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Overview of high-energy heavy ion collision physics

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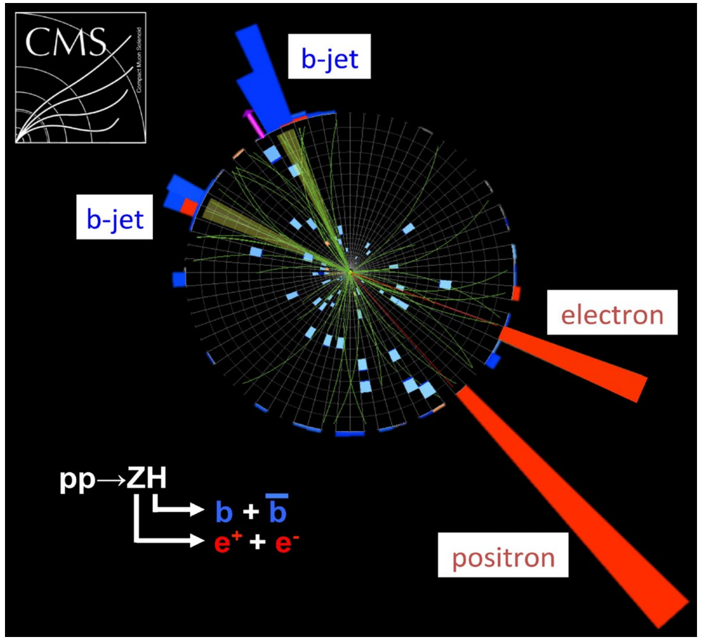
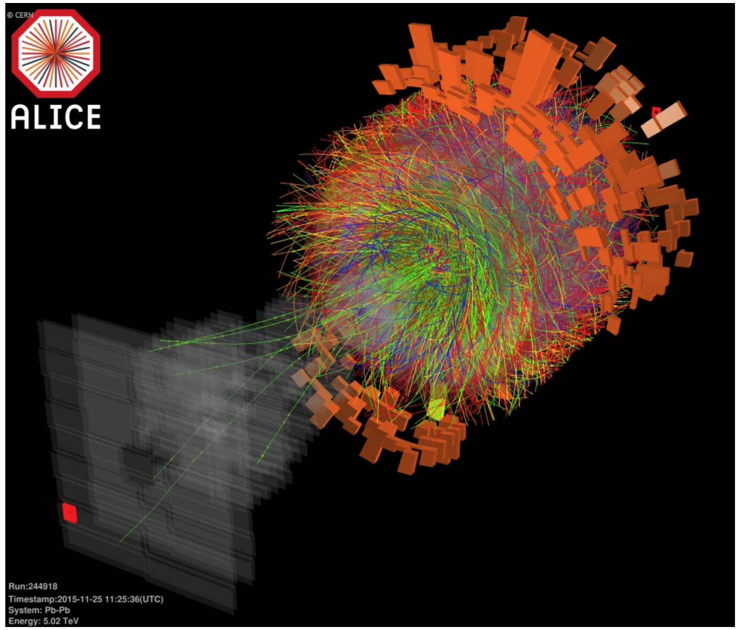
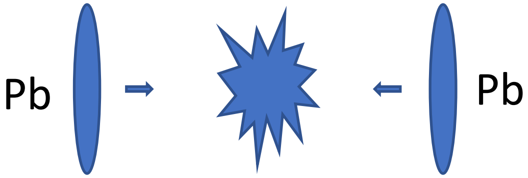
Why high-energy heavy ion collisions?

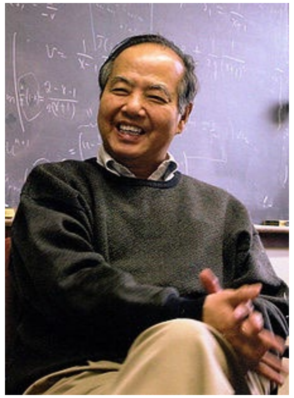






- More is different!
- Heavy Ion Collision (HIC) is NOT simple superposition of p-p collisions

0 Why high-energy heavy ion collisions?



"We should investigate ... … phenomena by distributing high energy or high nucleon density over a relatively large volume."
--- T.D. Lee, 1974

Report of the Workshop on
BEV/NUCLEON COLLISIONS OF HEAVY IONS - HOW AND WHY
November 29-December 1, 1974
Bear Mountain, New York

RELATIVISTIC HEAVY ION COLLISIONS

T. D. Lee
Columbia University, New York, N. Y. 10027

1982

I. Two Puzzles

At present, most physicists feel that we have finally arrived at a closed system of physical laws, with QCD for the strong interaction and a unifying gauge theory for the weak and electromagnetic forces, plus of course Einstein's theory of general relativity. However, there are a few things that are not completely satisfactory. Of the participating fundamental particles, only the leptons and the photon have been observed directly. The intermediate bosons and the graviton, we hope, can be detected in the near future. All the rest, the quarks and the gluon, we believe can never come out in the open and that therefore direct observation will always be impossible.

In view of this, our strong belief in this grand scheme must not be due entirely to direct experimental evidence, but rather be based on the esthetic simplicity of the theoretical foundation and the compelling conclusion of our mathematical deduction.

1. Missing symmetry

The basis of all these theories rests entirely on the symmetry[1] under local transformations with respect to either the internal gauge variables or the space-time variables. Yet, in reality, almost all the symmetry quantum numbers are found to be, or believed to be, not conserved. Even the best-established conservation law, that of the baryon number, is now also believed to be violated. Surely, this is somewhat puzzling.

2. Color confinement

Another puzzle is the problem of quark or color confinement, which makes half of the elementary particles, quarks and gluons, non-direct observables. The explanation of both puzzles is to invoke the properties of the vacuum.

different from zero:

$$\langle \phi \rangle_{vac} \neq 0 \,. \qquad (1)$$

In the second case, color confinement, we assume the QCD vacuum to be a condensed state of gluon pairs so that it is a perfect color dia-electric (i.e., color dielectric constant $\kappa = 0$). This is in complete analogy to the description of a superconductor as a condensed state of electron pairs in the BCS theory, which results in making the superconductor a perfect dia-magnet (with magnetic susceptibility $\mu = 0$). When we switch from QED to QCD we replace the magnetic field $\vec{H}$ by the color electric field $\vec{E}$, the superconductor by the QCD vacuum, and the QED vacuum by the interior of the hadron. As shown in Figure 1, the inside by the outside and the outside by the inside. Just as the magnetic field is expelled outward from the superconductor, the color electric field is pushed into the hadron by the QCD vacuum, and that leads to color confinement. This situation can be summarized as follows:

QED Superconductivity as a Perfect Diamagnet		QCD Vacuum as a Perfect Color Dielectric
$\vec{H}$	⟷	$\vec{E}$
$\mu_{inside} = 0$	⟷	$\kappa_{vacuum} = 0$
$\mu_{vacuum} = 1$	⟷	$\kappa_{inside} = 1$
inside	⟷	outside

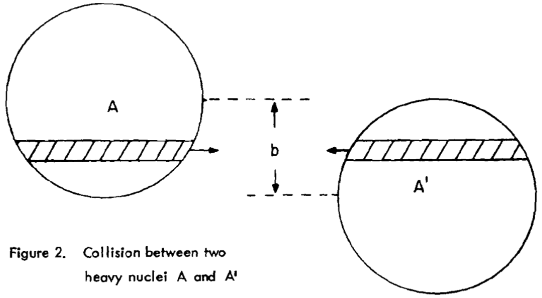


Figure 2. Collision between two heavy nuclei A and A'

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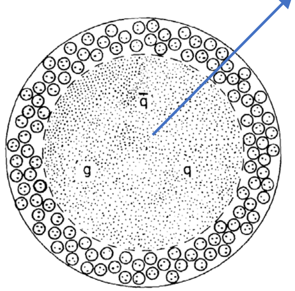
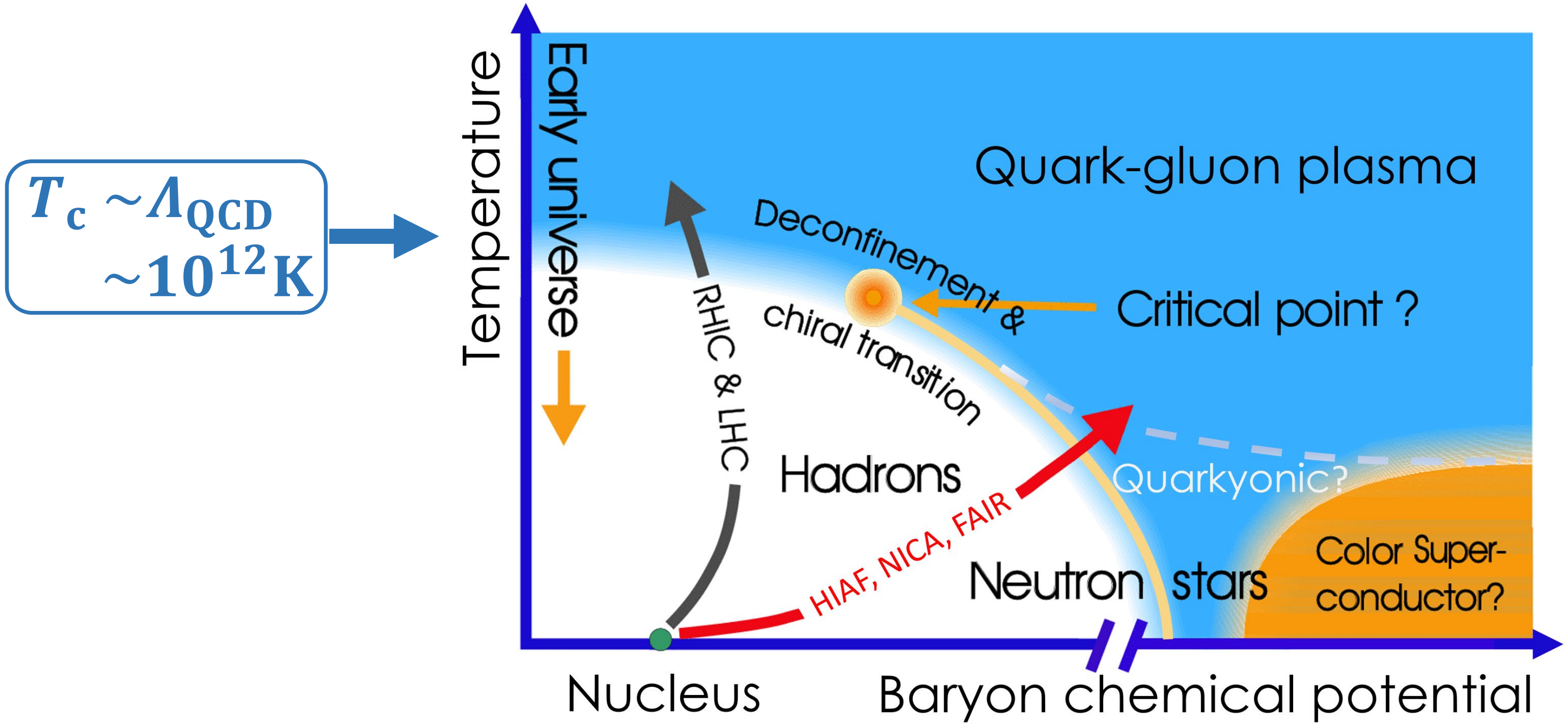


Figure 3.
An object whose interior is a quark-antiquark and gluon plasma.

