ソフトプローブ(理論)

村瀬功一 (京大基研)

ポストQM2023、名古屋大学KMI、2023/11/4

今回: 動的模型

全体まとめは QM Plenary Talk by 金久保さん 参照
“Collective Dynamics - Theoretical Overview”

= シミュレーションの枠組み
= 測定量(ハドロン終状態)とダイナミクスの接続
= 衝突反応の物理的理解の「形」

初期状態の模型

TRENTo, IP-Glasma, Glauber, CGC, AMPT, etc.

Pre-equilibrium dynamics

Free streaming, KøMPøST, EKT, KTIso, 2PI formalism, etc.

相対論的流体

粘性流体、(カイラル・抵抗)磁気流体、異方粘性流体、ゆらぐ流体、etc.

ハドロン微視的輸送模型

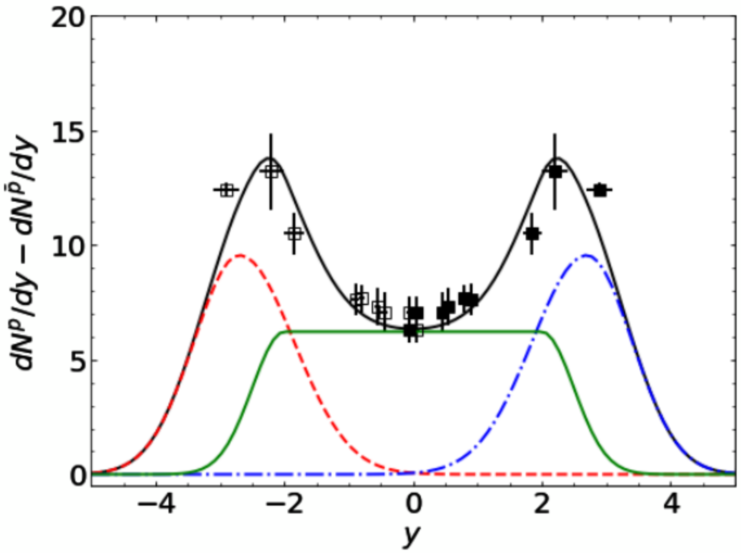
SMASH, UrQMD, JAM

Lipei Du (Collective I)

"Probing initial baryon stopping and EOS with v1(y) of identified particles"

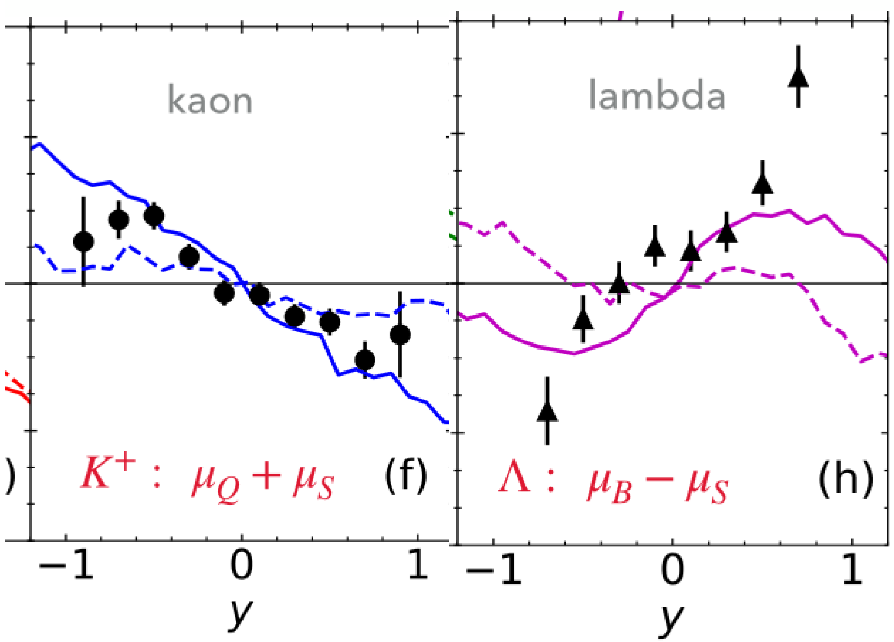
バリオン密度の初期条件

proton dN/dy & v1 を合わせる為にはPlateau 成分が必要



有限密度EOS

PID v1 を使って制限?



Solid: NEOS-B, Dashed: NEOS-BQS
(EOS by Monnai et al)

Grégoire Pihan (Collective II)

"What carries the baryon number?
Simulations of baryon and electric charge stopping in isobar collisions at RHIC"

Framework: iEBE-MUSIC

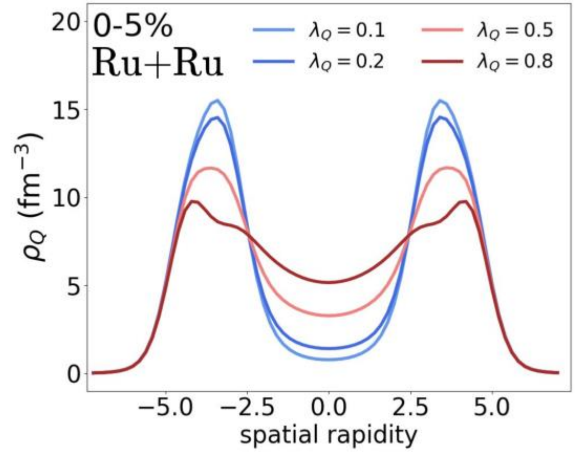
Baryon/Charge 初期条件

Baryon/electric charge densities: valence quarks + **string junction**

$$P(y^X_{P/T}) = (1-\lambda_X) y_{P/T} + \lambda_X \frac{e^{(y^X_{P/T}-(y_P+y_T)/2)/2}}{4\sinh((y_P-y_T)/4)}$$

$$X = B, Q$$

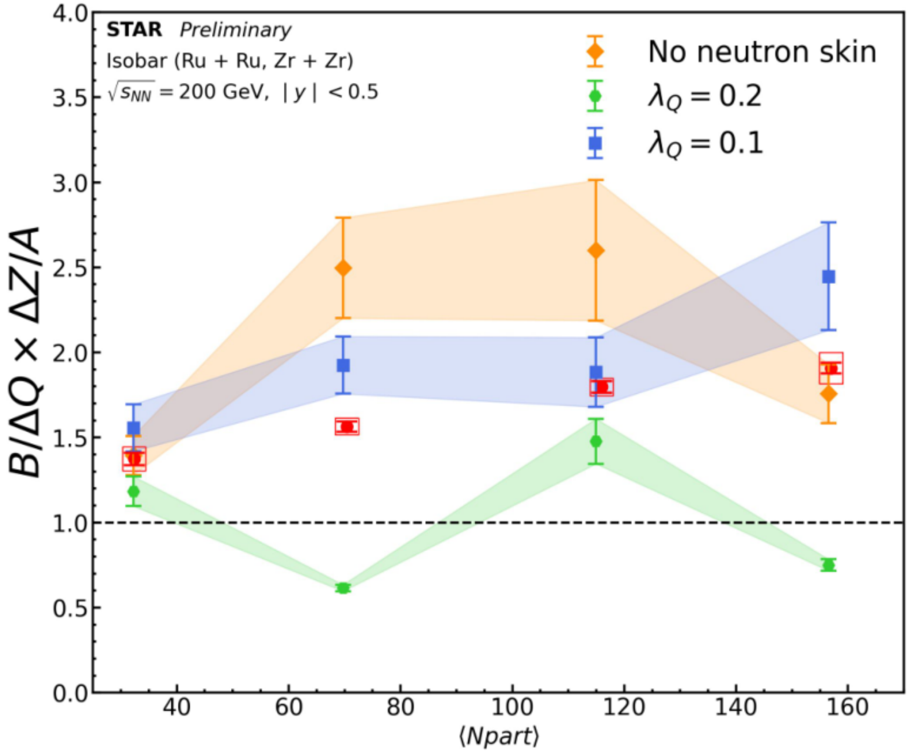
C. Shen and B. Schenke Phys. Rev. C **105**, 064905 (2022)
GP, A. Monnai, B. Schencke, C. Shen in Prep



Isobar → baryon stopping λ_B vs charge stopping λ_Q

Grégoire Pihan (Collective II)

"What carries the baryon number?
Simulations of baryon and electric charge stopping in isobar collisions at RHIC"



At final stage

➢ Equal stopping $\lambda_Q = \lambda_B = 0.2$

- Largely underestimate the experimental ratio
- ratio < 1.
- oscillatory behavior: remains to be understood

➢ Half stopping $\lambda_Q = \lambda_B/2 = 0.1$

- Compatible with experimental data
- slightly smaller λ_Q may match data!

