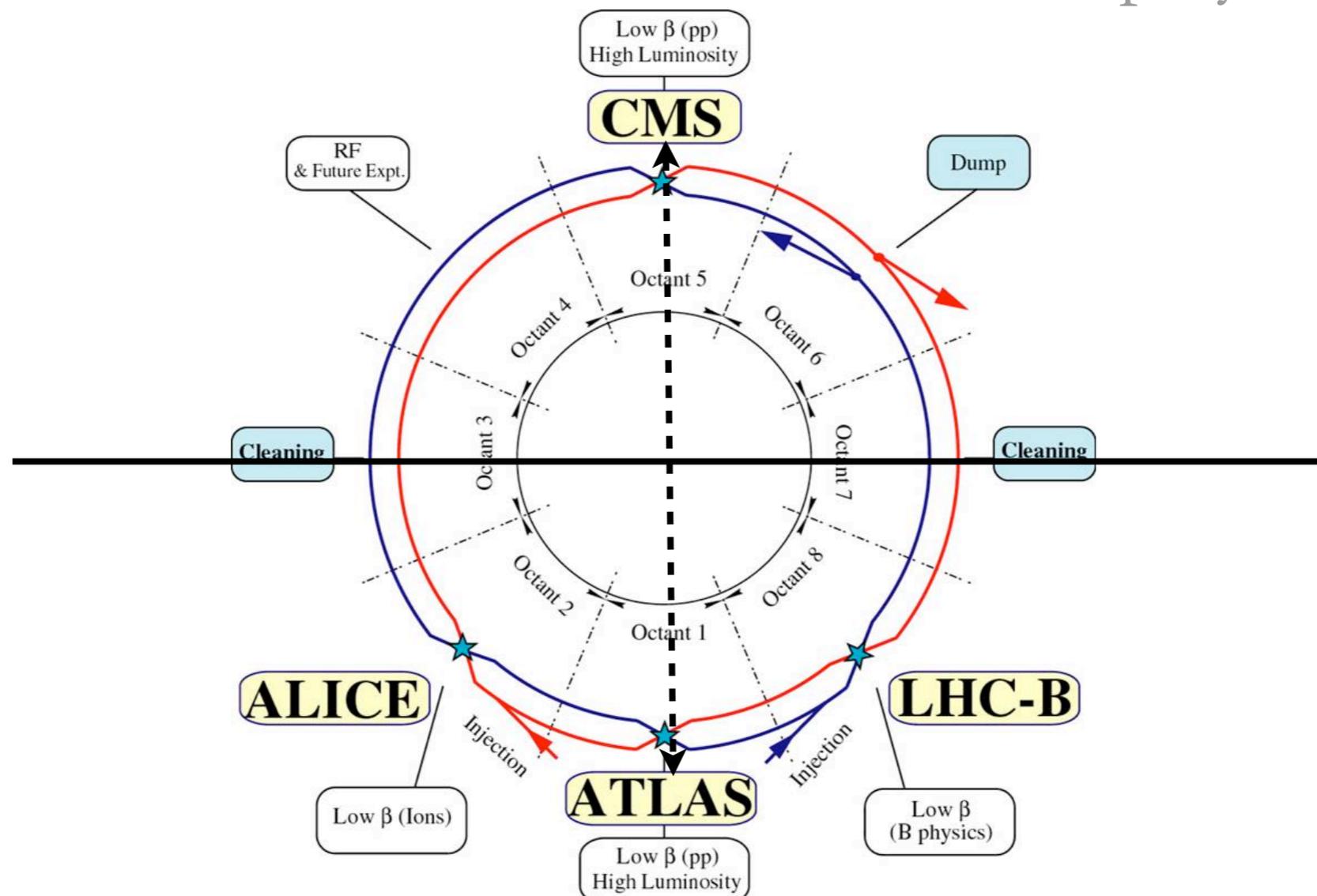


# Heavy-ion physics with CMS (and ATLAS)

(hard probes highlights)

Camelia Mironov

LLR/Ecole polytechnique



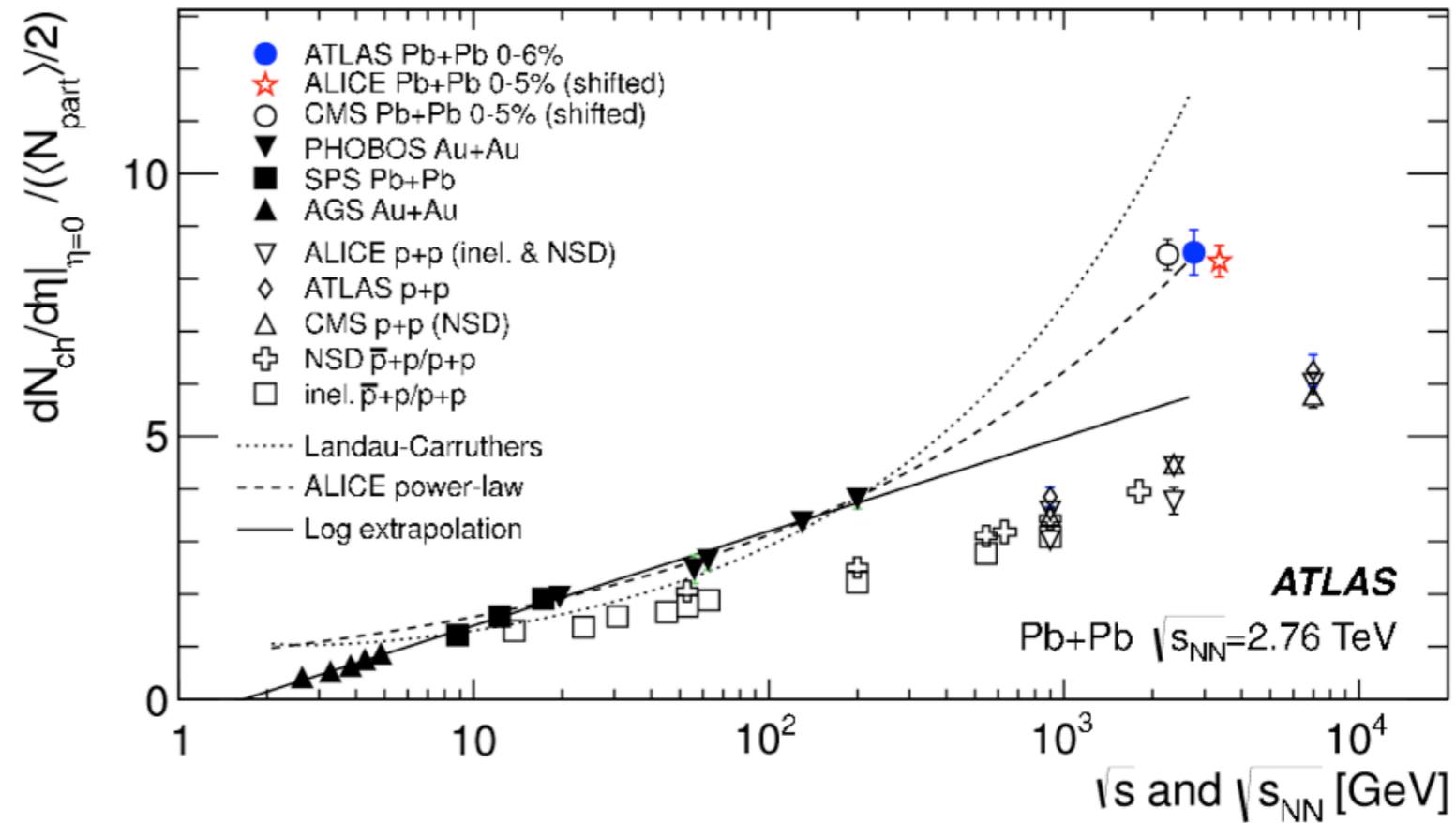
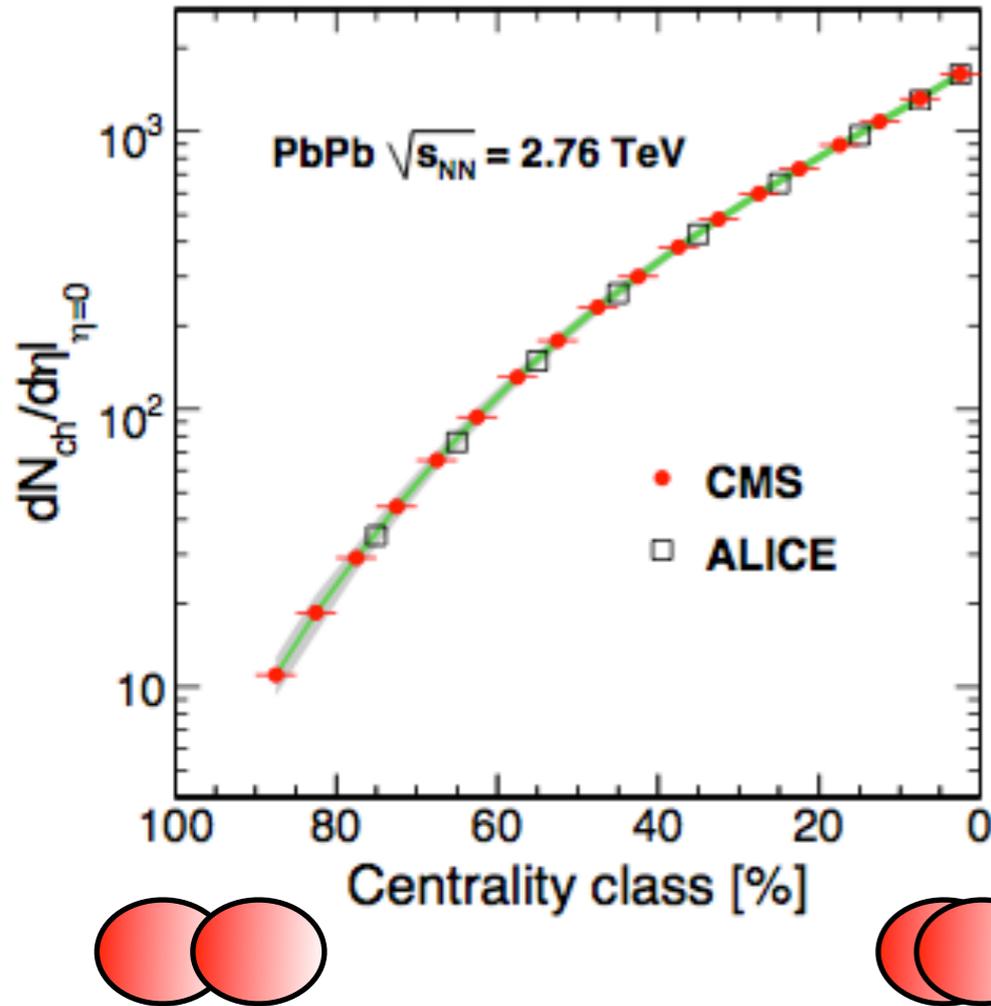
LM



# AA vs pp collisions

CMS, JHEP 1108 (2011)

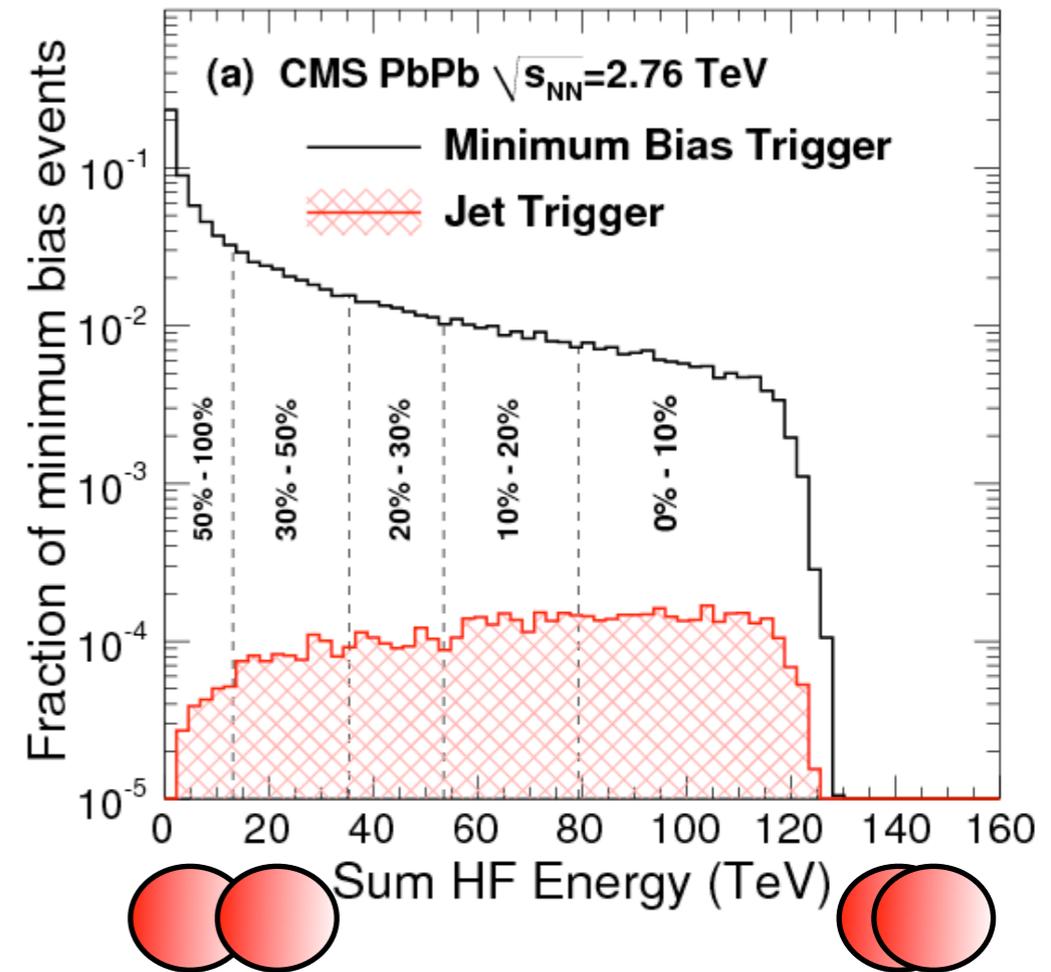
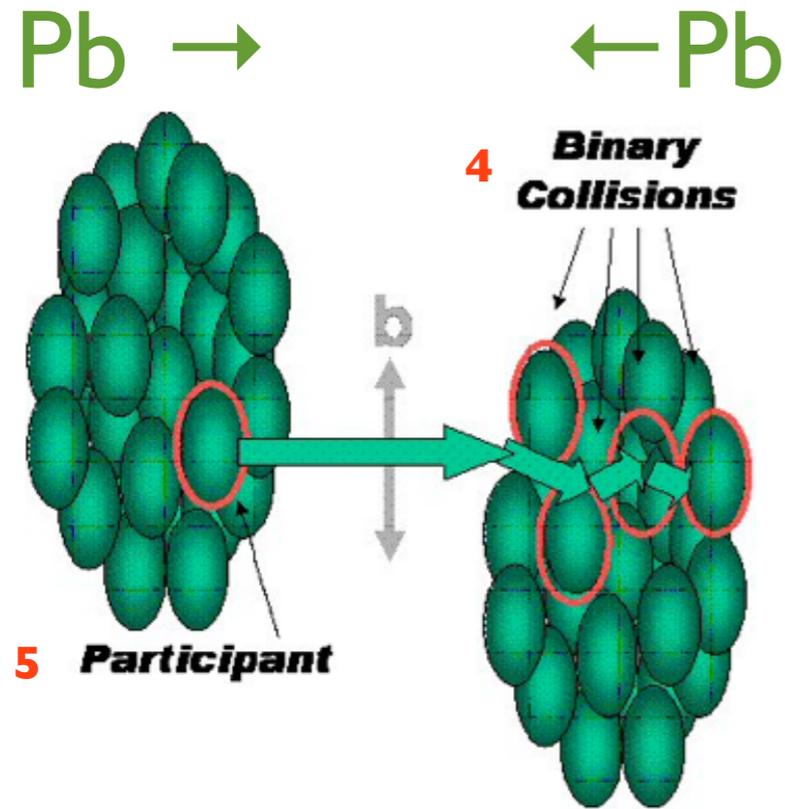
ATLAS, PLB 710 (2012)



⊙ AA is not just a superposition of pp events!

➡ Much higher charge particle density produced in AA compared to pp collisions

# AA collisions



⊙ Not all AA collisions are the same: centrality!

