Lecture 3, Part 1: Anisotropic flow

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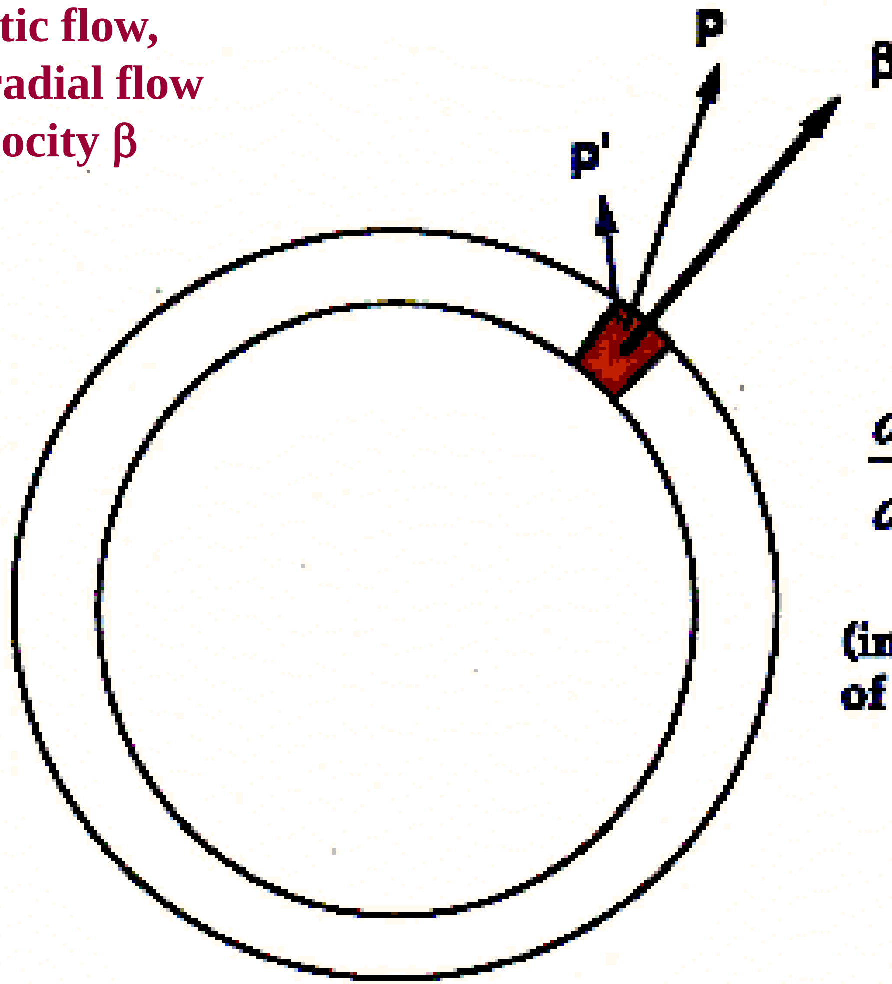
Emission from a Thermal Expanding Source

No elliptic flow,
strong radial flow
with velocity β

Cent Mid-
collisions

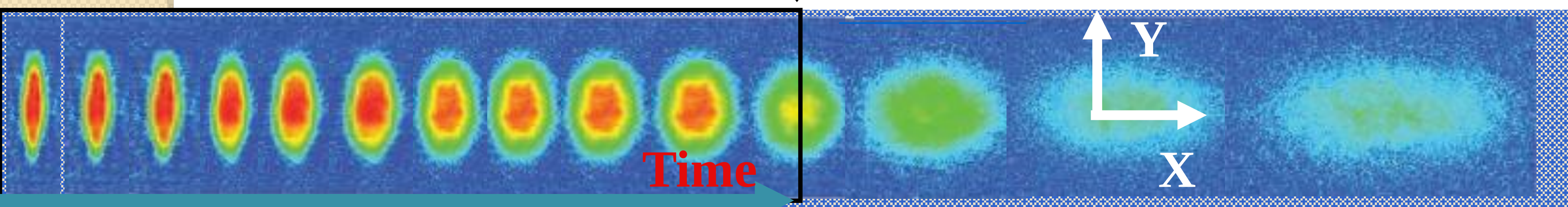
Reacti
plane

Dashed li
sphere ra

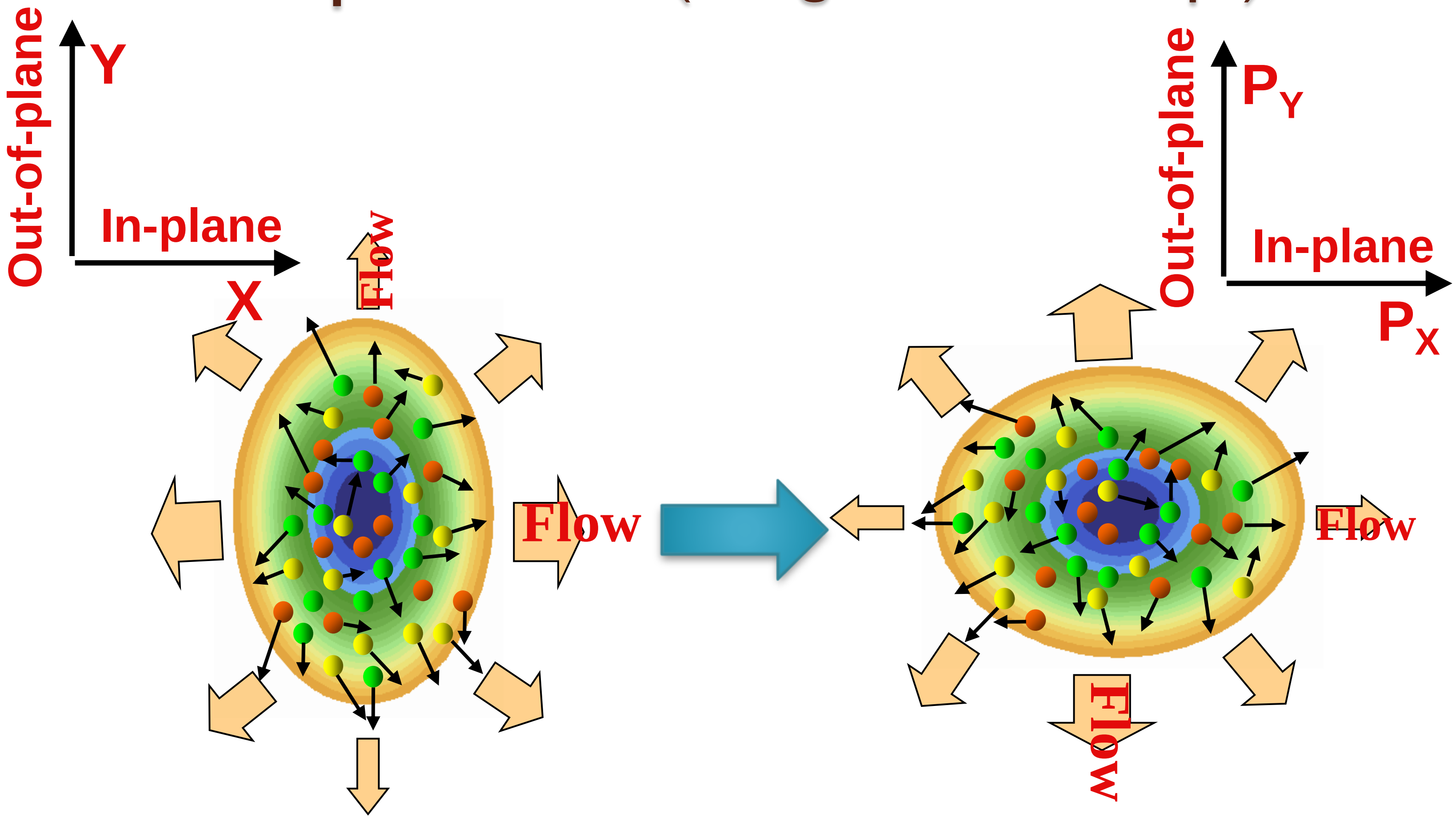


$$\frac{d^3N}{dp'^3} \approx e^{-E/T}$$

(in the rest frame
of each element)



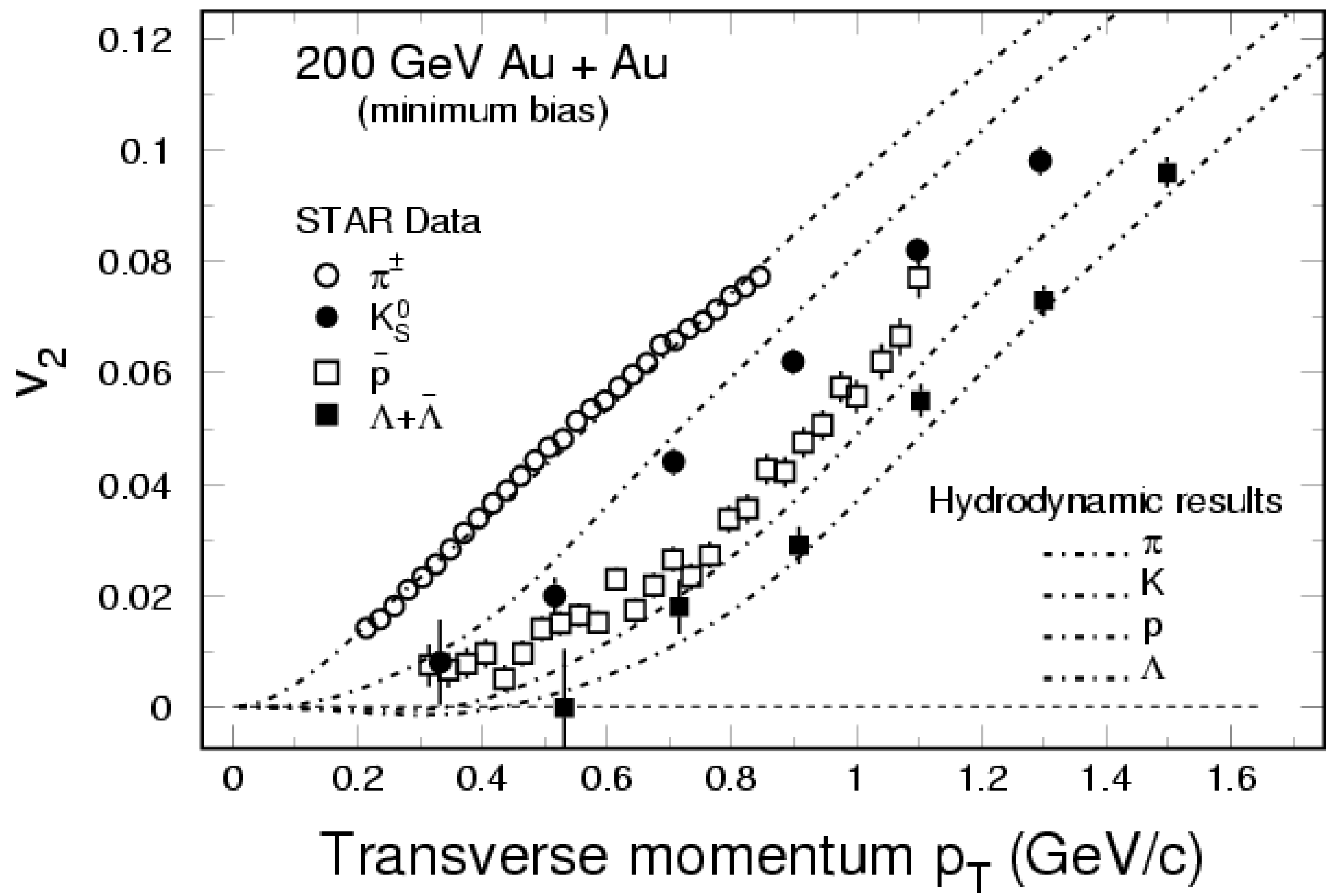
Elliptic Flow (the general concept)



•If no interactions (collectivity) between partons (hadrons), then particles will be emitted isotropically in momentum space.

•If interactions, then $p_x > p_y$. Anisotropy (v_2) is measure of interaction strength.

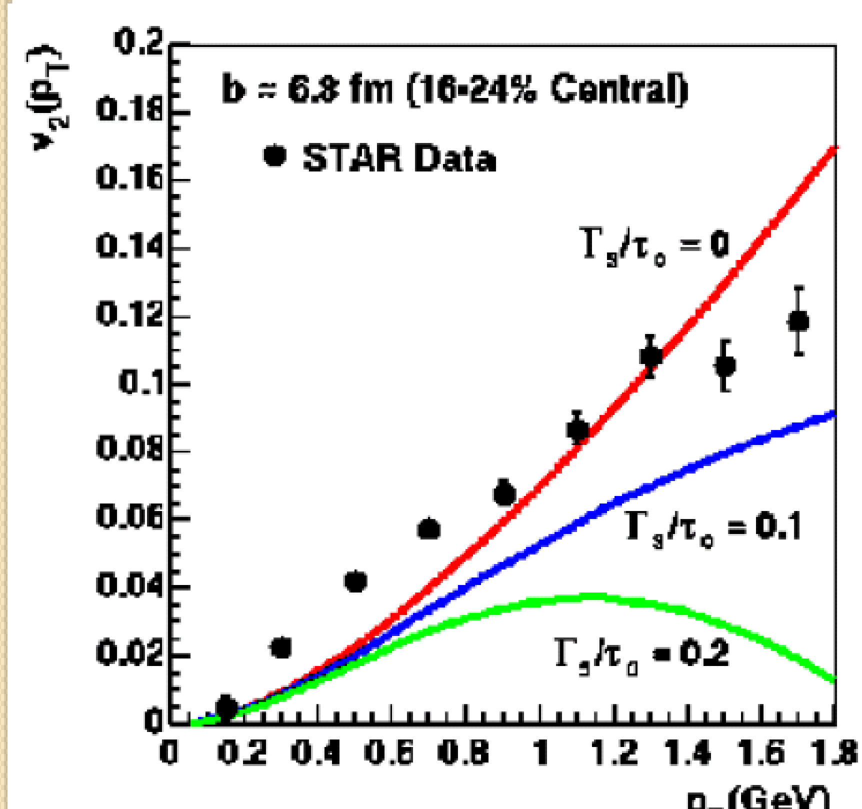
Elliptic flow described by fluid dynamics



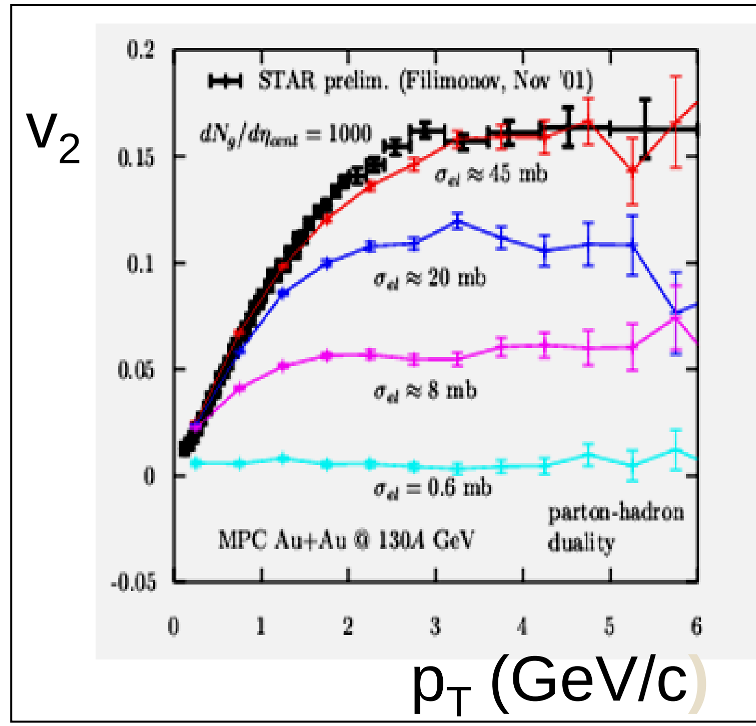
<u>Consequence:</u> if ideal hydrodynamics works (= zero mean free path) then the interaction strength between partons is maximum = strong coupling = ideal fluid behavior

How strong is the coupling ?

