A tale of three QGPs: the large, the small, and the exotic

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Colorado School of Mines
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University of Colorado Boulder

Утро в сосновом лесу

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Outline

- Part 0: introduction
  —History lesson, units, physical constants, some basics
- Part I: the large
  —Overview of conventional heavy ion physics with large nuclei
- Part II: the small
  —Some recent results from heavy ion physics with small nuclei
- Part III: the exotic
  —Opportunities to test fundamental symmetries with heavy ion physics

Learning goals for Part 0

- A bit of a history lesson
- "Natural units"
- A basic sense of scale
- Fundamentals of quantum chromodynamics (QCD)
  —quarks
  —gluons
  —hadrons and confinement

Historical Perspective

"Those who do not remember George Santayana are condemned to paraphrase him." - Unknown

- 400 BCE Democritus hypothesizes atoms
- 1687 Newton publishes *Philosophiae Naturalis Principia Mathematica*
- 1900 Planck's Law
- 1905 Einstein's 4 papers
- 1911 Rutherford scattering
- 1913 Bohr atom
- 1924 de Broglie wavelength
- 1925 Heisenberg's Matrix mechanics
- 1926 Schrödinger equation
- 1927 Dirac's relativistic quantum mechanics

Historical Perspective

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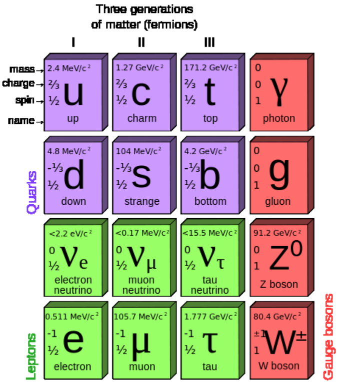
- 1963 Gell-Mann's Quark Model (particle zoo)
- 1965 Additional degree of freedom postulated for quarks by Han and Nambu
- 1969 Deep inelastic scattering experiments prove the existence of quarks
- 1972 Color charge and basic framework of **quantum chromodynamics**
- 1973 Asymptotic Freedom discovered by Gross, Politzer, and Wilczek
- 1975 Collins and Perry formulate a QCD plasma
- 1980 Shuryak coins term quark-gluon plasma (QGP)
- 2000 RHIC is operational
- 2010 First heavy ion collisions at LHC

What we've learned so far

The standard model of particle physics describes three of the four known fundamental forces in nature, the interactions of matter particles (fermions) as mediated by exchange particles (bosons)



- Electromagnetic force is responsible for interactions among charged particles
- Weak force is responsible for flavor dynamics, e.g. lepton decays and nuclear beta decays; all weak processes are maximally P-violating and slightly CP-violating
- Strong force binds protons and nucleons together into nuclei (residual) and quarks together into hadrons (fundamental)
- Gravity, the force responsible for interactions between massive bodes, is not part of the standard model. Don't ask...

What we've learned so far

Which view of the world is the right one? It depends!

	slow	**fast**
large	**Classical Physics** (most of our daily life is here!)	**Special Relativity** (effects noticeable in GPS and air travel)
small	**Quantum Mechanics** (solid state devices are based on small stuff)	**Quantum Field Theory** (only self-consistent way to combined QM and SR)

Note: GR effects **also** noticeable for GPS and air travel

Physical constants and units

- High energy physics makes physical constants very easy to remember!
- Planck's constant $\hbar = 1$
  —Shows up everywhere in quantum mechanics
- Speed of light $c = 1$
  —Shows up everywhere in special relativity
- Boltzmann's constant $k_B = 1$
  —Shows up everywhere in thermal physics and stat mech

Typical sizes and scales for heavy ion physics

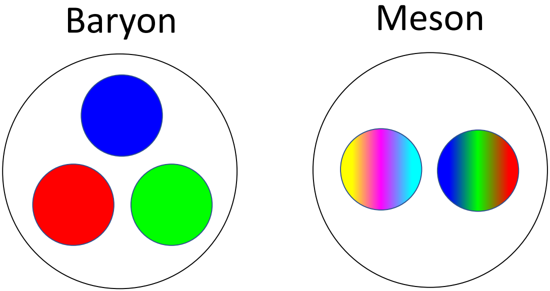
- Mass of proton $= 938.3$ MeV $= 1.007$ amu $= 1.673 \times 10^{-27}$ kg
- Typical energy $= 1$ GeV $= 1.602 \times 10^{-10}$ J
- Typical size $= 1$ fm $= 10^{-15}$ m
- Typical time $= 1$ fm $= 3.336 \times 10^{-24}$ s
- Typical temperature $= 200$ MeV $= 2.321 \times 10^{12}$ K

QCD as explained by approximate analogy to QED

QED		QCD	
electric charge	$\leftrightarrow$	color charge	coupling
electrons	$\leftrightarrow$	quarks	matter fermions
photons	$\leftrightarrow$	gluons	exchange bosons
atoms	$\leftrightarrow$	nucleons	(stable) bound states
molecules	$\leftrightarrow$	nuclei	compound states

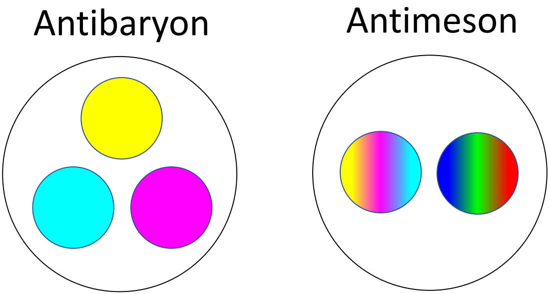
- Only one kind electric charge, three kinds of color charge
- Photons do not have electric charge, gluons do have color charge
- Extra credit: only one photon, eight different gluons (gauge group structure)

QCD bound states



- QCD bound states are generically called **hadrons**
- Typically grouped into two categories:
  —**Mesons** are made of quark and antiquark $q\bar{q}$ (e.g. pions)
  —**Baryons** are made of three quarks qqq (e.g. nucleons)
- Bound states must be color-singlet
  —rgb (baryons), $\bar{r}\bar{g}\bar{b}$ (antibaryons), $(r\bar{r} + g\bar{g} + b\bar{b})/\sqrt{3}$ (mesons)
- In fact all physical observables must be color-singlet
  —No bare quarks or gluons can be found in nature—confinement

QCD bound states



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QCD Potential and confinement

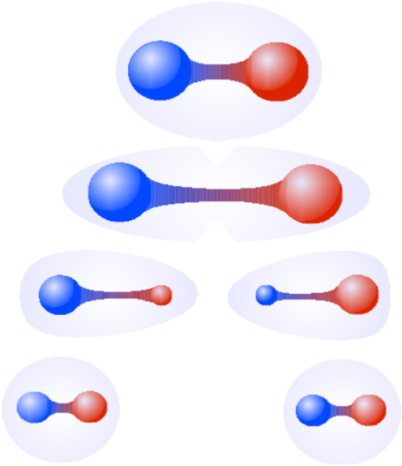
- The QED potential for l^+l^-

$$V(r) = -\frac{\alpha_{EM}}{r}$$

- The QCD potential for $q\bar{q}$

$$V(r) = -C_F\frac{\alpha_s}{r} + kr$$

- Linear rise of potential → greater separation means greater energy (and therefore confinement)
- New pairs of quarks are created when energy exceeds mass



The six flavors of quarks

flavor	charge	mass
down	-1/3 e	3.0–7.0 MeV
up	2/3 e	1.5–3.0 MeV
strange	-1/3 e	95 ± 25 MeV
charm	2/3 e	1.25 ± 0.09 GeV
bottom	-1/3 e	4.70 ± 0.07 GeV
top	2/3 e	174.2 ± 3.3 GeV

- No bound states with top quarks
  (so heavy they decay weakly before a bound state can be formed)
- All others can form bound states
  —Any combination of quarks you can imagine is allowed
  —Though some have to be part of a linear combination
  —Sometimes a single combination can be more than one particle

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A few examples

- $p = uud$, $n = udd$
- $\pi^+ = u\bar{d}$, $\pi^- = \bar{u}d$, $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$
- $\Lambda^0 = uds$, $\Lambda_c^+ = udc$, $\Lambda_b^0 = udb$
- $K^- = \bar{u}s$, $D^+ = \bar{d}c$, $B^- = \bar{u}b$
- $c\bar{c} = \eta_c, J/\psi, \chi_c, h_c$

Summary for Part 0

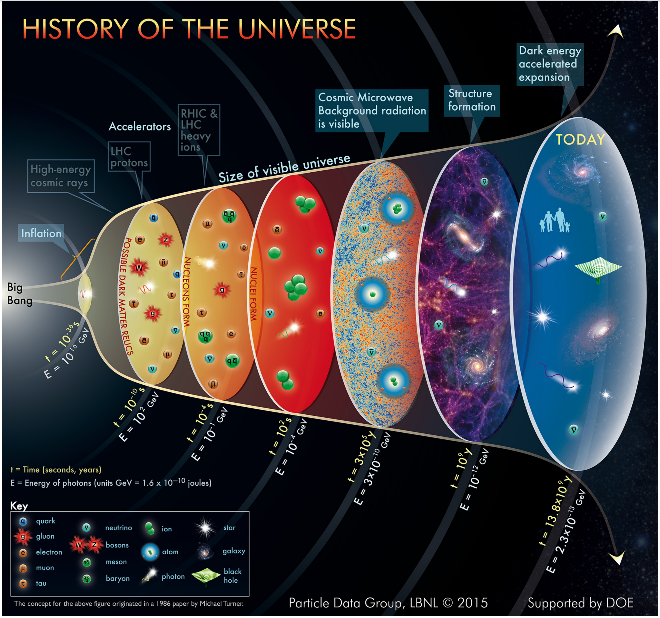
- QCD is the theory of strong interactions
- Quarks interact with each other via gluon exchange
- Gluons can also interact with each other
- There are three colors (and eight gluons)
- Bound states are color-singlet and are called hadrons
- Quarks and gluons can never be observed individually as free particles—confinement

Learning goals for Part I

The QGP:

- Is a phase of matter with approximately free quarks and gluons
- Existed in the very early universe
- Is created in the lab in collisions of large nuclei
  —Examples include $^{197}_{79}\text{Au}+^{197}_{79}\text{Au}$ and $^{208}_{82}\text{Pb}+^{208}_{82}\text{Pb}$
- Is hot and dense
- Suppresses energetic particles
- Behaves like a liquid

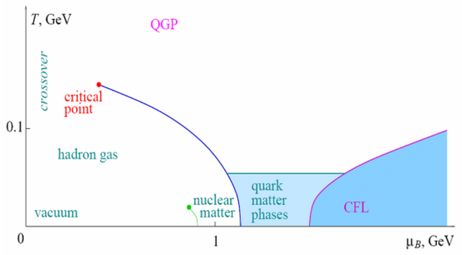
The history of the universe

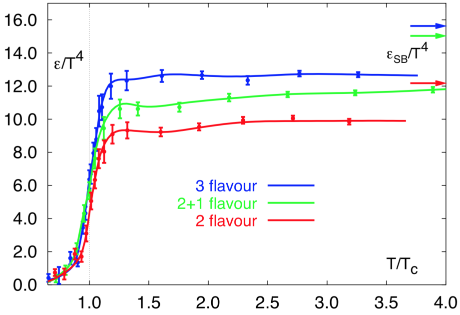


- The QGP is a system of approximately free quarks and gluons
- The early universe (few microseconds) was a QGP
- We can recreate the QGP in the lab in collisions of heavy nuclei at relativistic speeds
- Goal: study the properties of the QGP

Phases of QCD matter

See e.g. PHENIX, Nucl. Phys. A757, 184-283 (2005)





- The QCD phase diagram indicates hadrons, QGP, other possible exotic states
- The Lattice QCD calculation shows a large jump at the transition temperature

—Large increase in the number of degrees of freedom: $\varepsilon_{SB} = g\frac{\pi^2}{30}T^4$

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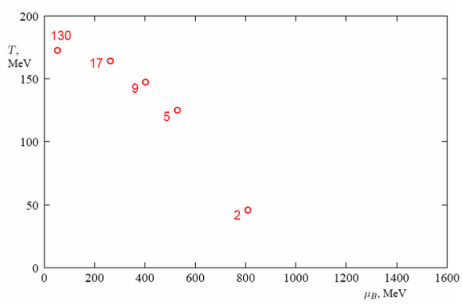
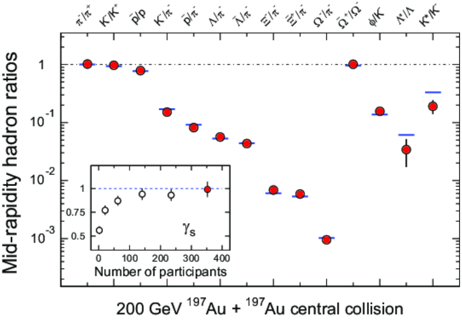
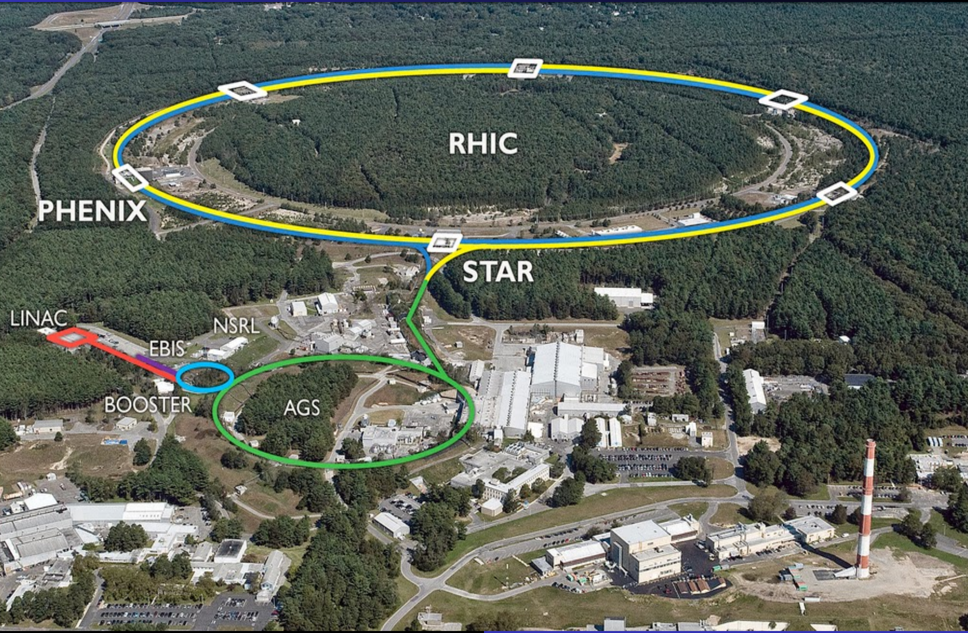




