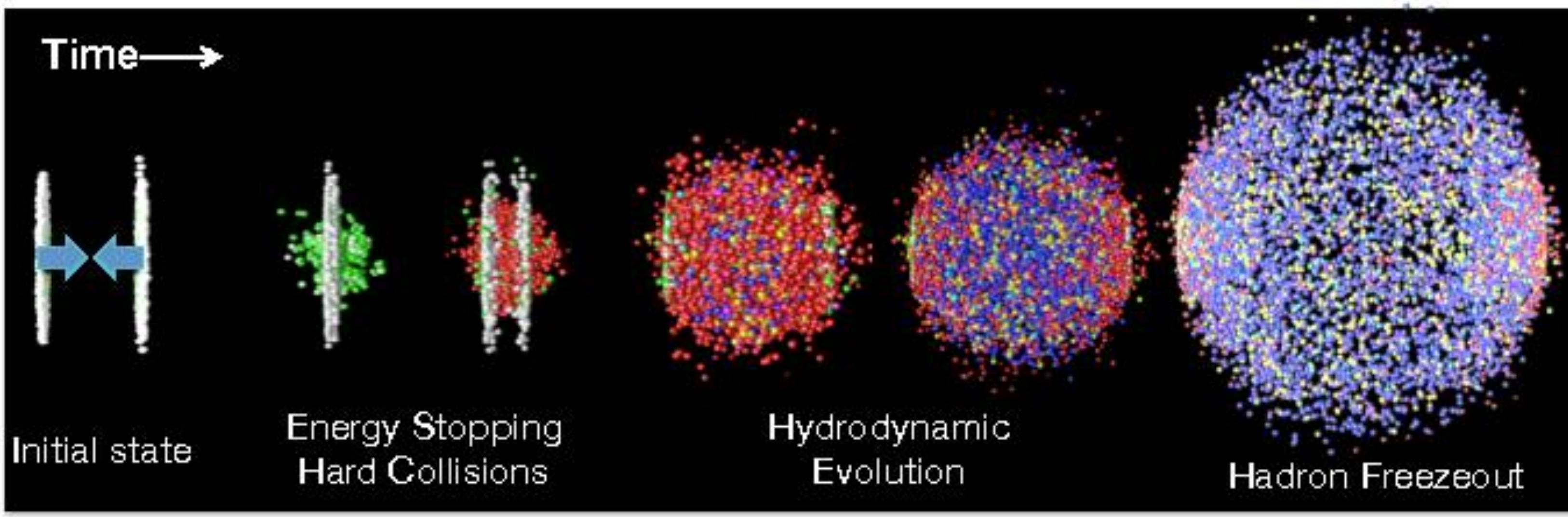
Particle Correlations

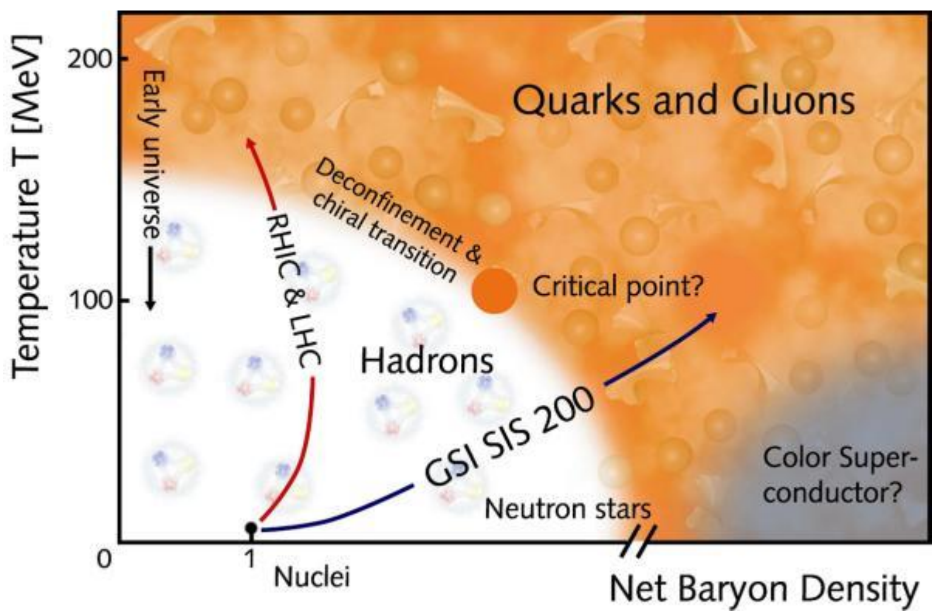
Fuqiang Wang
Purdue University

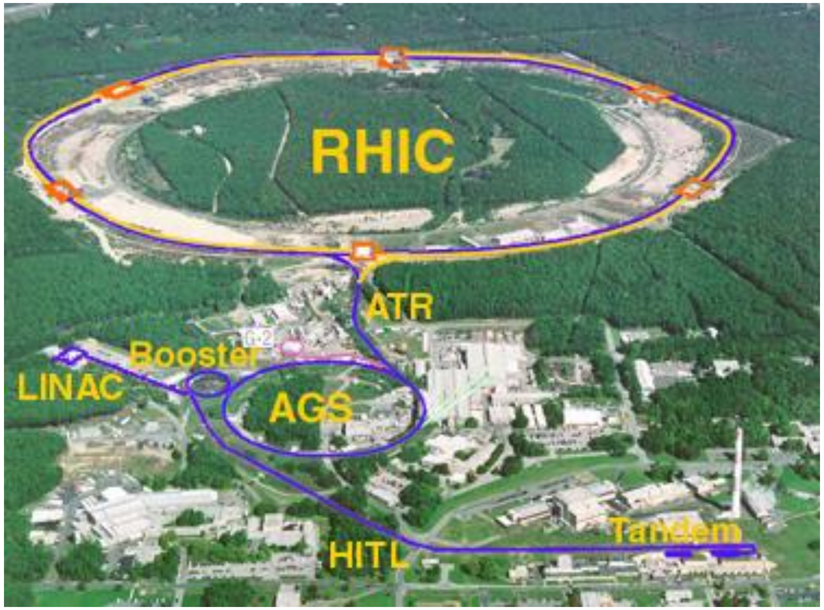
Outline

- Why particle correlations?
  - Few-body (jet-like) correlations
  - Many-body (flow) correlations
  - Analysis techniques
- Particle correlations in heavy-ion collisions
  - Near-side ridge correlation
  - Away-side double-peak correlation
  - Triangular flow background
- Particle correlations in small systems
  - Revisit two-particle acceptance correction
- Flow correlations
  - Some new idea: initial state anisotropy, quantum mechanics