Navier-Stokes type calculation of viscosity – near perfect liquid
Viscous force ~ 0



Simple pQCD processes do not generate sufficient interaction strength (2 to 2 process = 3 mb)

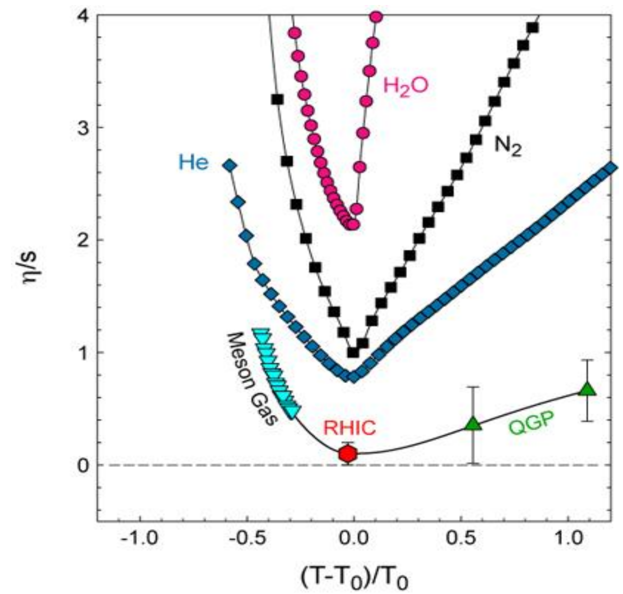


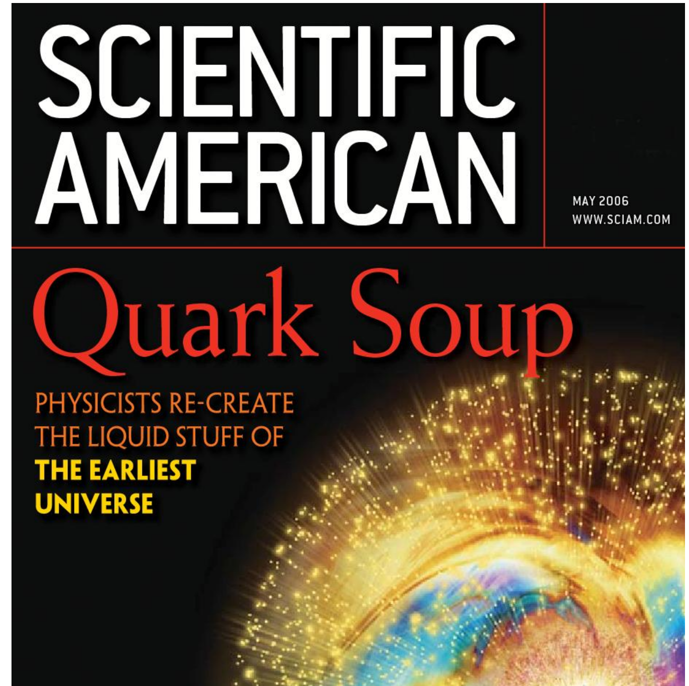
Recently revised through enhanced 2 to 3 processes (multi-parton) (BAMPS code, Frankfurt)

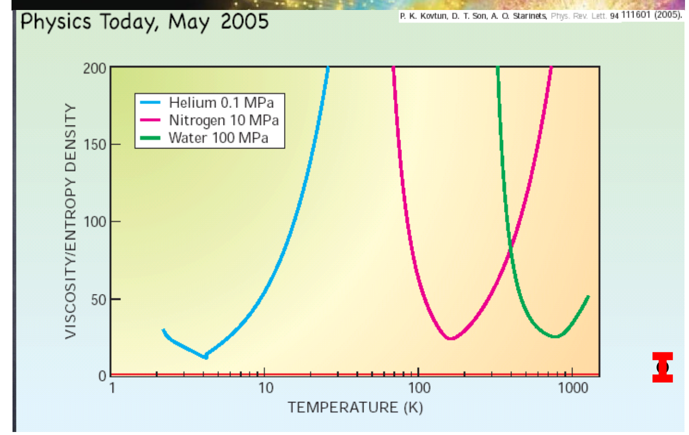
Lessons from RHIC: The Quark Soup

(AIP Science Story of 2006)

Lacey et. al, PRL.98:092301,2007







<u>The early universe behaves like a near perfect liquid,</u> not like a gas or plasma. 400 times less viscous than water, 10 times less viscous than superfluid helium !

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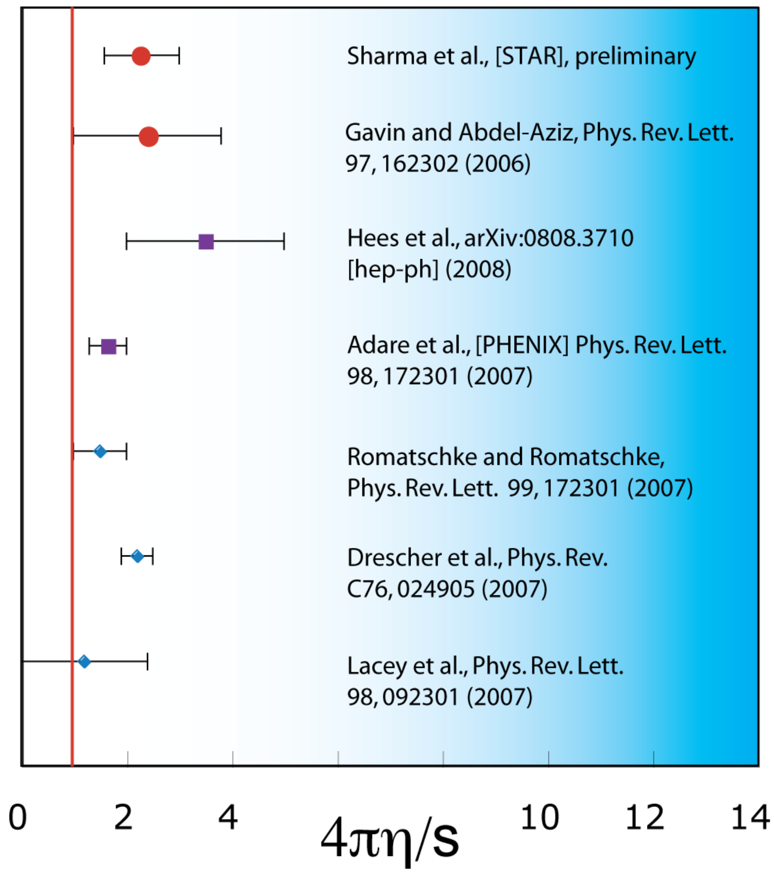
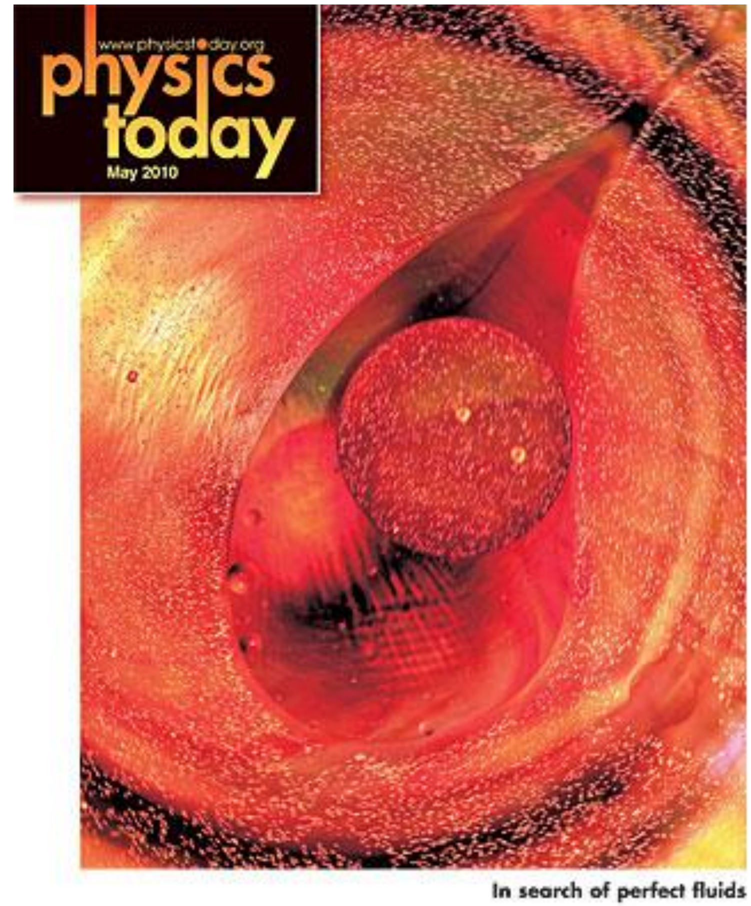
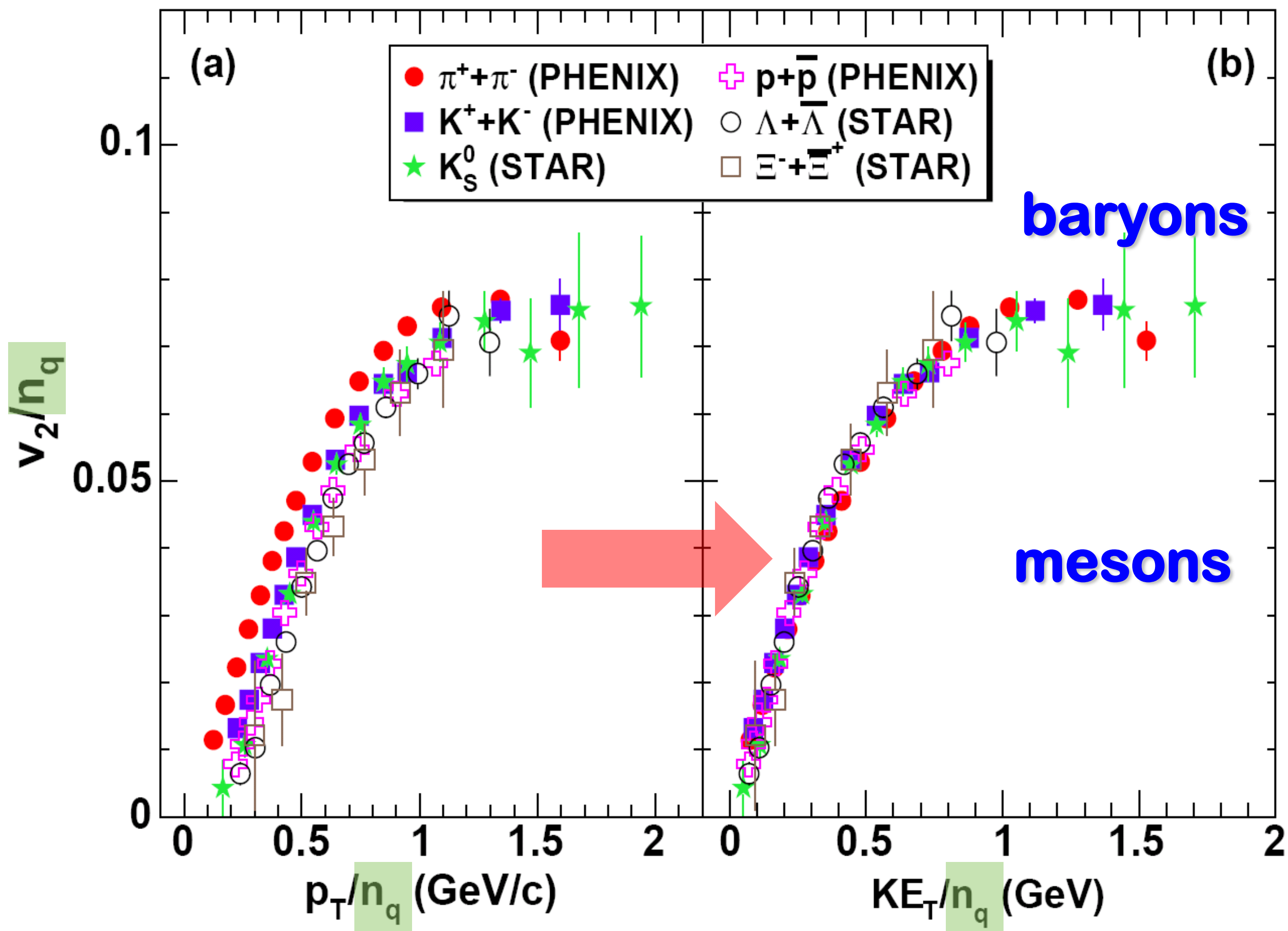
Experimental Verification





<u>Collective flow confirms the strong coupling nature of the deconfined matter produced at RHIC and the LHC</u>

How can light quark observables contribute ?



at low p_T: mass scaling (hadronic nature)

at mid p_T: quark scaling (partonic nature)

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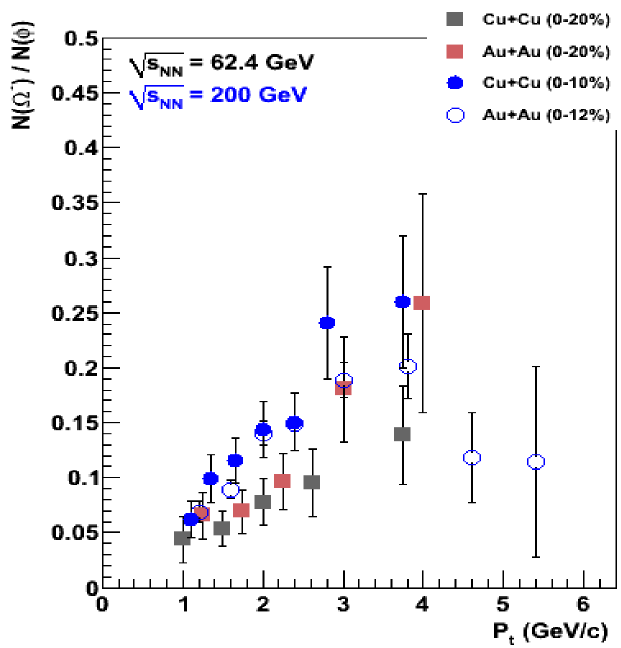
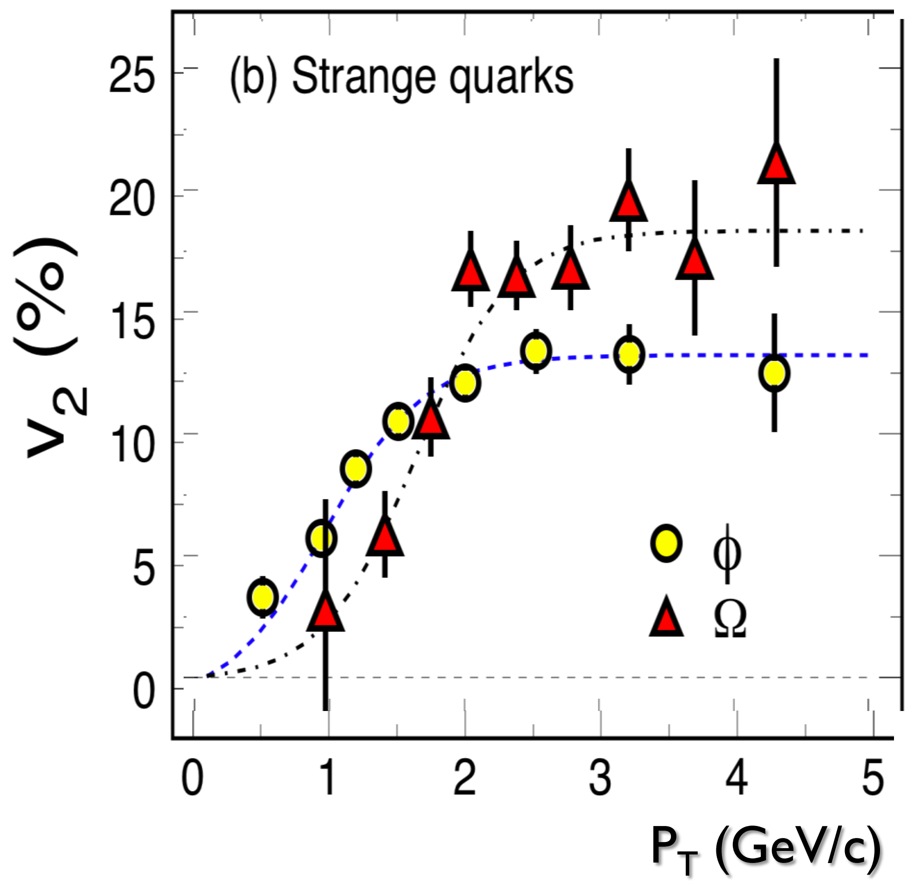
Confirmed by strange quark (Ω/ϕ) measurements

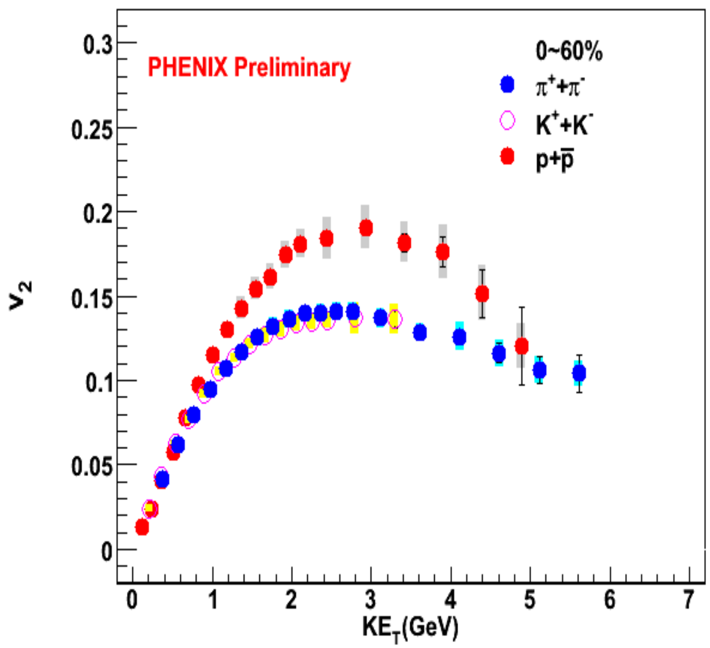
a consistent picture of deconfinement, partonic collectivity, partonic thermalization, and partonic coalescence