➢ No neutron skin $\lambda_Q = 0.1$

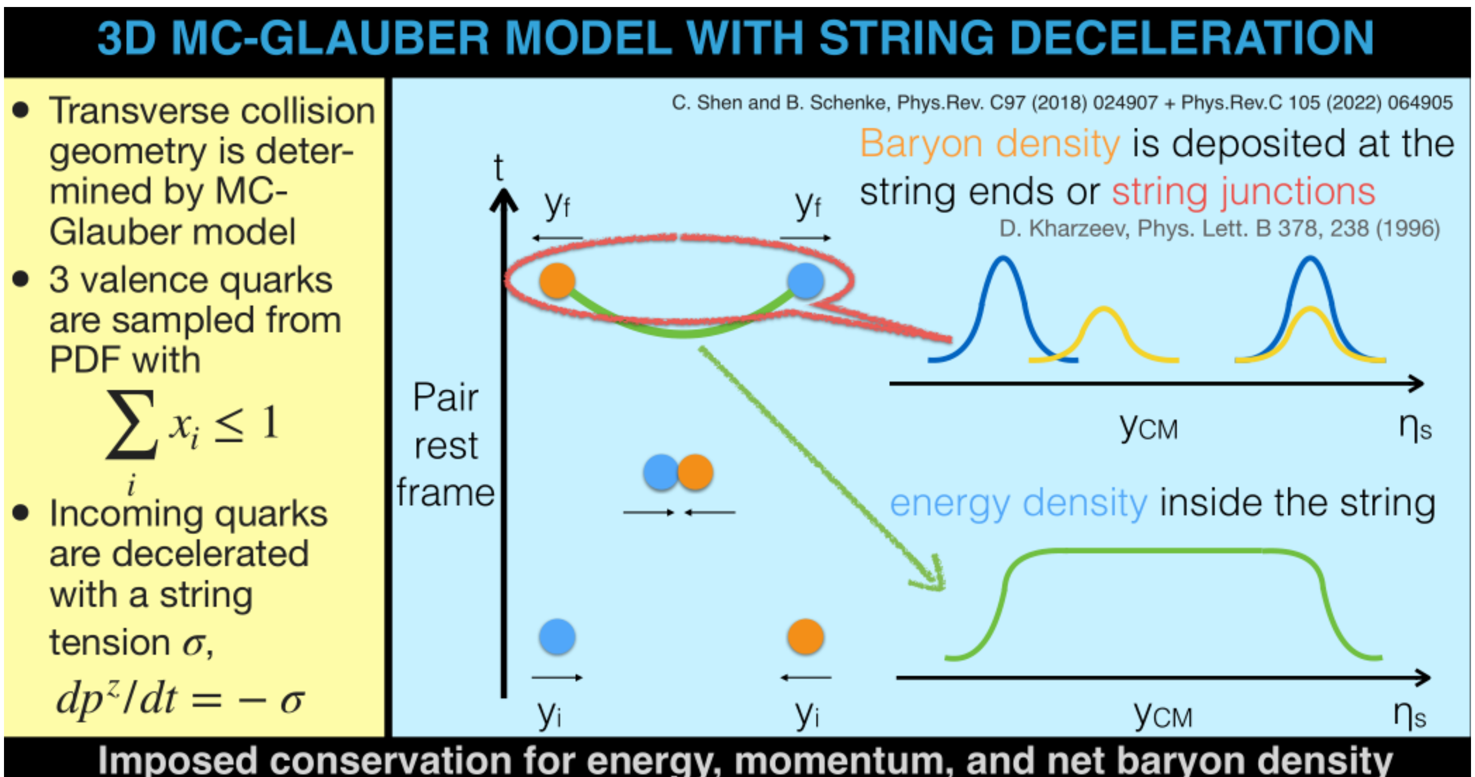
- Flat for a large range of Npart
- Cannot account for increasing behavior of the data

Comparison with STAR data at final stage advocates for a difference in baryon to electric charge stopping ratio!

Chun Shen (Finite T&μ I)

"Bayesian Inference of QGP Properties
and 3D Dynamics of Heavy-Ion Collisions
in the RHIC Beam Energy Scan Program"

Rapidity 依存性も含めてベイズ解析を行う。
バリオン密度の初期条件は?

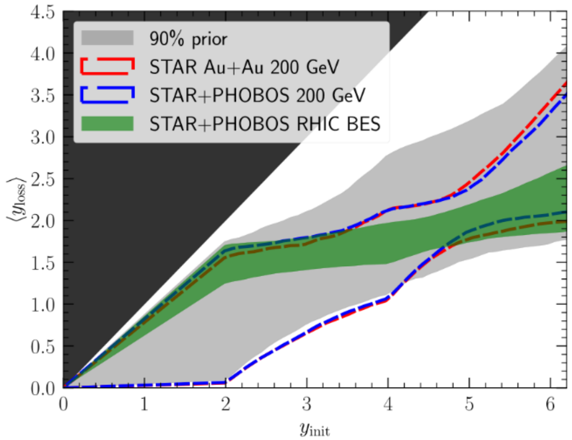


Chun Shen (Finite T&μ I)

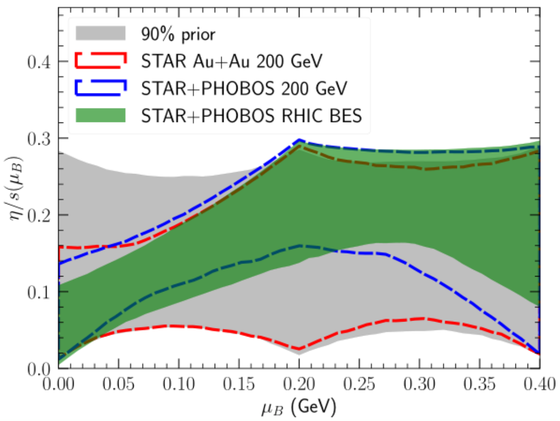
"Bayesian Inference of QGP Properties
and 3D Dynamics of Heavy-Ion Collisions
in the RHIC Beam Energy Scan Program"

iEBE-MUSIC / 3D 初期条件 (string deceleration)

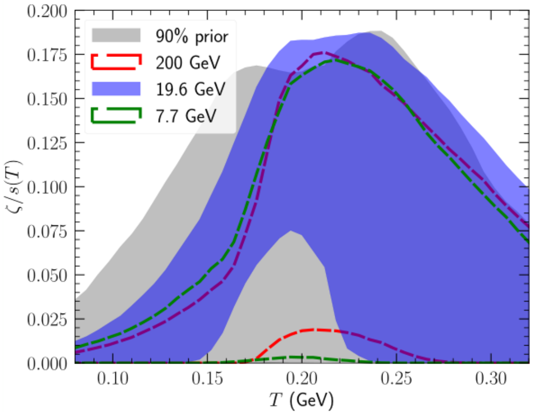
Initial stopping



Shear viscosity



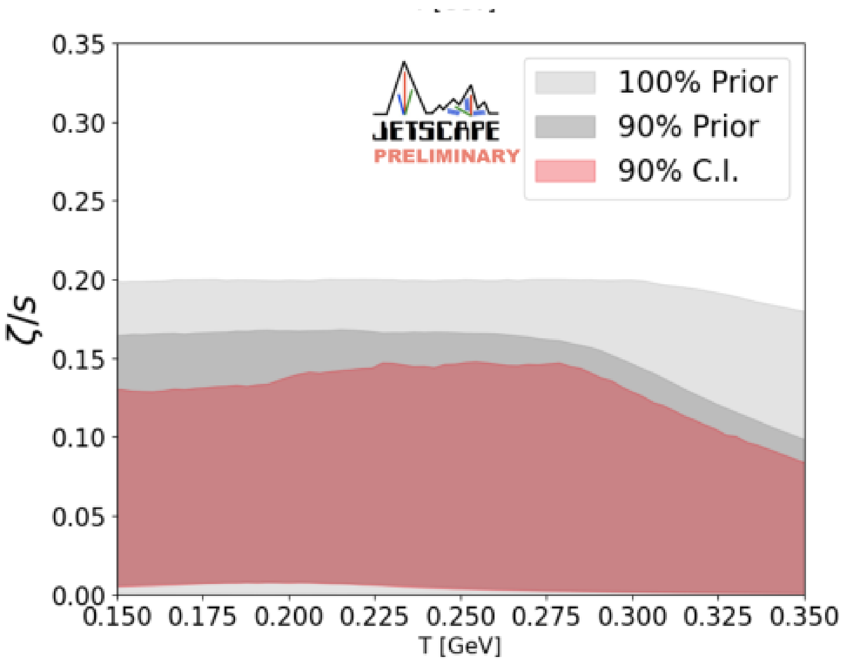
Bulk viscosity



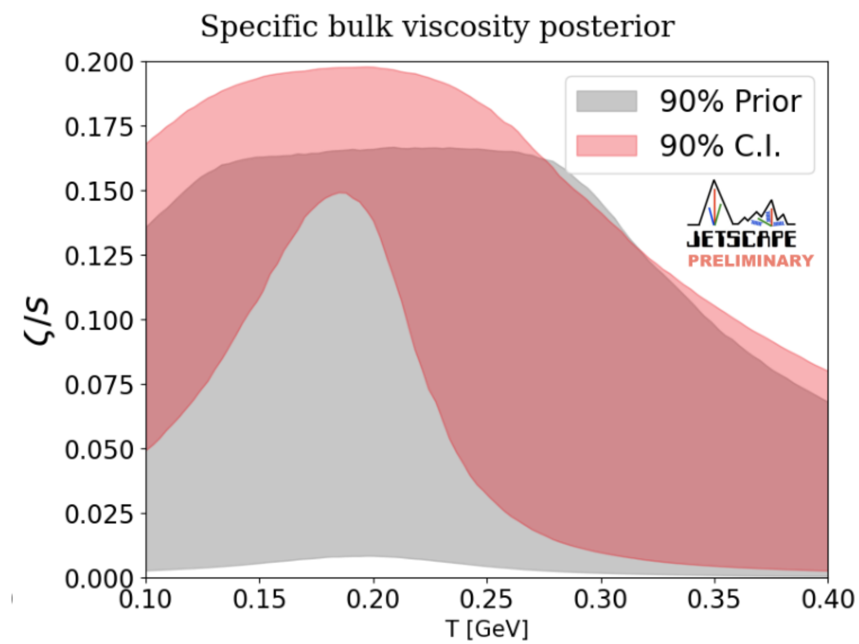
Andi Mankolli (Collective I)

“Rapidity-dependent Dynamics of the Initial State via 3D Multi-system Bayesian Calibration”

Mid-rapidity だけの Bayes 解析 (Bulk viscosity)



