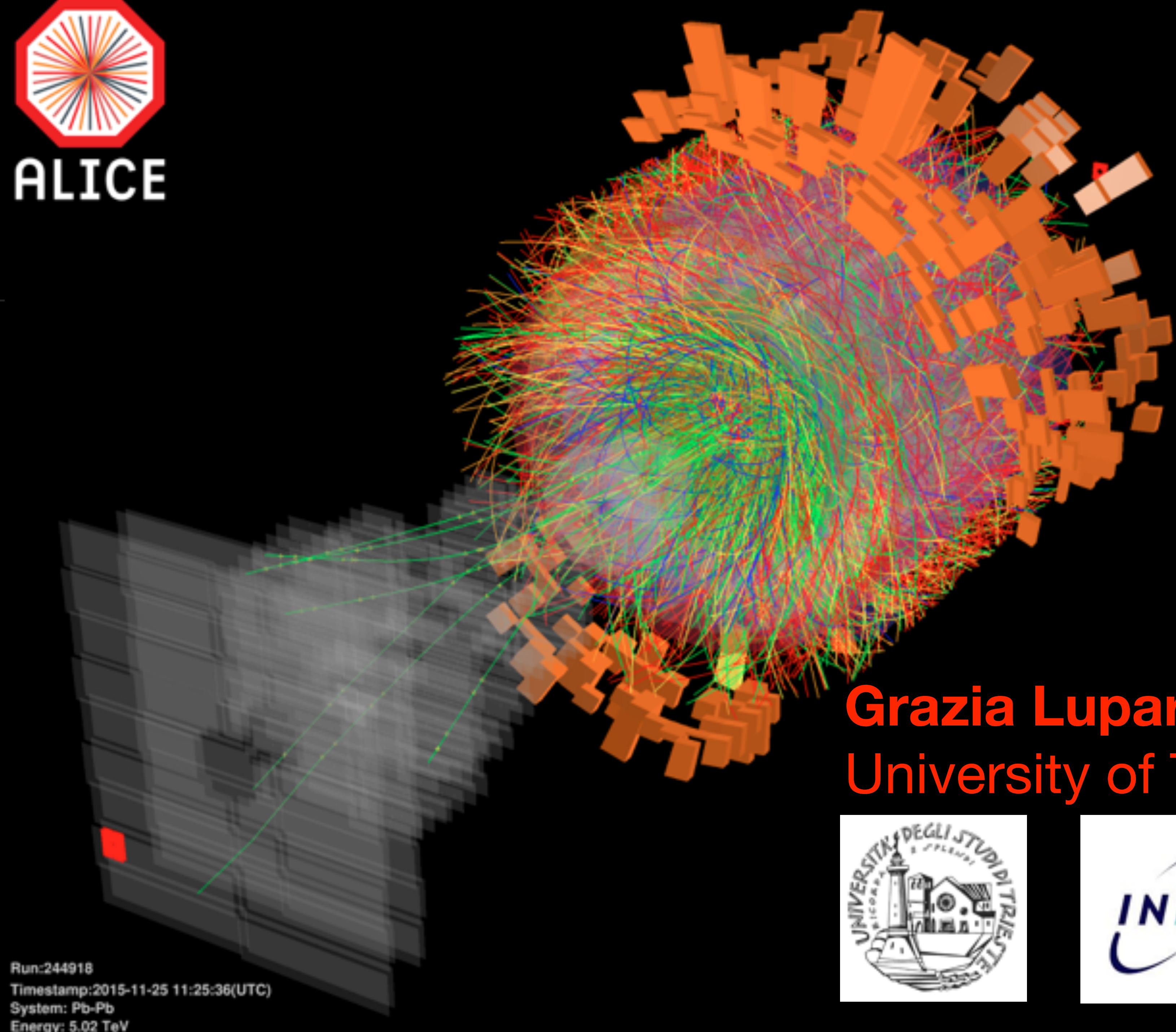
2016 Aspen Winter Conference on Particle Physics

Hard probes in Heavy-Ion collisions

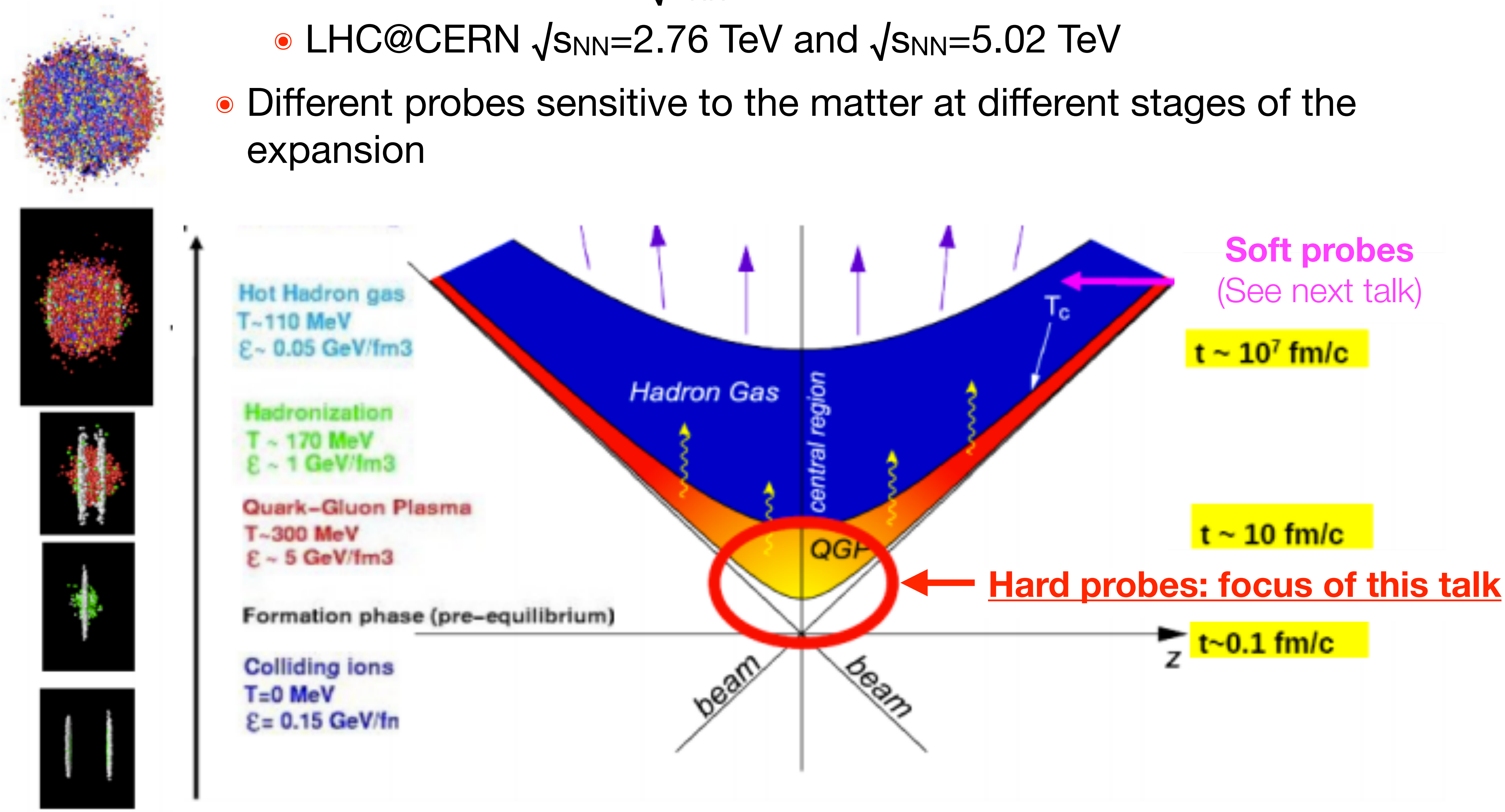
on behalf of ATLAS, CMS and ALICE Collaboration



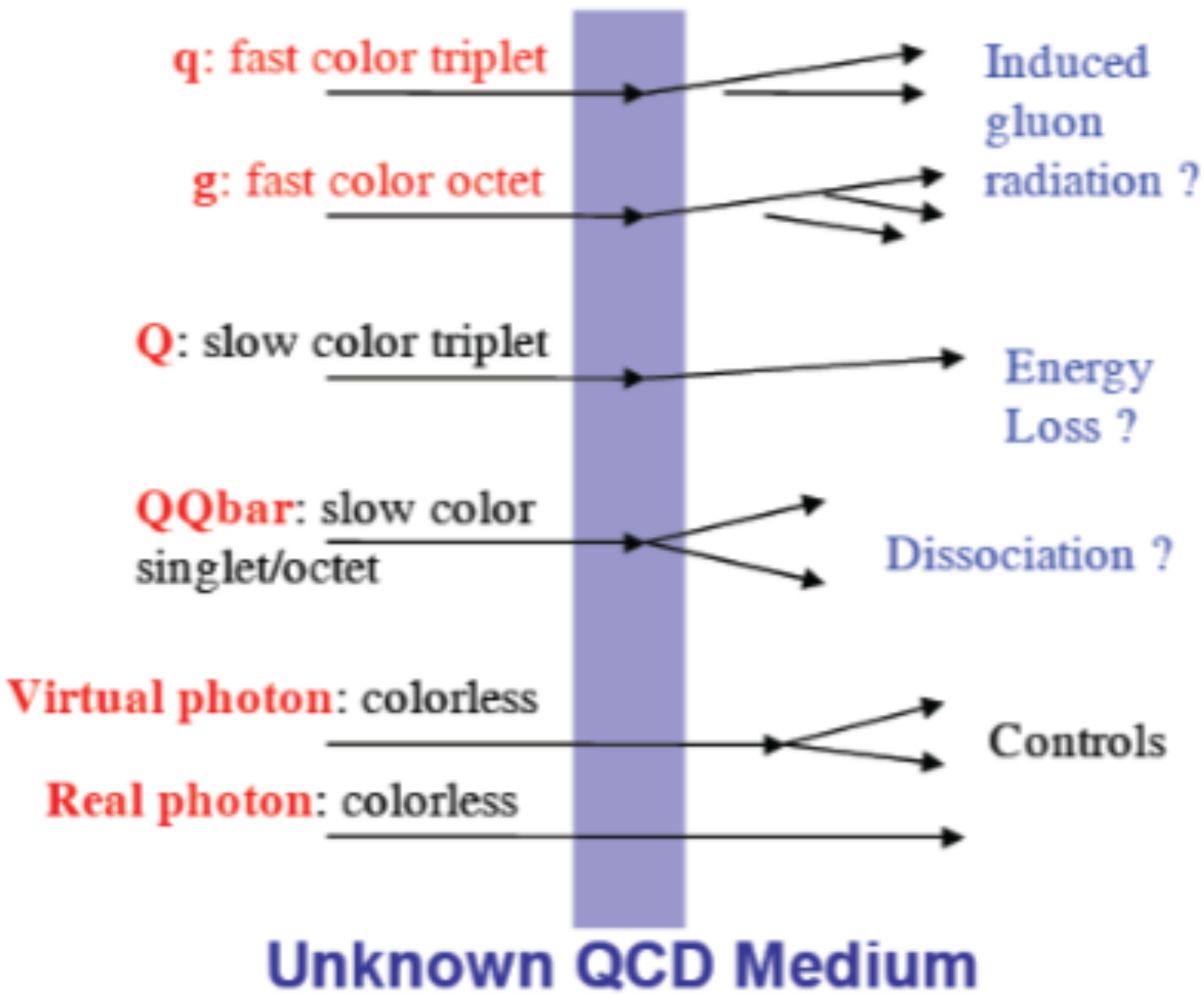
Grazia Luparello
University of Trieste & INFN-Trieste

Creating hot and dense matter in the lab

- **Nucleus-nucleus collisions** at the highest energies
  - RHIC@Brookhaven $\sqrt{s_{NN}}$=200 GeV
  - LHC@CERN $\sqrt{s_{NN}}$=2.76 TeV and $\sqrt{s_{NN}}$=5.02 TeV
- Different probes sensitive to the matter at different stages of the expansion



Hard Probes: tomography of the medium

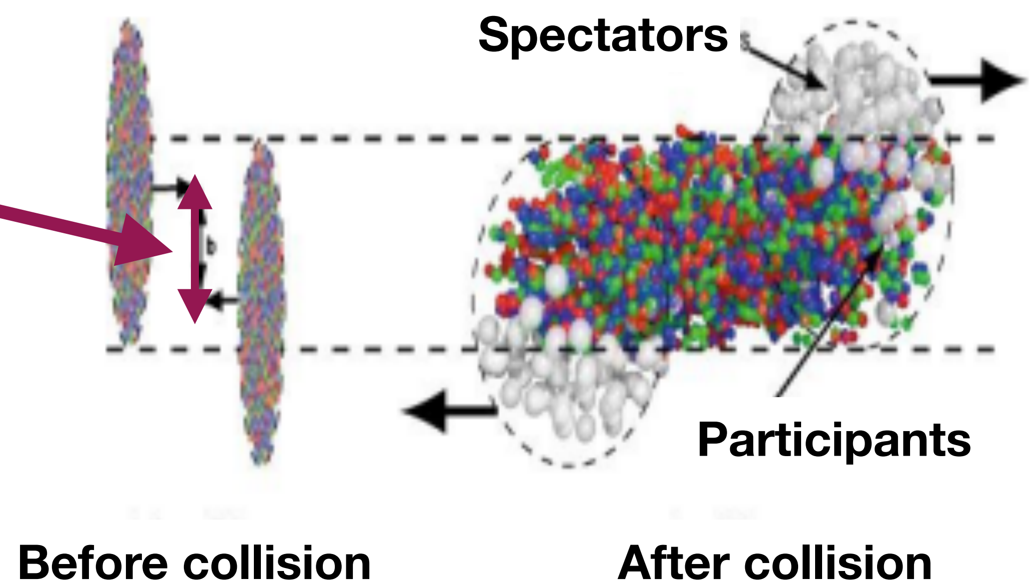


- **Jets, heavy-quarks (c,b), quarkonia**
  - Produced at the early stage of the collision in partonic processes with high Q^2
  - **Traverse the hot and dense medium interacting with its constituents -> probe the medium properties**
- **Photons, W and Z bosons**
  - Do not carry color charge
  - Provide informations about initial state and nuclear parton distribution functions

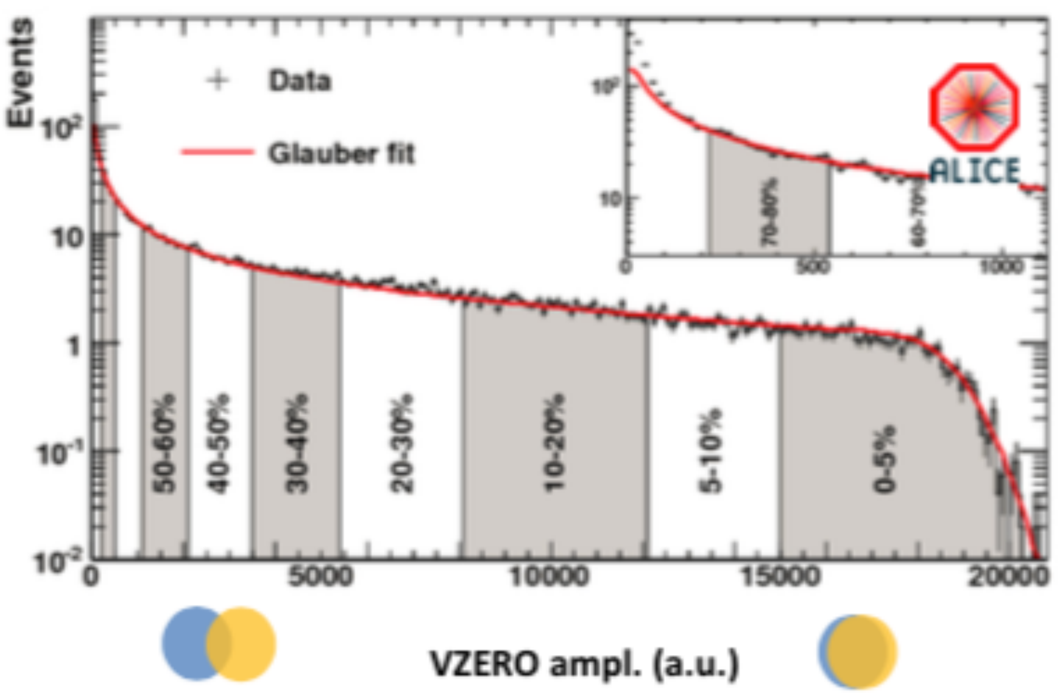
- Energy loss is different for gluons and light/heavy quarks
  - dead cone effect, color effect
- Parton interaction with medium not trivial: depends on strength of coupling, dynamics of fireball ...

Centrality in AA collisions

- Ions are large, R~7 fm, collisions occur with random impact parameter that cannot be directly measured
- Higher centrality -> hotter QGP



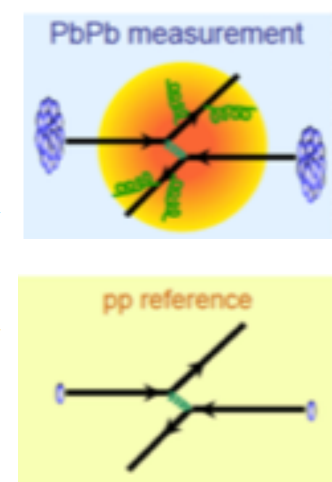
- The impact parameter has to be estimated based on measured quantities: e.g. N_{ch} , E_T , ZDC…
- Glauber model: connects centrality to a number of binary collisions (N_{coll}) and participants (N_{part})



How to observe hard probes

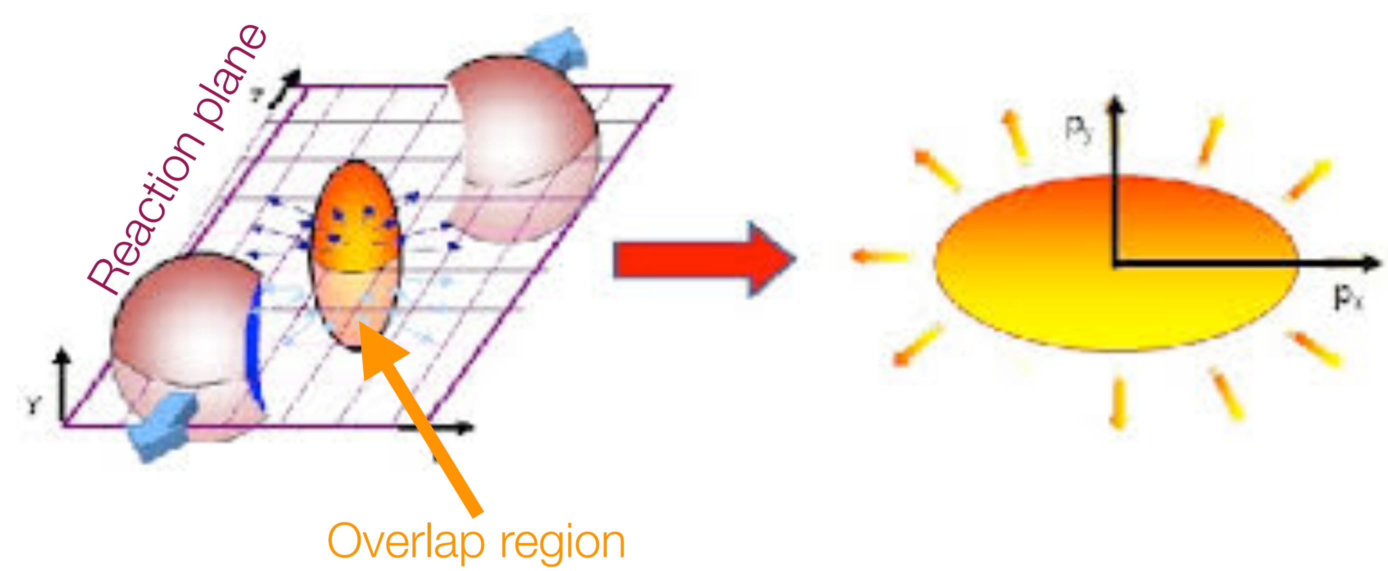
- **Nuclear Modification Factor (R_{AA})**
  - Production of hard probes in AA collisions is expected to scale with the number of nucleon-nucleon collisions N_{coll} in absence of medium effects **(binary scaling)**

$$R_{\rm AA} = \frac{1}{N_{\rm coll}} \frac{{\rm d}N_{\rm AA}/{\rm d}p_T}{{\rm d}N_{\rm pp}/{\rm d}p_T} \sim \frac{QCD\ medium}{QCD\ vacuum}$$



