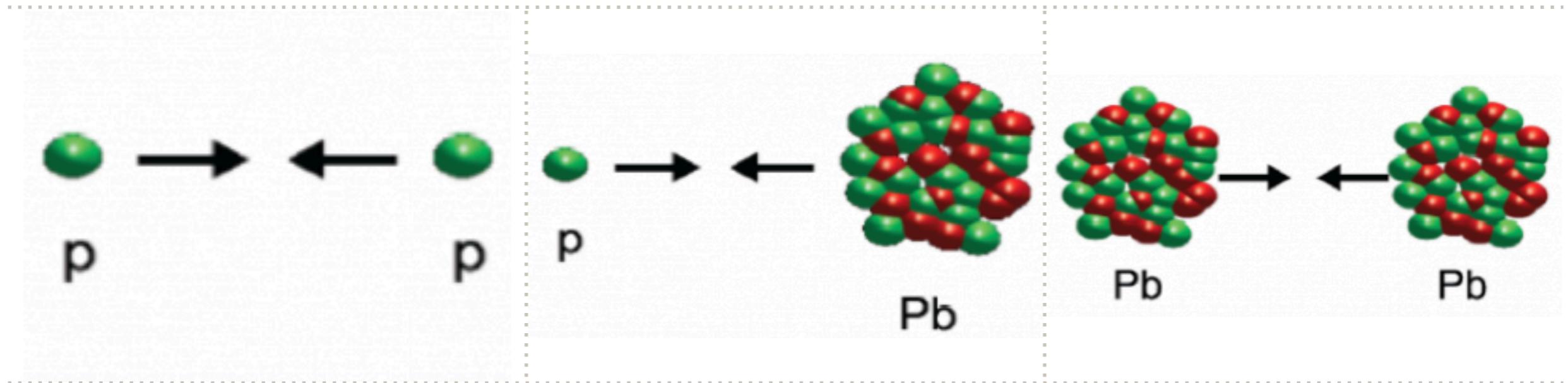




# LHC Heavy-Ion (HI) Program

## Collision systems



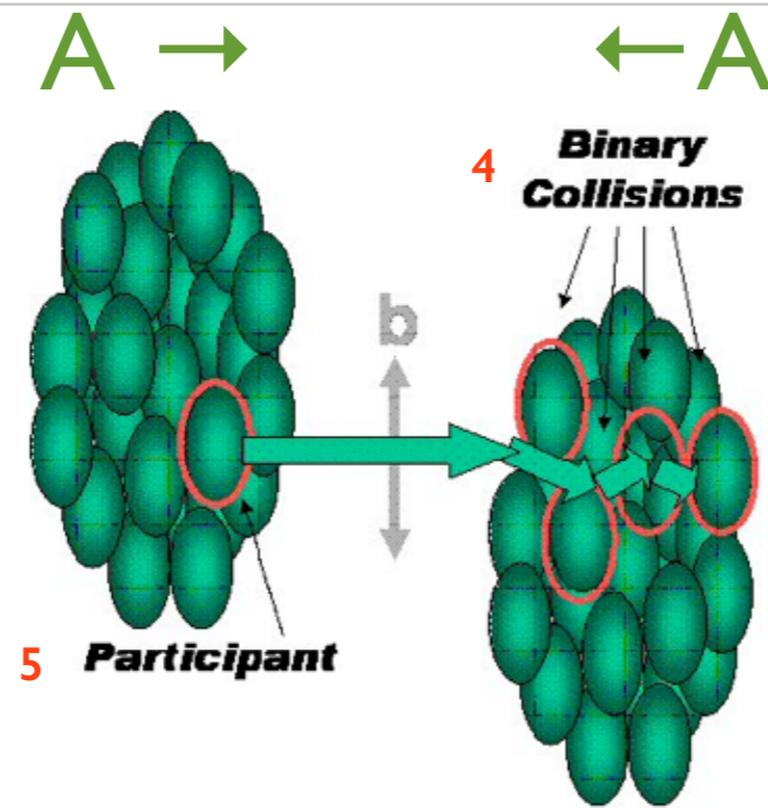
## Center of mass colliding energy (TeV)

2.76 (2011, 2013)  
5.02 (2015)  
7,13

—  
5.02 (2013)

2.76 (2010, 2011)  
5.02 (2015)

# Characterize HI collisions



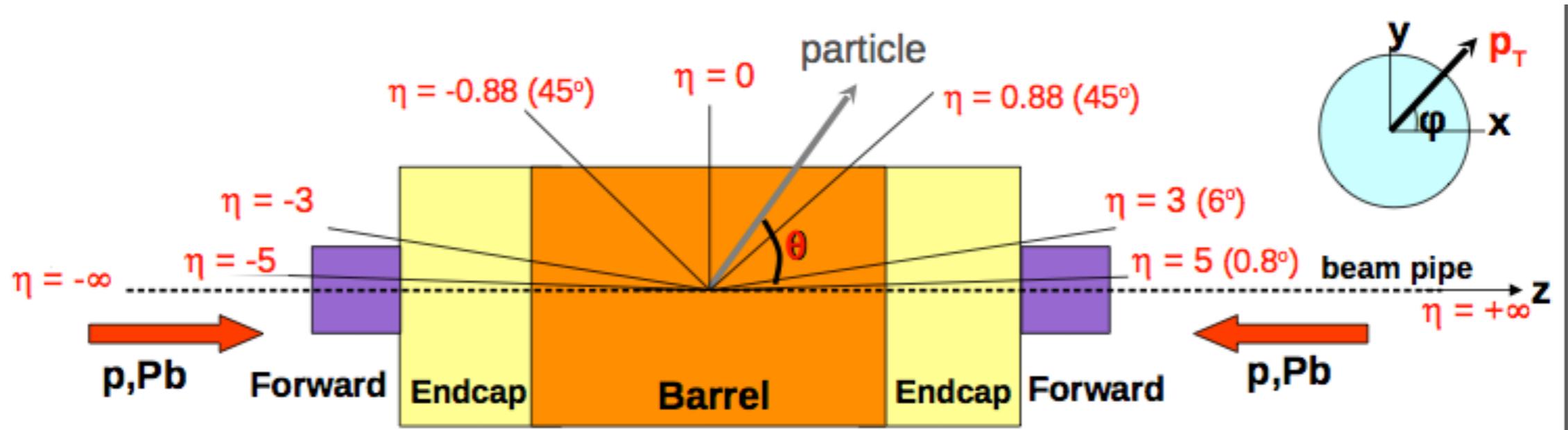
## ➔ 'Event-activity' characteristics (Data, Monte Carlo)

- ✓ central collisions: small impact parameter collision (high-multiplicity events, large energy deposited in calorimeters, etc)
- ✓ peripheral collision: large impact parameter collision

## ➔ At a certain colliding energy, for a certain impact parameter $b$

- ✓  $\langle N_{\text{part}} \rangle$  — number of incoming nucleons participating in the collision
- ✓  $\langle N_{\text{coll}} \rangle$  — number of equivalent nucleon-nucleon collisions
  - Glauber MC calculation

# Characterize HI collisions



## ➔ Particle production

✓ transverse momentum: component perpendicular on the beam axis

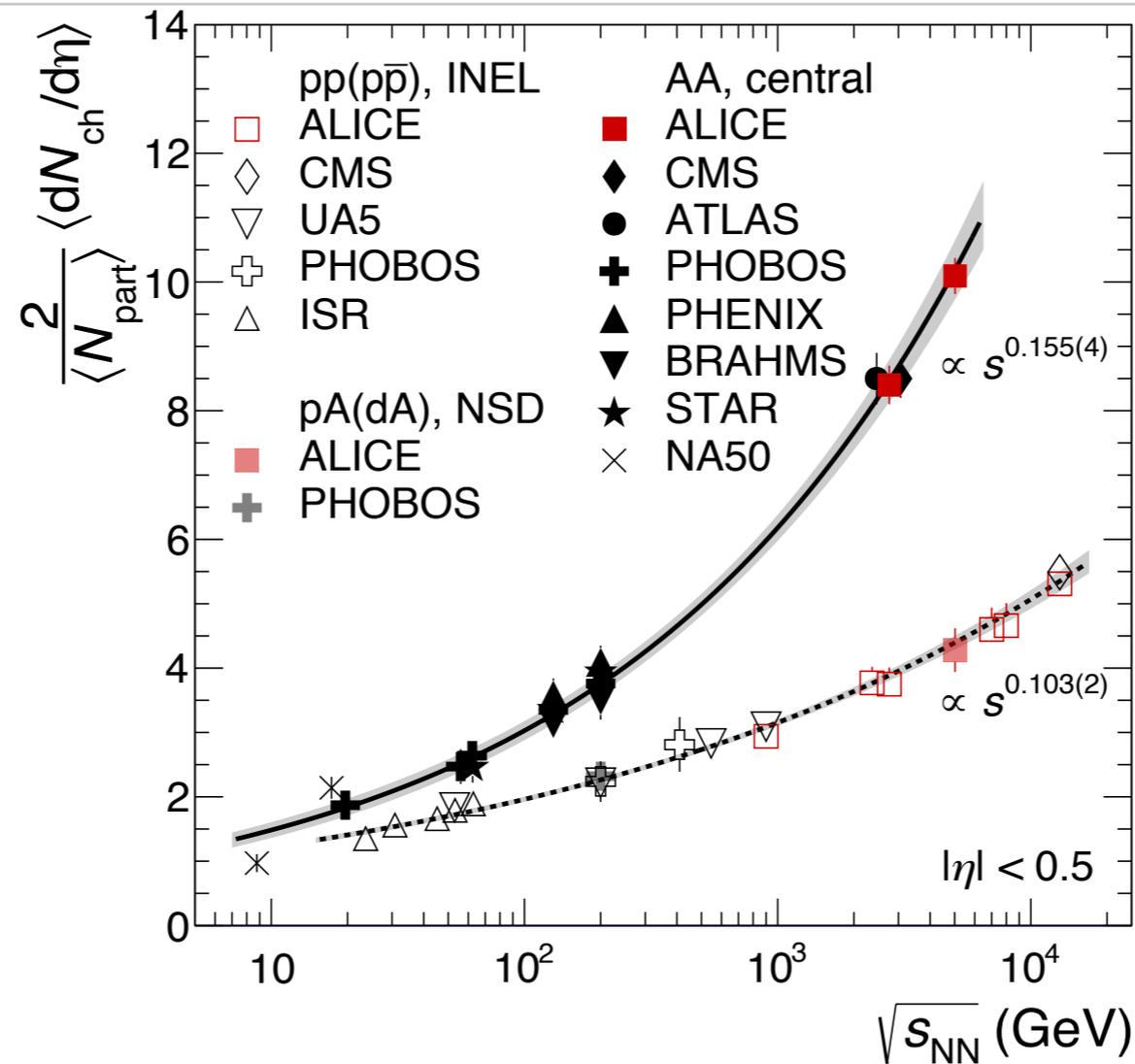
-  $p_T = p \cos\theta$

✓ pseudorapidity: angular position in detector

$$\eta = -\ln[\tan(\theta/2)]$$

# LHC vs RHIC

PRL 116 (2016)

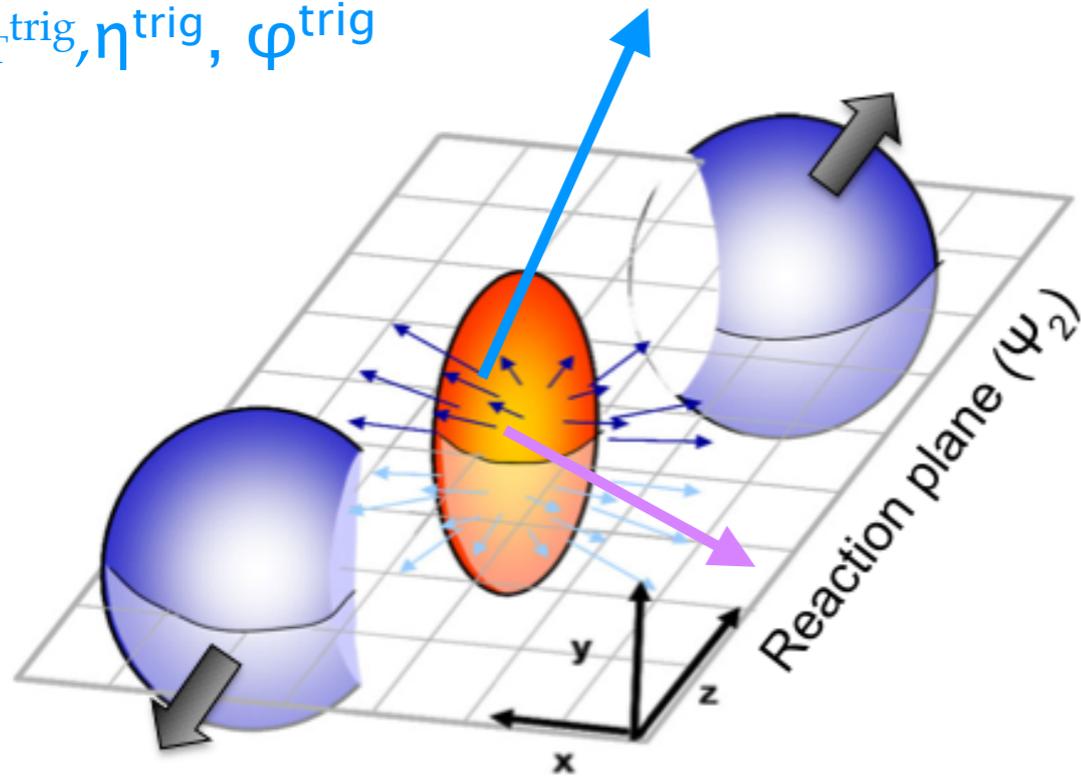


➔ The charged particle multiplicity per colliding nucleon pair measured at LHC for the most central collisions is

- ✓ ~2x that measured at RHIC, where the collision energy is factor 14 lower
- ✓ ~2x that measured at LHC in pp or pPb collisions at similar collision energy

# Analyzing HI collisions: 2-particle correlations

Trigger particle  
 $p_T^{\text{trig}}, \eta^{\text{trig}}, \varphi^{\text{trig}}$



Associated particle  
 $p_T^{\text{assoc}}, \eta^{\text{assoc}}, \varphi^{\text{assoc}}$

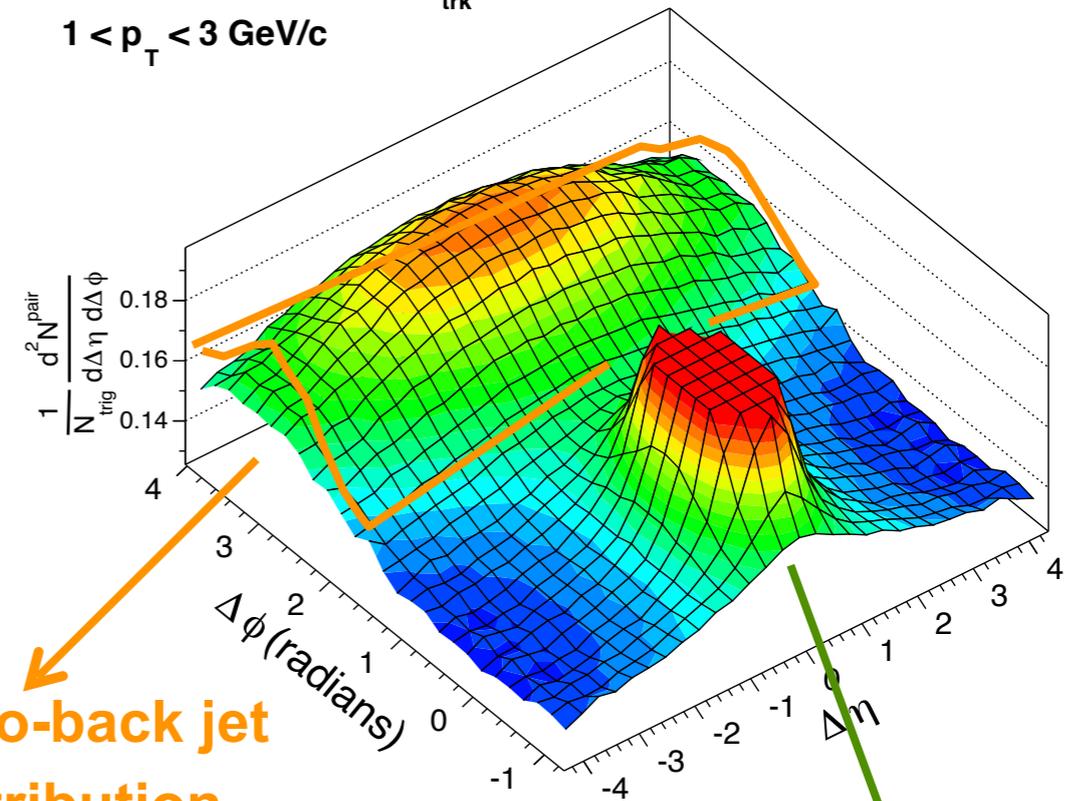
➔ Event-by-event

$$\Delta\eta = \eta^{\text{trig}} - \eta^{\text{assoc}}$$

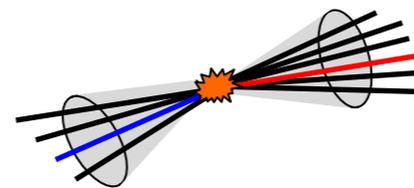
$$\Delta\phi = \varphi^{\text{trig}} - \varphi^{\text{assoc}}$$

CMS pp  $\sqrt{s} = 13$  TeV,  $N_{\text{trk}}^{\text{offline}} < 35$   
 $1 < p_T < 3$  GeV/c

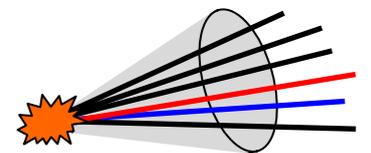
(a)



