The sounds of the Little Bang and the smallest drops of QGP

Edward Shuryak
Stony Brook

Strong and electroweak matter,
Lausanne July 2014

outline

- **sounds of the Little Bang**
- **collective flow of small systems: high multiplicity pp/pA at LHC and the radial flow puzzle**
- **reminder of min.bias pp/pA: strings, spaghetti, Lund model**
- **QCD strings and their interaction,spaghetti collapses at large string multiplicity, their sigma field collectivizes and creates QGP fireball**
- **explosive regime at ultra high energies**

Perturbations of the Big and the Little Bangs

Frozen sound (from the era long gone) is seen on the sky, both in CMB and in distribution of Galaxies

$$\frac{\Delta T}{T} \sim 10^{-5}$$

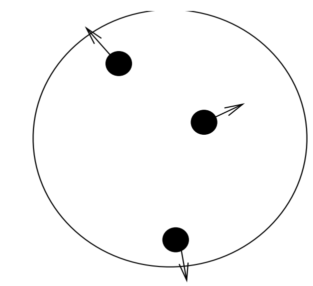
$$l_{maximum} \approx 210$$

$$\delta\phi \sim 2\pi / l_{maximum} \sim 1^{o}$$

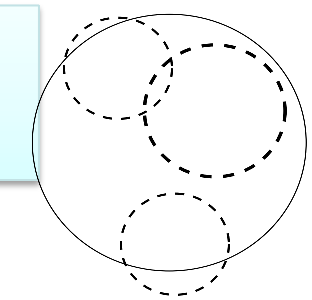
They are remnants of the sound circles on the sky, around the primordial density perturbations
Freezeout time O(100000) years

Initial state fluctuations
in the positions of participant nucleons
lead to perturbations of the Little Bang also

$$\frac{\Delta T}{T} \sim 10^{-2}$$



Freezeout time about 12 fm/c
Radius of the circle about 6 fm,
Comparable to the fireball size



PHYSICAL REVIEW C **80**, 054908 (2009)

Fate of the initial state perturbations in heavy ion collisions

Edward Shuryak
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA
(Received 20 July 2009; revised manuscript received 14 October 2009; published 13 November 2009)

S.Gubser, arXiv:1006.0006

found nice solution for nonlinear relativistic axially symmetric explosion of conformal matter

Working in the (τ, η, r, ϕ) coordinates with the metric

$$ds^2 = -d\tau^2 + \tau^2 d\eta^2 + dr^2 + r^2 d\phi^2, \qquad (3.2)$$

and assuming no dependence on the rapidity η and azimuthal angle ϕ, the 4-velocity can be parameterized by only one function

$$u_\mu = (-\cosh\kappa(\tau, r), 0, \sinh\kappa(\tau, r), 0) \qquad (3.3)$$

Omitting the details from [14], the solution for the velocity and the energy density is

$$v_\perp = \tanh\kappa(\tau, r) = \left(\frac{2q^2\tau r}{1 + q^2\tau^2 + q^2 r^2}\right) \qquad (3.4)$$

$$\epsilon = \frac{\hat{\epsilon}_0 (2q)^{8/3}}{\tau^{4/3}\left(1 + 2q^2(\tau^2 + r^2) + q^4(\tau^2 - r^2)^2\right)^{4/3}} \qquad (3.5)$$

Kappa is the transverse rapidity

q is a parameter fixing the overall size

The Fate of the Initial State Fluctuations in Heavy Ion Collisions. III The Second Act of Hydrodynamics

Pilar Staig and Edward Shuryak

all 4 variables can be separated

Comoving coordinates with Gubser flow:

Gubser and Yarom, arXiv:1012.1314

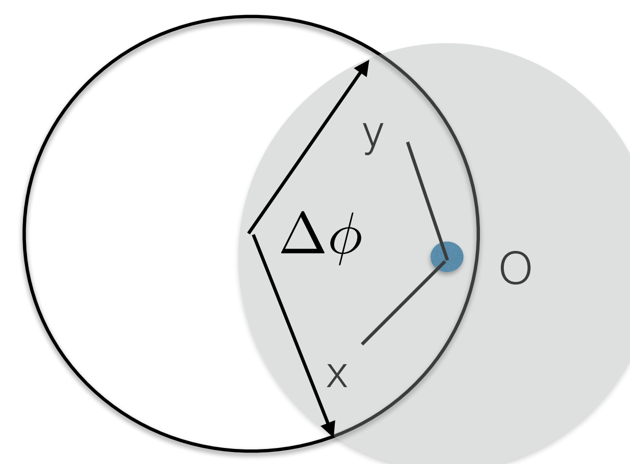
$$\sinh\rho = -\frac{1-q^2\tau^2+q^2r^2}{2q\tau}$$
$$\tan\theta = \frac{2qr}{1+q^2\tau^2-q^2r^2}$$

$$\frac{\partial^2\delta}{\partial\rho^2} - \frac{1}{3\cosh^2\rho}\left(\frac{\partial^2\delta}{\partial\theta^2} + \frac{1}{\tan\theta}\frac{\partial\delta}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2\delta}{\partial\phi^2}\right) + \frac{4}{3}\tanh\rho\frac{\partial\delta}{\partial\rho} = 0 \qquad (3.16)$$

We have seen that in the short wavelength approximation we found a wave-like solution to equation 3.16, but now we would like to look for the exact solution, which can be found by using variable separation such that $\delta(\rho,\theta,\phi) = R(\rho)\Theta(\theta)\Phi(\theta)$, then

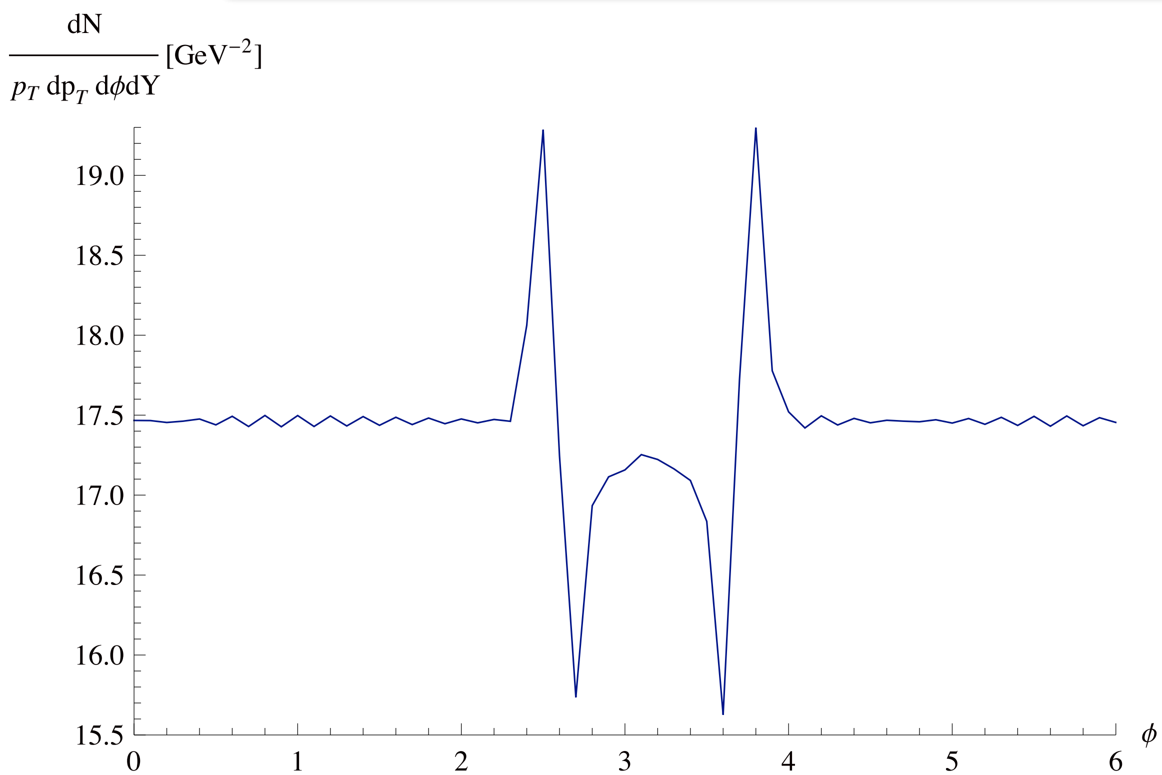
$$R(\rho) = \frac{C_1 P^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho) + C_2 Q^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho)}{(\cosh\rho)^{2/3}}$$
$$\Theta(\theta) = C_3 P_l^m(\cos\theta) + C_4 Q_l^m(\cos\theta)$$
$$\Phi(\phi) = C_5 e^{im\phi} + C_6 e^{-im\phi} \qquad (3.26)$$

