Anisotropic flow in relativistic nuclear collisions: (some) achievements and (some) open questions

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Outline

1. v_2/ε:
   - Understanding **initial conditions**
   - and fluctuations in those

2. Non-flow and **flow fluctuations.** Flow fluctuations in the Gaussian model and beyond. Evolution of notion of anisotropic flow.

3. **Azimuthal correlations and flow**.

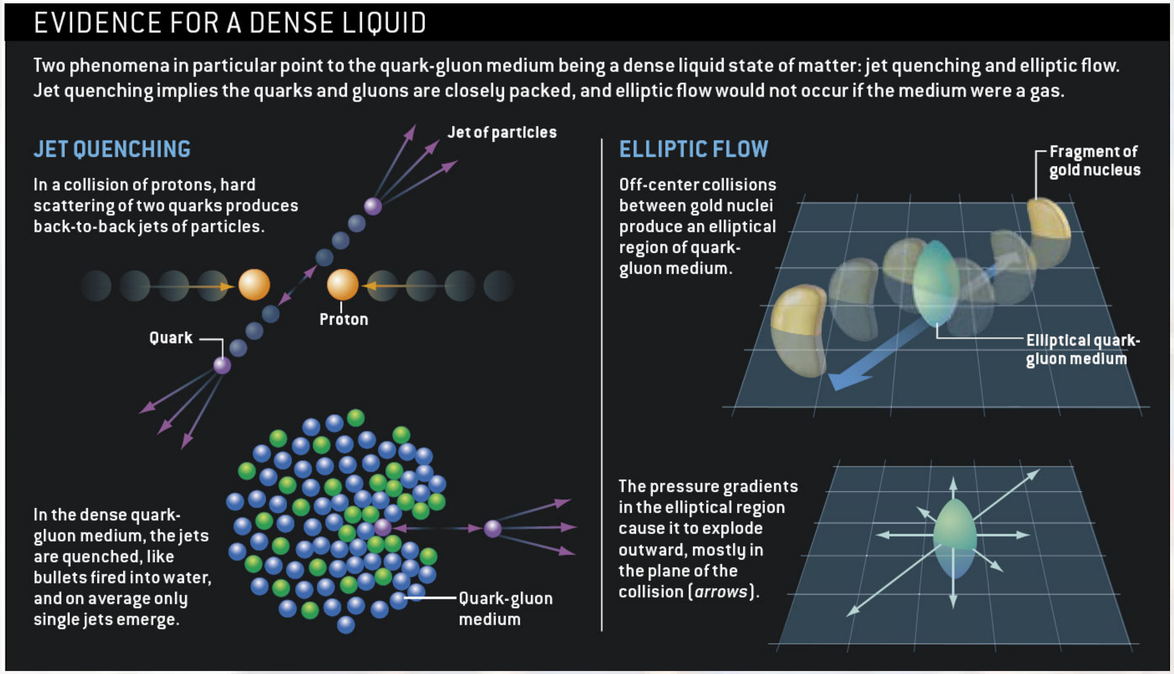
4. Anisotropic initial conditions ➔ v_2, v_1, a_1 and more.

5. Future: RHIC beam energy scan, LHC

Understanding methods ➔ better understanding of flow fluctuations ➔ … initial conditions ➔ evolution of concept of flow ➔ “interplay” of flow and non-flow ➔ understanding methods ➔ …

In many respects today the flow analysis requires much more effort than used to be.

Major RHIC discoveries



EVIDENCE FOR A DENSE LIQUID

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.

In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

ELLIPTIC FLOW

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).

Three major RHIC discoveries (my view):

1. Large elliptic flow
2. Jet quenching
3. Constituent quark scaling

Note the importance of item #3 observed in anisotropic flow "sector" (the observation in spectra would not constitute that strongly "partonic flow" - deconfinement !).

RHIC is now in the second phase – quantitative description of sQGP- and we need *precise measurements, comprehensive modeling, and detailed understanding of the results*. We have a real progress in all that over the last several years.

The use of the correct terminology and clear definitions become very important!

> "The physical picture emerging from the four (RHIC) experiments is consistent and surprising. The quarks and gluons indeed break out of confinement and behave collectively, if only fleetingly. But this hot mélange acts like a liquid, not the ideal gas theorists had anticipated."
>
> *M. Riordan, W. Zajc*, Sci. Am., May 2006, 34-41.

$$\frac{d^3N}{dp_t\,dy\,d\varphi}=\frac{d^2N}{dp_t\,dy}\frac{1}{2\pi}\left(1+2v_1\cos(\Delta\varphi)+2v_2\cos(2\Delta\varphi)+\ldots\right)$$

$$\Delta\varphi=\varphi-\Psi_{RP}$$

Directed flow

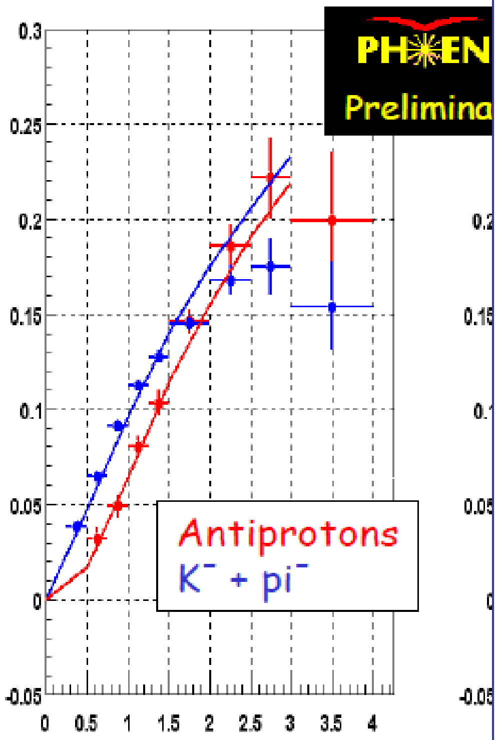
Elliptic flow

Note that the definition of anisotropic flow (event anisotropy?) involves knowledge of the "true" reaction plane.

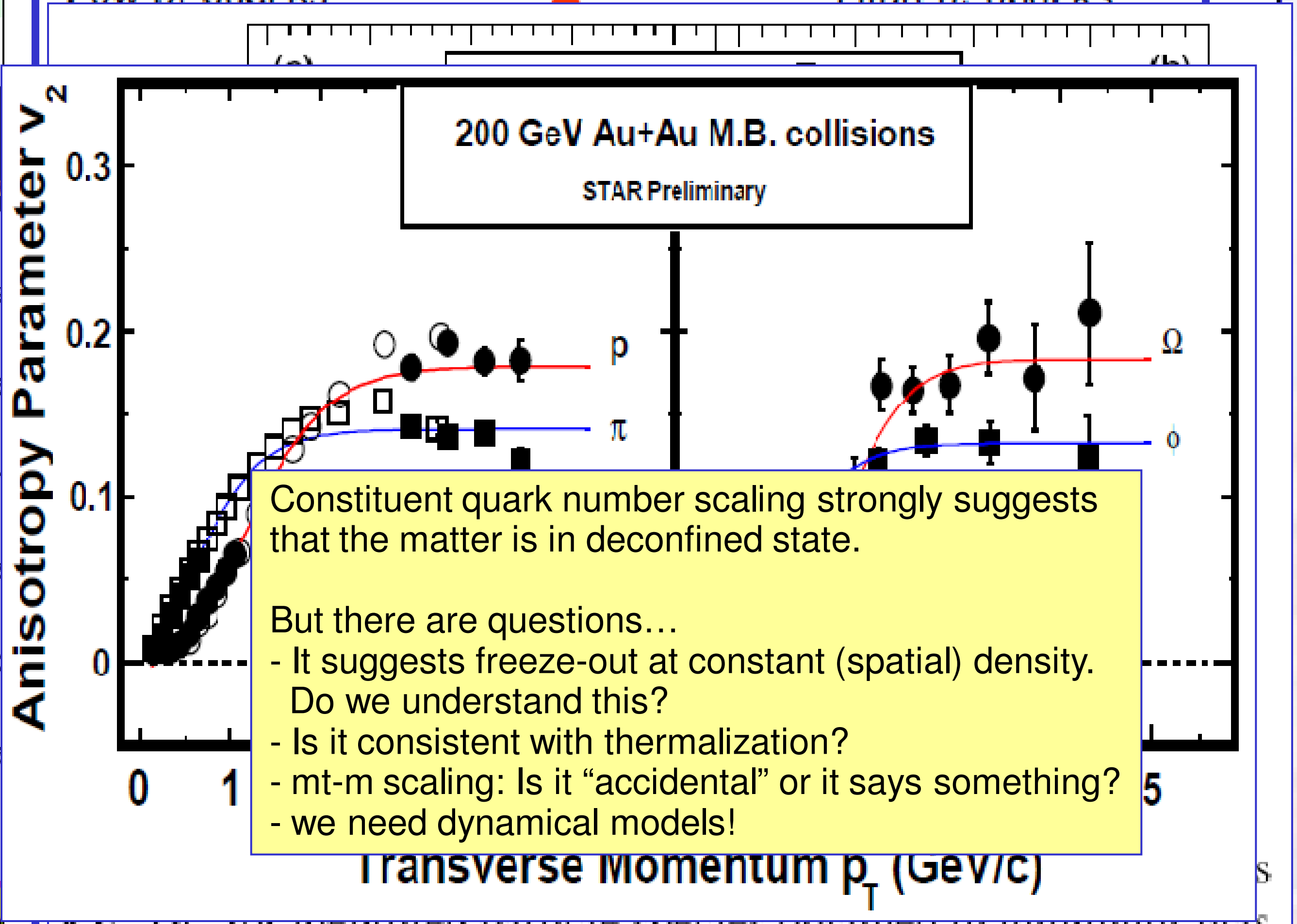
Number of constituent quark scaling

coalescence — fragmentation

Low p_T quarks — High p_T quarks



v_2(baryons) > v_2(mes

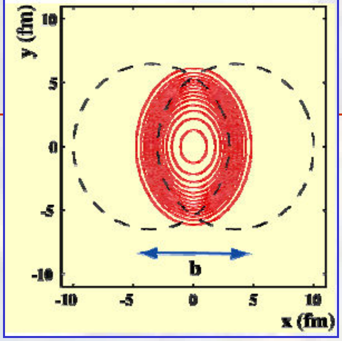


Constituent quark number scaling strongly suggests that the matter is in deconfined state.

But there are questions…
- It suggests freeze-out at constant (spatial) density. Do we understand this?
- Is it consistent with thermalization?
- mt-m scaling: Is it “accidental” or it says something?
- we need dynamical models!

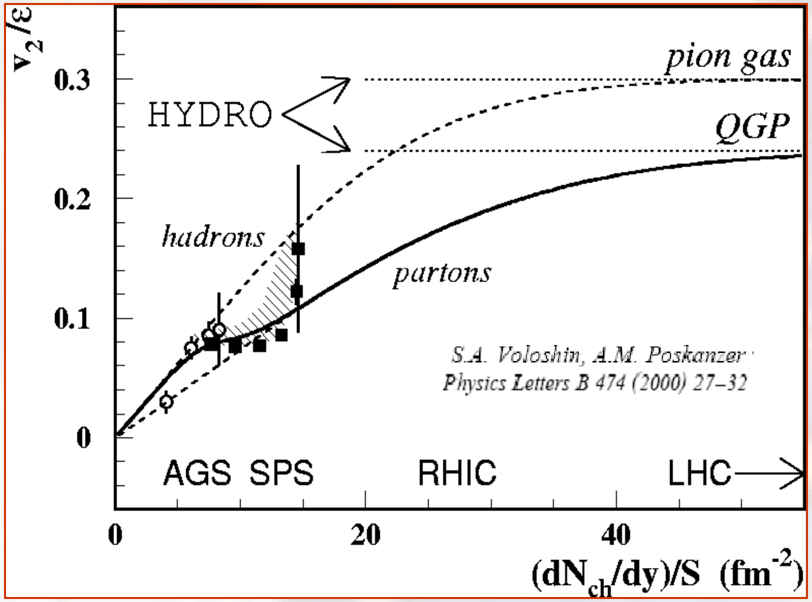
KE_T/n_q for identified particle species obtained in minimum-bias Au + Au collisions. The STAR data are from Refs. [24,43].

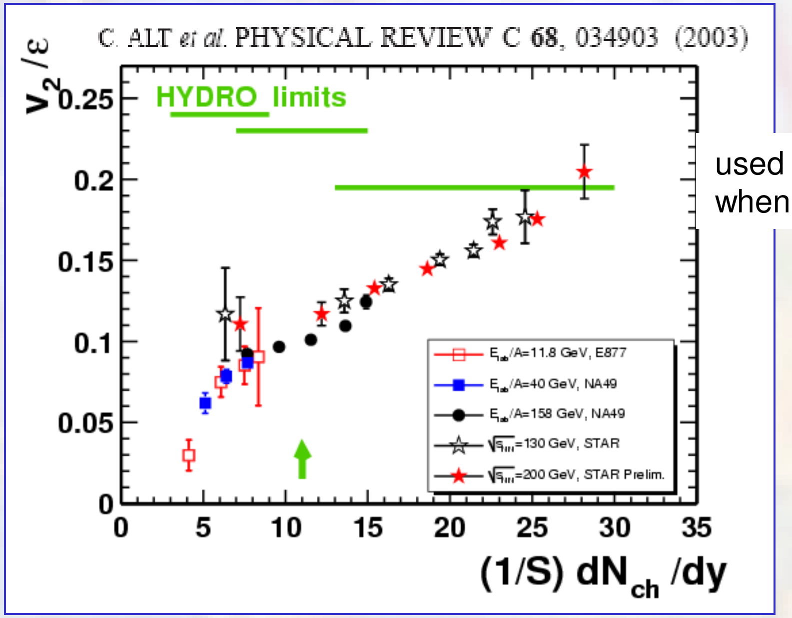
v_2/ε plot



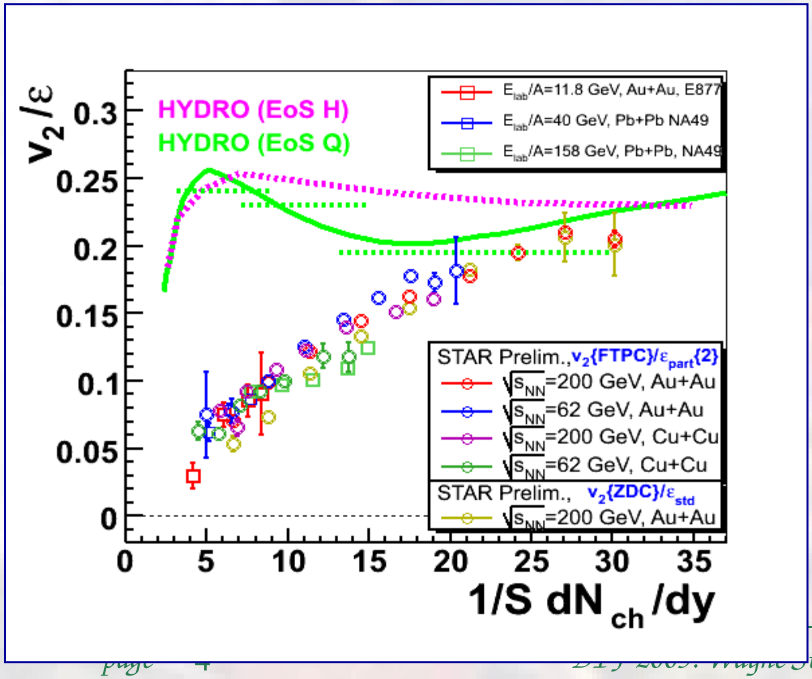
$$v_2 \equiv \left\langle \cos\left(2\left(\varphi_i - \Psi_{RP}\right)\right)\right\rangle$$

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




C. ALT *et al.* PHYSICAL REVIEW C 68, 034903 (2003)

used v2{4} whenever possible

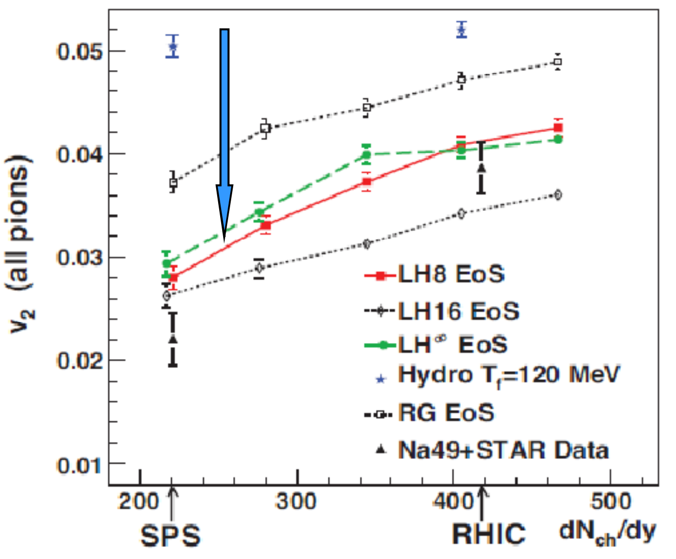


Findings:
- Viscosity leads to decrease of flow → $(v_2/\varepsilon)_{\text{theor}}$ down ~30%
- Initial eccentricity is likely higher than thought → $(v_2/\varepsilon)_{\text{theor}}$ up ~<50%
- “proper” selection of parameters in hydro → $(v_2/\varepsilon)_{\text{theor}}$ up ~20%
- “Correcting for flow fluctuations → $(v_2/\varepsilon)_{\text{exp}}$ down <~ 20%
- Initial flow field → $(v_2/\varepsilon)_{\text{theor}}$ up ~?

