第八届中国LHC物理研讨会

# Theory Overview of Heavy Ion Physics


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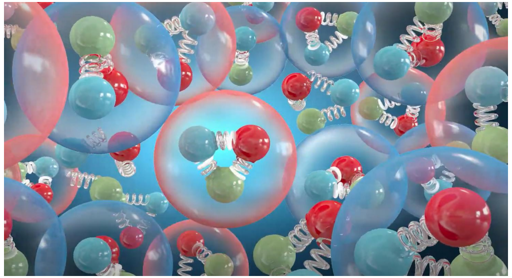
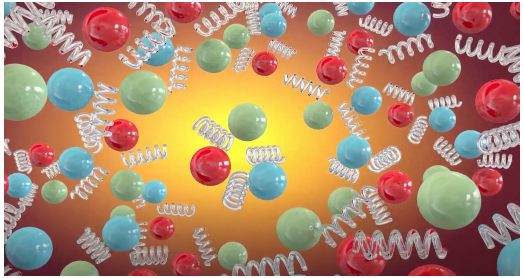
# Why relativistic heavy ion collisions

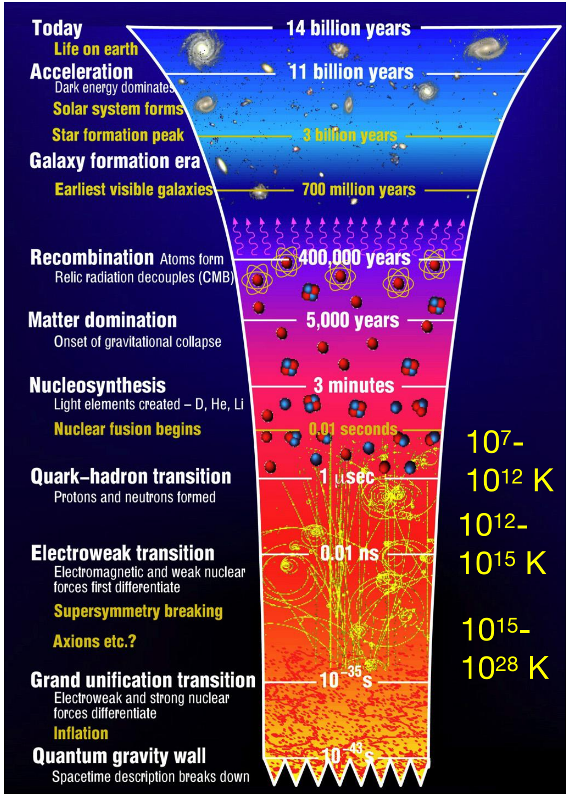


Confined

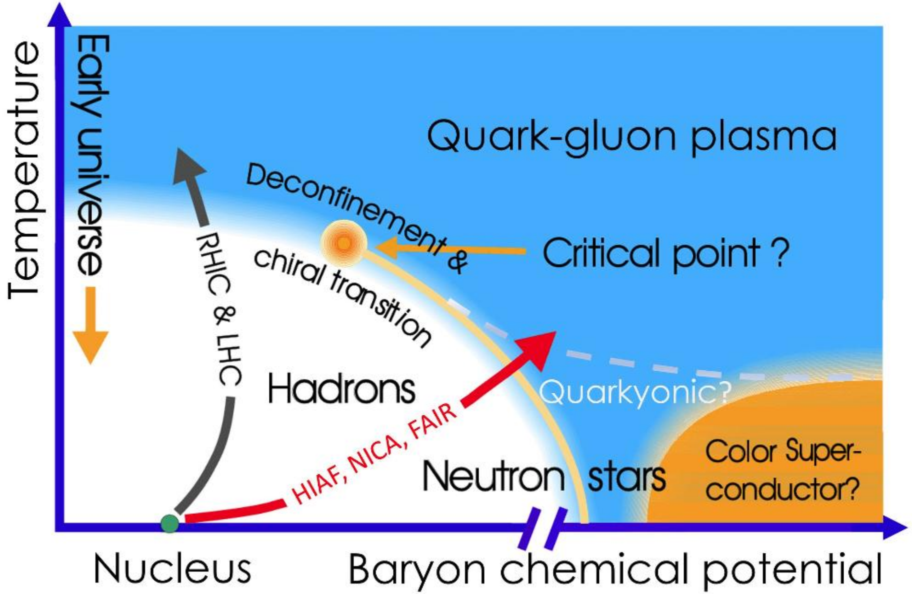


Deconfined

- ❑ **Quark confinement vs asymptotic freedom**
- ❑ **Quark-Gluon Plasma:**
  - ✓ phase diagram
  - ✓ chiral sysmmetry restoration, quark confinement
  - ✓ Topological phase transition

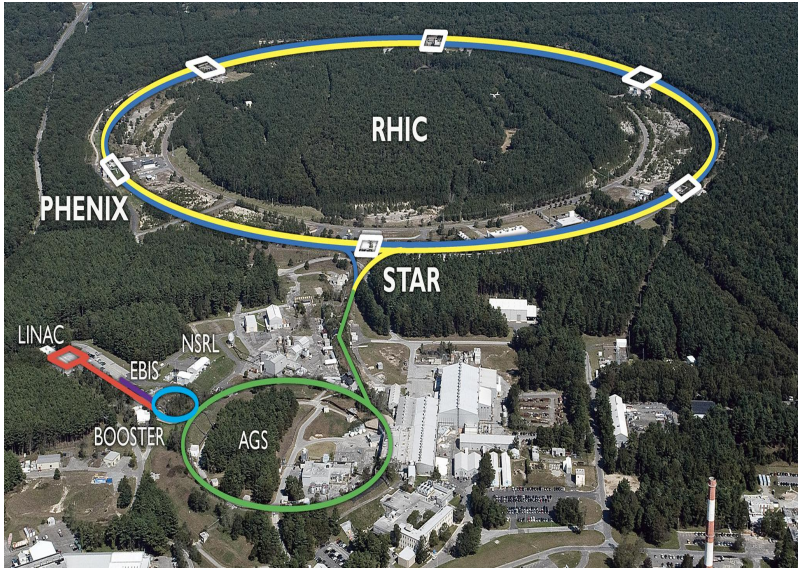


# Why relativistic heavy ion collisions




- ❑ Smooth Crossover at high T and low $\mu_B$
- ❑ Is there a first order phase transition at low T and high $\mu_B$?
- ❑ Is there a critical point?
- ❑ Neutron star can also probe it

# Currently Operating facilities

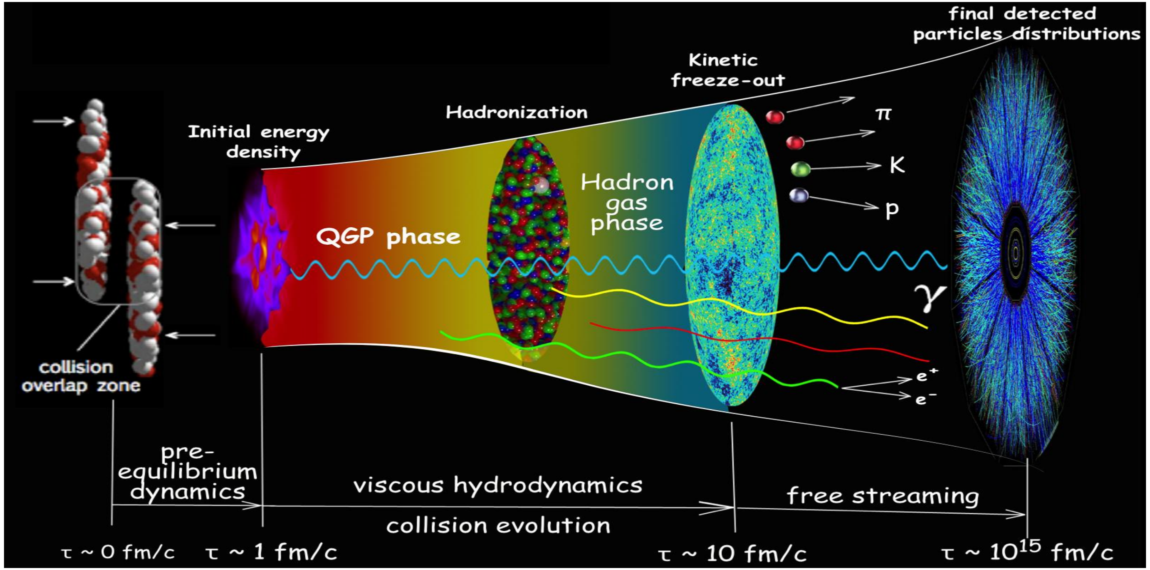




**RHIC@BNL, 2000-** **LHC@CERN, 2010-**

**3-200GeV@RHIC, 2.76-5.02TeV@LHC**

# Little Bangs




- ❑ **Initial non-equilibrium+Hydrodynamics+hadronization+hadron gas**
- ❑ **Design probes and observables to probe these stages**