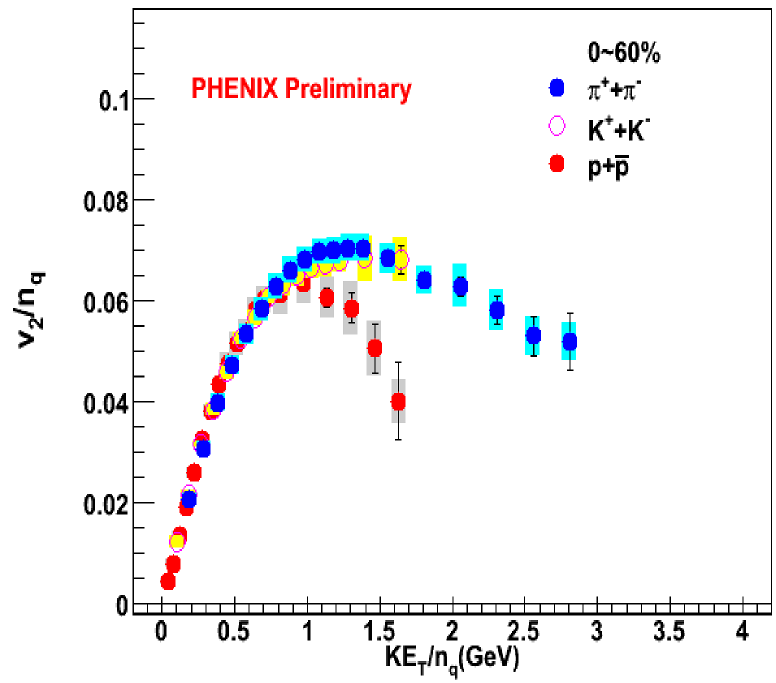




Breakdown of NCQ scaling

Transverse kinetic energy: $KE_T \approx m_T - m$, where $m_T^2 = p_T^2 + m^2$





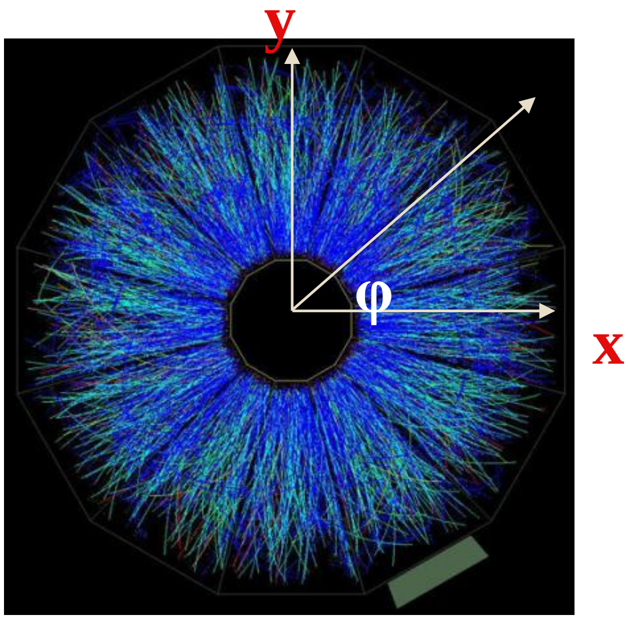
KE_T scaling works for baryons and mesons separately at moderate p_T

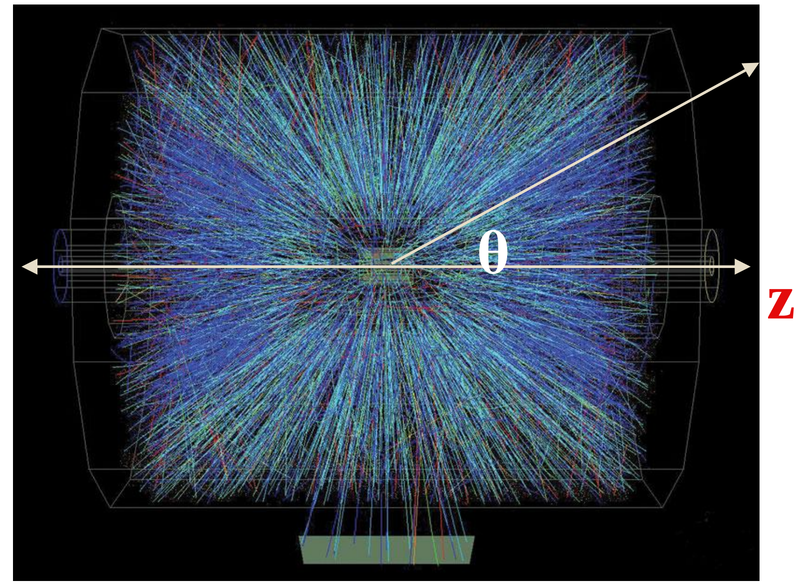
At low p_T KE_T/n_q scaling suggests flow established at partonic level; breaks down at KE_T/n_q>1 GeV

L3, Part 1: Fluctuations /Correlations

Definition of angular variables

- Momentum, azimuthal angle and pseudo-rapidity of the emitted particles are used to study the collision





- φ is the azimuthal angle and η is the pseudo-rapidity defined as:

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- A correlation study of the angular difference variables Δη and Δφ of the emitted particles.

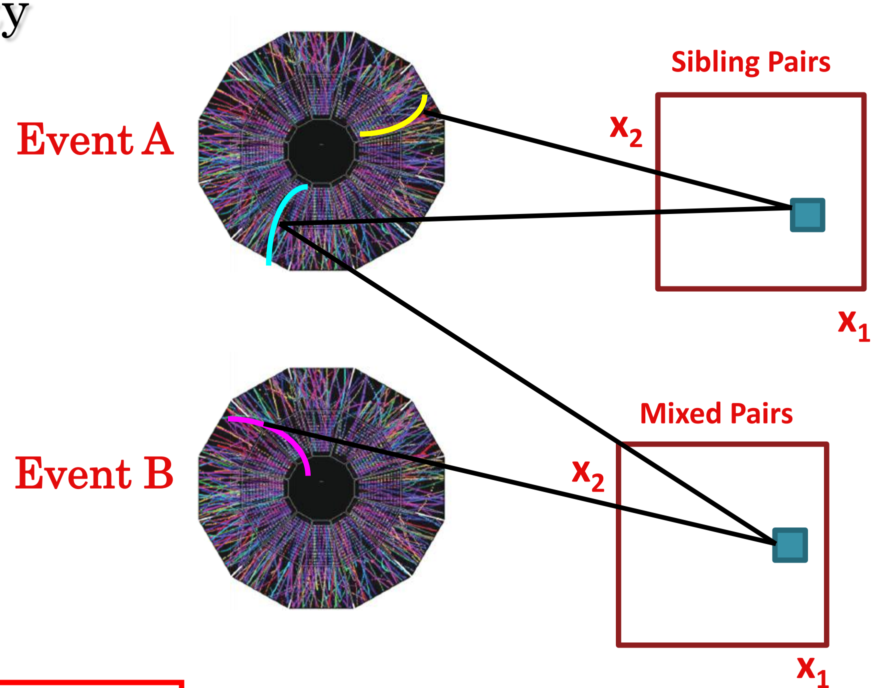
Correlation Measure (Pearson's coefficient)

- ρ = Two particle density
- Sibling Pairs

$$\rho_{sib}(p_t,\eta,\phi) = \frac{\overline{n_a n_b}}{Area}$$

- Mixed Pairs

$$\rho_{ref}(p_t,\eta,\phi) = \frac{\bar{n}_a \bar{n}_b}{Area}$$



- Final Measure:

$$\frac{\rho_{sib}-\rho_{ref}}{\sqrt{\rho_{ref}}} = \frac{\Delta\rho}{\sqrt{\rho_{ref}}} \rightarrow \boxed{\sqrt{\rho_{ref}'}\,\frac{\Delta\rho}{\rho_{ref}}}$$

Normalized Ref Pairs:
Total number of sibling to mixed pairs

$$\frac{dN_{ch}}{d\eta d\phi}$$

- Number of correlated pairs *per* final state particle

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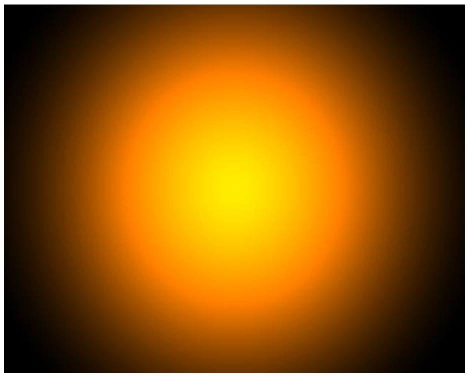
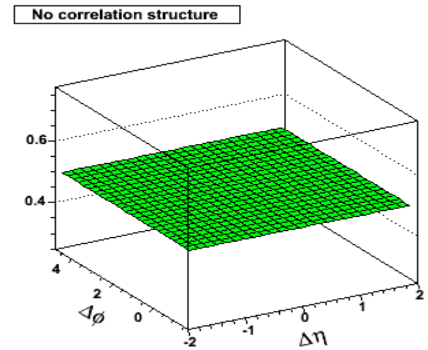
Di-hadron correlations – the original assumptions

- If a static thermalized system is formed, the emissions would be isotropic

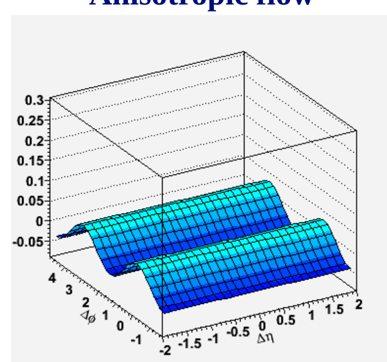




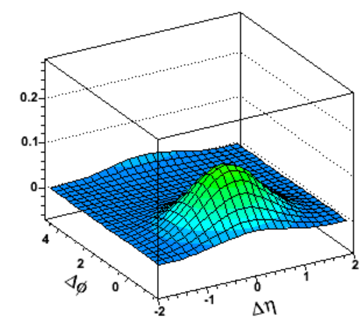
Equal probability for each particle in any direction of emission

- In high energy nuclear and particle physics we expect specific correlation effects
  - Resonance decay
  - Anisotropic flow
  - Jet fragmentation

Anisotropic flow



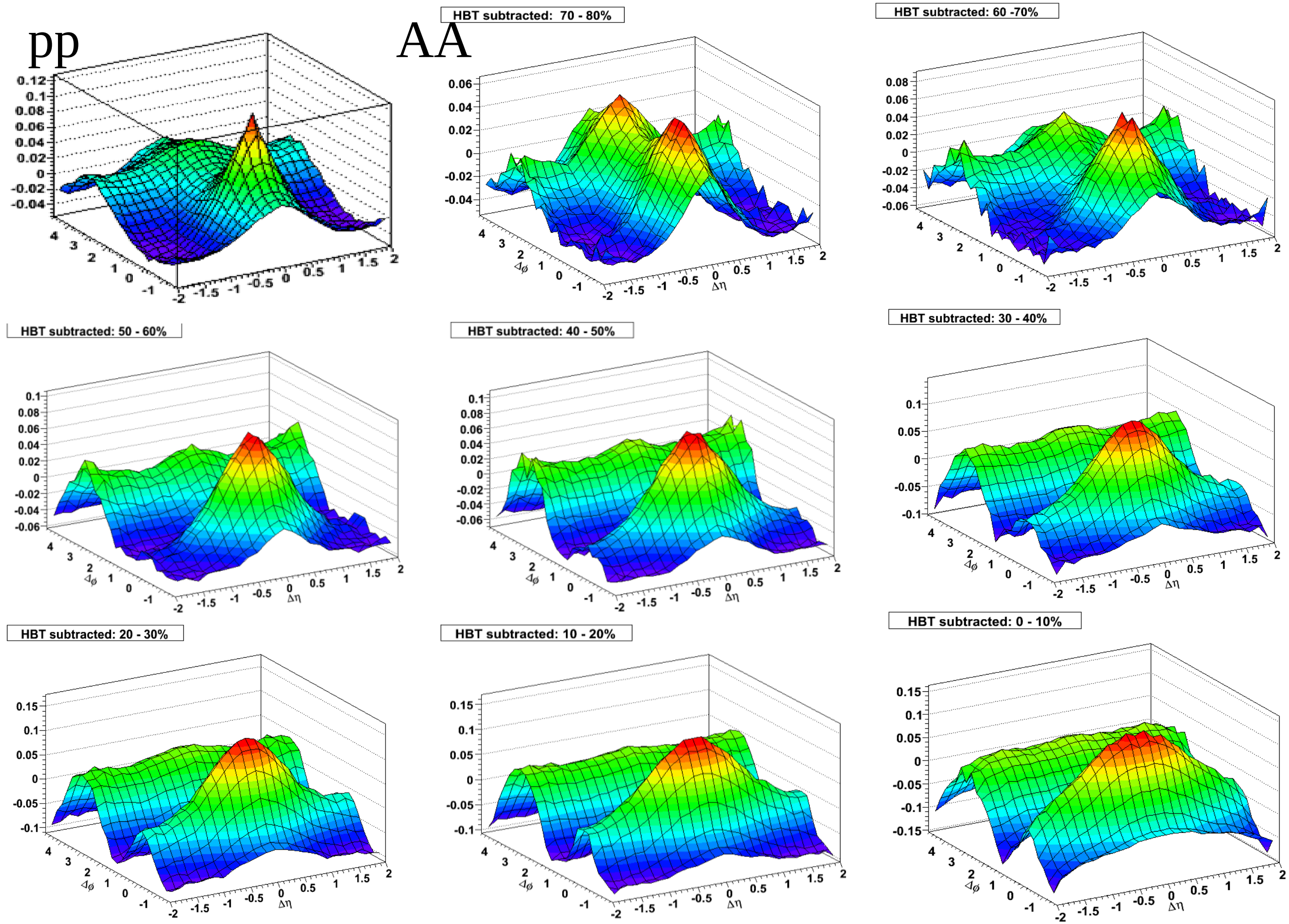
Jet fragmentation



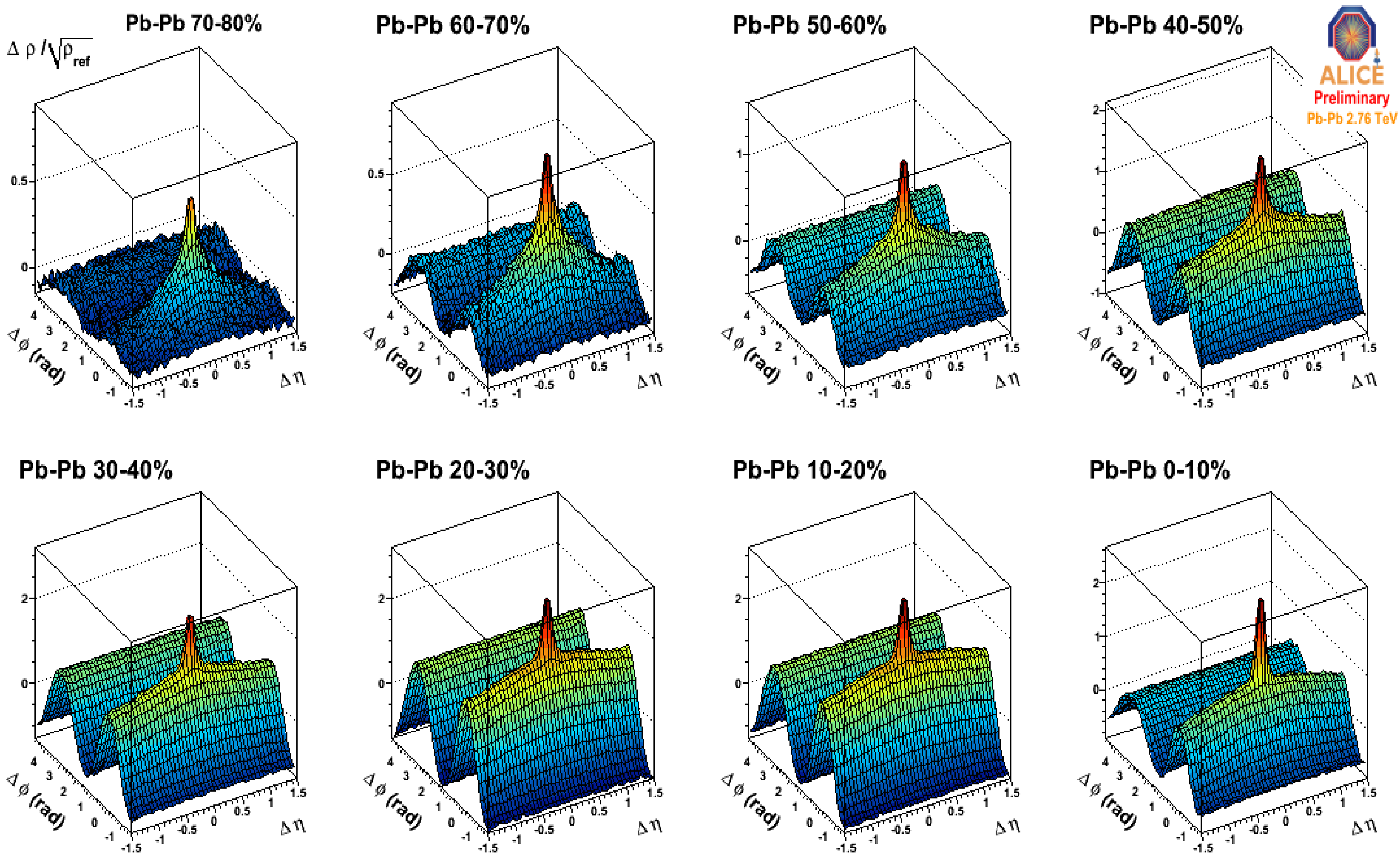
$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}}$$

