Heavy ion physics at the LHC

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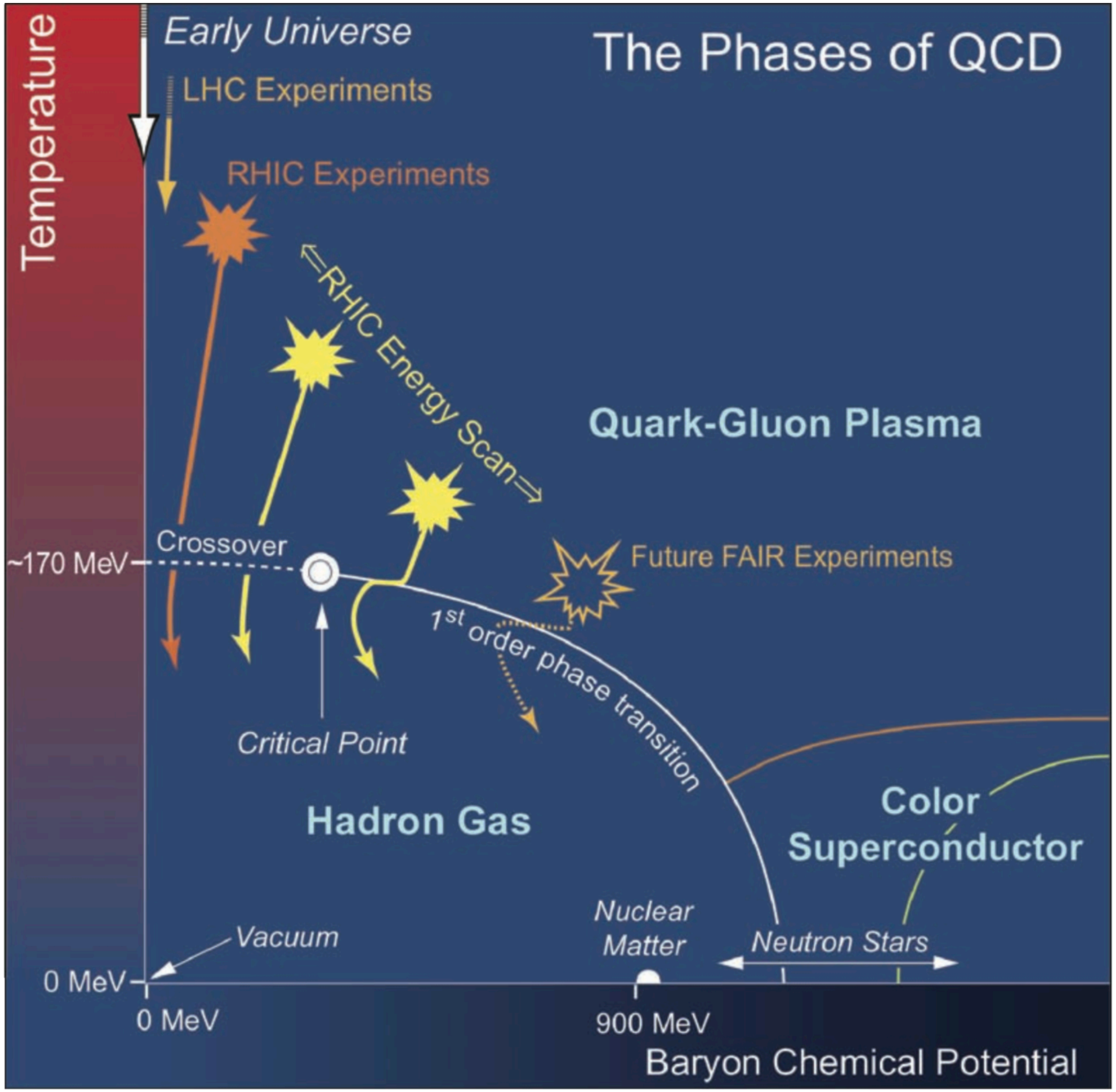
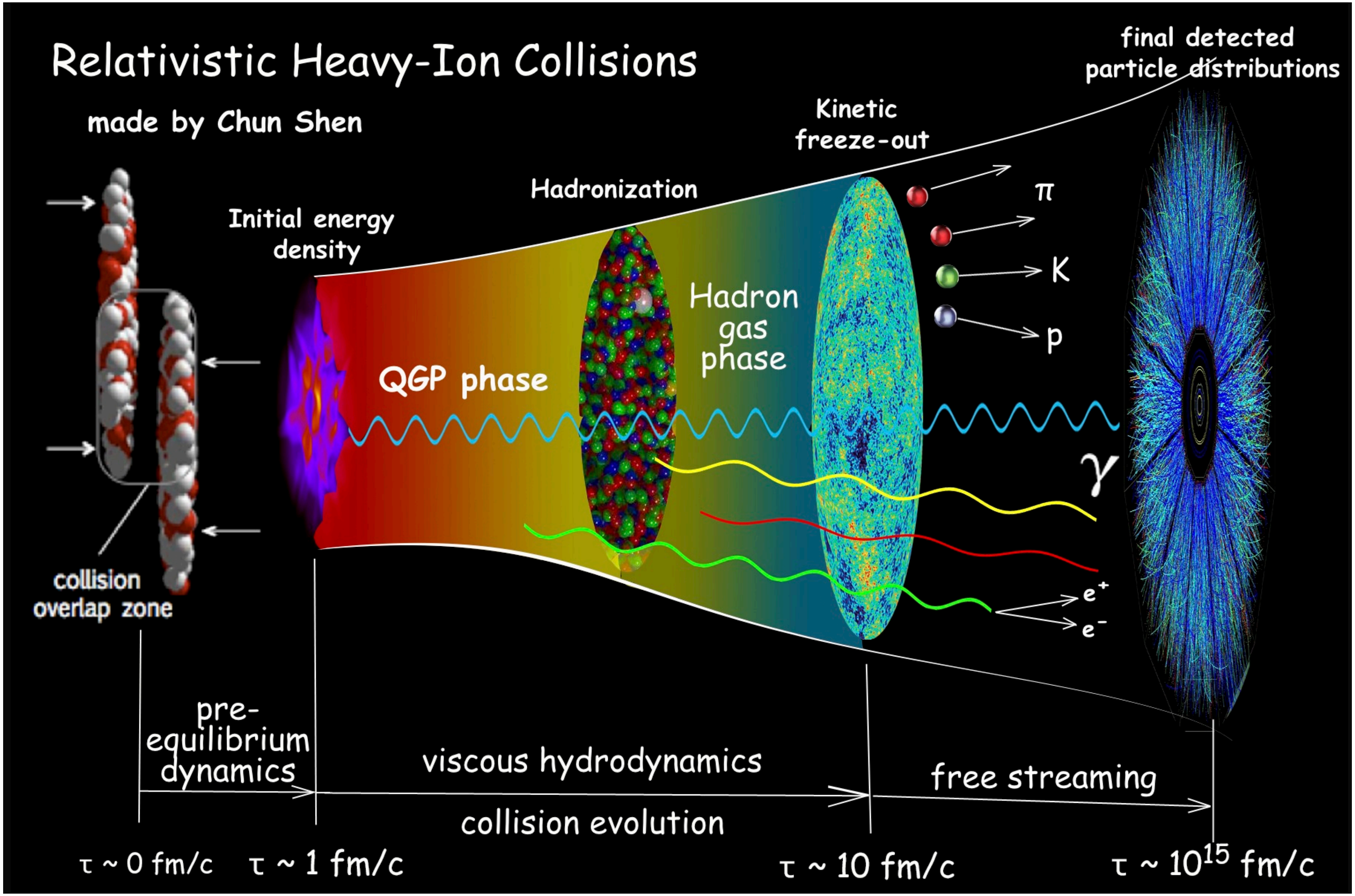
Dalian University of Technology Oct. 23-27, 2019

核子重如牛 对撞生新态

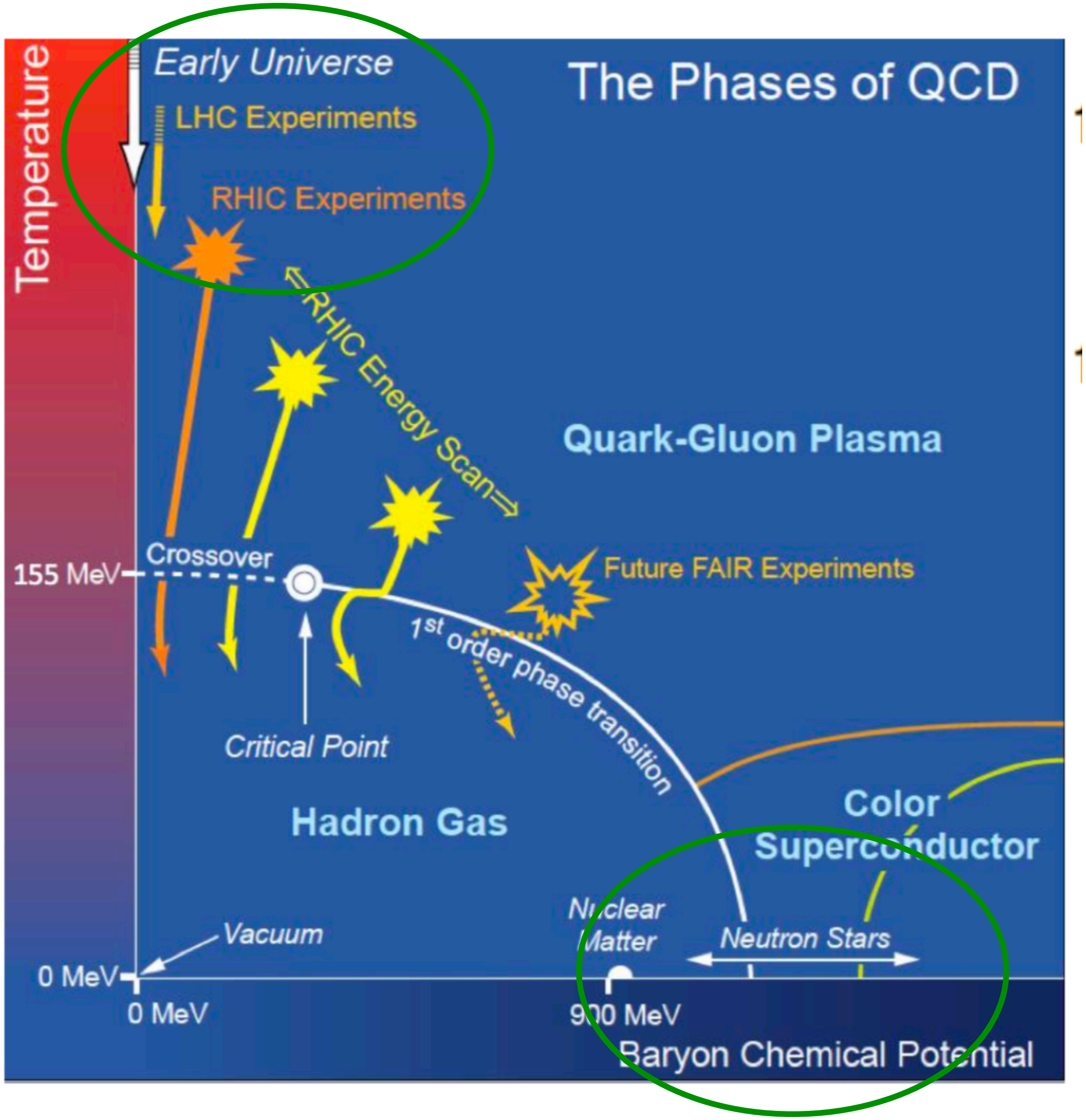


T.D. Lee (1974) and Collins (1975):
Heavy ion collision to create a new form of matter!