➡ data: energy deposited in forward calorimeters (both ATLAS and CMS)

➡ Glauber MC: map centrality to geometrical quantities

▶ number of elementary NN collisions ( $N_{coll}$ )

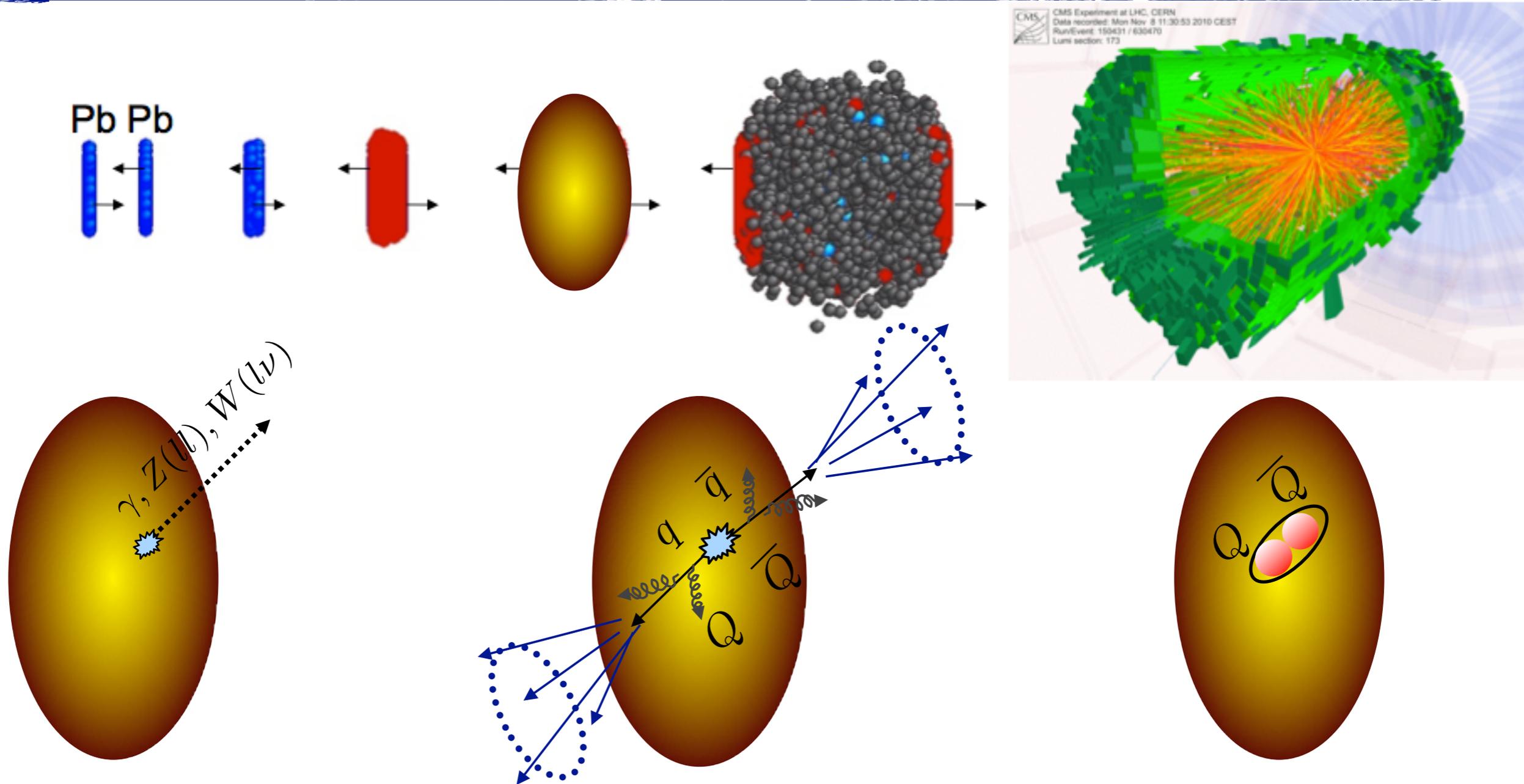
▶ number of participants ( $N_{part}$ )

⊙ Compare to pp ('vacuum' reference):

- = 1 no modification (hard probes)
- < 1 suppression

$$R_{AA} = \frac{N_{AA}}{N_{pp}} \frac{1}{N_{coll}}$$

# AA collisions

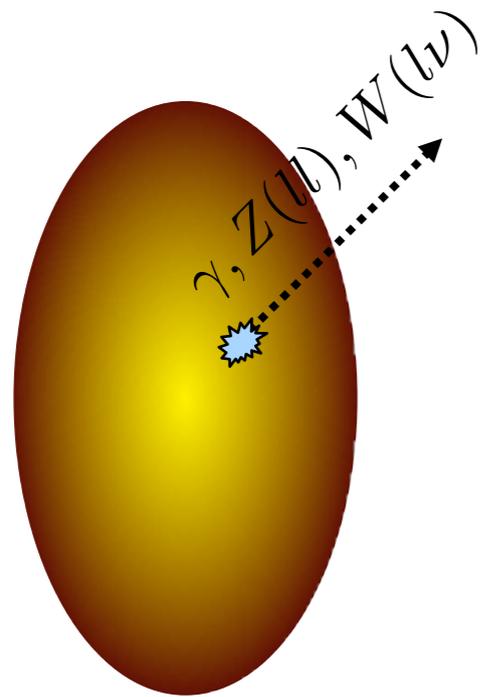


☉ Test medium evolution and properties via modifications of known probes

➡ jets: energy loss of light vs heavy partons

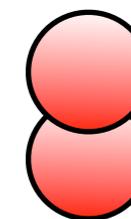
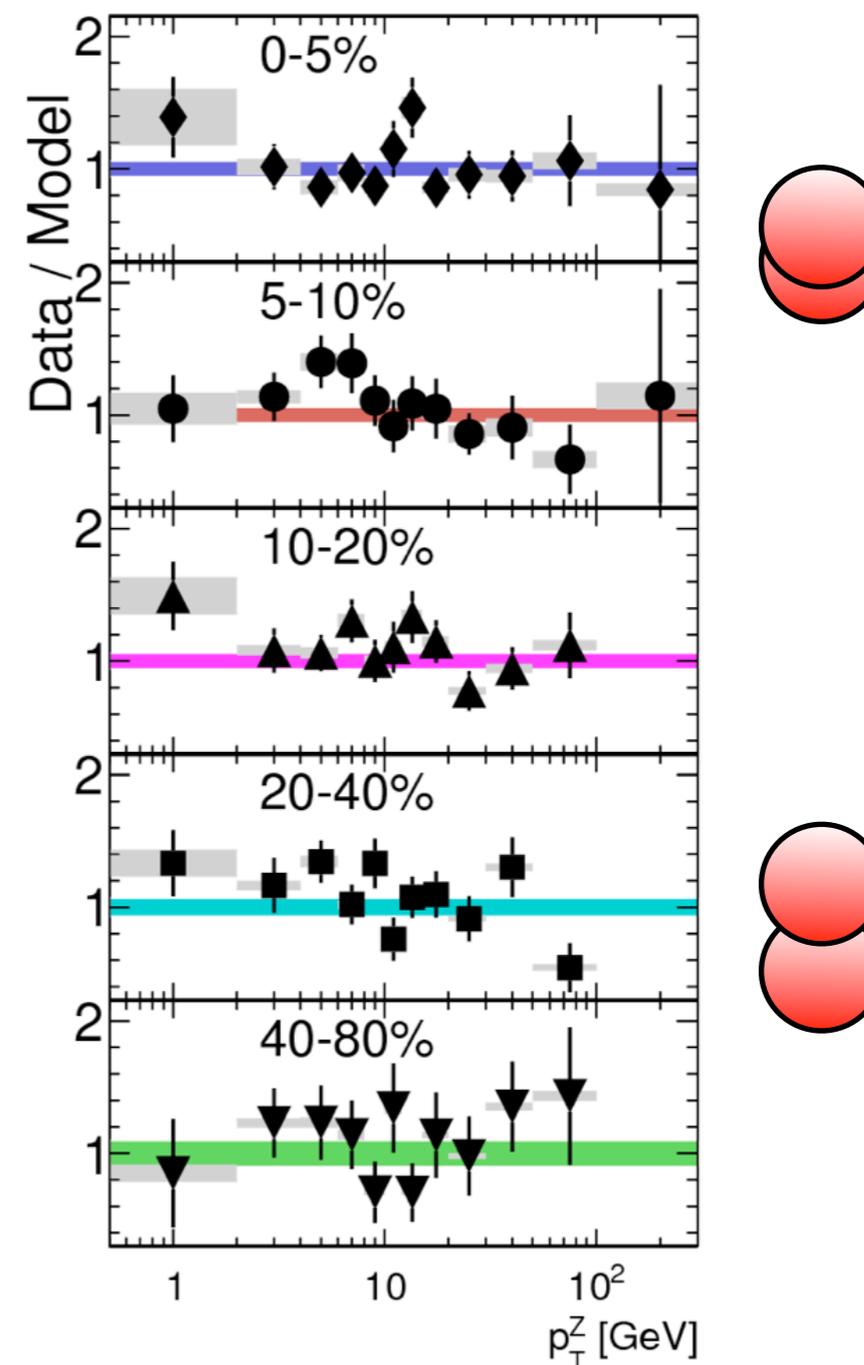
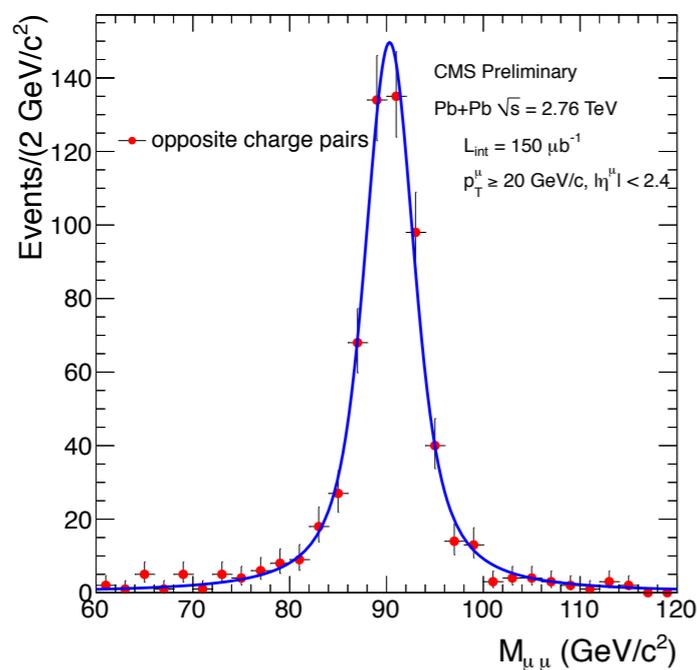
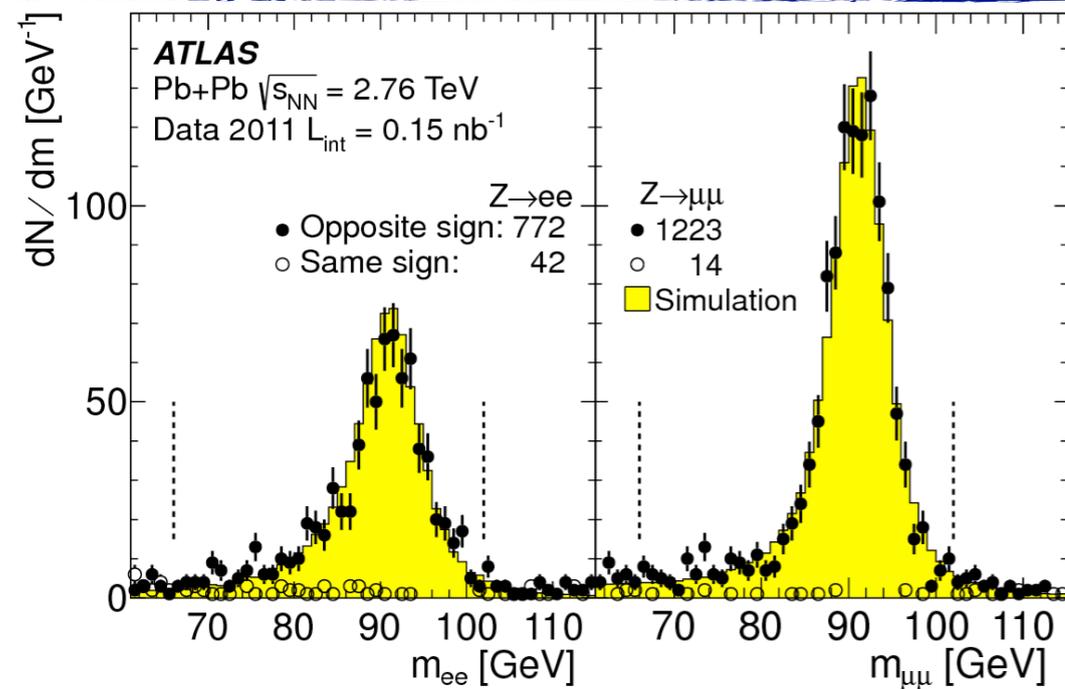
➡ quarkonia

➡ electroweak bosons: control probes



◎ Probes not affected by the medium: electroweak bosons

# Z → ll

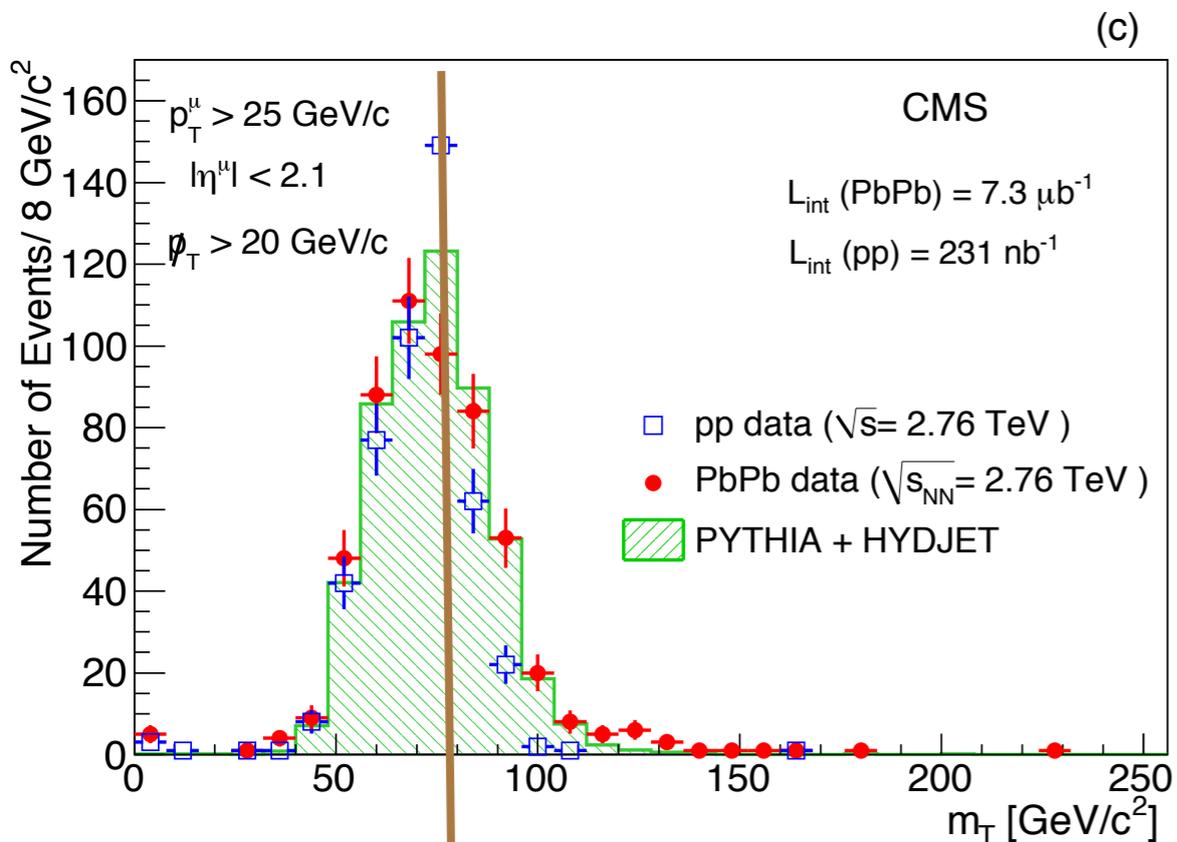
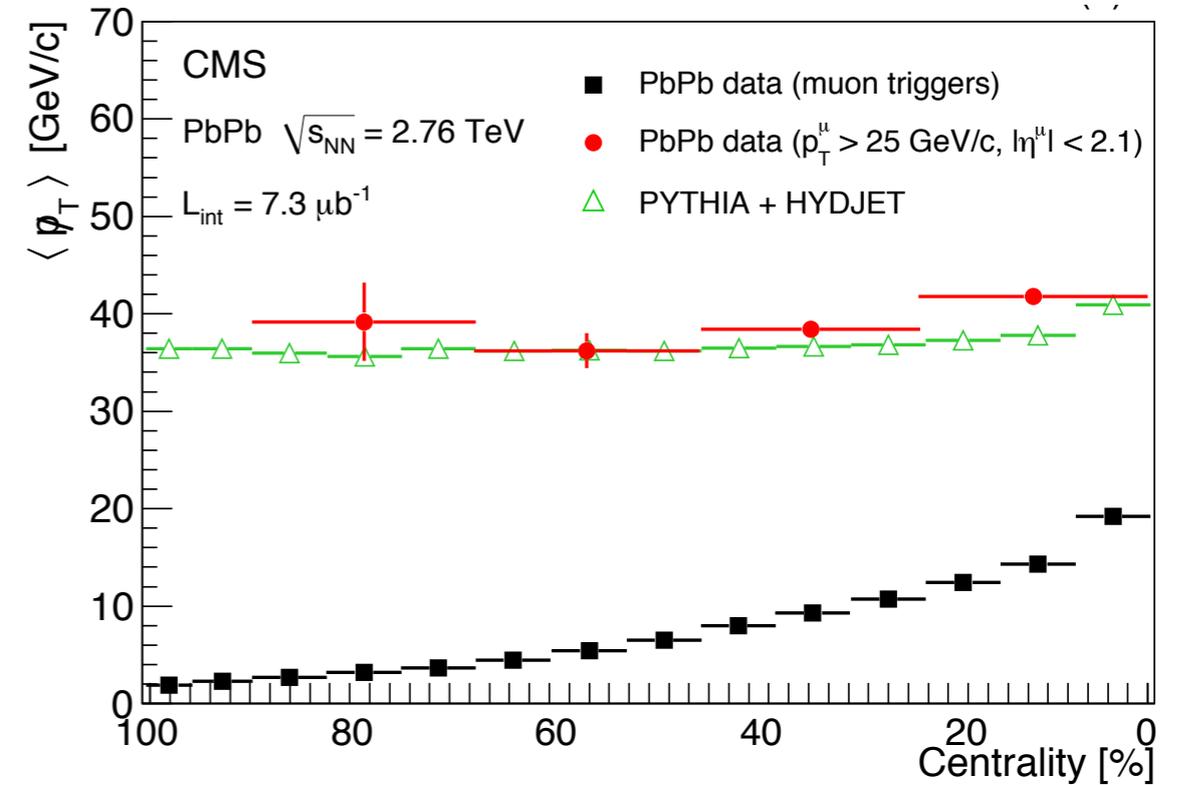
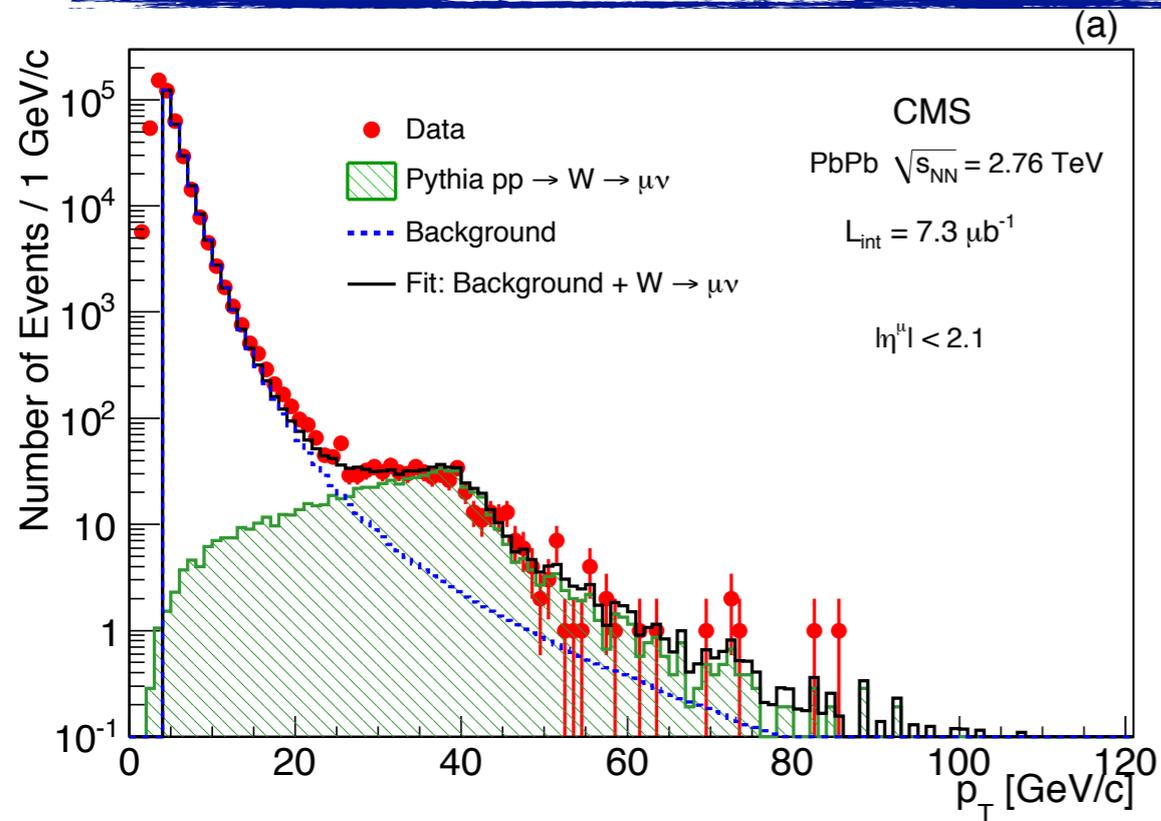