Number correlations in coordinate space as a f(centrality)

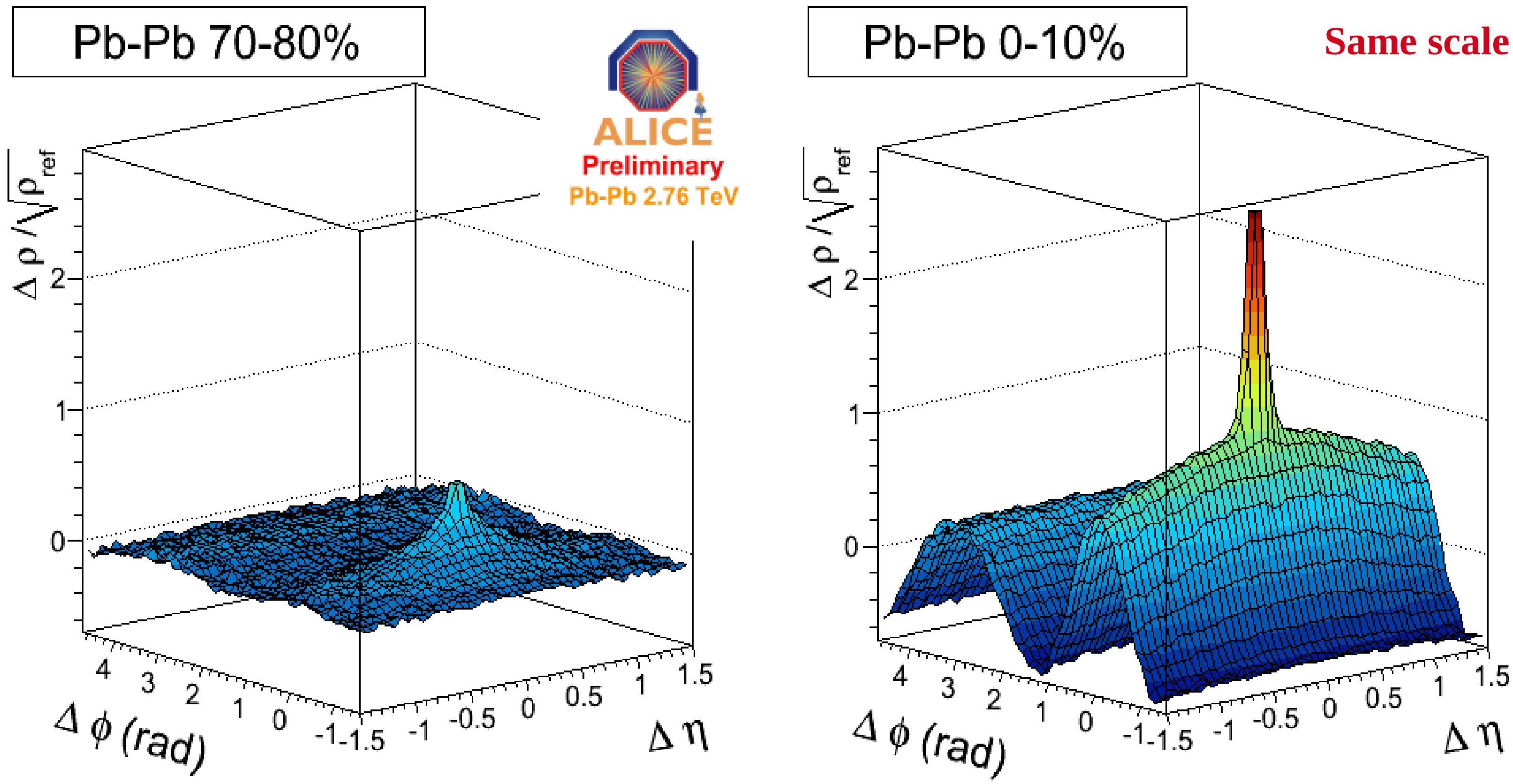
Lots of structure in RHIC emissions



…even more pronounced in ALICE



On the same scale from peripheral to central



Investigation of Fluctuating Initial Conditions

What if the initial energy density fluctuates and is not smooth (i.e. the nuclei cannot be described by hard spheres).

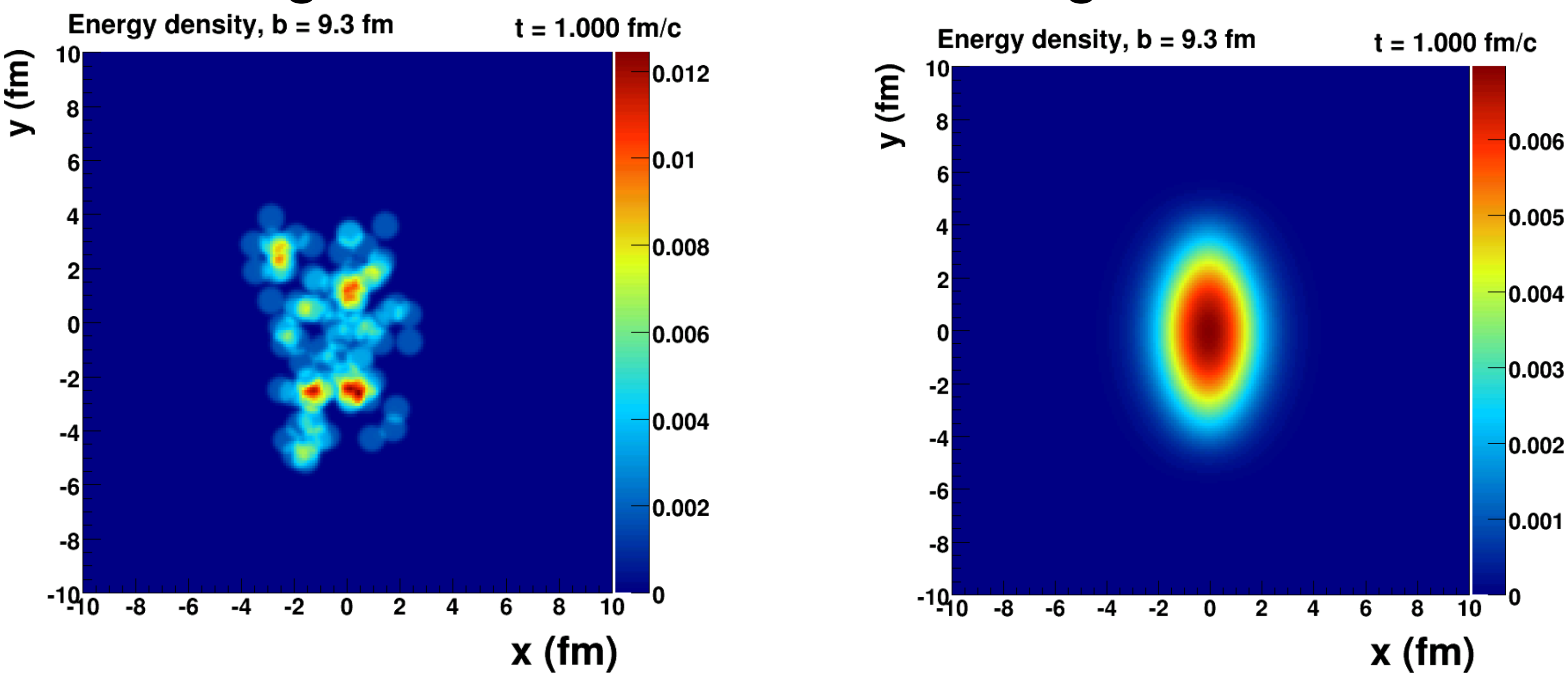
Viscous hydro code from M. Luzum and P. Romatschke

(http://hep.itp.tuwien.ac.at/~paulrom/codedown.html)(09001.488v1)

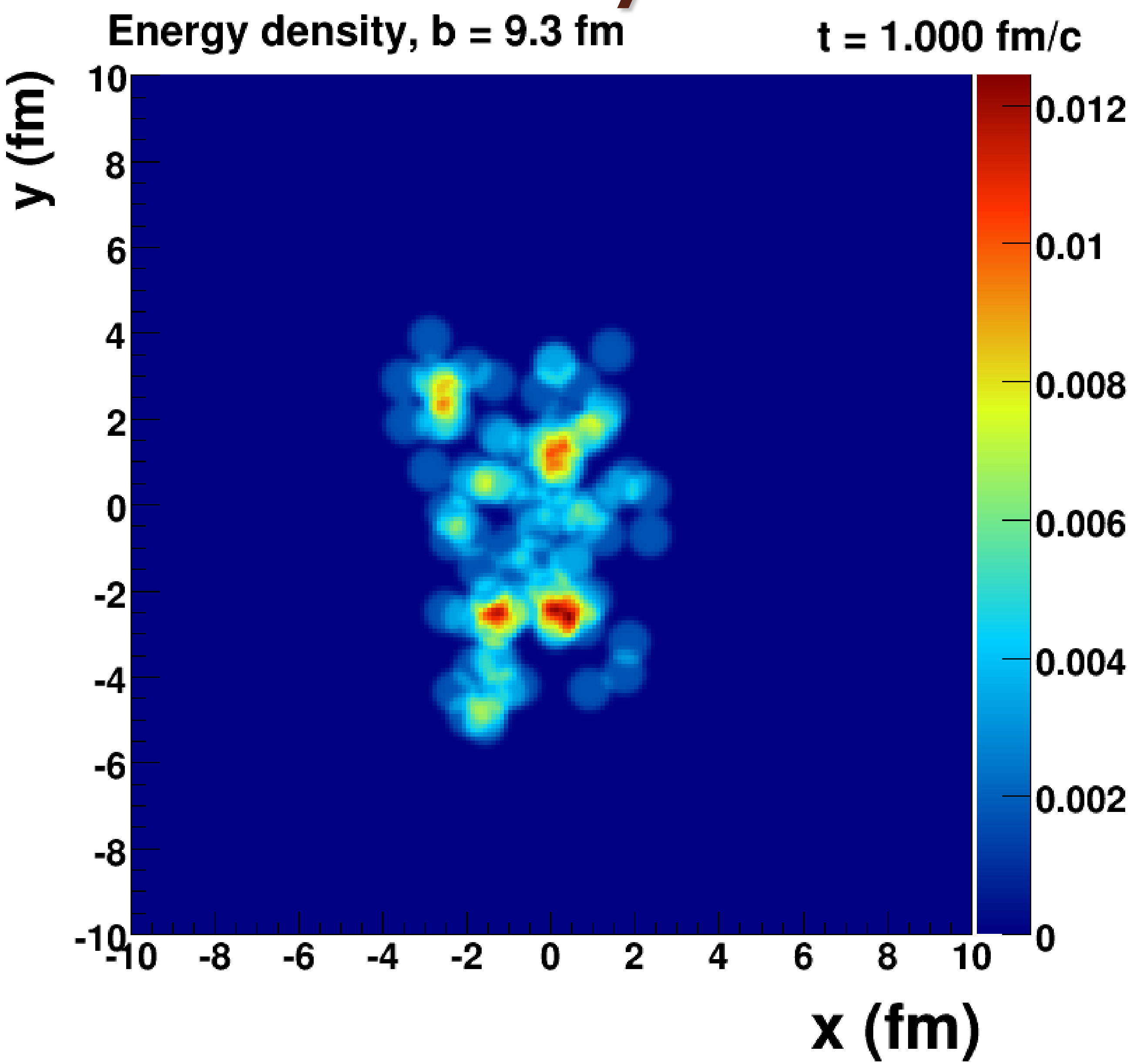
Settings: 200x200 grid, η/s = 0.08

a single event

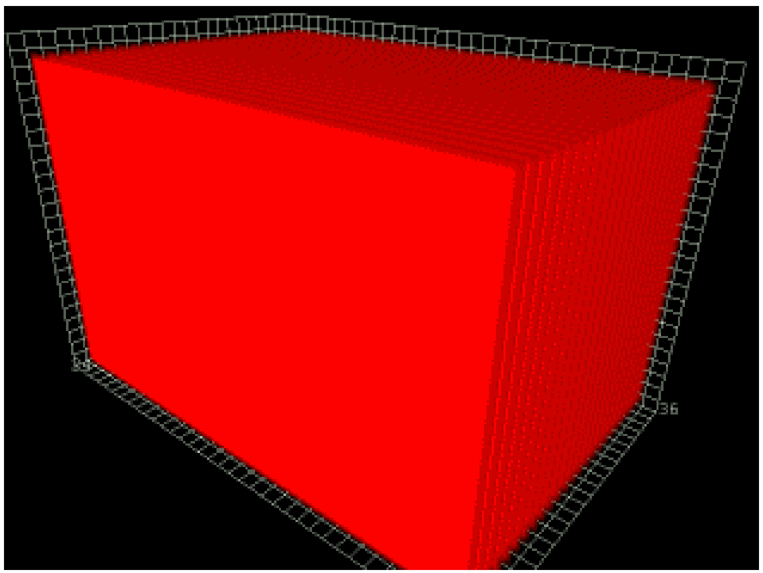
average over 1M Events



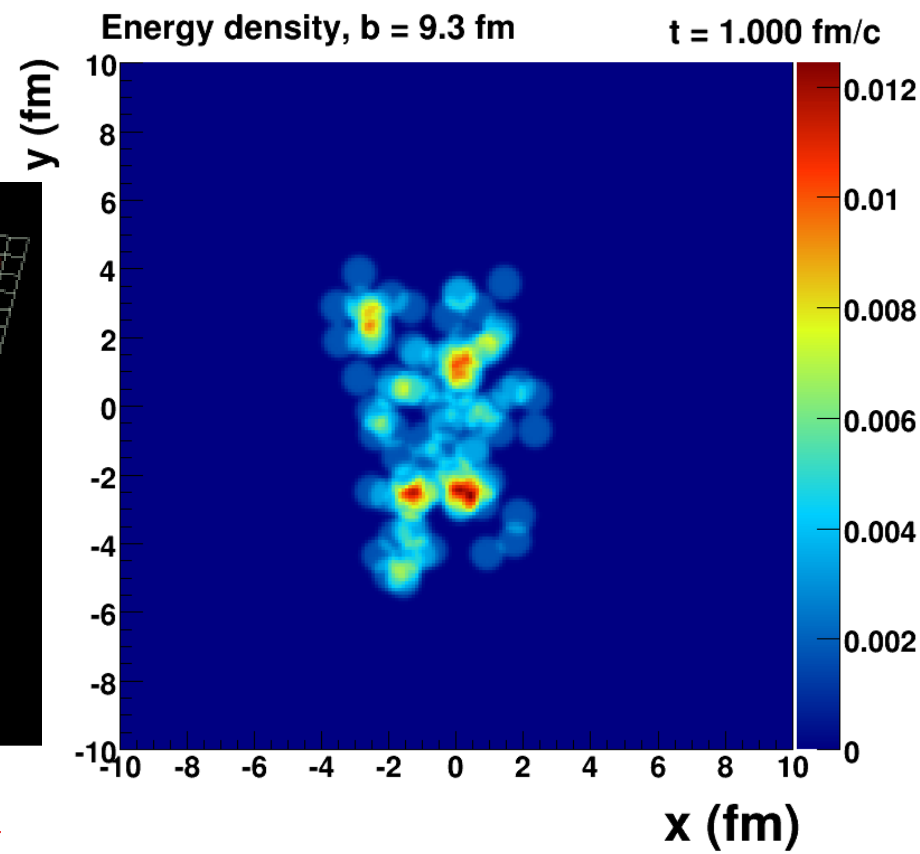
Time evolution of initial conditions in hydro



The cooling of the hot QCD vacuum and the hot QCD medium

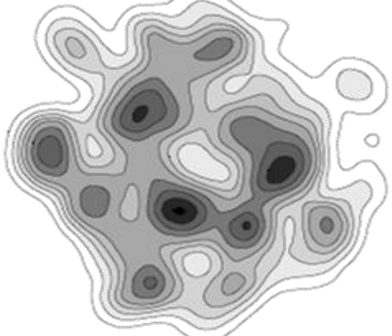


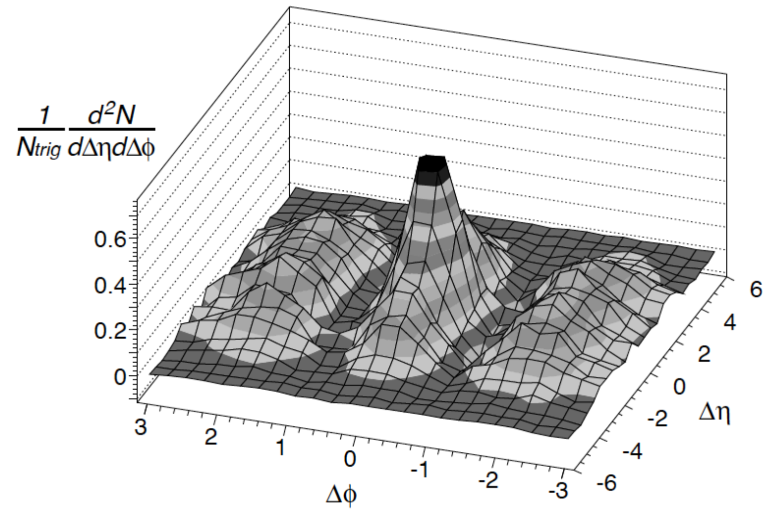
Lattice QCD calculation
Adelaide Group



Initial conditions plus radial expansion

Hama, Grassi, Kodama, Takahashi et. al.