Quark-gluon plasma (QGP)

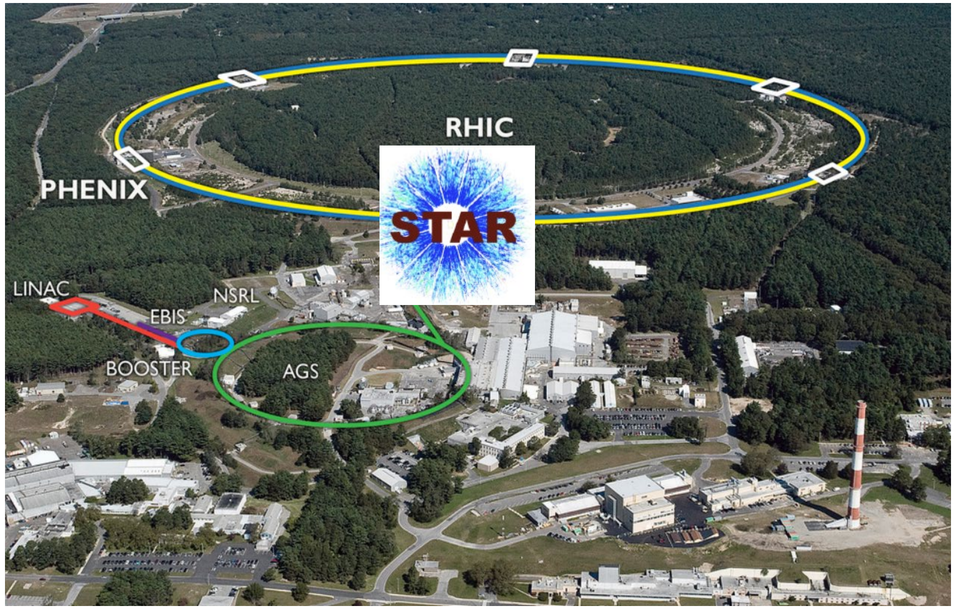
0 Why high-energy heavy ion collisions?

QCD phase diagram



- Confinement at IR
- Quark gluon plasma
- Chiral symmetry
- Critical point
- Quarkyonic matter
- Color superconductor
- … …

Currently operating high-energy heavy ion colliders



RHIC@BNL,2000 -

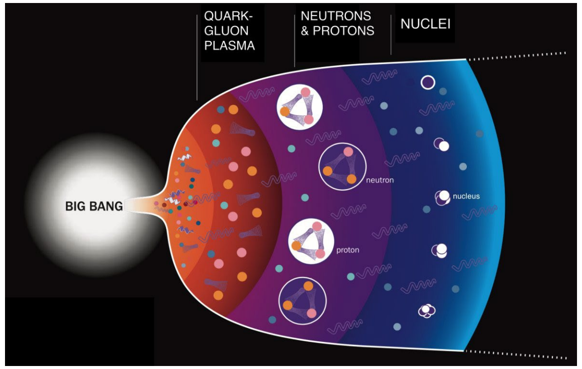
Top energy: Au + Au @ $\sqrt{s} = 200$ GeV

LHC@CERN, 2010 -

Top energy: Pb + Pb @ $\sqrt{s} = 5.02$ TeV

How to detect QGP?

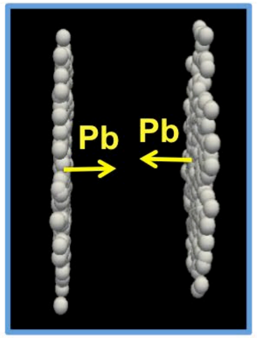
- **The big bang**



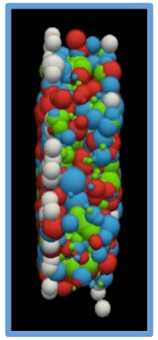
- **The little bang**

time

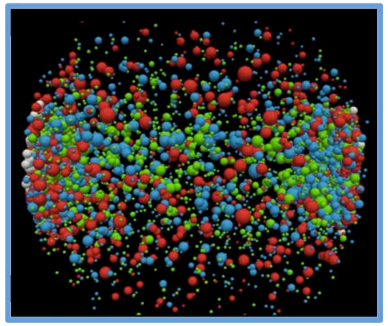
Pre-reaction



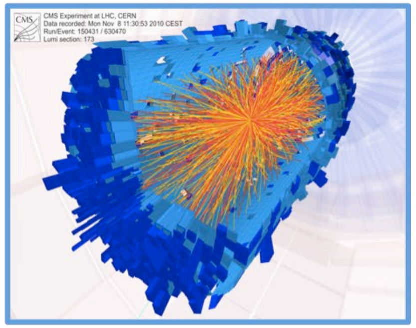
QGP



Hadronization



Detection



We need to find or design specific hadron (and lepton, photon) observables to probe QGP

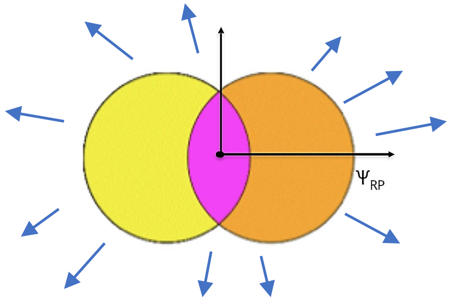
Content

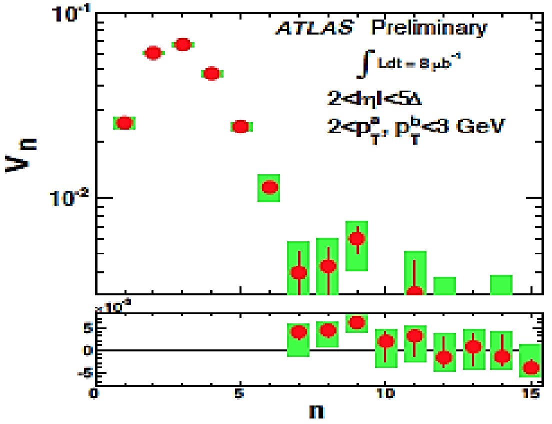
1. **Soft probes**
   - Collective flow and hydrodynamics
2. **Hard probes**
   - Jet and jet quenching
   - Heavy flavors
3. **Strong magnetic and vortical fields**
   - Chiral magnetic and vortical effects
   - Hadron spin polarization phenomena
4. **Summary**

1 Soft probes

1 Harmonic flows and collectivity

➢ Spectrum anisotropy in A + A collisions: harmonic flows

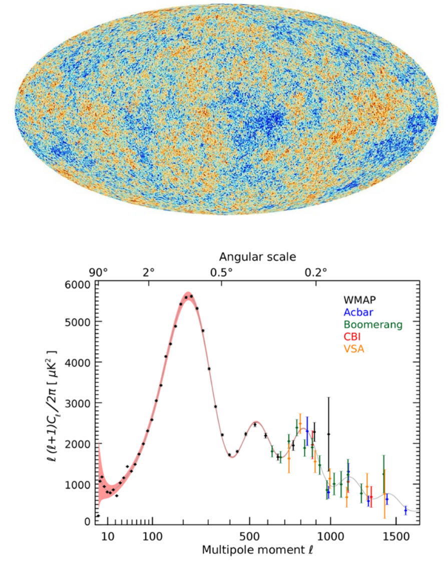




$$\frac{dN(p_T)}{d\phi} \sim 1 + 2v_1(p_T)\cos(\phi - \Psi_{\mathrm{RP}}) + 2v_2(p_T)\cos[2(\phi - \Psi_{\mathrm{RP}})] + \cdots$$

Directed flow (v_1) · Elliptic flow (v_2)

Cosmic Microwave Background Anisotropy



➢ Standard interpretation of low-pt flows: partonic hydrodynamic collectivity

- Conservation law: $\partial_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \text{viscous terms}$
- Equation of state: $P = P(\varepsilon)$
- Shear/bulk viscosities: $\eta/s,\ \zeta/s,\ \cdots$

Input for hydro. Constrained by comparison with experimental data of v_n

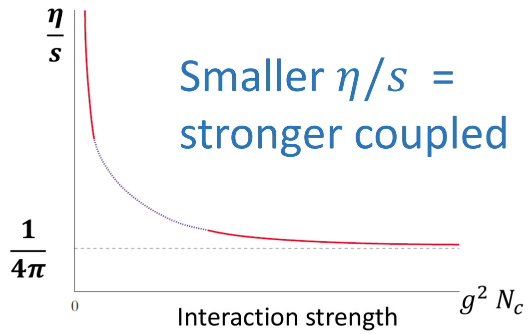
Harmonic flows and collectivity

➢ Specific shear viscosity η/s: perfectness of fluid (inner friction in fluid)

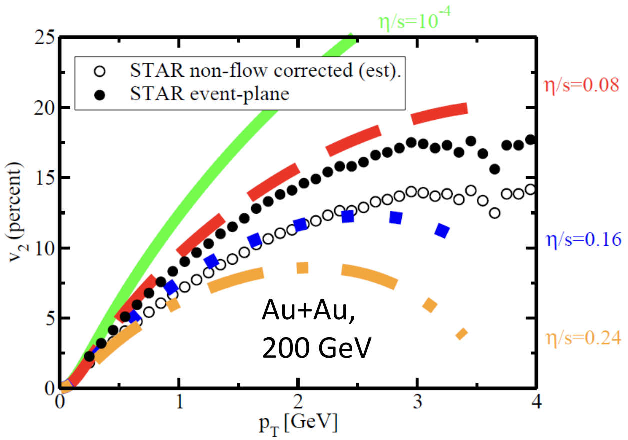
Wave propagating at the speed of sound c_s

$$\text{Perturbation} \propto \exp\left[i\, c_s\, k\, t - i\, \vec{k}\cdot\vec{x} - \left(\frac{4}{3}\frac{\eta}{s} + \frac{\zeta}{s}\right)\frac{k}{2T}\, k\, t\right]$$

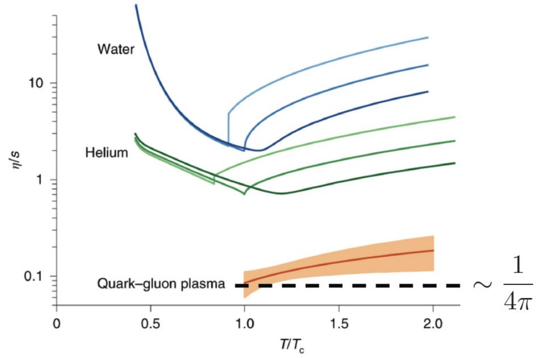
Decay rate of perturbation



➢ Elliptic flow and the perfectness of QGP



(Luzum, Romatschke 2008)



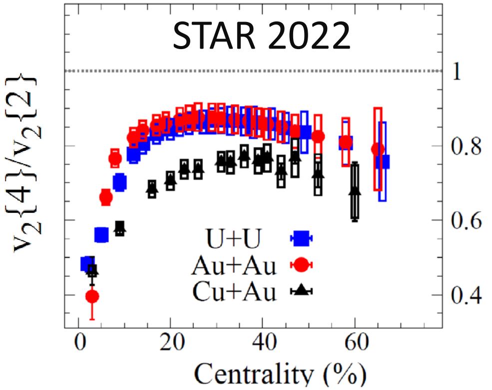
(Bernhard, Moreland, Bass 2019)

