The Tiniest Droplet of the (most) Perfect Fluid

Chin-Hao Chen
陳勁豪

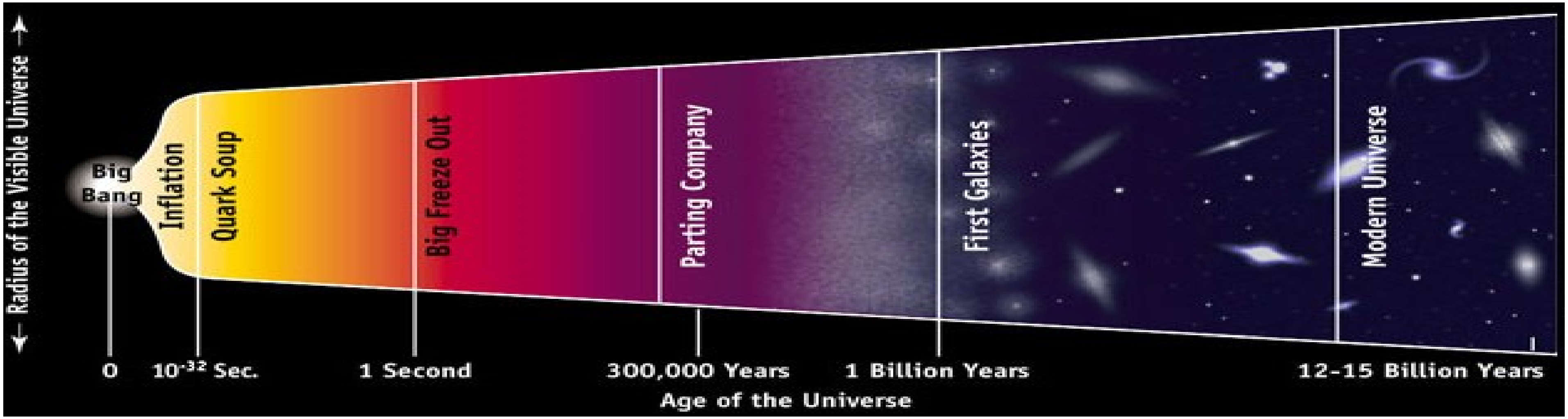
LeCosPA, NTU

CYCU, 2016/05/02

Outline

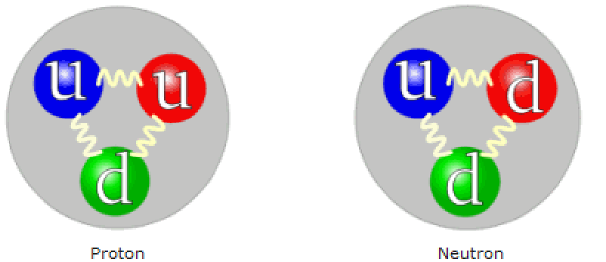
- What is quark gluon plasma (QGP)?
- Collective motion and initial state geometry
- From little bang to tiny bang

A hot, dense mess

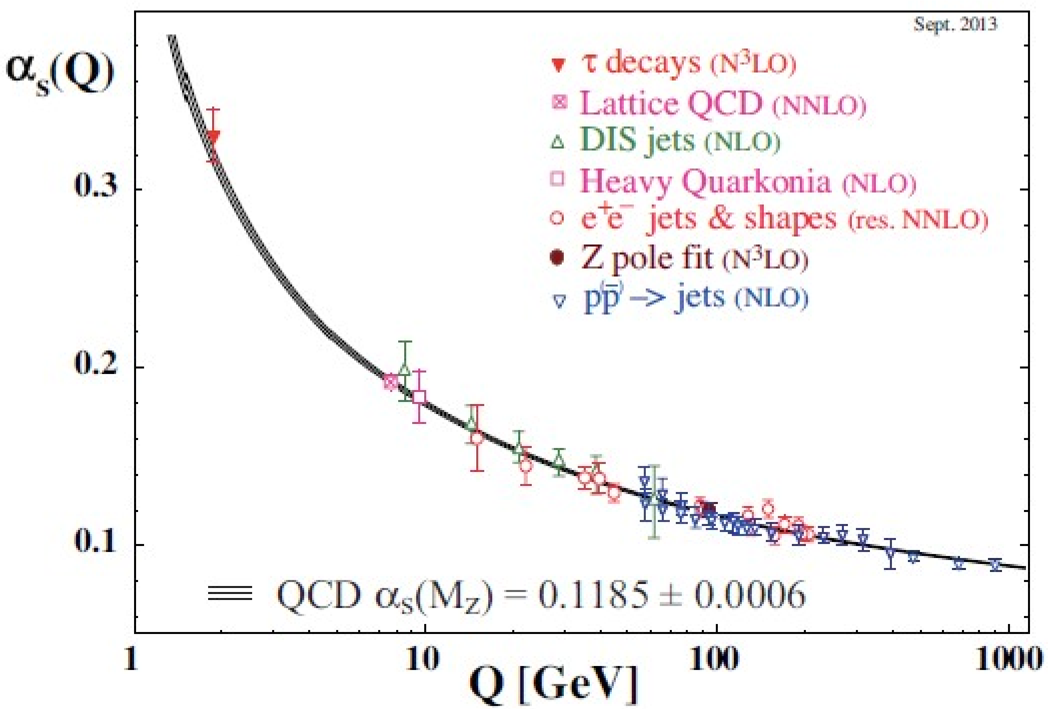


- At the beginning of the universe, it was supposed to be a high energy density state!
- How does it look like?

Quarks are confined



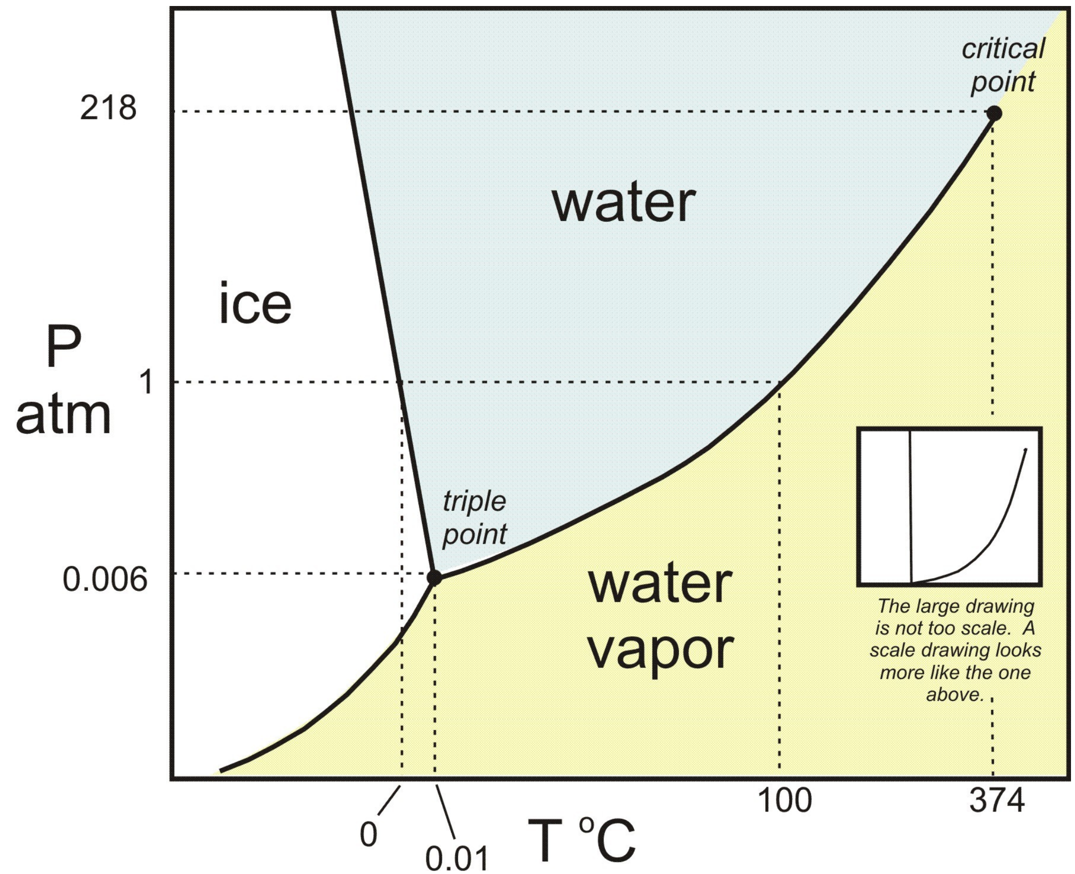
Quark composition of a proton and a neutron (diagrams from *Wikipedia*)



PDG 2014

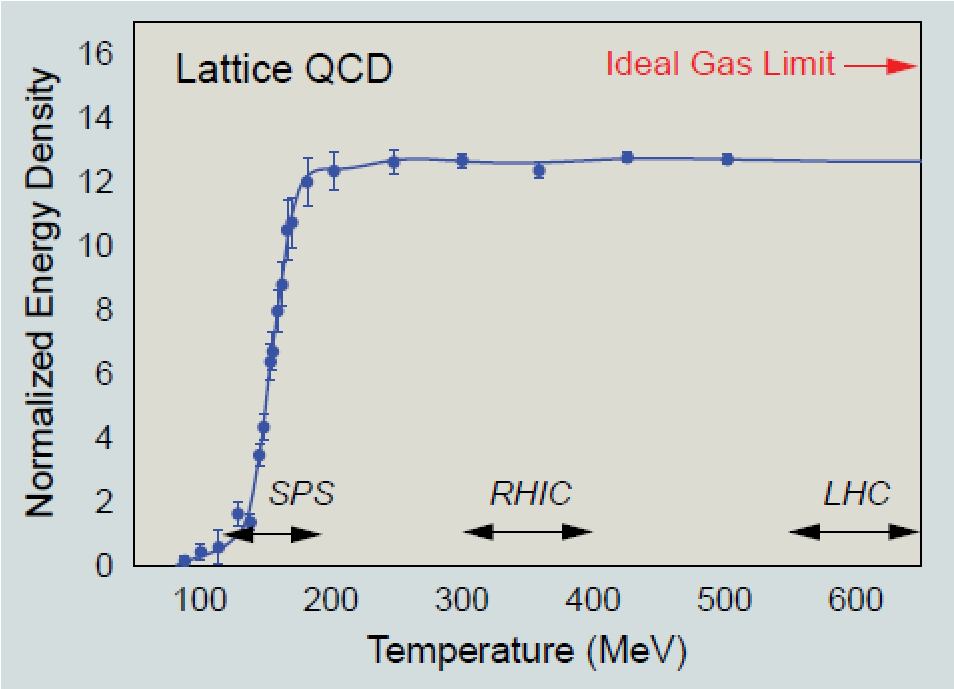
- Quarks are confined in protons and neutrons
- The further quarks apart, the stronger the force; the closer the quarks, the weaker the interaction
- What will happen if we increase the energy "high enough"?

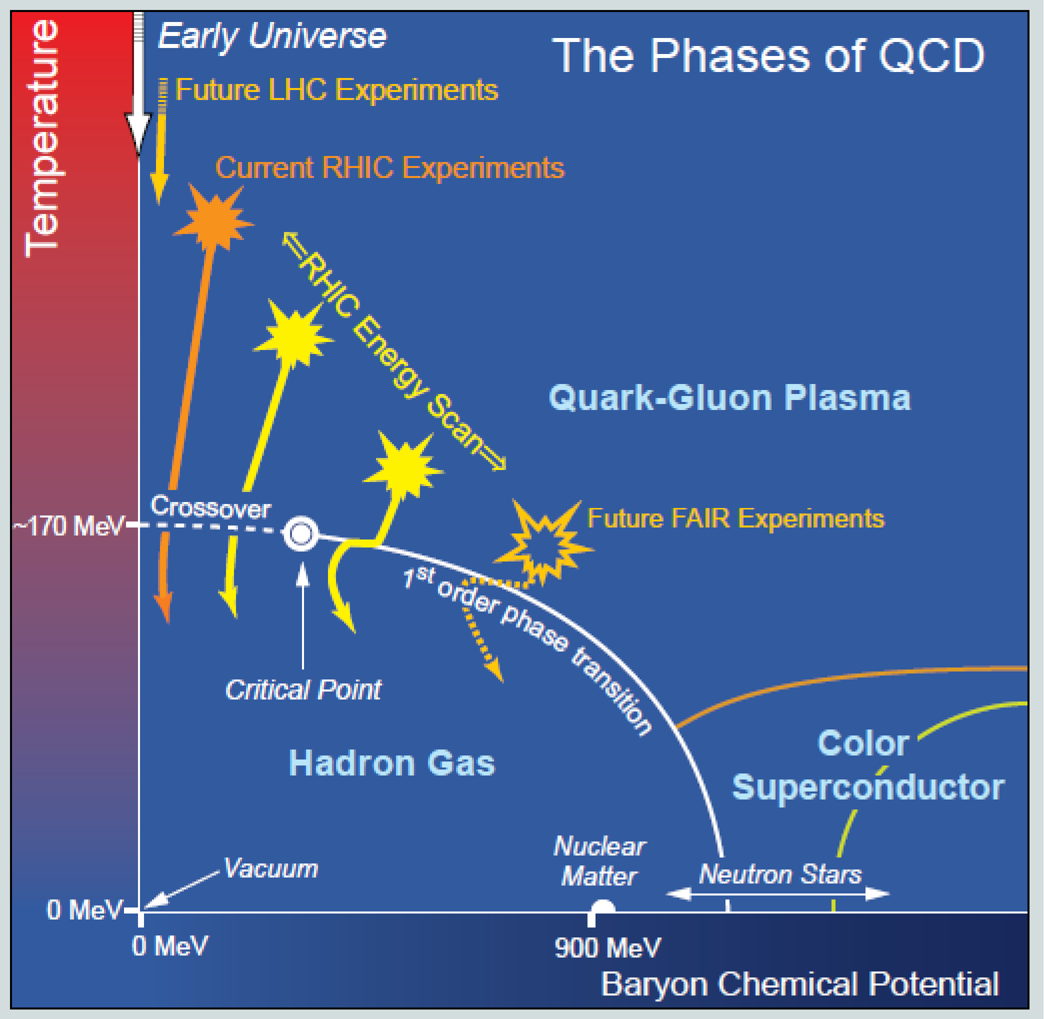
How do we melt the ice?



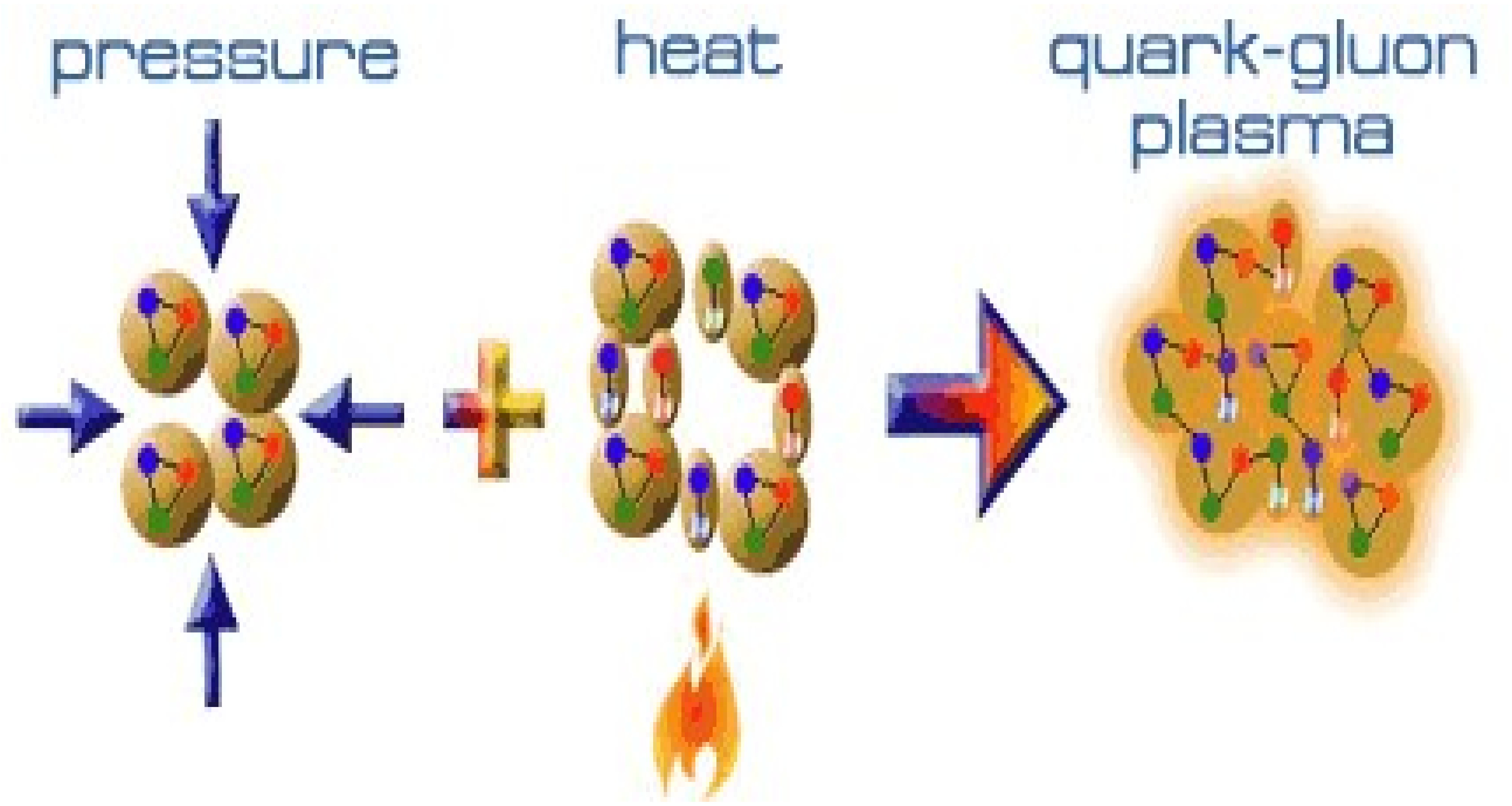
- We heat up the ice
- It will melt at critical temperature (0 Celsius)
- A phase transition from ice to water

Melt the nucleons!

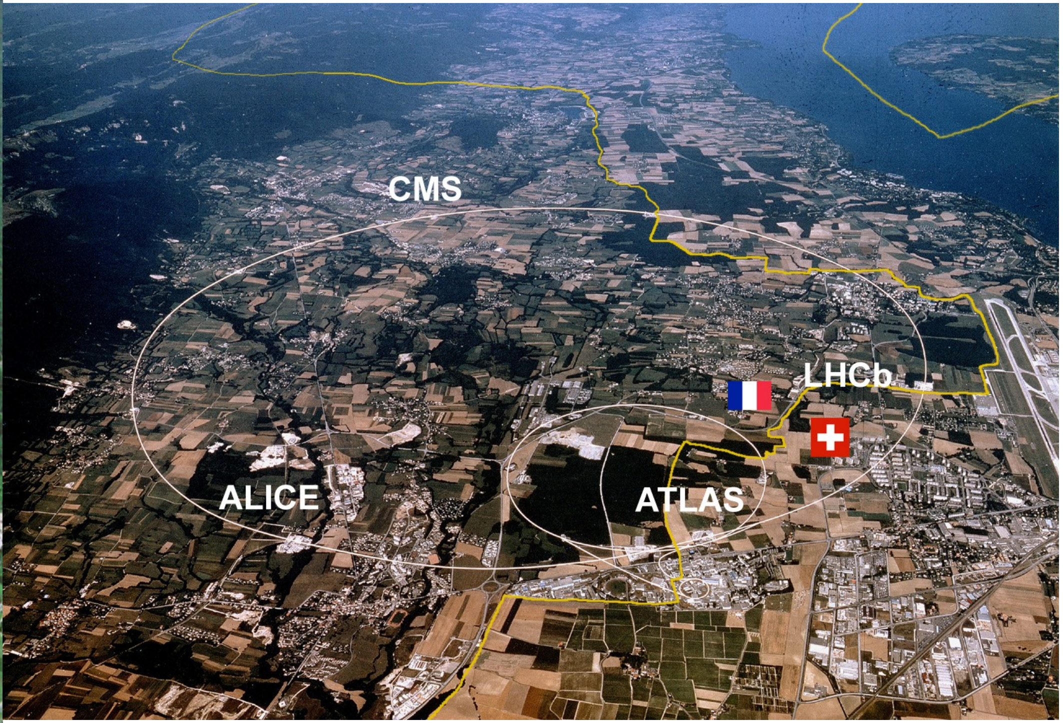




Ideally speaking...



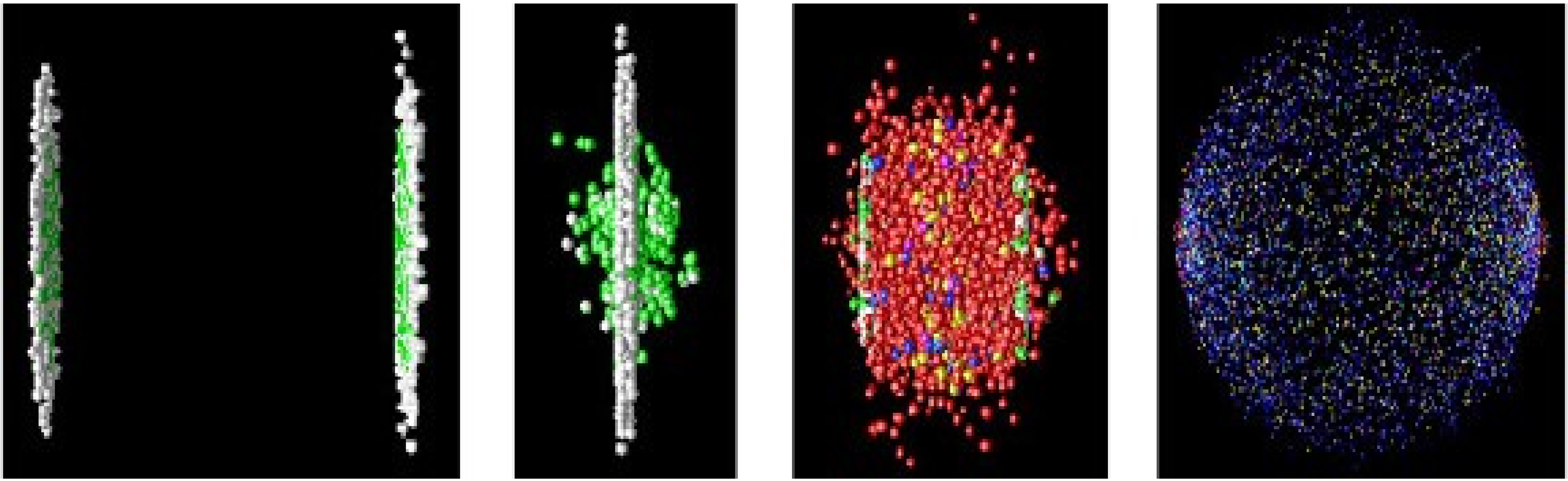
Creating the Mini-Bang



- RHIC
- Collides p+p, Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
- and other species (Cu+Cu, Cu+Au, U+U...) at various energies ($\sqrt{s_{NN}}$ = 7.7-200 GeV)!!

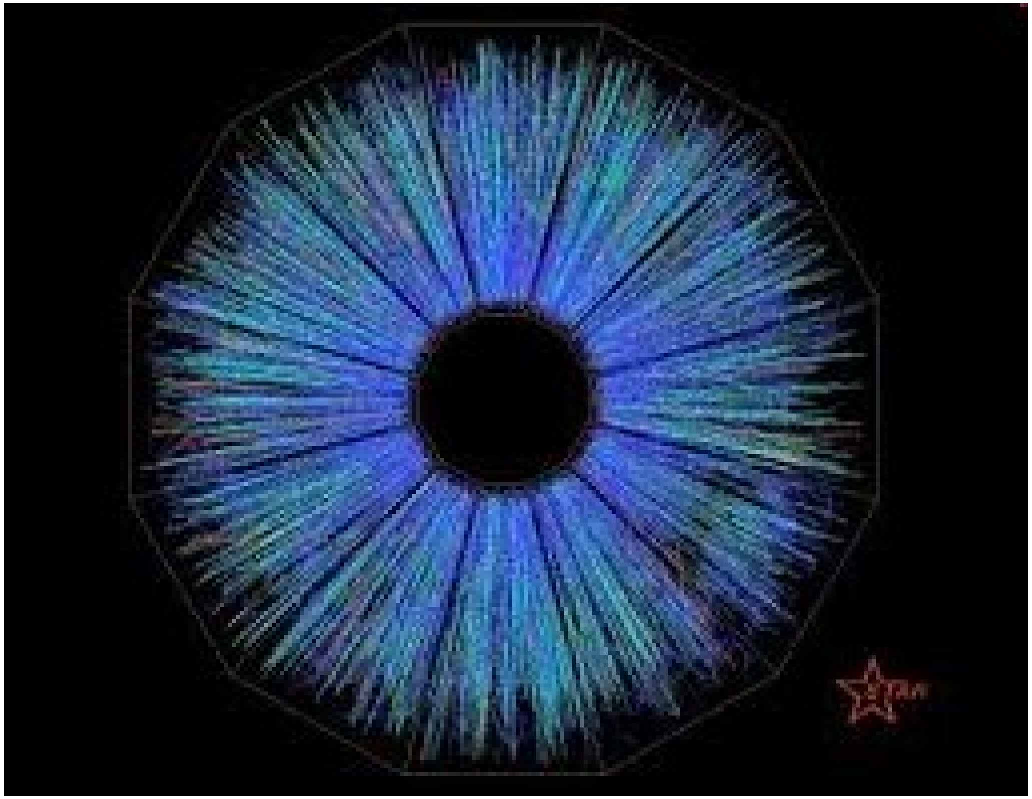
- LHC
- Collides p+p, p+Pb, Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 (5.02) TeV