- The QCD phase diagram indicates hadrons, QGP, other possible exotic states
- The Lattice QCD calculation shows a large jump at the transition temperature —Large increase in the number of degrees of freedom: $\varepsilon_{SB} = g\frac{\pi^2}{30}T^4$
- Particle ratios well described by thermal model, extract T and μ_B

The Relativistic Heavy Ion Collider



The Relativistic Heavy Ion Collider

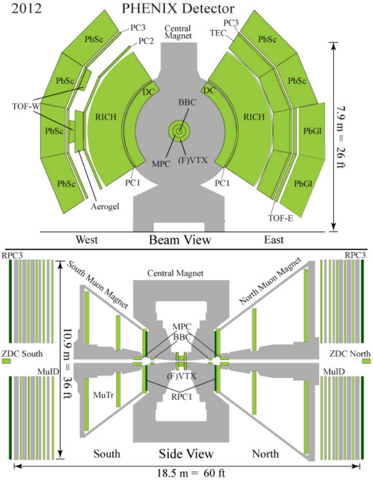
- RHIC is the only polarized proton collider in the world
- RHIC is one of two heavy ion colliders, the other being the LHC
- RHIC is a dedicated ion collider and is designed to collide many different species of ions at many different energies—vastly more flexible than the LHC

Collision Species	Collision Energies (GeV)
p↑+p↑	510, 500, 200, 62.4
p+Al	200
p+Au	200
d+Au	200, 62.4, 39, 19.6
^{3}He+Au	200
Cu+Cu	200, 62.4, 22.5
Cu+Au	200
Au+Au	200, 130, 62.4, 56, 39, 27, 19.6, 15, 11.5, 7.7, 5, ...
U+U	193

And lots more to come!

PHENIX

- Weighs approximately 3000 tons
- Three separate magnet systems (Central Arms and Muon North and South) weighing 1700 tons alone
- 16 detector subsystems and about 5,000,000 (silicon) plus 300,000 (other) electronics channels
- 30 feet tall, 40 feet wide, 60 feet long
- Very fast DAQ system—7 kHz, 1 GB/s
- Ideally suited for measurements of rare probes, electrons, muons, high p_T photons, etc.



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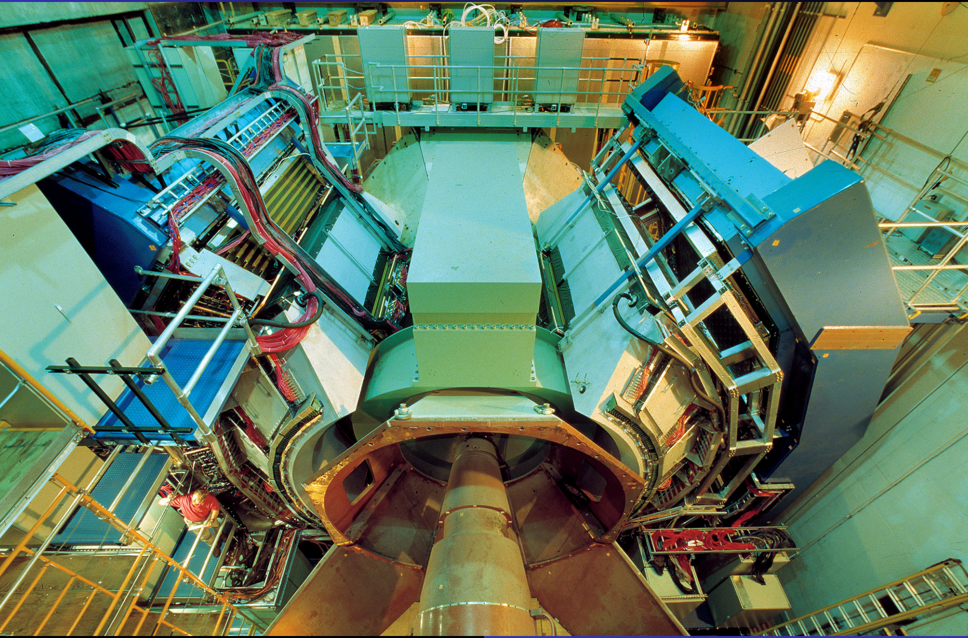
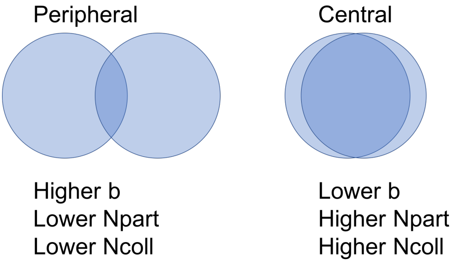


Centrality

- Need to characterize the overlap of the two nuclei
- b (impact parameter)—separation between the centers of the two nuclei
- N_{part}—number of nucleons in the overlap region
- N_{coll}—number of nucleon-nucleon collisions



Centrality	$\langle N_{\mathrm{part}} \rangle$	$\langle N_{\mathrm{coll}} \rangle$
Pb+Pb		
0-5%	382.7 ± 5.1	1685 ± 190
5-10%	329.7 ± 4.6	1316 ± 140
10-20%	260.5 ± 4.4	921 ± 96
20-30%	186.4 ± 3.9	556 ± 55
30-40%	128.9 ± 3.3	320 ± 32
40-50%	85.0 ± 2.6	171 ± 16
50-60%	52.8 ± 2.0	84.3 ± 7
60-70%	30.0 ± 1.3	37.9 ± 3
70-80%	15.8 ± 0.6	15.6 ± 1
p+p	$\equiv 2$	$\equiv 1$

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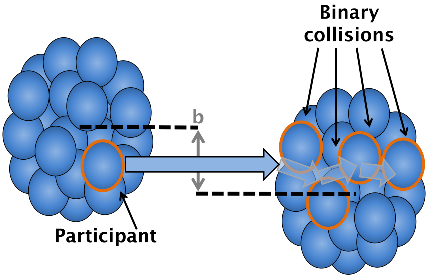

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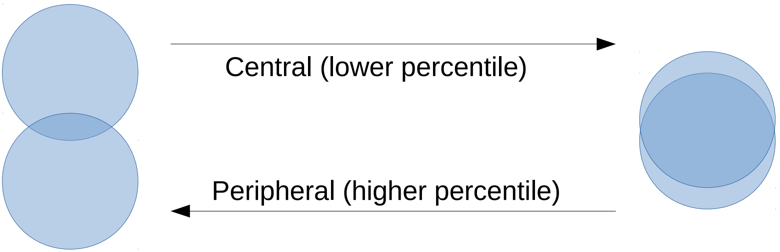
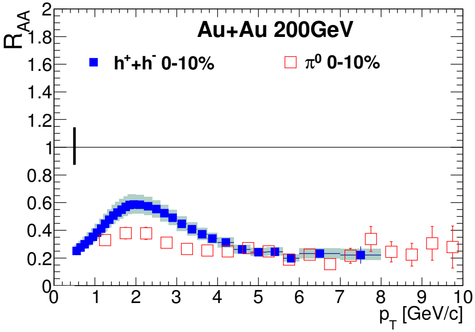
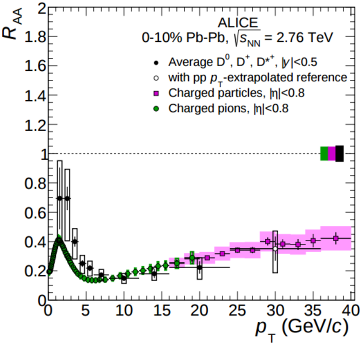


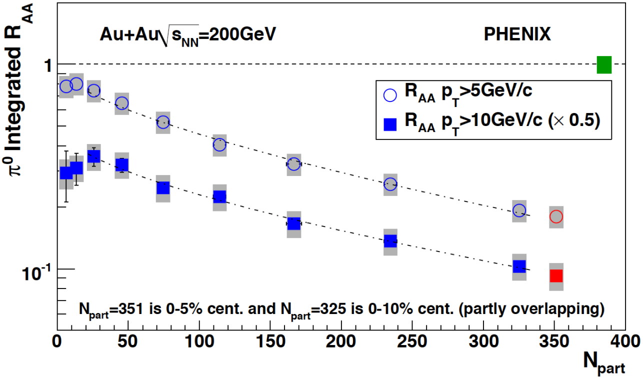
Suppression of high energy particles





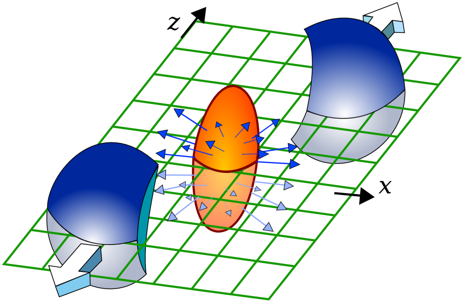
- $R_{AA} = \frac{N^{A+A}_{particles}}{N^{p+p}_{particles} \times N_{coll}}$
- $R_{AA} < 1$ means particles are suppressed
- Discussion point: what happens when you shoot a bullet into water? Electron into lead brick?

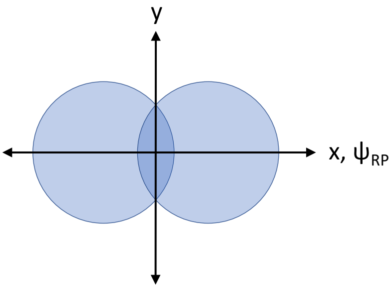
Suppression of high energy particles



- R_{AA} decreases (more suppression) with increasing N_{part} (bigger system)
- More medium → more stuff in the way → more suppresssion
- System size/geometry important aspect of suppression
- Discussion point: what happens when an electron goes through lead foil instead of lead brick?

Azimuthal anisotropy measurements

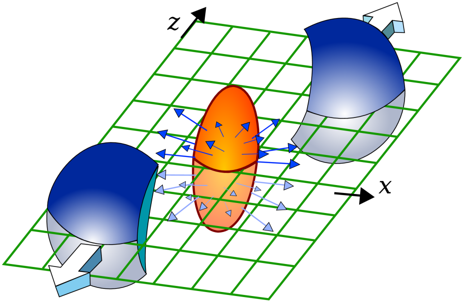


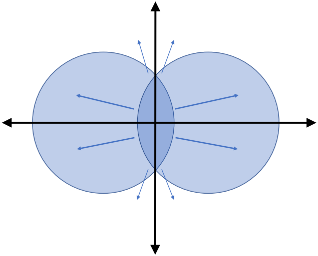


$$\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\phi \rangle + \langle r^2 \sin n\phi \rangle}}{\langle r^2 \rangle}$$

- Roughly constant pressure → larger pressure gradient "in plane" → **azimuthal anisotropy**—characterize with Fourier series
- Hydrodynamics translate initial shape (ε_n) into final state distribution (v_n)
- Overlap shape is approximately elliptical, so expect v_2 to be the largest

Azimuthal anisotropy measurements





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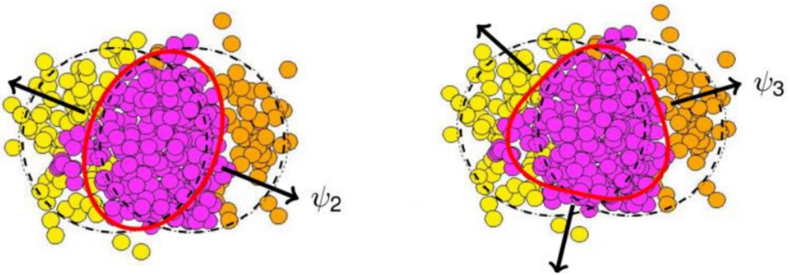
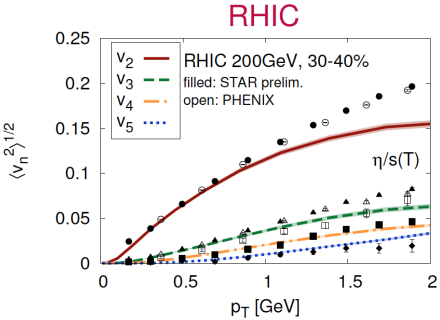
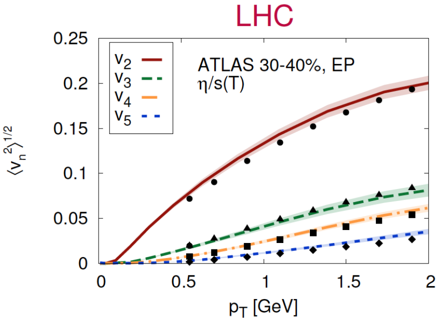
Symmetry Planes



- A nucleus isn't actually just a sphere
- Fluctuations in nucleon position can lead to interesting shapes
- Symmetry planes can be different for different harmonics

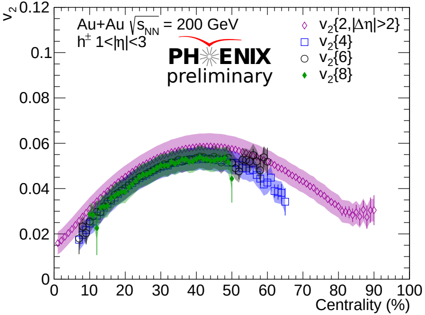
Data and theory for v_n

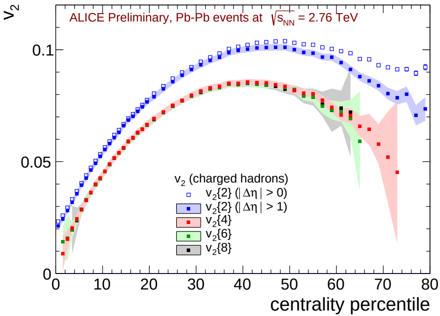




- Note that v_2 is the largest, as expected (elliptic shape→elliptic flow)
- Way, way, too much data to show, but here's one example
- The hydrodynamics theory describes the data for many v_n very well

Multiparticle measurements





- Multiparticle correlations: can use 2, 4, 6, 8, ... particles to measure v_n
- Insights into fluctuations
  —2 is above, 4,6,8 consistent → Gaussian-ish fluctuations
- Multiparticle correlations offer favorable combinatorics
  —Dilution factor $1/N^{k-1}$
  —Efficiently suppress few-particle correlations

Summary for Part I

The QGP:

- Is a phase of matter with approximately free quarks and gluons
- Existed in the very early universe
- Is created in the lab in collisions of large nuclei
- Is hot and dense
- Suppresses energetic particles
- Behaves like a liquid

Learning goals for Part II

- A major component of heavy ion physics nowadays is “small systems”
  —Nuclear collisions of small+large or even small+small
  —Examples include d+Au, p+Pb, and even p+p
- The matter created in small systems looks a lot like the matter in large systems
- This might be a revolution, or it might not be such a surprise
  —Opinions vary!
  —Discussion point: who knows about the MIT bag model?

