Heavy Ion Meeting
http://him.phys.pusan.ac.kr/~him

PURDUE UNIVERSITY

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Two heatedly debated topics in relativistic heavy ion collisions

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U.S. DEPARTMENT OF ENERGY

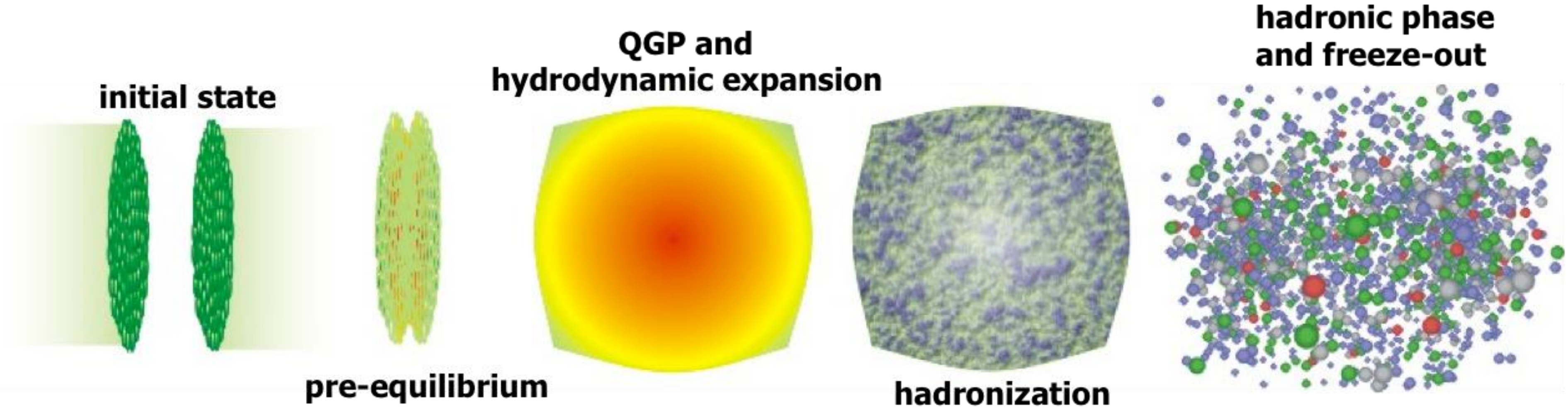
Two heatedly debated topics

- Anisotropies, hydrodynamic descriptions, nearly perfect fluidity
  - Is azimuthal anisotropy all from hydro?
  - How can we address the question?
  - Is quantum uncertainty principle at all relevant?
- Chiral magnetic effect, chiral magnetic wave, chiral vortical effect
  - Have we experimentalists exercised sufficient self-criticality?

- Charges from Iky
  - Where we are, on the way to look for the QGP?
  - Where to go, for more concrete conclusion on QGP?
  - What fundamental knowledge will we contribute?

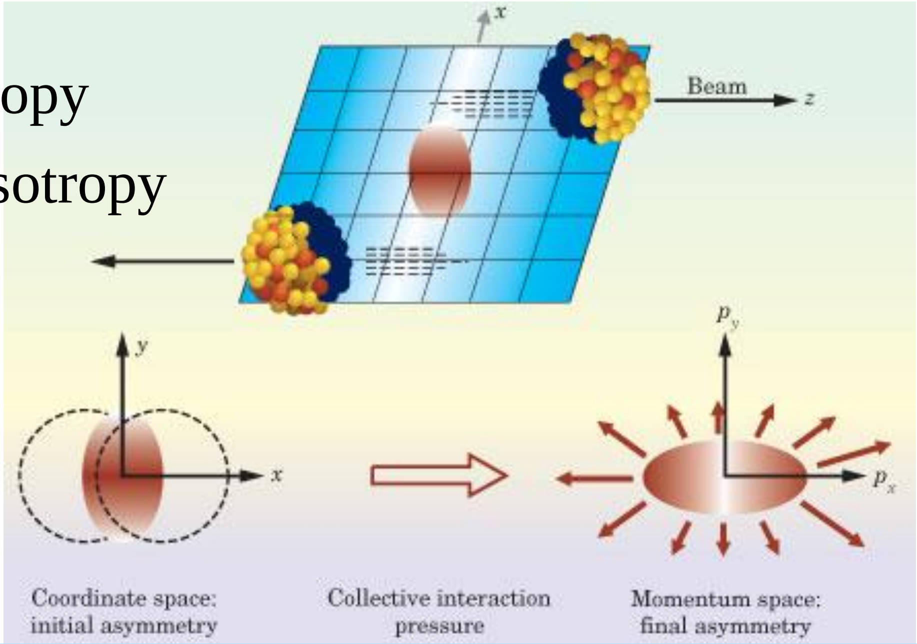
I will be critical.

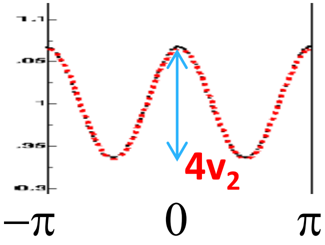
Azimuthal Anisotropy



$\vec{x}$-anisotropy

$\Rightarrow \vec{p}$-anisotropy



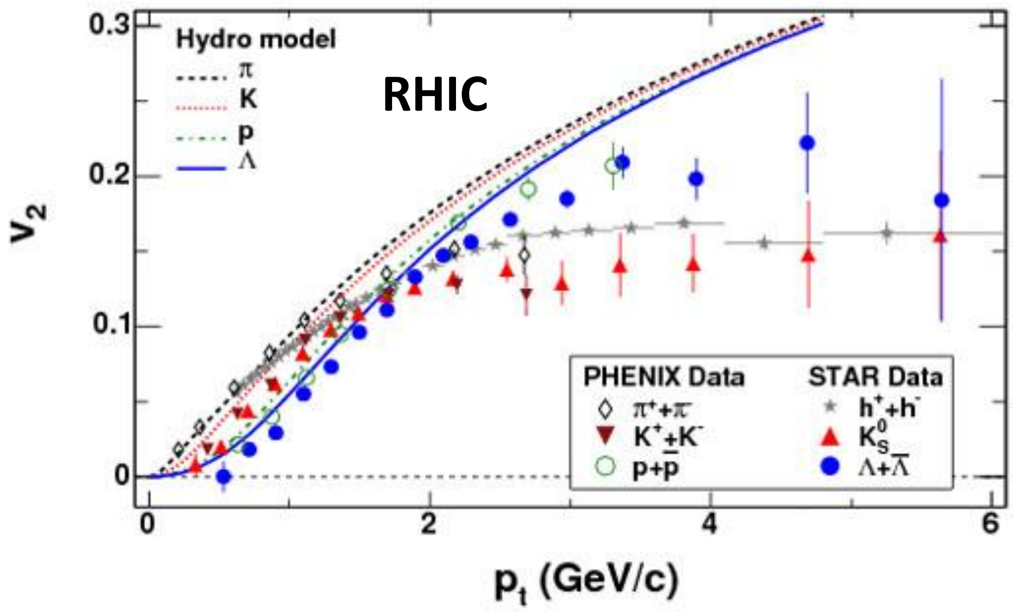


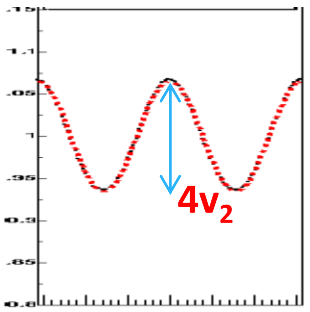
$$\varepsilon = \frac{\langle y^2 - x^2\rangle}{\langle y^2 + x^2\rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle$$

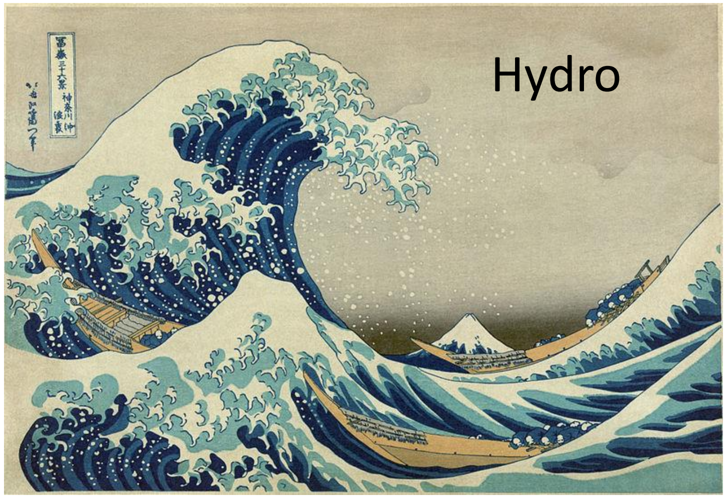
$$\varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

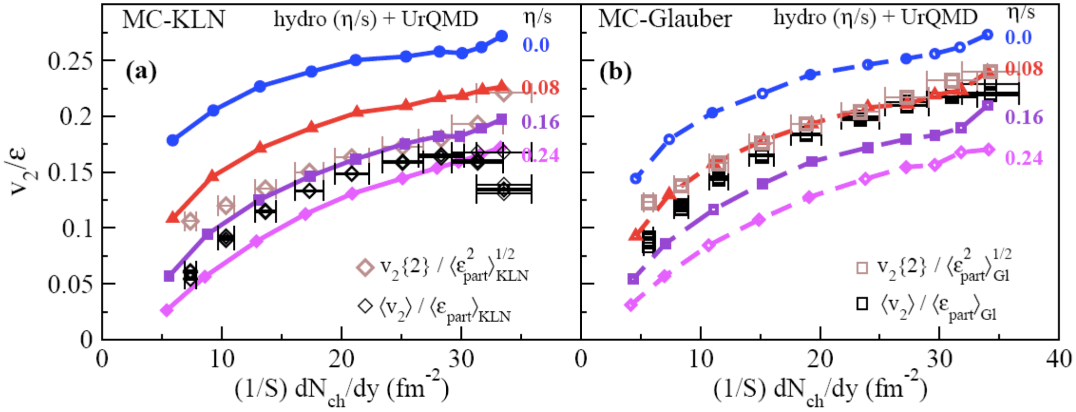
Elliptic flow measurements





$1+2v_2\cos2\phi$





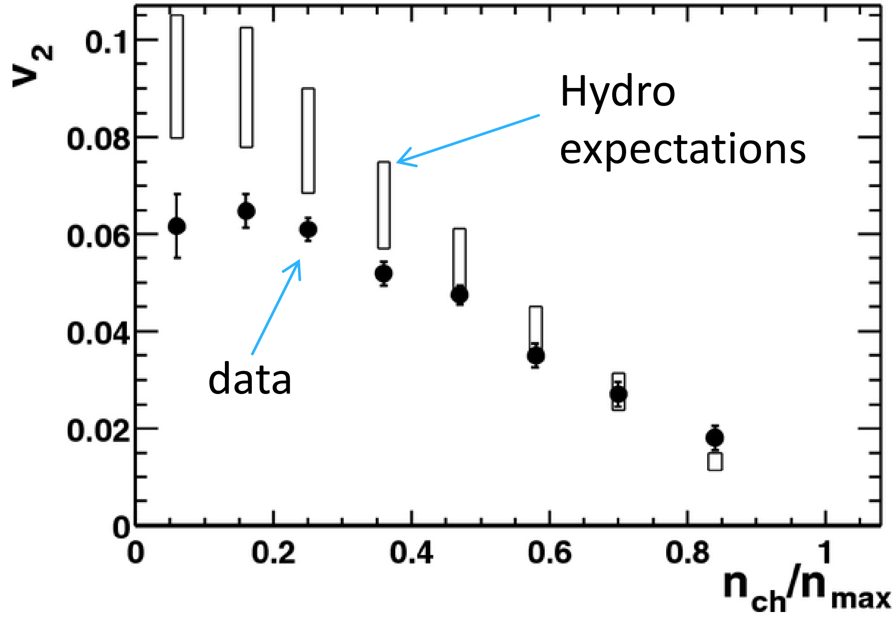
➔ ***Small value*** of specific viscosity over entropy ***η/s***

Model: Song *et al. arXiv:1011.2783*

Large flow, large energy loss

Au+Au 130 GeV

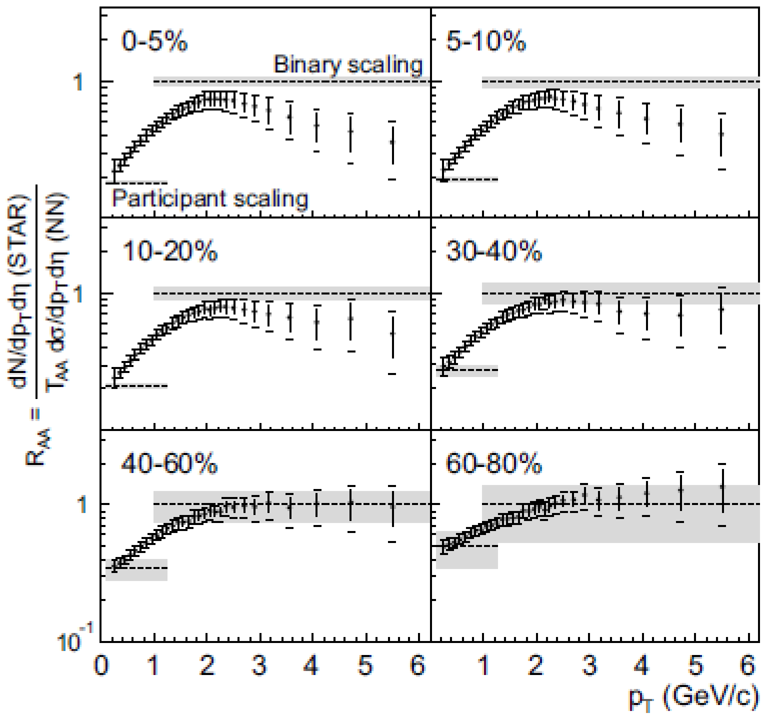
STAR, PRL**86** (2001) 402



Hydro expectations

data

STAR, PRL**89** (2002) 202301



BNL press release 2005

RHIC Scientists Serve Up "Perfect" Liquid

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

http://www.bnl.gov/newsroom/news.php?a=1303

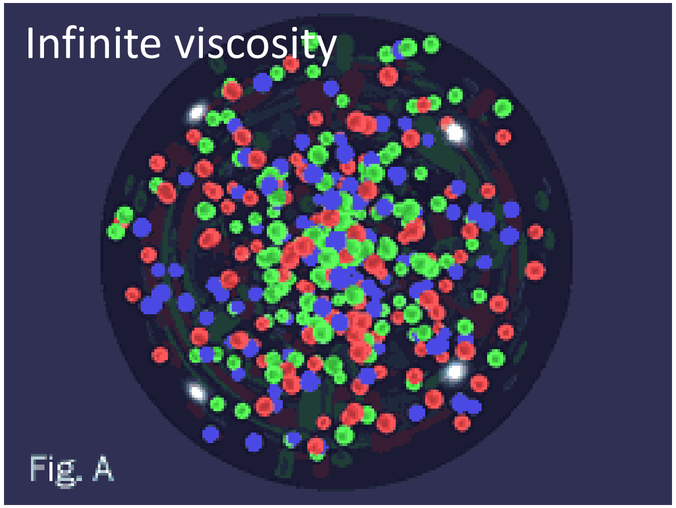


Fig. A

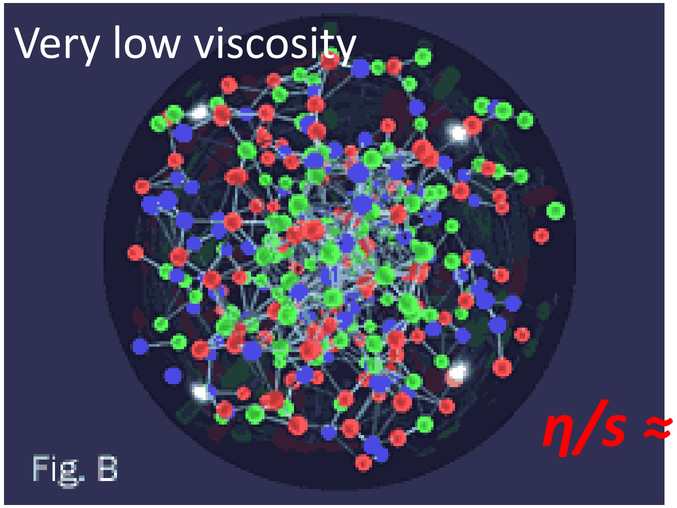
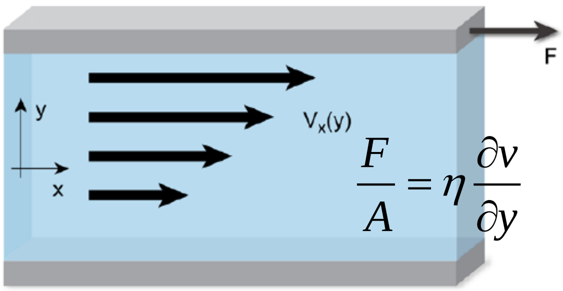
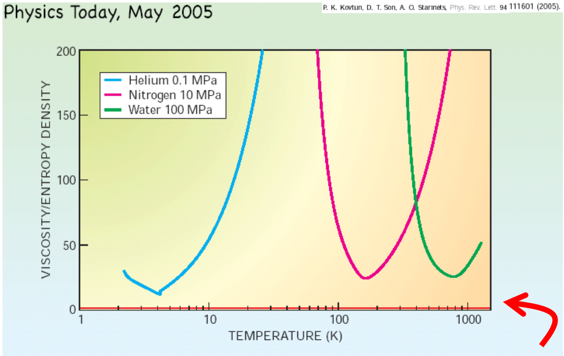


Fig. B

$\eta/s \approx (1\text{-}2)/4\pi$



$$\frac{F}{A} = \eta \frac{\partial v}{\partial y}$$



Physics Today, May 2005

P. K. Kovtun, D. T. Son, A. O. Starinets, Phys. Rev. Lett. 94 111601 (2005).

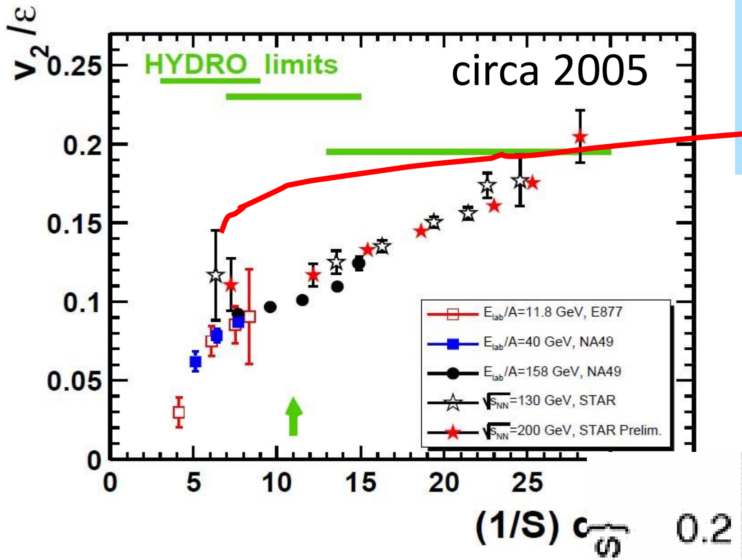
RHIC results

Viscosity quantum limit:

$$\eta = \frac{1}{3} n p l_{mfp} \qquad l_{mfp} = 1/(n\sigma)$$

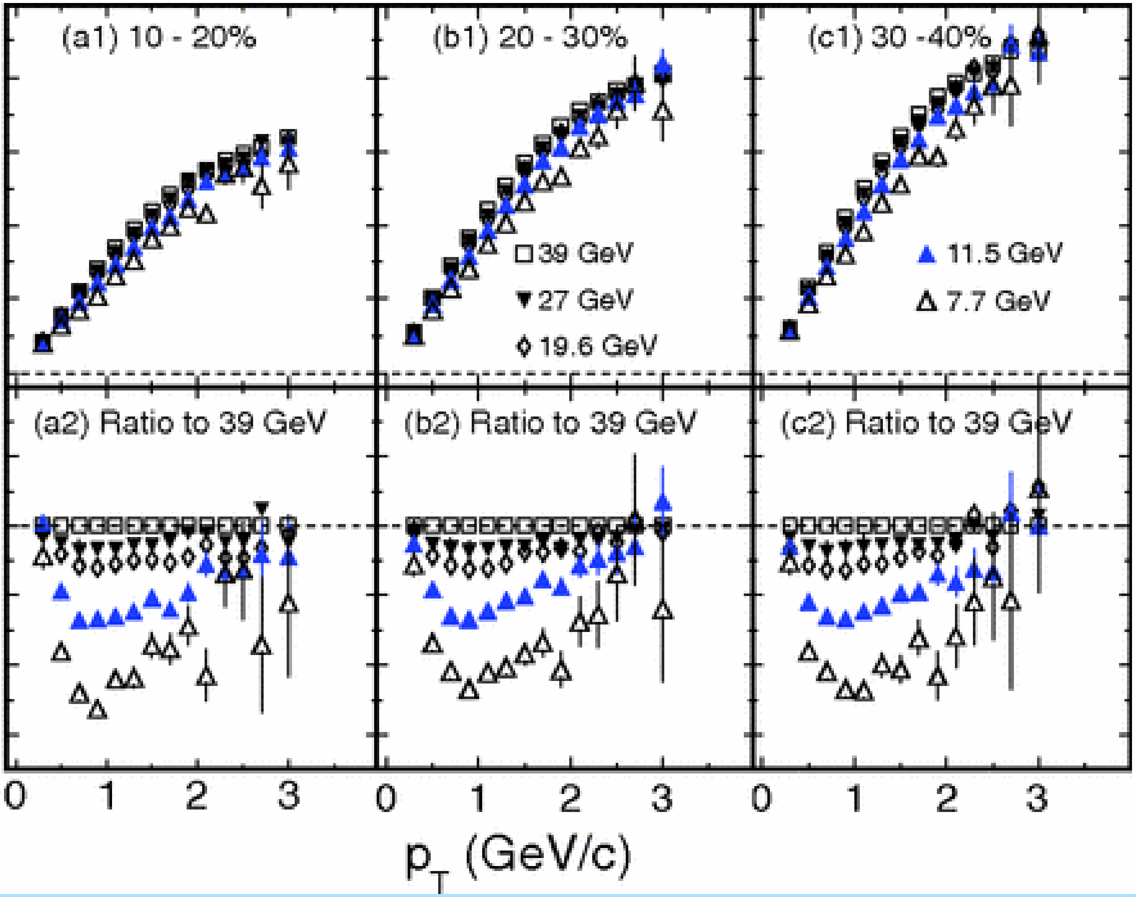
$$p l_{mfp} \geq \hbar \qquad s \sim 4n$$