# Outline

- QGP evolution
- QGP transport coefficient
- Hadronization
- QCD phase diagram
- Spin phenomena

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- ❑ QGP evolution
- ❑ QGP transport coefficient
- ❑ Hadronization
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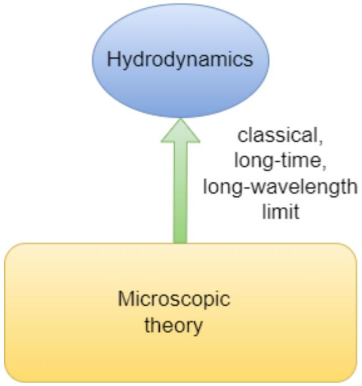
# 1. Success of visco-hydrodynamics in HICs




- ❑ Low $p_T$ dynamics
- ❑ Long wavelenght limit

$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$

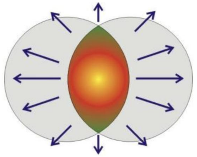
$$\partial_\mu T^{\mu\nu} = 0$$

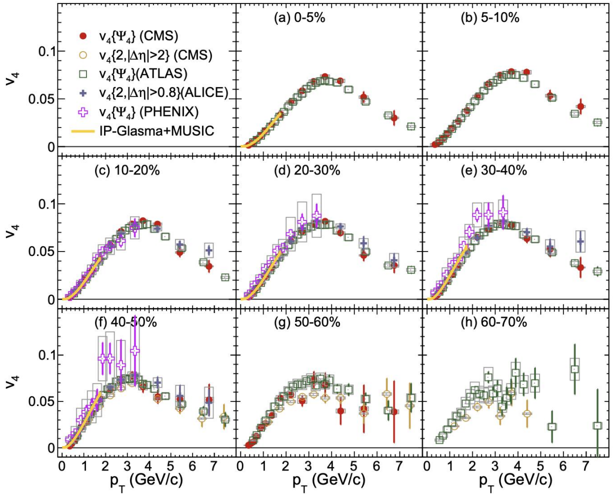
4 equations
10 unkowns

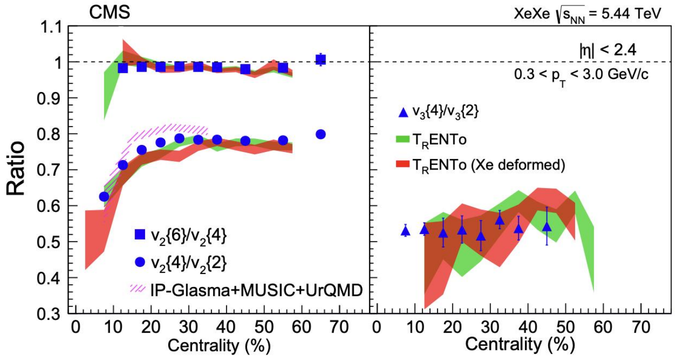
- Symmetric energy-momentum tensor

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + \Delta^{\mu\nu}(p(\epsilon) + \Pi) + \pi^{\mu\nu}$$

- Local energy density: $\epsilon$
- Flow vector: $T^{\mu\nu} u_\nu = -\epsilon u^\mu$
- Local 3-metric: $\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$ with $g^{\mu\nu} = \mathrm{diag}(-1, 1, 1, 1)$
- Equation of state: $p = p(\epsilon)$
- Bulk pressure: $\Pi$
- Shear tensor: $\pi^{\mu\nu} = \pi^{\nu\mu}, u_\mu \pi^{\mu\nu} = 0 = \pi^\mu_\mu$
- A symmetric rank-2 tensor has 10 d.o.f. $\Longrightarrow \epsilon, \Pi, u^i, \pi^{ij}$





# 1. Bayesian analysis

- Energy-momentum conservation laws

$$
\begin{aligned}
0 &= D\epsilon + (\epsilon + p + \Pi)\nabla_\alpha u^\alpha + \pi^\alpha_\mu \sigma^\mu_\alpha \\
0 &= (\epsilon + p + \Pi)Du_\alpha + c_s^2 \nabla_\alpha \epsilon + \nabla_\alpha \Pi + \Delta^\beta_\alpha \nabla_\mu \pi^\mu_\beta + \pi^\mu_\alpha D u_\mu
\end{aligned}
$$

- Relaxation equations

$$
\begin{aligned}
\tau_\Pi D\Pi + \Pi &= -\zeta \nabla_\alpha u^\alpha - \delta_{\Pi\Pi}\Pi\nabla_\alpha u^\alpha - \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} \\
\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} + \pi^{\mu\nu} &= -\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\nabla_\alpha u^\alpha - \tau_{\pi\pi}\pi^{\langle\mu}_\alpha \sigma^{\nu\rangle\alpha} - \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}
\end{aligned}
$$

## Observables

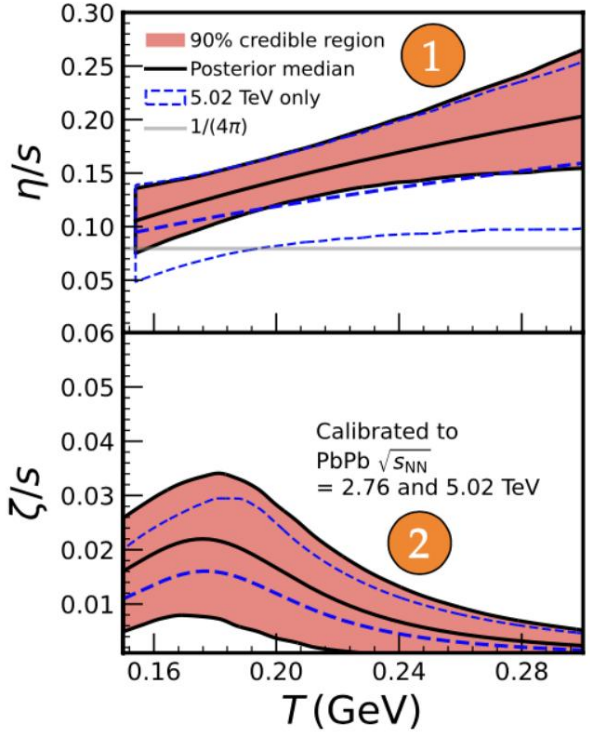
[2] Jyvaskyla (2022)

**2.76 TeV**

- $N_{ch}$
- NSC(3,2), NSC(4,2)
- NSC(2,3,4), NSC(2,3,5)
- PID[1] $\langle p_T \rangle$
- $v_2$ to $v_4$
- $\chi_{4,22}$ to $\chi_{6,mk}$
- $\rho_{4,22}$ to $\rho_{6,mk}$

**5.02 TeV**

- PID[2] mult. and $N_{ch}$
- NSC(3,2) to NSC(4,3)
- PID $\langle p_T \rangle$
- $v_2$ to $v_7$
- $\chi_{4,22}$ to $\chi_{6,mk}$
- $\rho_{4,22}$ to $\rho_{6,mk}$




- 2.7*10³ CPU-years for 8 parameters
- T dependence of QGP transport coefficient

# 1. Causality violations in visco-Hydro

Bemfica et al., PRL 2021

- Energy-momentum conservation laws

$$0 = D\epsilon + (\epsilon + p + \Pi)\nabla_\alpha u^\alpha + \pi_\mu^\alpha \sigma_\alpha^\mu$$
$$0 = (\epsilon + p + \Pi)Du_\alpha + c_s^2 \nabla_\alpha \epsilon + \nabla_\alpha \Pi + \Delta_\alpha^\beta \nabla_\mu \pi_\beta^\mu + \pi_\alpha^\mu Du_\mu$$

