Recent Developments in Heavy-Ion Theory

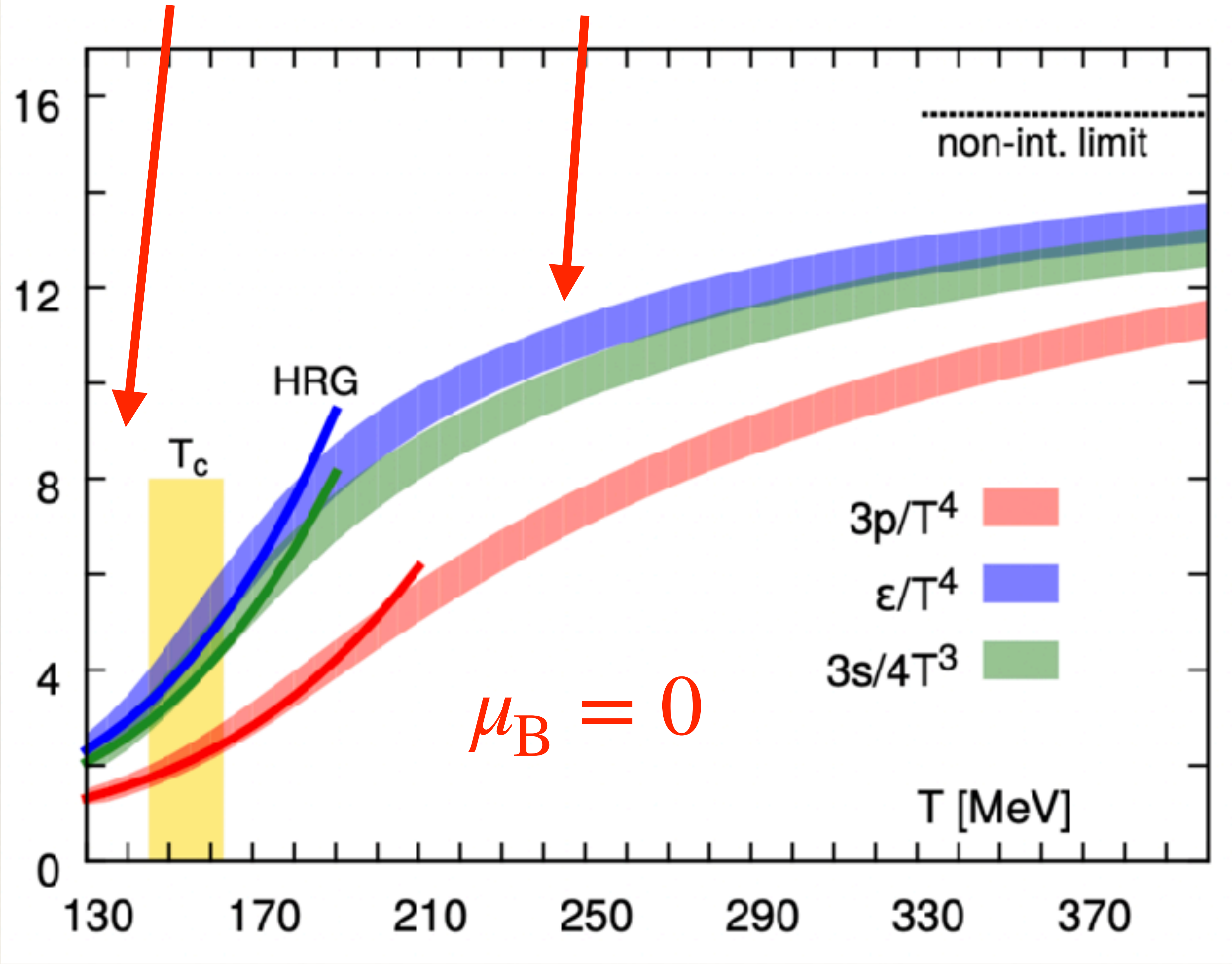
Shanshan Cao

Shandong University

QCD matter under extreme conditions

Lattice equation of state

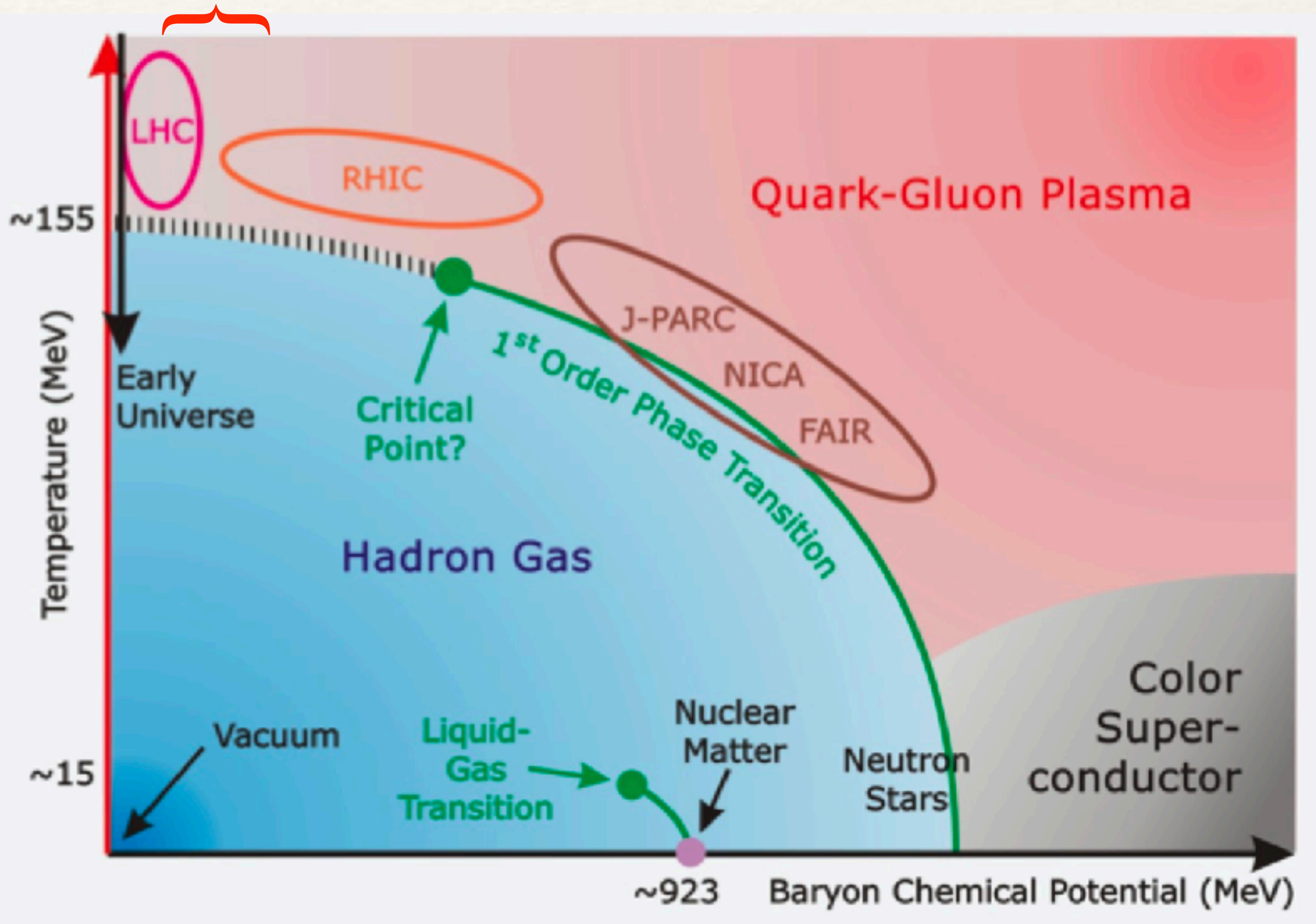
hadron gas quark-gluon plasma



[HotQCD, Phys. Rev. D 90 (2014) 094503]

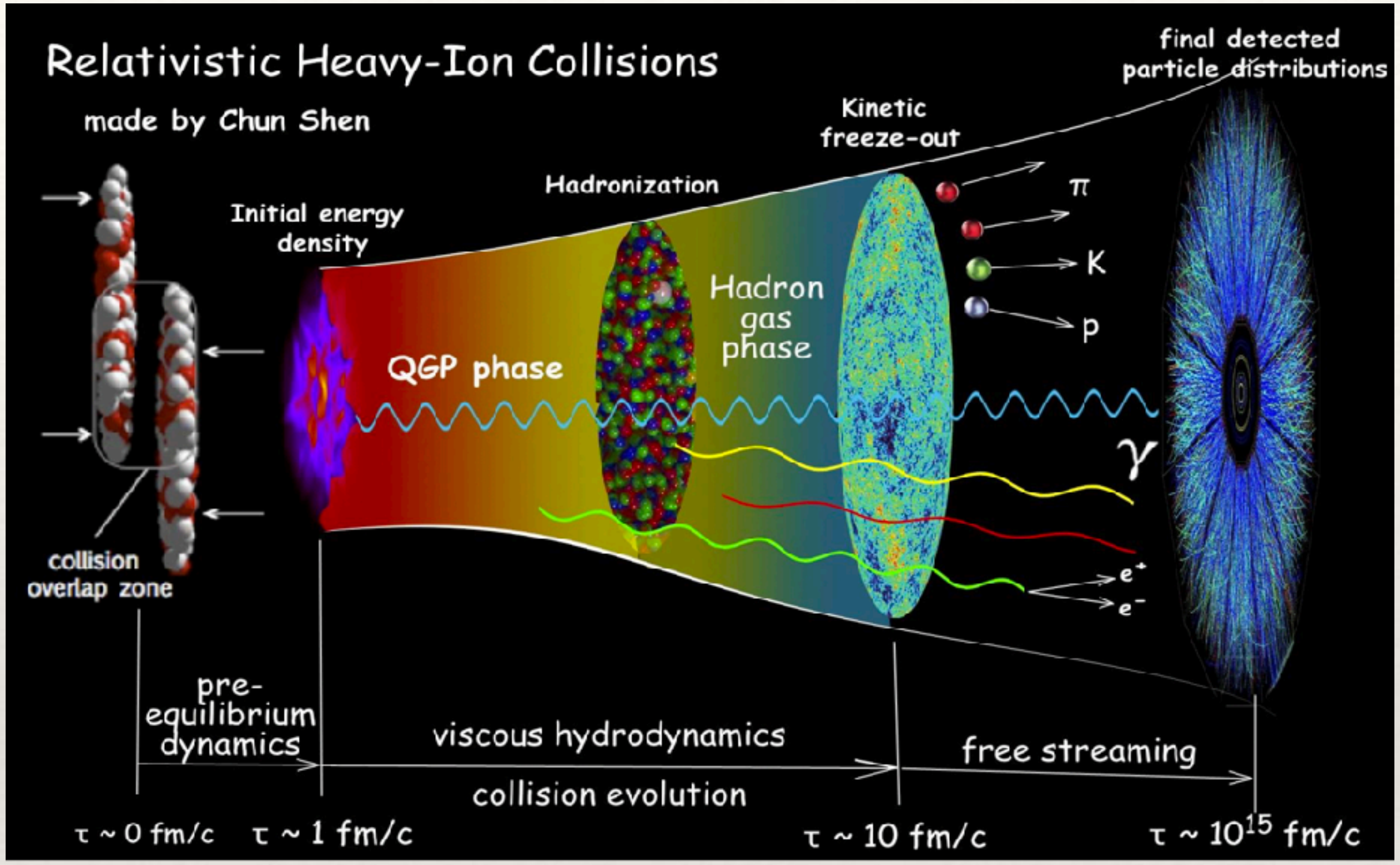
Exploring QCD phase diagram with current and future facilities

this talk



[by A. Steidl]

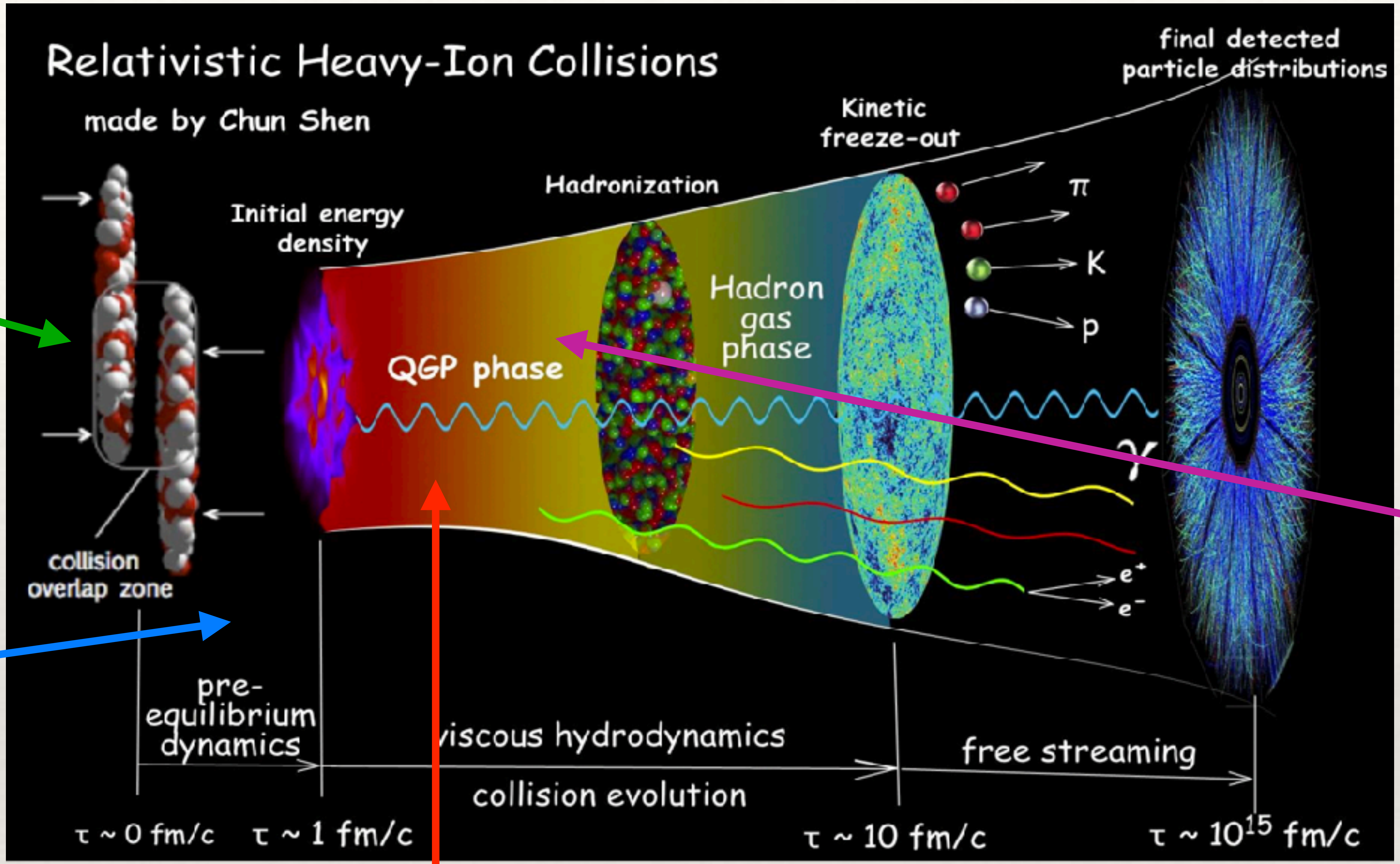
Questions and challenges for ultra-relativistic collisions



Questions and challenges for ultra-relativistic collisions

What is the initial condition?

How does nuclear matter thermalize?



How does deconfined state transit into confined state?