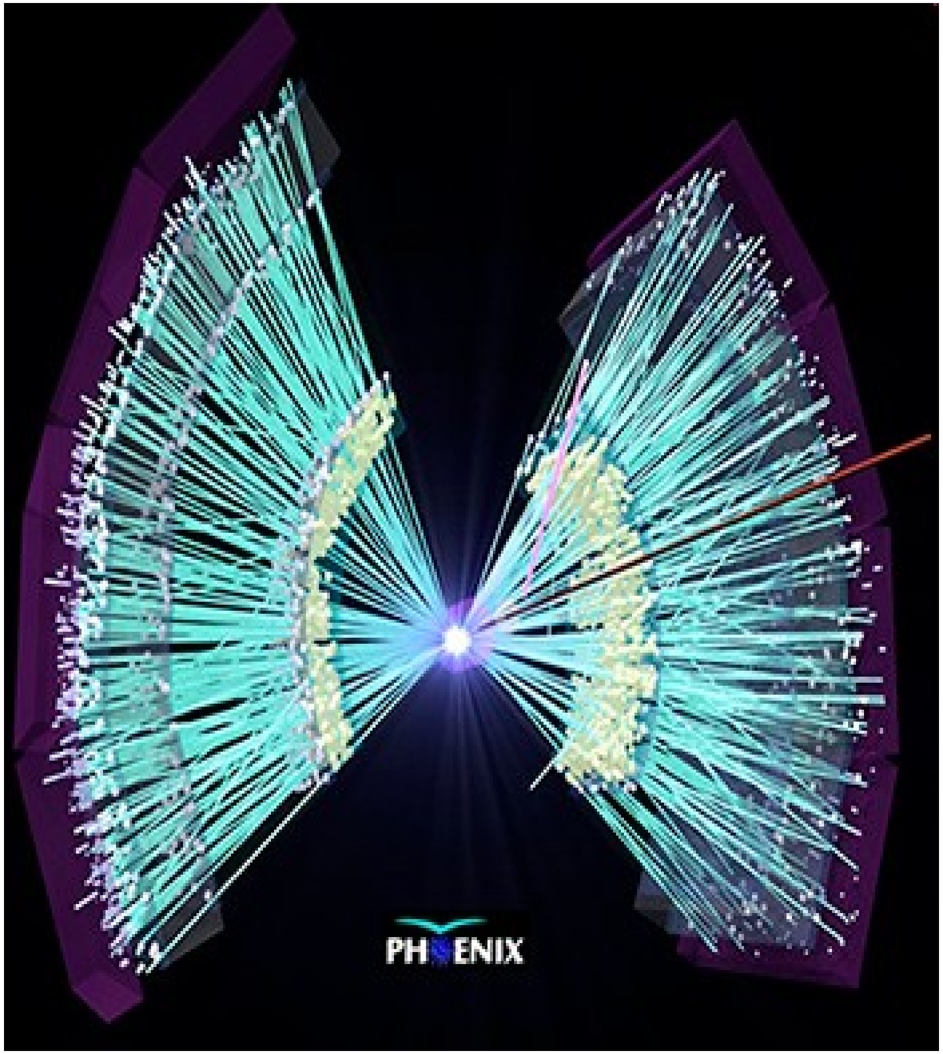
What happens in heavy ion collisions



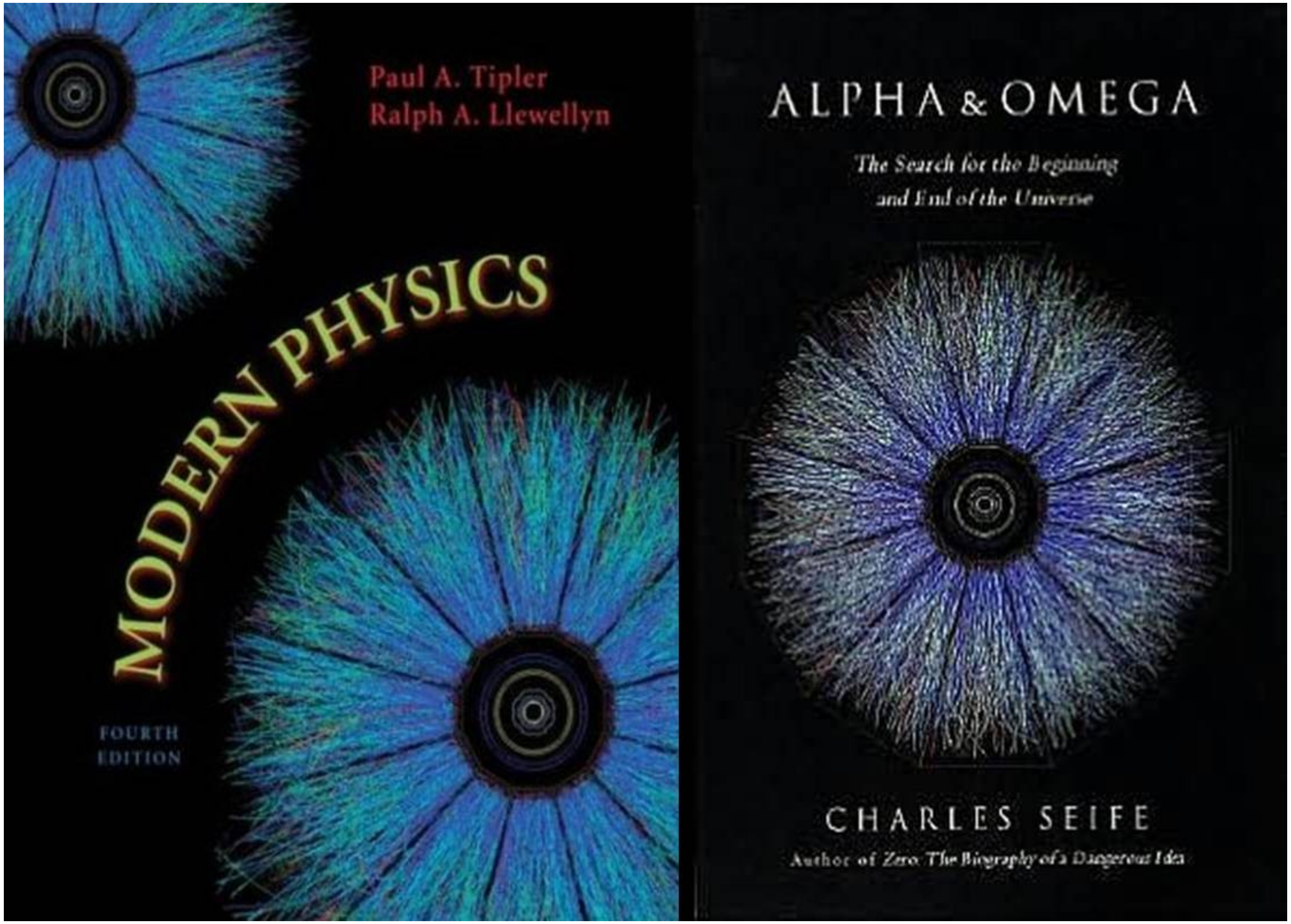
- The beams travel at 99.995% the speed of light.
- The two ions look flat as a pancake due to Relativity. ($\gamma\sim106$ at full energy collision @ RHIC).
- The two ions collide and smash through each other for 10^{-23} s
- The collision “melts” protons and neutrons, and liberates the quark and gluons.
- Thousands of particles are created and fly out from the collision area; plasma cools off.

Events viewed by detectors



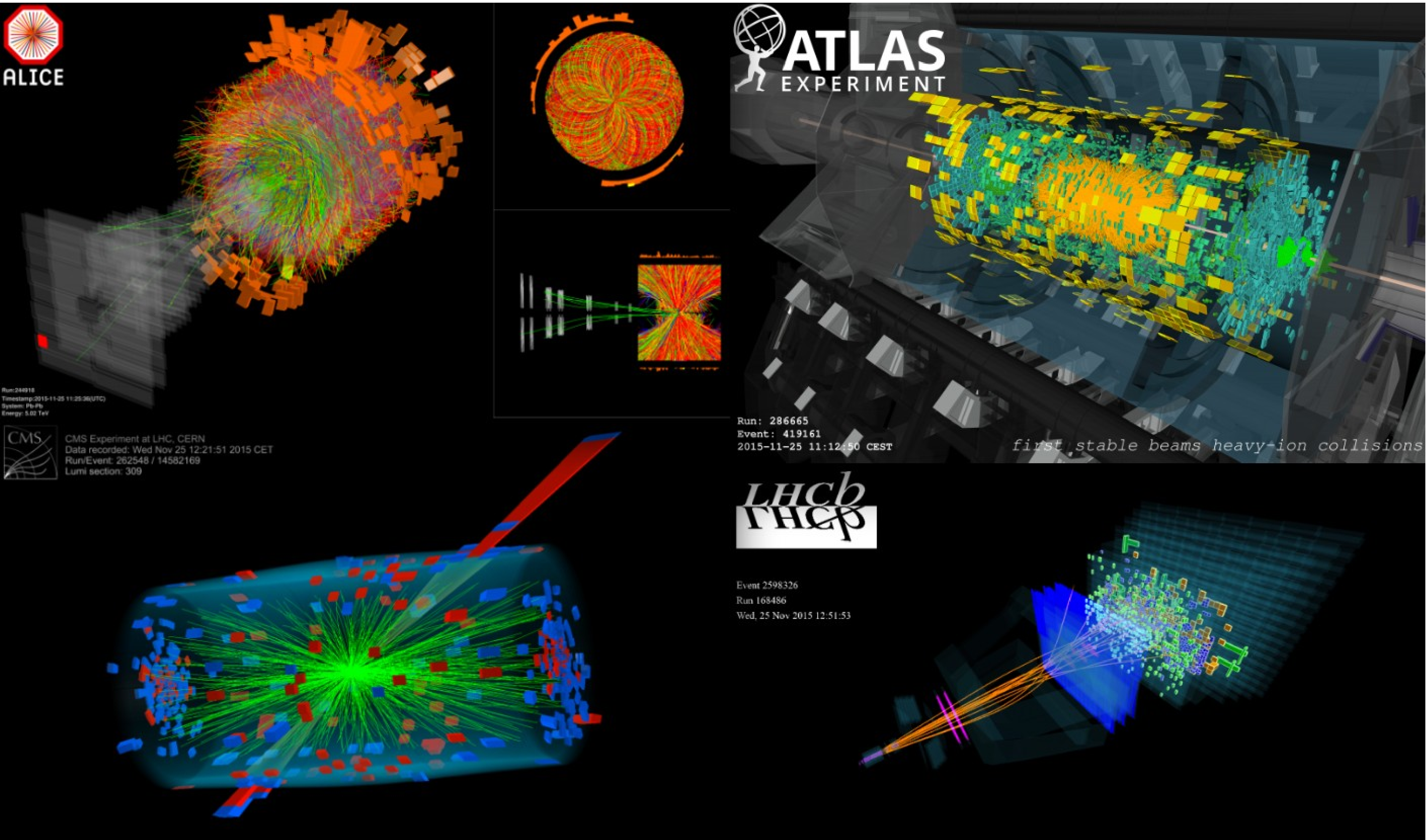


~1500 charged particles are created in one Au+Au collisions!



Seen in many places!

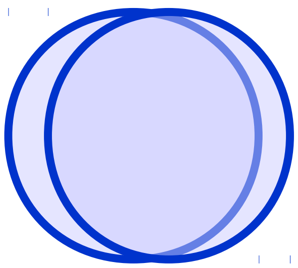
Pb-Pb @ 5.02 TeV @LHC



Some useful terminology

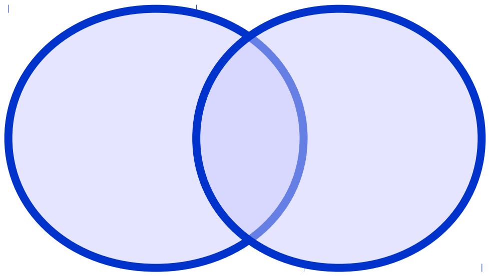
Au: 197 nucleons

Pb: 208 nucleons



Central collision:

the two nuclei collide “head on”. Most energetic collisions, with highest multiplicity. Roughly 300-350 participating nucleons.

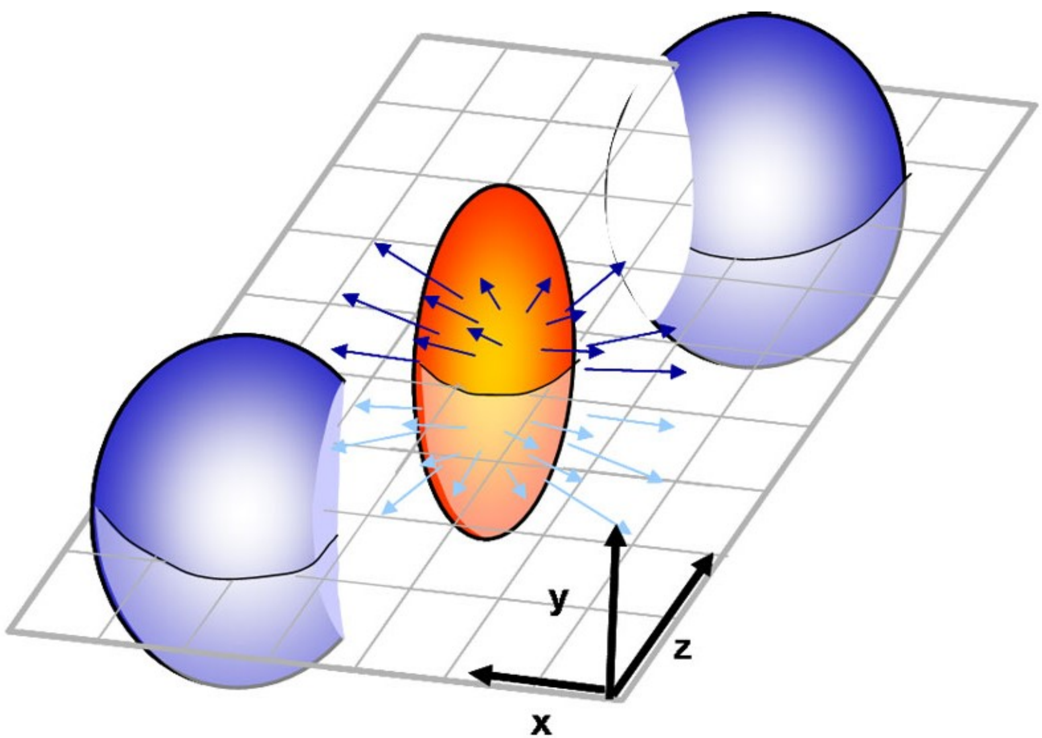


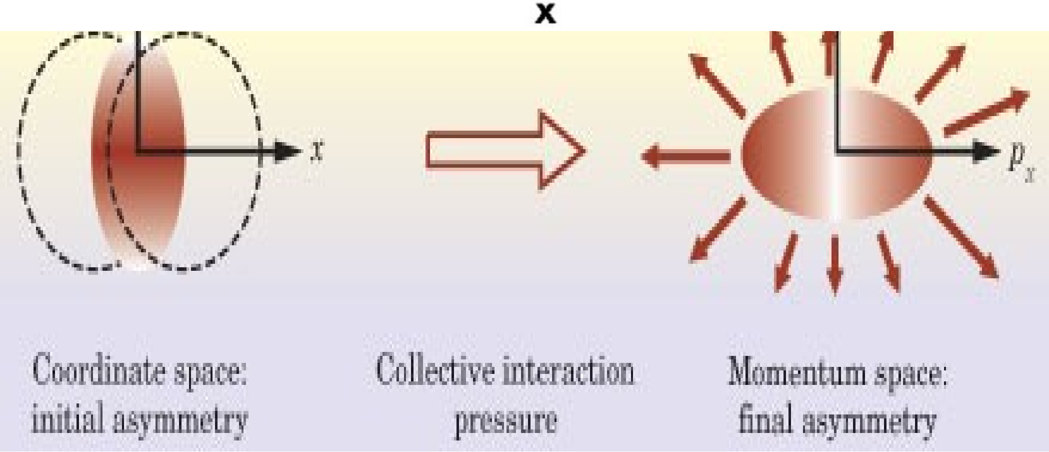
Peripheral collision:

the two nuclei touch by edge, with fewer multiplicity. Roughly ~10 participating nucleons

p+p collision: no QGP (at least at RHIC energy)

How do the particles move?

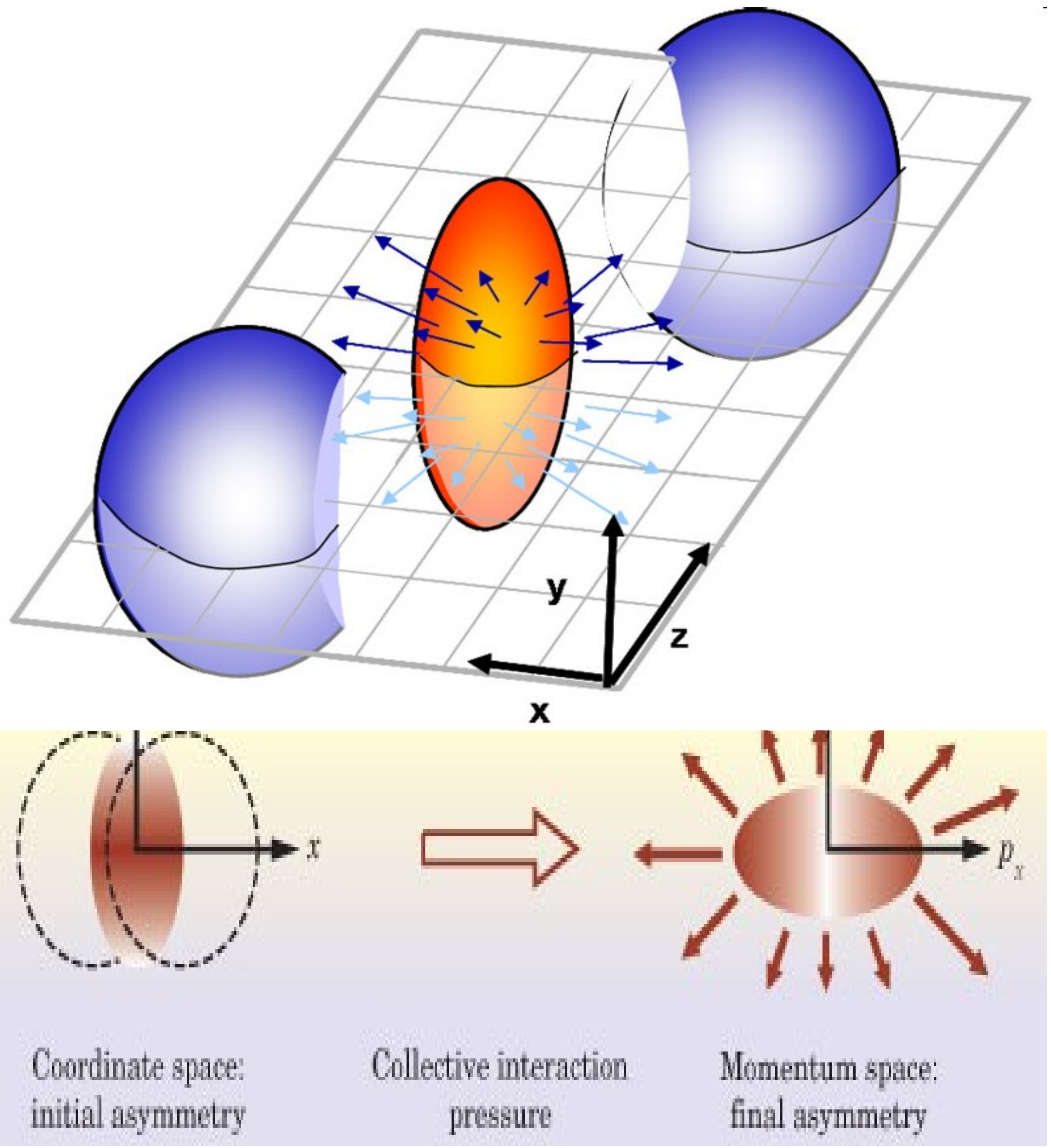




- Collision area has "almond" shape due to overlap geometry of the nuclei.
- Almond shape leads to un-uniform momentum distribution.
- Pressure gradient pushes the "almond" harder in the short direction.
- For a symmetric colliding area, $v_{odd} = 0$
- If $v_2 = 0$ → particle distributed homogeneously in ϕ direction

$$\frac{d^2N}{d\phi\, dp_T} = N_0\left(1 + 2\underline{v_2(p_T)}\cos(2\phi)\right)$$

How do we measure it?



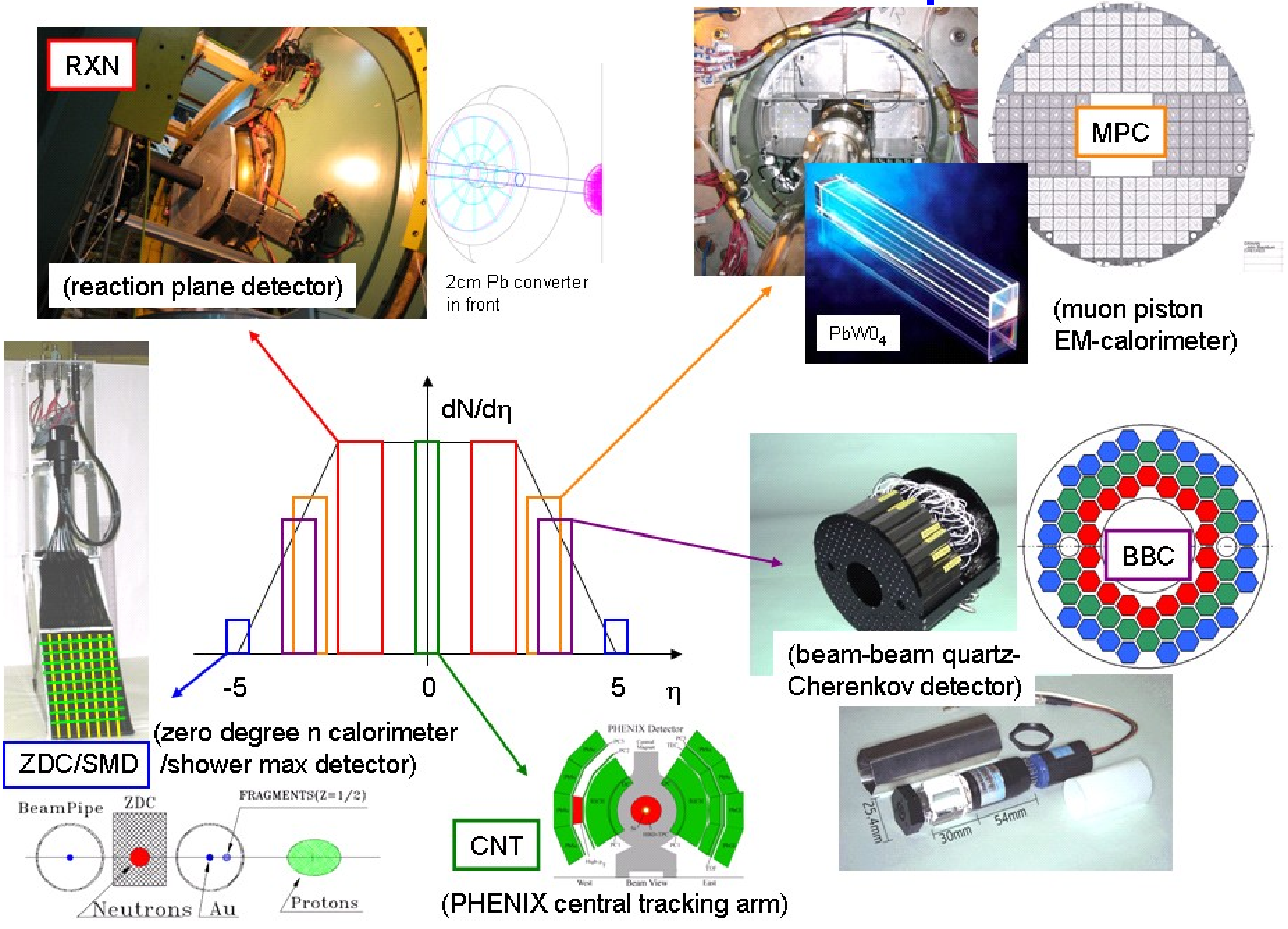
- Determine the direction of the event plane (ψ_2)

$$\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{Y_n = \sum_i w_i \sin(n\phi_i)}{X_n = \sum_i w_i \cos(n\phi_i)}\right)$$

- Measure the particle distribution (ϕ - ψ_2)

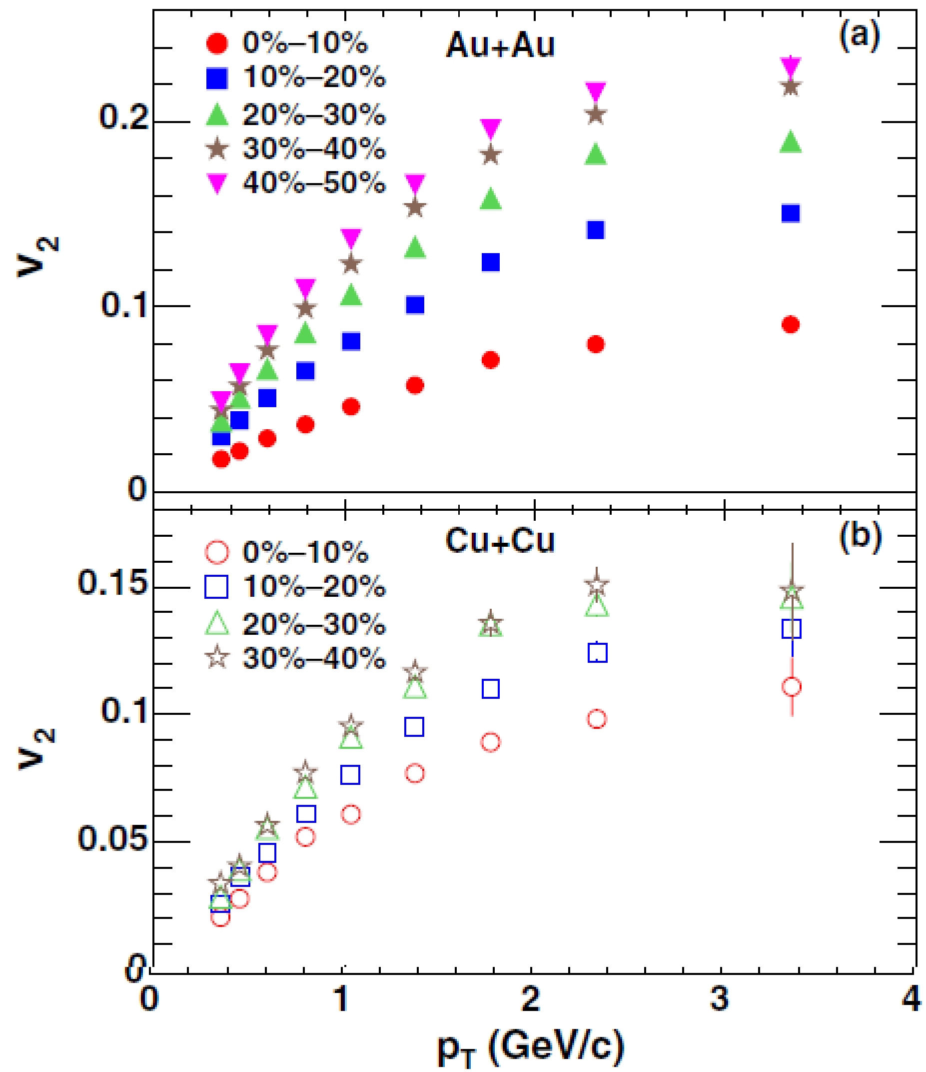
$$\frac{d^2N}{d\phi\, dp_T} = N_0(1 + 2v_2(p_T)\cos(2\phi)).$$

Determine the event plane

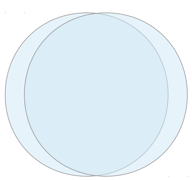


Phys. Rev. Lett. **98**, 162301 (2007)