● Reference: PYTHIA normalized to NNLO x-section, scaled by  $N_{coll}$

● **Z → ll is unmodified by the medium**

➔ initial state effects small (nPDF, isospin)

# $W \rightarrow \mu\nu$



Signature:

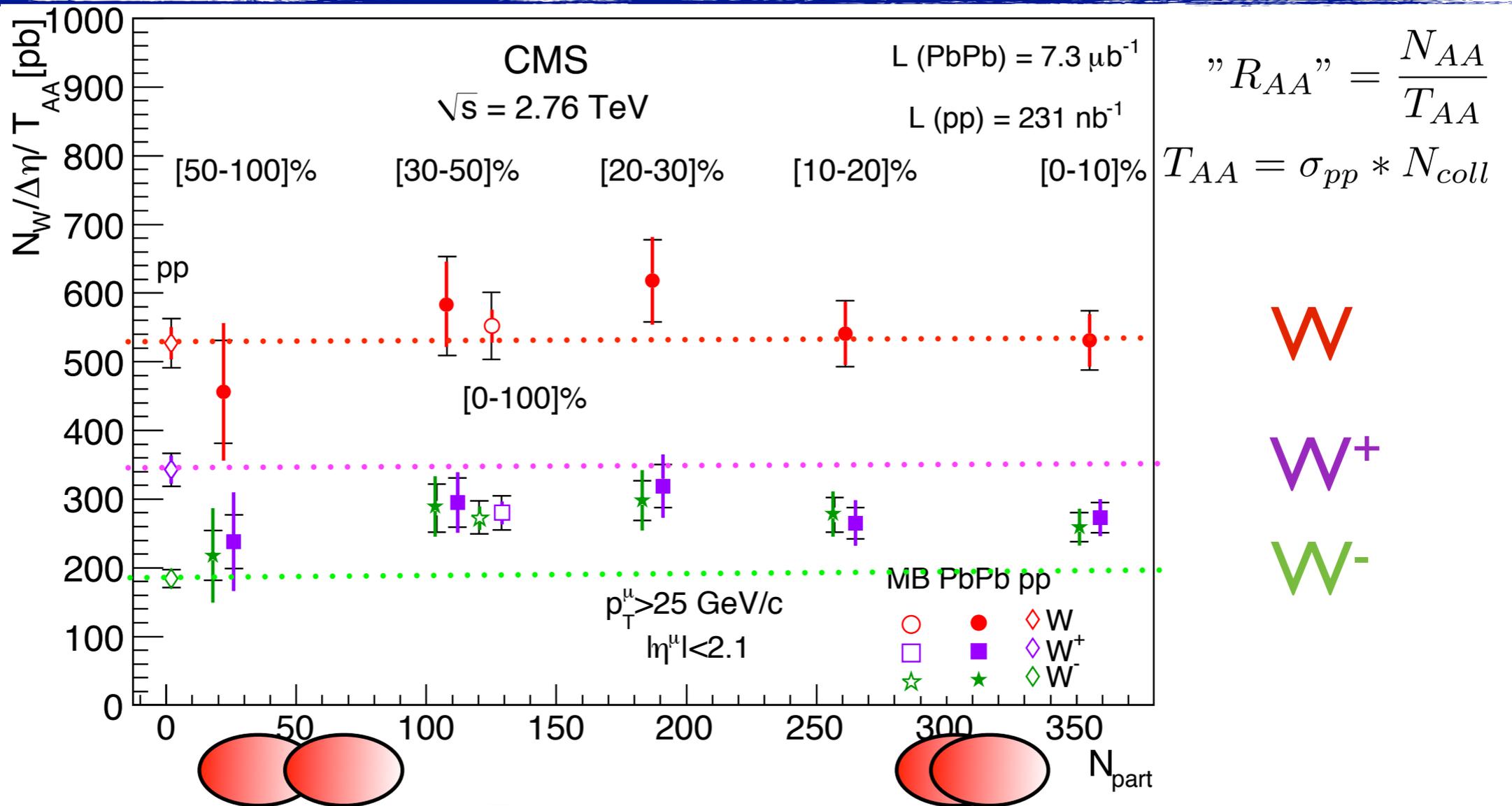
- ▶ high- $p_T$  muon
- ▶ significant momentum imbalance in transverse plane
  - ▶ reconstruct with charged tracks with  $p_T > 3$  GeV/c



Transverse mass:

- ▶ peak at  $m_T = M^W$
- ▶ almost background free with the selections made
- ▶ good agreement to MC

# $W \rightarrow \mu\nu$



Significant change in  $W^+(u+d)$  and  $W^-(d+u)$  between pp and PbPb

➡ isospin effect

▶ pp (u:d=4:2 = 2)  $\sigma(W^+) > \sigma(W^-)$

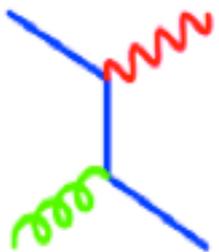
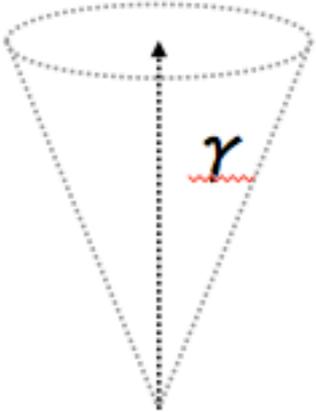
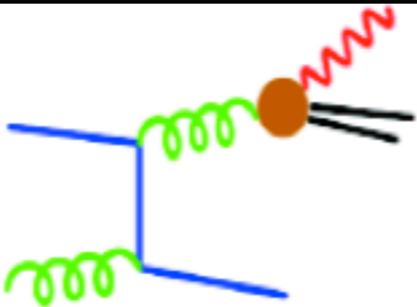
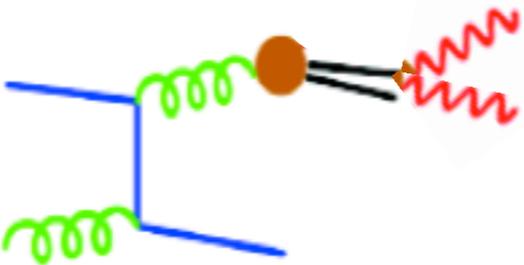
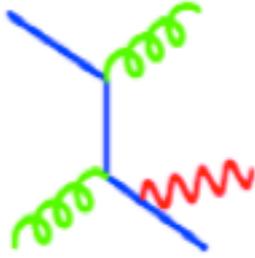
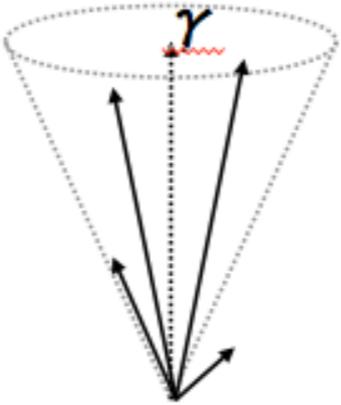
▶ PbPb (u:d=580:668 = 0.9)  $\sigma(W^+) < \sigma(W^-)$

$R_{AA}^{W(W^- + W^+)} = 1.04 \pm 0.07 \pm 0.12$

➡ consistent with binary scaling

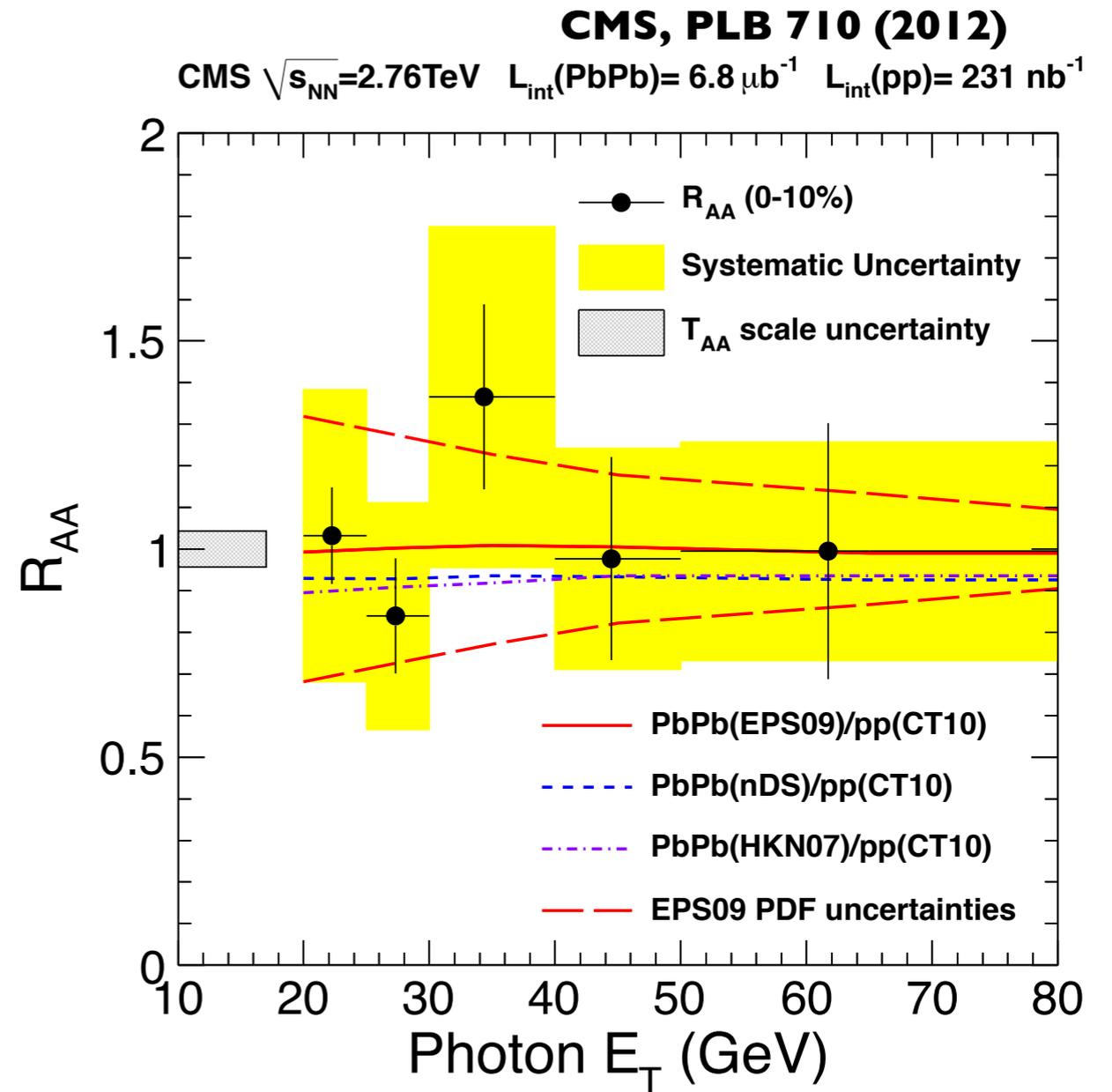
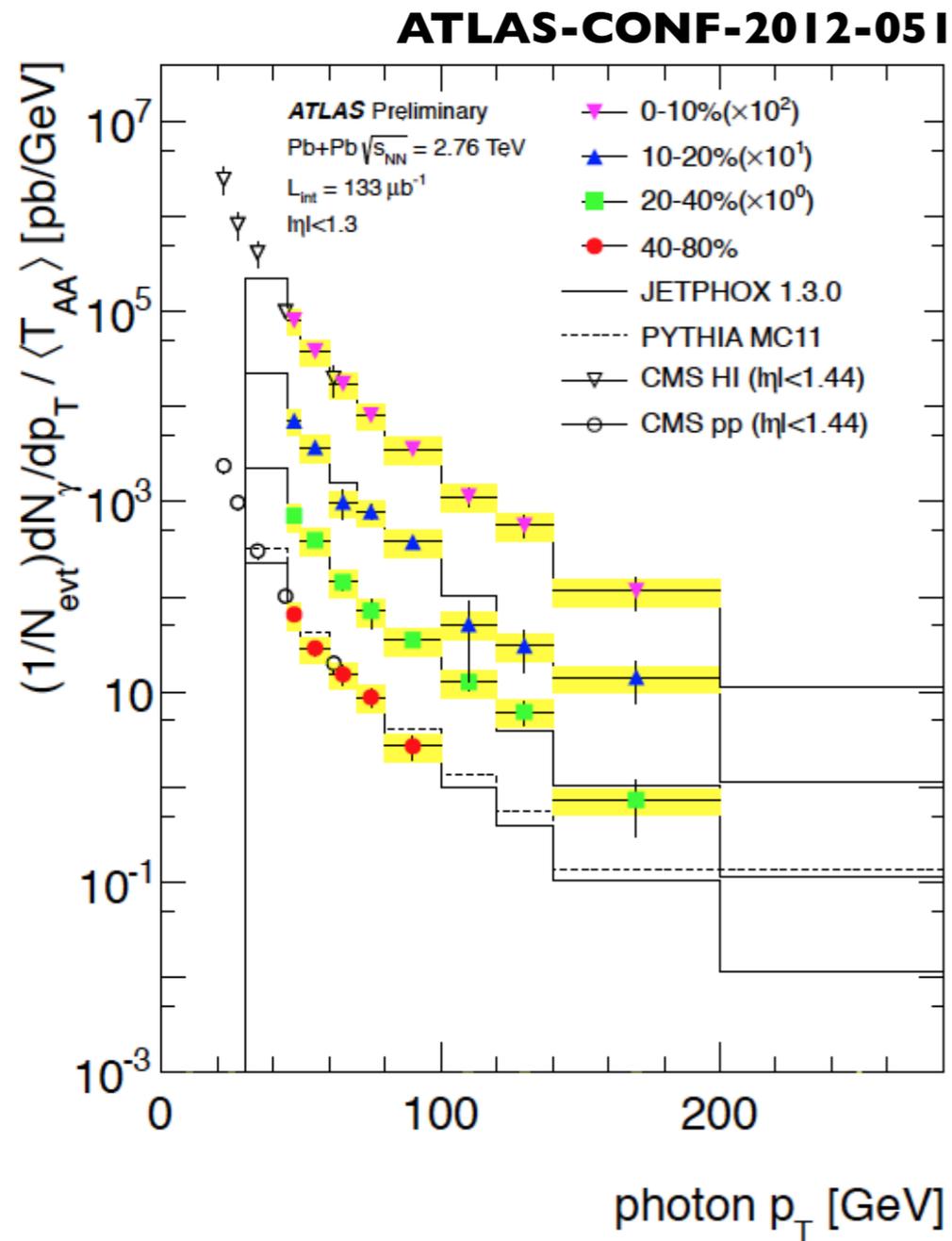
# Photons