Rapidity 依存性も考慮に入れた制限

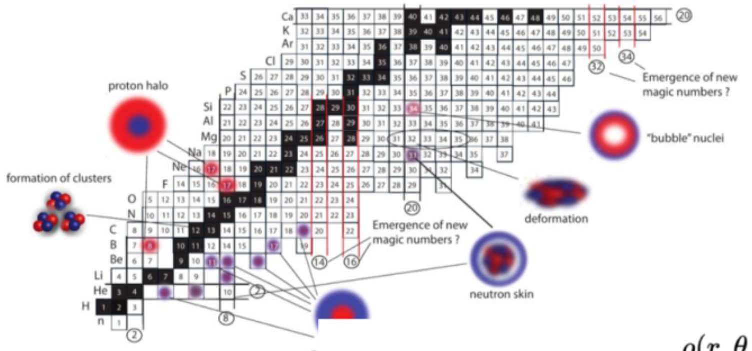


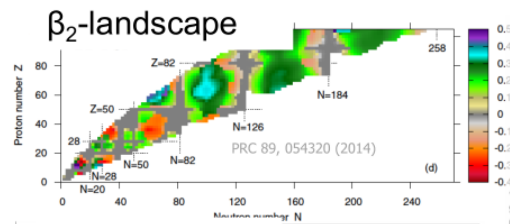
Jiangyong Jia (Initial State I)

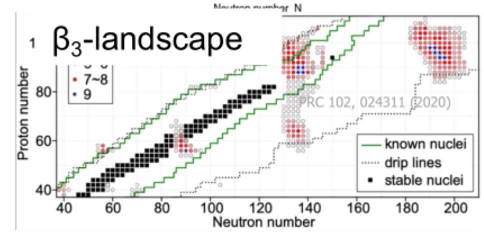
"Intersection between nuclear structure and heavy-ion collisions"

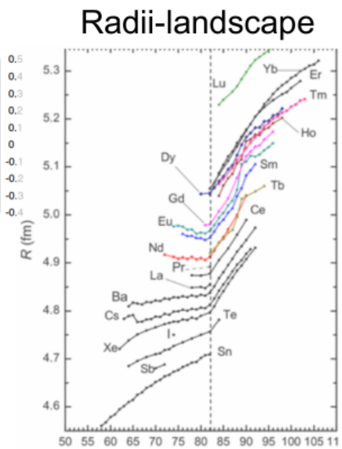
Collective structure of atomic nuclei

- Emergent phenomena of the many-body quantum system
  - clustering, halo, skin, bubble…
  - quadrupole/octupole/hexdecopole deformations
  - Non-monotonic evolution with N and Z

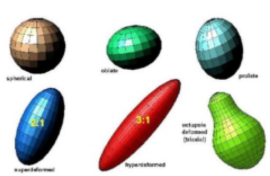




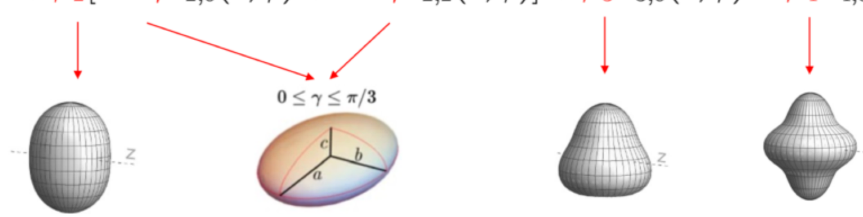




$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$



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



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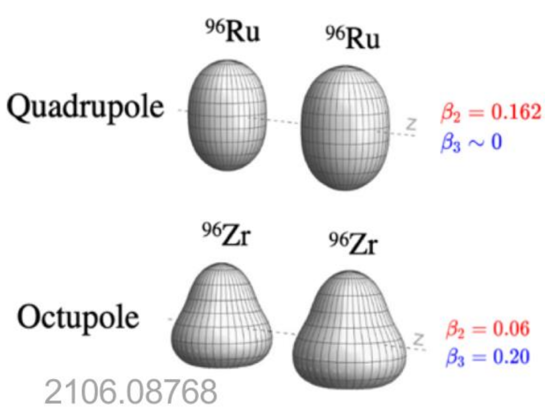
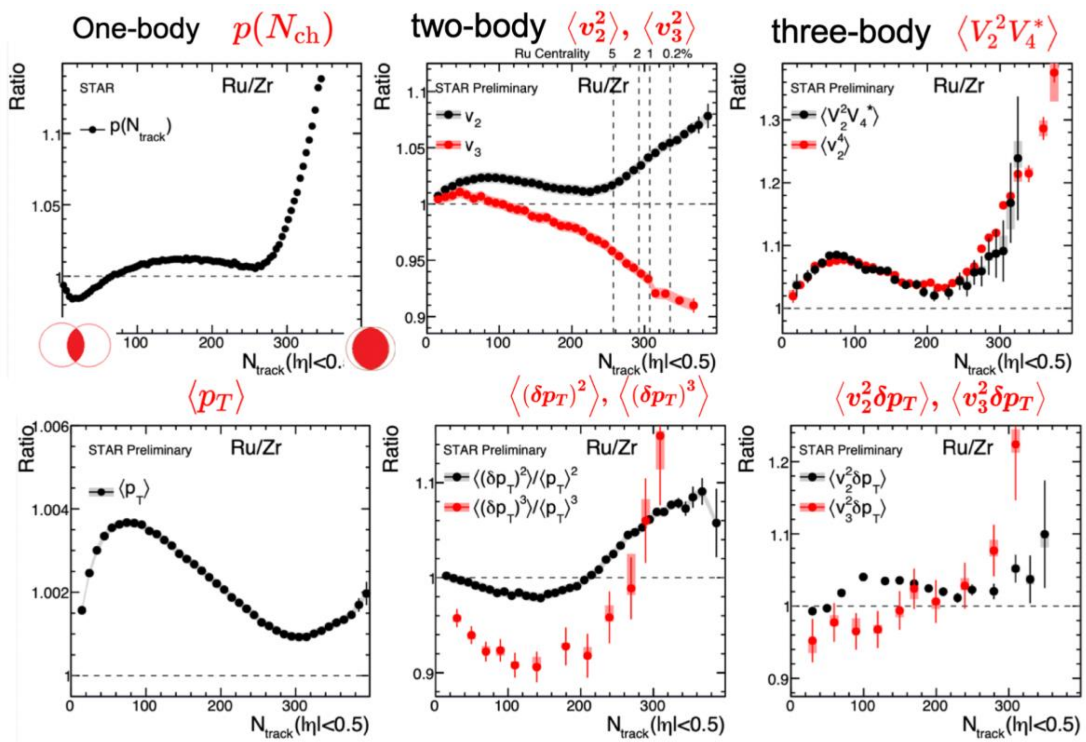
Jiangyong Jia (Initial State I)

"Intersection between nuclear structure
and heavy-ion collisions"

arXiv:2206.10449

Ratio O(Ru+Ru)/O(Zr+Zr)



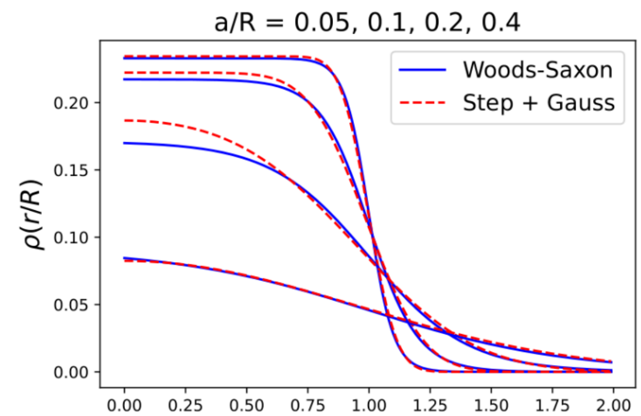


Matthew Luzum (Initial State I)

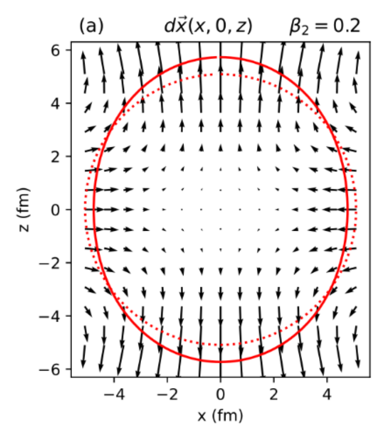
"Methods for systematic study of nuclear structure in high-energy collisions or: changing nuclei by shifting nucleons"