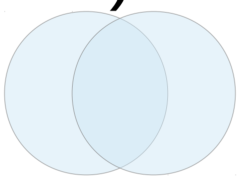
v_2 vs p_T



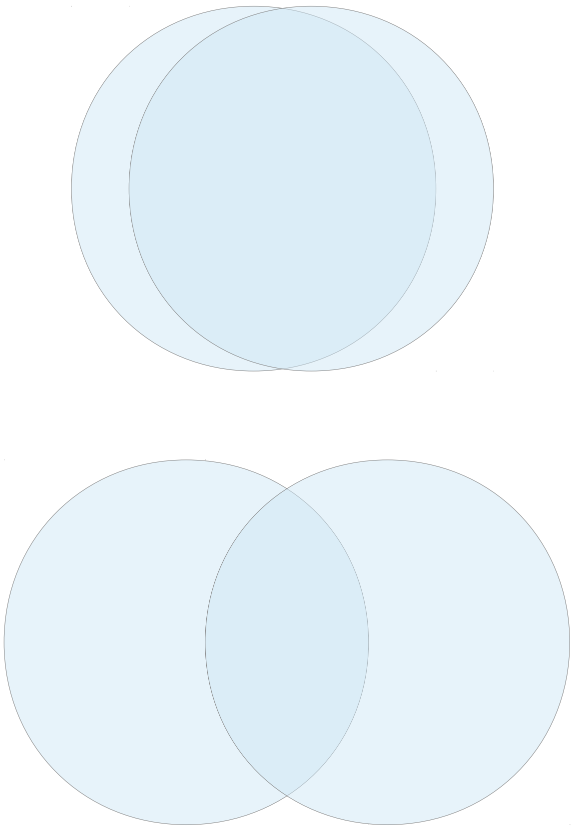
- Au+Au vs Cu+Cu
  - Size difference
  - Geometry difference (different eccentricity, ε_2)
- Non-zero v_2
- Central collisions (0-10%): smaller v_2



- Mid-central collisions (30-40%): larger v_2

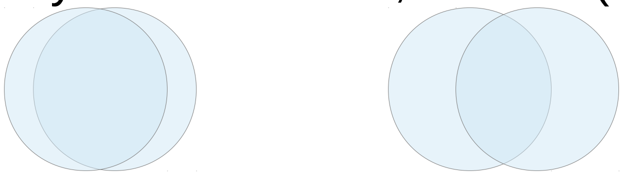


Geometry dependence

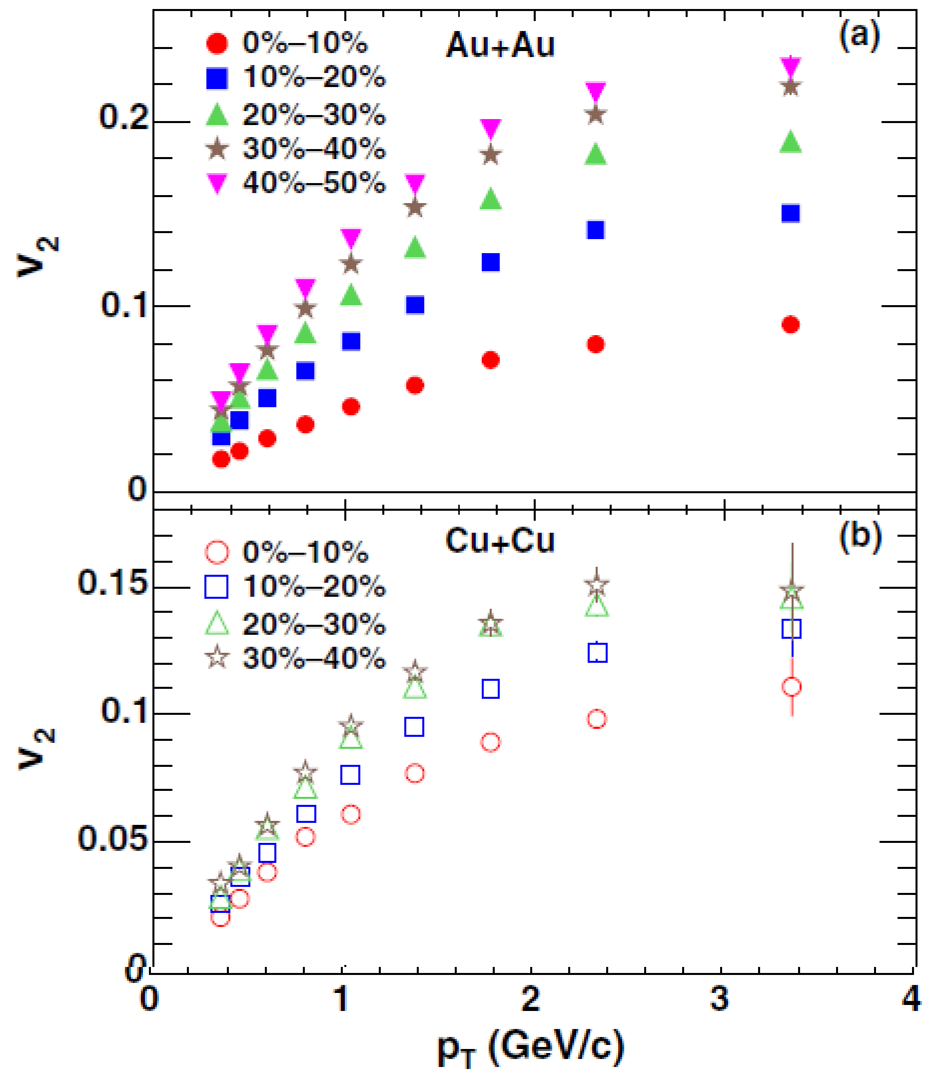


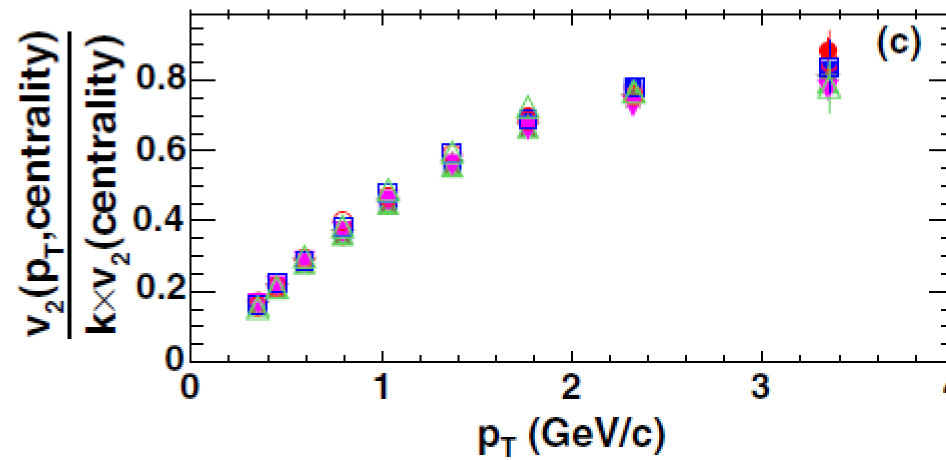
- Different geometry of the interaction area leads to different v_2
- Use the eccentricity to remove the geometrical contributions
- Central collision, $\varepsilon_2 \sim 0$
- ε_2 increases when moving to peripheral collisions

Phys. Rev. Lett. **98**, 162301 (2007)



v_2 vs p_T

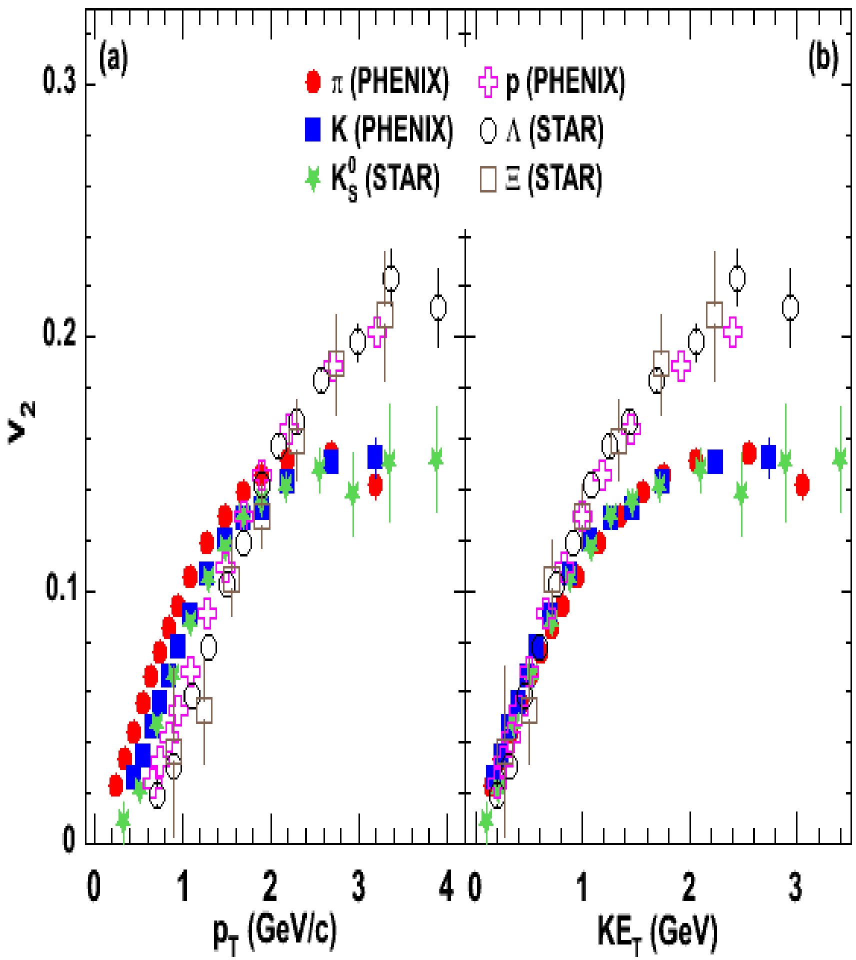


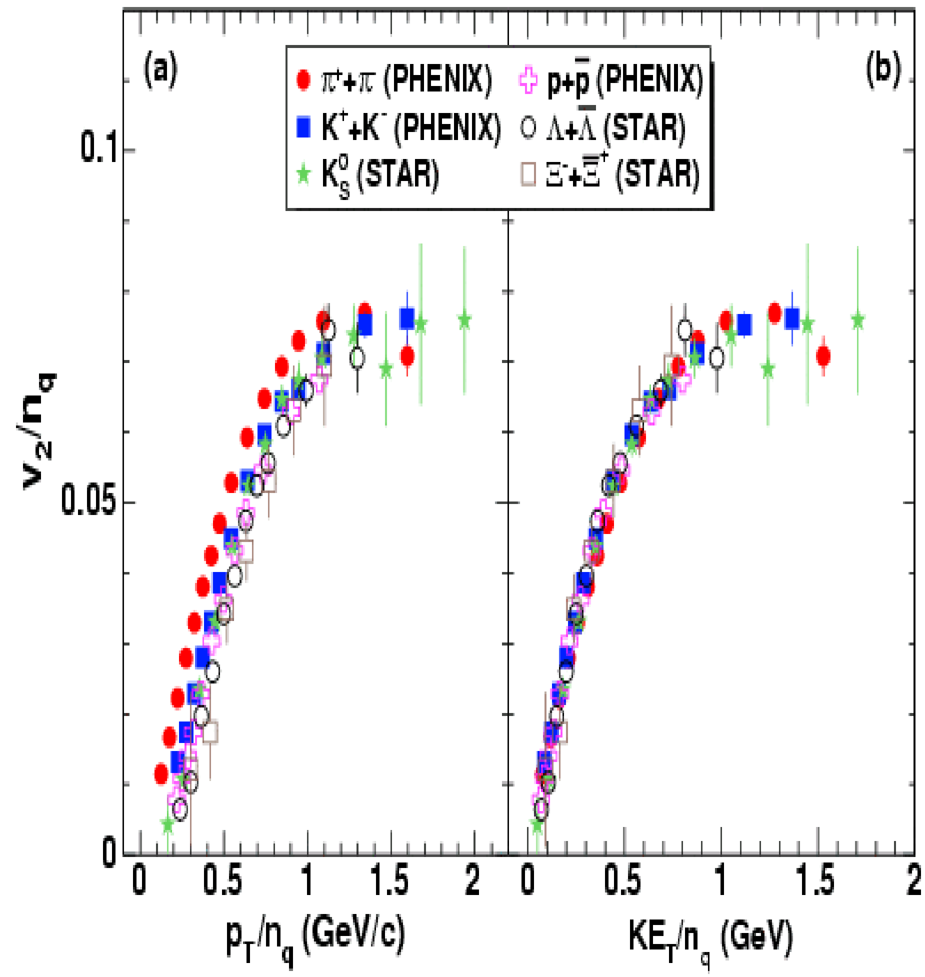


- After normalized by ε_2, Au+Au/Cu+Cu in different centralities follows a universal curve
- v_2 μ ε_2

Phys. Rev. Lett. **98**, 162301 (2007)

How do the particles flow?



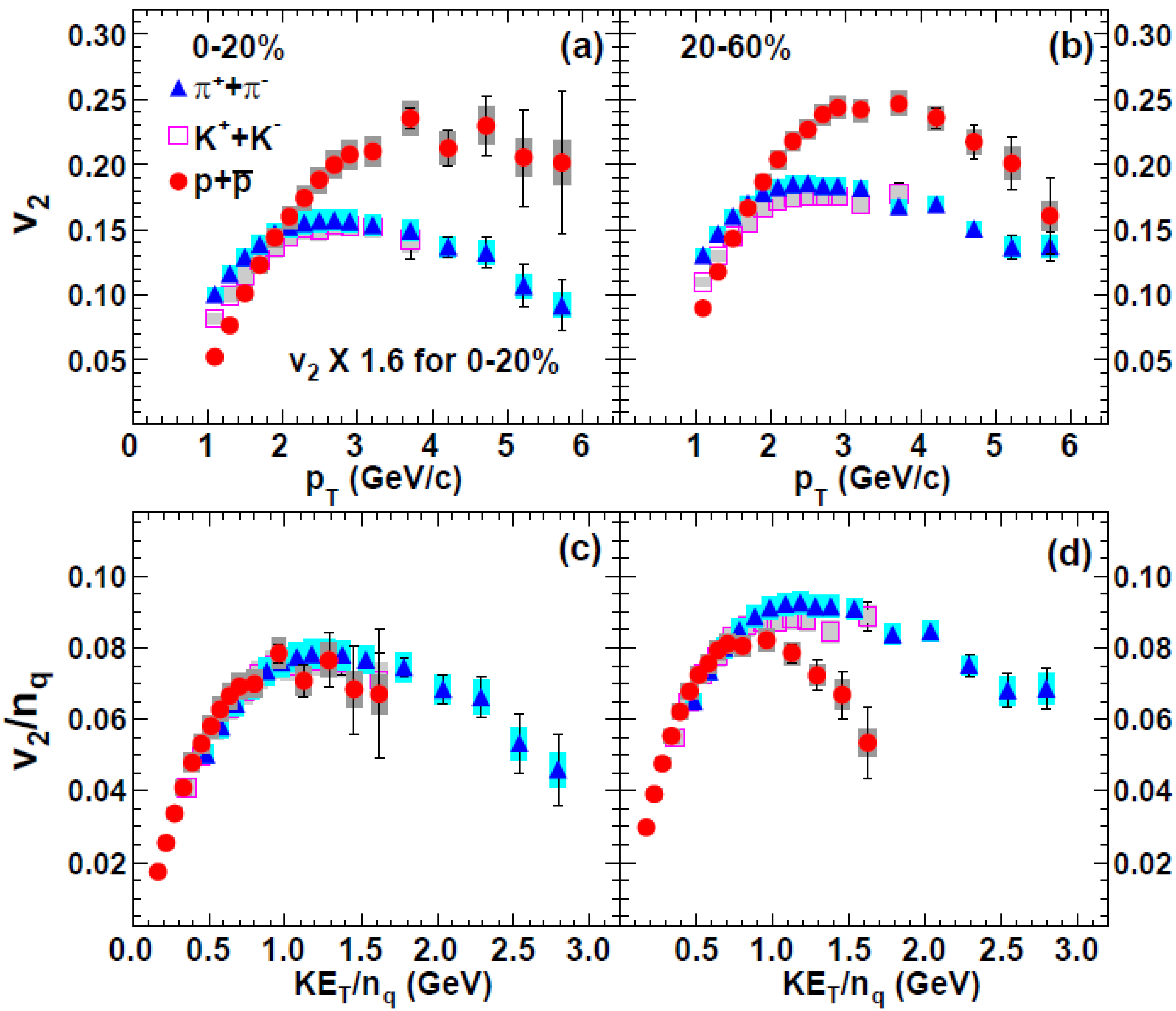


- v_2 is particle type dependent
- In higher p_T, the v_2 is saturated

- $v_{2,M}(p_T) \sim 2v_{2,q}(p_T/2)$
  $v_{2,B}(p_T) \sim 3v_{2,q}(p_T/3)$

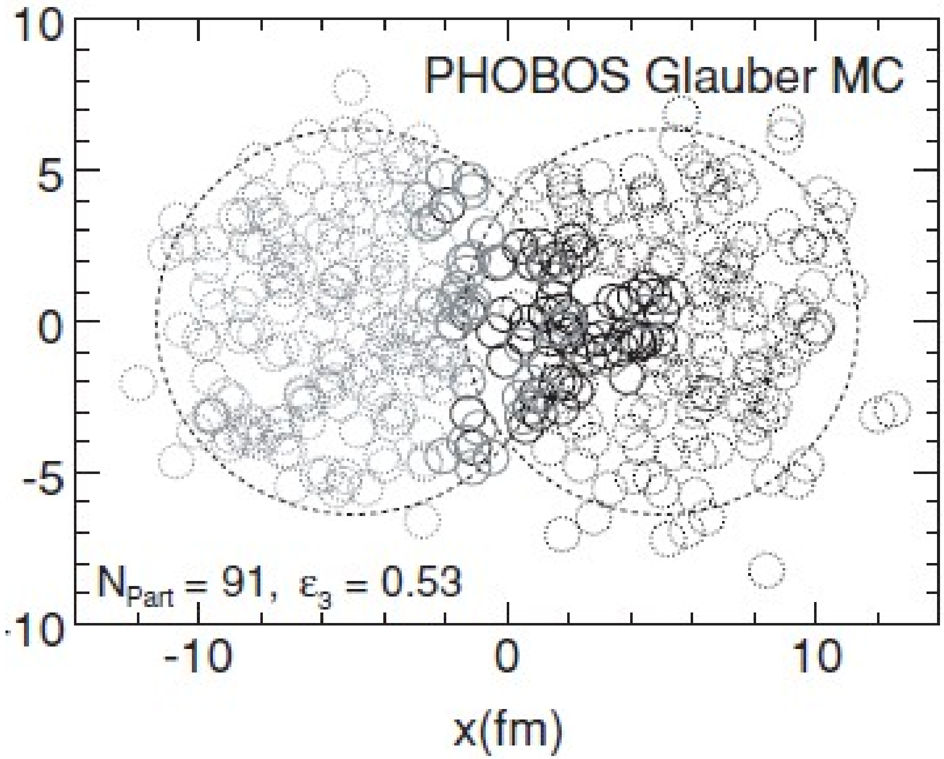
- The quarks have collective motion.

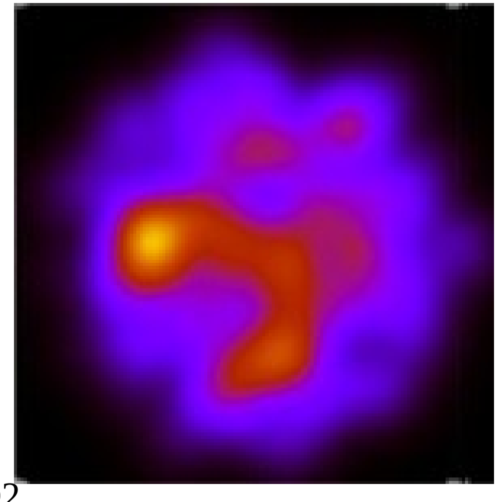
Moving to higher p_T



- Scaling breaks after 1GeV
- Different particle production mechanism
- High p_T → hard scattering

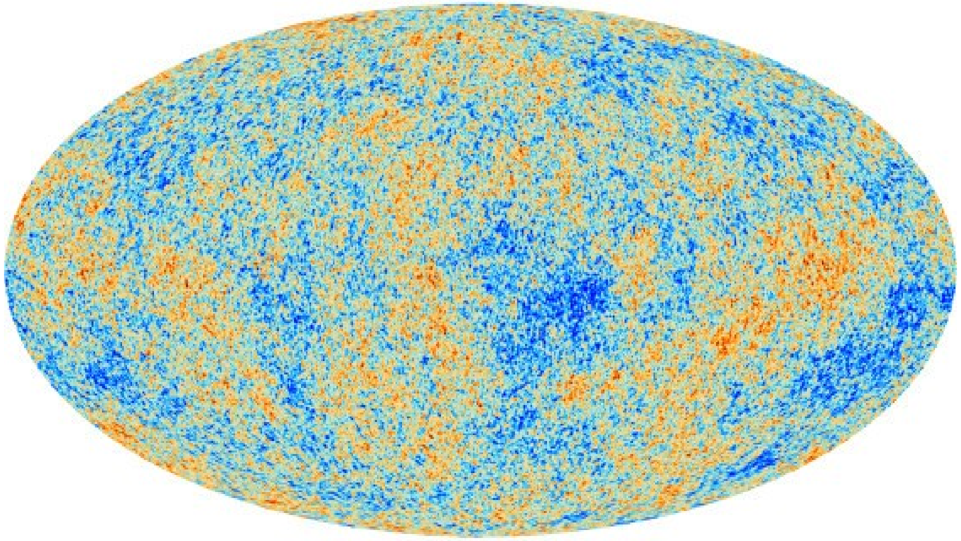
Measuring the shape fluctuations



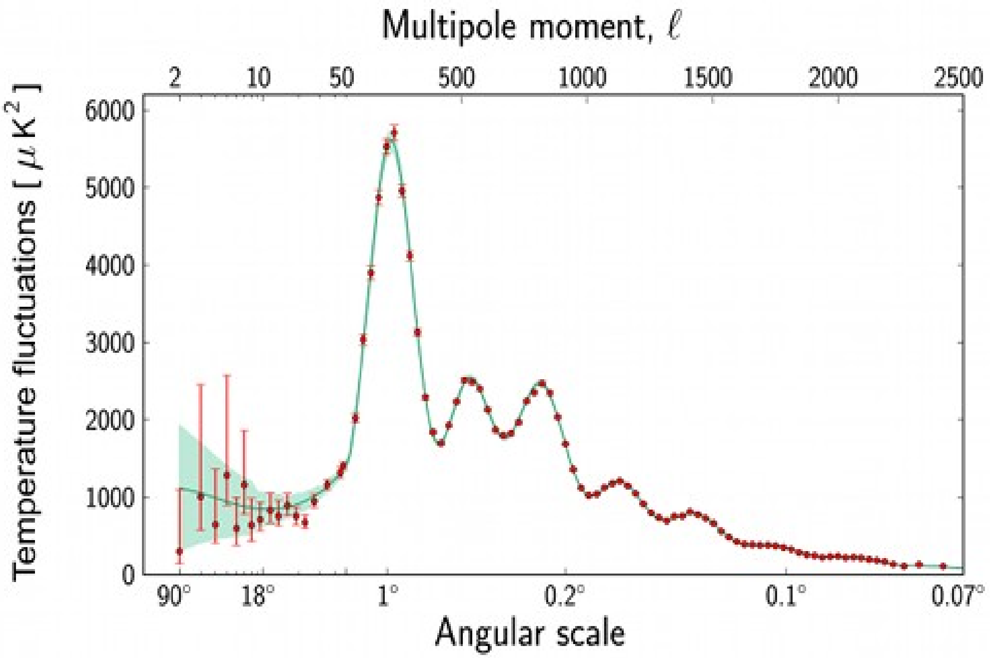


- The nucleus is not perfect in shape
- Nucleon distribution is not smooth
- Azimuthal symmetry of the colliding area no longer available
- v_{odd} is possible, due to shape fluctuations
- Measuring v_{odd}, effectively means measuring the fluctuations of the initial geometry
- More constraints to theory predictions!