Why does it work that well? (no ε^2 terms?)

Viscous effects. Eccentricity in CGC model.

D. Teaney, J. Lauret and E. V. Shuryak, Phys. Rev. Lett. **86**, 4783 (2001)



LH8 denotes the results obtained for an EoS with latent heat 0.8 GeV/fm^3.

DEREK TEANEY PHYSICAL REVIEW C **68**, 034913 (2003)

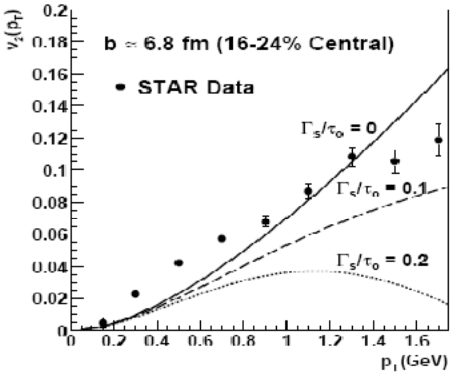


FIG. 3. Elliptic flow v_2 as a function of p_T for different values of Γ_s/τ_o. The data points are four-particle cumulant data from the STAR Collaboration [3]. Only statistical errors are shown. The difference between the ideal and viscous curves is linearly proportional to Γ_s/τ_o.

Tetsufumi Hirano [a,*], Ulrich Heinz [b], Dmitri Kharzeev [c], Roy Lacey [d], Yasushi Nara [e]

Physics Letters B 636 (2006) 299–304

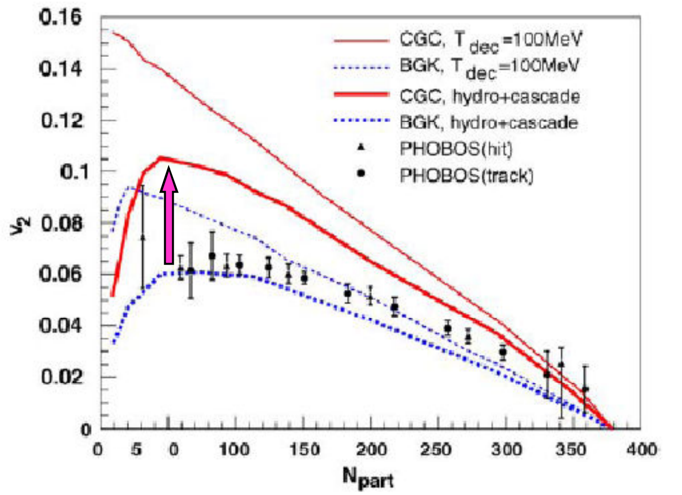


Fig. 2. (Color online.) p_T-integrated elliptic flow for charged hadrons at midrapidity ($|\eta| < 1$) from 200 A GeV Au + Au collisions, as a function of the number $N_{\rm part}$ of participating nucleons. The thin lines show the prediction from ideal fluid dynamics with a freeze-out temperature $T_{\rm dec} = 100$ MeV, for CGC (solid red) and BGK (dashed blue) initial conditions. The thick lines (solid red for CGC and dashed blue for BGK initial conditions) show the corresponding results from the hydro + cascade hybrid model. The data are from the PHOBOS Collaboration [19].

“late viscosity” was simulated by hydro+cascade MC.

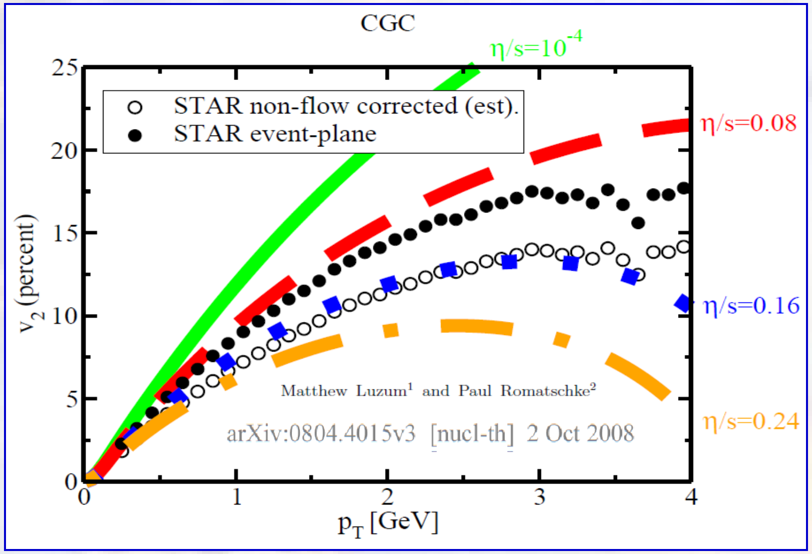
The details depend in particular on transverse coordinate dependence of the saturation scale, if entropy or energy density is used as a weight,…

Lappi, Venugopalan **Phys.Rev.C74:054905,2006**

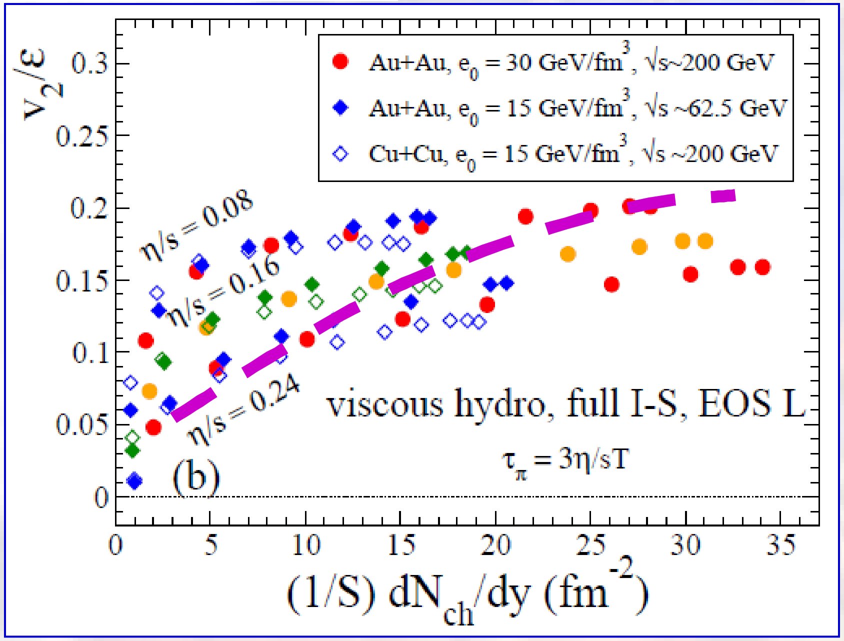
Viscous hydro calculations vs data

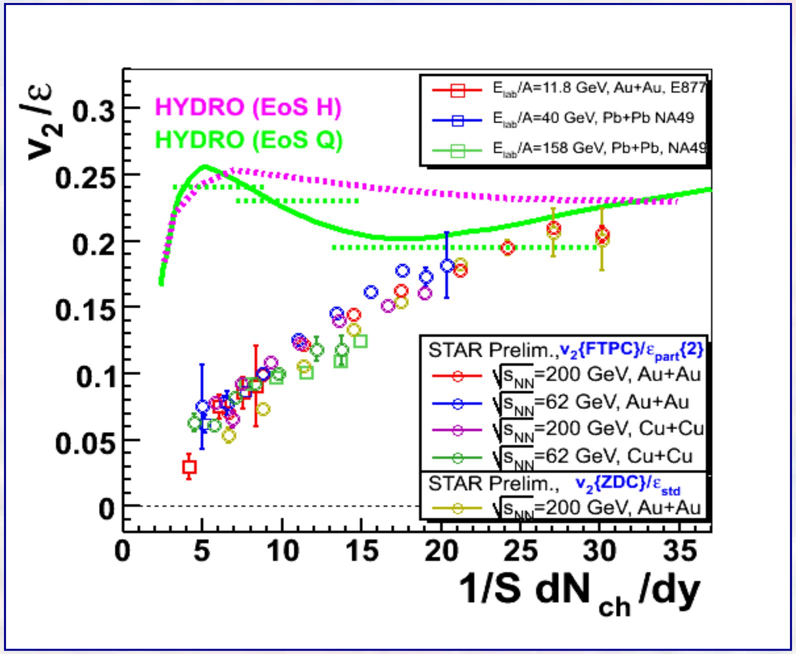
➔ η /s is about factor of 2 larger compared to the conjectured low limit of 1/(4π),

It is still the most “perfect” liquid!

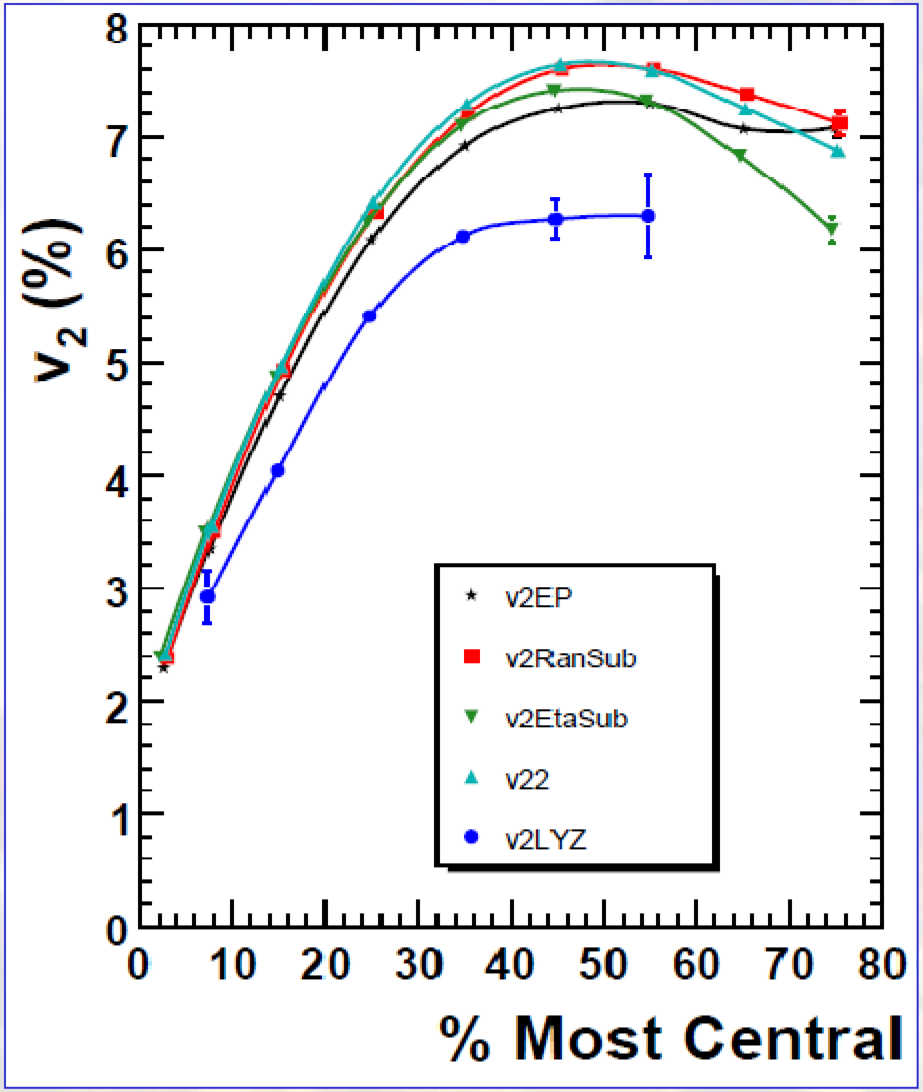


Huichao Song[1,*] and Ulrich Heinz[1,2]
arXiv:0805.1756v2 [nucl-th] 3 Jul 2008





Many methods ➔ many results?

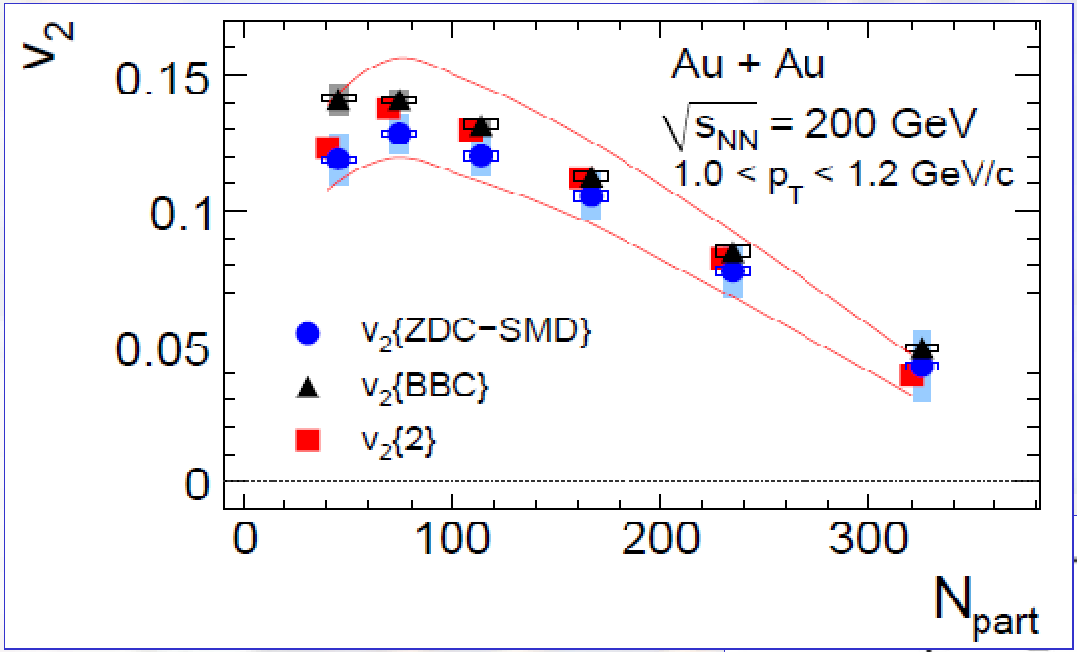


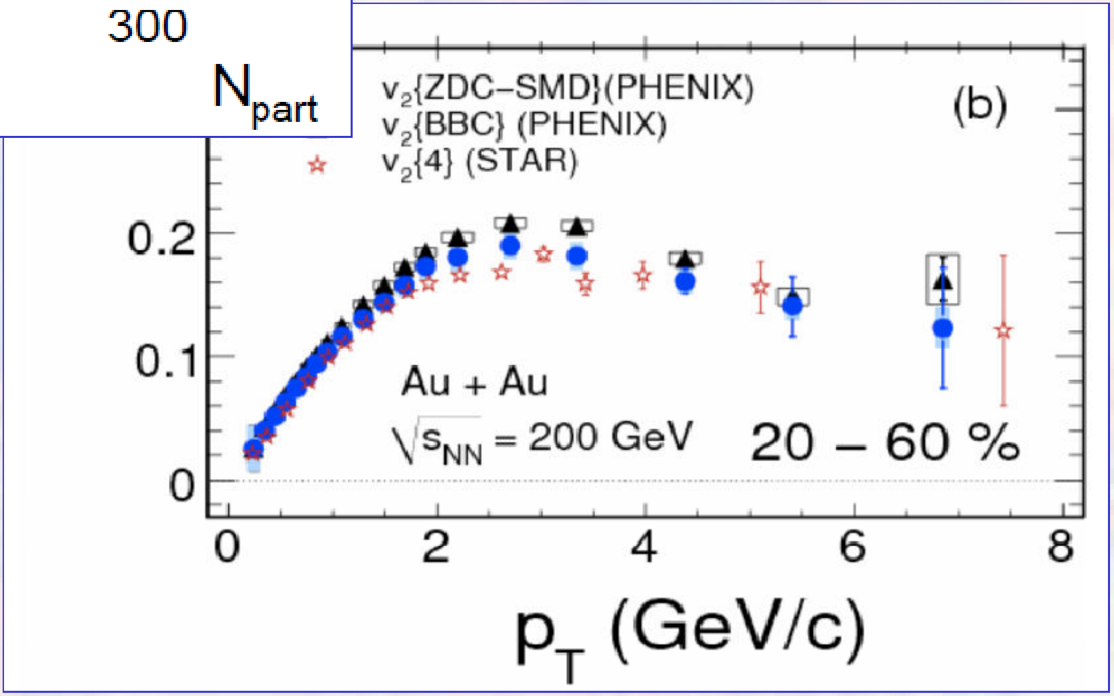
Which one compare to the model?

