Introduction to Heavy Ion Collisions – Experimental

Part1 Collective Flow

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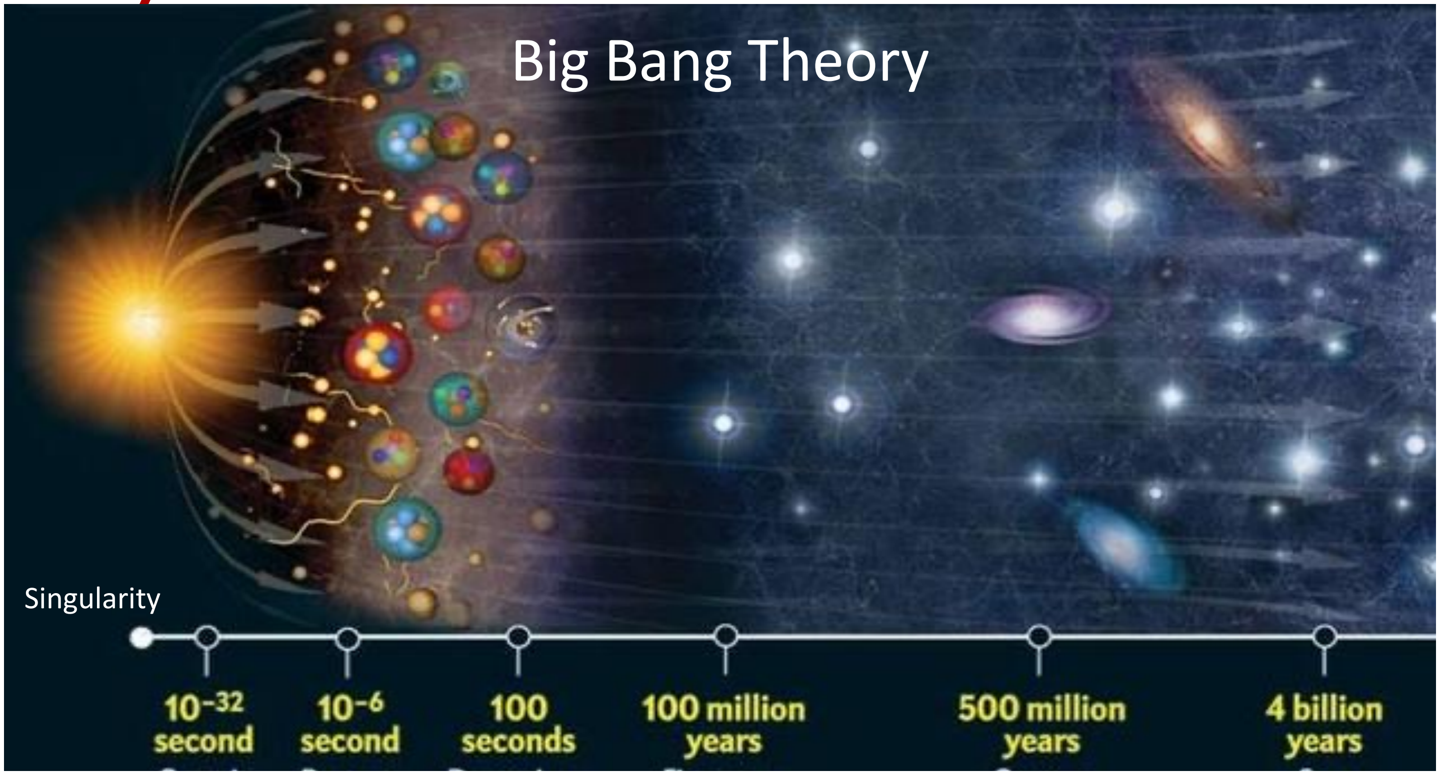
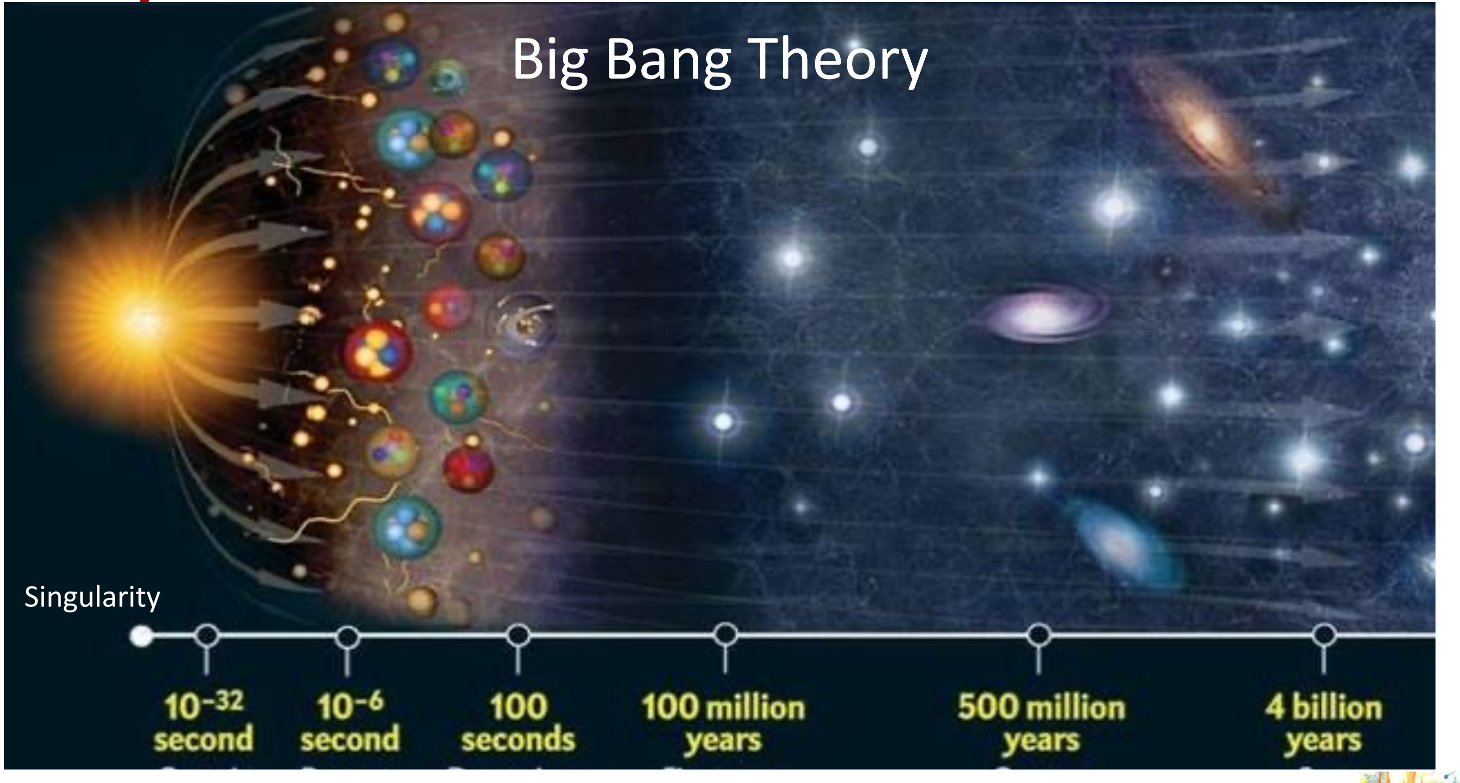
SHANDONG UNIVERSITY

The early universe



inflation protons Deuterium… first star first galaxy star formation peak

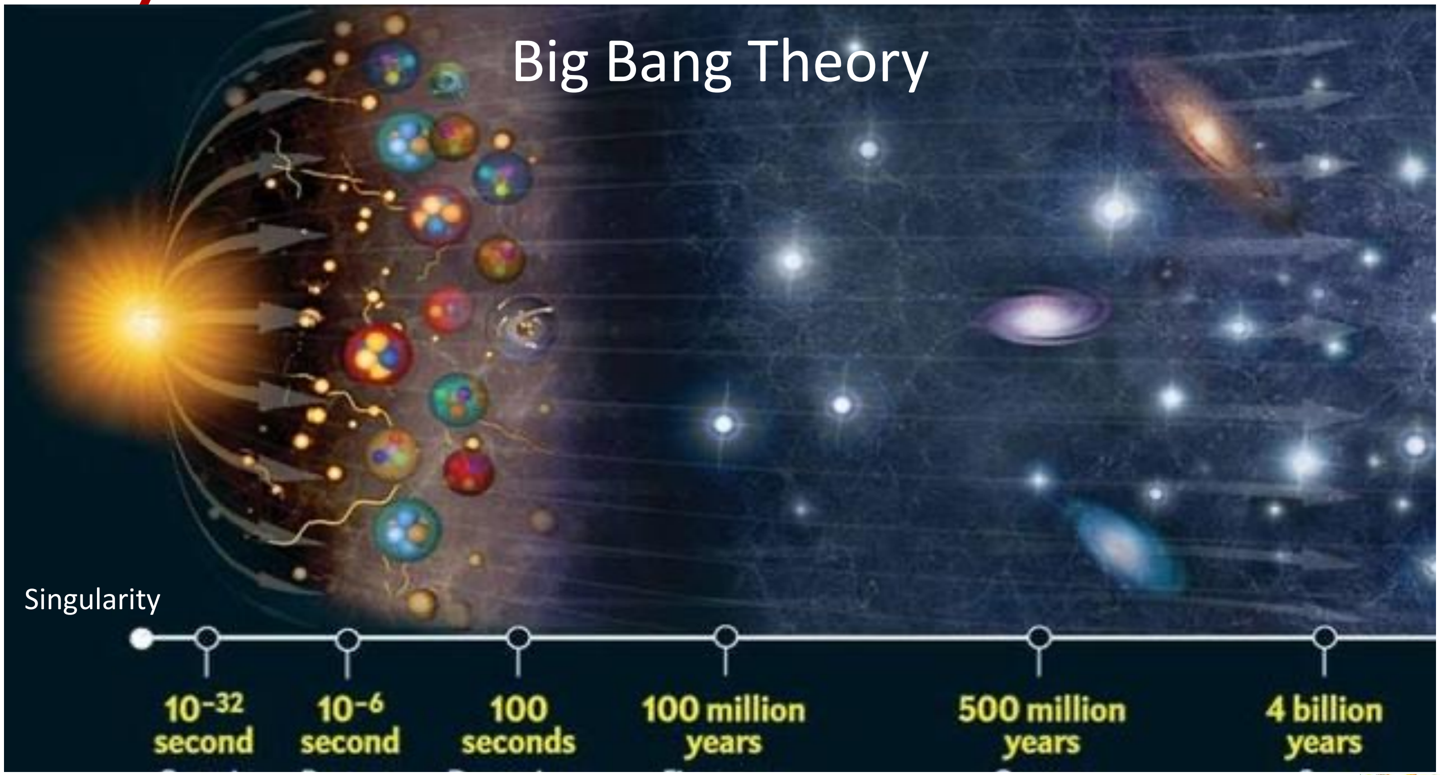
The early universe



inflation protons Deuterium… first star first galaxy star formatic

天地混沌如鸡子（**奇点**），盘古生其中（**暴胀**）
盘古在其中，一日九变（**质子–轻核元素产生**）
天日高一丈，地日厚一丈，盘古日长一丈。如此万八千岁，
天数极高，地数极深，盘古极长（**现今宇宙**）

The early universe



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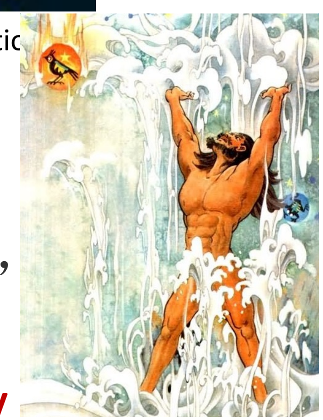

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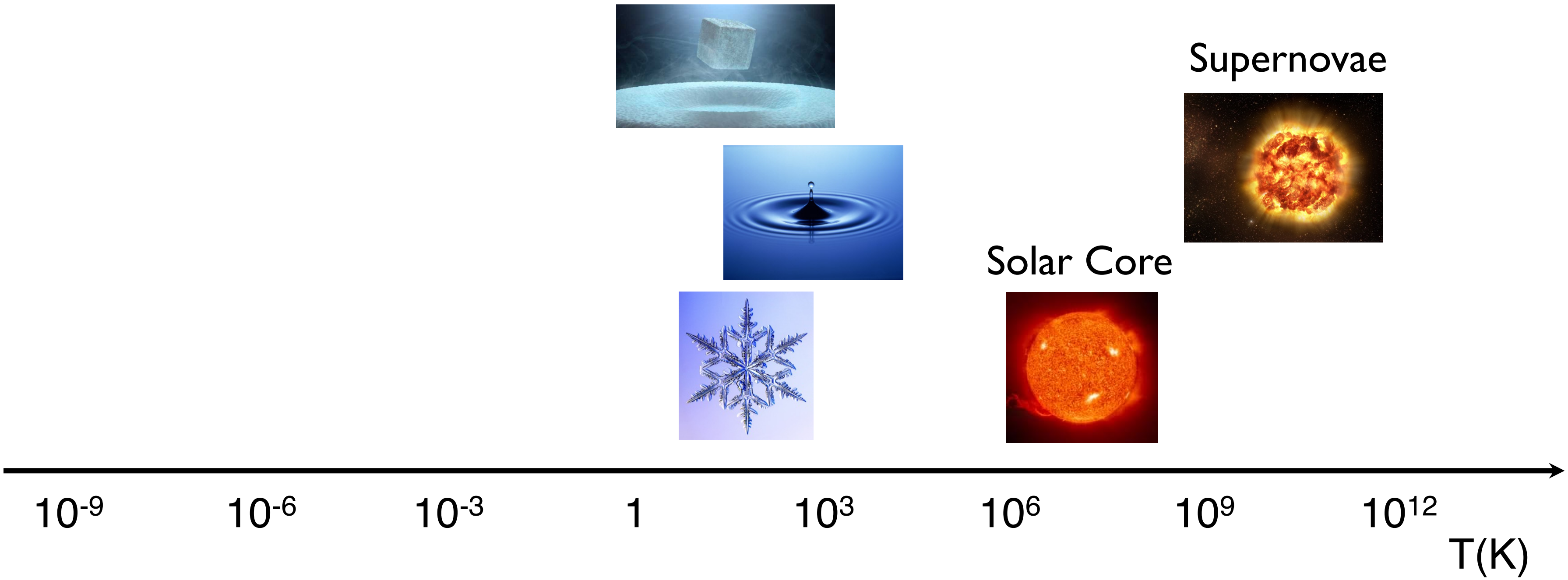
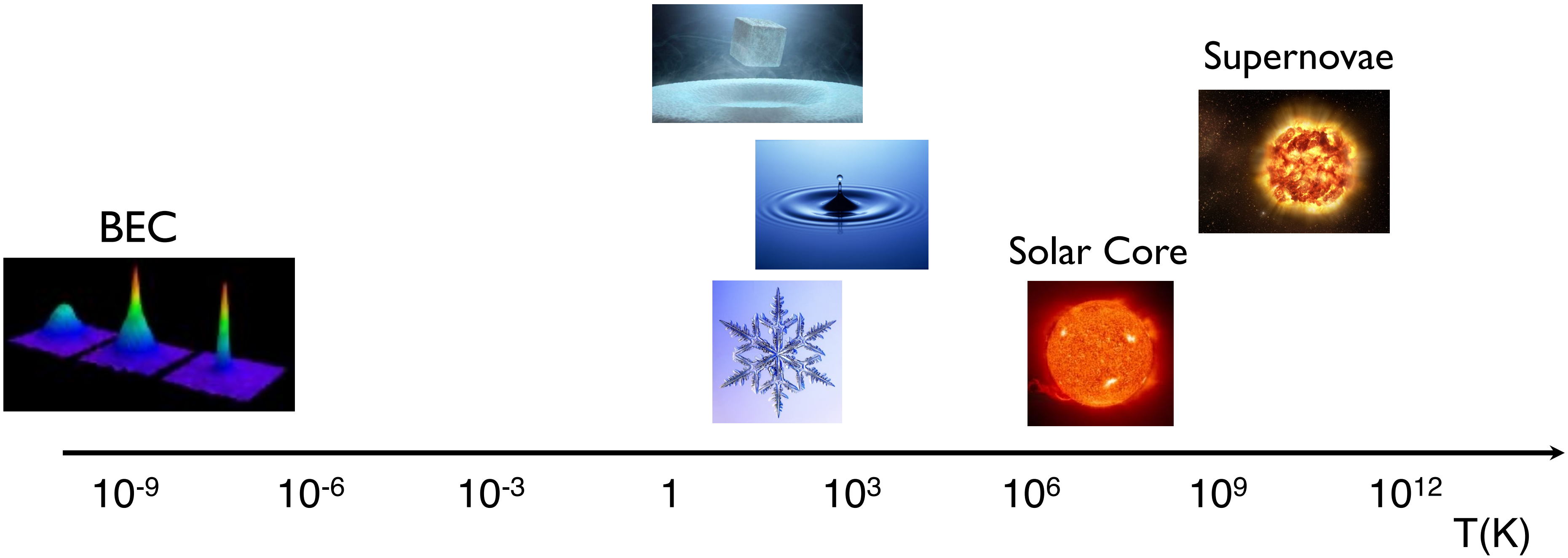
The early universe has high temperature/density

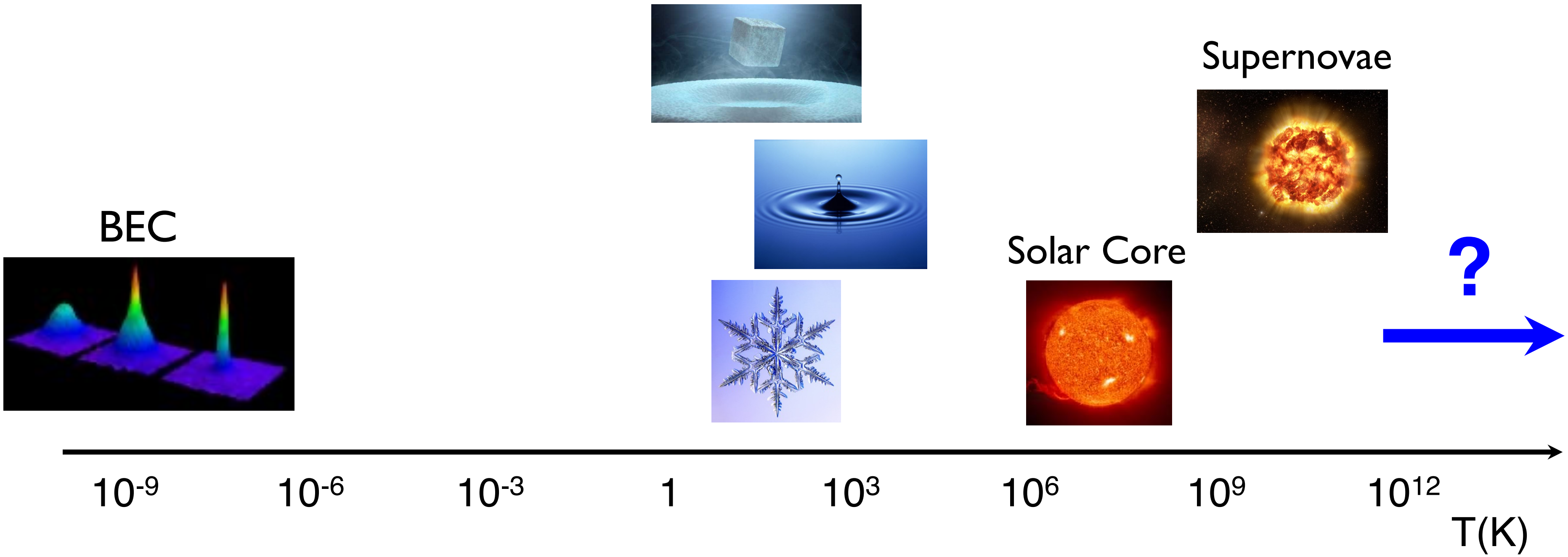
Phases of matter



Phases of matter

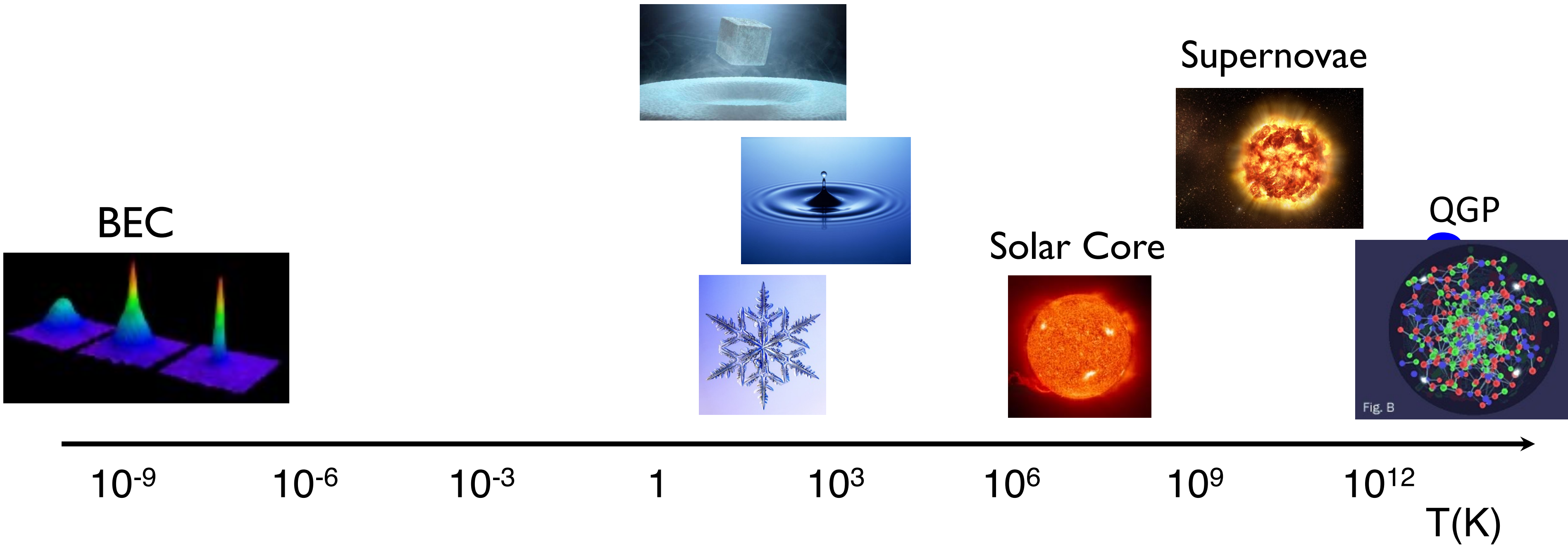


Phases of matter



What are the properties of matter at extremely high temperatures ($>10^{12}$ K)?

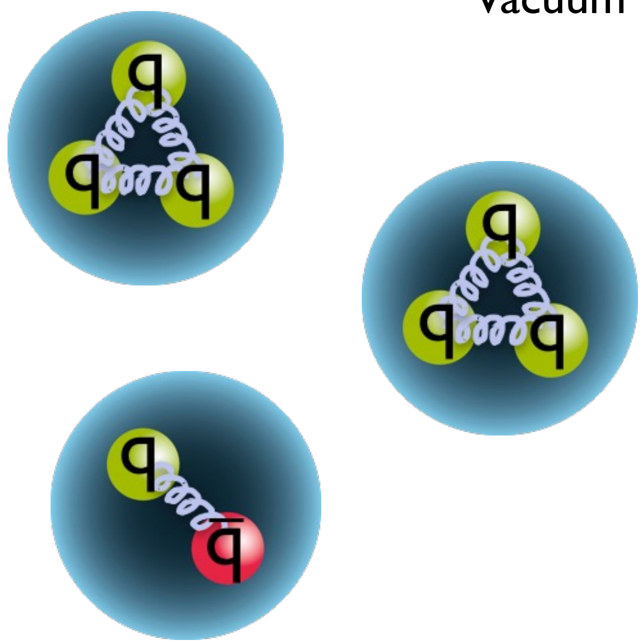
Phases of matter

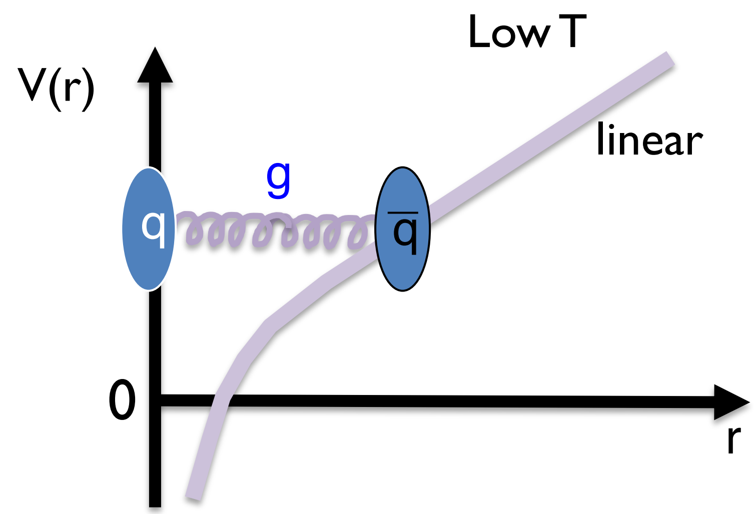


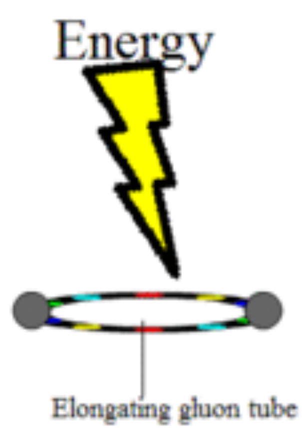
What are the properties of matter at extremely high temperatures ($>10^{12}$ K)?

Confinement → De-confinement

"Vacuum"



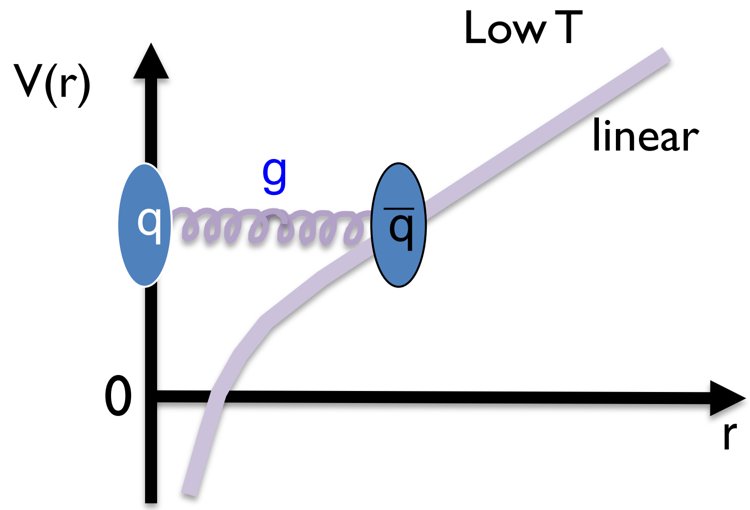




Confinement → De-confinement

"Vacuum"

Taken from "Cooking Master Boy"



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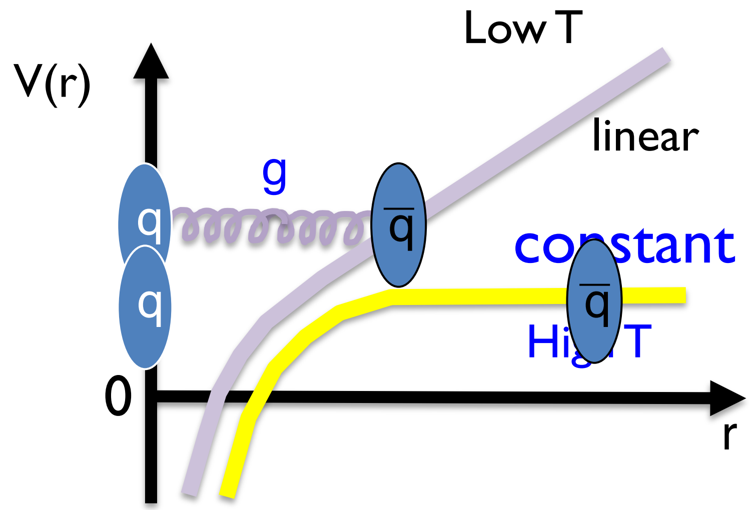

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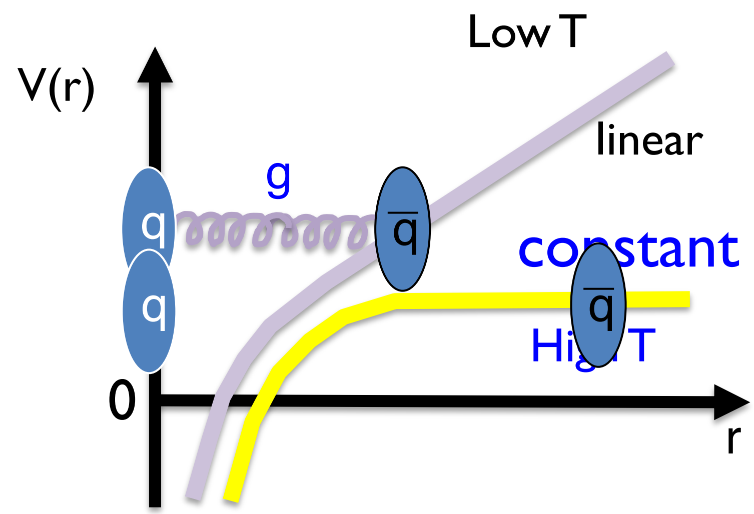
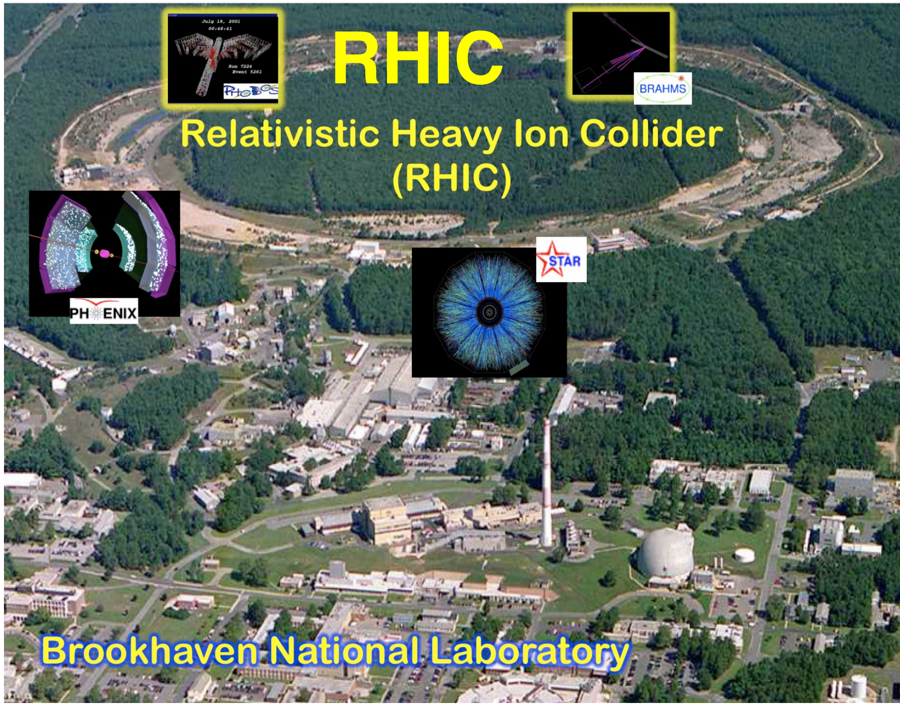
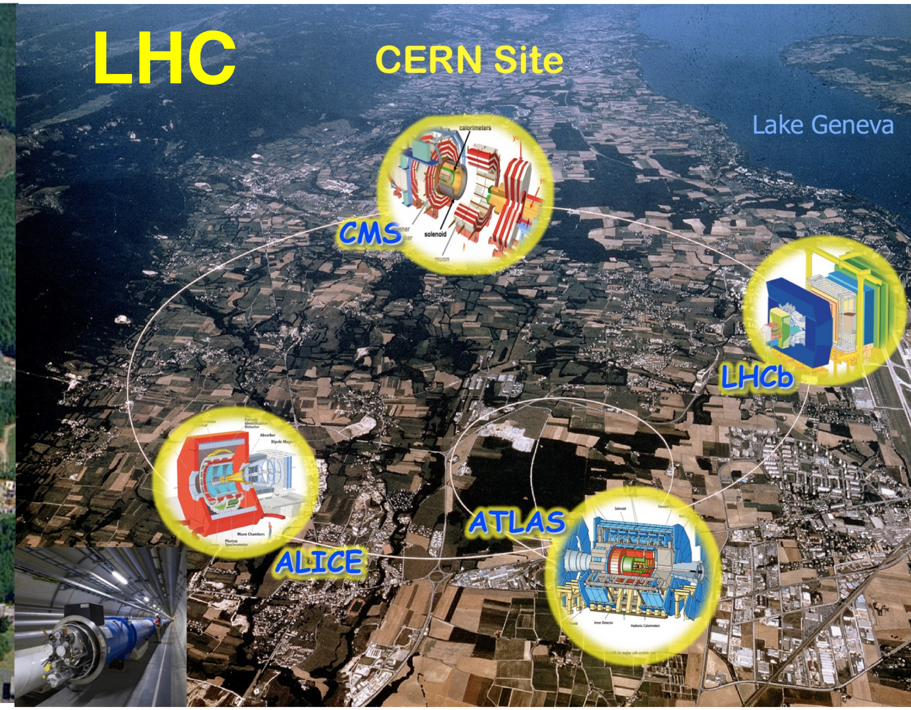


“Quark-Gluon Plasma”
(QGP)

T_C ~ 154 MeV ~ **2×10^{12} K**

Creating QGP in lab





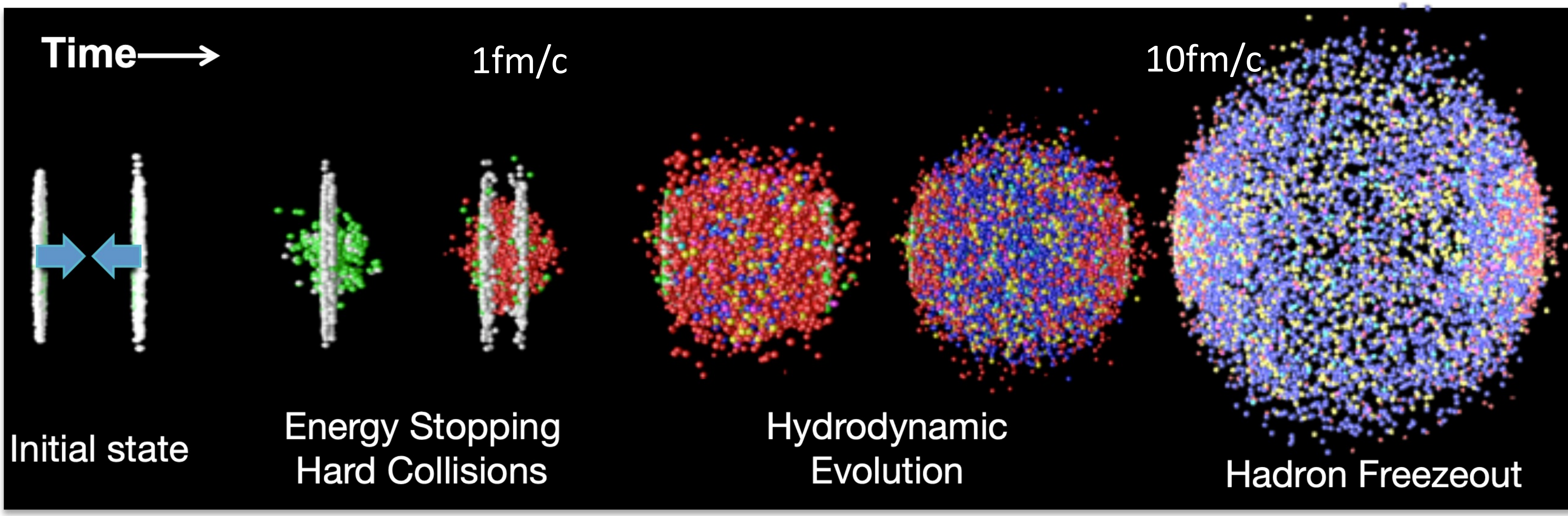
First collisions in 2000

- Diameter 1.2 km
- pp, dAu, CuCu, AuAu, UU, OO, …
- $\sqrt{s_{NN}}$ ~ **0.007 – 0.2 TeV**
- 99.995% speead of light

First collisions in 2010

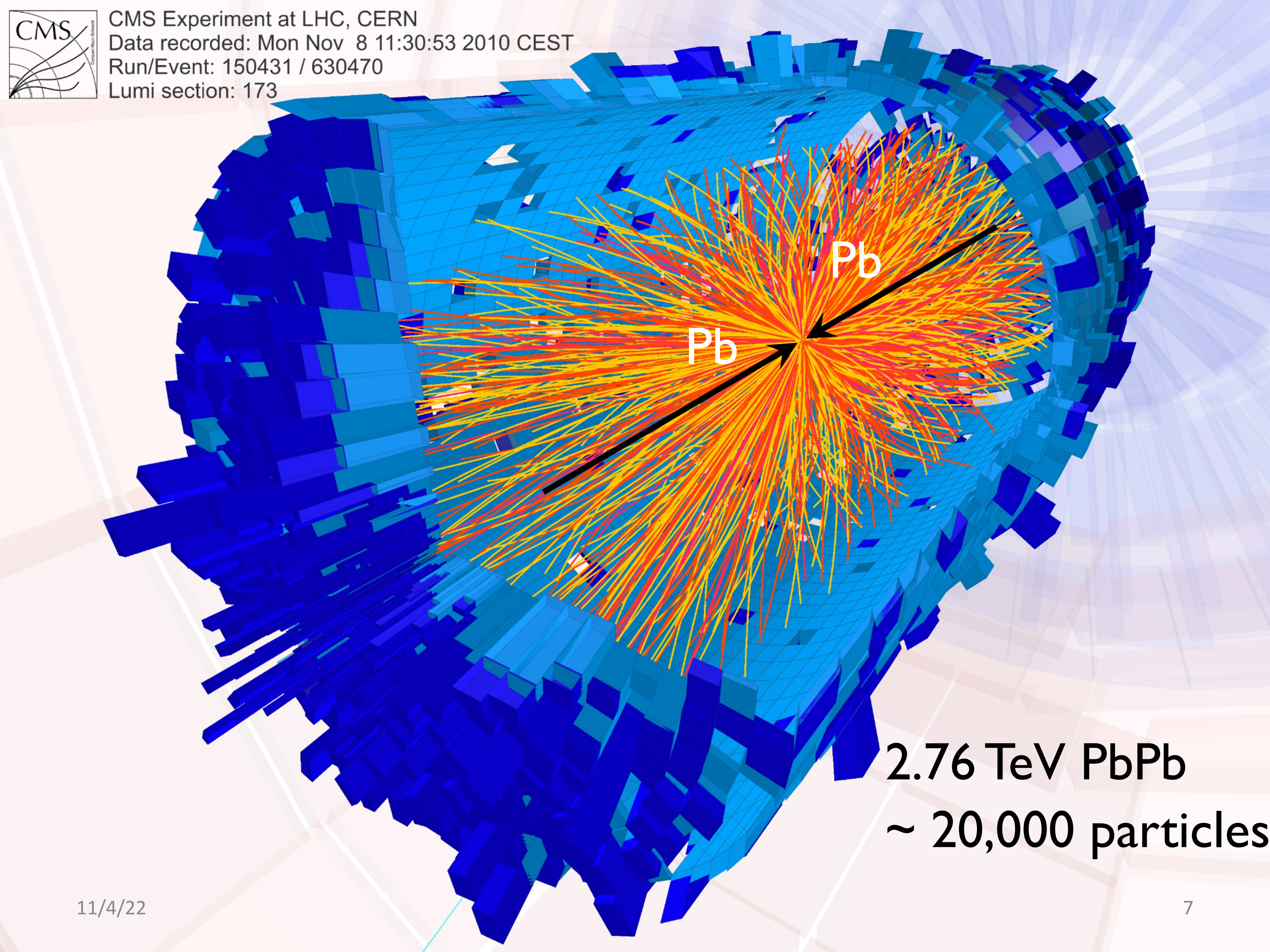
- Diameter 8.6 km
- pp, PbPb, pPb, XeXe
- $\sqrt{s_{NN}}$ ~ **5 – 8 TeV**
- 99.9999991% speead of light