Fluctuations in Cosmic Microwave Background



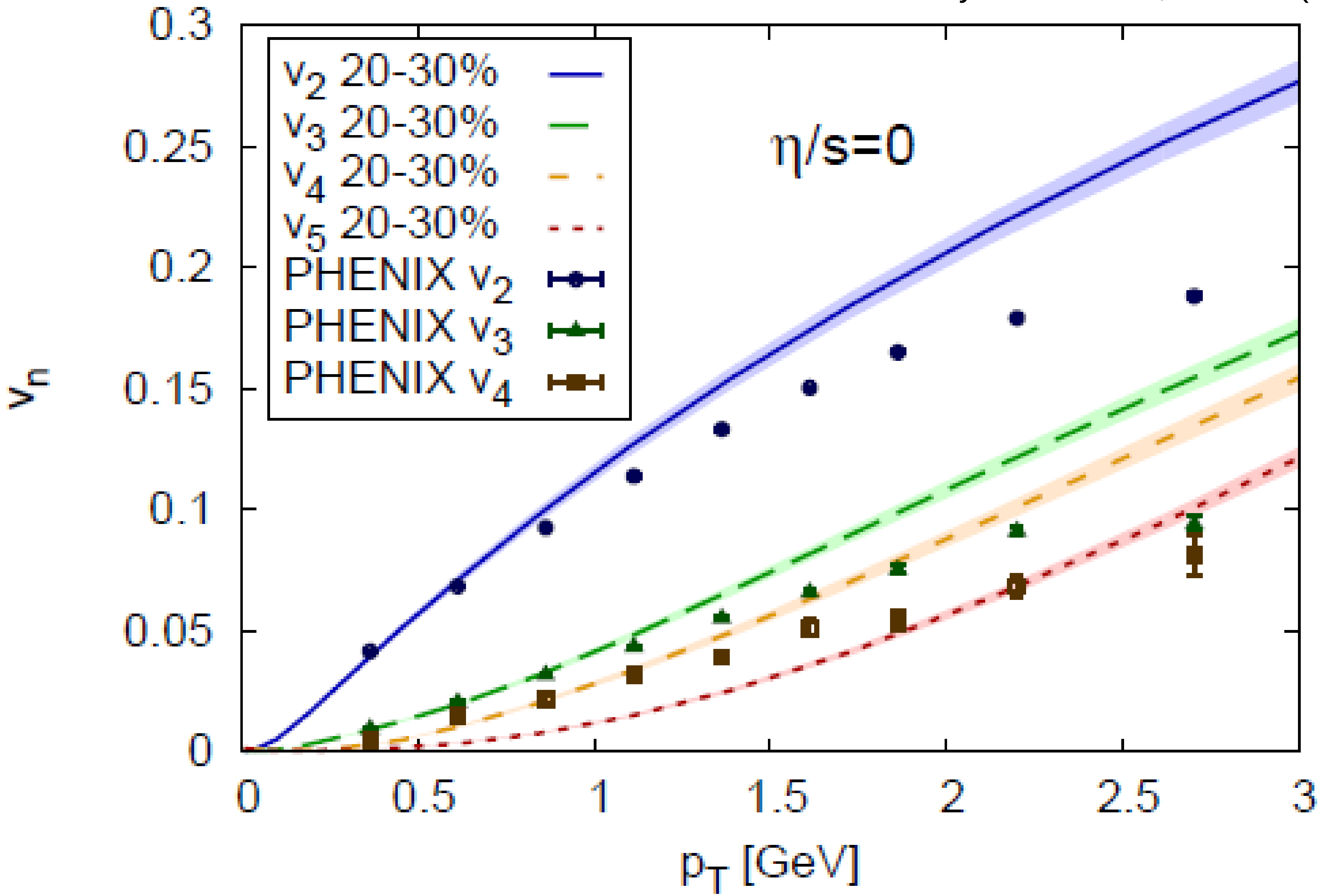
Measurement of CMB from Planck Satellite



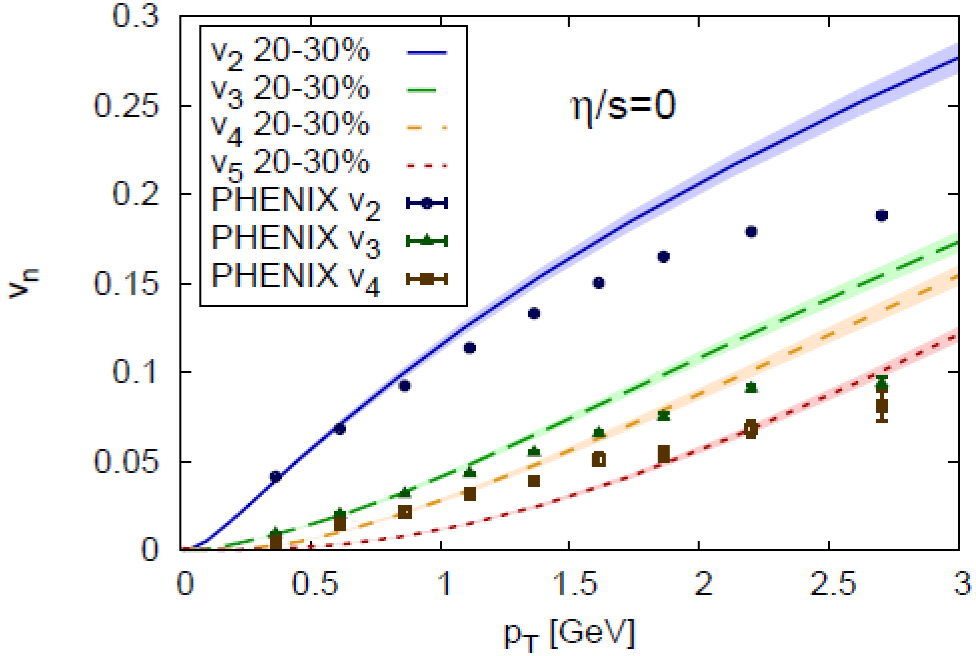
- Microwave background shows the tiny temperature fluctuations
- Multi-pole expansion shows the structure of the fluctuation distribution

v_2, v_3, v_4

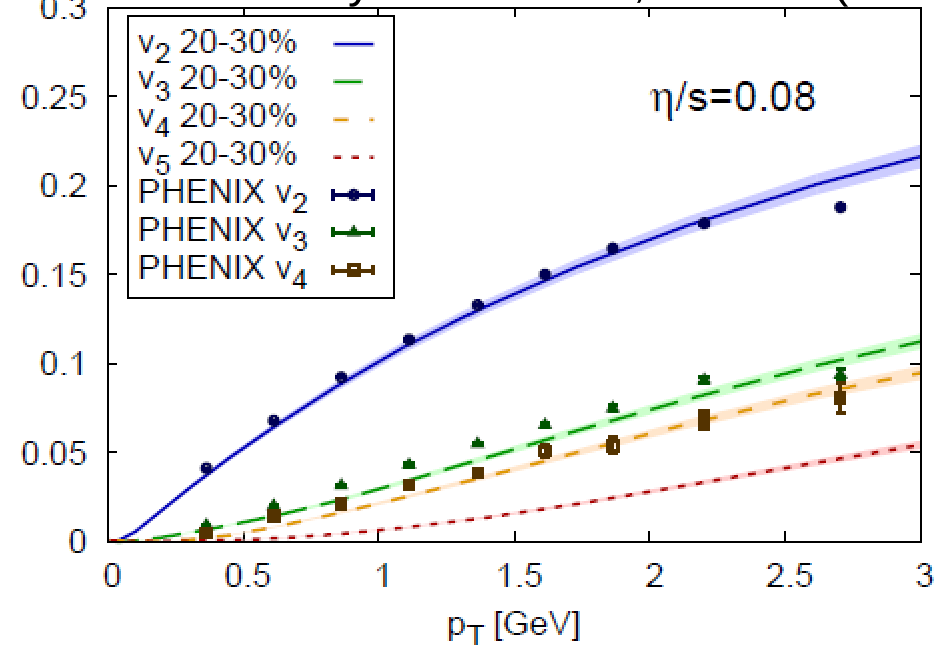
Phys. Rev. C **85**, 024901 (2012)

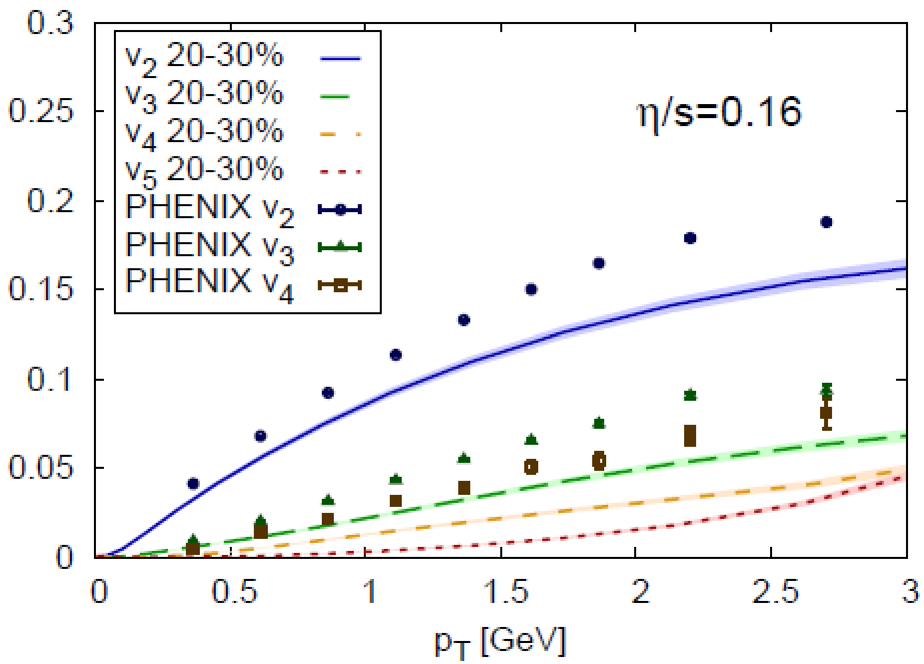


v_n vs viscosity



Phys. Rev. C **85**, 024901 (2012)





- Hydro + viscosity describes the data!
- $\eta/s = 1/4\pi$
- Universal lower bound from AdS/CFT

v_n and c_n

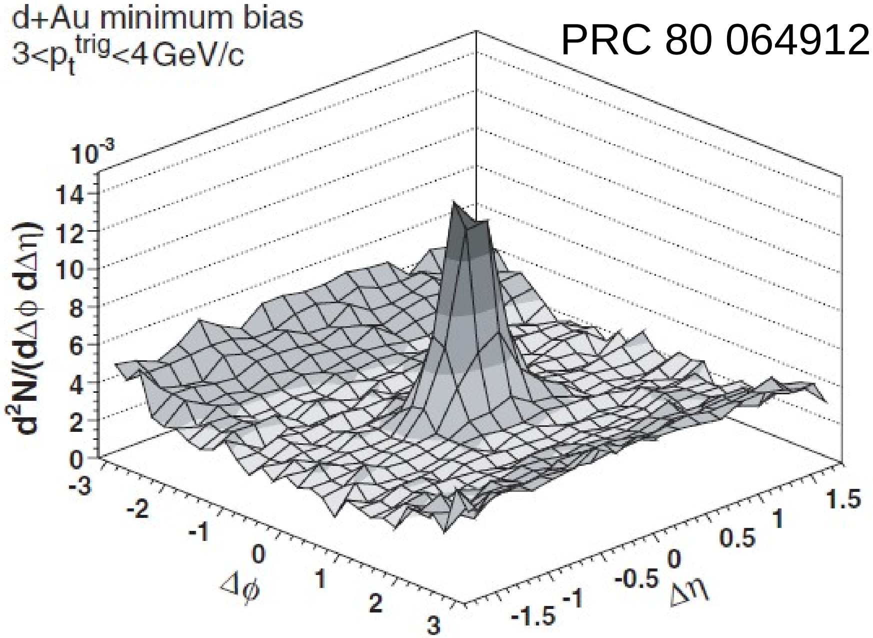
- Measuring the flow coefficient with event plane method
  - $dN/d\phi \propto 1 + \Sigma(2v_n * \cos(n(\phi-\Psi_n)))$
  - $v_n = \langle \exp(in(\phi-\Psi_n)) \rangle$
- Measuring the flow coefficient with two particle angular correlations
  - $\langle \exp(in(\phi_1 - \phi_2)) \rangle$

    $= \langle \exp(in(\phi_1 - \Psi_n + \Psi_n - \phi_2)) \rangle$

    $= \langle \exp(in(\phi_1 - \Psi_n) \rangle \langle \exp(-in(\phi_2 - \Psi_n)) \rangle$

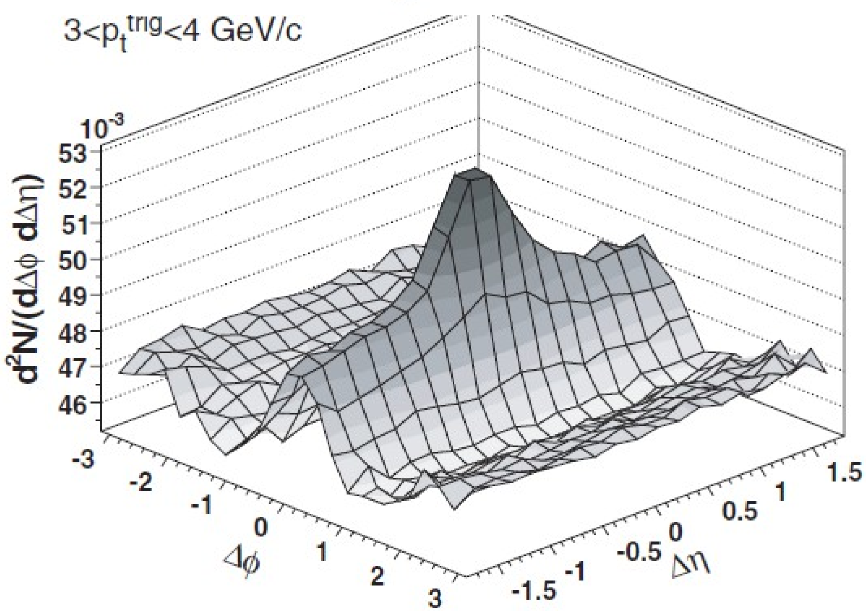
    $= v_n^1 * v_n^2$

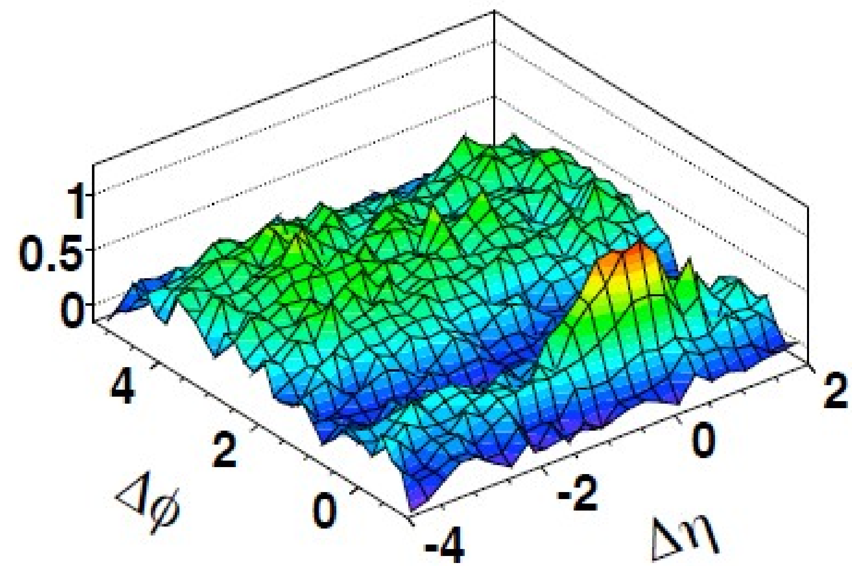
    $= c_n$



PRC 80 064912

Ridge: Sum of c_n





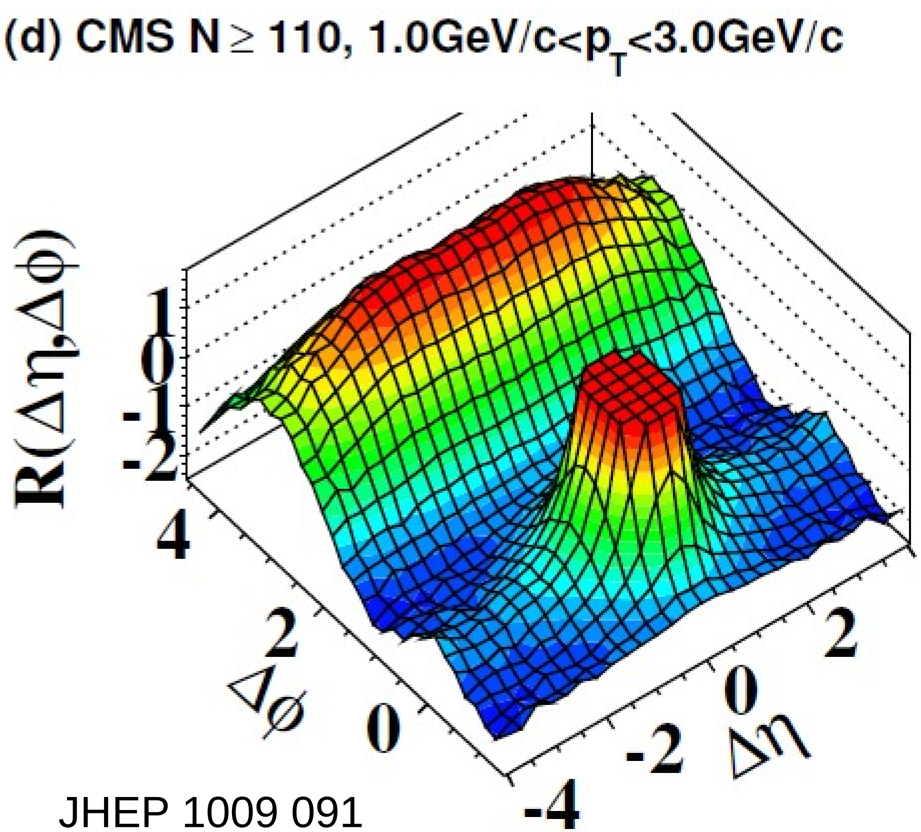
(b) Au+Au 0-30% (PHOBOS)

PRL 104 062301

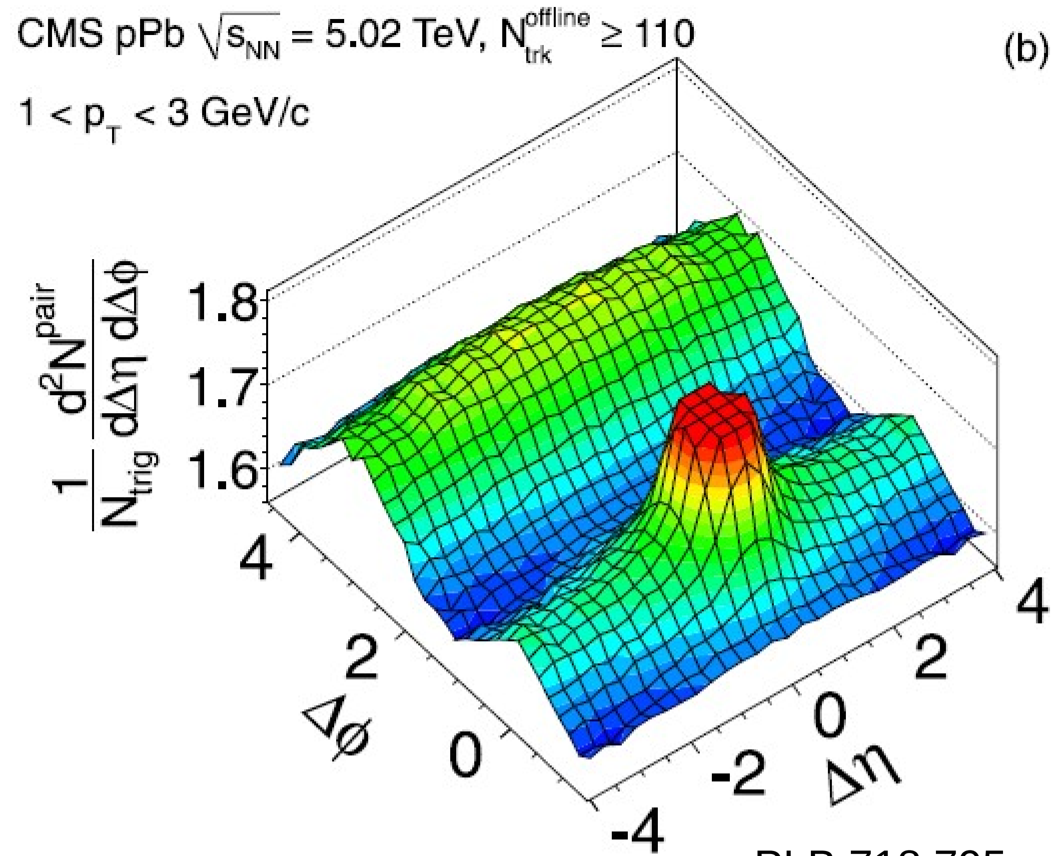
- Ridge (nearside long range correlation) appears in central Au+Au collisions, and extend to $|\Delta\eta| \sim 4$
- This structure is believed due to collective flow

Ridge at LHC

pp@7 TeV



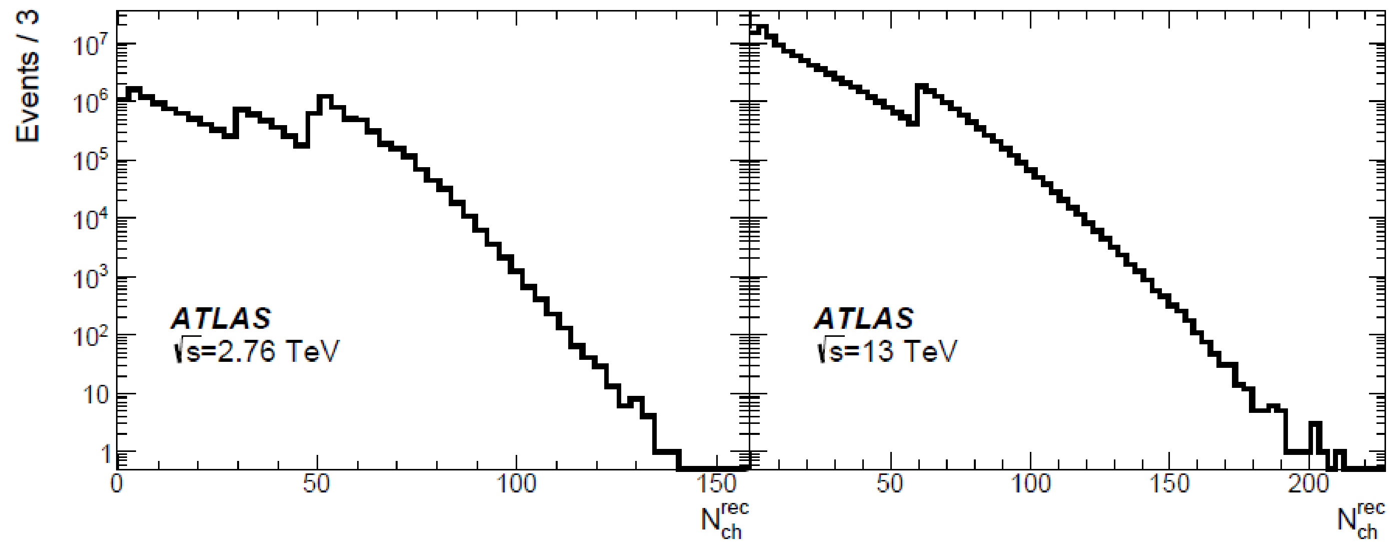
JHEP 1009 091



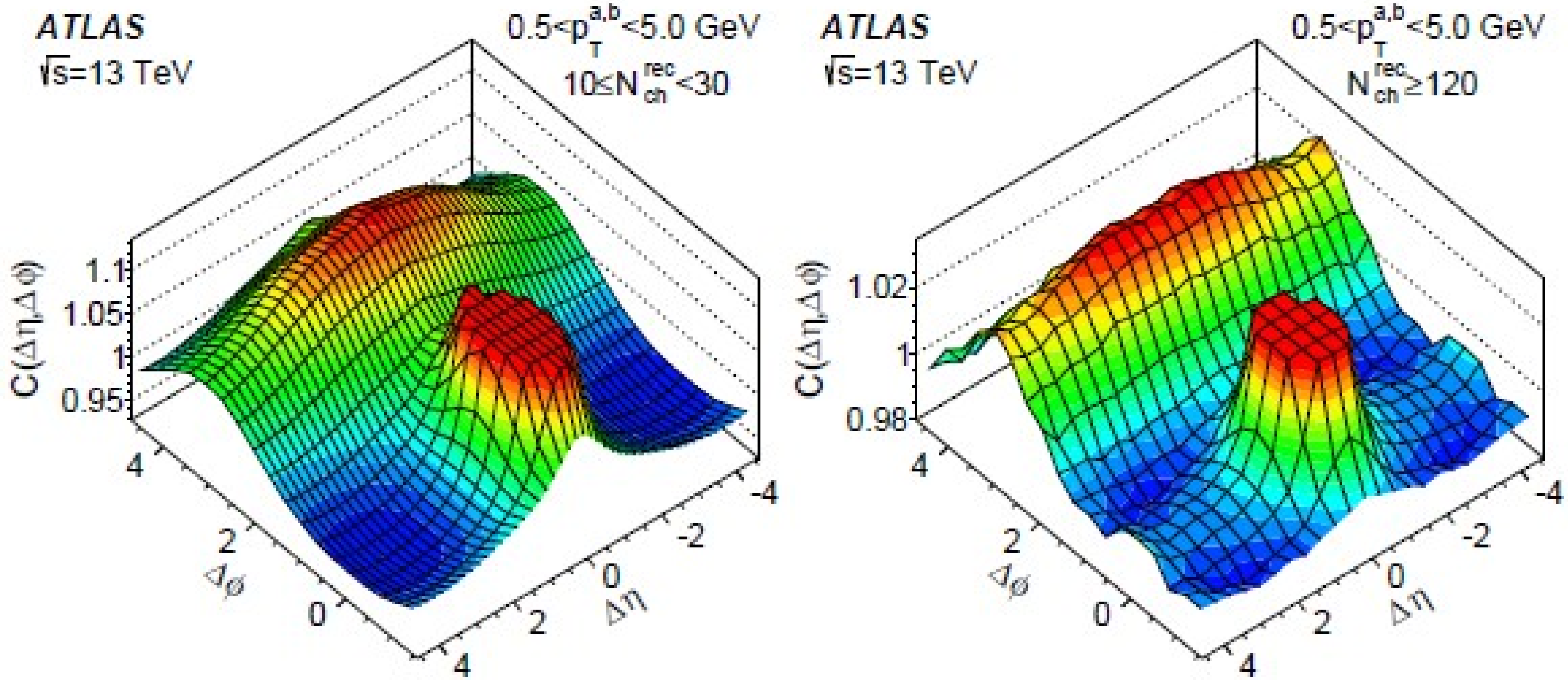
PLB 718 795

- Ridge appears at high multiplicity pp/pPb collisions
- Collective motion in pp/pPb?
- Something in common between pp/pPb/PbPb?

High multiplicity events in pp are rare!

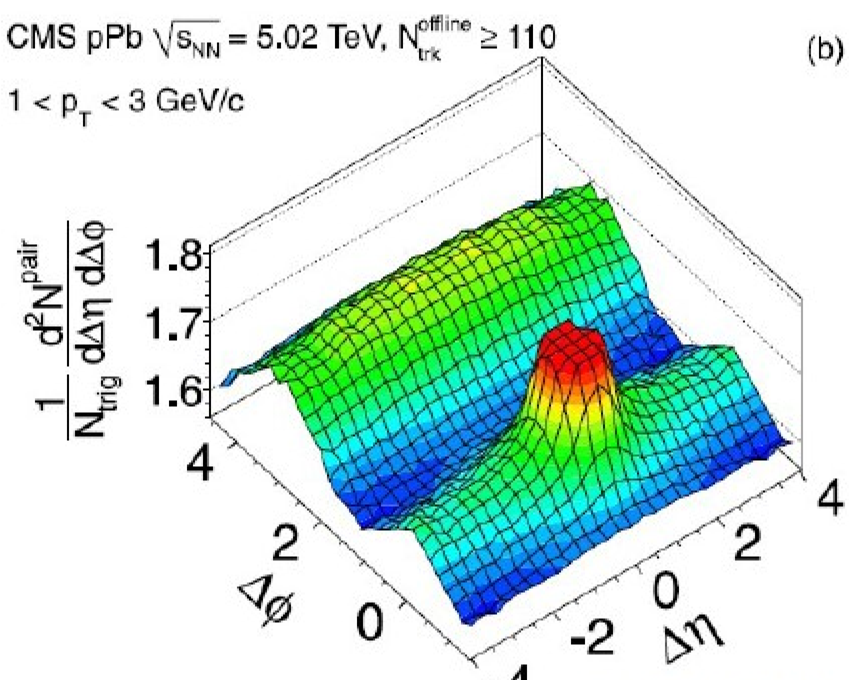


PRL 116 172301 (2016)

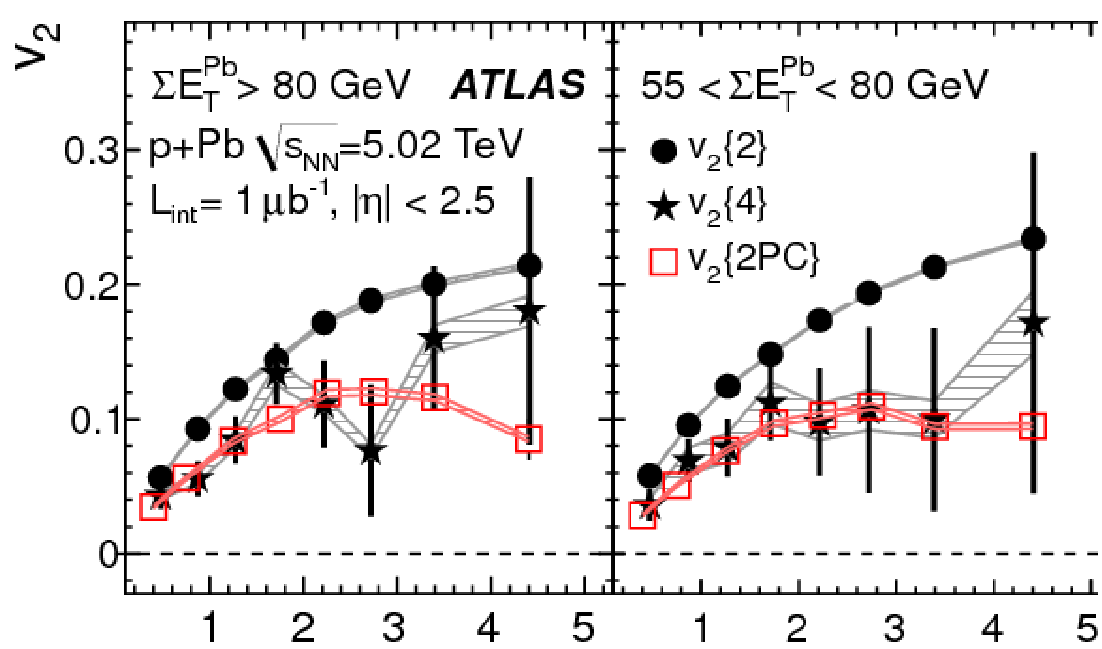


Tiny Bang in p+Pb?

