# Heavy Ion Physics

## Concepts, recent results and (some) future directions

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24-28 April 2017, Granada, Spain

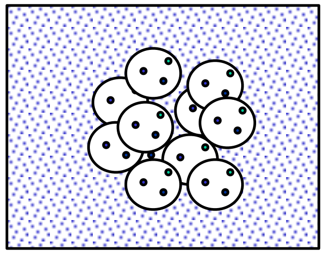
Physics Utrecht
ΕΜΜΕΦ

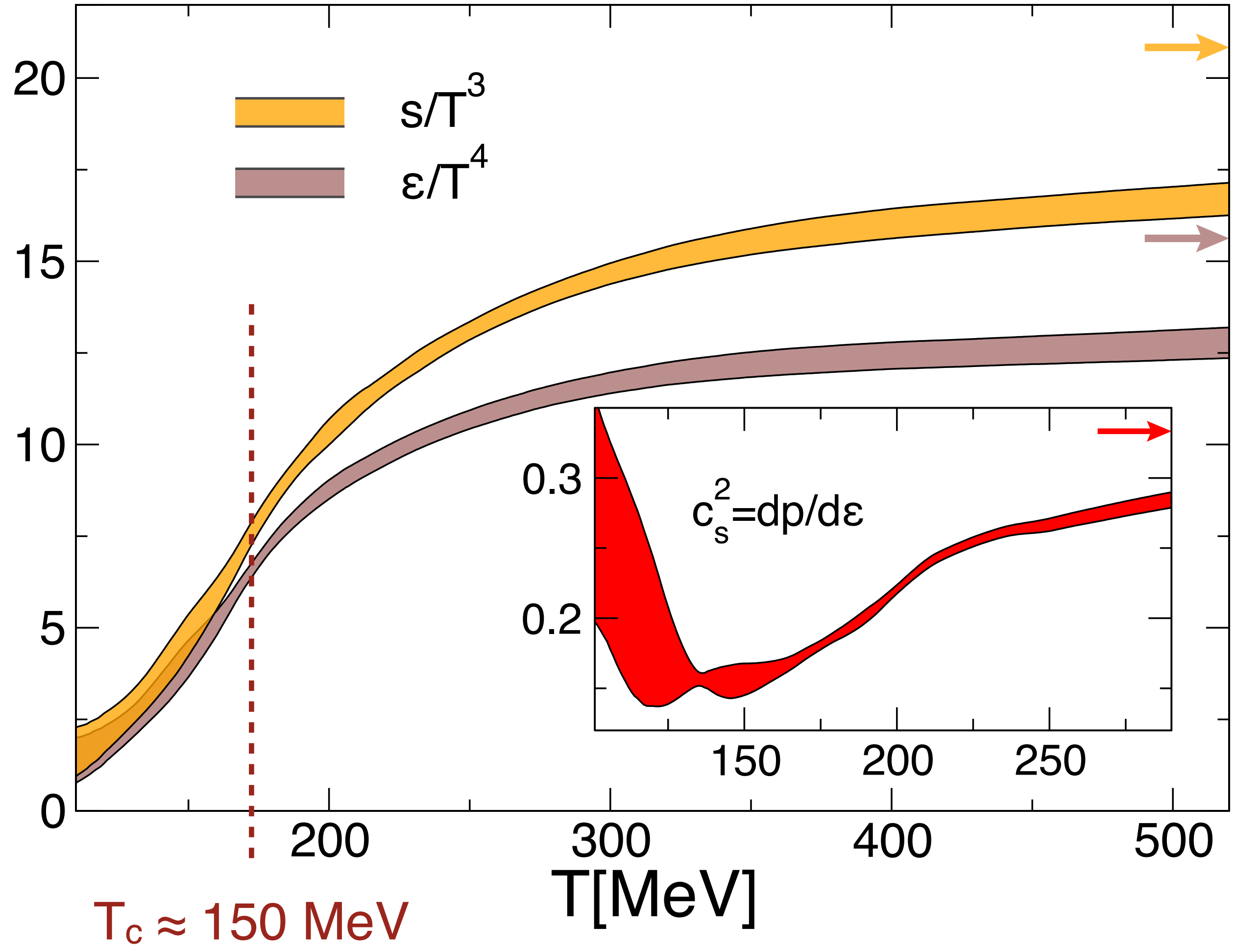
NIKHEF

# Introduction: Heavy Ion Physics

Equation of state
Energy density vs temperature

Nuclear matter



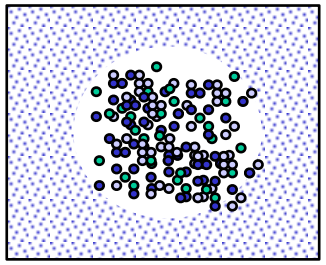


Borsanyi et al, PLB 730, 99

$\varepsilon \propto gT^4$

$g$: degrees of freedom

Quark Gluon Plasma



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

# Intro: RHIC and LHC

RHIC, Brookhaven

**Au+Au $\sqrt{s_{NN}}$= 200 GeV**

First run: 2000

STAR, PHENIX,
(PHOBOS, BRAHMS)

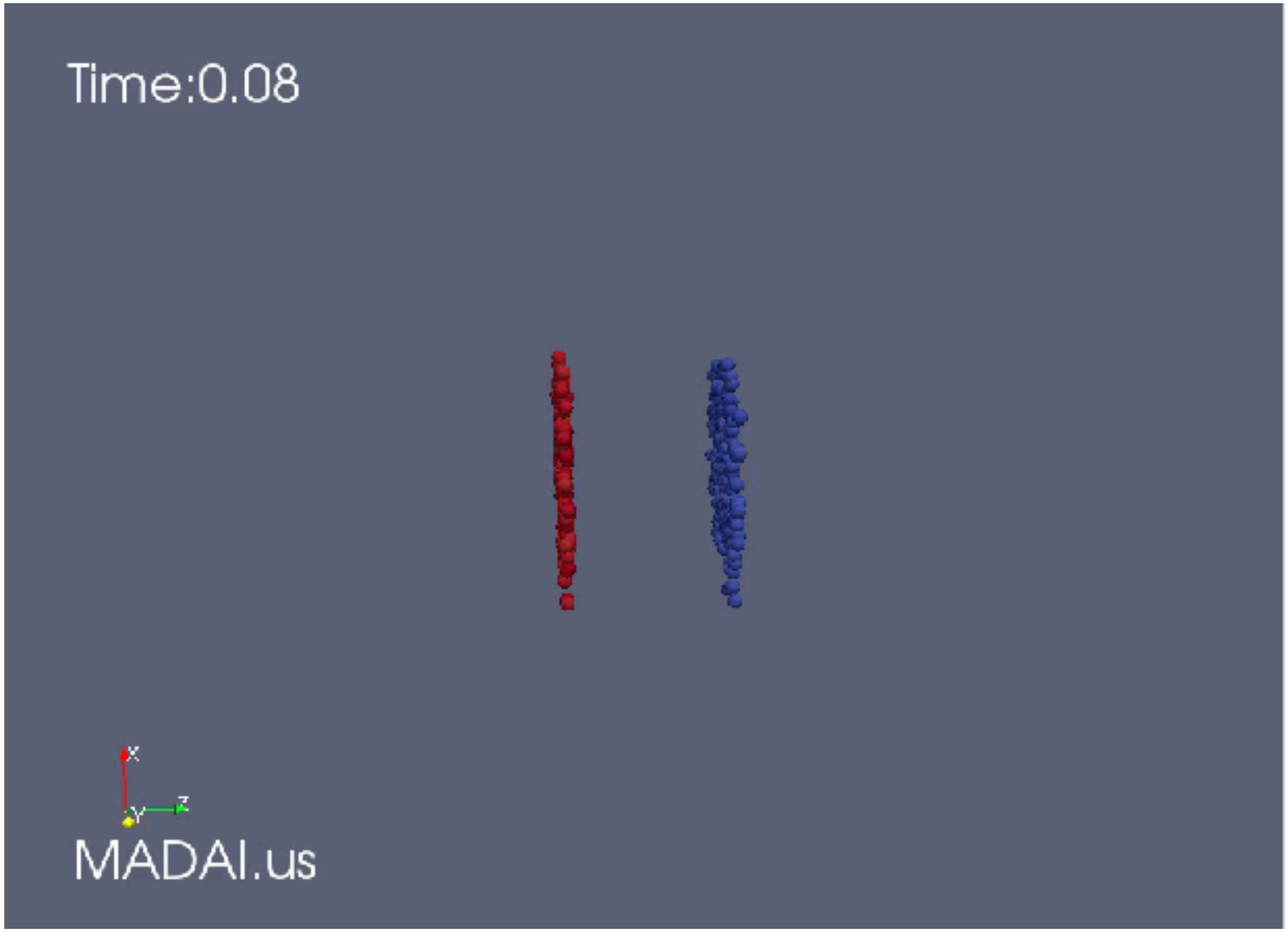
LHC, Geneva

**Run 2: Pb+Pb $\sqrt{s_{NN}}$= 5020 GeV**

First run: 2009/2010

ALICE, ATLAS,
CMS, LHCb

# Soft probes: anisotropic flow



MADAI

Initial state (spatial) anisotropy ⇒ Pressure gradients

⇒ anisotropic flow: momentum space anisotropy

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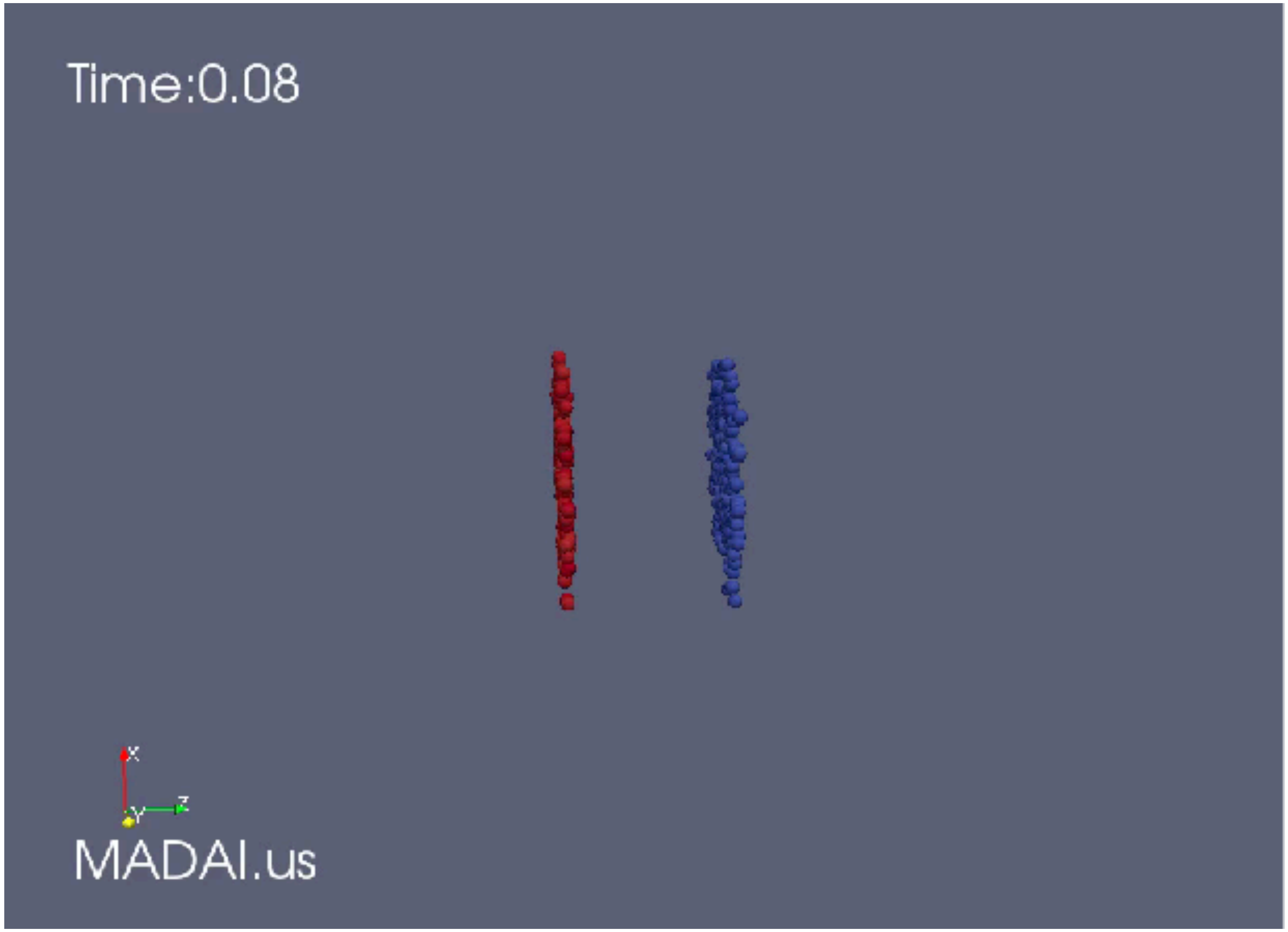

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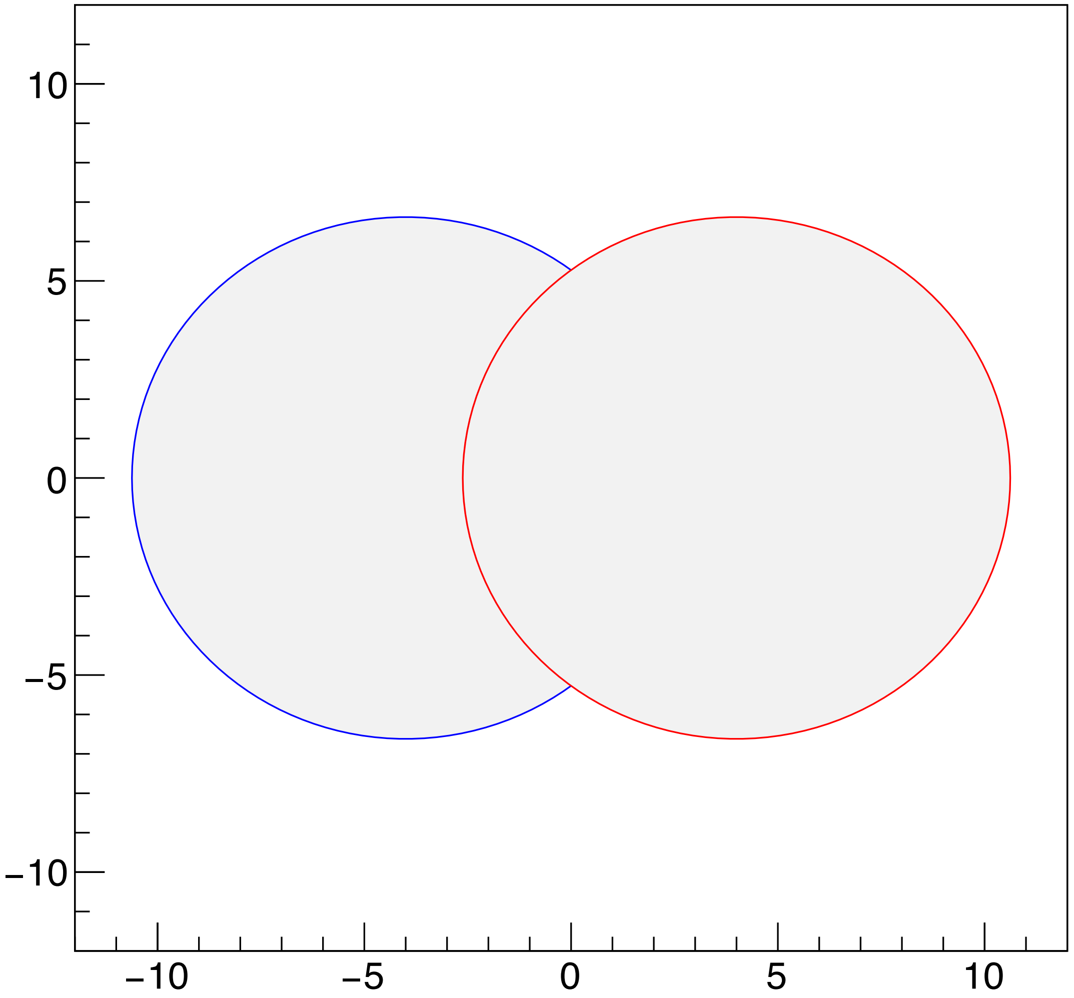
# Azimuthal anisotropy: initial and final states

MC event: location of nucleons



Characterise shape by angular moments:

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

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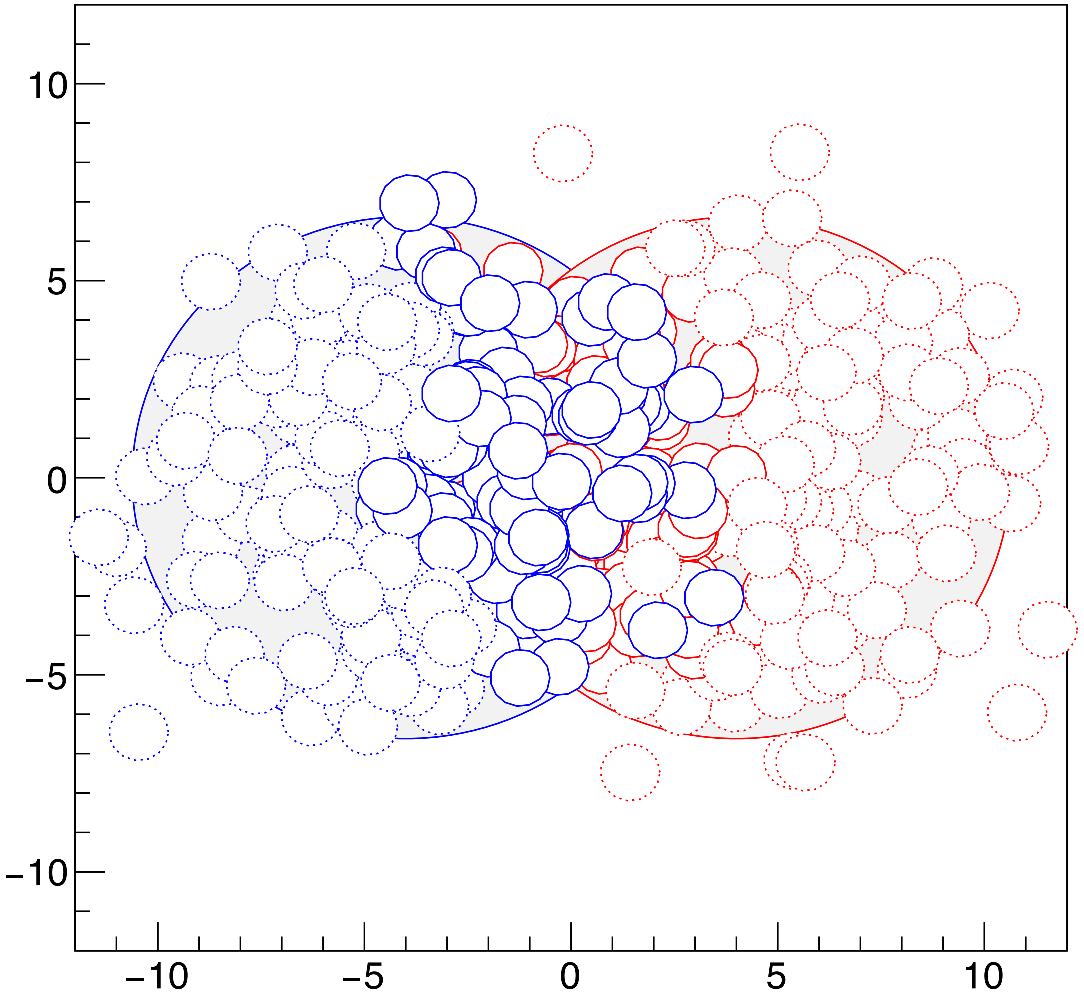

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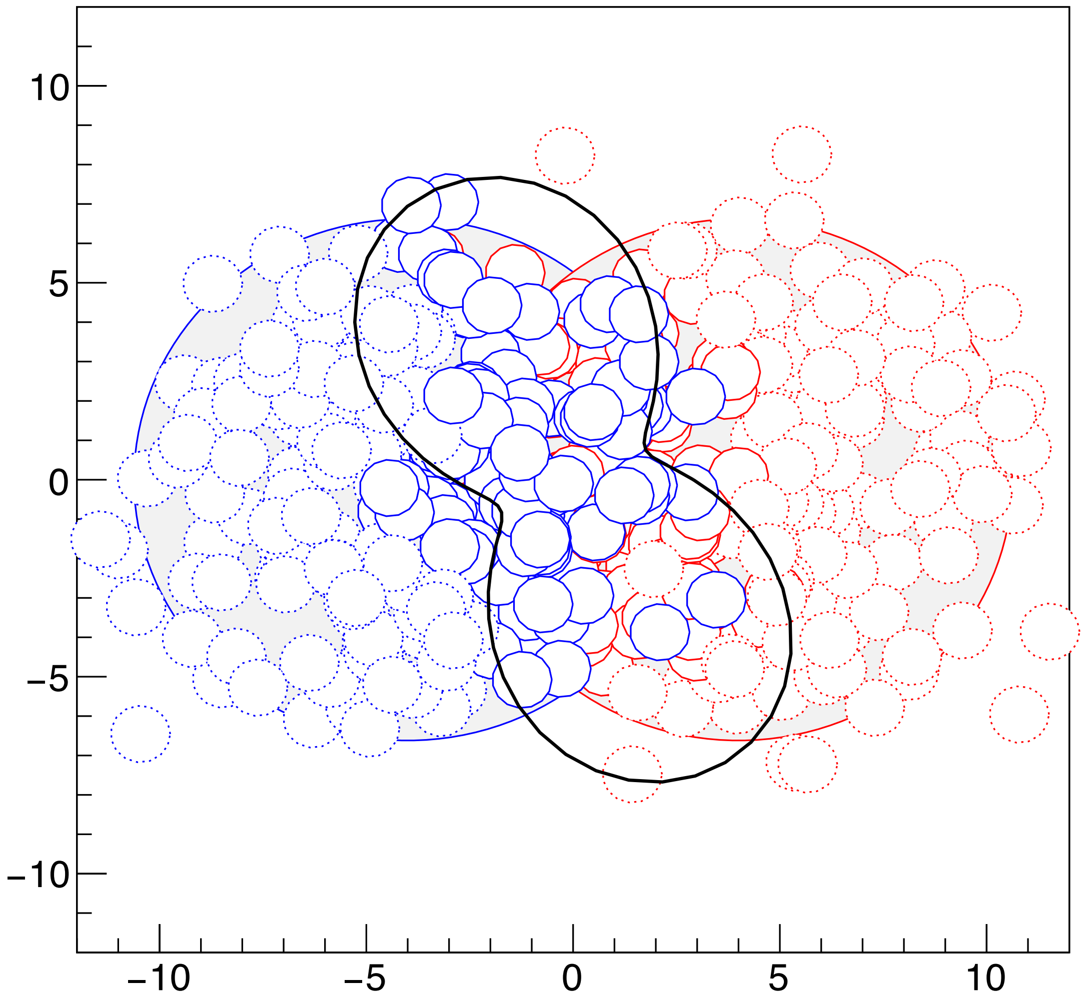

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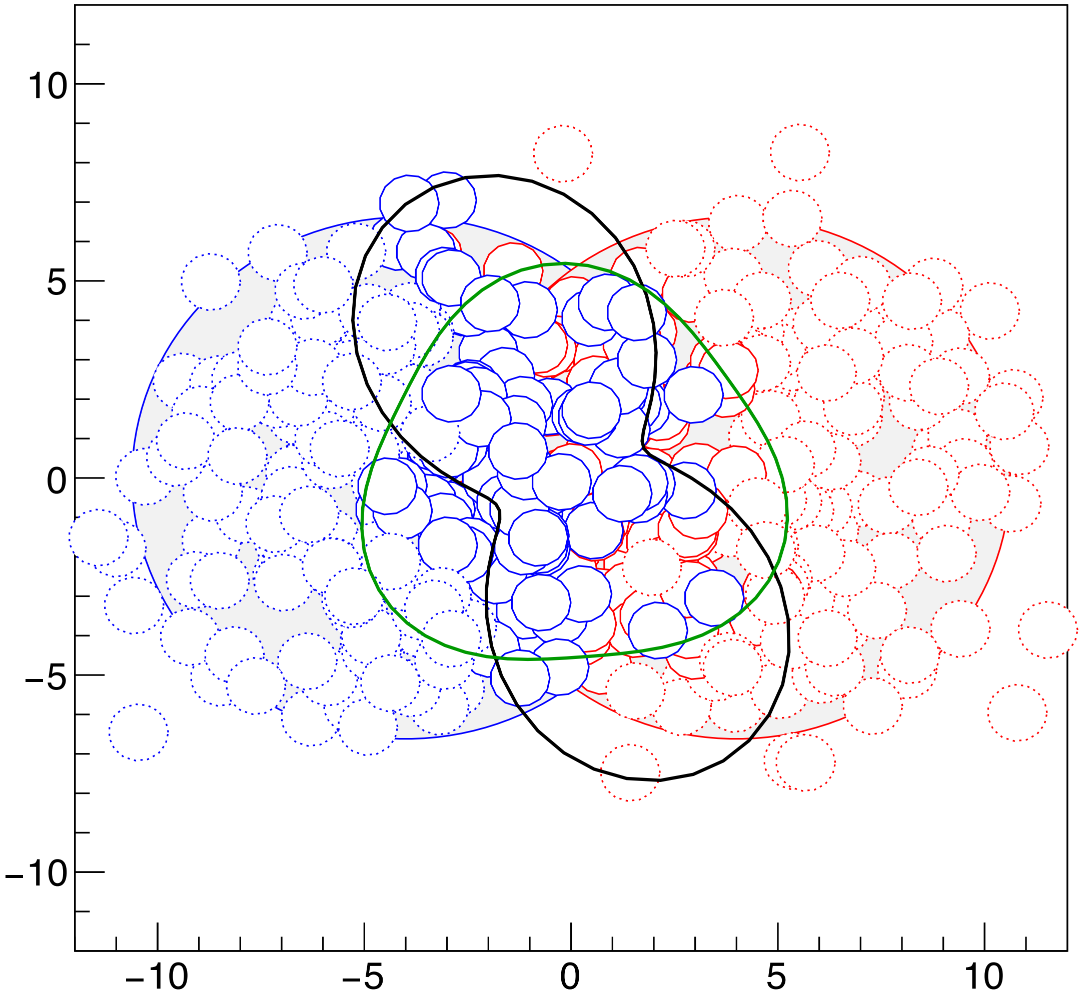

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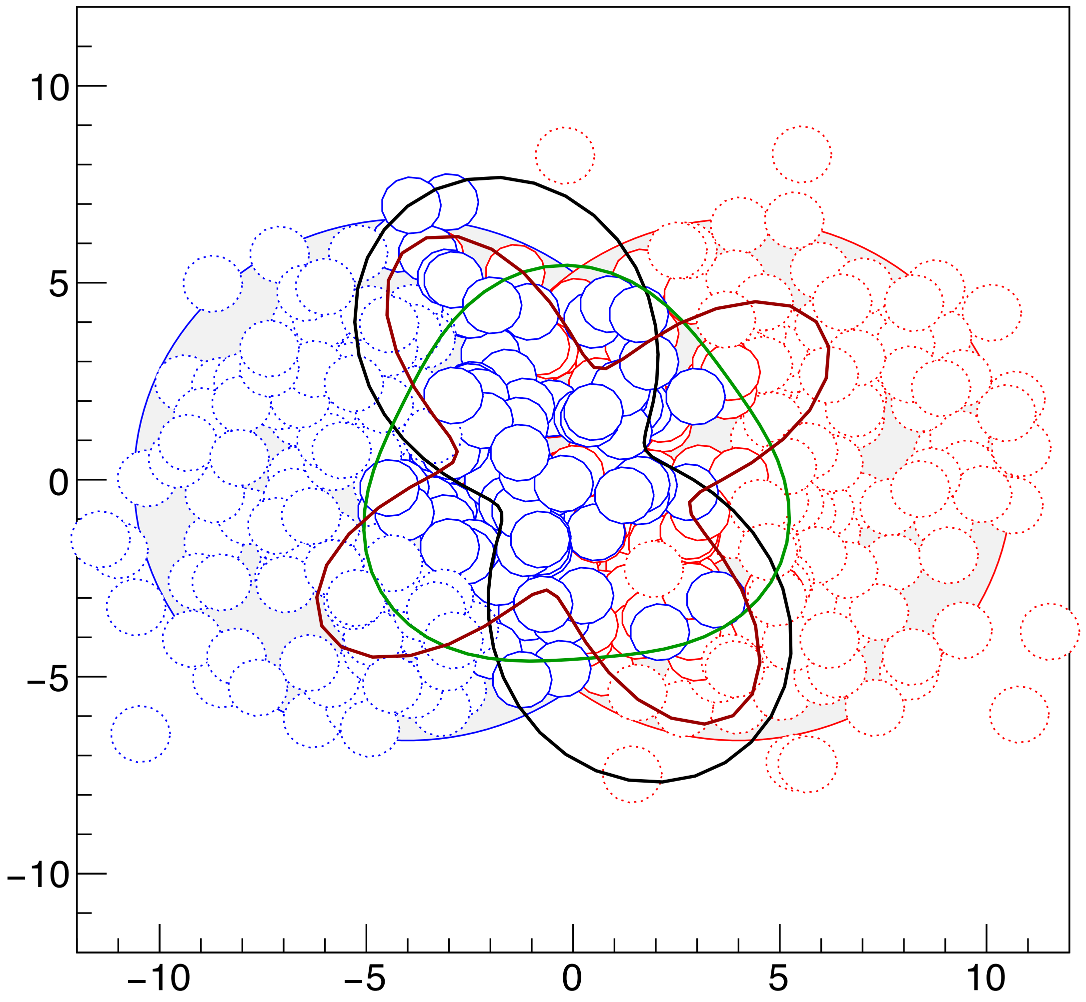

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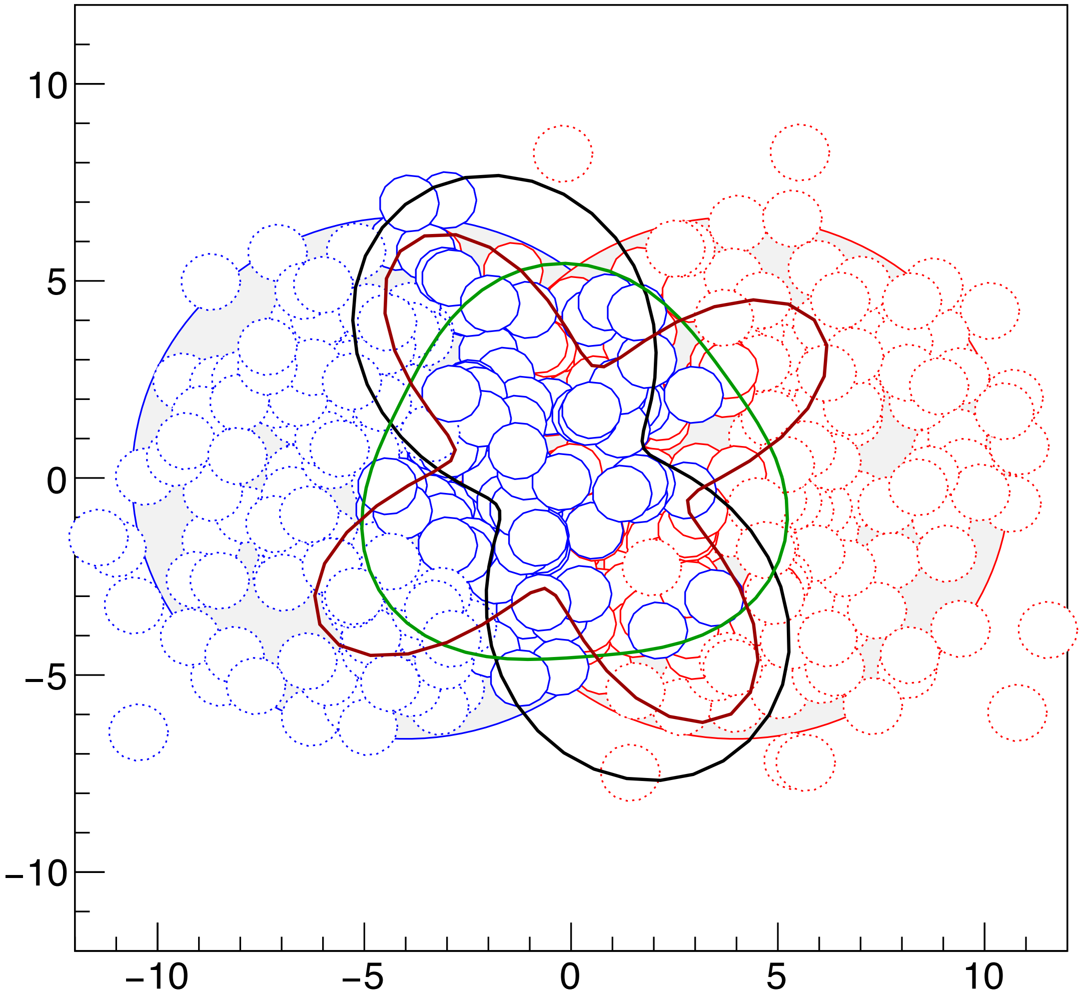

$$\nabla p = \rho \frac{d\vec{v}}{dt}$$

Initial state spatial anisotropies $\varepsilon_n$ are transferred into final state momentum anisotropies $v_n$ by pressure gradients, flow of the Quark Gluon Plasma

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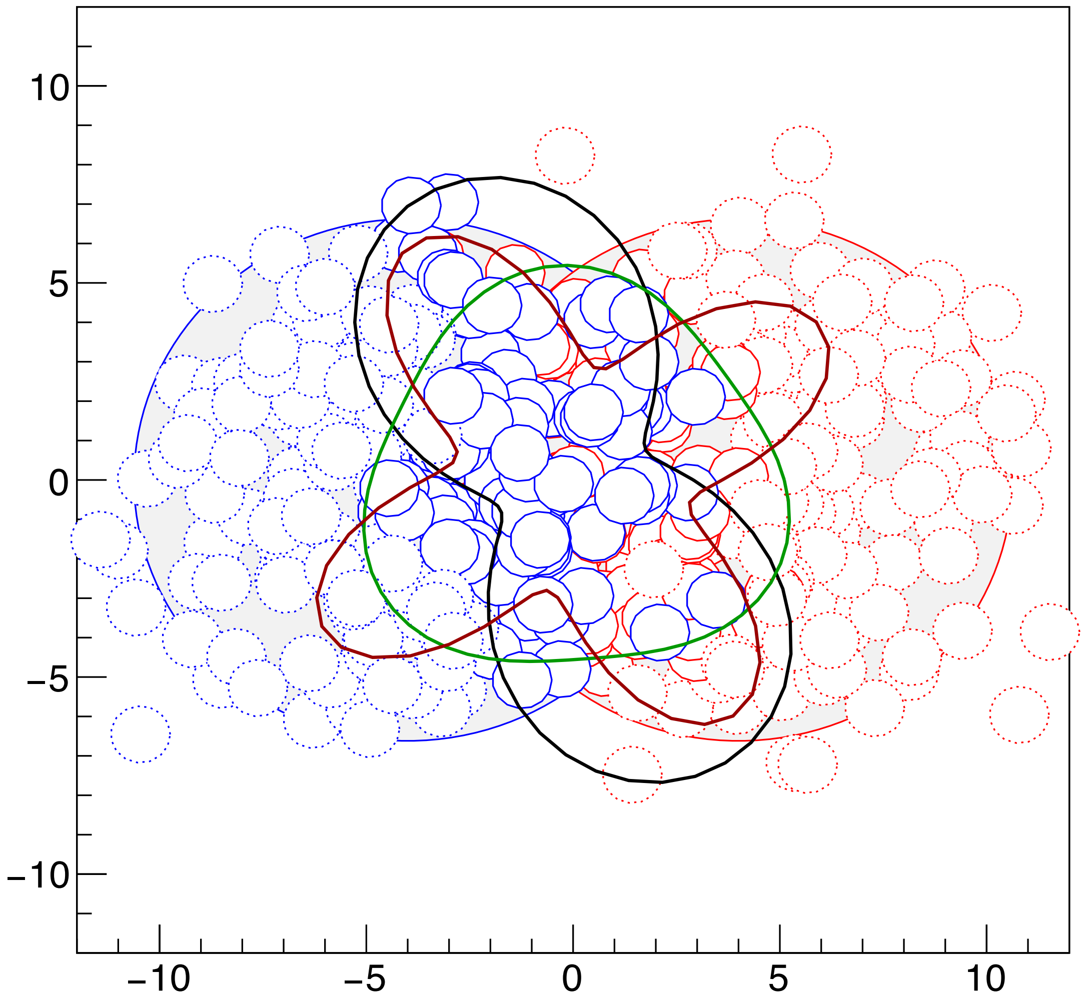

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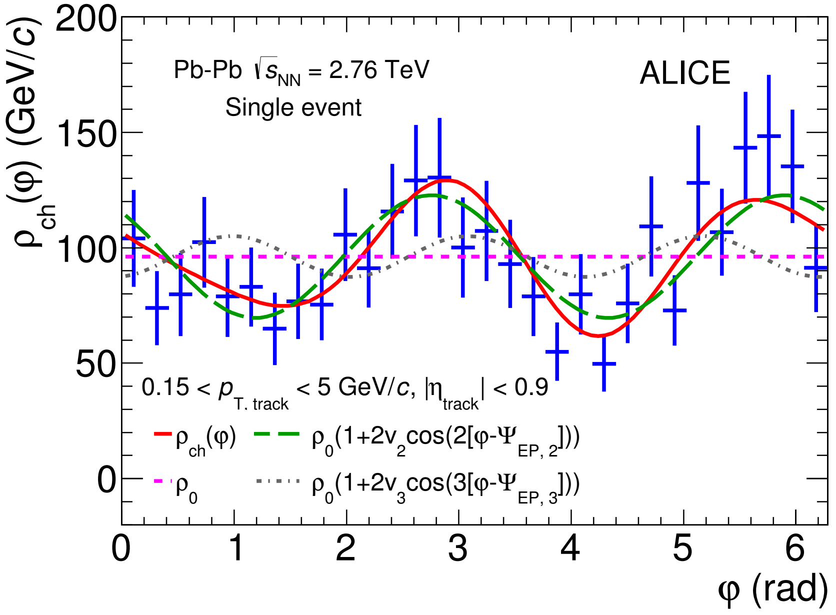
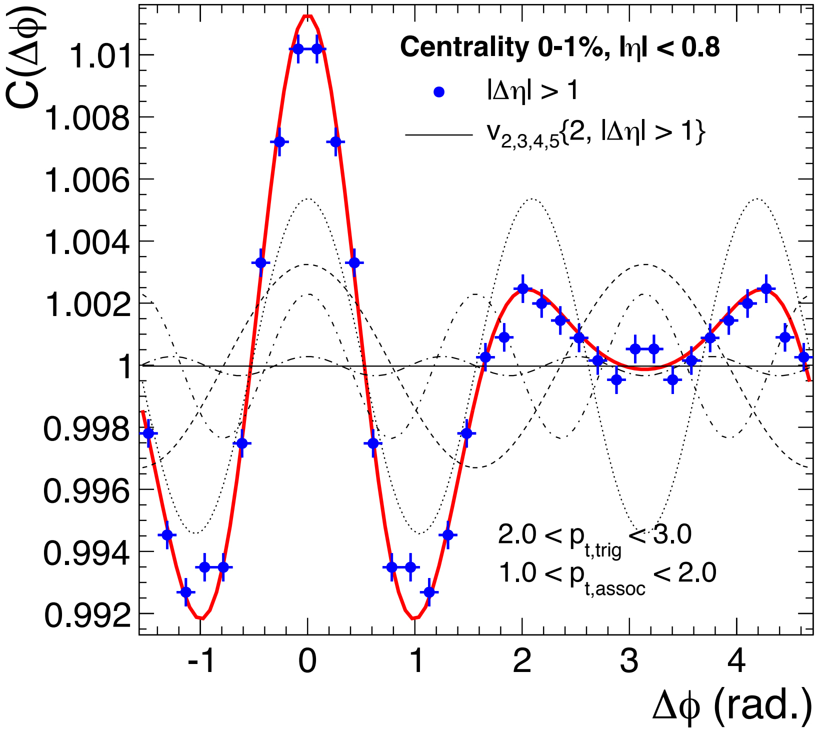
## Azimuthal distribution single event



ALICE, PLB 753, 511

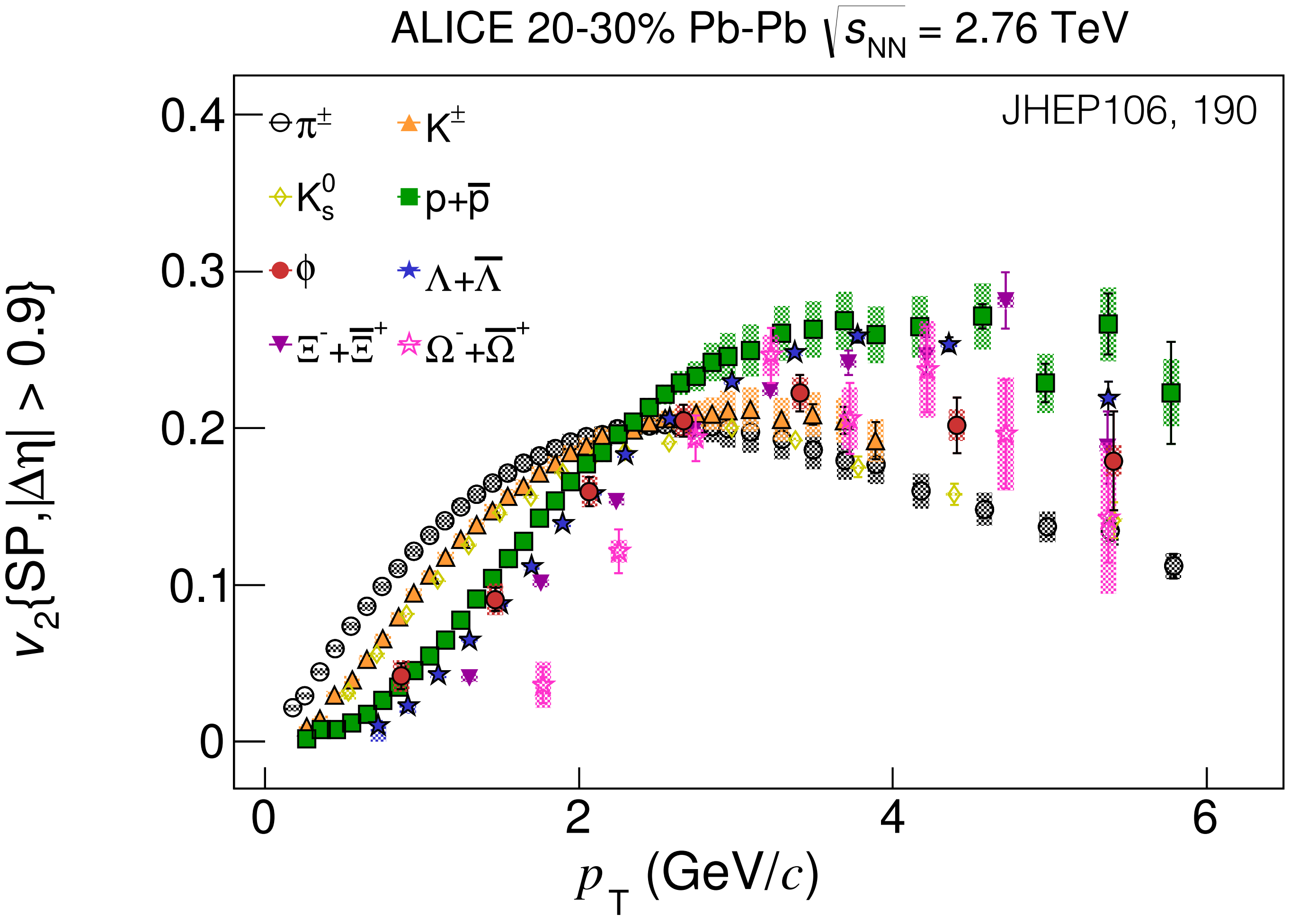
## Sum over many events



ALICE PRL. 107, 032301

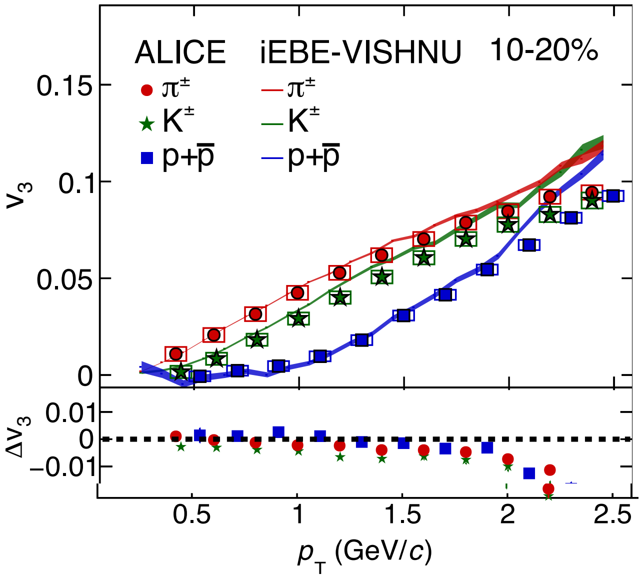
Initial state spatial anisotropies $\varepsilon_n$ are transferred into final state momentum anisotropies $v_n$ by pressure gradients, flow of the Quark Gluon Plasma

# Anisotropic flow results



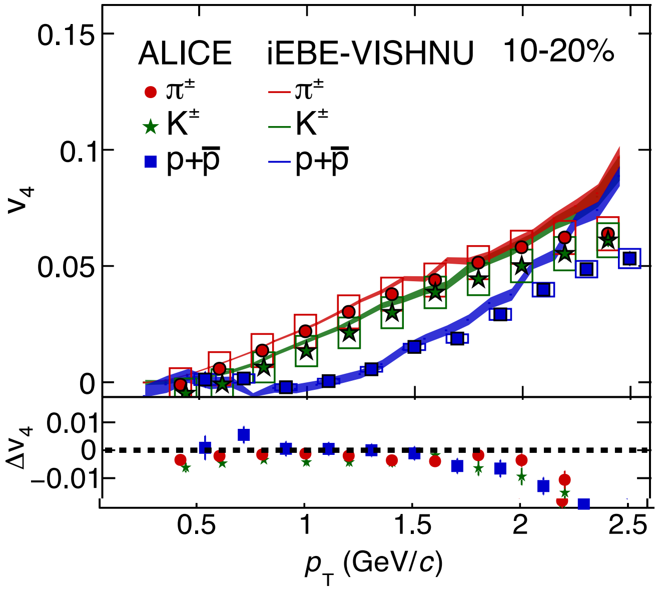
I-PUB-82677

$v_3$



arXiv:1606.06057

$v_4$



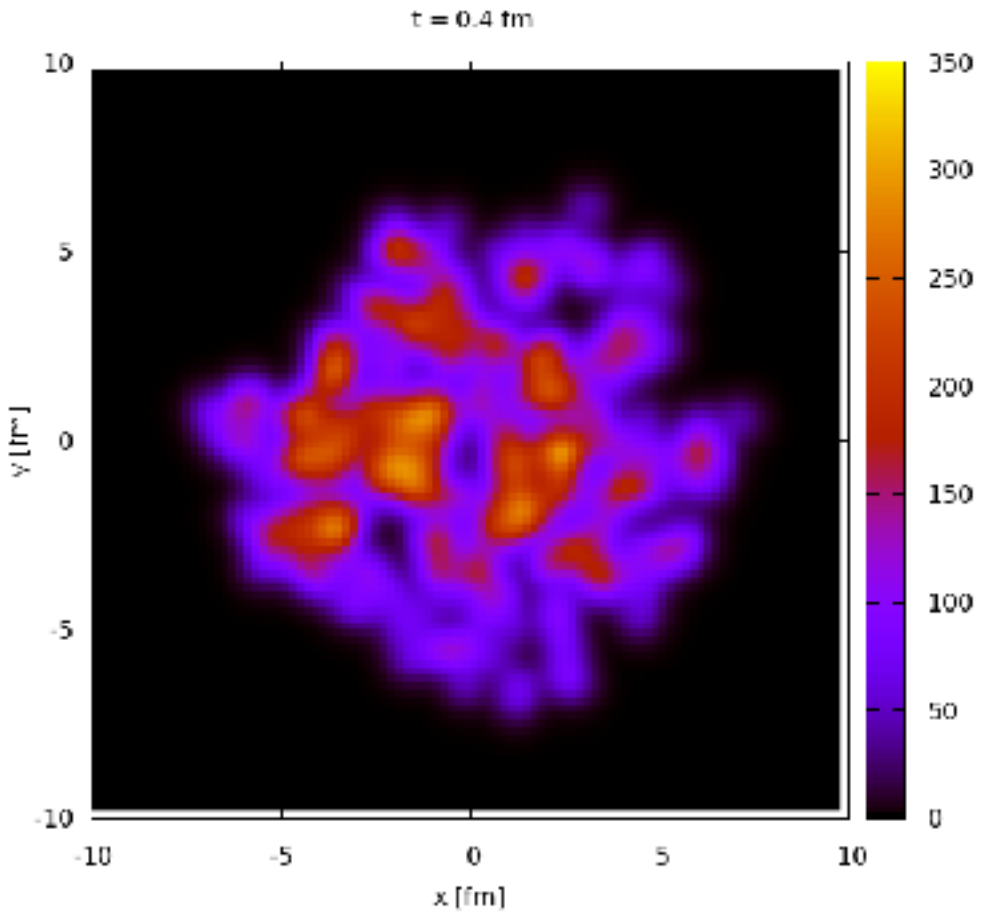
Mass-dependence of $v_2$ measures flow velocity: $p = \gamma m \beta$

Tests hydrodynamical description, freeze-out models

# Higher harmonics and viscosity

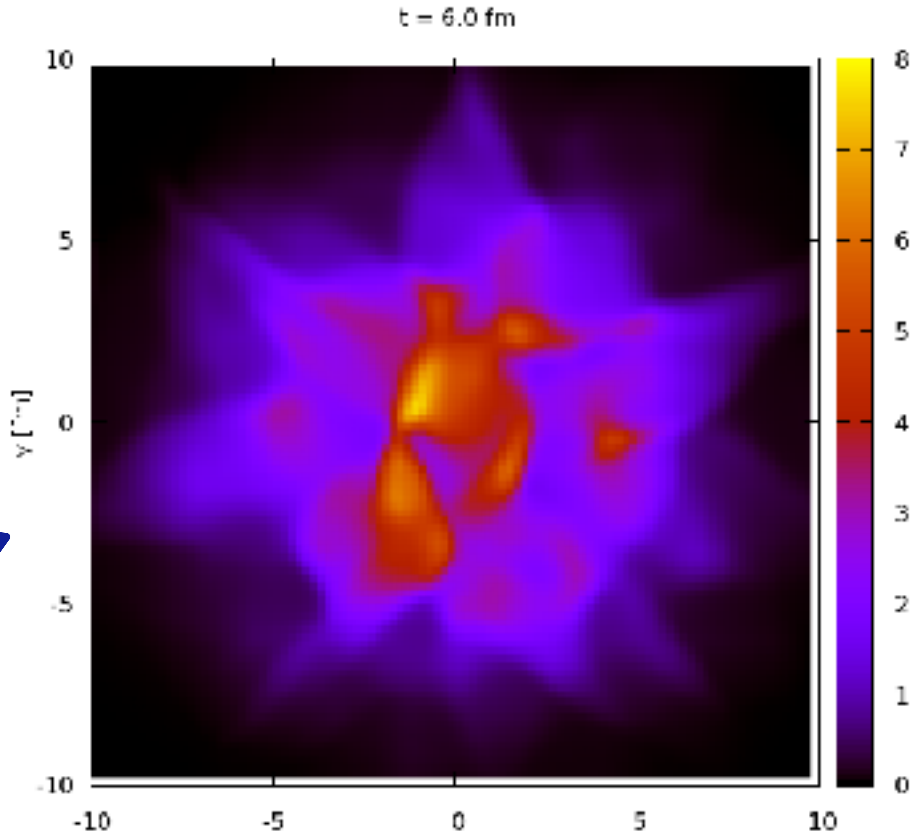
Schenke and Jeon, Phys.Rev.Lett.106:042301

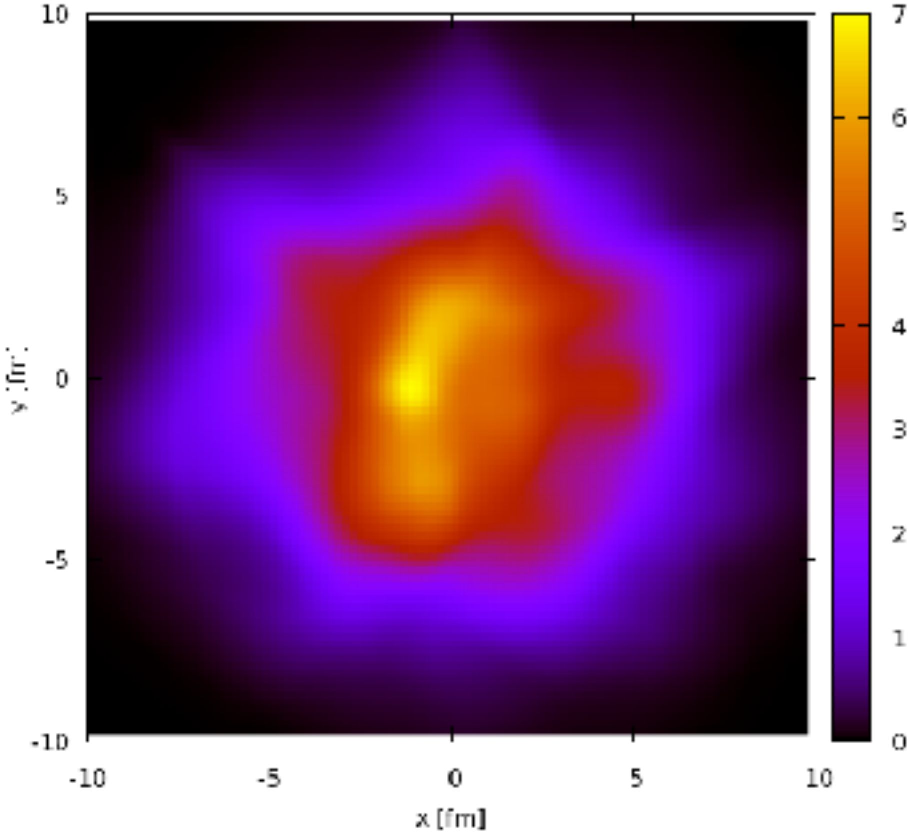
In general: initial state is lumpy



$\eta/s = 0$

$\eta/s = 0.16$





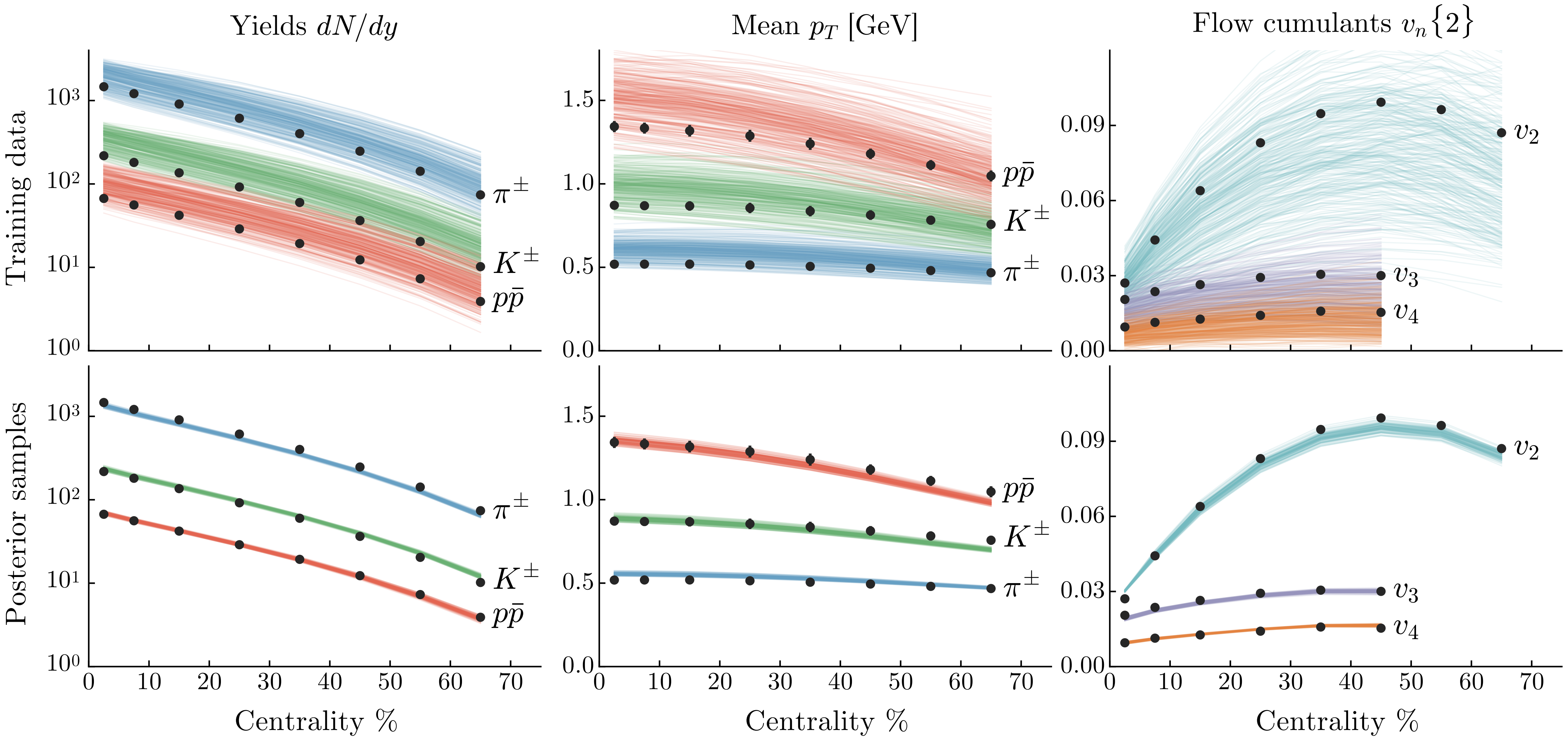
How much of this is visible in the final state, depends on shear viscosity $\eta$

and a number of other model parameters

# Global fit: input

J. E. Bernhard et al, arXiv: 1605.03954

## Experimental input: yields, mean $p_T$ and harmonic flow vs $p_T$



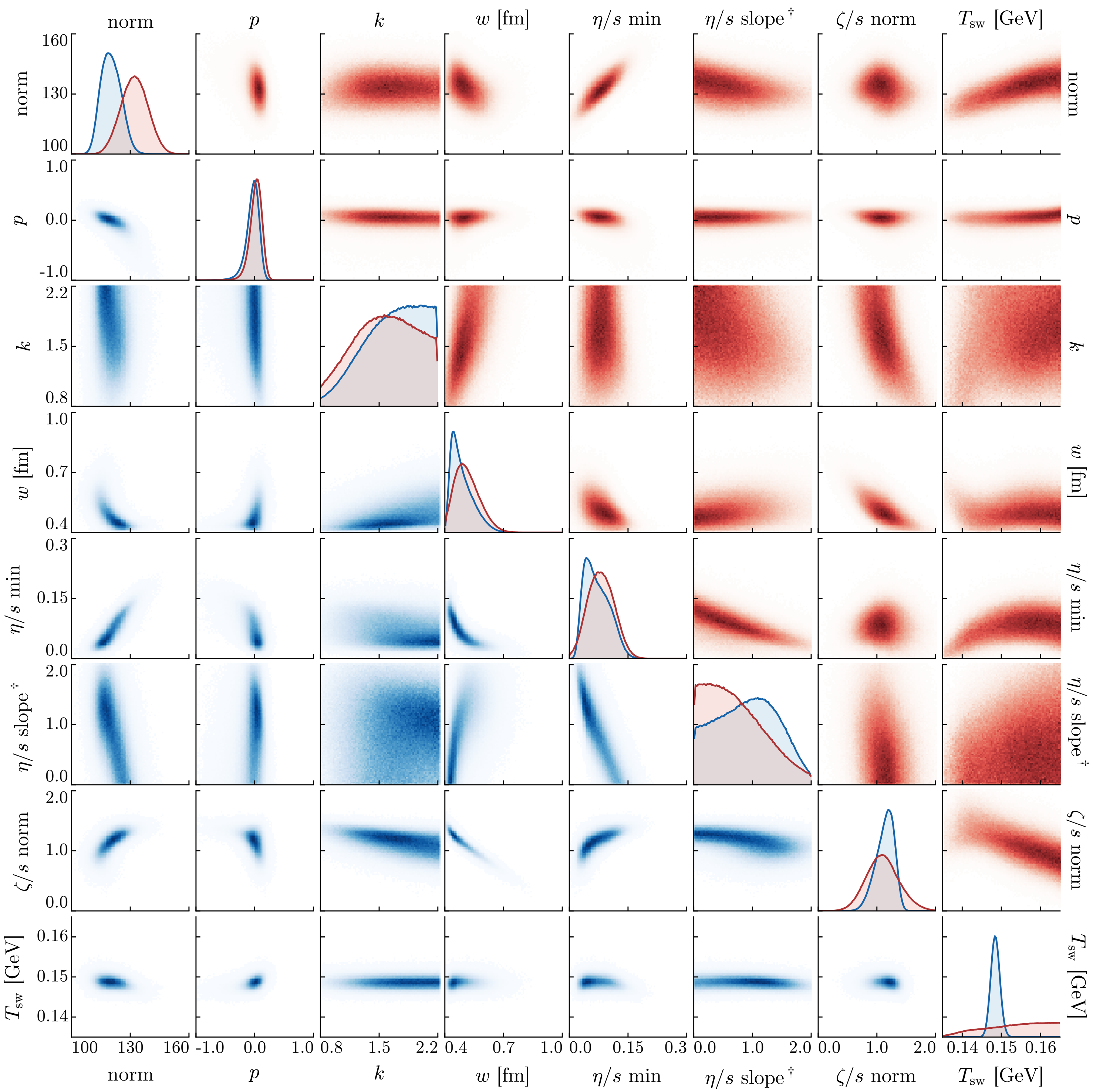
Model: initial anisotropies + medium response

Explores a large parameter space to investigate reliability/robustness of the modelling

# Global fit of initial state+hydrodynamics

J. E. Bernhard et al, arXiv: 1605.03954

$$\begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{pmatrix} = \begin{pmatrix} \text{Response} \\ \\ \\ \\ \end{pmatrix} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix}$$



$\varepsilon_n$ : initial spatial anisotropies from initial state model

$v_n$ : observed final state momentum anisotropy

Response: modeled by hydrodynamic evolution

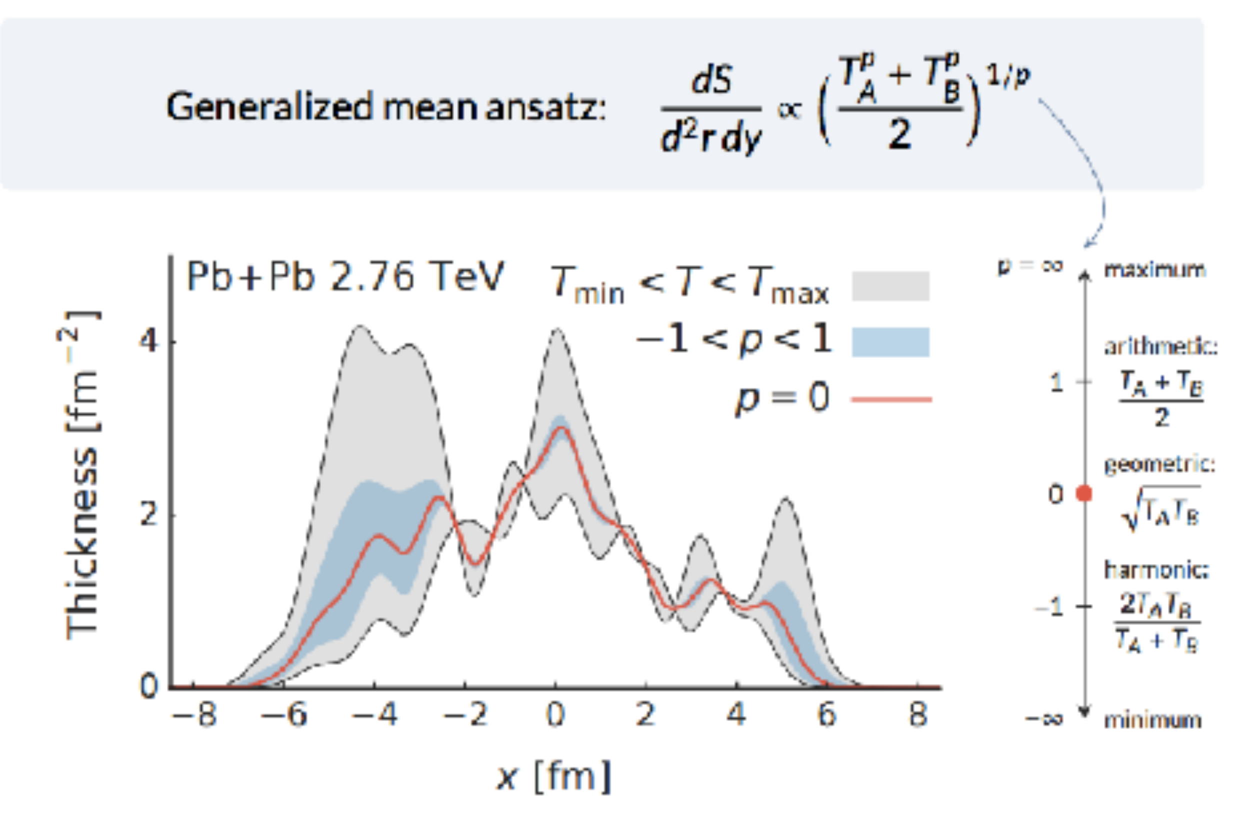
Total 9 parameters:

- 3 initial state $\Longrightarrow \varepsilon_n$
- 4 QGP $\Longrightarrow$ response
- 2 model parameters

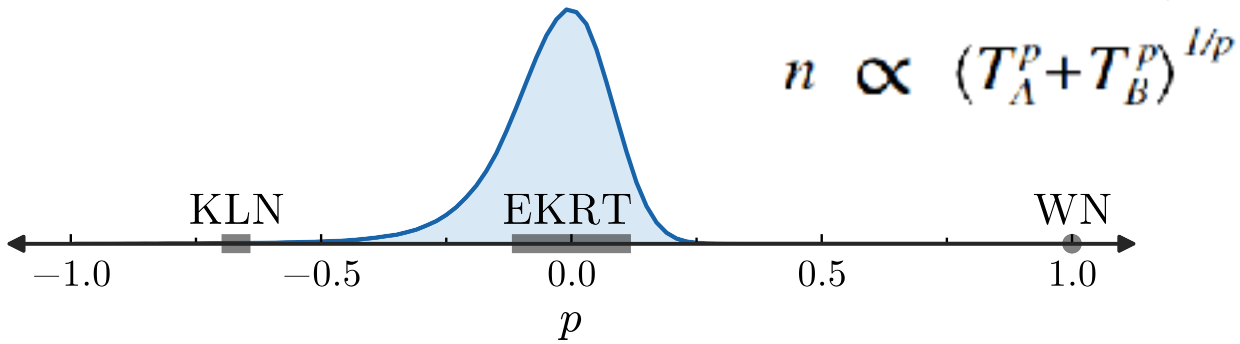
# A global fit to anisotropic flow: main results

J. E. Bernhard et al, arXiv: 1605.03954

Total 9 parameters:
- 3 initial state ⟹ $\varepsilon_n$
- 4 QGP ⟹ response
- 2 model parameters



Generalized mean ansatz: $\frac{dS}{d^2r\,dy} \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$

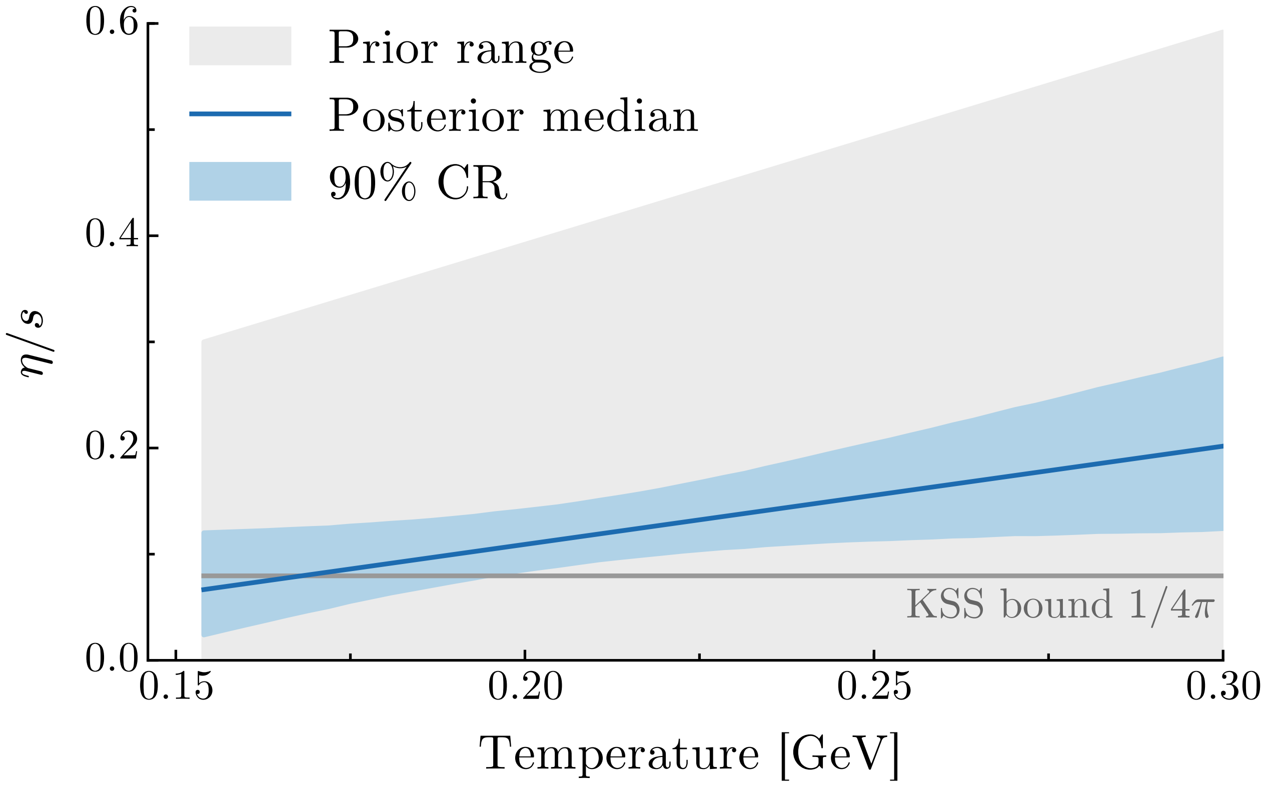


$$n \propto (T_A^p + T_B^p)^{1/p}$$

Multiplicity production model

Follows an effective 'saturation' model

## Viscosity of the QGP

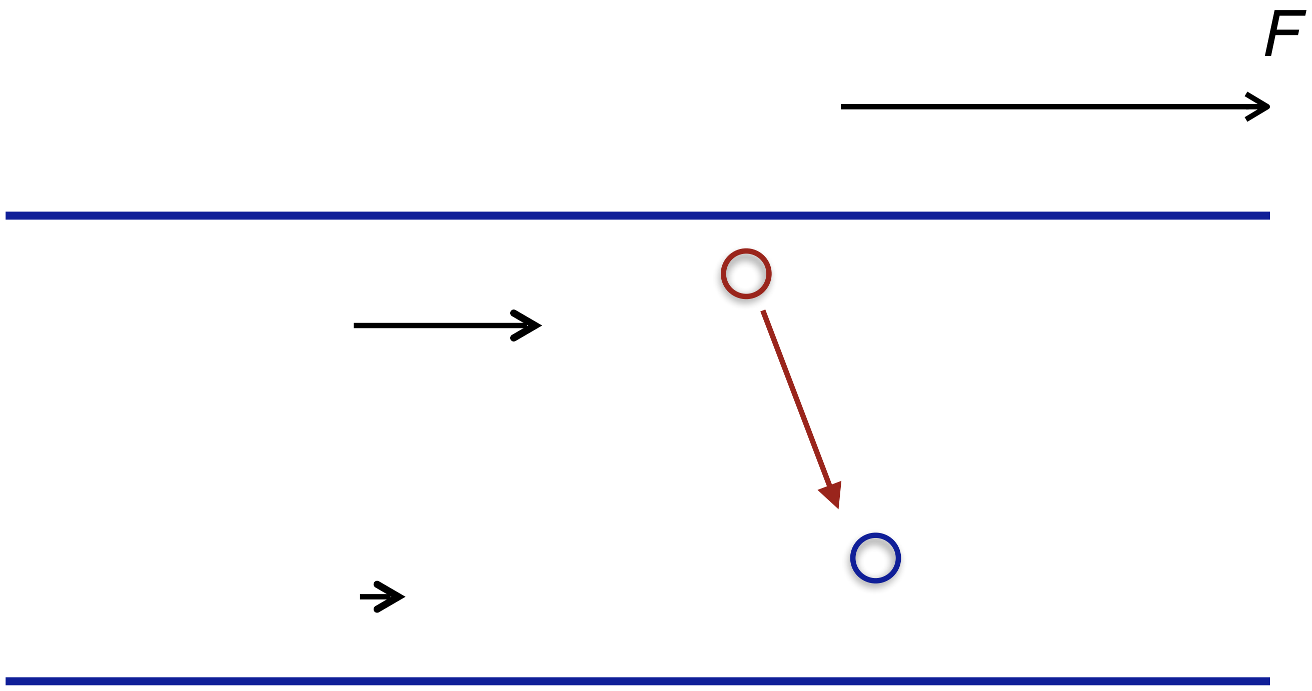


Fit constrains initial state geometry and transport properties at the same time

Viscosity close to lower bound

# Viscosity and mean free path (density)

Kinetic theory:



$$\frac{F}{A} = \eta \frac{dv}{dz}$$

Large mean free path $\lambda$ ⇒ momentum transport over large distance

Viscosity is proportional to mean free path $$\boxed{\eta = \frac{1}{3} n\bar{p}\lambda}$$