$$\eta / s > 1/4\pi$$

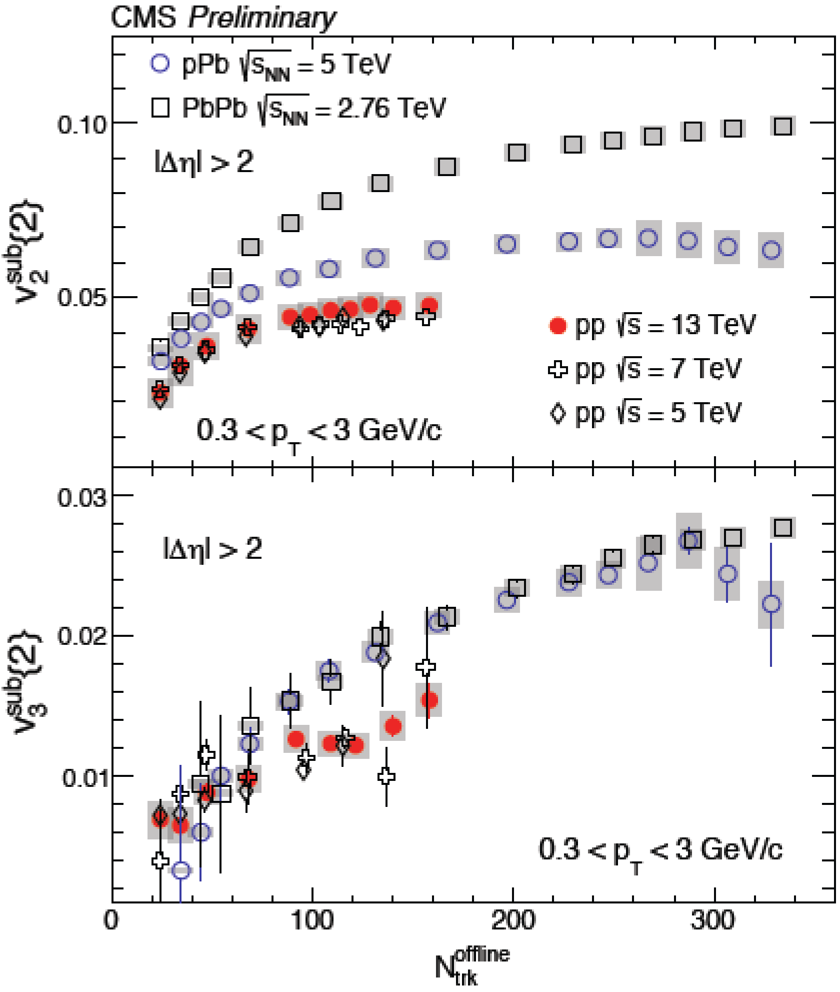


Very little energy dependence

circa 2013

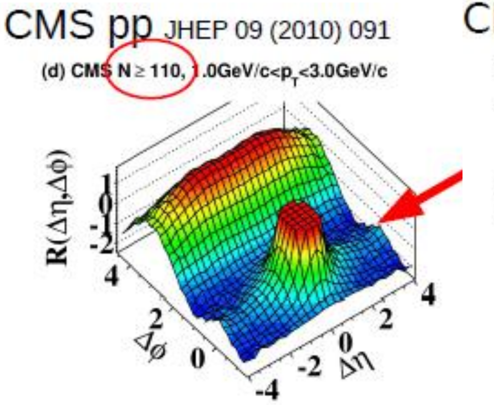


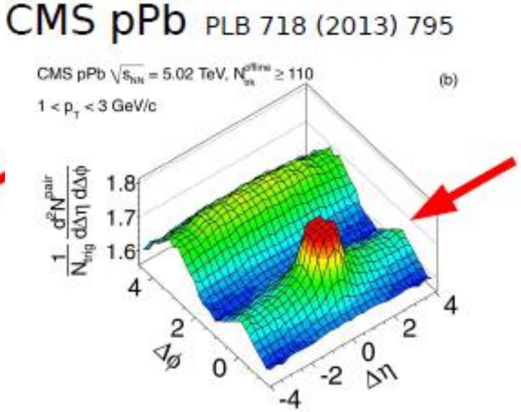
Small systems…

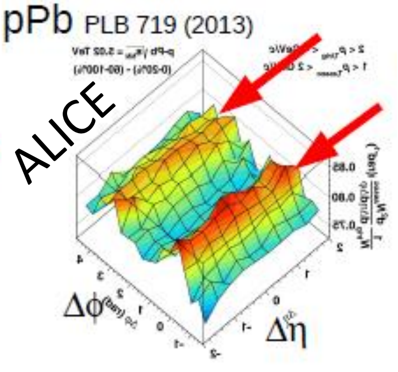


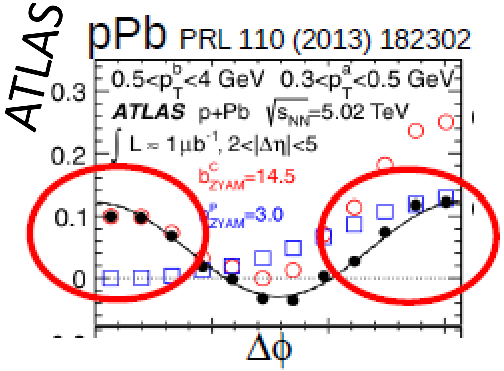
- Yeah…pPb, even pp creates a QGP!
- Maybe we need to rethink about the whole paradigm…

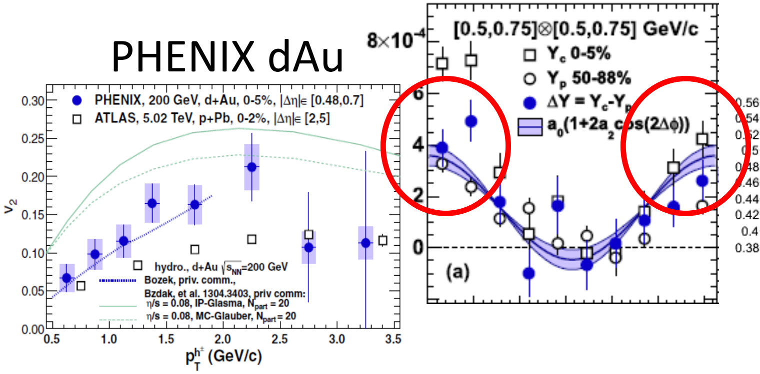
“flow” in small systems, and everywhere

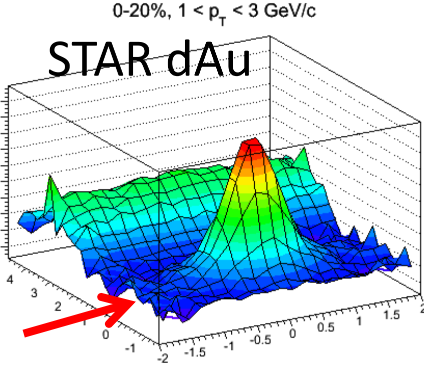


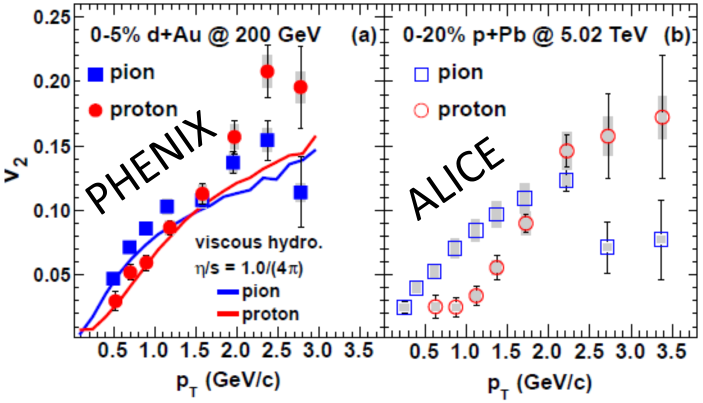


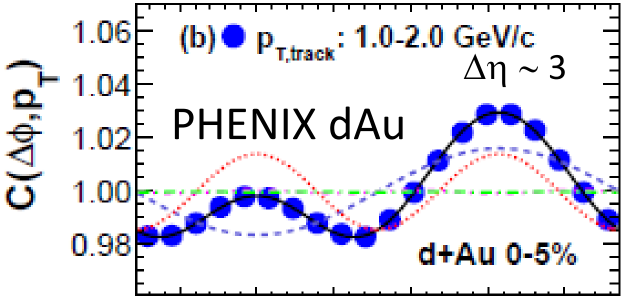


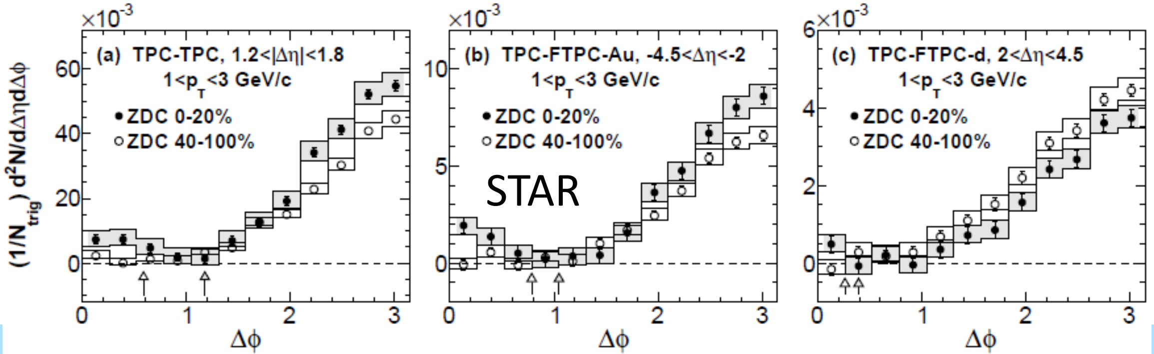




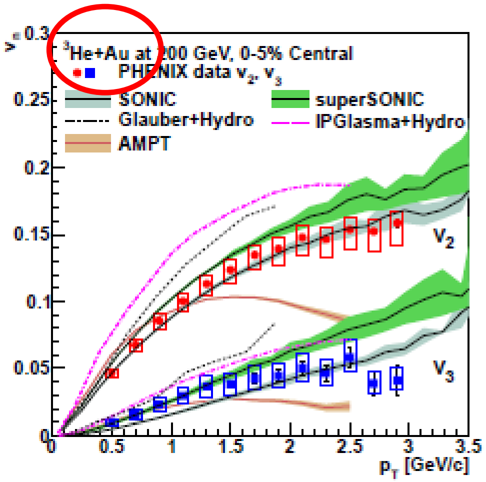




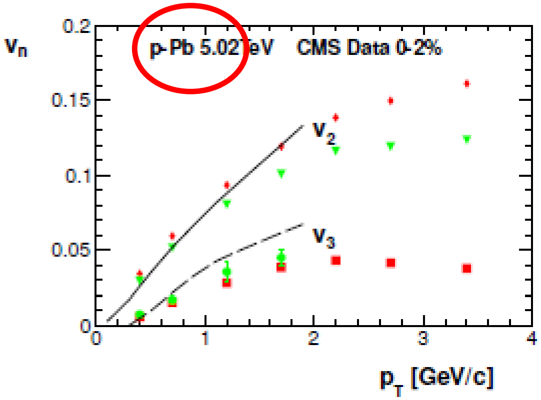


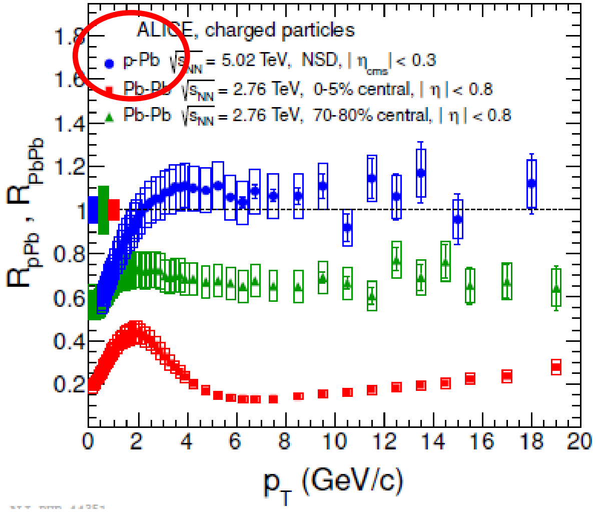


Strong anisotropy, but no energy loss



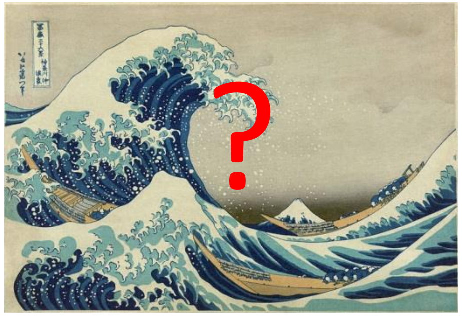
PHENIX, arXiv:1507.06273





PB, W.Broniowski, G. Torrieri arXiv:1306.5442; G.Y. Qin, B. Müller 1306.3439; I. Kozlov et al. 1405.3976; A. Bzdak et al. 1304.34003, K. Kawaguchi et al. Poster 206

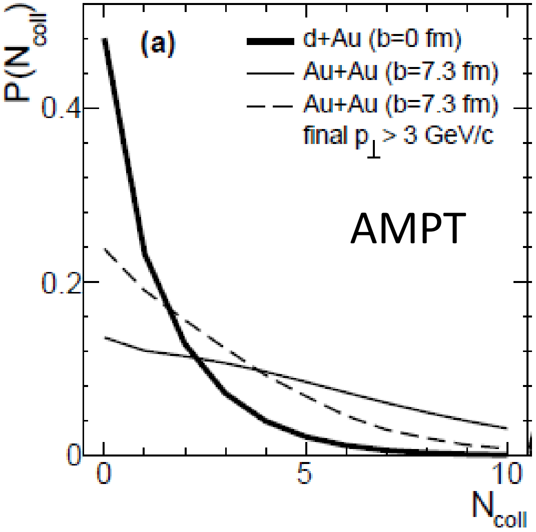
Is it really hydro?



Mean free path: $L_{mfp} = 1/\rho\sigma$

Prob. = $\exp(-L/L_{mfp}) = \exp(-\rho\sigma L)$

Opacity = $L/L_{mfp} = \rho\sigma L$

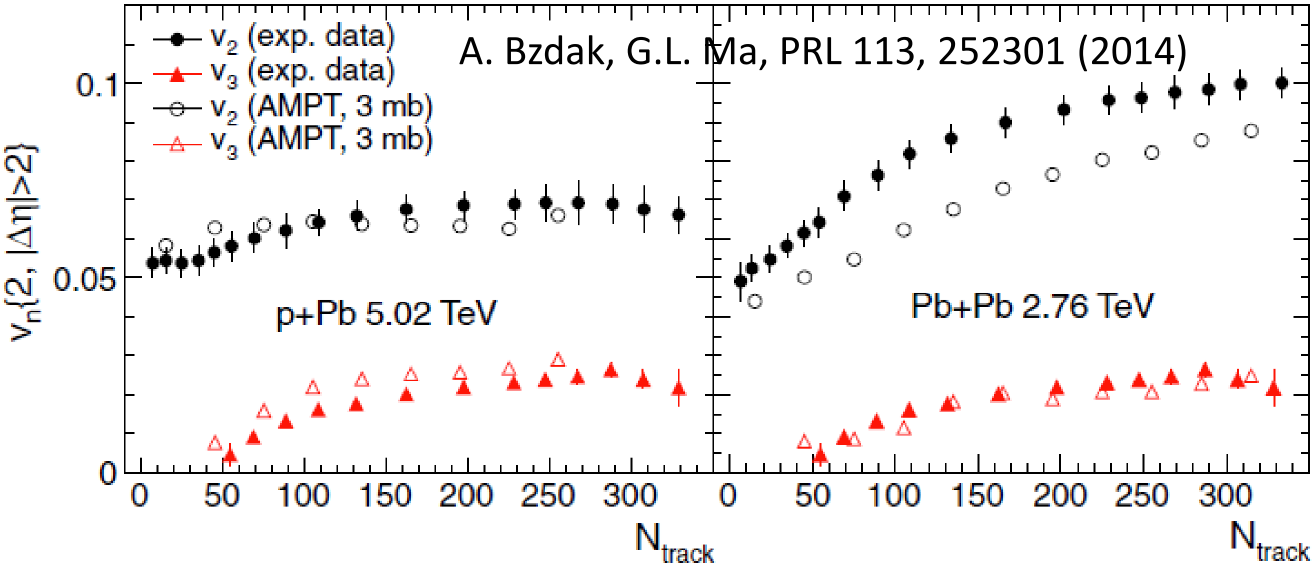


Low opacity in QGP modeled by AMPT

Hydro questionable

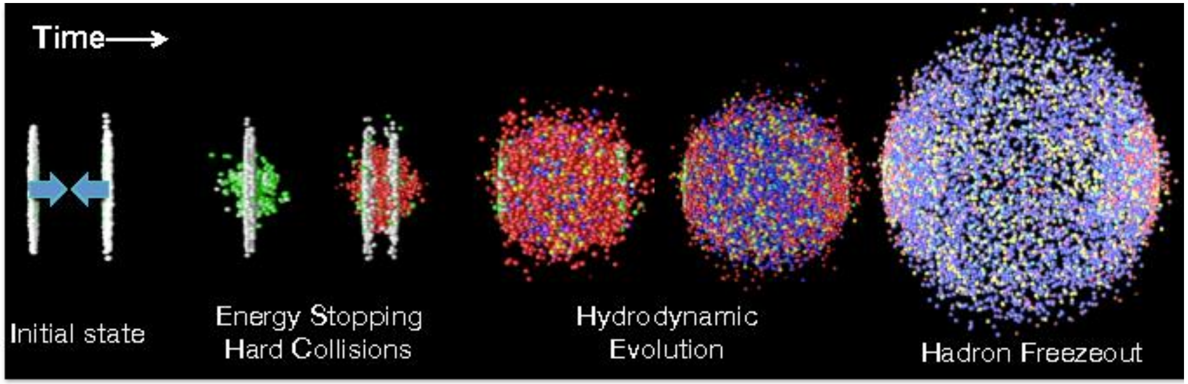
AMPT can describe the data too…

- AMPT: A Multi-Phase Transport (string melting turned on)
- Partons (quarks) liberated from nucleons and strings
- Parton cascading: elastic scattering with 3 mb cross-section
- Partons cease to interact: freeze-out, coalescence into hadrons

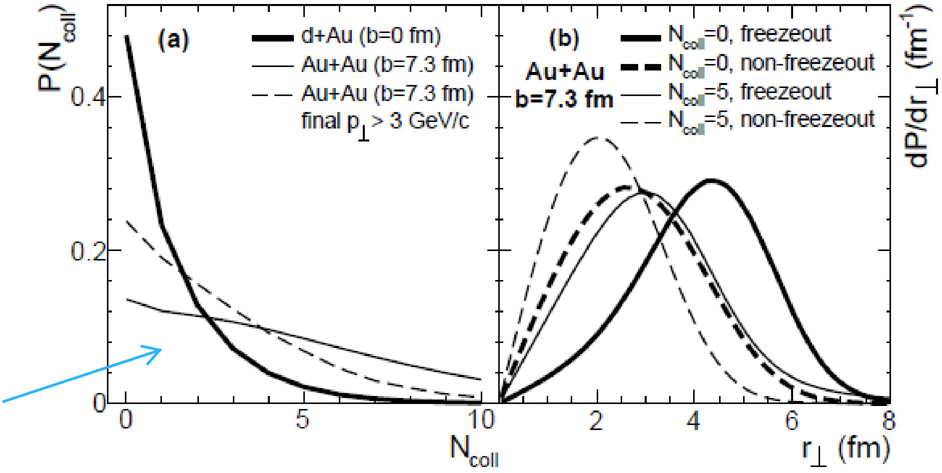


A. Bzdak, G.L. Ma, PRL 113, 252301 (2014)

Parton cascade history



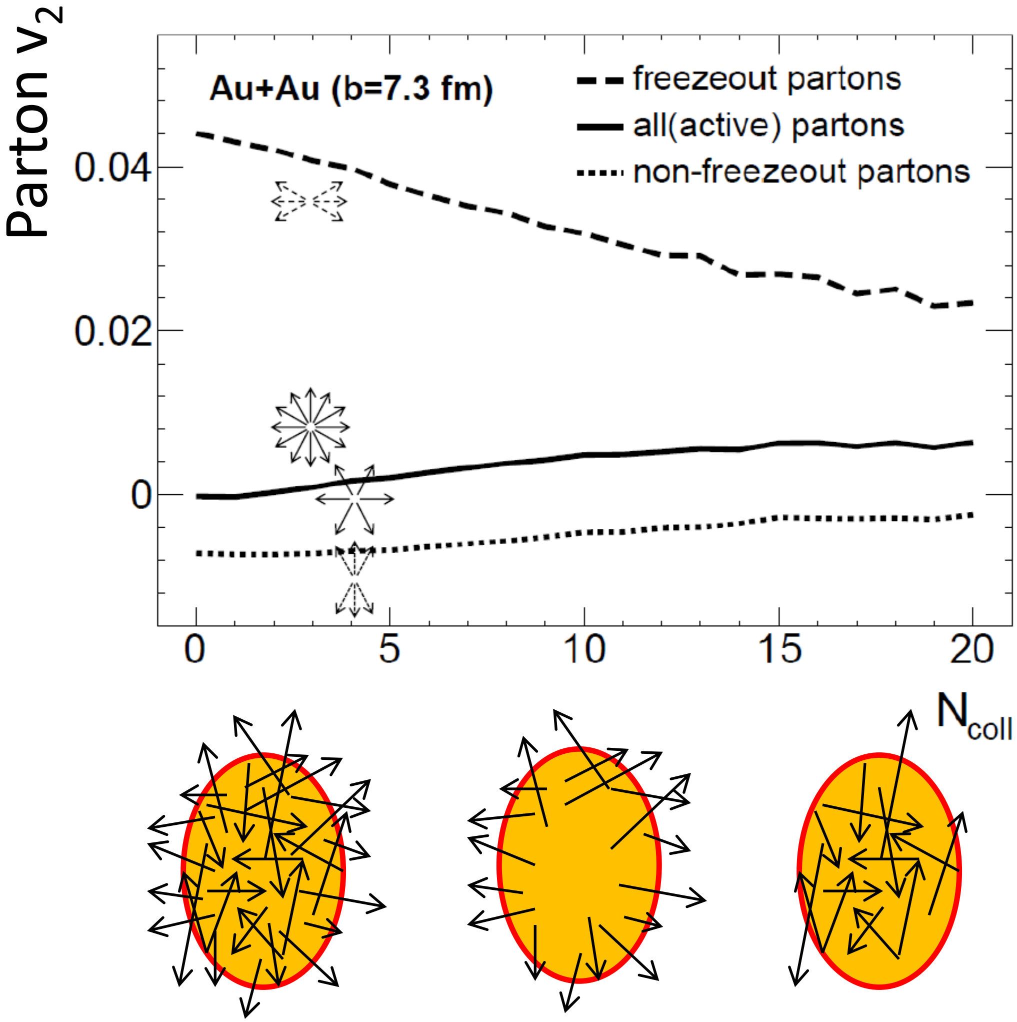
- Get into transport code
- Follow cascading history, microscopic interactions
- Investigate how parton v_n is generated



Low opacity in QGP modeled by AMPT

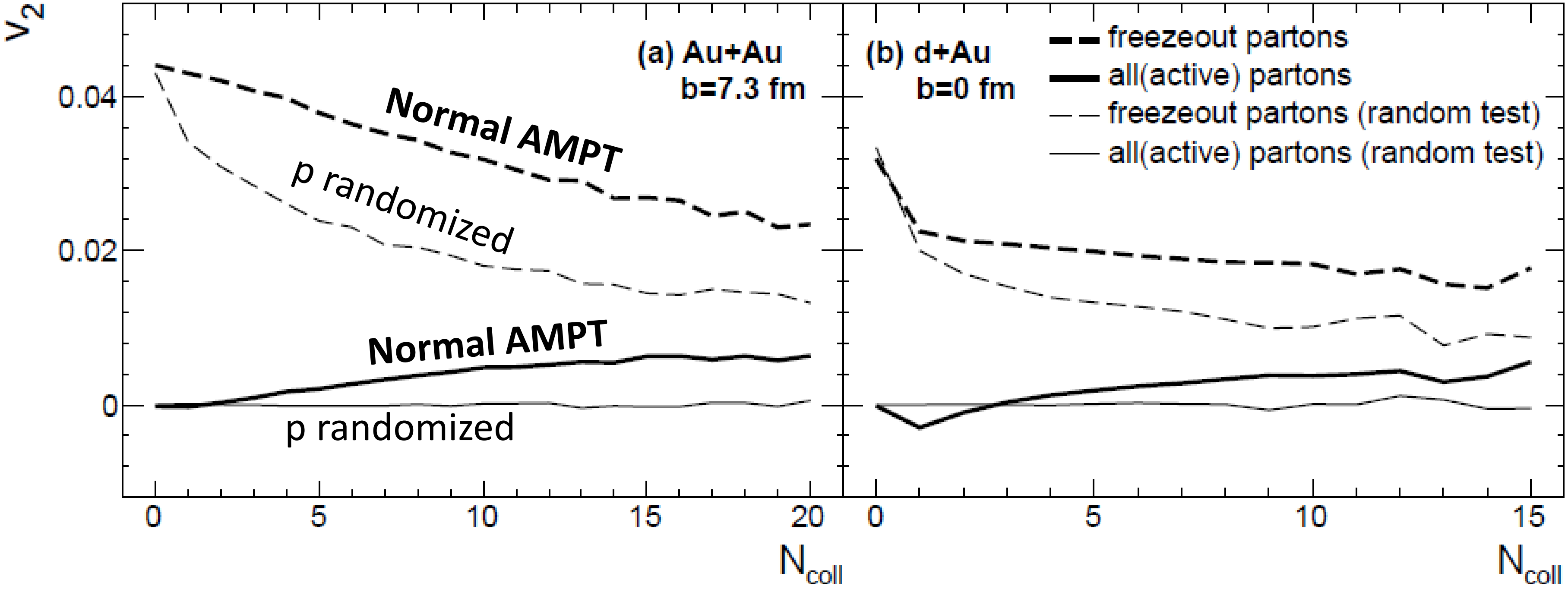
How is anisotropy developed in AMPT?