- Many sources of high- $p_T$  photons

|   |   |   |  |
|---|---|---|--|
|  <p><b>Direct</b></p>  <p>Isolated<br/>Blind to the medium</p> |  <p><b>Fragmentation</b></p>  |  <p><b>Meson decay</b></p> |  <p><b>Bremmstrahlung</b></p> |
|   |  <p>Not Isolated (hadronic activity from other fragments of the parton)<br/>Affected by the medium</p> |   |  |

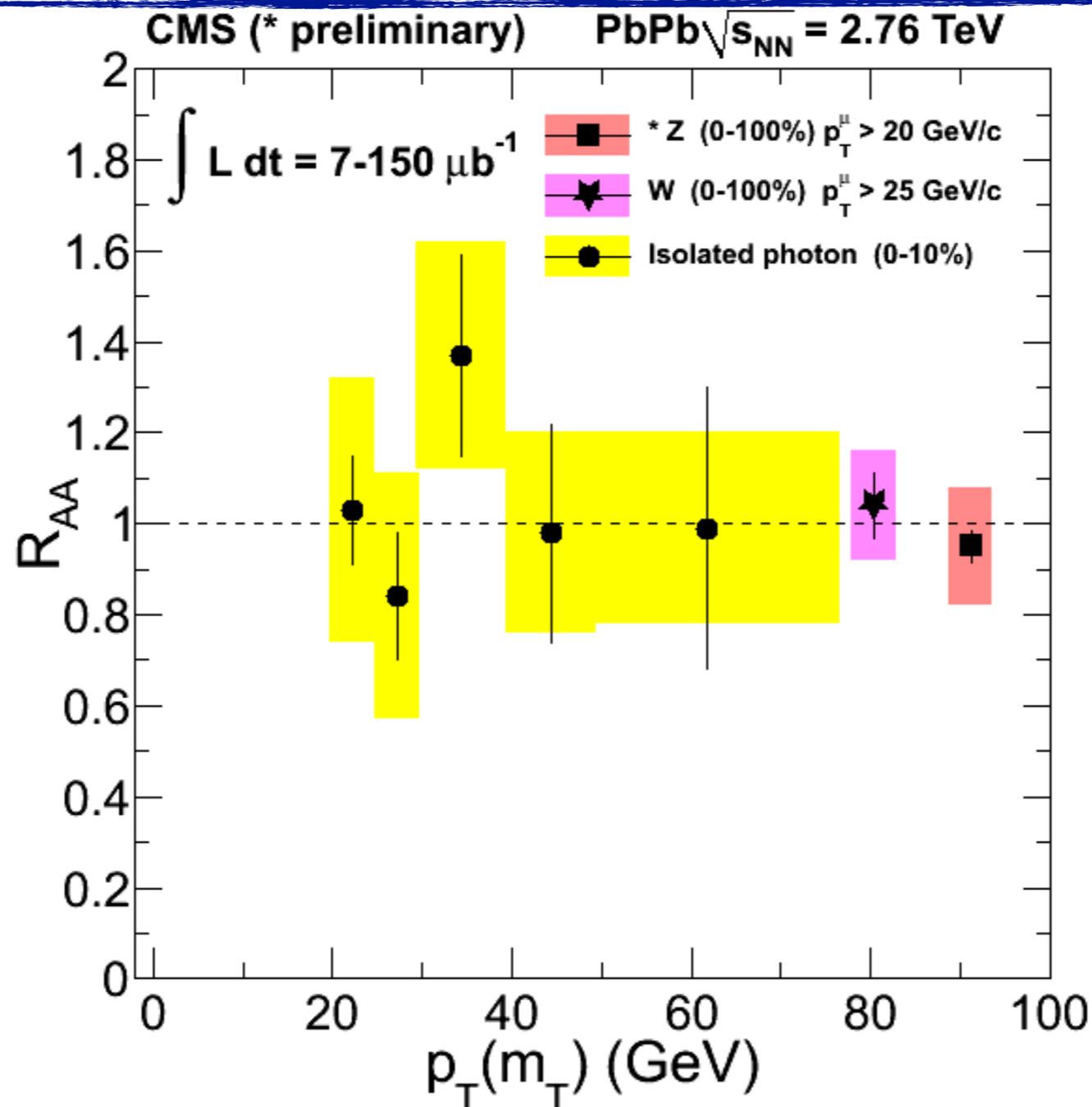
- Reconstruction steps:
  1. ECAL clusters candidates selection
  2. Clusters isolation

# Photons



☉  $R_{AA} \sim 1 \rightarrow$  photons are not modified by the medium  
 ➔ the light is blind!

# Electroweak bosons: Summary

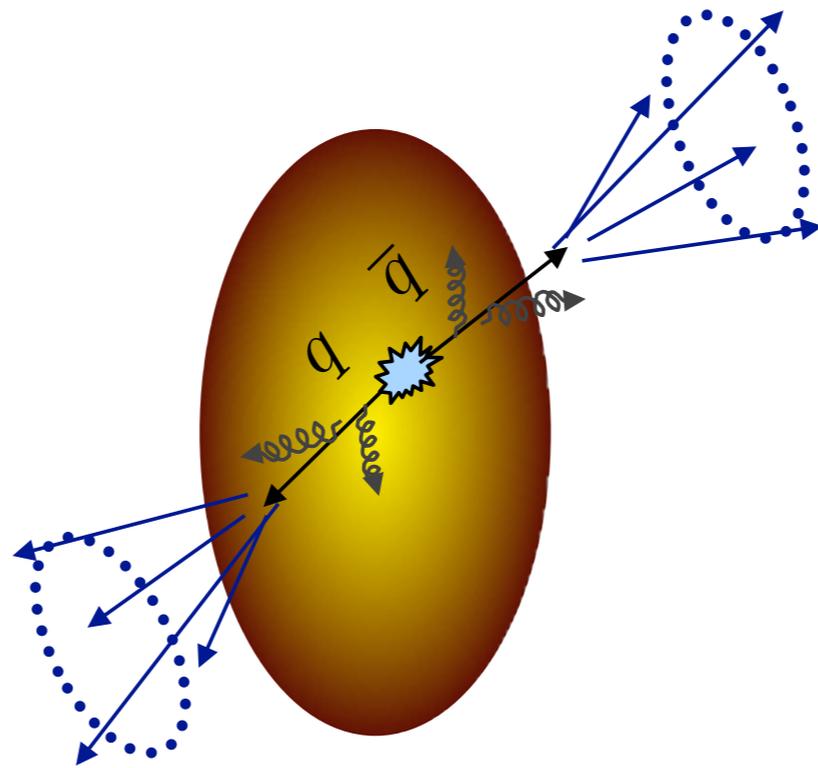


◎  $R_{AA} \sim 1$ : not modified by the medium!

➡ Experimental proof that the binary scaling hypothesis is valid

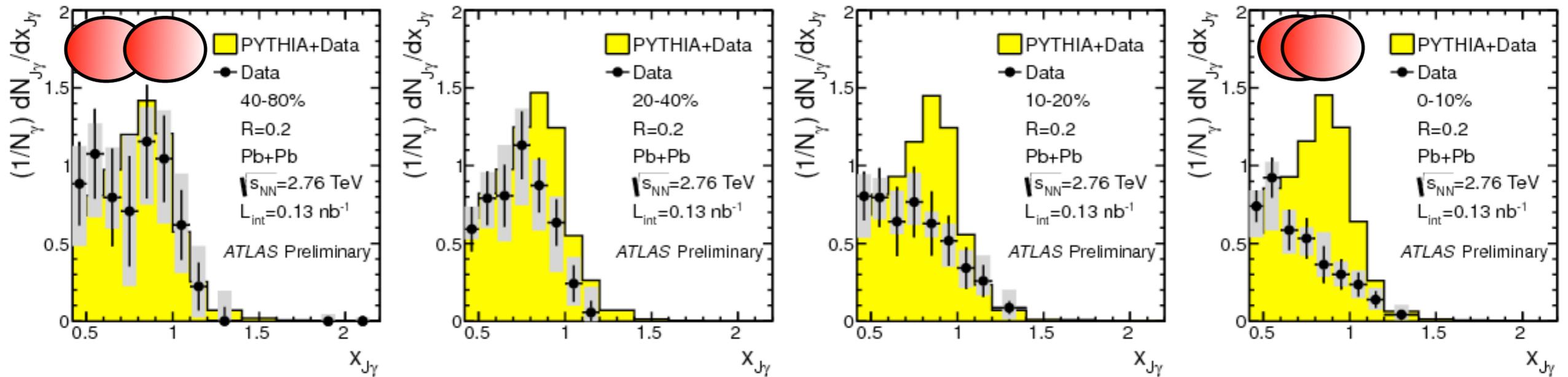
➡ use as 'in situ' reference for other processes

$$R_{AA} = \frac{N_{AA}}{N_{pp}} \frac{1}{N_{coll}}$$



⊙ Probes affected by the medium:  
➔ light partons

# Jets: $\gamma$ +jet

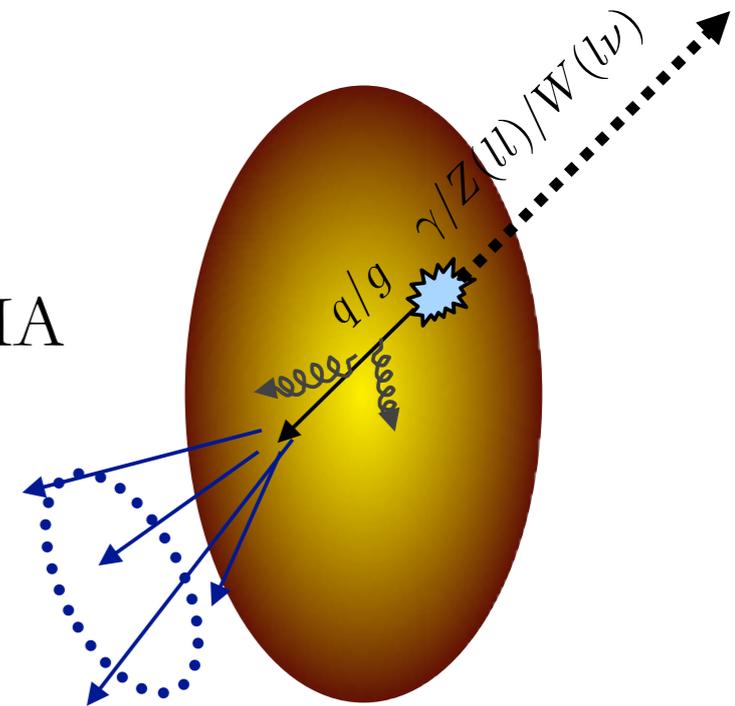


- The boson tag provides initial  $p_T$
- Transverse momentum balance:

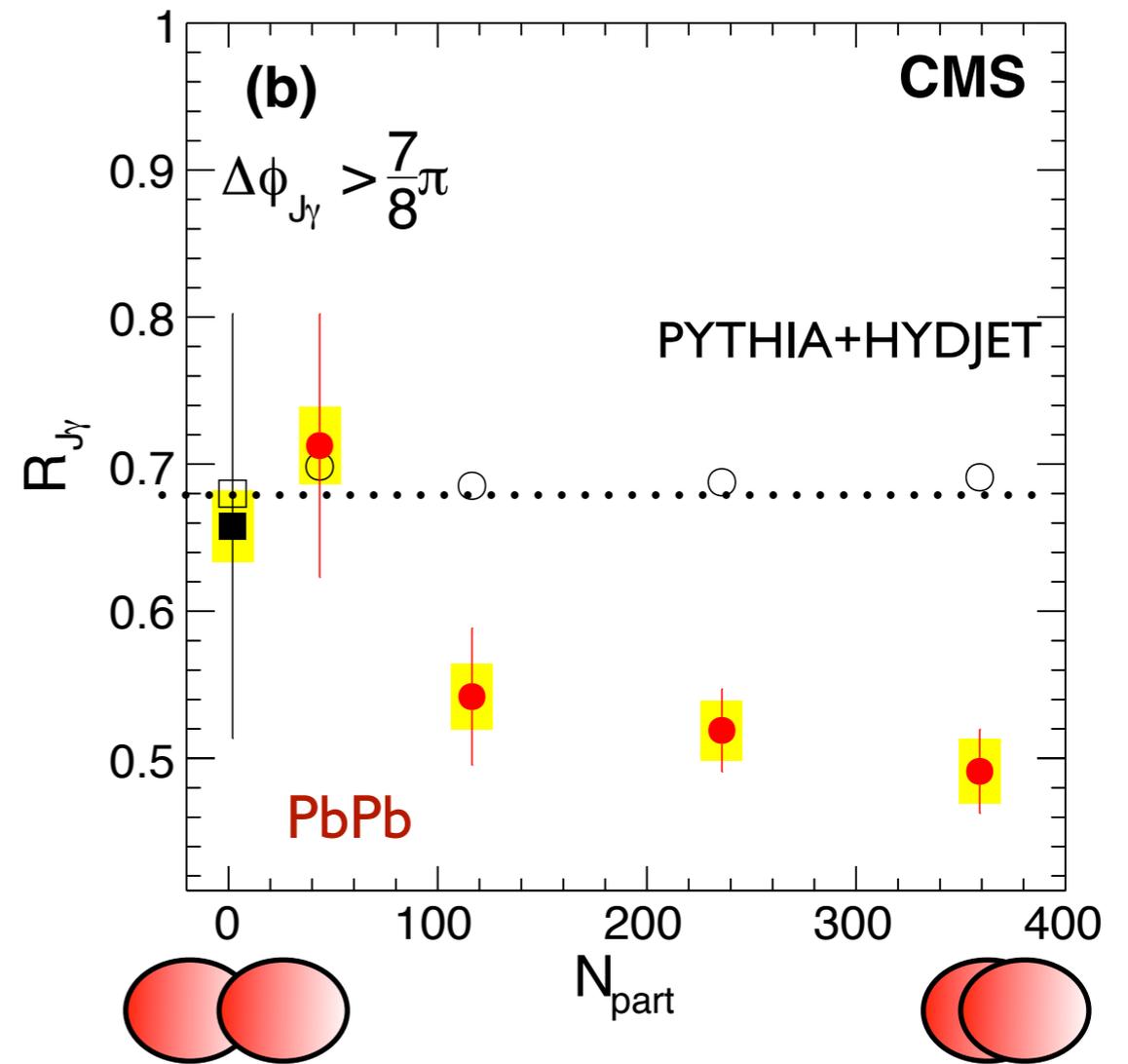
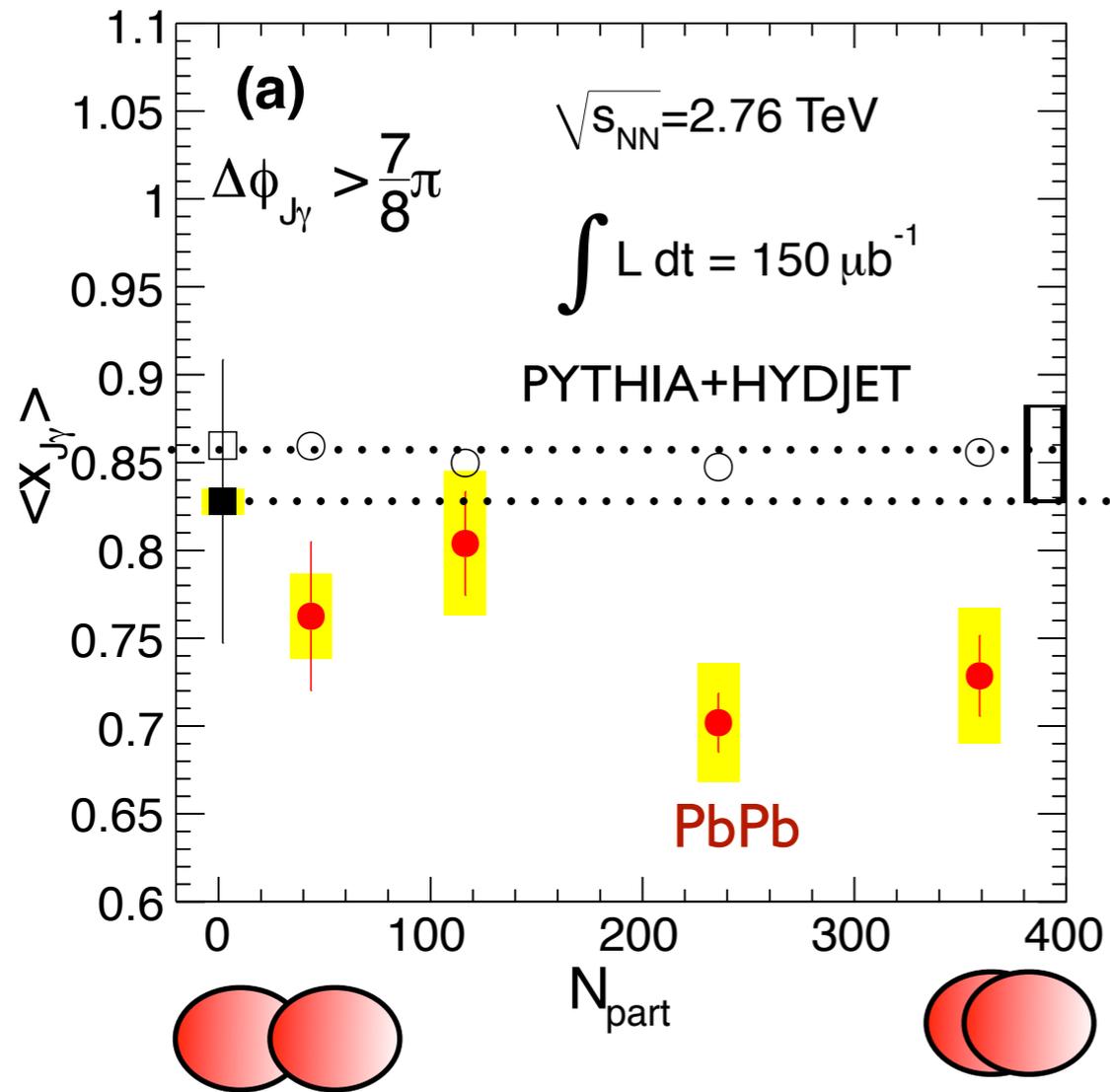
$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^\gamma}$$