What are the thermal and transport properties of the QGP?

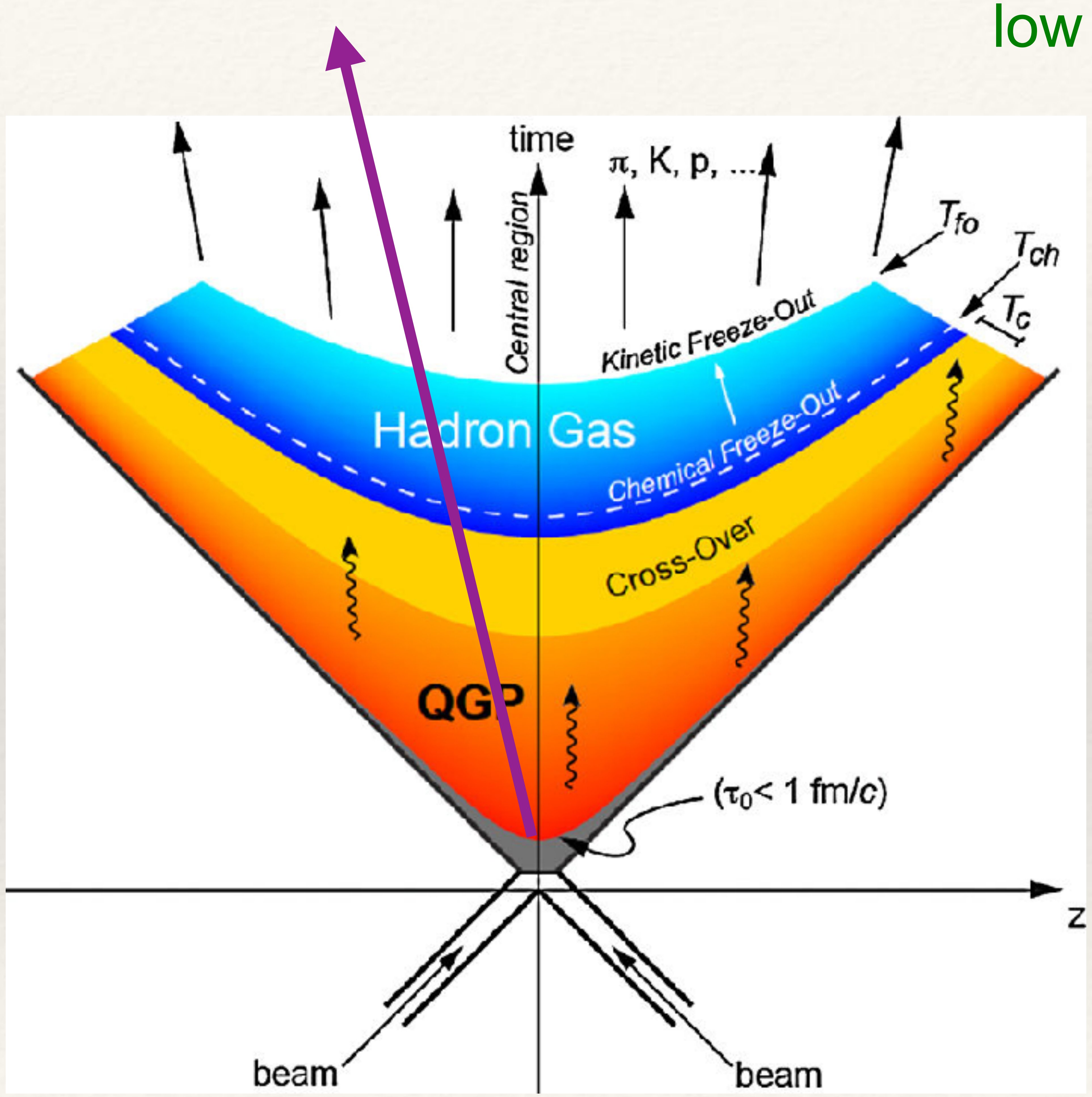
How do energetic particles interact with the QGP?

- **Challenges:** non-perturbative nature of QCD, many-body problem, …

Different probes of nuclear matter

Hard probes
jets and heavy quarks
from initial high-Q^2 processes

Soft probes
low p_T hadrons emitted by the QGP
from chemical freeze-out

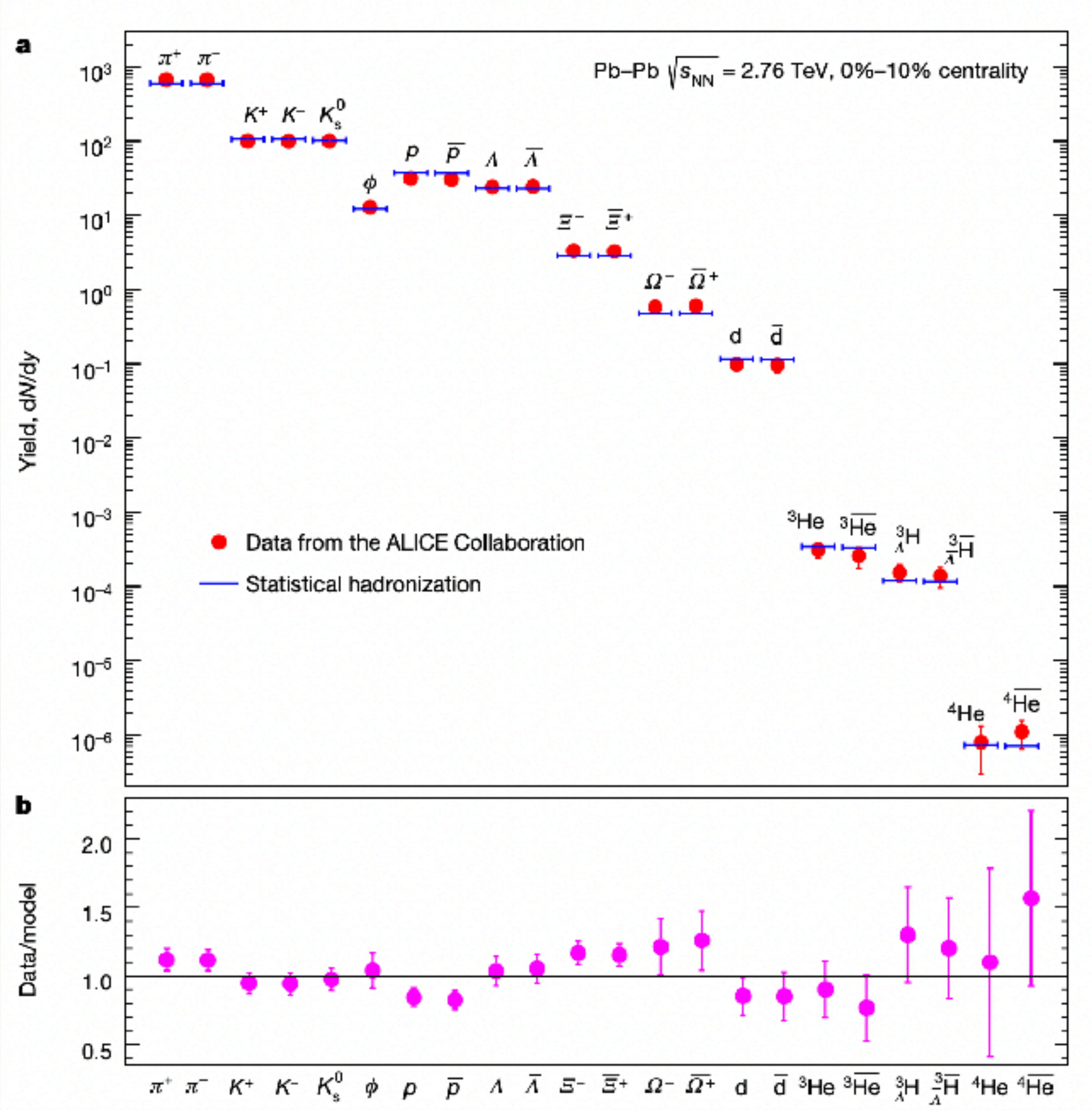


Electromagnetic probes
photons, di-leptons
from the whole evolution

[by M. Rybar / ATLAS]

Soft hadron yields

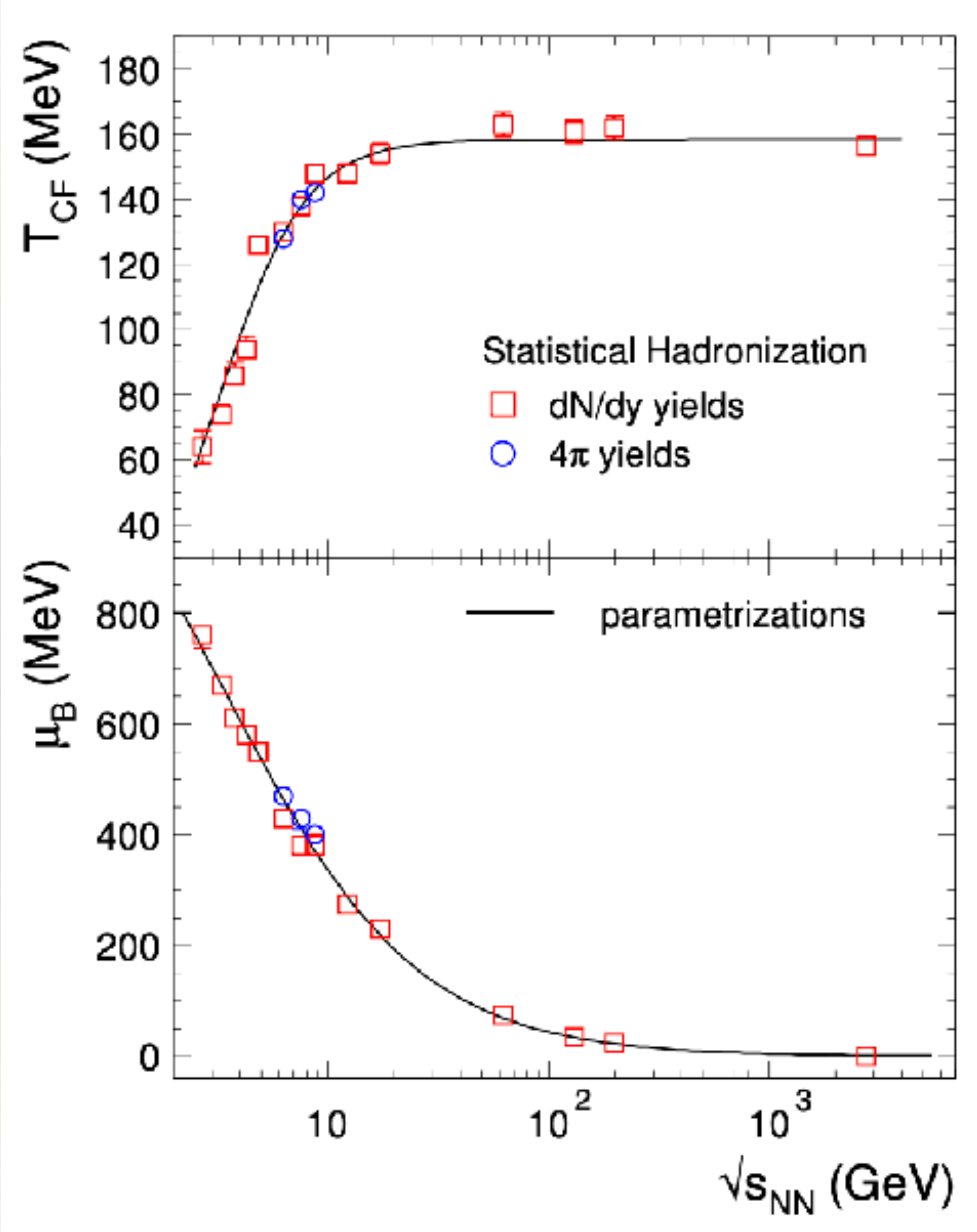
Surprisingly good description by the thermal model

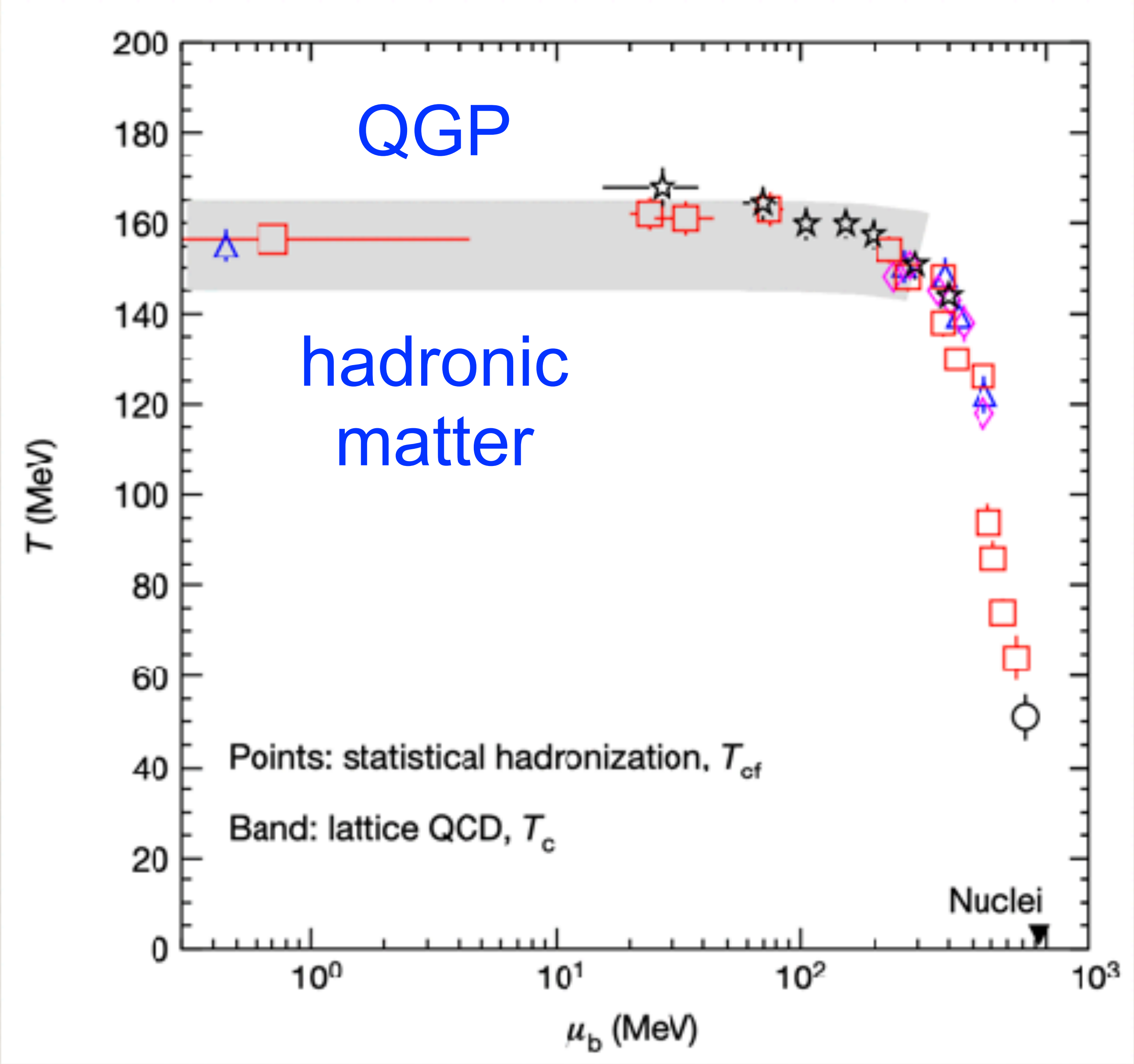


[Andronic *et al.*, Nature 561, 321 (2018)]

