Understanding properties of the QGP on the basis of correlation and fluctuation measurements at RHIC and LHC

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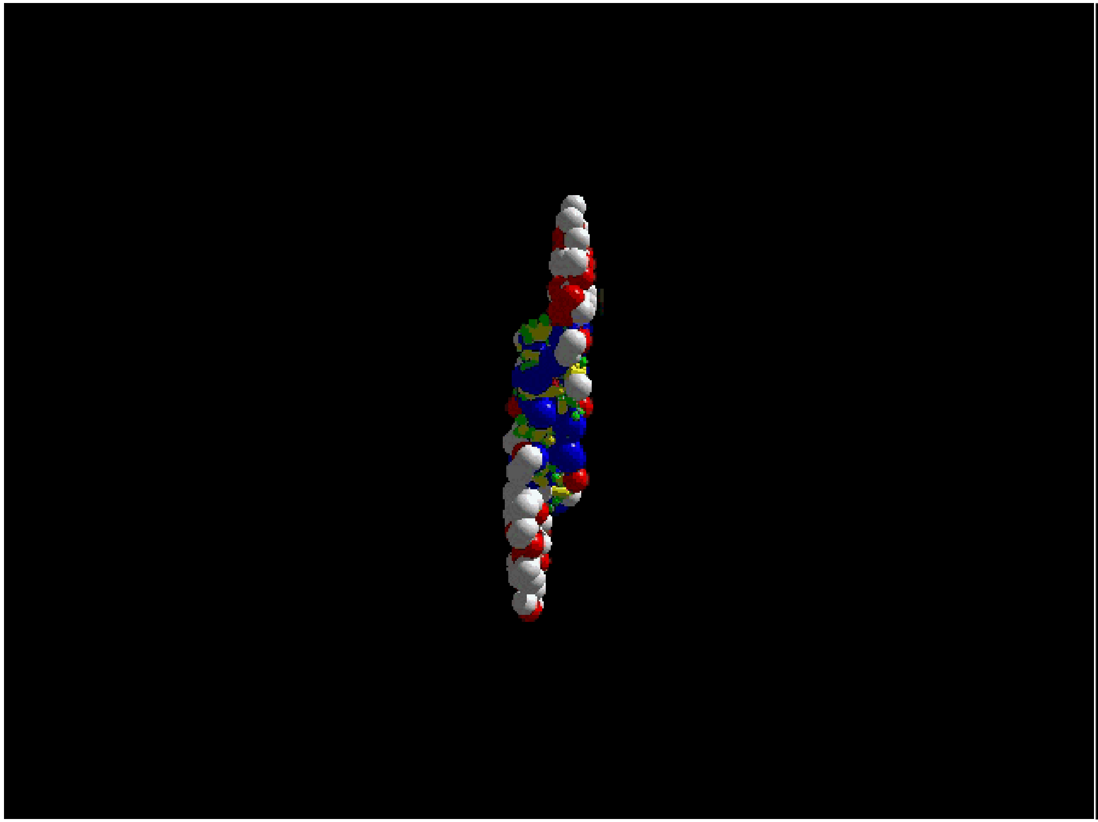
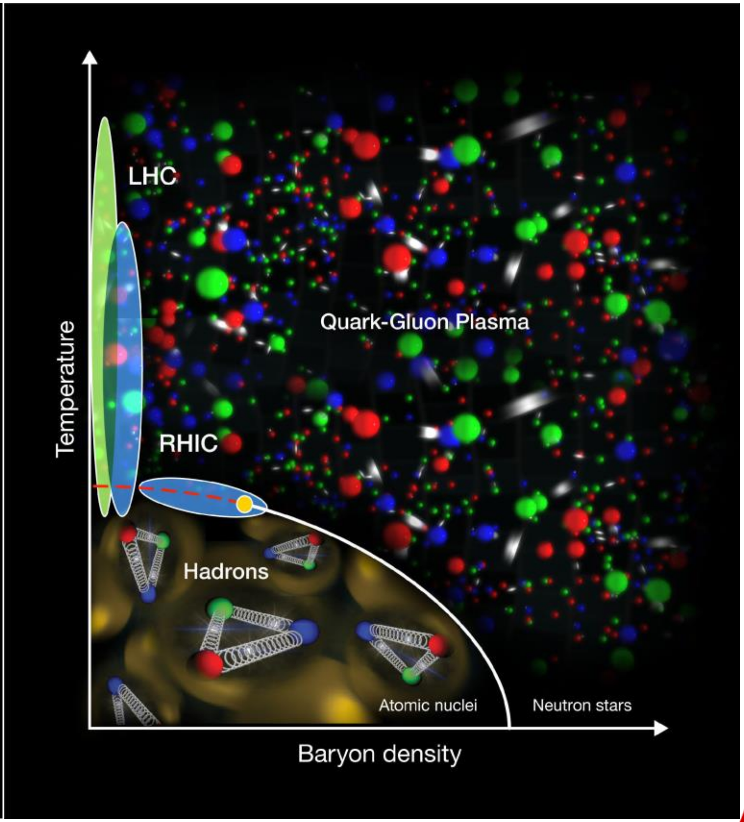
Overcoming the strong force using compressed matter at relativistic energies → QCD phase transition (deconfinement, chiral symmetry restored)





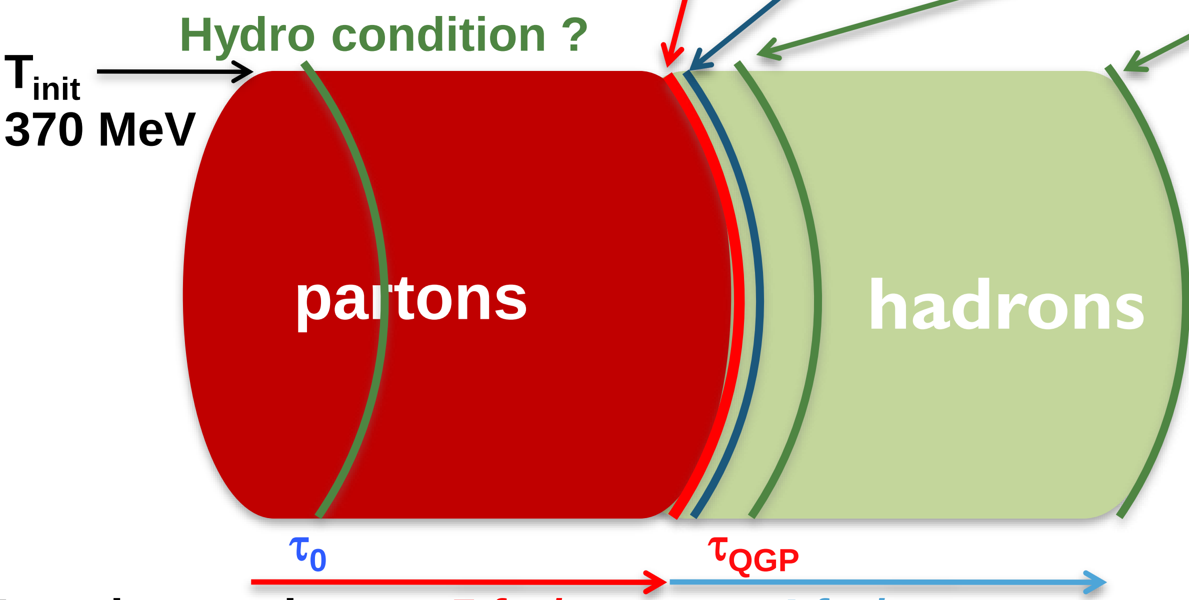
LHC: max. energy = max. T = max. transparency = min. density

RHIC: reduced energy and T = stopping = finite density

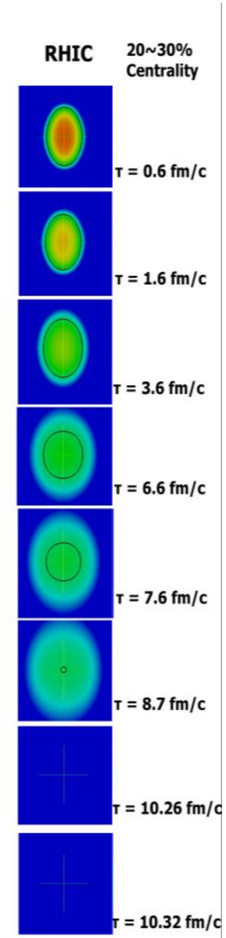
Evolution of a RHIC heavy ion collision

(as a function of temperature and time)

Model:	lQCD	SHM	Blastwave	
Effect:	hadronization	chemical f.o.	kinetic f.o.	
Freeze-out surface:	T_{crit}	T_{ch}	$T_{kin}(\Xi,\Omega)$	$T_{kin}(\pi,k,p,\Lambda)$
Temperature (MeV):	151	148	148	80
Expansion velocity (c):			$\beta=0.45$	$\beta=0.6$



Experiment: time: ~5 fm/c ~4 fm/c
(STAR, PRL 97:132301,(2006))



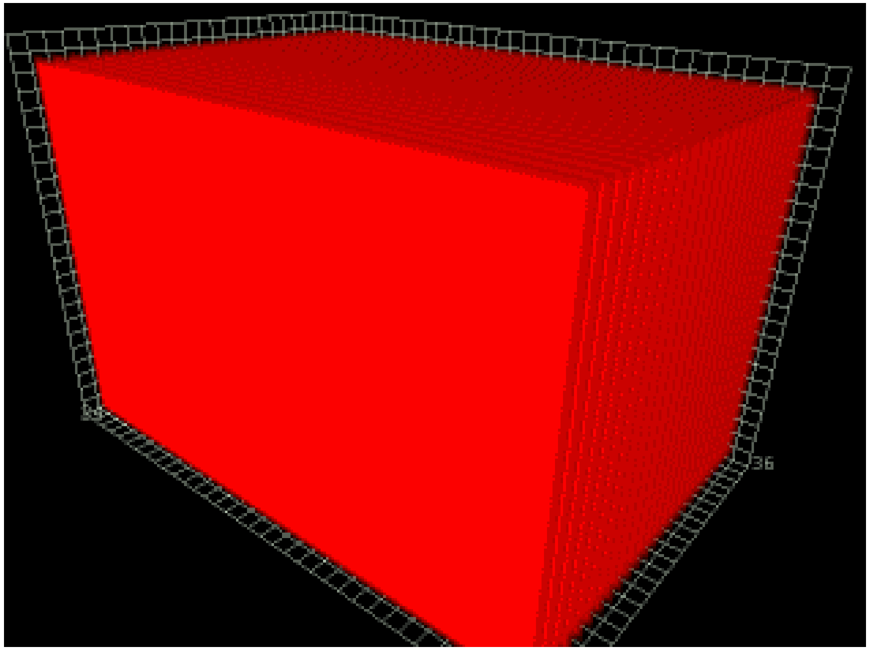
References:

Lattice QCD:
arXiv:1005.3508
arXiv:1107.5027

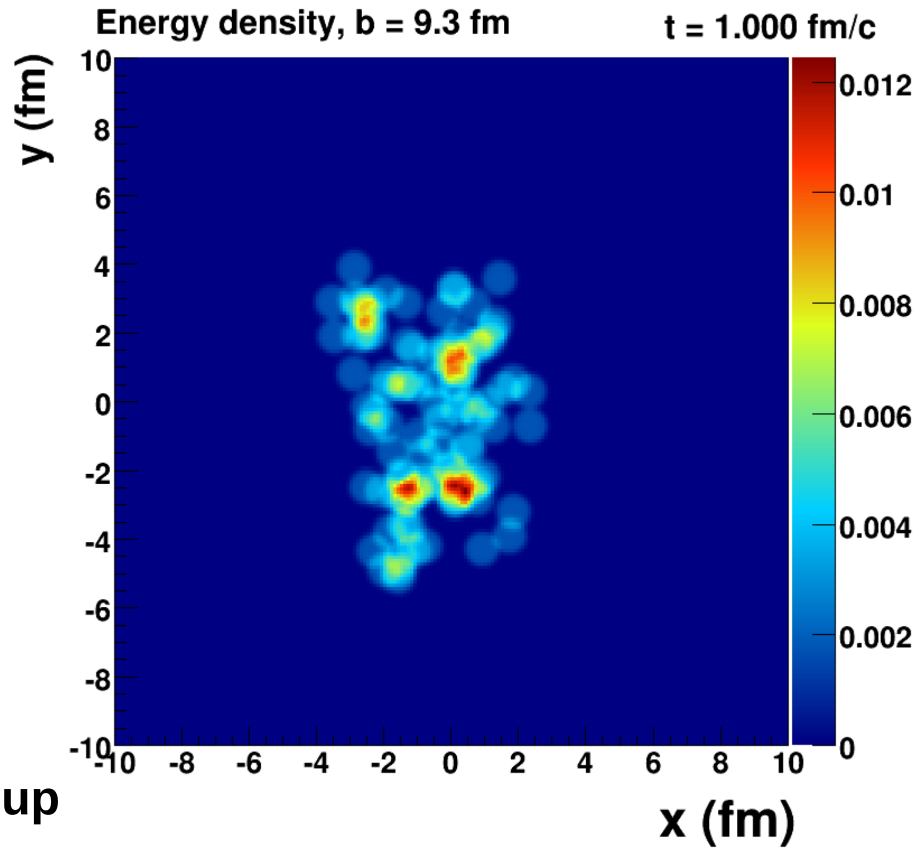
Statistical Hadronization:
hep-ph/0511094
nucl-th/0511071

Blastwave:
nucl-ex/0307024
arXiv:0808.2041

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

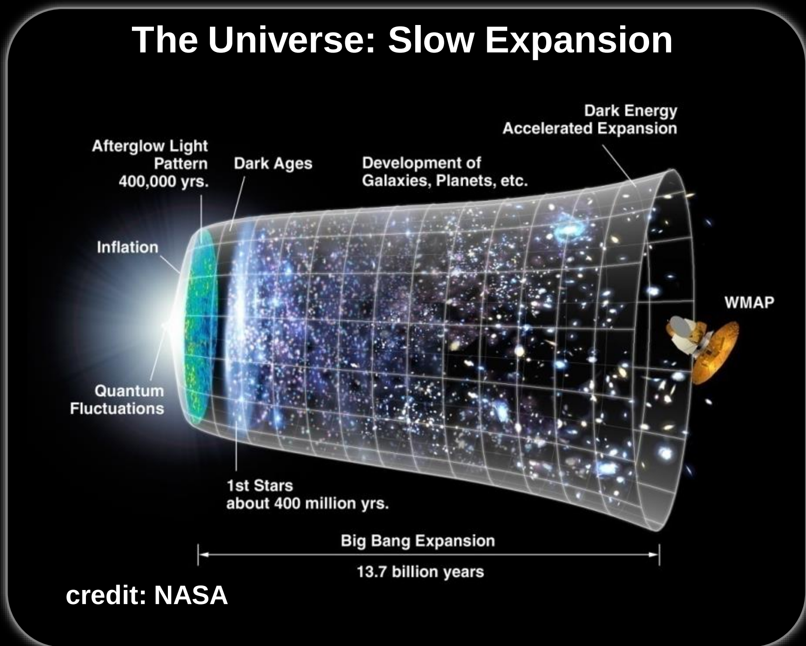


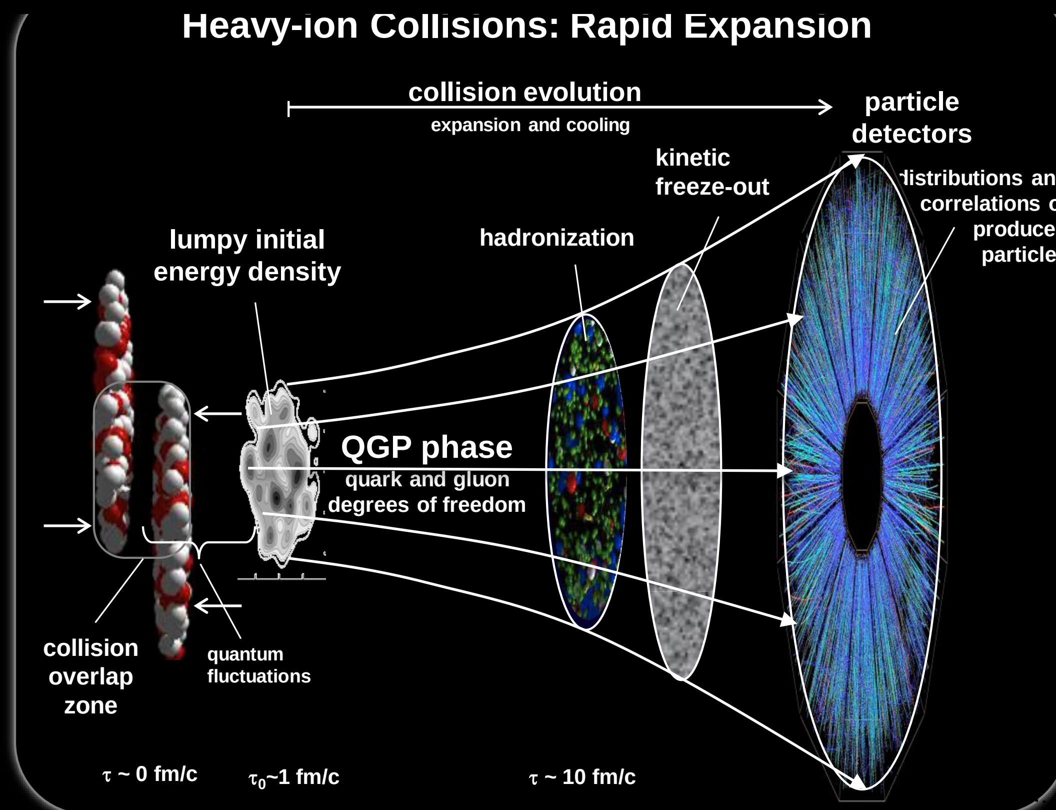
Lattice QCD calculation, Adelaide Group

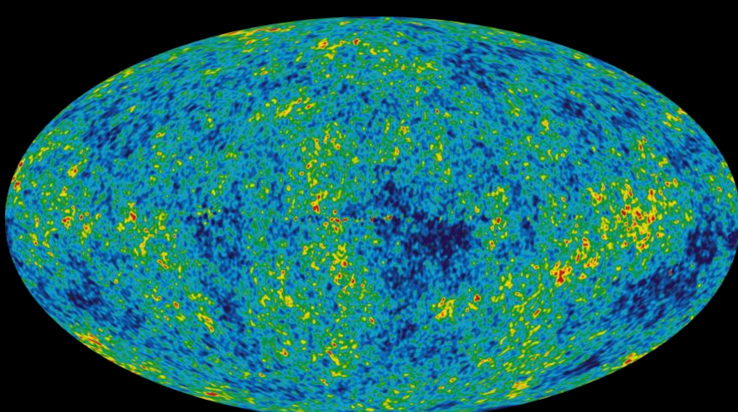


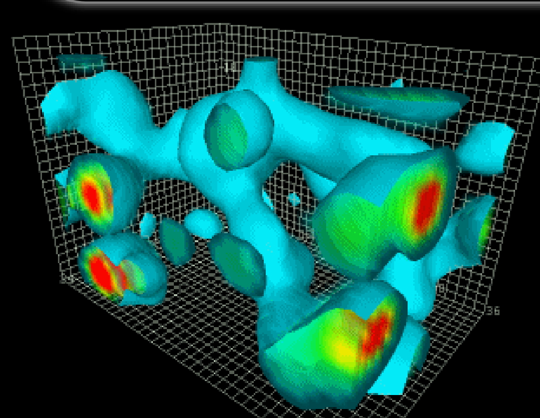
Time evolution of initial conditions in hydro (J. Nagle et al.)