1

Harmonic flows and collectivity

➢ More flow observables

- ➢ v_n flunctuation
- ➢ $v_n - v_m$ correlation
- ➢ Nolinearity
- ➢ Longitudinal decorrelation
- ➢ … …



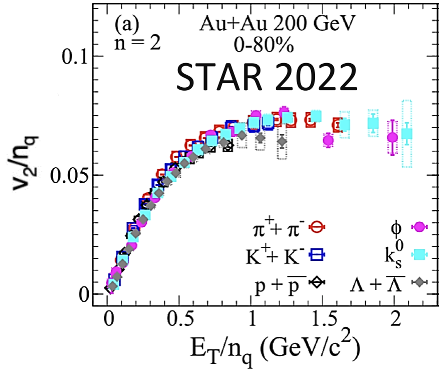
$$\frac{v_2\{4\}}{v_2\{2\}} \approx \frac{\text{Mean}-\text{Geometry}}{\text{Mean}-\text{Geometry} + \text{Fluctuations}}$$

➢ Seeking boundary of partonic collectivity: lower energy and smaller system size

- ➢ Number of constituent quark (NCQ) scaling: signature of flowing partonic degrees of freedom

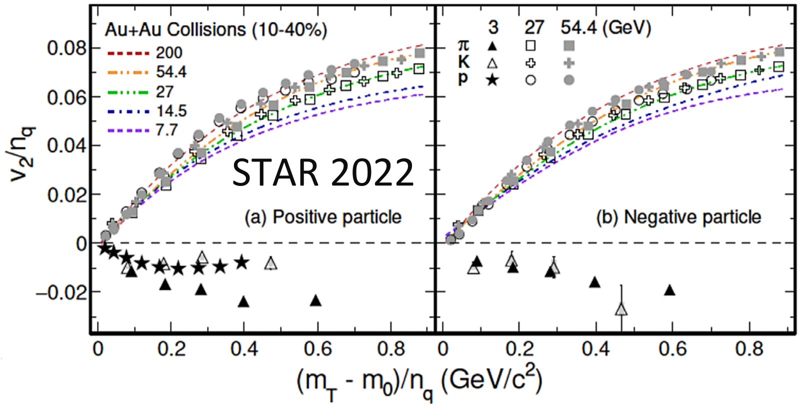
High energy, quarks flow the same way (i.e., thermalized):

$$1 + 2v_2^h(p_t)\cos(2\phi)$$
$$\propto [1 + 2v_2^q(p_t/n_q)\cos(2\phi)]^{n_q}$$
$$\approx 1 + 2n_q v_2^q(p_t/n_q)\cos(2\phi)$$



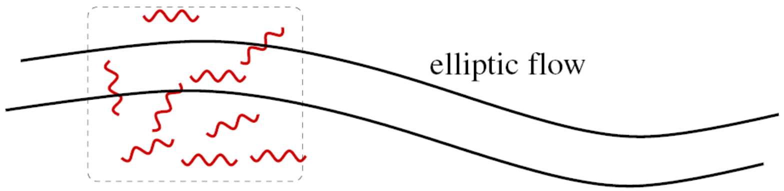
At 3 GeV, NCQ scaling is absent.

Hadronic interaction dominant.



Collectivity = hydrodynamics?

- **Applicability of hydrodynamics: local equilibrium and scale separation**



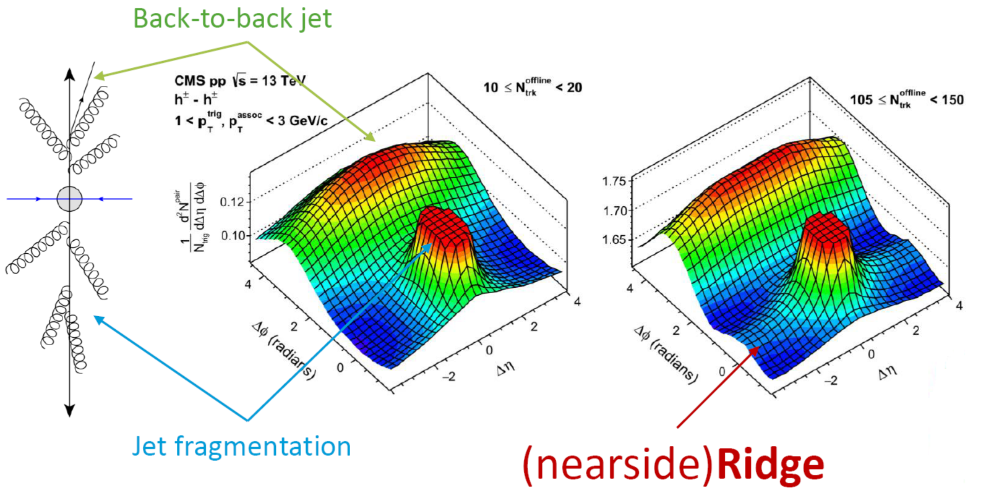
Separation of scales:
micro scale $l_{\text{mic}} \sim l_{\text{mfp}}$
macro scale $l_{\text{mac}} \sim 1/\partial \sim L$

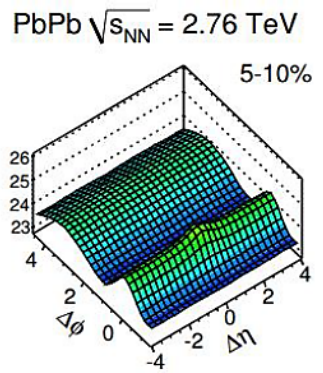
Knudsen number:
$Kn = l_{\text{mic}}/l_{\text{mac}} \ll 1$

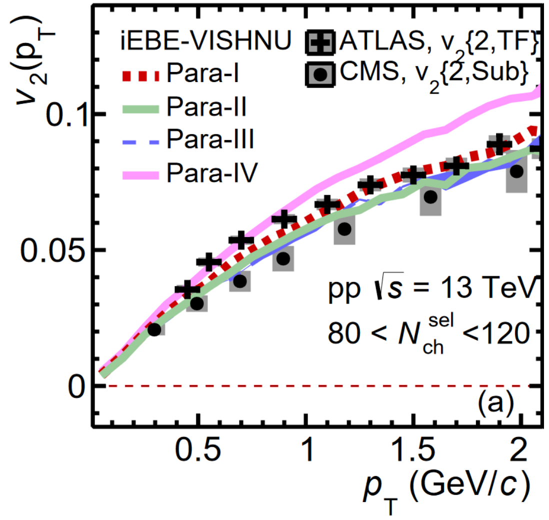
$F = -\nabla P$ + more gradients

Ideal hydro $(1/\text{system size})^n$

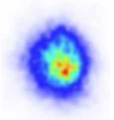
- **Surprisingly, collectivity observed in small p + p, p + Pb, d + Au, γ+Pb systems**







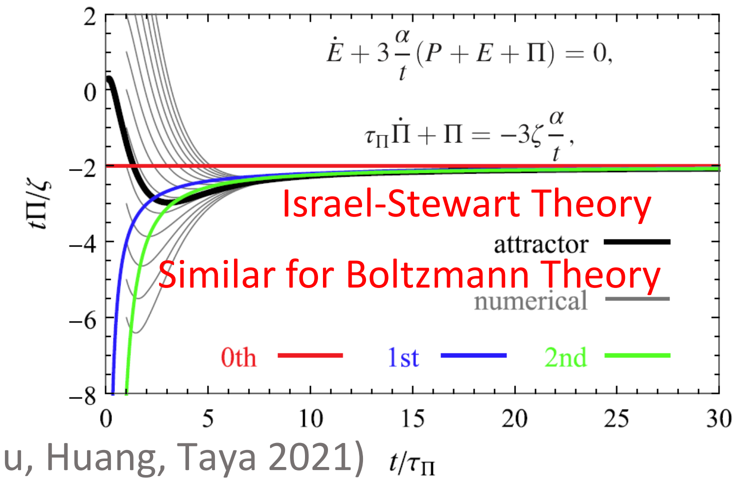
(Zhao, Zhou, Xu, Deng, Song 2018)



Finite geometry in p + p and p + Pb and hydro?

1 Collectivity = hydrodynamics?

- **Emergent hydro behavior non-equilib. systems: hydrodynamic attractor** (Heller, Spalinski 2015)
- **Simplest example: isotropically expanding fluid**



(Du, Huang, Taya 2021)

Inflational attractor

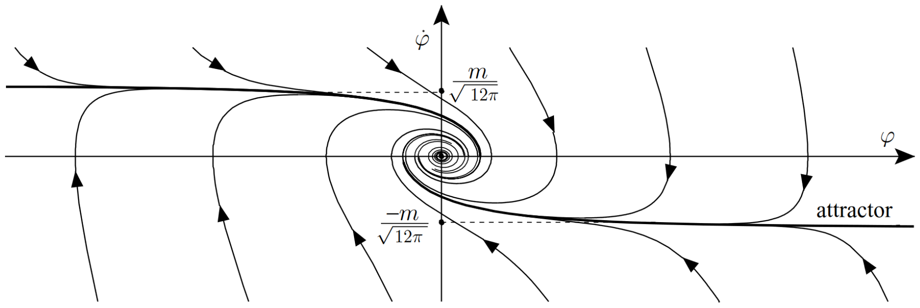
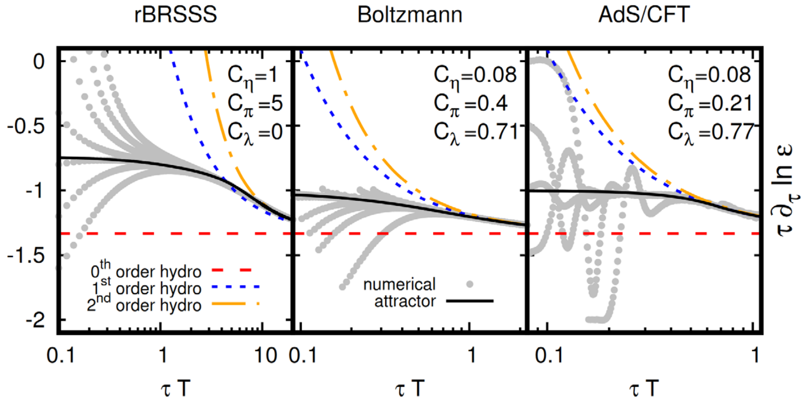
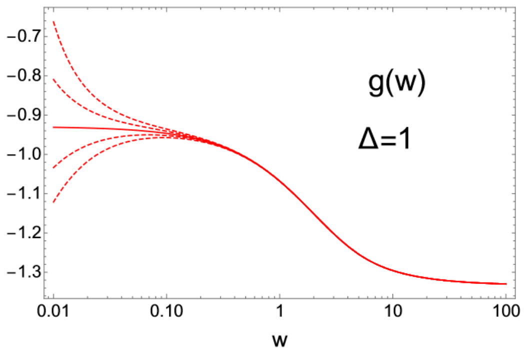


Fig. 5.3.