Note three bands: “v2[2}”, “v2{EP}”, “v2{4}”

Top of the line…

arXiv: 0905.1070 [nucl-ex]





Gaussian model of eccentricity fluctuations

Sergei A. Voloshin [a,*], Arthur M. Poskanzer [b], Aihong Tang [c], Gang Wang [d] Physics Letters B 659 (2008) 537–541

Model assumes Gaussian form for the distributions in ε_x and ε_y, (which is a very good approximation of MC Glauber calculations).

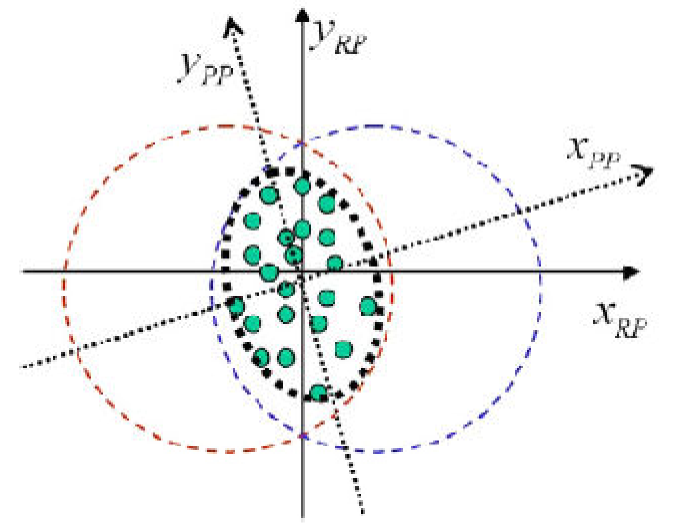


Fig. 1. The definitions of the *RP* and *PP* coordinate systems.

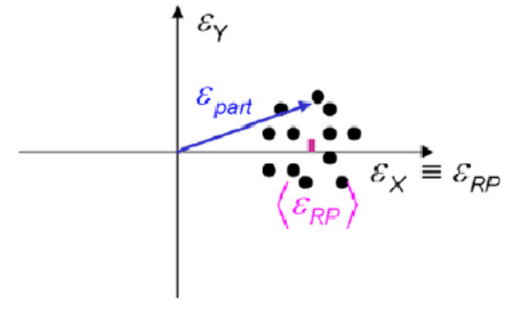


Fig. 3. Definition of $\varepsilon_{\text{part}}$.

$$v_2\{2\}^2 \equiv \langle\cos(2(\varphi_1-\varphi_2))\rangle = \langle v_2^2\rangle + \delta = \langle v_2\rangle^2 + \sigma_v^2 + \delta$$

$$v_2\{4\}^4 \equiv 2\langle\cos(2(\varphi_1-\varphi_2))\rangle^2 - \langle\cos(2(\varphi_1+\varphi_2-\varphi_3-\varphi_4))\rangle \approx 2\langle v_2^2\rangle^2 - \langle v_2^4\rangle$$

$$v_2 \propto \varepsilon; \quad v_2\{2\} = \langle v_2\rangle \sqrt{\langle\varepsilon^2\rangle} / \langle\varepsilon\rangle = \langle v_2\rangle \varepsilon_2\{2\} / \langle\varepsilon\rangle$$

$$v_2\{2\}^2 = \kappa^2\left(\langle\varepsilon_{RP}\rangle^2 + 2\sigma_\varepsilon^2\right) + \delta = \boxed{\langle v_{RP}\rangle^2} + \boxed{2\sigma_{vx}^2 + \delta}$$

$$v_2\{4\}^4 = 2\langle v_2^2\rangle^2 - \langle v_2^4\rangle = \bar{v}_2^4 = \langle v_{RP}\rangle^4$$

$$v_2\{6\}^6 = \left(\langle v_2^6\rangle - 9\langle v_2^4\rangle\langle v_2^2\rangle + 12\langle v_2^2\rangle^3\right)/4 = \langle v_{RP}\rangle^6$$

$$\boldsymbol{\varepsilon} = \{\varepsilon_x, \varepsilon_y\} = \left\{ \left\langle \frac{\sigma_y^2 - \sigma_x^2}{\sigma_x^2 + \sigma_y^2} \right\rangle_{\text{part}}, \left\langle \frac{2\sigma_{xy}}{\sigma_x^2 + \sigma_y^2} \right\rangle_{\text{part}} \right\}$$

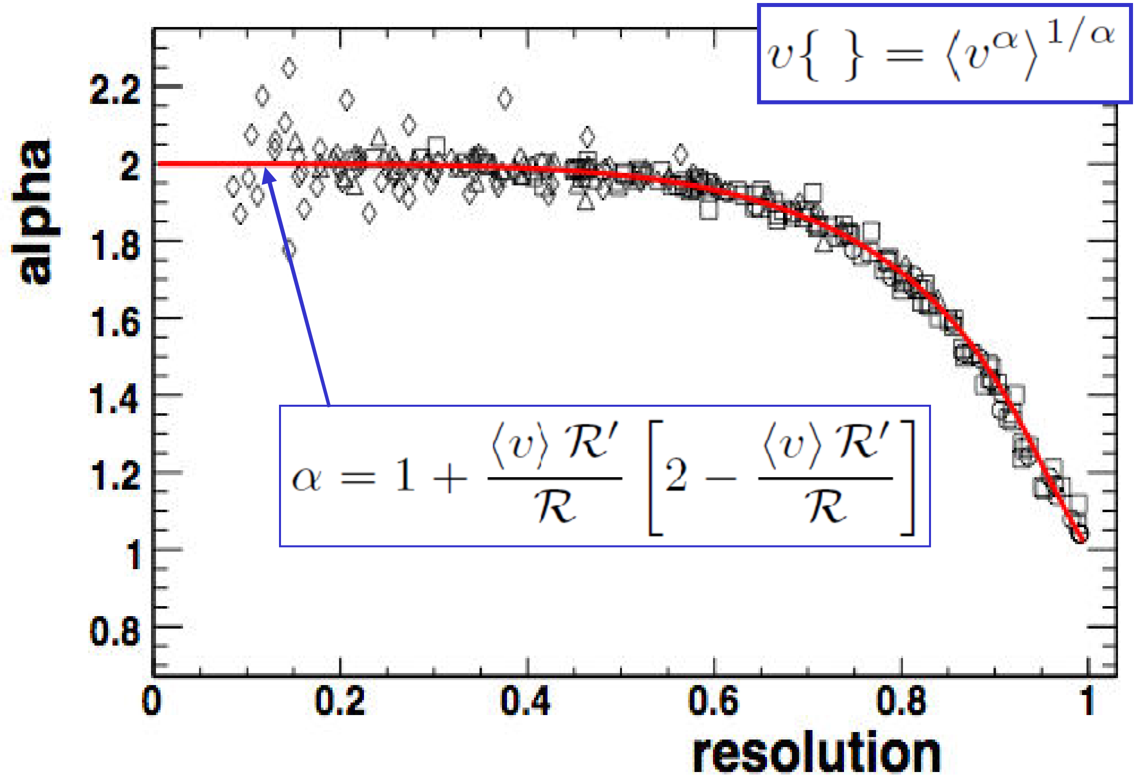
In this model it is not possible to separate flow fluctuations and non-flow effects (this can be traced to the fact that the Gaussian distribution has all cumulants higher than rank 2 equal to zero)

➔ $v_2\{4\}$ measures "true" elliptic flow (wrt reaction plane) – exactly what is needed for comparison with theory!

more complicated case: v{EP}

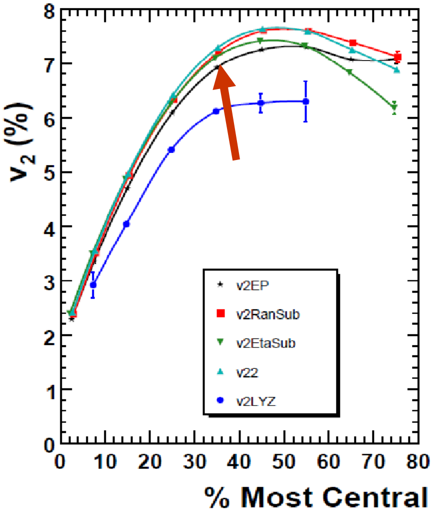
PHYSICAL REVIEW C 80, 014904 (2009)

Jean-Yves Ollitrault,[1] Arthur M. Poskanzer,[2] and Sergei A. Voloshin[3]



$$v\{\ \} = \langle v^{\alpha} \rangle^{1/\alpha}$$

$$\alpha = 1 + \frac{\langle v \rangle \mathcal{R}'}{\mathcal{R}} \left[2 - \frac{\langle v \rangle \mathcal{R}'}{\mathcal{R}} \right]$$



$$v\{\mathrm{EP}\} \equiv \frac{\langle \cos(\phi - \Psi_R) \rangle}{R}$$

$$R = \sqrt{\langle \cos(\Psi_A - \Psi_B) \rangle}$$

$$\mathbf{q} \cos \Psi_R = \frac{\mathbf{Q}}{\sqrt{N}} \cos \Psi_R = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} \cos \phi_j$$

$$\mathbf{q} \sin \Psi_R = \frac{\mathbf{Q}}{\sqrt{N}} \sin \Psi_R = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} \sin \phi_j$$

$$\mathcal{R}(\chi) = \frac{\sqrt{\pi}}{2} e^{-\chi^2/2} \chi \left[I_0\left(\frac{\chi^2}{2}\right) + I_1\left(\frac{\chi^2}{2}\right) \right] \qquad \chi_s = v\sqrt{N_s}$$

… but it is still not possible to separate the effect of fluctuations from non-flow.

How it works under simple assumption

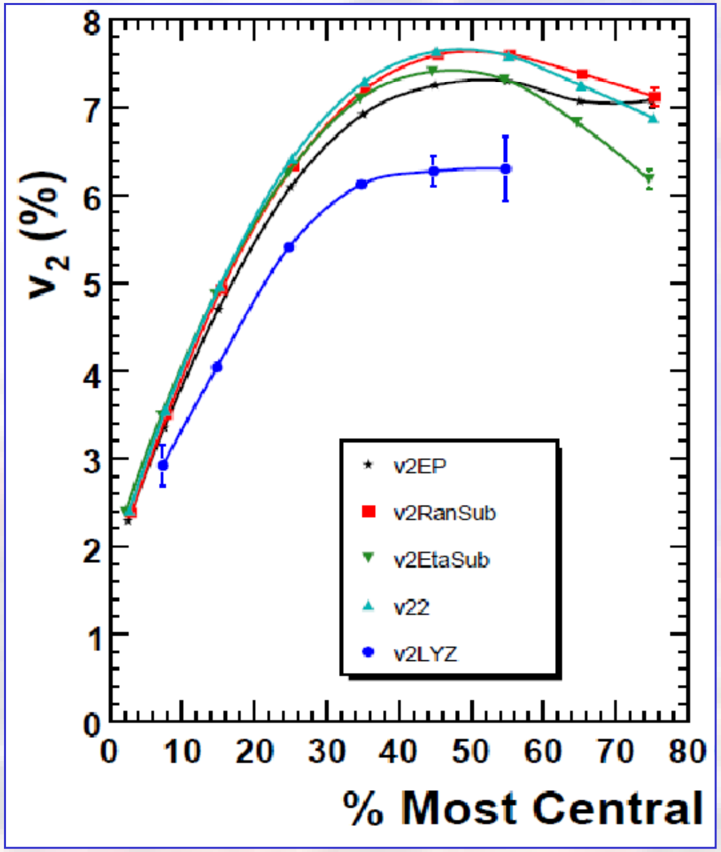
$$\sigma_{v2} = \frac{\sigma_\varepsilon}{\langle\varepsilon\rangle}\langle v_2\rangle$$