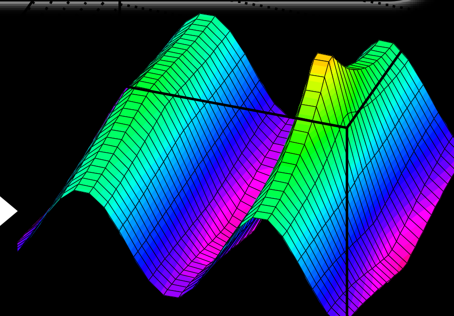
Ongoing analyses:
Analogy to early universe - evolution of fluctuations & correlations









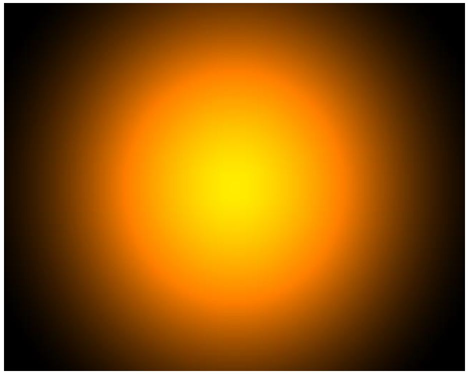


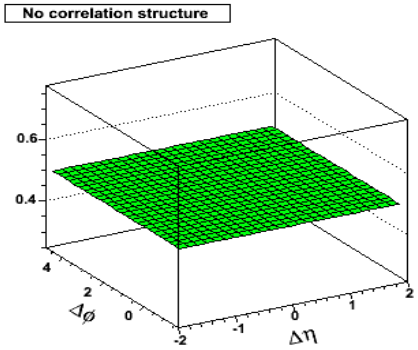
particle distribution in η and ϕ in STAR

Correlation Measurements

Smooth initial conditions ?

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

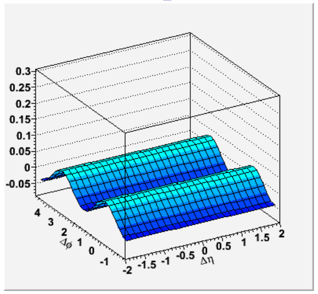




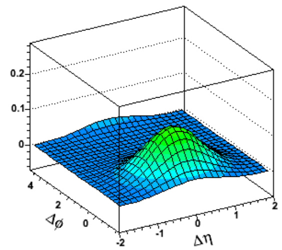
- **Equal probability for each particle in any direction of emission**

- **In high energy nuclear and particle physics we expect specific correlation effects**
  - **Resonance decay**
  - **Radial flow**
  - **Anisotropic flow (geometry)**
  - **Jet fragmentation**

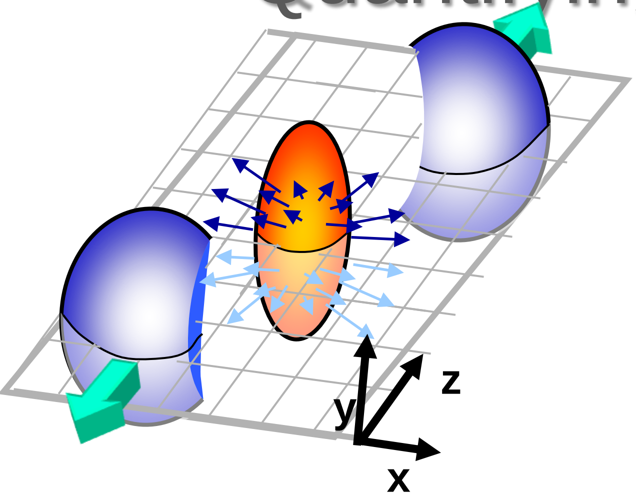
Anisotropic flow



Jet fragmentation



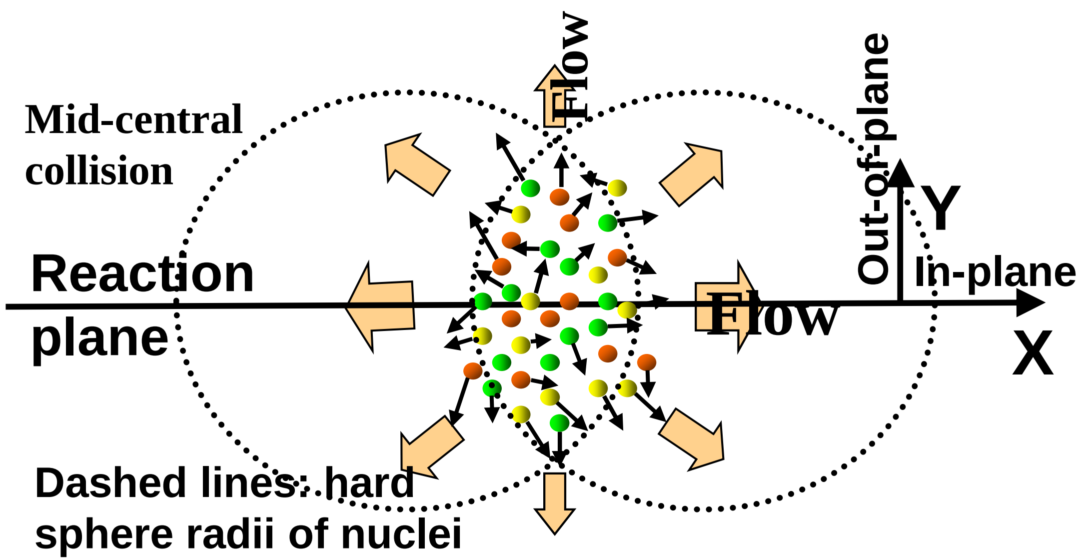
Quantifying anisotropy and collectivity



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

Directed flow

Elliptic flow



Hydrodynamics:

strong coupling,

small mean free path:

many interactions

NOT plasma-like

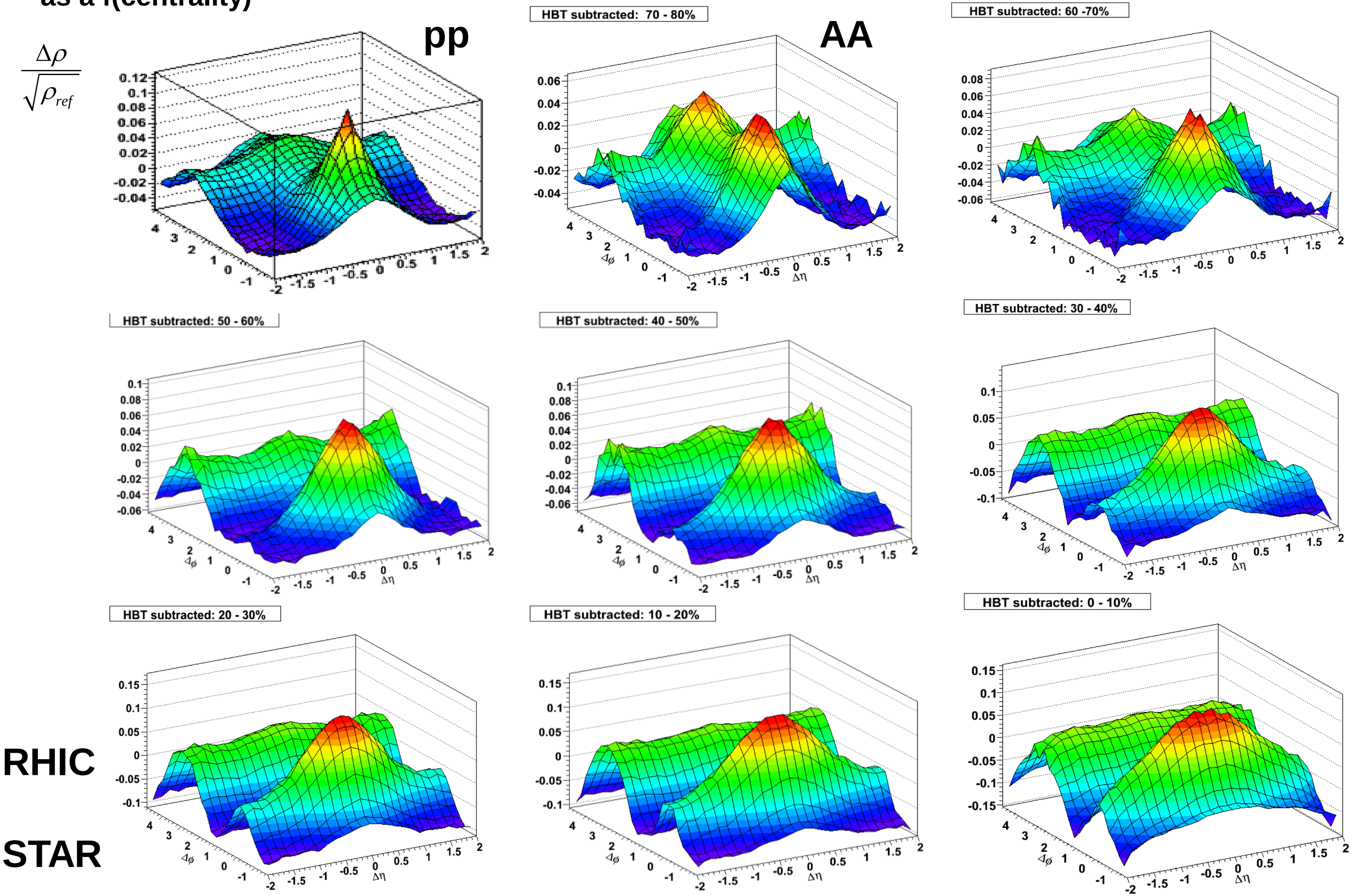
system behaves liquid-like.

Hydro measures level of viscosity/entropy ratio (η/s)

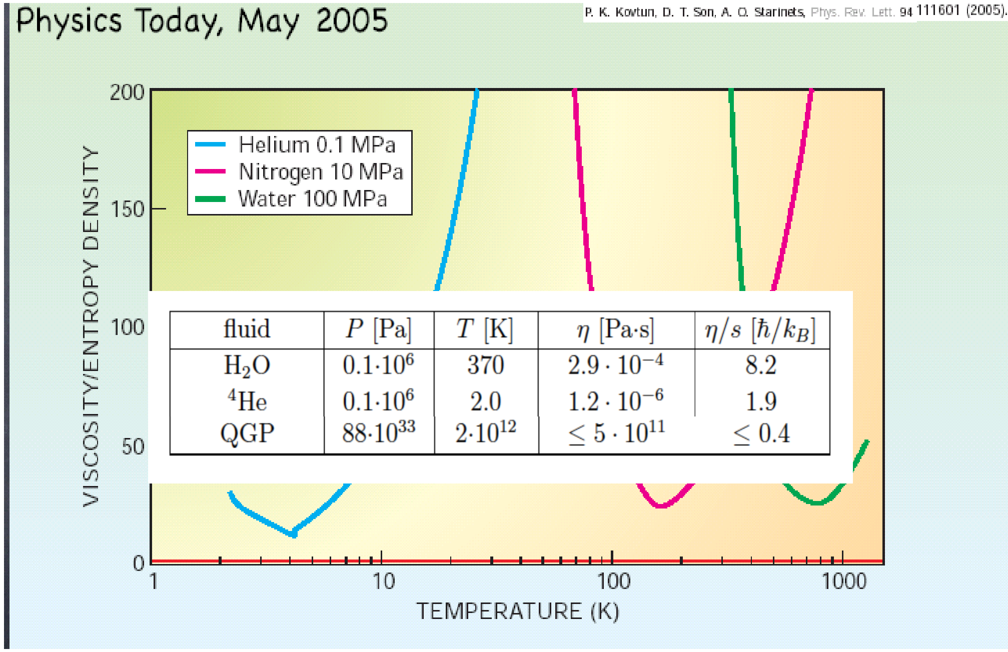
The smaller, the more ideal the liquid is (quantum limit = 1/4π = 0.08)

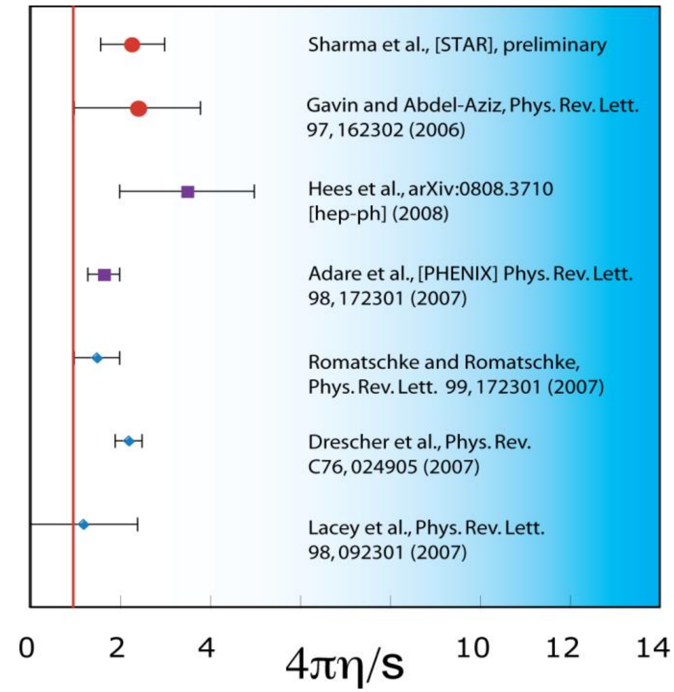
Lots of structure in emissions

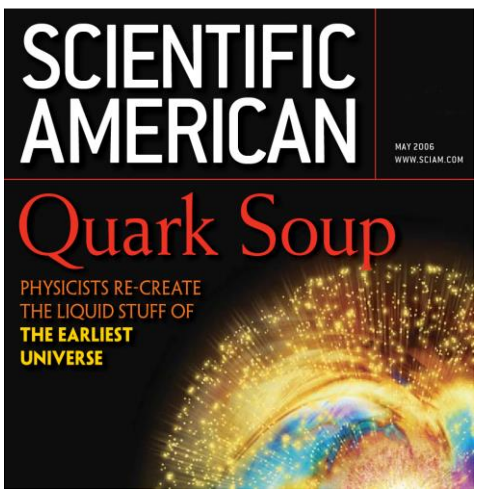
Number correlations in coordinate space as a f(centrality)

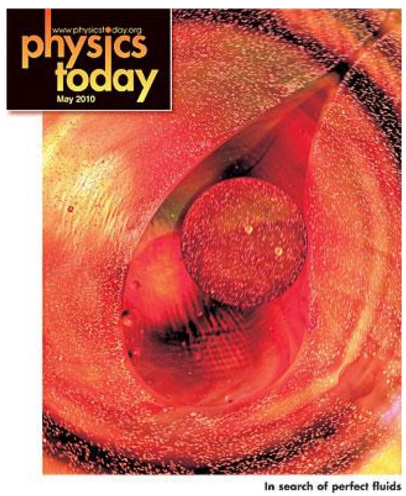


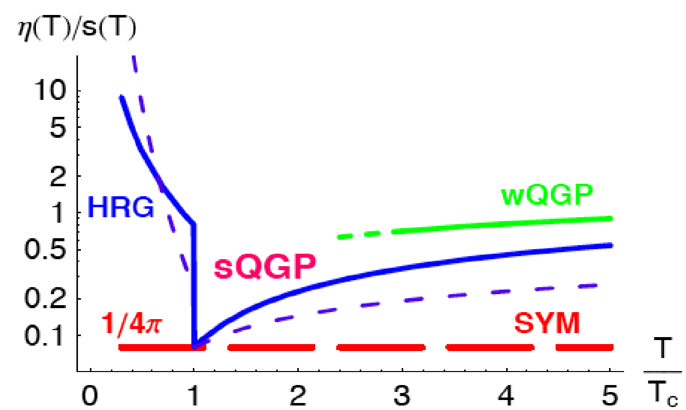
Lesson from RHIC – a near perfect Quark Soup ?



