

Recent Results from Heavy-Ion Collisions

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*rich field, too many results
this talk: my personal selection*

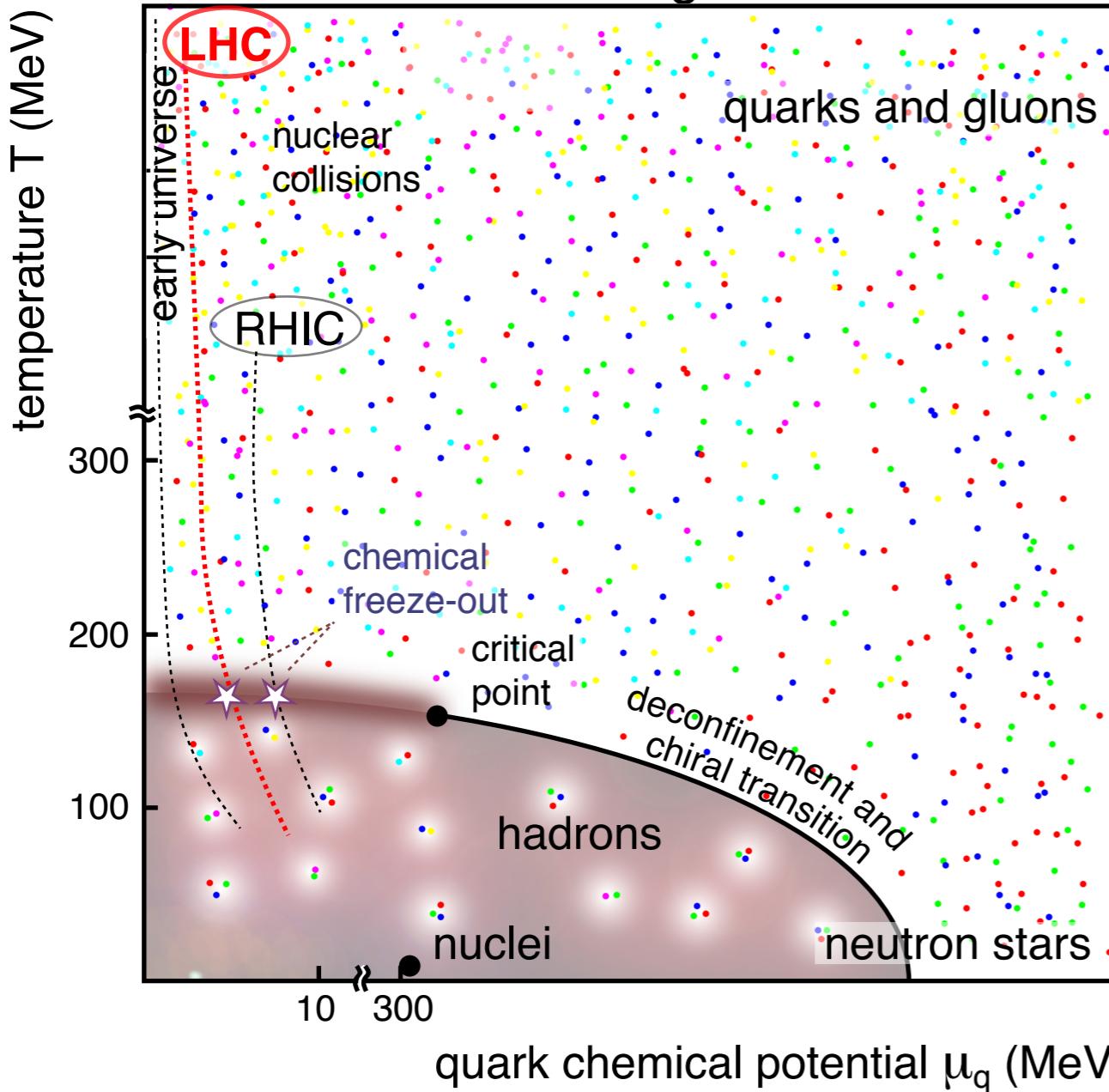
QCD@LHC 2016, Zürich

Outline

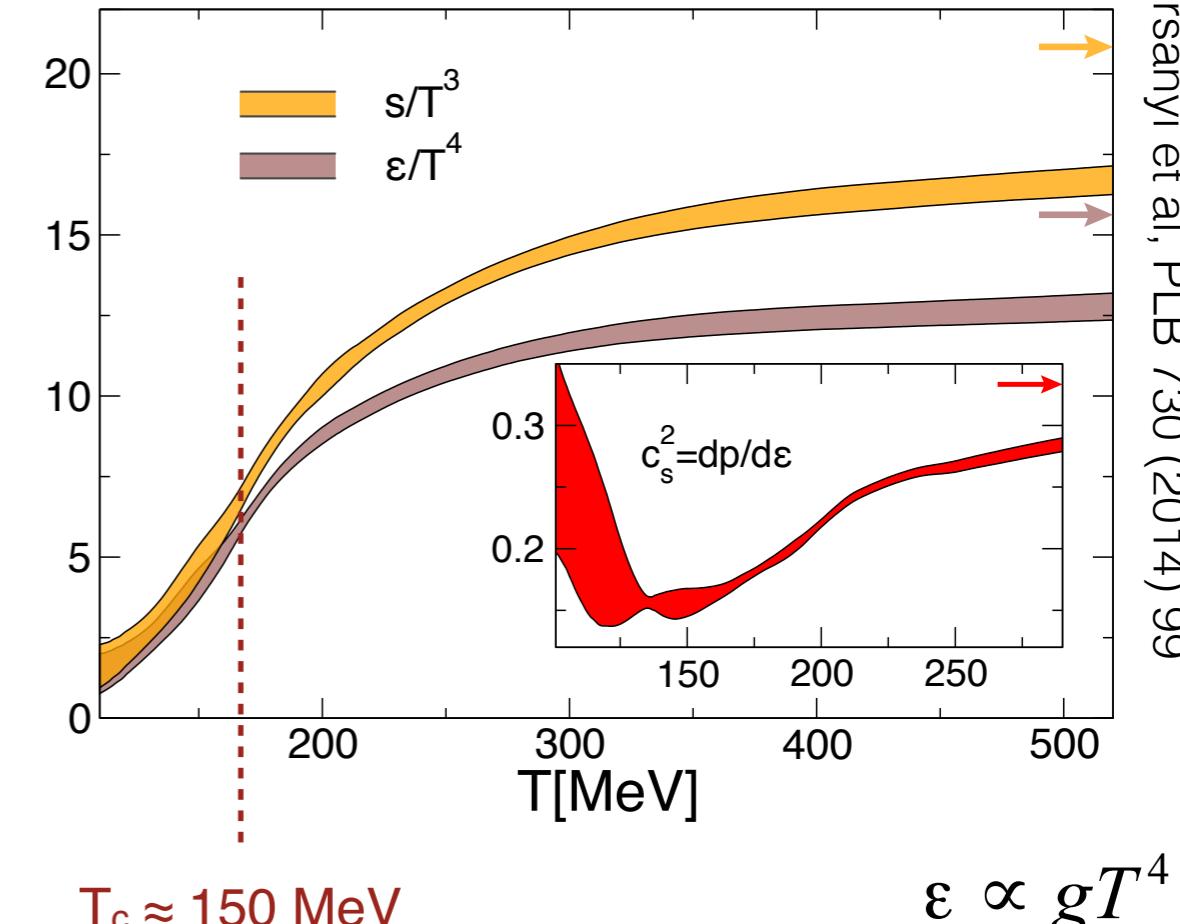
- Introduction
- Soft Probes: Hydrodynamic Flow
- Hard and EM Probes
 - Jet Quenching
 - Heavy Flavour (Open and Hidden)
 - Thermal Photons
- Collective Effects in Small Systems (?)
- Summary

Introduction: Heavy Ion Physics

Phase diagram



Equation of state
Energy density vs temperature



- Study the properties of many-body QCD systems
 - Properties of **equilibrium matter**: equation of state, transport coefficients, initial temperature
 - **Dynamics**: hadronisation, interactions of partons with the medium, Debye screening

Colliders for High-Energy Nuclear Collisions

RHIC, Brookhaven
 $\text{Au+Au } \sqrt{s_{\text{NN}}} = 200 \text{ GeV}$



First run: 2000
Dedicated heavy-ion machine

STAR, PHENIX,
(PHOBOS, BRAHMS)

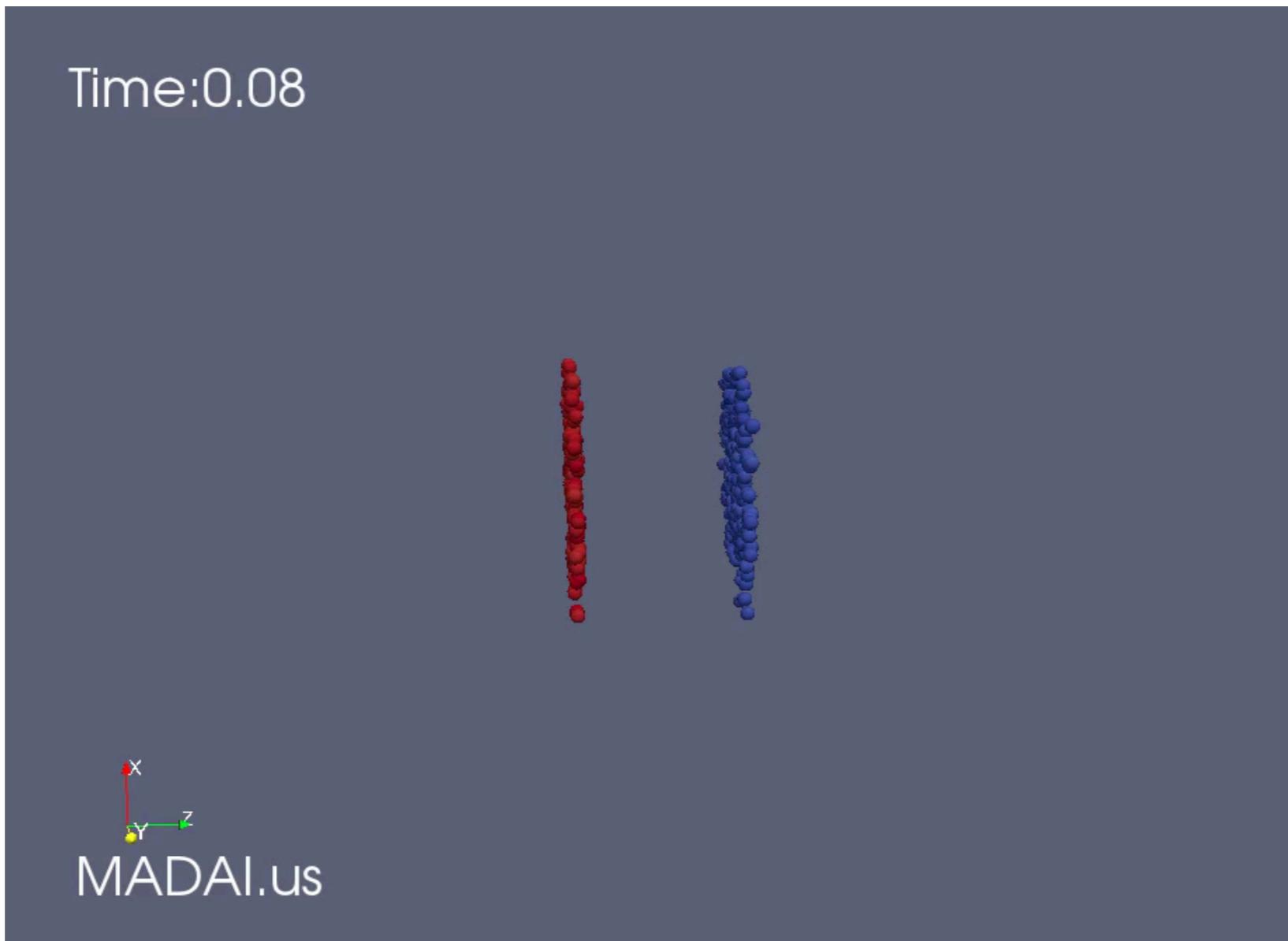
LHC, Geneva
Run 2: Pb+Pb $\sqrt{s_{\text{NN}}} = 5020 \text{ GeV}$



First run: 2009/2010
 $\approx 1 \text{ month/year heavy-ion running}$

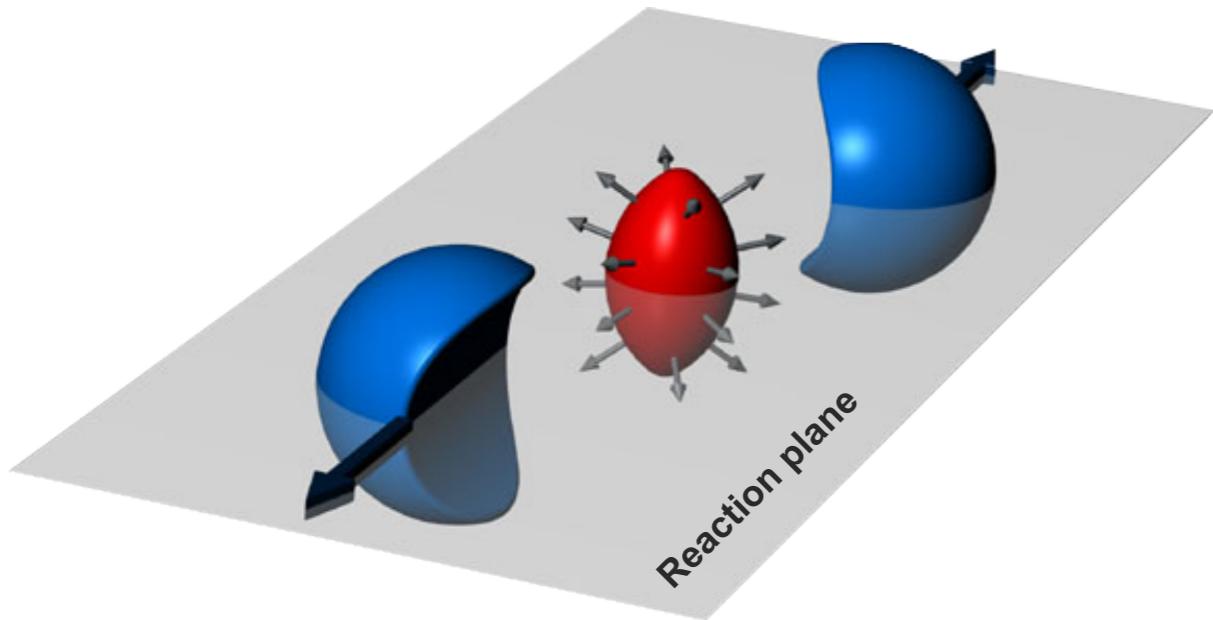
ALICE, ATLAS,
CMS, LHCb

Soft Probes: Hydrodynamic Flow

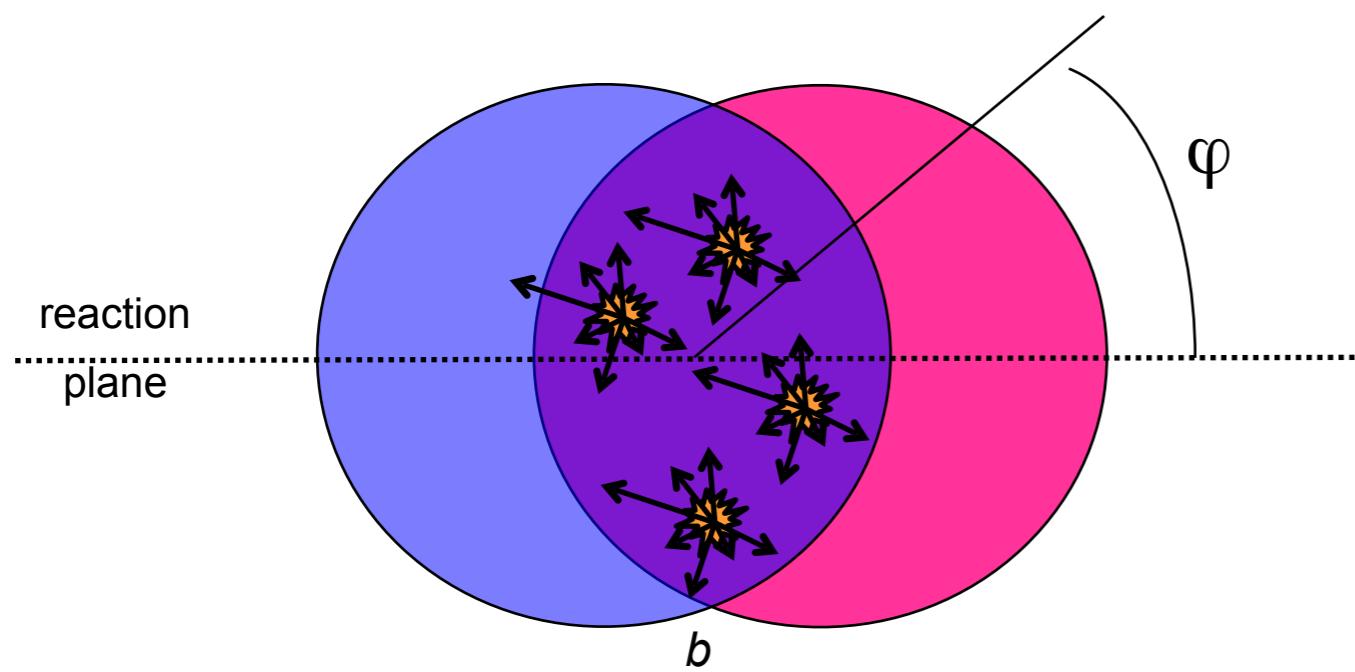


system evolution after some initial thermalisation time
can be described as a fluid
⇒ hydrodynamic flow

Elliptic Flow

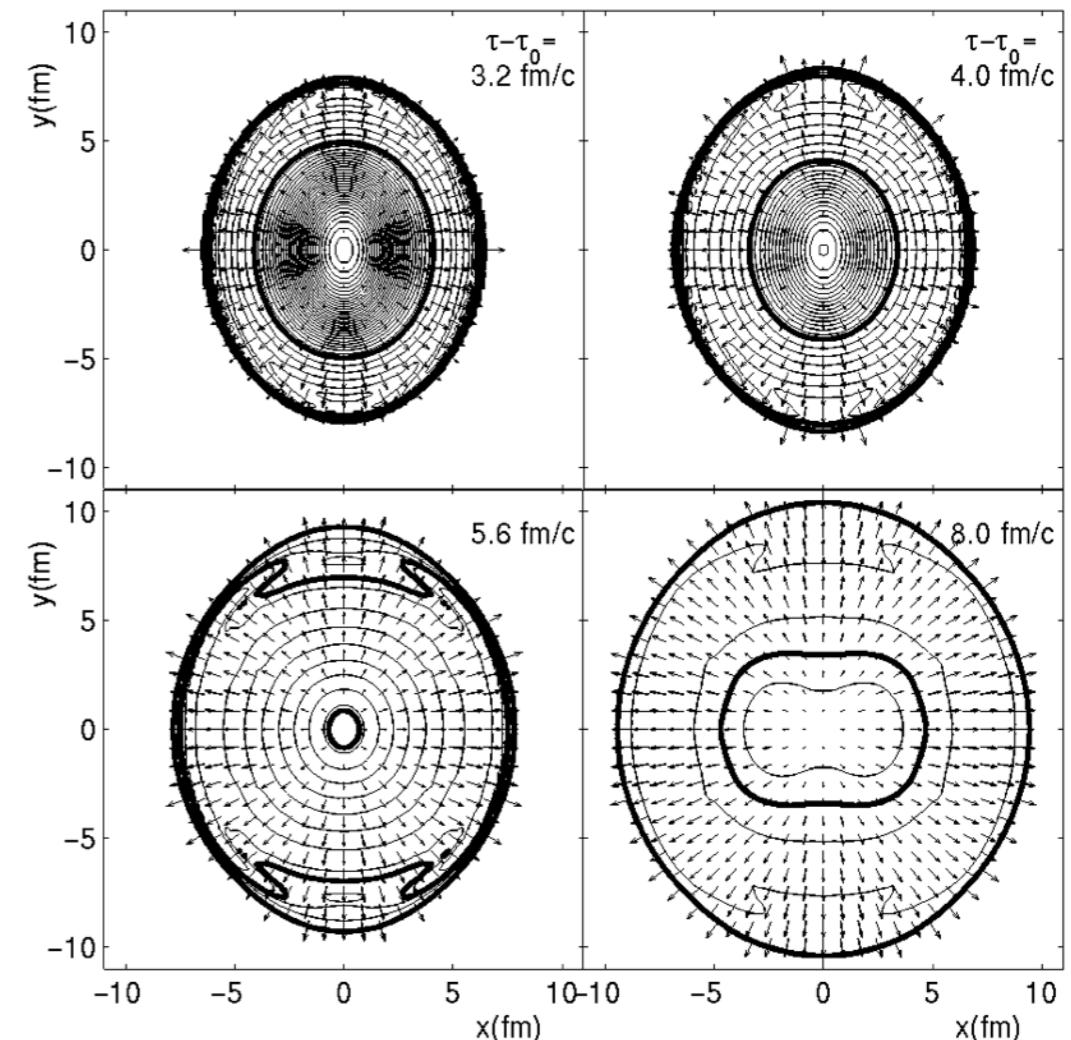


Anisotropy results in yield modulation
in azimuth relative to reaction plane



$$\frac{dN}{d\varphi} = N (1 + 2v_2 \cos 2\varphi)$$

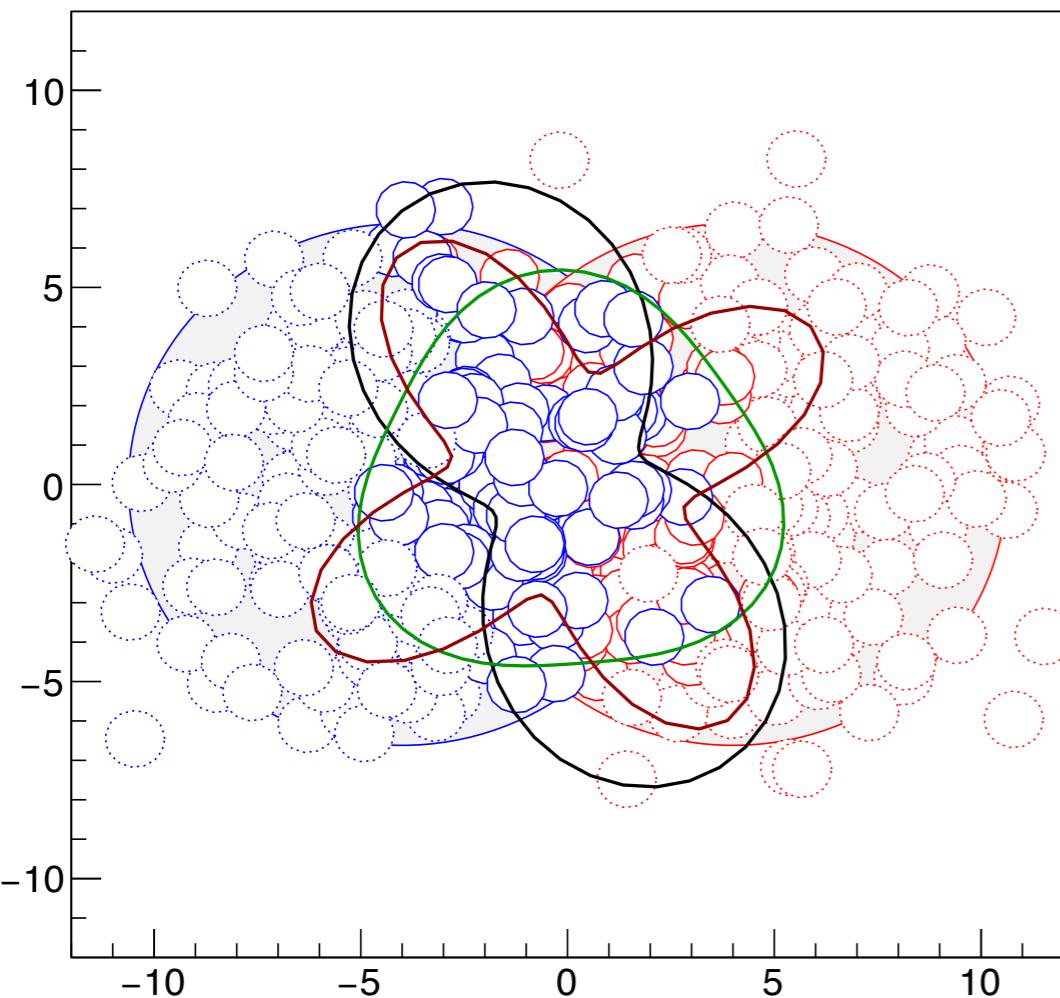
Hydrodynamical calculation



Anisotropy reduces during evolution
 v_2 more sensitive to early times

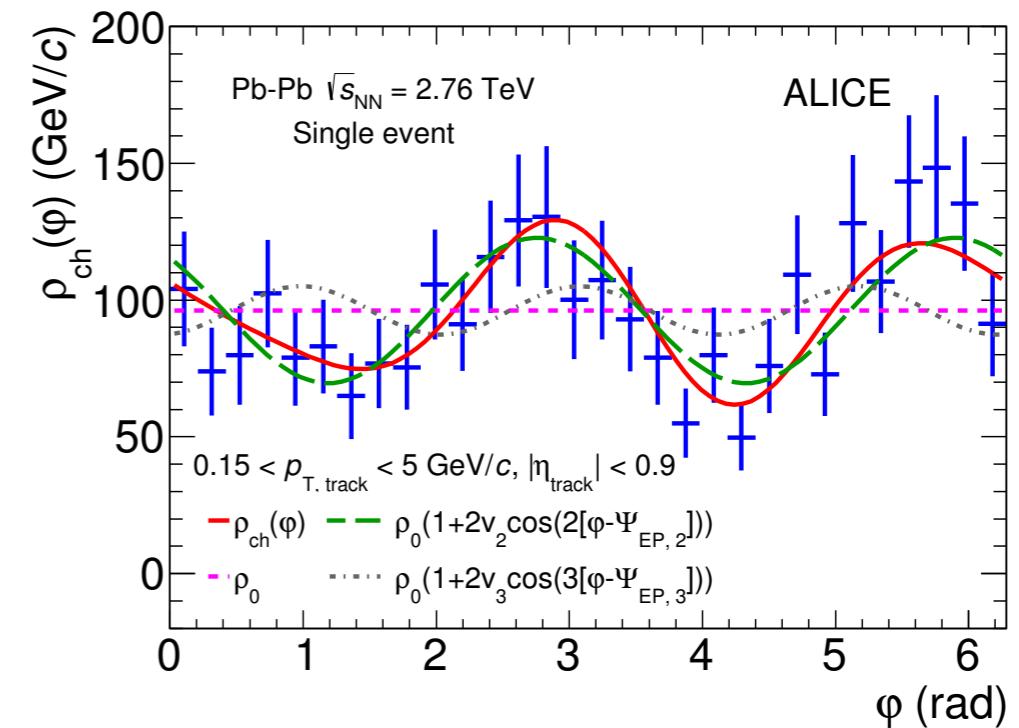
Azimuthal Anisotropy: Initial and Final State

MC event: location of nucleons

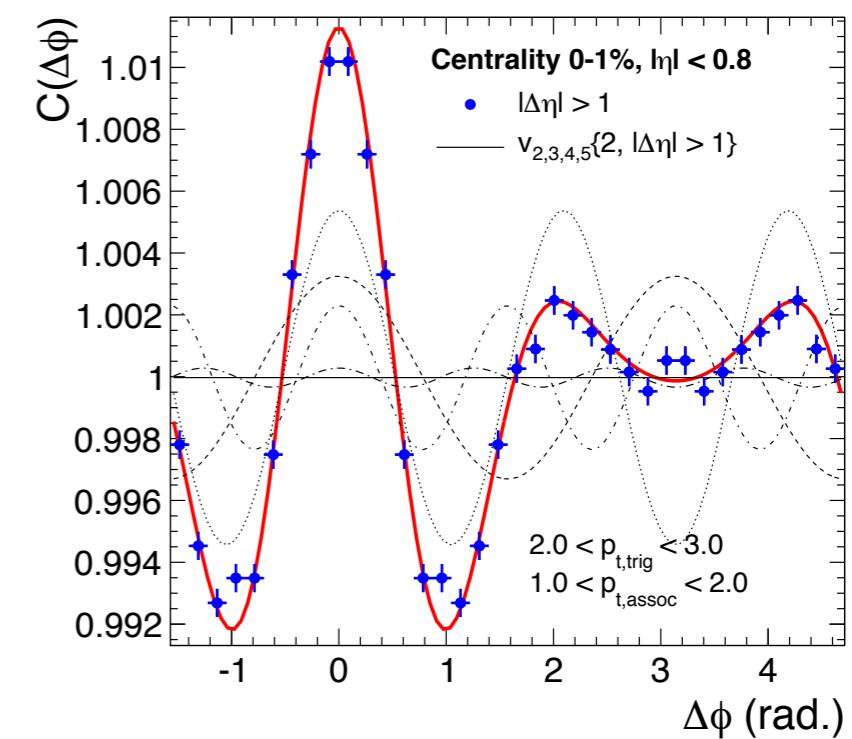


Initial state spatial anisotropies ε_n are transferred into final state momentum anisotropies v_n via collective flow of the Quark Gluon Plasma generated by pressure gradients