Extraction of thermal properties

Boltzmann statistics → $N_i = \frac{g_i V T^3}{2\pi^2} e^{\mu_i/T} \frac{m_i^2}{T^2} K_2\left(\frac{m_i}{T}\right)$

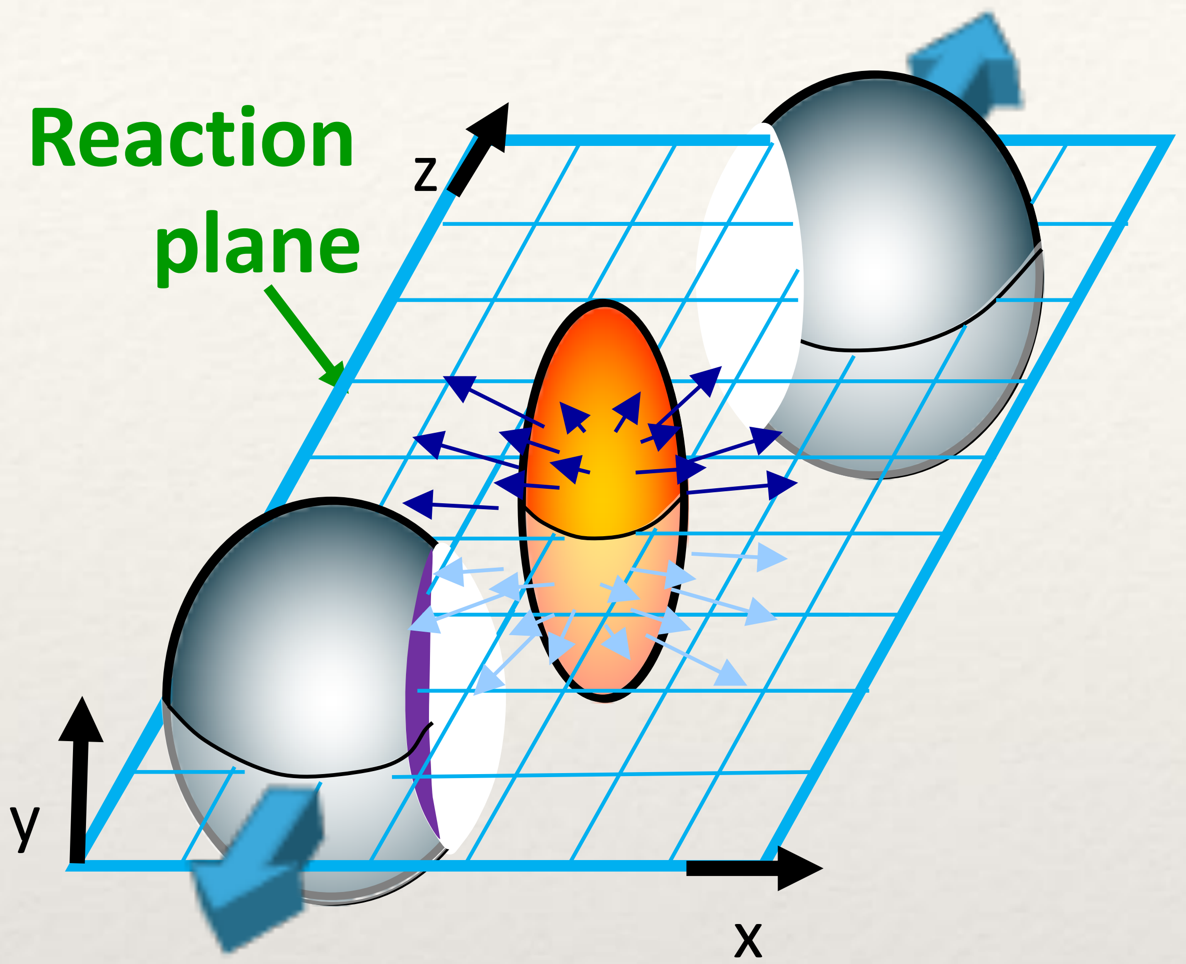




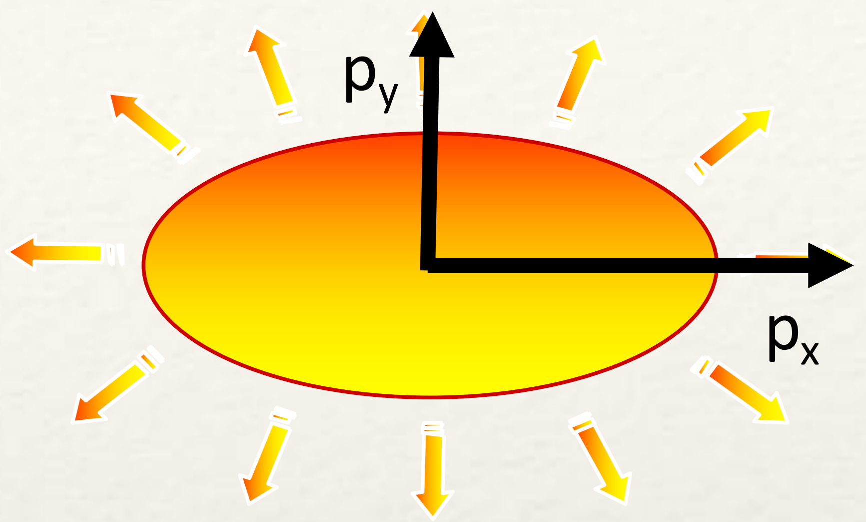
Limits:

- no dynamic information
- not valid at high p_T

Collective flow of soft hadrons



Geometric anisotropy



Elliptic flow:

$$v_2 \equiv \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

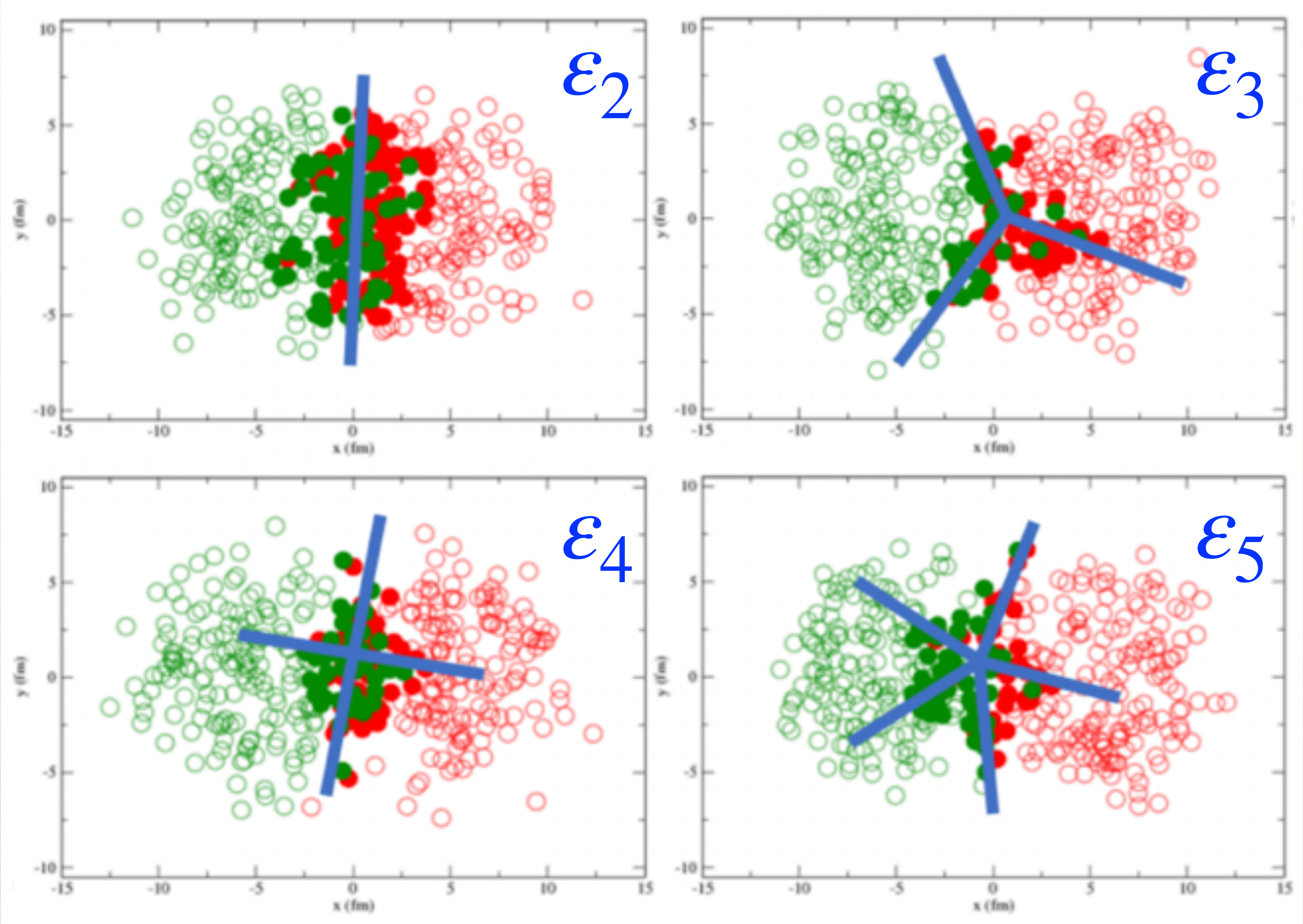
Momentum space anisotropy

Collective flow coefficients:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left\{1 + \sum_n 2v_n \cos\left[n\left(\varphi - \Phi_n\right)\right]\right\}$$

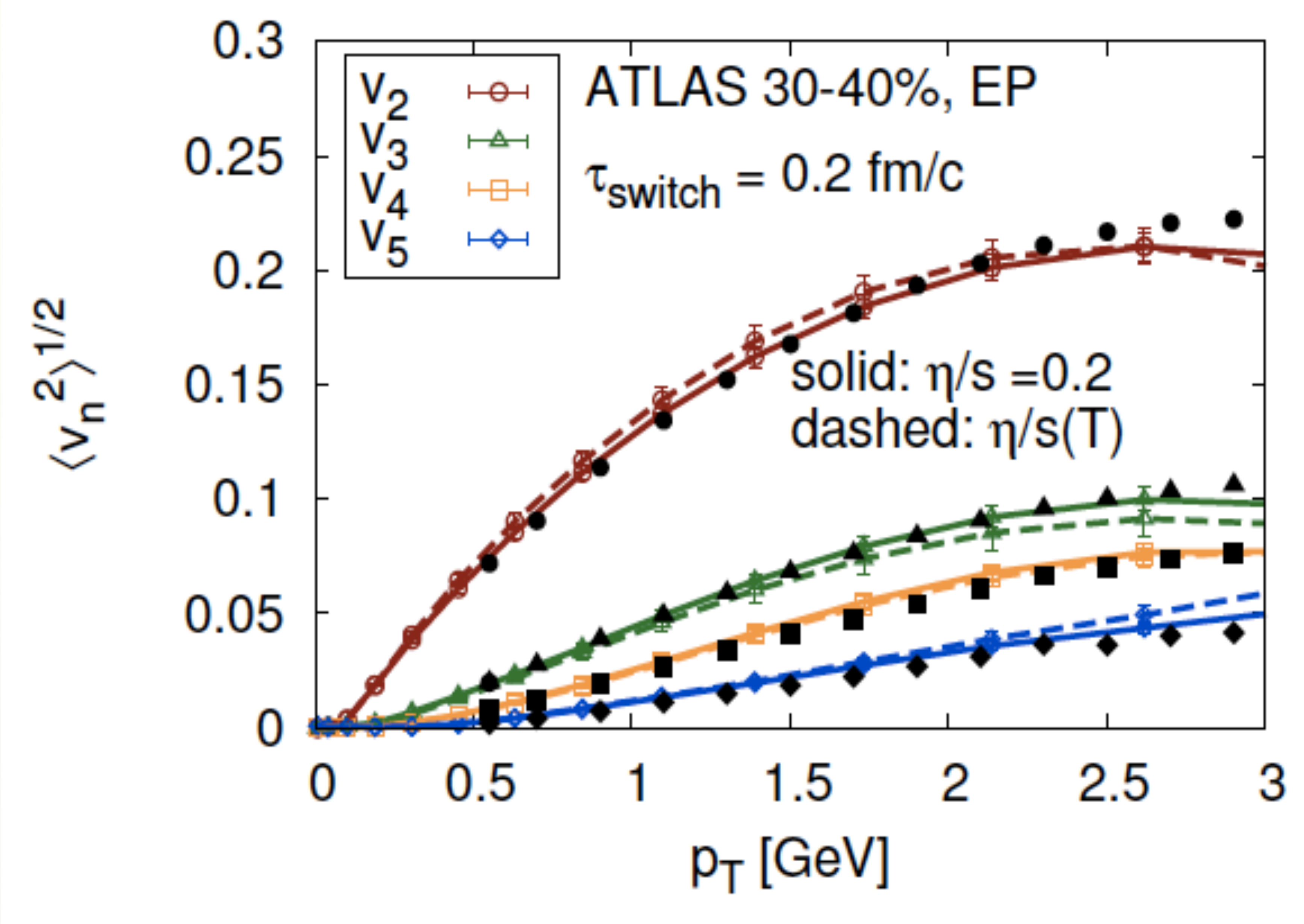
Successful description by hydrodynamic model

With initial state fluctuations



[Qin, Int. J. Mod. Phys. E 24 (2015) 02, 1530001]

Hydrodynamic calculation of v_n

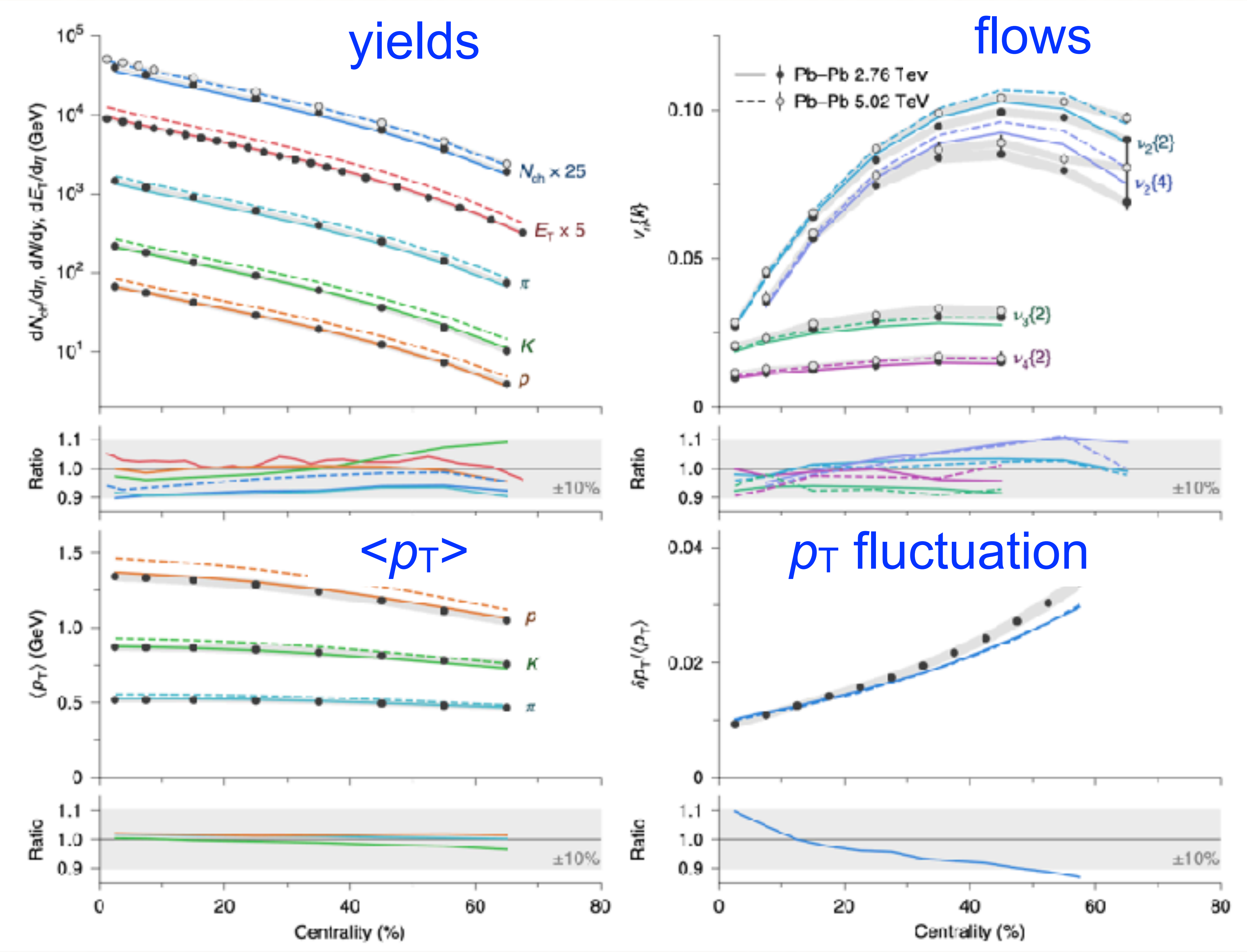


[Schenke *et al.*, PRL 108, 25231 (2012)]