$\lambda$ is inversely proportional to density $n$ $$\lambda = \frac{1}{n\sigma}$$

Low viscosity means large density!
(In the gas phase)

# Viscosity and mean free path (density)

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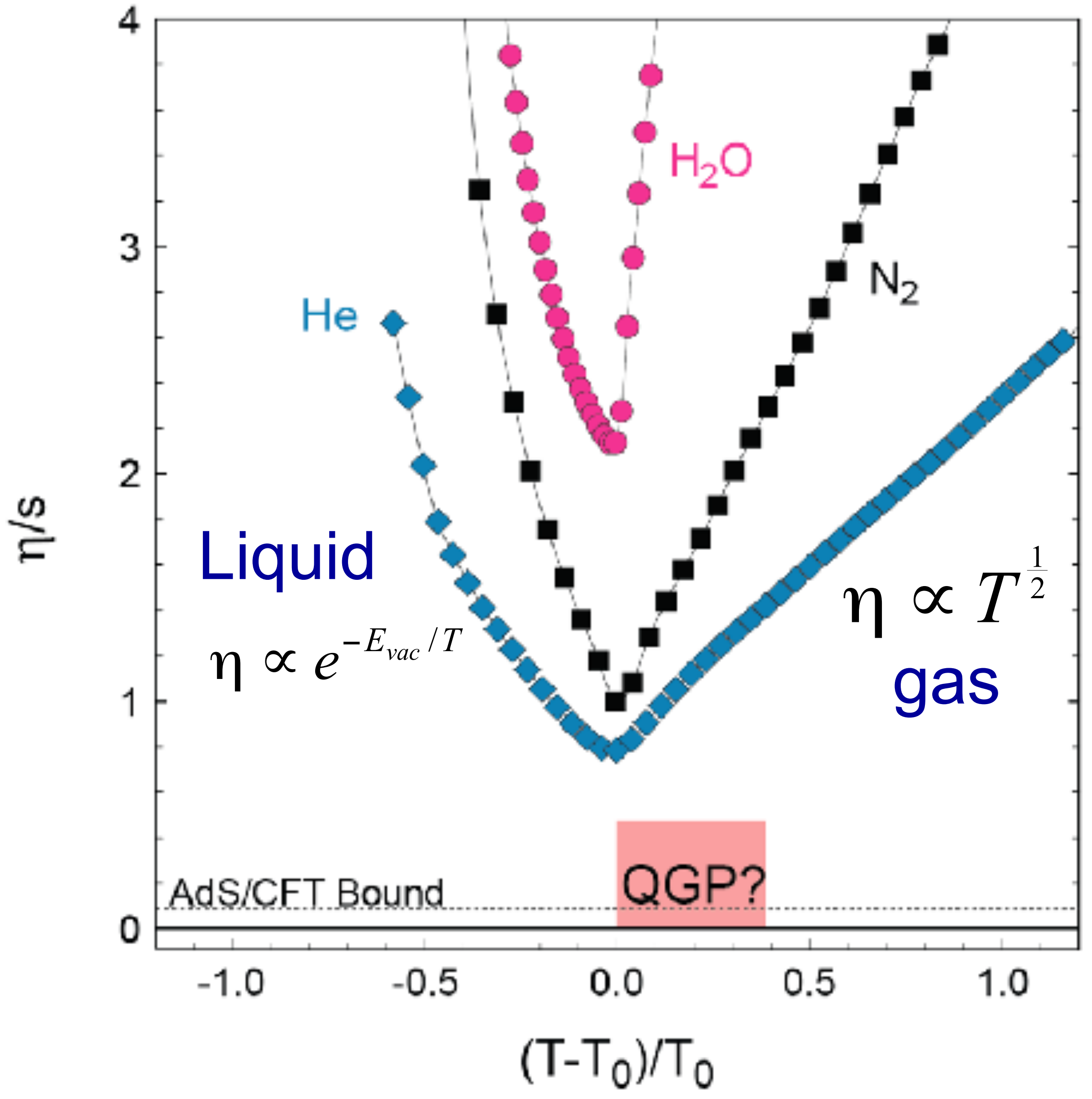
Temperature dependence of viscosity



Viscosity minimal at liquid-gas transition

QGP viscosity lower than any atomic matter

Large mean

arge distance

Viscosity

$p\lambda$

$\lambda$ is

Low viscosity means large density!
(In the gas phase)

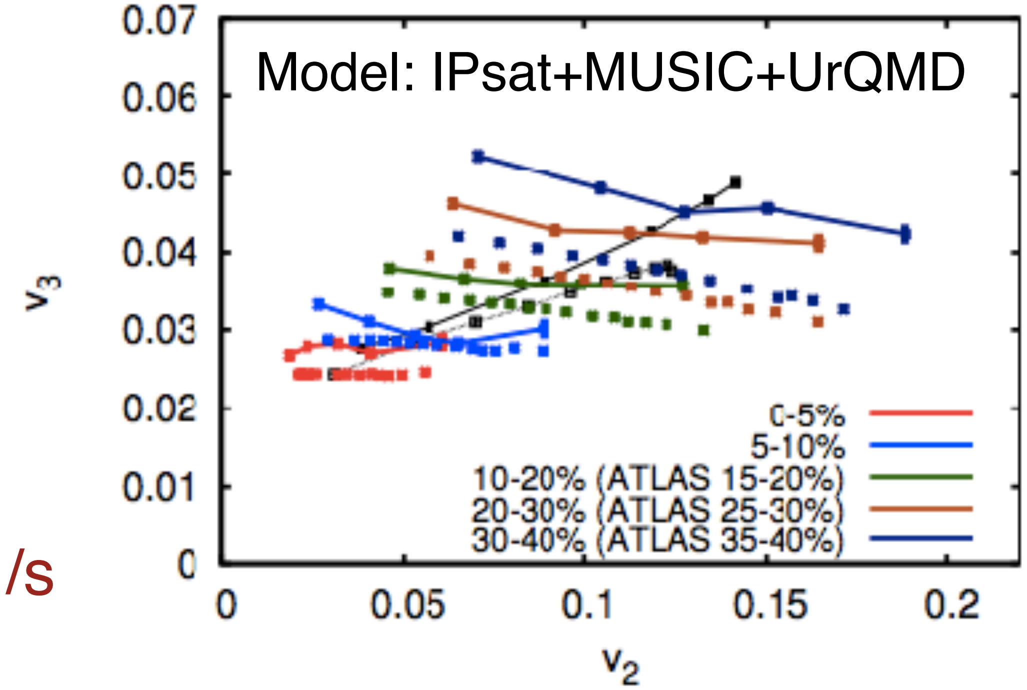
# Future directions

We have stress-tested the baseline (standard) model for flow from initial stages + hydrodynamics

More differential observables to:

- Further disentangle initial stages and evolution
- Improve sensitivity to temperature dependence η/s

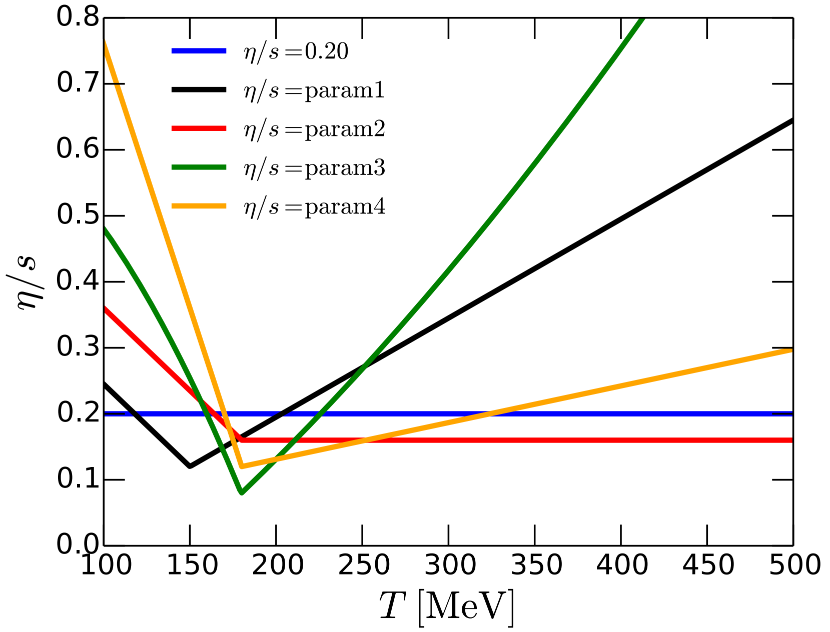
## Flow amplitude correlations



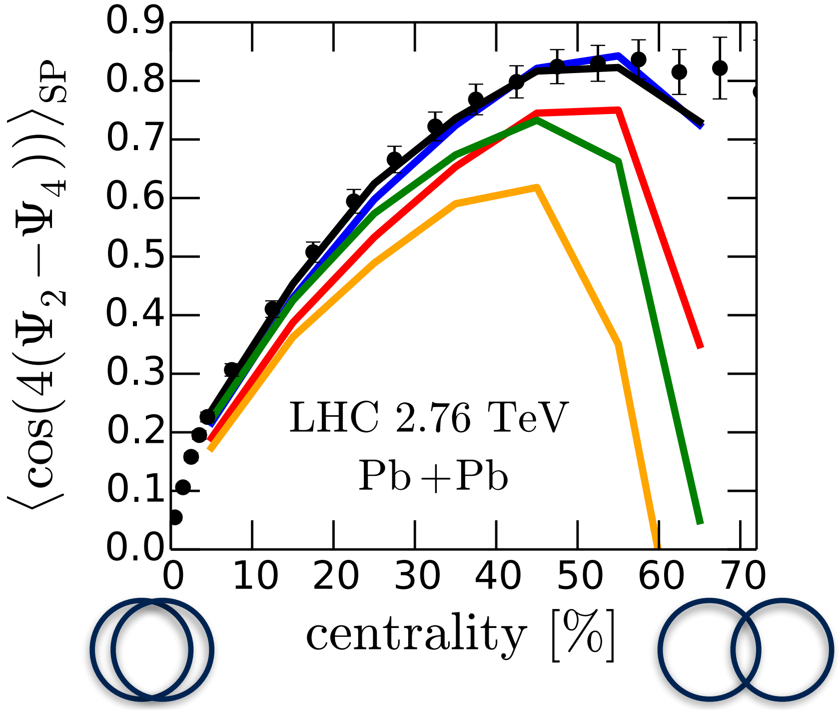
ATLAS, PRC **92**, 034903

S McDonald et al, arXiv:1704.05362

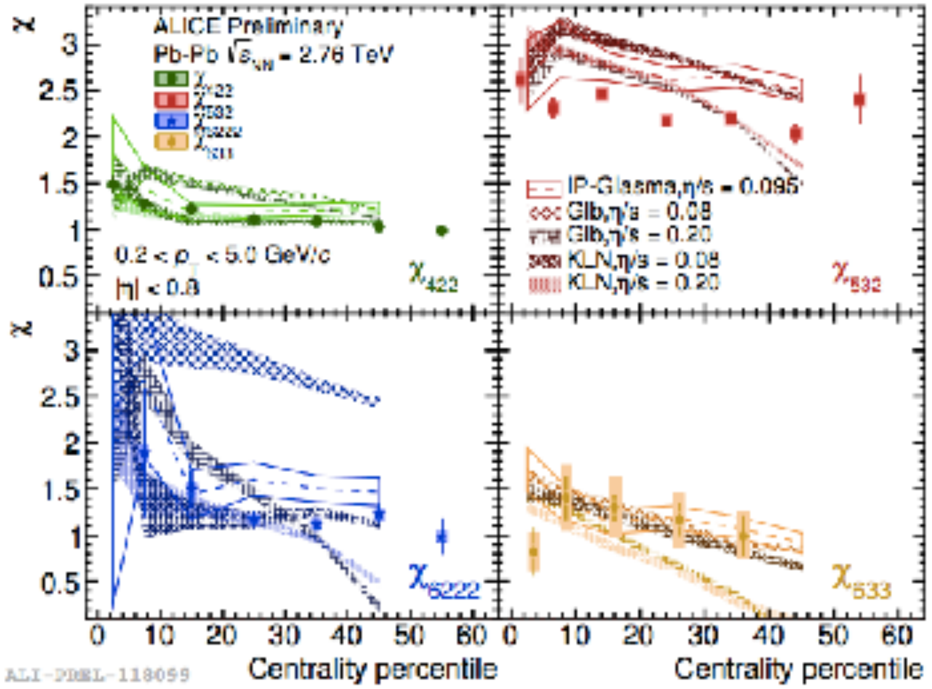
Model input: viscosity vs temperature



Event plane angle correlations



… more cross terms



ALICE, Y Zhou Quark Matter 2017

Niemi et al, arXiv:1509.02767, PRC93, 024907

# Small systems: pp and p-Pb

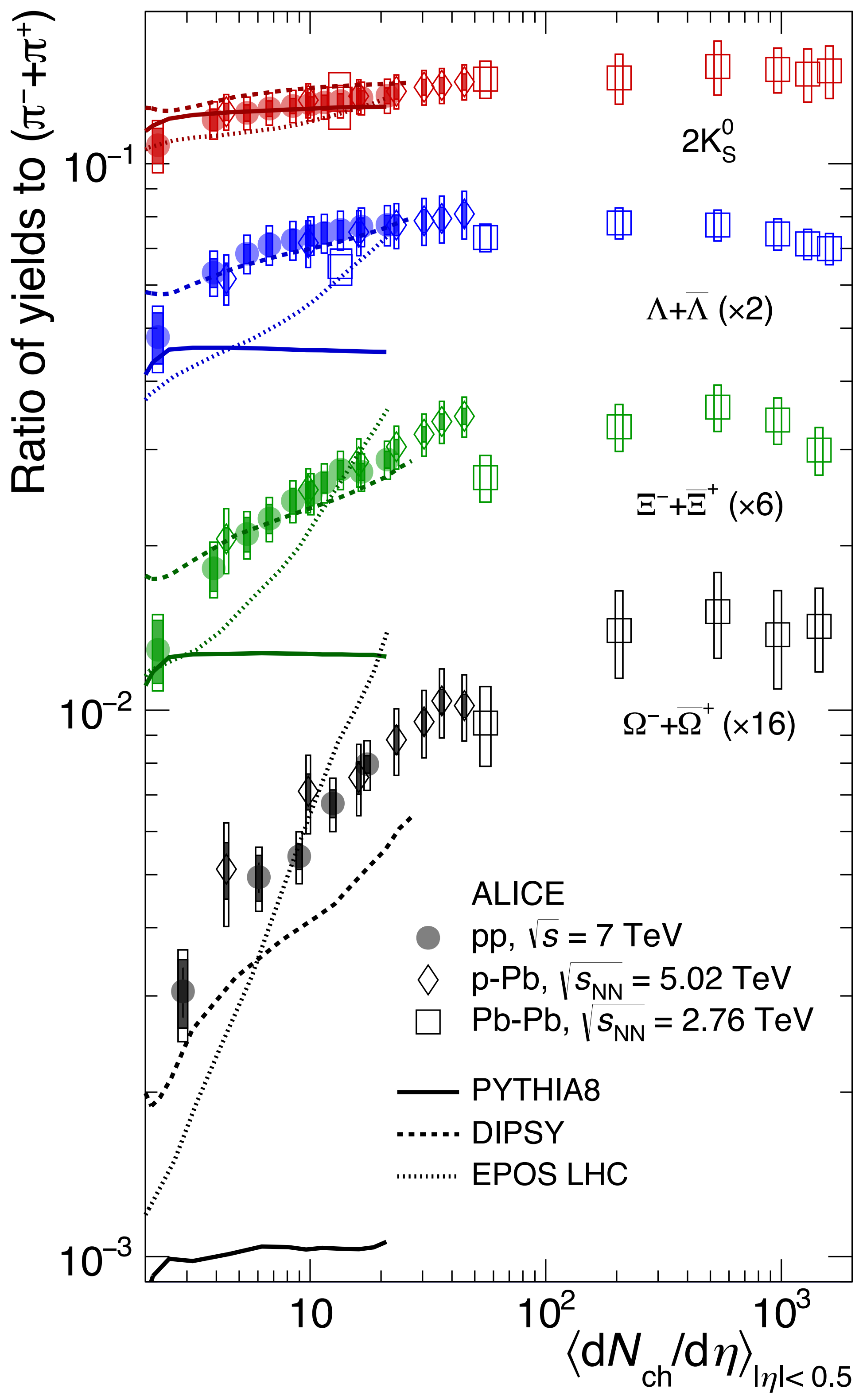
## Exploring the limits of fluid/collective behaviour

# Strangeness production in pp, p+Pb

particle yields in multiplicity bins

Fraction of strange hadrons increases with multiplicity

Large effect for multi-strange Ξ and Ω



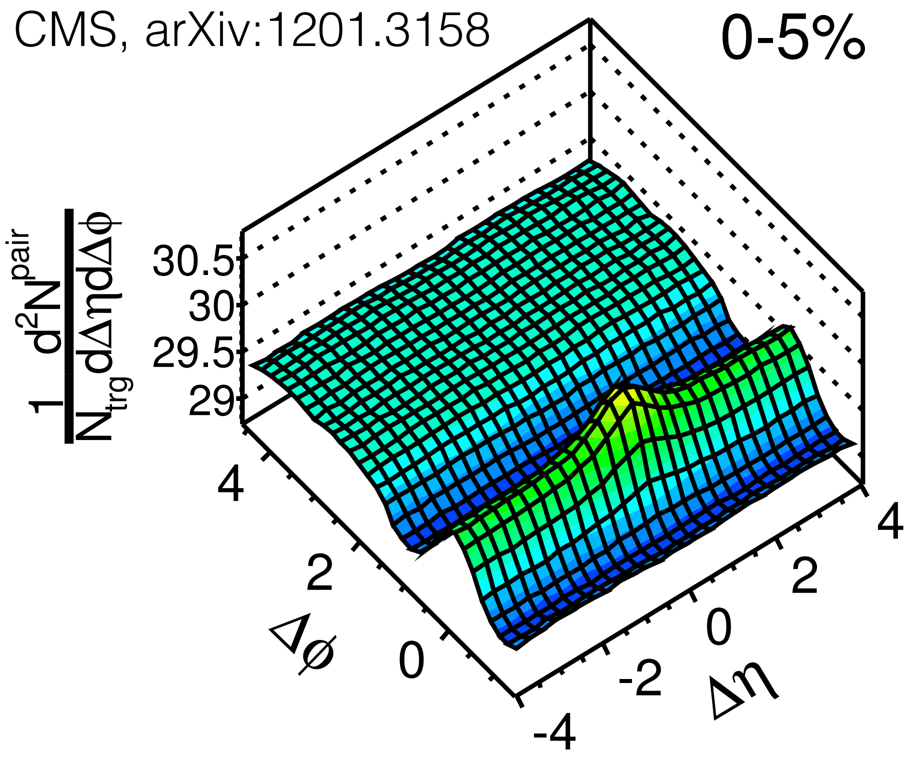
ALICE, arXiv:1606.07424, arXiv:1307.6796, arXiv:1512.07227

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

Paper out today: [Nature Physics]

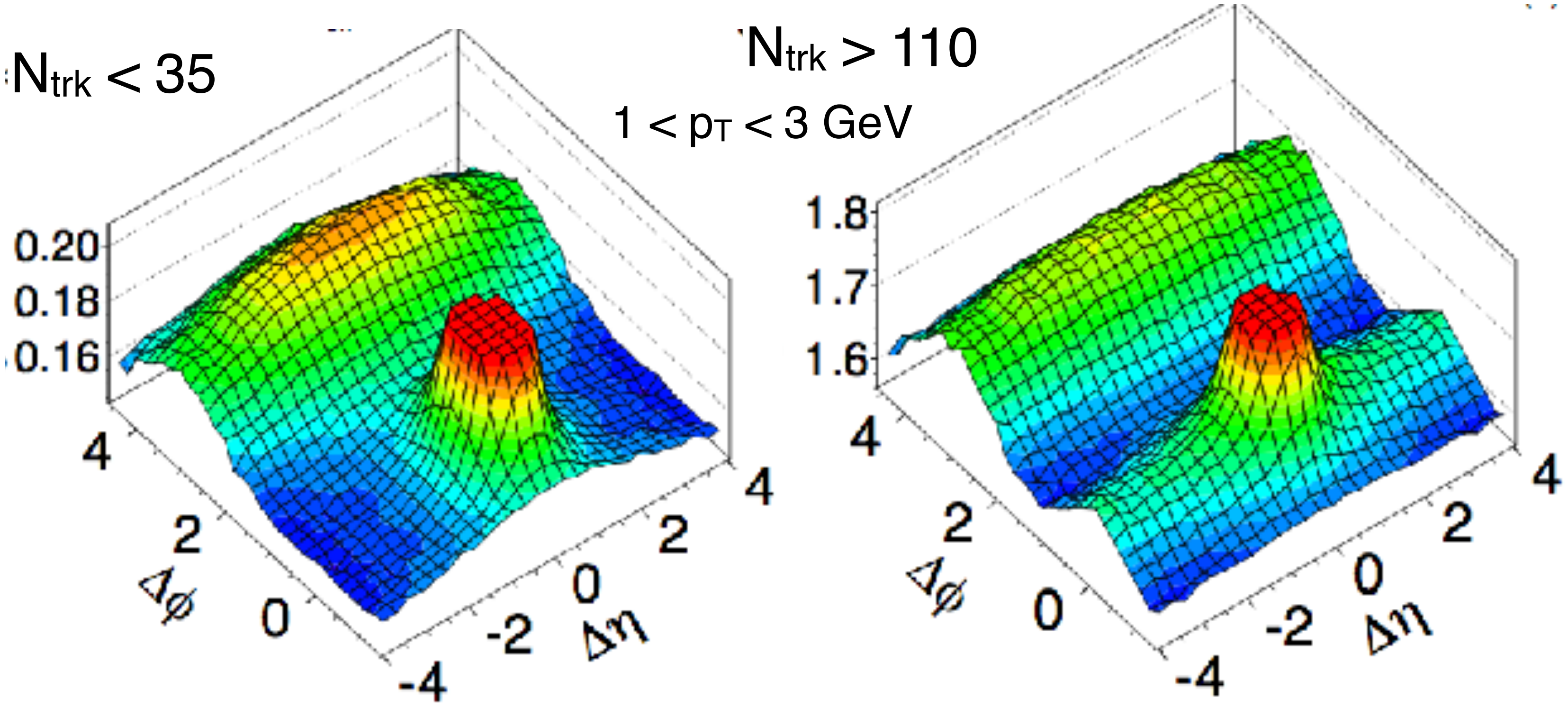
# Two-particle correlations in pp and Pb+Pb

Central Pb+Pb

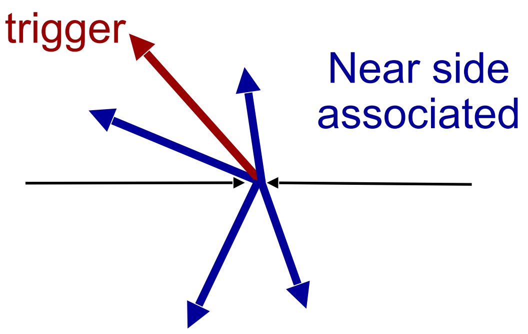

CMS, arXiv:1201.3158

p+p low multiplicity

p+p high multiplicity



CMS, PLB 718, 795



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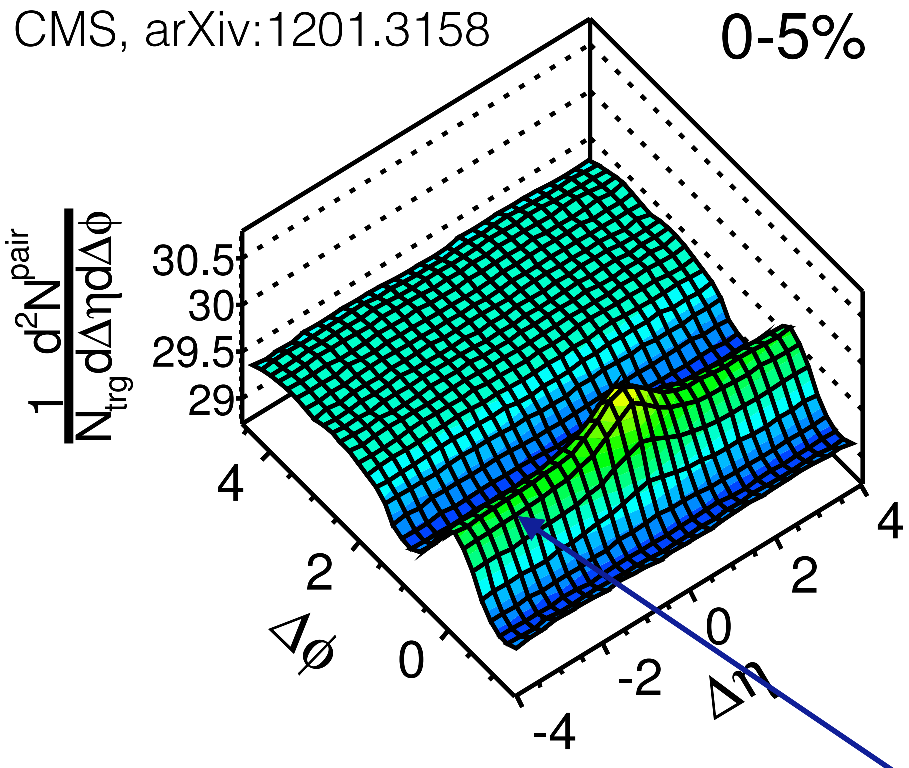

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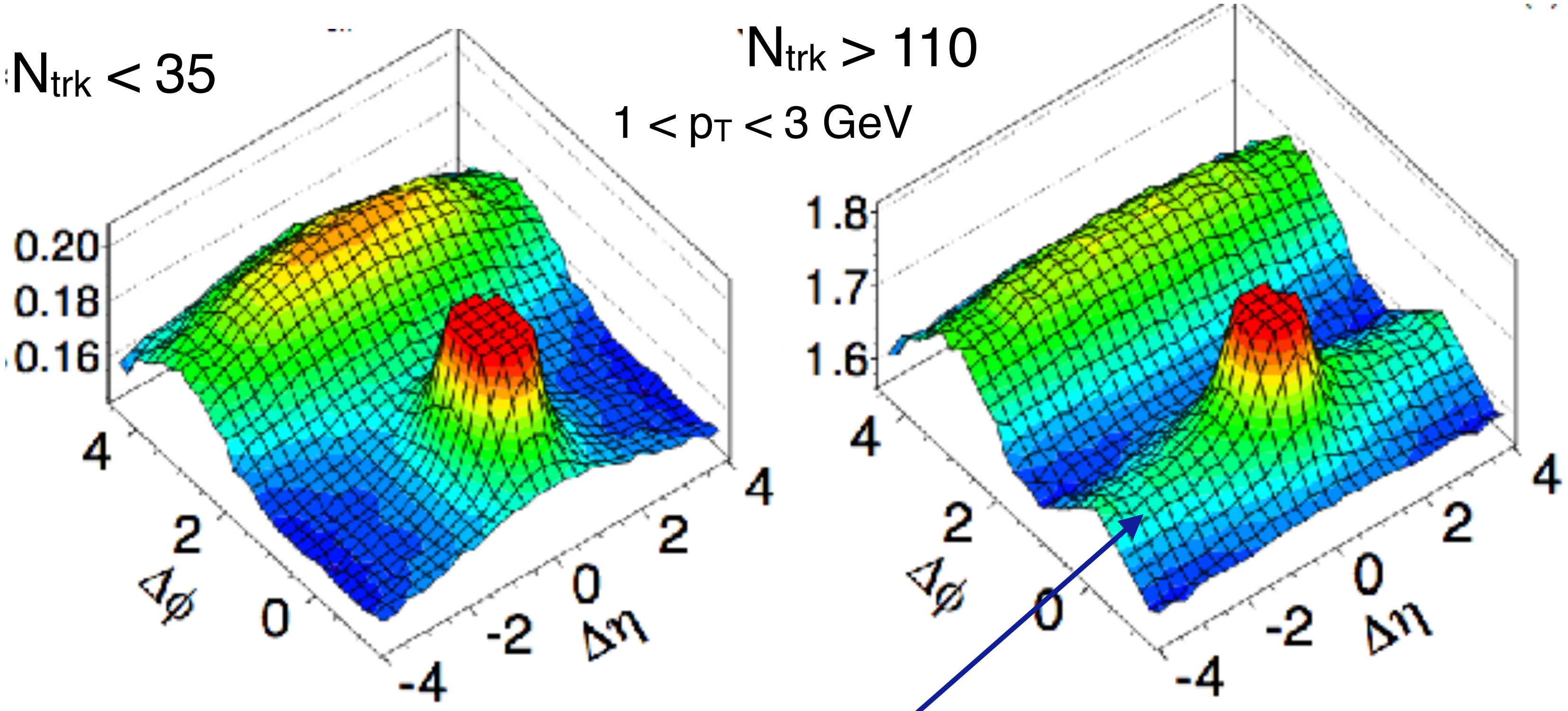
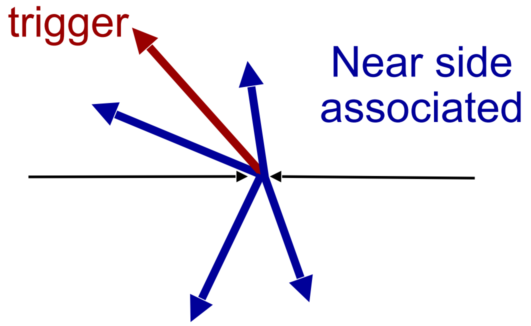


CMS, PLB 718, 795



Near-side long range correlation: indicates early time origin

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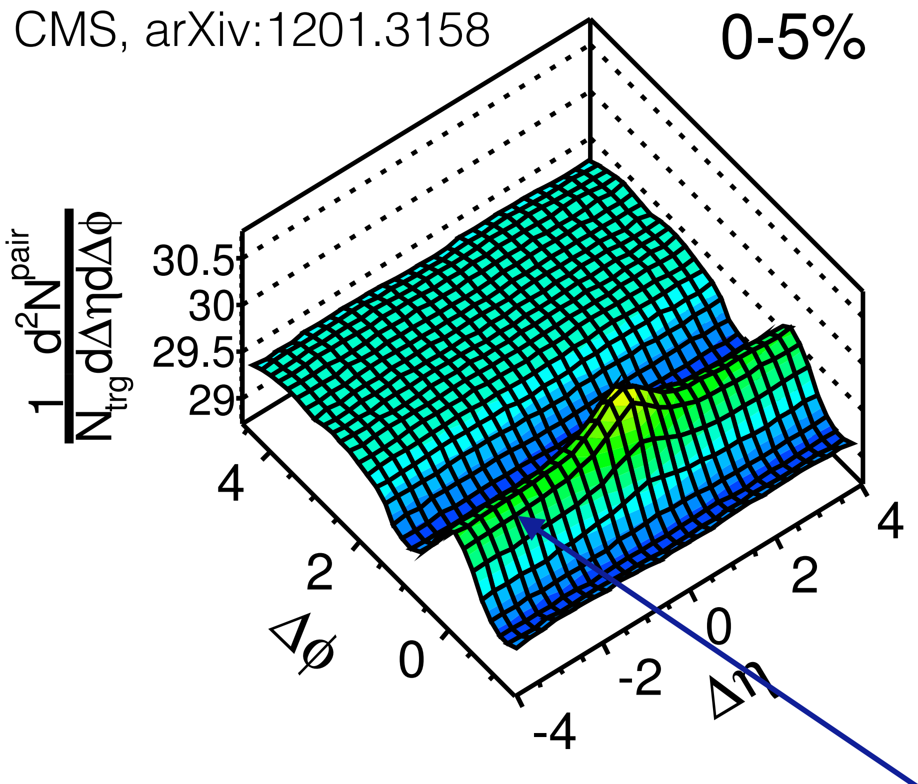

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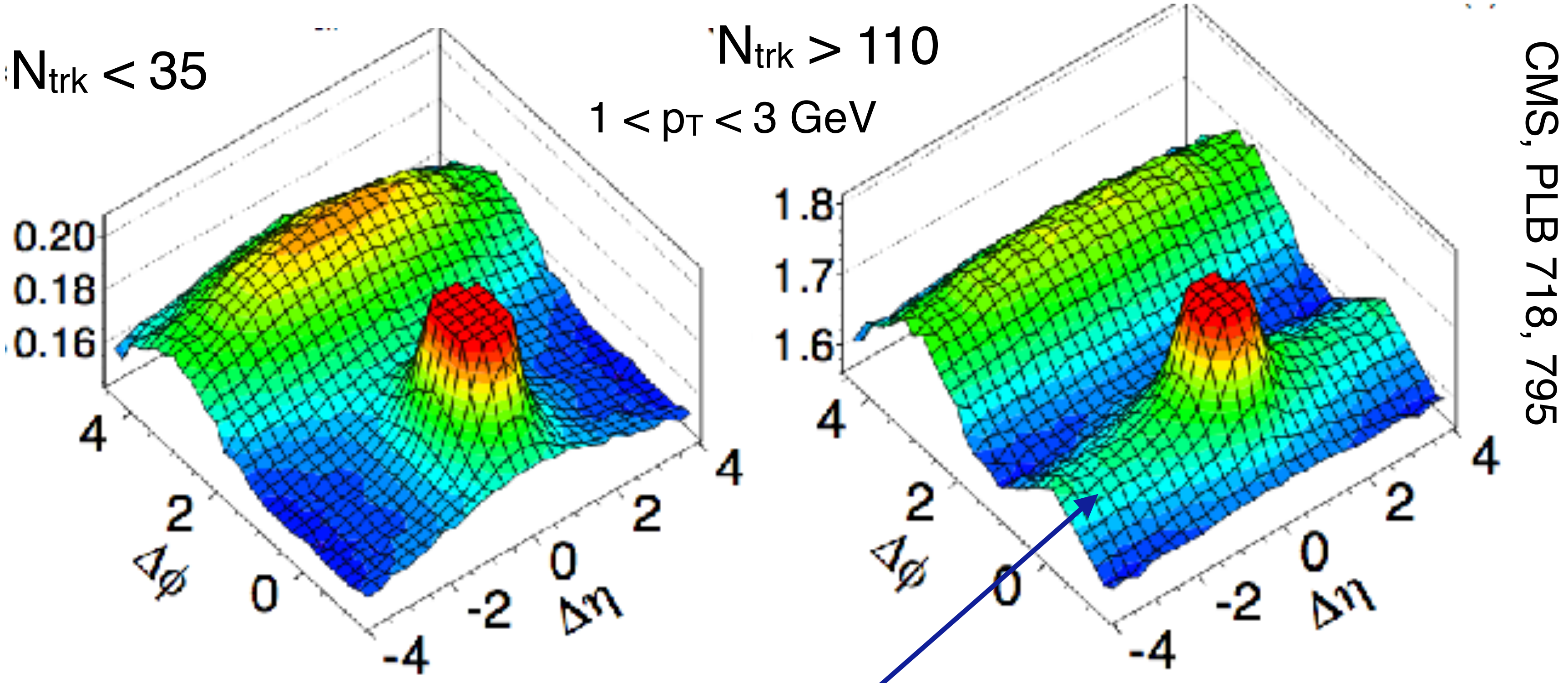
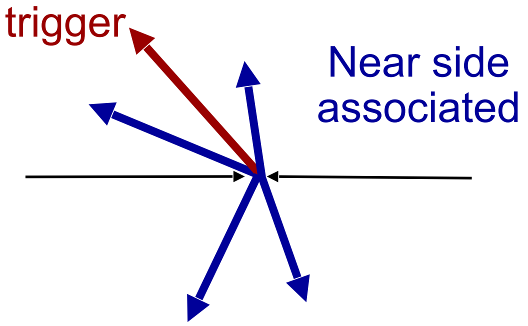
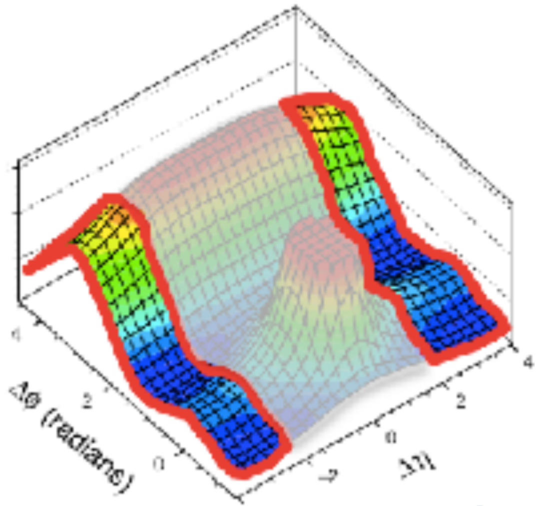


CMS, PLB 718, 795



Near-side long range correlation: indicates early time origin

Seen in high-multiplicity pp and p+Pb events

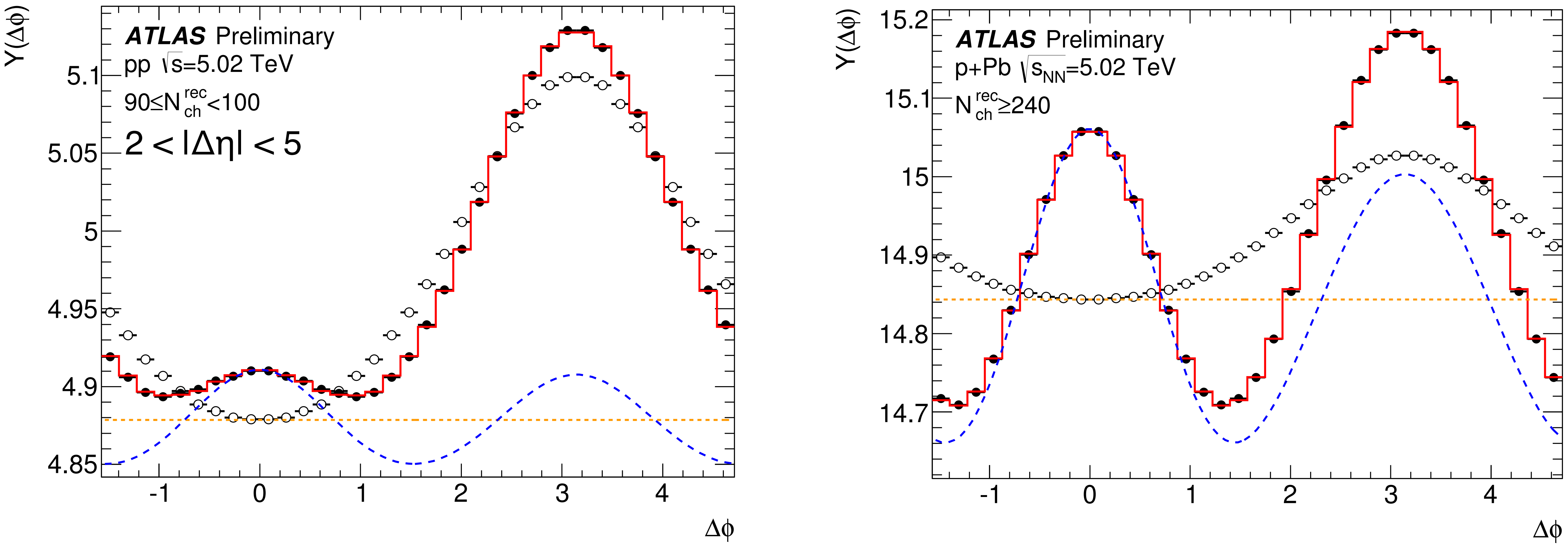


# Two-particle correlations

ATLAS-CONF-2016-026

High-multiplicity p+p

High-multiplicity p+Pb

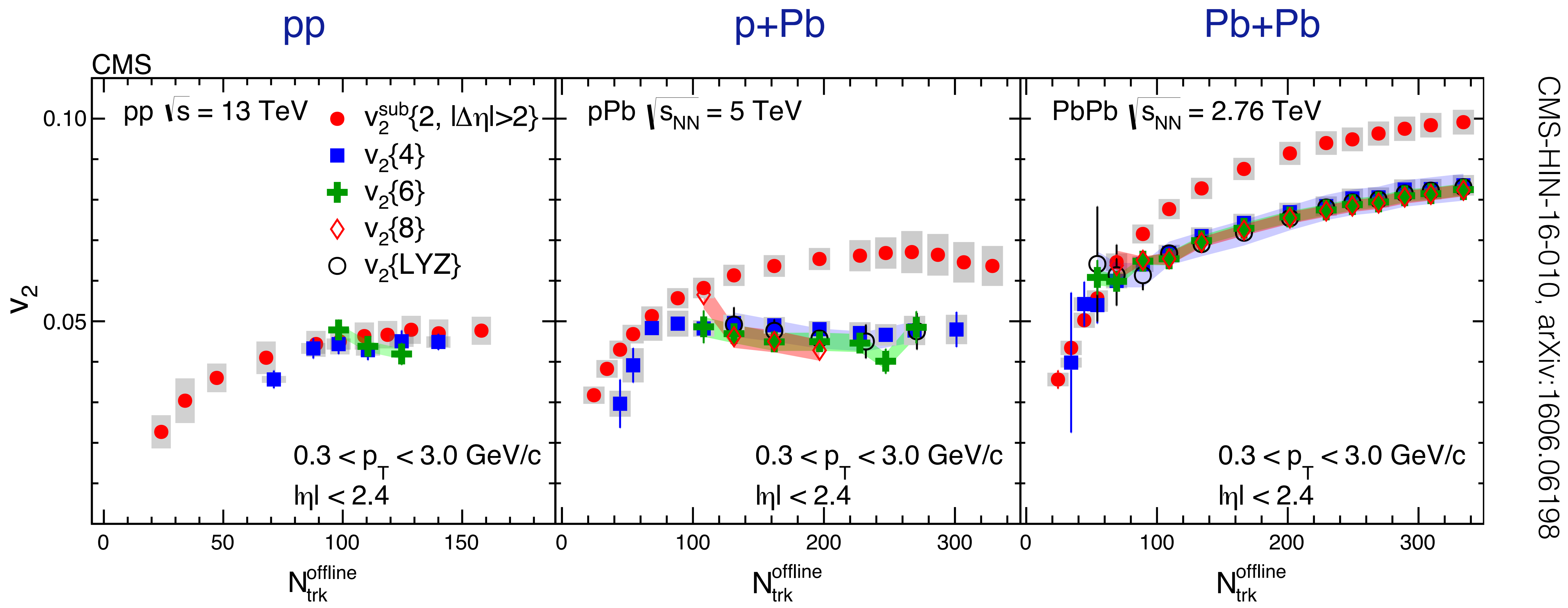


Clear change in shape from low multiplicity to high multiplicity:
no near-side peak in low multiplicity events

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

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

# Multi-particle correlations: testing collectivity

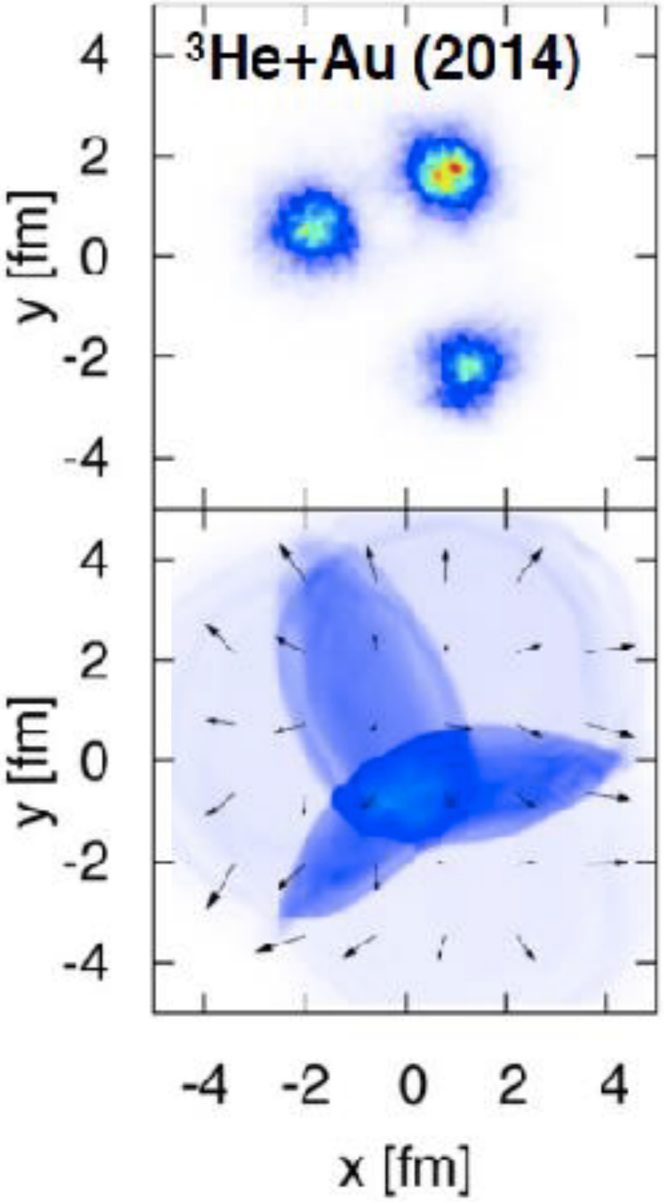


Multi-particle methods suppress few-particle (non-flow) correlations

Flow-like effect is indeed a multi-particle effect

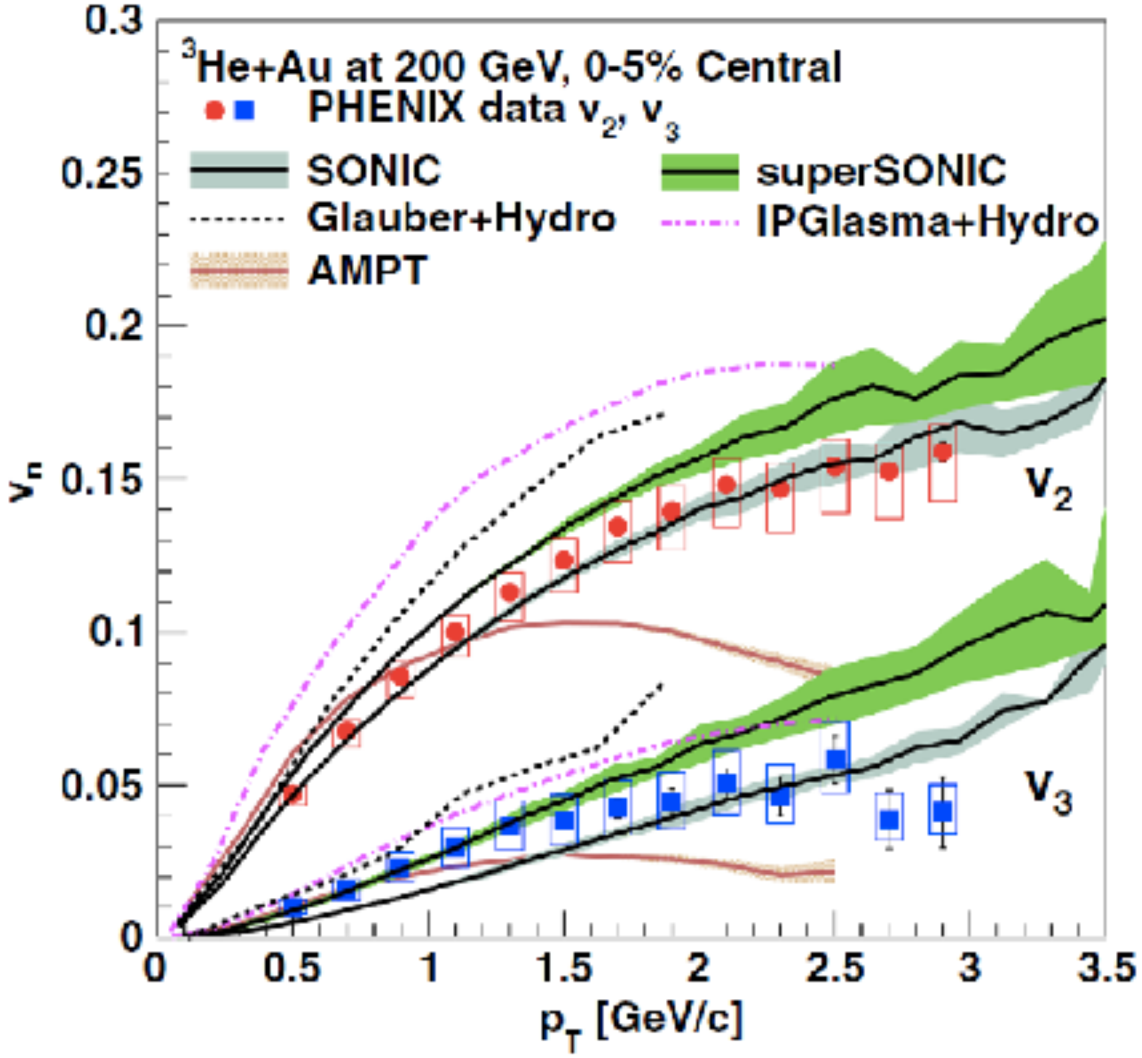
# Changing the projectile

Spatial profile of the collision



B Schenke et al

$v_2$ and $v_3$ from $^3$He+Au



PHENIX, PRL **115**, 142301

Sizable $v_3$ contribution seen with $^3$He

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

$^3$He gives explicit triangular contribution in initial state

Effect is driven by initial spatial configuration

# Flow effects in small systems

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

- Long range correlation
- 2- and 3-fold symmetries
- Dependence on initial geometry
- Many-particle correlations
- 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?

# Limits on hydrodynamic behaviour

**Naive expectation**: need at least a few collisions for each parton to reach thermal equilibrium and apply hydrodynamic

1) System size: $R > \lambda$

Would not expect azimuthal asymmetries in pp and p-Pb

Heiselberg and Levy, nucl-th/9812034,
W Lin et al,

2) Thermalisation time: $\tau > \dfrac{\lambda}{v}$

Fits to data: thermalisation times $\tau \approx$ 0.1-1 fm/c

pQCD calculation:
$\tau \gtrsim$ 6.9 fm/c

Baier et al, PLB 502, 51, PLB 539, 46

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**Turns out to be too strict**: (viscous) hydro describes non-thermal systems, see next slide

Naive expectations can be ‘bypassed’ in nature?

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Would not expect … ymmetries in pp and p-Pb

**Turns out to** … asymmetries also generated in kinetic with $R < \lambda$

Density to…

Heiselberg and Levy, nucl-th/9812034,
W Lin et al,

Closely related, since v ≈ c = 1

2) Ther… e: $\tau > \frac{\lambda}{v}$

Fits to data: thermalisation times $\tau \approx$ 0.1-1 fm/c

pQCD calculation:
$\tau \gtrsim 6.9$ fm/c

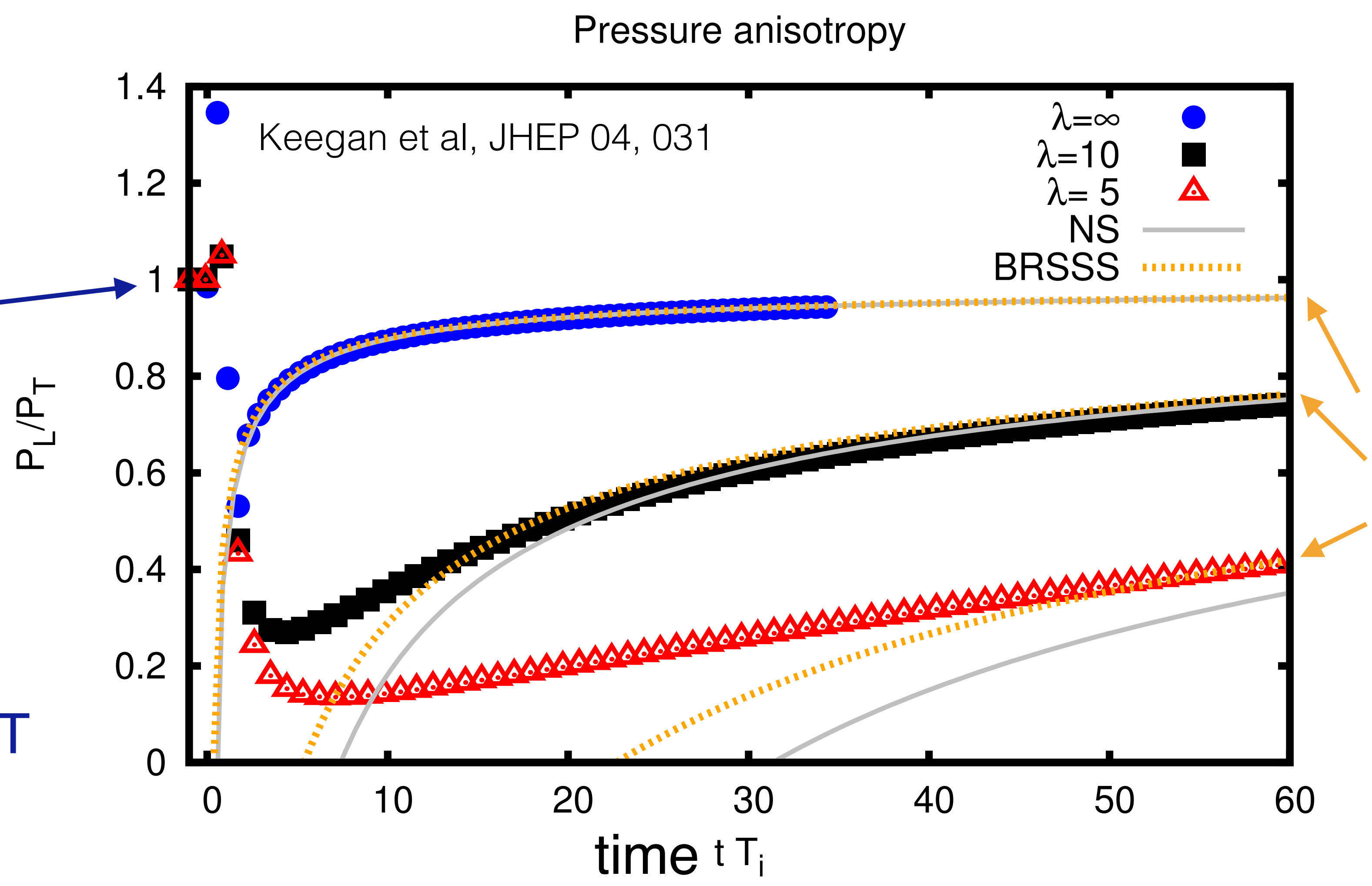
Baier et al, PLB 502, 51, PLB 539, 46

**Turns out to be too strict**: (viscous) hydro describes non-thermal systems, see next slide

Naive expectations can be 'bypassed' in nature?

# Hydrodynamic behaviour in non-thermalised system

$p_L/p_T = 1$ isotropy;
condition
for thermalisation



Lines:
viscous hydro

Non-equilibrium
expansion in AdS/CFT
kinetic theory

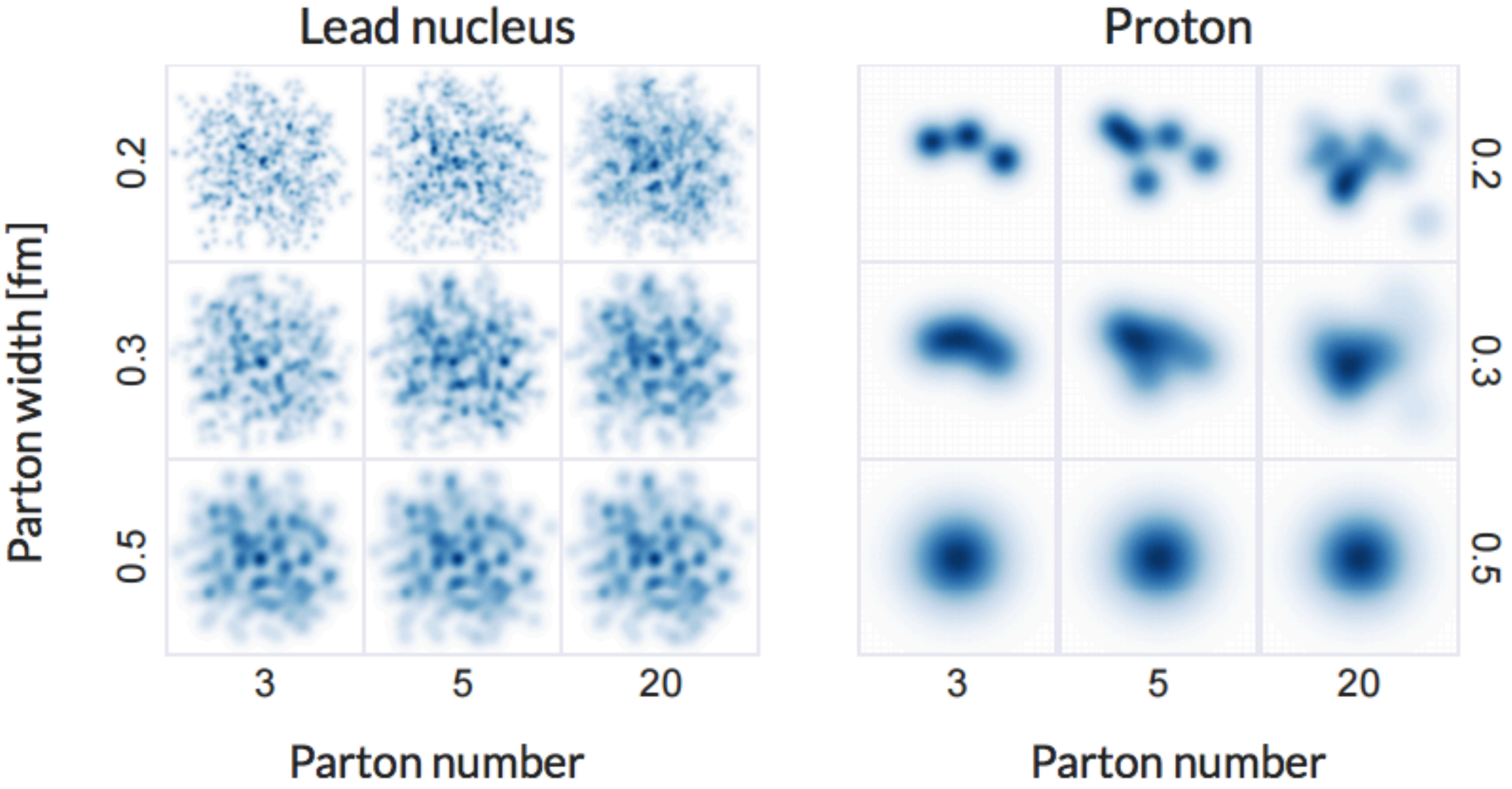
Emerging understanding:

Hydrodynamical description valid before thermalisation/isotropisation

Estimate of smallest (possible) system size with fluid behaviour: $r \approx 0.15$ fm

Weller, Romatschke, EPJC 77, 21

# Looking at sub-nucleon size fluctuations



Flow in p-Pb collisions shows sensitivity to proton sub-structure

Sensitivity even larger in pp

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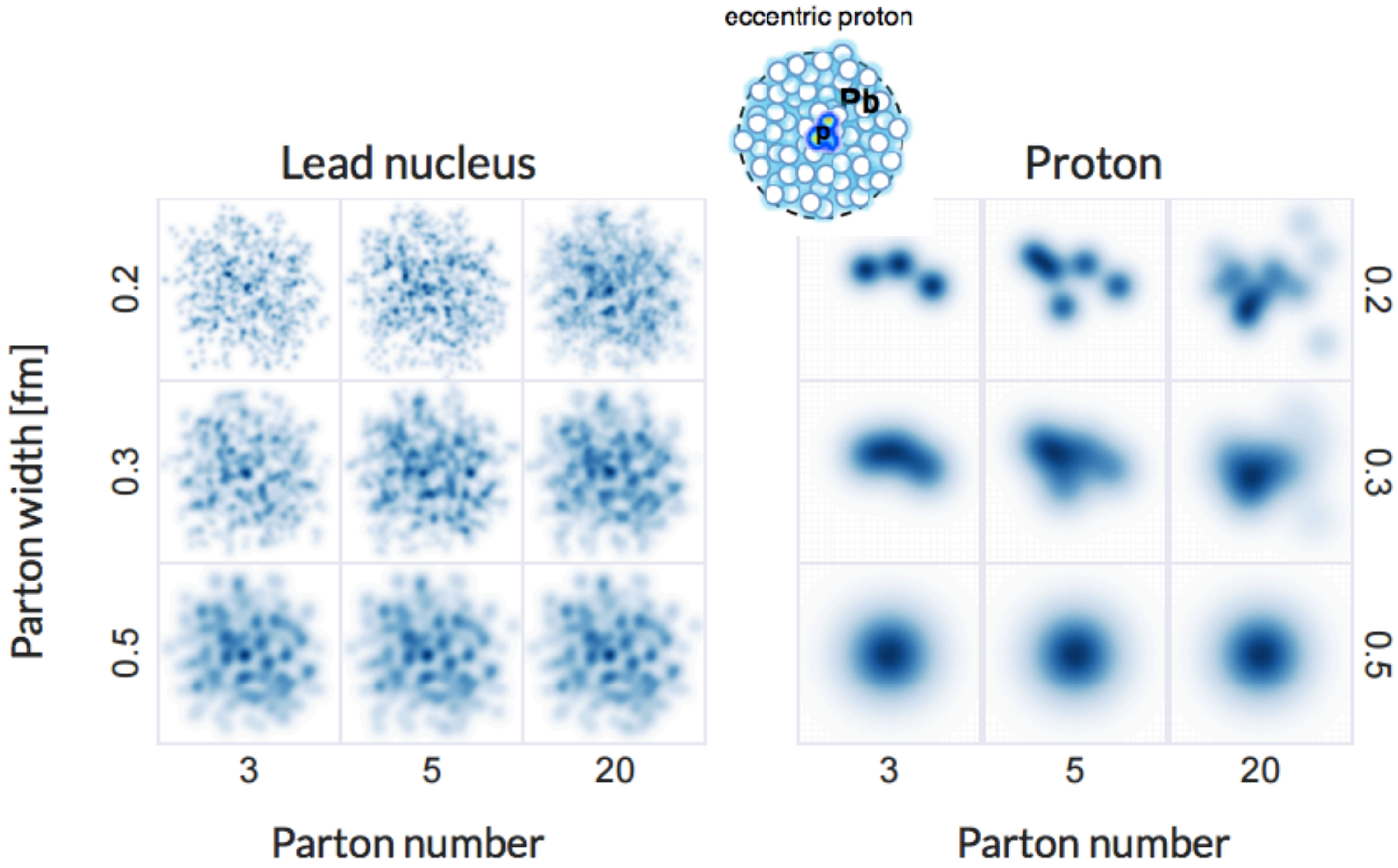

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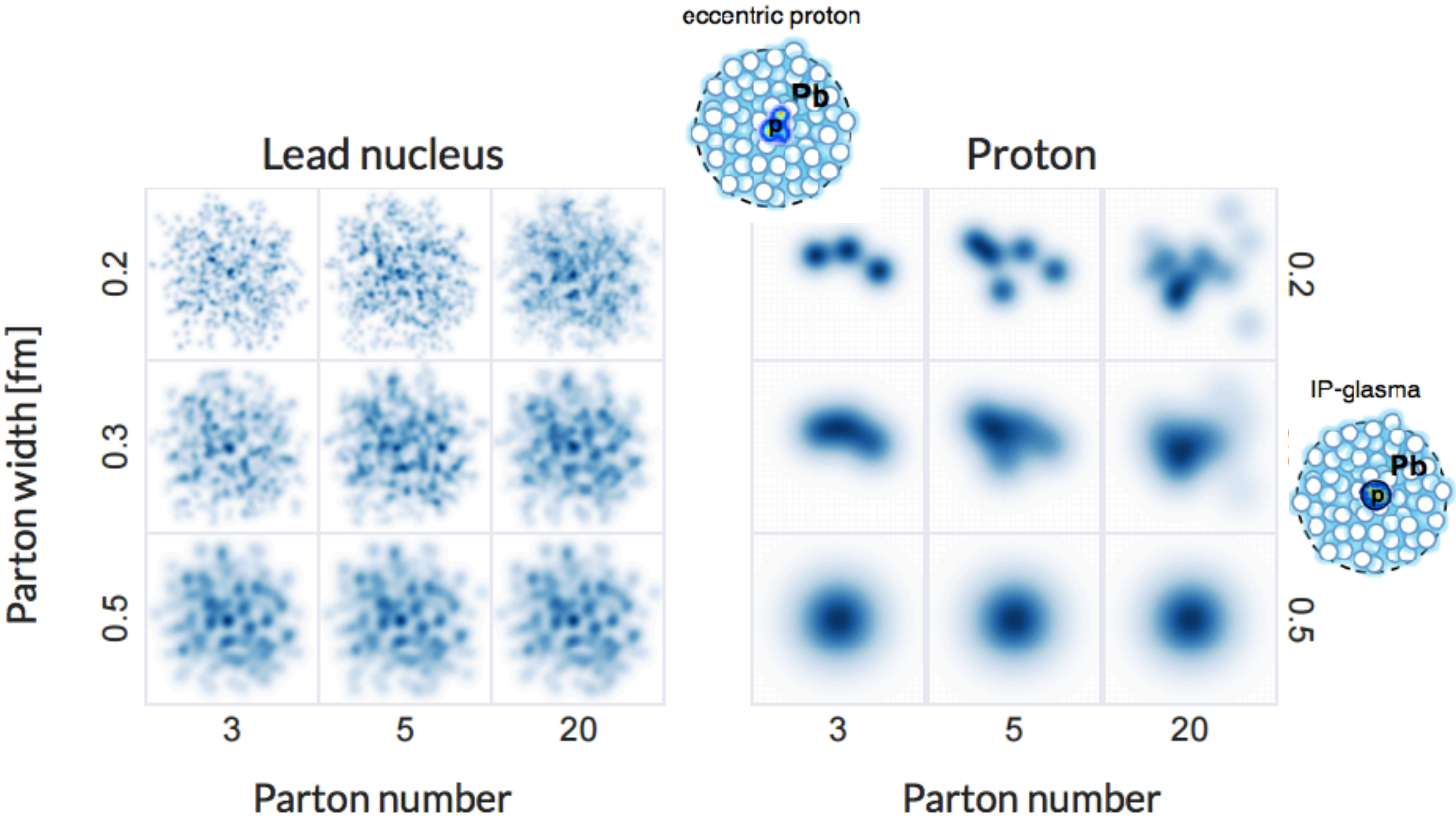

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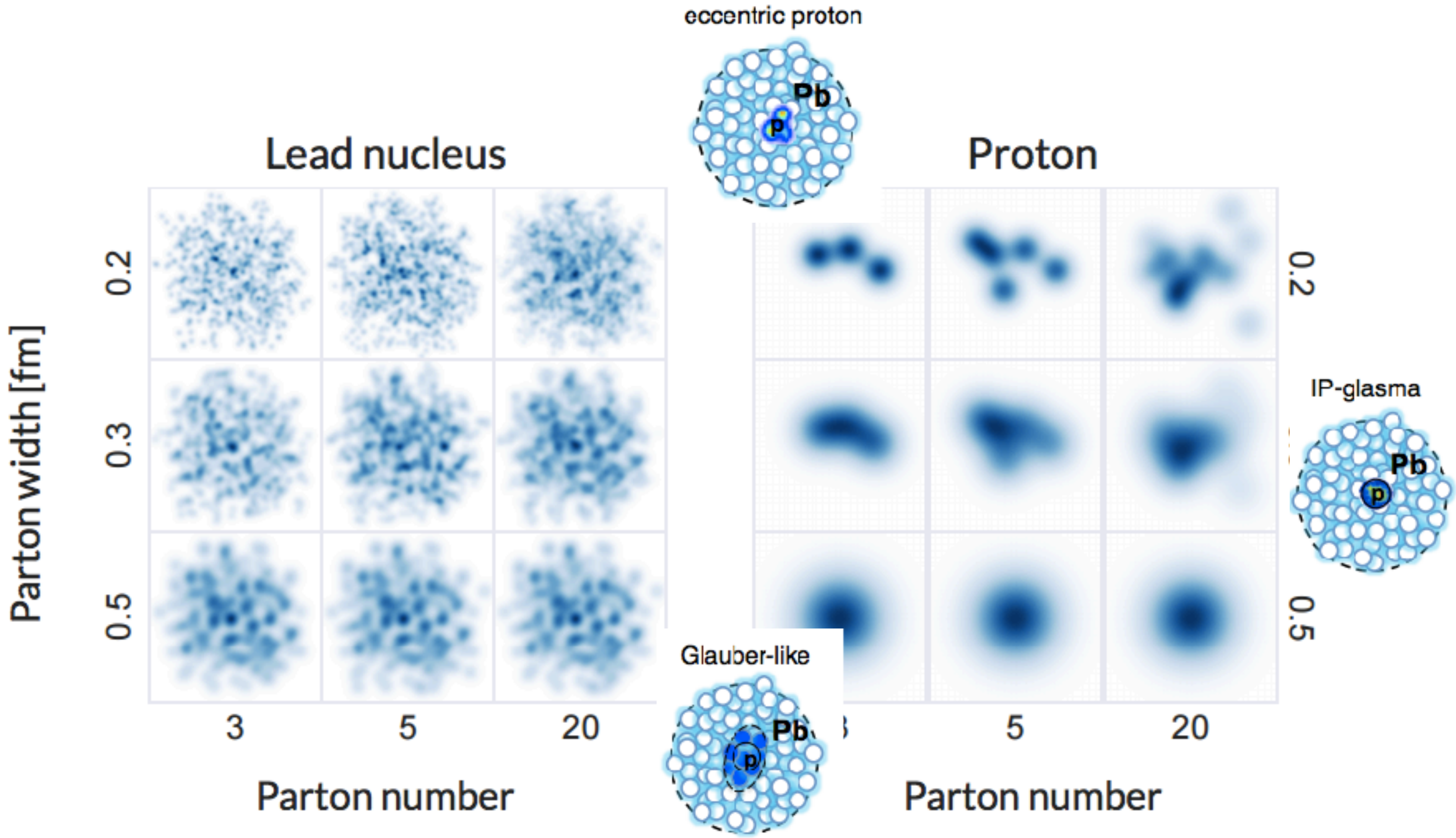

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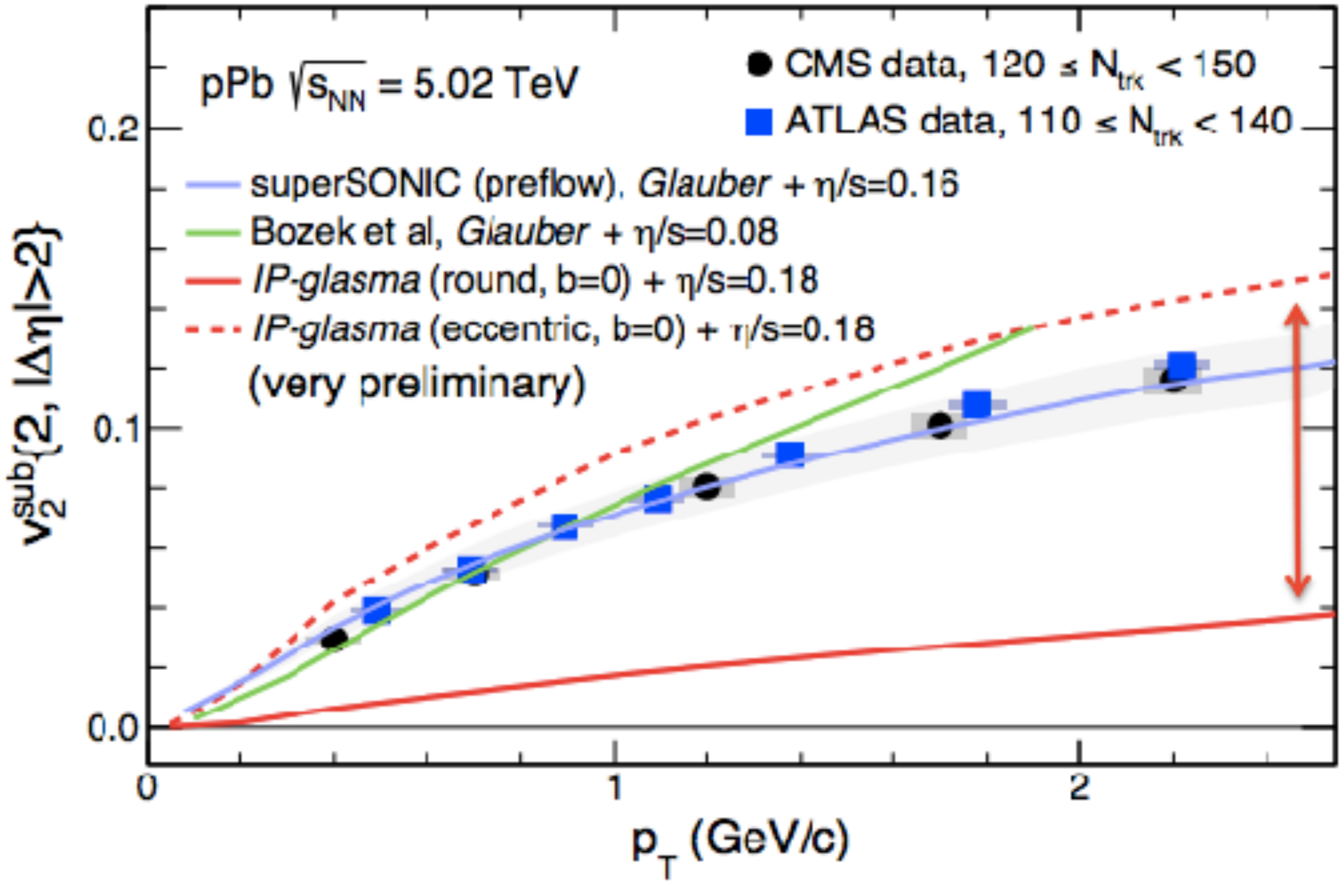
# Looking at sub-nucleon size fluctuations

