Heavy Ions

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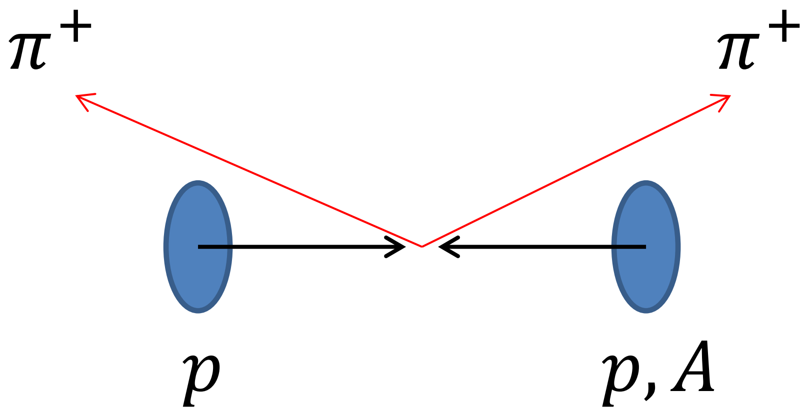
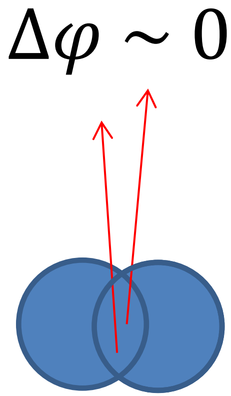
Collectivity in small systems
QCD critical point

Discovery at the LHC

proton-proton, $\sqrt{s} = 7000$ GeV

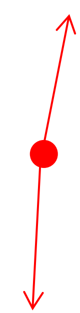
proton-lead, $\sqrt{s} = 5020$ GeV



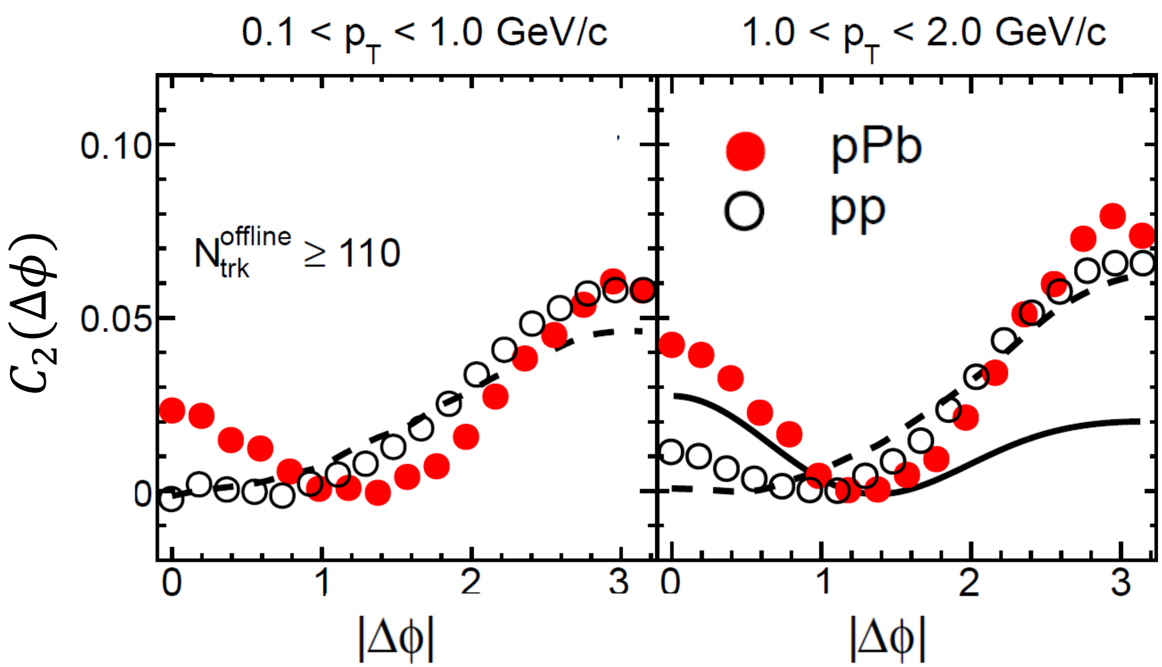


Particles with large rapidity separation prefer similar azimuthal angles (collimation)!

Back-to-back contribution also present (jets, obvious)



Experimental data (sample)



The effect is larger in p+Pb than p+p collisions — at the same multiplicity in $|\eta| < 2.4$ and $p_t > 0.4$ GeV

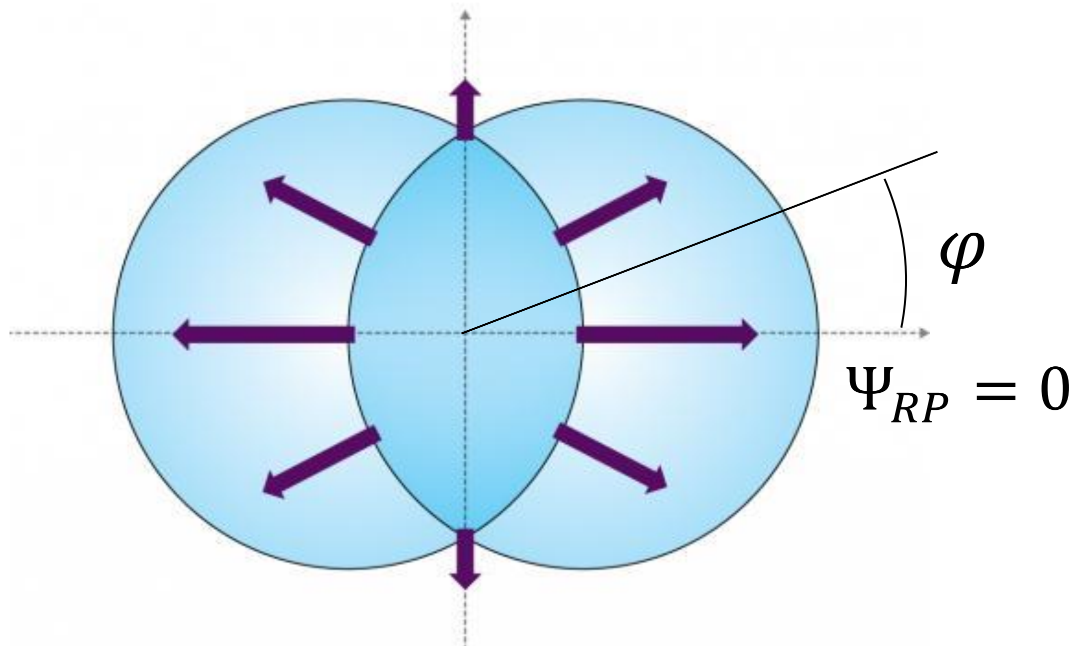
The more particles the stronger the effect — not shown here

CMS Coll., JHEP 1009 (2010) 091; PLB 718 (2013) 795
ALICE Coll., PLB 719 (2013) 29
ATLAS Coll., PRL 110, 182302 (2013)
PHENIX Coll., PRL 111, 212301 (2013), d+Au at 200 GeV

Elliptic flow

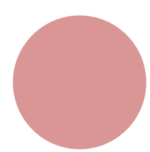
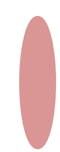
J.-Y. Ollitrault, PRD 46 (1992) 229

transverse plain of a heavy-ion collision



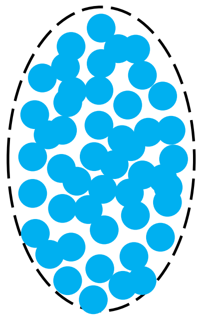
azimuthal angle

$$\frac{dN}{d\varphi} \sim 1 + 2\,\boldsymbol{v_2}\cos(2\varphi - 2\Psi_{RP}) + \cdots$$

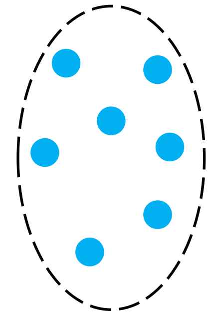
Hydrodynamics $v_2^2 \sim \epsilon_2^2$  $\epsilon_2 \approx 0$  $\epsilon_2 \approx 1$