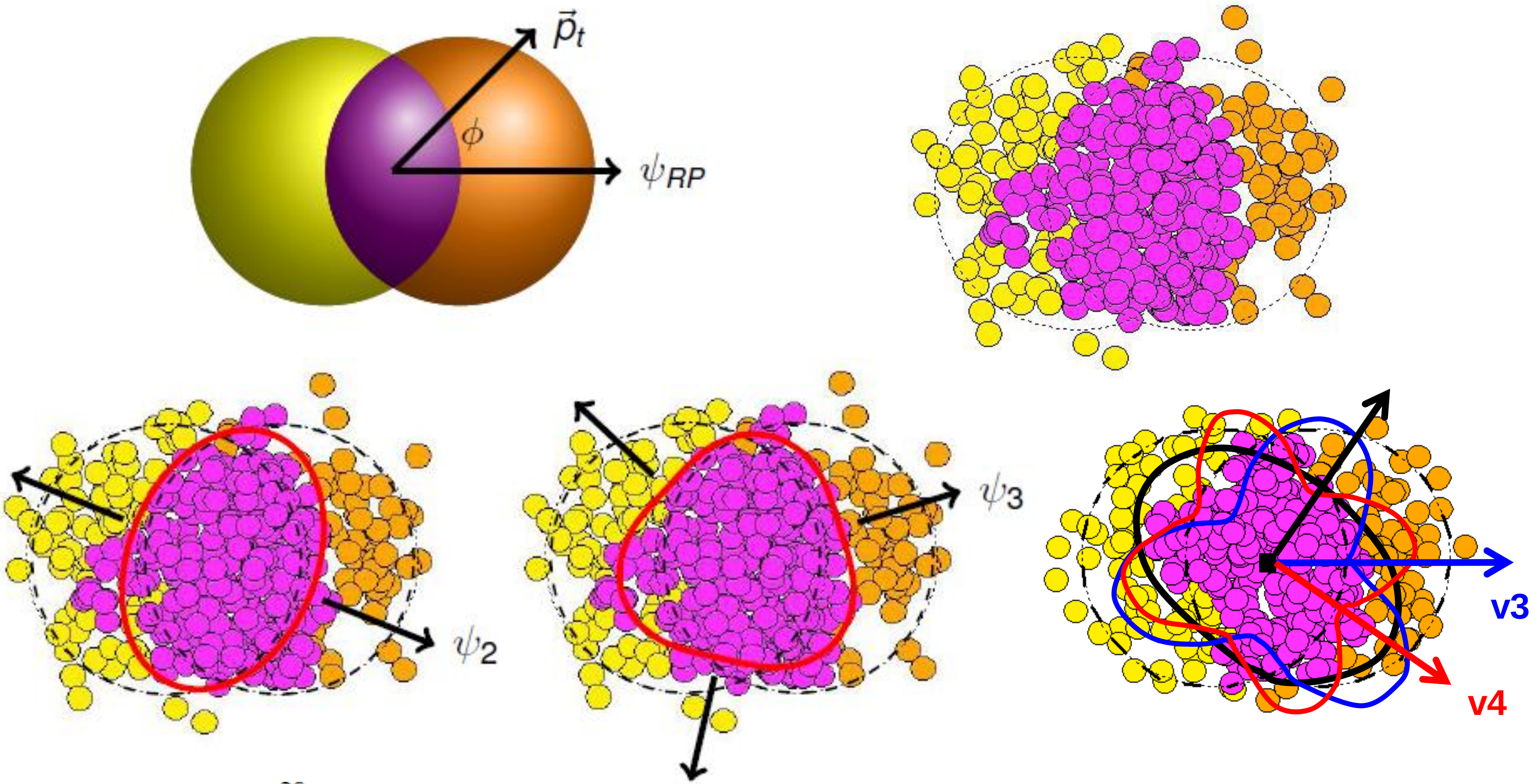








Higher harmonics of initial energy density fluctuations

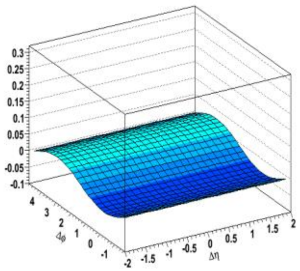
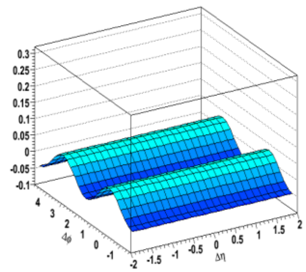
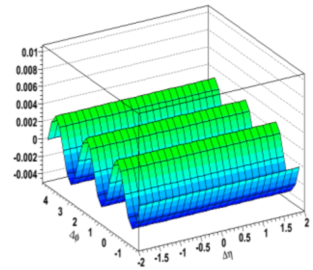
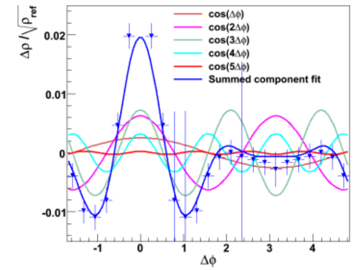


$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n \cos n(\phi - \psi_n) \Longrightarrow \left\langle \frac{dN_{\text{pairs}}}{d\Delta\phi} \right\rangle \overset{\text{(flow)}}{\propto} 1 + \sum_{n=1}^{\infty} 2 \left\langle v_n^{\,2} \right\rangle \cos n(\Delta\phi) \;\cdot\cdot$$

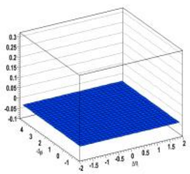
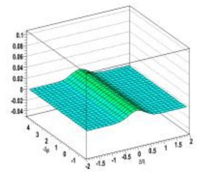
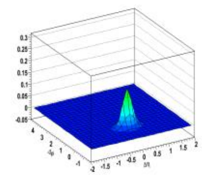
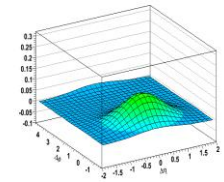
Example: Residual & fit decomposition for 30 – 40% centrality

Decomposition

Momentum conservation	*elliptic flow*	*triangular flow*	*higher harmonics*
cos(Δφ)	**cos(2 Δφ)**	**cos(3 Δφ)**	**……**

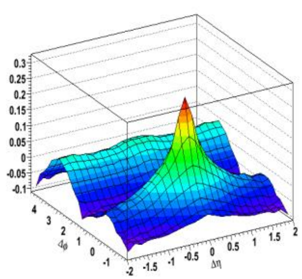
Offset **1d Gaussian** **Exponent** **2d Gaussian**

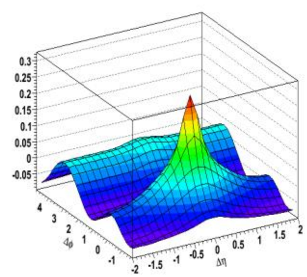
String fragmentation *resonances/HBT/e+e-* *modified jet fragmentation*

STAR
Cu+Cu 200GeV

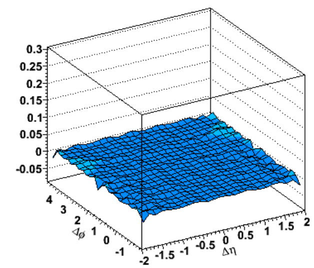
Data



Fit

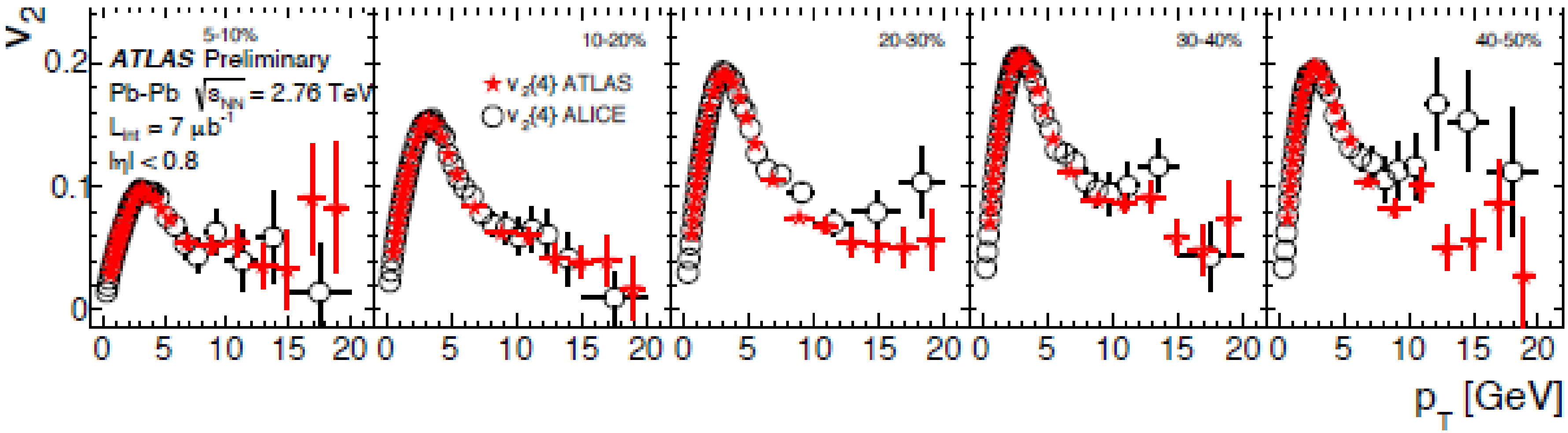


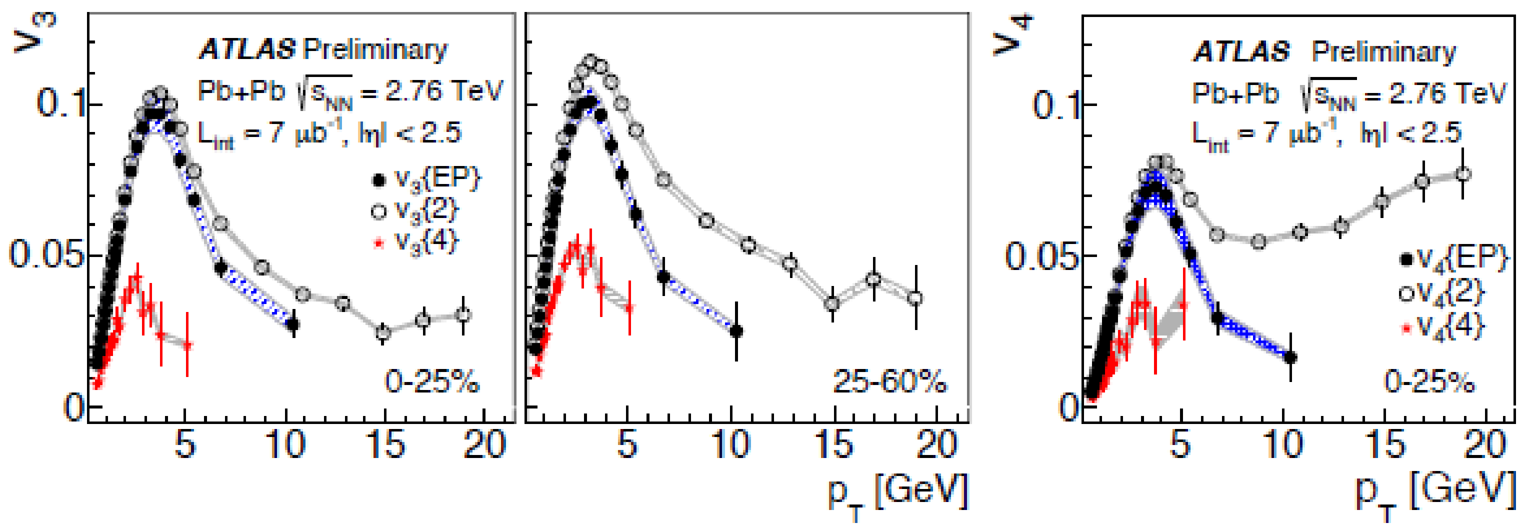
Residual



χ^2/#dof ≈ 1.6

Heavy Ion Flow at the LHC

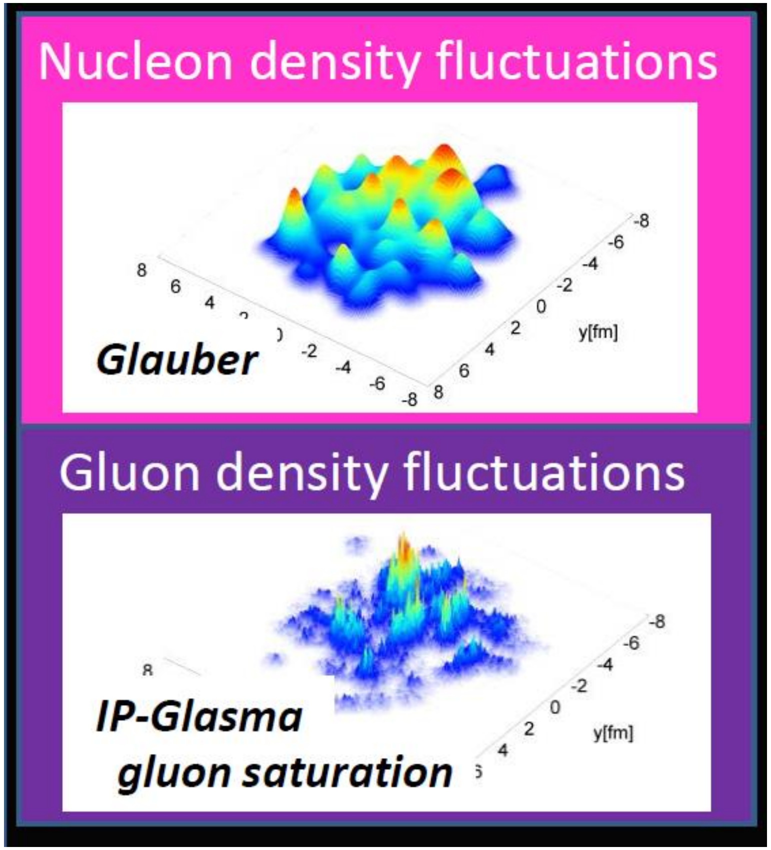




Significant precision to high pT and for higher order harmonics

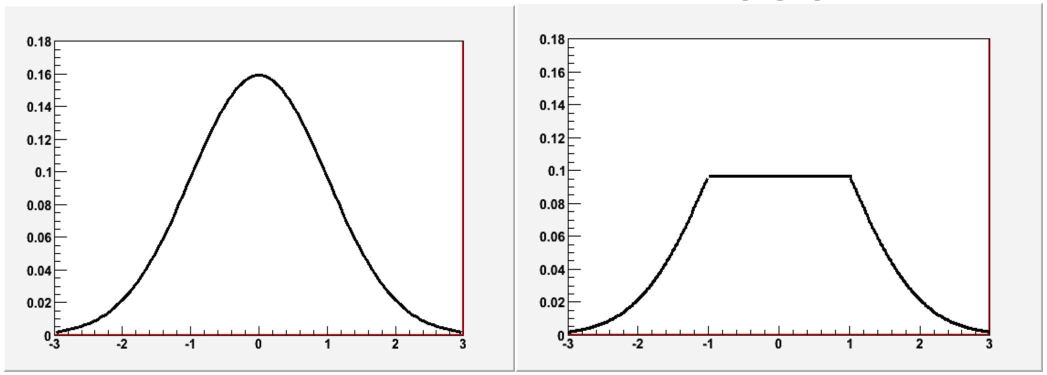
Initial State determines flow strength

Nucleonic or sub-nucleonic structure in density fluctuations ?

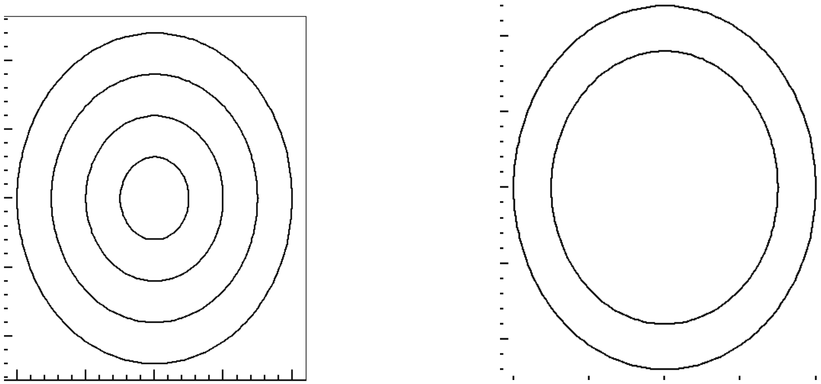


Radial gluon distribution

Glauber **CGC**



2-D density profile

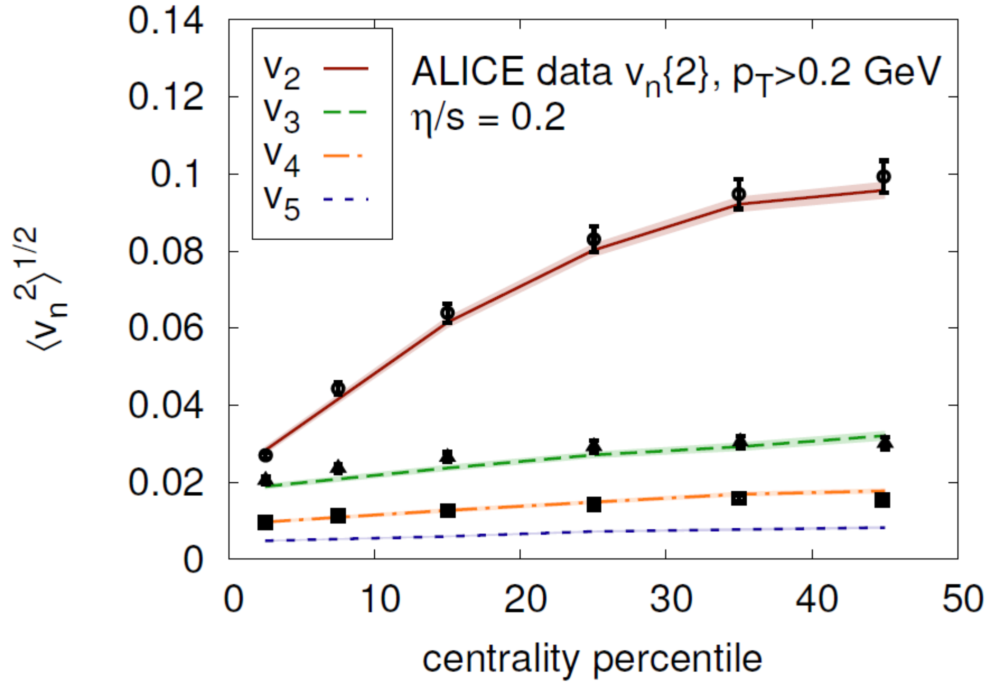


Smaller eccentricity **larger eccentricity**

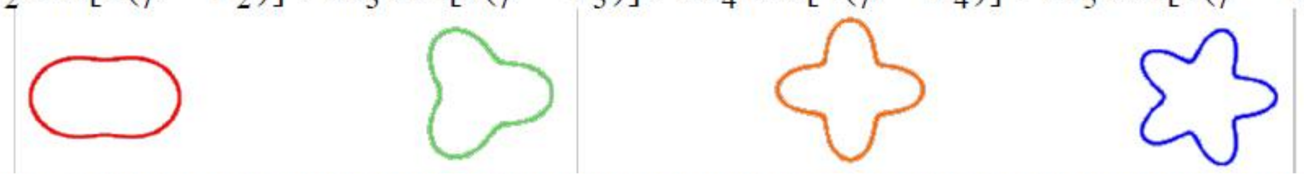
Flow measurements validate hydrodynamic modeling