- Relaxation equations

$$\tau_\Pi D\Pi + \Pi = -\zeta \nabla_\alpha u^\alpha - \delta_{\Pi\Pi}\Pi\nabla_\alpha u^\alpha - \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$
$$\tau_\pi \Delta_{\alpha\beta}^{\mu\nu} D\pi^{\alpha\beta} + \pi^{\mu\nu} = -\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\nabla_\alpha u^\alpha - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} - \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$

$$(\varepsilon + P + \Pi - |\Lambda_1|) - \frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) - \frac{\tau_{\pi\pi}}{2\tau_\pi}\Lambda_3 \geq 0, \qquad (5a)$$

$$(2\eta + \lambda_{\pi\Pi}\Pi) - \tau_{\pi\pi}|\Lambda_1| > 0, \qquad (5b)$$

$$\tau_{\pi\pi} \leq 6\delta_{\pi\pi}, \qquad (5c)$$

$$\frac{\lambda_{\Pi\pi}}{\tau_\Pi} + c_s^2 - \frac{\tau_{\pi\pi}}{12\tau_\pi} \geq 0, \qquad (5d)$$

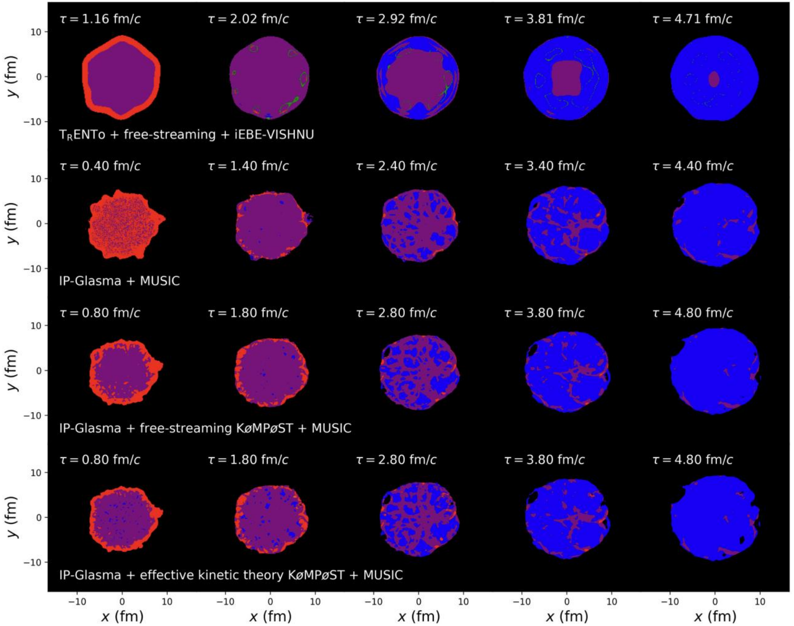
$$\frac{1}{3\tau_\pi}[4\eta + 2\lambda_{\pi\Pi}\Pi + (3\delta_{\pi\pi} + \tau_{\pi\pi})\Lambda_3] + \frac{\zeta + \delta_{\Pi\Pi}\Pi + \lambda_{\Pi\pi}\Lambda_3}{\tau_\Pi} + |\Lambda_1| + \Lambda_3 c_s^2 + \frac{\frac{12\delta_{\pi\pi} - \tau_{\pi\pi}}{12\tau_\pi}\left(\frac{\lambda_{\Pi\pi}}{\tau_\Pi} + c_s^2 - \frac{\tau_{\pi\pi}}{12\tau_\pi}\right)(\Lambda_3 + |\Lambda_1|)^2}{\varepsilon + P + \Pi - |\Lambda_1| - \frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) - \frac{\tau_{\pi\pi}}{2\tau_\pi}\Lambda_3} \leq (\varepsilon + P + \Pi)(1 - c_s^2), \qquad (5e)$$

$$\frac{1}{6\tau_\pi}[2\eta + \lambda_{\pi\Pi}\Pi + (\tau_{\pi\pi} - 6\delta_{\pi\pi})|\Lambda_1|] + \frac{\zeta + \delta_{\Pi\Pi}\Pi - \lambda_{\Pi\pi}|\Lambda_1|}{\tau_\Pi} + (\varepsilon + P + \Pi - |\Lambda_1|)c_s^2 \geq 0, \qquad (5f)$$

$$1 \geq \frac{\frac{12\delta_{\pi\pi} - \tau_{\pi\pi}}{12\tau_\pi}\left(\frac{\lambda_{\Pi\pi}}{\tau_\Pi} + c_s^2 - \frac{\tau_{\pi\pi}}{12\tau_\pi}\right)(\Lambda_3 + |\Lambda_1|)^2}{\left[\frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) - \frac{\tau_{\pi\pi}}{2\tau_\pi}|\Lambda_1|\right]^2}, \qquad (5g)$$

$$\frac{1}{3\tau_\pi}[4\eta + 2\lambda_{\pi\Pi}\Pi - (3\delta_{\pi\pi} + \tau_{\pi\pi})|\Lambda_1|] + \frac{\zeta + \delta_{\Pi\Pi}\Pi - \lambda_{\Pi\pi}|\Lambda_1|}{\tau_\Pi} + (\varepsilon + P + \Pi - |\Lambda_1|)c_s^2 \geq \frac{(\varepsilon + P + \Pi + \Lambda_2)(\varepsilon + P + \Pi + \Lambda_3)}{3(\varepsilon + P + \Pi - |\Lambda_1|)} \times \left\{1 + \frac{2\left[\frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) + \frac{\tau_{\pi\pi}}{2\tau_\pi}\Lambda_3\right]}{\varepsilon + P + \Pi - |\Lambda_1|}\right\}, \qquad (5h)$$

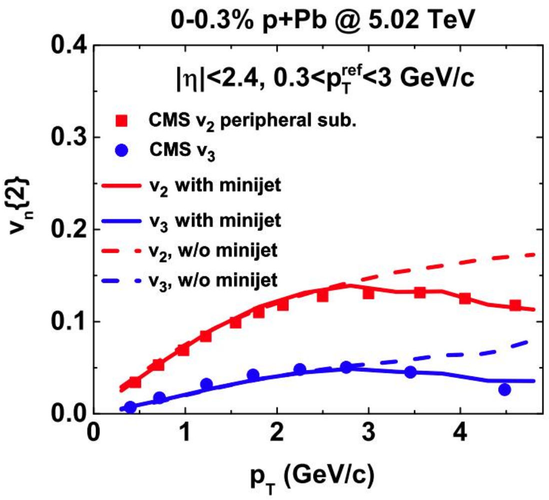
Plumberg et al., PRC 2022




- Causality means $v_s^2 < c^2$ (red point means acausal)
- Large violation of causality even in PbPb central collisions

# 1. Transport theory

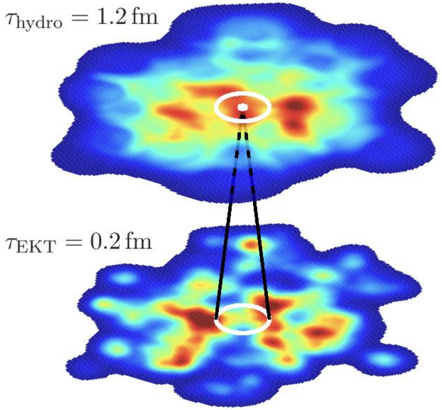
$$p_\mu \partial^\mu f(x,p) + m^* \partial^\mu m^* \partial_{p^\mu} f(x,p) = \mathcal{C}[f]$$




Sun et al., EPJC 2020

Kurkela et al., PRL 2019

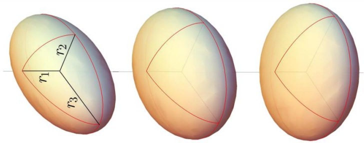
$$\partial_\tau f_{\mathbf{x},\mathbf{p}} + \frac{\mathbf{p}}{|\mathbf{p}|}\cdot \nabla_{\mathbf{x}} f_{\mathbf{x},\mathbf{p}} - \frac{p^z}{\tau}\partial_{p^z} f_{\mathbf{x},\mathbf{p}} = -\mathcal{C}_{2\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}] - \mathcal{C}_{1\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}].$$



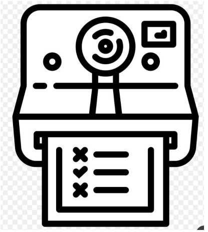

- ❑ Causality **guaranteed**
- ❑ Used also in pre-thermal equilibrium stage
- ❑ No consistent formulation and no precise prediction