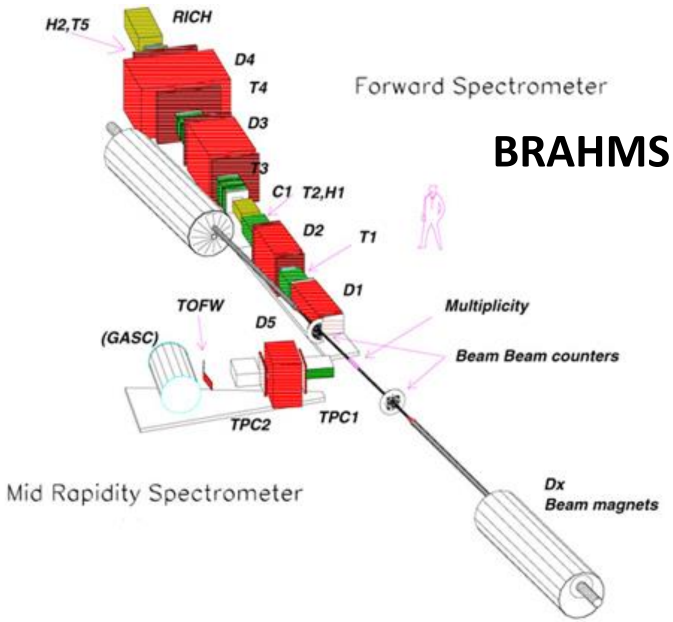
Artist's view of heavy-ion collisions



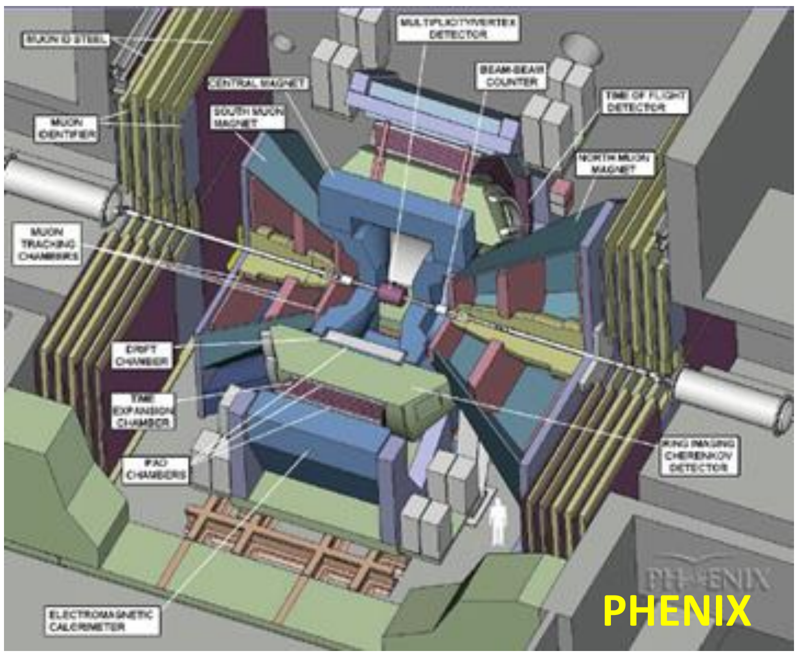


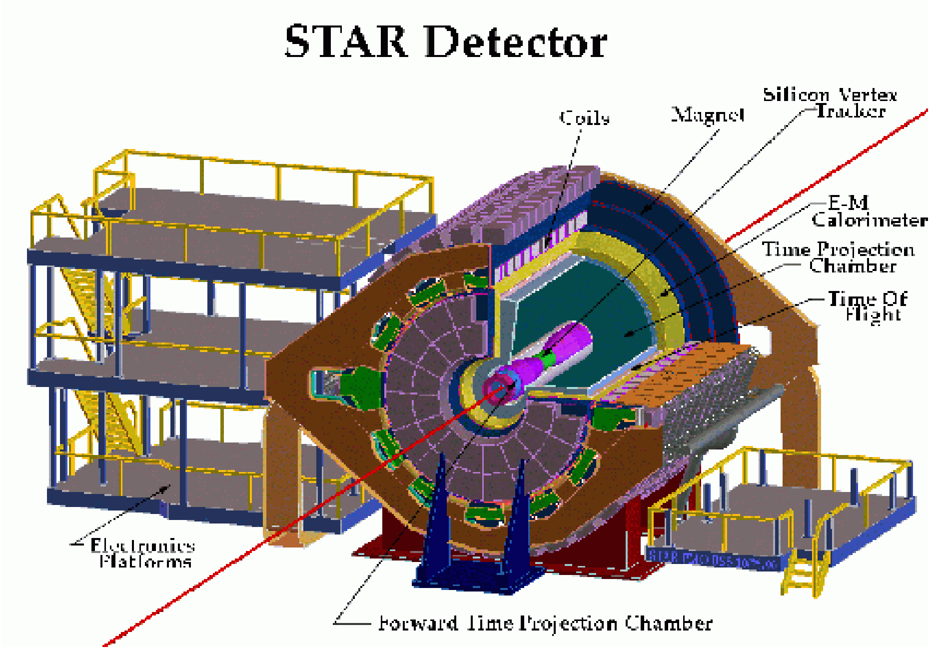

RHIC
ATR
Booster
LINAC
AGS
Tandem
HITL

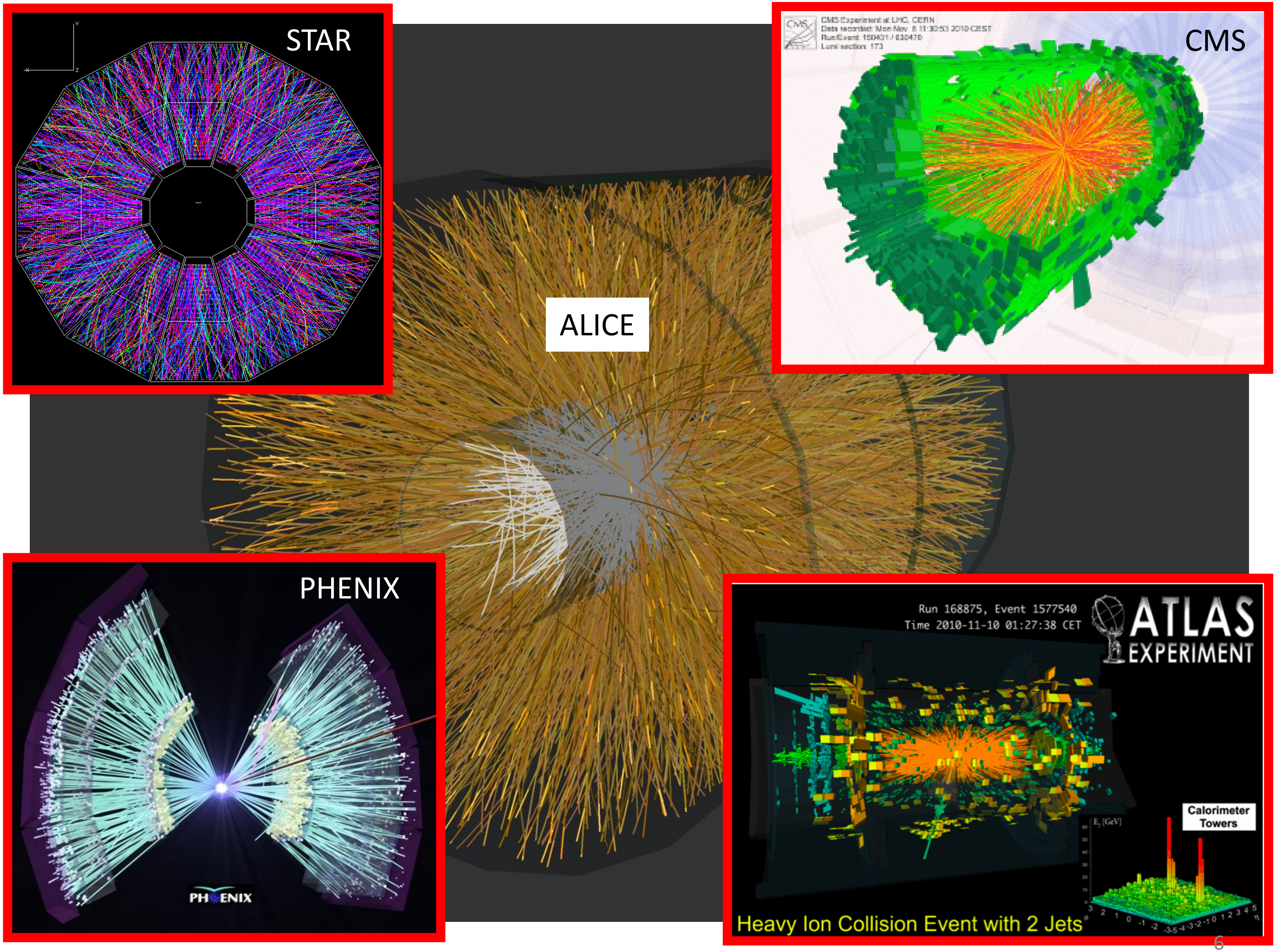
LHC


BRAHMS
Forward Spectrometer
Mid Rapidity Spectrometer
H2,T5
RICH
D4
T4
D3
T3
C1
T2,H1
D2
T1
D1
TOFW
(GASC)
D5
Multiplicity
Beam Beam counters
TPC2
TPC1
Dx
Beam magnets


OS


PHENIX
MULTIPLICITY/VERTEX DETECTOR
BEAM-BEAM COUNTER
TIME OF FLIGHT DETECTOR
CENTRAL MAGNET
SOUTH MUON MAGNET
NORTH MUON MAGNET
MUON TRACKING CHAMBERS
DRIFT CHAMBER
TIME EXPANSION CHAMBER
PAD CHAMBERS
RING IMAGING CHERENKOV DETECTOR
ELECTROMAGNETIC CALORIMETER


STAR Detector
Coils
Magnet
Silicon Vertex Tracker
E-M Calorimeter
Time Projection Chamber
Time Of Flight
Electronics Platforms
Forward Time Projection Chamber

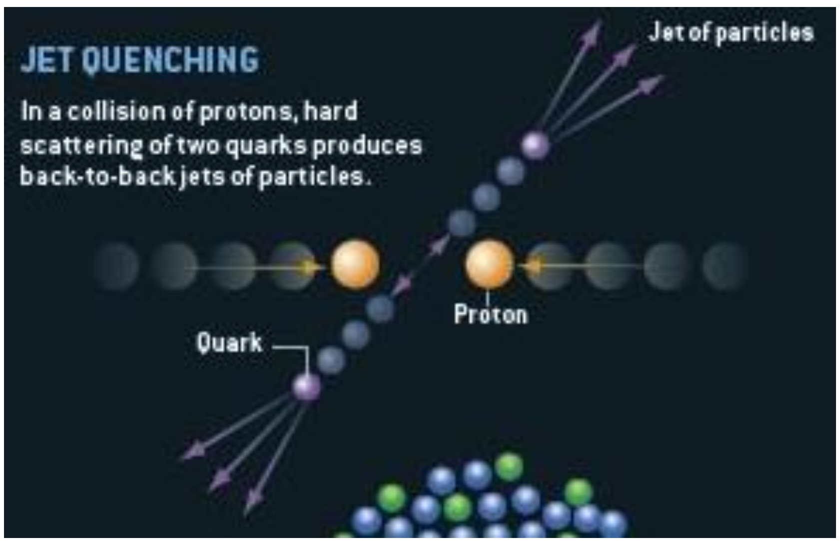

STAR
CMS Experiment at LHC, CERN
CMS
ALICE
PHENIX
PHENIX
Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET
ATLAS
EXPERIMENT
Calorimeter
Towers
Heavy Ion Collision Event with 2 Jets

Why particle correlations?

- Single particles can only measure production rates and kinematic distributions
- High-energy collisions are complex—need particle correlations to measure the complex structure of the collision system
- Particle correlations measure jet-like correlations, flow, etc.
- Majority of measurements in heavy-ion collisions are done by particle correlations

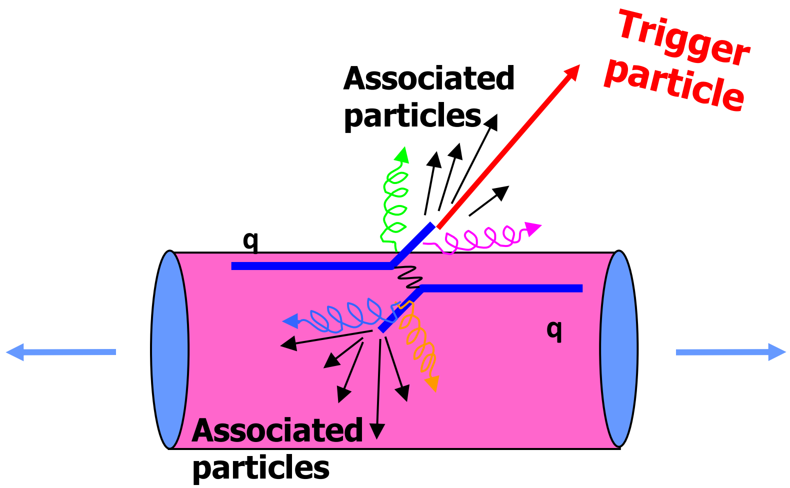
Two categories of correlations

- Few-body, e.g.
  - Jets
  - Resonance decays



- Many-body, event-wise
  - Collective flow

Analysis techniques



$$\Delta\phi = \phi_{assoc} - \phi_{trig}, \Delta\eta = \eta_{assoc} - \eta_{trig}$$

$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2N^{same}}{d\Delta\eta\Delta\phi}$$

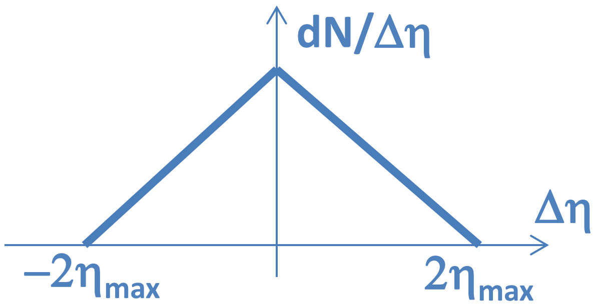
$$B(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2N^{mix}}{d\Delta\eta\Delta\phi}$$

- Tracking efficiency is corrected for associated particles.
- Trigger particles are often uncorrected, because correlations are normalized per trigger. Better to have trigger particle correction as well.
- Two-particle acceptance often corrected by mixed-events: $\boldsymbol{B}(\Delta\boldsymbol{\eta}, \boldsymbol{\Delta\phi}) / \boldsymbol{B}(\mathbf{0}, \boldsymbol{\Delta\phi})$.

$$dN / d\eta = \text{const.} \qquad (-\eta_{\max} < \eta < \eta_{\max})$$

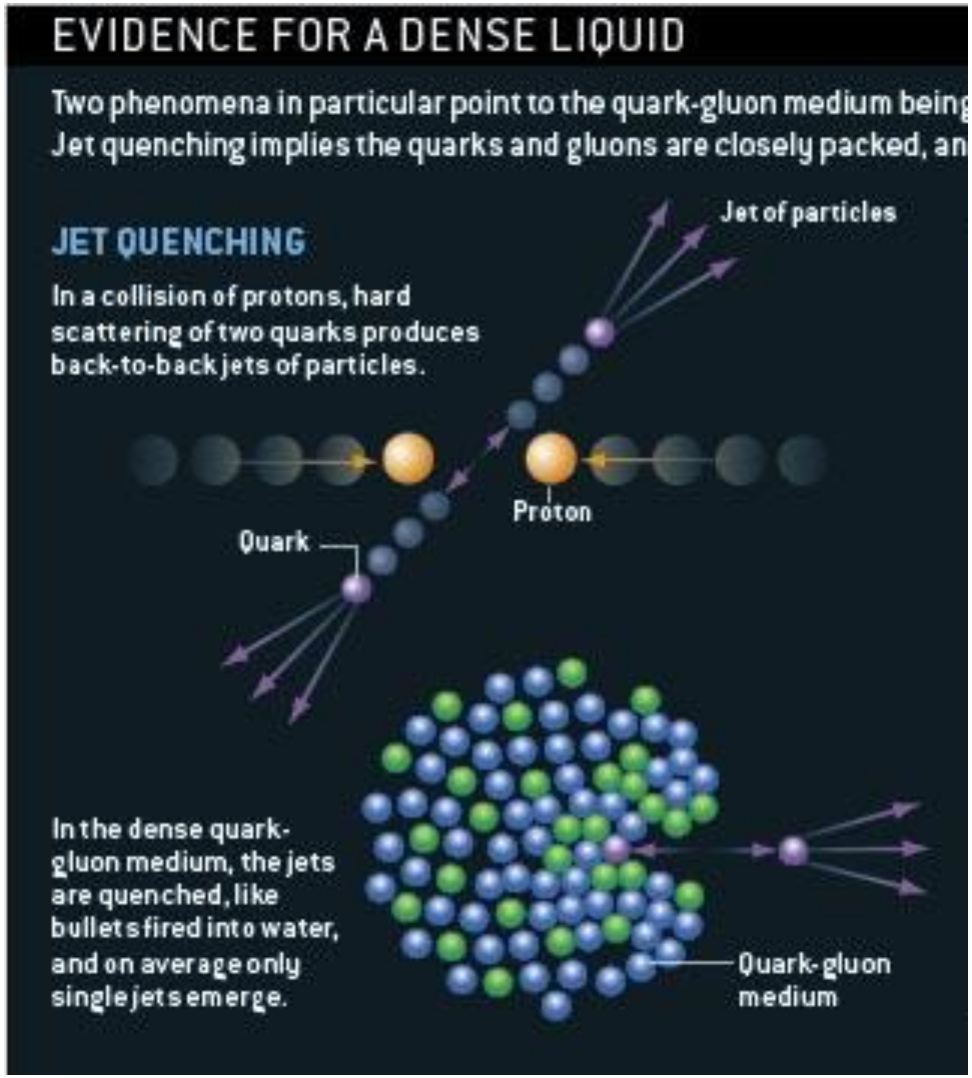
$$dN / d\Delta\eta = \int d\eta_1 \int d\eta_2 \left(\text{const} \times \text{const}\right) \delta(\eta_2 - \eta_1 - \Delta\eta)$$