Relativistic heavy ion collisions



Connection to other fields

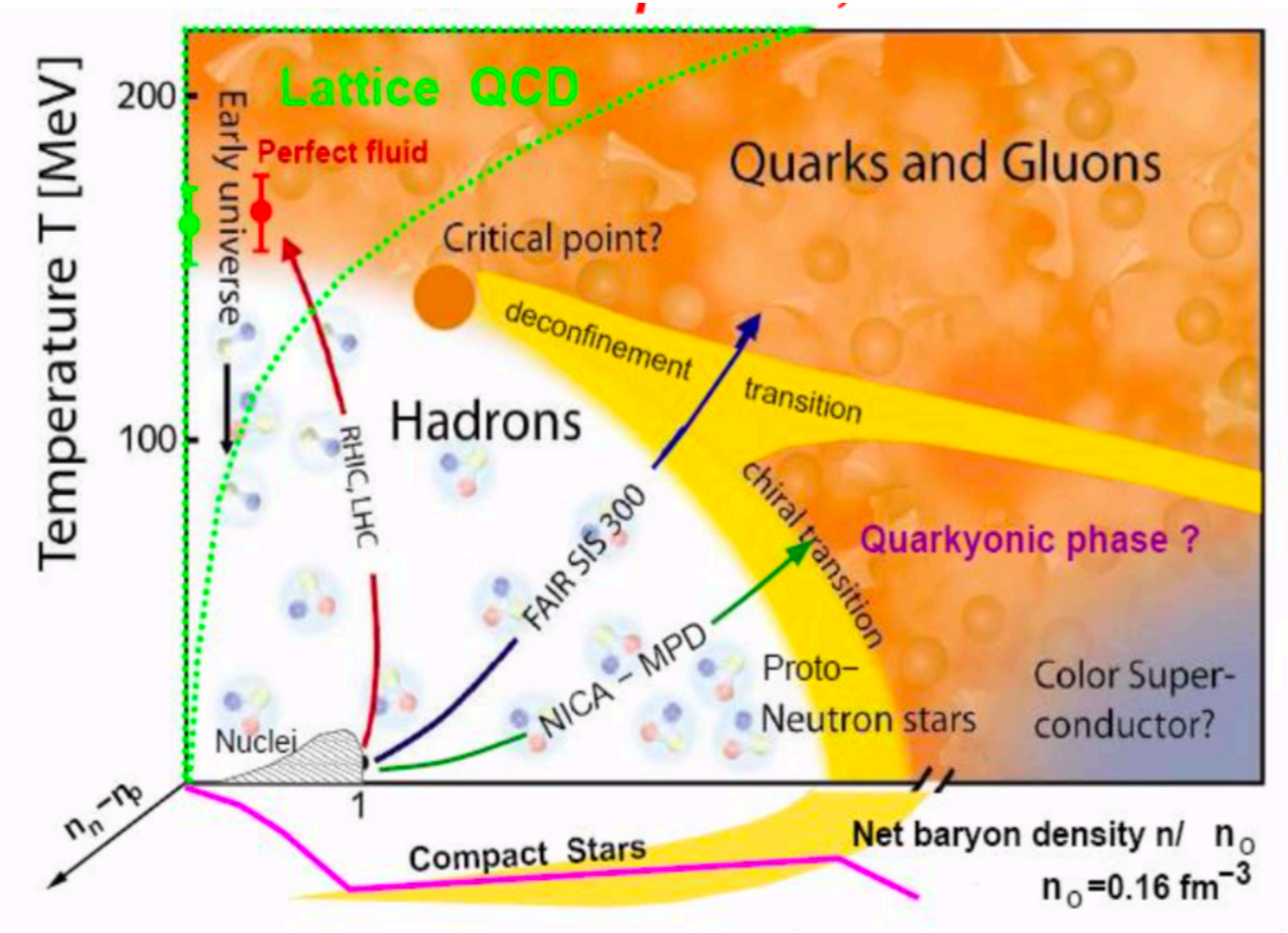


Outline

- Critical point
- Hard Probes
  - ➢ Jets and high pT hadrons
- Small systems
- Soft Probes
  - ➢ Magnetic fields and vorticity
- New development related to GPU
- Summary

Critical point

Phase diagram of QCD



Theoretical Prediction of critical point

- **Lattice QCD**
  - *Fodor, Katz, JHEP (2004)*
  - *Gavai, Gupta, NPA (2013)*
  - *Karsch et al., NPA (2016)*
  - *…*
- **Dyson-Schwinger equation**
  - *Liu, et al., PRD (2014); PRD (2016)*
  - *Zong et al., JHEP (2014)*
  - *Fischer et al., PRD (2014)*
  - *…*
- $\mu_B^E = 262\sim504\ MeV, T^E = 115\sim162MeV,$
- $\mu_B^E/T^E = 1.724\sim4.38$

- Theoretical methods
  - Lattice QCD
  - Dyson-Schwinger equation
  - Functional RG
  - AdS/CFT
  - Effective models
  - …

Fluctuations around critical point

- Near the critical point, correlation length $\xi \to \infty$
- Higher order cumulants/moments of conserved quantities (B, Q, S) are sensitive to ξ

Stephanov, PRL 2009; 2011; Asakawa, Ejiri, Kitazawa, PRL 2009

$$< \delta N >= N - < N >$$

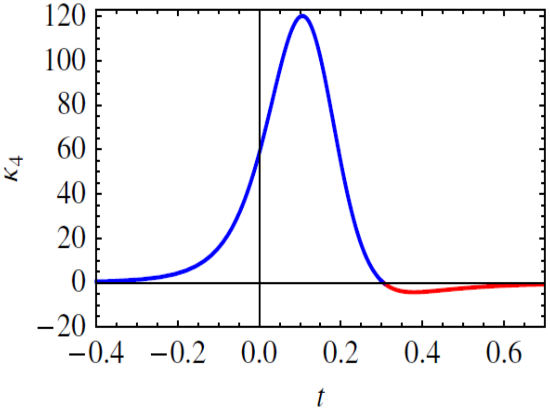
$$C_1 = M =< N >$$

$$C_2 = \sigma^2 =< (\delta N)^2 >$$

$$C_3 = S\sigma^3 =< (\delta N)^3 >$$

$$C_4 = \kappa\sigma^4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

$$\left\langle (\delta N)^3 \right\rangle_c \approx \xi^{4.5}, \qquad \left\langle (\delta N)^4 \right\rangle_c \approx \xi^7$$



- The sign of C_4 will tell us what kind of transition we have:

➢ C_4=0, far away critical point

➢ C_4<0, crossover

➢ C_4>0, first order phase transition

Hard Probes:

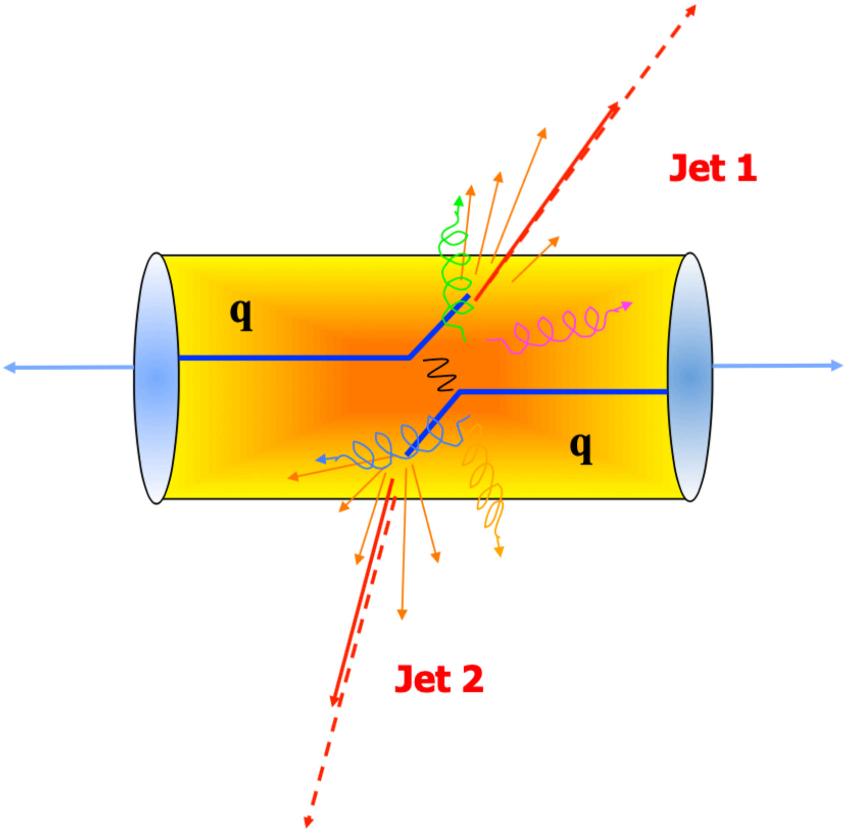
- Jets and high pT hadrons
- Heavy quarks

Also see Plenary Talks on Oct. 25
and Parallel Session on Oct. 24

- Quarkonia and electromagnetic probes

Also see Parallel Session on Oct. 25

Jet quenching



- Different with jets in pp
- Jets interact with medium
- A valuable tool to probe QGP
  - Energy loss
  - Deflection and broadening
  - Modification of jets structure
  - induced medium excitation

Jets interact with medium

- Elastic collisional kernel

Bjorken 1982;

Bratten,Thoma 1991;

Thoma, Gyulassy, 1991;

Mustafa,Thoma, 2005;

Peigne,Peshier, 2006;

Djordjevic, 2006;

Wicks et al (DGLV), 2007;

Qin et al (AMY), 2008;

…

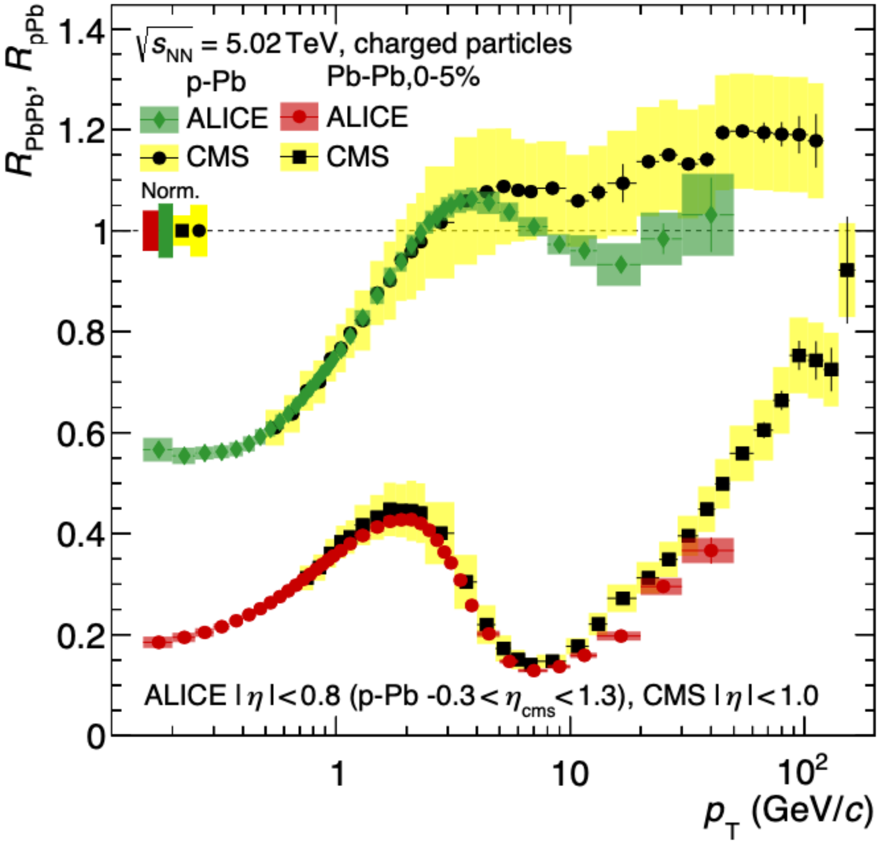
- Inelastic collisional kernel
  - *BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov*
  - *ASW: Amesto-Salgado-Wiedemann*
  - *AMY: Arnold-Moore-Yaffe (& Caron-Huot, Gale)*
  - *GLV: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)*
  - *HT: Wang-Guo (& Zhang, Wang, Majumder)*