L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, FW, arXiv:1502.05572



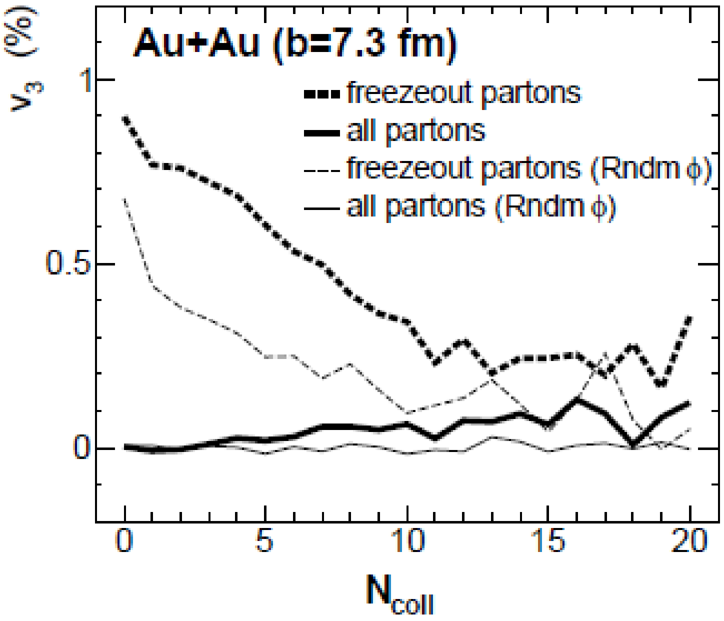
- Partons freeze out with large positive v_2, even when they do not interact at all.
- This is due to larger escape probability along x than y.
- Remaining partons start off with negative v_2, and become ~isotropic ($v_2 \sim 0$) after one more collision.
- Process repeats itself.
- Similar for v_3.
- Similar for d+Au collisions.

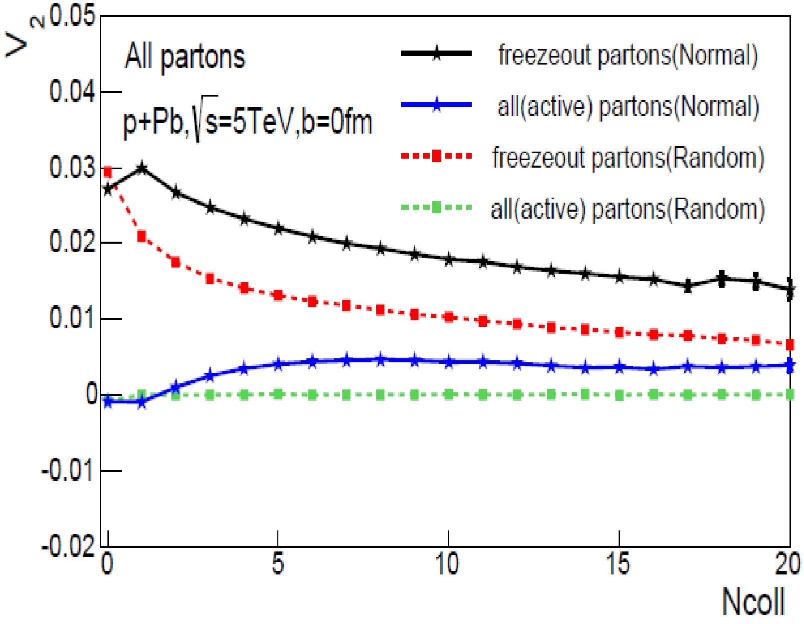
Majority anisotropy from escape



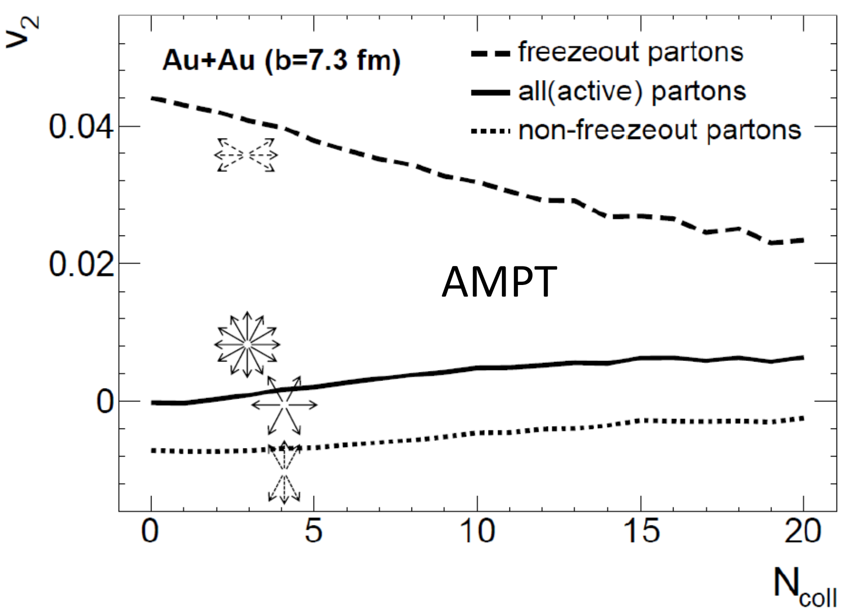
- Majority of anisotropy comes from the final-step “escape” mechanism.
- Escape yields a slightly larger v_2 in normal AMPT than in random case. The escape probability (parton sees) differs in these two cases.
- The partons start with small v_2 before escape (freezeout).
- This small v_2 is due to dynamics, result of hydrodynamic pressure push. It is this flow that is most relevant. However it plays a minor role.

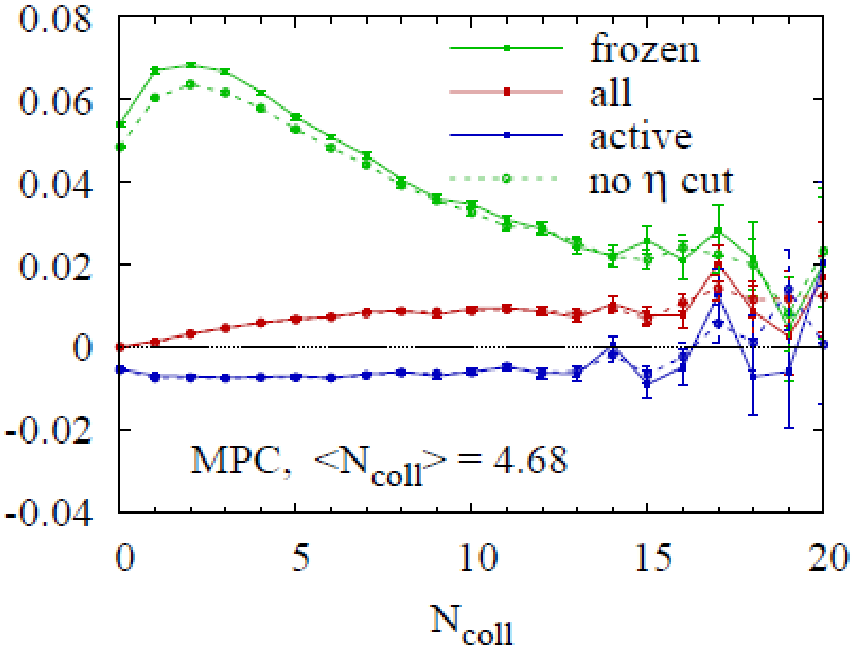
Similar for v_3 & LHC p+Pb





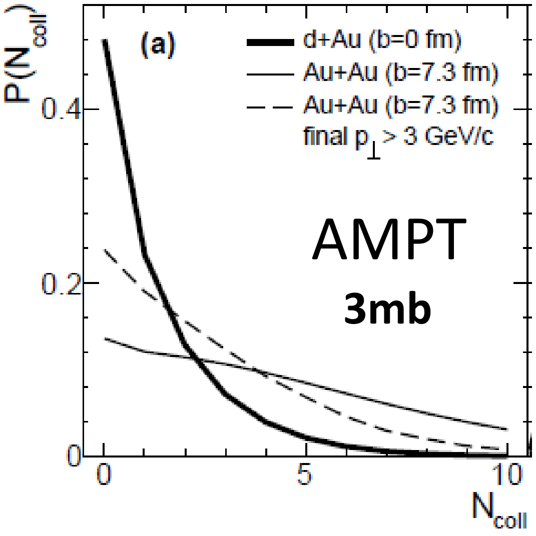
Is it general? AMPT vs MPC

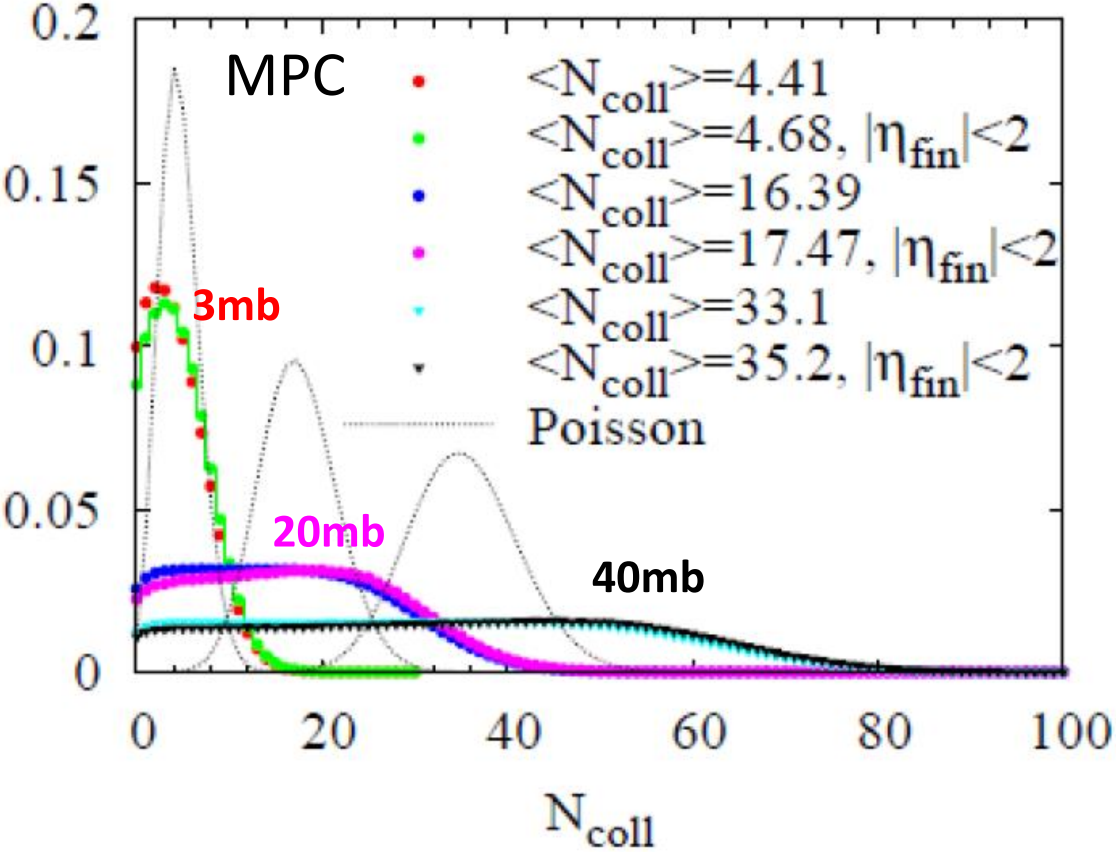


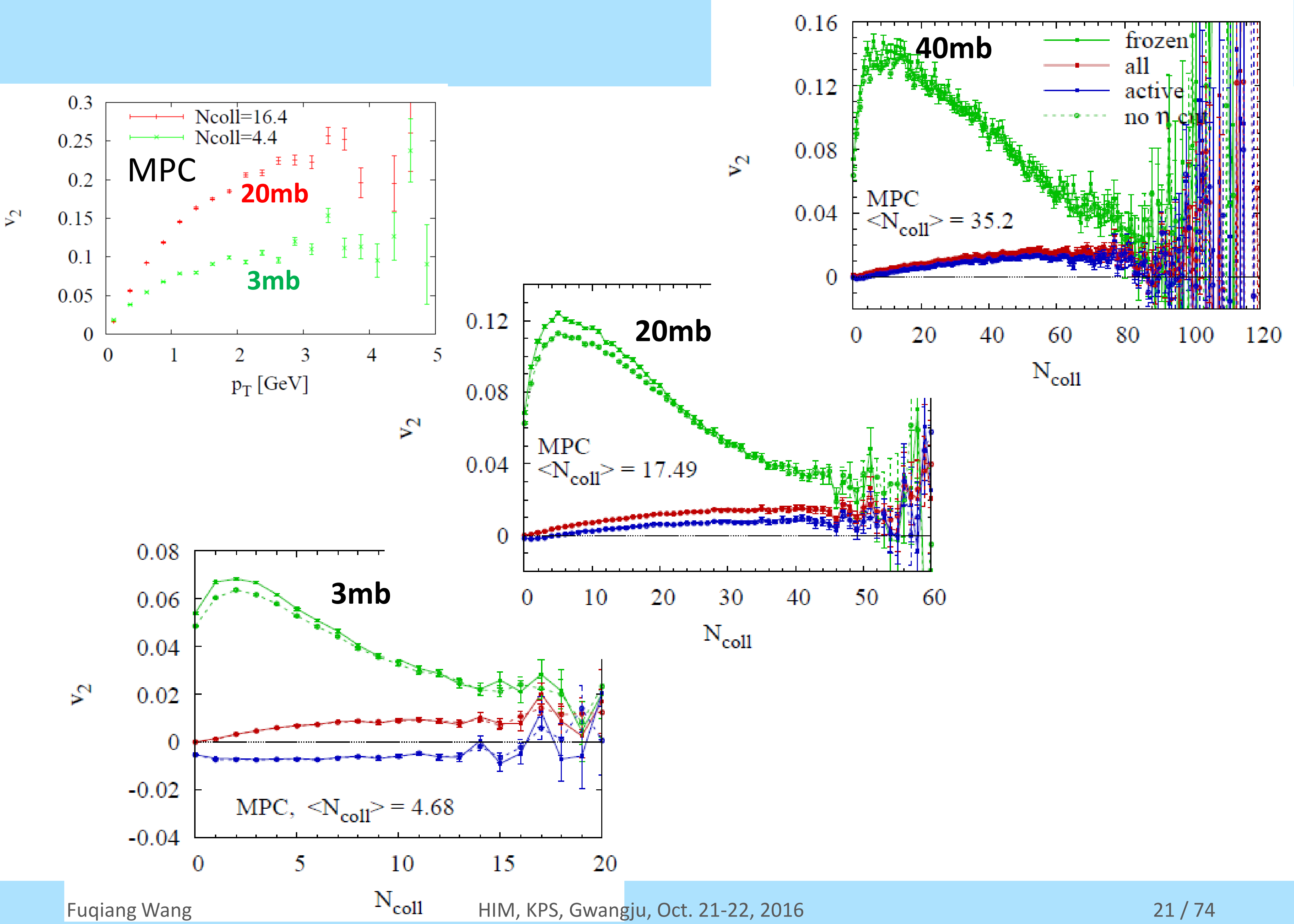


Yes, it is general to transport.

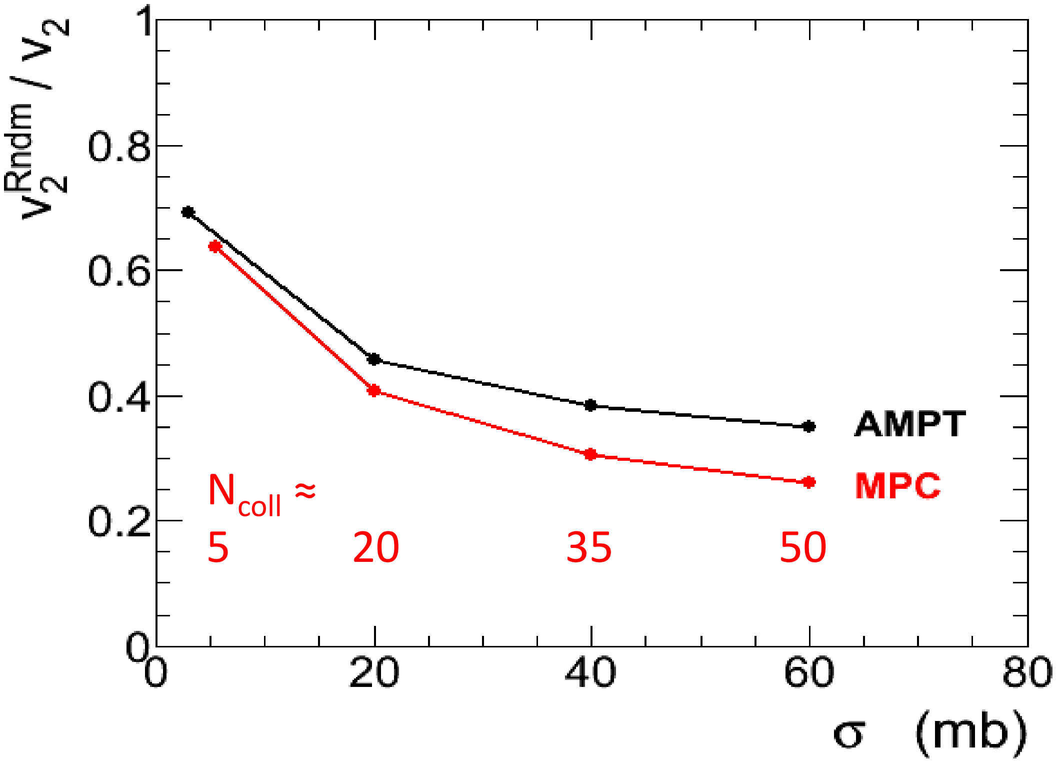
Increasing x-section → hydro?





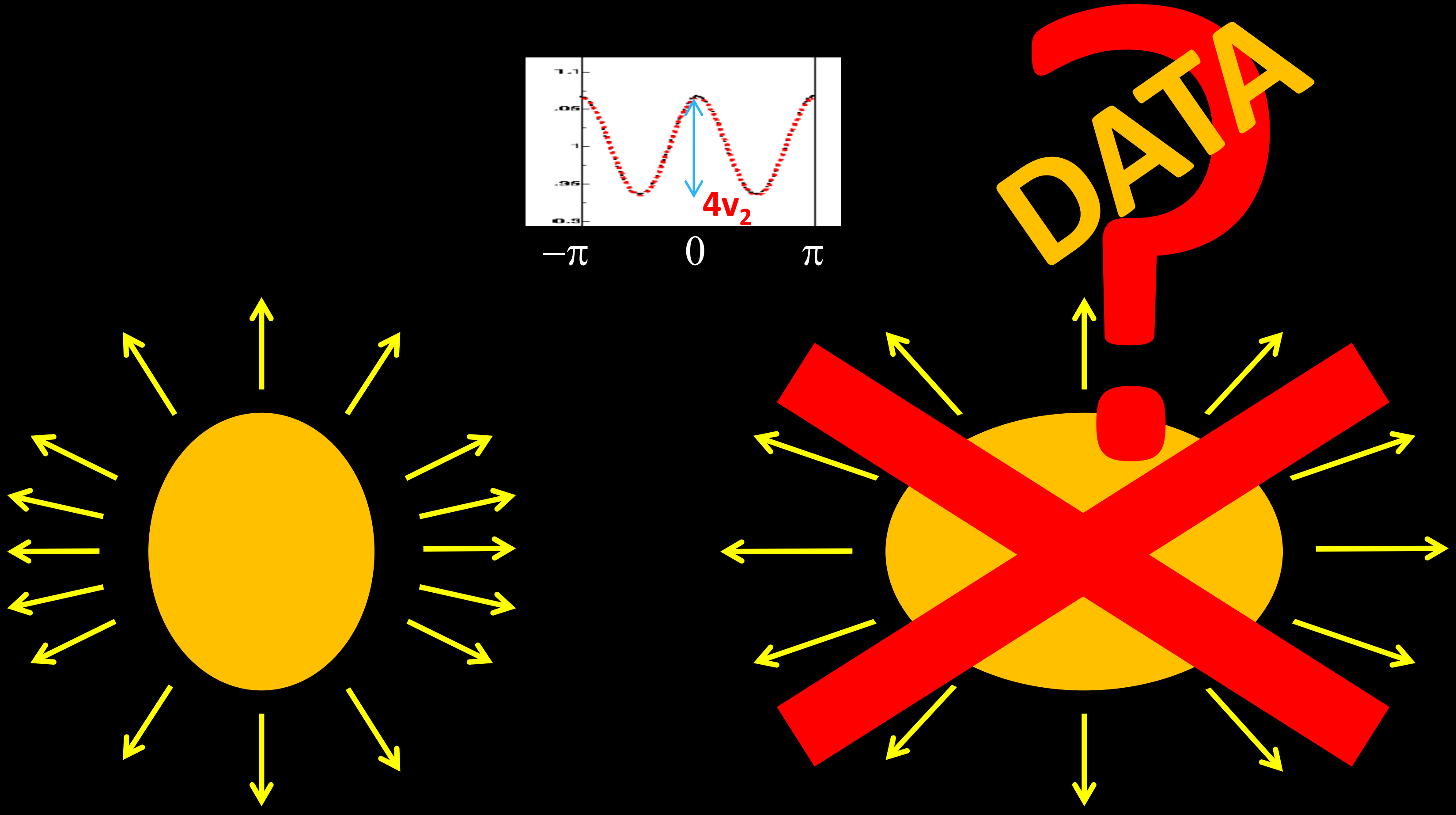

MPC
20mb
3mb
Ncoll=16.4
Ncoll=4.4
v_2
p_T [GeV]
0
0.05
0.1
0.15
0.2
0.25
0.3
0
1
2
3
4
5
40mb
frozen
all
active
no η cut
MPC
$\langle N_{coll} \rangle = 35.2$
0
0.04
0.08
0.12
0.16
0
20
40
60
80
100
120
N_{coll}
20mb
MPC
$\langle N_{coll} \rangle = 17.49$
0
0.04
0.08
0.12
0
10
20
30
40
50
60
3mb
MPC, $\langle N_{coll} \rangle = 4.68$
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0
5
10
15
20

