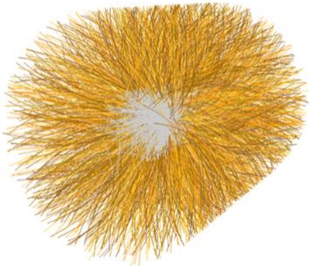

Introduction to Heavy-Ion Physics
Part III

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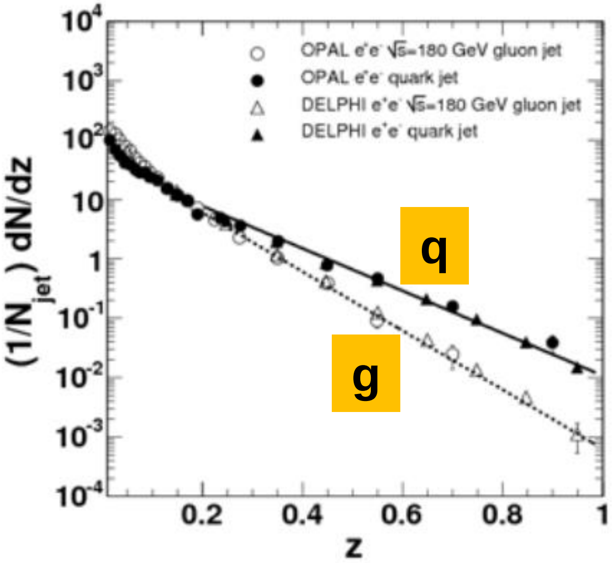
Francesca Bellini*, CERN

Summer Student Lectures 2019

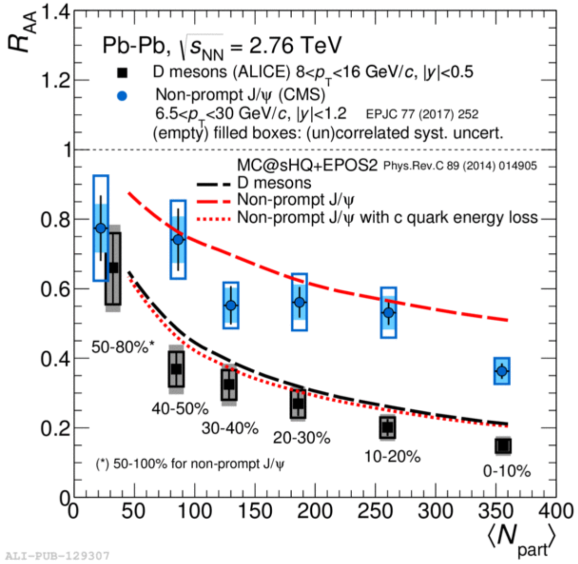
Recap Lecture II

- Energy loss in the medium by elastic and inelastic processes
- Quark-mass dependence expected
  - Fragmentation needs to be considered
  - Harder fragmentation of quark over gluon



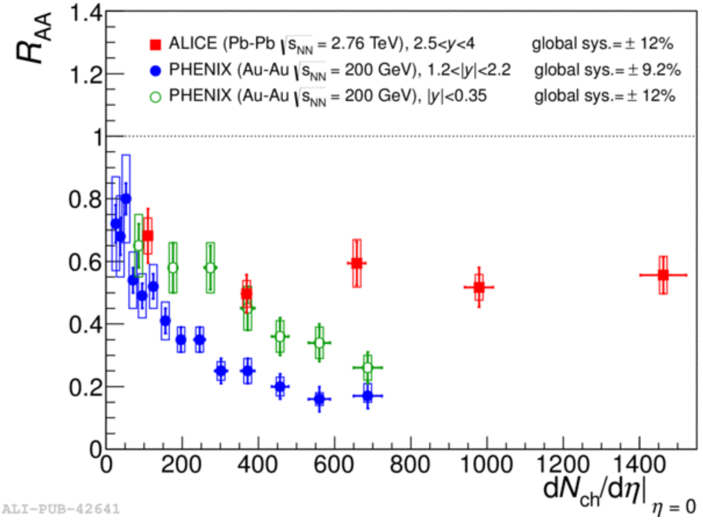
- R_{AA} of D and B mesons
  - Analysis complex due to small S/B ratio
  - Mass dependence of energy loss

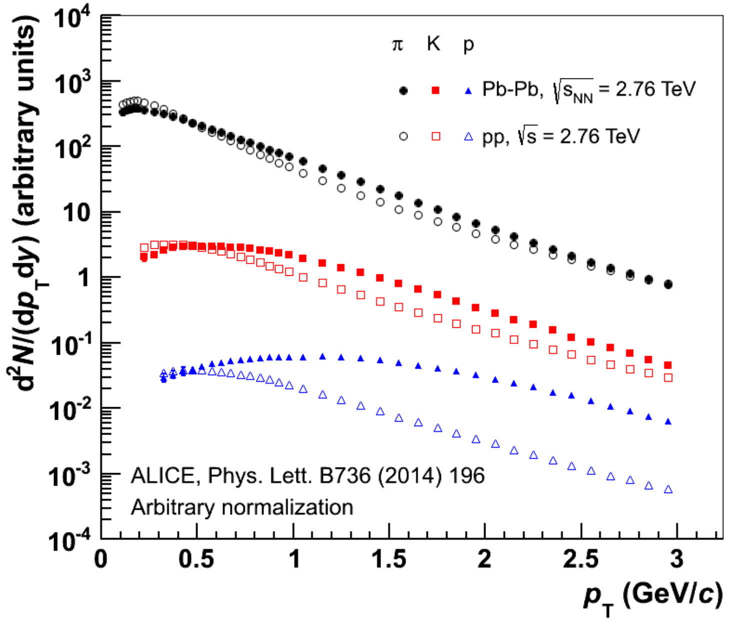
$$R_{AA}^{\pi} \approx R_{AA}^{D} < R_{AA}^{B}$$



Recap Lecture II

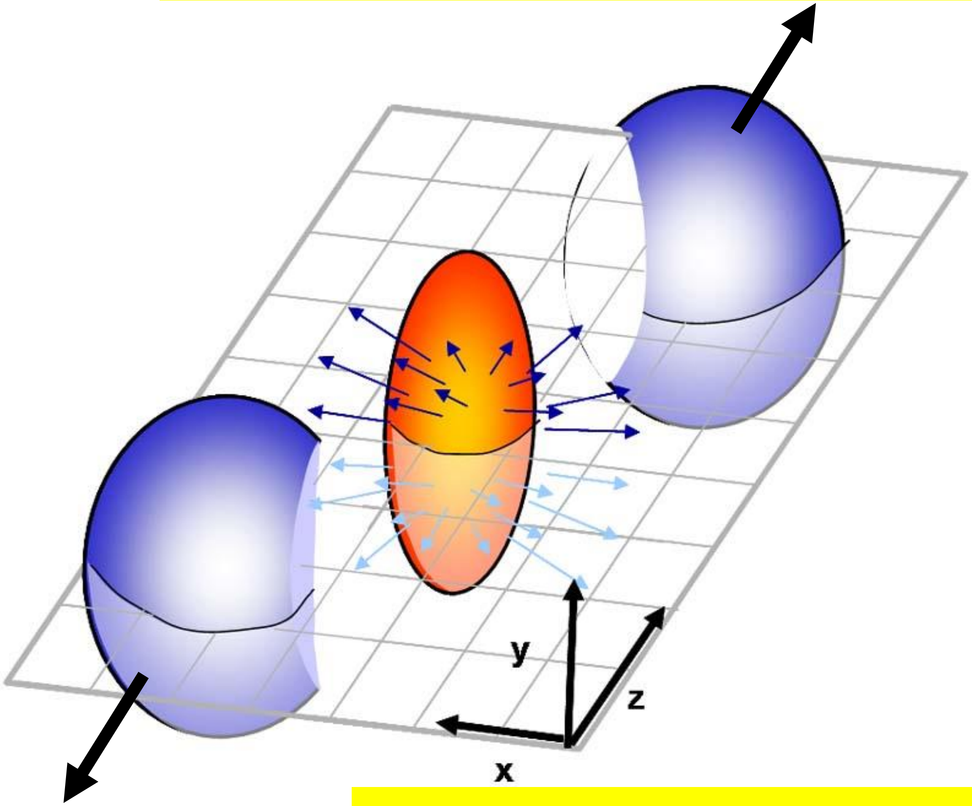
- Quarkonia (c-cbar, b-bar) “melt” due to color screening in the QGP
  - J/ψ suppression
  - Abundance of c at LHC so large that J/ψ regenerate statistically
  - States with lower binding energy are more suppressed
- Hadron yields described by statistical models for $\sqrt{s_{NN}}$ = 2-2760 GeV
  - Matter created in HI collisions is in local thermal equilibrium
- Expansion of QGP changes momenta of particles
  - Radial flow (dependent on particle mass)



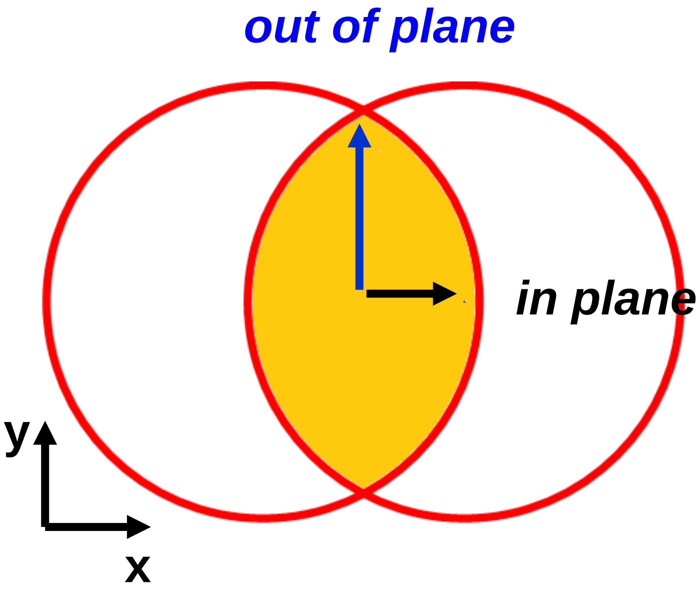


Elliptic Flow

Overlap of colliding nuclei not isotropic in non-central collisions



Defines *reaction plane* Ψ_{RP}
(spanned by beam axis
and impact parameter vector)



→ Pressure gradients dependent on direction

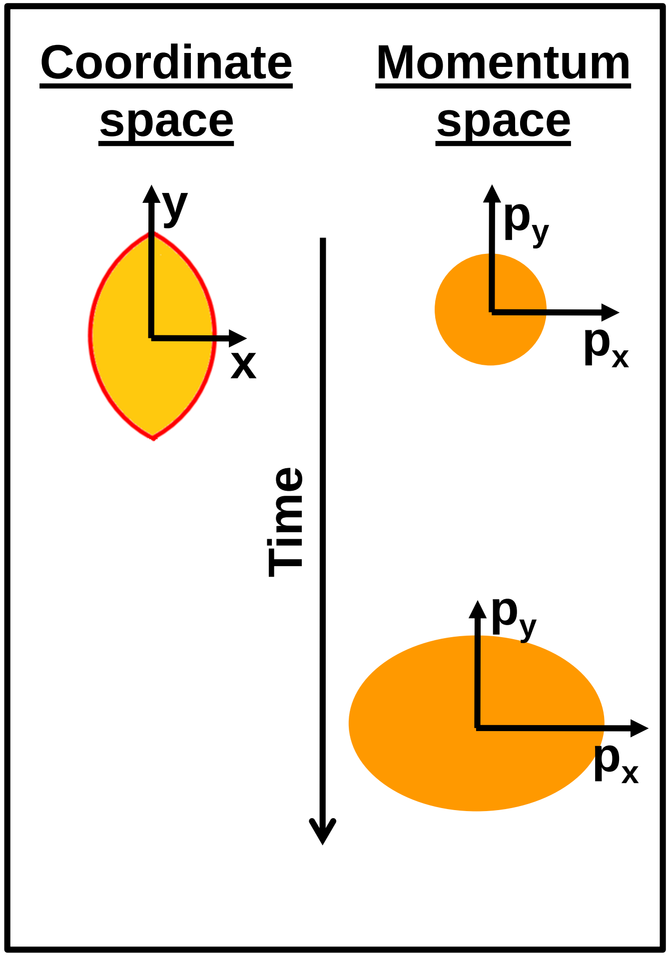
here: $\frac{dp_x}{dL} > \frac{dp_y}{dL}$

Elliptic Flow (2)

- Spatial anisotropy (almond shape)
  - Quantified by eccentricity ε

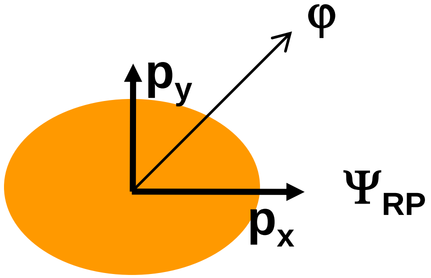
$$\varepsilon = \frac{y^2 - x^2}{y^2 + x^2}$$

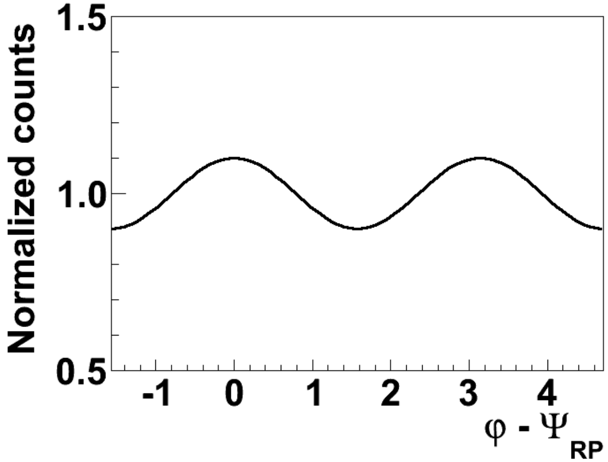
- Pressure gradient larger in-plane
- Pressure pushes partons
  - More in in-plane than out-of-plane
- Spatial anisotropy converts into momentum-space anisotropy
  - "Faster" particles in-plane
  - Measurable in the final state!



Elliptic Flow (3)

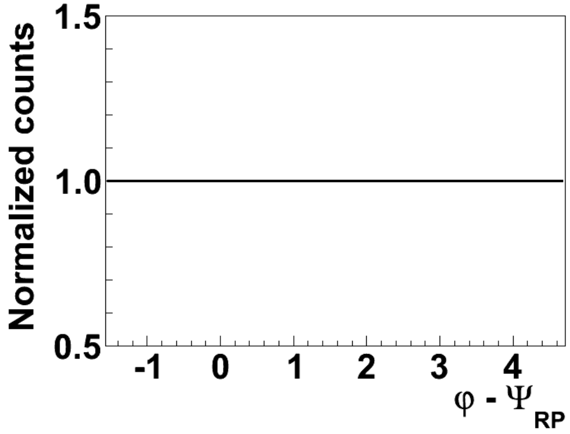
- Particles as a function of $\varphi - \Psi_{RP}$





$$\frac{dN}{d\varphi} = A\left(1 + 2v_2 \cos 2(\varphi - \Psi_{RP})\right)$$

- Define $v_2 = \langle \cos 2 (\varphi - \Psi_{RP}) \rangle$
  - Second coefficient of Fourier expansion
- Ψ_{RP} common *symmetry plane* (for all particles)
- What if there were no correlations with Ψ_{RP}?