\+ their Monte Carlo implementations :

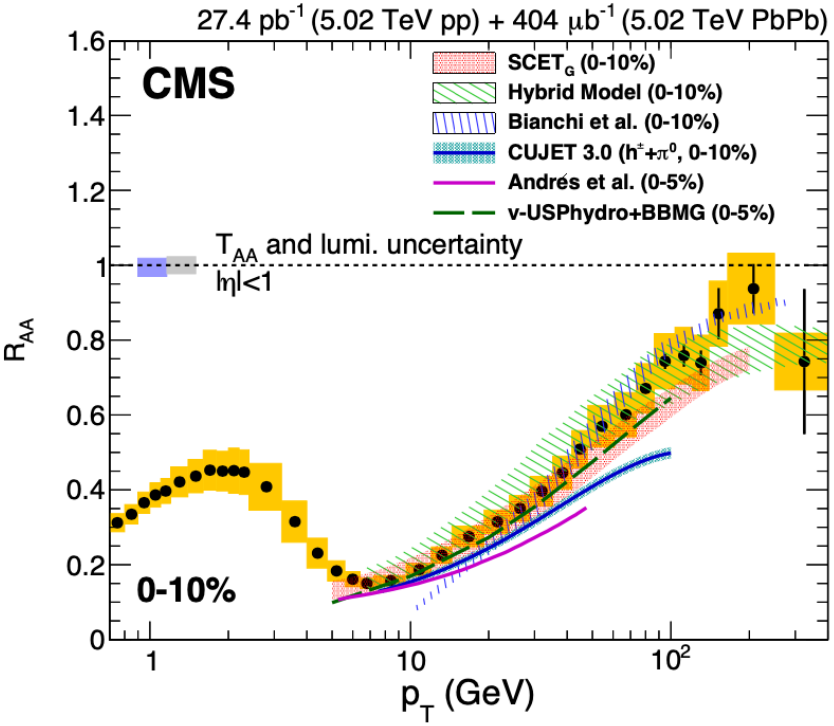
HIJING, Q-PYTHIA, PYQUEN, CUJET, JEWEL, MARTINI, LBT, CoLBT, JETSCAPE

RAA: Nuclear modification factor

ALICE, arXiv:1802.09145



CMS, JHEP (2017)



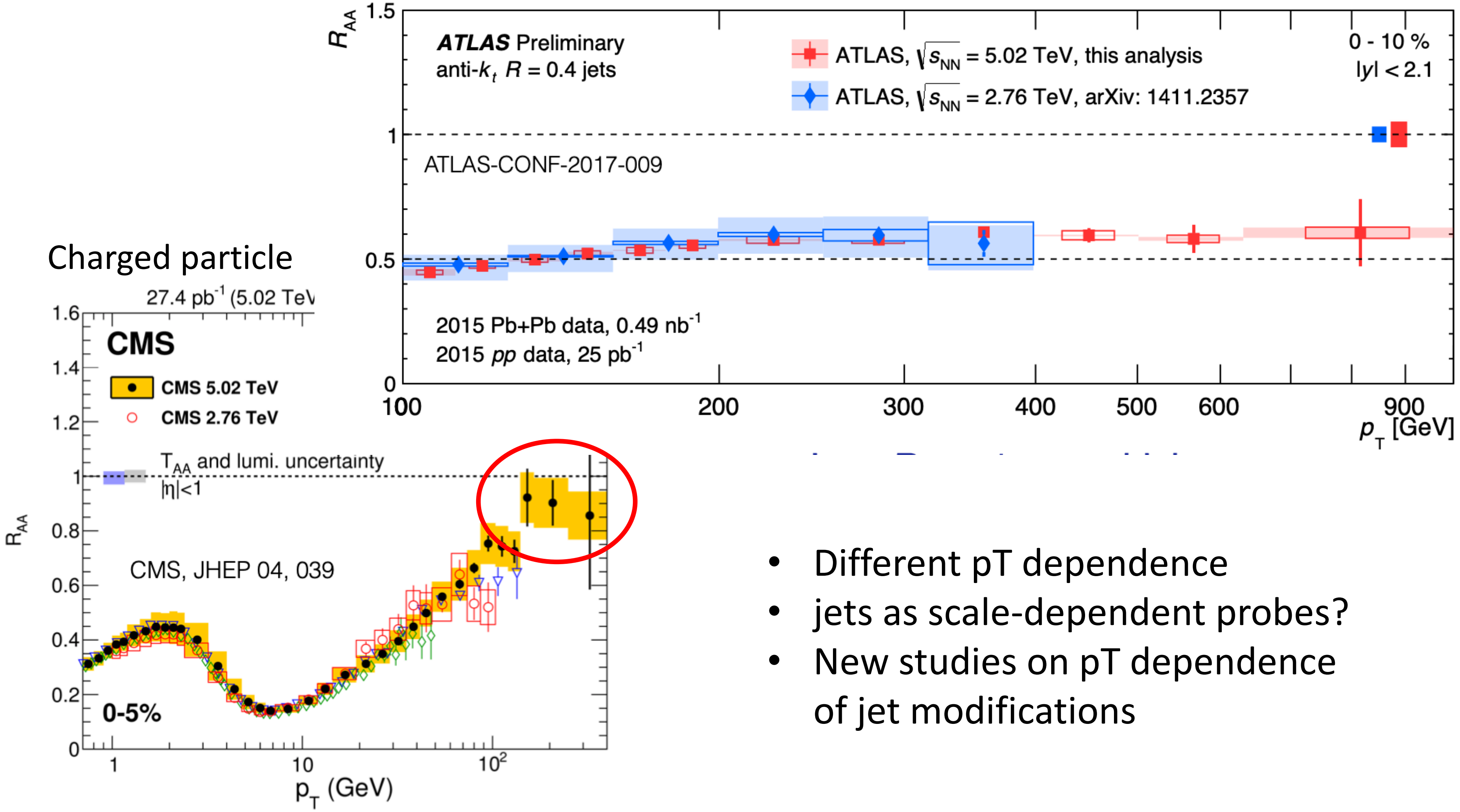
$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{dN^{AA} / d^2 p_T dy}{dN^{pp} / d^2 p_T dy}$$

- For nuclei collisions, RAA<1
  Medium effects

High pT jets and hadrons

High pT jets

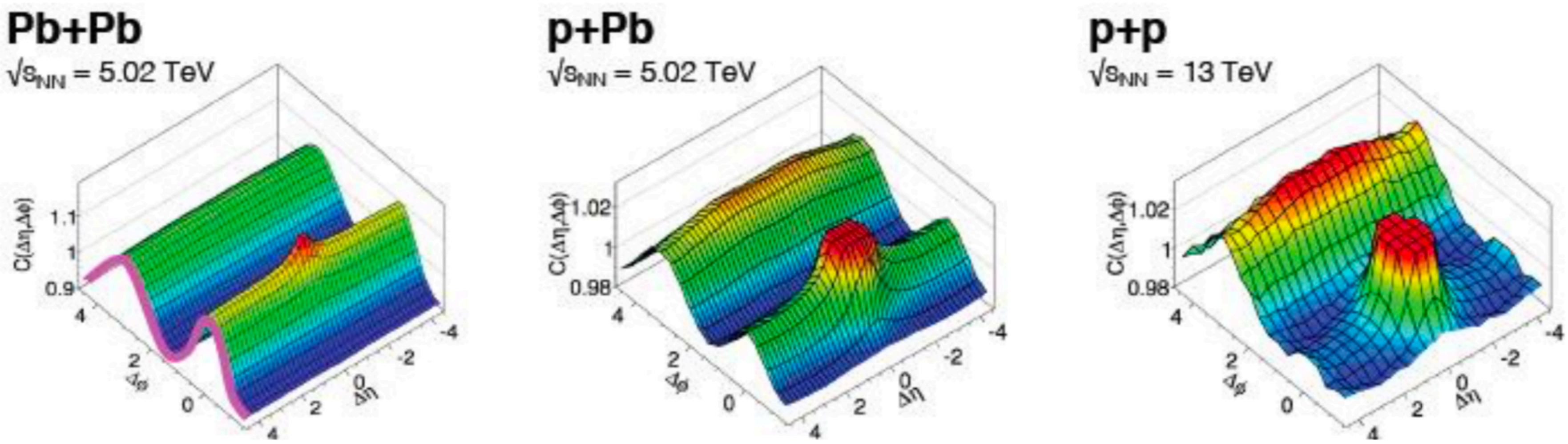
Charged particle

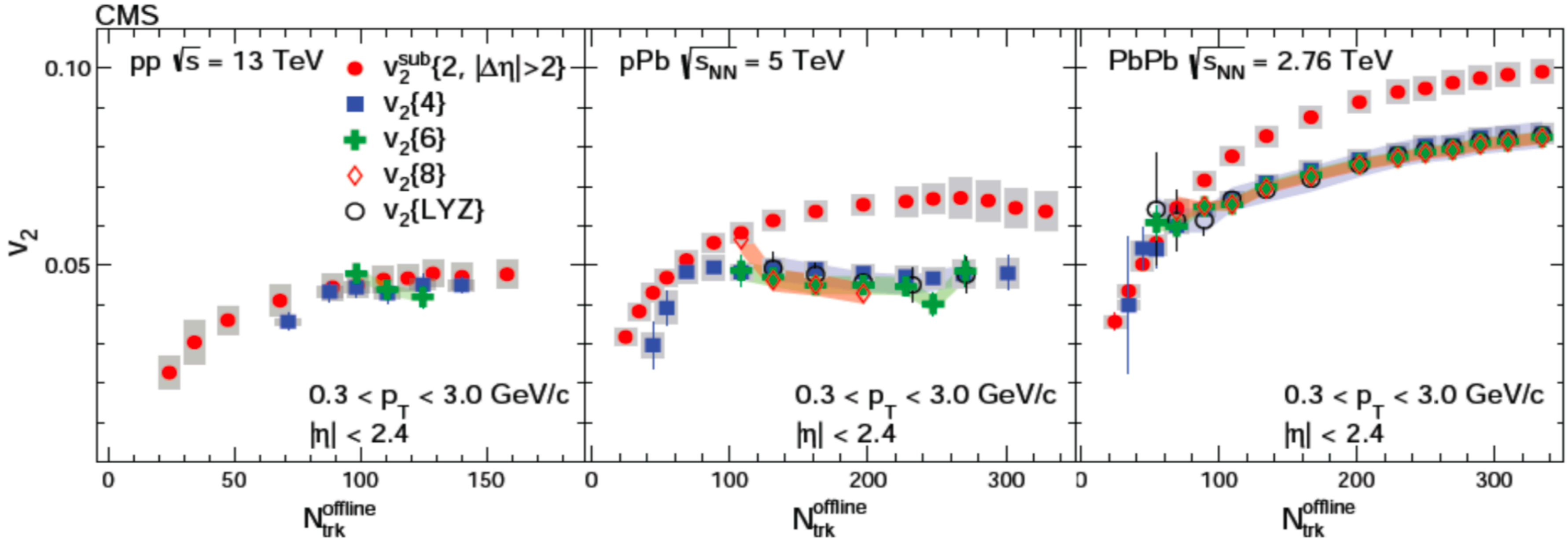


- Different pT dependence
- jets as scale-dependent probes?
- New studies on pT dependence of jet modifications

Small system

Flow in small systems





What is the dynamical origin of collectivity?