Media Attention

Physics World, September 22, 2017 (clickable link)
Phys.org, September 18, 2017 (clickable link)

Home » Physics » General Physics » September 18, 2017

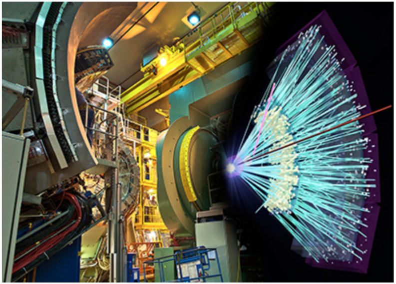
Possible evidence for small, short-lived drops of early universe quark-gluon plasma

September 18, 2017 by Karen Mcnulty Walsh

"To distinguish color glass condensate from QGP, we need more detailed theoretical descriptions of what these things look like," Belmont said.

Collider serves up drop of primordial soup

Sep 22, 2017



Tiny drop: PHENIX and reconstructed particle tracks from a QGP

PHENIX colleague Ron Belmont of the University of Colorado says it is still possible that the elliptical emission they have observed is due not to the formation of tiny QGPs but instead down to nuclear properties prior to collision. When accelerated close to light speed, time slows down for the heavy nuclei, which means, according to quantum chromodynamics, that they appear as a dense wall of gluons. The fact that these condensates are thicker in the centre of the nuclei might explain why particles generated in the collisions are not emitted in random directions, he says.

A very brief history of recent heavy ion physics

- 1980s and 1990s—AGS and SPS... QGP at SPS!
- Early 2000s—QGP at RHIC! No QGP at SPS. d+Au as control.
- Mid-late 2000s—Detailed, quantitative studies of strongly coupled QGP. d+Au as control.
- 2010—Ridge in high multiplicity p+p (LHC)! Probably CGC!
- Early 2010s—QGP in p+Pb!
- Early 2010s—QGP in d+Au!
- Mid 2010s and now-ish—QGP in high multiplicity p+p? QGP in mid-multiplicity p+p?? QGP in d+Au even at low energies???

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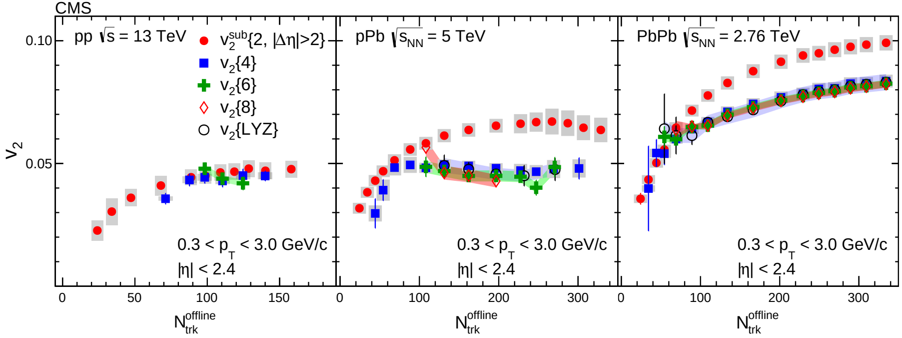
"Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it." —Jürgen Schukraft, QM17

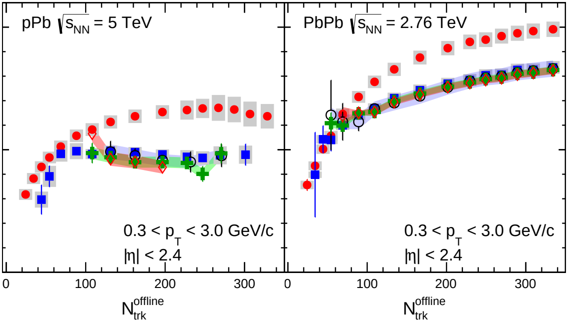
Multiparticle correlations in large and small systems

CMS, Phys. Lett. B 765 (2017) 193-220



Multiparticle correlations in large and small systems

CMS, Phys. Lett. B 765 (2017) 193-220



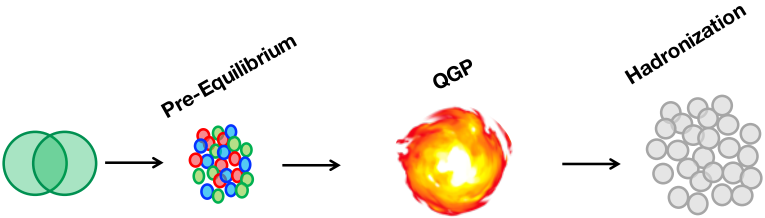
- The Pb+Pb part is basically the same as what I showed a few slides ago
- The p+Pb has a *strikingly* similar pattern as the Pb+Pb
- Flowing QGP in small systems?

Testing the hydro QGP picture in small systems

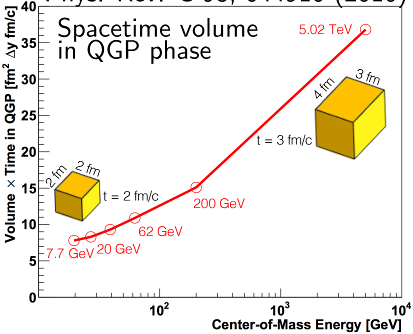
This is important, so let's get it right

- Fix the geometry, vary the size and lifetime
- Fix the size and lifetime, vary the geometry

Testing hydro by controlling system size and lifetime



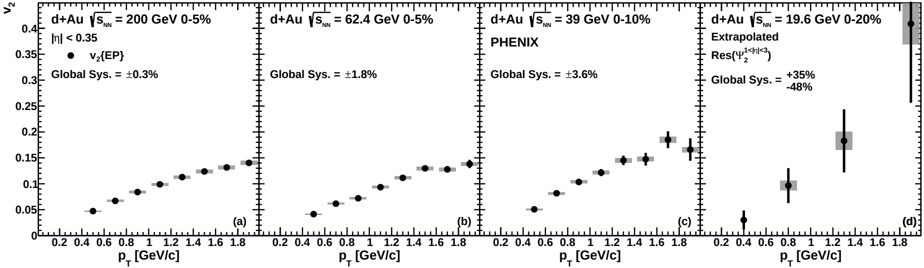
J.D. Orjuela Koop et al
Phys. Rev. C 93, 044910 (2016)



- Standard picture for A+A: QGP in hydro evolution
- What about small systems? And lower energies?
- Use collisions species and energy to control system size, test limits of hydro applicability

v_2 vs p_T, comparisons to theory

PHENIX, arXiv:1708.06983



- Event plane v_2 vs p_T measured for all energies

v_2 vs p_T, comparisons to theory

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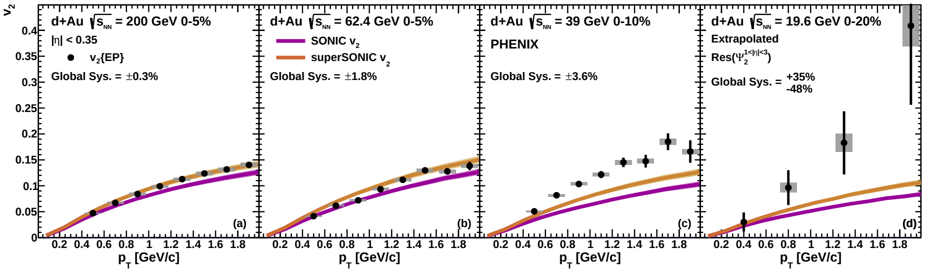
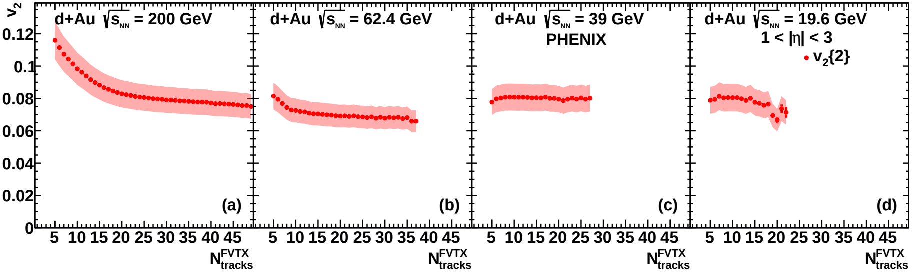


- Event plane v_2 vs p_T measured for all energies
- Hydro theory agrees with higher energies very well, far underpredicts lower energies—non-flow combinatorically favored at lower energies

$v_2\{2\}$ and $v_2\{4\}$ in the d+Au beam energy scan

PHENIX, arXiv:1707.06108



- $v_2\{2\}$ relatively constant with N_{tracks}^{FVTX} and collision energy

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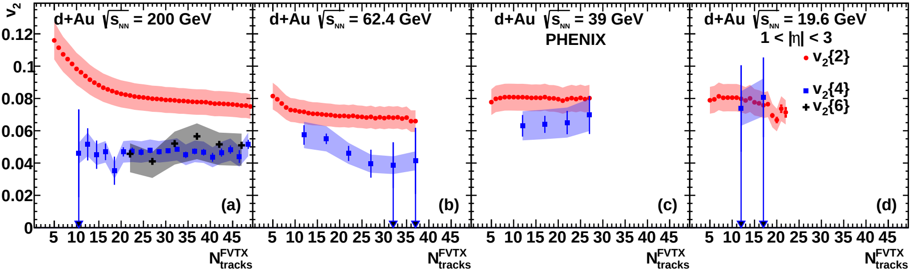
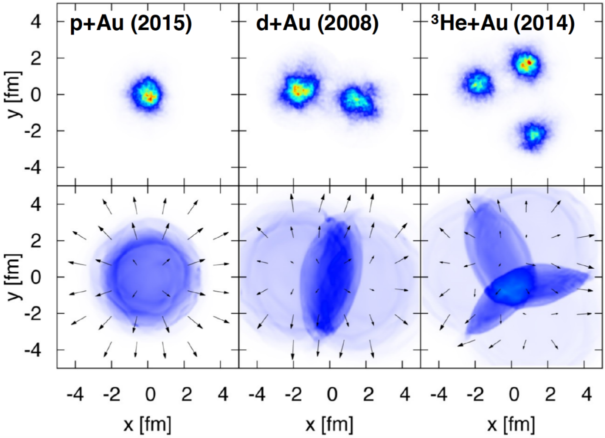


- $v_2\{2\}$ relatively constant with N_{tracks}^{FVTX} and collision energy
- Measurement of $v_2\{4\}$ in d+Au at all energies
- Measurement of $v_2\{6\}$ in d+Au at 200 GeV

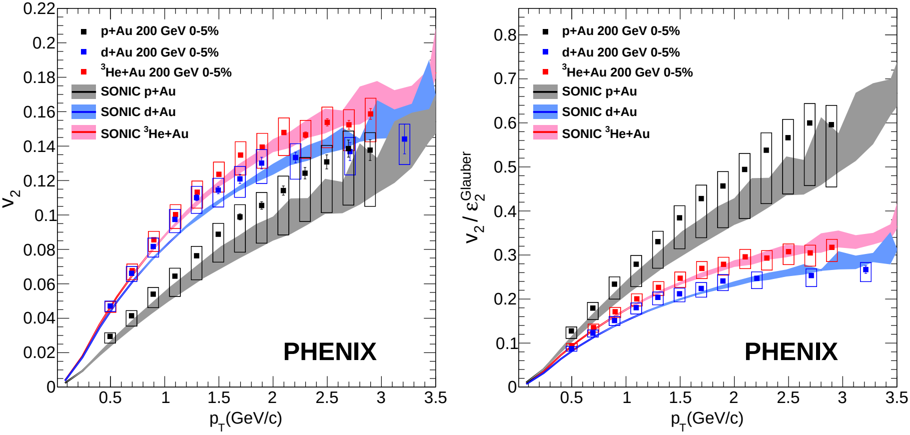
Testing hydro by controlling system geometry



- Hydrodynamics translates initial geometry into final state
- Test hydro hypothesis by varying initial state

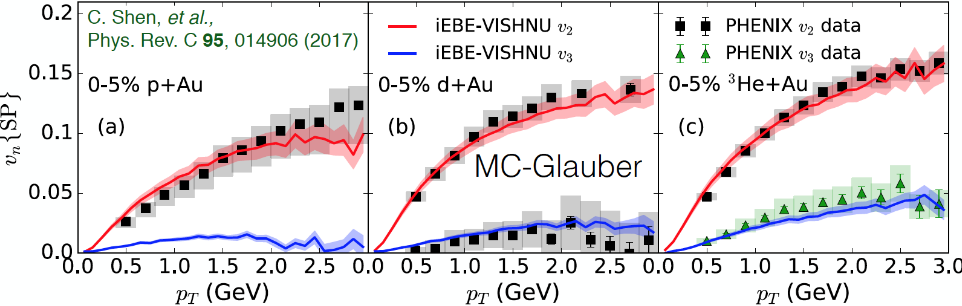
v_2 vs p_T in the geometry scan

PHENIX, Phys. Rev. C 95, 034910 (2017)



- Hydro theory describes the data extremely well
- Imperfect scaling with ε_2 captured by hydro

v_3 vs p_T in the geometry scan



- v_3 is non-zero and lower in d+Au compared to ^{3}He+Au
- Hydro theory shows excellent agreement with data
- Coming soon: v_3 in p+Au

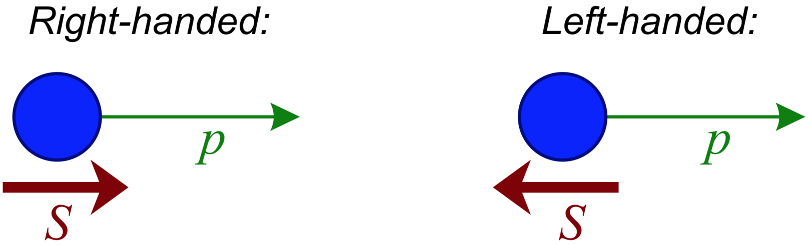
Summary for Part II

- Small systems is a hot topic in heavy ion physics
- We've even gotten some media attention for it
- The system created in small systems looks a like the one in large systems
- Hydro theory describes the data very well
  —Including and especially the initial geometry dependence

Learning goals for Part III

- Helicity is the projection of the spin along the trajectory
- Chirality is kind of like helicity, but more fundamental
- Parity (P) in 3 dimensions is the inversion of all spatial coordinates
- Charge-parity (CP) is parity and flipping the charges
- We can study fundamental symmetries of QCD with heavy ion physics by searching for P- and CP-violation

Helicity and Chirality



- Helicity is $\vec{s} \cdot \vec{p}$
  —Right-handed: spin along momentum
  —Left-handed: spin opposite to momentum
- Chirality is an internal quantum number
  —Same as helicity for massless particles
  —Evolves with time for massive particles (Higgs)

C, P, T, and CPT

- C is charge conjugation
  —Flip the sign of the charges
- P is parity inversion
  —Flip the spatial coordinates
- T is time reversal
  —Flip the time coordinate
- CPT is do all three of these at the same time
  —CPT theorem: any Lorentz invariant QFT is CPT invariant
  —C, P, T can be broken alone or in pairs as long as CPT is preserved

Parity

What is parity?