Measuring Elliptic Flow

$$\boxed{\mathbf{v_2 = < \cos 2\,(\varphi - \Psi_{RP}) >}}$$

Measure tracks

Measure reaction-plane angle

- Reaction plane angle
  - From the particles themselves

$$Q_x = \sum_i w_i \cos 2\varphi_i \qquad Q_y = \sum_i w_i \sin 2\varphi_i \qquad \Psi_{\mathrm{RP}} = \tan^{-1}(Q_x, Q_y)/2 \qquad \boxed{\textbf{weight w}}$$

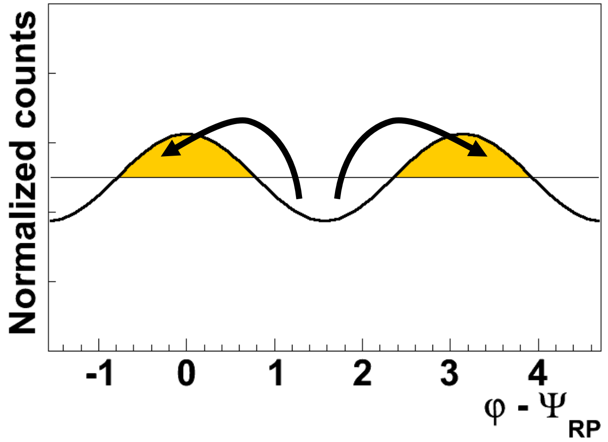
  - Ψ_{RP} approximates true reaction-plane angle (called *event plane*)
- Calculation of *integrated* $v_2 = < \cos 2\,(\varphi - \Psi_{RP}) >$
- $v_2(p_T)$ by considering only particles at given p_T
- Called *event plane method*, denoted v_2\{EP\}

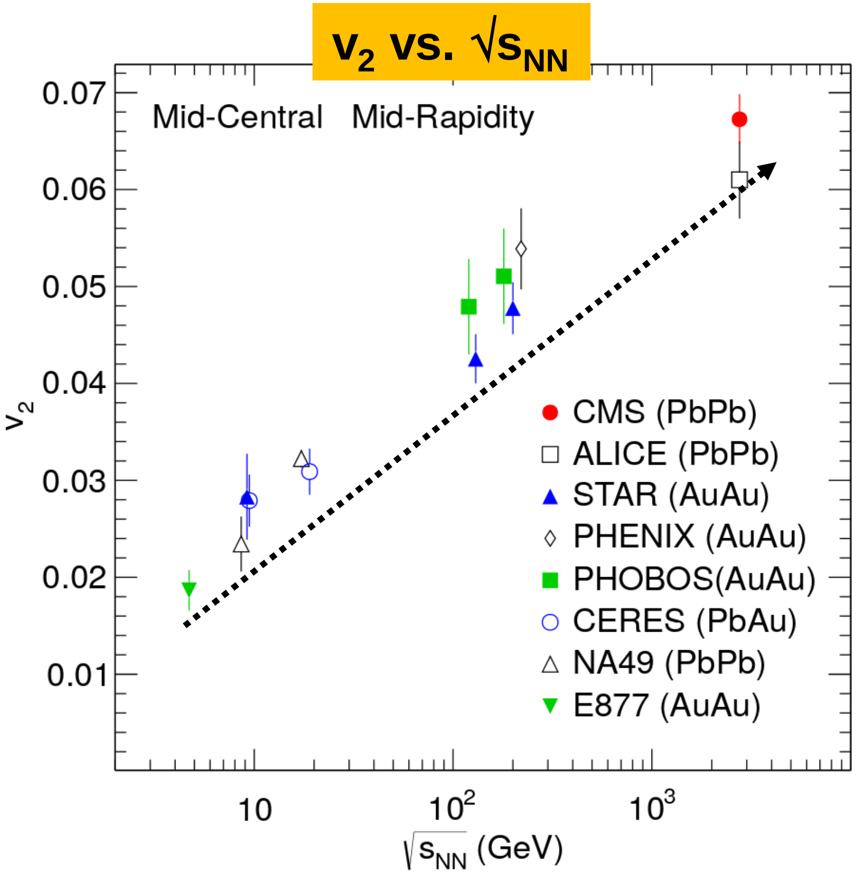
$\sqrt{s_{NN}}$ Dependence

- Increases with $\sqrt{s_{NN}}$
- At LHC v_2 ~ 0.06
  - What does that mean?

$$\frac{dN}{d\varphi} = A\left(1 + 2v_2 \cos 2(\varphi - \Psi_{RP})\right)$$

  - $2v_2$ = 12% of particles “move” from out-of-plane to in-plane

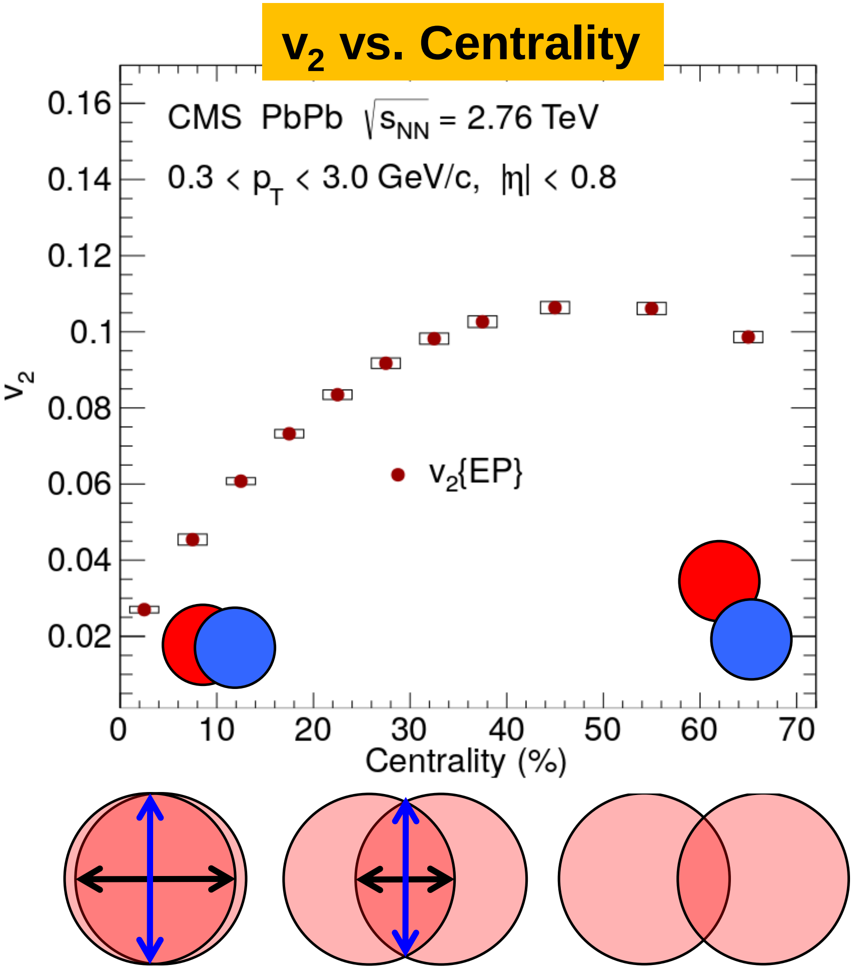




CMS, PRC 87(2013) 014902

Centrality Dependence

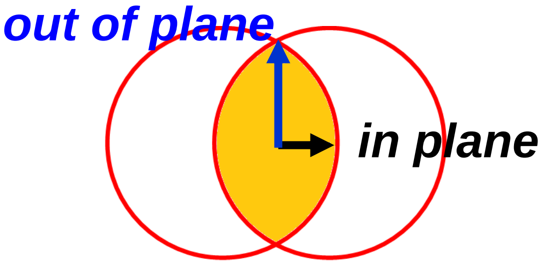
- Strong centrality dependence
- v_2 largest for 40-50%
- Spatial anisotropy very small in central collisions
- Largest anisotropy in mid-central collisions
- Small overlap region in peripheral collisions

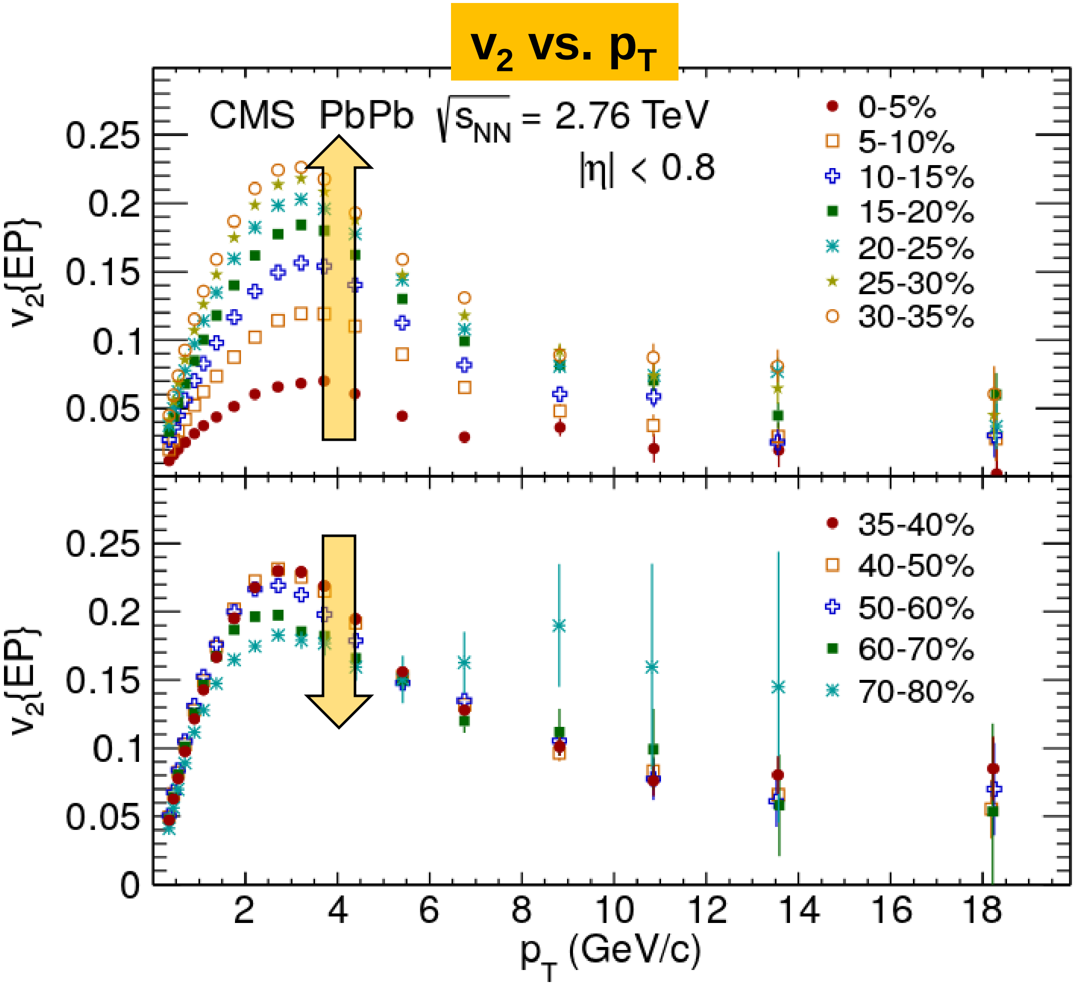


CMS, PRC 87(2013) 014902

p_T Dependence

- Centrality dependence independent of p_T
- Largest v_2 for p_T ~ 3 GeV/c
- Low and intermediate p_T, v_2 caused by collective expansion
- Large p_T, v_2 caused by *length-dependent jet quenching*
  - Longer path length out of plane than in plane





CMS, PRC 87(2013) 014902

Recap

- Pressure in dense medium affects momenta
- Isotropic expansion effect called *radial flow*

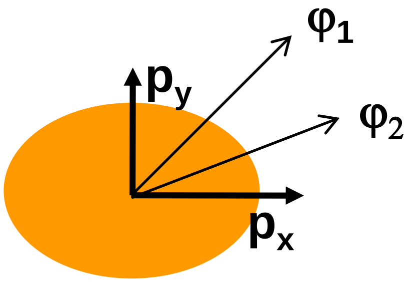
- Overlap of colliding nuclei causes spatial anisotropy
- Converted into momentum-space anisotropy in medium evolution
- Modulation of observed particles
- Quantified by $v_2 = < \cos 2 (\varphi - \Psi_{RP}) >$

What other methods exist to measure v_2?

What effect do jet-related particles have on v_2?

