夸克胶子等离子体理论进展

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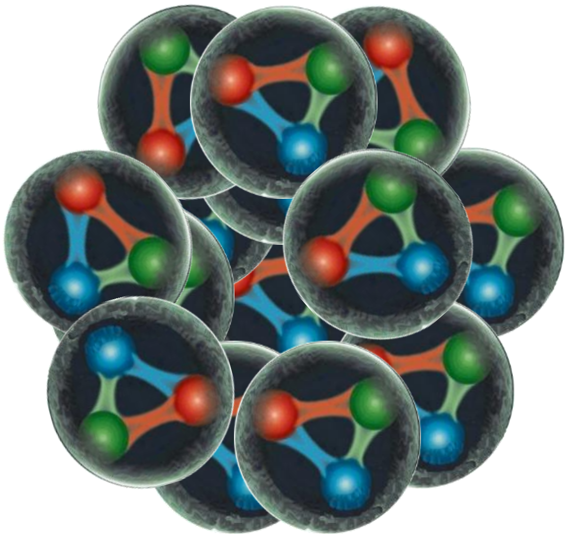
复旦大学，上海，2025年8月12-13日

Outline

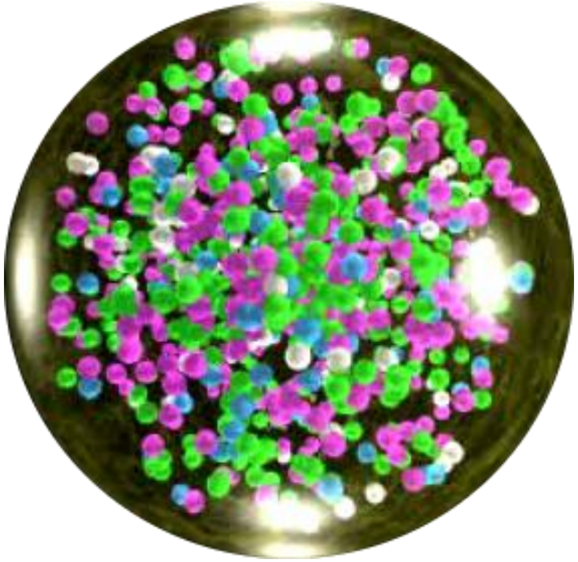
- Introduction
- Thermodynamics
- Flow and hydrodynamics
- Vorticity and spin polarization
- Jets and medium response
- Summary

Quark-gluon plasma: a new state of matter



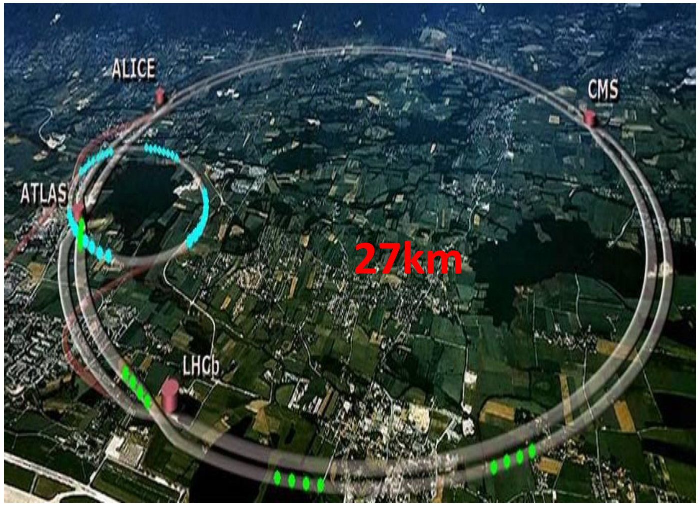
High Temperature

High Density

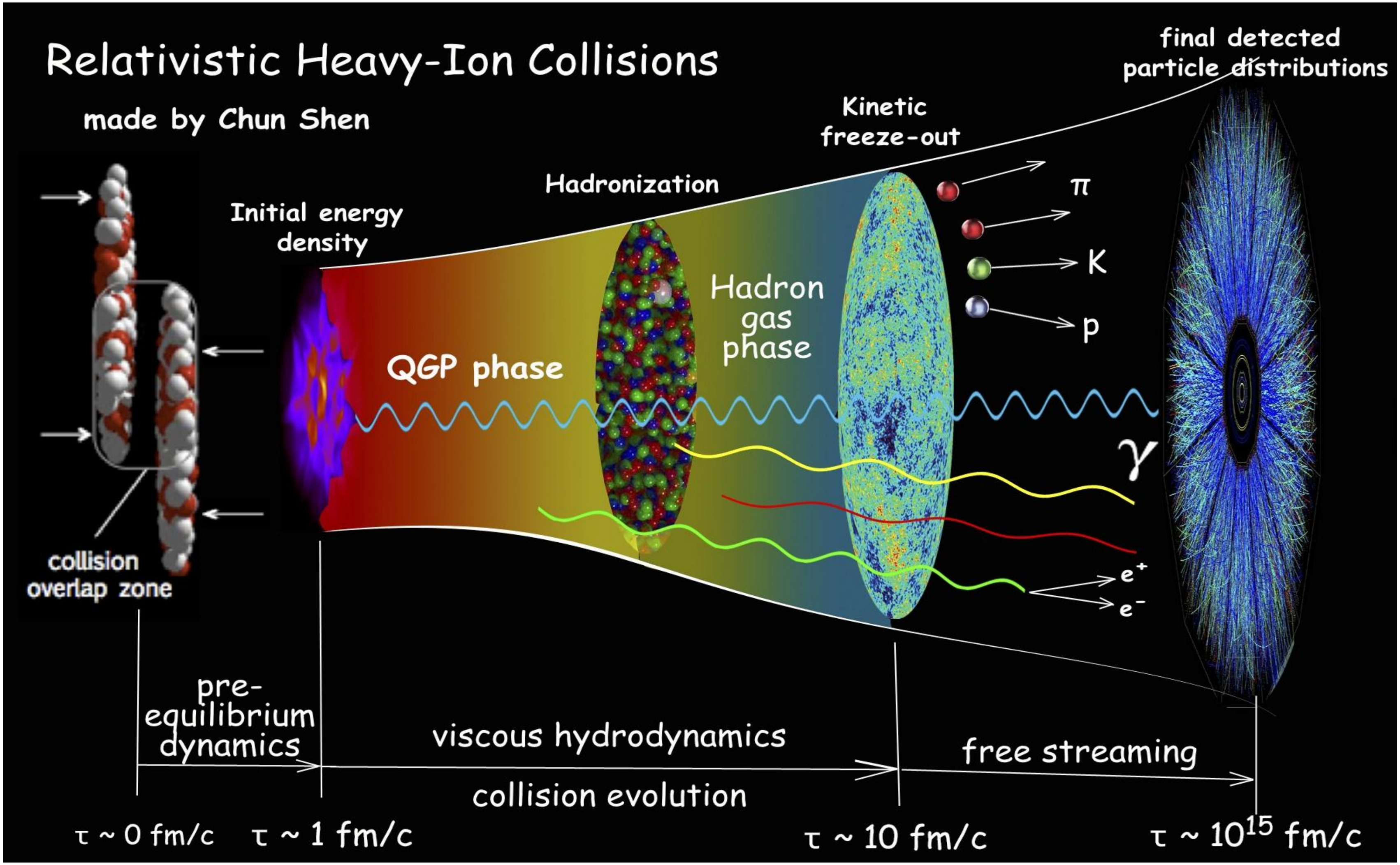


Relativistic Heavy-Ion Collider（RHIC）

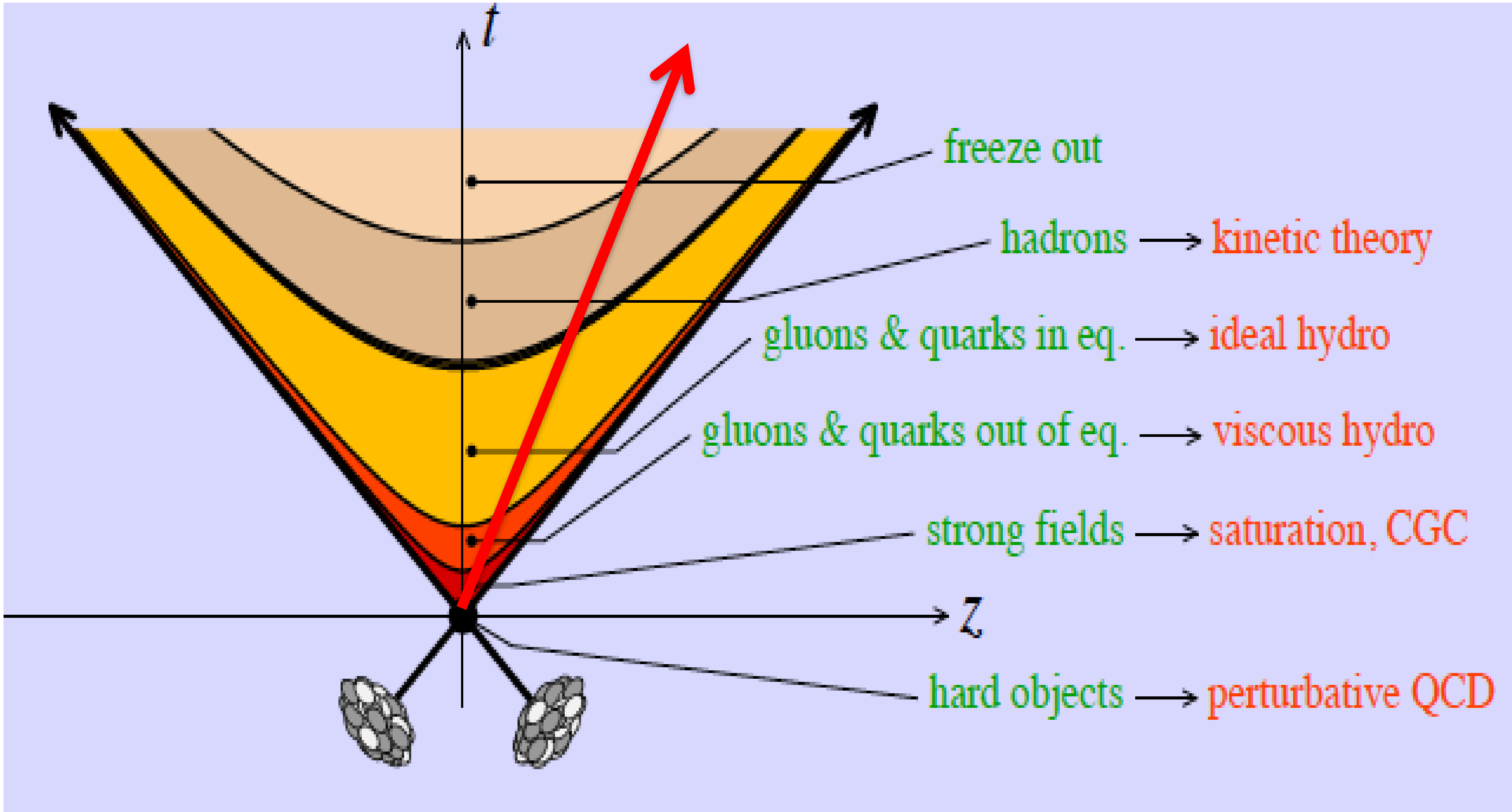
Large Hadron Collider（LHC）



The state of the art of QGP research in heavy-ion collisions



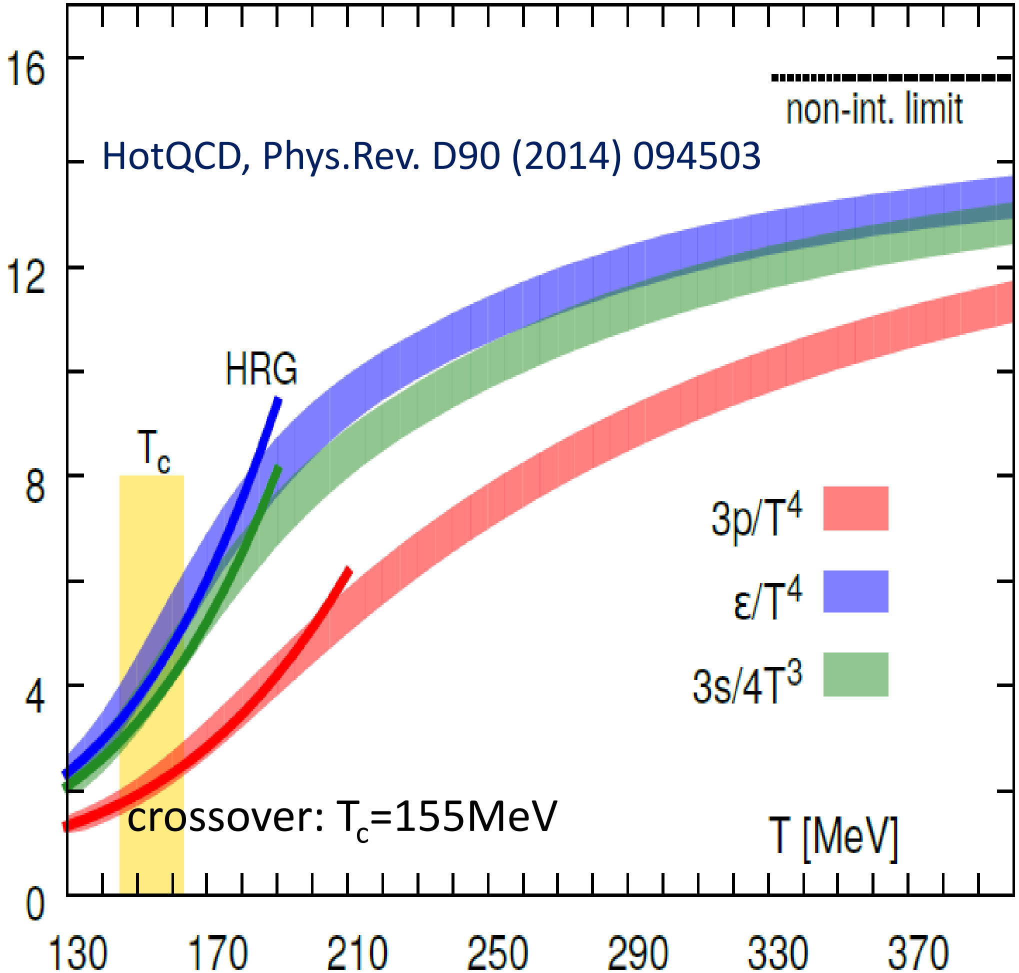
An interdisciplinary research field



Theoretical approaches: lattice QCD, perturbative QCD, effective field theories, relativistic hydrodynamics, transport and kinetic theory, thermal and statistical models, functional methods, AdS/CFT(QCD), Monte-Carlo, hybrid/multi-scale(stage) models, …

Thermodynamics

QCD thermodynamics from lattice



A transition (crossover) between hadronic matter and quark-gluon matter at $T_c \sim 155\text{MeV}$

$T < T_c$, HRG thermodynamics

$T \sim 400\text{MeV}$, not a non-interacting quark-gluon gas, but a strongly-interacting fluid

For a gas of massless particles,

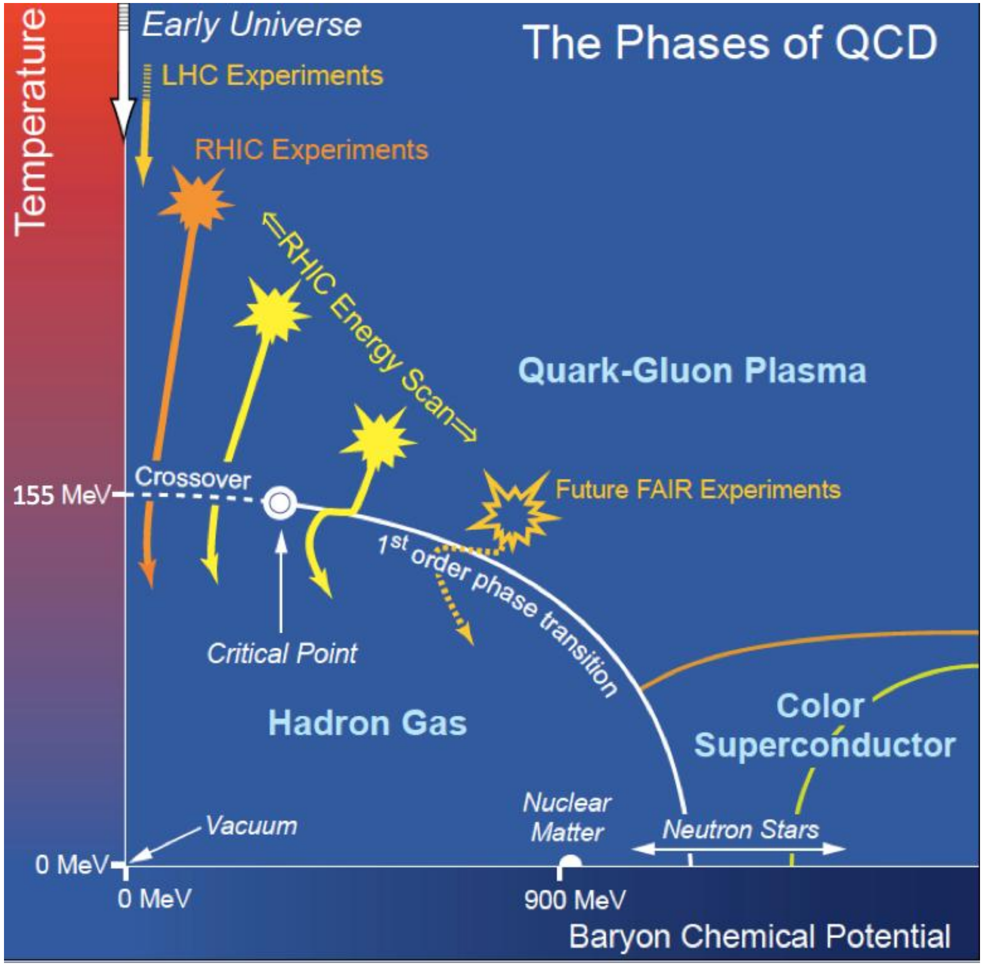
$P = d\frac{\pi^2}{90}T^4, s = d\frac{2\pi^2}{45}T^3, \varepsilon = 3P$

HOT!!!