$$\propto 1 - \frac{|\Delta\eta|}{2\eta_{\max}}$$



Particle correlations in heavy-ion collisions

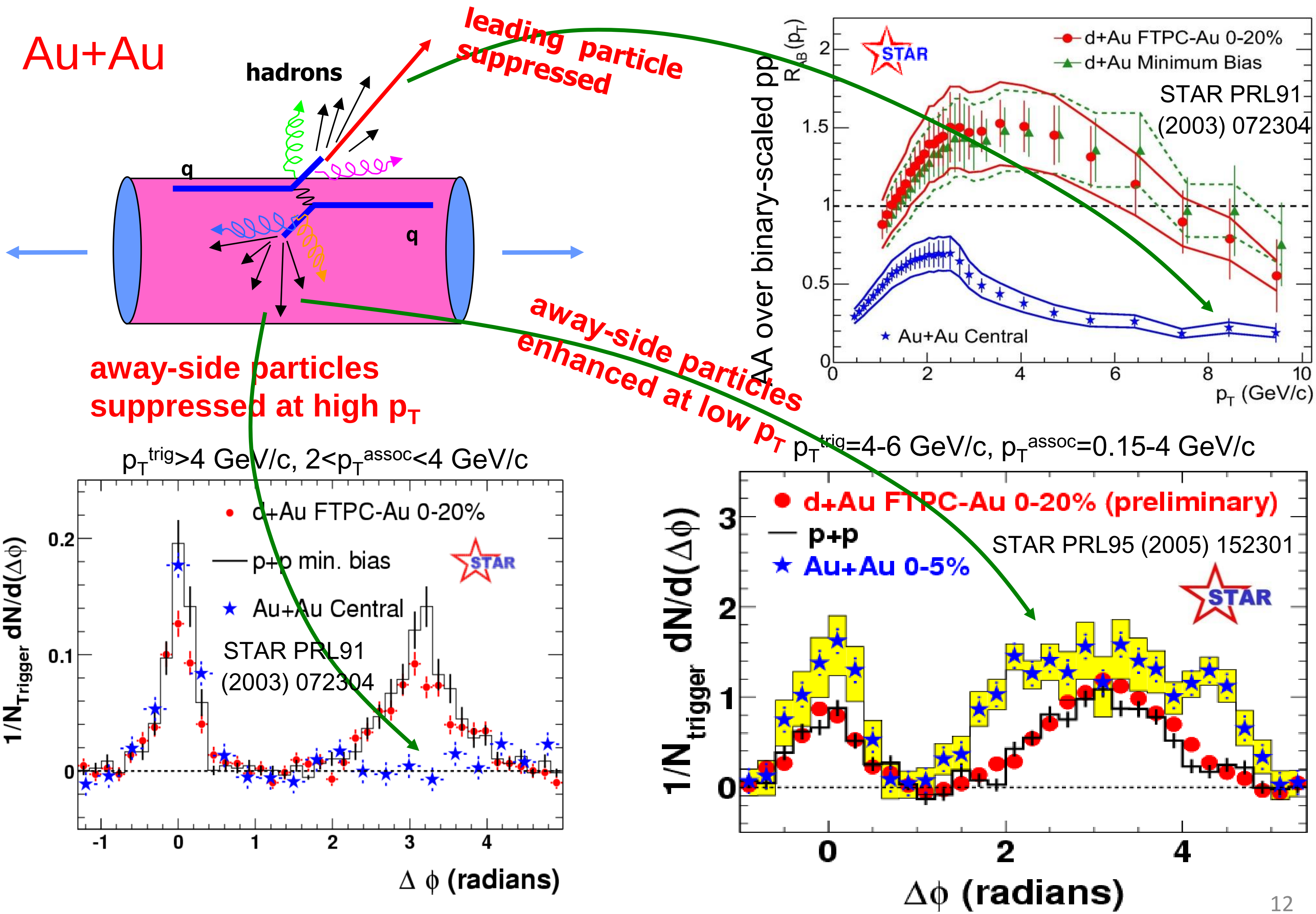
Jet correlations



- **Hard-scattering between partons in pp.**
- **Calculable by pQCD**
- **Fragmentation of partons produces back-to-back jets of hadrons.**
- **Jets are clustered in angle and rich in high-p_T particles.**

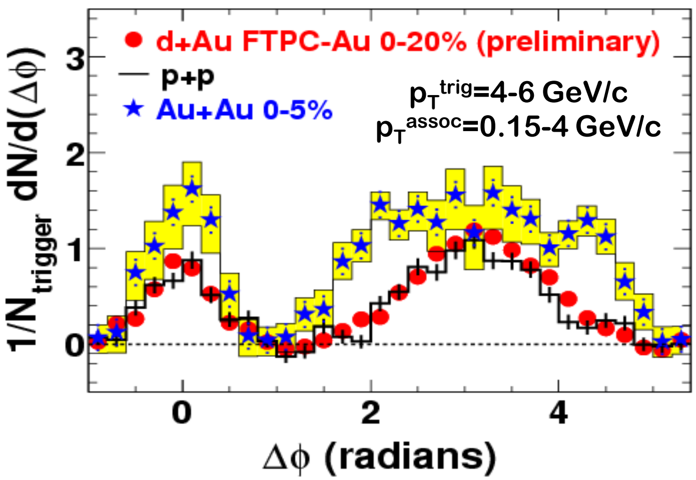
- **Jets produced in AA traverse and interact with the medium, lose energy and thus carry information of the medium.**

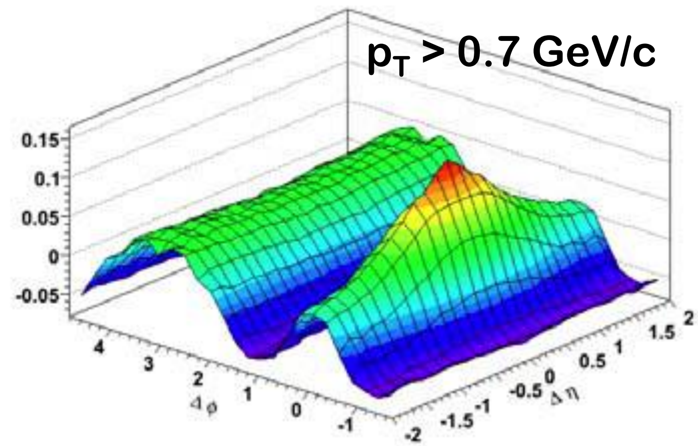
Particle correlations: focus on **away side**

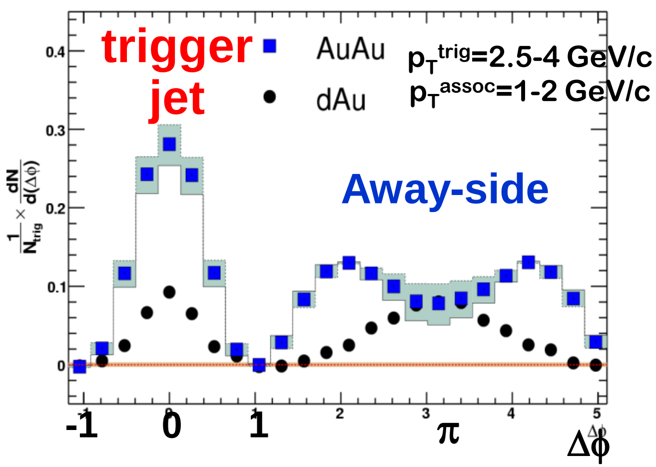


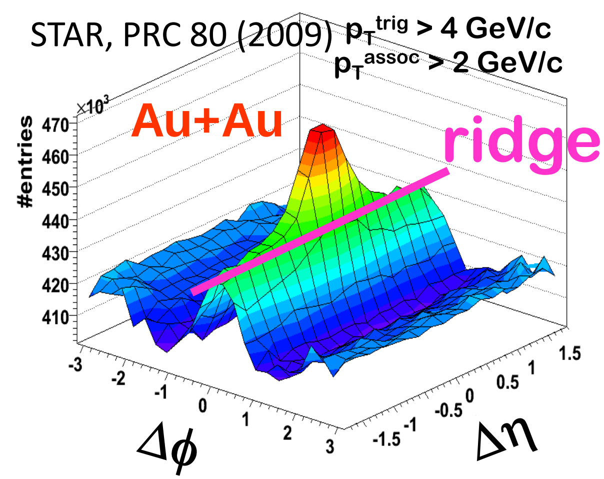
The **near-side** is also interesting

STAR, PRL 95 (2005); PRC82 (2010)

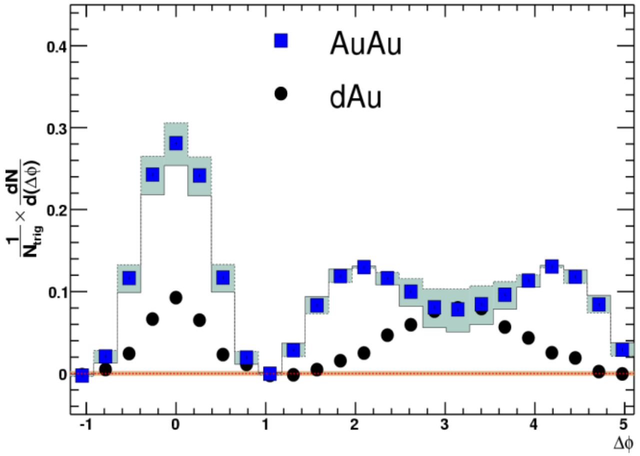




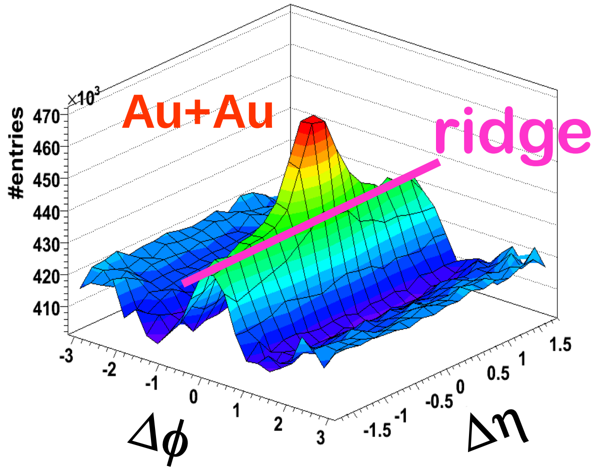


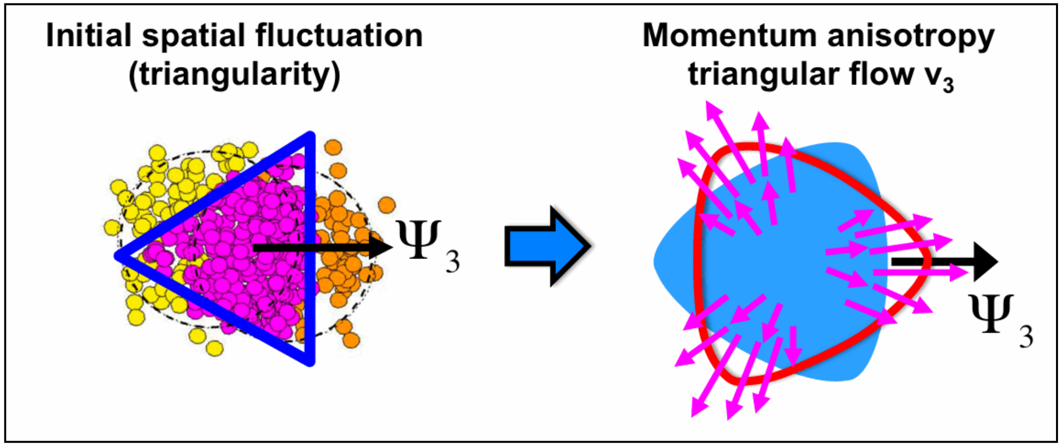


Triangular flow in heavy-ions



- Double-peak away-side correlations
- Long-range near-side ridge
- Triangular flow, v_3
- Other odd harmonics

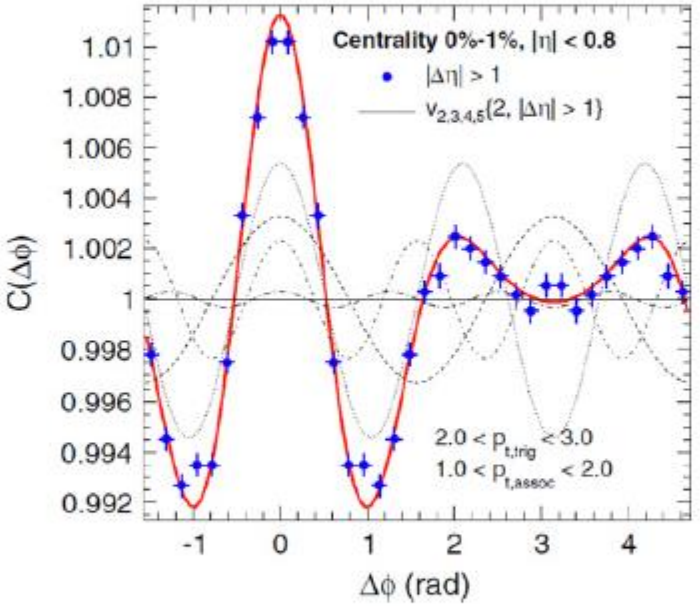




v_n are measured by two-particle correlations

- V_n from two-particle correlation
- Subtract v_n from two-particle correlation
- Almost a tautology
- Comparison to hydro gives us confidence that v_n are mostly from flow
- Quantitatively how much is flow and how much is nonflow— still an open question.