Two-Particle Correlations

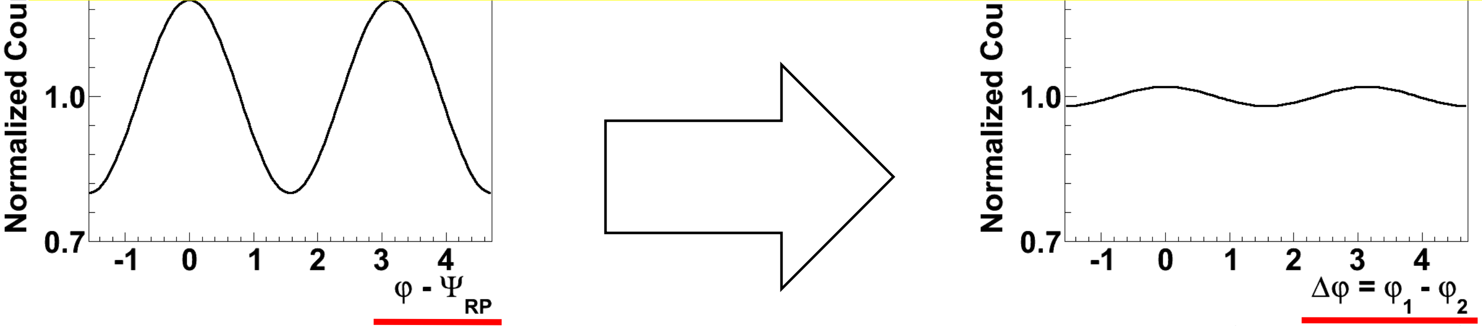
- Reaction-plane estimation can be experimentally tricky
- Rewrite $v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle$ as $v_2 = \left\langle e^{i2(\varphi - \Psi_{RP})} \right\rangle$
- v_2 can also be measured from 2-particle correlations



$$\left\langle e^{i2(\varphi_1 - \varphi_2)} \right\rangle = \left\langle e^{i2(\varphi_1 - \Psi_{RP} - (\varphi_2 - \Psi_{RP}))} \right\rangle =$$

$$= \left\langle e^{i2(\varphi_1 - \Psi_{RP})} \right\rangle \left\langle e^{i2(\varphi_2 - \Psi_{RP})} \right\rangle = \boxed{v_2^2}$$

Modulation smaller due to v_2 → $(v_2)^2$ but statistical power similar



$$v_2 = \left\langle e^{i2(\varphi - \Psi_{RP})} \right\rangle \qquad v_2^2 = \left\langle e^{i2(\varphi_1 - \varphi_2)} \right\rangle$$

Higher-Order Correlations

- Trivial extension to 4-particles (and higher-orders)

$$v_2^4 = \left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle$$

$$v_2^6 = \left\langle e^{i2(\varphi_1+\varphi_2+\varphi_3-\varphi_4-\varphi_5-\varphi_6)} \right\rangle$$

  - NB. sign is arbitrary as long as same amount of positive and negative angles
    → rotational symmetry

Cumulants

- Cumulants extract genuine n-particle correlations
- For 2-particle correlations

$$\langle x_1 x_2 \rangle = \underbrace{\langle x_1 \rangle \langle x_2 \rangle} + \langle x_1 x_2 \rangle_{\mathbf{c}}$$

measured correlation

lower order “correlations”

genuine 2-particle correlations

- Rewrite (trivially) $\langle x_1 x_2 \rangle_{\mathbf{c}} = \langle x_1 x_2 \rangle - \langle x_1 \rangle \langle x_2 \rangle$

φ dependence only from detector acceptance

- For 3-particle correlations

$$\langle x_1 x_2 x_3 \rangle = \langle x_1 \rangle \langle x_2 \rangle \langle x_3 \rangle + \langle x_1 x_2 \rangle_{\mathbf{c}} \langle x_3 \rangle + \langle x_1 x_3 \rangle_{\mathbf{c}} \langle x_2 \rangle + \langle x_2 x_3 \rangle_{\mathbf{c}} \langle x_1 \rangle + \underline{\langle x_1 x_2 x_3 \rangle_{\mathbf{c}}}$$

Higher-order cumulants zero → no genuine multi-particle correlation !
No matter what multi particles correlations (i.e. not cumulants) show

Cumulants for Elliptic Flow

- For uniform detector acceptance, cumulants of 2nd and 4th order:

$$c_2\{2\} = \left\langle e^{i2(\varphi_1-\varphi_2)} \right\rangle = v_2^2 \longleftarrow$$ **identical to two-particle correlation**

$$c_2\{4\} = \left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle - \underbrace{2\left\langle e^{i2(\varphi_1-\varphi_2)} \right\rangle^2}_{\text{lower orders are removed}} = -v_2^4$$

- $c_2\{4\}$ is genuine 4-particle correlations
  - I.e. if only pairs of particles are correlated → $c_2\{4\} = 0$

Flow Methods

- Now we have tons of methods to measure flow
  - Event plane
  - 2-particle and 4-particle correlations, …
  - 2-particle and 4-particle cumulants, …

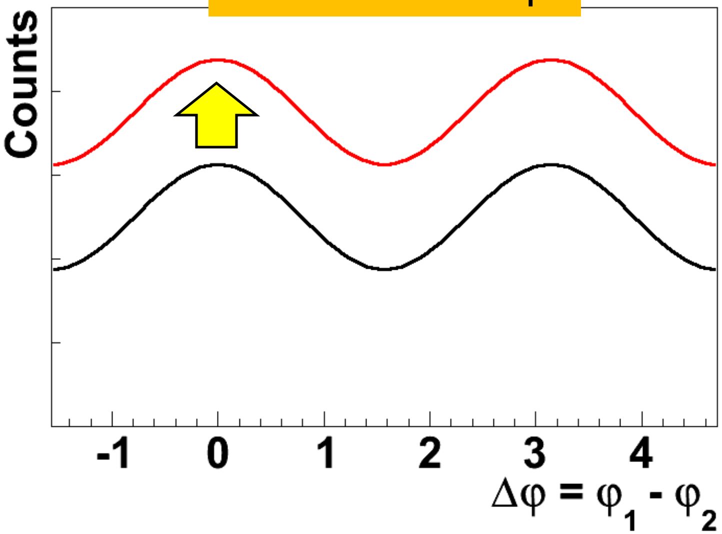
They all estimate v_2, so what?

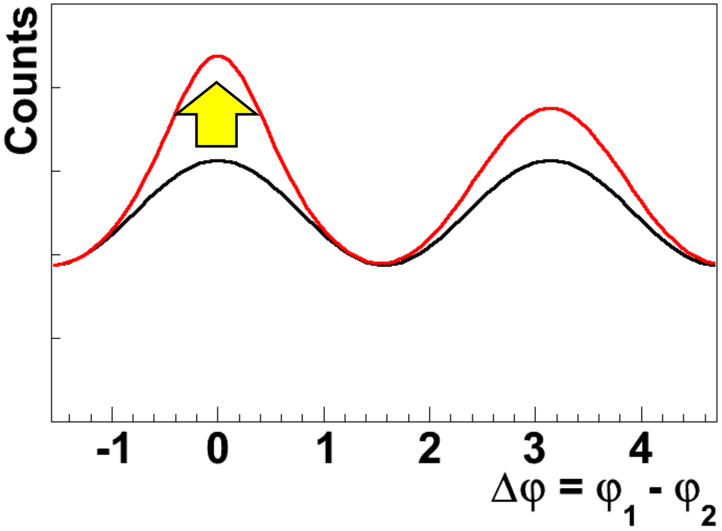
Let’s have a look, what spoils the flow measurement…

Non-Flow

- Particles are correlated through reaction plane Ψ_{RP}
- Additional isotropically distributed particles
  - Add to baseline, reduce cos $2\Delta\varphi$ magnitude, but don't distort shape
- Jets
  - Particles which exhibit correlations close in angle (within the same jet) and at $\Delta\varphi = \pi$ (back-to-back jet)
  - Distort Ψ_{RP} estimate
  - Distorts shape in 2 particle correlations
- A pure jet-signal results in $v_2 > 0$ (e.g. Pythia)

Counts vs. $\Delta\varphi$





Non-Flow (2)

- Different effect on different flow methods
- 2-particle correlations / cumulants

$$c_2\{2\} = \left\langle e^{i2(\varphi_1-\varphi_2)} \right\rangle = v_2^2 + \delta_2$$

non-flow **contribution**

- 4-particle correlations

$$\left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle = v_2^4 + 4v_2^2\delta_2 + 2\delta_2^2 + \delta_4$$

- 4-particle cumulants

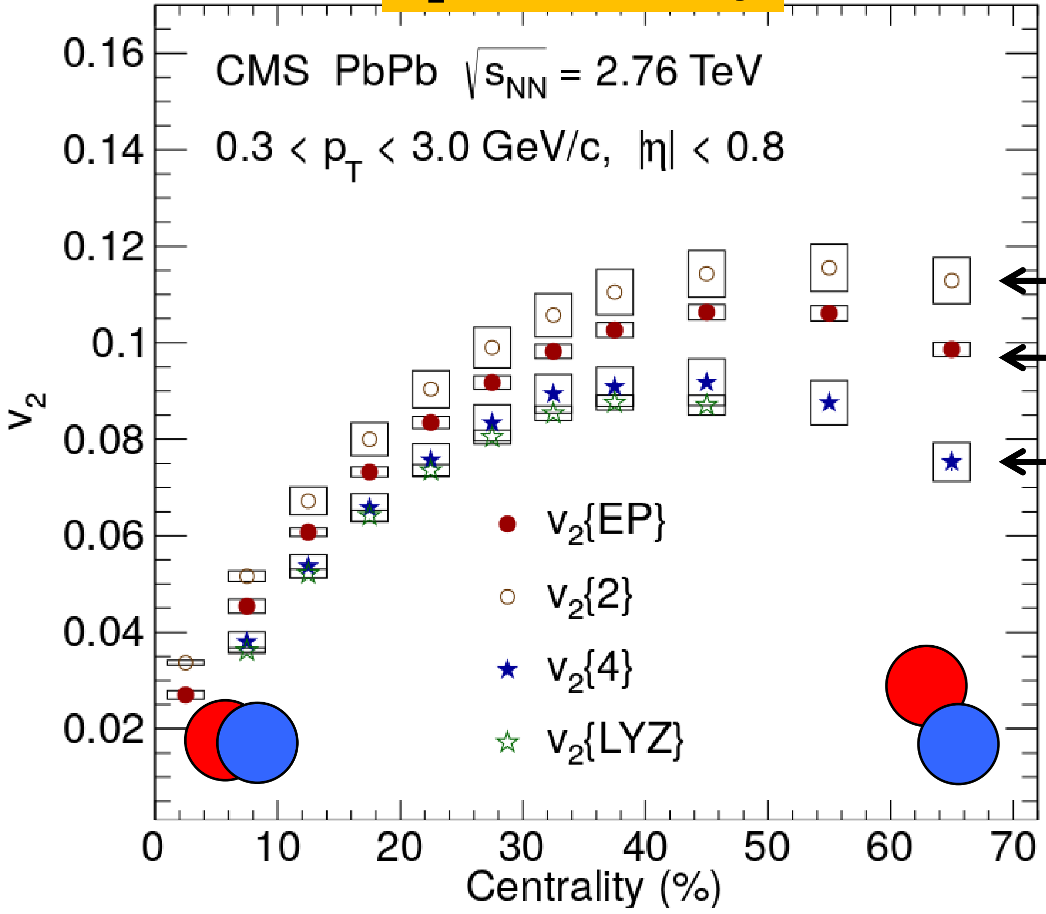
$$c_2\{4\} = \left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle - 2\left\langle e^{i2(\varphi_1-\varphi_2)} \right\rangle =$$

$$= v_2^4 + 4v_2^2\delta_2 + 2\delta_2^2 + \delta_4 - 2(v_2^2 + \delta_2) = \boxed{-v_2^4 + \delta_4}$$

Second order non-flow dropped out !

Experiment

v_2 vs. Centrality



$$v_2\{2\} = \sqrt{v_2^2 + \delta_2}$$

$$v_2\{EP\}$$

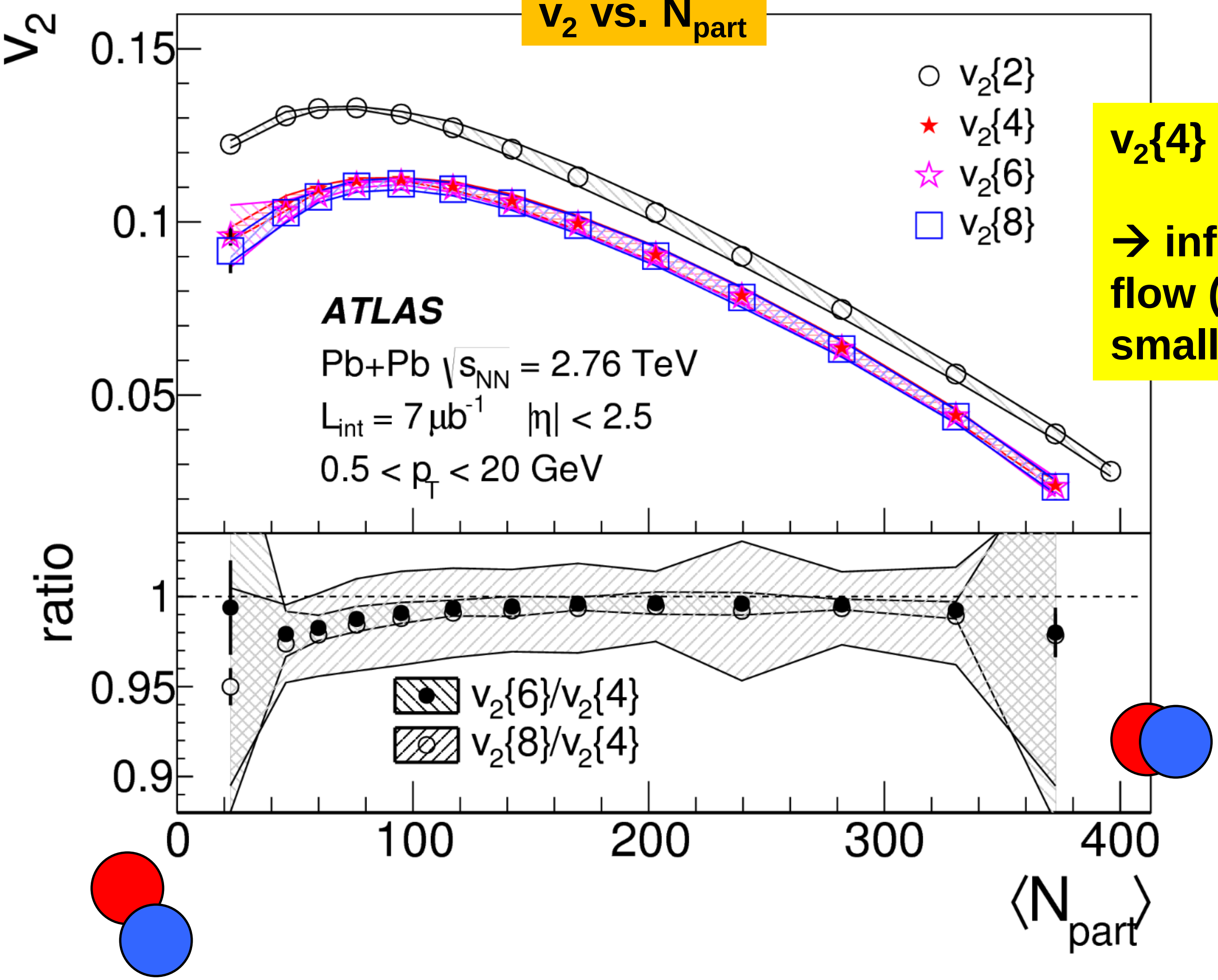
$$v_2\{4\} = \sqrt[4]{v_2^4 - \delta_4}$$

Larger non-flow influence* for $v_2\{2\}$ than $v_2\{4\}$

*** neglects fluctuations, see backup**

PRC 87(2013) 014902

Up to 8 Particles…



v_2 vs. N_{part}

$v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$

→ influence of non-flow (and fluctuations) small for >= 4 particles

EPJC (2014) 74: 3157

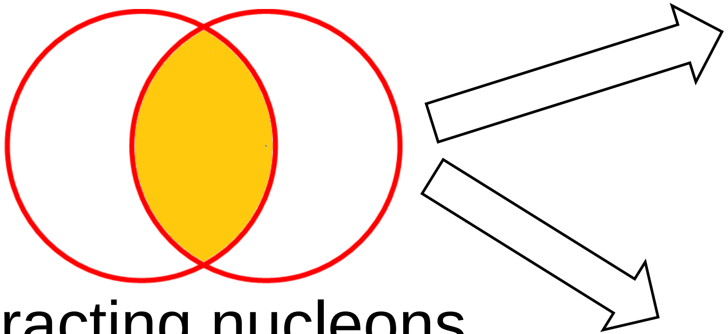
Recap

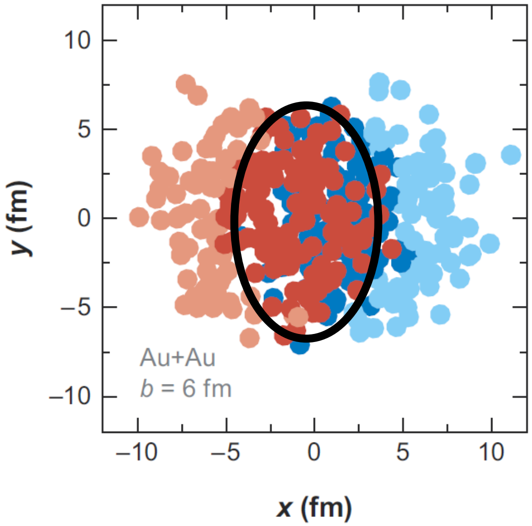
- Elliptic flow can be measured with different methods
- Cumulants of n^{th} order measure genuine n-particle correlations – not reducible to lower orders
- Mini(jets) and resonances distort the v_2 measurement
- Non-flow influence is different for different methods
  - The higher the order of the cumulant, the smaller the influence

For now we have discussed elliptic flow v_2 – is that all?