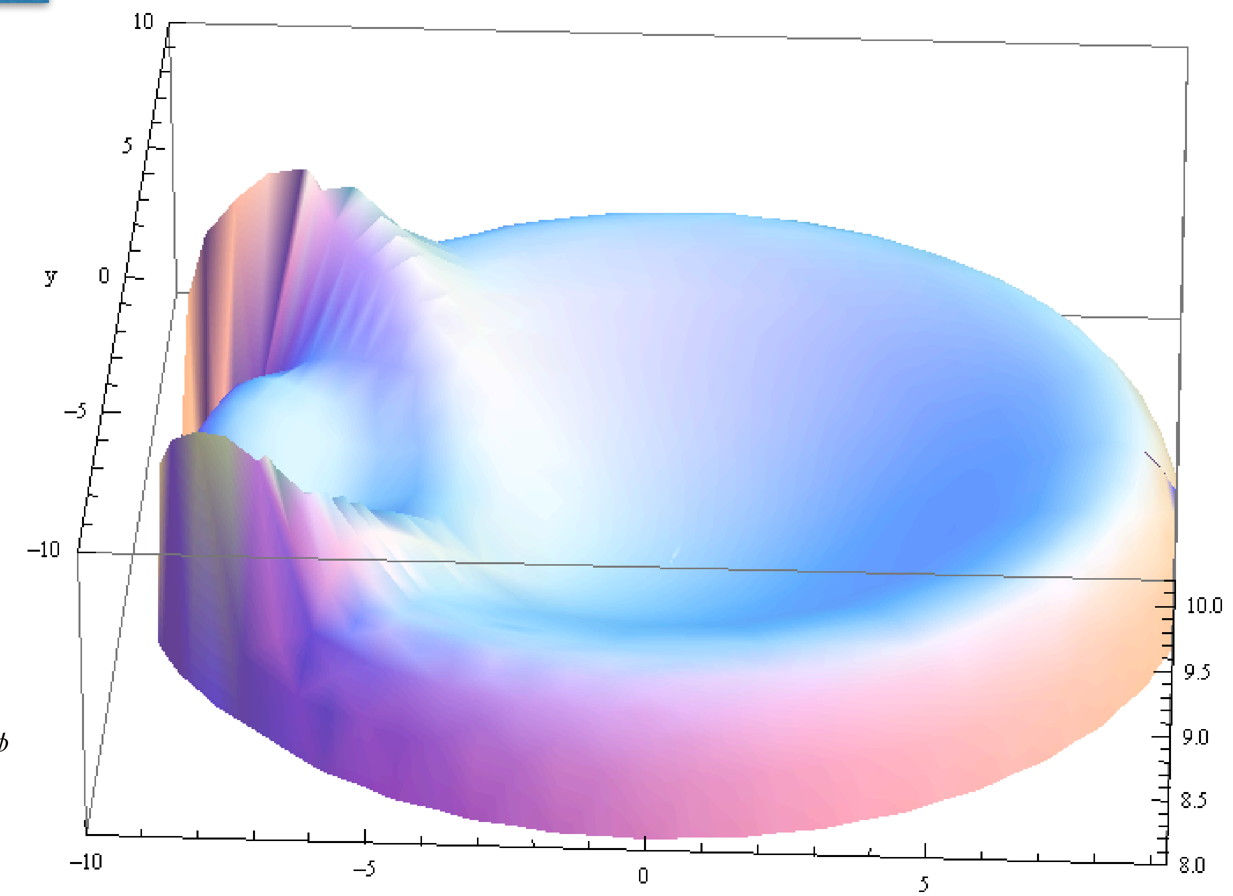
where $\lambda = l(l+1)$ and P and Q are associated Legendre polynomials. The part of the solution depending on θ and ϕ can be combined in order to form spherical harmonics $Y_{lm}(\theta,\phi)$, such that $\delta(\rho,\theta,\phi) \propto R_l(\rho)Y_{lm}(\theta,\phi)$.

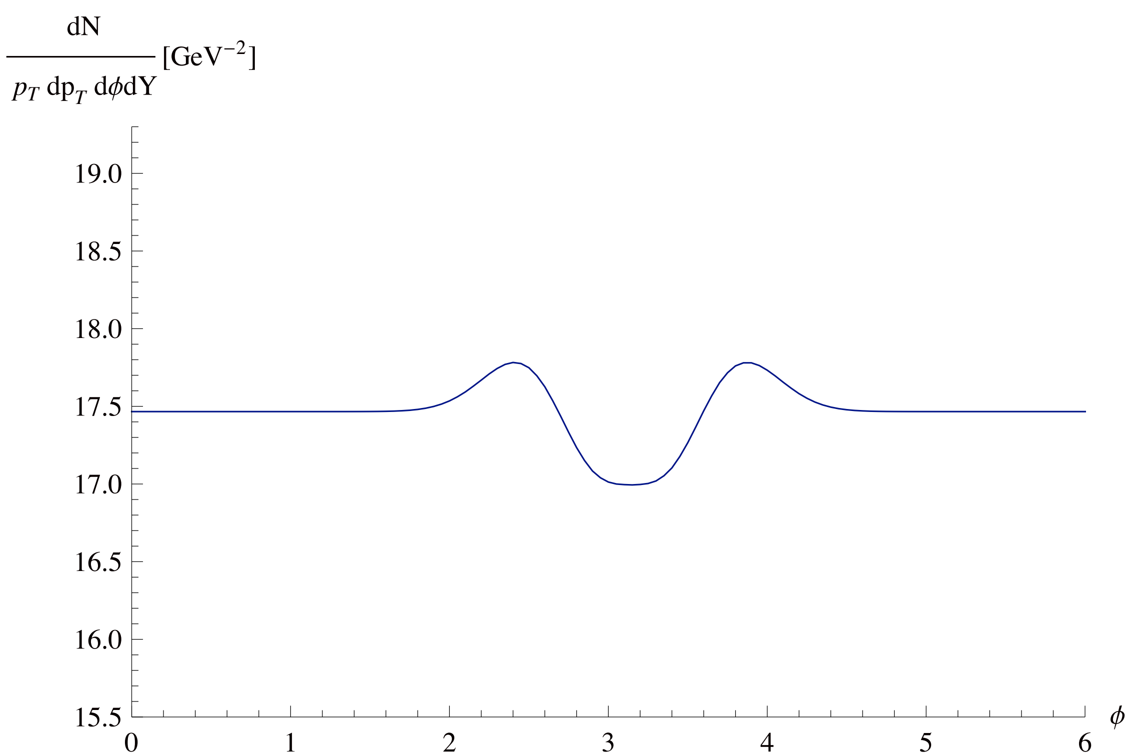


(a)

Single particle spectrum, without and with viscosity

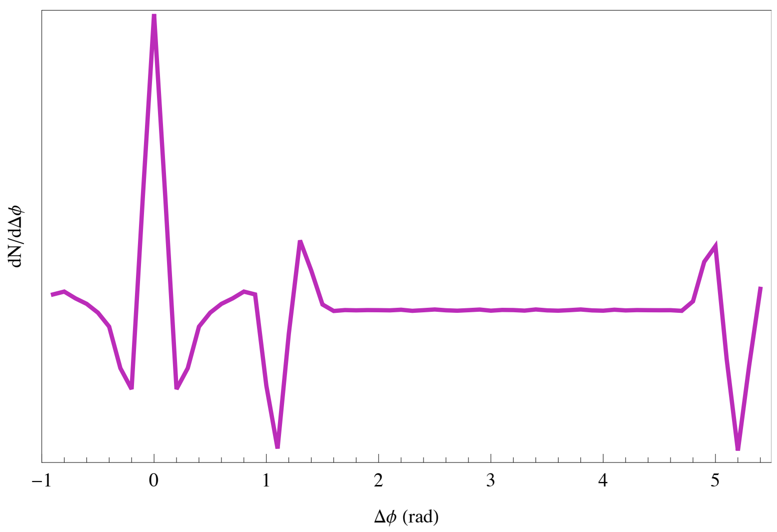


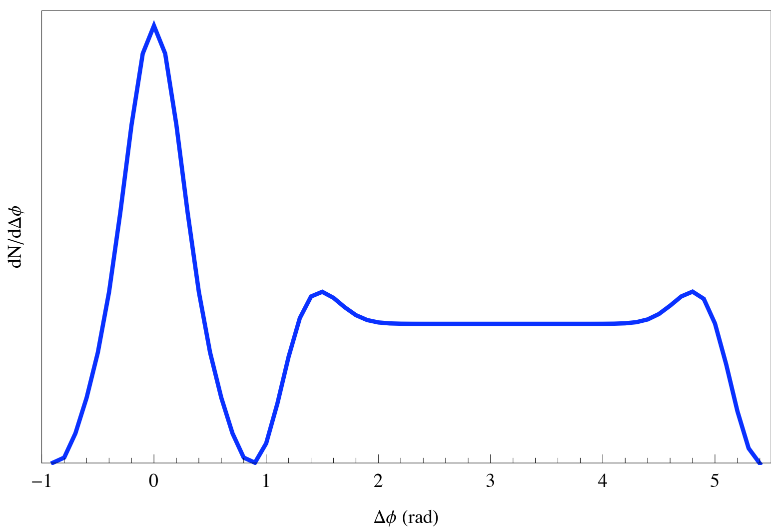




The modified freezeout Surface (right) leads to A modified angular distribution Of particles, with and without visco (left)