λ – mean free path

L – characteristic length scale



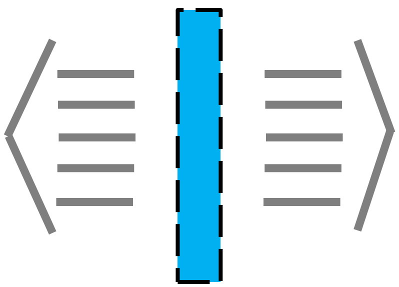
$\frac{\lambda}{L} \ll 1$

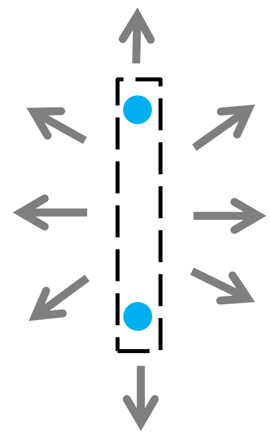


$\frac{\lambda}{L} \sim 1$

described by fluid dynamics

described by statistical mechanics



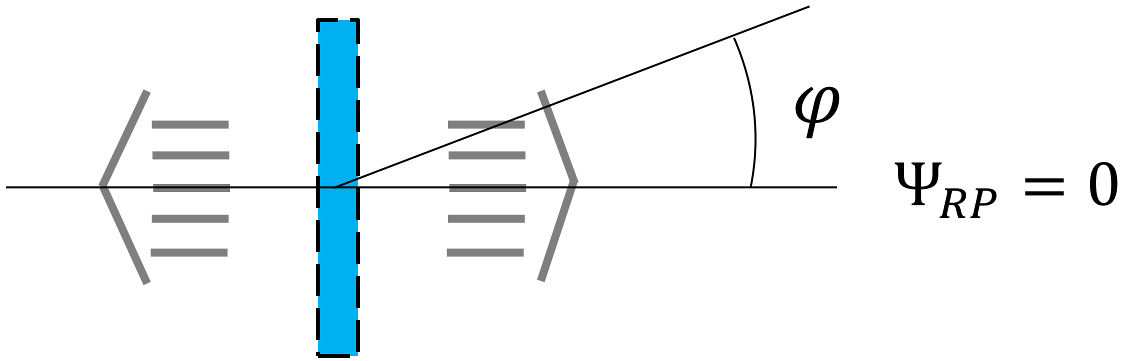


flow is anisotropic

"flow" is mostly isotropic

$v_2 = 0$

Let us consider an extreme case, particles only at 0 and π



There are obvious two-particle correlations

after integrating over Ψ_{RP}

$$\varphi_1 - \varphi_2 = 0 \quad \text{or} \quad \varphi_1 - \varphi_2 = \pi$$

2-particle correlation function is peaked at 0 and π and has minimum at $\pi/2$. For real v_2 it is $\cos(2[\varphi_1 - \varphi_2])$

There are also **multi-particle** correlations

Multi-particle correlations

N.Borghini, P.M.Dinh, J.-Y.Ollitrault, PRC 63 (2001) 054906

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

$$= \left\langle v_2^2 \right\rangle + c_2$$

c_m is non-flow

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

$$= -\langle v_2^4 \rangle + 2\left\langle v_2^2 \right\rangle^2 + c_4$$

if in each event $v_2 = \overline{v_2}$:

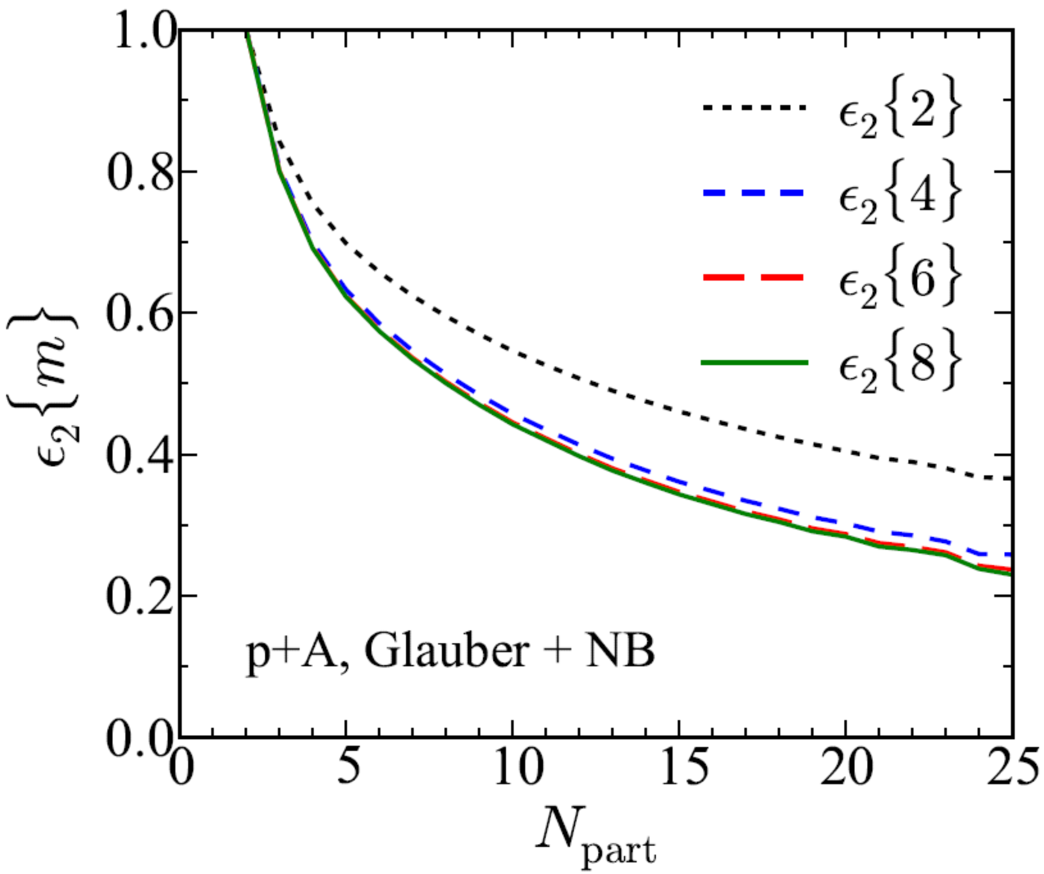
$$v_2\{2\} = \overline{v_2}$$

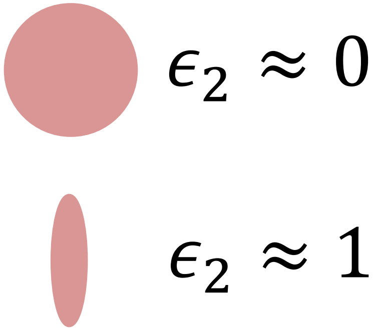
$$v_2\{m\} = \overline{v_2}$$

here $c_m = 0$

p+A, Glauber MC

for many other implementations
it looks similar



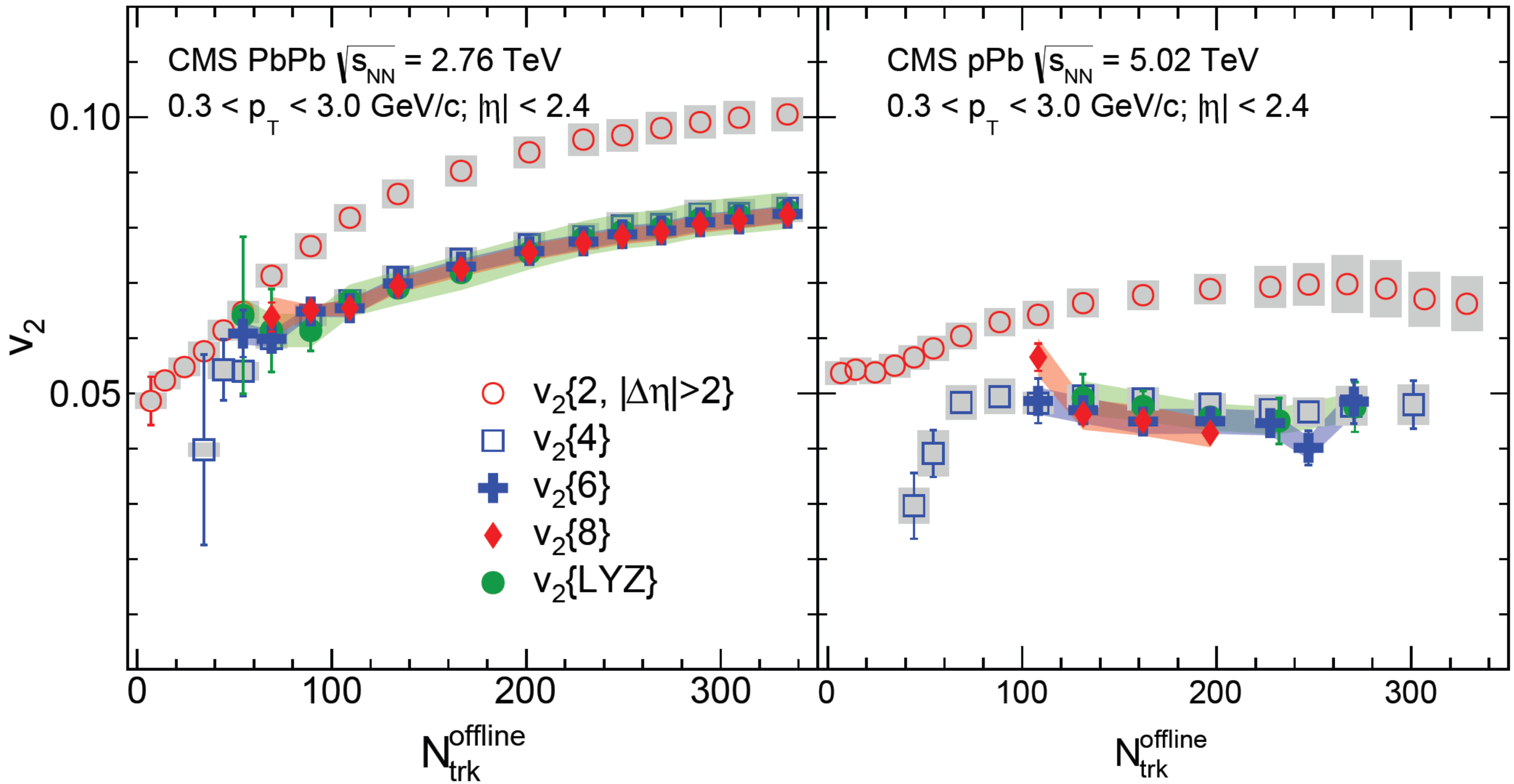


$$\left\langle \epsilon_2^{2n} \right\rangle = \frac{n! \lim\limits_{z\to 0} \frac{d^n}{dz^n} \left\langle I_0\left(2\sqrt{z} r^2\right)\right\rangle^N}{\lim\limits_{z\to 0} \frac{d^{2n}}{dz^{2n}} \left\langle e^{-r^2 z}\right\rangle^N}$$