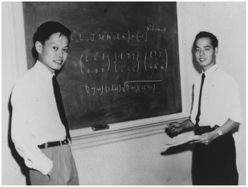
- In 3 space dimensions, parity is the simultaneous inversion of all three dimensions

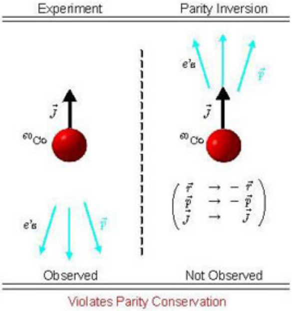
$$P \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

- Scalar quantities (e.g. mass, charge) are P-even
- Vector quantities (e.g. momentum, electric field) are P-odd
- Pseudo-vector quantities (e.g. angular momentum, magnetic field) are P-even $\vec{L} = \vec{r} \times \vec{p} \quad \rightarrow \quad \vec{L} = -\vec{r} \times -\vec{p}$
- Parity was long believed to be conserved in all laws of physics
- However...

P-violation in weak interactions

- Proposed by T.D. Lee and C.N. Yang, Phys. Rev. 104, 254 (1956)
- Discovered by C.S. Wu et. al., Phys. Rev. 105, 1314 (1957)





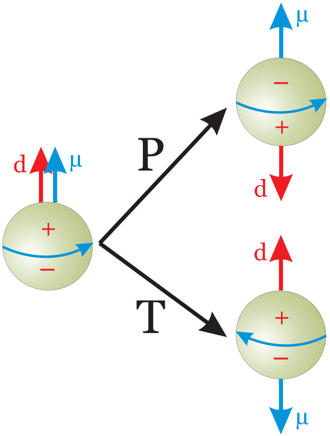
- Electron emission from $^{60}\text{Co} \rightarrow {}^{60}\text{Ni} + e + \overline{\nu}_e$ was found to be anti-parallel to the nuclear spin—parity violation
- Pauli was shocked and insisted the experiments be repeated
- Wu's experiment was repeatedly confirmed, and she *should* have gotten the Nobel Prize in physics, as Lee and Yang did...

CP-violation in weak interactions

- Fun fact: charged kaon decays violate parity, an effect that was observed but not understood until the Lee and Yang paper on the previous slide
- CP-violation in neutral kaon mixing: Phys. Rev. Lett. 13, 138 (1964)
- CP-violation in neutral kaon decays: Phys. Rev. Lett. 83, 22 (1999)
- Hard to do it justice in one slide, but:
  —There is slight mixing of the CP-even and CP-odd states
  —A CP-even state occasionally decays to a CP-odd state

P- and CP-violation in strong interactions

- A non-zero neutron electric dipole moment (nEDM) violates parity
- A non-zero nEDM also violates time reversal, by CPT theorem T-violation implies CP-violation
- Measurements consistent with zero, strict upper limits (2.9×10^{-26} e-cm)
- The observed absence is surprising because of "natural" CP-violating terms in the QCD Lagrangian



$$\mathcal{L} = -\frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a} - \frac{\theta g^2}{32\pi^2}F^{a}_{\mu\nu}\tilde{F}^{\mu\nu}_{a} + \overline{\psi}(i\not{D} - me^{i\theta'\gamma_5})\psi$$

Strong CP problem: $0 \leq \theta < 10^{-10}$

Topological charge and the QCD vacuum

Chern-Simons Current:

$$K^\mu = \frac{g^2}{32\pi^2}\varepsilon^{\mu\nu\alpha\beta}\left(A^a_\nu F^a_{\alpha\beta} - \frac{g}{3}f_{abc}A^a_\nu A^b_\alpha A^c_\beta\right)$$

Chern-Simons Number:

$$N_{CS} = \int d^3x\, K^0 \in \mathbb{Z}$$

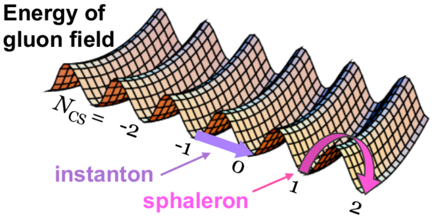
$U(1)_A$ anomaly:

$$\partial_\mu J^\mu_A = -\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

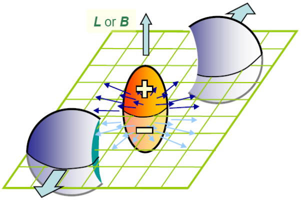
Topological charge:

$$\Delta N_{CS} = Q_w = \frac{g^2}{32\pi^2}\int d^4x\, F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a \in \mathbb{Z}$$

(Transitions are instantons and sphalerons)

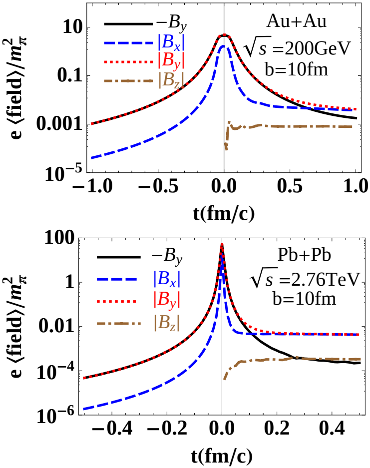


The magnetic field in heavy ion collisions

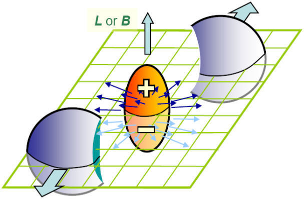


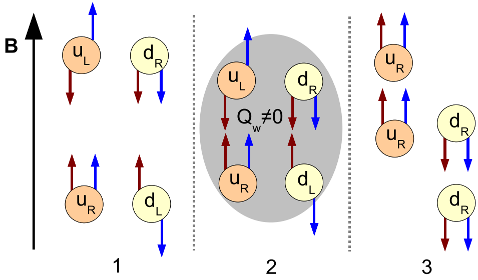
- The spectating protons are just moving charged particles, so they make a B-field
- The peak strength strength is roughly $10^{14\text{-}16}$ T—largest magnetic field in the known universe!
- The spectators nominally define both the magnetic field and the geometry, so $\psi_B \approx \psi_{RP}$

W.-T. Deng and X.-G. Huang
Phys. Rev. C 85, 044907 (2012)



The Chiral Magnetic Effect





- Chiral imbalance induced by quantum anomaly
- Alignment of spins by external magnetic field induces electric current of chiral quarks

$$\vec{J}_V = \frac{e^2}{2\pi^2}\mu_A\vec{B}$$

- $\vec{J}$: P-odd, C-odd, CP-even $\vec{B}$: P-even, C-odd, CP-odd
  —This current is both P- and CP-violating

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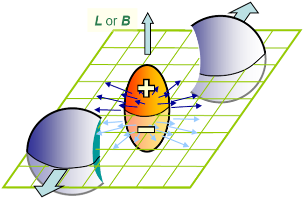

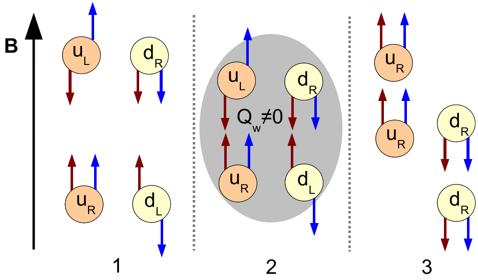

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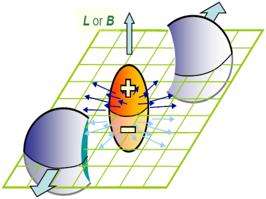
—This current is both P- and CP-violating
- How to measure?

The CME correlator

The Fourier expansion from before but now including P-odd sine terms

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty}[v_n \cos n\varphi + a_n \sin n\varphi] \qquad a_n = \langle \sin n\varphi \rangle$$



- Normally we ignore sine terms, but now we need them

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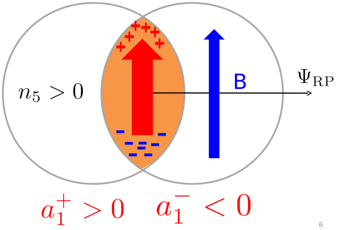

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- Positive particles go above the reaction plane $a_1^+ > 0$
- Negative particles go below the reaction plane $a_1^- < 0$

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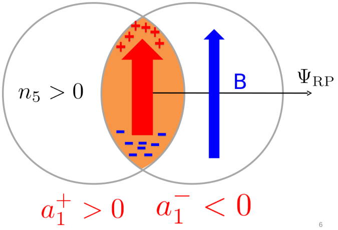

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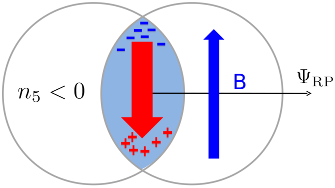
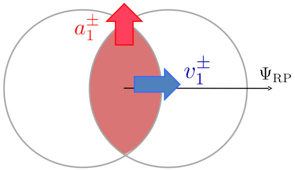


- Normally we ignore sine terms, but now we need them
- Positive particles go above the reaction plane $a_1^+ > 0$
- Negative particles go below the reaction plane $a_1^- < 0$
- However...
- Q_w fluctuates about $\langle Q_w \rangle = 0$, so $\langle a_1^{\pm} \rangle = 0$

The CME correlator

What to do? Measure 2 particle correlation with respect to the reaction plane (Voloshin, Phys. Rev. C 70 057901 (2004))

$$\langle \cos(\phi_a + \phi_b - 2\psi_{RP}) \rangle = \langle \cos\varphi_a \cos\varphi_b \rangle - \langle \sin\varphi_a \sin\varphi_b \rangle$$
$$= [\langle v_{1,a} v_{1,b} \rangle + B_{in}] - [\langle a_{1,a} a_{1,b} \rangle + B_{out}]$$



- Same sign $\langle a_1^{\pm} a_1^{\pm} \rangle > 0$
- Opposite sign $\langle a_1^{\pm} a_1^{\mp} \rangle < 0$
- Directed flow is rapidity-odd, $\langle v_1 v_1 \rangle \approx 0$
- Optimistically, $\langle \cos(\phi_a + \phi_b - 2\psi_{RP}) \rangle = -\langle a_{1,a} a_{1,b} \rangle$

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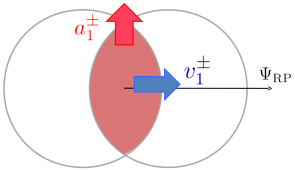

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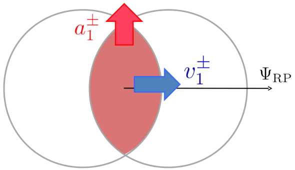

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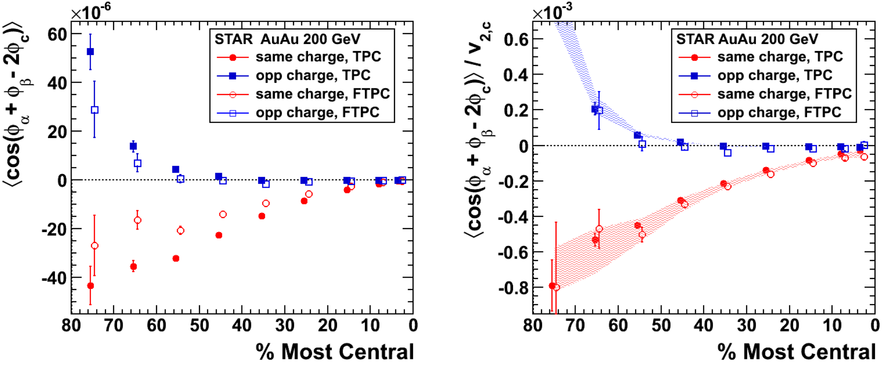
- Optimistically, $\langle \cos(\phi_a + \phi_b - 2\psi_{RP}) \rangle = -\langle a_{1,a} a_{1,b} \rangle$
- However...
- RP dependent backgrounds remain
- If dipole fluctuations, $\langle v_1 v_1 \rangle \neq 0$

The first CME results (STAR)

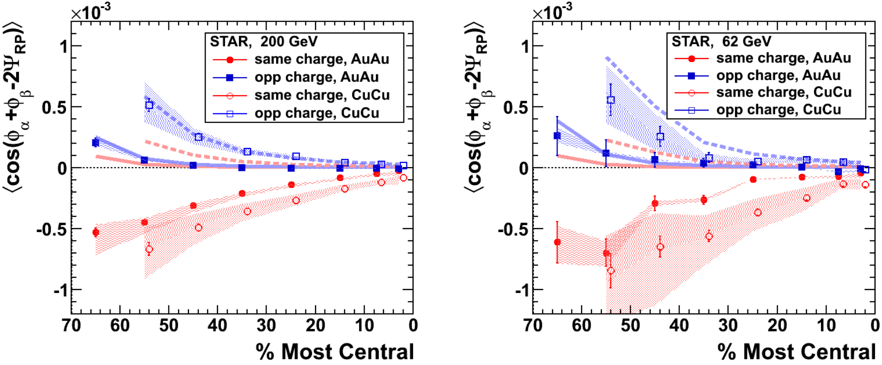
STAR, Phys. Rev. C 81, 054908 (2010)



- Strong negative correlation for same sign, consistent with CME expectation
- No correlation of opposite sign
  —Maybe the large medium destroys the opposite sign correlation?