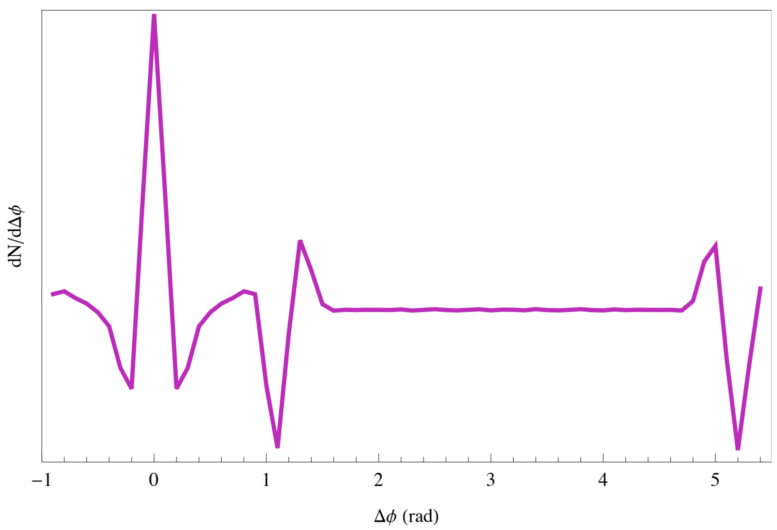
Left:4 pi eta/s=0, 2
Note shape change

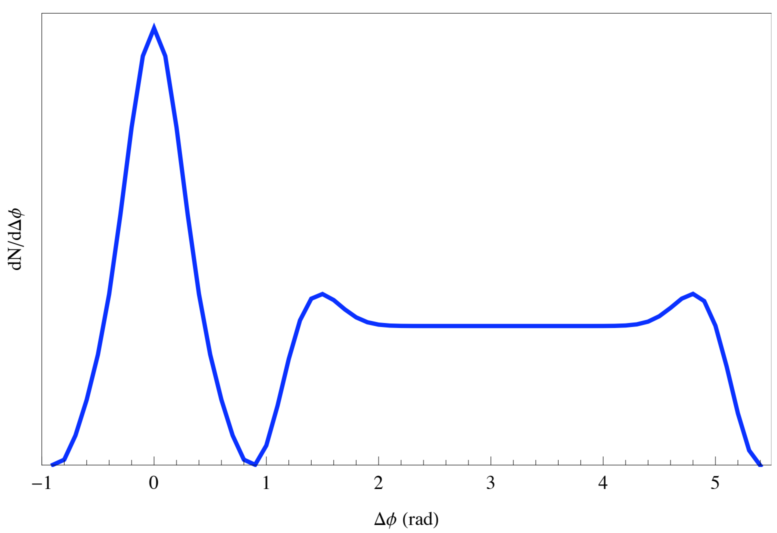


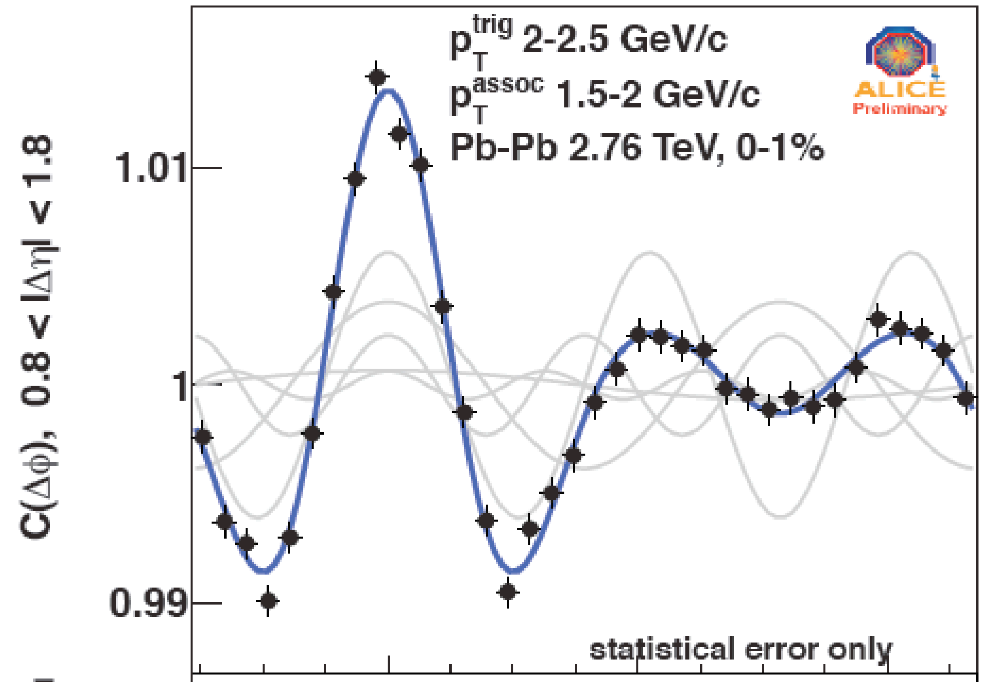


this result has been reported at QM before the data were presented

Left:4 pi eta/s=0, 2
Note shape change

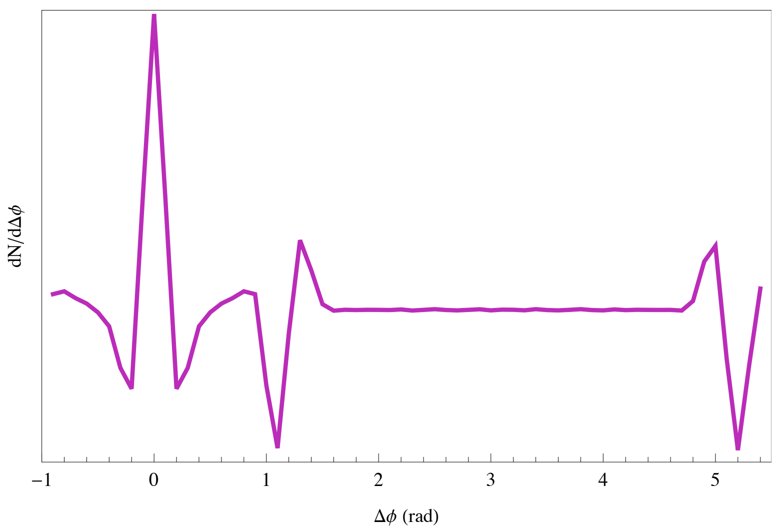


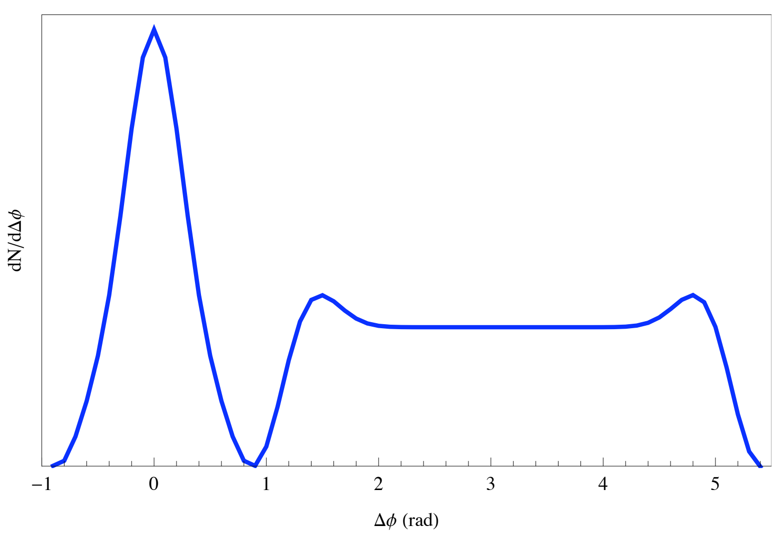


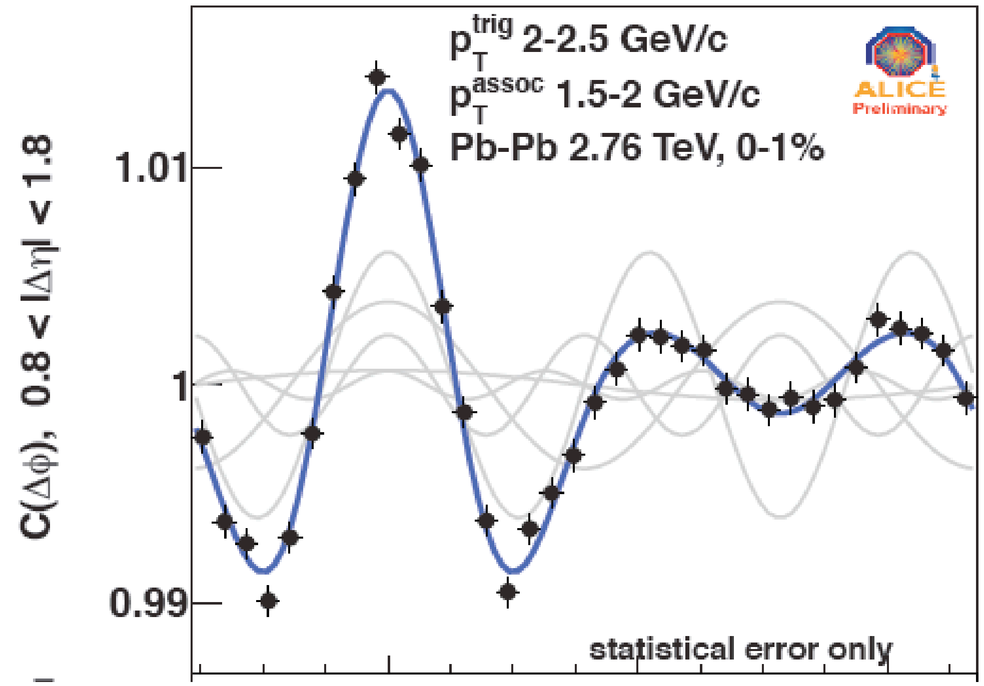


this result has been reported at QM before the data were presented

Left:4 pi eta/s=0, 2
Note shape change



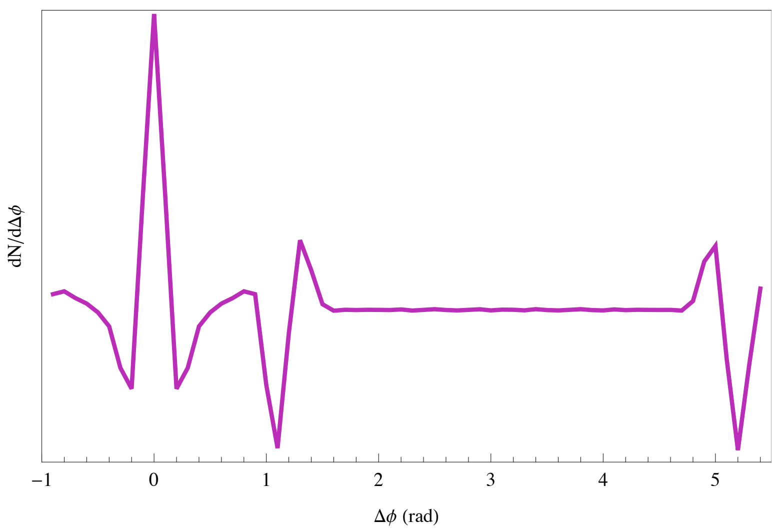


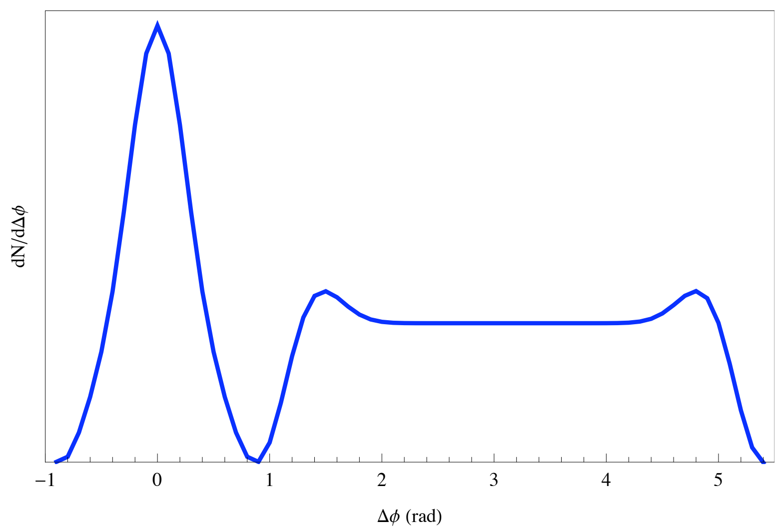


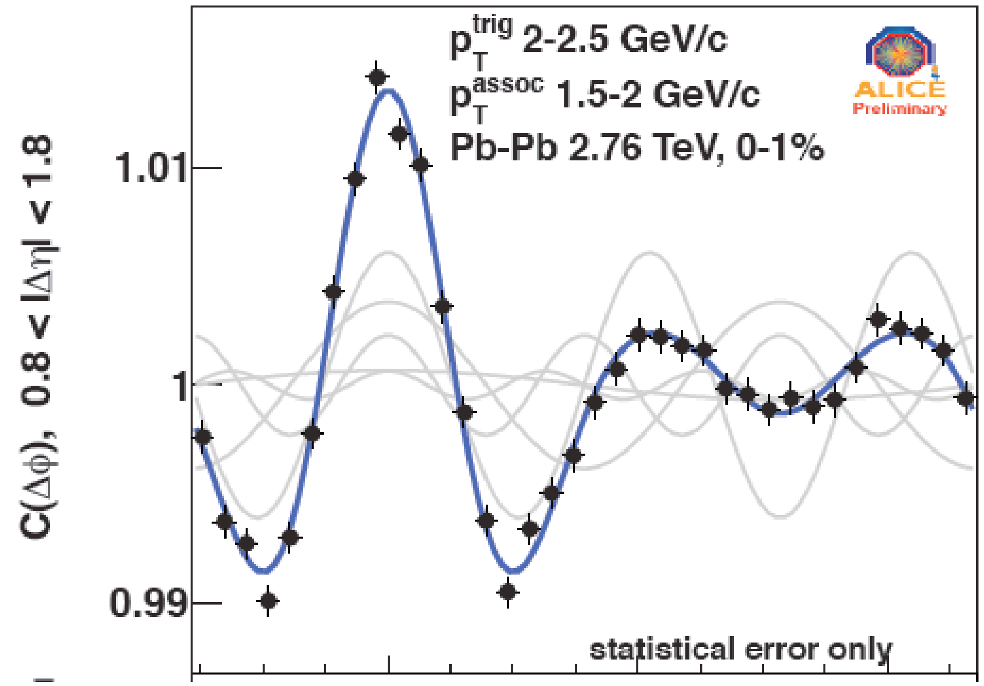
ALICE central 1% correlators
Note shape agreement
No parameters, just Green
Function from a delta function