RHIC: ~350MeV, LHC: ~470MeV

$$T_c = 155\text{MeV}/\text{k}_B = (155 * 10^6\text{eV})(1.6 * 10^{-19}\text{J/eV})/(1.38 * 10^{-23}\text{J/K}) = 1.8 * 10^{12}\text{K}$$

QCD phase diagram and critical point

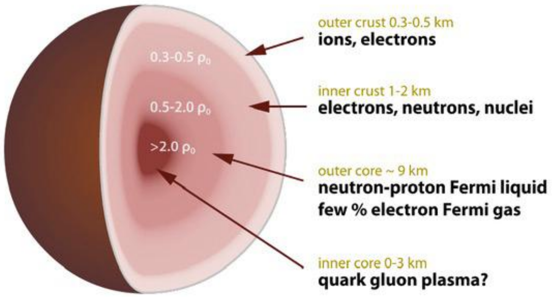


Low T & μ_B => hadrons (hadron matter)

T_c~155MeV, μ_B~0 => hadron matter melts into quark-gluon plasma (QGP)

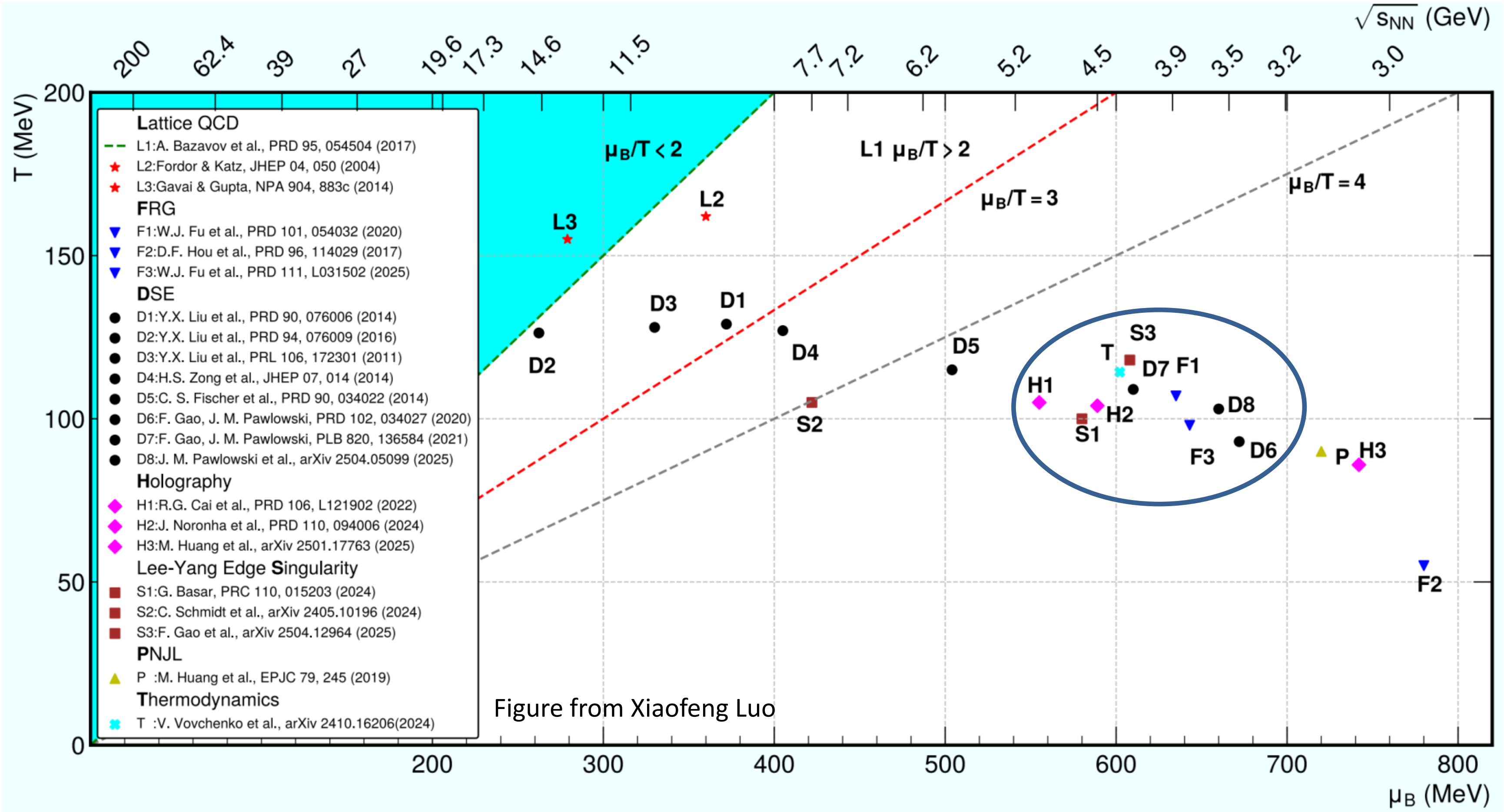
Very high T => early Universe

High μ_B => compact stars

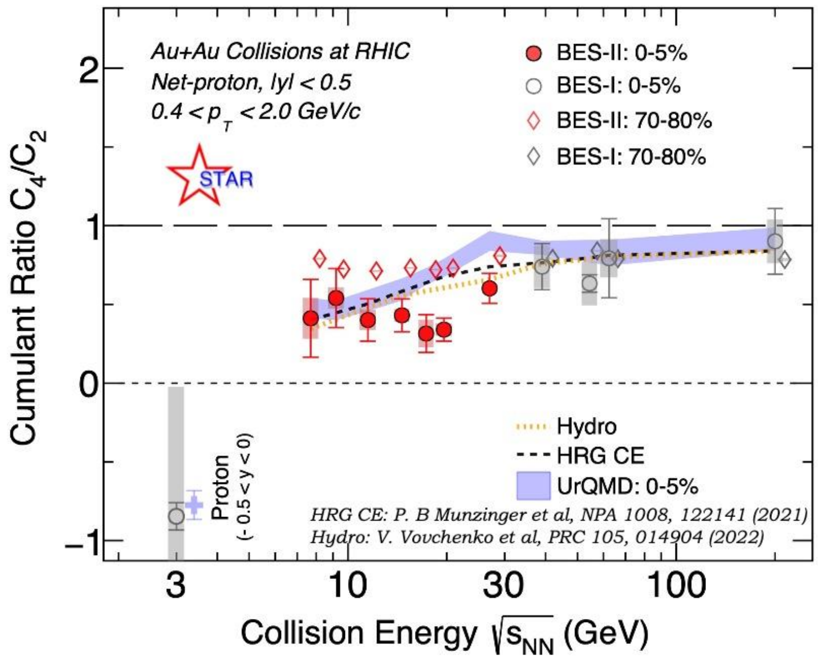


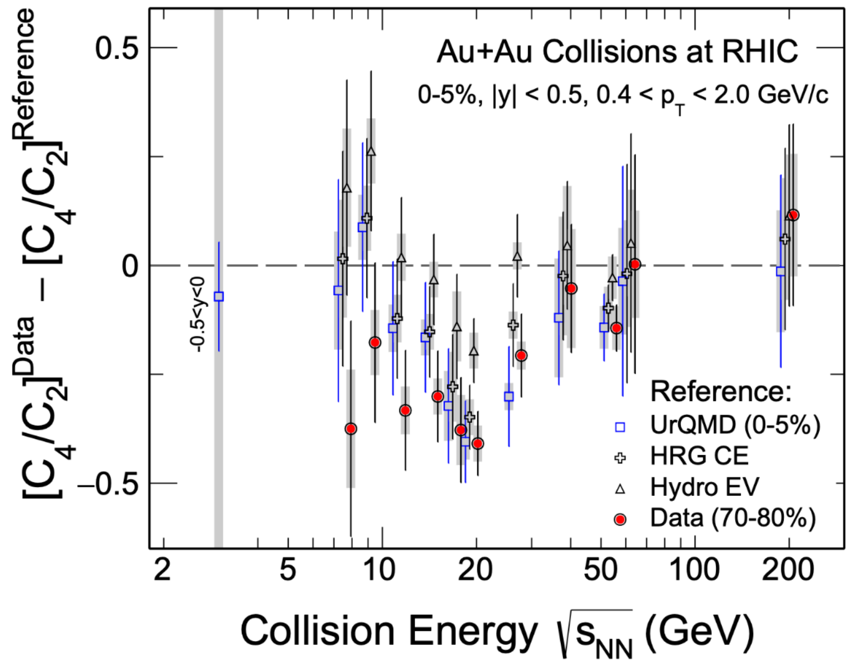
Lattice QCD disfavors CP for $\mu_B/T \leq 2$ & $T/T_c(\mu_B=0) > 0.9$ (Phys. Rev. D 95 (2017) 5, 054504)

CP predictions from various models



Search for CP: experimental status





For an infinite system, the correlation length at critical point should diverge, so do susceptibilities.

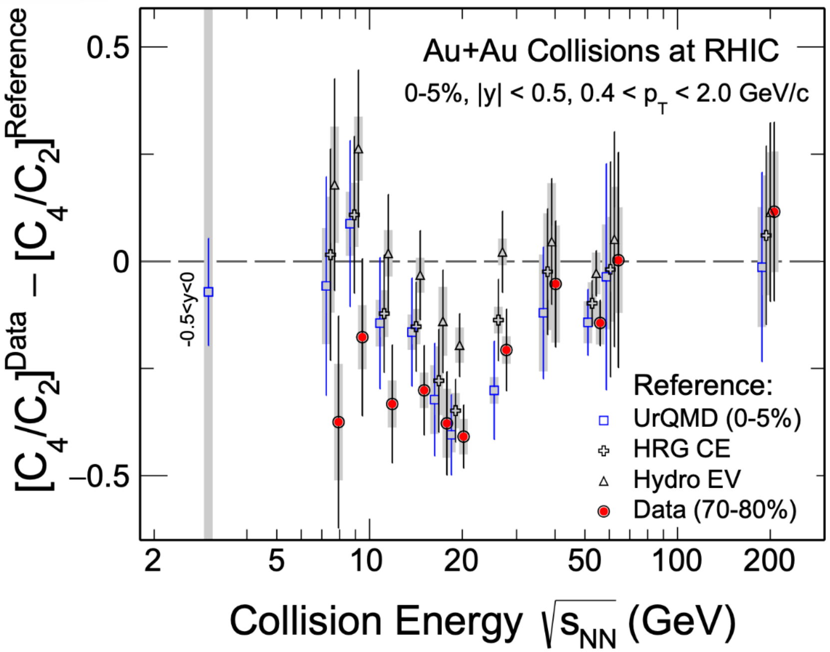
$$\langle(\delta N)^3\rangle \approx \zeta^{4.5}, \quad \langle(\delta N)^4\rangle \approx \zeta^7$$

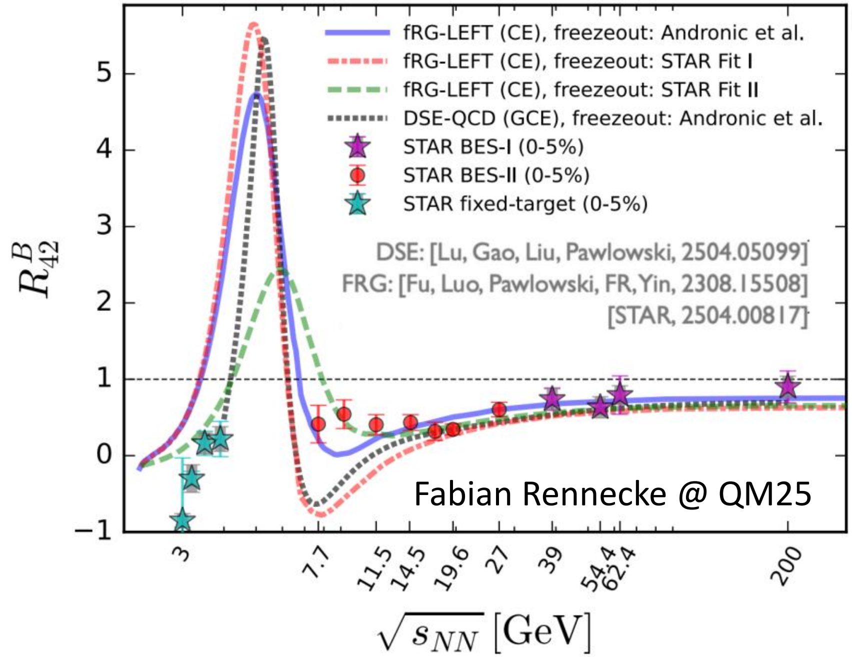
Cumulants of conserved quantities (e.g., B,Q,S) are sensitive to the correlation length and directly related to susceptibility ratios

$$\chi_{n,q} = \frac{1}{VT^3} C_{n,q} = \frac{\partial^n (p/T^4)}{\partial(\mu_q)^n}, \quad \frac{C_4}{C_2} = \kappa\sigma^2 = \frac{\chi_4}{\chi_2}$$

STAR BESII: 2.5σ deviations to non-CP baselines at 19.6 GeV.

On-going search for CP





$$\langle(\delta N)^3\rangle \approx \zeta^{4.5}, \quad \langle(\delta N)^4\rangle \approx \zeta^7 \qquad \chi_{n,q} = \frac{1}{VT^3} C_{n,q} = \frac{\partial^n (p/T^4)}{\partial(\mu_q)^n}, \quad \frac{C_4}{C_2} = \kappa\sigma^2 = \frac{\chi_4}{\chi_2}$$

STAR BESII: 2.5σ deviations to non-CP baselines at 19.6 GeV.

CP signal is there in theoretical calculation.

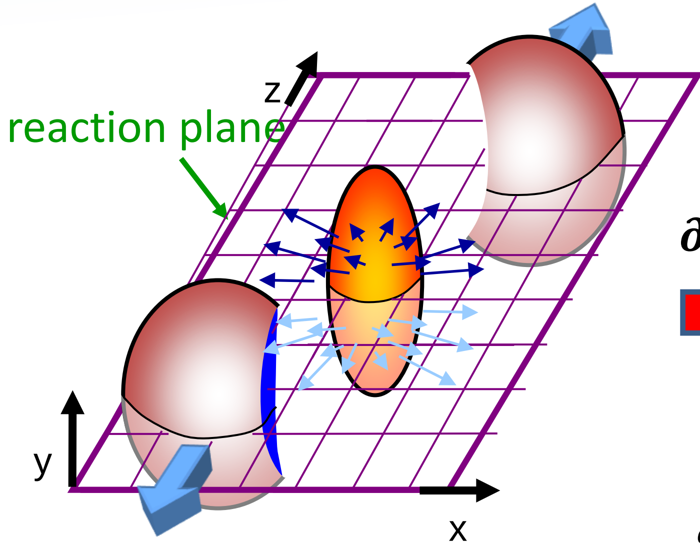
Can the future data from 4.5 GeV & 3 GeV Au-Au collisions answer this question?

How much signal is left in real world (i.e., fluctuating dynamically evolving medium)?

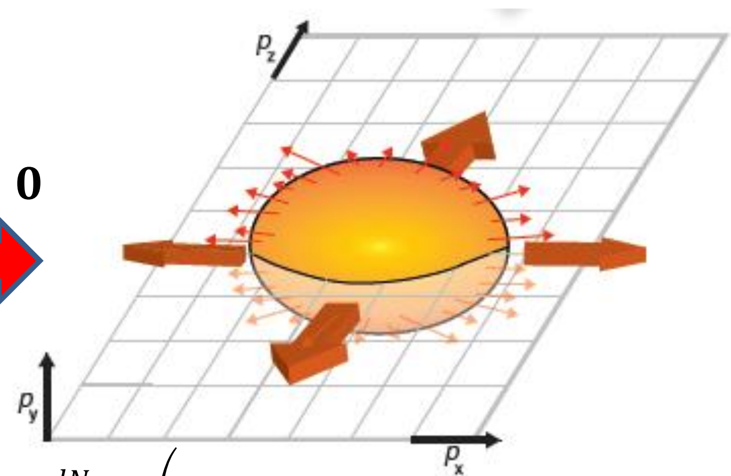
Precise dynamical modelling with CP is crucial to compare with data.