(Mukhanov, "Physical foundations of cosmology", 2005)

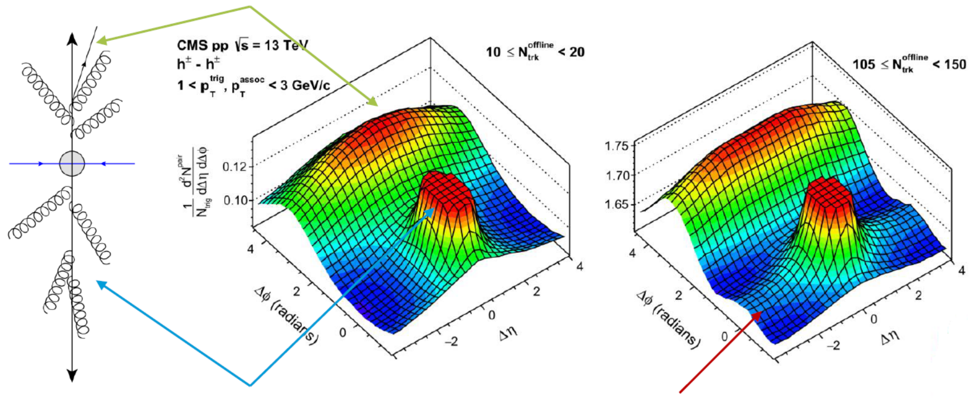
- **Hydro attractor in Bjorken expansion** (Romatschke 2017; Blaizot, Yan 2018-2022; Kurkela etal 2019)





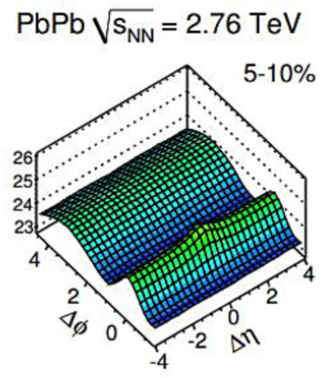
1 Collectivity = hydrodynamics?

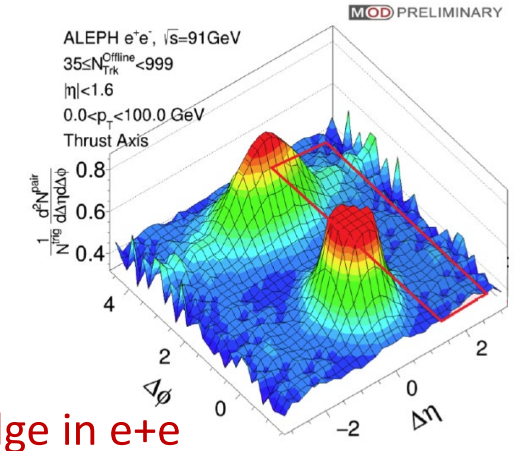
Back-to-back jet



Jet fragmentation

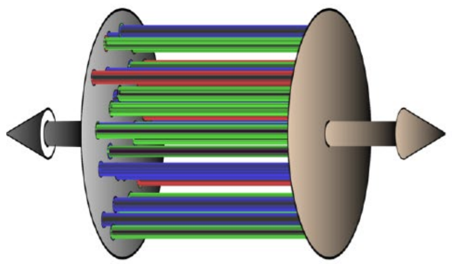
(nearside)**Ridge**

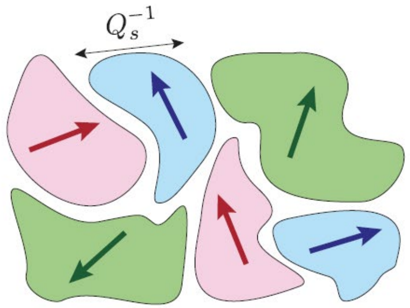


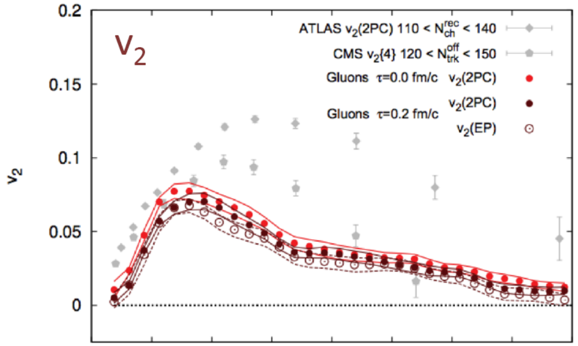


No ridge in e+e

- **Collectivity: Final stage interaction + hydro attractor or**
- **Collectivity: Initial stage correlation (mini jets, saturation, …)**





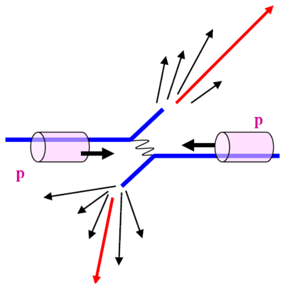


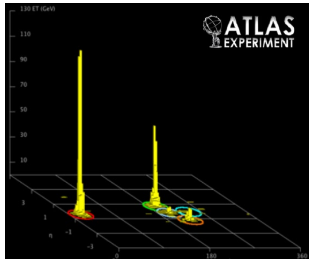
(Dumitru et al 2011; Dusling, Venugopalan 2012; Schenke et al 2015; Kovchegov, Skokov 2018; Schenke, Shen, Tribedy 2020; … …)

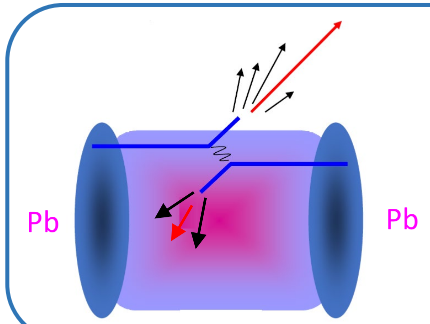
2 Hard probes

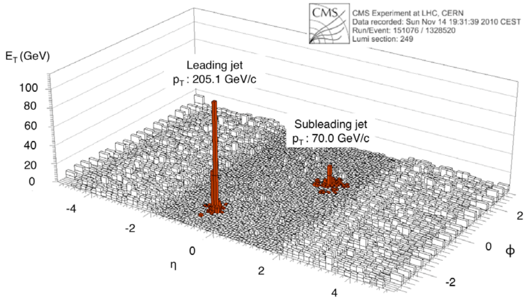
Jets in heavy ion collisions

➢ Jets in p + p and A + A collisions: Jet energy loss to QGP (quenching)





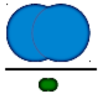




➢ Nuclear modification factor

Yields in A+A ↘

$$R_{AA} = \frac{1}{N_{\rm coll}} \frac{\frac{dN_{AA}}{dp_T}}{\frac{dN_{pp}}{dp_T}} = \frac{1}{T_{AA}} \frac{\frac{dN_{AA}}{dp_T}}{\frac{d\sigma_{pp}}{dp_T}} = \frac{1}{N_{\rm coll}}$$

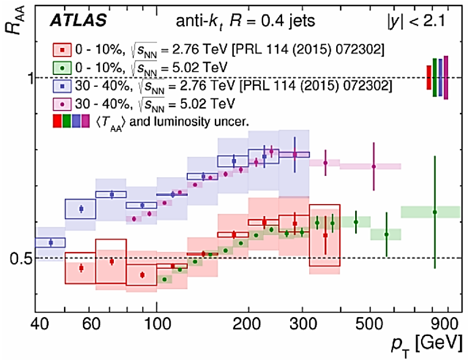


QCD in medium

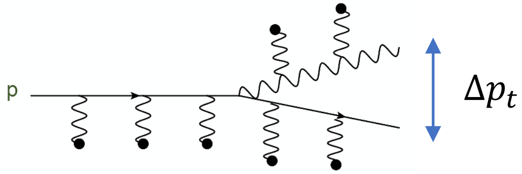
QCD in vacuum

pp reference

QGP is opaque to energetic jets

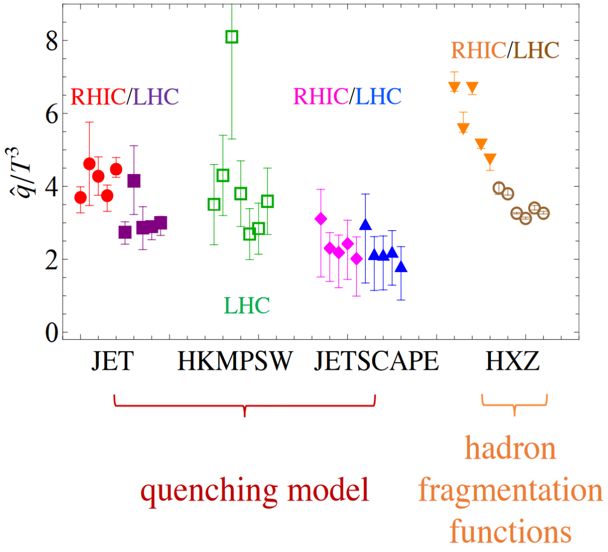


➢ Jet transport coefficient



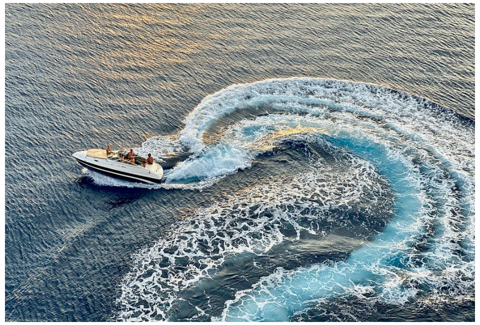
$$\hat{q} = \frac{d\langle \Delta p_t^2 \rangle}{dt}$$

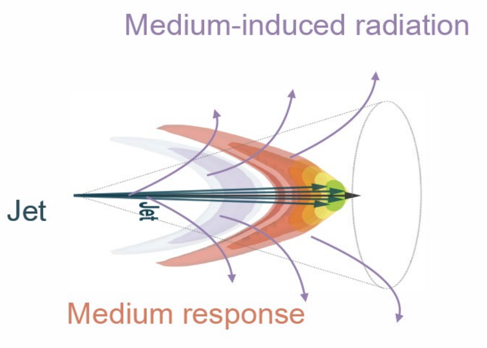
(Brewer 2022; JET 2013; Huss etal 2000; JETSCAPE 2021; Han, Xie, Zhang 2022)



Jets in heavy ion collisions

➤ QGP medium response to jet: jet energy deposited into soft sectors



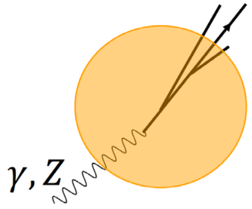


jet energy loss in QGP: $df/dt = C[f]$

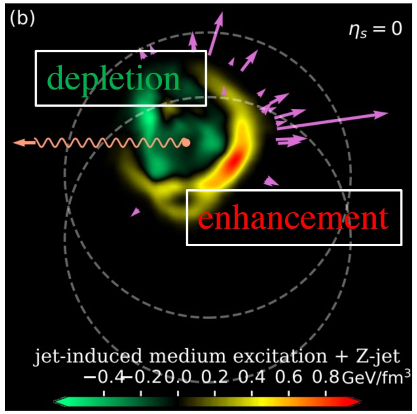
QGP response: $\partial_\mu T^{\mu\nu} = j^\mu = \int p^\mu f$

(Qin, Wang, Cao, Chang, Pang, He, Luo, et al 2017-)

➤ Jet induced wakes in QGP

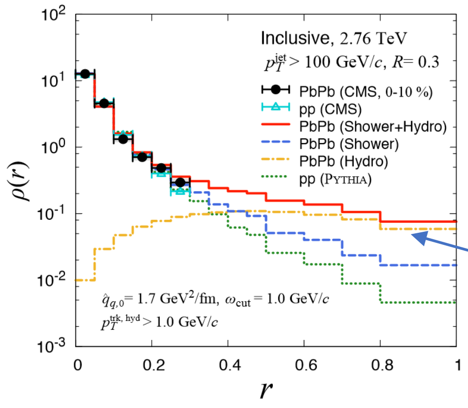


Jets selected by $p_T^{\gamma,Z}$



(Chen, Yang, He, Ke, Pang, Wang 2022)