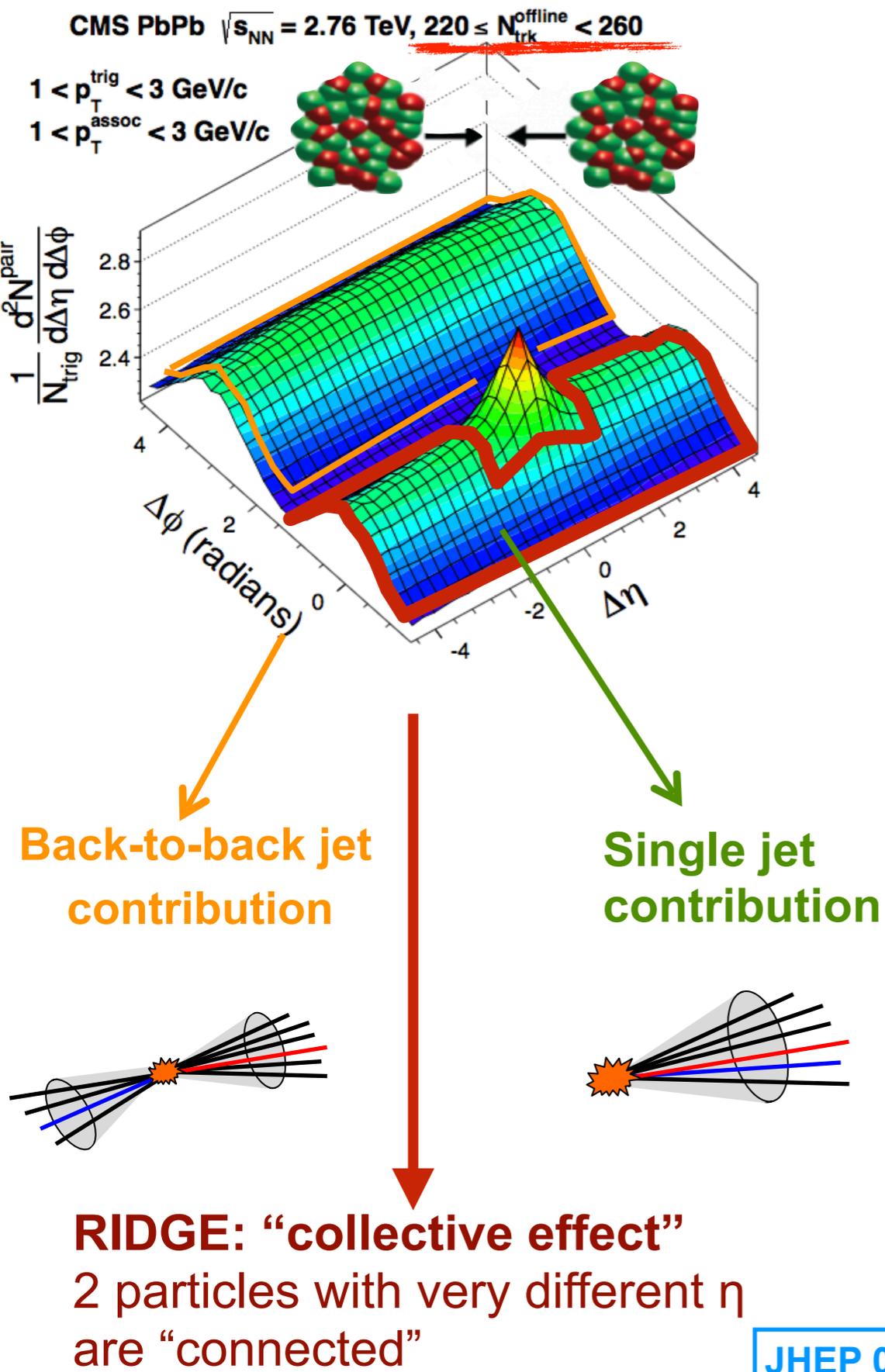
Back-to-back jet contribution



Single jet contribution



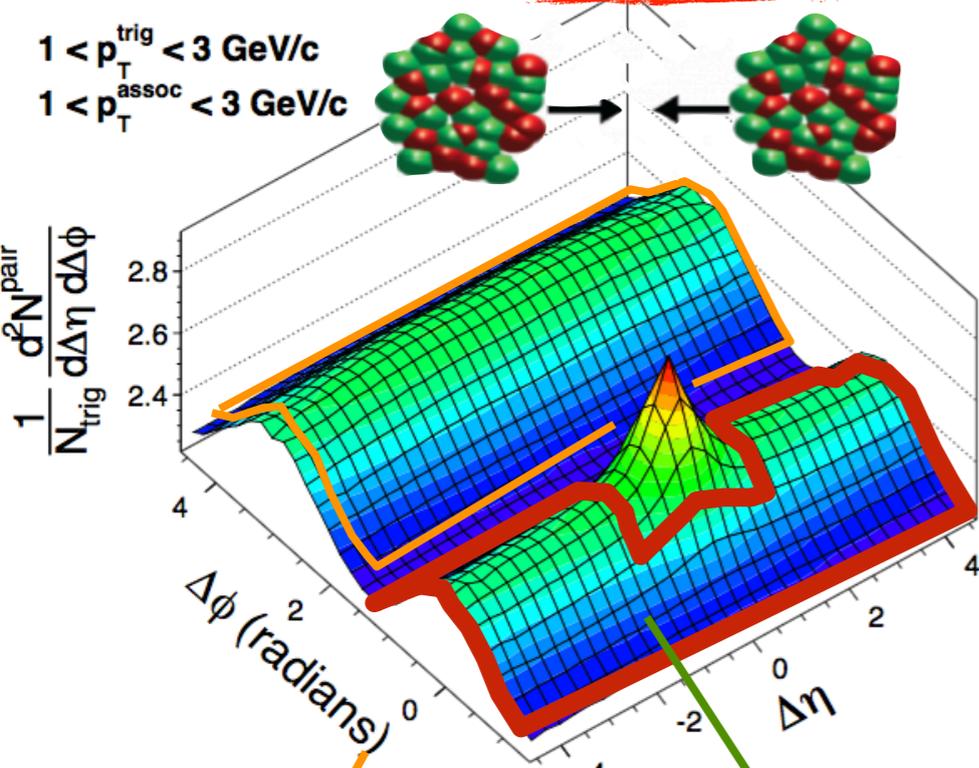
# Collective motion: 2-particle correlations



# Collective motion: 2-particle correlations

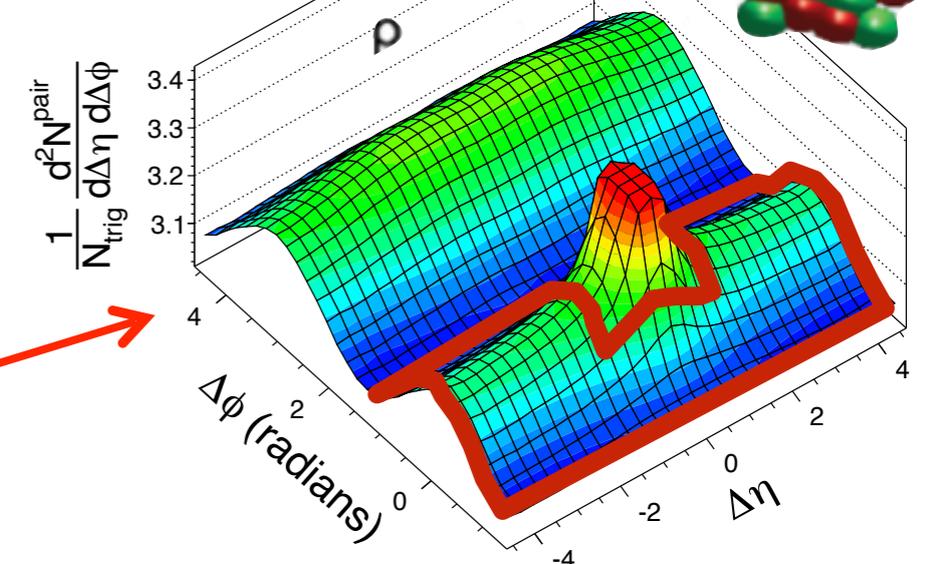
CMS PbPb  $\sqrt{s_{NN}} = 2.76$  TeV,  $220 \leq N_{trk}^{offline} < 260$

PLB 718 (2013)



(b) CMS pPb  $\sqrt{s_{NN}} = 5.02$  TeV,  $220 \leq N_{trk}^{offline} < 260$

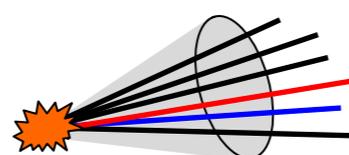
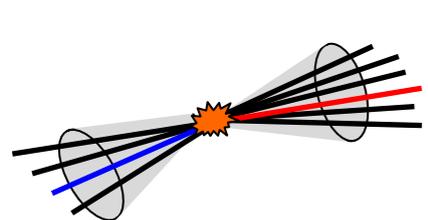
$1 < p_T^{trig} < 3$  GeV/c  
 $1 < p_T^{assoc} < 3$  GeV/c



RIDGE Also in pPb high-multiplicity events

Back-to-back jet contribution

Single jet contribution



**RIDGE: “collective effect”**  
 2 particles with very different  $\eta$   
 are “connected”

# Collective motion: pPb

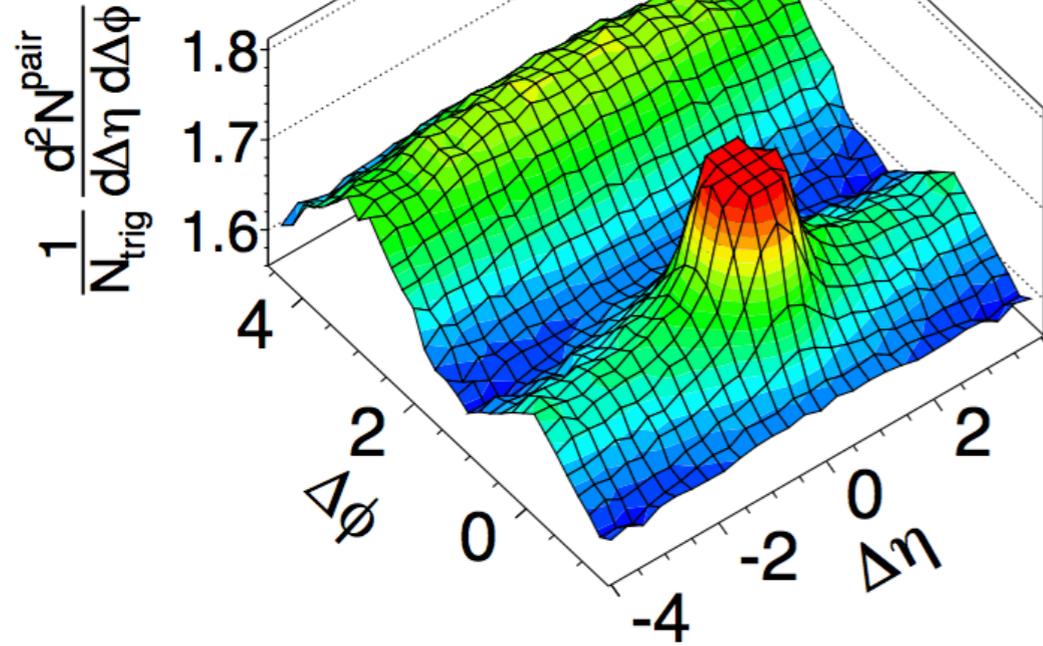
PLB 718 (2013)

PLB 719 (2013)

CMS pPb  $\sqrt{s_{NN}} = 5.02$  TeV,  $N_{\text{trk}}^{\text{offline}} \geq 110$

$1 < p_T < 3$  GeV/c

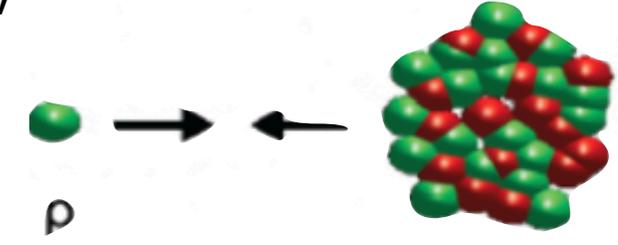
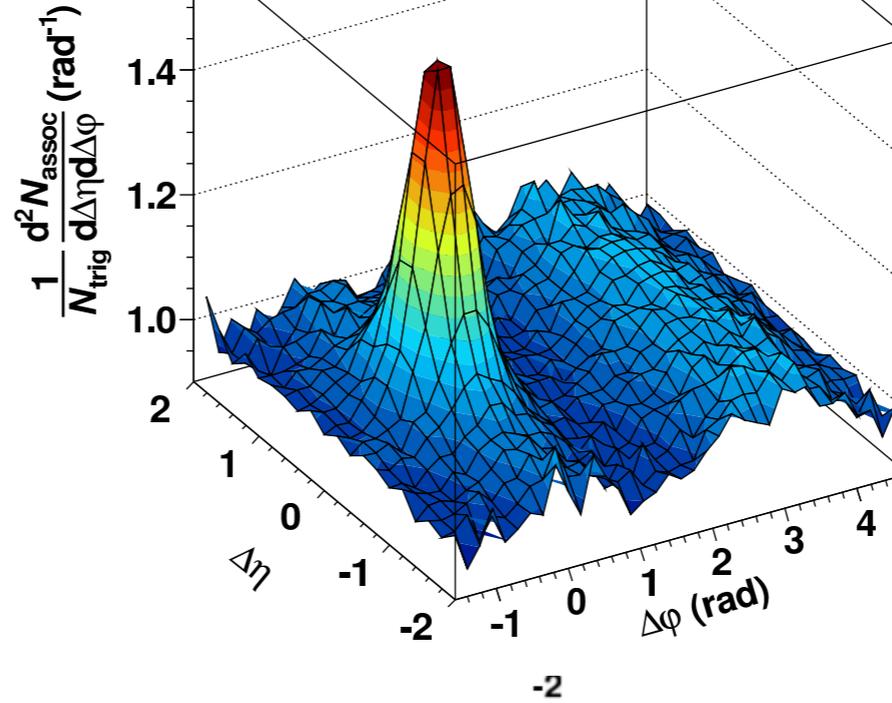
**CMS**



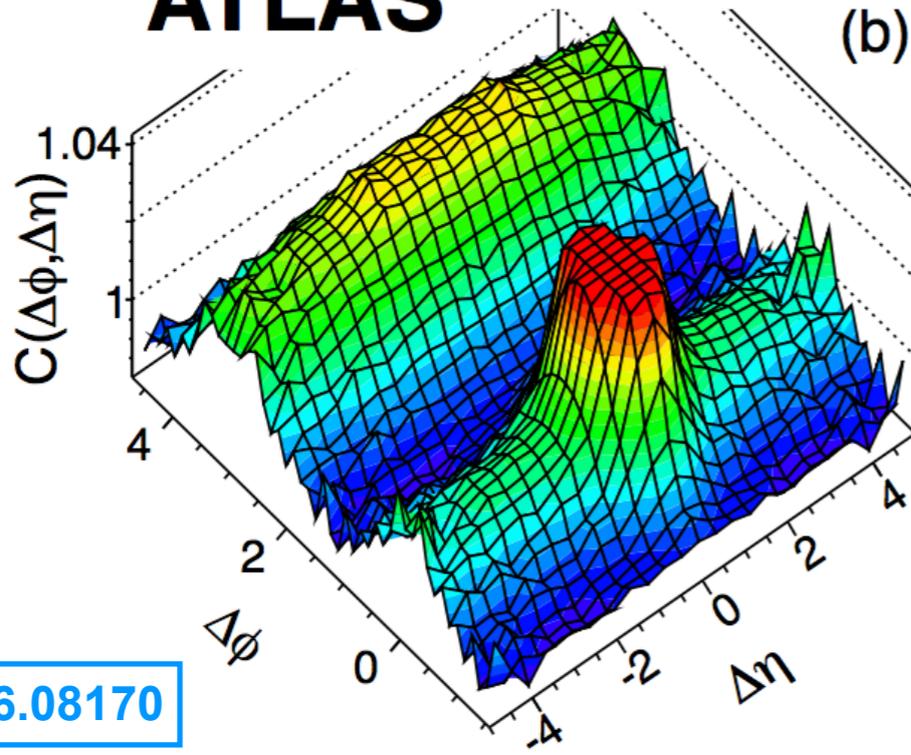
$2 < p_{T,\text{trig}} < 4$  GeV/c  
 $1 < p_{T,\text{assoc}} < 2$  GeV/c