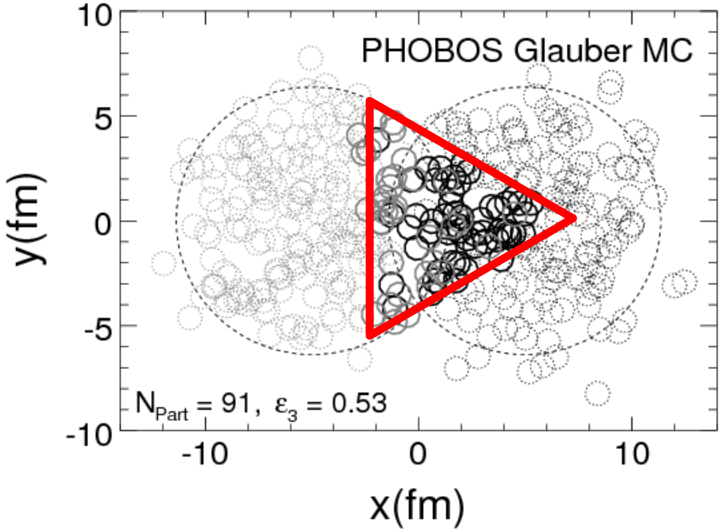
Higher-Order Flow

- Geometrical picture
  → 2nd order modulation (v_2)



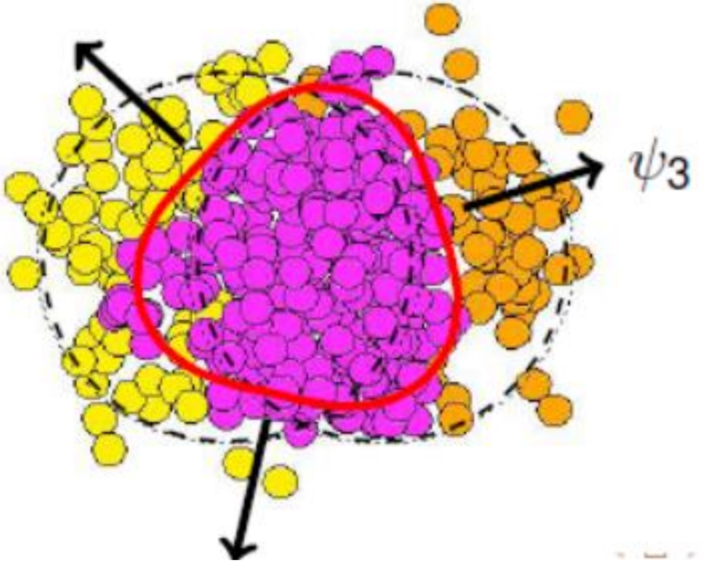


- In practice interacting nucleons need to be considered
  - E.g. estimated with Glauber MC
  - *Initial state density fluctuations*
- These produce all kinds of shapes
  - Elliptic, triangular, quadruple, …
  - And mixtures of those



nucl-ex/0701025, PRC81 (2010) 054905

Higher-Order Flow (2)



- Reaction plane Ψ_{RP} → nth order participant plane Ψ_n

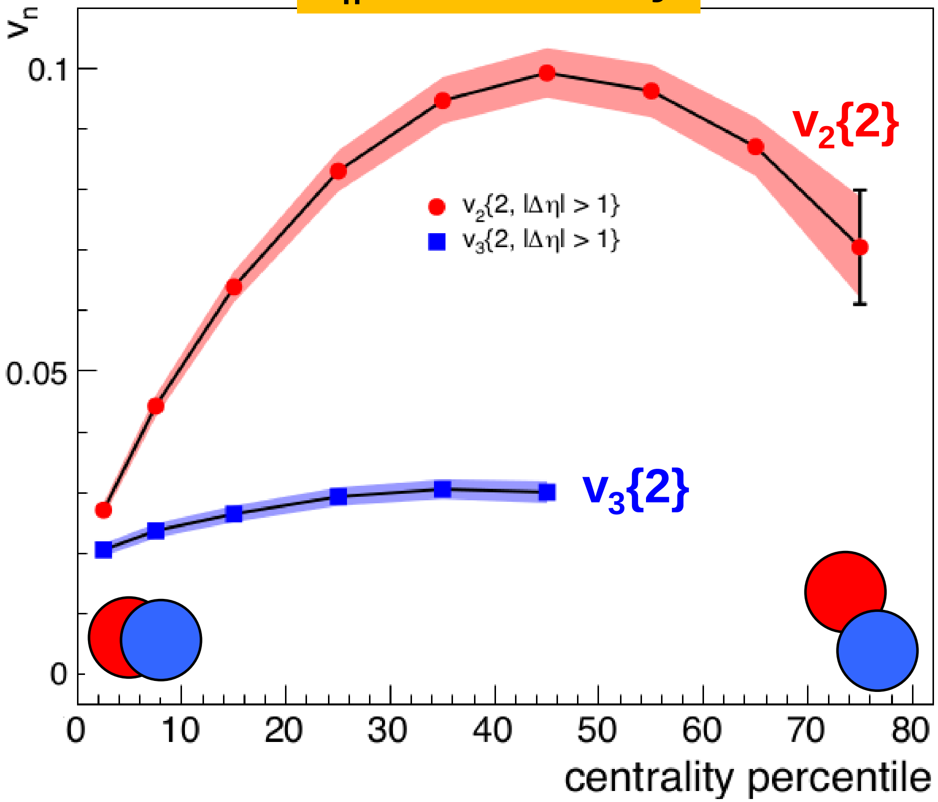
$$\frac{dN}{d\varphi} = A\left(1 + 2v_2\cos 2(\varphi - \Psi_{RP})\right) \Longrightarrow \frac{dN}{d\varphi} = A\left(1 + 2\sum_n \boxed{v_n}\cos n(\varphi - \boxed{\Psi_n})\right)$$

- Formalism can be trivially extended from v_2 to v_n
- E.g. $v_2^2 = \left\langle e^{i2(\varphi_1-\varphi_2)} \right\rangle \longrightarrow v_n^2 = \left\langle e^{in(\varphi_1-\varphi_2)} \right\rangle$

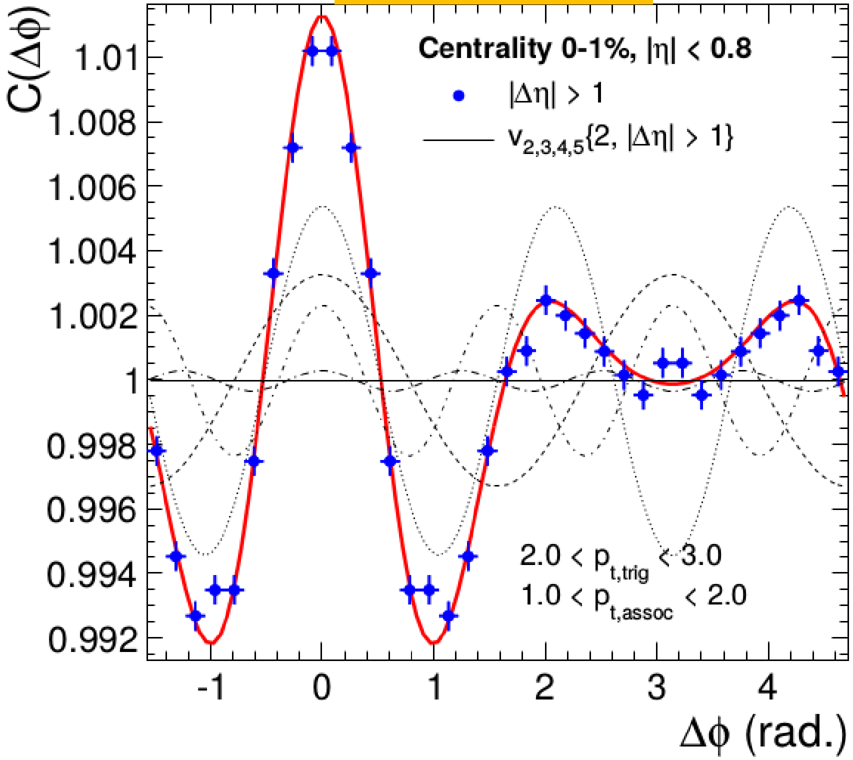
PRC81 (2010) 054905

Experiment

v_n vs. Centrality



$C(\Delta\varphi)$ vs. $\Delta\varphi$



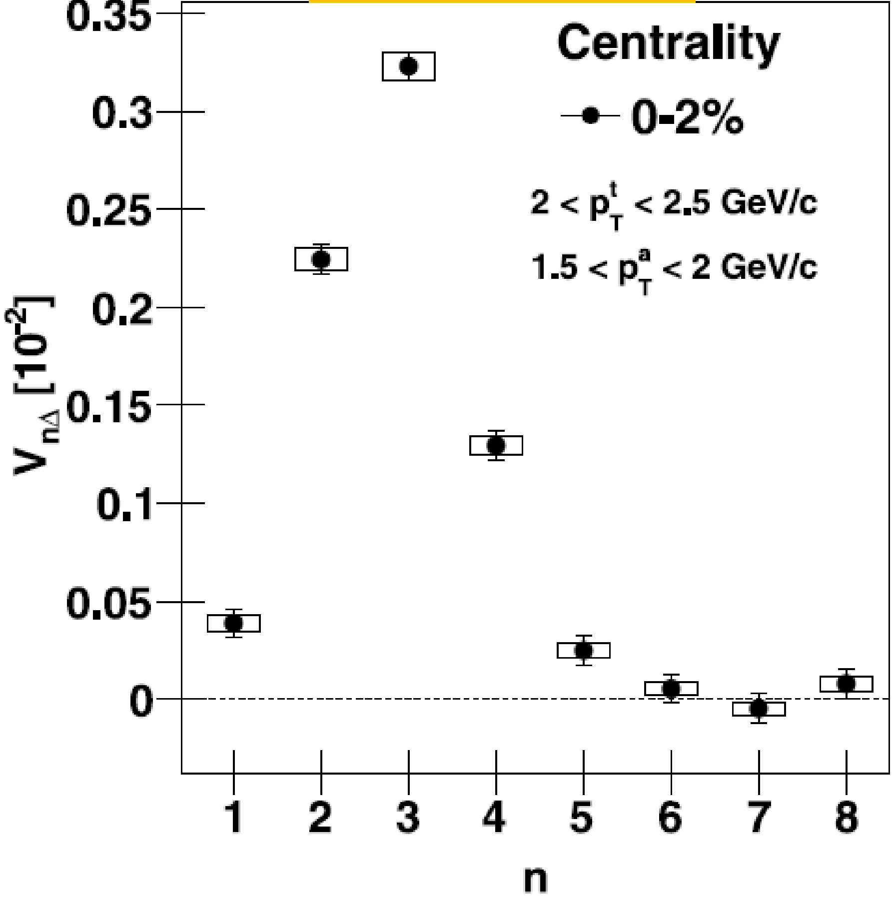
v_3 sizable
$v_3 \sim ½\ v_2$
Weaker centrality dependence

Two-particle correlations can be fully described by v_2 … v_5

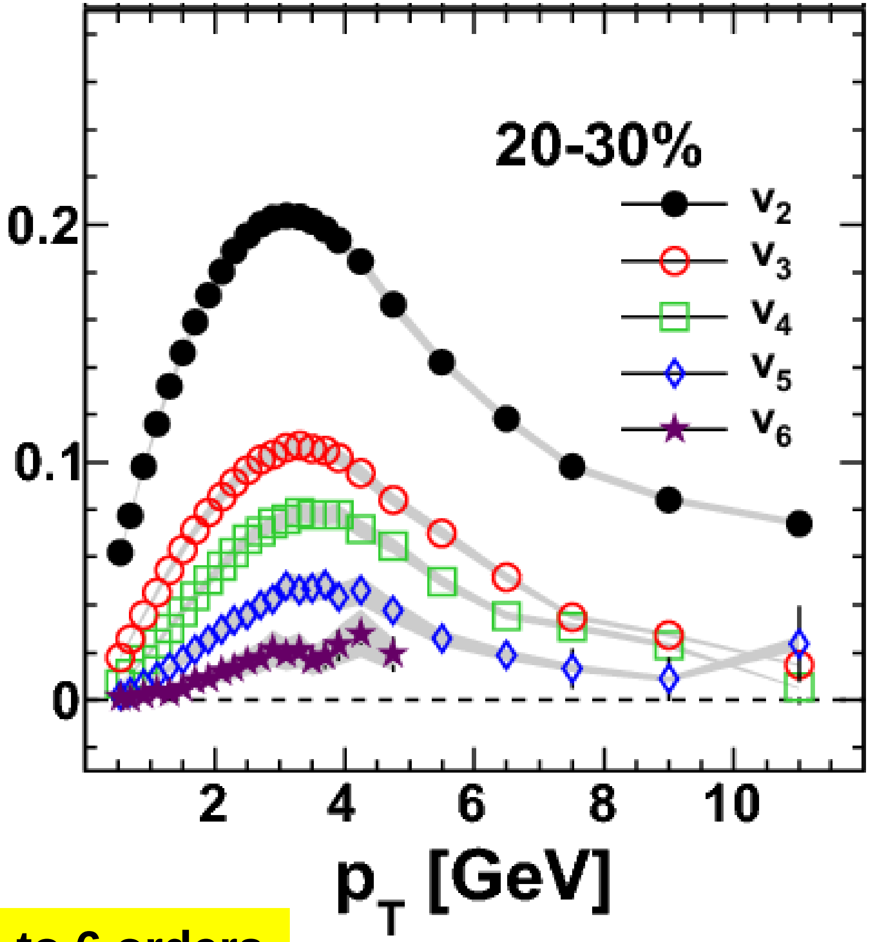
PRL107, 032301 (2011)

And even higher orders…

$V_{n\Delta} = (v_n)^2$ vs. n



v_n vs. p_T



Significant up to 6 orders

ATLAS-CONF-2011-074
PLB708 (2012) 249

Recap

- Geometry of overlapping nuclei → elliptic flow
- Initial-state density fluctuations lead to different ‘shapes’ of overlap region → flow at higher orders
- Flow measured up to 6th order

What does a medium need for collective effects?

What can we learn from these results?