➤ Jet shape function



$$r = \sqrt{(\eta_p - \eta_{jet})^2 + (\phi_p - \phi_{jet})^2}$$

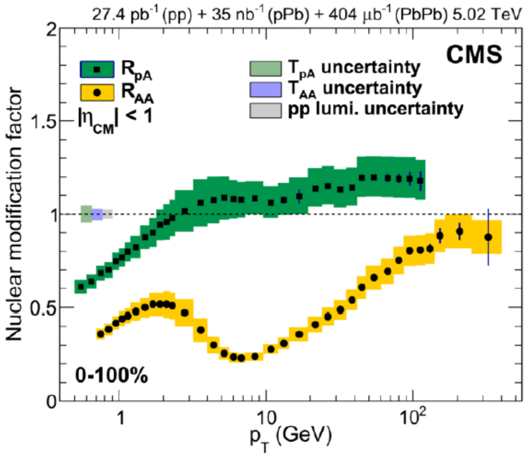
Describes energy distribution in jets

Enhanced soft particles generation away from jet

(Tachibana, Chang, Qin 2017)

2 Jets in heavy ion collisions

➢ No evidence of jet quenching is p + Pb and p + p collisions



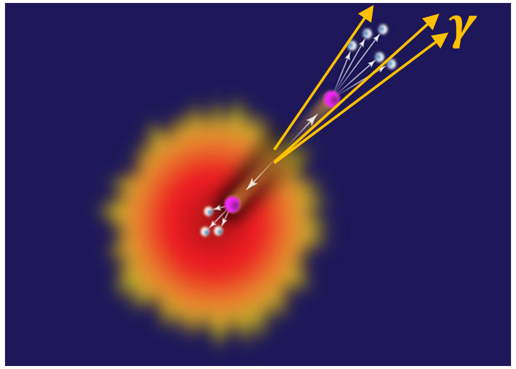
Puzzle: collectivity but no energy loss?

System size scan: p+p, O+O, p+O, Xe+Xe, Pb+Pb, …

2021	2022	2026-2027	>2030	time
OO (200 GeV) in STAR	Short OO, pO run (~7 TeV) in LHC Run 3	Possibility of OO, ArAr in sPHENIX	Long run of intermediate nuclei (Ar, Kr) in LHC Run 5	

➢ Jet as probe of topological domains

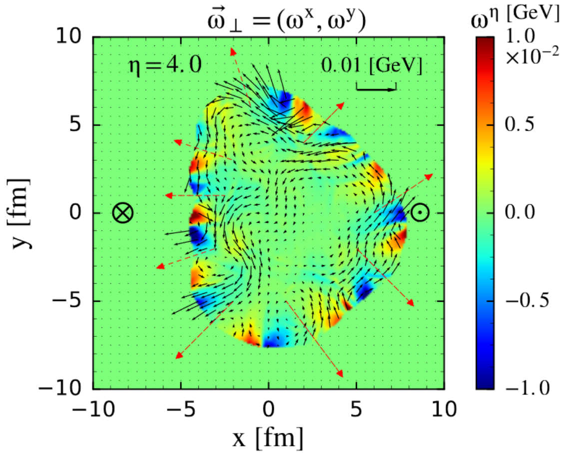
Chiral transition radiation (Huang, Tuchin 2018)



$$\frac{dN_\gamma^\pm}{d\omega} \propto \frac{E}{\omega}\left(\pm\kappa + \frac{m^2\omega^4}{2E^4}\right)$$

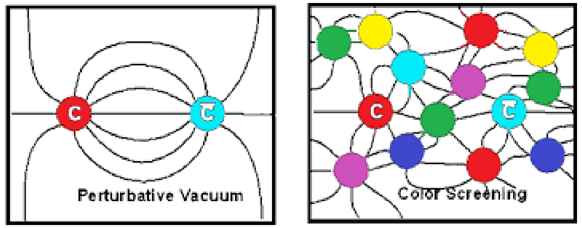
➢ Jet induced vorticity

(Pang, Peterson, Wang, Wang 2016)

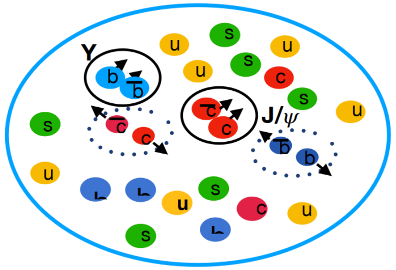


Heavy flavors

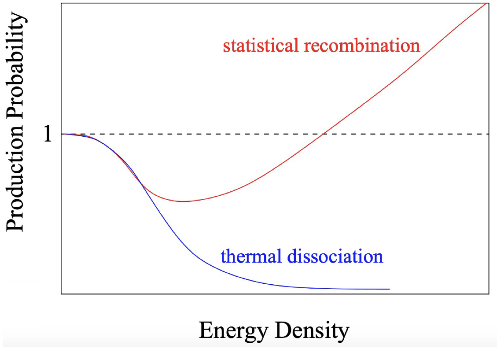
➢ Quarkonia suppression ("smoking gun" for QGP formation) and regeneration



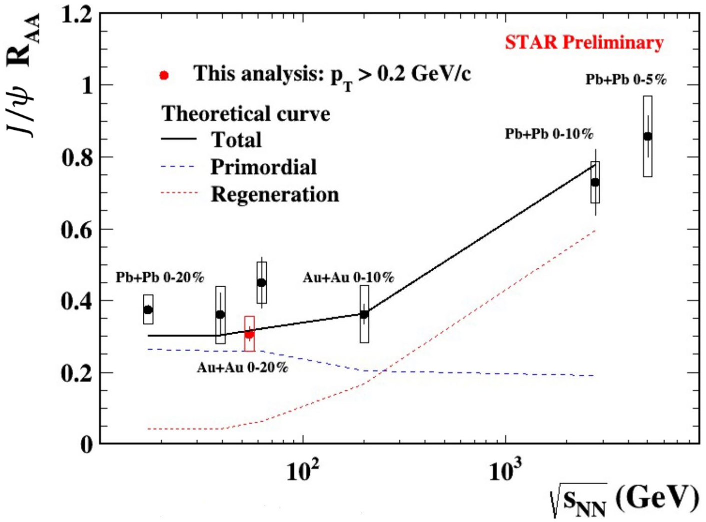
(Matsui, Satz 1986) Suppression



Regeneration

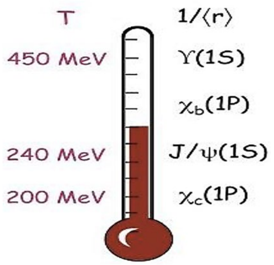


➢ Quantify quarkonia suppression and regeneration



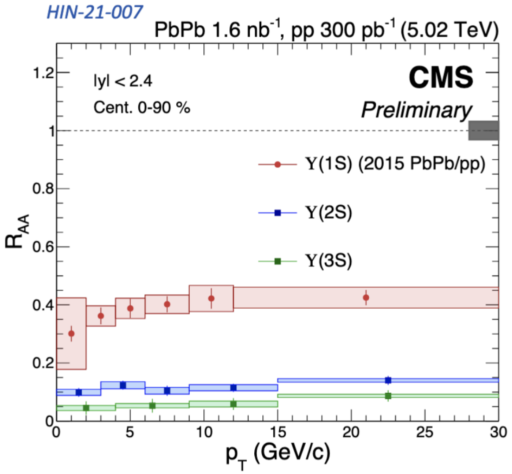
(Data: STAR 2017,2019,2021; ALICE 2014,2021; NA50 2000)

(Theory: Zhuang etal; Rapp etal; He etal)



Binding energy:
$\Upsilon(1S) > \Upsilon(2S) > \Upsilon(3S)$

Dissociation T:
$\Upsilon(1S) > \Upsilon(2S) > \Upsilon(3S)$

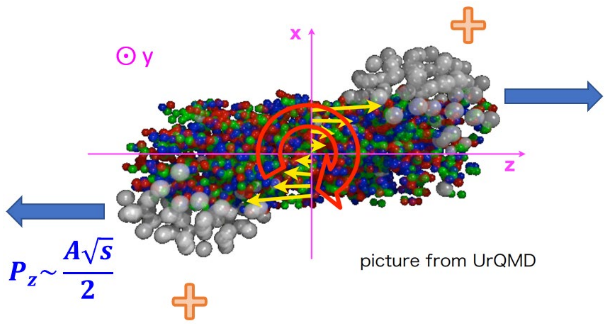


(CMS 2022)

3 Strong magnetic and vortical fields

Generation of magnetic and vortical fields

➢ For a non-central collision



$$J_0 \sim \frac{Ab\sqrt{s}}{2} \sim 10^7 \hbar$$

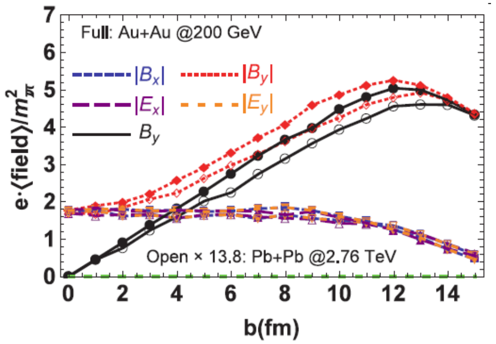
Global angular momentum

$$eB \sim \gamma \alpha_{\mathrm{EM}} \frac{Z}{b^2} \sim 10^{19}\ \mathrm{G}$$

Strong Magnetic field

(LHC Pb+Pb 2.76 TeV, b=10 fm)

➢ Theoretical calculations



$1\ \mathrm{MeV}^2 = e \cdot 1.6904 \times 10^{14}$ Gauss

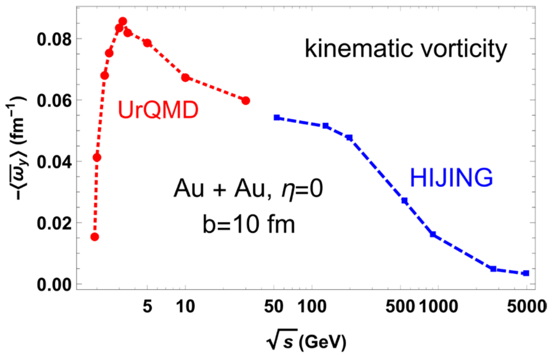
Strongest B field
RHIC: $eB \approx 10^{19}$G
LHC: $eB \approx 10^{21}$G

(Deng, Huang 2012)

(Theory: USTC, Tsinghua, Fudan, UCAS, CCNU, SDU, …)

$$\boldsymbol{\omega} = \frac{1}{2} \nabla \times \boldsymbol{v}$$

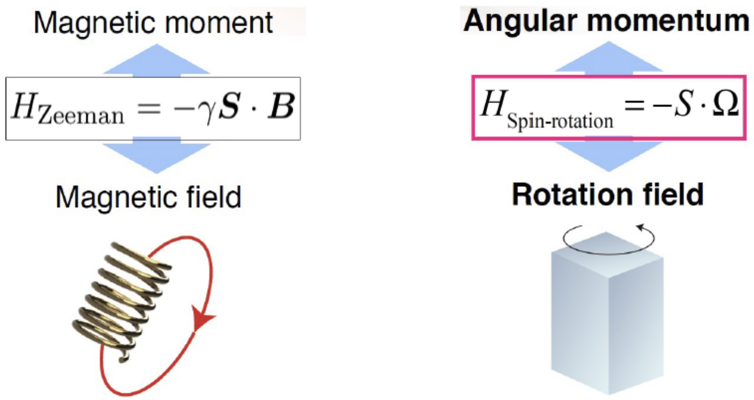
QGP: the most vortical fluid
Vorticity : $\omega \approx 10^{21} s^{-1}$