p-Pb  $\sqrt{s_{NN}} = 5.02$  TeV  
 0-20%

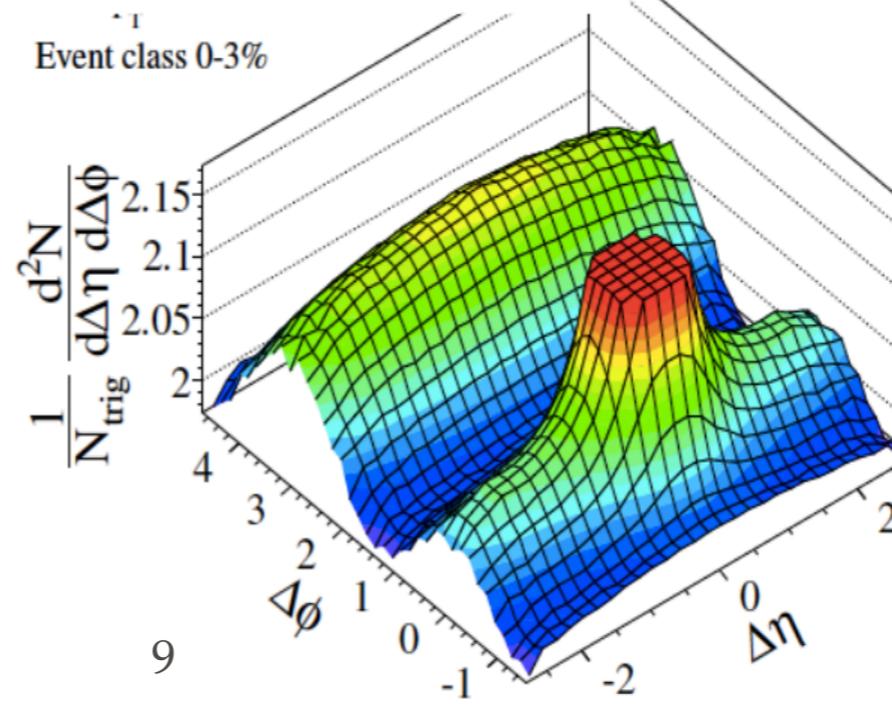
**ALICE**



**ATLAS**



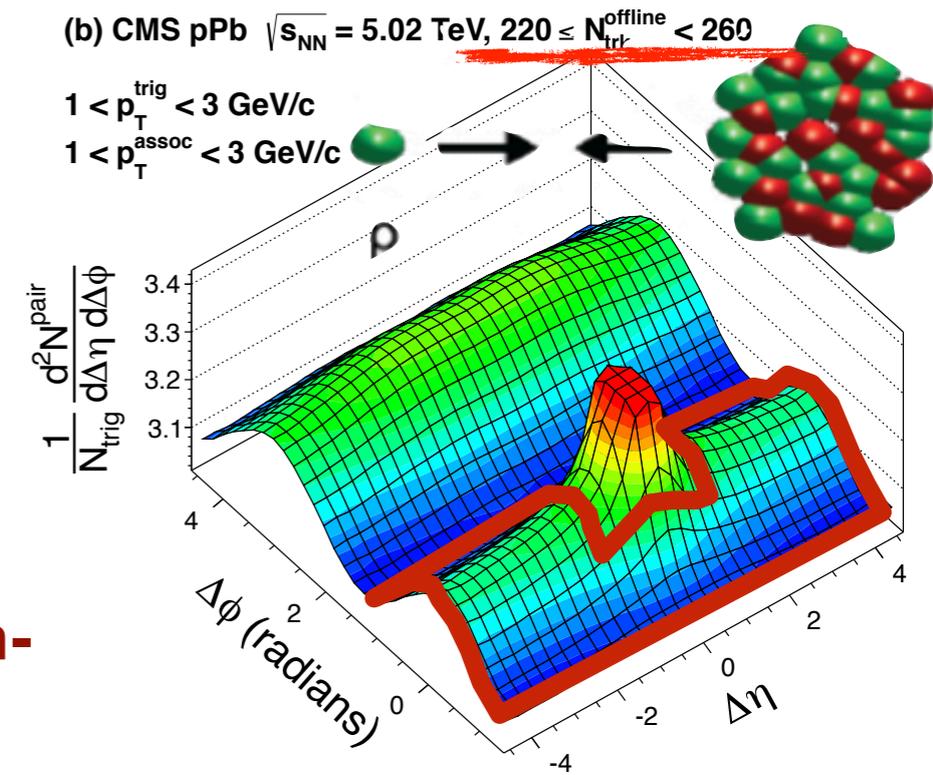
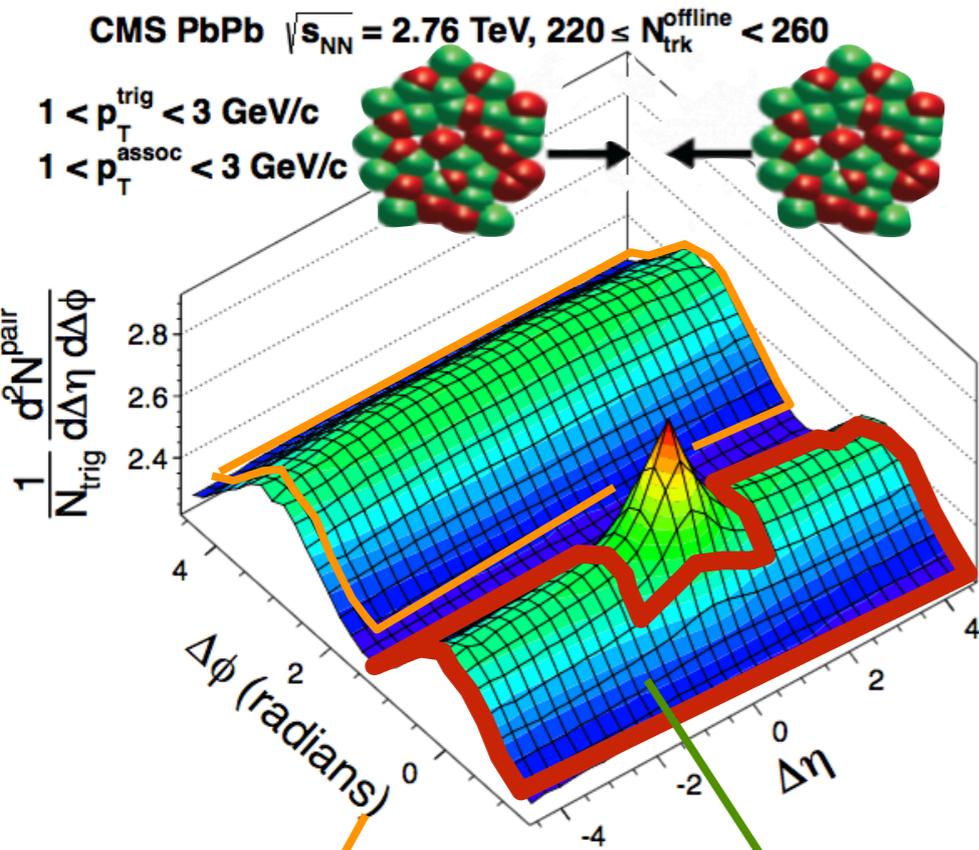
**LHCb (new!)**



arXiv:1606.08170

arXiv:1512.00439

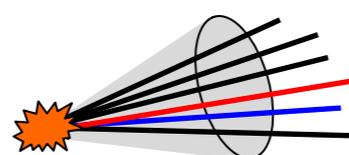
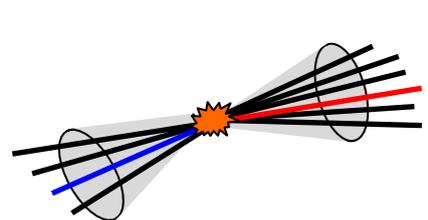
# Collective motion everywhere!



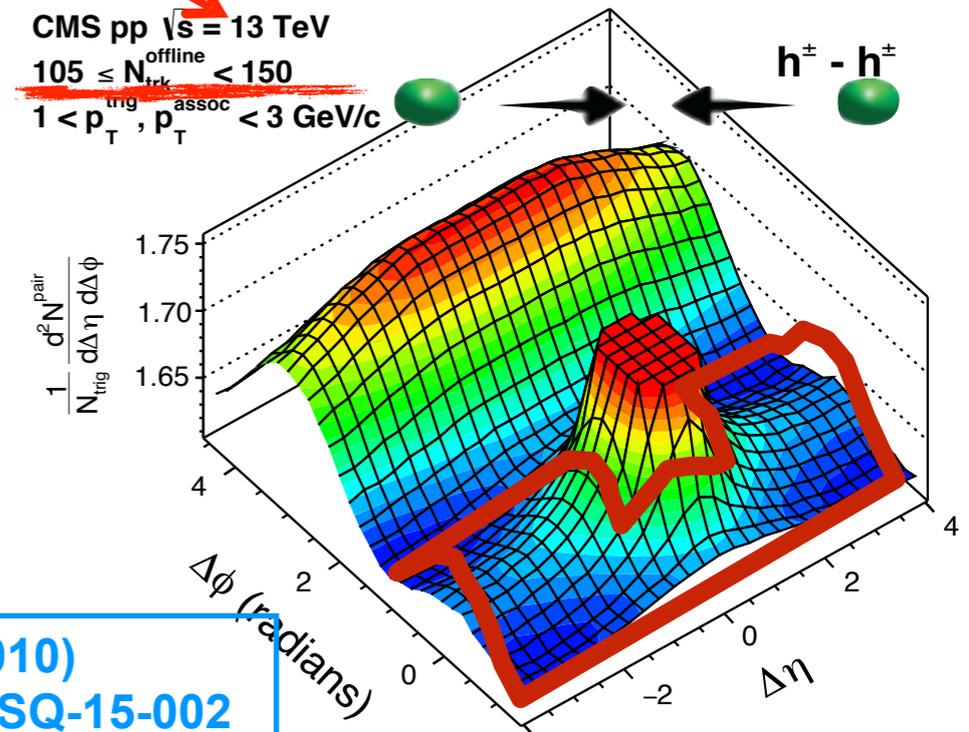
**RIDGE Also in pp high-multiplicity events**

**Back-to-back jet contribution**

**Single jet contribution**

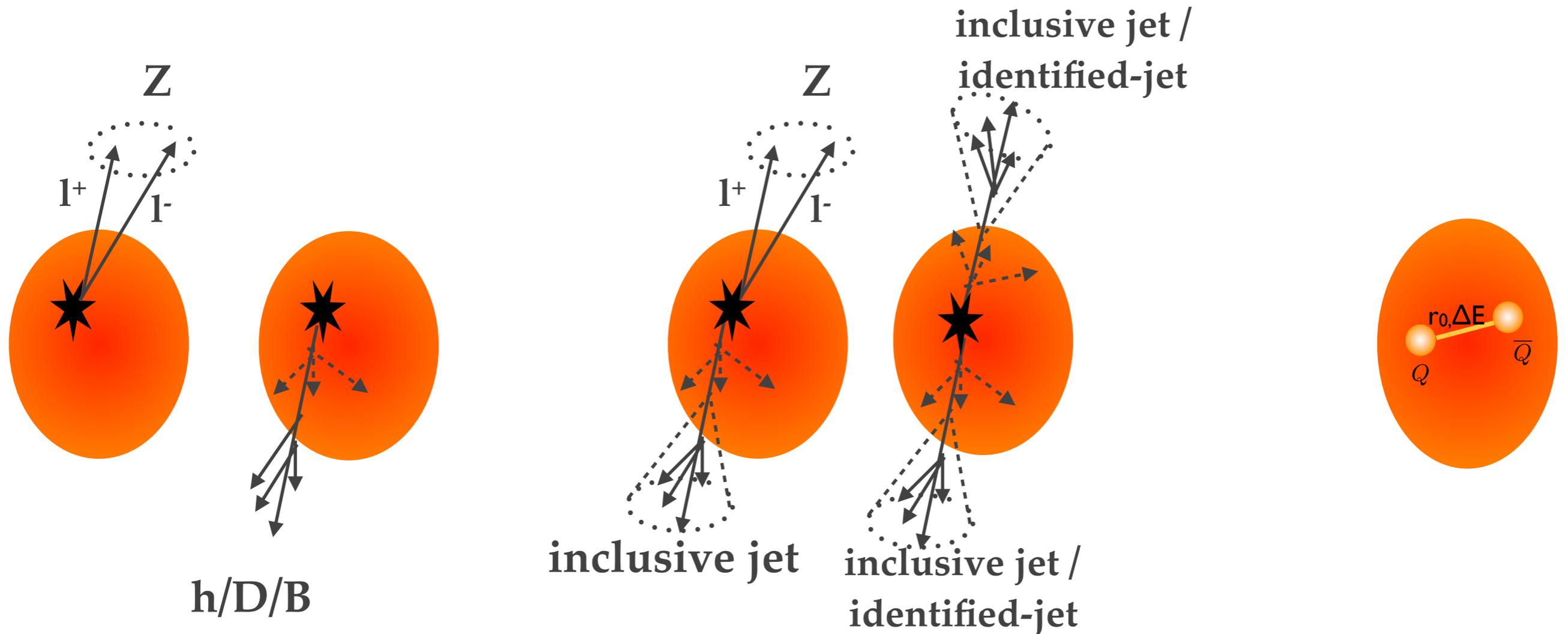


**RIDGE: “collective effect”**  
 2 particles with very different  $\eta$  are “connected”



JHEP 09 (2010)  
 CMS-PAS-FSQ-15-002  
 ATLAS-CONF-2016-026

# LHC: PbPb @ 2.76, 5.02 TeV



A) Individual hadrons

B) Reconstructed jets

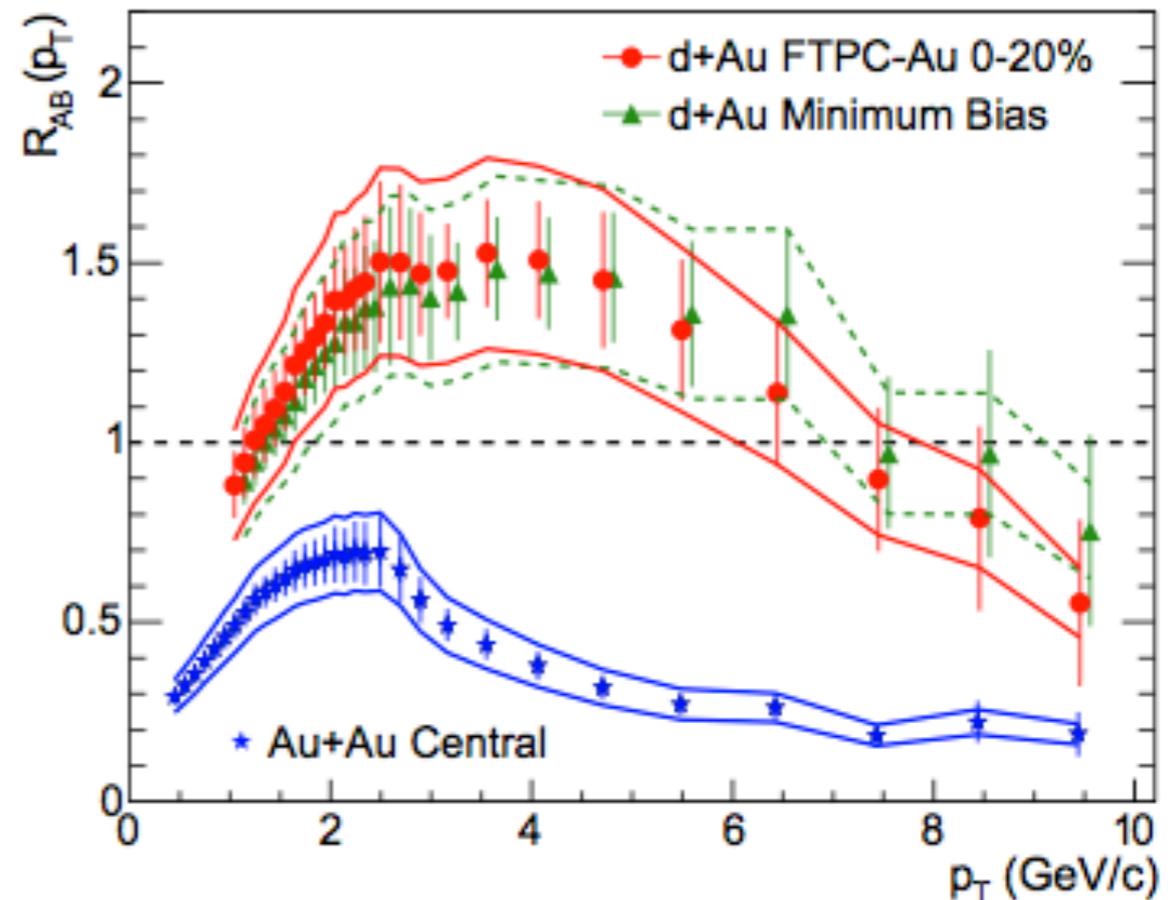
C) Quarkonia

➔ Questions one addresses with these measurements

- ✓ Is there a difference in how the light partons and heavy (charm and beauty) quarks interact with the medium?
- ✓ What are the properties of the medium created?

# Analyzing HI collisions: $R_{AA}$

$$R_{AA} = \frac{Yield(A + A)}{Yield(p + p) \langle N_{coll} \rangle}$$



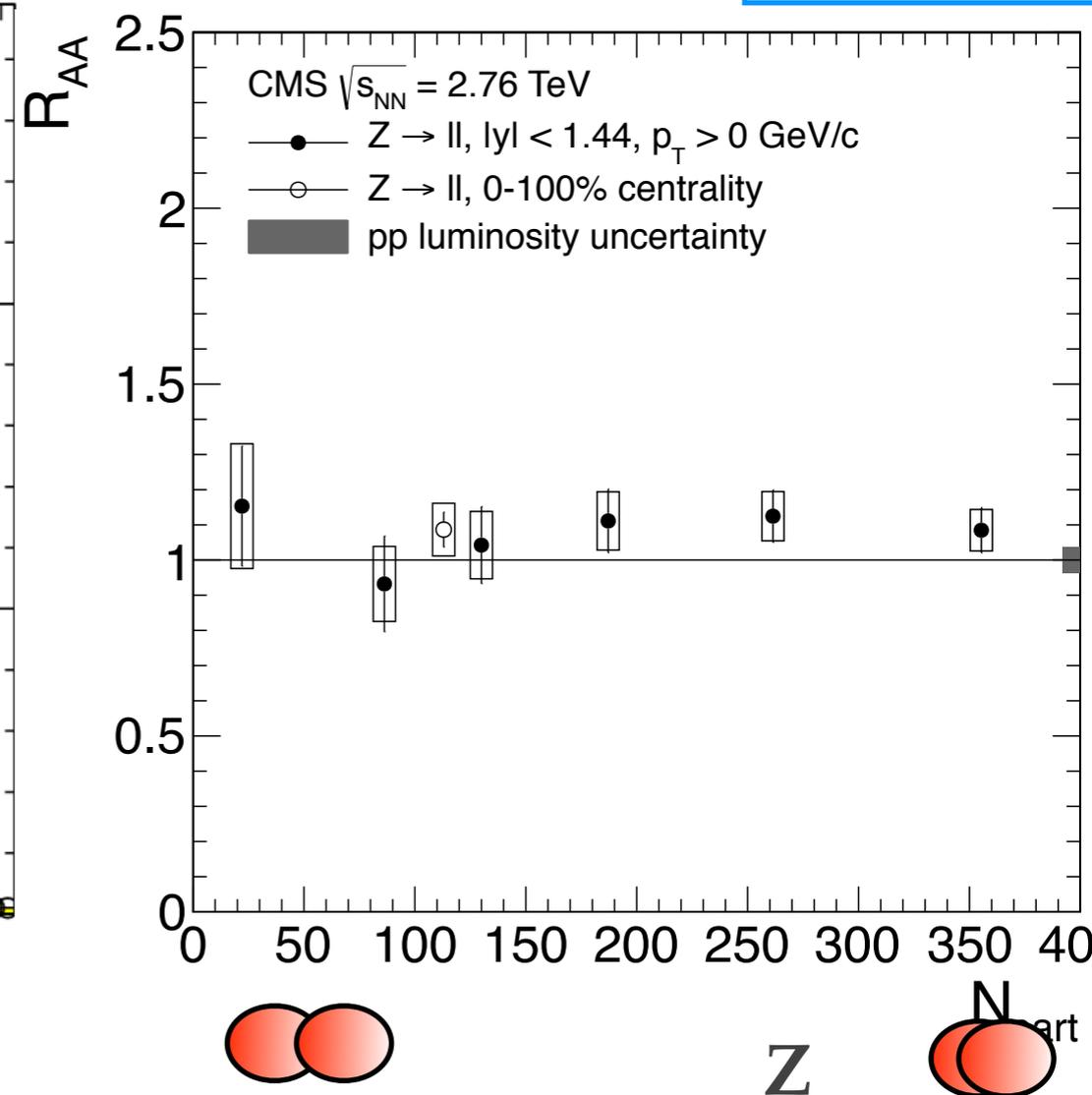
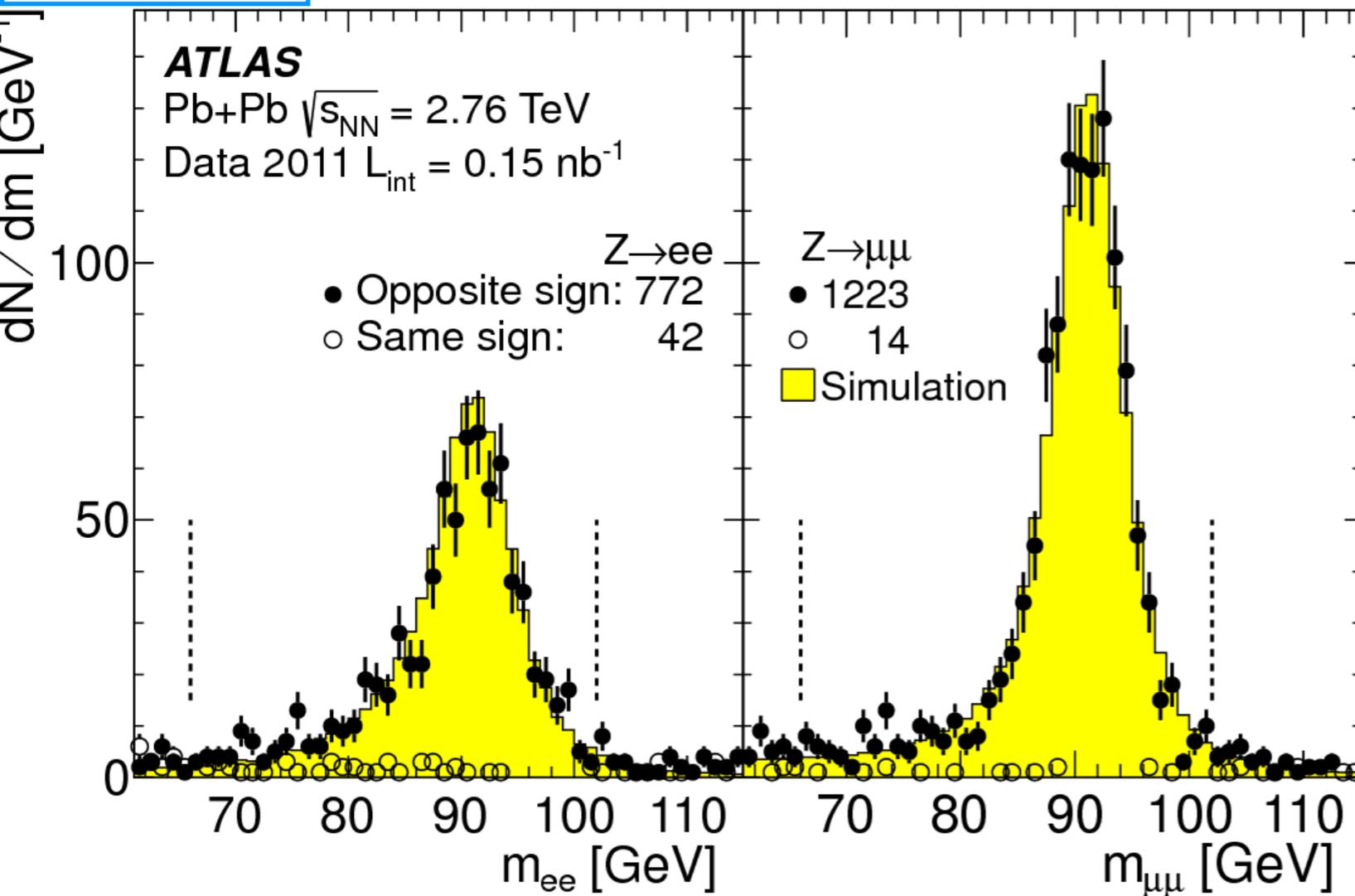
➔ Nuclear modification factor:

- ✓ if = 1 no medium effects
- ✓ if < 1 suppression (e.g. energy loss in the medium)
- ✓ if > 1 enhancement (e.g. kT broadening in the incoming nuclei)

# Z boson: in-situ reference

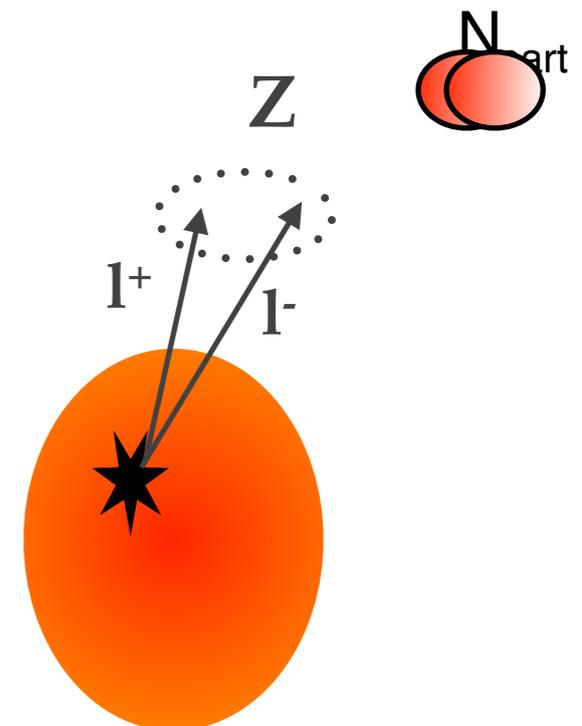
PRL 110 (2013)

JHEP 03 (2015)



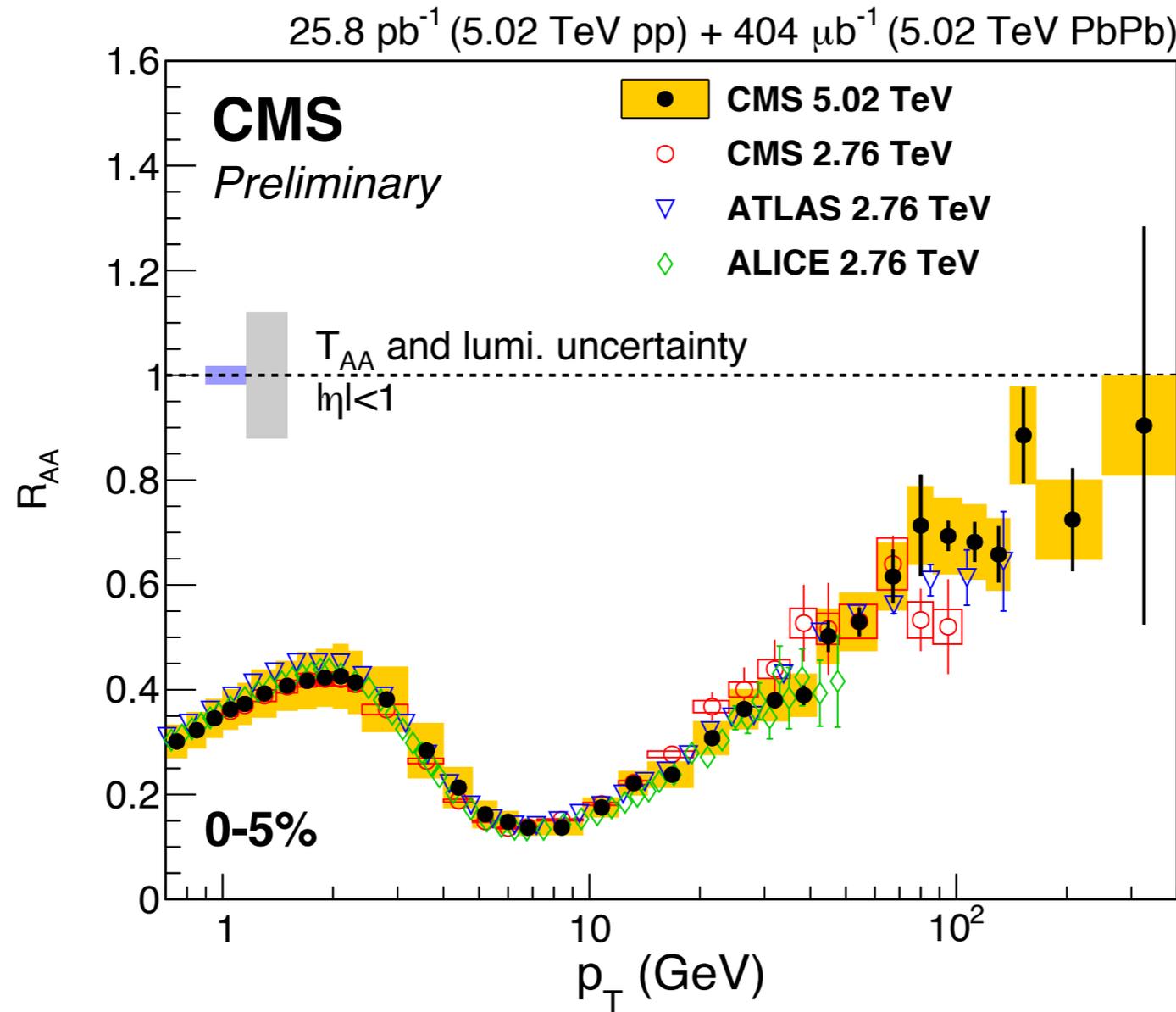
➔ Z boson measured for the first time in HI collisions

✓ confirm the Ncoll scaling:  $R_{AA} = 1$

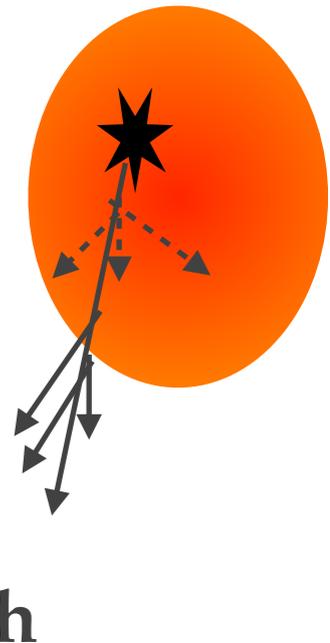


# Charged hadrons (gluons & u/d/s quarks)

CMS-PAS-HIN-15-015



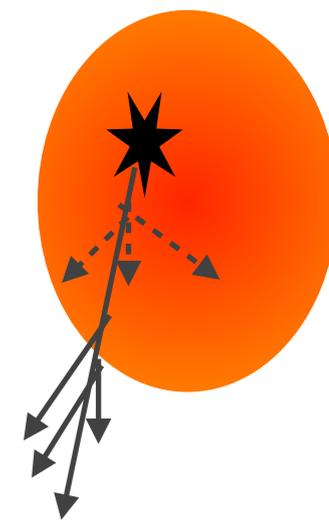
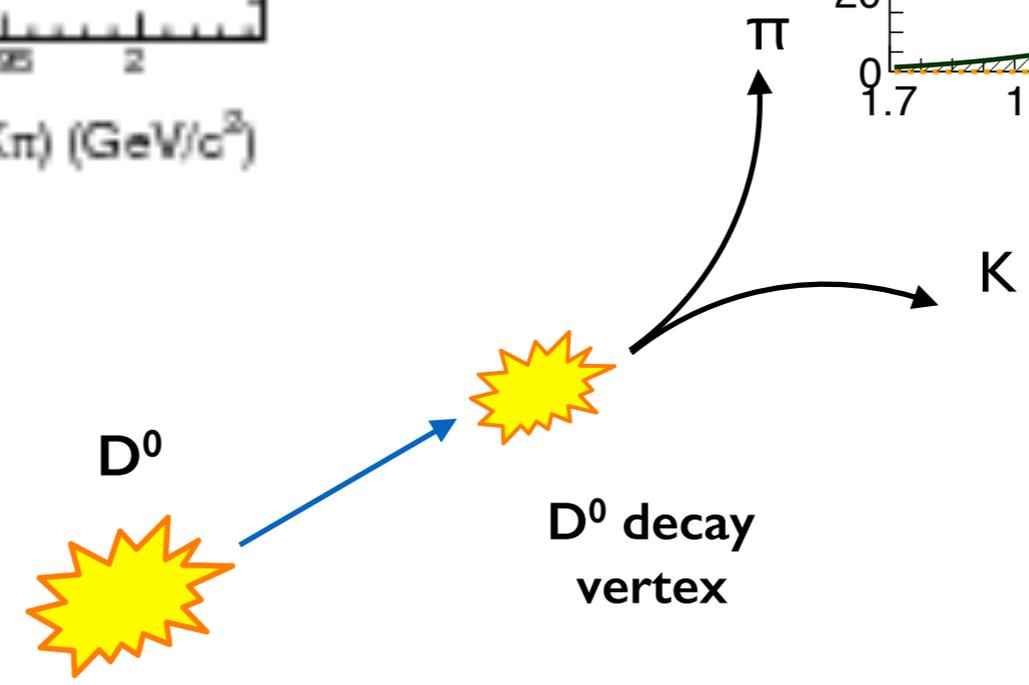
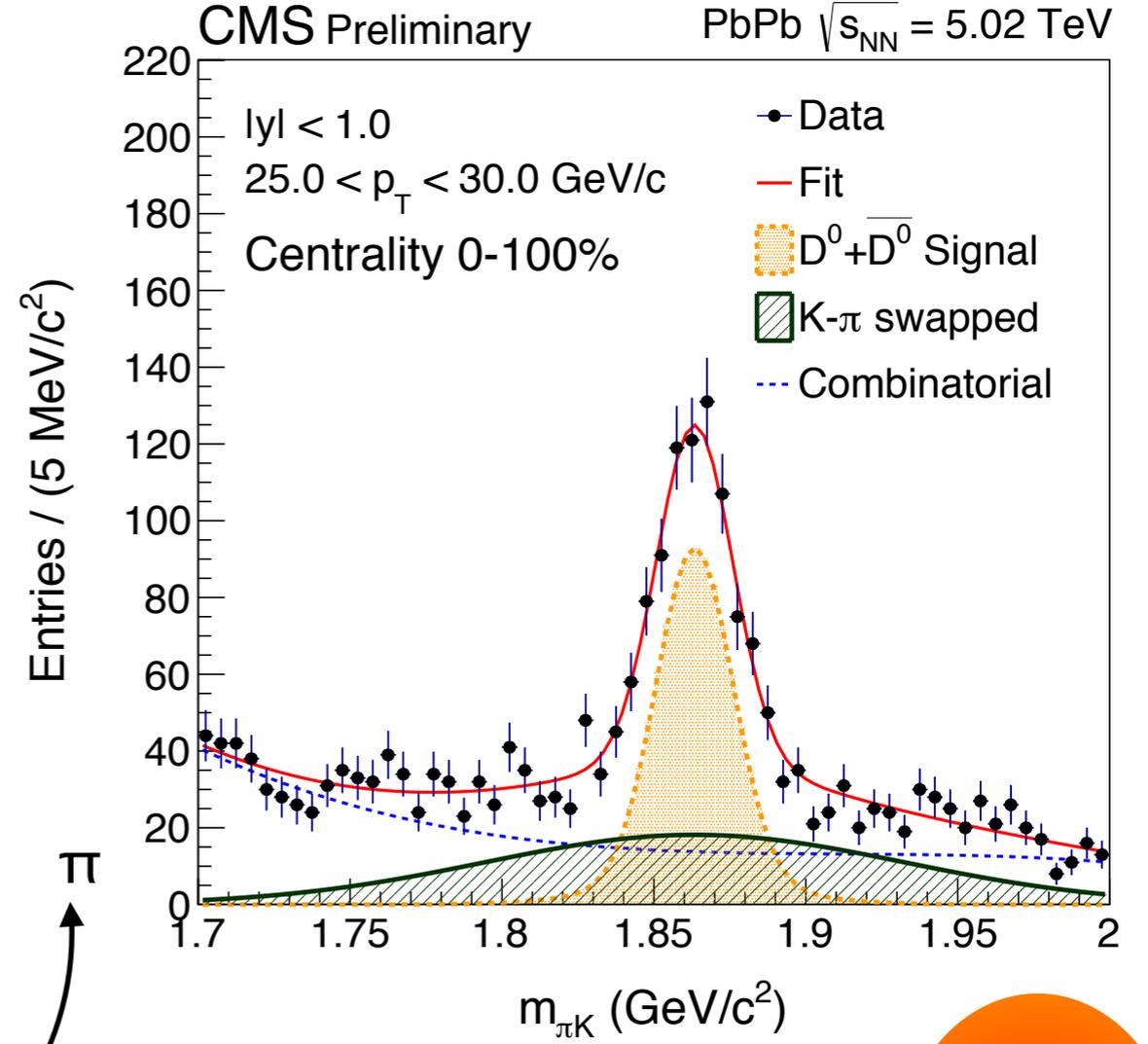
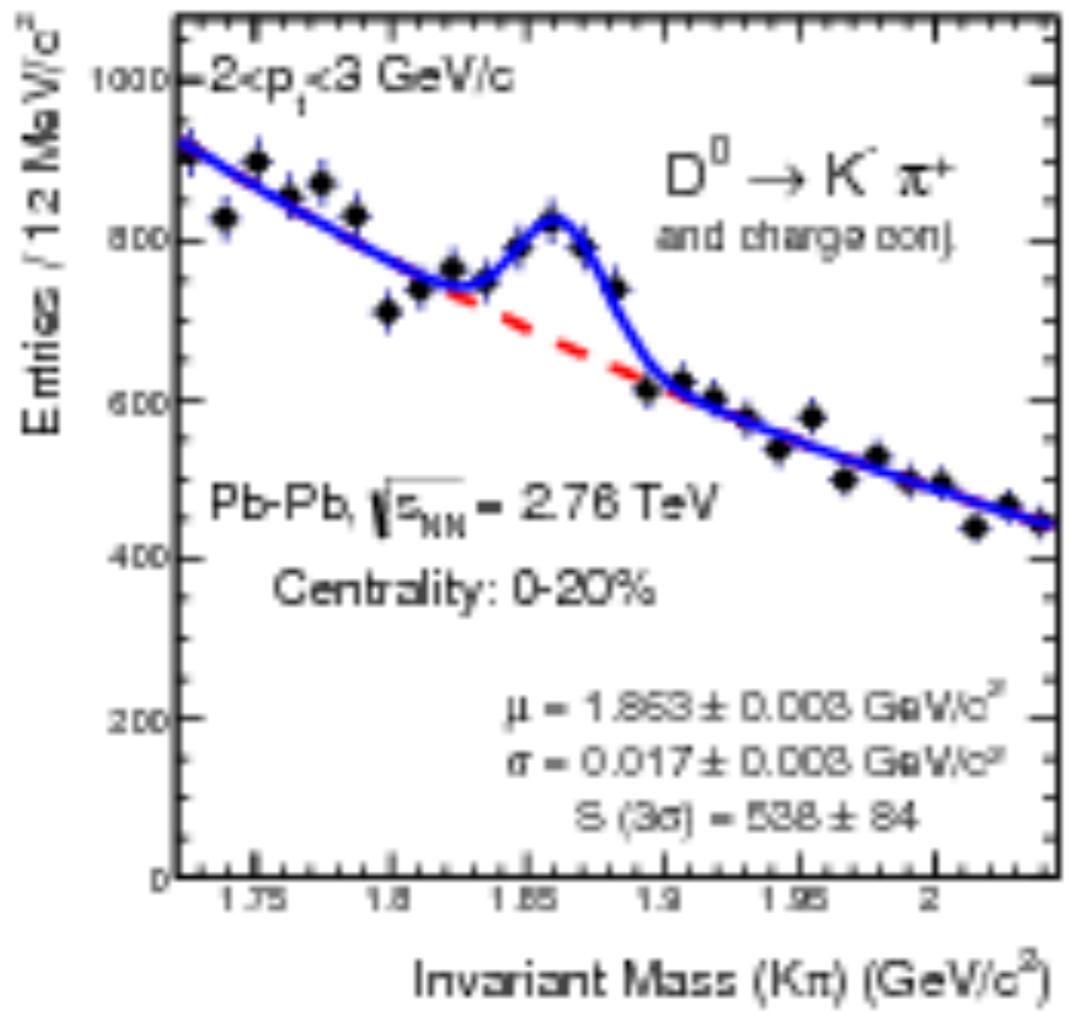
- ➔ Agreement between experiments at 2.76 TeV
- ➔ And same suppression at 2.76 TeV and 5 TeV