R_{AA} = 1: no medium effects
$R_{AA} \neq 1$: Effects from the medium
-> break up of binary scaling
E.g. parton energy loss in the medium, quarkonia melting
…but also **cold-nuclear-matter effects** may give $R_{AA} \neq 1$

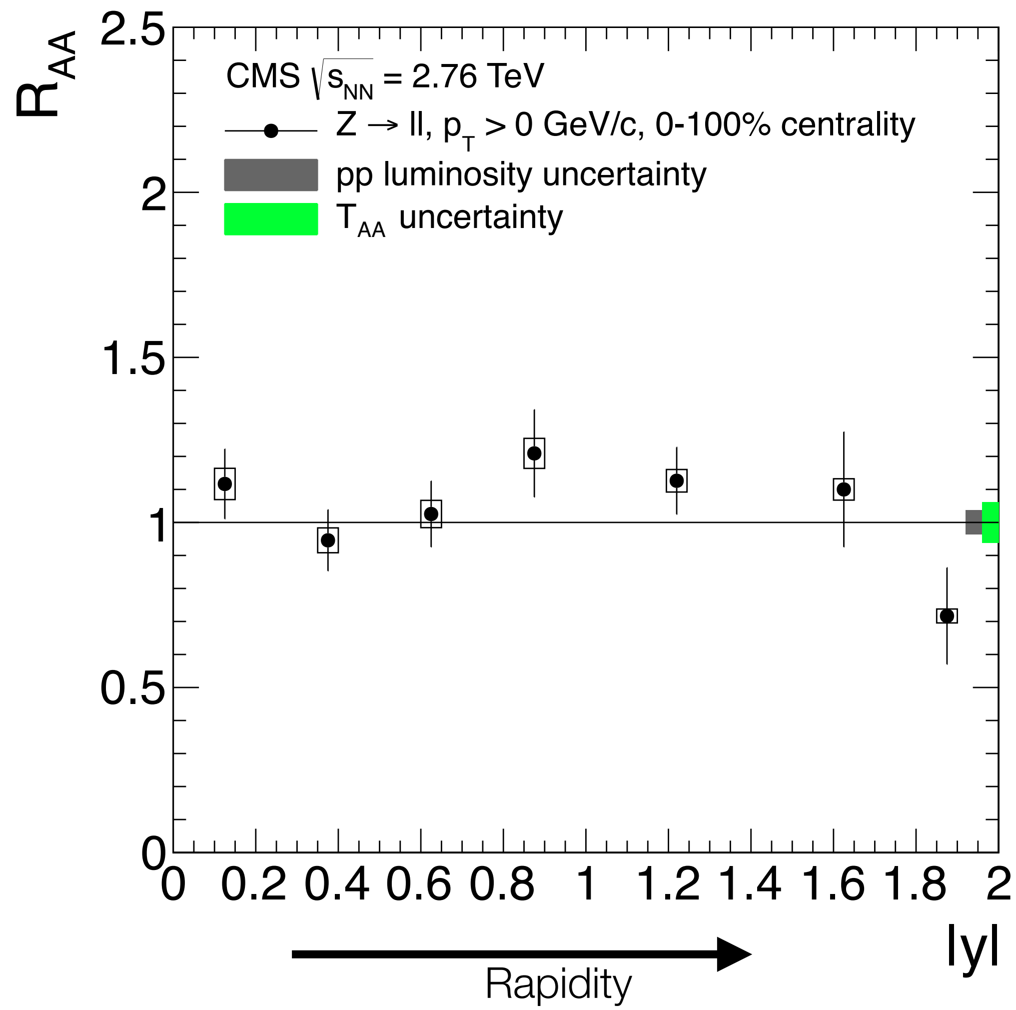
- **Azimuthal anisotropy (v_2)**
  - Initial lenticular shape of the overlap region
  - Creating pressure gradients
  - Results in more particles in the reaction plane



W and Z bosons
Photons

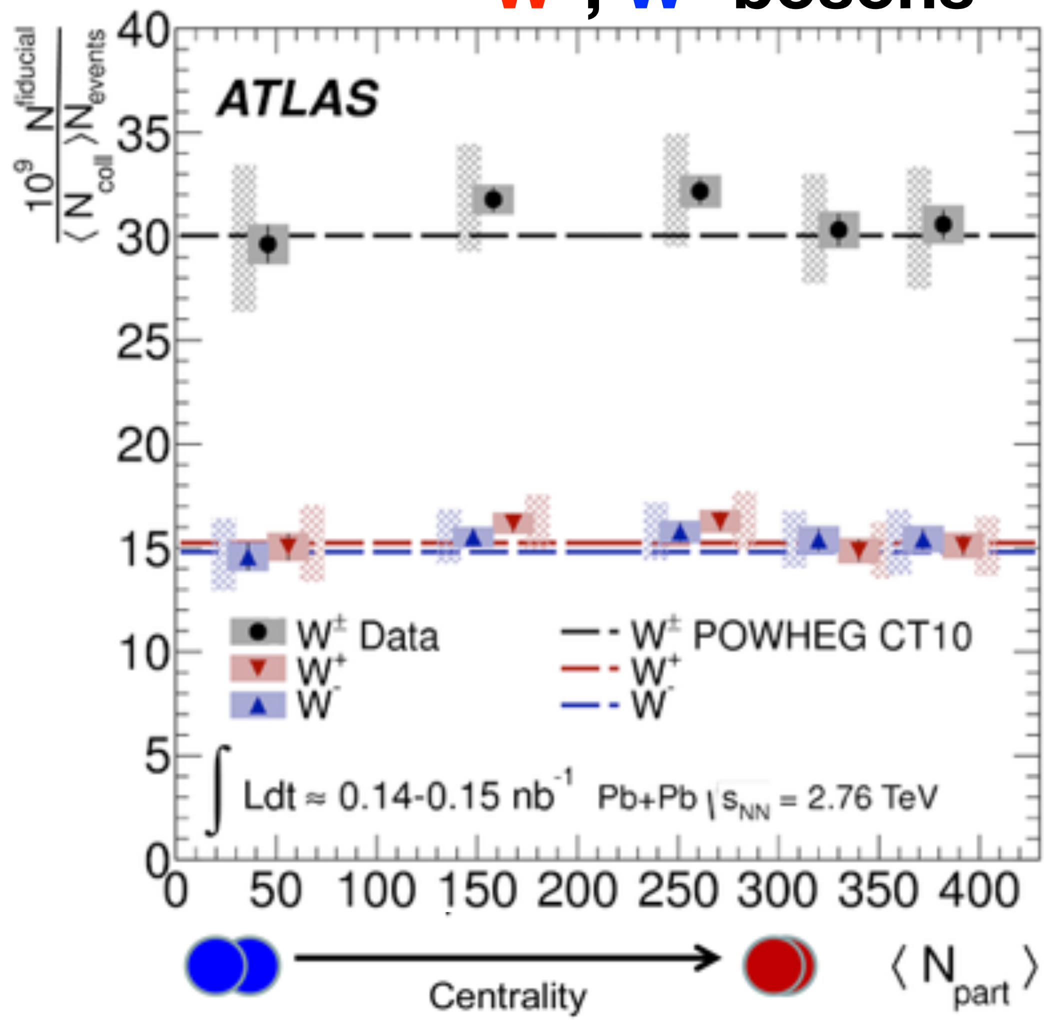
W and Z bosons

Z boson



CMS, JHEP03 (2015) 022
also ATLAS, PRL 110 (2013) 022301

W^+, W^- bosons

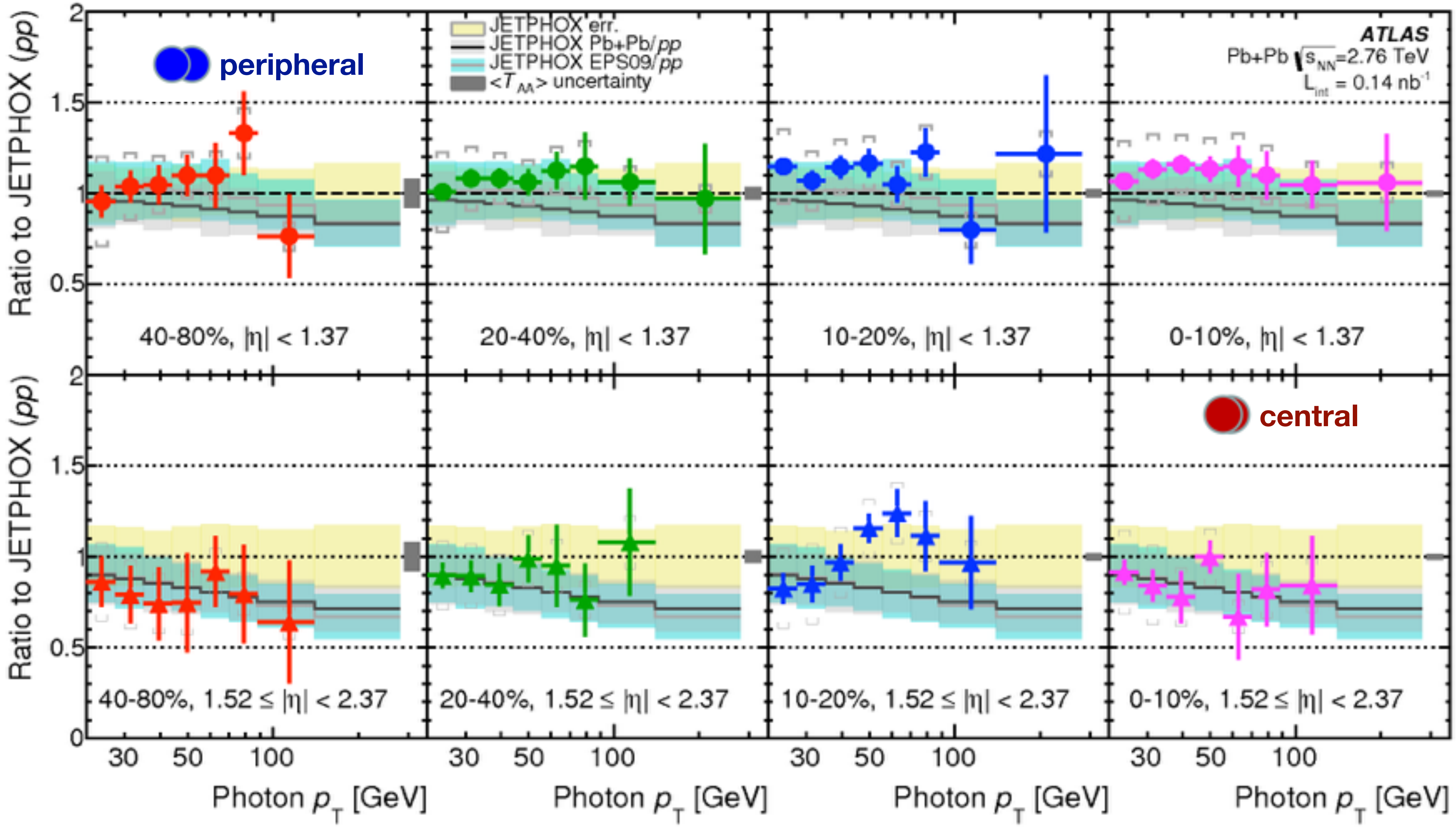


ATLAS, EPJ75 (2015) 23
also CMS, PLB 715 (2012) 66

- **No deviation from binary scaling is observed for W^+, W^- and Z**
  - W/N_{coll} compatible with NLO QCD calculations (similar for Z)

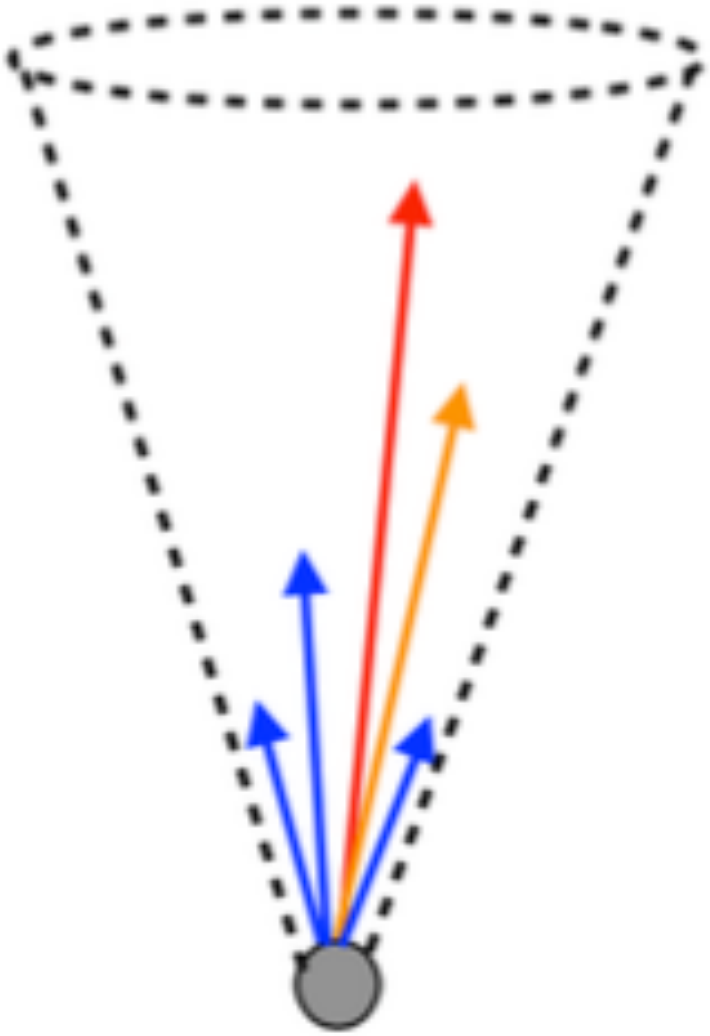
Isolated prompt photons

ATLAS, arXiv:1506.08552
also CMS, PLB 710 (2012) 256



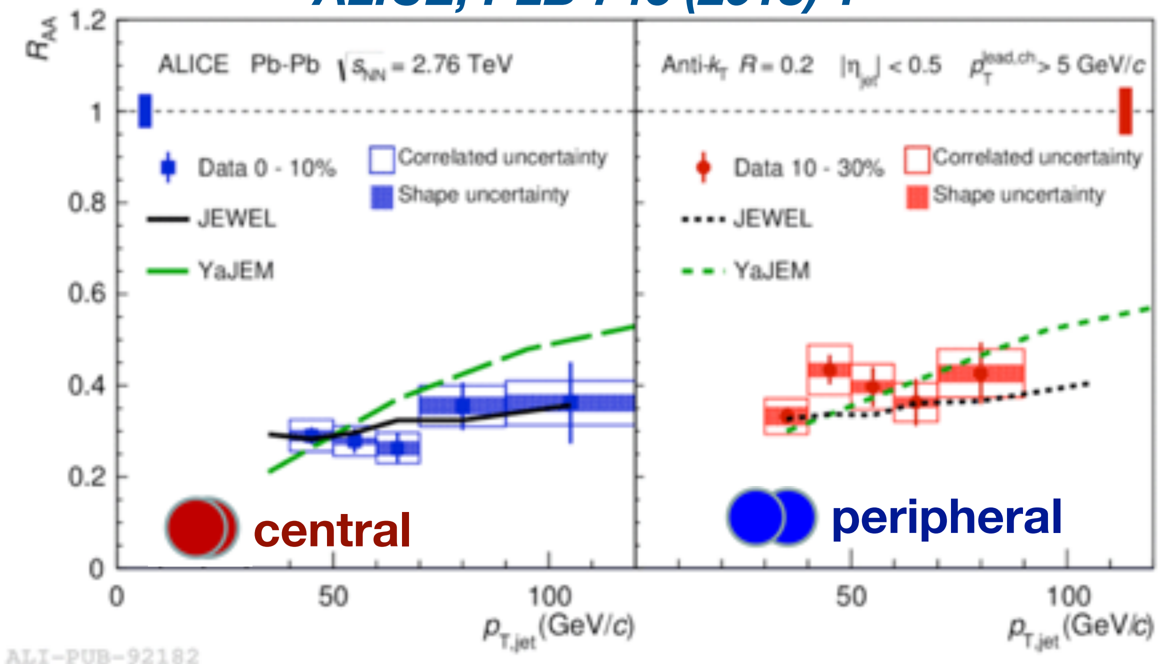
- $\langle T_{AA} \rangle$ scaled photon yields agree with NLO pQCD calculations