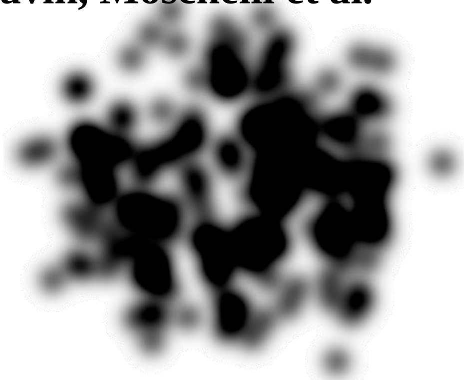


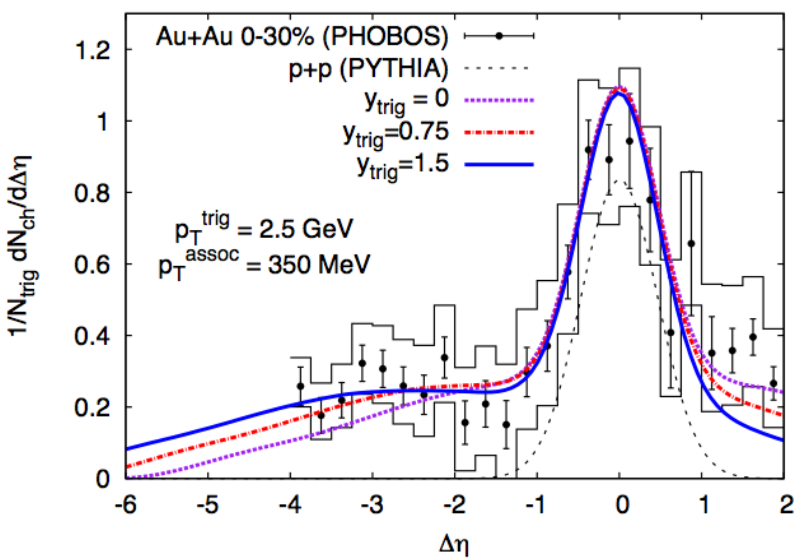


NexSPheRio

(color ropes due to nuclear density profile)

Dumitru, Gelis, McLerran, Gavin, Moschelli et al.





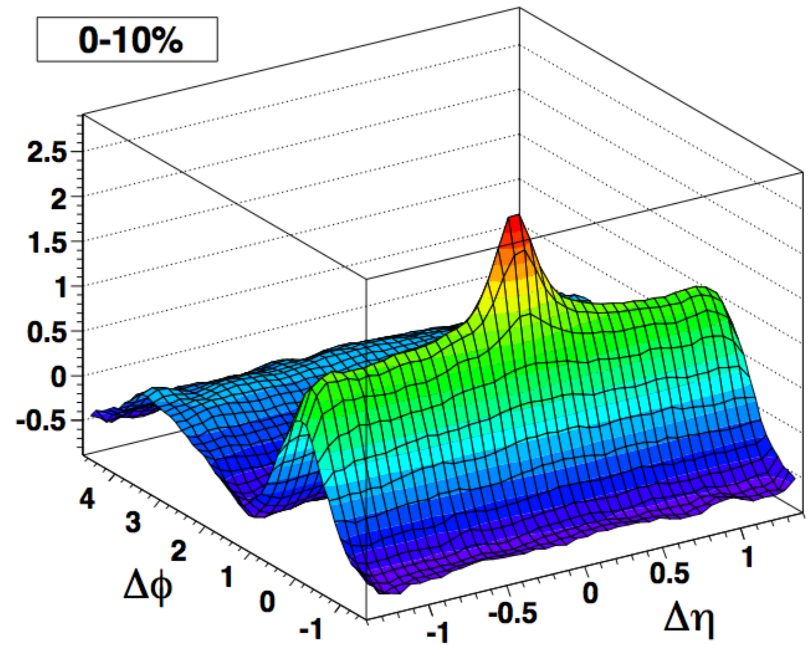
CGC &Glasma

(flux tubes due to initial gluon profile)

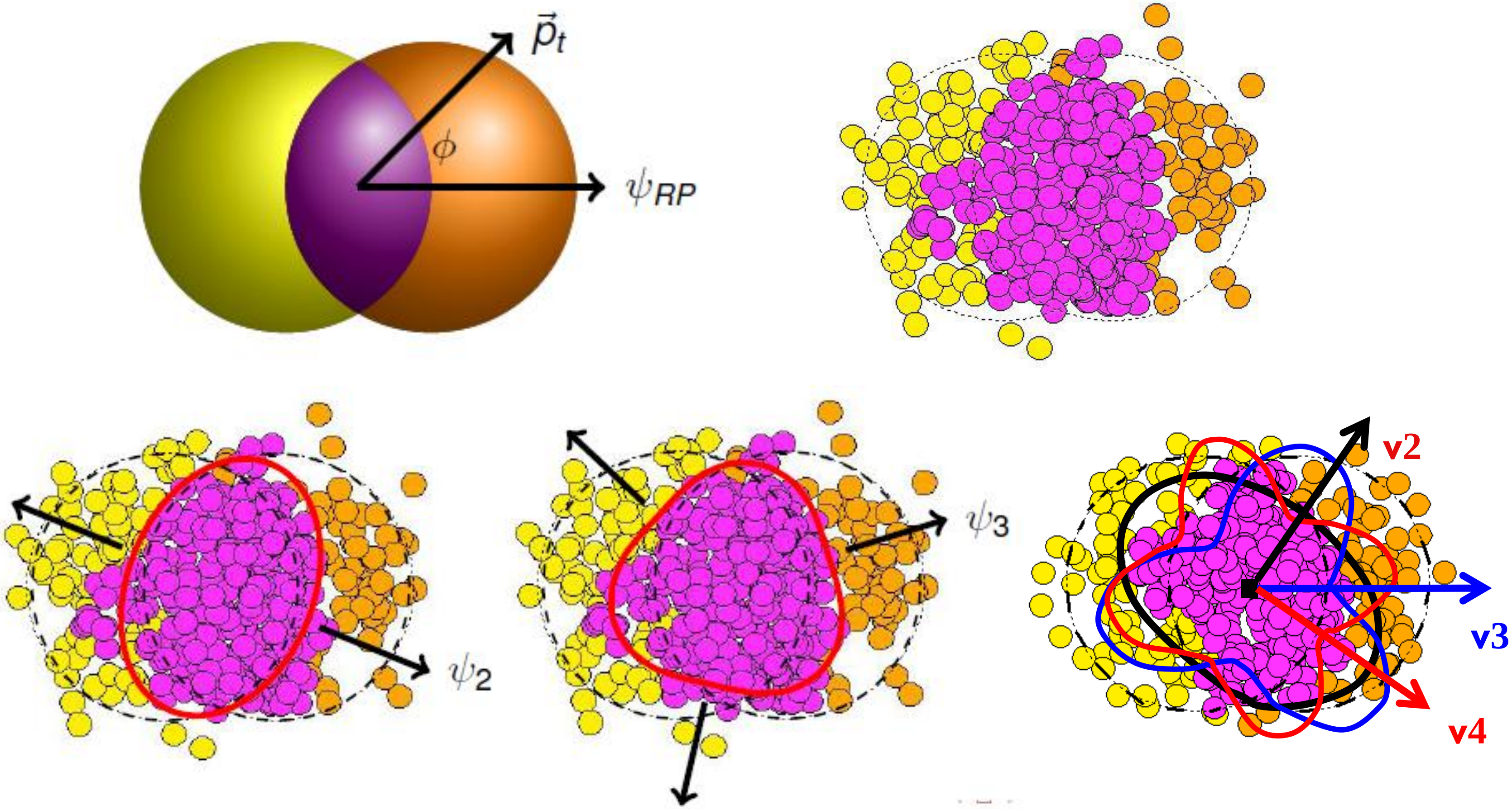
Many different ideas on origin

- **Initial energy density fluctuations**
  - Mishra et.al, Phys. Rev. C 77 (064902) 2008
  - Takahashi et.al, Phys. Rev. Lett. 103, 242301 (2009)
  - Alver and Roland, Phys. Rev. C 81 (2010) 054905
  - Werner et al, arXiv:1104.3269v1
  - Sorensen et al, arXiv:1101.1925v1
- **CGC flux tubes and/or radial flow**
  - Voloshin, Phys. Lett. B 632 (2006) 490
  - Dumitru, Gelis, McLerran, Venugopalan Nucl.Phys.A810:91-108,2008
  - Gavin, McLerran and Moschelli: Phys. Rev. C79 (200 051902
  - Moschelli and Gavin: Nucl.Phys.A836:43-58,2010
- **Modified mini-jets (pQCD related explanation)**
  - T.Trainor, Phys. Rev. C 80 (2009) 044901

Pb-Pb 2.76 TeV



Higher harmonics of initial energy density fluctuations



$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos\phi + 2v_1^s \sin\phi + 2v_2 \cos 2\phi + 2v_2^s \sin 2\phi + 2v_3 \cos 3\phi + \ldots$$

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \psi_n) \Longrightarrow \left\langle \frac{dN_{\text{pairs}}}{d\Delta\phi} \right\rangle \overset{\text{(flow)}}{\propto} 1 + \sum_{n=1}^{\infty} 2\left\langle {v_n}^2 \right\rangle \cos n(\Delta\phi)$$

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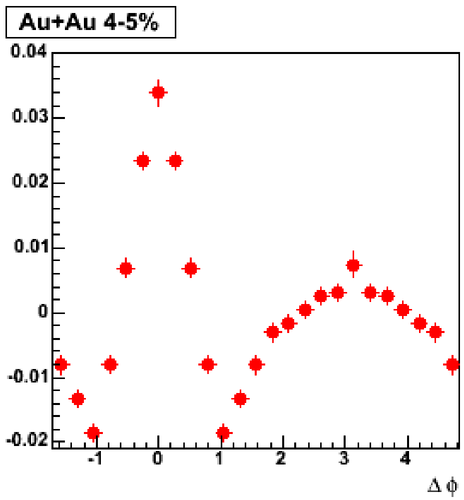
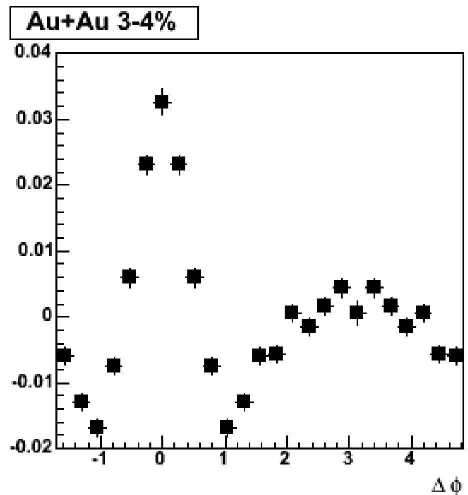
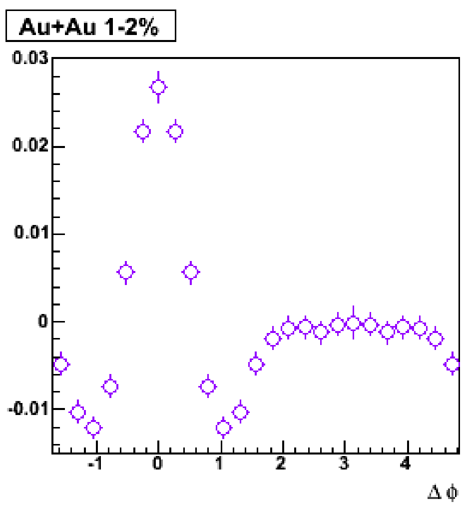
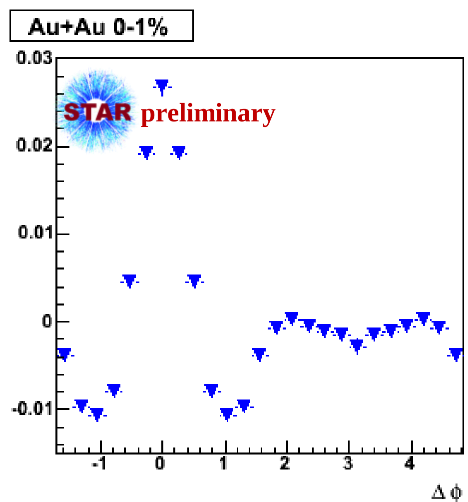
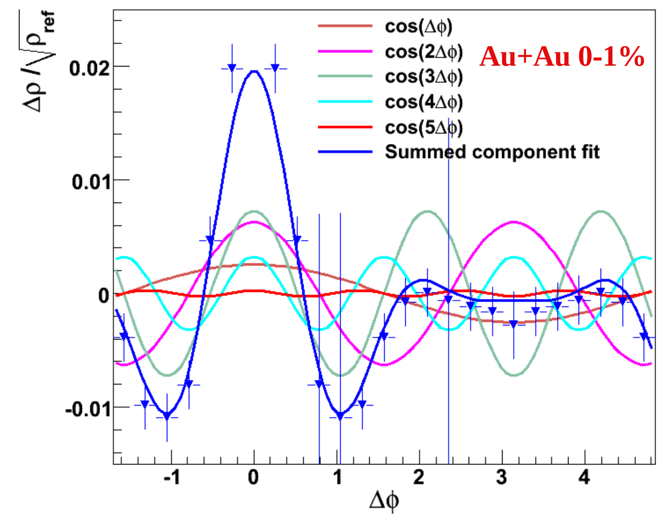
Centrality evolution of Δϕ di-hadron projections - evidence for higher harmonics -