ALICE, Phys. Rev. Lett. 107 (2011) 032301

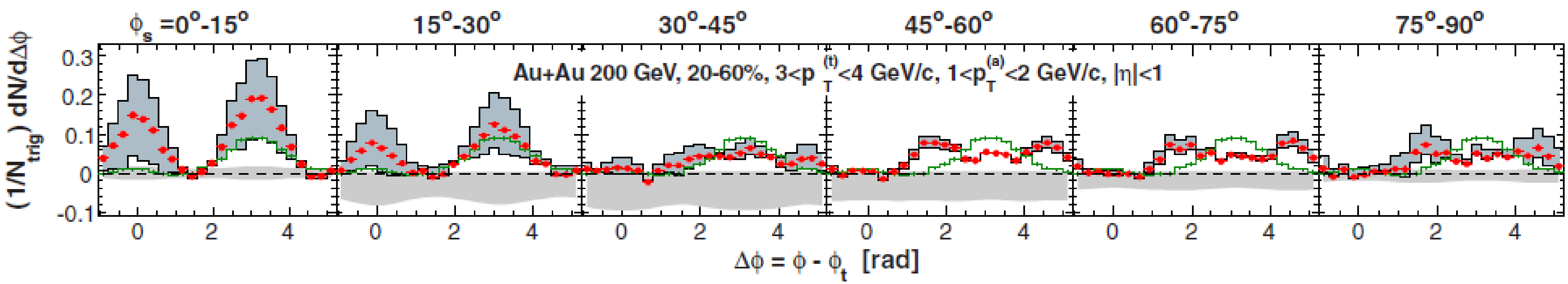


- Hydro has some tension to simultaneously describe v_2 and v_3
- Important to reduce/eliminate nonflow contributions to flow; do as best a job as we can.

EP-dep. correlation with v_n subtraciton

Strategy:

- Measure v_n by two-particle correlation with one particle at as low p_T as feasible, to maximally reduce nonflow contaminations.
- Subtract v_n measurements from two-particle correlations at high and intermediate p_T.



Open questions:

- Effect of jets on event plane reconstruction?
- Are any remaining correlations still coming from hydro flow, i.e. jets are completely gone?

Particle correlations in small systems

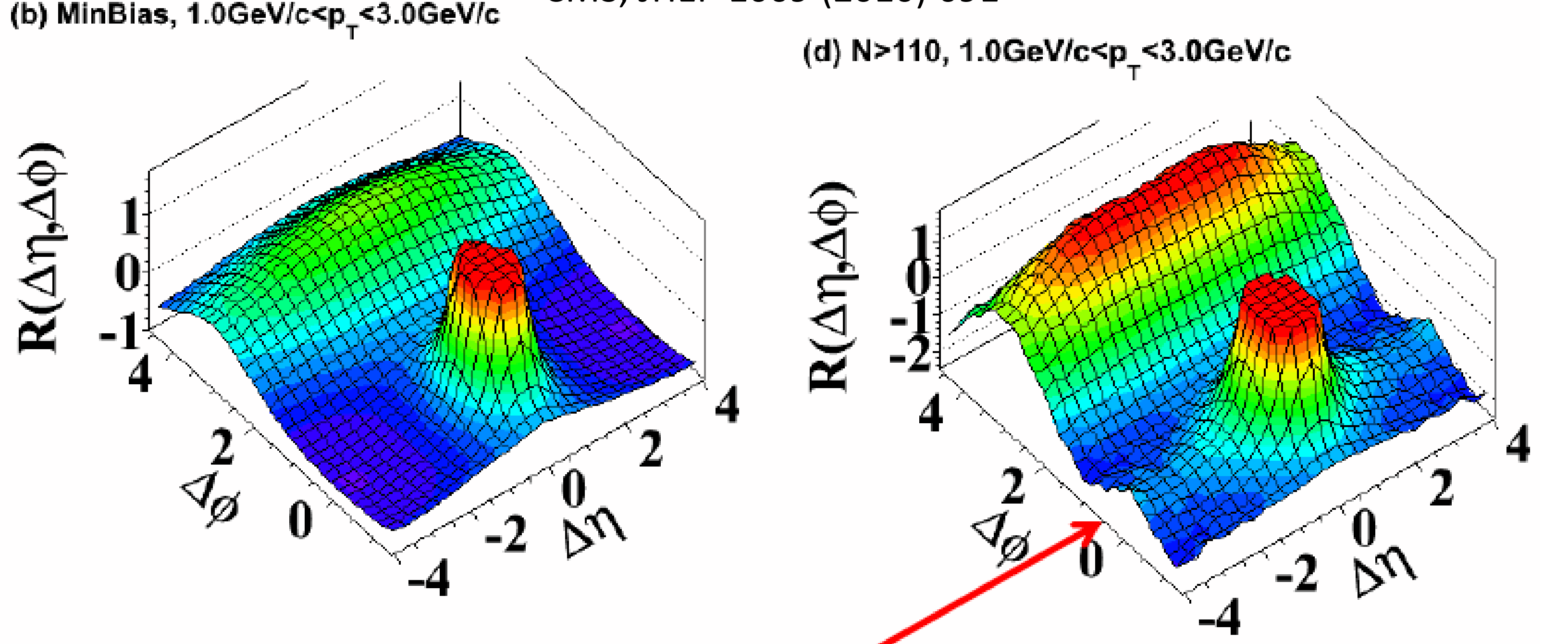
Ridge in small systems

usual p-p collision ⟷ high multiplicity p-p collision

Minimum Bias
no cut on multiplicity

High multiplicity data set
and N>110

CMS, JHEP 1009 (2010) 091



New "ridge-like" structure extending to large $\Delta\eta$ at $\Delta\phi \sim 0$

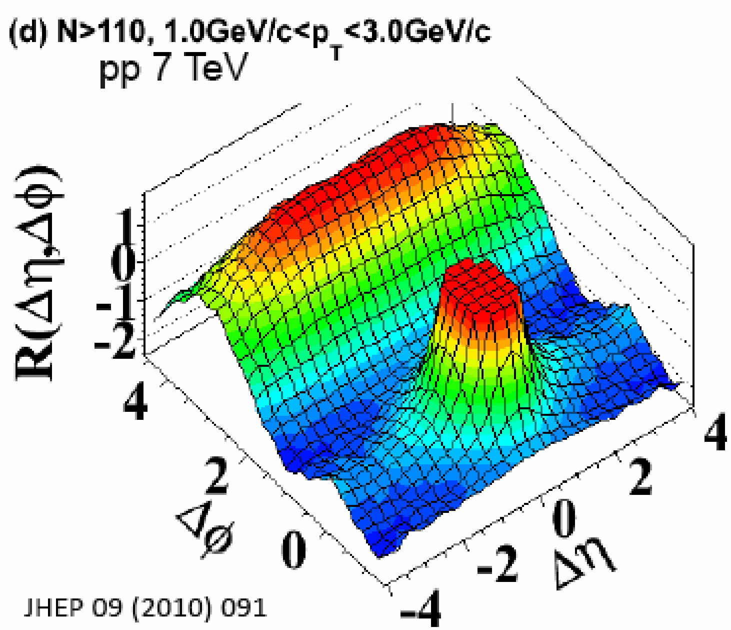
- Why wasn’t it discovered long ago by HEP?
- Two types of discoveries:
  - Theoretically predicted, and experimentally verified
  - Surprises
- HEP moved on to more exclusive processes
- There may be still important physics that were missed in last half century

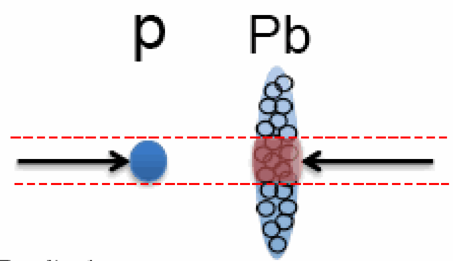
p-p collision (high Mult.)

p-Pb collision (high Mult.)

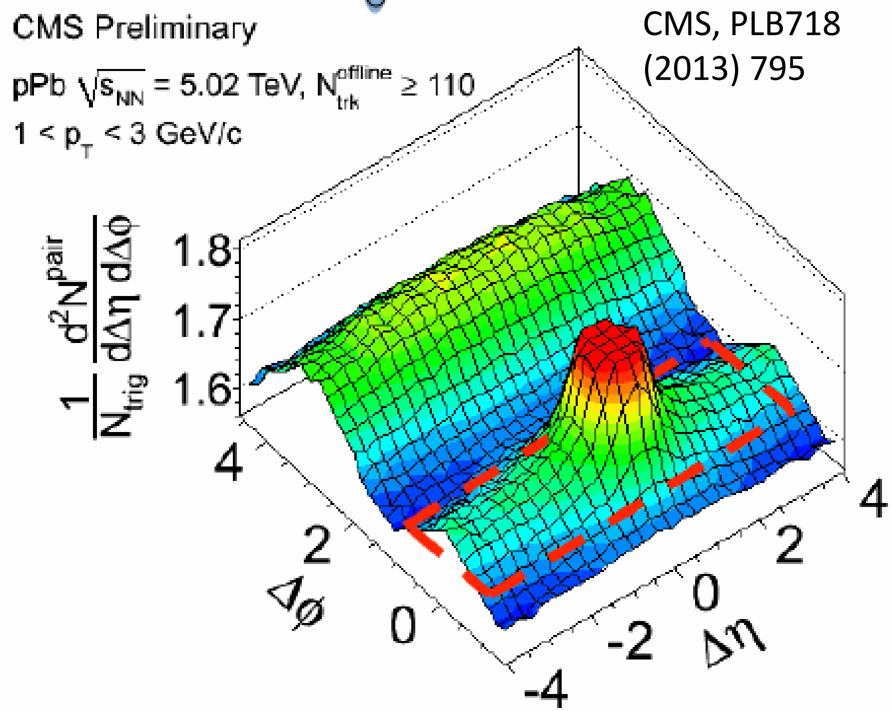
Physical origin unclear

CMS, JHEP 1009 (2010) 091





CMS, PLB718 (2013) 795

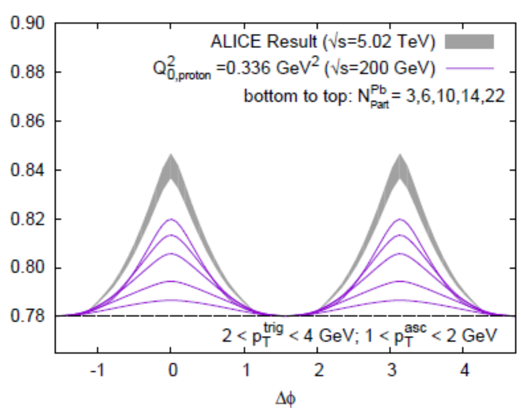


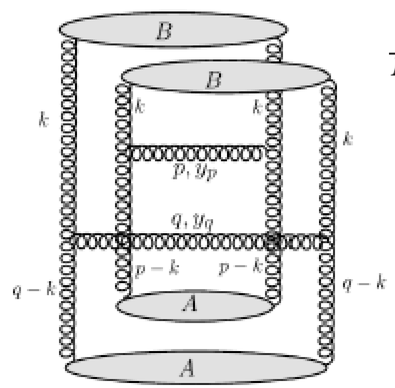
Much bigger than pp

CGC/Glasma

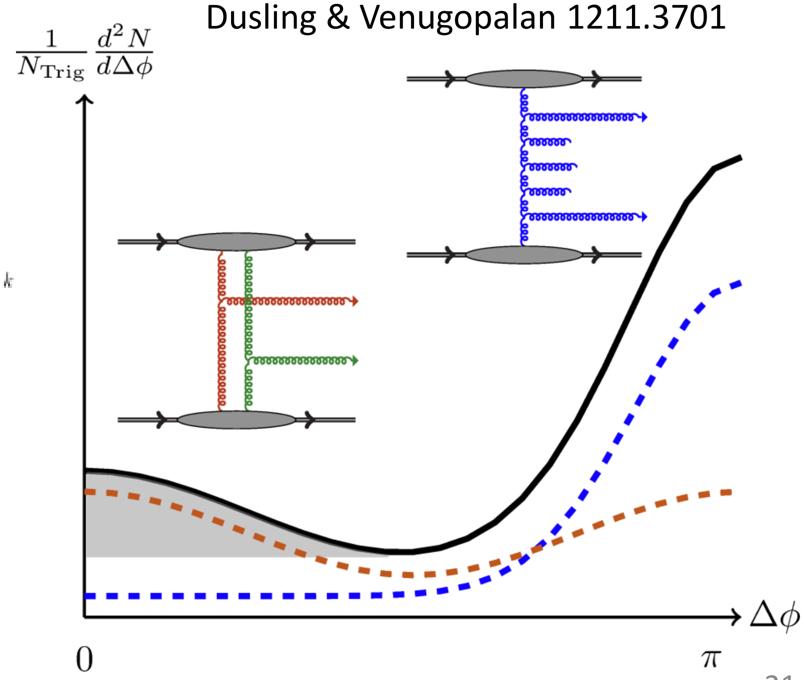
There is an intrinsic correlation in azimuthal angle coming from the two-particle production process, such as the one shown in Fig. 11 [92]. There is only a single loop momentum k_T in this two-particle production process, causing correlations. Because the single gluon distribution peaks at the saturation scale Q_s, large probability is found for production of two particles with their momenta p_T and q_T parallel to each other such that $|p_T - k_T| \sim Q_s$ and $|q_T - k_T| \sim Q_s$. These processes therefore cause small angle correlations at $\Delta\phi = 0$. Because the correlations originate from the very early times of the collision, $\tau_{\text{init.}}$, they can persistent to large rapidity differences, $\Delta y = 2\ln(\tau_{\text{f.o.}}/\tau_{\text{init.}})$ where $\tau_{\text{f.o.}}$ is the particle freeze-out proper time.