- Final state effects

Hydrodynamics

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

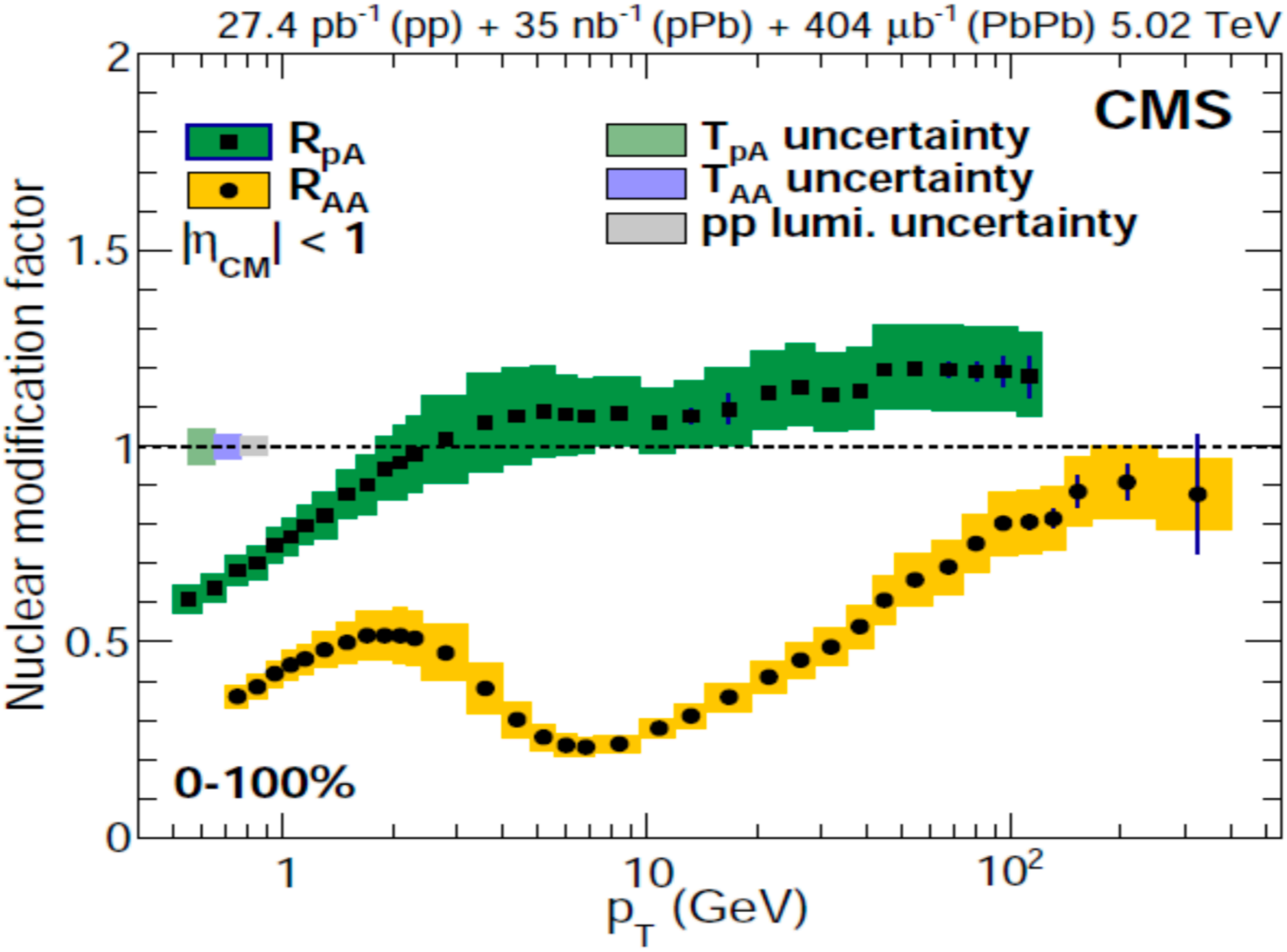
VS

- Initial state effects

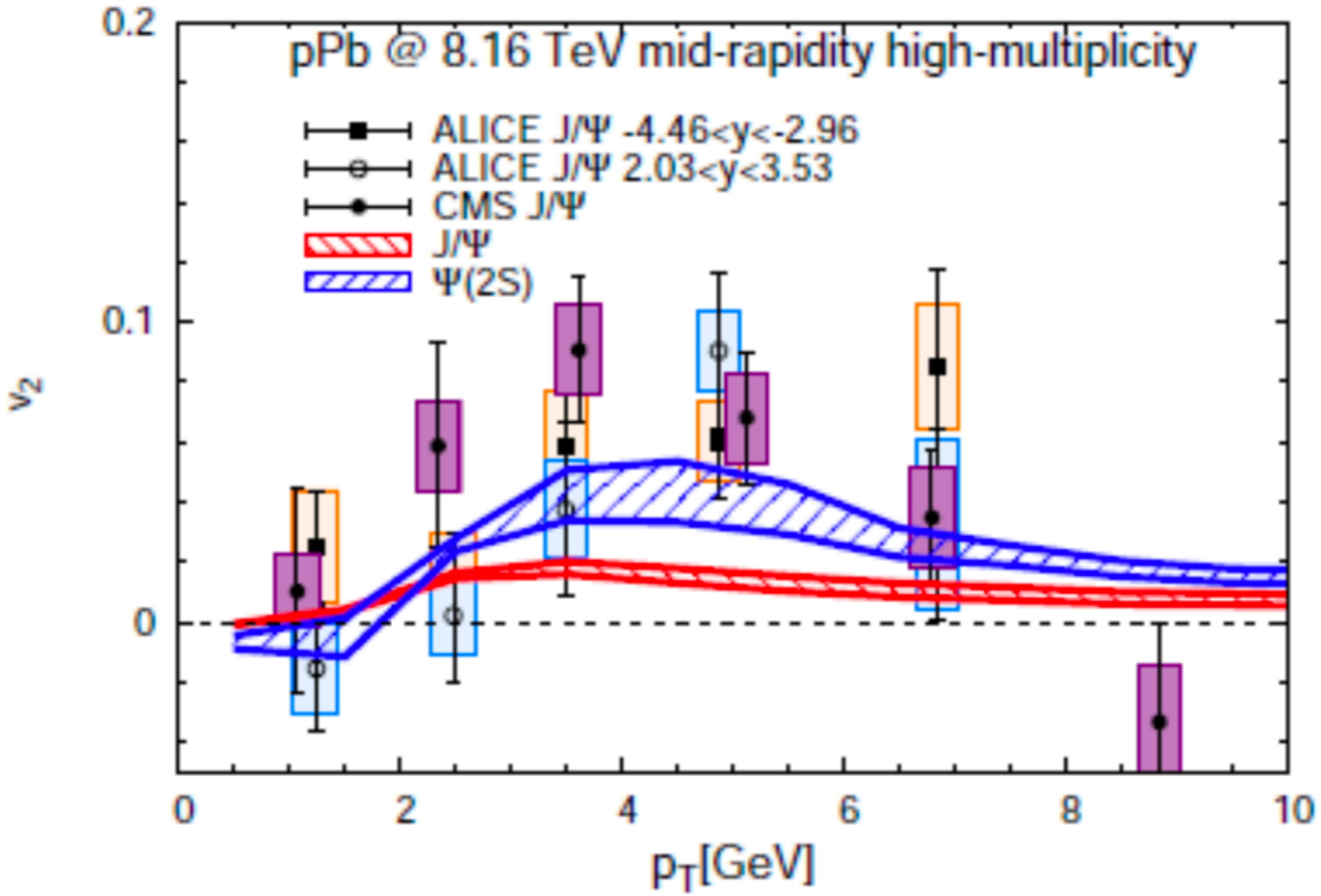
Color Glass Condensate (CGC)

- *Dusling, Mace, Venugopalan, PRL (2018), PRD (2018), 1705.00745; 1706.06260;*
- *Du, Rapp, JHEP (2019)*
- *Zhang, Marquet, Qin, Wei, Xiao, PRL 2019*
- *…*

No jet quenching in small systems



J/Psi v2 in small systems



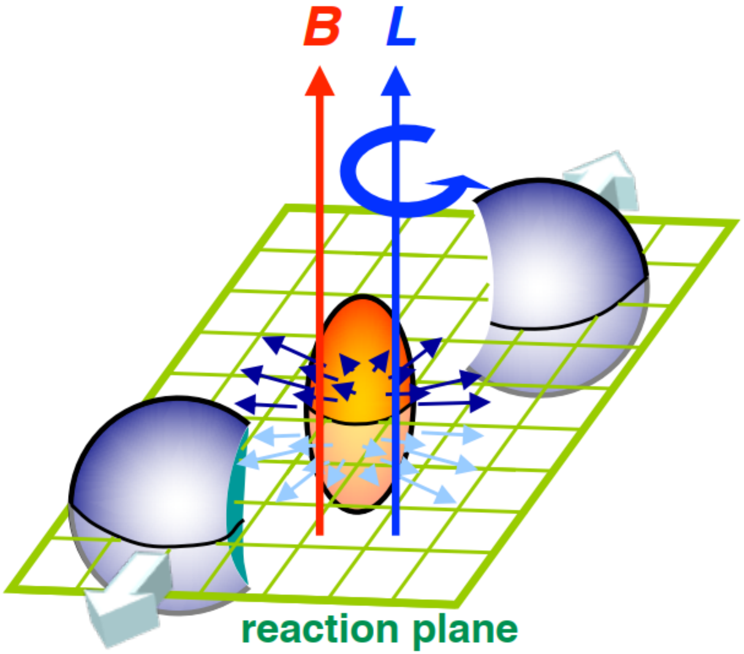
Soft Probes:

- Particle yields and spectra
- Collective flow
- Fluctuations and correlations

- Magnetic fields and voriticty

Magnetic fields and vorticity

Huge angular momentum

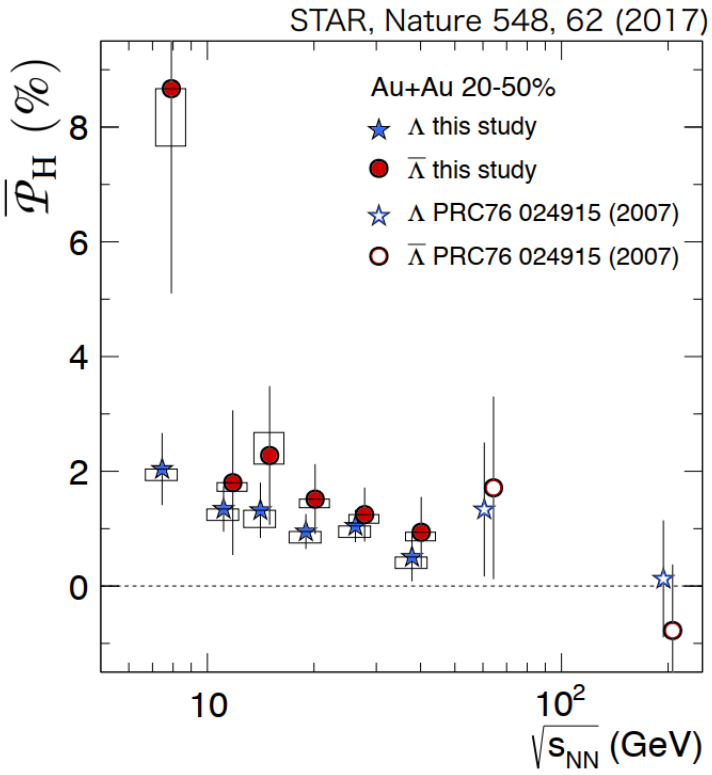


- Huge global orbital angular momenta are produced

$$L \sim 10^5 \hbar$$

- How do orbital angular momenta be transferred to the matter created?

Global Polarization of Λ and $\bar{\Lambda}$



The Fastest Fluid

by Sylvia Morrow

Superhot material spins at an incredible rate.