Azimuthal distribution single event



Average over many events

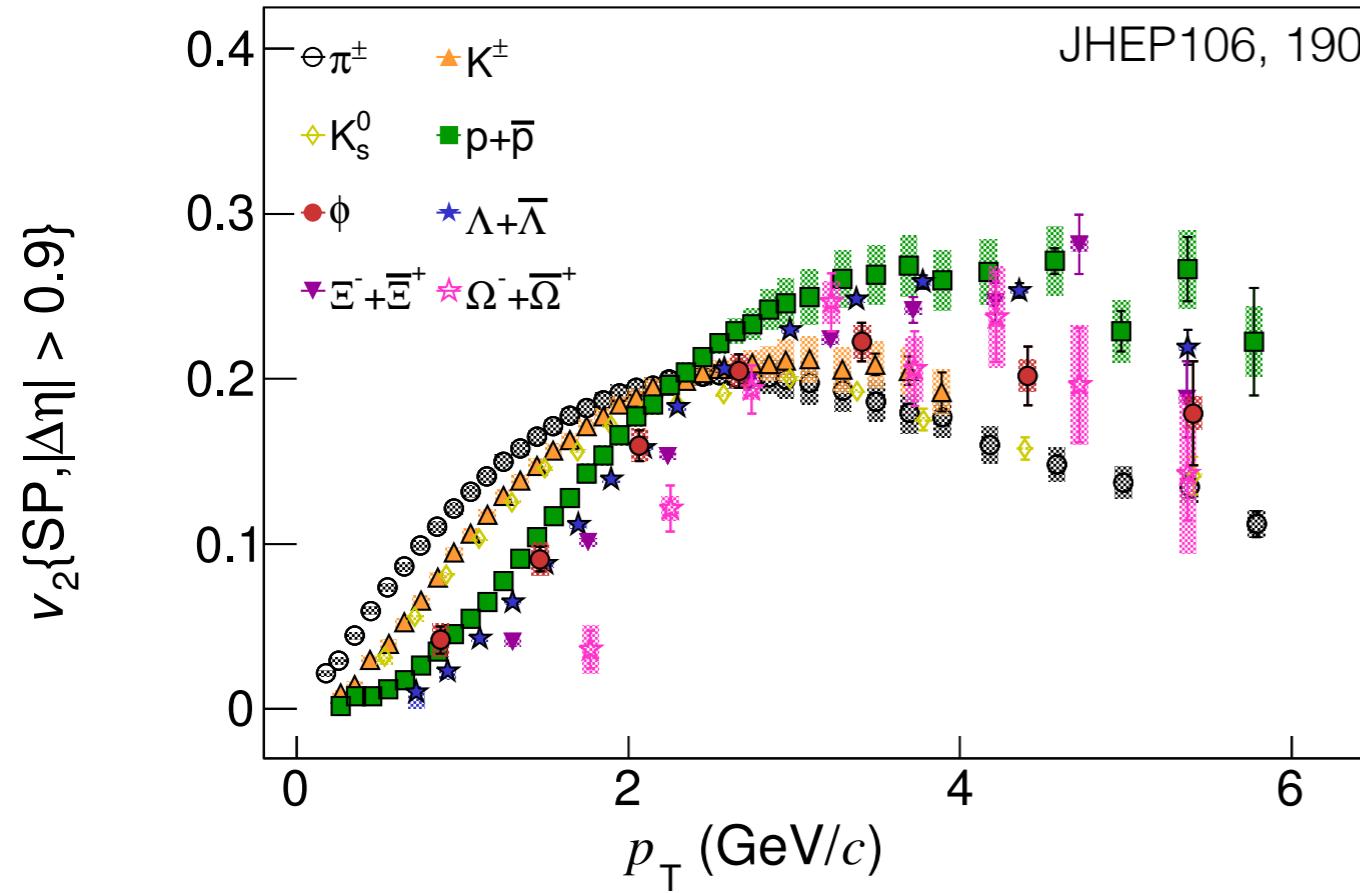


ALICE, PLB 753 (2016) 511

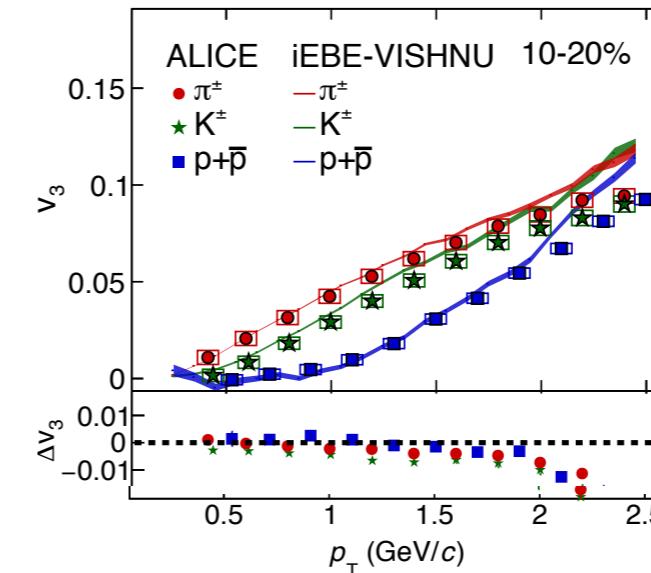
ALICE, PRL. 107 (2011) 032301

Anisotropic Flow Results

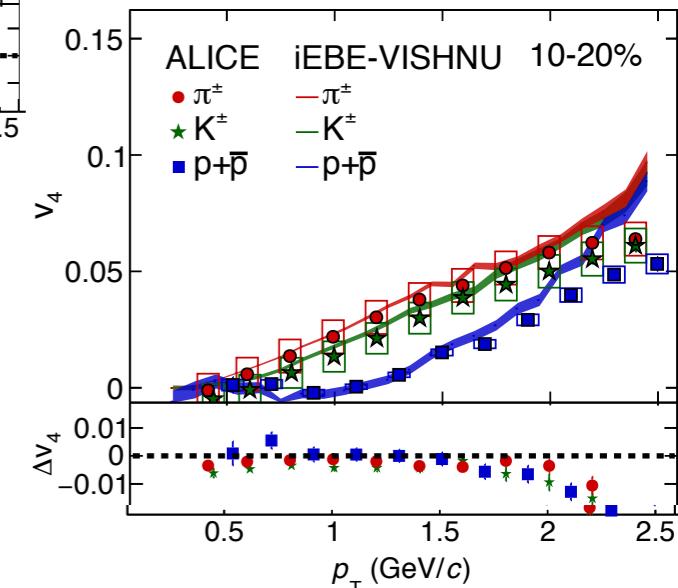
ALICE 20-30% Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV



v_3



v_4



I-PUB-82677

Mass-dependence of v_n introduced by radial flow velocity

Via strength and mass dependence test

- paradigm of hydrodynamical description
- medium properties (equation of state)
- freeze-out properties

Global Fit to Flow Results

$$\begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{pmatrix} = \text{Response} \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{pmatrix}$$

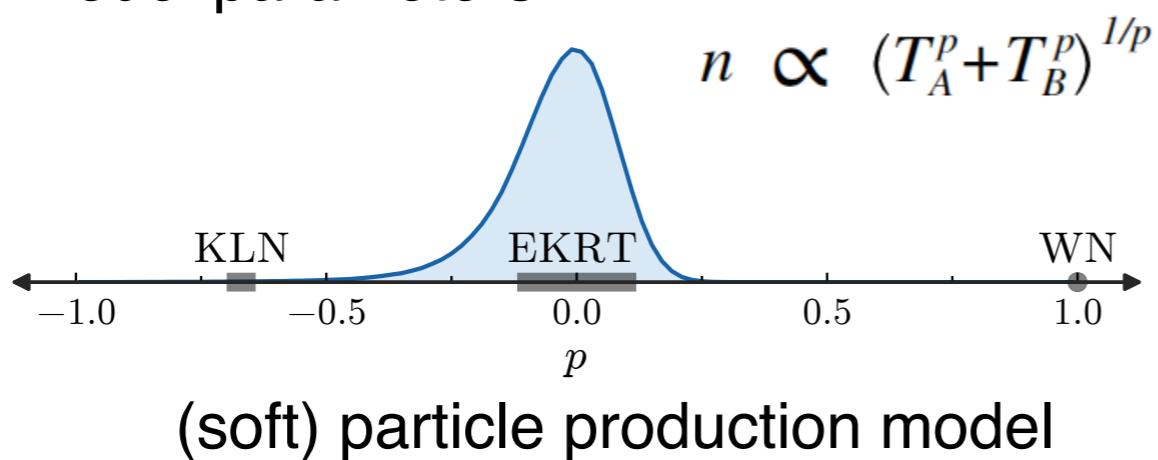
ϵ_n : initial spatial anisotropies from initial state model

v_n : observed final state momentum anisotropy

Response: modeled by hydrodynamic evolution + hadronic cascade

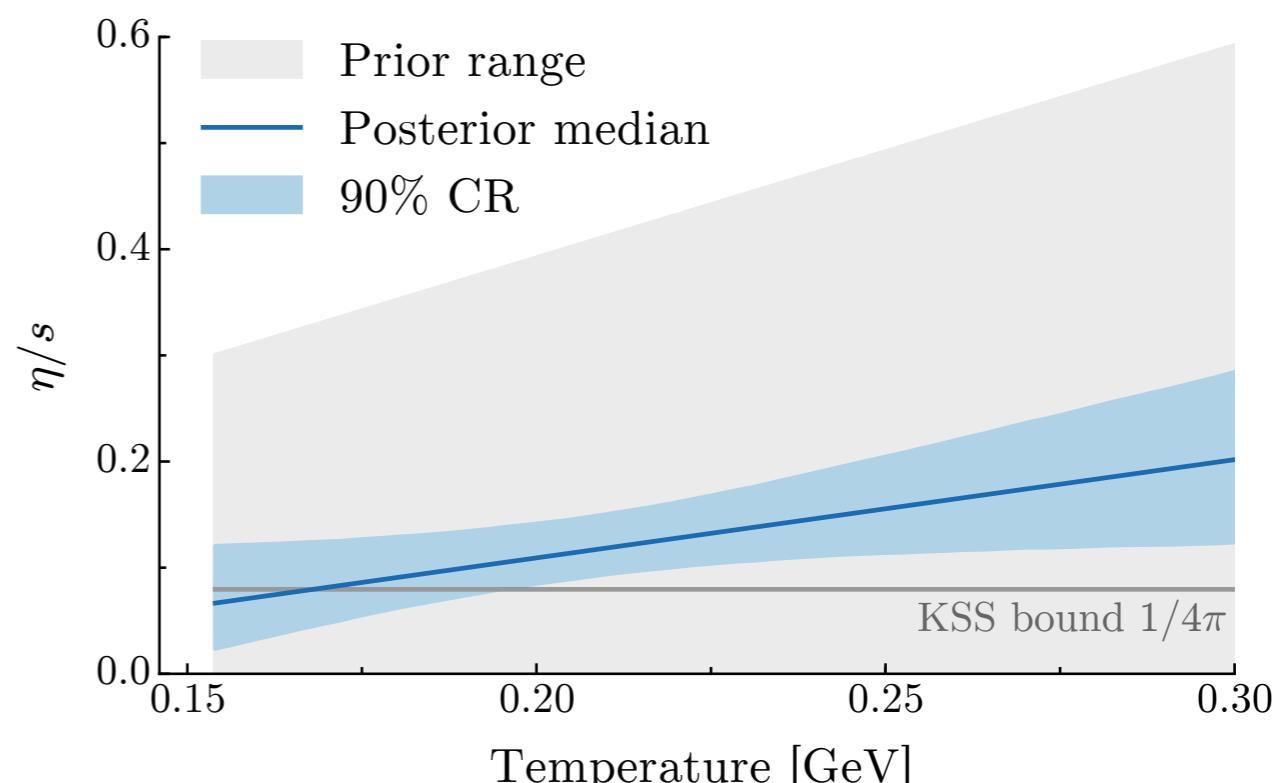
Total 9 parameters:

- 3 initial state $\Rightarrow \epsilon_n$
- 3 QGP \Rightarrow medium response
- 3 model parameters



J. E. Bernhard et al, arXiv: 1605.03954

viscosity of the QGP



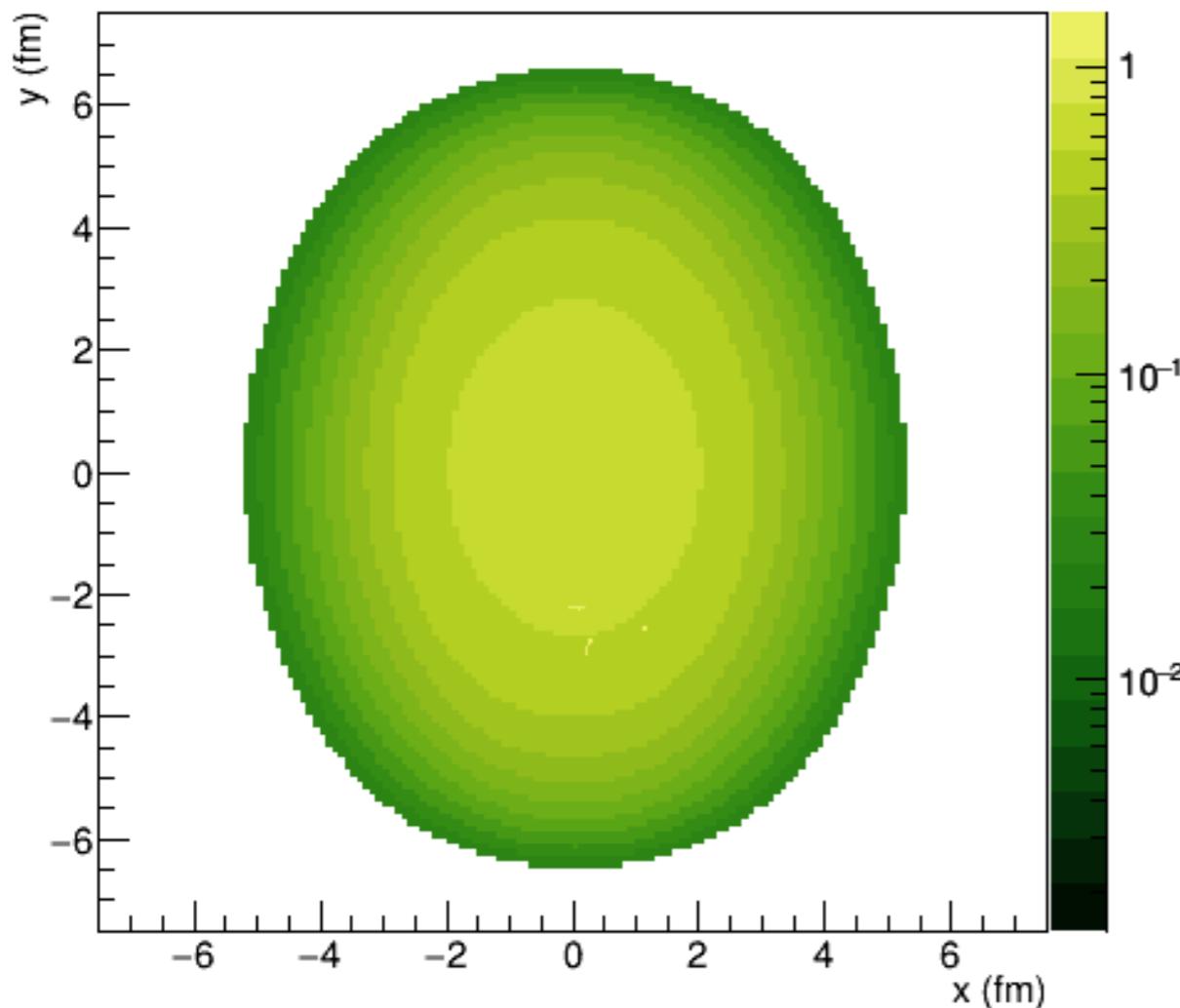
Fit constrains initial state geometry and transport properties at the same time

Here: viscosity – close to lower bound

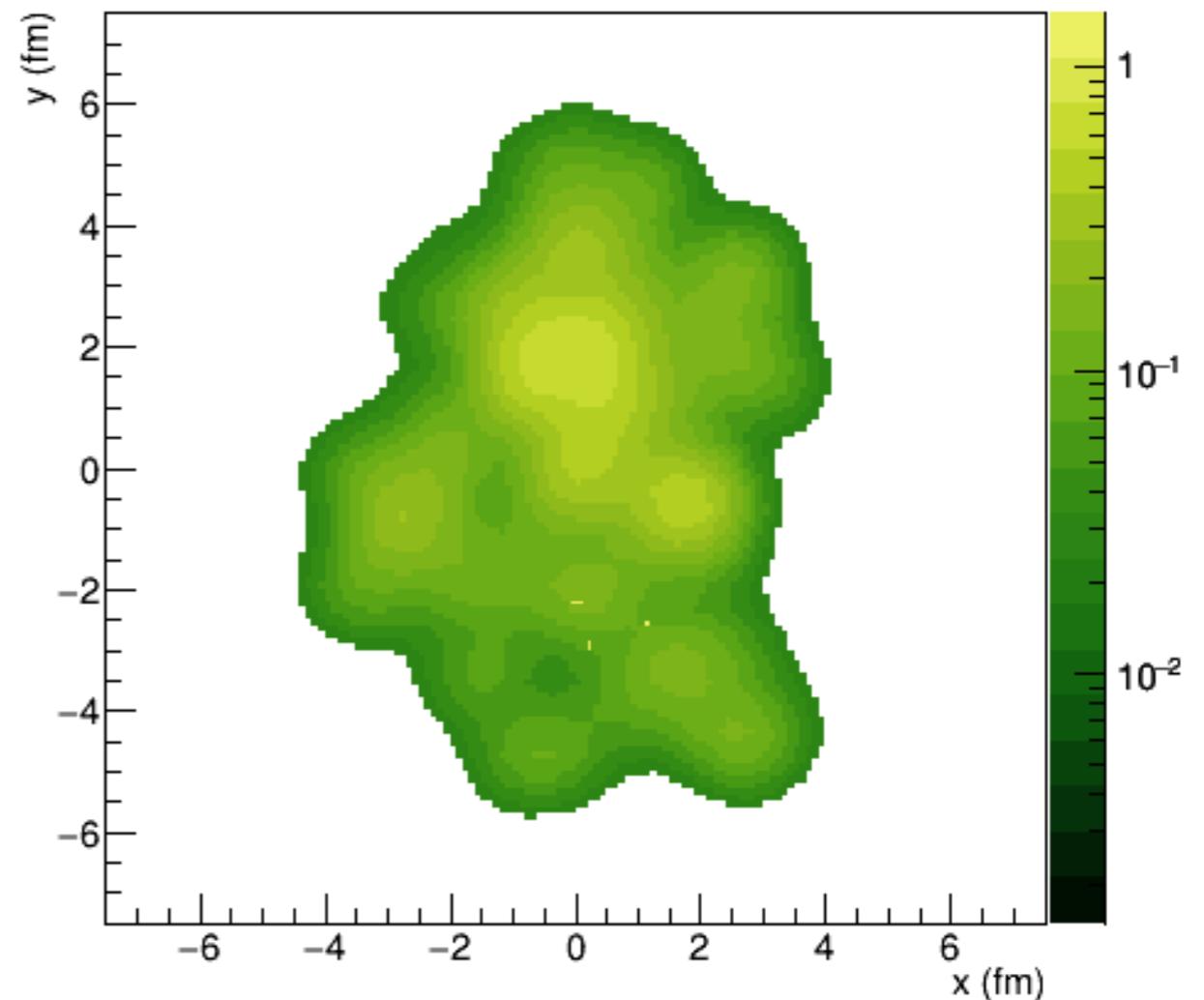
Hard Probes: Probing the Medium

R Bertens, JEWEL simulation

$N_{\text{eff, jewel}}, \tau = 0.60 (\text{fm}/c)$



$N_{\text{eff, hydro}}, \tau = 0.60 (\text{fm}/c)$



Hard probes: high p_T or mass (Q^2)

Example: high energy partons

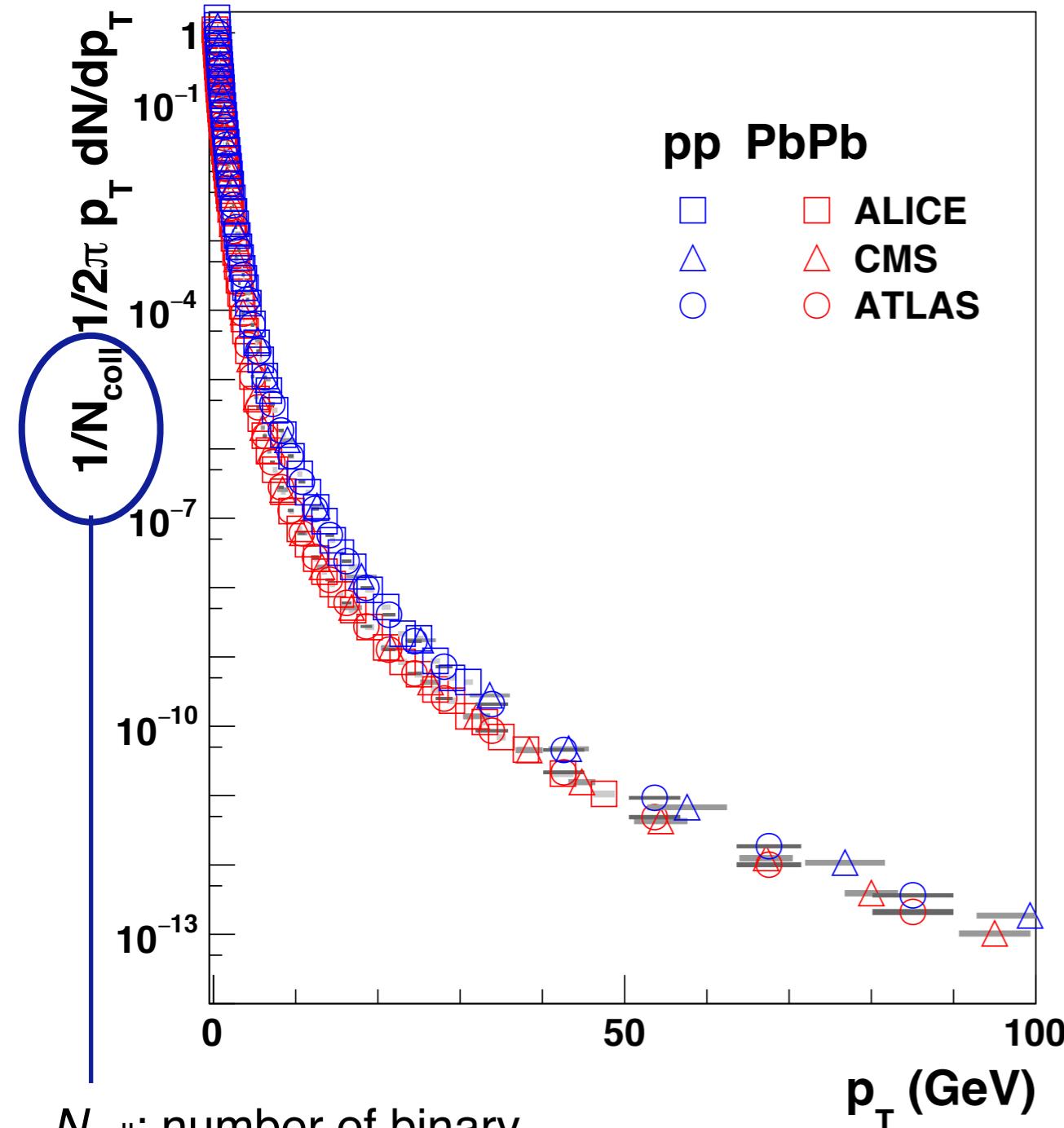
Hard-scatterings produce quasi-free partons
⇒ Probe medium through energy loss (aka jet-quenching)

Expected to be dominant for approximately $p_T > 5 \text{ GeV}$

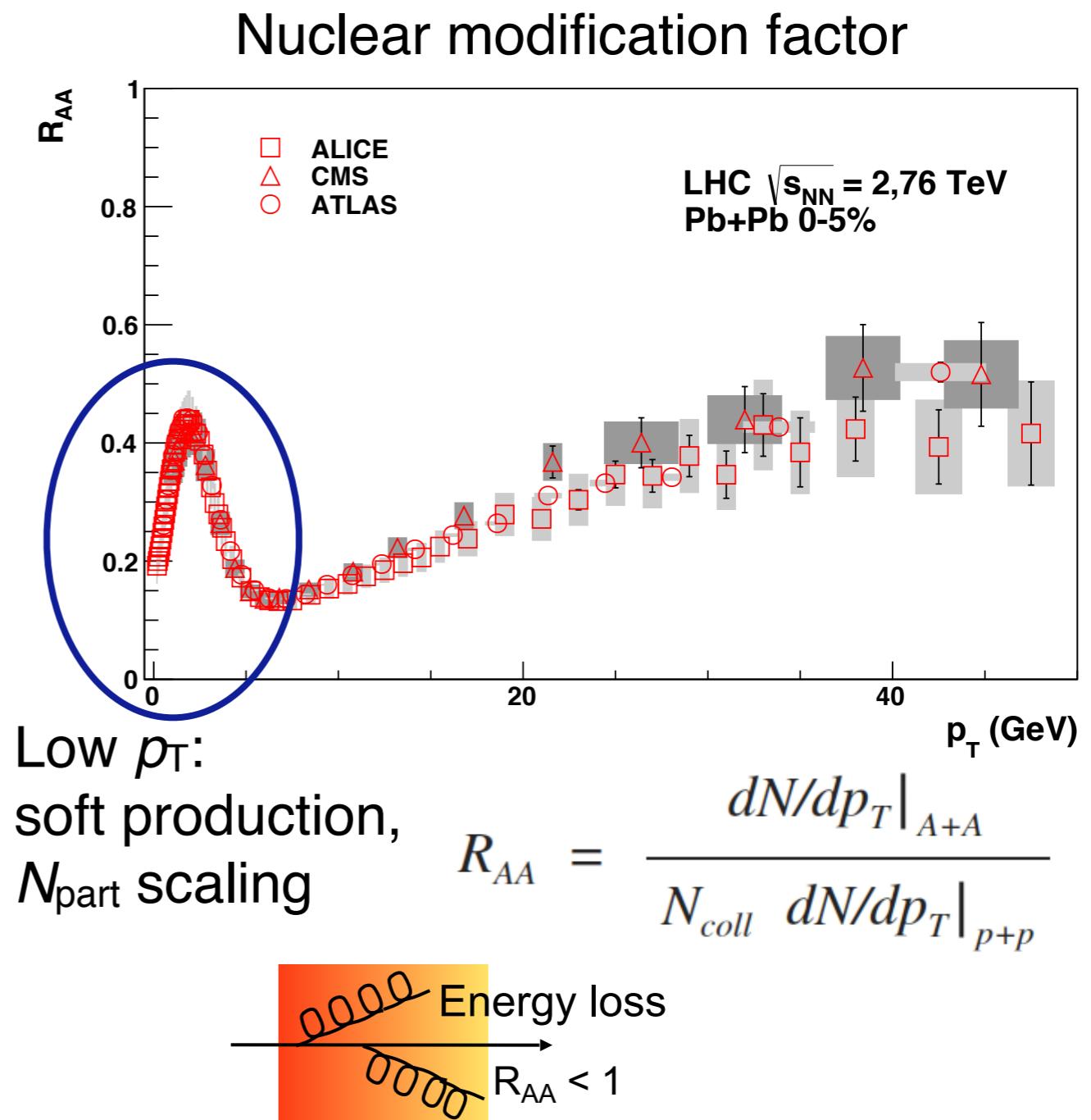
Nuclear modification: Pb+Pb

ALICE, PLB720 (2013) 52
 CMS, EPJC 72 (2012) 1945
 ATLAS, JHEP09 (2015) 050

Charged particle p_T spectra



N_{coll} : number of binary nucleon-nucleon collisions



Pb+Pb: clear suppression ($R_{AA} < 1$): parton energy loss

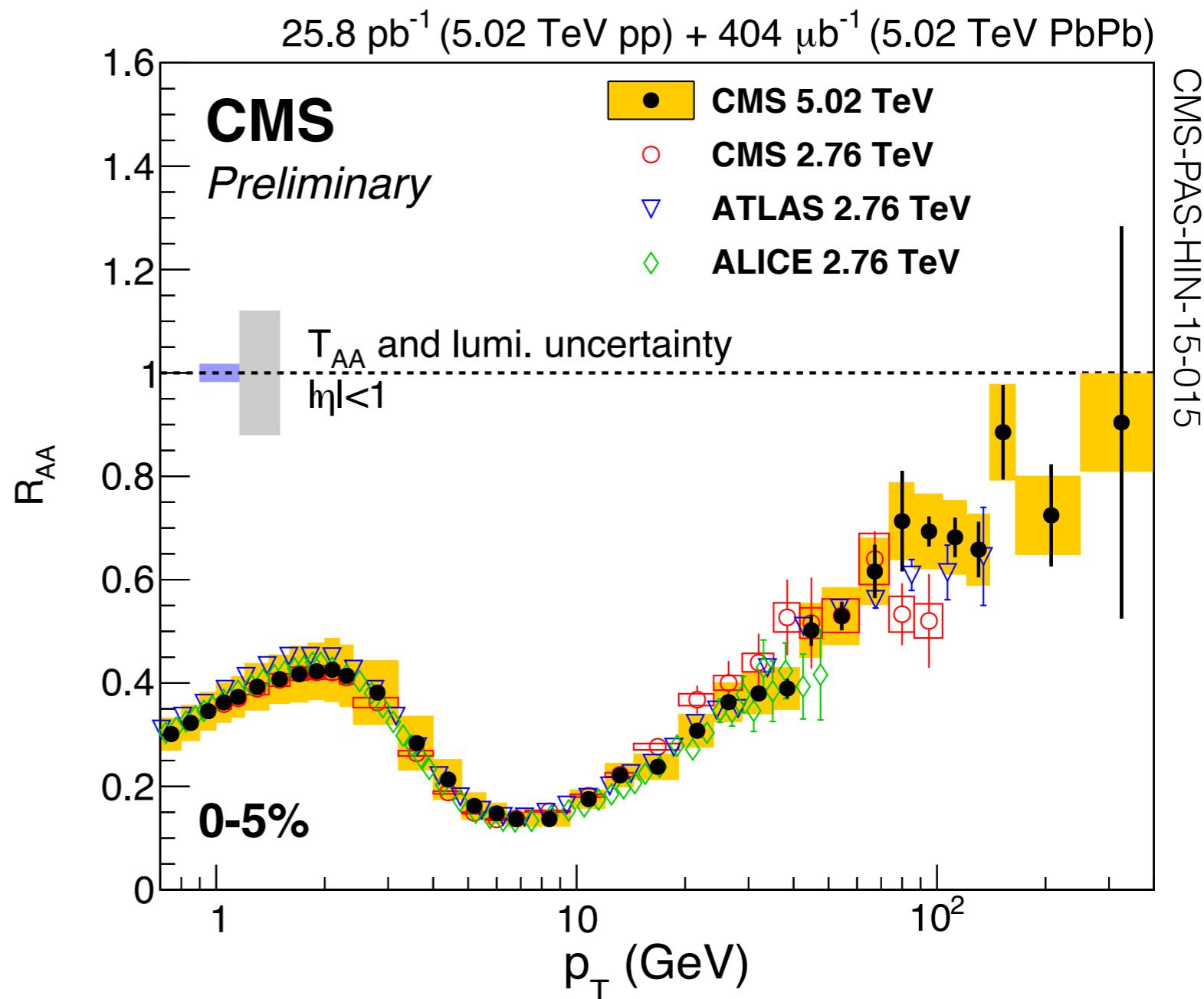
Nuclear modification factor R_{AA} – Run 2