Jets

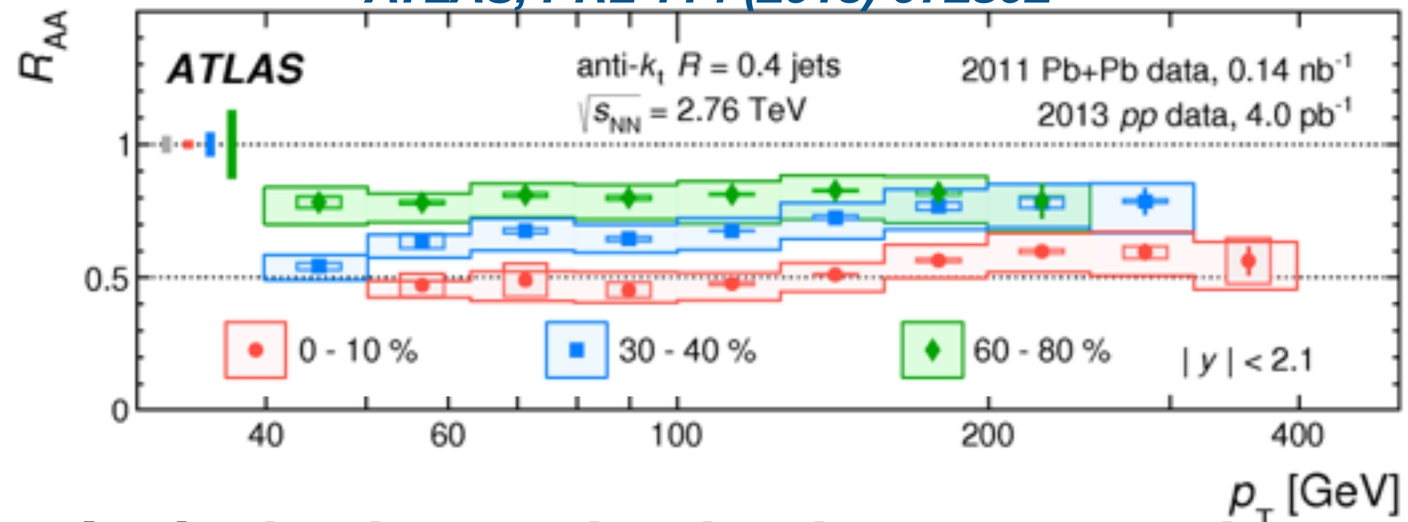


Jets R_{AA}

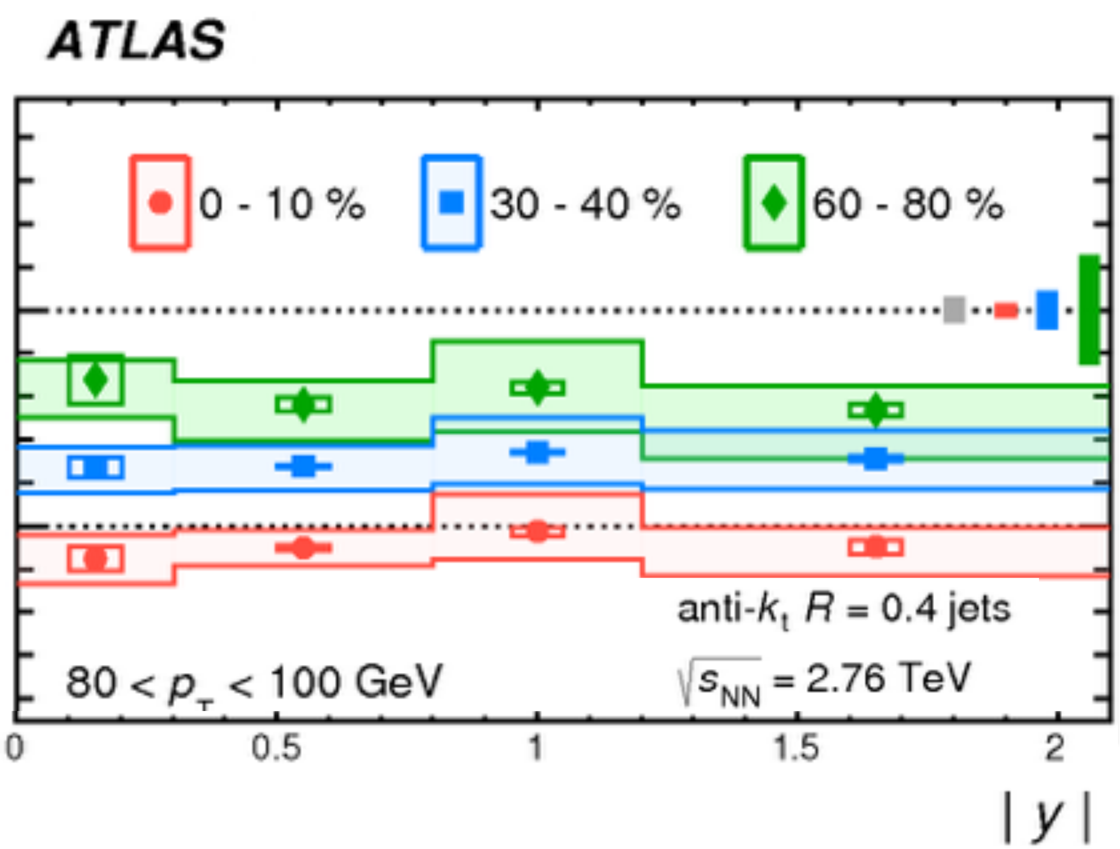
ALICE, PLB 746 (2015) 1



ATLAS, PRL 114 (2015) 072302



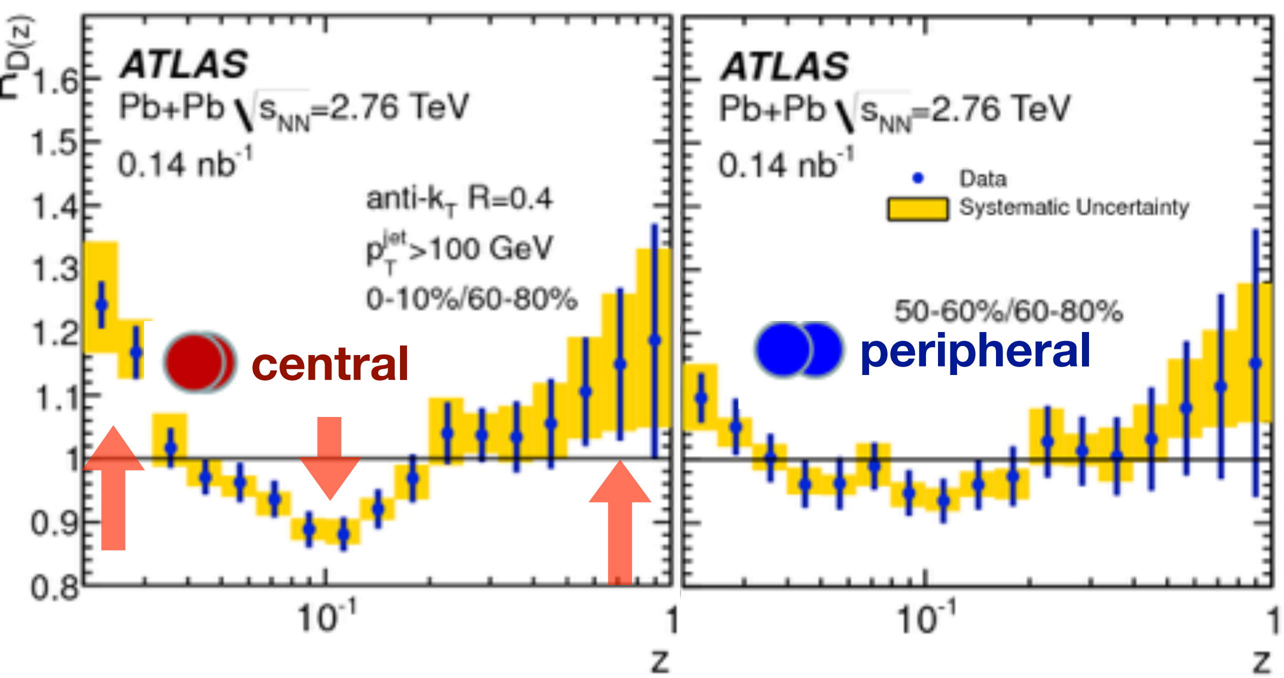
- **Inclusive jet production is suppressed in Pb-Pb collisions**



- R_{AA} is flat vs rapidity
- Quark/gluon fraction and slope of the jet p_T spectra change with y

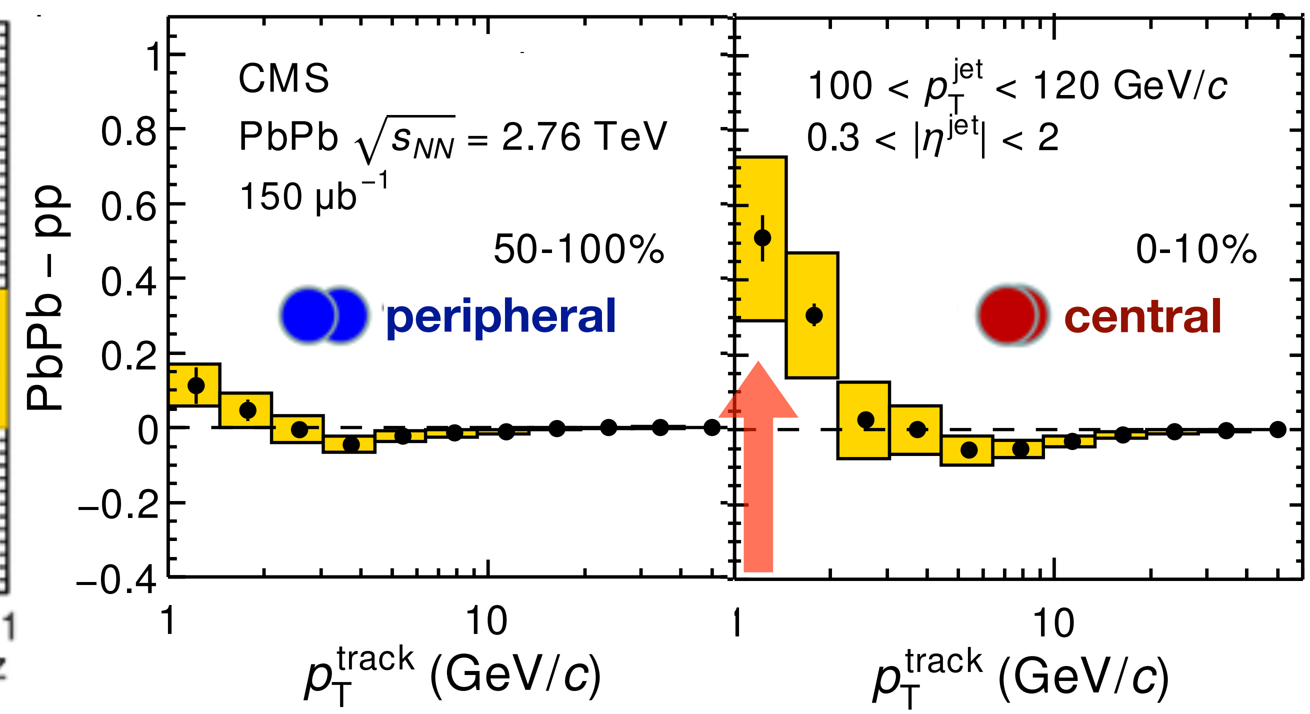
Is the internal structure of jets modified?

ATLAS, PLB 739 (2014) 320



$z = p_{||}^{Trk} / p^{Jet}$

CMS, PRC 90 (2014) 024908

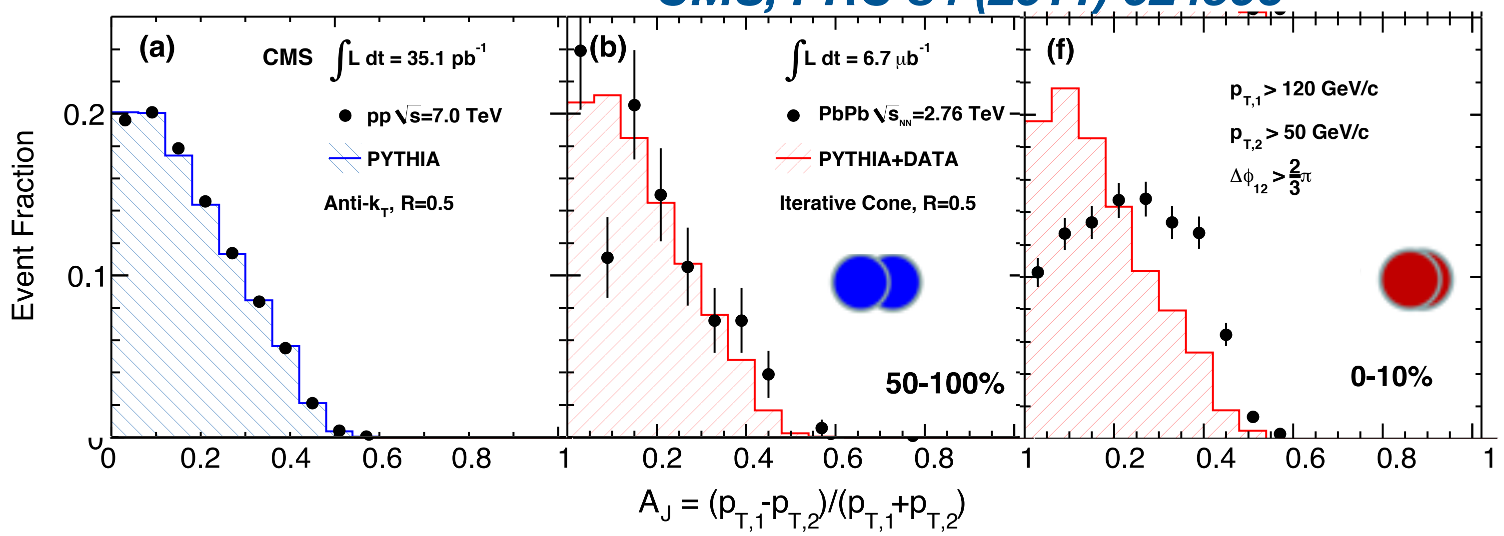


Spectrum of tracks inside the jet cone

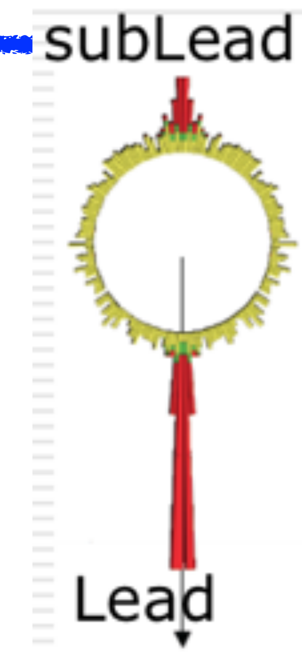
- Fragmentation functions are modified in central Pb-Pb collisions
- Excess of low pT particles inside the jet cone in central Pb-Pb collisions with respect to pp

Where does the lost energy go?

CMS, PRC 84 (2011) 024906



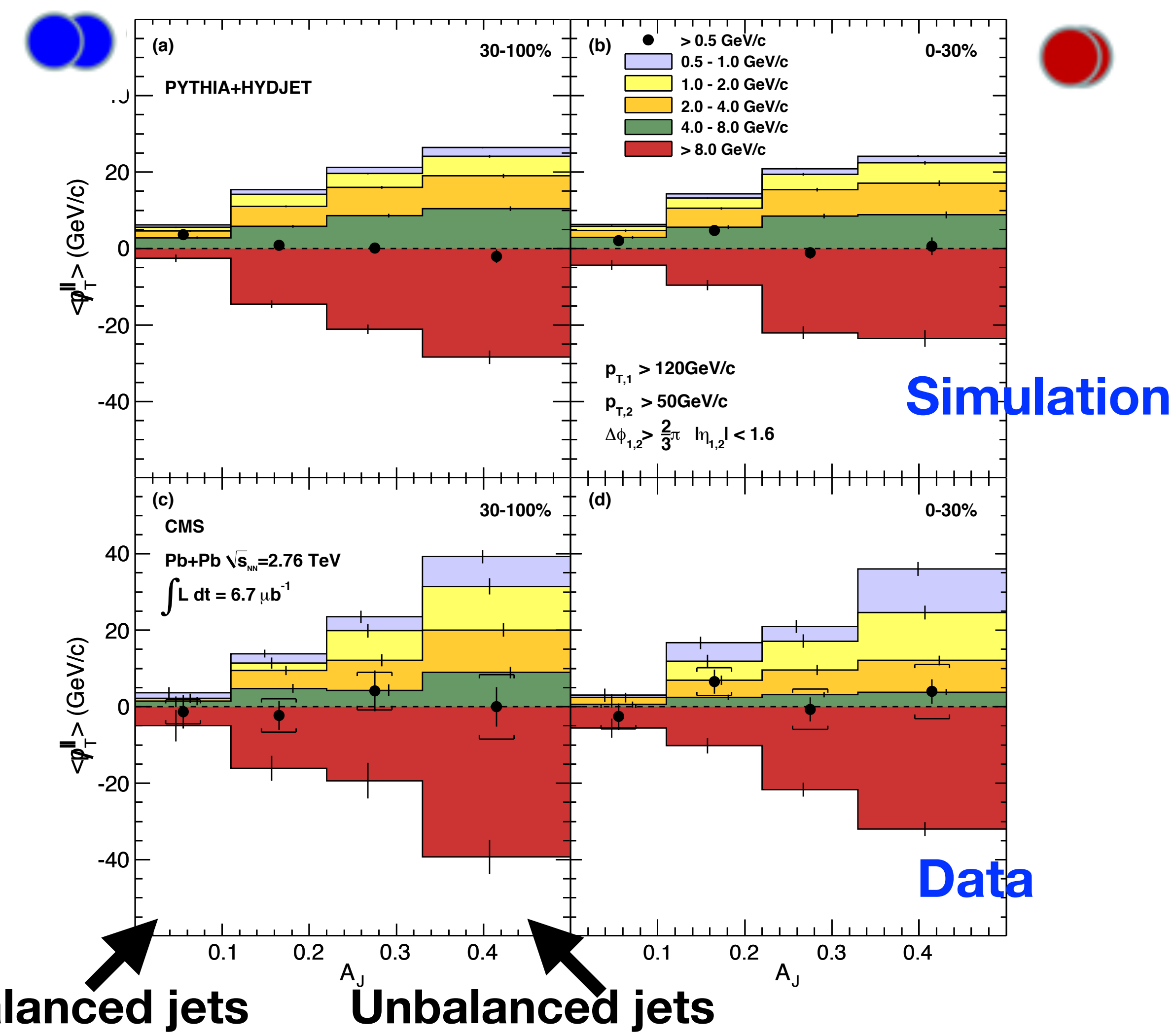
$$A_J = \frac{p_T^{lead} - p_T^{sublead}}{p_T^{lead} + p_T^{sublead}}$$



- **Significant imbalance of leading and sub-leading jet p_T observed in central Pb-Pb collisions**
- **Missing p_T:**

$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos(\phi_i - \phi_{Dijet})$$

- Overall momentum balanced
- Larger contribution from low p_T particles



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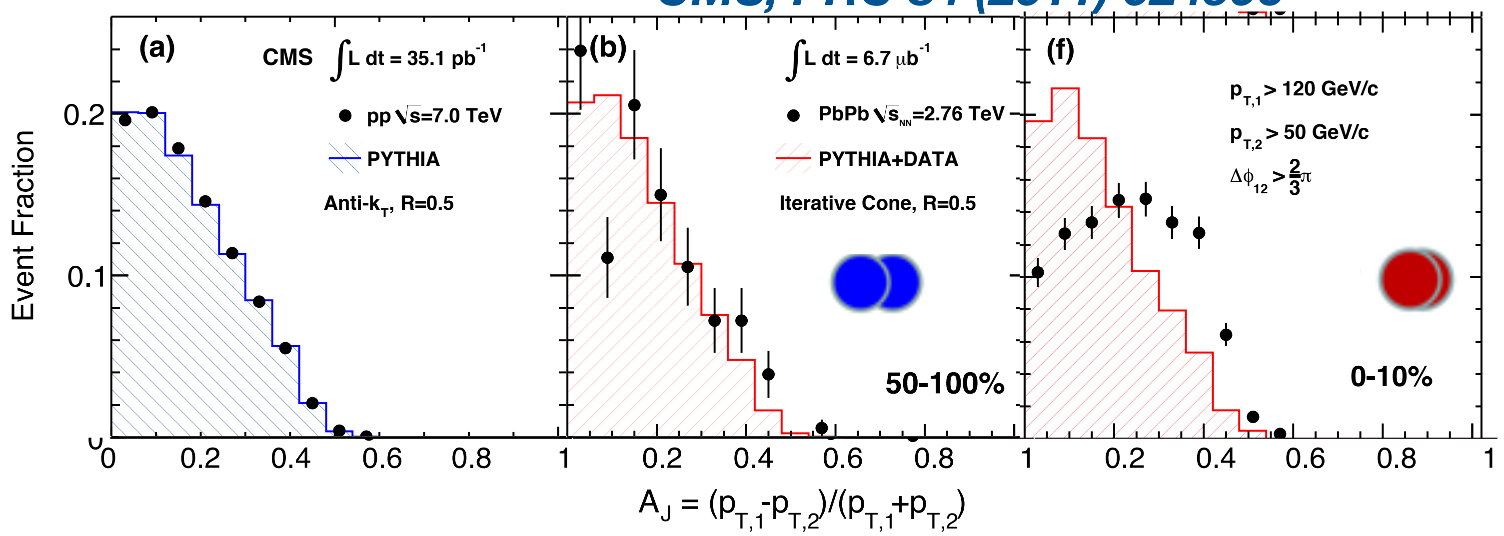
CMS, PRC 84 (2011) 024906



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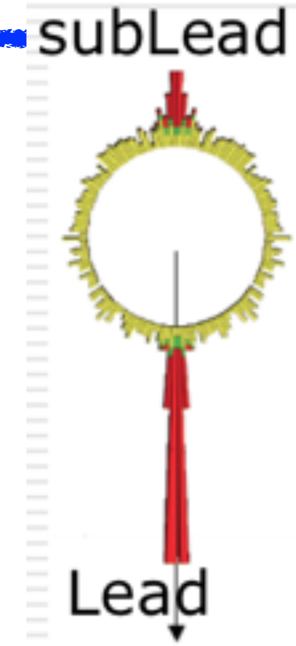

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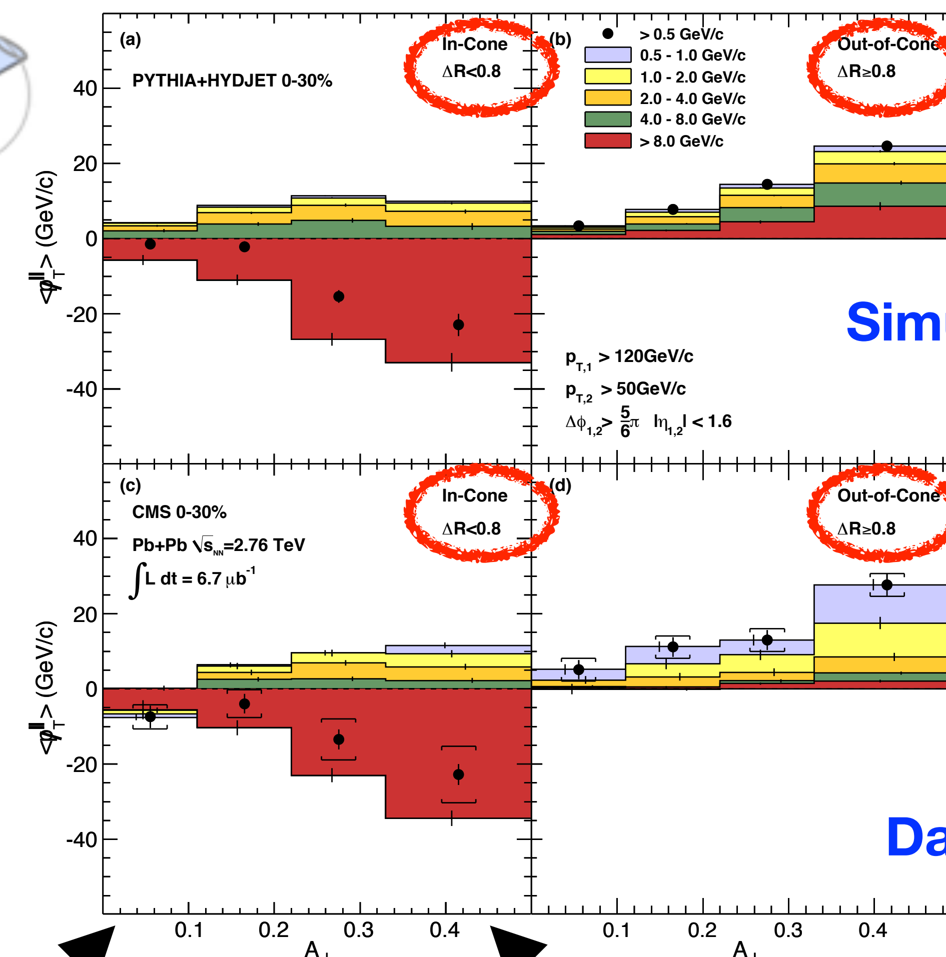
- **Missing p_T:**