Recent theory development: a hybrid approach with hydro and IC

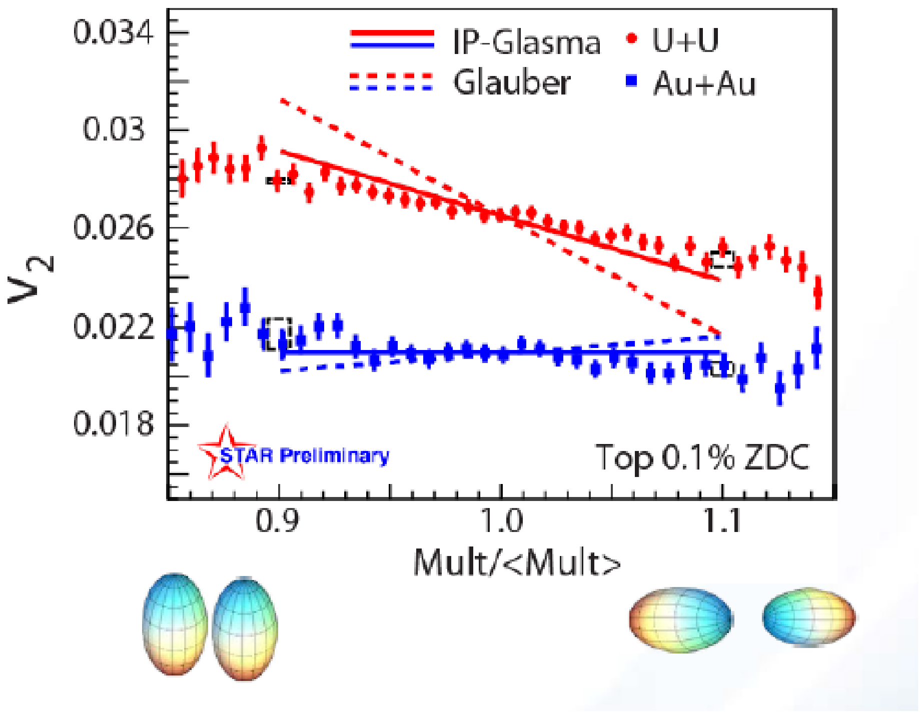
IP-Glasma IC and viscous hydro (MUSIC) (McGill+BNL, PRL 110,012302 (2013)

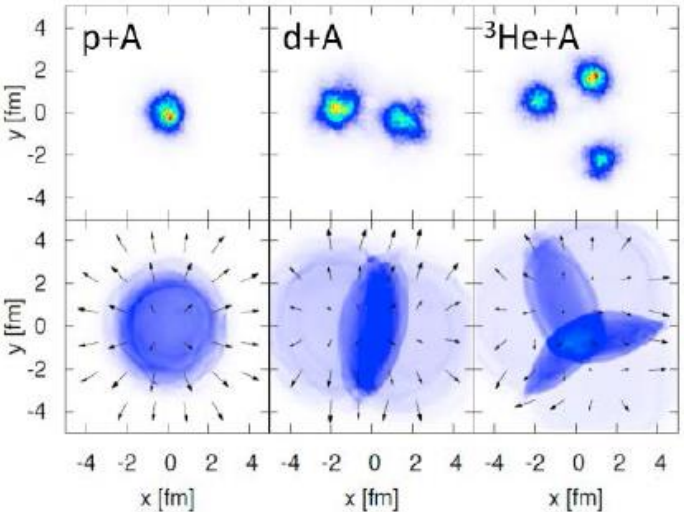


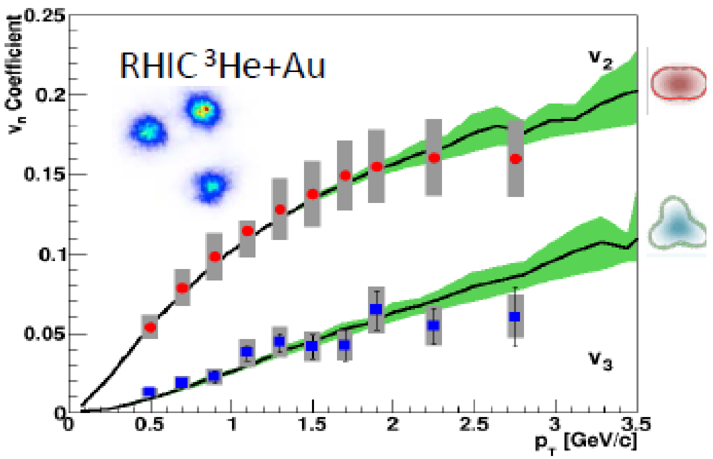
$$\frac{dN}{d\phi} = 1 + 2v_2\cos[2(\phi-\Psi_2)] + 2v_3\cos[3(\phi-\Psi_3)] + 2v_4\cos[4(\phi-\Psi_4)] + 2v_5\cos[5(\phi-\Psi_5)] +$$



Resolving the sub-nucleonic quantum structure: From the largest to the smallest systems





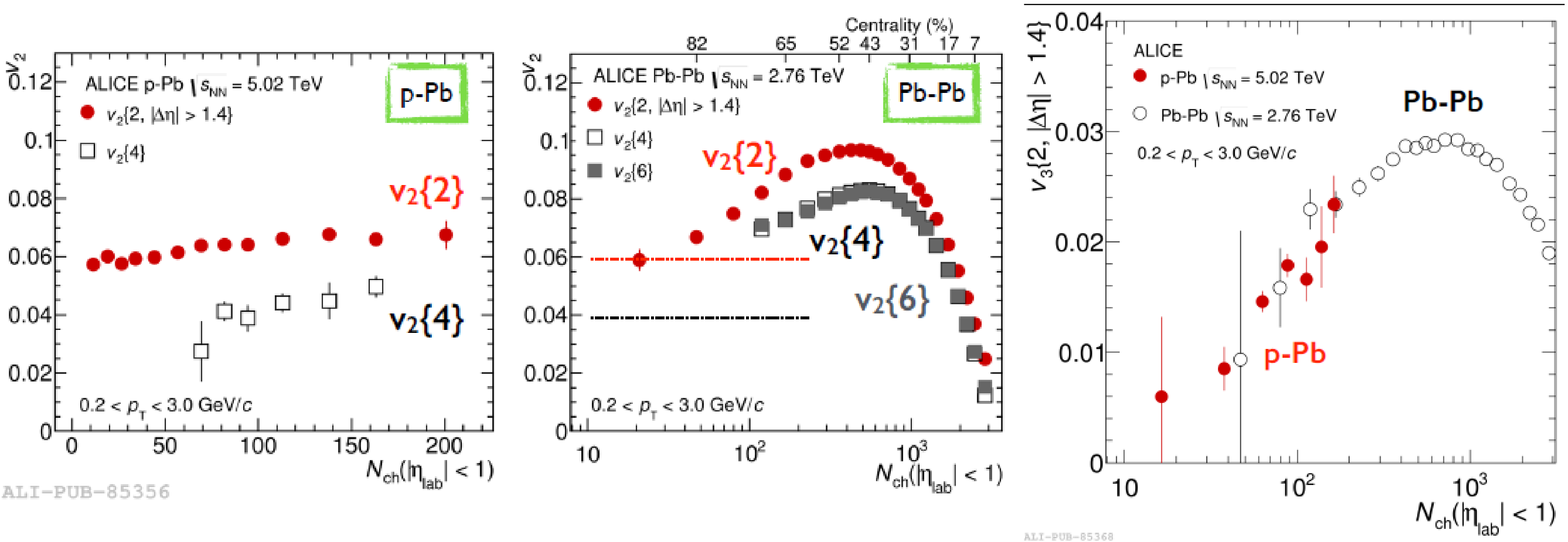


IP-Glasma more consistent with U+U data than Glauber

Initial State fluctuations occur at parton level

Can we resolve the number of sub-nucleonic scattering centers in small systems?

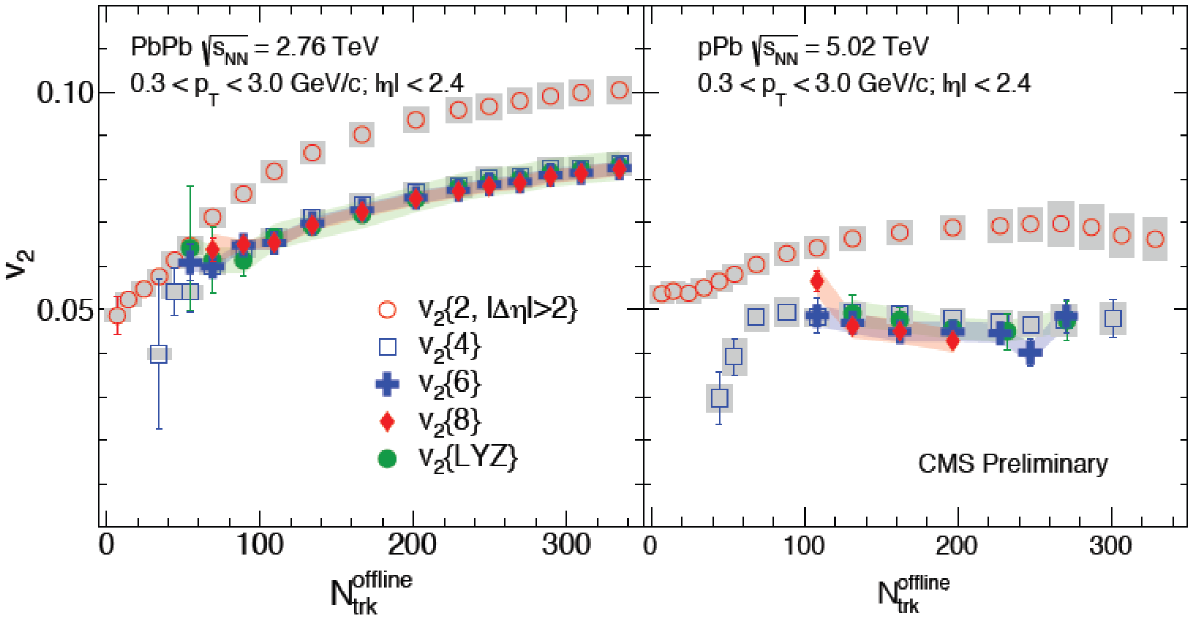
Multi-particle correlations in small systems (pPb, dAu, even pp?)

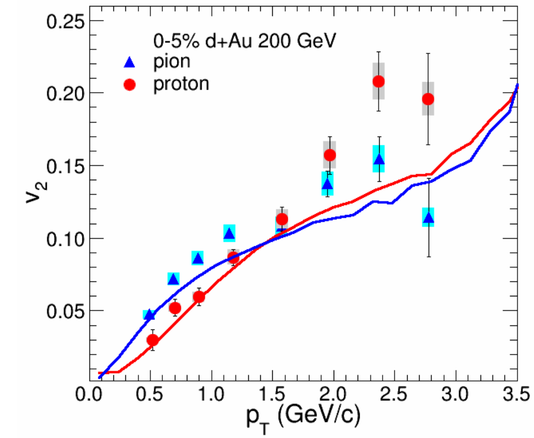


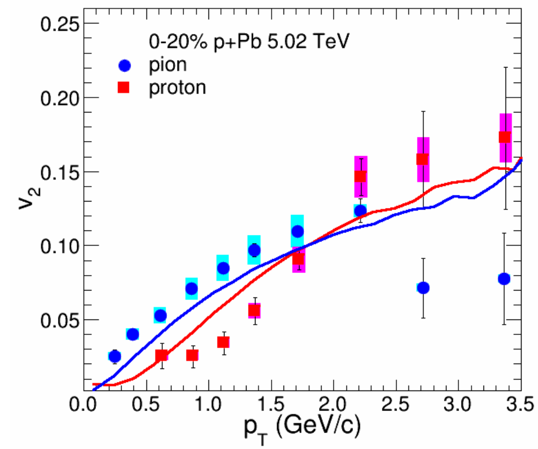
- v2 in p-Pb is smaller than v2 in Pb-Pb at comparable multiplicities
- v3 in p-Pb is similar to v3 in Pb-Pb at comparable multiplicities
- Multi-particle v2 is a strong hint of collectivity

The dagger in the heart for non-flow explanations ?

PbPb **pPb**

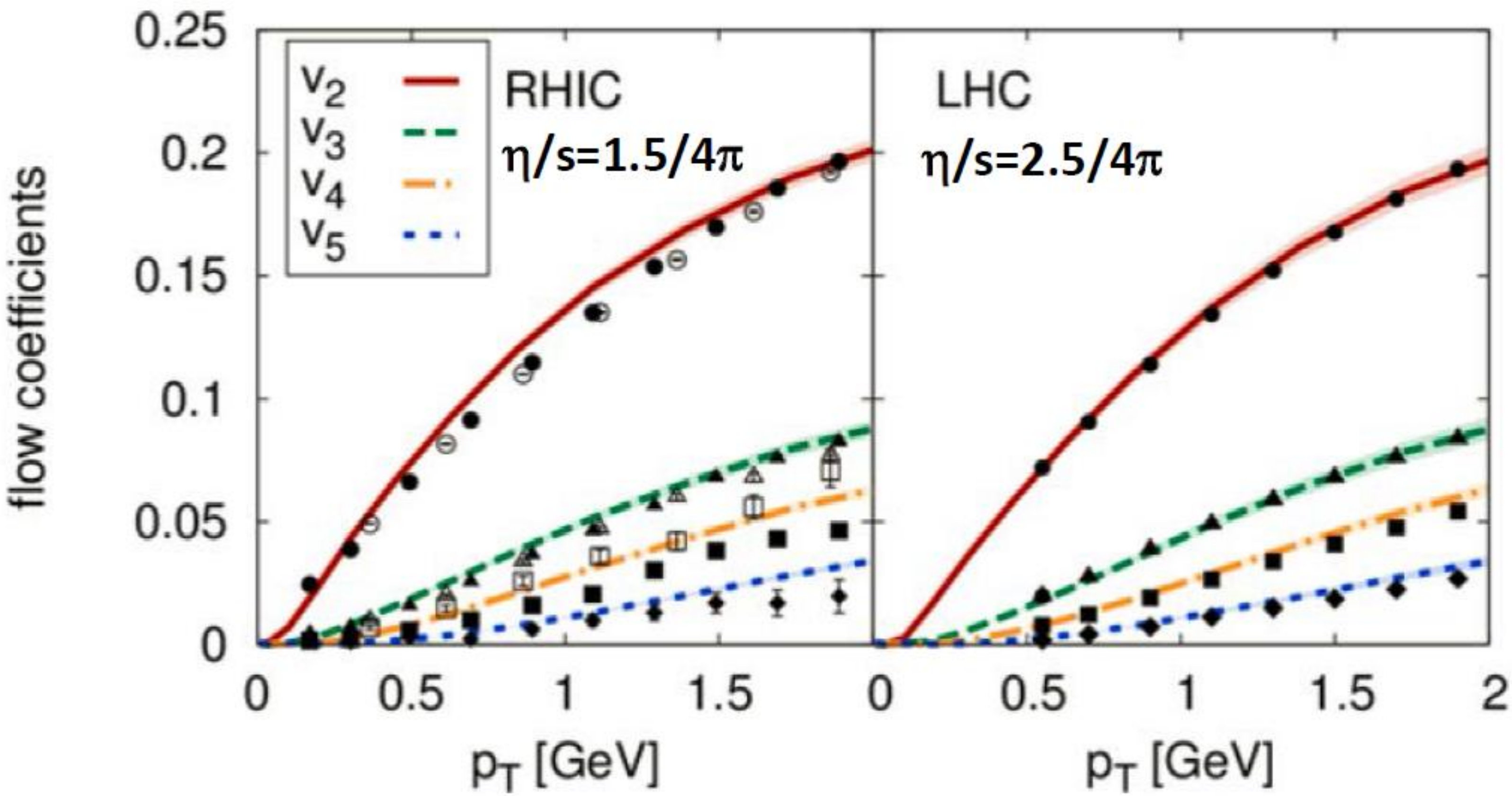






This is a mass dependent multi-particle correlation,
i.e. it must be a collective phenomenon ?
Multi-gluon interactions can explain two-particle correlations (Gyulassy)

Flow measurements constrain initial conditions



- LHC fit to v_n's yields $\eta/s = 0.20$, RHIC fit yields $\eta/s = 0.12$
- Different η/s indicates temperature dependence of viscosity ?