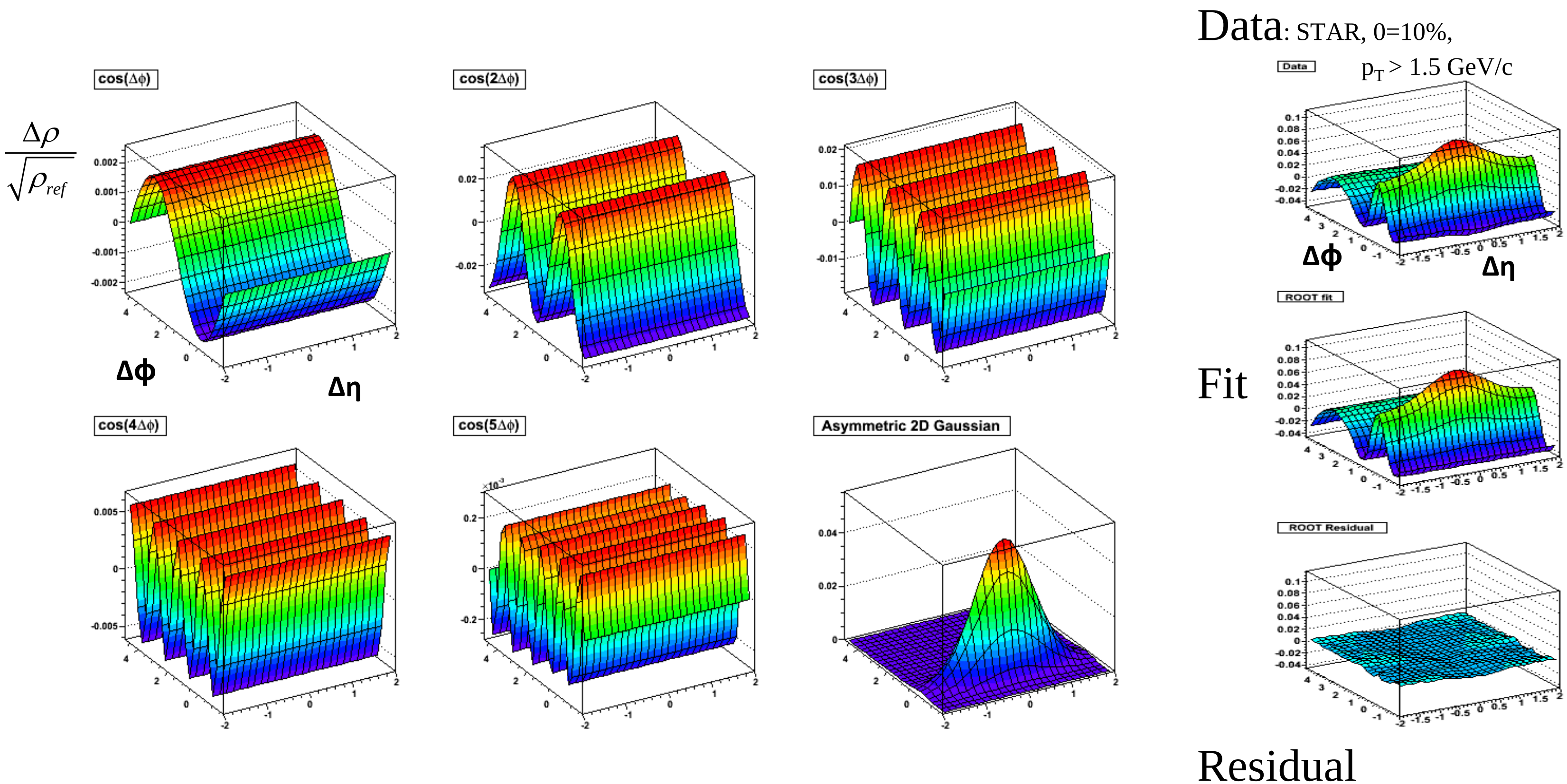






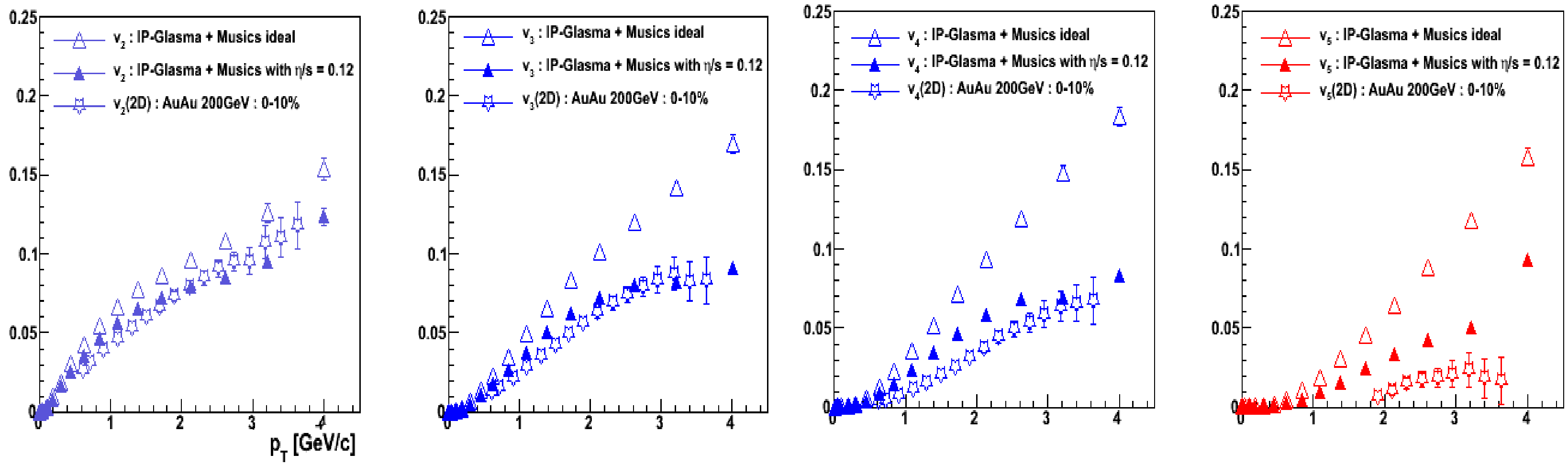
Di-hadron correlation analysis

- applied to determine centrality and p_T dependence of long range correlations in $\Delta\eta$. Combined fit function for initial density fluctuations and medium modified jet (remainder): v1 to v5 plus 2d Gaussian.

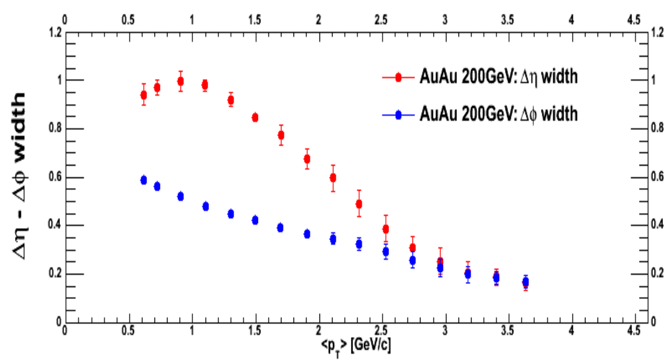


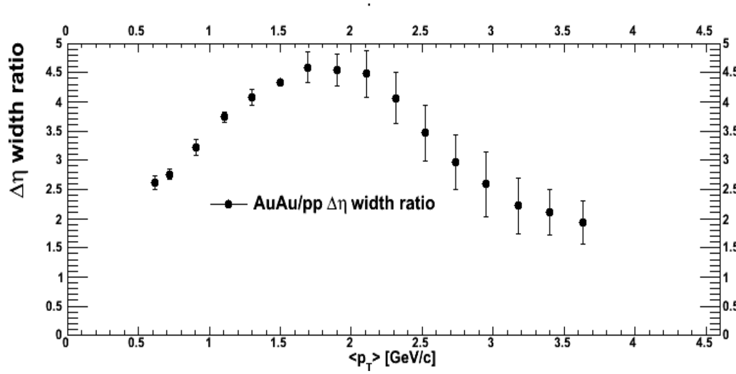
Di-hadron correlations in STAR

- Major result on harmonics: sensitivity to viscosity



- Major result on remainder: jet medium modification

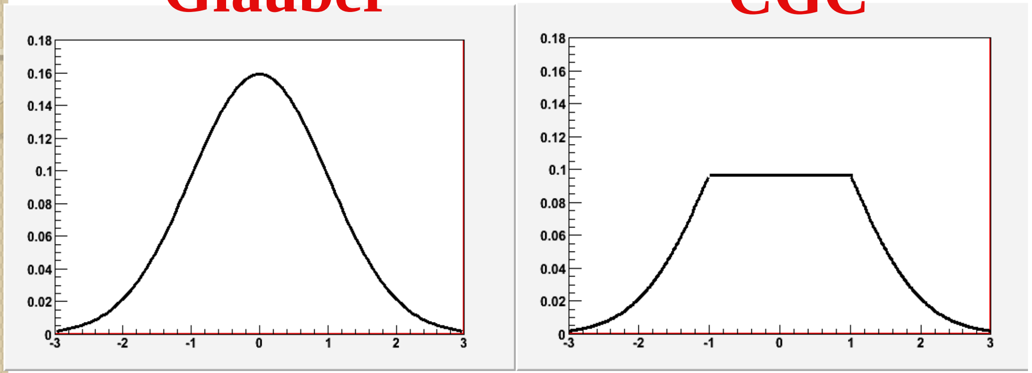




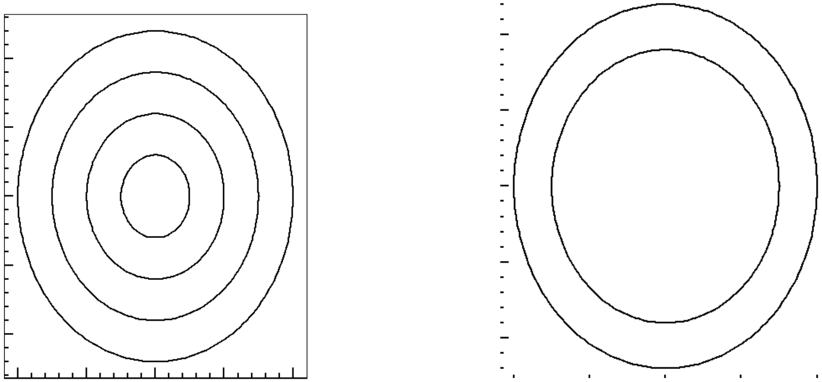
Initial State determines flow strength

Radial gluon distribution

Glauber **CGC**



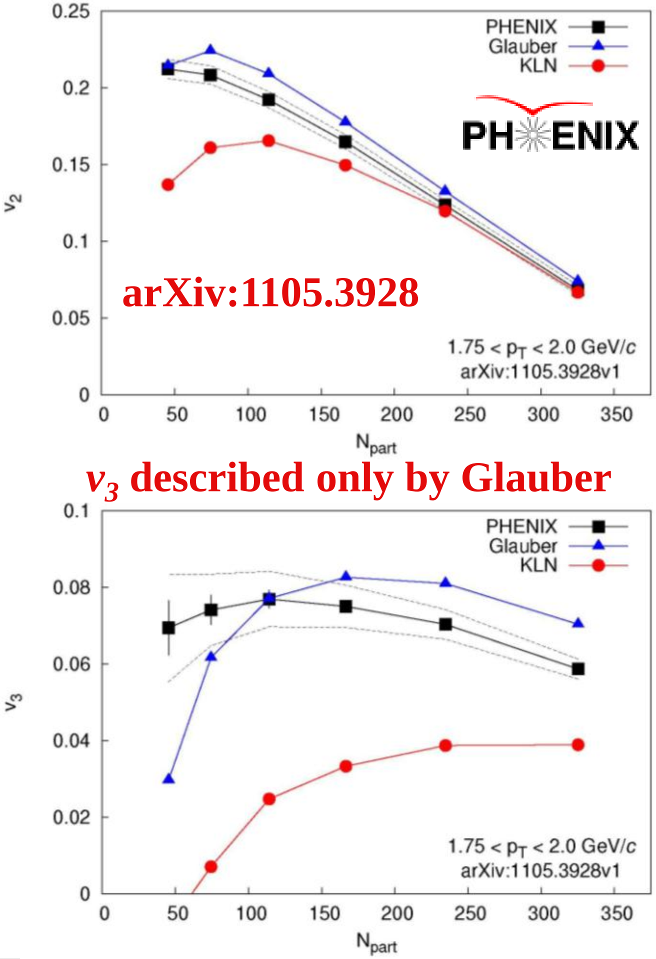
2-D density profile



Smaller eccentricity **larger eccentricity**

v_2 described by Glauber and CGC

v_3 described only by Glauber

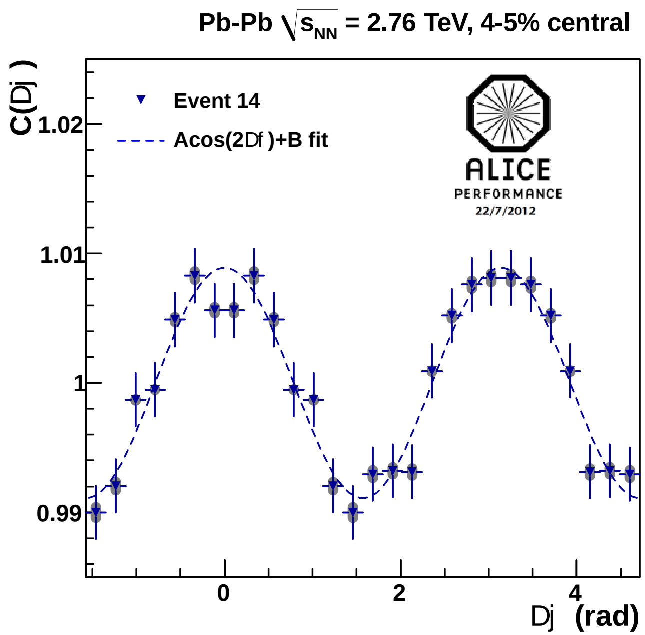


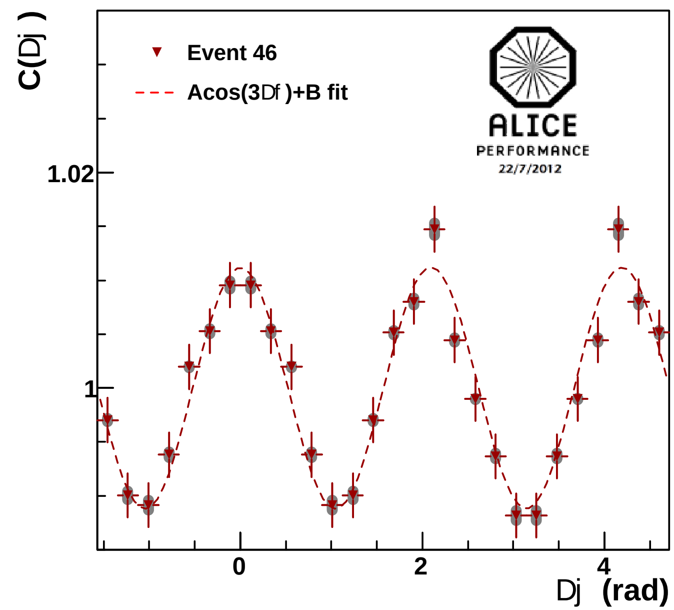
Theory calculation: Alver et al., PRC82,034913

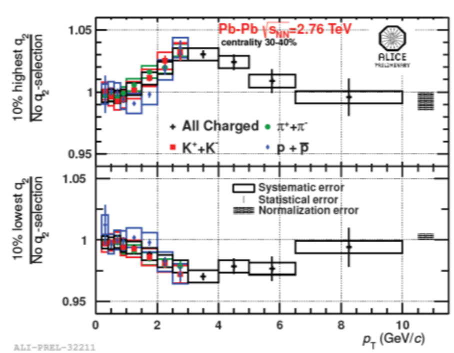
weak centrality dependence of v_3 => fluctuations origin

An exciting prospect for the future: Event engineering

- The e-by-e statistics at the LHC enable event classification on the basis of harmonics measurements. (PLB 719 (2013) 394)







- Future studies: explore fluctuations and multiplicity distributions e-by-e.

Lattice QCD predictions for QCD transition

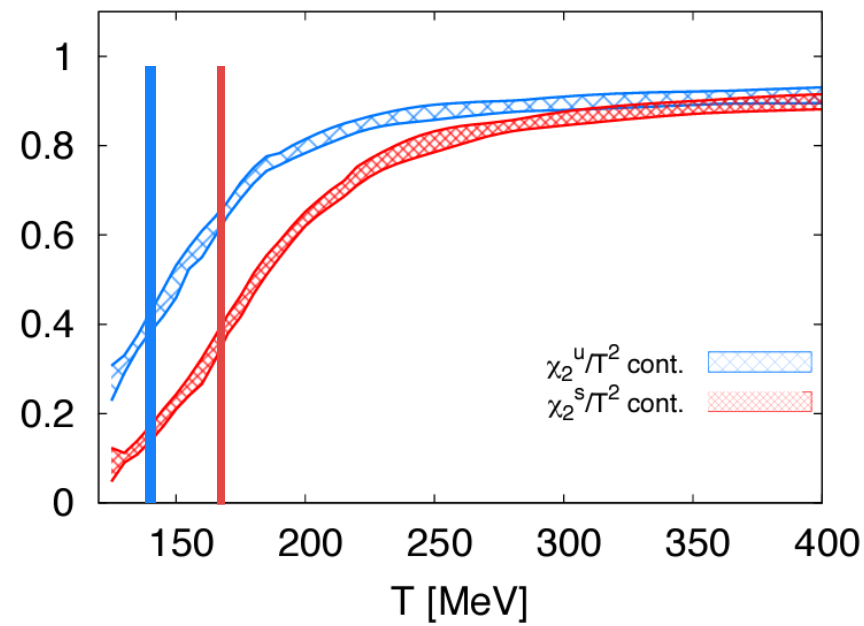
- Recent high resolution lattice calculations have yielded reliable continuum extrapolations for all relevant order parameters of the QCD phase transition.

<u>The conclusions are:</u>

A.) that the transition is an analytic crossover for an extended range of temperatures (ΔT around 100 MeV)

B.) that in the crossover region there might be indications of a flavor hierarchy during hadronization (heavier flavors freeze out at higher temperatures, more abundant if emission is statistical).