this result has been reported at QM before the data were presented

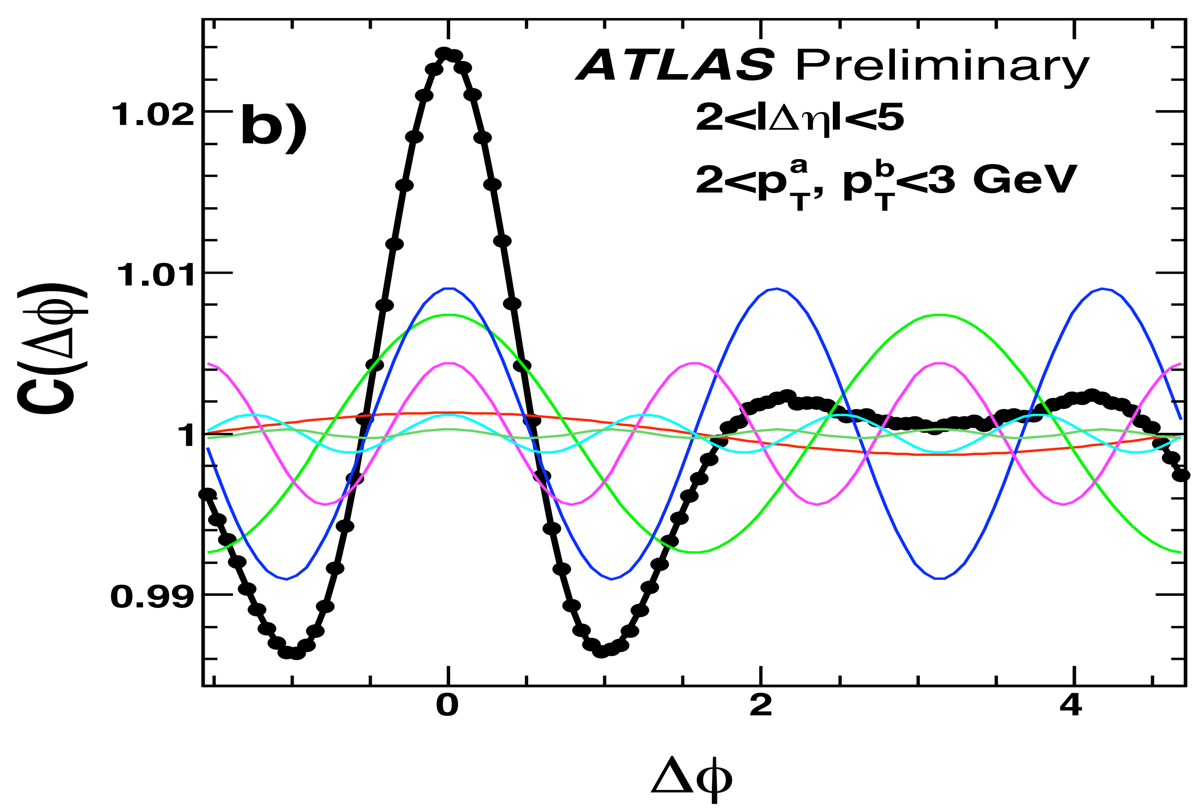
Left:4 pi eta/s=0, 2
Note shape change





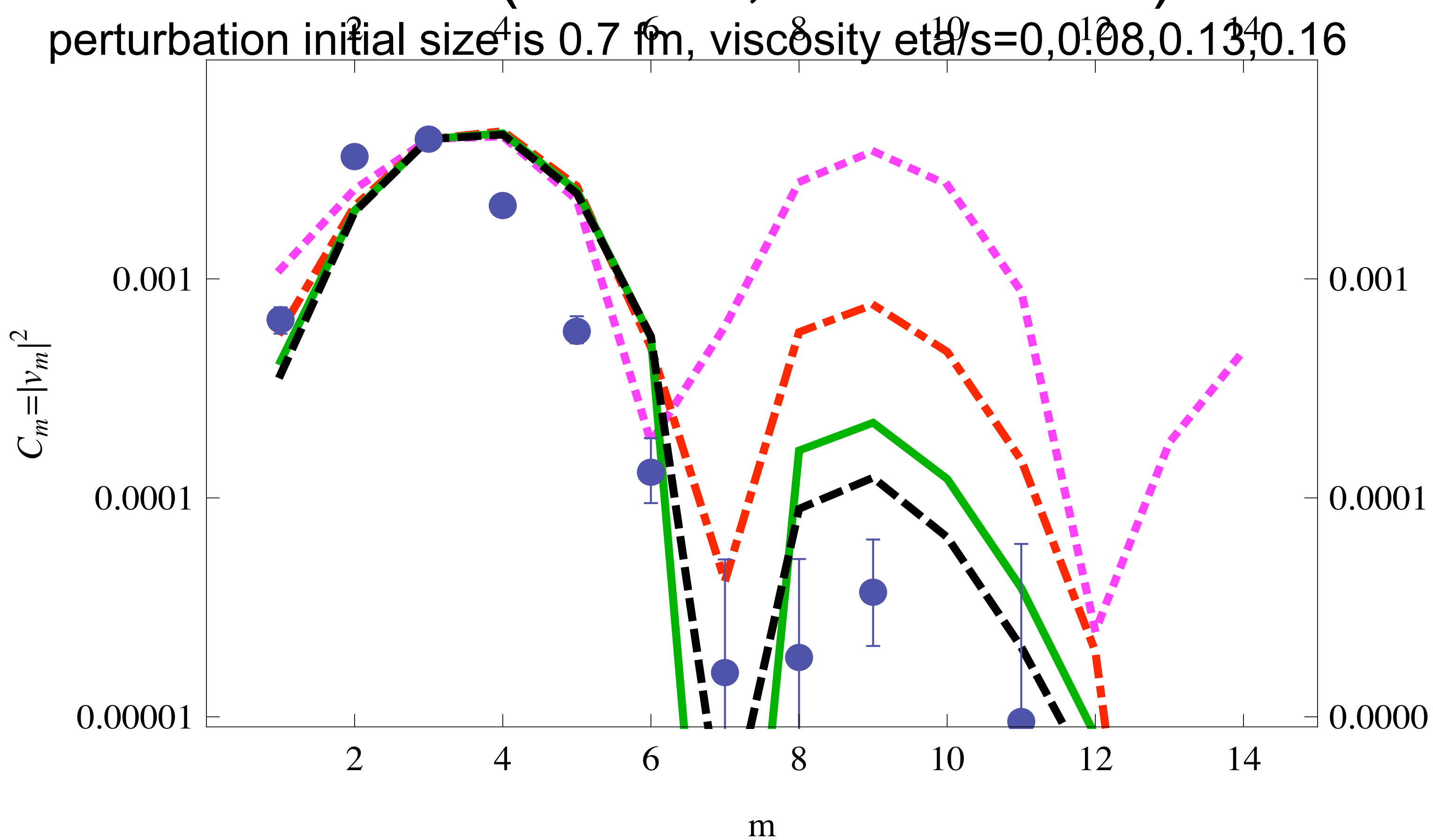


ALICE central 1% correlators
Note shape agreement
No parameters, just Green
Function from a delta function

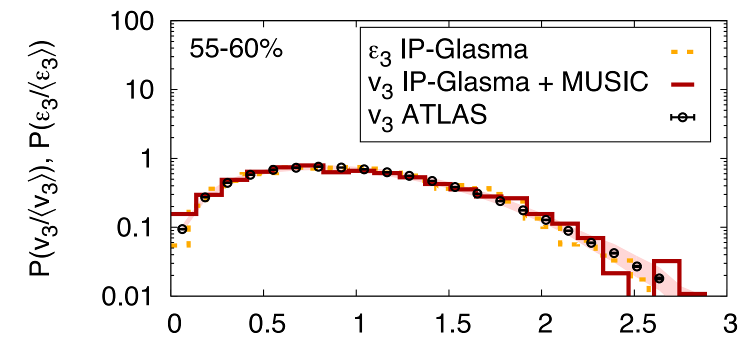


this result has been reported at QM before the data were presented

The power spectrum is very sensitive to viscosity, and it has acoustic minima/ maxima (at m=7,12 and m=9)

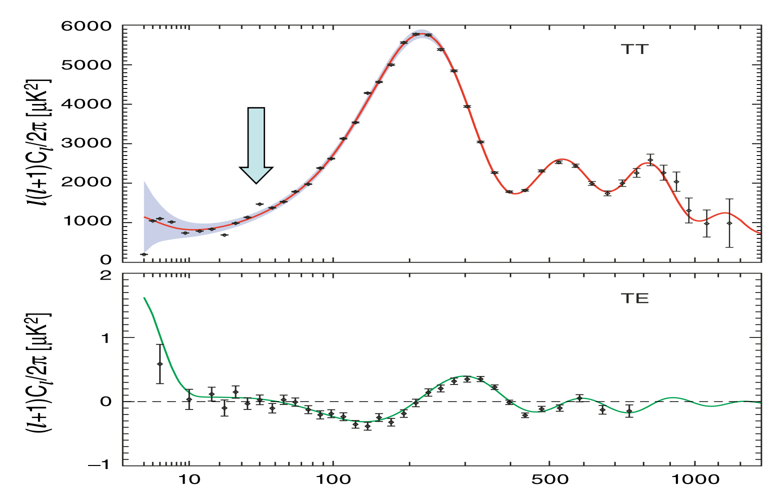


Schenke+Venugopalan



no noize seen so far other than from the initial conditions

Plenty of evidences for acoustic behavior, but still no experimental evidences for maxima



So what? Why is hydro's success for the Little Bang so exciting?