Flow and hydrodynamics

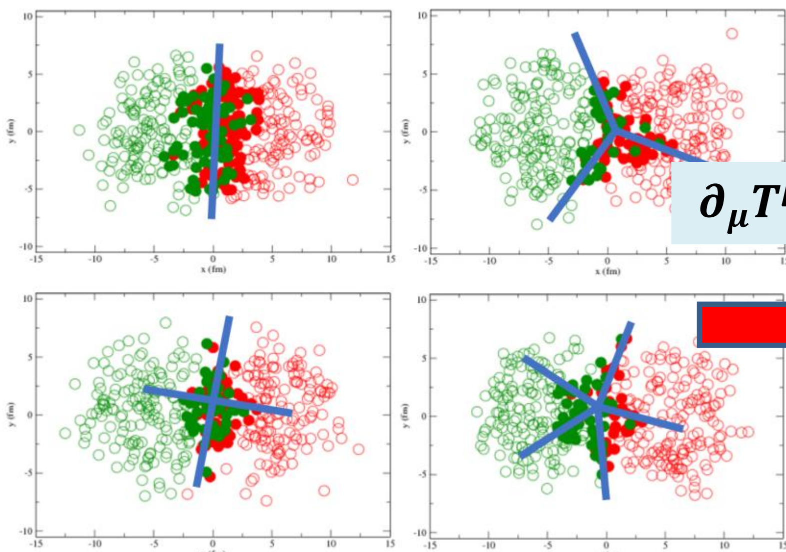
Flow paradigm in heavy-ion collisions



$$\partial_\mu T^{\mu\nu} = 0$$



$$\frac{dN}{p_T dp_T dy d\phi} = \frac{dN}{2\pi p_T dp_T dy}\left(1 + \sum_n 2v_n(p_T, y)\cos\{n[\phi - \Psi_n(p_T, y)]\}\right)$$



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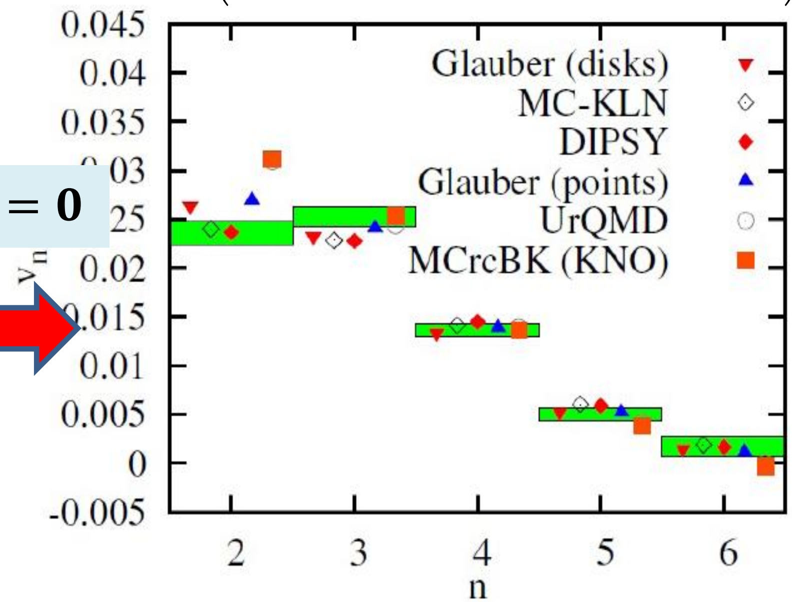


Relativistic viscous hydrodynamics

- Energy-momentum conservation (near-equilibrium long-wavelength behavior)

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = \varepsilon U^\mu U^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

- Equations of motion (Israel-Stewart viscous hydrodynamics):

$$\dot{\varepsilon} = -(\varepsilon + P + \Pi)\theta + \pi^{\mu\nu}\sigma_{\mu\nu}$$

$$(\varepsilon + P + \Pi)\dot{U}^\alpha = \nabla^\alpha(P + \Pi) + \dot{U}_\mu\pi^{\mu\nu} - \Delta^\alpha_\nu\nabla_\mu\pi^{\mu\nu}$$

$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\theta + \Pi\zeta T\partial_\alpha\left(\frac{\tau_\Pi}{2\zeta T}U^\alpha\right)\right]$$

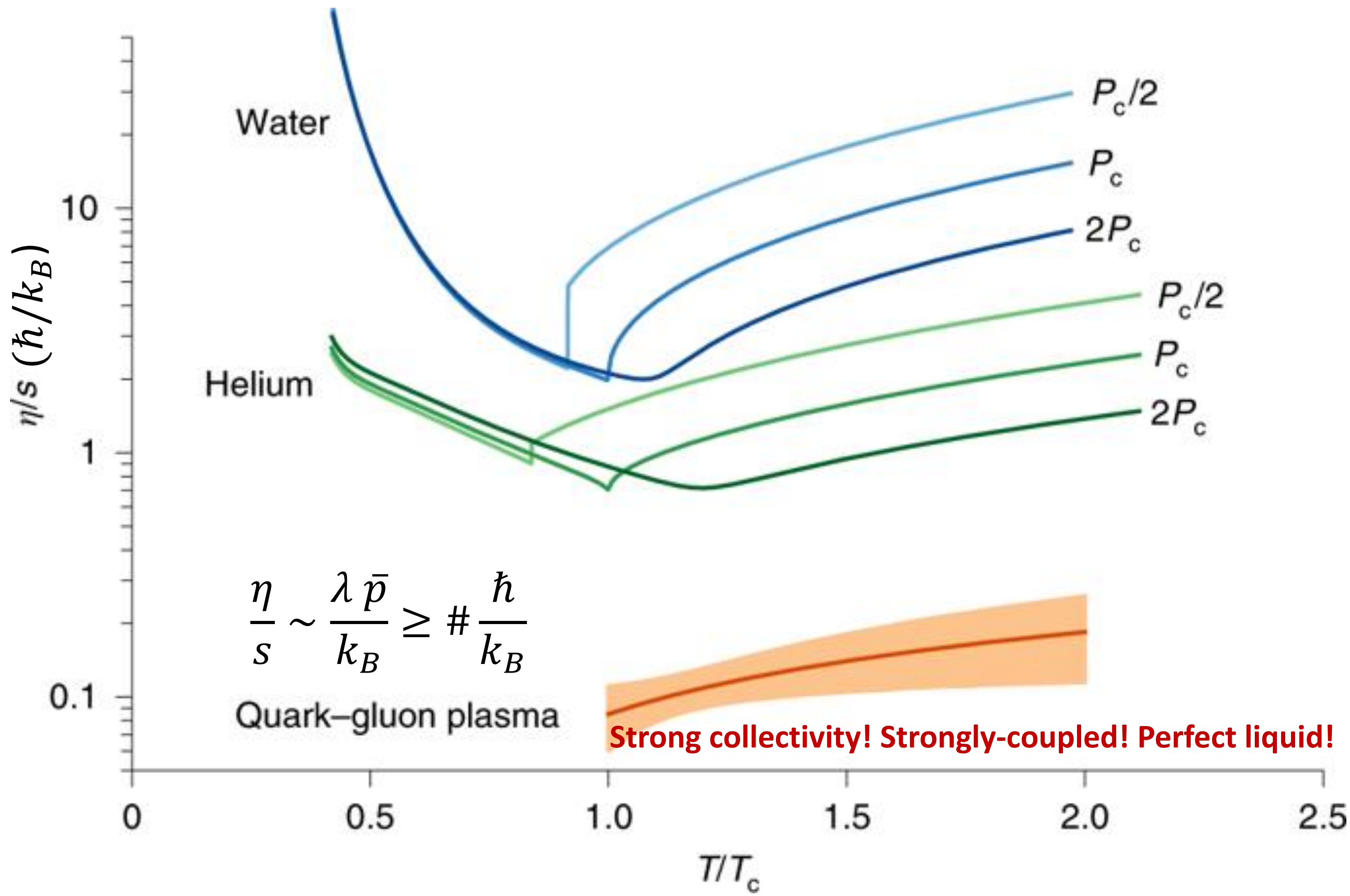
$$\Delta^{\mu\nu}_{\alpha\beta}\dot{\pi}^{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu} + \pi^{\mu\nu}\eta T\partial_\alpha\left(\frac{\tau_\pi}{2\eta T}U^\alpha\right)\right]$$

- Equation of state: $P = P(\varepsilon)$

- Hydro Code: MUSIC, iEBE-VISHNU, vHLLE, ECHO-QGP, SONIC, aHydro, CLVisc
- IC Code: Glauber, IP-Glasma, TRENTo, EKRT, AMPT, UrQMD/SMASH

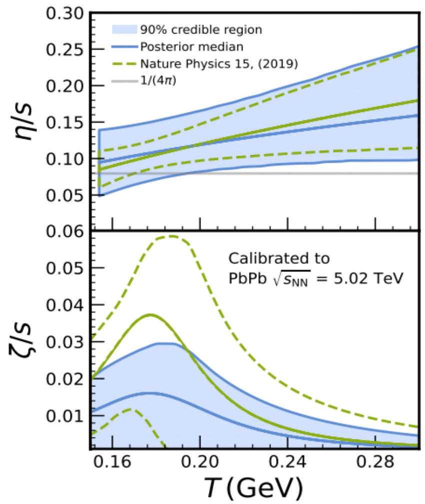
arXiv:0902.3663; arXiv:1301.2826; arXiv:1301.5893; arXiv:1311.1849; arXiv:1401.0079…

Most perfect fluid

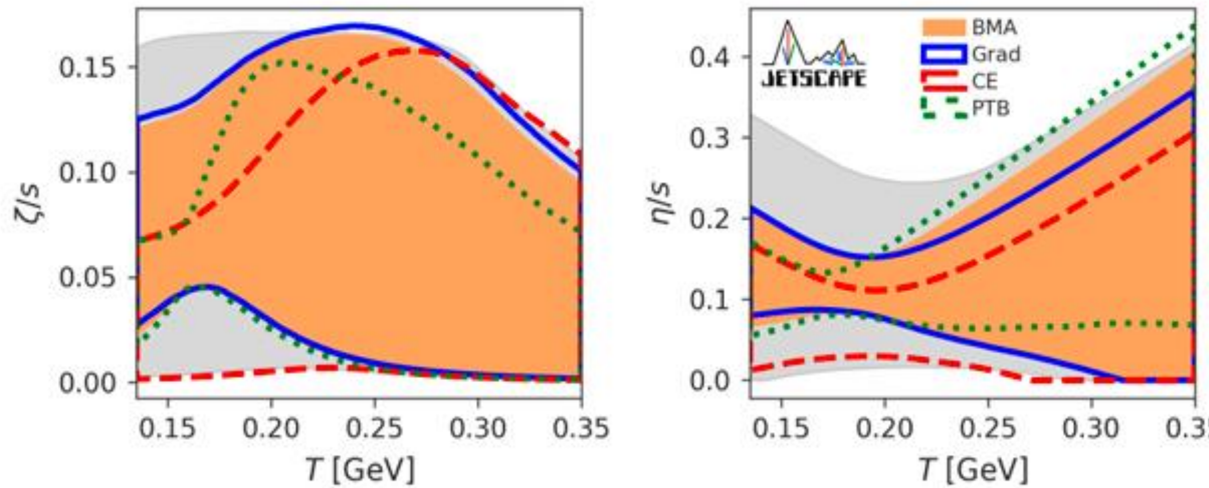


Bernhard, Moreland, Bass, Nature Physics 2019

Bayesian extraction of QGP viscosity

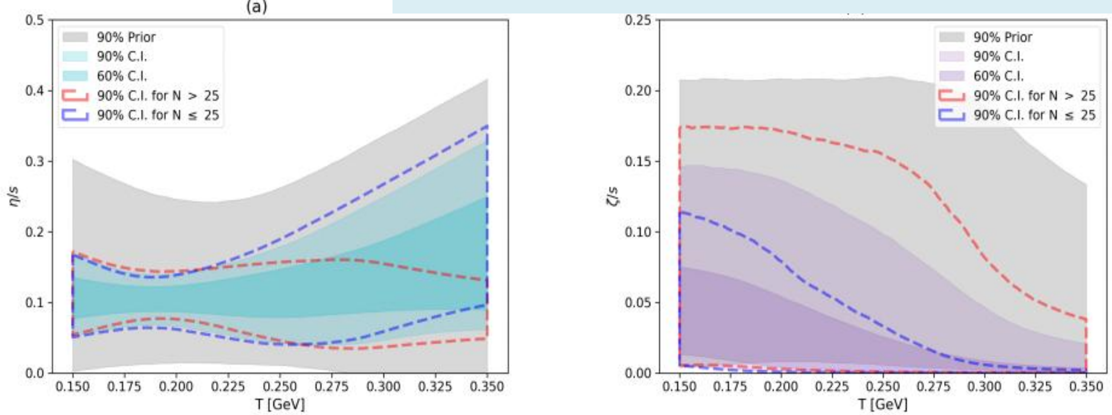


Phys.Rev.C 104 (2021) 5, 054904

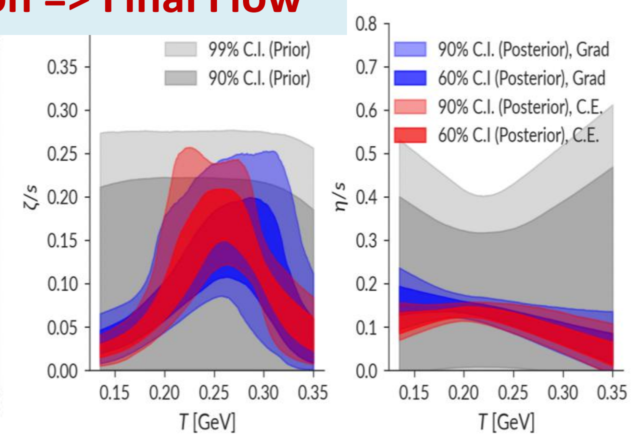


Phys.Rev.Lett. 126 (2021) 24, 242301

Initial Geometry + Strong Interaction => Final Flow



Phys.Rev.C 108 (2023) 5, 054905

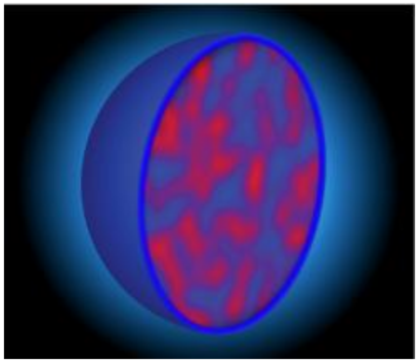


Phys.Rev.C 109 (2024) 6, 065207

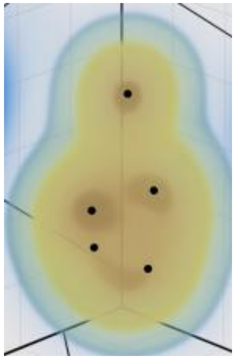
From final collectivity to initial nuclear structure

The generalized Woods-Saxon distribution

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + \exp[\frac{r - R(\theta,\phi)}{a_0}]}$$



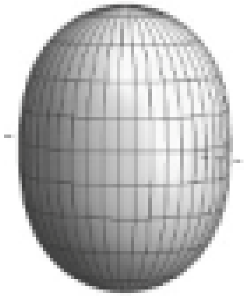
neutron skin



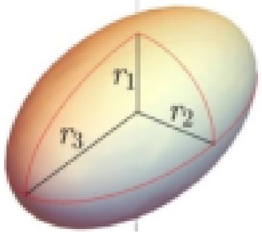
α cluster

$$R(\theta,\phi) = R_0(1 + \beta_2[\cos\gamma Y_{2,0}(\theta,\phi) + \sin\gamma Y_{2,2}(\theta,\phi)] + \beta_3 Y_{3,0}(\theta,\phi) + \beta_4 Y_{4,0}(\theta,\phi))$$

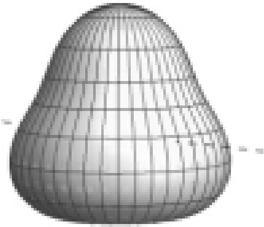
Initial Geometry + Strong Interaction => Final Flow