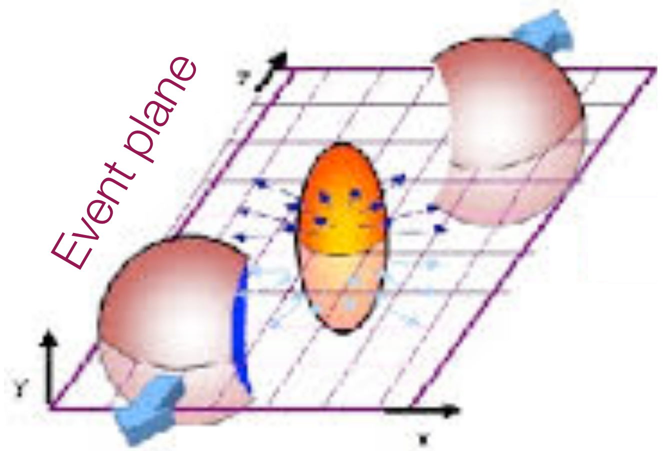
$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{Dijet}\right)$$

- The momentum difference in the di-jet is balanced by low p_T particles at large angles relative to the away side jet axis

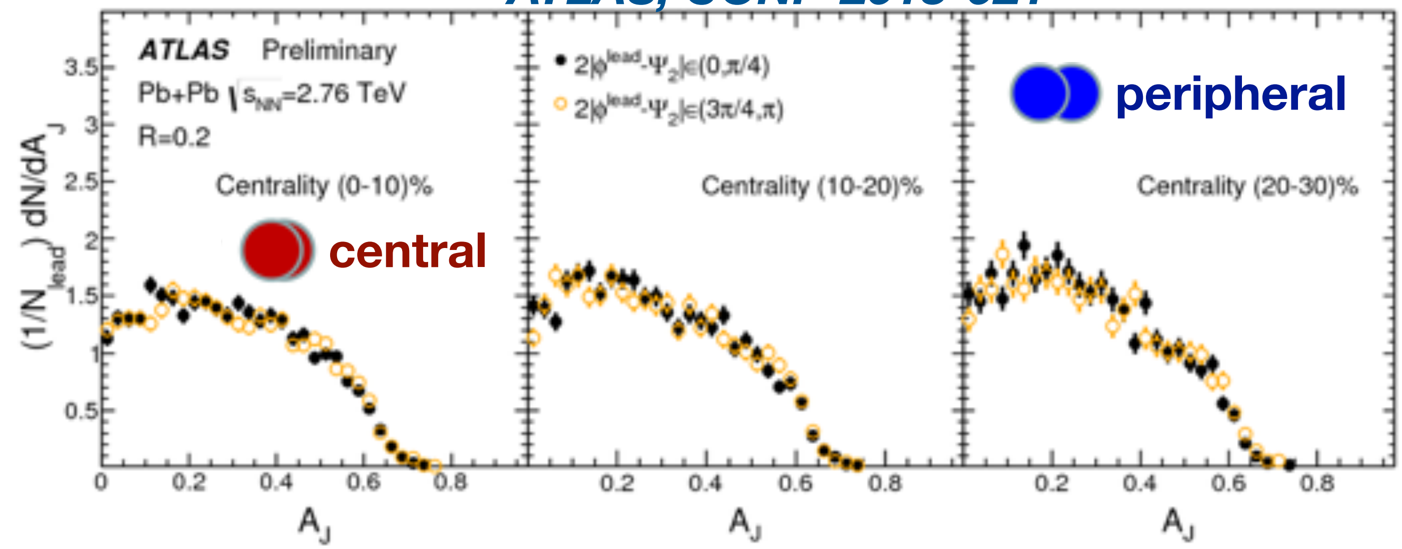


Balanced jets **Unbalanced jets**

Path length dependence of dijet asymmetry



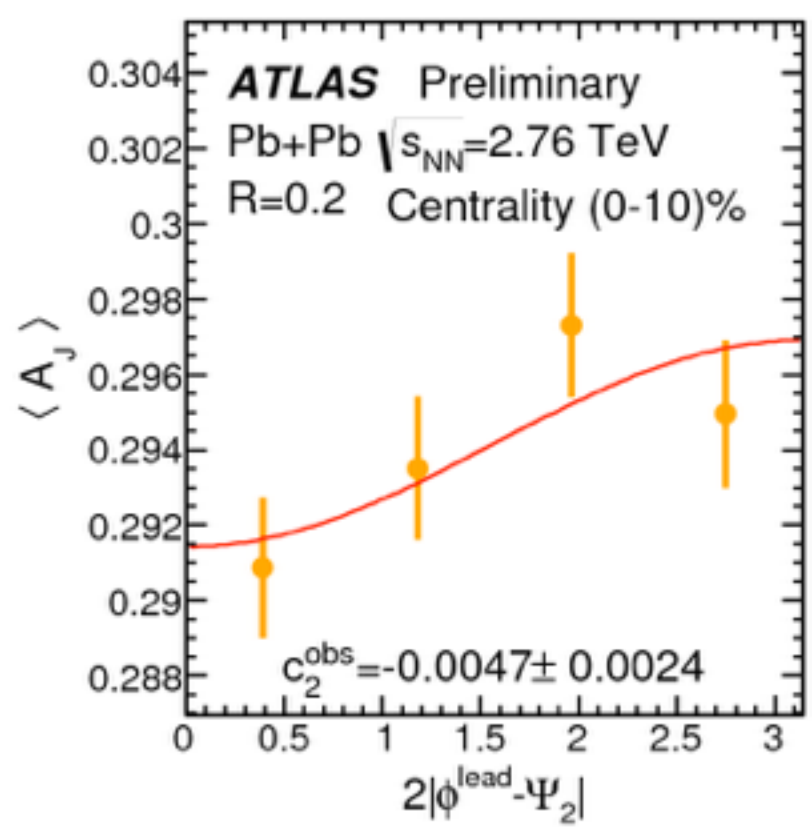
ATLAS, CONF-2015-021

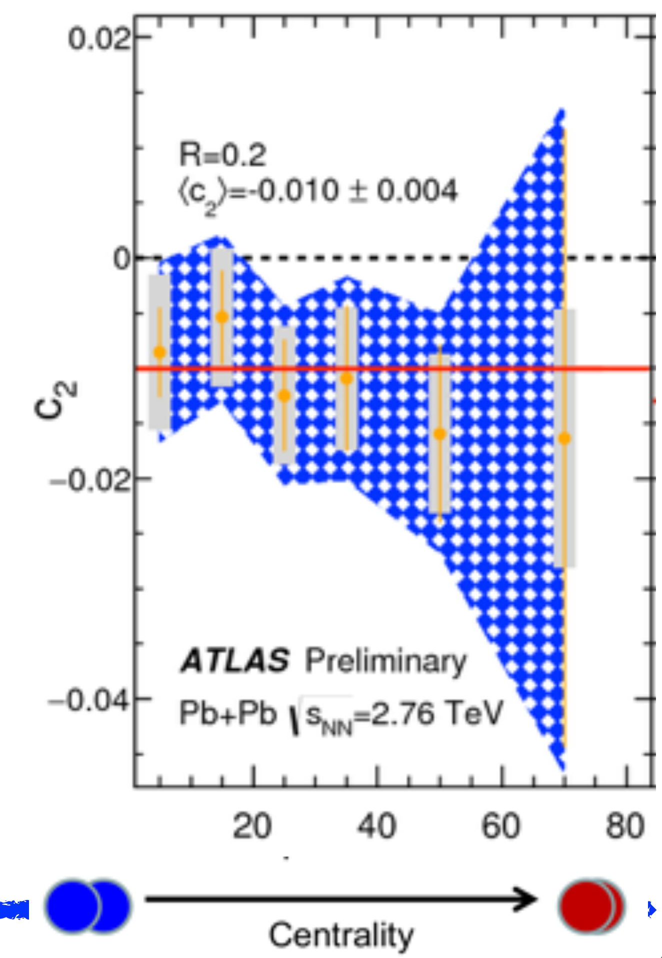


- Study dijet asymmetry A_j vs event plane and extract elliptical modulation c_2

$$\langle A_J\rangle(\varphi^{lead}-\psi_2) = A_{J,0}\left(1+2c_{2,obs}\cos\left(2(\varphi^{lead}-\psi_2)\right)\right)$$

- c_2 is small (< 2%) and negative
- Indicate larger A_j for leading jets oriented out-of-plane than for in-plane ones

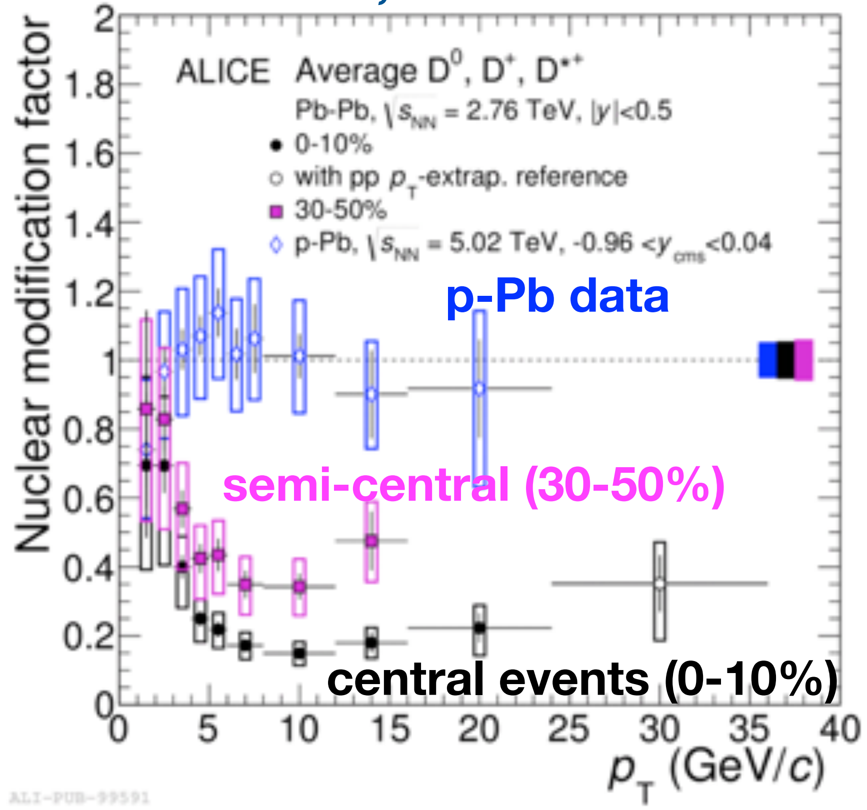




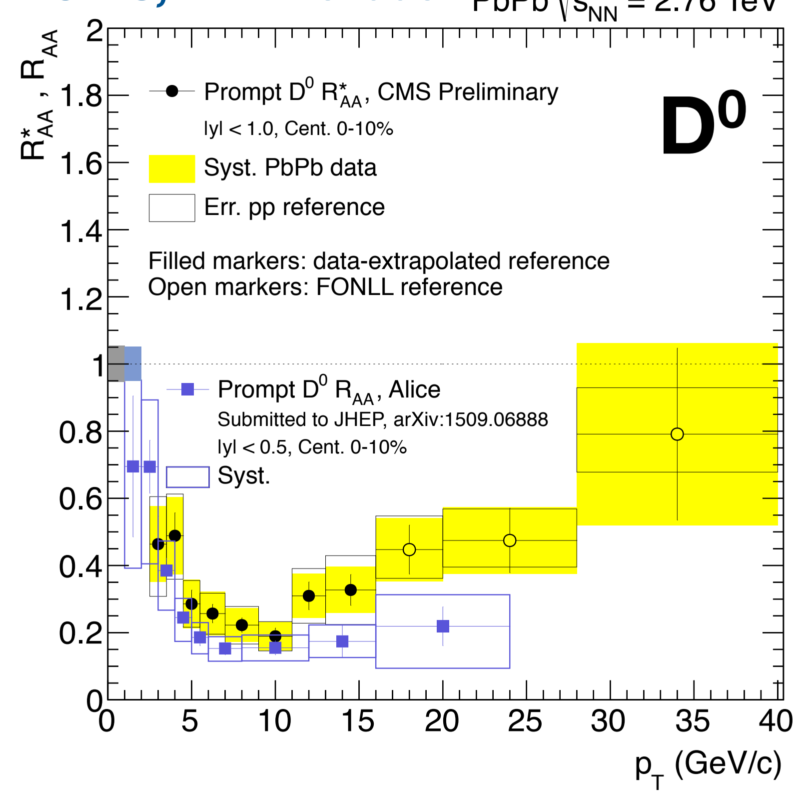
Heavy-flavour

Charm R_{AA}

ALICE, arXiv:1509.06888

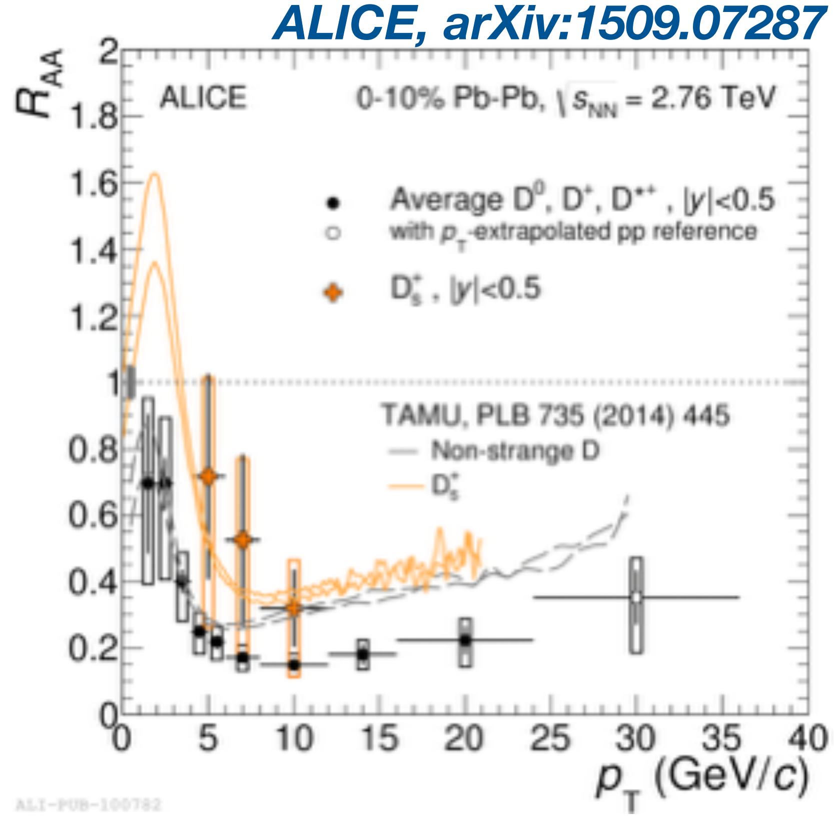


CMS, HIN-15-005



- **Observed suppression in central Pb-Pb collisions at the LHC** due to strong interaction of charm quarks with the medium

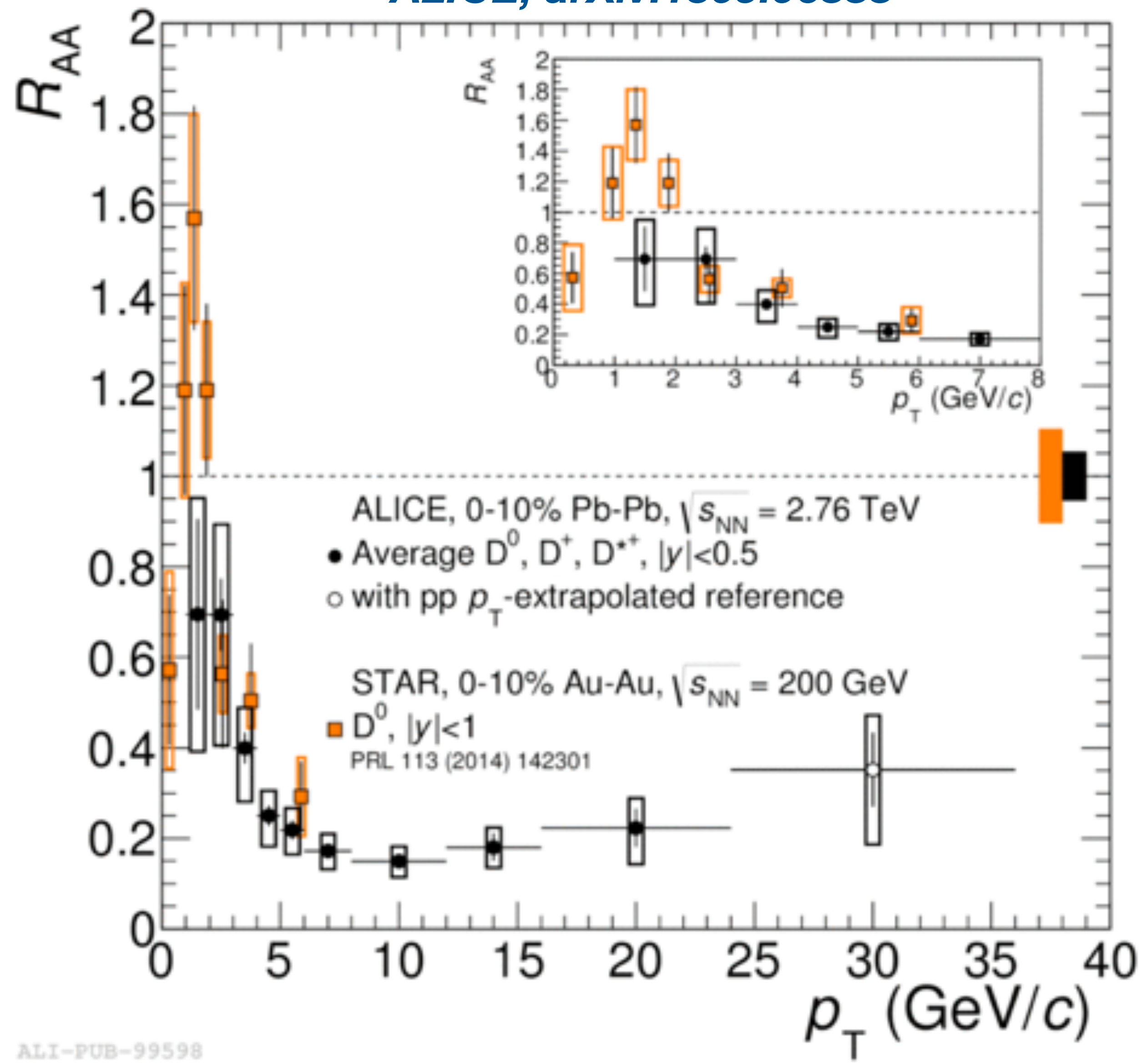
ALICE, arXiv:1509.07287



- Hint for less suppression of D_s^+ compared to **non-strange D mesons** at LHC and RHIC
- Expected if recombination plays a role in charm hadronization