- Peripheral collisions: shape and yield compatible with PYTHIA
- Increasing the collision centrality:

- ➡ shift towards small  $x_{J\gamma}$
- ➡ decrease of the yield



# Jets: $\gamma$ +jet



● Jet-photon balance drops by 14% compared to pp

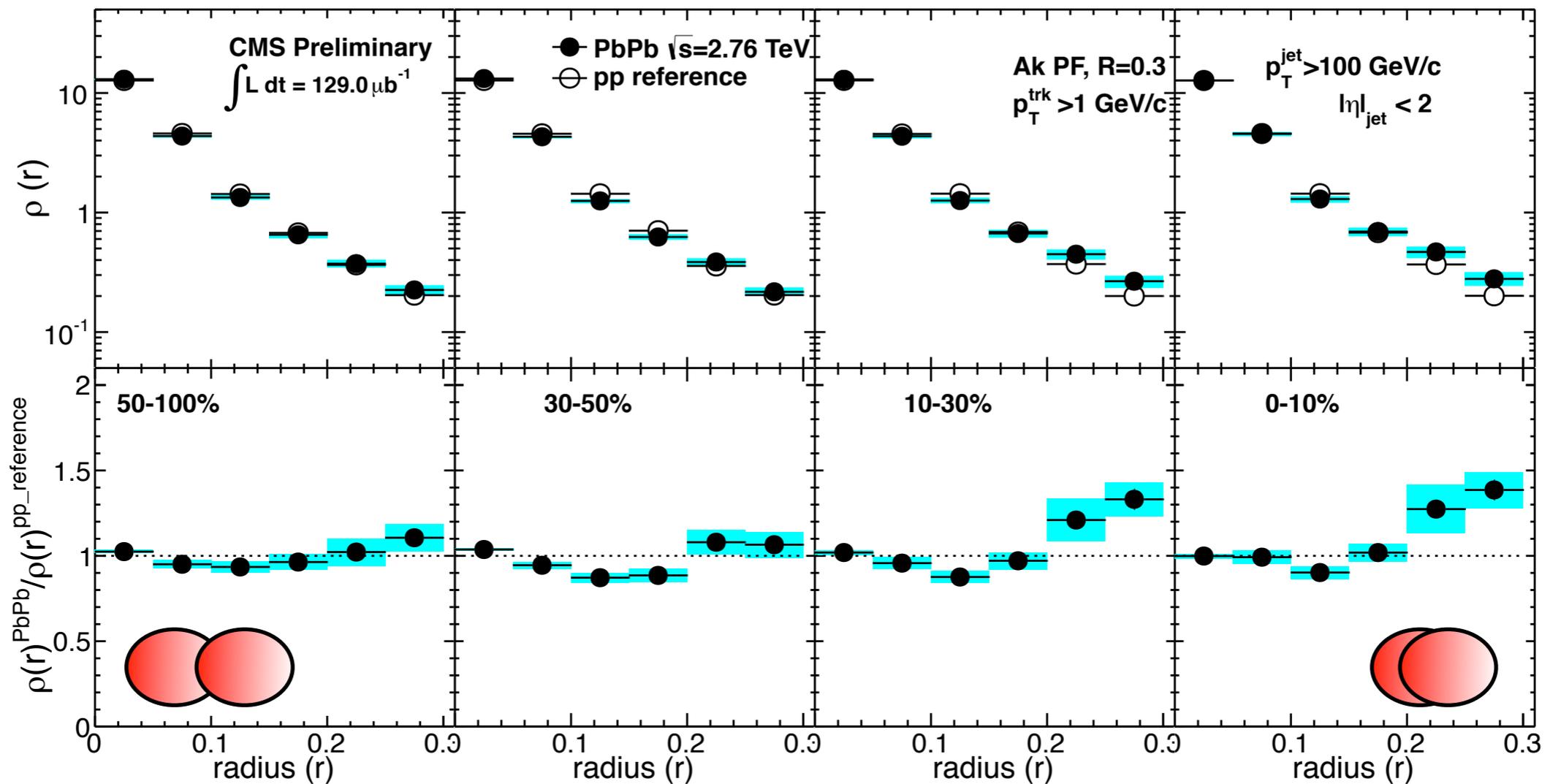
➡ jets lose energy

● Average fraction of isolated photons with an associated jet partner drops by 20%

➡ some of the jets are 'lost'

# Jets: what happens with them in PbPb?

CMS-PAS-HIN-12-013



⊙ Does the shape change compared to pp?

➡ how the transverse momentum is distributed around the jet axis

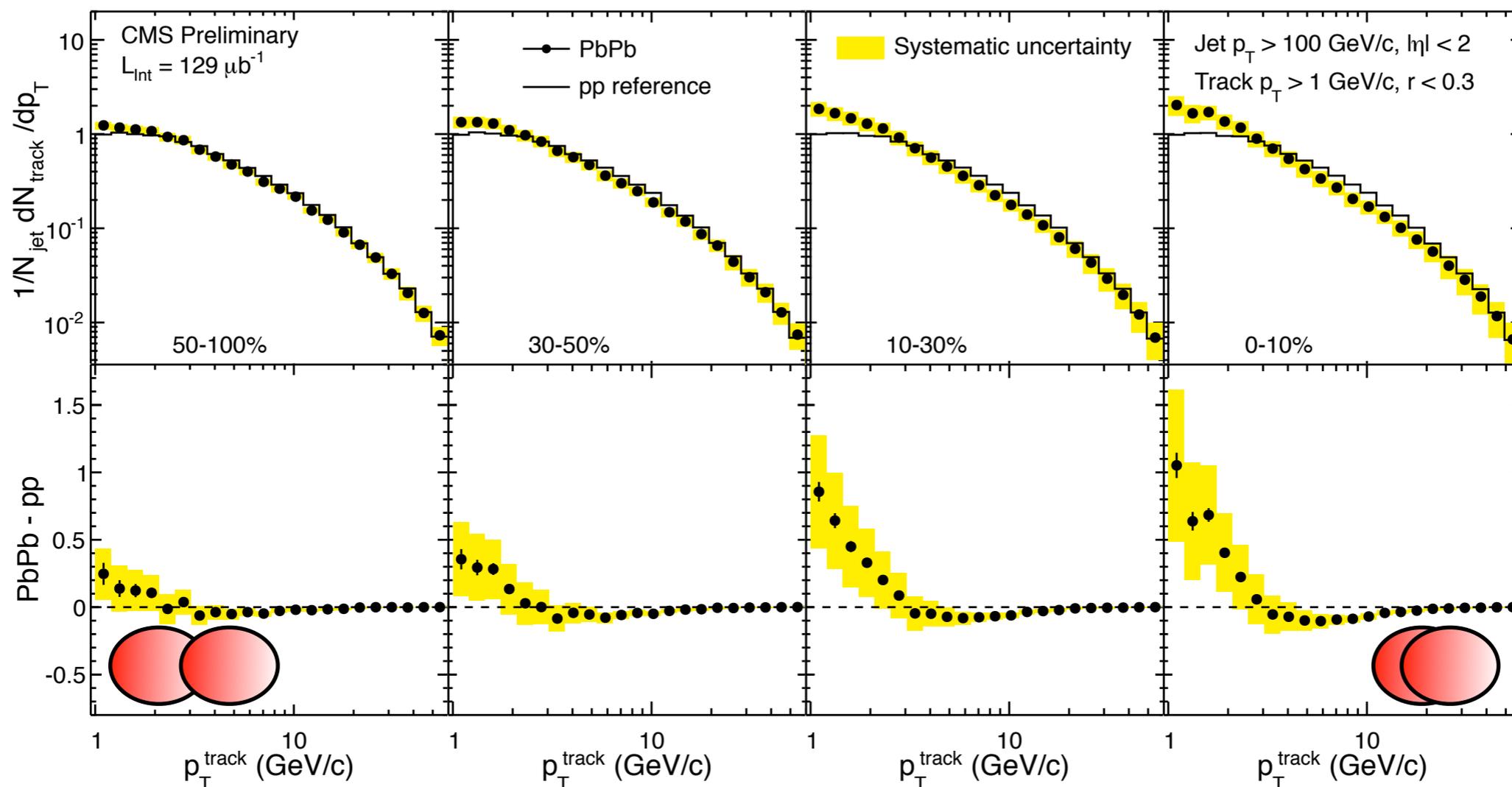
⊙ Broadening of the jet structure in central PbPb collisions

➡ at small radii (closed to the jet axis): same distribution as in pp

➡ at large radii (away from the jet axis): more contribution than in pp

# Jets: what happens with them in PbPb?

CMS-PAS-HIN-12-013



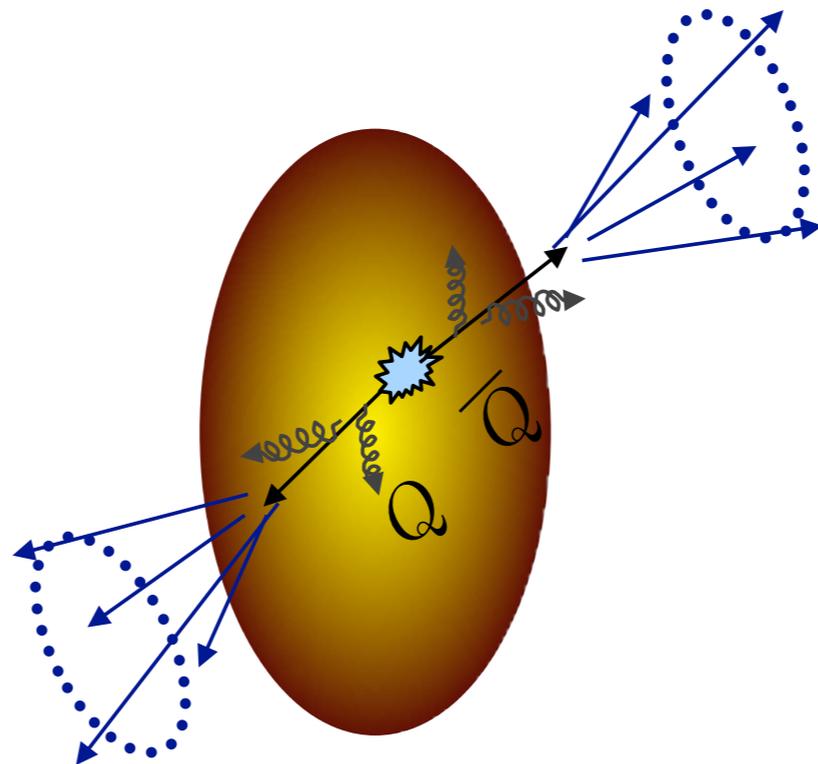
⊙ Does their fragments distribution changes compared to pp?

➡ track distribution inside the jet

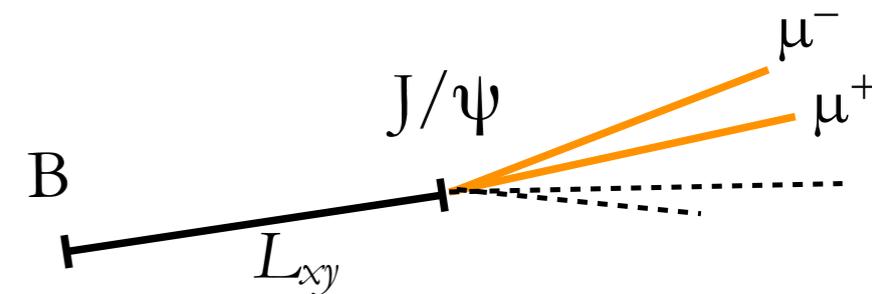
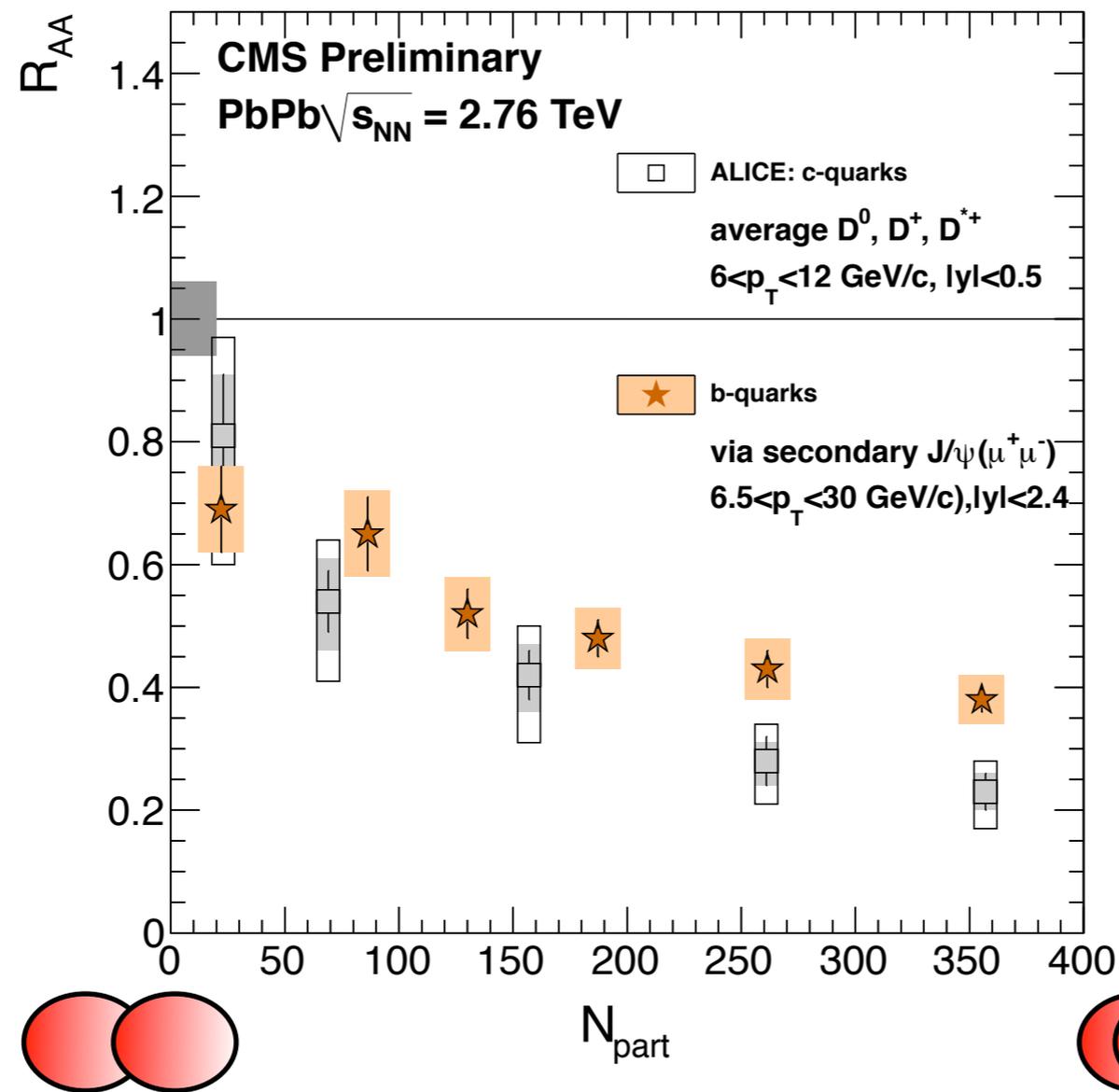
⊙ Yes, in the intermediate and small  $p_T$  region