# 1. Public available code and applications in nuclear structure

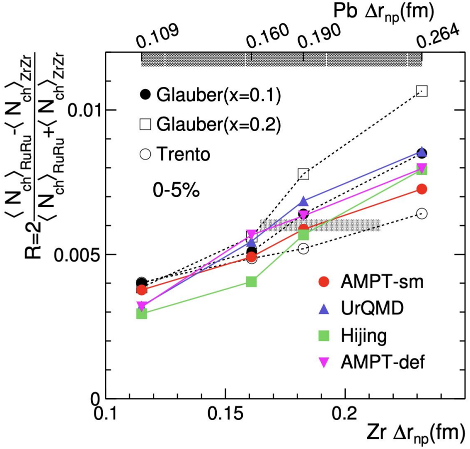
- ❑ **Hydro: MUSIC, SONIC, ECHO-QGP, CLVISC, vHLLE, VISHNU**
- ❑ **Transport: UrQMD, AMPT, SMASH, PHSD, Hijing**



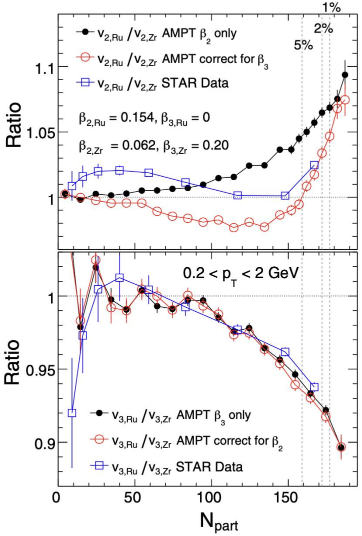

**A snapshot of nucleon distri.**



Li et al., PRL 2020

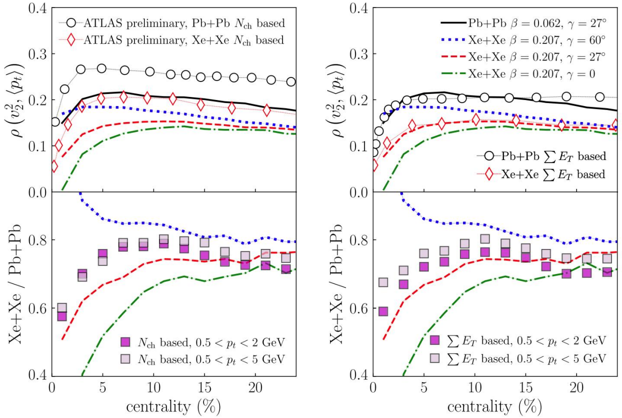



Zhang et al., PRL 2022




$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{[r - R(\theta,\phi)]/a}},$$
$$R(\theta,\phi) = R_0(1 + \beta_2 Y_2^0 + \beta_3 Y_3^0 + \beta_4 Y_4^0),$$

Bally et al., PRL 2022

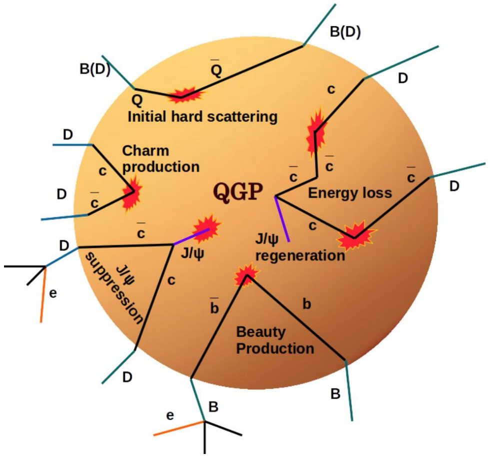


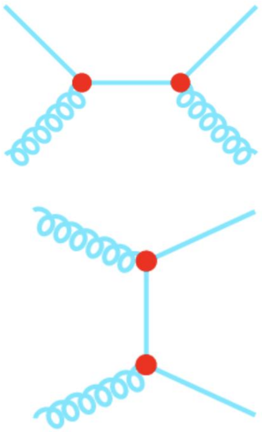

$$R(\theta,\varphi) = R_0\{1 + \beta[\cos\gamma Y_{20}(\theta,\varphi) + \sin\gamma Y_{22}(\theta,\varphi)]\}$$

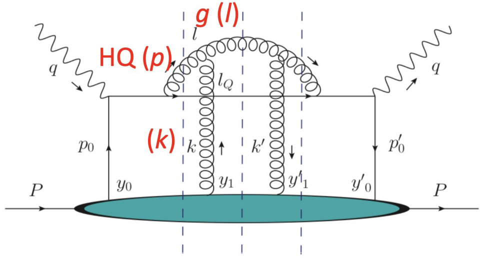
# Outline

- ❑ QGP evolution
- ❑ QGP transport coefficient
- ❑ Hadronization
- ❑ QCD phase diagram
- ❑ Spin phenomena

# 2. Heavy quarks and jets and their diffusions






- ❑ **Heavy quarks and jets as a probe of QGP**
  - ✓ **clear production (hard scattering)**
  - ✓ **long thermalization time (~fm/c)**

- ❑ **Two dominate processes**
  - ✓ **elastic parton scattering**
  - ✓ **inelastic gluon emission**

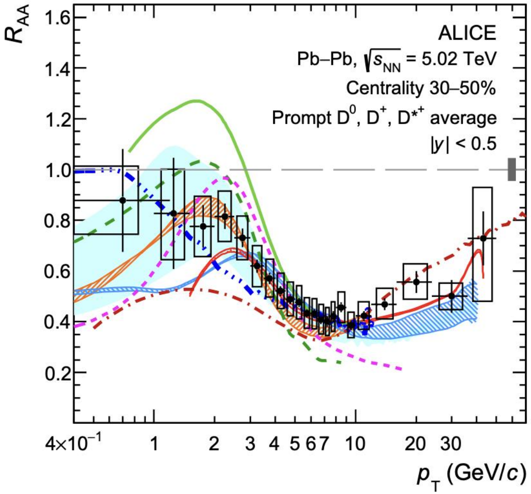
# 2. Transport coefficients

$$p_1 \cdot \partial f_1(x_1, p_1) = E_1(C_{\mathrm{el}} + C_{\mathrm{inel}})$$

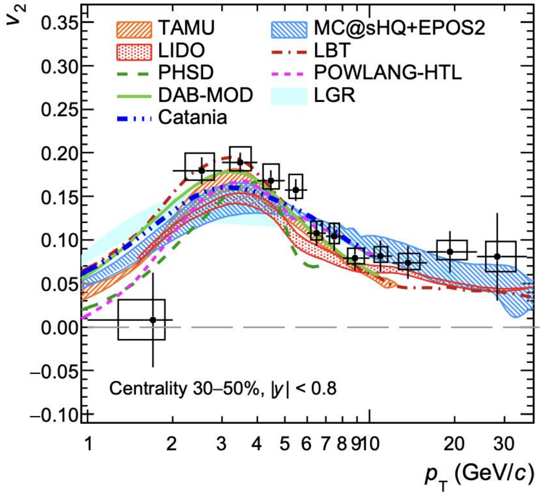
$$D_s = \frac{d(\Delta\vec{x})^2}{dt}$$

$$\hat{q} = \frac{d(\Delta\vec{p}_T)^2}{dt}$$

$$R_{\mathrm{AA}}(p_{\mathrm{T}}, y) = \frac{1}{\mathcal{N}} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y}$$




$$\frac{2\pi}{N} \frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$




ALICE Coll., JHEP 2022

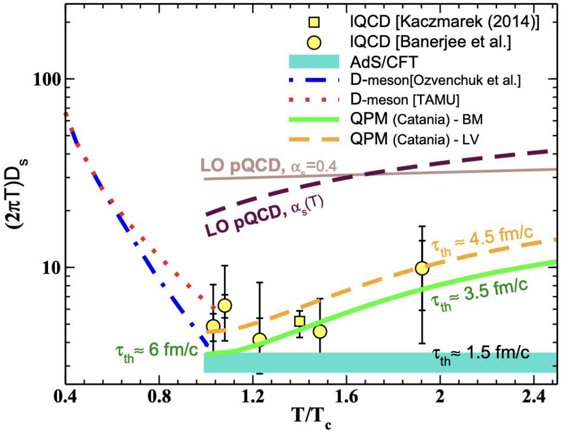
- **Two transport coefficients (coordinate and momentum)**
- **$R_{AA}$ and $V_n$ probe the interaction strength**
  - ✓ **Smaller $R_{AA}$ and larger $V_n$ mean larger interaction strength (larger qhat or smaller $D_s$)**