AB, P. Bozek, L. McLerran, NPA 927 (2014) 15
L. Yan, J.-Y. Ollitrault, PRL 112 (2014) 082301
AB, V. Skokov, NPA 943 (2015) 1

CMS data

CMS Coll., PRL 115, 012301 (2015)



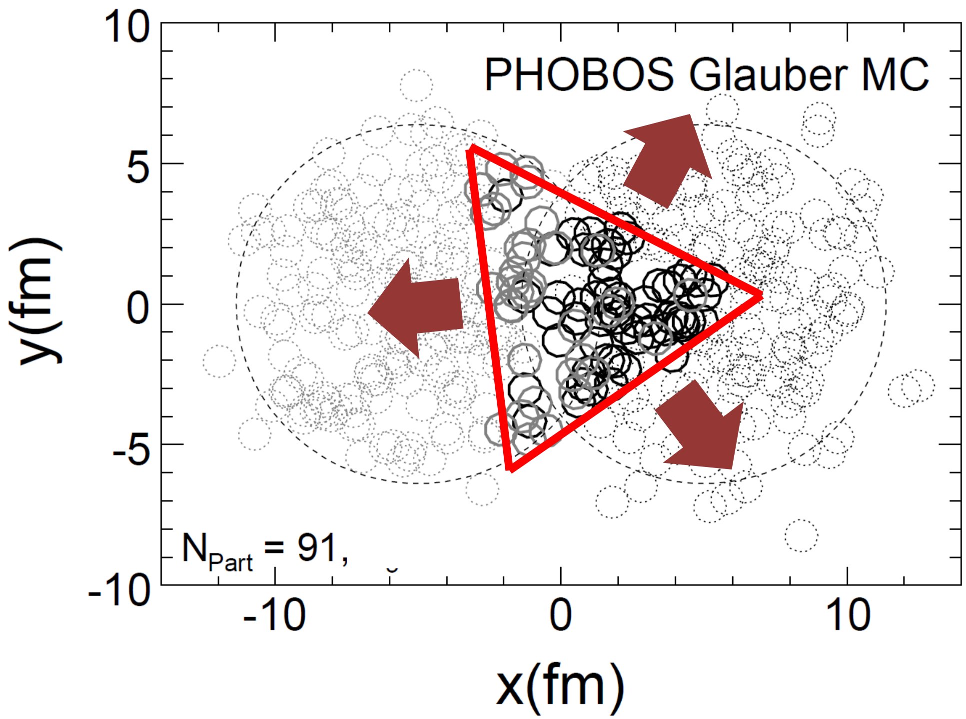
$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$$

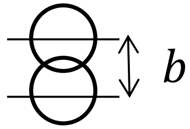
collectivity beyond reasonable doubt

Triangular flow

B. Alver, G. Roland,
PRC 81 (2010) 054905

Sometimes system looks like a triangle





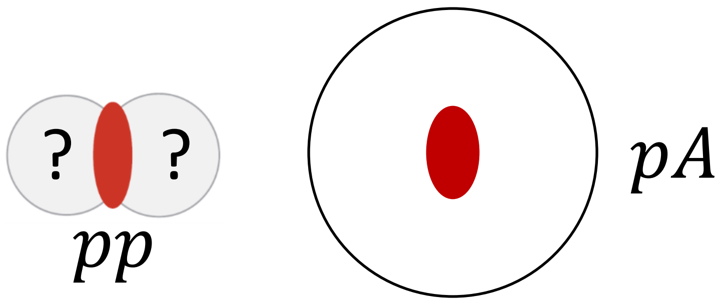
$$\sigma_{in}(b) \sim e^{-b^2/\gamma}$$

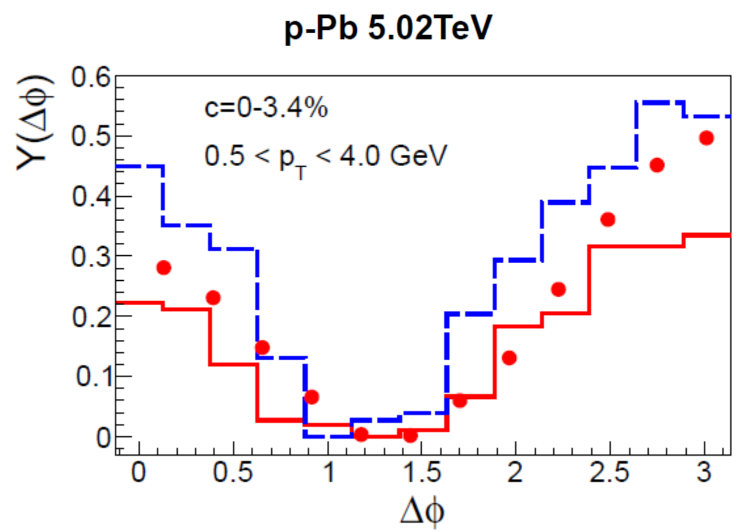
inelastic cross-section

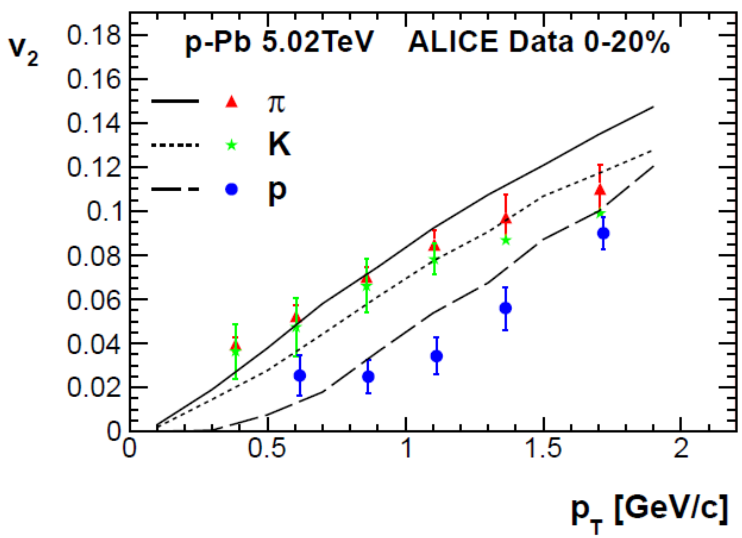
$$C_2(\Delta\varphi) \sim \langle \boldsymbol{v}_3^2 \rangle \cos(3\Delta\varphi)$$

$$\Delta\varphi = \varphi_1 - \varphi_2$$

Perhaps we can apply hydrodynamics to high-multiplicity pp and pA collisions. The interaction region is small but dense.







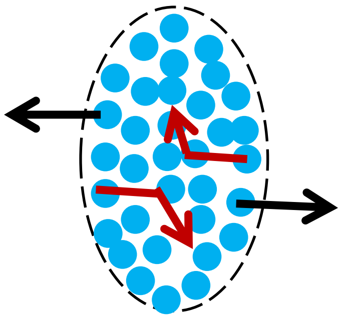
Standard hydro can fit data for p+Pb

P.Bozek, PRC 85 (2012) 014911; P.Bozek, W.Broniowski, G.Torrieri, PRL 111 (2013) 172303
AB, B.Schenke, P.Tribedy, R.Venugopalan, PRC 87 (2013) 064906
E.Shuryak, I.Zahed, PRC 88, 044915 (2013)
K.Werner, B.Guiot, Iu.Karpenko, T.Pierog, PRC 89, 064903 (2014)
G.Qin, B.Müller, PRC 89, 044902 (2014)