QGP evolution



1 fm/c ≈ 3×10^{-24} s

Extremely short-lived matter

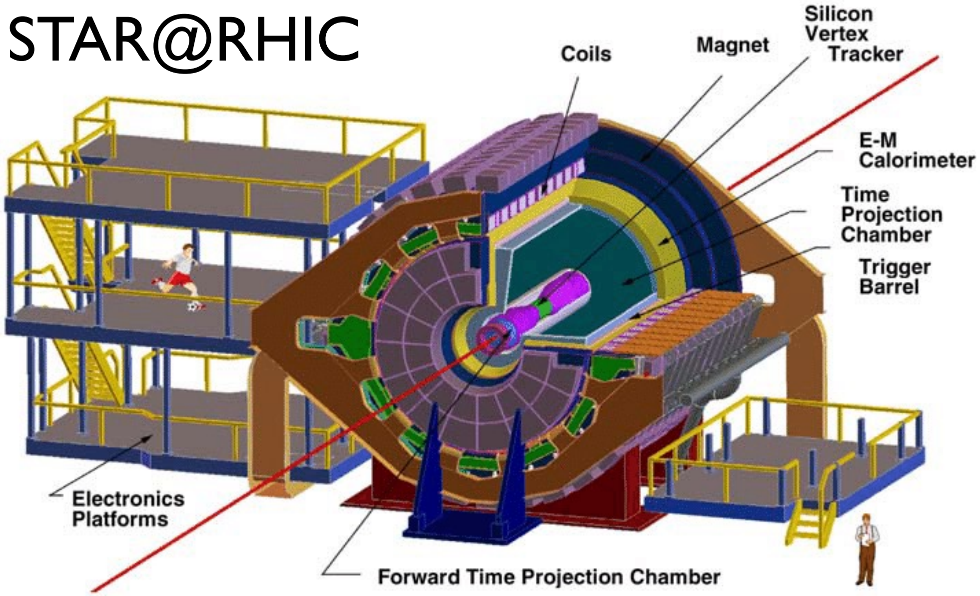


2.76 TeV PbPb

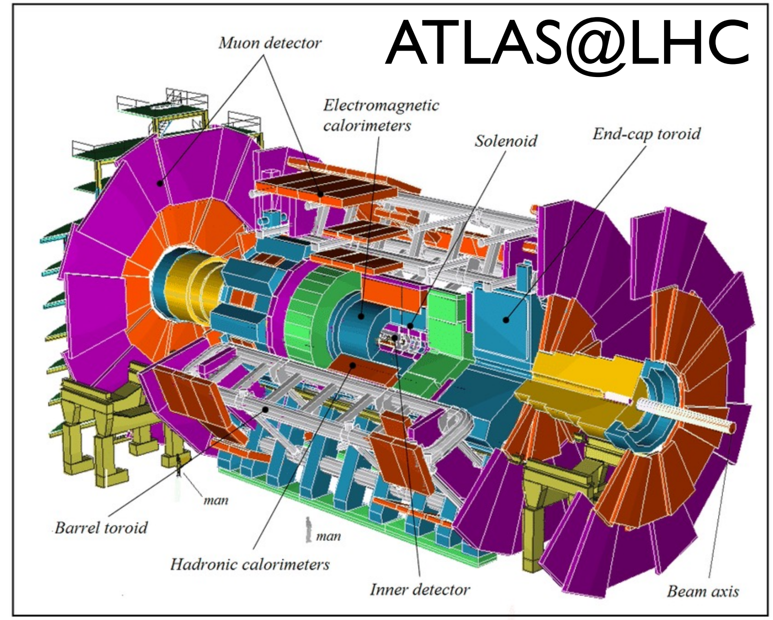
~ 20,000 particles

Detectors

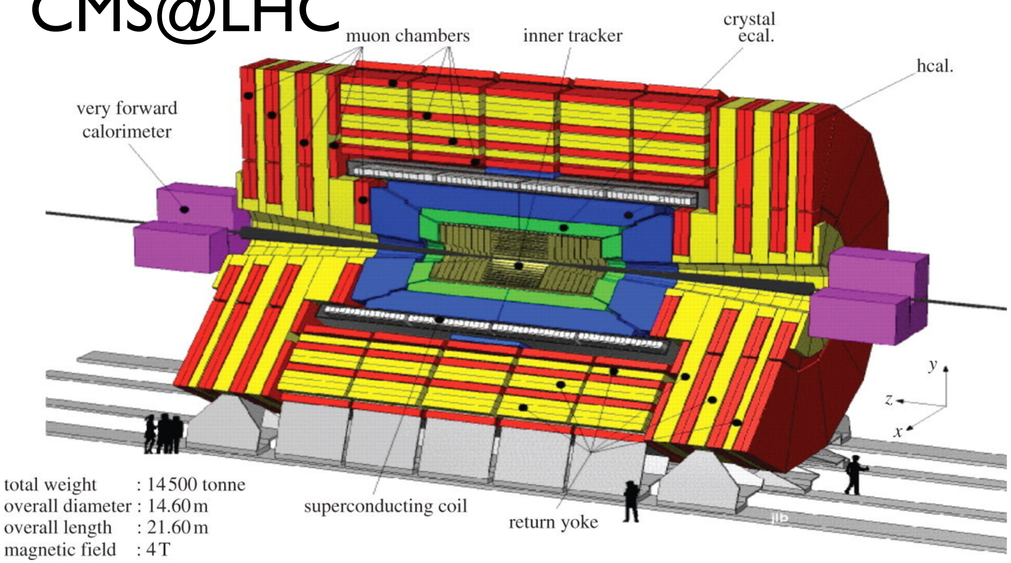
STAR@RHIC

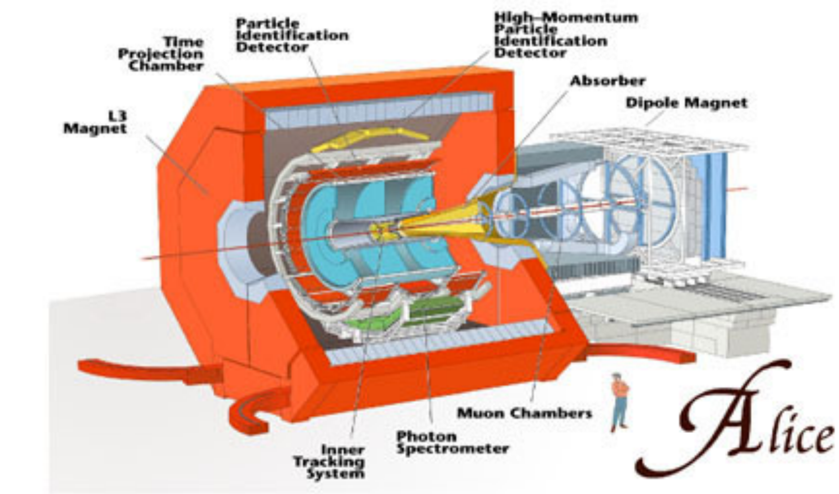


ATLAS@LHC

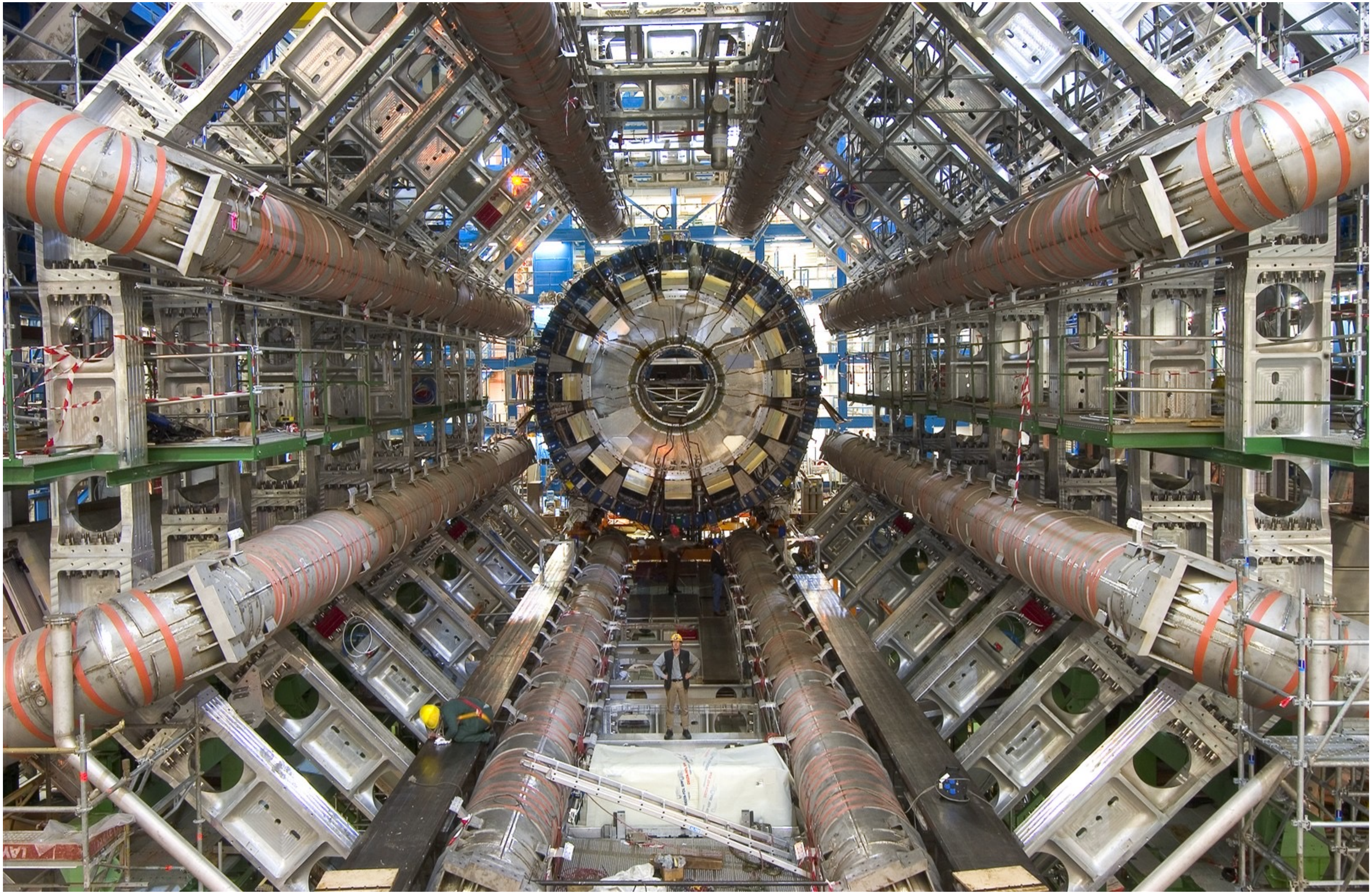


CMS@LHC





Detectors



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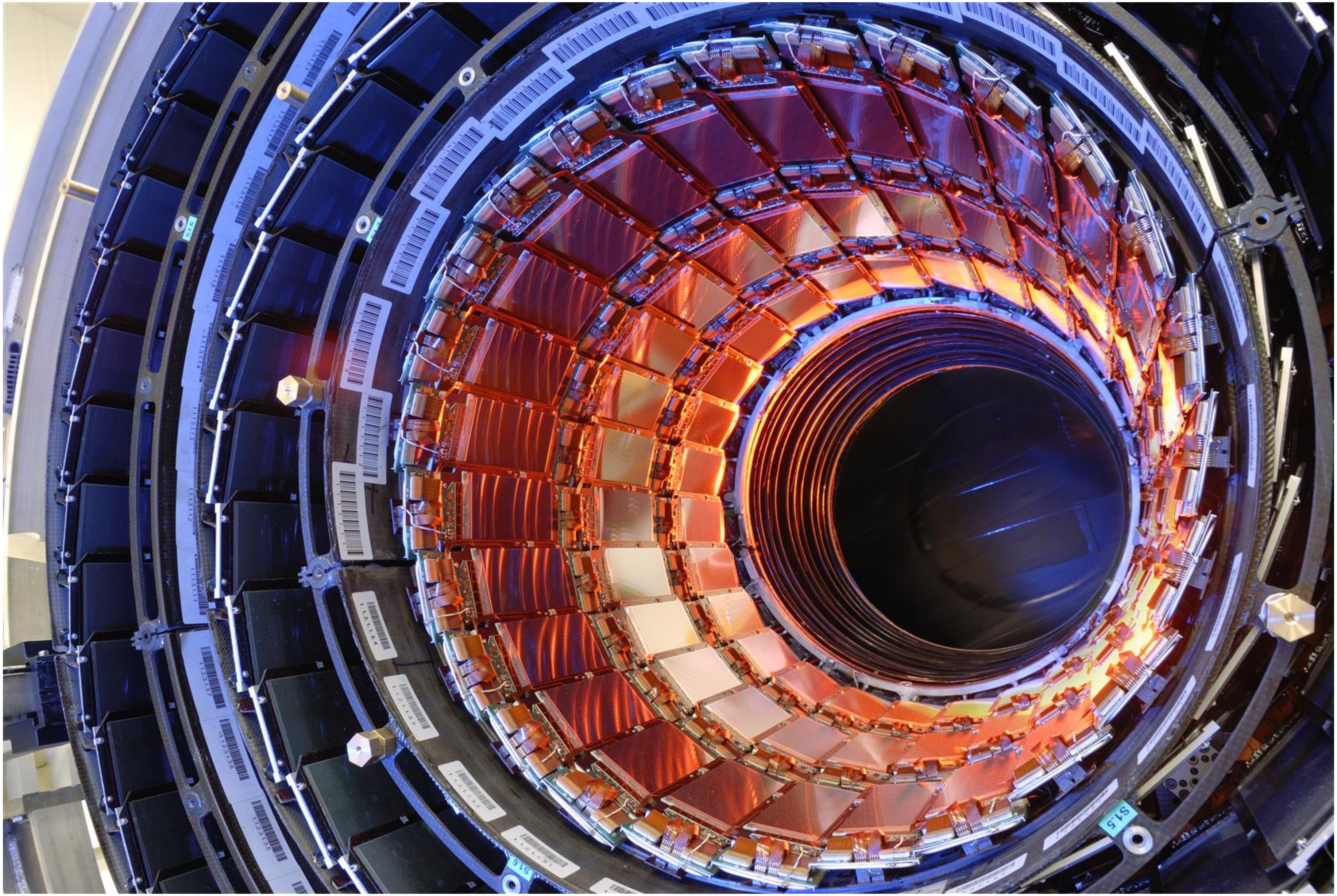

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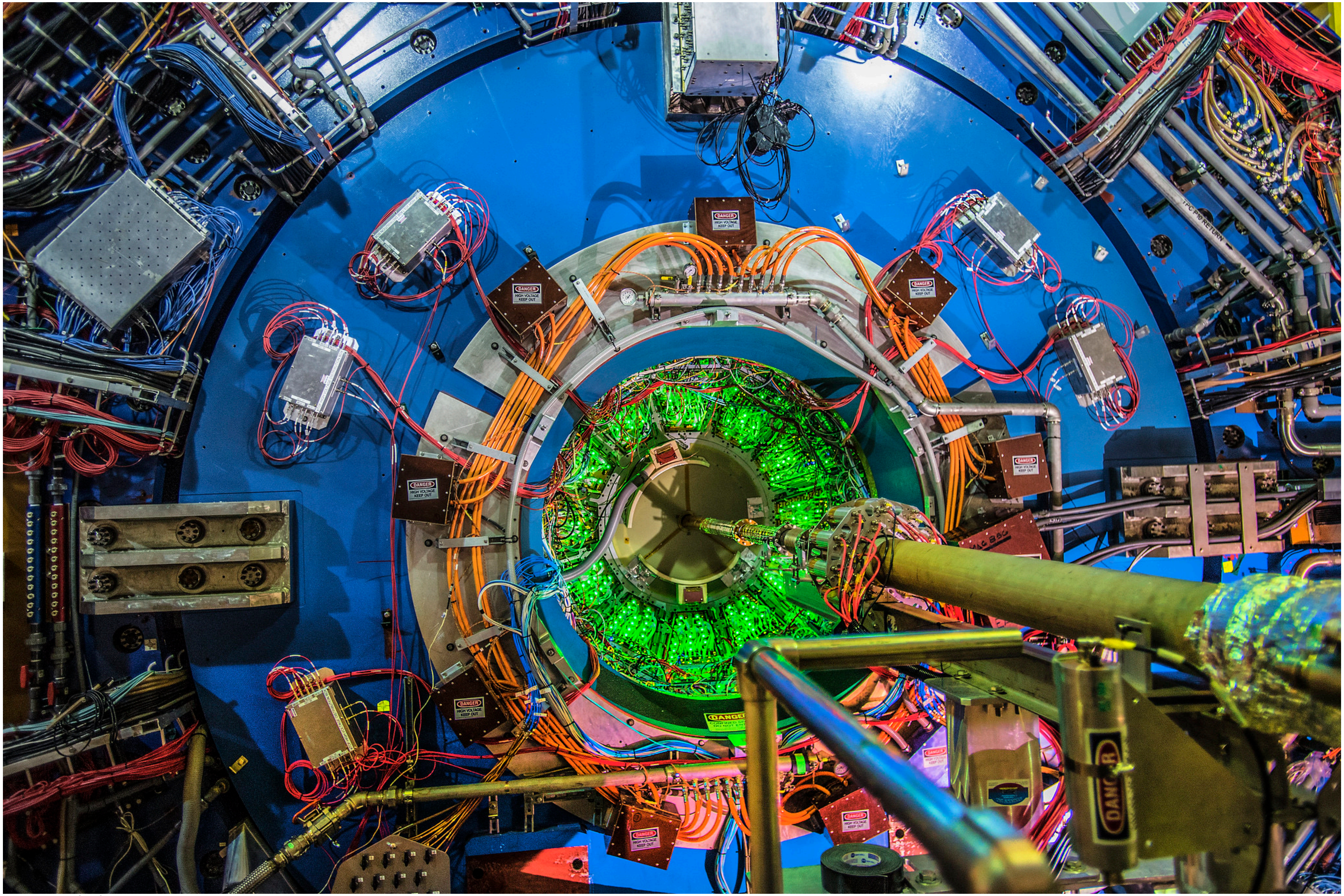
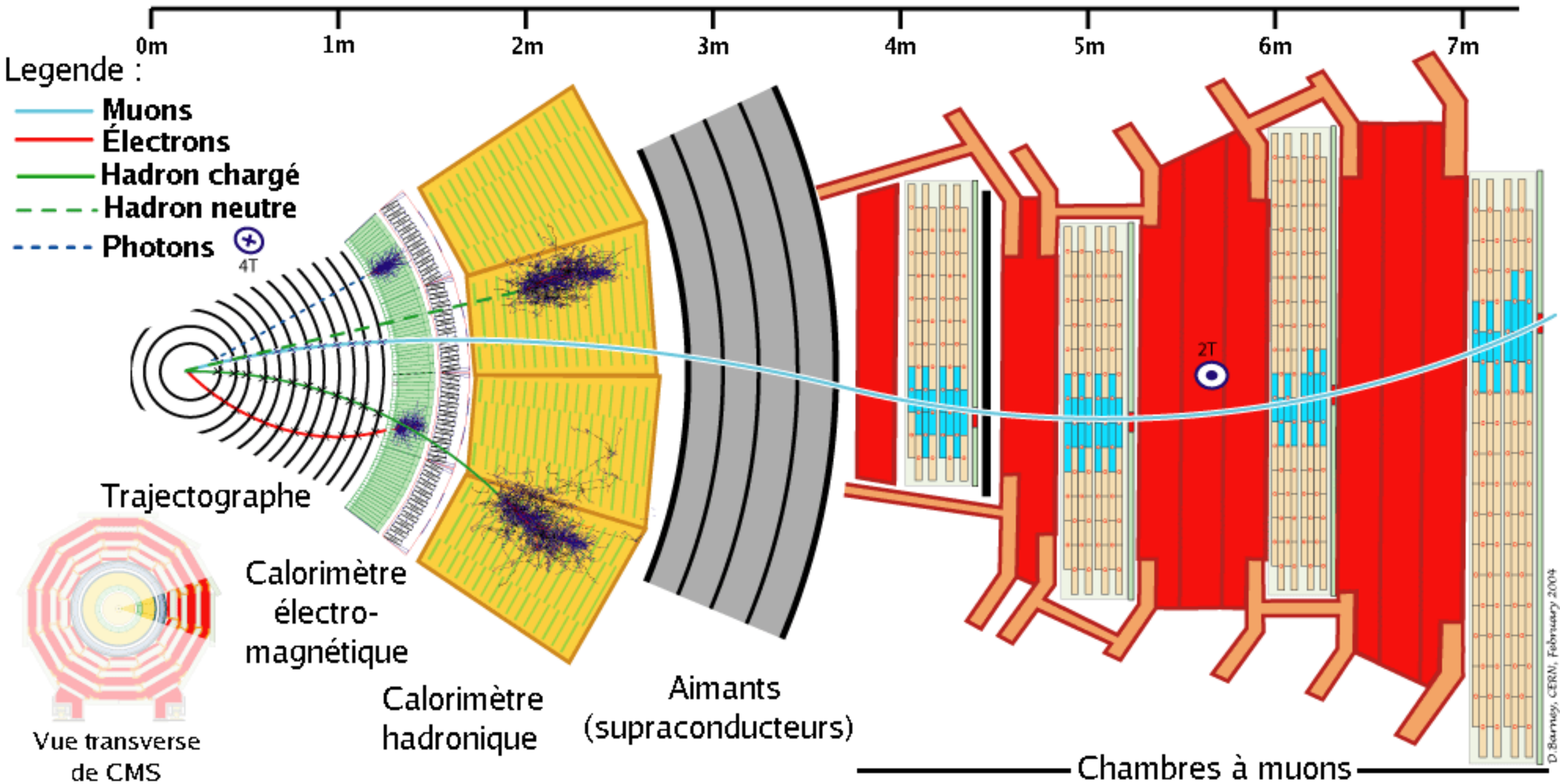


Particle journey



Discovery of a strongly coupled QGP

BROOKHAVEN NATIONAL LABORATORY Newsroom Media & Communications Office

RHIC Scientists Serve Up "Perfect" Liquid (2005)

New state of matter more remarkable than predicted -- raising many new questions

Monday, April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

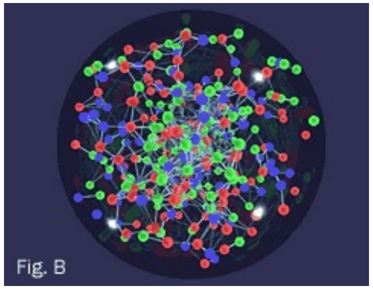


Fig. B

Discovery of a strongly coupled QGP

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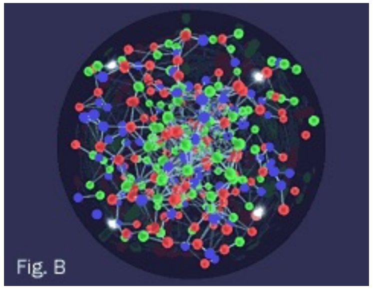
Strongly coupled like a *liquid*, instead of gas



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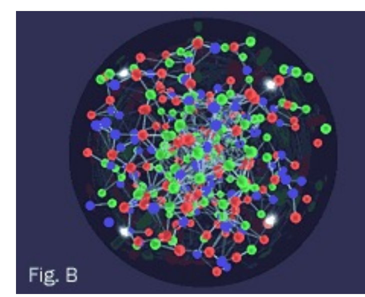
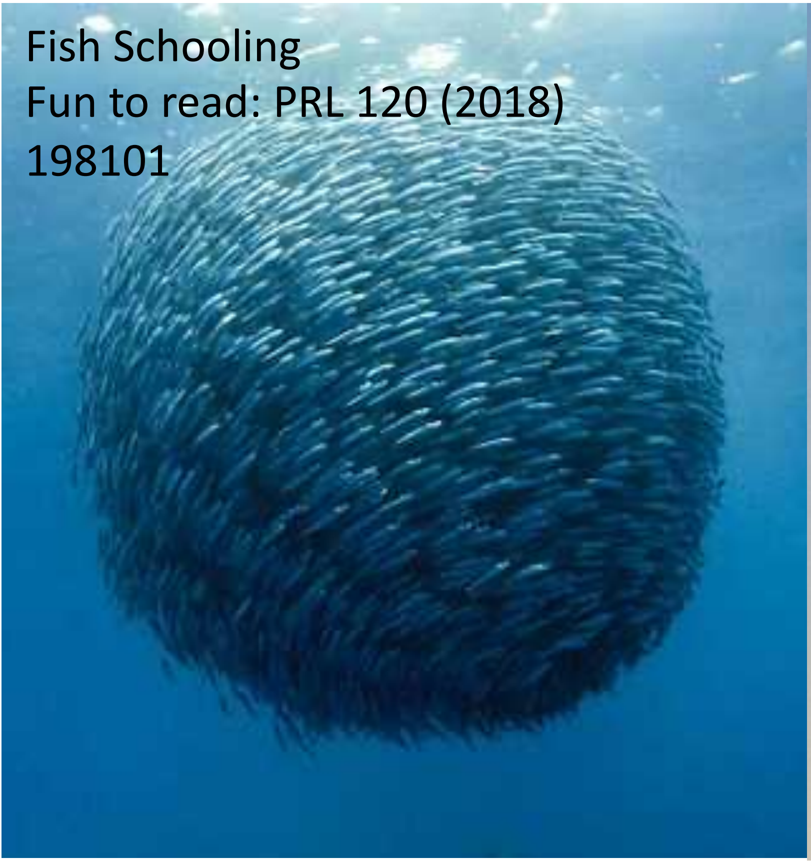
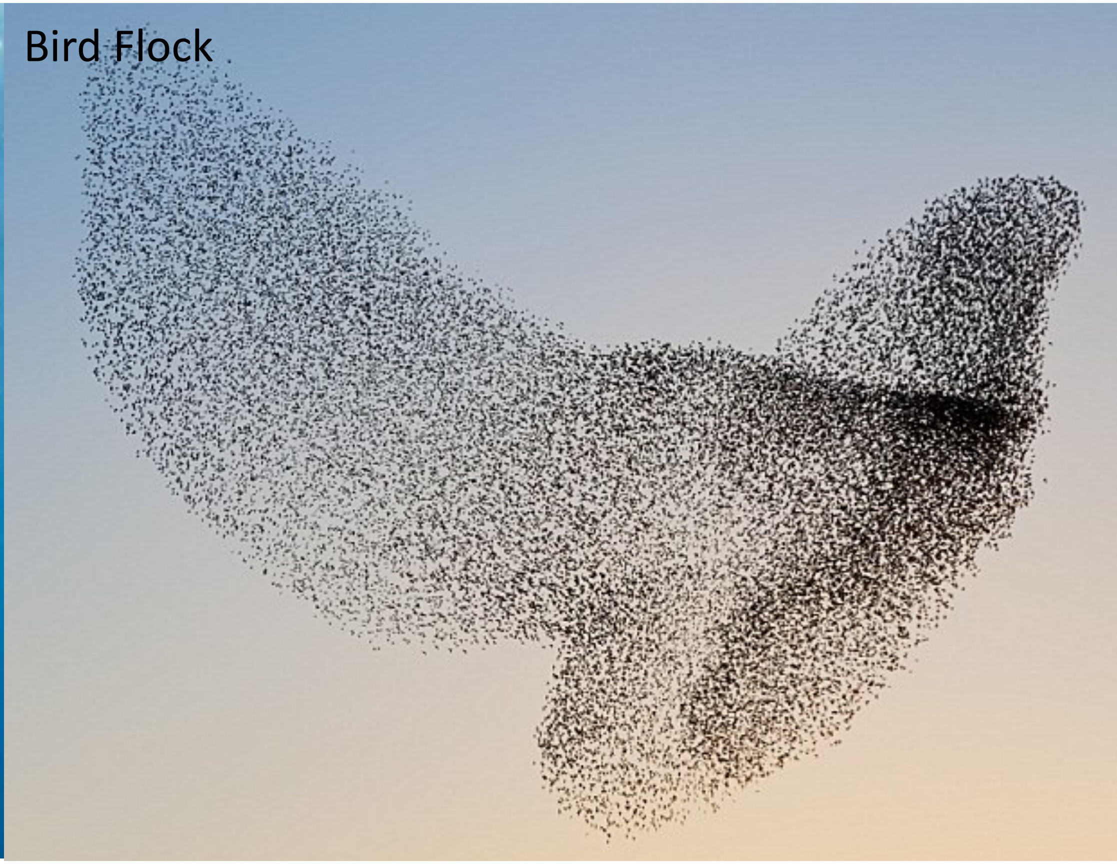
Strongly coupled like a *liquid*, instead of gas

Important evidence from collectivity



Collectivity



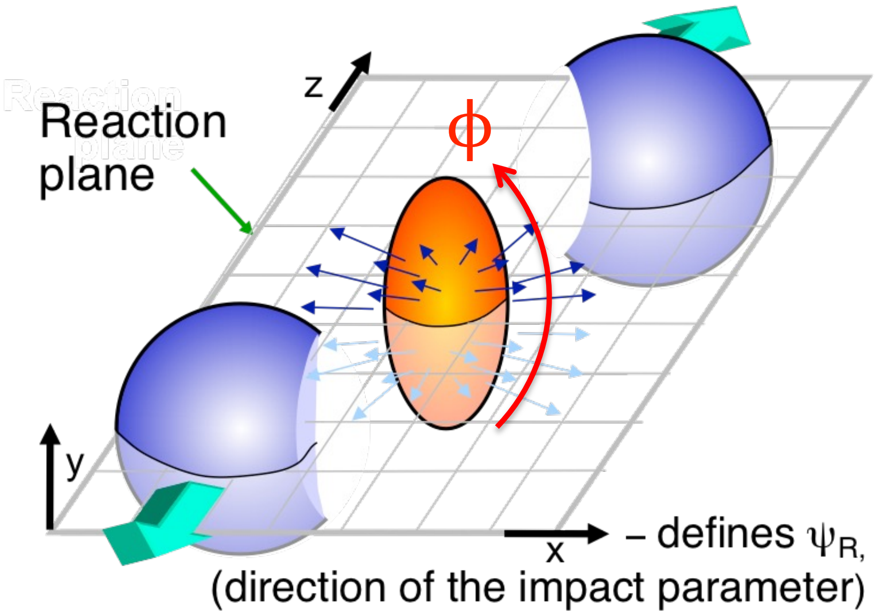


Collectivity

Collectivity

Collectivity – Evidence of fluidity

Off-center AA collision



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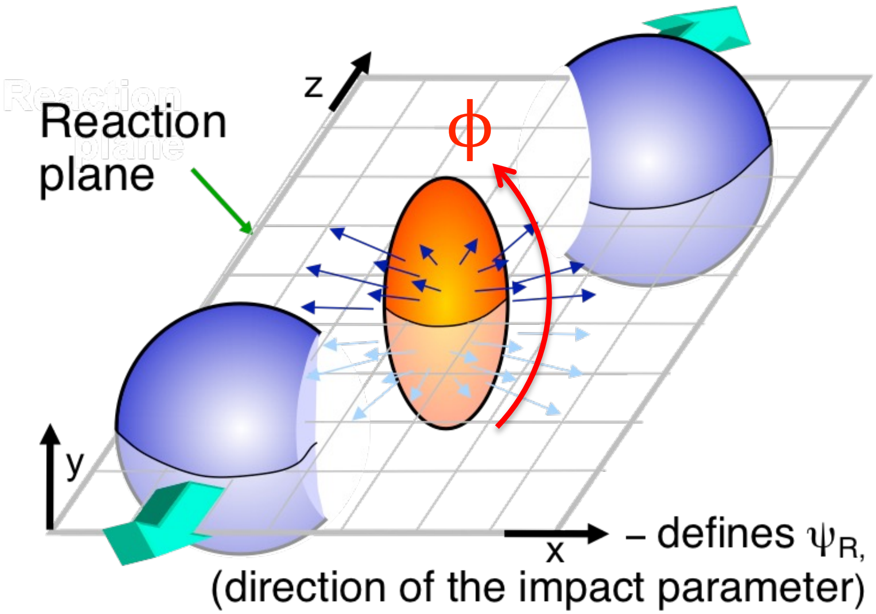
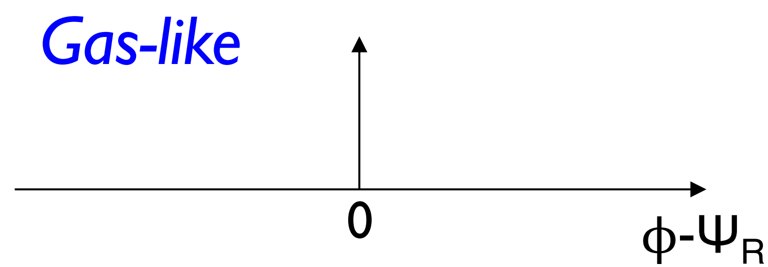


Momentum anisotropy



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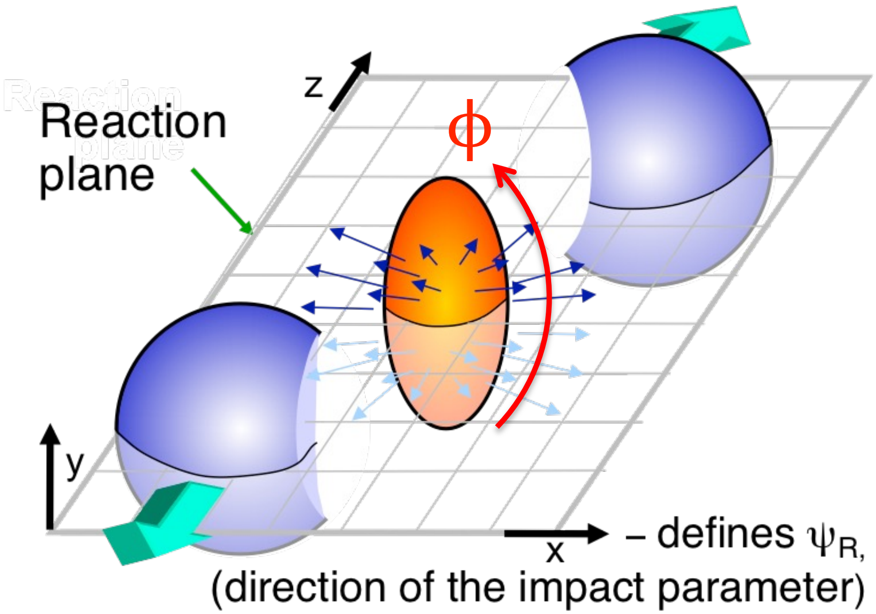

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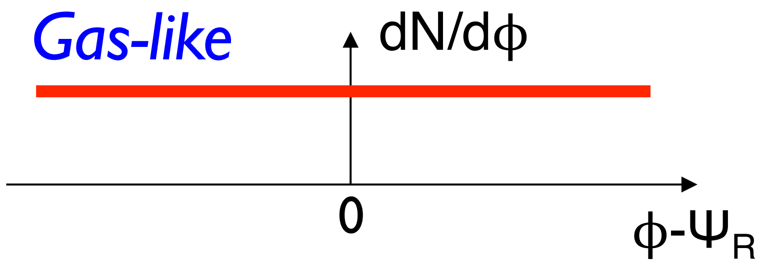

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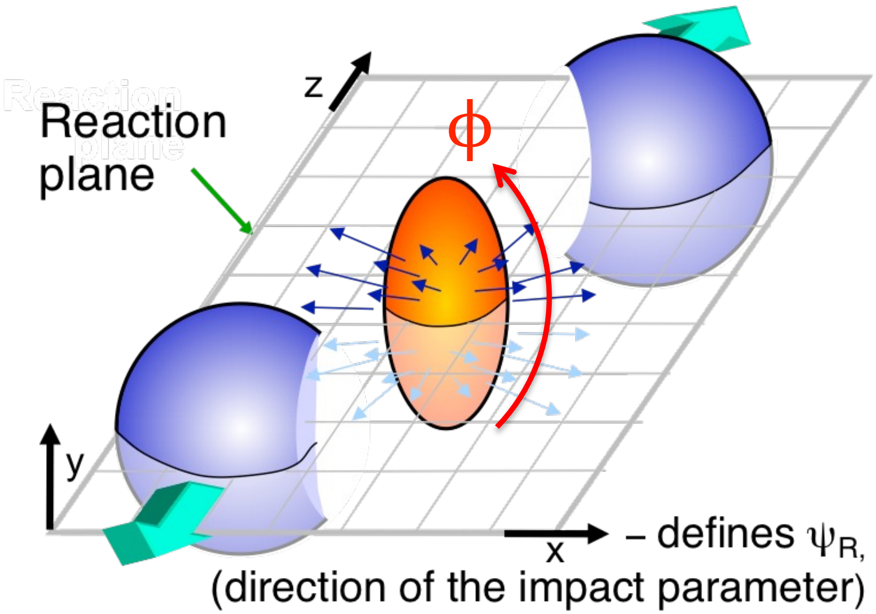

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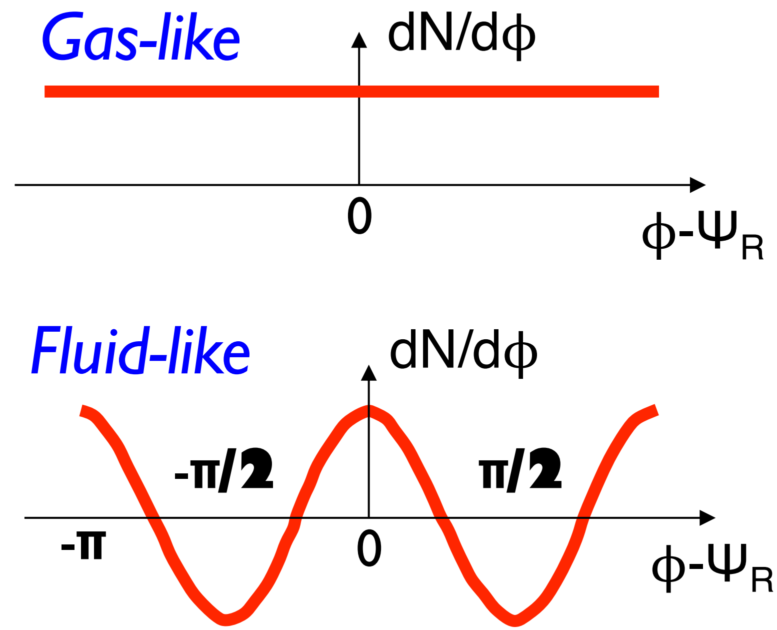
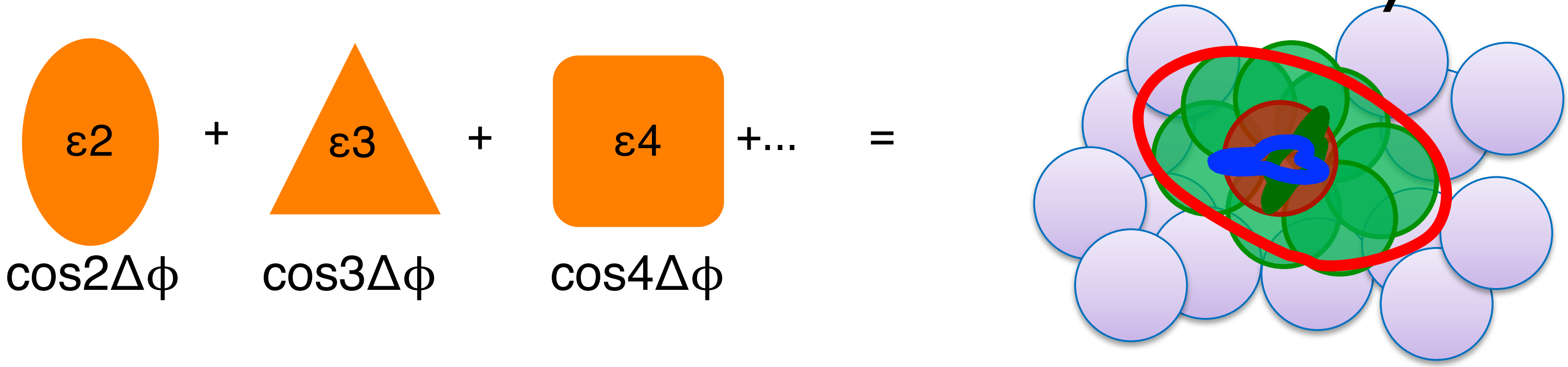


Collectivity – Evidence of fluidity

Initial Geometry



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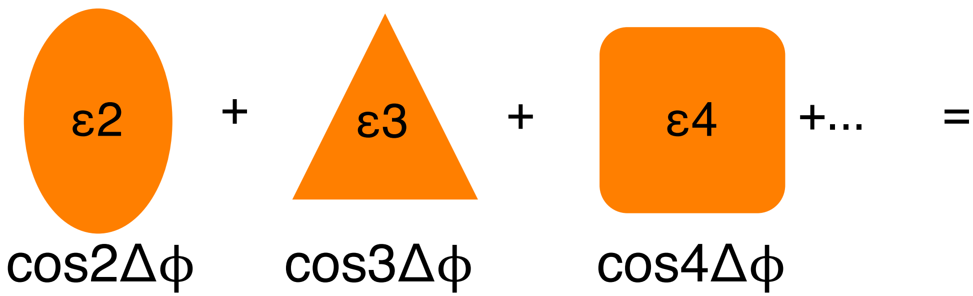

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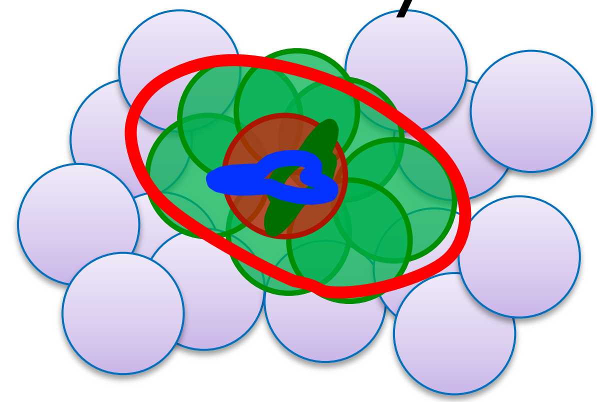
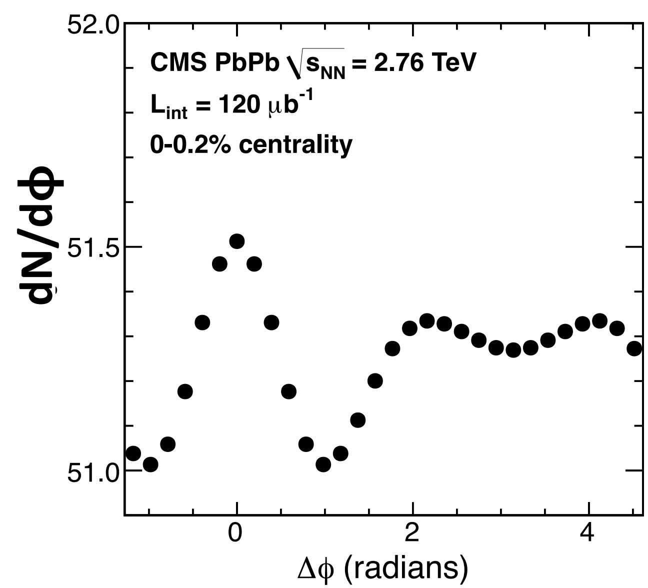
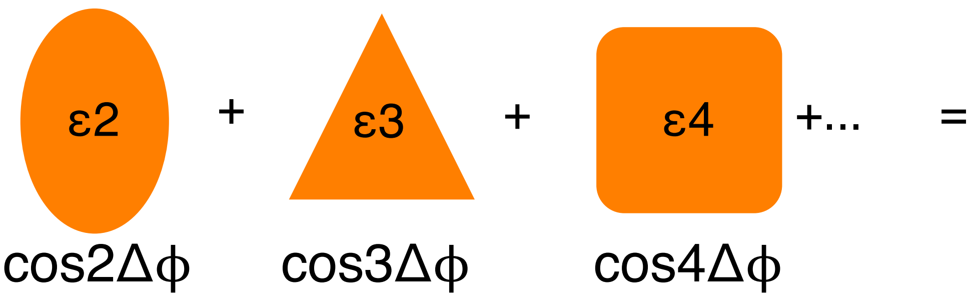


Particle distribution



Collectivity – Initial to final



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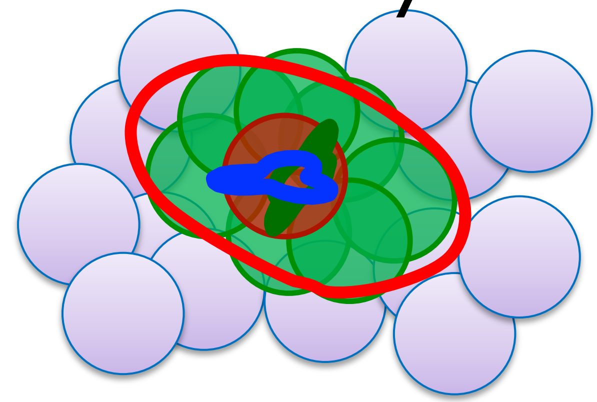
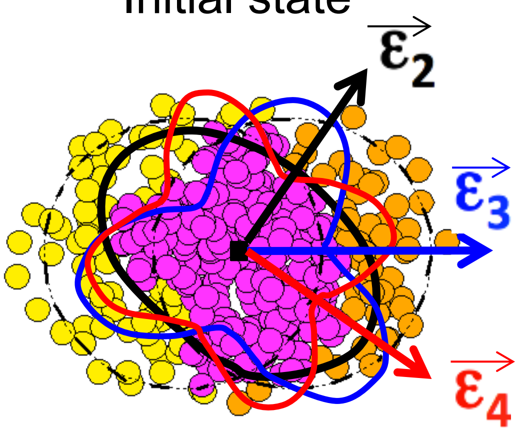
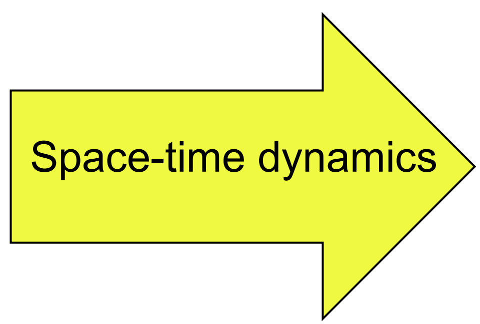


Initial state



Hydro-response



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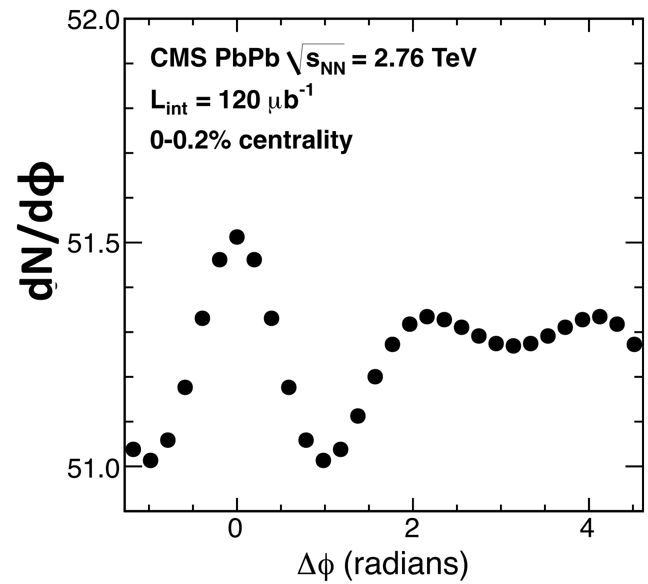

$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} \equiv -\frac{\langle r^n e^{in\phi} \rangle}{\langle r^n \rangle}$$

Brief intro to hydrodynamics

ISBN: 9781108483681
arXiv: 1712.05815

Energy-momentum conservation

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

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Energy-momentum conservation

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

Ideal hydro: System always in local equilibrium

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$

Hydro response controlled by QCD Equation of State P(ε)

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Viscous hydro: Including near-equilibrium corrections

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

Bulk Pressure (Π)   Shear Tensor ($\pi^{\mu\nu}$)

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Bulk Pressure (Π) — Shear Tensor ($\pi^{\mu\nu}$)