Hydrodynamics

- Calculating space-time evolution of QGP from first principles (QCD Lagrangian) is too complex (non-abelian, strong coupling, many-body system, …)
- Expanding medium can be described macroscopically with hydrodynamical models
  - Conservation of energy-momentum
  - Conservation of charges, mainly baryon number
  - Local thermodynamical equilibrium

$$\partial_\mu T^{\mu\upsilon} = 0$$

$$\partial_\mu N_i^\mu = 0$$

$$N_i^\mu = n u^\mu$$

$$T^{\mu\upsilon} = (\varepsilon + P) u^\mu u^\upsilon - P g^{\mu\mu}$$

- Needed input
  - Initial conditions
  - Equation of State (EoS), from lattice QCD
  - Relativistic fluid dynamics
    - Perfect or dissipative (→ transport coefficients)

Hydrodynamics (2)

- Once dynamics well described, hydrodynamic “output” can be used in other calculations: jet quenching, J/ψ melting, etc.

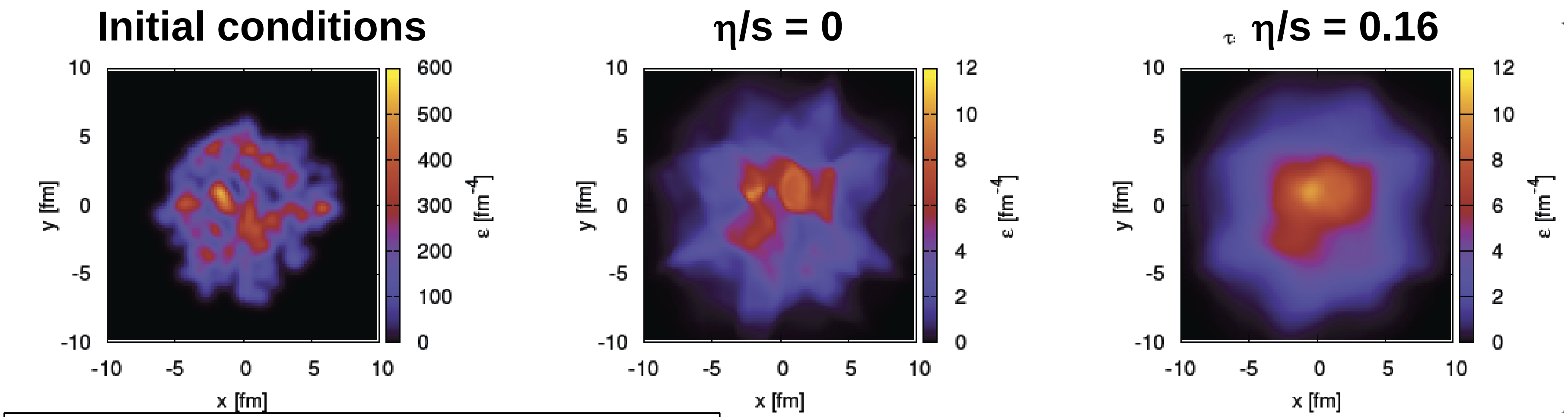
- Flow observables:
  Initial-state anisotropies → final-state anisotropies
  - Translate from initial-state eccentricity ε_n to final-state flow v_n

- Deduce conclusions on initial conditions, EoS and transport coefficients by data comparison

Shear Viscosity

- Shear viscosity washes out initial-state anisotropies
  - Expressed as η/s (shear viscosity over entropy)
  - Ideal hydrodynamics : η/s = 0 → **not to confuse with ideal (free streaming) gas → no interactions**
  - Viscous hydrodynamics : η/s > 0
  - Large influence on higher-order flow

Density in collision region (x vs. y)

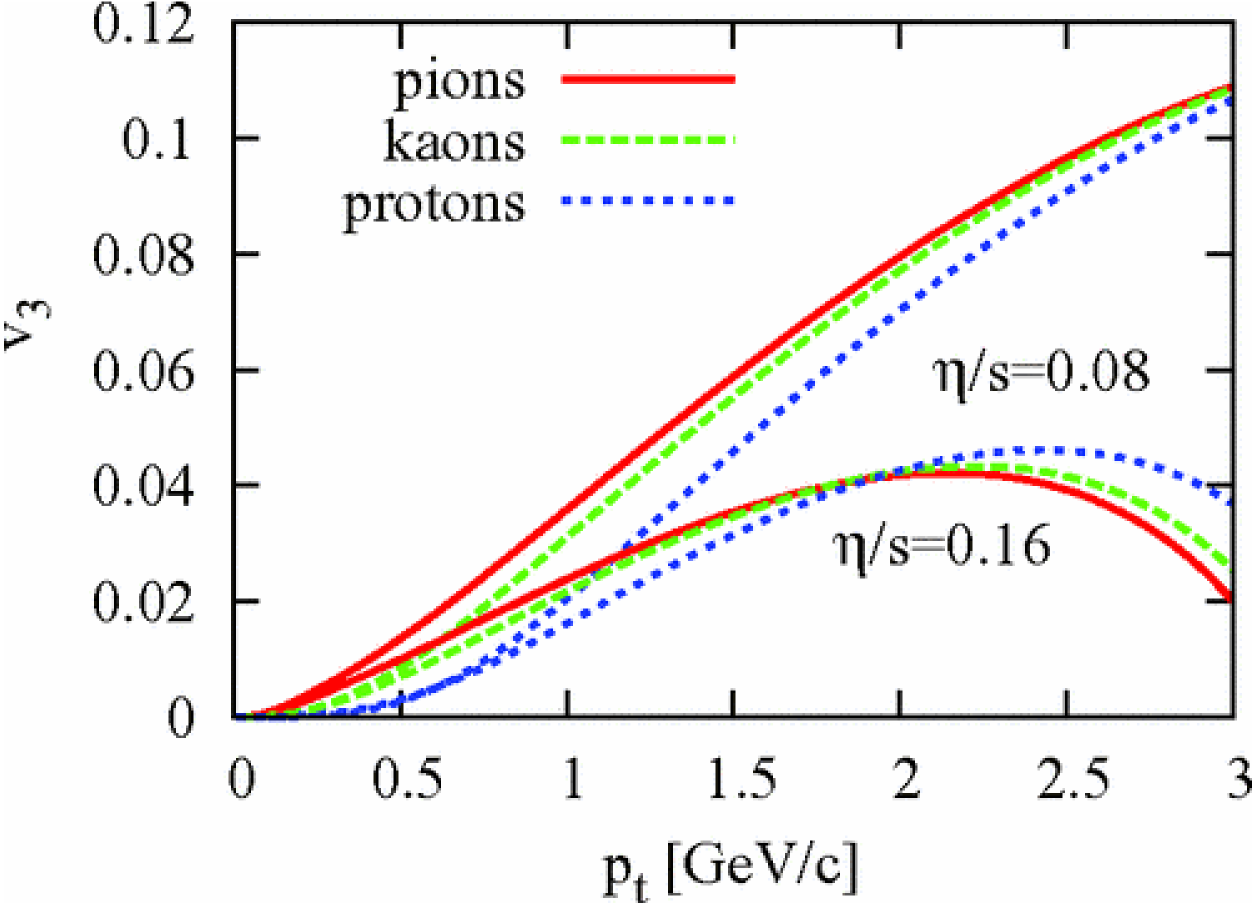


Water: η/s ~ 30 | Olive oil η/s ~ 240

MUSIC, Sangyong Jeon

Example: Shear Viscosity

v_3 vs. p_T



$\eta/s = 0.08$

Larger η/s reduces flow

$\eta/s = 0.16$

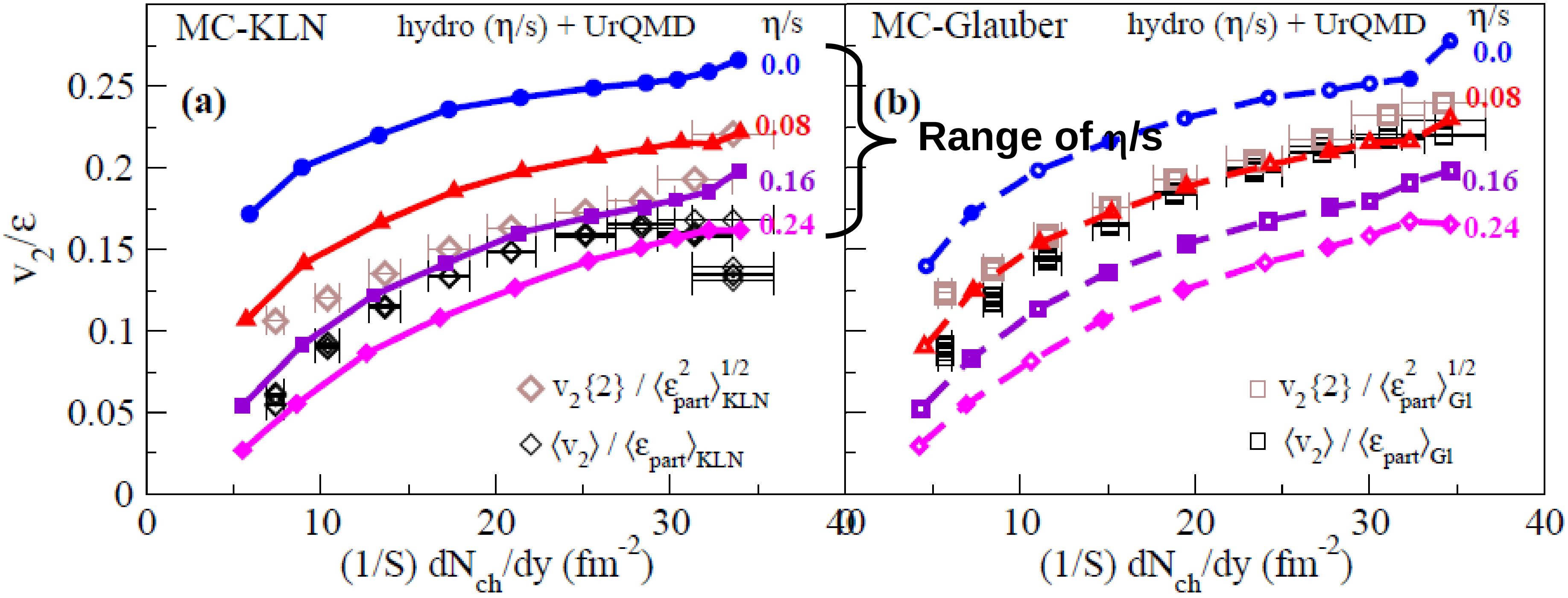
Shear viscosity hampers the build-up of flow !

PRC 82, 034913 (2010)

Hydro vs. Data

MC-KLN ⟵ Initial conditions ⟶ MC-Glauber

Eccentricity-scaled v_2



Range of η/s

Multiplicity per overlap area **Multiplicity per overlap area**

MC-KLN with η/s = 0.16 or MC-Glauber with η/s = 0.08

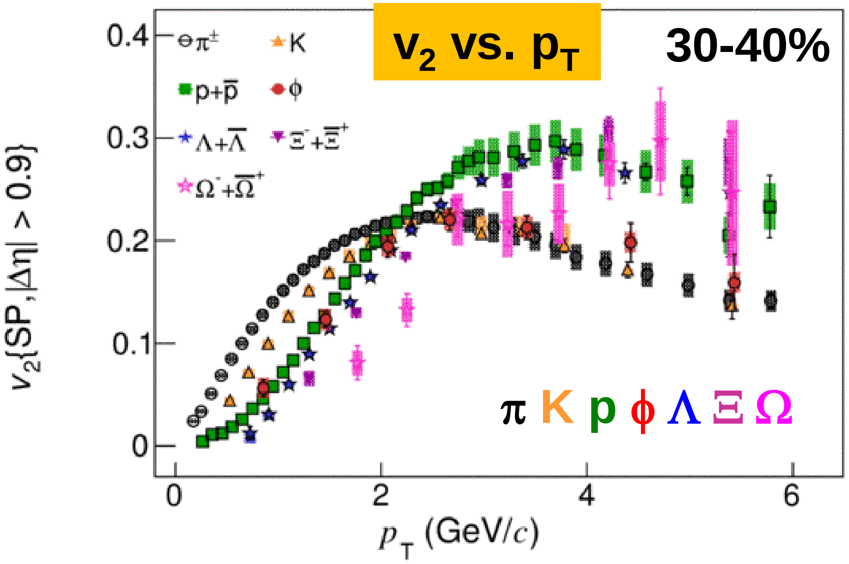
Water: η/s ~ 30 | Olive oil η/s ~ 240

Annu.Rev.Nucl.Part.Sci. 63 (2013) 123 (Data: STAR 200 GeV)

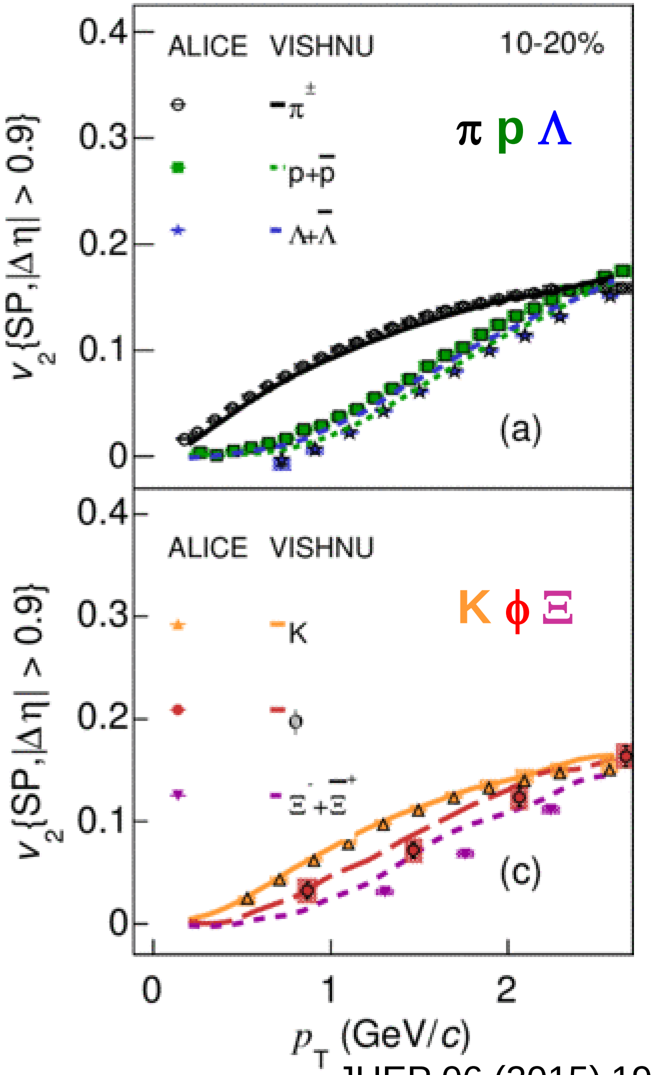
Hydro vs. Data (2)

v_2 vs. p_T

- v_2 measured for 7 different species



- Strong species dependence
  - Different masses and quark content
- Stringent test for hydro
  - Very good agreement with VISHNU (hydro + hadronic cascade model (UrQMD), initial conditions MC-KLN, η/s ~ 0.16)