効率的な核子分布のサンプル方法を提案

Idea1: Step function 分布でサンプルした r1 と Gauss 分布でサンプルした r2 を足して核子の位置とする。



Idea2: ∇(球面調和関数) に沿って核子の位置を移流方程式で移動させることによって原子核変形を行う。

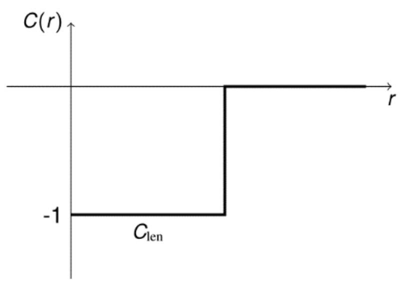


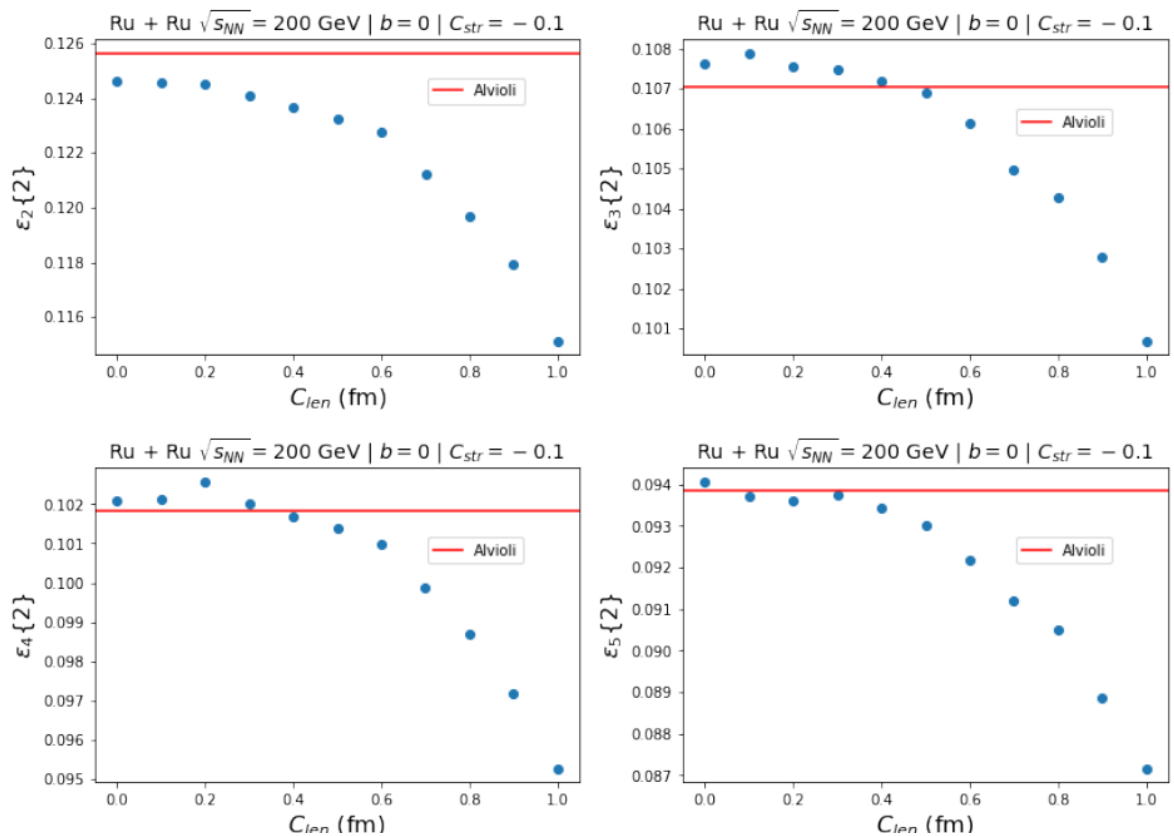
Idea3: 核子を反発させて位置を修正することによって short-range correlation を導入する。

Matthew Luzum (Initial State I)

"Methods for systematic study of nuclear structure in high-energy collisions or: changing nuclei by shifting nucleons"

Short-range correlation 排除半径に基づくもの vs 現実的なもの(Alvioli)





$\varepsilon_n\{2\}$ で比較

同時に合わせる
ことはできない。

Wenbin Zhao (Initial State II)

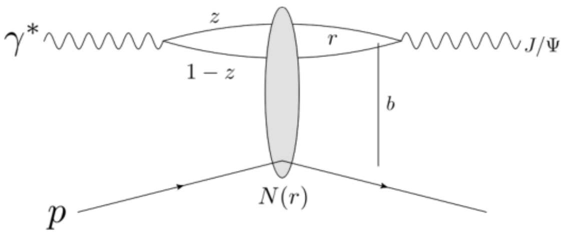
"Multi-scale Imaging of Nuclear Geometries"

Ultra-peripheral collisions (UPC)

Coherent and incoherent processes

- **Coherent** $\sigma_{\text{coherent}} \sim |\langle \mathcal{A} \rangle_\Omega|^2$

Target stays intact, (Iinitial state> = Ifinal state>)
Probes the average shape of the target.



- **Incoherent** $\sigma_{\text{incoherent}} \sim \langle |\mathcal{A}|^2 \rangle_\Omega - |\langle \mathcal{A} \rangle_\Omega|^2$

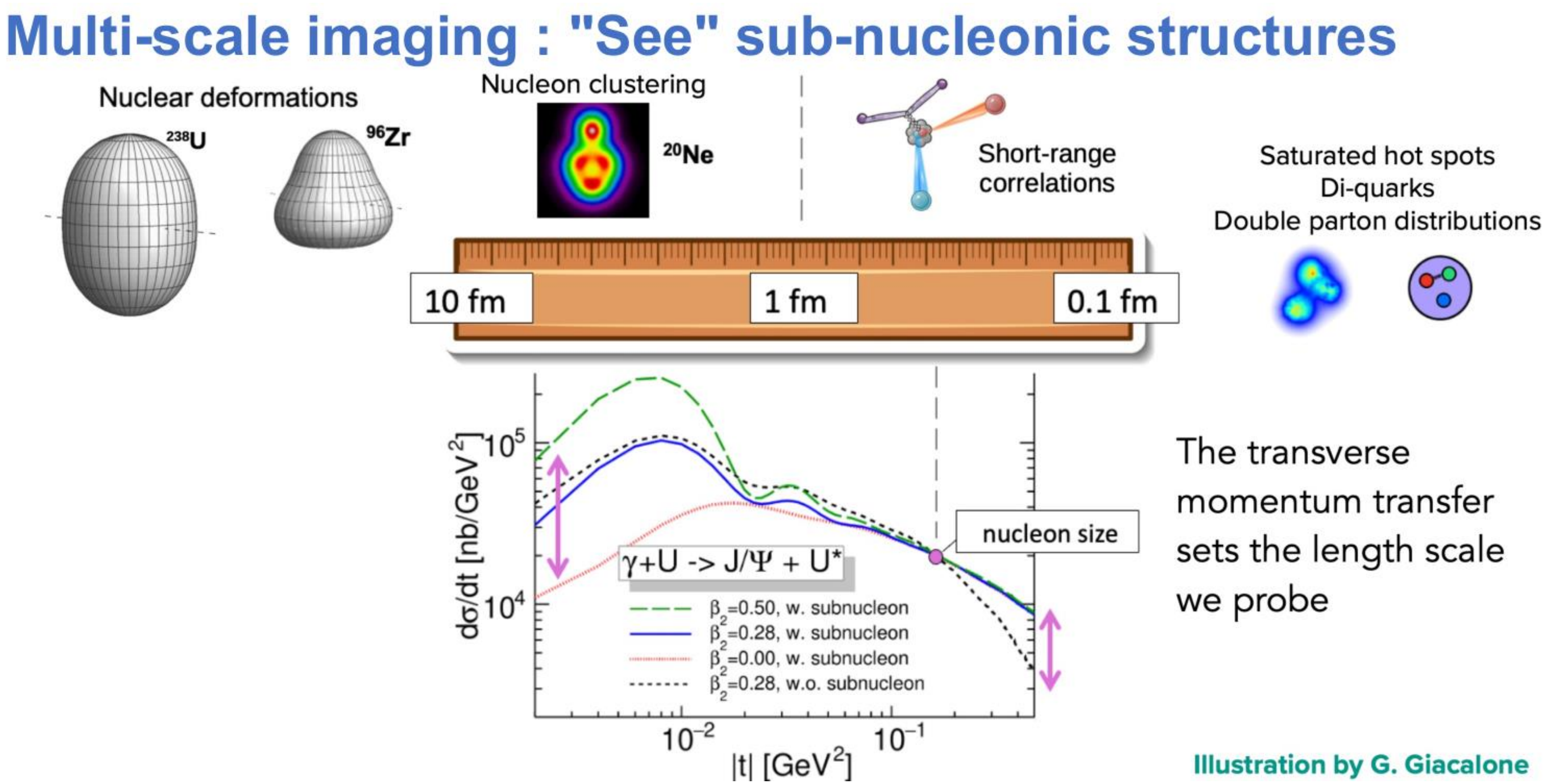
Target breaks apart, (|initial state> ≠ |final state>)

Probes the variance of event-by-event initial state fluctuations in target structure.

Miettinen, Pumplin, PRD 18, 1978; Caldwell, Kowalski, 0909.1254; Mäntysaari, Schenke, 1603.04349; Mäntysaari, 2001.10705

Wenbin Zhao (Initial State II)