The first CME results (STAR)

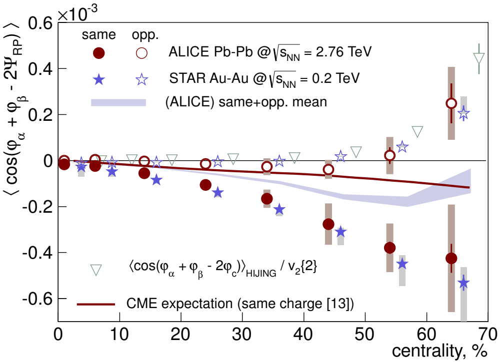
STAR, Phys. Rev. C 81, 054908 (2010)



- Strong negative correlation for same sign in both Au+Au and Cu+Cu
- Positive correlation of opposite sign for Cu+Cu
  —Maybe the medium is small enough to preserve the correlation?

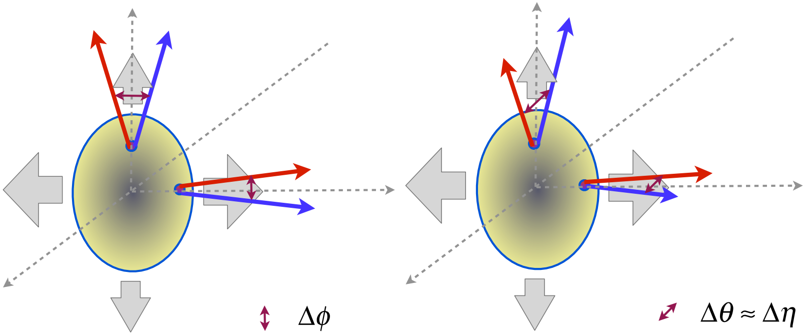
ALICE results on the CME

ALICE, Phys. Rev. Lett. 110, 012301 (2013)



- ALICE results consistent with STAR results
- Naïve expectation is for weaker correlation due to shorter B-field lifetime

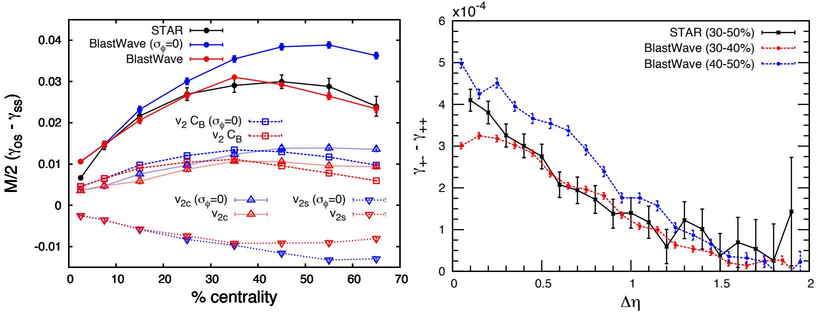
Backgrounds



- LCC: local charge conservation—charges are created in $\pm$ pairs at a single space-time point
- Angle between pairs is collimated by the radial+anisotropic flow background
- Simple and intuitive mechanism for generating charge-dependent angular correlations

Backgrounds

S. Schlichting and S. Pratt, Phys. Rev. C 83 014913 (2011)

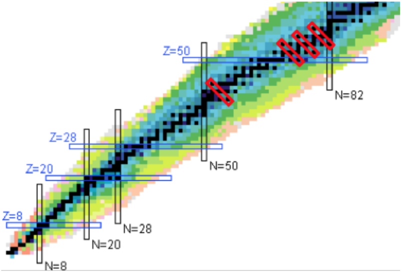


- Construct a simple model of LCC+flow using the Blastwave model
- Results show very good agreement with STAR CME correlator results (OS-SS)
- However, the absence of OS correlation and the strong SS correlation is not explained in this (simple) model
- This may indicate that the CME correlator results contain a combination of background and new physics
- Regardless, we need a dedicated study to confront the backgrounds

Isobaric collisions

Why isobars?

- Different Z means different B-field (change signal)
- Same A means same multiplicity (fix background)
- Similar shape means similar v_2 (fix background)



Requirements $\Delta Z = 4$ and non-zero abundance

Low Z nucl	High Z nucl	B^2 ratio
$^{96}_{40}$Zr	$^{96}_{44}$Ru	1.21
$^{124}_{50}$Sn	$^{124}_{54}$Xe	1.17
$^{130}_{52}$Te	$^{130}_{56}$Ba	1.16
$^{136}_{54}$Xe	$^{136}_{58}$Ce	1.15

- Lighter pairs offer higher B^2 ratio (good)
- Heavier pairs offer higher multiplicity
  —better EP resolution (good), more detector occupancy (bad)
- Which is the best is non-trivial, but Zr/Ru is the run plan

Isobaric collisions

Nuclear structure is more important than previously thought in heavy ions

- Most nuclei are not spherical, and the deviations from sphericity can vary widely
- Ellipticity shape parameter β_2 affects the initial eccentricity ε_2 in heavy ion collisions and therefore the measured v_2
- Recent STAR results: v_2 much higher in ultra-central U+U compared to ultra-central Au+Au
- Deformation may also affect B-field

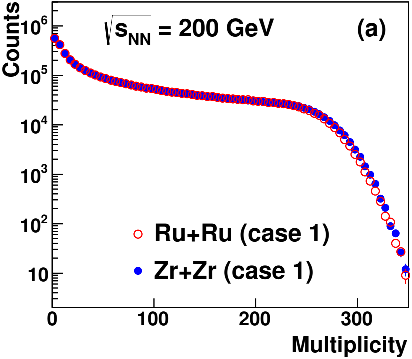
Possible problem: Zr/Ru are not spherical, may not have the same shape, shape parameters not especially well-known

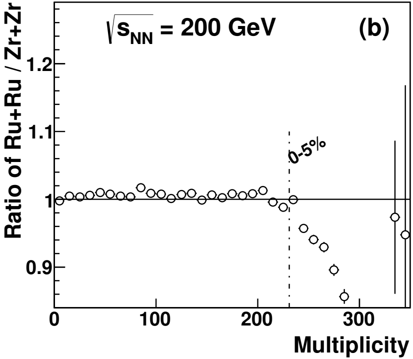
- Case 1: $\beta_2[^{96}_{40}\text{Zr}] = 0.080$, $\beta_2[^{96}_{44}\text{Ru}] = 0.158$
- Case 2: $\beta_2[^{96}_{40}\text{Zr}] = 0.217$, $\beta_2[^{96}_{44}\text{Ru}] = 0.053$

Opportunity: measure v_2 in ultra-central Zr+Zr and Ru+Ru to determine relative β_2

Isobaric collisions

CME Task Force Report, arXiv:1608.00982





Possible problem: Zr/Ru are not spherical, may not have the same shape
Solution: for the most part this doesn't actually matter

- Solution 1: Multiplicities are identical except for very central

Isobaric collisions

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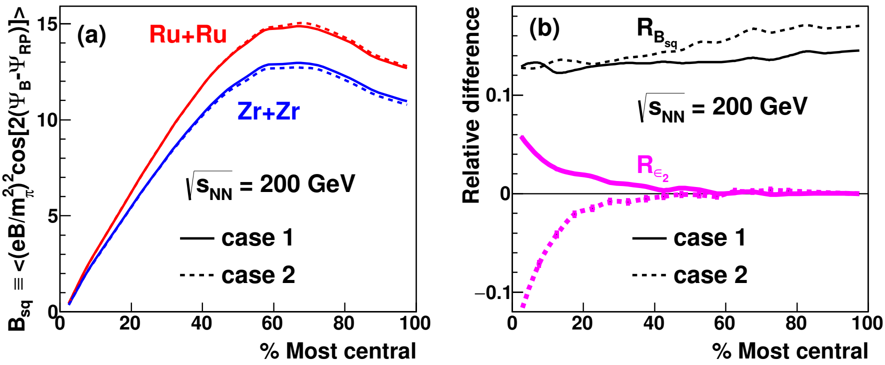

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- Solution 2: B-field and eccentricity aren't so different

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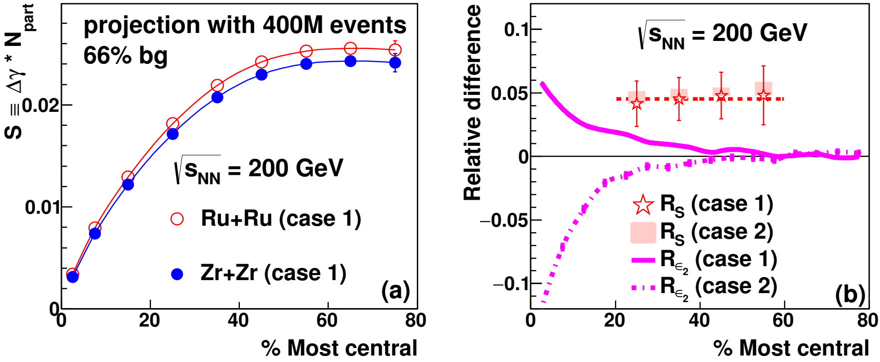

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Solution: for the most part this doesn't actually matter

- Solution 1: Multiplicities are identical except for very central
- Solution 2: B-field and eccentricity aren't so different
- Solution 3: Expected signal difference stronger than differences in ε_2

Isobaric collisions

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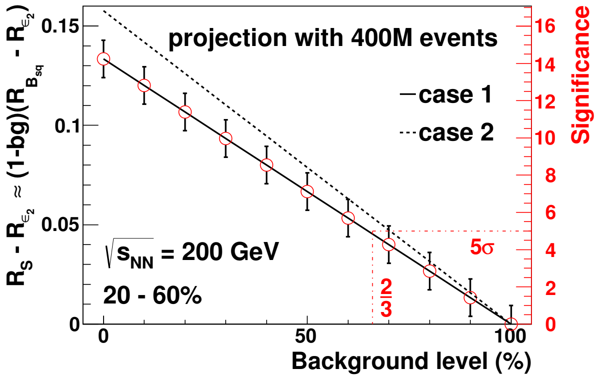

If we have 400M events for Zr+Zr and Ru+Ru:

- If 100% CME: 16σ separation between Zr+Zr and Ru+Ru
- If 33% CME: 5σ separation between Zr+Zr and Ru+Ru
- If 20% CME: 3σ separation between Zr+Zr and Ru+Ru

Good news! Latest run plan is 3.5 weeks for each: 1.2B events for each

Summary for Part III

- Topological transitions in the QCD vacuum lead to P- and CP-violating effects
- Such effects may be measurable in heavy ion physics
- The measurements so far indicate significant background contamination
- Isobaric collisions in 2018 will hopefully shed light on the issue

Summary for Part III

- Topological transitions in the QCD vacuum lead to P- and CP-violating effects
- Such effects may be measurable in heavy ion physics
- The measurements so far indicate significant background contamination
- Isobaric collisions in 2018 will hopefully shed light on the issue
- "The optimist regards the future as uncertain." —Eugene Wigner

Final thoughts

- Collisions of large nuclei create the quark gluon plasma, a state of matter that existed in the early universe
- Collisions of small+large and small+small nuclei also appear to create the QGP, or at least something very similar to the matter created in collisions of large nuclei
- Collisions of large nuclei create the largest magnetic field in the known universe
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- Collisions of large nuclei create the largest magnetic field in the known universe
- We hope to test fundamental symmetries of QCD using heavy ion physics
- Thanks!

Additional Material

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Physical constants and units

Planck's constant $\hbar = 1$

- Shows up everywhere in quantum mechanics
- Energy has same units as frequency: $E = \hbar\omega \rightarrow E = \omega$
- Momentum has same units as wavenumber: $p = \hbar k \rightarrow p = k$
  —$p = h/\lambda_{dB} \rightarrow p = 1/(2\pi\lambda_{dB})$
- More obvious relationship between energy and time, momentum and space
  —$\Delta E \Delta t \geq \hbar/2 \rightarrow \Delta E \Delta t \geq 1/2$
  —$\Delta p \Delta x \geq \hbar/2 \rightarrow \Delta p \Delta x \geq 1/2$
- Partial aside: Noether's theorem
  —Invariance in time → conservation of energy
  —Invariance in space → conservation of momentum

Physical constants and units

Speed of light $c = 1$

- Shows up everywhere in special relativity
- Energy, momentum, and mass all have the same units

$$E = pc \rightarrow E = p$$
$$E = mc^2 \rightarrow E = m$$
$$E^2 = p^2c^2 + m^2c^4 \rightarrow E^2 = p^2 + m^2$$

- We use units of energy (usually MeV or GeV) describe all these things
  —Example: electron mass is 0.511 MeV, proton mass is 938 MeV ($\sim$ 1 GeV)
- Time and distance have the same units
  —Typical scale (size **and** time) is 1 fermi = 1 femtometer
  —1 fm $= 10^{-15}$ m $= 3.336 \times 10^{-24}$ s (3.336 yoctoseconds)

Physical constants and units

$\hbar c = 197.3$ MeV fm

- Key lesson from special relativity: time and space are not so different!
- That means energy and momentum are not so different
- Covariant four vectors:

$$x_\mu = (t, -x, -y - z) \qquad = (t, -\vec{r})$$
$$p_\mu = (E, -p_x, -p_y, -p_z) = (E, -\vec{p})$$

Physical constants and units

Speed of light $c = 1$

- Big consequences for E&M!
- Vacuum permittivity ϵ_0 and permeability μ_0

$$\epsilon_0\mu_0 = \frac{1}{c^2} \rightarrow \epsilon_0 = \mu_0 = 1$$

- Fine structure constant:

$$\alpha_{EM} = \frac{e^2}{4\pi\epsilon_0\hbar c} \rightarrow \alpha_{EM} = \frac{e^2}{4\pi}$$

- Electric charge is dimensionless!
- Discussion point: not what you're used to, but makes perfect sense—what does charge really *mean*?