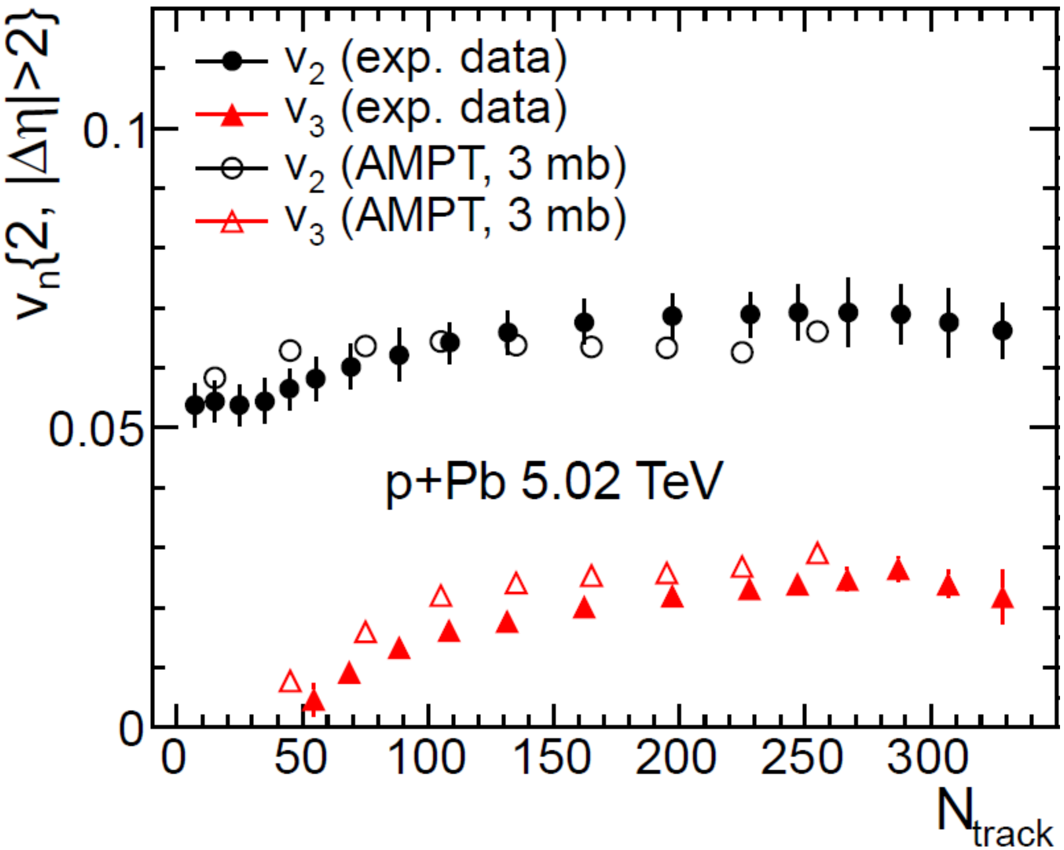
AMPT model (elastic scatterings of *partons*)

Z.W. Lin, C.M. Ko, B.A. Li, B. Zhang, S. Pal, PRC 72 (2005) 064901

$$\frac{d\sigma_{gg}}{dt} \simeq \frac{9\pi\alpha_s^2}{2(t-\mu^2)^2}$$



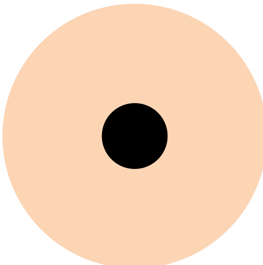
$\boldsymbol{\sigma = 1.5 - 3}$ **mb**



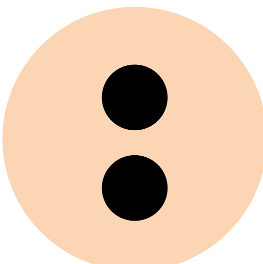
AB, G.L. Ma, PRL 113 (2014) 252301
G.L. Ma, AB, PLB 739 (2014) 209

PHENIX: p+Au, d+Au, He3+Au

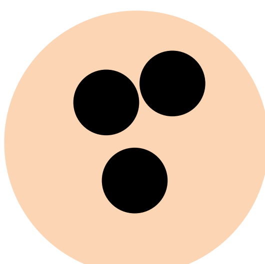
p+Au



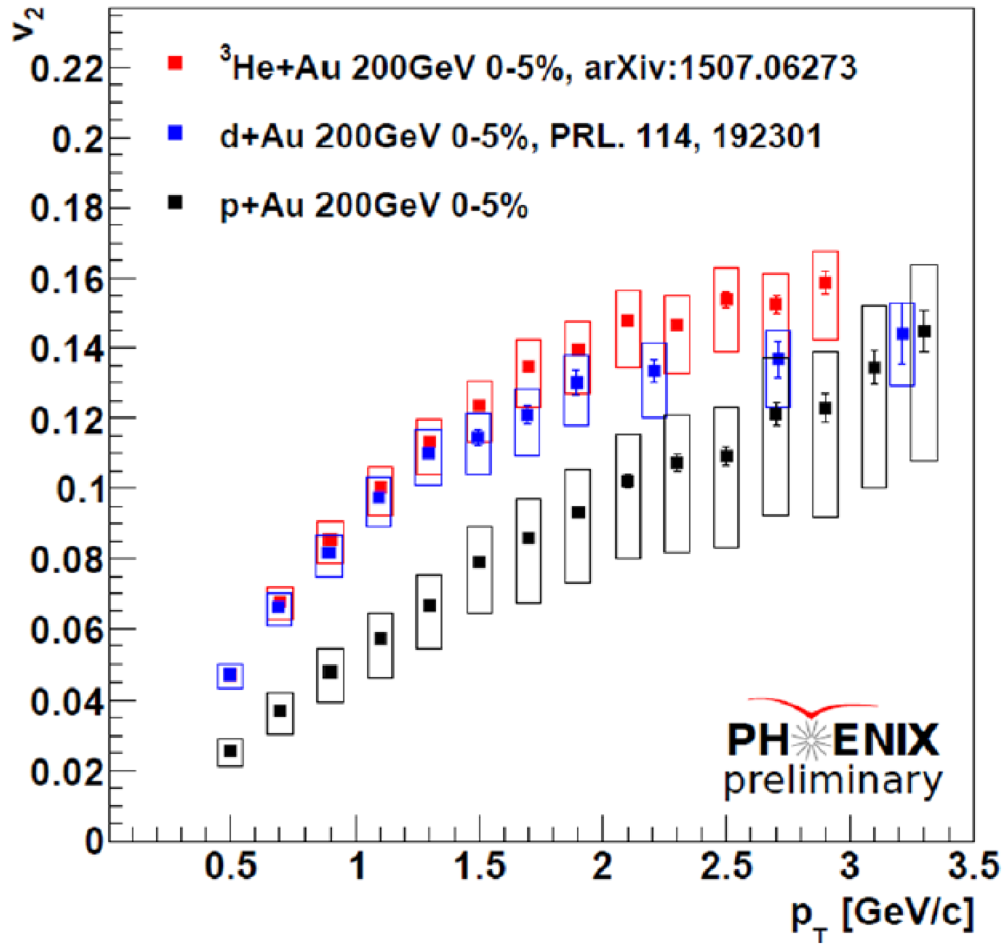
d+Au



He3+Au



$$v_2^{^3HeAu} \geq v_2^{dAu} > v_2^{pAu}$$

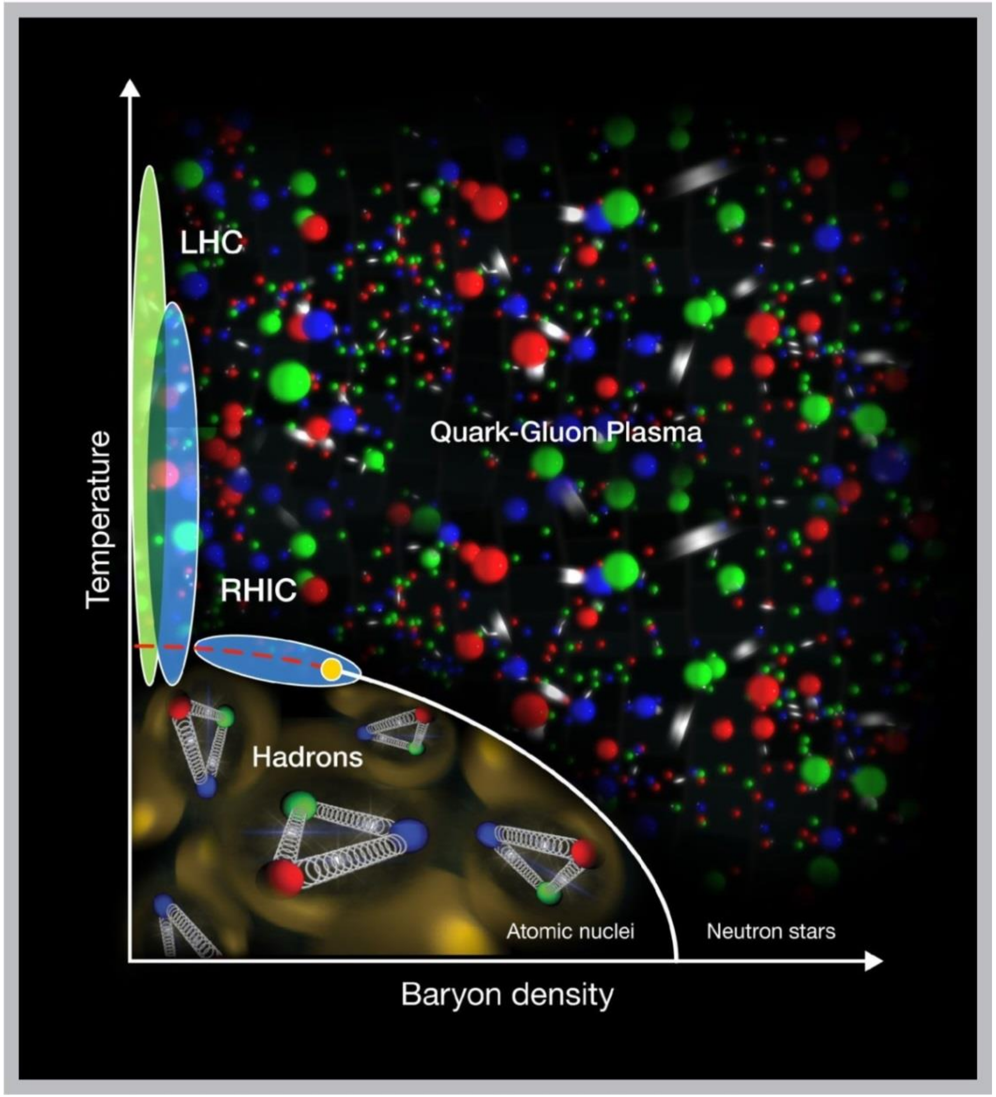


Clear response to global geometry.