- $\sqrt{s_{NN}}$<62.4GeV , we observe the signal for polarization of Λ and $\bar{\Lambda}$
- ➢ The lower energy, the stronger polarization effects
- ➢ $P_{\bar{\Lambda}} > P_{\Lambda}$

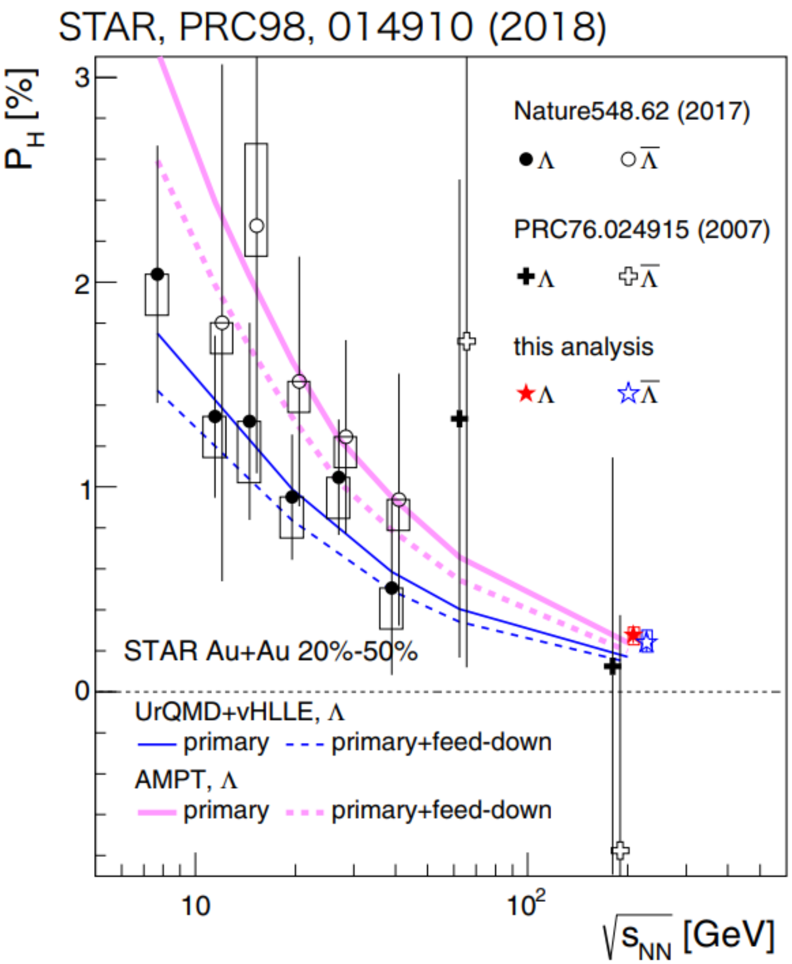
$$P_{\Lambda} \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_{\Lambda}B}{T}$$

$$P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_{\Lambda}B}{T}$$

ω = (9 ± 1)x10^{21}/s, *greater than previously observed in any system.*

Liang, Wang, PRL (2005)
Betz, Gyulassy, Torrieri, PRC (2007)
Becattini, Piccinini, Rizzo, PRC (2008)
Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC (2017)
Fang, Pang, Q. Wang, X. Wang, PRC (2016)

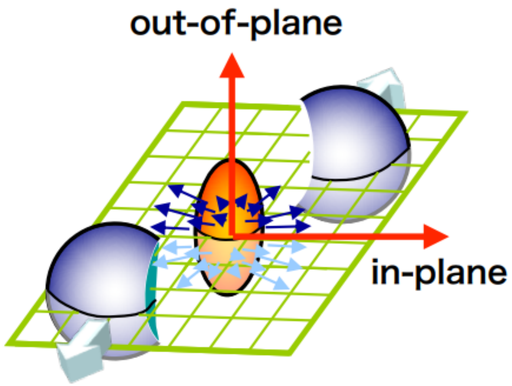
Simulations from hydro and AMPT

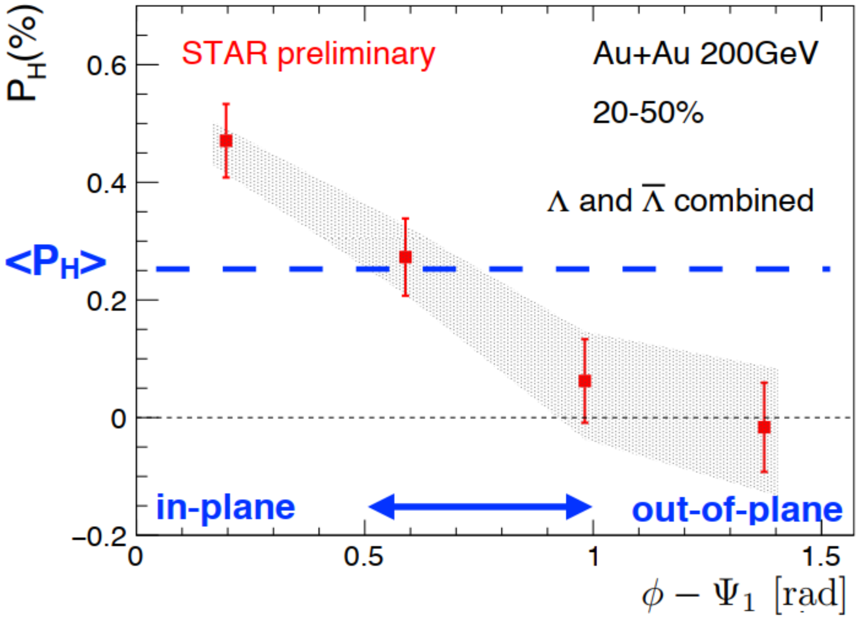


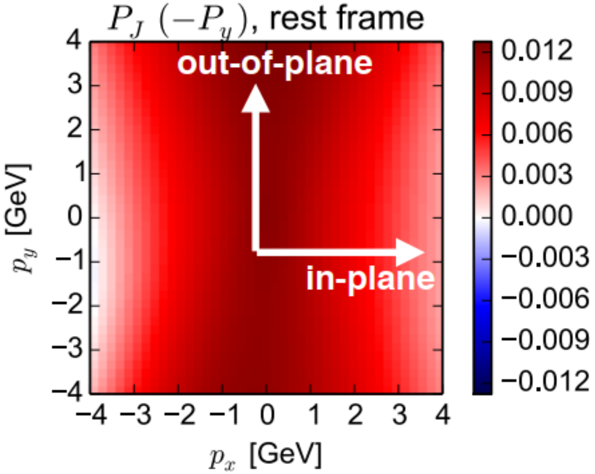
The results from both UrQMD+hydro and AMPT are consistent with the experimental data.

- *UrQMD+vHLLE: Karpenko, Becattini, EPJC(2017)*
- *AMPT: Li, Pang, Wang, Xia, PRC (2017)*

Puzzle: Local Polarization







- Exp data:

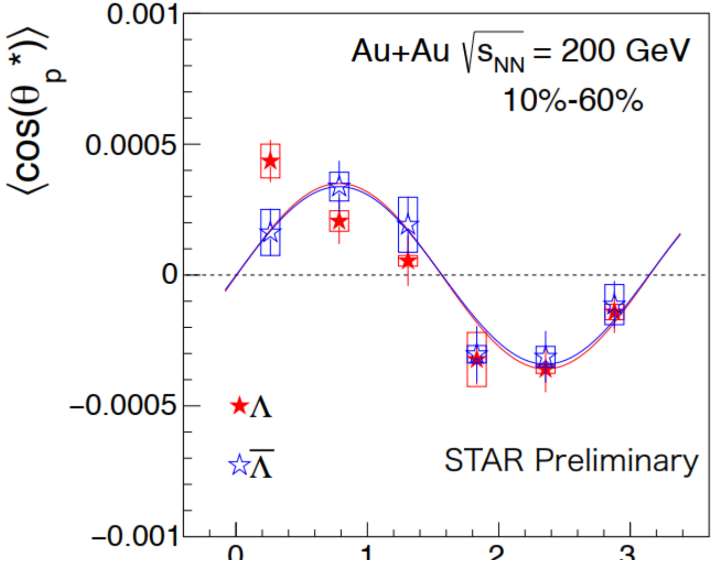
P_H in-plane > P_H out-of-plane

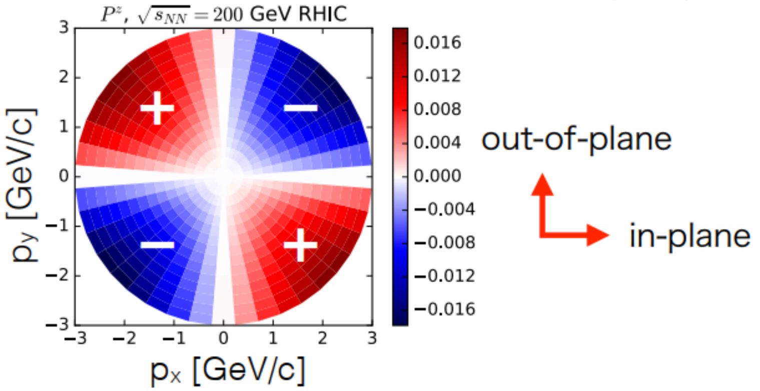
- Simulations:

Sign is opposite of expected!

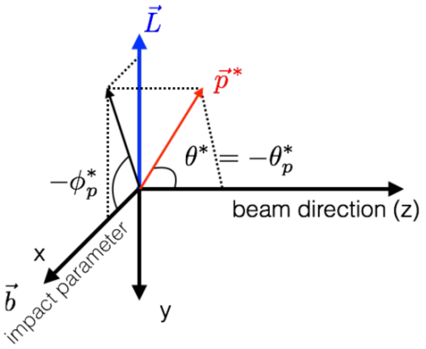
Puzzle: Polarization alone the beam direction

Again, sign is opposite of expected!





UrQMD : *Becattini, Karpenko, PRL (2018)*



$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P_H} \cdot \mathbf{p}_p^*)$$

$$\langle\cos\theta_p^*\rangle = \int \frac{dN}{d\Omega^*}\cos\theta_p^* d\Omega^*$$

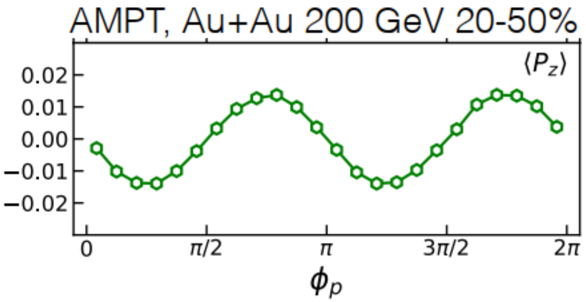
$$= \alpha_H P_z \langle(\cos\theta_p^*)^2\rangle$$

$$\therefore\ P_z = \frac{\langle\cos\theta_p^*\rangle}{\alpha_H\langle(\cos\theta_p^*)^2\rangle}$$

$$= \frac{3\langle\cos\theta_p^*\rangle}{\alpha_H}$$ (if perfect detector)

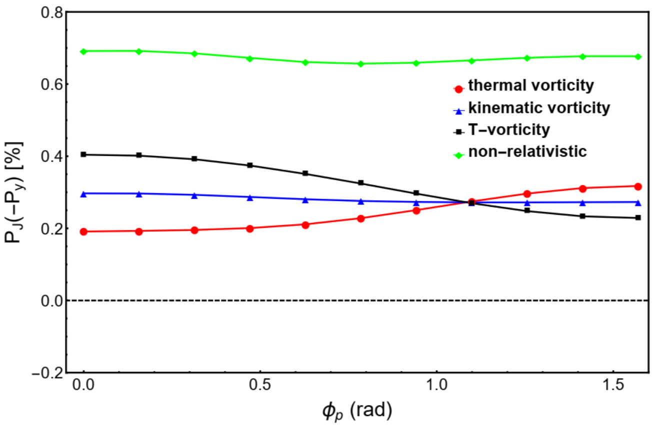
α_H: hyperon decay parameter

θ_p^*: θ of daughter proton in Λ rest frame



AMPT: *Xia, Li, Tang, Wang, PRC (2018)*

What kind of vorticity do exp. measure?