Wei Li, B Schenke, QM17 talk



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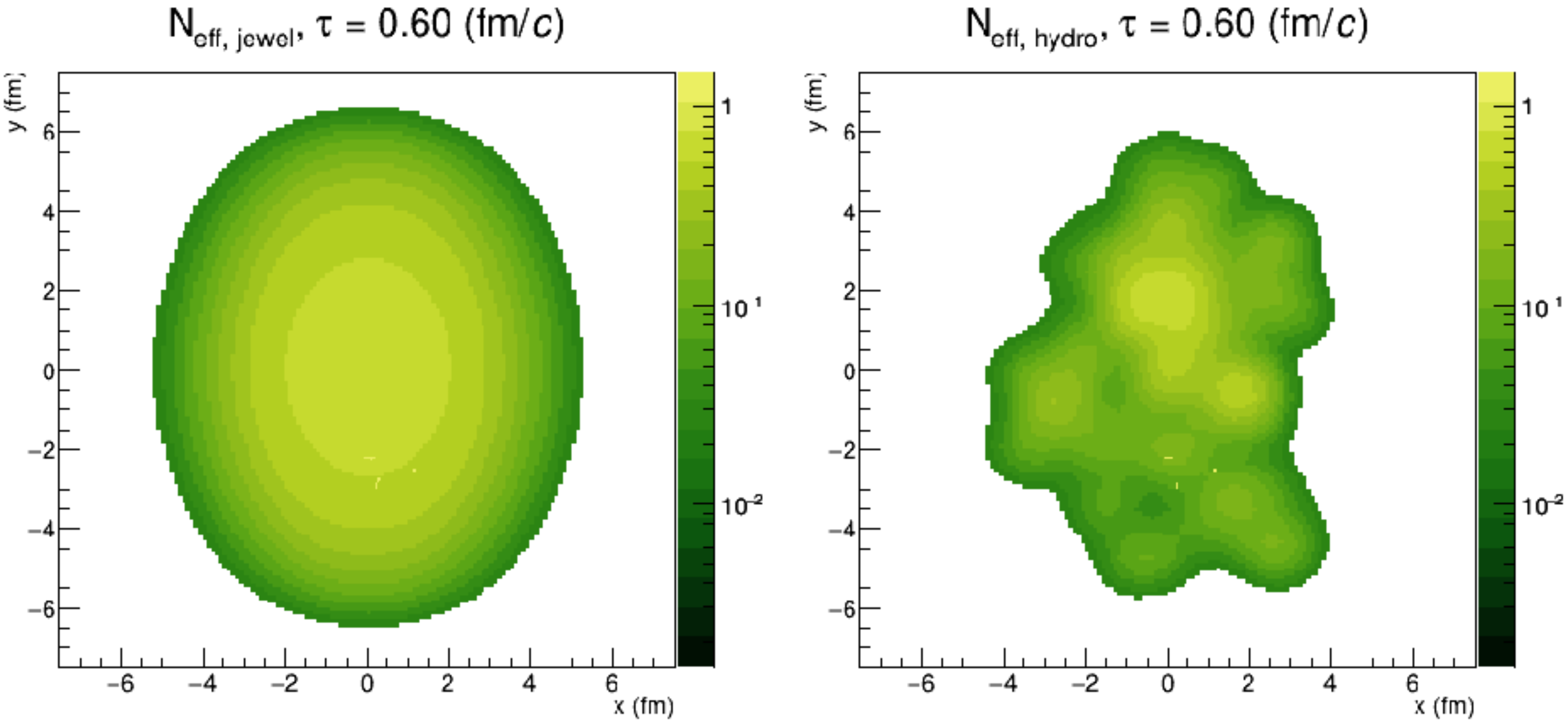
# Higher $p_T$: probes of the QGP

R Bertens, JEWEL simulation



**Hard probes**

Hard-scatterings produce quasi-free partons

⇒ Probe medium through energy loss

Expected to be dominant for $p_T > 5$ GeV or so

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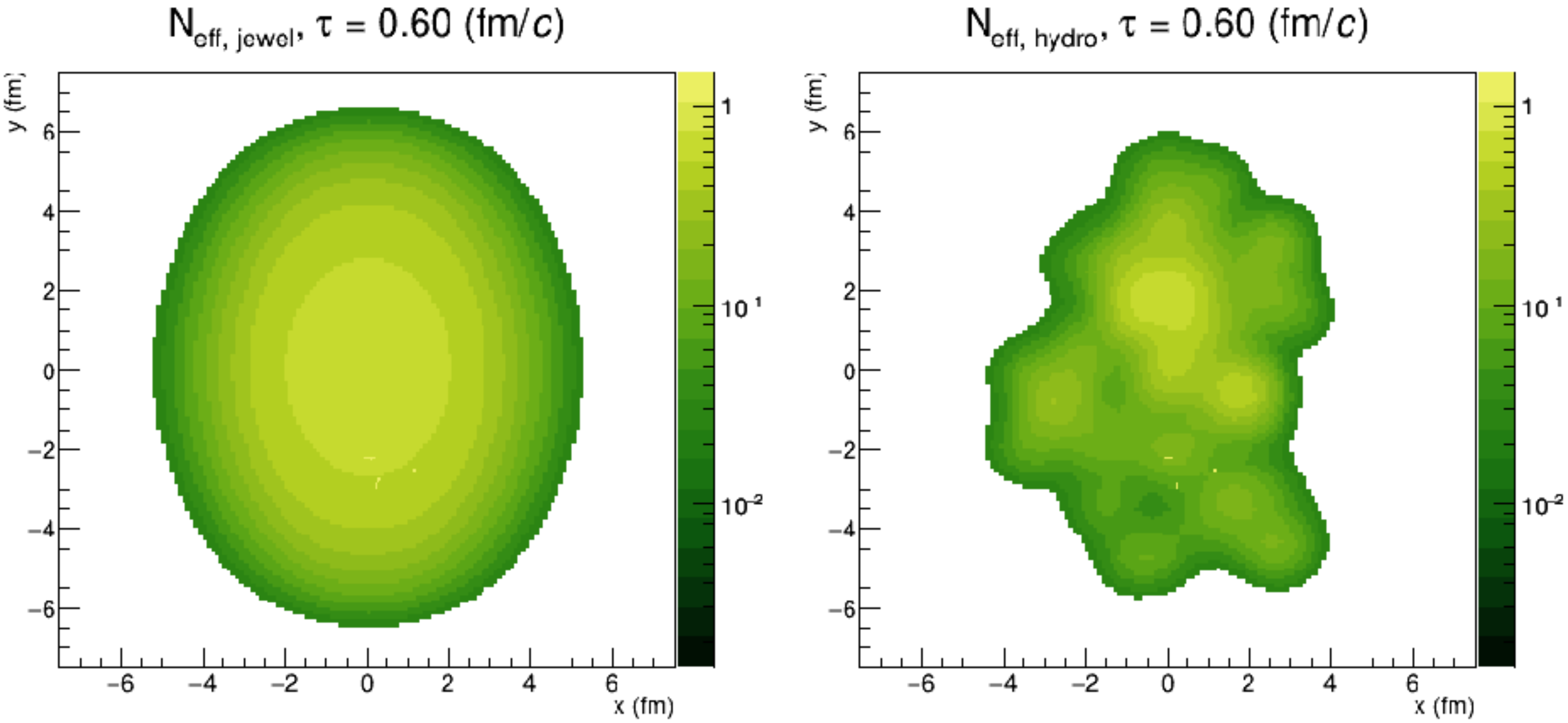

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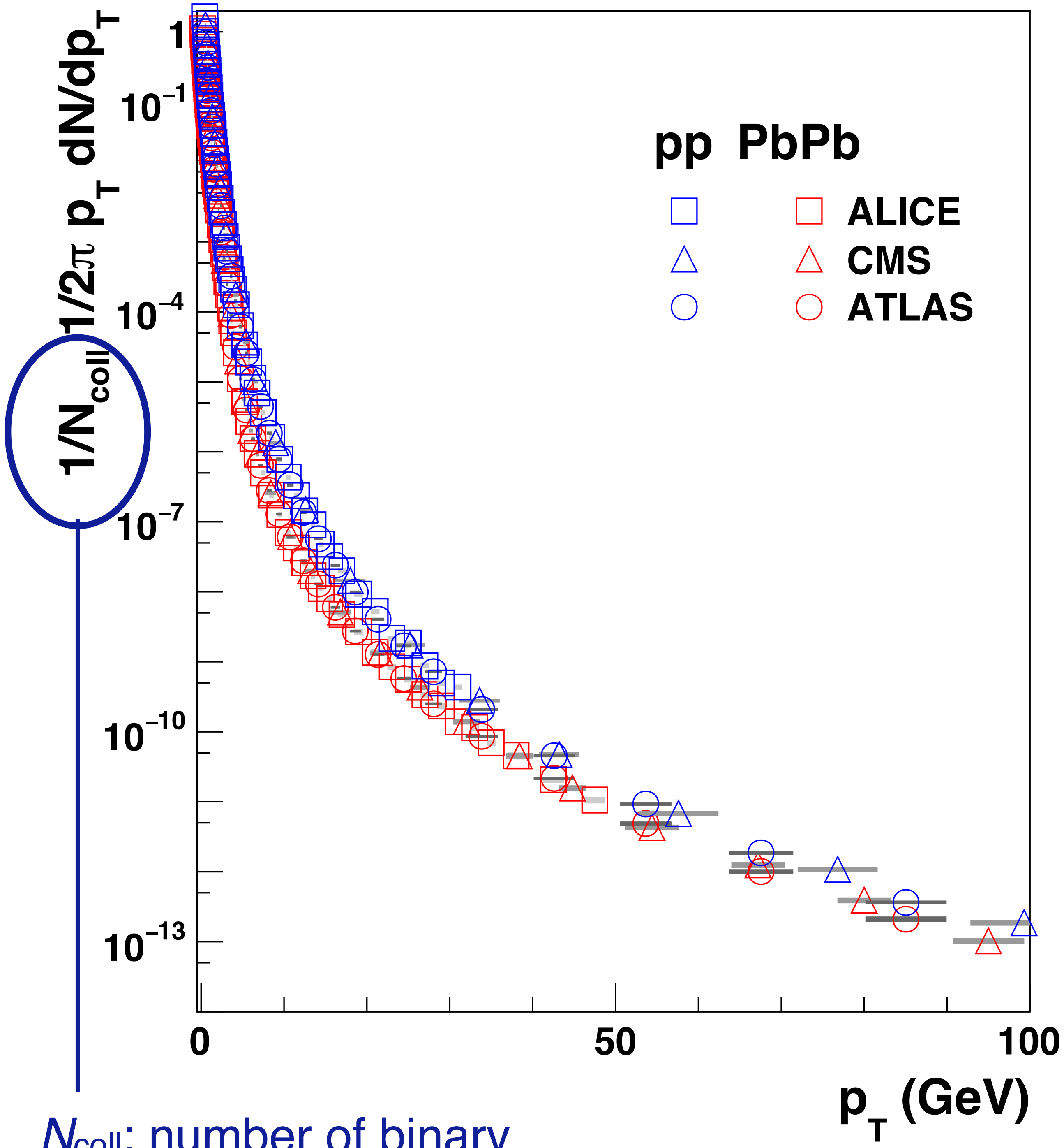
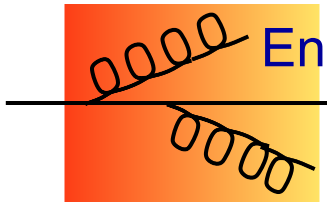
# Nuclear modification: Pb+Pb

ALICE, PLB720, 52
CMS, EPJC, 72, 1945
ATLAS, arXiv:1504.04337

## Charged particle $p_T$ spectra



$N_{\text{coll}}$: number of binary nucleon-nucleon collisions



Energy loss

$R_{AA} < 1$

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CMS, EPJC, 72, 1945
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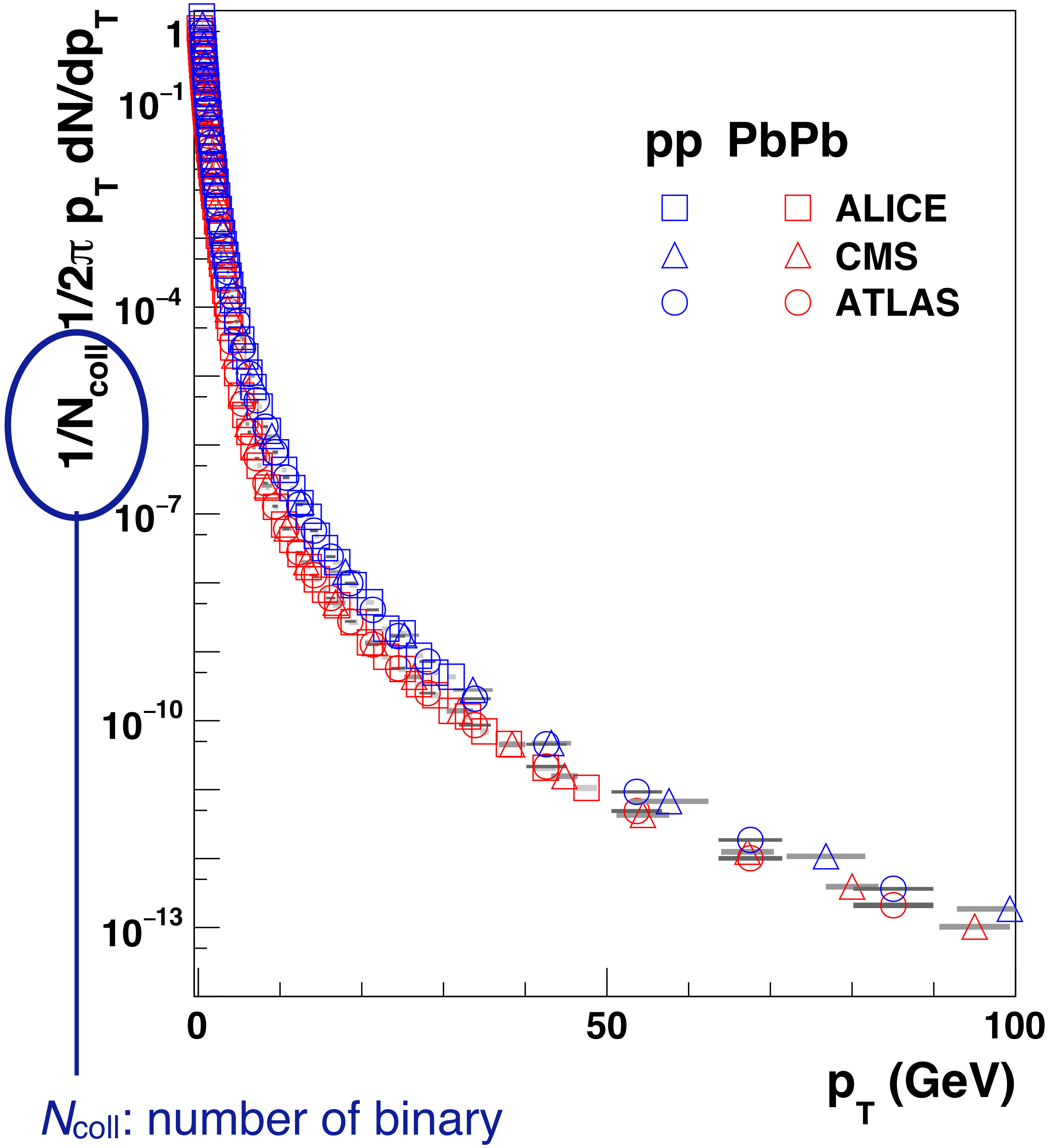
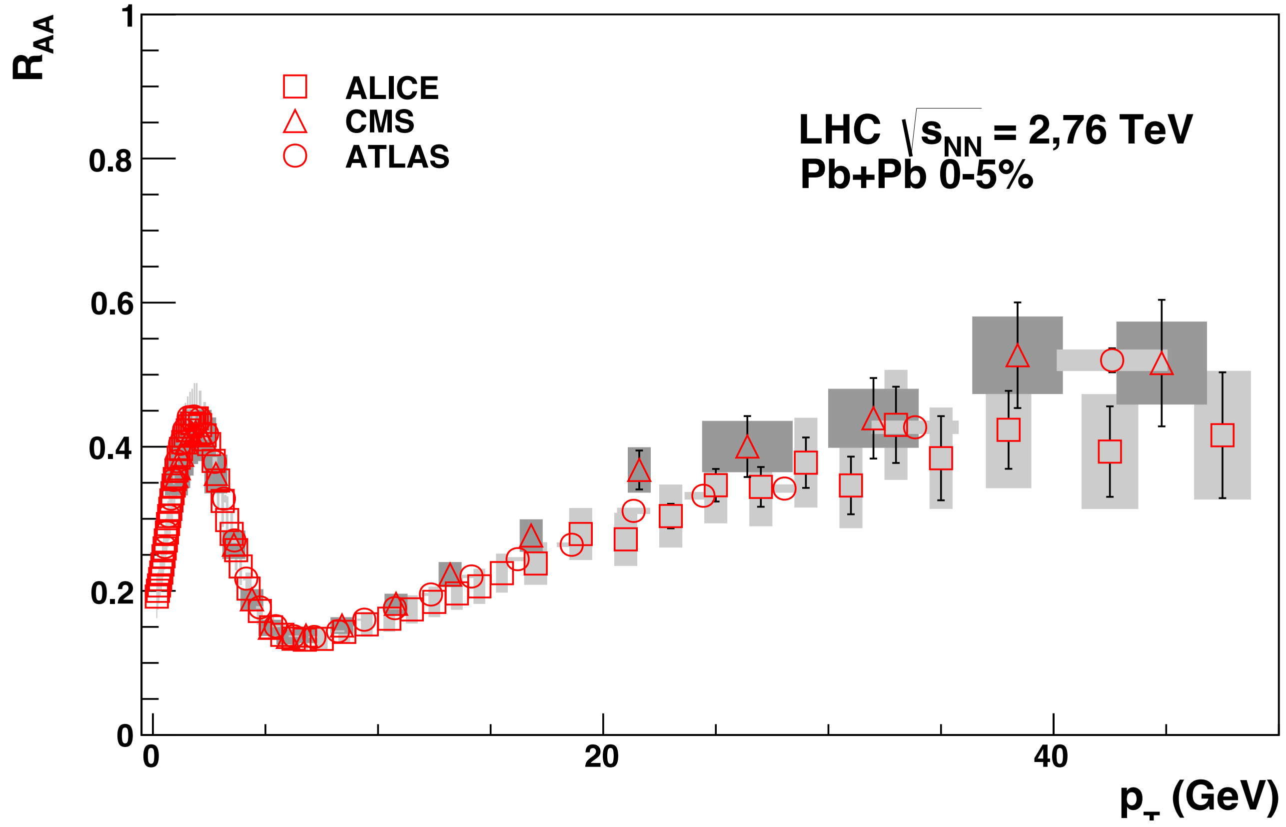
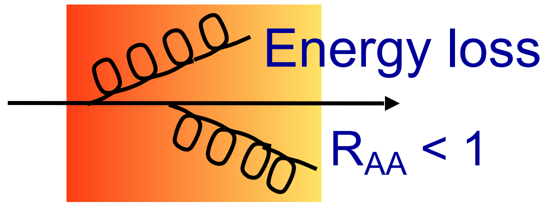


$N_{\mathrm{coll}}$: number of binary nucleon-nucleon collisions

## Nuclear modification factor



$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$



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

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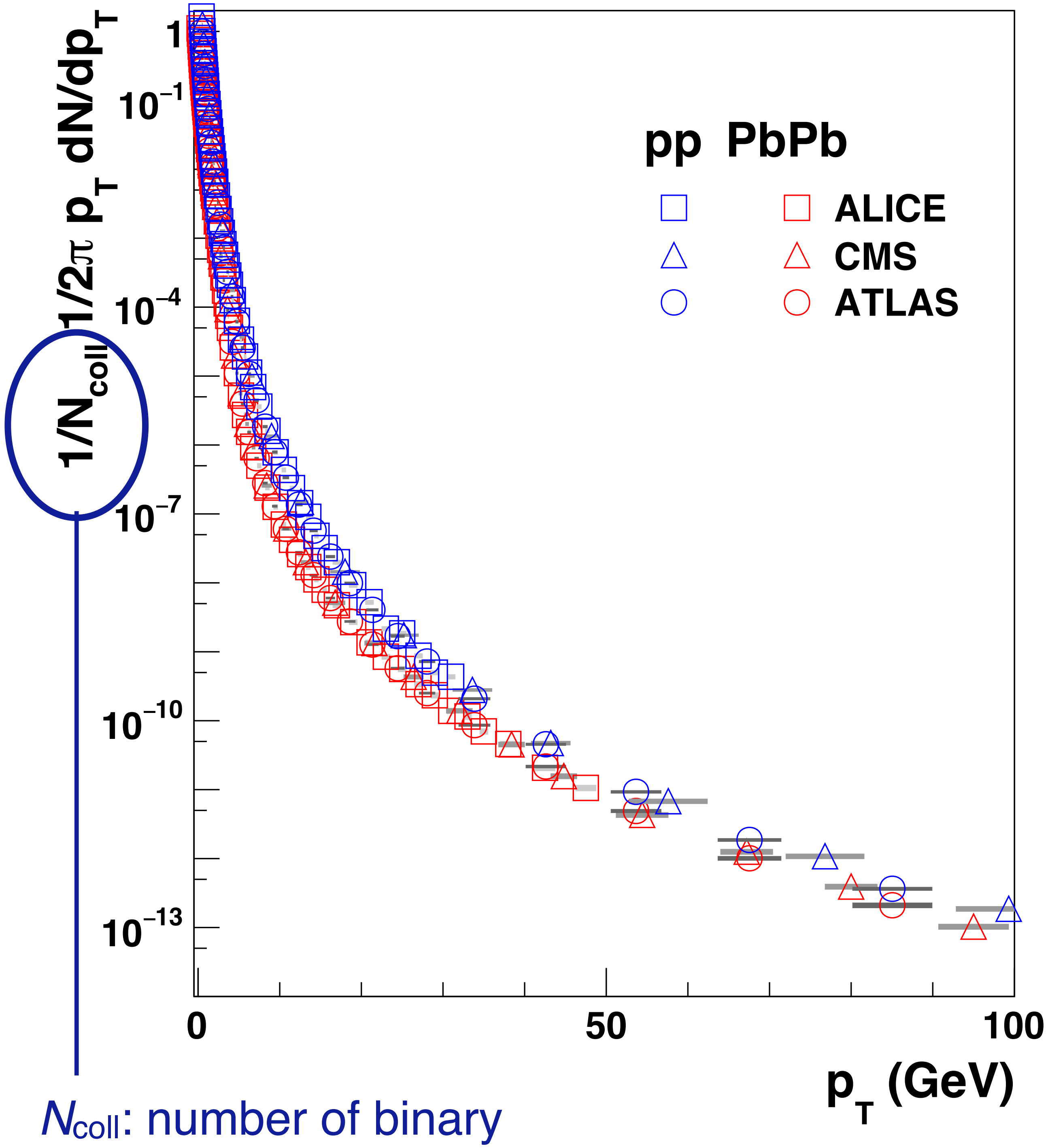

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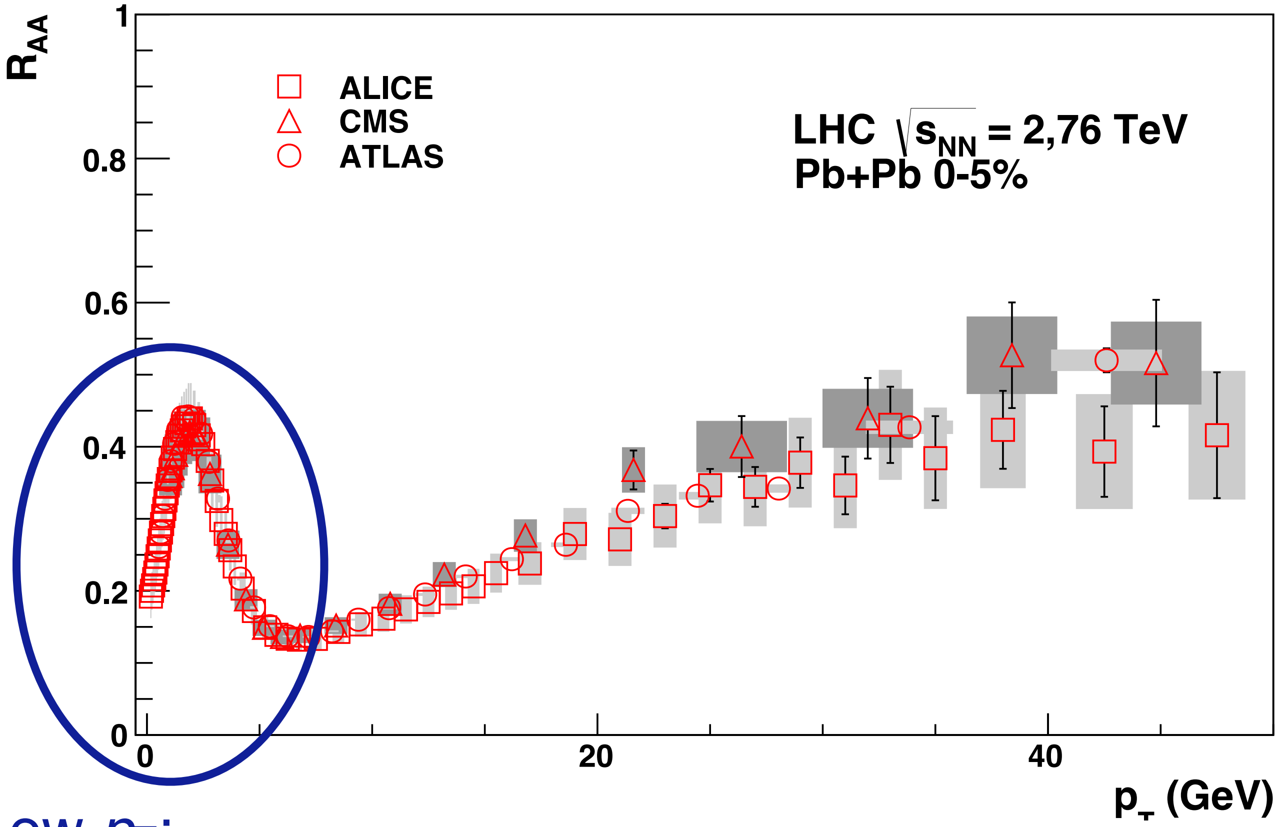
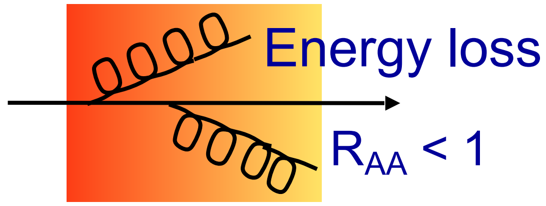
## Nuclear modification factor



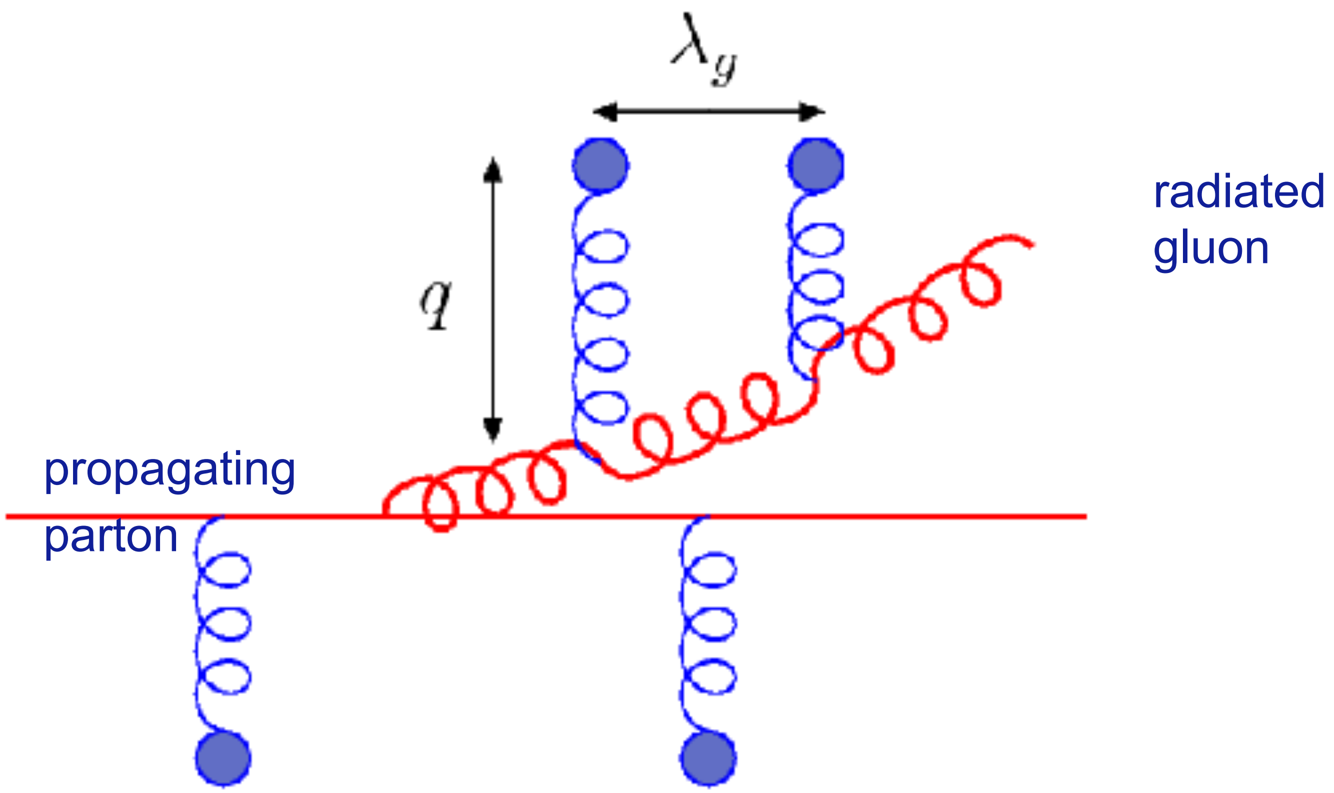
Low $p_T$:
soft production,
$N_{part}$ scaling

$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$



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

# Medium-induced radiation



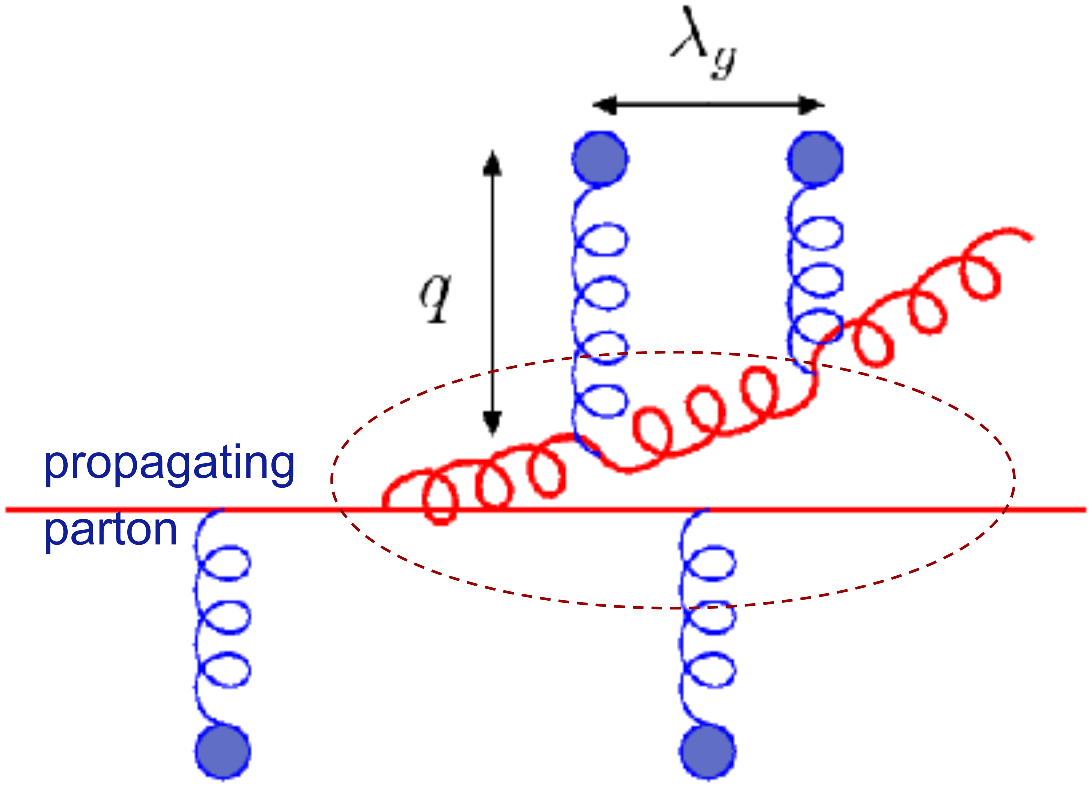
Energy loss depends on density: $\lambda \propto \frac{1}{\rho}$

and nature of scattering centers
(scattering cross section)

Transport coefficient $\hat{q} \equiv \frac{\langle q_\perp^2 \rangle}{\lambda}$

# Medium-induced radiation

Landau-Pomeranchuk-Migdal effect
Formation time important



radiated
gluon

Radiation sees
length ~$\tau_f$ at once

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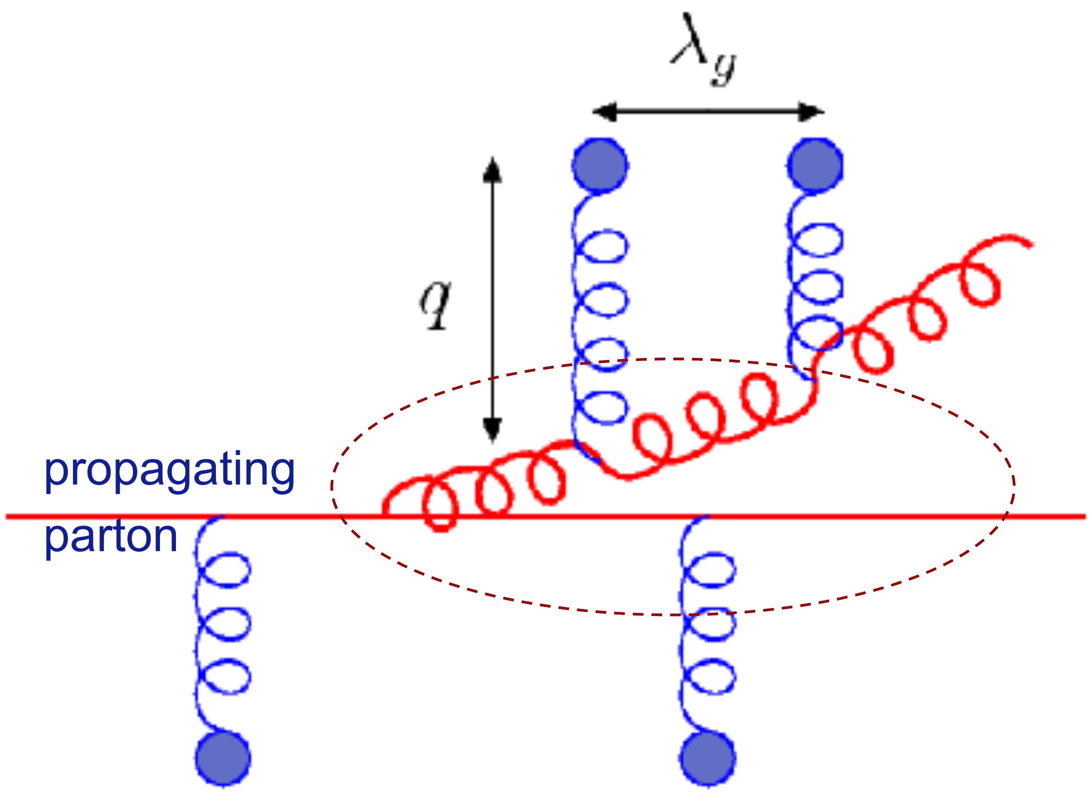
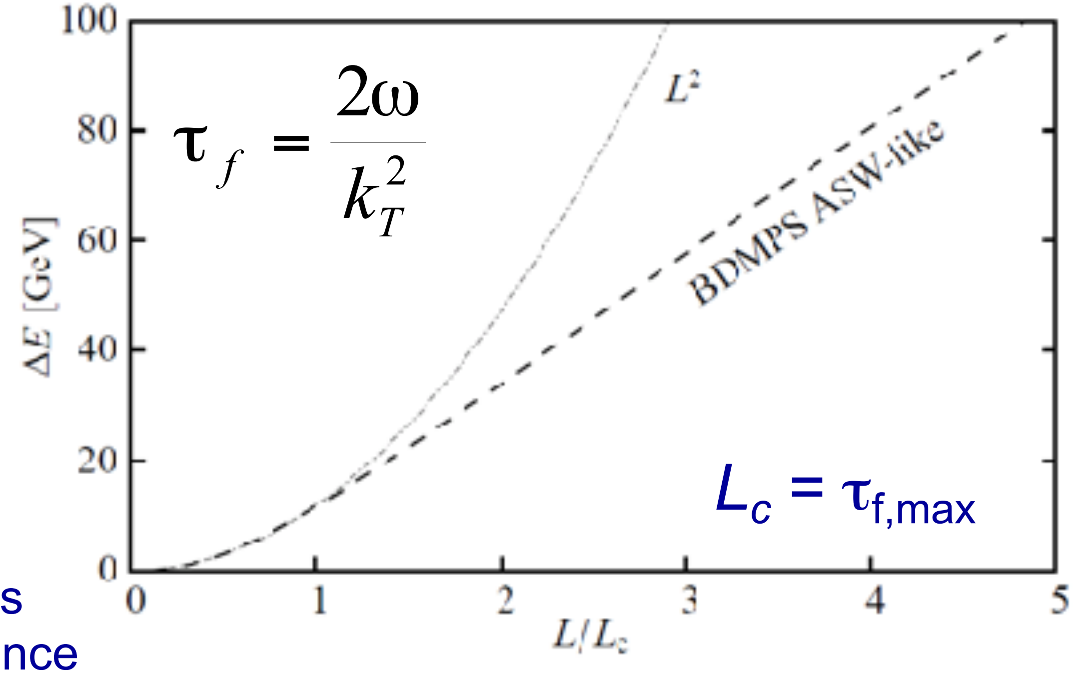


propagating parton

radiated gluon

Radiation sees length ~$\tau_f$ at once

Zapp, QM09



$$\tau_f = \frac{2\omega}{k_T^2}$$

$L_c = \tau_{f,max}$

If $\lambda < \tau_f$, multiple scatterings add coherently

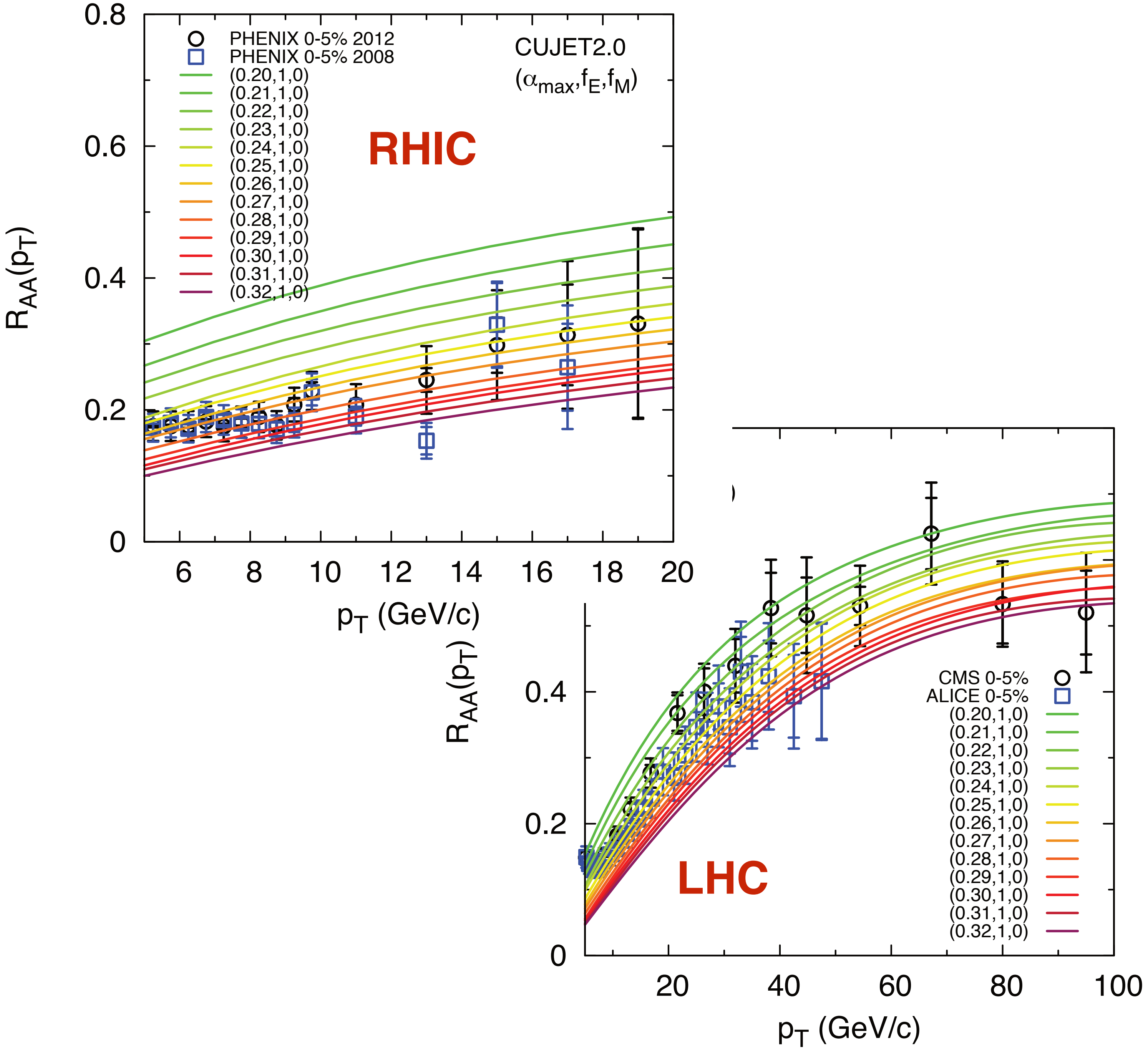
Energy loss depends on density: $\lambda \propto \frac{1}{\rho}$

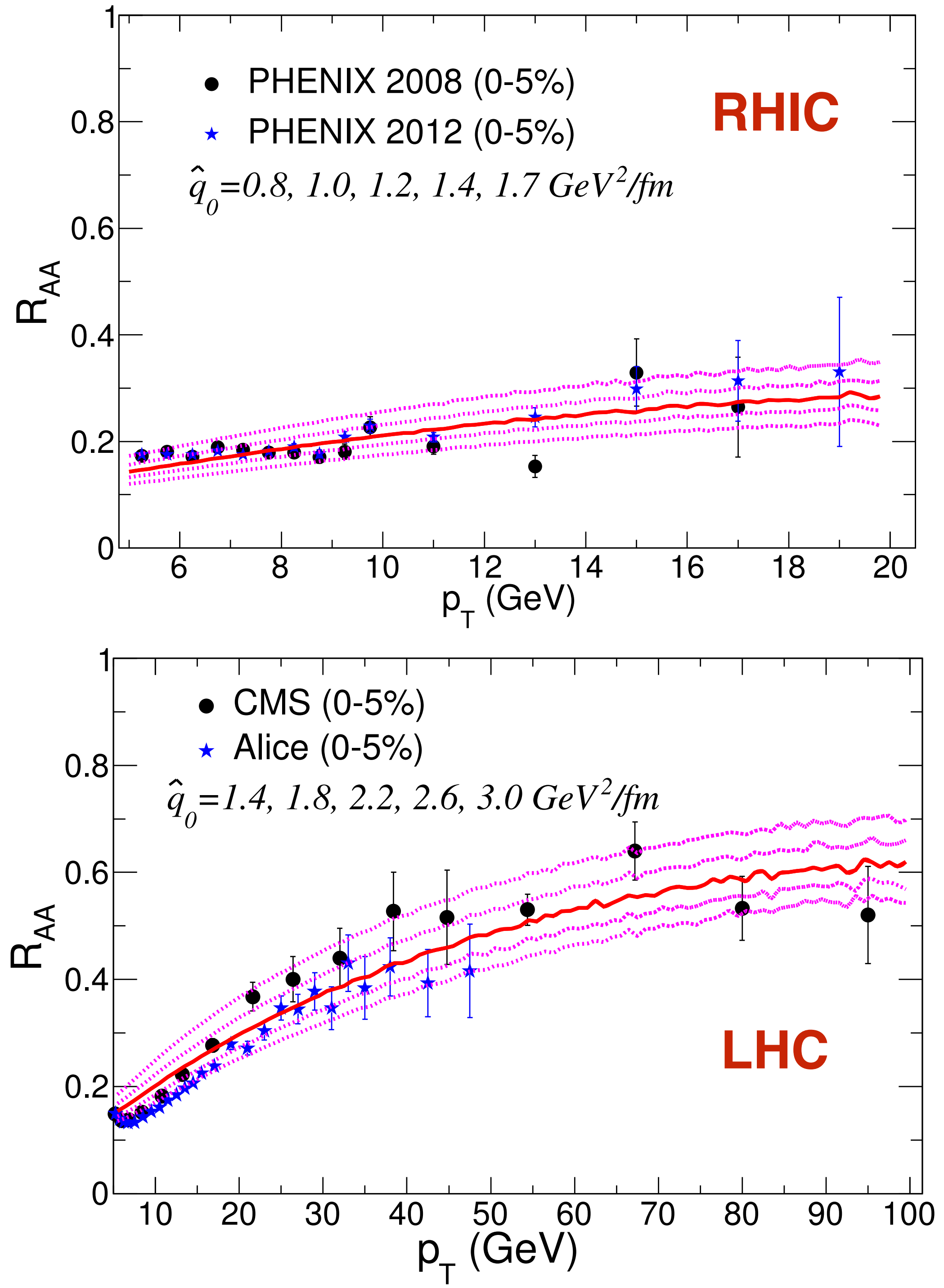
and nature of scattering centers
(scattering cross section)

Transport coefficient $\hat{q} \equiv \frac{\langle q_\perp^2 \rangle}{\lambda}$

$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

# RHIC and LHC





Burke et al, JET Collaboration, arXiv:1312.5003

Systematic comparison of energy loss models with data

Medium modelled by Hydrodynamics (2+1D, 3+1D)

$p_T$ dependence matches reasonably well

# Summary of transport coefficient study

RHIC: $\sqrt{s_{NN}}$ = 200 GeV

$$\hat{q} = 1.2 \pm 0.3 \ \mathrm{GeV}^2/\mathrm{fm}$$

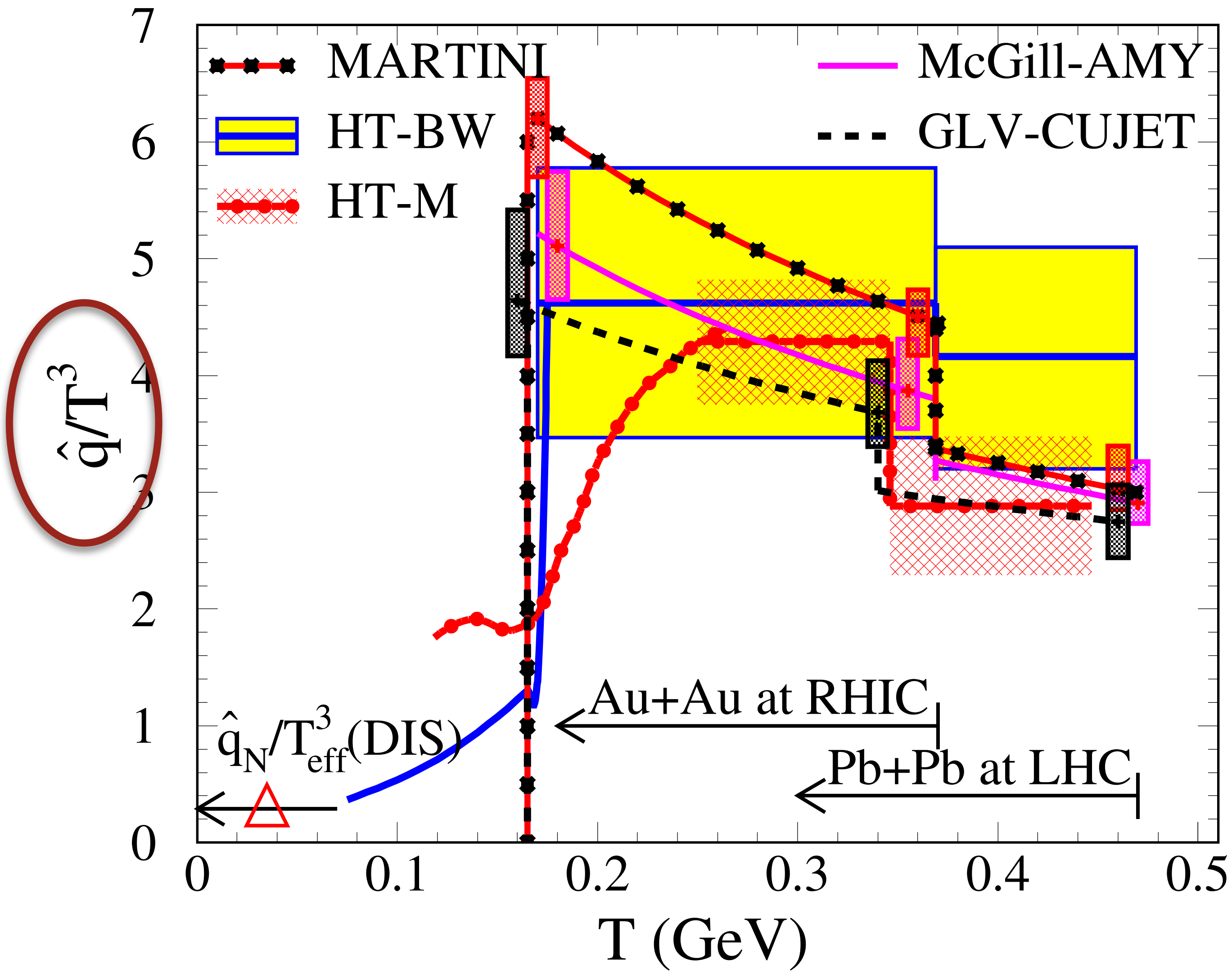
($T_i$ = 370 MeV)

LHC: $\sqrt{s_{NN}}$ = 2760 GeV

$$\hat{q} = 1.9 \pm 0.7 \ \mathrm{GeV}^2/\mathrm{fm}$$

($T_i$ = 470 MeV)

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



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$\hat{q}$ values from different models consistent

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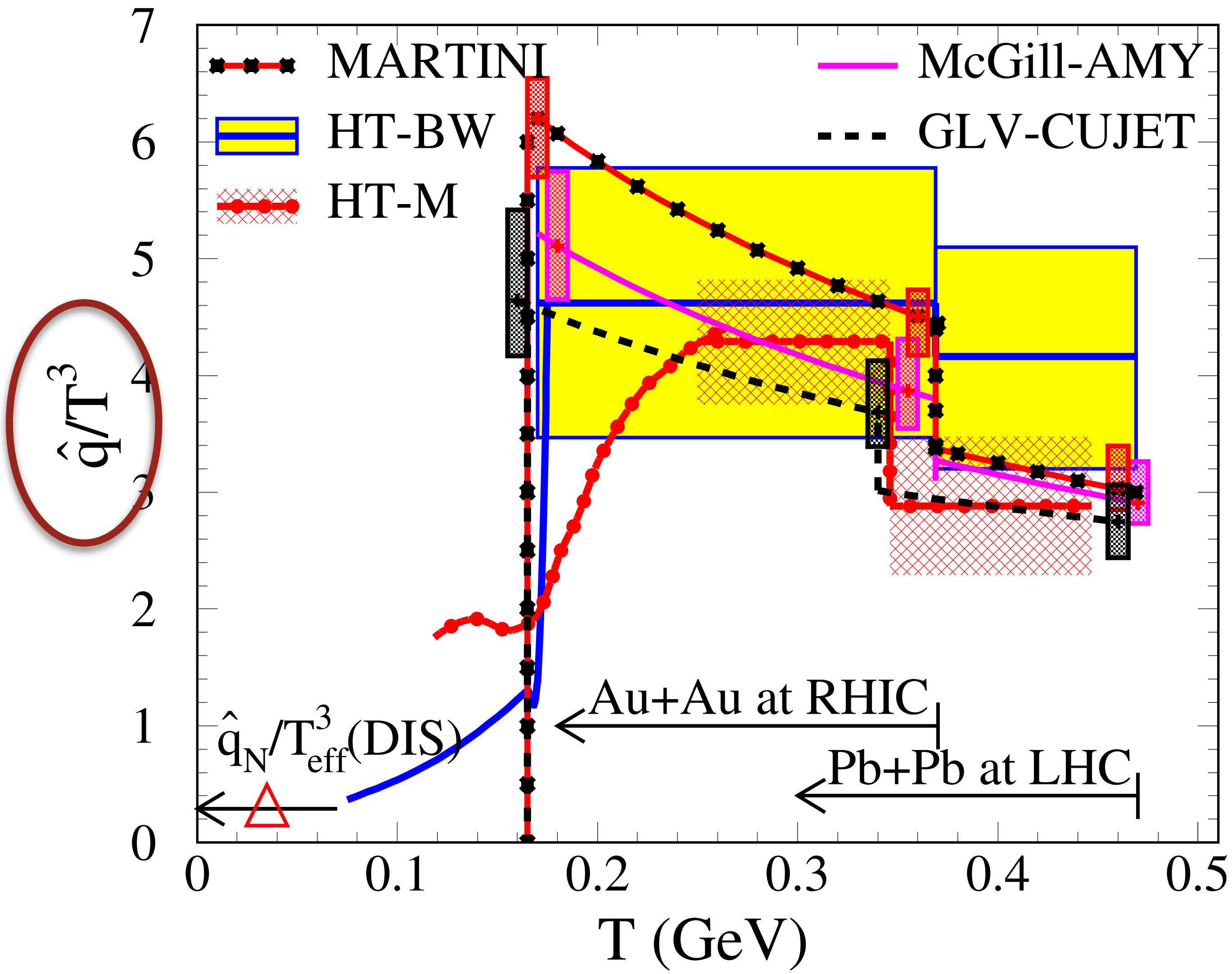

Burke et al, JET Collaboration, arXiv:1312.5003

$\hat{q}$ values from different models consistent

Arnold and Xiao, arXiv:0810.1026

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

Sizeable uncertainties from $\alpha_S$, treatment of logs etc expected

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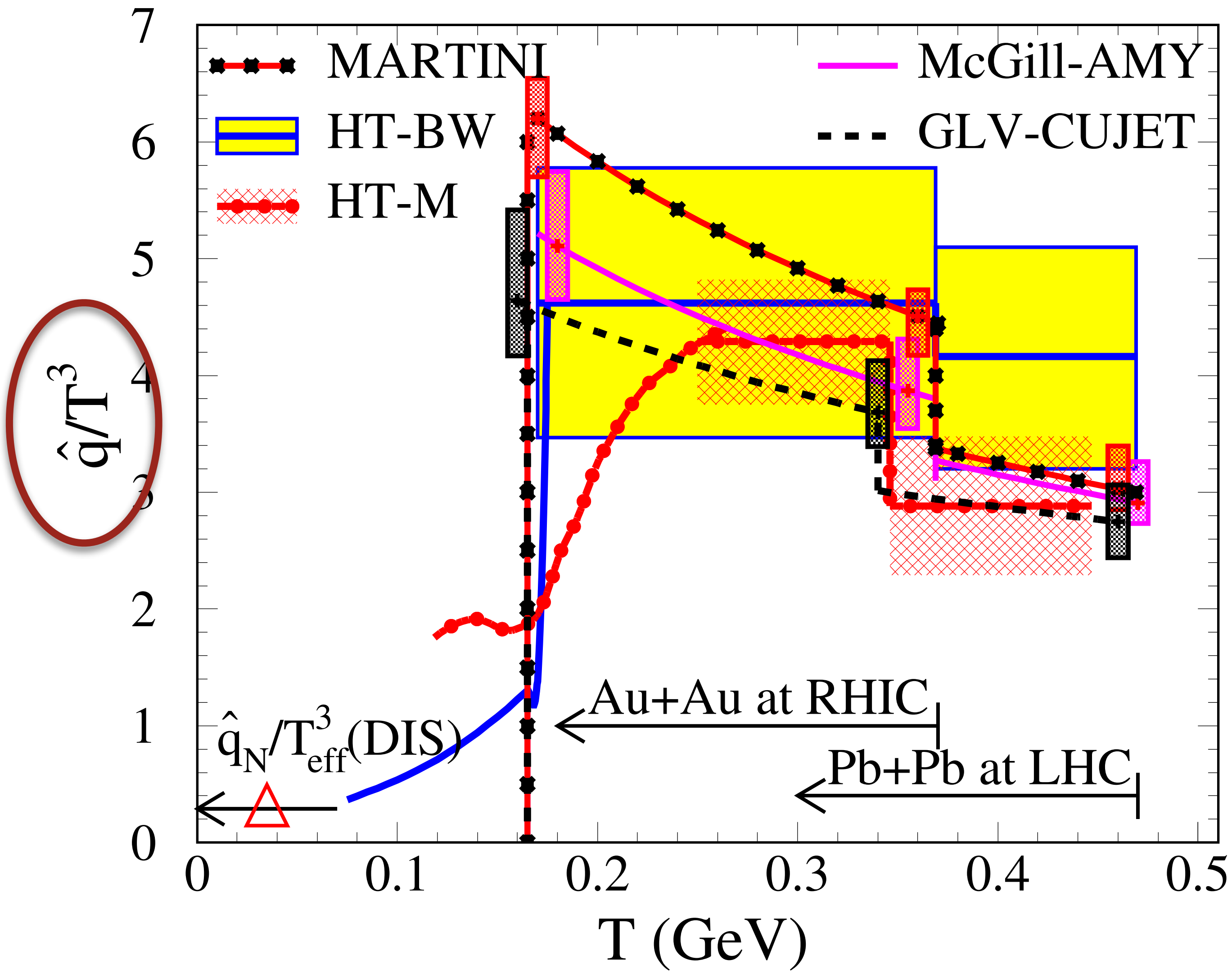

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Sizeable uncertainties from $\alpha_S$, treatment of logs etc expected

Values found are in the right ballpark compared (p)QCD estimate

Magnitude of parton energy loss is understood

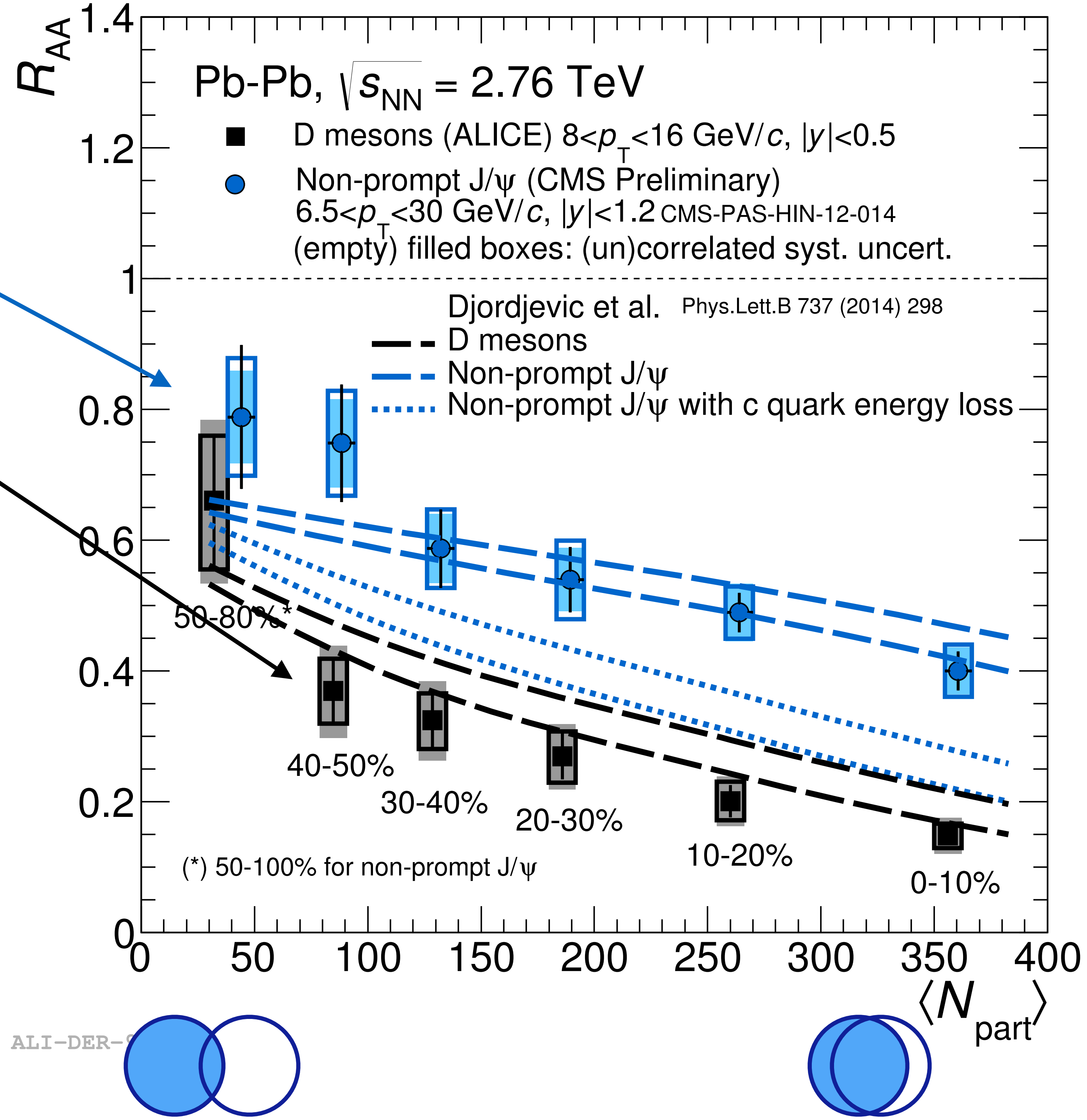
# Heavy flavour $R_{AA}$; mass dependence

Compare

beauty: non-prompt J/Ψ

charm: D-mesons

ALICE, JHEP11, 205



Larger suppression for charm than for beauty

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

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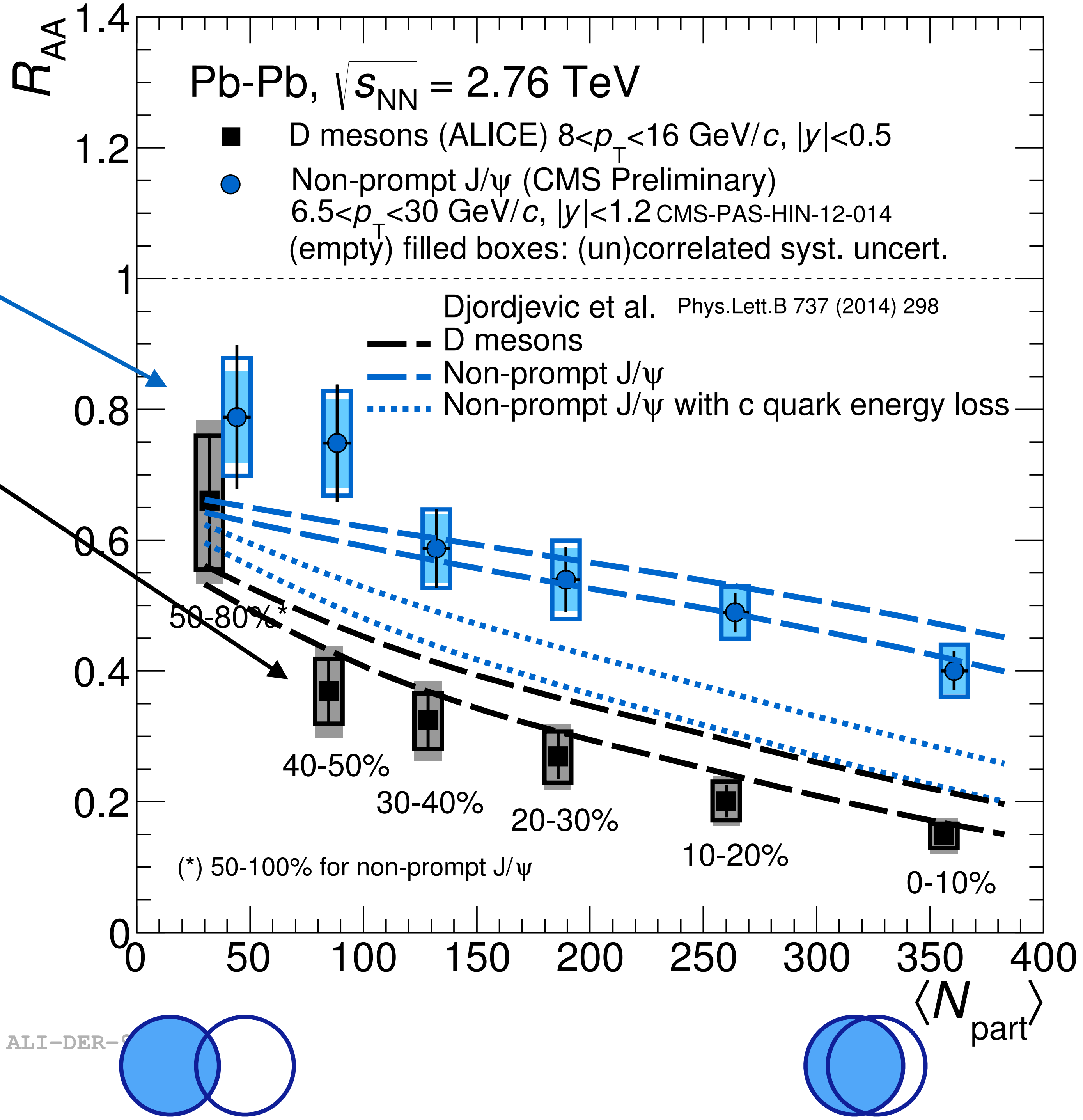

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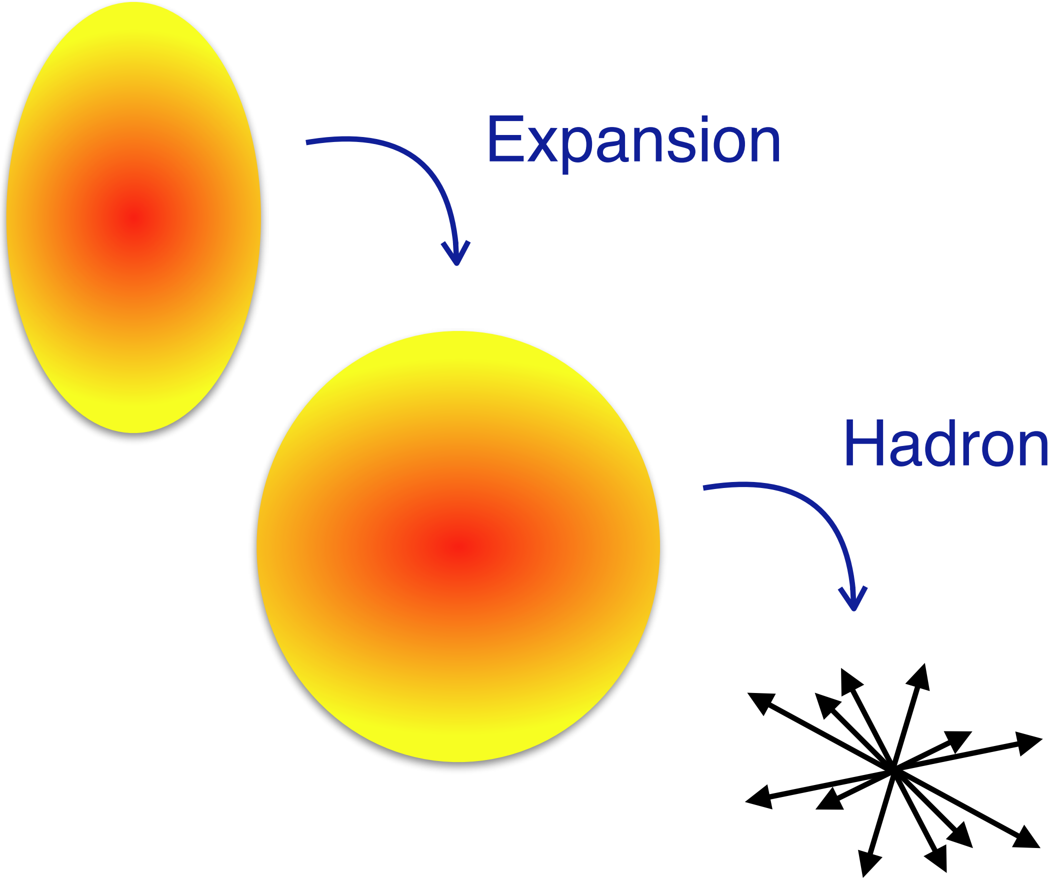
Agrees with expected ‘dead-cone effect’
energy loss reduced when $v < c$

Indicates radiative energy loss: induced gluon bremsstrahlung

# Azimuthal anisotropy: two mechanisms

## Hydrodynamical expansion

Dominant effect at low $p_T$

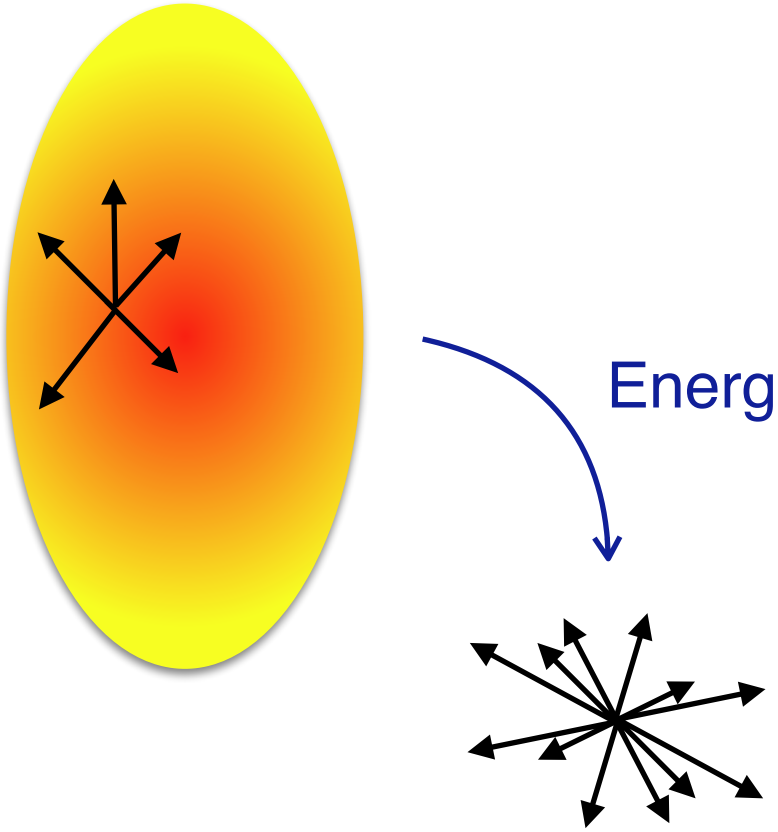


$$\nabla p = \rho \frac{d\vec{v}}{dt}$$

Conversion of pressure gradients into momentum space anisotropy

## Parton energy loss

Dominant effect at high $p_T$



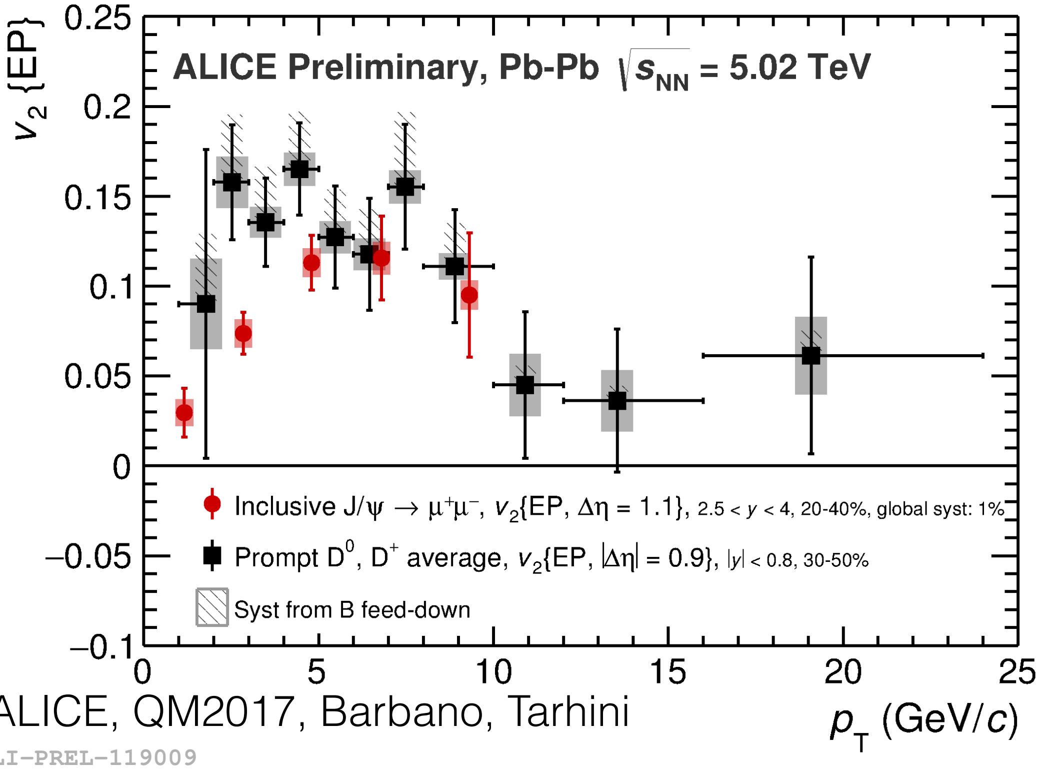
$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