Relative escape contribution



- **Escape contribution still sizeable even at x10 larger x-sections.**

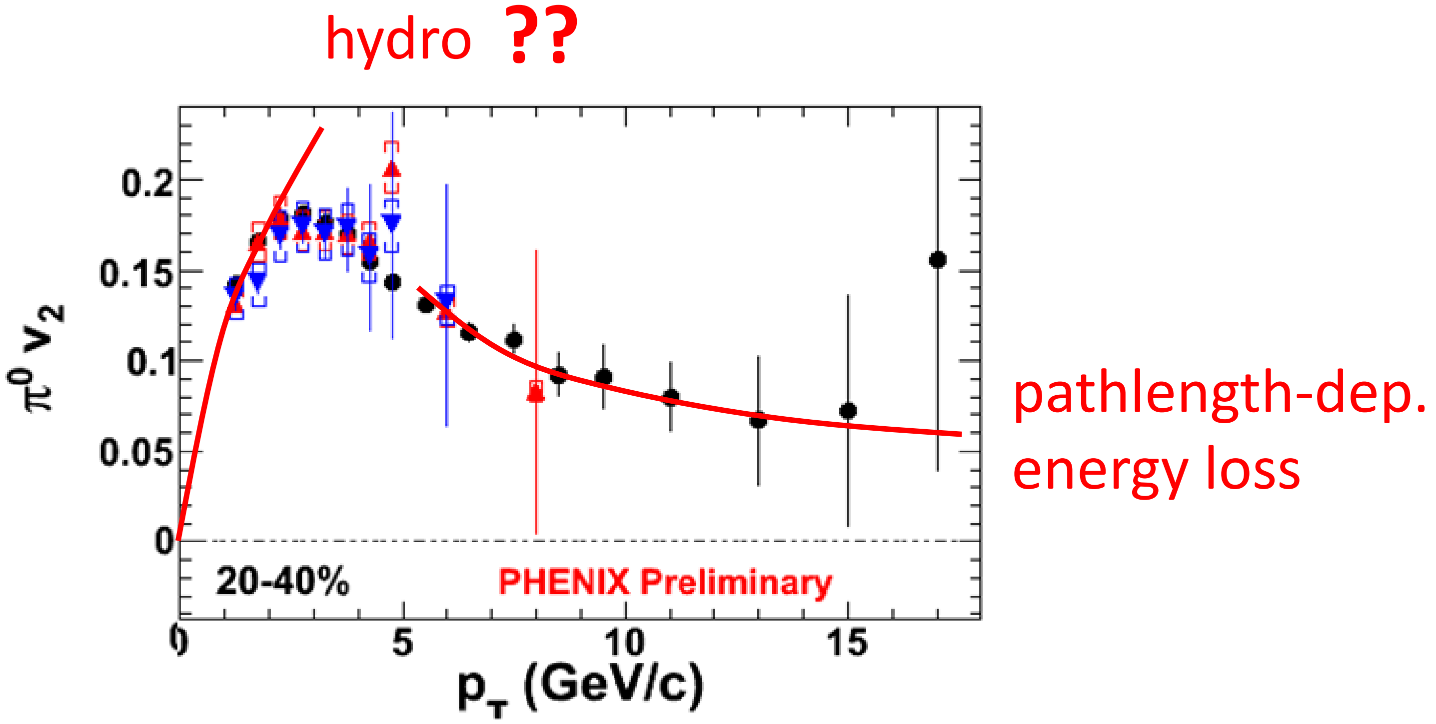
Anisotropy mechanism



No expansion

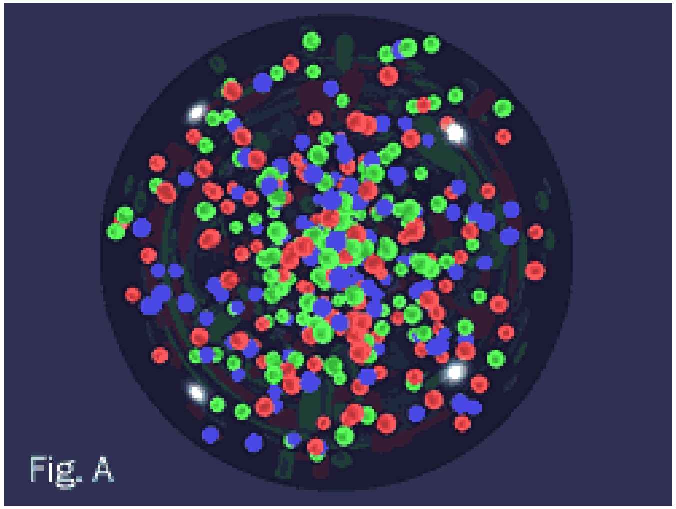
Expansion, flow

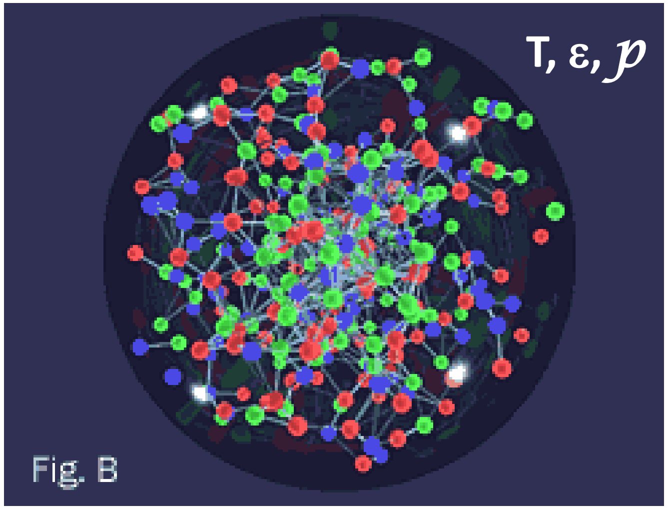
Our flow paradigm?



Our Paradigm

ca 2005





Local equilibrium**??**
Collective velocity field**??**

Ncoll ~ a few:

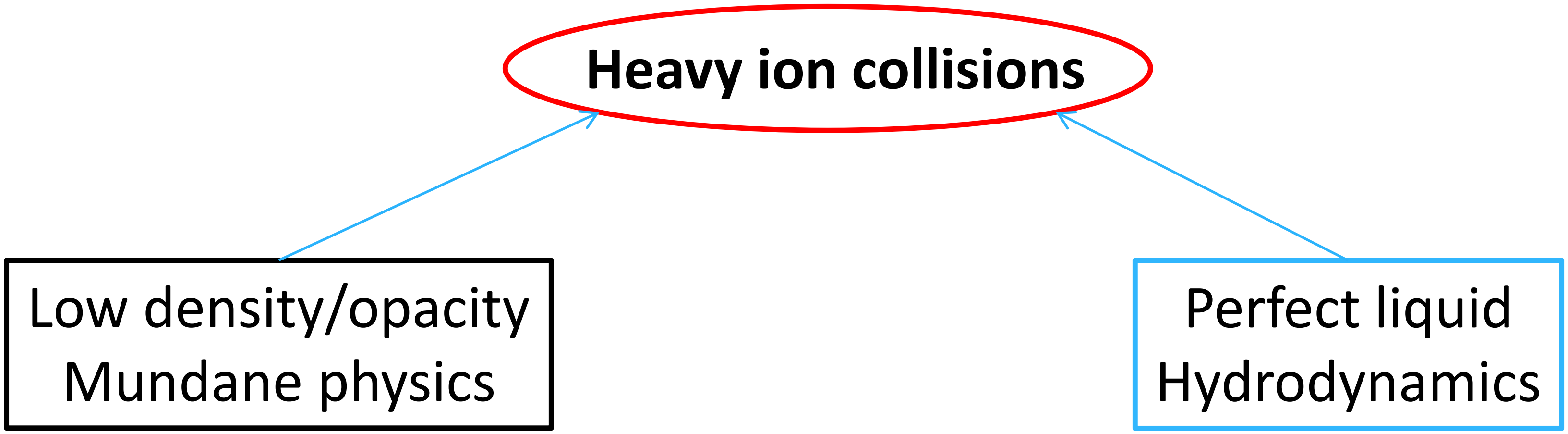
Already enough to equilibrate and generate large hydrodynamic flow?
Might there be another mechanism to generate large anisotropy?

Many open questions

- Many interesting features in small and large systems. Can hydro describe them all?
- Is hydro simply a model with many parameters too?
- Are we really right that the majority of the measured anisotropy is indeed hydro flow?
  Transport models say no.
- Is the “nearly perfect liquid” actually far from perfect?
- …

Which is real?

- Hydrodynamics have pressure driven evolution only. Energy-momentum cell freeze-out controlled by local T, ε. The escape mechanism is not obviously present in hydro.
- Escape anisotropy has all characteristics of “flow” so multi-particle correlations etc. It’s just not hydro flow.
- Hydrodynamics describe data well. AMPT also describes data well.
- Majority v_2 in AMPT is from escape. Are data v_n from hydro?
- Which is more real? How to distinguish?
  - Pressure push generates radial flow
  - Escape mechanism does not generate radial flow

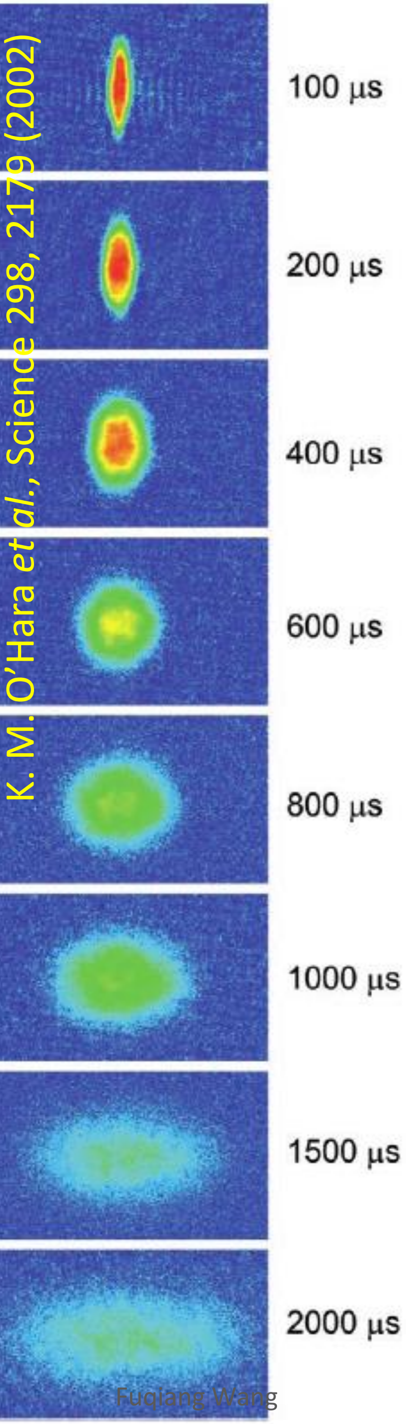


Heavy ion collisions

Low density/opacity
Mundane physics

Perfect liquid
Hydrodynamics

Need experimental test!



K. M. O'Hara *et al.*, Science 298, 2179 (2002)

Cold Atom System

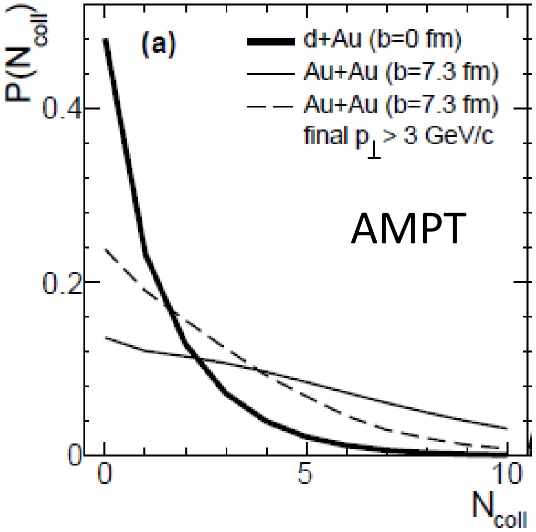
Opacity: $\rho\sigma L$

$a \approx 5\times10^{-5}$ cm
$\sigma_{int} \approx 10^{-8}$ cm^2
$\rho \approx 5\times10^{13}$ /cm^3
$L_{mfp} \approx 2\times10^{-6}$ cm
$L \approx 2\times10^{-3}$ cm
$L/L_{mfp} \approx$ ~~1000~~ 0-1

X10^{-3}

Very ~~high~~ low opacity for the cold atom system

Indeed hydro!

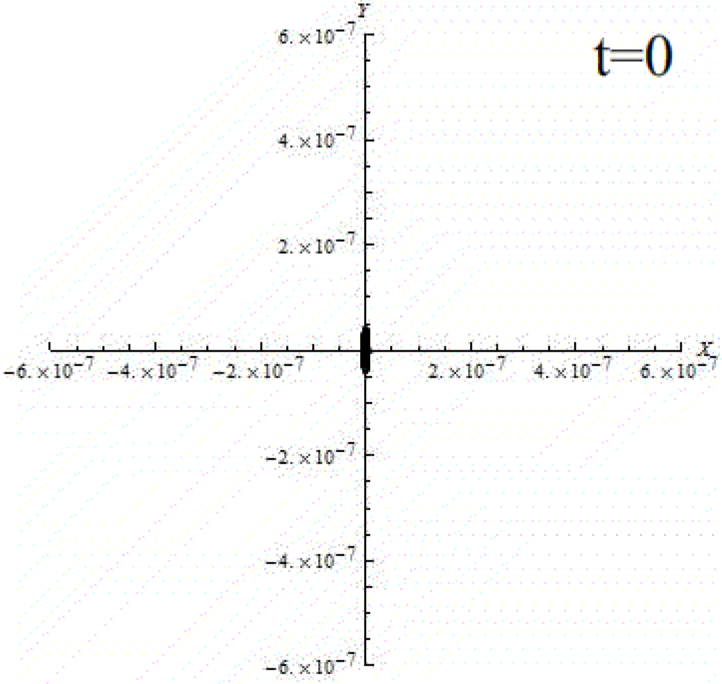


Low opacity in QGP modeled by AMPT

To emulate QGP with cold atoms

$\rho\sigma_{int}L$: reduce opacity by 10^3
1000 → 1

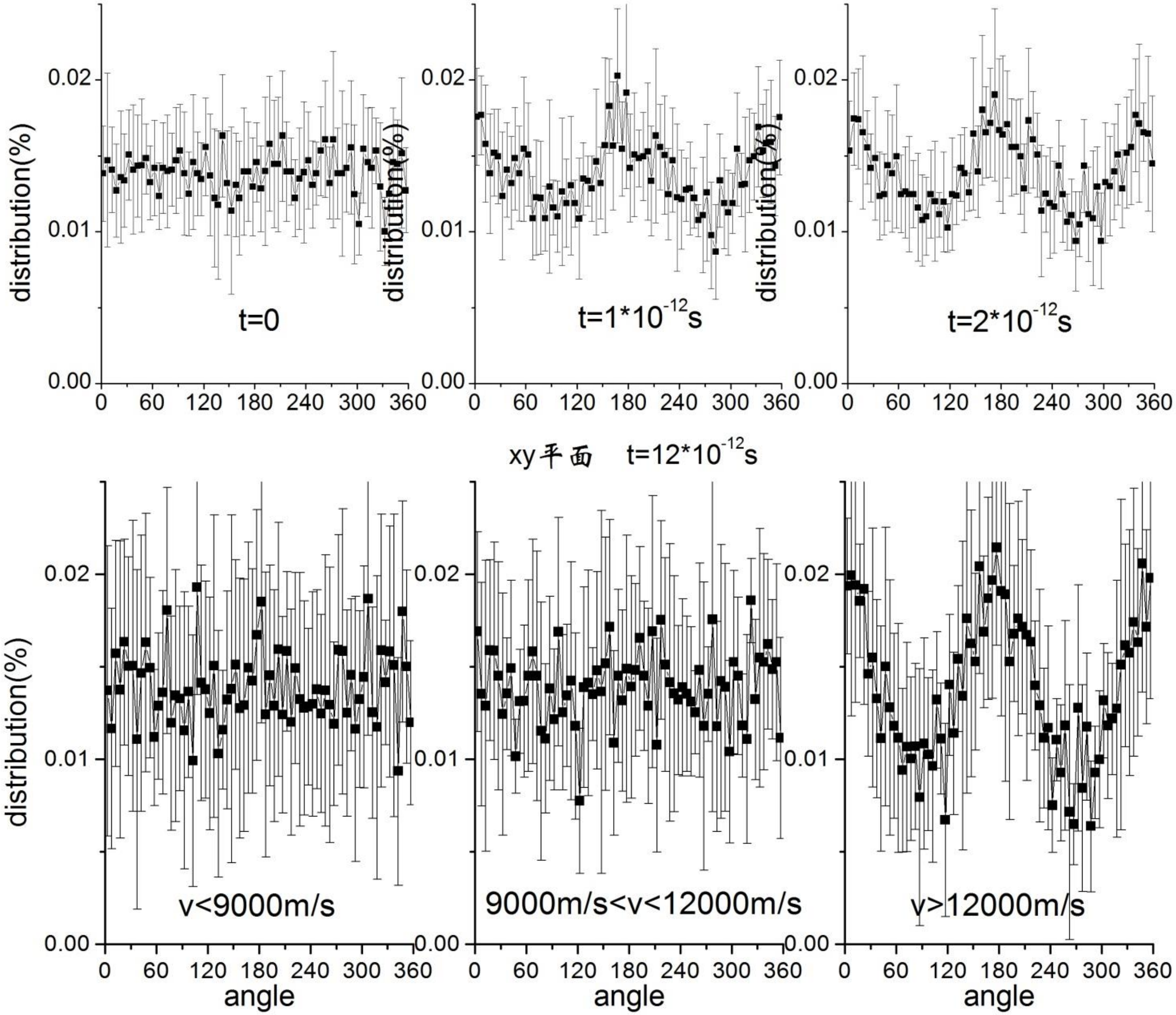
Anisotropic ion trap is also viable



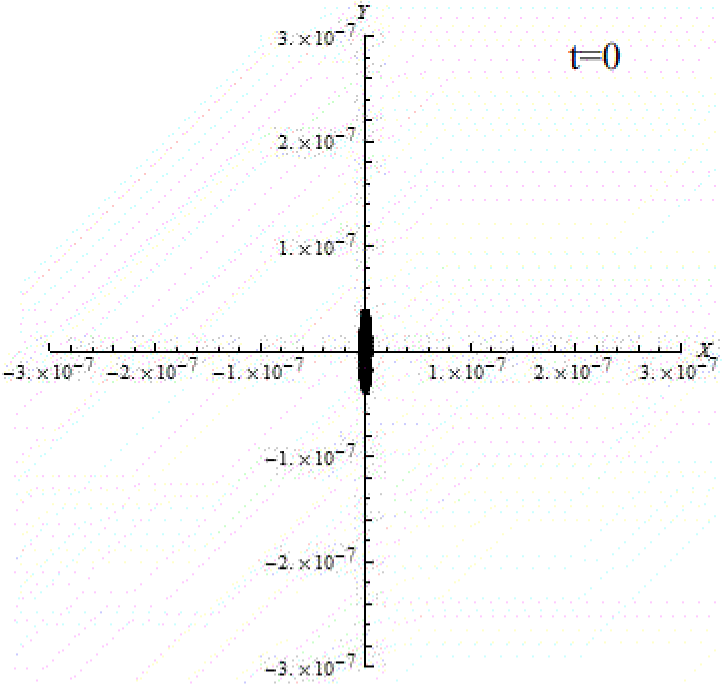
- Coulomb interactions
- Can change trap size and anisotropy, and ion density

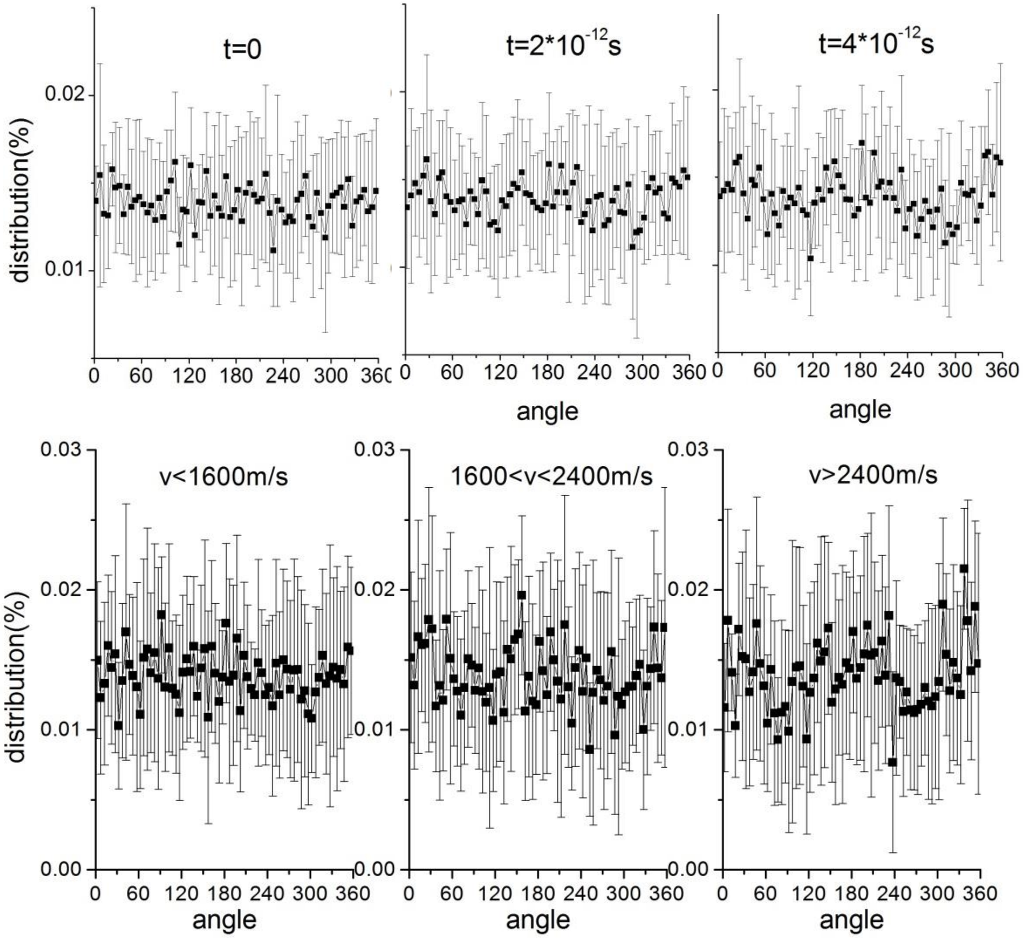
Ion trap: Coulomb

- Lx=10nm
  Ly=80nm
  Lz=100nm
- Number of ions =1000
- Initial thermal velocity 2000m/s



Ion trap: Coulomb with hard core

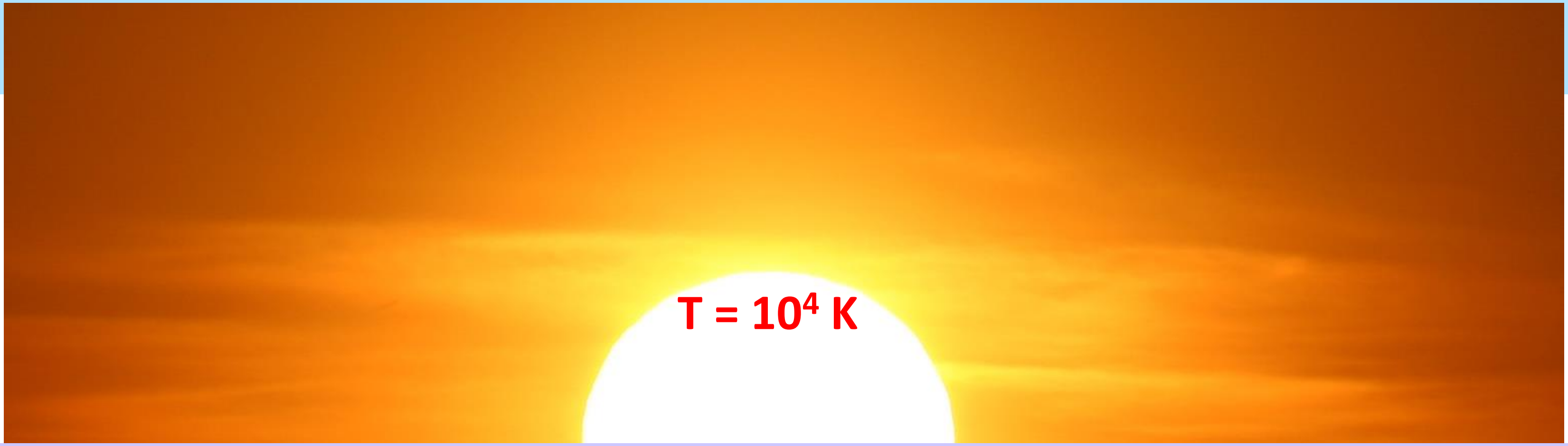


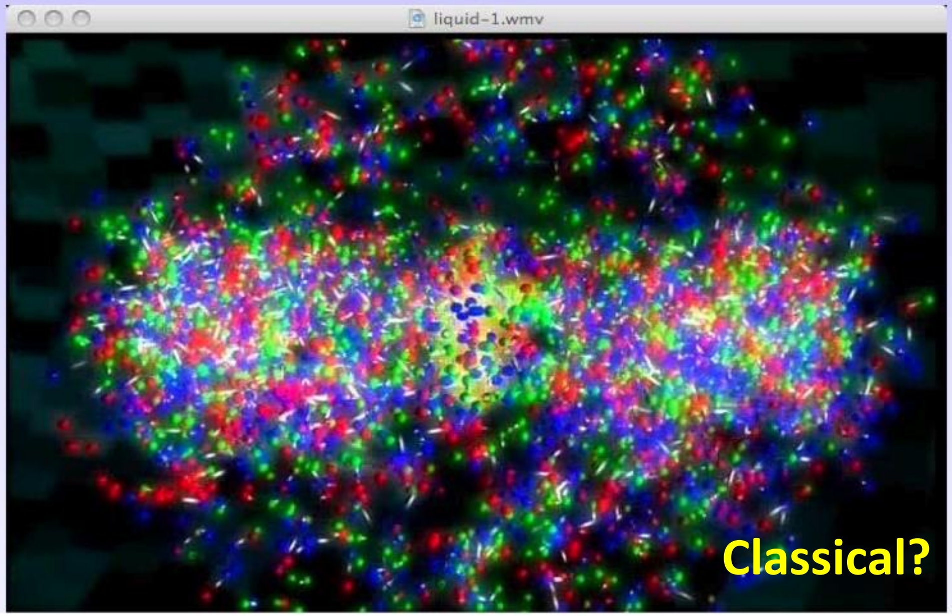


$\rho\sigma_{int}L \sim 1$

Is quantum uncertainty principle at all relevant?