(Deng, Huang 2016; Deng, Huang, Ma, Zhang 2020)

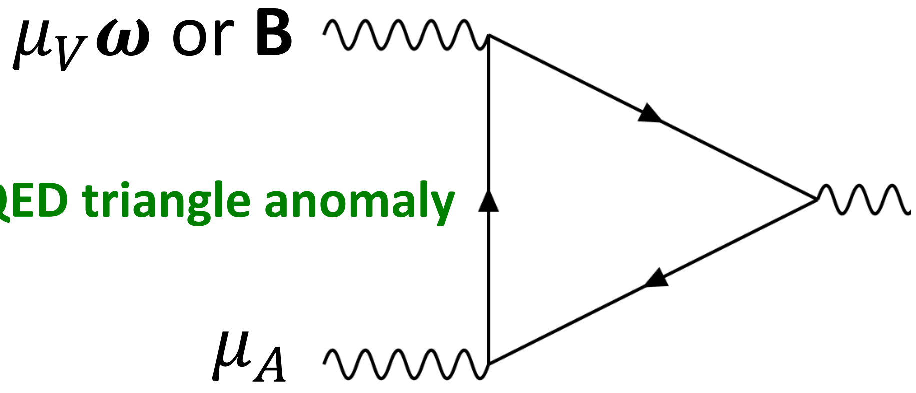
Chiral magnetic and vortical effects

- **Spin polarization by B field, vorticity (rotation), and momentum**



Massless: spin polarized (slaved) by momentum

- **When the system has net chirality: $\boldsymbol{\mu_A = \mu_R - \mu_L \neq 0}$**



$$J_V = \frac{\boldsymbol{B}}{2\pi^2}\mu_A$$ Chiral magnetic effect (CME)

$$J_V = \frac{\mu_V \boldsymbol{\omega}}{\pi^2}\mu_A$$ Chiral vortical effect (CVE)

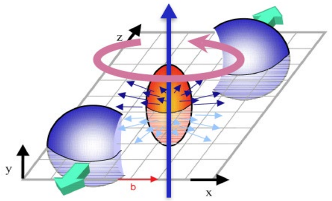
(Kharzeev etal 2007; Erdmenger etal 2009; Son, Surowka 2009; …)

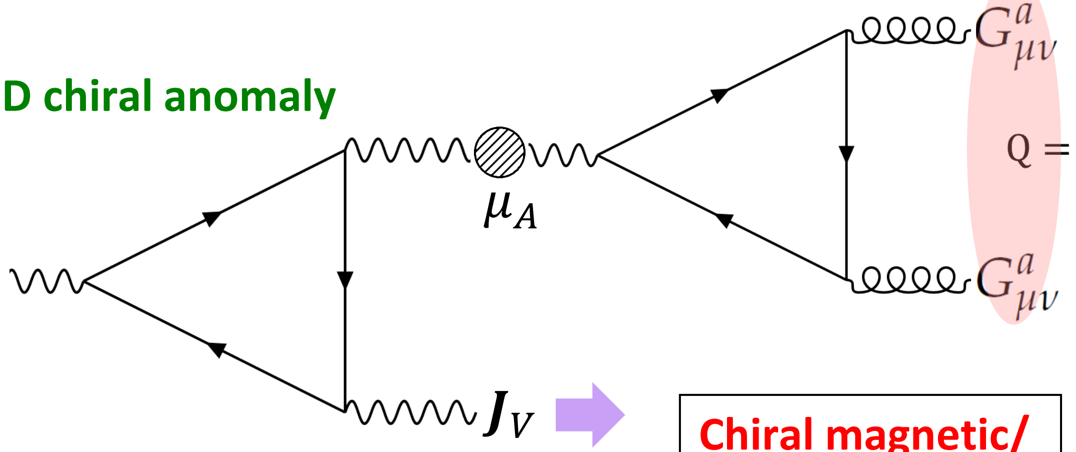
3 CME and CVE probe QCD topological sector

QCD chiral anomaly

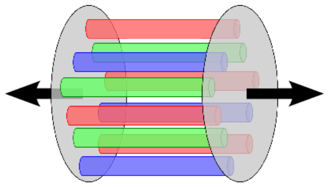
QED chiral anomaly

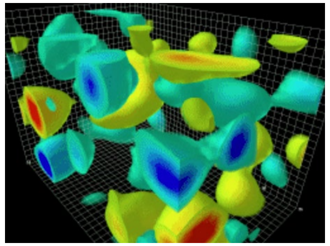
B, ω



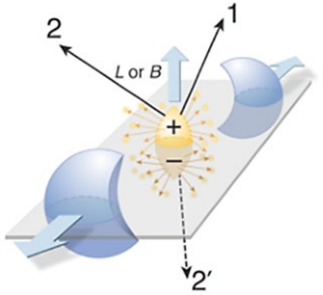


$$Q = \frac{1}{32\pi^2}\int d^4x\, G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$





Chiral magnetic/ vortical effects

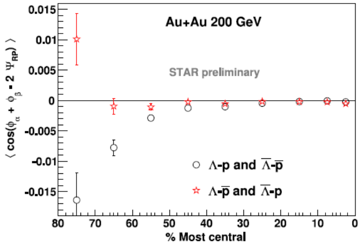


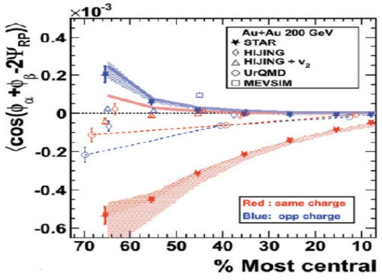
Initial state topological fluctuations

Local P and CP violation

Observable: e.g. γ-correlator

(see next page)

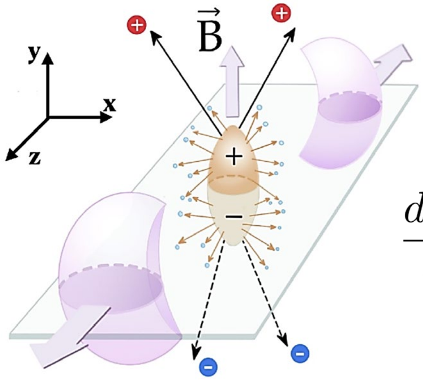




(STAR 2009 -, ALICE 2012 - , CMS 2017 -,)

3 CME observables

- **Event-by-event charge separation w.r.t. the reaction plane**



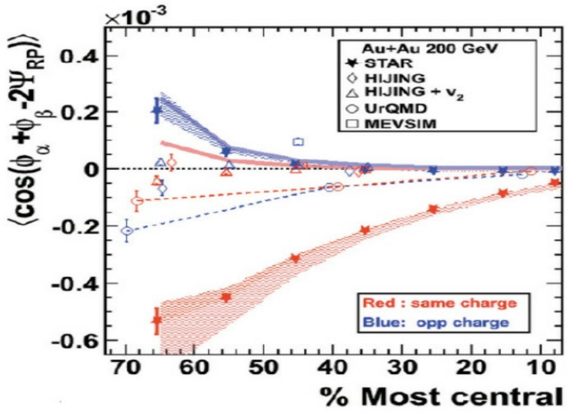
$$\frac{dN_\pm}{d\phi} \propto 1 + 2a_\pm \sin(\phi - \Psi_{\rm RP})$$

- **Direct measurement of a is impossible. But its fluctuation a^2 can be measured: γ-correlator** (Voloshin 2004)

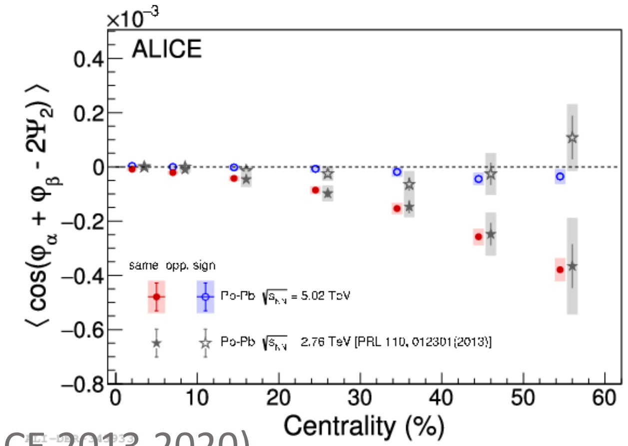
$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP}) \rangle$$

CME $$\begin{cases} \gamma_{++} \approx \gamma_{--} \equiv \gamma_{\rm SS} < 0 \\ \gamma_{+-} \approx \gamma_{-+} \equiv \gamma_{\rm OS} > 0 \end{cases}$$

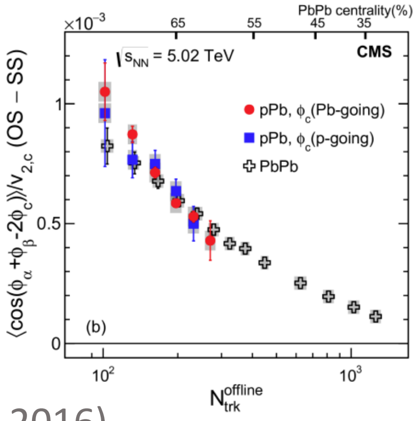
- **A lot of results collected from RHIC and LHC**



(STAR 2009)



(ALICE 2013,2020)

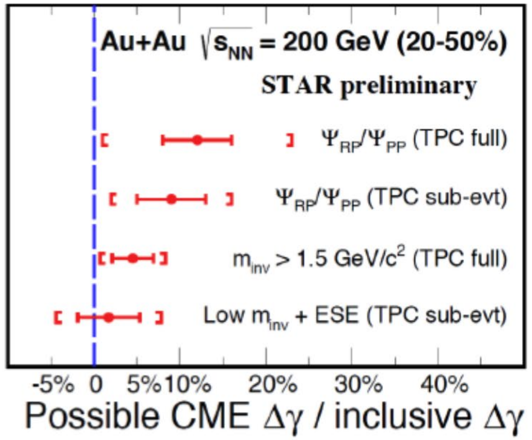


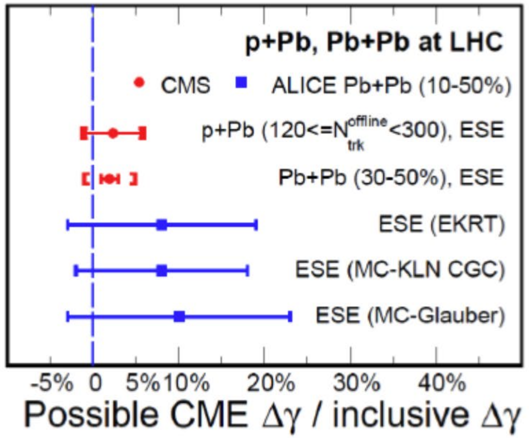
(CMS 2016)

CME observables

➢ Strong back ground contamination

One eccentric geometry gives two outcomes, B field and v_2. Difficult to disentangle them.