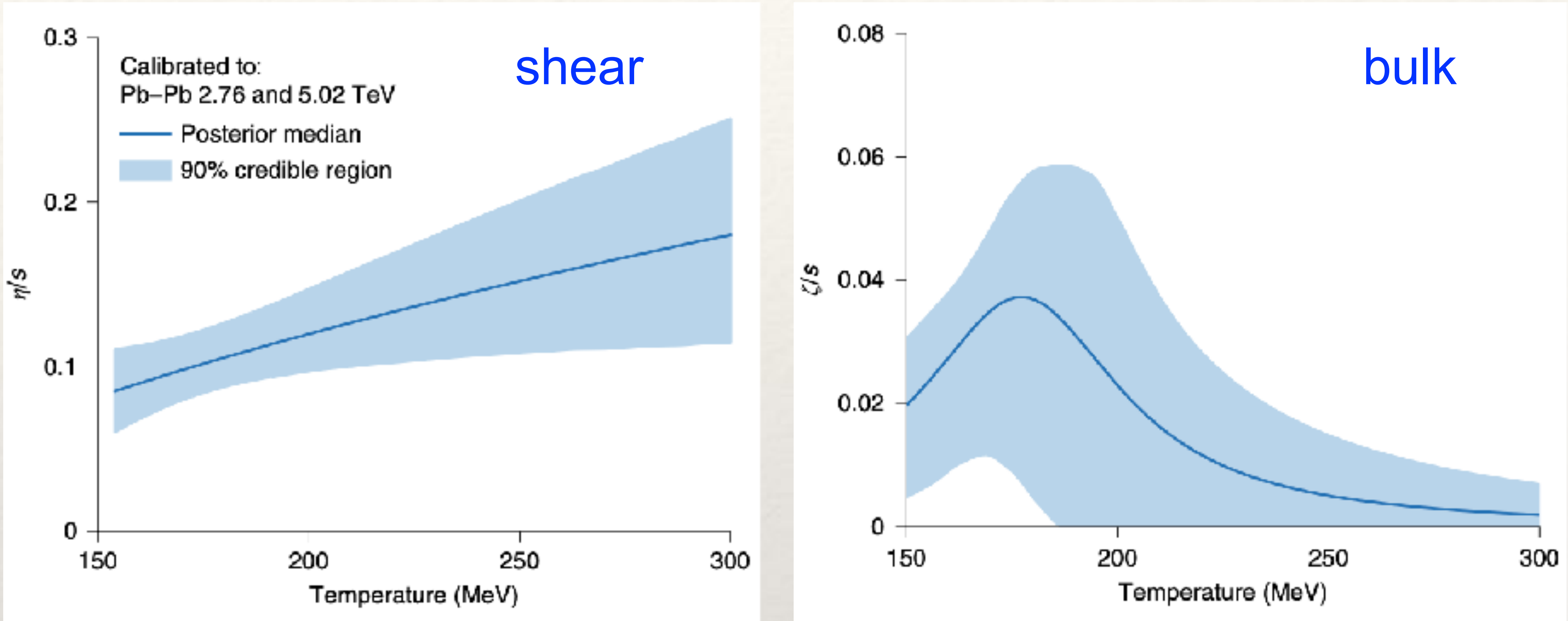
- **Small shear viscosity** extracted from model to data comparison
- QGP is a **strongly coupled system** and displays properties close to ideal fluid

Constraints on the QGP properties

Bayesian calibration of hydrodynamic model



Shear and bulk viscosities of the QGP

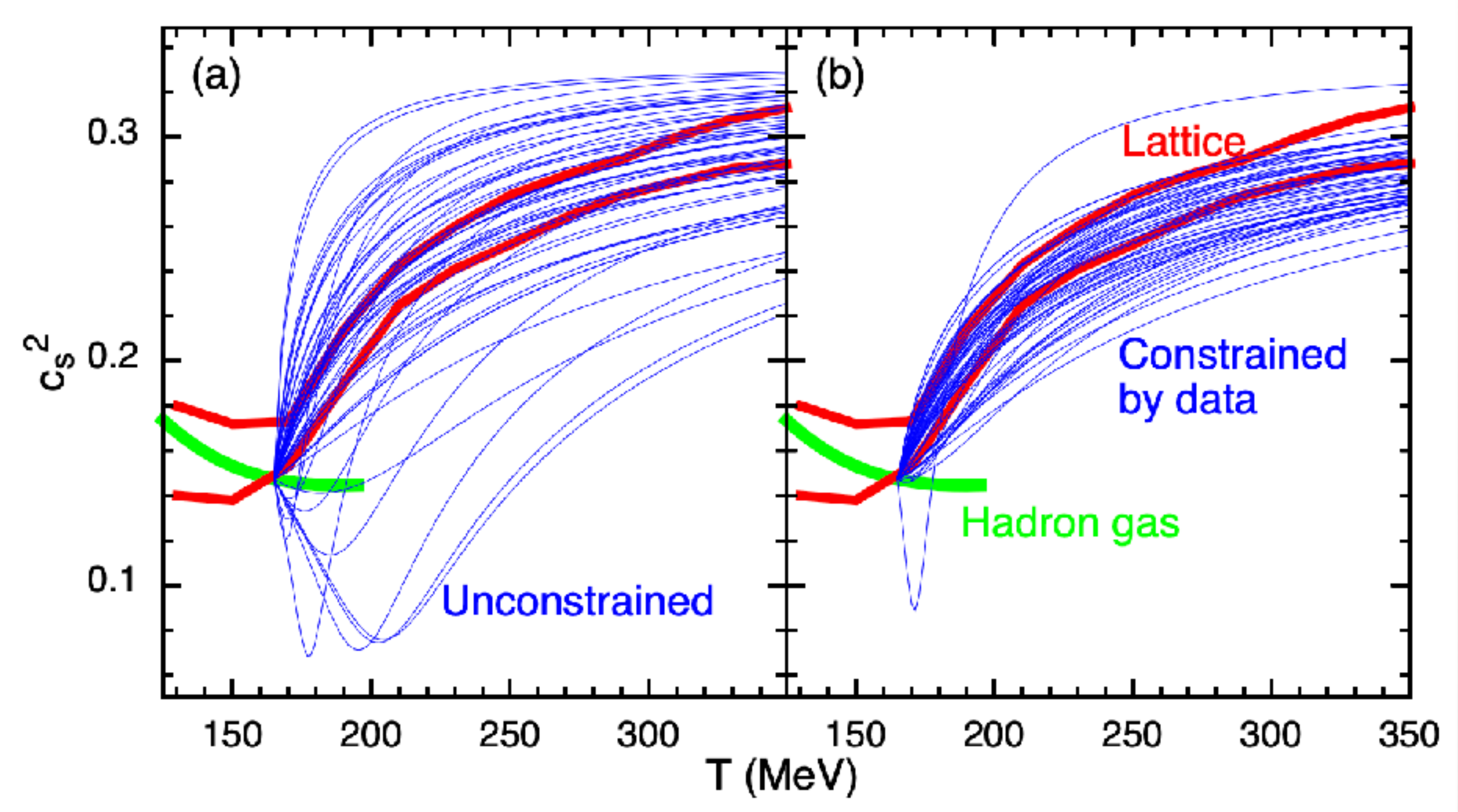


[Bernhard, Moreland, Bass, Nature Phys. 15 (2019) 11, 1113]

New challenges:

- ALICE measurement of collective flow coefficients up to the 9th order [JHEP 05 (2020) 085]
- Expect more stringent constraints on model calculations and the extracted QGP properties

Constraints on the QGP Equation of State (EoS)



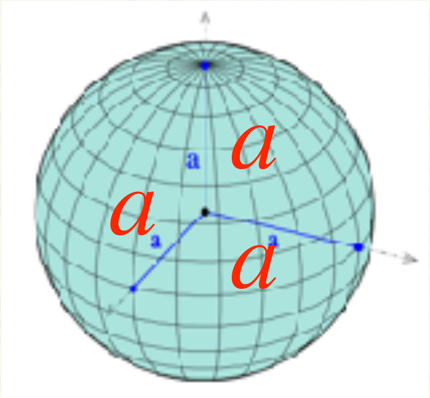
[Pratt, *et al.*, Phys. Rev. Lett. 114 (2015) 202301]

- Bayesian calibration on the p, K, π yields, v_2 of π, and two-particle femtoscopic source sizes from ALICE measurements
- Experimental data prefer an EoS that is consistent with the Lattice QCD prediction

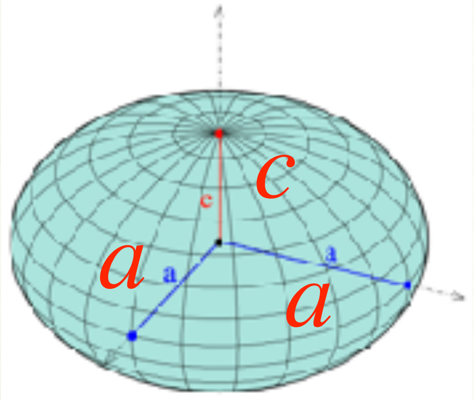
Constraints on the Nucleus Geometry

Nucleon distribution (Woods Saxon)

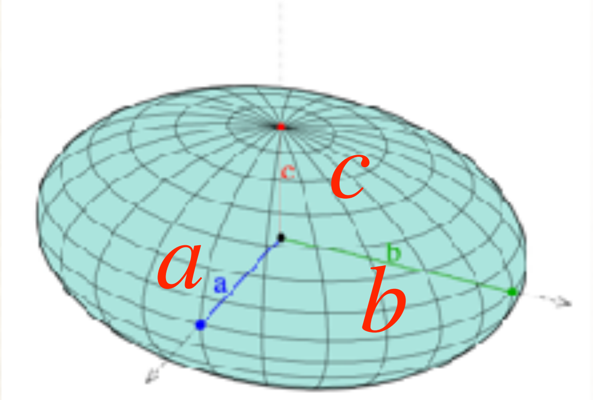
$$\rho(\vec{r}) = \left\{ 1 + \exp\left[r - R_0 \left(1 + \beta_2 \left[Y_2^0(\theta,\phi)\cos\gamma + Y_2^2(\theta,\phi)\sin\gamma \right] \right) \right] \right\}^{-1}$$



$\beta_2 = 0$



$\beta_2 \neq 0, \gamma = 0$



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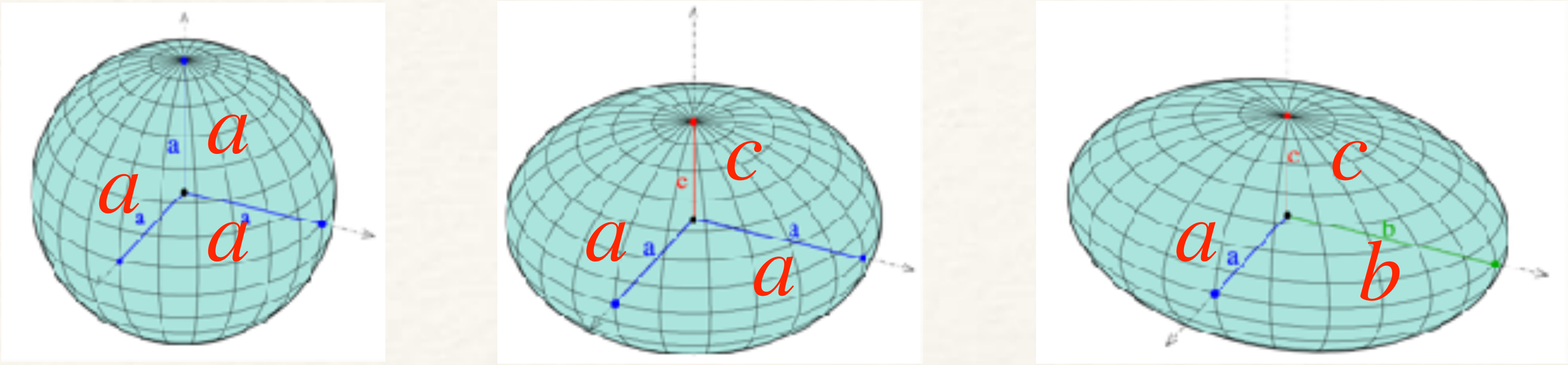
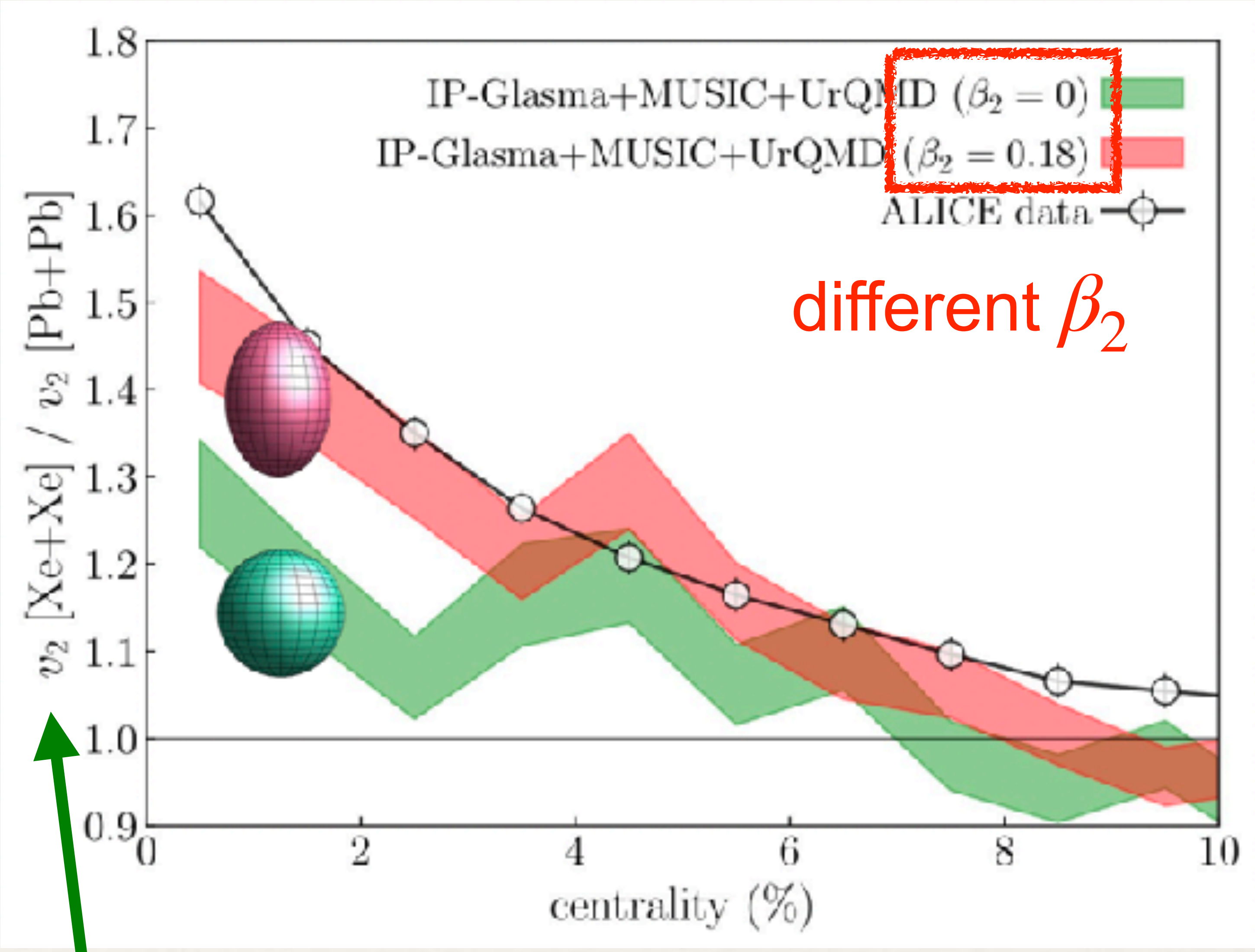