Dusling and Venugopalan, arXiv:1302.7018



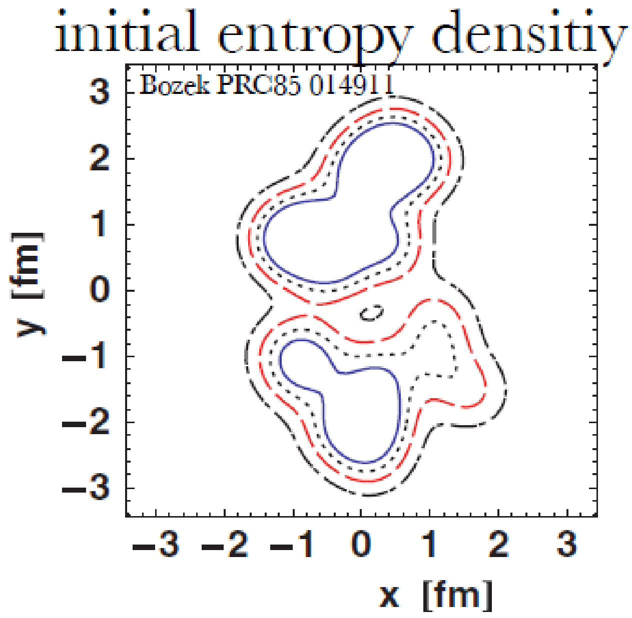


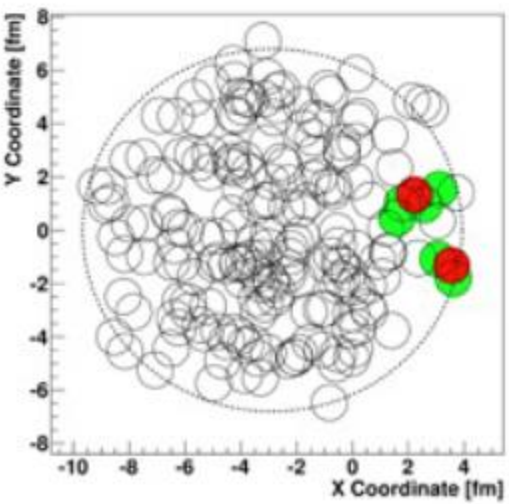
Dusling & Venugopalan 1211.3701



Another explanation: Hydro flow

- In heavy-ions, subtract v_2 → non-zero finite correlation: near-side large $\Delta\eta$ ridge, away-side double peak → v_3
- In pp, pA (and possibly dA) systems, subtract uniform pedestal → non-zero finite correlation: large $\Delta\eta$ ridge → v_2 (and v_3)



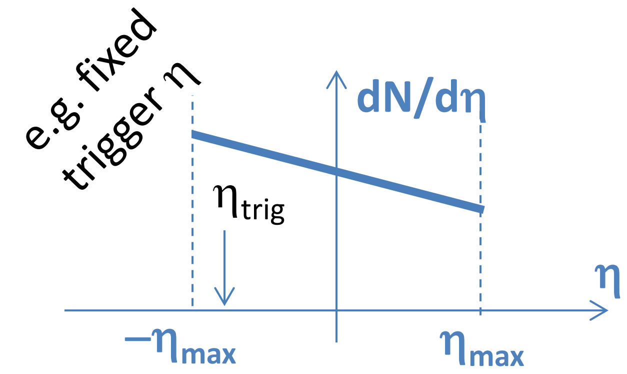


Acceptance correction *revisited*

L.Xu,C.H.Chen,FW, PRC**88** (2013) 064907

- Two-particle acceptance correction by mixed-events is, in principle, wrong.

$$\frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}\Big/\frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$



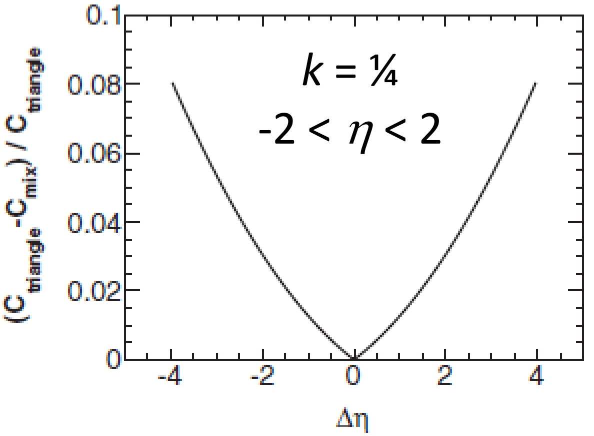
- Should just be corrected by single particle efficiencies: $\frac{1}{N_{trig}}\frac{d^2N}{d\Delta\eta d\Delta\varphi}\Big/\varepsilon_{trig}\varepsilon_{assoc}$

- How much error it makes?

$$\frac{dN}{d\eta} \propto 1 + k\frac{\eta}{\eta_m},$$

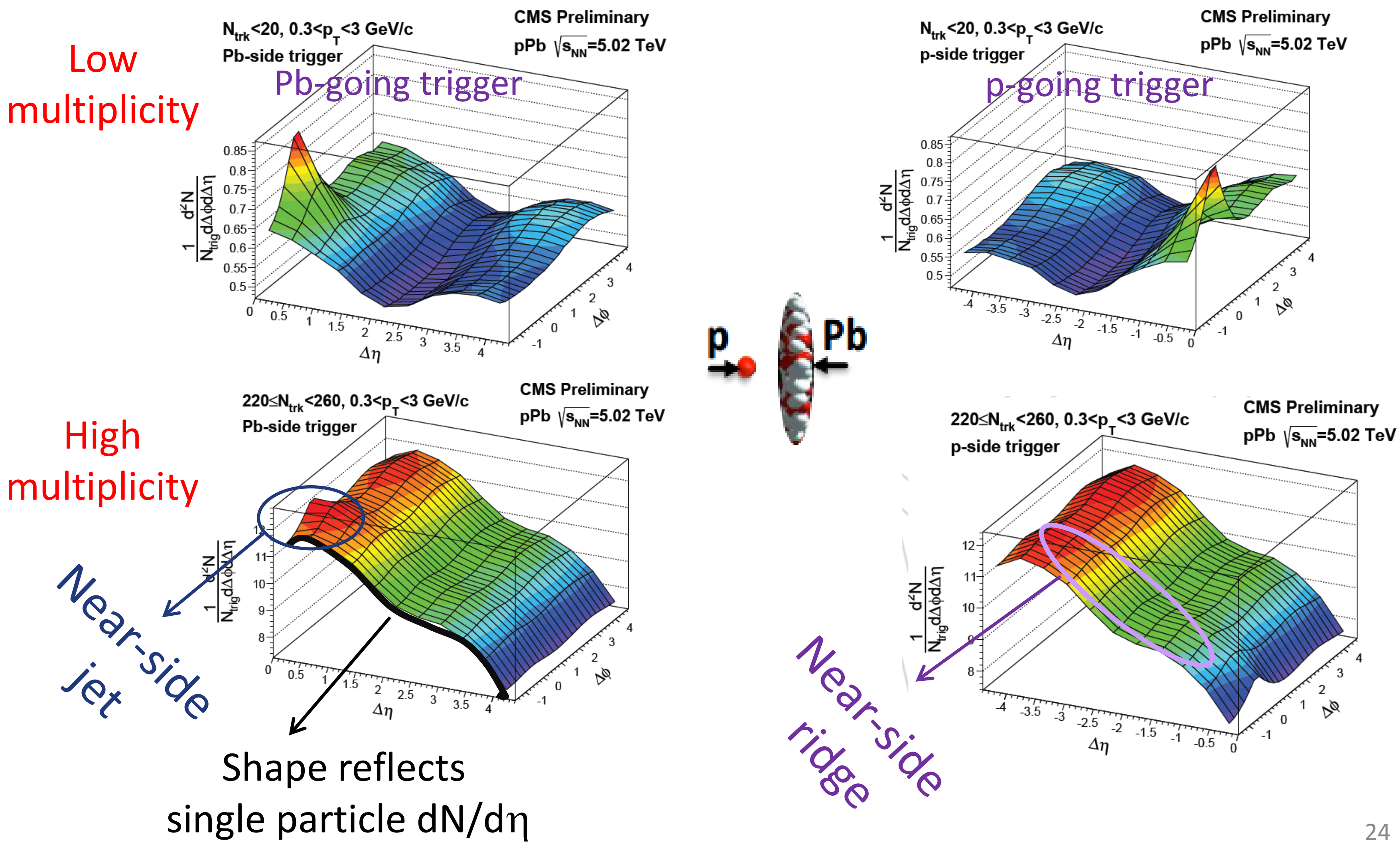
$$\frac{dN}{d\Delta\eta} \propto \int_{\eta_1}\int_{\eta_2}\left(1+k\frac{\eta_1}{\eta_m}\right)\left(1+k\frac{\eta_2}{\eta_m}\right) \times \delta(\eta_2-\eta_1-\Delta\eta)d\eta_1 d\eta_2$$
$$= \int_{\max(-\eta_m,-\eta_m-\Delta\eta)}^{\min(\eta_m,\eta_m-\Delta\eta)}\left(1+k\frac{\eta_1}{\eta_m}\right)\left(1+k\frac{\eta_1+\Delta\eta}{\eta_m}\right)d\eta_1$$
$$= (2\eta_m-|\Delta\eta|)\left\{1+\frac{1}{6}k^2\left[2-2\frac{|\Delta\eta|}{\eta_m}-\left(\frac{\Delta\eta}{\eta_m}\right)^2\right]\right\}.$$

$$\frac{C_{\rm triangle}-C_{\rm mix}}{C_{\rm triangle}} = \frac{k^2}{6+2k^2}\frac{|\Delta\eta|}{\eta_m}\left(2+\frac{|\Delta\eta|}{\eta_m}\right)$$