Difference between light and strange flavor



C. Ratti et al., PRD 85, 014004 (2012)
R. Bellwied, arXiv:1205.3625

A short primer on QCD susceptibilities

$$\Omega(T,\mu) \equiv \ln \mathcal{Z}(V,T,\mu)/VT^3$$

Grand potential of QCD

$$\frac{p_{SB}}{T^4} = \Omega^{(0)}(T,\mu) = \frac{8\pi^2}{45} + \sum_{f=u,d,..}\left[\frac{7\pi^2}{60} + \frac{1}{2}\left(\frac{\mu_f}{T}\right)^2 + \frac{1}{4\pi^2}\left(\frac{\mu_f}{T}\right)^4\right]$$

Infinite T limit SB gas

First derivative of grand potential with respect to chemical potential is the density (density of quarks), equals zero at μ=0.

Second derivative is susceptibility (variation of density with respect to infinitesimal change in chemical potential).

$$\frac{\chi_{ff}(T,\mu)}{T^2} = \frac{\partial^2\Omega(T,\mu)}{\partial(\mu_f/T)^2} \quad , \quad \frac{\chi_{fk}(T,\mu)}{T^2} = \frac{\partial^2\Omega(T,\mu)}{\partial(\mu_f/T)\partial(\mu_k/T)}$$

Fluctuation of system. **Correlation between conserved quantities**

Diagonal and non-diagonal susceptibilities

$$\frac{\chi_{uu}(T,\mu_q)}{T^2} = \; = 2c_2^{uu} + 12c_4^{uu}\left(\frac{\mu_q}{T}\right)^2 + 30c_6^{uu}\left(\frac{\mu_q}{T}\right)^4 + \cdots$$

$$\frac{\chi_{ud}(T,\mu_q)}{T^2} = \; = 2c_2^{ud} + 12c_4^{ud}\left(\frac{\mu_q}{T}\right)^2 + 30c_6^{ud}\left(\frac{\mu_q}{T}\right)^4 + \cdots$$

Taylor expansion of susceptibilities

Susceptibility ratios in lattice QCD = higher moment ratios of multiplicity distribution

Susceptibility ratios proposed as a model independent measure of Tch at μ=0 (arXiv:1202.4173)

$$\kappa_B \sigma_B^2 \equiv \frac{\chi_{4,\mu}^B}{\chi_{2,\mu}^B} = \frac{\chi_4^B(T)}{\chi_2^B(T)} \left[\frac{1 + \frac{1}{2}\frac{\chi_6^B(T)}{\chi_4^B(T)}(\mu_B/T)^2 + \ldots}{1 + \frac{1}{2}\frac{\chi_4^B(T)}{\chi_2^B(T)}(\mu_B/T)^2 + \ldots} \right]$$

At μ=0: higher order expansion terms are zero, therefore χ2 ~ c2, χ4 ~ c4, χ6 ~ c6, etc.

- The first four cumulants are

$$C_1 = \langle(\delta x)\rangle \qquad C_2 = \langle(\delta x)^2\rangle$$

$$C_3 = \langle(\delta x)^3\rangle \quad C_4 = \langle(\delta x)^4\rangle - 3\langle(\delta x)^2\rangle^2$$

- We can then define

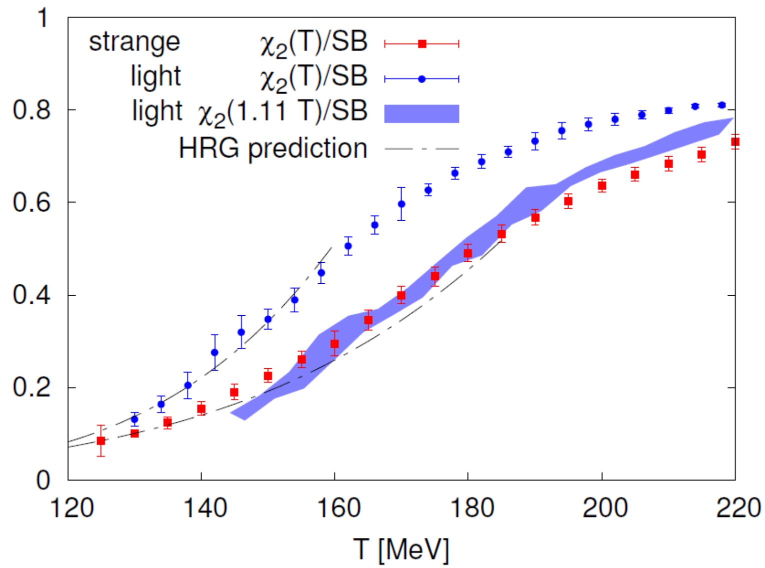
$$\text{Variance: } \sigma^2 = C_2 \qquad \text{Standard deviation: } \sigma = \sqrt{C_2}$$

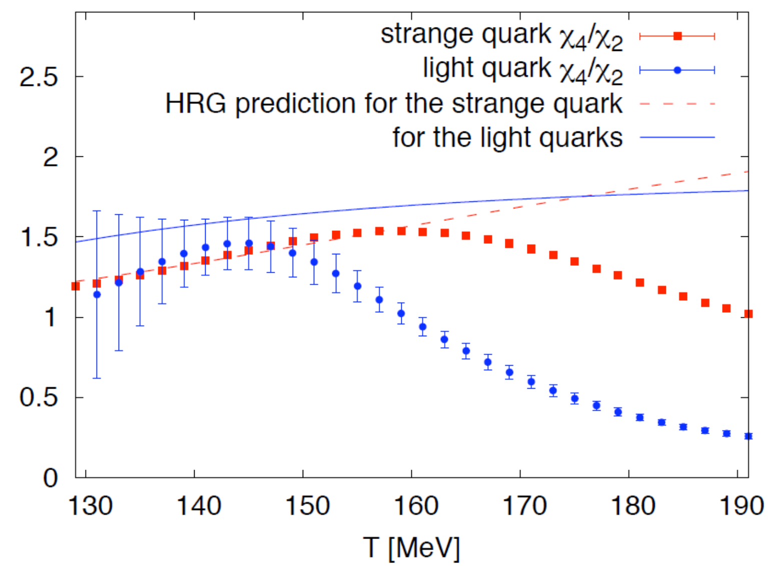
$$\text{Skewness: } S = C_3 / C_2^{3/2} \qquad \text{Kurtosis: } \kappa = C_4 / C_2^2$$

$$S\sigma = C_3 / C_2 \quad \kappa\sigma^2 = C_4 / C_2$$

Most recent results

- Latest results are based on continuum extrapolations of flavor dependent higher order susceptibility ratios and signal a flavor hierarchy in the QCD crossover region (Bellwied et al., arXiv:1305.6297)



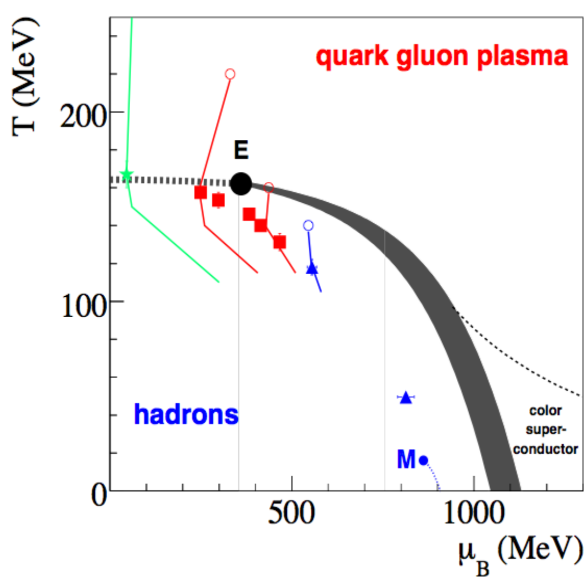


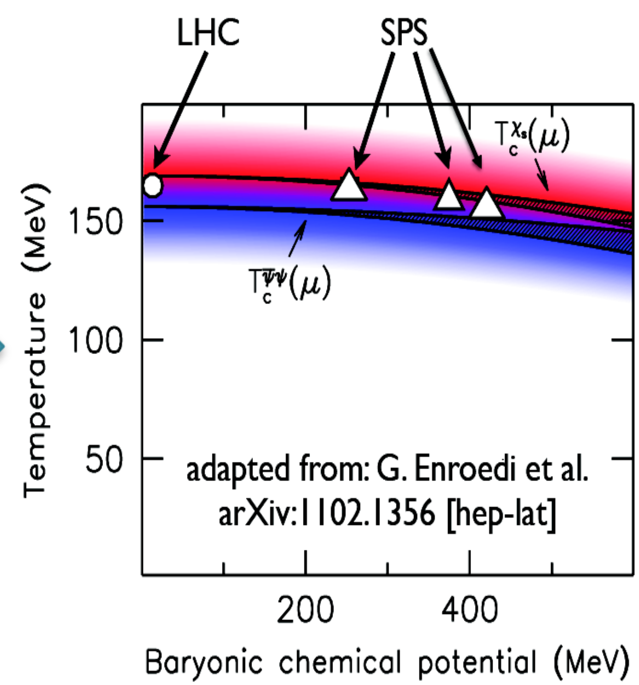
- Analysis of PID higher moments in ALICE and STAR has started.
- $\kappa\sigma^2 = \chi_4/\chi_2$ is a good thermometer for hadronization.
- Strong fluctuations in ks2 for net-charge (charge number) and net-protons (baryon number) as a function of energy might also indicate critical point in phase diagram.

Alternate explanation: non-equilibrium proton annihilation after hadronization

Idea based on enhanced in-medium annihilation cross sections in hadronic transport codes, e.g. UrQMD

- *Steinheimer, Aichelin, Bleicher, arXiv:1203.5302*
- *Karpenko, Sinyukov, Werner, arXiv:1204.5351*
- *Becattini et al., arXiv:1201.6349*



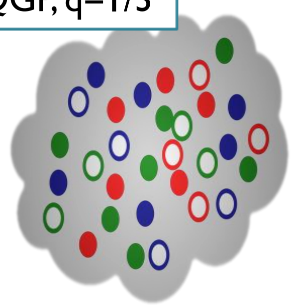


Charge fluctuations

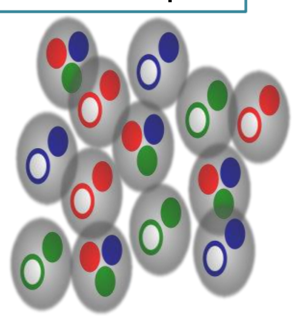
$$n_{(+-,dyn)} = \frac{\langle N_+(N_+ - 1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_- - 1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+N_-\rangle}{\langle N_+\rangle\langle N_-\rangle}$$

- e-by-e net charge fluctuations depend on charge carriers
- PRL110, 152301(2013)

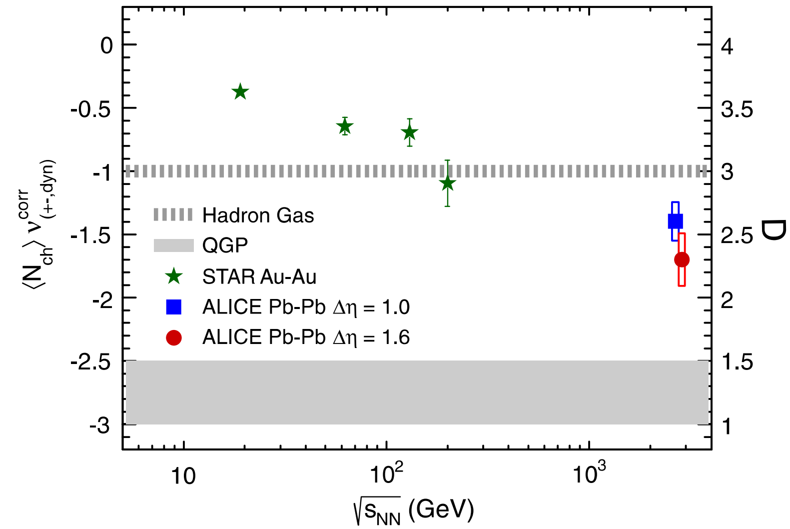
QGP, q=1/3



Hadron Gas, q=1



Jeon, Koch, PRL 85, 2072 (2000).
Asakawa et al., *PRL 85, 2076 (2000).*

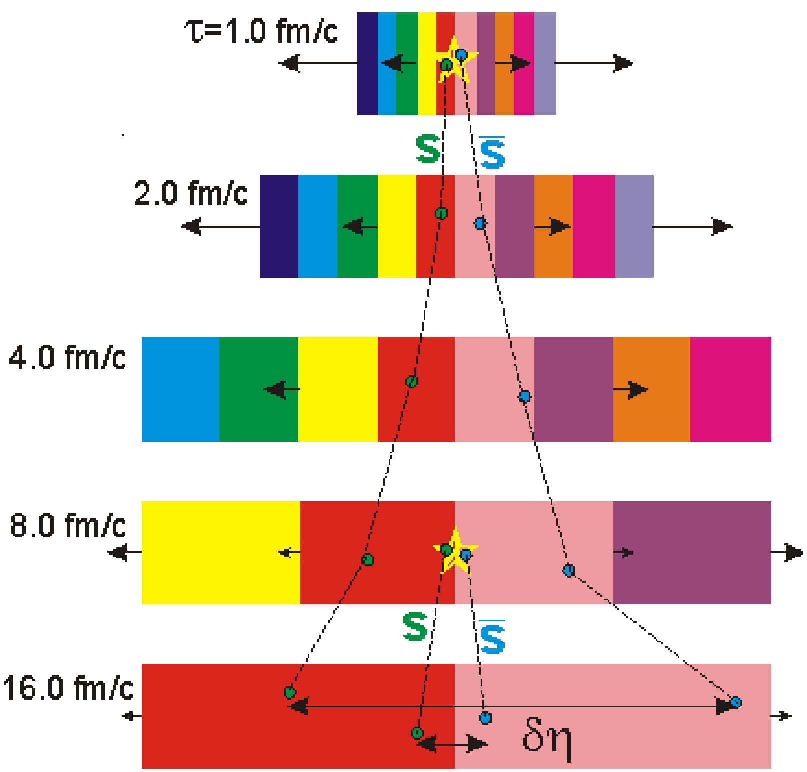


- Small value in ALICE consistent with onset of partial charge carriers

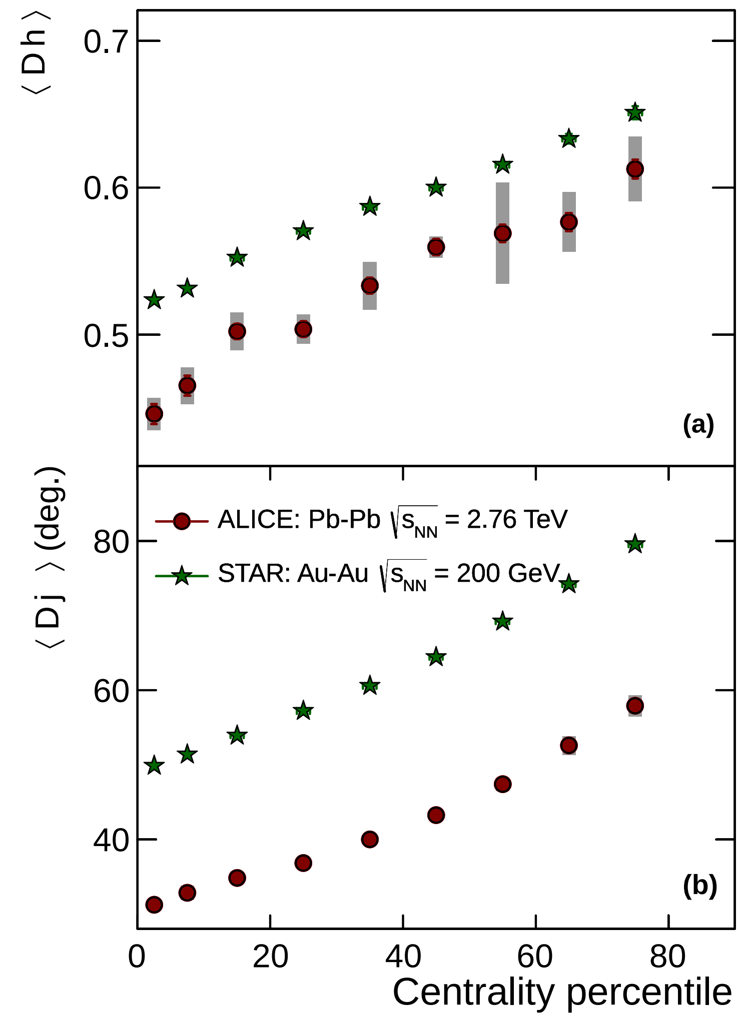
Balance function

$$B(\Delta\eta) = \frac{1}{2}\left\{ \frac{N_{+-}(\Delta\eta) - N_{++}(\Delta\eta)}{N_{+}} + \frac{N_{-+}(\Delta\eta) - N_{--}(\Delta\eta)}{N_{-}} \right\}$$