➡ at high- $p_T$ : no change

➡ at low- $p_T$  ( $p_T < 3 \text{ GeV}/c$ ): excess of tracks



⊙ Probes affected by the medium:  
➔ heavy quarks



☉ Theory: energy loss is quark mass dependent

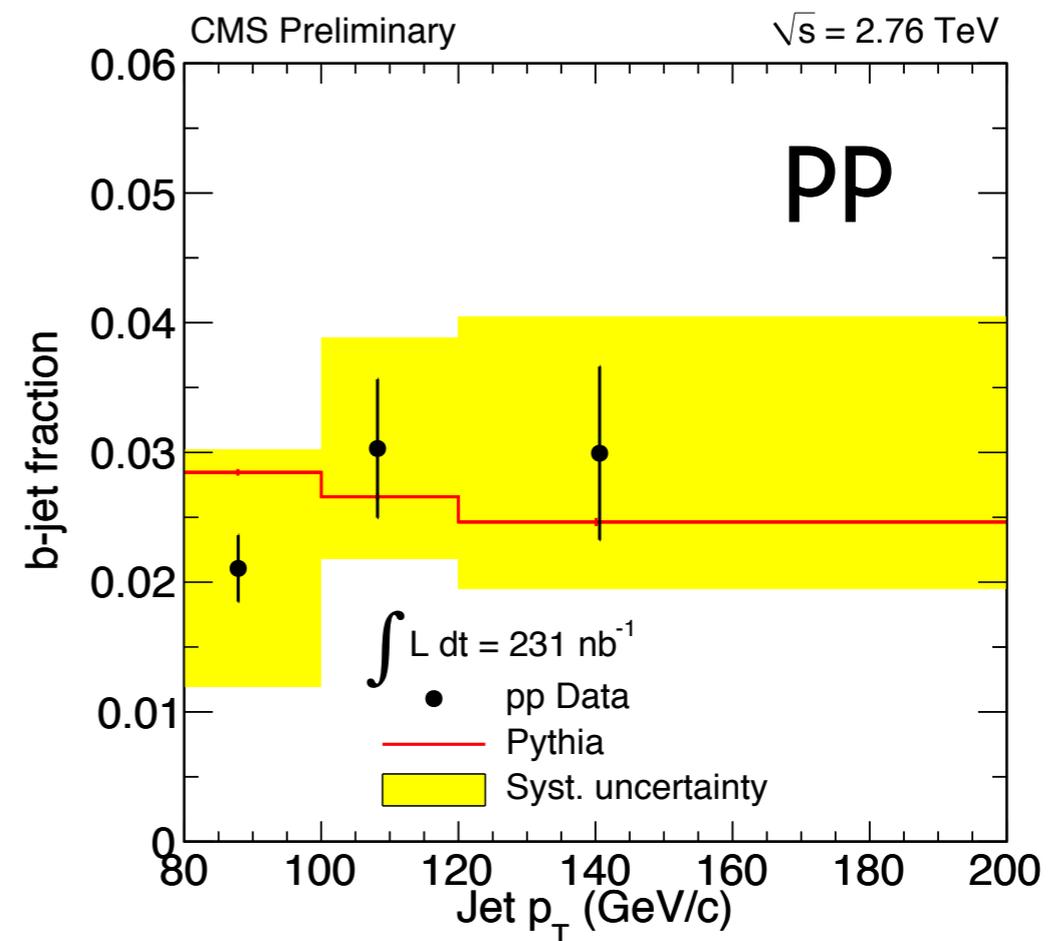
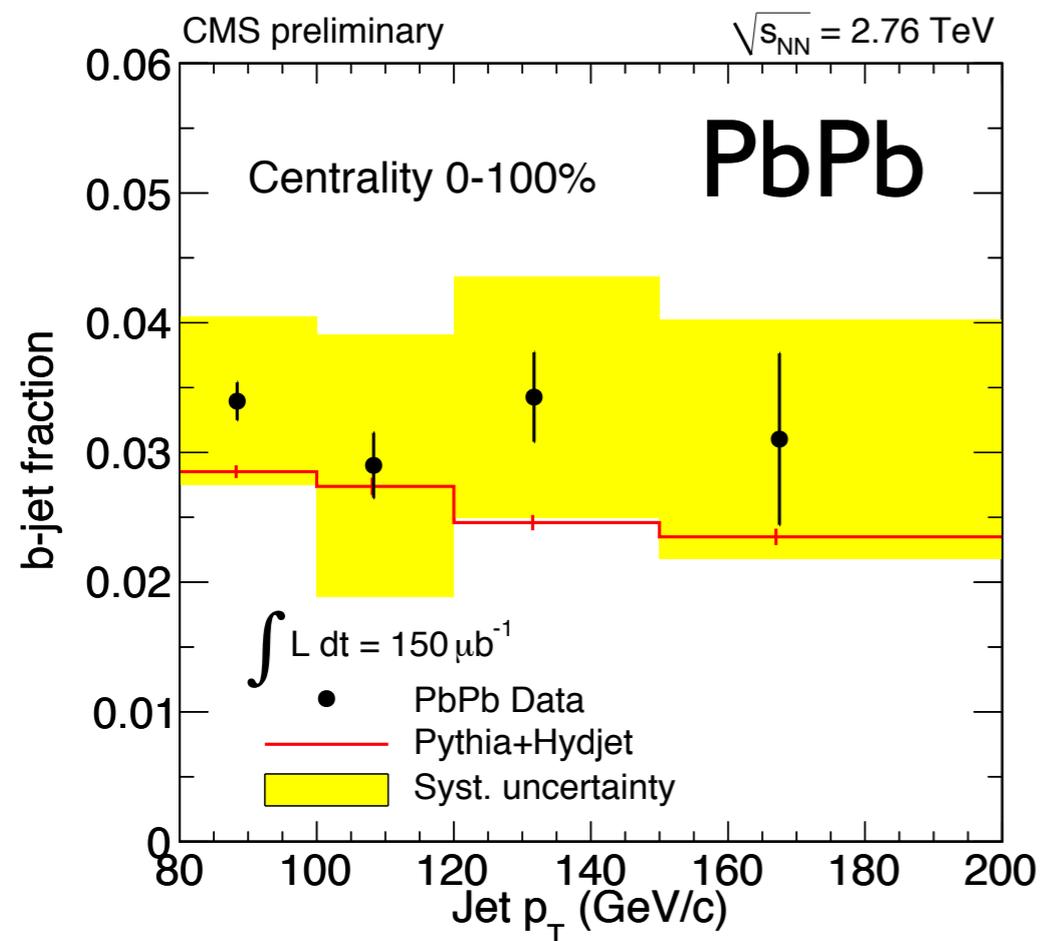
☉ In central PbPb collisions:  $R_{AA}^{beauty} > R_{AA}^{charm}$

➡ b-quarks are less suppressed than the c-quarks

▶ hypothesized, but never experimentally proven (b measured separately in HI, only by CMS)

# Open heavy-beauty: $p_T > 80$ GeV/c

CMS-PAS-HIN-12-003



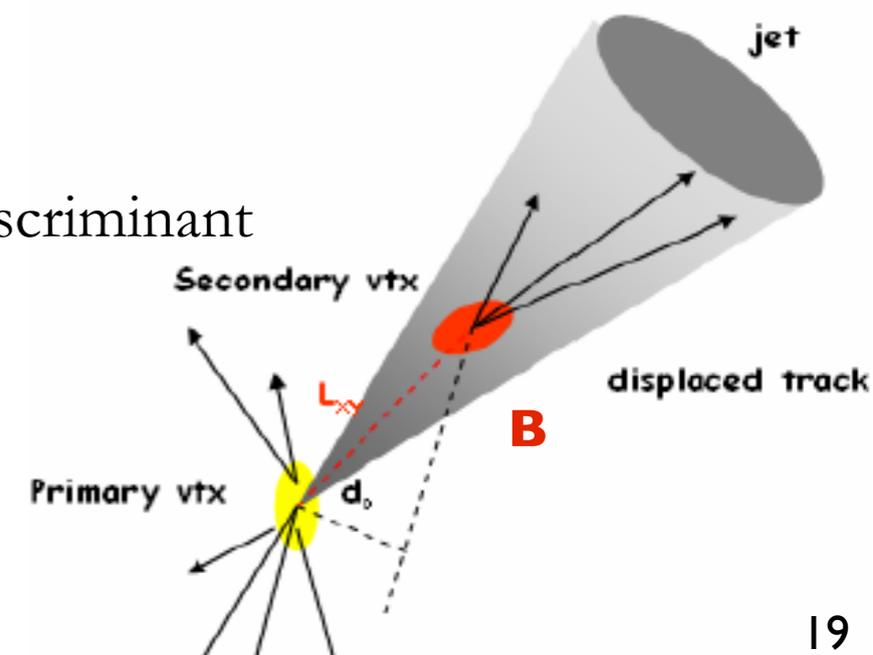
## ● b-tagged jets

➔ Simple Secondary Vertex High Efficiency (SSVHE)

- ▶ reconstructed SV, using the flight distance of the SV as a discriminant
- ▶ fit to the SV mass  $\rightarrow$  b-jet fraction

## ● PbPb and pp b-jet fraction are the same

➔ also consistent with MC within uncertainties

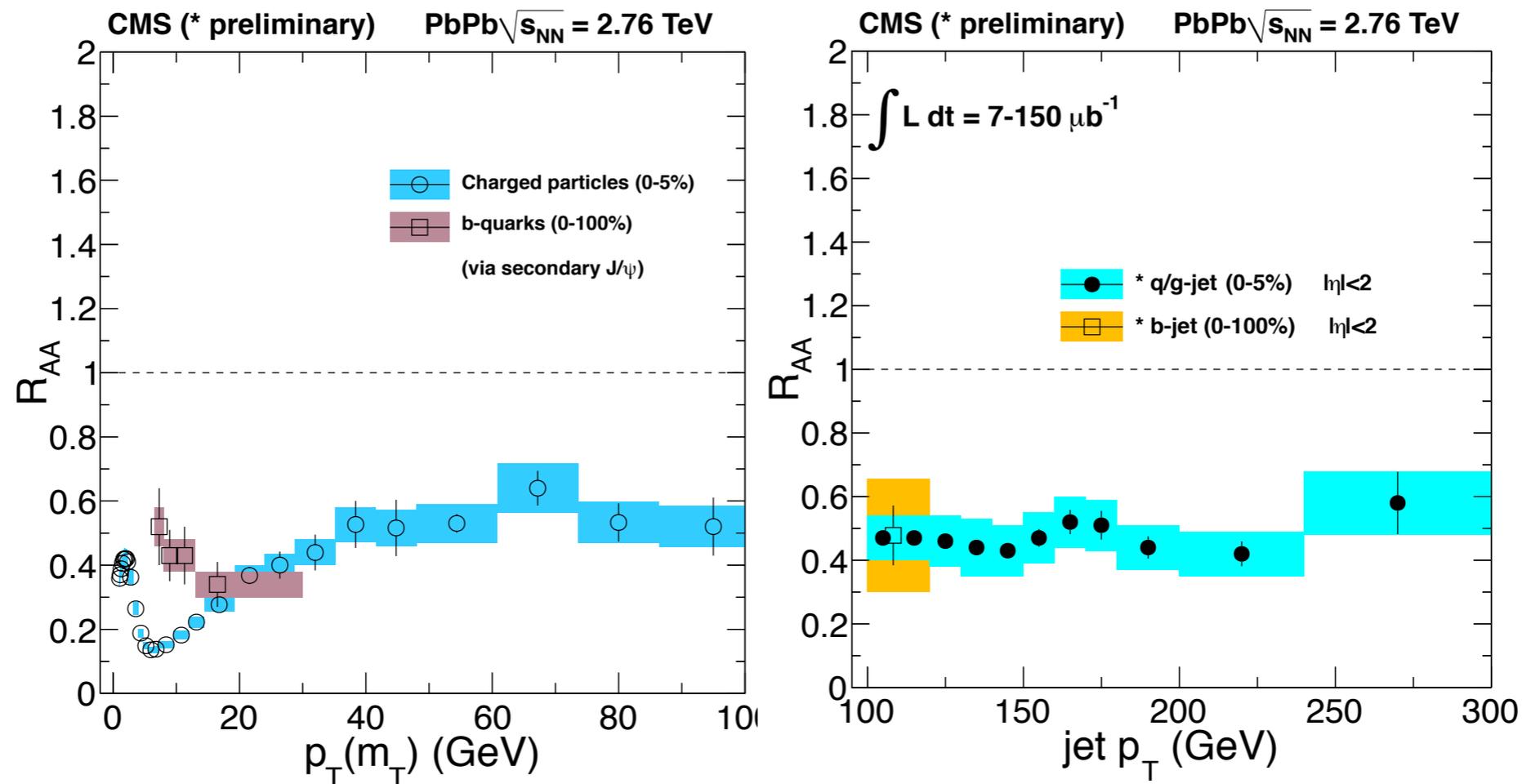


# Colored probes: Summary

CMS-PAS-HIN-12-003

CMS-PAS-HIN-12-004

CMS-PAS-HIN-12-014



◎  $R_{AA} < 1$ : colored probes are suppressed!

◎ Low- $p_T$ :

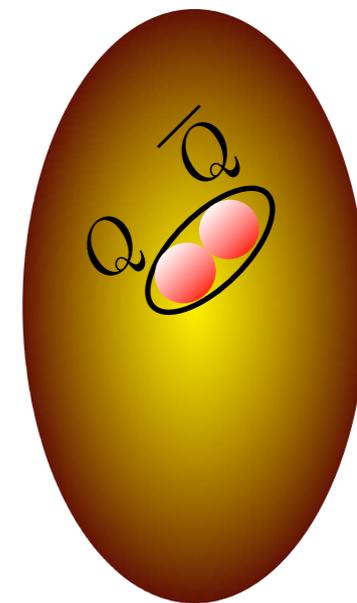
➡ different suppression pattern for heavy quarks compared to light partons remnants

◎ High- $p_T$ :

➡ data disfavor a scenario in which b-jets suffer no energy loss ( $p_T > 100$  GeV/c)

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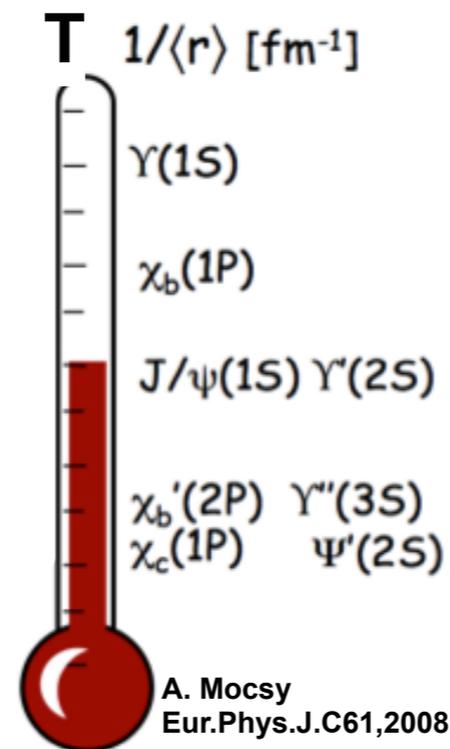
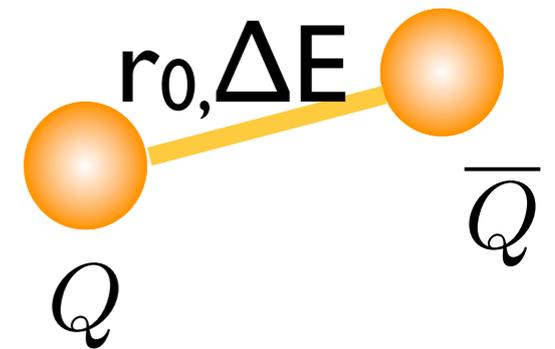
☉ Probes affected by the medium:  
➔ quarkonia