- True that already in the 19th century sound vibrations in the bulk (as well as of drops and bubbles) have been well developed (Lord Rayleigh, …)

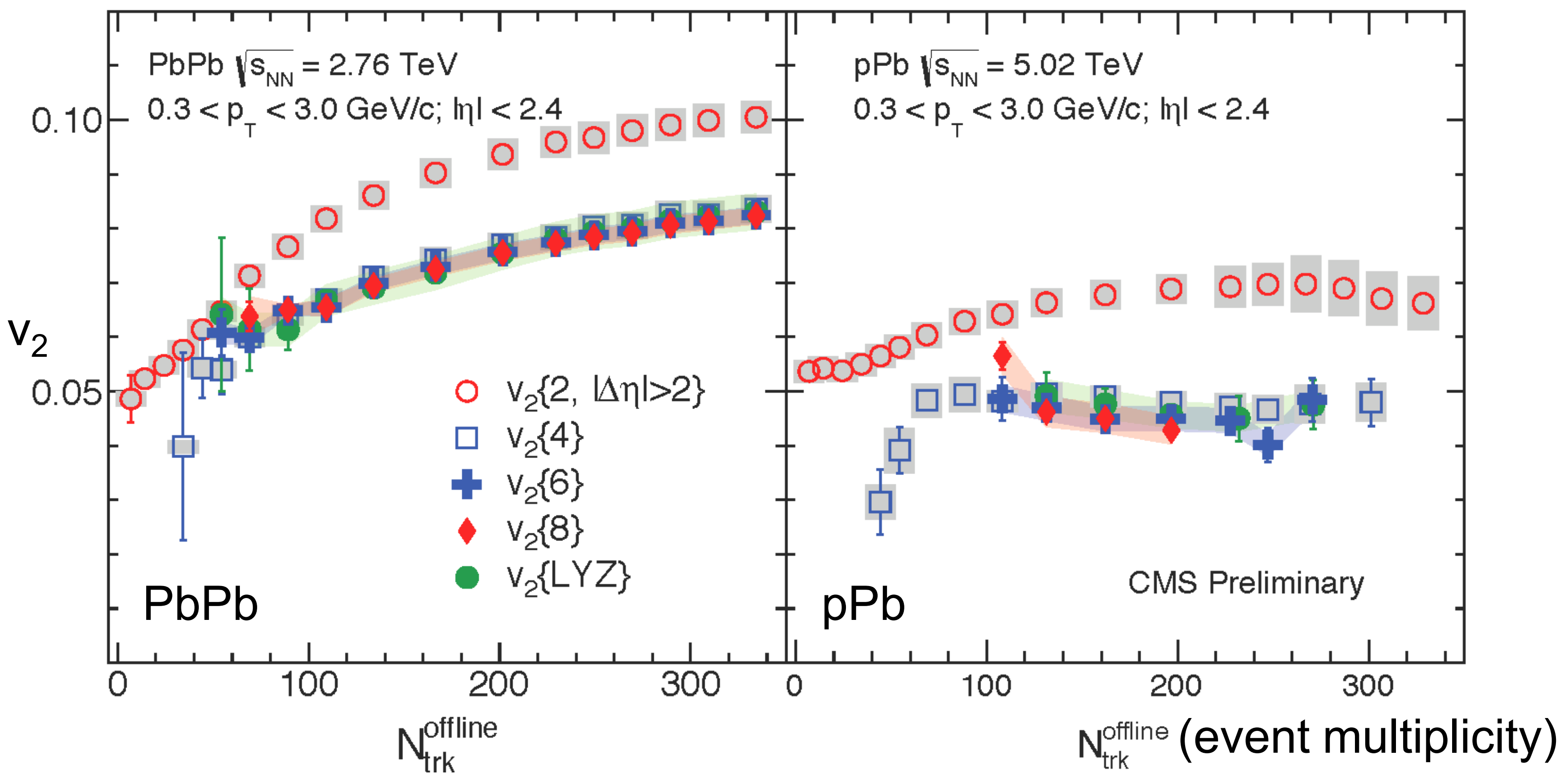
- But, those objects are macroscopic still have 10^20 molecules…

- Little Bang has about 10^3 particles (per unit rapidity) or 10 of them per dimension. So the first application of hydro was surprising: only astonishingly small viscosity saved it…

- And now we speak about the 10th harmonics! How a volume cell with O(1) particles can act as a liquid?

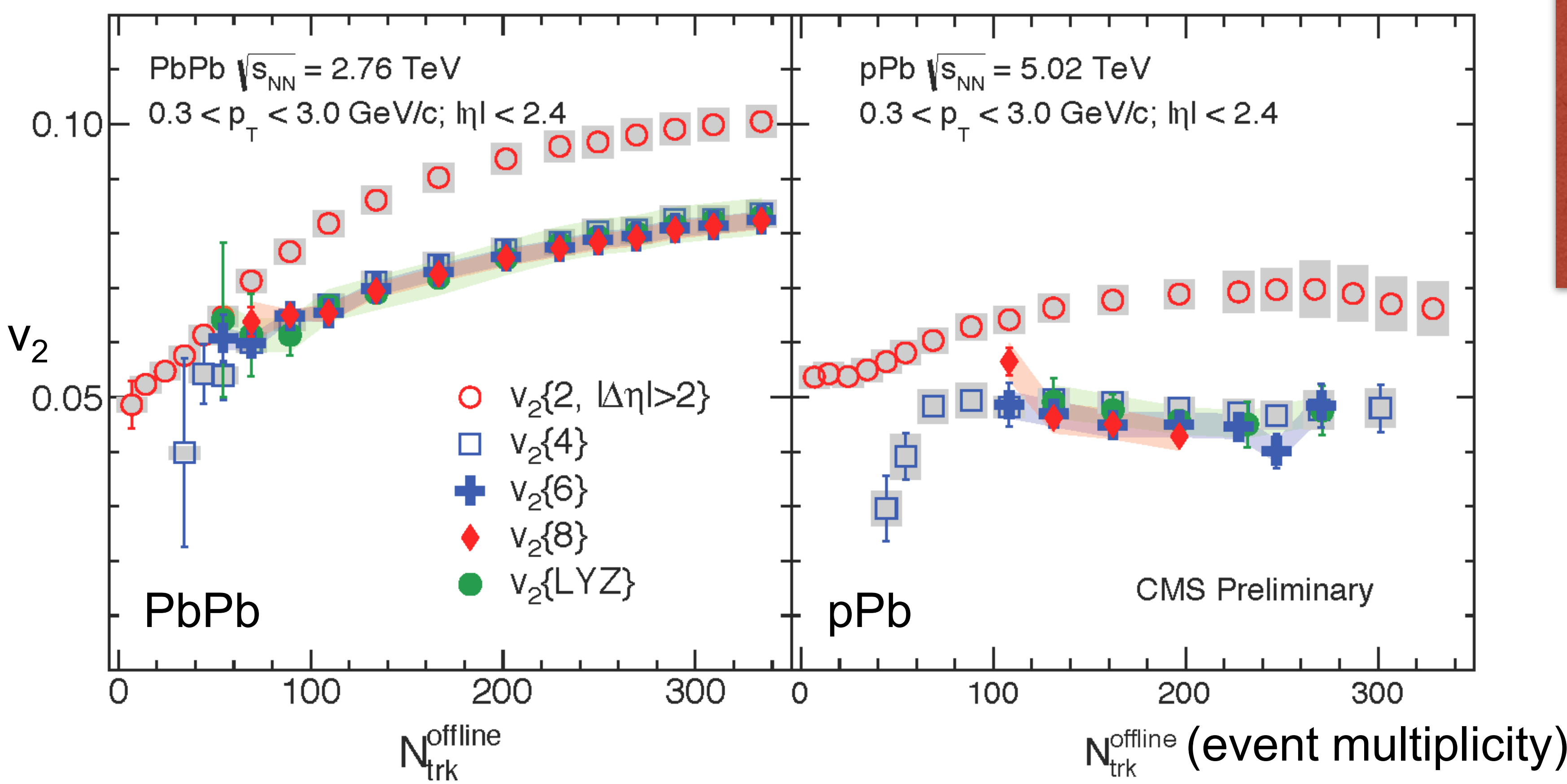
Further discoveries at LHC: high multiplicity pp and pA show explosive behavior

the smallest drops of sQGP



CMS at QM2014 has shown this "killer plot":
In PbPb and pPb one finds that v_2 calculated from 4,6,8 secondaries are the same =>
truly collective deformation of the whole event