$\beta_2 = 0$ $\quad$ $\beta_2 \neq 0, \gamma = 0$ $\quad$ $\beta_2 \neq 0, \gamma \neq 0$

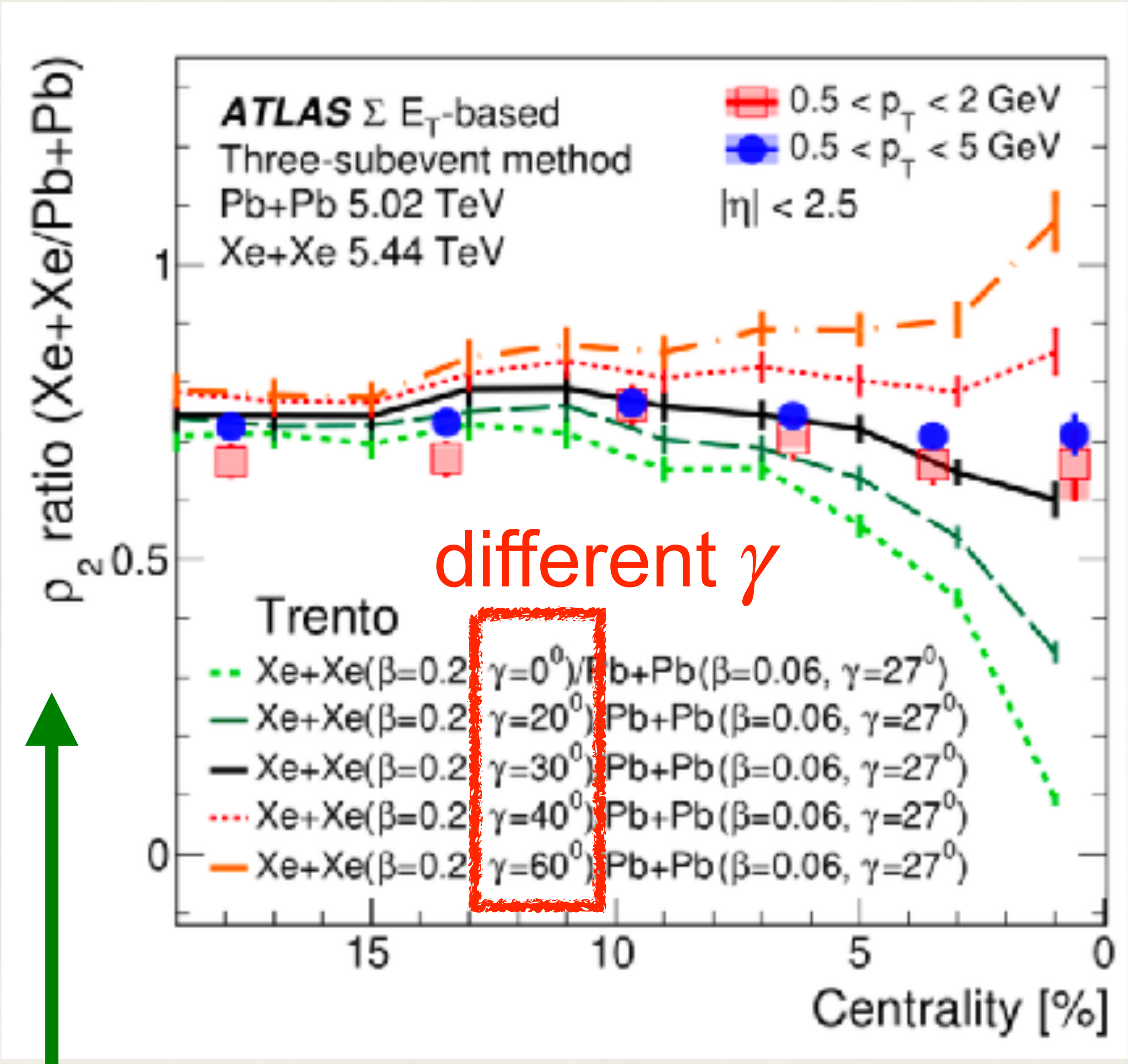
Deformation of Xe



v_2

[Bally *et al.*, arXiv:2209.11042]

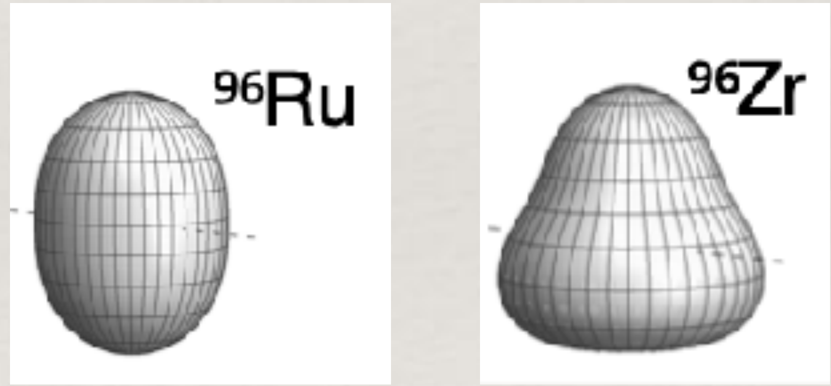
Triaxial structure of Xe



Correlation between v_2^2 and δp_T
(Pearson coefficient)

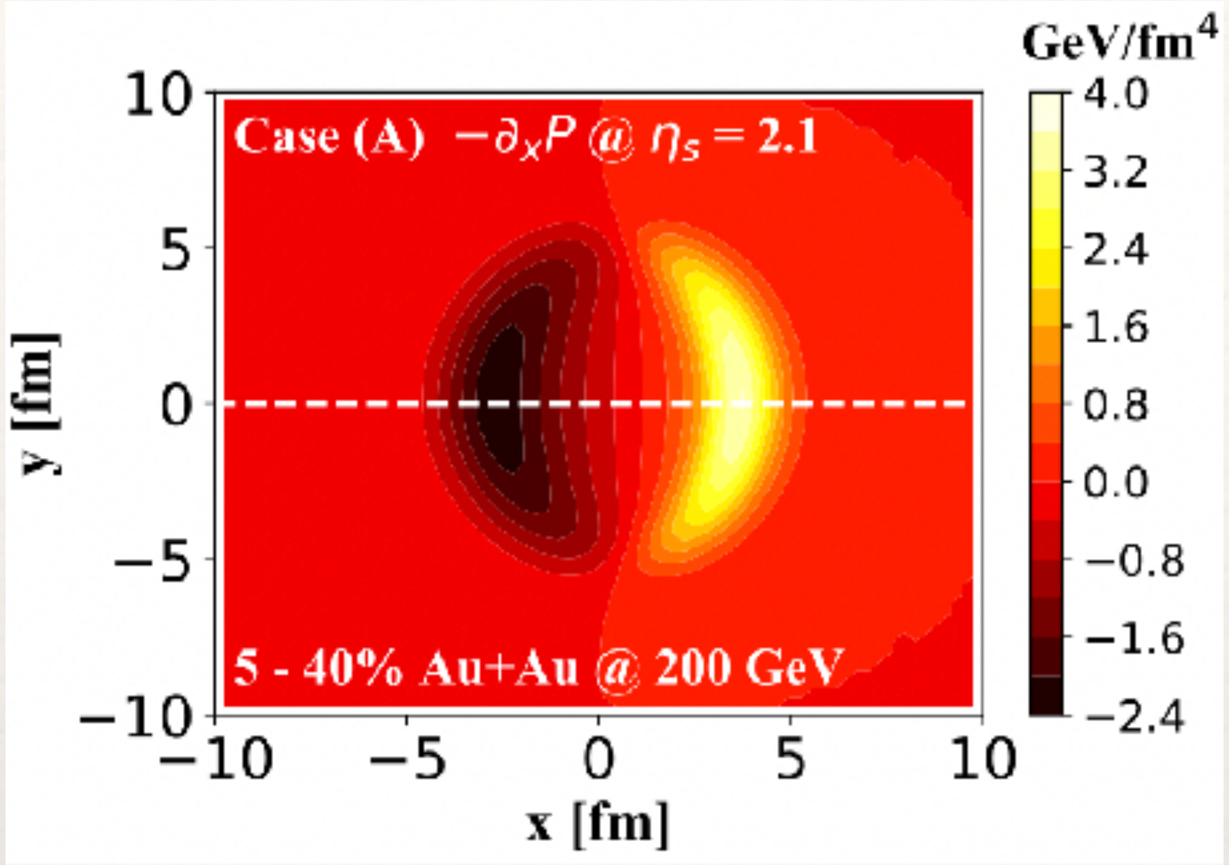
Other developments:

- Nuclear Geometry of Ru and Zr at RHIC



- Constrain the nucleon size using the Pearson coefficient
  [Giacalone *et al.*, Phys. Rev. Lett. 128 (2022) 4, 042301]

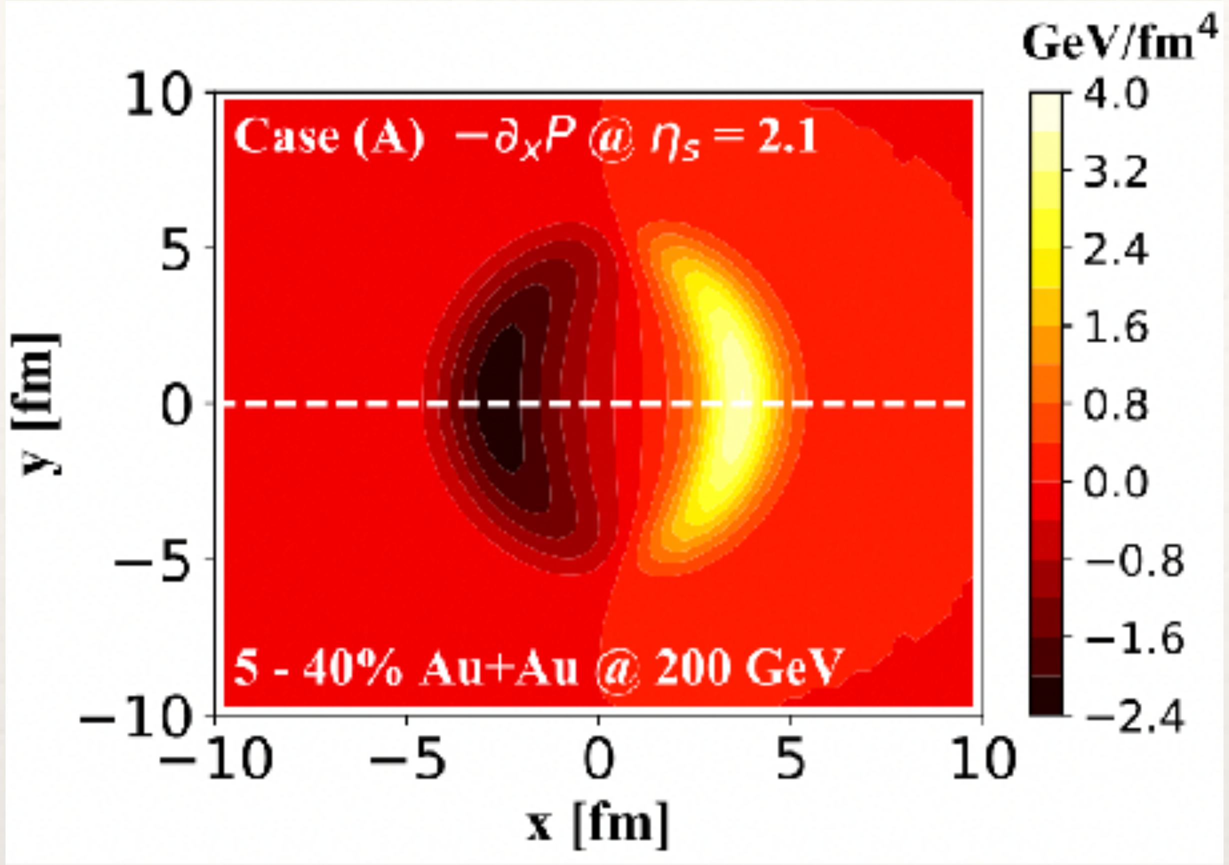
Directed flow and longitudinal geometry of the QGP