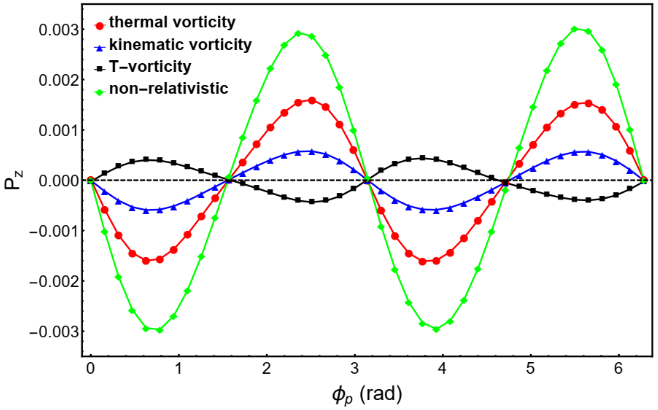
Wu, Pang, Huang, Q. Wang, 2019

Kinematic vorticity: $\omega^{(K)}_{\mu\nu} = -\frac{1}{2}(\partial_\mu u_\nu - \partial_\nu u_\mu)$

Relativistic extension of the non-relativistic vorticity: $\omega^{(\mathrm{NR})}_{\mu\nu} = \epsilon_{\nu\mu\rho\eta} u^\rho \omega^\eta$

Temperature vorticity: $\omega^{(T)}_{\mu\nu} = -\frac{1}{2}[\partial_\mu (T u_\nu) - \partial_\nu (T u_\mu)]$

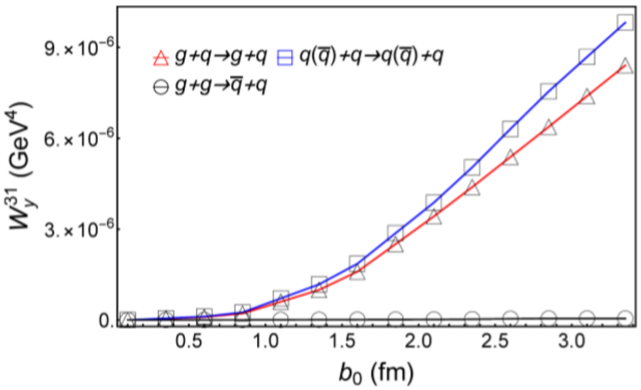
Thermal vorticity: $\omega^{(\mathrm{th})}_{\mu\nu} = -\frac{1}{2}[\partial_\mu (\beta u_\nu) - \partial_\nu (\beta u_\mu)]$

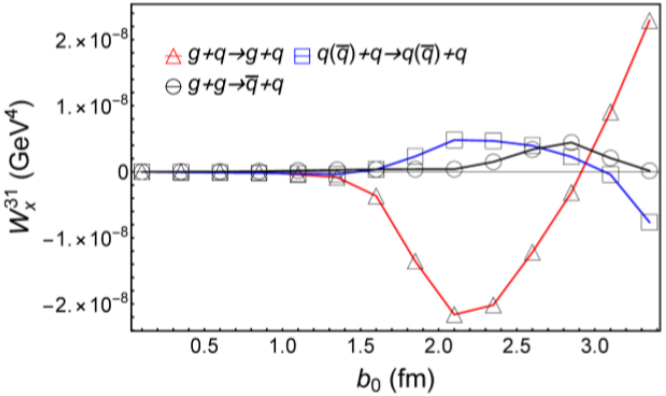


- By using the T-voriticity instead of the thermal vorticity, the simulations are consistent with the exp. data!

What kind of vorticity do exp measure?

How does OAM transfer to particles?





Zhang, Fang, Q. Wang, X.N. Wang, 2019

$$
\begin{aligned}
\boxed{\frac{d^4\mathbf{P}_{AB\to 12}(X)}{dX^4}} = & -\frac{1}{(2\pi)^4}\int \frac{d^3p_A}{(2\pi)^3 2E_A}\frac{d^3p_B}{(2\pi)^3 2E_B}\frac{d^3p_{c,1}}{(2\pi)^3 2E_{c,1}}\frac{d^3p_{c,2}}{(2\pi)^3 2E_{c,2}} \\
& \times |v_{c,A}-v_{c,B}| \int d^3k_{c,A} d^3k_{c,B} d^3k'_{c,A} d^3k'_{c,B} \\
& \times \phi_A(\mathbf{k}_{c,A}-\mathbf{p}_{c,A})\phi_B(\mathbf{k}_{c,B}-\mathbf{p}_{c,B})\phi_A^*(\mathbf{k}'_{c,A}-\mathbf{p}_{c,A})\phi_B^*(\mathbf{k}'_{c,B}-\mathbf{p}_{c,B}) \\
& \times \delta^{(4)}(k'_{c,A}+k'_{c,B}-p_{c,1}-p_{c,2})\delta^{(4)}(k_{c,A}+k_{c,B}-p_{c,1}-p_{c,2}) \\
& \times \frac{1}{2}\int d^2\mathbf{b}_c \exp\left[i(\mathbf{k}'_{c,A}-\mathbf{k}_{c,A})\cdot\mathbf{b}_c\right] \mathbf{b}_{c,j}[\Lambda^{-1}]^{\nu}_{j} \boxed{\frac{\partial(\beta u_\rho)}{\partial X^\nu}} \\
& \times [p_A^\rho - p_B^\rho]\, f_A(X,p_A)\, f_B(X,p_B) \boxed{\Delta I_M^{AB\to 12}} \mathbf{n}_c
\end{aligned}
$$

Polarization rate for quarks (anti-quarks)

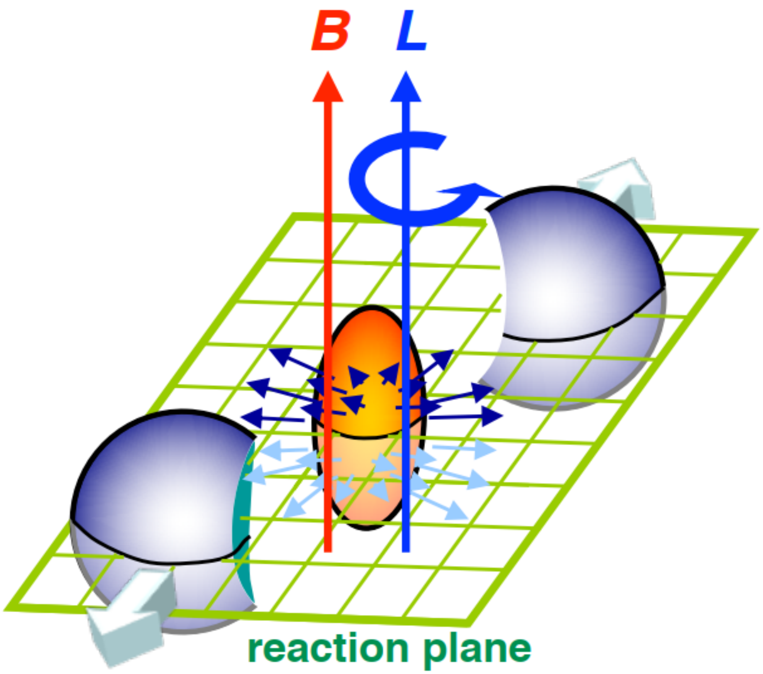
Microscopic contribution, contains spin-orbit coupling

Macroscopic contribution, vorticity (angular momentum)

$$\equiv \frac{\partial(\beta u_\rho)}{\partial X^\nu}\mathbf{W}^{\rho\nu}$$

- Do not need to assume the local spin equilibrium!
- Final Particles are polarized through interaction

Strong magnetic field

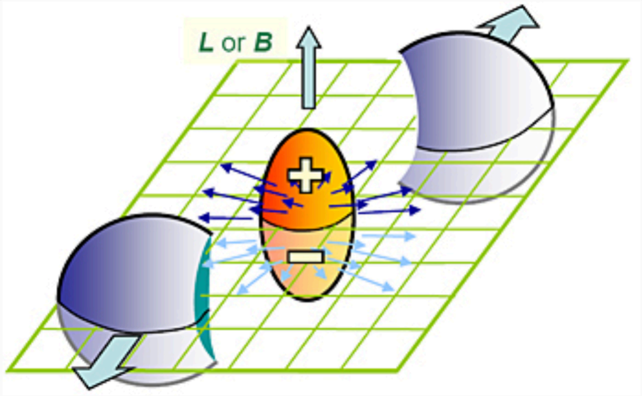


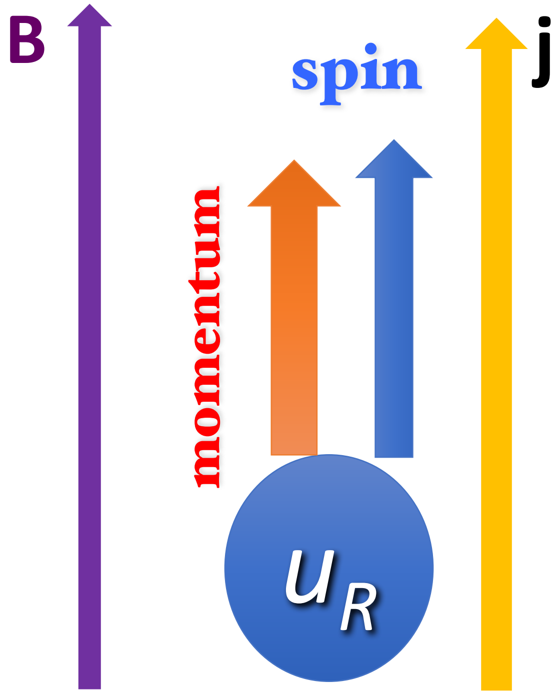
- Very strong magnetic fields are produced

$$eB \sim 10^{17} - 10^{18} \mathrm{Gauss}$$

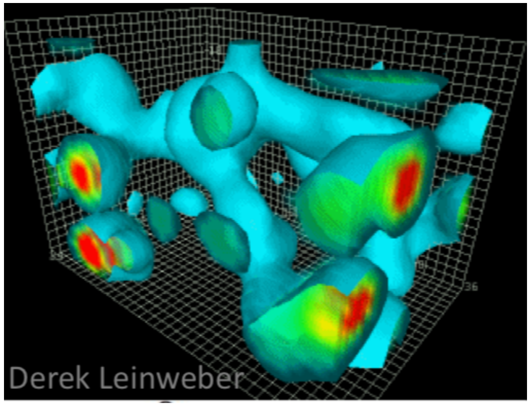
- Novel quantum transport effects induced by magnetic fields

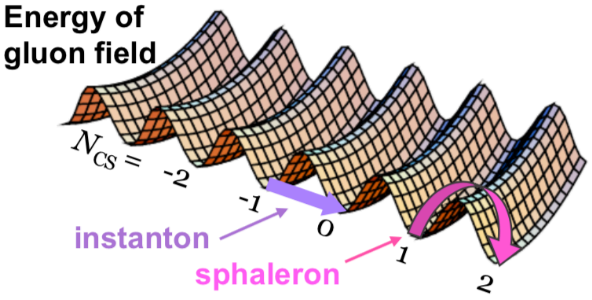
Chiral magnetic effect





- Magnetic fields
- Nonzero axial chemical potential
- Number of Left handed fermions ≠ Number of Right handed fermions