More energy loss along long axis than short axis

Expect different mechanisms at low, high $p_T$, qualitatively similar effects
Heavy flavour probes the full range

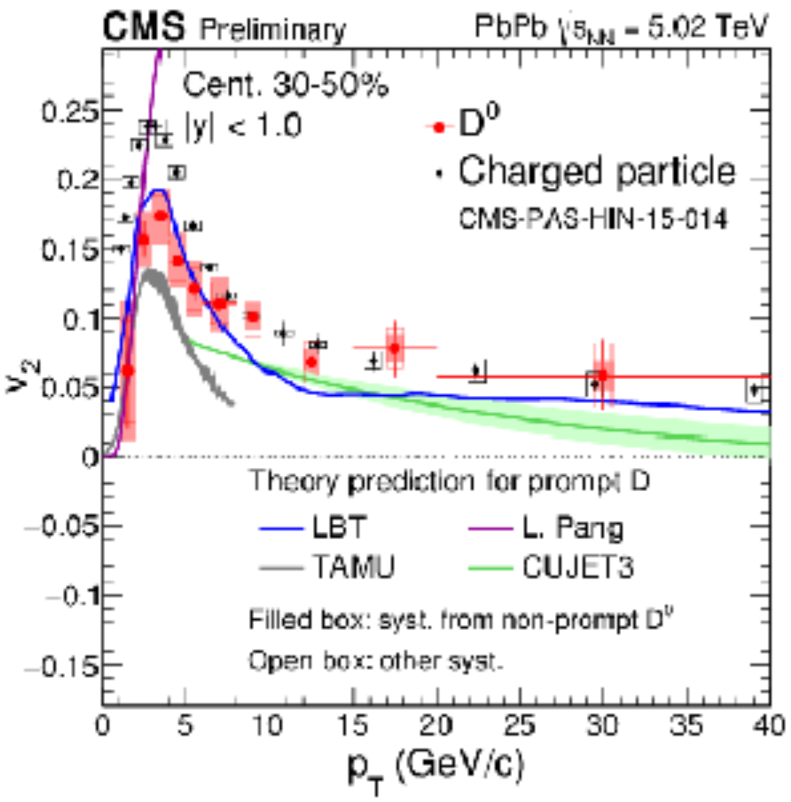
# Charm $v_2$, $v_3$

## J/Ψ and D meson $v_2$

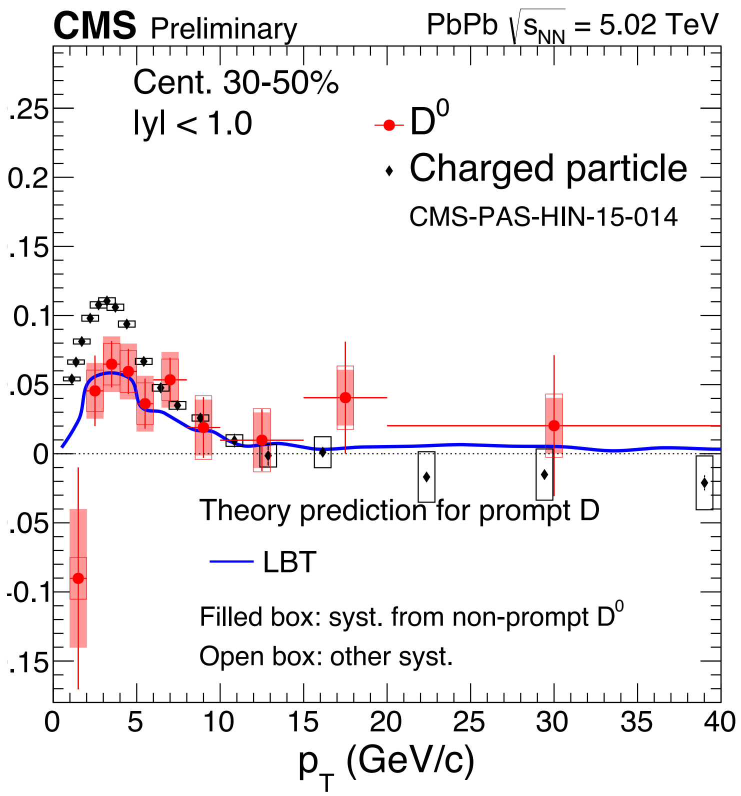


ALICE, QM2017, Barbano, Tarhini

## D meson $v_2$



## D meson $v_3$

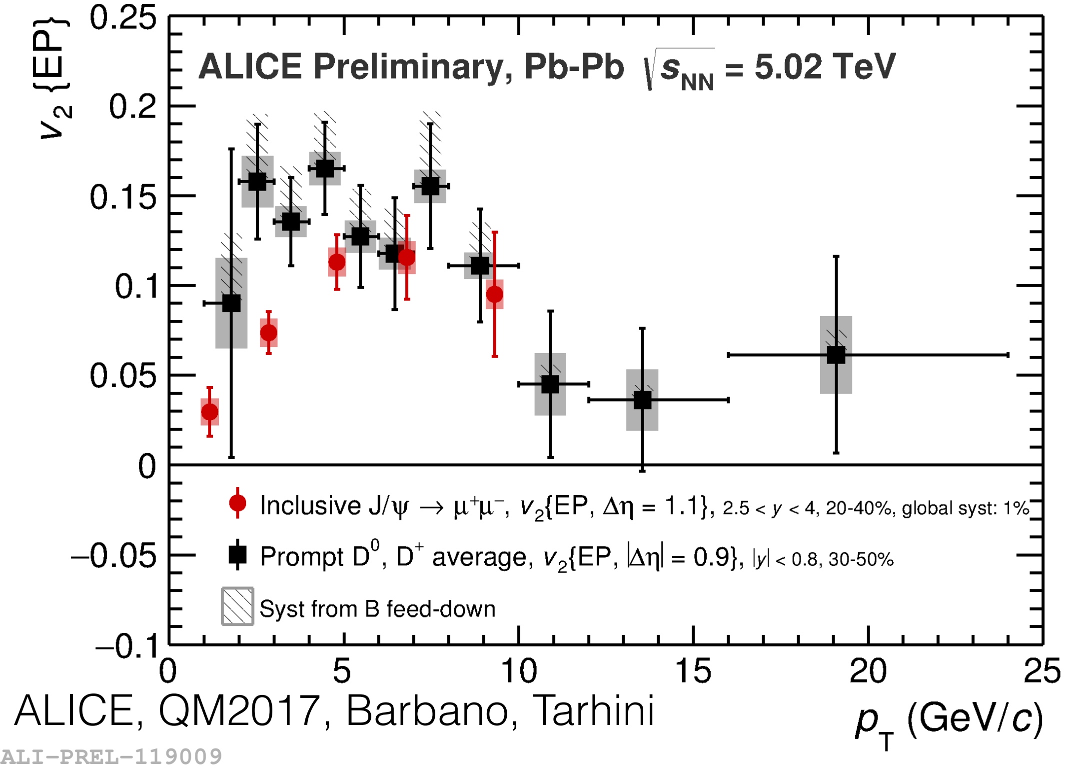


Models: PRC 94 014909, PLB 735 445, JHEP 1602 169 and PRD 91 074027

Azimuthal anisotropy of heavy quarks
very similar to light quarks (pions)

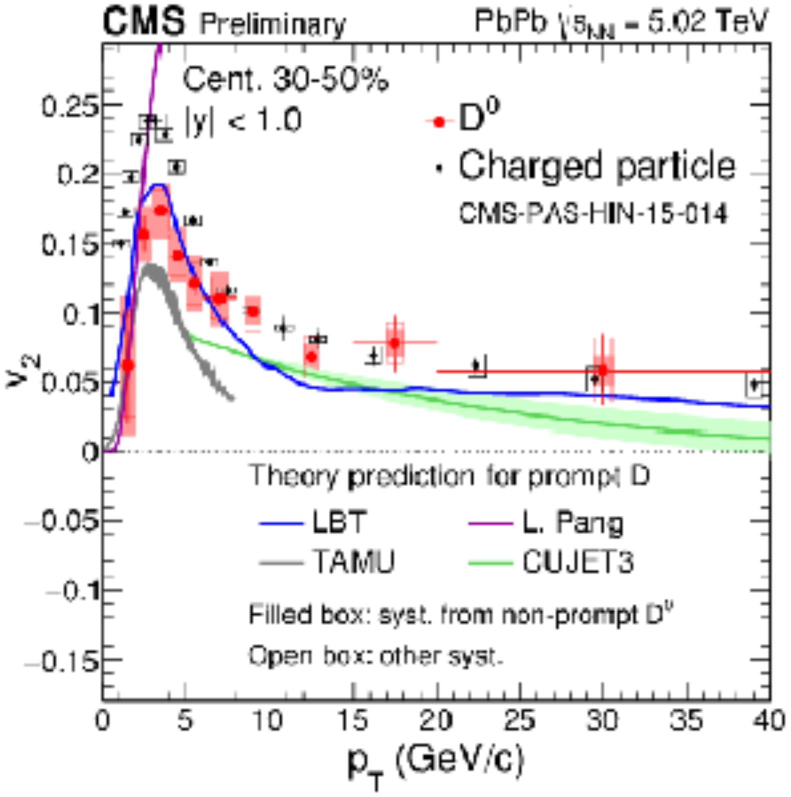
# Charm $v_2$, $v_3$

J/$\Psi$ and D meson $v_2$



ALICE, QM2017, Barbano, Tarhini

D meson $v_2$



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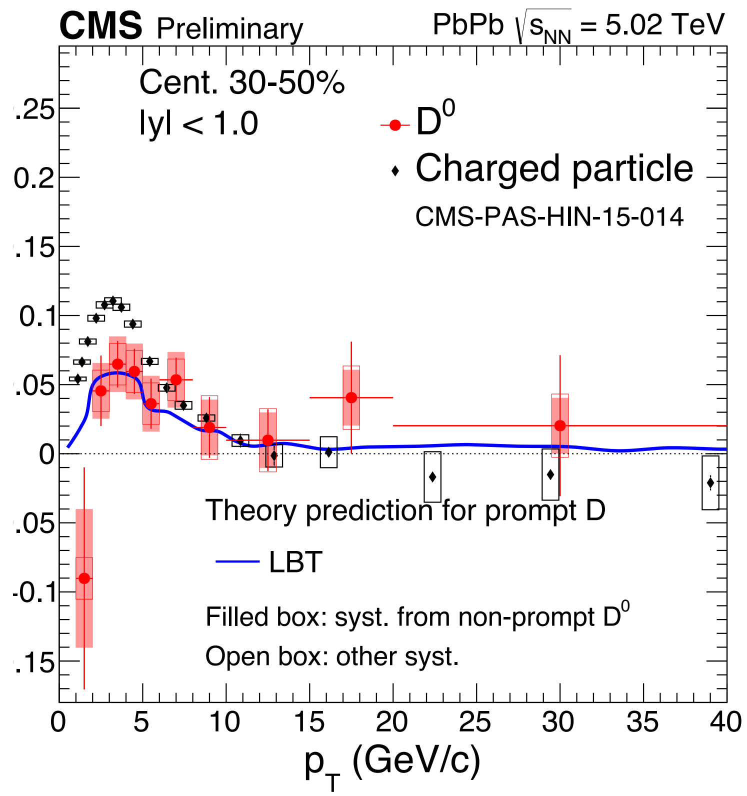


Models: PRC 94 014909, PLB 735 445, JHEP 1602 169 and PRD 91 074027

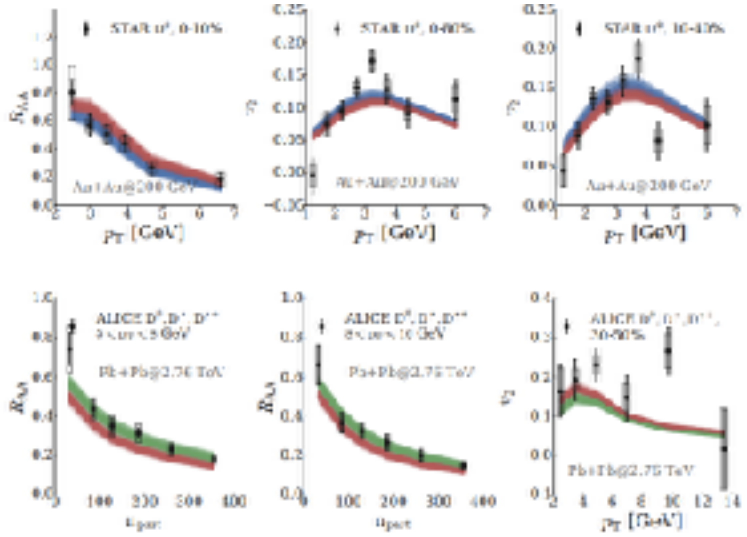
Azimuthal anisotropy of heavy quarks
very similar to light quarks (pions)

Heavy quarks ‘feel’ the flow of the Quark Gluon Plasma

# Heavy Flavour diffusion coefficients

## Duke fit: $R_{AA}$, $v_2$, RHIC+LHC

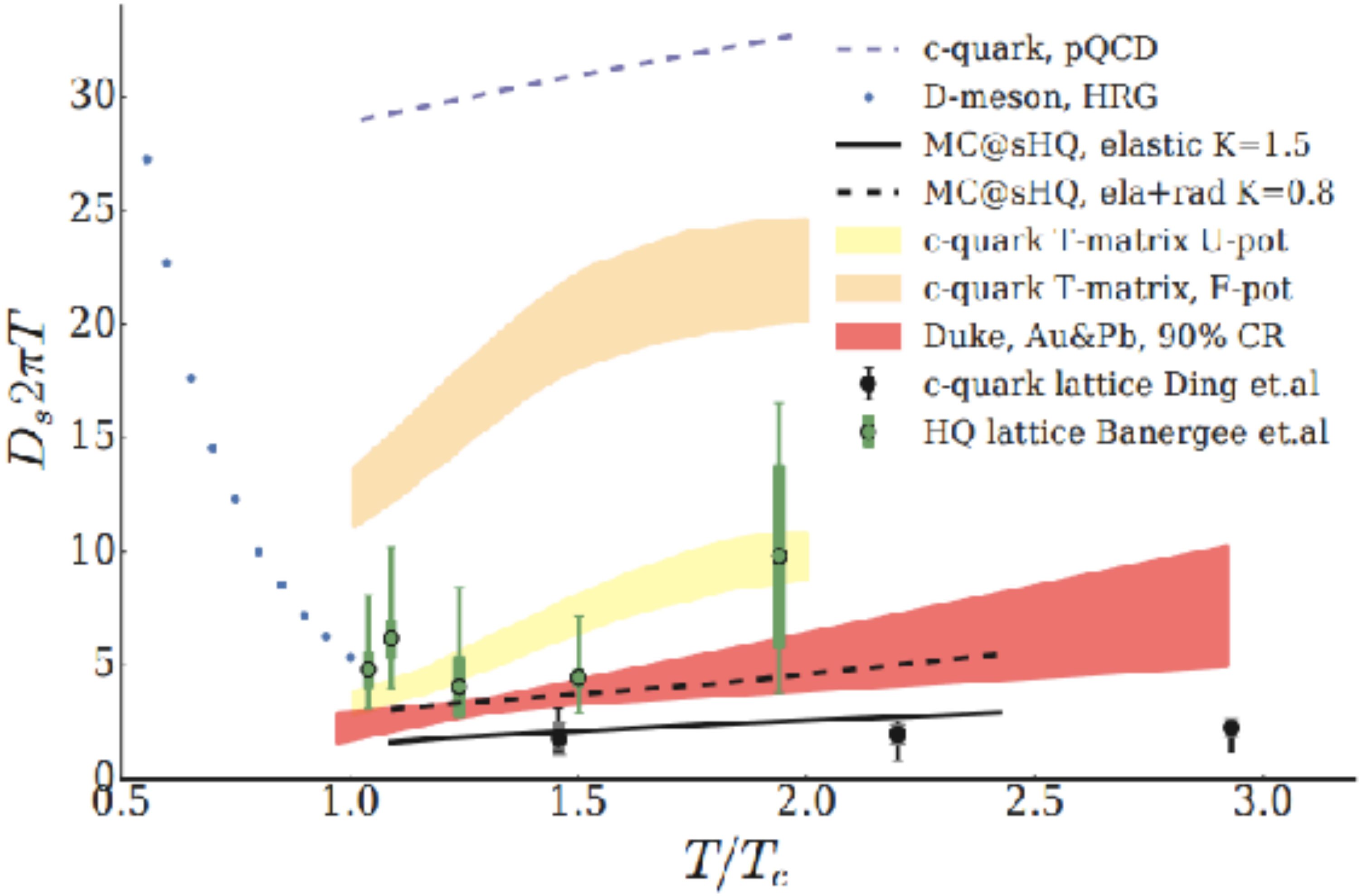
Y Xu, Quark Matter 2017



Physical model: Langevin Transport

Cao et al, PRC 92, 024907

## Comparison of various models/fits



F.Riek,and R.Rapp,
Phys.Rev.C 82,035201(2010)

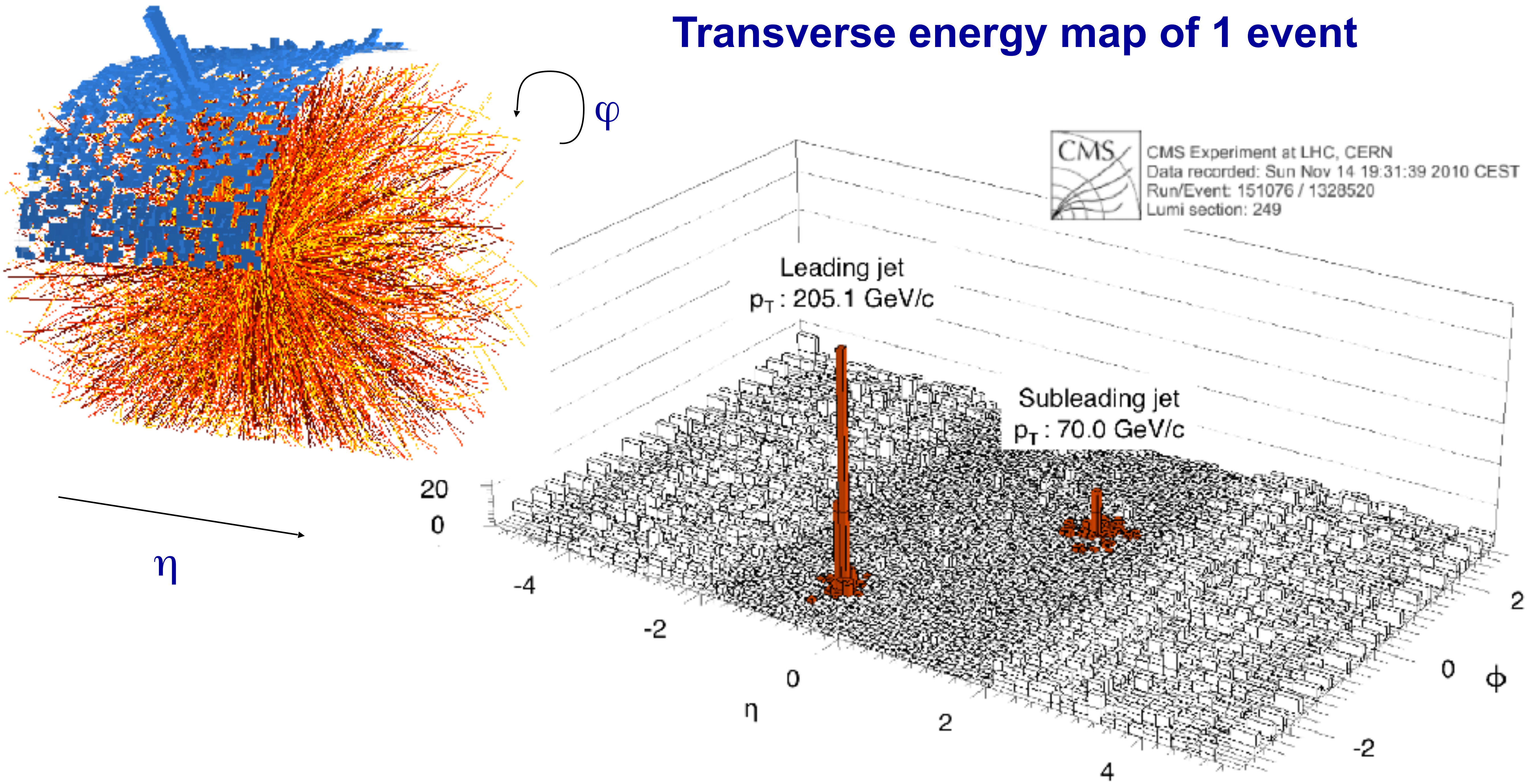
H.Ding,A.Francis,O.Kaczmarek,et.al,
Phys.Rev.D 86,014509(2012)

M.He,R.J.Fries,and R.Rapp,
Phys.Rev.Lett 11,112301(2013)

D.Banerjee,S.Datta,R.Gavai,P.Majumdar,
Phys.Rev.D 85,014510(2012)

First comparisons of heavy flavour transport coefficients
Still early days; work needed to understand (dis-)agreements

# Jets at LHC



**ALICE**

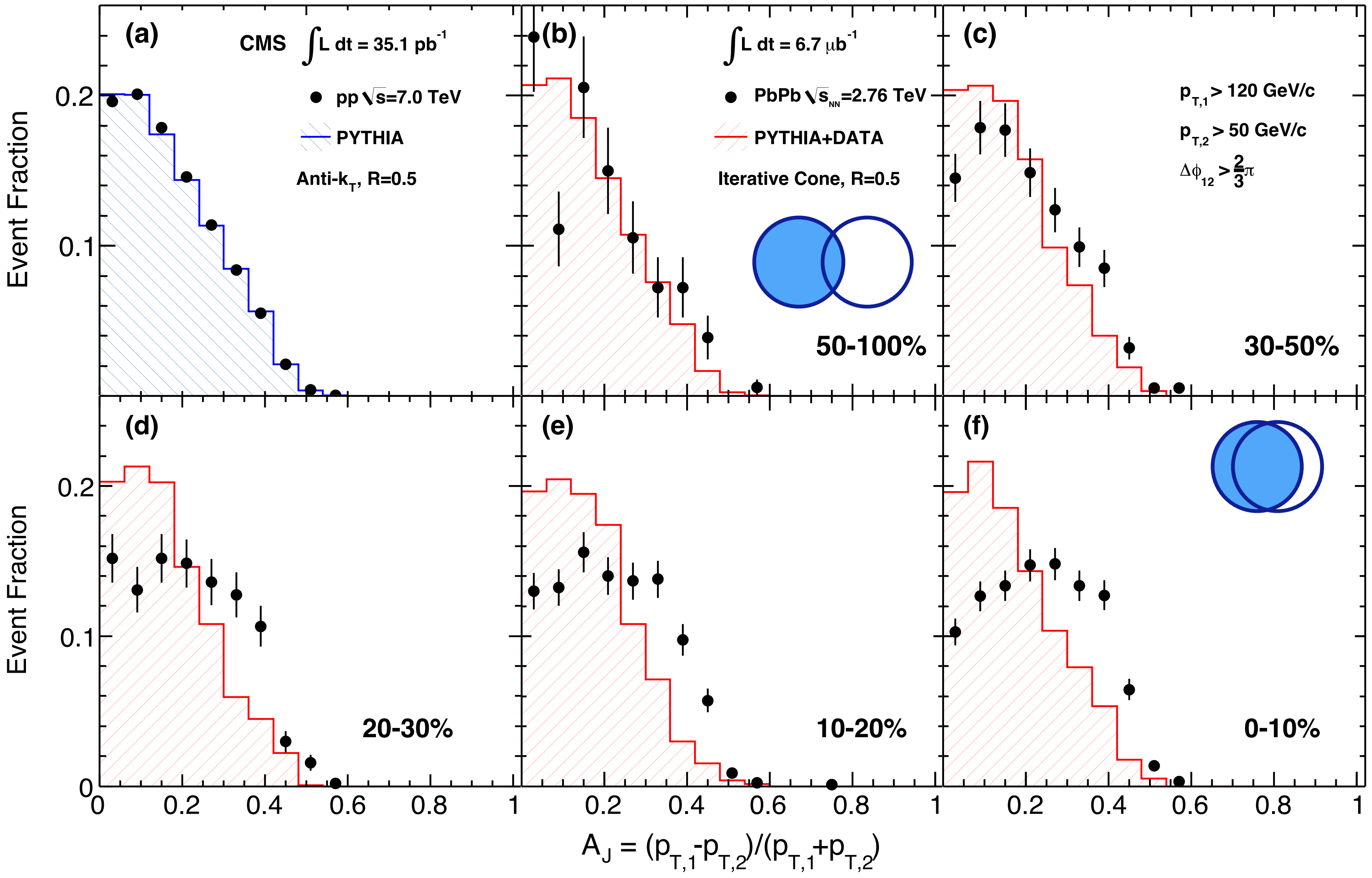
**Transverse energy map of 1 event**

Clear peaks: jets of fragments
from high-energy quarks and gluons

**And a lot of uncorrelated ‘soft’ background**

# Di-jet momentum balance

CMS, PRC 84, 024906



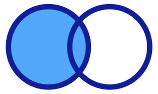
Balanced di-jet: $A_j = 0$

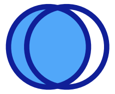
Already pp, balance is not perfect: out-of-cone radiation and three-jet events

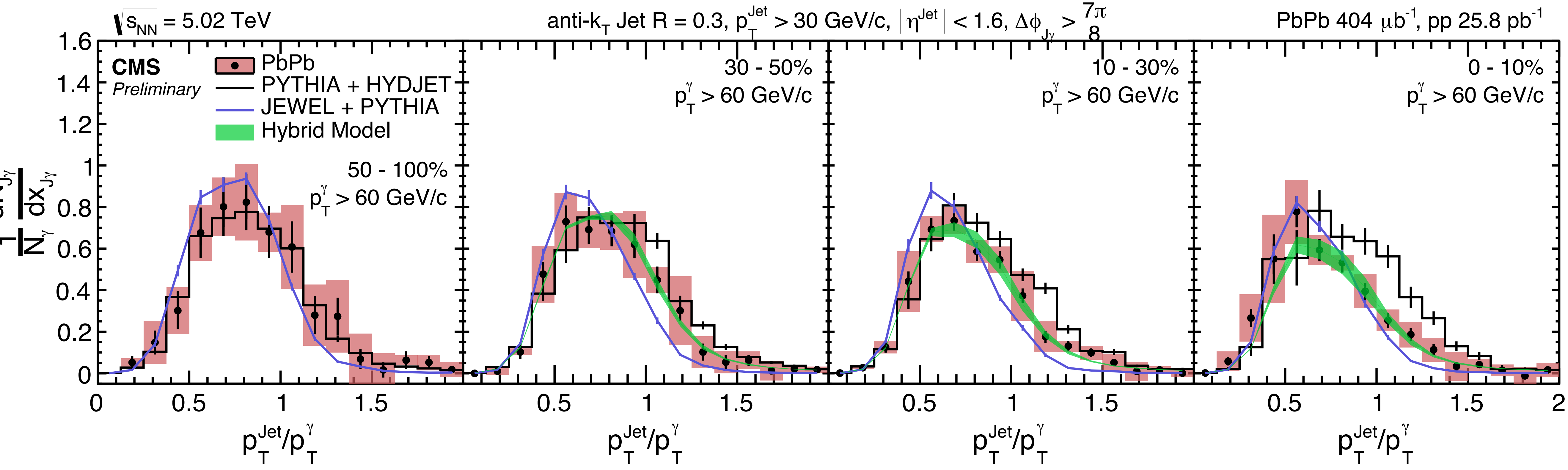
Imbalance in Pb-Pb is much larger: energy loss

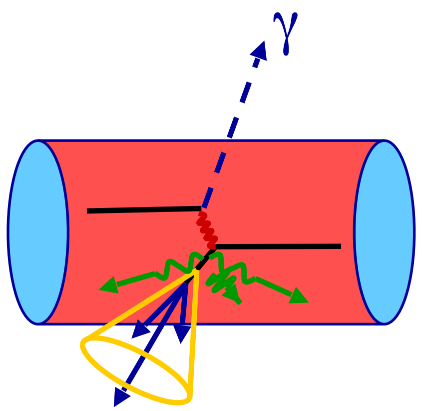
# Photon-jet $p_T$ balance

CMS-PAS-HIN-16-002









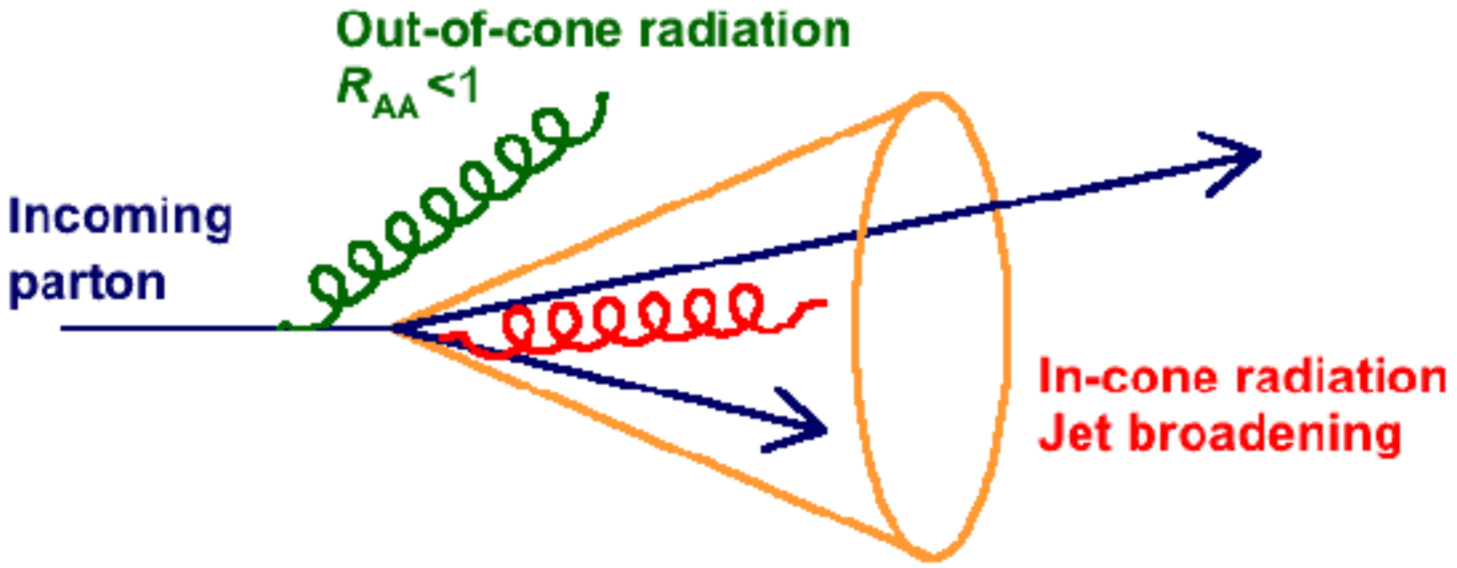
Photon does not lose energy in the QGP
Directly measures energy loss of jets
Sensitive to energy loss fluctuations

Recoil jet loses energy in the Quark Gluon Plasma

# Jets: zooming in on energy loss

Goal: measure energy loss distributions

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



Jet radius *R*

$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

For finite R: study out-of-cone radiation and in-cone jet modifications

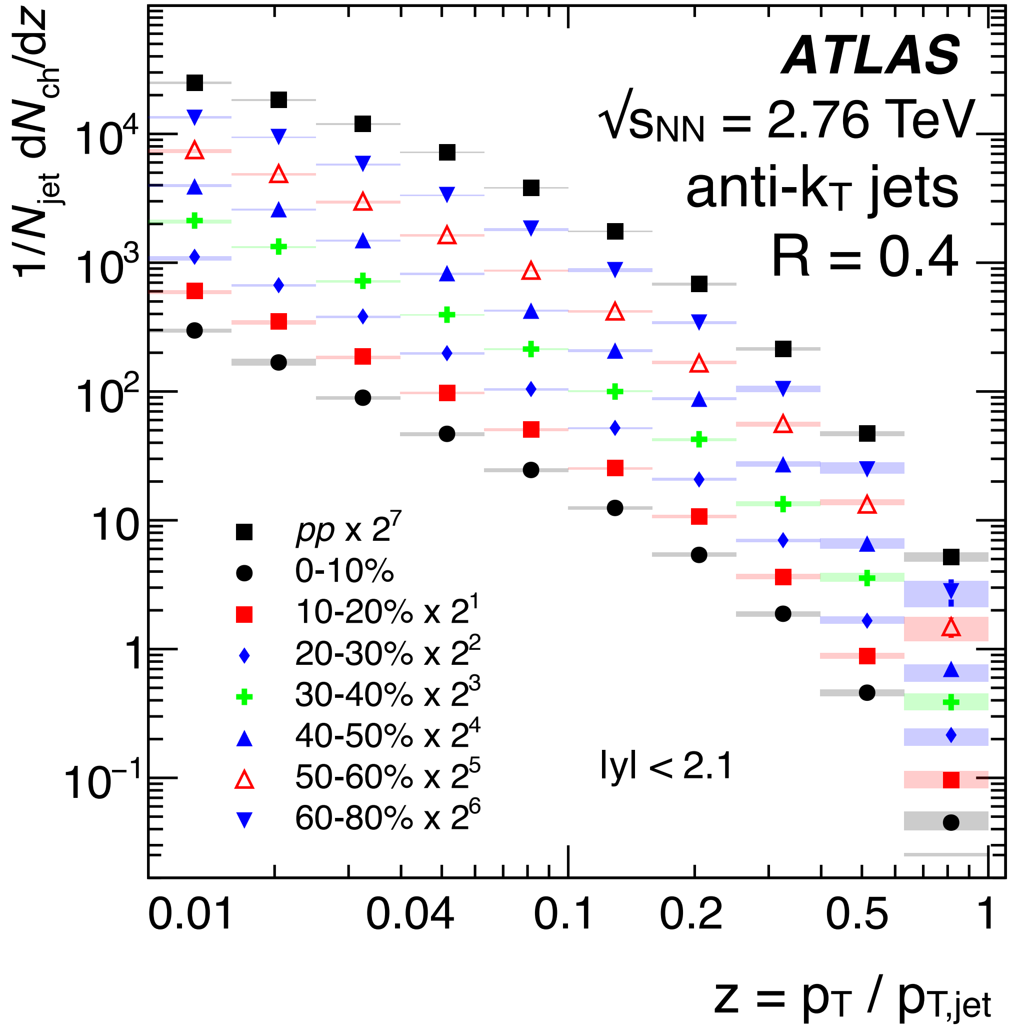
Limiting behaviour: for *large enough R*, expect $R_{AA}$ = 1 (no suppression)

# In-cone: longitudinal distributions

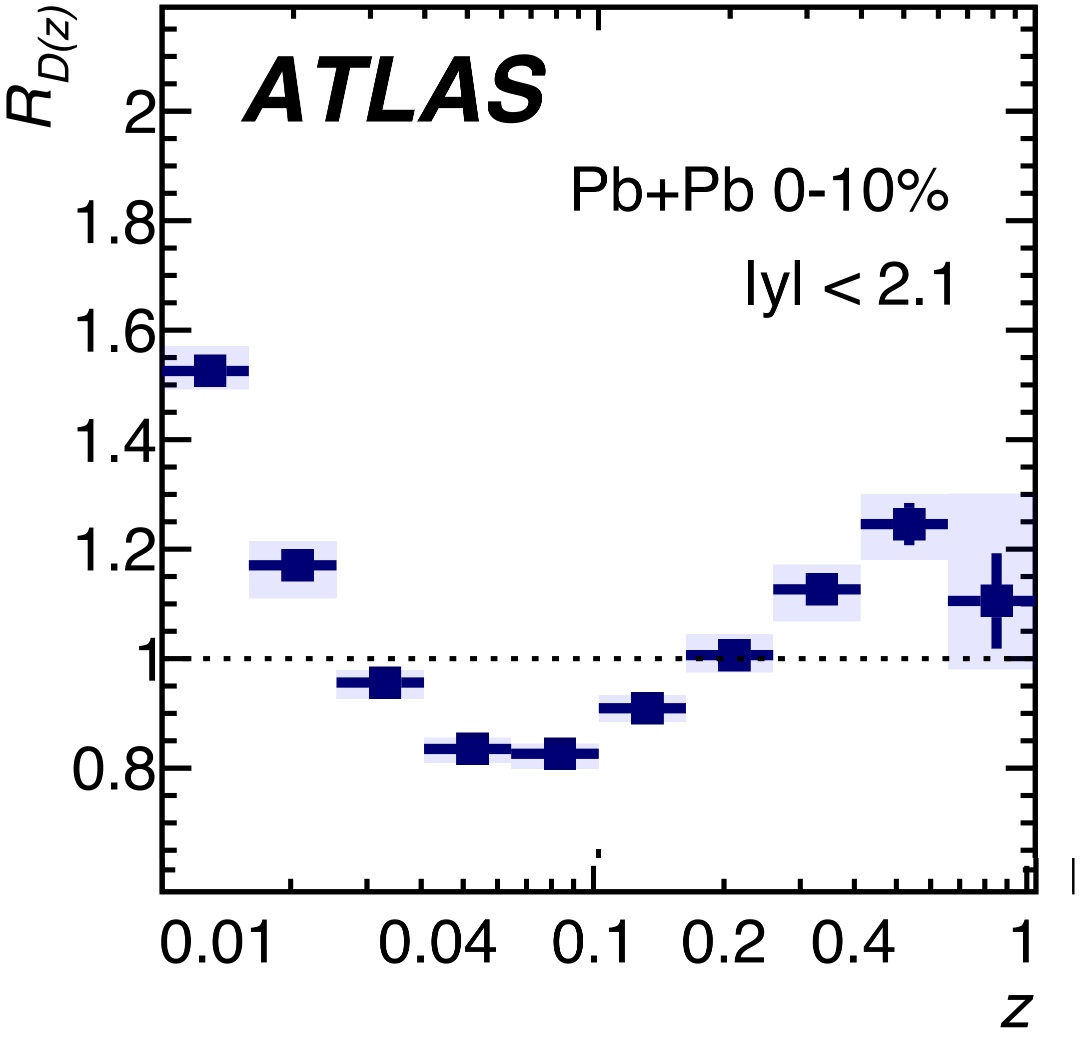
ATLAS, arXiv:1702.00674

also: CMS, PRC90, 024908

Fragment distributions



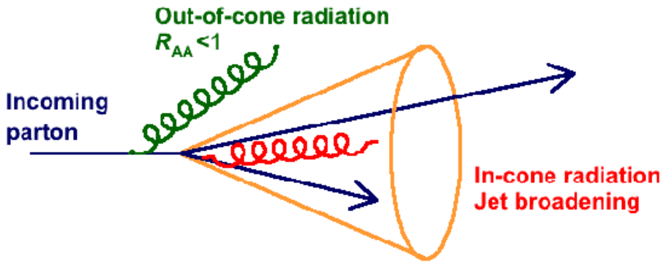
Ratio: Pb/pp



Enhancement at low $p_T$

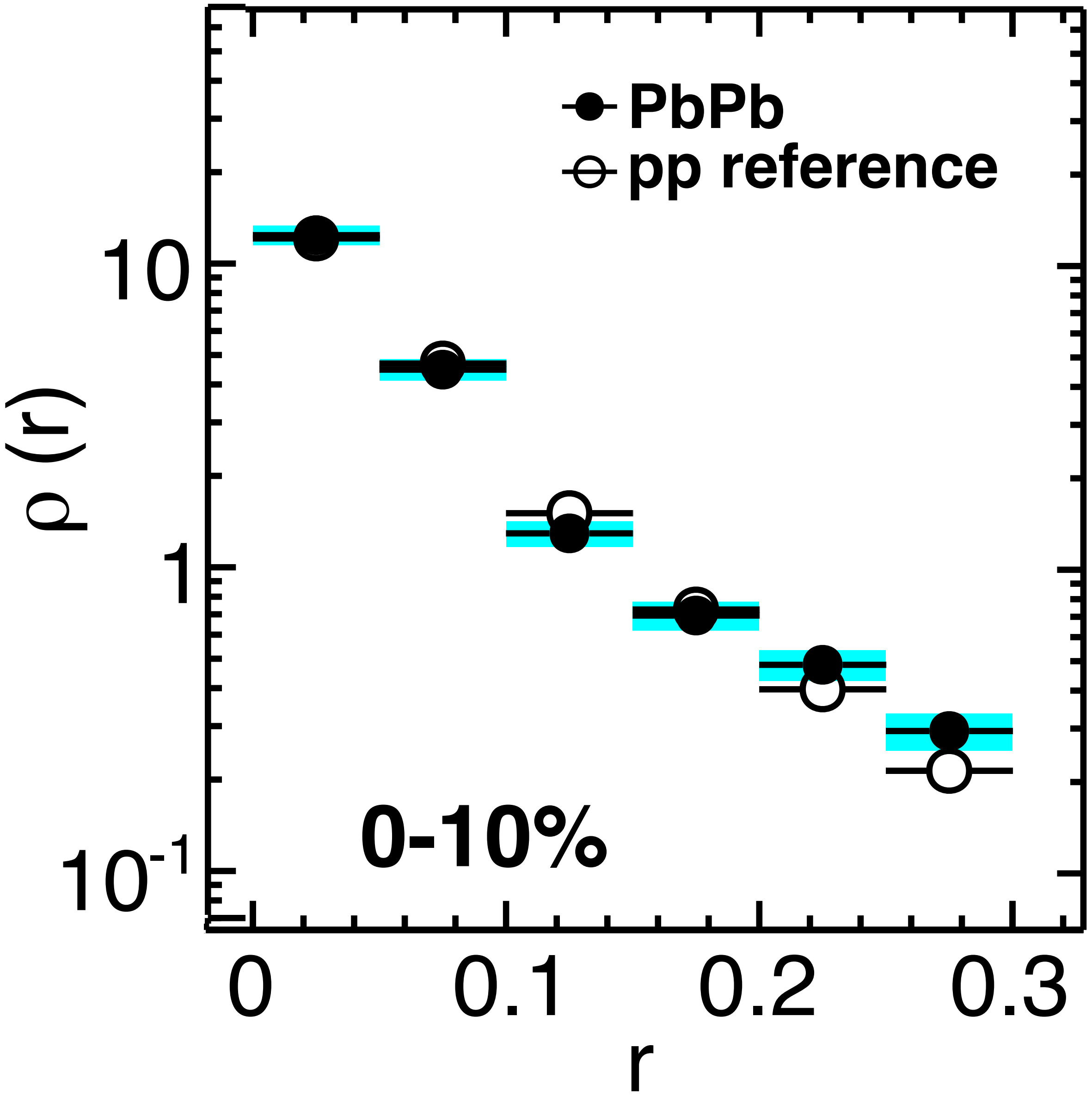
Suppression at intermediate $p_T$

Softening of the fragmentation



# In-cone: radial distribution of momentum flow

Radial distribution of momentum flow



Most of the jet energy is at small *r*

CMS, arXiv:1310.0878 CMS PAS HIN-12-013

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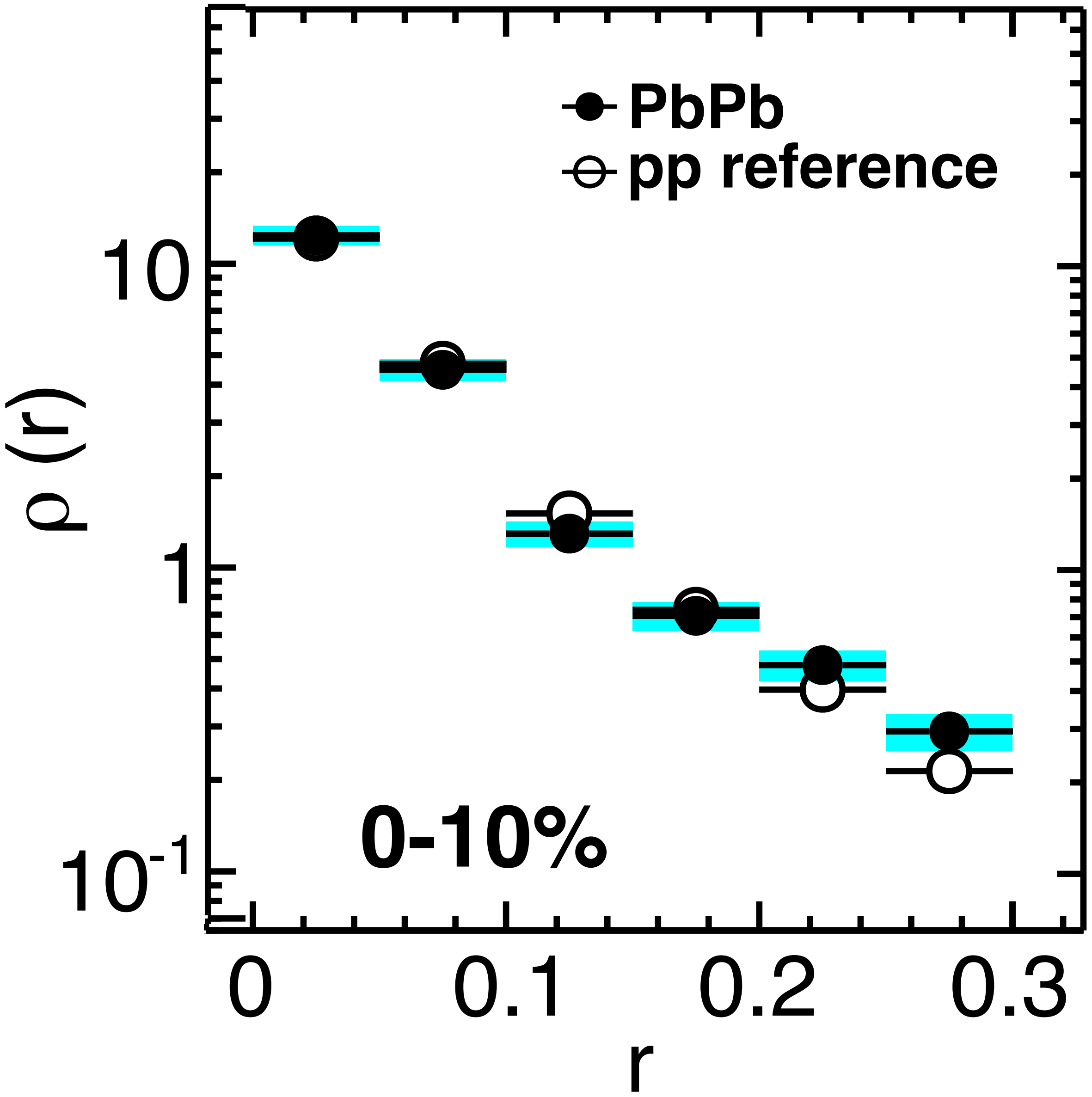
Radial distribution of momentum flow



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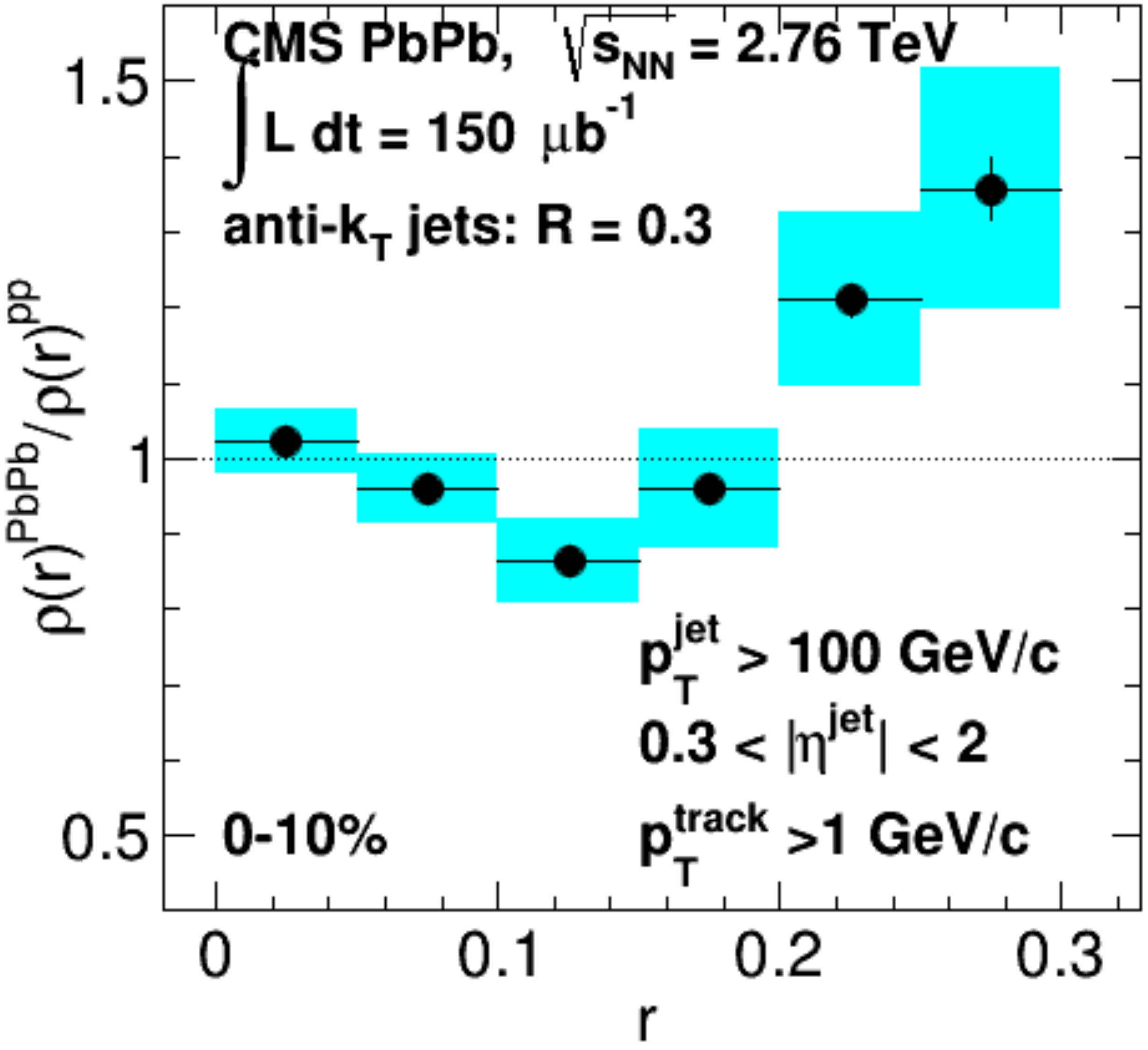


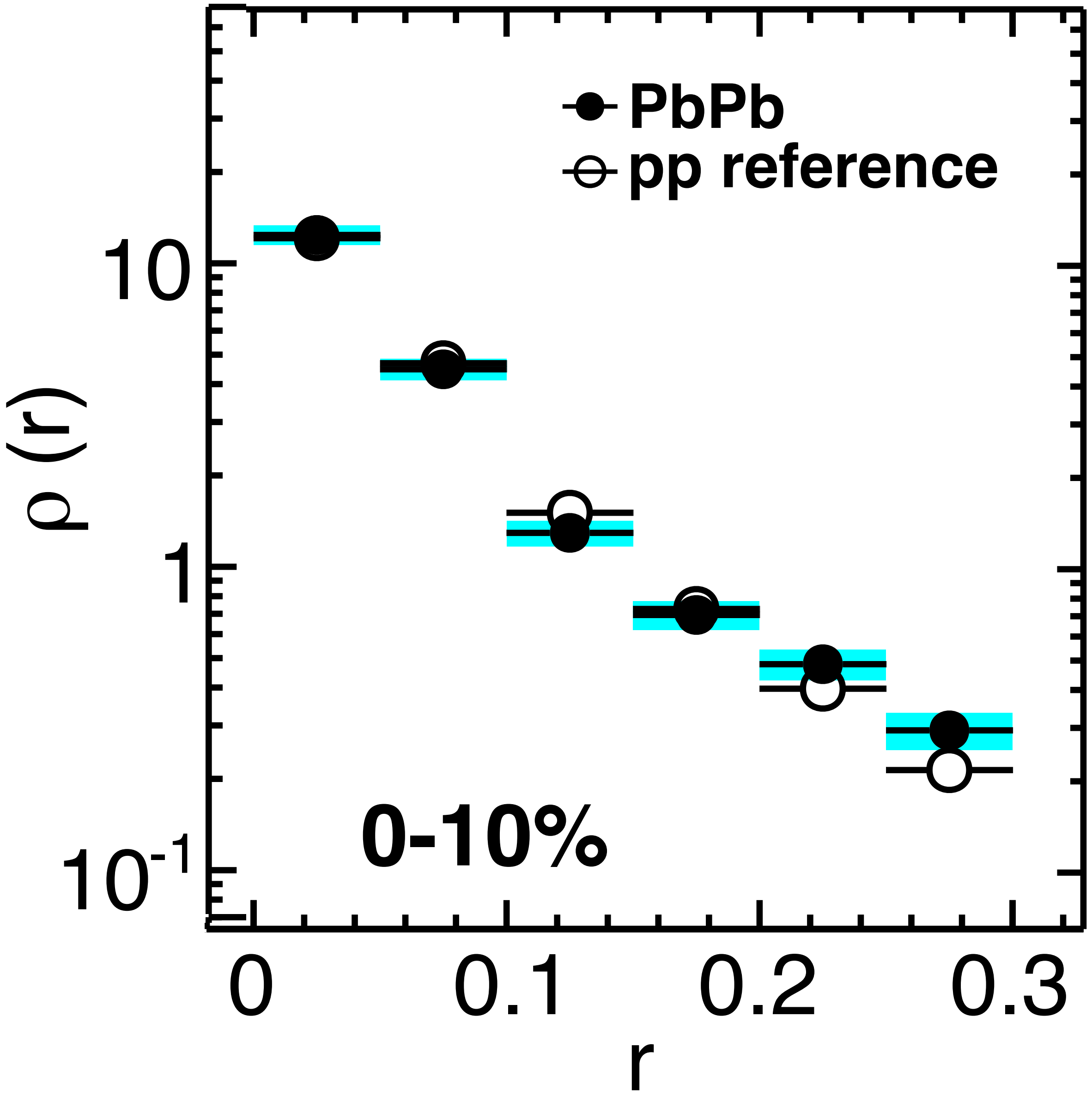
Modification in Pb—Pb: decrease at intermediate *r*, increase at large *r*

CMS, arXiv:1310.0878

CMS PAS HIN-12-013

# In-cone: radial distribution of momentum flow

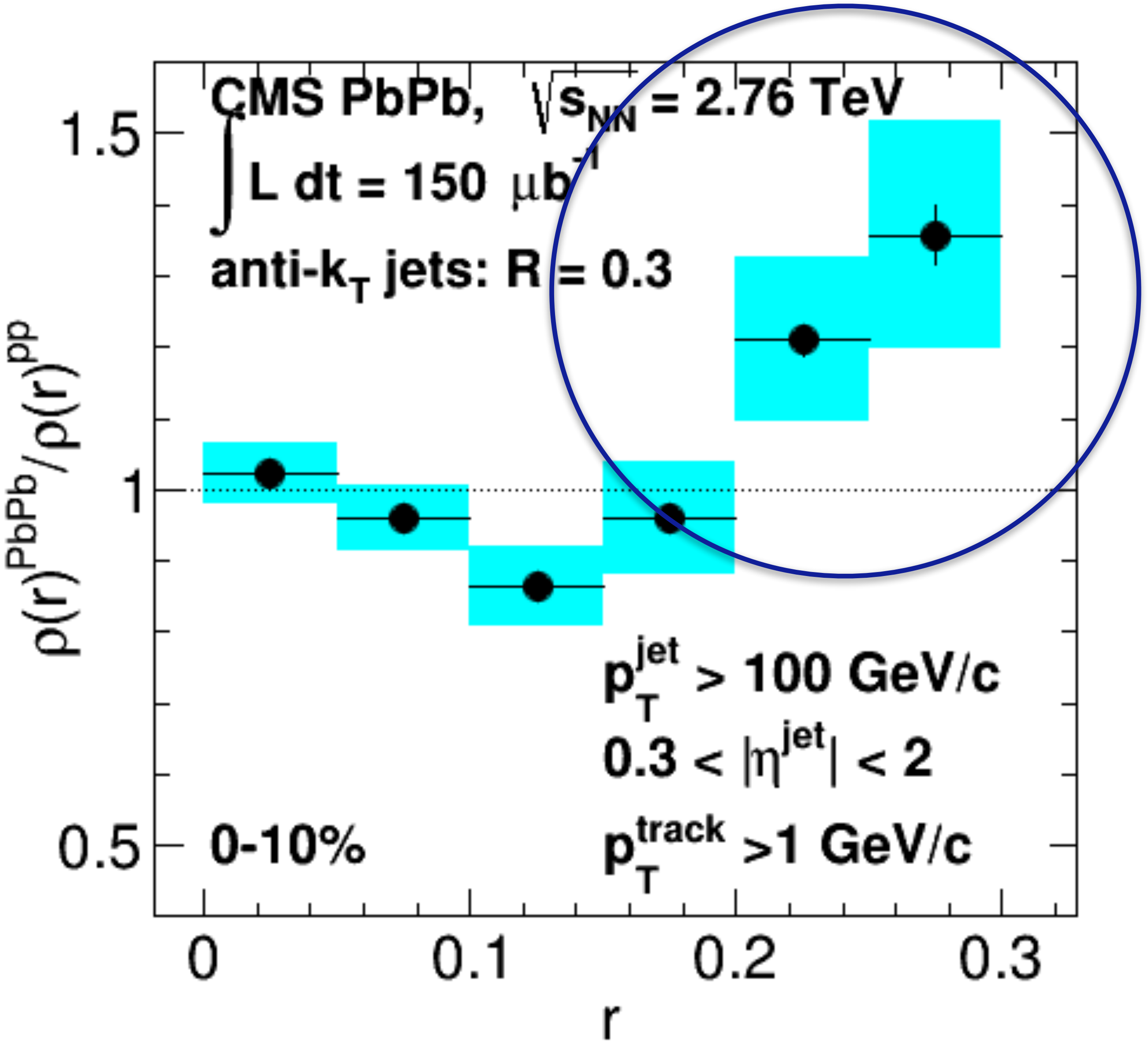
Radial distribution of momentum flow



Most of the jet energy is at small *r*

Ratio Pb—Pb/pp

Will this continue at even larger *R*?



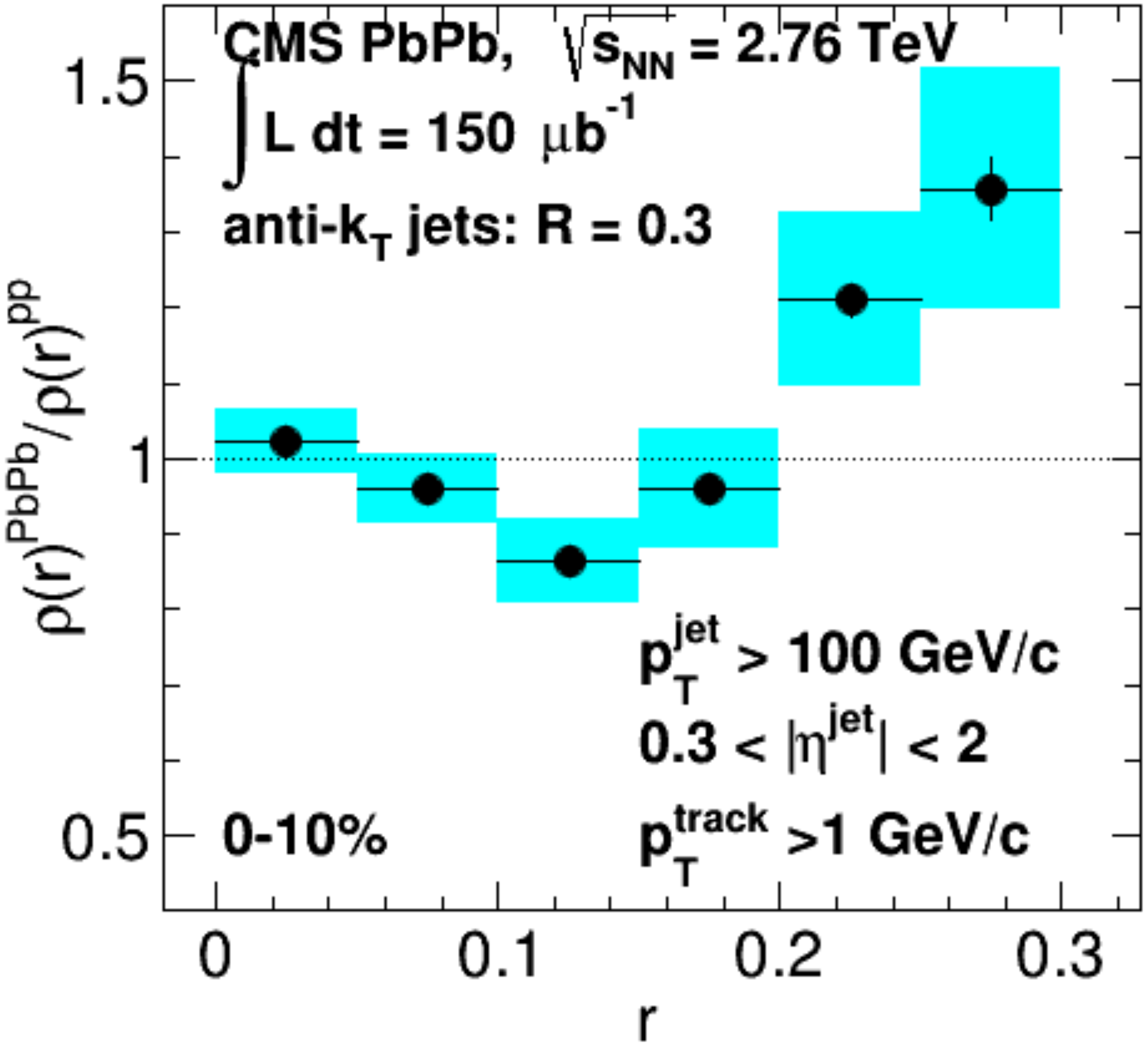
CMS, arXiv:1310.0878

CMS PAS HIN-12-013

Modification in Pb—Pb: decrease at intermediate *r*, increase at large *r*

# Radial distribution, large *R*

Ratio Pb—Pb/pp



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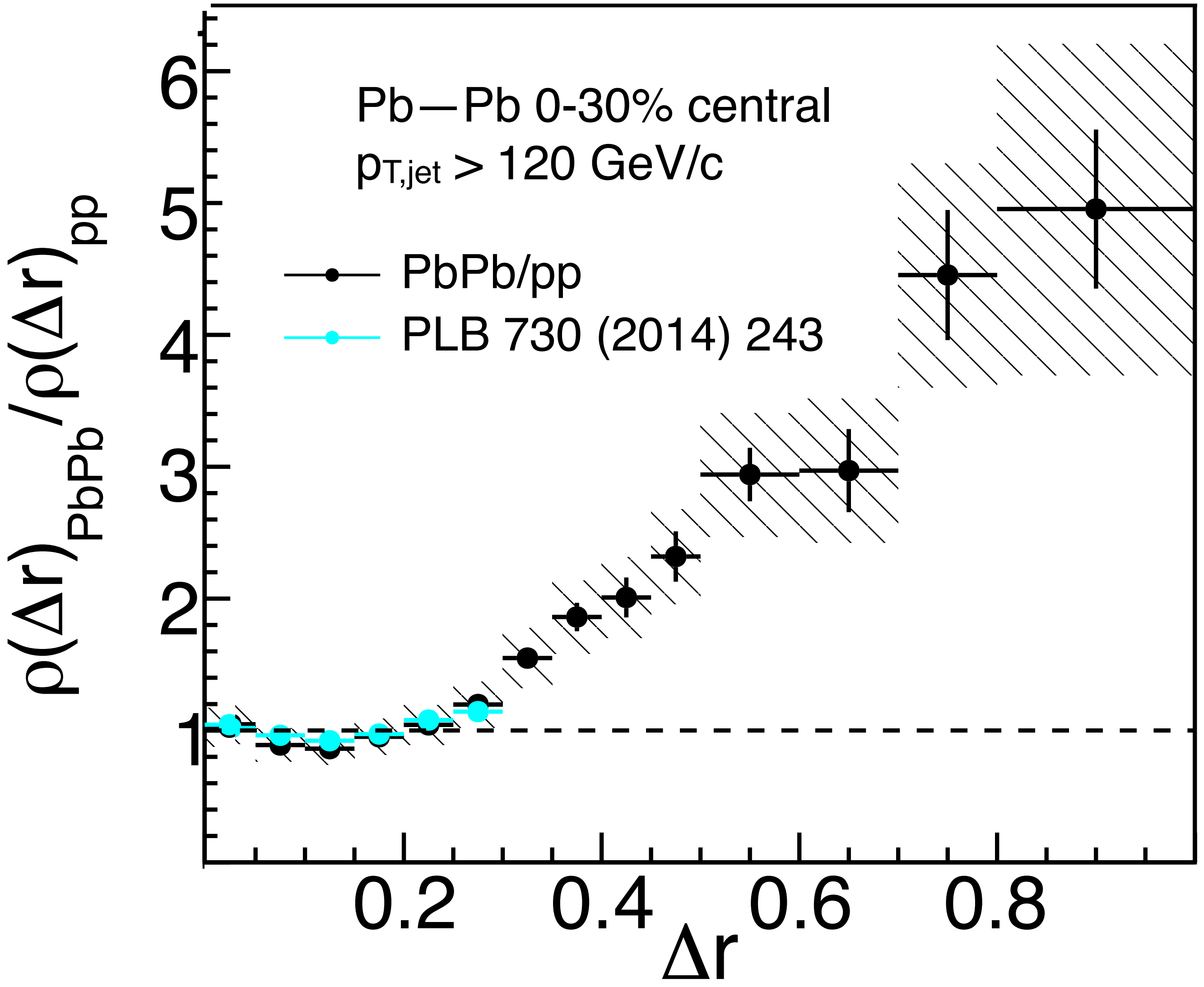
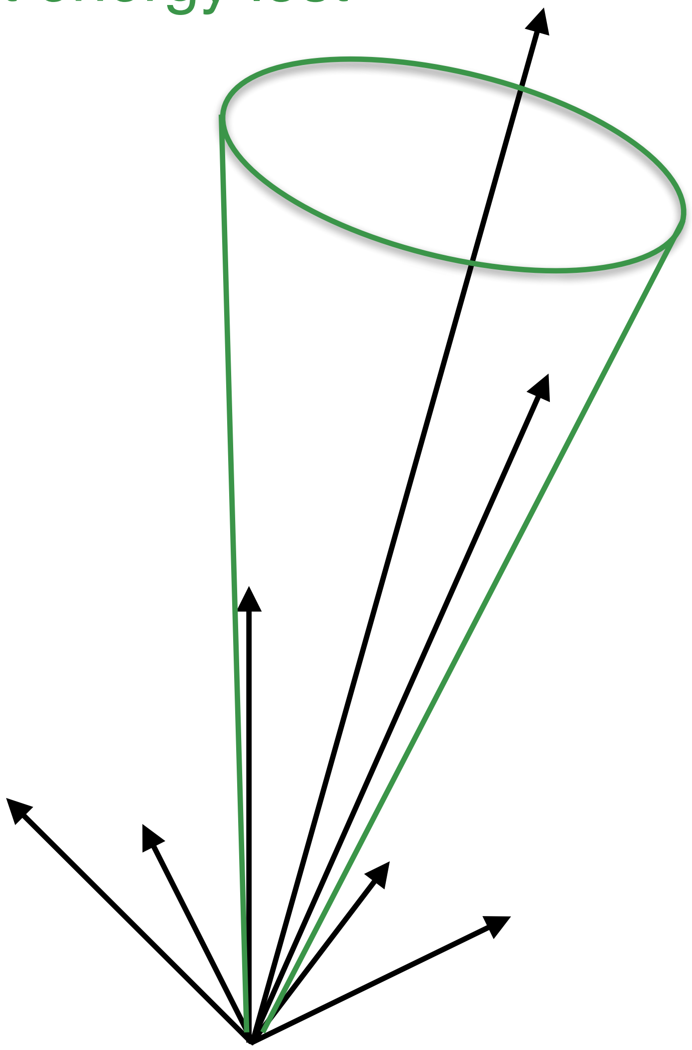


CMS, arXiv:1609.02466

Increase of energy flow continues at large *r*

No sign of a limit
or 'typical radiation angle'

# The emerging picture



**Jet core**
Structure almost unmodified,
but energy lost

- Fragmentation in the vacuum after energy loss?
- Or scales: medium does not resolve hard fragments?

**Lost energy** distributed to
large angles and soft fragments

Multiple interactions?
Related to thermalisation in the medium?

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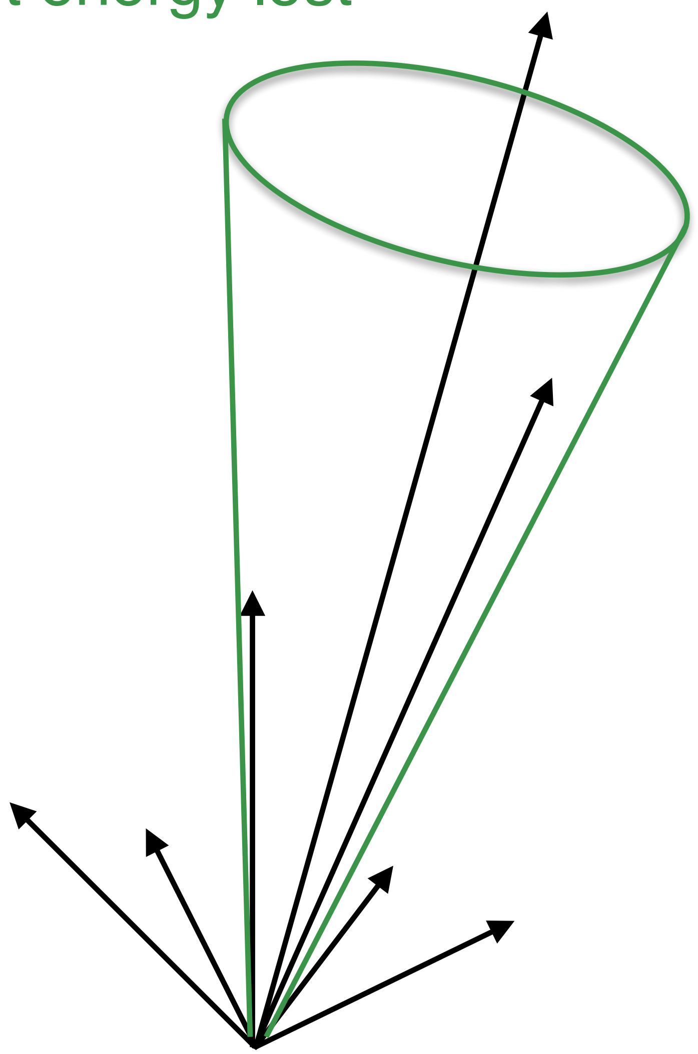

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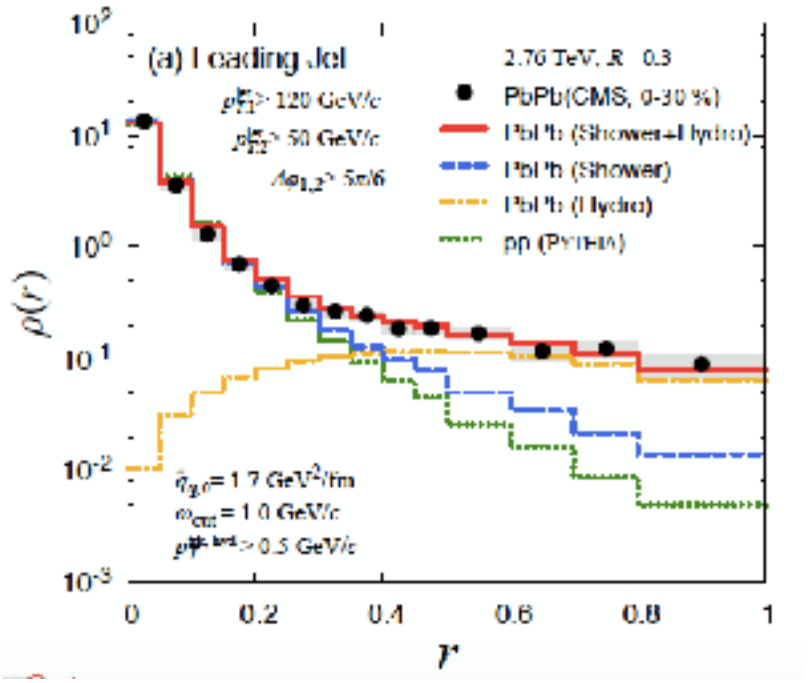

Y Tachibana et al, arXiv:1701.07951

**Lost energy** distributed to
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Multiple interactions?
Related to thermalisation in the medium?