JHEP 06 (2015) 190

Summary
Collective Flow & Hydrodynamics

- Quark-gluon plasma expands rapidly (up to ~0.65c)
- Spatial anisotropy of collision region causes anisotropic flow quantified as Fourier coefficients v_n
  - Measured up to 6th order
  - Initial-state fluctuations influence v_n
- Well described by viscous hydrodynamics with a very low shear viscosity (η/s ~ 0.08 – 0.16) “perfect liquid”

Hydrodynamical models describe collective flow

→

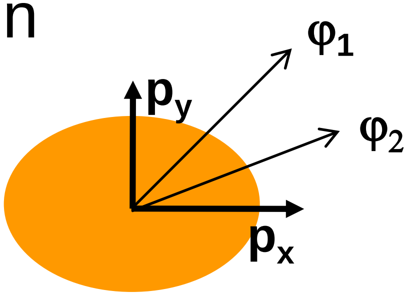
Matter created in HI collisions is in local thermal equilibrium

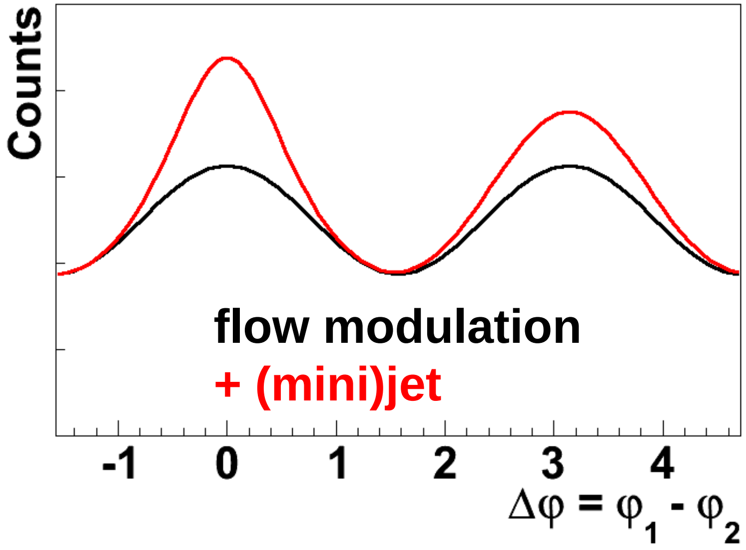
Collectivity in Small Systems

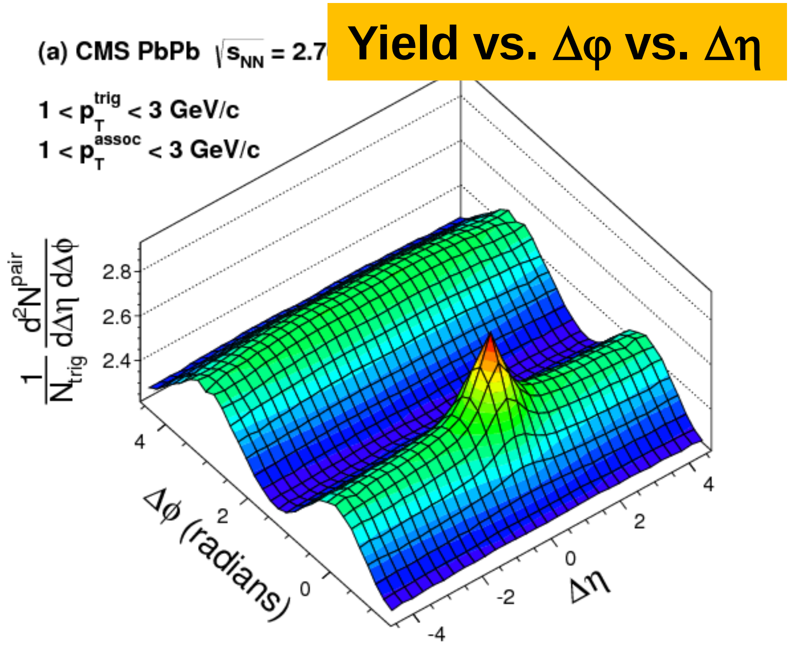
Some surprises…

Recap Two-Particle Correlations

- For v_n measurement, we discussed contribution from flow and non-flow ((mini)jets)
- This can also be looked at in two dimensions
  - Azimuth $\Delta\varphi$ and pseudorapidity $\Delta\eta$

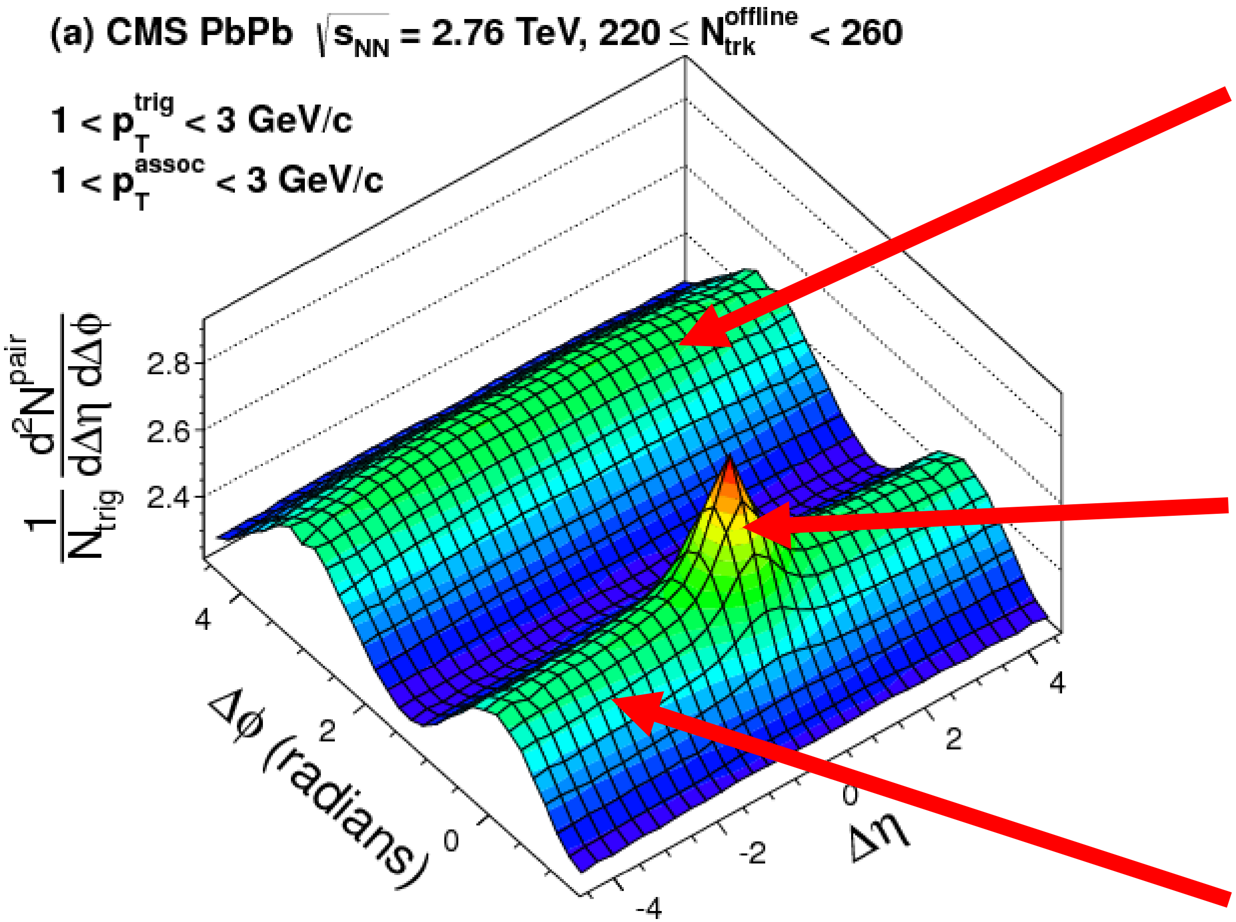






Yield vs. $\Delta\varphi$ vs. $\Delta\eta$

Typical Two-Particle Correlation

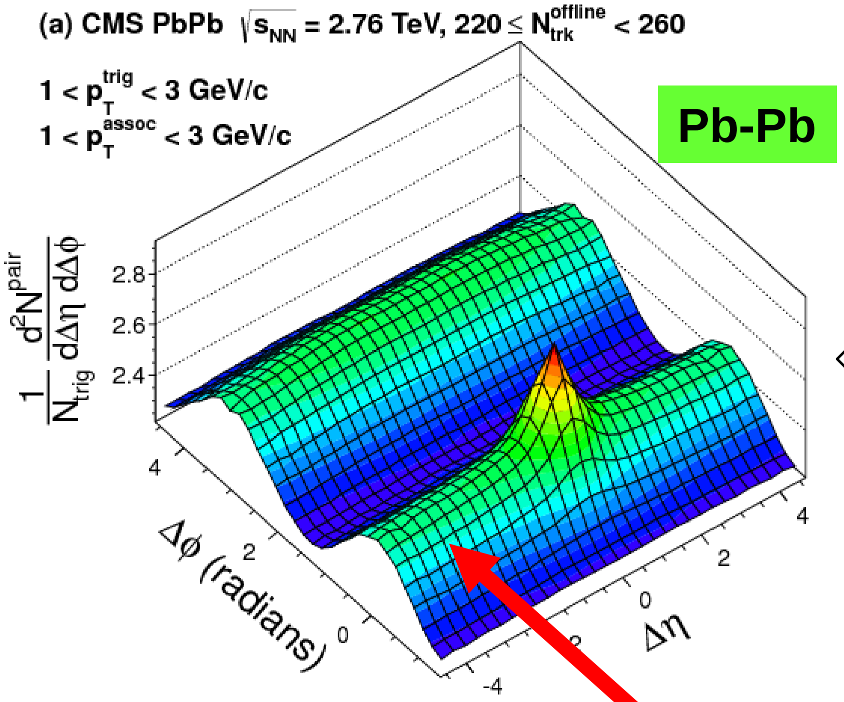


Away-side jet + flow
($\Delta\varphi \sim \pi$, elongated in $\Delta\eta$)

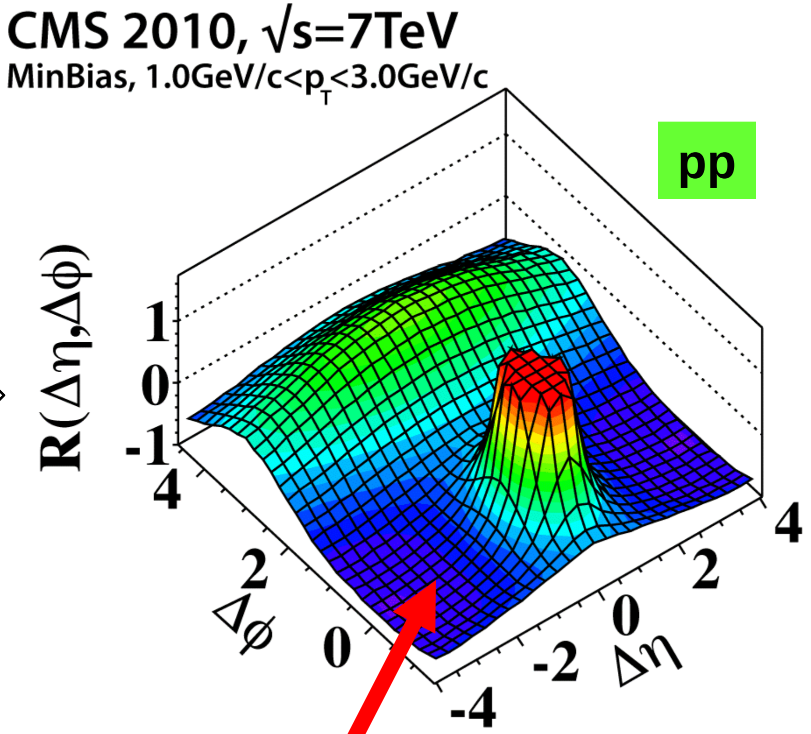
Near-side jet
+ resonances, ...
($\Delta\varphi \sim 0$, $\Delta\eta \sim 0$)

Near-side flow ridge
($\Delta\varphi \sim 0$, elongated in $\Delta\eta$)

Pb-Pb vs. pp



Pb-Pb



pp

Near-side ridge (flow) only in Pb-Pb

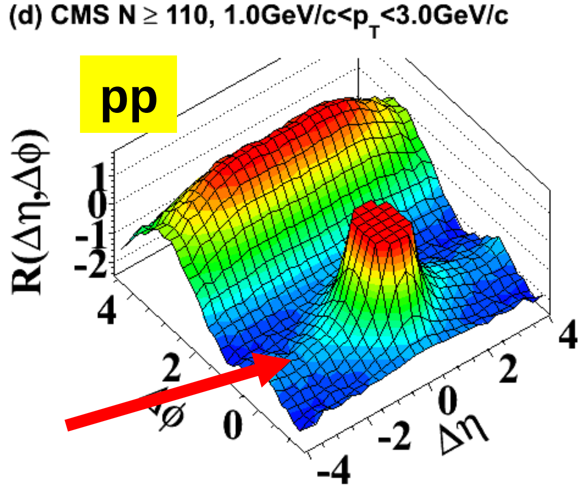
at least everyone thought so for a long time…

here: $\eta = \eta_{lab}$

Near-Side Ridge

- …observed in very high-multiplicity pp collisions
  - 0.005% events with highest multiplicity

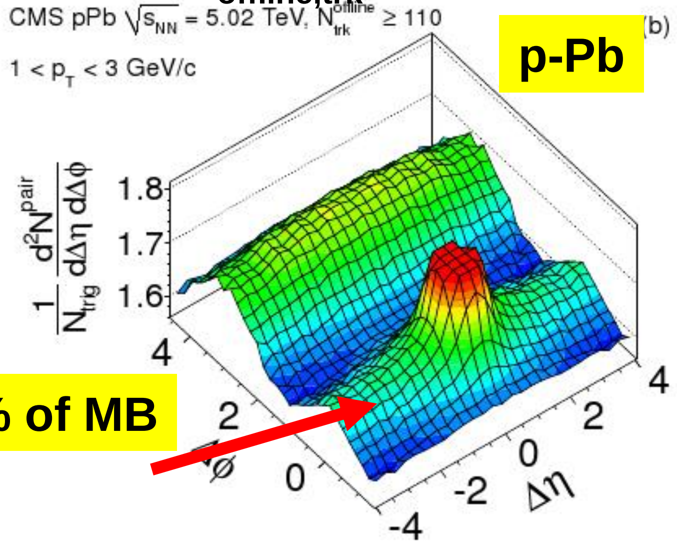
0.005% of MB



CMS, JHEP09(2010)091

$N_{offline,trk} > 110$

- …observed in high multiplicity p-Pb collisions
  - ~40% events with highest multiplicity
  - Surprisingly large magnitude