# 2. Transport coefficients by far

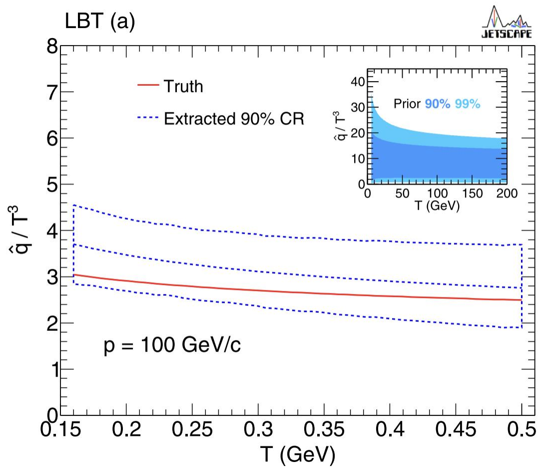
$$D_s = \frac{d(\Delta\vec{x})^2}{dt}$$

$$\hat{q} = \frac{d(\Delta\vec{p}_T)^2}{dt}$$

Scardina et al., PRC 2017




Cao et al., PRC 2021



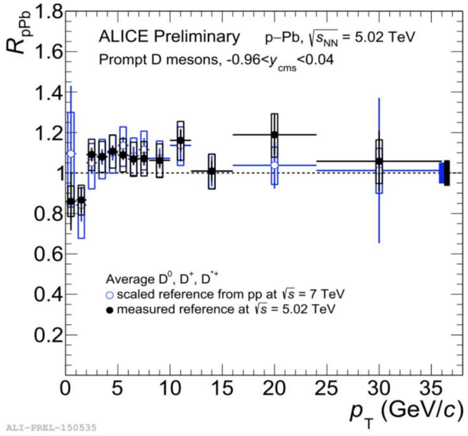

❑ **qualitative determination of $D_s$ and qhat**

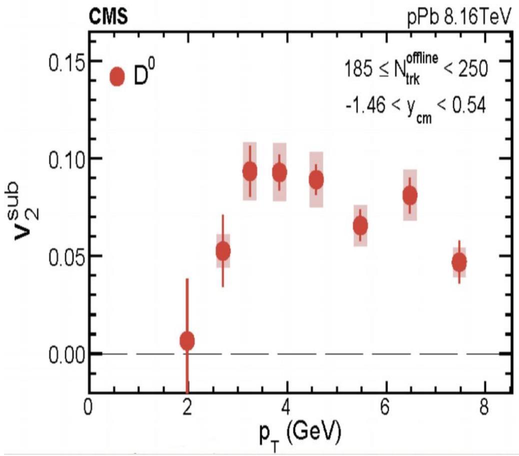
**See talk by Xing Wenjing**
**See talk by Mao Yaxian**

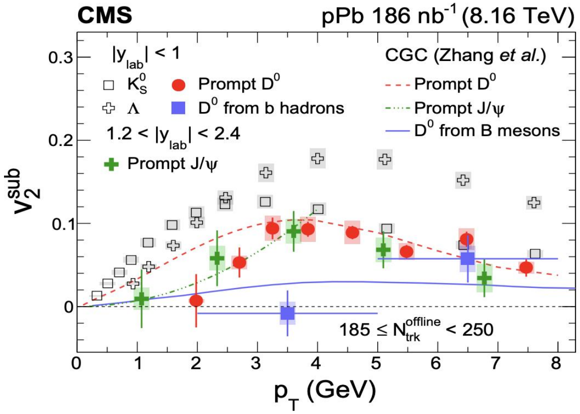
# 2. Challenges by small system collisions



Zhang et al., PRL 2019




- ❑ **Sizeable $v_2$ and small $R_{pA}$ suppression. Not explained by QGP interaction**
- ❑ **The initial states effect by CGC (dense gluon field) can explain $R_{pA}$ and $v_2$**
- ❑ **PHENIX sees the $R_{pA}$ suppression of $\psi$(2S)**
  - ✓ **May be both CGC and QGP? $R_{pA}$ and $v_n$ vs centrality**

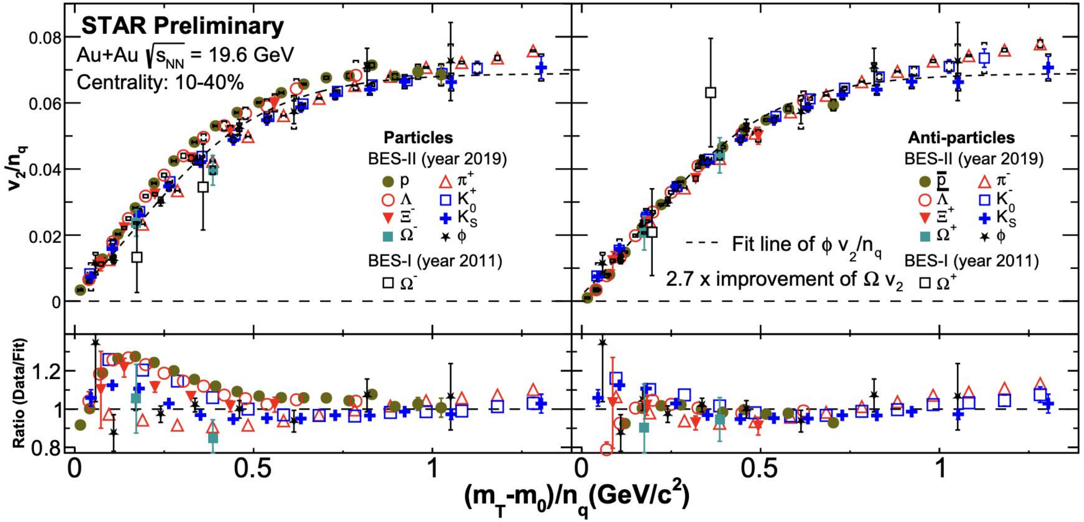
**See talk by Wang Jianqiao**
**See talk by Fu Baochi**
**See talk by Lu Zhiyong**

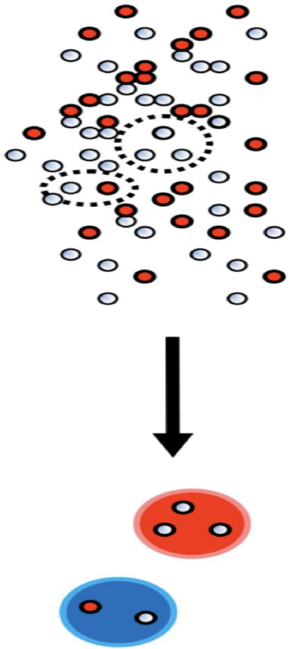
# Outline

- ❑ QGP evolution
- ❑ QGP transport coefficient
- ❑ **Hadronization**
- ❑ QCD phase diagram
- ❑ Spin phenomena

# 3. Hadronization of light quark hadron

- The spectra and $v_2$ can be described well by statistical mechanics in low $p_T$ and Fragmentation in high $p_T$
- NCQ scaling suggests coalescence



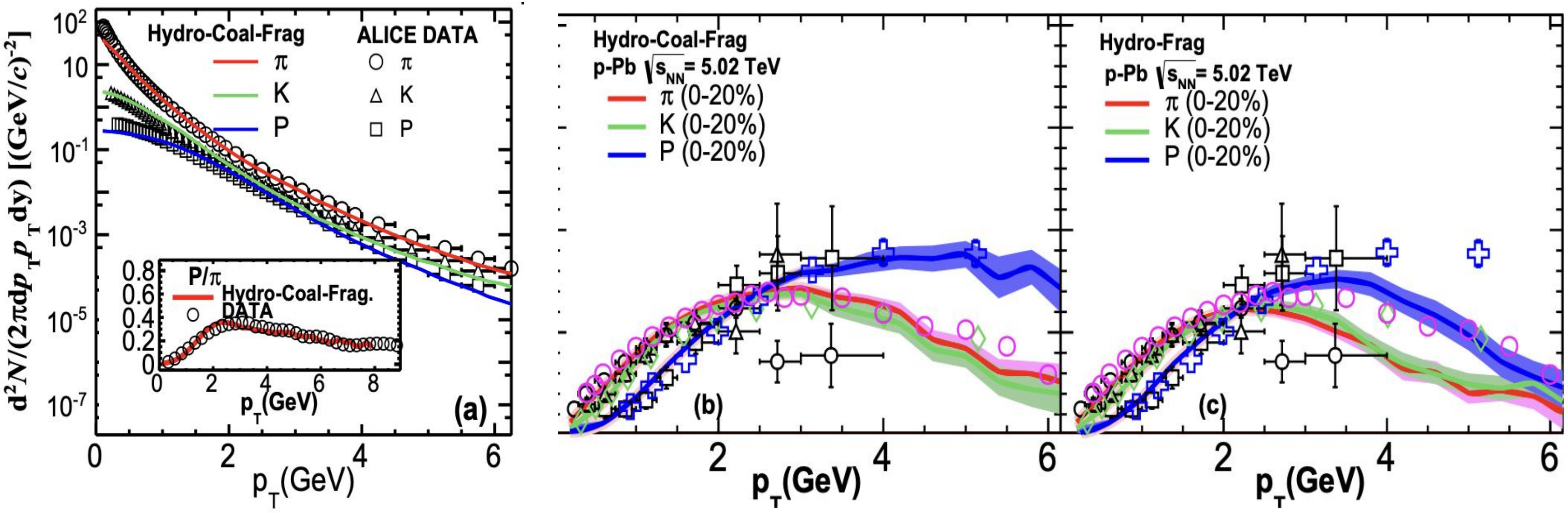
# 3. Hadronization of light quark hadron