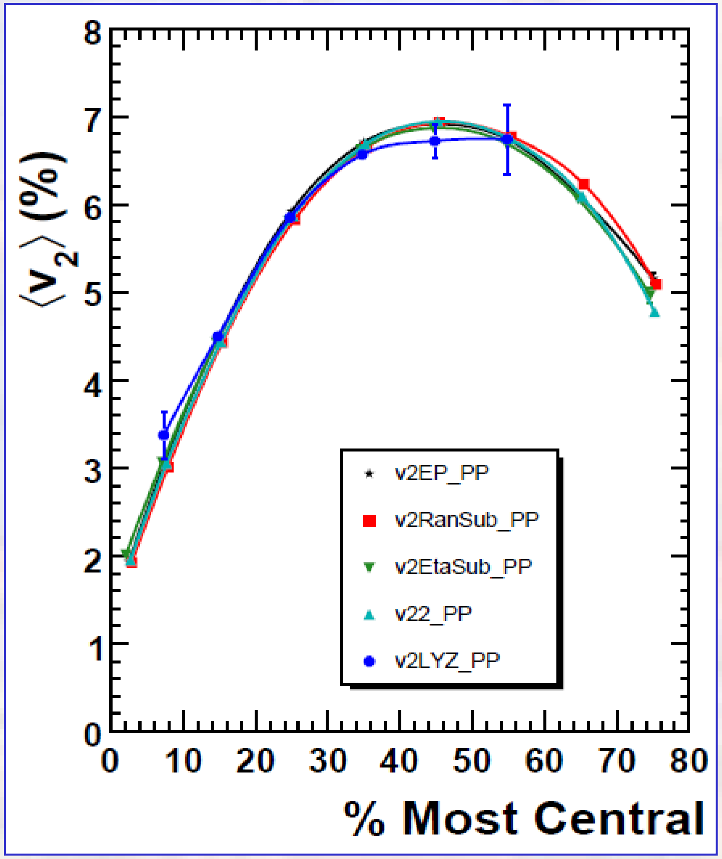
MC Glauber ε participant

$$\delta_2 = 2\ \delta_{pp}/N_{\rm part} \qquad \delta_{pp} = 0.0145$$

$$\delta_{\rm etaSub} = 0.5\ \delta_2$$

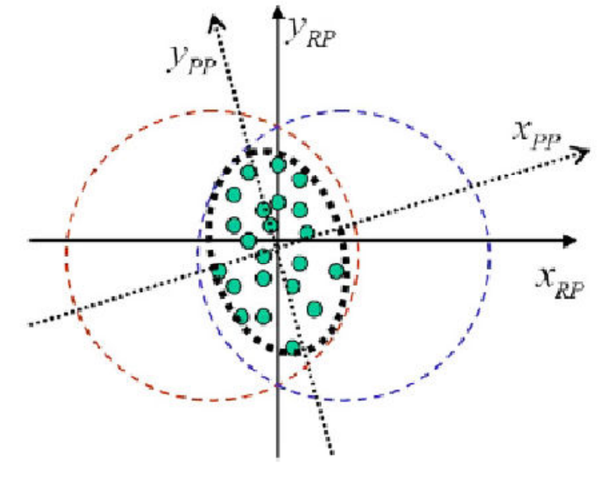
less nonflow





Fluctuating initial conditions: further details

J. Takahashi *et al.*,arXiv:0902.4870v1



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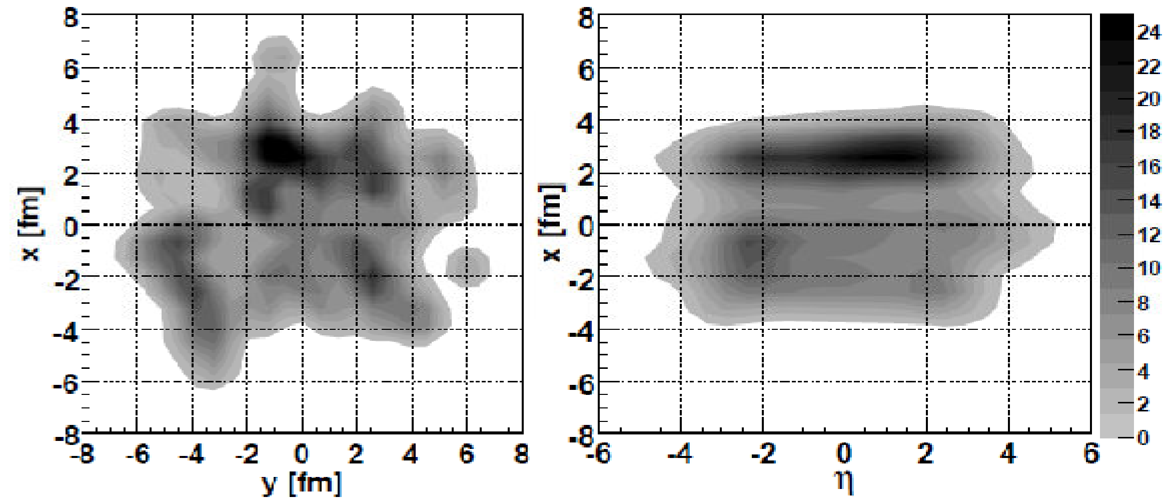
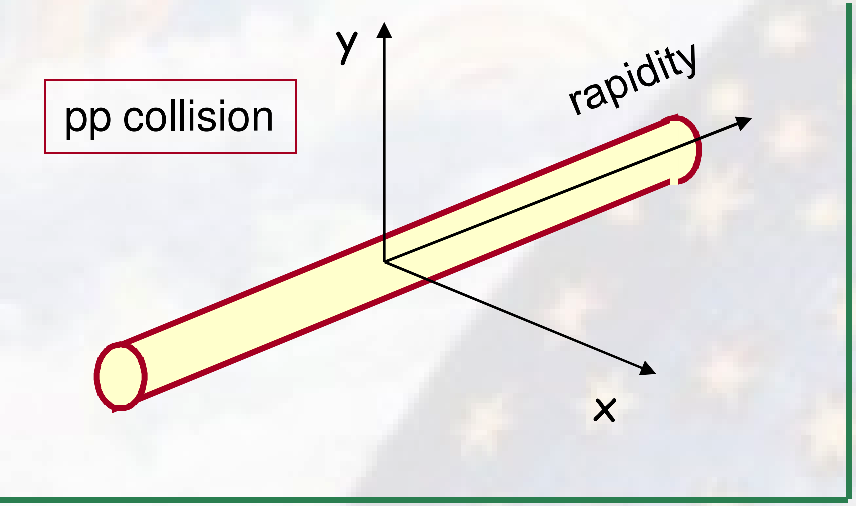


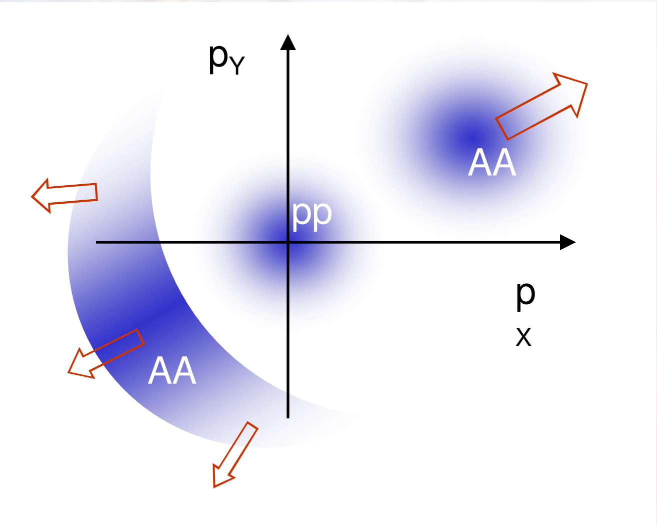
Evolution of a concept of anisotropic flow:
system response to azimuthally asymmetric initial conditions
(one does not need a “true” reaction plane).

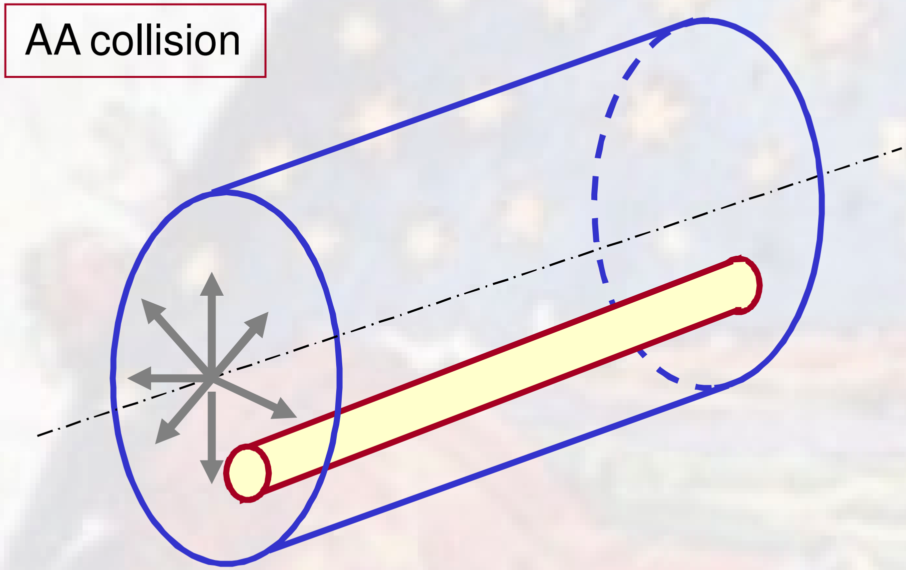
Radial expansion ➔ 2-part azimuthal correlations

[arXiv:nucl-th/0312065]



All particles produced in the same NN-collision (qq-string) experience the transverse radial “push” that is
(a) in the same direction (leads to correlations in phi)
(b) the same in magnitude (→ correlations in p_t)

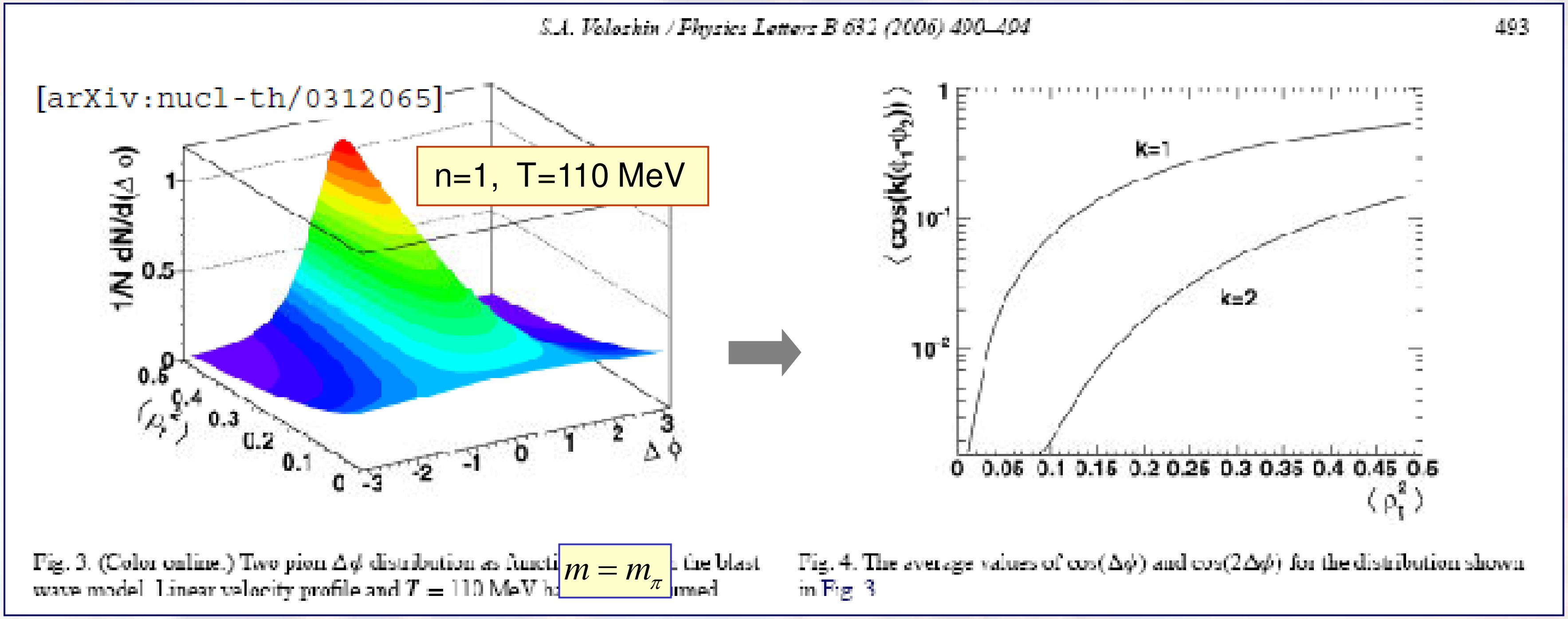




Particle correlations existed in pp – become modified.

→ Long range rapidity correlations become narrow in phi – “ridge” develops
→ Stronger 2-particle pt correlation in narrow phi bins.
→ Narrowing of the charge balance function ($\Delta p_z \approx m_t \sinh(\Delta y)$) -- increase in m_t → decrease in rapidity separation)
→ Charge correlations become narrow in phi.
Azimuthal Balance function
→ stronger in-plane than out-of-plane, etc.

Radial expansion ➔ 2-part azimuthal correlations



S.A. Voloshin / Physics Letters B 632 (2006) 490–494 493

[arXiv:nucl-th/0312065]

n=1, T=110 MeV

Fig. 3. (Color online.) Two pion $\Delta\phi$ distribution as functi the blast wave model. Linear velocity profile and $T = 110$ MeV ha umed

$m = m_\pi$

Fig. 4. The average values of $\cos(\Delta\phi)$ and $\cos(2\Delta\phi)$ for the distribution shown in Fig. 3.

Figures are shown for particles from the same NN collision. Dilution factor to be applied!

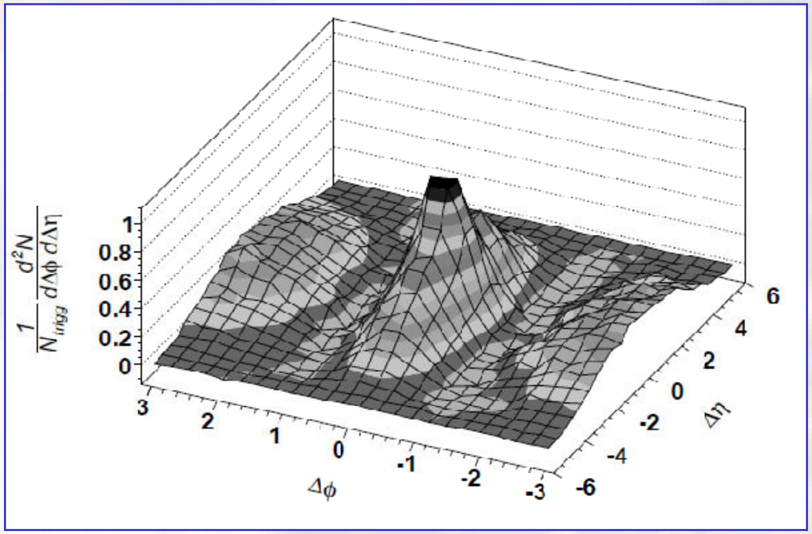
!!! - the large values of transverse flow, $\rho_t^2 > 0.25$, would contradict "non-flow" estimates in elliptic flow measurements

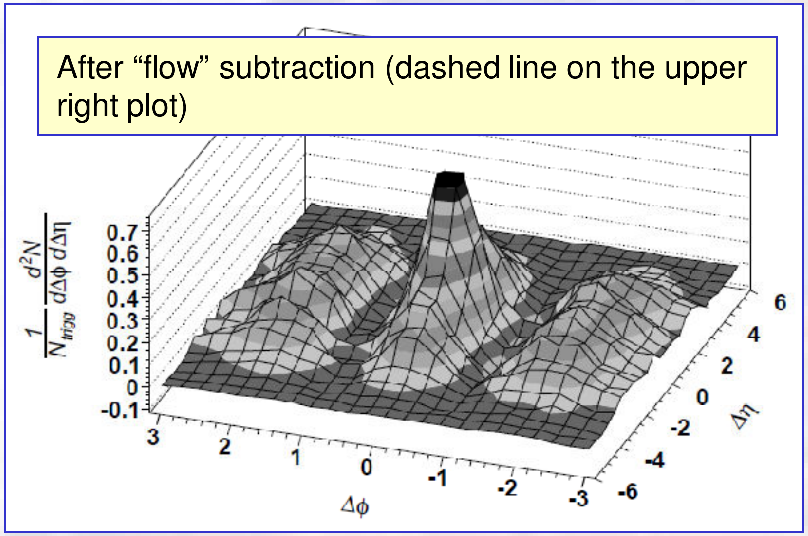
If the average would be taken over all particles including the particles from other NN collisions, the momentum conservation contribution [16] cannot be neglected; it can greatly reduce the effect. Note, however, that the momentum conservation effects are expected to be small for the (azimuthal) charge balance function.