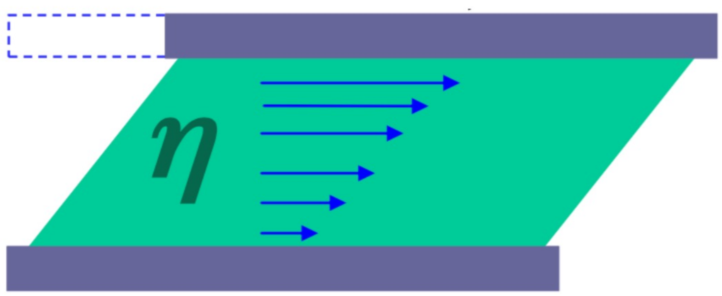
With 1st order gradient expansion

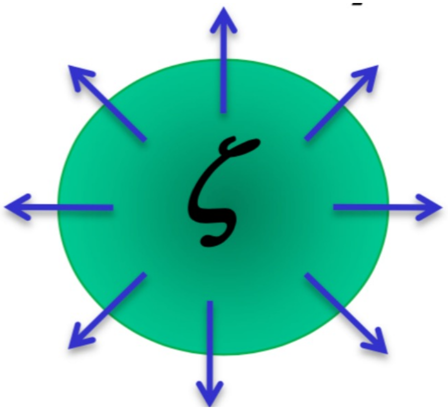
$$\pi^{\mu\nu} = -\eta\sigma^{\mu\nu}$$

$$\Pi = -\zeta\nabla\frac{1}{\lambda}u^\lambda$$

η: Shear viscosity

ζ: Bulk viscosity





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Bulk Pressure (Π)   Shear Tensor ($\pi^{\mu\nu}$)

With 2[nd] order gradient expansion

$$\begin{aligned}
\pi^{\mu\nu} &= -\eta\sigma^{\mu\nu} + \eta\tau_\pi\left[{}^{<}D\sigma^{\mu\nu>} + \frac{\nabla_\lambda^\perp u^\lambda}{3}\sigma^{\mu\nu}\right] + \kappa\left[R^{<\mu\nu>} - 2u_\lambda u_\rho R^{\lambda<\mu\nu>\rho}\right] + \lambda_1\sigma^{<\mu}{}_\lambda\sigma^{\nu>\lambda} \\
&\quad + \lambda_2\sigma^{<\mu}{}_\lambda\Omega^{\nu>\lambda} + \lambda_3\Omega^{<\mu}{}_\lambda\Omega^{\nu>\lambda} + \kappa^* 2u_\lambda u_\rho R^{\lambda<\mu\nu>\rho} + \eta\tau_\pi^*\frac{\nabla_\lambda^\perp u^\lambda}{3}\sigma^{\mu\nu} + \bar{\lambda}_4\nabla_\perp^{<\mu}\ln\epsilon\nabla_\perp^{\nu>}\ln\epsilon \\
\Pi &= -\zeta\left(\nabla_\lambda^\perp u^\lambda\right) + \zeta\tau_\Pi D\left(\nabla_\lambda^\perp u^\lambda\right) + \xi_1\sigma^{\mu\nu}\sigma_{\mu\nu} + \xi_2\left(\nabla_\lambda^\perp u^\lambda\right)^2 \\
&\quad + \xi_3\Omega^{\mu\nu}\Omega_{\mu\nu} + \bar{\xi}_4\nabla_\mu^\perp\ln\epsilon\nabla_\perp^\mu\ln\epsilon + \xi_5 R + \xi_6 u^\lambda u^\rho R_{\lambda\rho}\,.
\end{aligned}$$

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Energy-momentum conservation

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

Viscous hydro: Including near-equilibrium corrections

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

Bulk Pressure (Π) Shear Tensor ($\pi^{\mu\nu}$)

With 2nd order gradient expansion

$$\begin{aligned}
\pi^{\mu\nu} \;=\;& -\eta\sigma^{\mu\nu} + \eta\tau_\pi\left[{}^{<}D\sigma^{\mu\nu>} + \frac{\nabla^\perp_\lambda u^\lambda}{3}\sigma^{\mu\nu}\right] + \kappa\left[R^{<\mu\nu>} - 2u_\lambda u_\rho R^{\lambda<\mu\nu>\rho}\right] + \lambda_1\sigma^{<\mu}{}_\lambda\sigma^{\nu>\lambda} \\
& + \lambda_2\sigma^{<\mu}{}_\lambda\Omega^{\nu>\lambda} + \lambda_3\Omega^{<\mu}{}_\lambda\Omega^{\nu>\lambda} + \kappa^* 2u_\lambda u_\rho R^{\lambda<\mu\nu>\rho} + \eta\tau^*_\pi\frac{\nabla^\perp_\lambda u^\lambda}{3}\sigma^{\mu\nu} + \bar{\lambda}_4\nabla^{<\mu}_\perp \ln\epsilon\nabla^{\nu>}_\perp \ln\epsilon \\
\Pi \;=\;& -\zeta\left(\nabla^\perp_\lambda u^\lambda\right) + \zeta\tau_\Pi D\left(\nabla^\perp_\lambda u^\lambda\right) + \xi_1\sigma^{\mu\nu}\sigma_{\mu\nu} + \xi_2\left(\nabla^\perp_\lambda u^\lambda\right)^2 \\
& + \xi_3\Omega^{\mu\nu}\Omega_{\mu\nu} + \bar{\xi}_4\nabla^\perp_\mu \ln\epsilon\nabla^\mu_\perp \ln\epsilon + \xi_5 R + \xi_6 u^\lambda u^\rho R_{\lambda\rho}\,.
\end{aligned}$$

ab.initio calc. for QGP not easy, relies on **model/data** comparison

Collectivity – how to measure

- Single particle distribution

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n} v_n cosn(\phi - \Phi_n)\right]$$

Event Plane (Φ_n)

Anisotropic Flow (v_n)

Collectivity – how to measure

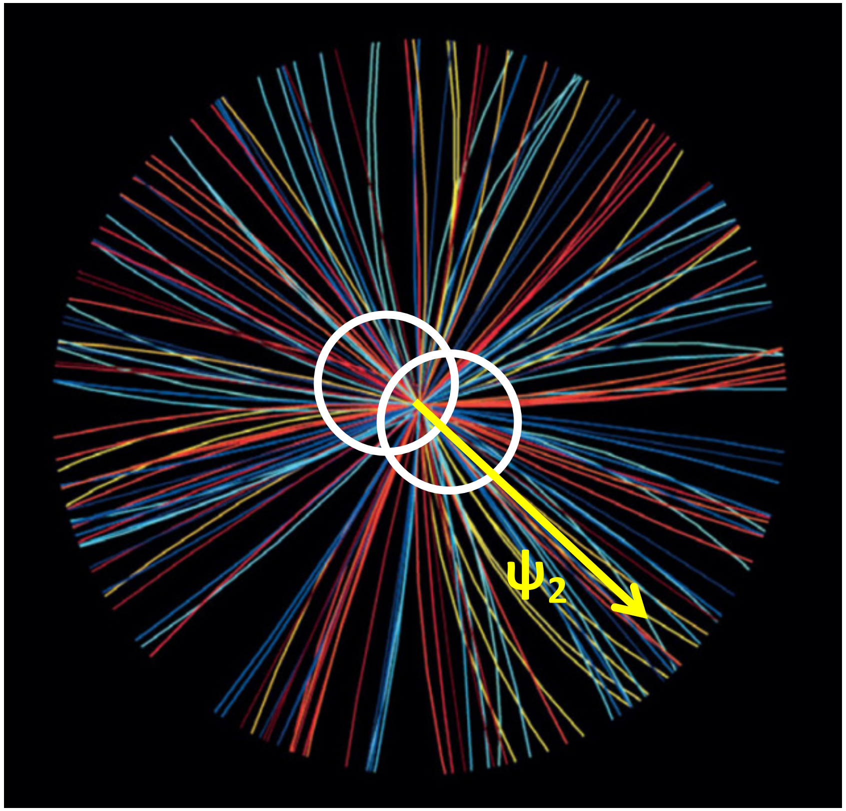
- Single particle distribution

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_n v_n cosn(\phi - \Phi_n)\right]$$

Event Plane

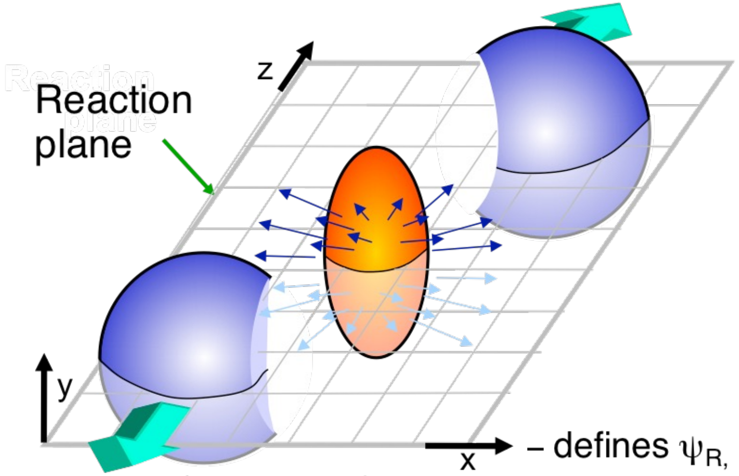
Anisotropic Flow

- Event Plane method



Event Plane from emitted particles

$$\psi_n = \frac{1}{n} tan^{-1} \frac{\sum_i \sin(n\phi_i)}{\sum_i \cos(n\phi_i)}$$



– defines ψ_R, (direction of the impact parameter)

Collectivity – how to measure

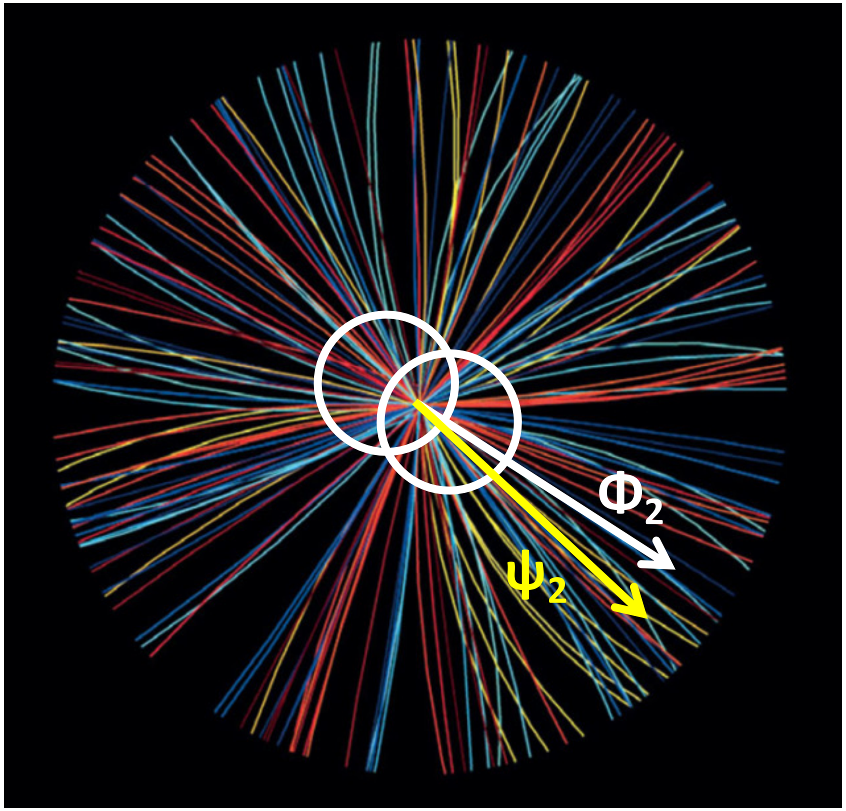
- Single particle distribution

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n} v_n cos n(\phi - \Phi_n)\right]$$

Event Plane (→ Φ_n)

Anisotropic Flow (→ v_n)

- Event Plane method



Event Plane from emitted particles

$$\psi_n = \frac{1}{n} tan^{-1} \frac{\sum_i \sin(n\phi_i)}{\sum_i \cos(n\phi_i)}$$

Event Plane Resolution

$$\mathcal{R}_n \propto \cos n(\Phi_n - \psi_n)$$

$$v_n = v_n^{obs} / \mathcal{R}_n$$

R_n cannot be perfectly determined!

Collectivity – how to measure

- Particle pair distribution

$$V_{n\Delta,ab} = v_{n,a} v_{n,b} \text{ when } \Phi_n^a = \Phi_n^b$$

$$\frac{dN^{pair}}{d\Delta\phi} = \frac{N^{pair}}{2\pi}\left[1 + 2\sum_n V_{n\Delta,ab} \cos n(\phi_a - \phi_b)\right]$$

Collectivity – how to measure

- Particle pair distribution

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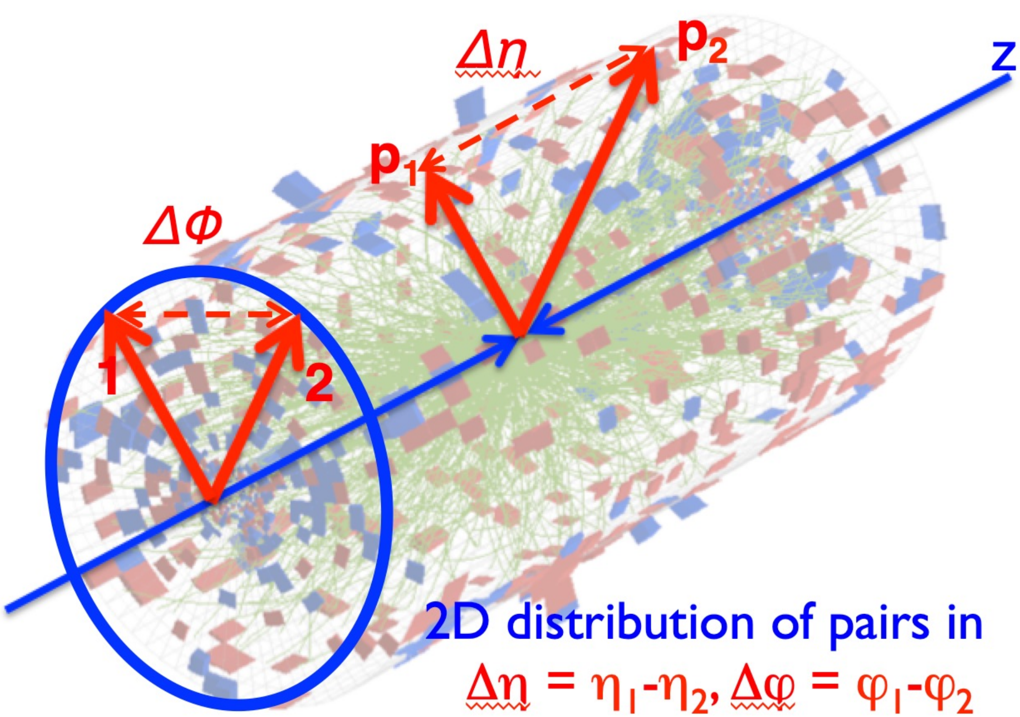
- Two particle correlation method



Collectivity – how to measure

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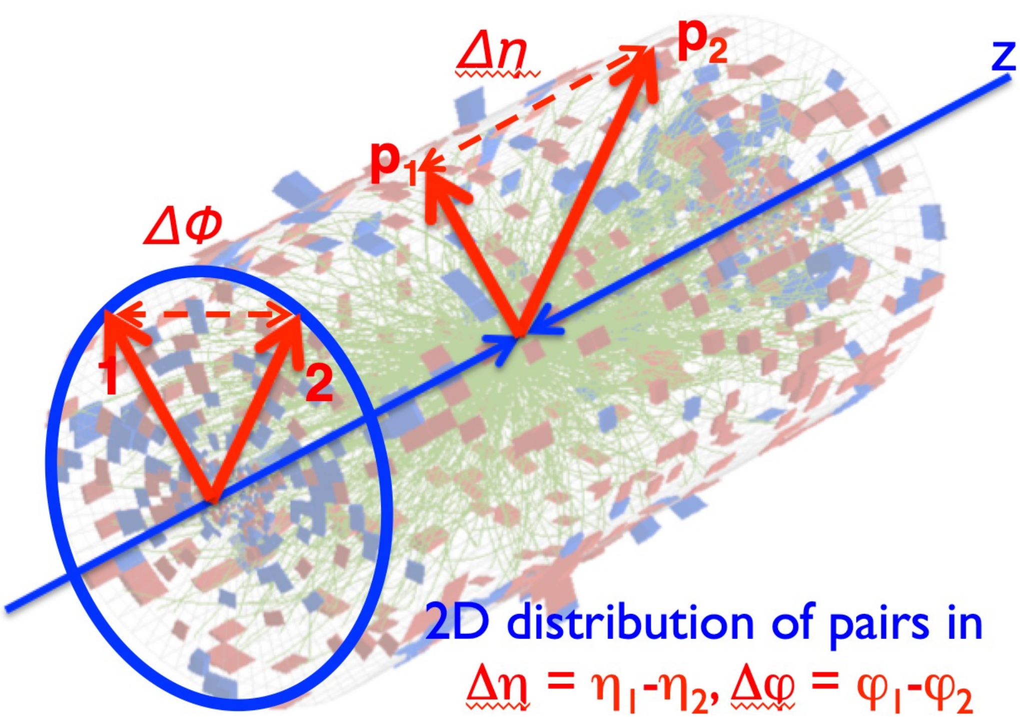

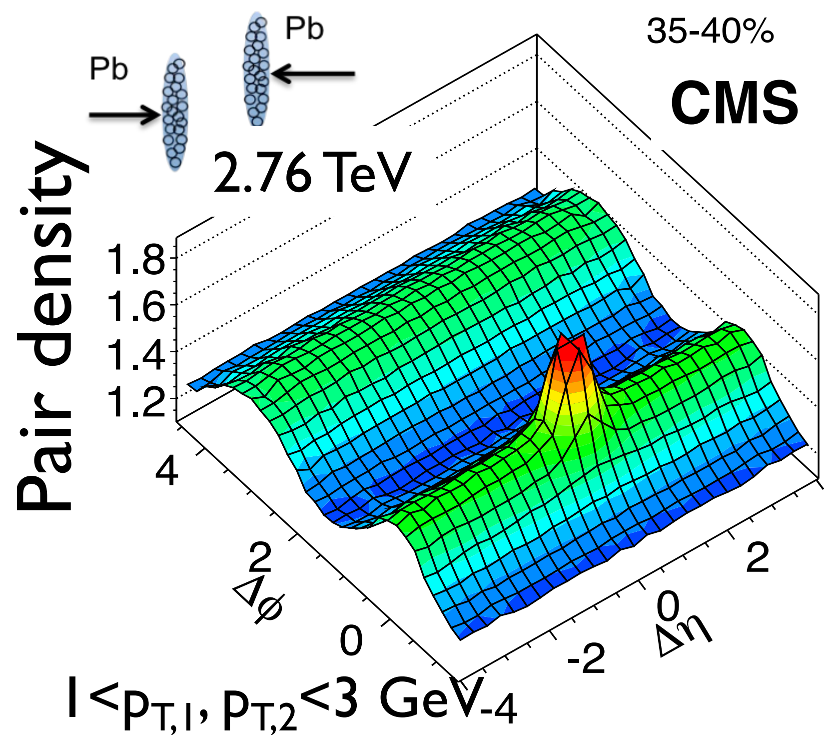

Collectivity – how to measure

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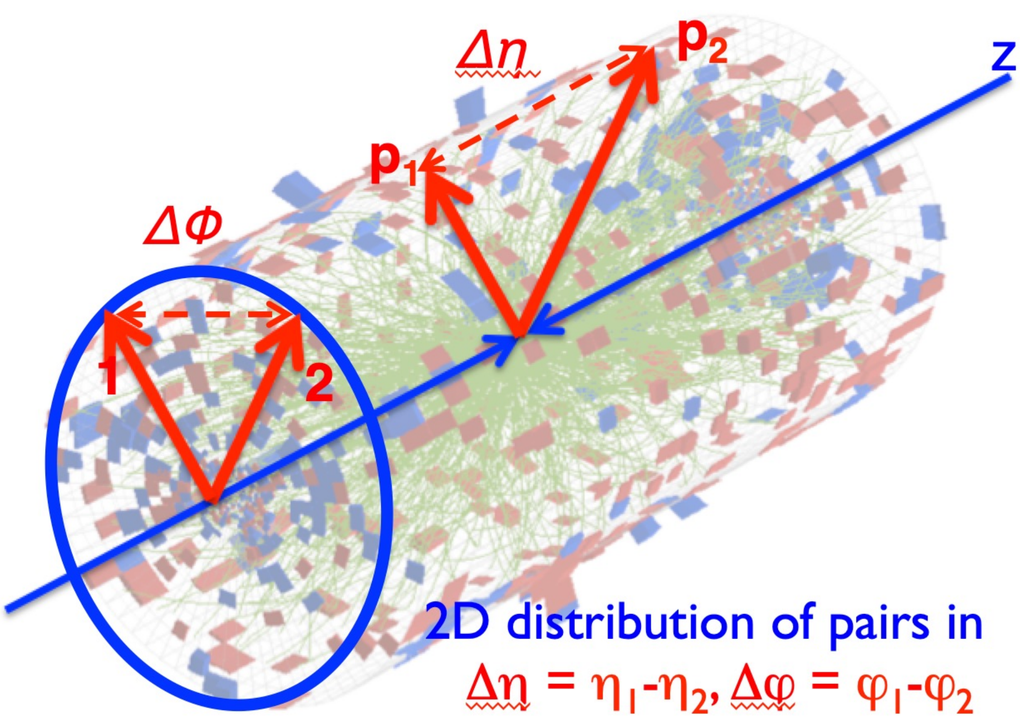

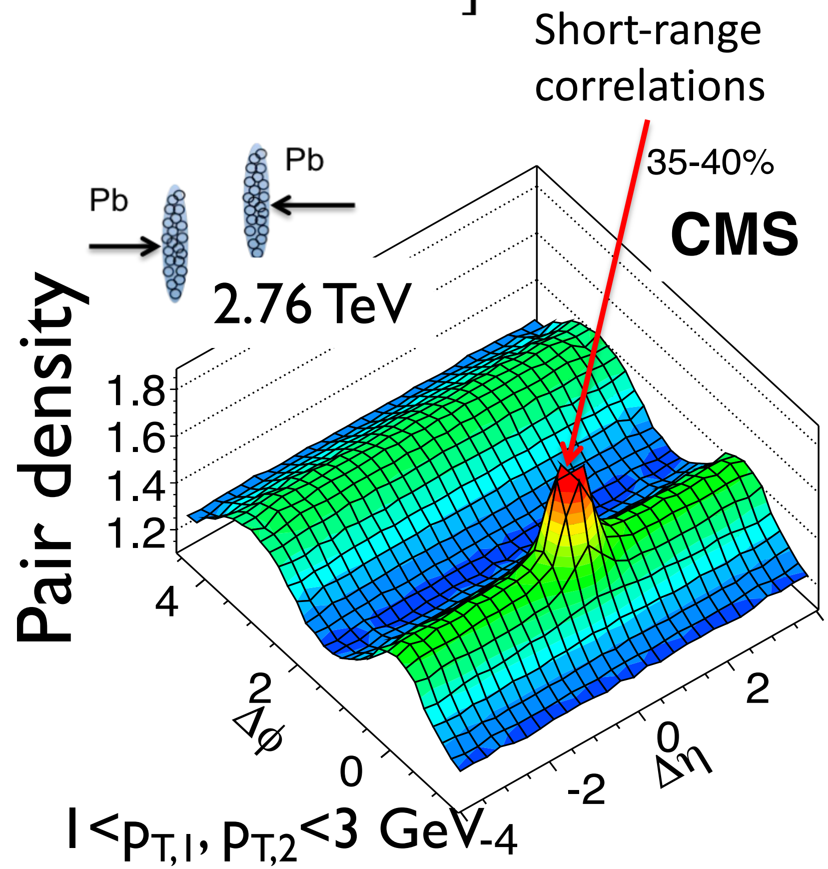

Collectivity – how to measure

- Particle pair distribution

$$V_{n\Delta,ab} = v_{n,a} v_{n,b} \quad \text{when } \Phi_n^a = \Phi_n^b$$

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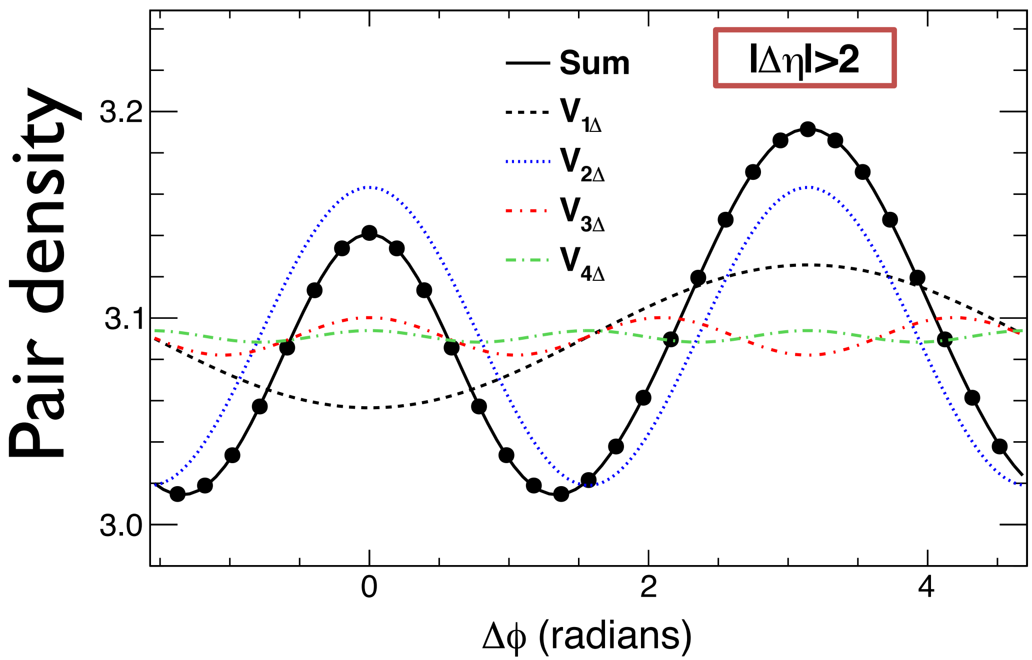
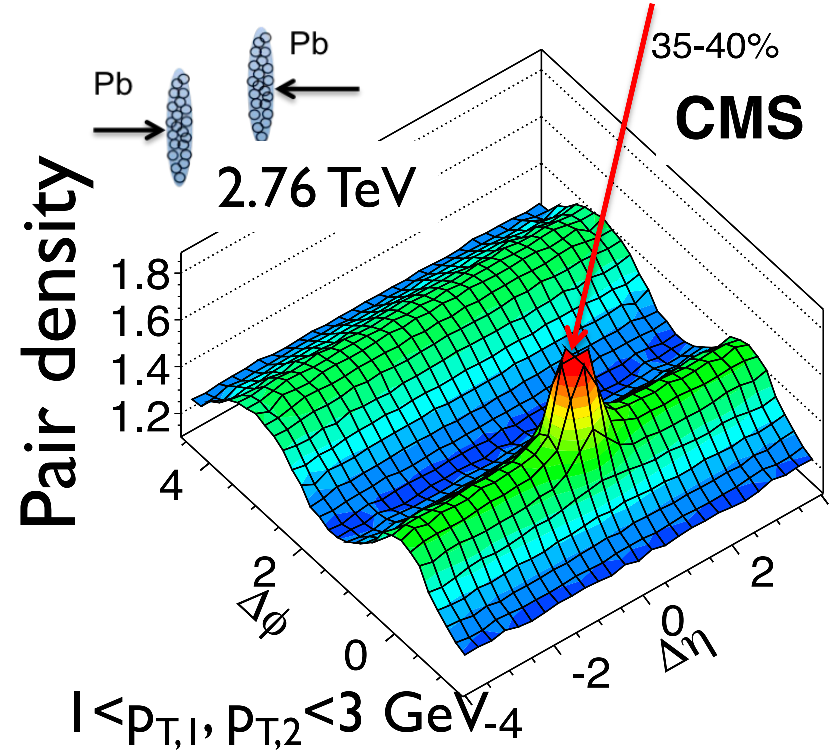
- Two particle correlation method





Collectivity – how to measure

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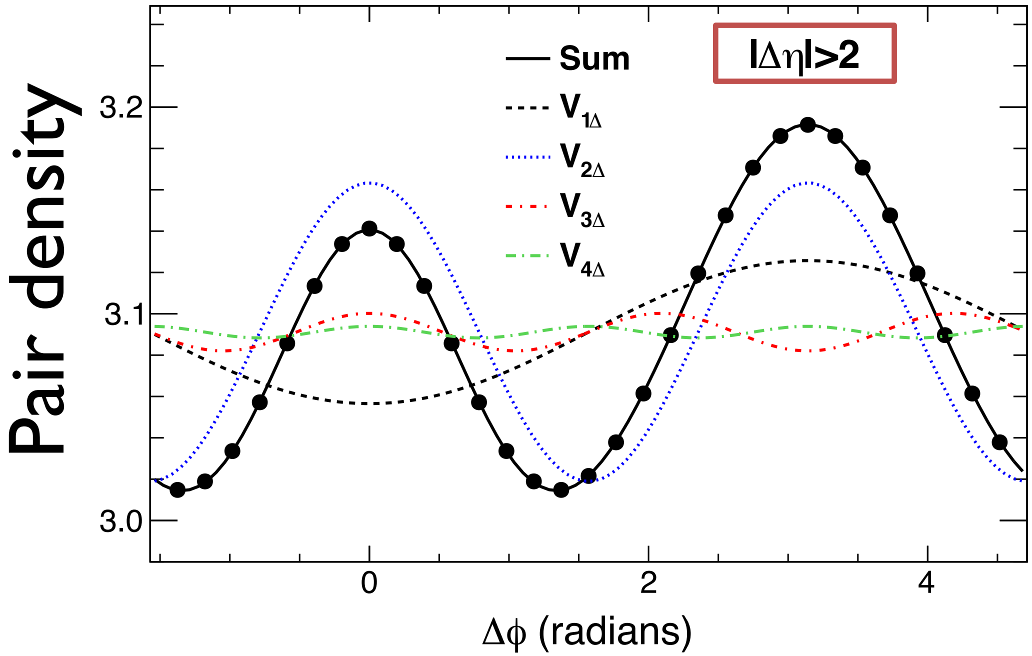
$$\frac{dN^{pair}}{d\Delta\phi} = \frac{N^{pair}}{2\pi}\left[1 + 2\sum_n V_{n\Delta,ab} \cos n(\phi_a - \phi_b)\right]$$

- Two particle correlation method



Fourier analysis:

$$\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2V_{1\Delta}\cos(\Delta\phi) + 2V_{2\Delta}\cos(2\Delta\phi) + 2V_{3\Delta}\cos(3\Delta\phi) + 2V_{4\Delta}\cos(4\Delta\phi) + \ldots$$

$$V_{n\Delta} = v_{n,a} v_{n,b}$$

Collectivity – how to measure

- Multi-particle distribution

$$\frac{dN_1}{d\phi_1}..\frac{dN_m}{d\phi_m} \Rightarrow v_{n_1} v_{n_2}..v_{n_m} \cos(n_1\phi_1 + n_2\phi_2 + \cdots + n_m\phi_m)$$

Collectivity – how to measure

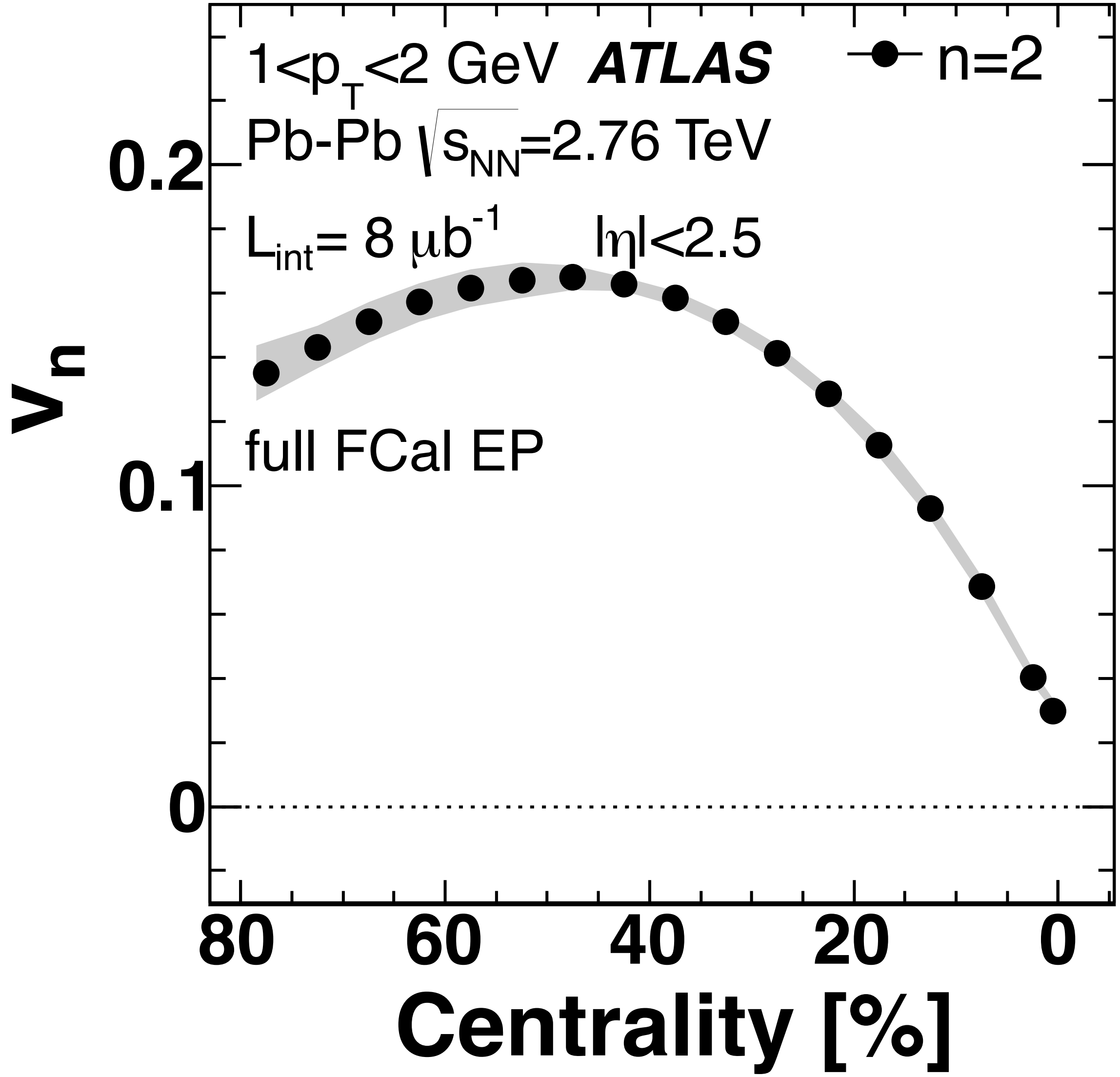
- Multi-particle distribution

$$\frac{dN_1}{d\phi_1}..\frac{dN_m}{d\phi_m} \Rightarrow v_{n_1} v_{n_2}..v_{n_m} \cos(n_1\phi_1 + n_2\phi_2 + \cdots + n_m\phi_m)$$

- Cumulant method
  - PRC 83 (2011) 044913, $v_n\{m\}$ with multi-particle correlation
  - PRC 89 (2014) 064904, Symmetric Cumulant (*Standard Candles*)
  - PRC 90 (2014) 024905, Asymmetric Cumulant
- $v_n\{m\}$ – Less sensitive to few particle correlation
- SC – Event-by-event correlation between v_n and v_m
- AC – Initial geometry fluctuation & non-linear mixing between v_n, v_m

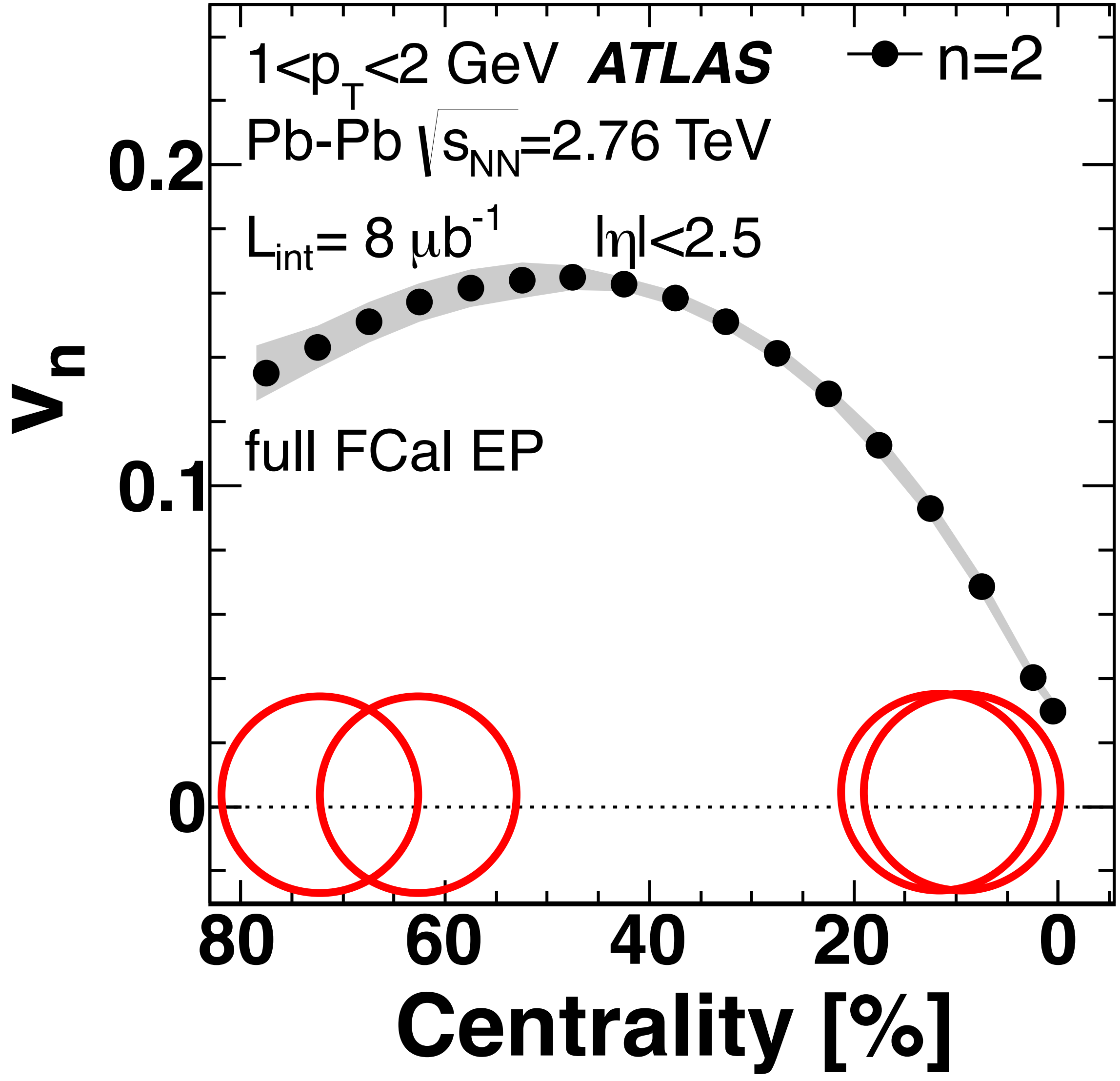
v_2 vs centrality

PRC 86 (2012) 014907



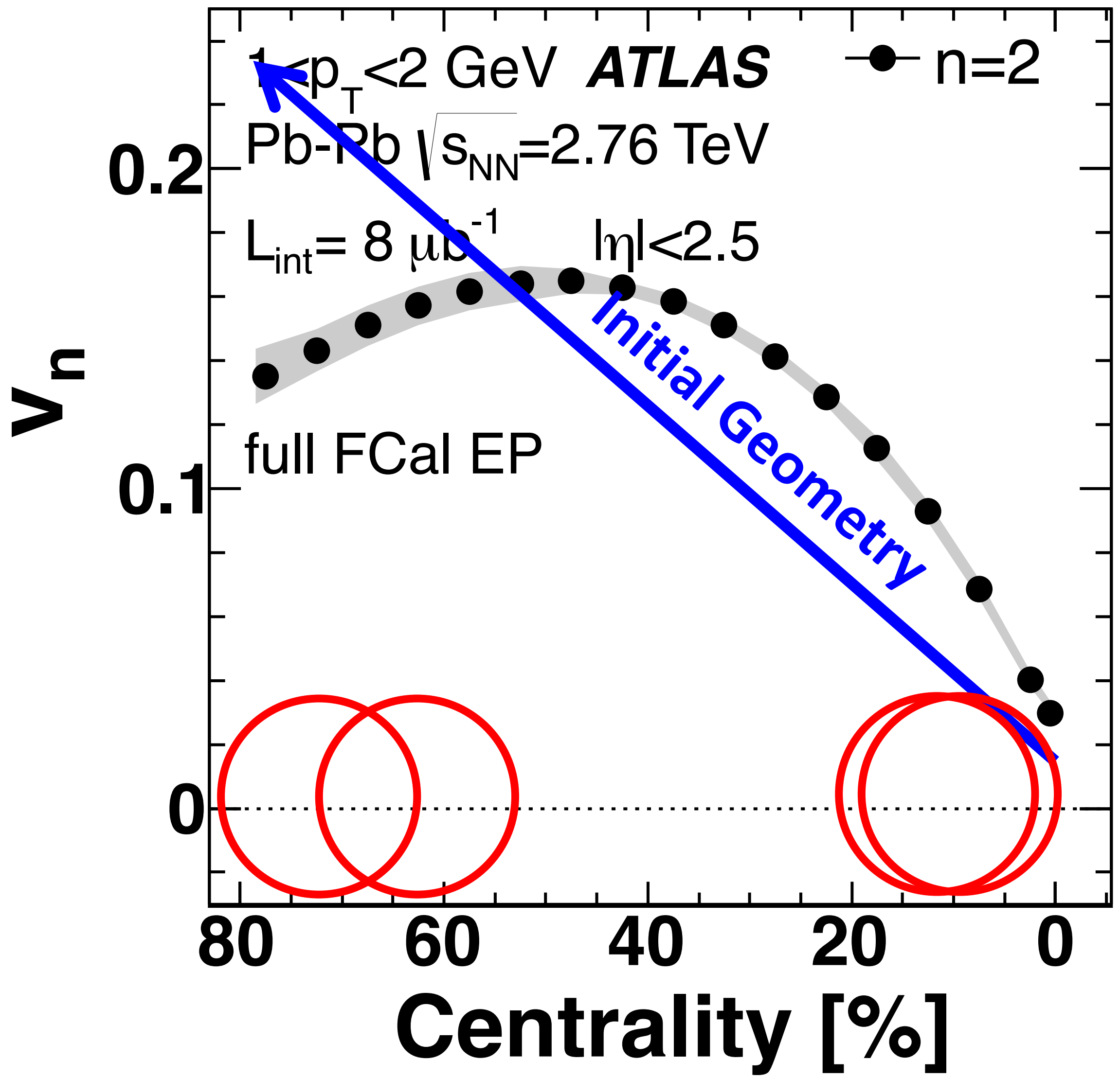
v_2 vs centrality

PRC 86 (2012) 014907



v_2 vs centrality

PRC 86 (2012) 014907

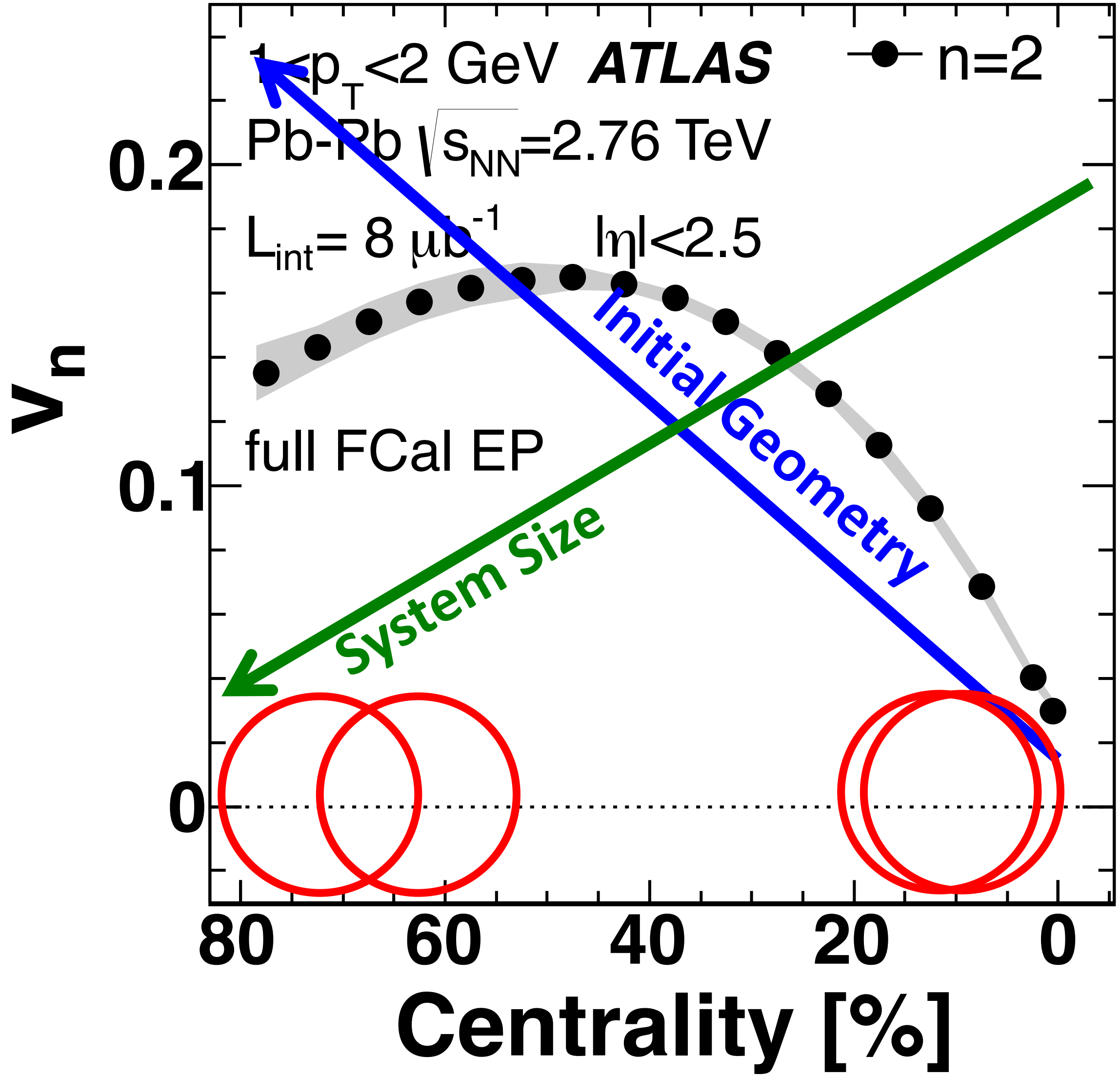


Geometry response:

$$v_n \propto A\varepsilon_n$$

v_2 vs centrality

PRC 86 (2012) 014907



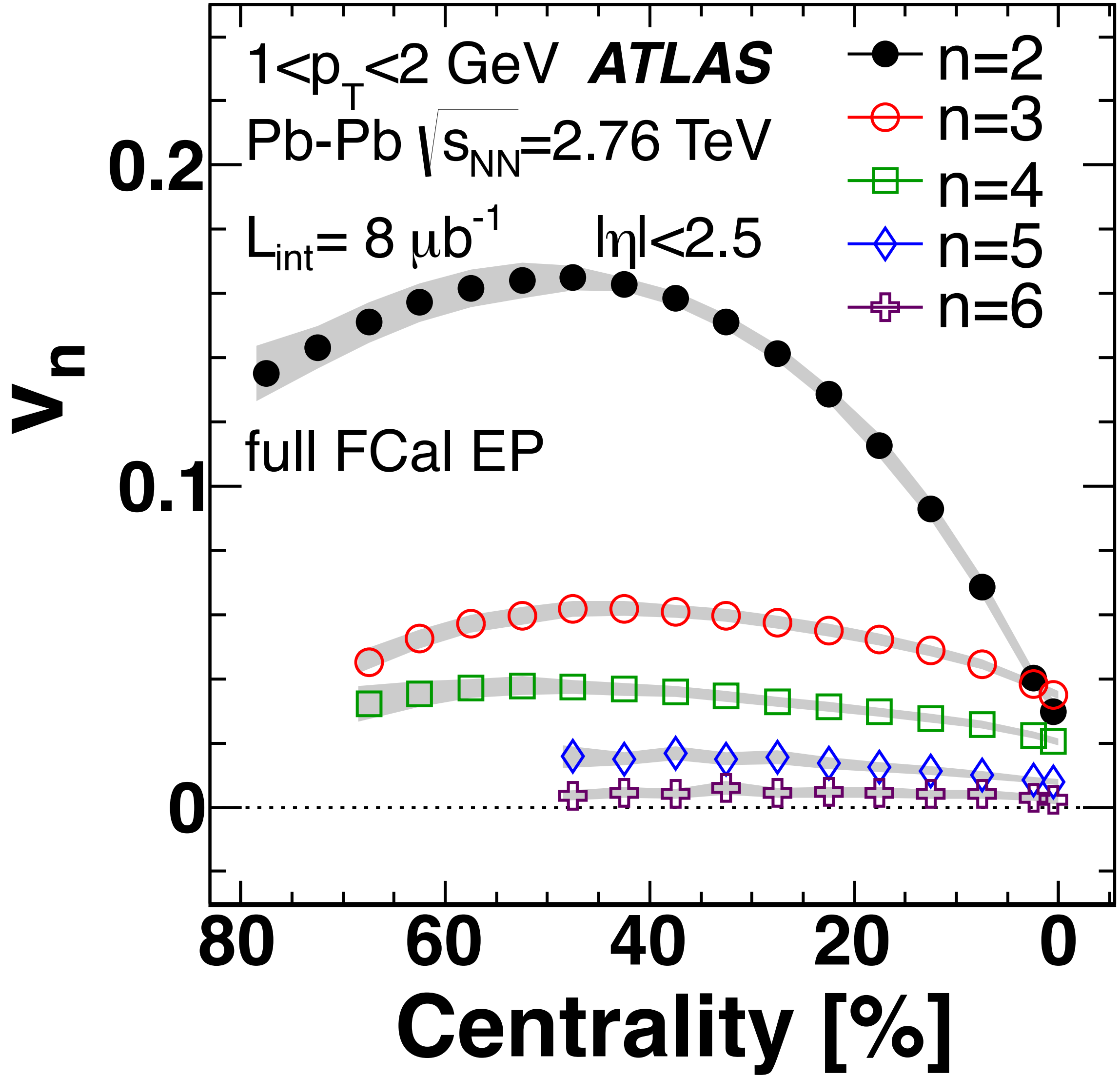
Geometry response:

$$v_n \propto A\varepsilon_n$$

System Size:
Less interactions develop less flow

v_n vs centrality

PRC 86 (2012) 014907



Geometry response:

$$v_n \propto A\varepsilon_n$$

System Size:
Less interactions
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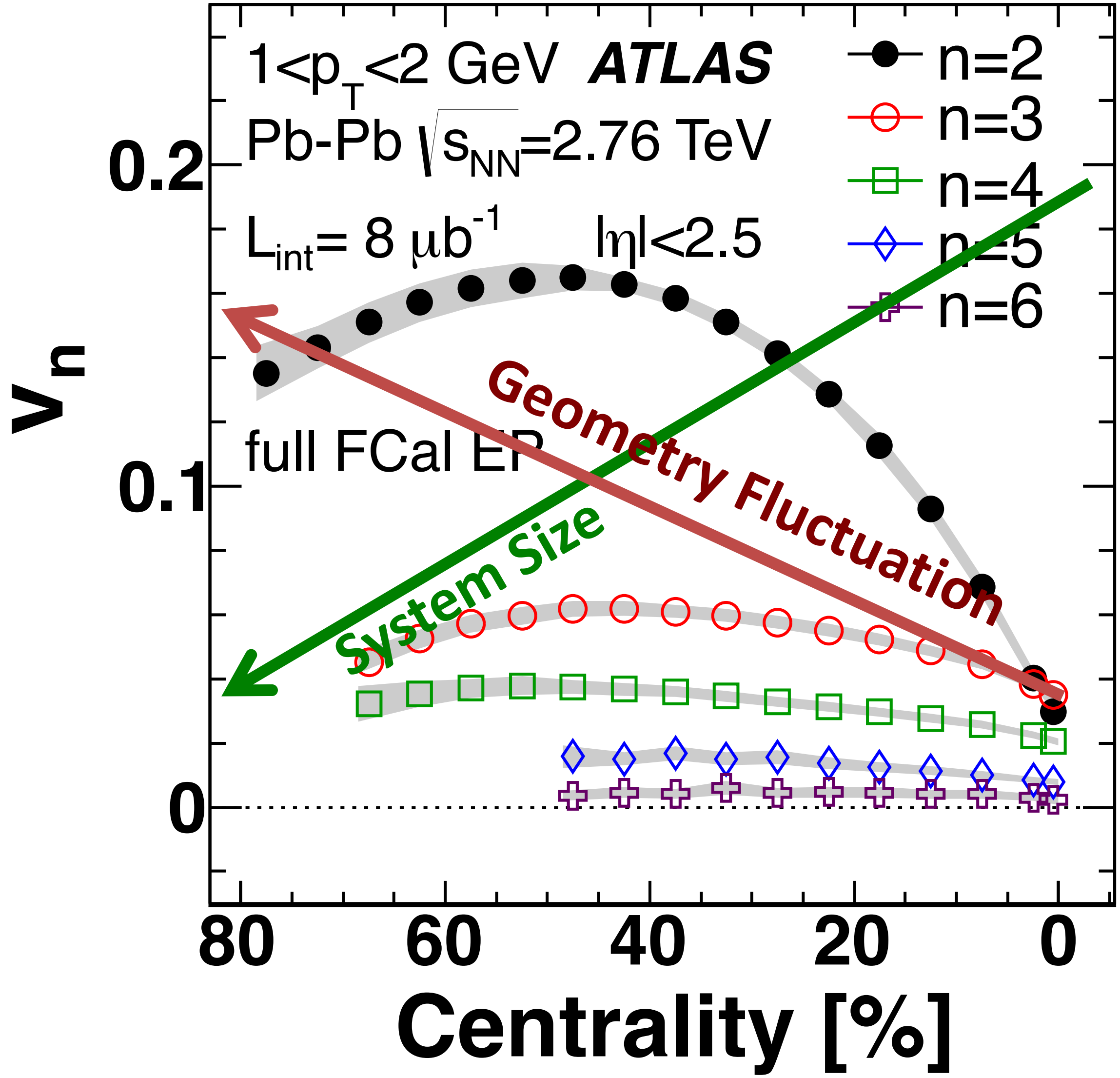
Eccentricity from
Geometry Fluctuation

v_n vs centrality

PRC 86 (2012) 014907



Geometry response:

$$v_n \propto A\varepsilon_n$$

System Size:
Less interactions develop less flow

Eccentricity from Geometry Fluctuation:

$$GF \propto 1/N_{par}$$

v_n vs centrality across systems

PRC 98 (2018) 021902

Constrain on viscosity from acoustic model: viscous attenuation

$$\ln(v_n/\varepsilon_n) \propto -n^2 \left\langle \frac{\eta}{s}(T) \right\rangle \langle N_{ch} \rangle^{-1/3}$$

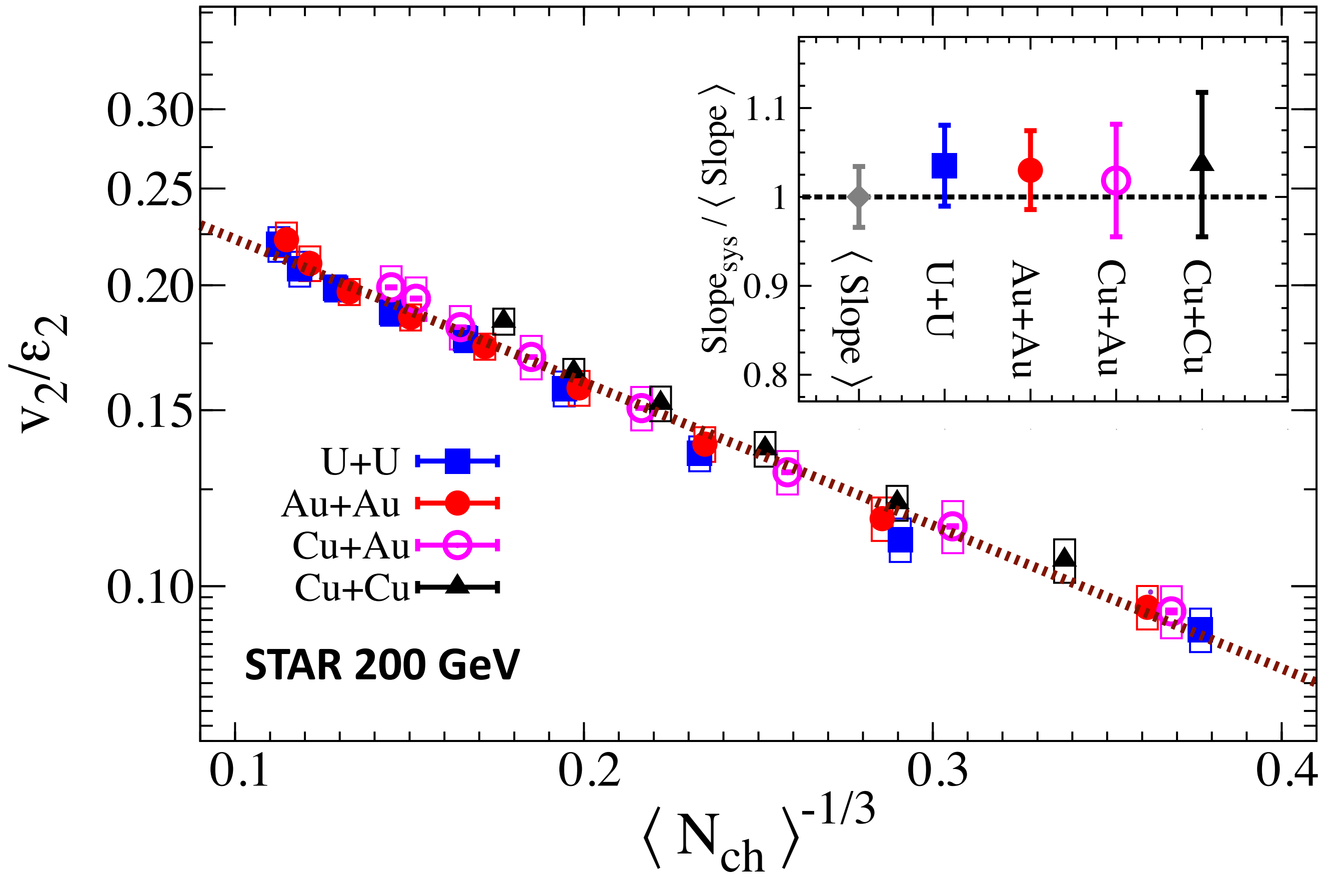
v_n vs centrality across systems

PRC 98 (2018) 021902

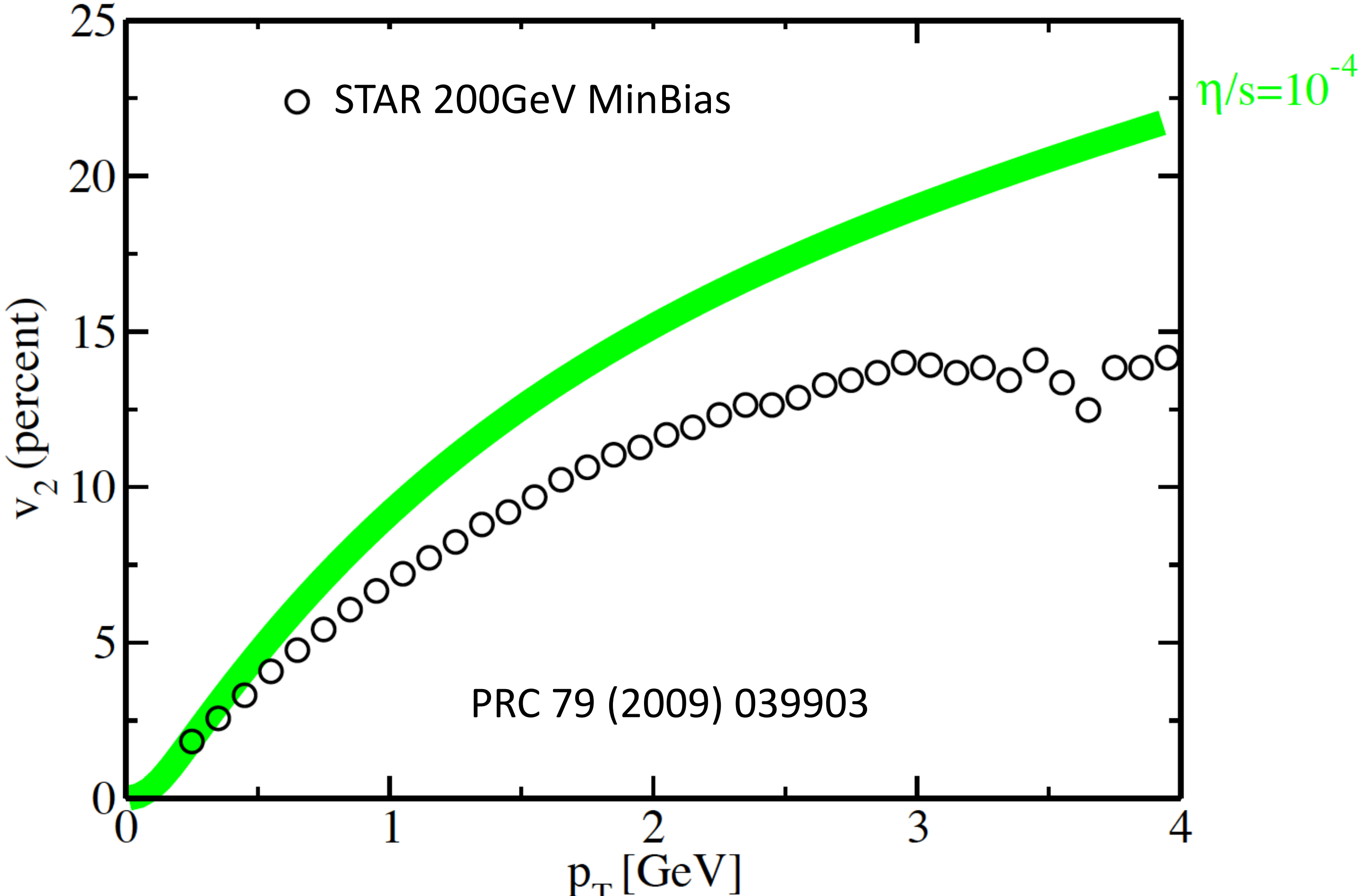
Constrain on viscosity from acoustic model: viscous attenuation

$$\ln(v_n/\varepsilon_n) \propto -n^2 \left\langle \frac{\eta}{s}(T) \right\rangle \langle N_{ch} \rangle^{-1/3}$$

PRL 122 (2019) 172301

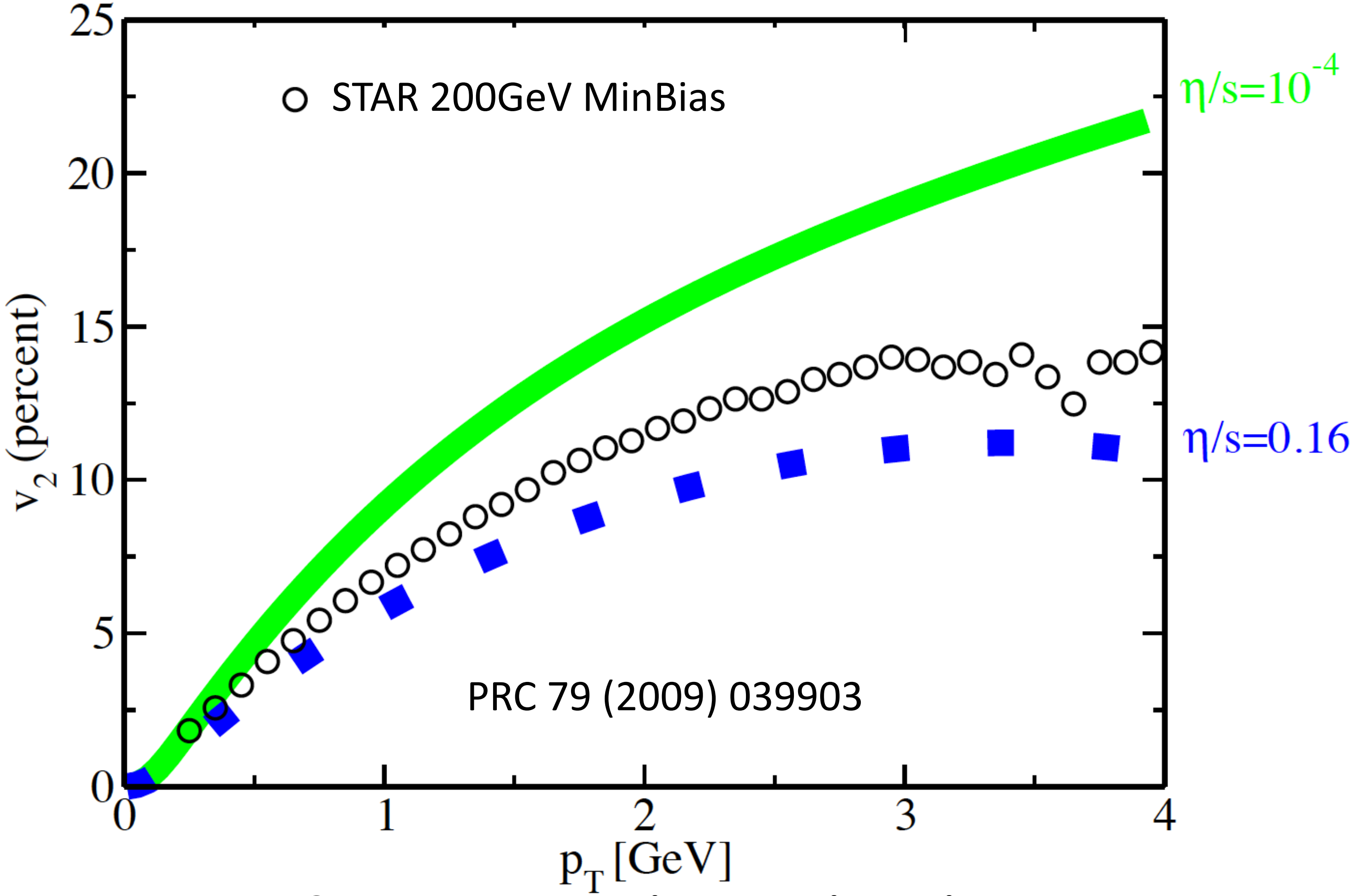


v_2 vs p_T – constrain viscosity



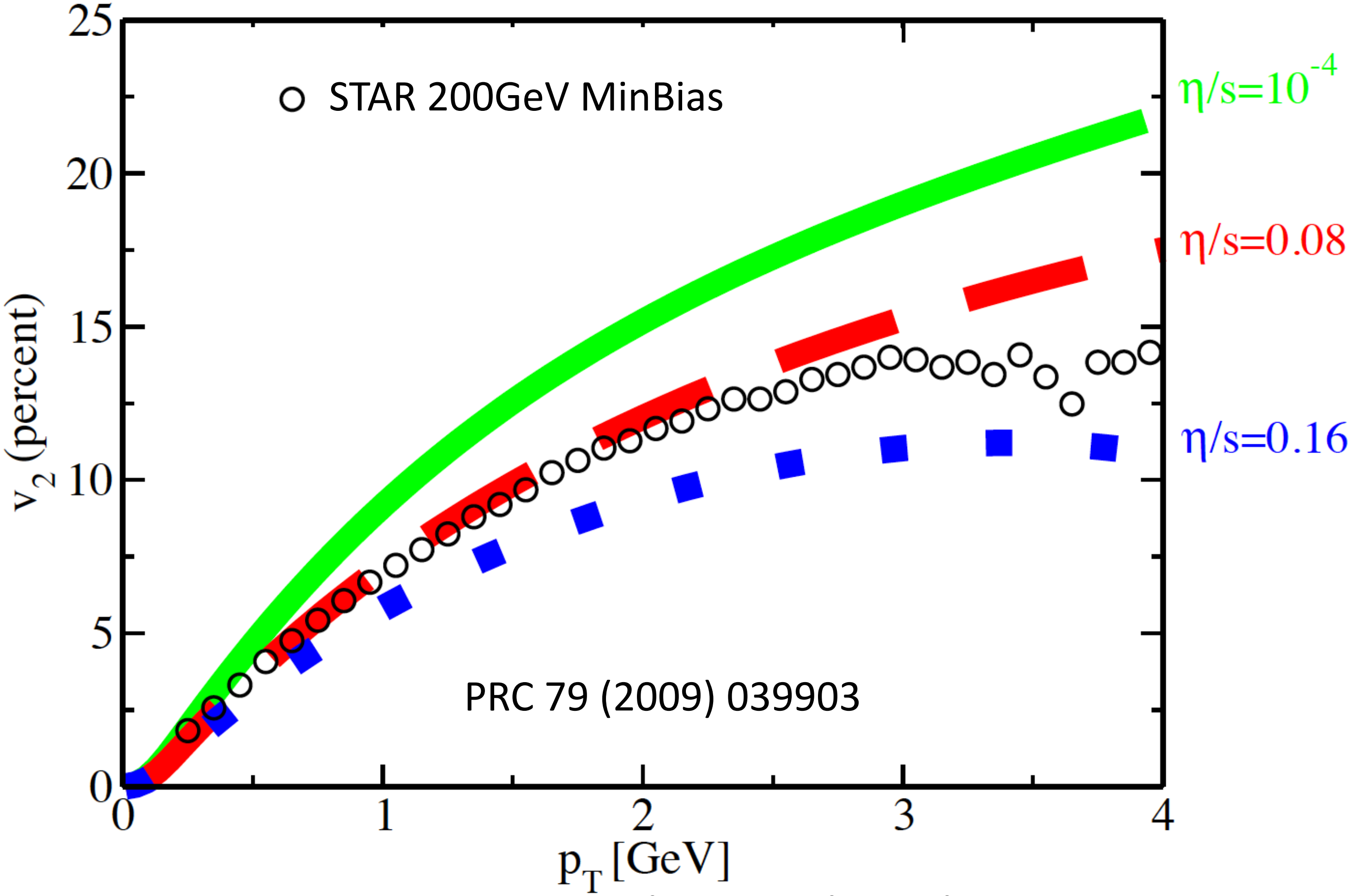
Need viscosity to match data

v_2 vs p_T – constrain viscosity



Strong constraint on viscosity

v_2 vs p_T – constrain viscosity

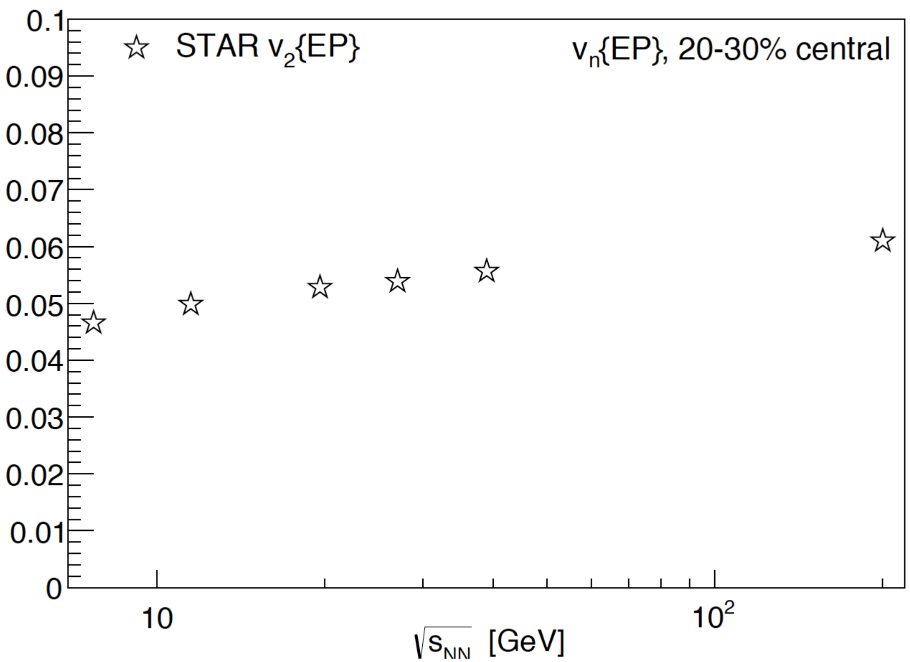


Strong constraint on viscosity

Reveal the nature of "perfect" fluid

Ads/CFT lower limit $\eta/s = 1/4\pi \approx 0.078$, PRL 94 (2005) 11601

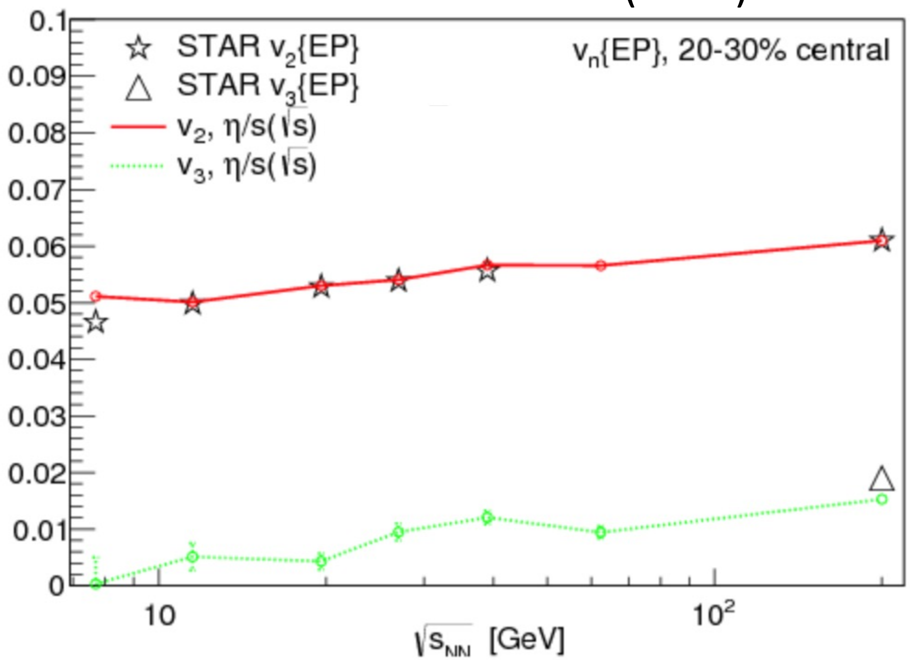
v_n vs. energy – viscosity vs. energy



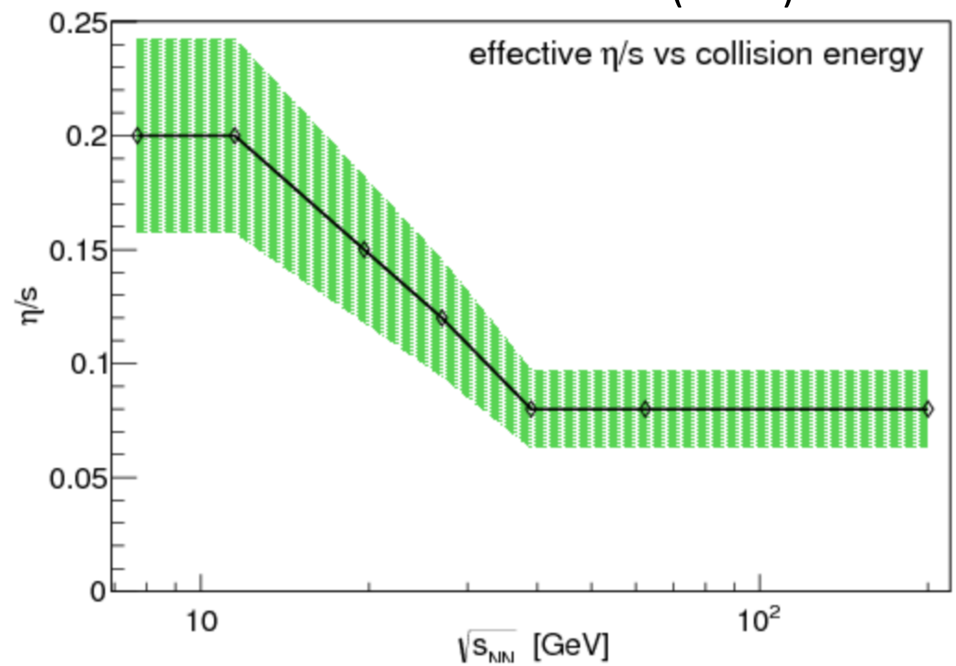
v_2 increases with collision energy

v_n vs. energy – viscosity vs. energy

PRC 91 (2015) 064901



PRC 91 (2015) 064901

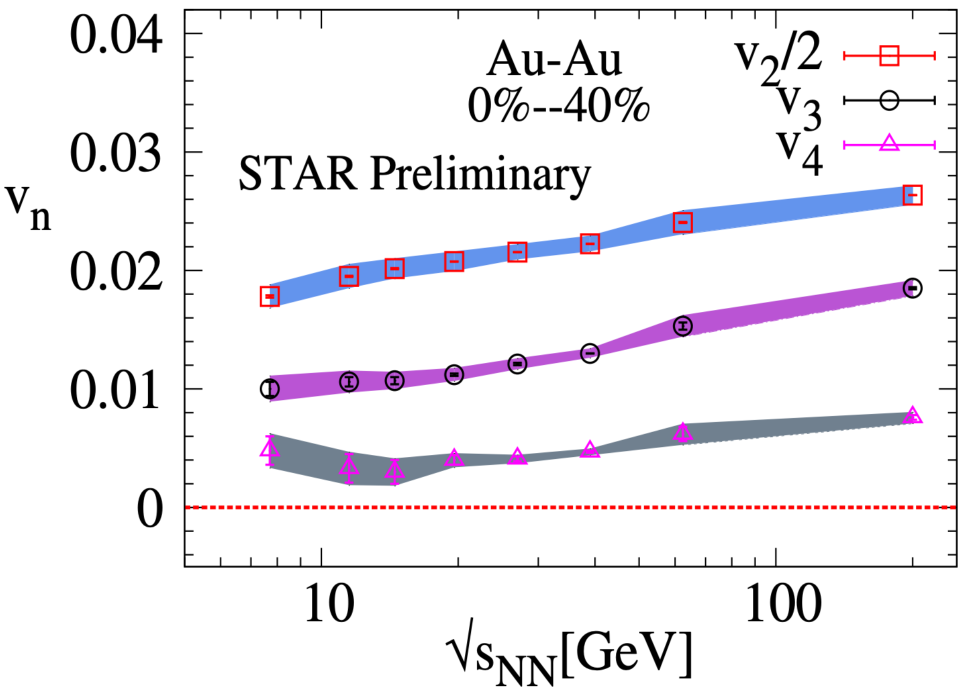


v_2 increases with collision energy

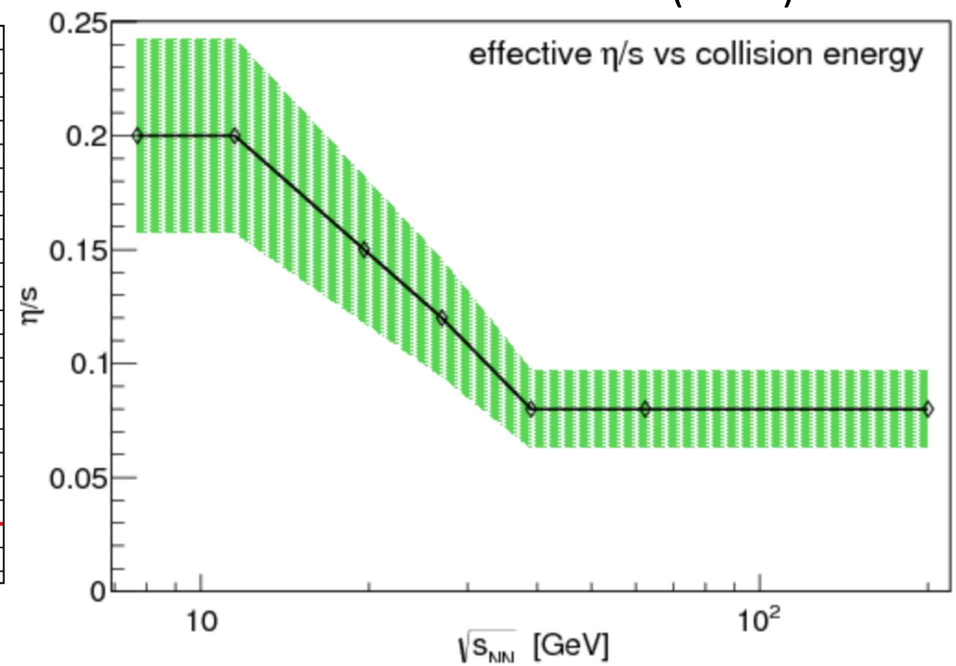
Indication of collision energy dependent viscosity

v_n vs. energy – viscosity vs. energy

JPCS 779 (2017) 1



PRC 91 (2015) 064901



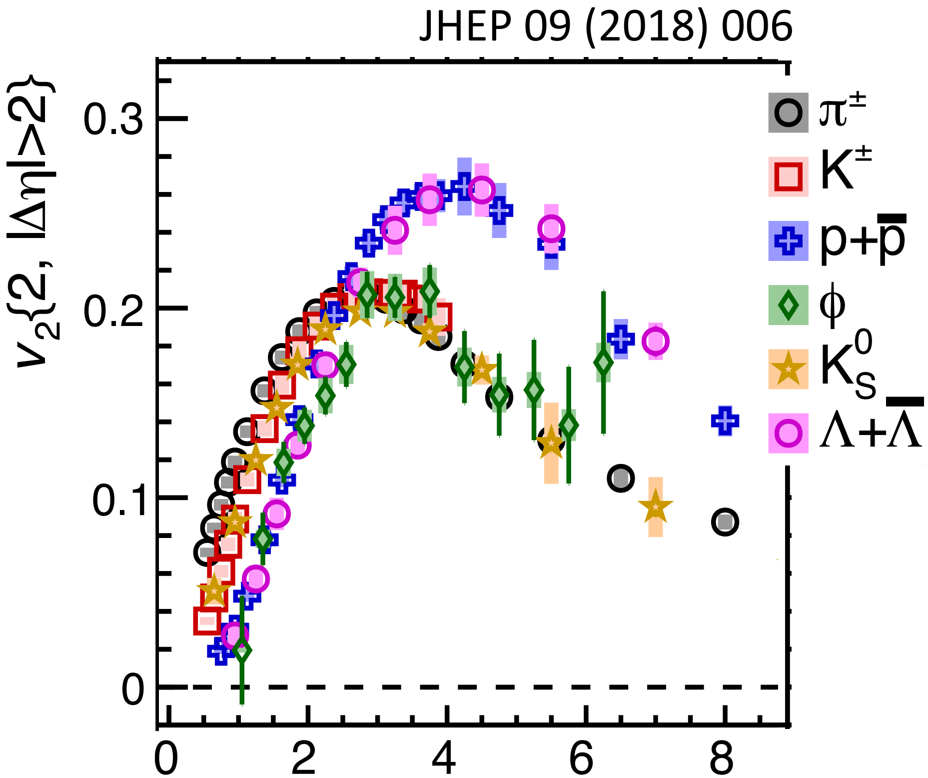
v_2 increases with collision energy

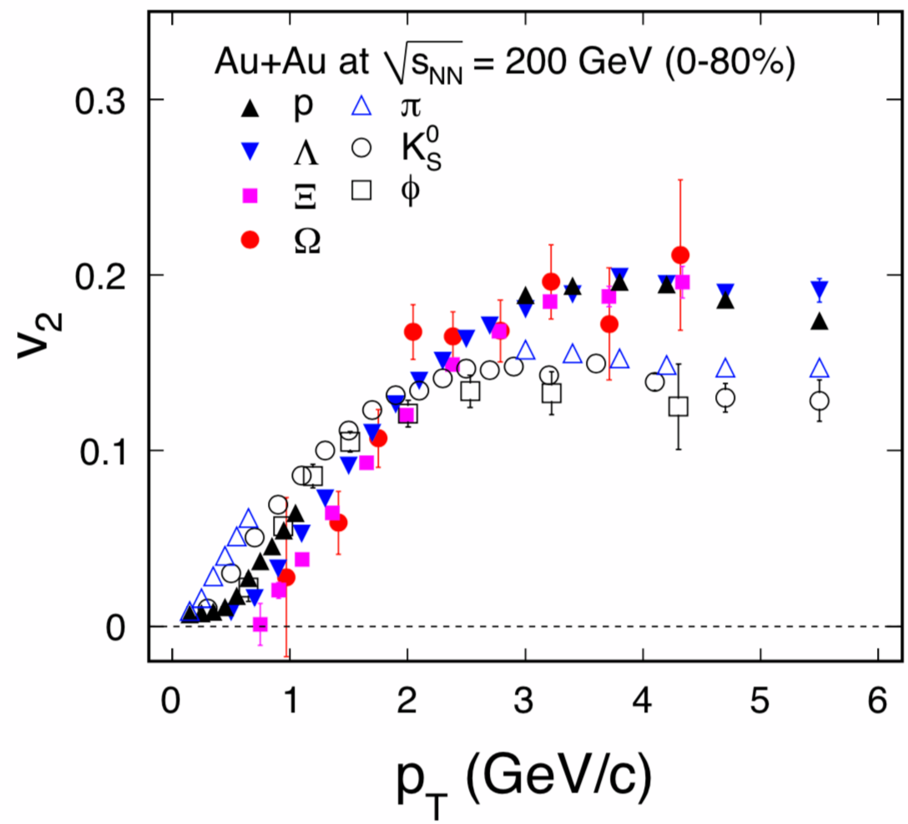
Indication of collision energy dependent viscosity