# D mesons (charm quarks)

JHEP 09 (2012)

CMS-PAS-HIN-16-001



Primary

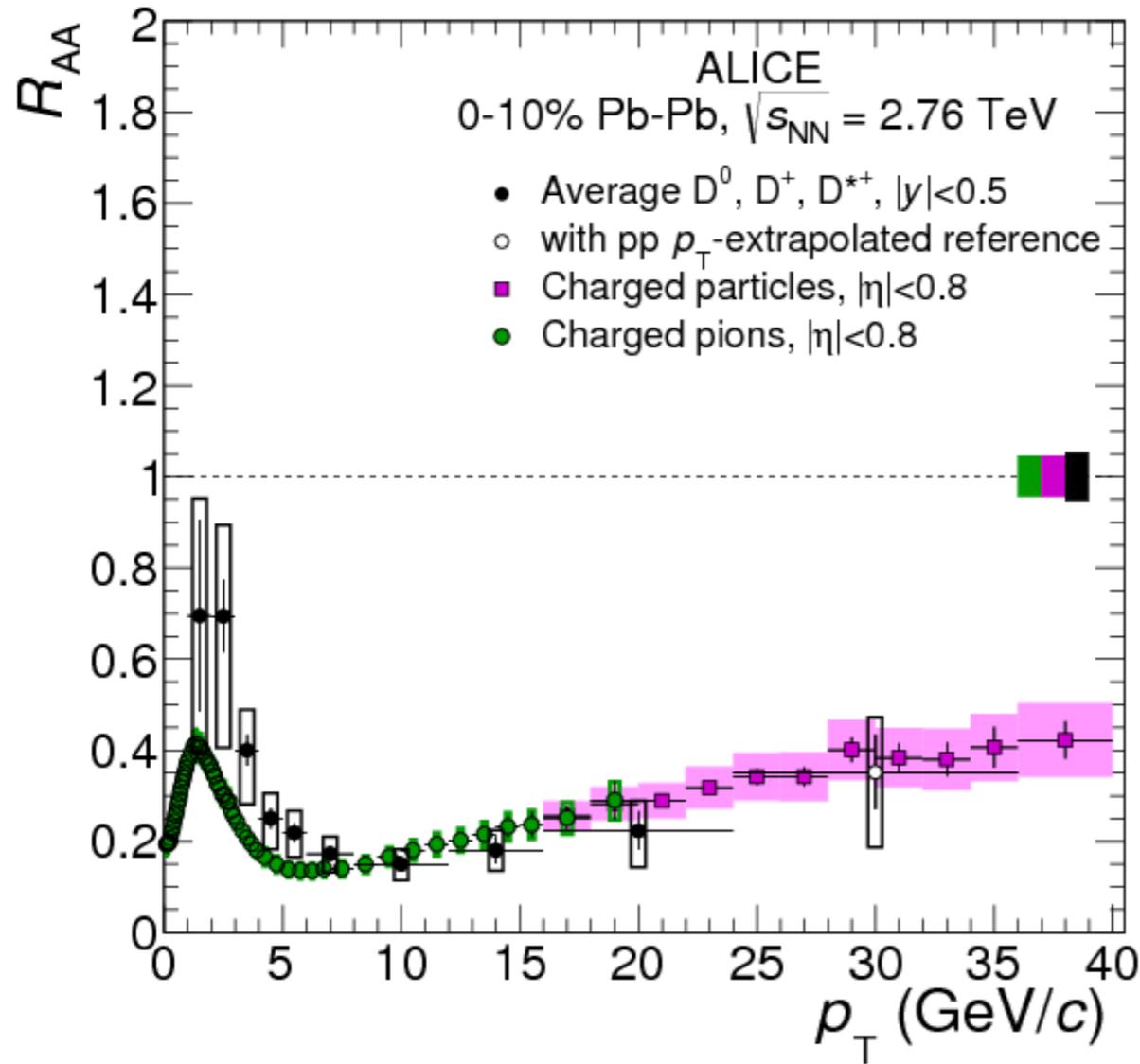
15

D

# Charm vs Light

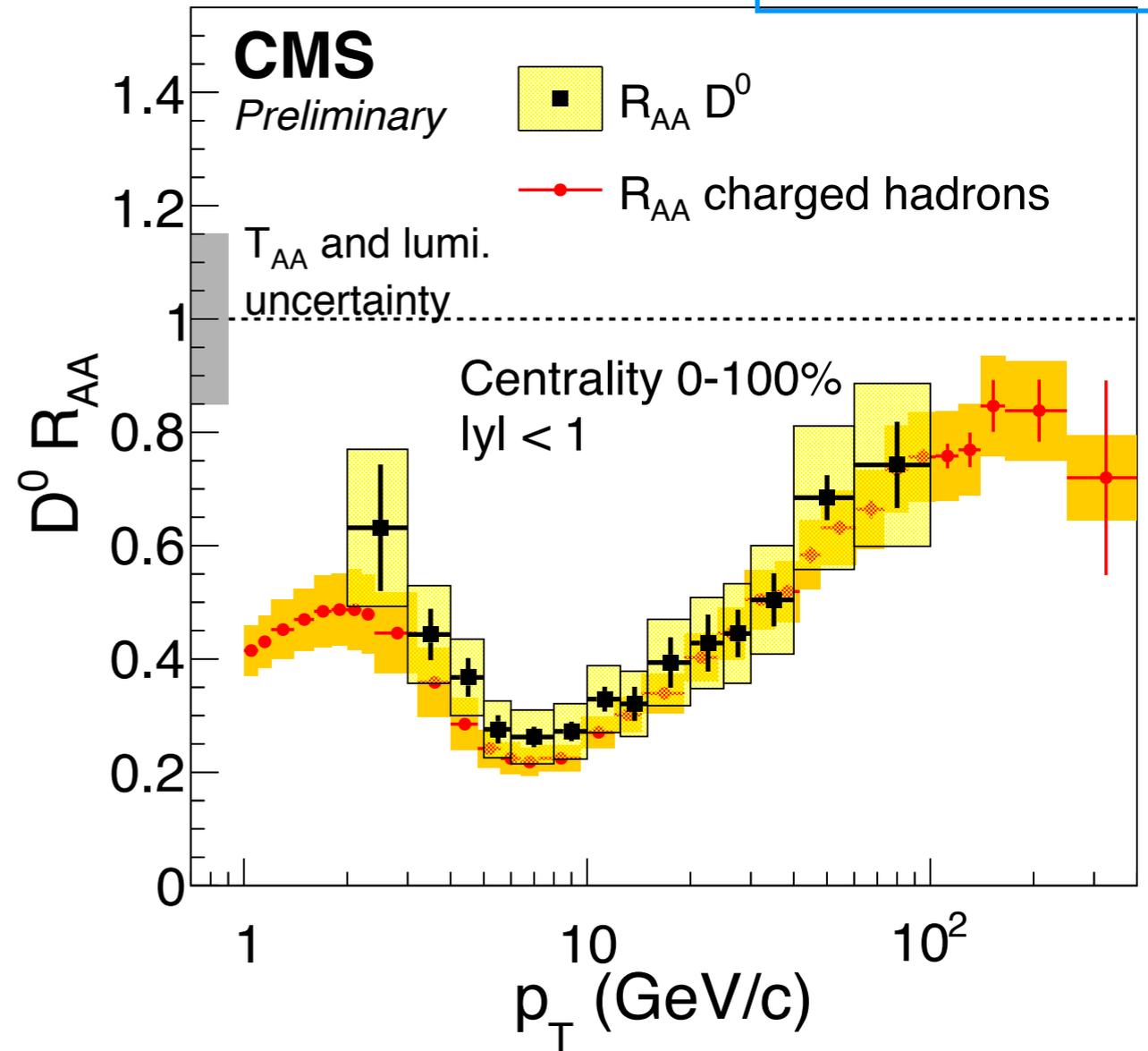
JHEP 03 (2016)

2.76 TeV



5.02 TeV

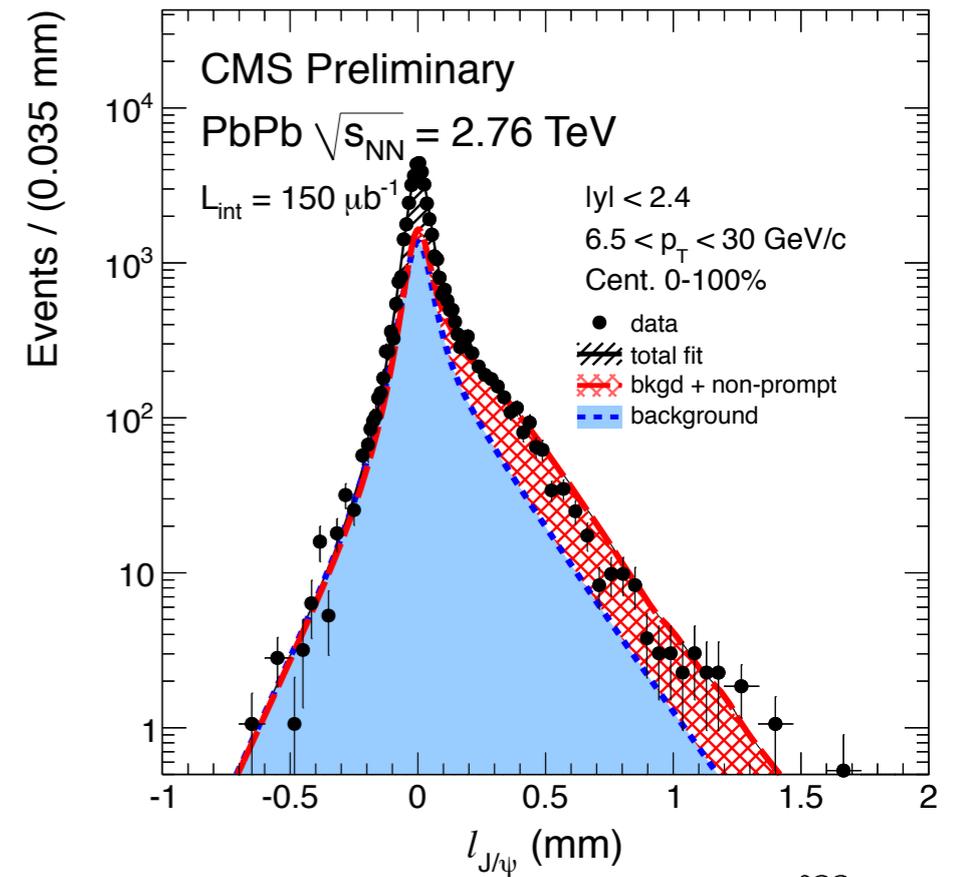
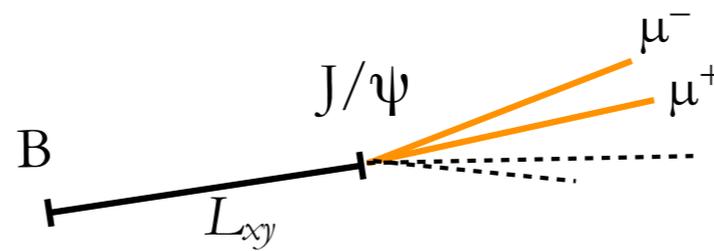
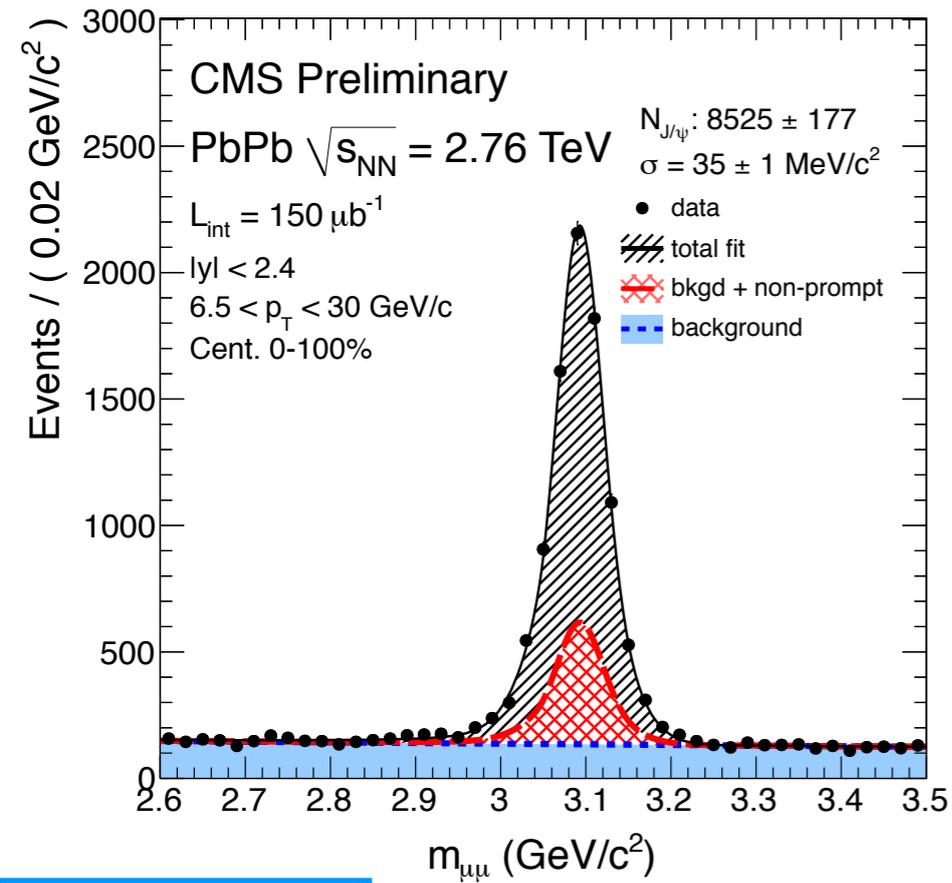
CMS-PAS-HIN-16-001  
CMS-PAS-HIN-15-015



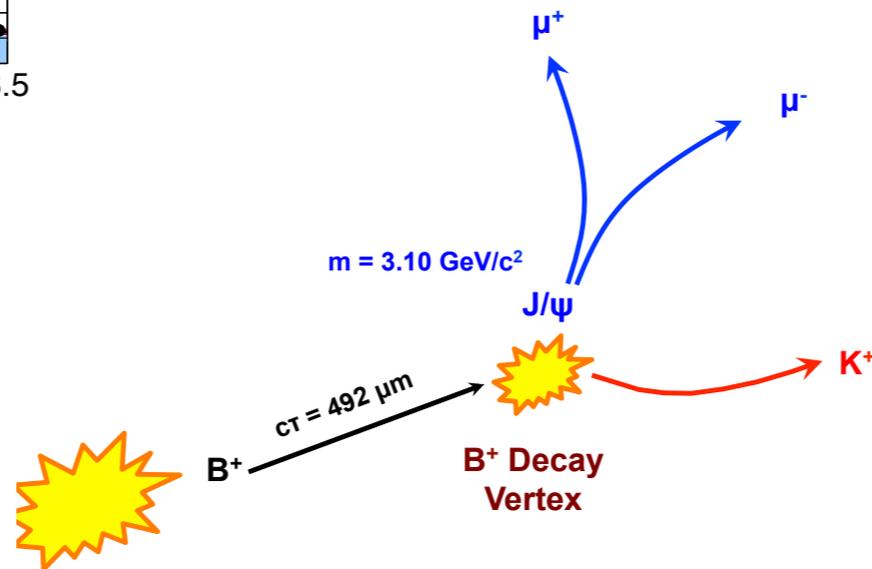
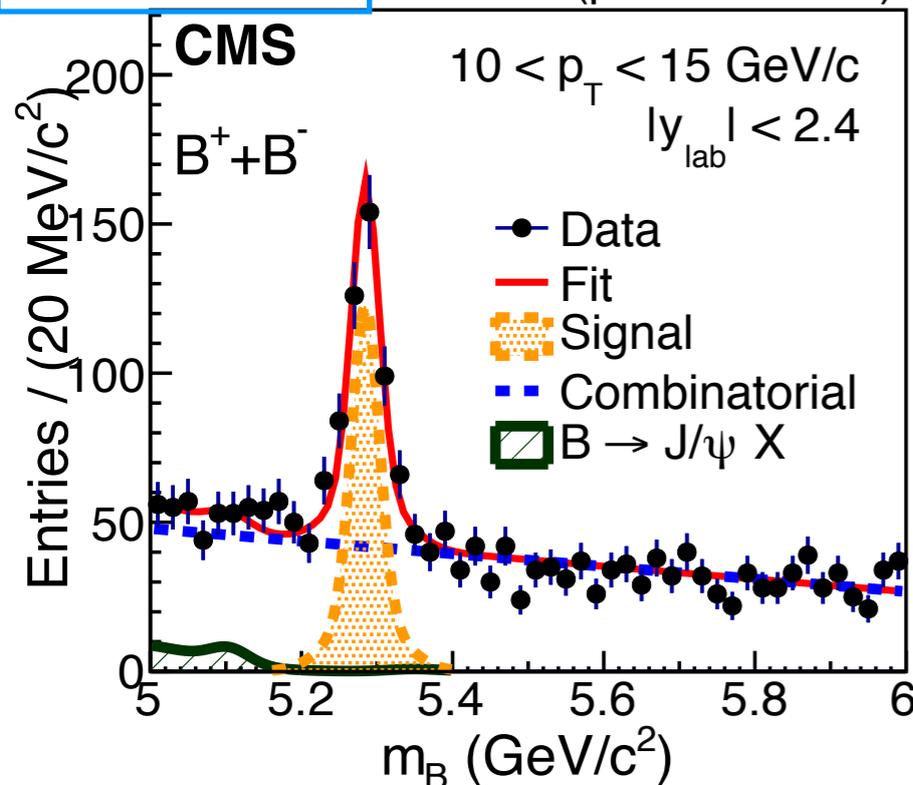
➔ At high- $p_T$  (~4-5 GeV/c) light partons (quarks and gluons) and charm quarks 'products' have same  $R_{AA}$

# B(J/ψX) mesons (beauty quark)

CMS-PAS-HIN-12-014



PRL 116 (2016) 34.6 nb<sup>-1</sup> (pPb 5.02 TeV)