- In p+Pb collisions in LHC, some collective flow like structure are shown, how about RHIC?

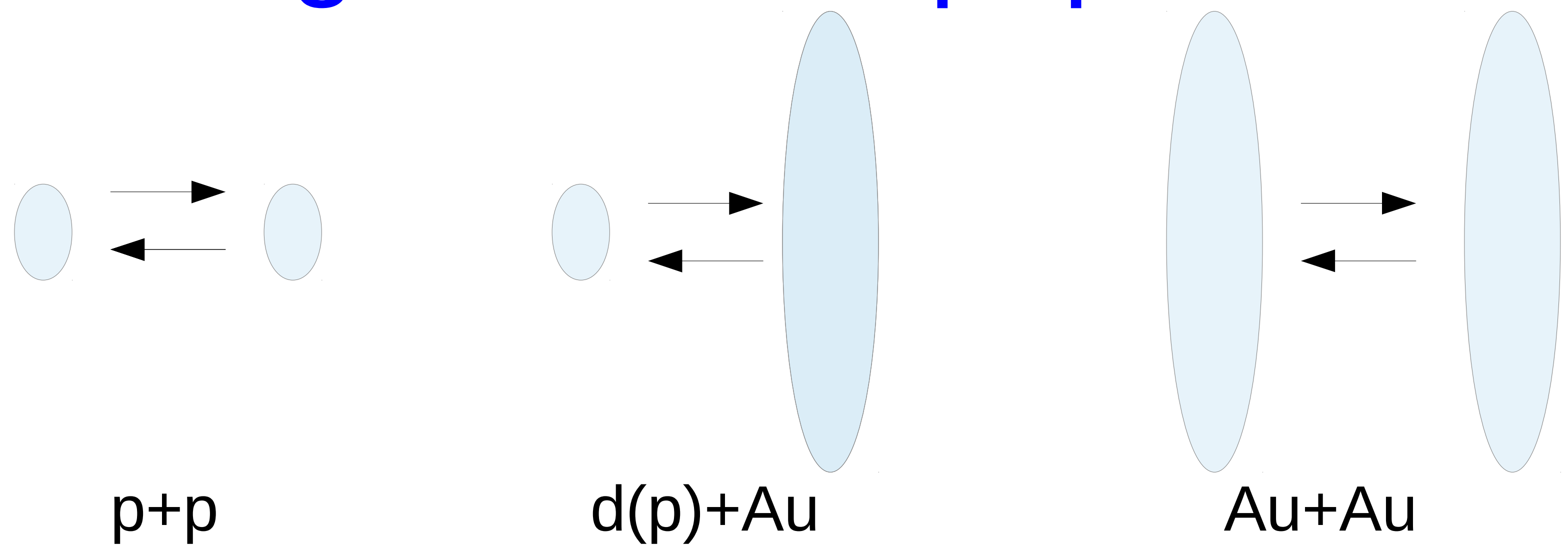


PLB 718 795



PLB 725 060

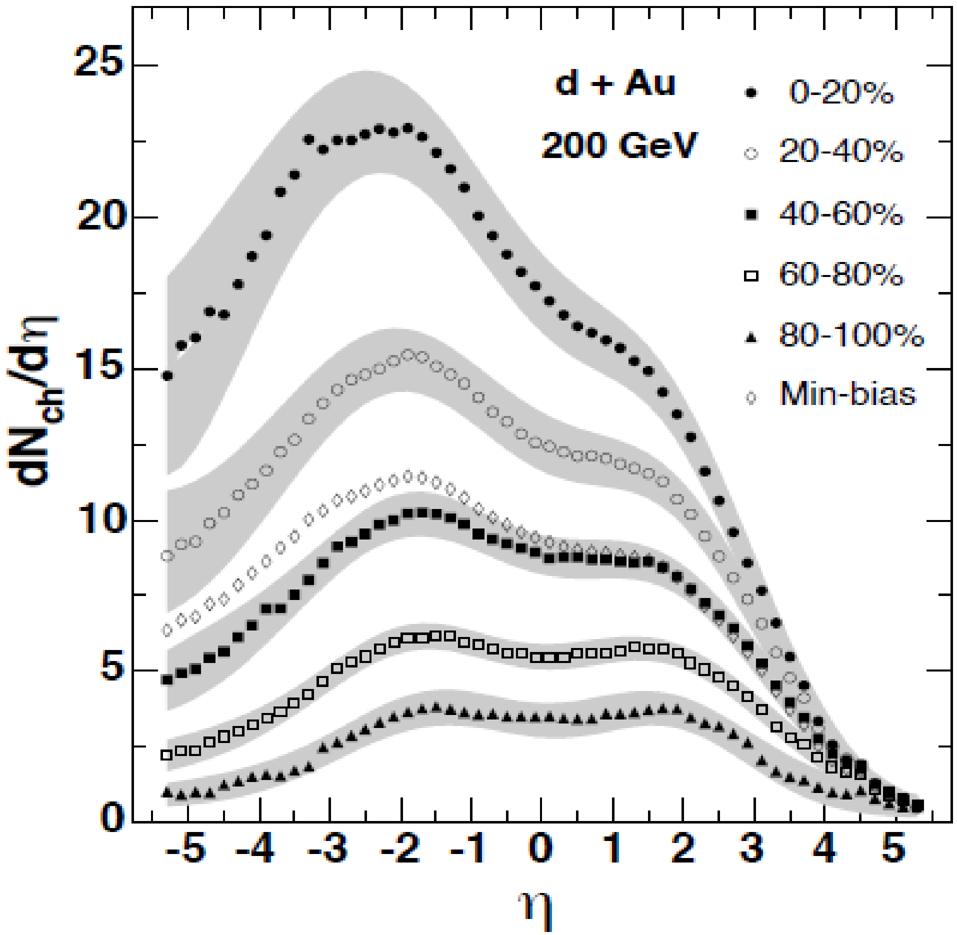
d+Au: bridge between p+p and Au+Au



- p+p: baseline reference
- d+Au: baseline reference, cold nuclear effect
- Au+Au: hot nuclear effect

- Is d+Au really just a reference?
- Do we create something hot in this tiny system?

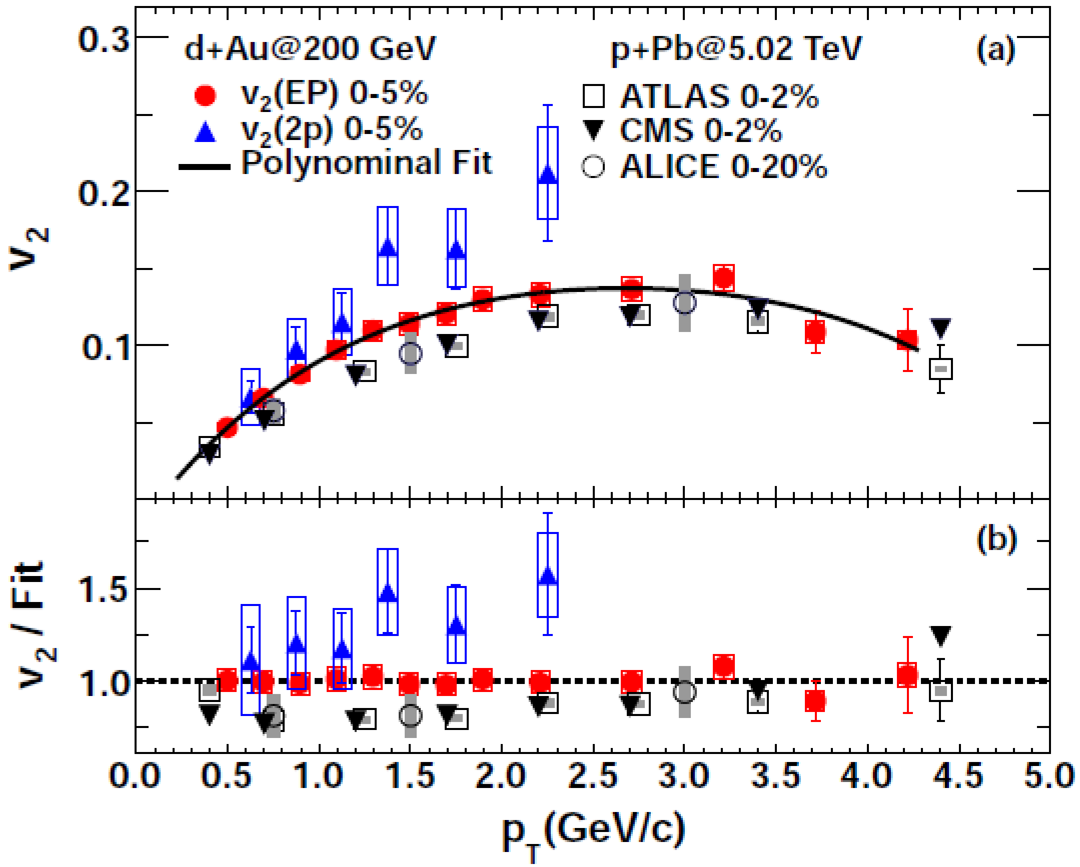
Central-forward (backward) correlation



PRC 72 031901

- The multiplicity distributions in d+Au collisions are asymmetric
- Measure the two-particle correlations of one particle at mid-rapidity (with central arm spectrometer, |η|<0.35) and another particle at forward calorimeter (with Muon Piston Calorimeter, 3.1<|η|<3.9)

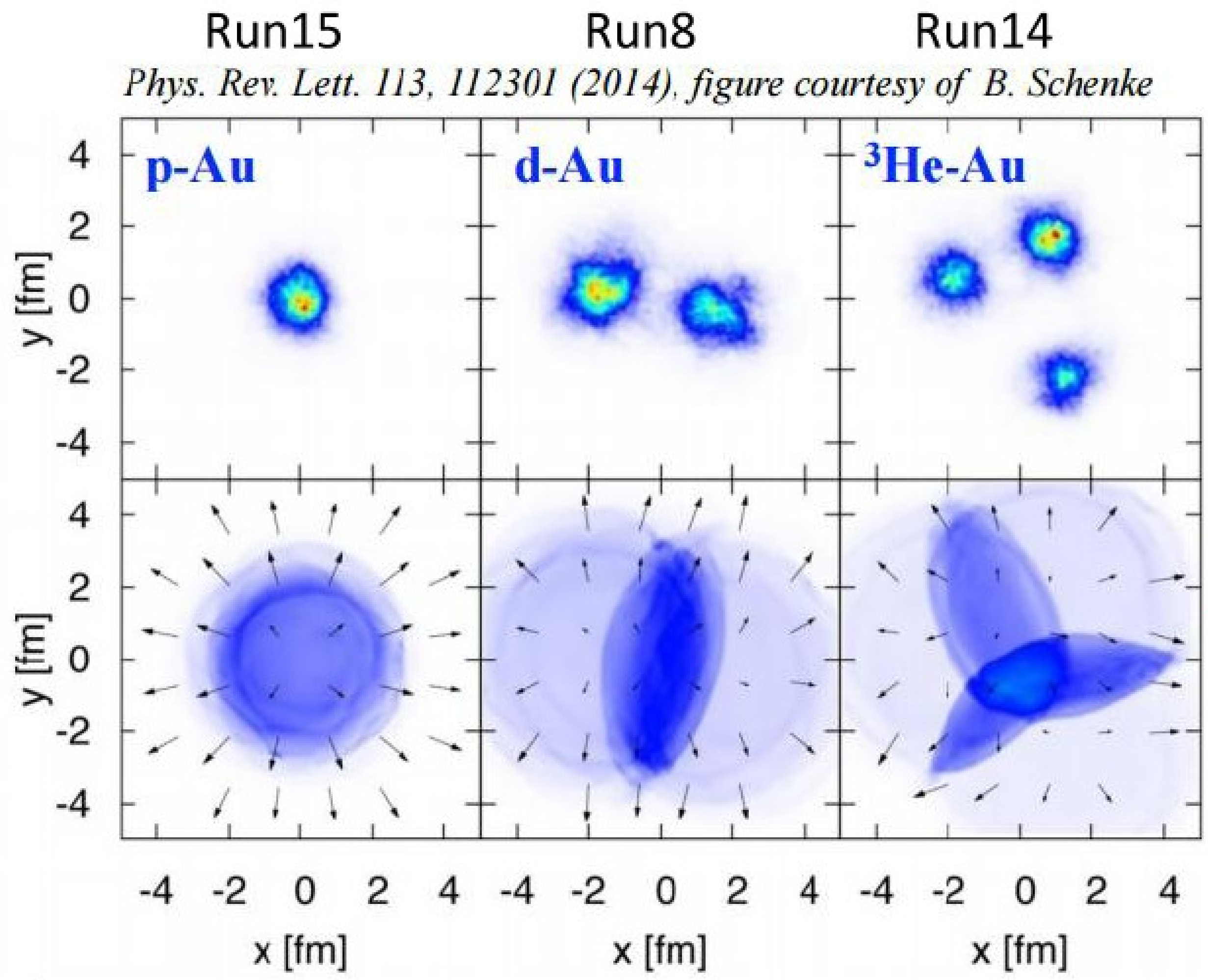
Charged hadron v_2 in d+Au



PRL 114 192301
Editor's Suggestion

- Substantial amount of flow in dAu
- Similar behavior between RHIC and LHC

As easy as 1, 2, 3



- p+Au,
  d+Au,
  ^{3}He+Au
- Use central collisions to probe the initial state geometry
- From initial state geometry to final state anisotropy

TABLE I. Monte Carlo Glauber characterization results.

System	N_{part}	N_{coll}	ε_2	ε_3
0%–5% ^{3}He+Au	25.0±1.6	26.1±2.0	0.50±0.02	0.28±0.02
0%–5% d+Au	17.3±1.2	18.1±1.2	0.54±0.04	0.19±0.01

Phys. Rev. Lett. 115, 142301 (2015)

v_2 and v_3 of ^{3}He+Au

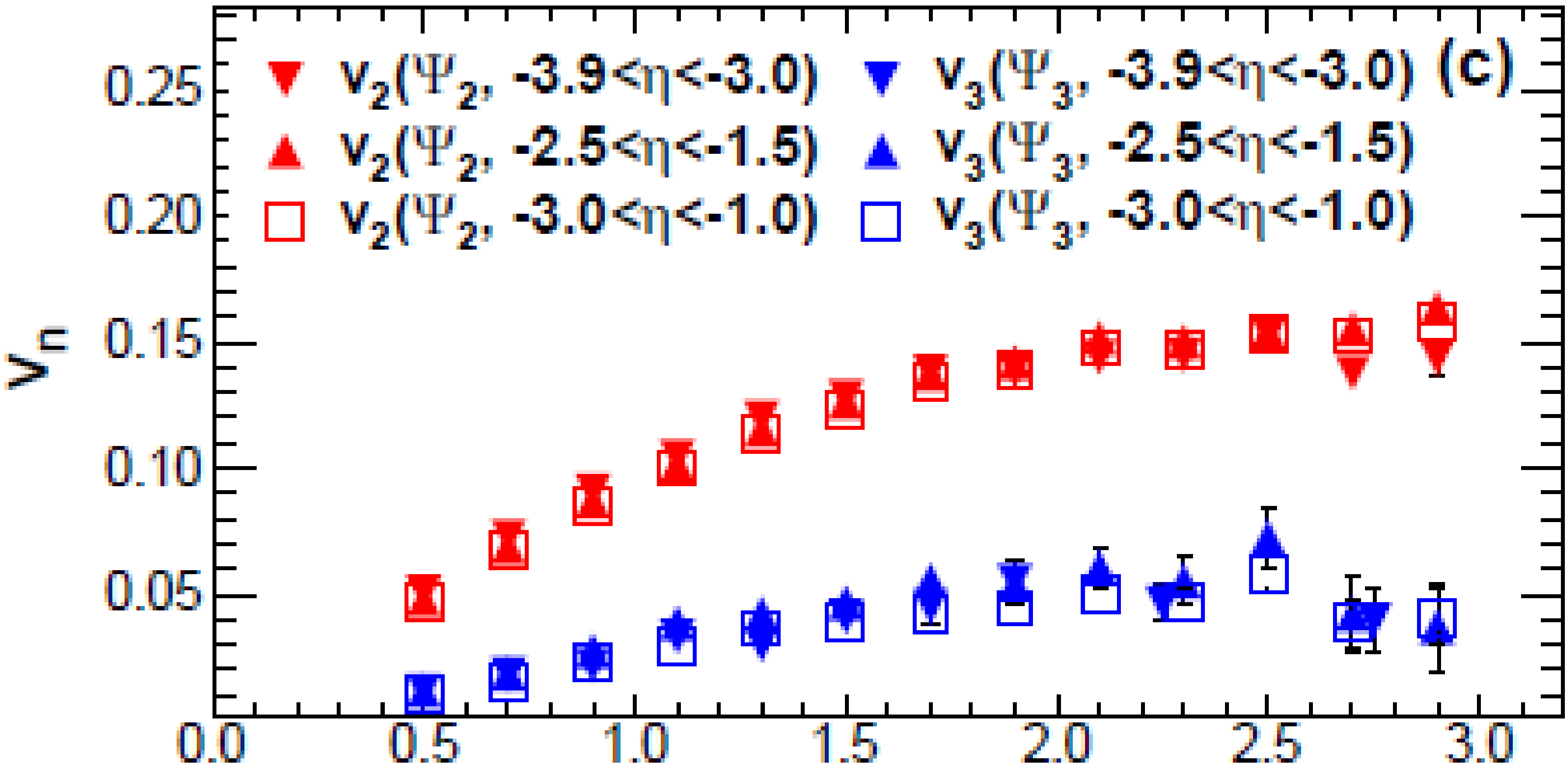
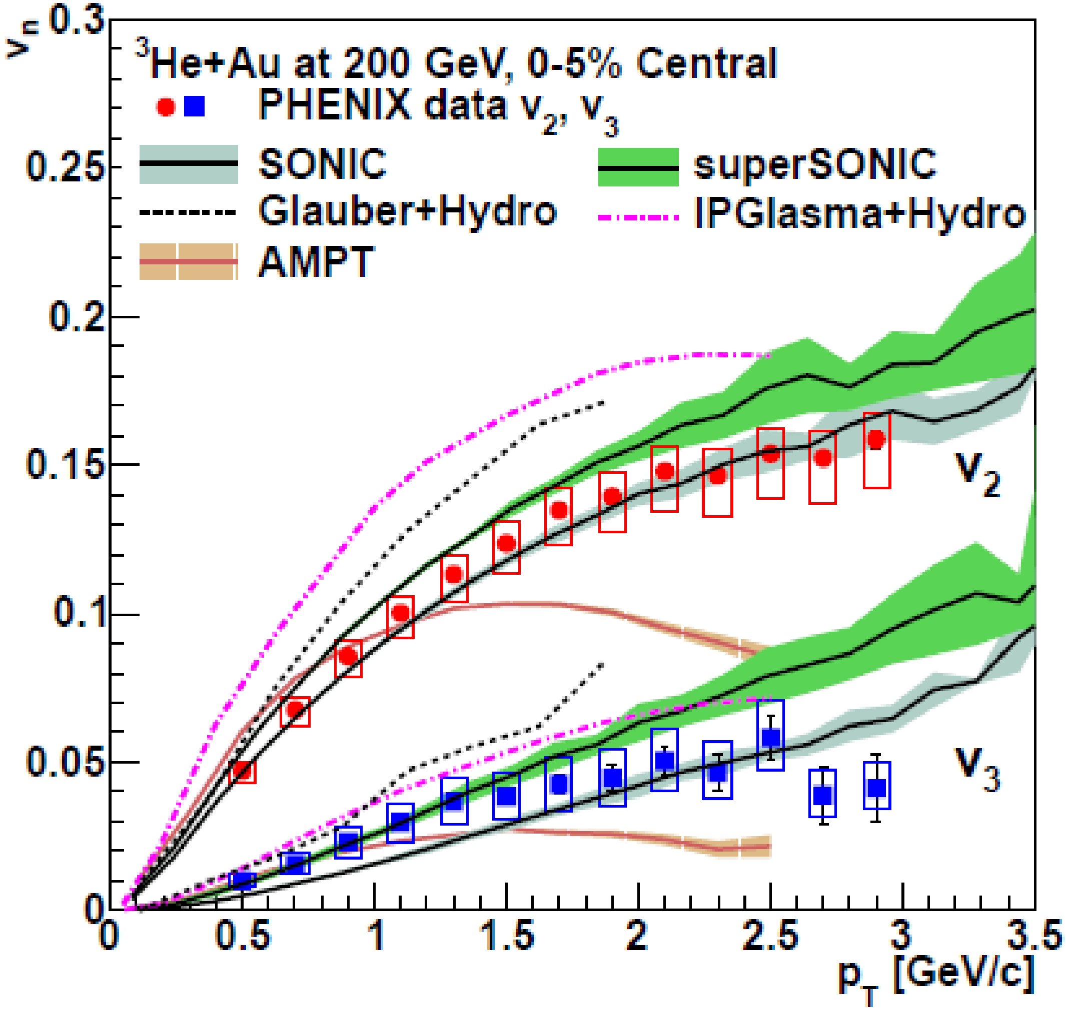


TABLE I. Monte Carlo Glauber characterization results.

System	N_{part}	N_{coll}	ε_2	ε_3
0%–5% ^{3}He+Au	25.0±1.6	26.1±2.0	0.50±0.02	0.28±0.02
0%–5% d+Au	17.3±1.2	18.1±1.2	0.54±0.04	0.19±0.01

Substantial v_2 and v_3!

Hydrodynamics still works in small system



v_2 in various small systems

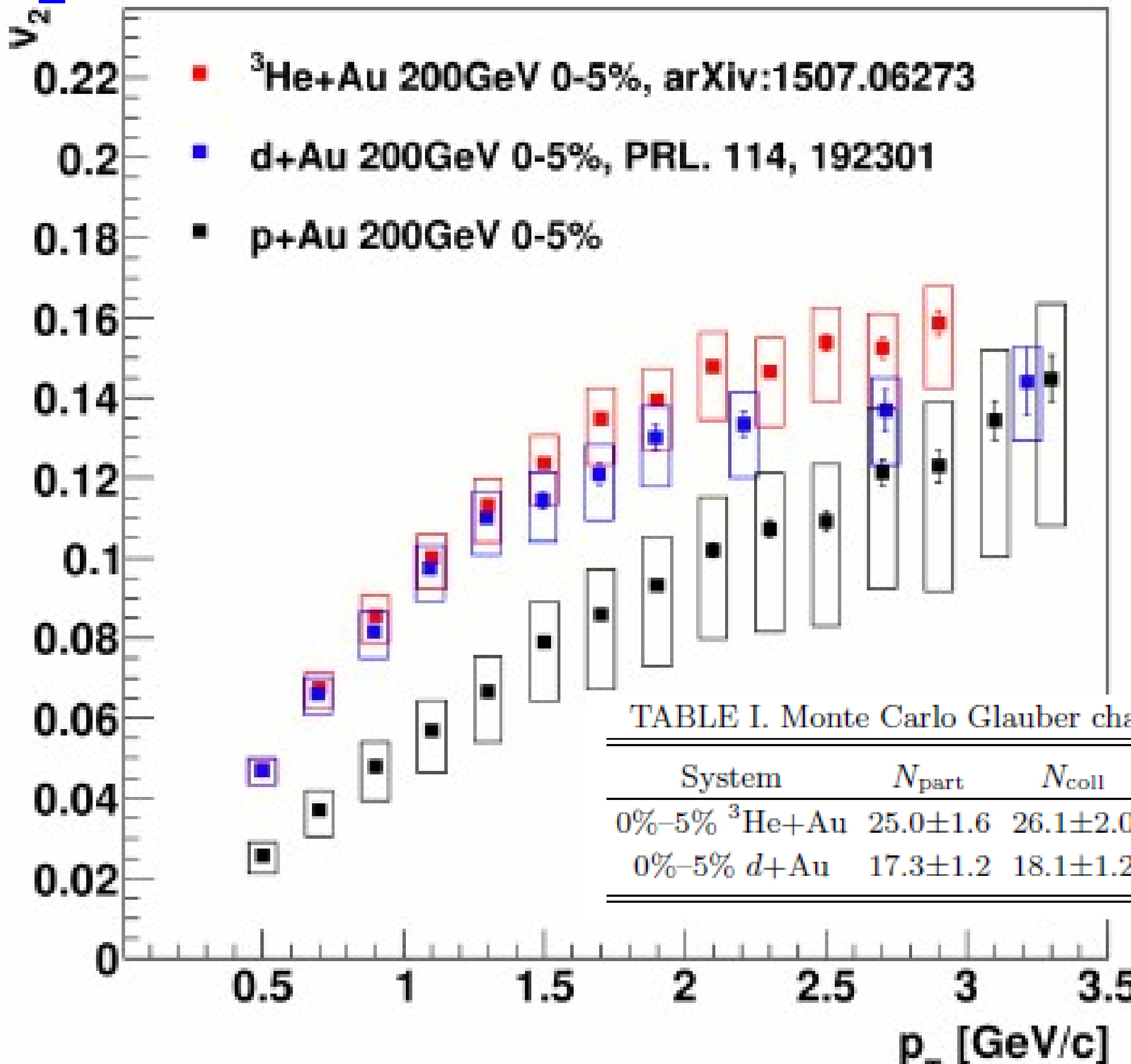


TABLE I. Monte Carlo Glauber characterization results.