New results available for further investigation

v_n vs PID

v_n vs PID – mass ordering



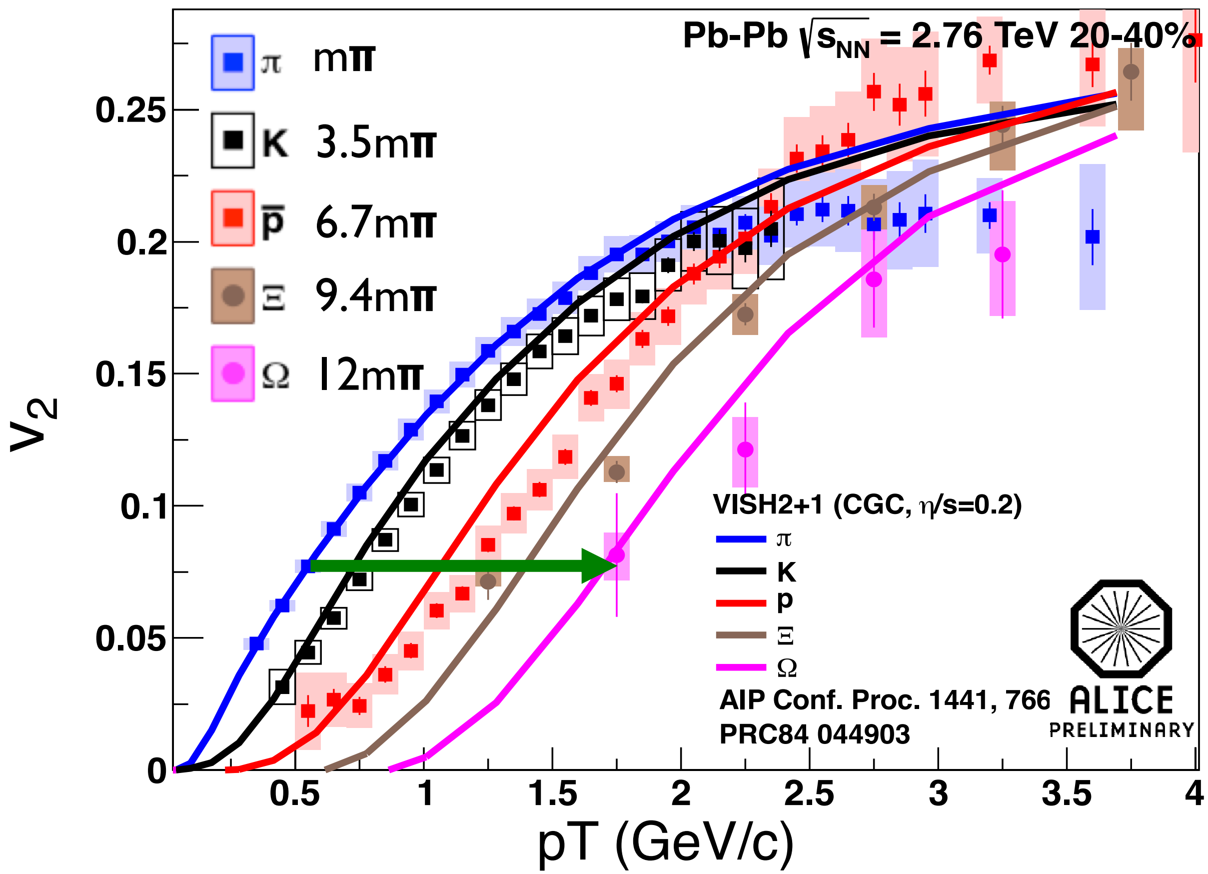


Mass ordering at low p_T <≈ 3GeV

Heavier particle has smaller v_n at same p_T

v_n vs PID – mass ordering

mass



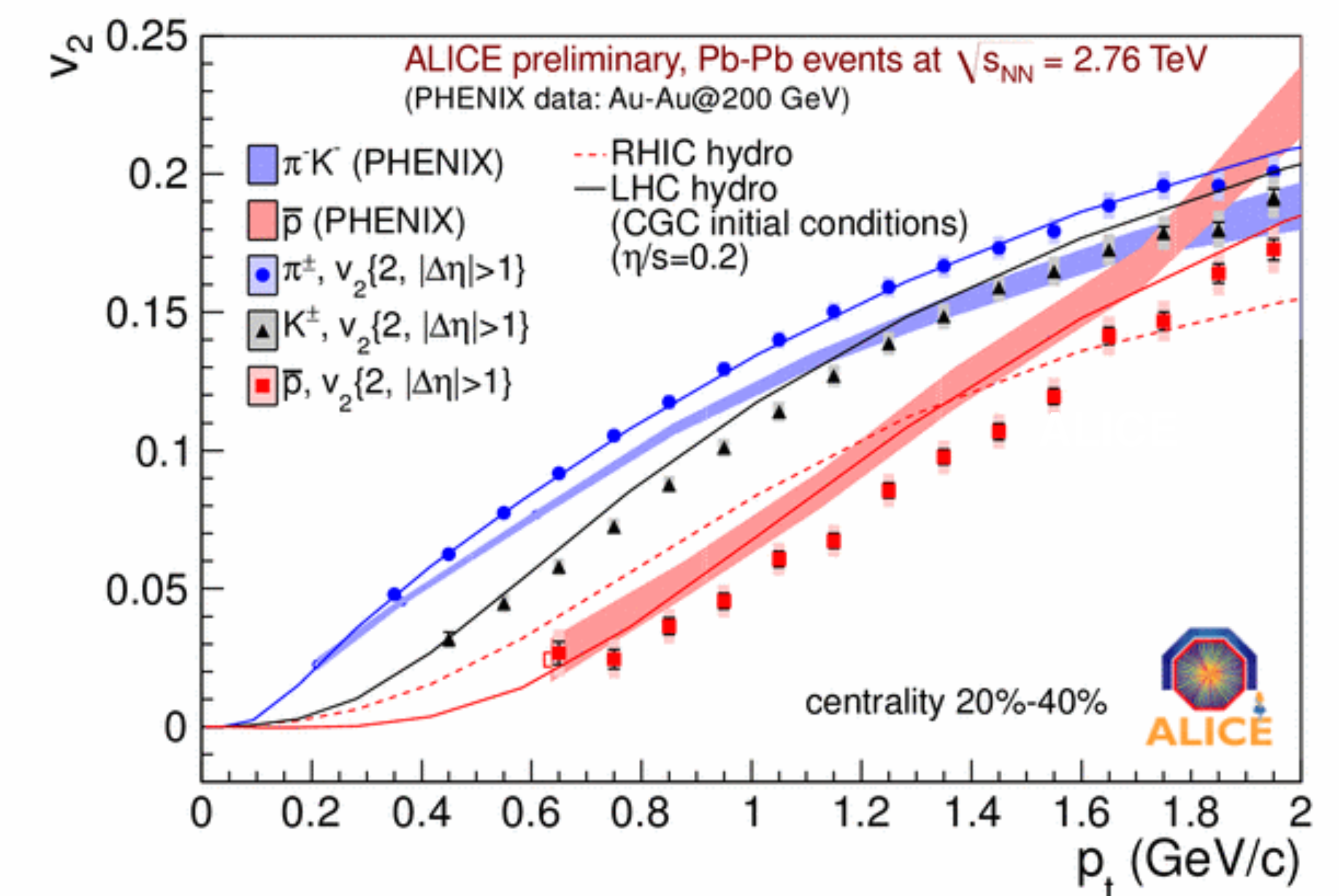
Boost: $\Delta p_T \sim m\beta_T$

Mass ordering at low p_T <≈ 3GeV

Heavier particle has smaller v_n at same p_T

Predicted by hydro: common boost from pressure gradient

v_n vs PID – mass ordering



Mass ordering at low p_T <≈ 3GeV

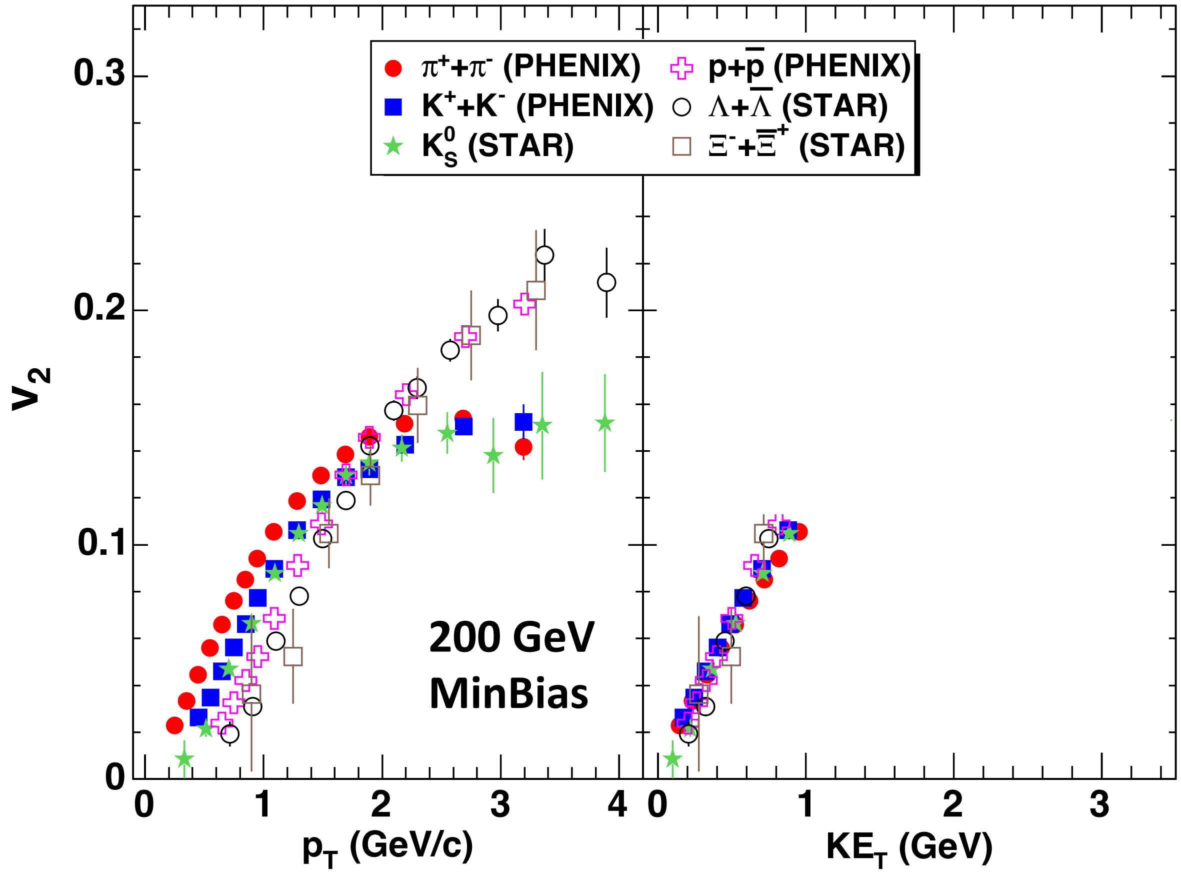
Heavier particle has smaller v_n at same p_T

Predicted by hydro: common boost from pressure gradient

Indicate larger boost @ LHC energies

v_n vs PID – KE_T scaling

PRL 98 (2007) 162301



$$KE_T = \sqrt{m^2 + p_T^2} - m$$

Pressure gradient

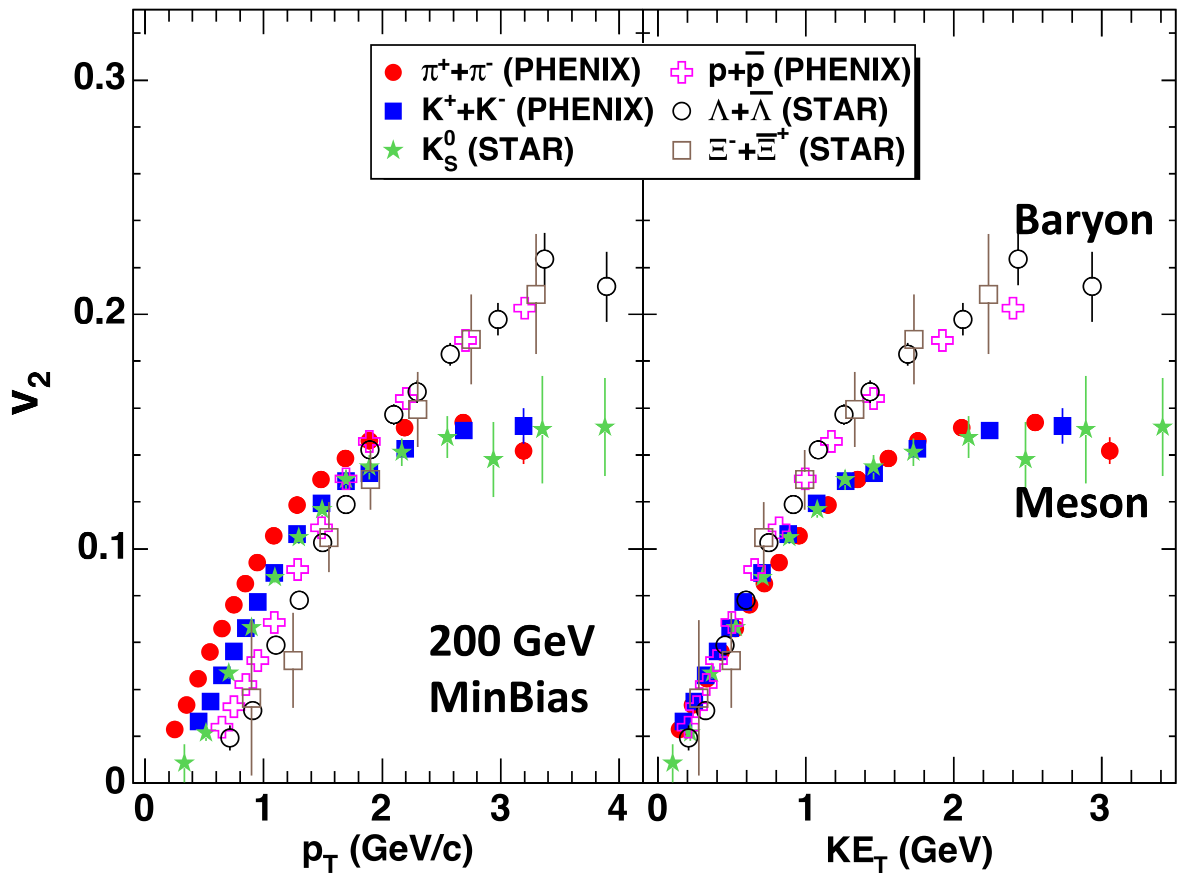
⇕

collective kinetic energy

KE_T scaling @ $KE_T <\approx$ 1GeV: Hydro pressure gradient

v_n vs PID – Quark Coalescence

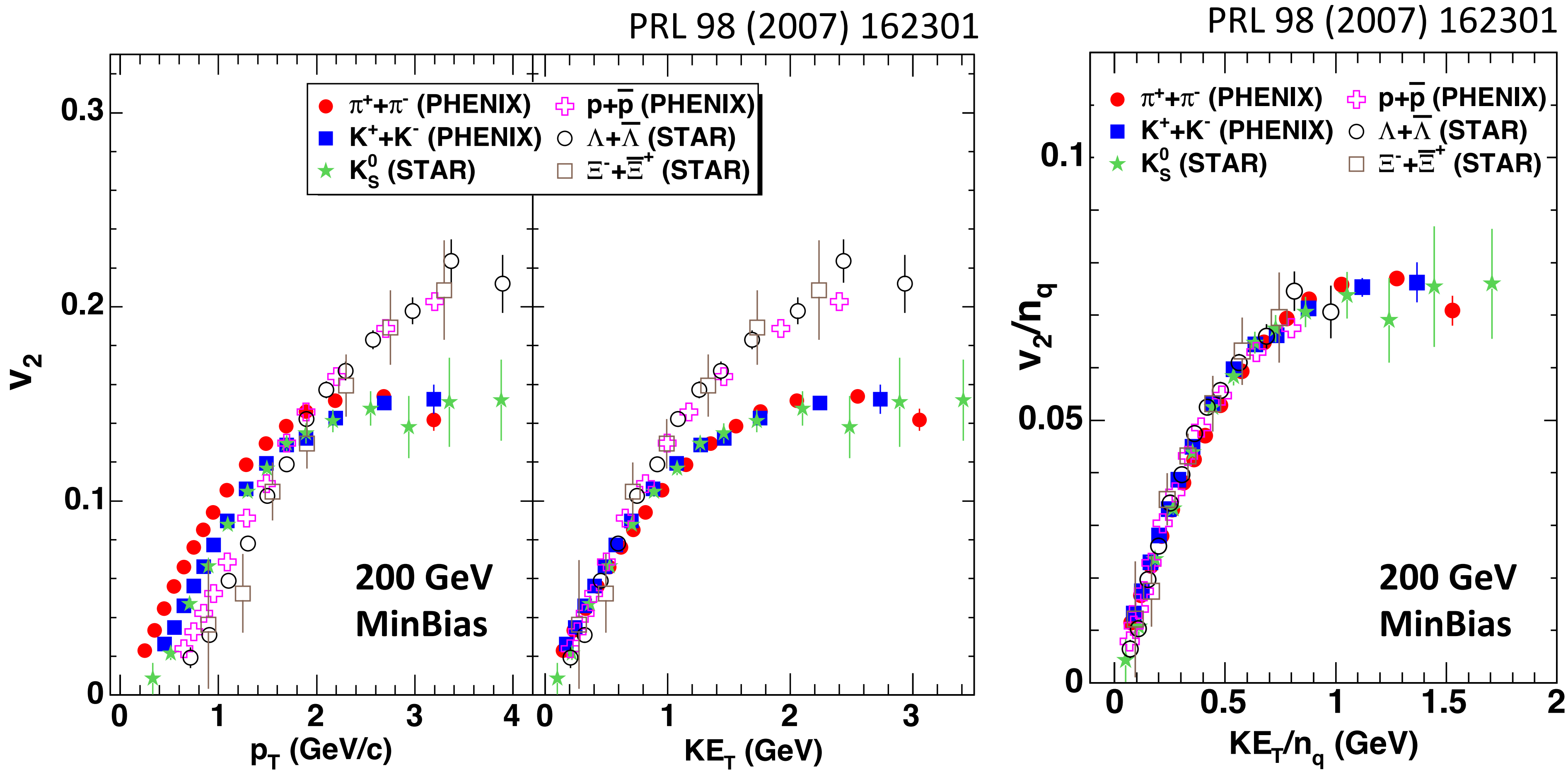
PRL 98 (2007) 162301



KE_T scaling @ KE_T <≈ 1GeV: Hydro pressure gradient

Meson/Baryon splitting: Quark coalescence

v_n vs PID – NCQ scaling

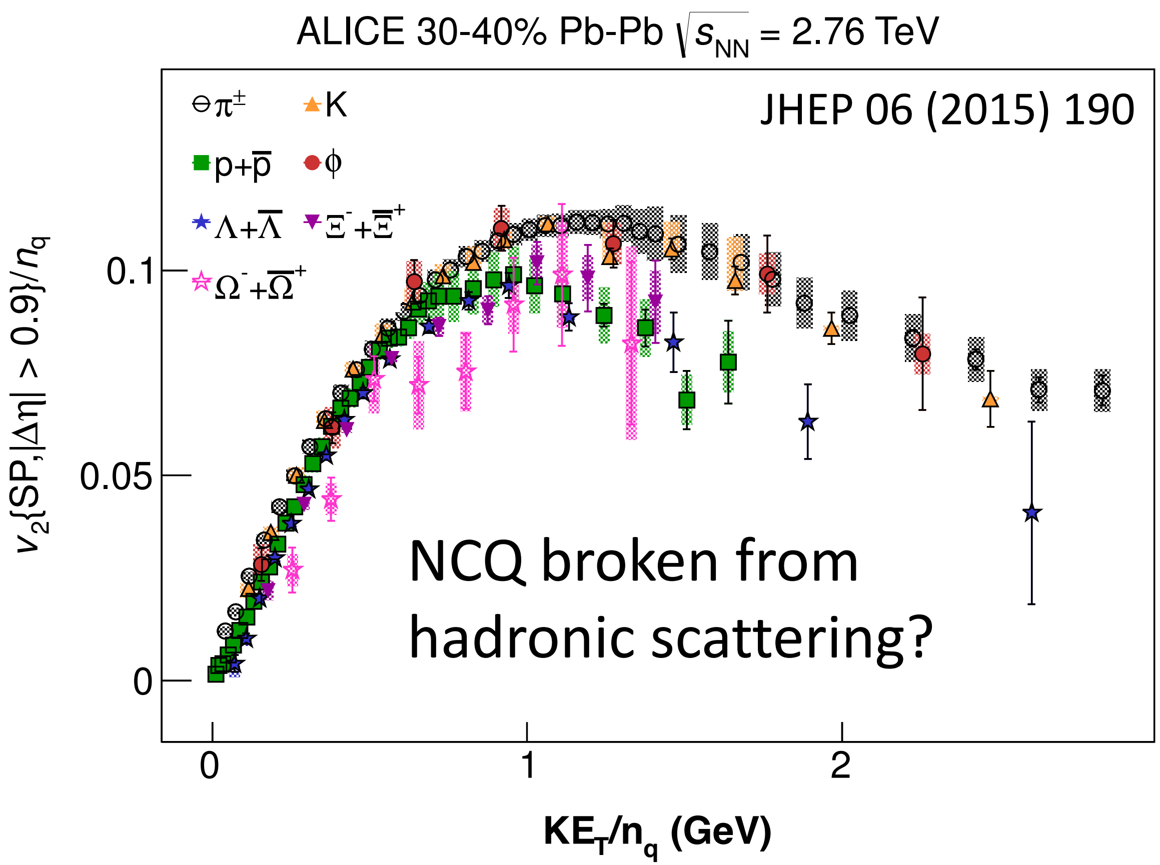


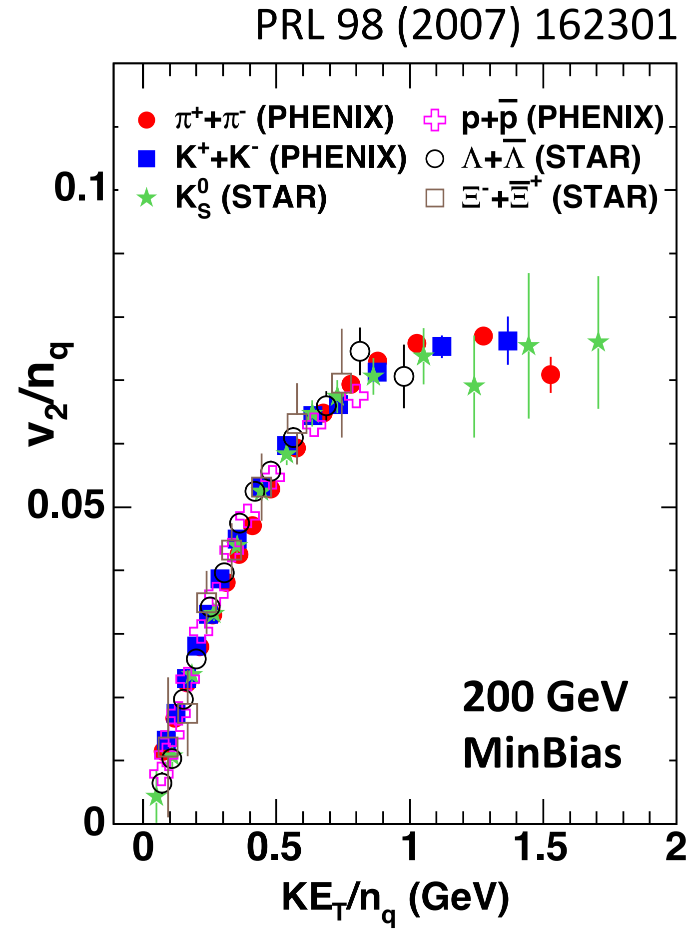
KE_T scaling @ KE_T <≈ 1GeV: Hydro pressure gradient

Meson/Baryon splitting: Quark coalescence

Number of Constituent Quark scaling: Parton degree of freedom

v_n vs PID – NCQ scaling





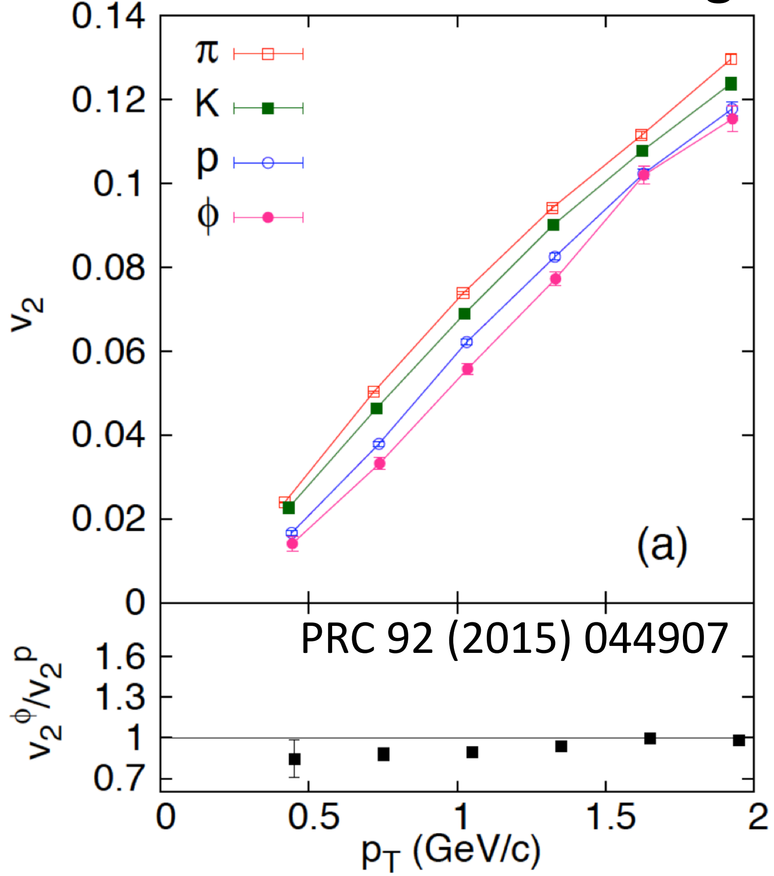
KE_T scaling @ KE_T <≈ 1GeV: Hydro pressure gradient

Meson/Baryon splitting: Quark coalescence

Number of Constituent Quark scaling: Parton degree of freedom

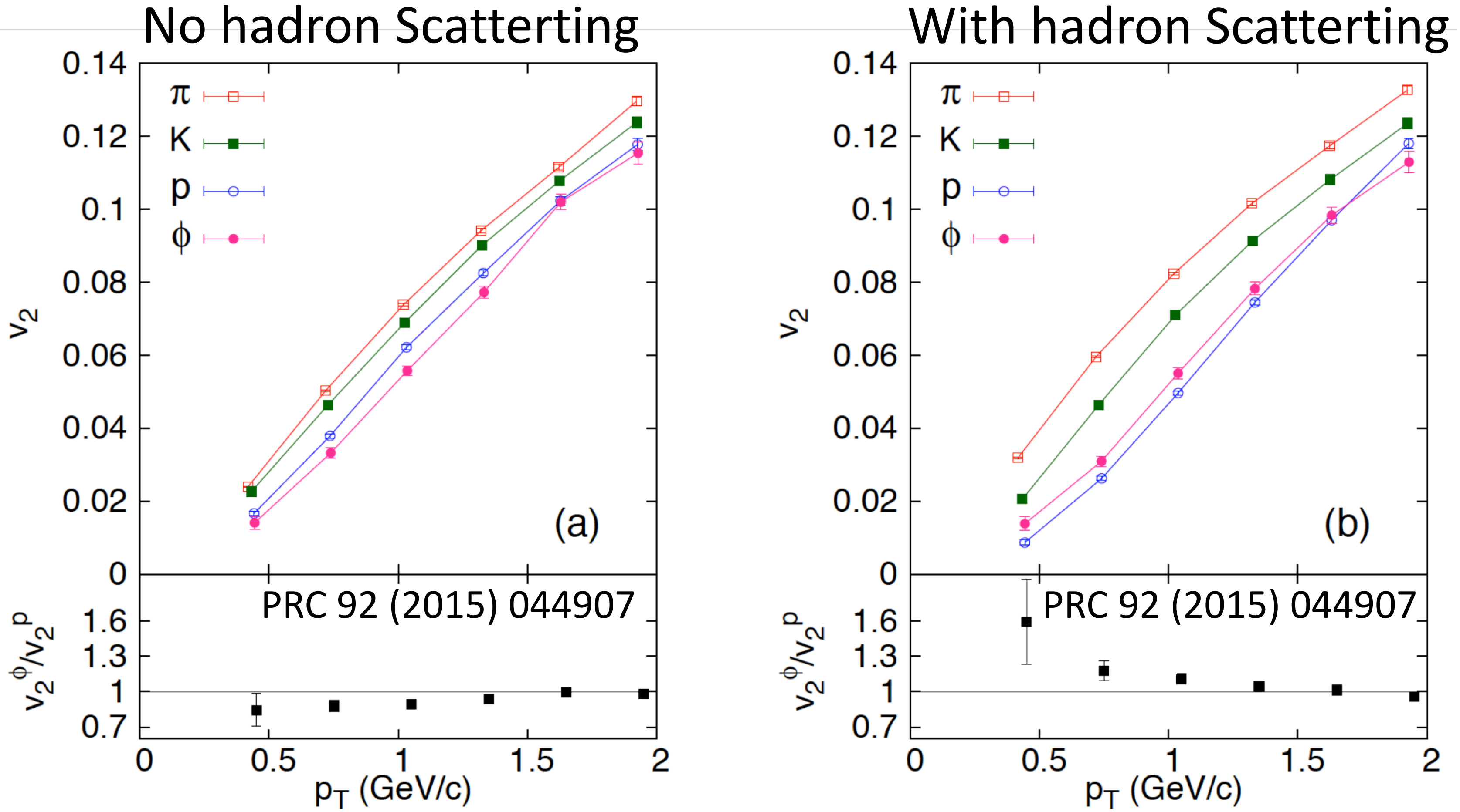
v_n vs PID – impact of hadronic phase

No hadron Scatterting



Ideal hydro + hadron cascade (JAM)

v_n vs PID – impact of hadronic phase

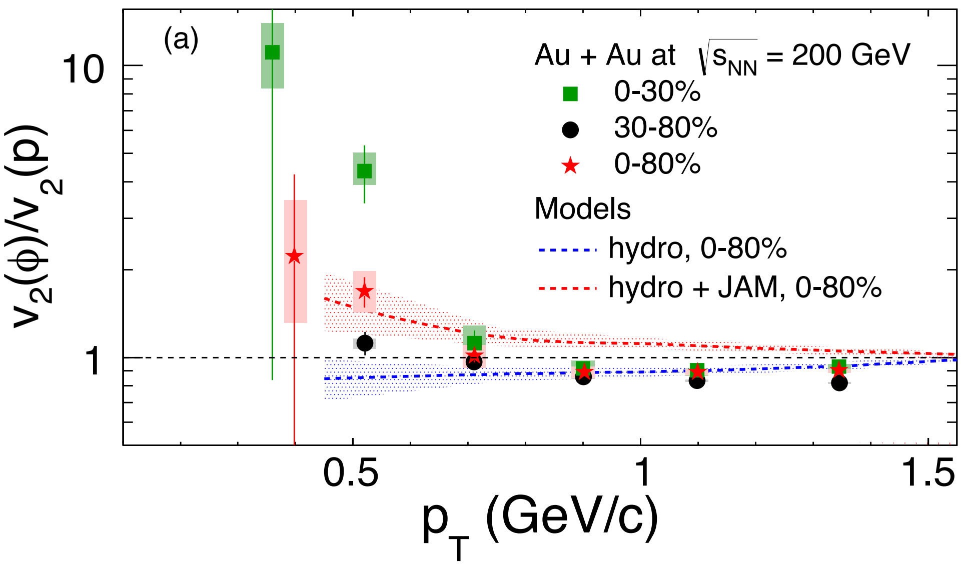


Ideal hydro + hadron cascade (JAM)

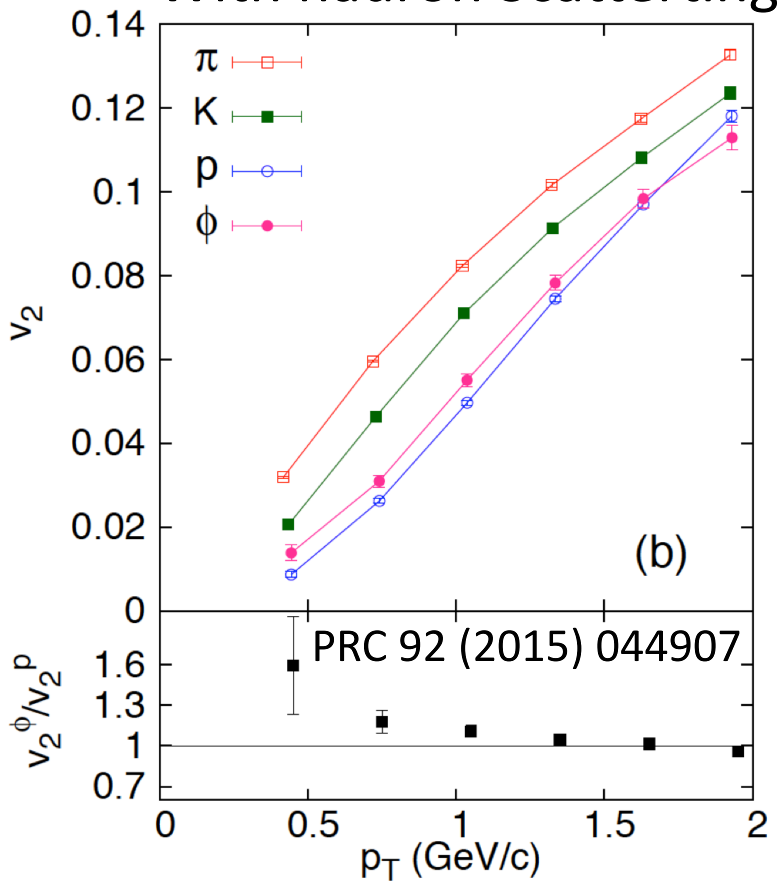
Small hadron cross section breaks mass ordering for ϕ

v_n vs PID – impact of hadronic phase

PRL 116 (2016) 062301



With hadron Scatterting

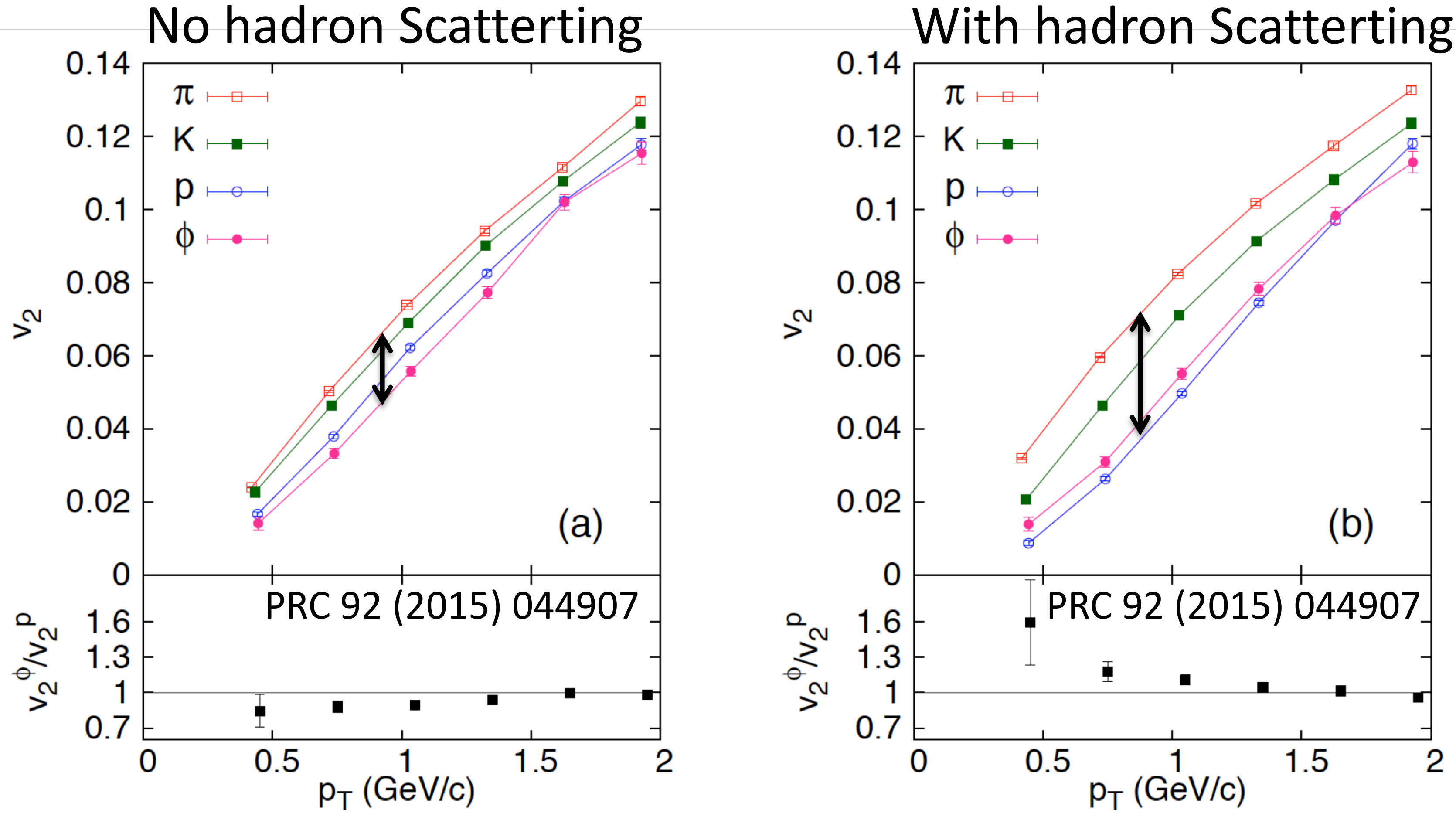


Ideal hydro + hadron cascade (JAM)

Small hadron cross section breaks mass ordering for ϕ

Confirmed by data

v_n vs PID – impact of hadronic phase

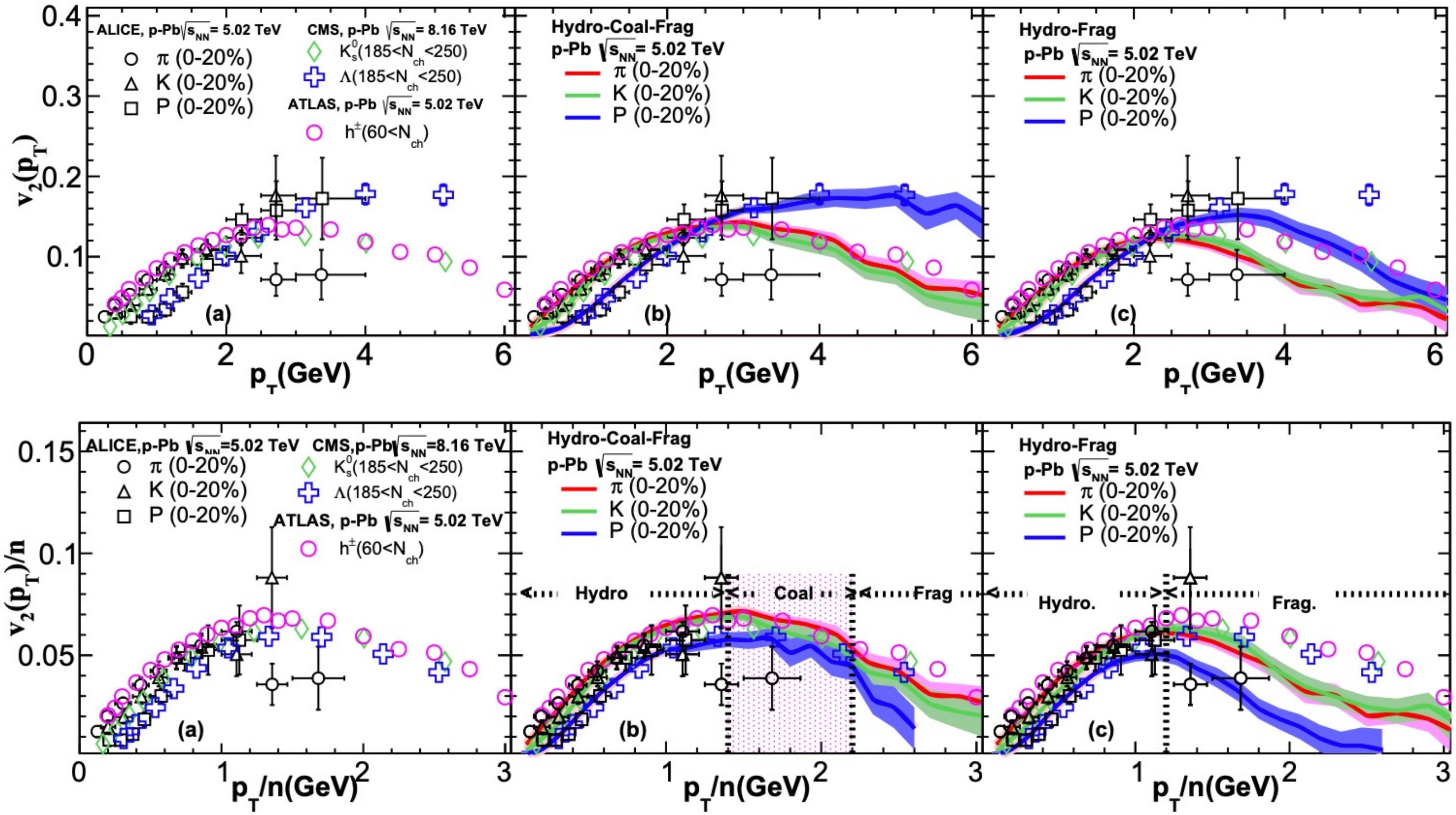


Ideal hydro + hadron cascade (JAM)

Small hadron cross section breaks mass ordering for phi

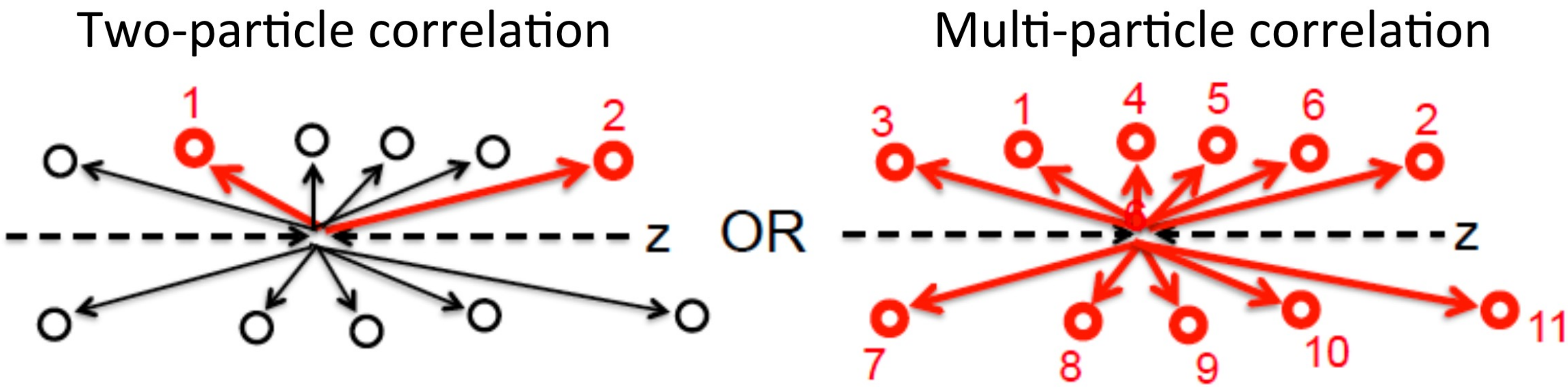
Confirmed by data; **implication on NCQ scaling?**

v_n vs PID – impact from coalescence?