# Future directions

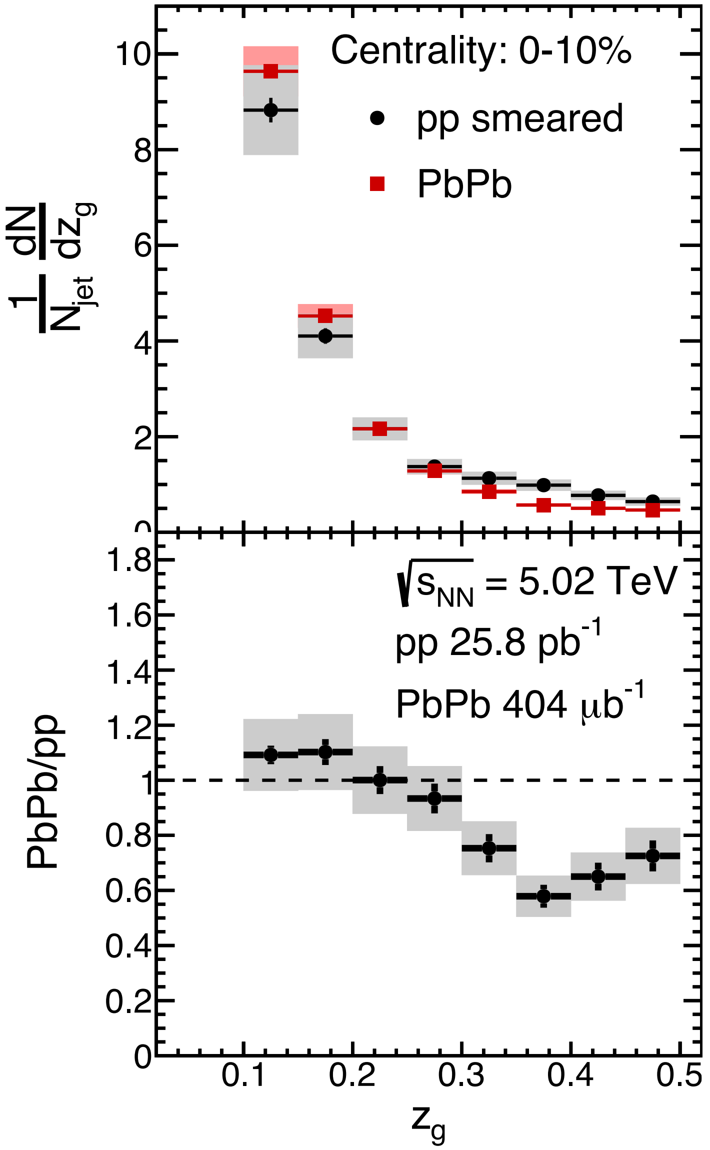
- Further understanding of momentum balance; transport to large angles
- Direct measurements of angular decorrelation, measure transverse kicks
- Jet shape variables to zoom in on particular aspects of the radiation

Jet shape variables

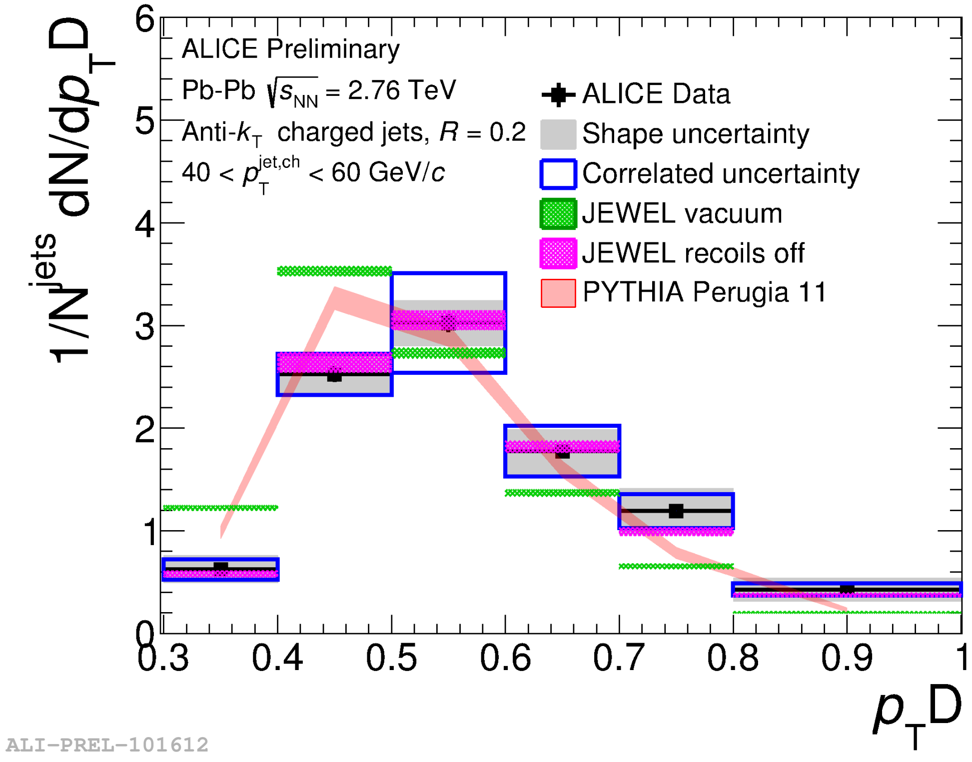
**jet-by-jet quantity** access to **strongly modified jets**?

- Jet mass
- $p_T$ dispersion
- $z_g$ groomed splitting variable

$z_g$ splitting variable



$p_T$ dispersion



# Summary

**Things that we know:**

- QGP behaves like a liquid with extremely low viscosity $\eta/s \approx 0.1$
  - Implies short mean free path: high density, strong interactions (quasi-particle picture may not be applicable)
- High-momentum partons lose energy in the QGP
  - Magnitude of basic effect in agreement with expectations from (p)QCD
  - Charm/beauty difference indicates radiative energy loss dominates

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**Things that we wonder about:**

- pp, p+Pb show flow-like behaviour
  - What is the physical mechanism?
  - Does this have implications for understanding Pb+Pb? Or vice versa?
- Energy loss: can we study the large-angle radiation?
  - Theory tools for jet-measurements under active development
  - Can we calculate soft radiation?

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  - Can we calculate soft radiation?

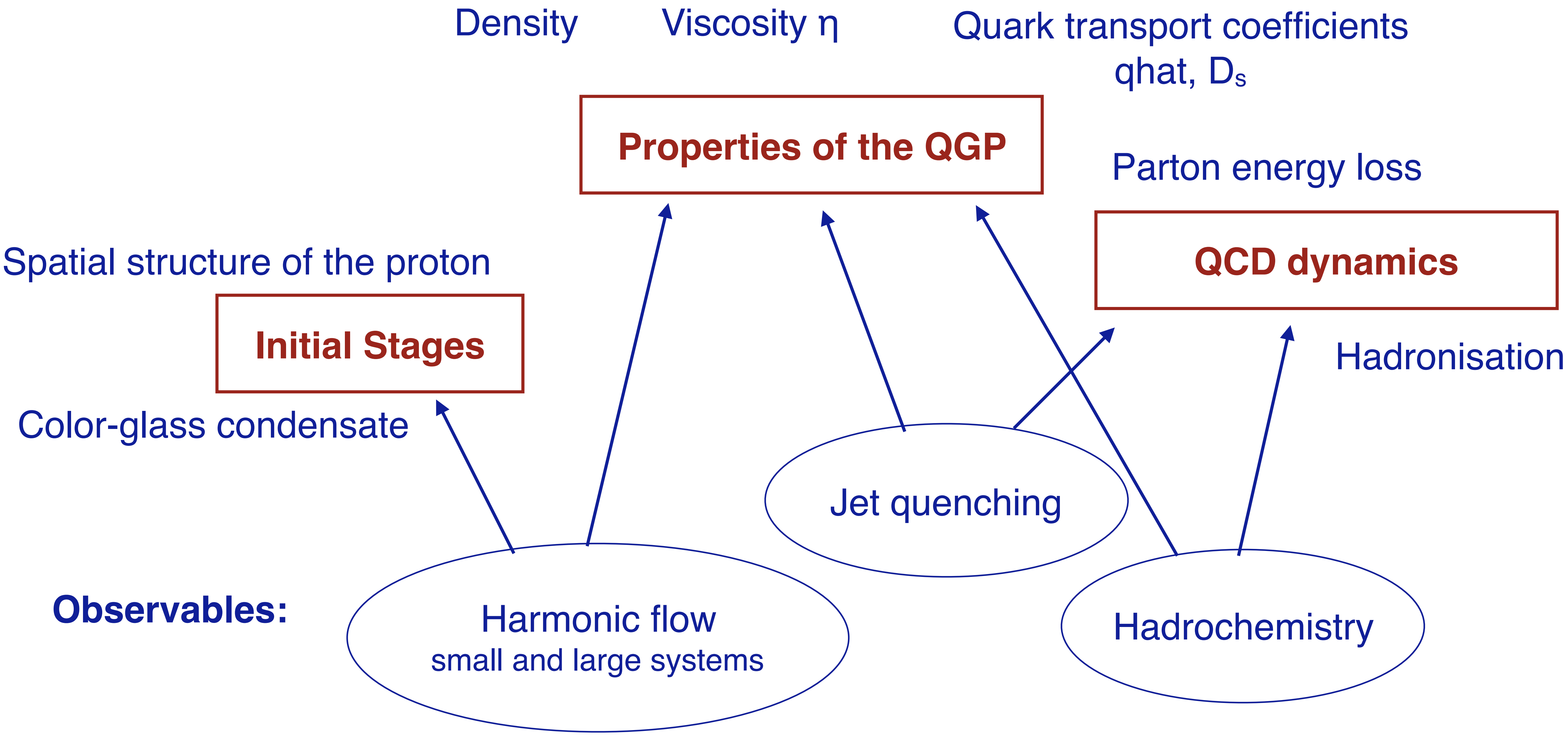
Bright future for LHC, RHIC runs: heavy flavour $R_{AA}$, $v_2$, including low $p_T$,
high-statistics jet observables; zoom in on jet quenching; di-leptons for thermal radiation

# Thank you for your attention

NB, several topics not covered due to time:

- Thermal radiation
- Quarkonia: melting and regeneration
- QCD critical point

# Connecting the concepts



Density

Viscosity η

Quark transport coefficients
qhat, $D_s$

**Properties of the QGP**

Parton energy loss

Spatial structure of the proton

**QCD dynamics**

**Initial Stages**

Hadronisation

Color-glass condensate

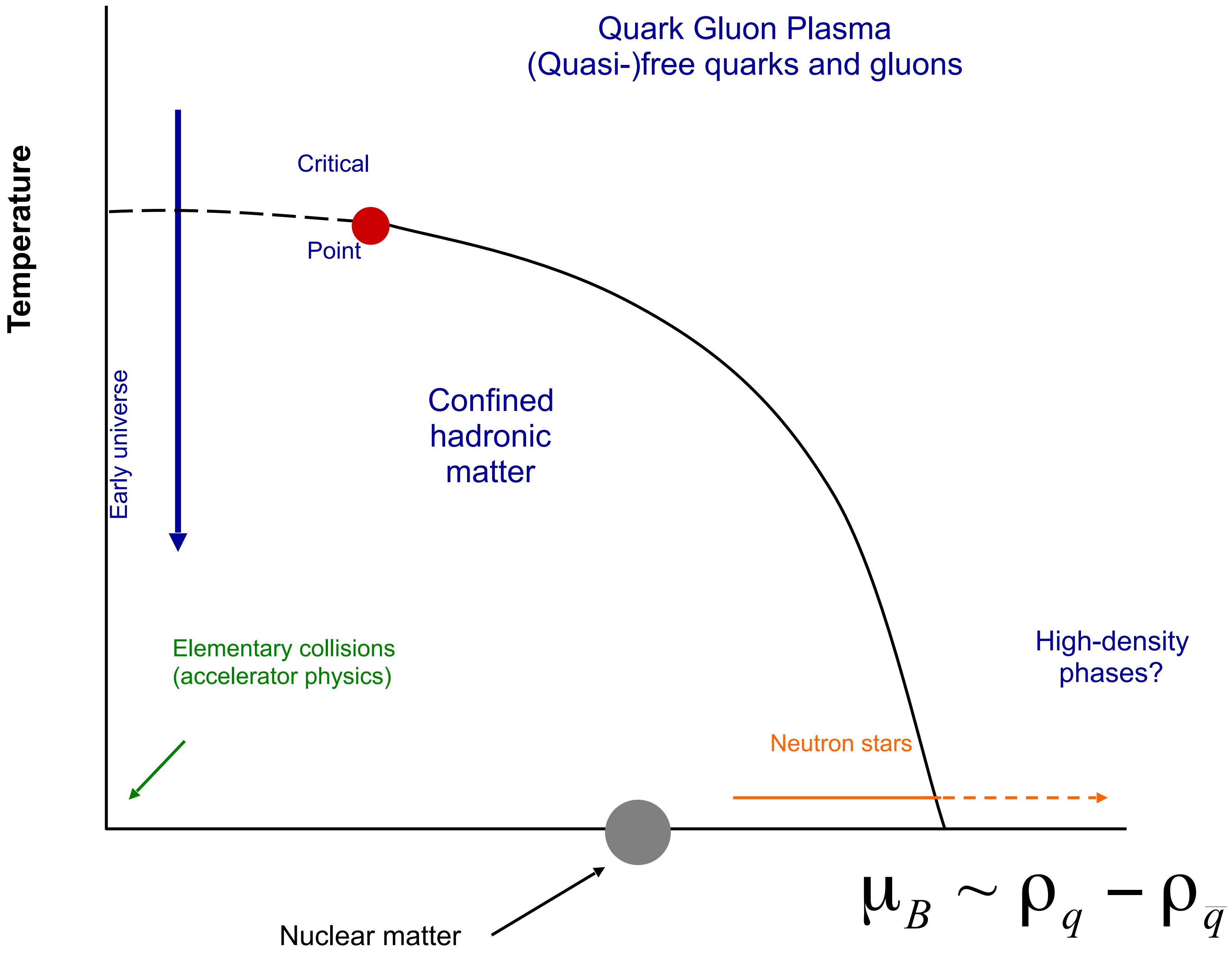
Jet quenching

**Observables:**

Harmonic flow
small and large systems

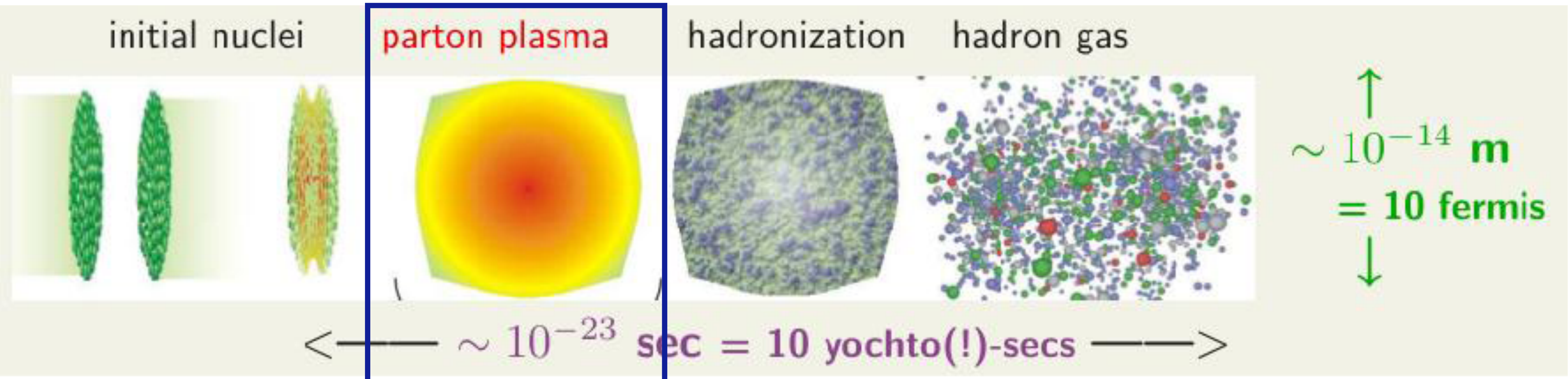
Hadrochemistry

# QCD phase diagram



$\mu_B \sim \rho_q - \rho_{\bar{q}}$

# Time evolution in a heavy ion collision



Quark Gluon Plasma/Liquid

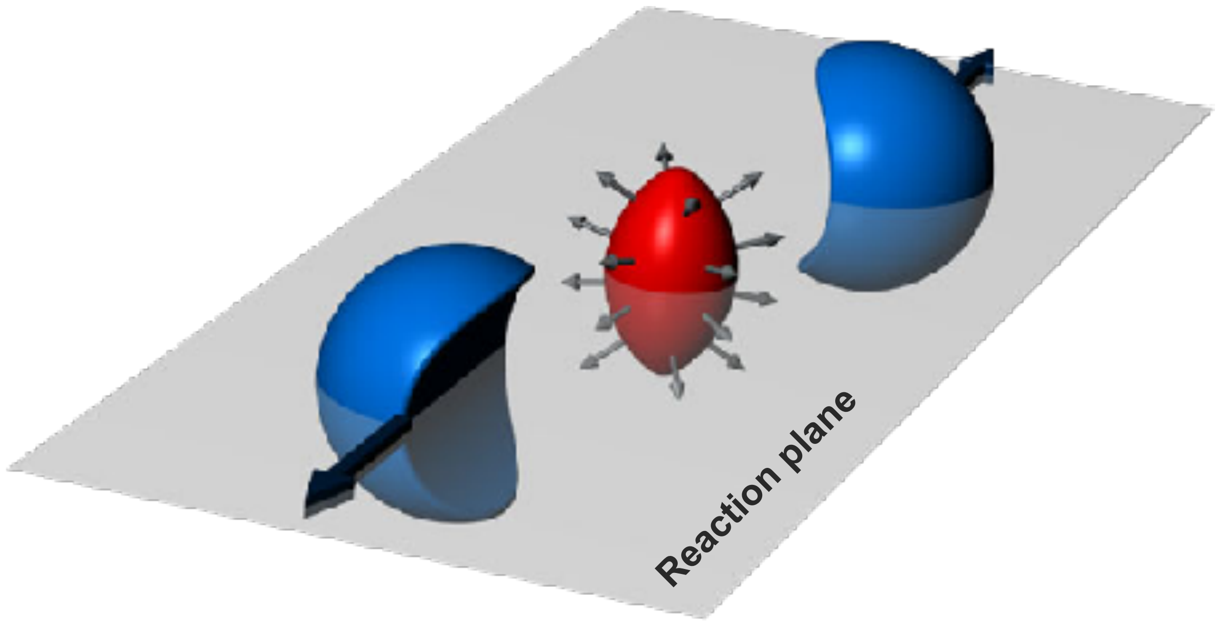
(near) thermal equilibrium

**Pre-equilibrium**

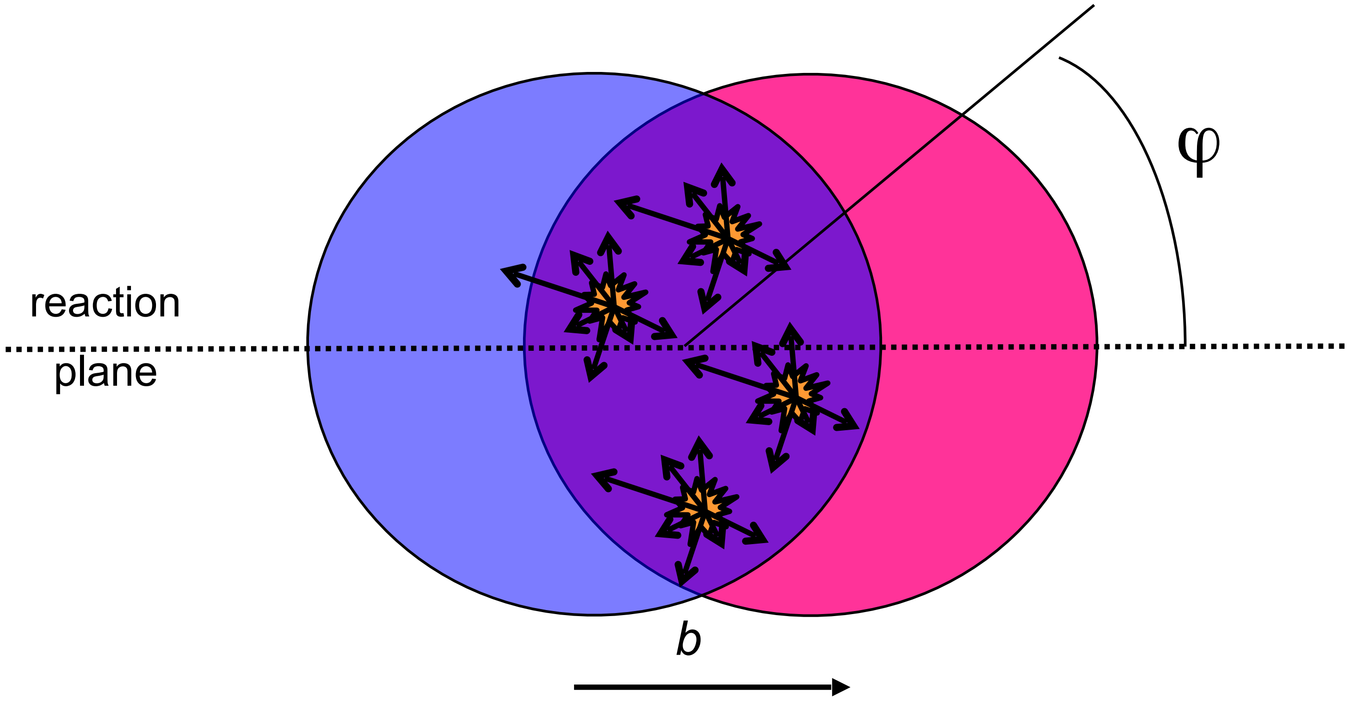
**Freeze-out (post-equilibrium)**

Expectation: main difference between heavy ion collisions and pp, p+Pb
volume + density ⇒ rescattering during evolution ⇒ approach to thermal equilibrium

# Elliptic flow

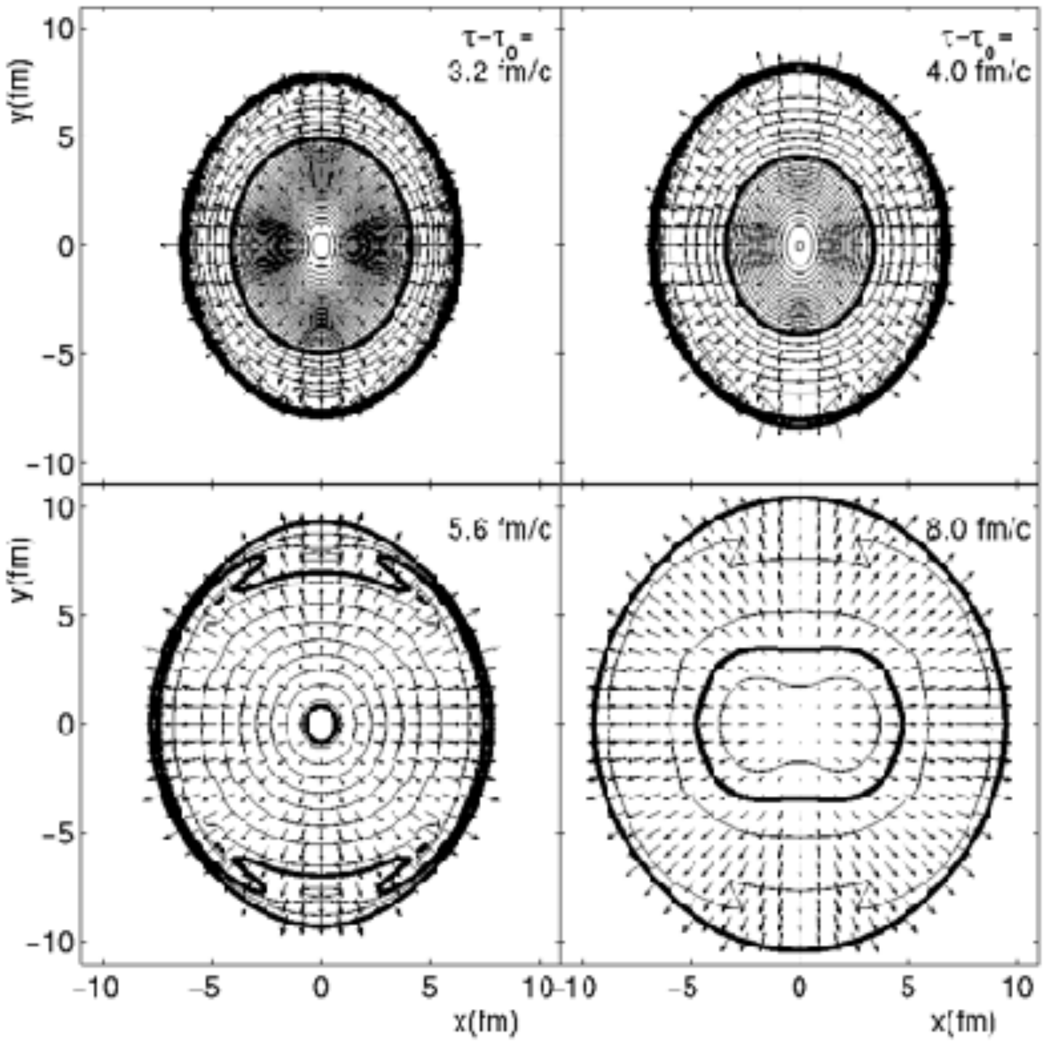


Elliptic flow:
Yield modulation in-out reaction plane



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

Hydrodynamical calculation



Anisotropy reduces during evolution

$v_2$ more sensitive to early times

# Radial and elliptic flow

Spectra change from pp to Pb+Pb:

- Increase in mean $p_T$
- Larger effect for larger mass

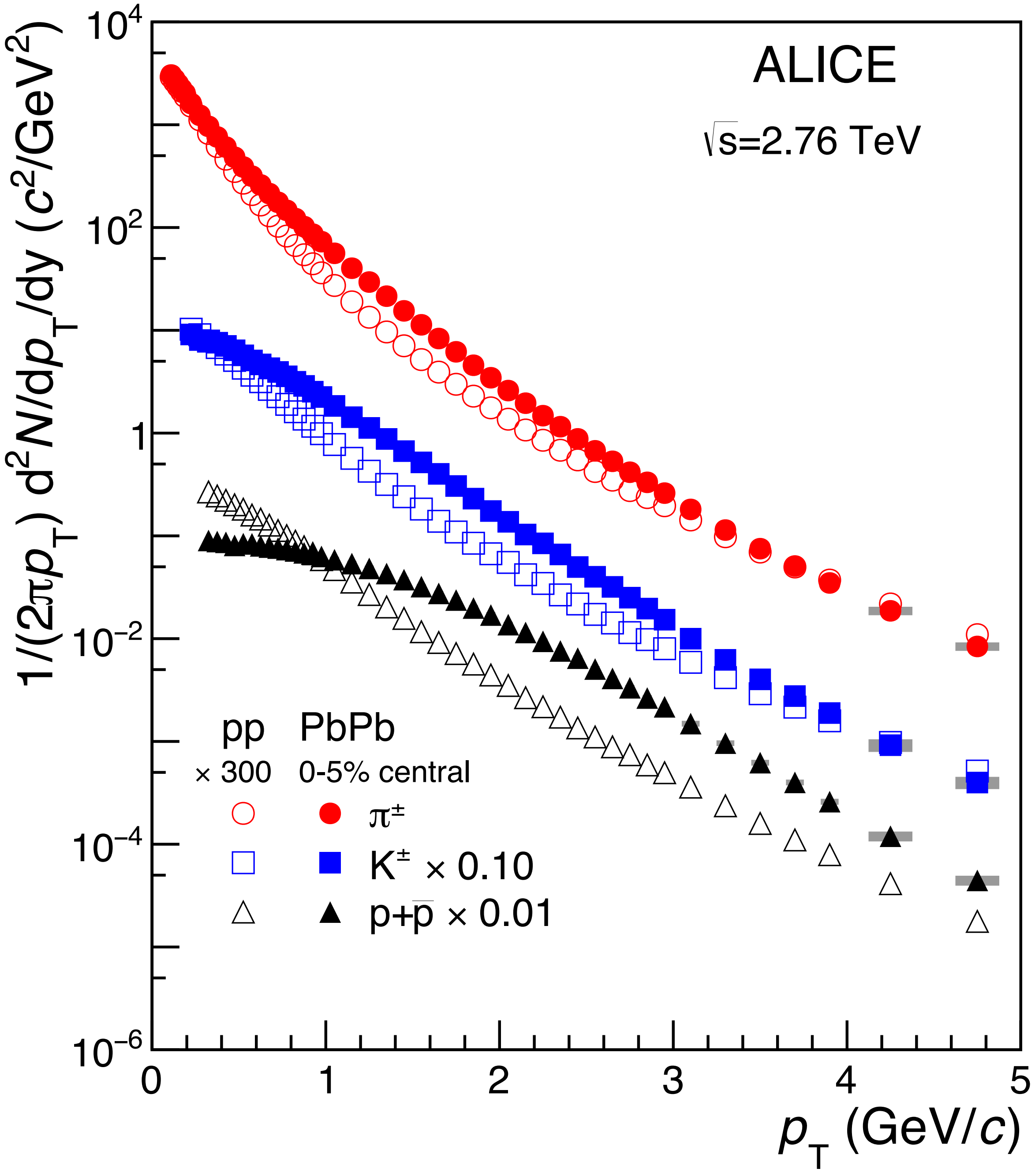
**First indication of collective behaviour**

Pressure leads to radial flow

Same Lorentz boost ($\beta$) gives larger momentum for heavier particles

($m_p > m_K > m_\pi$)

Transverse momentum distribution



ALICE, PLB 736, 196

# Flow in small systems: comparisons to hydro

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?

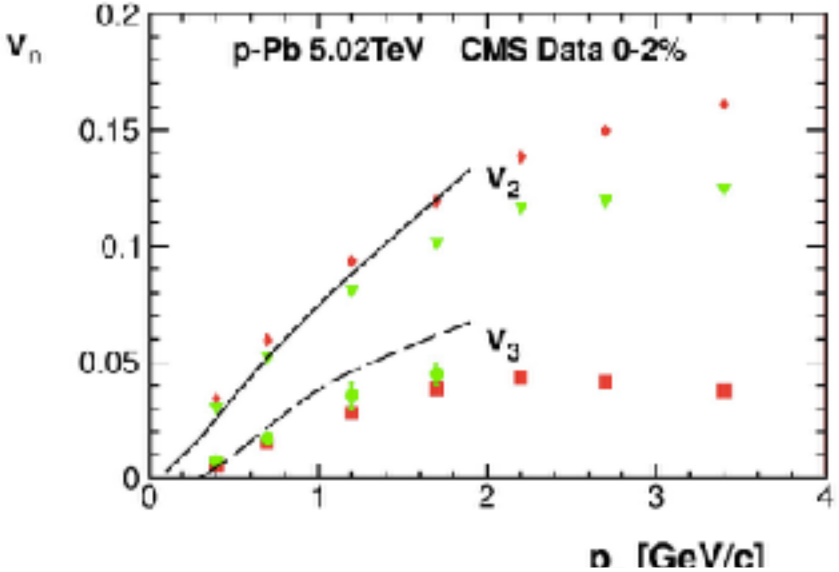
Is there enough time, volume to thermalise?

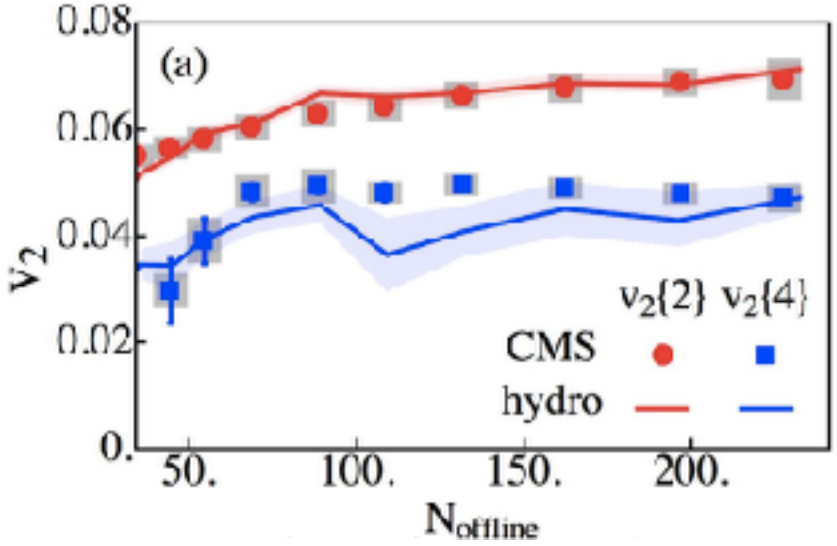
- Hydrodynamisation (isotropisation) of a dense gluon system?
- Partonic/hadronic rescattering?
- How many scatterings/what density is needed to approximate fluid behaviour?

Many recent developments;
active discussion on interpretation

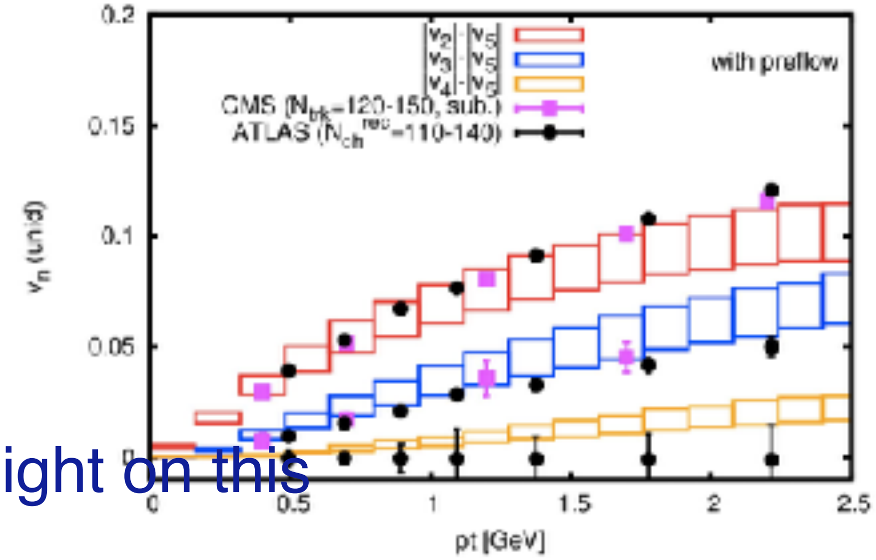
Large sample of p-Pb collisions from 2016 run to shed more light on this

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



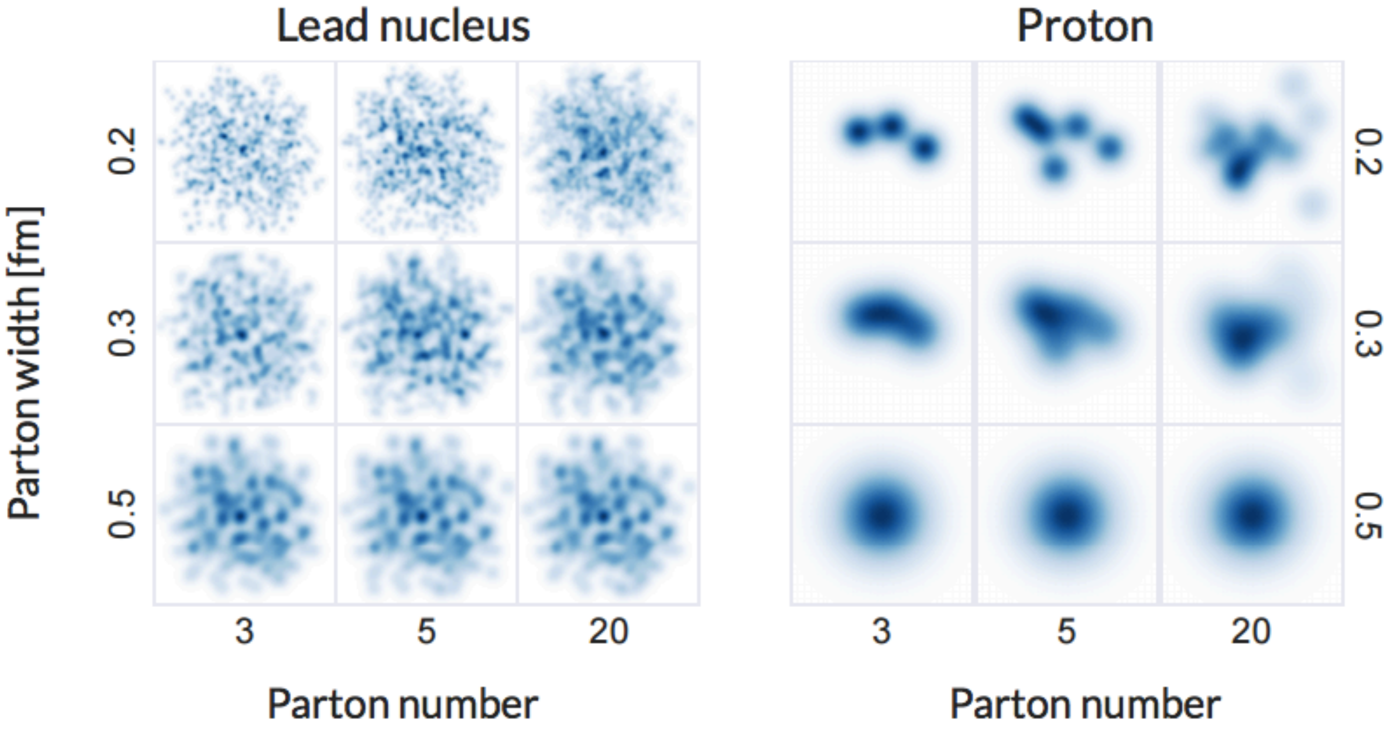


Kozlov et al, Nucl. Phys. A931 (2014)



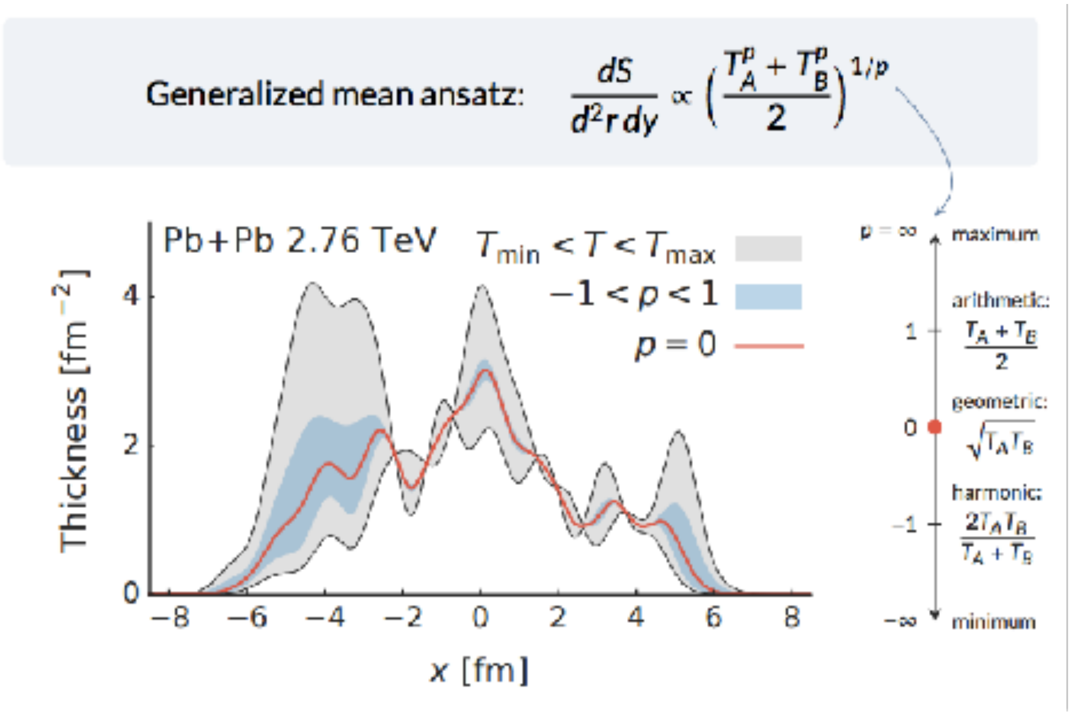
Romatschke, EPJC75, 305

# Lumpiness of the proton — fits



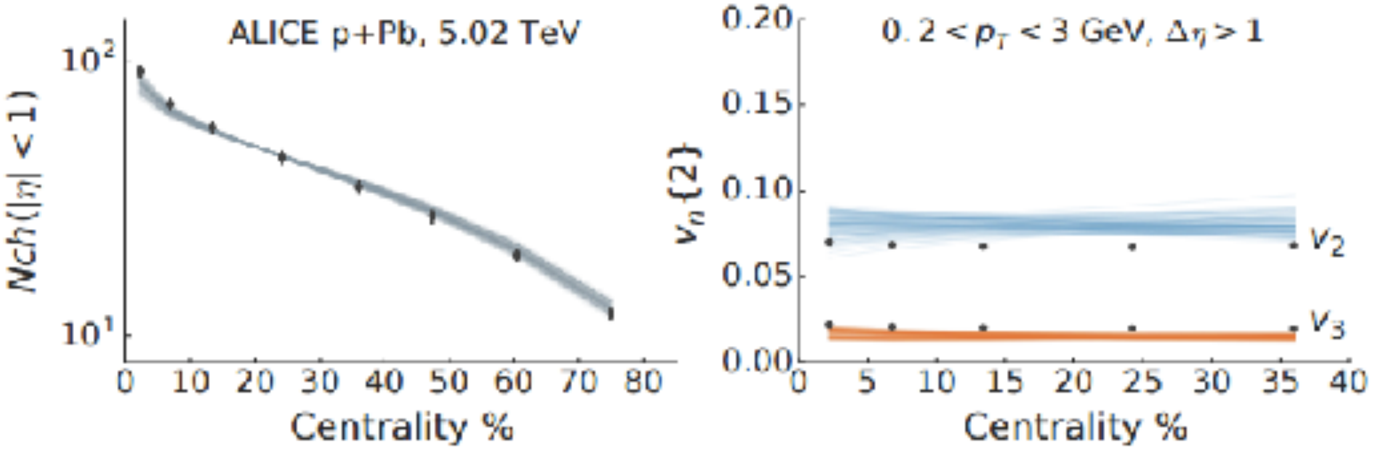
nucleon width fixed, $w = 0.5$ fm

J. S. Moreland, QM17 talk



Ad-hoc model for proton lumpiness:

- nucleon width
- number of sources/partons
- parton width



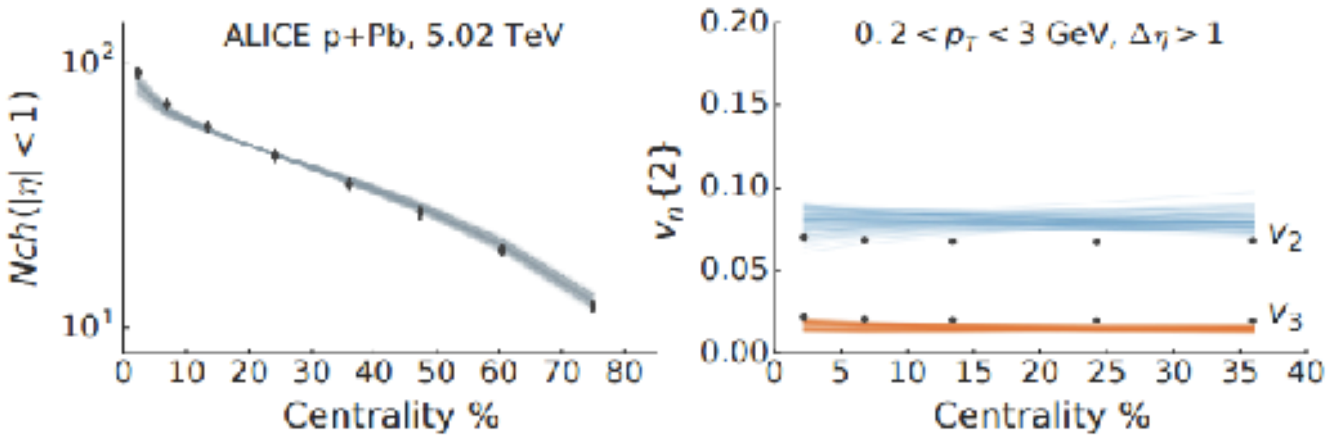
Data: ALICE, PRC 90, 054901 [1406.2474]

Gaussian Process Emulator + Bayesian fit technique also being applied for p-Pb

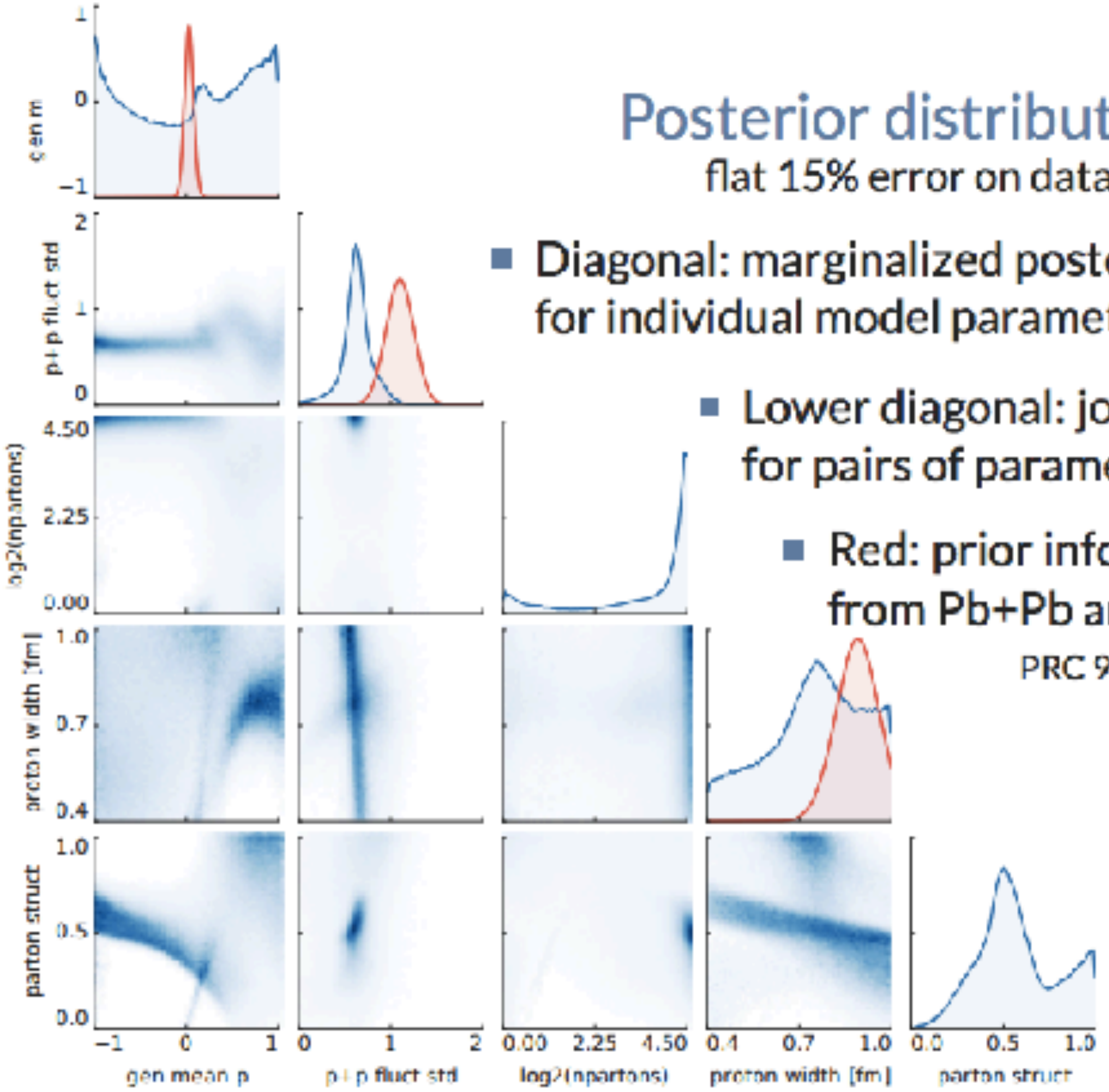
Access to lumpiness of the proton

# Lumpiness of the proton — Fits

S. Moreland



Data: ALICE, PRC 90, 054901 [1406.2474]



## Posterior distribution

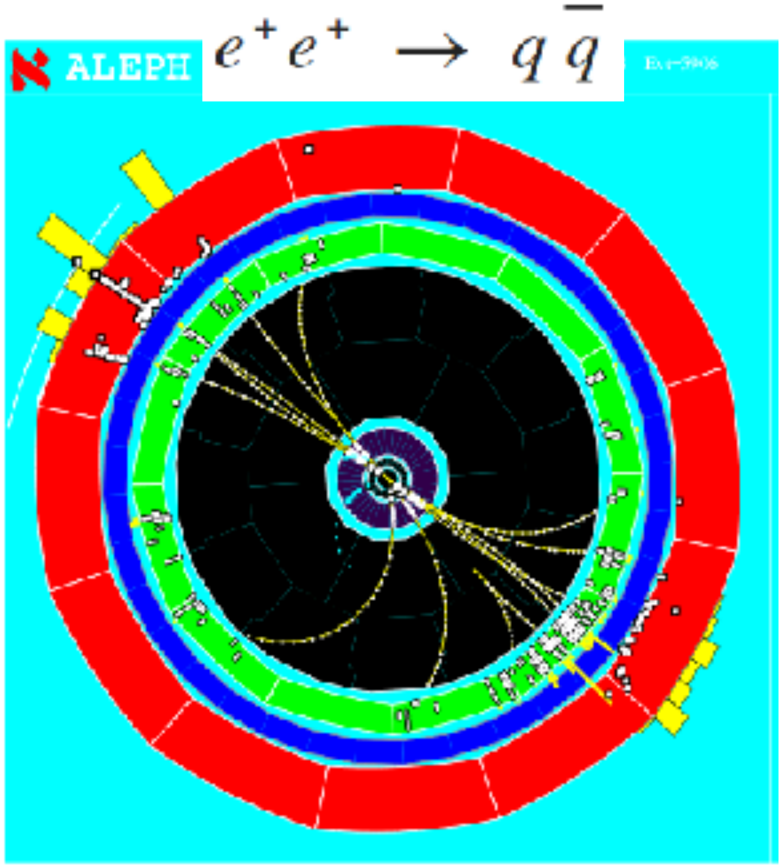
flat 15% error on data

- Diagonal: marginalized posterior dist. for individual model parameters
- Lower diagonal: joint dist's for pairs of parameters
- Red: prior information from Pb+Pb analysis

PRC 94, 024907

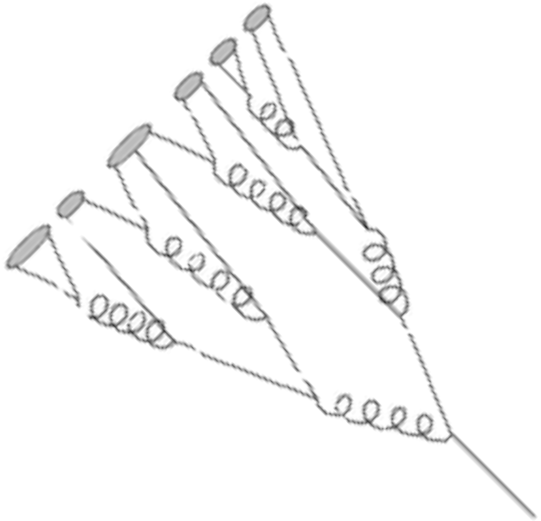
# Jet reconstruction

Experiment view



$e^+e^+ \rightarrow q\,\bar{q}$

Theory/model view



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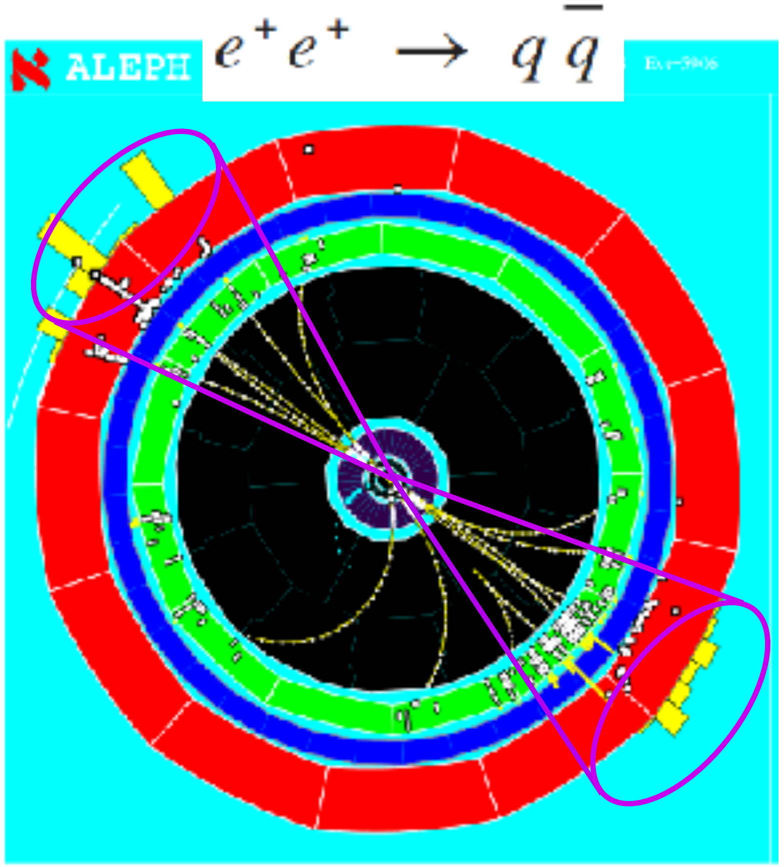

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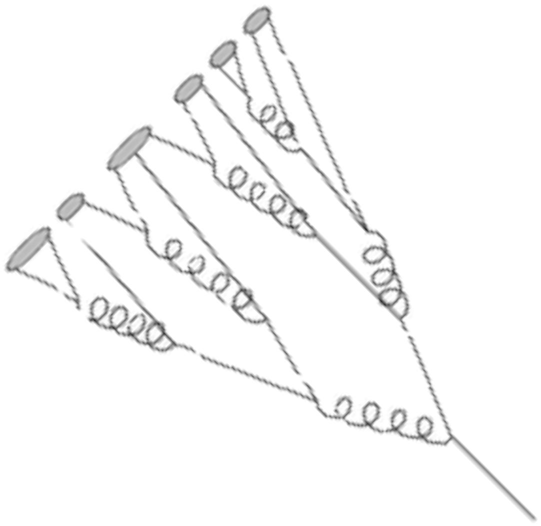
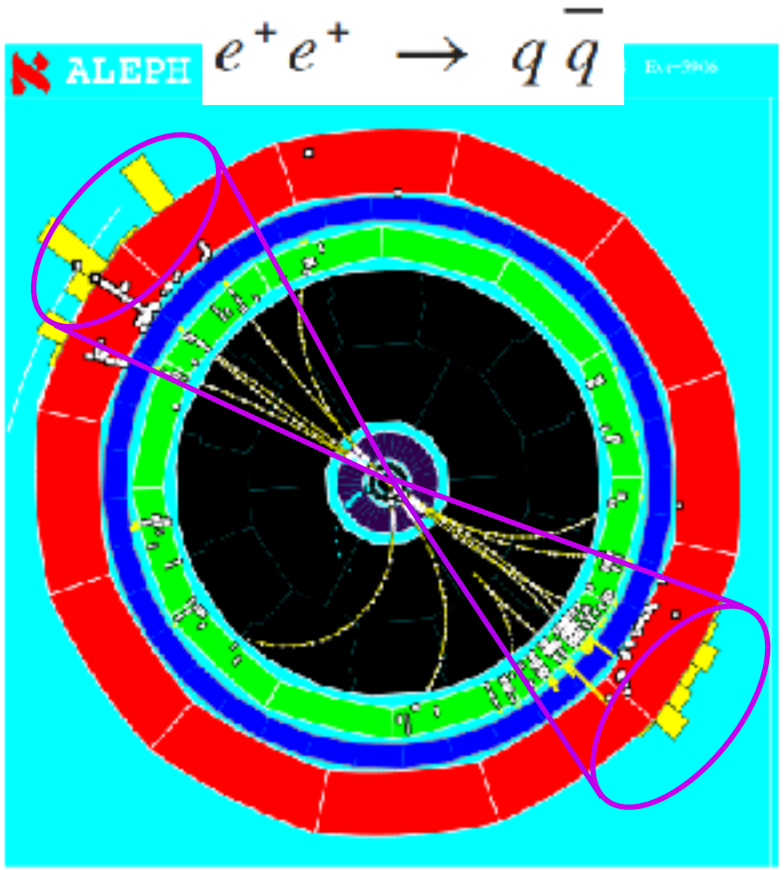


Jet reconstruction: group particles together and add momenta
Several algorithms available; conceptually: draw cones, size *R*

# Jet reconstruction

Experiment view



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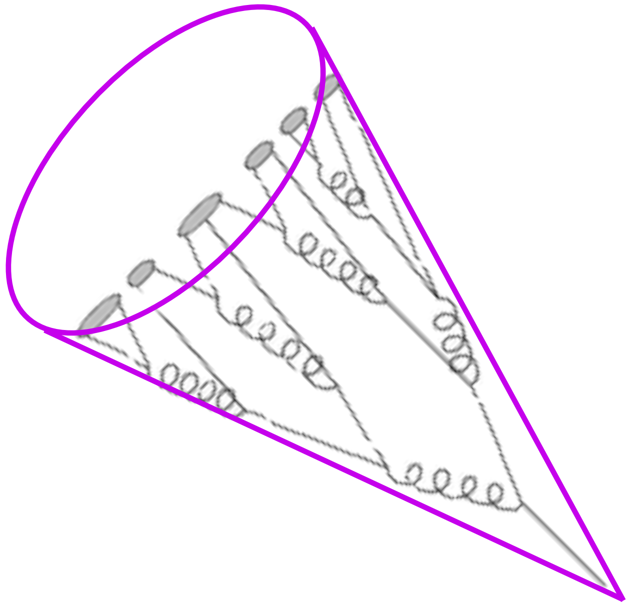
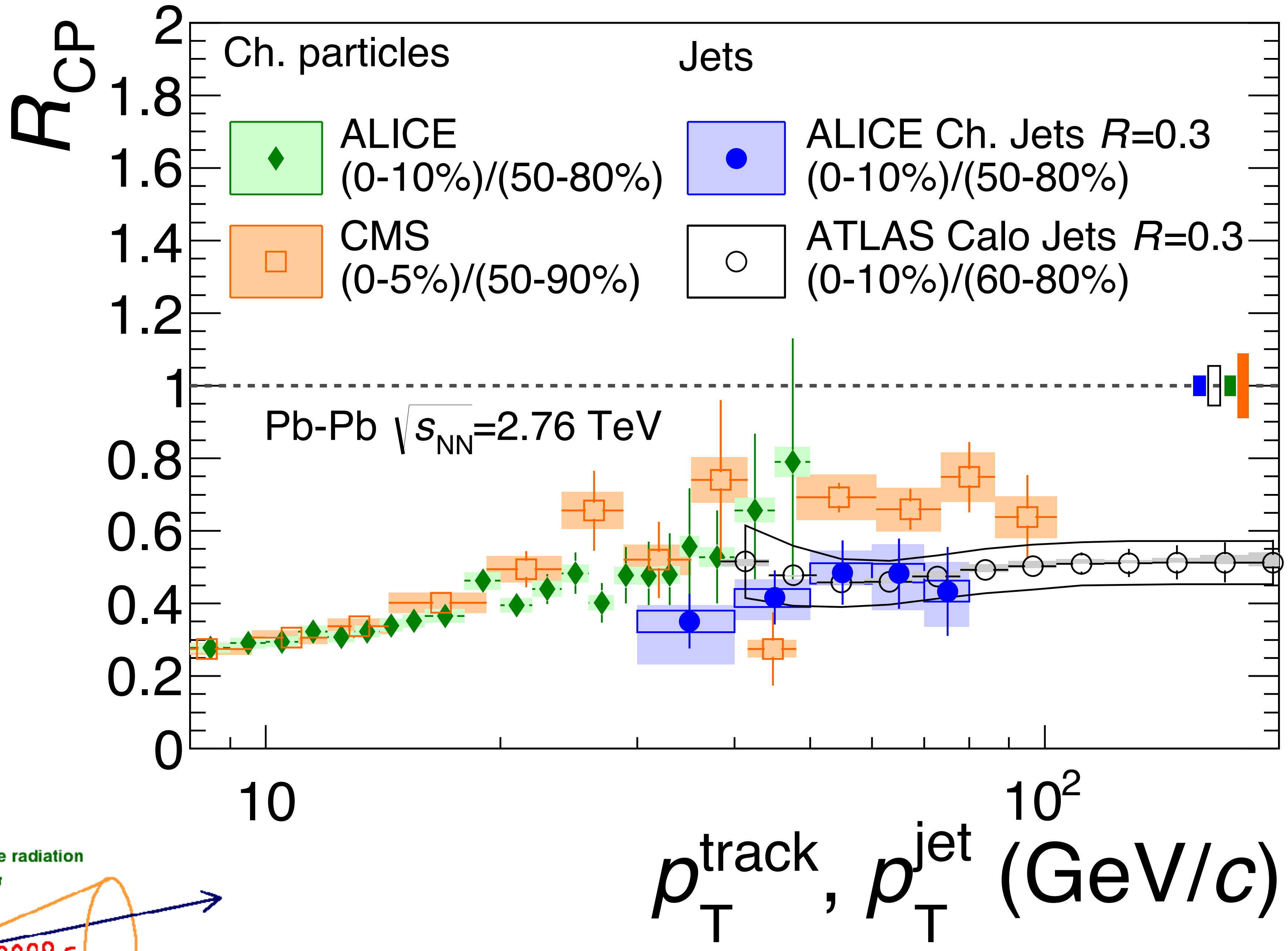
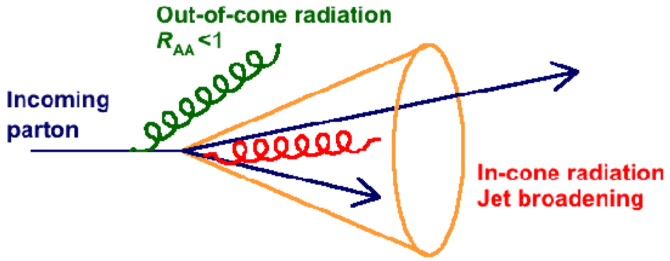


Jet reconstruction: group particles together and add momenta
Several algorithms available; conceptually: draw cones, size *R*

The summed momentum is a measure of the parton energy; accuracy depends on *R*

# Comparing hadrons and jets

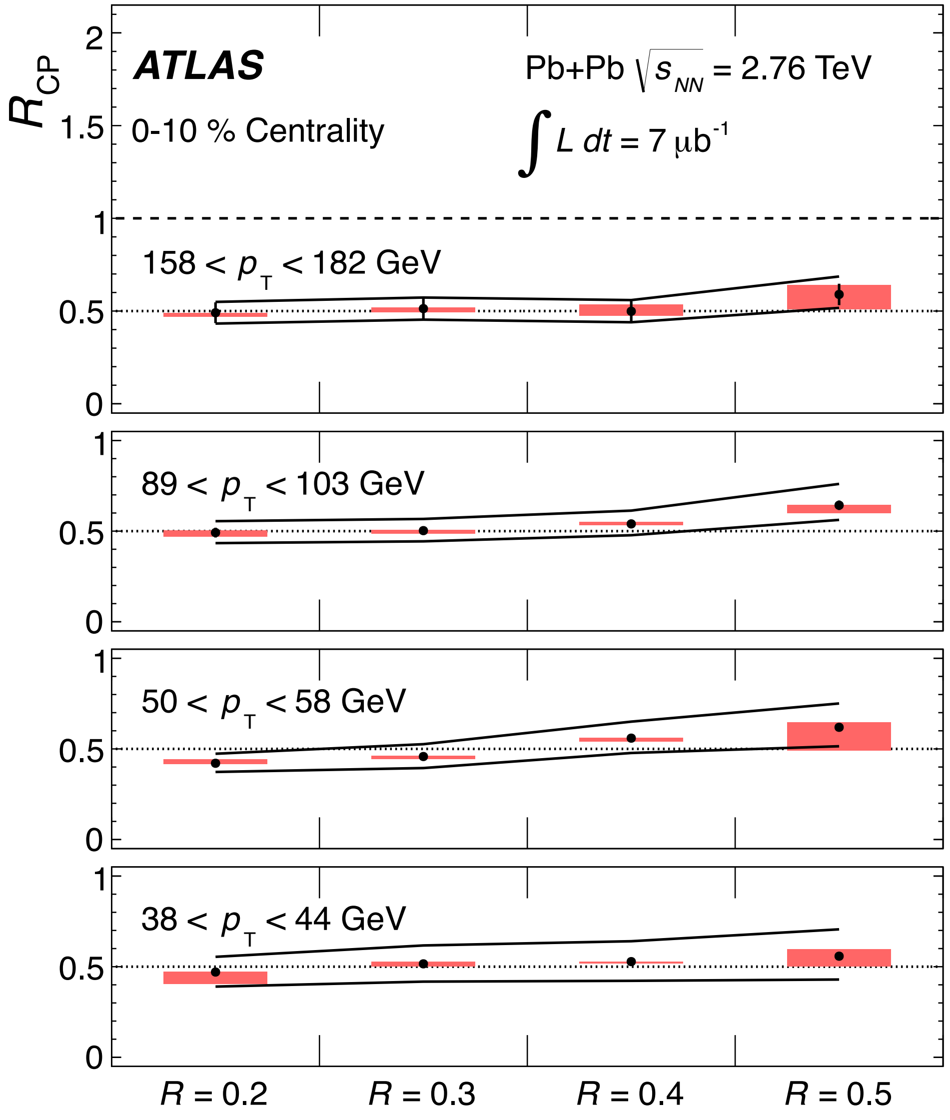




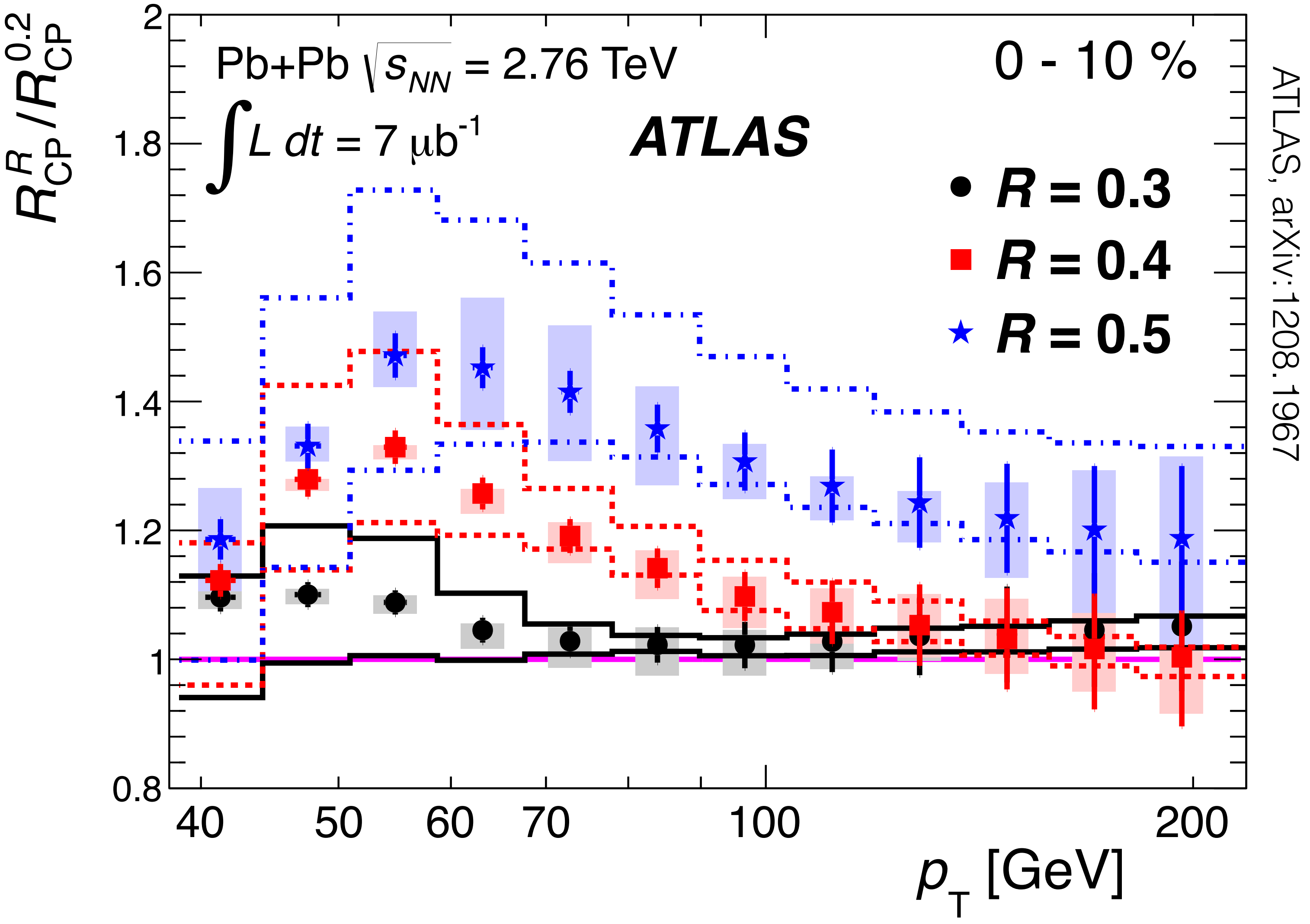
Suppression of hadron (leading fragment) and jet yield similar

Lost energy is transported to large angles ($R$ > 0.3)

# Increasing *R* to recover the energy

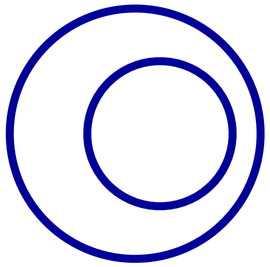


Ratio of spectra with different *R*



ATLAS, arXiv:1208.1967

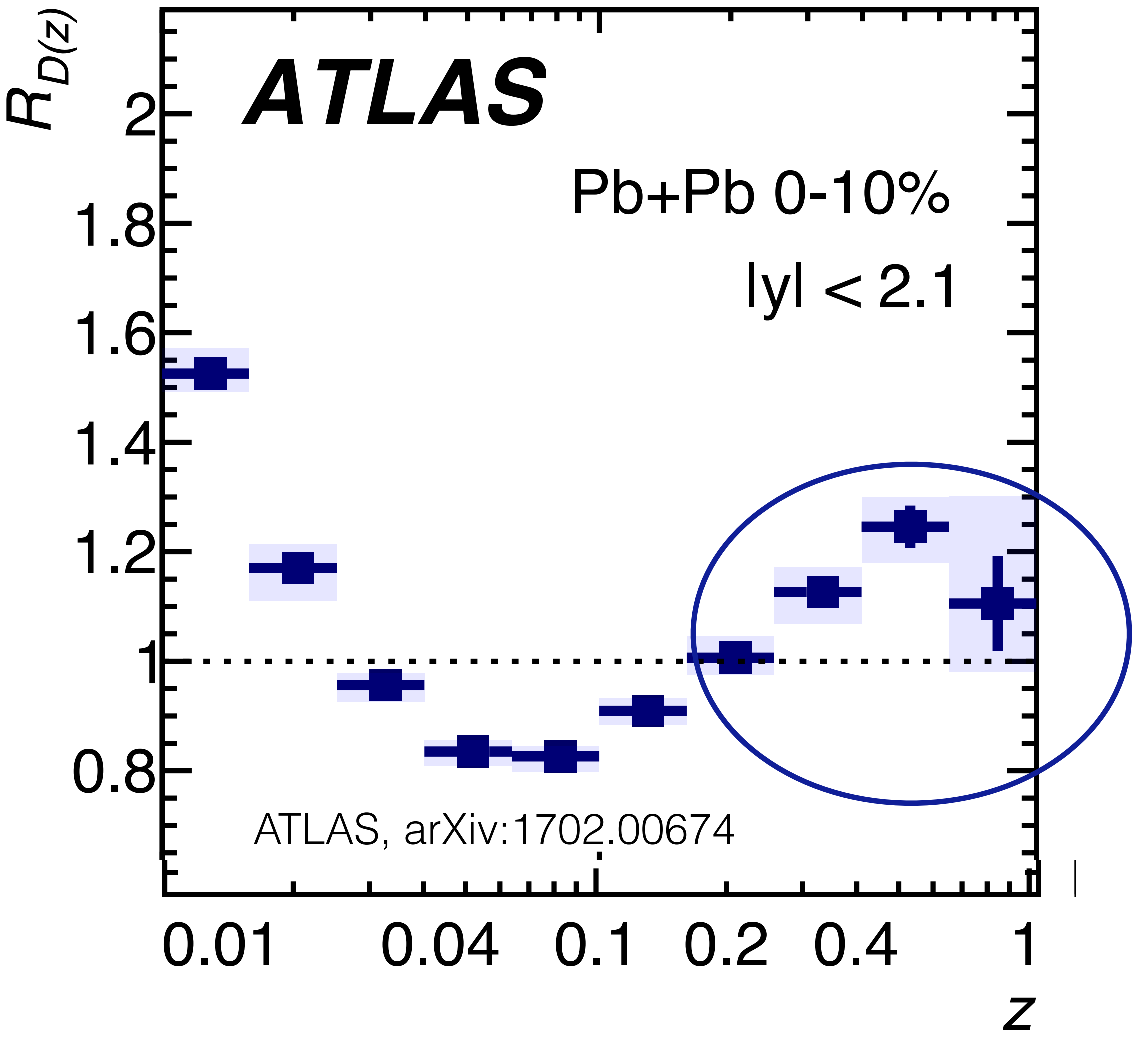
Larger jet cone: ‘catch’ more radiation → Jet broadening