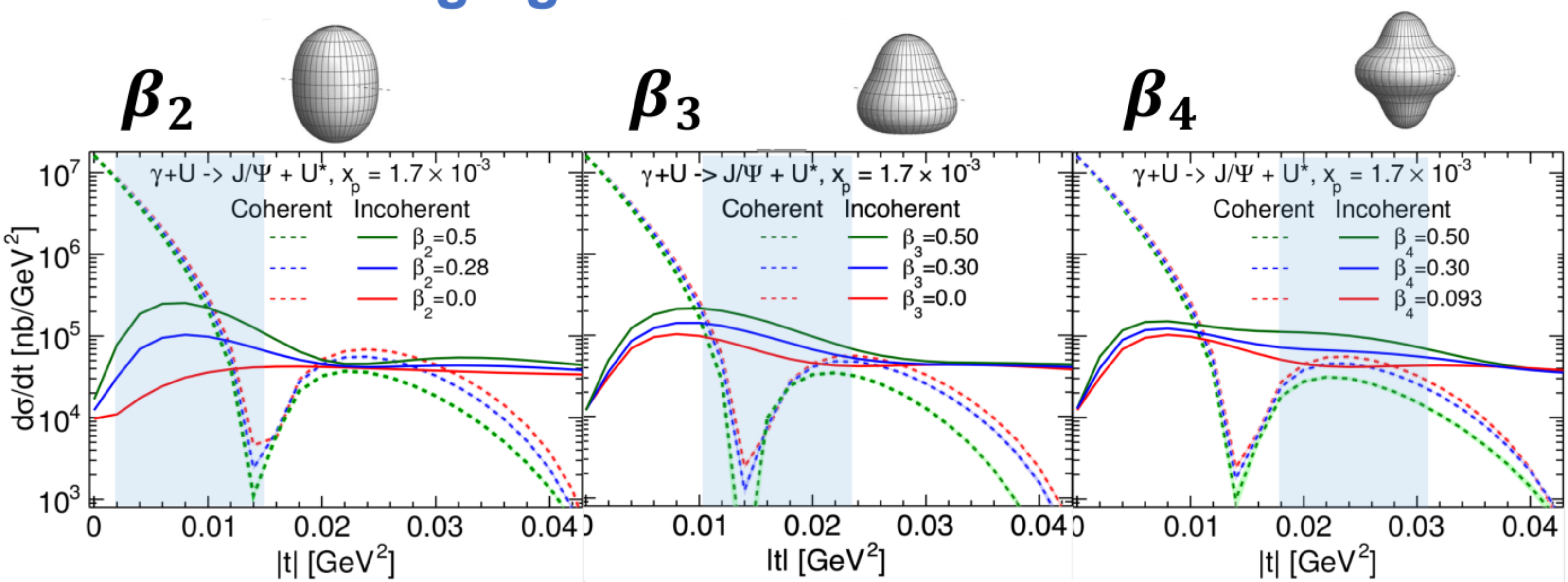
“Multi-scale Imaging of Nuclear Geometries”



Wenbin Zhao (Initial State II)

“Multi-scale Imaging of Nuclear Geometries”

Multi-scale imaging: Nuclear deformations



- β_2 , β_3 and β_4 manifest themselves at different |t| regions (different length scales).

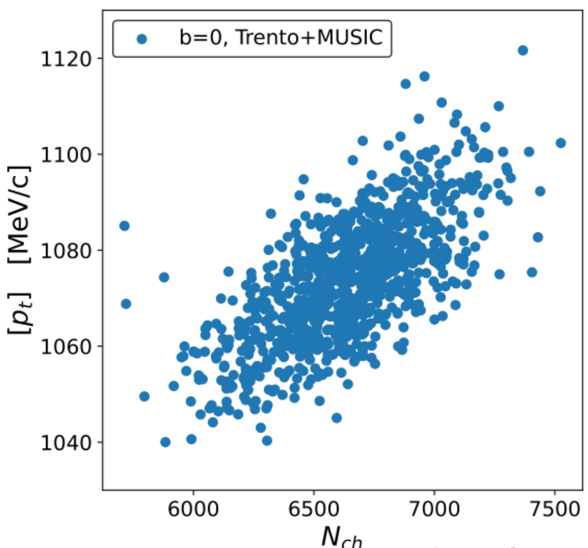
Rupam Samanta (Collective II)

“Thermalization of QGP through transverse momentum fluctuation in ultra-central Pb+Pb collision”

arXiv:2306.09294

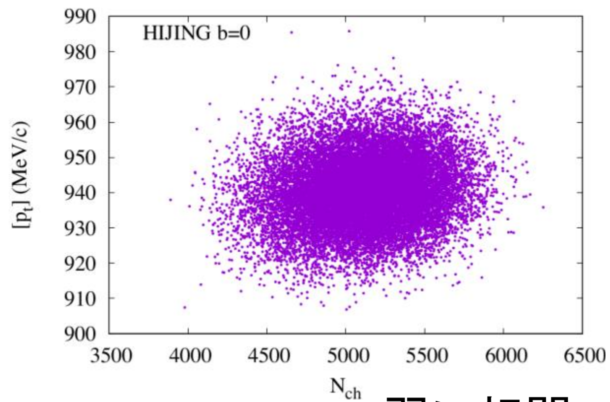
$[p_t]$-N_{ch} scatter for fixed impact param b=0

Hydro

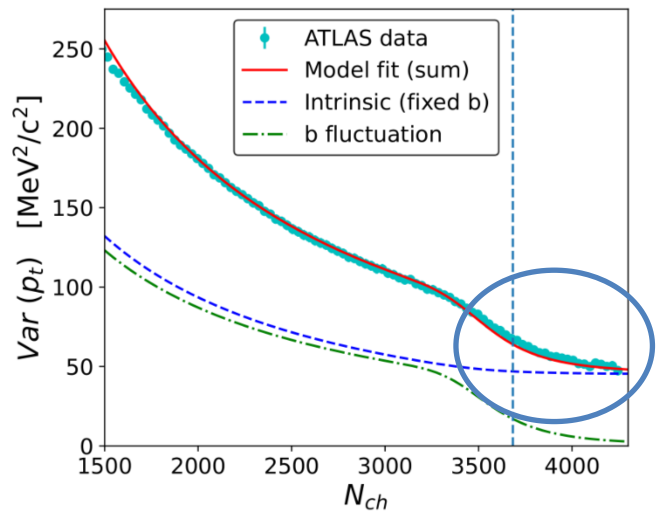


強い相関

HIJING



弱い相関



→ Ultra-central の [pt] vs Nch を見れば描像の違いを見ることができる?

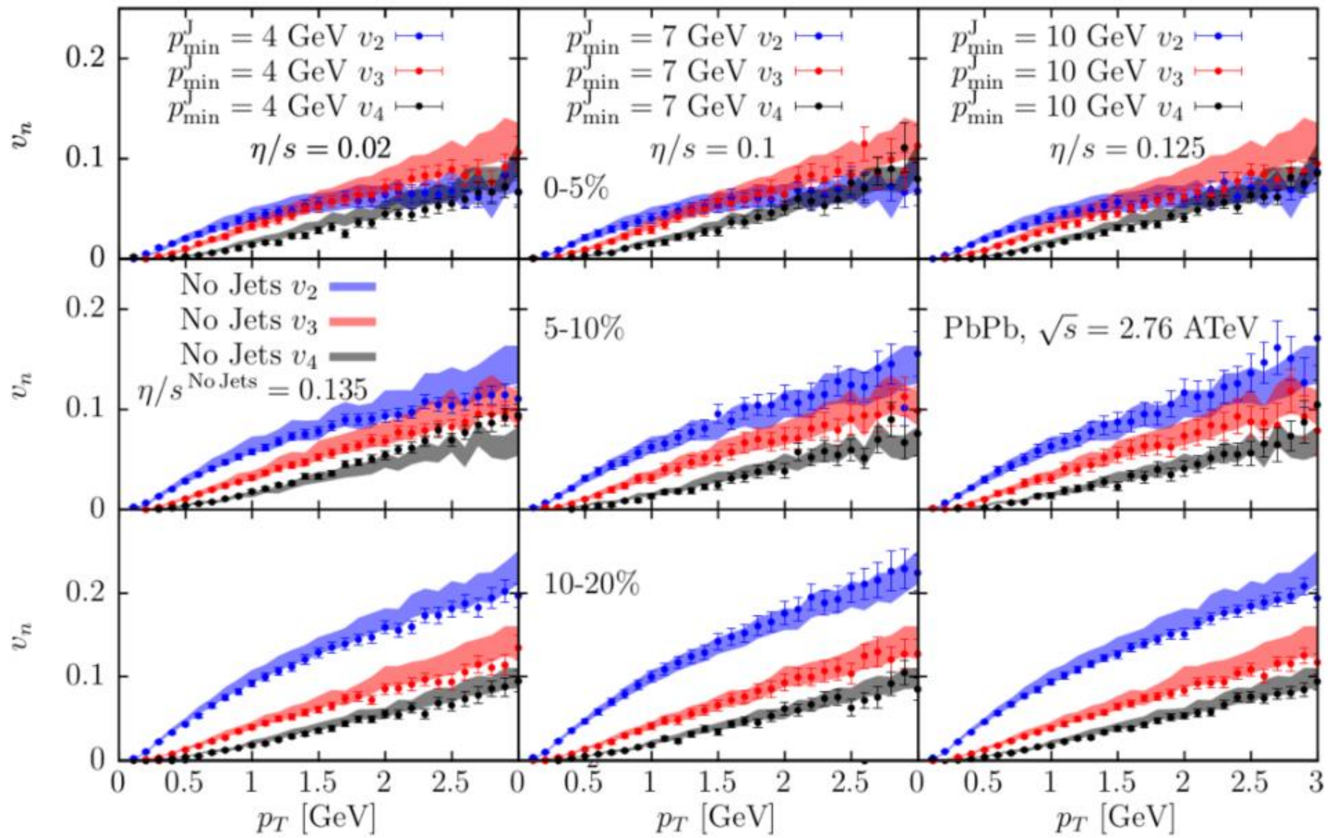
Ultra-central では b ゆらぎが抑制。実験の knee は Hydro の証拠?