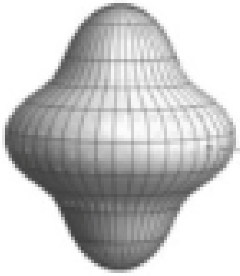
Quadrupole



Triaxial

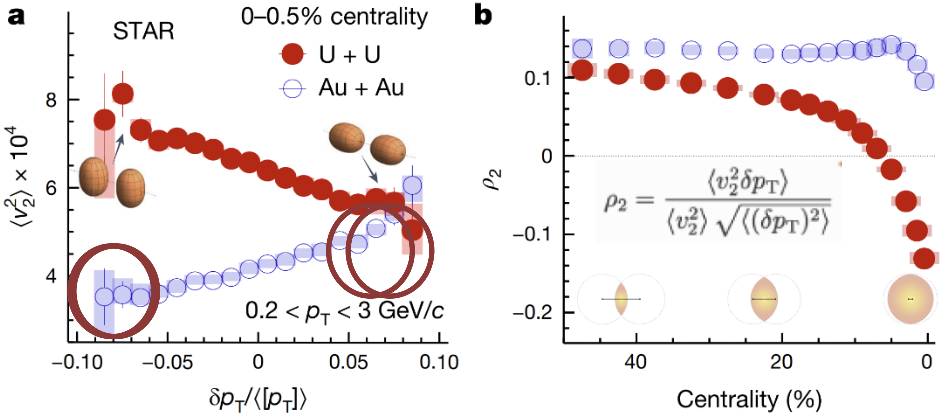


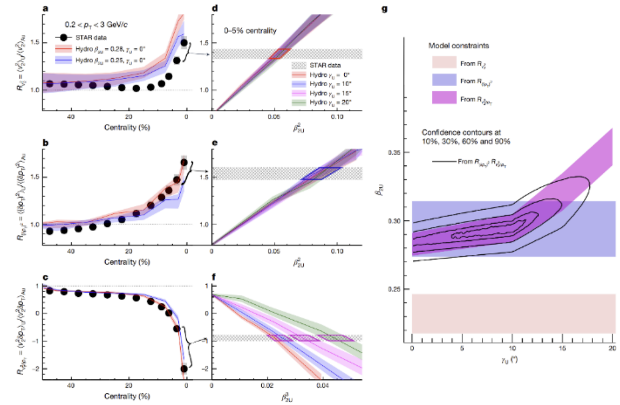
Octuple



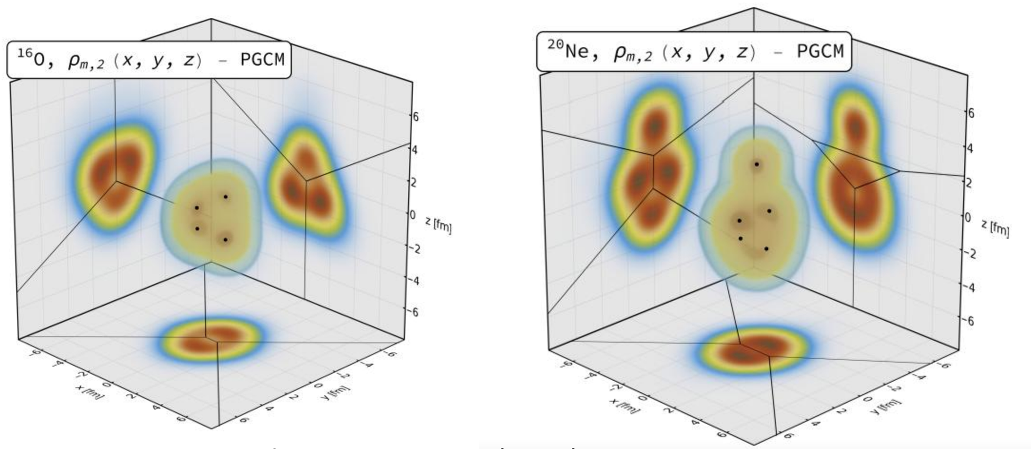
Hexadecapole

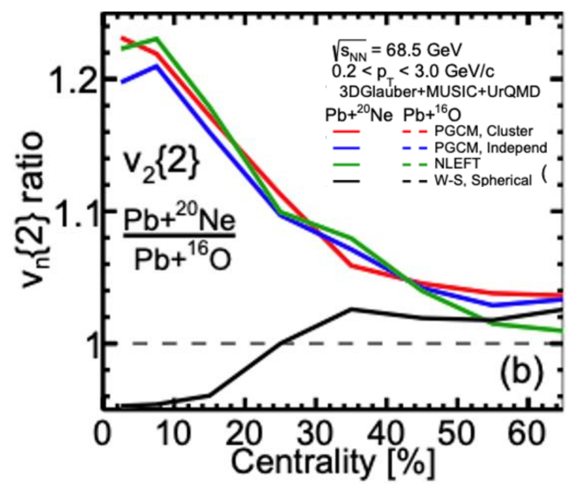
From final collectivity to initial nuclear structure





Nature 635 (2024) 8037, 67-72

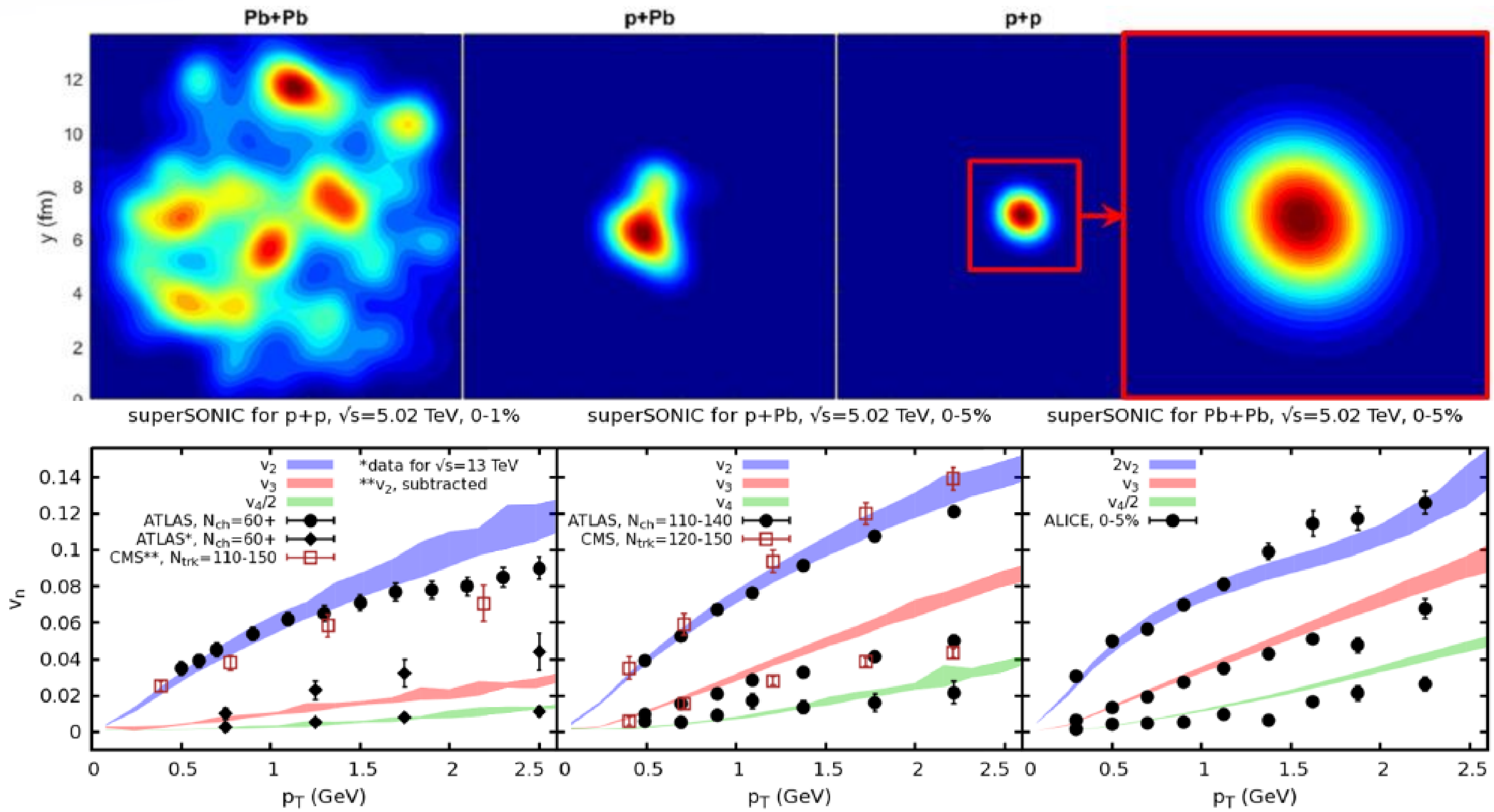




Phys.Rev.Lett. 135 (2025) 1, 012302

The ratios (U+U/Au+Au) can largely cancel final state effects and is sensitive to the intrinsic deformation of U:
$\beta_2^{\mathrm{U}} = 0.286 \pm 0.025, \gamma_{\mathrm{U}} = 8.7^{\circ} \pm 4.5^{\circ}$
v_n (Pb+Ne/Pb+O) is sensitive to α-clustering structure, which can be confirmed by SMOG2 program at LHCb.

Flow in small systems: mini-QGP?



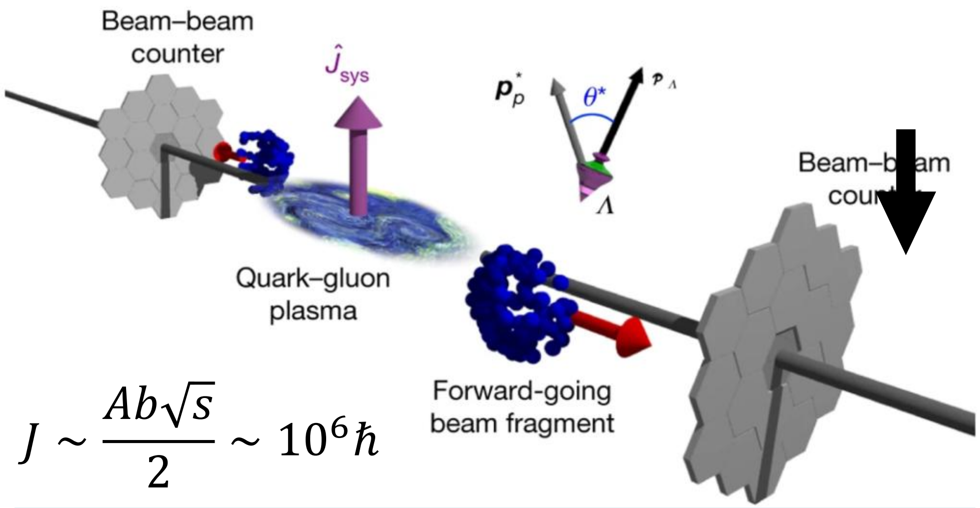
Flow harmonics can be viewed as the final-state effect due to hydrodynamic evolution of small systems with certain amount of initial anisotropy.

Still under active debate!

Bozek, Broniowski, Torrieri, PRL 2013; Bzdak, Schenke, Tribedy, Venugopalan, PRC 2013; GYQ, Muller, PRC 2014; Bzdak, Ma, PRL 2014; Weller, Romatschke, PLB 2017; Zhao, Zhou, Xu, Deng, Song, PLB 2018; etc.

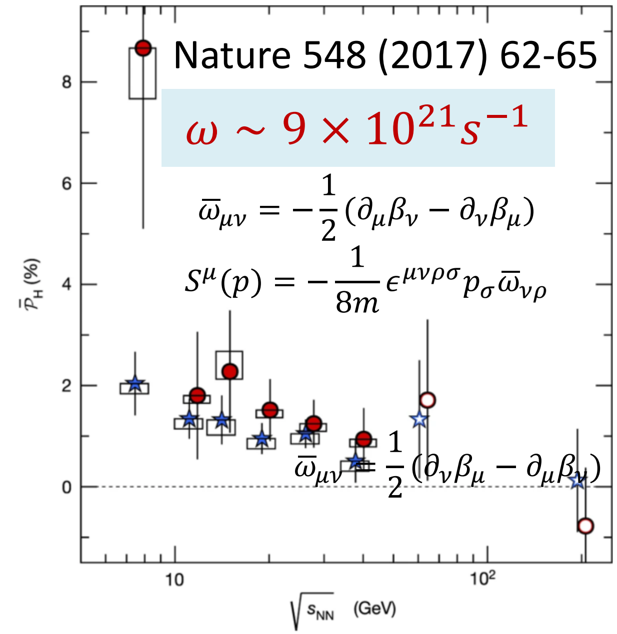
Vorticity and spin polarization

Most vortical fluid



$$J \sim \frac{Ab\sqrt{s}}{2} \sim 10^6\hbar$$

Spin-Orbital Coupling => Global Polarization



Nature 548 (2017) 62-65

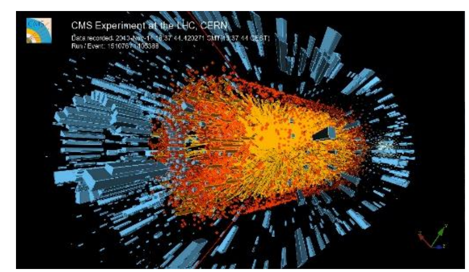
$$\omega \sim 9 \times 10^{21} s^{-1}$$

$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$$

$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_\sigma \varpi_{\nu\rho}$$

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu)$$

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_H |\mathcal{P}_H| \cos\theta^*) \qquad P_\Lambda \sim \frac{\omega}{2T}$$



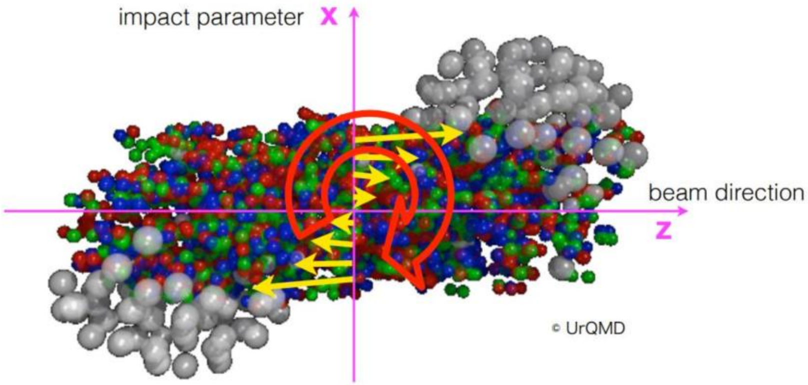
10^{-16}/s

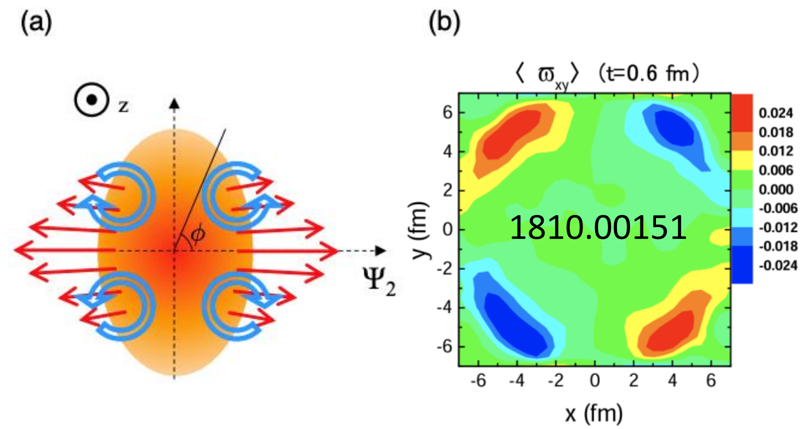
10^{-2}-10^{2}/s

10^{20}-10^{21}/s

Liang, Wang, PRL (2005); Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC (2017), etc.

Local polarization in QGP: sign puzzle

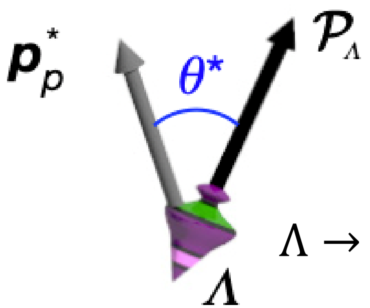




$$\omega_{\mu\nu} = -\frac{1}{2}(\partial_\mu u_\nu - \partial_\nu u_\mu) \quad \bar{\omega}_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$$

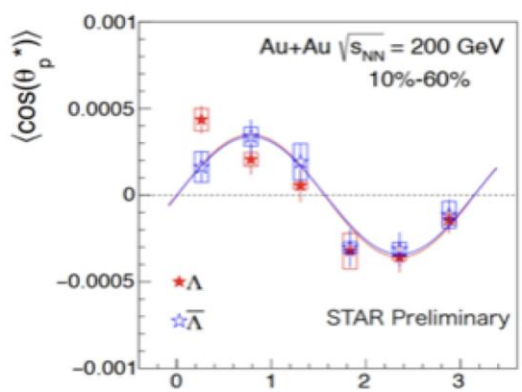
Global OAM => Global Polarization

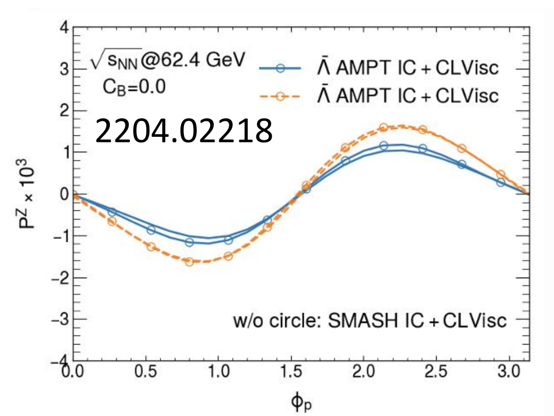
Local Vortical Structure ?=> Local Polarization