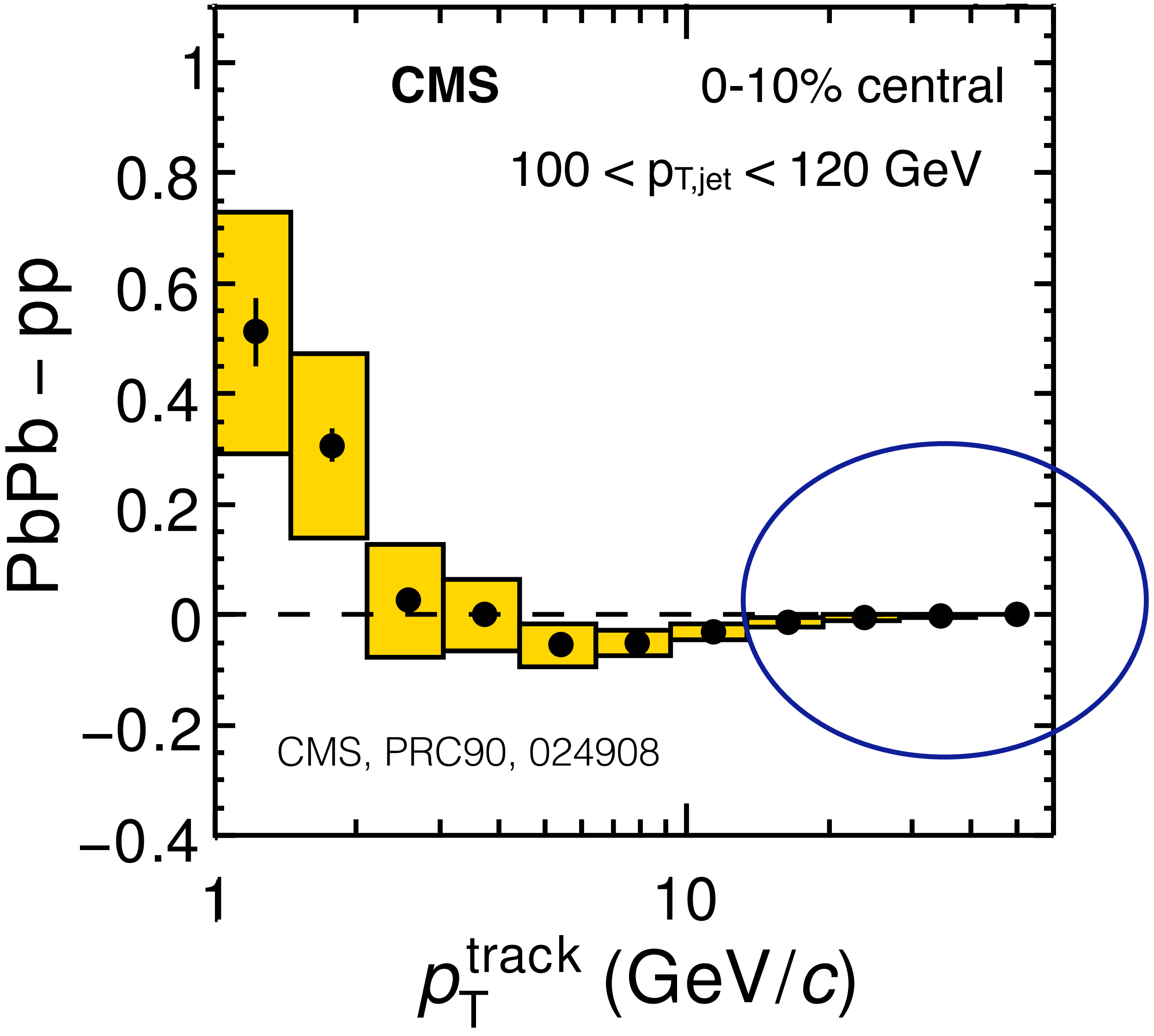
However, *R* = 0.5 still has $R_{AA}$ < 1
– Hard to see/measure the radiated energy

# Longitudinal distribution in jets: ATLAS vs CMS

Ratio: Pb-Pb/pp

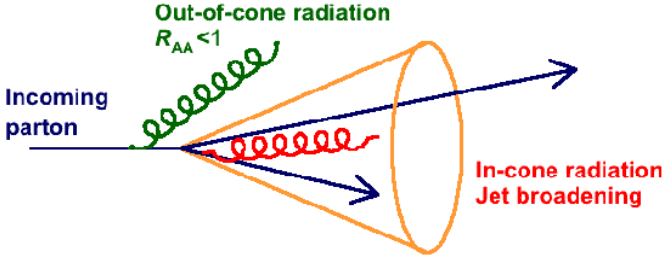


Difference: PbPb - pp



Subtle, but qualitative difference:
no modification at large *z* in CMS, enhancement in ATLAS measurement

# In-cone: longitudinal distributions

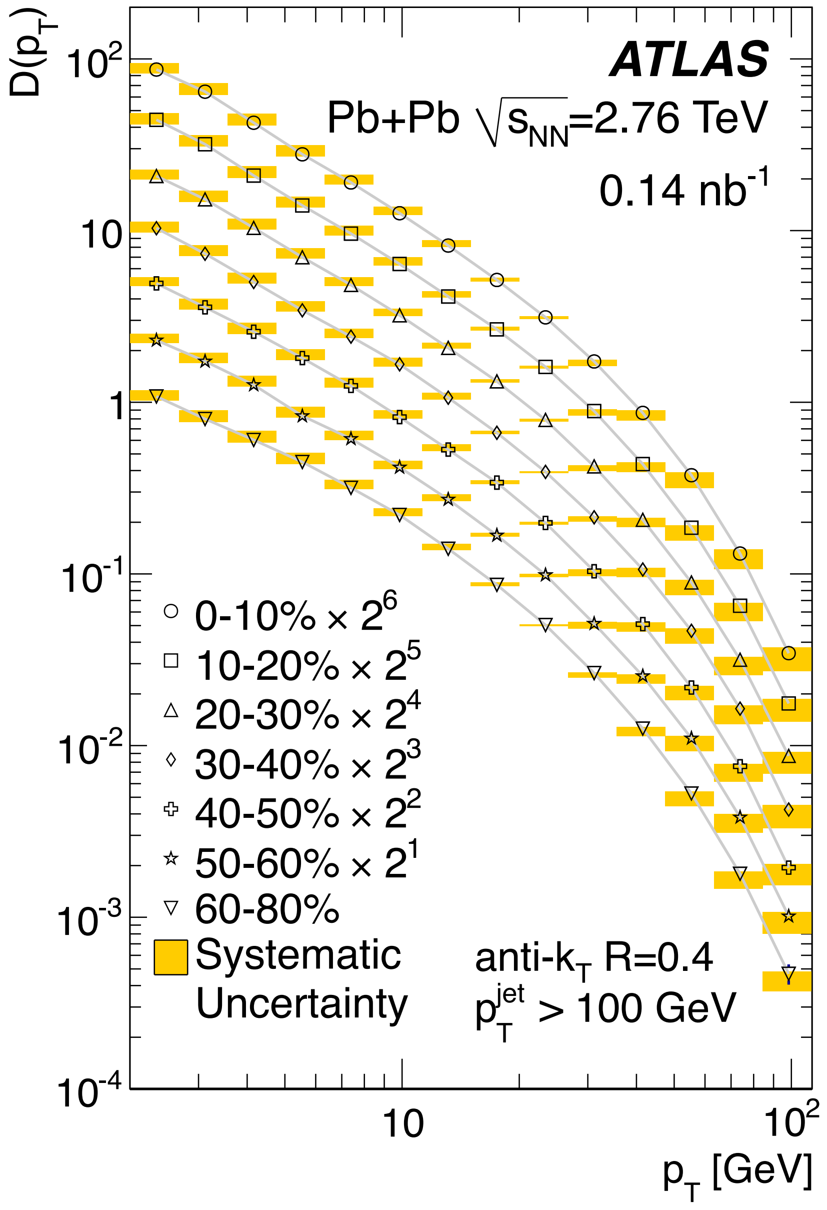


$$\left.\frac{dN}{dp_T}\right|_{particles} = \left.\frac{dN}{dp_T}\right|_{jets} \otimes D(p_T)$$

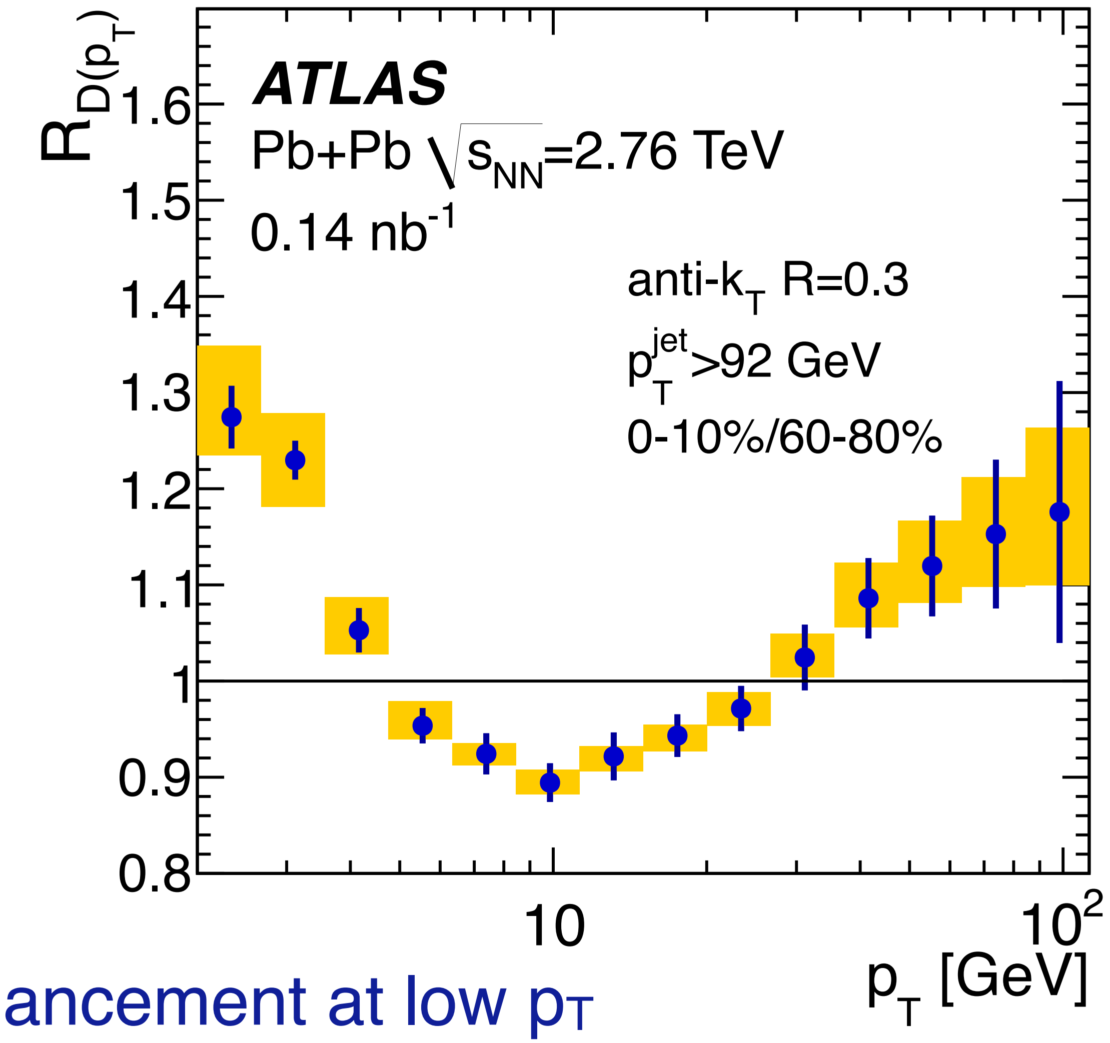
ATLAS, PLB 739, 320

Fragment distributions

$p_{T,jet}$ > 100 GeV/c



Ratio central/peripheral



Enhancement at low $p_T$

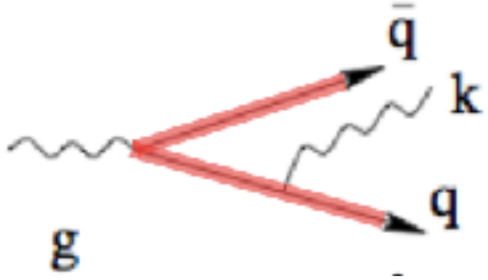
Suppression at intermediate $p_T$

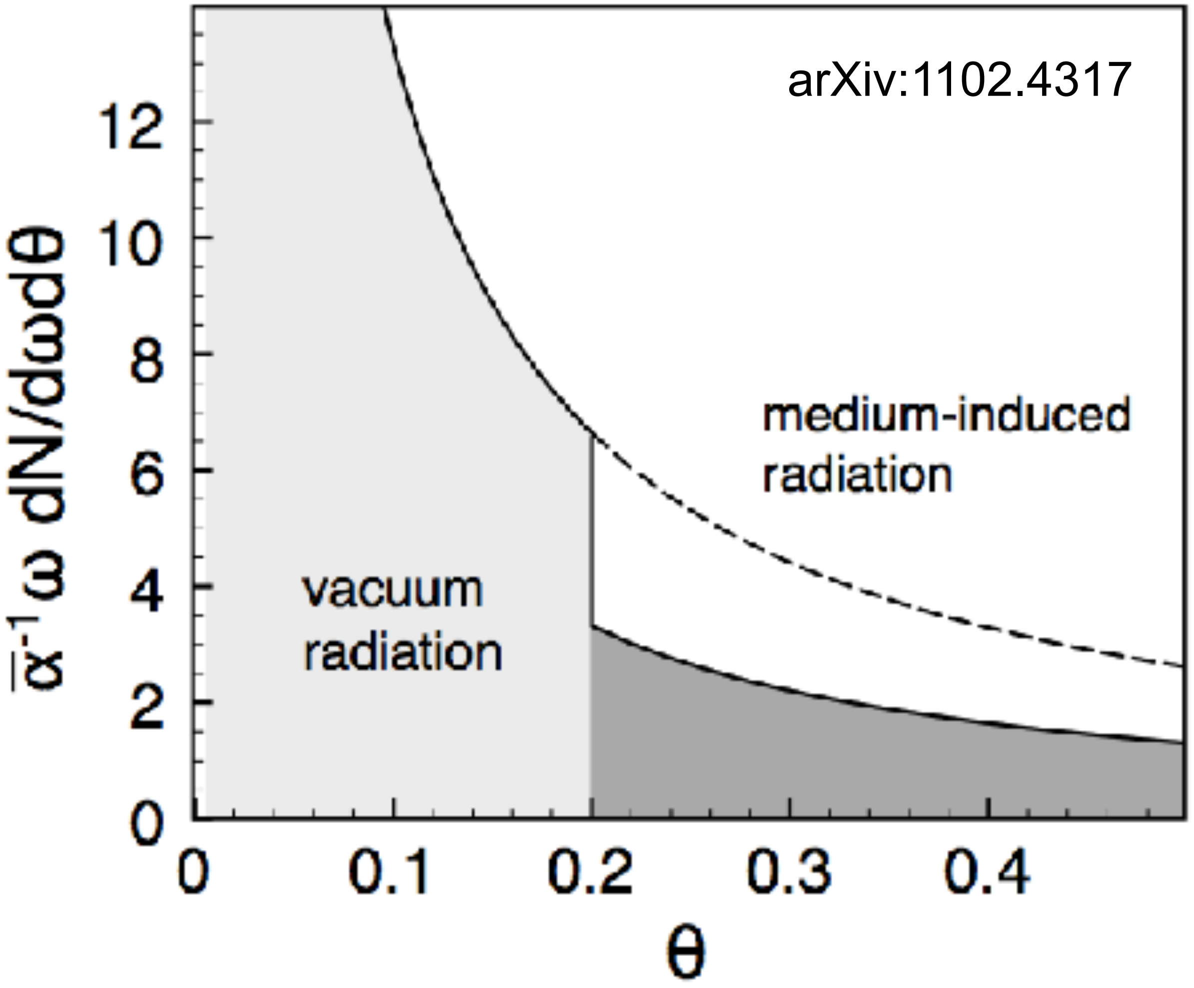
Softening of the fragmentation;
consistent with energy loss expectation

# (anti-) Angular ordering in the medium

Salgado, Mehtar-Tani, Tywoniuk et al
PRL106, 122002 and follow-ups

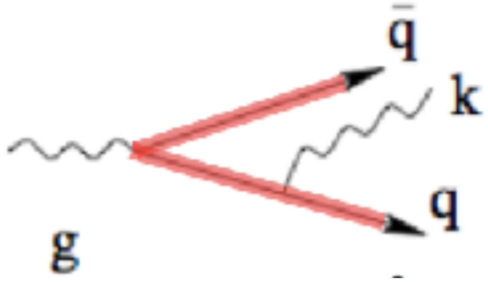
arXiv:1210.7765



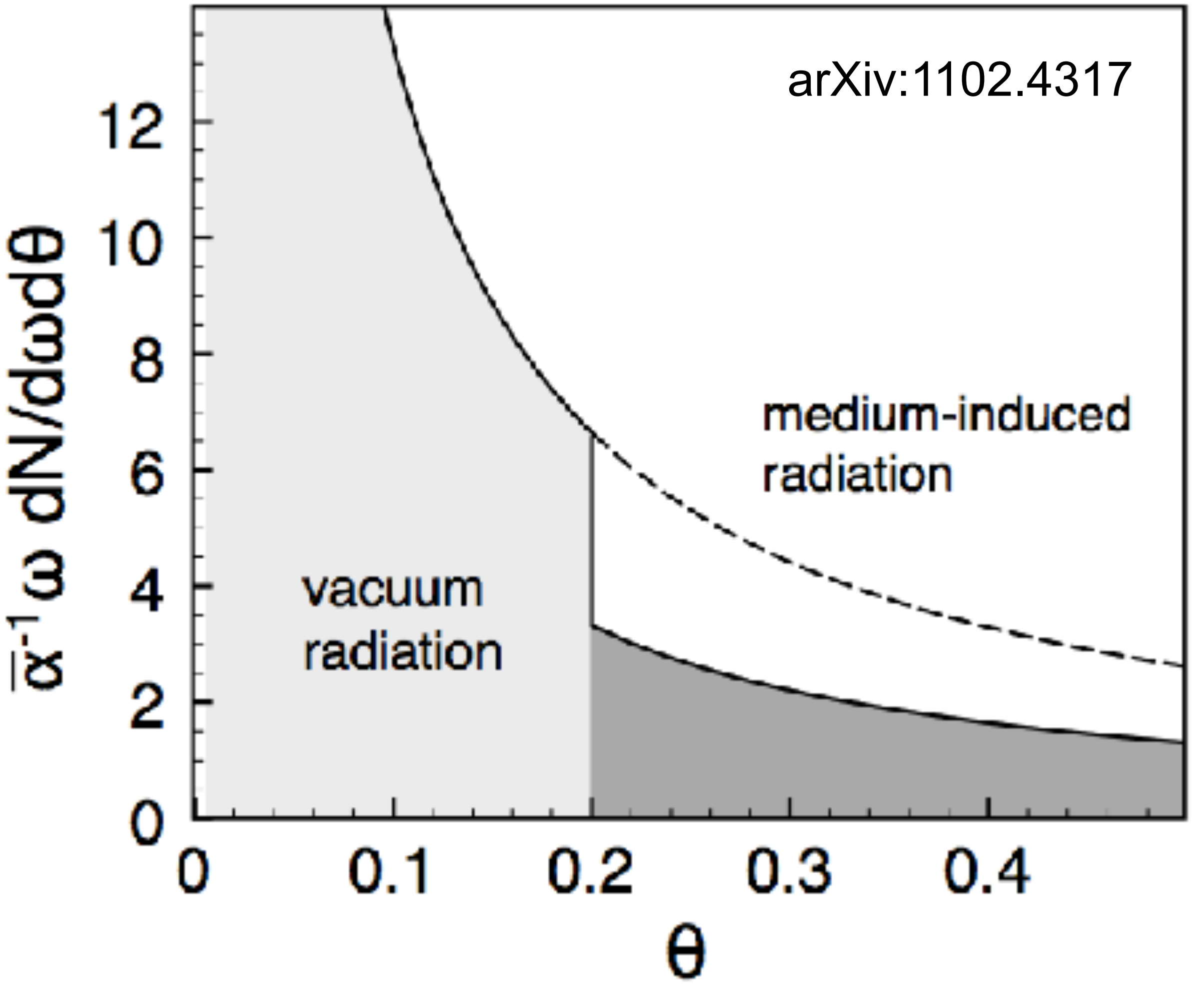

arXiv:1102.4317

Vacuum radiation: angular ordering
subsequent radiations are at smaller angles
In-medium: opposite effect
radiation outside cone preferred

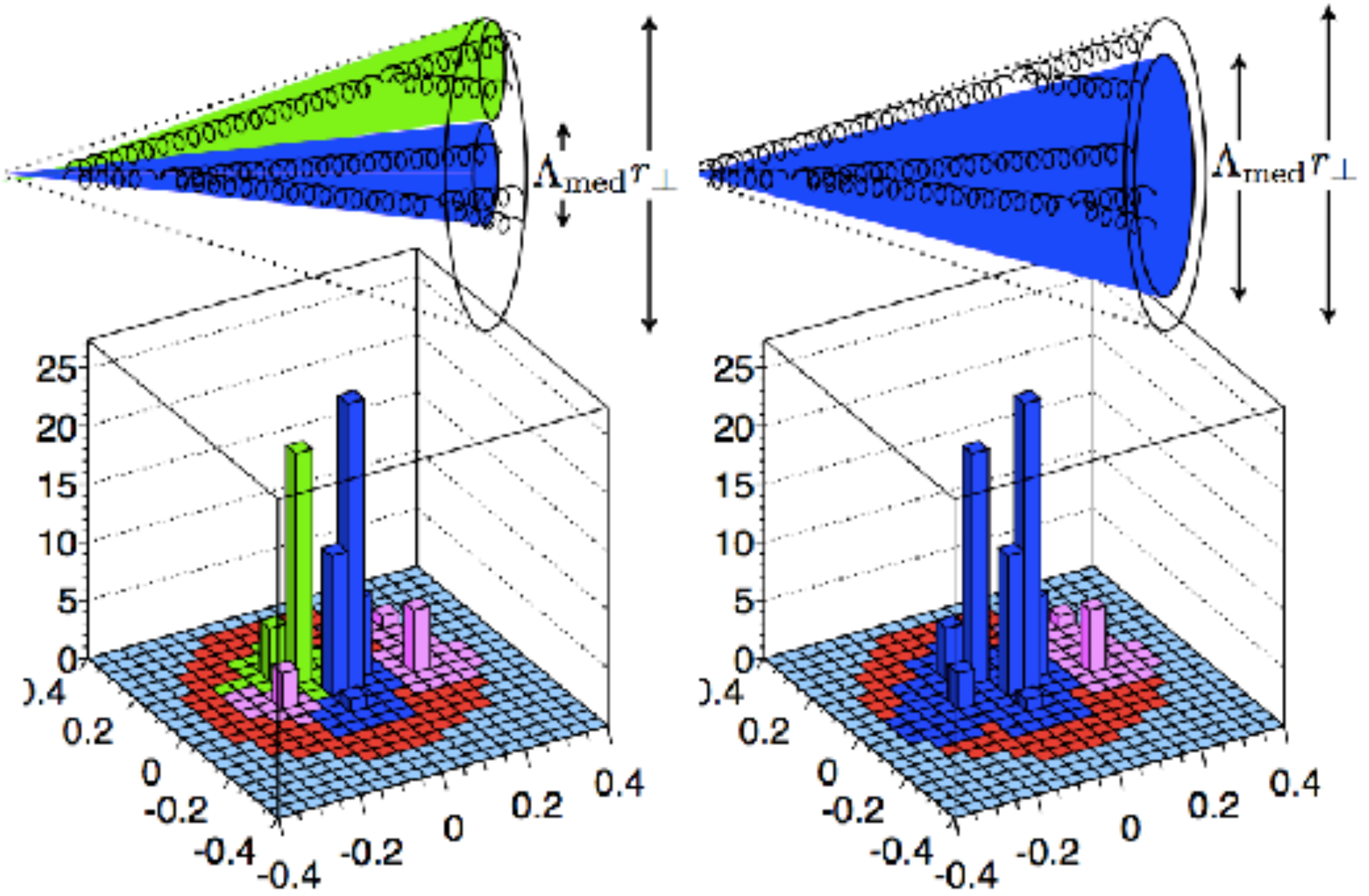
# (anti-) Angular ordering in the medium



Salgado, Mehtar-Tani, Tywoniuk et al
PRL106, 122002 and follow-ups



arXiv:1210.7765



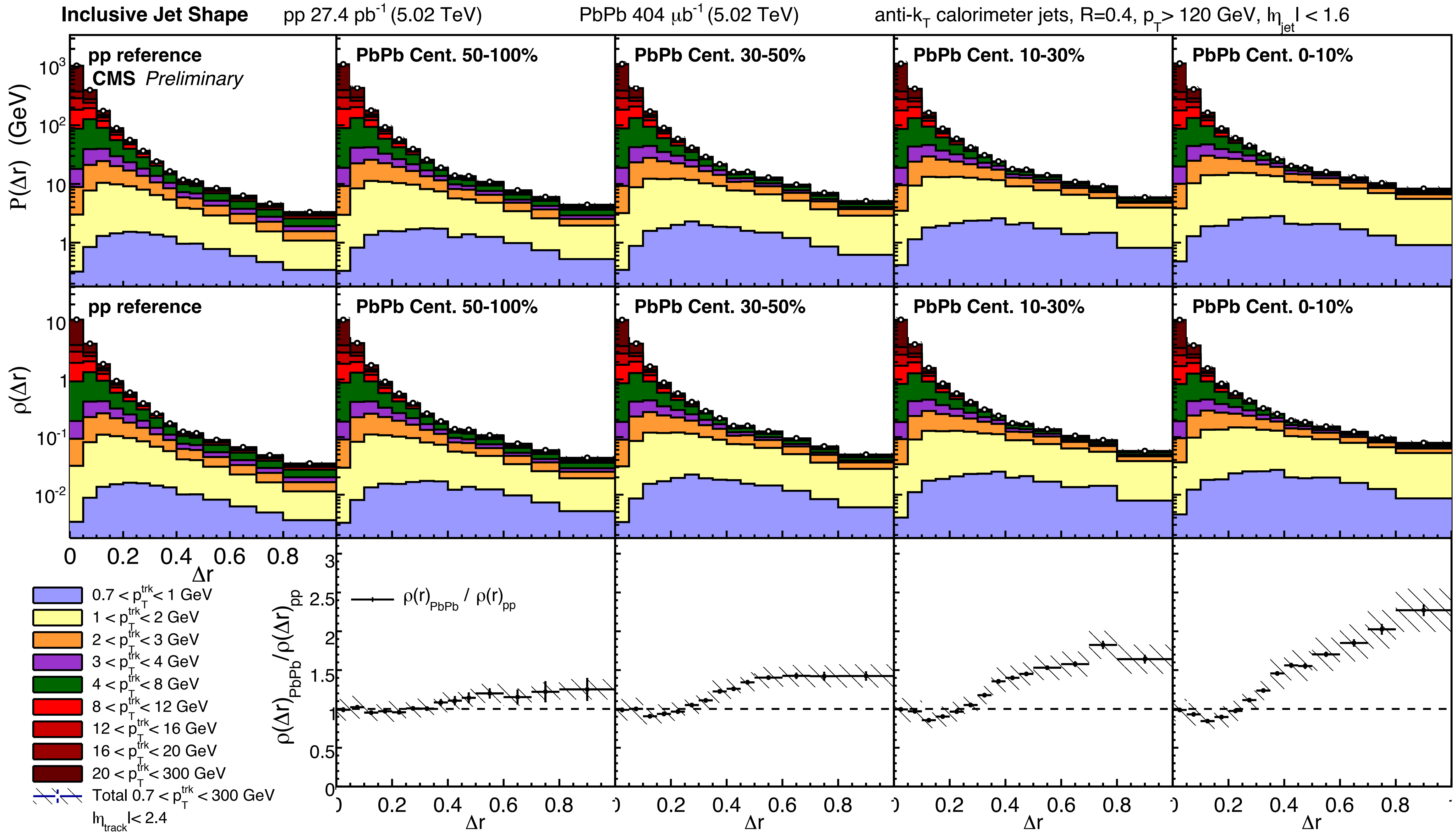
Vacuum radiation: angular ordering
subsequent radiations are at smaller angles
In-medium: opposite effect
radiation outside cone preferred

Two resolution scales:
medium scale vs opening angle

Ongoing development
Full implications not yet worked out

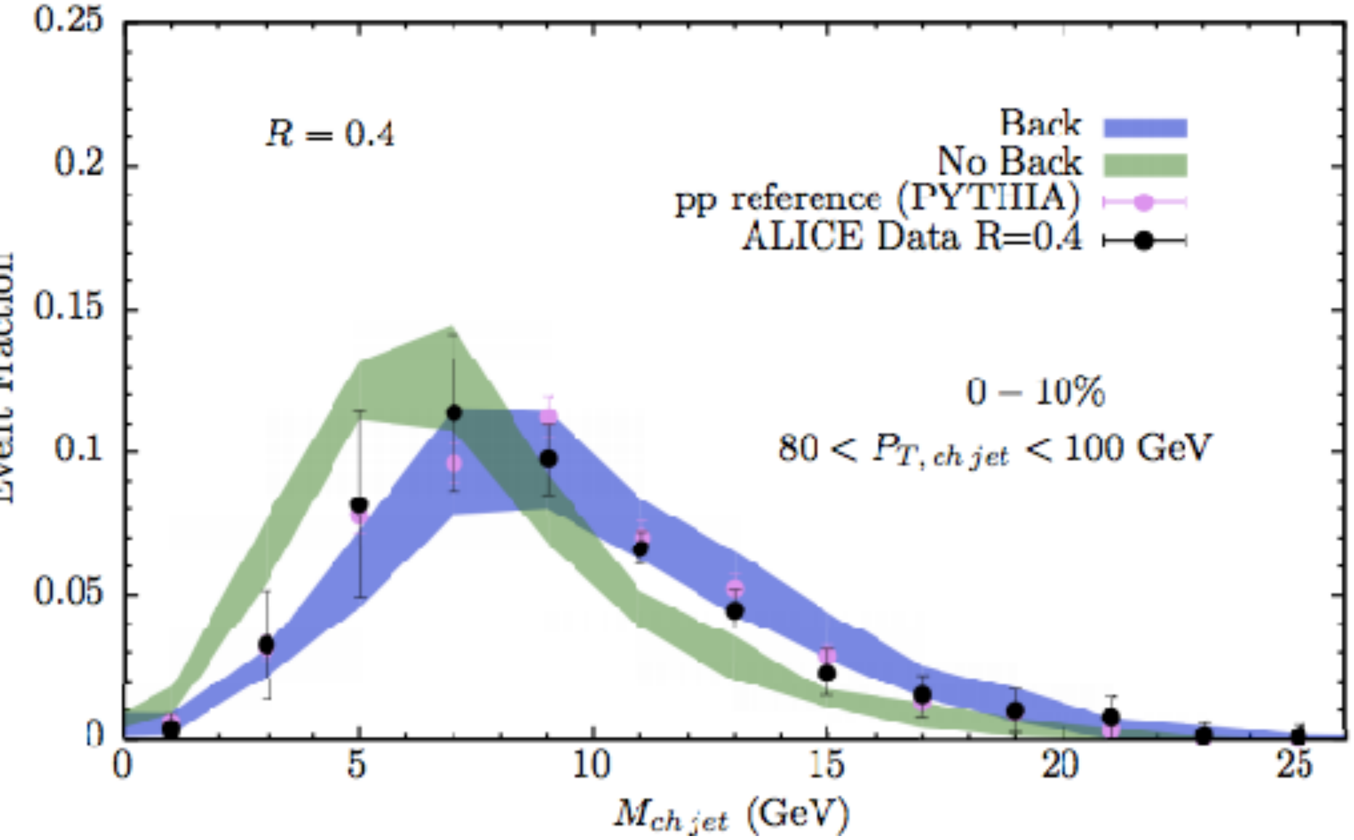
# Radial profiles in pT bins

CMS-PAS-HIN-16-020



# Jet structure and medium response

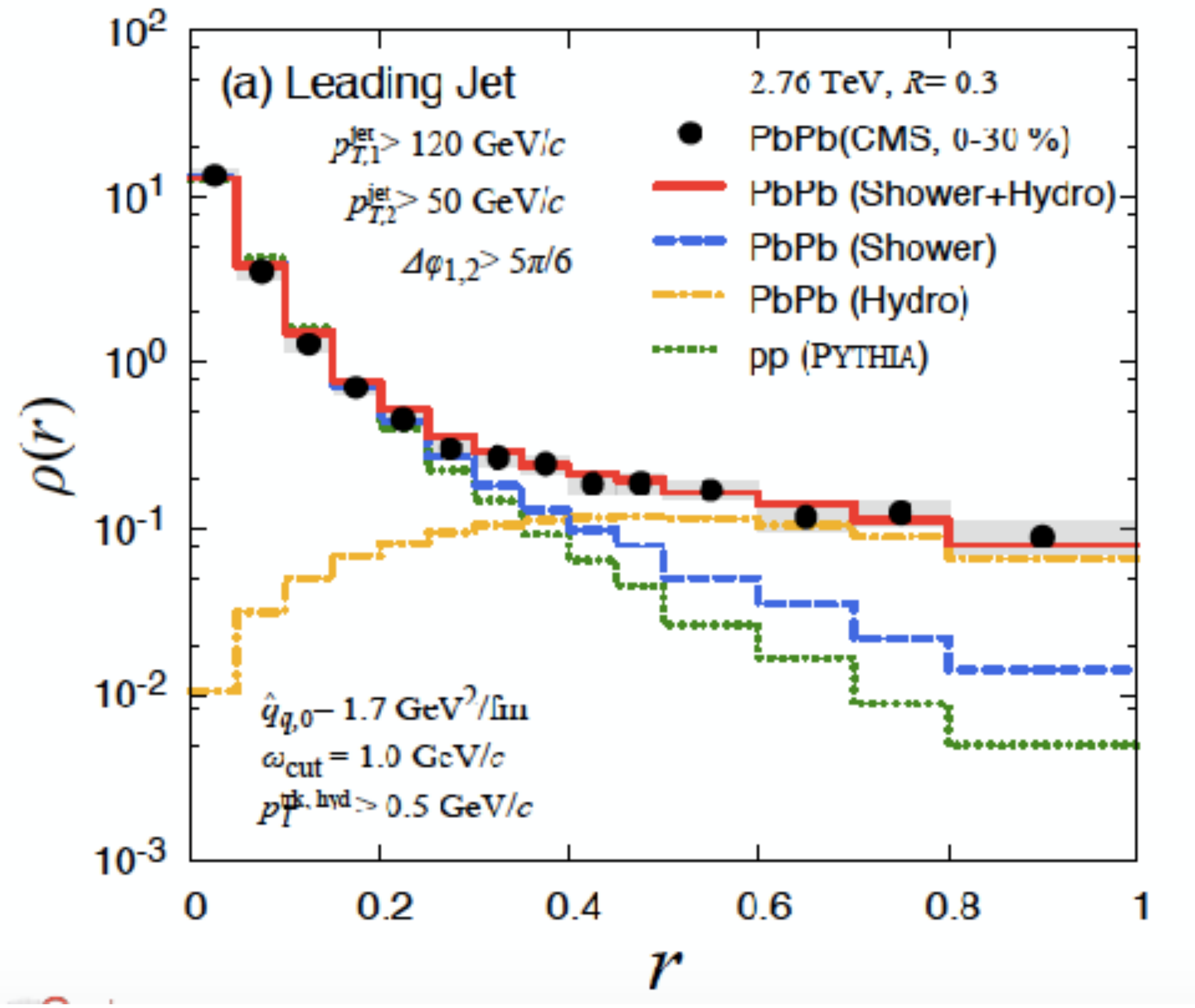
Jet mass



K Rajagopal, parallel talk

Hybrid strong/weak model
w, w/o medium response

Jet radial profile



Y Tachibana et al, arXiv:1701.07951

Linearized Boltzmann Transport Model

Measurements with soft fragments are sensitive to medium response/reinteractions

Theory treatment of medium response/momentum balance under development

NB: distinction jet/medium is not unique: model/prescription dependent

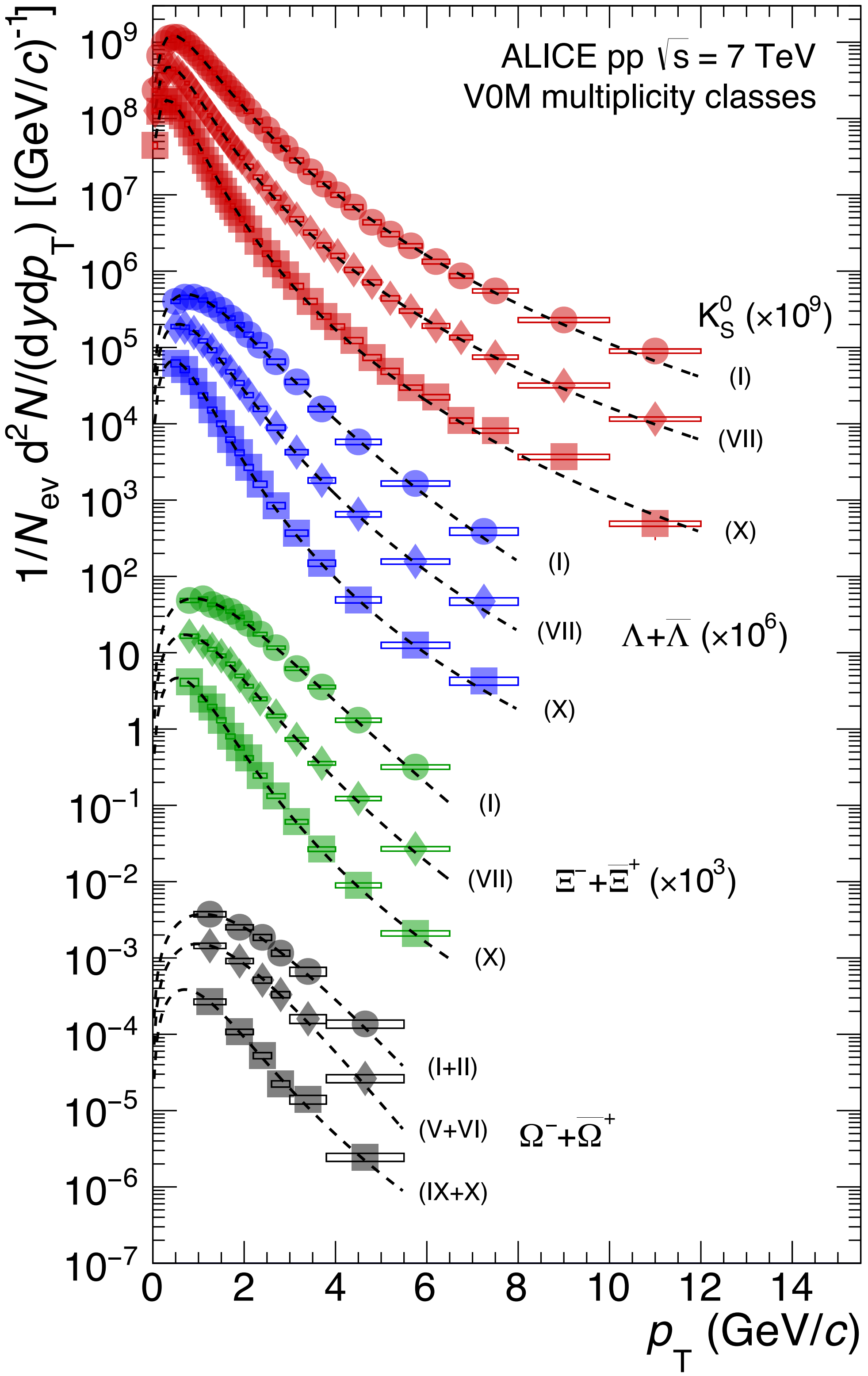
# Hints of collective effects in p+p, p+Pb

# $p_T$ spectra, mean $p_T$ vs multiplicity in pp

$p_T$ spectra in
multiplicity-selected pp collisions

Mean $p_T$ increases with multiplicity

What drives this increase?
Can it be pressure or something equivalent?



ALICE, arXiv:1606.07424, arXiv:1307.6796, arXiv:1512.07227

# Mean $p_T$ overview pp

Mean $p_T$ in pp collisions
also increases
with multiplicity and particle mass

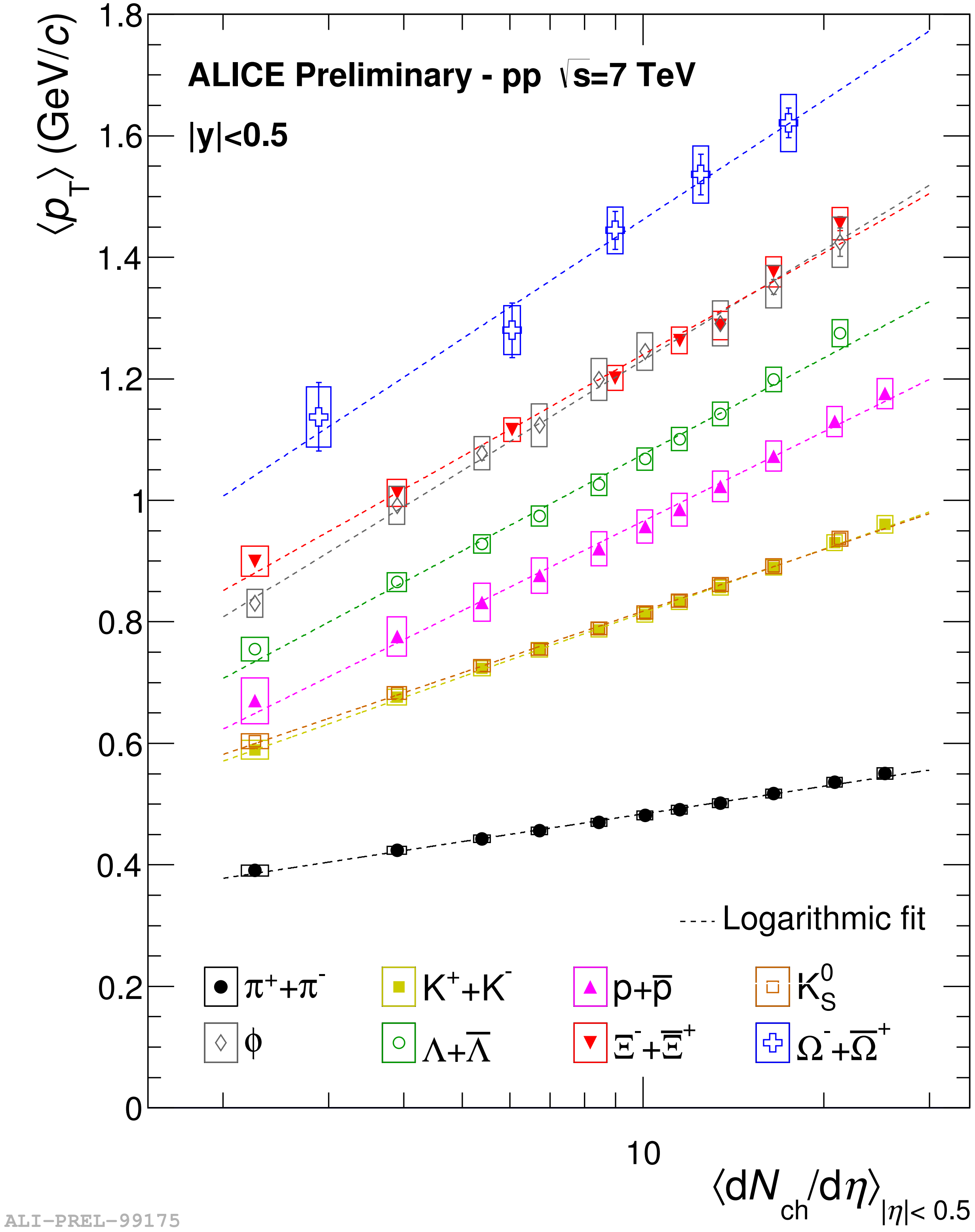
Multiple (initial state) interactions
or proto-flow?

Or are they the same?

Logarithmic fit 'to guide the eye':

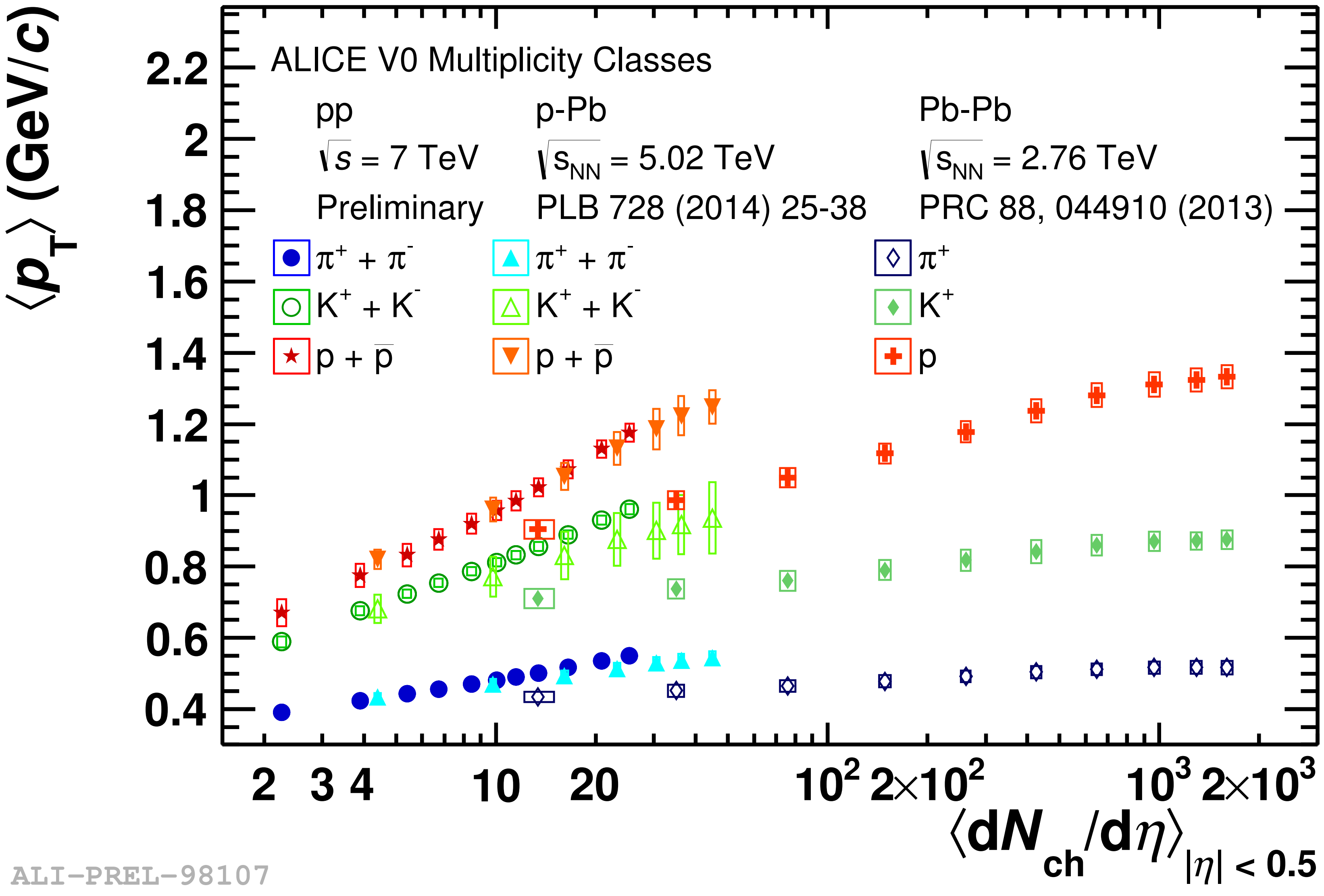
$$\langle p_T \rangle \propto \log \, dN/d\eta$$

QM15 talk, L Bianchi



# Mean $p_T$ overview pp, p+Pb, Pb+Pb

QM15 talk, A Ortiz



Increasing mean $p_T$ trend continues in p+Pb

Raises question: is there flow, collective behaviour in pp, p+Pb?

And how is it generated?

# Flow in small systems: comparisons to hydro

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?

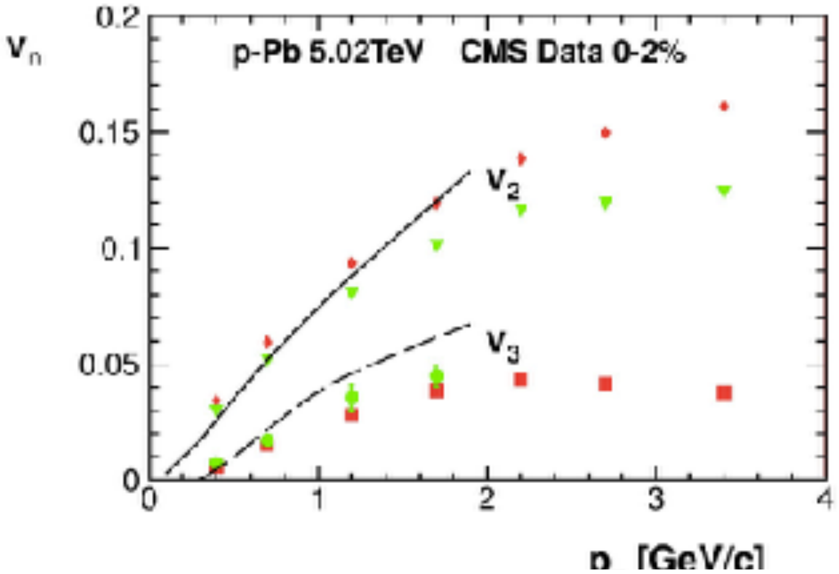
Is there enough time, volume to thermalise?

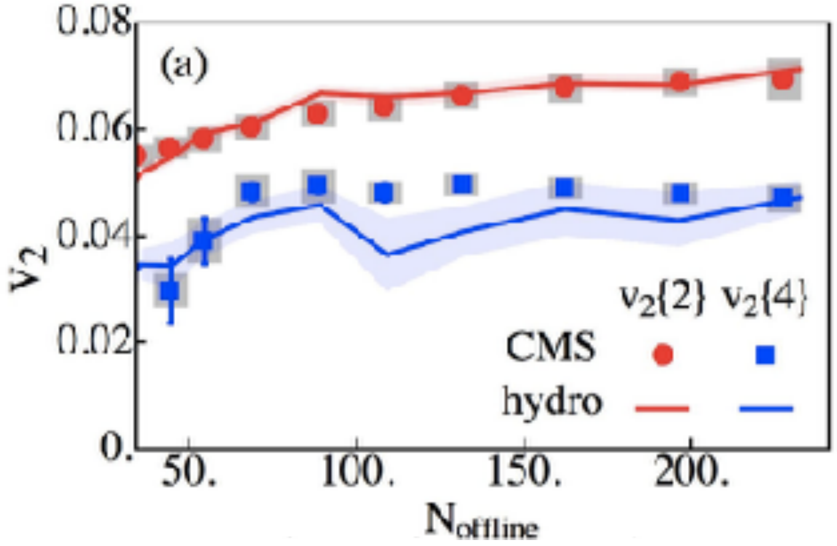
- Hydrodynamisation (isotropisation) of a dense gluon system?
- Partonic/hadronic rescattering?
- How many scatterings/what density is needed to approximate fluid behaviour?

Many recent developments;
active discussion on interpretation

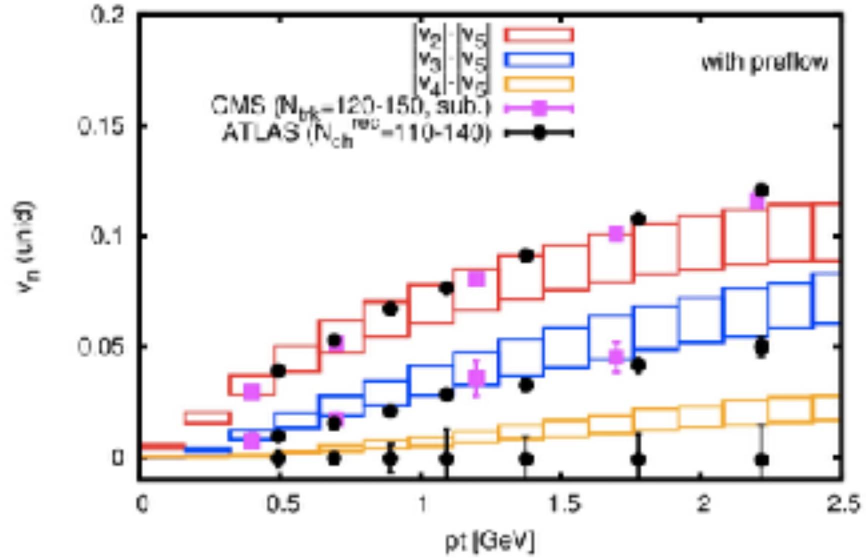
2016 p+Pb run to shed more light on this

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





Kozlov et al, Nucl. Phys. A931 (2014)



Romatschke, EPJC75, 305

# Hydro fit model parameters

J. E. Bernhard et al, arXiv: 1605.03954

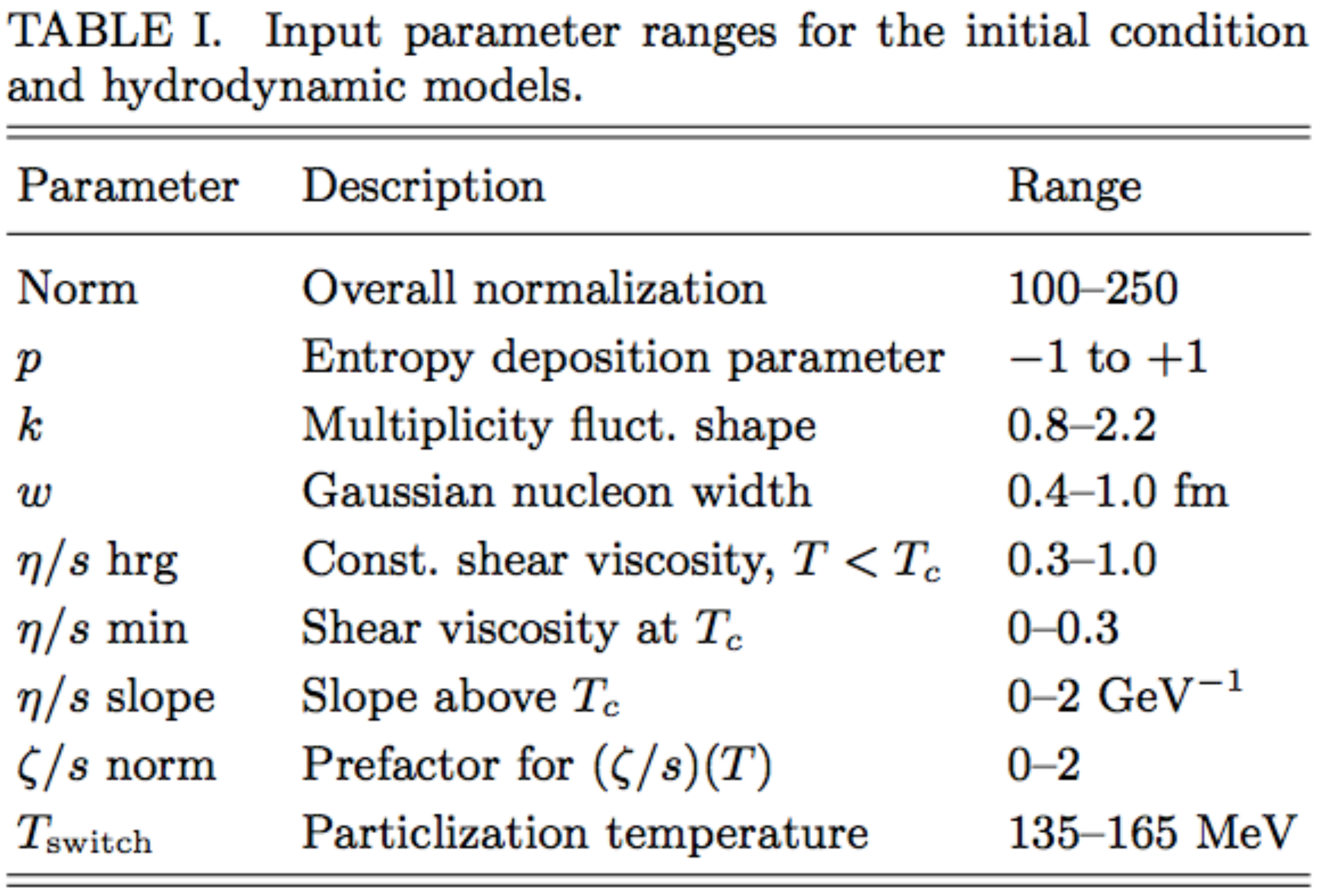
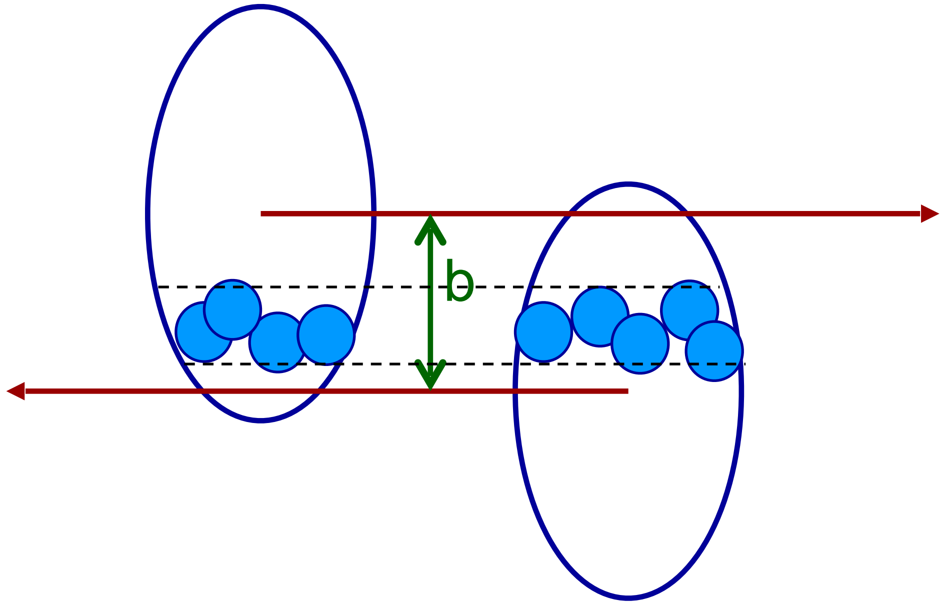


TABLE I. Input parameter ranges for the initial condition and hydrodynamic models.

| Parameter | Description | Range |
|---|---|---|
| Norm | Overall normalization | 100–250 |
| $p$ | Entropy deposition parameter | $-1$ to $+1$ |
| $k$ | Multiplicity fluct. shape | 0.8–2.2 |
| $w$ | Gaussian nucleon width | 0.4–1.0 fm |
| $\eta/s$ hrg | Const. shear viscosity, $T < T_c$ | 0.3–1.0 |
| $\eta/s$ min | Shear viscosity at $T_c$ | 0–0.3 |
| $\eta/s$ slope | Slope above $T_c$ | 0–2 $\mathrm{GeV}^{-1}$ |
| $\zeta/s$ norm | Prefactor for $(\zeta/s)(T)$ | 0–2 |
| $T_{\mathrm{switch}}$ | Particlization temperature | 135–165 MeV |

# Nuclear geometry: $N_{\mathrm{part}}$, $N_{\mathrm{coll}}$



Two limiting possibilities:

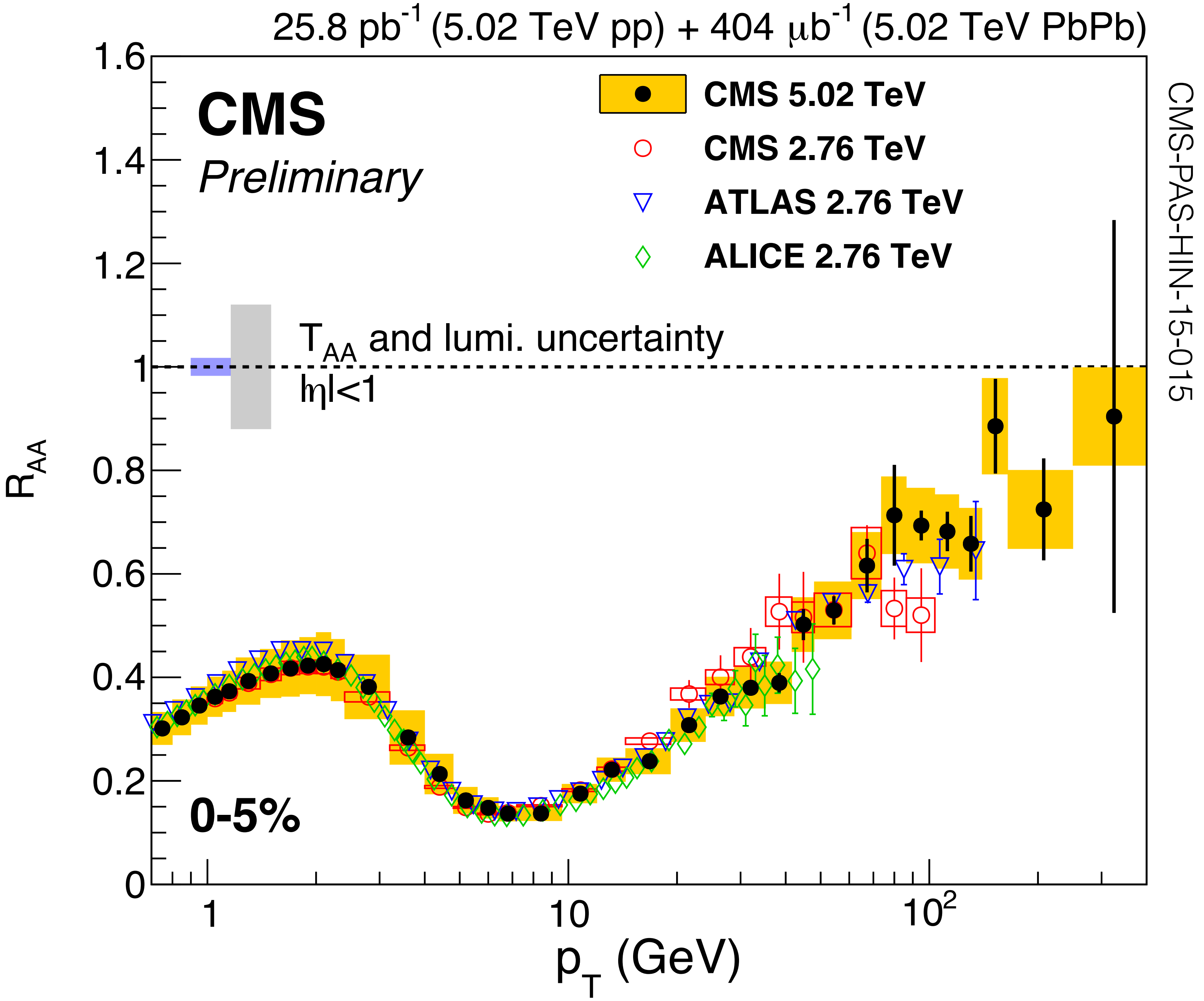
- Each nucleon only **interacts once**, ‘wounded nucleons’
  $N_{\mathrm{part}} = n_A + n_B$ (ex: 4 + 5 = 9 + …)
  Relevant for soft production; long timescales: $\sigma \propto N_{\mathrm{part}}$
- Nucleons **interact with all** nucleons they encounter
  $N_{\mathrm{coll}} = n_A \times n_B$ (ex: 4 x 5 = 20 + …)
  Relevant for hard processes; short timescales: $\sigma \propto N_{\mathrm{coll}}$

# Nuclear modification factor $R_{AA}$

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

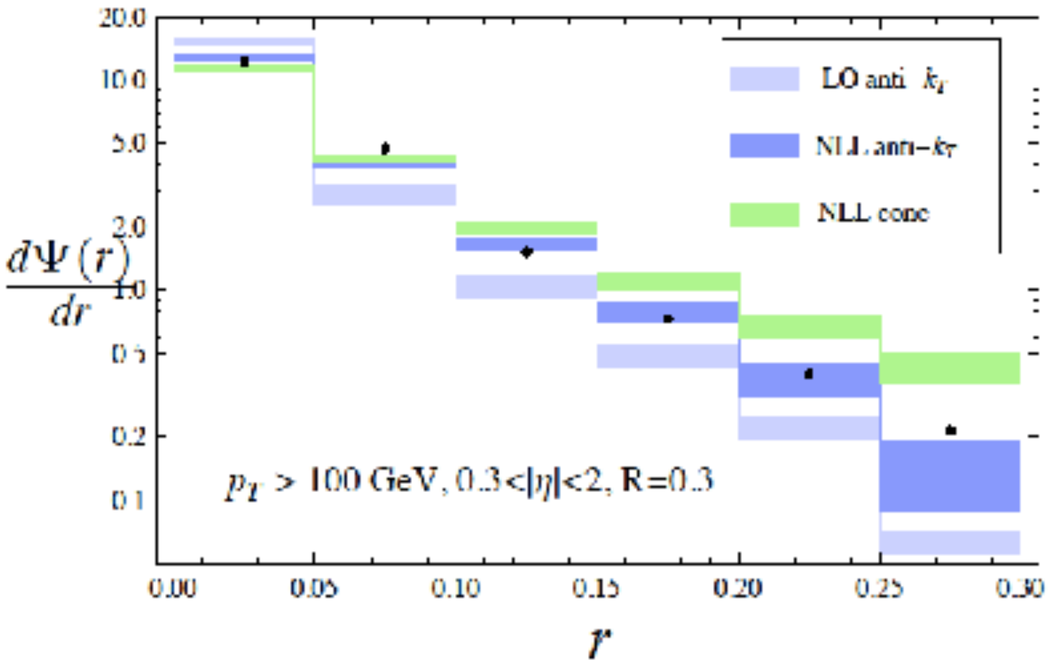


Expect $\Delta E \propto \hat{q} \ln E$ in high energy limit E >> ΔE

# Soft-collinear Effective Theory

Y-T Chien, I Vitev, JHEP 1412, 061 and 1605, 023

## Radial profile pp



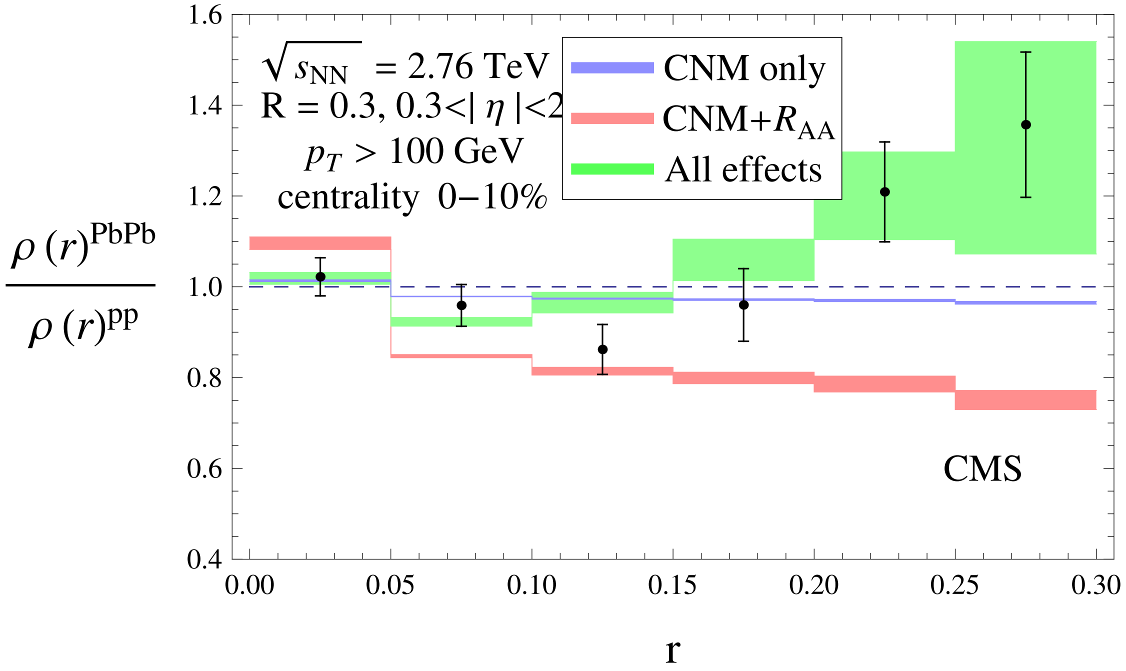
Need resummation
to properly describe radial profile

Radial profile well described by SCET

*R* dependence too strong?