Mayank Singh (Collective I)

"Quenching minijets in a concurrent jet+hydro framework"

Minijet → Flow に影響: 粘性係数決定に影響(Bayes 解析に必要)

band: jet なし、点: jet あり



Chiho Nonaka (New Theory III)

“Charge-dependent Anisotropic Flow in Relativistic Resistive Magneto-hydrodynamic Expansion”

流体+電磁場のダイナミクス (オーム抵抗)

■ RRMHD equation

➢ Conservation law + Maxwell eq. + Ohm’s law

$$\partial_\mu T^{\mu\nu} = F^{\nu\lambda} J_\lambda$$

$$J^\mu = J_c^\mu + q u^\mu$$

Ohm’s law

$$\vec{J} = q\vec{v} + \underbrace{\sigma\gamma[\vec{E} + \vec{v}\times\vec{B} - (\vec{v}\cdot\vec{E})\vec{v}]}_{=:\vec{J}_c}$$

Ampere’s law

$$\partial_t \vec{E} - \nabla\times\vec{B} = -\vec{J}$$

$$\partial_t \vec{E} - \nabla\times\vec{B} = q\vec{v}$$

$$\partial_t \vec{E} = \vec{J}_c$$

operator splitting

- Integration with quasi-analytic solutions

$$\vec{E}_\perp = -\vec{v}\times\vec{B} + \left(E_\perp^0 + \vec{v}\times\vec{B}\right)\exp(-\sigma\gamma t)$$

$$\vec{E}_\parallel = E_\parallel^0 \exp(-\sigma t/\gamma)$$

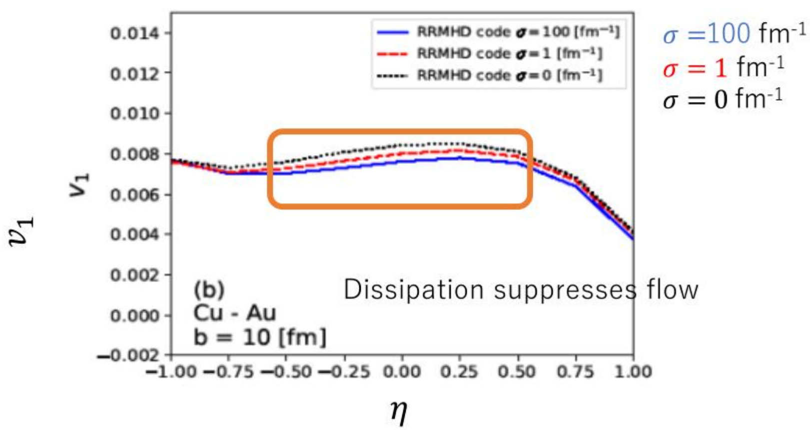
Chiho Nonaka (New Theory III)

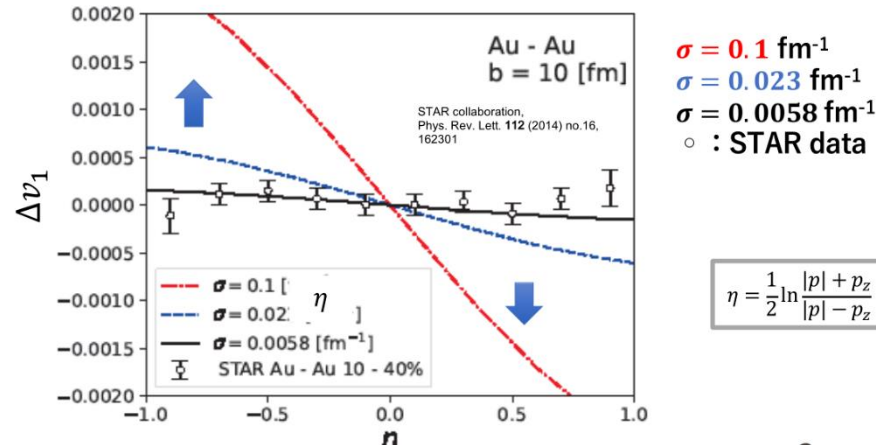
"Charge-dependent Anisotropic Flow in Relativistic Resistive Magneto-hydrodynamic Expansion"

Directed flow

$$\Delta v_1 = v_1^{\pi^+}(\eta) - v_1^{\pi^-}(\eta)$$

- Cu-Au collisions $(\sqrt{s_{NN}} = 200\ \text{GeV})$
  - Decreases with conductivity
  - Dissipation suppresses flow in the Cu direction



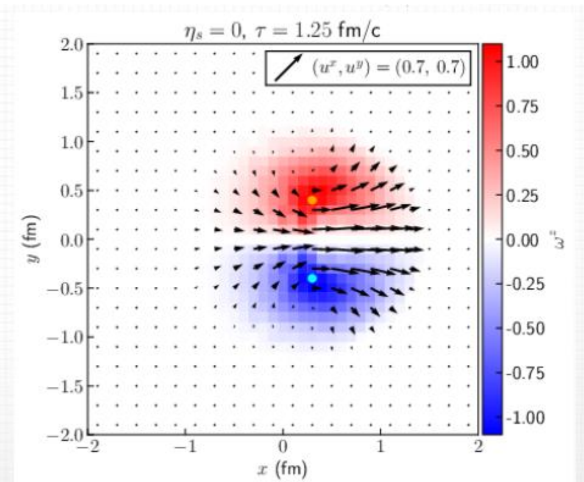


$$\eta = \frac{1}{2}\ln\frac{|p| + p_z}{|p| - p_z}$$

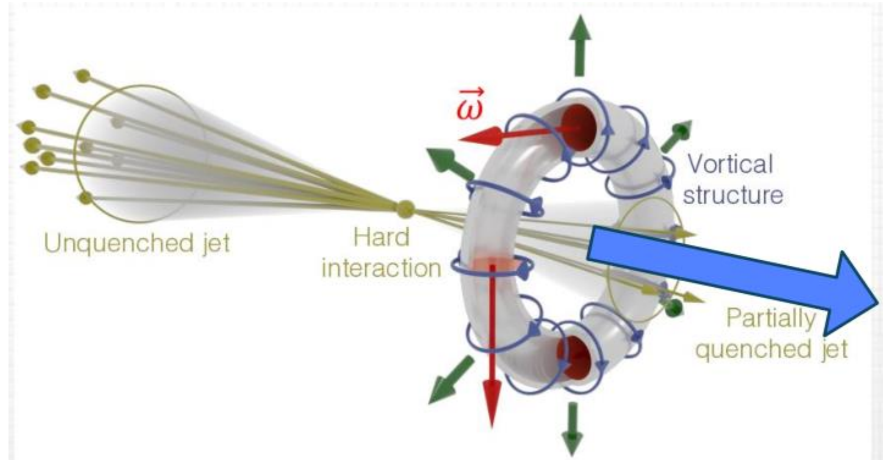
Willian M. Serenone (Chirality I)

“QGP vortex rings as a new probe for jet-induced medium response and longitudinal dynamics”

arXiv:2305.02428



W. M. Serenone *et. al.*, Phys. Lett. B **820**, 136500 (2021)



Ring-observable proposal: $R^t_\Lambda = \left\langle \frac{\vec{P}_\Lambda \cdot (\hat{t} \times \vec{p})}{|\hat{t} \times \vec{p}|} \right\rangle_{p_\perp, y}$

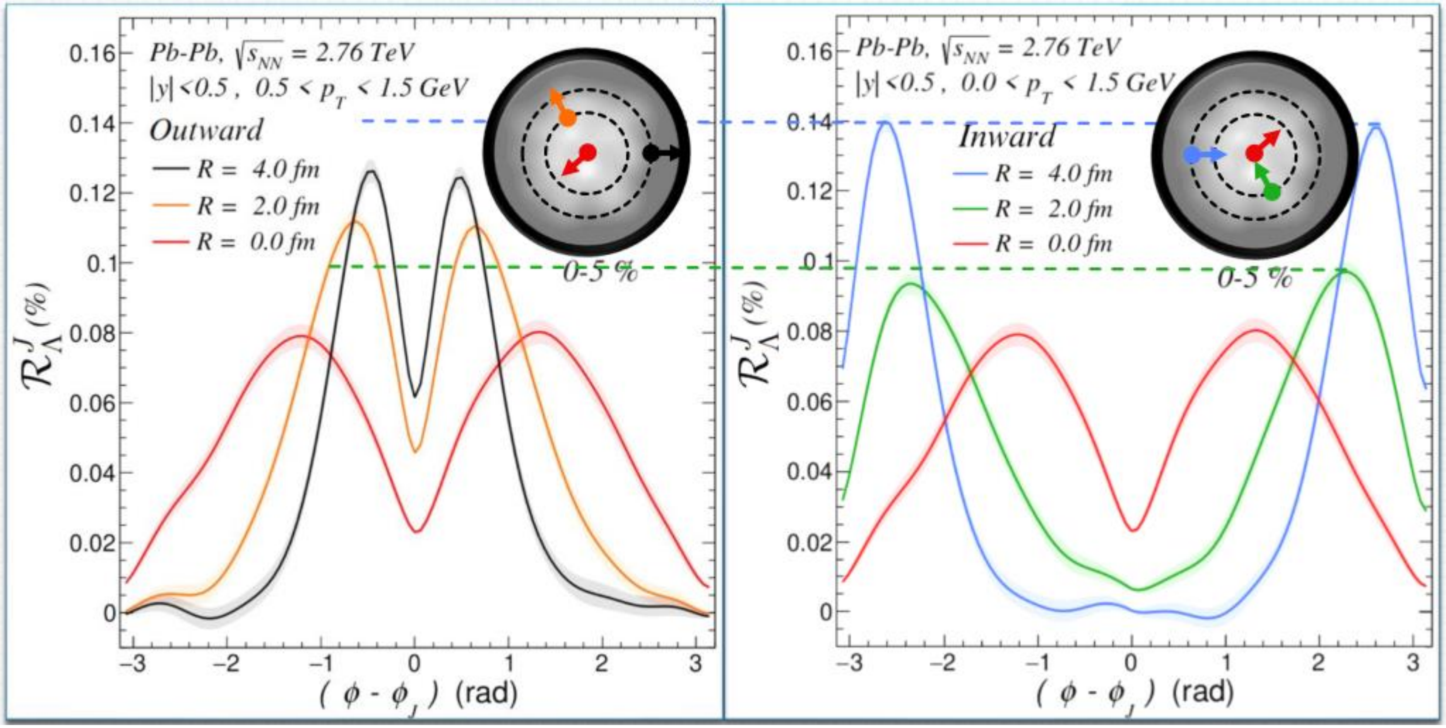
P_Λ: Λ polarization vector, p: momentum

Willian M. Serenone (Chirality I)