QCD critical point

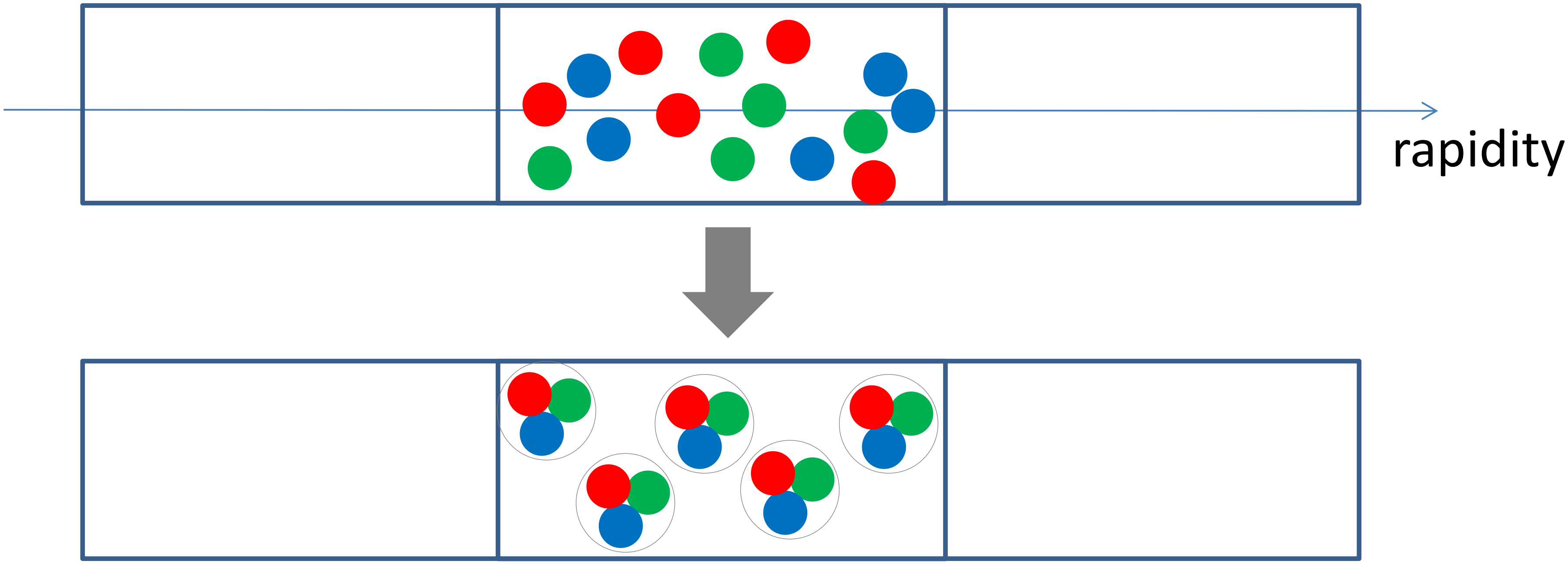
Why heavy-ion collisions?

Z. Fodor, S.D. Katz
JHEP 0203 (2002) 014
critical point



S. Jeon, V. Koch
PRL 85 (2000) 2076

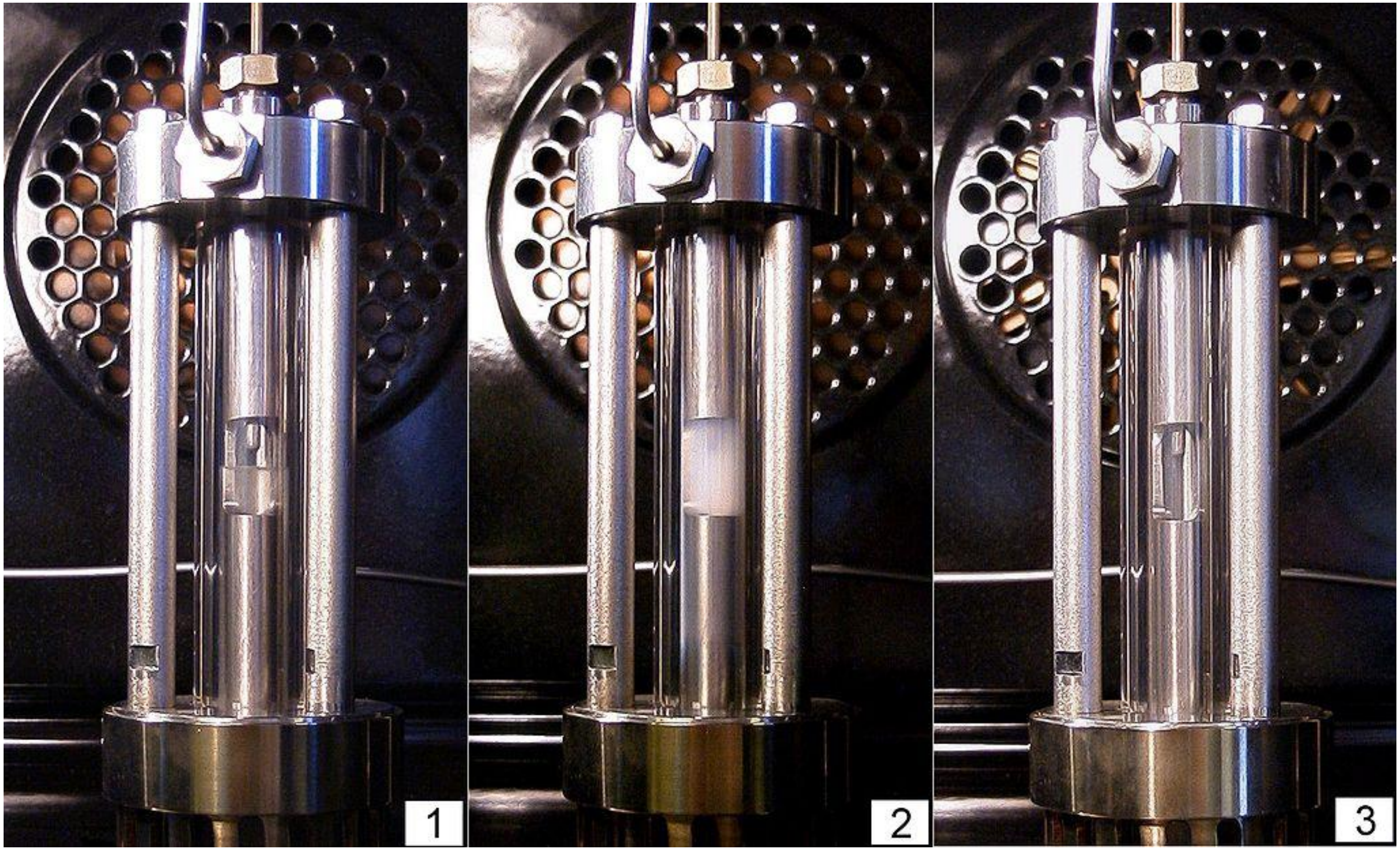
In general phase transition influence fluctuations



Suppose that $\langle n_q^2 \rangle - \langle n_q \rangle^2 = \langle n_q \rangle$ $\qquad n_q = 3n_p$

$$9\langle n_p^2 \rangle - 9\langle n_p \rangle^2 = 3\langle n_p \rangle \qquad \langle n_p^2 \rangle - \langle n_p \rangle^2 = \frac{1}{3}\langle n_p \rangle$$