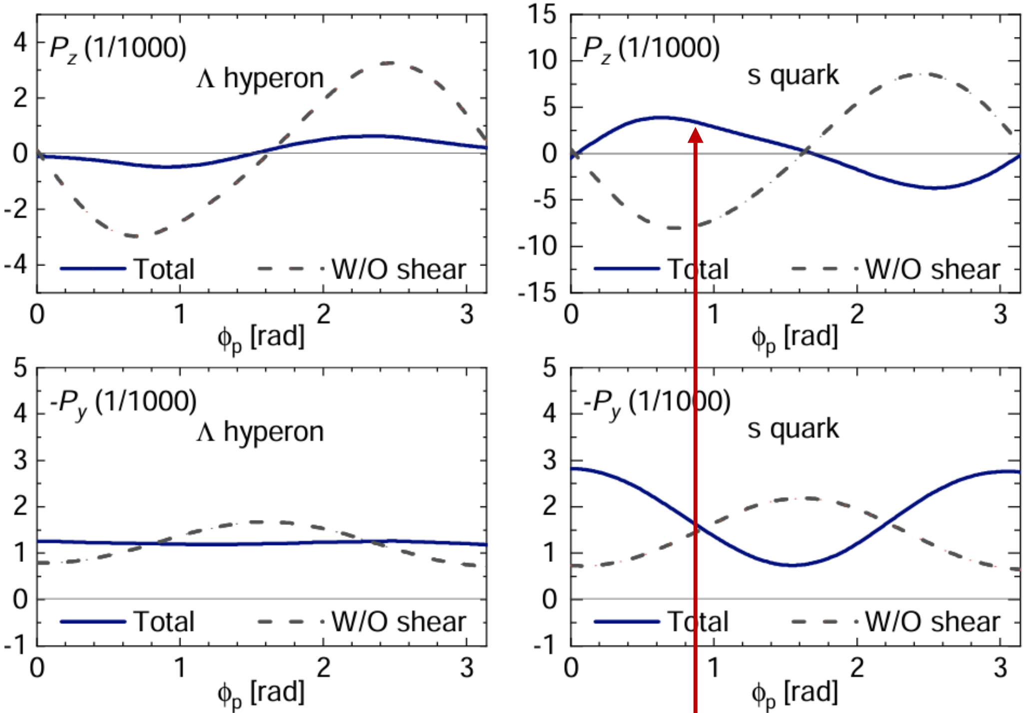
$$\Lambda \rightarrow p + \pi^-$$

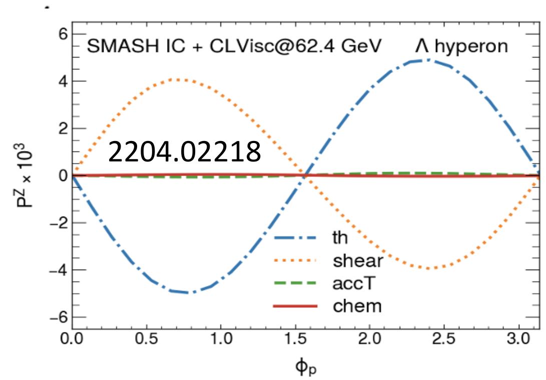
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_H |\mathcal{P}_H| \cos\theta^*)$$





Beyond vorticity: shear and more





$$\mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) = \int d\Sigma^{\sigma} F_{\sigma} \epsilon^{\mu\nu\alpha\beta} p_{\nu} \partial_{\alpha} \frac{u_{\beta}}{T}$$

$$\mathcal{S}^{\mu}_{\text{shear}}(\mathbf{p}) = \int d\Sigma^{\sigma} F_{\sigma} \frac{\epsilon^{\mu\nu\alpha\beta} p_{\nu} u_{\beta}}{(u\cdot p)T} \times p^{\rho}(\partial_{\rho} u_{\alpha} + \partial_{\alpha} u_{\rho} - u_{\rho} D u_{\alpha})$$

$$\mathcal{S}^{\mu}_{\text{accT}}(\mathbf{p}) = -\int d\Sigma^{\sigma} F_{\sigma} \frac{\epsilon^{\mu\nu\alpha\beta} p_{\nu} u_{\alpha}}{T} \left(D u_{\beta} - \frac{\partial_{\beta} T}{T} \right)$$

$$\mathcal{S}^{\mu}_{\text{chemical}}(\mathbf{p}) = 2\int d\Sigma^{\sigma} F_{\sigma} \frac{1}{(u\cdot p)} \epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta} \partial_{\nu} \frac{\mu}{T}$$

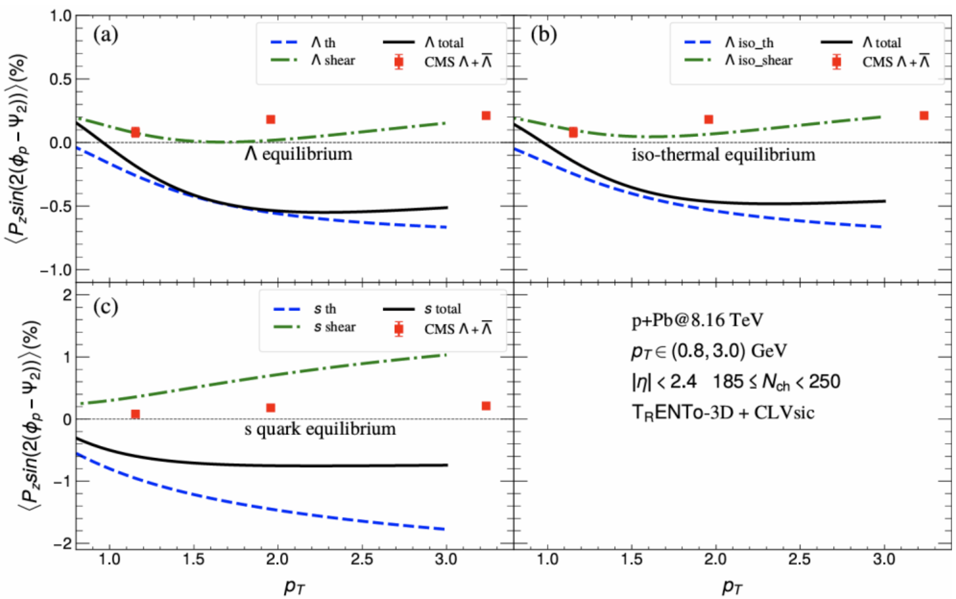
$$\mathcal{S}^{\mu}_{\text{EB}}(\mathbf{p}) = 2\int d\Sigma^{\sigma} F_{\sigma} \left[\frac{\epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta} E_{\nu}}{(u\cdot p)T} + \frac{B^{\mu}}{T} \right]$$

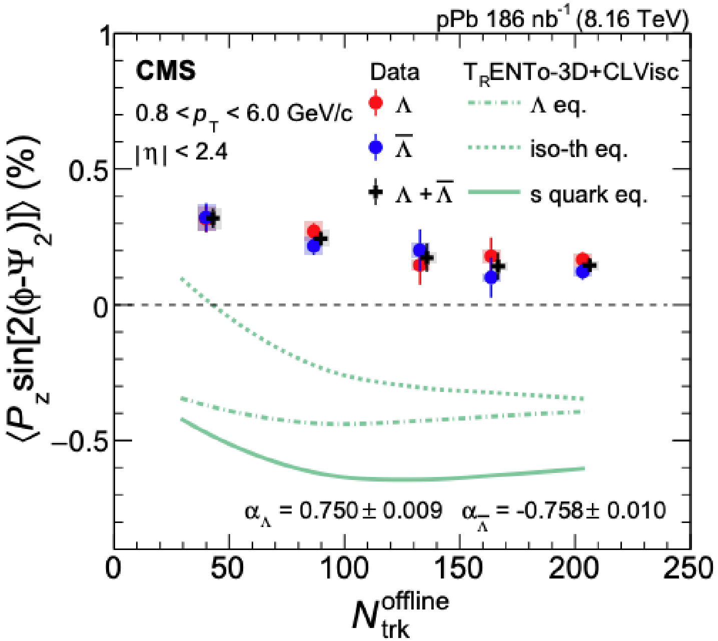
$$P^{\mu}(\mathbf{p}) = P^{\mu}_{\text{thermal}}(\mathbf{p}) + P^{\mu}_{\text{shear}}(\mathbf{p}) + P^{\mu}_{\text{accT}}(\mathbf{p}) + P^{\mu}_{\text{chemical}}(\mathbf{p}) + P^{\mu}_{\text{EB}}(\mathbf{p}),$$

Shear-induced polarization gives positive sign to local spin polarization and is indispensable to analyze the spin polarization induced by hydrodynamic gradient.
Shear-induced polarization and the memory of strange quarks is required for the local spin polarization to agree with data qualitatively.

Phys.Rev.Lett. 127 (2021) 14, 142301； Phys.Rev.Lett. 127 (2021) 27, 272302

Sign puzzle in p-Pb collisions

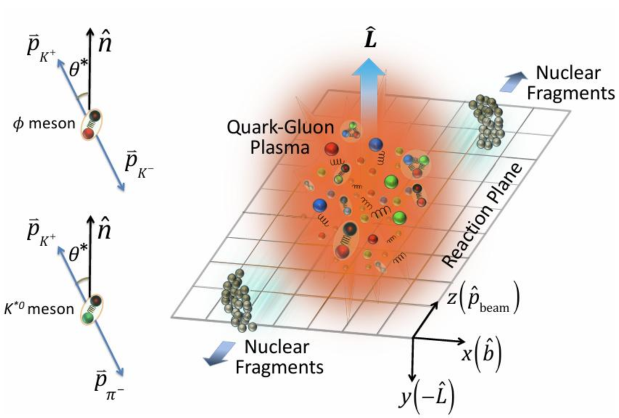


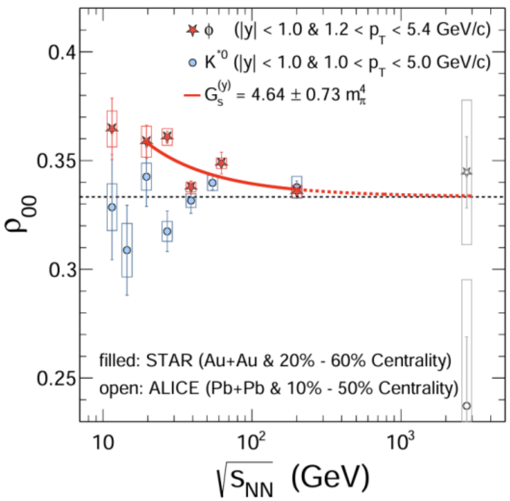


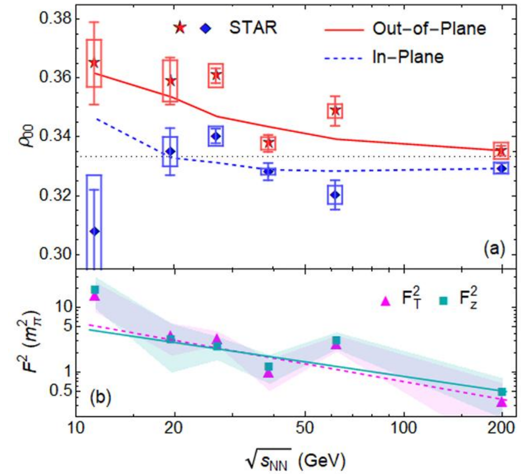
Shear-induced polarization gives a positive contribution, while **thermal vorticity** induced polarization provides an opposite sign, similar to AA collisions.
The total polarization is always negative except in very low multiplicity (inconsistent with data), which indicates **thermal vorticity** and **shear tensors** **cannot explain the data.**

Phys.Rev.C 111 (2025) 4, 044901

Spin alignment of ϕ: new avenue







Nature 614 (2023) 7947, 244-248 Phys.Rev.Lett. 131 (2023) 4, 042304

Global spin alignment for ϕ is very large, while that for K^{*0} is consistent with zero.

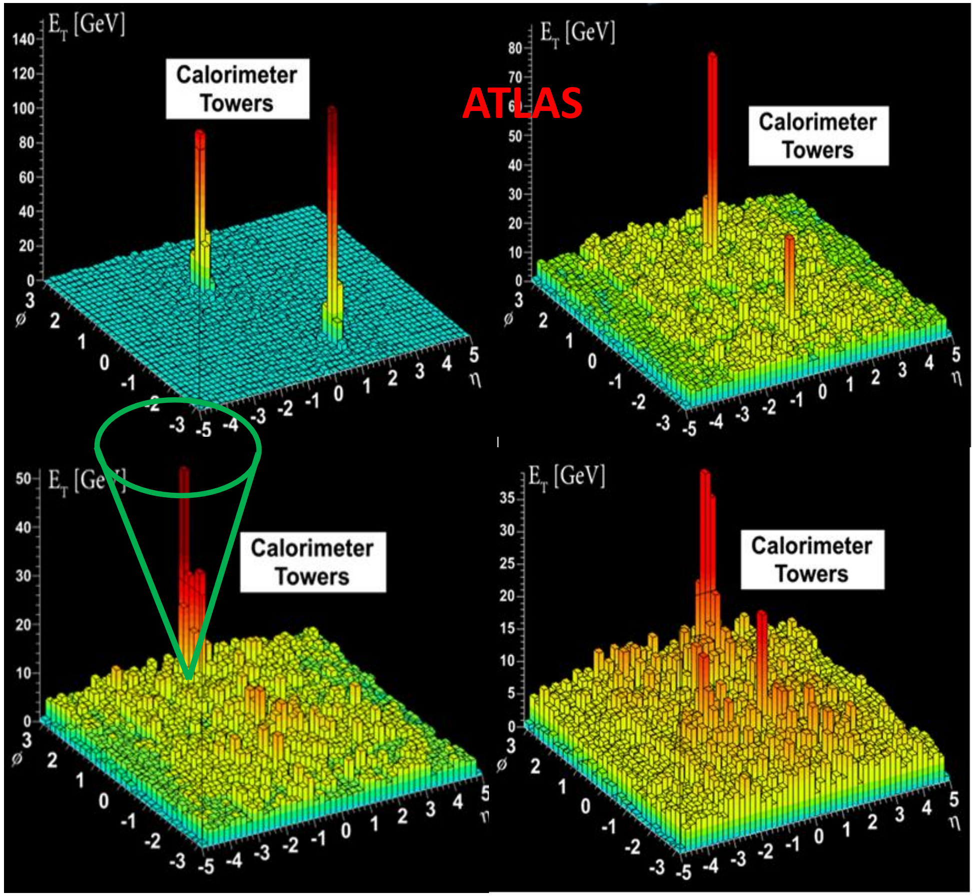
The observed spin-alignment pattern and magnitude for ϕ cannot be explained by conventional vorticity mechanisms.

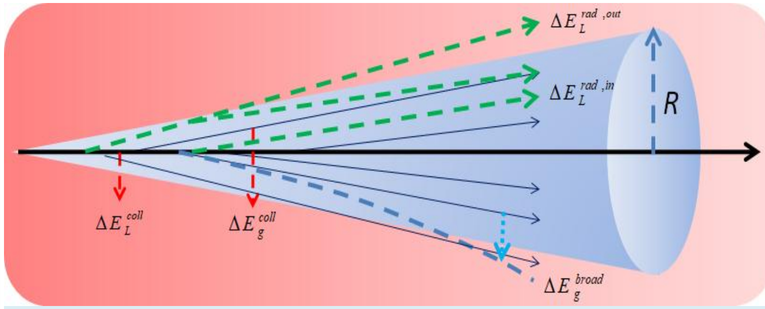
The local correlation or fluctuation of ϕ fields can explain the observed ϕ spin alignment, opening a new avenue for studying strong force fields.

$$\rho_{00}(x,\mathbf{k}) \approx \frac{1}{3} + C_1\left[\frac{1}{3}\boldsymbol{\omega}'\cdot\boldsymbol{\omega}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\omega}')^2\right] + C_2\left[\frac{1}{3}\boldsymbol{\varepsilon}'\cdot\boldsymbol{\varepsilon}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\varepsilon}')^2\right]$$
$$- \frac{4g_\phi^2}{m_\phi^2 T_{\rm h}^2} C_1\left[\frac{1}{3}\mathbf{B}'_\phi\cdot\mathbf{B}'_\phi - (\boldsymbol{\epsilon}_0\cdot\mathbf{B}'_\phi)^2\right] - \frac{4g_\phi^2}{m_\phi^2 T_{\rm h}^2} C_2\left[\frac{1}{3}\mathbf{E}'_\phi\cdot\mathbf{E}'_\phi - (\boldsymbol{\epsilon}_0\cdot\mathbf{E}'_\phi)^2\right]$$

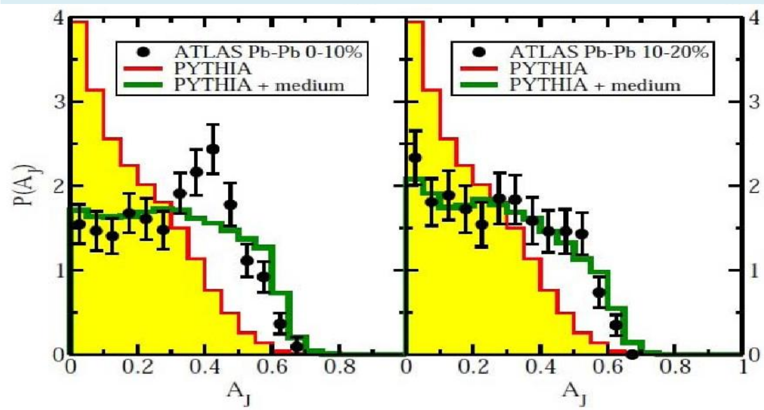
Jets and medium response

QGP is highly opaque to jets





Dijet momentum imbalance



GYQ, Muller, PRL, 2011, etc.

$$\Delta E_{rad} \propto \alpha_s C_R \hat{q} L^2$$

$$A_J = \frac{E_{J,1} - E_{J,2}}{E_{J,1} + E_{J,2}}, \Delta\phi = |\phi_1 - \phi_2|$$

LHC can produce abundant high-energy jets with hundreds/thousands of GeV, providing an unprecedented opportunity for studying jets and jet quenching.