- **Intermediate $p_T$ data needs coalescence**

$$\frac{dN_M}{d^3\mathbf{P}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1,\mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2) \times W_M(\mathbf{y},\mathbf{k})\delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2)\,,$$

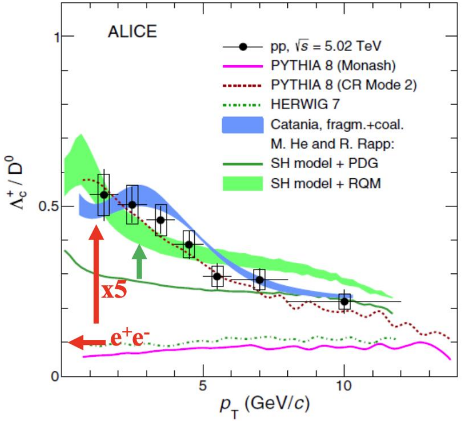
$$\frac{dN_B}{d^3\mathbf{P}_B} = g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1) \times f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3) W_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) \times \delta^{(3)}(\mathbf{P}_B - \mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3). \quad (1)$$

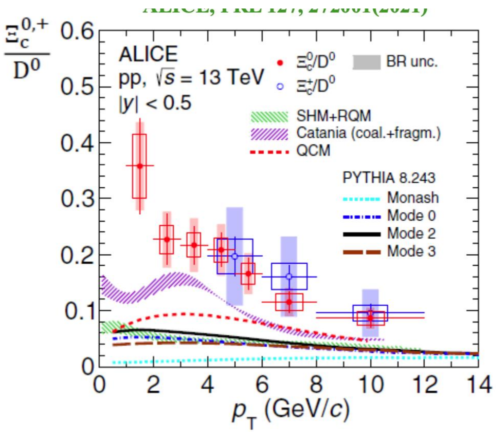
Zhao et al., PRL 2020

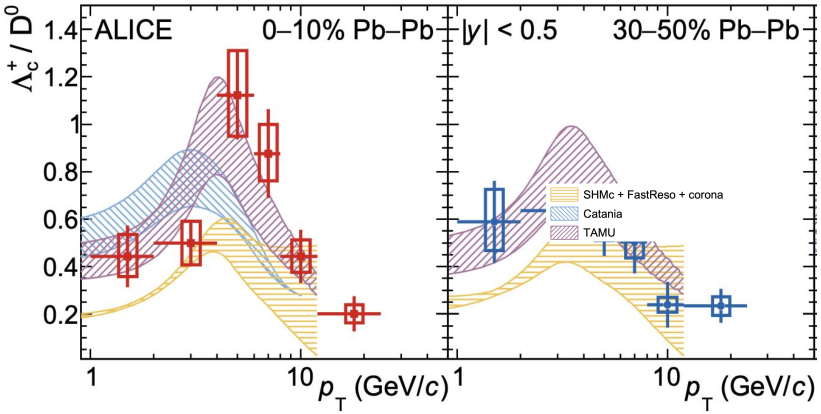


# 3. Hadronization of heavy quark hadron

- **Fragmentation+coalescence in HF hadrons**
  - ✓ **What is the formal and consistent formulation of coalescence**
  - ✓ **Need to understand why coalescence is a sharp process**




ALICE Coll., PRL 2021

ALICE Coll., arxiv 2112.08156

**See talk by Zhu Jianhui**
**See talk by Cheng Tiantian**

# Outline

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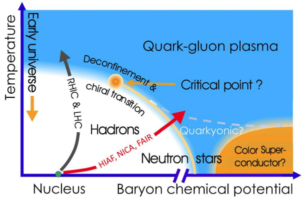
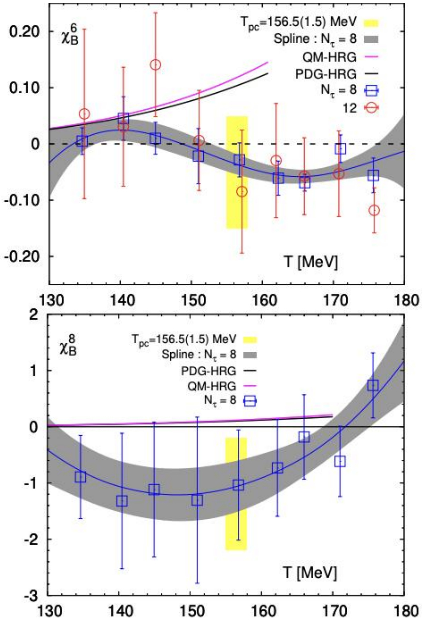
- ❑ Spin phenomena

# 4. Efforts at finite $\mu_B$

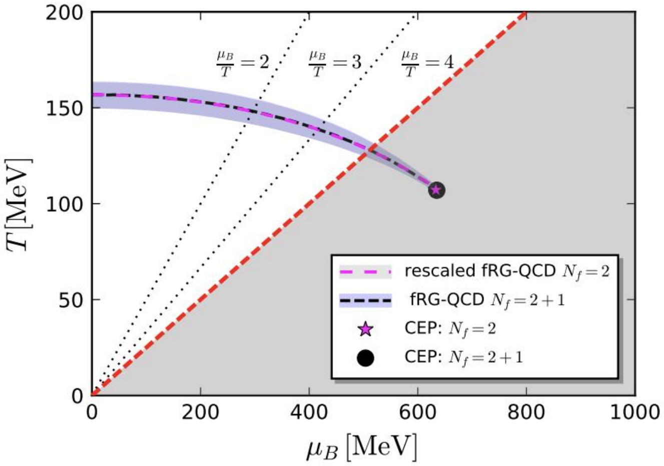



$$\chi_n^X(T,\vec{\mu}) = \frac{1}{VT^3}\frac{\partial^n \ln Z(T,\vec{\mu})}{\partial \hat{\mu}_X^n}$$

HotQCD Coll., PRD 2020




Fu et al., PRD 2021




$$\Gamma_k = \int_x \Big\{ Z_{q,k}\bar{q}\big[\gamma_\mu\partial_\mu - \gamma_0(\mu + igA_0)\big]q + \frac{1}{2}Z_{\phi,k}(\partial_\mu\phi)^2 + h_k\,\bar{q}\,(\tau^0\sigma + \boldsymbol{\tau}\cdot\boldsymbol{\pi})\,q + V_k(\rho, A_0) - c\sigma\Big\}, \quad (1)$$

- ❑ **LQCD calculation of higher moments**
- ❑ **QCD assisted effective theory with fRG can reproduce well LQCD result**
- ❑ **Still problems At $\mu_B$/T>4**

# 4. Dynamical phase transition theory-Hydro

$$D\phi_Q = -\Gamma_Q(\phi_Q - \bar{\phi}_0)$$
$$\partial_\mu T^{\mu\nu} = 0$$

$$\phi_{\boldsymbol{Q}}(x) \sim \int_{\Delta\boldsymbol{x}} \left\langle \delta\frac{s}{n}(t, \boldsymbol{x}+\tfrac{1}{2}\Delta\boldsymbol{x})\,\delta\frac{s}{n}(t, \boldsymbol{x}-\tfrac{1}{2}\Delta\boldsymbol{x}) \right\rangle e^{i\boldsymbol{Q}\cdot\Delta\boldsymbol{x}}$$

$$T^{\mu\nu} = e\,u^\mu u^\nu - p_{(+)}\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$p_{(+)}(e,n) = p(e,n) + \Delta p(e,n,\phi(e,n))$$

$$\Delta p = \left[-(e+p)\Delta\beta + n\Delta\alpha + \Delta s\right]/\beta_{(+)}$$

$$\Delta s(e,n,\phi) \equiv \int dQ\,\Delta s_Q$$

$$= \int dQ \frac{Q^2}{(2\pi)^2}\left[\log\frac{\phi_Q}{\bar{\phi}_Q(e,n)} - \frac{\phi_Q}{\bar{\phi}_Q(e,n)} + 1\right]$$

$$\Delta\beta = \int dQ \frac{Q^2}{(2\pi)^2}\frac{\phi_Q - \bar{\phi}_Q}{(\bar{\phi}_Q)^2}\left(\frac{\partial\bar{\phi}_Q}{\partial e}\right)_n,$$

$$\Delta\alpha = -\int dQ \frac{Q^2}{(2\pi)^2}\frac{\phi_Q - \bar{\phi}_Q}{(\bar{\phi}_Q)^2}\left(\frac{\partial\bar{\phi}_Q}{\partial n}\right)_e$$