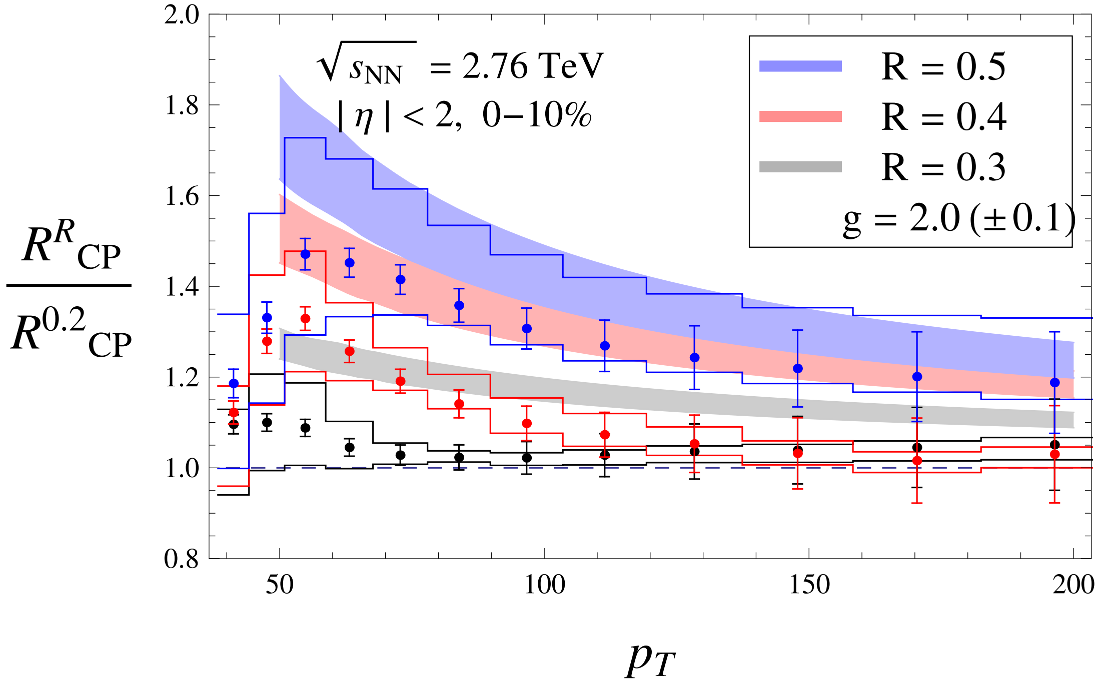
Predictions for $\gamma$-jet available

## Radial profile Pb+Pb



CMS, arXiv:1310.0878

## *R*-dependence of $R_{AA}$

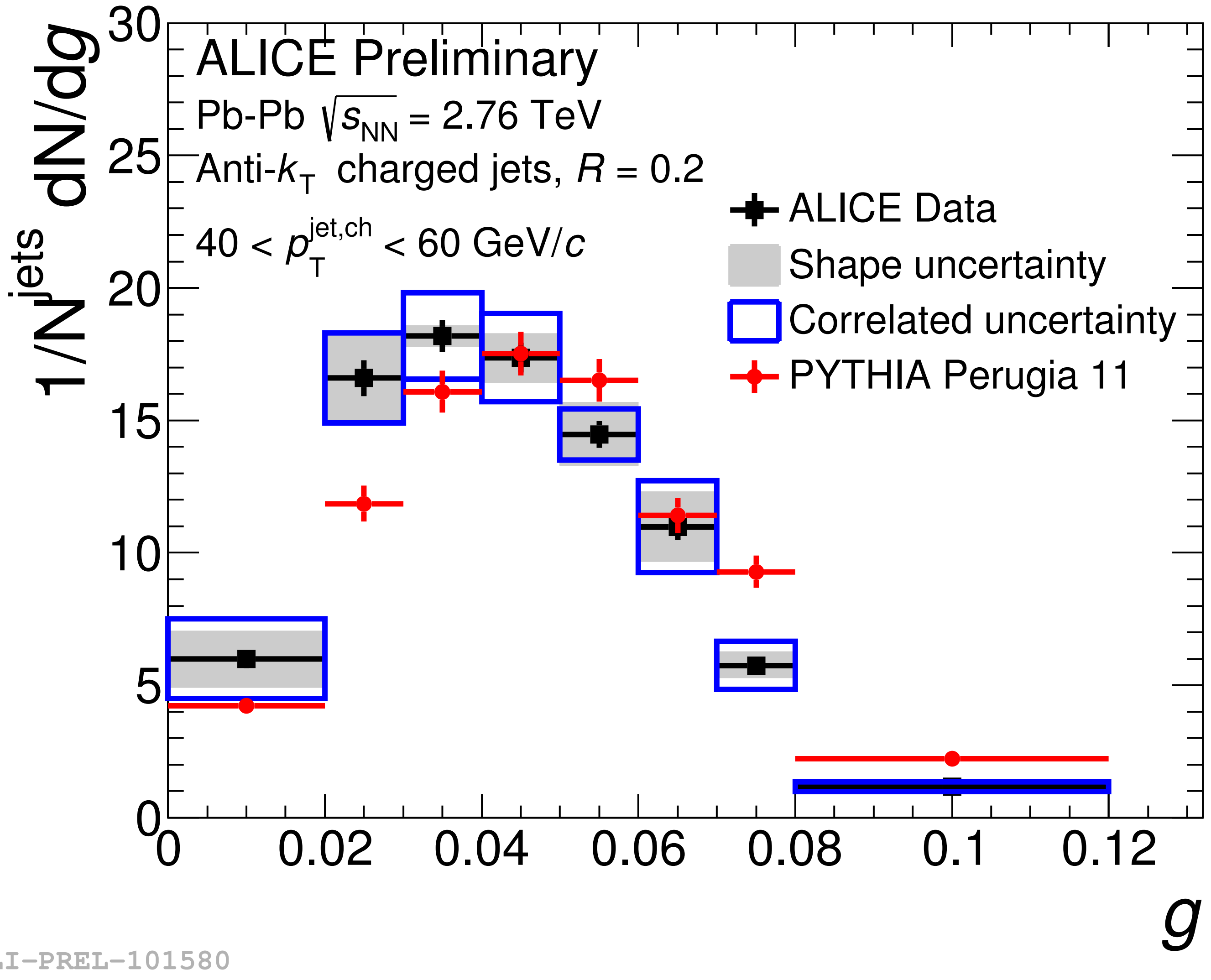


ATLAS, arXiv:1208.1967

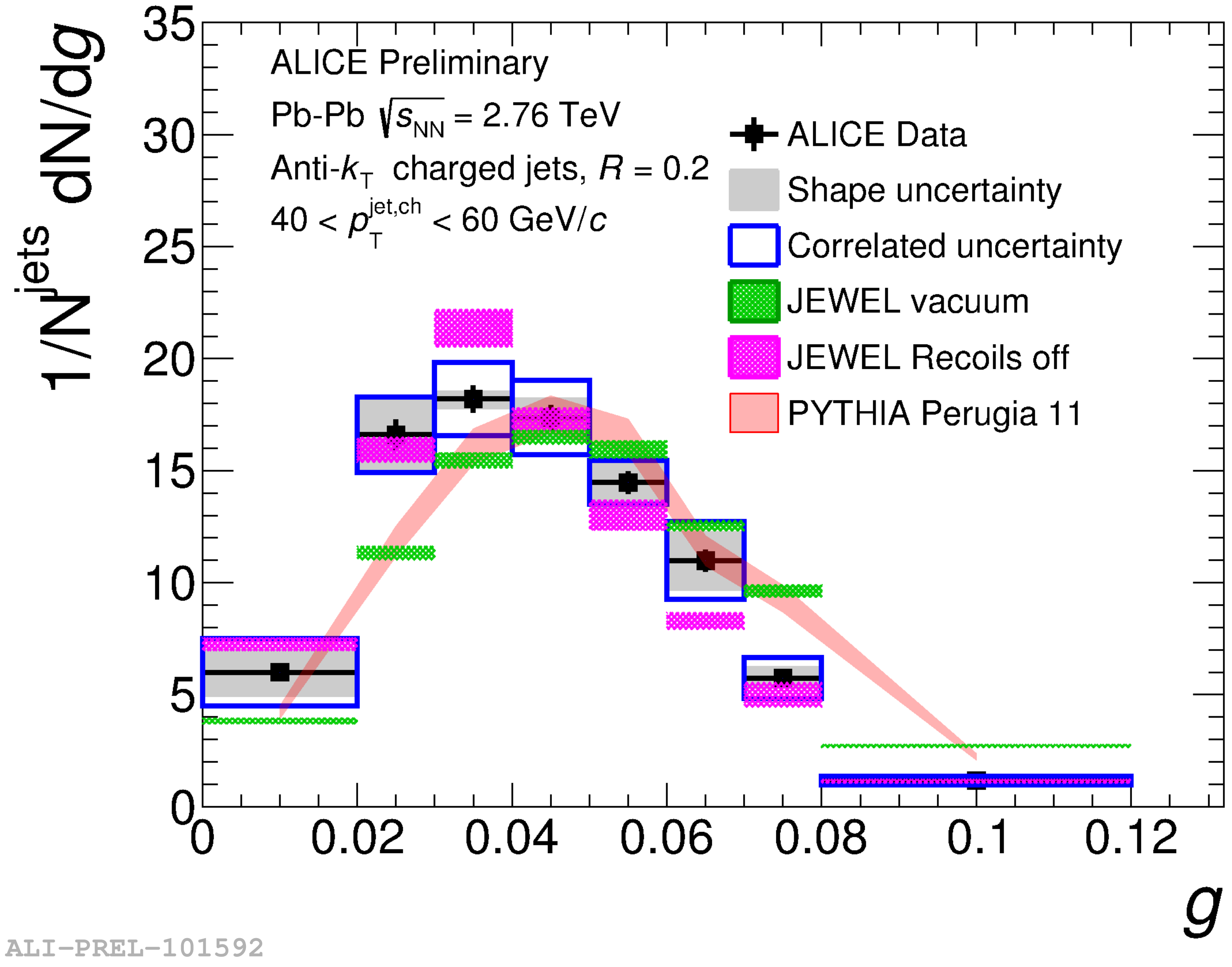
# Jet shapes: radial moment

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

L. Cunqueiro, Quark Matter



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



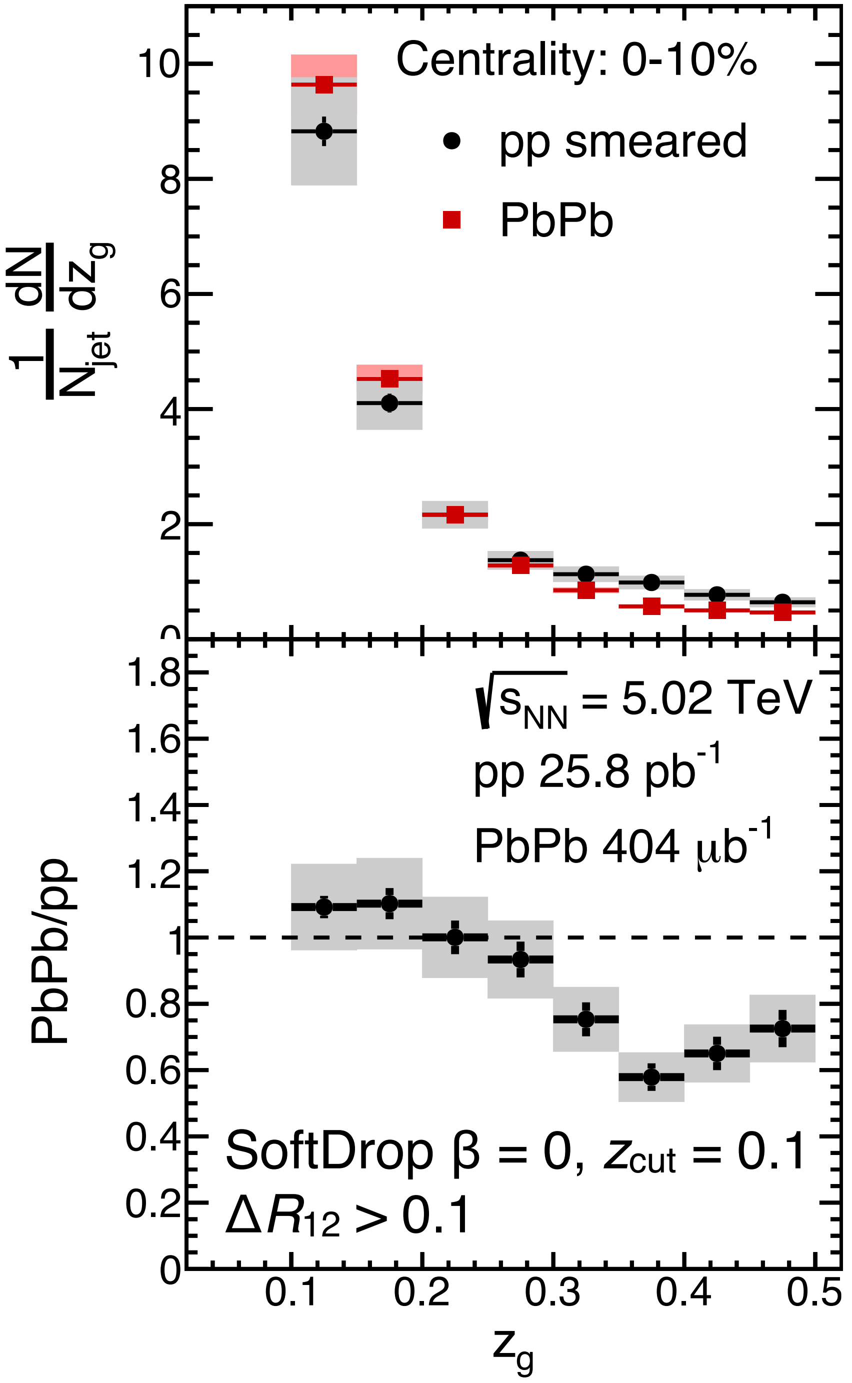
JEWEL model shows similar trend

Jets in medium narrower than in vacuum

# Splitting fraction

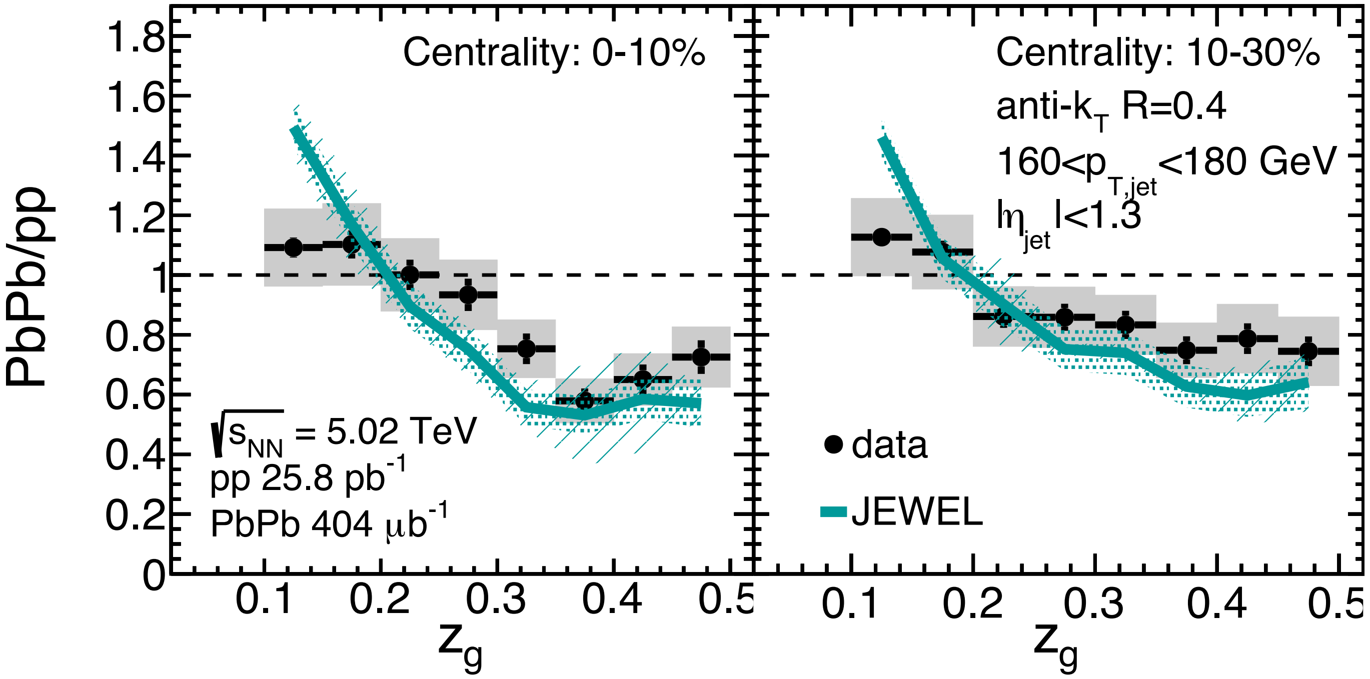
SoftDrop grooming, momentum fraction of the first splitting: sensitive to splitting function

Larkoski et al, PRD 91, 111501

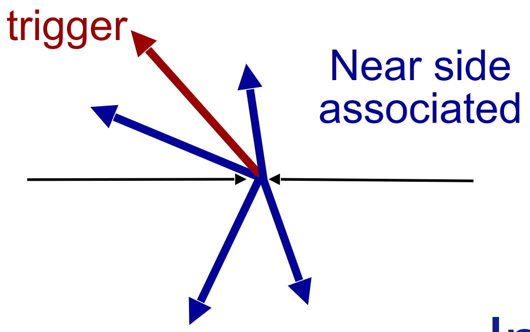


$\langle z_g \rangle$ lower in Pb+Pb: softer fragmentation

CMS-PAS-HIN-16-006



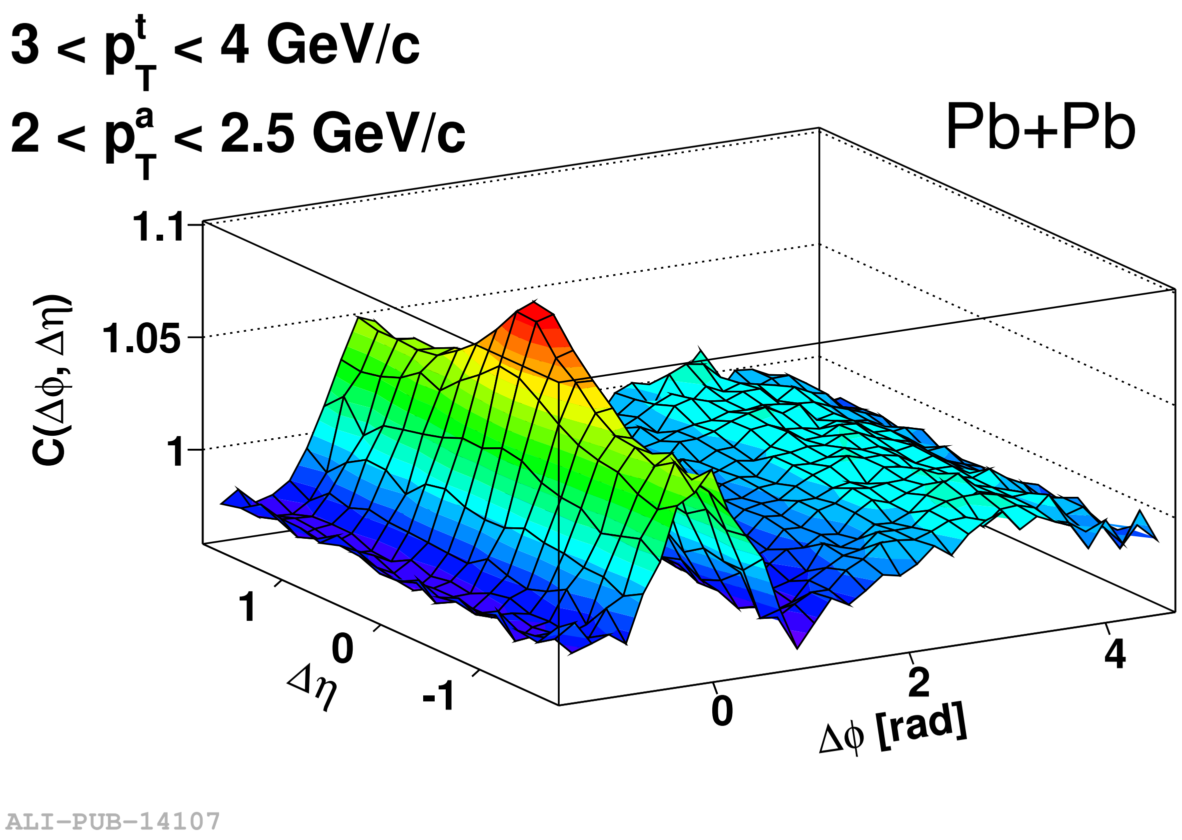
Comparison to JEWEL MC generator: good (qualitative) agreement



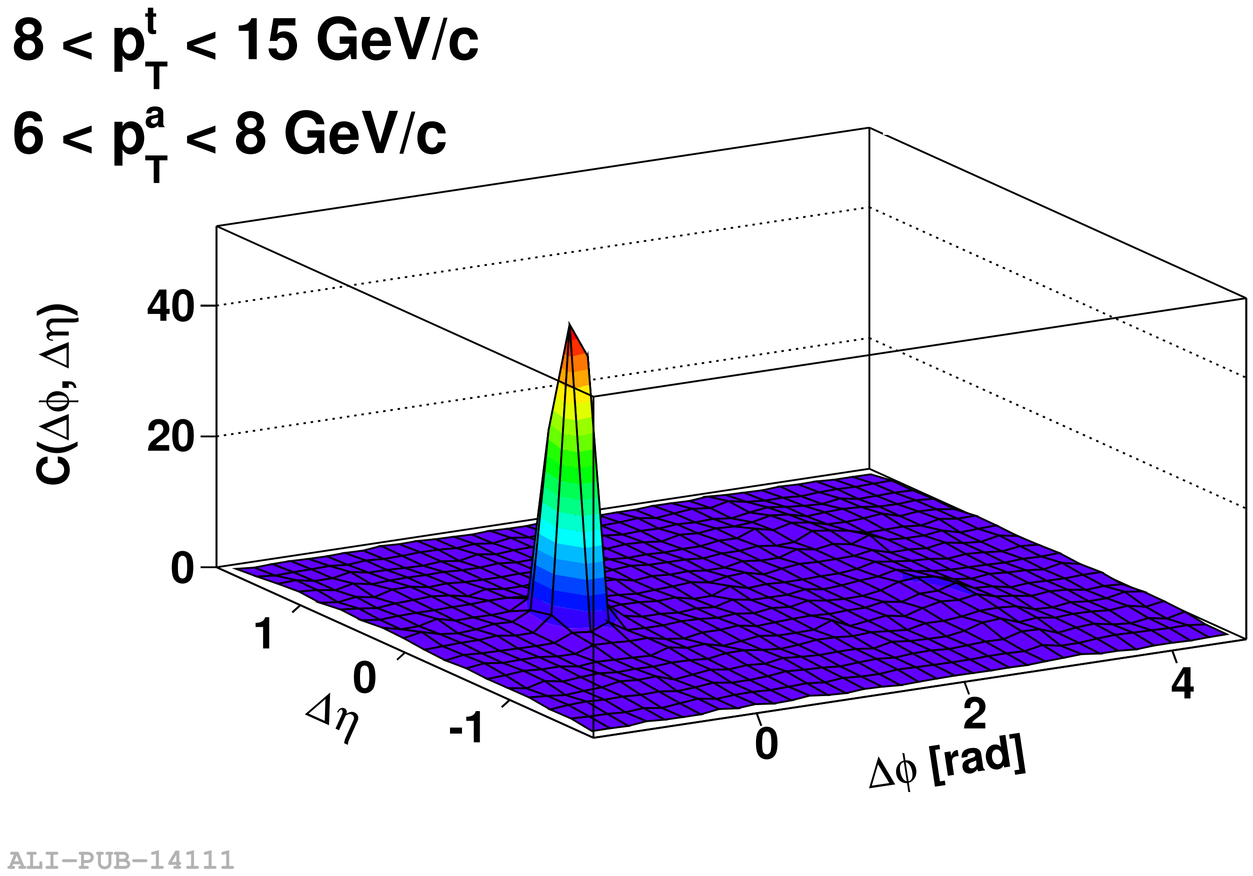
# 2-particle correlations

PLB 708, 249

## Intermediate $p_T$



## High $p_T$



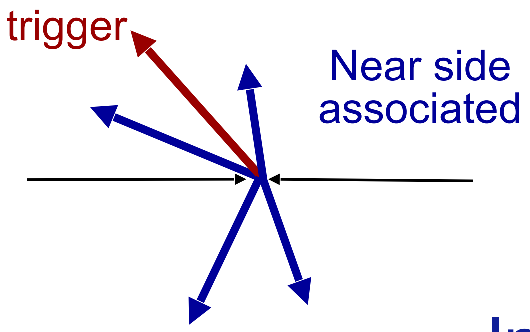
**Near-side peak: jets** (+decays): larger at high $p_T$

**Flow $v_2$, $v_3$: long range correlation** (early times+ long expansion)

Near side long range correlation: flow ($v_2$, $v_3$)

Most prominent at lower $p_T$

**Away-side: recoil jet** also gives a long-range correlation ($\eta_1 \neq \eta_2$)



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PLB 708, 249

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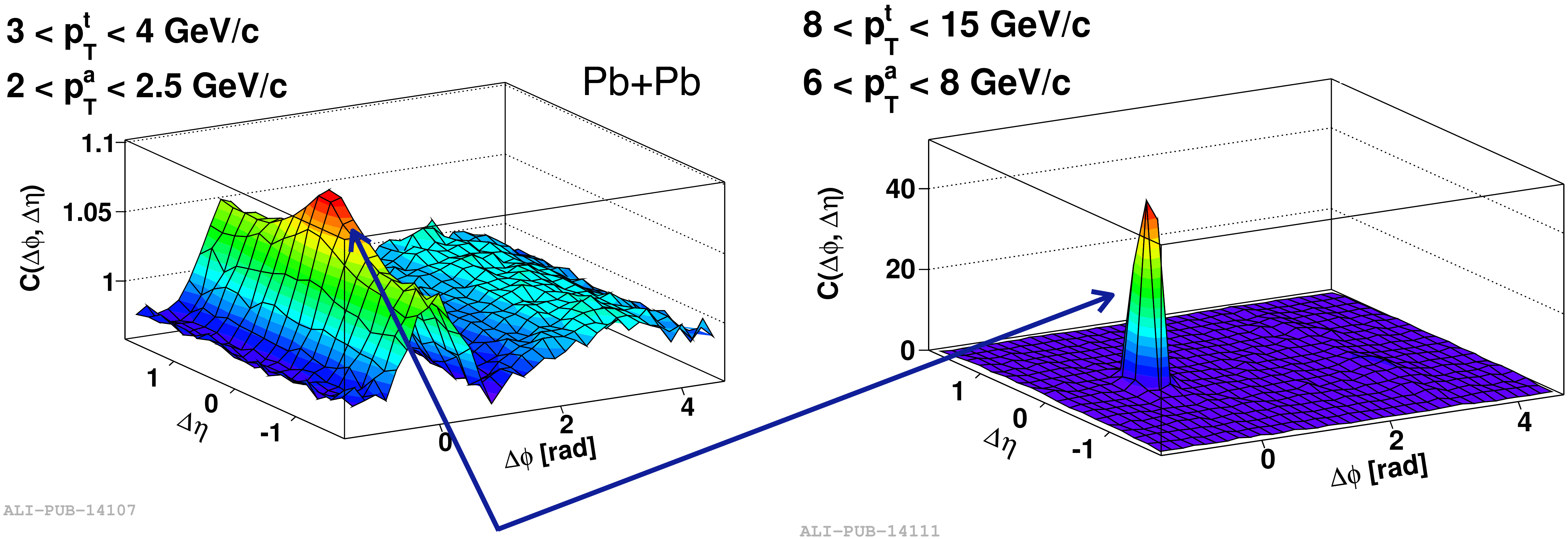
High $p_T$



ALI-PUB-14107

ALI-PUB-14111

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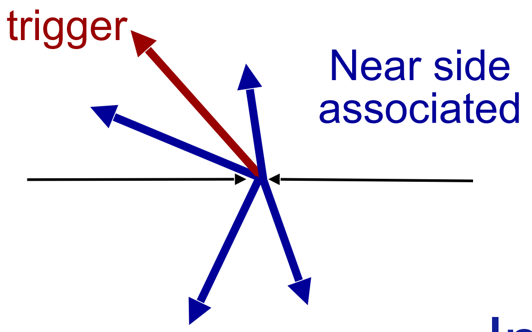

# 2-particle correlations

PLB 708, 249

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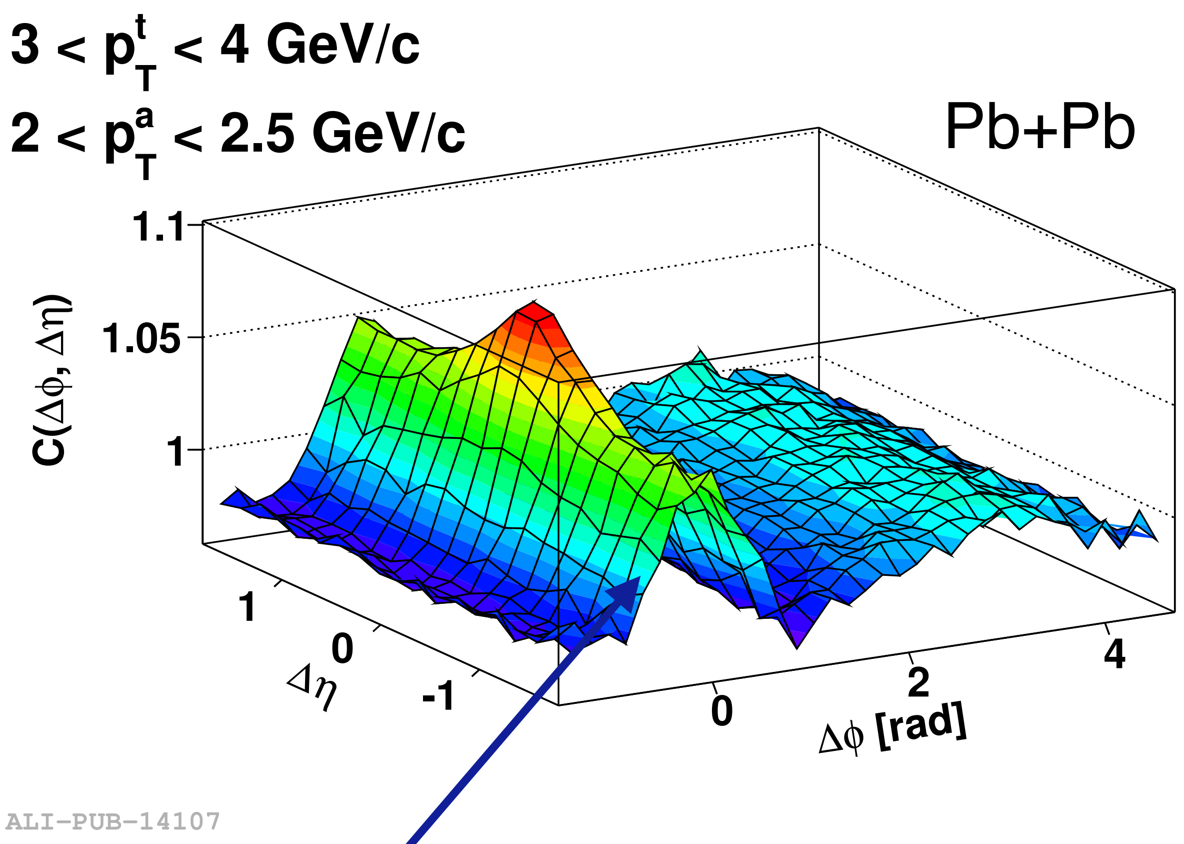

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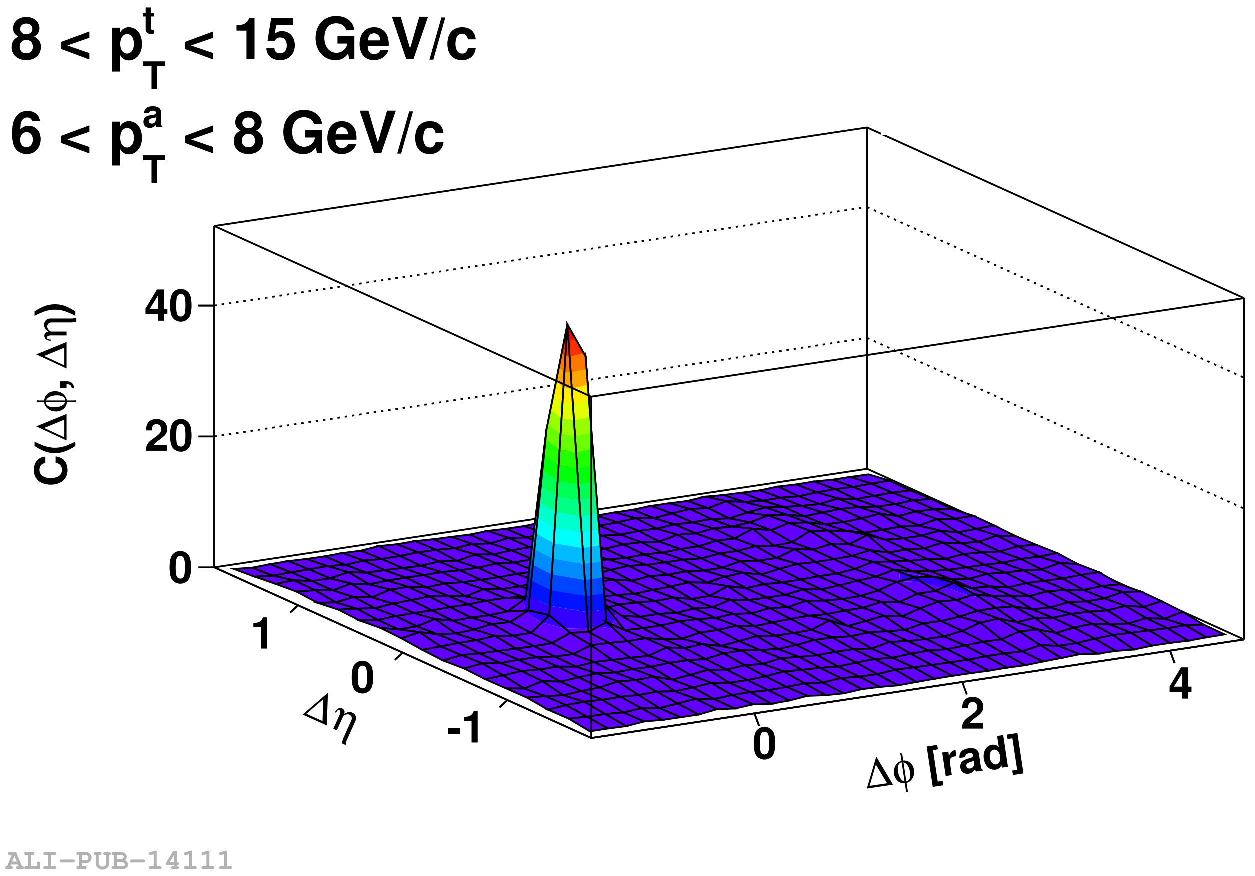

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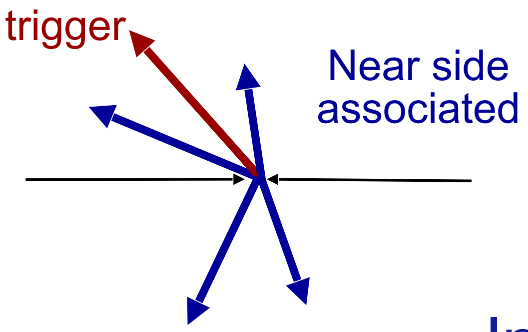
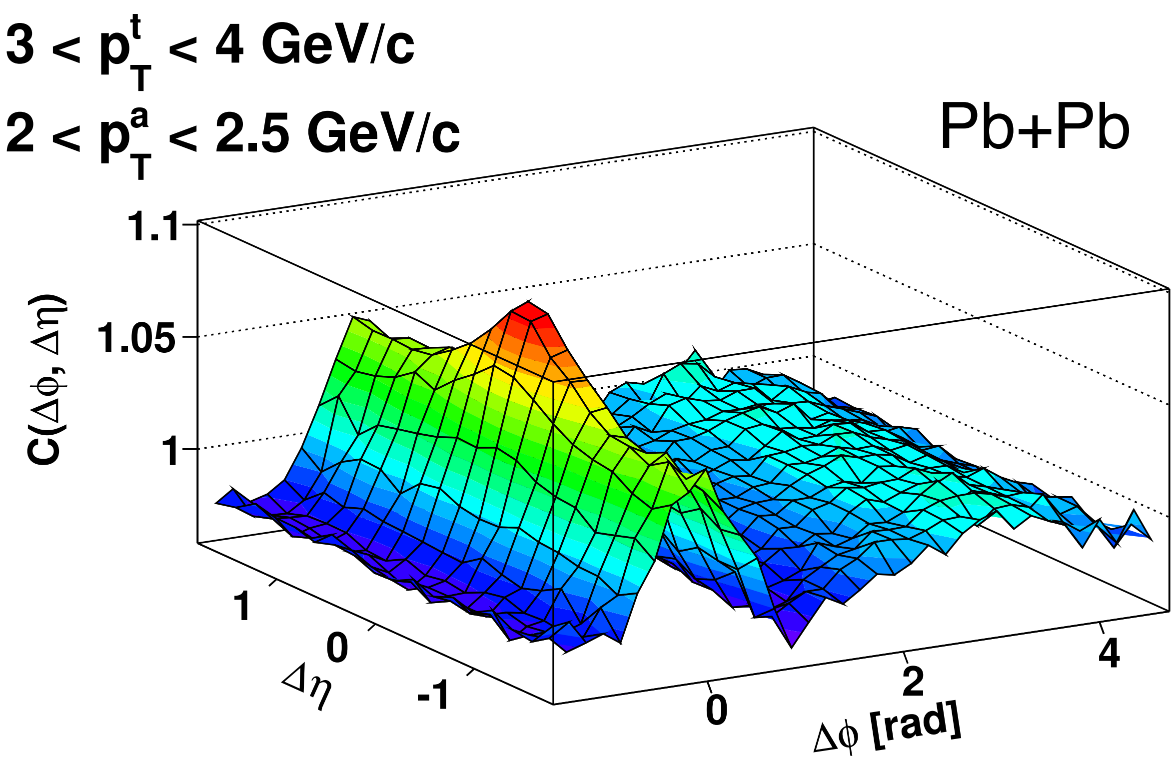


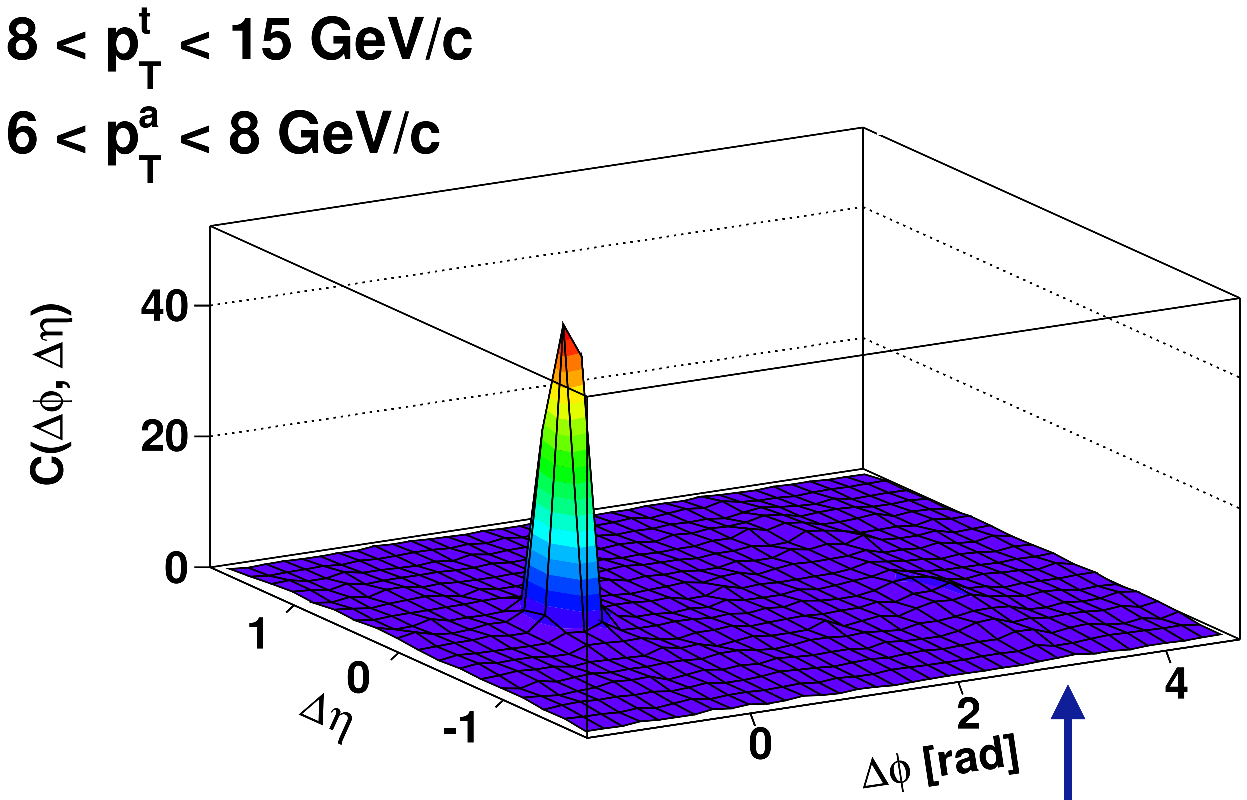
PLB 708, 249

Intermediate $p_T$



ALI-PUB-14107

High $p_T$



ALI-PUB-14111

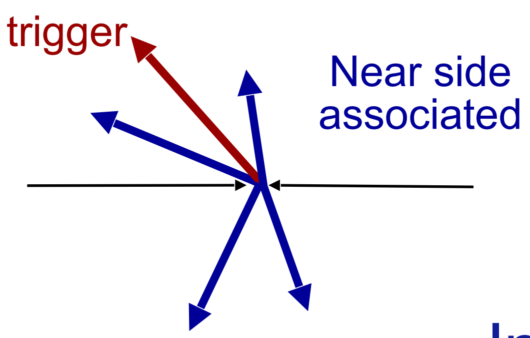
**Near-side peak: jets** (+decays): larger at high $p_T$

**Flow $v_2$, $v_3$: long range correlation** (early times+ long expansion)

Near side long range correlation: flow ($v_2$, $v_3$)

Most prominent at lower $p_T$

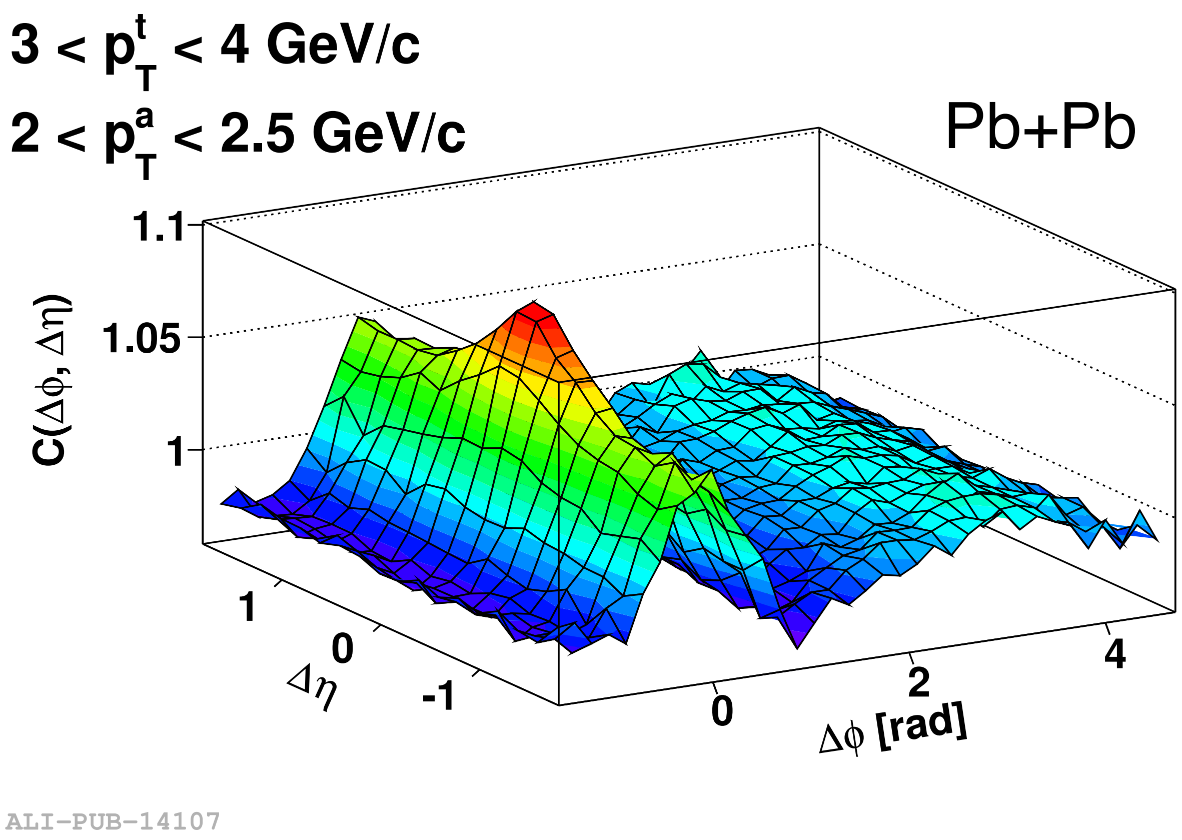
**Away-side: recoil jet** also gives a long-range correlation ($\eta_1 \neq \eta_2$)



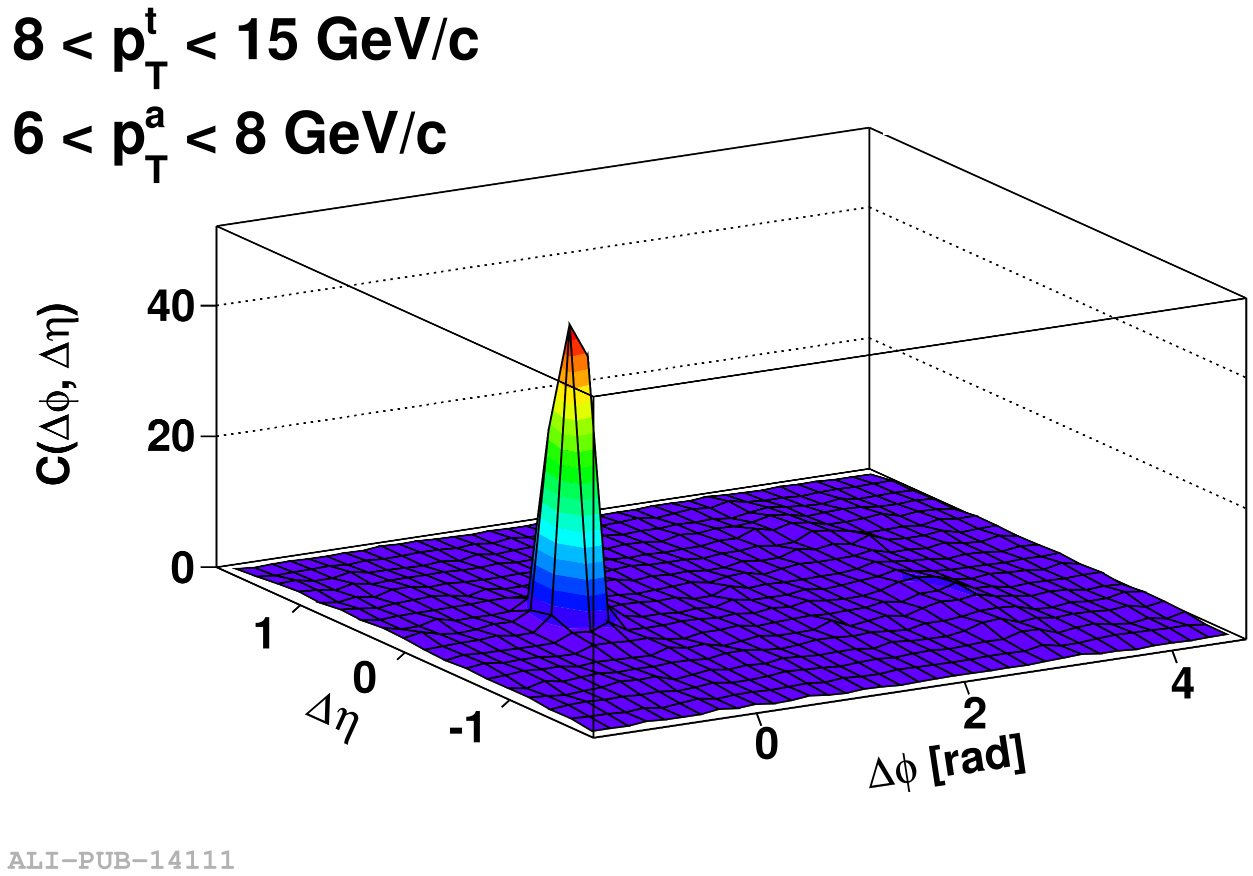
# 2-particle correlations

PLB 708, 249

Intermediate $p_T$



High $p_T$



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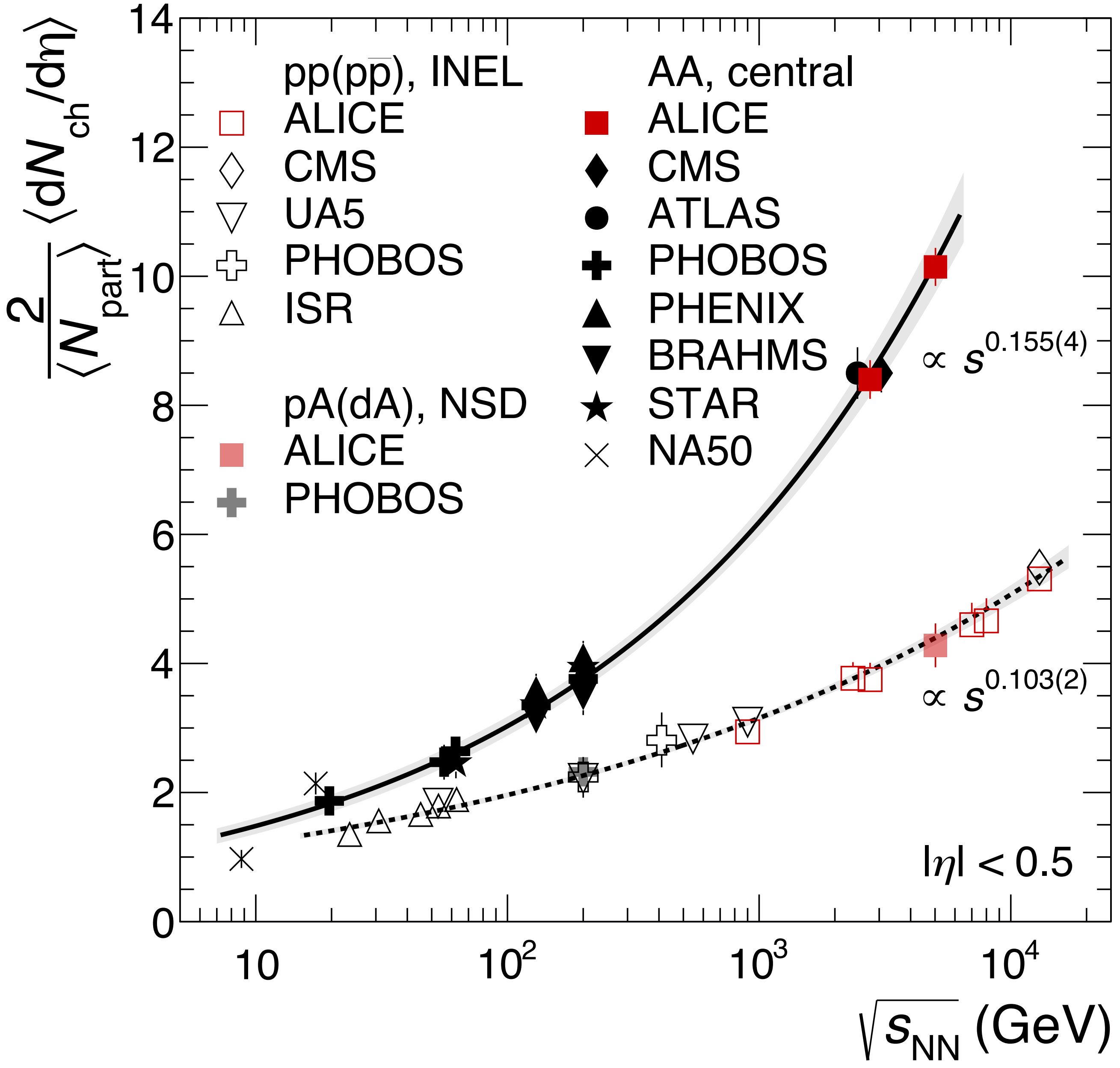
# Multiplicity $dN_{ch}/d\eta$ in pp, Pb+Pb

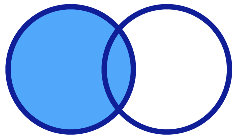
PLB 753, 319

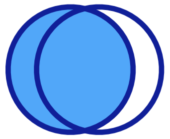


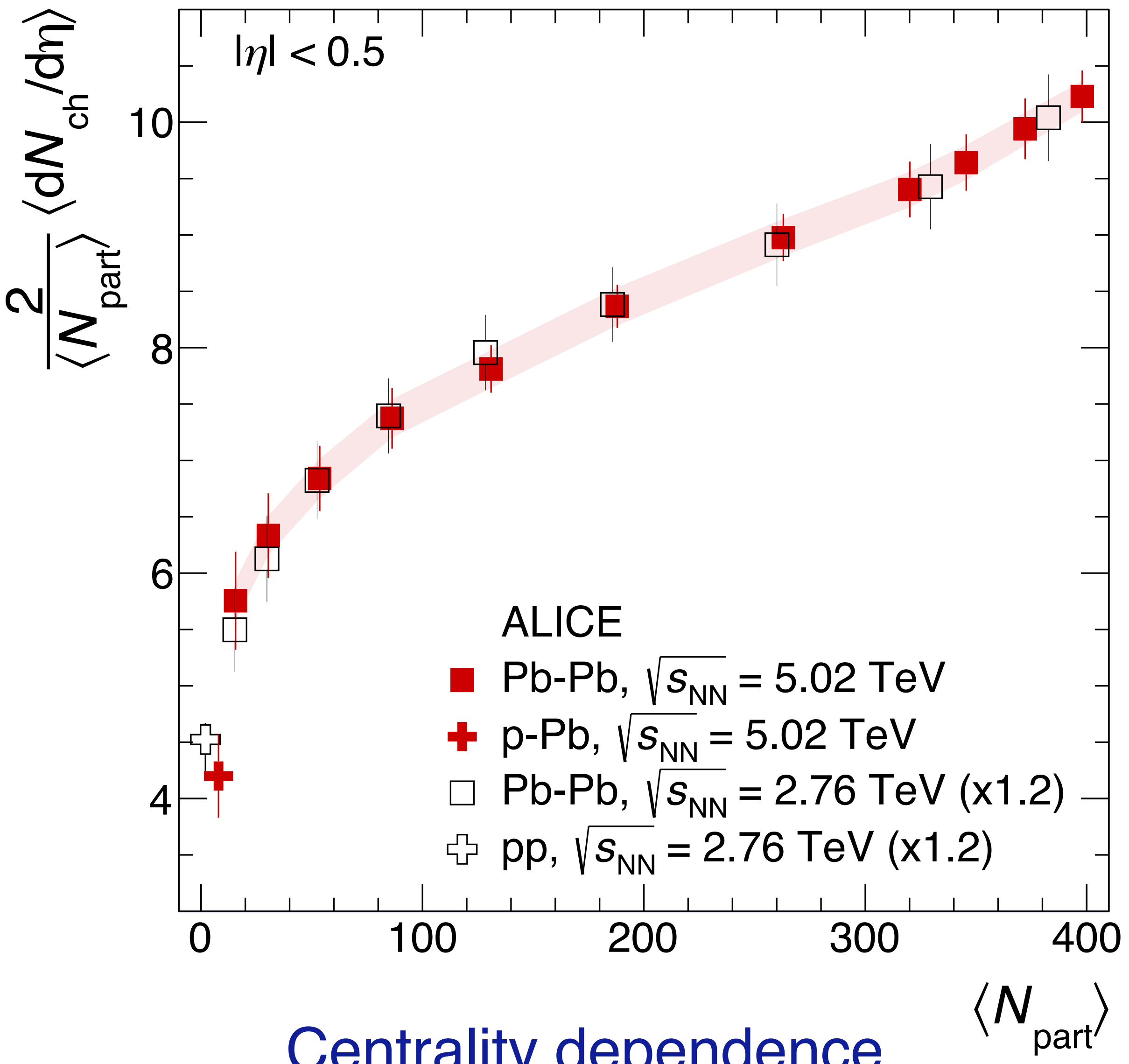
First results from Run-2: multiplicity at new energies

Trend continues to rise faster for AA than pp:
conversion of energy to particles in AA is more efficient (larger 'stopping')

# Multiplicity vs centrality PbPb





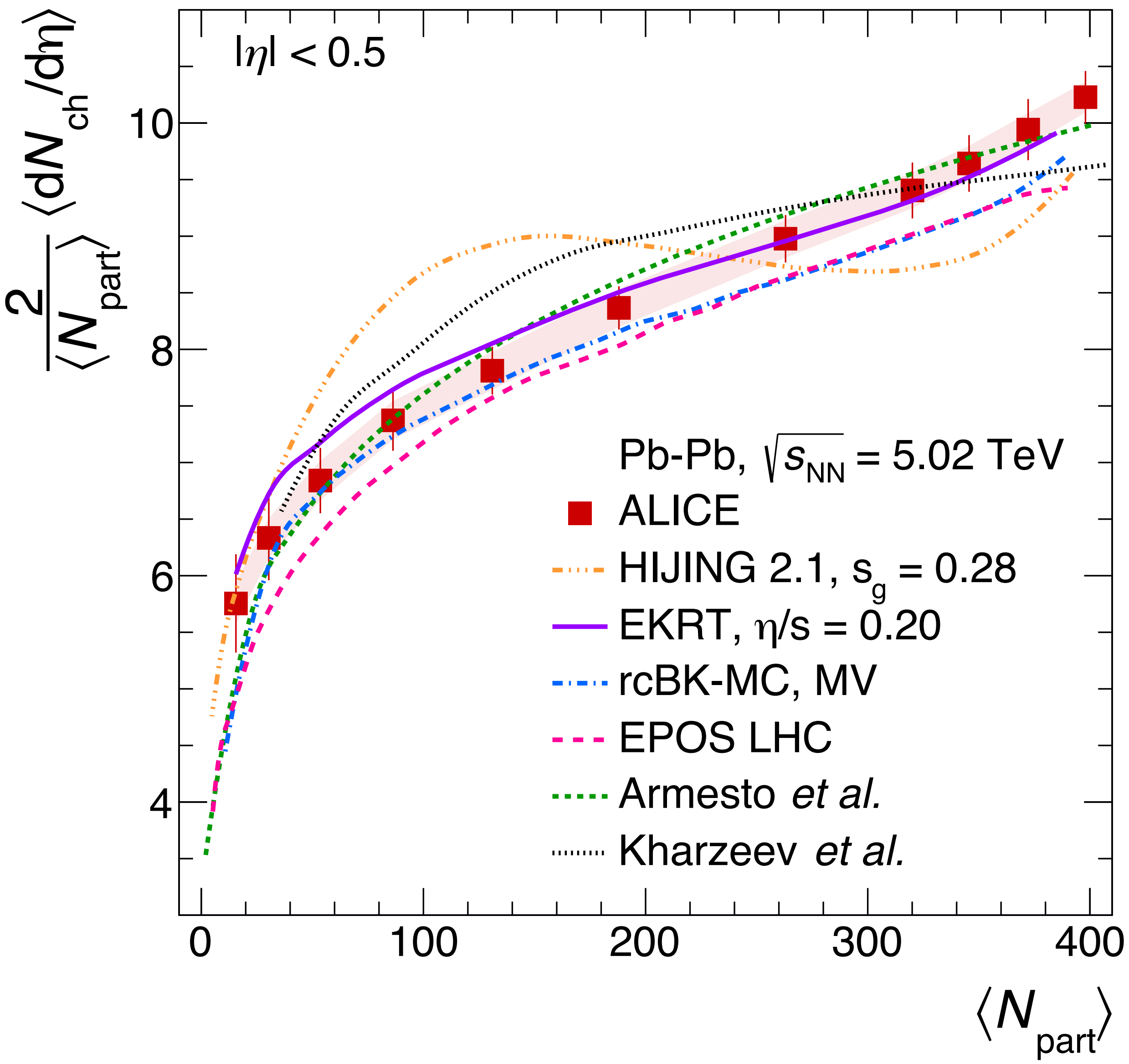


Centrality dependence
very similar at 5.02 and 2.76 TeV
(overall factor 1.2)

Driven by geometry

No change in contribution
hard vs soft processes

arXiv:1509.07299

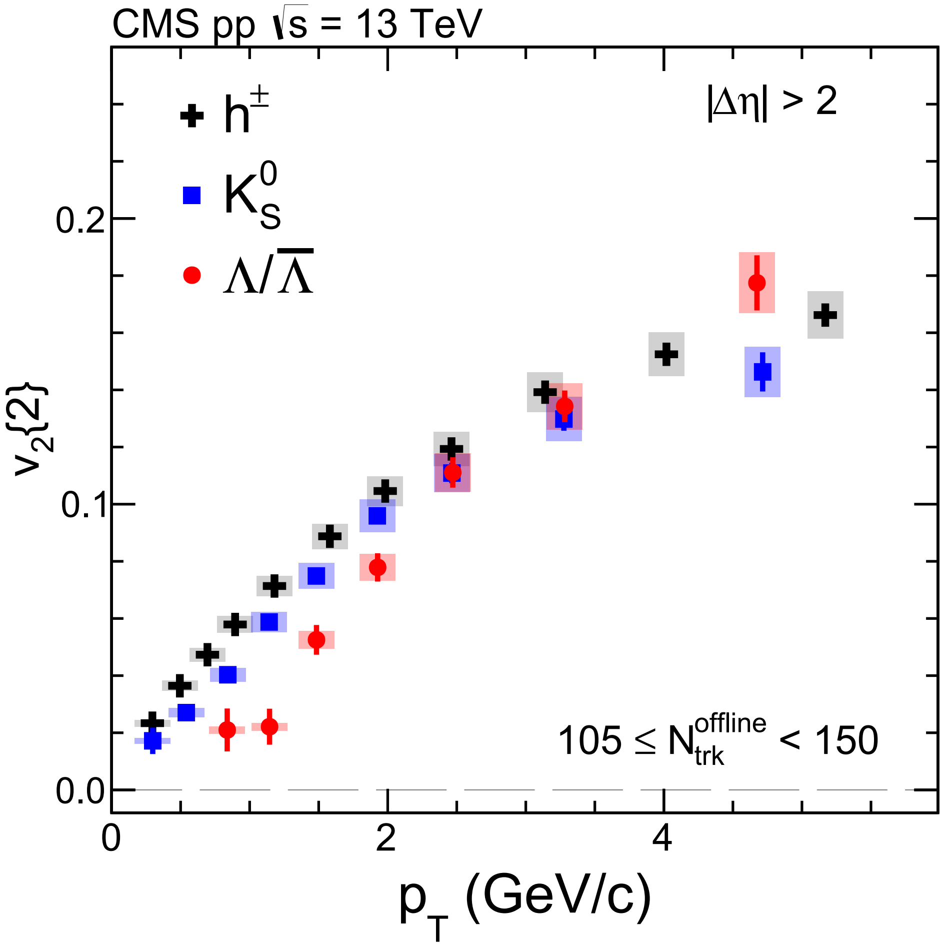


Model comparisons:

Soft physics models agree
Hijing: some deviations

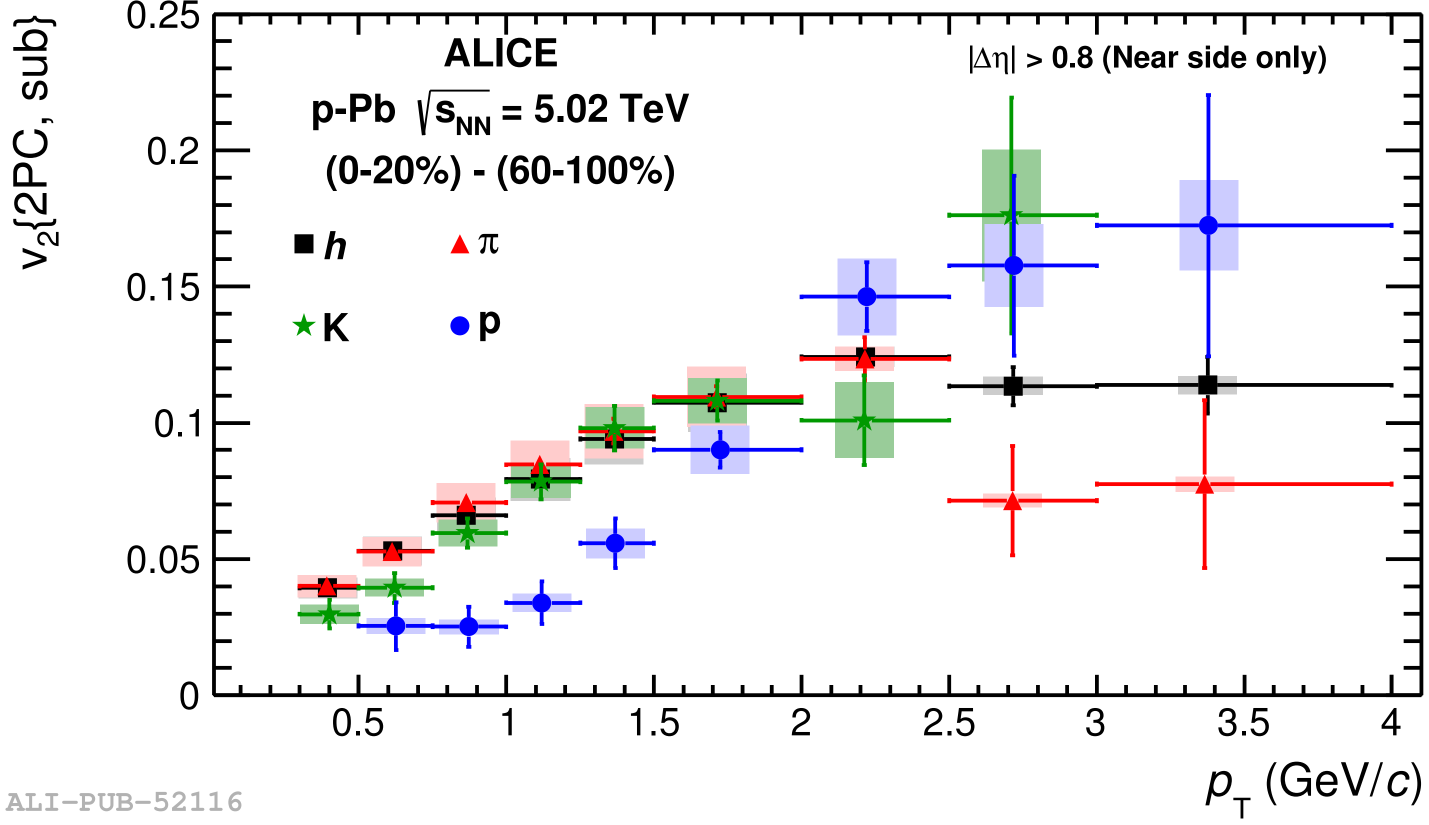
# $v_2$ from di-hadron correlations

p+p



p+Pb

ALICE, PLB 726,164



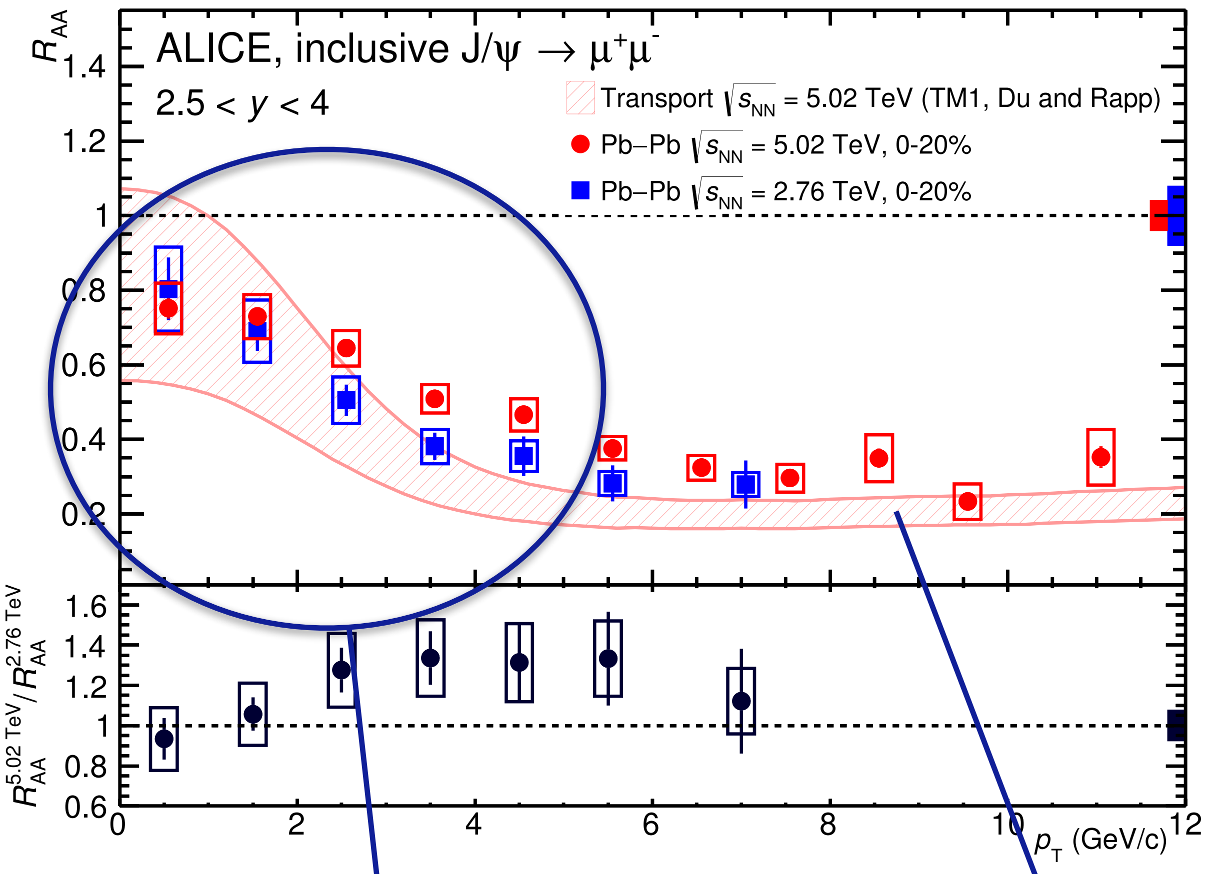
Similar ‘mass ordering’ observed for $v_2$ from two-particle correlations in p+Pb

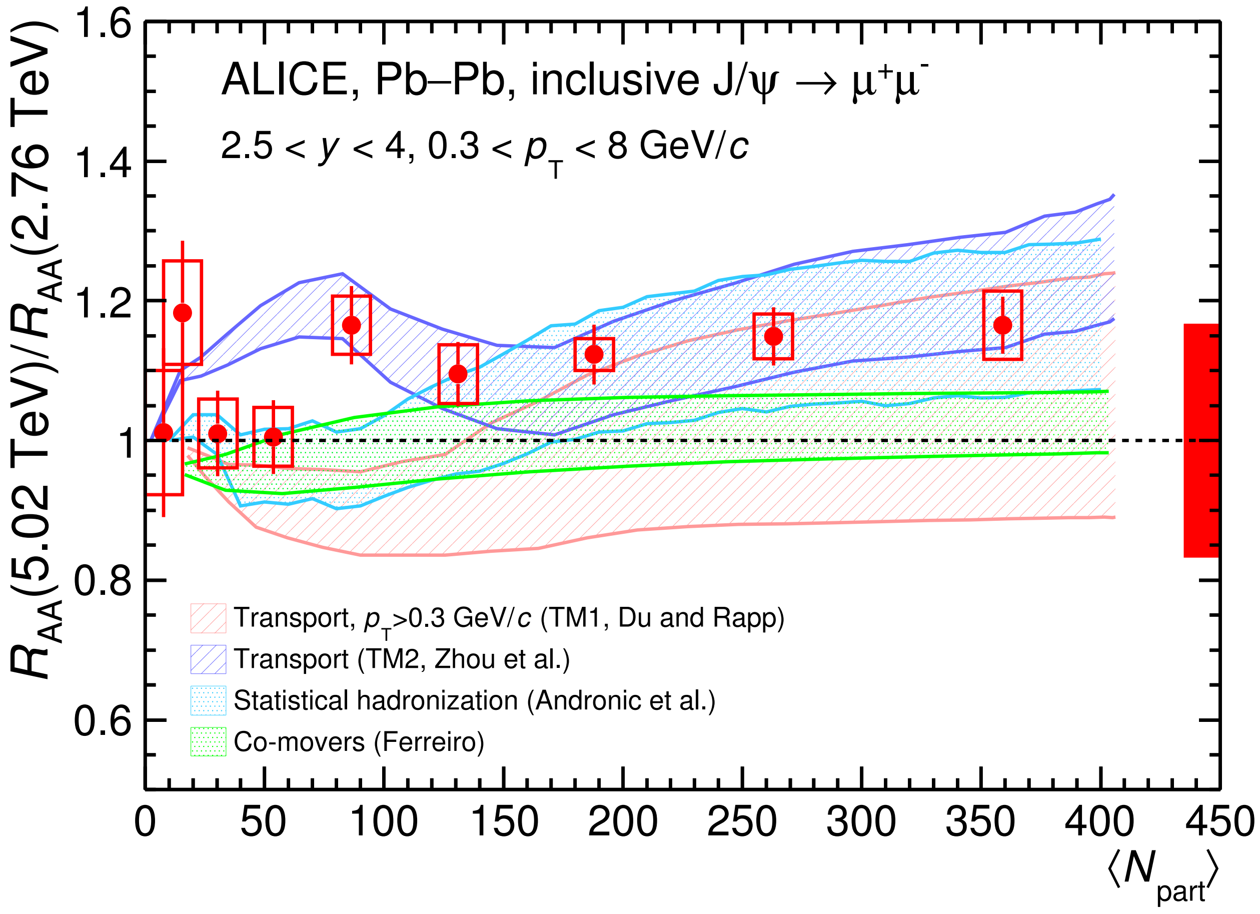
Is this also pressure-driven?