3.1% of MB

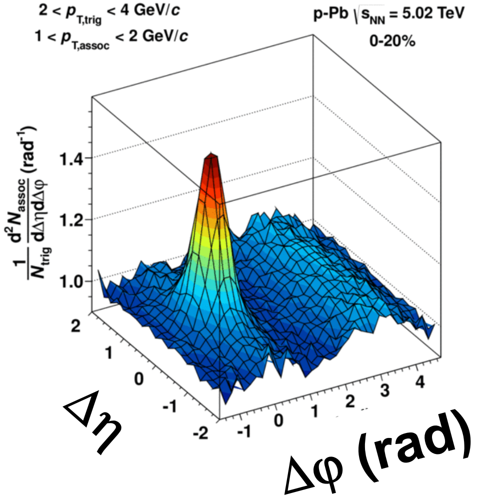
CMS, PLB718 (2013) 795

here: $\eta = \eta_{lab}$

The Double Ridge

- Subtraction procedure to “isolate” ridge contribution from jet correlations
  - No ridge seen in 60-100% and similar to pp

0-20%



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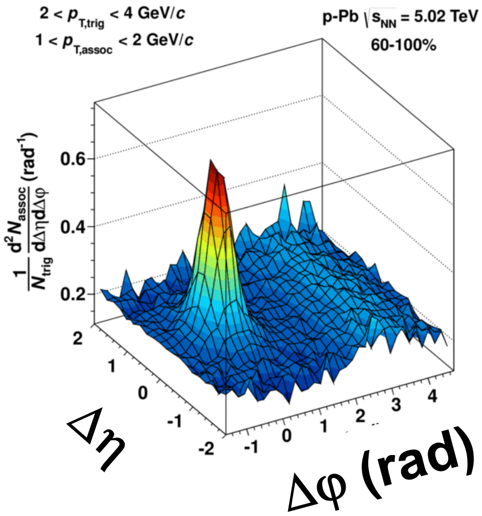
60-100%



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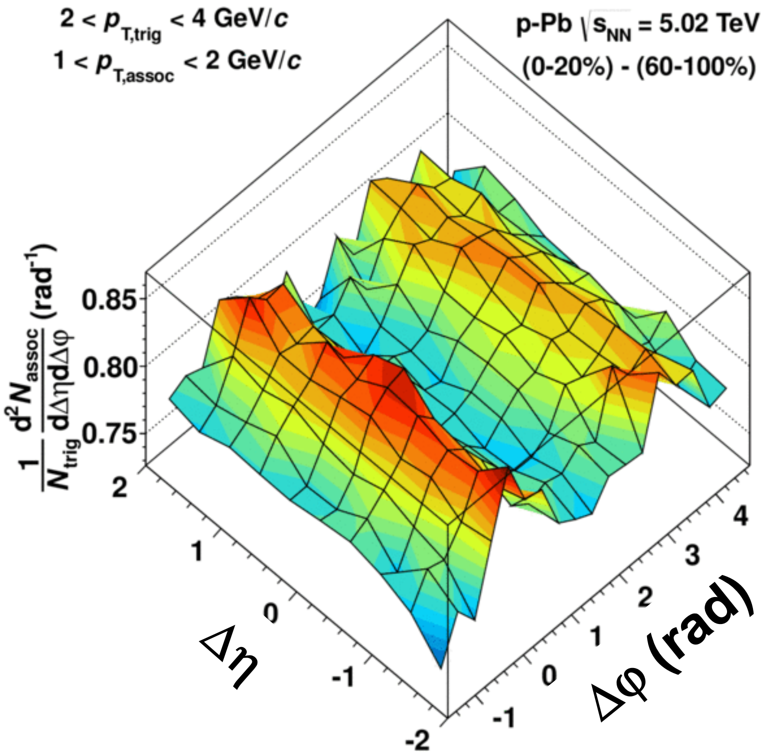


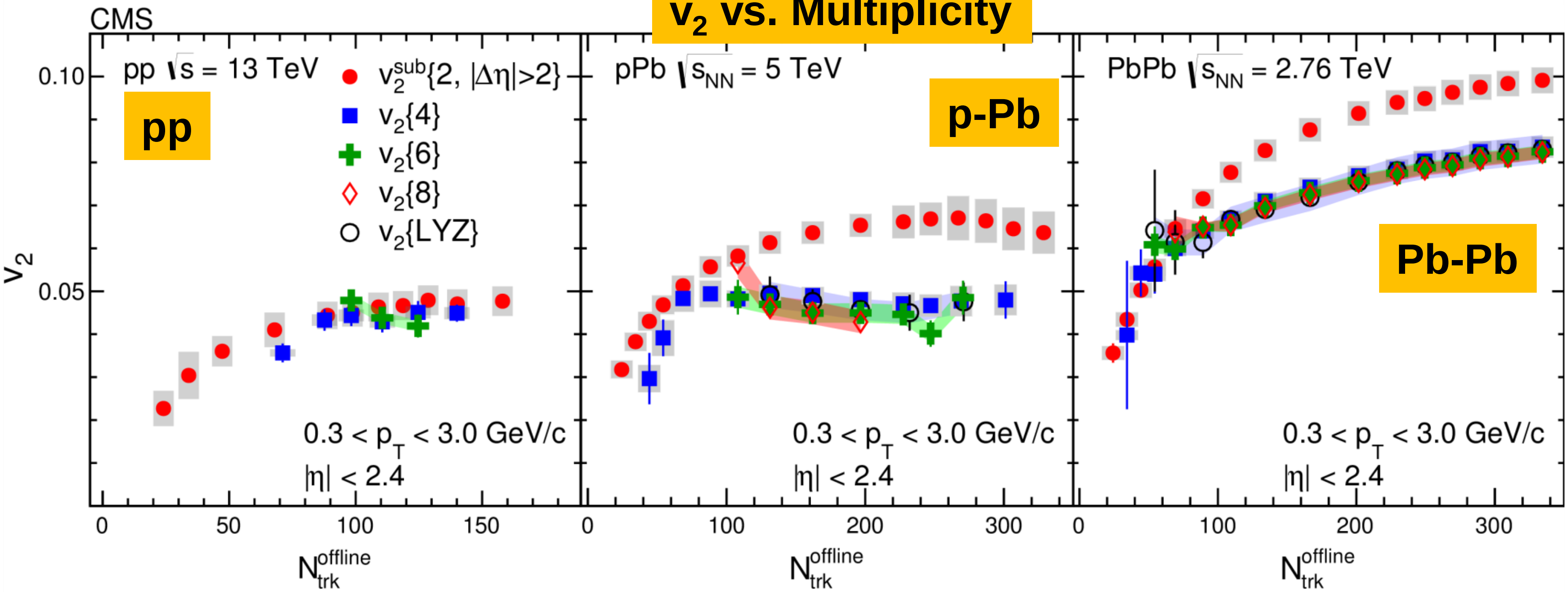
Two ridges !

ALICE, PLB719 (2013) 29

Today's Understanding

- Various "HI observables" in p-Pb and high-multiplicity pp
  - v_2, v_3, …
  - Multi-particle correlation $v_2\{4\} = v_2\{6\} = v_2\{8\}$
  - Mass ordering of particle species E.g. $v_2\{p\} < v_2\{\pi\}$ for $p_T < 2$ GeV/c

v_2 vs. Multiplicity

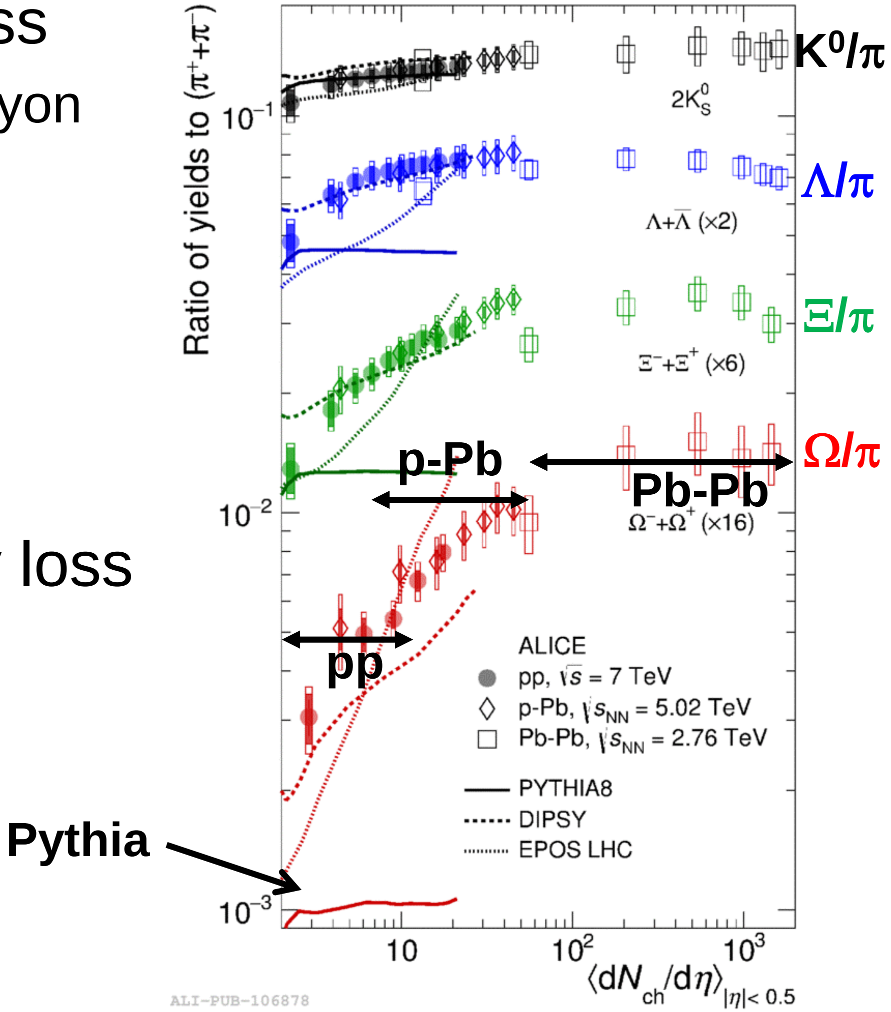


PLB 765 (2017) 193

Today’s Understanding (2)

- Particle ratios and strangeness
  - Smooth increase of strange baryon production
  - From pp, over p-Pb to Pb-Pb
  - Multiplicity dependence not reproduced by MC generators
- But: No sign of parton energy loss

Strange / π ratio vs. N_{ch}



Nature Phys. 13 (2017) 535

Summary Collectivity in Small Systems

- Typical Pb-Pb collision effects observed in pp and p-Pb
- Paradigm shift in interpretation of small systems
- Many hints that (mini) QGP is created in high-multiplicity p-Pb collisions (and pp collisions?)

For LHC	pp	p-Pb	Pb-Pb
Size collision region (fm^2)	2	12	150
Volume at freeze-out (fm^3)	25	160	5000
Energy density (GeV/fm^3)	?	3 (?)	10

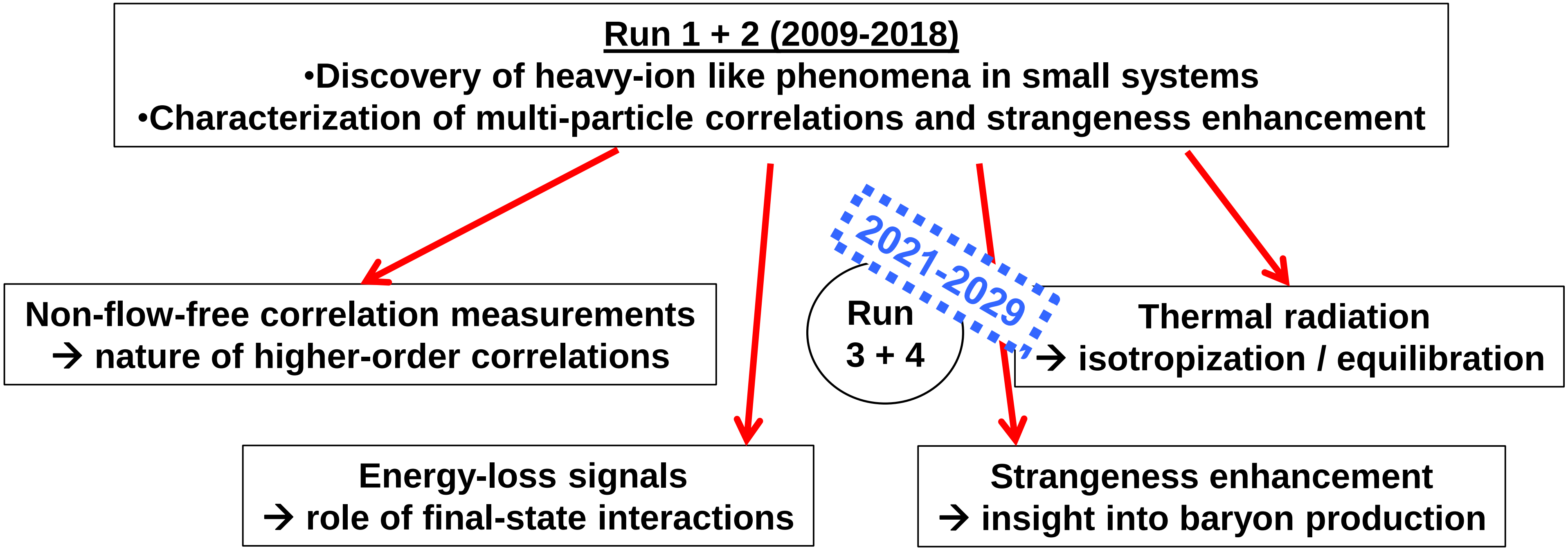
- Debate on influence of the initial state effect as opposed to a collective approach (rescattering)

⇨ more info

Topic of ongoing exciting research – Stay tuned… or even better: join in!

What Next?

- Observations challenge two paradigms at once
  - For how small systems does the HI “standard model” remain valid?
  - Can the standard tools for pp physics remain standard?