Asymmetry in $\pm\hat{x}$

$v_1 = \langle p_x / p_T \rangle \neq 0$

Directed flow and longitudinal geometry of the QGP



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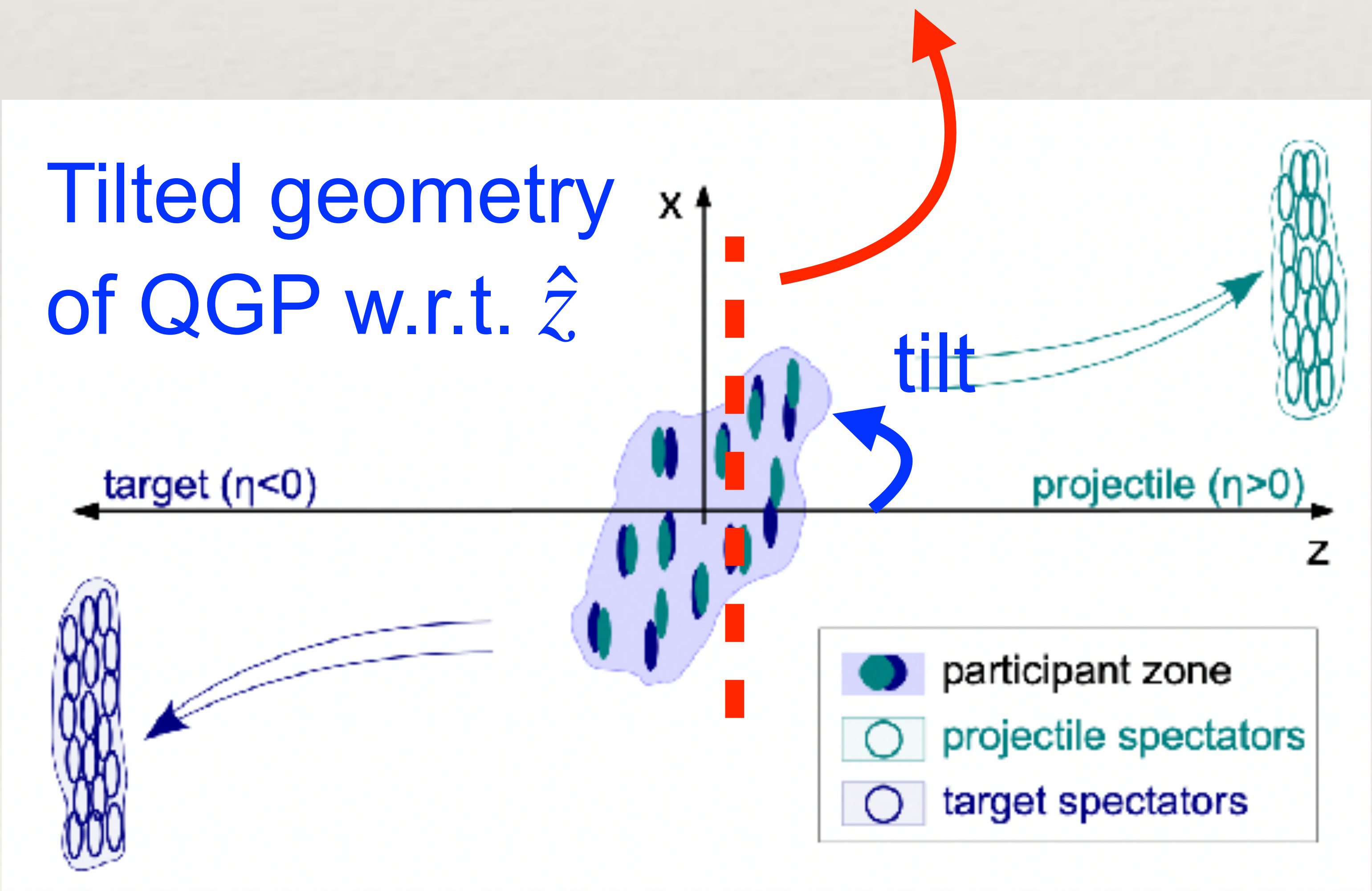
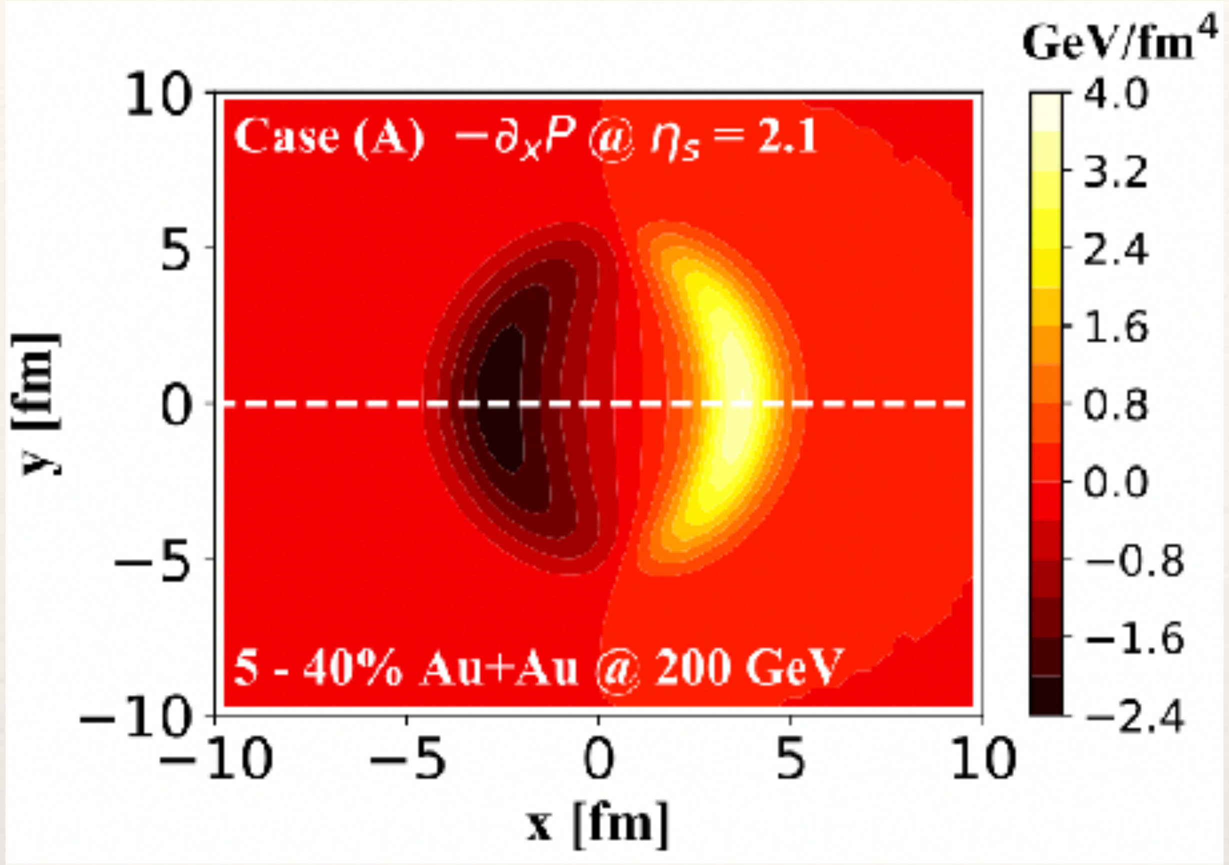


[ALICE, Phys. Rev. Lett. 111 (2013) 23, 232302]

Directed flow and longitudinal geometry of the QGP



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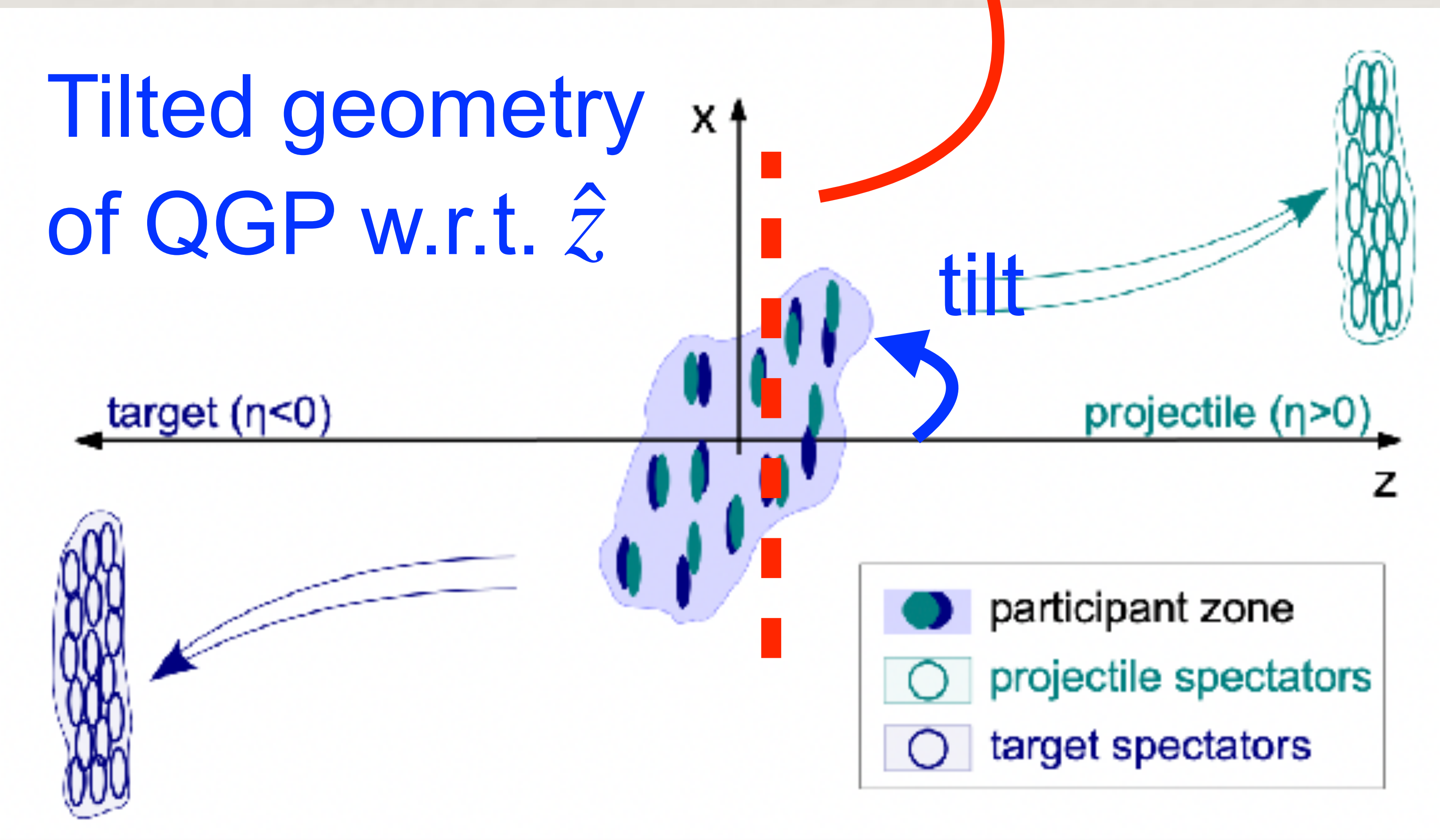
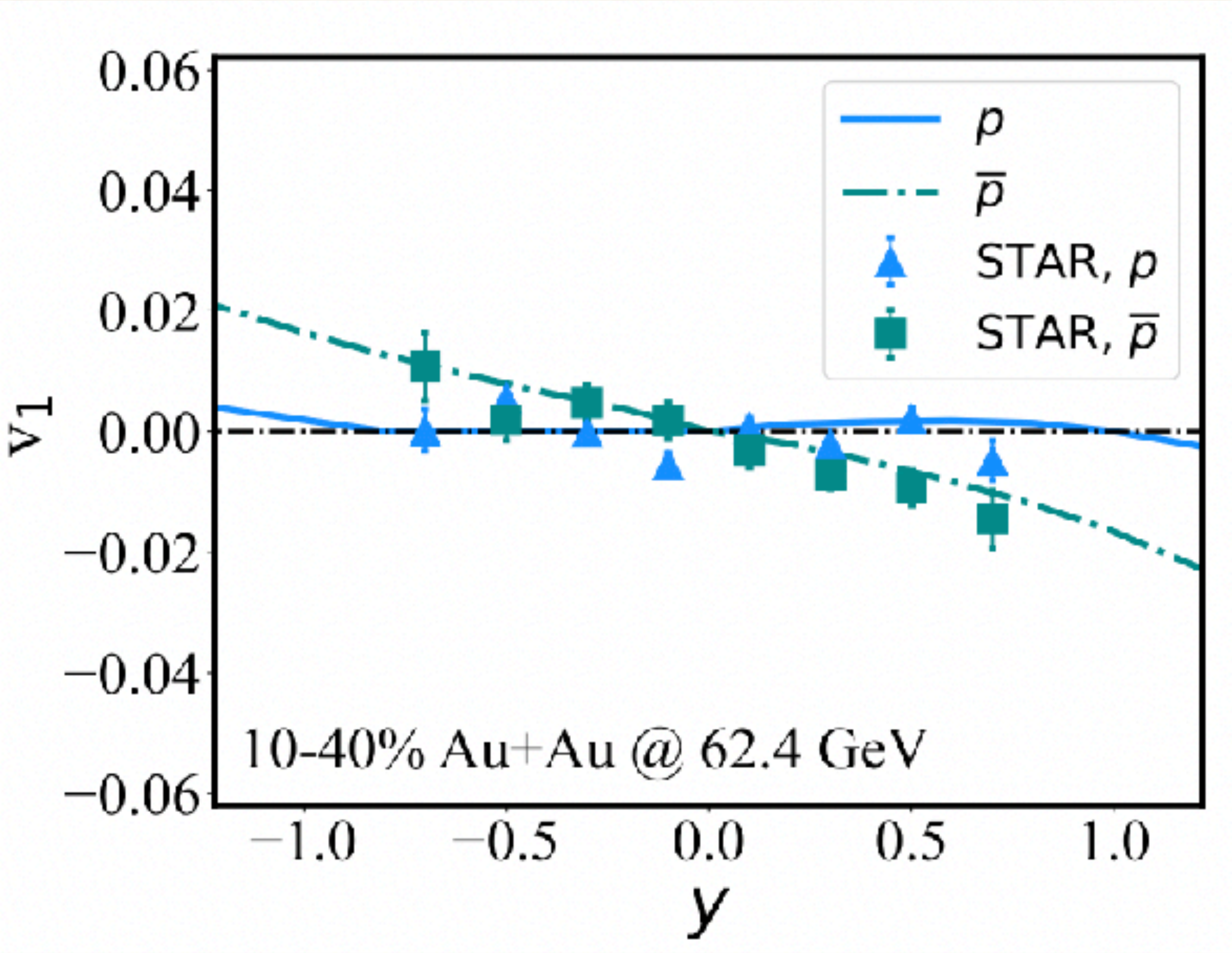


[ALICE, Phys. Rev. Lett. 111 (2013) 23, 232302]