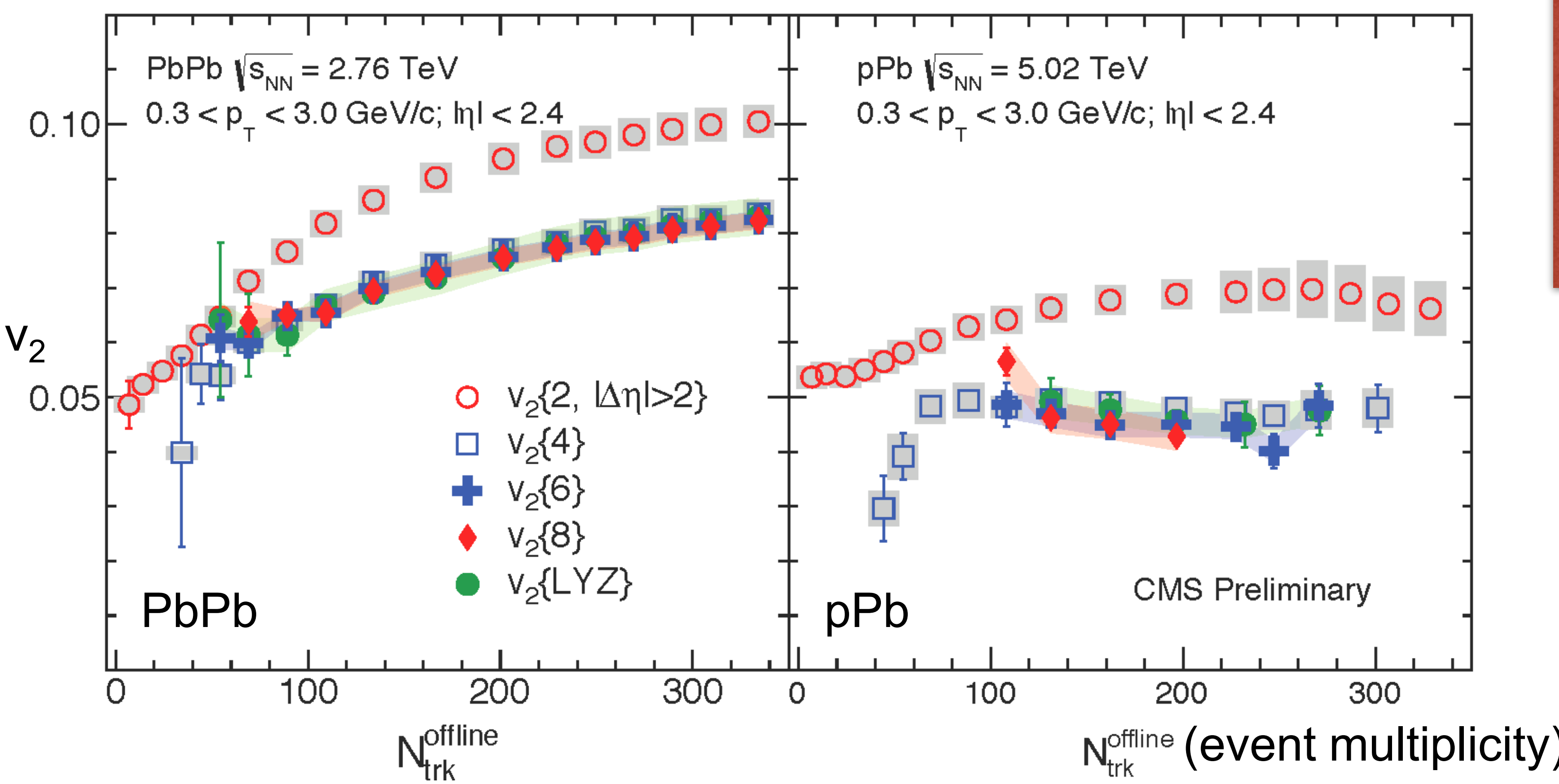
the smallest drops of sQGP



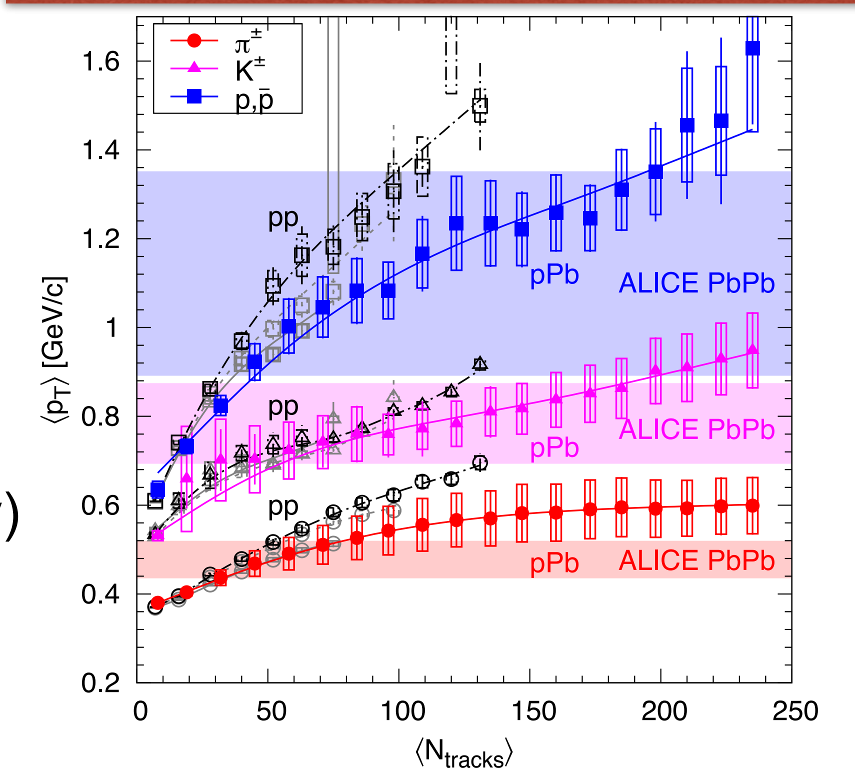
The radial flow:
pp stronger than pA
which is stronger than AA!
Why?

CMS at QM2014 has shown this "killer plot":
In PbPb and pPb one finds that v2 calculated from 4,6,8 secondaries are the same =>
truly collective deformation of the whole event

the smallest drops of sQGP

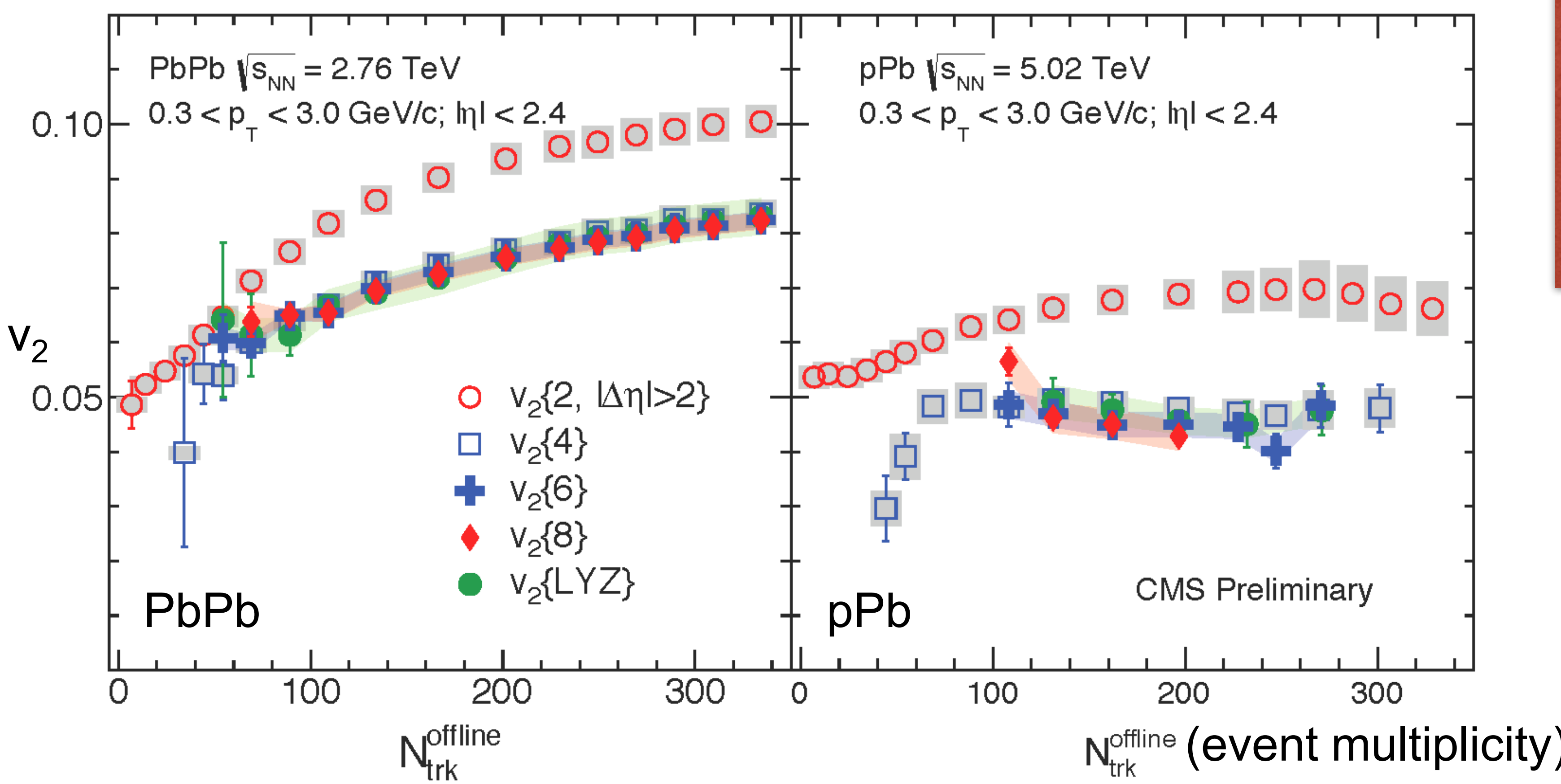


The radial flow:
pp stronger than pA
which is stronger than AA!
Why?

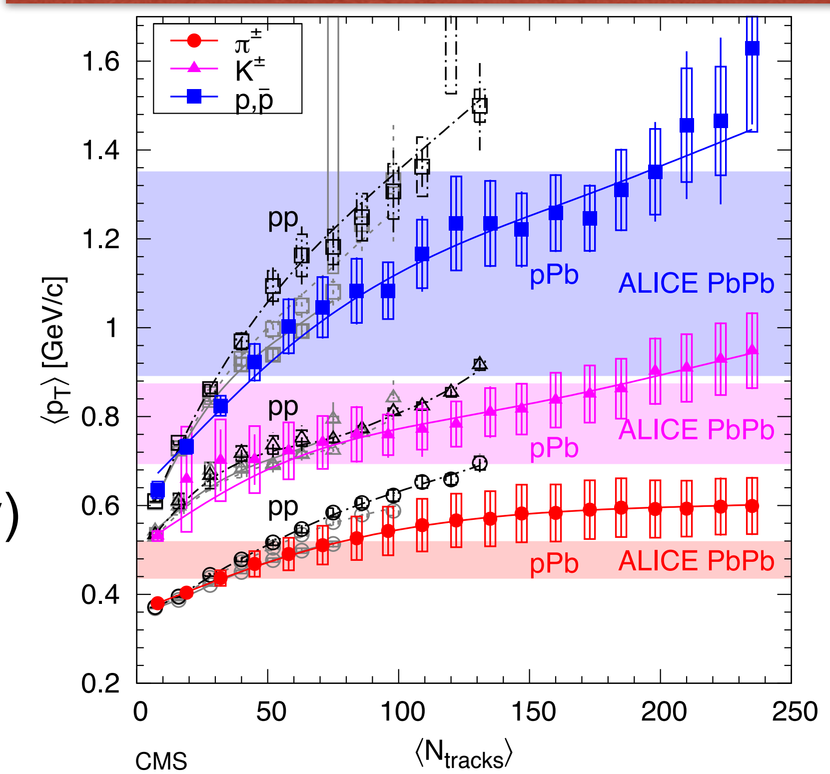


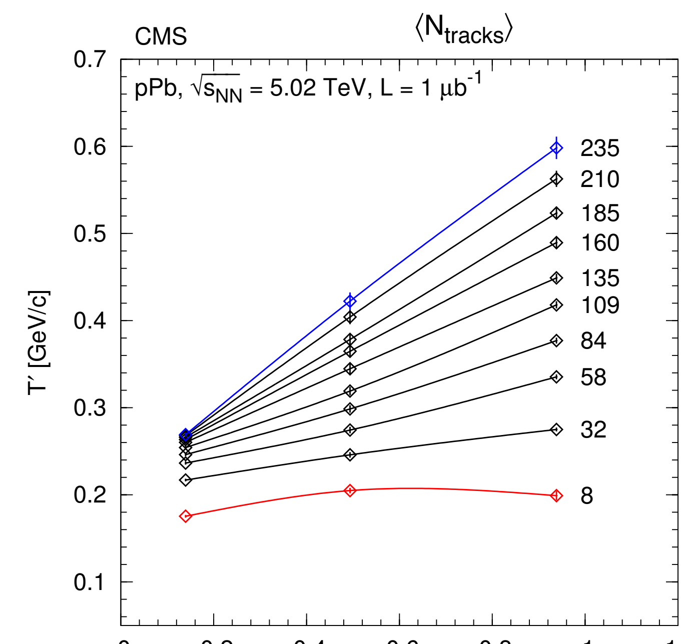
CMS at QM2014 has shown this "killer plot":
In PbPb and pPb one finds that v2 calculated from 4,6,8 secondaries are the same =>
truly collective deformation
of the whole event