Charm R_{AA} @ LHC and RHIC

ALICE, arXiv:1509.06888



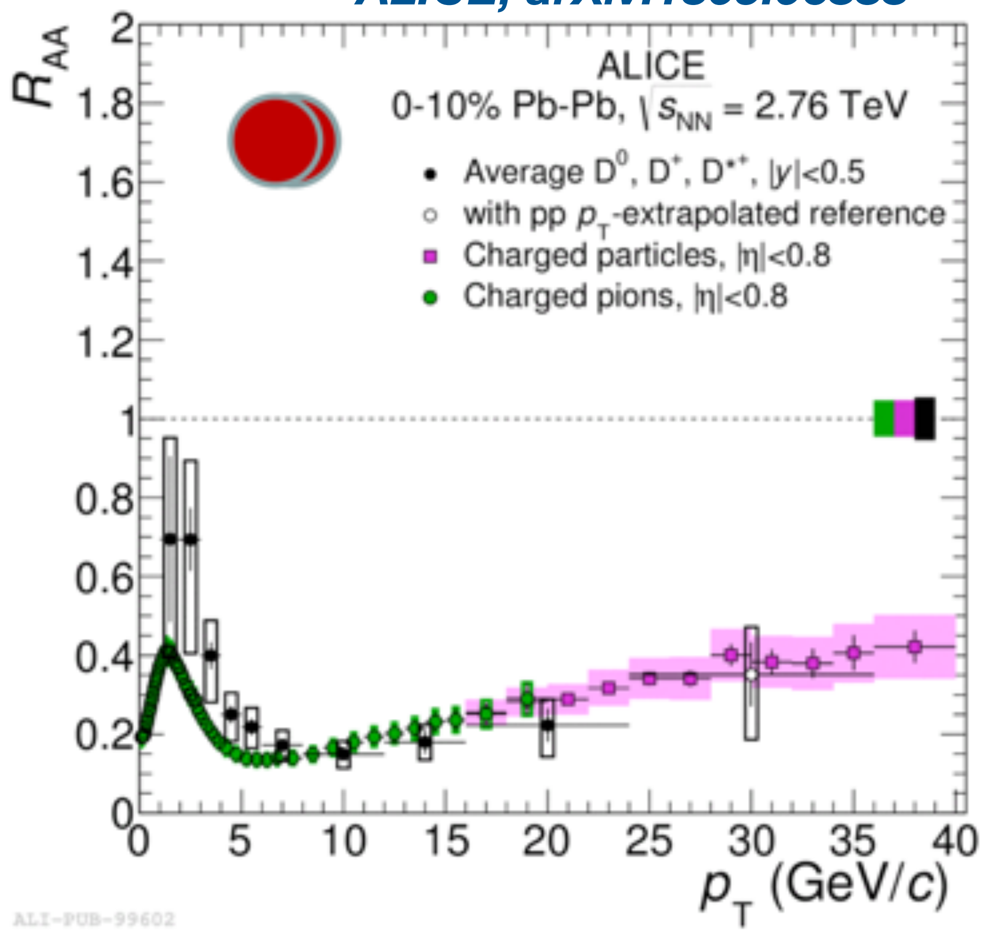
- Some difference between **LHC** and **RHIC**?
  - different shape of pp reference
  - different modification of nPDFs
  - different radial flow
  - different impact of coalescence

- some models describe both measurements reasonably well (e.g. TAMU, PLB 735(2014)445)

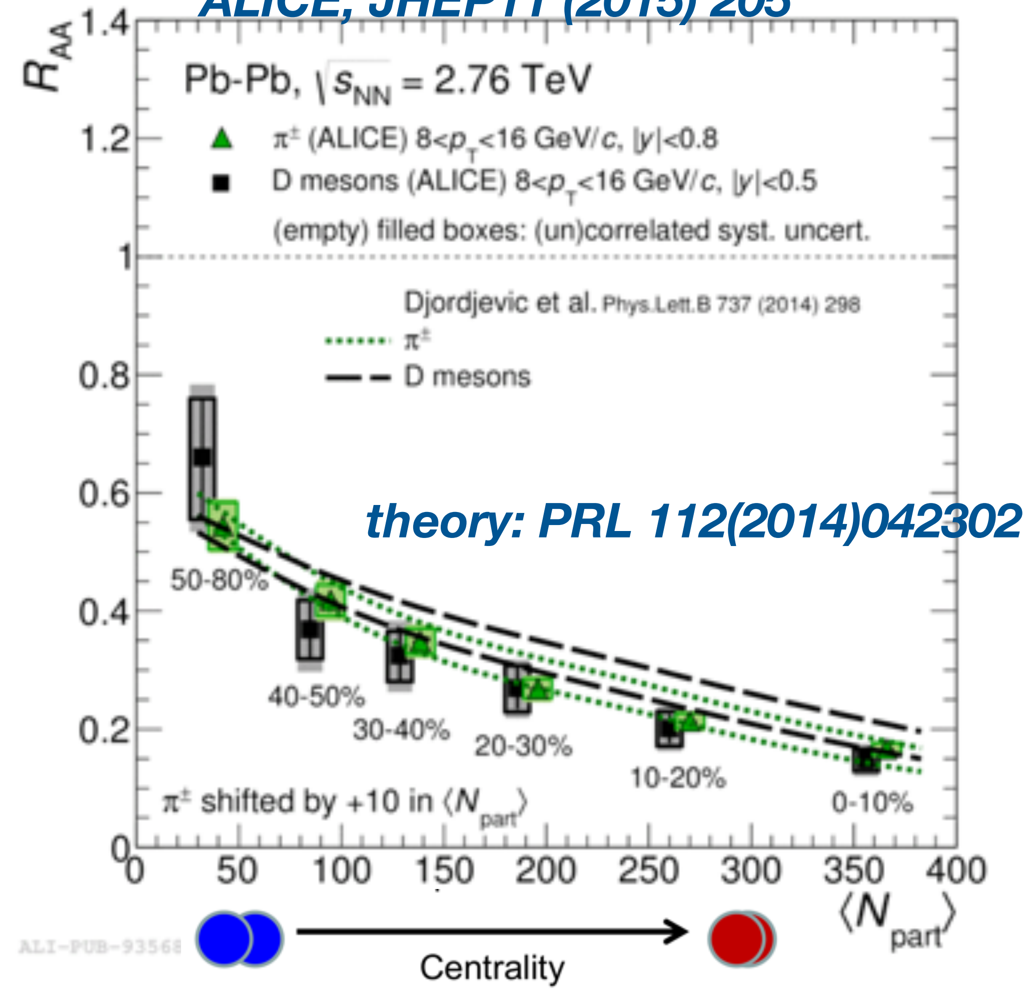
Mass ordering of the energy loss?

Expected: $\Delta E_{gluons} > \Delta E_{light} > \Delta E_{charm} > \Delta E_{beauty} \rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

ALICE, arXiv:1509.06888



ALICE, JHEP11 (2015) 205



- **D meson** and **pion** R_{AA} are compatible within uncertainties
- Agreement with models including:
  - energy loss hierarchy: ΔE(g) > ΔE(u,d,s) > ΔE(c)
  - different shapes of the parton p_T distributions
  - different fragmentation functions

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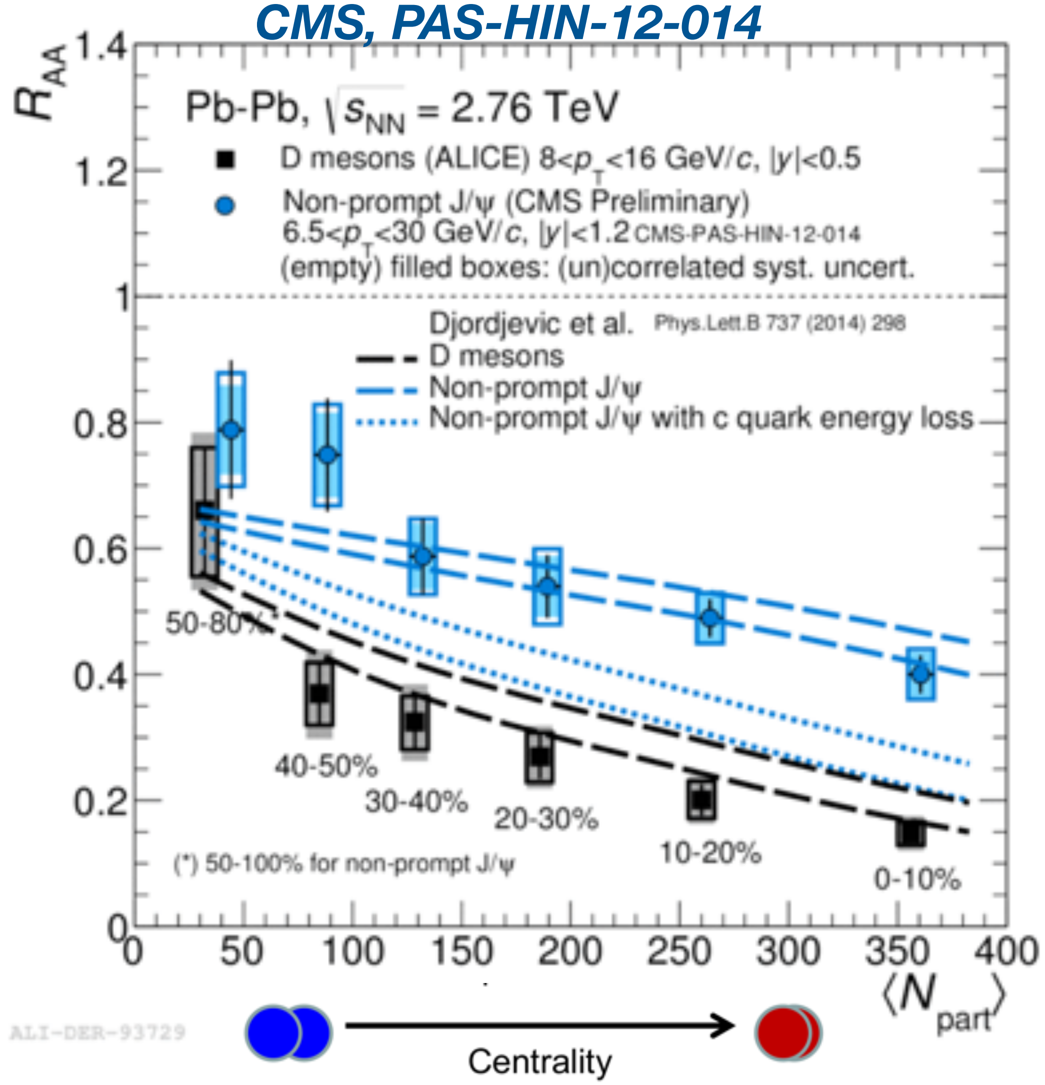
ALICE, JHEP11 (2015) 205
CMS, PAS-HIN-12-014



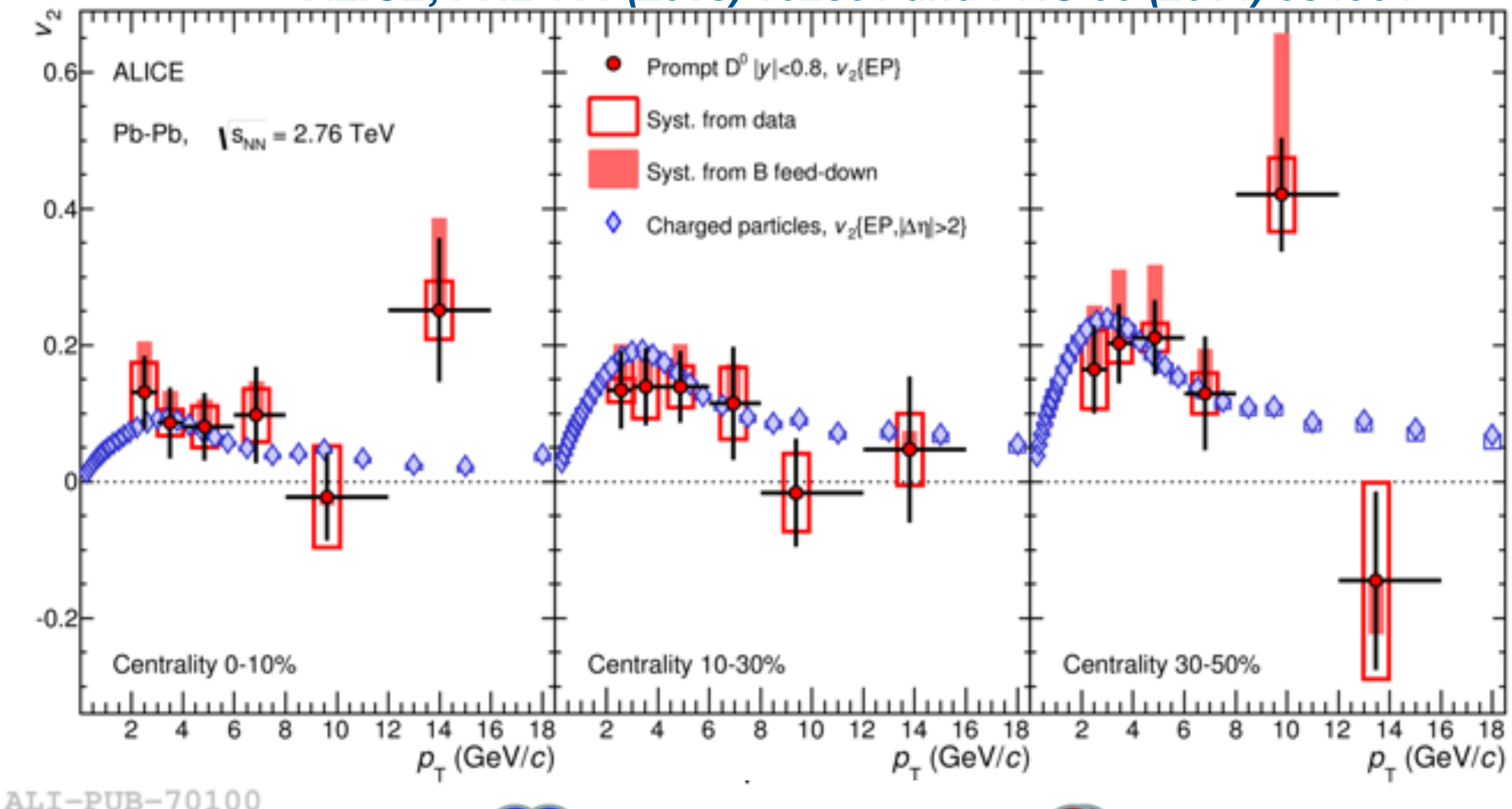
- **D mesons** and **non-prompt J/ψ**
- Similar <p_T> for D and B mesons
- **Indications for R_{AA}(D) < R_{AA}(J/ψ ← B) in central Pb-Pb collisions**
- Confirmed by CMS D^0 measurements
  CMS, HIN-15-005

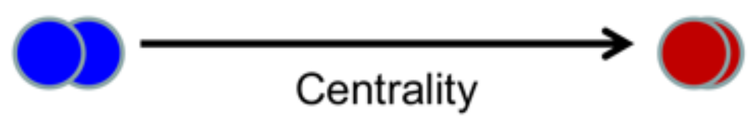
Consequence of mass difference of c and b quarks in pQCD based model calculation
Djordjevic, PLB734(2014) 286

- pQCD models including mass-dependent energy loss predicts difference between the R_{AA} of D mesons and non-prompt J/ψ similar to the observation
- similar for other calculations (BAMPS, WHDG, Vitev et al.)

Charm flow

ALICE, PRL 111 (2013) 102301 and PRC 90 (2014) 034904

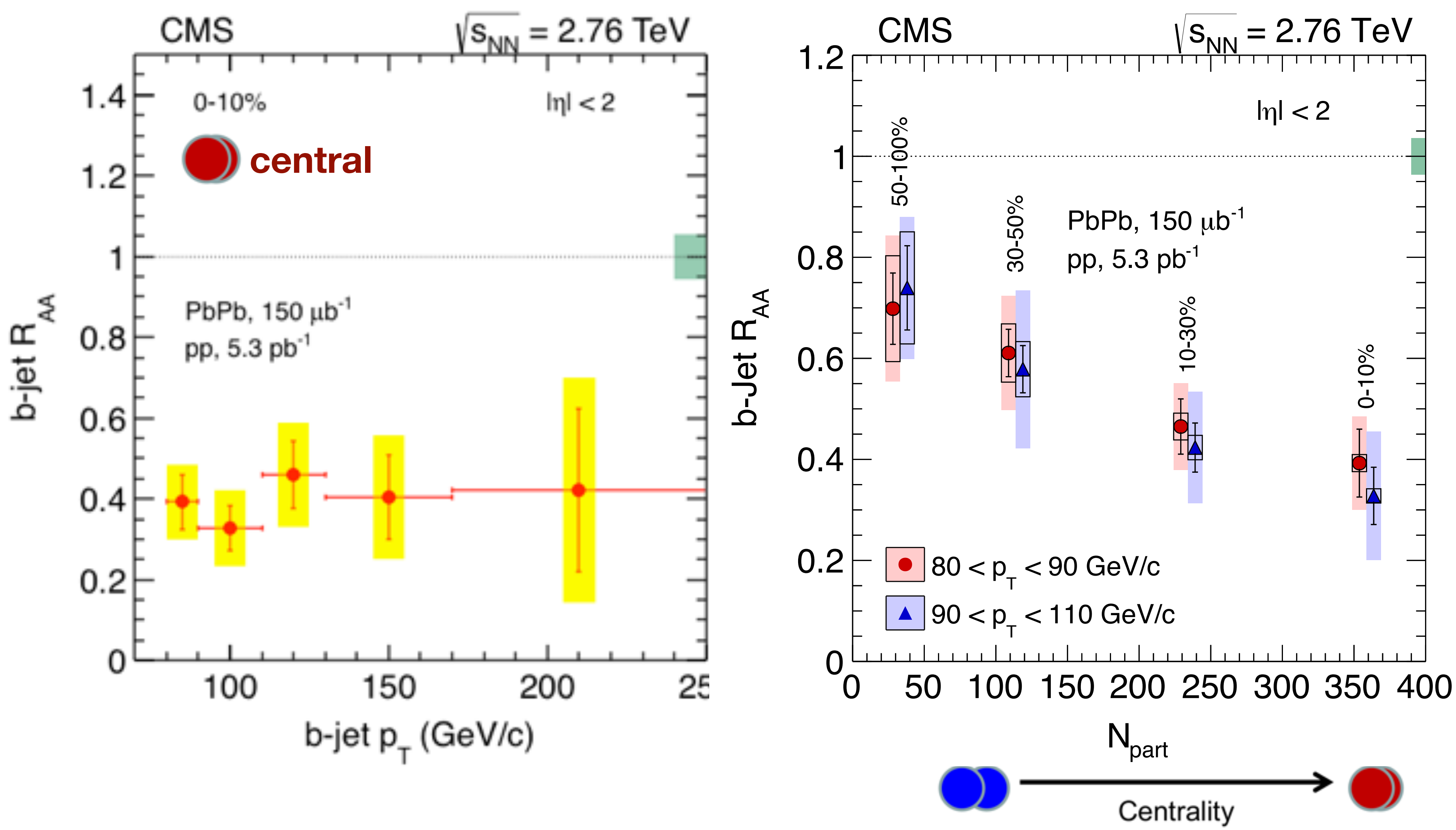




- D-meson $v_2 > 0$ and similar to charged-particle v_2 at the LHC
- Hints for increasing v_2 with decreasing centrality
- Significant interaction of charm quark with the medium
  - Collective interaction of charm quarks with the medium

b jets

CMS, PRL 113 (2014) 132301

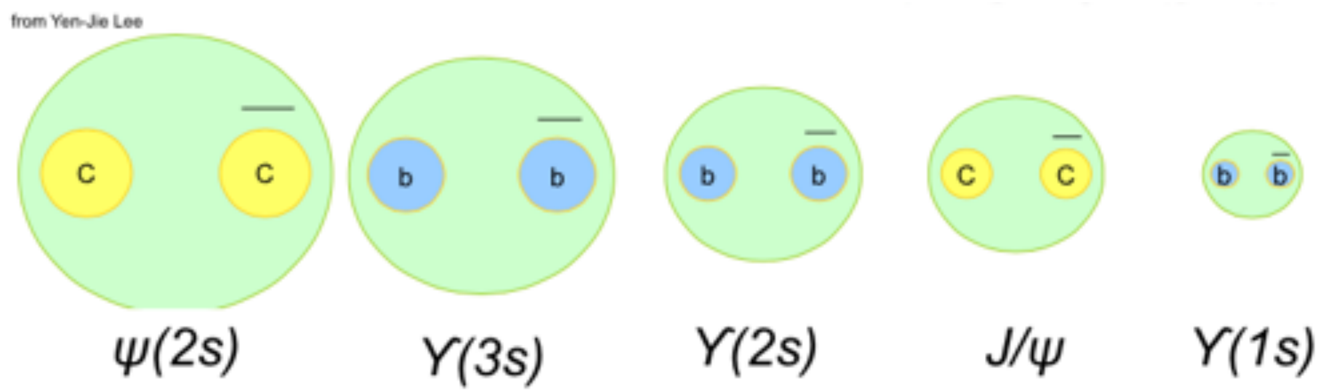


- Fully reconstructed b-jets in Pb-Pb collisions suppressed wrt measured pp refence
- Qualitatively consistent with light-flavour jet suppression
- b-jet suppression shows strong centrality dependence