“QGP vortex rings as a new probe for jet-induced medium response and longitudinal dynamics”

様々な位置・角度でジェットを置き流体計算 → R_Λ を計算

Ribeiro *et. al.*, arXiv: 2305.02428

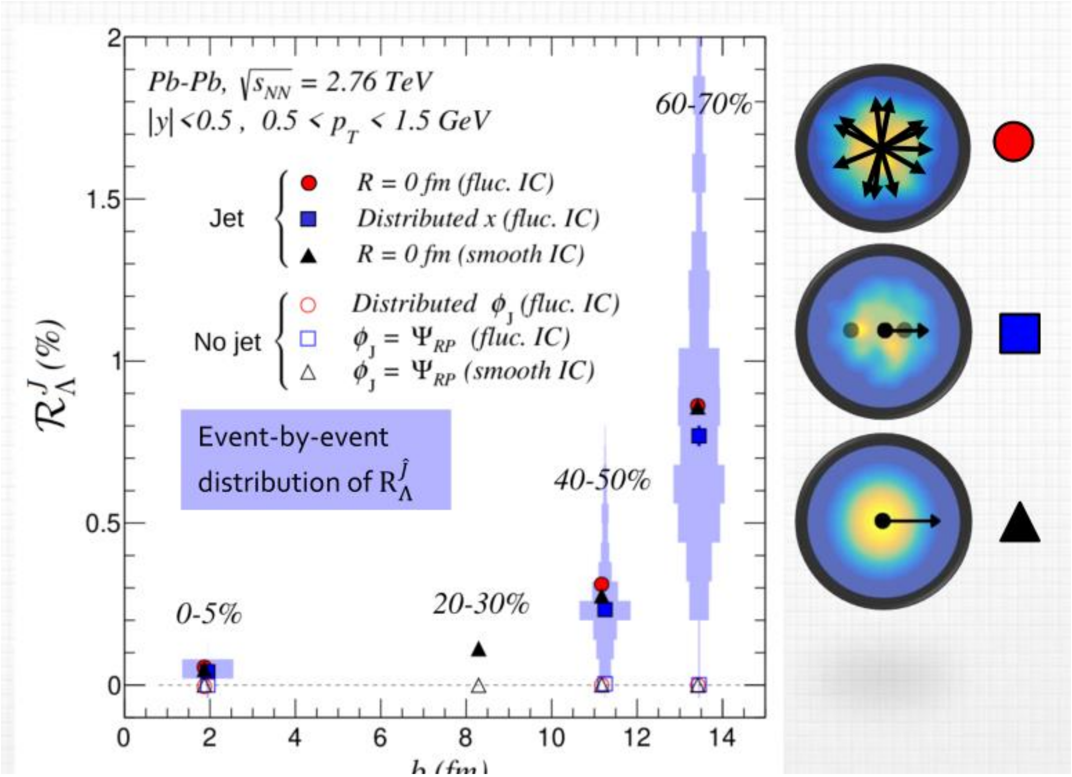


内向きの方が大きく出る

Willian M. Serenone (Chirality I)

“QGP vortex rings as a new probe for jet-induced medium response and longitudinal dynamics”

イベント平均 & 方位角 φ 平均



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Zhong Yang (Jets IV)

"Jet-flow coupling in heavy-ion collisions and the jet-induced diffusion wake"

CoLBT-hydro model

1. LBT for energetic partons(jet shower and recoil)

2. Hydrodynamic model for bulk and soft hadrons: CLVisc

3. Sorting jet partons according to a cut-off parameter p^0_{cut}

   hard partons: $p\partial f(p) = -C(p) \quad (p \cdot u > p^0_{cut})$

   soft and negative partons:

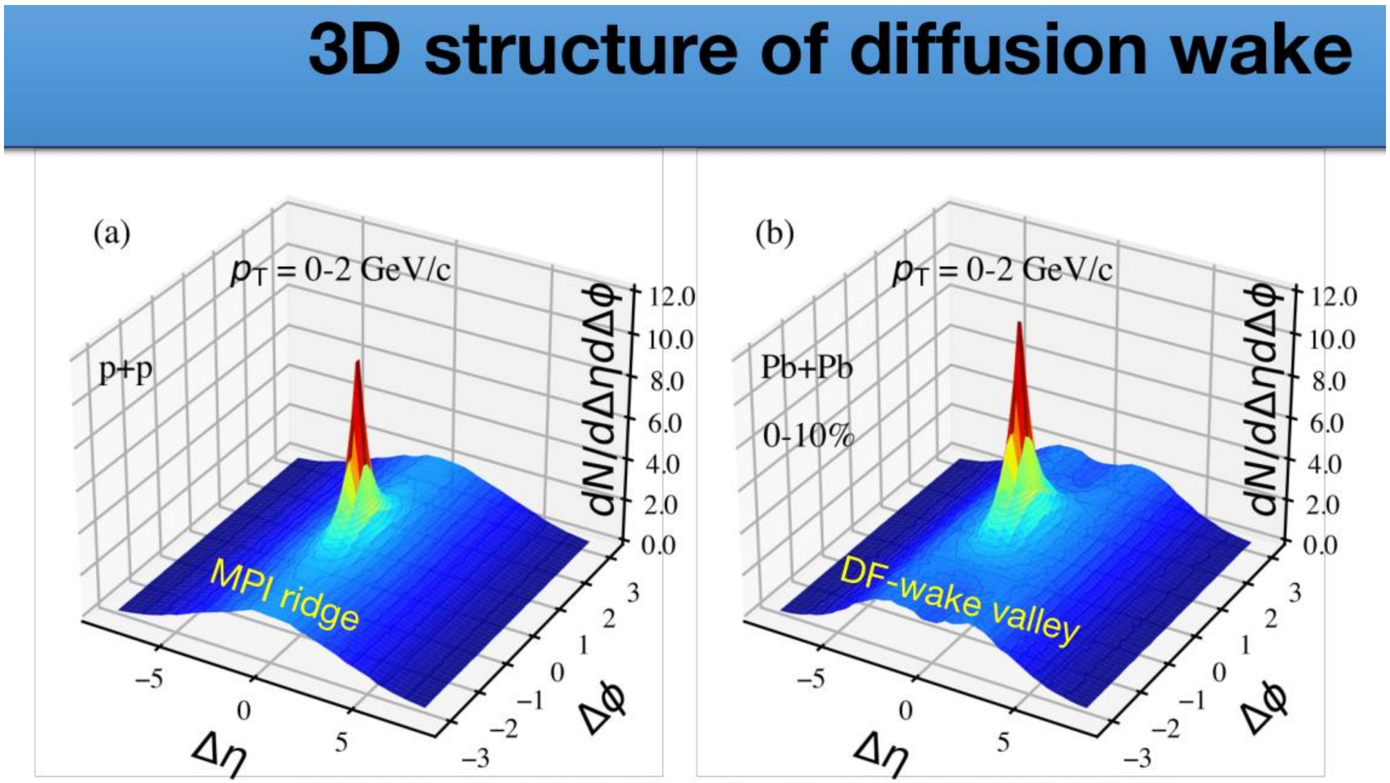
$$j^\nu = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p \cdot u)$$

4. Updating medium information by solving the hydrodynamic equation with source term

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

Zhong Yang (Jets IV)

"Jet-flow coupling in heavy-ion collisions and the jet-induced diffusion wake"