New run 2 result:
 R_{AA} for 5 TeV Pb+Pb collisions

Values similar to 2.76 TeV
expected: medium density similar
(multiplicity increase 20%)

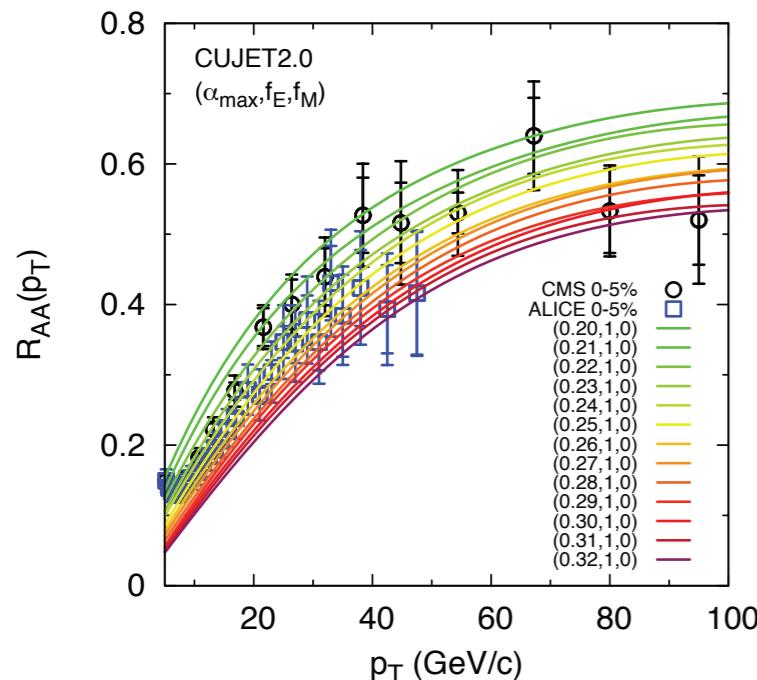
Increase vs p_T indicates
 $\Delta E/E$ decreases with E

Expect $\Delta E \propto \hat{q} \ln E$ in high energy limit $E \gg \Delta E$

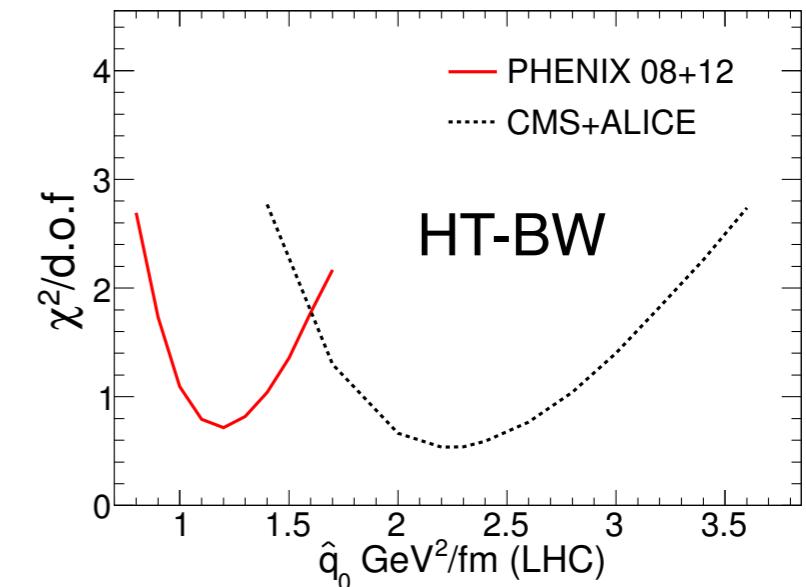
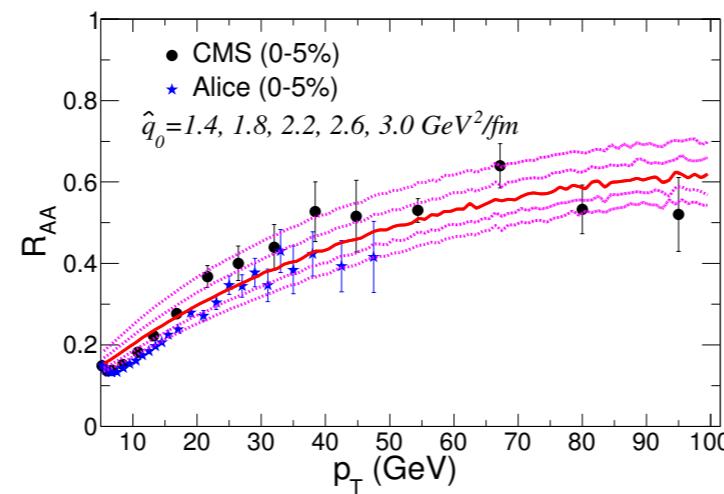


R_{AA} vs models

Burke et al, JET Collaboration, PRC 90 (2014) 014909



'Analytical models'



Several formalisms/approximations for parton energy loss exist
Allows to determine medium properties, transport coefficient

$$\begin{aligned} & \text{RHIC:} \\ & \hat{q} = 1.2 \pm 0.3 \text{ GeV}^2/\text{fm} \\ & (\text{T}=370 \text{ MeV}) \end{aligned}$$

$$\begin{aligned} & \text{LHC:} \\ & \hat{q} = 1.9 \pm 0.7 \text{ GeV}^2/\text{fm} \\ & (\text{T}=470 \text{ MeV}) \end{aligned}$$

HTL expectation: $\hat{q} \approx 24 \alpha_s^2 T^3 \approx 2 T^3$

Sizeable uncertainties from α_s , treatment of logs etc expected

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

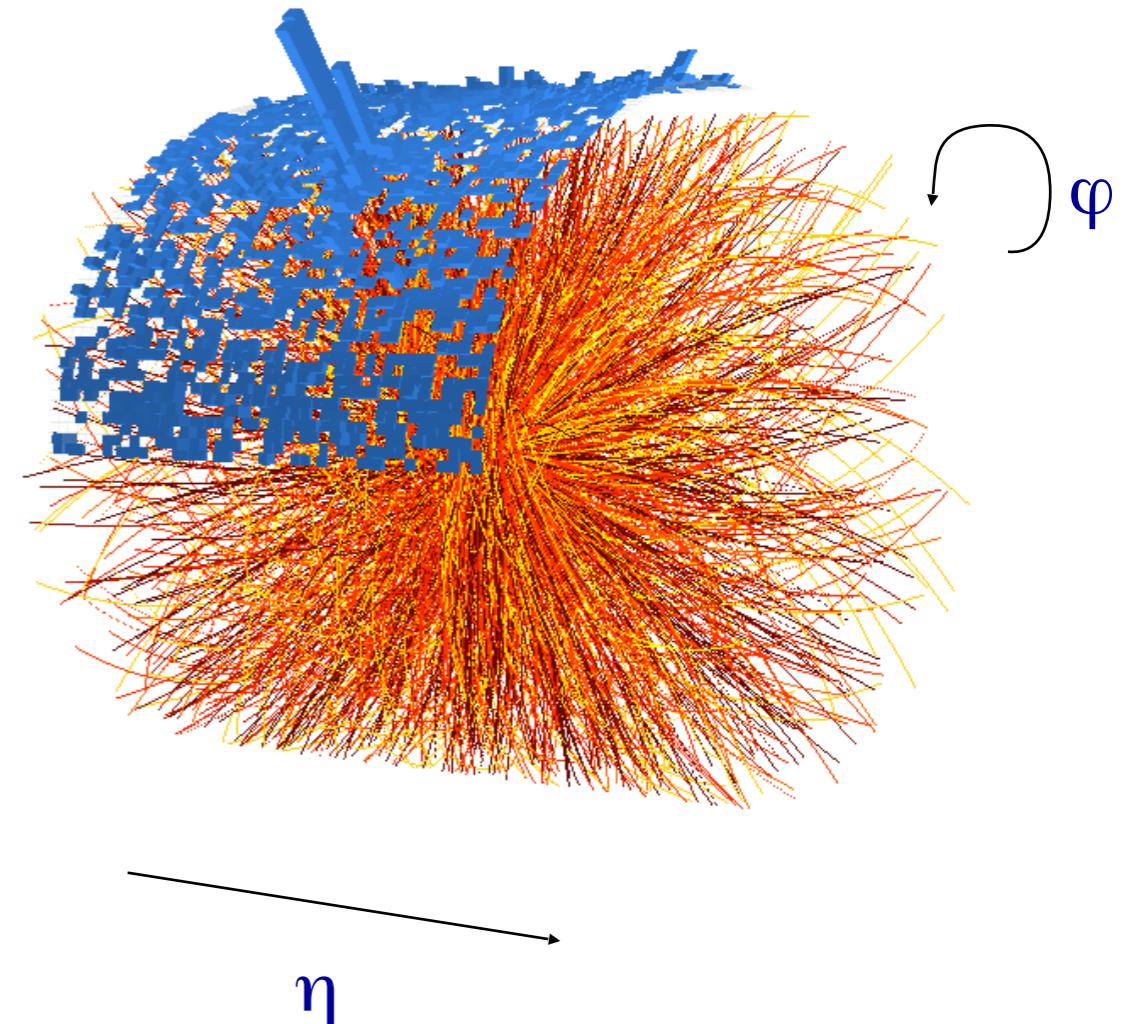
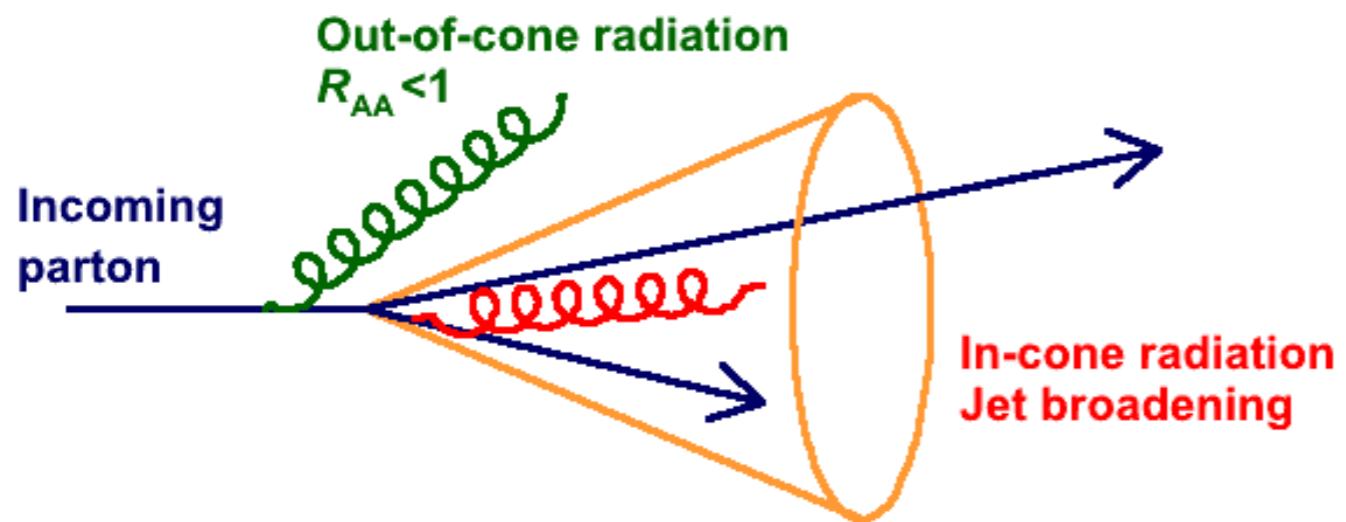
Arnold and Xiao, PRD 78 (2008) 125008

Values found are in the right ballpark compared to (p)QCD estimate
Magnitude of parton energy loss is understood

Jets: reconstructing the partons

Goal: measure energy loss distributions

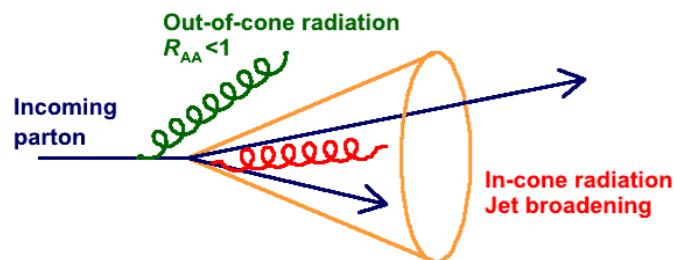
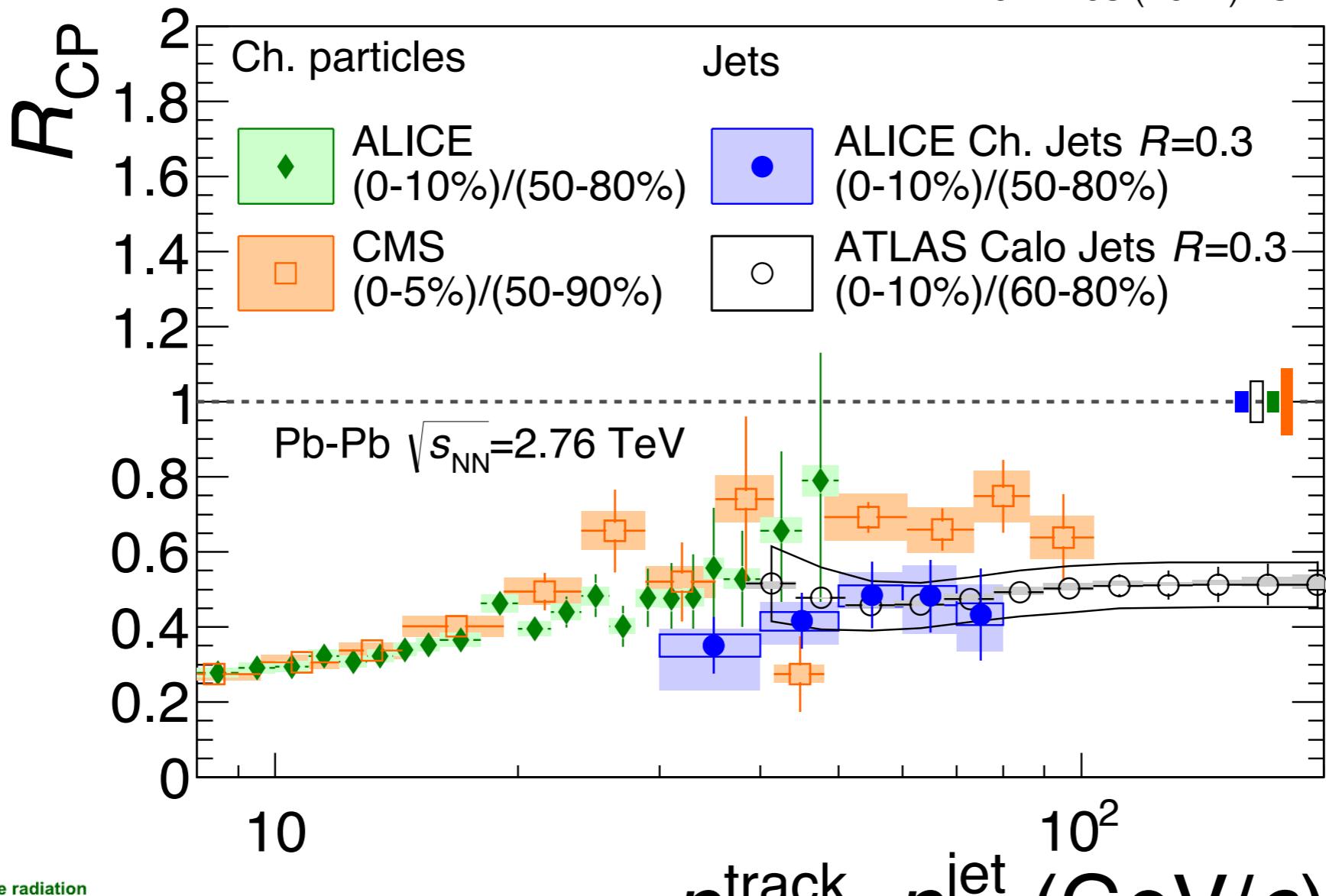
- Longitudinal (fragmentation function)
- Transverse (jet profiles)



Simple expectation: R_{AA} should increase with jet cone radius (integrate more of the energy)

Comparing hadrons and jets

JHEP03 (2014) 13

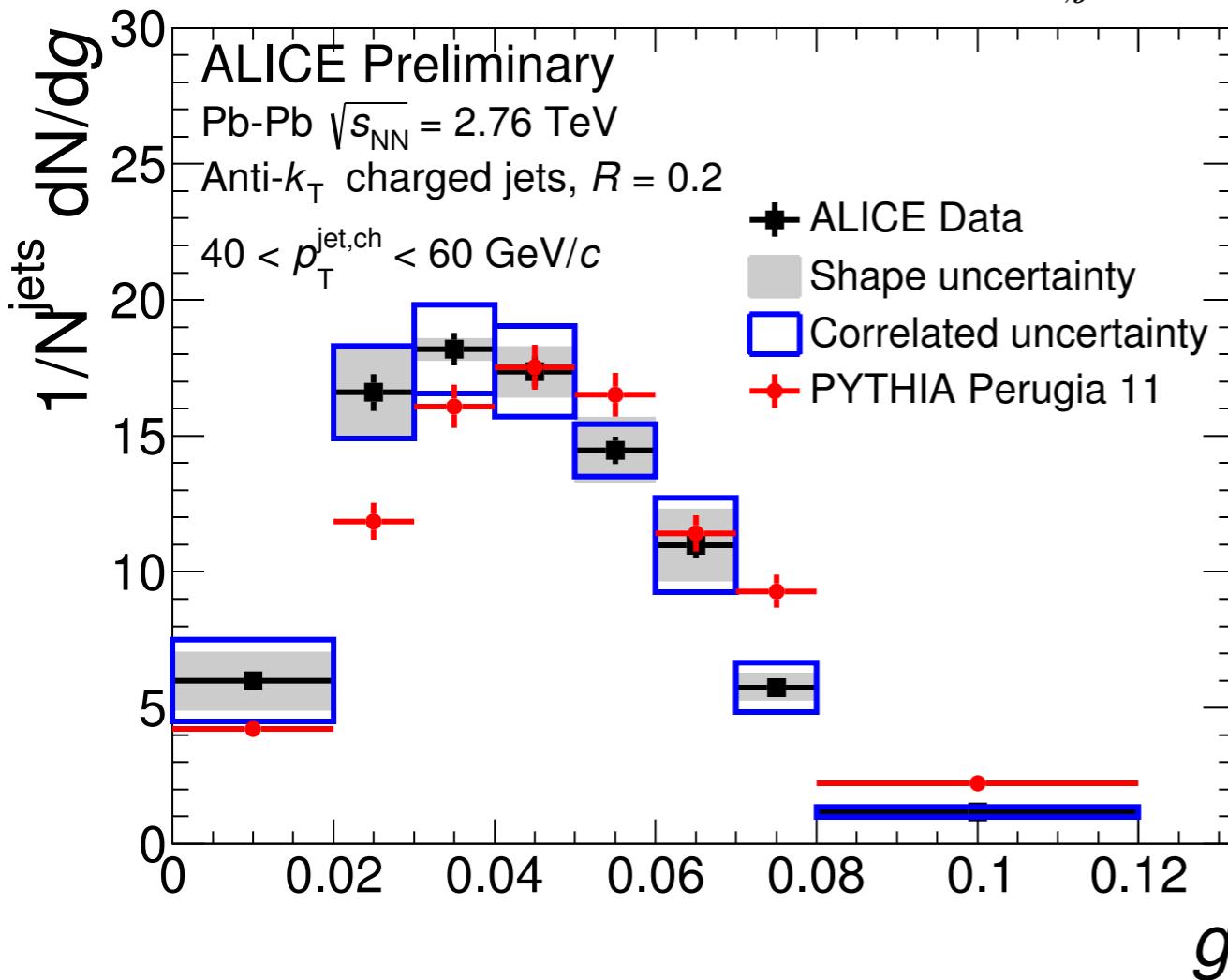


Suppression of hadron (leading fragment) and jet yield similar
Lost energy is transported to large angles ($R > 0.3$)

Jet Shapes: Radial Moment

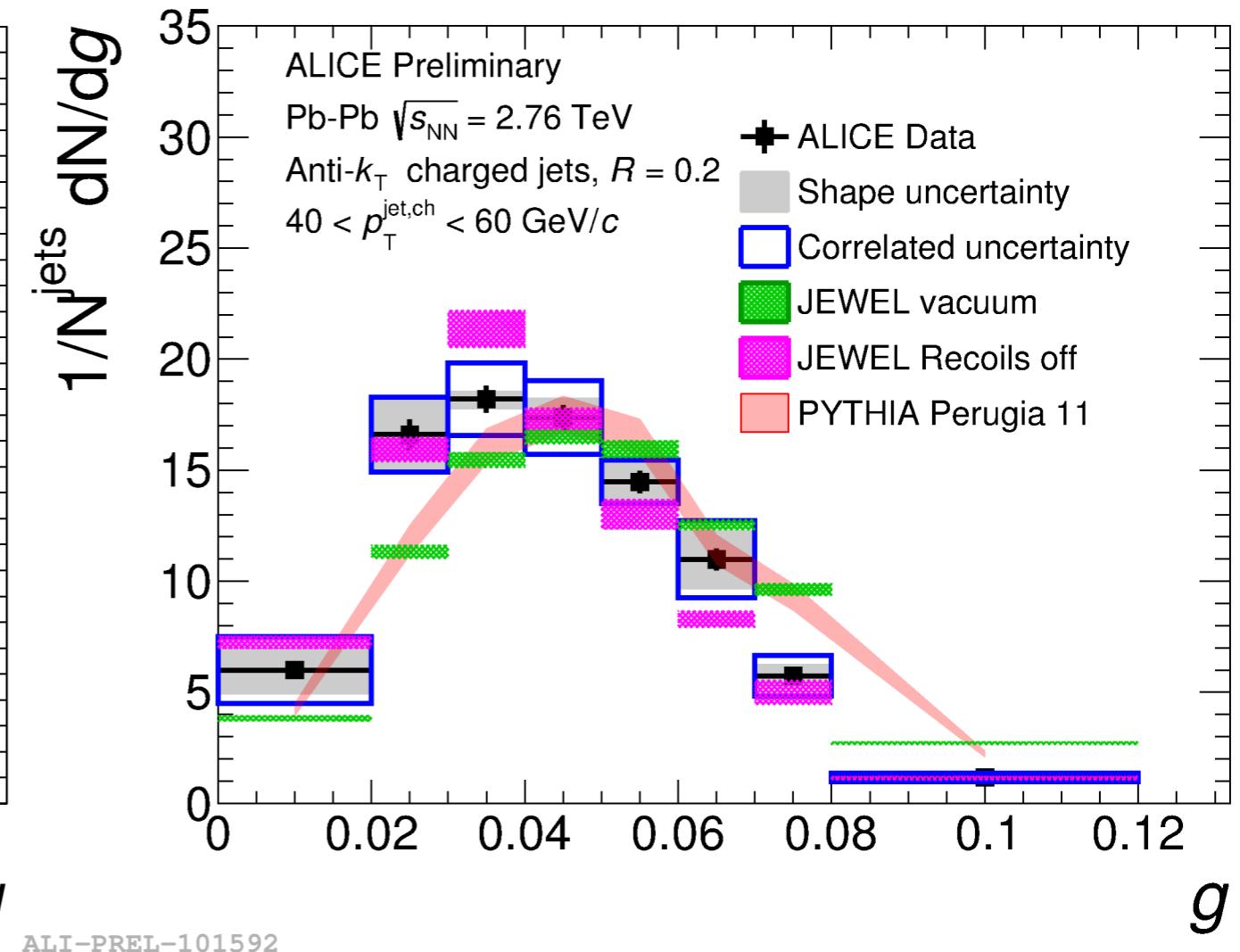
p_T-weighted jet width $g \equiv \frac{\sum_{\text{tracks}} p_{T,i} \cdot r}{p_{T,\text{jet}}}$

D. Caffari, talk at ICHEP



ALI-PREL-101580

Radial moment smaller in Pb+Pb
than pp (PYTHIA)