- correlation of balancing charges depends on hadronization time
- PLB 723 (2013) 267



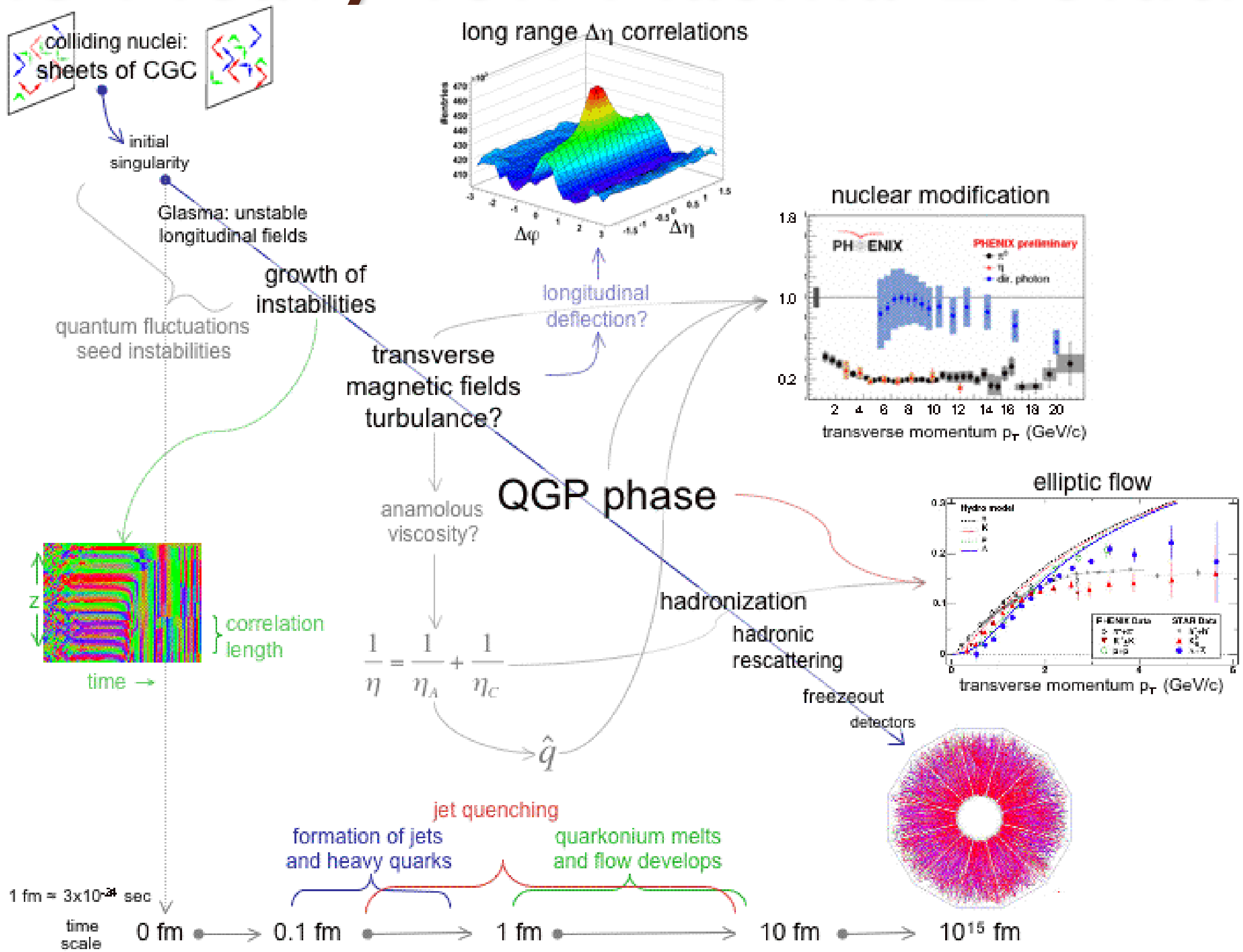
Bass, Danielewicz, Pratt, PRL 85, 2689 (2000).



- Decrease in width consistent with increase in t_{had}

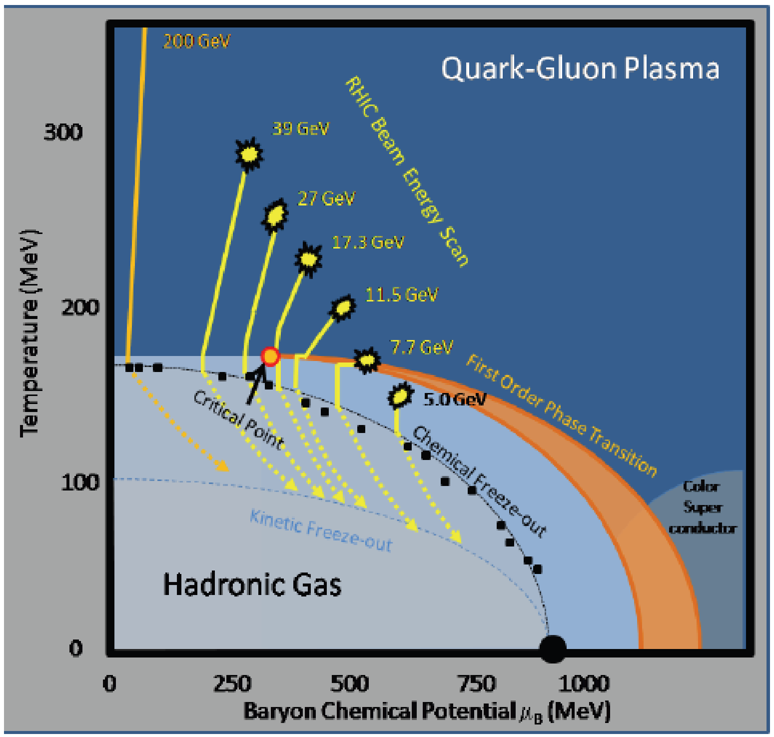
L3, Part 2: Conclusions / Future

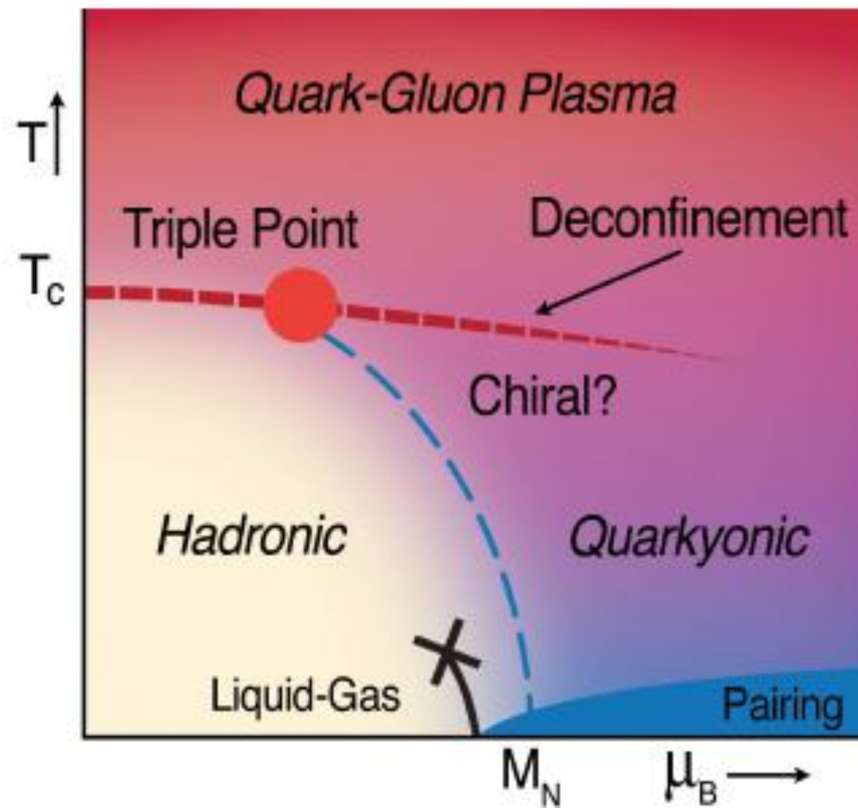
The Heavy Ion Plasma Evolution



Coherent story except for early thermalization and strong coupling near the transition which cannot be easily reconciled with pQCD

Where does it all begin / end ?
Energy dependence of QCD matter

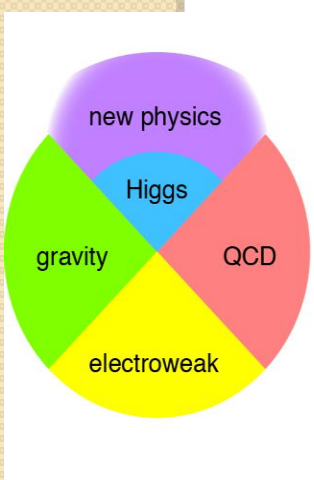


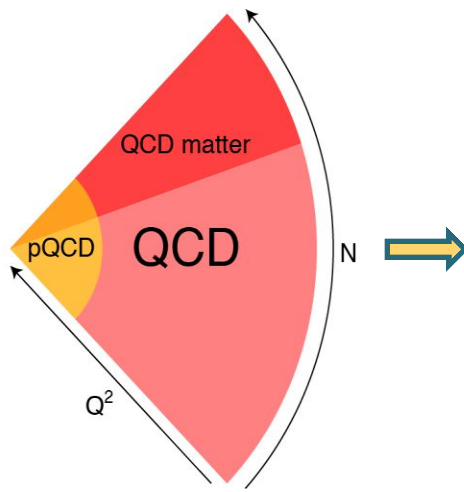


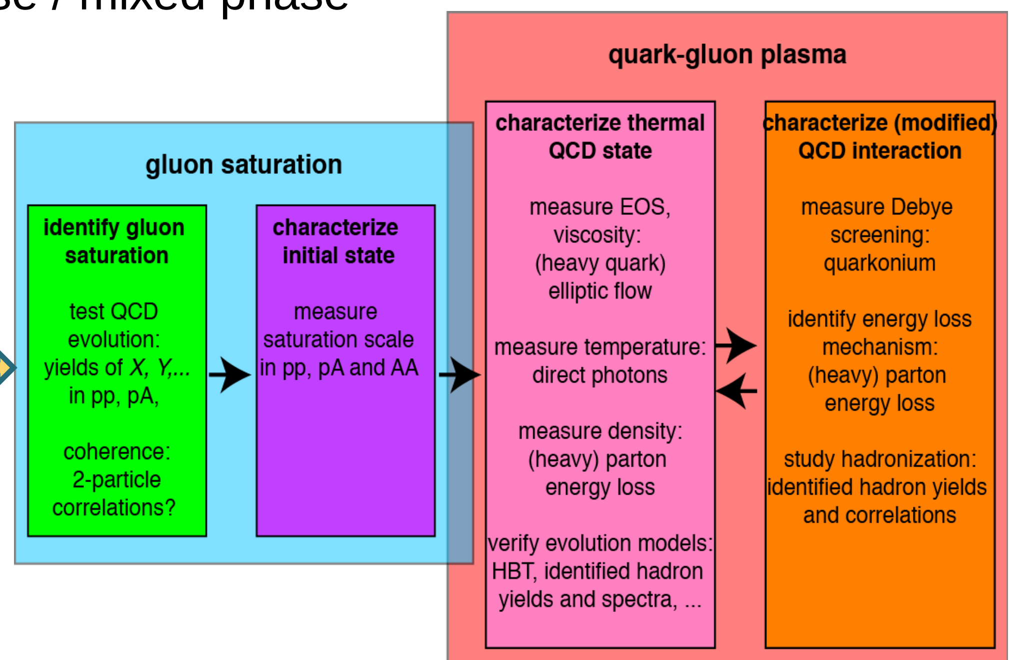
<u>The future:</u> high energy at LHC, low energy at FAIR / RHIC

The lesson from RHIC for high T QCD matter: focus on the difference between medium and vacuum

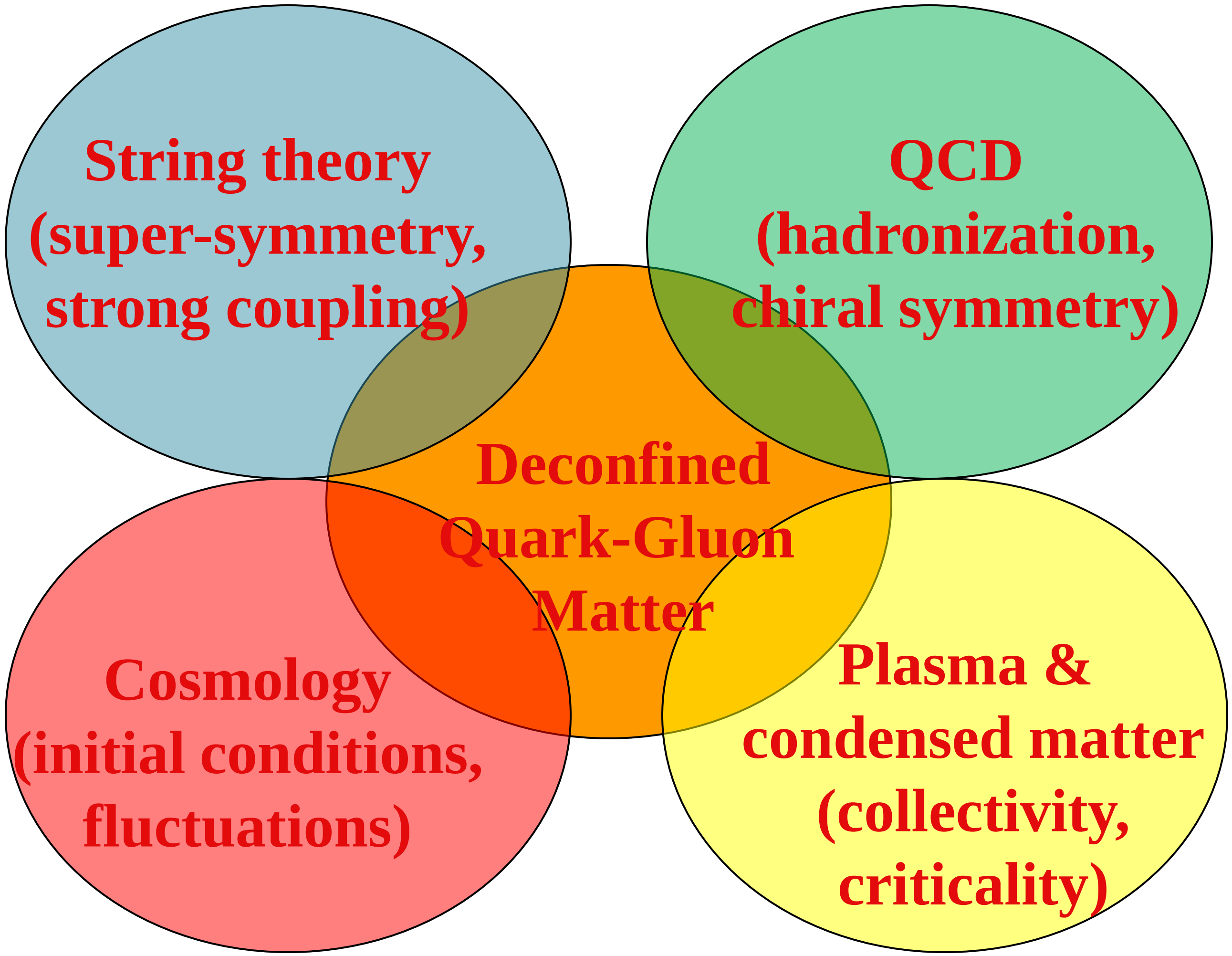
- QCD matter may be more weakly interacting at very high T, *but will not be described by pQCD in the original sense*.
- QCD case is not just an analogy to classical thermodynamics, there will be *new emergent phenomena*
  - Strong modification of coupling (interaction strength) and mass at high T
  - Matter formation in medium and vacuum (hadronization) ?
  - Properties of liquid phase / mixed phase







Relativistic Heavy Ion Collisions have come a long way



Suggestions for further reading

- **QCD: The Modern Theory of the Strong Interaction**
  F. Wilczek, *Ann. Rev. Nucl. Part. Sci. 32 (1982) 177*
- **Symmetry breaking and quark confinement,** *Concepts of Particle Physics Vol I and II*, K. Gottfried and V.F. Weisskopf, *Oxford Press (1984)*
- **The first second of the universe**
  D.J. Schwarz, *arXiv:astro-ph/0303574*
- **The phase diagram of QCD**
  S. Hands, *arXiv:physics/0105022*
- **String Theory and the Quark Gluon Plasma**
  M. Natsuume, *arXiv:hep-ph/0701201*
- **Transition from Hadron Matter to Quark-Gluon Plasma**
  H. Satz, *Ann. Rev. Nucl. Part. Sci. 35 (1985) 245*
- **The Search for the Quark-Gluon Plasma**
  J. Harris and B. Muller, *Ann. Rev. Nucl. Part. Sci. 46 (1996) 71*