# Quarkonia: J/Ψ suppression

ALICE, arXiv:1606.08197

Run 2: 5 TeV Pb+Pb





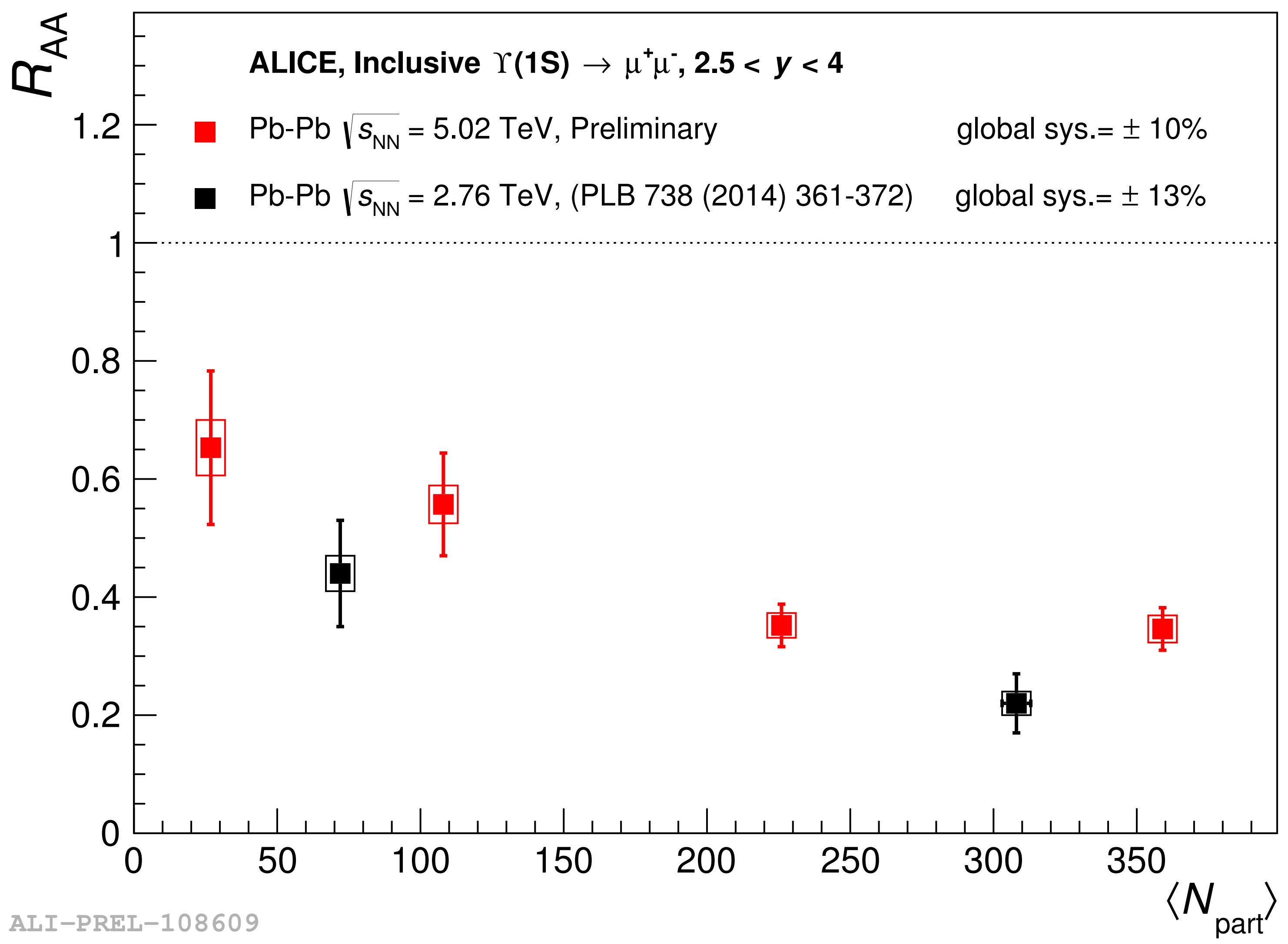
Increase by recombination:
No sign of energy dependence

Compatible with model expectations
(small effects expected)

Suppression by quarkonium melting

# Quarkonia: ϒ suppression

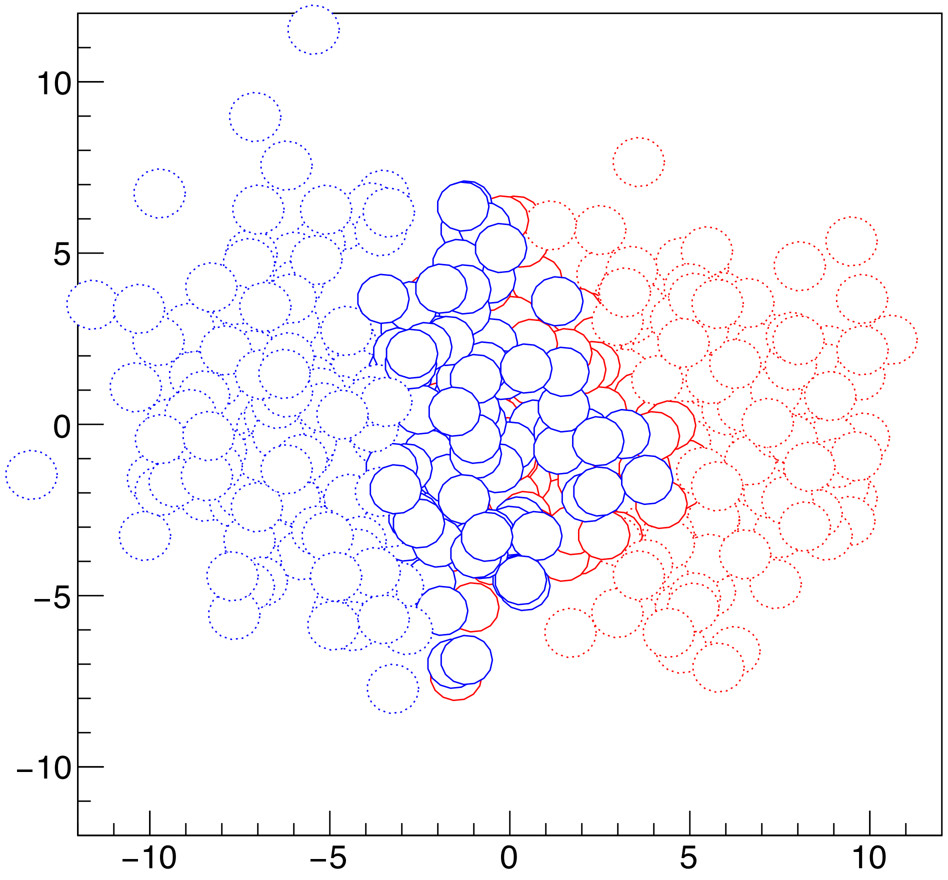
Run 2: 5 TeV Pb+Pb



ϒ suppression at 5 TeV similar to 2.76 TeV

# Initial state: colliding nuclear matter

MC event: location of nucleons

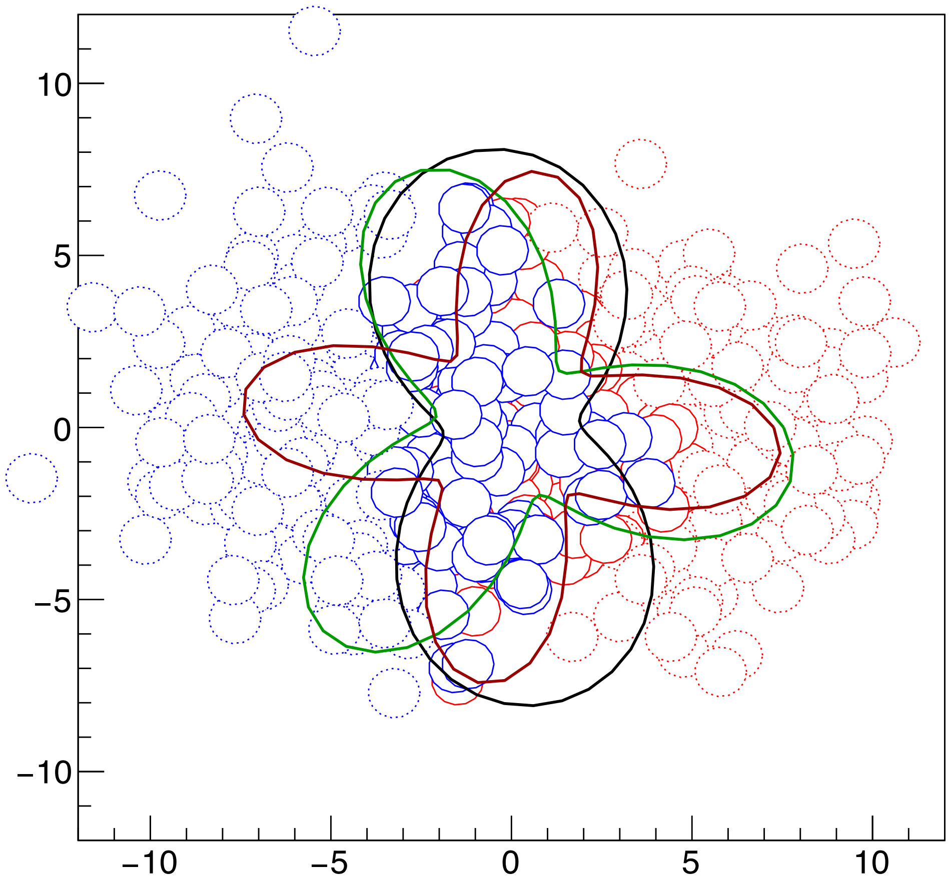


Characterise shape by angular moments:

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

# Initial state: colliding nuclear matter

MC event: location of nucleons



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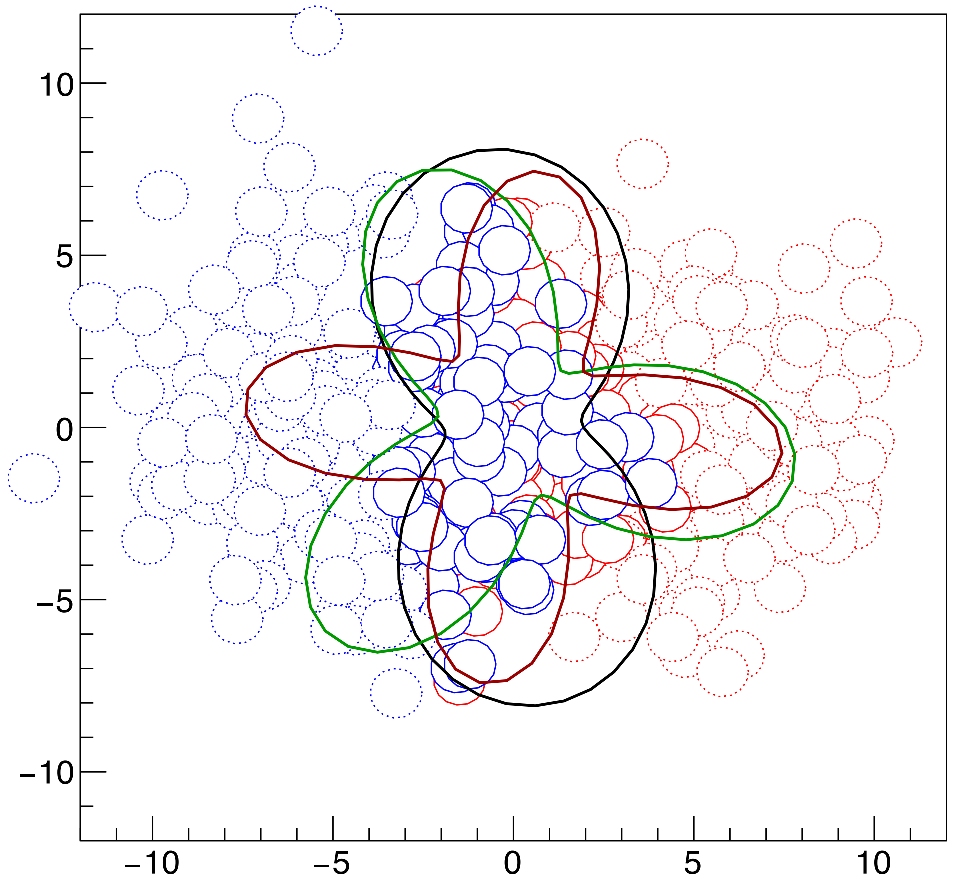
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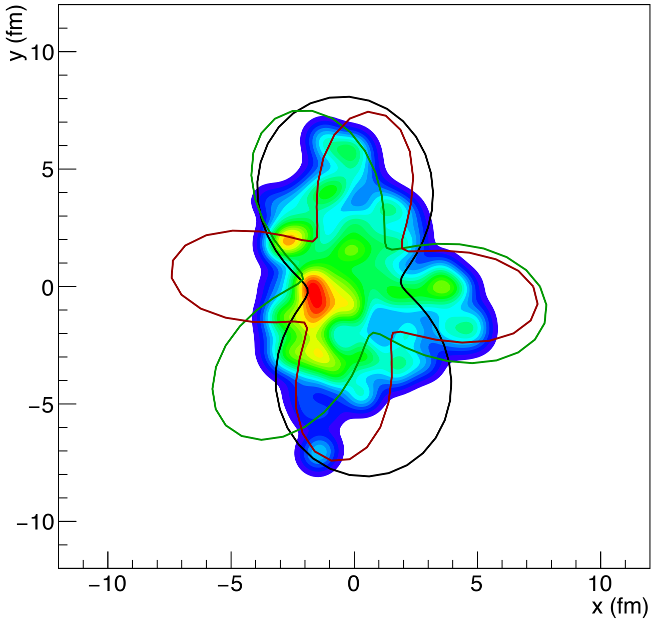
with gaussian smoothing

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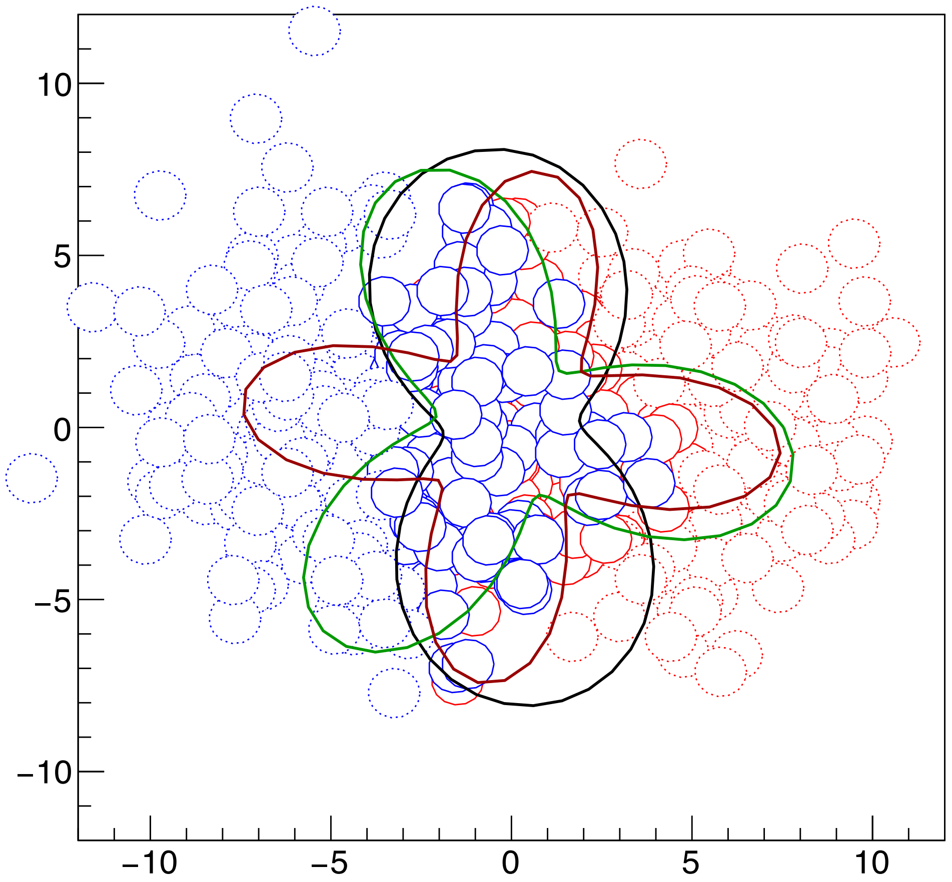
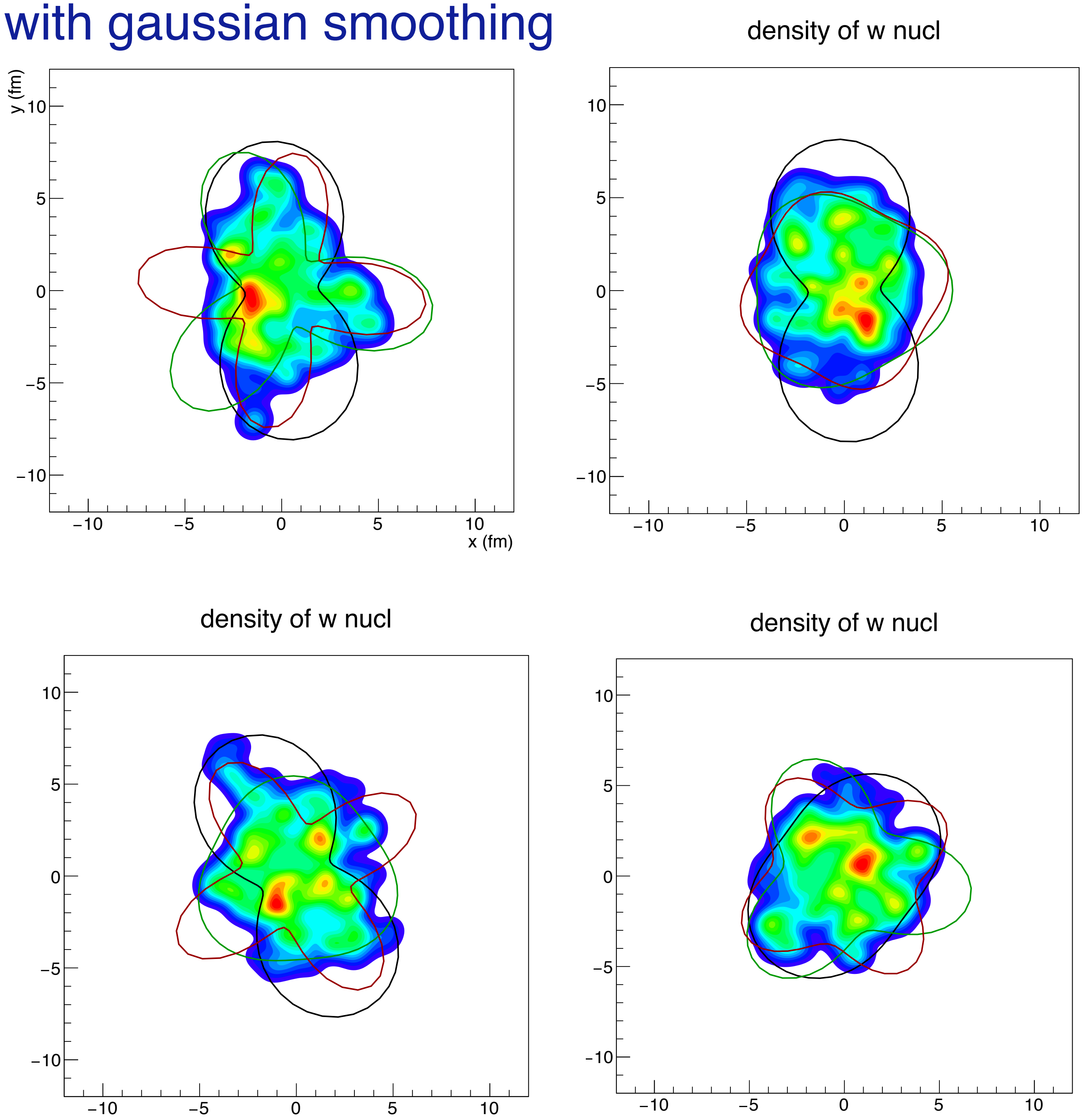
MC event: location of nucleons



with gaussian smoothing


density of w nucl

density of w nucl

density of w nucl

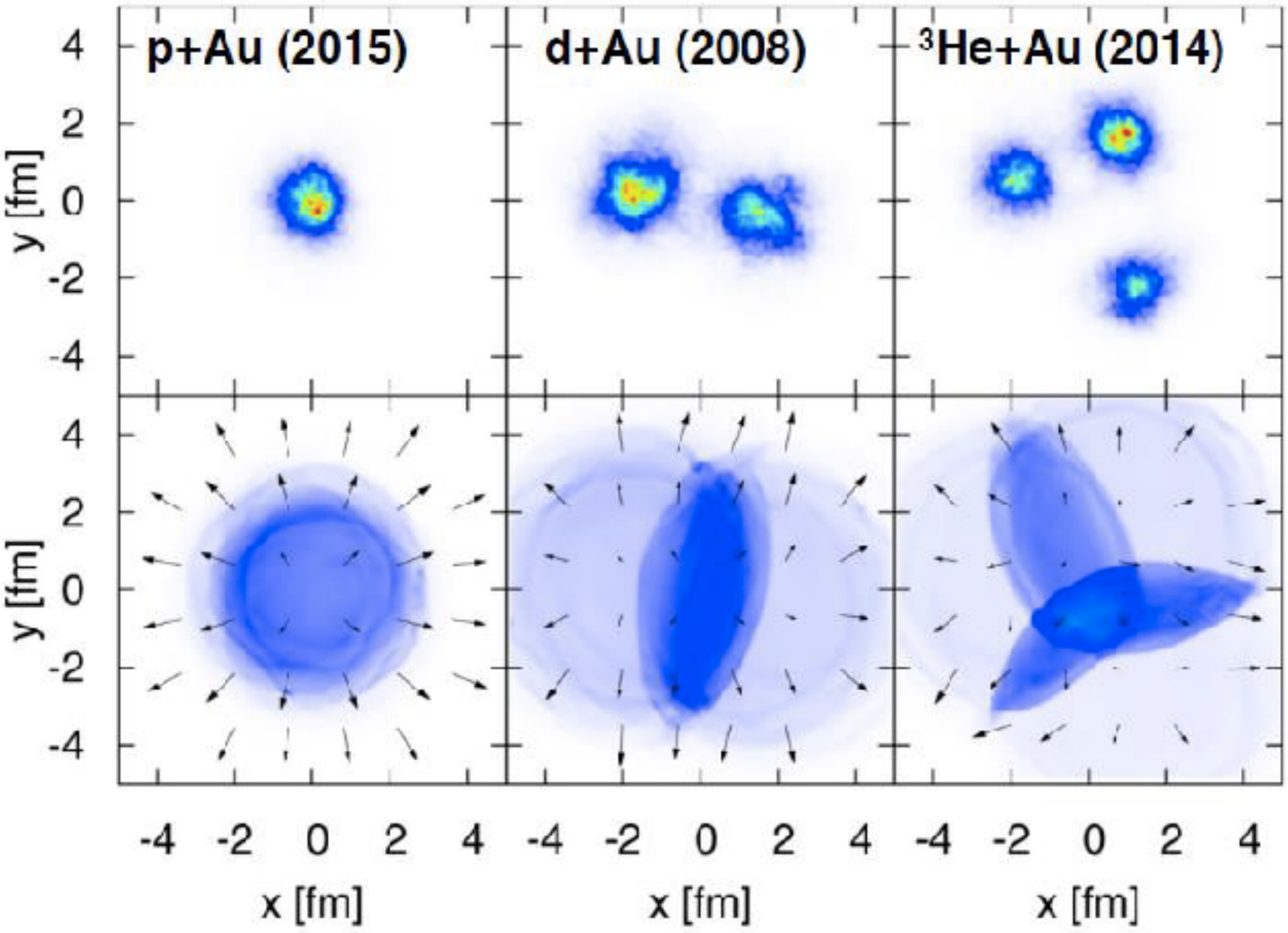
Characterise shape by angular moments:

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

Symmetry planes change from event to event

Orientation measured for every event

# Changing the projectile



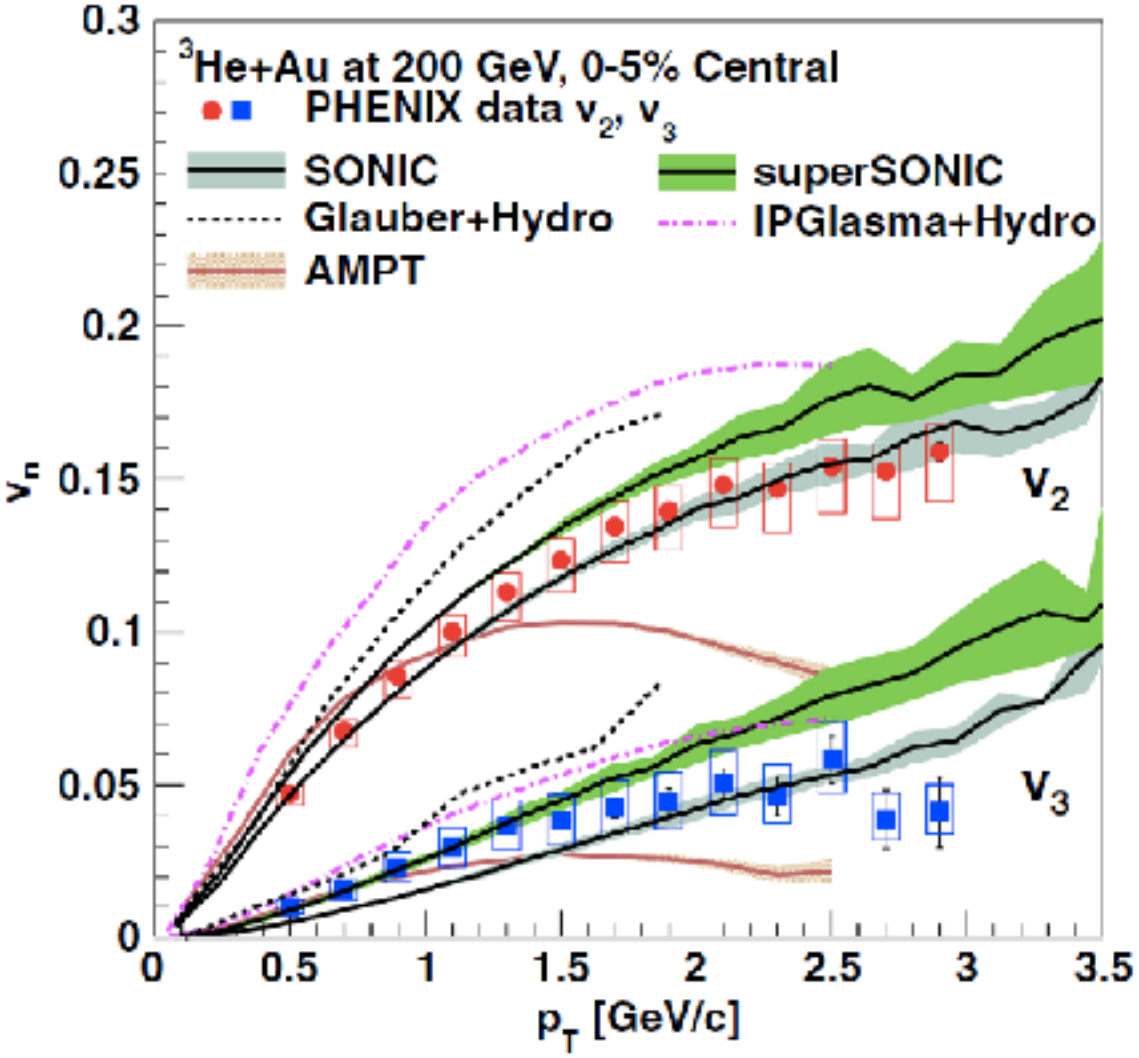
B Schenke

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

$^3$He gives explicit triangular contribution in initial state

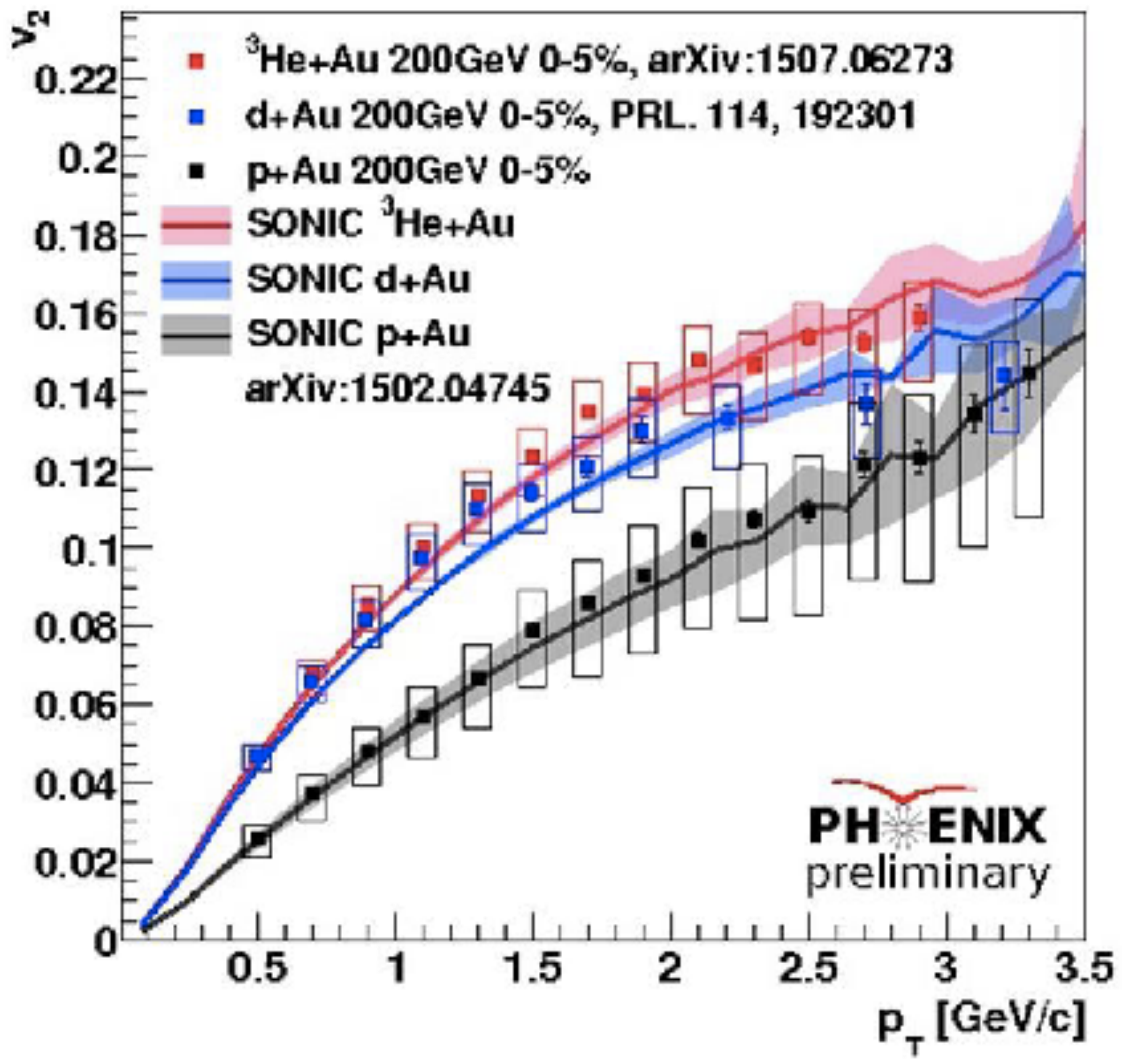
# Changing the projectile

$v_2$ and $v_3$ from $^3$He+Au



PHENIX, PRL 115 (2015) 142301

$v_2$ in p+Au, d+Au, $^3$He+Au



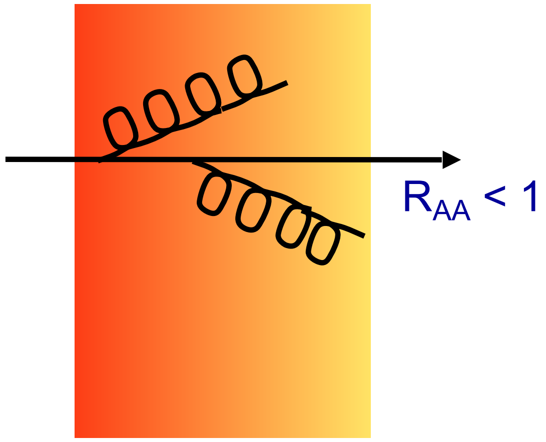
Sizable $v_3$ contribution seen with $^3$He
—> Effect is driven by initial spatial configuration

$v_2$ smallest for p+Au,
as expected from geometry

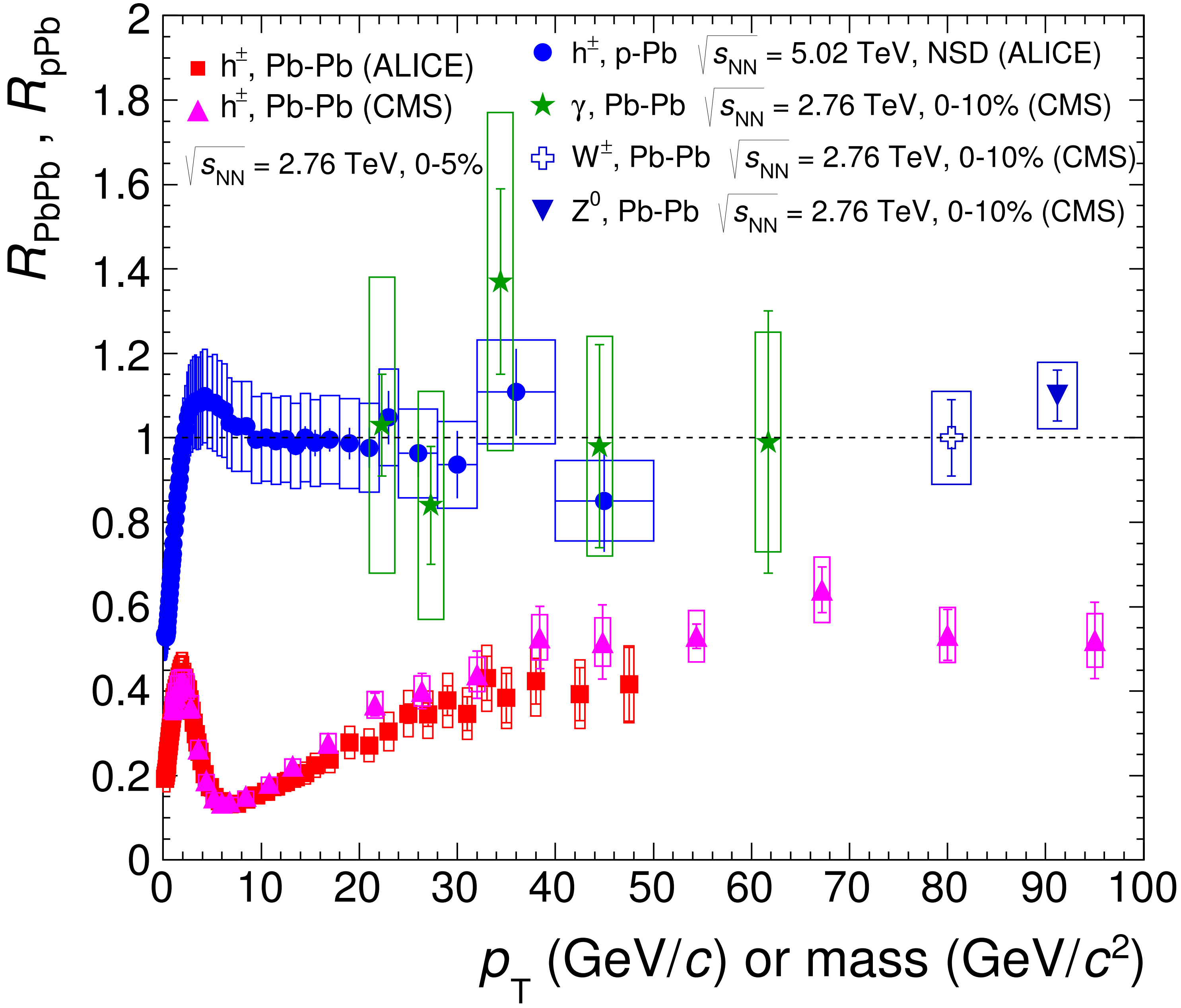
# $R_{AA}$ overview

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

Hadrons: energy loss



ALICE: PLB 720, 52; EPJ. C74, 3054
CMS: http://arxiv.org/abs/1410.4825 (Z0)
EPJ. C72, 1945; PLB 710, 256; PLB 715, 66



ALI-DER-95222

# $R_{AA}$ overview

ALICE: PLB 720, 52; EPJ. C74, 3054
CMS: http://arxiv.org/abs/1410.4825 (Z0)
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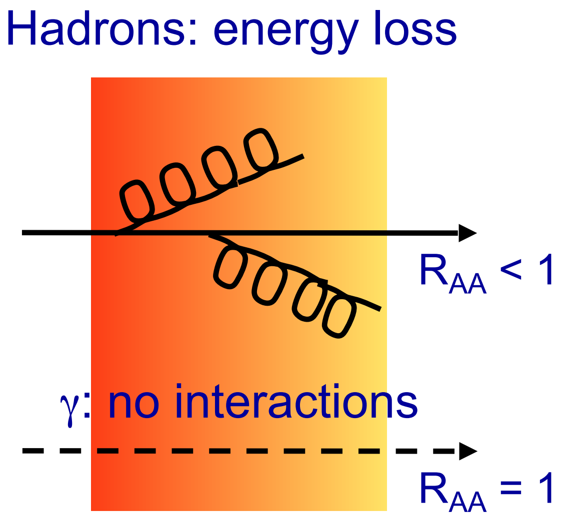
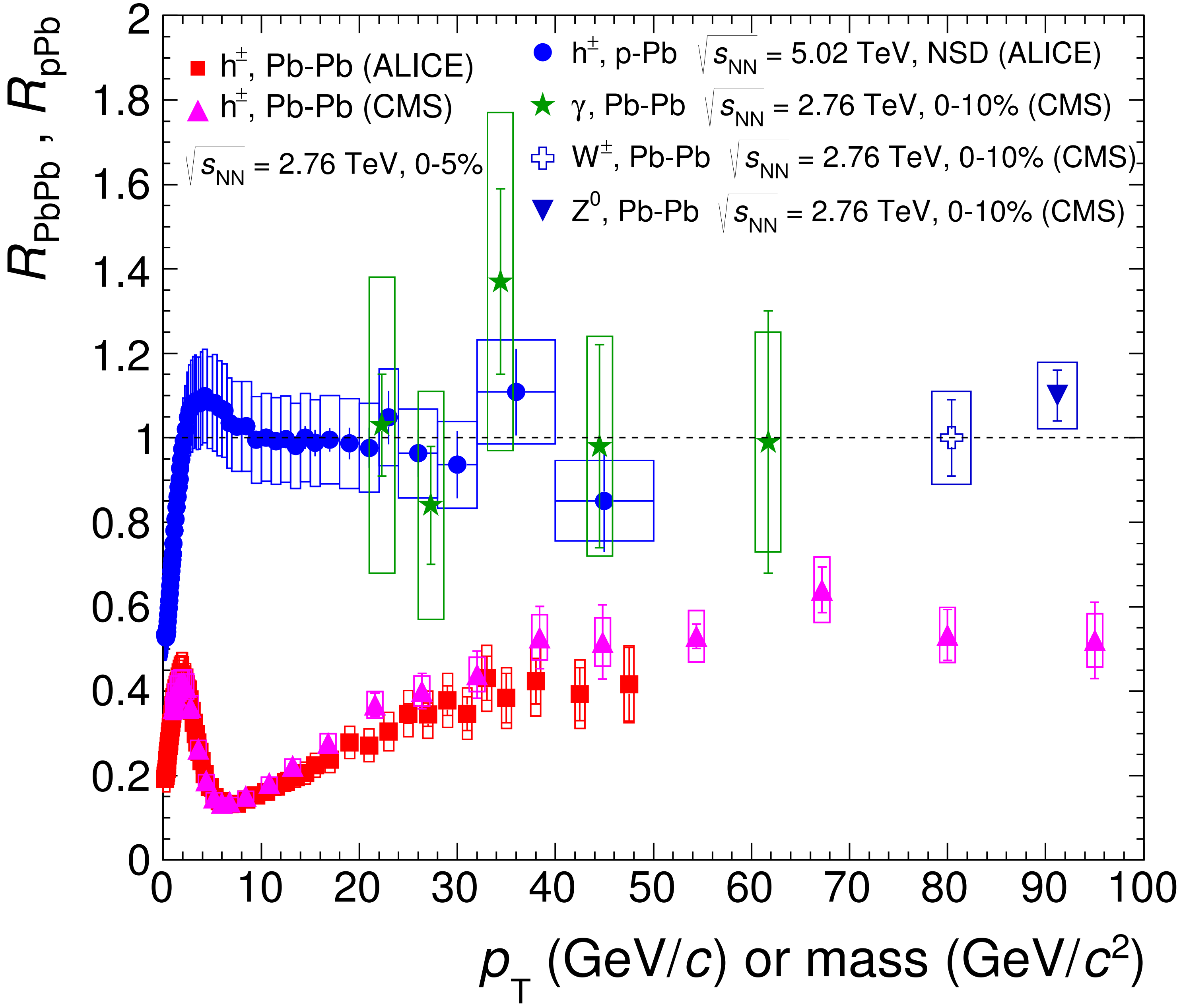
*$R_{AA} < 1$* for hadrons:
Parton energy loss





ALI-DER-95222

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

# $R_{AA}$ overview

ALICE: PLB 720, 52; EPJ. C74, 3054
CMS: http://arxiv.org/abs/1410.4825 (Z0)
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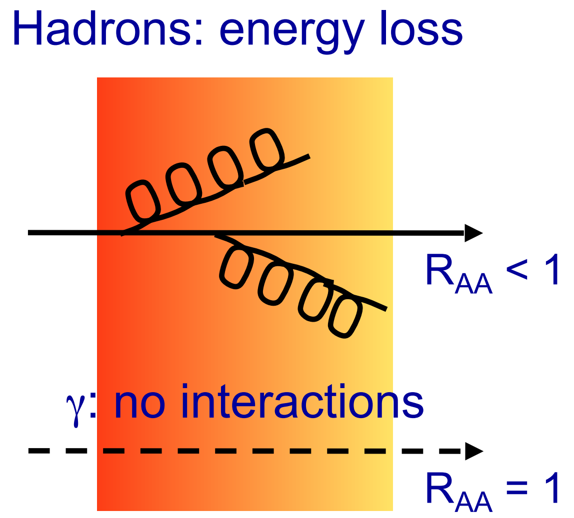
$R_{AA} < 1$ for hadrons:
Parton energy loss

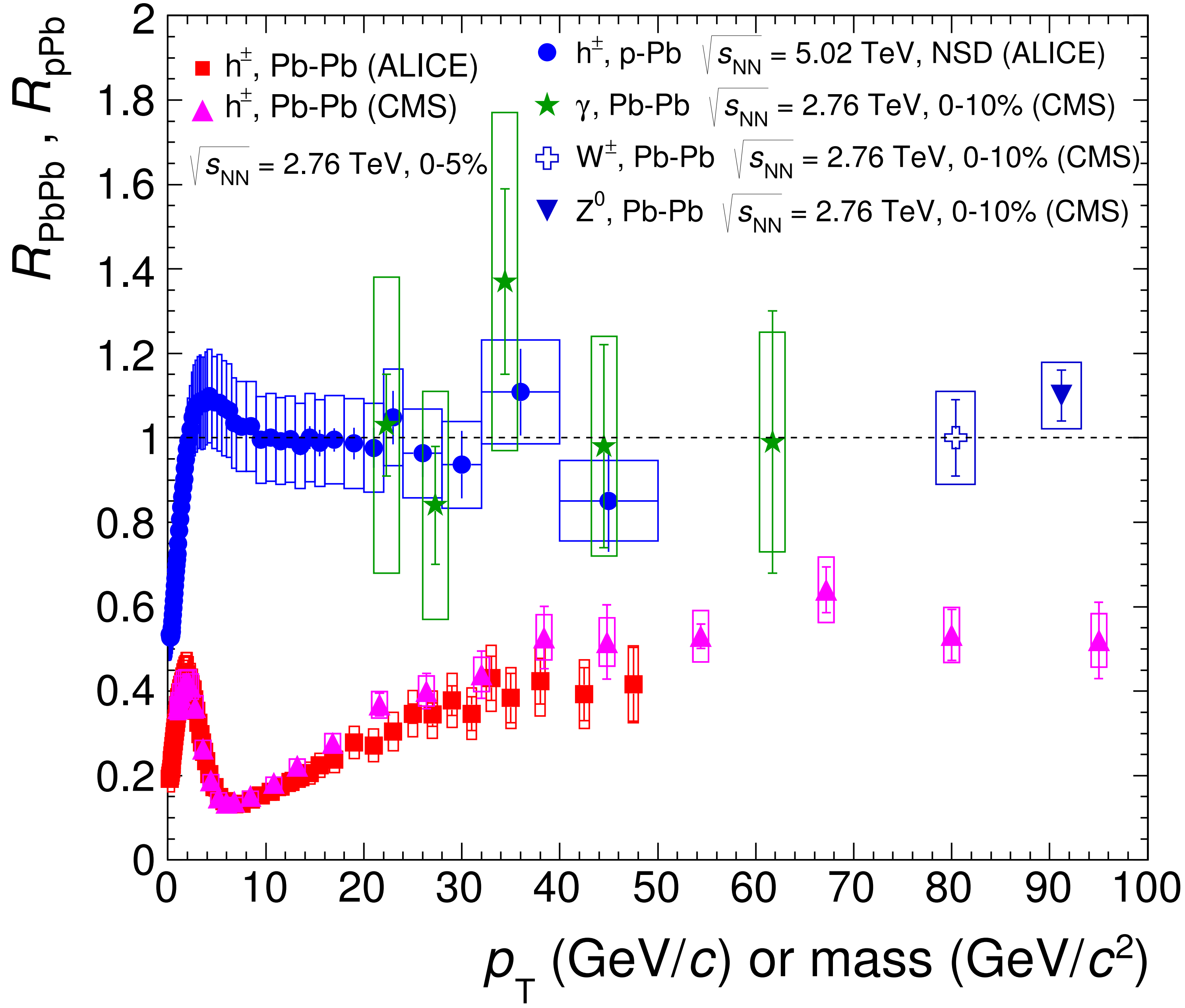


Hadrons: energy loss

$R_{AA} < 1$

γ: no interactions

$R_{AA} = 1$



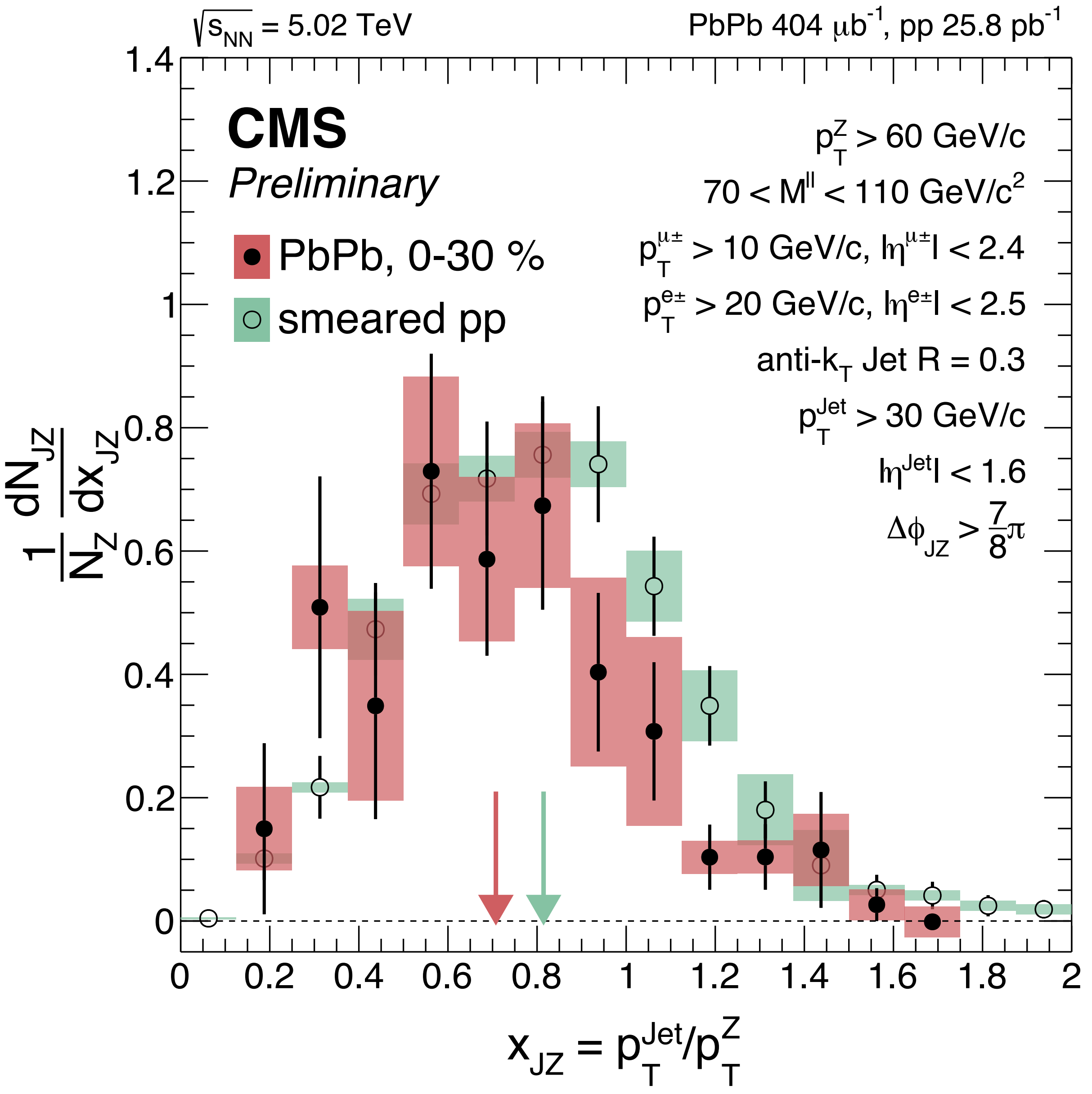
ALI-DER-95222

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

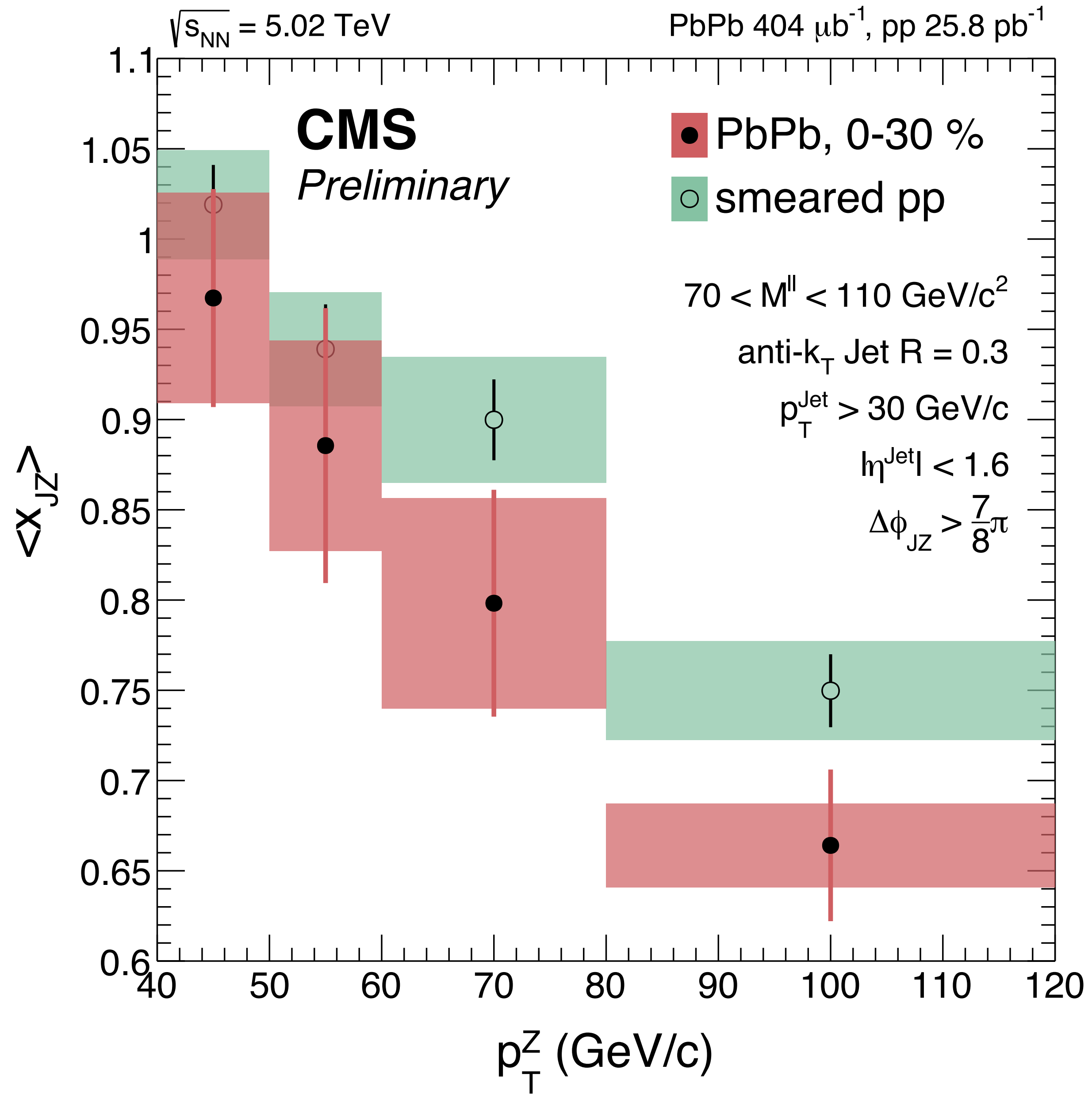
**p+Pb**: $R_{pPb} \approx 1$ at high $p_T$
No/very small 'cold nuclear matter' effects on high-$p_T$ probes

# Z-jet imbalance

CMS-PAS-HIN-15-013

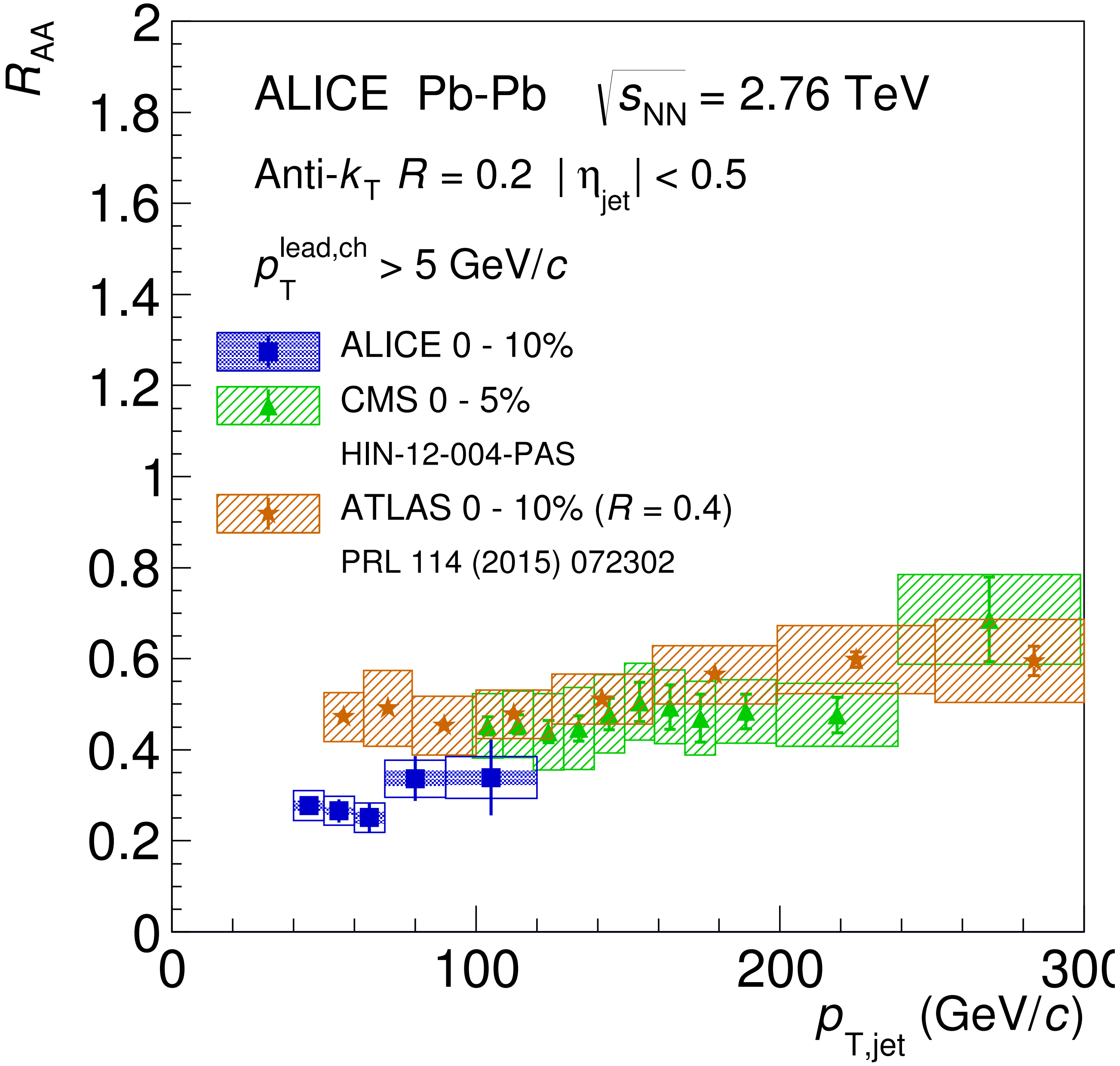


Recoil jet $p_T$ reduced by energy loss

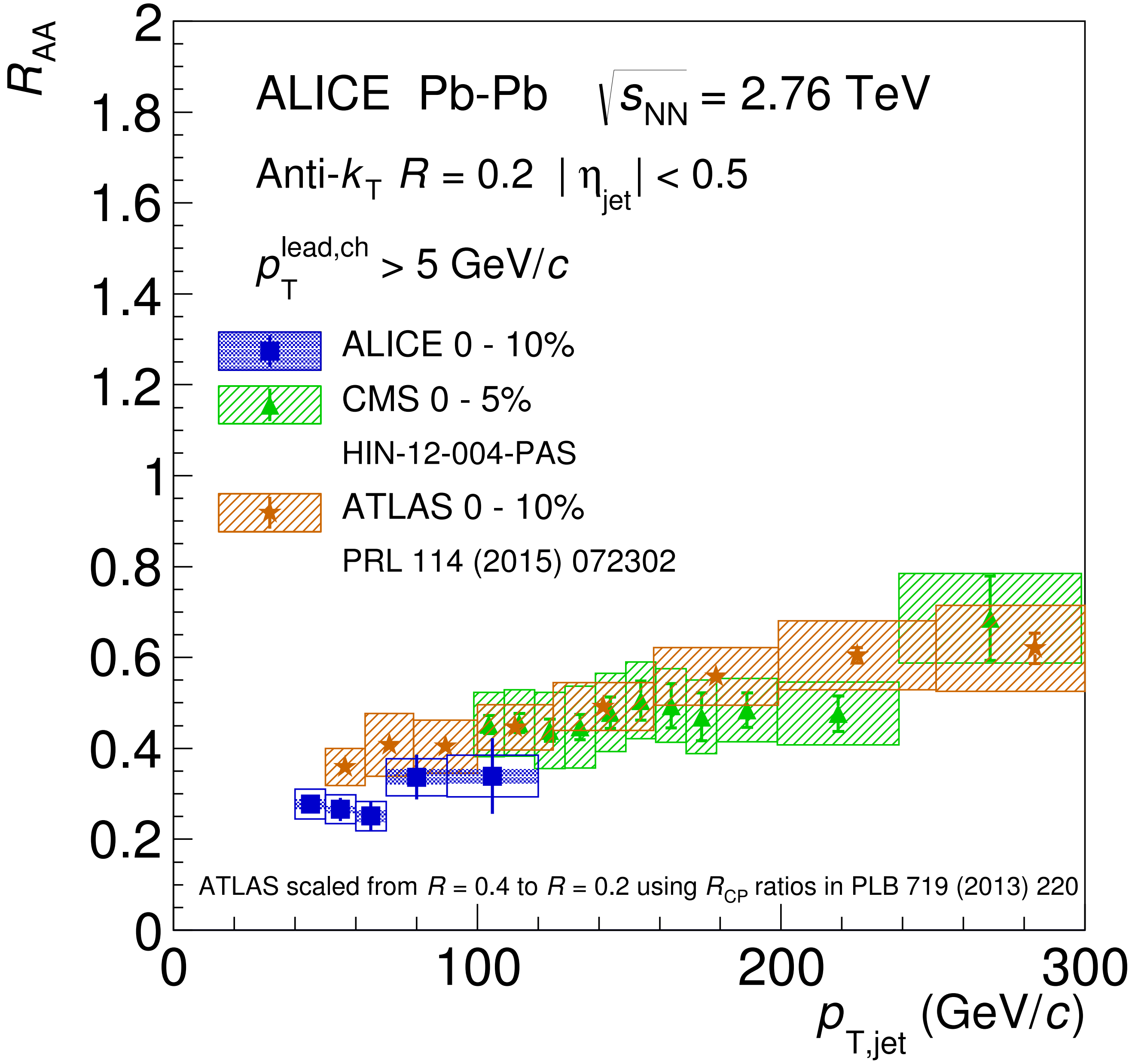


Effect persists up to high $p_T$

# Jet $R_{AA}$ comparison



ALI-DER-92548



ALI-DER-92552

Good agreement between the experiments

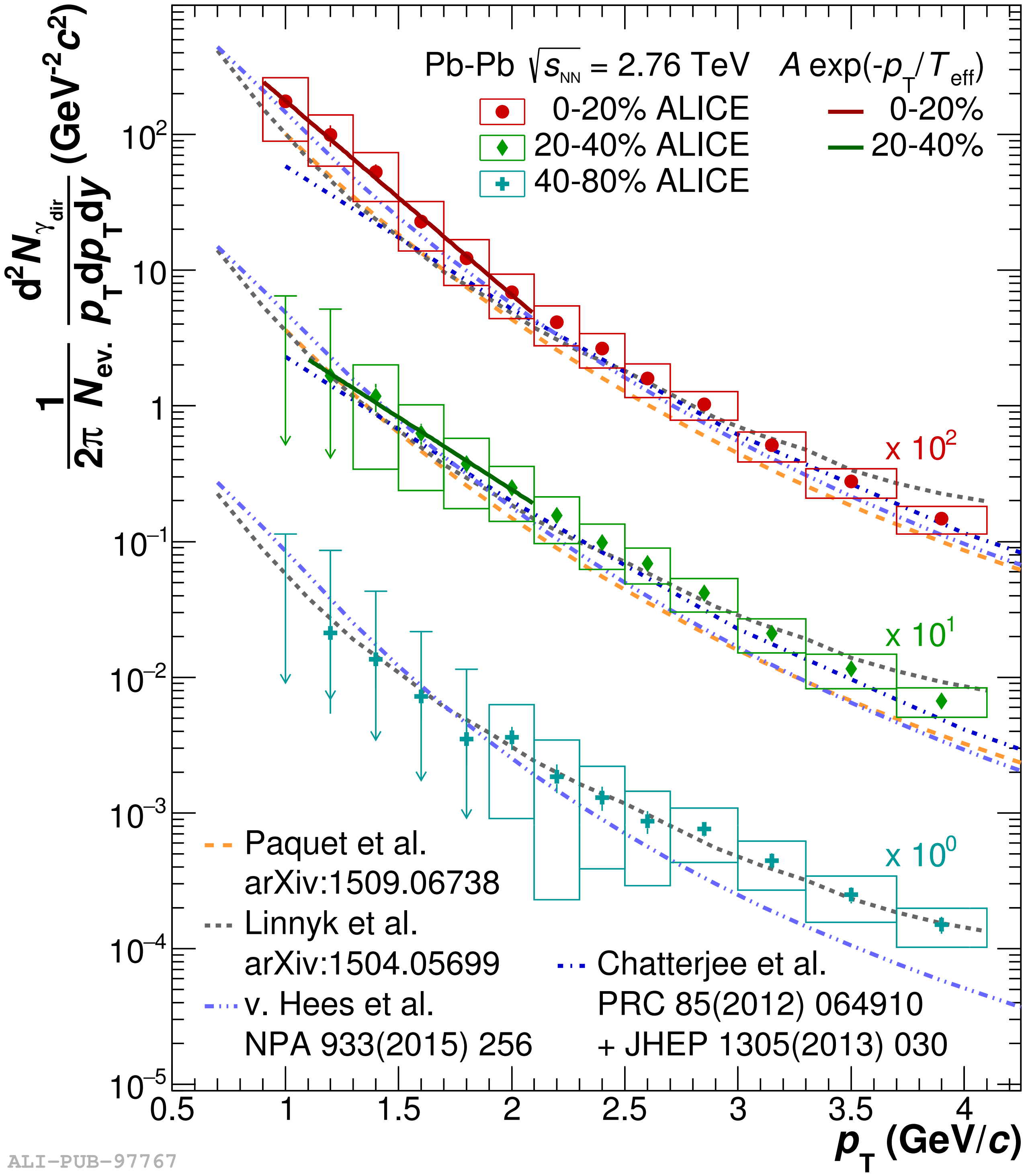
# Direct photons

Main expected sources:

- High $p_T$: hard scattering; quark-gluon Compton process
- Low $p_T$: thermal radiation

Excess at low $p_T$ in central collisions indicates thermal photon production

arXiv:1509.07324



# Jet shapes

Measure particle distribution inside jets on a jet-by-jet basis

Radial moment (girth)

$$g \equiv \frac{\sum_{\text{tracks}} p_{T,i} \ r}{p_{T,\text{jet}}}$$

$p_T$-weighted jet width

$$p_{T,jet} = \sum_{tracks} p_{T,i}$$

$p_T$-dispersion

$$p_{T,D} \equiv \frac{\sqrt{\sum_{\text{tracks}} p_{T,i}^2}}{p_{T,\text{jet}}}$$

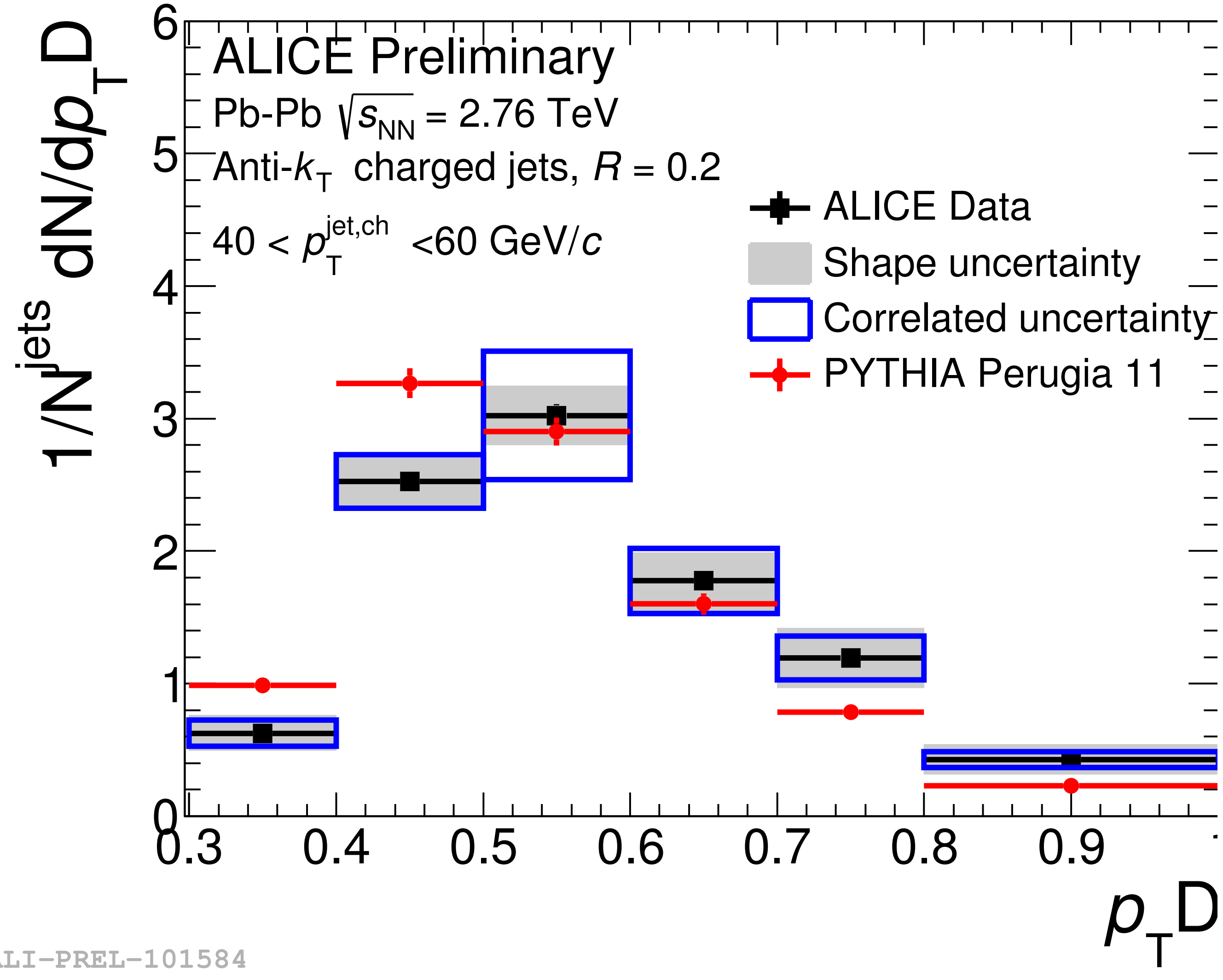
(Normalised) spread of $p_T$

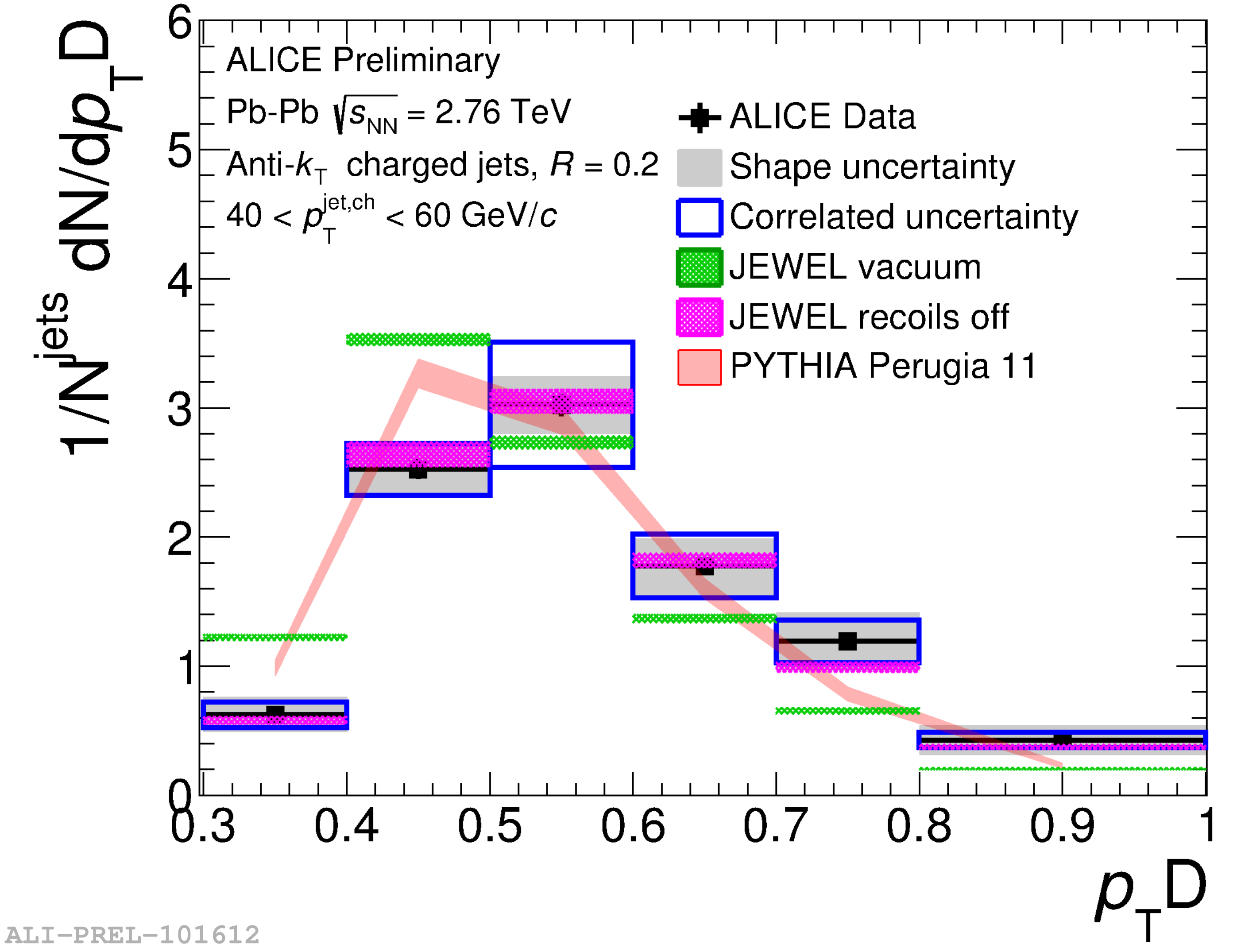
Anti-correlated with multiplicity

Large range of jet shape variables can be explored
So far, focused on two: 1 transverse, 1 longitudinal

# Jet shapes: $p_{T,D}$

QM talk, Cunqueiro





$p_{T,D}$ slightly larger in Pb+Pb than pp (PYTHIA)

JEWEL model shows similar trend

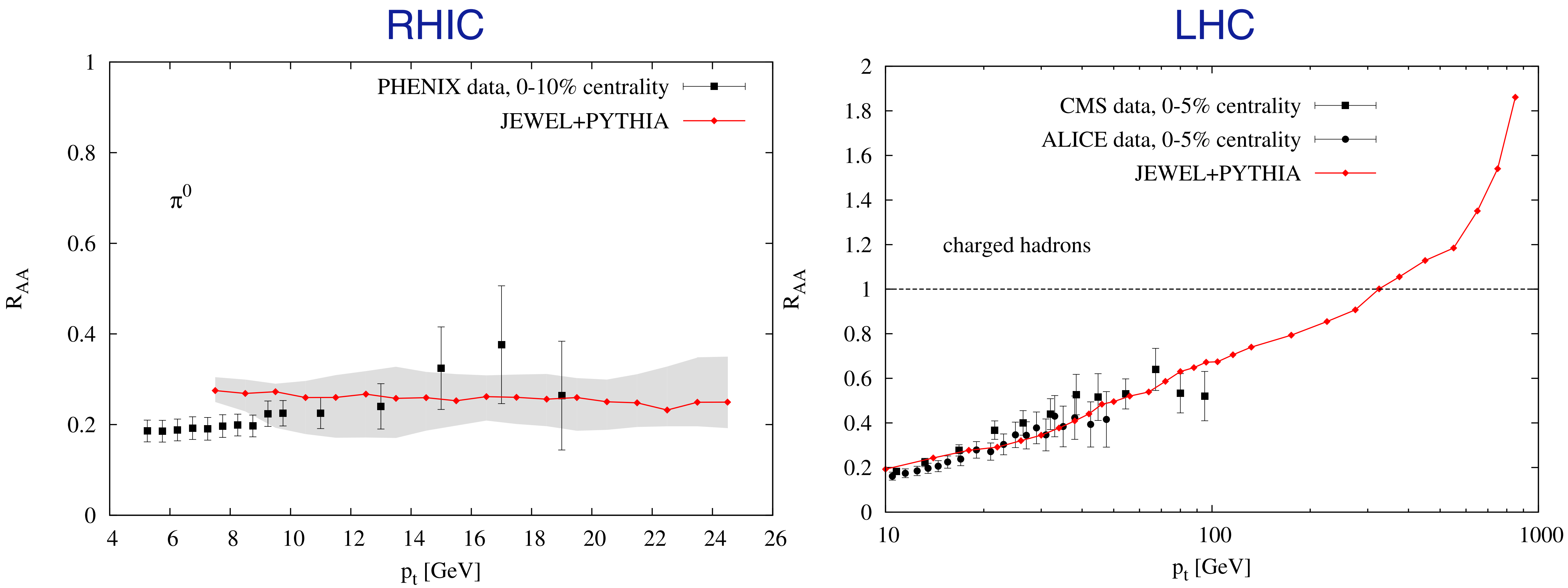
Larger $p_{T,D}$: smaller multiplicity and/or harder fragment distribution

# MC tools: JEWEL

Publicly available

Zapp, Krauss, Wiedemann, arXiv:1212.1599

Elastic+radiative energy loss; follows BDMPS-Z in appropriate limits
Medium: Bjorken-expanding Glauber overlap



$T_i$ = 350 MeV @ $\tau_0$ = 0.8 fm/$c$

$T_i$ = 530 MeV @ $\tau_0$ = 0.5 fm/$c$

Good agreement with JET collaboration values