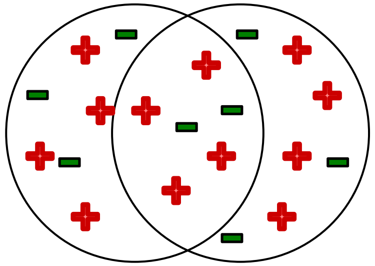


Average signal fraction:

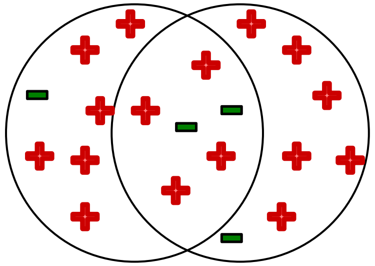
tiny at 2.76 TeV@LHC

8±4±8 % at 200 GeV@RHIC

➢ Isobar collisions: fix v_2 but vary B field



Vs



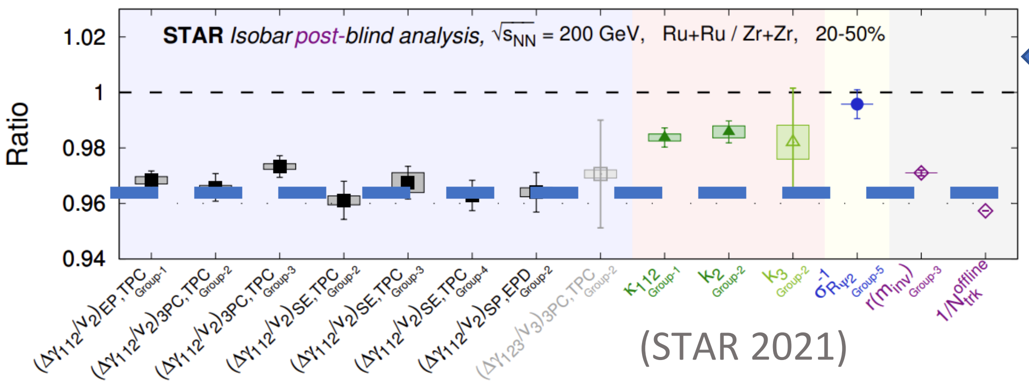
$^{96}_{40}Zr + ^{96}_{40}Zr$

$^{96}_{44}Ru + ^{96}_{44}Ru$

3 Isobar collisions

➢ The first experimental result

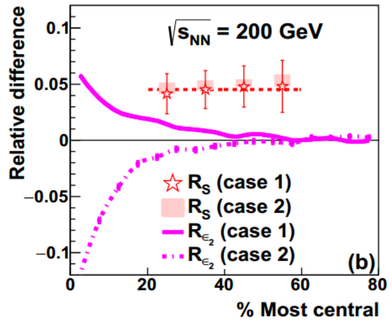
First run: 2018 @ RHIC
3.1B events for each type of collision



(STAR 2021)

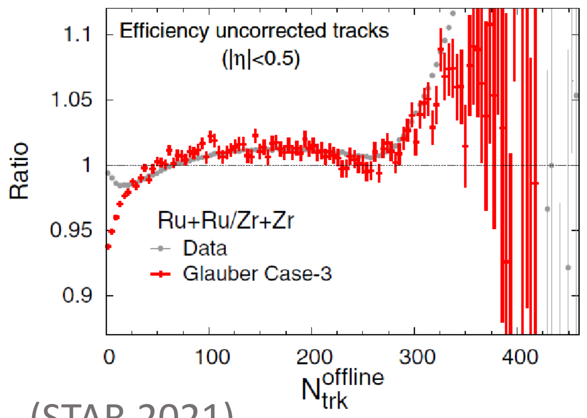
If bg=90%, theory prediction is here

New baseline?

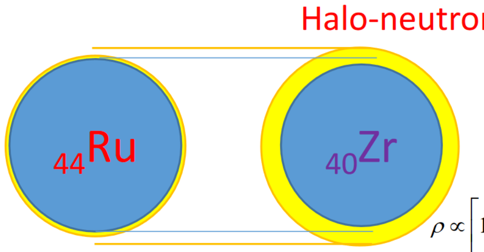


(Deng, Huang, Ma, Wang 2016)

➢ Why data opposite to theory: isobar collisions detect neutron skin (halo)



(STAR 2021)



$$\rho \propto \left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1}$$

Consistent with nuclear density functional calculation

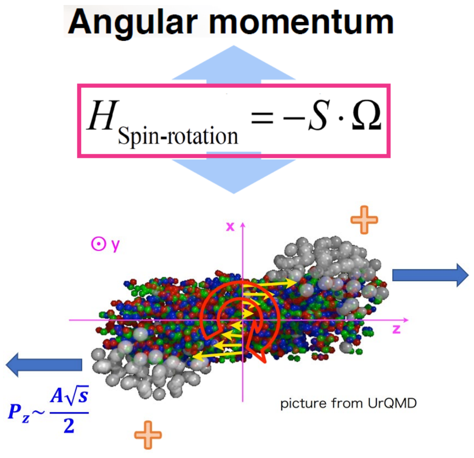
(Xu, Li, Chen, Wang etal 2018-2022)

New baseline needed (non-flow subtraction)

Global spin polarization

- **From global angular momentum to vorticity to hyperon spin polarization**

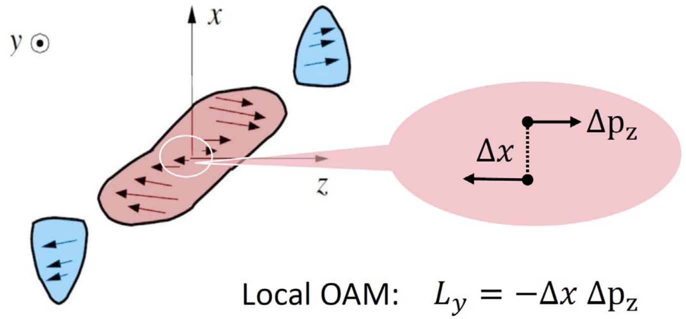
(at thermal equilibrium)



$$\frac{dN_s}{d\boldsymbol{p}} \sim e^{-(H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S})/T}$$

$$\mathrm{P} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \sim \frac{\omega}{2T}$$

- **The original idea was proposed by Liang and Wang**



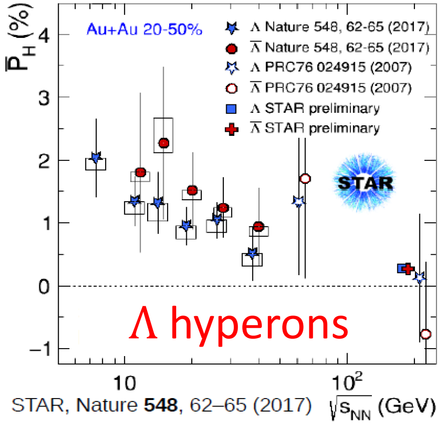
(Figure by J. H. Gao)

$$\mathrm{P} = -\frac{\pi \mu p}{2E(E+m)}$$

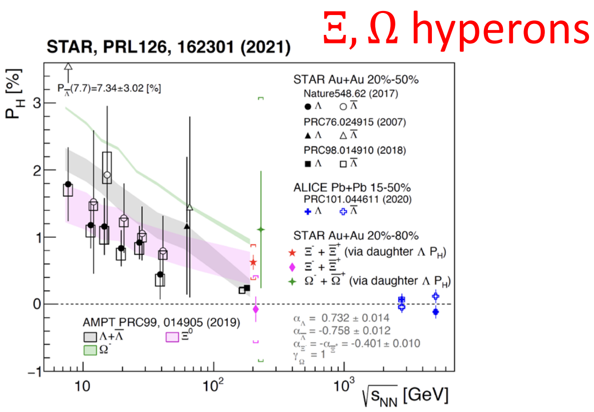
(Liang, Wang 2004)

Global spin polarization

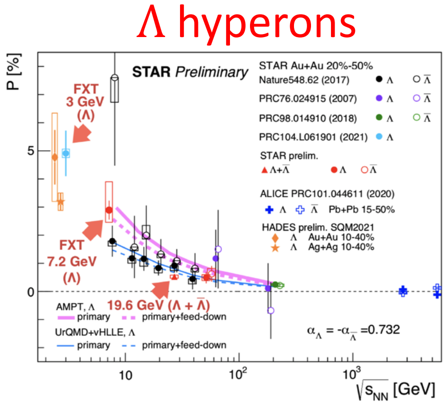
➢ Hyperon global (i.e., integrated) spin polarization: experimental results



(STAR 2017)

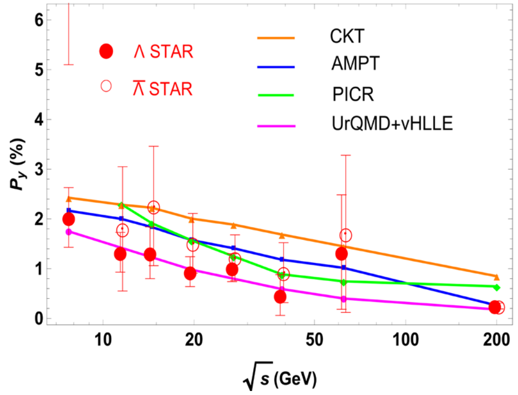


(STAR 2021; ALICE 2020)

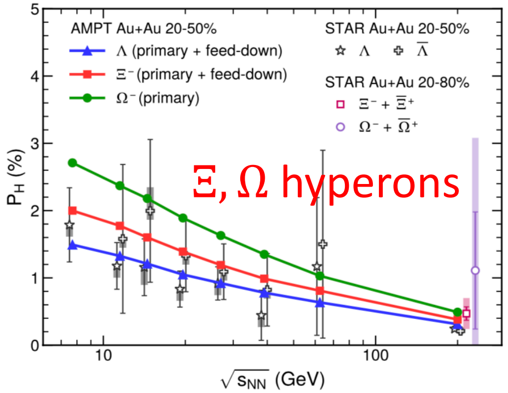


(STAR 2022; HADES 2021)

➢ Hyperon global spin polarization: theoretical results based on thermal vorticity



(Li, Pang, Wang, Xia 2017; Sun, Ko 2017; Wei, Deng, Huang 2019; Xie, Wang, Csernai 2017; Karpenko, Becattini 2016)



(Li, Xia, Huang, Huang 2021)

Initial angular momentum

⬇

Thermal vorticity

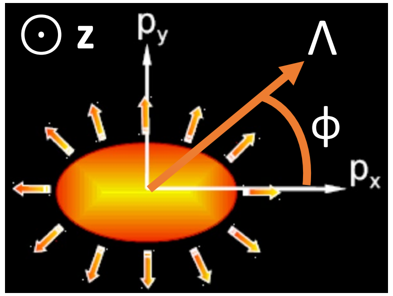
⬇

Global spin polarization

☺

Local spin polarization

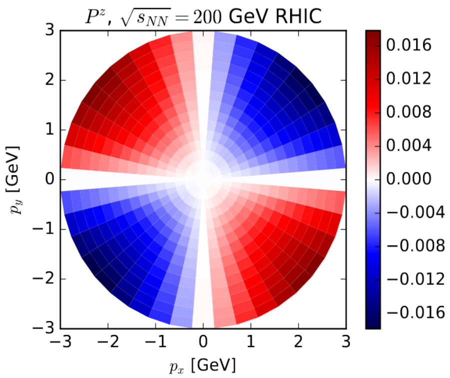
- **How the spin polarization is distributed in different ϕ?**



$$P_{y,z}(\phi) = \frac{N_{y,z}(\phi) - N_{y,z}(\phi)}{N_{y,z}(\phi) + N_{y,z}(\phi)}$$