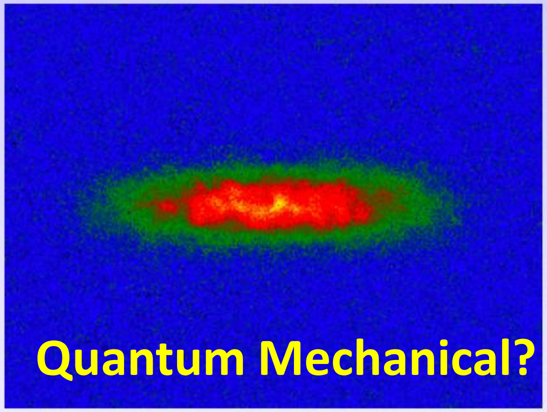
Hot QGP vs Cold Atoms





Quark-gluon plasma $T = 10^{12}$ K **BIG BANG**

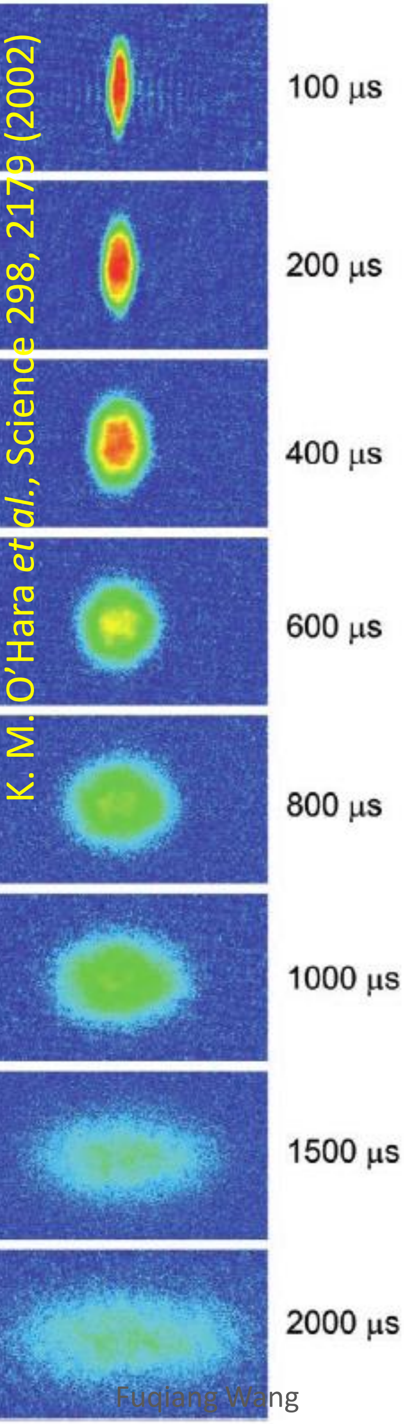
Computer simulation of RHIC collision



Ultracold atomic gas

$T = 10^{-7}$ K

Is QGP classical?



K. M. O'Hara *et al.*, Science 298, 2179 (2002)

Li: M~6000 MeV
T~1μK~10^{-16}MeV
x~20μm, y~100μm
p~$(TM)^{1/2}$~10^{-6}MeV

p quan~1/r~10^{-8}MeV
E quan~$1/(mr^2)$~10^{-20}MeV
Negligible!

Cold atoms are **hot**,
"classical" w.r.t. trap size.

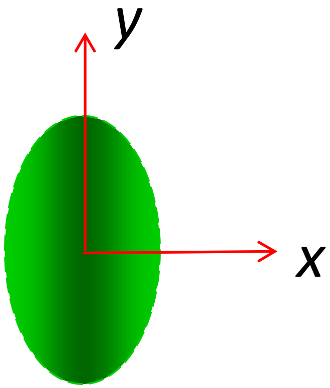
q,g: M~0 MeV
T~200 MeV
x~3fm, y~4fm
p~200MeV

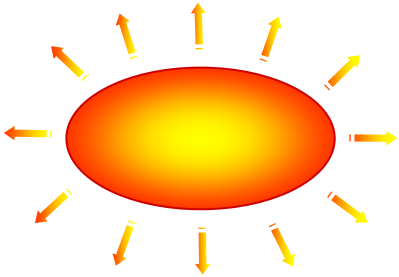
p quan~1/r~200MeV
E quan~200 MeV
Comparable!

QGP is **cold**,
quantum mechanical.

Kolb, Heinz, nucl-th/0305084; Lisa et al. New J. Phys. **13** (2011) 065006

QM uncertainty principle



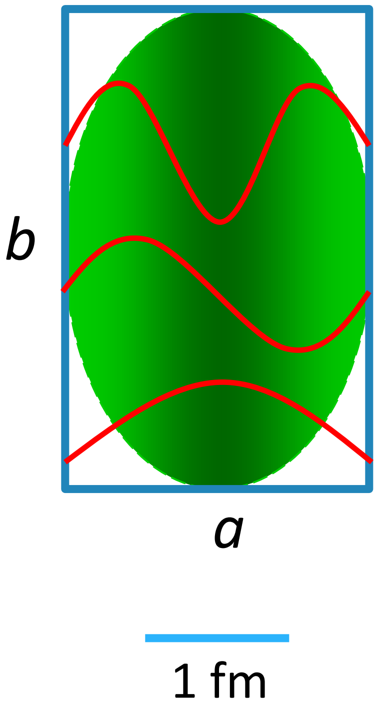


$$\Delta x \cdot \Delta p > \hbar / 2$$

$$p_x > p_y$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Infinite square well



$$-\frac{\hbar^2}{2m}\nabla^2\psi = E\psi \quad \Rightarrow \quad \psi \propto \begin{cases} \cos\frac{n_{odd}\pi}{a}x \\ \sin\frac{n_{even}\pi}{a}x \end{cases}$$

Take even mode for example:

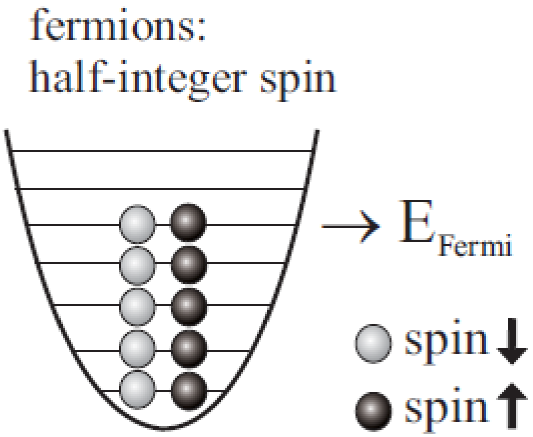
$$\langle p_x^2\rangle = \hbar^2 k^2 \ ; \quad \langle x^2\rangle = \frac{a^2}{4} - \frac{2}{k^2} \ ; \quad k = \frac{n_{odd}\pi}{a}$$

$$\sqrt{\langle p_x^2\rangle \cdot \langle x^2\rangle} = \hbar\sqrt{\frac{k^2a^2}{4} - 2} = \hbar\sqrt{\frac{\pi^2}{4}n_{odd}^2 - 2} > \hbar/2$$

$$v_2 = \frac{\langle p_x^2\rangle - \langle p_y^2\rangle}{\langle p_x^2\rangle + \langle p_y^2\rangle} = \frac{b^2 - a^2}{b^2 + a^2} = \varepsilon \quad \text{for all } n.$$

Single state anisotropy

Harmonic oscillator



$$\left(-\frac{\hbar^2}{2m}\nabla^2+\frac{1}{2}m\omega^2x^2\right)\psi=E\psi\ ;\qquad E=\left(n+\frac{1}{2}\right)\hbar\omega$$

$$\left\langle\frac{p_x^2}{2m}\right\rangle=\left\langle\frac{1}{2}m\omega^2x^2\right\rangle=\frac{E}{2}=\frac{1}{2}\left(n+\frac{1}{2}\right)\hbar\omega$$

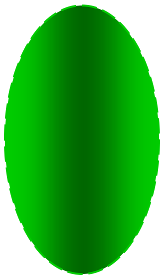
$$\sqrt{\left\langle p_x^2\right\rangle\left\langle x^2\right\rangle}=\left(n+\frac{1}{2}\right)\hbar$$

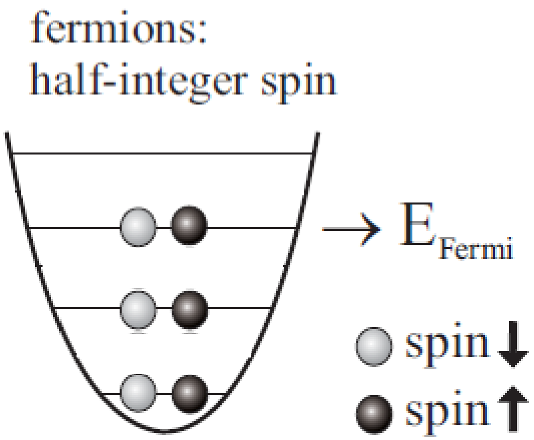
$$v_2=\frac{\left\langle p_x^2\right\rangle-\left\langle p_y^2\right\rangle}{\left\langle p_x^2\right\rangle+\left\langle p_y^2\right\rangle}=\frac{\omega_x-\omega_y}{\omega_x+\omega_y}$$

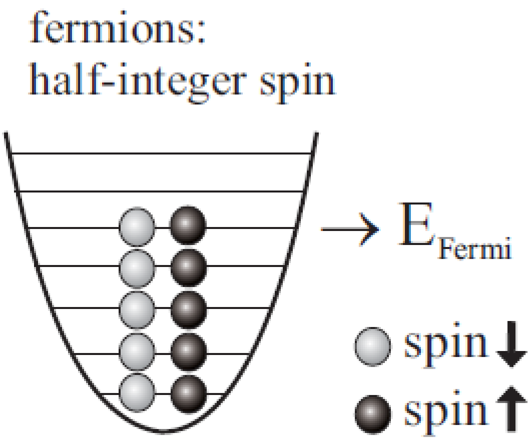
$$\varepsilon=\frac{\left\langle y^2\right\rangle-\left\langle x^2\right\rangle}{\left\langle y^2\right\rangle+\left\langle x^2\right\rangle}=\frac{\omega_x-\omega_y}{\omega_x+\omega_y}$$

$v_2=\varepsilon$ for each and all n

Thermal probability







x, y at same Fermi energy, so different number of filled energy levels.

At high temperature, classical limit, sum is approximated by integral:

$$\frac{dN}{d\mathbf{p}} = N\frac{\int d\mathbf{r}\, e^{-H_1(\mathbf{p},\mathbf{r})/T}}{\int d\mathbf{r}\, d\mathbf{p}\, e^{-H_1(\mathbf{p},\mathbf{r})/T}} = N\frac{e^{-K(\mathbf{p})/T}}{\int d\mathbf{p}\, e^{-K(\mathbf{p})/T}}$$

then it’s independent of potential.
It’s isotropic at all temperature because $K=(p_x^2+p_y^2)/2m$ is isotropic.

Thermal probability weight

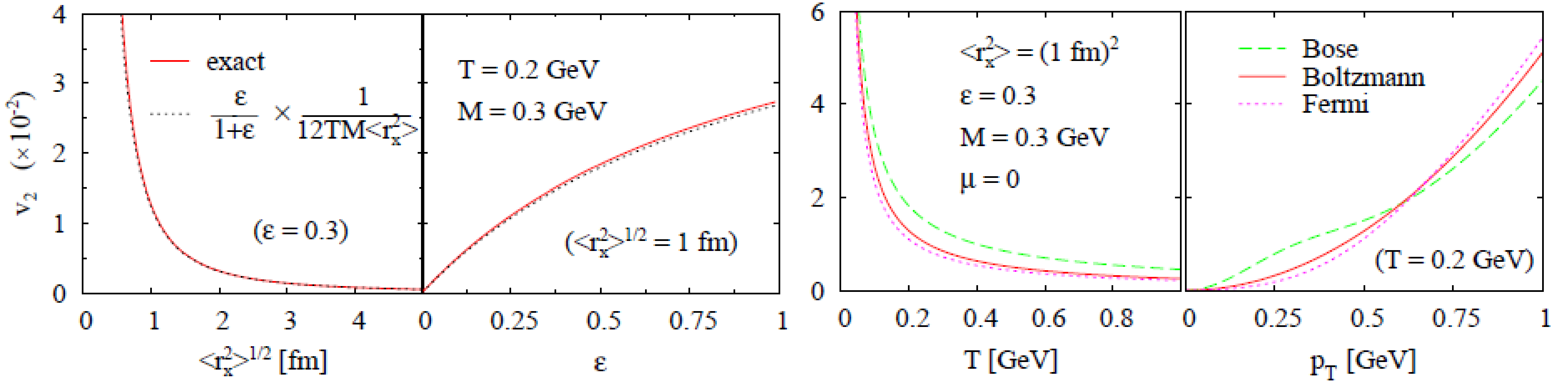
D. Molnar, FW, and C.H. Greene, arXiv:1404.4119

$$\rho(\mathbf{r}) \equiv \frac{dN}{d\mathbf{r}} = \frac{1}{Z}\sum_j |\psi_j(\mathbf{r})|^2 \, e^{-E_j/T} \qquad f(\mathbf{p}) \equiv \frac{dN}{d\mathbf{p}} = \frac{1}{Z}\sum_j |\psi_j(\mathbf{p})|^2 \, e^{-E_j/T}$$

$$Z \equiv \textstyle\sum_j e^{-E_j/T}$$

$$\langle p_i^2 \rangle = \frac{M\omega_i}{2} \coth\frac{\omega_i}{2T} \, , \quad \langle r_i^2 \rangle = \frac{1}{2M\omega_i} \coth\frac{\omega_i}{2T} \, .$$

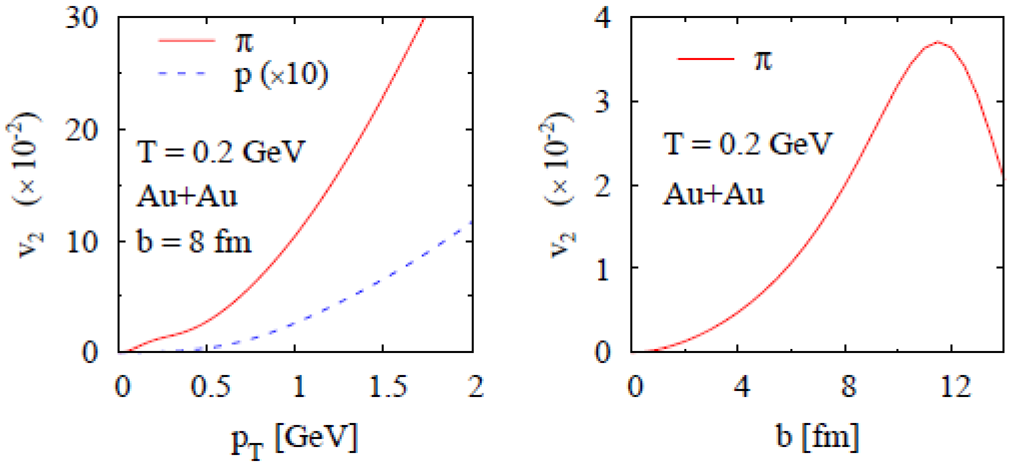
$$\bar{v}_2 \approx \frac{\hbar^2}{12 k_B T M \langle r_x^2 \rangle} \cdot \frac{\varepsilon}{1+\varepsilon} \qquad v_{2n}(p_T) = h_n\left(\frac{p_T^2}{2MT}(S_y - S_x)\right) \, , \quad S_i \equiv \frac{T}{\omega_i}\tanh\frac{\omega_i}{2T}$$



Quantum physics anisotropy

D. Molnar, FW, and C.H. Greene, arXiv:1404.4119

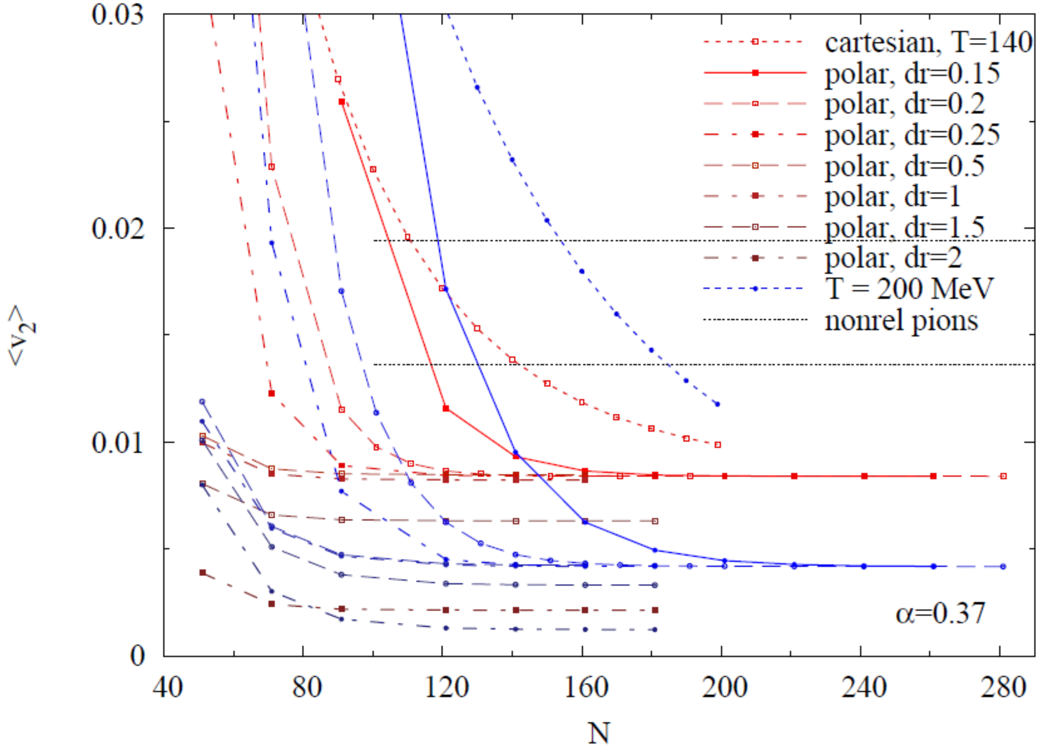
$$\bar{v}_2 \approx \frac{\hbar^2}{12 k_B T M \langle r_x^2 \rangle} \cdot \frac{\varepsilon}{1+\varepsilon}$$



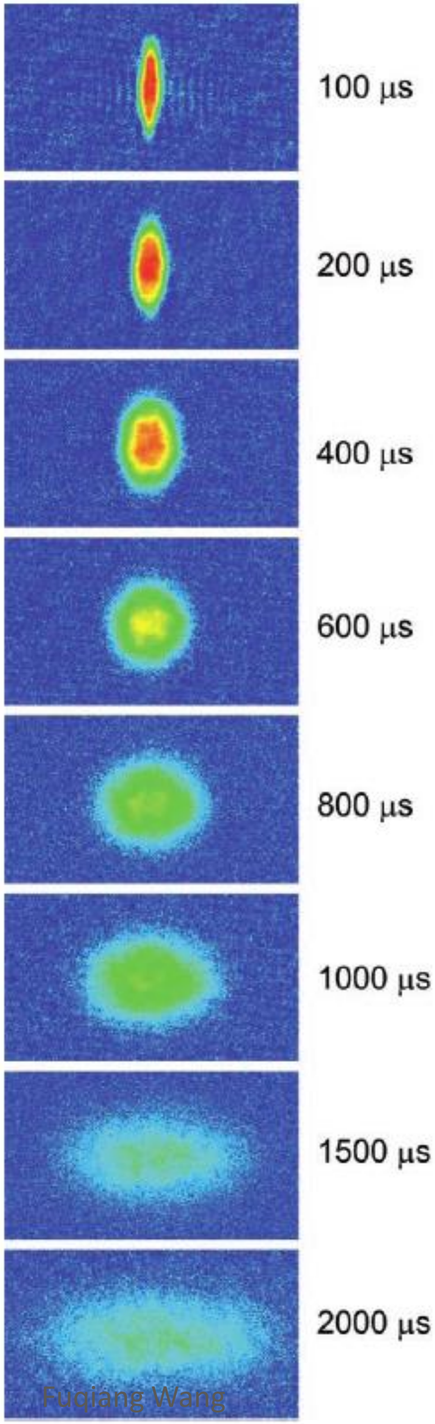
$b = 8$ fm: $\langle r_x^2 \rangle^{1/2} = 1.5$ fm and $\langle r_y^2 \rangle^{1/2} = 2.2$ fm.

$$\rho(\mathbf{r}) \propto \exp\left(-\sum_i \frac{r_i^2}{2\langle r_i^2 \rangle}\right), \quad f(\mathbf{p}) \propto \exp\left(-\sum_i \frac{p_i^2}{2\langle p_i^2 \rangle}\right)$$

Relativistic quantum mechanical calculation



- Much harder calculation. The last two years were spent on it.
- Use of polar coord. and wise choice of base functions.
- Converges with ~200 eigenstates.
- Effect is ~1% at T=140 MeV and 0.5% at T=200 MeV.



Cold atoms

Strong elliptic anisotropy

K. M. O'Hara *et al.*, Science 298, 2179 (2002).

Lithium atoms M ~ 6000 MeV
Temperature T ~ 1 μK ~ 10^{-16} MeV
Trap size x ~ 20 μm, y ~ 100 μm

Typical momentum $(TM)^{1/2}$ ~ 10^{-6} MeV
Intrinsic momentum quantum ~ 1/r ~ 10^{-8} MeV, negligible.

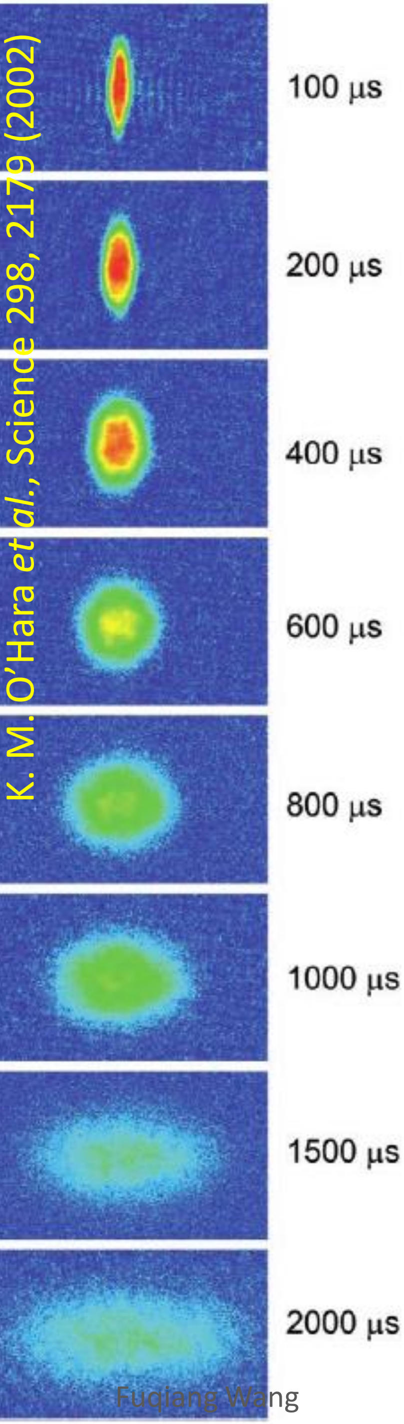
Typical energy ~ T ~ 10^{-16} MeV
Intrinsic energy quantum $1/(mr^2)$ ~ 10^{-20} MeV, negligible.