Physical constants and units

Boltzmann's constant $k_B = 1$

- Shows up everywhere in thermal physics and stat mech
- Entropy:

$$S = k_B \ln \Omega$$

- Discussion point: what should the units of S be?
- Temperature:

$$T = \frac{\partial U}{\partial S}$$

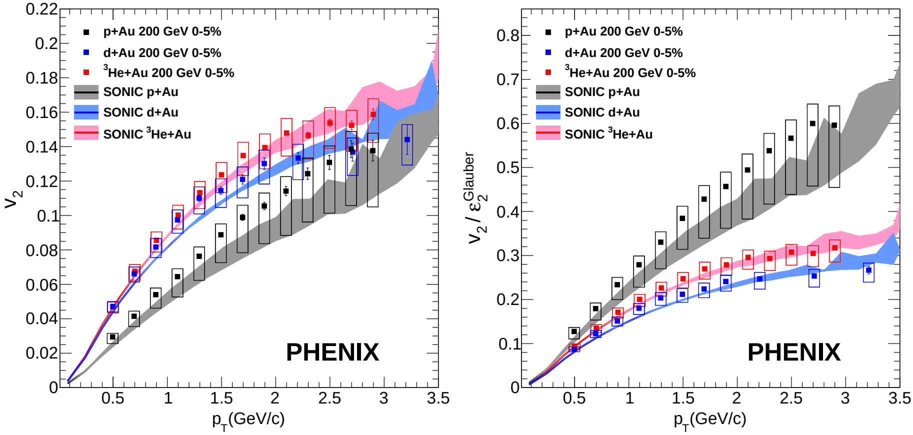
- Discussion point: what should the units of T be?
- Example: 200 MeV $= 2.321 \times 10^{12}$ K

CP-violation in weak interactions

- Strong eigenstates
  —$K^0 = s\bar{d}$ (not a CP eigenstate)
  —$\overline{K^0} = \bar{s}d$ (not a CP eigenstate)
- CP-invariant weak eigenstates:
  —$K_1 = (s\bar{d} + \bar{s}d)/\sqrt{2}$ (CP even)
  —$K_2 = (s\bar{d} - \bar{s}d)/\sqrt{2}$ (CP odd)
- True composition:
  —$K_S = K_1 + \epsilon K_2$
  —$K_L = K_2 + \epsilon K_1$
- In 1964, K_L found to occasionally decay to two pions (CP even state)
  —This is due to the fact that the K_L has a slight contribution from K_1
  —This is therefore called "indirect" CP violation
- In 1999, K_S and K_L were separated into K_1 and K_2 modes, and each were found to have decay modes with opposite CP
  —This is called "direct" CP violation

v_2 vs p_T in the geometry scan

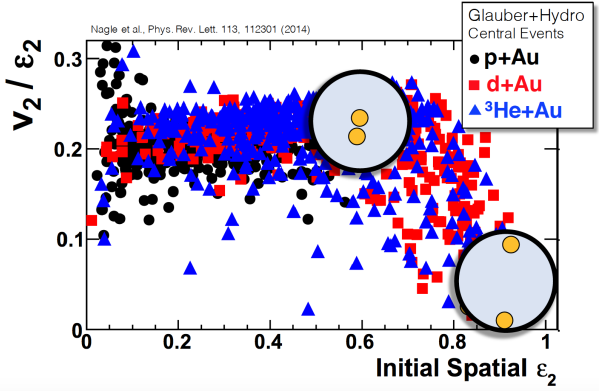
PHENIX, Phys. Rev. C 95, 034910 (2017)



- Hydro theory describes the data extremely well
- Imperfect scaling with ε_2 captured by hydro
  —Disconnected hot spots

v_2 vs p_T in the geometry scan

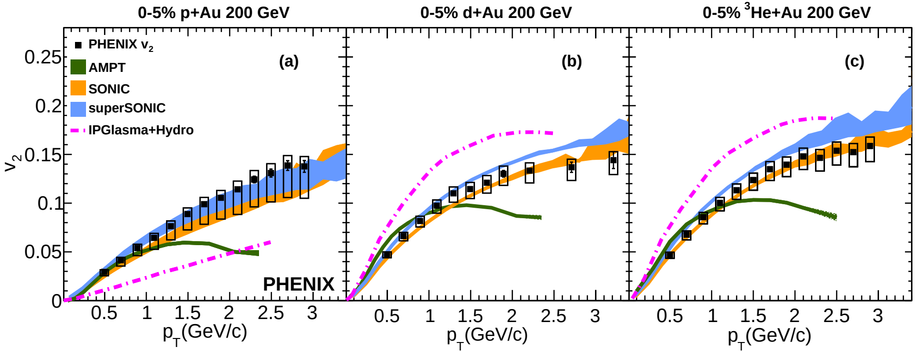
J.L. Nagle et al, Phys. Rev. Lett. 113, 112301 (2014)



- v_2/ε_2 relationship breaks for very large ε_2
- The hydro hotspots are so far apart that they never connect
  —Efficiency to translate ε_2 into v_2 goes down

v_2 vs p_T in the geometry scan

PHENIX, Phys. Rev. C 95, 034910 (2017)



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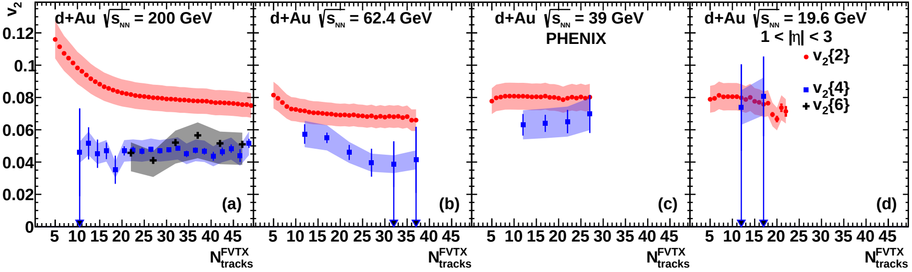
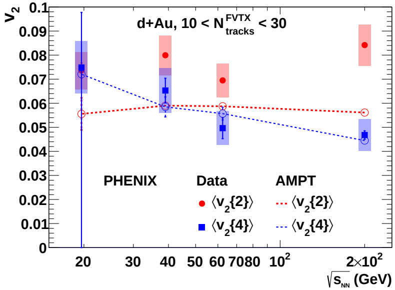
$v_2\{2\}$ and $v_2\{4\}$ in the d+Au beam energy scan

PHENIX, arXiv:1707.06108

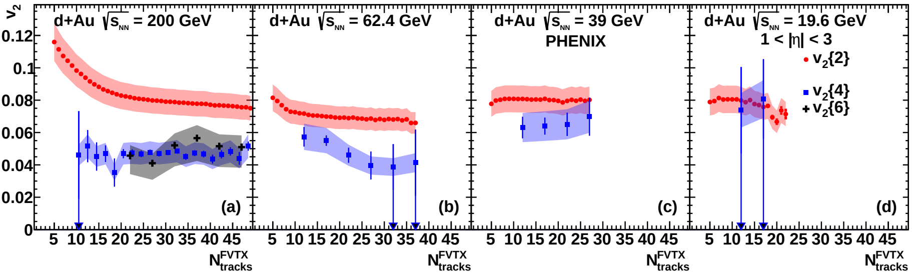


- Select $10 < N^{FVTX}_{tracks} < 30$, integrate
- AMPT sees similar trend
- Fluctuations?



Can we get a better handle on the non-flow?

PHENIX, arXiv:1707.06108



- $v_2\{2\}$ and $v_2\{4\}$ vs N_{tracks}^{FVTX}, all tracks anywhere in FVTX

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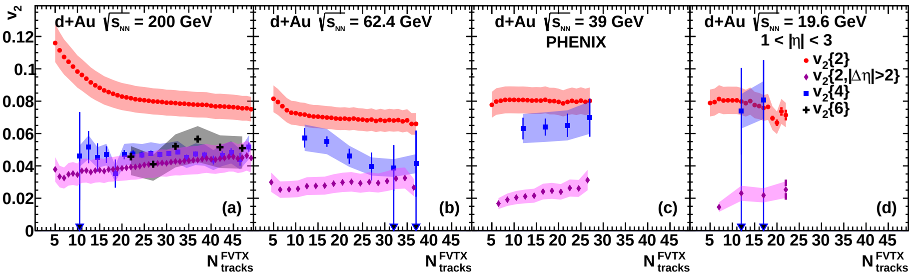

- $v_2\{2\}$ and $v_2\{4\}$ vs N^{FVTX}_{tracks}, all tracks anywhere in FVTX
- $v_2\{2,|\Delta\eta|>2\}$ vs N^{FVTX}_{tracks}, one track backward, the other forward

$$v_2\{2,|\Delta\eta|>2\} = \sqrt{v_2^2+\sigma^2} \qquad v_2\{2\} = \sqrt{v_2^2+\sigma^2+\delta}$$

$$v_2\{4\} \approx \sqrt{v_2^2-\sigma^2}$$

- How to understand this?

Two-particle estimates of v_2 when using subevents

- $dN_{ch}/d\eta$ and v_2 are larger at backward rapidity, so $v_2\{2\}$ and $v_2\{4\}$ are weighted towards backward
- $v_2\{2, |\Delta\eta| > 2\}$ is weighted equally between forward and backward as $\sqrt{v_2^B v_2^F}$
- $v_2^B > v_2^F$, so $v_2^2 > v_2^B v_2^F$

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- The fluctuations are not actually the variance but rather the covariance ς_{BF}
- $\sqrt{v_2^2 + \sigma^2} \rightarrow \sqrt{v_2^B v_2^F + \varsigma_{BF}}$
- Correlation strength between forward and backward $|\varsigma_{BF}| \leq \sigma_B \sigma_F$—fluctuations can contribute less than expected

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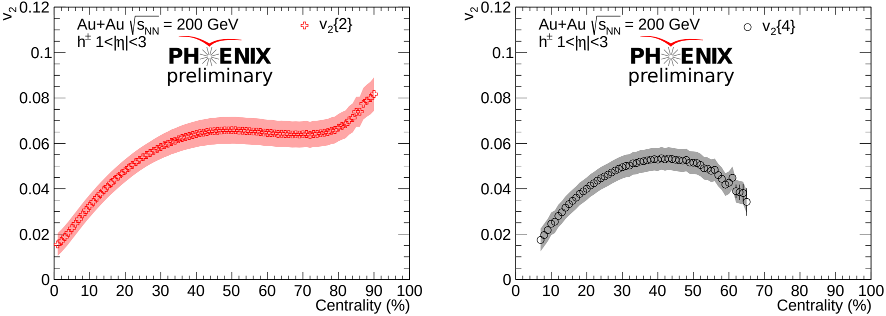
- Correlation strength between forward and backward $|\varsigma_{BF}| \leq \sigma_B \sigma_F$—fluctuations can contribute less than expected
- Event plane decorrelation small in Au+Au but could be larger in d+Au
- But that's already encoded in the v_2 vs η measurement discussed earlier

Understanding two-particle estimates of v_2 when using subevents



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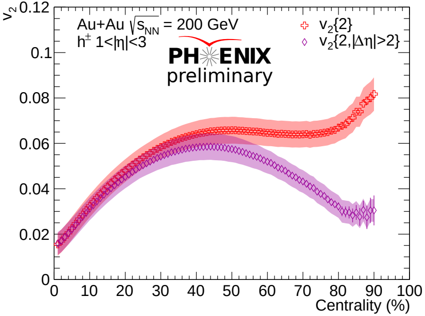

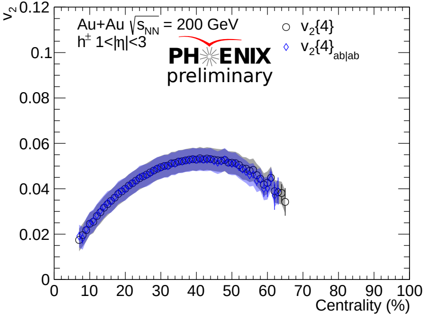

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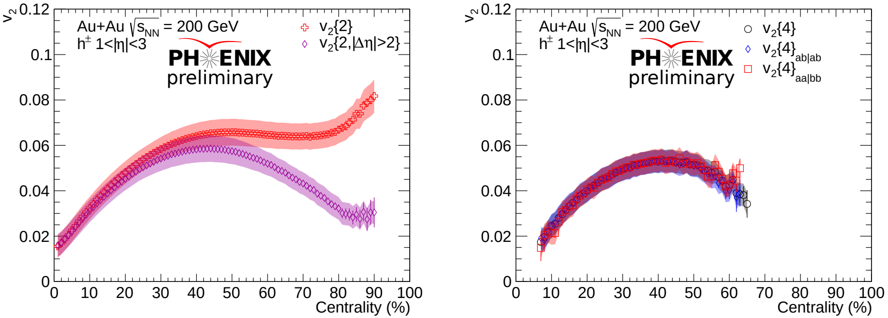
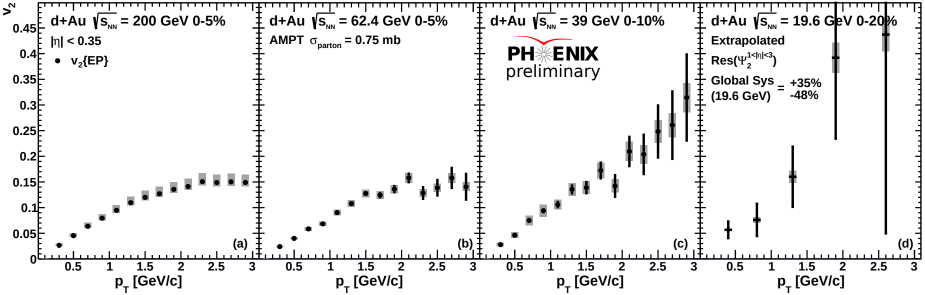