Coalescence of
quenched jet particle and bulk particle
can break the scaling

v_n from multi-particle correlation



Multi-particle (>2) cumulants:

$$\langle\langle 6\rangle\rangle = \left\langle\left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\right\rangle\right\rangle$$

$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\cdot\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\cdot\langle\langle 2\rangle\rangle^3$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

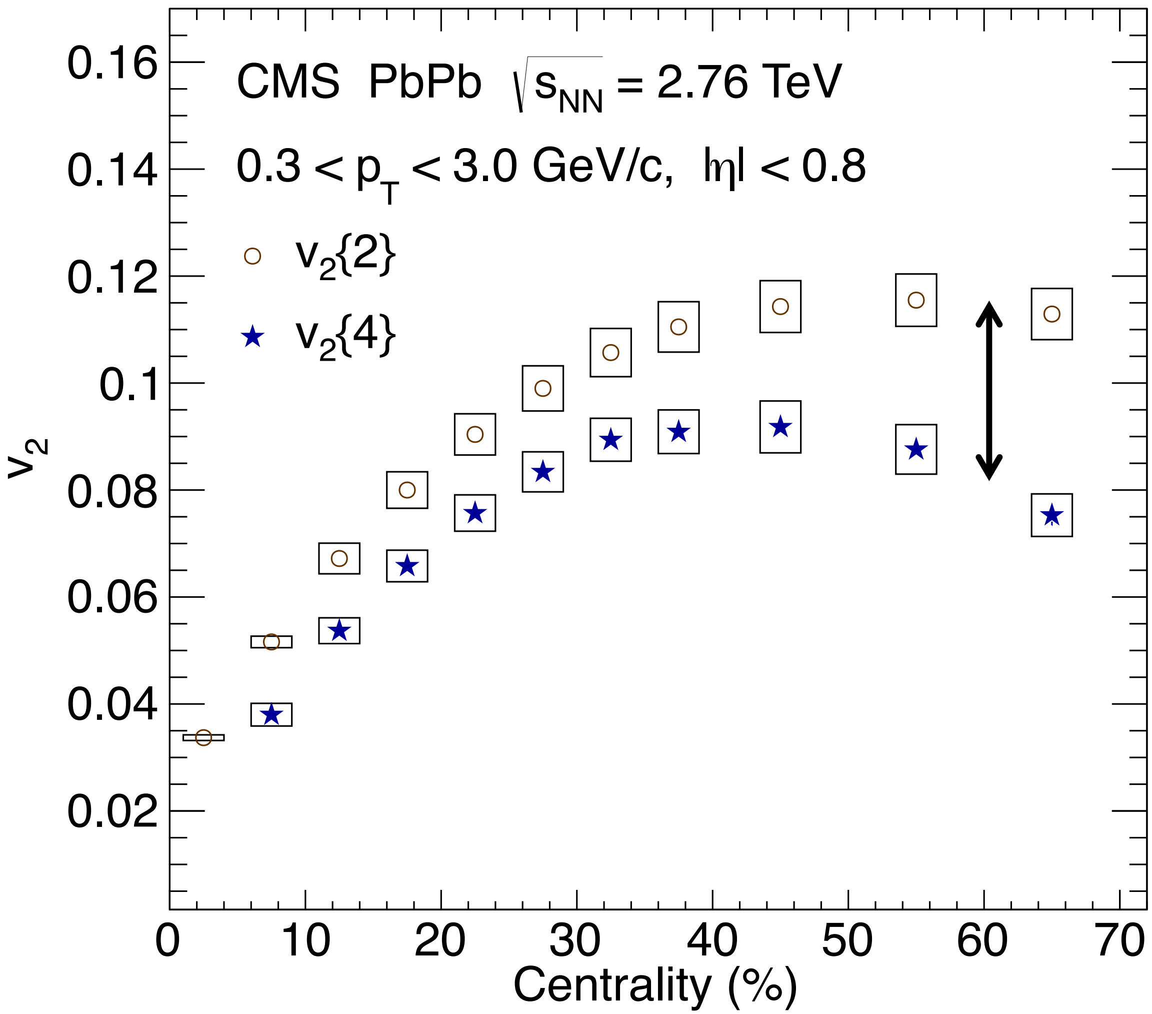
$$v_n\{6\} = \sqrt[4]{\frac{1}{4}c_n\{6\}}$$

Q-cumulant, PRC 83 (2011) 044913

$v_n\{4\} \approx v_n\{6\} \approx \ldots \rightarrow$ system is collective

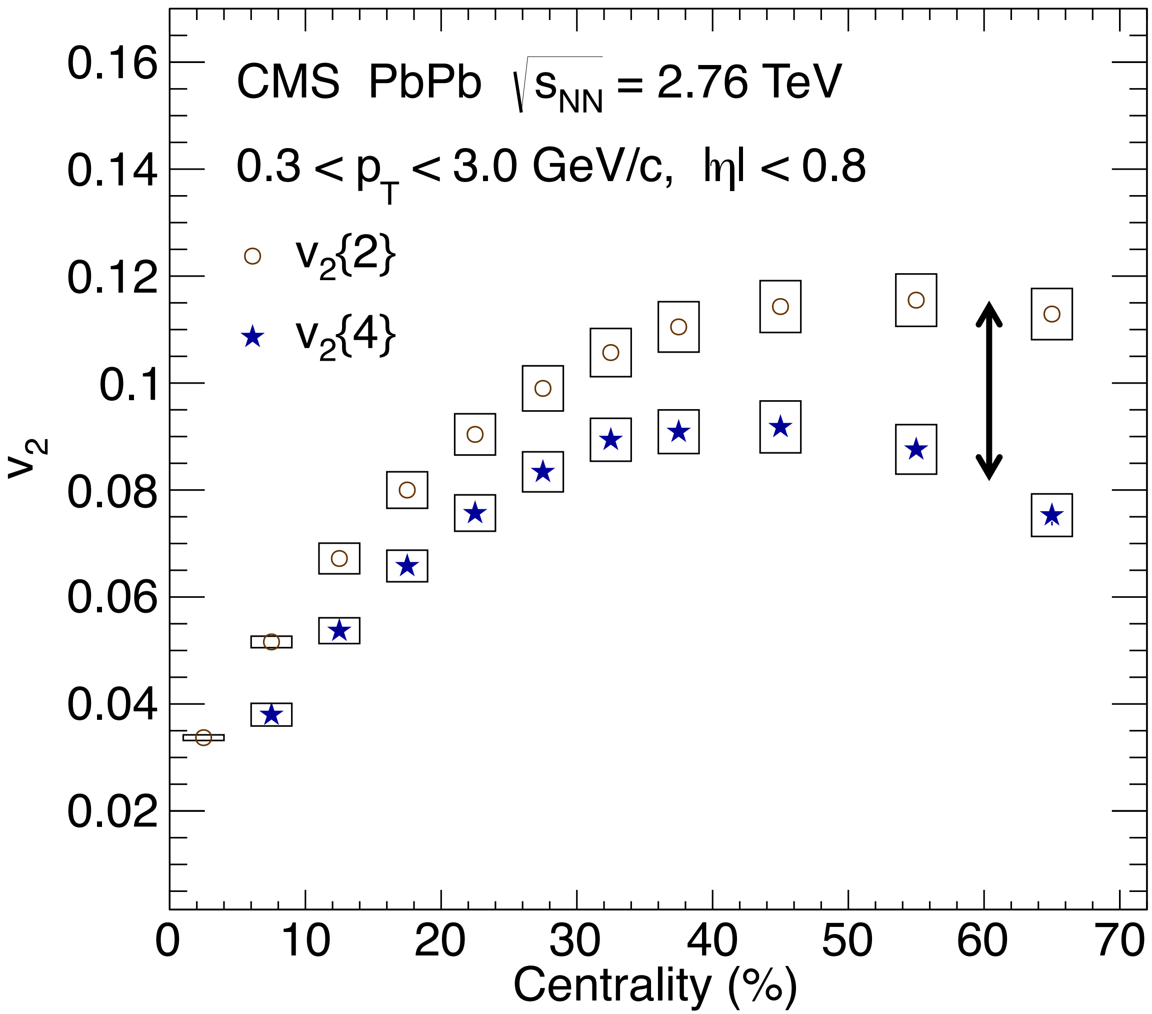
v_n from multi-particle correlation

PRC 87 (2013) 014902

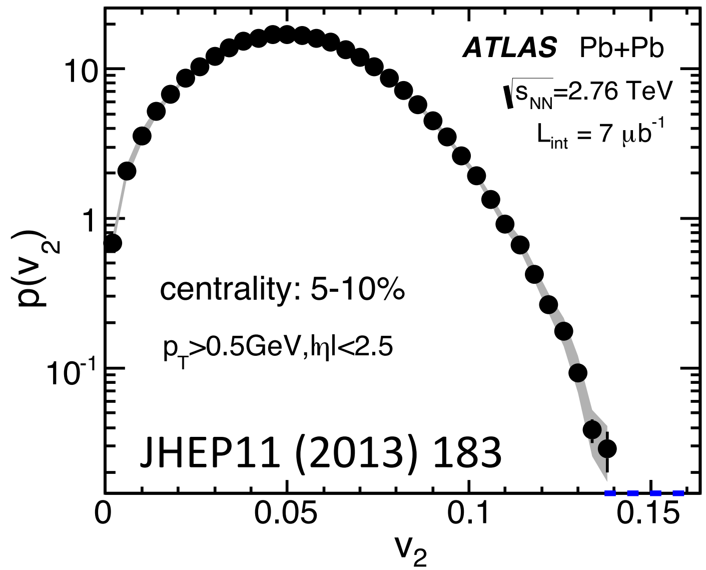


v_n from multi-particle – flow fluctuation

PRC 87 (2013) 014902



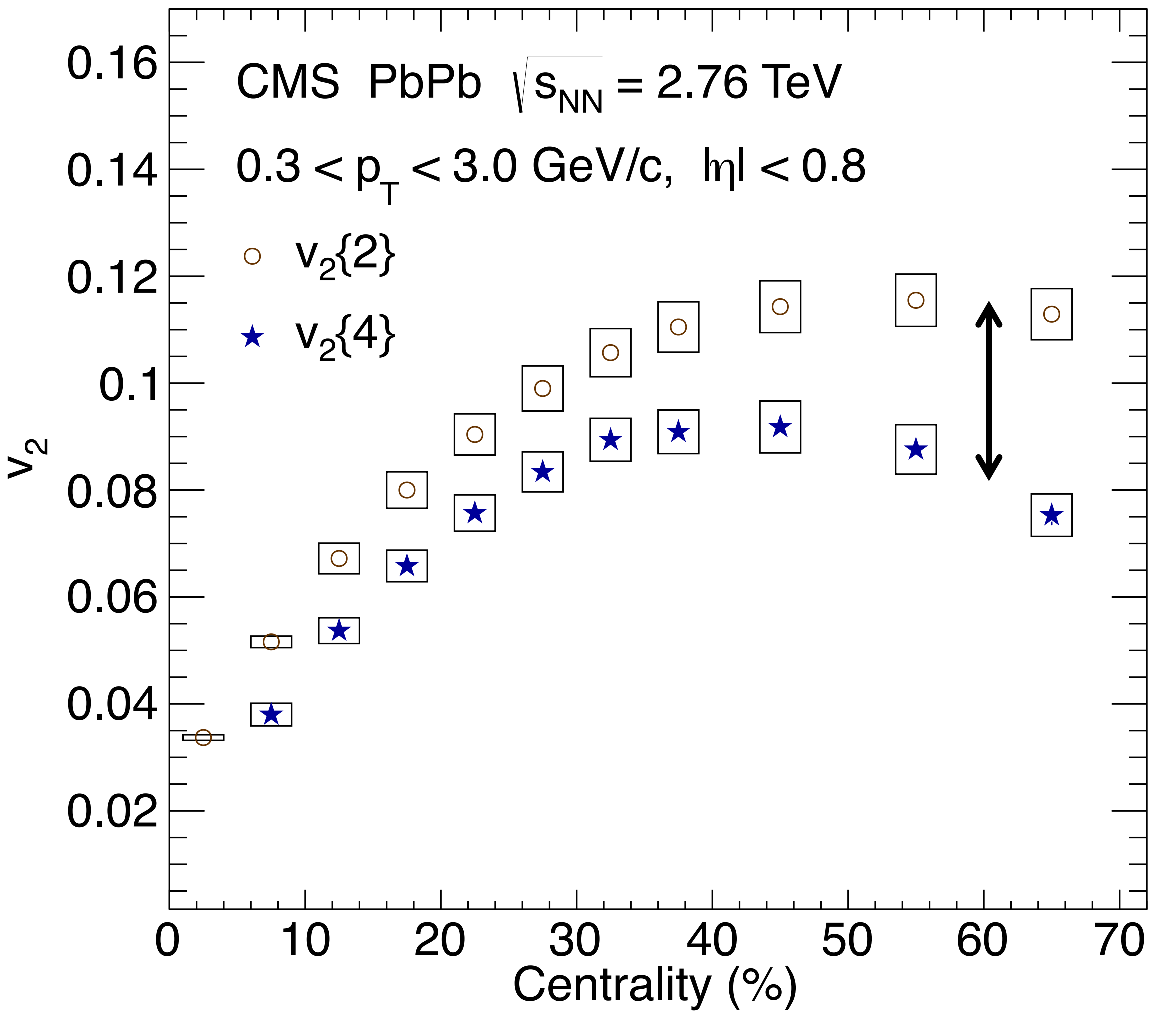
Event-by-Event
Flow Fluctuation



JHEP11 (2013) 183

v_n from multi-particle – flow fluctuation

PRC 87 (2013) 014902



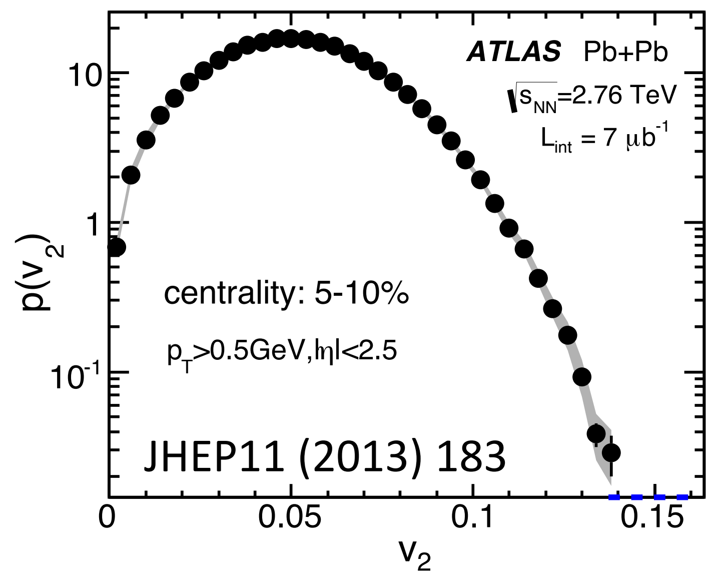
Event-by-Event
Flow Fluctuation

$$v_n\{2\}^2 = \langle v_n^2 \rangle = \langle v_n \rangle^2 + \sigma_{v_n}^2$$

$$v_n\{4\}^2 = \left(2\langle v_n^2\rangle^2 - \langle v_n^4\rangle\right)^{\frac{1}{2}}$$

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

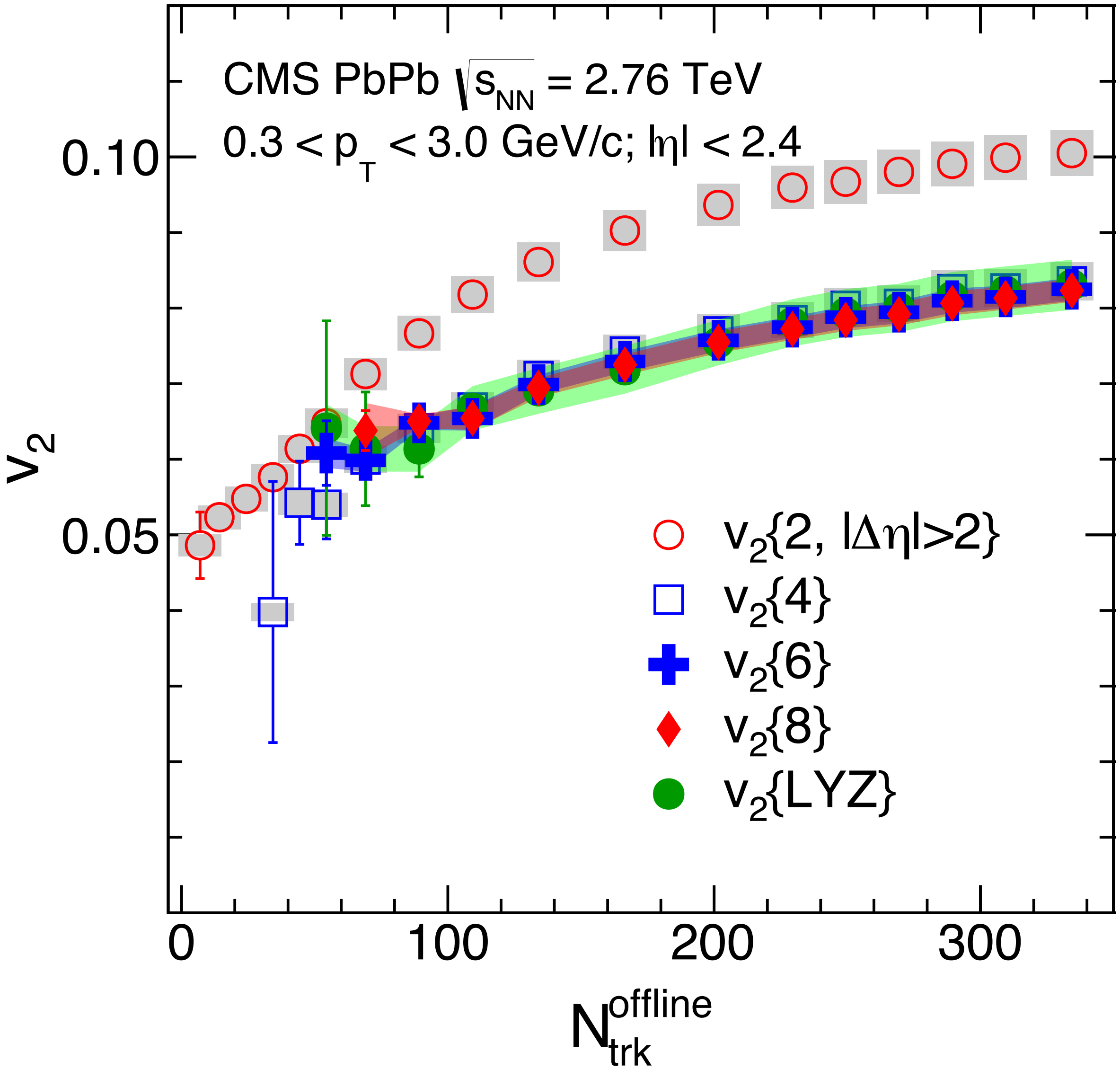
PRC 80 (2009) 014904



JHEP11 (2013) 183

v_n from multi-particle – flow fluctuation

PRL 115 (2015) 012301



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

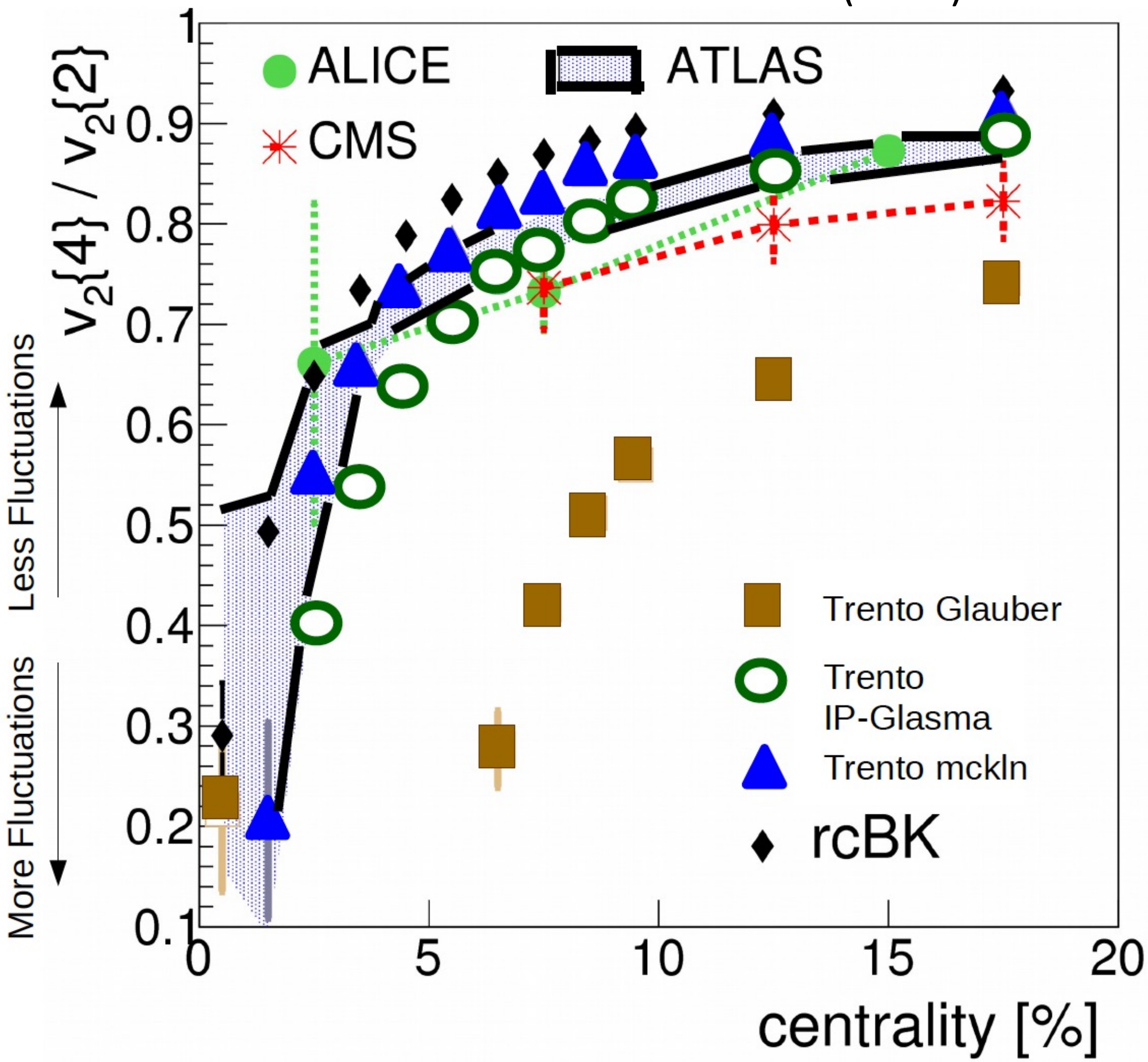
PRC 80 (2009) 014904

$v_2\{4,6,8,LYZ\}$ indicate multi-particle nature of correlation

More implications on flow fluctuation see EPJC 74 (2014) 3157

v_n from multi-particle – constrain initial-state

PRC 95 (2017) 054910



Event-by-Event
Flow Fluctuation

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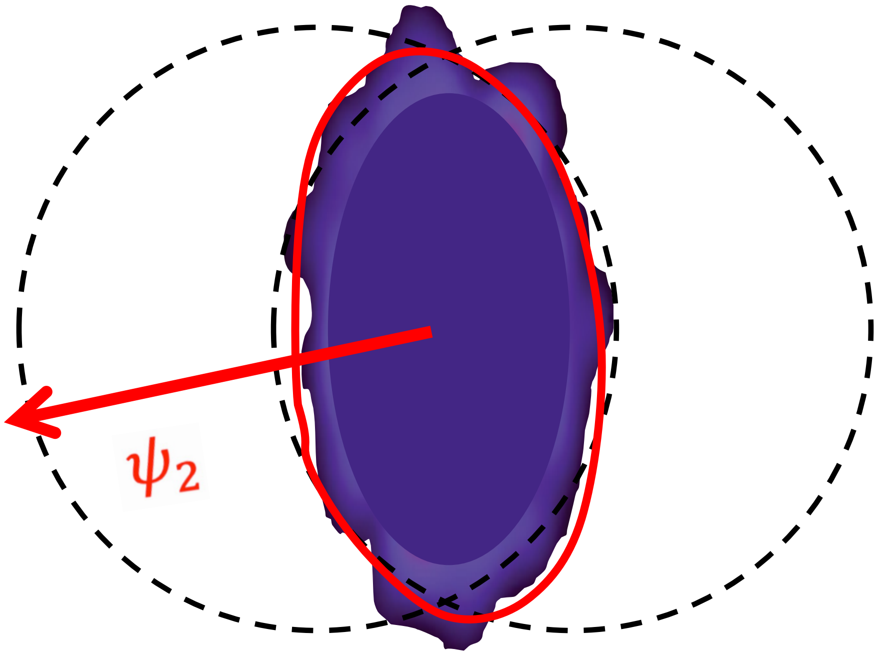
$$\approx \langle v_n \rangle^2 - \sigma_{v_n}^2$$

PRC 80 (2009) 014904

Strong constraints on initial state models
MC Glauber fails!

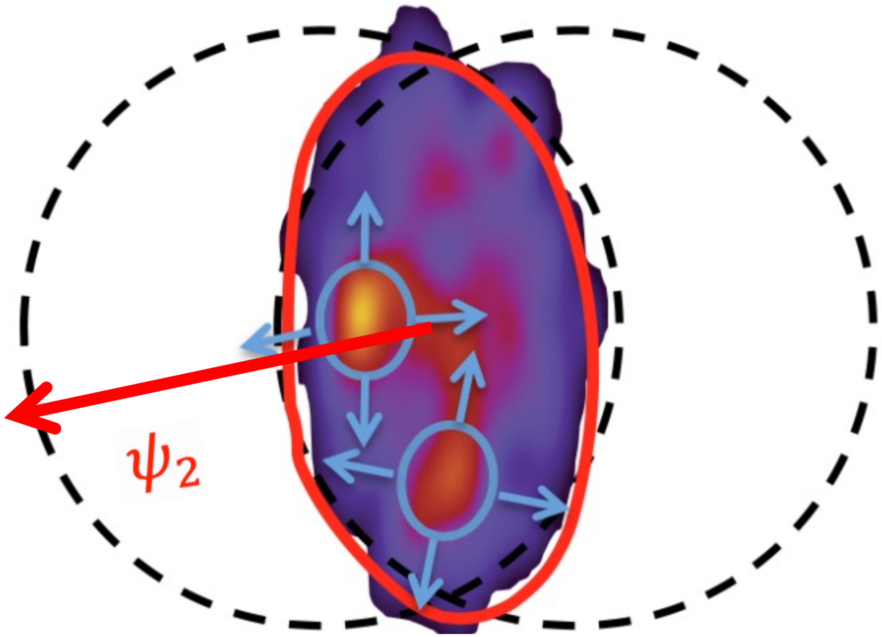
TRENTO: PRC 92(2015) 011901
rcBK: arXiv:1011.5161

Decorrelation – Transeverse



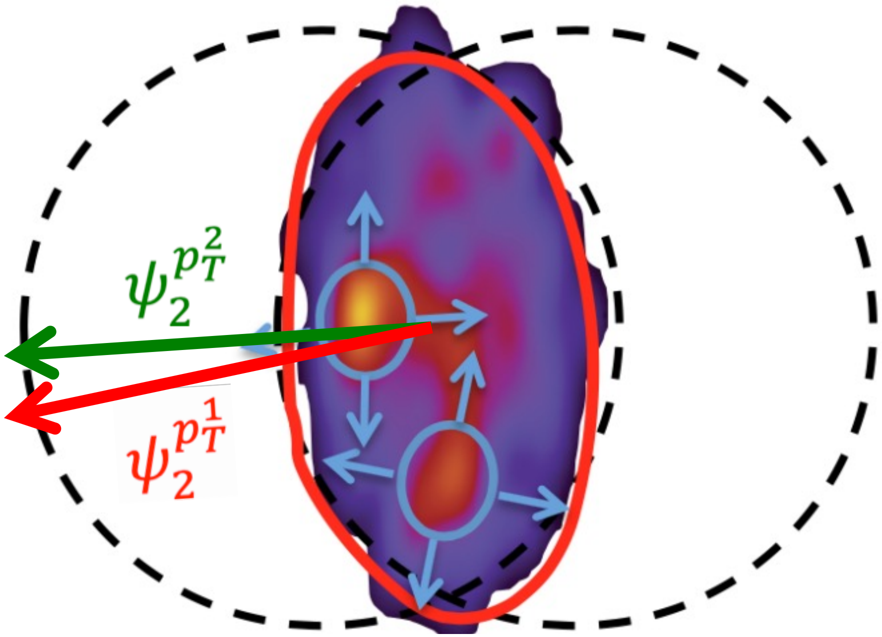
All particle share the same event plane

Decorrelation – Transeverse



Local hot spots push particles to higher p_T

Decorrelation – Transeverse

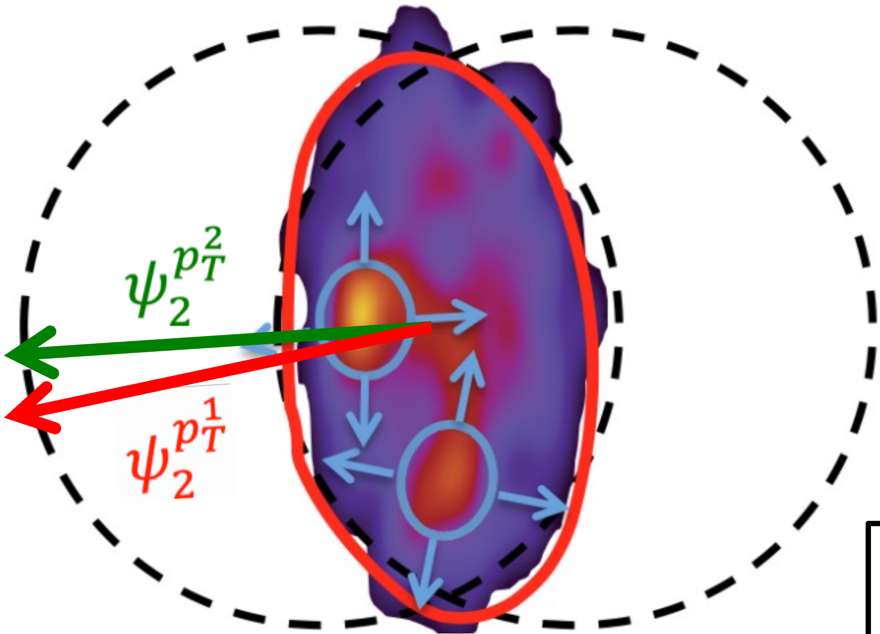


Local hot spots push particles to higher p_T

AND

result in different event planes for different p_T range

Decorrelation – Transeverse



Local hot spots push particles to higher p_T
AND
result in different event planes for different p_T range

Factorization breaking

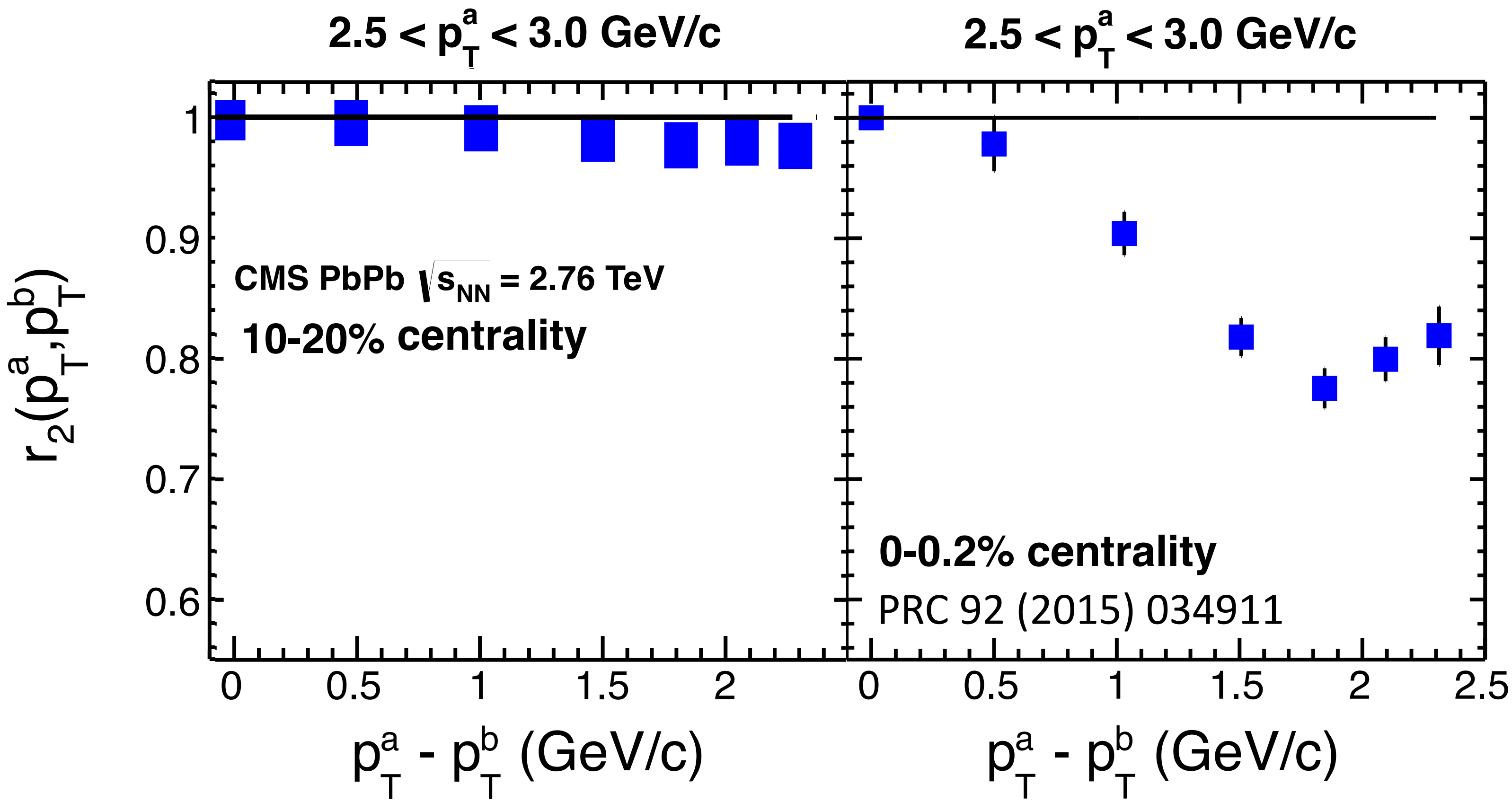
$$V_{n\Delta}(p_T^a, p_T^b) \neq v_n(p_T^a) \times v_n(p_T^b)$$

Effects measurable by

$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}} \sim \left\langle cos\left[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))\right]\right\rangle$$

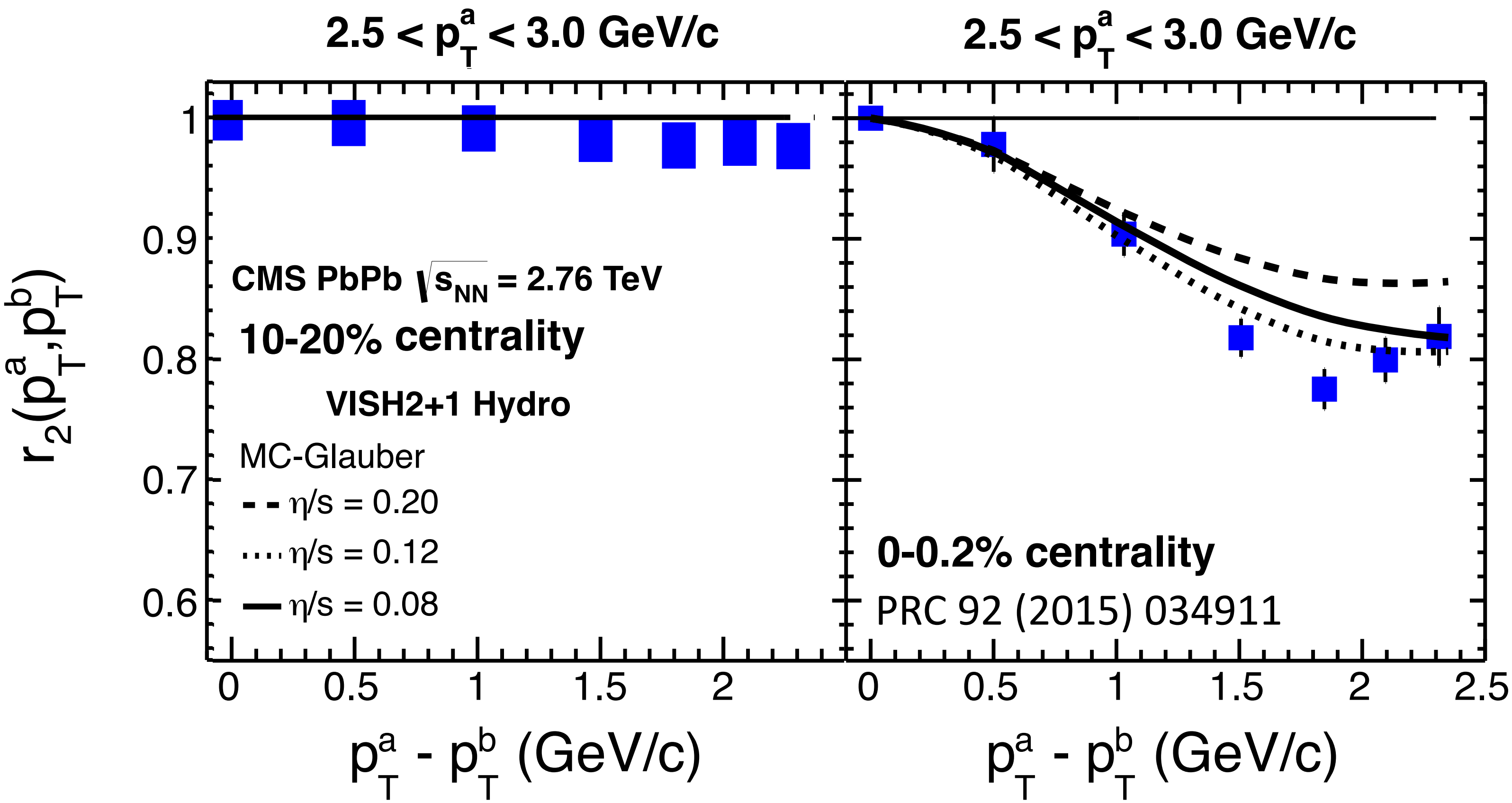
PRC 92 (2015) 034911

Decorrelation – p_T



Most prominent at central collisions where fluctuation dominates

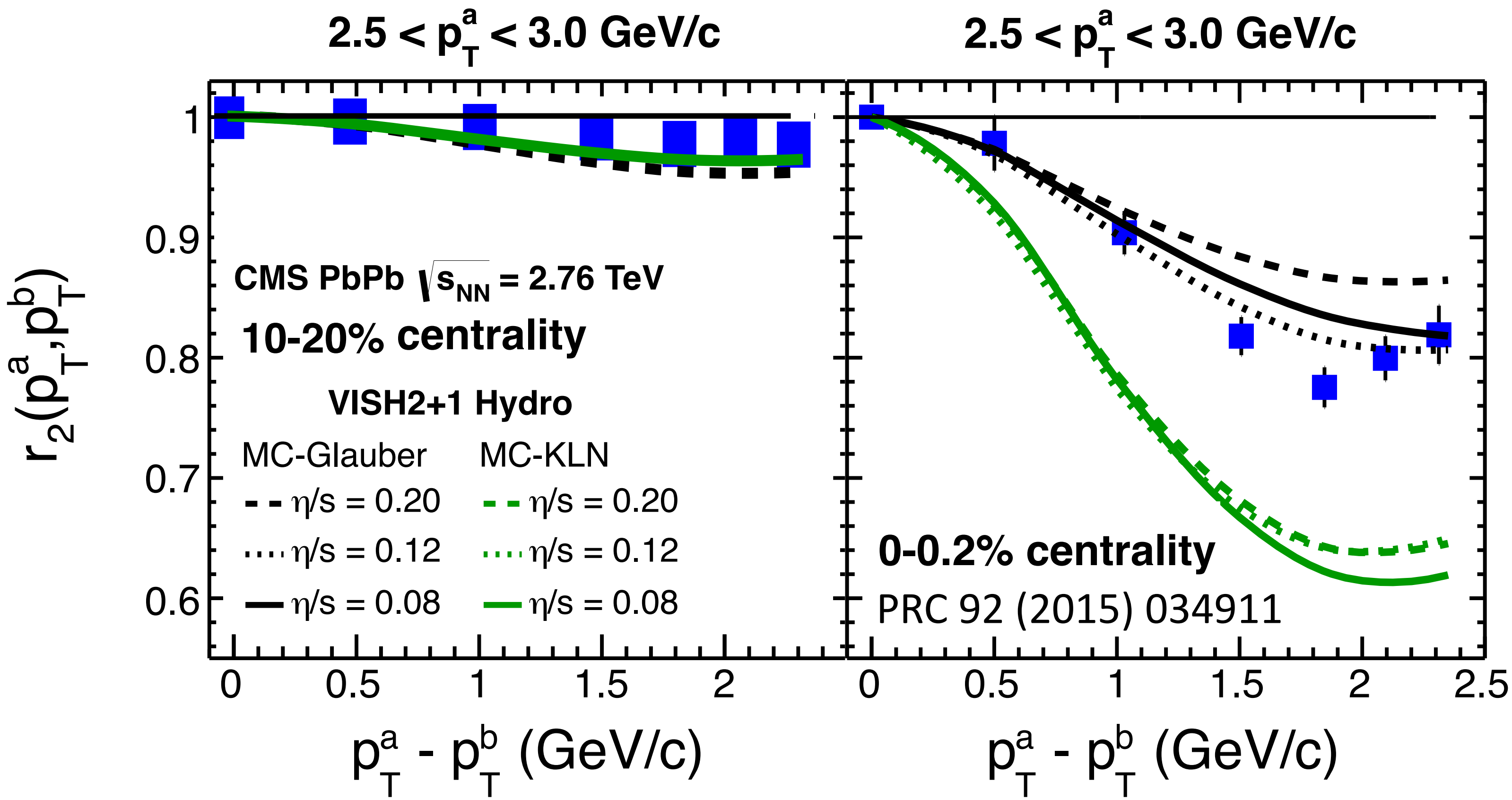
Decorrelation – p_T



Most prominent at central collisions where fluctuation dominates

Some dependence on η/s

Decorrelation – p_T

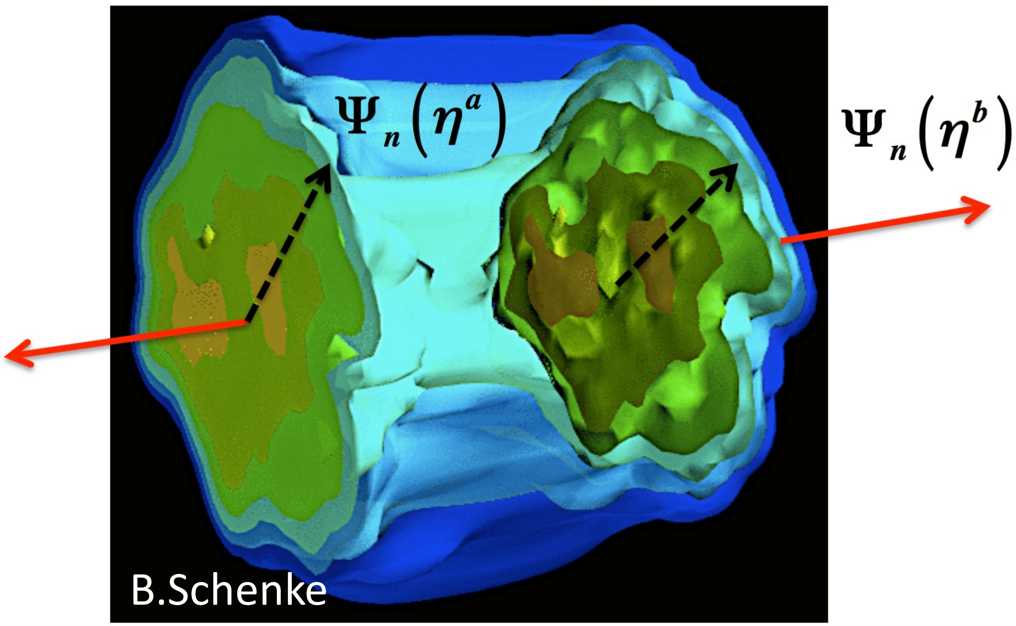


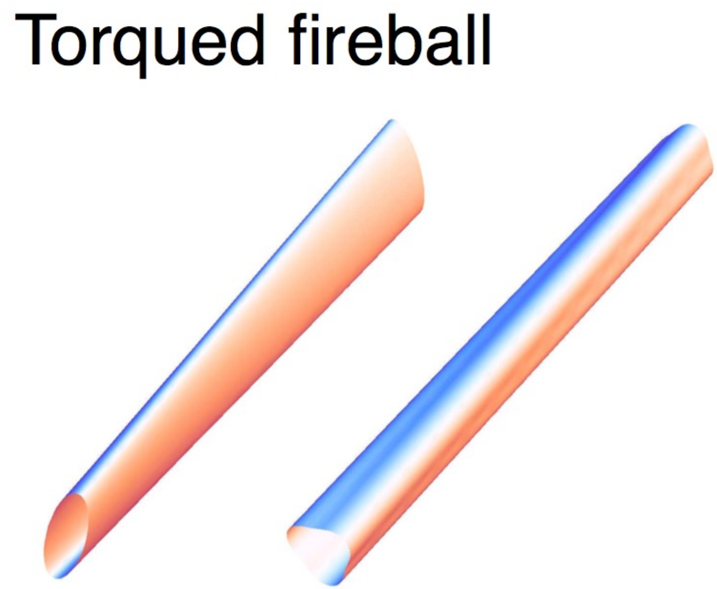
Most prominent at central collisions where fluctuation dominates