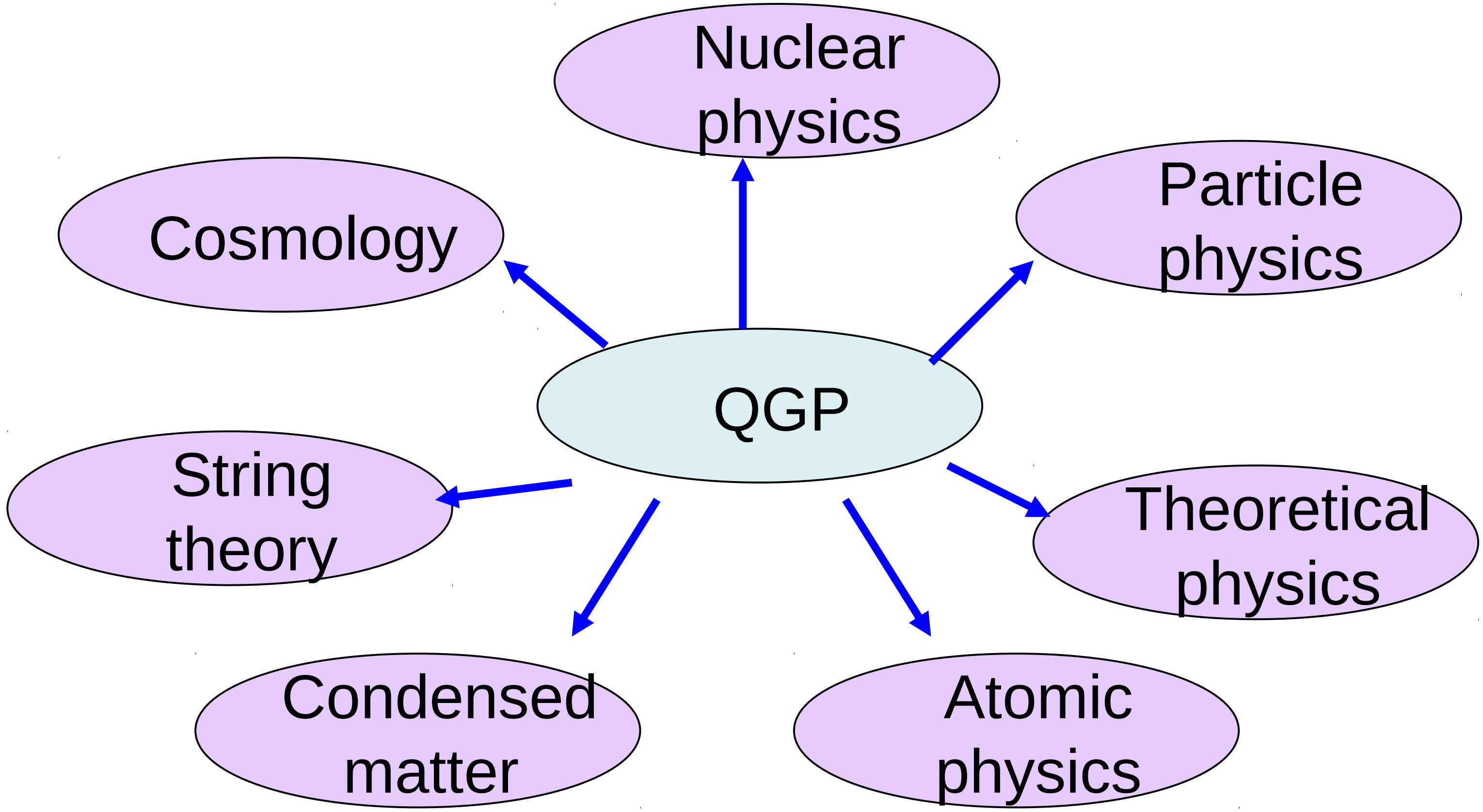
System	$N_{\rm part}$	$N_{\rm coll}$	ε_2	ε_3
0%–5% ^{3}He+Au	25.0±1.6	26.1±2.0	0.50±0.02	0.28±0.02
0%–5% d+Au	17.3±1.2	18.1±1.2	0.54±0.04	0.19±0.01

- $v_2(^3\text{HeAu}) \sim v_2(\text{dAu}) > v_2(\text{pAu})$

Summary

- Collective flow in QGP
- Quark flows
- Even small system flows, and still follows hydrodynamics

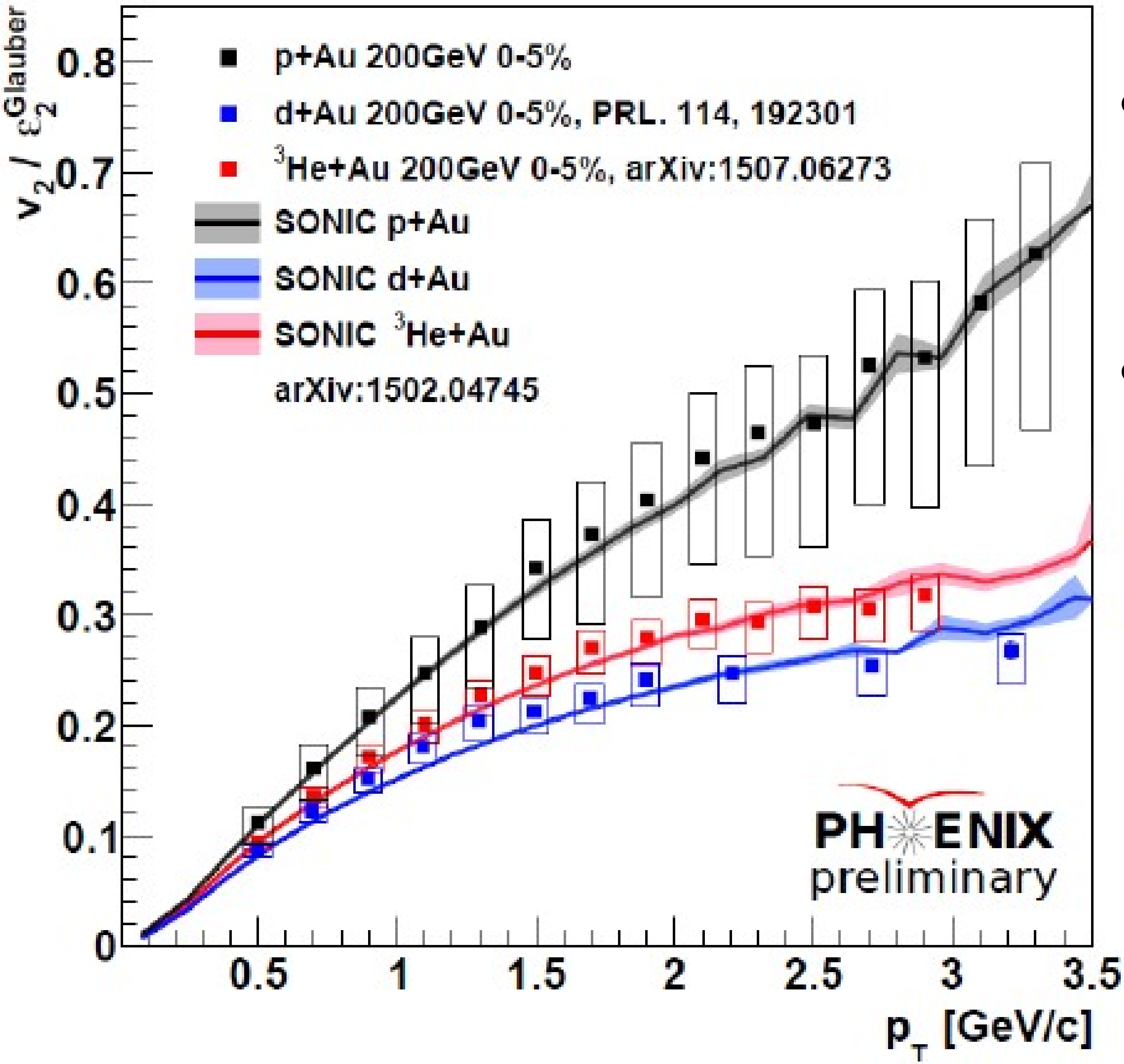
Connection with other area of physics



QGP is highly active!!

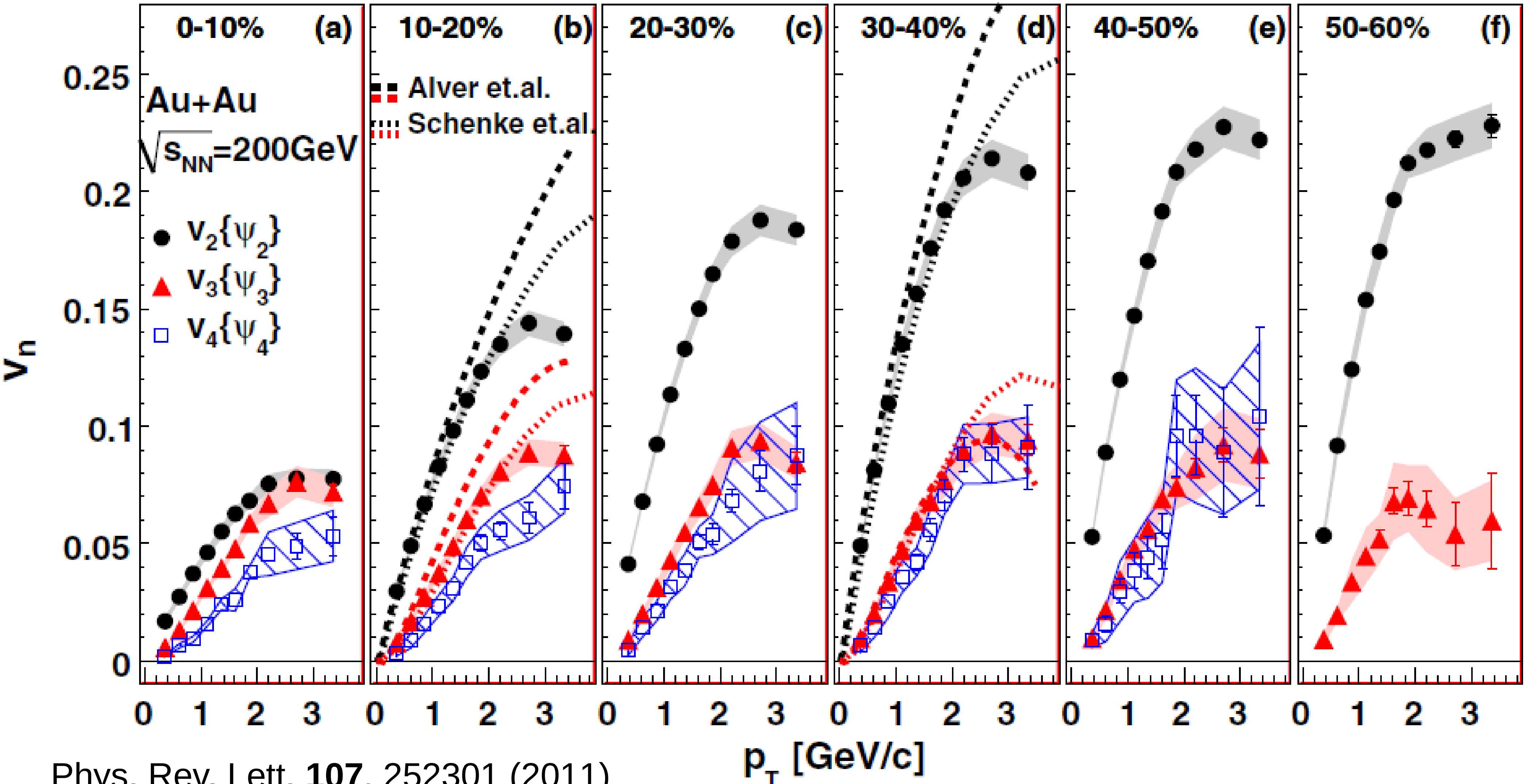
Backup slides

v_2/ε_2



- Data well described by SONIC
- SONIC: Glauber initial state + viscous hydro

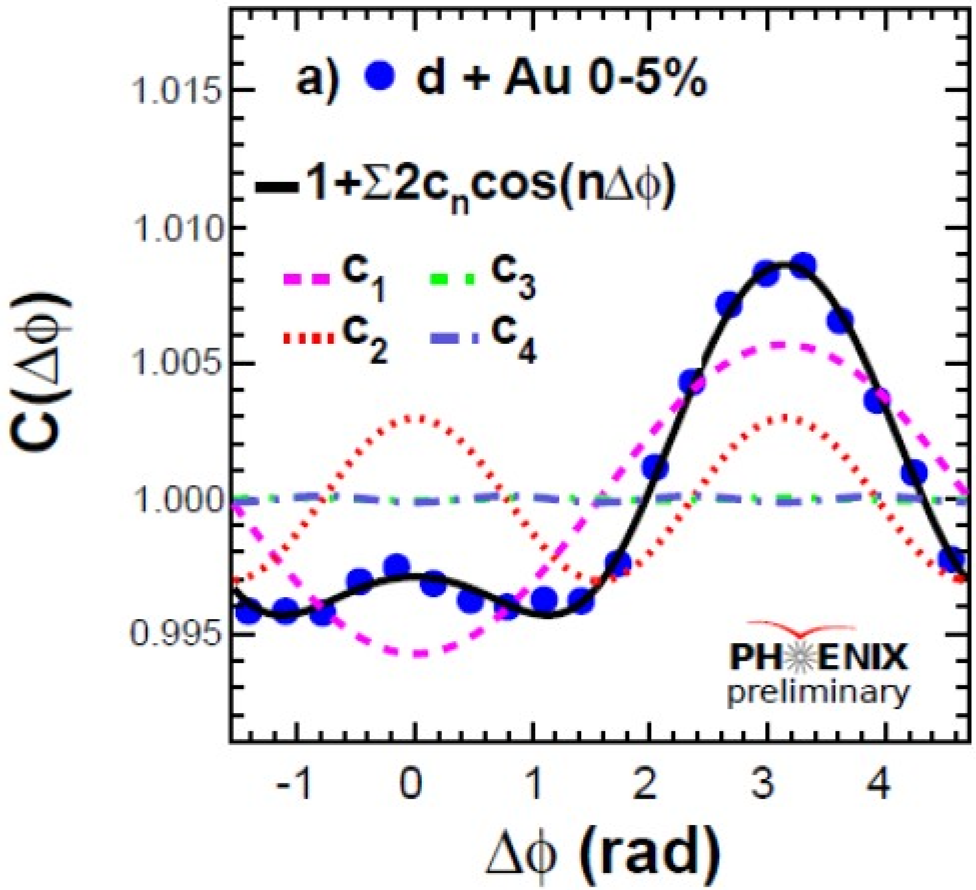
$v_n(\Phi_n)$ vs p_T



Phys. Rev. Lett. **107**, 252301 (2011)

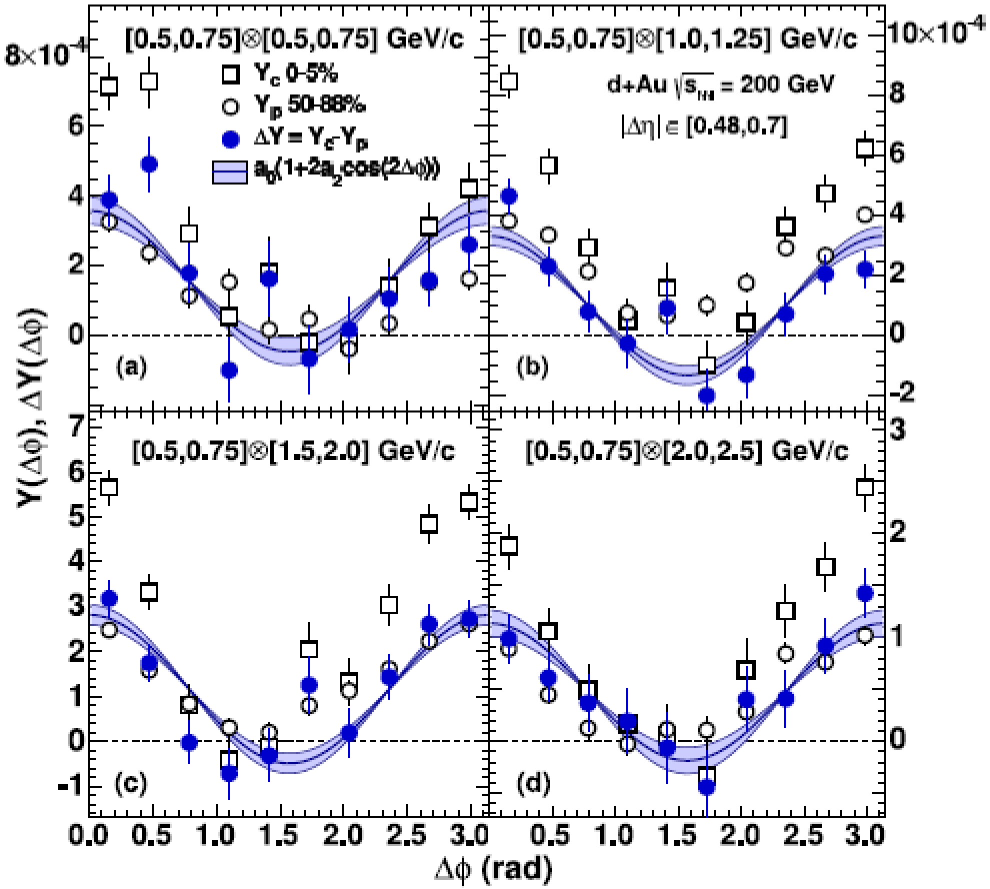
- All v_n increases with p_T
- v_3 is independent from centrality

Ridge in d+Au at $|\Delta\eta| > 6$



By correlating clusters in both muon piston calorimeter (MPC), $3.1<|\eta|<3.9$, the long range correlation at $\Delta\phi \sim 0$ is still preserved

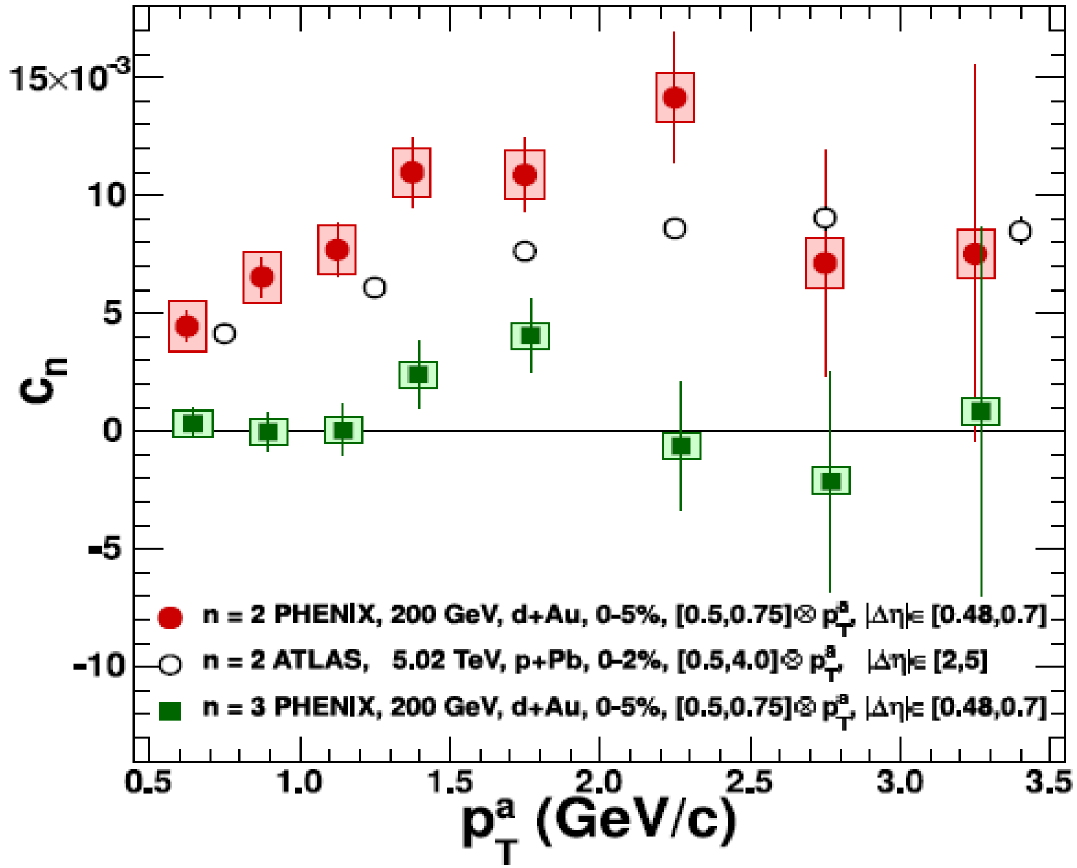
CF in central d+Au collisions



PRL 111 212301 (2013)

- 0.48<|Δη|<0.7
- Use ZYAM to subtract the underlying background
- The per trigger yield correlation in 0-5% d+Au collisions is larger than d+Au 50-88%
- After subtracting 50-88%, the remaining correlation function has a v_2-like ($\cos 2\Delta\phi$) shape

c_2 (c_3) vs p_T



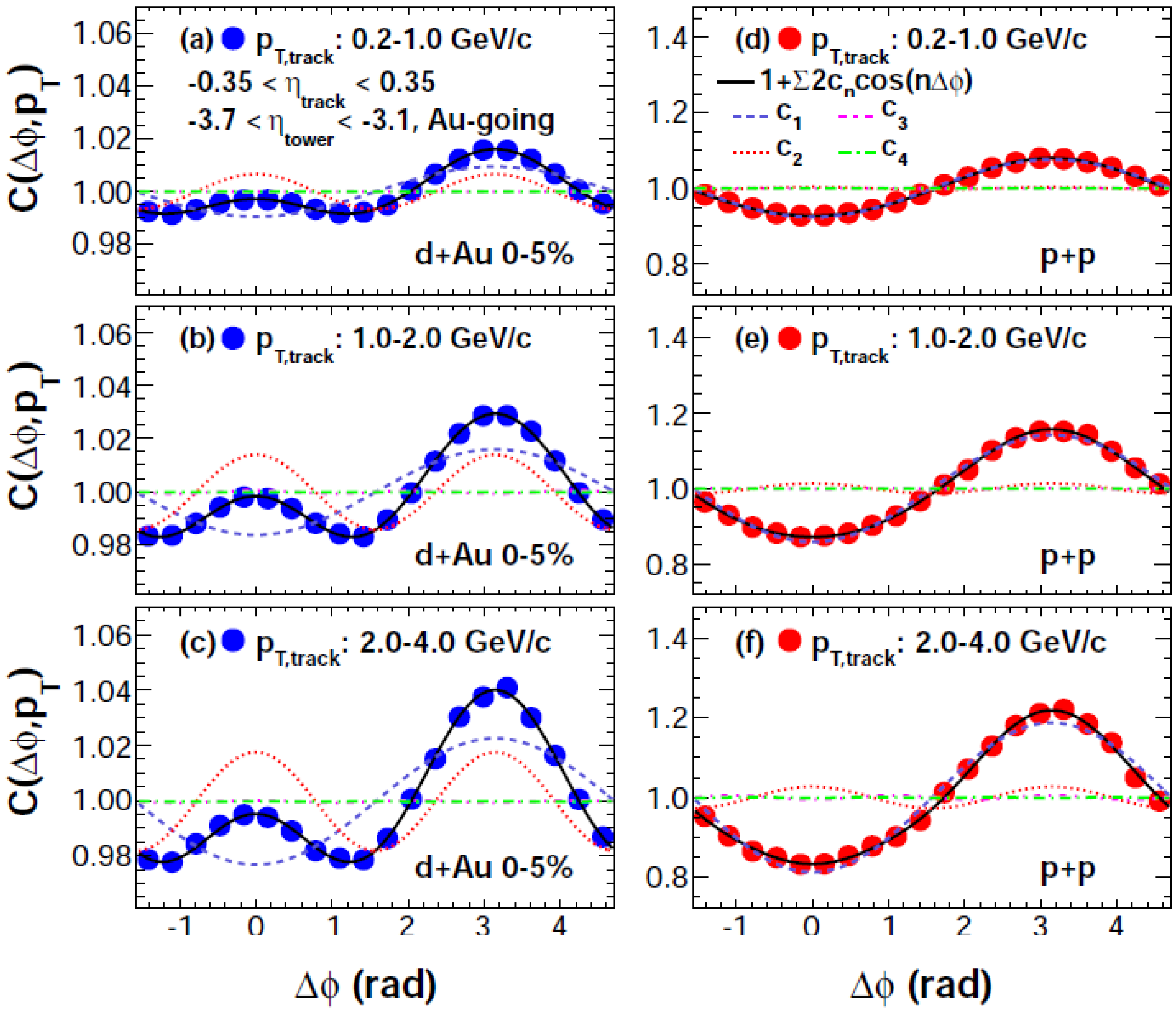
PRL 111 212301 (2013)

- $c_n = v_n^A * v_n^B$
- Significant c_2, and c_2 increases with p_T
- c_3 is consistent with 0, basically no c_3 (or v_3) contribution in d+Au!