the smallest drops of sQGP



The radial flow:
pp stronger than pA
which is stronger than AA!
Why?



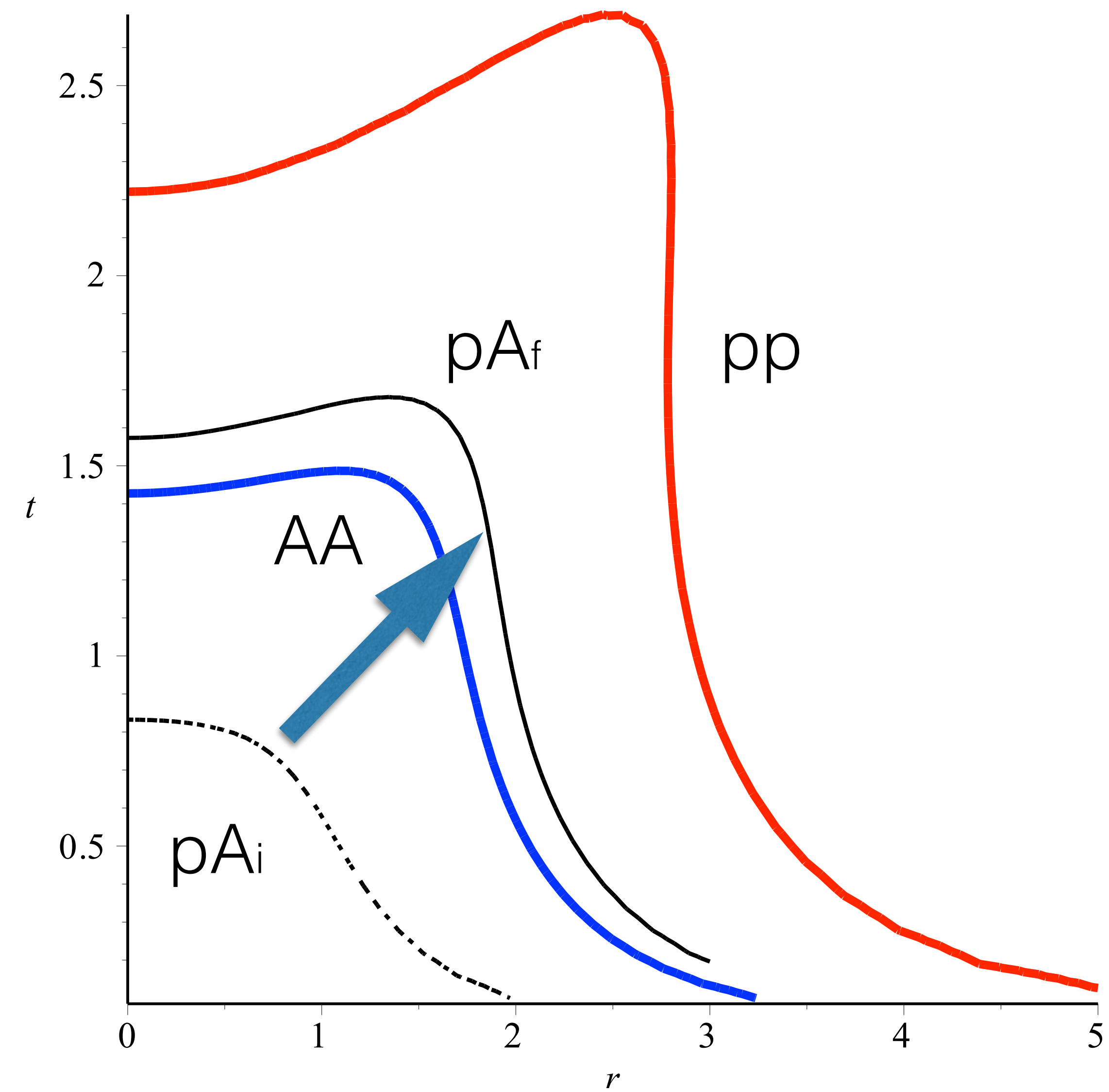


CMS at QM2014 has shown this "killer plot":
In PbPb and pPb one finds that v2 calculated from
4,6,8 secondaries are the same =>
truly collective deformation
of the whole event

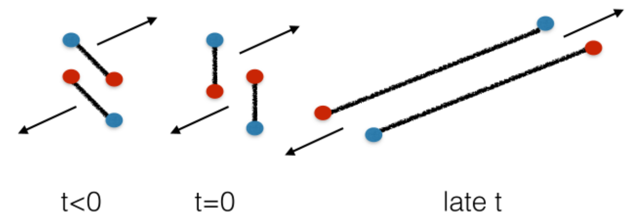
sQGP is near-conformal: so why is explosion of a small fireball so surprising?

Scale transformation:
R(PbPb)=6.5 fm
R(pPb)=O(bNN) =1.6 fm=f R(PbPb)
so for a scale invariance
one needs the entropy density
s(pPb)=s(PbPb)/f^3
which is not the case!

Compression by at least a factor 2 of the pA size is needed to get the radial flow observed



brief history of QCD strings



- **1960's: Regge phenomenology, Veneziano amplitude. Strings have exponentially growing density of states N(E)**

- **1970's Polyakov,Susskind => Hagedorn phenomenon near deconfinement**

- **1980's: Lund model (now Pythia,Hijing): string stretching and breaking**

- **1990-now lattice studies. Dual Abrikosov flux tubes. (Very few) papers on string interaction**

- **2013 Zahed et al: holoraphic Pomeron and its regimes** *(cannot speak about it in few min's)*

string interaction via sigma meson exchange

T. Iritani, G. Cossu and S. Hashimoto, arXiv:1311.0218

our fit uses
the sigma mass
600 MeV

$$\frac{\langle \sigma(r_\perp) W \rangle}{\langle W \rangle \langle \sigma \rangle} = 1 - C K_0(m_\sigma \tilde{r}_\perp)$$

$$\tilde{r}_\perp = \sqrt{r_\perp^2 + s_{string}^2}$$

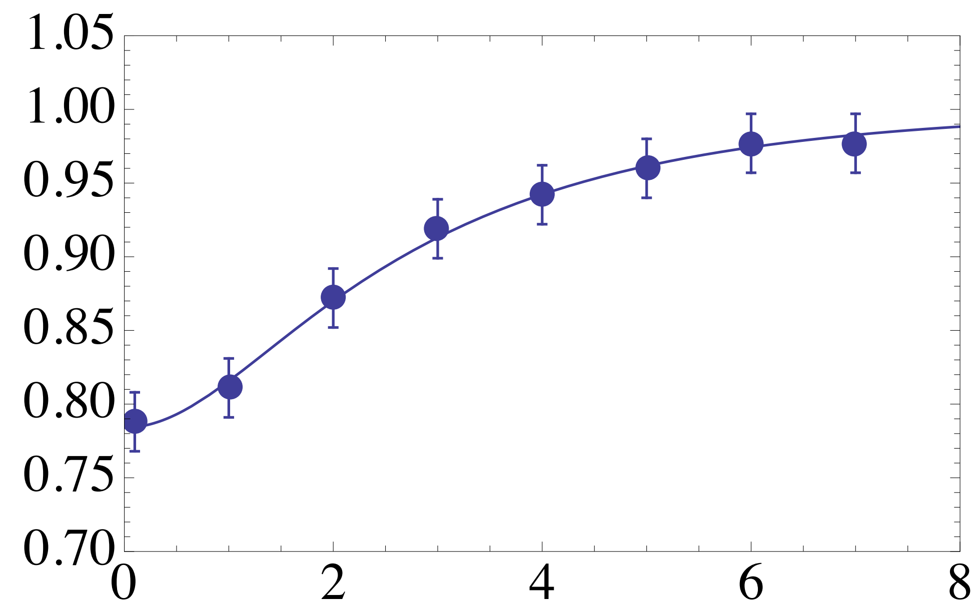


FIG. 2. (Color online). Points are lattice data from [12], the curve is expression (8) with $C = 0.26$, $s_{string} = 0.176\,\text{fm}$.