Rapidity-odd distribution of v_1

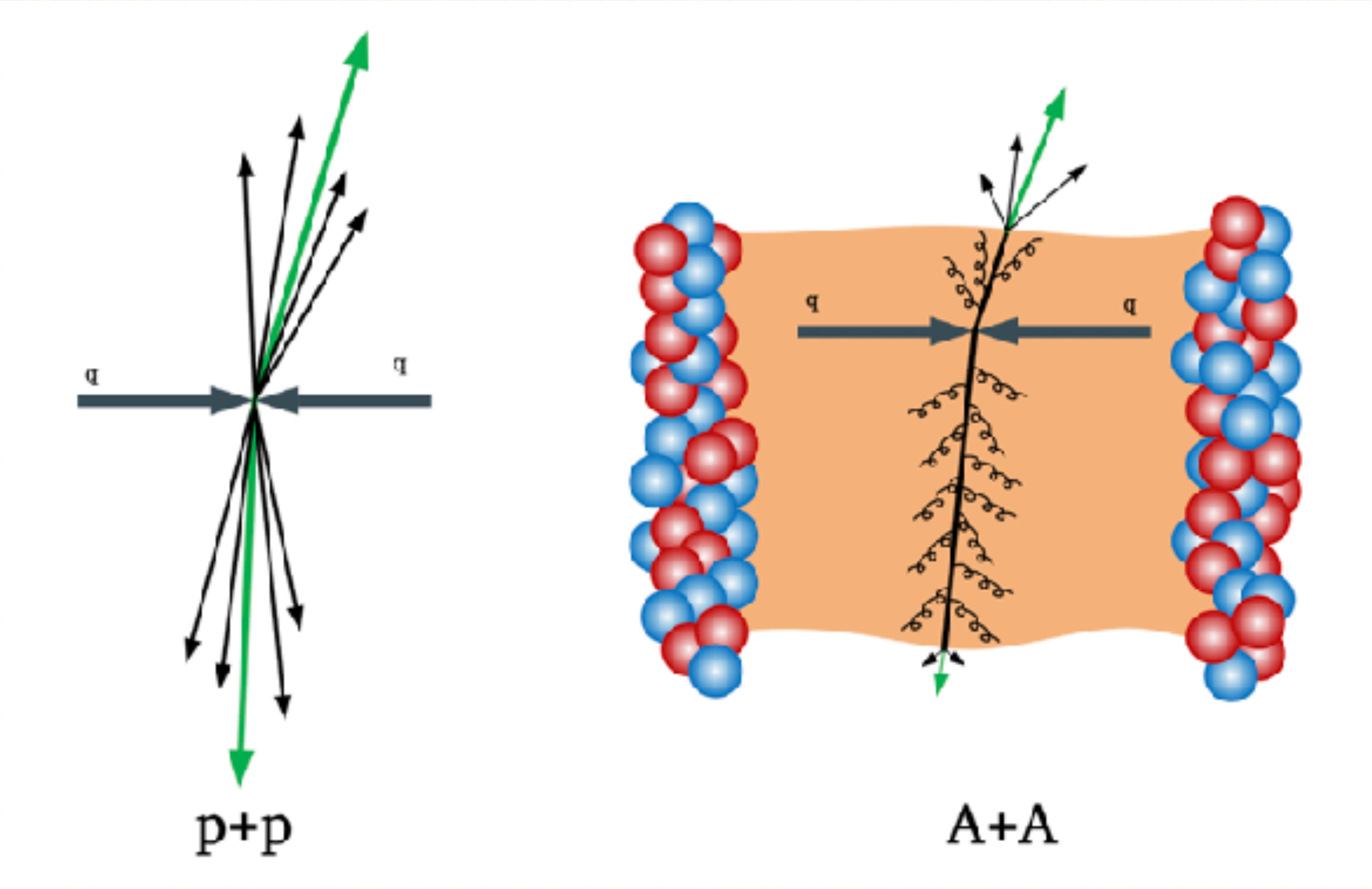


- Titled energy density → average $v_1(y)$
- Tilted baryon density → v_1 split between $p, \bar{p}$
- Challenges in understanding v_1 at low beam energies

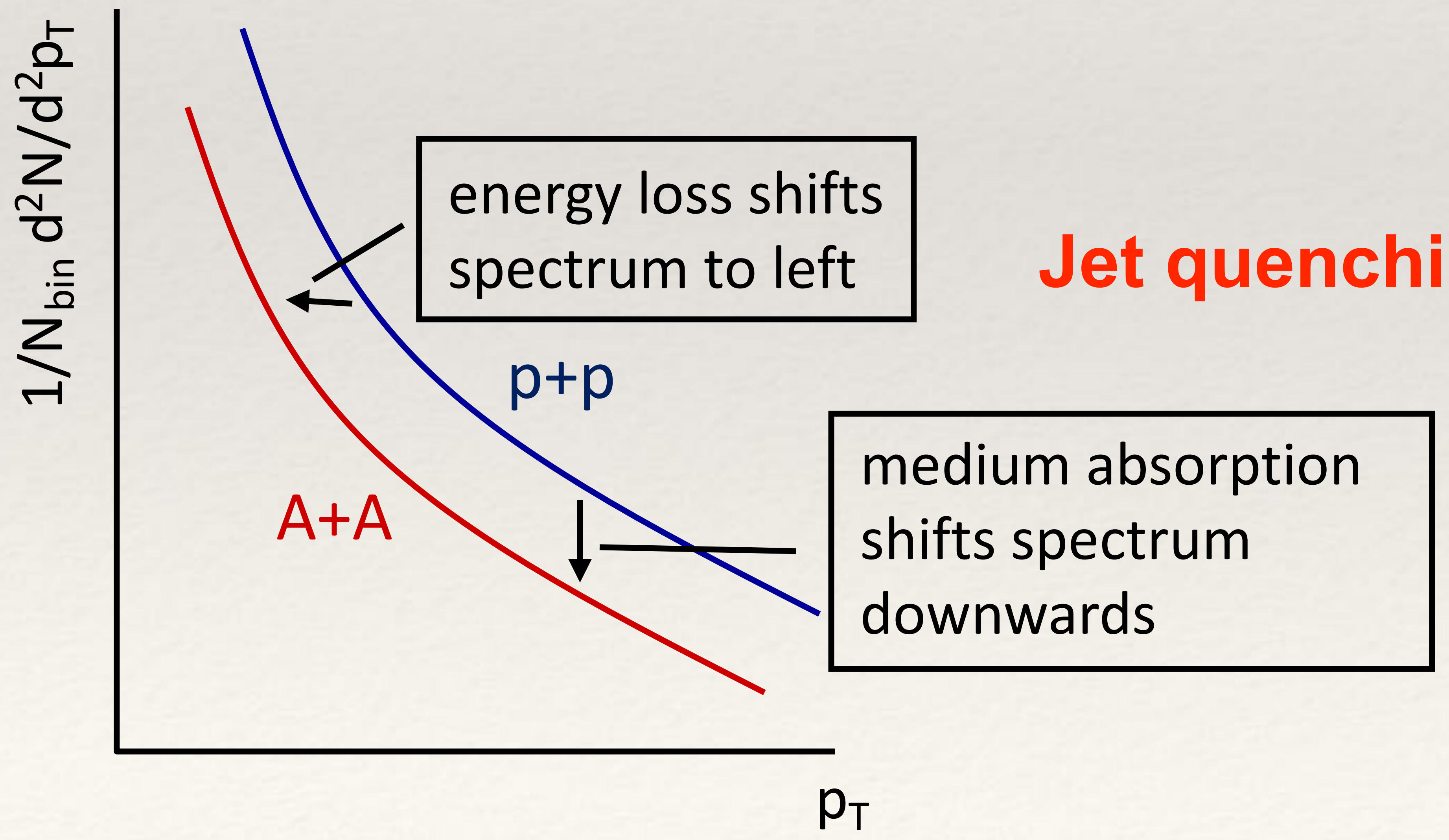
[Bozek, Phys. Rev. C 106 (2022) 6, L061901]

[Jiang, Wu, SC, Zhang, Phys. Rev. C 107 (2023) 3, 034904]

Nuclear modification of hard probes



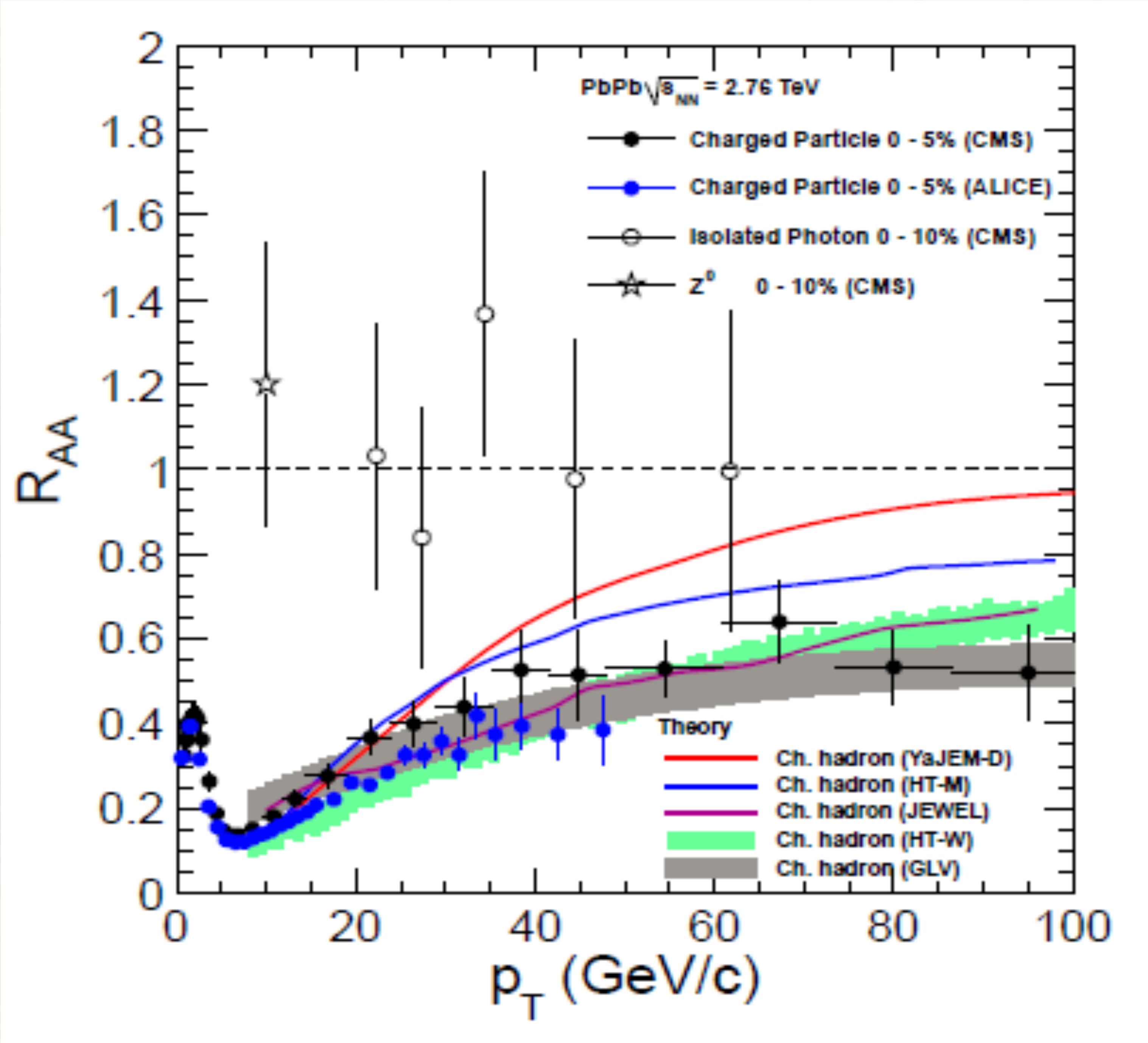
[by M. Rybar / ATLAS]



Jet quenching

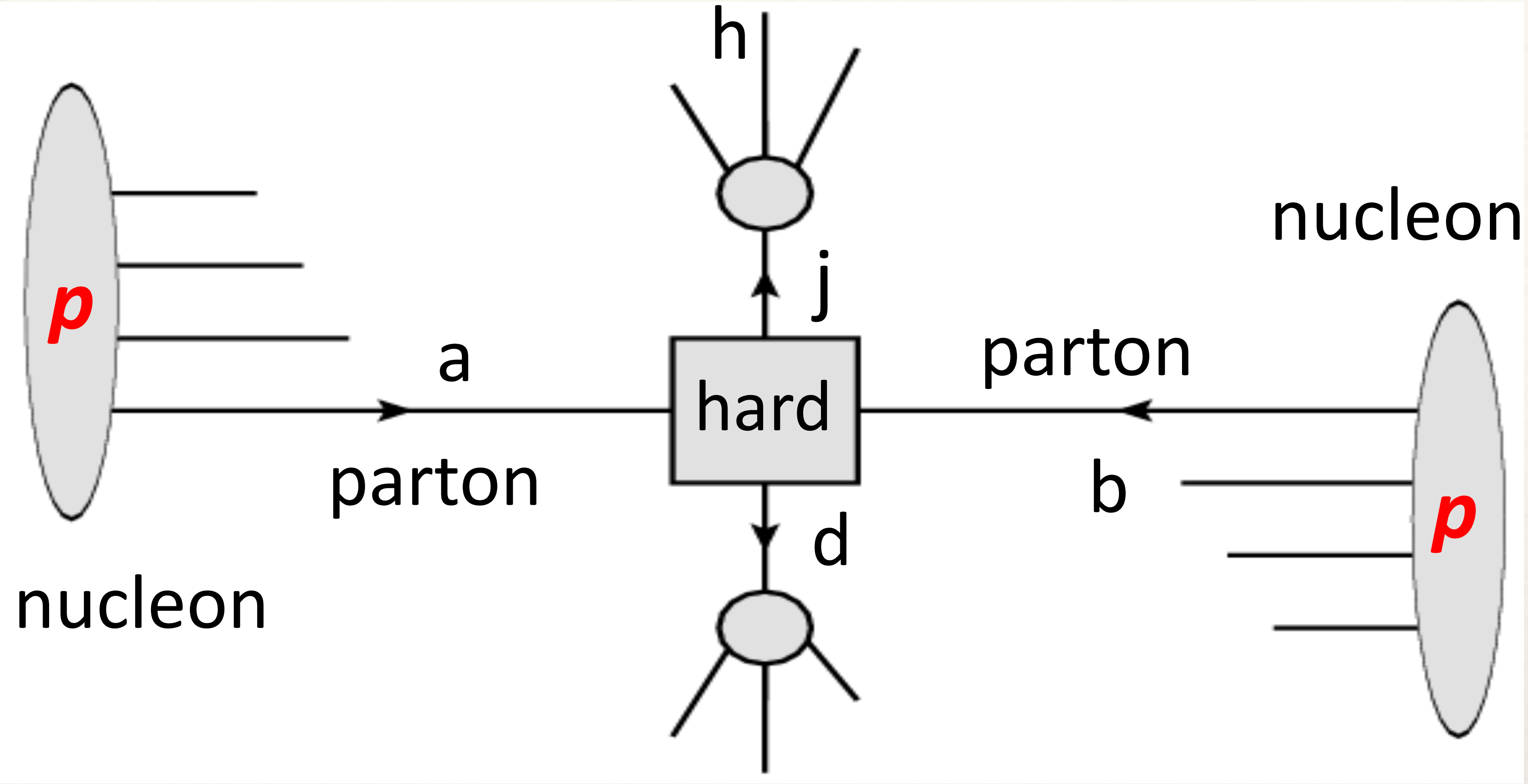
Nuclear modification factor

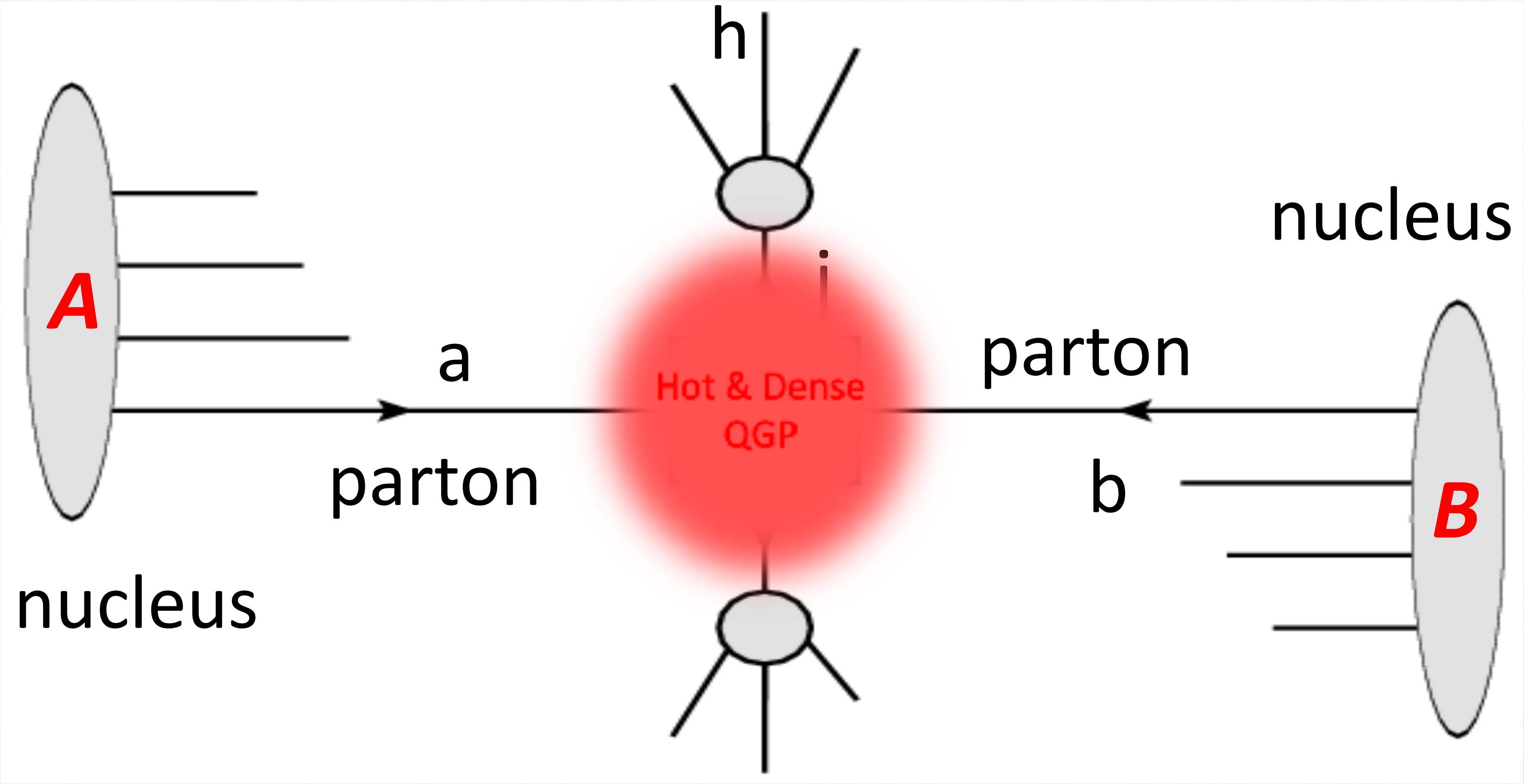
$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_\perp}{d^2N^{pp}/dydp_\perp \times \langle N_{coll}^{AA} \rangle}$$