Stephanov et al., JHEP 2018

$$\partial_t n_B(\mathbf{x},t) = \Gamma\nabla^2\left(\mathcal{F}'[n_B]\right) + \nabla\cdot\mathbf{J}(\mathbf{x},t)$$

$$\mathbf{J}(\mathbf{x},t) = \sqrt{2T\Gamma}\,\boldsymbol{\zeta}(\mathbf{x},t)$$

$$\langle\zeta_i(\mathbf{x},t)\zeta_j(\mathbf{x}',t')\rangle = \delta(\mathbf{x}-\mathbf{x}')\delta(t-t')\delta_{ij}$$

$$\mathcal{F}[n_B] = T\int d^3x\left(\frac{m^2}{2n_c^2}(\Delta n_B)^2 + \frac{K}{2n_c^2}(\nabla n_B)^2 + \frac{\lambda_3}{3n_c^3}(\Delta n_B)^3 + \frac{\lambda_4}{4n_c^4}(\Delta n_B)^4 + \frac{\lambda_6}{6n_c^6}(\Delta n_B)^6\right)$$

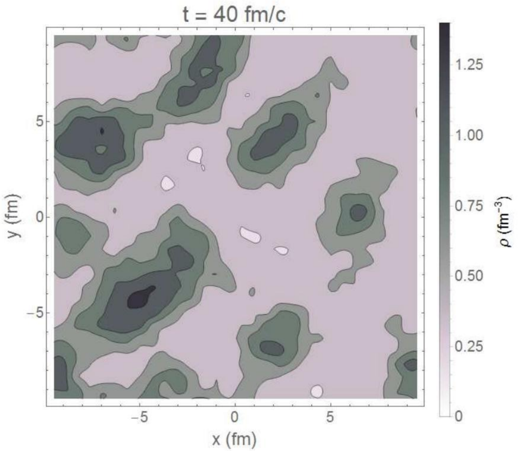
Nahrgang et al., PRD 2019

- ❑ **Deterministic method (Hydro+) vs Stochastic method**
- ❑ **How to apply first order phase transition?**

# 4. Dynamical phase transition theory-Transport

$$\partial_{X^0} f_a(X,\mathbf{p}) + \frac{p^{i\pm}}{E_{\mathbf{p}^\pm}}\partial_{X^i} f_a(X,\mathbf{p})$$
$$-\partial_{X^i} V_a^S(X)\frac{M_a}{E_{\mathbf{p}^\pm}}\partial_{p_i} f_a(X,\mathbf{p}) \mp \partial_{X^i} V_0^V(X)\partial_{p_i} f_a(X,\mathbf{p})$$
$$\mp\partial_{X^i} V_j^V(X)\frac{p^{j\pm}}{E_{\mathbf{p}^\pm}}\partial_{p_i} f_a(X,\mathbf{p}) = \mathcal{C}[f_a], \qquad (4)$$

$$\mathcal{L}_{NJL}^S = \bar{q}(i\not{\partial} - m_0)q + \frac{G_S}{2}\sum_{a=0}^{8}\left[(\bar{q}\lambda^a q)^2 + (\bar{q}i\gamma_5\lambda^a q)^2\right]$$
$$-K\left[\det{}_f\left(\bar{q}(1+\gamma_5)q\right) + \det{}_f\left(\bar{q}(1-\gamma_5)q\right)\right], \qquad (1)$$

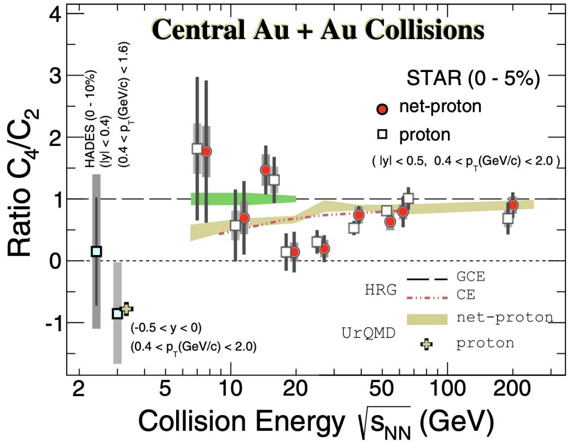



Li et al., PRC 2017

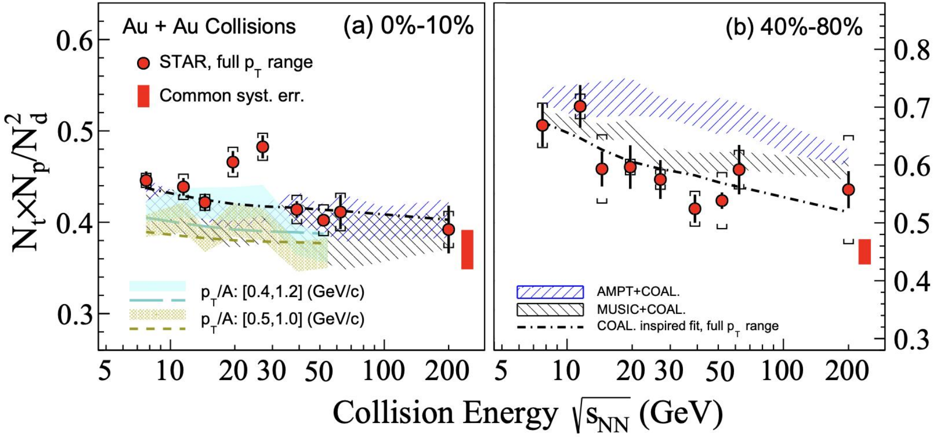
- ❑ **Dynamical generation of first order phase transition**
- ❑ **More reliable effective theory? How to include second order phase transition?**

# 4. Comparison with experiments

STAR Coll, PRL 2022




STAR Coll, arXiv 2209.08058

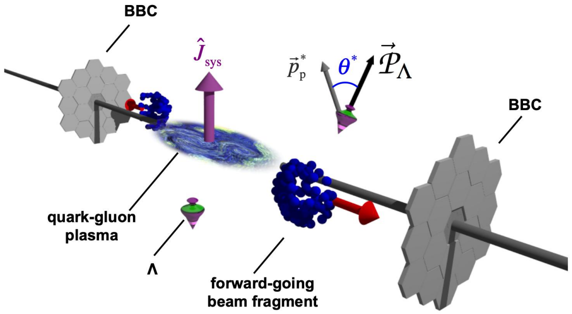


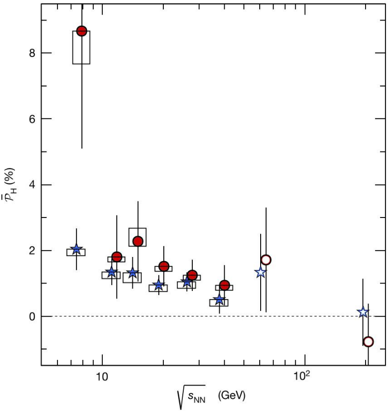

- ❑ **Nonmonotonic varaiation**
  - ✓ **need theoretical input**

# Outline

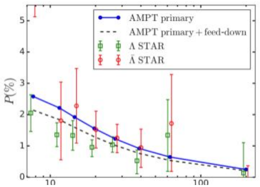
- QGP evolution
- QGP transport coefficient
- Hadronization
- QCD phase diagram
- Spin phenomena