Derek Leinweber



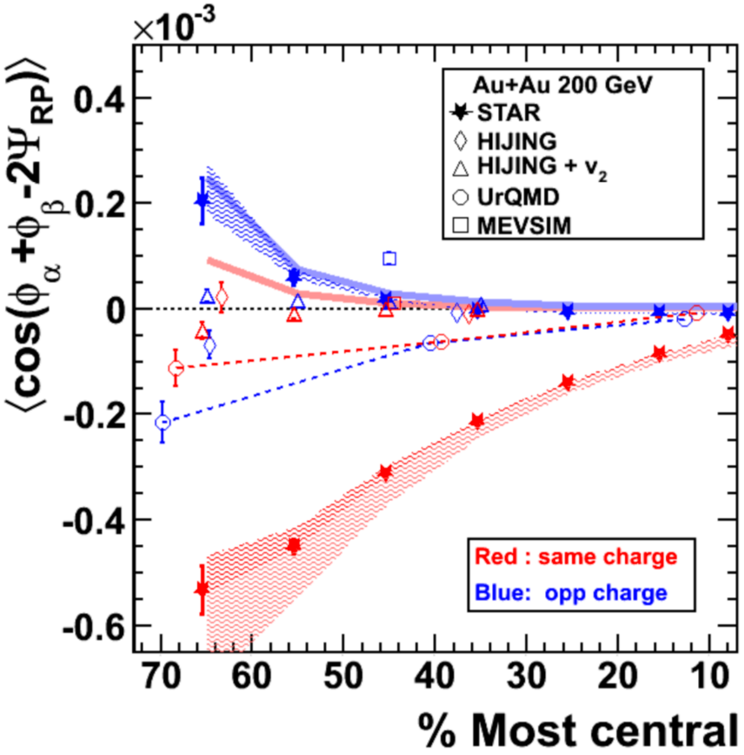
- Charge current: charge separation

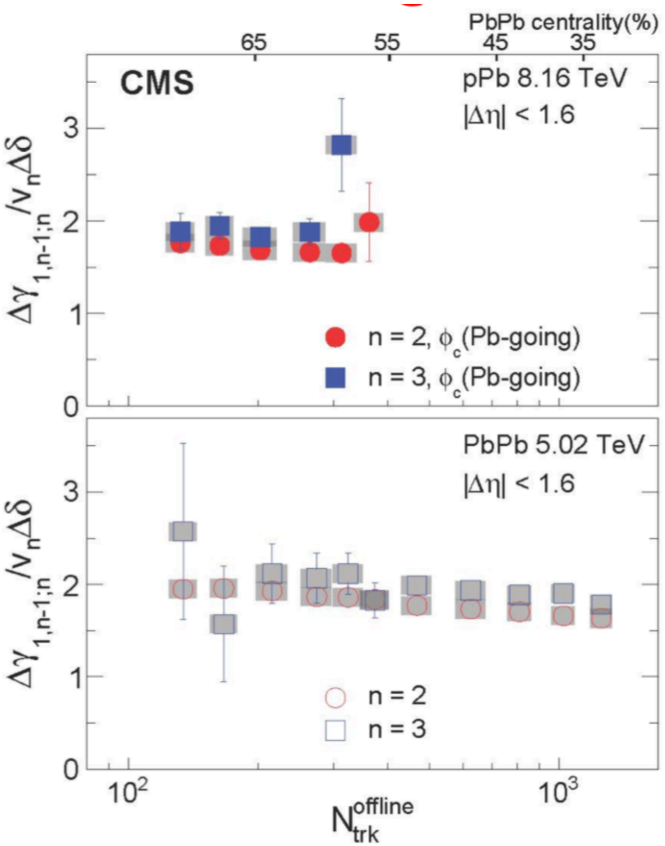
$$\boxed{\mathbf{j} = \frac{e^2}{2\pi^2}\mu_5 \mathbf{B},}$$

Kharzeev, Fukushima, Warrigna, (08,09), etc. ...

Signal VS background

Waiting for the results from Isobar

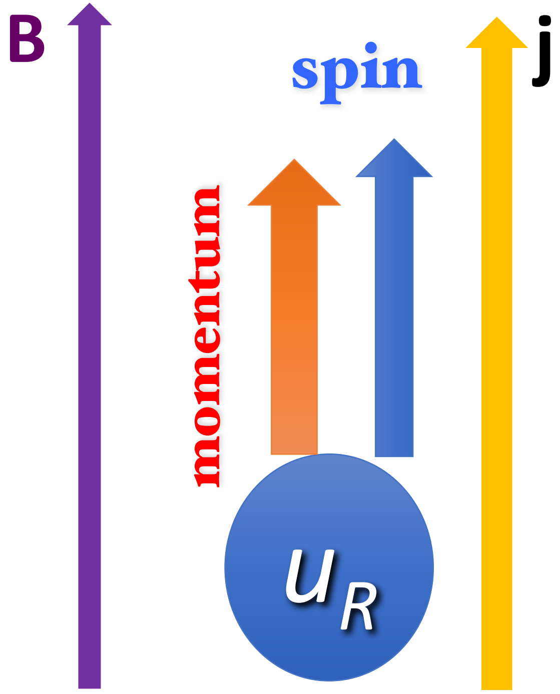




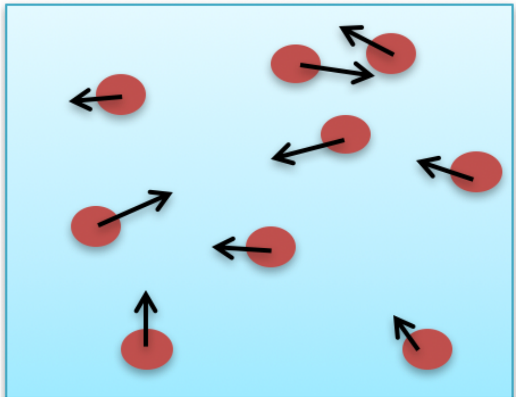
STAR PRL 103, 251601(2009);
PRC 81, 054908

CMS PRL 118, 122301 (2016);
PRC 97, 044912

Microscopic vs Macroscopic

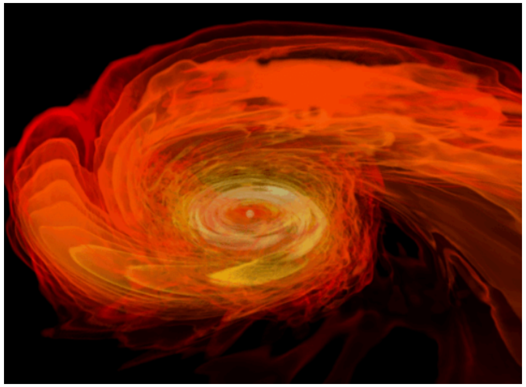


microscopic



Chiral kinetic theory

macroscopic



Anomalous magneto-hydrodynamics

Microscopic: Chiral kinetic theory

$$\sqrt{G}\partial_t f + \sqrt{G}\dot{\mathbf{x}}\cdot\nabla_x f + \sqrt{G}\dot{\mathbf{p}}\cdot\nabla_p f = C[f].$$

- **Particle's effective velocity:**

$$\sqrt{G}\dot{\mathbf{x}} = \frac{\partial\varepsilon}{\partial\mathbf{p}} + \hbar\left(\frac{\partial\varepsilon}{\partial\mathbf{p}}\cdot\boldsymbol{\Omega}\right)\mathbf{B} + \hbar\mathbf{E}\times\boldsymbol{\Omega},$$

- **Effective force:**

$$\sqrt{G}\dot{\mathbf{p}} = \mathbf{E} + \frac{\partial\varepsilon}{\partial\mathbf{p}}\times\mathbf{B} + \hbar(\mathbf{E}\cdot\mathbf{B})\boldsymbol{\Omega},$$

- **Berry curvature**

$$\sqrt{G} = 1 + \hbar\mathbf{B}\cdot\boldsymbol{\Omega}, \quad \boldsymbol{\Omega} = \frac{\mathbf{p}}{2|\mathbf{p}|^3},$$

- **Wigner function**
  - **hydrodynamics, equilibrium**

Chen, SP, Q. Wang, X.N. Wang, PRL 2013
Gap,Liang, SP, Wang, Wang, PRL 2012

  - **out-of-equilibrium, quantum field theory**

Hidaka, SP, Yang, PRD(RC) (2017)

- **Non-linear effects**

Hidaka, SP, Yang, PRD 2017
SP, Wu, Yang, PRD 2015; PRD 2016;

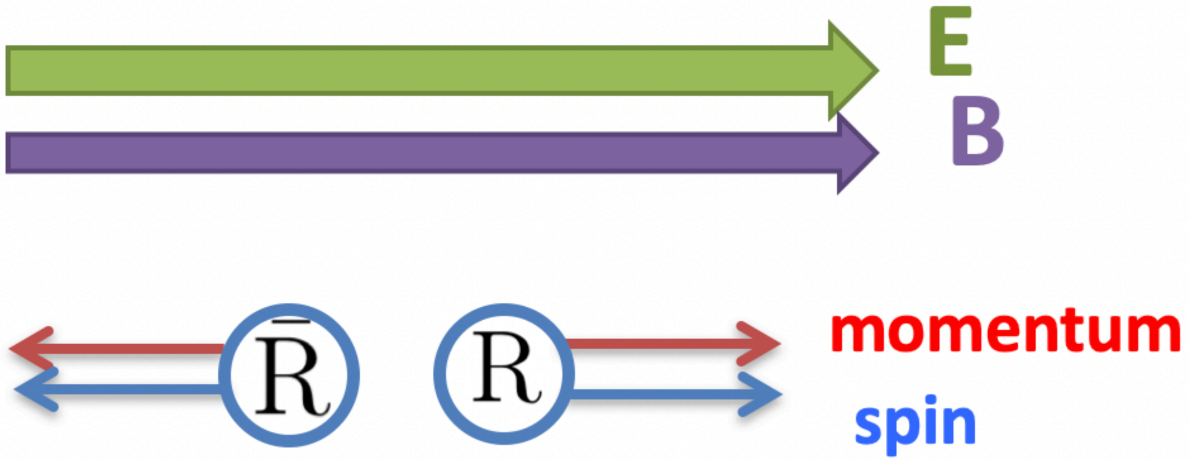
- **Lattice**

SP, Yamamoto, NPA 2017

Also see other approaches:

Yamamoto, Son PRL 2012; PRD 2013; Stephanov, Yin PRL 2012; Chen, Son, Stephanov, Yee, Yin, PRL 2014; Chen, Pang, SP, Wang PRD 2014; Huang,Su, Jiang, Liao, Zhuang, PRD 2018; Muller, Venugopalan, PRD 2017

Schwinger mechanics and chirality production



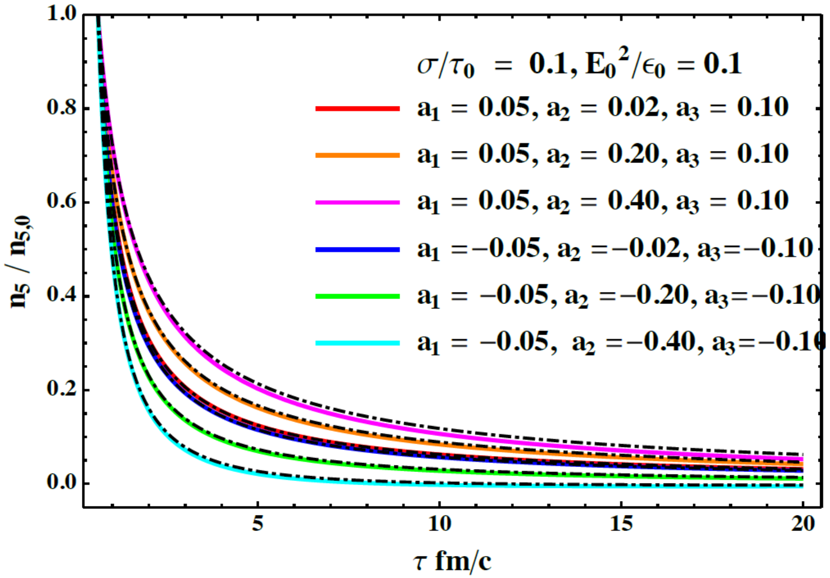
$$\frac{1}{2}\partial_t n_5 = \text{Schwinger Pair Production rate}$$