If the momentum conservation effect is approximated by the first harmonic, the amplitude can be estimated from the momentum of the tag particle + "associates" from the same NN collision

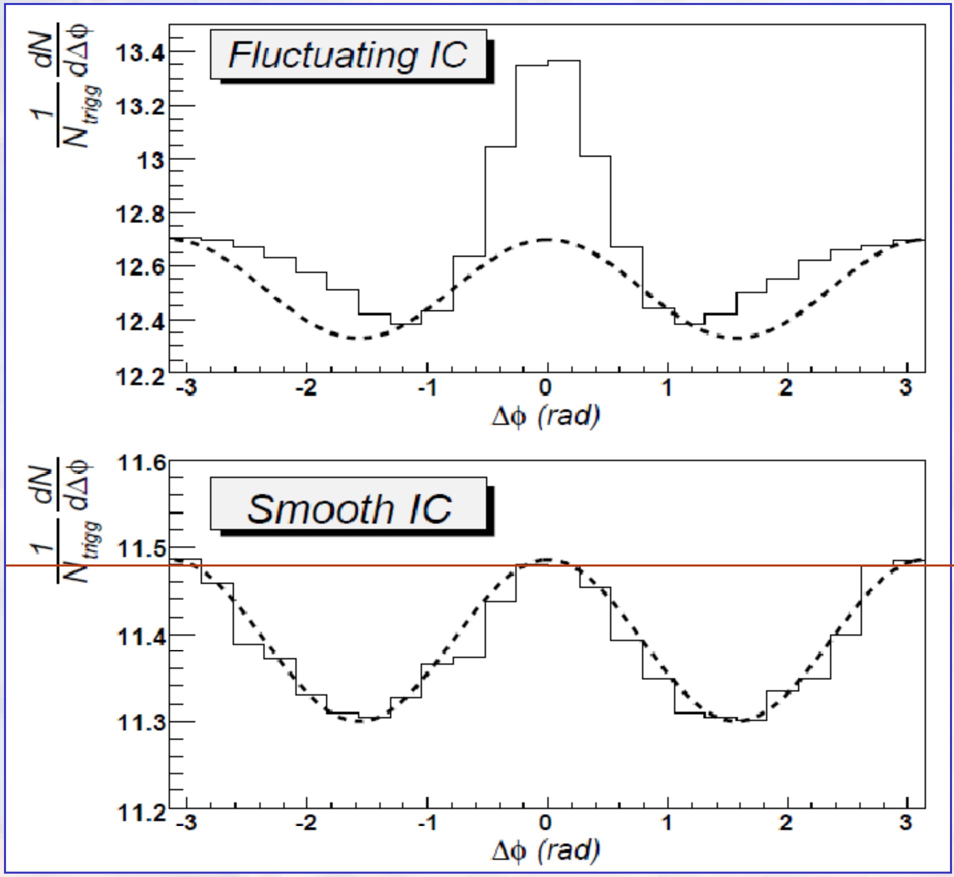
Correlation function

J. Takahashi *et al.*,arXiv:0902.4870v1

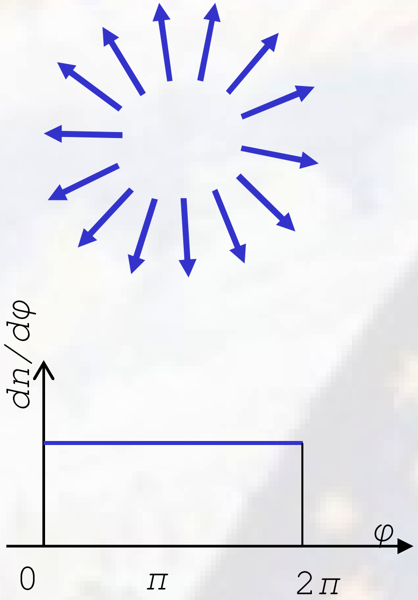




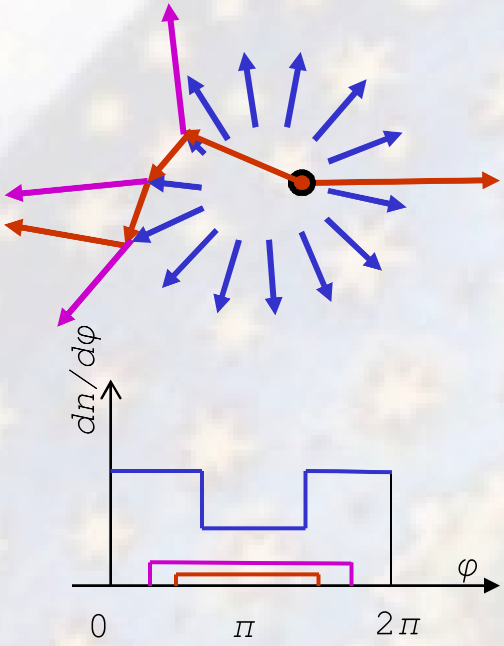
After “flow” subtraction (dashed line on the upper right plot)



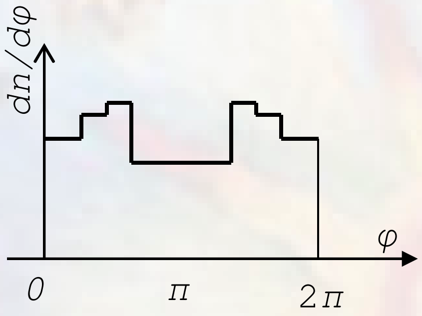
Simple "model" - does not fit to the two component picture



On the top I sketch an event without flow. On the bottom, shown with blue line, is the corresponding azimuthal distribution,



Then I put a "hard" collision in the middle. I concentrate on the away side – suppose the trigger (taken at φ=0) escapes without interaction. The particles from "background", which interacted with particles from the hard collision I denote in violet. At the bottom three distributions in corresponding colors.



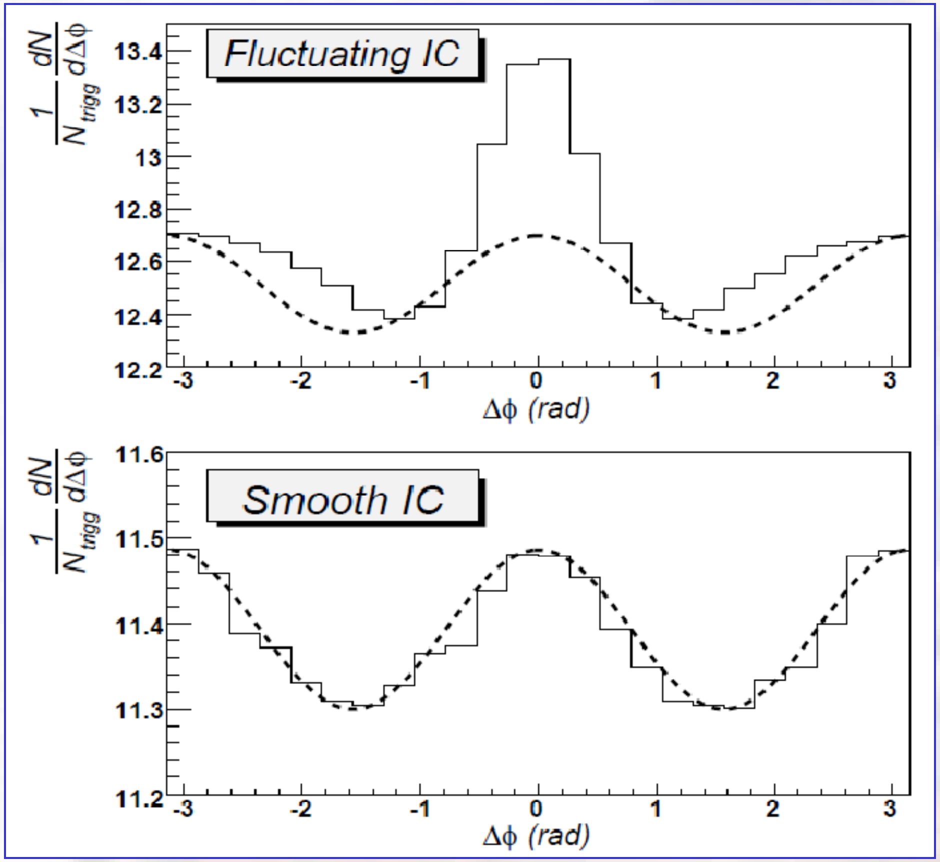
The resulting distribution.
The question is:
how one can split all these particles into 2 components?

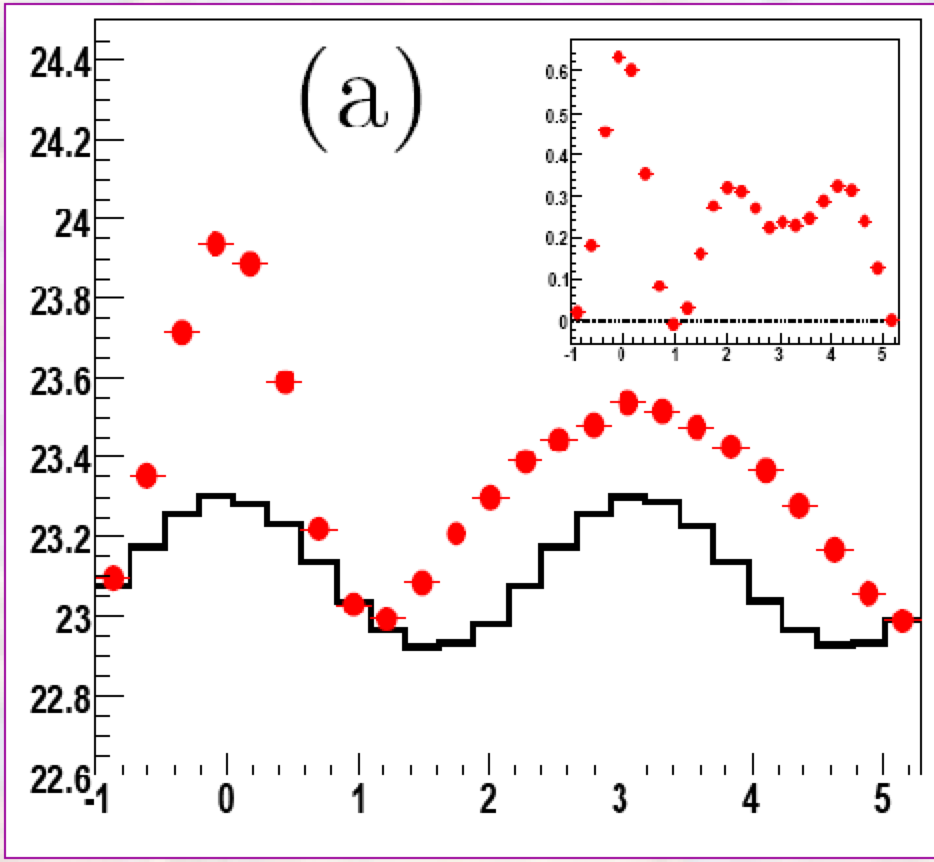
Conclusion: Modified "jets" ←→ modified flow "background"

Side note: difficult to avoid negative regions in the correlation functions

Note that in all simulations "supporting" ZYAM the two component model was assumed from the very beginning.

“Mach” cone


Fluctuating IC
$\frac{1}{N_{trigg}}\frac{dN}{d\Delta\phi}$
13.4
13.2
13
12.8
12.6
12.4
12.2
-3
-2
-1
0
1
2
3
Δϕ (rad)
Smooth IC
$\frac{1}{N_{trigg}}\frac{dN}{d\Delta\phi}$
11.6
11.5
11.4
11.3
11.2
-3
-2
-1
0
1
2
3
Δϕ (rad)


(a)
24.4
24.2
24
23.8
23.6
23.4
23.2
23
22.8
22.6
-1
0
1
2
3
4
5
0.6
0.5
0.4
0.3
0.2
0.1
0
-1
0
1
2
3
4
5

How far are we from the "hydro limit"?

R. S. Bhalerao, J. P. Blaizot, N. Borghini and J. Y. Ollitrault, Phys. Lett. B **627**, 49 (2005).

$$\frac{v_2}{\varepsilon} = \frac{v_2^{\rm hydro}}{\varepsilon}\,\frac{1}{1+K/K_0}$$

$$\frac{1}{K} = \frac{\sigma}{S}\frac{dN}{dy}c_s$$

$$K_0 \simeq 0.7$$

Comparing these numbers to the experimental data points one observes that deviations from ideal hydrodynamics are as large as 30%, even for central Au-Au collisions.

Our two estimates $\sigma = 4.3$ mb (Glauber initial conditions) and $\sigma = 7.6$ mb (CGC initial conditions) thus translate into $\lambda = 0.60$ fm, $\eta/s = 0.19$ and $\lambda = 0.34$ fm, $\eta/s = 0.11$, respectively.

Hans-Joachim Drescher,[1] Adrian Dumitru,[2] Clément Gombeaud,[3] and Jean-Yves Ollitrault[3]

PHYSICAL REVIEW C 76, 024905 (2007)

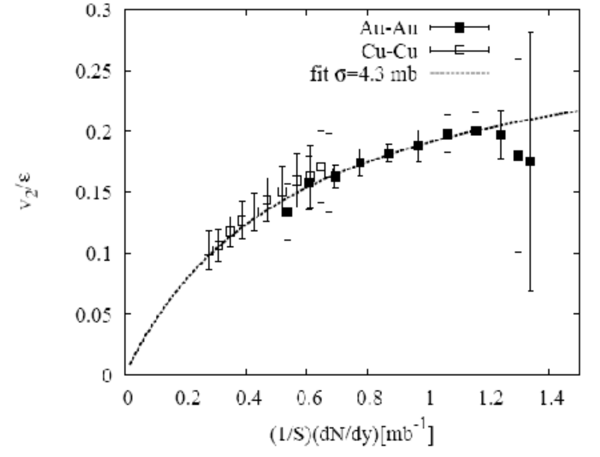


FIG. 1: Variation of the scaled elliptic flow with the density, assuming initial conditions from the Glauber model. The line is a 2-parameter fit using Eqs. (2) and (4).

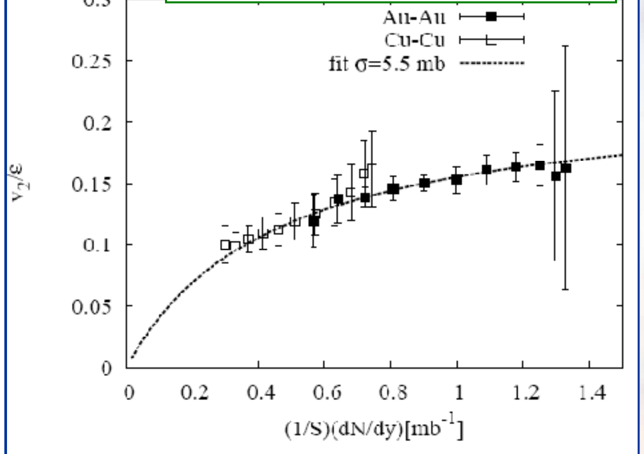
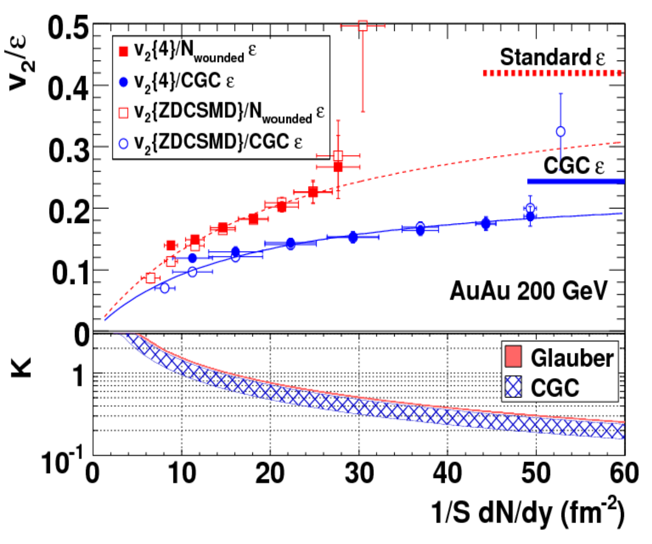


FIG. 2: Same as Fig. 1, using CGC initial conditions.

- Even central Au+Au collisions are about 30-50% away from ideal hydro limit.

- η /s is about factor of 2 -- 4 larger compared to the conjectured low limit of 1/(4π),

Note: assumed constant speed of sound - no phase transitions, change in initial conditions with energy, 2d, boost invariance, etc..