The Idea of Quark-Gluon Plasma

- Typical nucleon energy density (energy inside the nucleon) is about 0.13 GeV/fm^3.
- Higher temperature → higher energy density → create more new particles (by $E = mc^2$)
- When the energy density exceeds 1GeV/fm^3, many new particles are made → packed close together
- Matter will exist not as hadrons (protons, neutrons…), but as independent quarks and gluons.
- In this medium, the quarks and gluons are deconfined.
- It is called "Quark–Gluon Plasma "

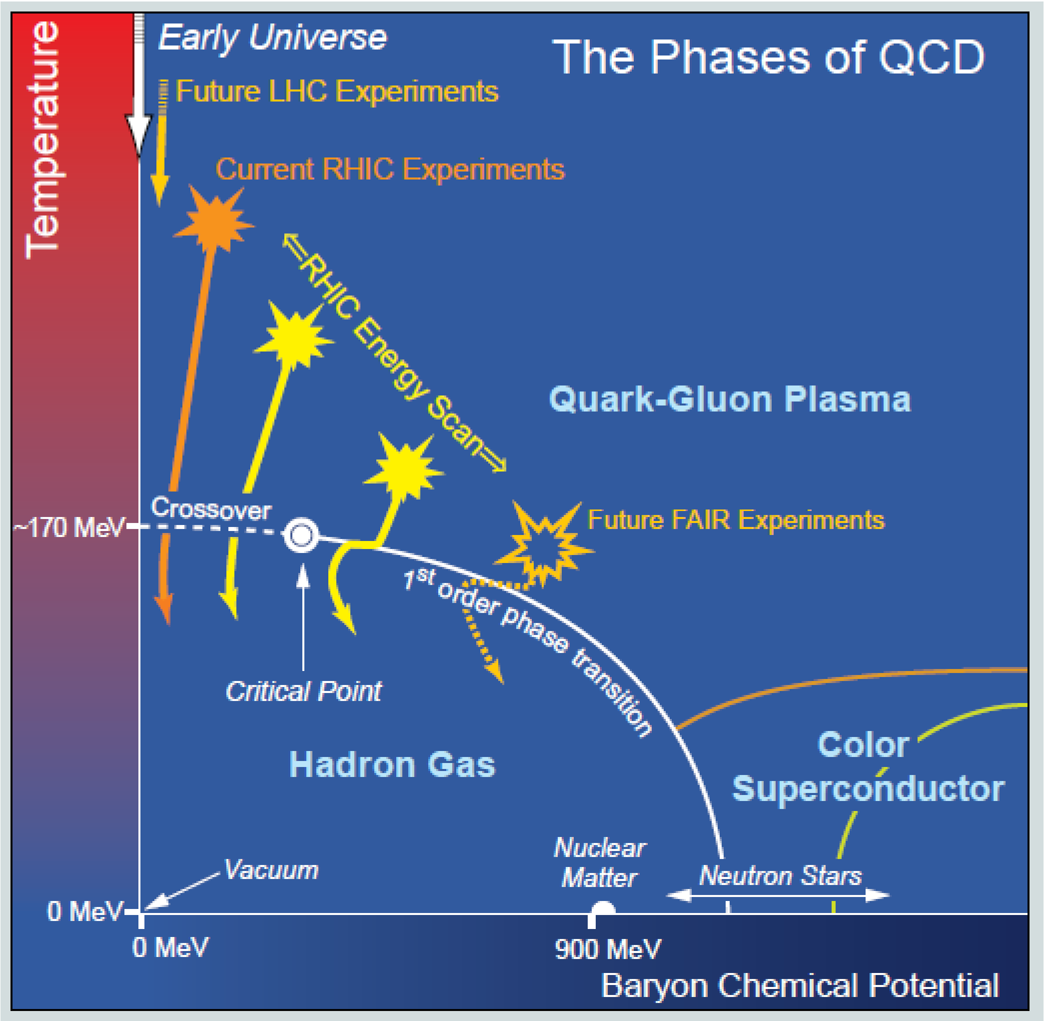
η separated long range correlations



arxiv 1404.7461

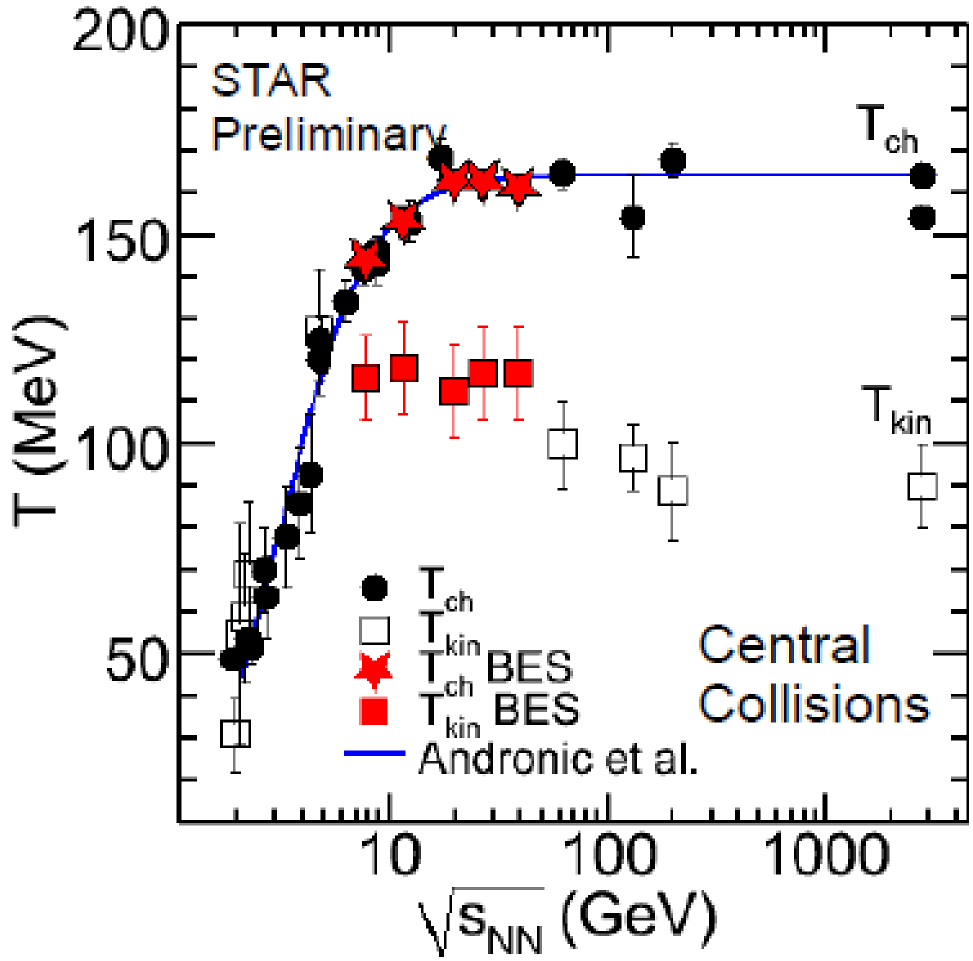
- p+p: dominate by c_1 or $\cos\Delta\phi$ correlations (conservation of momentum)
- d+Au: enhancement at $\Delta\phi$ ~ 0, which is the “ridge”

Searching for the critical point



- From QGP to hadron Gas
- Can we find the critical point?
- Changing the colliding energy!

T_{ch} vs $\sqrt{s_{NN}}$



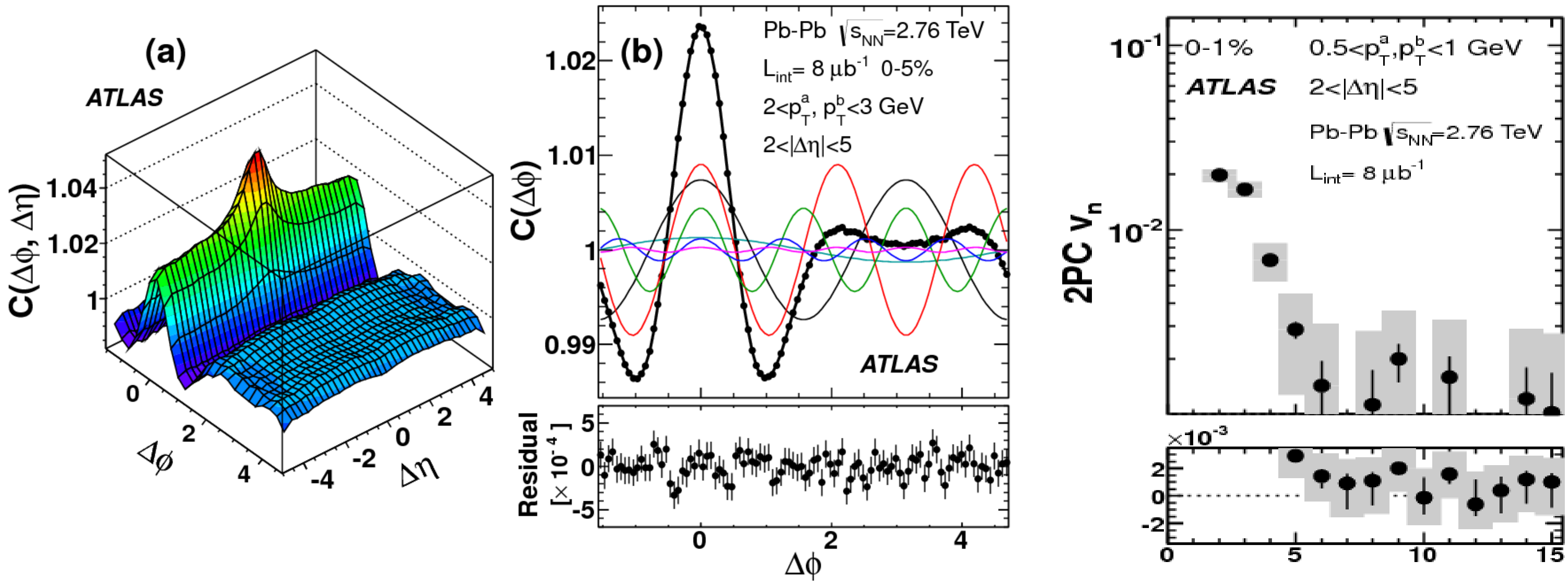
T_{ch}: inelastic interactions between particles stops

T_{kin}: elastic interactions stops

- Saturation at ~ 10 GeV?

Measuring the flow harmonics in HIC

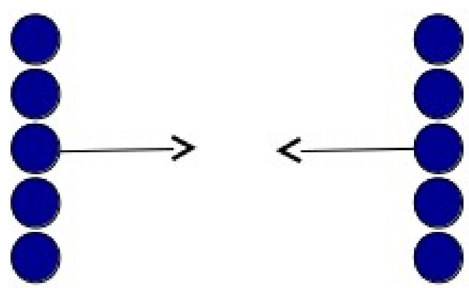
Phys. Rev. C **86**, 014907 (2012) (ATLAS)



- Measuring the particle pair azimuthal correlation, $C(\Delta\phi)$
- Fourier decompose the correlation function

N_{part} and N_{coll}

(a)



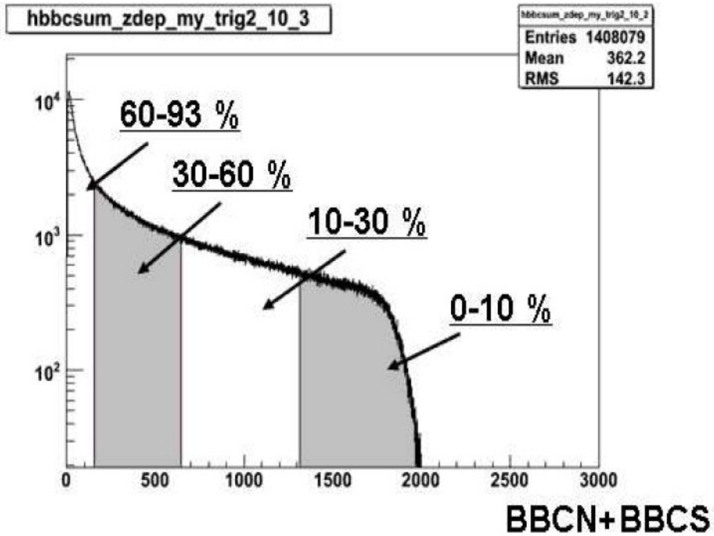
- N_{part}: number of nucleons participating in collisions

(b)

Both cases has N_{part} = 10, but
(a) has N_{coll} = 5, (b) has N_{coll} =25

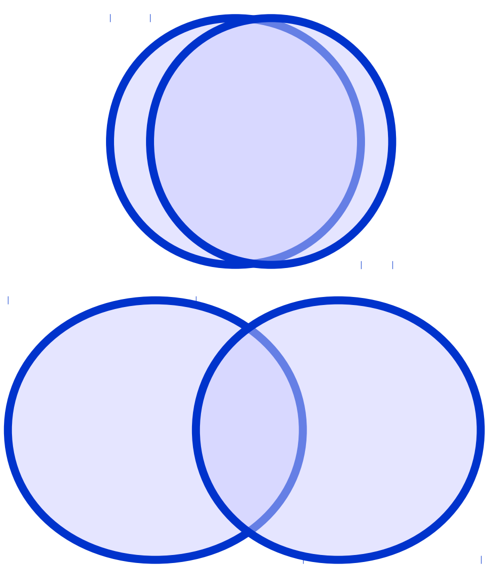
- N_{coll}: number of total binary collisions

Some useful terminology



p_T : transverse momentum

Centrality: a percentage of the total nuclear interaction cross-section



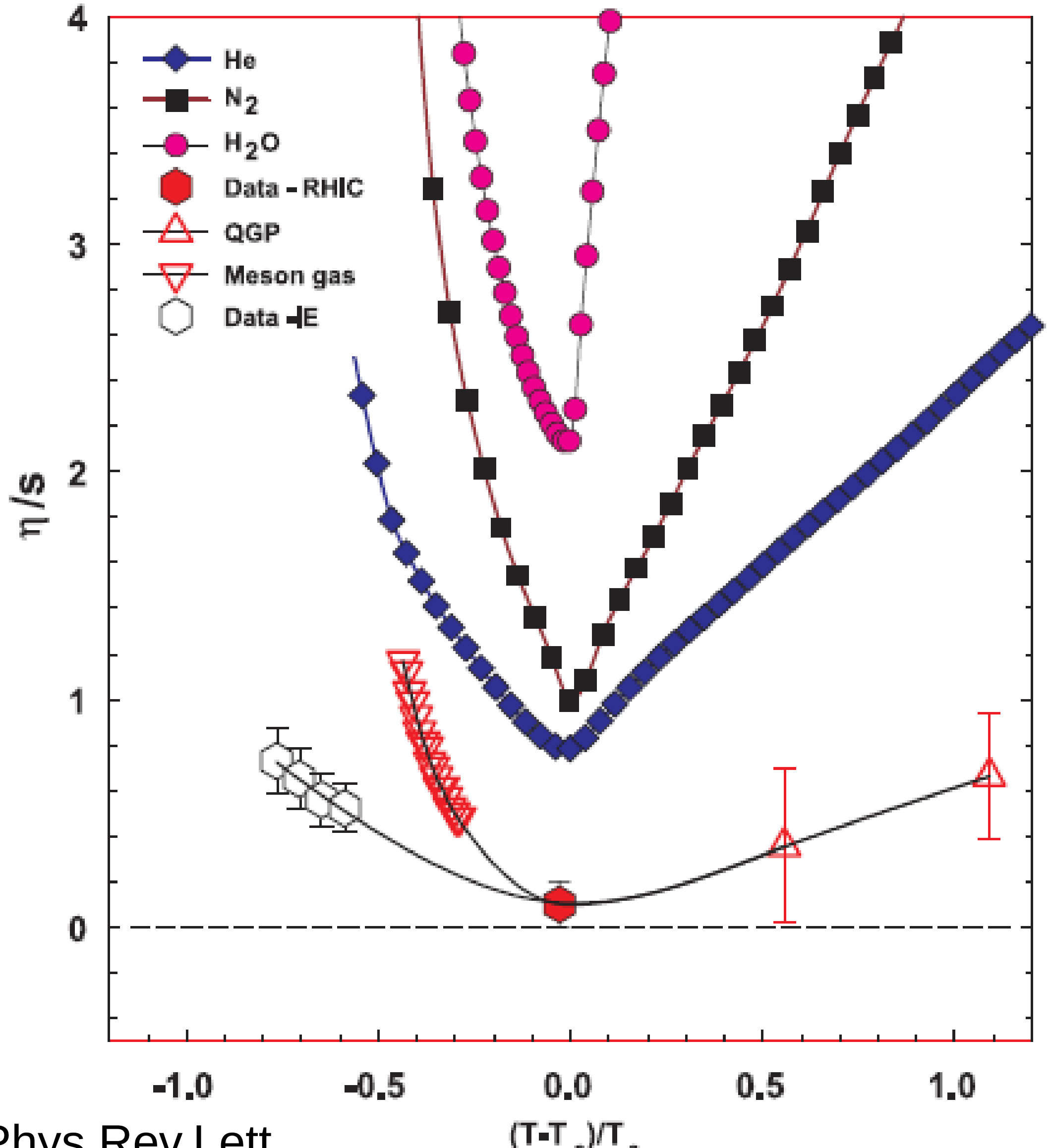
Central collision: the two nuclei collide “head on”. Most energetic collisions, with highest multiplicity (0-10%)

Peripheral collision: the two nuclei touch by edge (60-92%)

How do we measure the temperature of QGP?

- Measure the spectrum of direct photon in p+p as baseline
- Measure the spectrum of direct photon in Au+Au
- The “extra photons” in Au+Au must come from thermal radiation from QGP

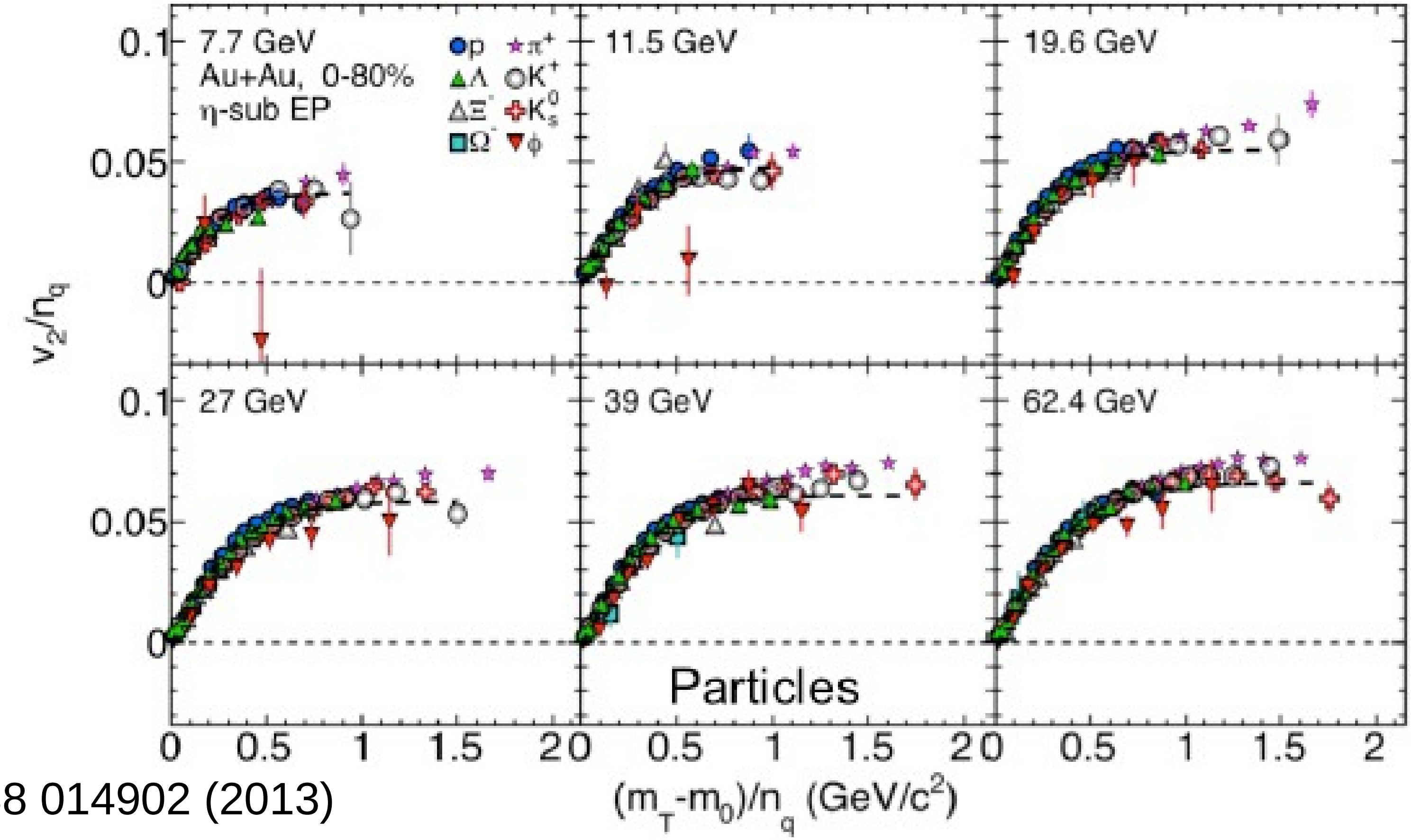
Can η/s help us find the critical point?



Phys.Rev.Lett. 98:092301,2007

- Universal lower bound:
  $\eta/s = 1/4\pi \sim 0.08$
- QGP has the lowest η/s among most atomic and molecular substances
- Lowest η/s ~T_c?

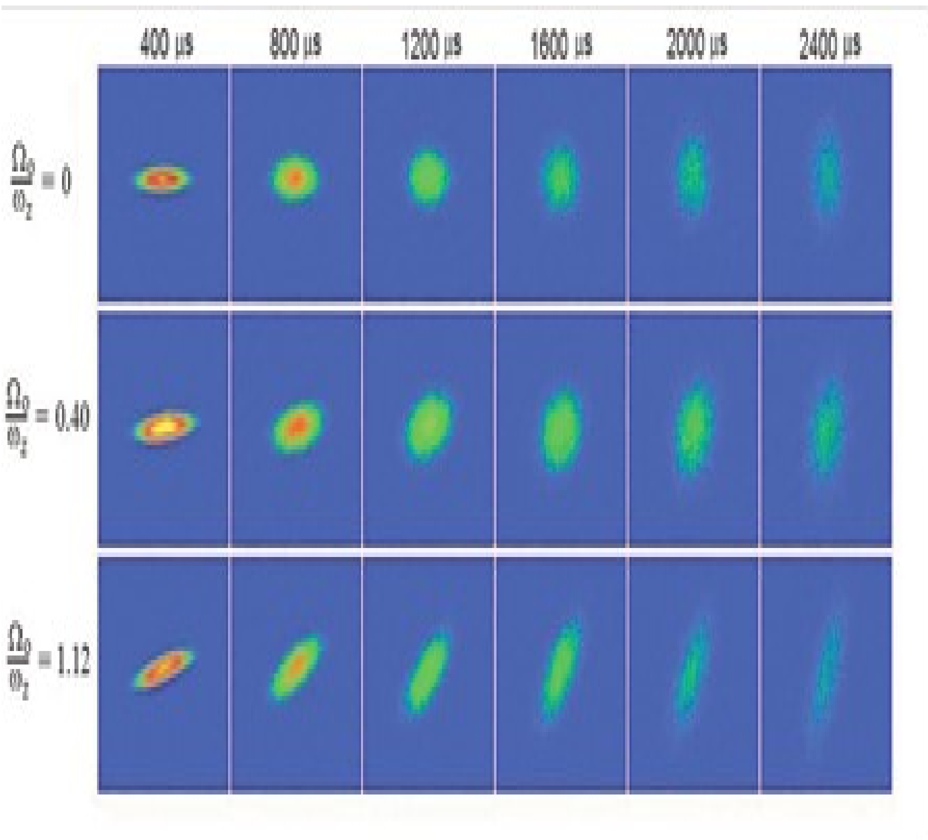
Valence quark scaling?

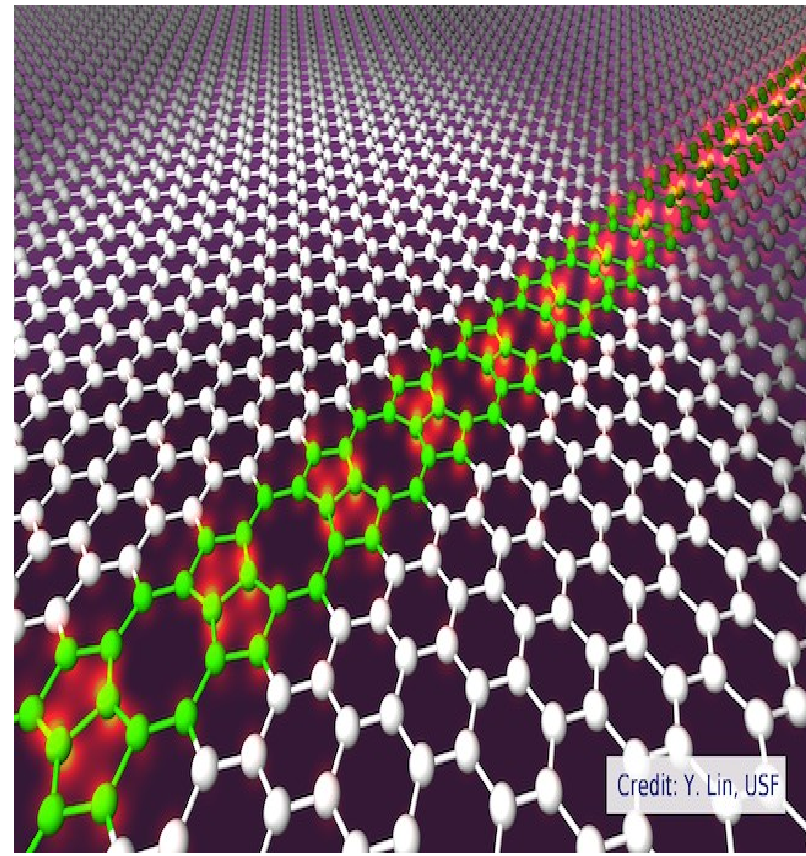


PRC 88 014902 (2013)

- No obvious deviation from valence quark scaling → free quark even at 7.7 GeV?

Other perfect fluid?



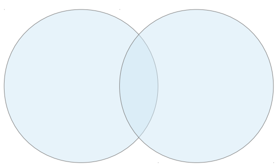


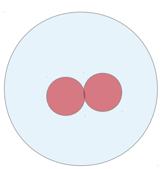
- Cold atomic gas
- T ~ 10^{-9} K

- Electrons in graphene (2010 Nobel Physics)
- T ~ room temperature

System size dependence

- Peripheral Au+Au and central d+Au



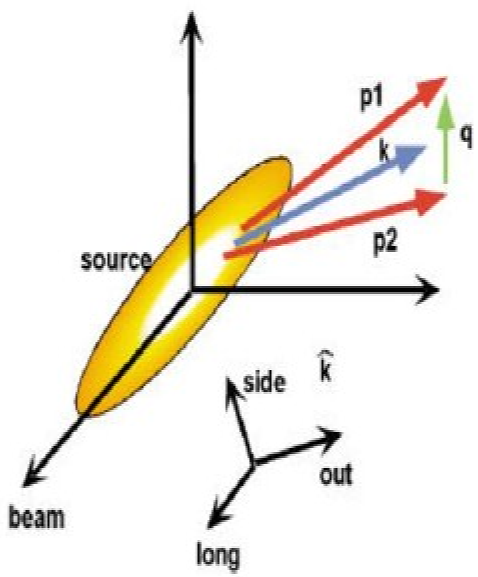


System	<Ncoll>	<Npart>
Au+Au 60-92%	14.8 ± 3.0	14.7 ± 2.9
d+Au 0-20%	15.1 ± 1.0	15.3 ± 0.8

- Similar number of collisions, and number of participants
- Any difference between the two?