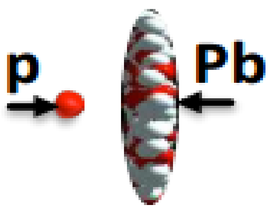
Dihadron per trigger pair density

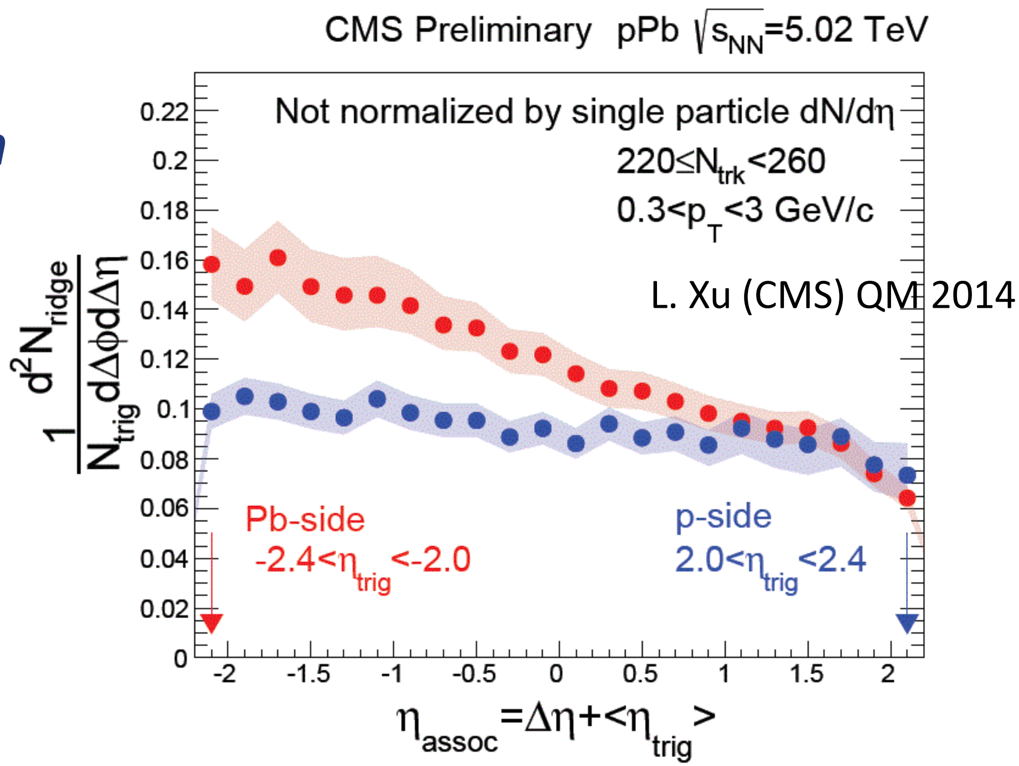
L. Xu (CMS) QM 2014



Ridge yield vs η_{assoc}

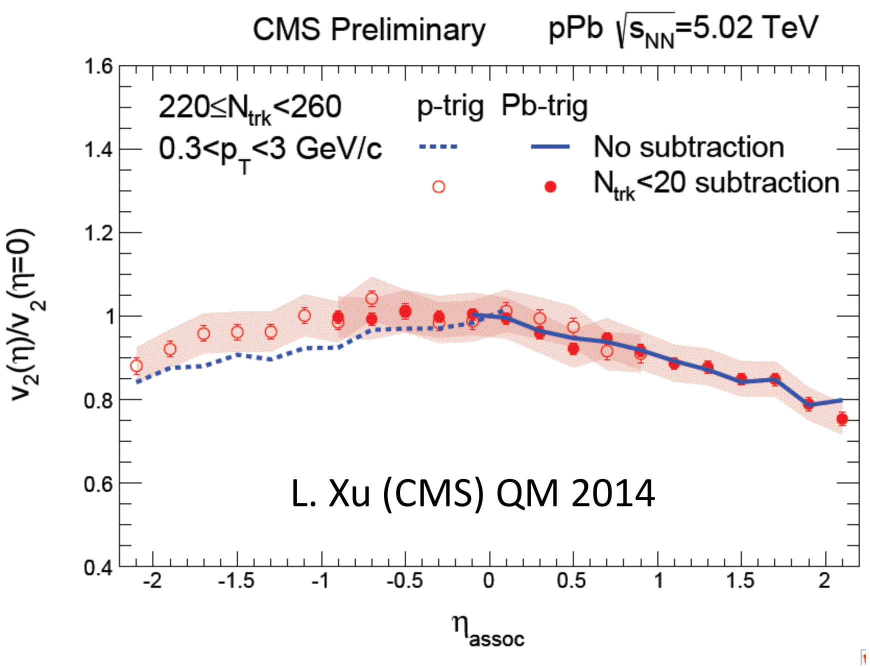
Near-side ridge after jet subtraction





- Near-side ridge yield: different η dependences for p-going and Pb-going triggers

η-dependence of $v_2(\eta)/v_2(0)$

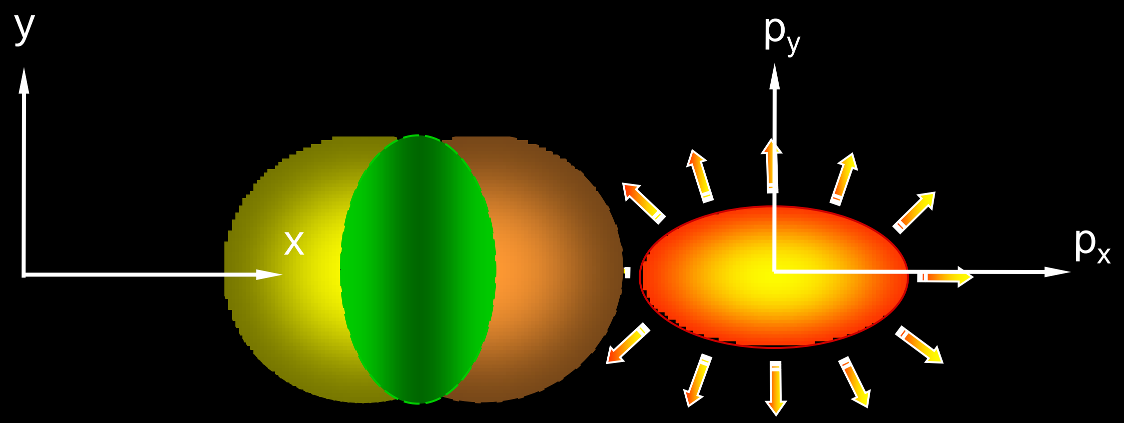


- v_2 shape is η dependent in p+Pb!
- v_2 asymmetric about mid-rapidity

Flow correlations

Anisotropy Parameter v_2

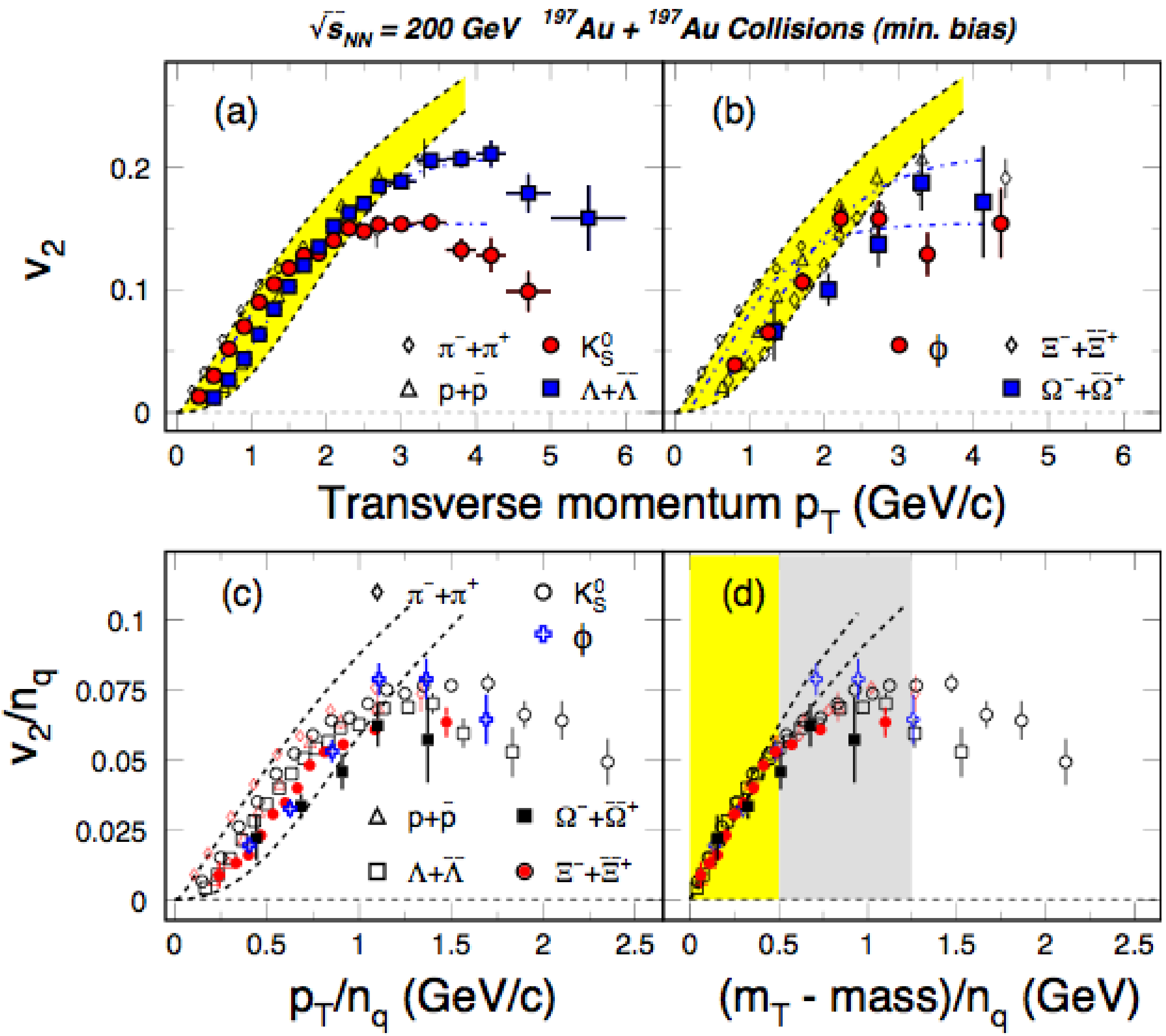
coordinate-space-anisotropy ➔ momentum-space-anisotropy



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

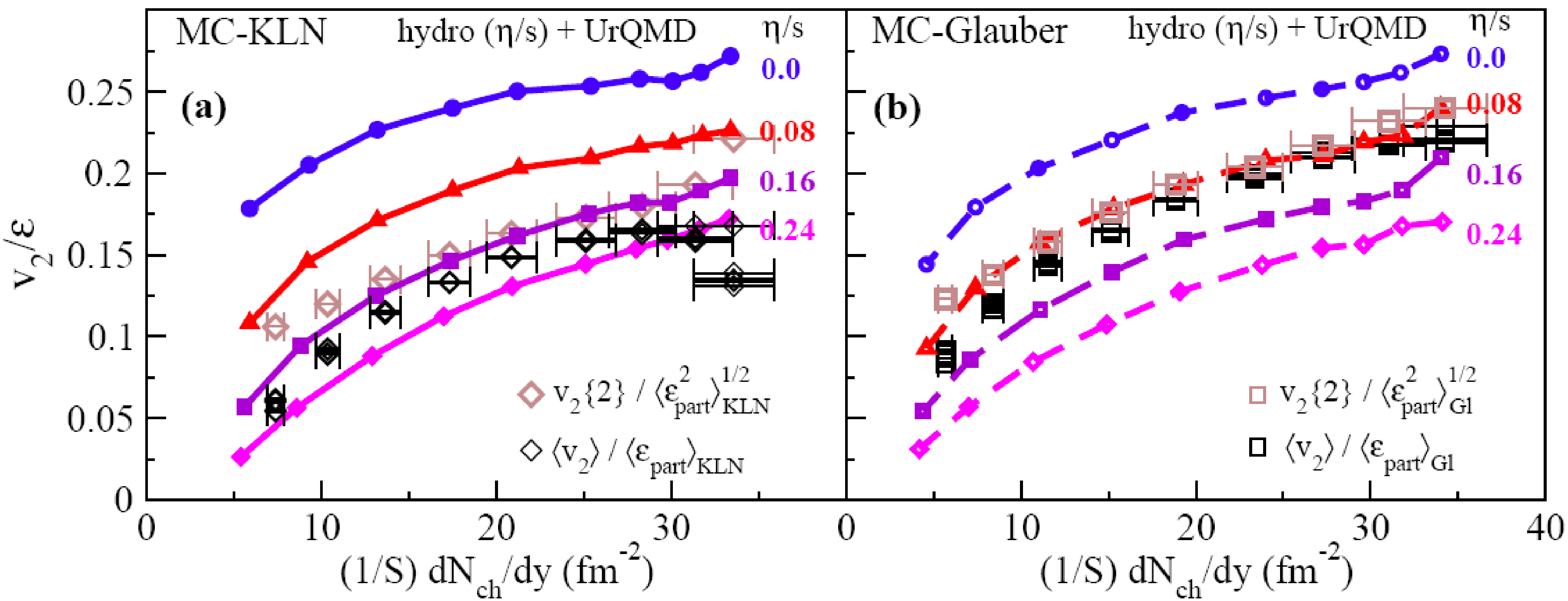
Collectivity, Deconfinement at RHIC



- Low p_T ($\leq$ 2 GeV/c): hydrodynamic mass ordering
- High p_T (> 2 GeV/c): ***number of constituent quarks scaling***