- Two-particle correlation without eta gap has significant non-flow
- Can't disentangle flow/non-flow/decorrelation effects (by looking at this plot)
- Four particle correlation with and without subevents is identical
- Non-flow and decorrelations don't affect four-particle results in Au+Au
- Decorrelation effects present but small (few %) in Au+Au

v_2 vs p_T, comparisons to AMPT

PHENIX, arXiv:1708.06983



- Event plane v_2 vs p_T measured for all energies

v_2 vs p_T, comparisons to AMPT

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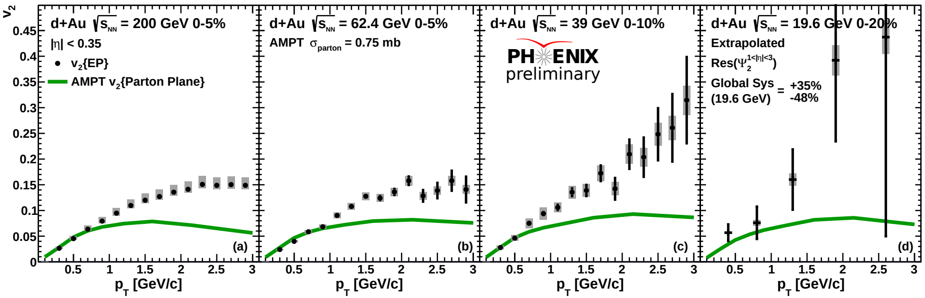

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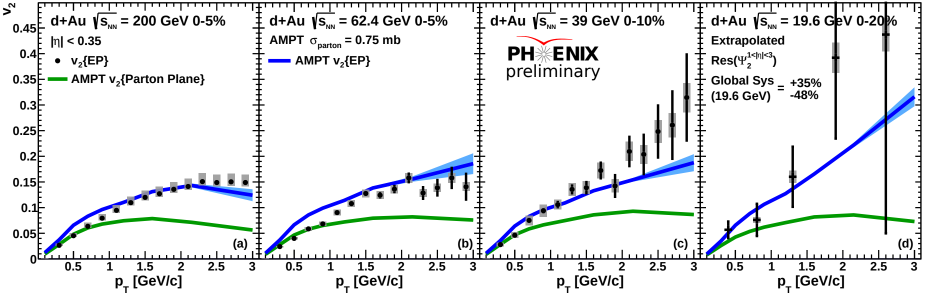

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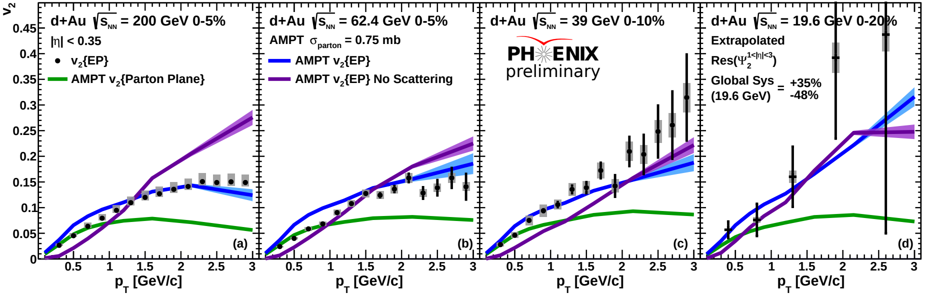
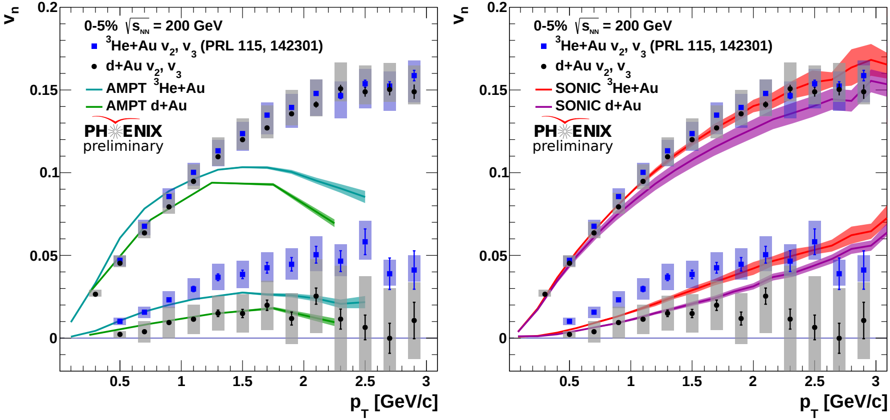


- Event plane v_2 vs p_T measured for all energies
- AMPT flow only shows good agreement at low p_T
- AMPT flow+non-flow shows reasonable agreement for all p_T
- AMPT non-flow only far under-predicts for low p_T, too high for high p_T

v_3 vs p_T—a further test of geometry engineering



- v_3 is non-zero and lower in d+Au compared to ^{3}He+Au
- Excellent further confirmation that geometry engineering works
- Hydro predictions show excellent agreement with data

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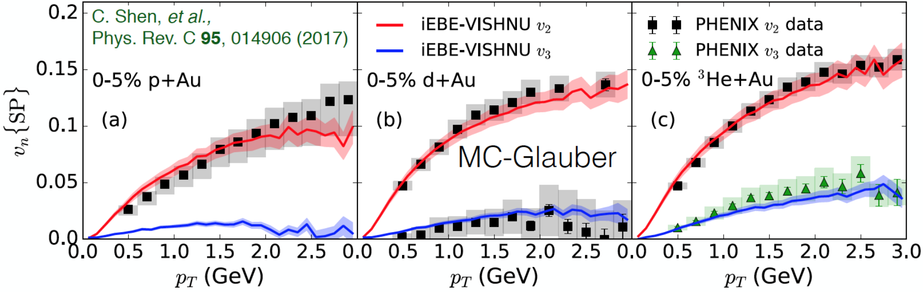

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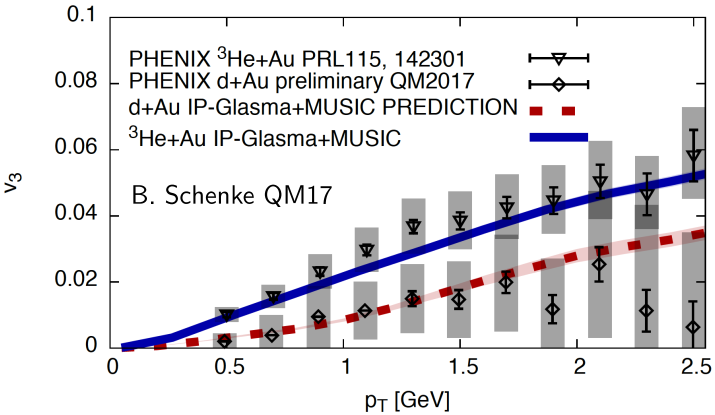

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Intermission

Clearly, "fluctuations" are doing a lot of work for us. What do we mean, and how well do we understand them?

Cumulants: a closer inspection

- We always say $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \sqrt{v_2^2 - \sigma^2}$

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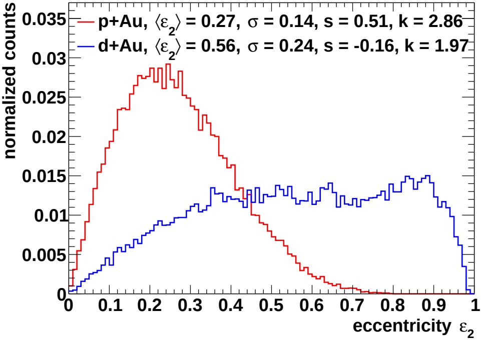
  - Gaussian fluctuations
  - Small relative variance, $\sigma / v_n \ll 1$
- Are these assumptions valid? Let's have a look...

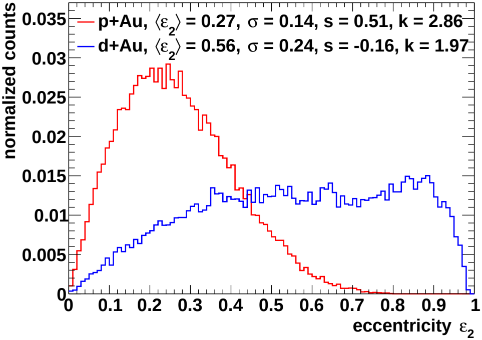
Eccentricity distributions and cumulants



	p+Au	d+Au
$\langle\varepsilon_2\{2\}\rangle$	0.303	0.610
$\langle\varepsilon_2\rangle$	0.270	0.560
$\langle\varepsilon_2\{4\}\rangle$ Approx.	0.232	0.505
$\langle\varepsilon_2\{4\}\rangle$ Exact	0.166	0.508

- Eccentricity cumulants: $\varepsilon_2\{2\} = (\langle\varepsilon_2^2\rangle)^{1/2}$, $\varepsilon_2\{4\} = (-(\langle\varepsilon_2^4\rangle - 2\langle\varepsilon_2^2\rangle^2))^{1/4}$
- We don't have the v_n distribution but in the hydro limit $v_n \propto \varepsilon_n$

Eccentricity distributions and cumulants



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- We don't have the v_n distribution but in the hydro limit $v_n \propto \varepsilon_n$
- Gaussian? No. Small relative variance? No.

Back to basics (a brief excursion)

The (raw) moments of a probability distribution function $f(x)$:

$$\mu_n = \langle x^n \rangle \equiv \int_{-\infty}^{+\infty} x^n f(x) dx$$

The moment generating function:

$$M_x(t) \equiv \langle e^{tx} \rangle = \int_{-\infty}^{+\infty} e^{tx} f(x) dx = \int_{-\infty}^{+\infty} \sum_{n=0}^{\infty} \frac{t^n}{n!} x^n f(x) dx = \sum_{n=0}^{\infty} \mu_n \frac{t^n}{n!}$$

Moments from the generating function:

$$\mu_n = \left. \frac{d^n M_x(t)}{dt^n} \right|_{t=0}$$

Key point: the moment generating function uniquely describe $f(x)$

Back to basics (a brief excursion)

Can also uniquely describe $f(x)$ with the cumulant generating function:

$$K_x(t) \equiv \ln M_x(t) = \sum_{n=0}^{\infty} \kappa_n \frac{t^n}{n!}$$

Cumulants from the generating function:

$$\kappa_n = \left. \frac{d^n K_x(t)}{dt^n} \right|_{t=0}$$

Since $K_x(t) = \ln M_x(t)$, $M_x(t) = \exp(K_x(t))$, so

$$\mu_n = \left. \frac{d^n \exp(K_x(t))}{dt^n} \right|_{t=0}, \quad \kappa_n = \left. \frac{d^n \ln M_x(t)}{dt^n} \right|_{t=0}$$

End result: (details left as an exercise for the interested reader)

$$\mu_n = \sum_{k=1}^{n} B_{n,k}(\kappa_1, ..., \kappa_{n-k+1}) \qquad = B_n(\kappa_1, ..., \kappa_{n-k+1})$$

$$\kappa_n = \sum_{k=1}^{n} (-1)^{k-1}(k-1)! B_{n,k}(\mu_1, ..., \mu_{n-k+1}) \quad = L_n(\kappa_1, ..., \kappa_{n-k+1})$$

Back to basics (a brief excursion)

Evaluating the Bell polynomials gives

$$\langle x \rangle = \kappa_1$$
$$\langle x^2 \rangle = \kappa_2 + \kappa_1^2$$
$$\langle x^3 \rangle = \kappa_3 + 3\kappa_1\kappa_2 + \kappa_1^3$$
$$\langle x^4 \rangle = \kappa_4 + 4\kappa_1\kappa_3 + 3\kappa_2^2 + 6\kappa_1^2\kappa_2 + \kappa_1^4$$

One can tell by inspection (or derive explicitly) that κ_1 is the mean, κ_2 is the variance, etc.

Back to basics (a brief excursion)

Subbing in $x = v_n$, $\kappa_2 = \sigma^2$, we find

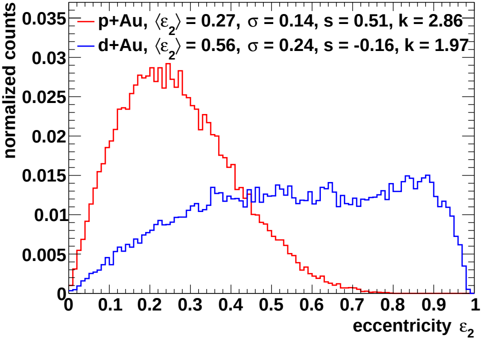
$$\left(\langle v_n^4 \rangle = v_n^4 + 6v_n^2\sigma^2 + 3\sigma^4 + 4v_n\kappa_3 + \kappa_4\right)$$
$$-\left(2\langle v_n^2 \rangle^2 = 2v_n^4 + 4v_n^2\sigma^2 + 2\sigma^4\right)$$
$$\rightarrow$$
$$\langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2 = -v_n^4 + 2v_n^2\sigma^2 + \sigma^4 + 4v_n\kappa_3 + \kappa_4$$

Skewness s: $\kappa_3 = s\sigma^3$
Kurtosis k: $\kappa_4 = (k-3)\sigma^4$

$$v_n\{2\} = (v_n^2 + \sigma^2)^{1/2}$$
$$v_n\{4\} = (v_n^4 - 2v_n^2\sigma^2 - 4v_n s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

So the correct form is actually much more complicated than we tend to think...