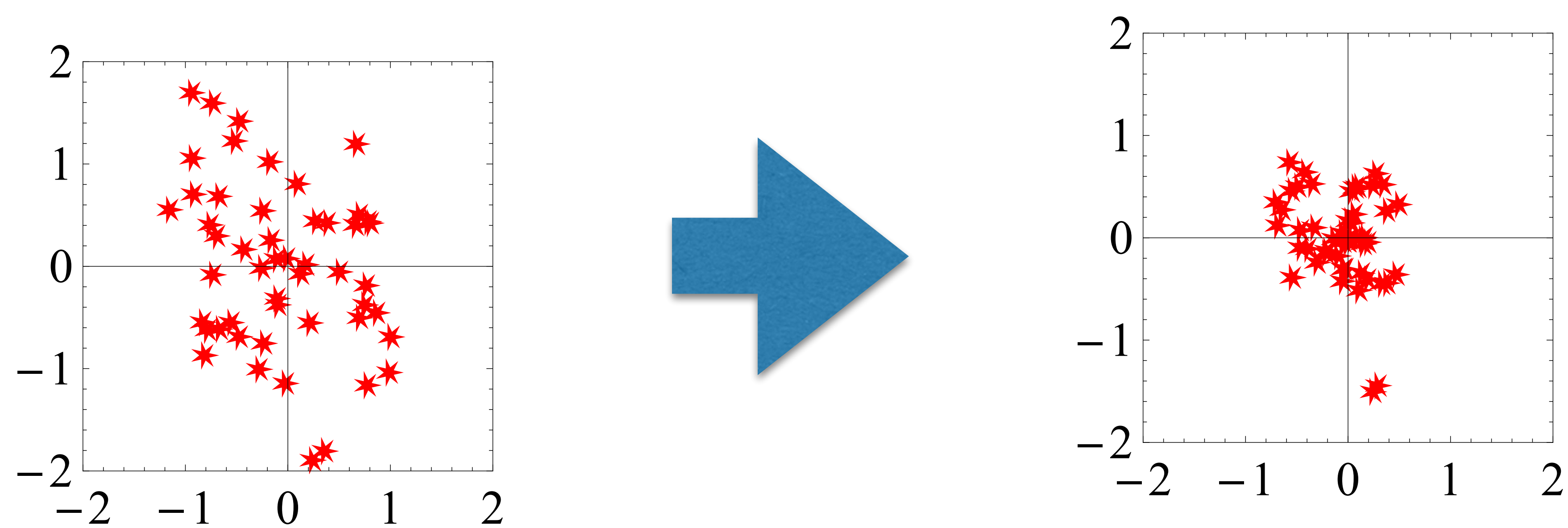
So the sigma cloud around a string is there!

2d spaghetti collapse

Basically strings can be viewed as a 2-d gas of particles with unit mass and forces between them are given by the derivative of the energy (8) , and so

$$\ddot{\vec{r}}_i = \vec{f}_{ij} = \frac{\vec{r}_{ij}}{\tilde{r}_{ij}}(g_N \sigma_T) m_\sigma 2K_1(m_\sigma \tilde{r}_{ij}) \qquad (19)$$

with $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ and “regularized” $\tilde{r}$ (9).



t=0.1 and 1 fm/c

collective sigma field

before and after collapse

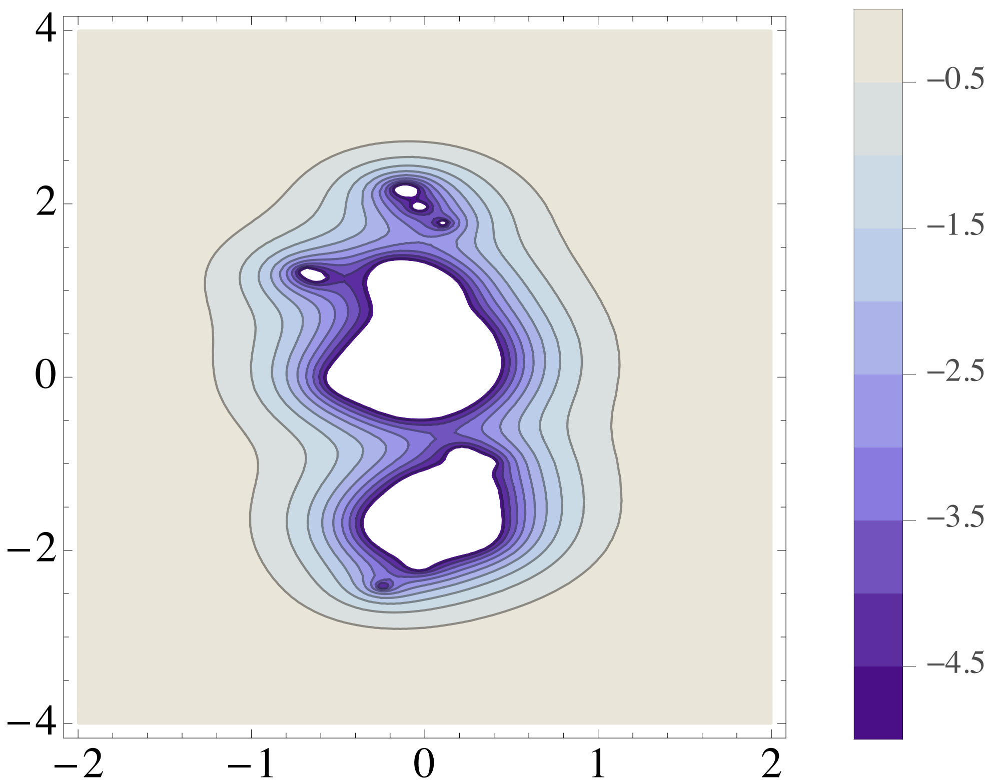


FIG. 10: Instantaneous collective potential in units $2g_N\sigma_T$ for an AA configuration with $b = 11\,\text{fm}$, $g_N\sigma_T = 0.2$, $N_s = 50$ at the moment of time $\tau = 1\,\text{fm}/c$. White regions correspond to the chirally restored phase.

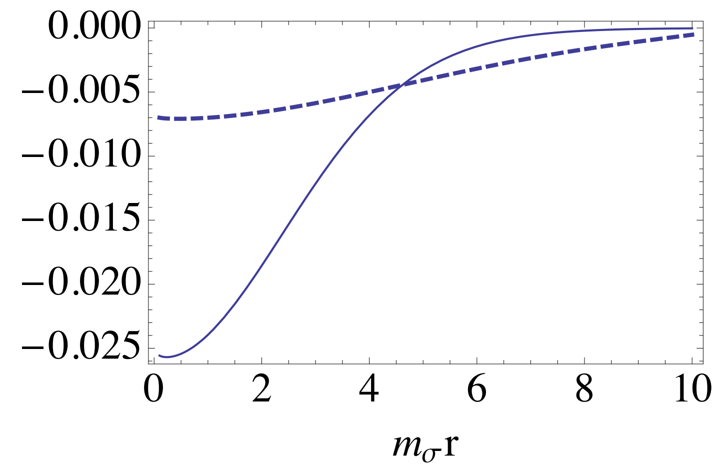


FIG. 4: The mean field (normalized as explained in the text) versus the transverse radius in units of inverse m_σ. The dashed and solid curves correspond to the source radii $R = 1.5$ and $0.7\,\text{fm}$, respectively.

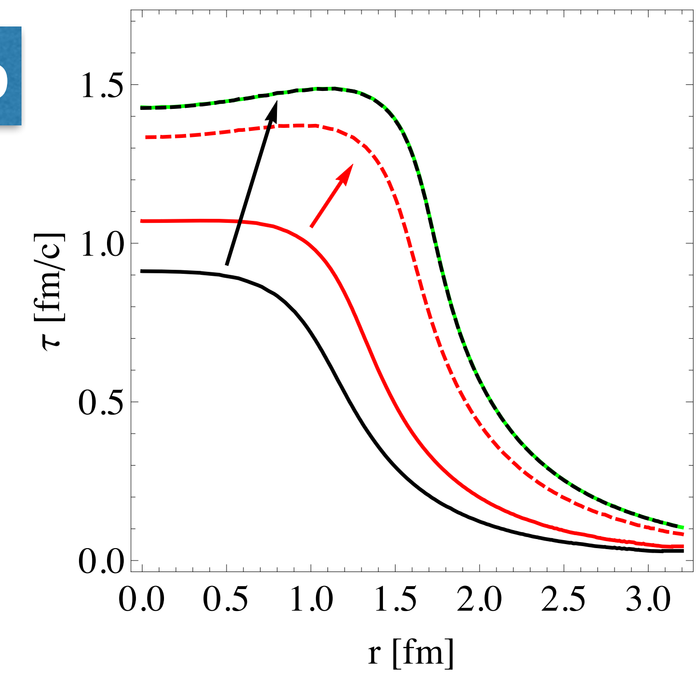
Field gradient at the edge leads to quark pair production: QCD analog of Hawking radiation

explosive regime at ultra high energies

$$E^{ultra\,high} < 10^{20}\,eV$$
$$\sqrt{s^{ultra\,high}} \approx 450TeV$$
$$\sqrt{s^{LHC}} = 8\,TeV$$
$$\frac{dN_{ch}}{dy}^{ultra\,high} \approx 3\frac{dN_{ch}}{dy}^{LHC}$$

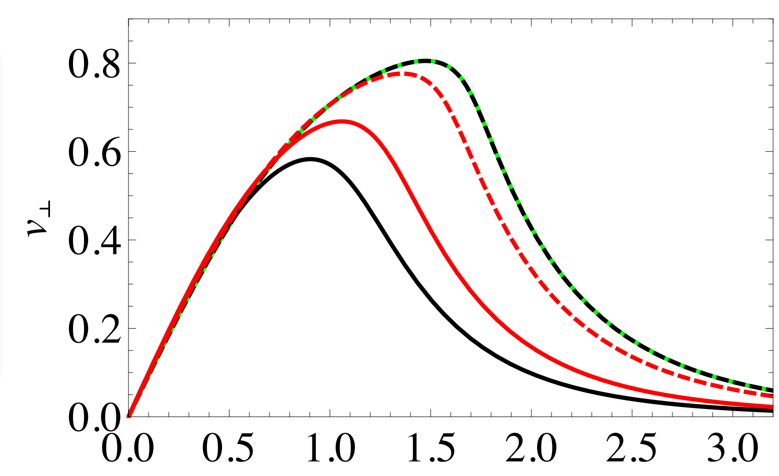
GKZ bound, p+CMB->pi+p

Green=central PbPb, the benchmark black=light-light (OO) red=FeO arrows indicate results after collapse



so even pp may get from 10^-6 into 100% explosive regime! futhermore targets are N,O nuclei and projectile are O or even Fe, so the radial flow changes mean pt

Conclusion: expected explosion strength like in the central PbPb at LHC



An "explosive regime" should dominate the ultra-high energy collisions, Tigran Kalaydzhyan and Edward Shuryak, in progress

Thanks to collaborators
P.Staig, T. Kalaydzhyan ,I.Zahed

Summary

- initial state perturbations create observed signals, well described by (linearized) hydrodynamics
- Strings interact attractively via the sigma field, as seen of the lattice
- Spaghetti (multiple strings) collapses (when >30) and makes denser fireball, which explains larger radial flow in pA then AA:
- Ultra high cosmic rays events should go to the same explosive regime, with strength comparable to central PbPb at LHC
- Others: holographic Pomeron and its phases
- string balls interpolate toward black holes (size, entropy).we studied QCD string balls and found that their QCD analog —> self supporting high entropy balls in the mixed phase