ALI-PREL-101592

JEWEL model shows
similar trend

Jets in medium narrower than in vacuum

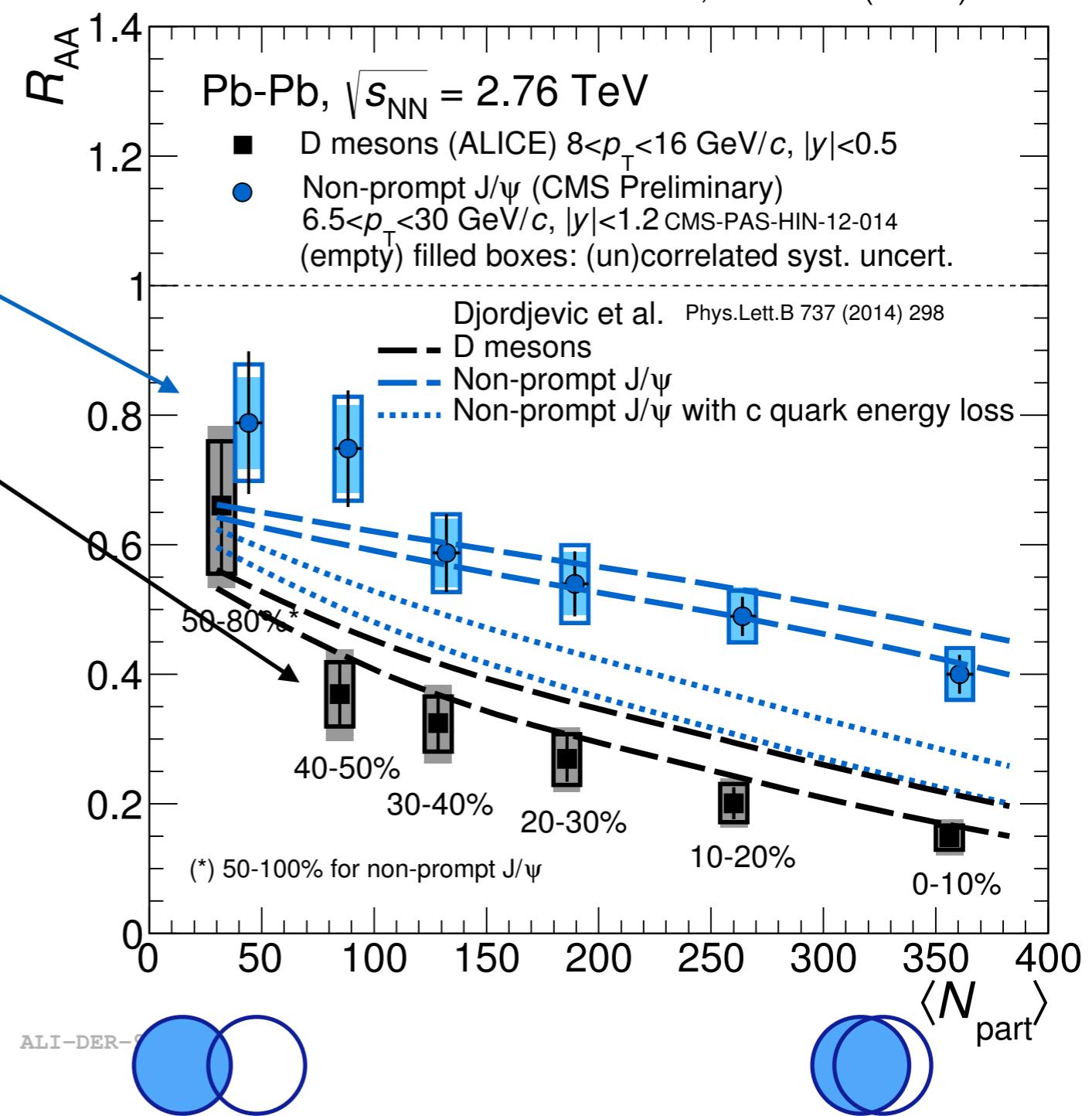
Heavy Flavour R_{AA} – Mass Dependence

ALICE, JHEP11 (2015) 205

Compare
beauty: non-prompt J/ψ
charm: D-mesons

Larger suppression for
charm than for beauty

Agrees with expected
'dead-cone effect'
energy loss reduced when $v < c$

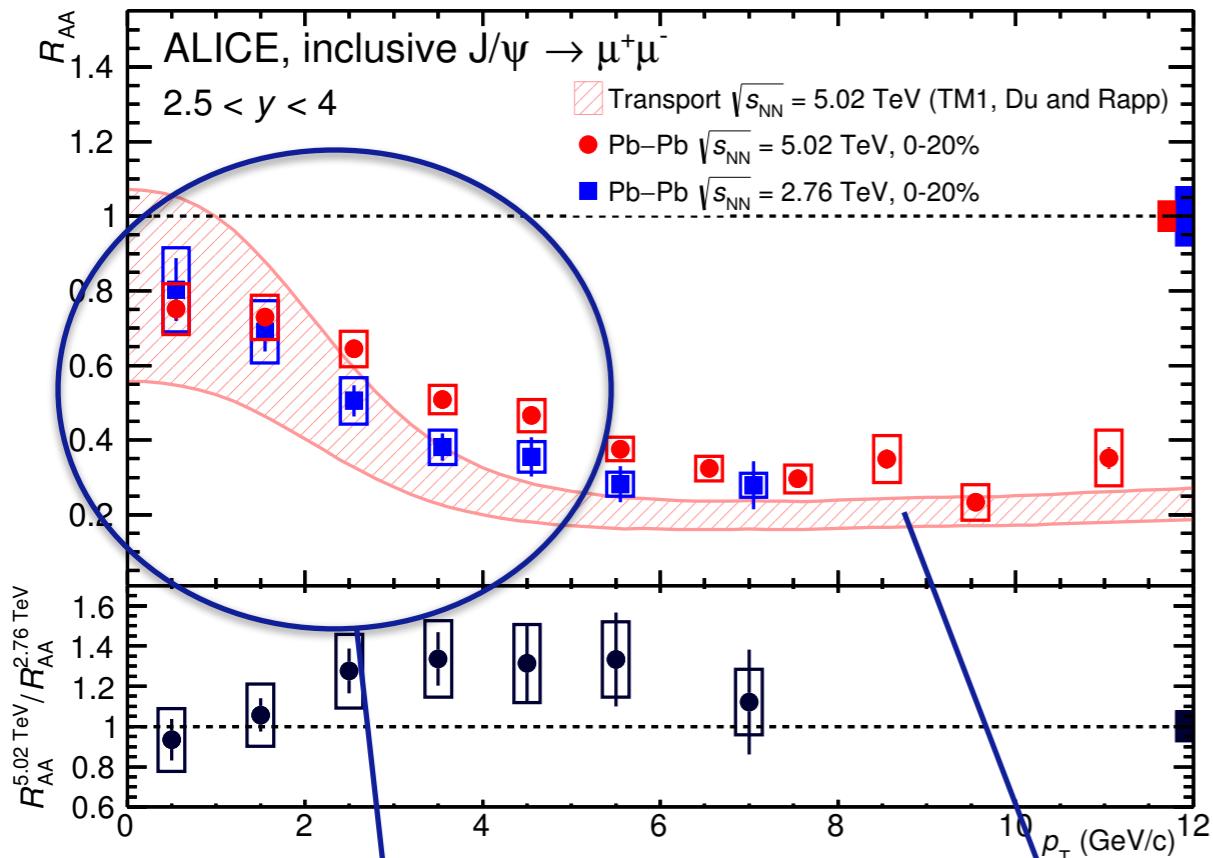


Indicates radiative energy loss: induced gluon bremsstrahlung

Quarkonia: J/ Ψ Suppression

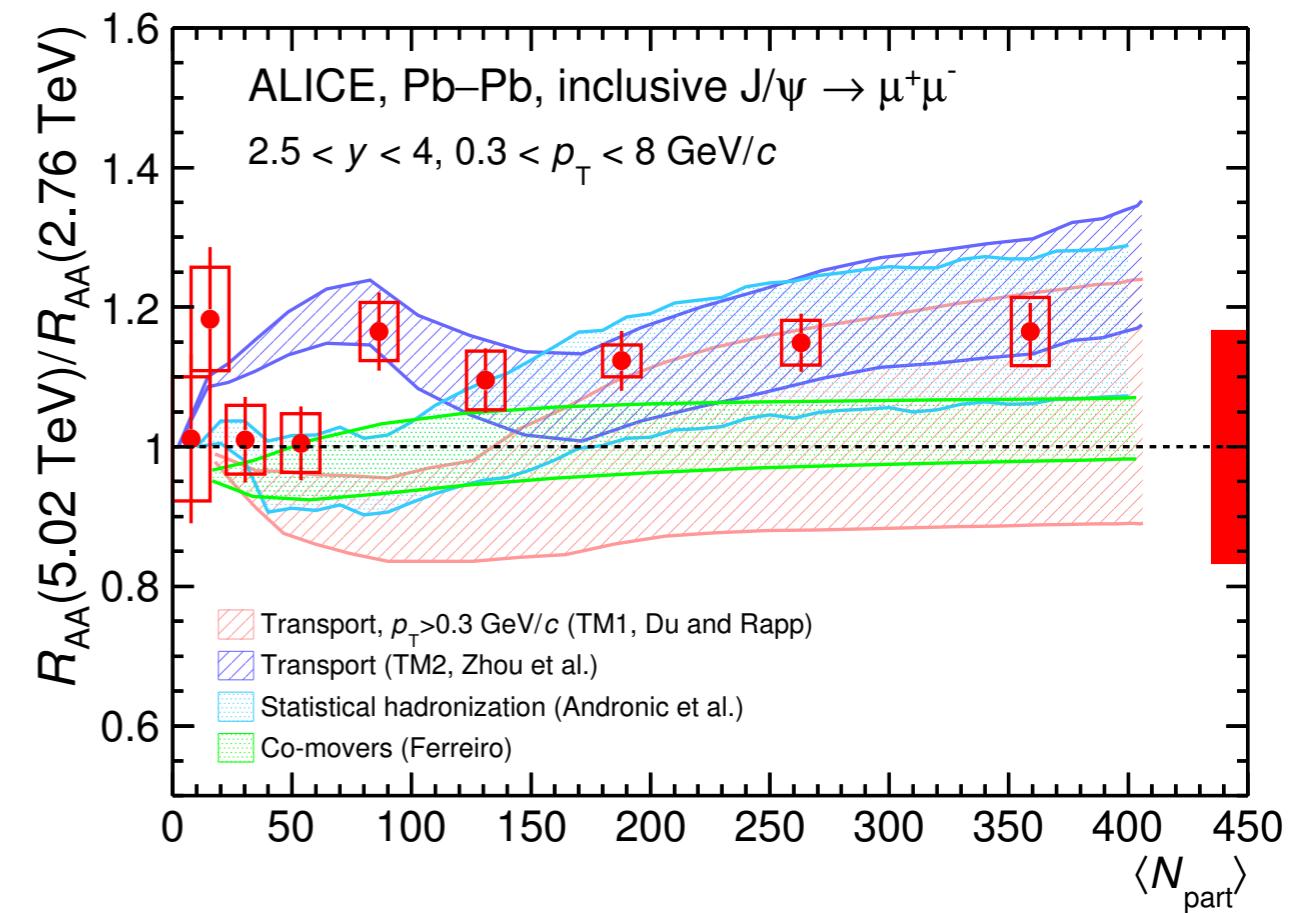
ALICE, arXiv:1606.08197

Run 2: 5 TeV Pb+Pb



Increase by recombination:
 No sign of energy dependence

Suppression by quarkonium melting

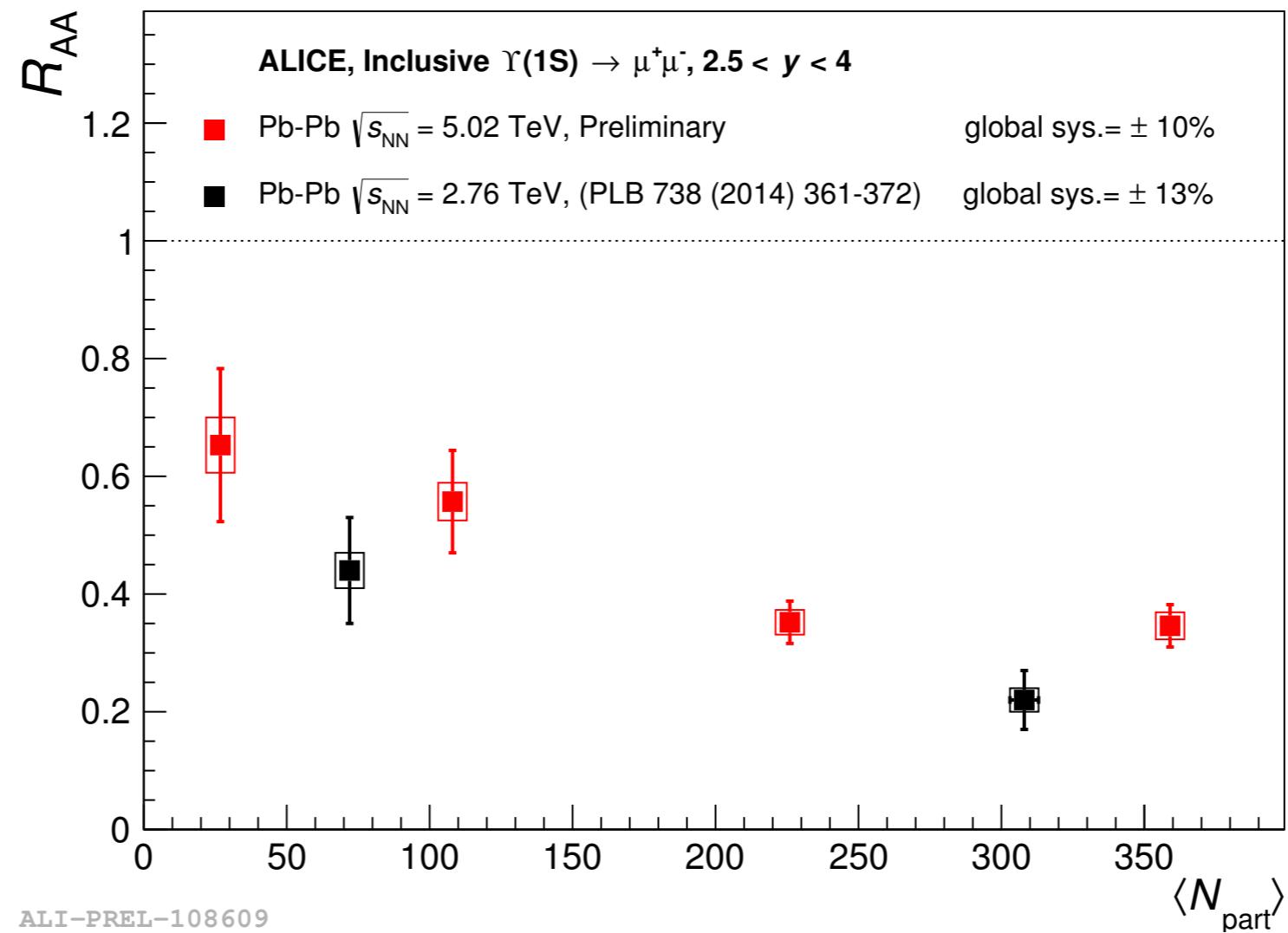


Compatible with model expectations
 (small effects expected)

Quarkonia: Υ Suppression

A. Lardeux, talk at SQM 2016

Run 2: 5 TeV Pb+Pb



Υ suppression at 5 TeV similar to 2.76 TeV

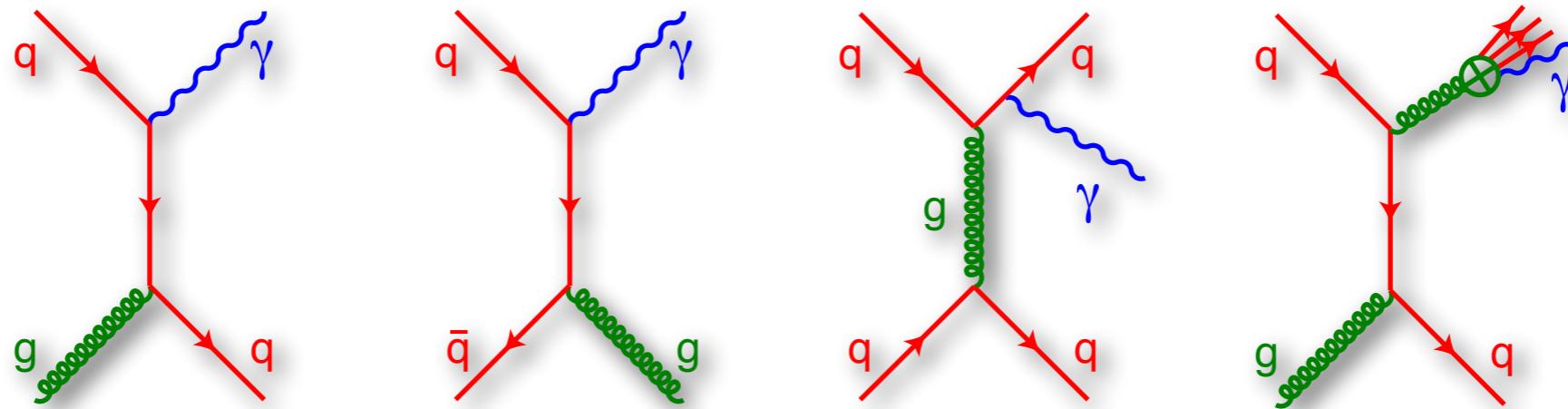
EM Probes: Direct Photons

EM (and weak) probes:

- no strong interactions
- information on initial or early state

Thermal photons

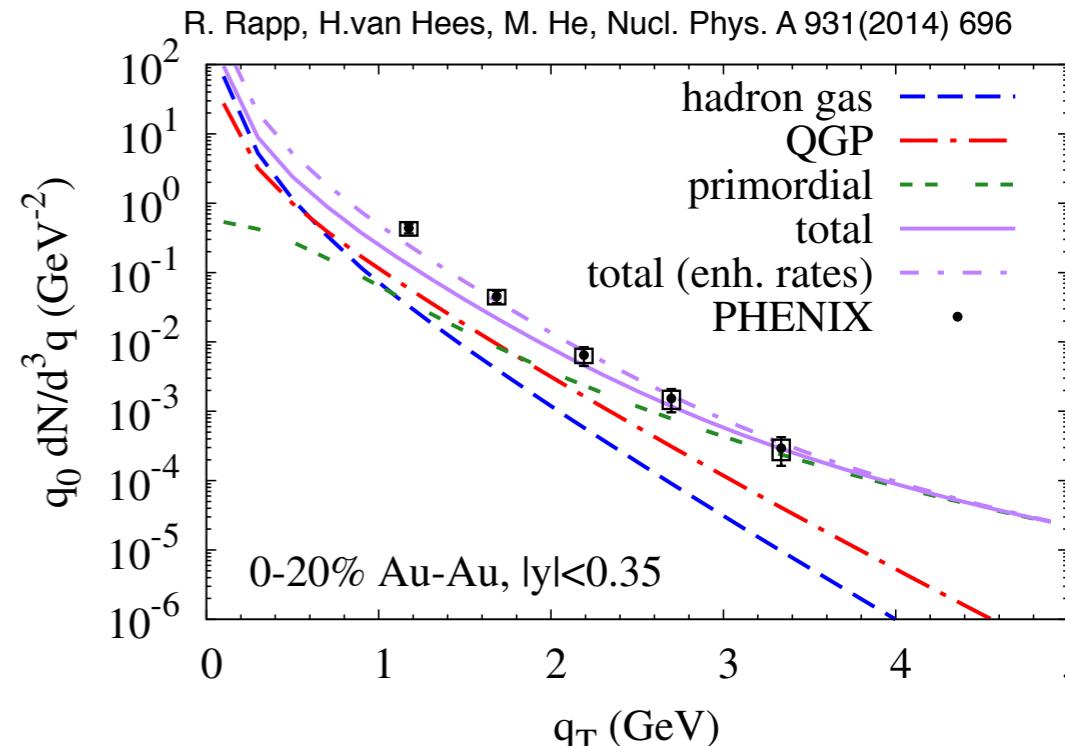
- thermally produced and emitted throughout collision history
- **sensitivity to initial temperature of Quark Gluon Plasma**
- small signal: difficult measurement
 - main background: abundant decay photons



Direct Photon Puzzle at RHIC

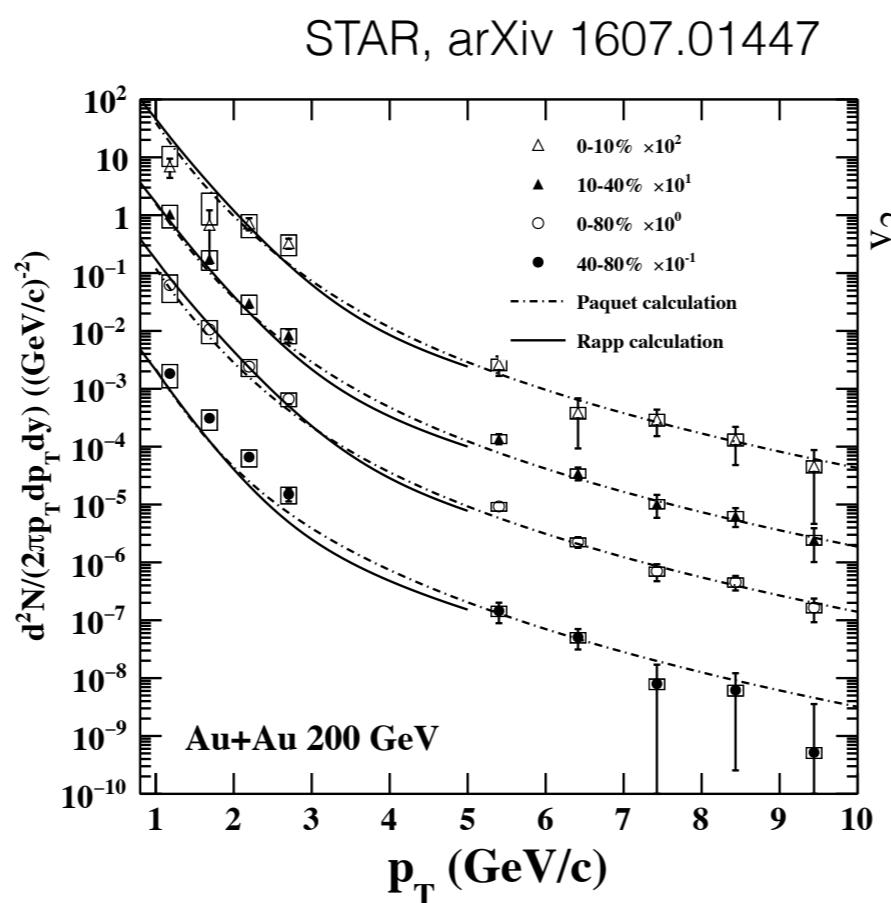
PHENIX results in 200 GeV Au–Au:

- Via real and zero-mass virtual photons
- Large yield + large anisotropy
- Challenging for theory:
 - Large yield favours early emission
 - Large anisotropy favours late emission

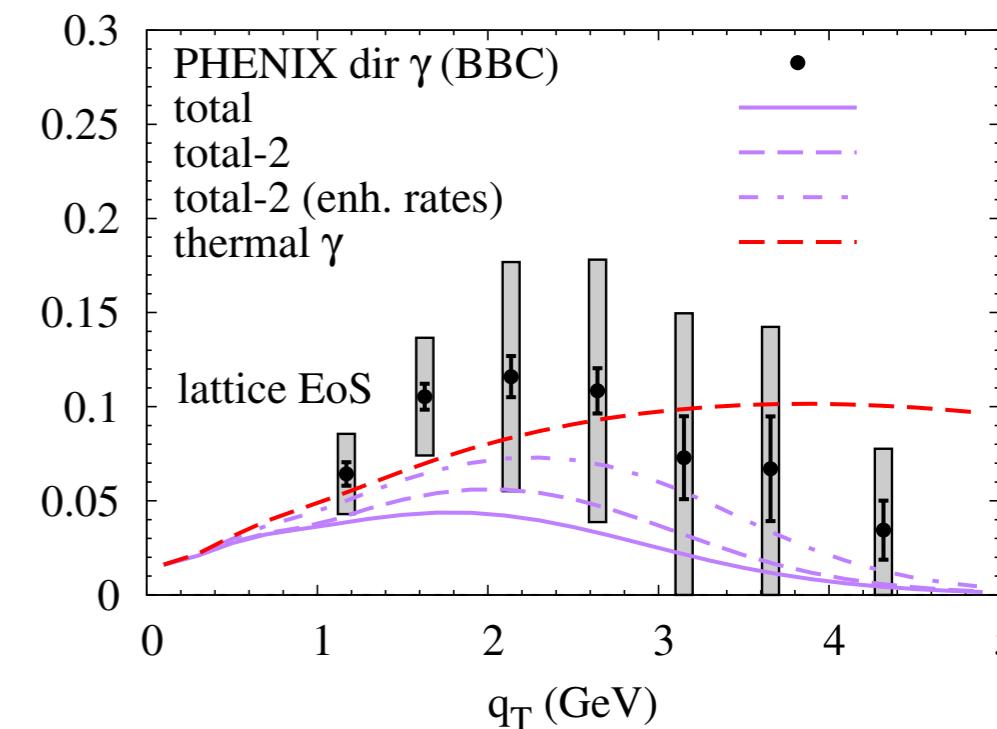


New STAR results:

- yield via zero-mass virtual photons
- better agreement with theory
- but: different centrality



Direct photon puzzle!?



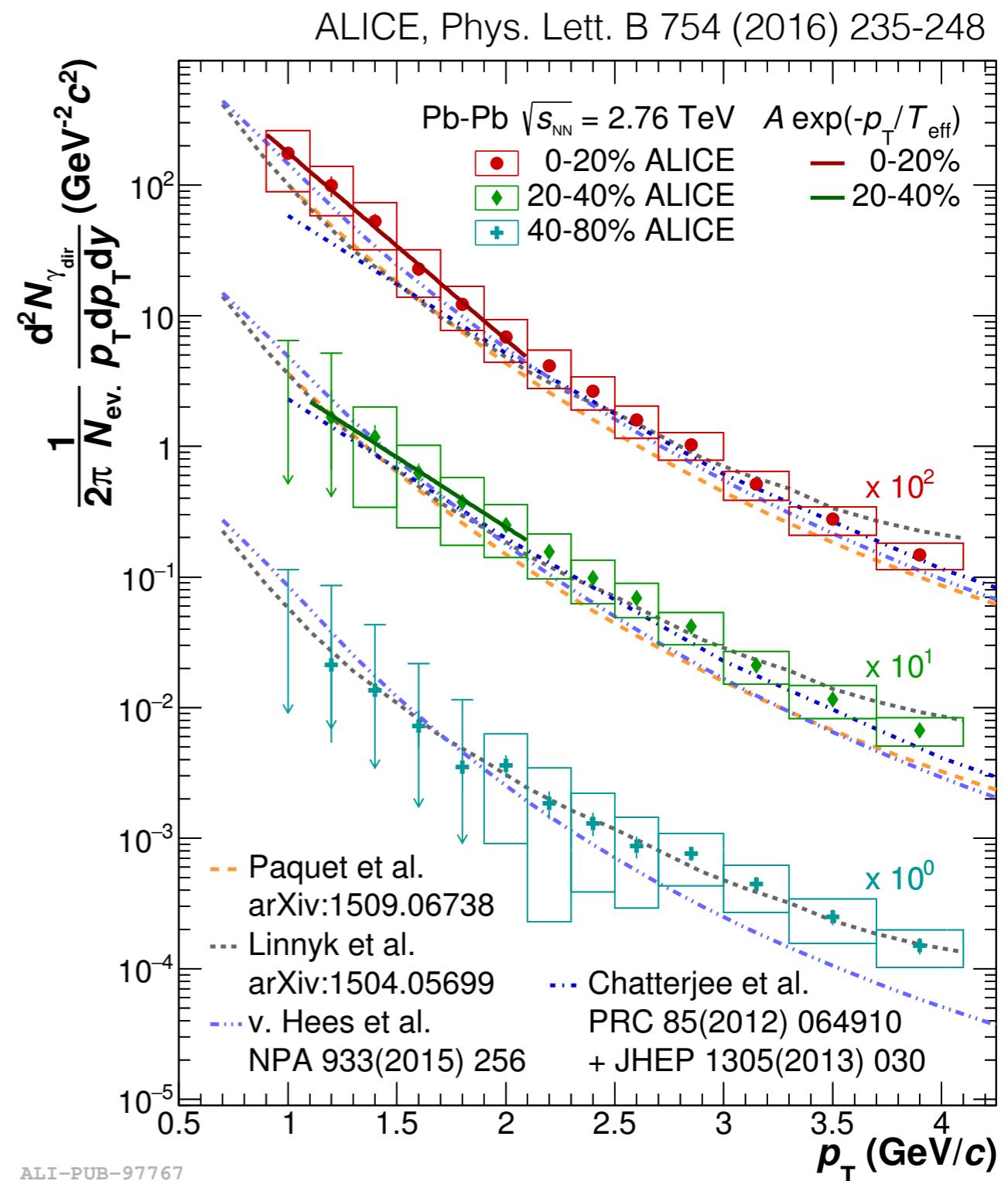
Direct Photons at LHC

Direct photon measurement in Pb–Pb at 2.76 TeV

- prompt (pQCD) photons dominating at high p_T
- thermal photon excess at low p_T

Expect higher initial temperature

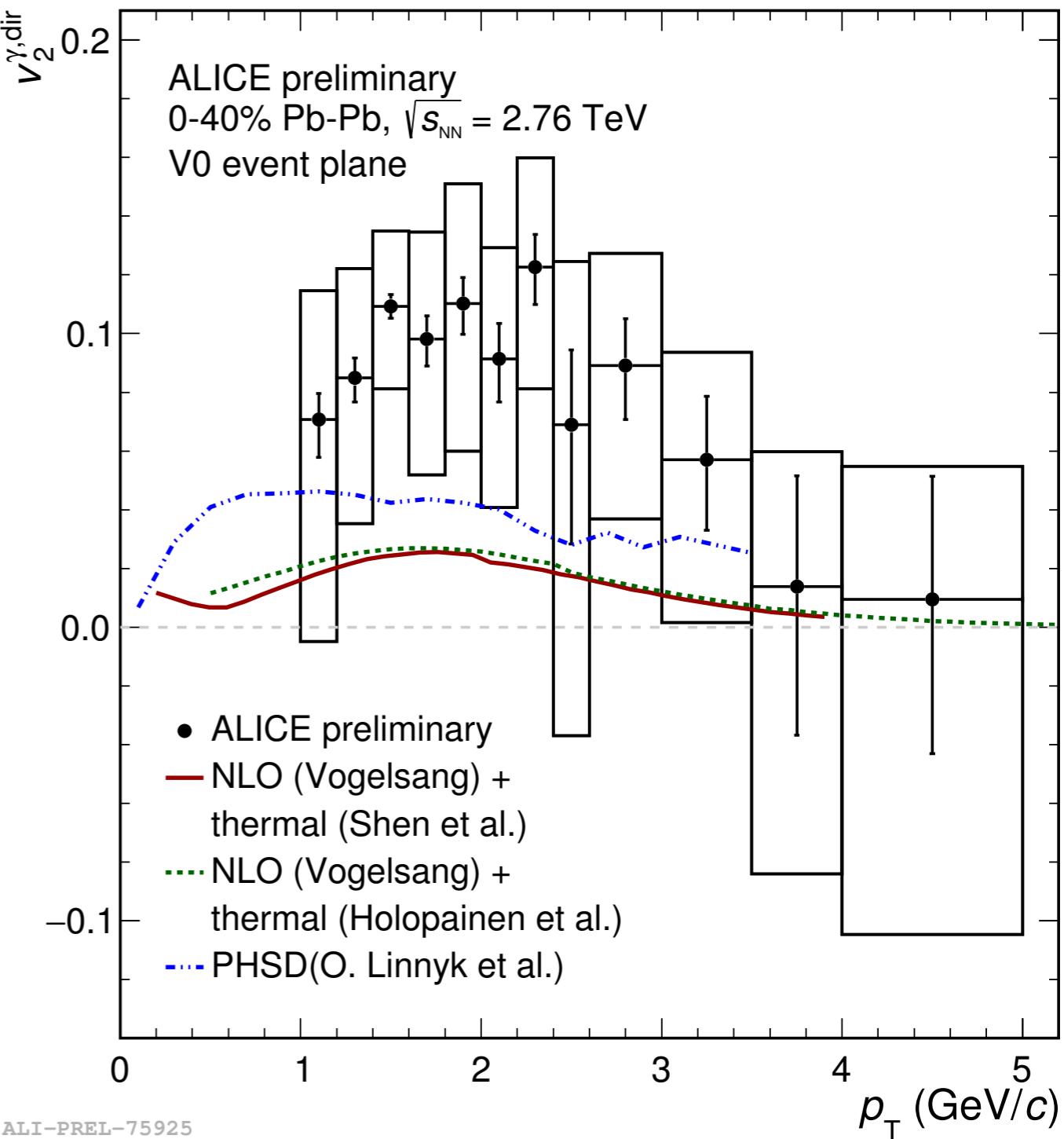
- Reasonably well described by theory
 - initial temperature at $r=0$ for central collisions $T \approx 700$ MeV



Direct Photon Flow at LHC: Status

D. Lohner (ALICE), JoP: Conf. Series 446 (2013) 012028

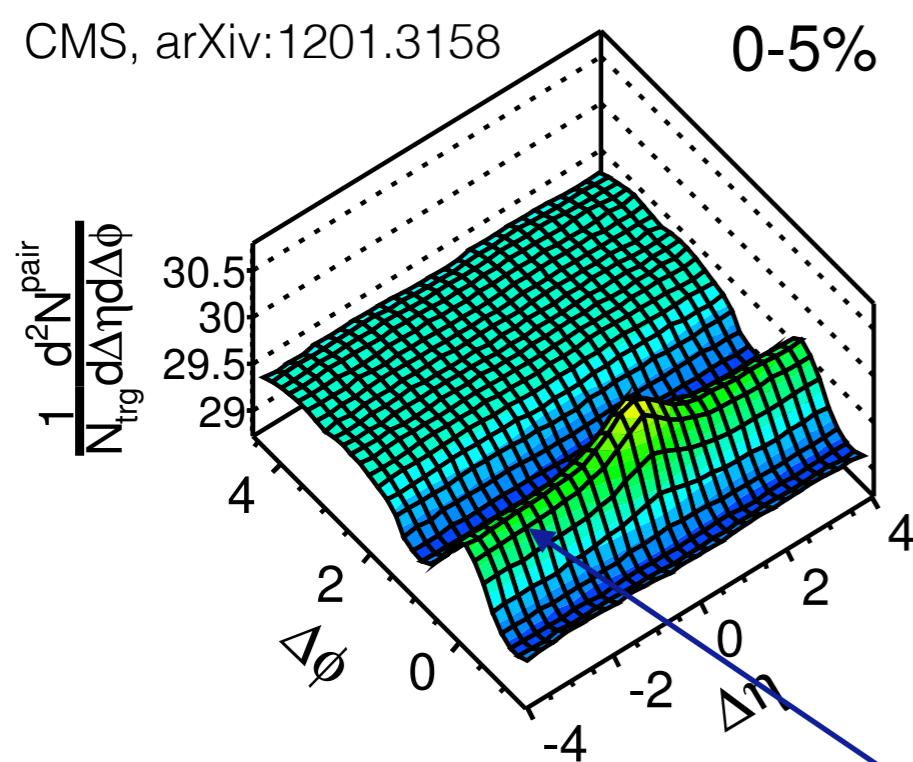
- preliminary results for central collisions (0-40%)
 - use preliminary extracted photon yields to extract direct photon flow
- comparison of direct photon flow to theoretical models
 - large uncertainties
 - under-prediction by models
- final results in preparation
 - using final direct photon yields
 - revisit error estimates