A typical framework: LBT+Hydro

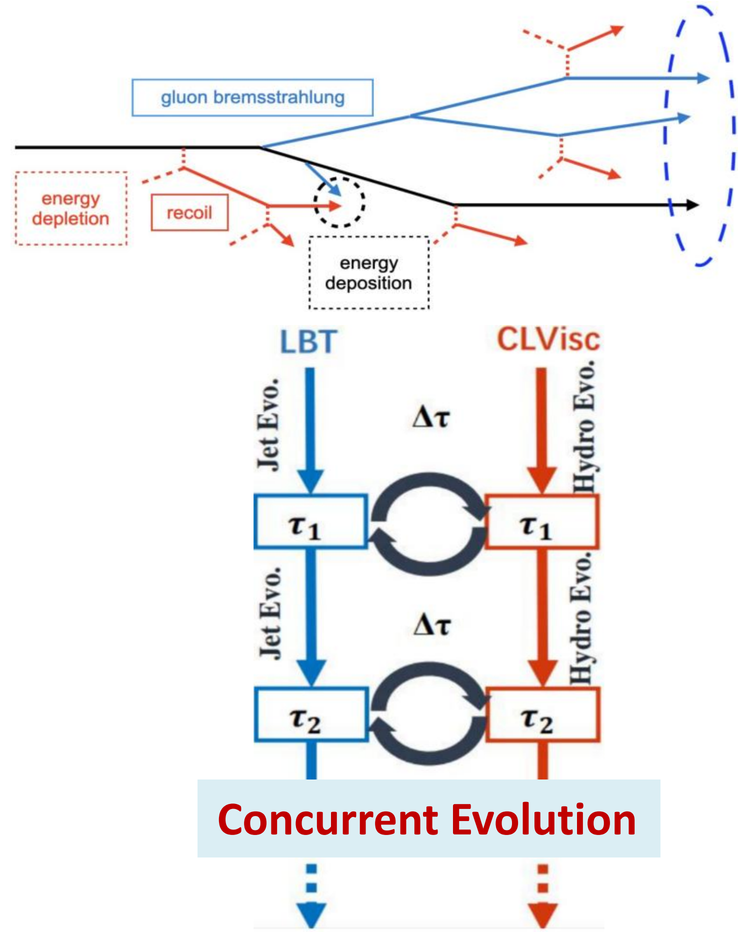
- **Linear Boltzmann Transport (LBT)** model for hard parton (jet shower and recoil) evolution
- **Hydrodynamics (CLVisc)** model for the bulk evolution
- Sort jet and recoil partons according to a cut-off parameter
  - Hard partons (**LBT**): $\boldsymbol{p \cdot \partial f(x,p) = C[f]}$ for $p \cdot u > p^0_{cut}$
  - Soft partons (**source**):

$$J^\nu(x) = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p \cdot u)$$

- Update medium information by solving the hydrodynamics equation with source term (**CLVisc**)

$$\boldsymbol{\partial_\mu T^{\mu\nu}(x) = J^\nu(x)}$$

- Final hadron spectra:
  - Hadronization of hard partons
  - Jet-induced medium response via Cooper-Frye

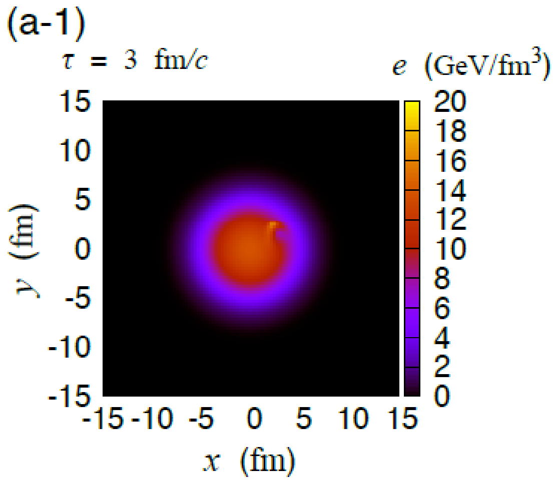


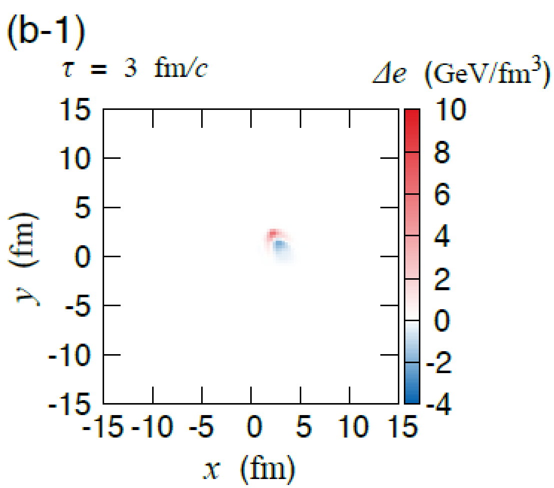
LBT: He, Luo, Wang, Zhu, Cao, GYQ, etc., 1503.03313, 1605.06447, 1703.00822, 2306.13742.

CLVisc: Pang, Wang, Wang, Petersen, Wu, GYQ, 1205.5019, 1802.04449, 2107.04949.

CoLBT: W. Chei, T. Luo, S. Cao, L.G. Pang, X. N. Wang, Phys.Lett.B 777 (2018) 86-90.

Jet quenching & medium response

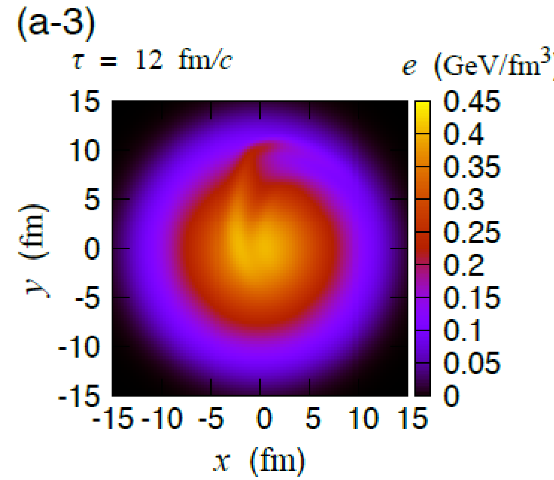


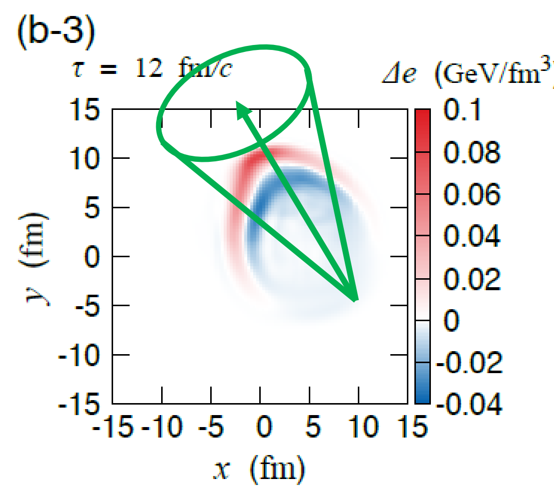


Jet loses and deposits energy and momentum into the medium, and induces V-shape wave fronts **(medium excitation)**

The wave fronts carry energy and momentum, propagate forward and outward, which depletes the energy behind the jet **(diffusion wake)**

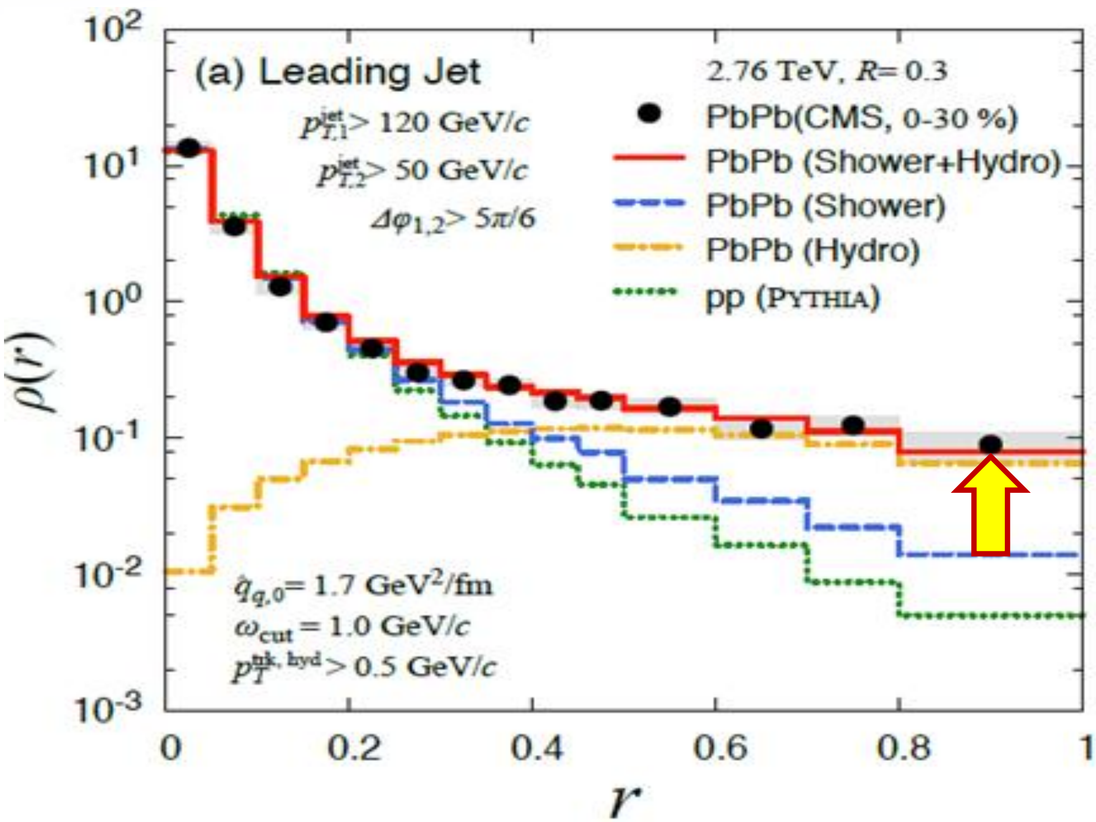
Jet-induced flow and the radial flow of medium are pushed and distorted by each other

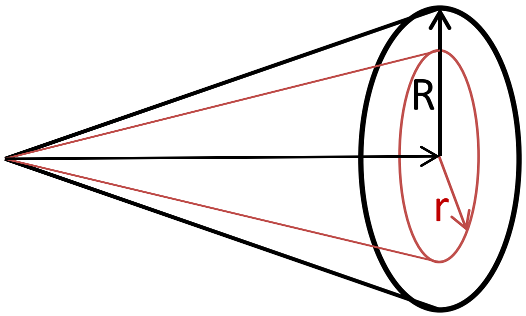




Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Jet-induced medium response



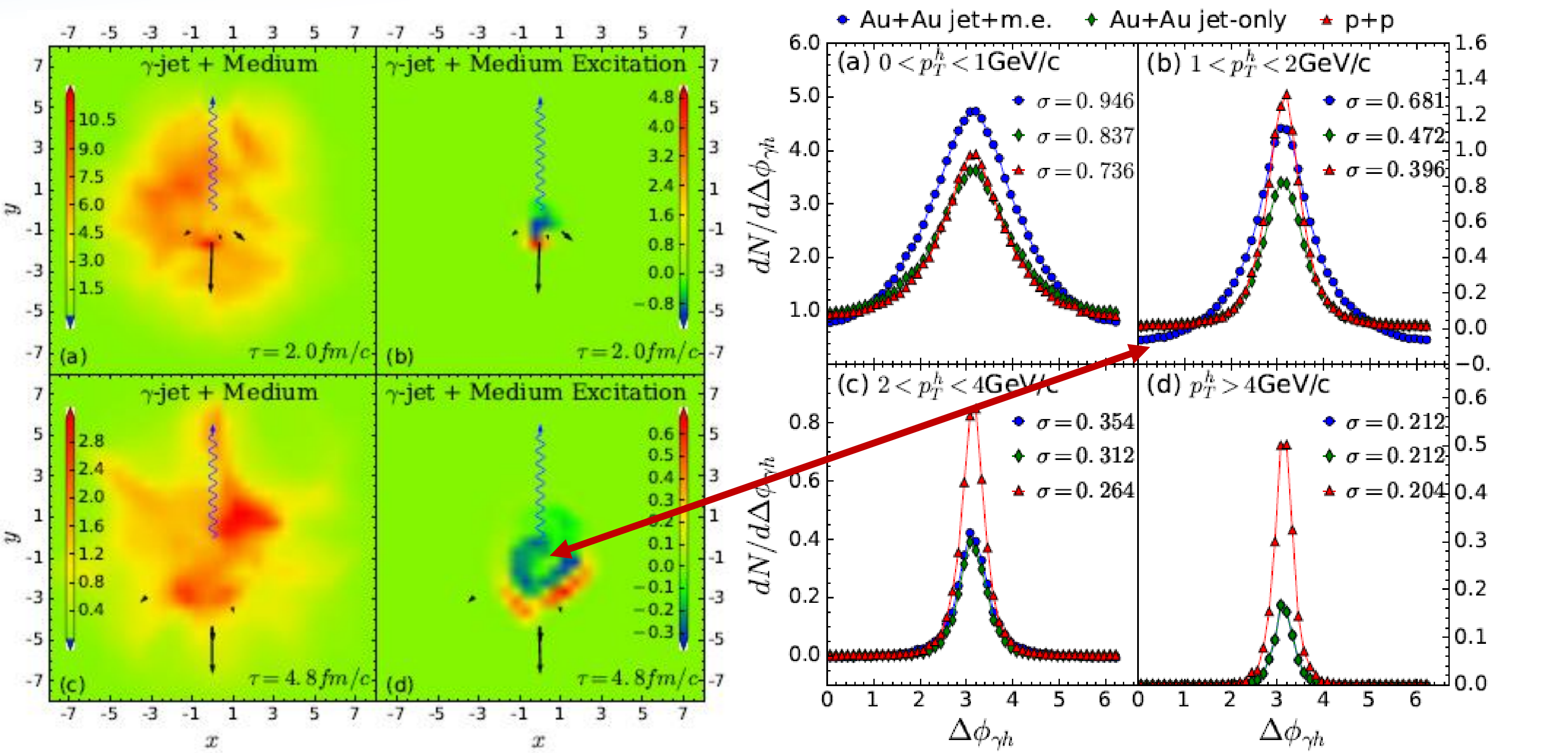


The contribution from the hydro part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.

Signal of medium response in full jet shape at large r.

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Diffusion wake from CoLBT-Hydro

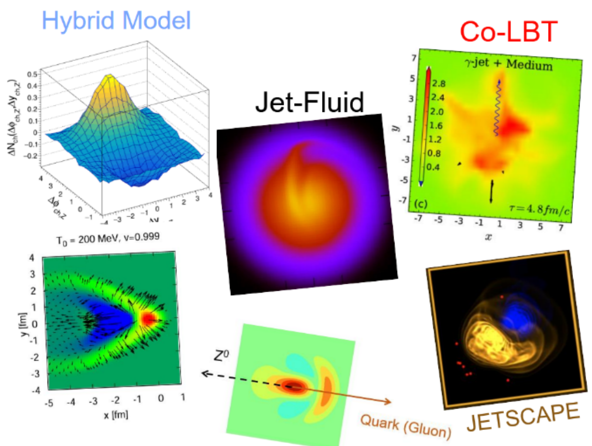


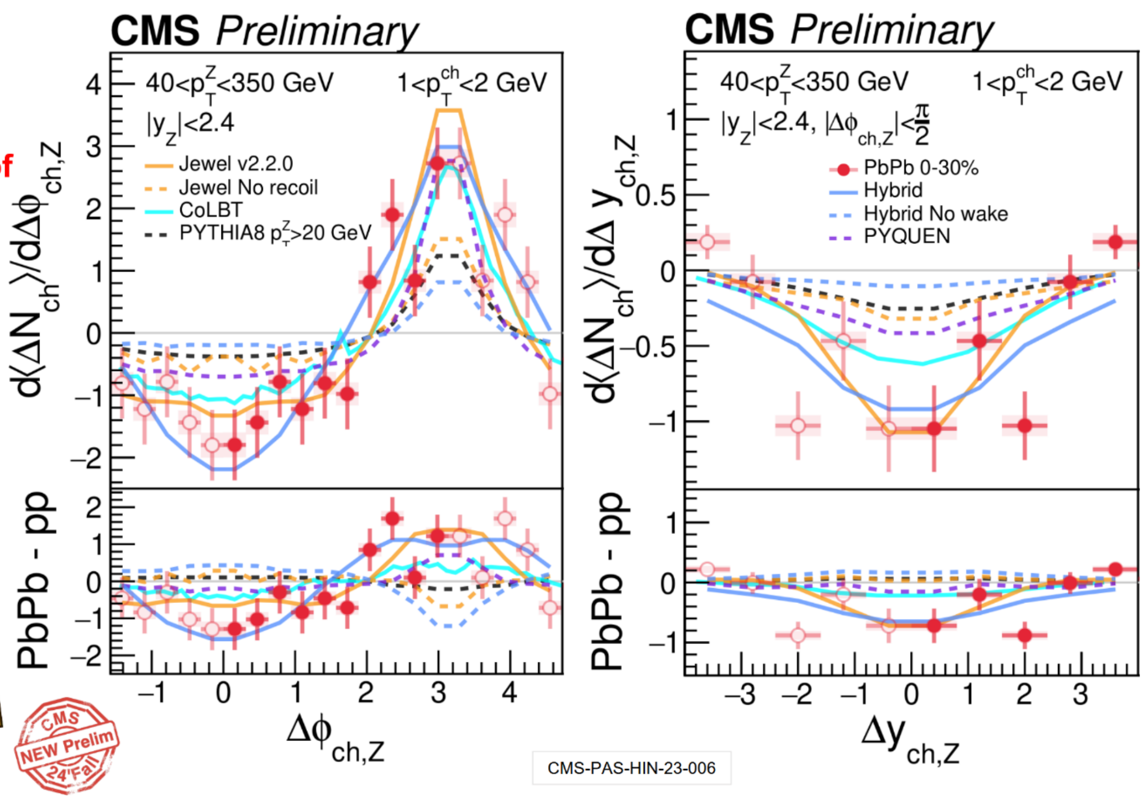
Hard hadrons in jet direction are suppressed due to parton energy loss.
Soft hadrons in jet direction are enhanced due to jet-induced medium excitation and has significantly broadened azimuthal distribution relative to jet direction.
Soft hadrons in γ direction are **depleted** due to a **diffusion wake** behind the jet.