➔ First b-quark products measurement

✓  $B \rightarrow J/\psi + X$

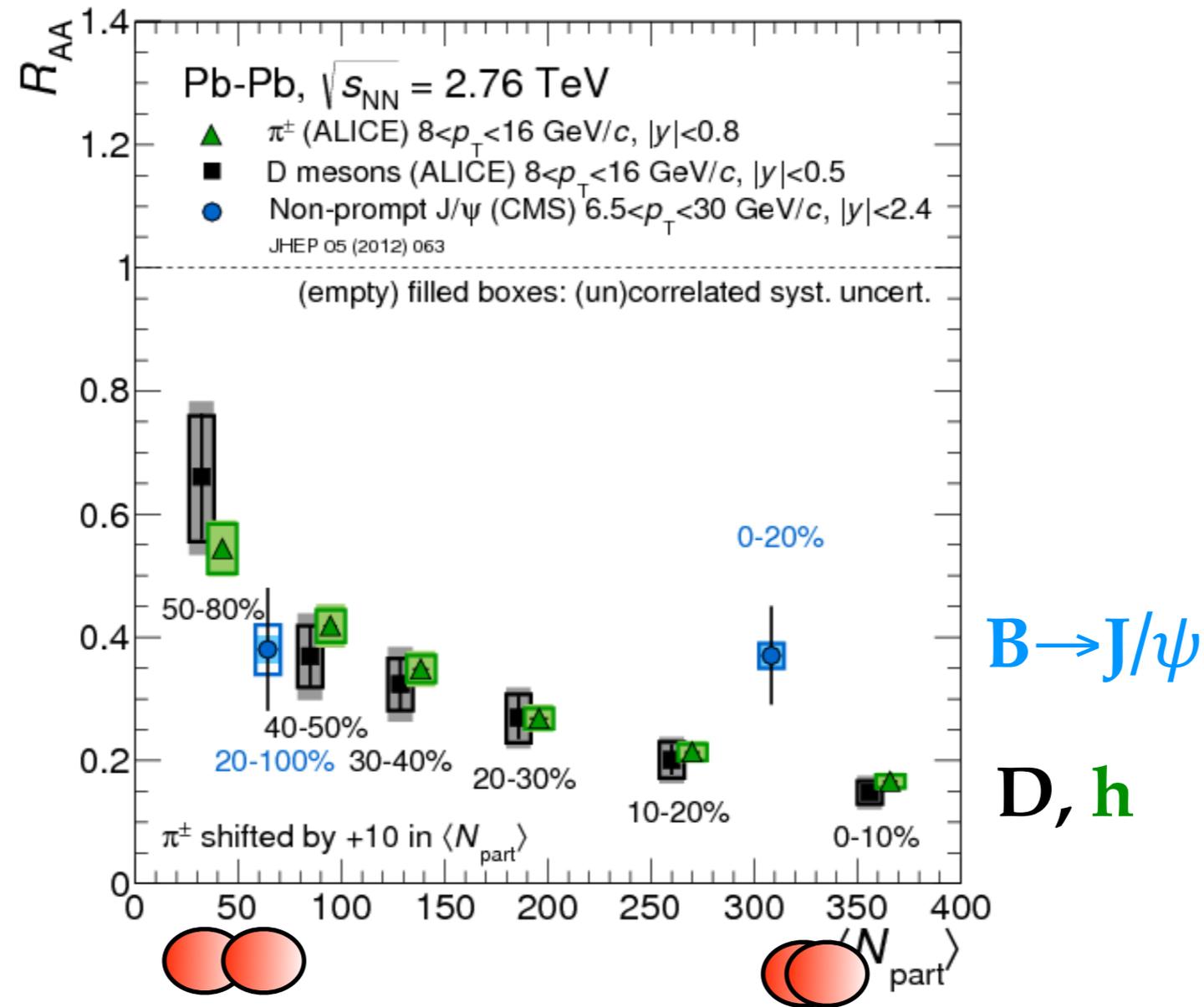
➔ First exclusive B reconstructed in pA collisions

✓  ${}_{17}^B \rightarrow J/\psi + K$

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

# Beauty vs Charm vs Light

JHEP 11 (2015)

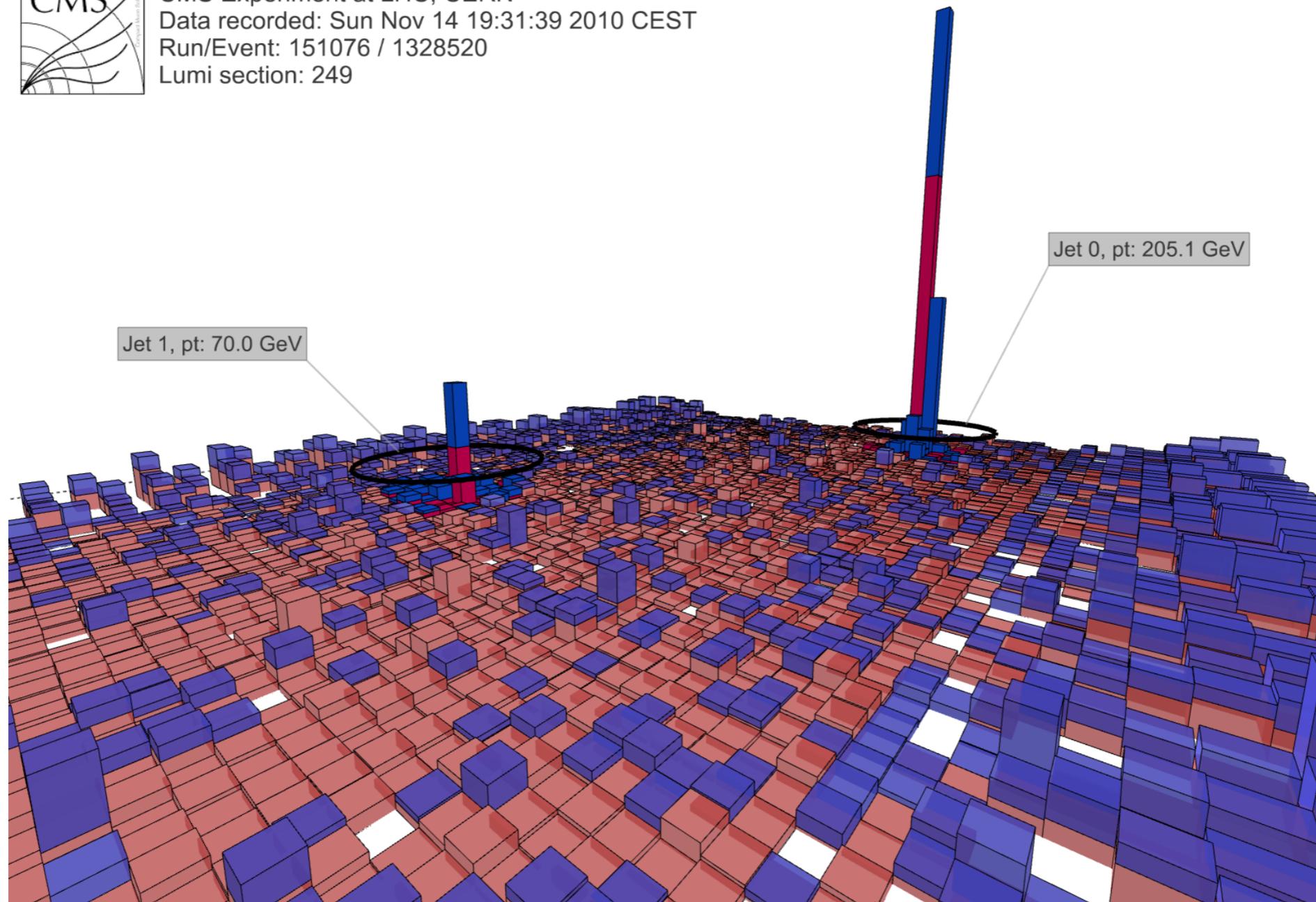


➔ Smaller measured suppression between the b-quark products and charm or gluon/light-quarks products

# Fully reconstructed jets



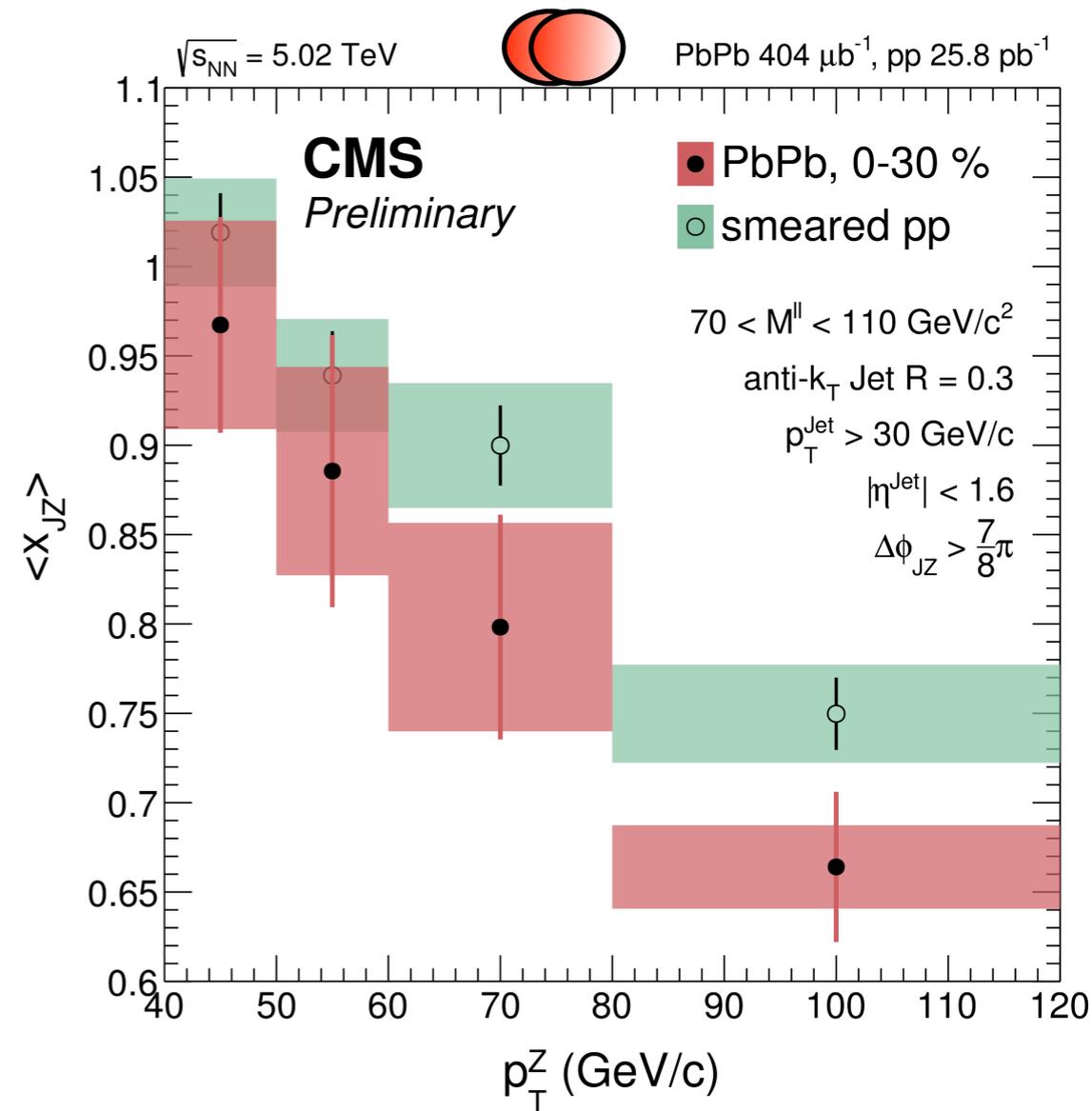
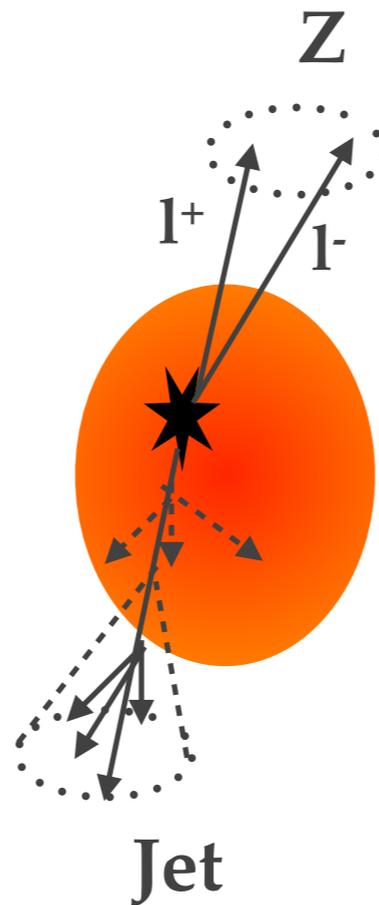
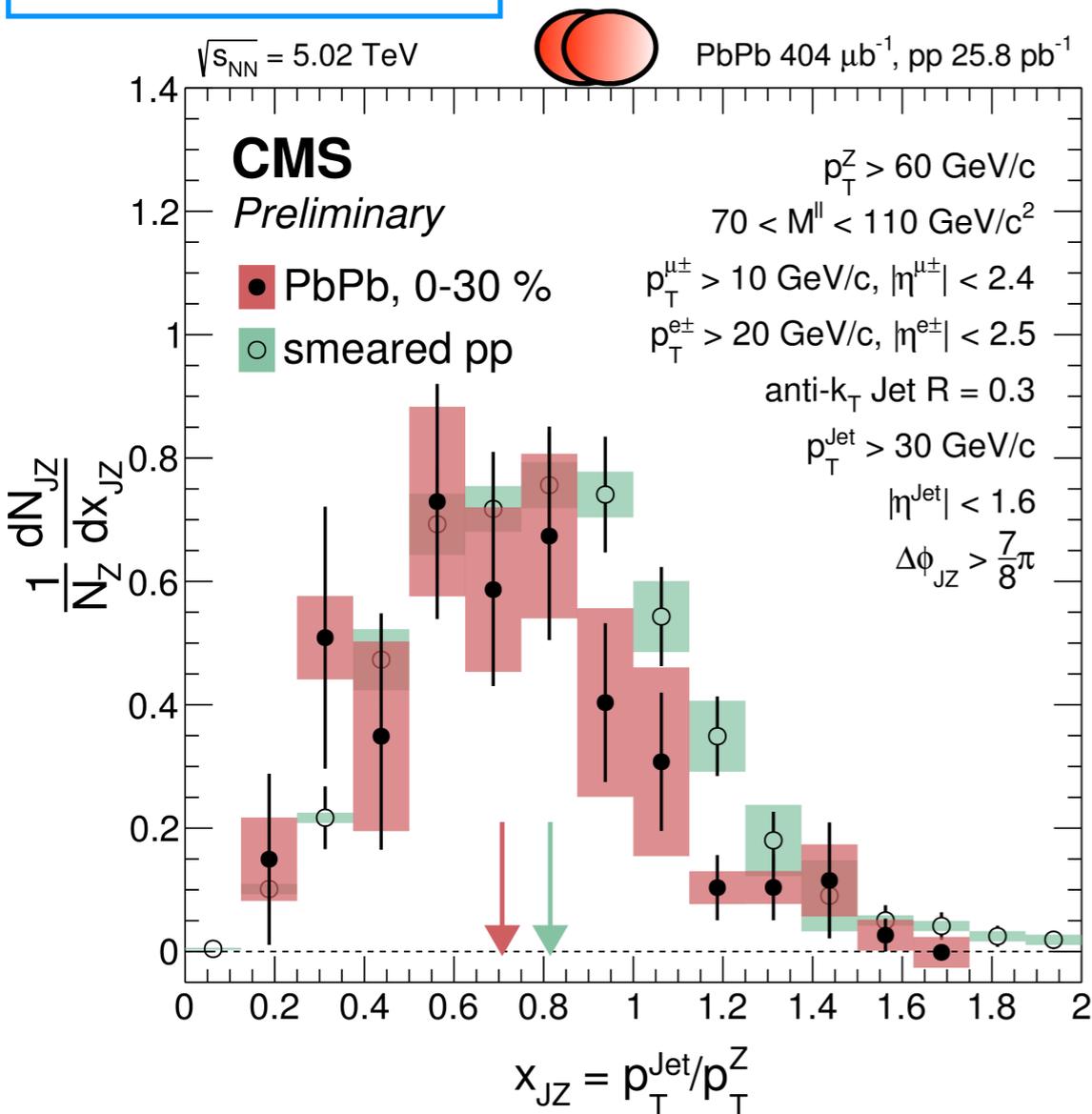
CMS Experiment at LHC, CERN  
Data recorded: Sun Nov 14 19:31:39 2010 CEST  
Run/Event: 151076 / 1328520  
Lumi section: 249



... in the kinematic regions where we can

# Z+jet: in-situ reference

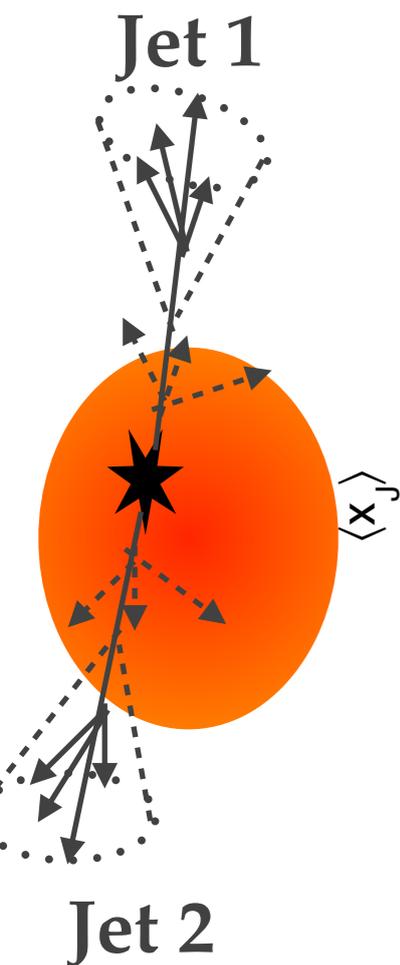
CMS-PAS-HIN-15-013



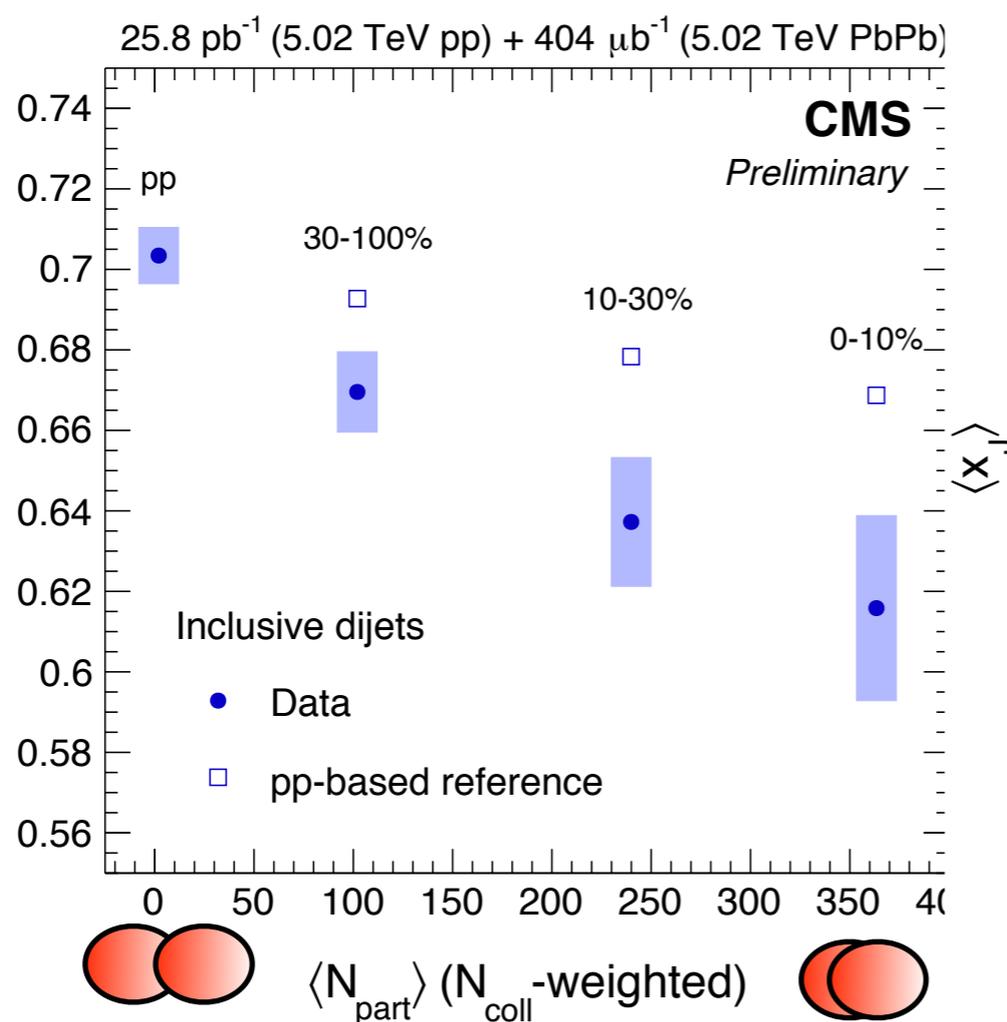
- ➔ Central PbPb  $x_{JZ}$  distributions shifted to lower values wrt pp at all Z- $p_T$ : the back-parton suffers energy loss in the medium
- ✓ theoretical models: energy loss directly related to the medium density