Cold Lithium atoms are actually "hotter" than the hot QGP.

$$\bar{v}_2 \approx \frac{\hbar^2}{12 k_B T M \langle r_x^2 \rangle} \cdot \frac{\varepsilon}{1+\varepsilon} \quad \sim 10^{-5}$$

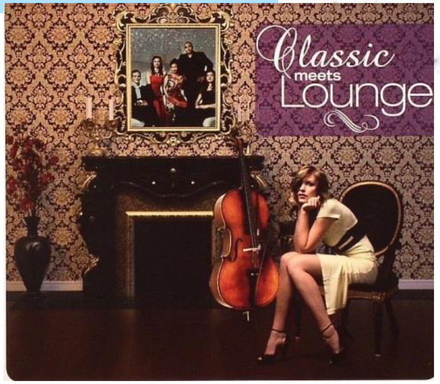
The observed large v_2 is indeed due to strong interactions.

Is quantum v_2 real in QGP?



K. M. O'Hara *et al.*, Science 298, 2179 (2002)

- It should be… but need experiment to verify (cold atom experiment)
- Cold atoms are "classical." Make it Quantum Mechanical.
- Would be neat to verify QM and uncertainty principle



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T~1μK~10^{-16}MeV	T~200 MeV
x~20μm, y~100μm	x~3fm,y~4fm
p~$(TM)^{1/2}$~10^{-6}MeV	p~200MeV
p quan~1/r~10^{-8}MeV	p quan~1/r~200MeV
E quan~$1/(mr^2)$~10^{-20}MeV	E quan~200 MeV
Negligible!	Comparable!
Cold atoms are **hot**, **classical.**	**QGP** is **cold**, **quantum mechanical.**

x10^{-4}

X10^{-2}

Kolb, Heinz, nucl-th/0305084; Lisa et al. New J. Phys. **13** (2011) 065006

Chiral magnetic effect

Symmetries and conservation laws

Symmetry	Micro. Conservation Law	Emergent Macro. Hydro
translational invariance	energy and momentum conserved	$\partial_\mu T^{\mu\nu} = 0$
phase invariance	charge conserved	$\partial_\mu J^{\mu} = 0$

WHAT ABOU "HALF"-SYMMETRY???
i..e ANOMALY?!
— classical symmetry that is broken in quantum theory

Slide stolen from Jinfeng Liao

Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

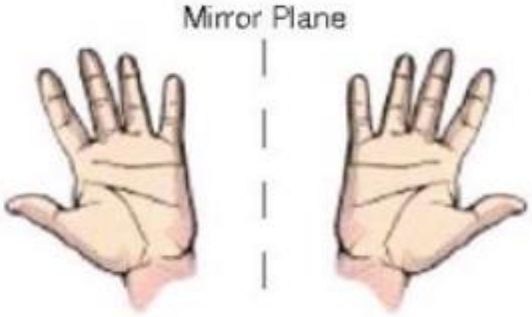
Classical symmetry:

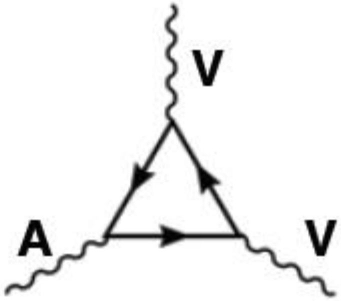
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

$$\mathcal{L} \to i\bar{\Psi}_L\gamma^\mu\partial_\mu\Psi_L + i\bar{\Psi}_R\gamma^\mu\partial_\mu\Psi_R$$

$$\Lambda_A : \Psi \to e^{i\gamma_5\theta}\Psi$$

$$\partial_\mu J_5^\mu = 0$$





Broken at QM level:

$$\partial_\mu J_5^\mu = C_A \vec{E}\cdot\vec{B}$$

$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$$

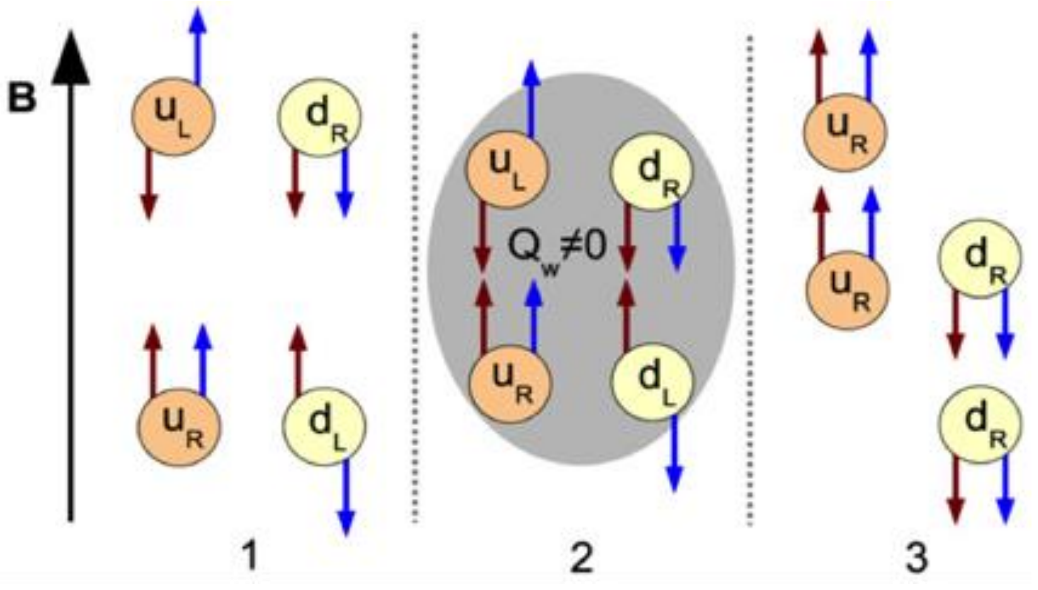
* C_A is universal anomaly coefficient

* Anomaly is intrinsically QUANTUM effect

Slide stolen from Jinfeng Liao

Chiral Magnetic Effect (CME)

D. Kharzeev, et al. NPA 803, 227(2008)

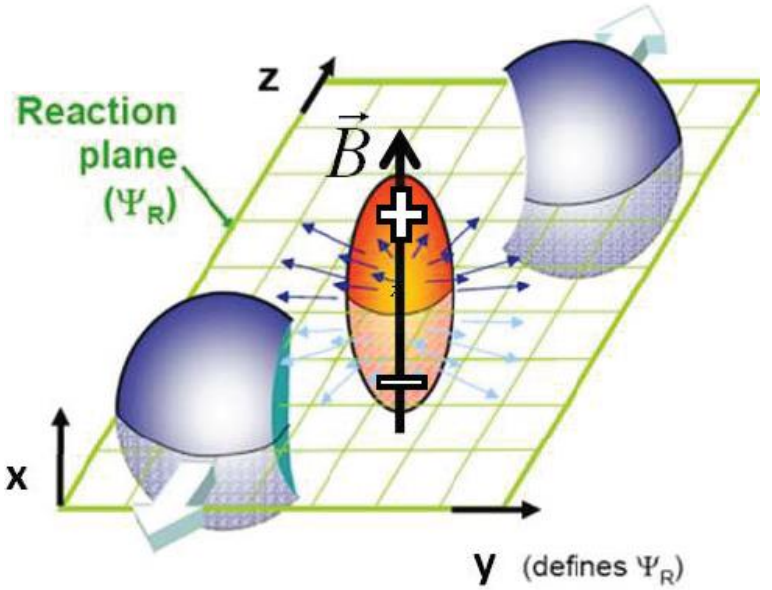


non-conservation of axial currents. Axial Ward-identity

$$\partial^\mu j^5_\mu = 2\sum_f m_f \langle \bar{\psi}_f i\gamma_5 \psi_f \rangle_A - \frac{N_f g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

$$Q_\mathrm{w} = \frac{g^2}{32\pi^2}\int \mathrm{d}^4x\, F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

$$(N_L - N_R)_{t=\infty} = 2N_f Q_\mathrm{w}$$

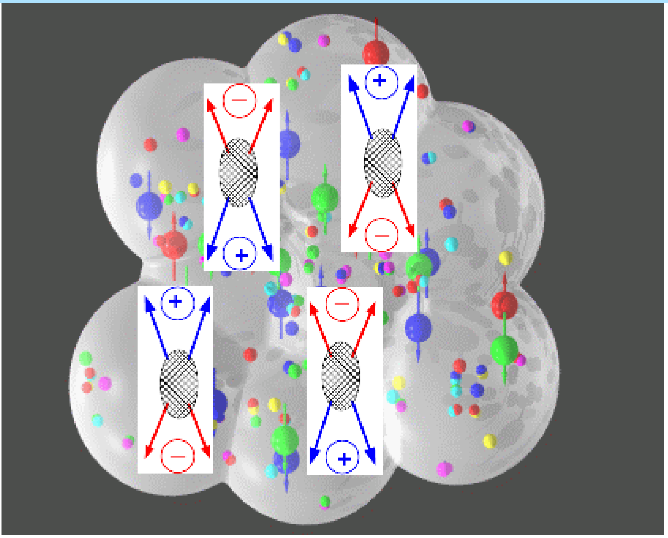


Peak magnetic field ~ 10^{15} T !

Electric charge separation alone the B field

$$\frac{dN_\pm}{d\phi} \propto 1 + 2a_\pm \cdot \sin\left(\phi^\pm - \Psi_{RP}\right)$$

Three-particle correlator observable



Kharzeev, PLB633:260 (2006)
Kharzeev, McLerran, Warringa, NPA803:227 (2008)

S. Voloshin, PRC 70 (2004) 057901

CME + P-odd domain → charge separation across RP

$$\frac{dN_\pm}{d\varphi} \propto 1 + 2v_1 \cos\varphi^\pm + 2a_\pm \cdot \sin\varphi^\pm + 2v_2 \cos 2\varphi^\pm + \ldots$$

A direct measurement of the *P*-odd *"a"* should yield *zero*

$$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \rangle =$$

$$\langle \cos(\varphi_\alpha - \psi_{RP}) \cos(\varphi_\beta - \psi_{RP}) \rangle - \langle \sin(\varphi_\alpha - \psi_{RP}) \sin(\varphi_\beta - \psi_{RP}) \rangle$$

$$= \langle v_{1,\alpha} v_{1,\beta} \rangle - \langle a_\alpha a_\beta \rangle$$

$$\gamma = \langle \cos(\varphi_\alpha + \varphi_\beta - \psi_{RP}) \rangle = \left[\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in} \right] - \left[\langle a_\alpha a_\beta \rangle + B_{out} \right]$$

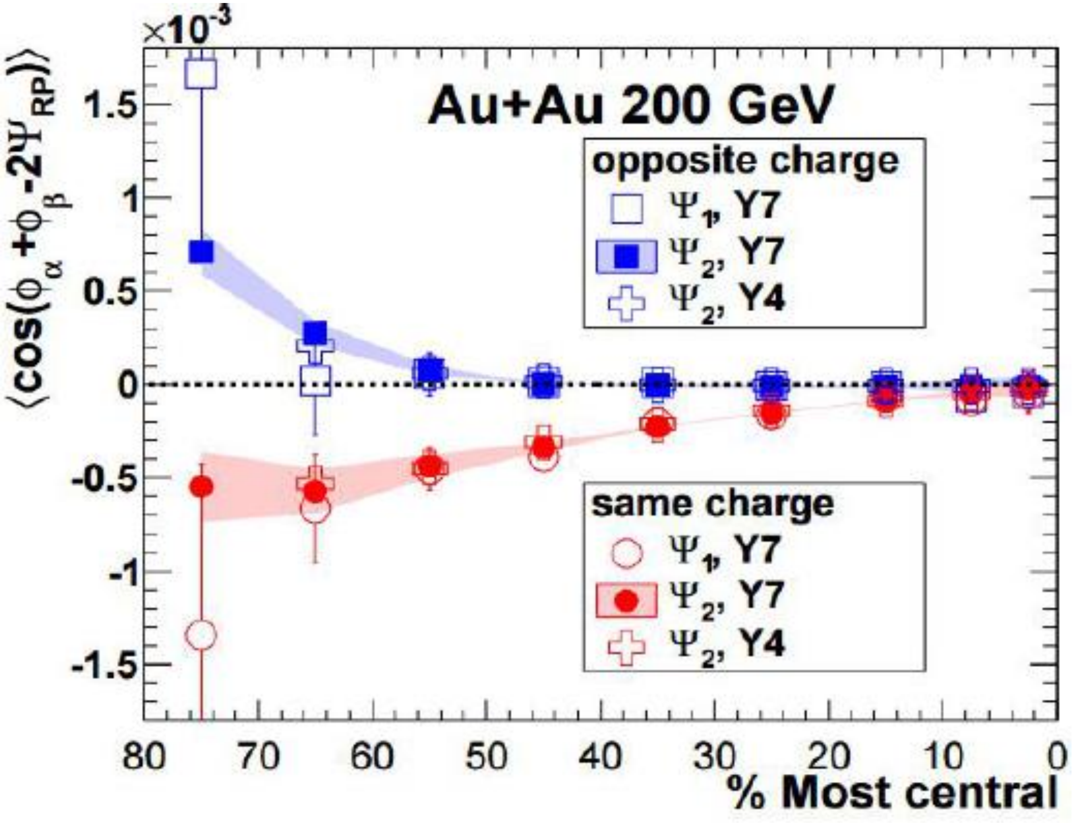
Directed flow: known to be small expected to be the same for SS and OS

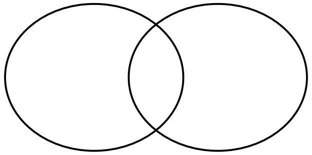
P-even quantity: what we're looking for; still sensitive to charge separation

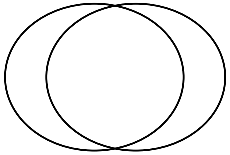
Non-flow/non-parity effects: The hope was that these cancel out

Charge “Separation” Signal

STAR collaboration, PRL 103(2009)251601; PRC 81(2010)54908; PRC 88 (2013) 64911





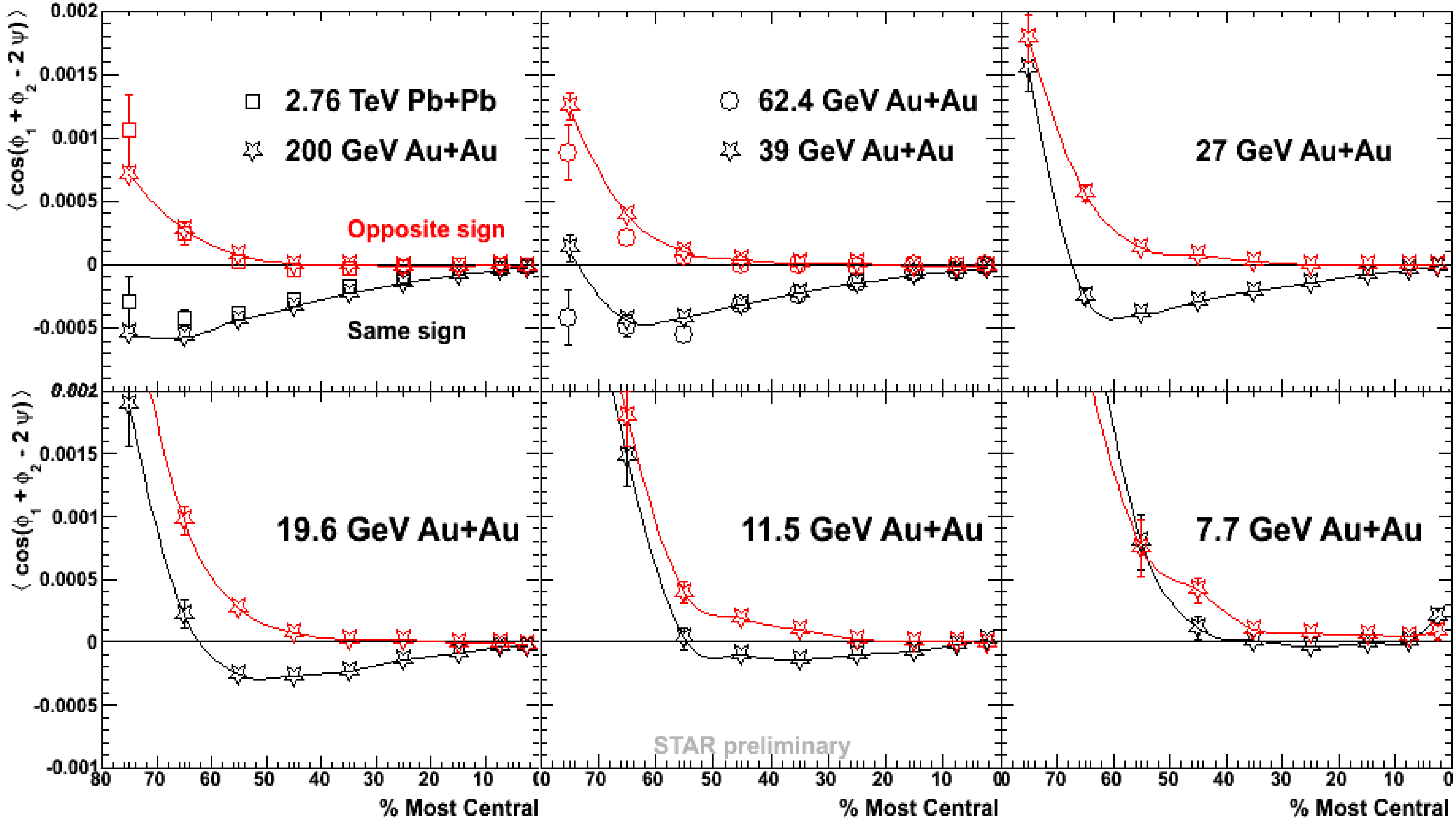


- Correlator indicates charge separation signal
- Confirmed with 1st-order EP (from spectator neutron v_1)

Beam Energy Scan data

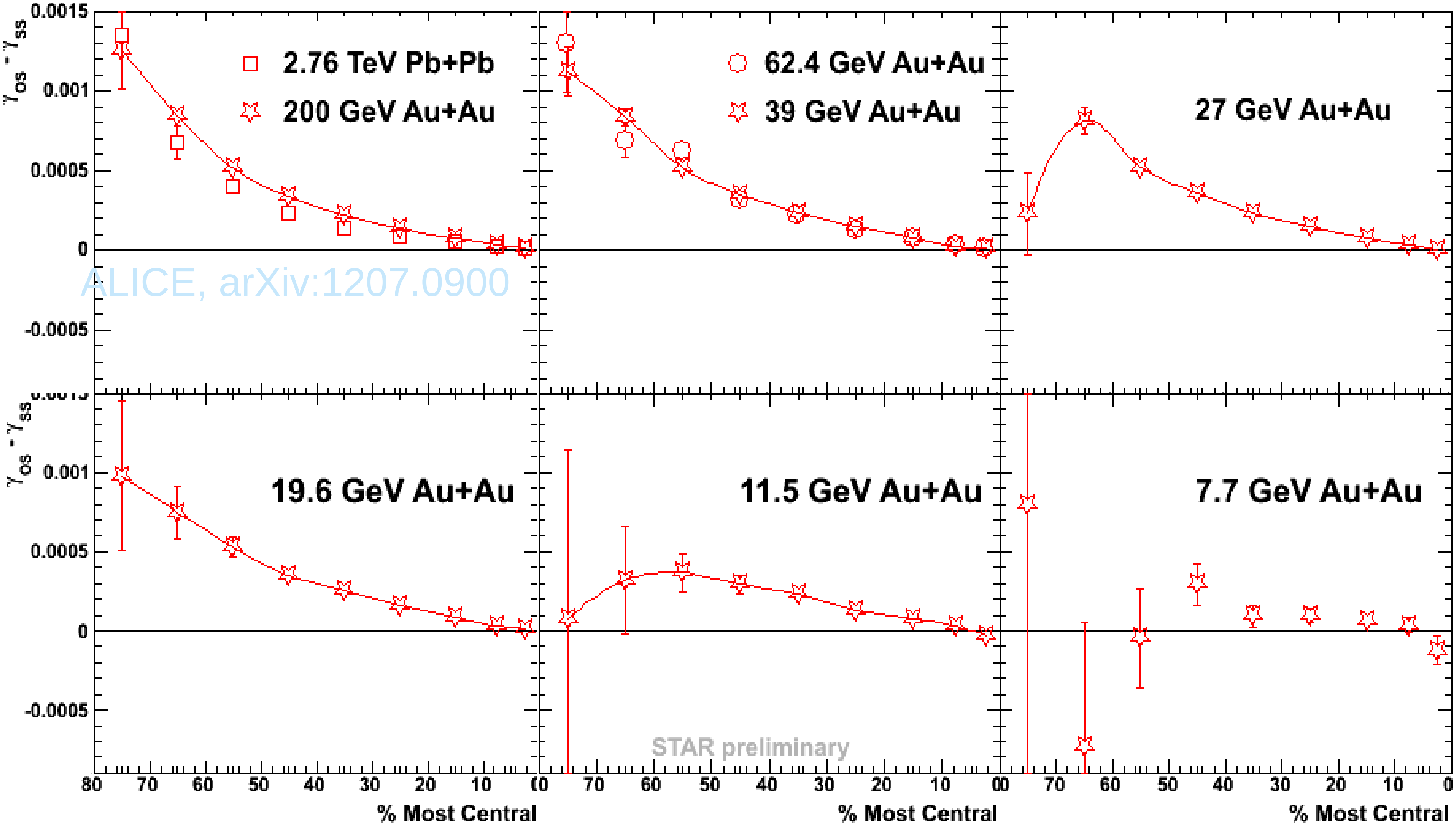
ALICE, arXiv:1207.0900

STAR, PRL 113 (2014) 052302



From 2.76 TeV to 7.7 GeV, changes start to show from the peripheral collisions.

Consider OS-SS to be signal...



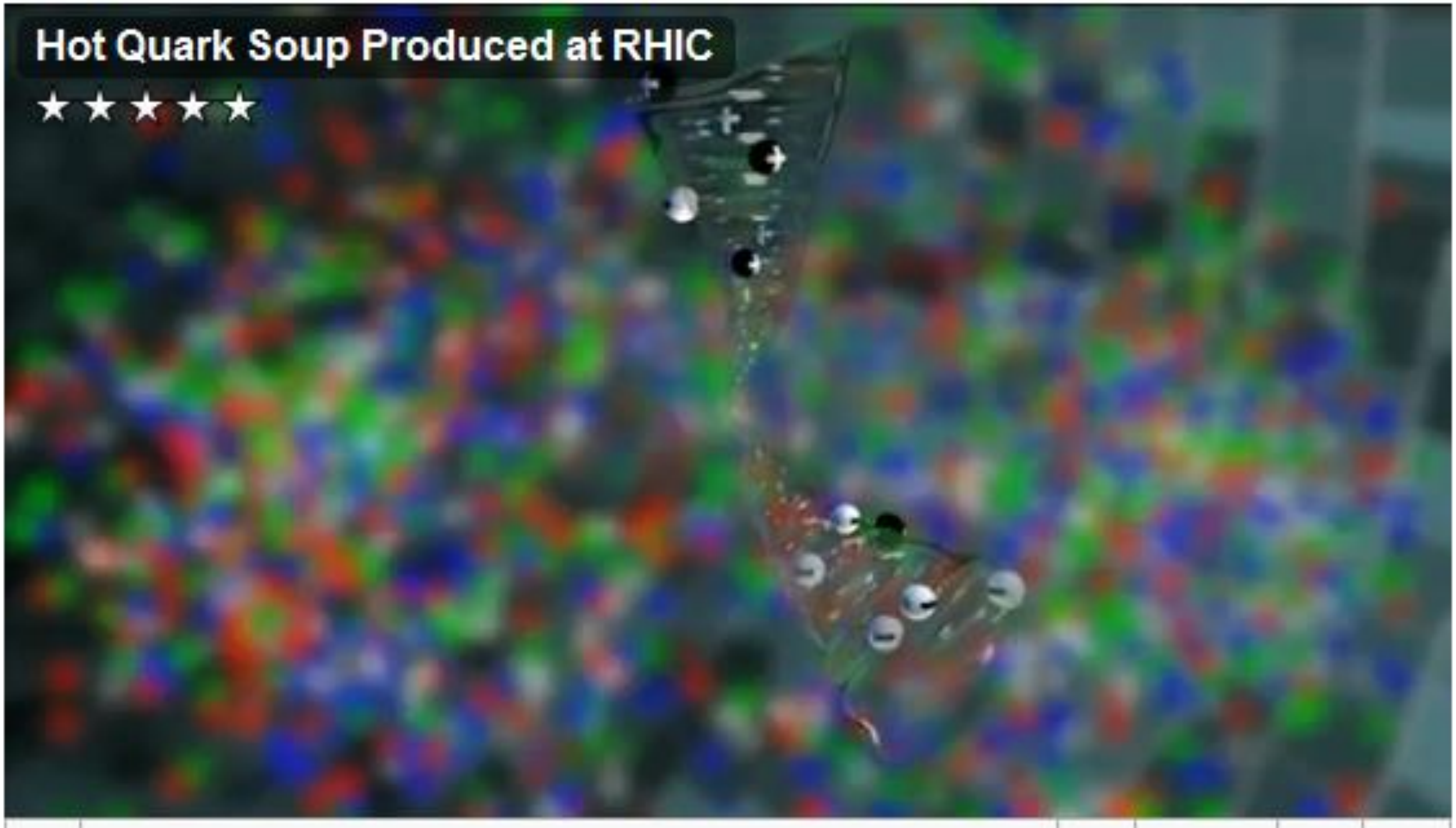
The signal seems to be disappearing at 7.7 GeV, but the statistical errors are large.