Chen, Cao, Luo, Pang, Wang, PLB 2018, arXiv:1704.03648

Evidence of diffusion wake from CMS

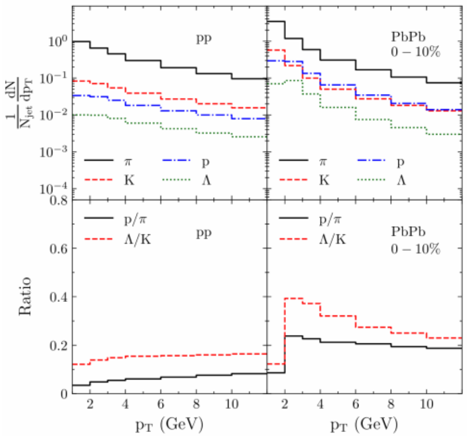
- First p_T^{ch} differential measurement of Z^0-hadron correlation in azimuthal angle and rapidity
- We report the **first direct evidence of medium response in QGP**
- High statistics analysis with Run3+4 data in the near future

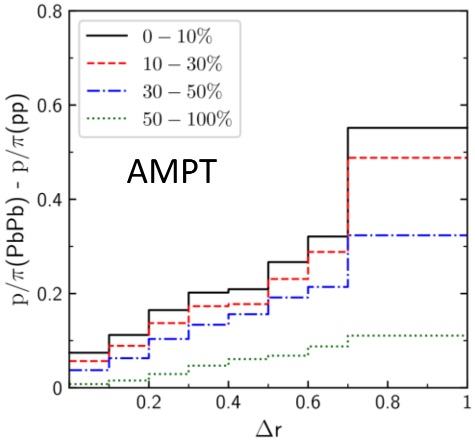


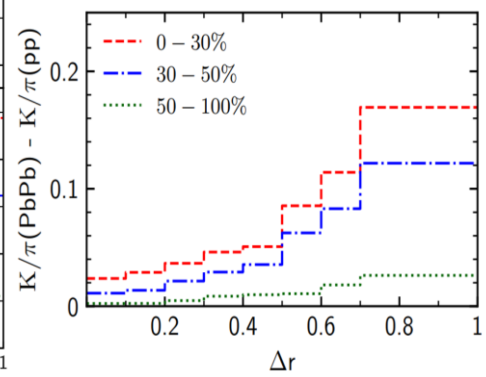


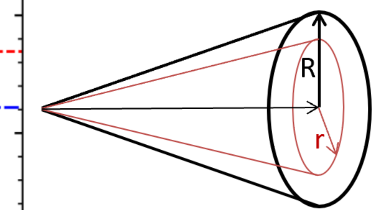
Next: use jet-induced medium response (diffusion wake) to probe QGP properties?

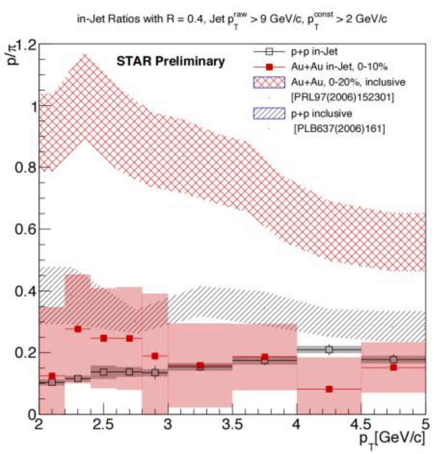
B/M & strangeness enhancement around jets

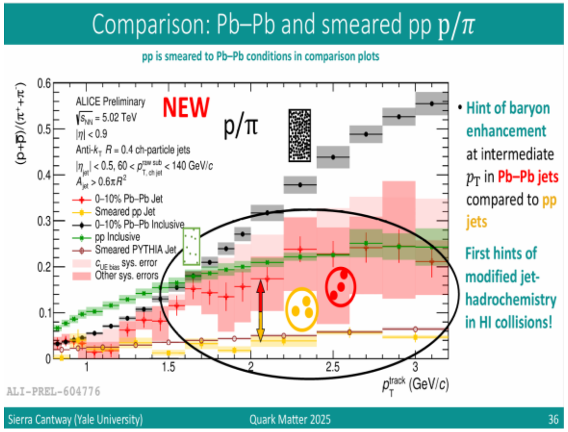


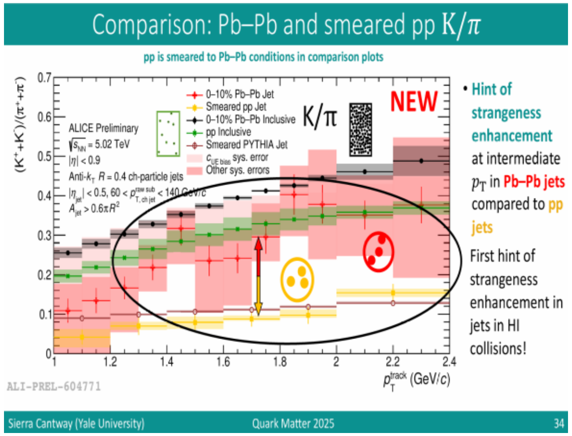








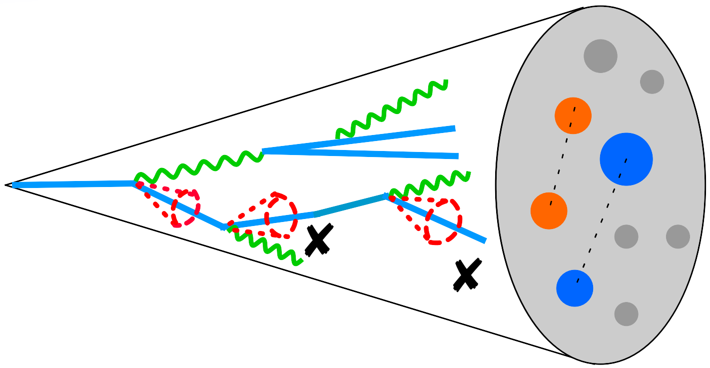




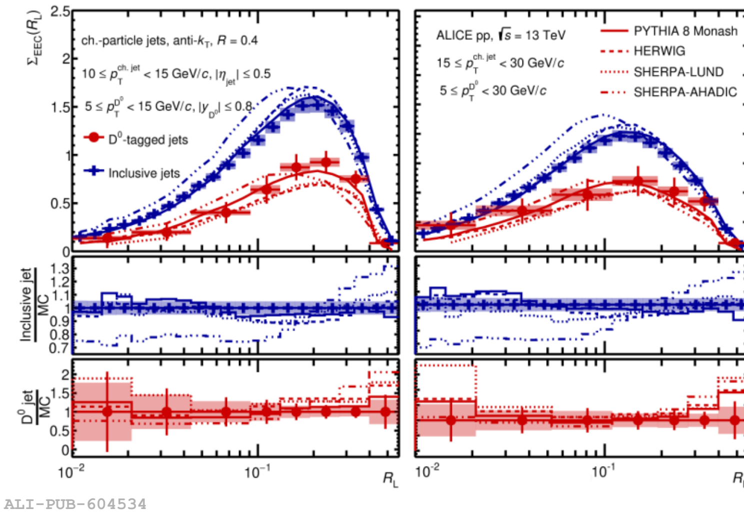
For intermediate p_T (2-4GeV) regime, the enhancement of jet-induced B/M & strange/non-strange is stronger for larger distance because the lost energy from quenched jets can diffuse to large angle.

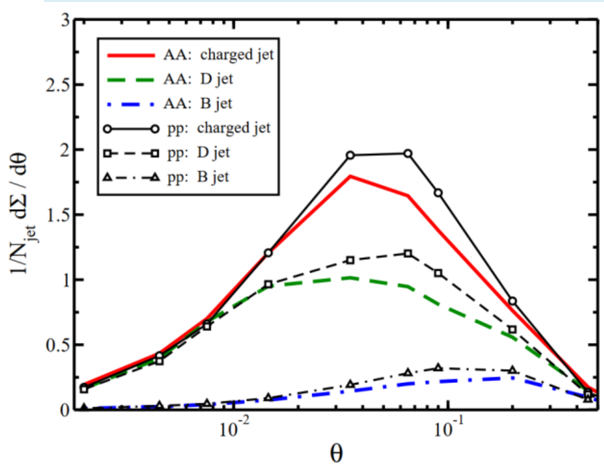
Luo, Mao, GYQ, Wang, Zhang, Phys.Lett.B 837 (2023) 137638; Luo, Cao, GYQ, Phys.Lett.B 866 (2025) 139520

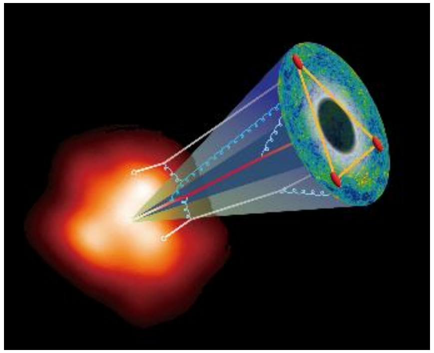
Jet substructure (e.g., EEC) in QGP

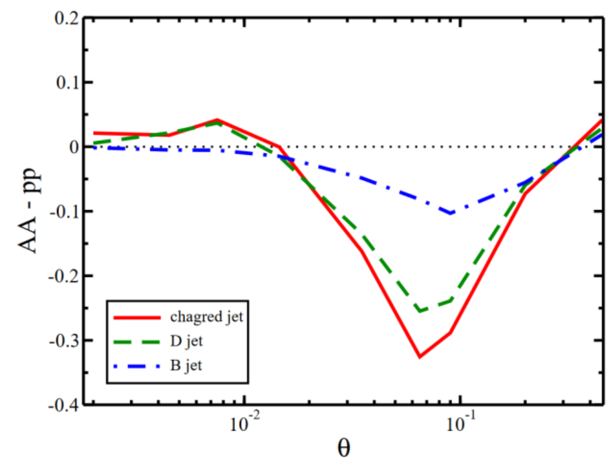


Jet EECs can probe the physics of jet-medium interaction at different scales, e.g., mass, medium-induced radiation, medium response, etc.









Komiske, IMoult, Thaler, Zhu, PRL 130, 051901 (2023); Liu, Zhu, PRL 130, 091901 (2023); Liu, Liu, Pan, Yuan, Zhu, PRL 130, 181901 (2023); Andres, Dominguez, Elayavalli, Holguin, Marquet, PRL 130 (2023) 26, 262301; Yang, He, Moult, Wang, PRL 132 (2024) 1, 1; Xing , Cao, GYQ, Wang, PRL 134, 052301 (2025)

Summary and outlook

- The QGP produced in RHIC & LHC heavy-ion collisions is the hottest, most perfect, most vortical and highly-opaque fluid on Earth!
- Precise determination of QGP transport properties with combined theory and experiment
- Exploring QCD at high baryon density and locating the critical point
- Systematic modeling of spin dynamics and polarization in QGP evolution
- Unified framework for QGP evolution and multi-scale probes of QGP (jets, heavy quarks, EM radiation, …)
- Quantitative description of early-time dynamics and rapid thermalization
- Full understanding of QCD matter from weakly-coupled quark-gluon gas at very high T to strongly-interacting QGP at relatively “low” T?
- Integrating machine learning and AI

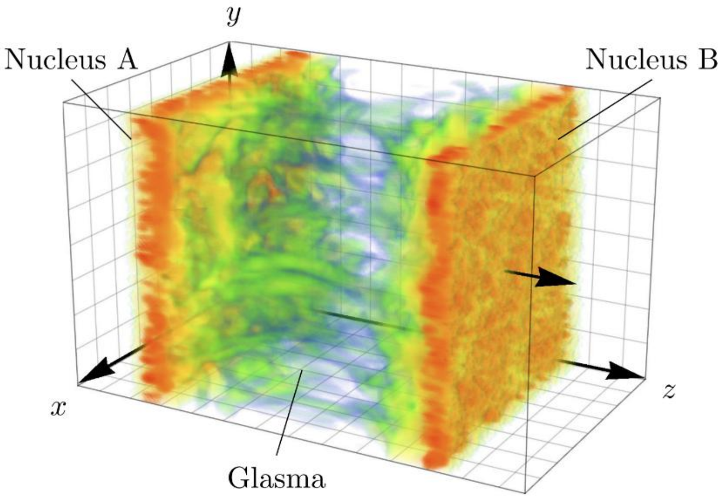
Pre-QGP stage & thermalization

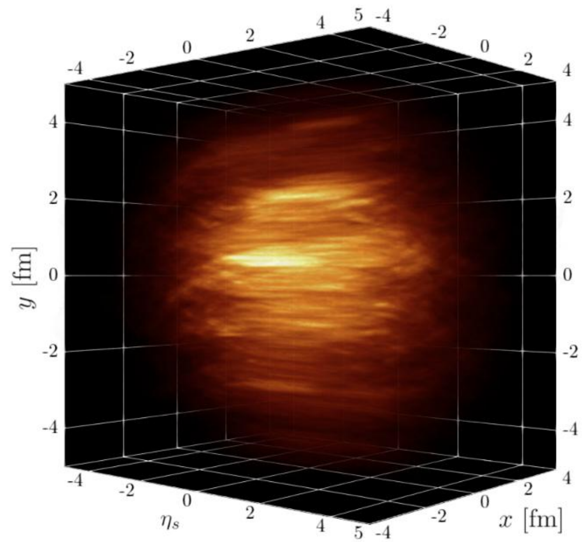
- Heavy-ion collisions experience different stages
  - Initial state (before collision), pre-QGP stage, QGP and hadrons.
- What is the nature of the pre-QGP stage in heavy-ion collisions? How does the system thermalize?

- Key physics: non-equilibrium many-body QCD.
- Two typical pictures: classical waves versus quasiparticles
  - Classical strong fields & glasma, Yang-Mills equation
  - Quasiparticles, QCD effective kinetic theory simulations

3D Glasma

- The color-glass condensate (CGC) and glasma approach provides a description for nuclei before the collision, as well as the collision itself, and the subsequent pre-equilibrium evolution of the glasma.
- Within the CGC effective theory, collisions of nuclei with finite longitudinal thickness in classical (3+1)D Yang-Mills simulations form longitudinal color flux tubes with transverse domains $\sim 1/Q_s$

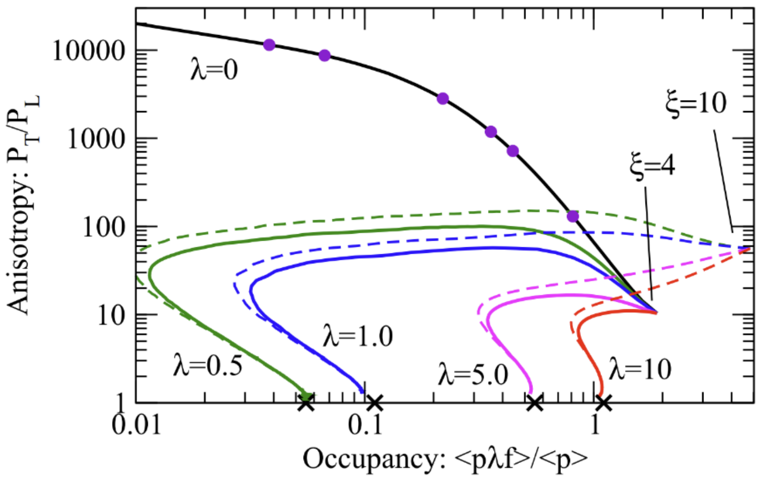


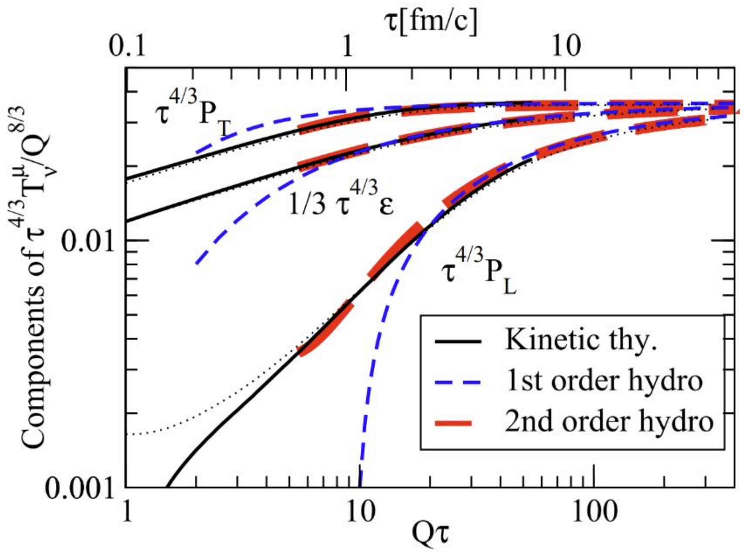


Ipp, Muller, Phys.Lett.B 771 (2017) 74-79; Ipp, Leuthner, Muller, Schlichting, Schmidt, Kayran, Singh, Phys.Rev.D 109 (2024) 9, 094040; etc.