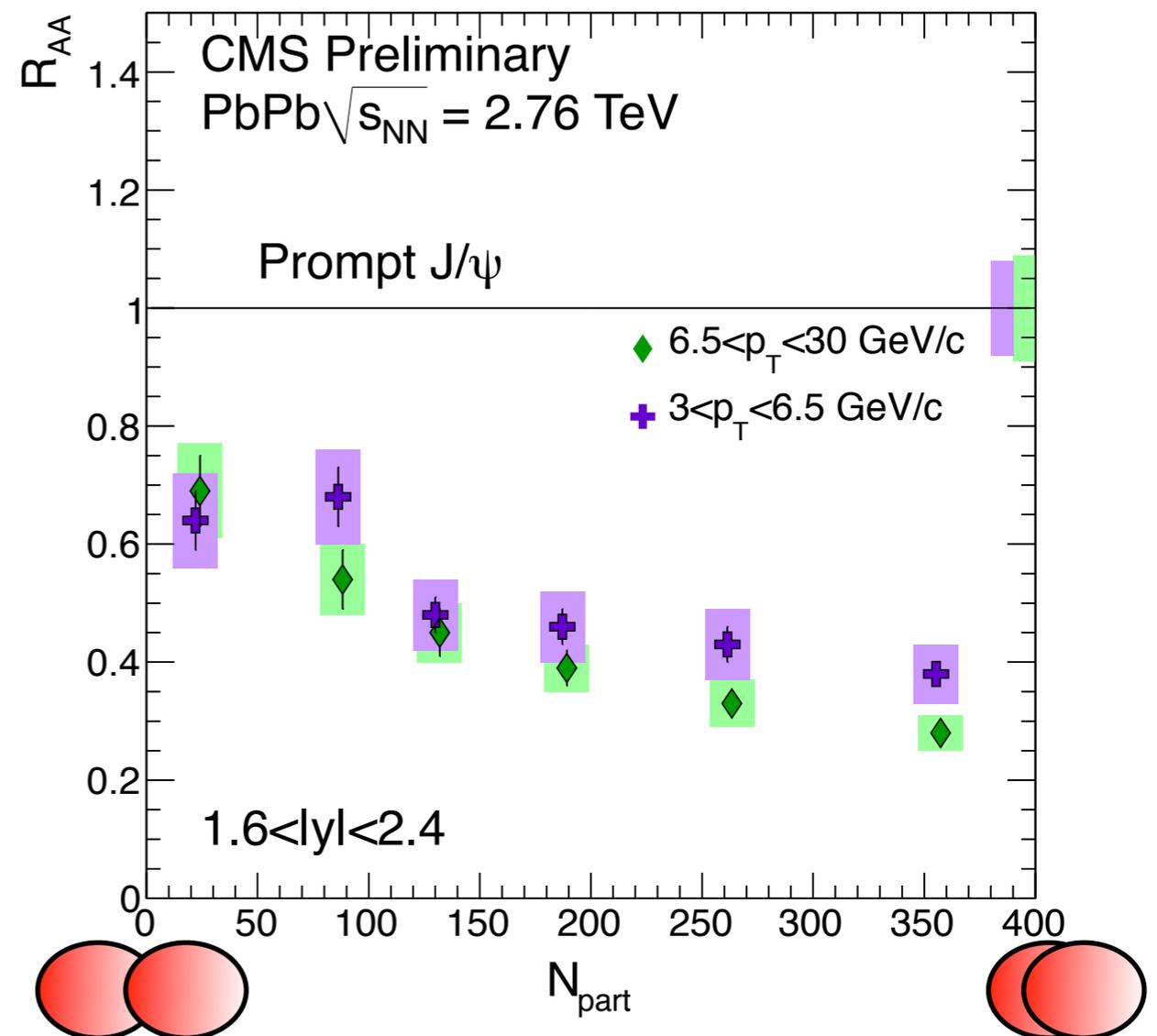
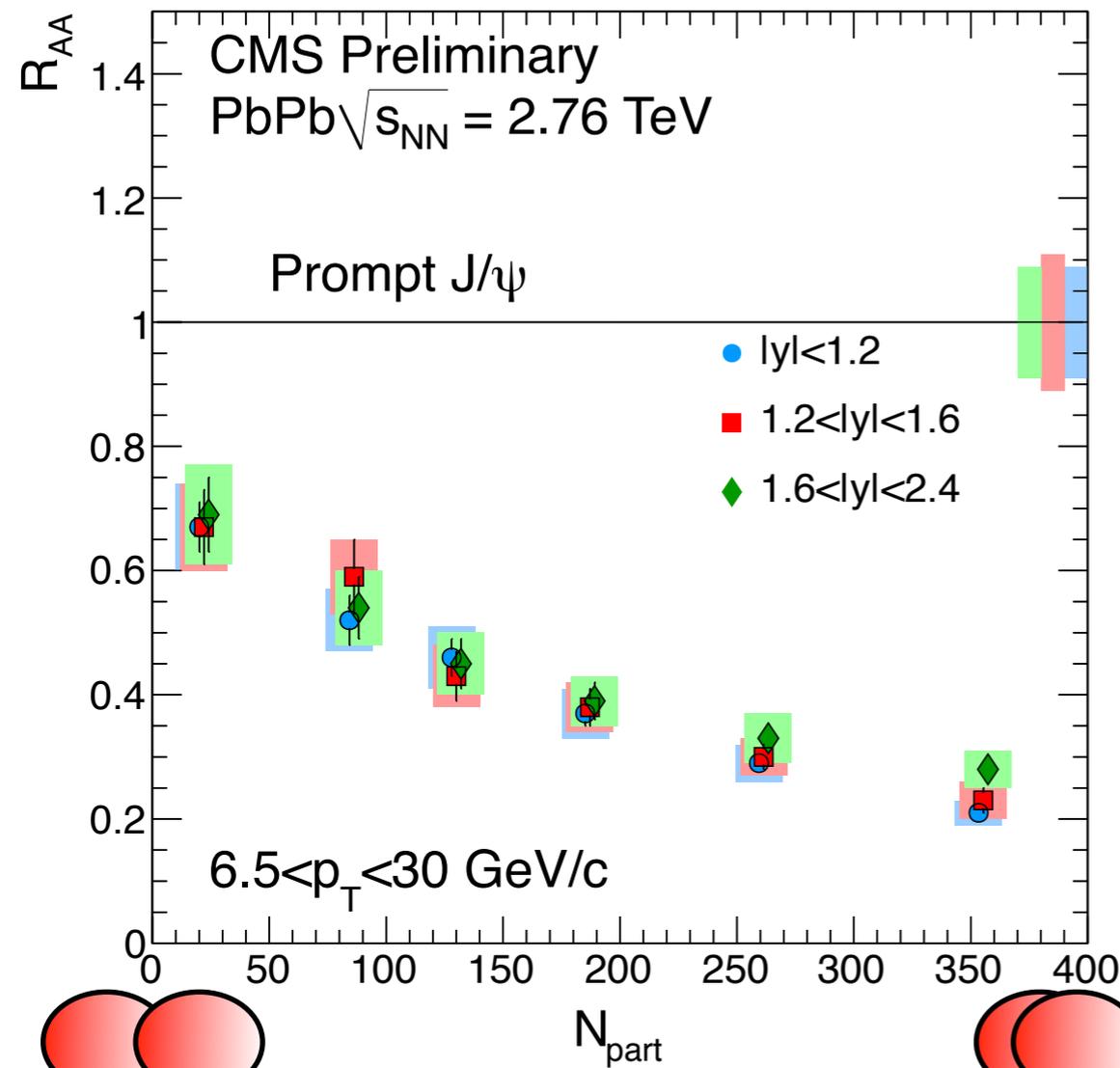
# Quarkonia

|                        | $\Psi(2S)$ | $\Upsilon(3S)$ | $\Upsilon(2S)$ | $J/\psi$ | $\Upsilon(1S)$ |
|------------------------|------------|----------------|----------------|----------|----------------|
| $\Delta E(\text{GeV})$ | 0.05       | 0.20           | 0.54           | 0.64     | 1.10           |

$$\Delta E = 2M_{D/B} - M_{cc/bb}$$



- Quarkonia in a deconfined, colored charged medium should suffer Debye screening  
 → screening at different medium temperatures  $T$  for different states: sequential melting
- Quarkonia: thermometer of the QGP



●  $p_T > 6.5$  GeV/c:

➡ suppression by a factor  $\sim 5$  in central PbPb collisions

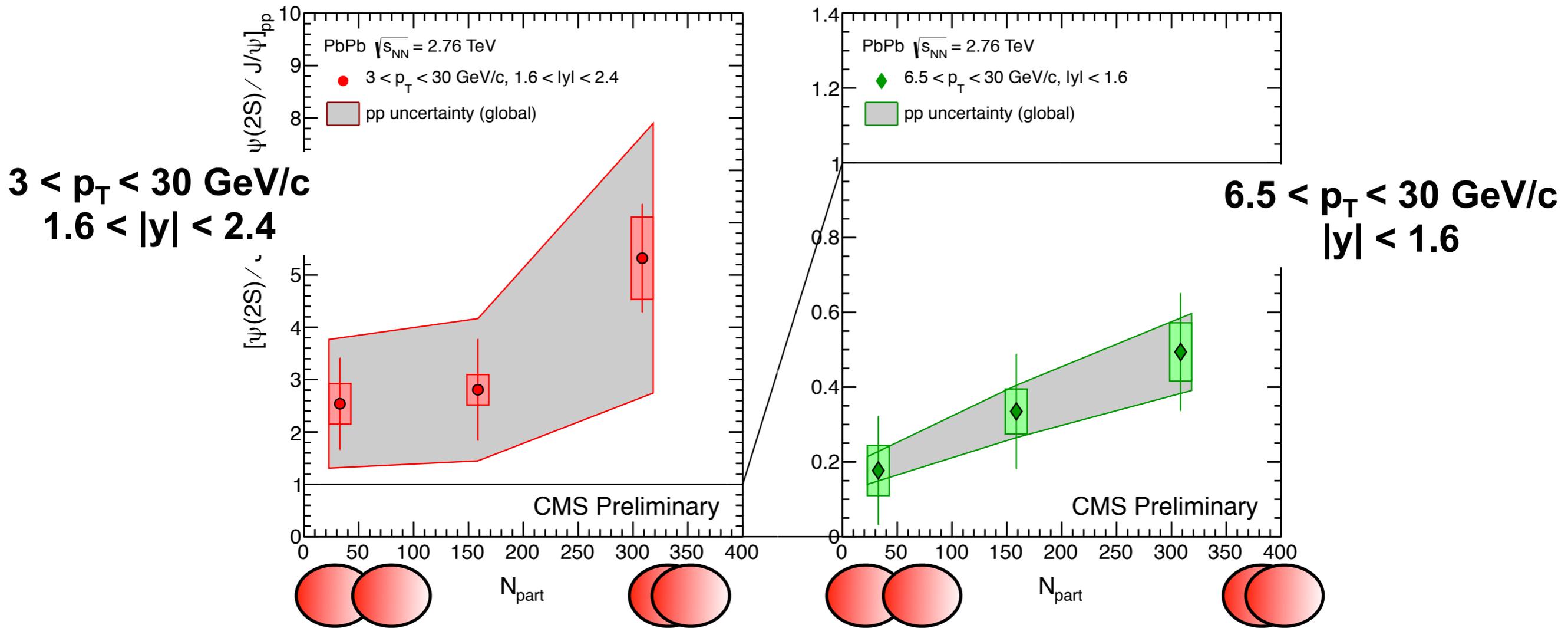
➡ no rapidity dependence

●  $1.6 < |y| < 2.4$ :

➡ hints of less suppression at lower- $p_T$

# Charmonia: $\psi(2S)$ vs $J/\psi$

CMS-PAS-HIN-12-007

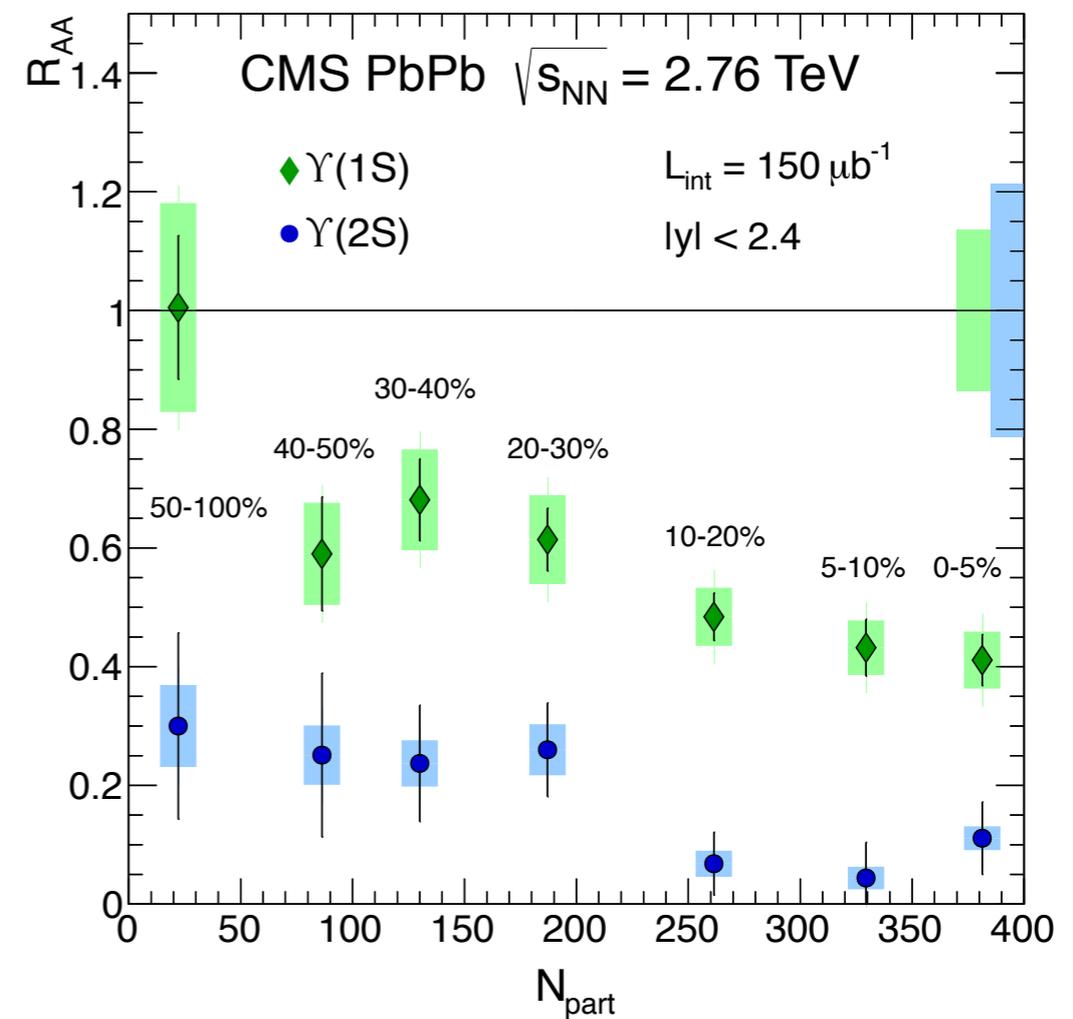
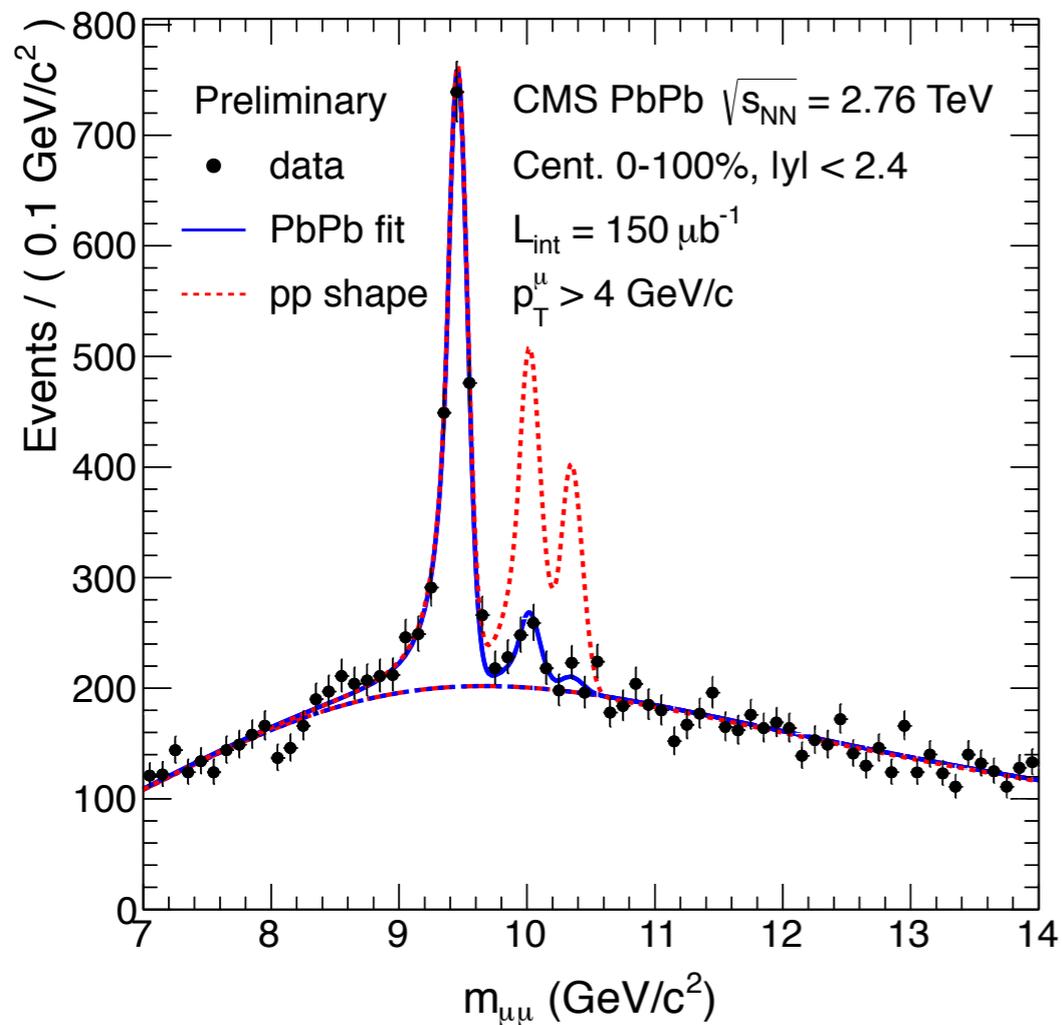


$$\frac{N_{\psi(2S)}/N_{J/\psi}|_{PbPb}}{N_{\psi(2S)}/N_{J/\psi}|_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$$

● **High-p<sub>T</sub>:**  $R_{AA}^{0-100\%}(\psi(2S)) = 0.11 \pm 0.03(\text{stat}) \pm 0.02(\text{syst}) \pm 0.02(\text{pp})$

● **Lower-p<sub>T</sub> (<2σ):**  $R_{AA}^{0-100\%}(\psi(2S)) = 1.54 \pm 0.32(\text{stat}) \pm 0.22(\text{syst}) \pm 0.76(\text{pp})$  <sub>24</sub>