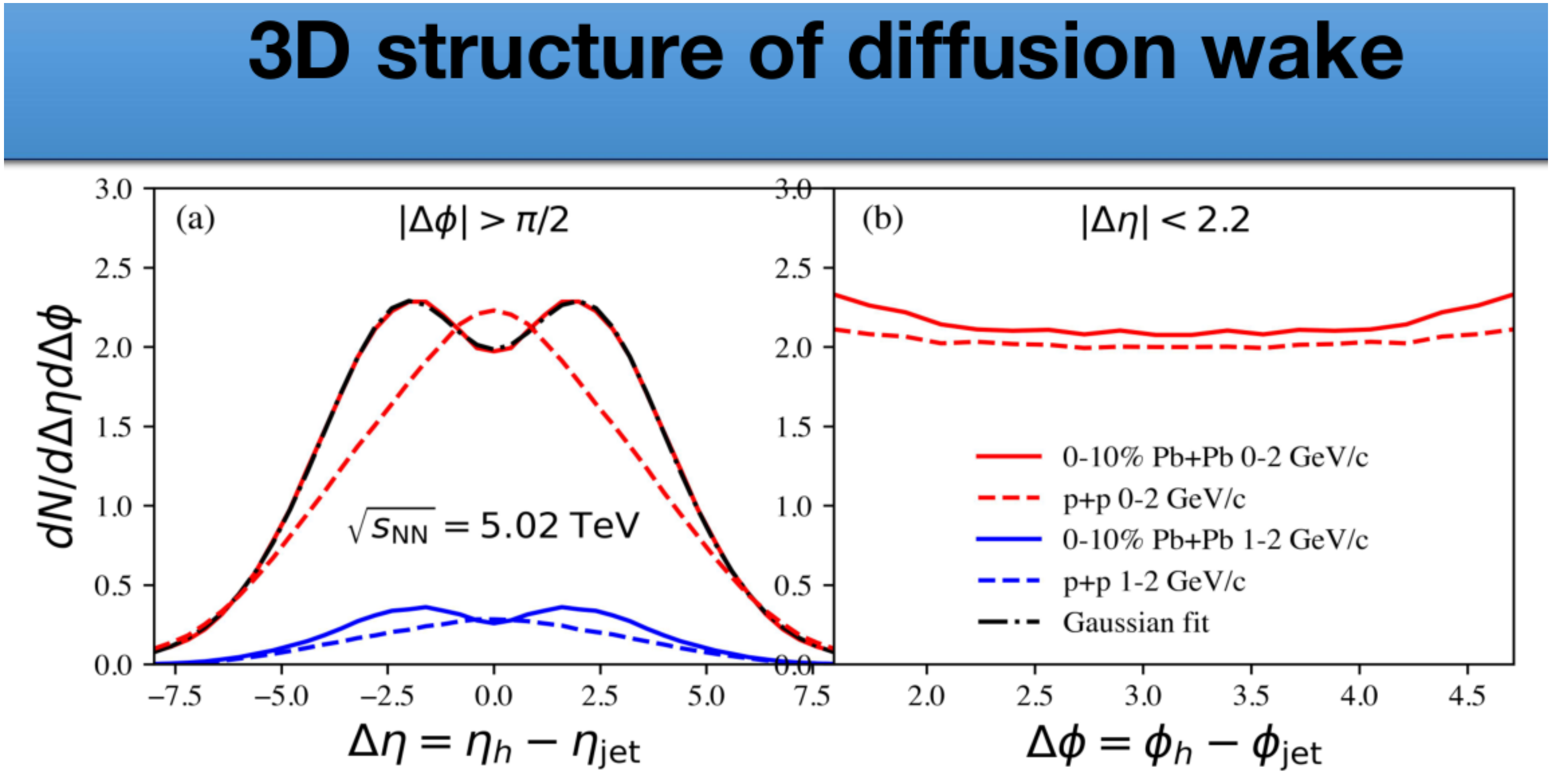


Yang, Luo, Chen, Pang, Wang, Phys.Rev.Lett., 2023,130(5):052301

Zhong Yang (Jets IV)

“Jet-flow coupling in heavy-ion collisions and the jet-induced diffusion wake”

これまでは diffusion wake の Δφ 依存性を見ていたが Δη 依存性も見る



Yang, Luo, Chen, Pang, Wang, Phys.Rev.Lett., 2023,130(5):052301

まとめ: 今後の動的模型の発展の方向

- **原子核変形・核子分布** (分野横断的方向性)
  ← 方位角異方性、UPC、UCC、…
- **Baryon-charge-strangeness currents**
  (EOS、初期条件、輸送係数)
- **Mini-jets、jet-induced medium response**、…
- **ベイズ解析**: 個別物理のパラメータ決定にも
  (初期条件、mini-jets、VAH、…)
- **軽原子核・ハイパー核の生成過程**
  (CP signal, hadron spectroscopy & femtoscopy)
- **臨界・一次相転移のダイナミクス**

OTHERS

Nick Abboud (Chirality I)

"A new causal and stable theory of viscous chiral hydrodynamics"

arXiv:2308.02928

Fixing the bad term

NA, E. Speranza, J. Noronha
arXiv:2308.02928

$$T^{\mu\nu} = (\varepsilon + \mathcal{A})u^\mu u^\nu + (P + \Pi)\Delta^{\mu\nu} + \mathcal{Q}^\mu u^\nu + \mathcal{Q}^\nu u^\mu + \mathcal{T}^{\mu\nu}$$

$$J_5^\mu = (n_5 + \mathcal{N}_5)u^\mu + \mathcal{J}_5^\mu$$

BAD

$$\cdots$$

$$\mathcal{Q}^\nu = \theta_1 \nabla_\perp^\mu \varepsilon + \theta_2 D u^\mu + \theta_3 \nabla_\perp^\mu n_5 + \theta_E E^\mu + \xi_{T\omega}\omega^\mu + \xi_{TB} B^\mu$$

hydrodynamic frame
=
definition of
hydrodynamic fields
$\varepsilon,\ n_5,\ u^\alpha$

frame transformation

$$u^\mu \to u^\mu - \frac{\xi_{T\omega}}{\varepsilon + P}\omega^\mu$$

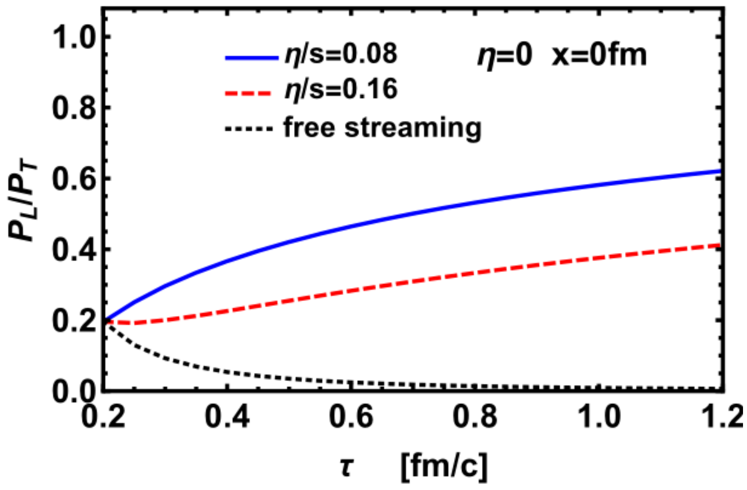
因果律・安定性・etc で問題のある項は
フレームの取り直しで消去できる

Piotr Bozek (Sep 5 Collective I)

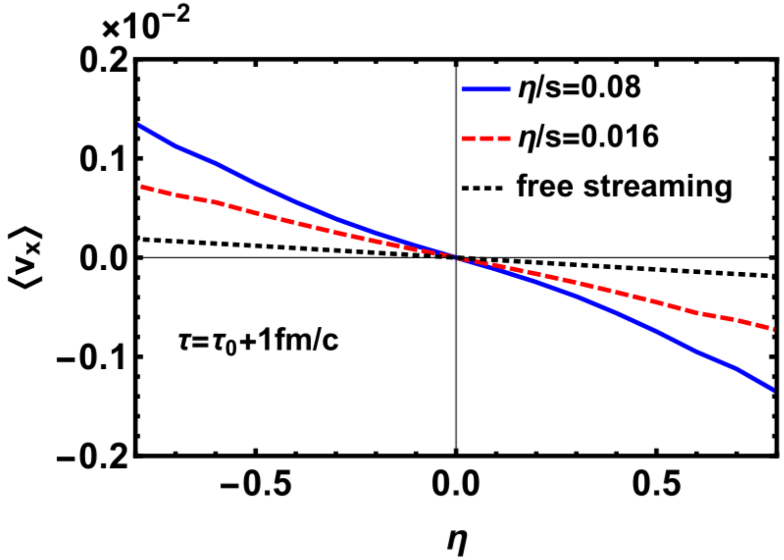
“Can we observe effects of the early nonequilirium dynamics in the collective flow”

Method: 2+1D Kinetic theory (cylindrical sym)

Equlibration rate



Directed flow



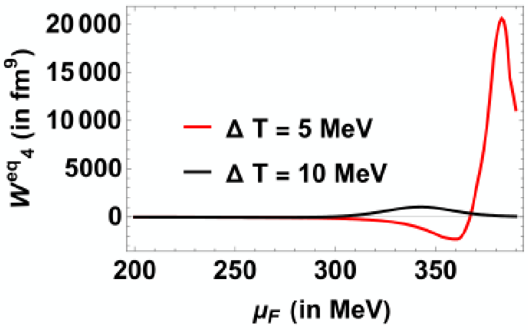
Directed flow probes equlibration rate

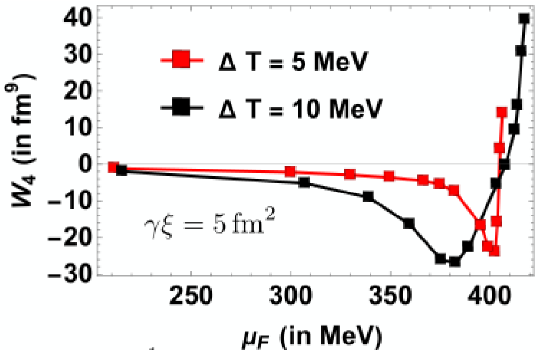
Maneesha Pradeep (Sep 5 CP I)

"Critical expectations : Non-Gaussian cumulants of Particle multiplicity near the critical point"

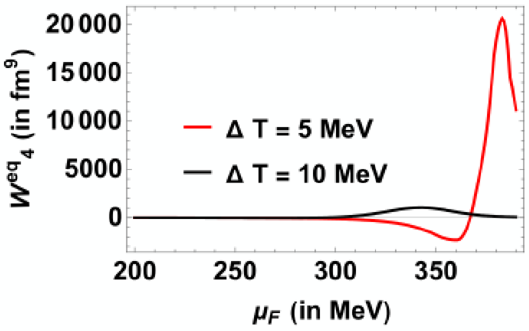
手法: Hydro+

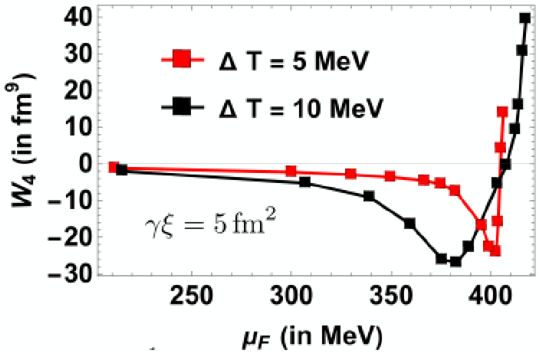
4pt correlation





3pt correlation





Wei-jie Fu (Sep 5 CP I)

“Baryon number fluctuations at high baryon density”

手法: First-principles QCD within fRG