QCD effective kinetic theory

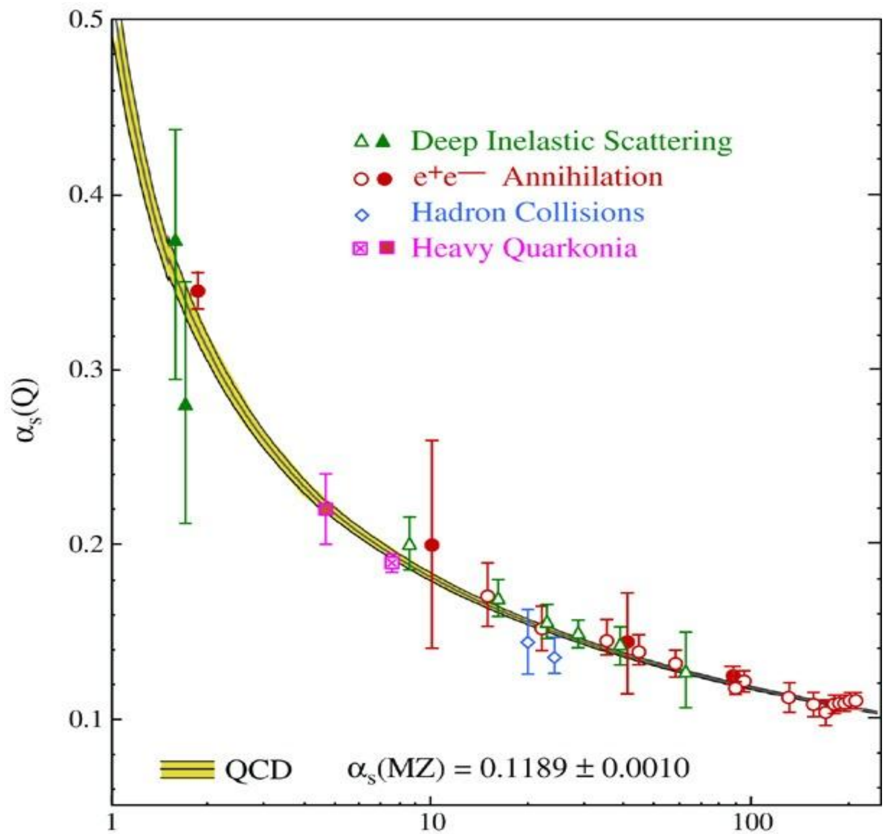
- Classical Yang-Mills theory can not reach thermalization or equilibrium
- EKT can provide the bridge: when quasiparticles have formed, kinetic theory becomes applicable
- Start with a classical Yang-Mills simulation and then pass the system to EKT at some later time
- Smooth transition from EKT to hydrodynamics: the system can be approximately described by viscous hydrodynamics before $\tau \lesssim 1\text{fm}/c$
- Pre-QGP evolution should be included in the multi-stage frameworks





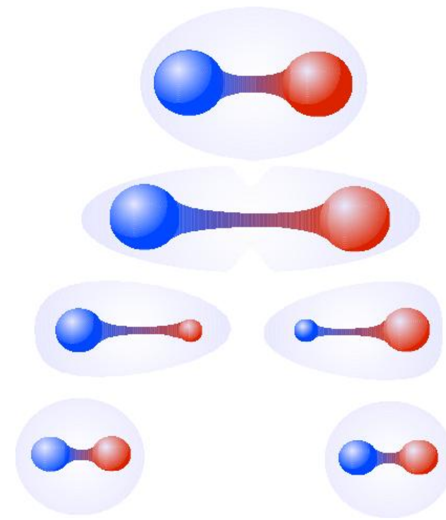
Kurkela, Zhu, Phys.Rev.Lett. 115 (2015) 18, 182301; etc.

QCD: confinement & asymptotic freedom



Long Distance Q [GeV] Short Distance

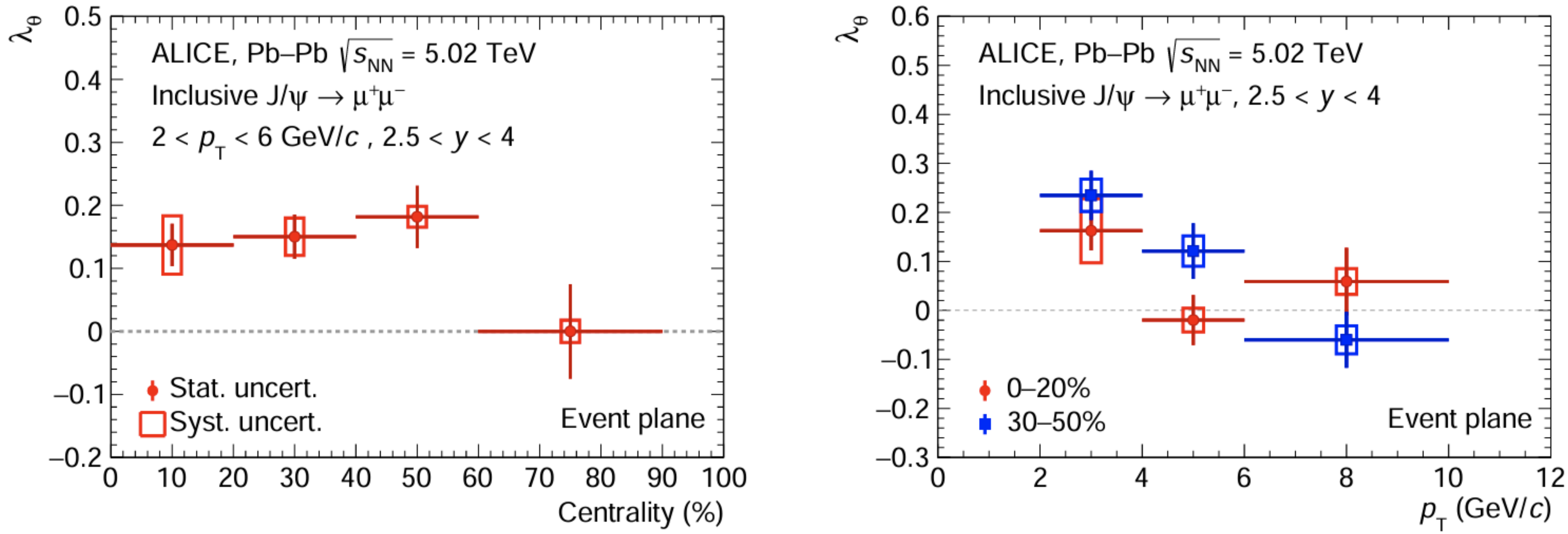
Confinement Asymptotic Freedom



2004 Nobel Prize: *"for the discovery of asymptotic freedom in the theory of the strong interaction".*

David Gross, David Politzer, Frank Wilczek

Spin alignment of J/ψ



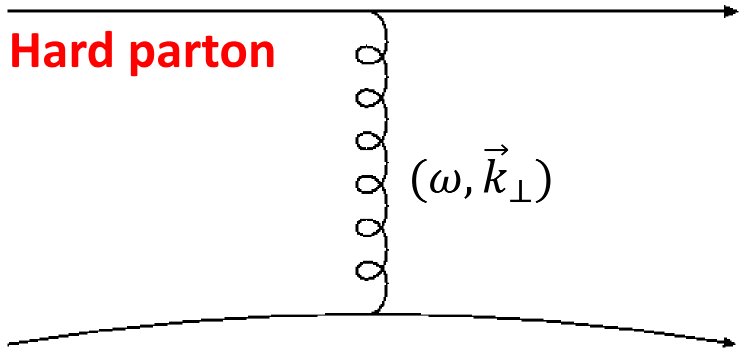
$$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right) \qquad \lambda_\theta \propto (1-3\rho_{00})/(1+\rho_{00}) \qquad \rho_{00} < \frac{1}{3}$$

The spin alignment J/ψ for seems not be fully understood within the framework of effective strong force models.

The polarization could be connected with large vorticity and strong magnetic field.

Phys.Rev.Lett. 131 (2023) 4, 042303

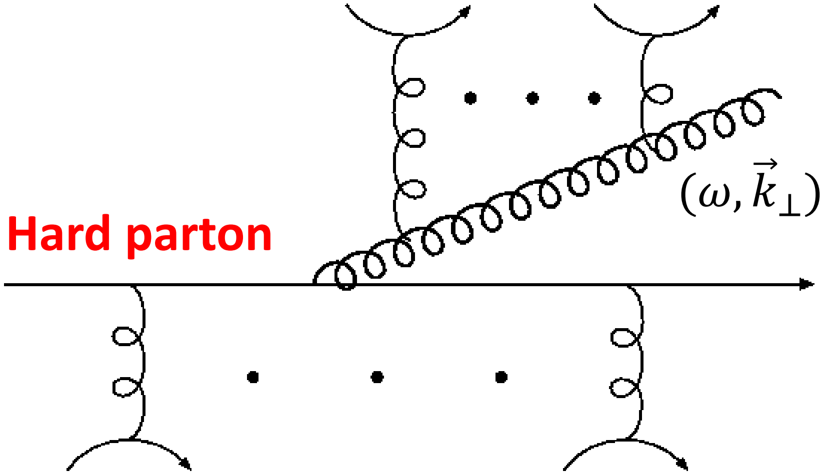
Hot nuclear matter effect



Elastic (collisional)

$$\frac{d\Gamma_{coll}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic, 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008; …



Inelastic (radiative)

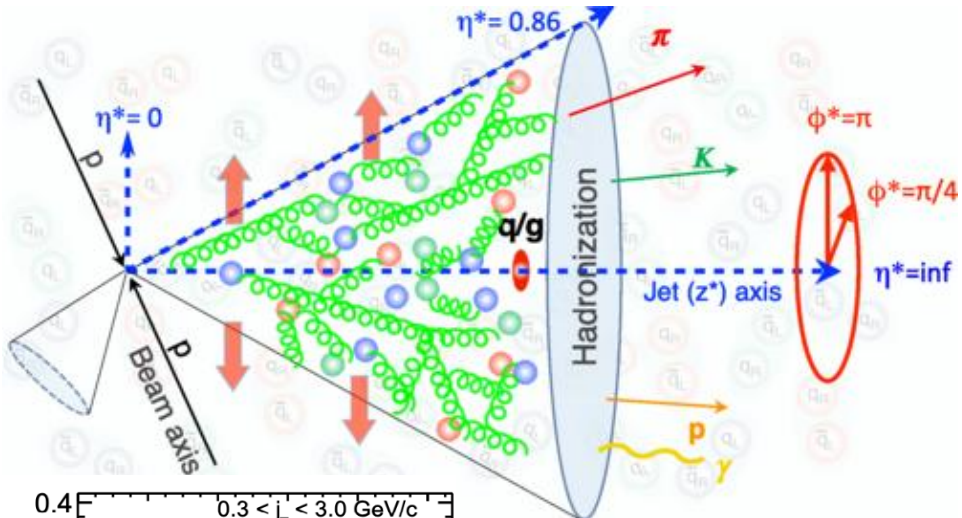
$$\frac{d\Gamma_{rad}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

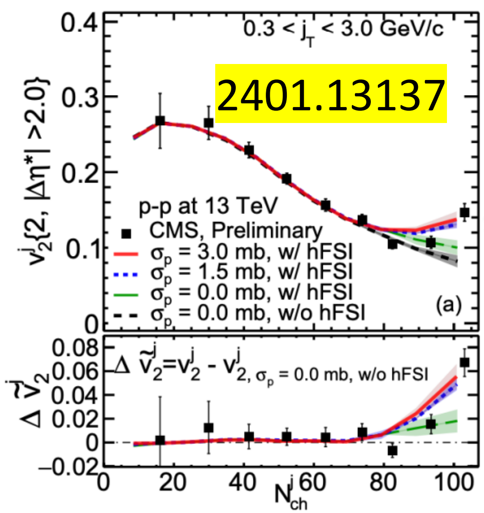
BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe (& Caron-Huot, Gale)
GLV: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)
HT: Wang-Guo (& Zhang, Wang, Majumder)

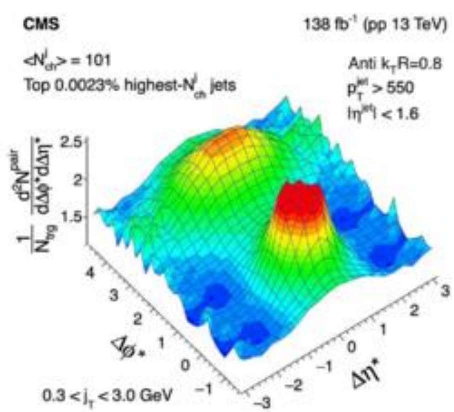
Monte-Carlo approaches of jet quenching

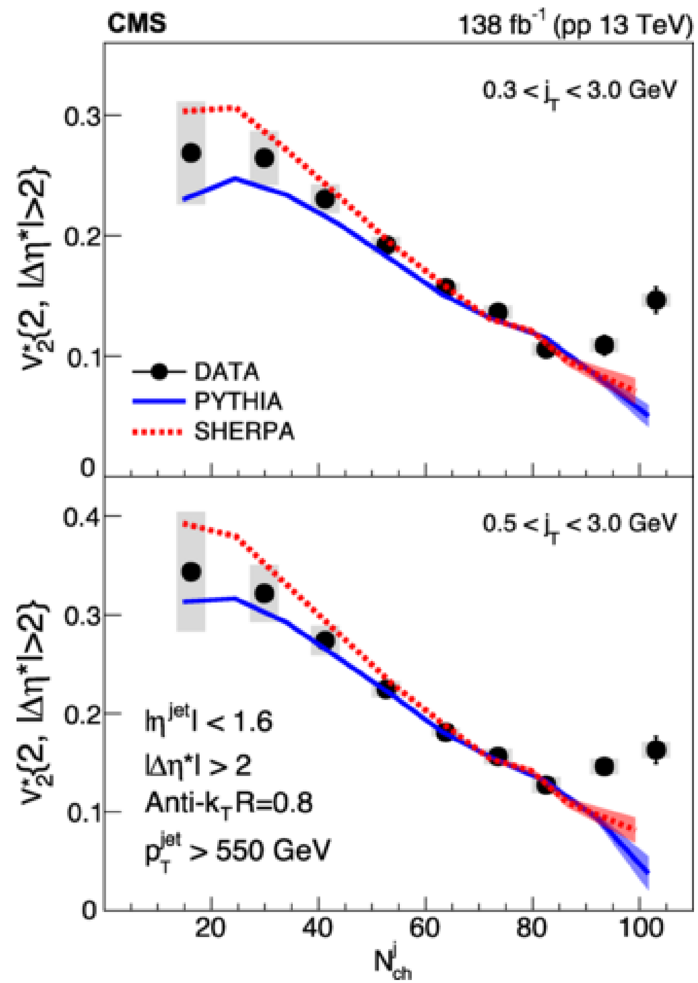
- **JEWEL** (*Jet Evolution With Energy Loss*): K. Zapp , G. Ingelman, J. Rathsman, J. Stachel, U. A. Wiedemann, Eur.Phys.J.C 60 (2009) 617-632; JHEP 03 (2013) 080.
- **Q-Pythia** (A medium-modified implementation of final state radiation): N. Armesto, L. Cunqueiro and C. A. Salgado, Eur.Phys.J.C 63 (2009) 679-690.
- **MARTINI** (*Modular Algorithm for Relativistic Treatment of heavy IoN Interactions*): B. Schenke, C. Gale, S. Jeon, Phys.Rev.C 80 (2009) 054913
- **LBT** (*Linear Boltzmann Transport Model*): Y. He, T. Luo, X. N. Wang, Y. Zhu, Phys.Rev.C 91 (2015) 054908; T. Luo, Y. He, S. Cao, X. N. Wang, Phys.Rev.C 109 (2024) 3, 034919; S. Cao, T. Luo, GYQ, X. N. Wang, Phys.Rev.C 94 (2016) 1, 014909; Phys.Lett.B 777 (2018) 255-259.
- **Hybrid** (*A Hybrid Strong/Weak Coupling Approach to Jet Quenching*): J. Casalderrey-Solana, D. C. Gulhan, J. G. Milhano, D. Pablos, K. Rajagopal, JHEP 10 (2014) 019
- **MATTER** (*Modular-All-Twist-Transverse-and-Elastic-scattering-induced-Radiation*): A. Majumder, Phys.Rev.C 88 (2013) 014909.
- **LIDD**: W. Ke, Y. Xu, S. A. Bass, Phys.Rev.C 98 (2018) 6, 064901.
- **CoLBT-Hydro**: W. Chei, T. Luo, S. Cao, L.G. Pang, X. N. Wang, Phys.Lett.B 777 (2018) 86-90.
- **JETSCAPE** (*Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope*): 1903.07706 [nucl-th].

Enhanced v_2 in high multiplicity jet









v_2 enhancement in high multiplicity jets seems to be explained by final-state partonic & hadronic interactions (in AMPT)? What is critical at N_{ch}=80-100? Other explanations?