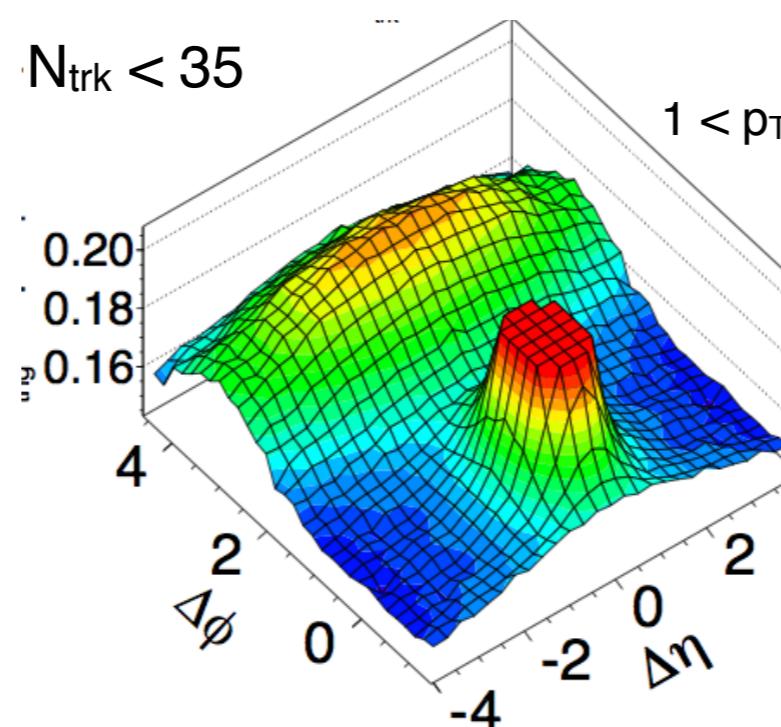
Collective Effects in Small Systems (?)

pp and Pb+Pb – the Ridge

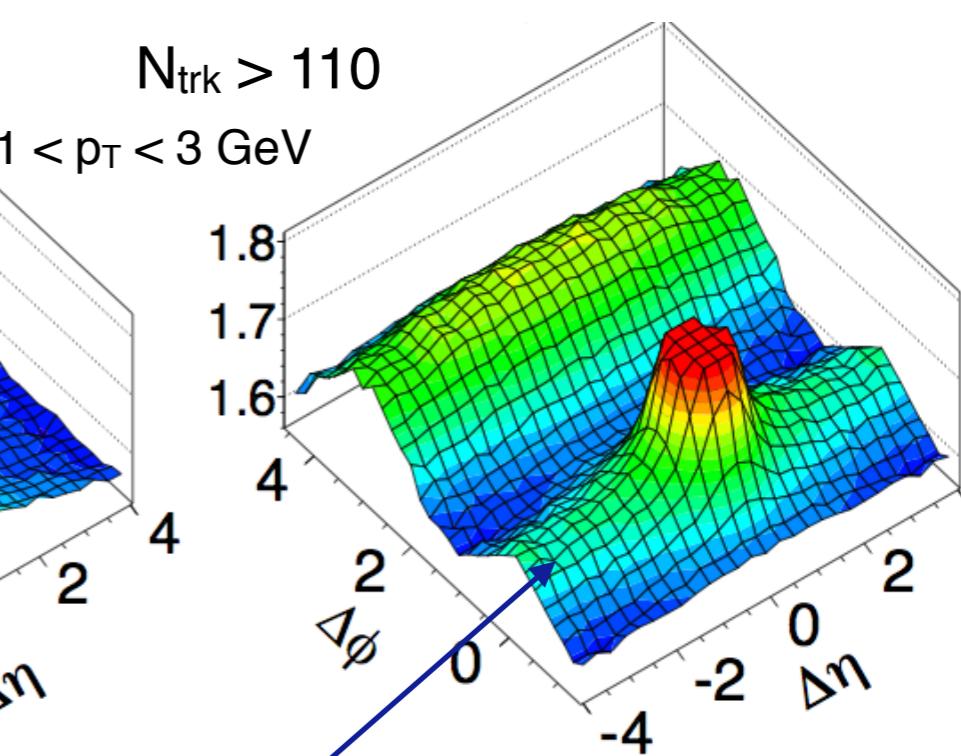
Central Pb+Pb



p+p low multiplicity



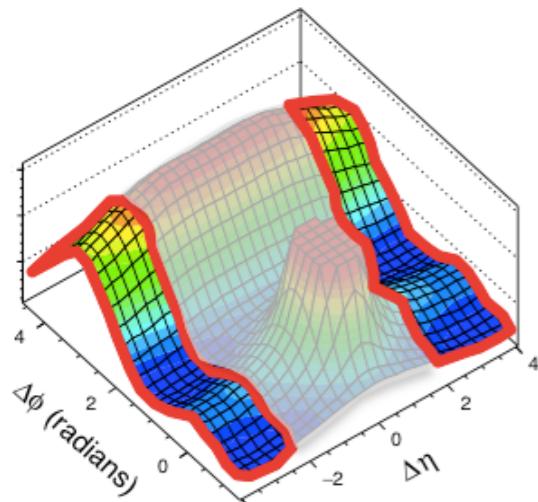
p+p high multiplicity



Near-side long range correlation: indicates early time origin

Seen in high-multiplicity pp and p+Pb events

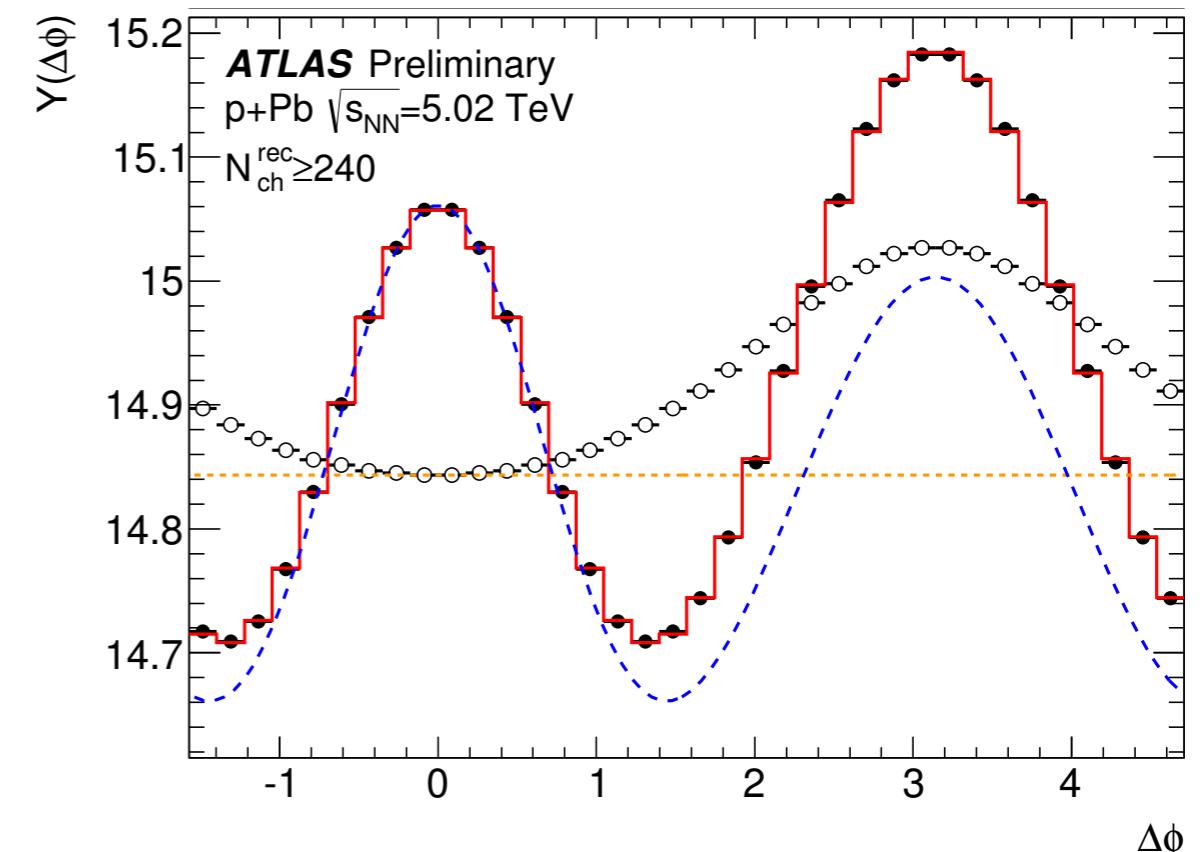
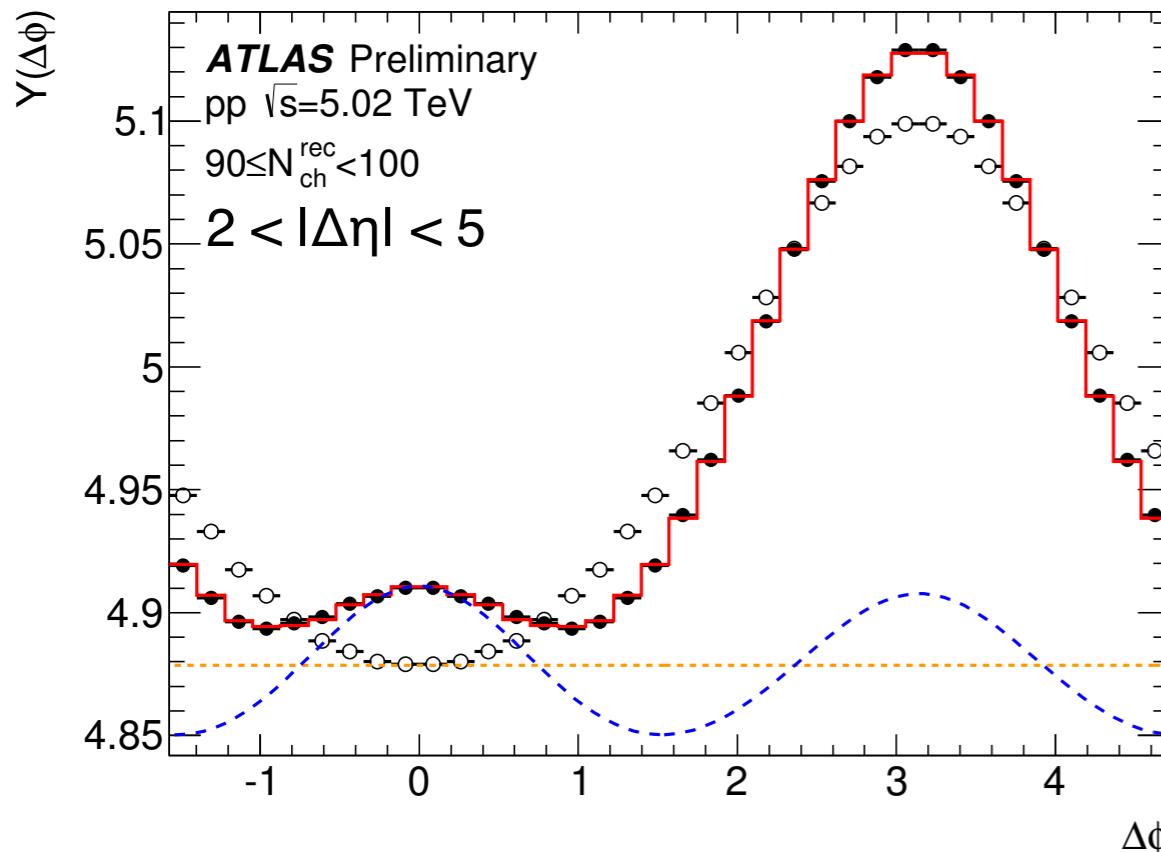
Two-Particle Correlations



High-multiplicity p+p

ATLAS-CONF-2016-026

High-multiplicity p+Pb

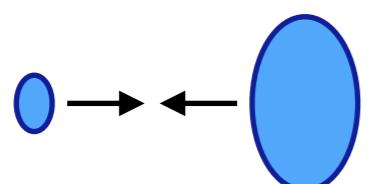
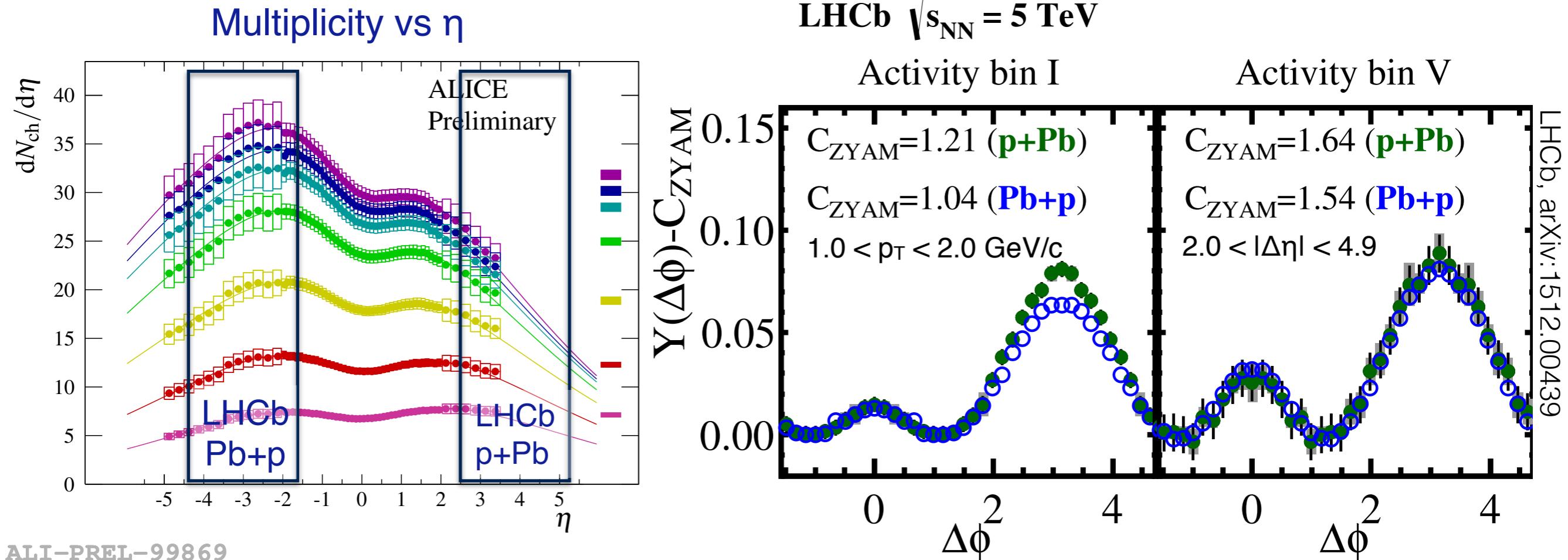


Clear change in shape from low multiplicity to high multiplicity:
no near-side peak in low multiplicity events

Away-side also affected: well described by dipole term ($\cos(2 \Delta\varphi)$)

Smooth evolution from pp to p+Pb: effect stronger in p+Pb

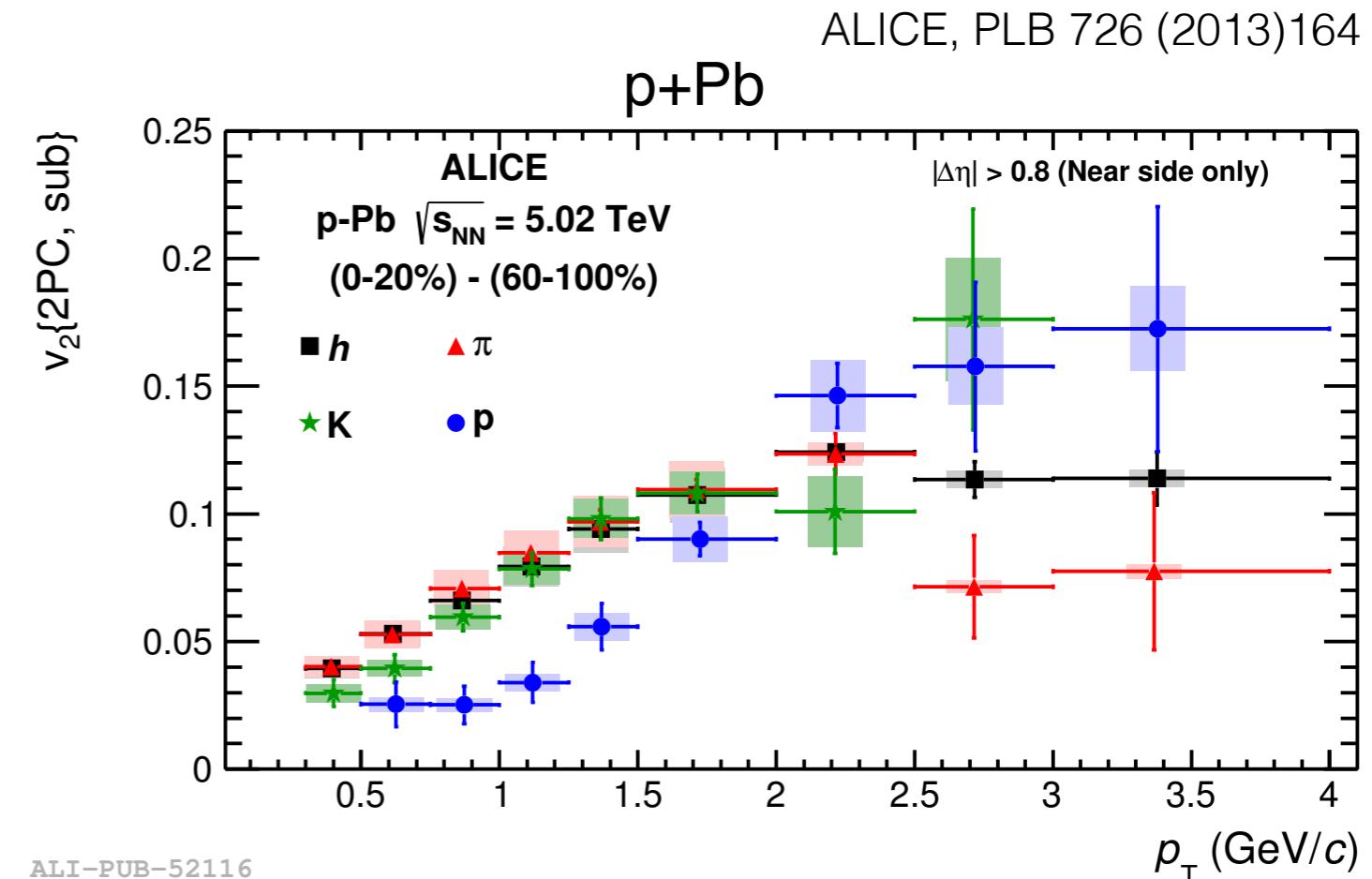
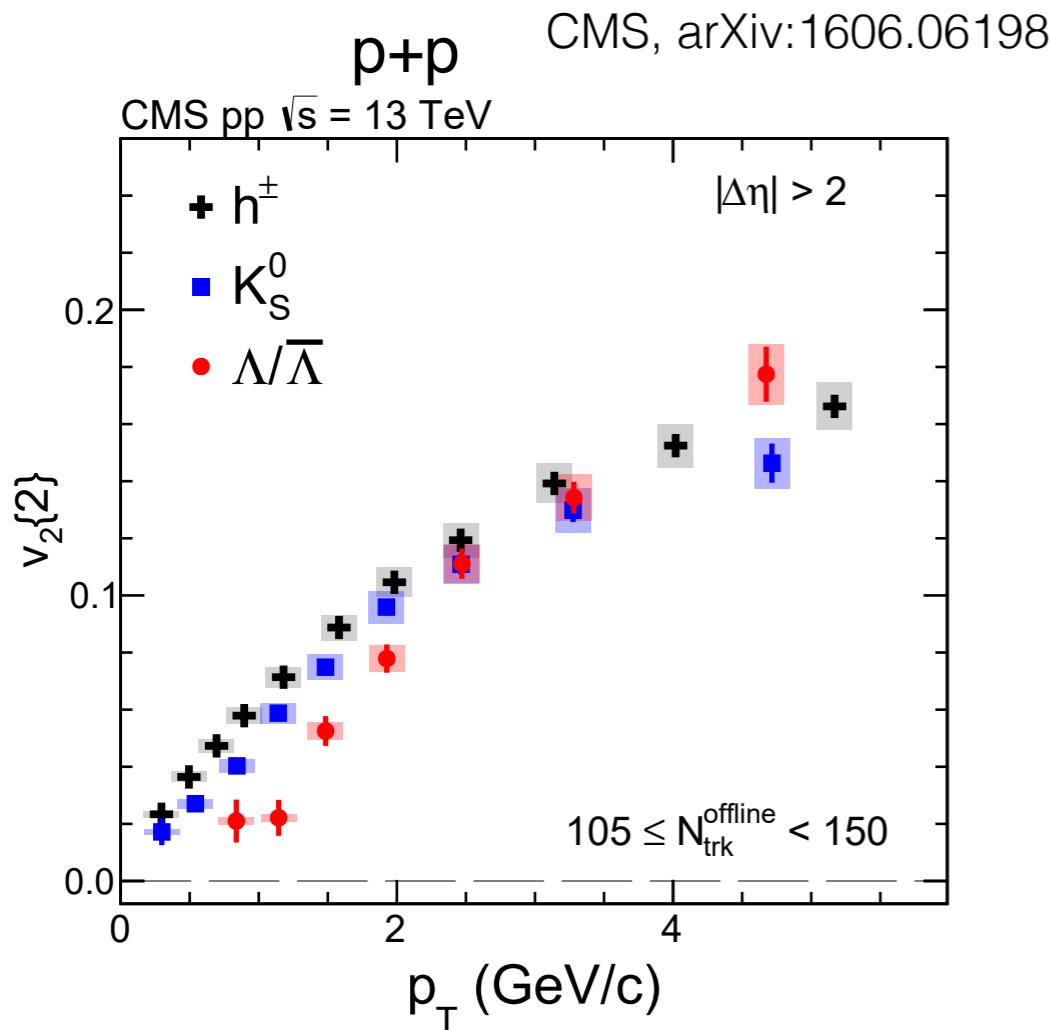
More on p+Pb



p+Pb is an asymmetric system

Near-side ridge identical
for forward and backward trigger particles

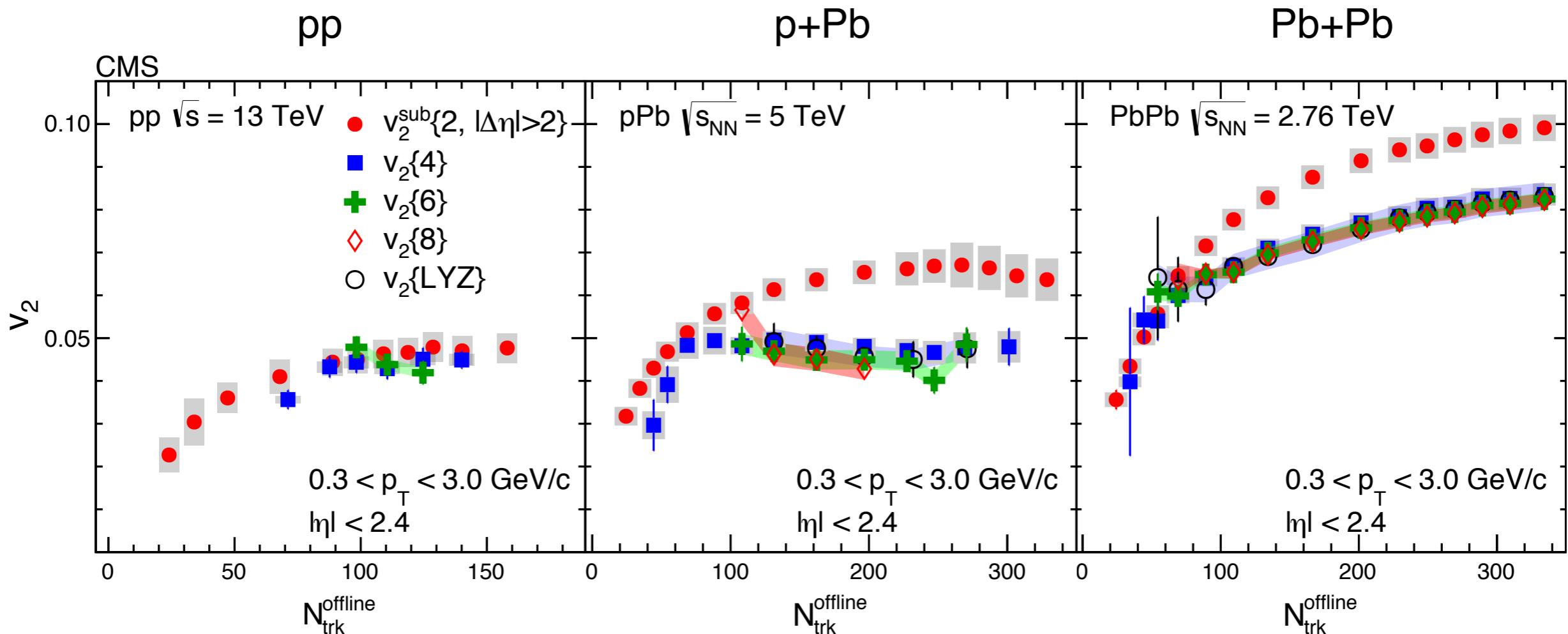
v_2 from Di-hadron Correlations



Similar ‘mass ordering’ observed for v_2 from two-particle correlations in high-mult. pp and p–Pb

Is this also pressure-driven?

Multi-Particle Correlations: Testing Collectivity



Multi-particle methods suppress few-particle (non-flow) correlations

Flow-like effect is indeed a multi-particle effect

Flow in Small Systems: Comparisons to Hydro

P. Bozek, W. Broniowski and G. Torrieri,
Phys. Rev. Lett. 111, 172303 (2013)

Many aspects of the observed ridge have a natural explanation in hydrodynamics:

- Long range correlation
- 2- and 3-fold symmetries
- Dependence on initial geometry
- Particle mass dependence

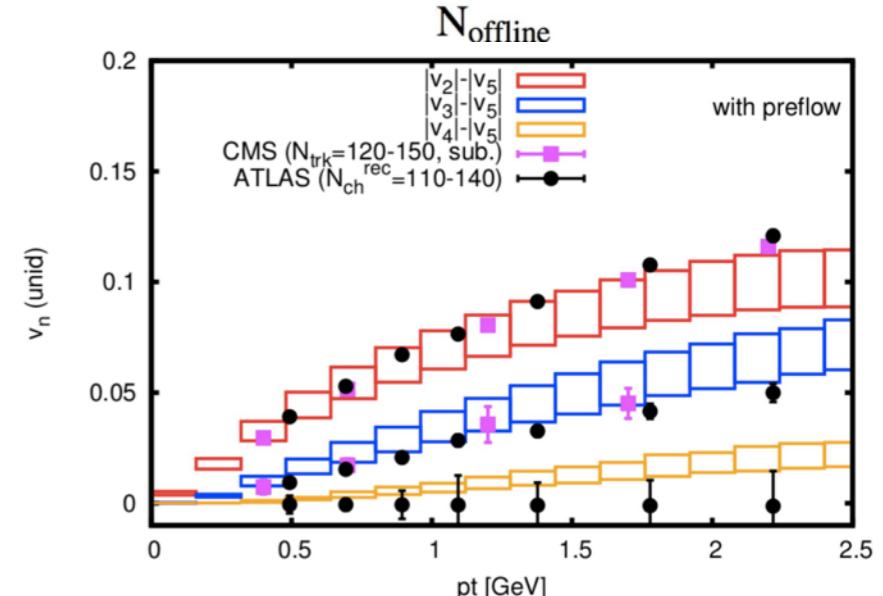
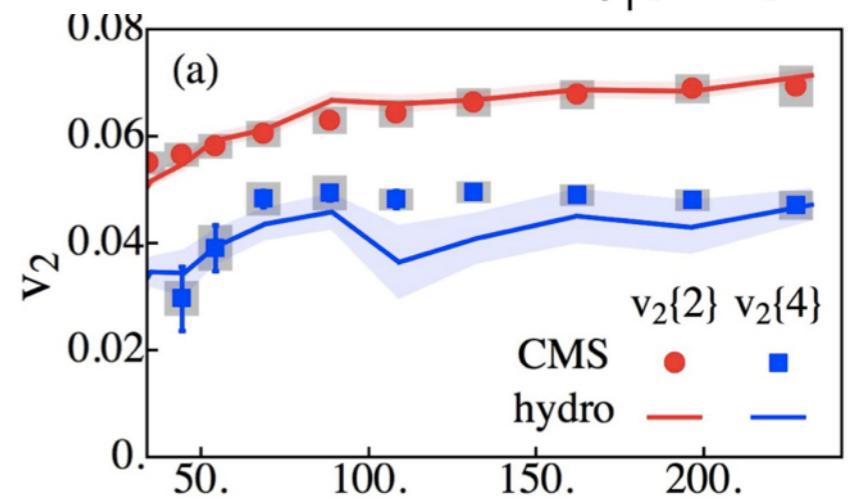
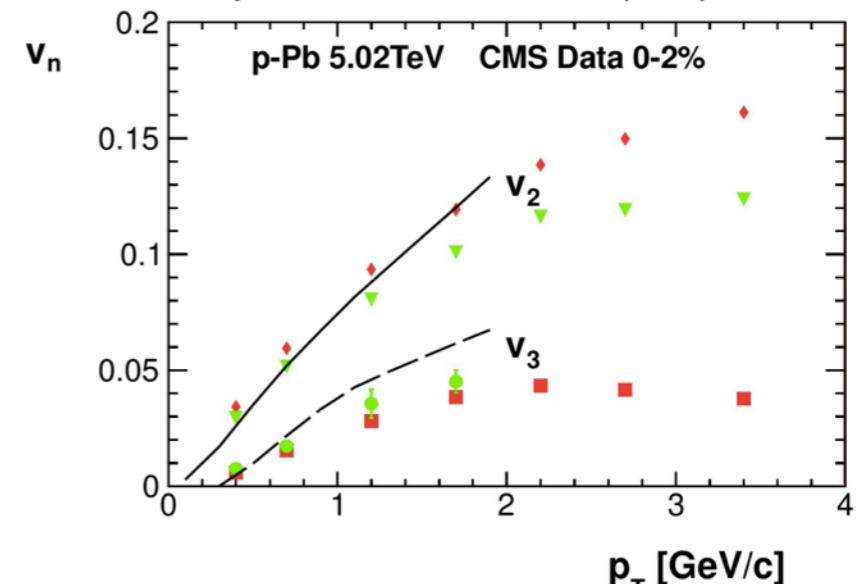
Why would the system behave as a fluid?