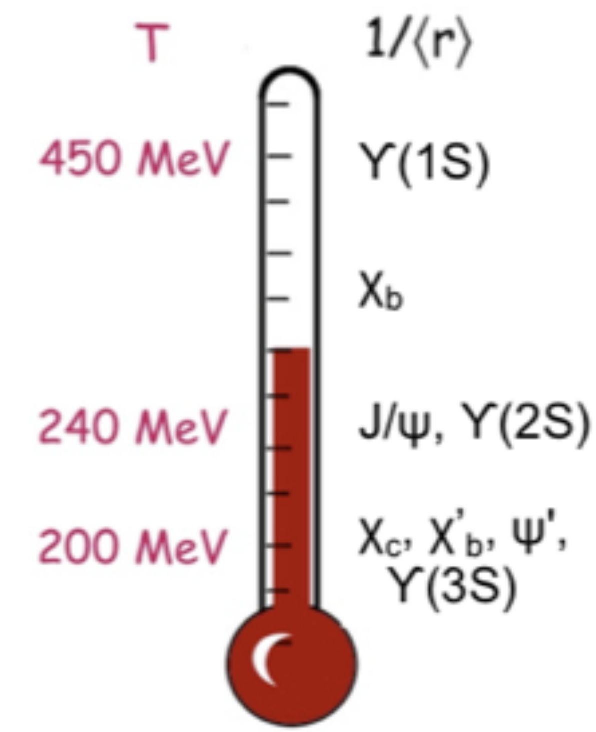
Quarkonia

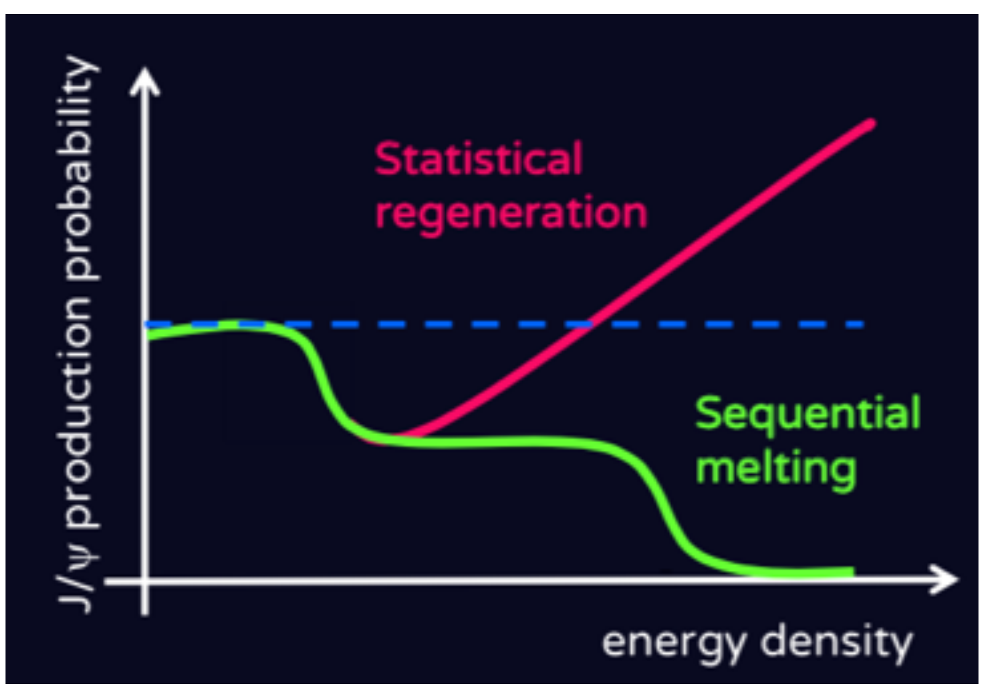
Quarkonia as QCD thermometer?

- **Sequential melting**: *Matsui & Satz, PLB 168 (1986) 415*
  - differences in the quarkonia binding energies lead to a sequential melting with increasing temperature
  - Potentially a thermometer for the QGP



Examples of melting temperatures





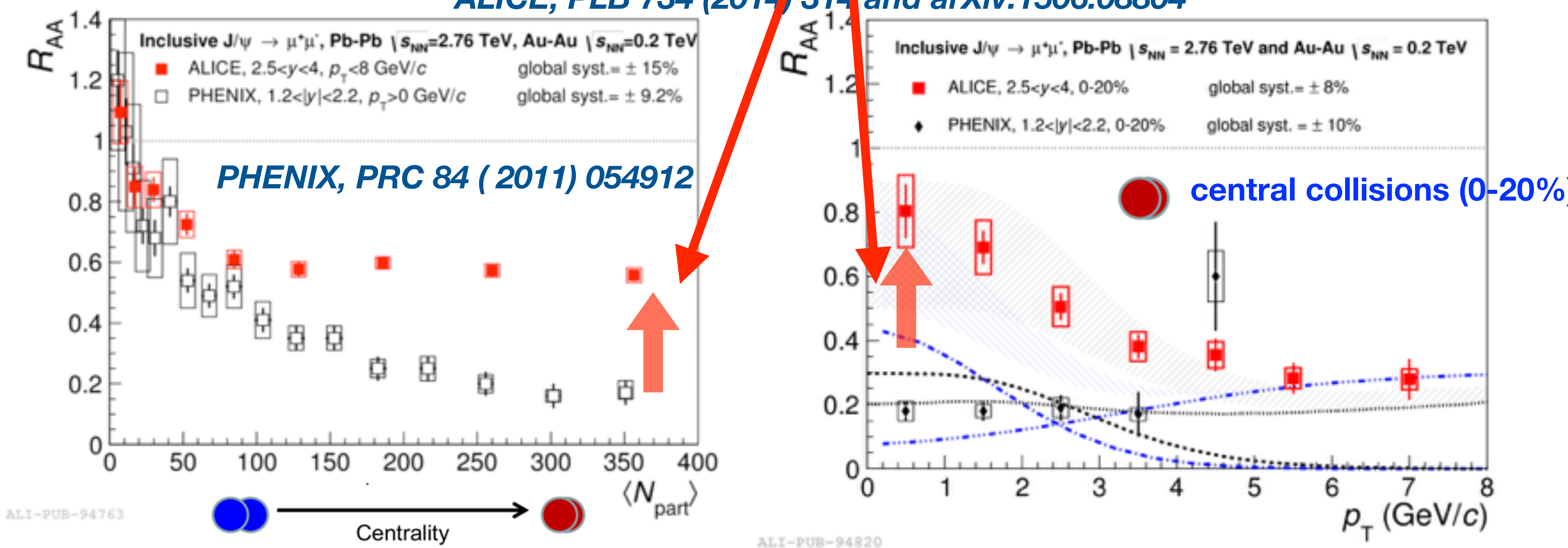
- **Regeneration**
  - Increasing the collision energy the cc pair multiplicity increases
  - Enhanced quarkonia production via (re)combination

P. Braun-Muzinger, J. Stachel, PLB (2000) 490
R. Thews et al, PRC63 (2001) 054905

Evidence for recombination

- **Low p_T J/ψ are less suppressed at RHIC than at LHC** (in spite LHC larger energy densities)

ALICE, PLB 734 (2014) 314 and arXiv:1506:08804



- An indication that J/ψ are formed again from uncorrelated cc pairs (~100 in a central collision)

ψ(2s)

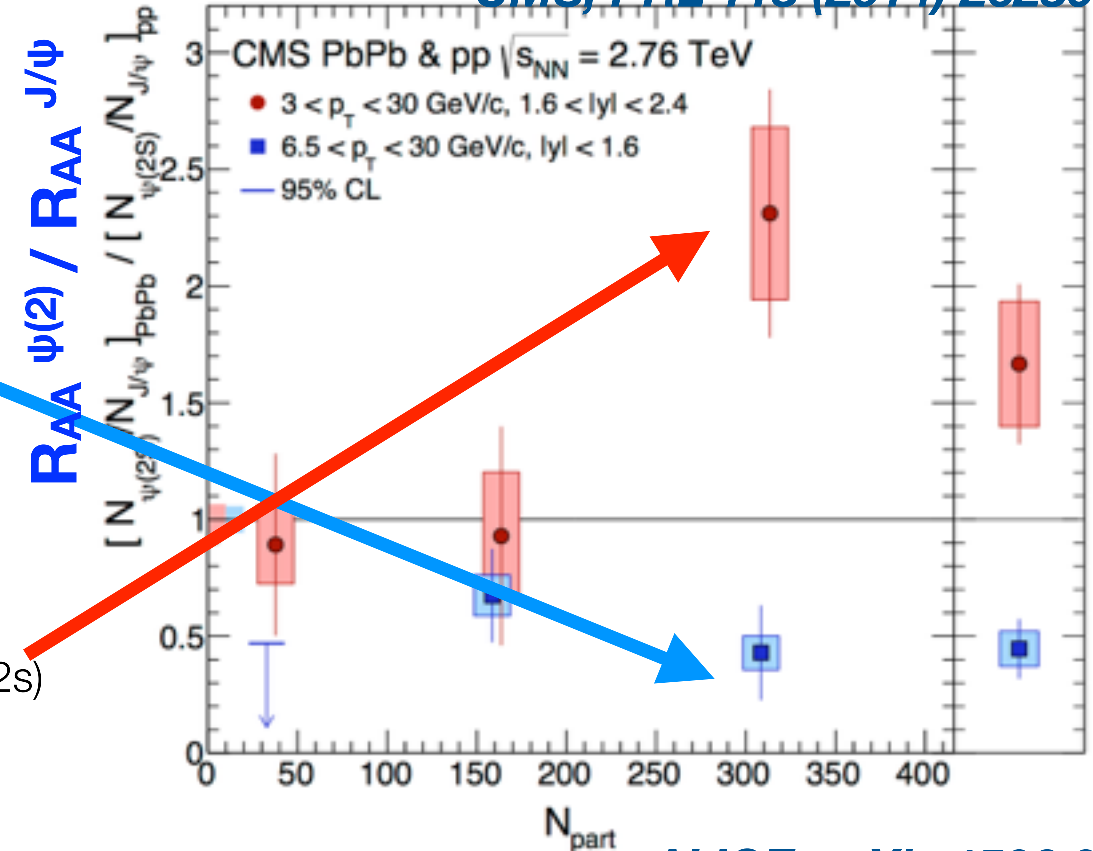
- **ψ(2s) production modified in AA with strong kinematic dependencies**

- High-p_T mid-rapidity → $R_{AA}^{J/\psi} > R_{AA}^{\psi(2s)}$
  - Stronger suppression of weakly bound ψ(2s) with respect to J/ψ as expected from sequential melting

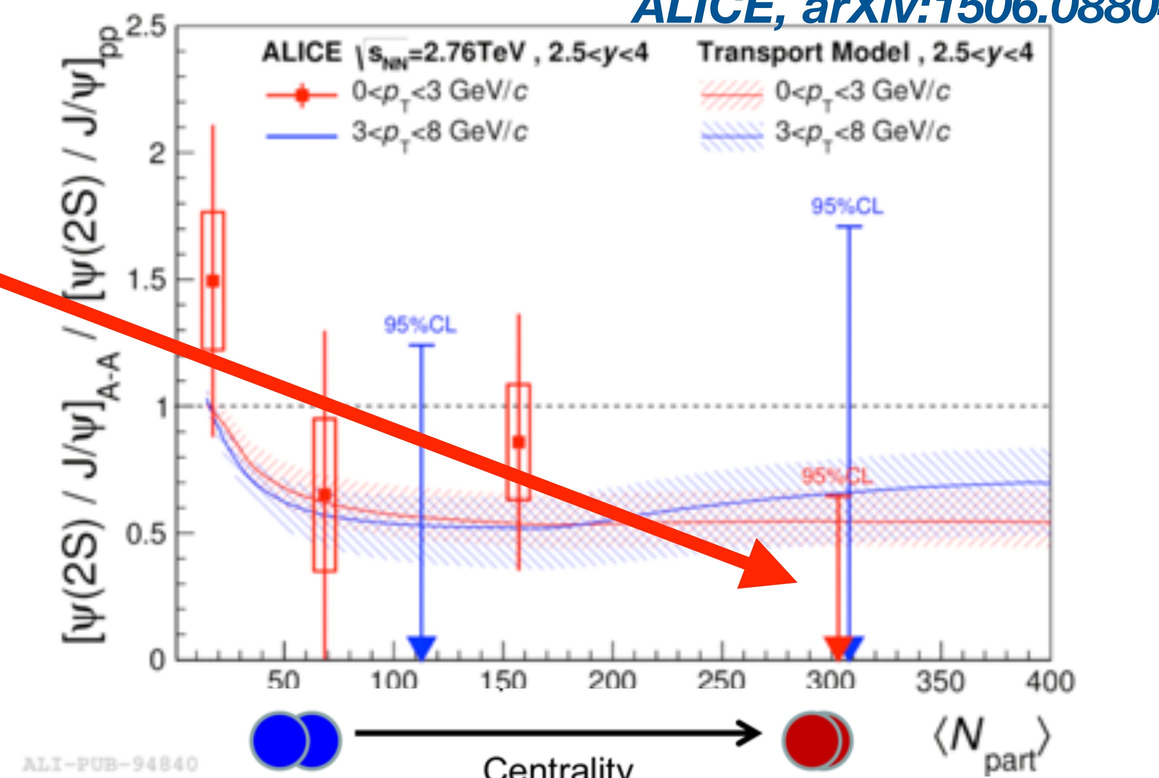
- Moderate p_T forward-rapidity → $R_{AA}^{J/\psi} < R_{AA}^{\psi(2s)}$

- Low p_T forward-rapidity → $R_{AA}^{J/\psi} > R_{AA}^{\psi(2s)}$
  - Trend in agreement with transport models and with statistical hadronization approach

CMS, PRL 113 (2014) 262301

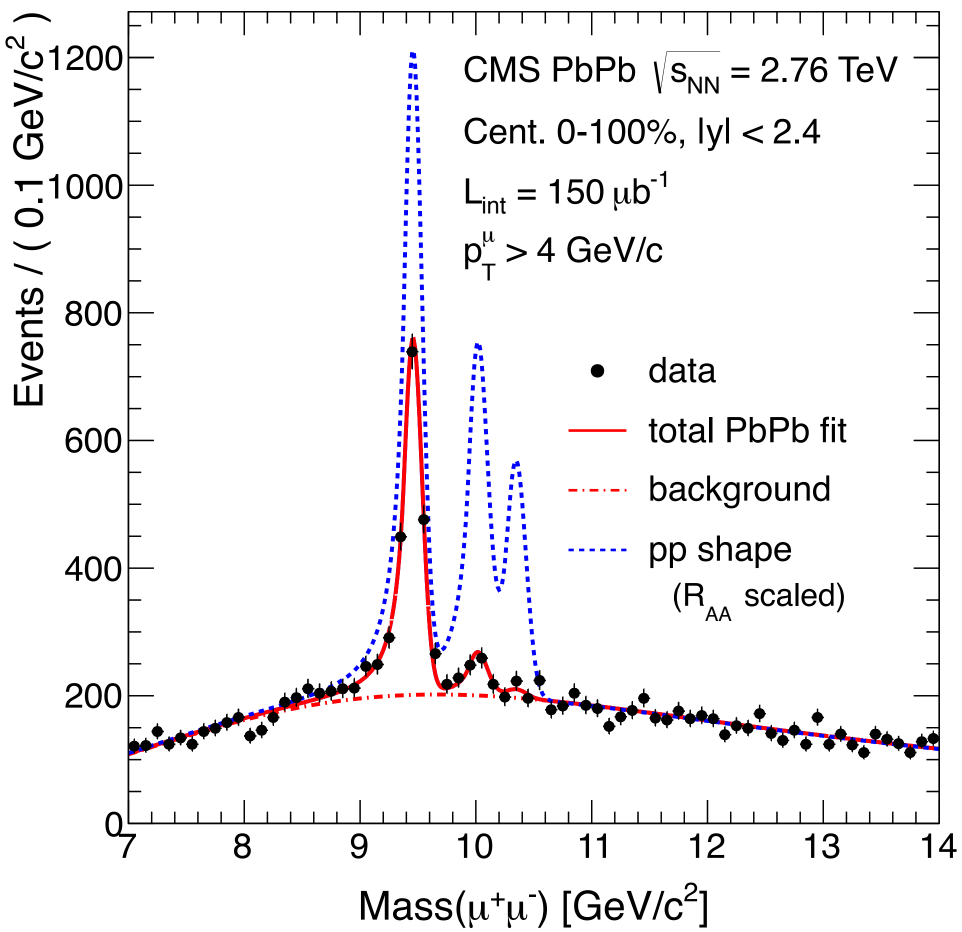


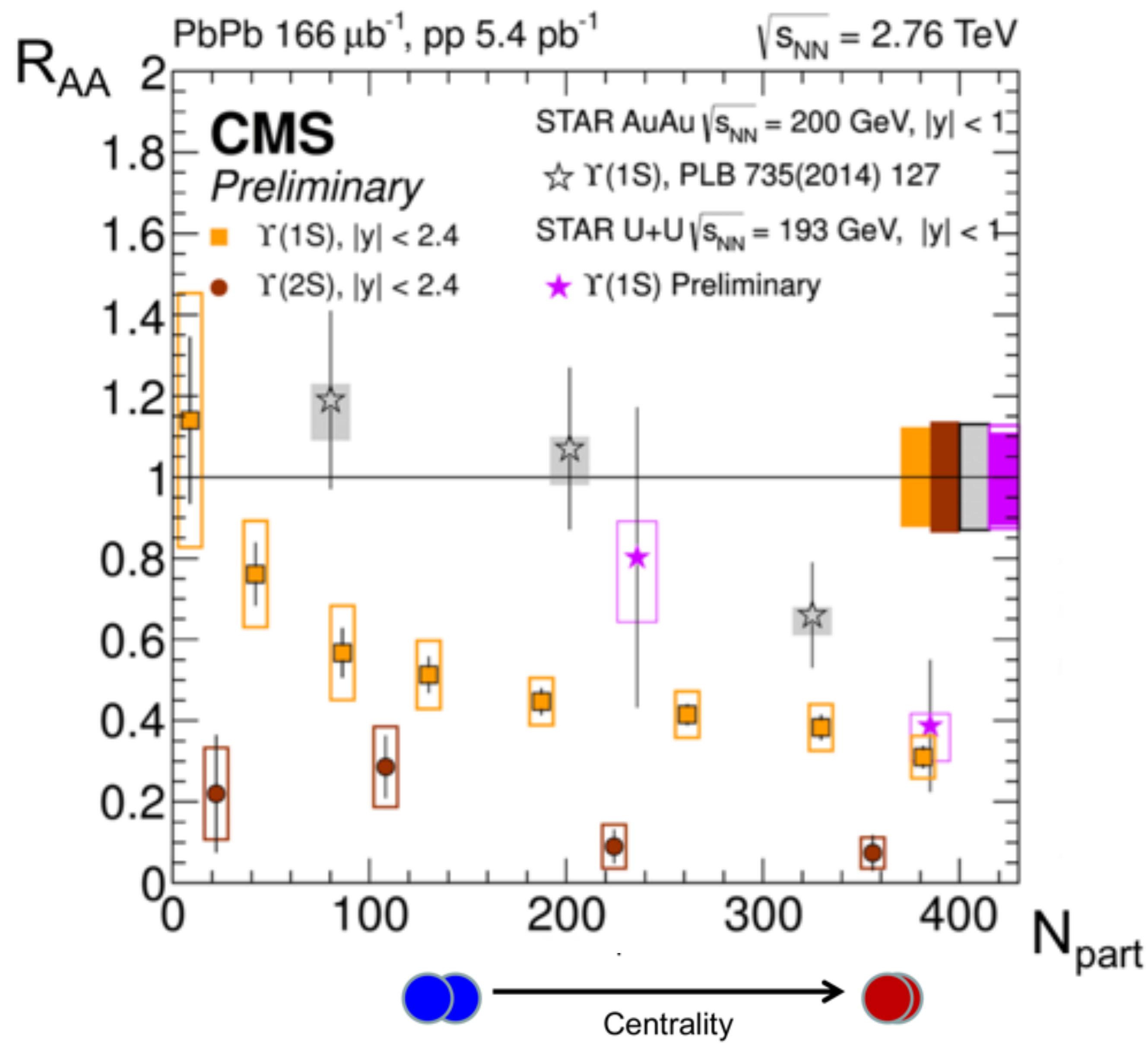
ALICE, arXiv:1506.08804



Υ(ns)

CMS, PRL 109 (2012) 222301 and HIN-15-001
STAR, PLB 735 (2014) and preliminay U+U