A power spectrum for QGP = analog to the WMAP

An acoustic horizon in fluid dynamics (e.g. arXiv:1101.1926)

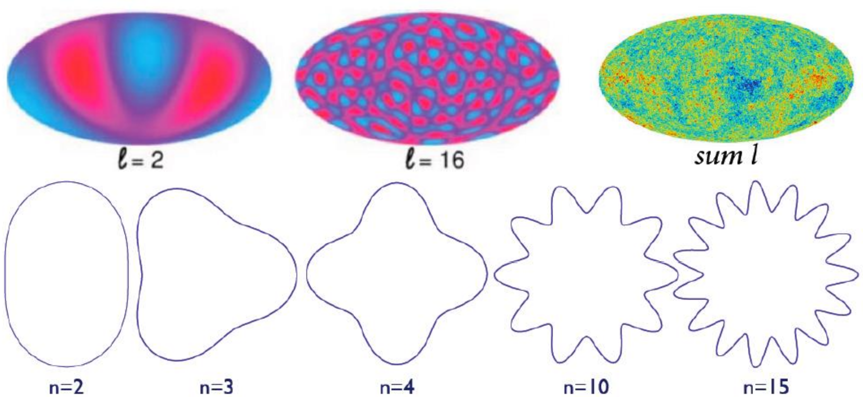
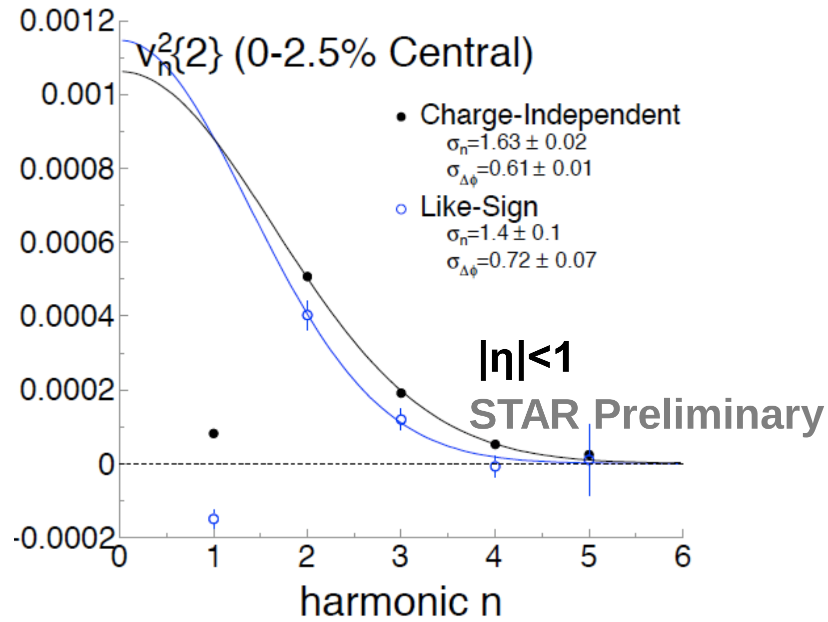
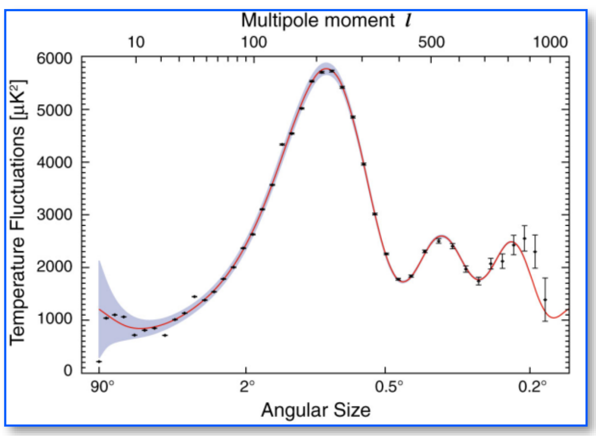


Figure 1: Top: the length scales in the CMB. Bottom: the length scales probed with higher *n* in heavy-ion collisions.





Gaussian width can be related to length scales like mean free path, acoustic horizon, 1/(2πT)…

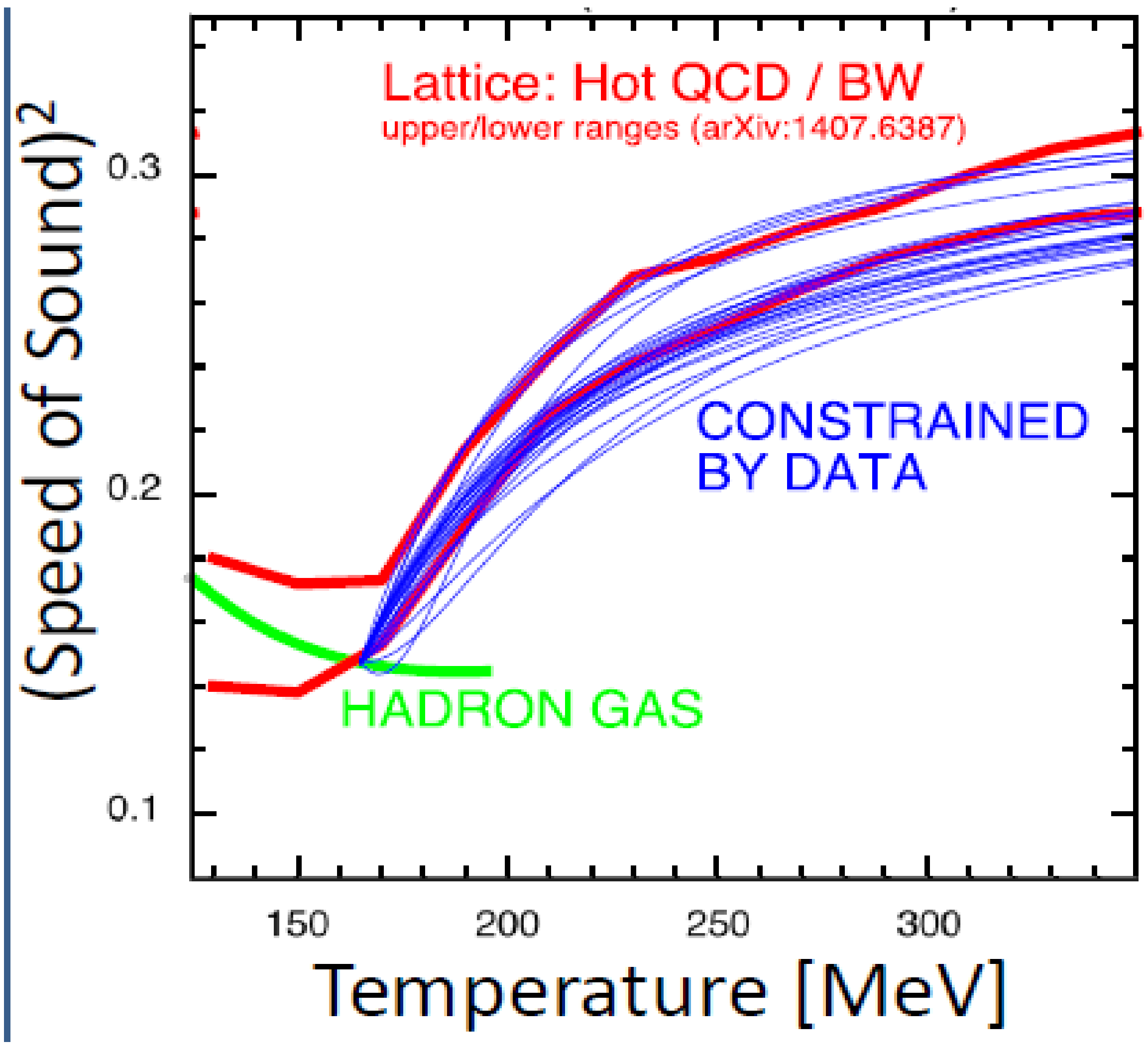
How much more does the full harmonics spectrum constrain the medium parameters (e.g η/s) ?

Experimental confirmation of QCD EoS

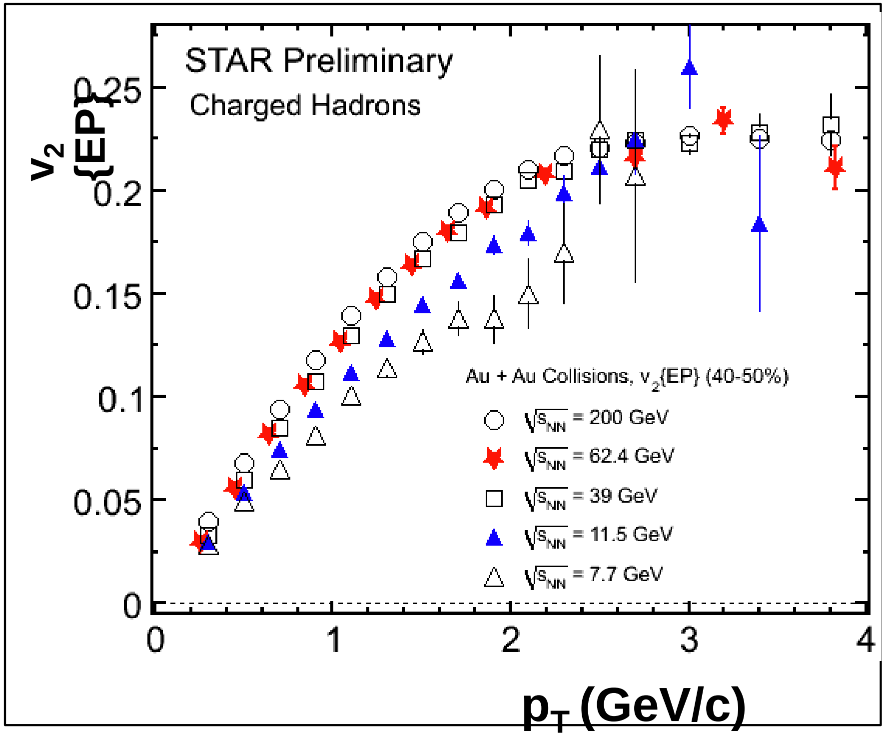
Using multi-variate analysis on RHIC & LHC data

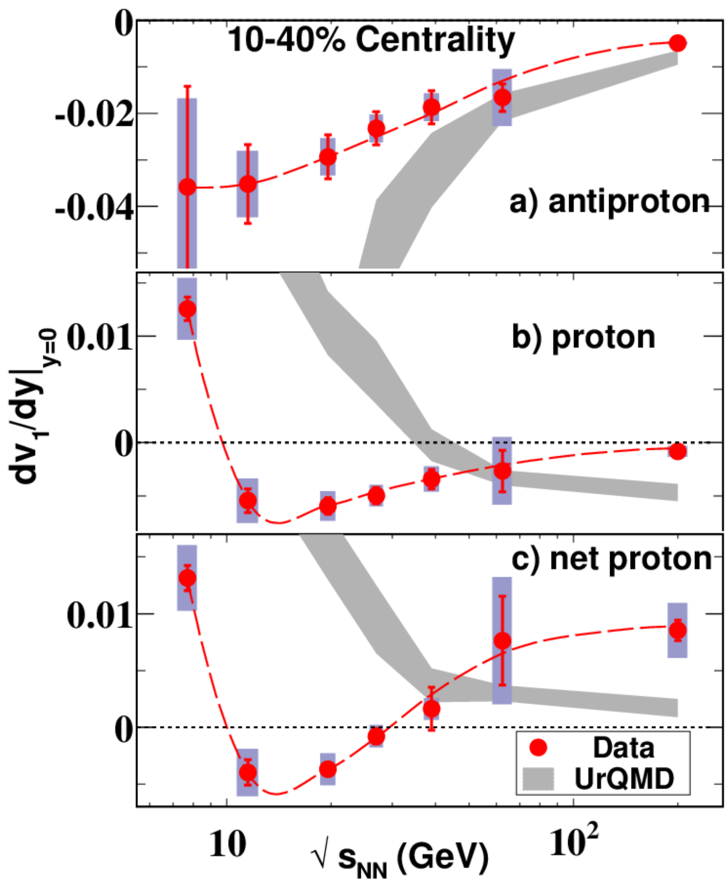
(from latest climate/cosmology techniques)

S. Pratt et al.
PRL 114 (2015)



What happens at lower energies ?

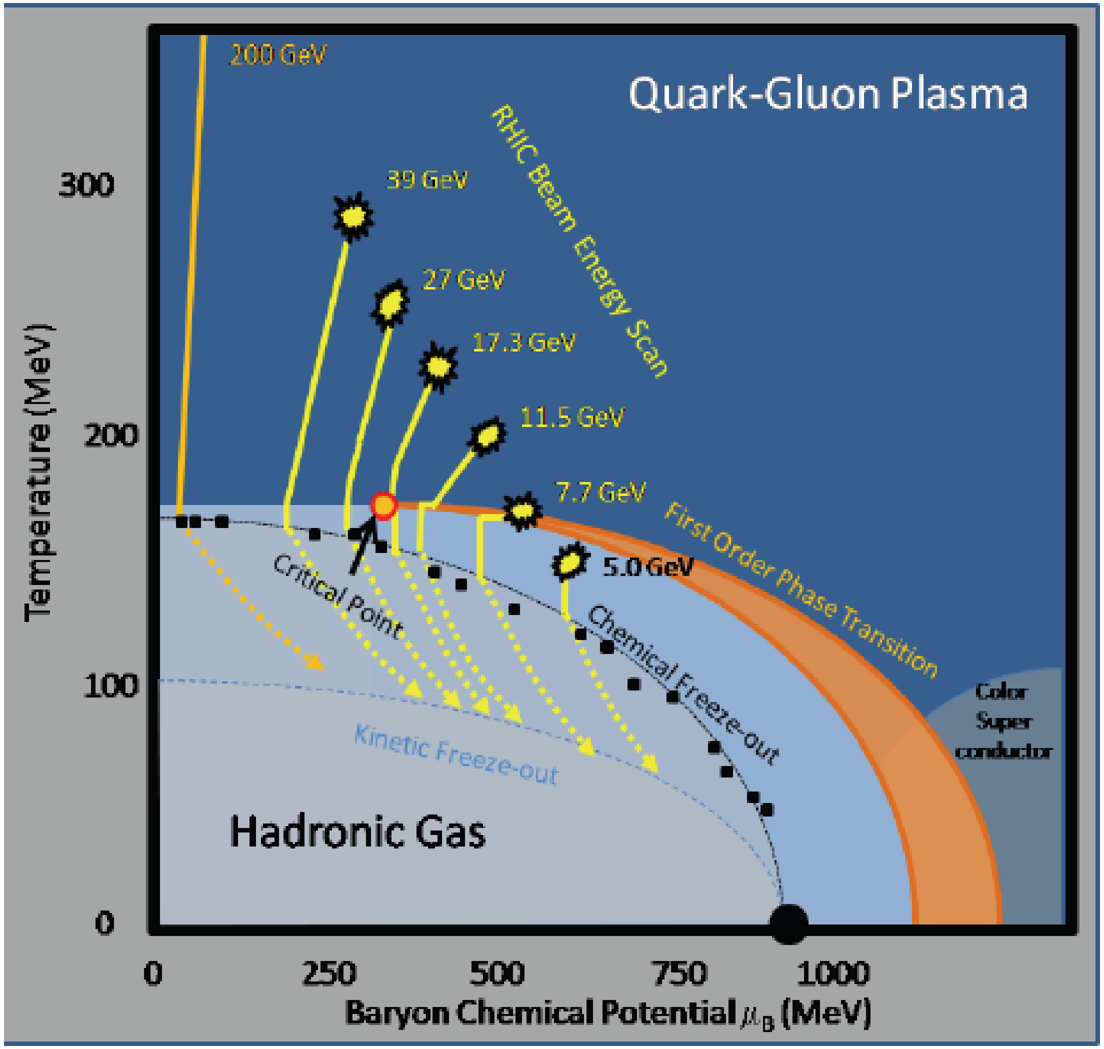




From LHC energies down to 39 GeV v2 stays almost constant. Below these energies the system does not follow ‘ideal’ hydro anymore.

This coincides with a sign change in v1. Softest point ? Changing EOS.

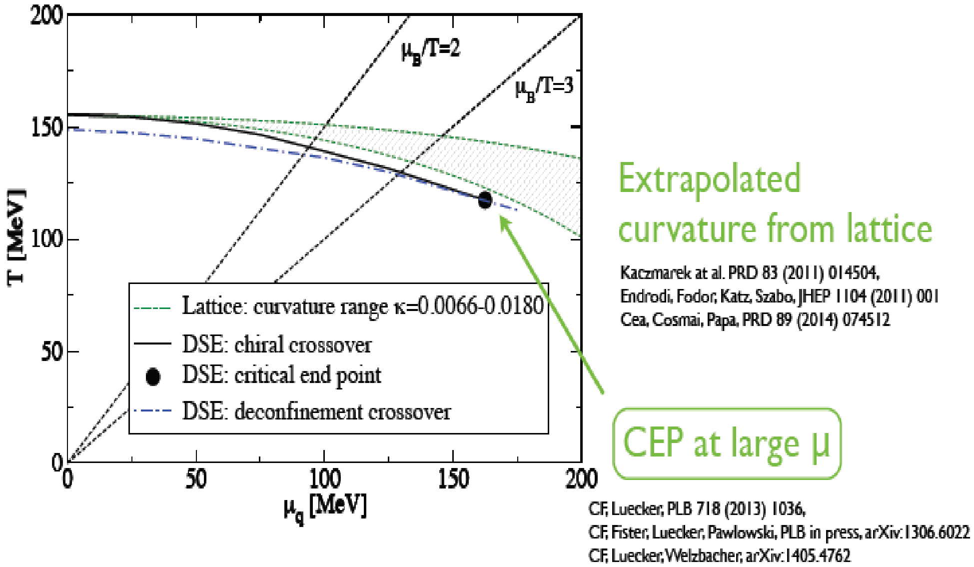
Fluctuation Measurements

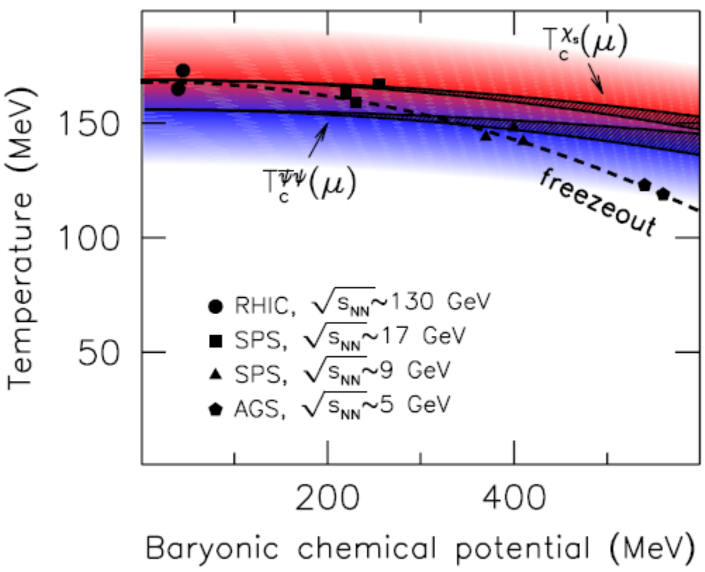


The critical point (theoretical approach)

- For a Gaussian distribution: skewness and kurtosis are zero.
- Look for non-Gaussian distribution near critical point
- Baseline for net-quantitites: Skellam (folded Poissonians)
- Fluctuations depend on correlation length