Run 1 + 2 (2009-2018)

•Discovery of heavy-ion like phenomena in small systems

•Characterization of multi-particle correlations and strangeness enhancement

Run 3 + 4

2021-2029

Non-flow-free correlation measurements → nature of higher-order correlations

Energy-loss signals → role of final-state interactions

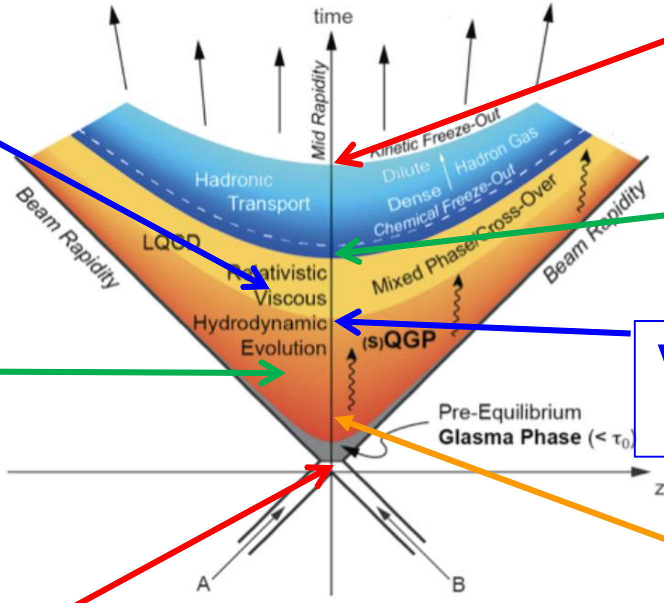
Strangeness enhancement → insight into baryon production

Thermal radiation → isotropization / equilibration

Chance to find unified description of underlying dynamics across system size

Summary
Medium Evolution

$dN_{ch}/d\eta$ ~ 1600 particles



Courtesy B.Hippolyte

Large pressure
↓
collective flow

Dense medium
↓
Energy loss,
Quarkonia melting

Density fluctuations
↓
spatial anisotropies

Kinetical freeze-out
~ 90 MeV

Chemical freeze-out
~ 155 MeV

Viscous hydrodynamics
η/s ~ 0.08 – 0.16

Initial temperature*
~ 300 MeV

Values for central $\sqrt{s_{NN}}$ = 2.76 TeV collisions (LHC)
* from direct photons (not discussed)

Take-Home Messages

- Dense colored strongly coupling medium is produced in heavy-ion collisions (the *Quark-Gluon Plasma*)
  - Particle production is strongly suppressed
- Created matter is in local thermal equilibrium
  - Particle production described by statistical models
  - Expansion described by viscous hydrodynamics “perfect liquid”
- Recent discoveries and observations in p-Pb collisions hint at collective “QGP-like” effects in small systems
  - Universal description across system size?

Thank you for your attention

Many thanks for useful discussions and inspiring previous lectures to Federico Antinori, Davide Caffarri, Leticia Cunqueiro, Andrea Dainese, Michele Floris, Alexander Kalweit, Andreas Morsch, Raimond Snellings, Alberica Toia

Backup

Fluctuations

- Initial-state density fluctuations cause higher-order flow
- For a given order
  - Value is not the same event by event
  - Usually we look at averages

$$\left\langle e^{in(\varphi_1-\varphi_2)}\right\rangle = v_n^2 \text{ means actually } \left\langle \left\langle e^{in(\varphi_1-\varphi_2)}\right\rangle_{tracks}\right\rangle_{events} = \langle\langle 2\rangle\rangle = \langle v_n^2\rangle$$

$$\langle\langle 4\rangle\rangle = -\langle v_n^4\rangle \text{ etc.}$$

  - However we look for $\langle v_n\rangle$
- $\langle v_n\rangle^k = \langle v_n^k\rangle$ without fluctuations

non-flow not shown for simplicity

for $\sigma_{v_n} << \langle v_n\rangle$

Deviates with fluctuations

$$v_n\{2\} = \langle v_n^2\rangle^{1/2} \approx \langle v_n\rangle \boxed{+\frac{1}{2}\frac{\sigma_{v_n}^2}{\langle v_n\rangle}} \qquad v_n\{4\} = \langle v_n^4\rangle^{1/4} \approx \langle v_n\rangle \boxed{-\frac{1}{2}\frac{\sigma_{v_n}^2}{\langle v_n\rangle}}$$

fluctuation

average

Fluctuations (2)

- v_2 distribution is broad
- Influence of fluctuations significant
- Estimate of fluctuations

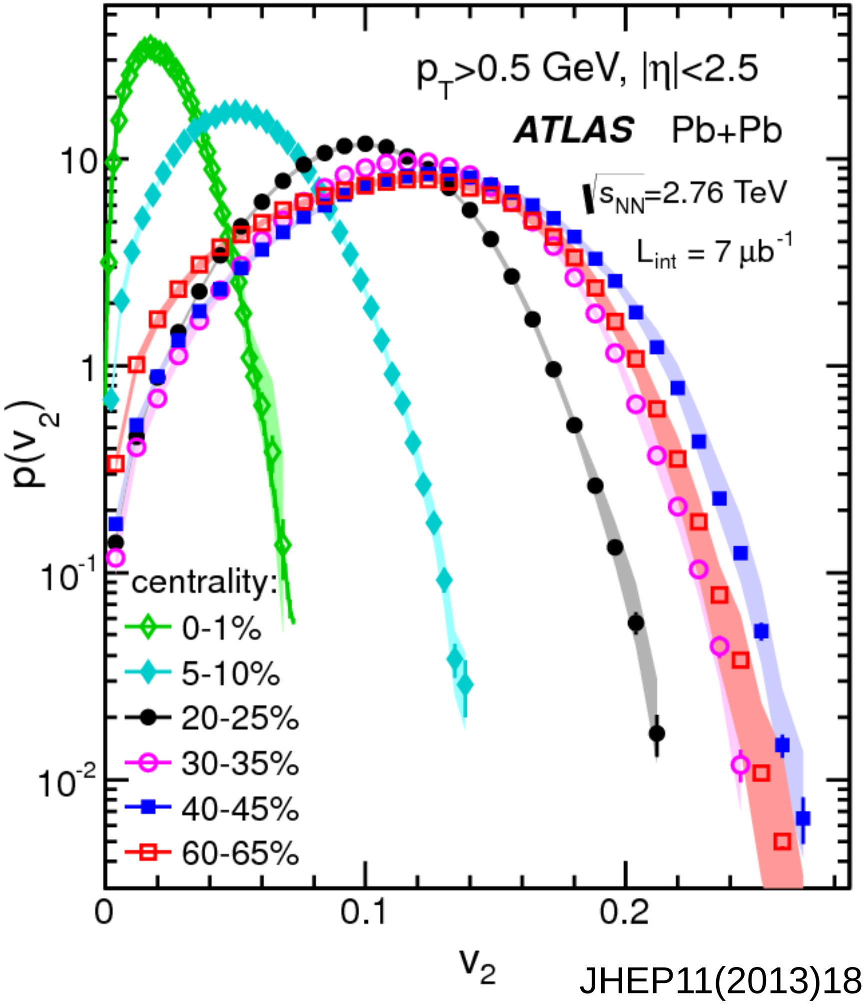
$$v_n\{2\} \approx \langle v_n \rangle + \frac{1}{2}\frac{\sigma_{v_n}^2}{\langle v_n \rangle}$$

$$v_n\{4\} \approx \langle v_n \rangle - \frac{1}{2}\frac{\sigma_{v_n}^2}{\langle v_n \rangle}$$

$$\frac{\sigma_{v_n}}{\langle v_n \rangle} \approx \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}}$$

$$\boxed{\textbf{for } \sigma_{v_n} << \langle v_n \rangle}$$

$P(v_2)$ vs v_2



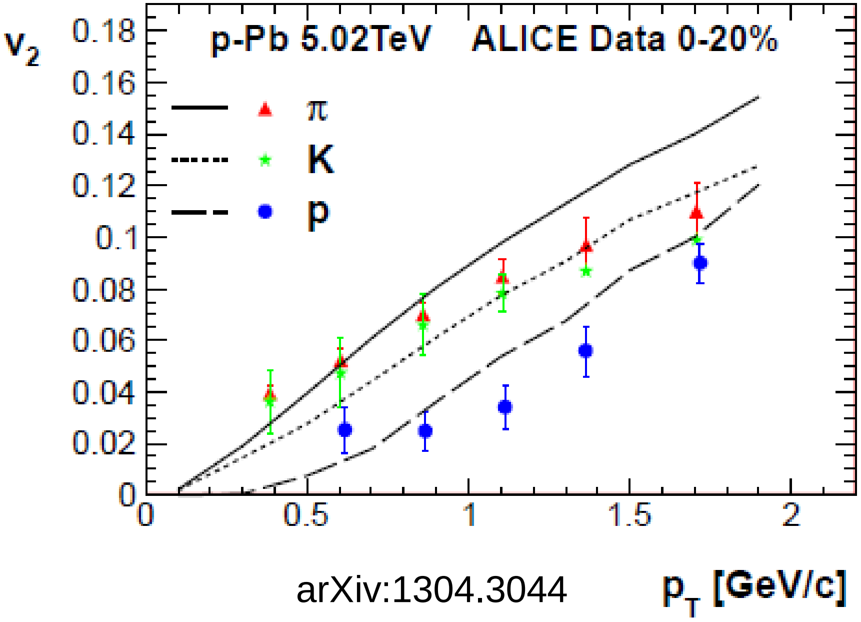
JHEP11(2013)183

Interpretation

Hydro?

- Observed effects associated to hydrodynamical evolution in Pb-Pb collisions
- Hydrodynamics in p-Pb collisions?
  - Number of interactions?
  - Sufficient time for constituents to see each other?
- Hydrodynamics in p-Pb collisions reproduces measurements
  - Assuming 0.2-0.6 fm/c for beginning of hydro evolution

v_2: Hydro vs. Data



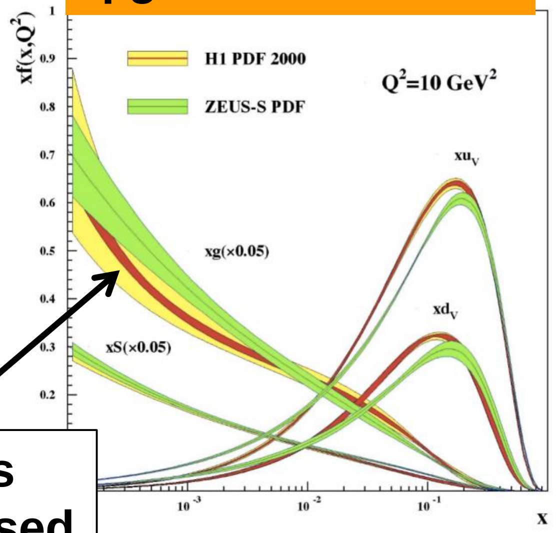
arXiv:1304.3044

Interpretation

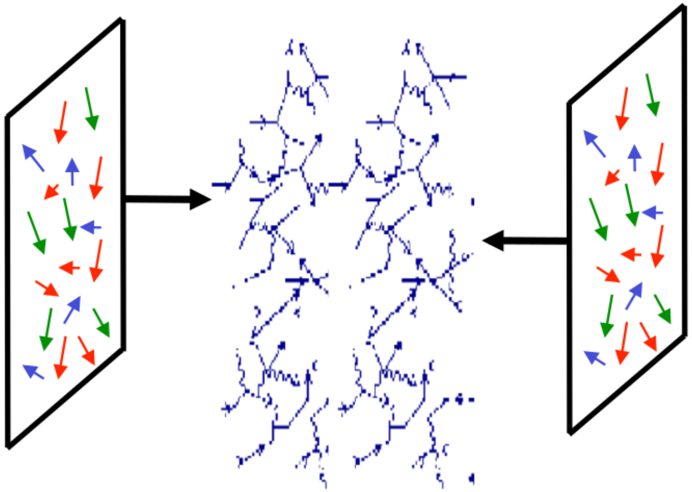
Initial-state effect?

- At low x, gluon density rises
- In nucleus density increases by $A^{1/3} \sim 6$ → saturation
- Model of *Color Glass Condensate*

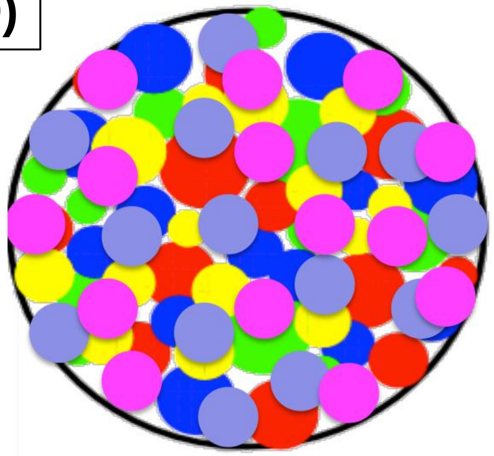
q/g densities vs. x



Gluons (suppressed by factor 20)

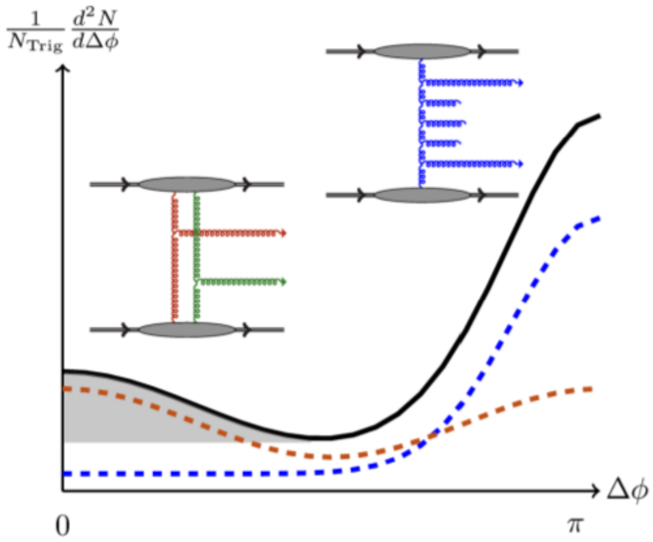


Color: gluon color charge
Glass: solid on short time scale, liquid on large time scales
Condensate: high density



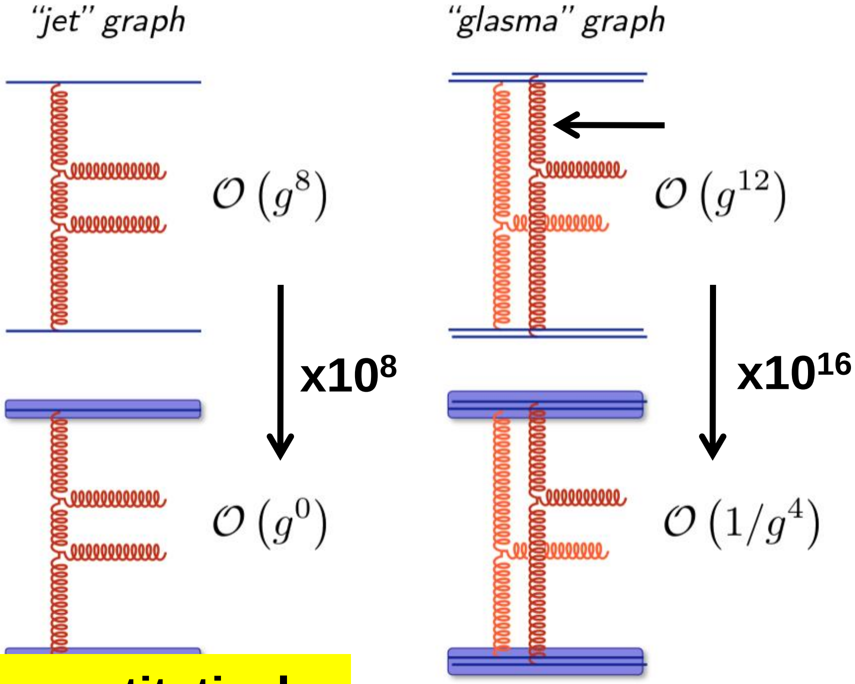
Interpretation (2)
Initial-state effect?

- Saturation enhances certain graphs by orders of α_S
  - Glasma graph enhanced by twice the order of magnitudes than jet graph



Low color density

High color density



Within these models, ridge can be calculated quantitatively

Then there are lots of other qualitative ideas…

PRD 87, 094034 (2013)