Critical opalescence



We study cumulants of $P(n)$, n is baryon/charge number

$$c_2 = \langle (n - \langle n \rangle)^2 \rangle = \sigma^2$$

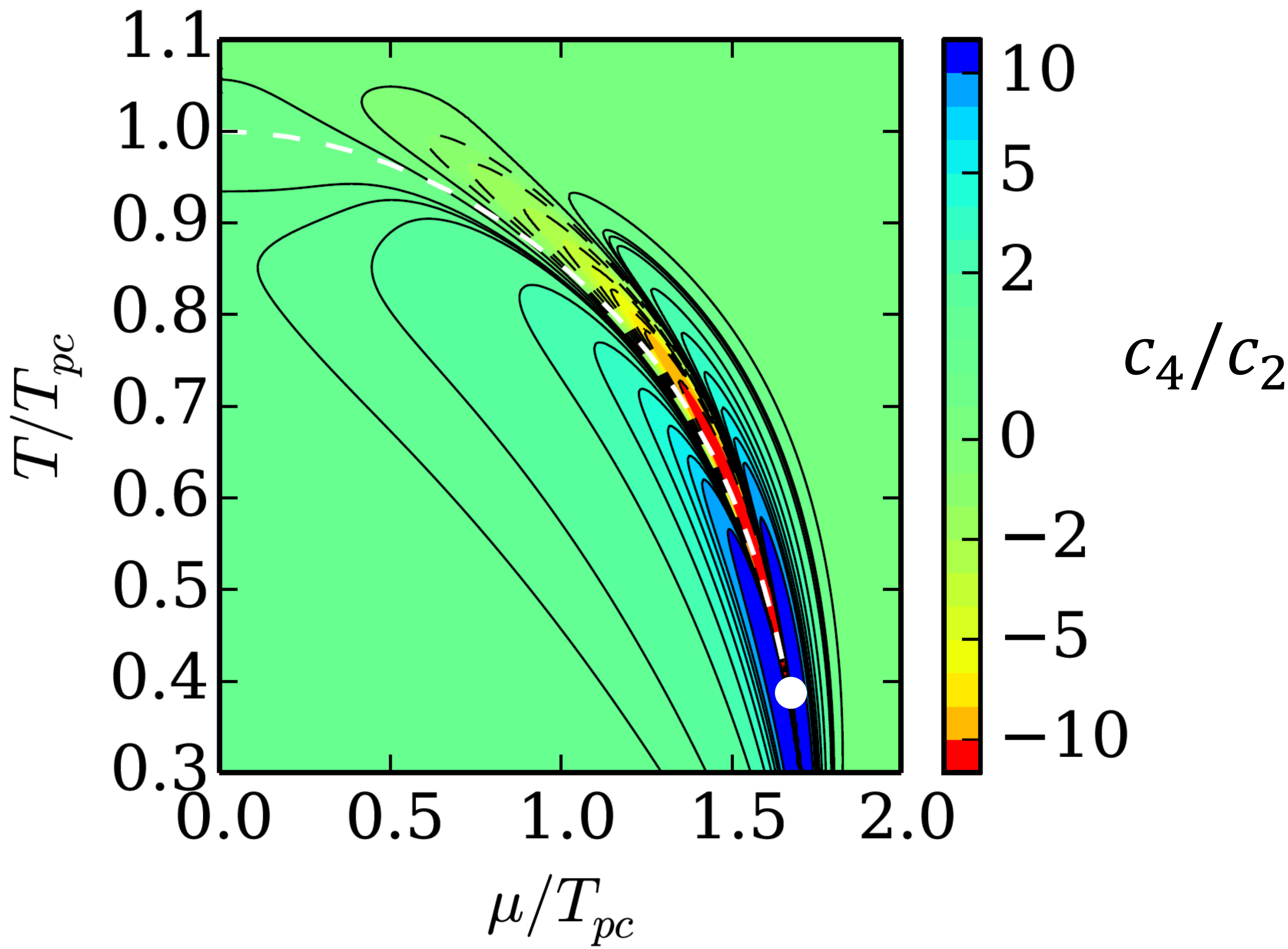
$$c_3 = \langle (n - \langle n \rangle)^3 \rangle = S\sigma^3$$

$$c_4 = \langle (n - \langle n \rangle)^4 \rangle - 3c_2^2 = \kappa\sigma^4$$

$$\kappa\sigma^2 = c_4/c_2$$

$$s\sigma = c_3/c_2$$

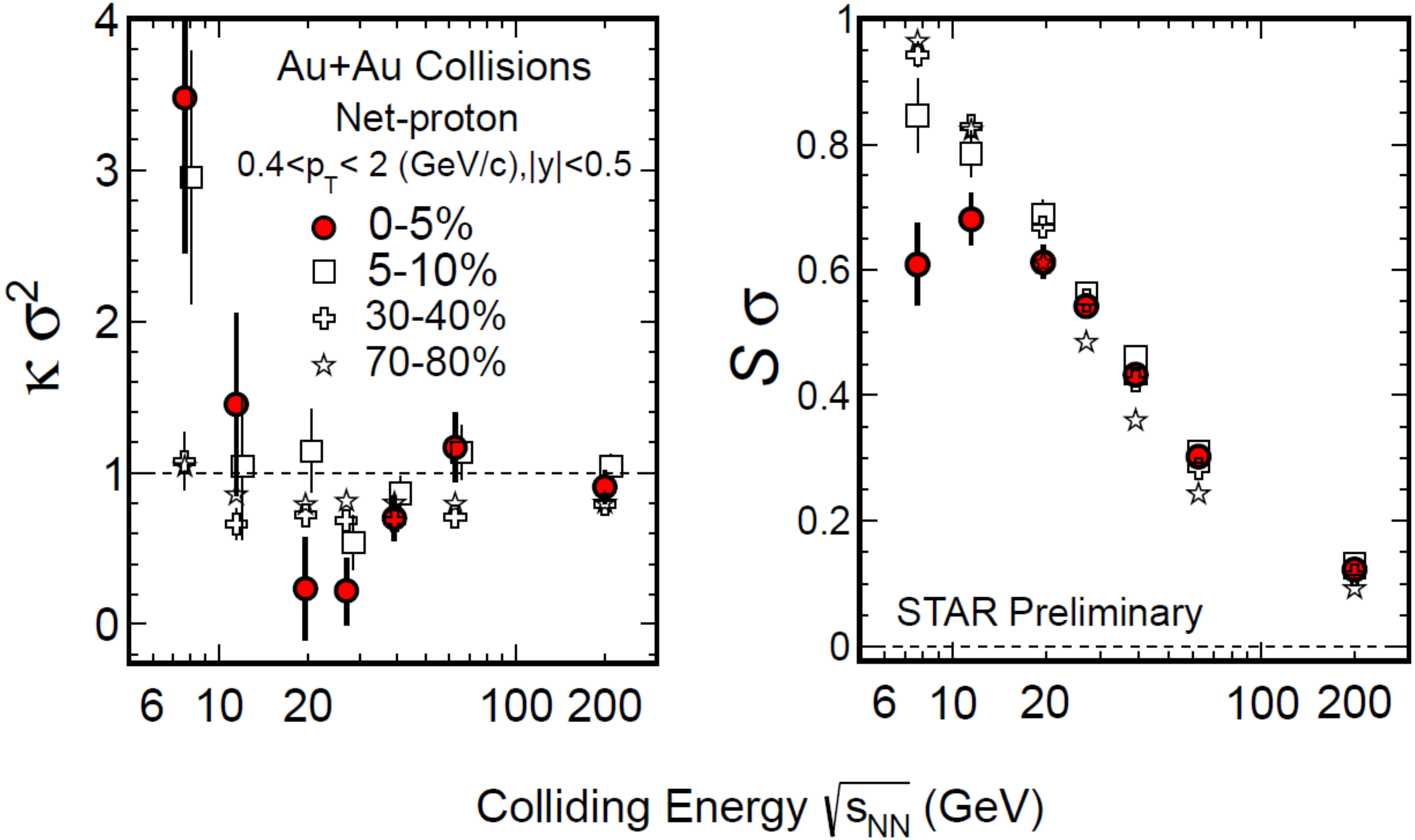
Polyakov-loop-extended-Quark-Meson-Model (PQM)



V.Skokov, private communication

STAR data

STAR, arXiv:1503.02558



$$\kappa\sigma^2 = c_4/c_2 \qquad s\sigma = c_3/c_2$$

Problems:

- Limited detector efficiency
- Neutrons are not measured
- Baryon stopping
- Very short time
- Non critical contribution (global baryon conservation, volume fluctuation, …)
- New observables?

M.Kitazawa, M.Asakawa PRC 86 (2012) 024904; PRC 86 (2012) 069902
AB, V.Koch, PRC 86 (2012) 044904; PRC 91 (2015) 2, 027901
AB, V.Koch, V.Skokov, PRC 87 (2013) 1, 014901
V. Skokov, B. Friman, K. Redlich, PRC 88 (2013) 034911

Conclusions

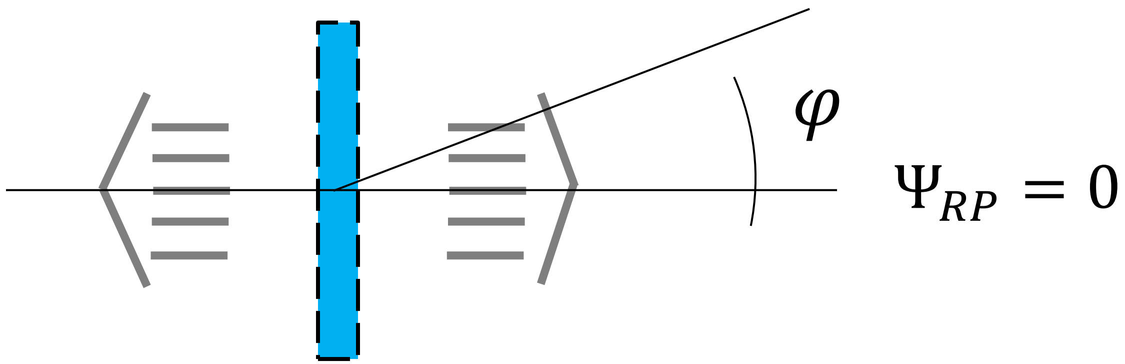
Collectivity in p+p and p+A collisions

Clear response to global geometry

Promising studies of QCD critical point

Backup

For two particles



$$\rho_2(\varphi_1, \varphi_2; \Psi_{RP}) = \rho(\varphi_1; \Psi_{RP}) * \rho(\varphi_2; \Psi_{RP})$$

$$1 + 2\boldsymbol{v_2} \cos(2\varphi_1 - 2\Psi_{RP}) + \cdots$$

$$1 + 2\boldsymbol{v_2} \cos(2\varphi_2 - 2\Psi_{RP}) + \cdots$$

when integrated over Ψ_{RP} $\rightarrow$ $1 + 2\boldsymbol{v_2^2} \cos(2\varphi_1 - 2\varphi_2)$