'Bubbles' of Broken Symmetry in Quark Soup at RHIC

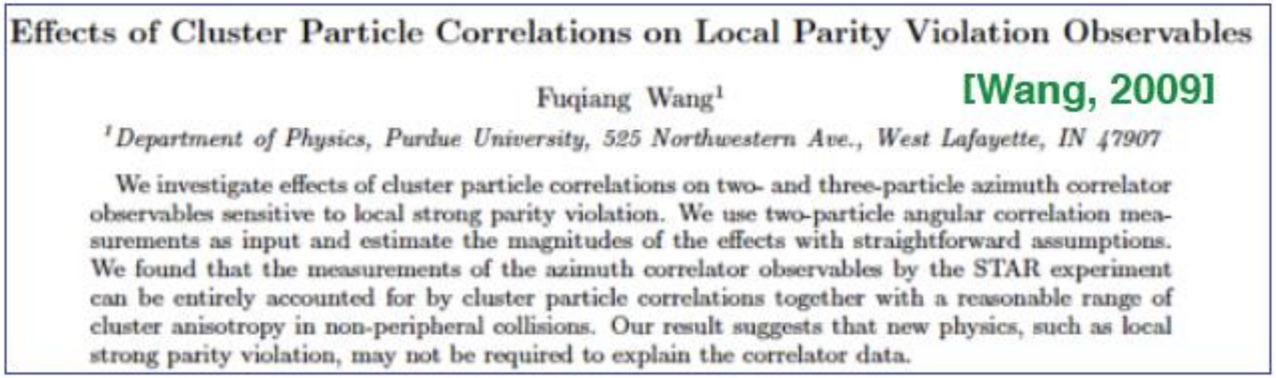
Data suggest symmetry may ‘melt’ along with protons and neutrons

February 15, 2010

UPTON, NY — Scientists at the Relativistic Heavy Ion Collider (RHIC), a 2.4-mile-circumference particle accelerator at the U.S. Department of Energy’s Brookhaven National Laboratory, report the first hints of profound symmetry transformations in the hot soup of quarks, antiquarks, and gluons produced in RHIC’s most energetic collisions. In particular, the new results, reported in the journal *Physical Review Letters*, suggest that "bubbles" formed within this hot soup may internally disobey the so-called "mirror symmetry" that normally characterizes the interactions of quarks and gluons.



Elliptic flow driven background



Effects of Cluster Particle Correlations on Local Parity Violation Observables

Fuqiang Wang[1]

[Wang, 2009]

[1] *Department of Physics, Purdue University, 525 Northwestern Ave., West Lafayette, IN 47907*

We investigate effects of cluster particle correlations on two- and three-particle azimuth correlator observables sensitive to local strong parity violation. We use two-particle angular correlation measurements as input and estimate the magnitudes of the effects with straightforward assumptions. We found that the measurements of the azimuth correlator observables by the STAR experiment can be entirely accounted for by cluster particle correlations together with a reasonable range of cluster anisotropy in non-peripheral collisions. Our result suggests that new physics, such as local strong parity violation, may not be required to explain the correlator data.

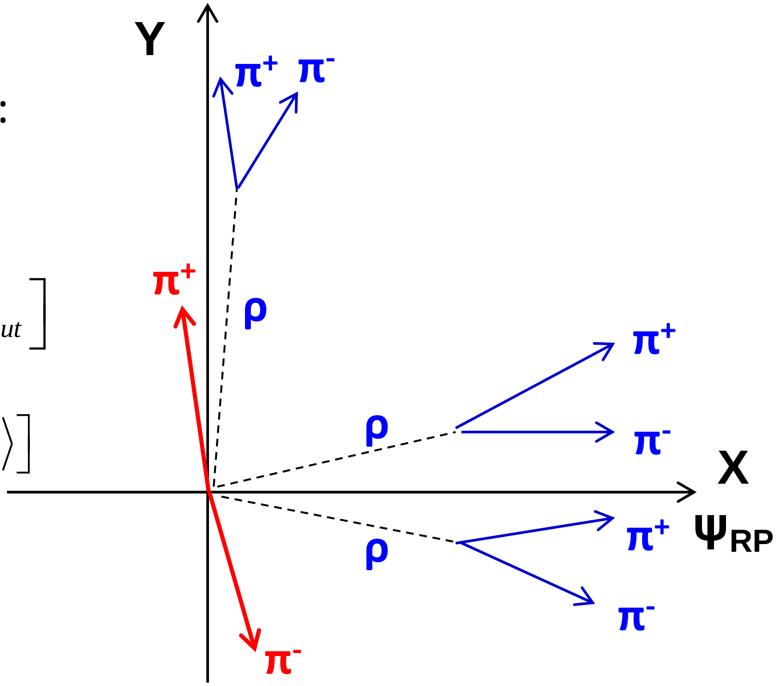
As pointed out at the same time of the STAR publications, the backgrounds may not be negligible:
[2009~2010] Wang; Bzdak, Koch, Liao; Pratt; …

$$\gamma = \left\langle \cos(\varphi_\alpha + \varphi_\beta - \psi_{RP}) \right\rangle = \left[\left\langle v_{1,\alpha} v_{1,\beta} \right\rangle + B_{in} \right] - \left[\left\langle a_\alpha a_\beta \right\rangle + B_{out} \right]$$

$$= (1-f)\left[\left\langle \cos(\varphi_\alpha - \psi_{RP}) \cos(\varphi_\beta - \psi_{RP}) \right\rangle - \left\langle \sin(\varphi_\alpha - \psi_{RP}) \sin(\varphi_\beta - \psi_{RP}) \right\rangle \right]$$

$$+ f \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \cos 2(\varphi_\rho - \psi_{RP}) \right\rangle$$

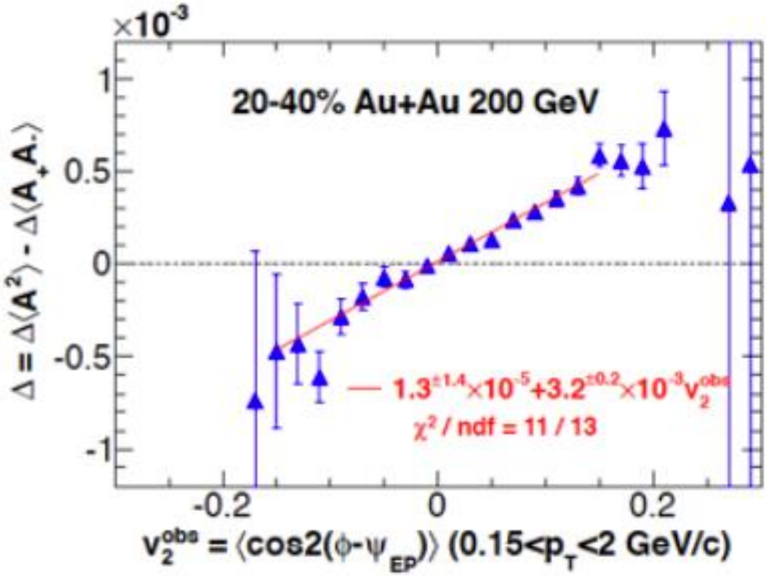
$$= (1-f)\left[\left\langle v_{1,\alpha} v_{1,\beta} \right\rangle - \left\langle a_\alpha a_\beta \right\rangle \right] + f \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \right\rangle v_{2,\rho}$$



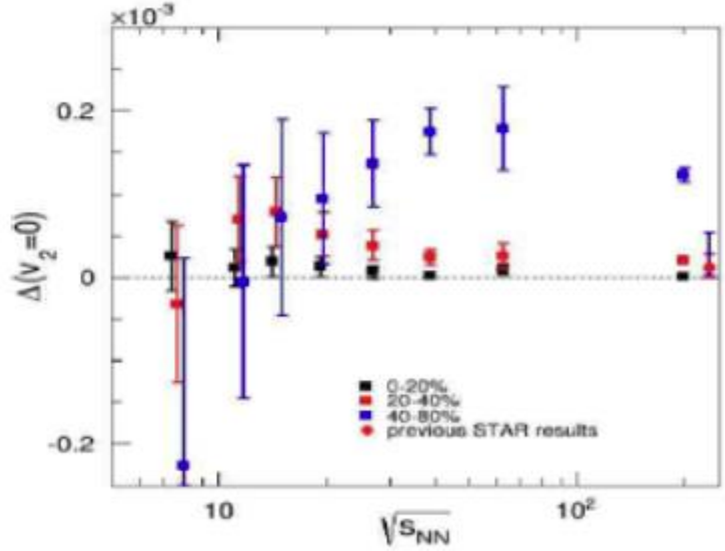
Suppressing flow-driven background

Clearly there are flow driven background contributions:
need to develop ways to suppress such backgrounds!

Event shape selection method



[STAR2013, by Purdue group]



[STAR2015@QM15]

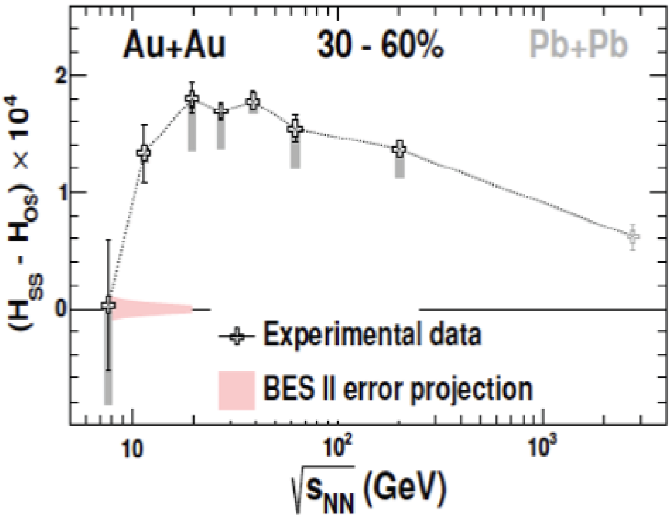
The imfamous kappa parameter

Making sense of data in a two-component picture

[Bzdak, Koch, JL, 2012; Blocynski, Huang, Zhang, JL, 2013]

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{\mathrm{RP}}) \rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$

H: “CME Signal”
F: “Flow Driven Background”



[STAR PRL 2014]

[also measured by ALICE@LHC]

$$H_{CME} \to 2a_1^2$$

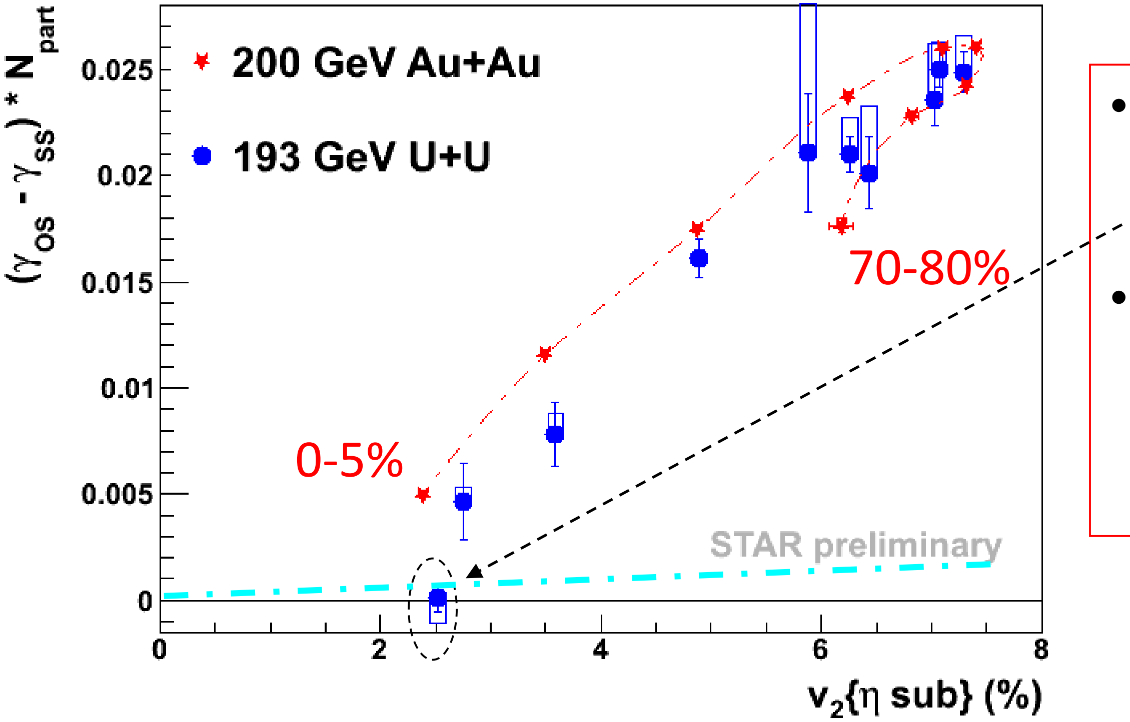
Encouraging experimental evidence for CME in QGP — can we quantitatively compute CME signal?

$$\kappa = \frac{\gamma_{bkgd}}{v_2 F} = \frac{\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \rangle_{bkgd}}{\langle \cos 2(\varphi_\beta - \psi_{RP}) \rangle \langle \cos(\varphi_\alpha - \varphi_\beta) \rangle} = ?$$
$$F \equiv \langle \cos(\varphi_\alpha - \varphi_\beta) \rangle$$

$$\kappa = \frac{\langle \cos(\varphi_\alpha - \varphi_\beta) \cos 2(\varphi_\beta - \psi_{RP}) \rangle_{bkgs}}{\langle \cos(\varphi_\alpha - \varphi_\beta) \rangle \langle \cos 2(\varphi_\beta - \psi_{RP}) \rangle} = \frac{\gamma_{bkgd}}{v_2 F} = 1-2?$$

$$\kappa = \frac{\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \cos 2(\varphi_\rho - \psi_{RP}) \rangle_{bkgd}}{\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \rangle \langle \cos 2(\varphi_\rho - \psi_{RP}) \rangle} = \frac{\gamma_{bkgd}}{v_{2,\rho} F_\rho} = 1-2$$
$$F_\rho \equiv \langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_\rho) \rangle$$

LPV in UU



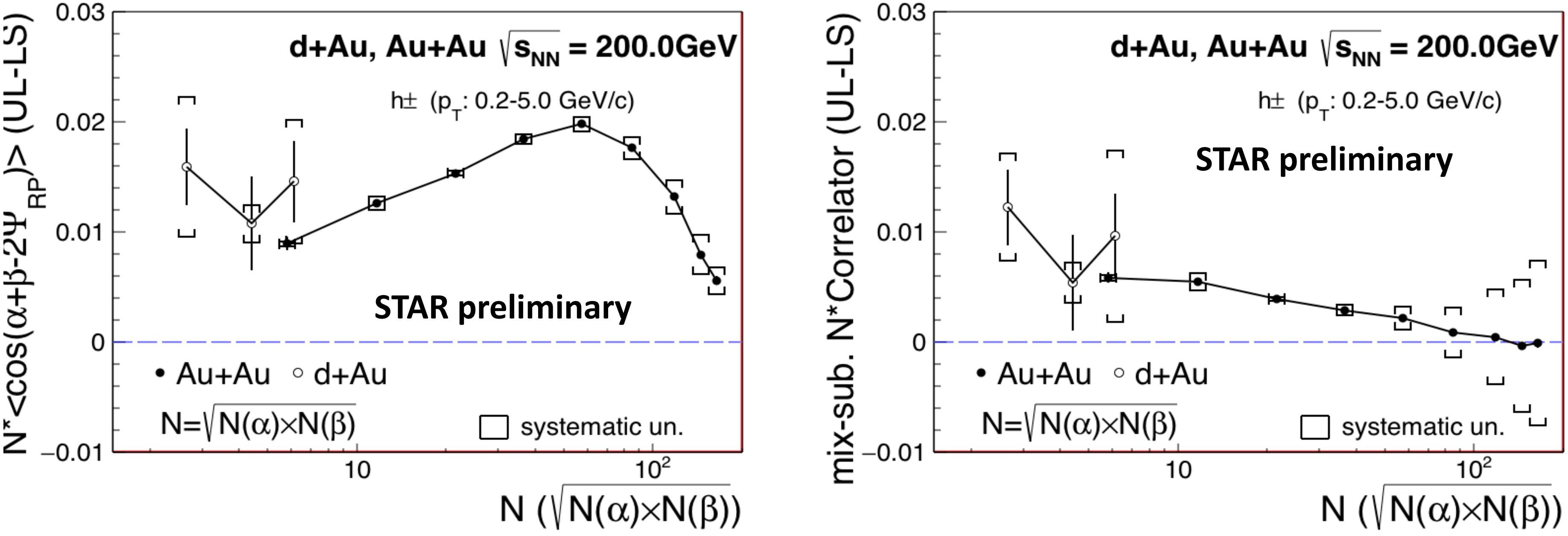
- A dedicated trigger selected events with 0-1% spectator neutrons.
- With the magnetic field suppressed, the charge separation signal disappears (while v_2 is still ~ 2.5%).

Logic: With finite v_2, there should be no background, but signal is zero → v_2-bkgd model is wrong → signal=0 is actually expected from CME picture → the finite signals in non-central collisions likely come from CME because v_2-bkgd model can be wrong there too.

What I think is going on: v_2 is $v_2\{2\}$, dominated by fluctuations in ultracentral collisions. The bkgd source v_2 is likely uncorrelated with the $v_2\{2\}$ from final-state particles.

Small systems

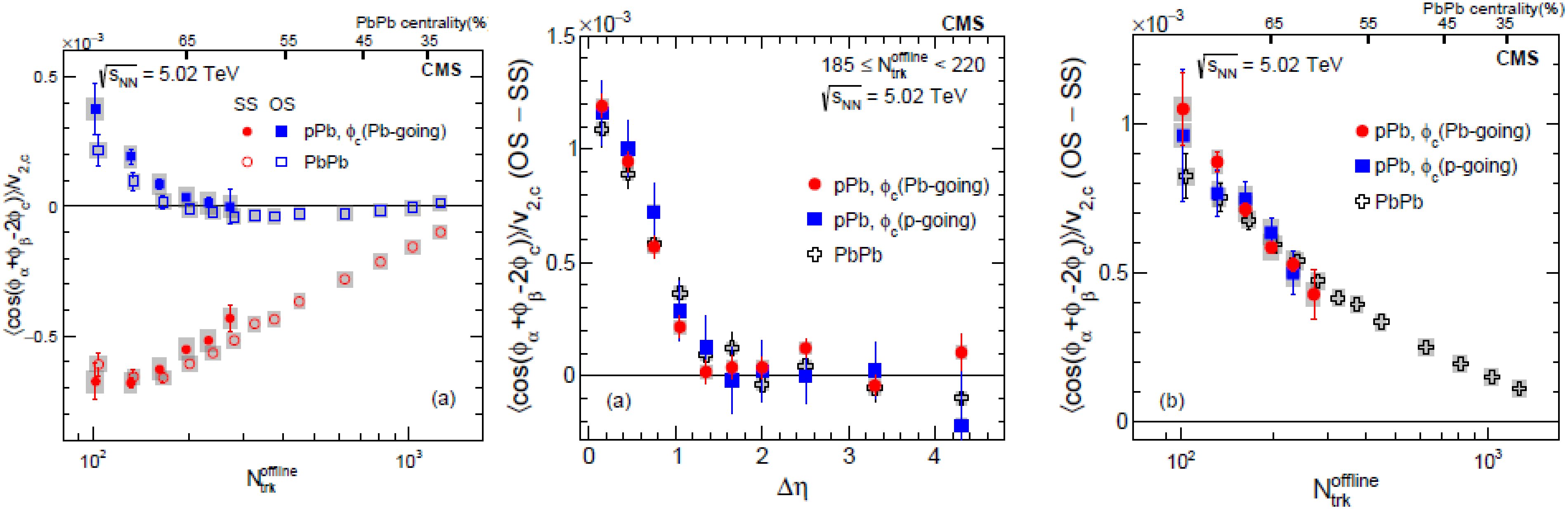
Jie Zhao for STAR, ISMD2016



- At same multiplicity d+Au and Au+Au show similar charge separation
- More data needed for d+Au collisions.

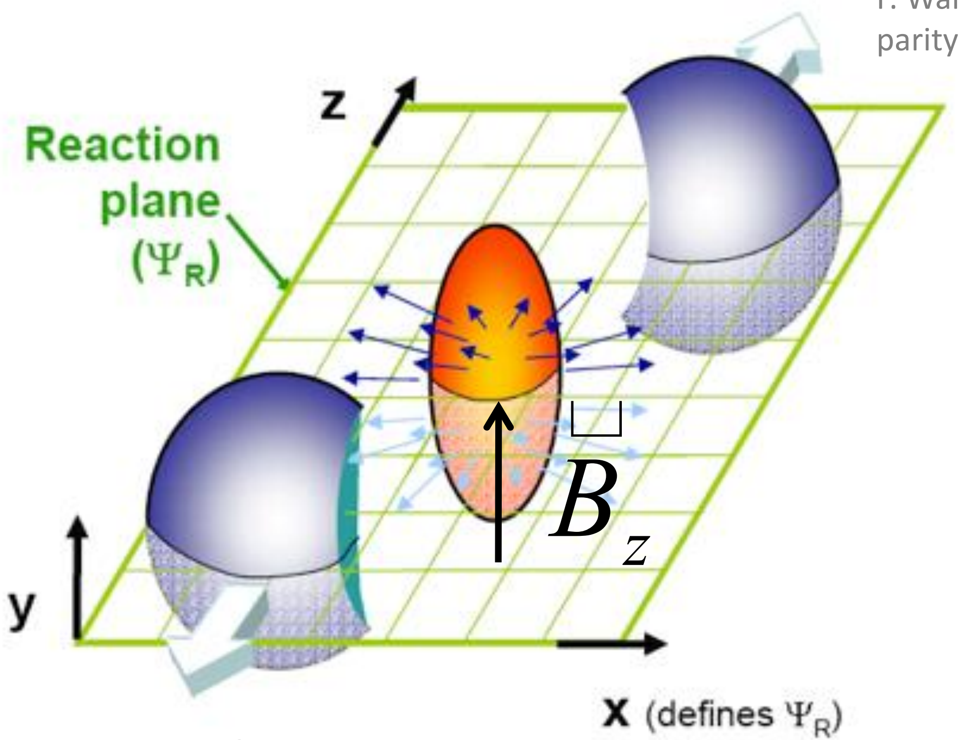
LHC/CMS results

CMS, arXiv:1610.00263

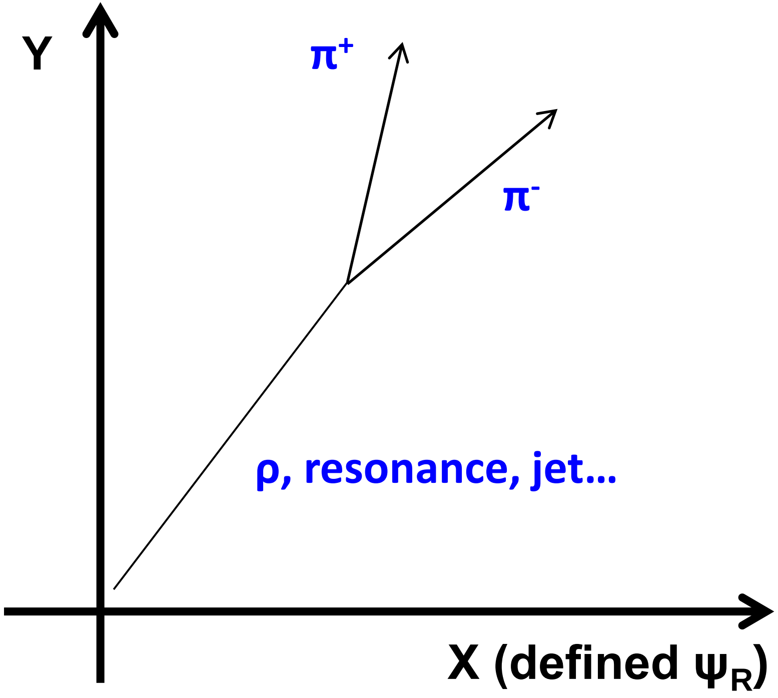


The difference between same and opposite sign particles as functions of $\Delta\eta$ and multiplicity is found to agree for pPb and PbPb collisions, possibly indicating a common underlying mechanism that generates the observed correlation. These results challenge the CME interpretation for the observed charge-dependent azimuthal correlations in nucleus-nucleus collisions at RHIC and the LHC.