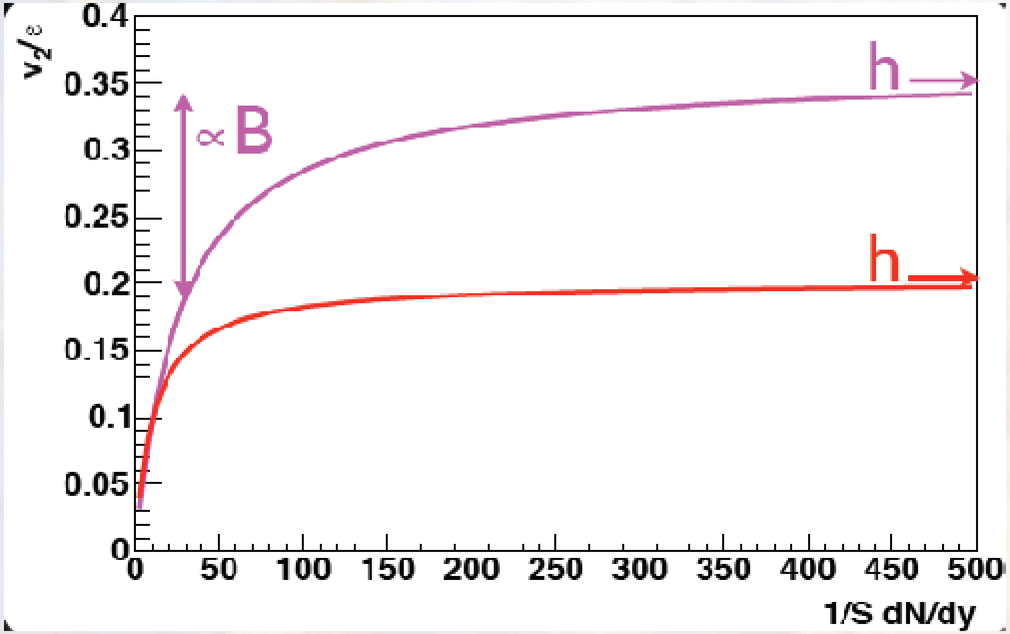
note that there is a difference of a factor of "2" in the definitions of S

from R. Snellings (QM09)

$$\frac{v_2}{\varepsilon} = \frac{h}{1 + B/(\frac{1}{S}\frac{dN}{dy})}$$

h related to EoS; large h → hard EoS

B ∝ viscous correction



Fit to hydro calculations

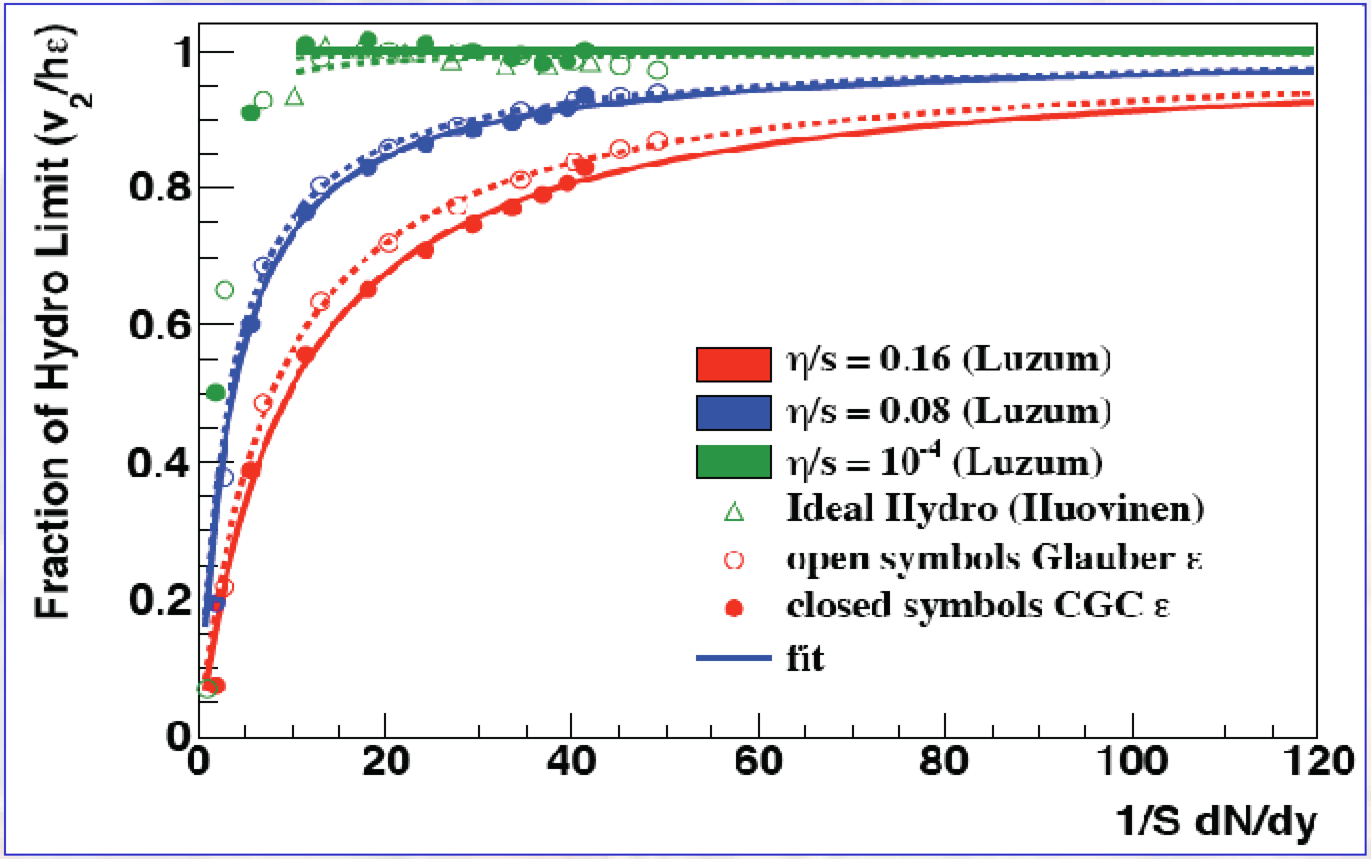
$$\frac{v_2}{h\varepsilon} = \frac{1}{1 + B / \left(\frac{1}{S}\frac{dN}{dy}\right)}$$

h= 0.20 ± 0.02

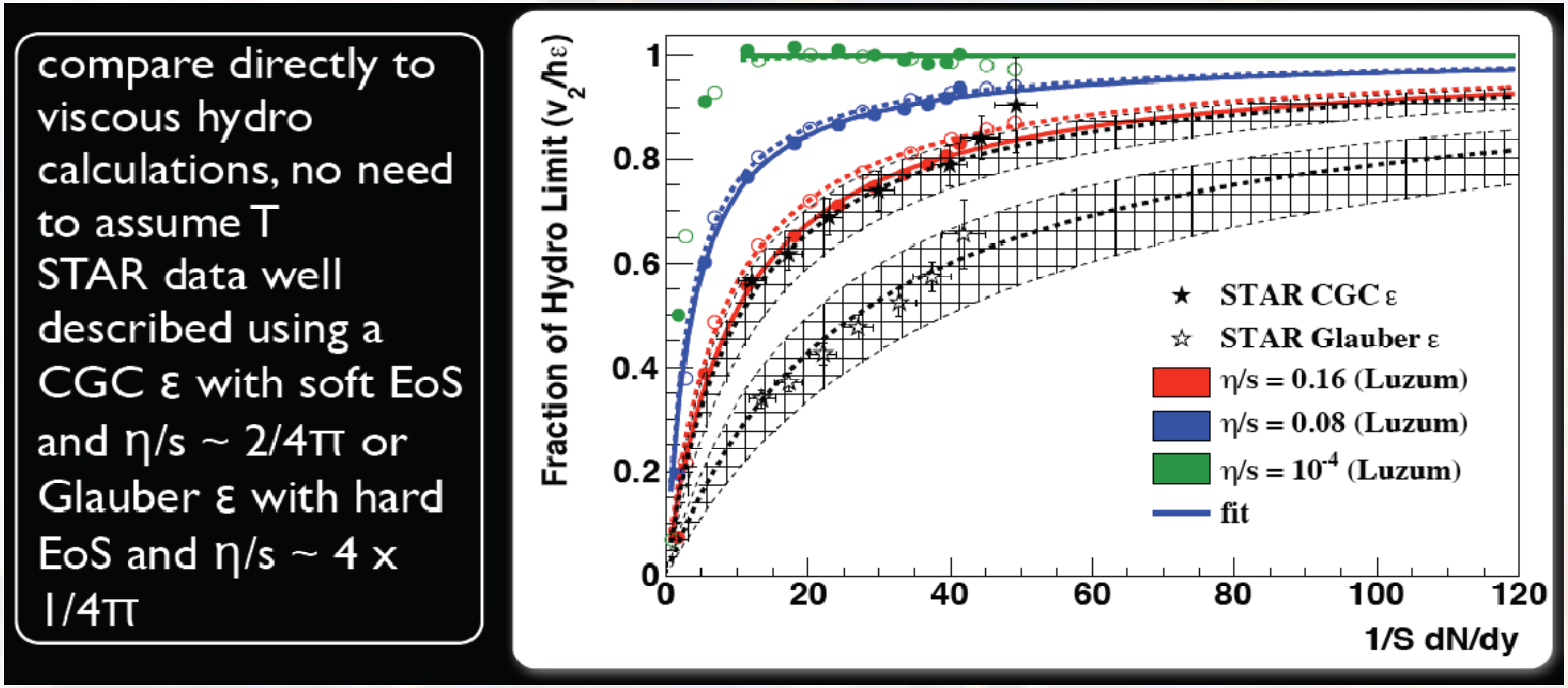
B = 0.70 ± 0.05

B = 0.33 ± 0.03

B = 10^{-7}



Direct comparison and fit



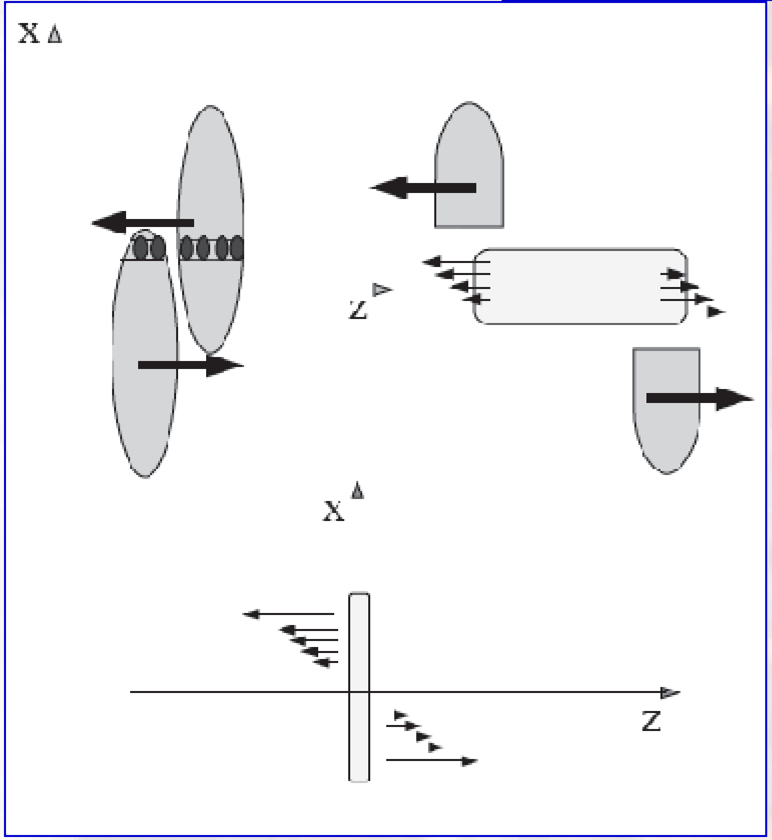
compare directly to viscous hydro calculations, no need to assume T

STAR data well described using a CGC ε with soft EoS and η/s ~ 2/4π or Glauber ε with hard EoS and η/s ~ 4 x 1/4π

R. Snellings. QM2009

Modification of the initial conditions

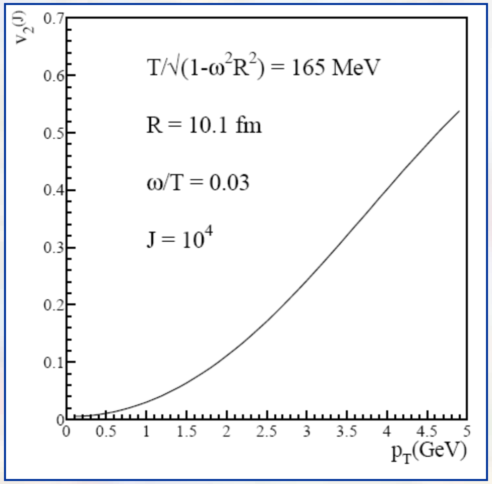
Initial flow field is non-isotropic. It might be an important effect to include into calculations!
Revival of interest to the picture of rotating system (Dremin, Kharzeev, …)



Contribution to the in-plane expansion due to initial (longitudinal) velocity gradient

$$\rho_0\gamma_0^3 \frac{\partial u_i}{\partial t}\Big|_{t=0} = -\frac{1}{4}\frac{\partial \rho\gamma^2}{\partial x_i}\Big|_{t=0} + \frac{1}{4}2\rho_0\gamma_0^4 v_{z0}\frac{\partial v_{z0}}{\partial x_i}\Big|_{t=0}$$

F. Becattini F. Piccinini
J. Rizzo
arXiv:0711.1253v2



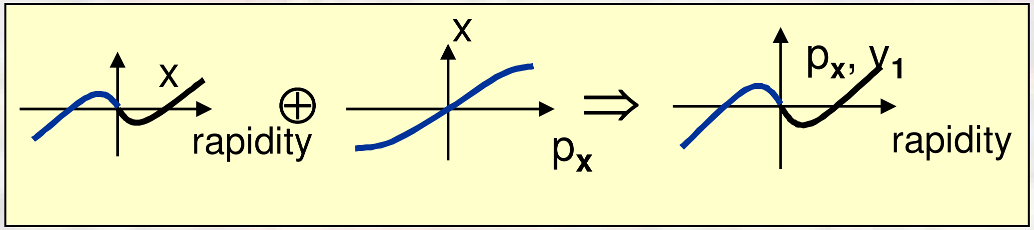
It must also lead to directed flow! Indeed…

Directed flow as effect of transient matter rotation in hadron and nucleus collisions

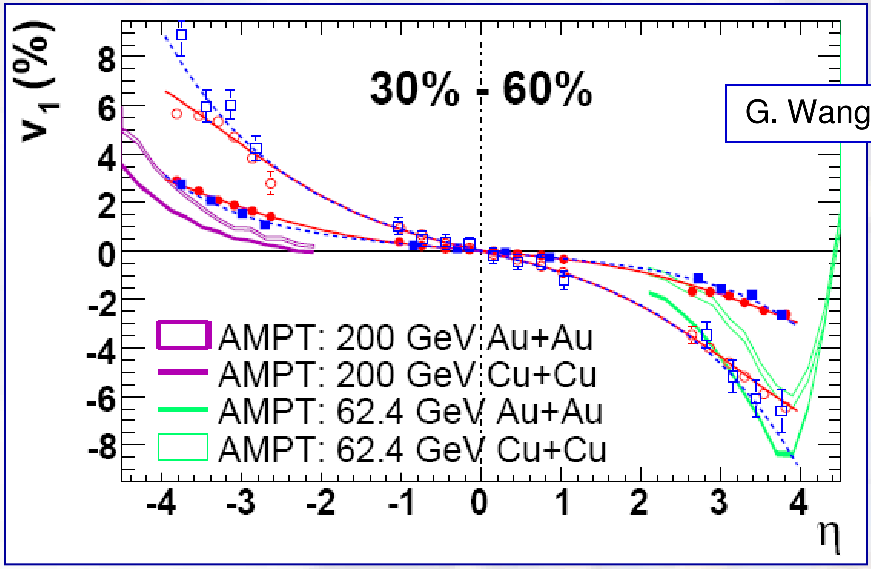
arXiv:0709.4090v3

S.M. Troshin, N.E. Tyurin

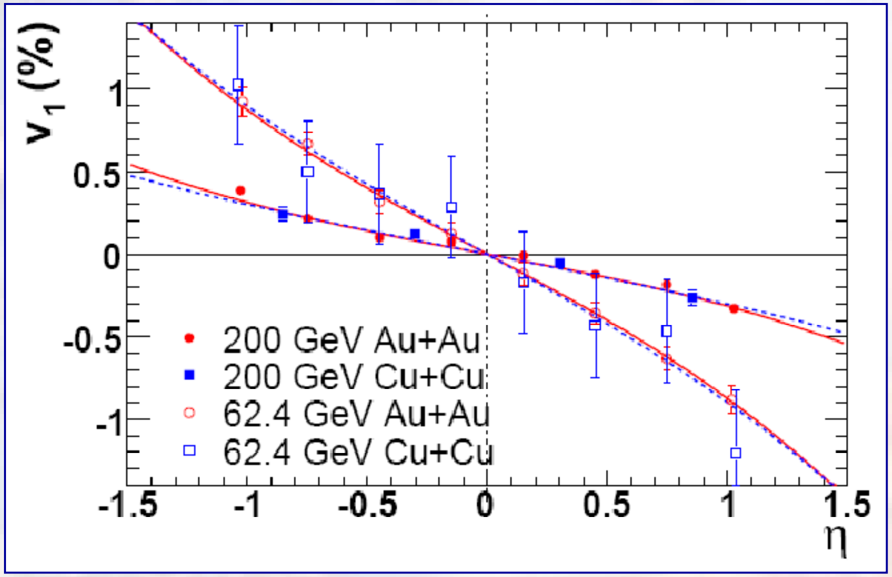
R. J. M. Snellings, H. Sorge, S. A. Voloshin, F. Q. Wang and N. Xu, Phys. Rev. Lett. 84, 2803 (2000) [arXiv:nucl-ex/9908001].