Eccentricity distributions and cumulants



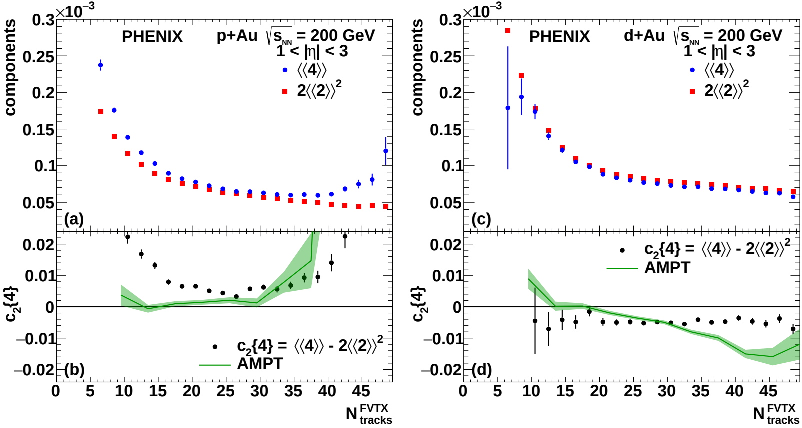
	p+Au	d+Au
ε_2^4	0.00531	0.0983
$2\varepsilon_2^2\sigma^2$	0.00277	0.0370
$4\varepsilon_2 s\sigma^3$	0.00147	-0.0053
$(k-2)\sigma^4$	0.00031	-0.0001

$$\varepsilon_2\{4\} = (\varepsilon_2^4 - 2\varepsilon_2^2\sigma^2 - 4\varepsilon_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

- the variance brings $\varepsilon_2\{4\}$ down (this term gives the usual $\sqrt{v_2^2 - \sigma^2}$)
- positive skew brings $\varepsilon_2\{4\}$ further down, negative skew brings it back up
- kurtosis > 2 brings $\varepsilon_2\{4\}$ further down, kurtosis < 2 brings it back up

  —recall Gaussian has kurtosis $= 3$

Eccentricity distributions and cumulants



$$v_2\{4\} = (v_2^4 - 2v_2^2\sigma^2 - 4v_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

- Eccentricity fluctuations alone go a long way towards explaining this
- Additional fluctuations in the (imperfect) translation of ε_2 to v_2?

Chirality

What is chirality?

- Chirality is an internal quantum number, equal to $-1(L)$ or $+1(R)$
- For massless particles it is equal to sign of energy times helicity $(p_0\vec{s}\cdot\vec{p}/|p_0 s|)$, for massive particles it is different (and it evolves with time—Higgs)
- Chirality is a Lorentz invariant, while helicity is not for massive particles
- Helicity and chirality are P-odd, meaning they change sign under parity transformation
- Any state can be written as the sum of the left and right components, i.e.
  $\psi = \psi_R + \psi_L$
- The chirality operator is the Dirac gamma matrix γ^5 and has eigenvalues of ± 1
  $\gamma^5\psi_R = +\psi_R, \quad \gamma^5\psi_L = -\psi_L, \quad \gamma^5\overline{\psi}_R = -\overline{\psi}_R, \quad \gamma^5\overline{\psi}_L = +\overline{\psi}_L$
- The chiral projection operators can be constructed from γ^5
  $P_{R,L} = \frac{1}{2}(1 \pm \gamma^5)$

Chirality

A brief word on notation and terminology

- Typically any vector quantity can be written as the sum of the chiral quantities
- The vector current is the sum of left- and right-handed current $J_V^\mu = J_R^\mu + J_L^\mu$
- Typically any axial quantity can be written as the difference of the chiral quantities
- The axial current is the difference of left- and right-handed current $J_A^\mu = J_R^\mu - J_L^\mu$
- The same is also true with chemical potentials, number densities, etc.

  $n_V = n_R + n_L, \qquad n_A = n_R - n_L$
- Symmetry groups can also be represented this way, $G_R \times G_L = G_V \times G_A$

Chirality

Chiral symmetry and breaking

- Chiral symmetry is invariance of the Lagrangian under independent rotations of L and R fermions
- Chiral symmetry is broken whenever there is mixing between L and R

$$m\overline{\psi}\psi = m(\overline{\psi}_R + \overline{\psi}_L)(\psi_R + \psi_L) = m(\overline{\psi}_R\psi_R + \overline{\psi}_L\psi_L + \overline{\psi}_R\psi_L + \overline{\psi}_L\psi_R)$$

- Simplified QCD Lagrangian with massless quarks:

$$\mathcal{L} = \mathcal{L}_{\text{glue}} + \overline{\psi}_R \not{D} \psi_R + \overline{\psi}_L \not{D} \psi_L$$

- This Lagrangian is invariant under separate unitary rotations in flavor space for R and L:

$$\overline{\psi}_{R,L} \not{D} \psi_{R,L} \to \overline{\psi}_{R,L} V^{\dagger}_{R,L} \not{D} V_{R,L} \psi_{R,L} = \overline{\psi}_{R,L} \not{D} V^{\dagger}_{R,L} V_{R,L} \psi_{R,L} = \overline{\psi}_{R,L} \not{D} \psi_{R,L}$$

- Rewriting the symmetries:

$$\begin{aligned} U(N_f)_R \times U(N_f)_L &\to SU(N_f)_R \times SU(N_f)_L \times U(1)_R \times U(1)_L \\ &\to SU(N_f)_V \times SU(N_f)_A \times U(1)_V \times U(1)_A \end{aligned}$$

Chirality

Chiral symmetry and breaking

- In general, there are three categories of symmetry breaking
  –explicit: not actually present in the Lagrangian
  –spontaneous: present in the Lagrangian but lost in the equations of motion
  –anomalous: present in the classical theory but lost in quantization
- QCD has explicit chiral symmetry breaking due to the non-zero Higgs masses of the quarks
- QCD has spontaneous chiral symmetry breaking of $SU(N_f)_A$, which is what gives rise to the hadron masses (98% of the mass of the visible universe is due to the spontaneous symmetry breaking)
- QCD has anomalous breaking of $U(1)_A$ symmetry
- Chiral symmetry summary:

Symmetry	Status	Meaning or effect
$SU(N_f)_V$	Approximate	flavor symmetry, pseudo-Goldstone b
$SU(N_f)_A$	Spontaneously broken	98% of nucleon mass
$U(1)_V$	Exact	baryon conservation
$U(1)_A$	Anomalously broken	chiral anomaly

How to calculate B-field

Start with the Biot-Savart Law for moving point charges:

$$\vec{E} = \frac{e}{4\pi\varepsilon_0} \frac{1 - v^2/c^2}{(1 - v^2 \sin^2\theta/c^2)^{3/2}} \frac{\hat{r}}{r^2},$$

$$\vec{B} = \frac{1}{c^2}[\vec{v} \times \vec{E}],$$

where $\sin\theta = |\hat{r} \times \hat{v}|$. Take $\sin\theta = 1$ (true at $t = 0$).

$$\vec{E} = \frac{e}{4\pi\varepsilon_0} \frac{1 - v^2/c^2}{(1 - v^2/c^2)^{3/2}} \frac{\hat{r}}{r^2} = \frac{e}{4\pi\varepsilon_0} \gamma \frac{\hat{r}}{r^2}$$

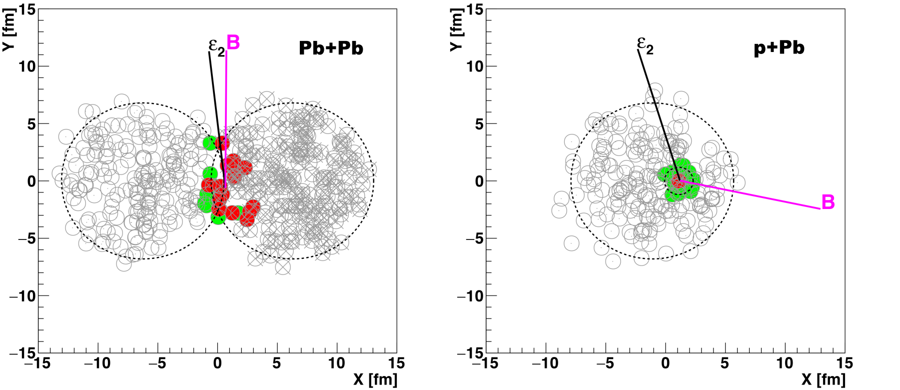
Since $\hat{r} \equiv \hat{E}$ and we've set $\sin\theta = 1$, we have $\vec{v} \times \vec{E} = v\vec{E}$, so we get

$$\vec{B} = \frac{v}{c^2}\vec{E} = c\frac{e\mu_0}{4\pi}\beta\gamma\frac{1}{r^2}\hat{r}.$$

Pick a point (or region to average over) for evaluation, plug and chug constants, profit!
Theorists like to give $\hbar eB/c^2$—10^{15} Tesla $\leftrightarrow$ 3.04 m_π^2

Magnetic field calculations for Pb+Pb and p+Pb

R. Belmont and J.L. Nagle, Phys. Rev. C 96, 024901 (2017)



- Pb+Pb: impact parameter, ψ_2, and ψ_B appear strongly correlated
- p+Pb: impact parameter, ψ_2, and ψ_B appear uncorrelated

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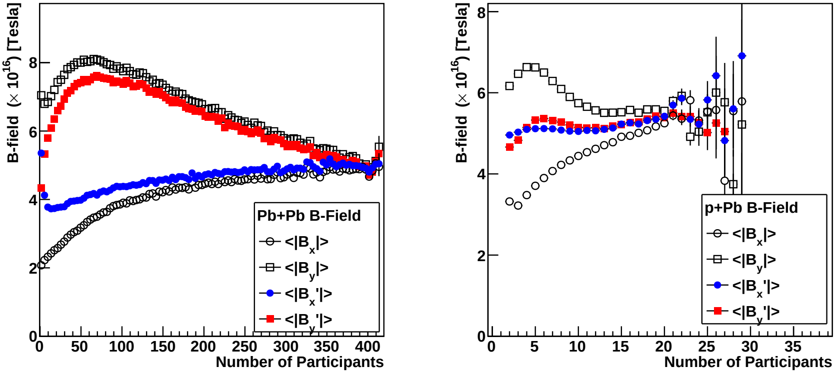
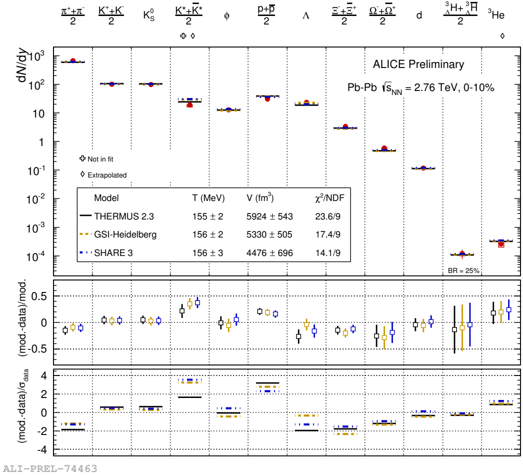


- Very strong magnetic fields in both cases ($\sim 150\ m_\pi^2$ for central collisions)
- Impact parameter along x, ψ_2 along x'
- Average x' and y' components equal means no correlation between ψ_2 and ψ_B

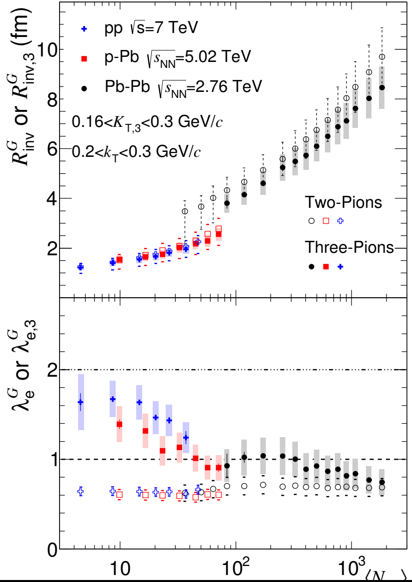
Thermal fits to ALICE data



- Thermal model assumes grand canonical ensemble
- Few parameters—T and V, μ_B fixed in this case (free at lower energies)
- Reproduces integrated yields of many different particle species over many orders of magnitude
- Sometimes ratios are used instead of yields, so V drops out and T and μ_B are the only free parameters
- Works extremely well over a very wide range

Quantum correlations and system size

Phys. Lett. B 739 (2014) 139-151



- Quantum correlations can be used to estimate the system size R
  $\Delta x \Delta p \gg 2\pi\hbar$ (classical)
  $\Delta x \Delta p \approx 2\pi\hbar$ (quantum)
- Generally 2 indistinguishable particles are used
- ALICE the first to report 3-particle quantum correlations, which do not contain background from other kinds of 2-particle correlations

Quantum correlations and system size

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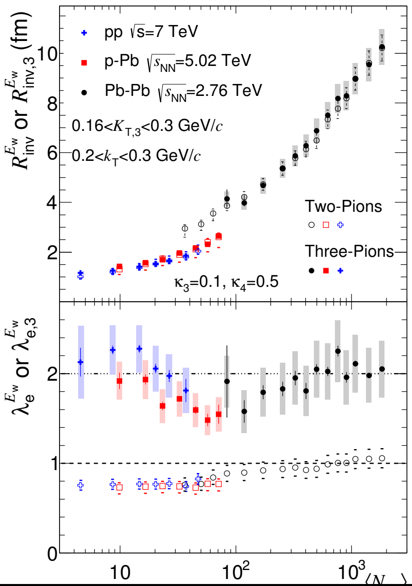

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Quantum correlations and system size

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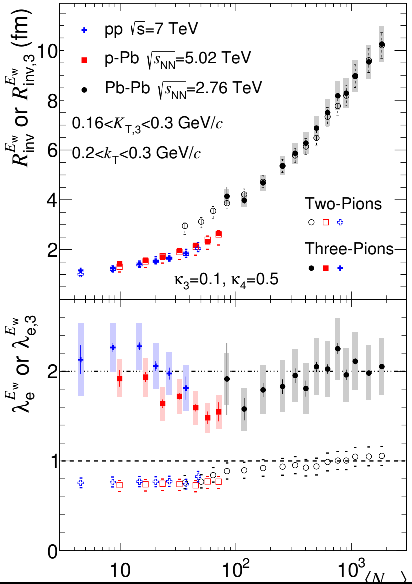

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- Use of non-Gaussian function to fit correlation improves quality of fit and agreement between 2- and 3-particle correlations
- Parameter λ very close to chaotic limit—incoherent emission
- pp and p-Pb close together, Pb-Pb separate