Some dependence on η/s

Very sensitive to initial state geometry

Decorrelation – Longitudinal





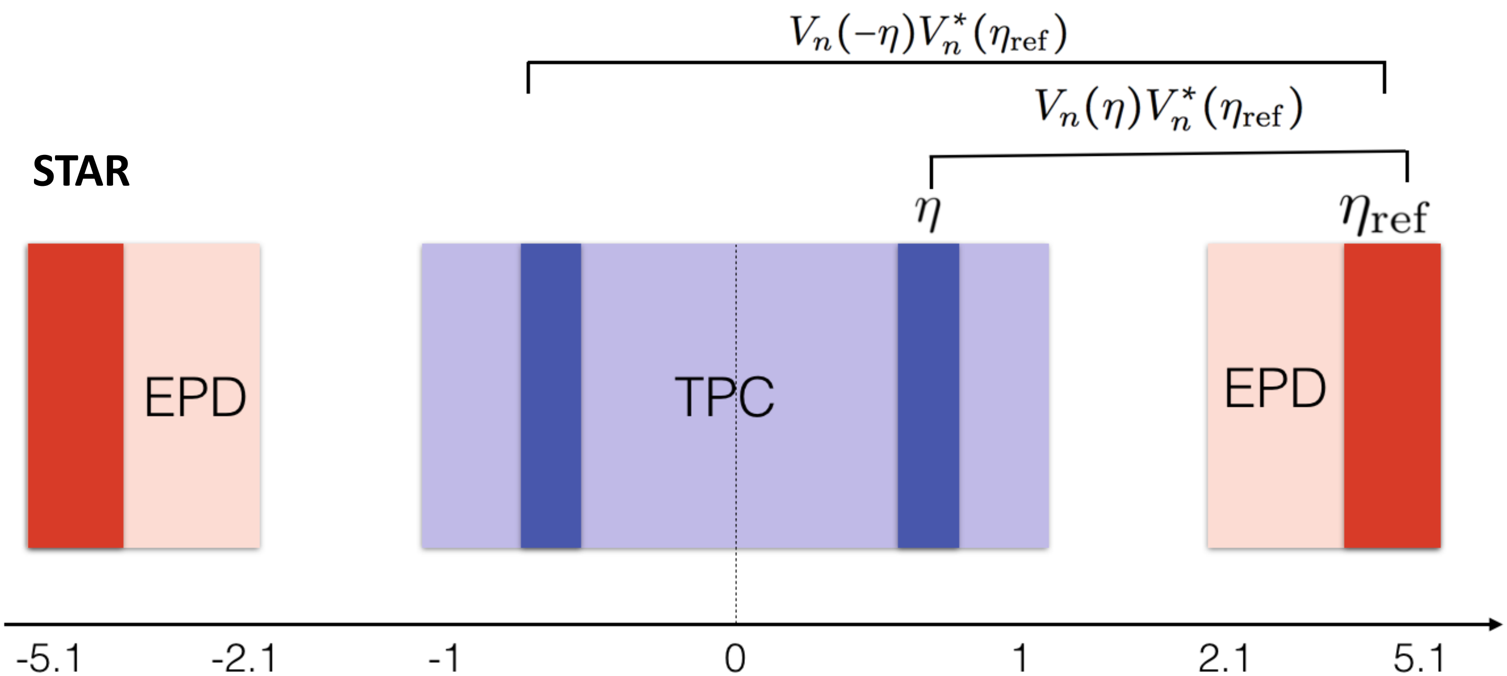
PRC 83 (2011) 034911

Event Plane decorrelation along longitudinal direction
Provide constraints on how system evolves in 3D

Decorrelation – Longitudinal

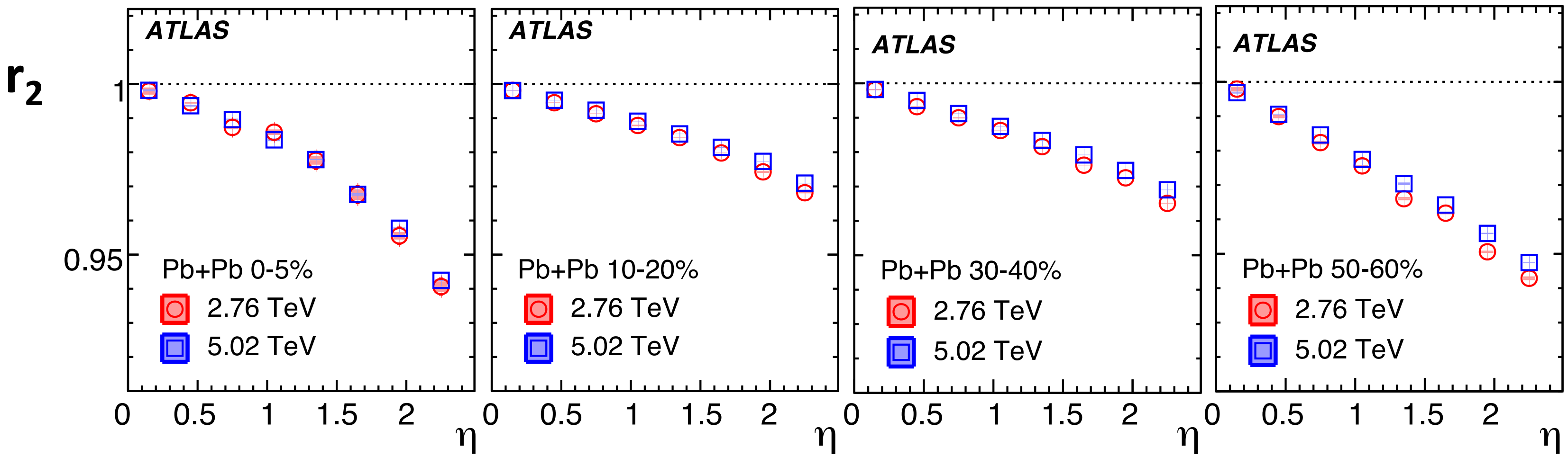
Effects measurable by

$$r_n(\eta) = \frac{\langle V_n(-\eta)V_n^*(\eta_{\rm ref})\rangle}{\langle V_n(\eta)V_n^*(\eta_{\rm ref})\rangle} = \frac{\langle v_n(-\eta)v_n(\eta_{\rm ref})\cos n(\Psi_n(-\eta)-\Psi_n(\eta_{\rm ref}))\rangle}{\langle v_n(\eta)v_n(\eta_{\rm ref})\cos n(\Psi_n(\eta)-\Psi_n(\eta_{\rm ref}))\rangle}$$



Decorrelation – Longitudinal

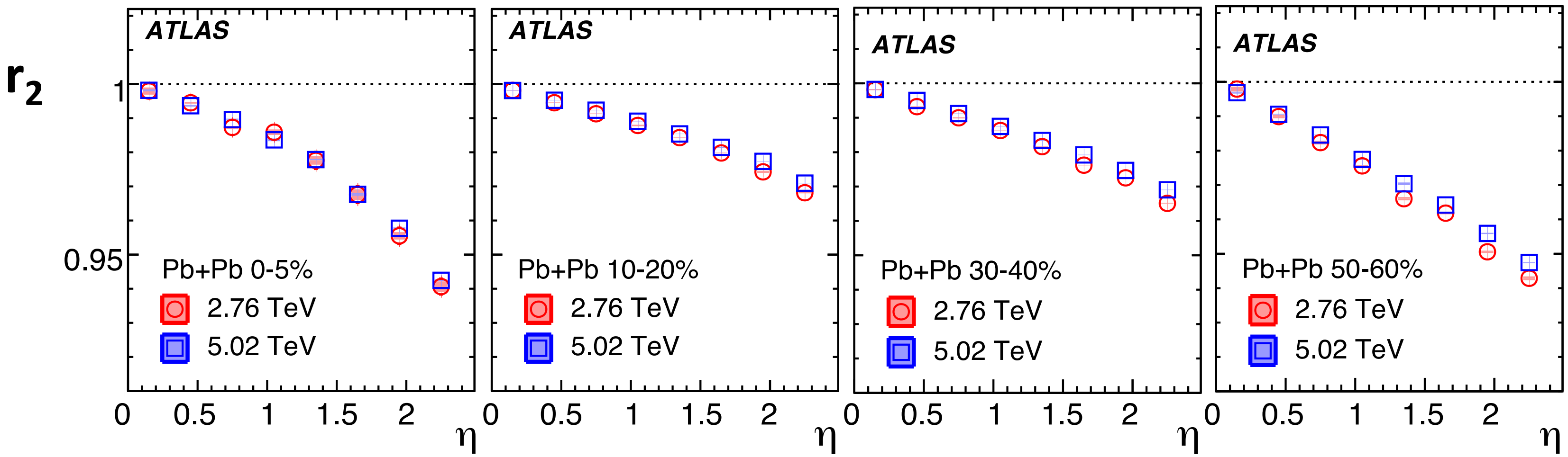
EPJC 76 (2018) 142



r_2: Centrality dependence; Initial geometry + fluctuation

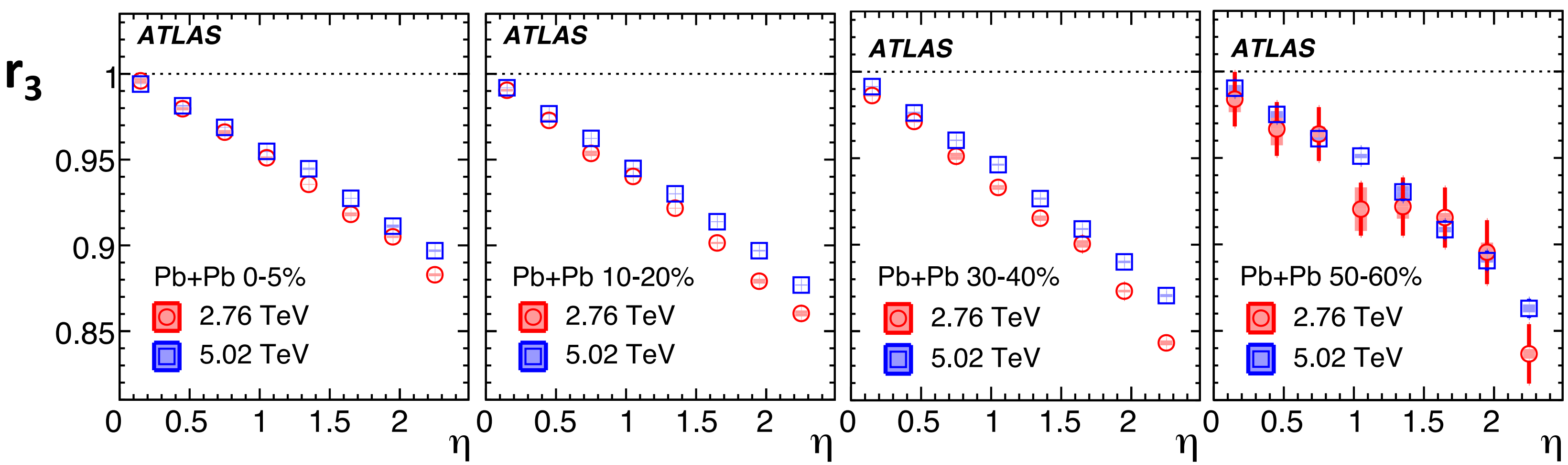
Decorrelation – Longitudinal

EPJC 76 (2018) 142

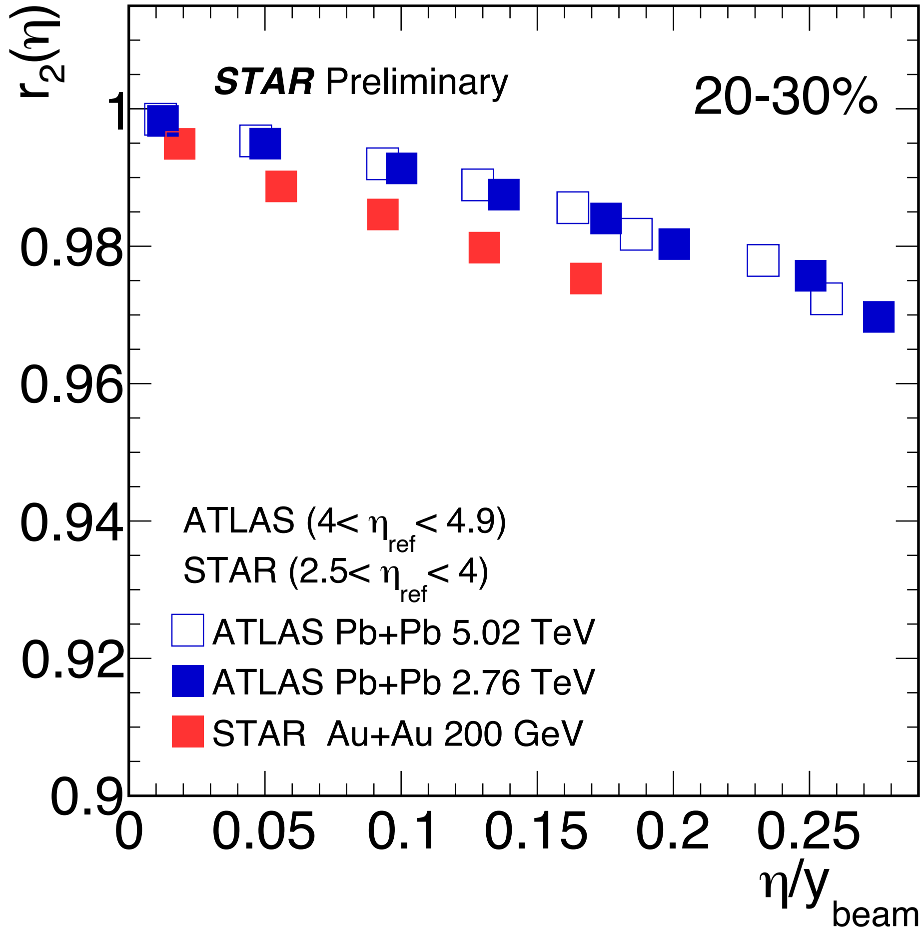


r_2: Centrality dependence; Initial geometry + fluctuation

r_3: No centrality dependence; Pure fluctuation

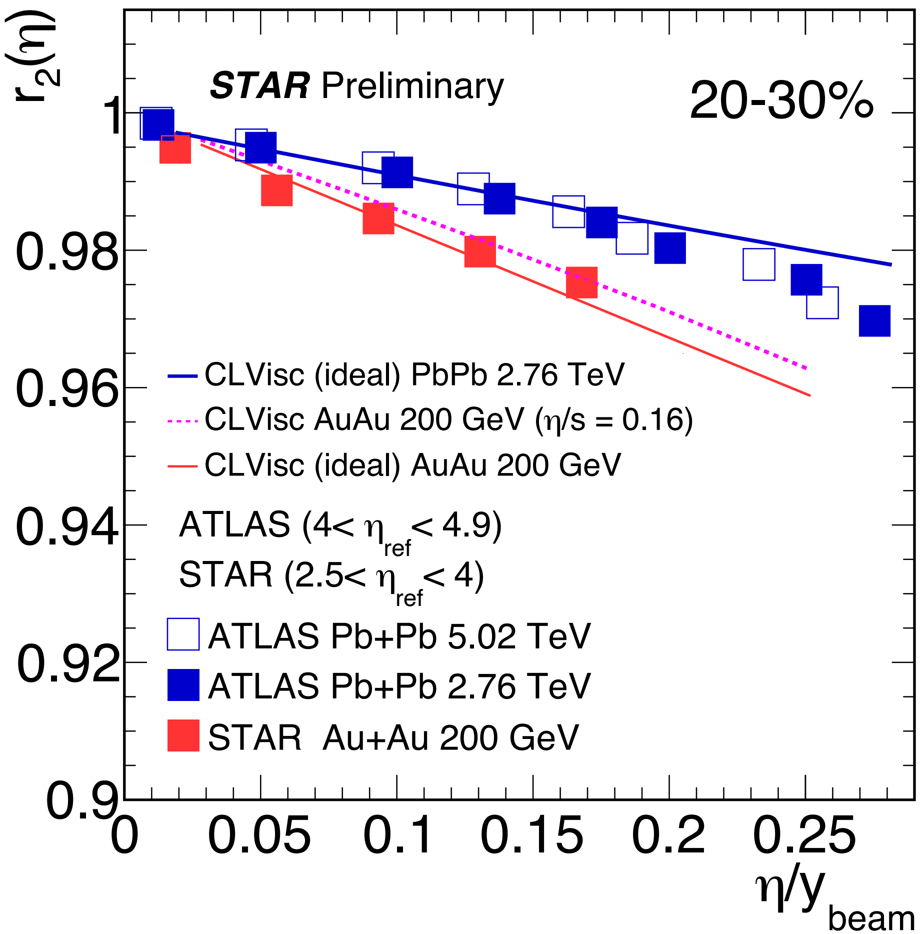


Decorrelation – Longitudinal



Larger effect seen at RHIC than LHC

Decorrelation – Longitudinal



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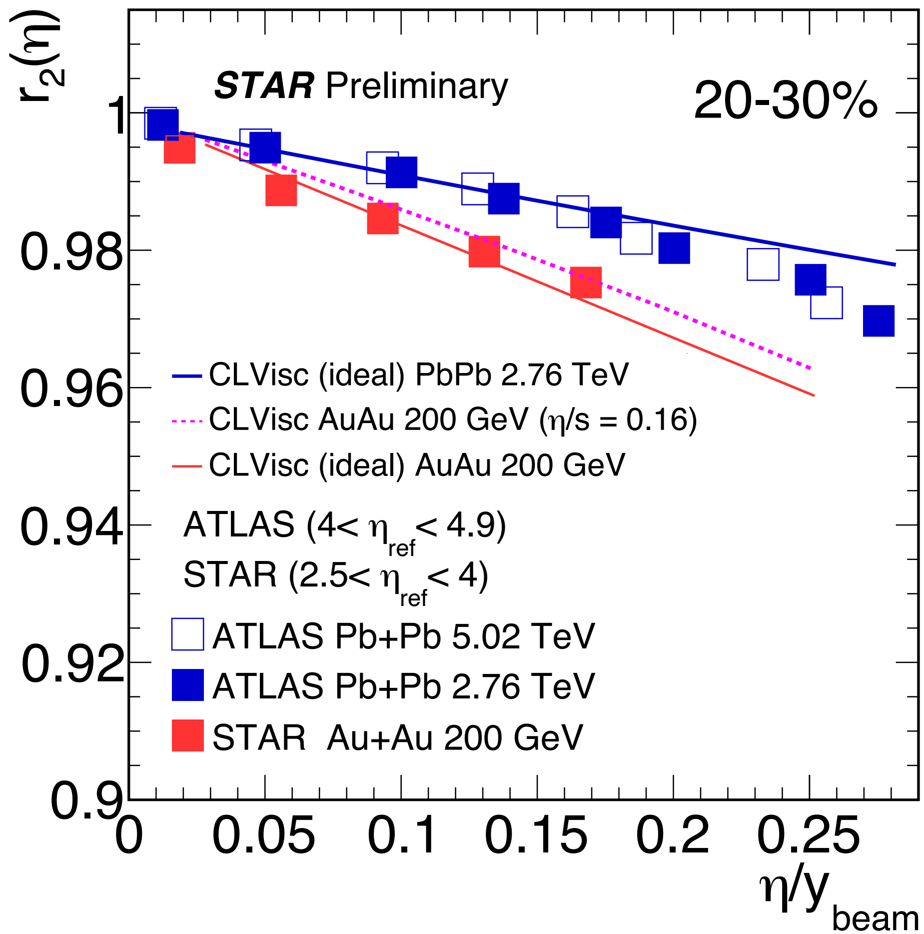
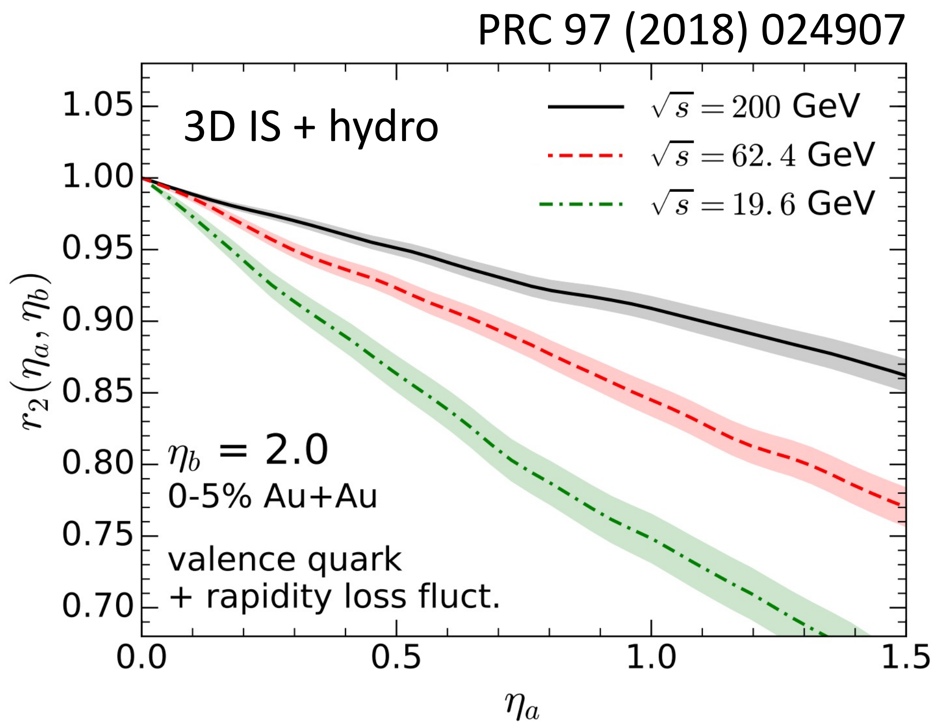
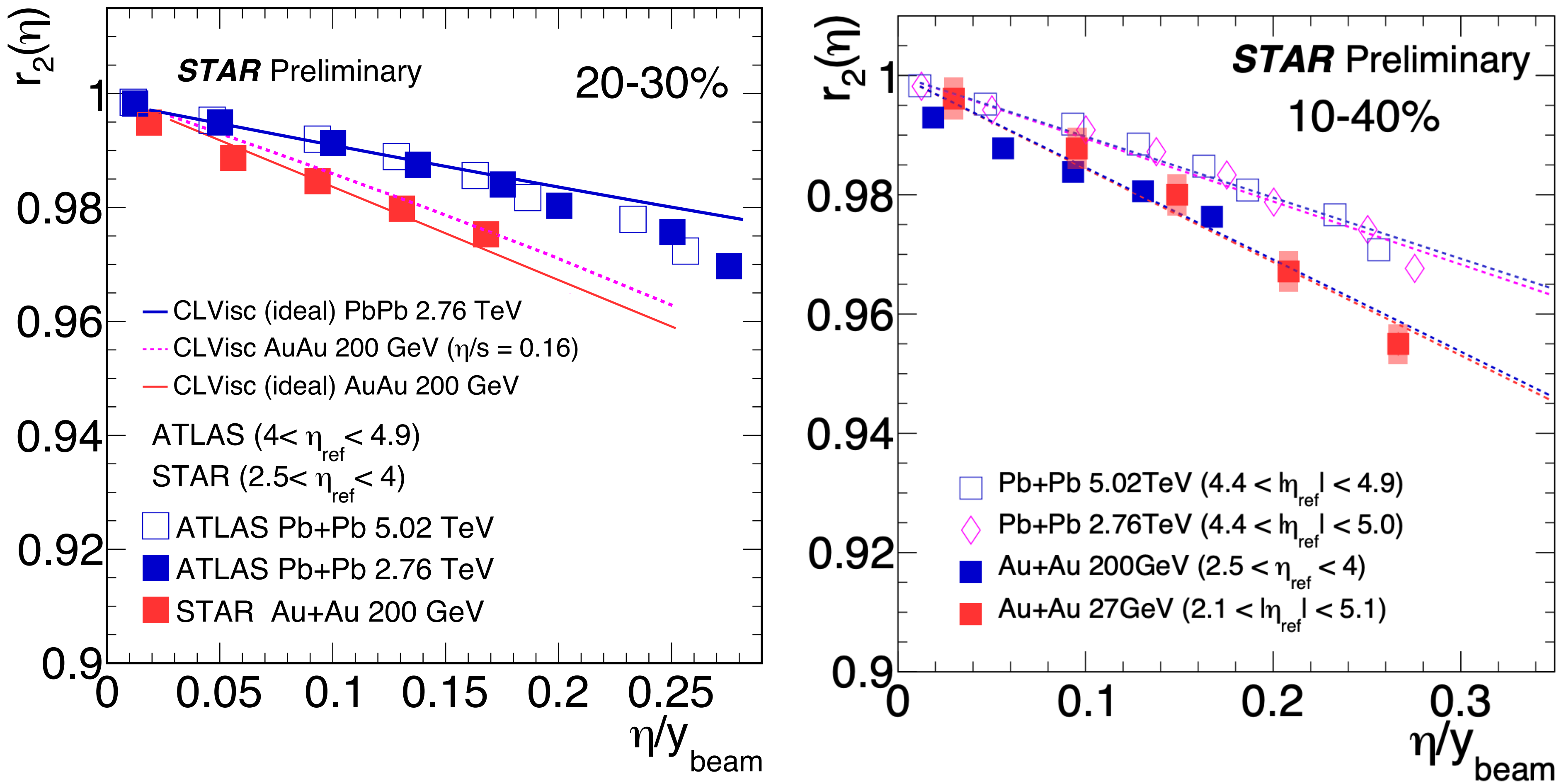




Larger effect seen at RHIC than LHC

3D IS + Hydro predicts larger decorrelation at lower energies

Decorrelation – Longitudinal



Larger effect seen at RHIC than LHC

3D IS + Hydro predicts larger decorrelation at lower energies

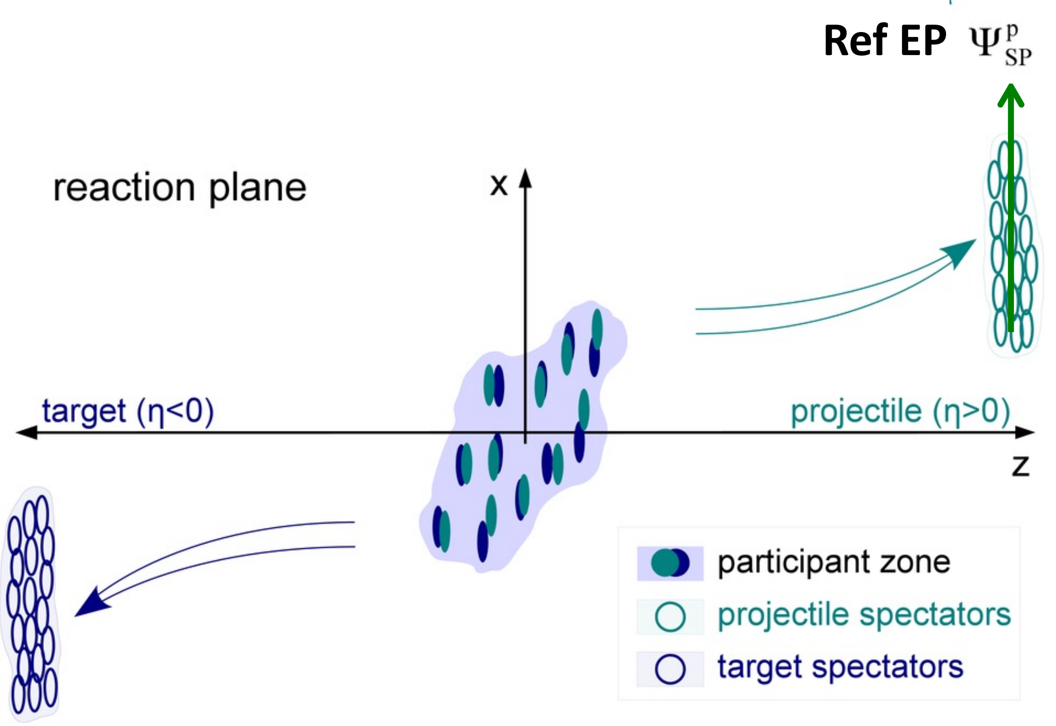
Data suggest same decorrelation at lower RHIC energy?

Directed flow v_1

$$v_1 = \langle \cos(\phi - \psi_{sp}) \rangle$$

Preferred moving direction at different rapidity

Collision symmetry $v_1(\eta) = -v_1(-\eta)$



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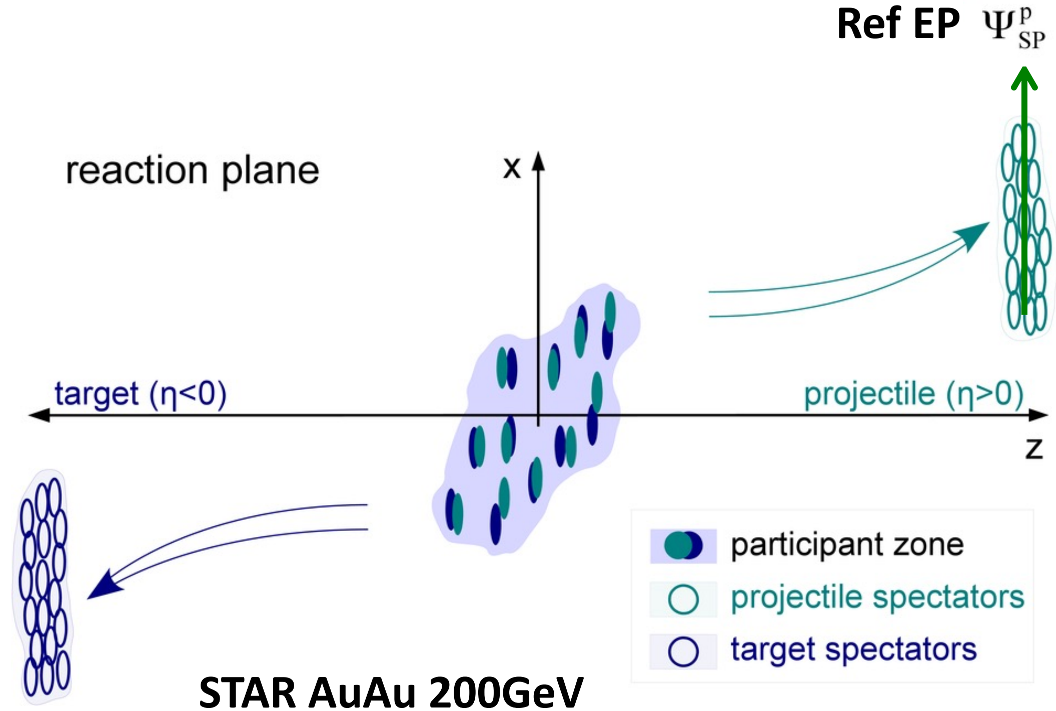
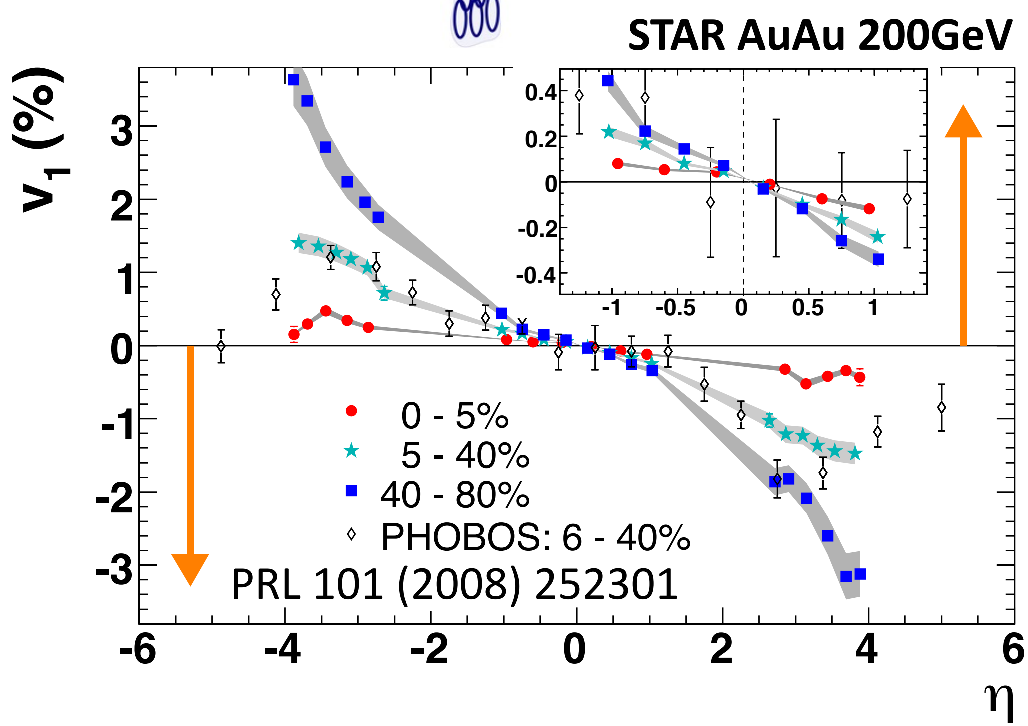
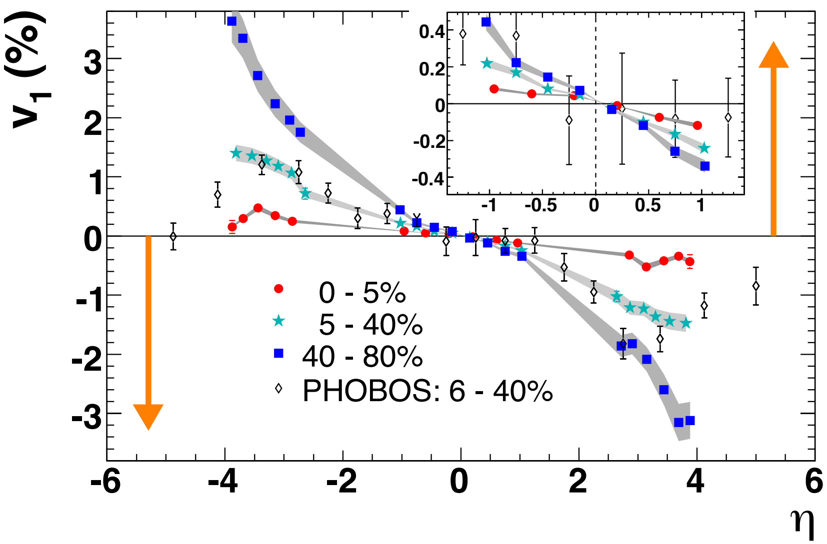
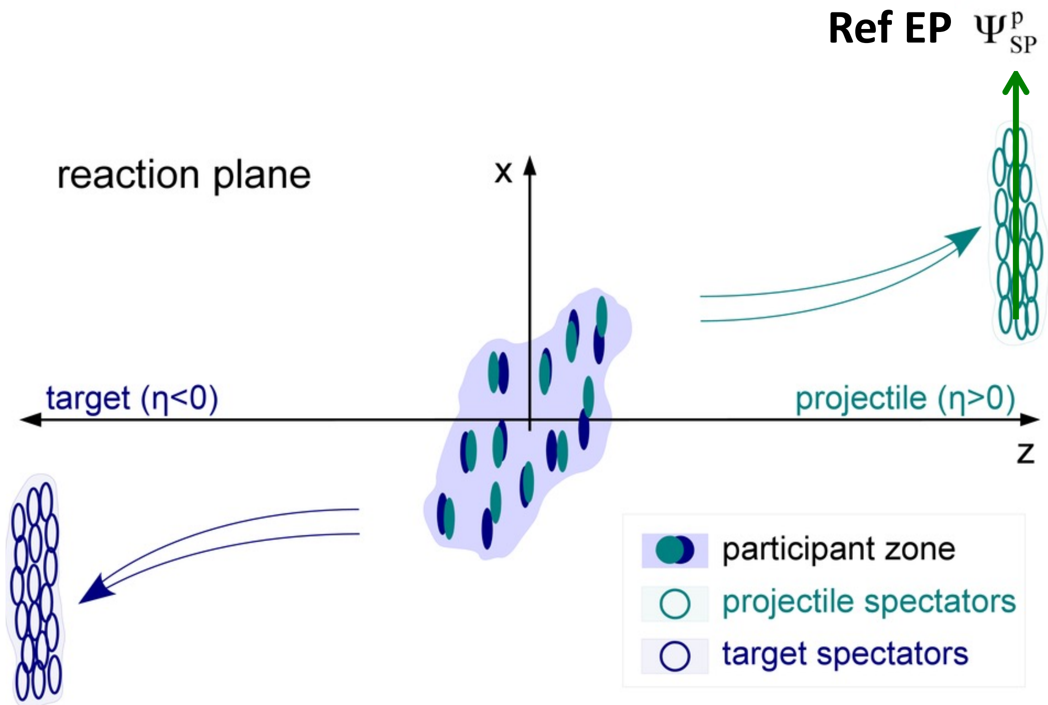


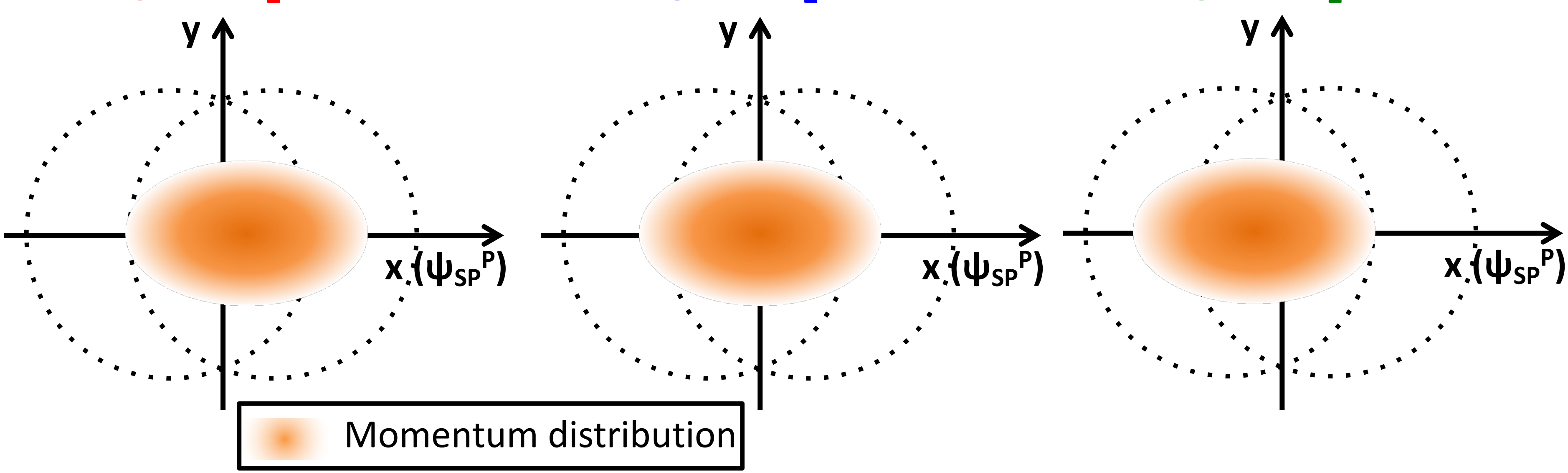


Directed flow v_1

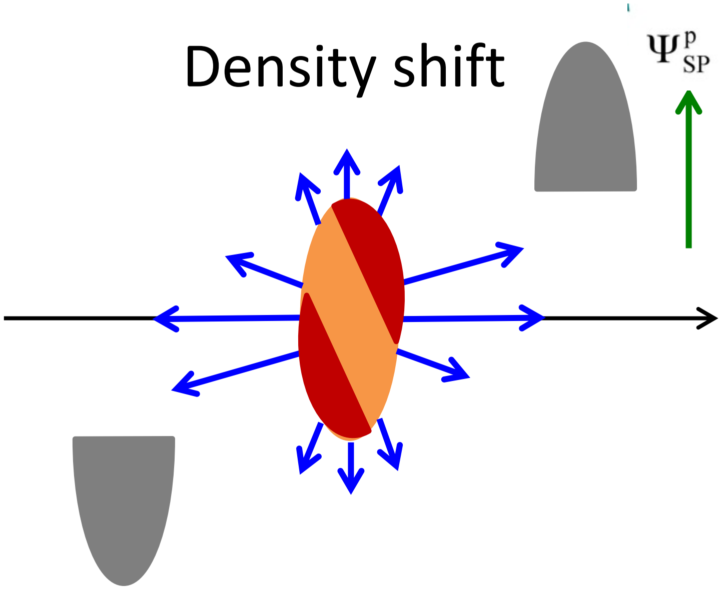




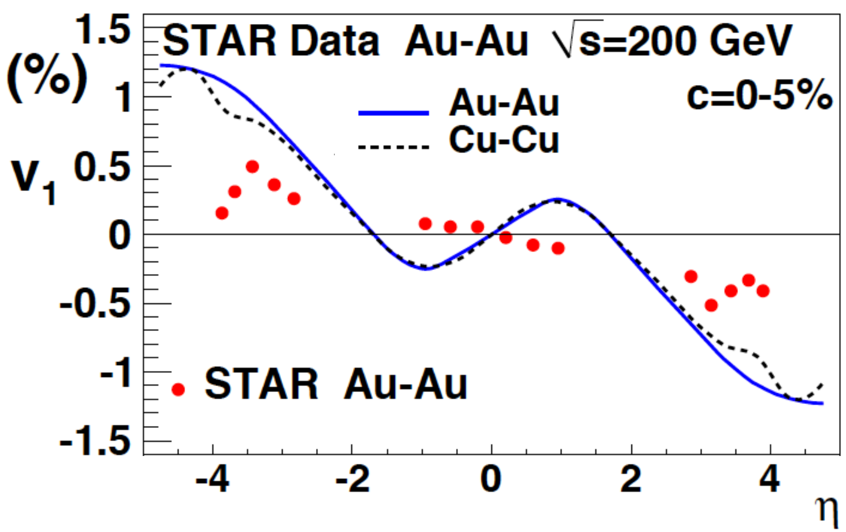
$\eta < 0, v_1 > 0$ $\eta = 0, v_1 = 0$ $\eta > 0, v_1 < 0$