Directed flow



G. Wang (STAR), QM2006



Not quantitatively explained by any model (even close)!
Error-bars at the level of $< 10^{-3}$!

AuAu and CuCu are very similar at the same centrality!

(Magenta curves are polynomial fits to guide the eye)

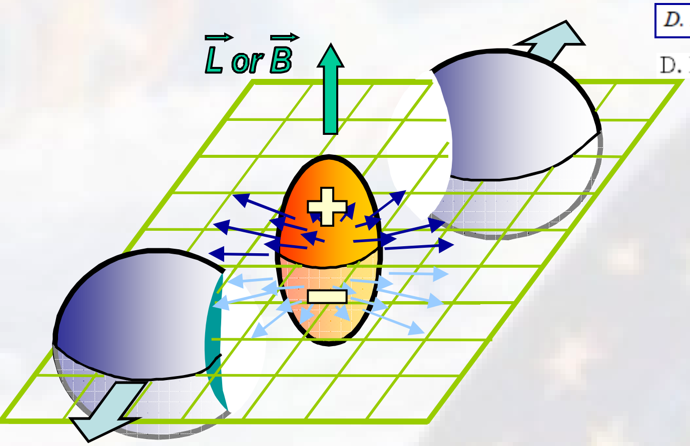
High accuracy of these measurements achieved by
- using STAR ZDC-SMD ("spectator neutrons")
- 3 –particle correlations (mixed harmonics)

3 particle correlations measure the difference in correlations projected into the reaction plane and out-of-plane directions making use of strong elliptic flow to define the plane..

$$\langle\cos(\phi_a+\phi_\beta-2\phi_c)\rangle = \langle\cos(\phi_a+\phi_\beta-2\Psi_{RP})\rangle \; v_{2,c}$$

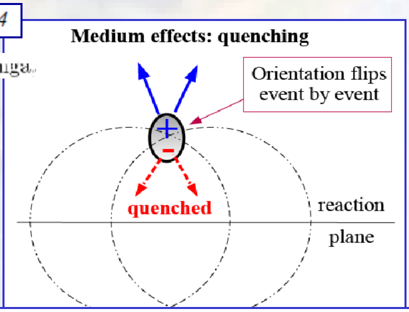
$$\begin{aligned}&\langle\cos(\phi_\alpha+\phi_\beta-2\Psi_{RP})\rangle\\ &= \underline{\langle\cos(\phi_\alpha-\Psi_{RP})\cos(\phi_b-\Psi_{RP})\rangle} - \underline{\langle\sin(\phi_\alpha-\Psi_{RP})\sin(\phi_b-\Psi_{RP})\rangle}\\ &\approx \; v_{1,a}v_{1,b}\end{aligned}$$

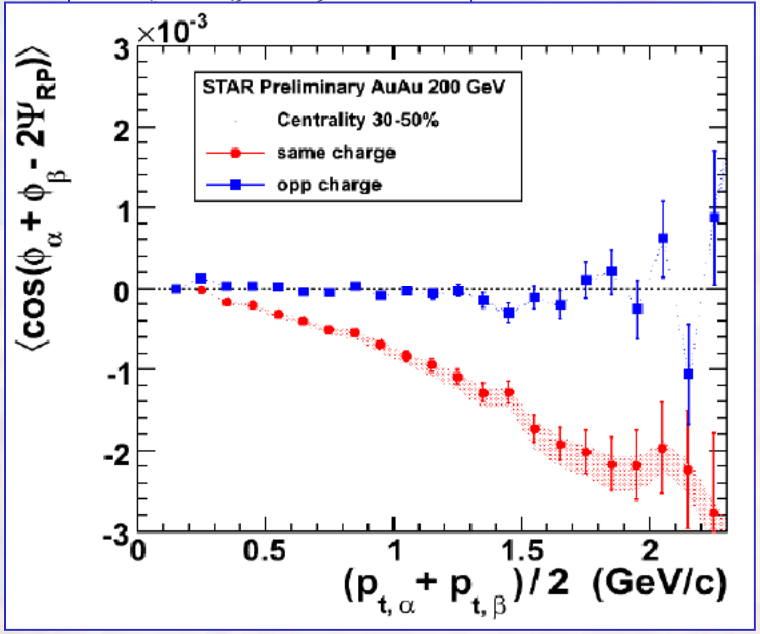
Probe for the strong parity violations

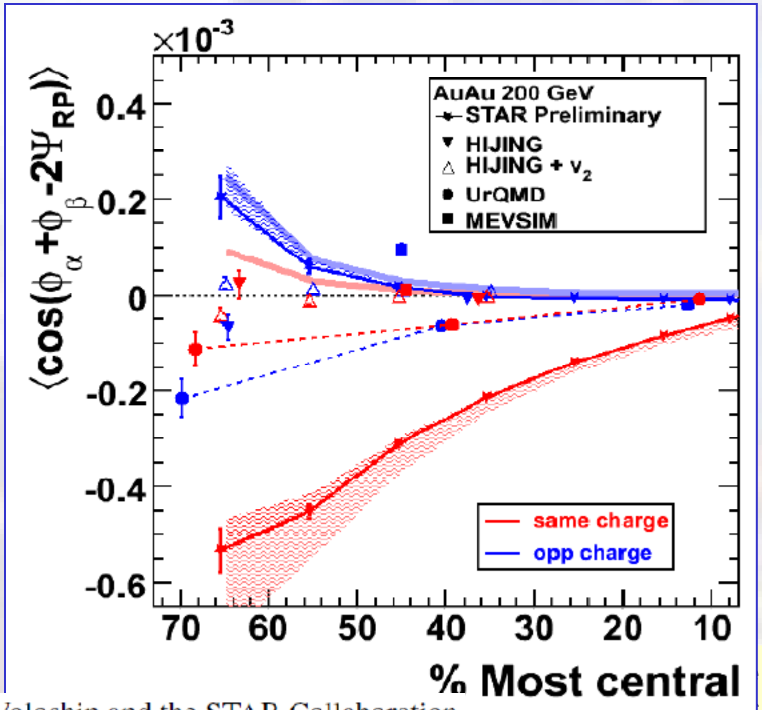


D. Kharzeev / Physics Letters B 633 (2006) 260–264

D. E. Kharzeev, L. D. McLerran and H. J. Warringa,
arXiv:0711.0950 [hep-ph]







Sergei A. Voloshin and the STAR Collaboration
arXiv:0907.2213v1 [nucl-ex] 13 Jul 2009

rtainty from
flowing clusters(e.g. decay of
flowing resonances)

> Qualitatively the results agree with the magnitude and gross features of the theoretical predictions for $\mathcal{P}$-violation in heavy ion collisions, except, probably, transverse momentum dependence. Though a particular observable used in our analysis is $\mathcal{P}$-even and in principle might be sensitive to other, not parity violating, effects, so far, with systematics checks mentioned above, we could not identify such that would explain the observed correlations.

Nearest future: RHIC Beam energy scan

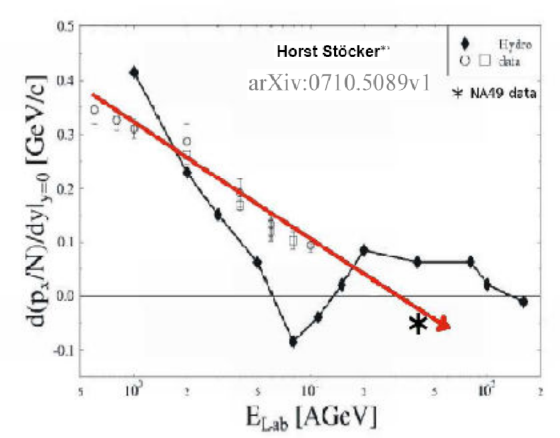
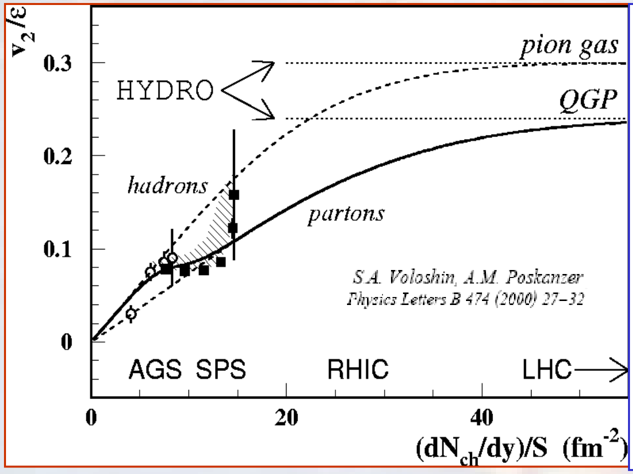
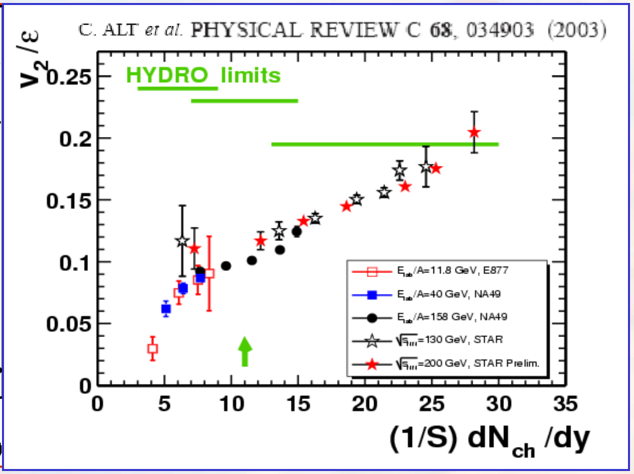


Figure 5: The proton dp_x/dy-slope data measured by SIS and AGS compared to a one-fluid hydrodynamical calculation. A linear extrapolation of the AGS data indicates a collapse of flow at $E_{Lab} \approx 30A$ GeV (see also Ref. [46]). The point at $40A$ GeV is calculated using the NA49 central data (cf. Alt *et al.*) [38].

Low energy scan: Search for the phase transition
1. Collapse of directed flow
2. Non-monotonic behavior of v2/eps, and/or
   scaling violation (may also reflect change in the initial
   conditions (e.g. participant Glauber → CGC)





U=U Collisions

ADVANTAGE OF U+U OVER Au+Au COLLISIONS AT . . .

PHYSICAL REVIEW C 73, 034911 (2006)
C. NEPALI, G. FAI, AND D. KEANE

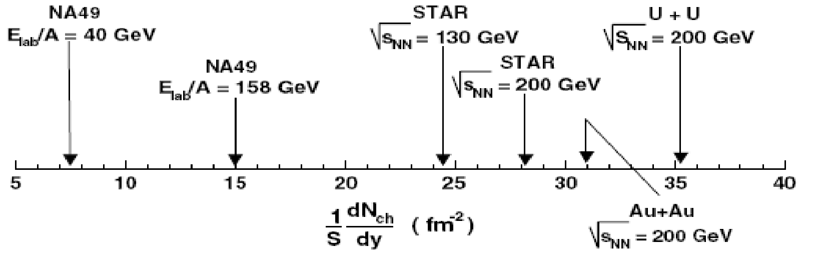
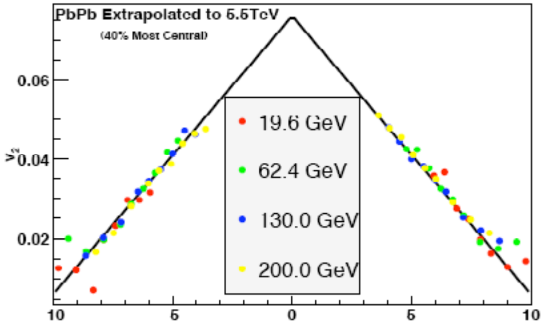


FIG. 8. Maximum values of $(1/S)dN_{ch}/dy$. Values from NA49 and STAR correspond to central Pb+Pb [19] and central Au+Au [5], respectively. The results labeled Au+Au $\sqrt{s_{NN}}$ = 200 GeV and U+U $\sqrt{s_{NN}}$ = 200 GeV correspond to the top 5% in $dN_{ch}/d\eta$ from the present simulation.

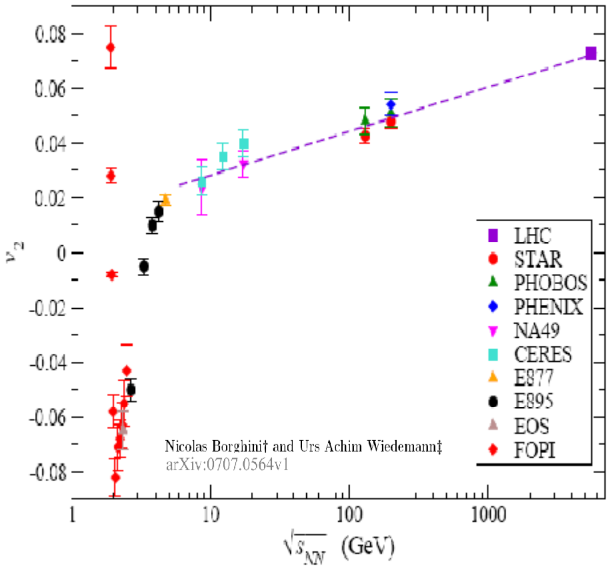
With upgrades we will have
1. Higher pt reach
2. Better PID, and more

LHC



Wit Busza arXiv:0710.2293v1

Figure 11 Extrapolation of the elliptic flow parameter v_2 measured by Phobos at $\sqrt{s_{NN}}$ = 19.6, 62.4, 130.0 and 200 GeV for the 40% most central AuAu collsions [13], to PbPb at $\sqrt{s_{NN}}$ = 5.5 TeV. See text.