# Bottomonia



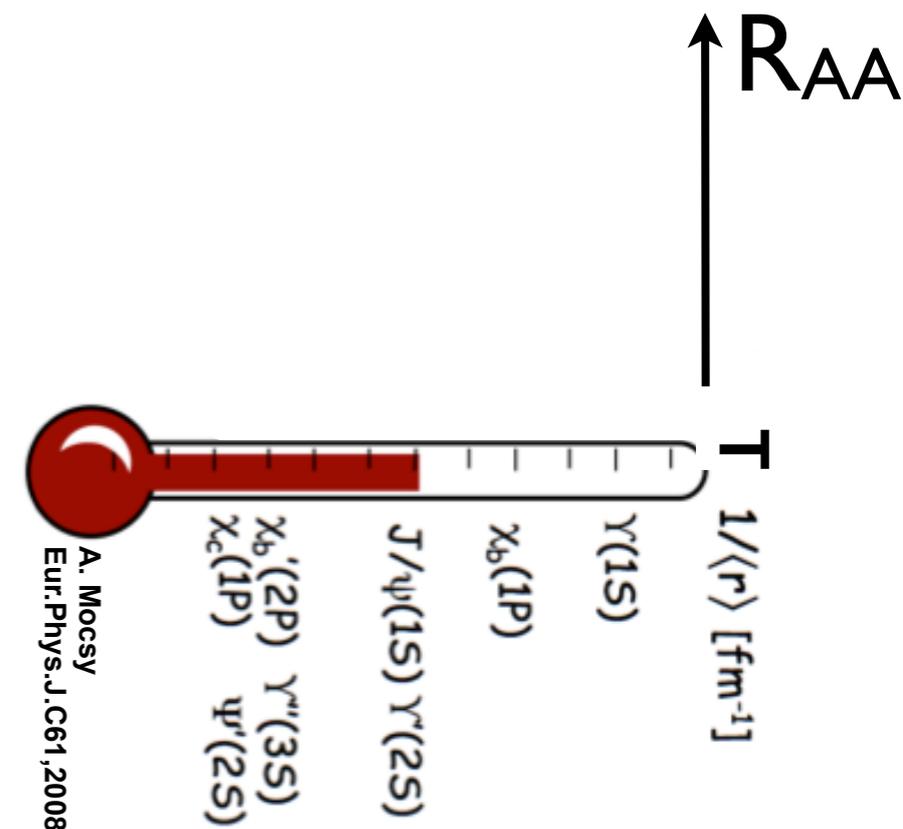
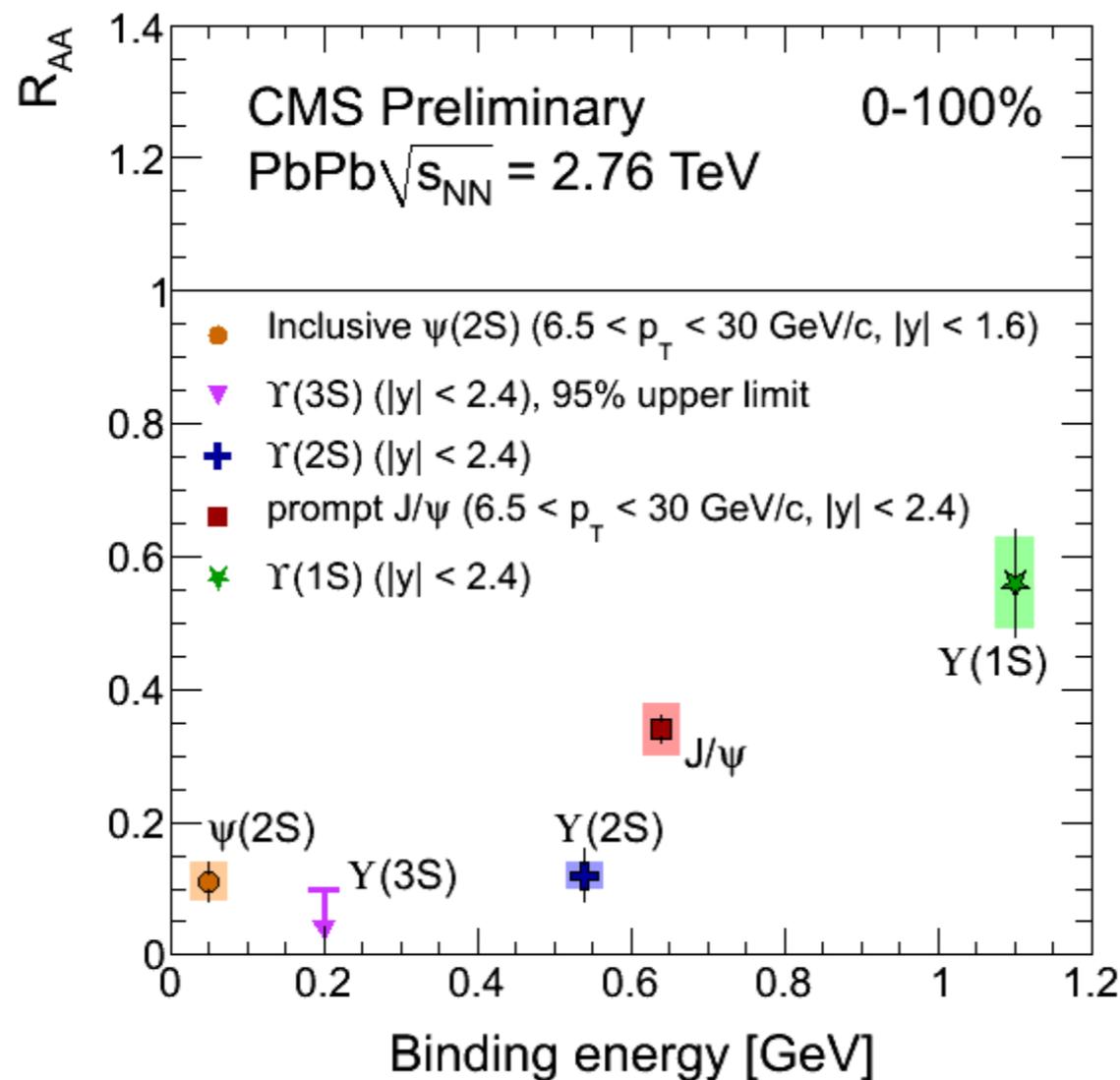
## ● Centrality integrated $R_{AA}$

- $Y(1S): 0.56 \pm 0.08 \pm 0.07$
- $Y(2S): 0.12 \pm 0.04 \pm 0.02$
- $Y(3S): < 0.1$  at 95% CL

## ● $R_{AA}^{Y(3S)} < R_{AA}^{Y(2S)} < R_{AA}^{Y(1S)}$

➔ ordered suppression ➔ sequential melting

# Quarkonia: summary



● The sequential melting map is experimentally drawn (for the 1st time)

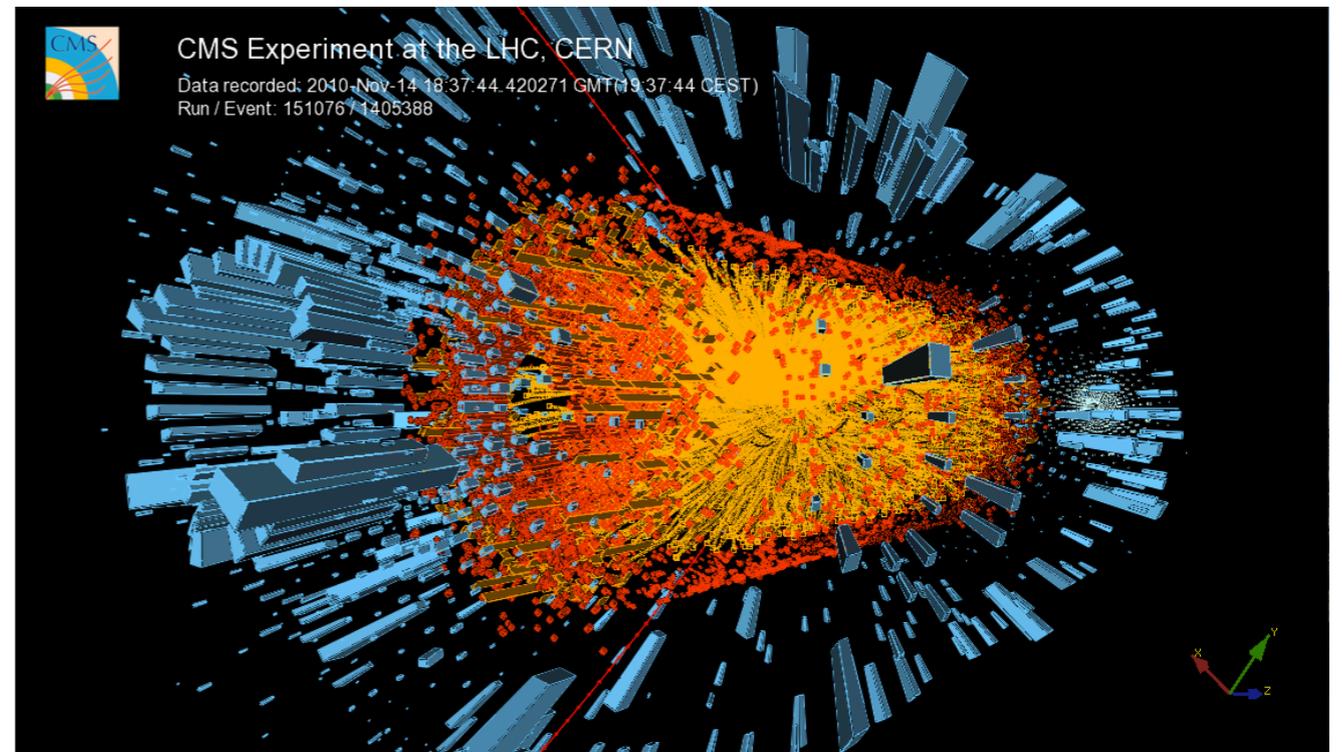
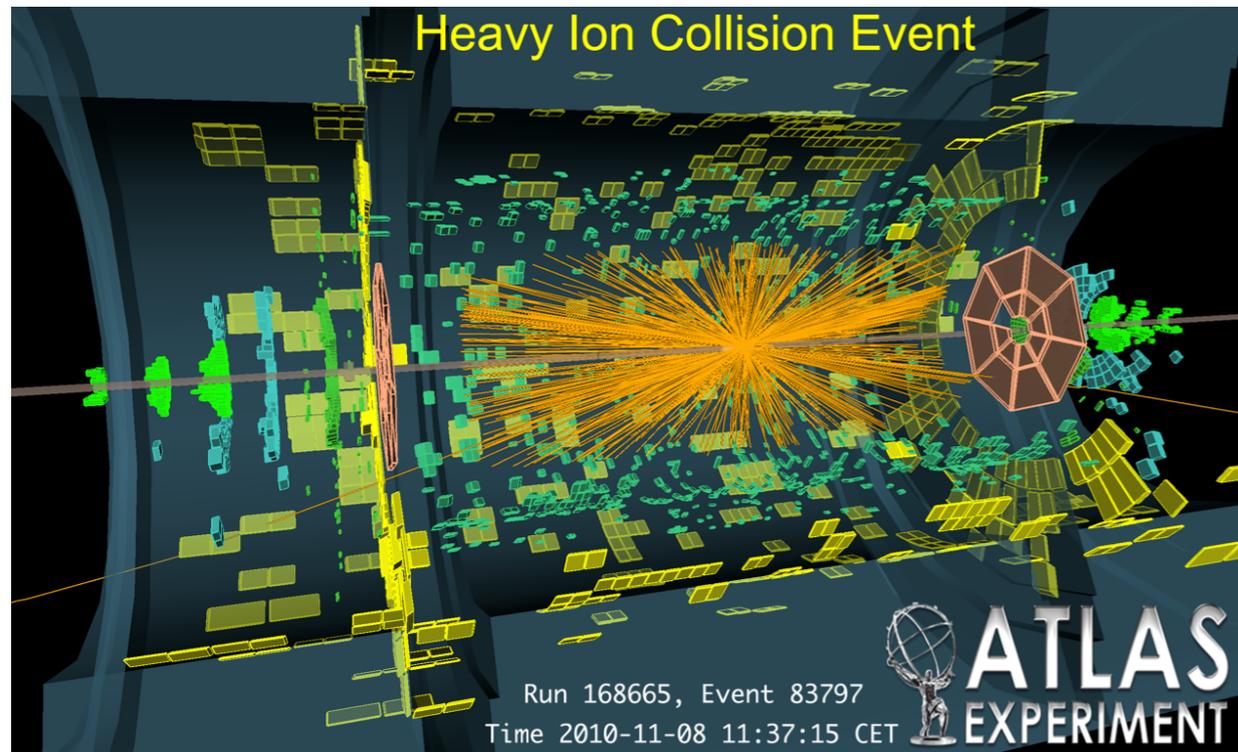
➔ looser bound states are more suppressed than the tighter bound states

● ... experimentally sketched (for the 1st time): map includes

➔ hot and cold nuclear matter effects: will get answer from the pPb run

➔ feed-down contributions have to be also considered

# Instead of conclusion ...

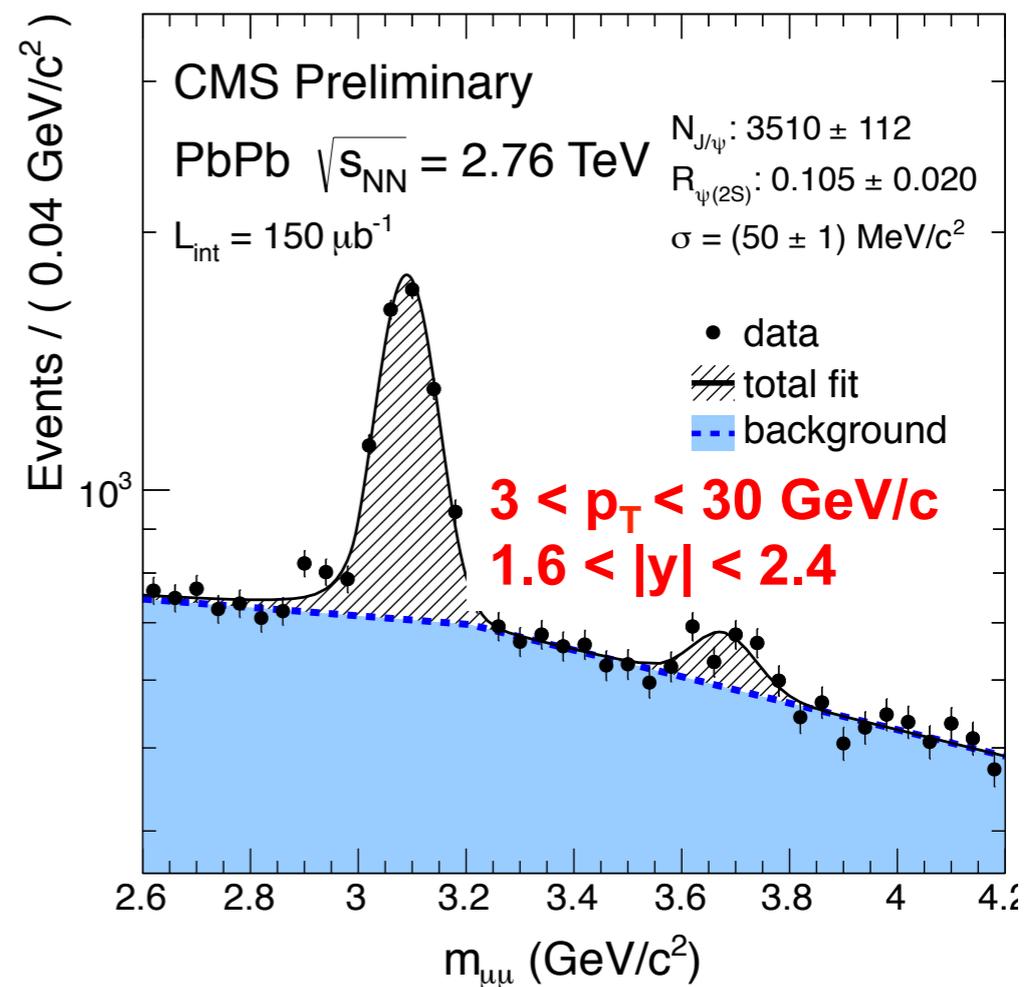
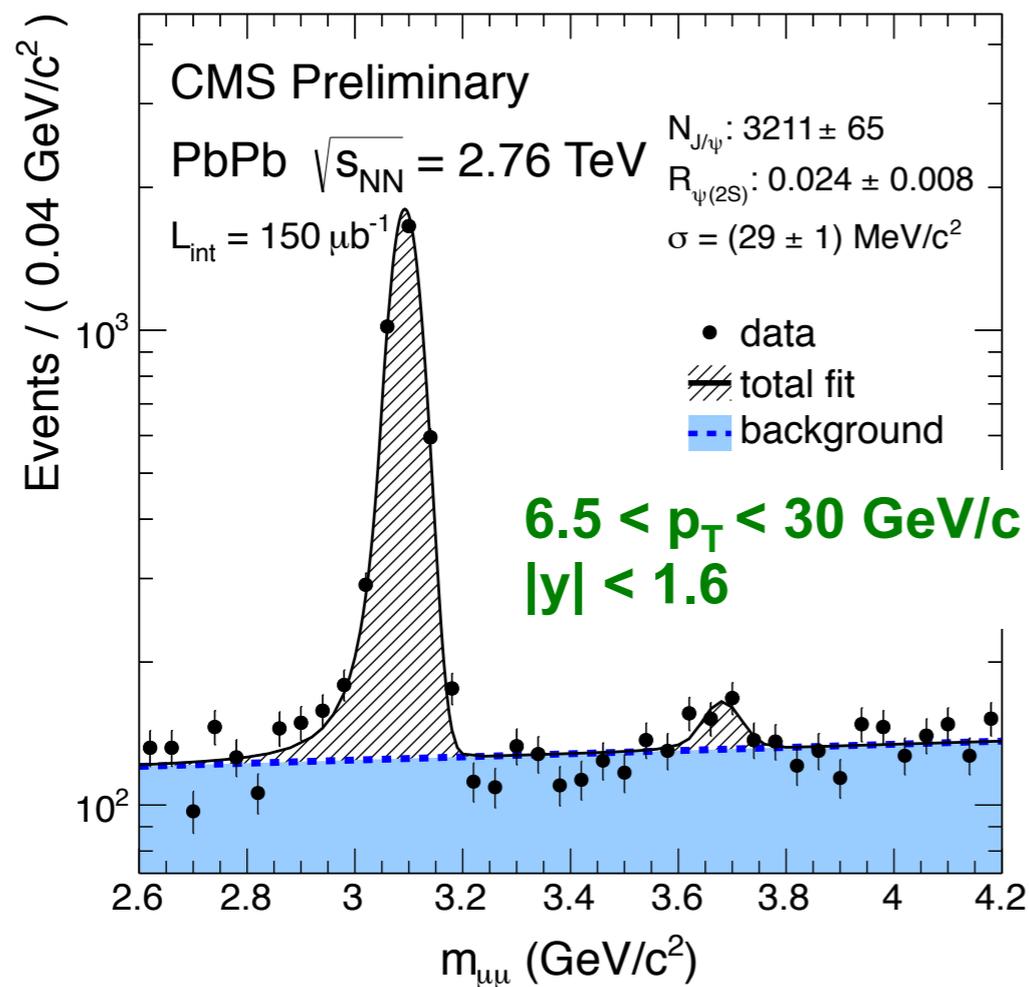


<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults>

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN>



## $\psi(2S)$ vs $J/\psi$ : PbPb 0-20 %



- We do see  $\psi(2S)$  at high- $p_T$  and low- $p_T$  in PbPb