→ Quark degrees of freedom, deconfinement, ***Partonic Collectivity,***

Comparison with Hydrodynamics

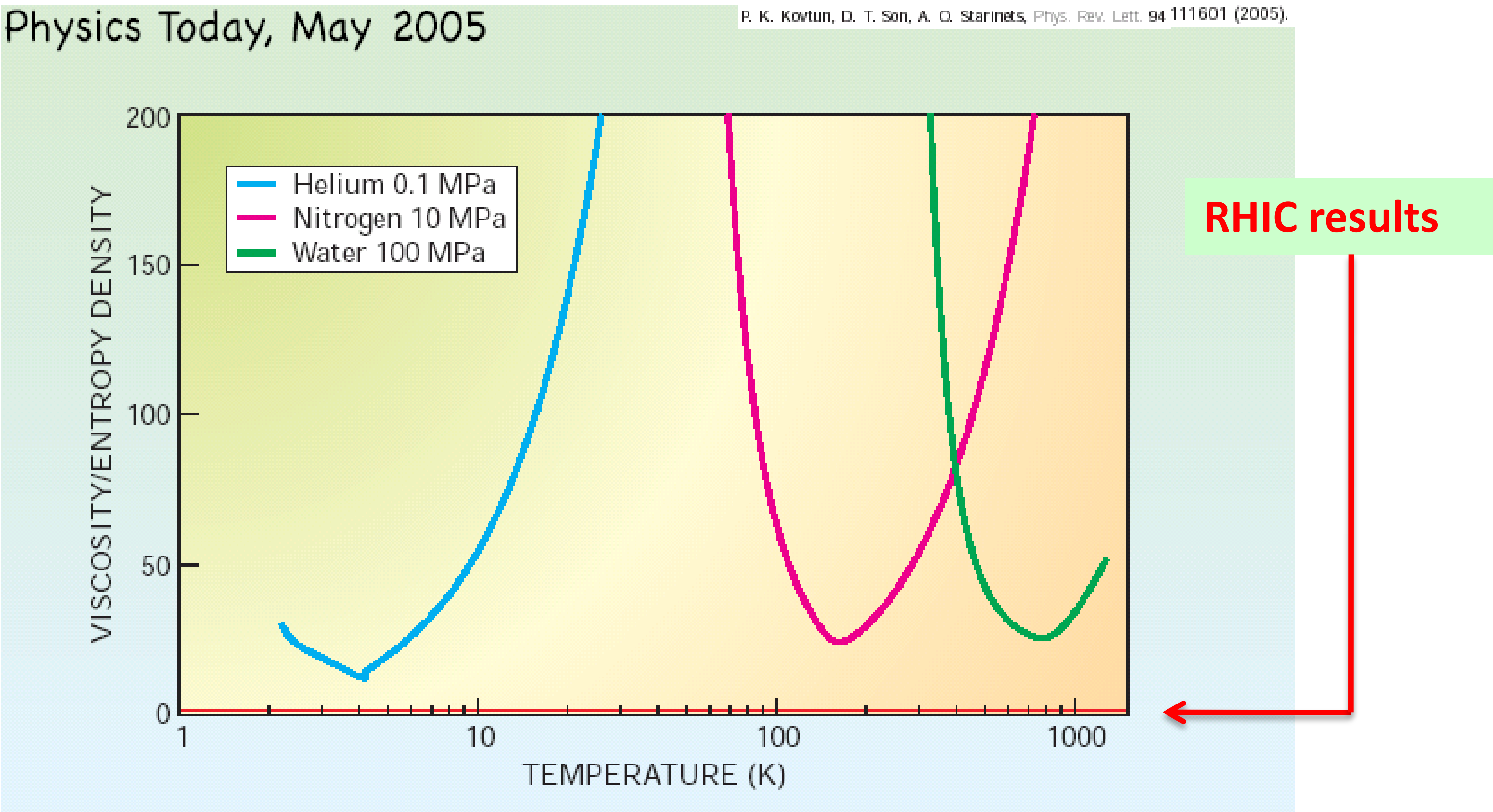


Model: Song *et al. arXiv:1011.2783*

➔ ***Small value*** of viscosity to entropy density ratio ***η/s***

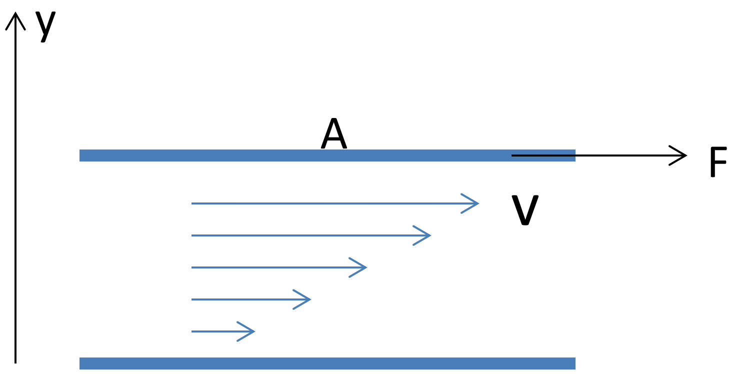
➔ Model uncertainty dominated by ***initial eccentricity ε***

Low *η/s* for QCD Matter at RHIC



- ***η/s* ≥ 1/4π**
- ***η/s***(QCD matter) < ***η/s***(QED matter)

Viscosity quantum limit



$$\frac{F}{A} = \eta \frac{\partial v}{\partial y}$$

$$\eta = \frac{1}{3} n p l_{mfp}$$

$$l_{mfp} = 1/(n\sigma)$$

$$p l_{mfp} \geq \hbar$$

$$s \sim 4 n k_B$$

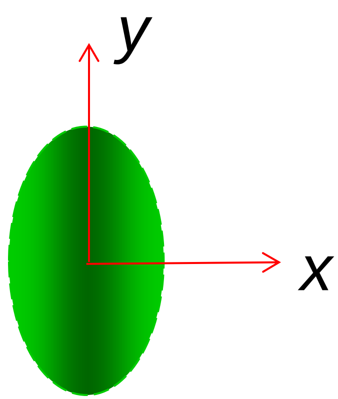
$$\eta / s > \hbar / 4\pi k_B$$

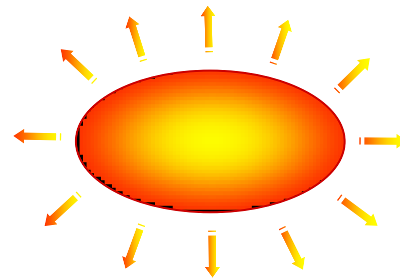
$$\eta / s > 1/4\pi$$

Kovtun, Son, Starinets, PRL 94 (2005) 111601
Schafer, arXiv:0912.4236

Does it have to be all pressure-driven hydro flow?

Uncertainty principle





$$\Delta x \cdot \Delta p > \hbar / 2$$

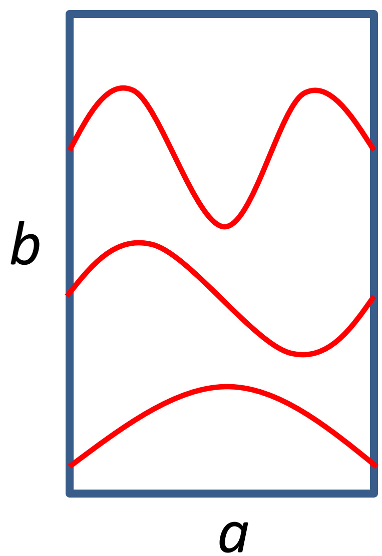
$$p_x > p_y$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

D. Molnar, FW, and C.H. Greene, arXiv:1404.4119

Infinite square well

Freshmen QM-I



$$-\frac{\hbar^2}{2m}\nabla^2\psi = E\psi \quad \Rightarrow \quad \psi \propto \begin{cases} \cos\frac{n_{odd}\pi}{a}x \\ \sin\frac{n_{even}\pi}{a}x \end{cases}$$

Take even mode for example:

$$\left\langle p_x^2 \right\rangle = \hbar^2 k^2 \; ; \quad \left\langle x^2 \right\rangle = \frac{a^2}{4} - \frac{2}{k^2} \; ; \quad k = \frac{n_{odd}\pi}{a}$$

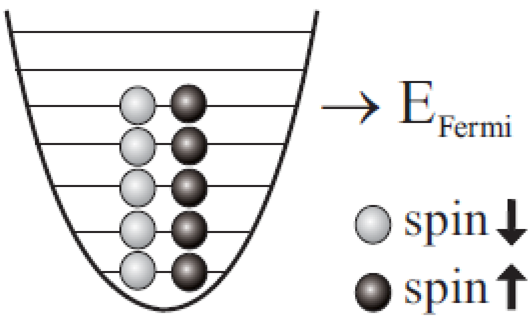
$$\sqrt{\left\langle p_x^2 \right\rangle \cdot \left\langle x^2 \right\rangle} = \hbar\sqrt{\frac{k^2 a^2}{4} - 2} = \hbar\sqrt{\frac{\pi^2}{4} n_{odd}^2 - 2} > \hbar / 2$$

$$v_2 = \frac{\left\langle p_x^2 \right\rangle - \left\langle p_y^2 \right\rangle}{\left\langle p_x^2 \right\rangle + \left\langle p_y^2 \right\rangle} = \frac{b^2 - a^2}{b^2 + a^2} = \varepsilon \quad \text{for all } n.$$

Harmonic oscillator

Freshmen QM-I

$$\left(-\frac{\hbar^2}{2m}\nabla^2+\frac{1}{2}m\omega^2x^2\right)\psi=E\psi\ ;\qquad E=\left(n+\frac{1}{2}\right)\hbar\omega$$



$$\left\langle\frac{p_x^2}{2m}\right\rangle=\left\langle\frac{1}{2}m\omega^2x^2\right\rangle=\frac{E}{2}=\frac{1}{2}\left(n+\frac{1}{2}\right)\hbar\omega$$

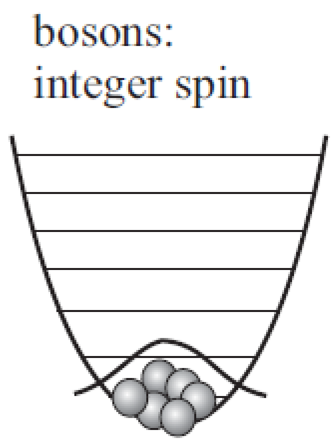
$$\sqrt{\left\langle p_x^2\right\rangle\left\langle x^2\right\rangle}=\left(n+\frac{1}{2}\right)\hbar$$

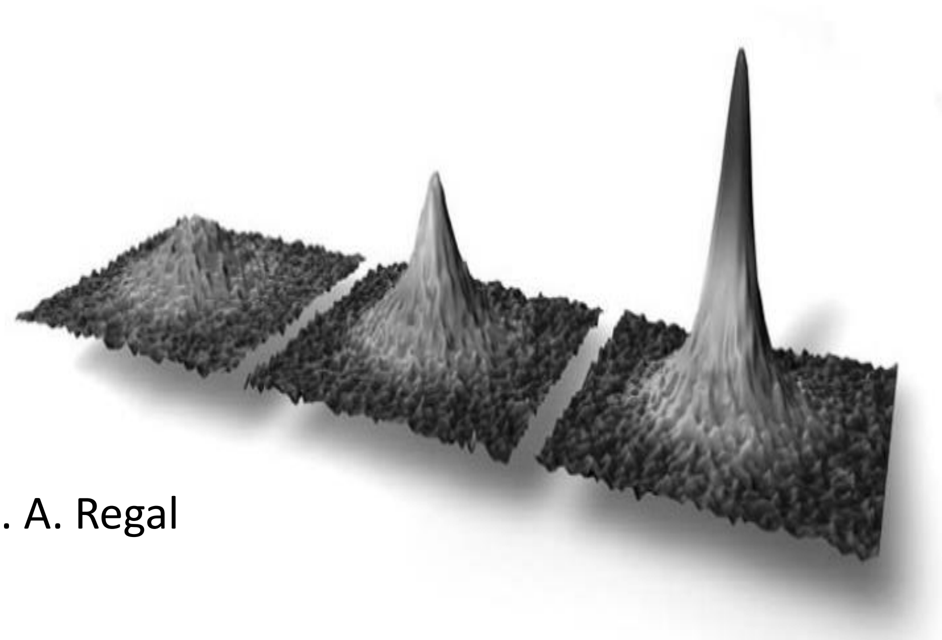
$$v_2=\frac{\left\langle p_x^2\right\rangle-\left\langle p_y^2\right\rangle}{\left\langle p_x^2\right\rangle+\left\langle p_y^2\right\rangle}=\frac{\omega_x-\omega_y}{\omega_x+\omega_y}$$

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

$v_2=\varepsilon$ for each and all n

Bose-Einstein Condensate

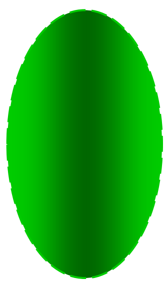


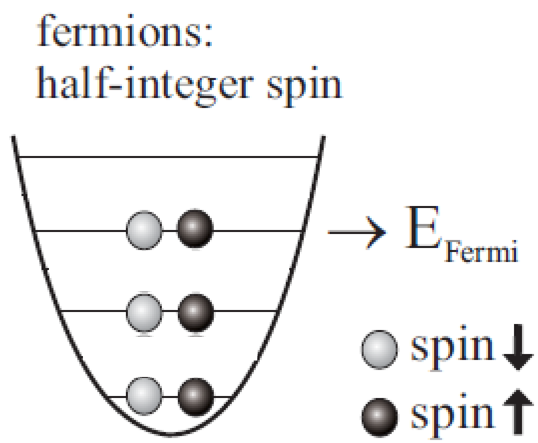


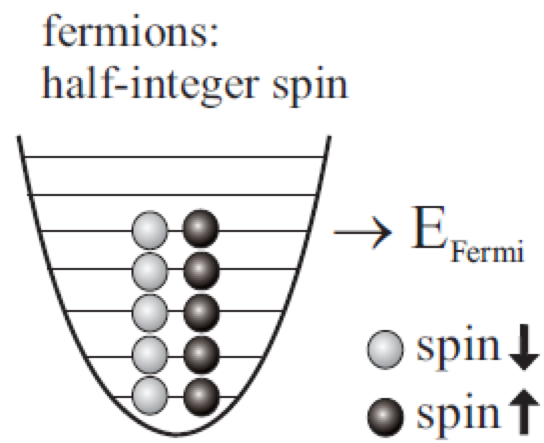
D. S. Jin and C. A. Regal

Single ground state in anisotropic trap → large momentum anisotropy

Thermal probability







x, y at same Fermi energy, so different number of filled energy levels.