- **Sequential suppression observed**
- $R_{AA}^{\Upsilon(3s)} < R_{AA}^{\Upsilon(2s)} < R_{AA}^{\Upsilon(1s)}$
- Υ(1s) suppressed also in central Au-Au and U-U collisions at RHIC

$R_{AA}(1s) = 0.43 \pm 0.03 \pm 0.07$
$R_{AA}(2s) = 0.13 \pm 0.03 \pm 0.02$
$R_{AA}(3s) < 0.14$ (95% CL)

Summary

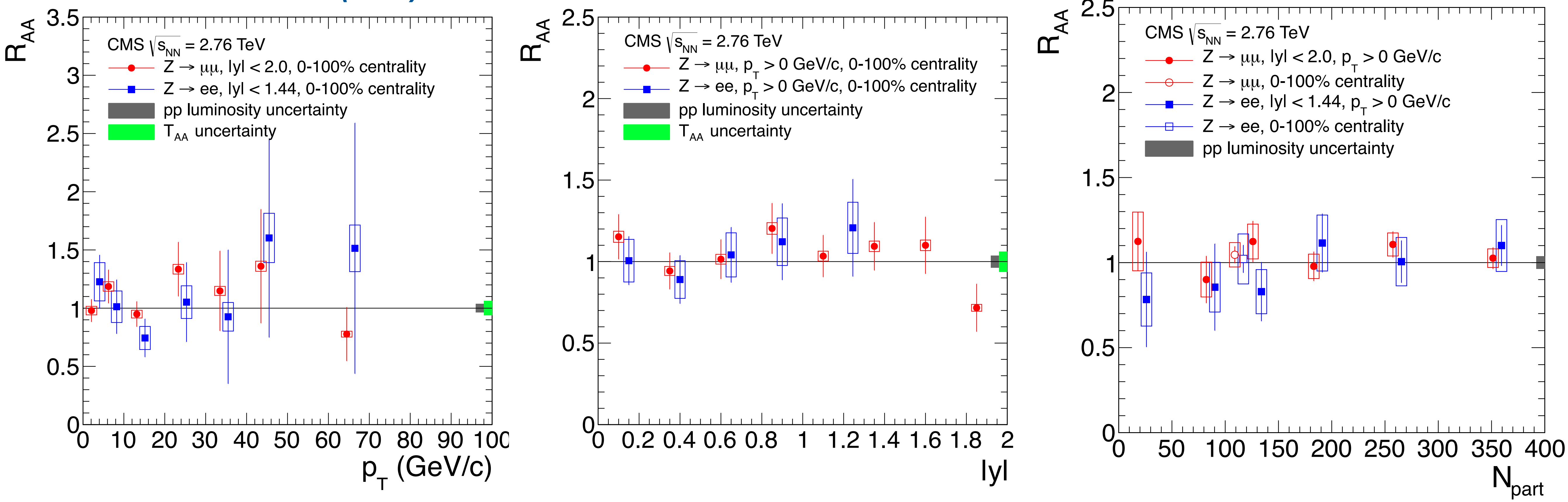
- **EM probes**
  - Unmodified by the medium
- **Jets**
  - Jets are quenched wrt pp and their fragmentation functions are modified
  - Dijet asymmetry is studied
- **Open heavy-flavour**
  - Open heavy-flavour strongly suppressed in Pb-Pb collisions wrt pp collisions
  - First indication of mass effect in the parton energy loss in the medium
  - Strong charm v_2 observed
- **Quarkonia**
  - J/Ψ low p_T measurement suggest a substantial contribution from recombination
  - Upsilon family subsequently suppressed

First data from LHC Run 2 at $\sqrt{s_{NN}}$ = 5.02 TeV already available… stay tuned!

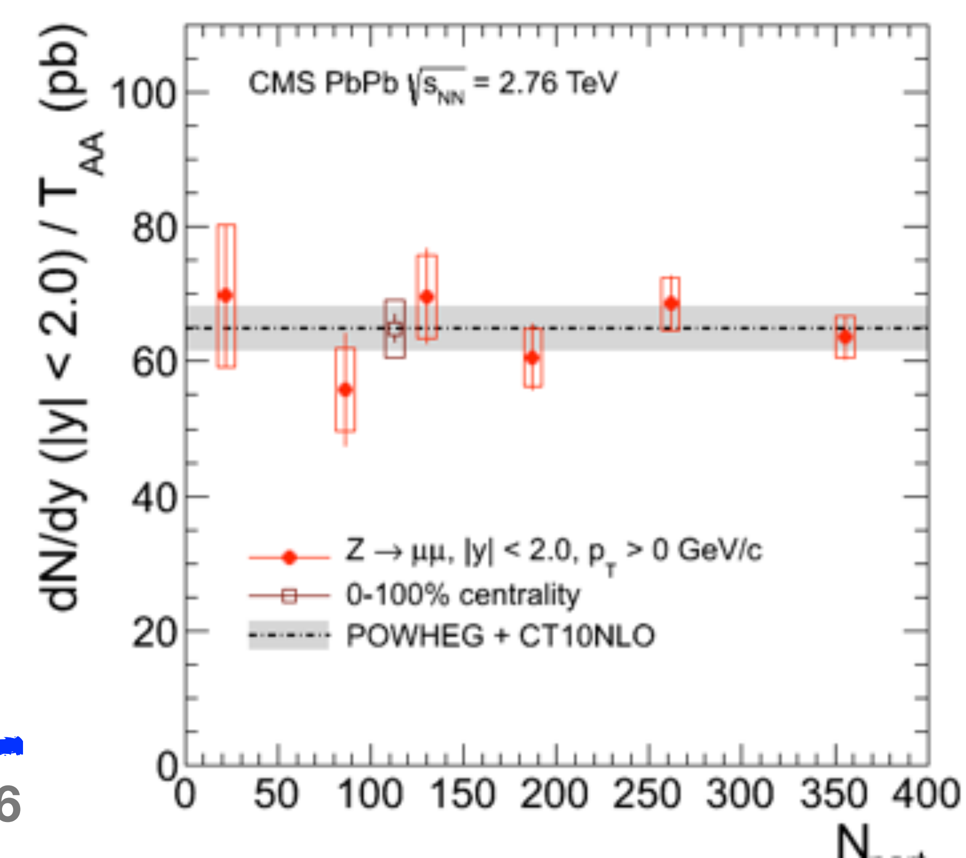
Back-up slides

W and Z bosons

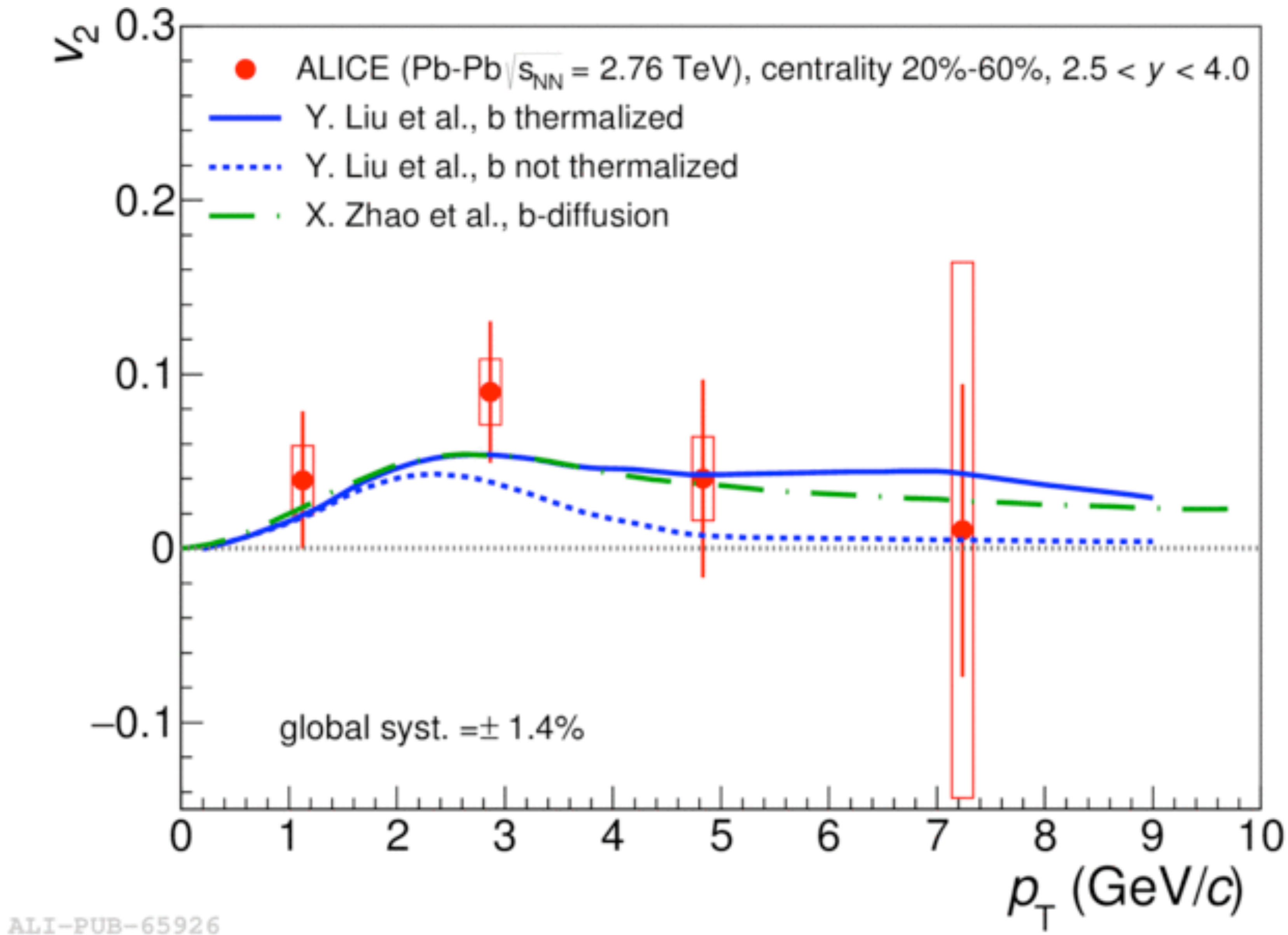
JHEP03 (2015) 022



- R_{AA} compatible with unity

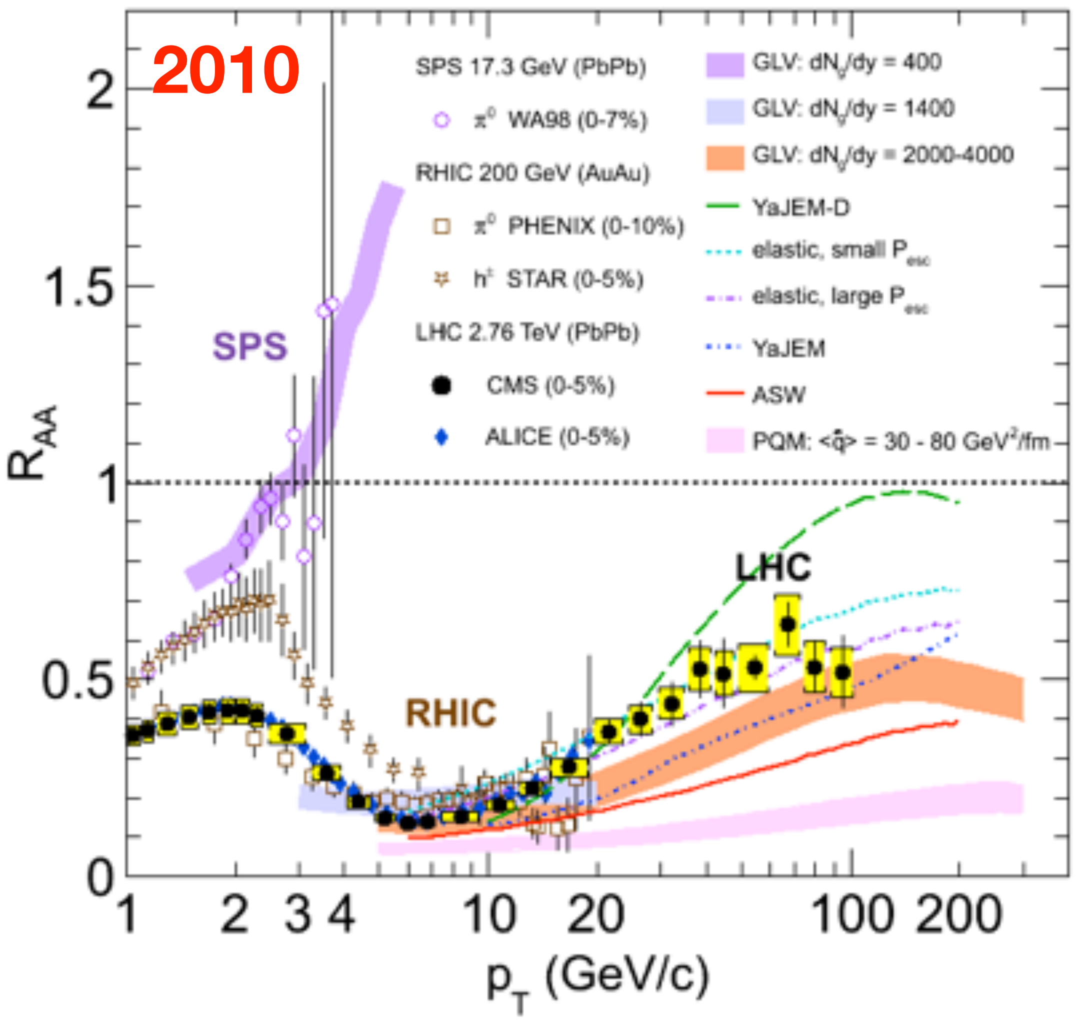


J/ψ flow?

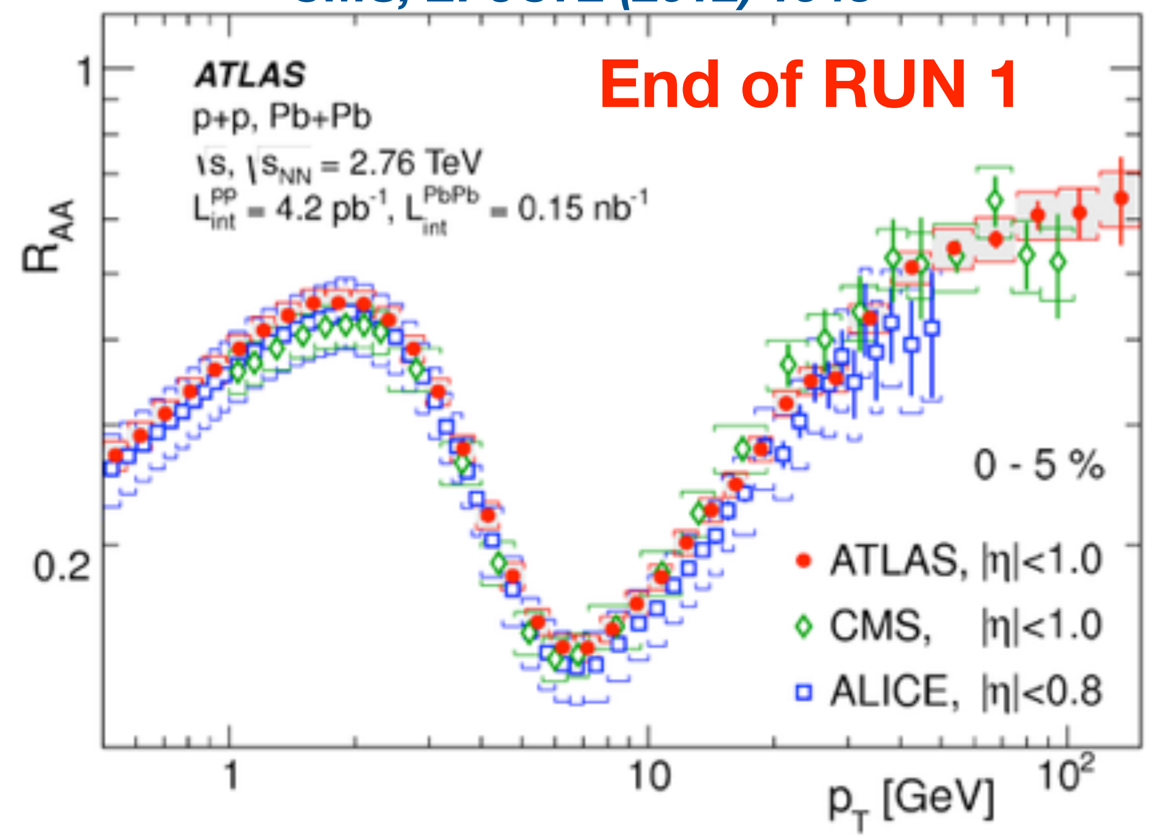


v_2
ALICE (Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV), centrality 20%-60%, 2.5 < y < 4.0
Y. Liu et al., b thermalized
Y. Liu et al., b not thermalized
X. Zhao et al., b-diffusion
global syst. =± 1.4%
0.3
0.2
0.1
0
–0.1
0 1 2 3 4 5 6 7 8 9 10
p_T (GeV/c)
ALI-PUB-65926

Charged particle R_{AA}



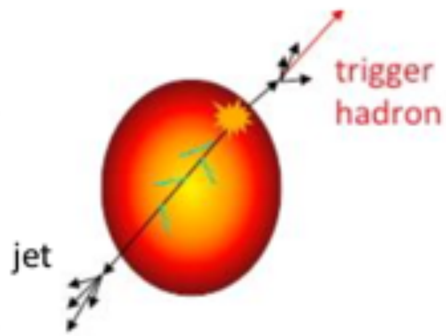
ALICE, PLB 720 (2013) 52
ATLAS, JHEP09 (2015) 050
CMS, EPJC72 (2012) 1945



- R_{AA}(LHC) < R_{AA}(RHIC) for p_T < 10 GeV/c
- Minimum R_{AA} ~ 0.14 at p_T = 6-7 GeV/c
- Increase of R_{AA} with p_T but even at p_T ~ 100 GeV/c R_{AA} <1