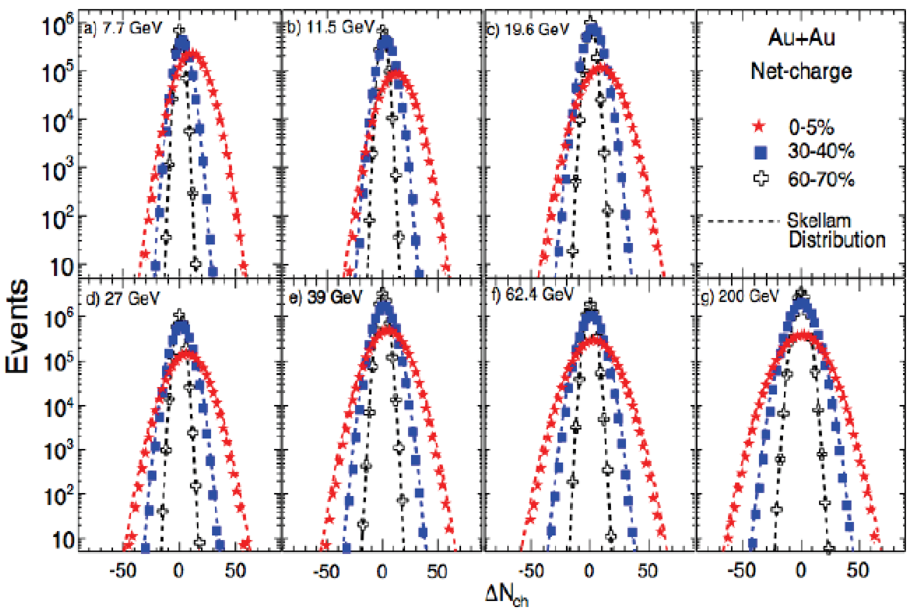
Theories / Models: PNJL, Dyson Schwinger, Lattice, NLSM



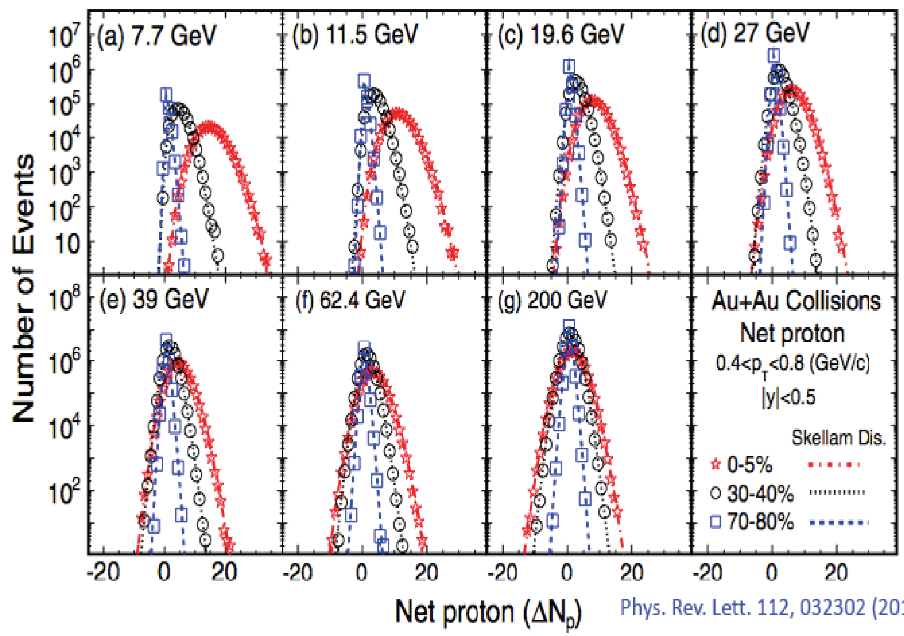


The critical point (experimental approach): measure net-distributions and calculate moments

Net-charge distribution



Net-Proton distribution



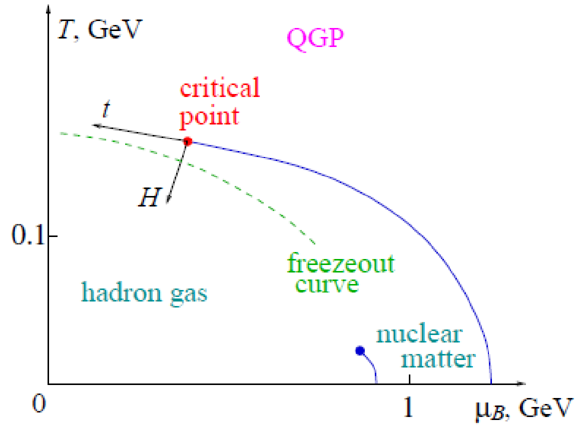
Phys. Rev. Lett. 112, 032302 (2014).

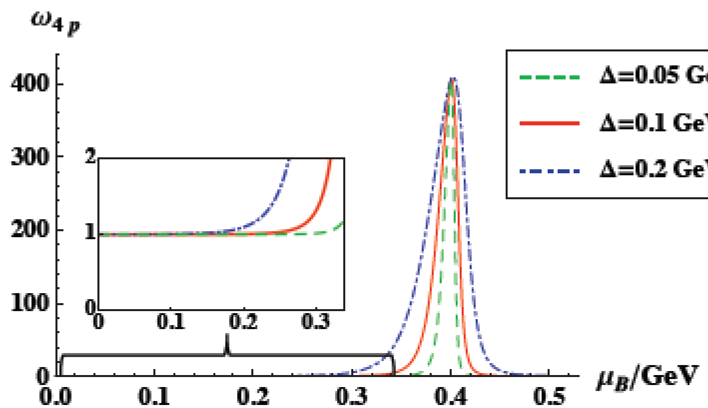
STAR distributions: the means shift towards zero from low to high energy

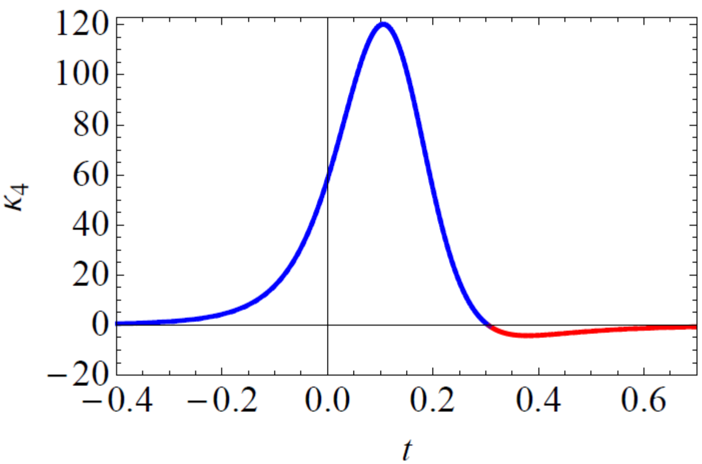
Then: calculate moments (c1-c4: mean, variance, skewness, kurtosis)

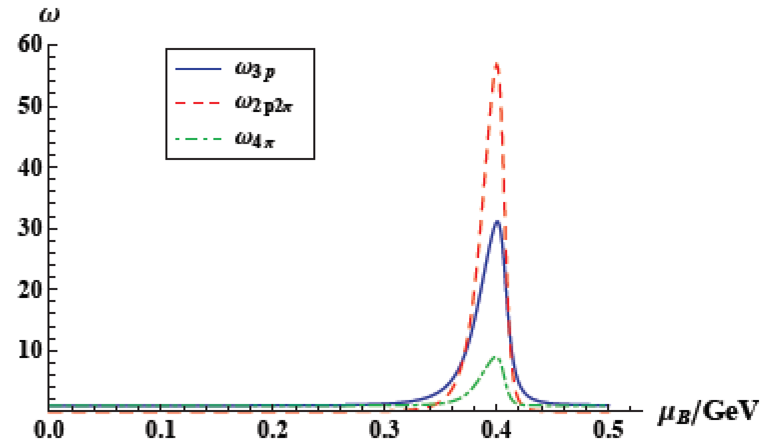
Theory: key predictions

- **The sigma field is isospin blind and its coupling can be applied to each particle species** (net-baryon = net-proton = proton distribution)
- **The coupling strength depends on the particle mass**, i.e. proton should show the strongest fluctuations, pions should not show much fluctuations (net-charge might be flat, net-protons need to show fluctuations)
- **The higher the moment, the stronger the fluctuations. Kurtosis changes its sign near critical point**





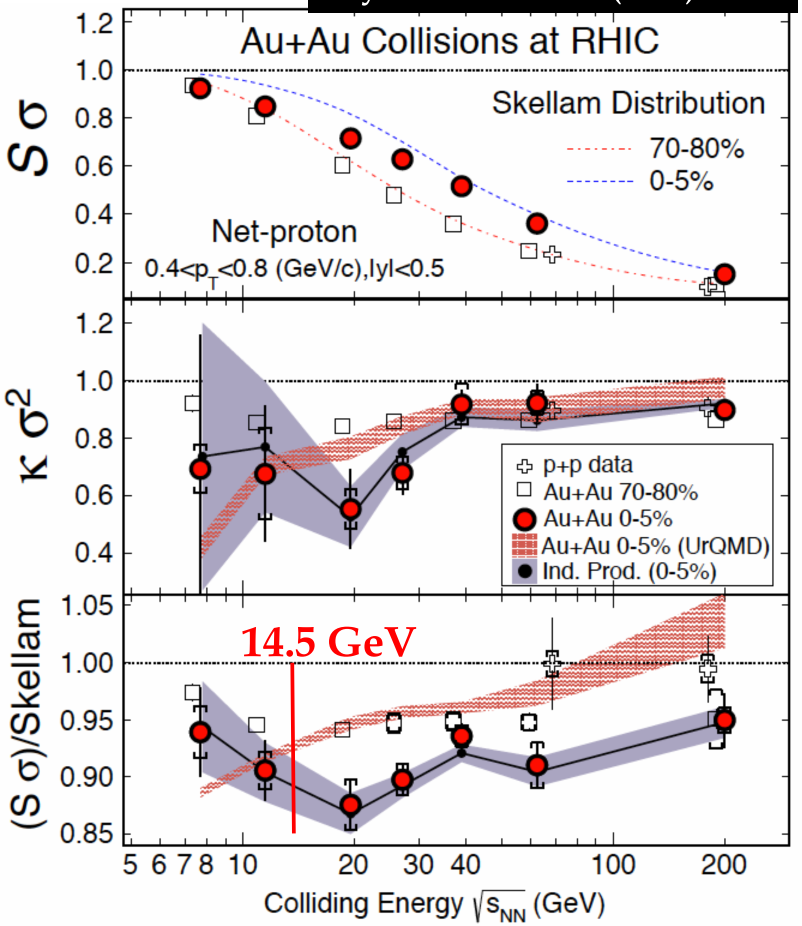




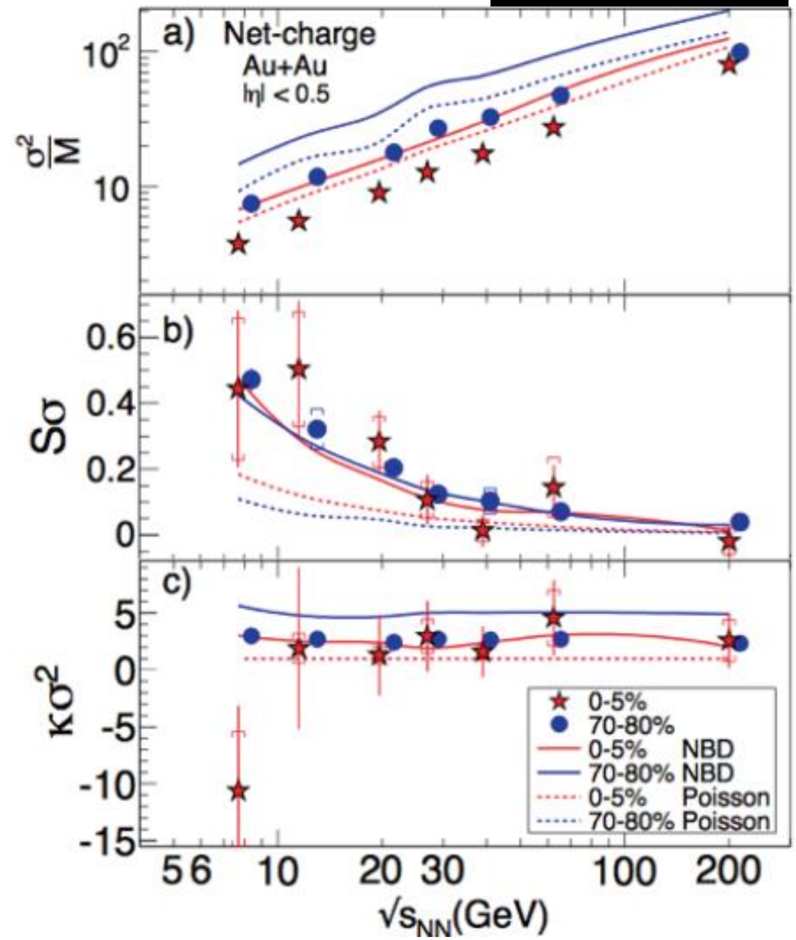
Searching for the critical point

Measuring higher moments of net-charged and net-protons (STAR)

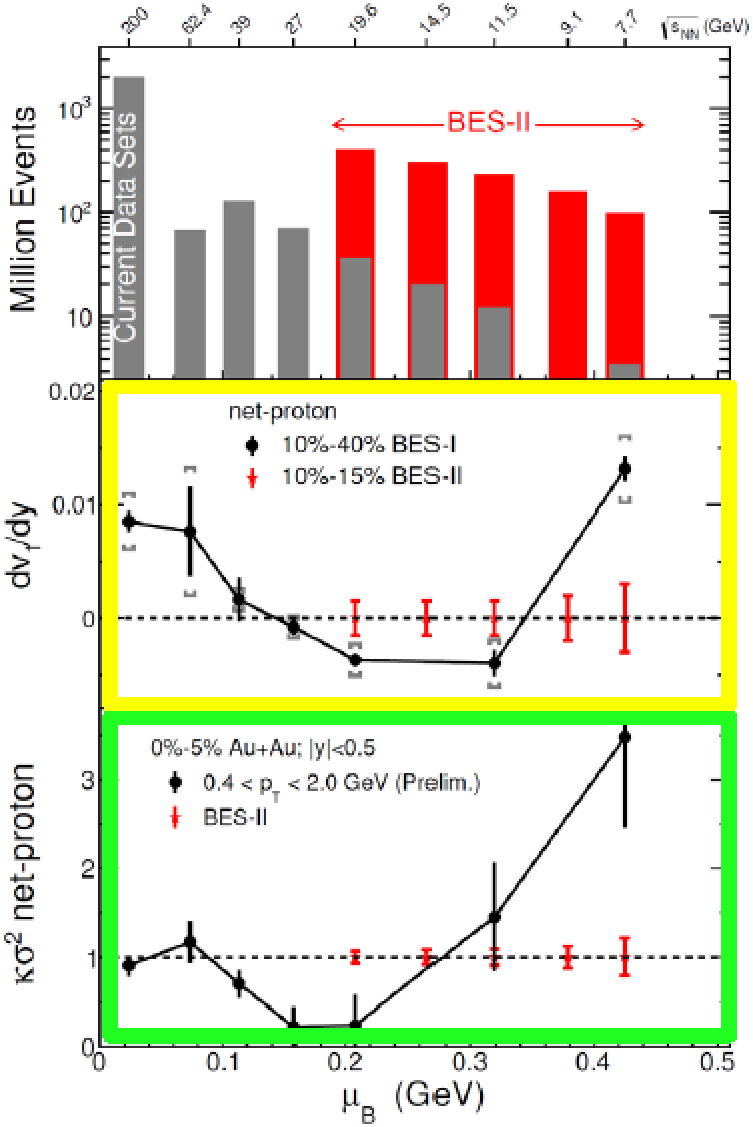
Phys. Rev. Lett. 112 (2014) 32302



arXiv:1402.1558



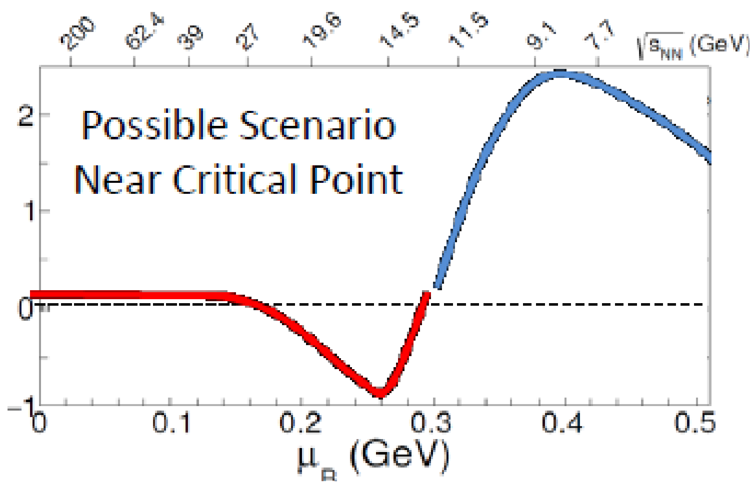
The latest (preliminary) RHIC results



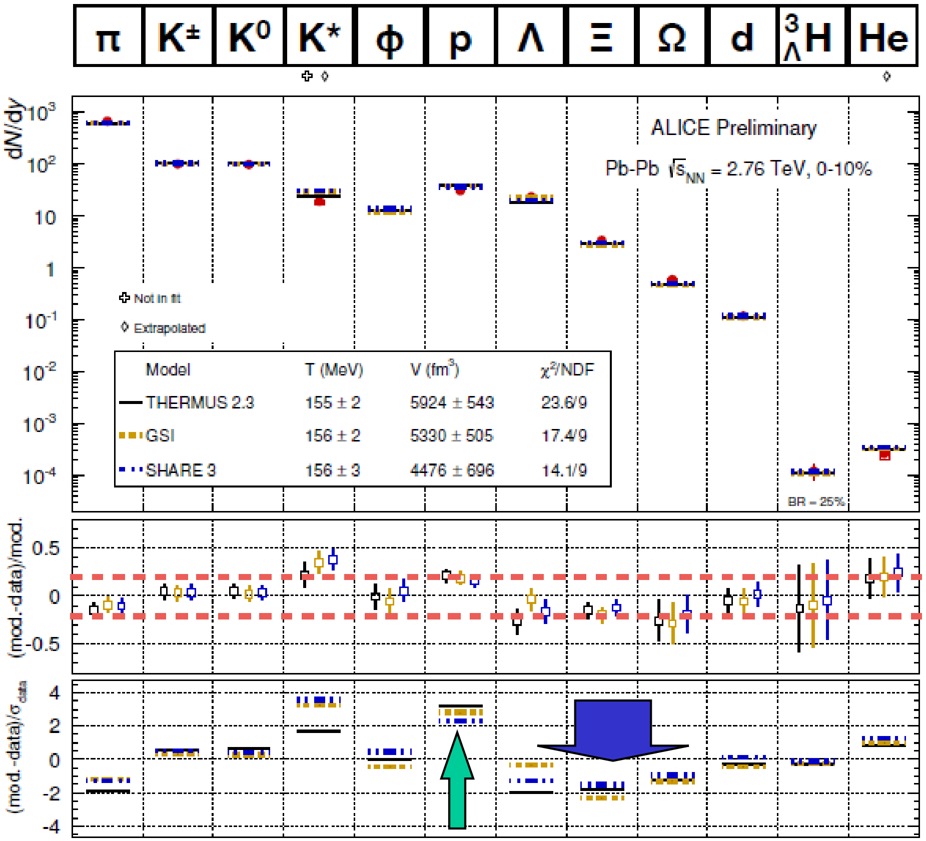
Minima in v1 slope and kurtosis fluctuations coincide.