At high temperature, classical limit, sum is approximated by integral:

$$\frac{dN}{d\mathbf{p}} = N\frac{\int d\mathbf{r}\, e^{-H_1(\mathbf{p},\mathbf{r})/T}}{\int d\mathbf{r}\, d\mathbf{p}\, e^{-H_1(\mathbf{p},\mathbf{r})/T}} = N\frac{e^{-K(\mathbf{p})/T}}{\int d\mathbf{p}\, e^{-K(\mathbf{p})/T}}$$

then it's independent of potential.

It's isotropic at all temperature because $K=(p_x^2+p_y^2)/2m$ is isotropic.

Is QGP hot?

Size r ~ 1 fm
Intrinsic momentum/energy scale ~ 1/r ~ 200 MeV

QGP temperature T ~ 300 MeV
Typical momentum/energy ~ T ~ 300 MeV

QGP is **not** hot at all.
Quantum effect must be present.

Thermal probability weight

$$\rho(\mathbf{r}) \equiv \frac{dN}{d\mathbf{r}} = \frac{1}{Z}\sum_j |\psi_j(\mathbf{r})|^2\, e^{-E_j/T}$$

$$f(\mathbf{p}) \equiv \frac{dN}{d\mathbf{p}} = \frac{1}{Z}\sum_j |\psi_j(\mathbf{p})|^2\, e^{-E_j/T}$$

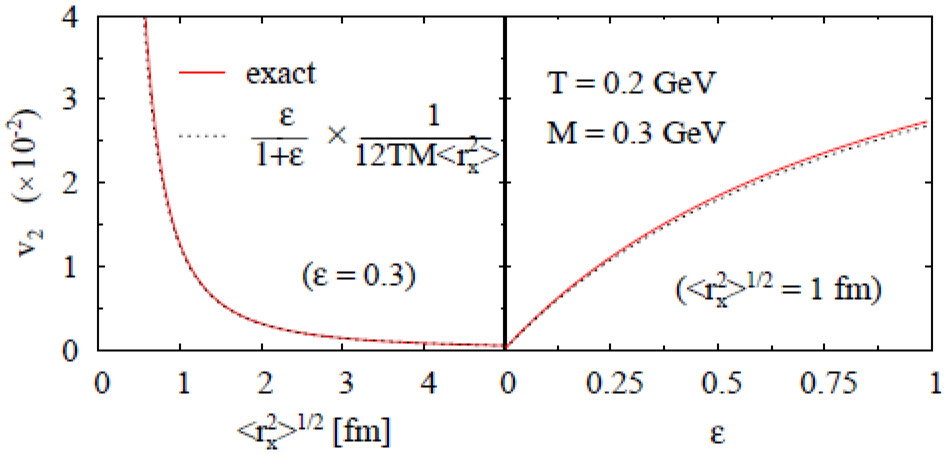
$$Z \equiv \textstyle\sum_j e^{-E_j/T}$$

$$\langle p_i^2 \rangle = \frac{M\omega_i}{2}\coth\frac{\omega_i}{2T}$$

$$\langle r_i^2 \rangle = \frac{1}{2M\omega_i}\coth\frac{\omega_i}{2T}\,.$$

Initial v_2 from QM

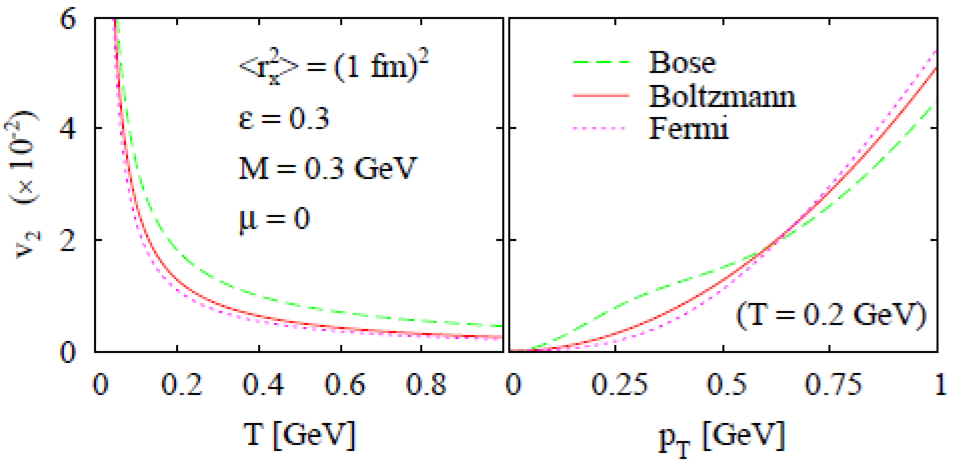
$$\bar{v}_2 \approx \frac{\hbar^2}{12 k_B T M \langle r_x^2 \rangle} \cdot \frac{\varepsilon}{1+\varepsilon}$$



D. Molnar, FW, and C.H. Greene, arXiv:1404.4119

$$\bar{v}_2 \approx \frac{\hbar^2}{12 k_B T M \langle r_x^2 \rangle} \cdot \frac{\varepsilon}{1+\varepsilon}$$

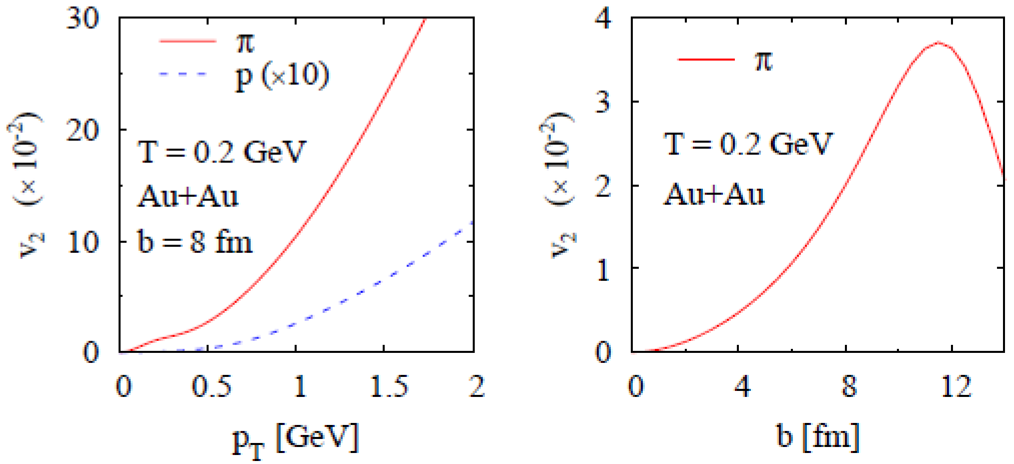
$$v_{2n}(p_T) = h_n\left(\frac{p_T^2}{2MT}(S_y - S_x)\right) \ , \quad S_i \equiv \frac{T}{\omega_i}\tanh\frac{\omega_i}{2T}$$



D. Molnar, FW, and C.H. Greene, arXiv:1404.4119

Typical Au+Au collisions

$$b = 8 \text{ fm: } \langle r_x^2 \rangle^{1/2} = 1.5 \text{ fm and } \langle r_y^2 \rangle^{1/2} = 2.2 \text{ fm}$$

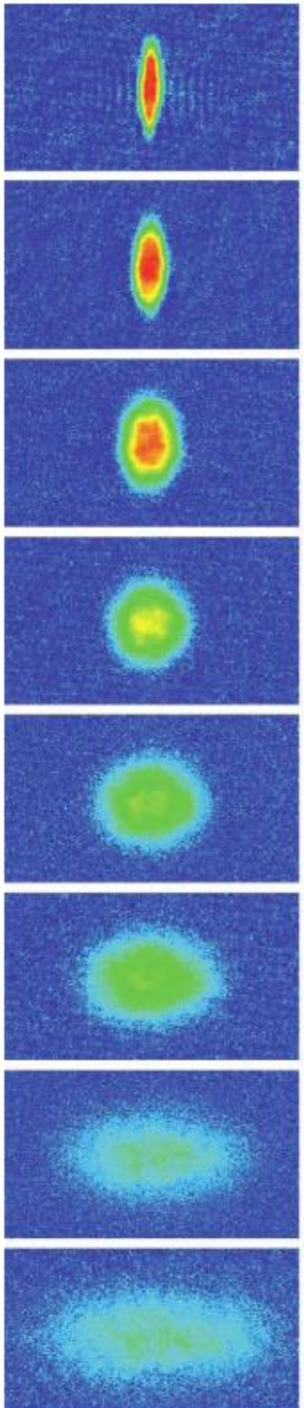


D. Molnar, FW, and C.H. Greene, arXiv:1404.4119

Transverse profile from SHO

$$\rho(\mathbf{r}) \propto \exp\left(-\sum_i \frac{r_i^2}{2\langle r_i^2\rangle}\right) , \quad f(\mathbf{p}) \propto \exp\left(-\sum_i \frac{p_i^2}{2\langle p_i^2\rangle}\right)$$

This may not correspond exactly to heavy-ion collision energy density profile, but close.



Cold atoms

Strong elliptic anisotropy

K. M. O'Hara *et al.*, Science 298, 2179 (2002).

Lithium atoms M ~ 6000 MeV
Temperature T ~ 1 μK ~ 10^{-16} MeV
Trap size x ~ 20 μm, y ~ 100 μm

Typical momentum $(TM)^{1/2}$ ~ 10^{-6} MeV
Intrinsic momentum quantum ~ 1/r ~ 10^{-8} MeV, negligible.

Typical energy ~ T ~ 10^{-16} MeV
Intrinsic energy quantum $1/(mr^2)$ ~ 10^{-20} MeV, negligible.

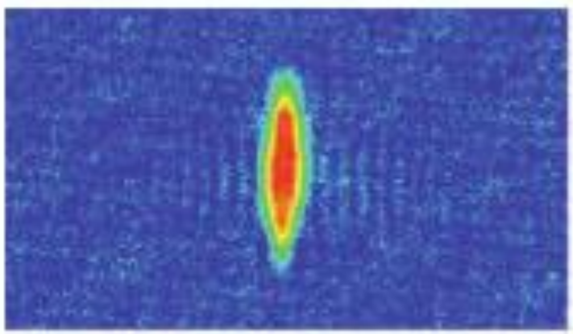
Cold Lithium atoms are actually "hotter" than the hot QGP.

$$\bar{v}_2 \approx \frac{\hbar^2}{12 k_B T M \langle r_x^2 \rangle} \cdot \frac{\varepsilon}{1+\varepsilon} \quad \sim 10^{-5}$$

The observed large v_2 is indeed due to strong interactions.

Is quantum v_2 real?

- It should be… but need experiment to verify
- Would be neat to verify QM and uncertainty principle



Cold atom experiment

- Need trap size **x100 smaller**
- Or need **nano-Kelvin** temperature

Proposing a cold atom quantum simulator for high-energy nuclear physics

Control the interaction

- Hydrodynamics is only an assumption
- Is initial QM v_2 important after hydro evolution?
- When does hydro sets in and takes over?
- Will the initial QM v_2 be washed out by hydro?
- Current hydro implementation is classical
- Need to incorporate QM into hydro: quantum hydrodynamics

Shooting fast atoms through trap

- jet-quenching partonic energy loss mechanisms are far from clear. A very active and extensive field
- Can we gain insights from cold atoms?
- Shoot fast atoms through cold atom system

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Probing strongly interacting atomic gases with energetic atoms

Yusuke Nishida
Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA and Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
(Received 26 October 2011; revised manuscript received 9 April 2012; published 29 May 2012)

We investigate properties of an energetic atom propagating through strongly interacting atomic gases. The operator product expansion is used to systematically compute a quasiparticle energy and its scattering rate both in a spin-1/2 Fermi gas and in a spinless Bose gas. Reasonable agreement with recent quantum Monte Carlo

- External hard probes under full control

Summary

- **Particle correlations are a powerful tool to study pp, pA, AA collisions**
- **Unambiguous signal of strongly interacting QGP from high-p_T jet-quenching data.**
- **Low p_T anisotropic flow data indicate hydrodynamic behavior of sQGP. Extracting transport properties (such as η/s) from measured data still need extra effort. Initial anisotropy may not be neglected.**
- **There should be indispensable information at intermediate p_T from jet-medium interactions (not discussed in this lecture). Need creative mind and novel approaches.**