# Beauty vs Light

CMS-PAS-HIN-16-005

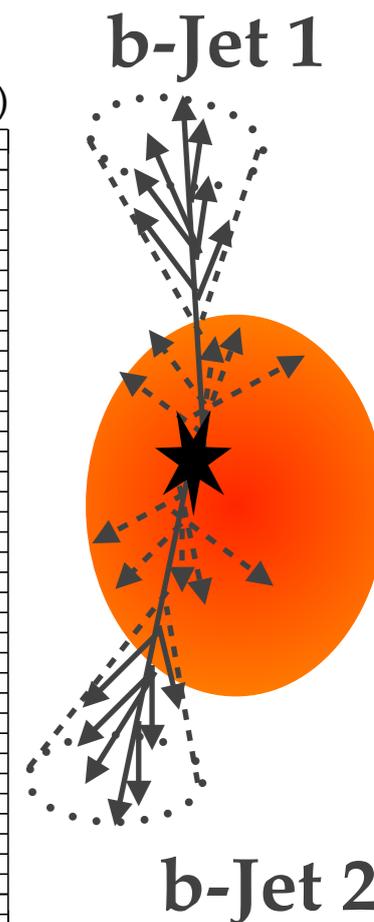
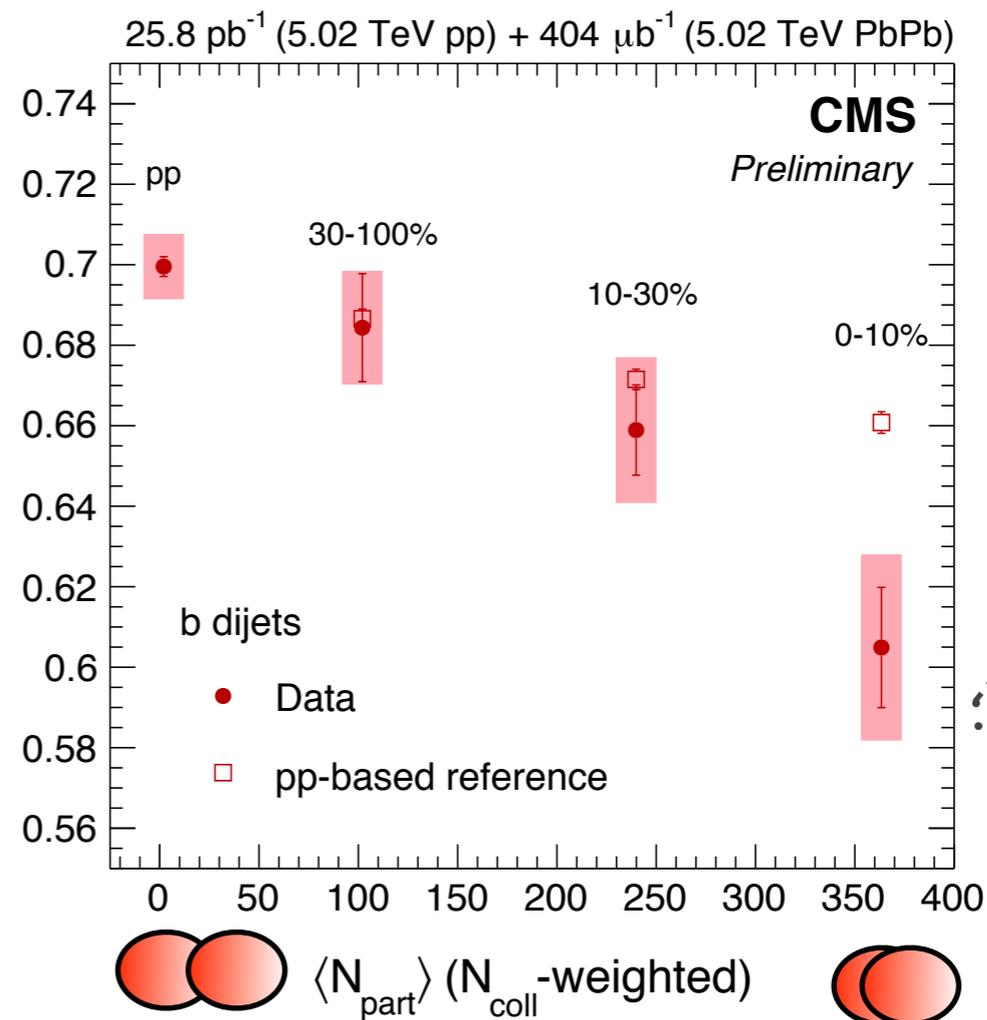


$$x_J = \frac{p_T^{Jet2}}{p_T^{Jet1}}$$



$$p_T^{Jet2} > 40 GeV/c$$

$$p_T^{Jet1} > 100 GeV/c$$

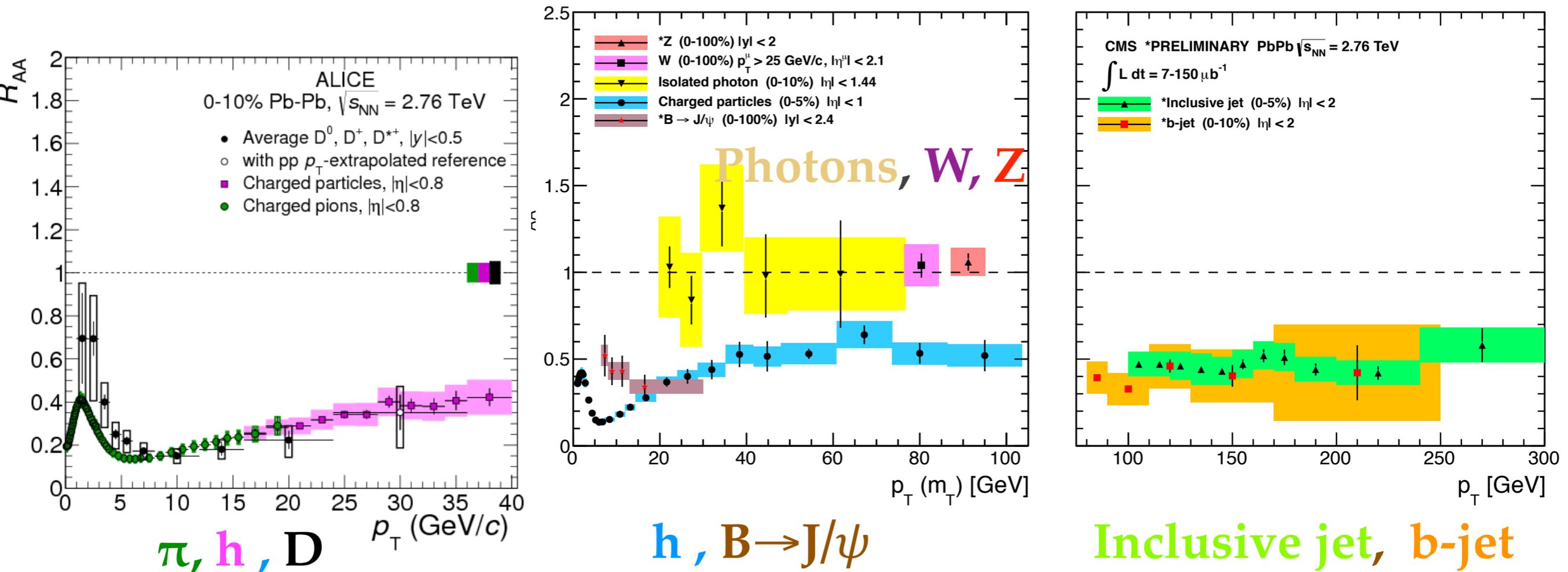


➔ **Blue**: Inclusive-dijets imbalance increases from peripheral to central PbPb collisions

➔ **Red**: Imbalance of b-dijets measured for the first time

✓ similar to that of inclusive jets (**red** vs **blue**)

# LHC: the full picture

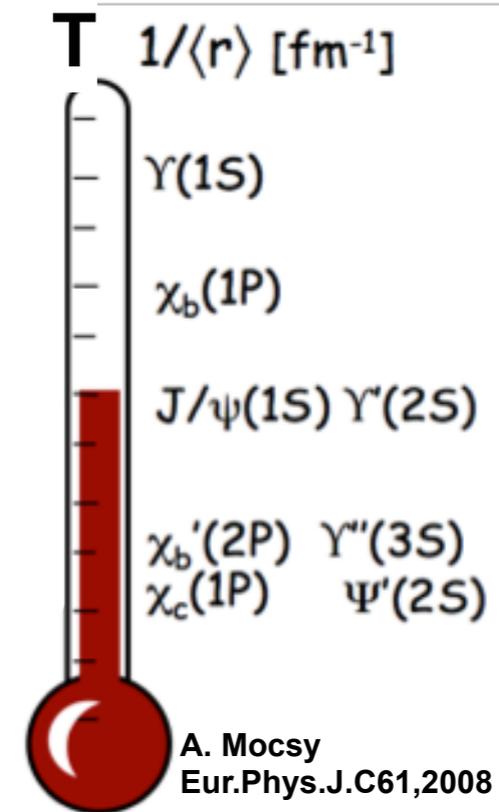
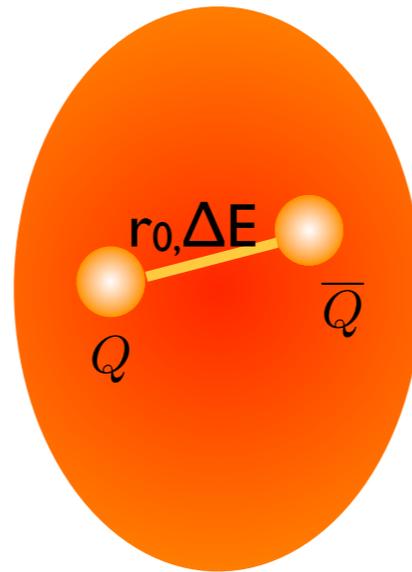


➔ Probes 'blind' to the medium: photons, Z, W

➔ Probes affected by the medium:

- ✓ low- $p_T$ : different suppression pattern for b-quark vs c/q/gluon products
- ✓ high- $p_T$ : similar suppression pattern no matter the color of the pattern

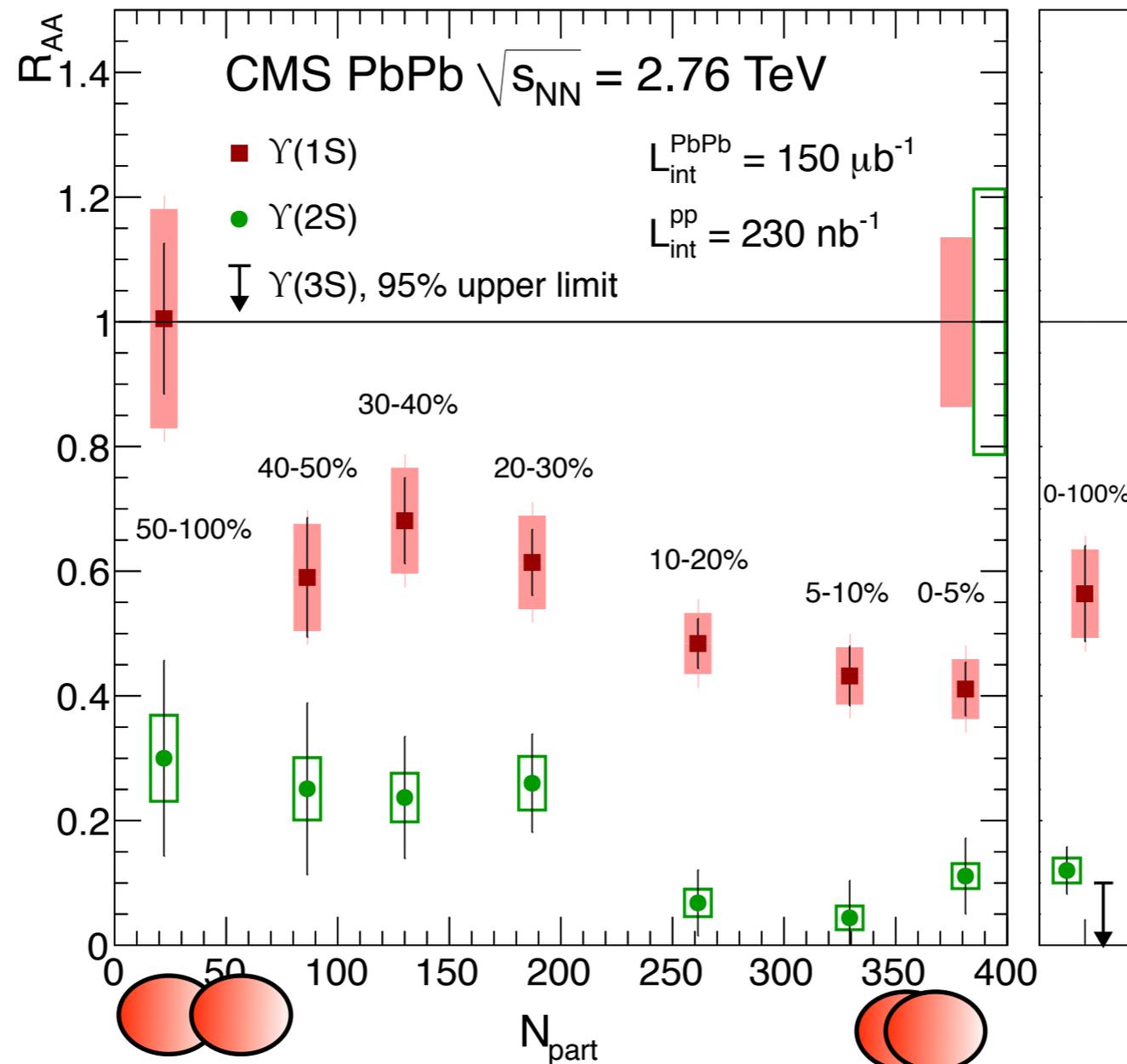
# Quarkonia



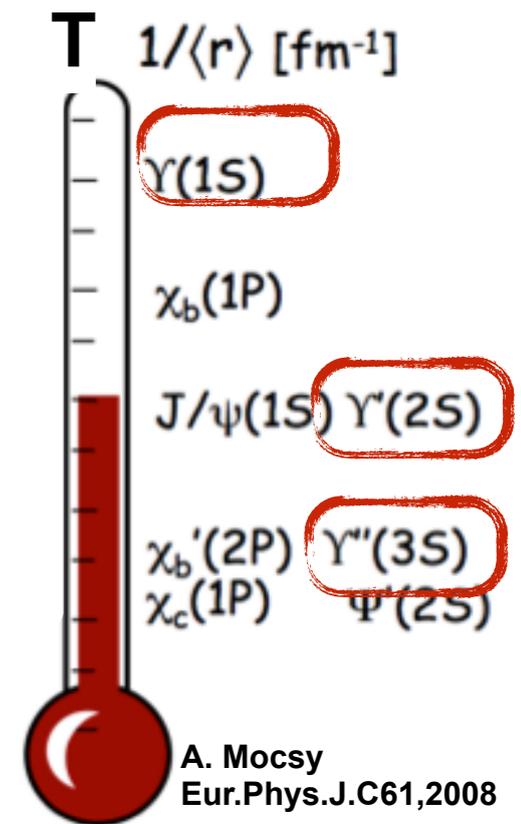
- ➔ Onia in a deconfined partonic medium: color screening at different medium temperatures for different states (depending on binding energy)
  - ✓ sequential melting / destruction of the states
- ➔ Onia: thermometer of the medium