Is there enough time, volume to thermalise?

- Hydrodynamisation (isotropisation) of a dense gluon system?
- Partonic/hadronic rescattering?
- How many scatterings/what density is needed to approximate fluid behaviour?

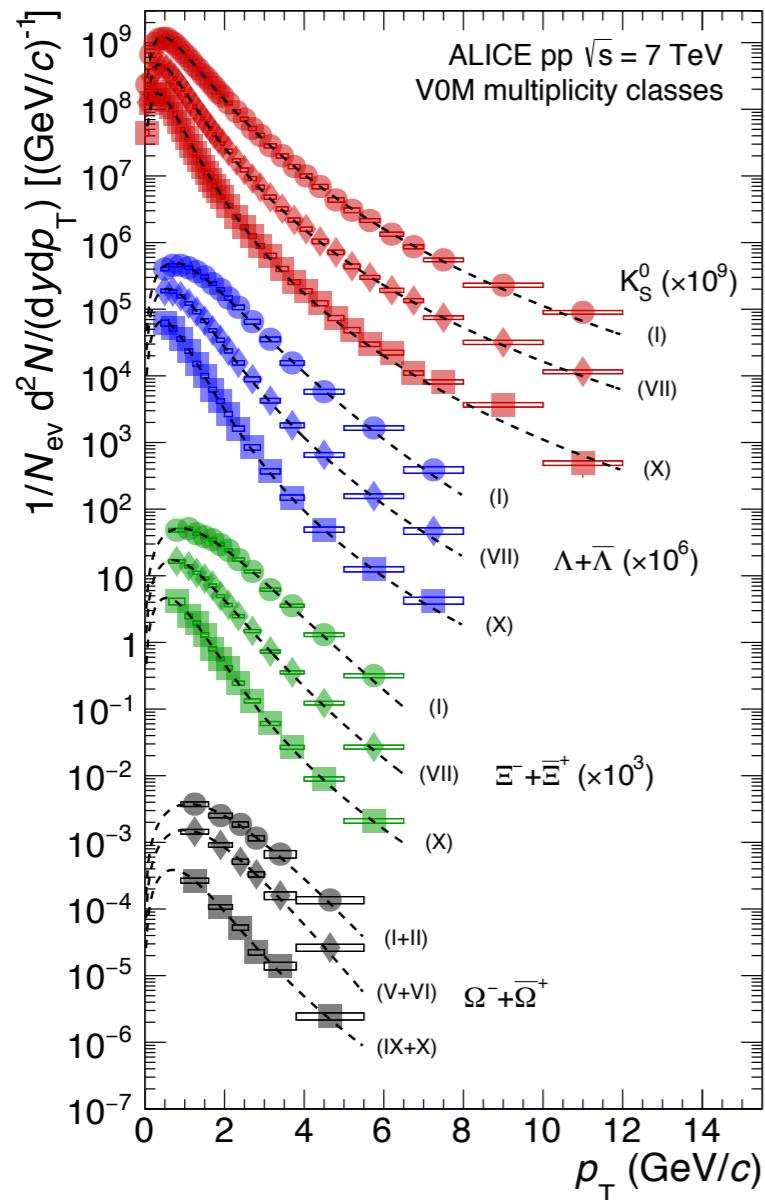
Many recent developments;
active discussion on interpretation

2016 p+Pb run to shed more light on this



Strangeness Production in pp, p+Pb

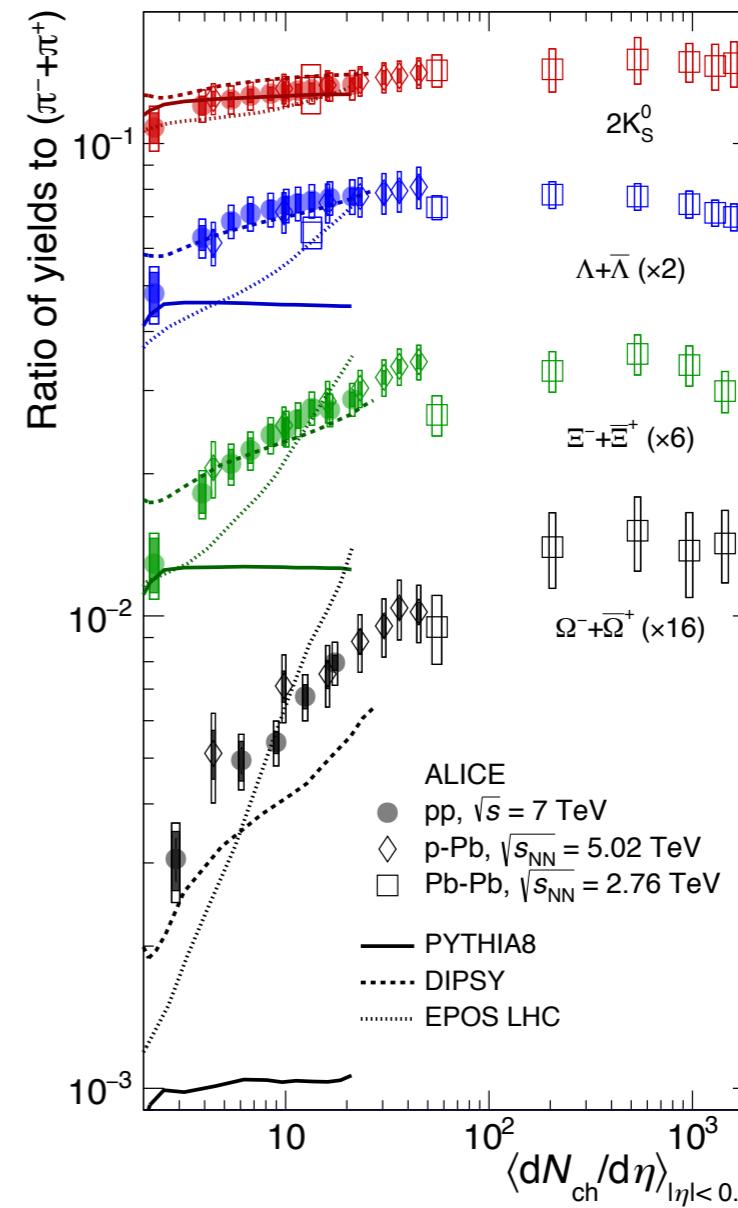
p_T spectra in multiplicity-selected pp collisions



Mean p_T increases with multiplicity

Similar enhancement in PbPb has been interpreted as thermalisation; global equilibration of the strangeness yield. Are they related?

particle yields in multiplicity bins



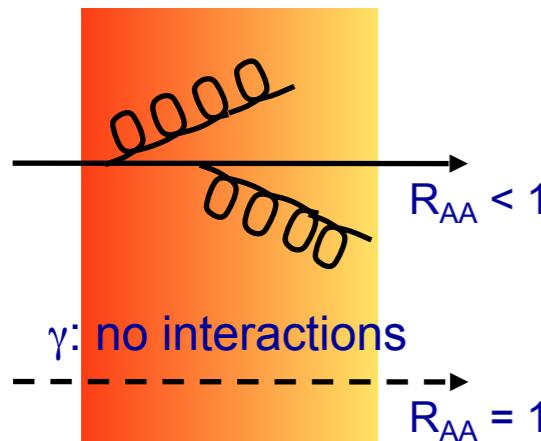
Fraction of strange hadrons increases with multiplicity

Large effect for multi-strange Ξ and Ω

Energy Loss in Small Systems

$R_{AA} < 1$ for hadrons:
Parton energy loss

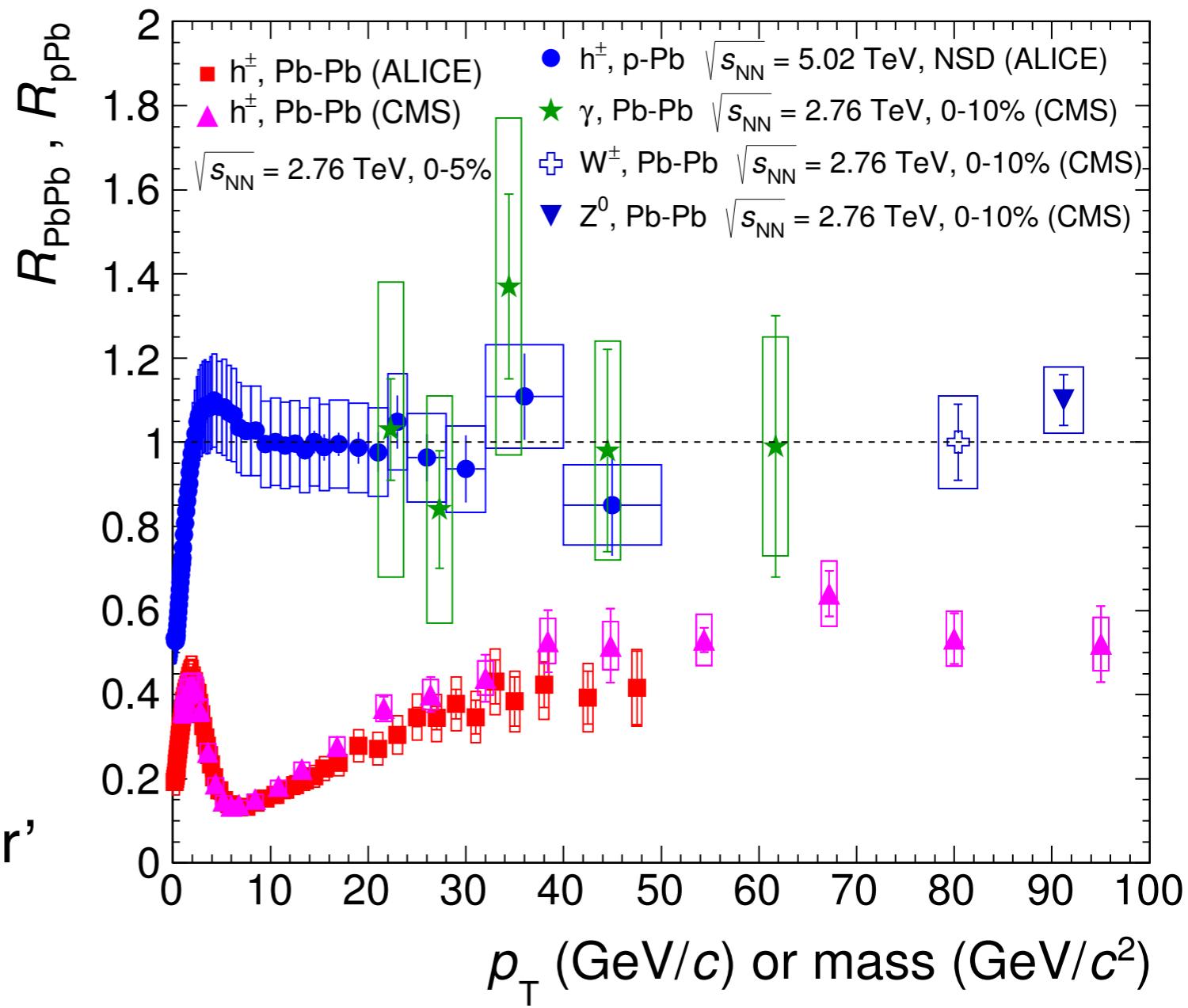
Hadrons: energy loss



$R_{AA} \approx 1$ for γ, Z, W :
No energy loss for
electromagnetic and weak probes

p+Pb: $R_{pPb} \approx 1$ at high p_T
No/very small ‘cold nuclear matter’
effects on high- p_T probes

ALICE: PLB 720, 52; EPJ. C74, 3054
CMS: JHEP 03 (2015) 022 (Z^0)
EPJ. C72, 1945; PLB 710, 256; PLB 715, 66

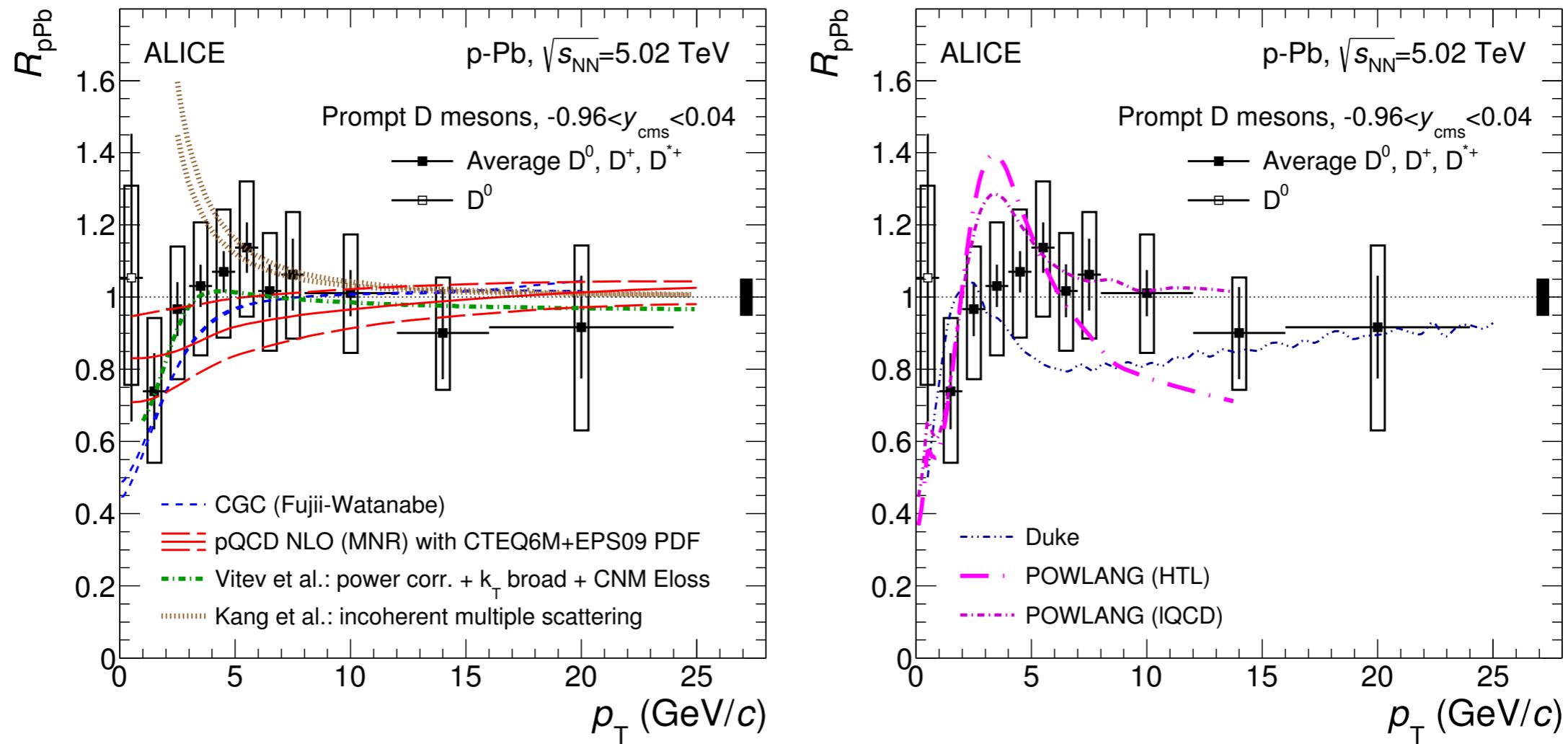


ALI-DER-95222

If there is a thermalised medium in p+Pb: path length not long enough?

Open Charm Production in p+Pb

prompt D production at midrapidity

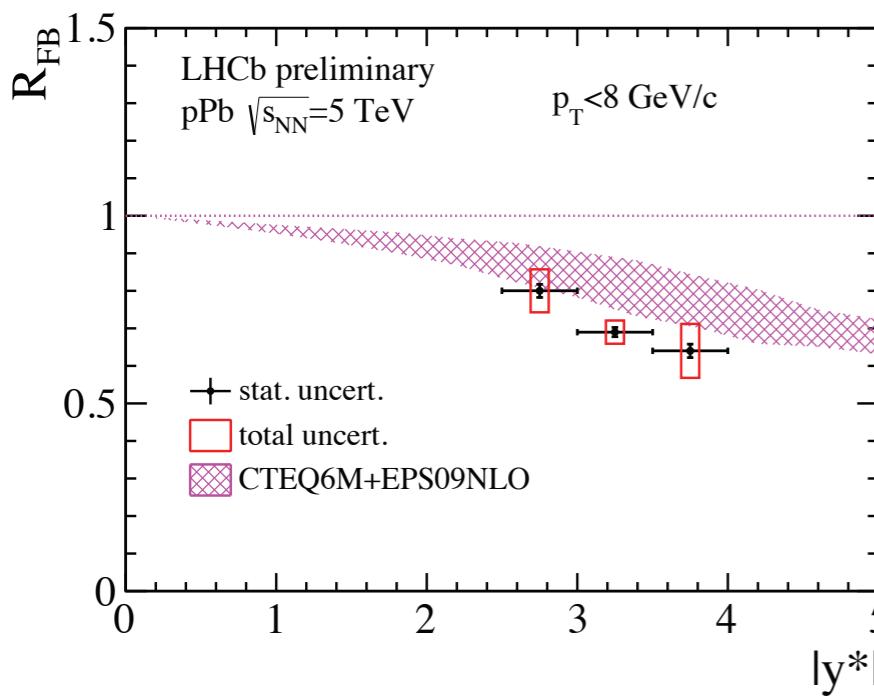
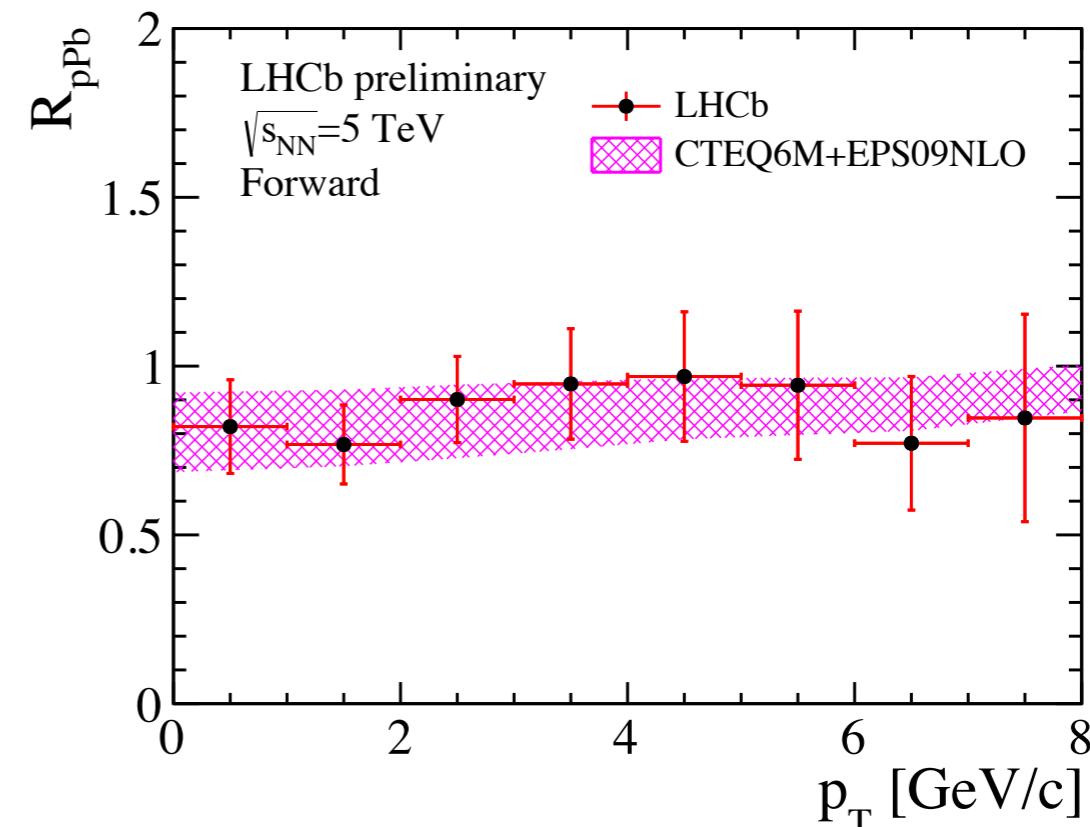
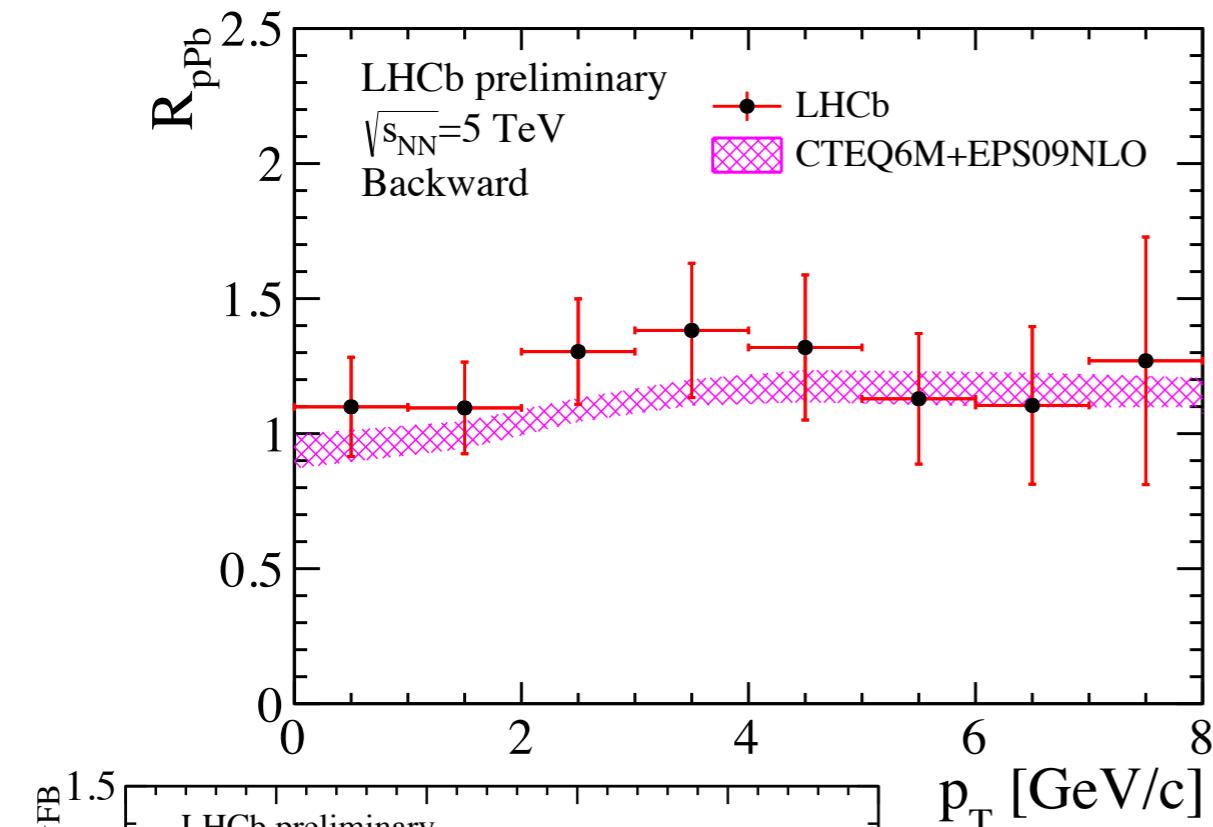


no strong modifications in data
 not yet sensitive to small expected cold nuclear modifications
 or in medium modifications

Open Charm Production in p+Pb

prompt D production backward & forward
 backward rapidity
 (Pb-going)

forward rapidity
 (p-going)

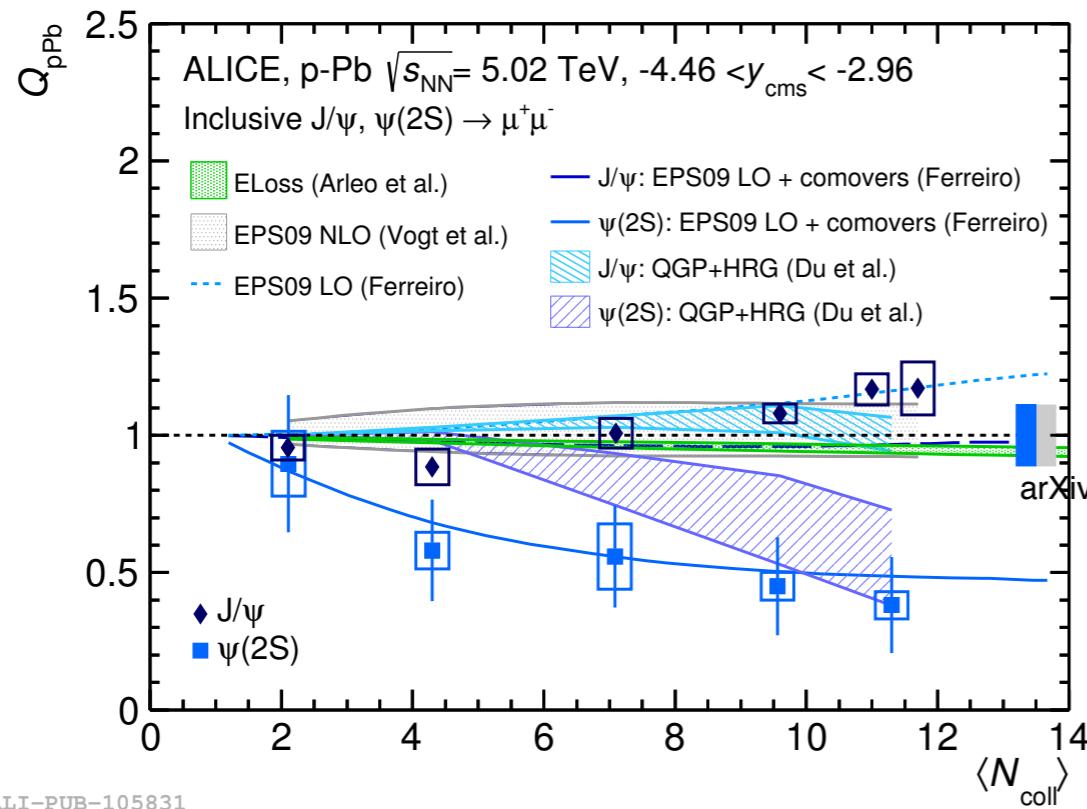


no strong modifications –
 data consistent with nuclear
 shadowing

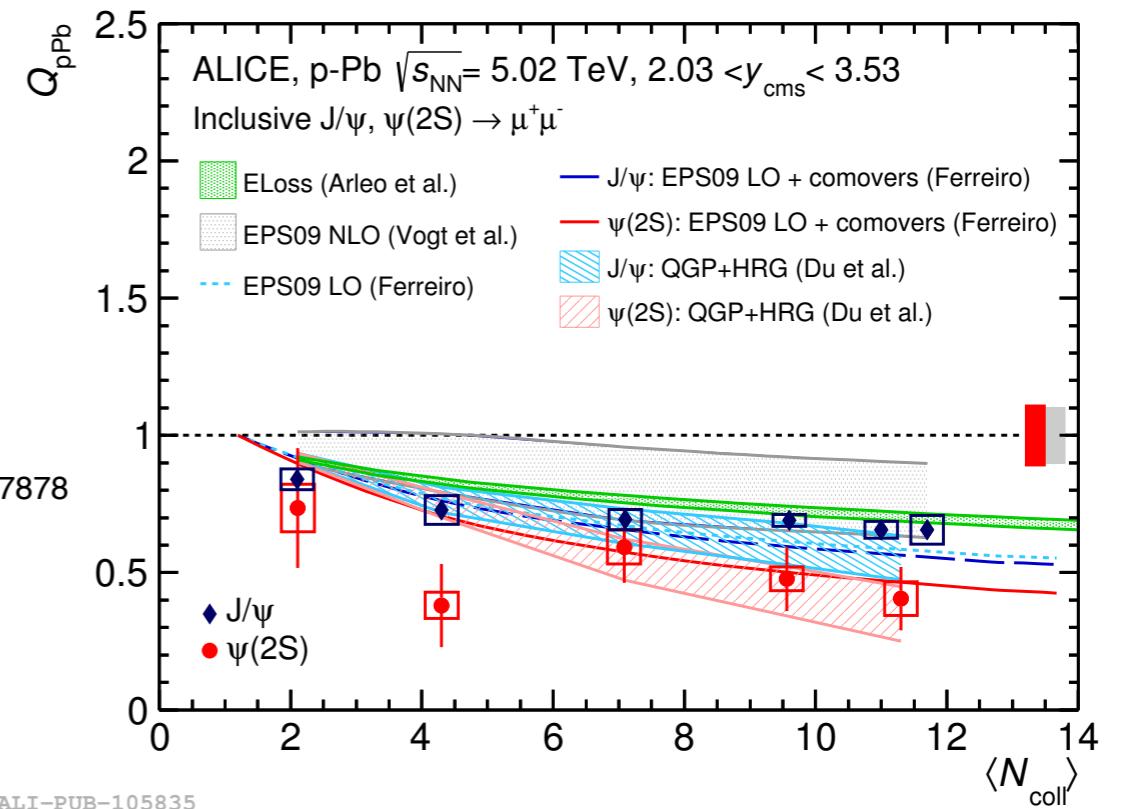
Quarkonium Production in p+Pb

J/ Ψ , Ψ' production

backward rapidity
(Pb-going)



forward rapidity
(p-going)



J/ Ψ – forward: suppression/backward: hint of enhancement
consistent with shadowing

Ψ' – forward + backward: strong suppression
needs additional suppression mechanism
energy loss?, comovers?

consistent results on prompt charmonium from LHCb, arXiv:1601.07878

Summary

Recent results show/confirm:

- QGP behaves like a liquid with extremely low viscosity $\eta/s \approx 0.1$
 - Implies short mean free path: high density, strong interactions
- High-momentum partons lose energy in the QGP
 - Overall magnitude in agreement with expectations
 - Charm/beauty difference indicates radiative energy loss dominates
- Quarkonium production shows a balance of Debye screening and regeneration

Open questions:

- pp, p+Pb show flow-like behaviour
 - What is the physical mechanism?
 - No modification of hard probes?
 - Does this have implications for understanding Pb+Pb? Or vice versa?
- Thermal photon radiation
 - Theoretically understood?