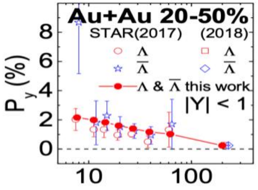
# 5. Spin phenomena in HICs

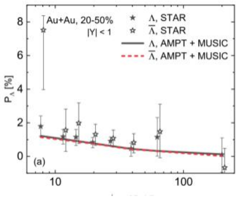


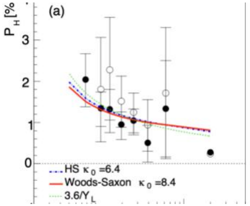




STAR Coll, Nature 2017



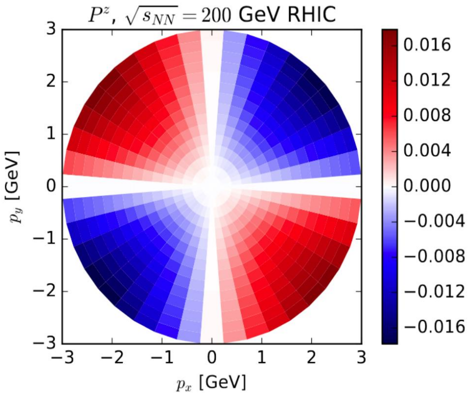



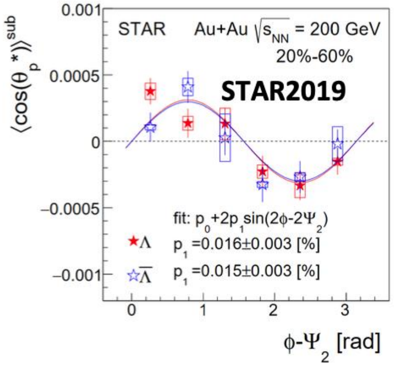




- ❑ **Highly rotating QGP with rotation speed $10^{22}$ $s^{-1}$**
- ❑ **Good agreement between experiments and theories using statistical method on global spin polarization**

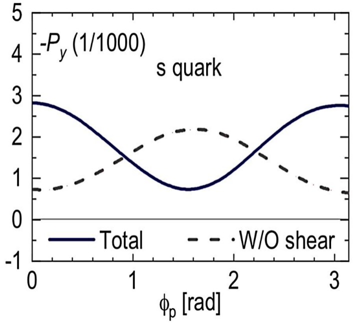
# 5. Angular dependence of longitudinal spin polarization



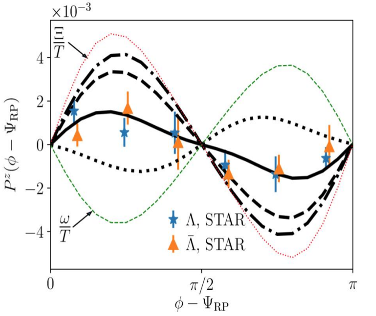

Becattini et al., PRL 2018




STAR Coll., PRL 2019




Fu et al., PRL 2021




Becattini et al., PRL 2021

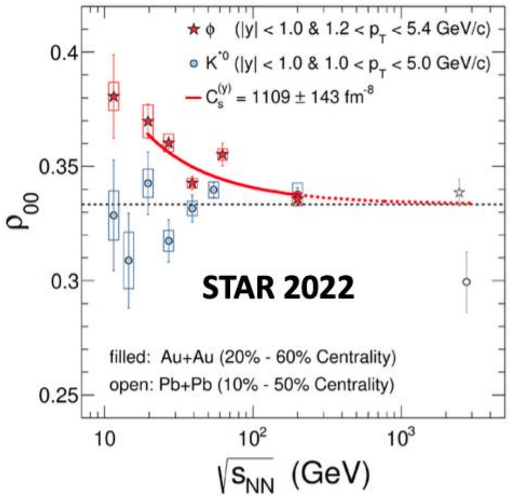
$$\varpi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma \beta_\rho - \partial_\rho \beta_\sigma), \quad \xi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma \beta_\rho + \partial_\rho \beta_\sigma)$$

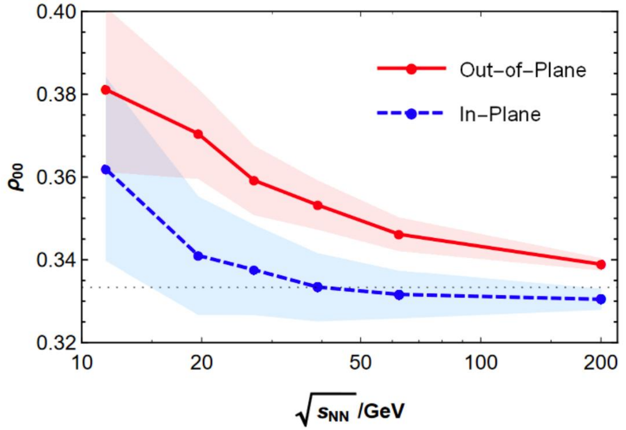
- ❑ **Thermal vorticity can not reproduce experimental data**
- ❑ **Thermal shear can but a non-global thermal equilibrium effect**
  - ✓ **need spin transport theory**

# 5. Vector meson spin alignment

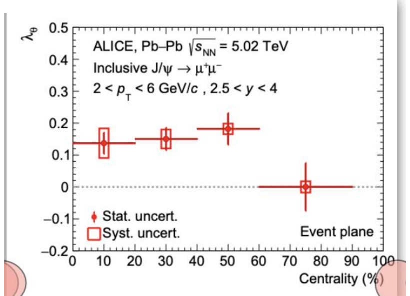
$$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right) \quad \lambda_\theta \propto (3\rho_{00}-1)/(1-\rho_{00})$$

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times [(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$

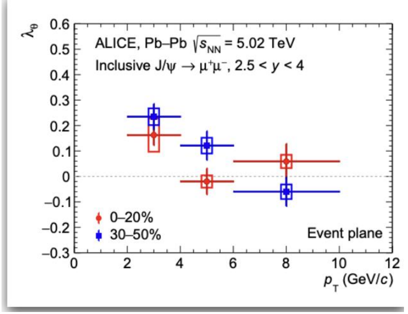



Sheng et al., arXiv 2205.15689




ALICE Coll., arXiv 2204.10171

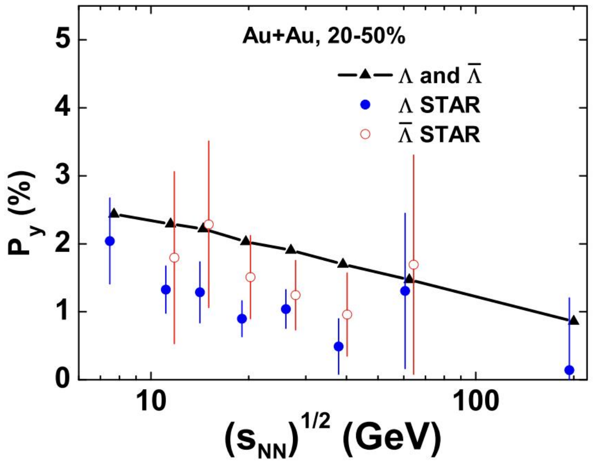



- ❑ **Vector meson spin alignment can not be described by vorticity**

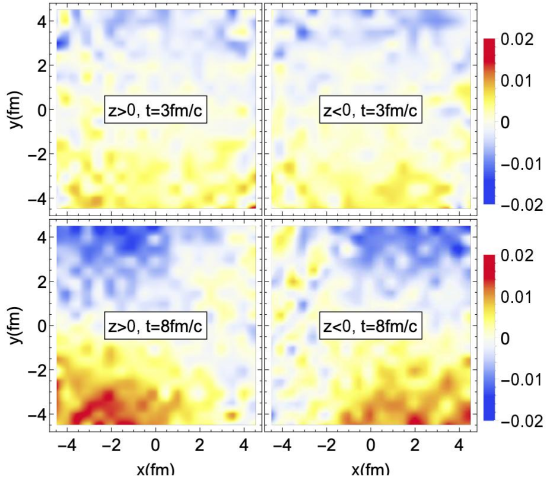
**See talk by Bai Xiaozhi**

- ❑ ***ϕ* field may explain it**
  - ✓ **need to calculate *ϕ* field theoretically**
  - ✓ **need to understand charm meson spin**

# 5. Transport theory




Sun et al., PRC 2017




Liu et al., PRL 2020

- ❑ **Chiral kinetic theory can describe well global and local spin polarization**
  - ✓ **fully dynamic**
  - ✓ **need to develop to include finite mass**

# Summary

- There are many materials that I do not cover
  - ✓ anomalous phenomena, exotic particles in HICs, UPC, HQ diffusion in Glamsa, quarkonia production, neutron star……

See talk by Wu Wenya
See talk by Li Tianqi

- Much achievements and more problems
  - ✓ hydro valid range, small systems, $\mu_B$/T>4, pseudogauge dependence with spin, other spin puzzle

Thank you for your attentions!