Latest STAR kurtosis results over extended momentum range show rise in fluctuations at higher mB.(caution: rapidity dependence not well understood)

BES-II runs in 2019/2020 at RHIC deliver necessary statistics



Chemical freeze-out parameters at RHIC & LHC: The ‘proton or strange quark anomaly ?’



This looks like a good fit, but it is not

χ^2/NDF improves from 2 to 1 when pions and protons are excluded.

Fit to pions and protons alone yield a temperature of 148 MeV.

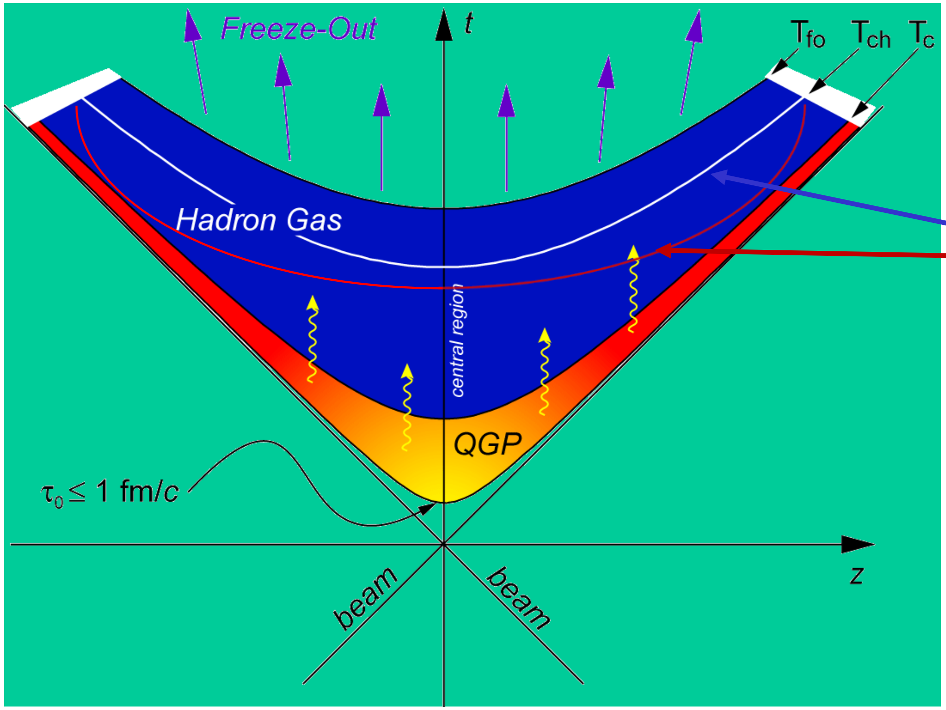
Several alternate explanations:

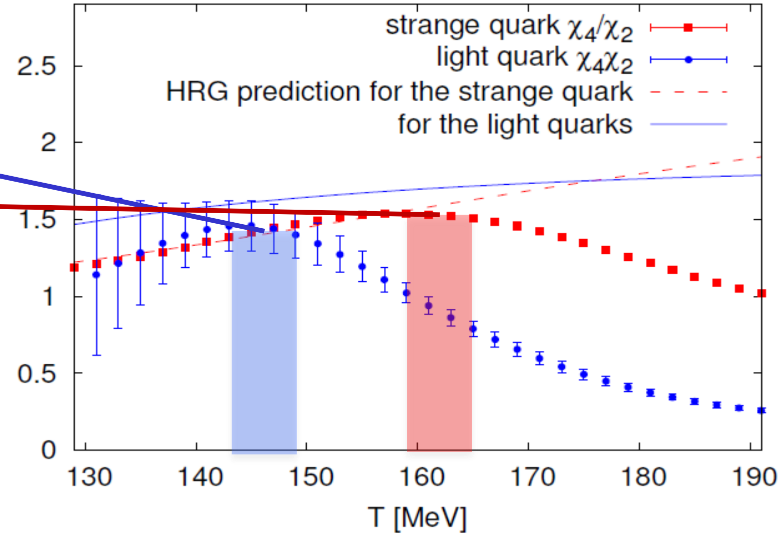
- ***Different T_{ch} for light and strange***
- Inclusion of Hagedorn states
- Non-equilibrium fits
- Baryon annihilation

A novel fluctuation analysis

Use different higher moments ratios to determine the chemical freeze-out parameters (T,μ_B) from first principle lattice QCD and compare to HRG

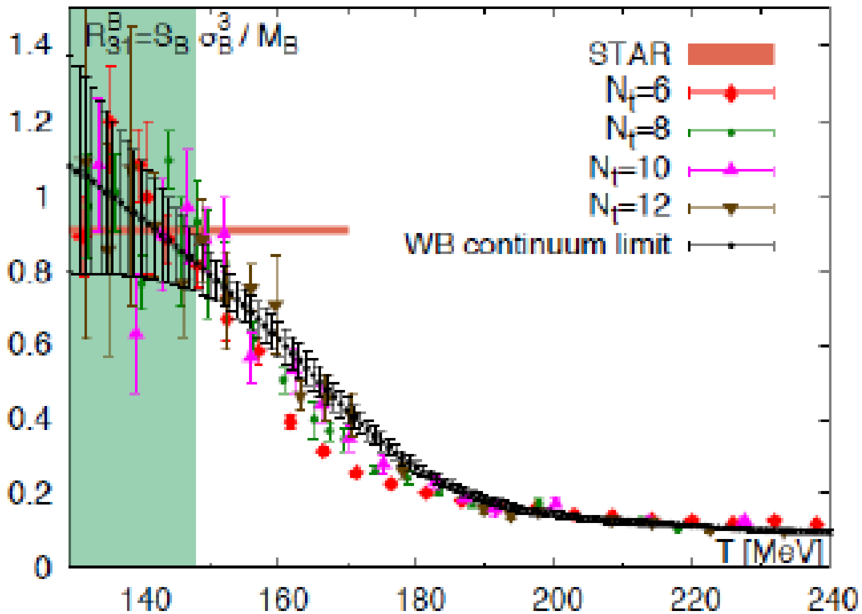
(Karsch:1202.4173): $$\kappa_B\sigma_B^2 \equiv \frac{\chi_{4,\mu}^B}{\chi_{2,\mu}^B} = \frac{\chi_4^B(T)}{\chi_2^B(T)}\left[\frac{1+\frac{1}{2}\frac{\chi_6^B(T)}{\chi_4^B(T)}(\mu_B/T)^2+\ldots}{1+\frac{1}{2}\frac{\chi_4^B(T)}{\chi_2^B(T)}(\mu_B/T)^2+\ldots}\right]$$

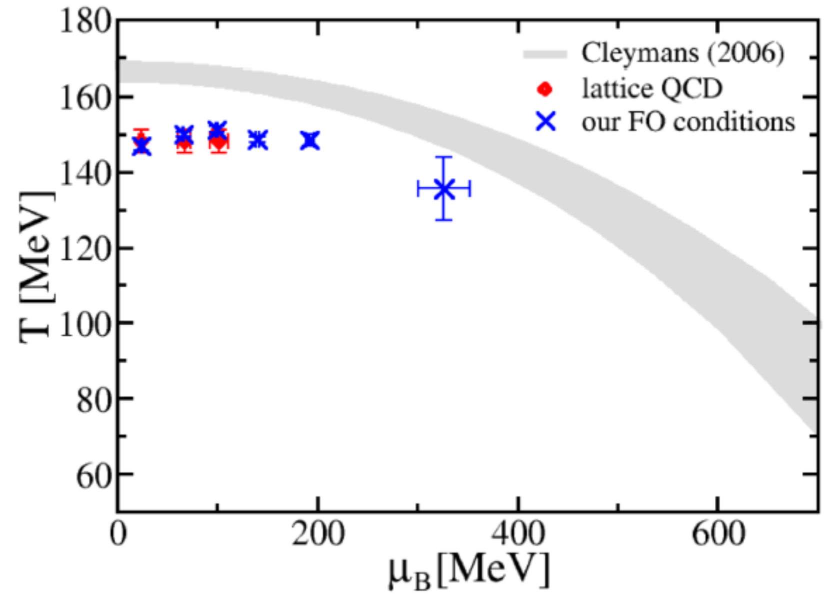




R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

Consistency between data, HRG, and lattice





$\sqrt{s}$ [GeV]	$\mu_{B,ch}$ [MeV]	T_{ch} [MeV]
11.5	326.7±25.9	135.5±8.3
19.6	192.5±3.9	148.4±1.6
27	140.4±1.4	148.5±0.7
39	99.9±1.4	151.2±0.8
62.4	66.4±0.6	149.9±0.5
200	24.3±0.6	146.8±1.2

lattice QCD : S. Borsanyi et al., arXiv:1403.4576

Simultaneous HRG fit to net-charge and net-protons (P.Alba et al., arXiv: 1403.4903)

Higher moments are more sensitive to freeze-out conditions than particle yields. Proton and charge fluctuations, which are dominated by light quarks show lower chemical freeze-out temperature.

Conclusions – Discussion points

- *particle correlation measurements at RHIC and LHC establish the collectivity of the QCD phase of matter.*

- *viscosity at LHC is slightly larger than at RHIC,* but still close to the quantum limit, which is in agreement with strong coupling expectations.

- *small system show collective effects which can be described by hydrodynamics,* whereas the description via multi parton interactions is difficult for multi-particle correlation measurements (v2(4) and above, v3)

- the precise multi-particle measurements enable insight into *the density distribution in the sub-nucleonic structure of the smallest and largest systems.*

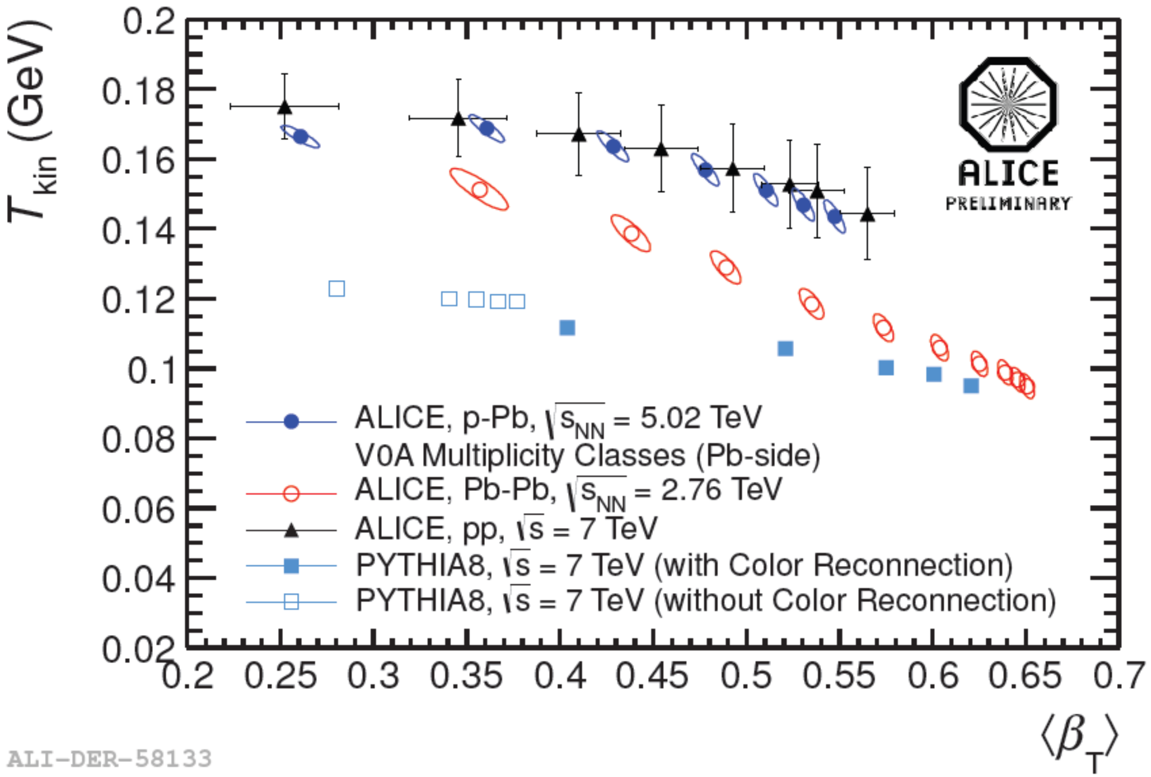
- measurements at lower energies *establish a QCD transition point.*

- *is this point a critical point ?* The results are suggestive but still inconclusive.

- fluctuations also allow us to determine freeze-out surfaces from first principle and might hint at a *intriguing flavor hierarchy during the QCD transition*.

Backup

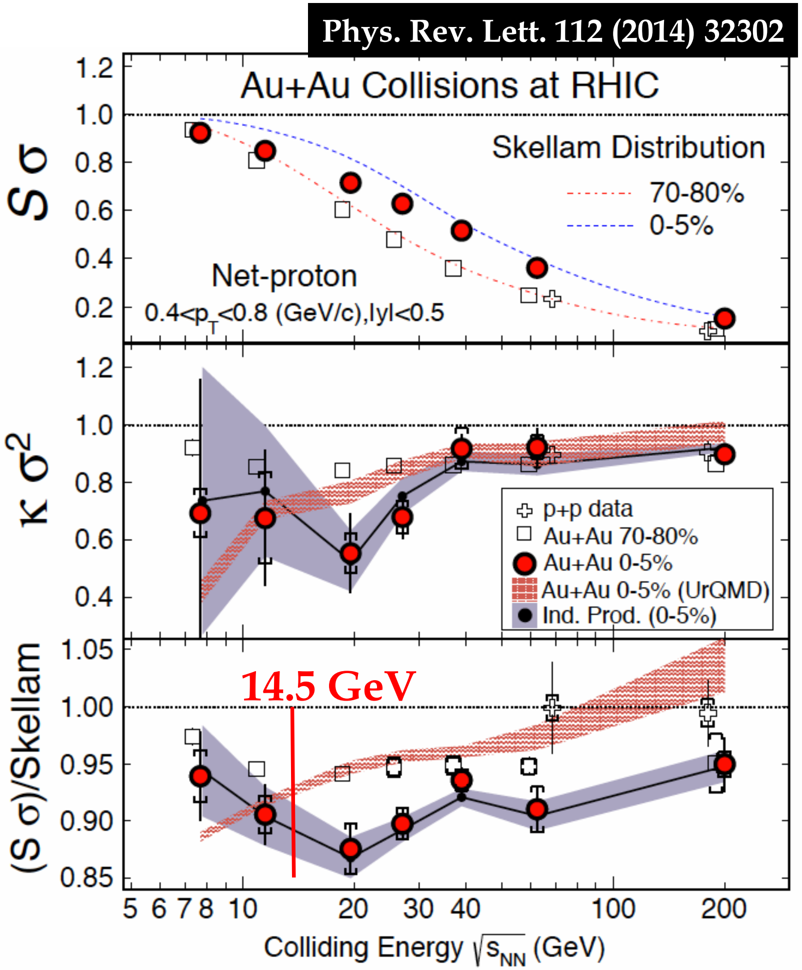
How small is too small ?



Buzz of the month:

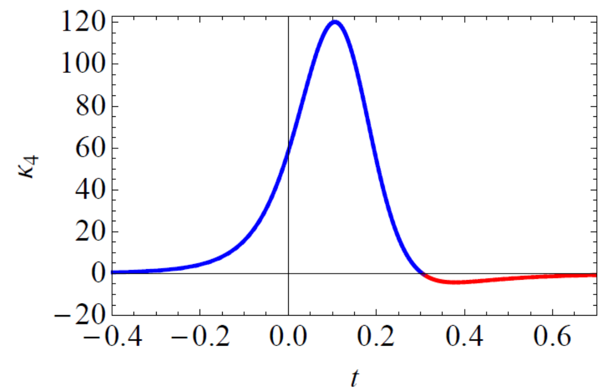
multi-parton interactions = color reconnection = pomeron ladders = partonic cascade ?

What goes down must come up….