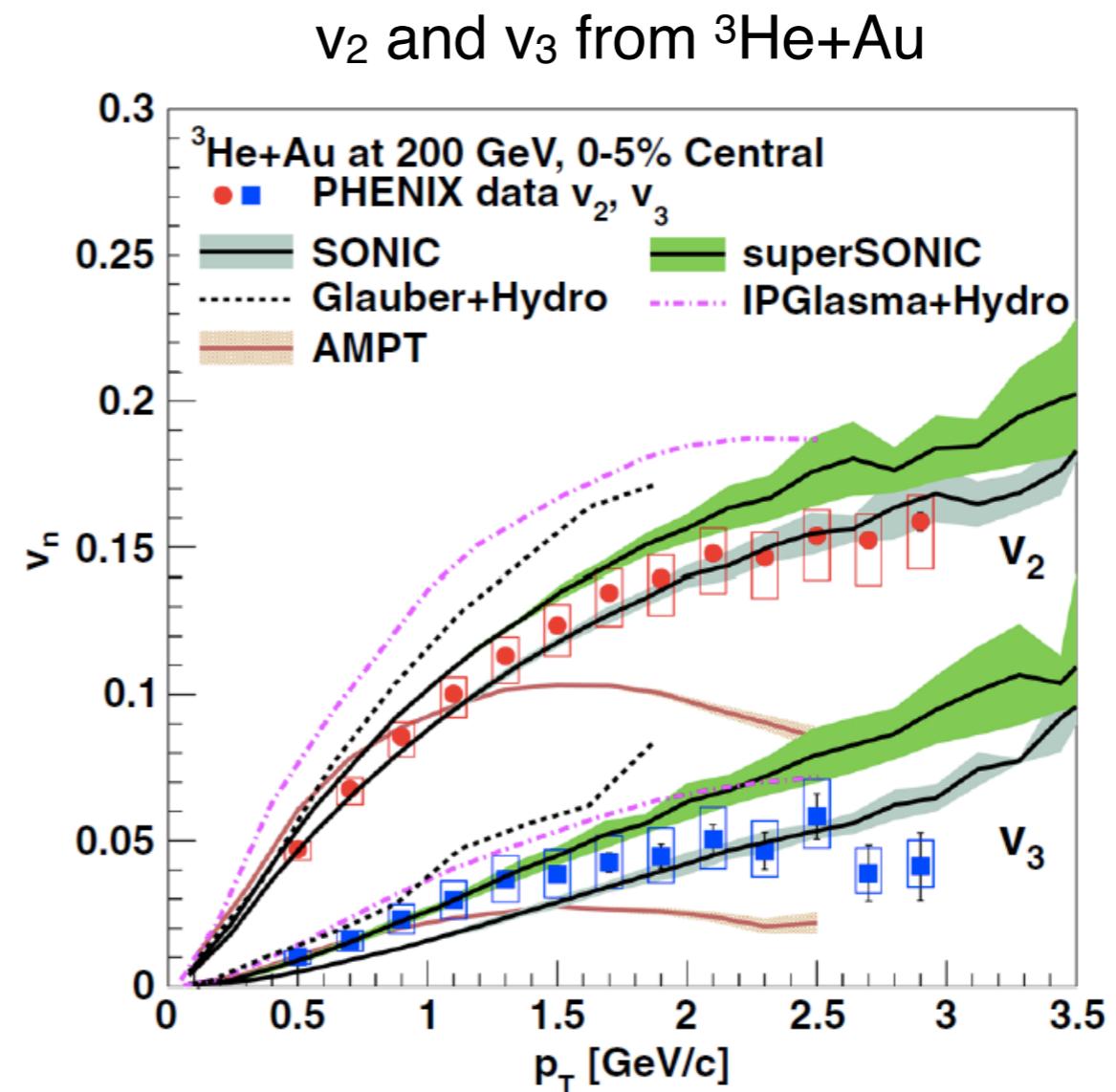
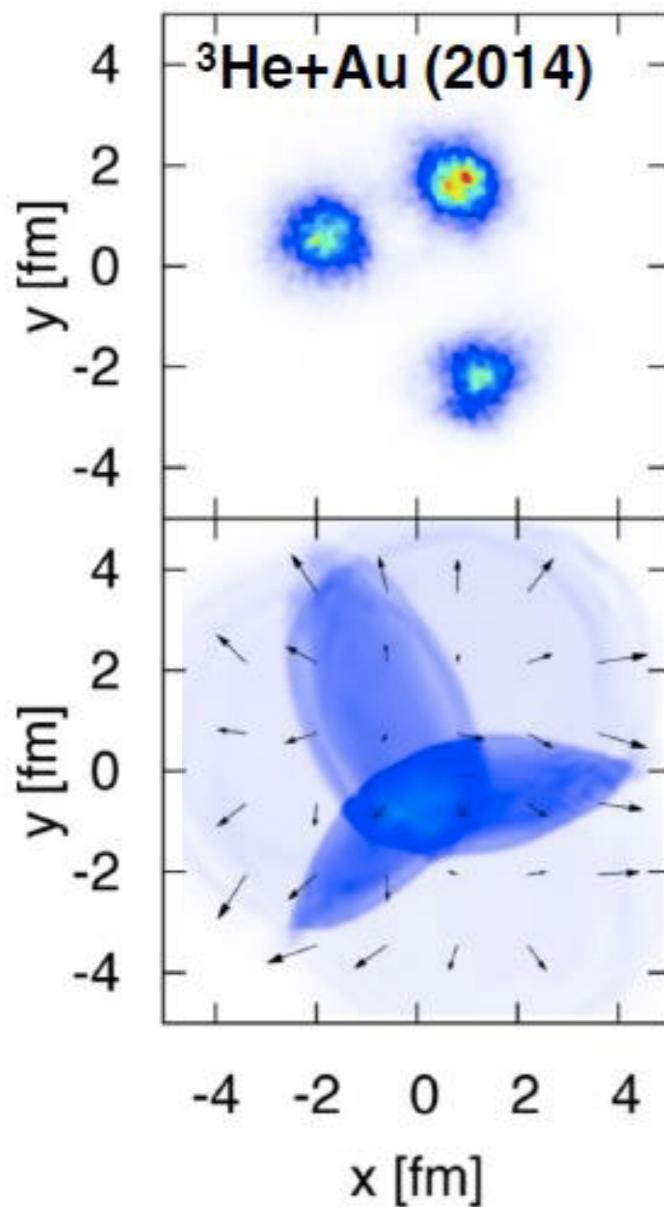
Caveat: many topics not covered due to time.

Thank you for your attention

Backup

Changing the projectile

B Schenke



Sizable v_3 contribution seen with ${}^3\text{He}$

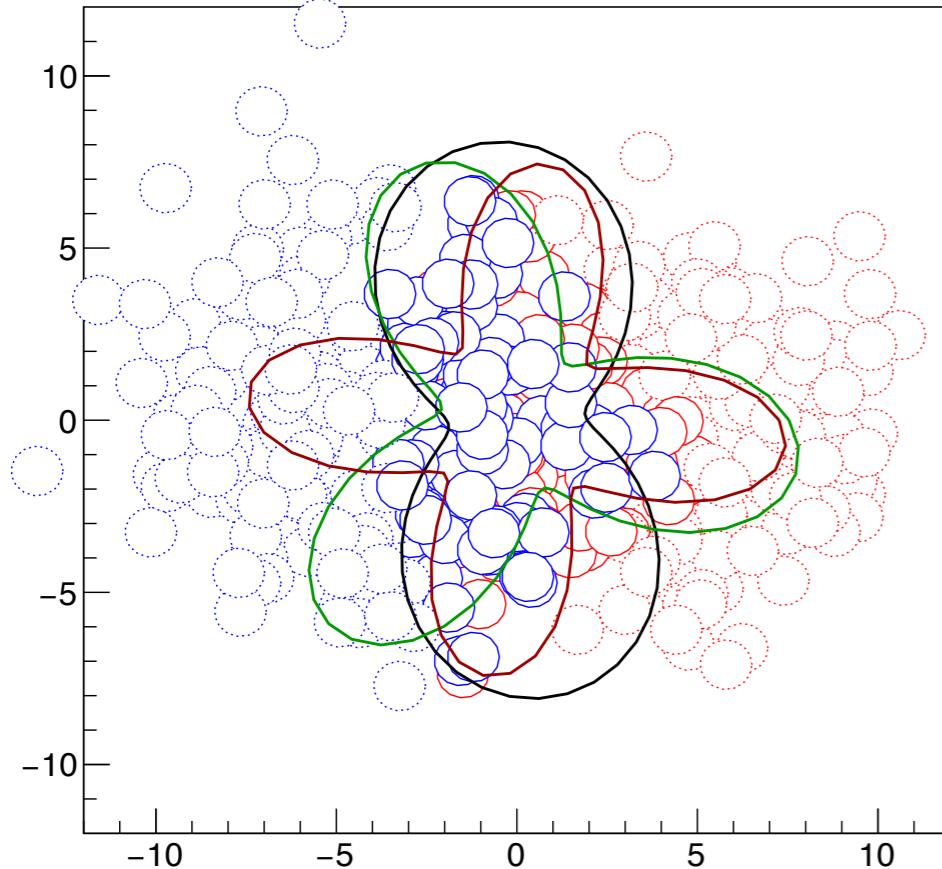
RHIC has collided a variety of small nuclei with Au to explore geometric effects

${}^3\text{He}$ gives explicit triangular contribution in initial state

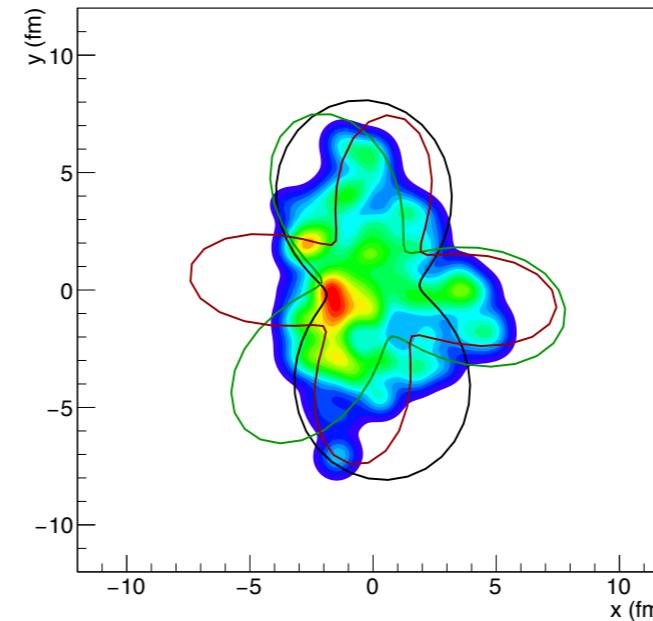
Effect is driven by initial spatial configuration

Initial state: colliding nuclear matter

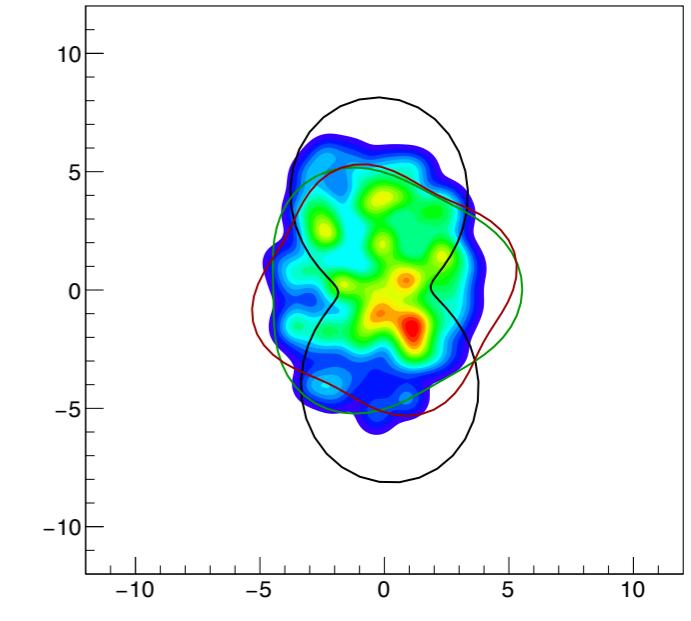
MC event: location of nucleons



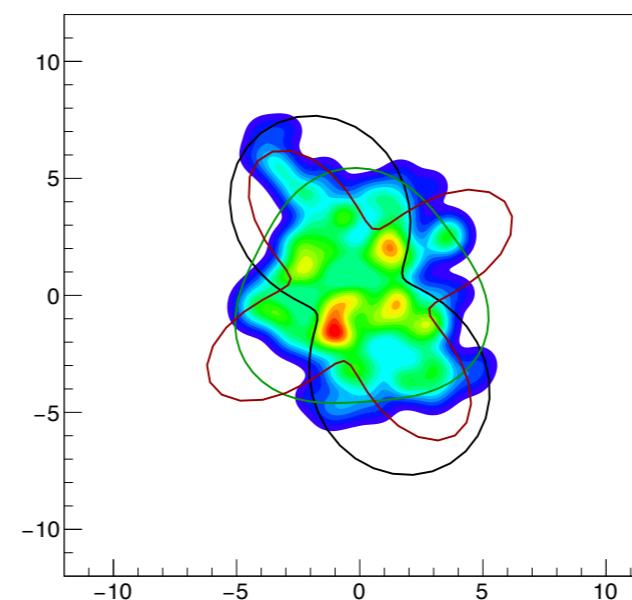
with gaussian smoothing



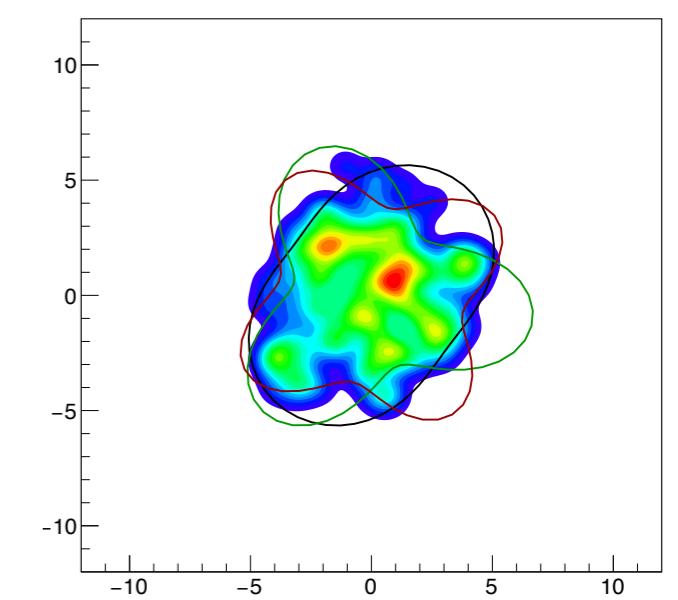
density of w nucl



density of w nucl



density of w nucl



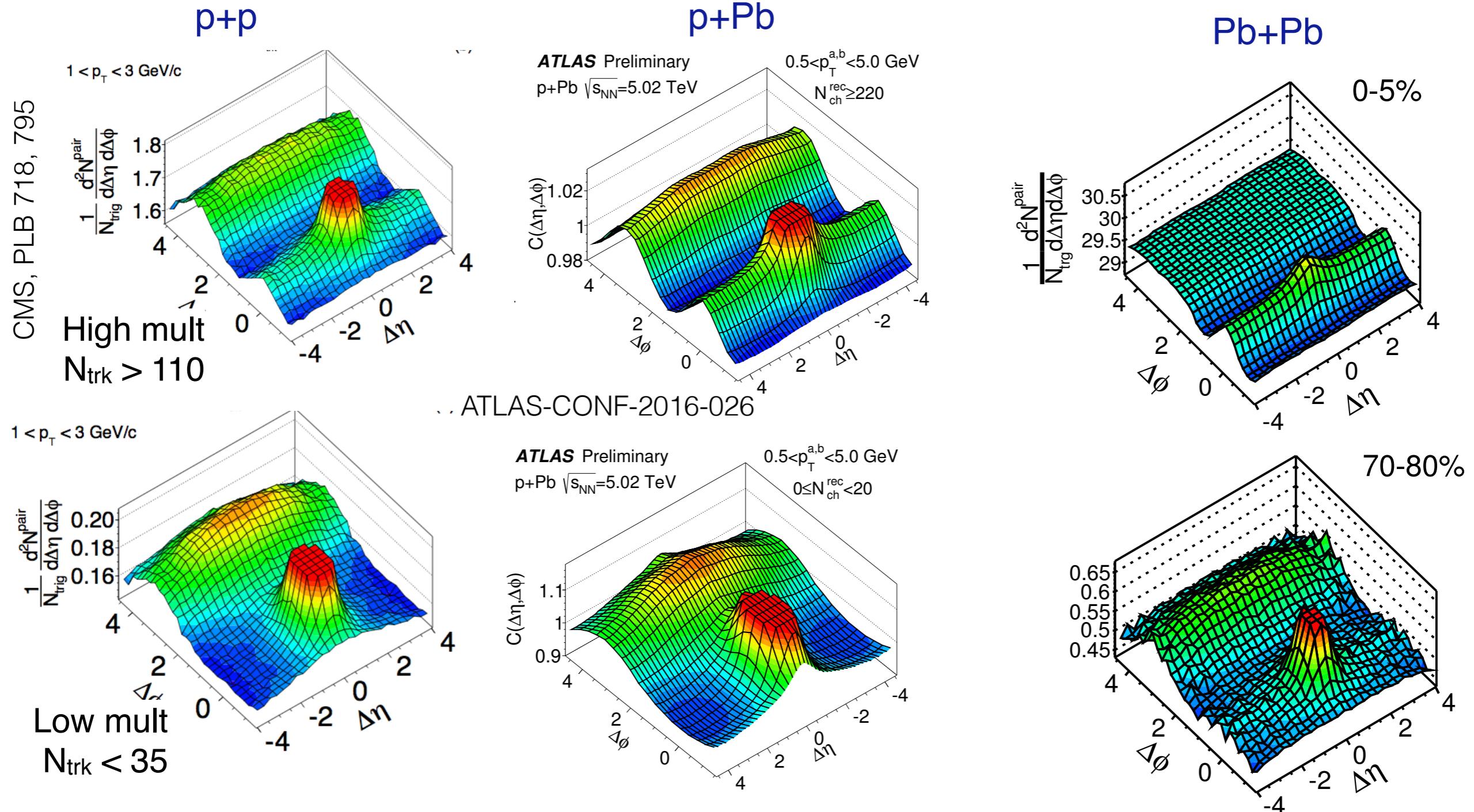
Characterise shape by angular moments:

$$\varepsilon_n = \frac{\sum r^2 (\cos^2 n\varphi + \sin^2 n\varphi)}{\sum r^2}$$

Symmetry planes change from event to event
Orientation measured for every event

Two-particle correlations

Talks | Lakomov, S Padula, A Sickels



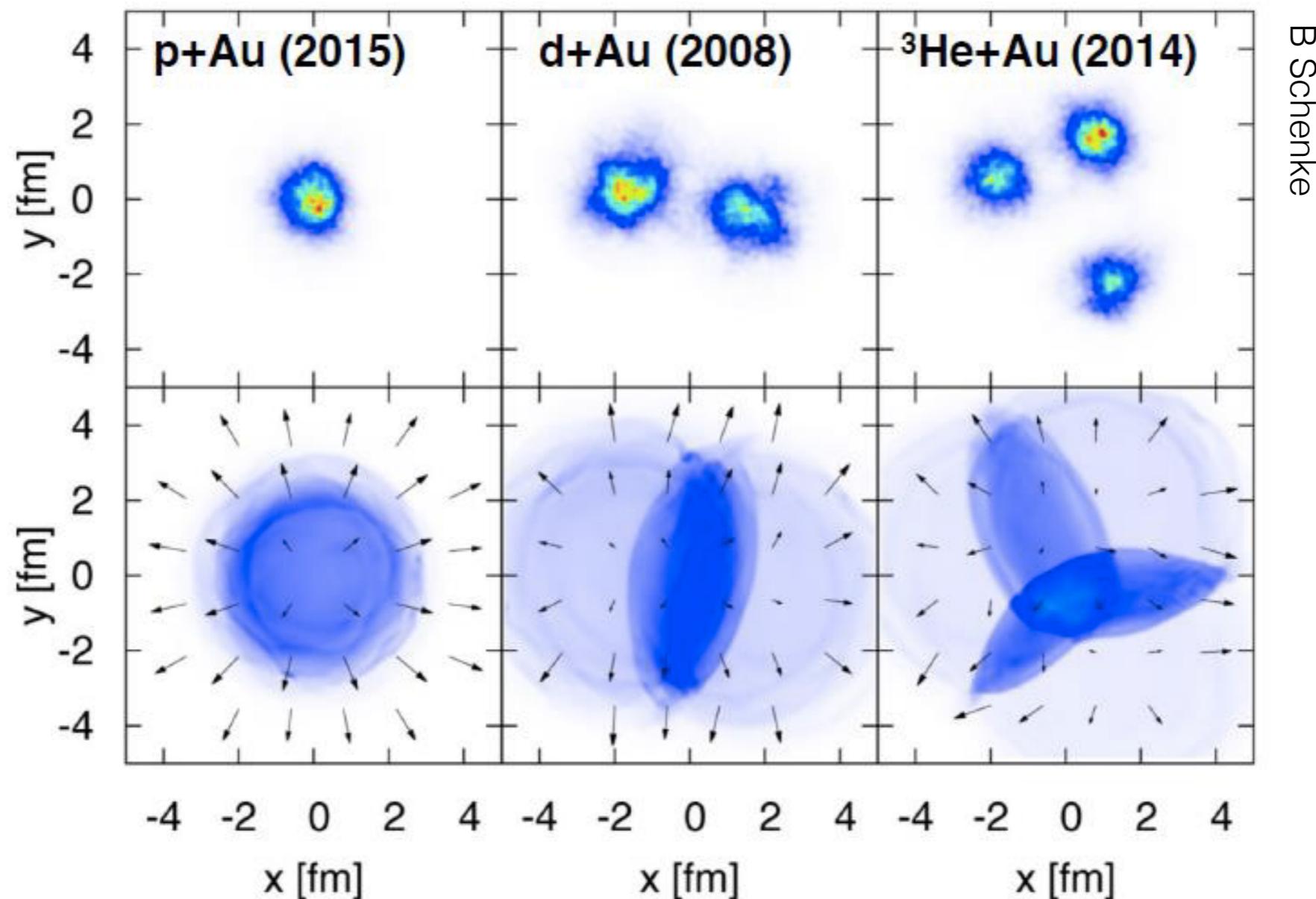
Near side long range correlation: indicates early formation
 Strength strongly depends on multiplicity/centrality
 Looks very much like flow

LHCb, arXiv:1512.00439
 ALICE, PLB 726, 164

CMS, arXiv:1201.3158

Changing the projectile

Talk S Campbell



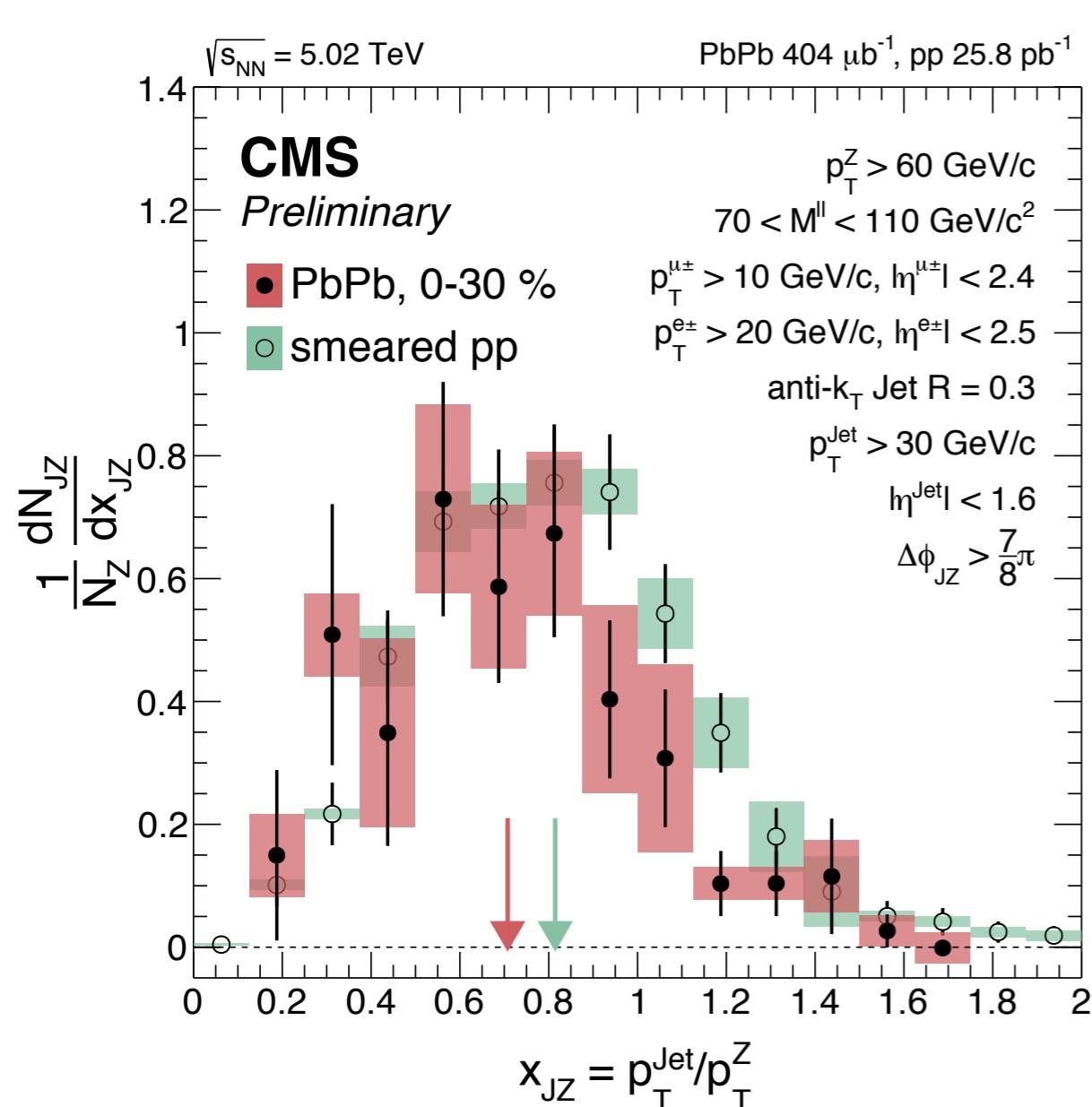
RHIC has collided a variety of small nuclei with Au to explore geometric effects