The size of the fireball

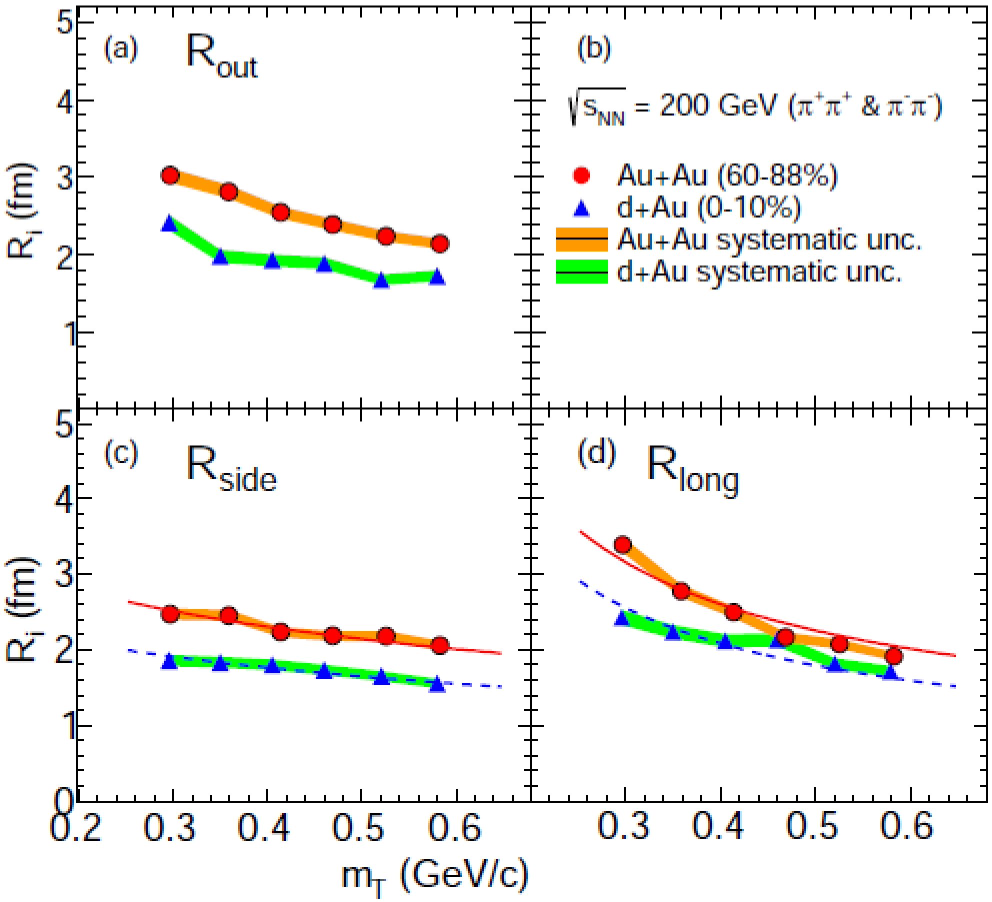
- To measure the size of the fireball, we use the HBT (Hanbury-Brown and Twiss) correlation to measure the size of the fireball at freeze-out

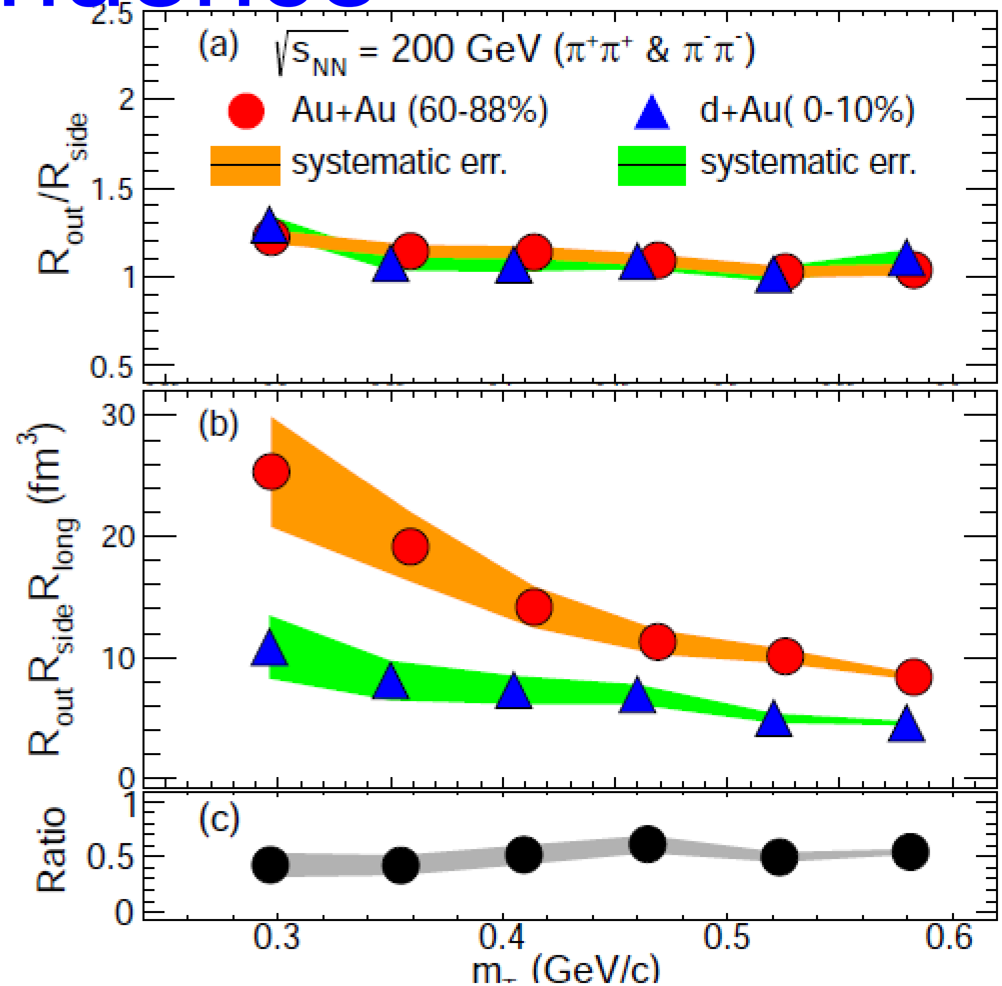


- 3D Gaussian distribution
- out: direction of mean transverse momentum of the pair
- Side: orthogonal to out
- long: beam direction

m_T dependence

arxiv 1404.5291

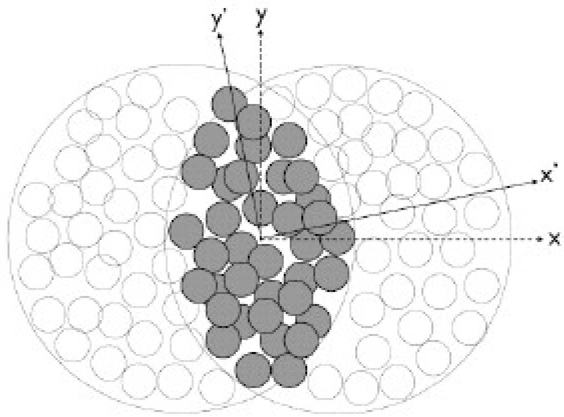




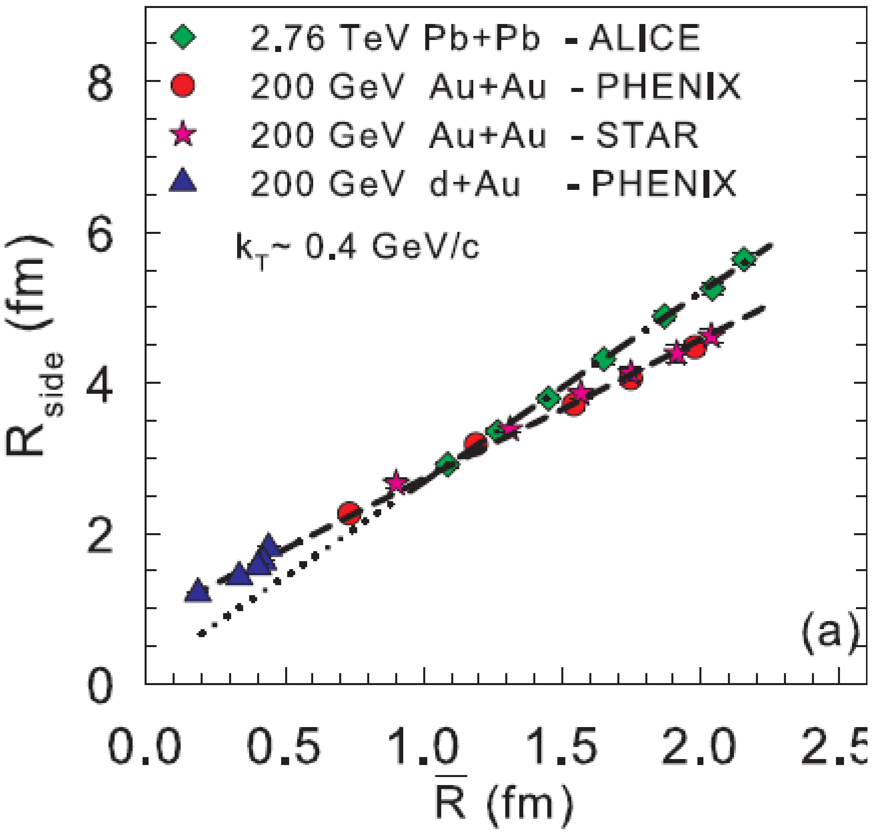
- Similar m_T dependence between dAu and AuAu

- V(dAu) < V(AuAu)
- m_T dependence of volume is similar

Dependence in R

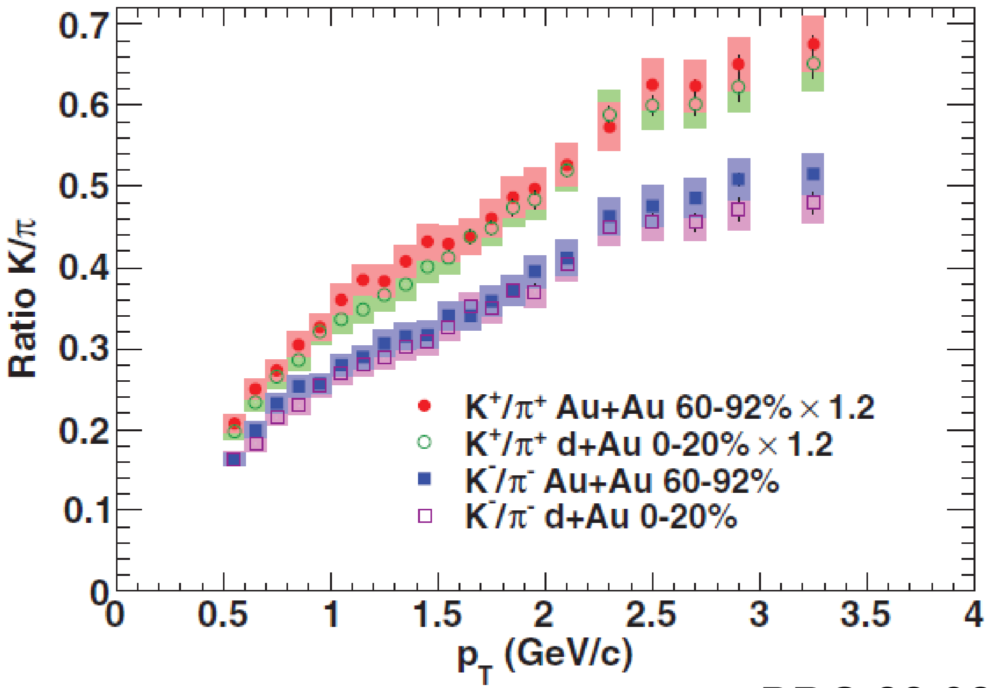


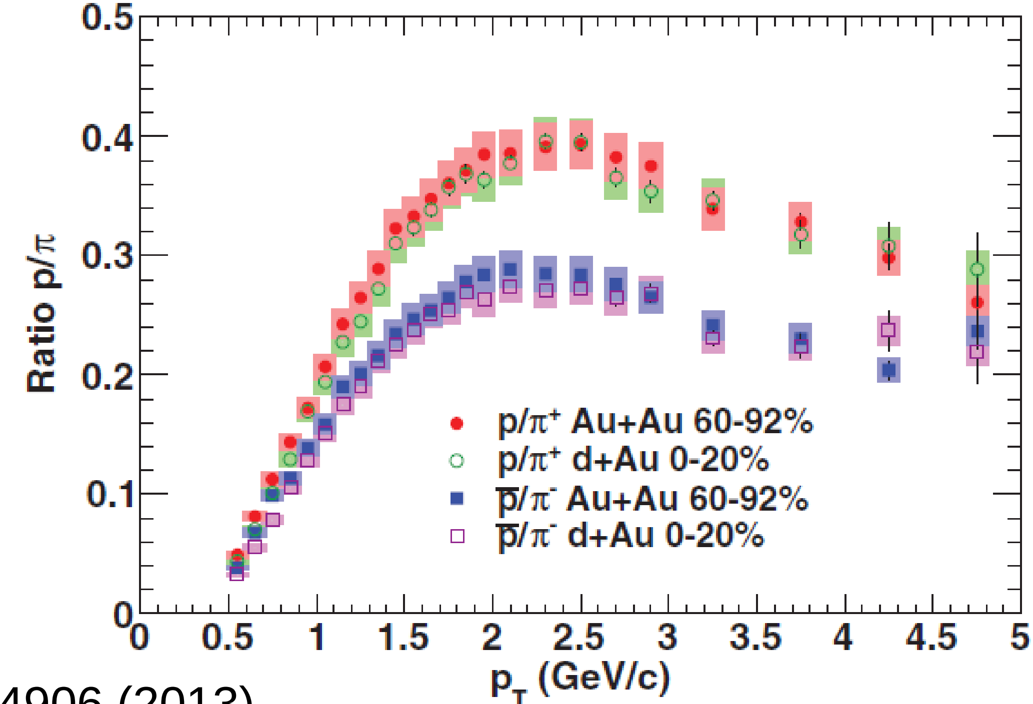
arxiv 1404.5291



- $1/R = \mathrm{sqrt}(1/\sigma_x^2 + 1/1/\sigma_y^2)$
- Linear dependence and nice scaling between Au+Au and d+Au
- Different slope between Pb+Pb (2.76 TeV) and Au+Au (0.2 TeV)

K/π and p/π ratio in d+Au and Au+Au





PRC 88 024906 (2013)

- The K/π and p/π ratios in peripheral Au+Au and central d+Au are the same
- Similar chemical compositions in both systems

Particle physics in 1 minute

- 6 quarks, 6 leptons
- Quarks combined into hadrons
  - Meson-> 2 quarks
  - Baryons -> 3 quarks
- Photons, Z, W and gluons are particles that carry forces
- Quarks have "colors". The law describing their behavior is Quantum ChromoDynamics (QCD)

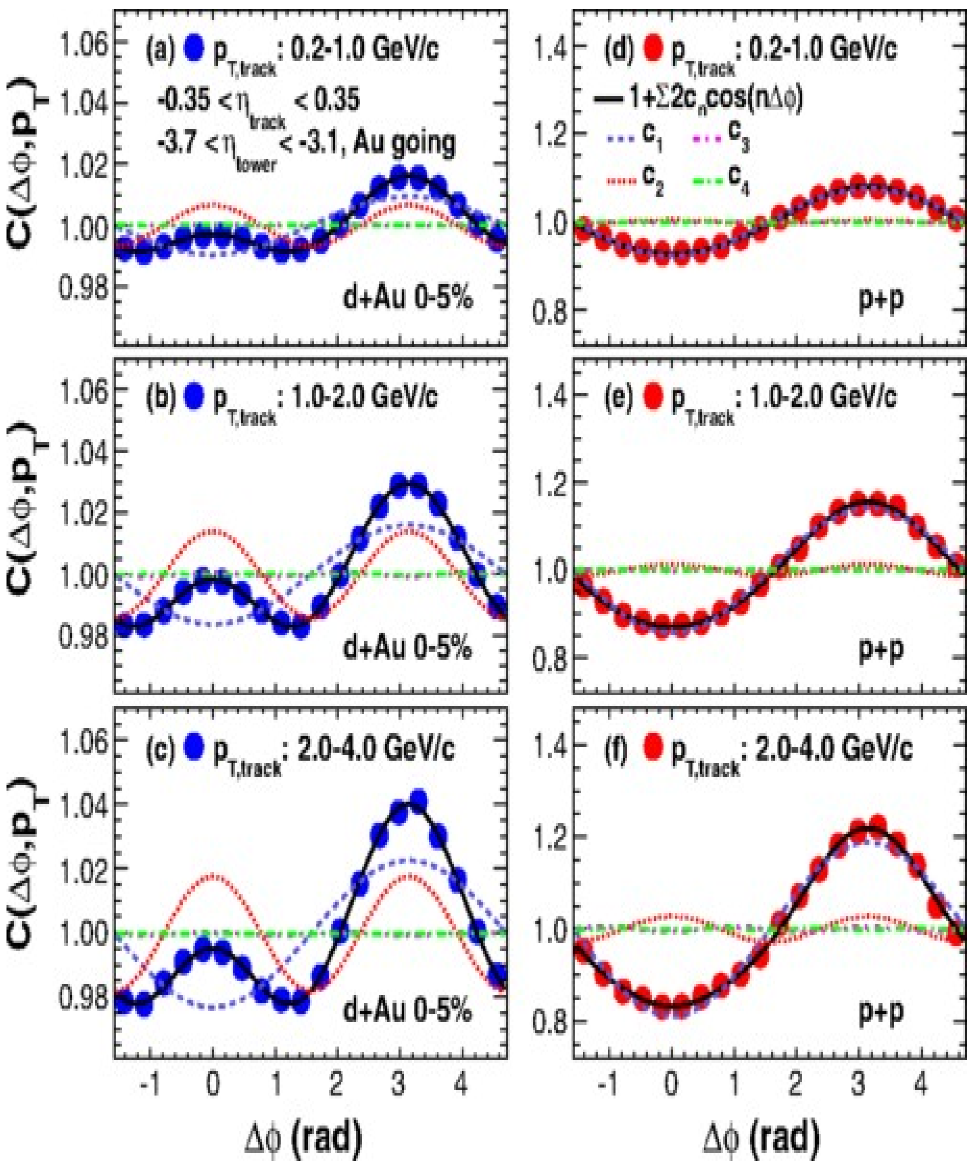
d+Au at RHIC vs p+Pb at LHC

- Smaller energy (0.2 TeV vs 5.02 TeV)
- Slightly different initial state geometry (d vs p)

- Can we see v_2 in central d+Au collisions?

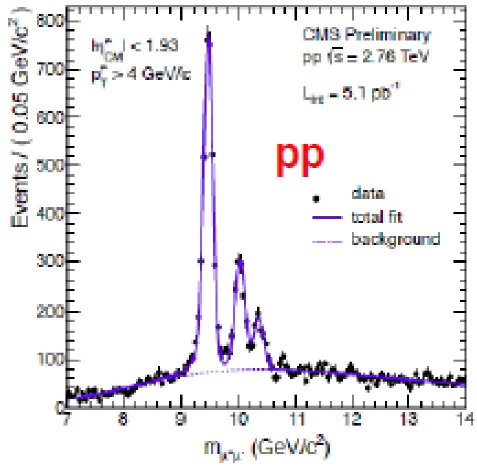
PRL 114 192301
Editor's Suggestion

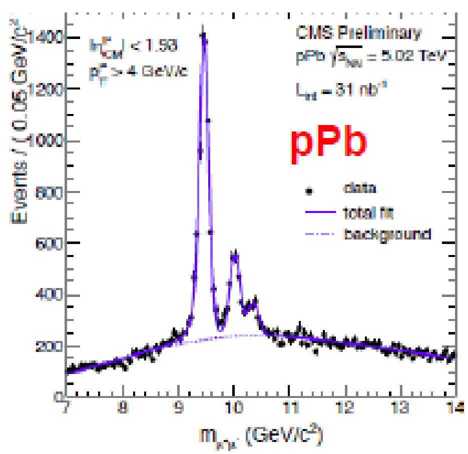
Long range correlation

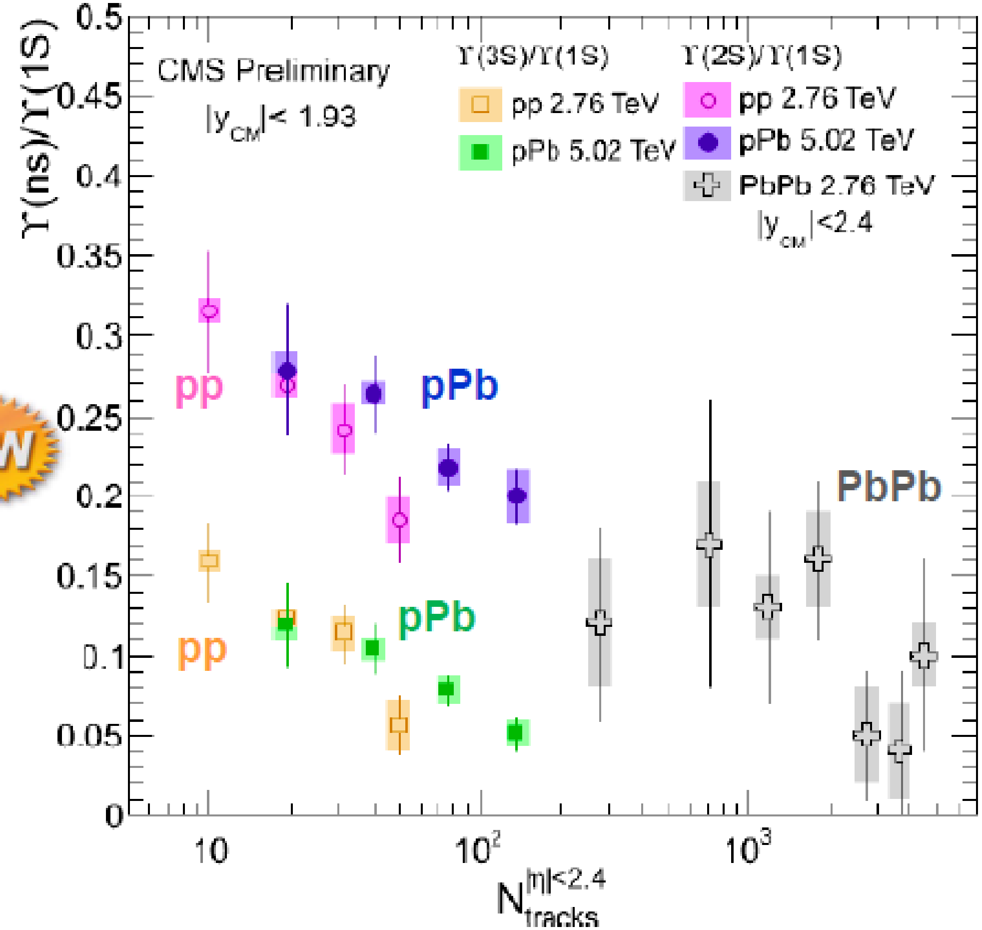


- For p+p, it is dominated by c_1 (conservation of momentum)
- When mid-rapidity particles are correlated with Au-going side, there is significant correlations at $\Delta\phi$ ~0
- c_1 and c_2 are comparable in central d+Au collisions

Υ (1S,2S,3S) and event activity

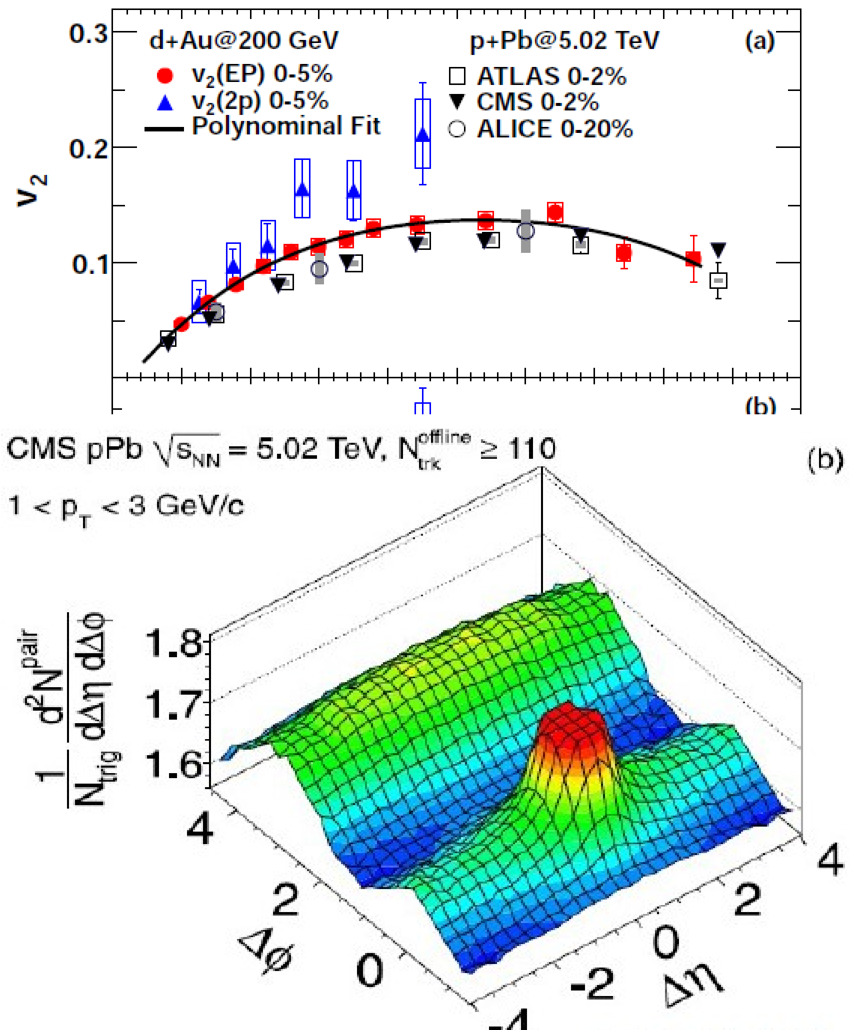






- Less suppression of excited states in pPb compared to PbPb
- Interesting behavior vs event activity in all collision systems
- What is the correct reference for PbPb collisions ?

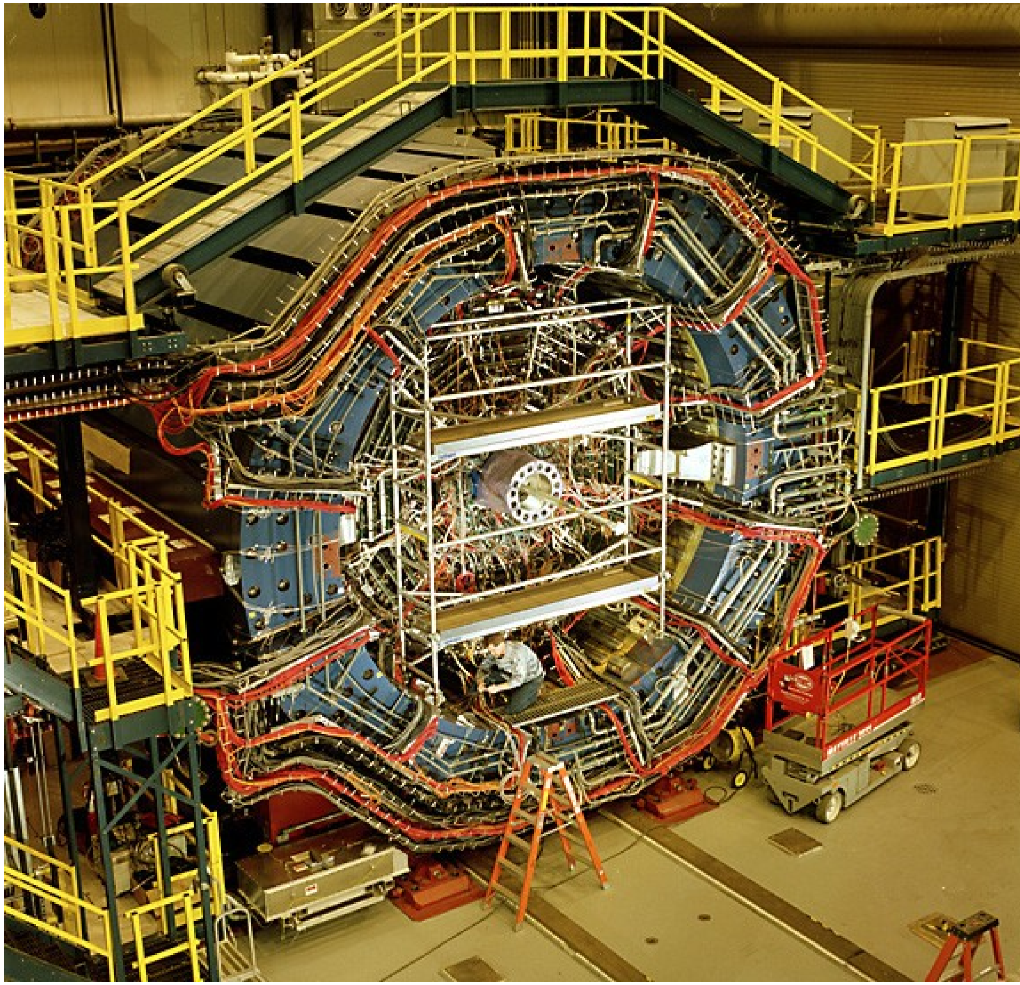
Open questions



PLB 718 795

- Is QGP created in small systems (pp, pA)?
- Is multiplicity/energy density the key to link pp/pA/AA?
- Unified explanations?

Detectors at RHIC



STAR
specialty: large acceptance measurement of hadrons

PHENIX
specialty: rare probes, leptons, and photons

What is viscosity

- Viscosity is the resistivity of the fluid
- Low viscosity: milk
- High viscosity: honey
- Low viscosity means the energy can transfer through the fluid very fast
- no viscosity = “ideal fluid”