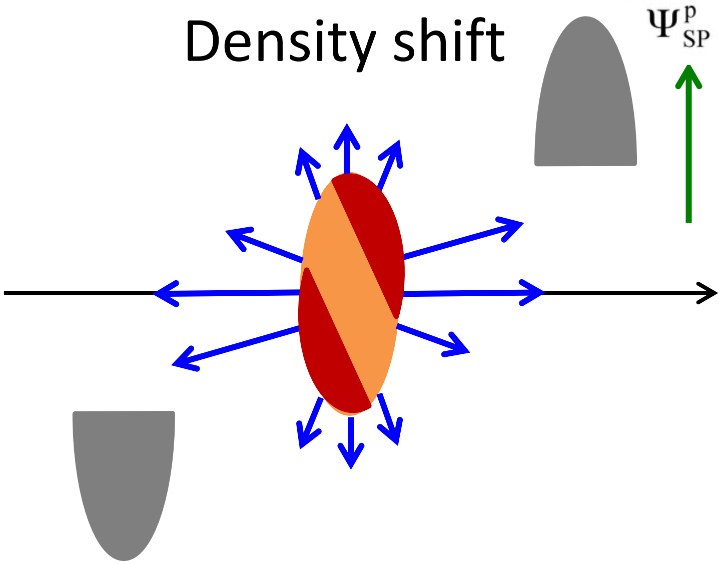
Directed flow v_1

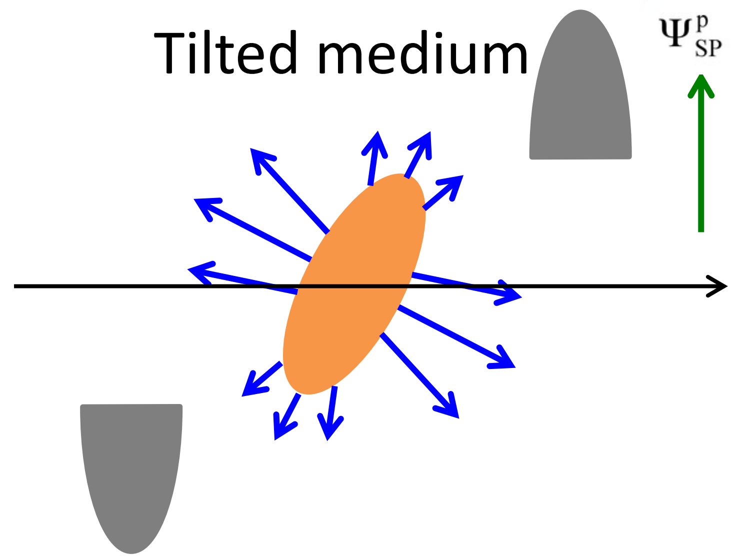


PRC 81 (2010) 054902

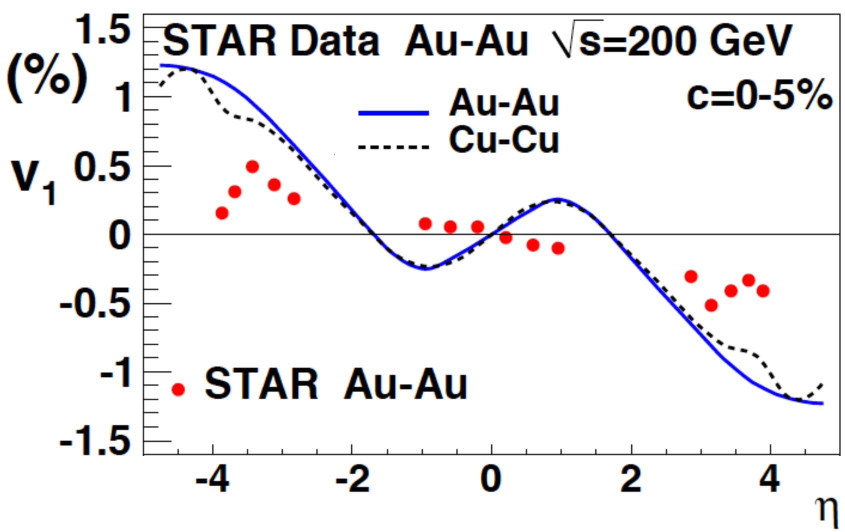


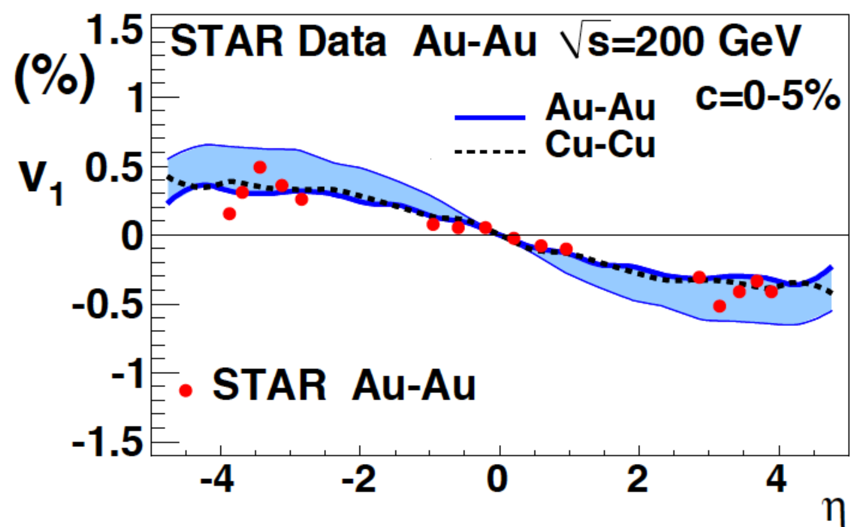
Directed flow v_1





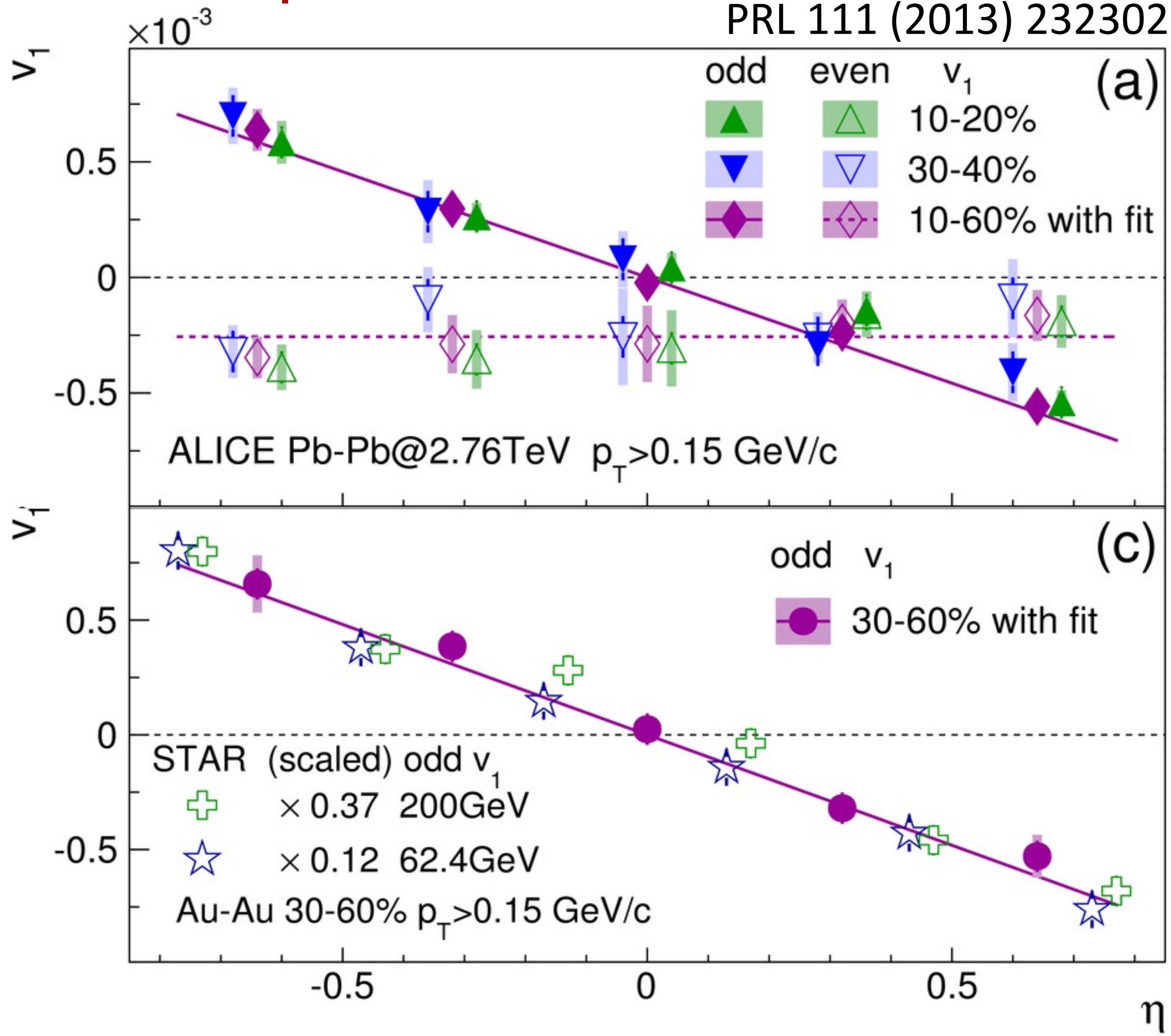
PRC 81 (2010) 054902





Directed flow v_1

PRL 111 (2013) 232302



Larger slope of v_1^{odd} at RHIC energies: smaller tilt at LHC

Directed flow v_1

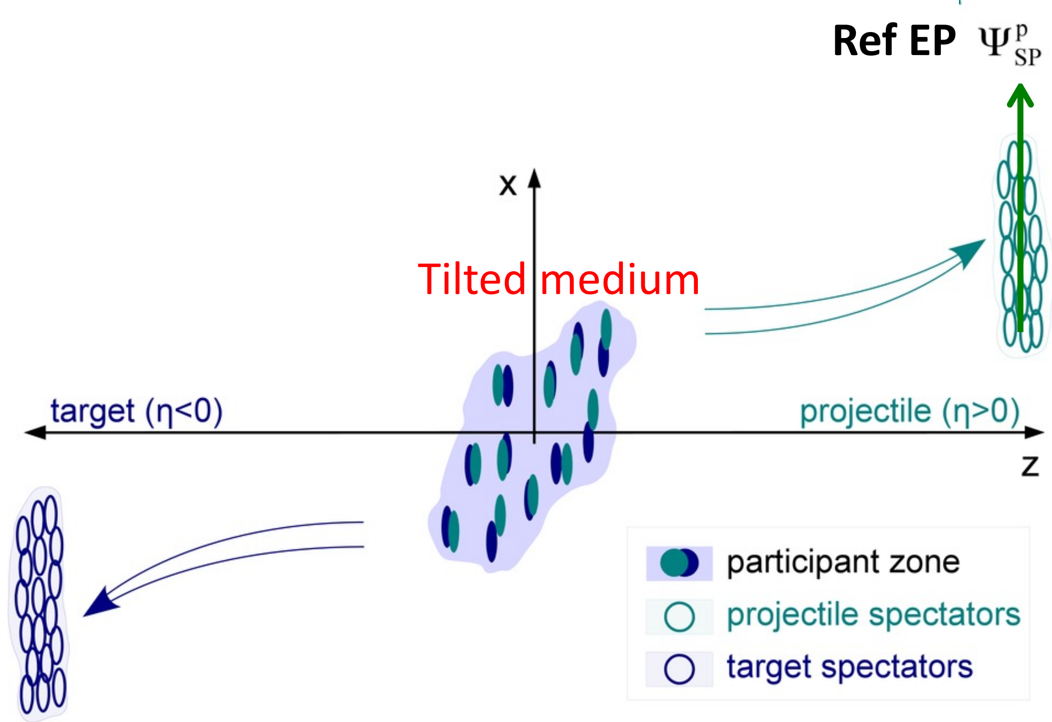
$$v_1 = \langle \cos(\phi - \psi_{sp}) \rangle$$

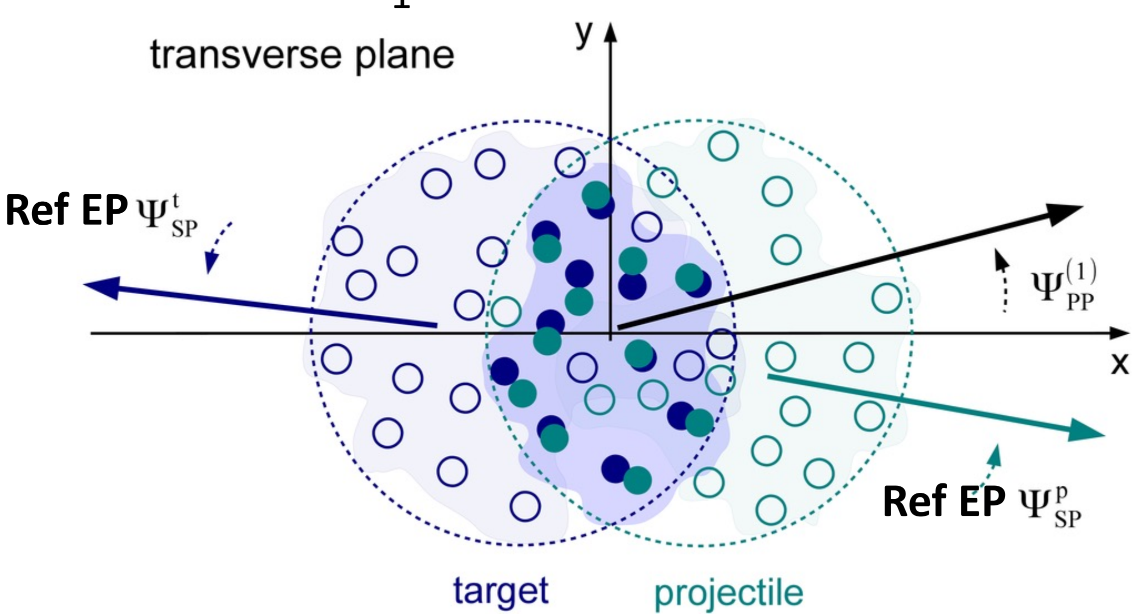
Preferred moving direction at different rapidity

Collision symmetry

$v_1(\eta) = -v_1(-\eta)$

v_1^{odd}





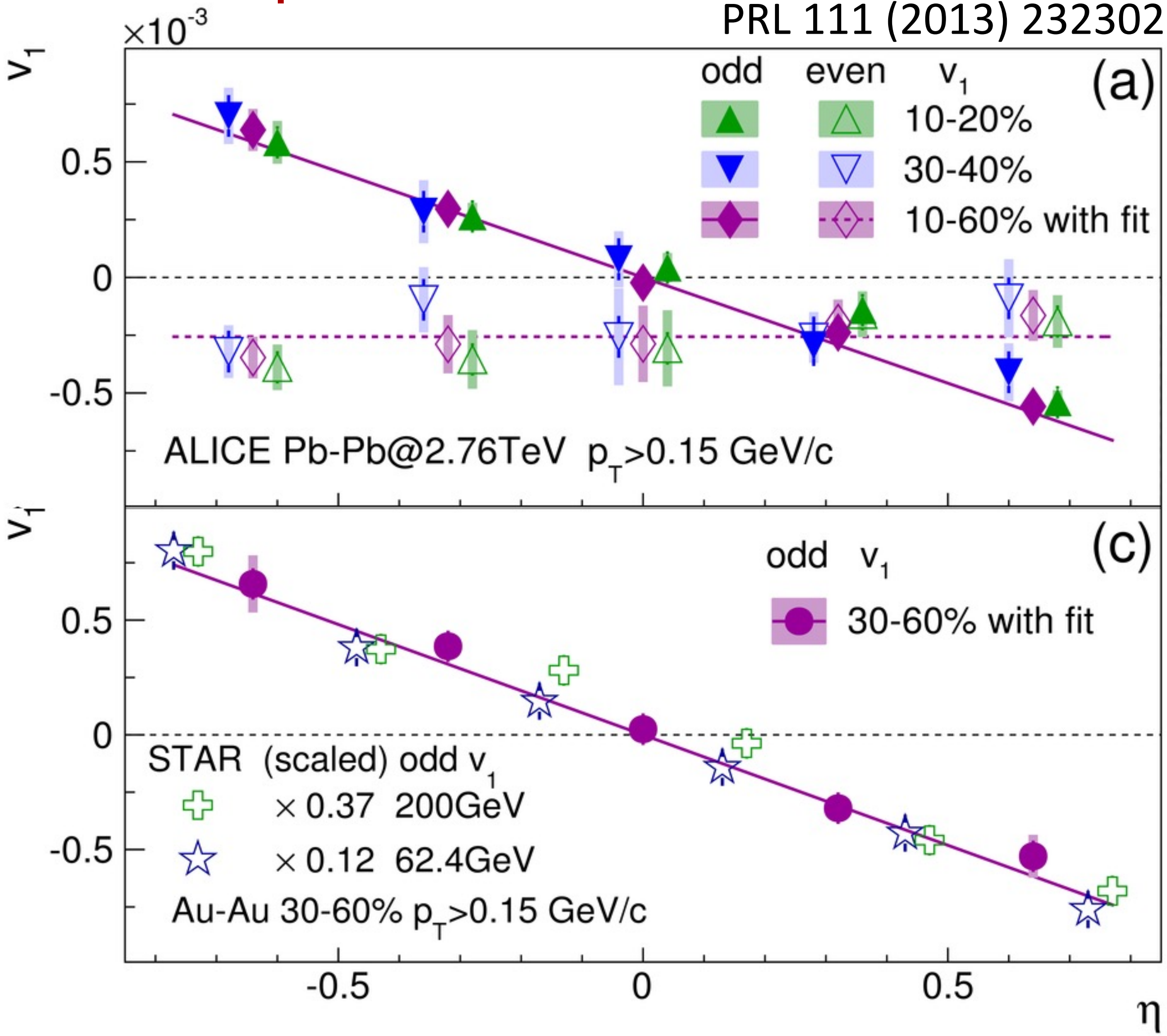
Transverse plane geometry fluctuation

$v_1(\eta) = v_1(-\eta)$

v_1^{even}

Directed flow v_1

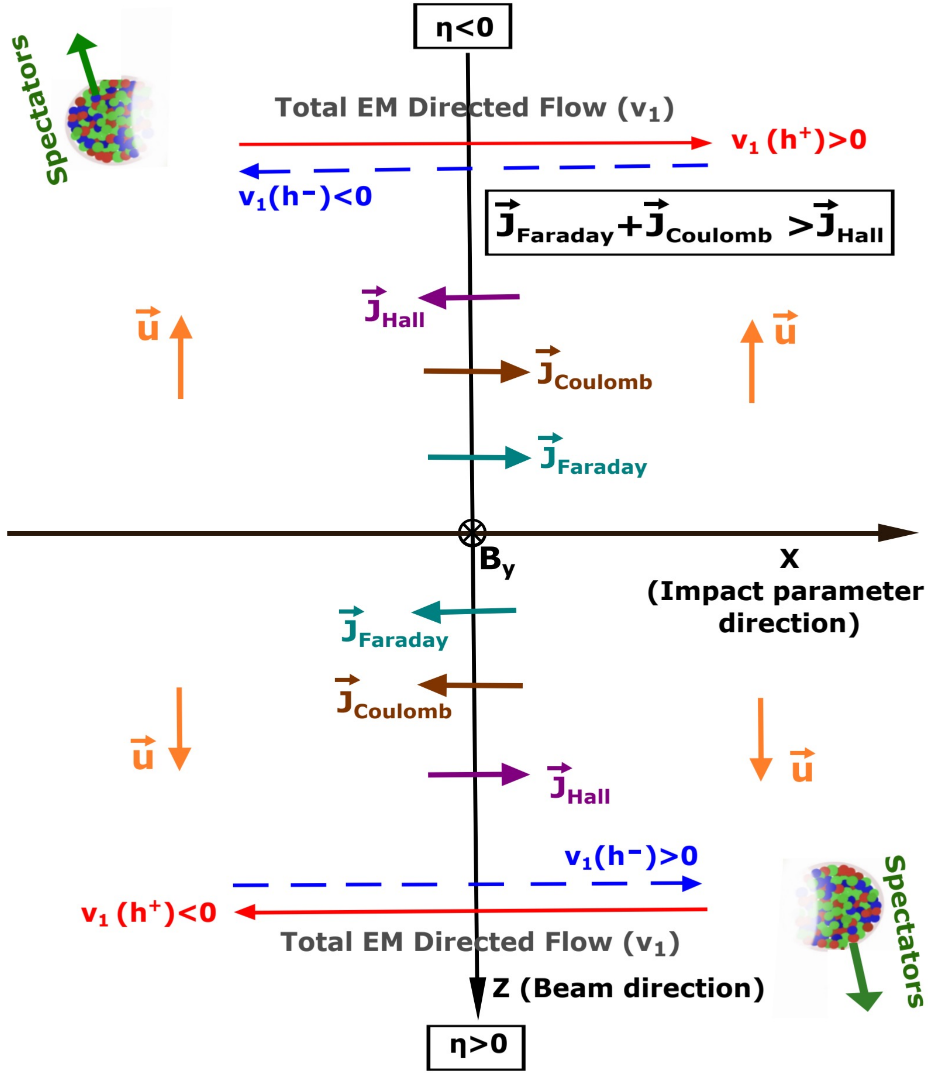
PRL 111 (2013) 232302



Larger slope of v_1^{odd} at RHIC energies: smaller tilt at LHC

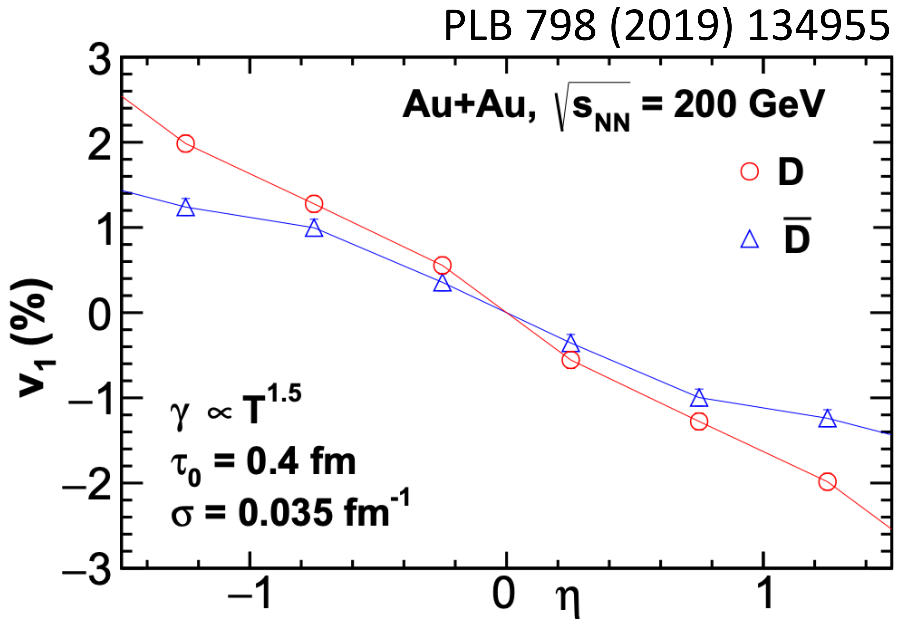
Non-zero v_1^{even}: sizable geometry fluctuation

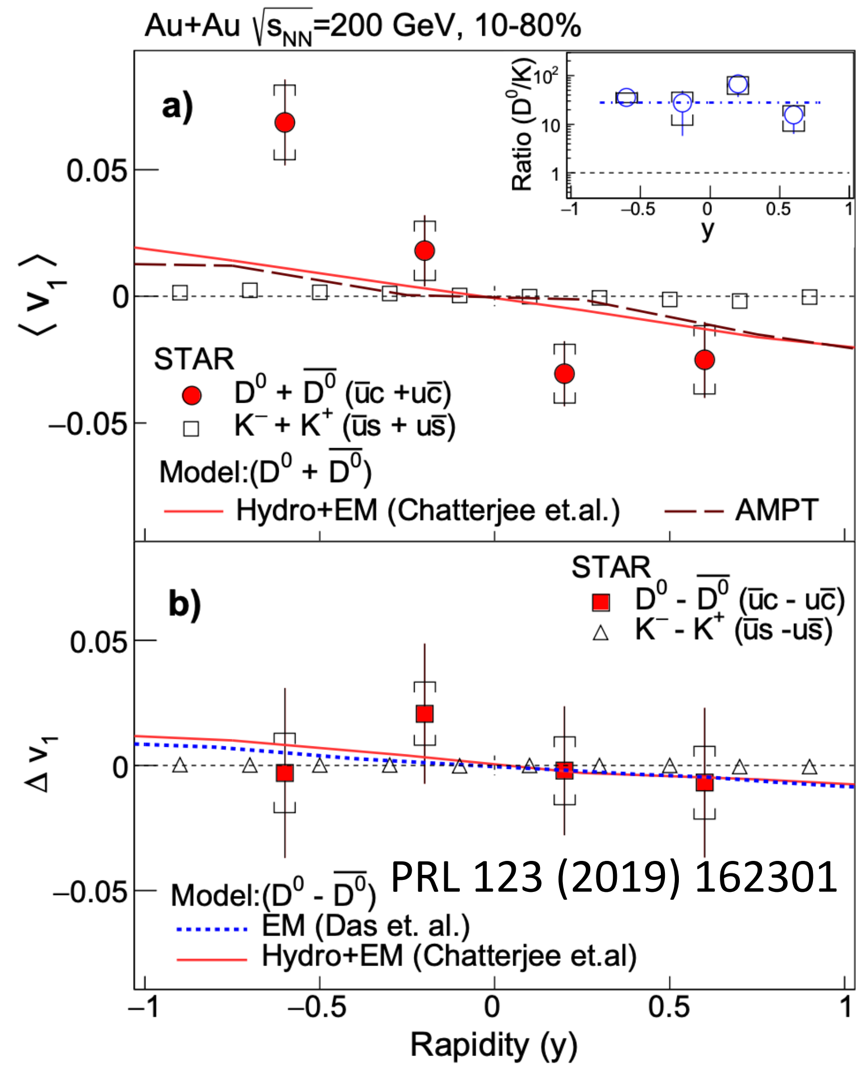
Directed flow v_1 – B & E field effects



Main electro-magnetic effects on v_1

Directed flow v_1 – B & E field effects



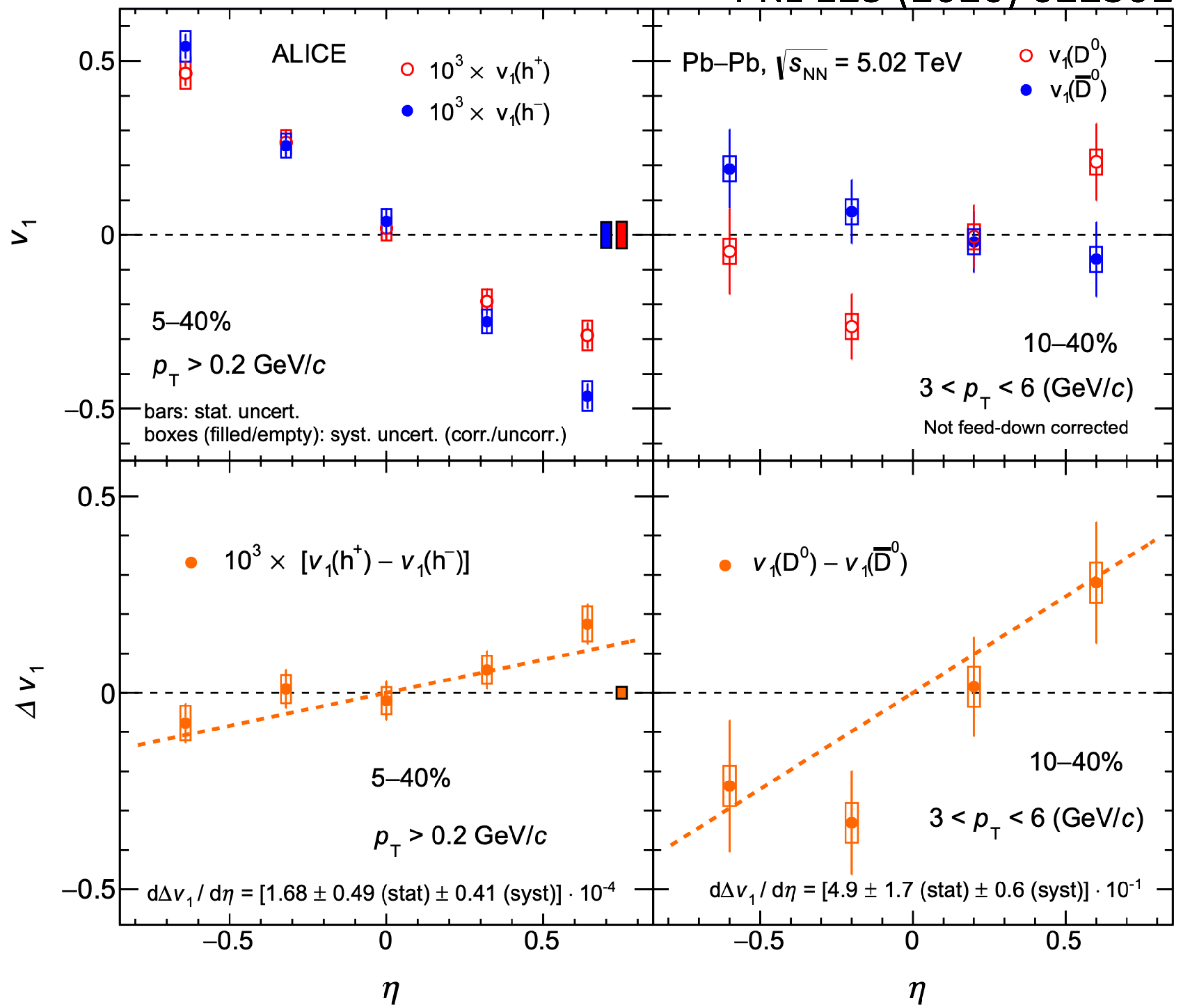


Models predict negative slope of Δv_1 @ RHIC

Faraday + Coulomb > Hall

Directed flow v_1 – B & E field effects

PRL 125 (2020) 022301



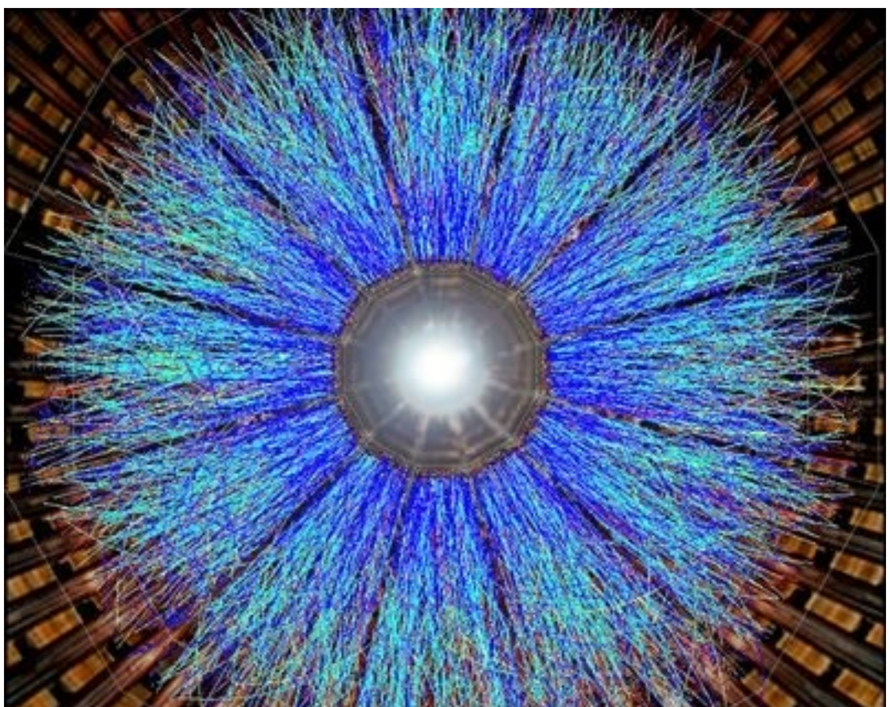
Hint of positive slope of Δv_1 @ LHC

Faraday + Coulomb < Hall

Summary

Collective flow measurements are versatile tools to study all stages of heavy ion collision

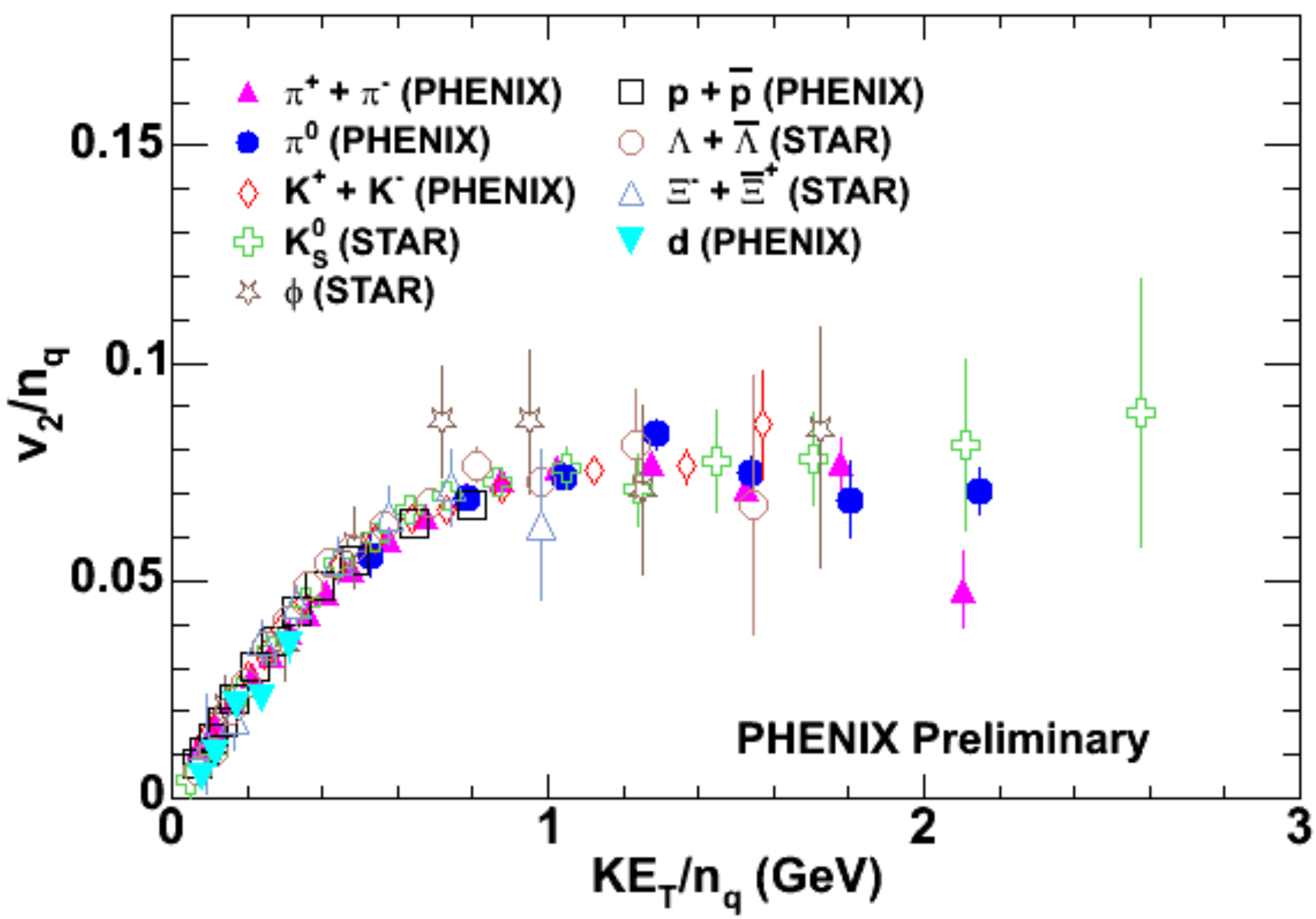
- QGP viscosity ⇔ v_n vs centrality; v_n vs energy; v_n vs p_T; …
- Initial state ⇔ multi-particle v_n; decorrelation; v_1; …
- Hadronic phase ⇔ PID v_n; …
- …



Questions to
zhenyuchen@sdu.edu.cn

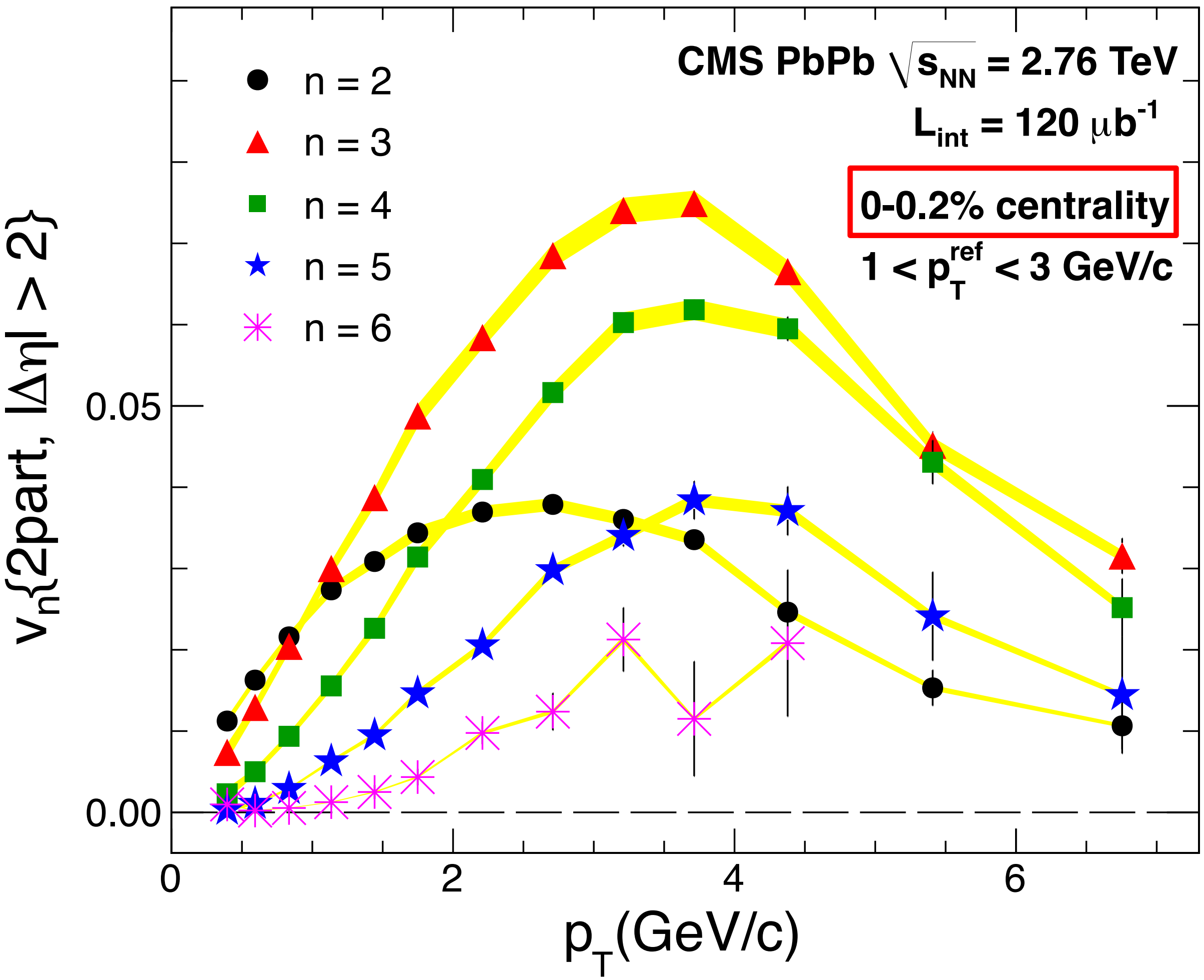
Back up

NCQ



π⁺ + π⁻ (PHENIX)
π⁰ (PHENIX)
K⁺ + K⁻ (PHENIX)
K⁰S (STAR)
ϕ (STAR)
p + p̄ (PHENIX)
Λ + Λ̄ (STAR)
Ξ⁻ + Ξ̄⁺ (STAR)
d (PHENIX)
PHENIX Preliminary
v2/nq
KET/nq (GeV)
0
0.05
0.1
0.15
0
1
2
3

v_n vs centrality



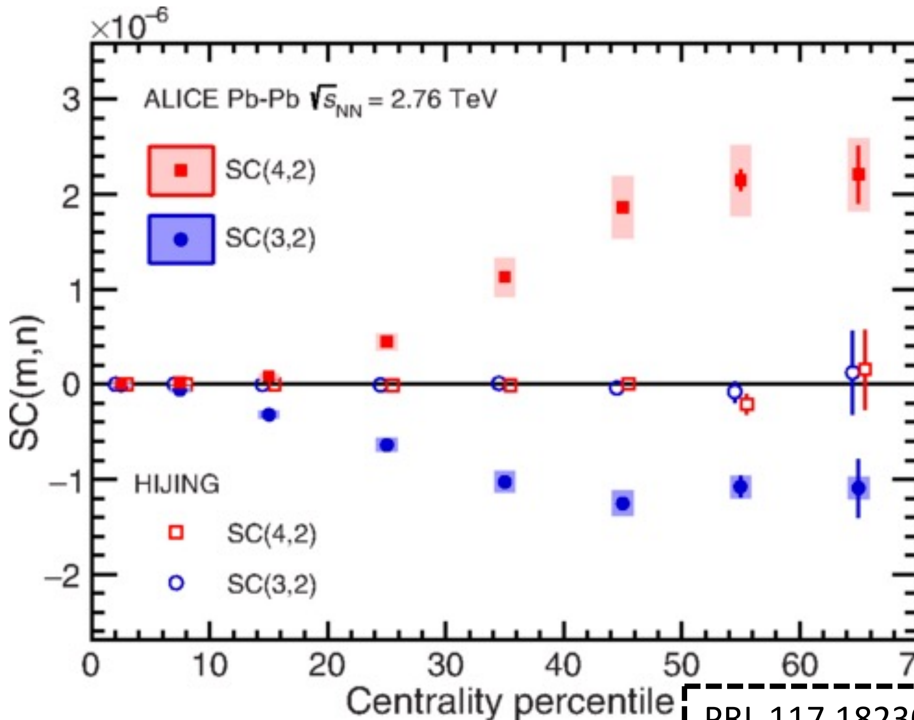
Probe geometry fluctuation with Ultra-Central-Collision

Symmetric cumulants

- Correlation between harmonics:

$$SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$

- Symmetric Cumulant (SC) developed by ALICE
  - Based on 4-particle cumulant technique
  - Non-flow highly suppressed at high multiplicity



PRL.117,182301

SC(2,3) < 0 ➔ v_2 and v_3 are **anti-correlated**
SC(2,4) > 0 ➔ v_2 and v_4 are **correlated**

Symmetric cumulants

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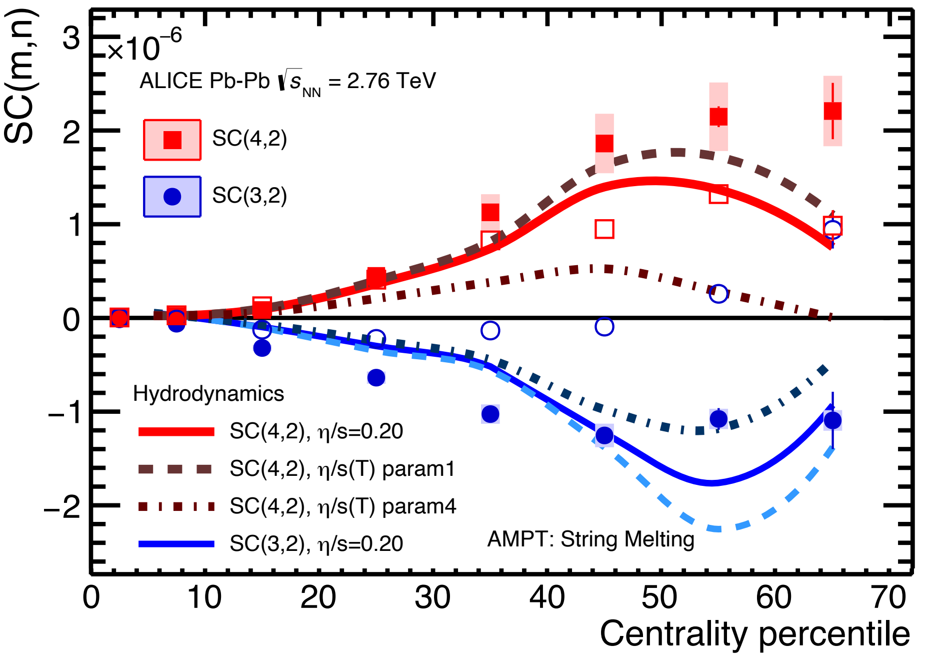


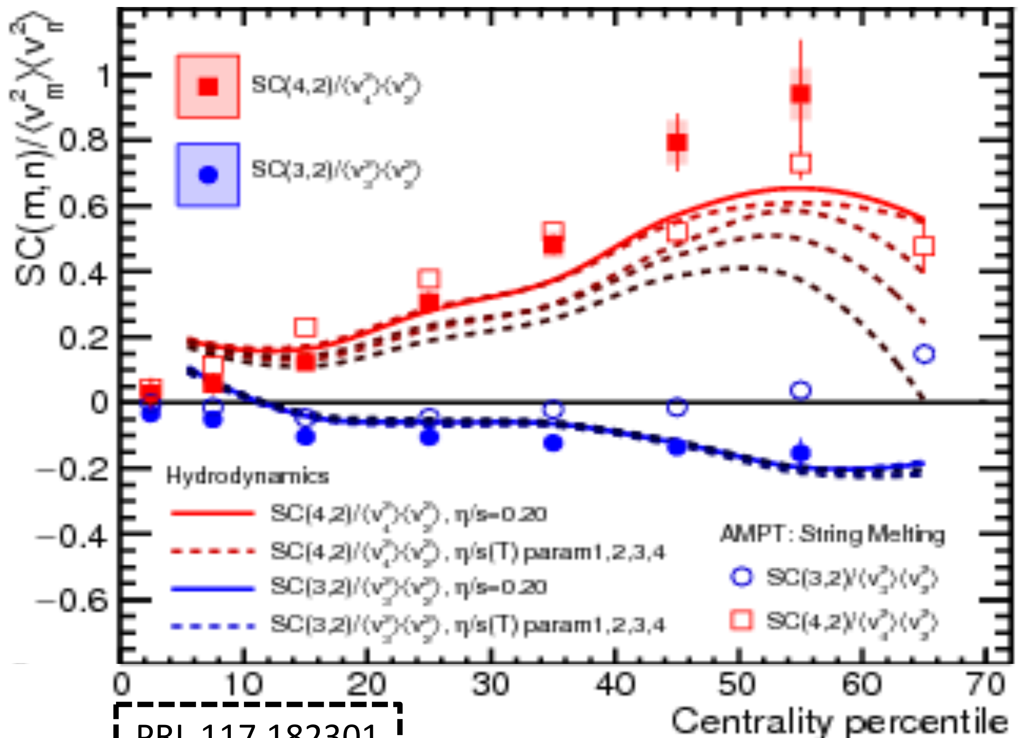
PRL.117,182301

SC(2,3) < 0 ➔ v_2 and v_3 are **anti-correlated**

SC(2,4) > 0 ➔ v_2 and v_4 are **correlated**

Symmetric cumulants

- SC normalized by <v_n^2><v_m^2>
- Normalized SC(2,4)
  - Probe Initial State fluctuation
  - Sensitive to medium response
- Normalized SC(2,3)
  - Probe Initial State fluctuation
  - **Insensitive** to medium response



PRL.117,182301

- Constraints on models
  - Giacalone et al. **arxiv 1605.08303**
  - Gardim et al. **arxiv 1608.02982**
  - Norhona-Holster et al. **arxiv 1609.05171**
  - Welsh et al. **arxiv 1609.09418**
  - Zhu et al. **arxiv 1608.05305**

Mass ordering broken for phi