^3He gives explicit triangular contribution in initial state

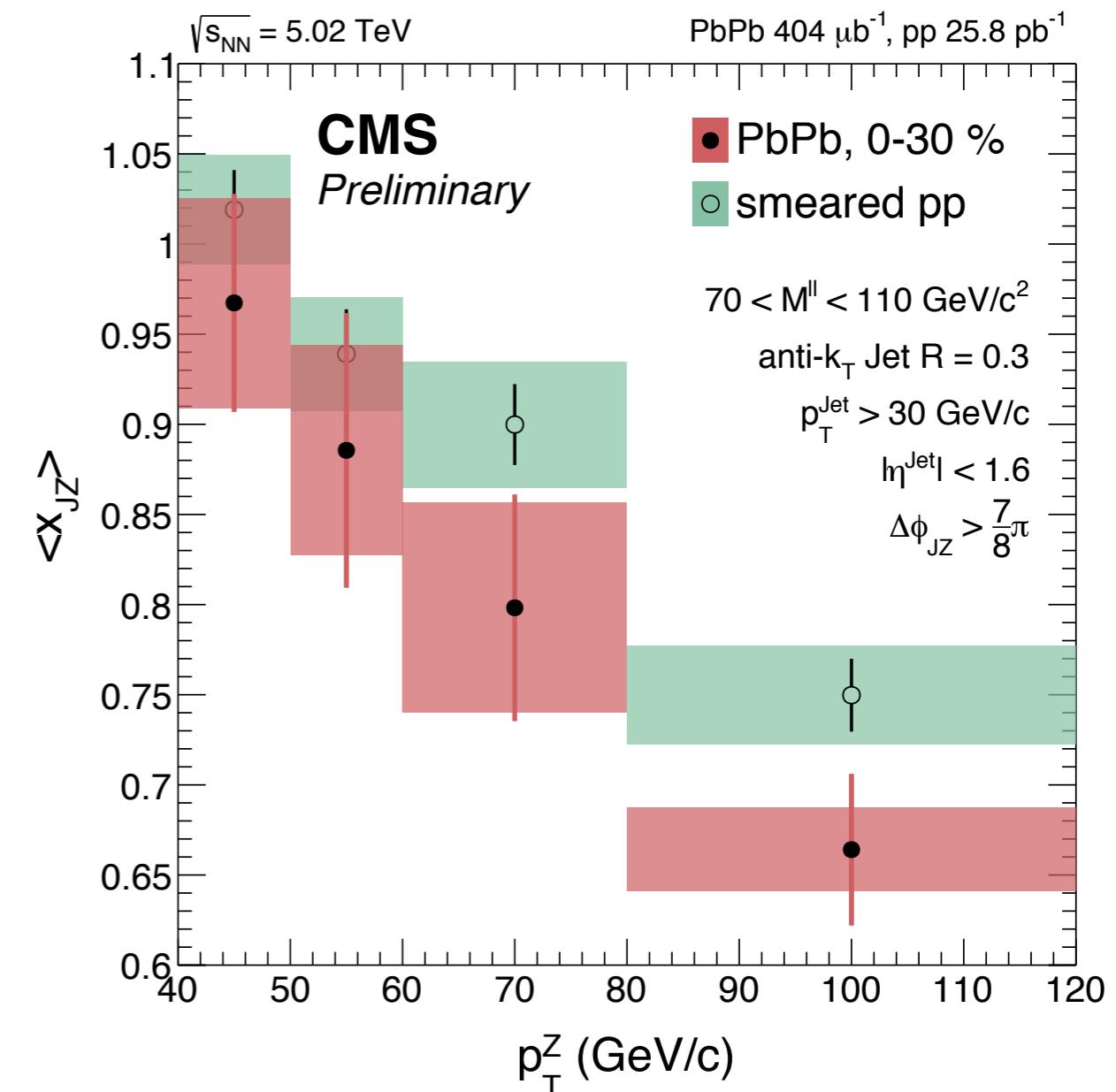
B Schenke

Z-jet imbalance

CMS-PAS-HIN-15-013



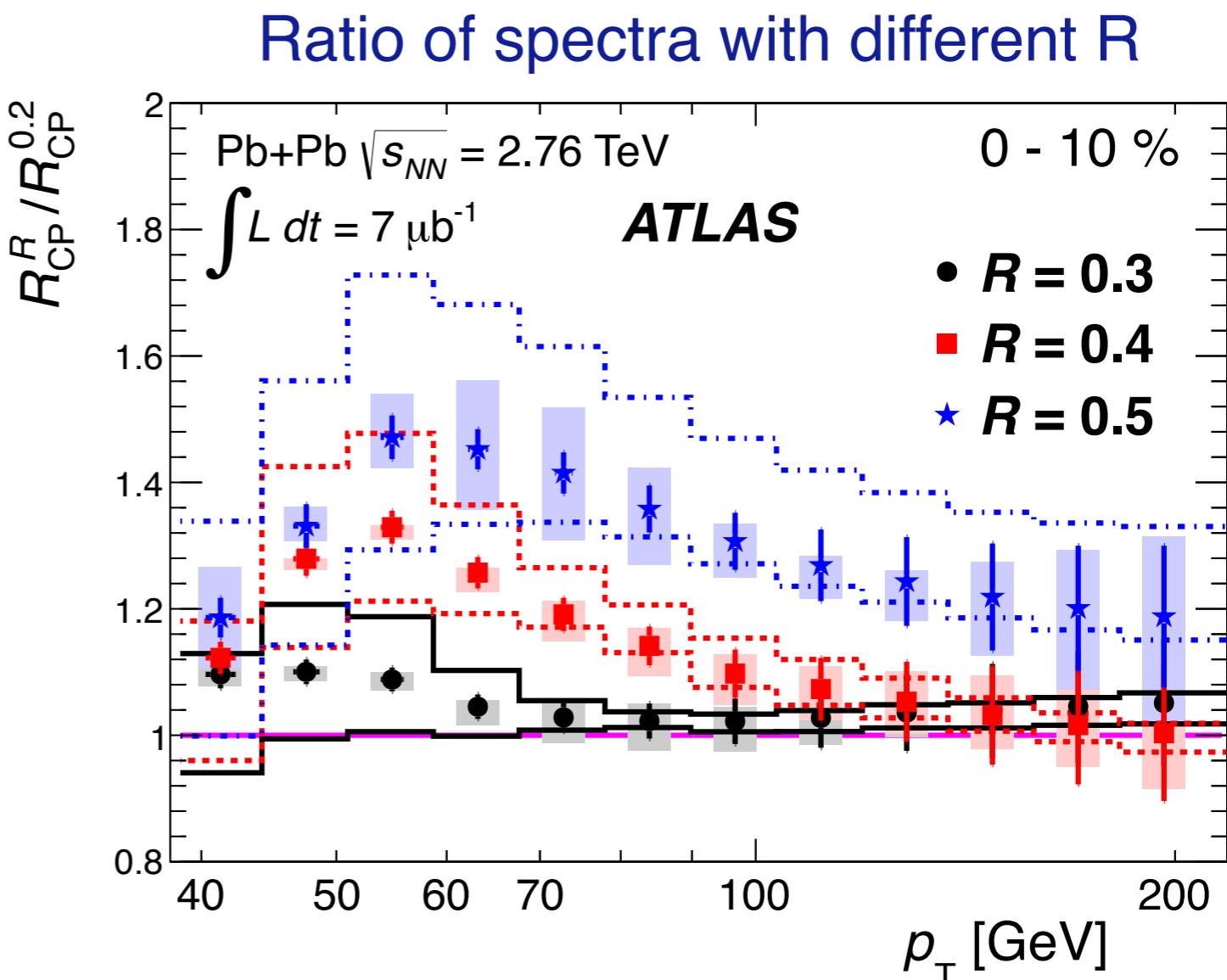
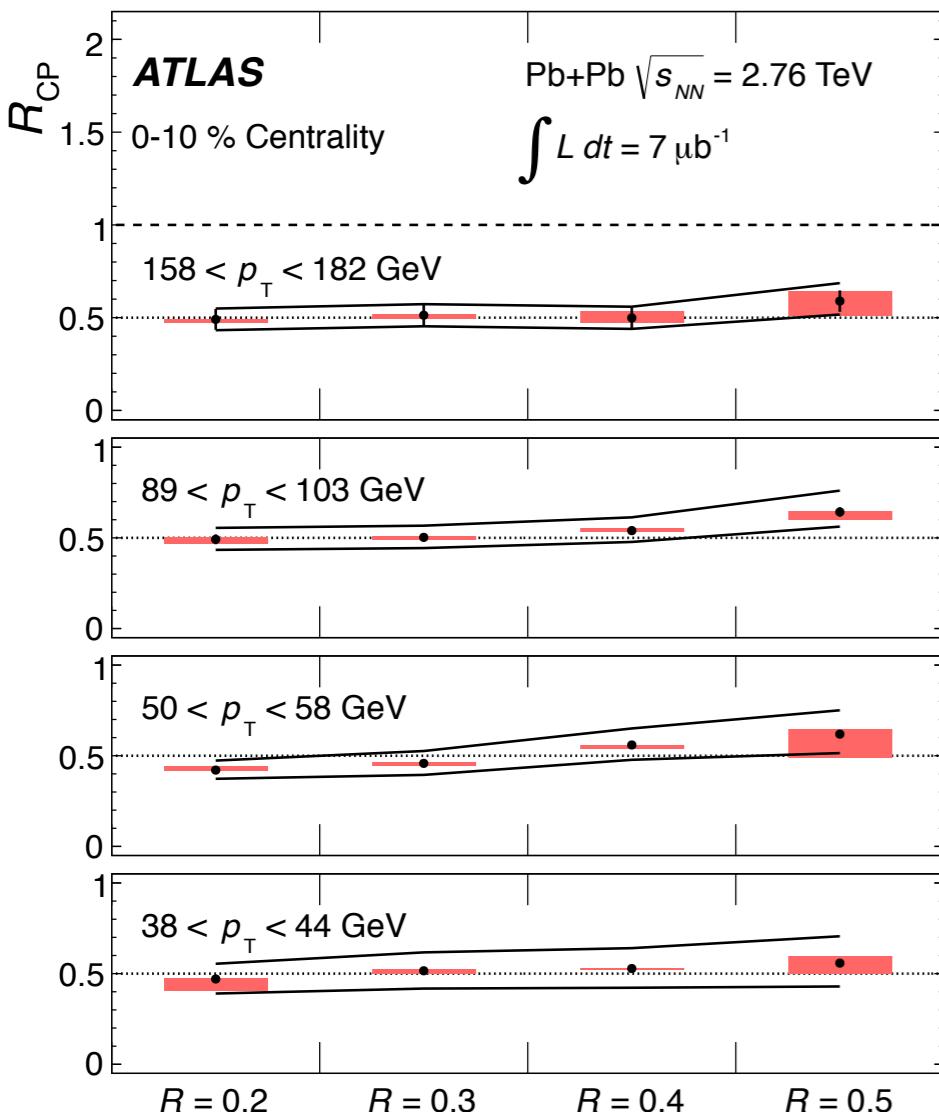
Recoil jet p_T reduced by energy loss



Effect persists up to high p_T

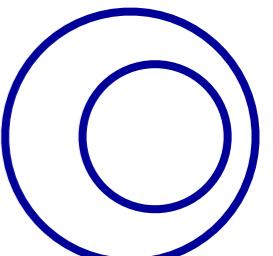
Increasing R to recover the energy

Talks M Spousta, Y-T Chien



ATLAS, arXiv:1208.1967

Larger jet cone: ‘catch’ more radiation → Jet broadening

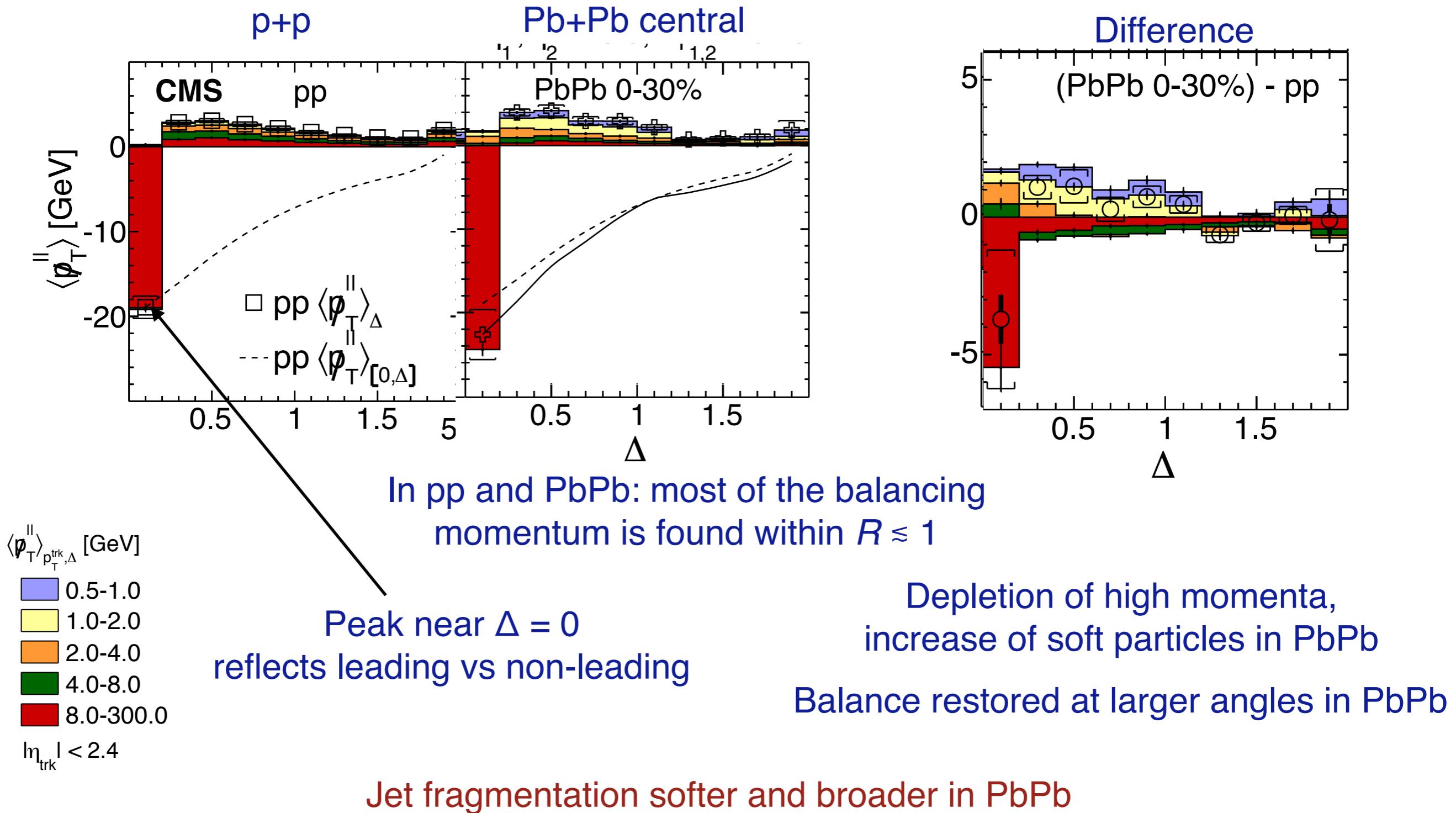


However, $R = 0.5$ still has $R_{AA} < 1$
 – Hard to see/measure the radiated energy

Studying out-of-cone radiation

Momentum balance as a function of distance to the recoil jet axis

CMS, JHEP 2016-01, 006



Outlook/future plans

- 2016 p+Pb run
 - 2 energies: 5 and 8 TeV
 - Explore collectivity in small systems; extend to heavy flavour
 - Mostly at 5 TeV: large MB data sample
 - Initial state: nuclear modification of PDFs with jets, electroweak probes
 - Mostly at 8 TeV: large integrated luminosity
- 2018 Pb+Pb run
 - Increase statistics for hard probes: jet shapes, γ -jet, weak-boson jet measurements

So how is the lost energy distributed?

Most results point towards

- Relatively large loss: 5-10 GeV per jet
- Distributed to large angles ($R > 0.5$) and soft particle production (few GeV)

This is dramatically different from vacuum jets:

- Most energy carried by a small number of particles in the jet core $R < 0.2$

... But reconstructed jets in Pb—Pb events look quite similar to pp

Focus of the field: understanding this apparent paradox:

- Measurements: new observables, e.g. jet shape
- Modeling: event generators (JEWEL, YaJEM etc)
- Theory: exploring multi-particle emission in QCD
(anti-angular ordering, democratic splittings due to color flow, thermalisation etc)

Intro 2: Hard and soft processes

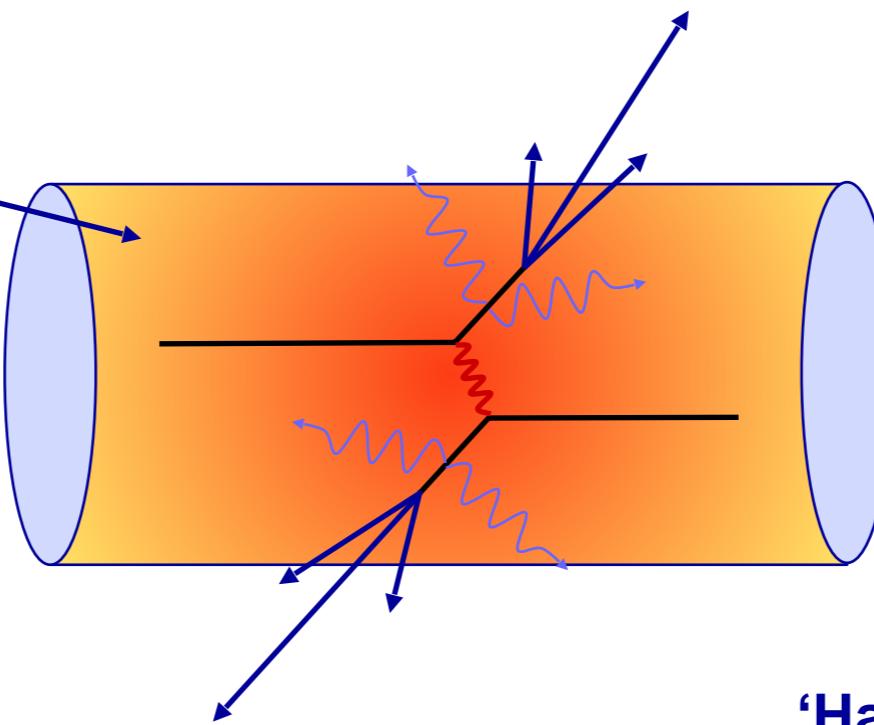
Heavy-ion collisions produce
'quasi-thermal' QCD matter

Dominated by soft partons
 $p \sim T \sim 100\text{-}300 \text{ MeV}$

'Bulk observables'

Study hadrons produced by the QGP
Typically $p_T < 1\text{-}2 \text{ GeV}$

Physical model/picture:
hydrodynamical flow,
thermodynamics



'Hard probes'

Hard-scatterings produce 'quasi-free' partons
⇒ Probe medium through energy loss
 $p_T > 5 \text{ GeV}$

Physical model/picture:
hard scattering+parton energy loss

Two basic approaches to learn about the QGP

- 1) Bulk observables
- 2) Hard probes

Radial and elliptic flow

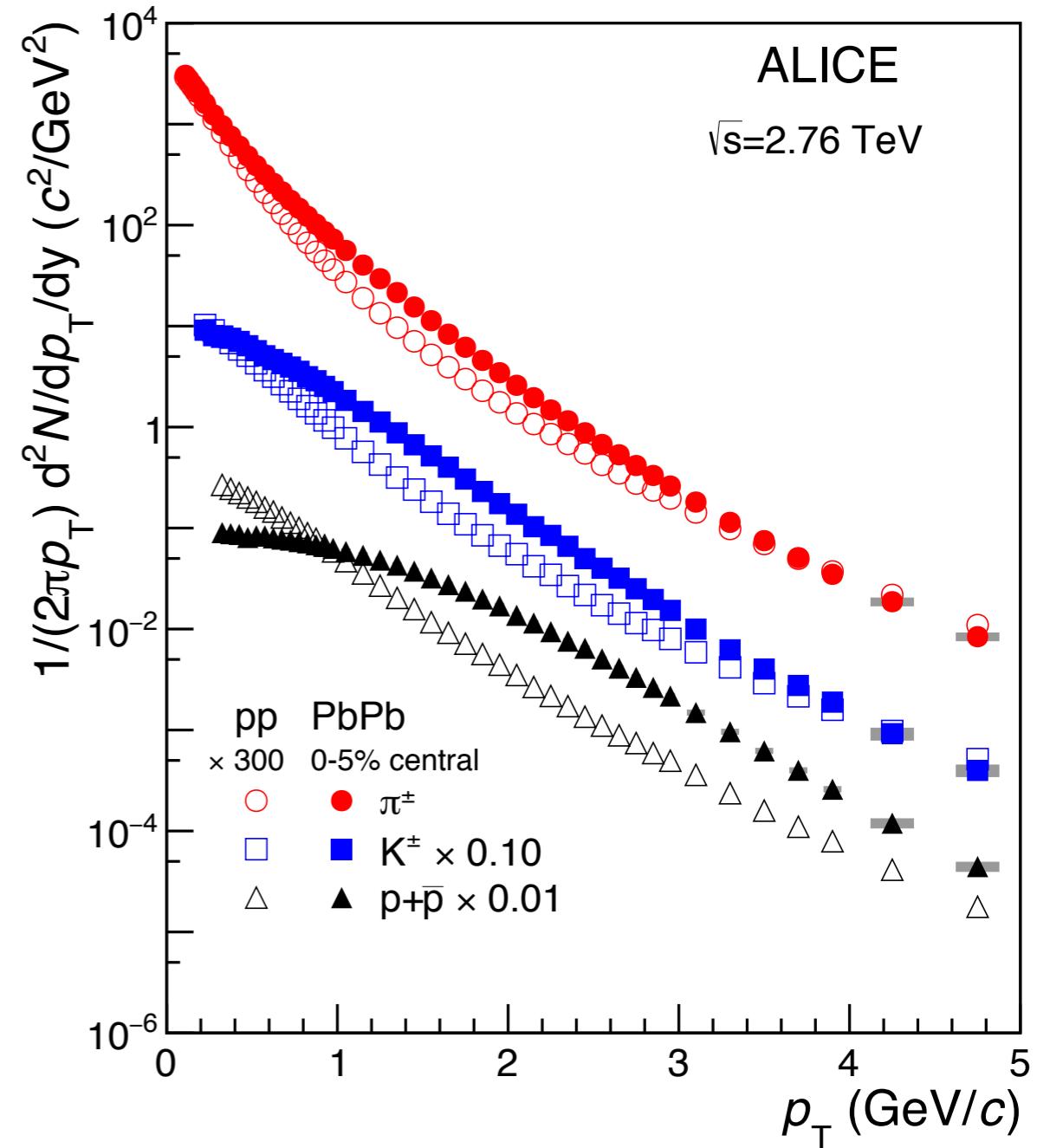
ALICE. PLB 736. 196

- Spectra change from pp to Pb+Pb:
- Increase in mean p_T
 - Larger effect for larger mass

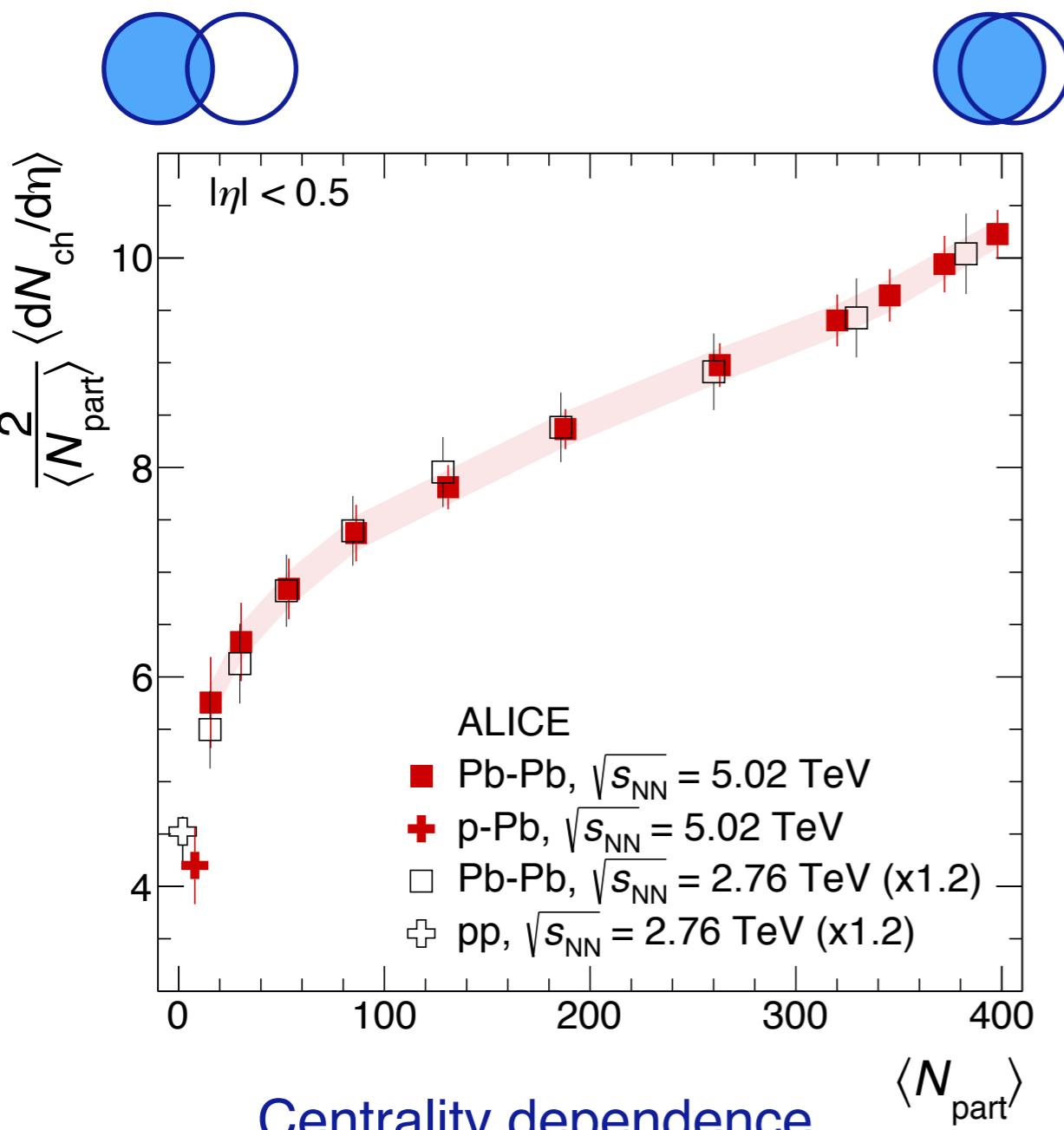
First indication of collective behaviour

Pressure leads to radial flow

Same Lorentz boost (β) gives larger momentum for heavier particles
 $(m_p > m_K > m_\pi)$

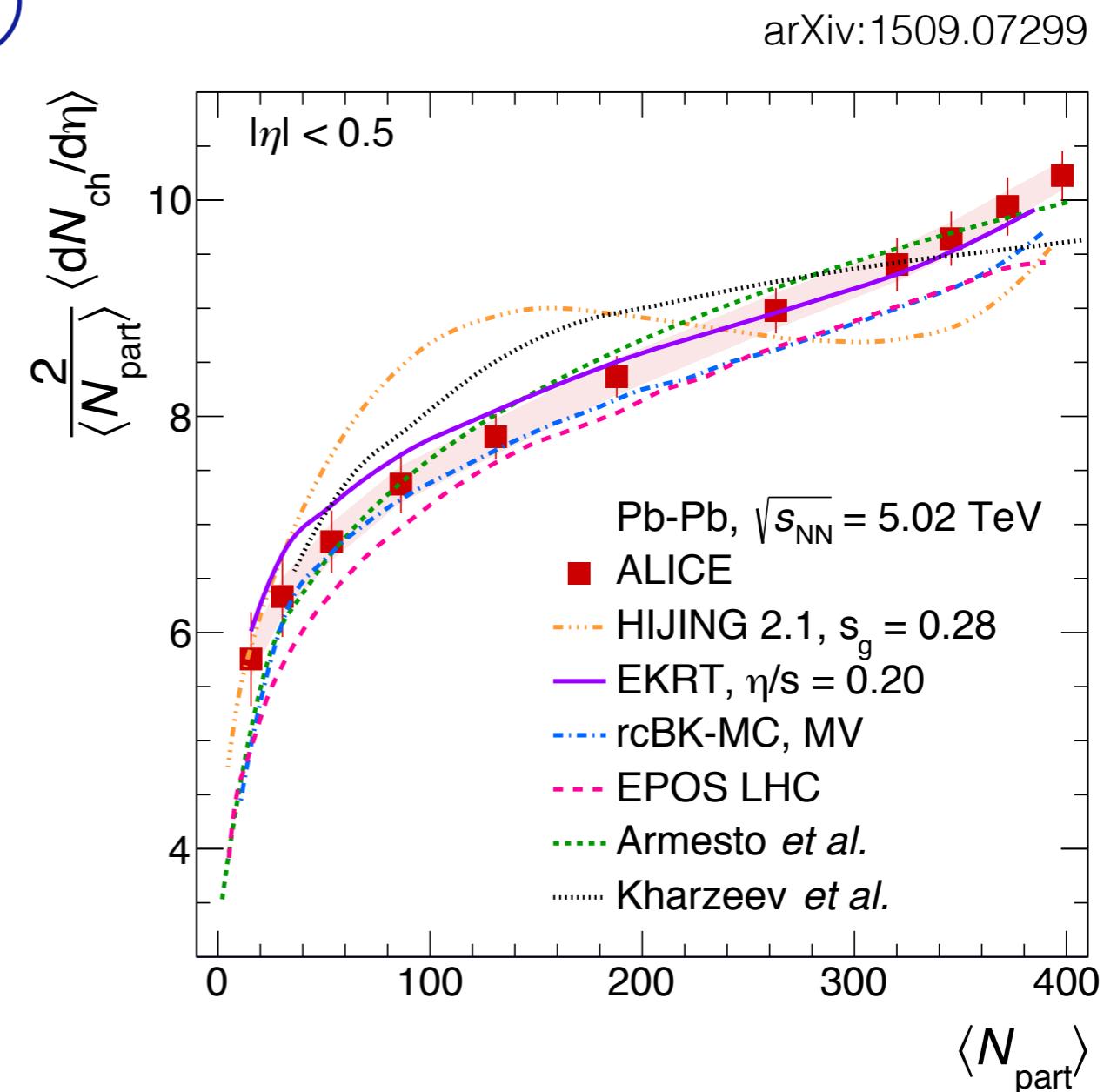


Multiplicity vs centrality PbPb



Centrality dependence
very similar at 5.02 and 2.76 TeV
(overall factor 1.2)

Driven by geometry
No change in contribution
hard vs soft processes



Model comparisons:
Soft physics models agree
Hijing: some deviations

Comparison to pQCD expectation

JET paper: $\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$

Burke et al, arXiv:1312.5003

HTL expectation: $\hat{q} = 2\pi C_R \alpha_s^2 N \ln\left(\frac{q_{max}^2}{m_D^2}\right)$
 $N = \frac{\zeta(3)}{\zeta(2)} \left(1 + \frac{1}{4} N_f\right) T^3$

$$\hat{q} \approx 24 \alpha_s^2 T^3 \approx [2 T^3]$$

Constant depends on α_s (took $\alpha_s = 0.3$) and jet E (via \ln)
plus uncertainties due to assumptions, low momentum cut-off etc

Values found are in ‘reasonable agreement’ with pQCD estimate