# Sequential melting: $\Upsilon(1S, 2S, 3S)$

PRL 109 (2012)



$$R_{AA}^{\Upsilon(1S)} > R_{AA}^{\Upsilon(2S)} > R_{AA}^{\Upsilon(3S)}$$

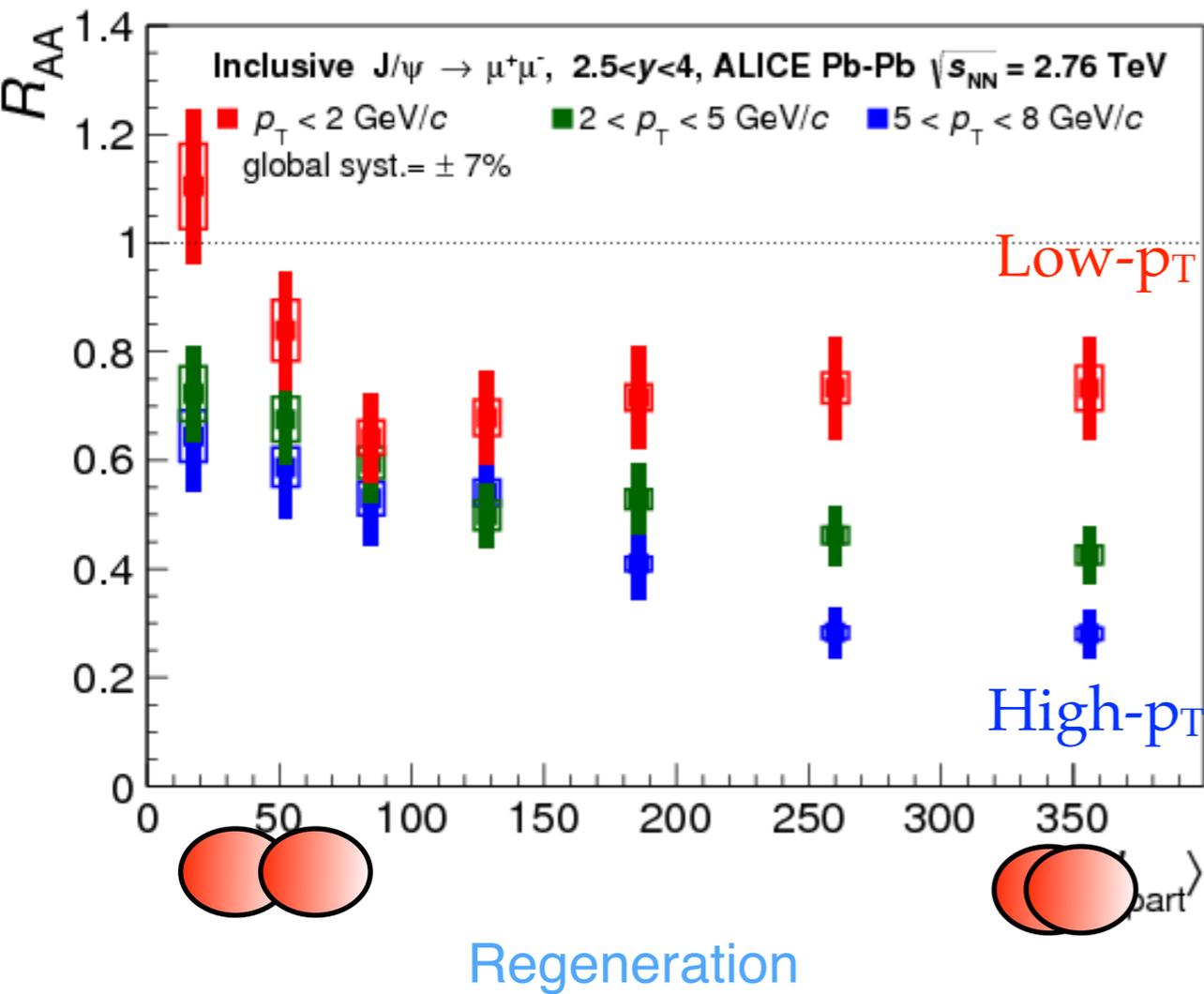


➔ Sequential melting (proposed as key proof for existence of a QGP), first experimental proof of color screening picture

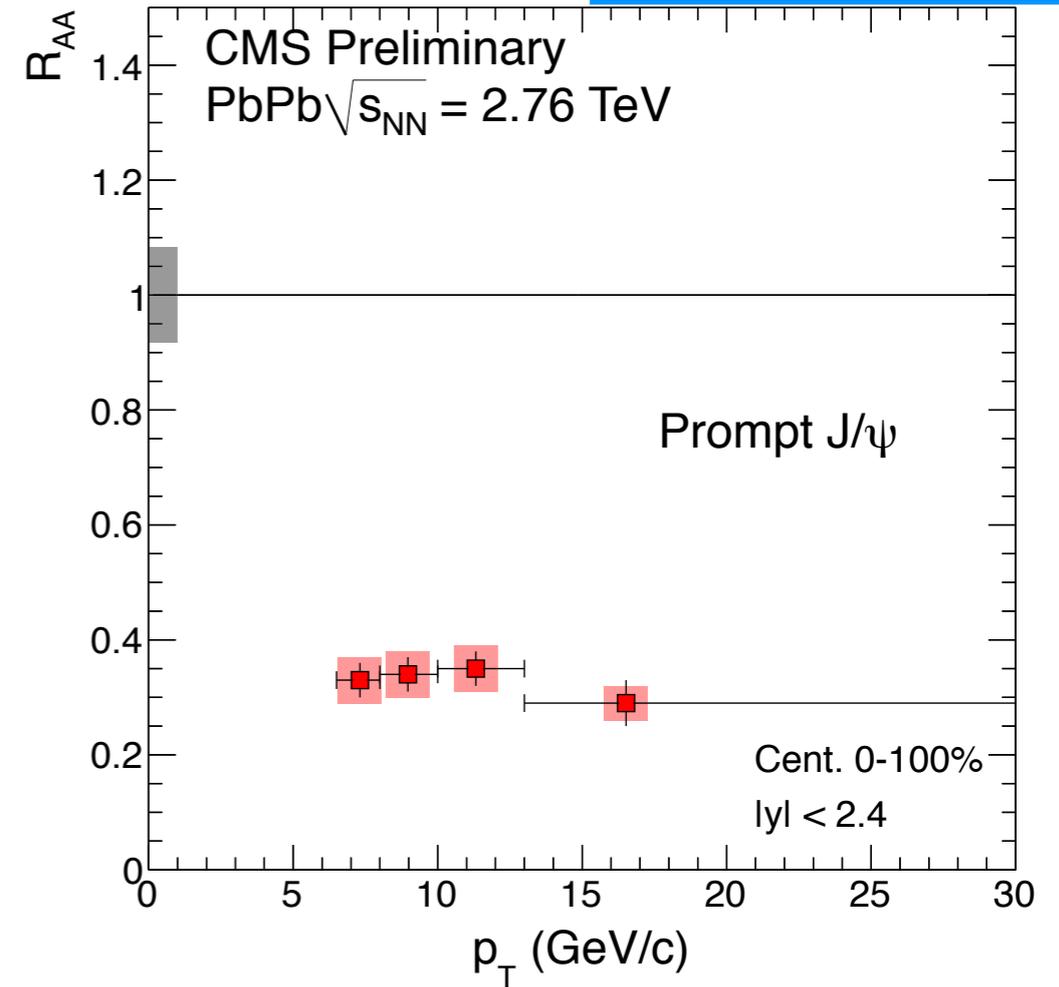
# Quarkonium phenomena: $J/\psi$

JHEP 05 (2016)

CMS-PAS-HIN-12-014



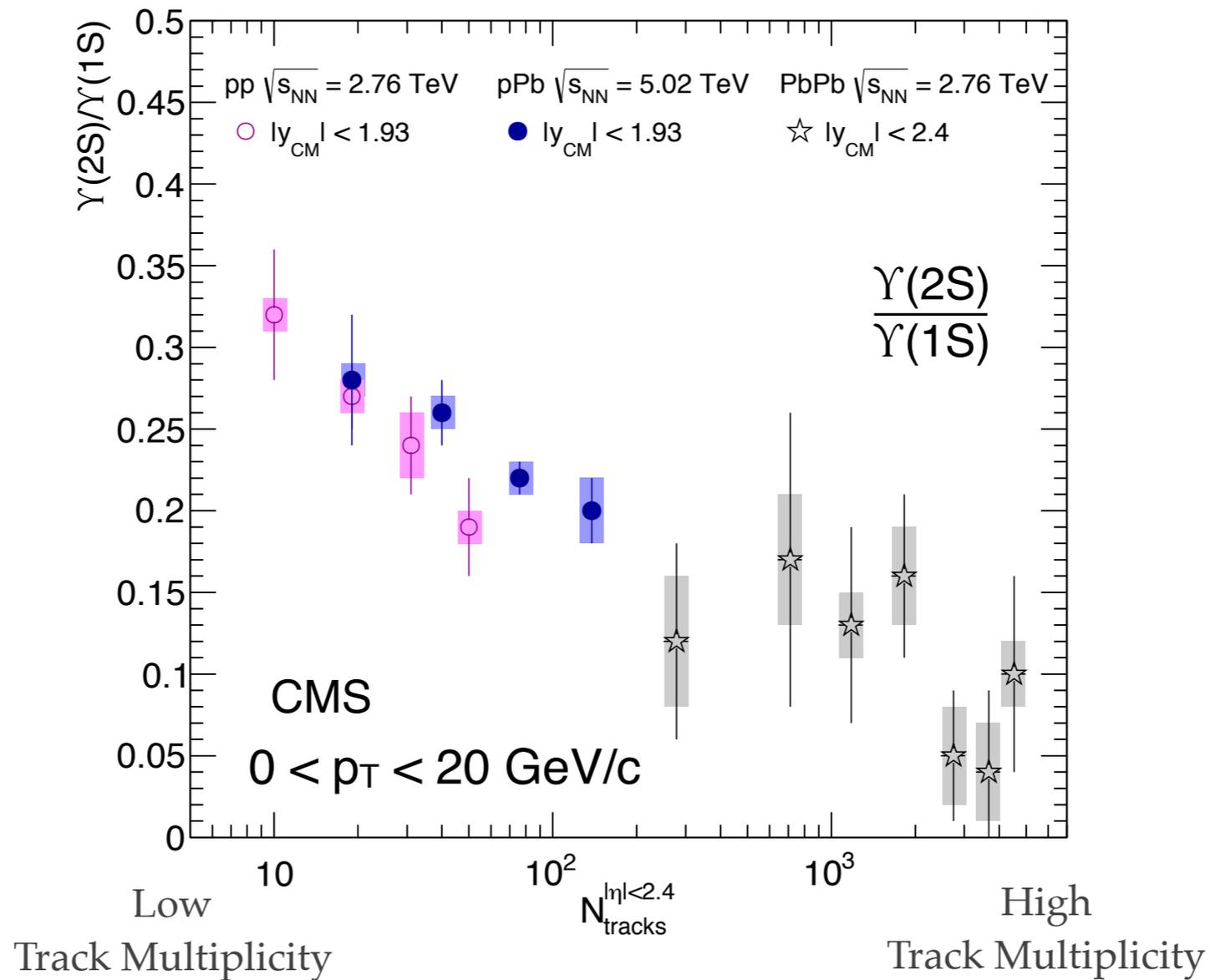
Puts back some  $Q\bar{Q}$



Destroys and/or shifts the kinematics via partonic/hadronic interactions

➔ Experimental confirmation of (old) theoretical ideas

# pp, pPb, PbPb

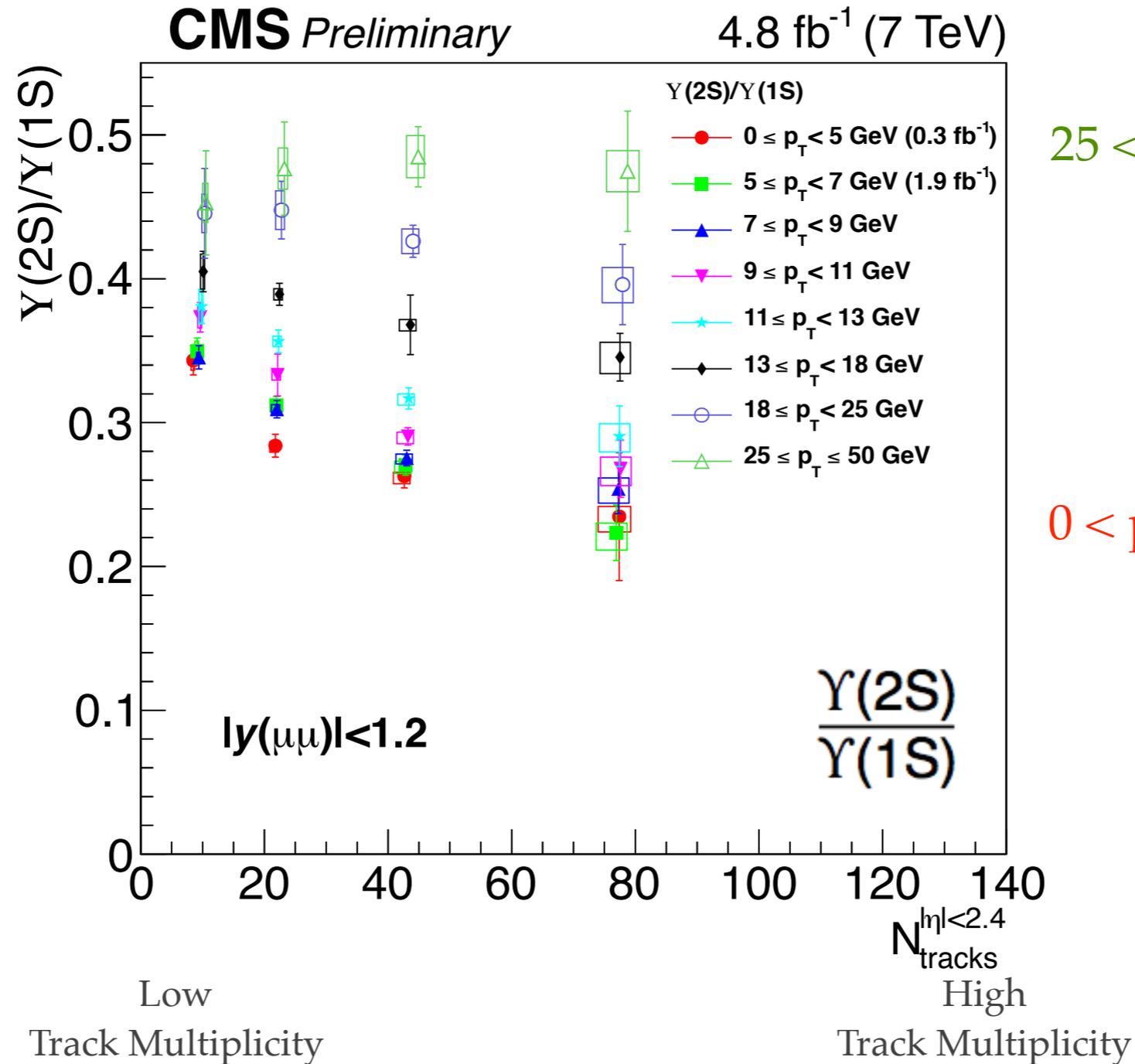


➔ Sequential patterns also in pp & pPb

- ✓ not clear whether it was the “medium” affecting the states (as in PbPb), or the state affecting the “medium”

# pp@7TeV

CMS-PAS-BPH-14-009



$25 < p_T < 50$  GeV/c

$0 < p_T < 5$  GeV/c

➔ Decrease of the excited / ground state ratio confirmed at 7TeV

➔ The ratio decreases strongly at lower  $p_T$

✓ in PAS: stronger indications that it is not the state affecting the “medium”

# LHC heavy-ions: Summary

---

## ➔ Precision, Diversity and Surprises

### ✓ Precision:

- charged hadrons measured up to  $400\text{GeV}/c$
- separate measurements of charm & beauty quarks products

### ✓ Diversity

- identified hadrons AND fully reconstructed jets

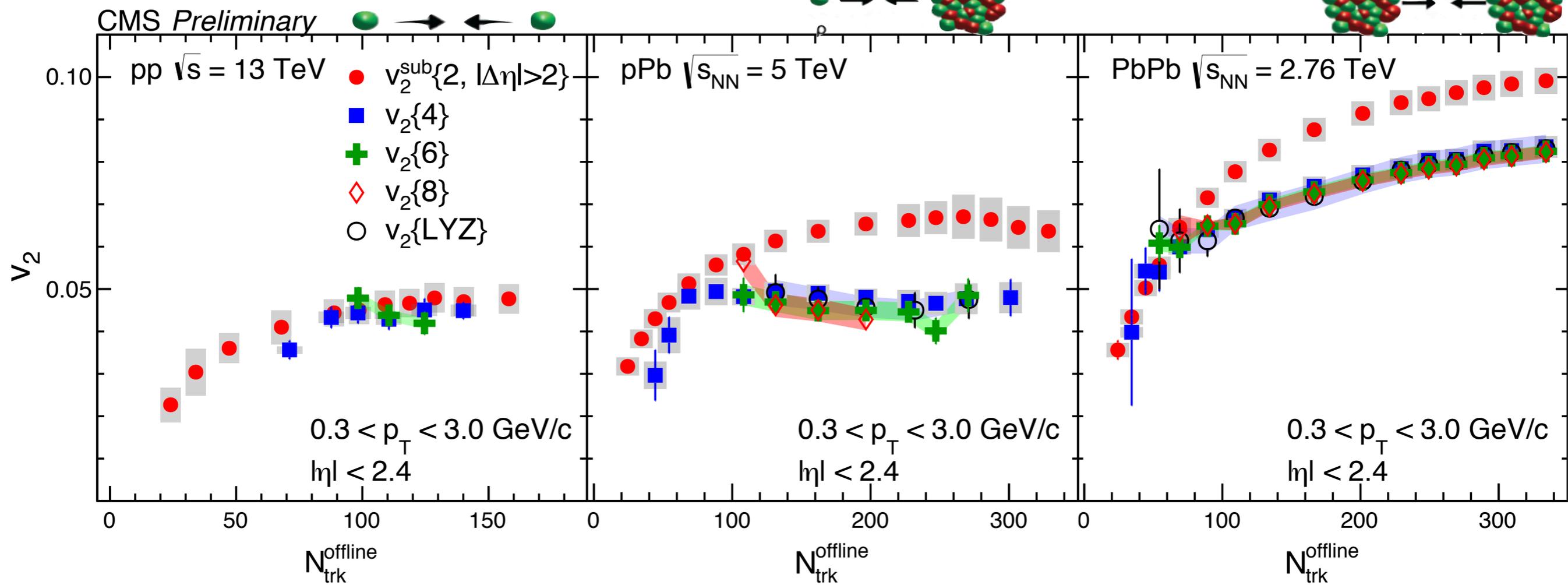
### ✓ Surprises:

- collectivity also in pPb and pp collisions
- 'sequential' pattern for onia also observed in pp and pPb collisions

# Extra stuff

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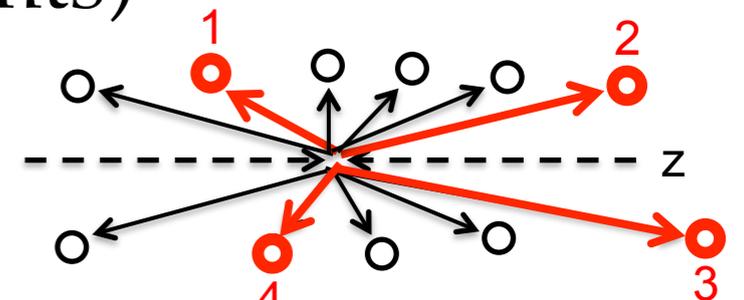
# LHC: ... collective motion EVERYWHERE



$$\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} \left\{ 1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right\}$$

➔ 4 (6, 8) -particle cumulant (average over all events)

✓  $c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2, \quad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$



30  $\langle 4 \rangle \approx \langle \cos[n(\phi_1 + \phi_2 - \phi_3 - \phi_4)] \rangle$