Nicolas Borghini† and Urs Achim Wiedemann‡
arXiv:0707.0564v1

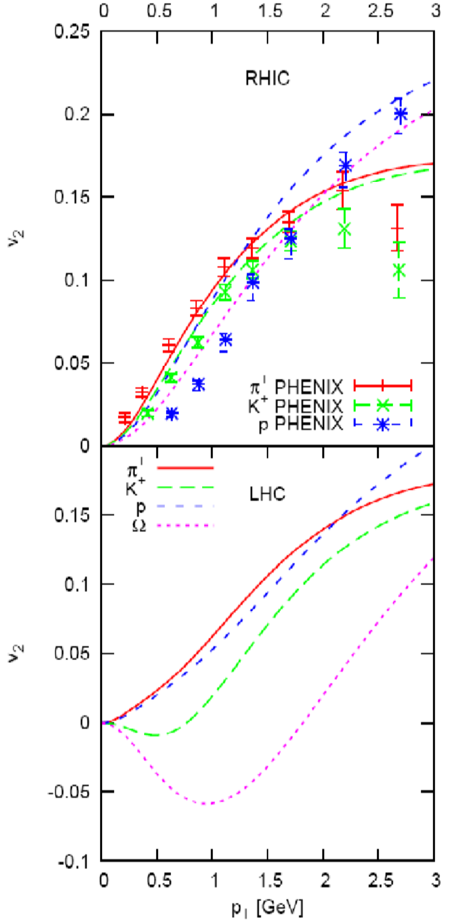
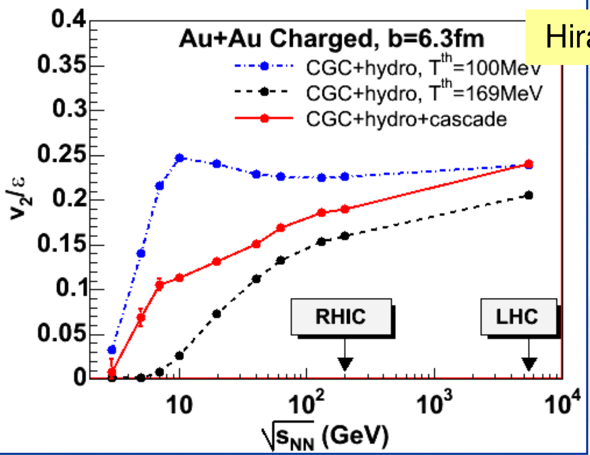


FIG. 3: Elliptic flow parameter v_2 as a function of the transverse momentum p_t for mid-central (b = 8 fm) Au+Au/Pb+Pb reactions as obtained from the recombination approach. The lines indicate the calculations for π^+, K^+, p and Ω^-. **Upper Panel:** v_2 at RHIC ($\sqrt{s}$ = 200 GeV) compared to PHENIX data [15]. **Lower Panel:** Prediction for LHC ($\sqrt{s}$ = 5.5 TeV).

"Naive" extrapolations lead to elliptic flow values at LHC up to 50% larger than at RHIC.



Hirano, et al., QM2006

- Predictions are made.
- Collaborations ready

Looking forward for the first collisions

Conclusions

1. Significant progress in understanding of
   - the role of viscosity
   - initial conditions
   - flow fluctuations

2. New ideas for the anisotropic flow are being developed, such as
   - role of non-zero vorticity (system rotation)

3. Directed flow still remains under explored.

3. Constiuent quark number scaling needs full understanding.

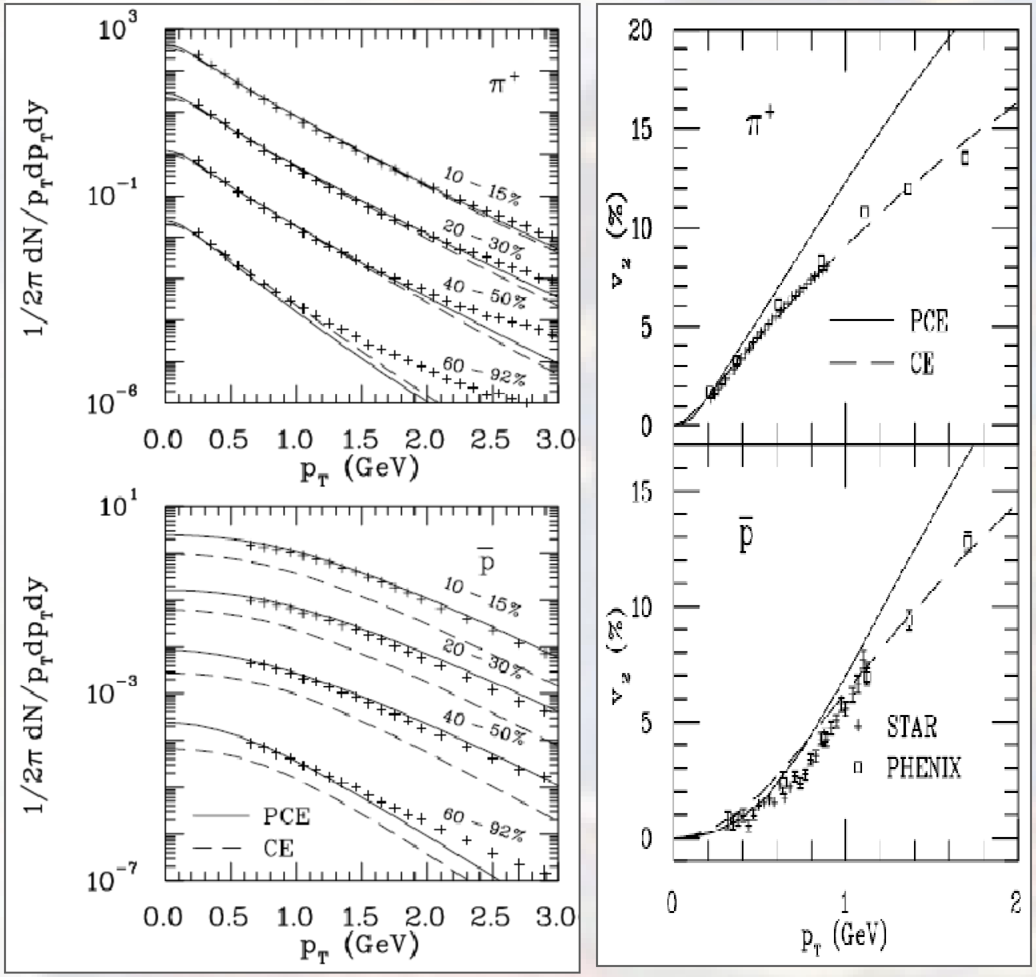
Azimuthal correlations analyses of non-central collisions established to be one of the most informative direction in HIC studies (+ Global polarization, parity violation studies, etc.)

Bright and exciting future at RHIC and LHC!

Backup slides

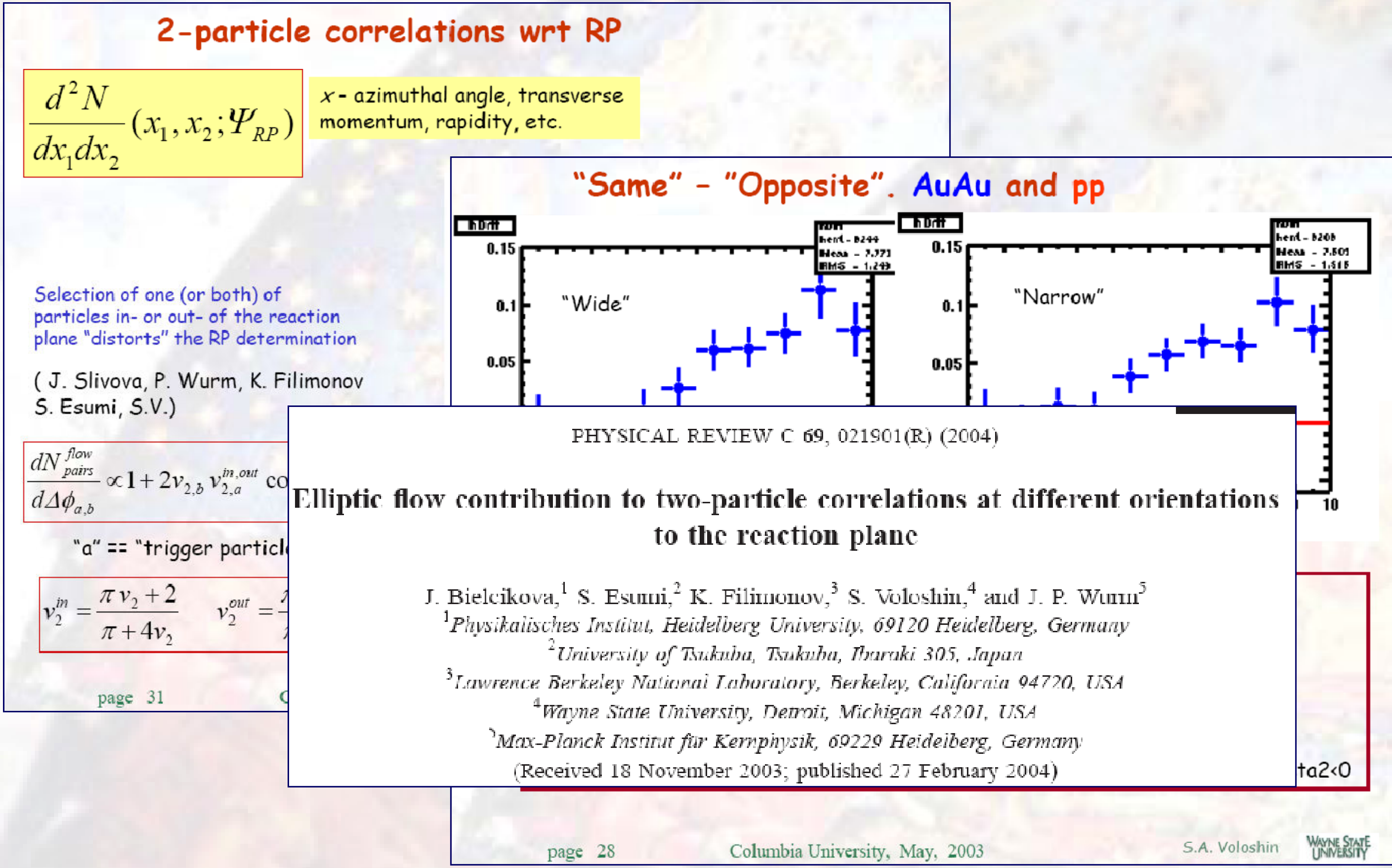
Ideal Hydro → Viscous hydro

Pasi Huovinen
arXiv:0710.4379v1



Ideal hydro, if tuned to spectra, over predicts elliptic flow! Including viscosity might improve agreement with data.

2-particle correlations relative to the Reaction Plane



2-particle correlations wrt RP

$$\frac{d^2N}{dx_1dx_2}(x_1,x_2;\Psi_{RP})$$

x - azimuthal angle, transverse momentum, rapidity, etc.

Selection of one (or both) of particles in- or out- of the reaction plane "distorts" the RP determination

(J. Slivova, P. Wurm, K. Filimonov S. Esumi, S.V.)

$$\frac{dN^{flow}_{pairs}}{d\Delta\phi_{a,b}} \propto 1+2v_{2,b}\,v^{in,out}_{2,a}\ \mathrm{co}$$

"a" == "trigger particl

$$v_2^{in}=\frac{\pi v_2+2}{\pi+4v_2} \qquad v_2^{out}=$$

page 31

"Same" - "Opposite". AuAu and pp

ta2<0

page 28 Columbia University, May, 2003 S.A. Voloshin

PHYSICAL REVIEW C 69, 021901(R) (2004)

Elliptic flow contribution to two-particle correlations at different orientations to the reaction plane

J. Bielcikova,[1] S. Esumi,[2] K. Filimonov,[3] S. Voloshin,[4] and J. P. Wurm[5]
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[2] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[3] *Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4] *Wayne State University, Detroit, Michigan 48201, USA*
[5] *Max-Planck Institut für Kernphysik, 69229 Heidelberg, Germany*

(Received 18 November 2003; published 27 February 2004)

Correlation functions (cumulants)

$$C_2(x_1,x_2) = \rho_2(x_1,x_2) - \rho_1(x_1)\rho_1(x_2)$$

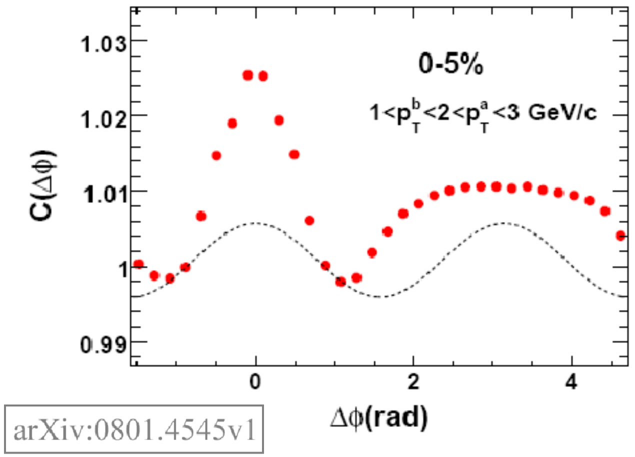
$$R_2(x_1,x_2) = \frac{C(x_1,x_2)}{\rho_1(x_1)\rho_1(x_2)} \qquad \left[B(y_1,y_2) = \frac{C_2(y_1,y_2)}{\rho_1(y_1)} \right]$$

$$\int dx \rho_1(x) = \langle n \rangle$$

$$\int dx_1 \int dx_2 \rho_2(x_1,x_2) = \langle n(n-1) \rangle$$

$$C_3 = \rho_3(x_1,x_2,x_3) - C_2(x_1,x_2)\rho_1(x_3) - C_2(x_1,x_3)\rho_1(x_2) - C_2(x_2,x_3)\rho_1(x_1) - \rho_1(x_1)\rho_1(x_2)\rho_1(x_3)$$

Note that cumulants are the only "true" indicators of correlations. If cumulant is zero, there is no way to prove that correlations (e.g due to clustering or temperature fluctuations) exists (though they might be present).



arXiv:0801.4545v1

FIG. 2: (Color online) The correlation function for $2 < p_T^a < 3$, $1 < p_T^b < 2$ GeV/c in 0-5% Au+Au collisions. The dashed line represents the estimated elliptic flow modulated combinatoric background using zero yield at minimum (ZYAM) method (see Section.III E).

Would the interpretation of the figure on the left change (as leading to the two bump structure on the away side)?

Not much, in a sense that if one compare the cumulant (close to shown in red points) to the cumulant expected from "only elliptic flow" (different from dash curve only in normalization), the difference will exhibits the same two bumps. But one will be free from confusing picture that there are indeed two components behind this result.

“Consequences” – possible misinterpretations

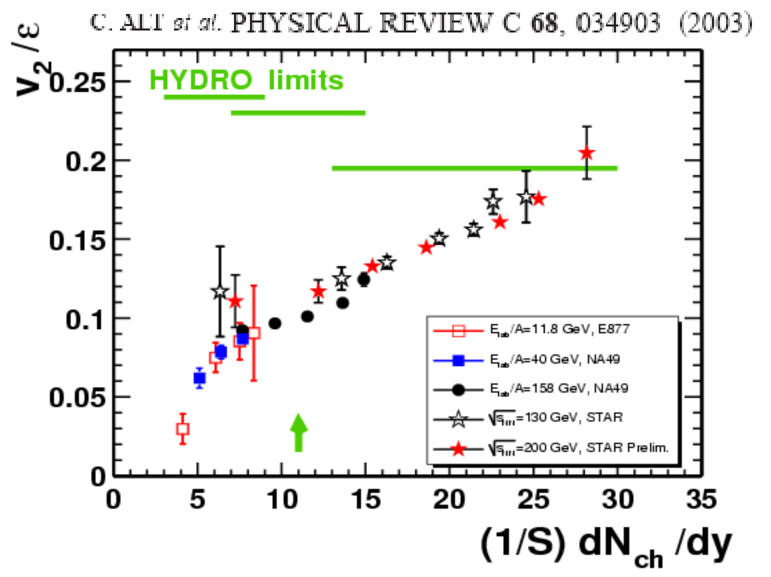
- If the “background” is not correctly identified (and from the above I would conclude that in many cases we just do not know how to do it) we can fool ourselves (and others) talking about the pt spectra of associated particles, Mach cones, etc.

For example, having two back-to back jets with, e.g. 10 GeV each, and redistributing this 10 GeV among 100 particles but counting above “background” only 5, we would conclude that we have a component carrying 2 GeV per particle, which would have nothing to do with reality. Similar can be said about baryon/meson ratios in the “correlated part”, etc.

conclusions

1. We should take ZYAM and similar with **much** of caution….
2. We should always include in publications “raw” data, namely single, two, and three particle densities (+ cumulants, etc) before we apply any manipulations to them. I put “raw” in quotation marks, as those, are to be corrected for efficiencies, etc. Otherwise we can be at risk that in a few years the publications can be useless.

Differential flow,


C. ALT *et al.* PHYSICAL REVIEW C 68, 034903 (2003)

$v_2\{4\}$ and "standard" ε was used in this plot!

The maximum flow is reached at higher transverse momenta in more central collisions
➔ indicates higher degree
of "thermalization" in more central collisions