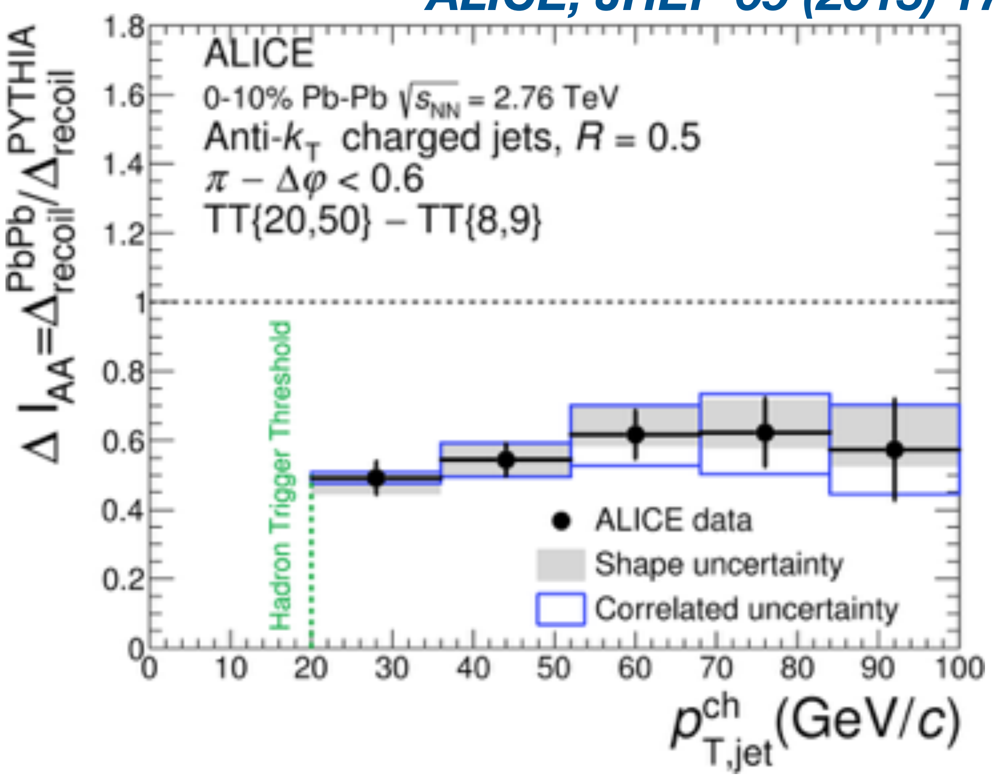
Semi inclusive recoil jets

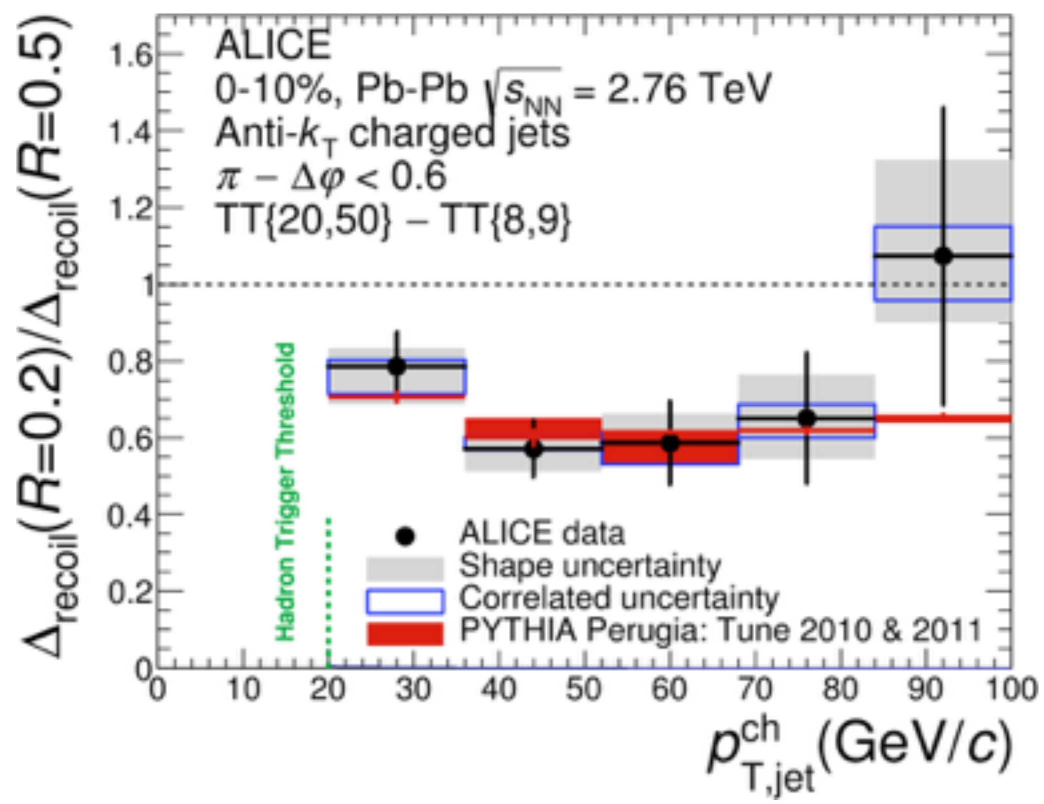
- Study intra and inter-jet angular broadening
- Directly comparable with pQCD



$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_T}\bigg|_{p_{T,trig} \in TT_{Sig}} - \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_T}\bigg|_{p_{T,trig} \in TT_{Ref}}$$

ALICE, JHEP 09 (2015) 170

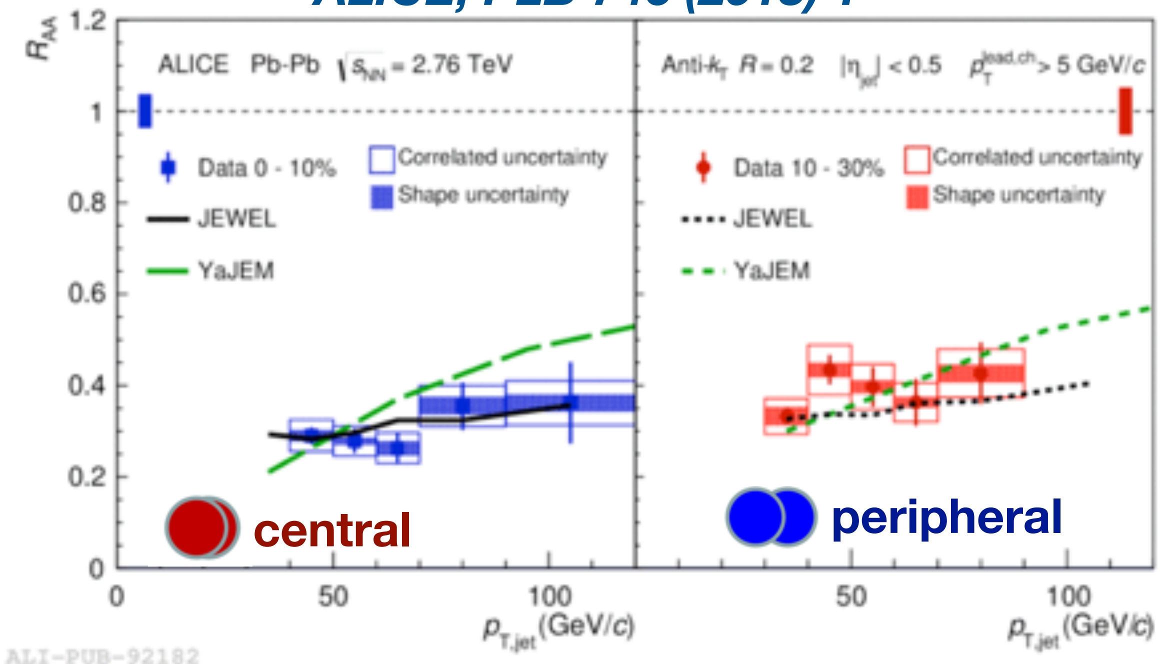




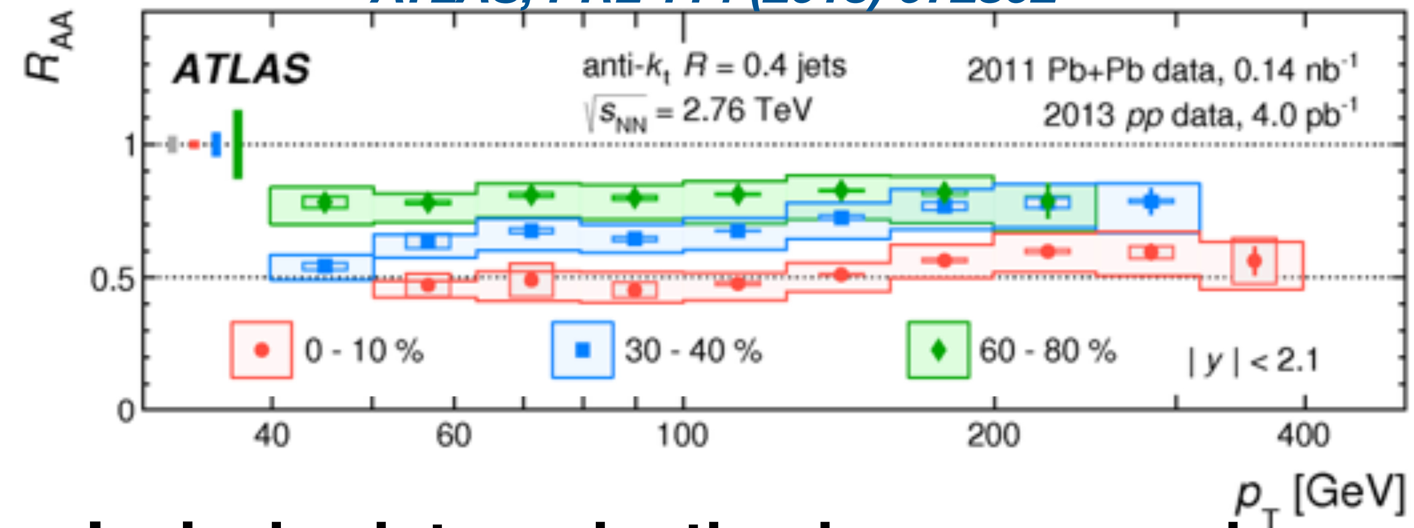
- Recoil jet yields are suppressed ($\Delta I_{AA} < 1$):
  - Suppression slowly decreases with jet p_T
- No evidence of intra-jet broadening:
  - Δrecoil for R=0.2/0.5 similar in pp and central Pb-Pb collisions

Jets modification

ALICE, PLB 746 (2015) 1

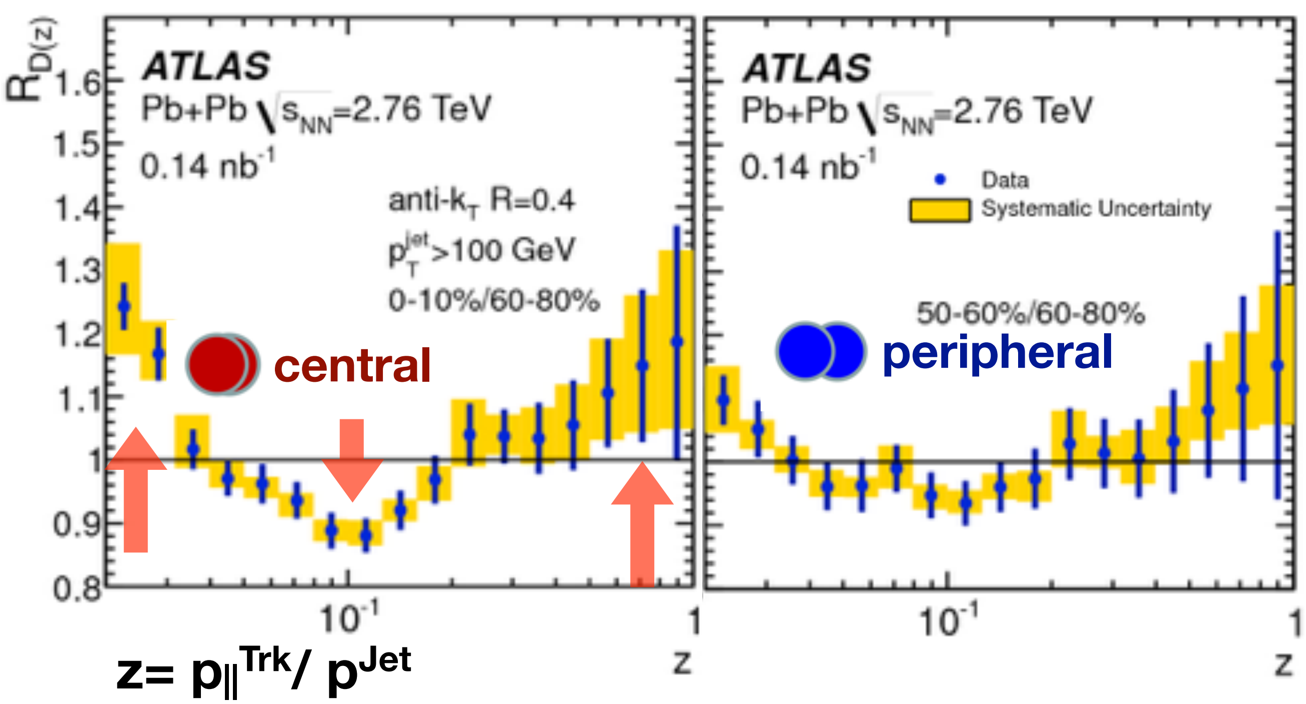


ATLAS, PRL 114 (2015) 072302

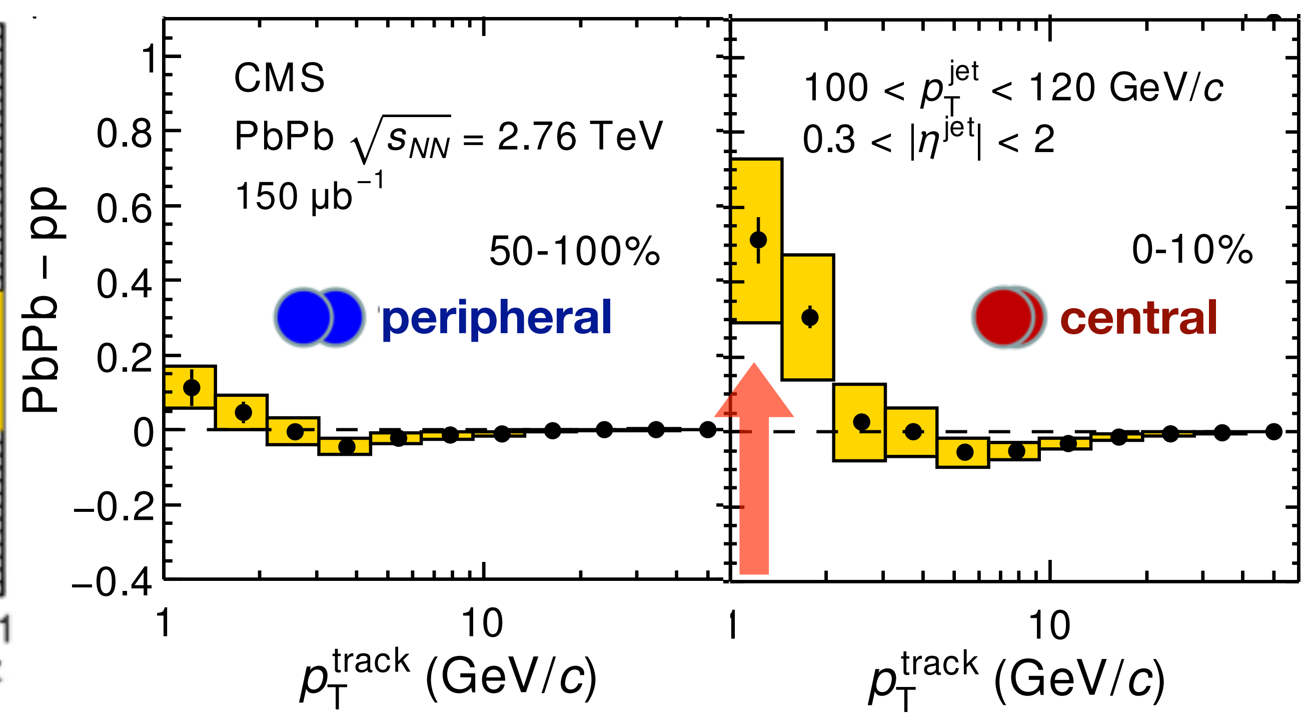


- Inclusive jet production is suppressed in Pb-Pb collisions

ATLAS, PLB 739 (2014) 320



CMS, PRC 90 (2014) 024908

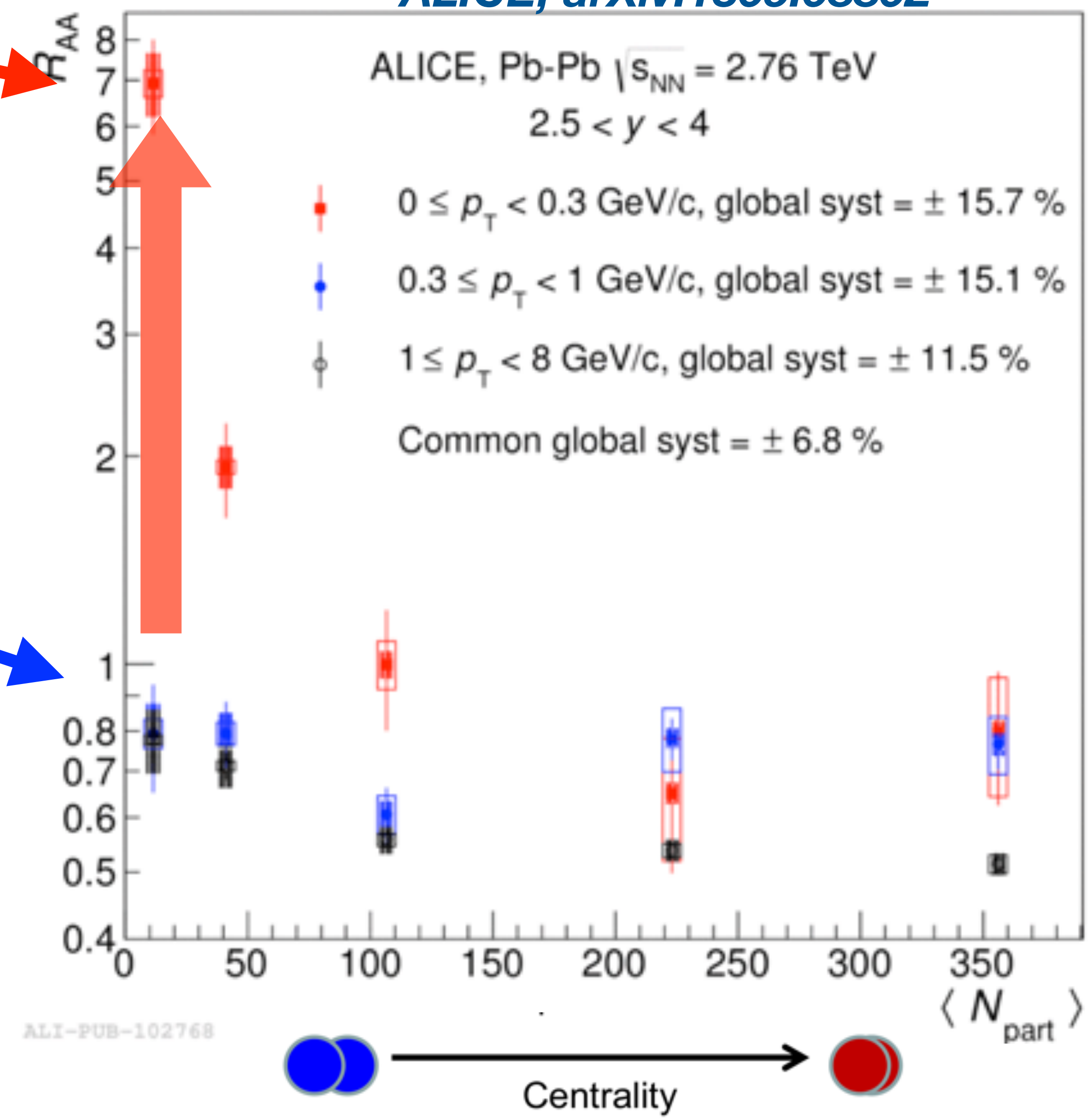


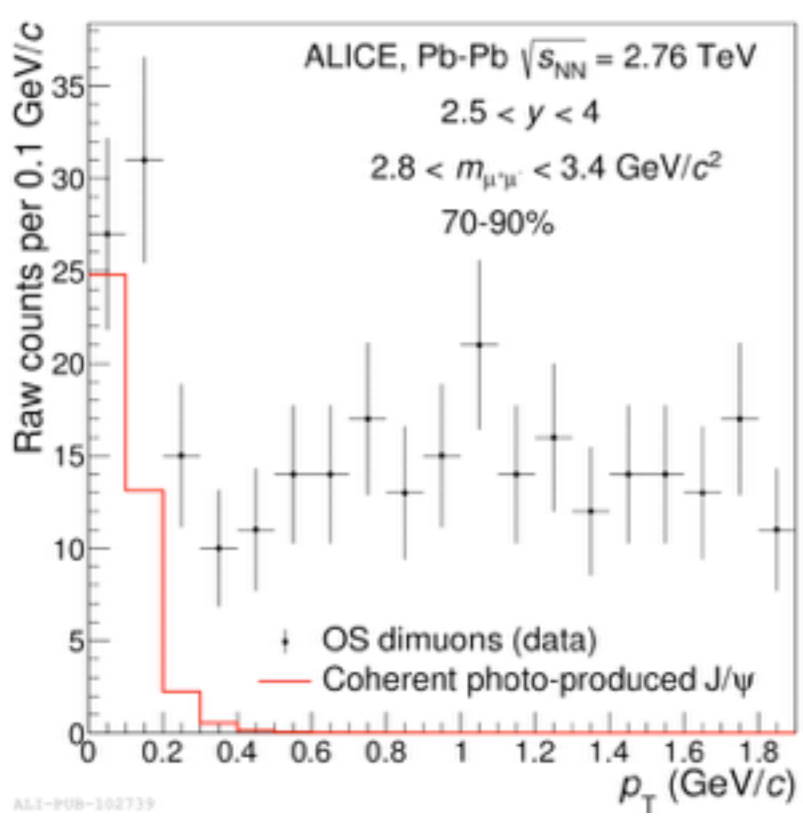
- Internal structure of jets is modified

Very low p_T J/ψ

- **Strong R_{AA} enhancement in peripheral collisions**
  - Significance of the excess is 5.4 (3.4)σ in 70-90% (50-70%)
  - Behaviour not predicted by transport model
- The excess is "removed" requiring $p_T^{J/\psi}$ > 0.3 GeV/c

ALICE, arXiv:1509.08802





- Excess might be due to coherent J/ψ photoproduction in PbPb (as measured also in UPC)