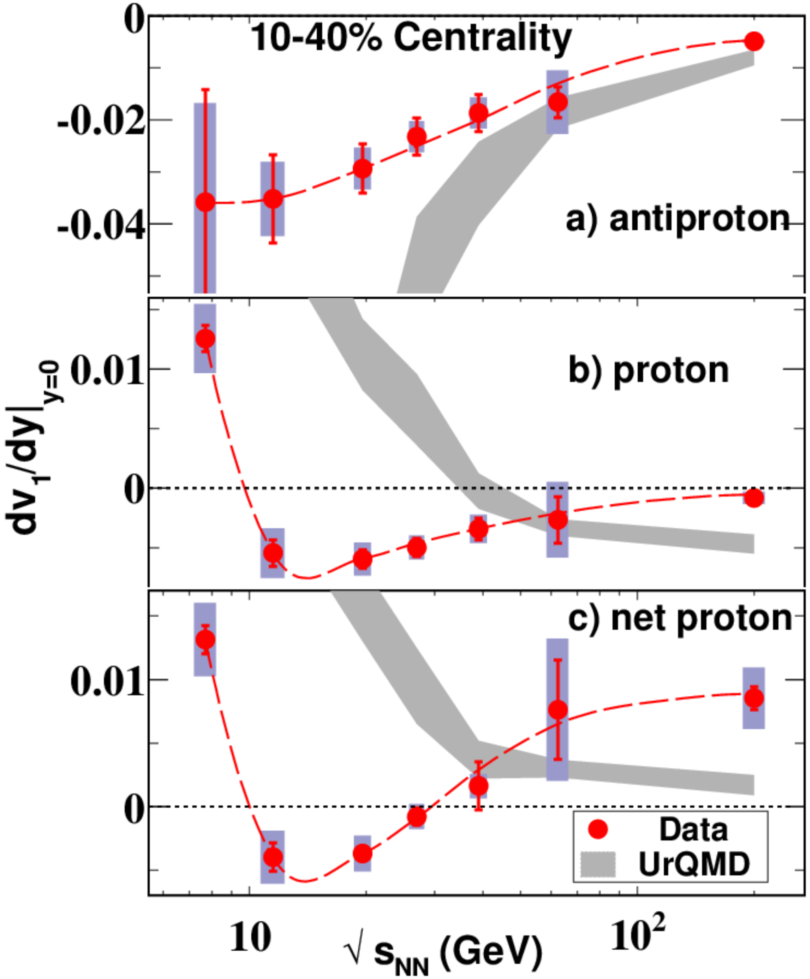
The lack of structure in the net-charge compared to the net-protons can be understood by the different coupling of specific species to the sigma field

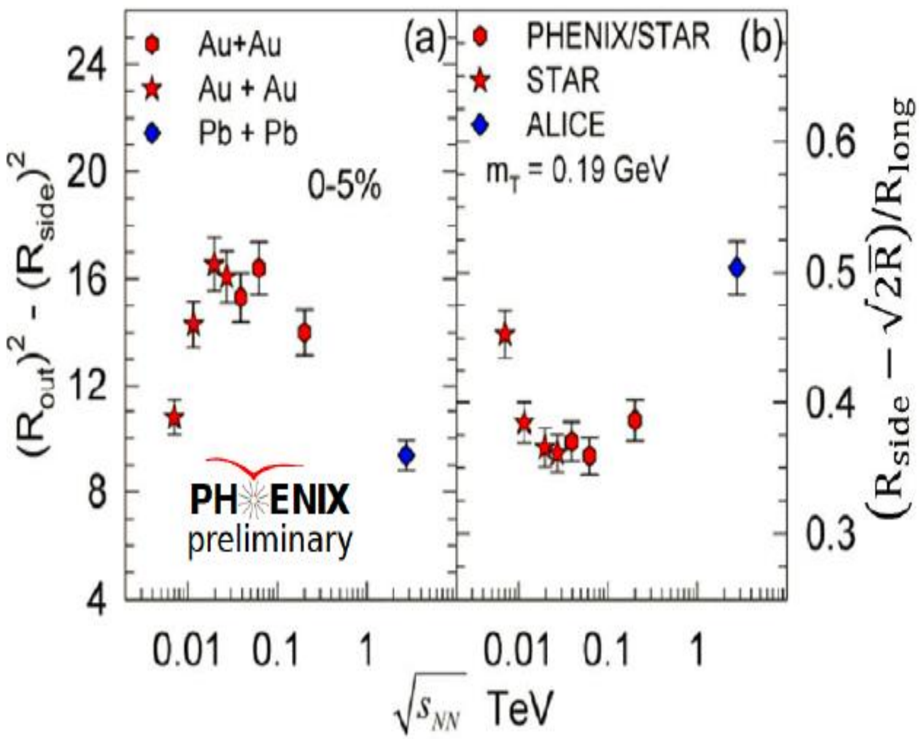
But the negatvie kurtosis that might cause the dip near 20 GeV needs to be followed by a strong enhancement (positive kurtosis) at lower energies. The trends in the 14.5 GeV data provide a crucial test.



The softest point (changing EOS)

Measuring directed flow (v_1) and HBT in BES (STAR, PHENIX)





Topics I plan to address

- Correlation Measurements at RHIC and the LHC
  - The softest point (flow and HBT measurements at RHIC)
  - Critical point searches at RHIC
  - Chemical freeze-out parameters
  - Low mass diletpons

- Fluctuation Measurements at RHIC and the LHC
  - Critical point searches at RHIC
  - Thermalization of charm
  - NCQ scaling and recombination

- Small systems – hot or not ?
  - Flow and particle production in pp and pPb
  - Color reconnection – is it interesting ?

The model descriptions

From Initial State to Initial Conditions

Weakly coupled, strongly interacting system = high gluon density = CGC ?

multi-parton interactions = color reconnection = pomeron ladders

The evolution

Transport: multi-parton interactions = partonic cascade ?

(BAMPS, EPOS, AMPT)

Or

Hydrodynamics

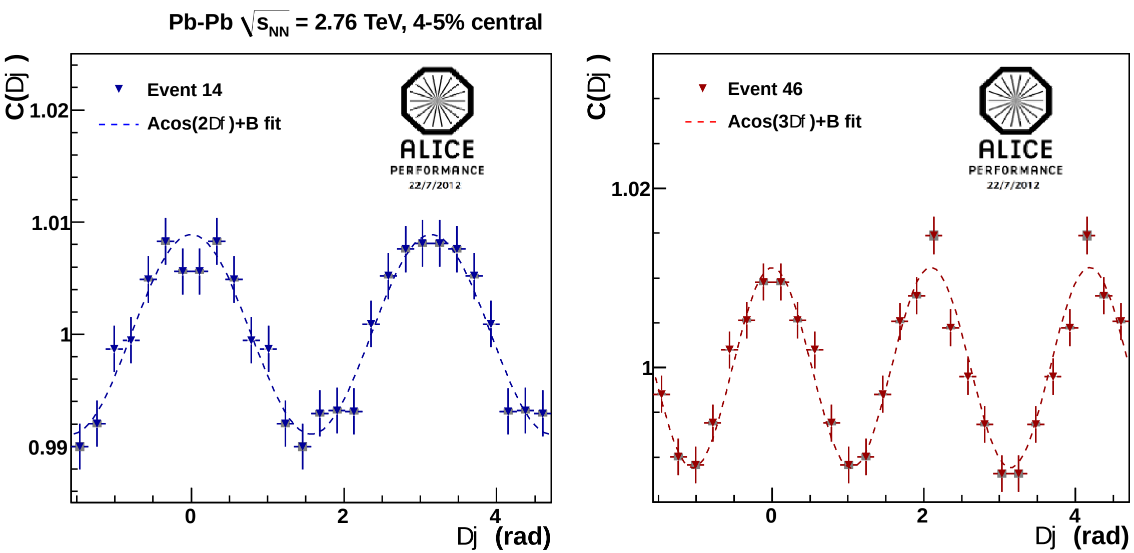
(hybrid codes, IP-Glasma, Echo-QGP, VISHNU)

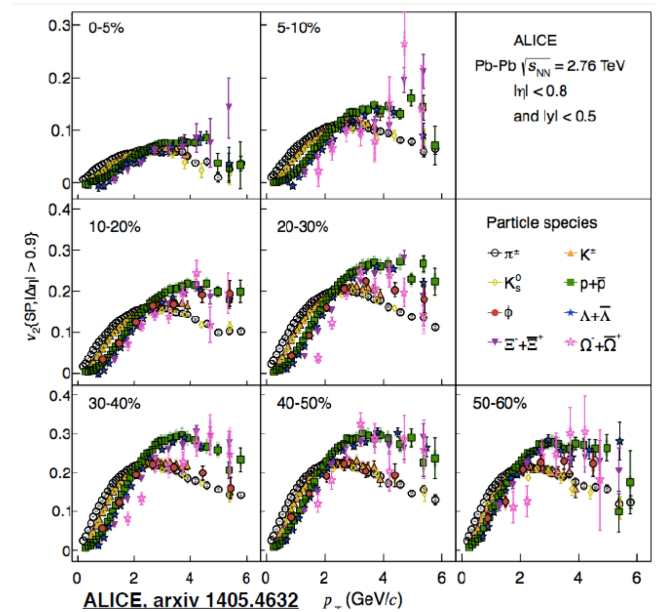
Hadronization

Cooper-Frye, lattice QCD, SHM-HRG

An exciting prospect for the future: Event engineering

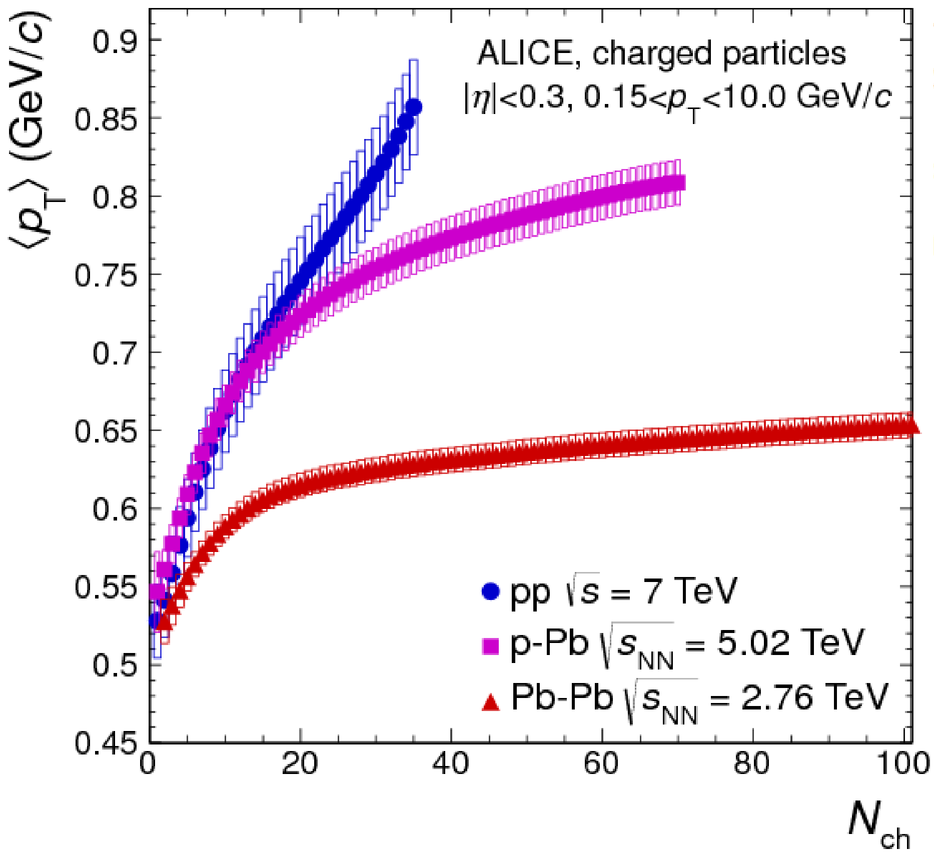
- The e-by-e statistics at the LHC enable event classification on the basis of harmonics measurements. (PLB 719 (2013) 394)

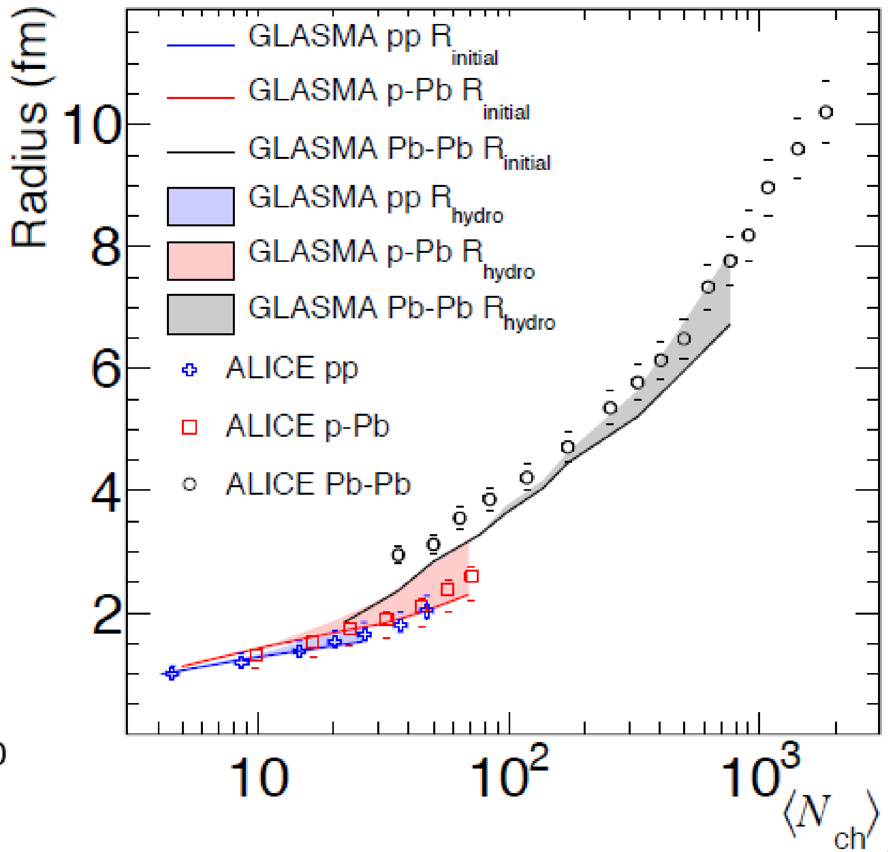




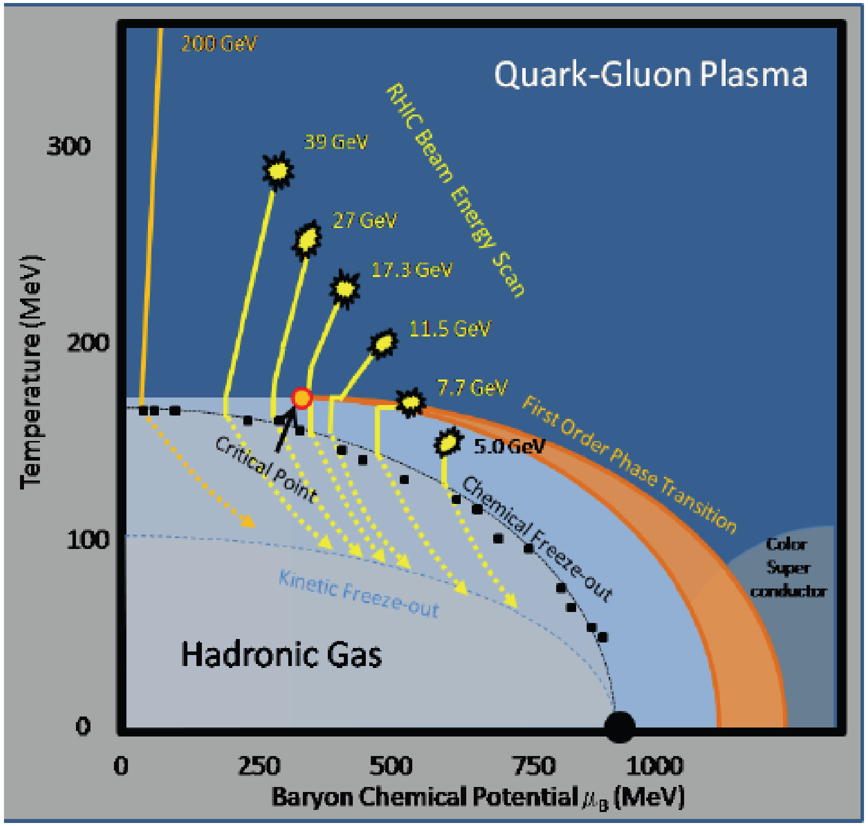
Future studies: explore PID dependent dynamic fluctuations and multiplicity distributions e-by-e.

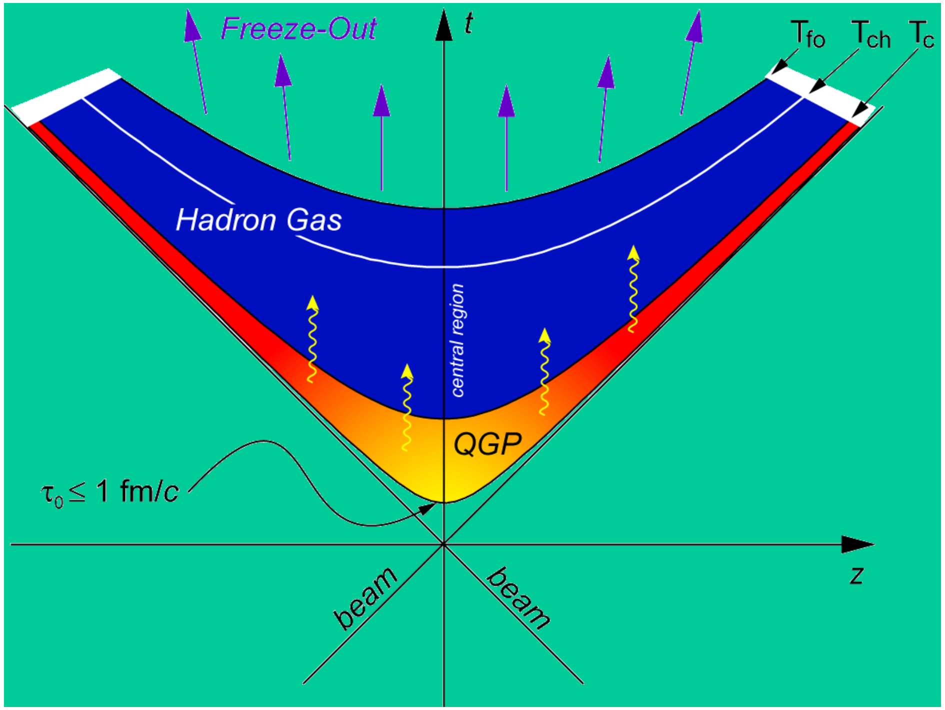
System size evolution of kinematics and source





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





Rapidity dependence of STAR net-proton kurtosis fluctuations