$$\int d\Psi_{RP}\, \rho_2(\varphi_1, \varphi_2; \Psi_{RP}) \sim 1 + 2v_2^2 \cos(2\varphi_1 - 2\varphi_2)$$

$$\int d\Psi_{RP}\, \rho_4(\varphi_1, \varphi_2, \varphi_3, \varphi_4; \Psi_{RP}) \sim$$

$$1 + 2v_2^2 \cos(2\varphi_1 - 2\varphi_2) + \cdots$$

$$+ 2v_2^4 \cos(2\varphi_1 + 2\varphi_2 - 2\varphi_3 - 2\varphi_4) + \cdots$$

Particles are correlated through the reaction plane

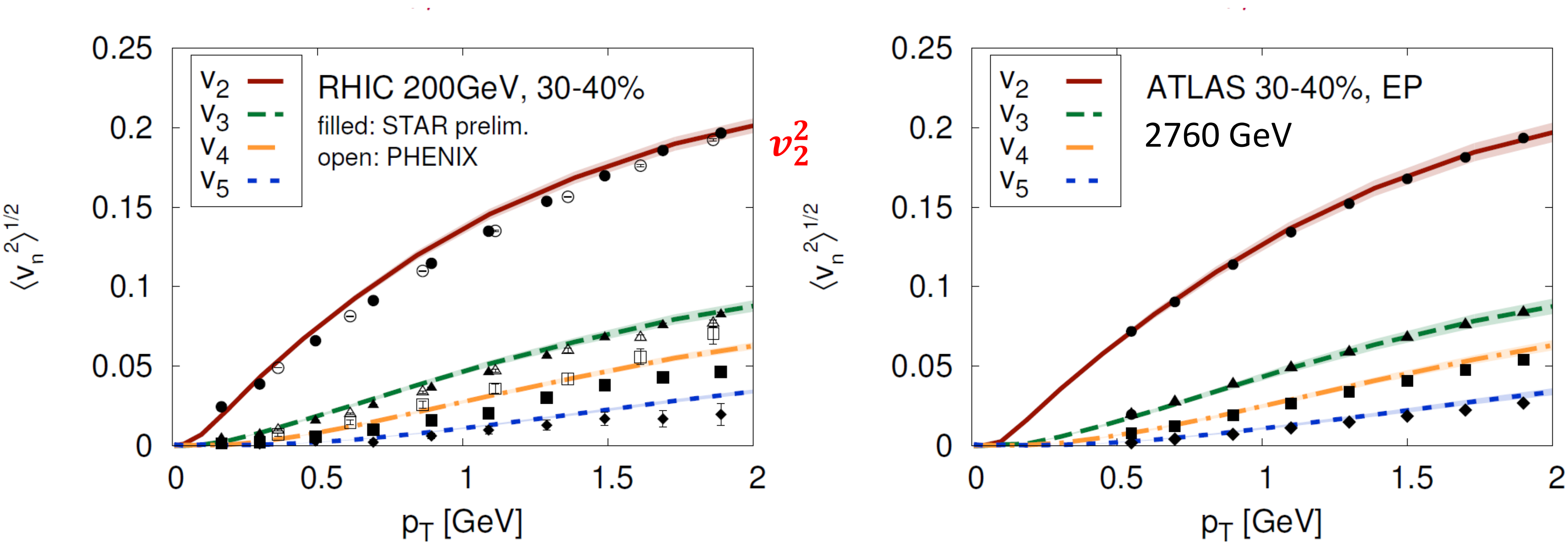
Strengths of 2-, 4-, …, N-particle correlations are the same!

$$f_4(p_1, p_2, p_3, p_4; \Psi_{RP}) = f(p_1; \Psi_{RP}) * f(p_2; \Psi_{RP}) * f(p_3; \Psi_{RP}) * f(p_4; \Psi_{RP})$$

In general:

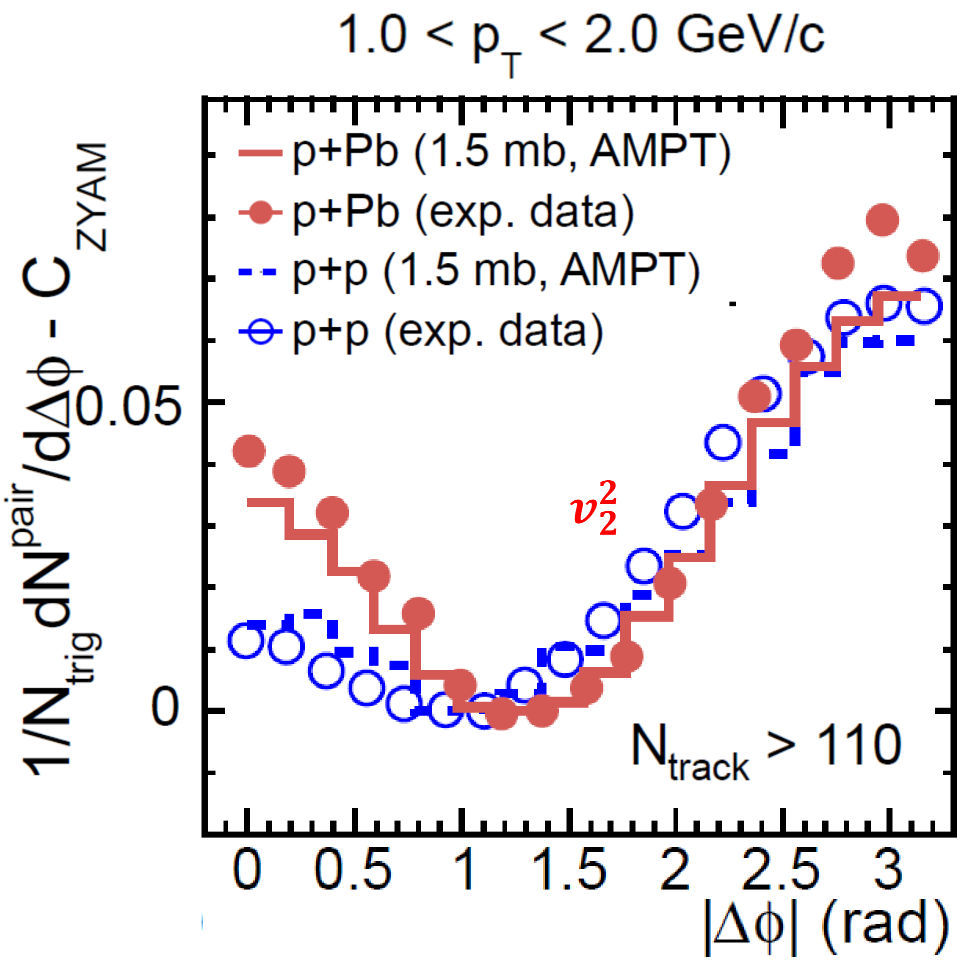
$$C_2(\Delta\varphi) \sim \sum_{n=1} \langle v_n^2 \rangle \cos(n\Delta\varphi)$$

At RHIC (Au+Au) and the LHC (Pb+Pb) hydro is successful



C. Gale et al., PRL 110 (2013) 012302

AMPT two-particle correlation function in p+p and p+Pb



G.L. Ma, AB, PLB 739 (2014) 209

In general:

$$g(t) = \ln\left(\sum_n P_B(n) e^{nt}\right)$$

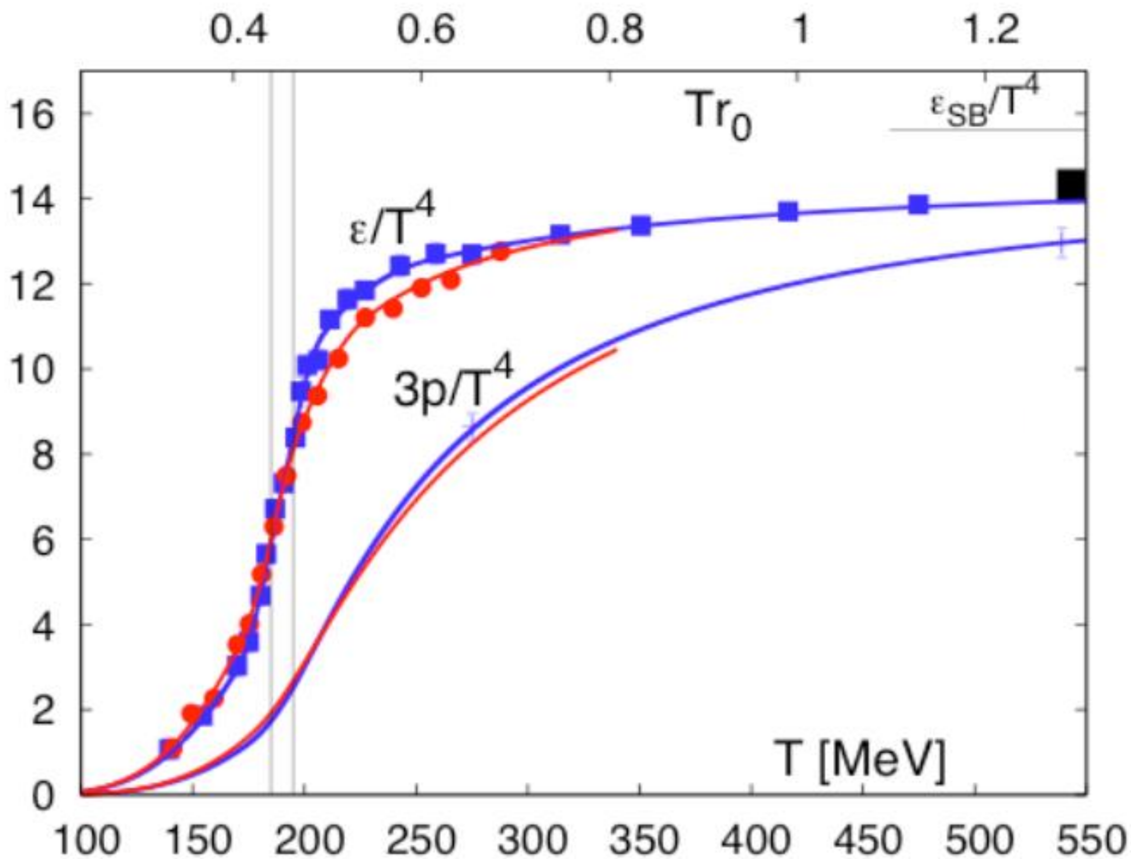
cumulant generating function

$$g(t) = \sum_{k=1}^{\infty} c_k \frac{t^k}{k!}$$

n-th derivative with respect to t (at $t = 0$) gives c_n

$P_B(n)$ – net baryon/proton/charge distribution

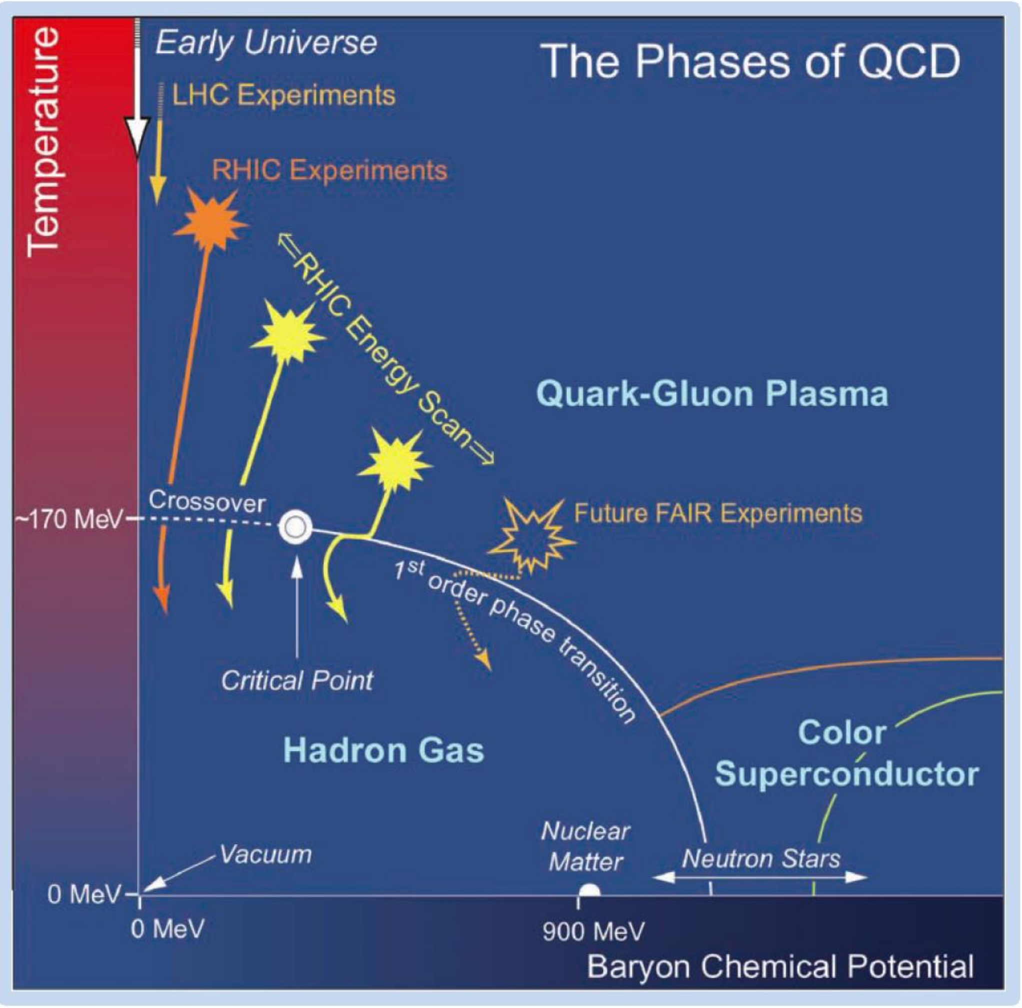
Lattice QCD



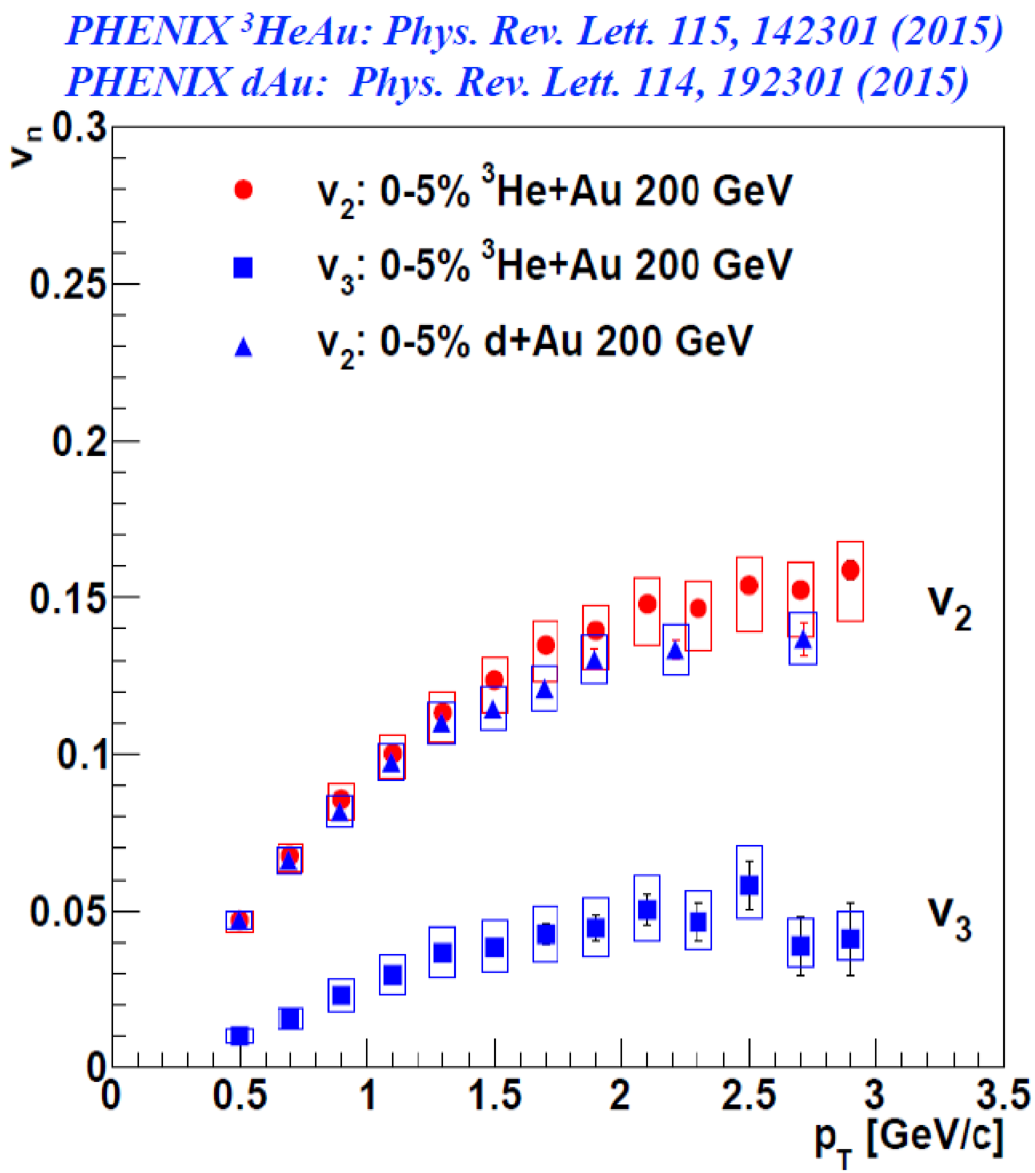
Cross over from hadron gas to sQGP at $T \approx 200$ MeV (10^{12} K)

Y.Aoki et al., Nature 443 (2006) 675

More details



v_3 in He3+Au



PHENIX ³HeAu: Phys. Rev. Lett. 115, 142301 (2015)
PHENIX dAu: Phys. Rev. Lett. 114, 192301 (2015)
v2: 0-5% ³He+Au 200 GeV
v3: 0-5% ³He+Au 200 GeV
v2: 0-5% d+Au 200 GeV
v2
v3
vn
pT [GeV/c]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.5
1
1.5
2
2.5
3
3.5

PHENIX data vs models