Resonances and Jets effect



F. Wang, "Effects of cluster particle correlations on local parity violation observables", Phys.Rev.C 81 (2010) 064902



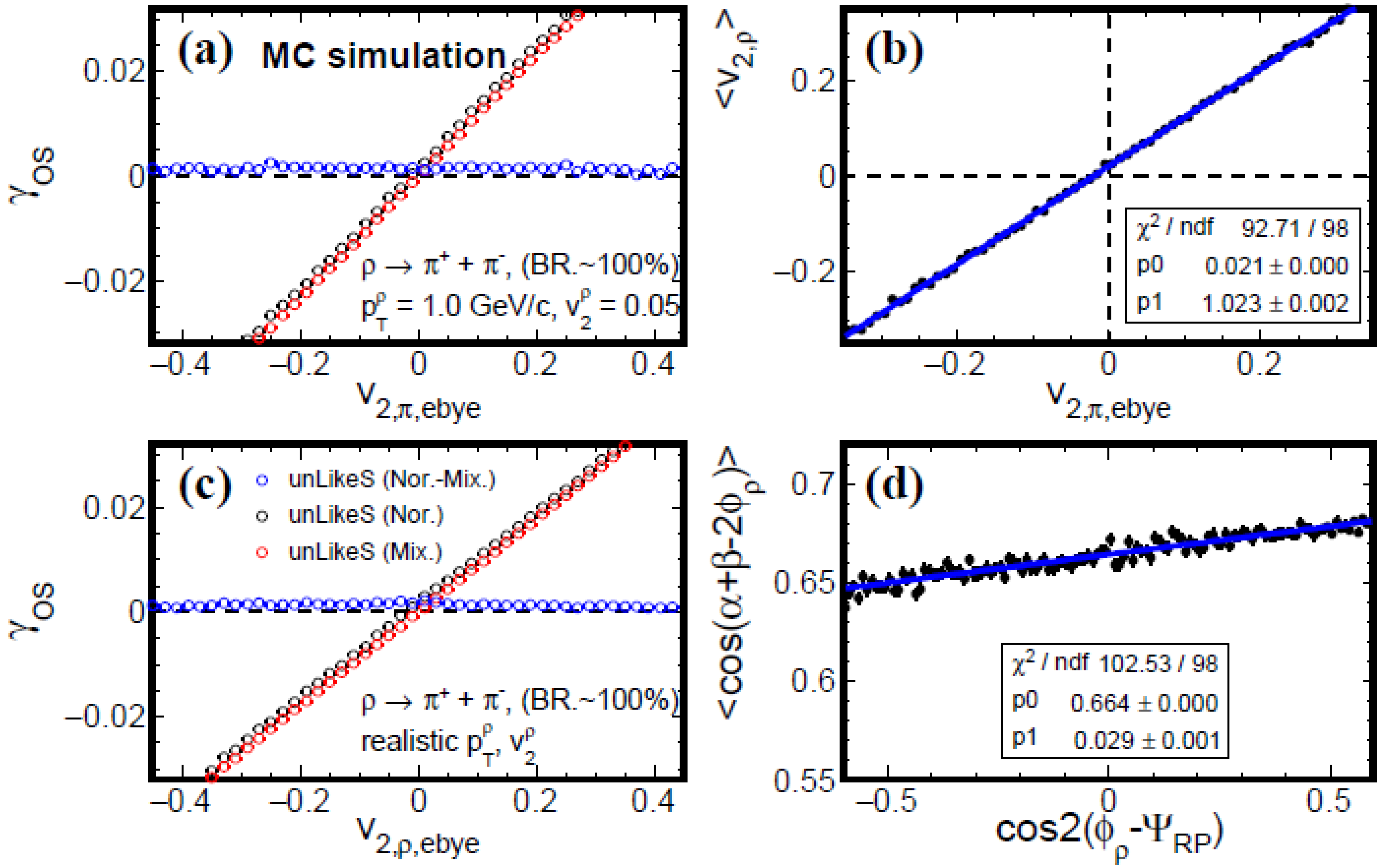
Y -> α + β

$$\langle cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle \sim \langle cos(\Delta\phi)\rangle * \langle cos2(\phi_\gamma - \Psi_{RP})\rangle$$

- Flow -> might be dominant source of background for CME signals
- Flowing clusters produce CME like signal

Event shape selection method does not completely eliminate background

Wang, Zhao, arXiv:1608.06610



Resonances decay simulation

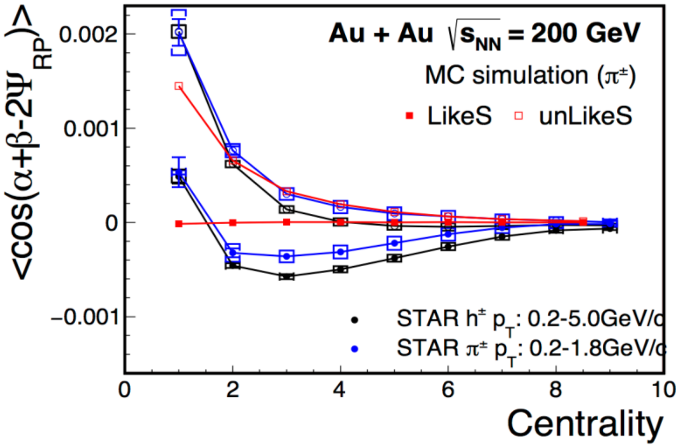
	dN/dy	B.R.
$\rho \to \pi^+ + \pi^-$	~16.7	~100%
$\eta \to \pi^+ + \pi^- + \pi^0$	~7.86	~22.9%
$\eta \to \pi^+ + \pi^- + \gamma$	~7.86	~4.2%
$\omega \to \pi^+ + \pi^- + \pi^0$	~9.87	~89.2%
$\omega \to \pi^+ + \pi^-$	~9.87	~1.5%

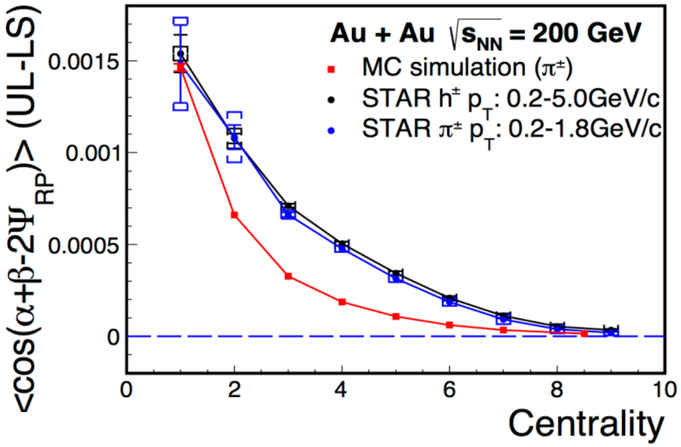
STAR, Phys. Rev. C 92, 024912 (2015)

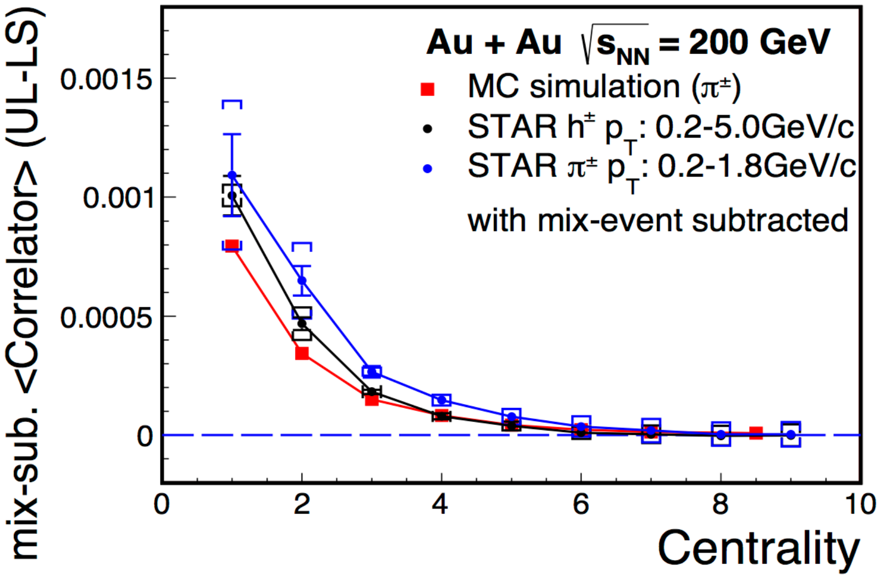
- ρ/inclusive π ratio from STAR 40-80% ~0.169 for all centrality,
- fixed ρ/η, ρ/ω ratio from the MB data.
- consider ρ, η and ω to π contributions, fixed ρ/η, ρ/ω ratio.
- total resonance/"direct" π ~0.39

Resonances decay simulation

Fuqiang Wang, Jie Zhao, arXiv:1608.06610





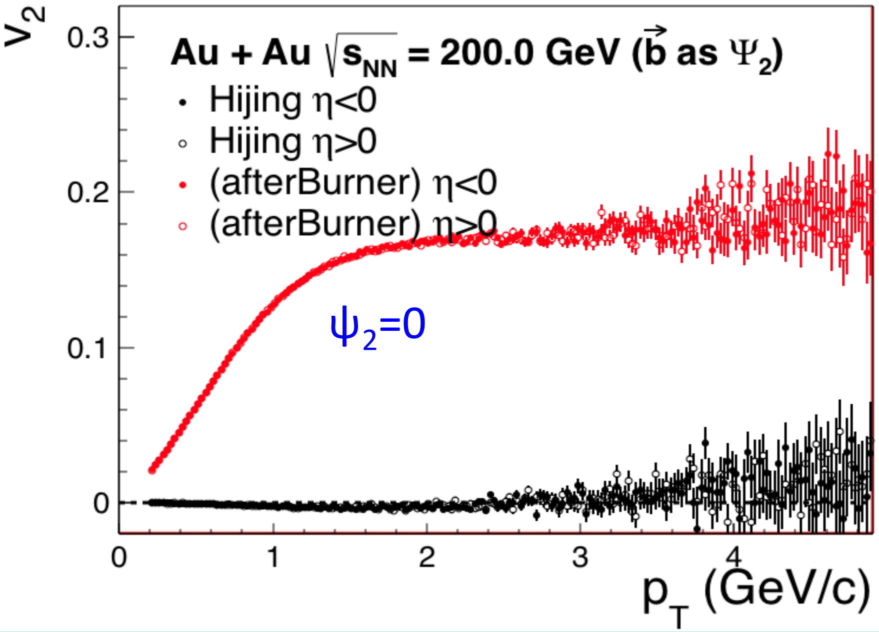


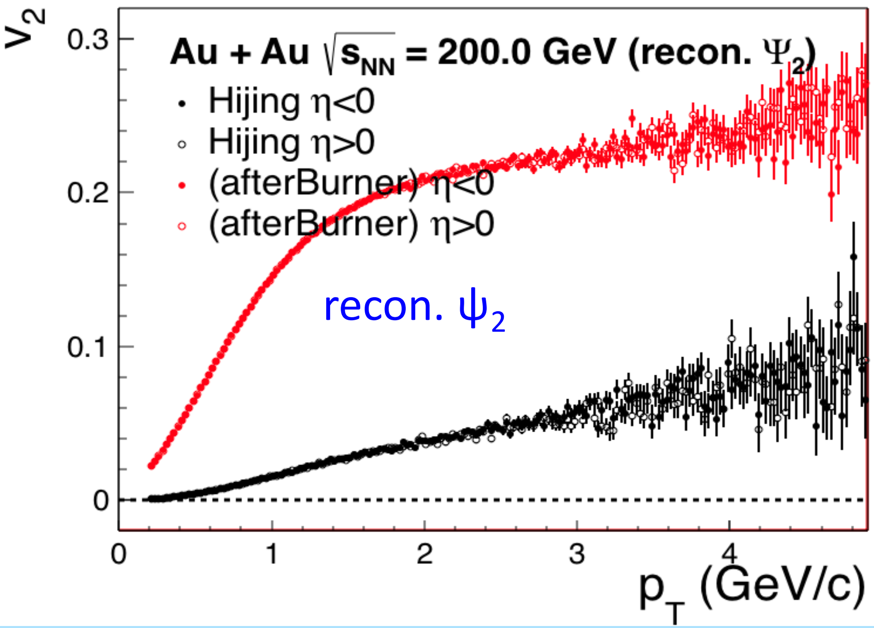
Jet effects with Hijing simulation

- Hijing with b: 9-14fm
- Final state pi, k, p reconstructed event plane,
  or impact parameter direction as event plane (ψ_2=0).
- afterburner flow with respect to the
  event plane

$$\delta = -\frac{v_2^{\mathrm{ini}}\{\mathrm{PP}\}\sin 2\left(\phi_{\mathrm{ini}} - \Psi_2^{\mathrm{PP}}\right)}{1 + 2v_2^{\mathrm{ini}}\{\mathrm{PP}\}\cos 2\left(\phi_{\mathrm{ini}} - \Psi_2^{\mathrm{PP}}\right)}.$$

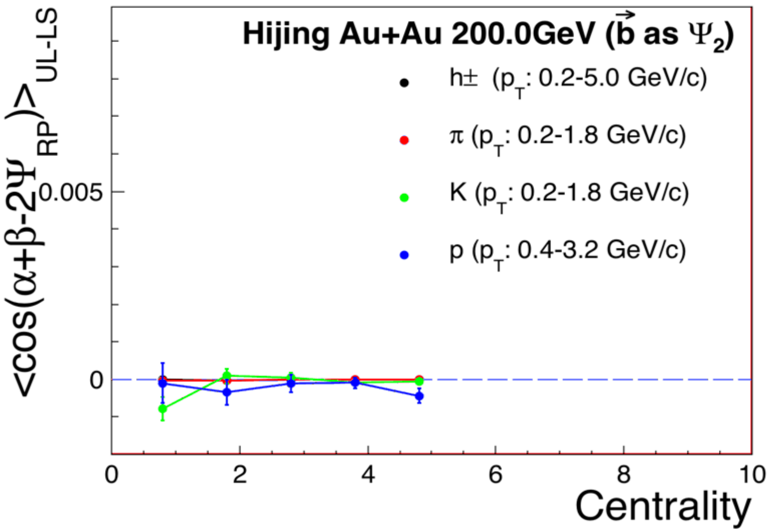
Liang Zhang, Feng Liu, Fuqiang Wang, Phys. Rev. C 92, 054906 (2015)

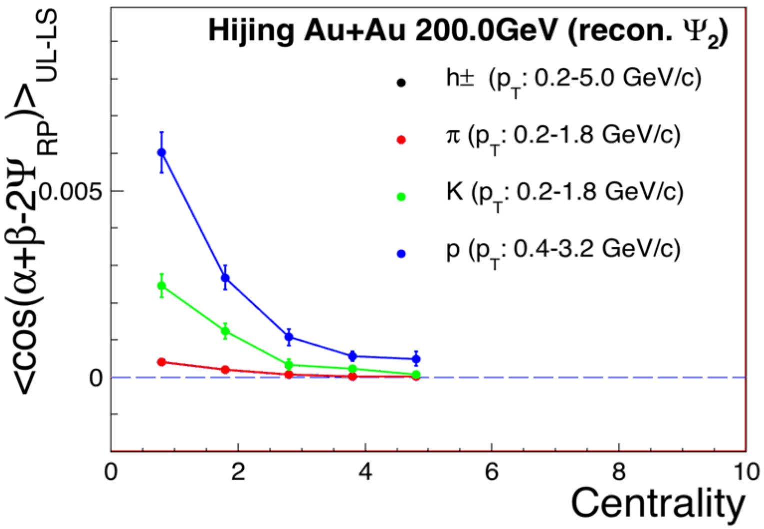




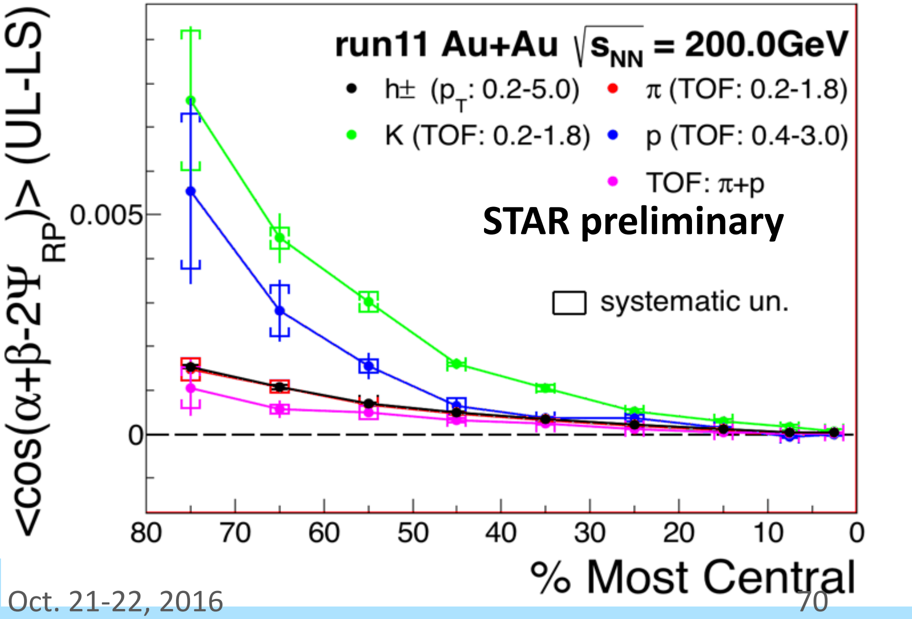
Jet effects with Hijing simulation

Jie Zhao, Fuqiang Wang (Hard Probes 2016)





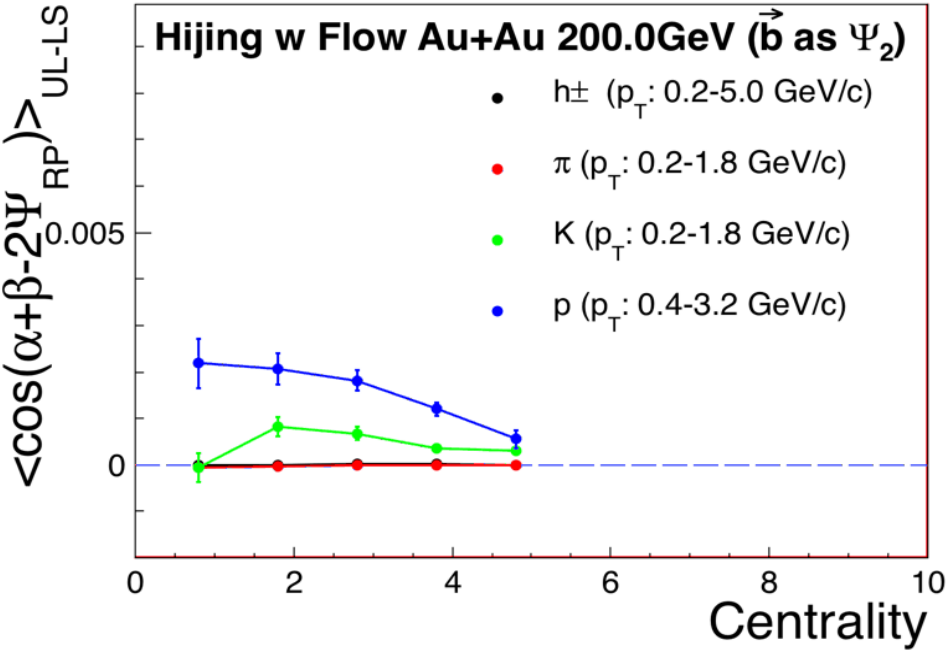
- The charge separation signal is zero with default Hijing and the ture event plane.
- The charge separation signal with reconstructed event plane in Hijing is comparable to experimental data.

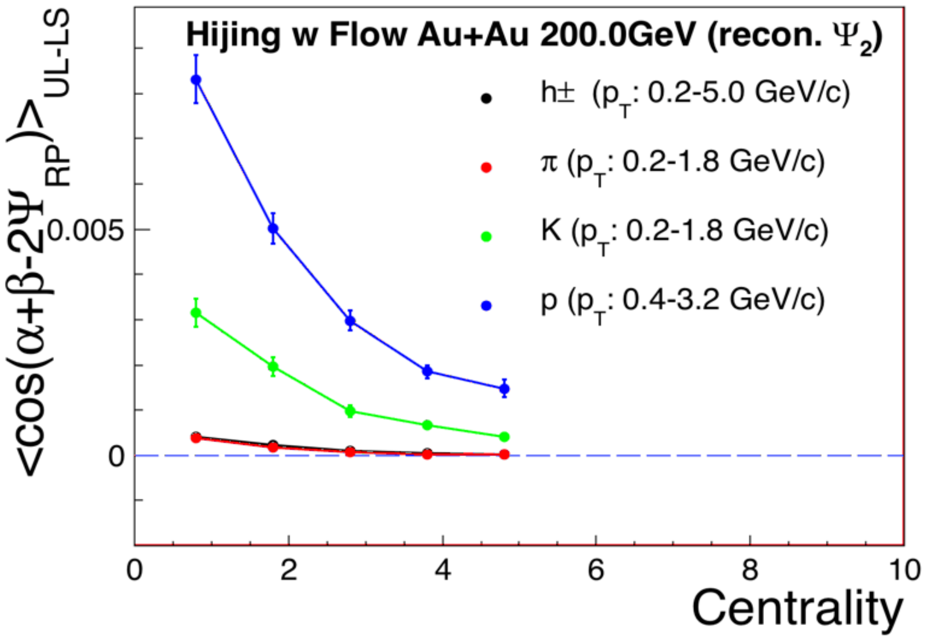


Jet effects with Hijing simulation

afterburner flow effect

Jie Zhao, Fuqiang Wang (Hard Probes 2016)





- With flow afterburner, the charge separation signal increases.
- The results indicate that jets can mimic a CME signal.

Final remarks

- The more I think, the more skeptical I am about our established paradigm.

- What have we learned from heavy ion collisions?
  Spontaneously, I can give you a long list of findings.
  What *fundamental* physics have we learned?
  I cannot give you a clear answer.

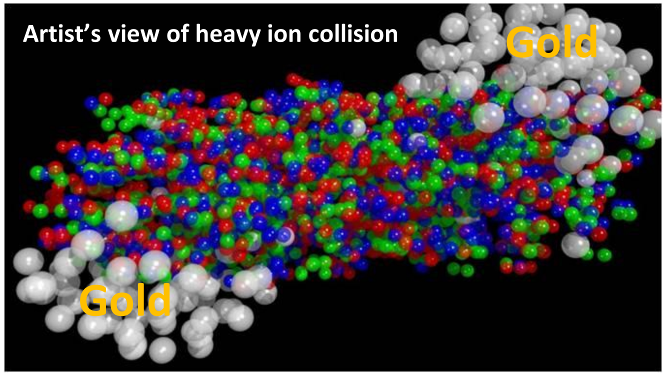
- We must be self critical. We must ask hard questions.
  We must think out of the box.

Where we are?

- Where we are, on the way to look for the QGP?
- Where to go, for more concrete conclusion on QGP?

- What fundamental knowledge will we contribute?

Fundamental physics we can contribute



Emergent phenomenon can be highly nontrivial at various levels, each with its own principles. Understanding these are NO LESS fundamental than the basic laws: "More is different"!

More is different! *P. W. Anderson*

High energy nuclear physics
nucleus-nucleus collision
Many body physics
Nuclear Matter

High energy Nuclear Physics: Condensed Matter physics of QCD

F. Wilczek @ QM2014

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

It *embodies* many deep aspects of relativistic quantum field theory (confinement, asymptotic freedom, anomalies/instantons, spontaneous symmetry breaking ...)