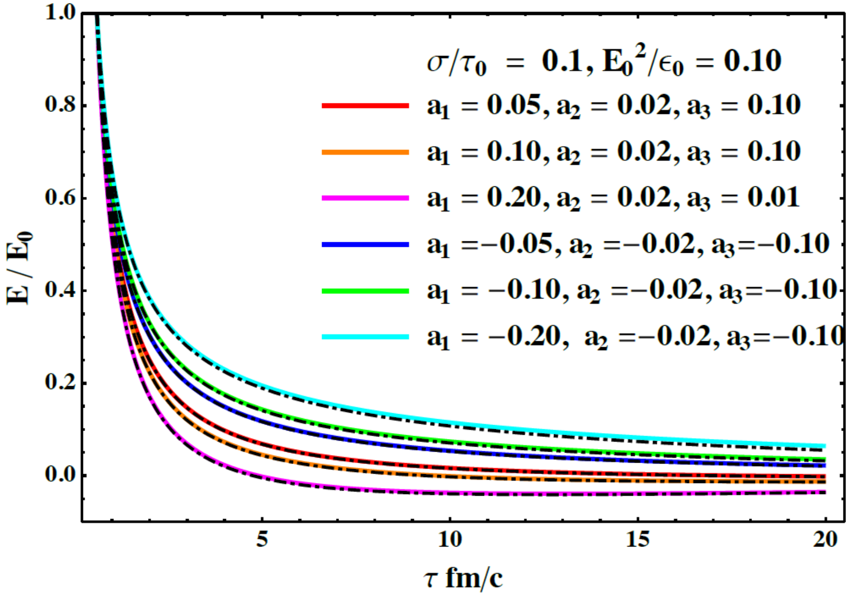
- Proposed by: *Fukushima, Kharzeev, Warringa PRL 2010*

- Proved by us: *Copinger, Fukshima, SP, PRL 2018*

➢ A new non-perturbative way to compute the dynamical quantities under strong electromagnetic fields

Macroscopic: Anomalous magneto-hydrodynamics





Siddique, R-j. Wang, SP, Q. Wang, PRD 2019

- Analytic solutions:
  - ➢ chiral density

$$n_5(\tau) = n_{5,0}\left(\frac{\tau_0}{\tau}\right)\{1+a_2 e^{\sigma\tau_0}[\mathrm{E}_1(\sigma\tau_0)-\mathrm{E}_1(\sigma\tau)]\},$$

$$\mathrm{E}_n(z) \equiv \int_1^\infty dt t^{-n} e^{-zt}$$

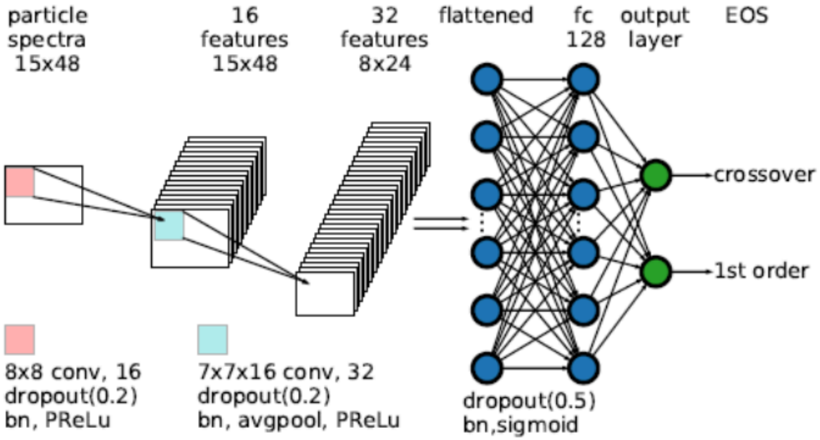
- Decay behavior in the Lab frame:
  - ➢ By decays ~ 1/τ
  - ➢ Bx decays ~ exp(- σ τ)/ τ

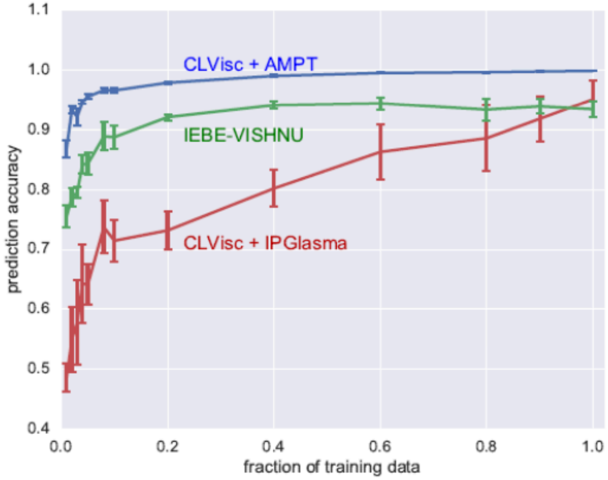
Much slower than decaying in vacuum

New development related to GPU

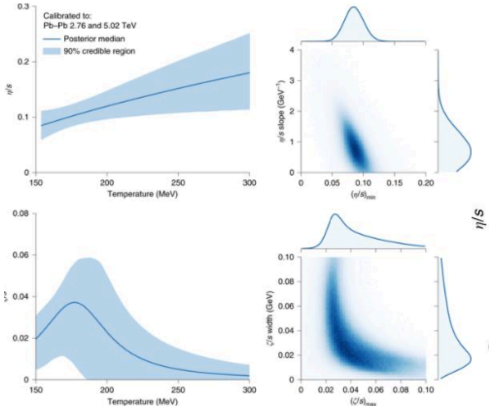
Deep learning

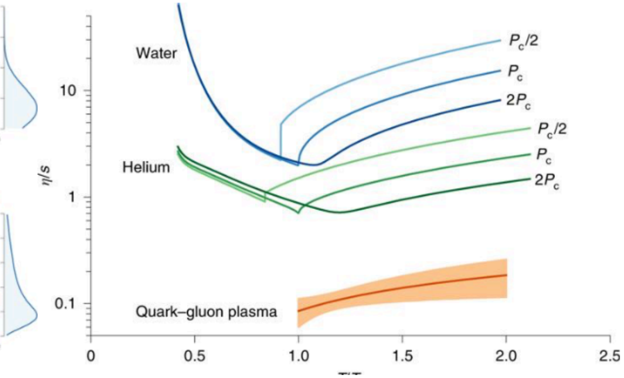
Pang, Zhou, Su, Petersen, Stocker, Wang, Naure Commun. 2018





Bernhard, Moreland, Bass, Nature Physics 2019





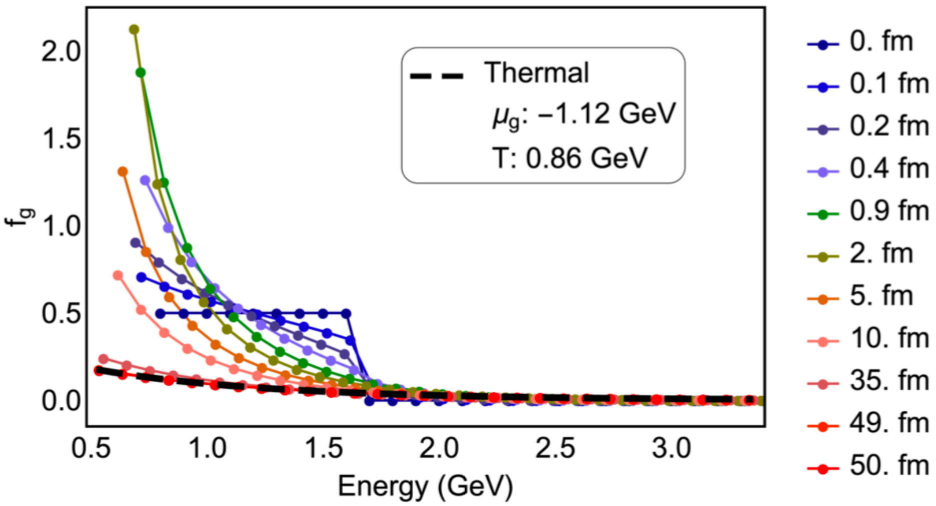
- A new way to connect the final states observables with the QGP properties

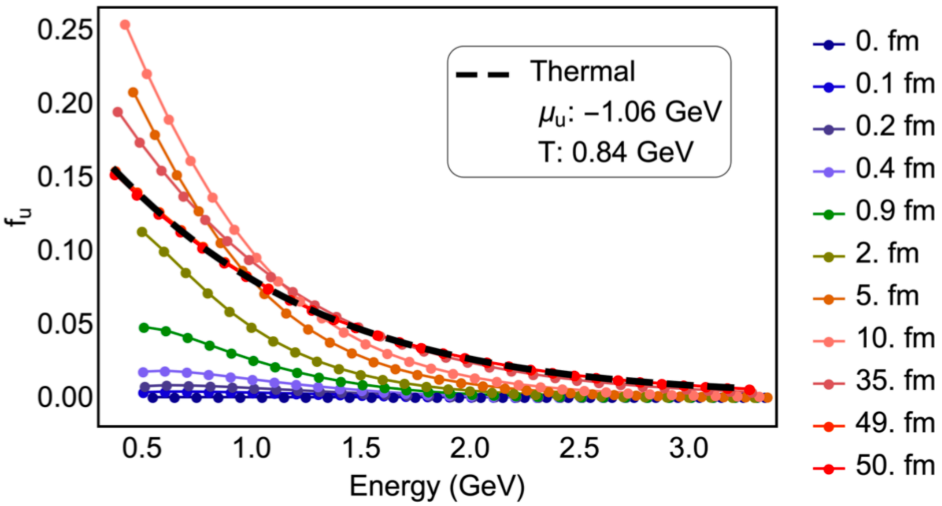
Solving Boltzmann equation on GPU

Zhang, Wu, SP, Qin, Wang, in preparation

A new framework to solving complete Boltzmann equation

- Full collisional integral (5 dimensional), not test particle method
- High performance: a few days VS years!
- A new method to guarantee the particle number conservation





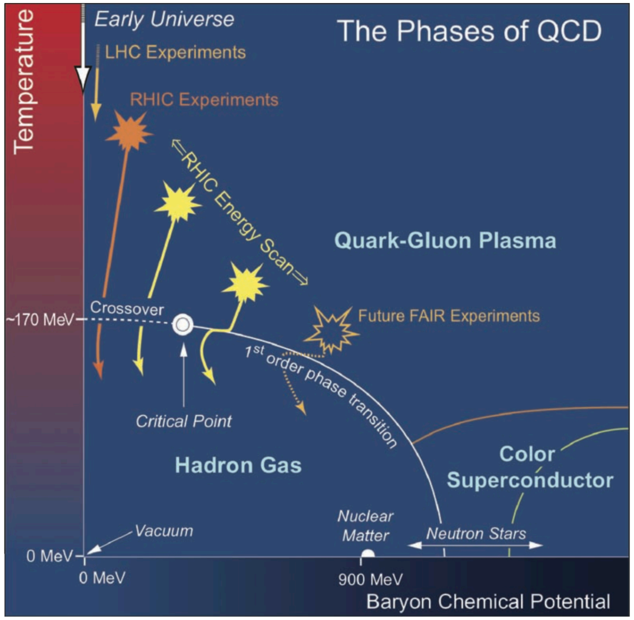
Summary

Summary from Quark Matter 2018:

Improving our understanding of the parton nature of the QGP

… of small systems

… and of energetic probes of the plasma



Thank you for your time!

Ref:

- Leeuwen et. al, Quark Matter 2018 Summary
- Pengfei Zhuang, Plenary Talk at 第十八届全国中高能核物理大会
- Guangyou Qing, Plenary Talk at 第十七届全国核物理大会
- Qun Wang, Plenary Talk at The 5th Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions
- Xiaofeng Luo, Plenary Talk at 第十八届全国中高能核物理大会