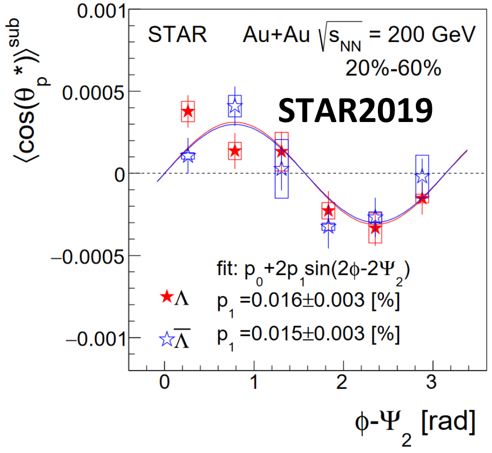
- **Experiments opposite to theory based on thermal vorticity: spin sign problem**

1) longitudinal polarization vs ϕ

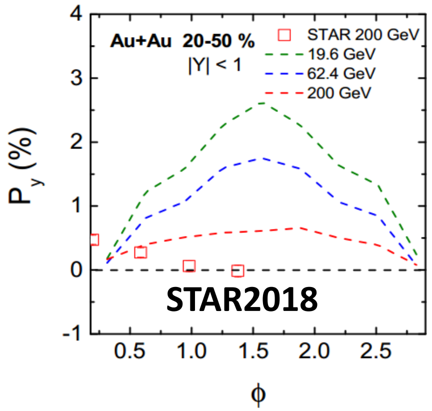


(Becattini, Karpenko 2018)

Vs



2) Transverse polarization vs ϕ

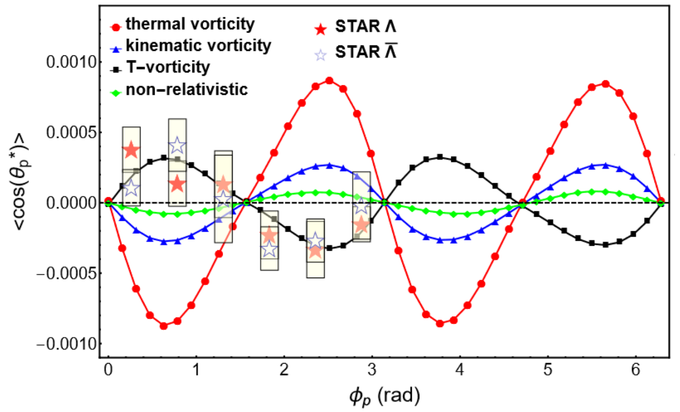


(Wei-Deng-XGH 2019)

Local spin polarization

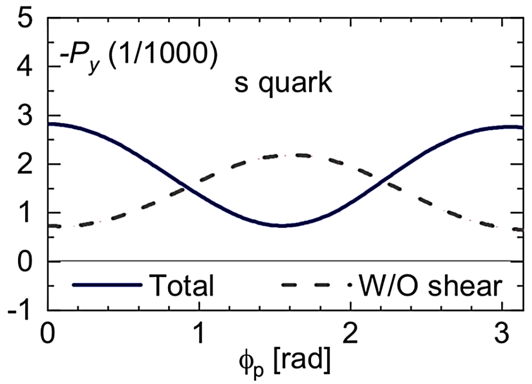
➢ If spin is not globally thermalized by thermal vorticity:

Spin potential is determined by T-vorticity

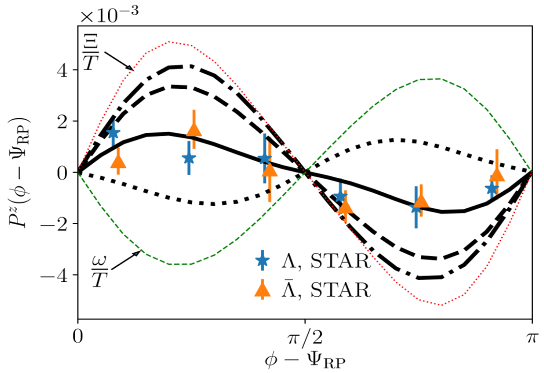


(Wu, Pang, Huang, Wang 2019)

Shear tensor contribution



(Fu, Liu, Song, Yin 2021)



(Becattini etal 2021)

➢ Dynamic theories for spin transport and polarization are developing

- ➢ **Spin hydrodynamics**：Fluid velocity, temperature, and spin density evolve together
- ➢ **Spin kinetic theory**：Particle and spin phase-space distribution functions evolve together

Vector meson spin alignment

- **Vector meson spin density matrix from $q+\bar{q}\rightarrow V$** (Liang, Wang 2004)

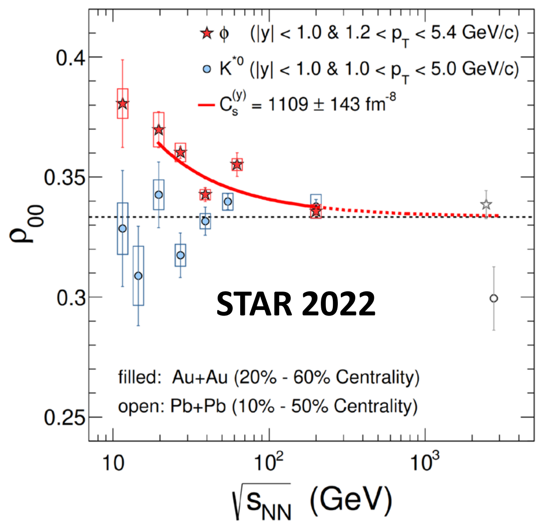
$$\rho^V = \begin{pmatrix} \frac{(1+P_y^q)(1+P_y^{\bar{q}})}{3+P_y^q p_y^{\bar{q}}} & 0 & 0 \\ 0 & \frac{1-P_y^q P_y^{\bar{q}}}{3+P_y^q p_y^{\bar{q}}} & 0 \\ 0 & 0 & \frac{(1-P_y^q)(1-P_y^{\bar{q}})}{3+P_y^q p_y^{\bar{q}}} \end{pmatrix} \xrightarrow{P_q \approx P_{\bar{q}}} \rho_{00} = \frac{1-P_y^2}{3+P_y^2} \approx \frac{1}{3} - \frac{4}{9}P_y^2$$

Spin alignment parameter

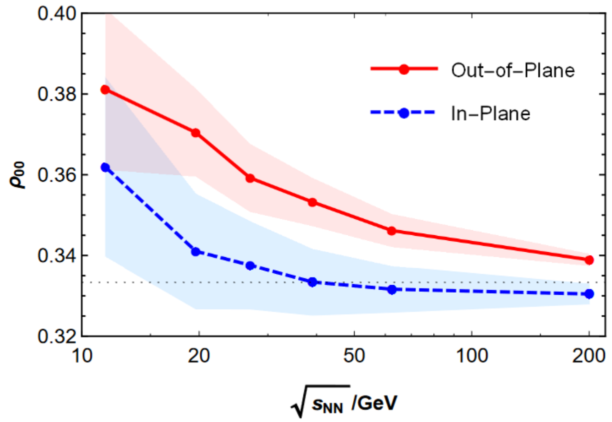
Expectation: spin alignment is a 10^{-4} level phenomenon

- **Global spin alignment for ϕ, K^{*0}**

Puzzle: ϕ-meson $\rho_{00} > \frac{1}{3}$ and too big!



A recent theory

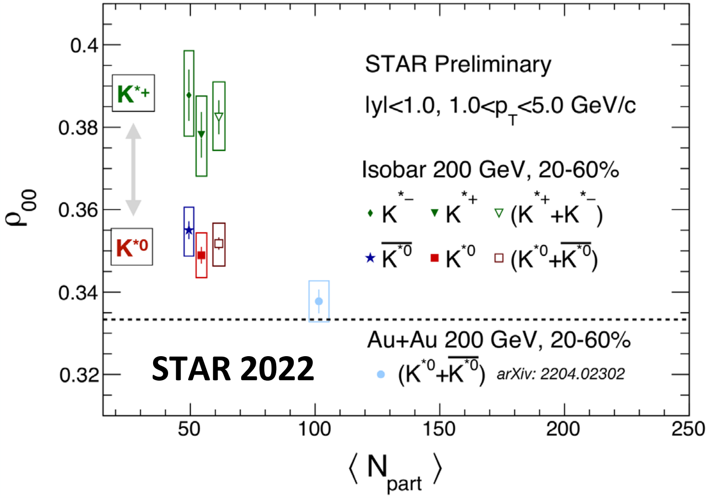


$$\rho_{00}(x,\mathbf{0}) - \frac{1}{3} \propto \left\langle (g_\phi \mathbf{B}^\phi_{x(y)})^2 \right\rangle \quad \left\langle (g_\phi \mathbf{E}^\phi_{x(y)})^2 \right\rangle$$

(Sheng, Oliva, Liang, Wang, Wang 2022)

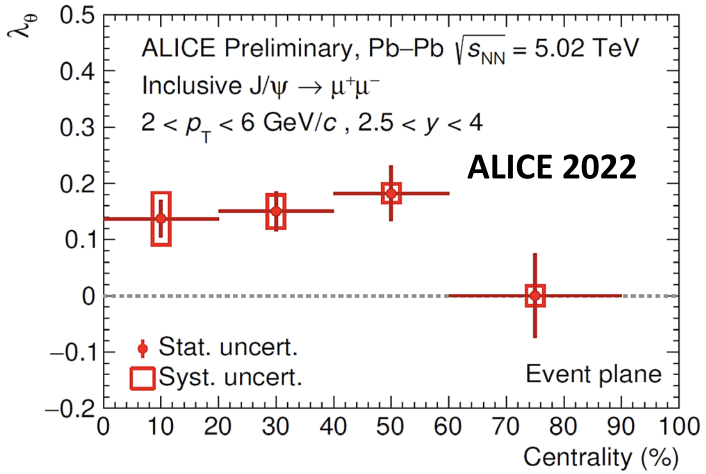
Vector meson spin alignment

➢ Global spin alignment in isobar collisions



Puzzle: charge sensitive but $K^{*+}(u\bar{s})$ larger than $K^{*0}(d\bar{s})$, opposite to B-effect

➢ Global spin alignment of $J/\psi \to l^+l^-$



$$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right) \qquad \rho_{00} - \frac{1}{3} = \frac{2}{3}\frac{\lambda_\theta}{3+\lambda_\theta}$$

Puzzle: Λ polarization at LHC is very small but a big J/ψ spin alignment

4 Summary

4

Summary

- **Rich many-body physics of QCD studied at RHIC and LHC heavy-ion program**
  - Strongly coupled QGP droplet is an extreme matter: hottest, most perfect fluid, strongest magnetic field, most vortical fluid
  - Strong quenching of jets in QGP, medium response important
  - Collectivity seen in p + p and p + Pb (hydro attractor, initial glasma, …)
  - CME as a probe to topological sector of QCD under searching
  - Subatomic "spintronics"
  - … …
- **Uncovered (but surely very interesting):** Critical point and fluctuations, heavy flavor flows, jet substructure, photons and dileptons, UPC, exotic hadrons and hypernuclei production, … …
- **More discussions at Parallel 3: heavy ion physics (Aug. 09 afternoon, Aug. 10-11 full day)**

Thank you