[Mueller *et al.*, Ann. Rev. Nucl. Part. Sci. 62, 361 (2012)]

Theoretical framework of jet quenching





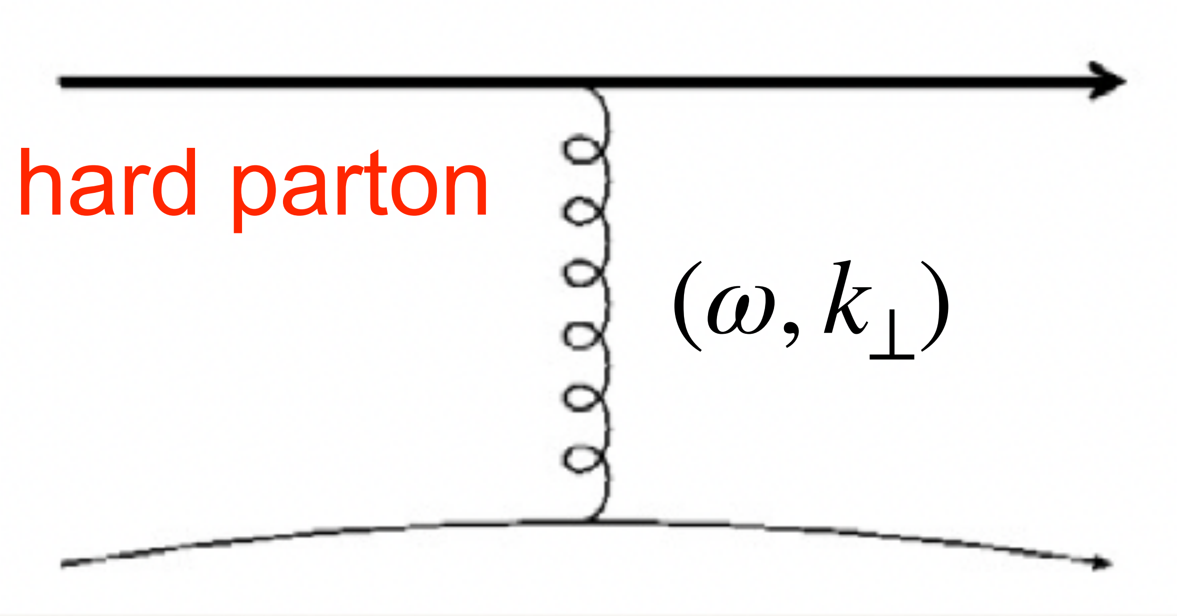
$$d\sigma_h = \sum_{abjd} f_{a/p} \otimes f_{b/p} \otimes d\sigma_{ab\to jd} \otimes D_{h/j}$$

$$d\tilde{\sigma}_h = \sum_{abjd} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jd} \otimes \tilde{D}_{h/j}$$

- $f_{a/p}, f_{b/p} \to f_{a/A}, f_{b/B}$: cold nuclear matter (initial state) effect, e.g., shadowing, Cronin, … , measured in *pA* collisions
- $D_{h/j} \to \tilde{D}_{h/j}$: medium modified fragmentation function, hot nuclear matter (final state) effect
- Factorization assumption: $\tilde{D}_{h/j} = \sum_{j'} P_{j\to j'} \otimes D_{h/j'}$, nuclear modification on parton *j*

Elastic and inelastic scatterings

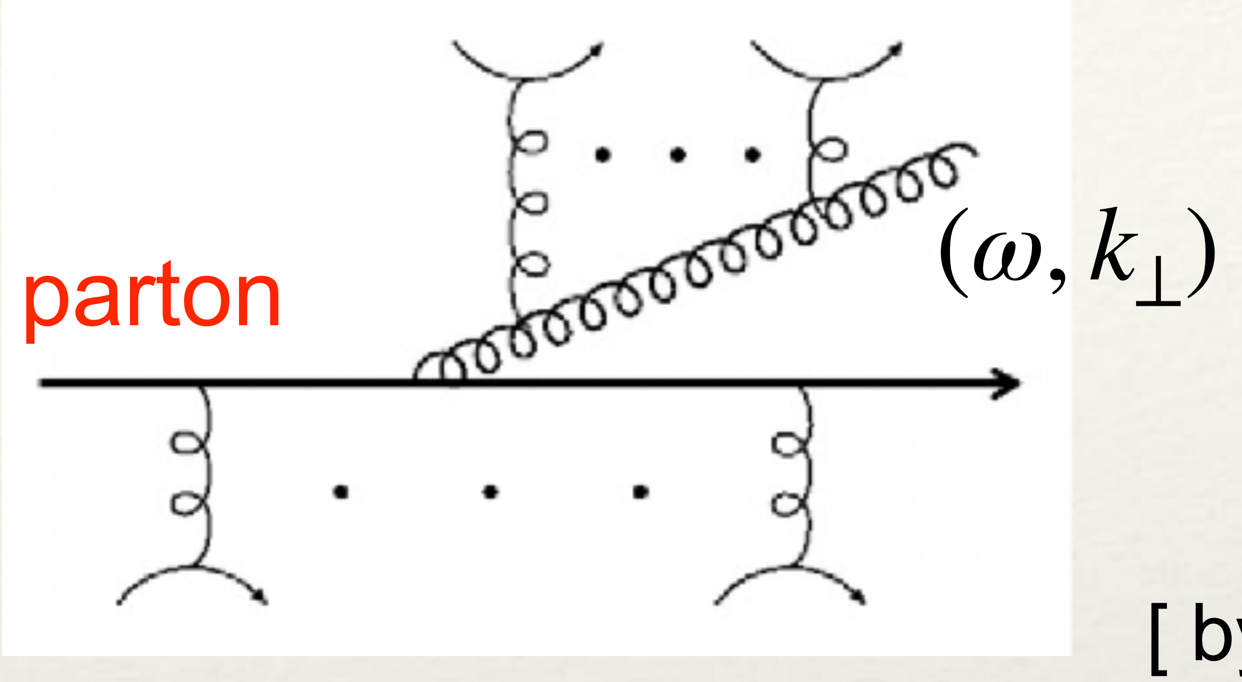
Elastic (collisional)



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

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

Inelastic (radiative)



[by G.-Y. Qin]

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

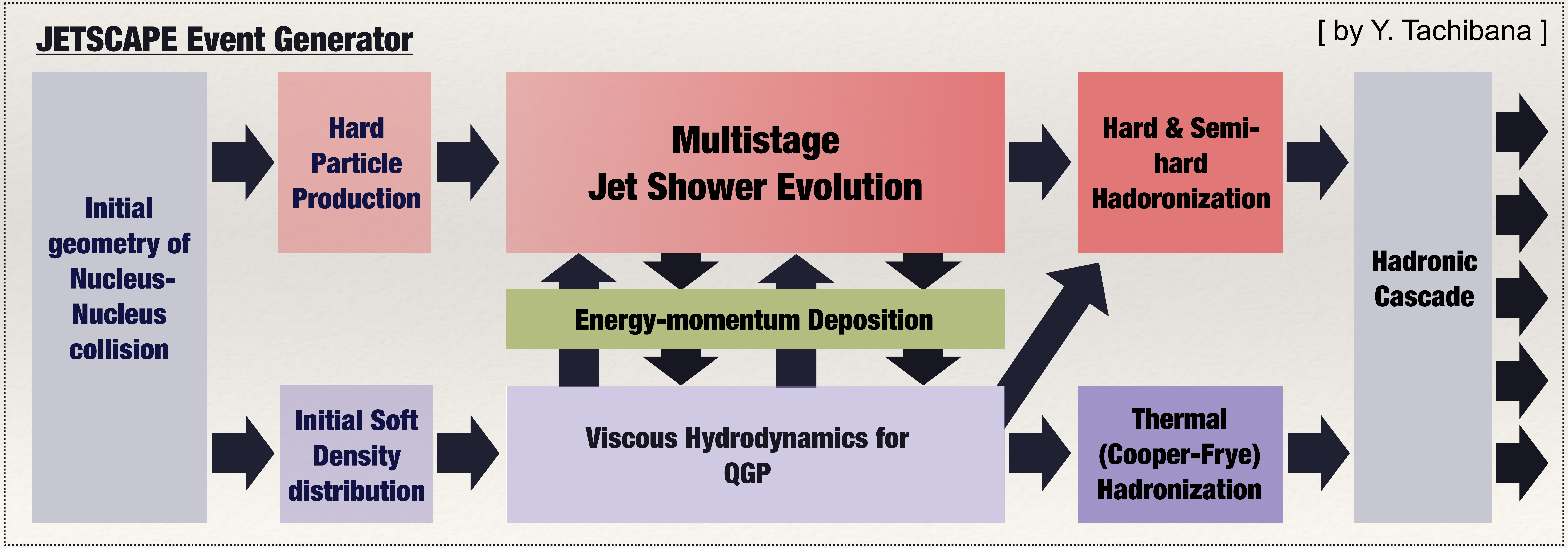
BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe (& Caron-Huot, Gale)
GLV: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)
HT: Wang-Guo (& Zhang, Wang, Majumder)

Systematic comparisons and reviews:

Bass *et al.*, Phys.Rev.C 79 (2009) 024901; Majumder and Van Leeuwen, Prog. Part. Nucl. Phys. 66 (2011) 41; JET, Phys. Rev.C 90 (2014) 1, 014909; Qin and Wang, Int. J. Mod. Phys. E 24 (2015) 11, 1530014

Multistage jet evolution framework

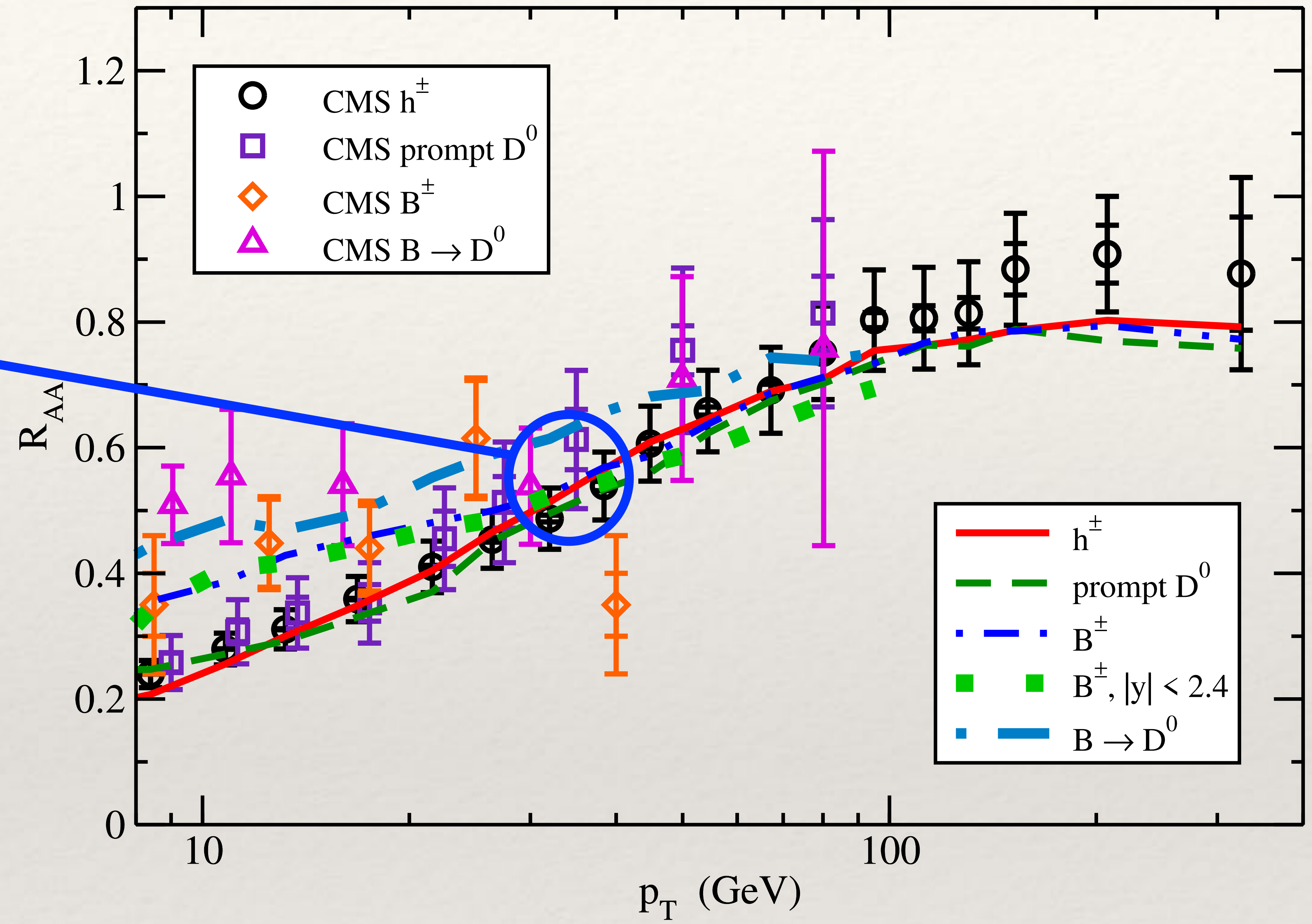
- Multistage: high Q^2 — DGLAP-type of evolution; low Q^2 — transport; thermal scale — strongly coupled approach; …
- Monte-Carlo event generator package for heavy-ion collisions — JETSCAPE
- Open Access: GitHub github.com/JETSCAPE [arXiv:1903.07706]



Successful perturbative QCD calculation at high p_T

NLO production + parton interaction with hydrodynamic medium + fragmentation

Merging of *D* and *B* R_{AA} at p_T ~ 40 GeV



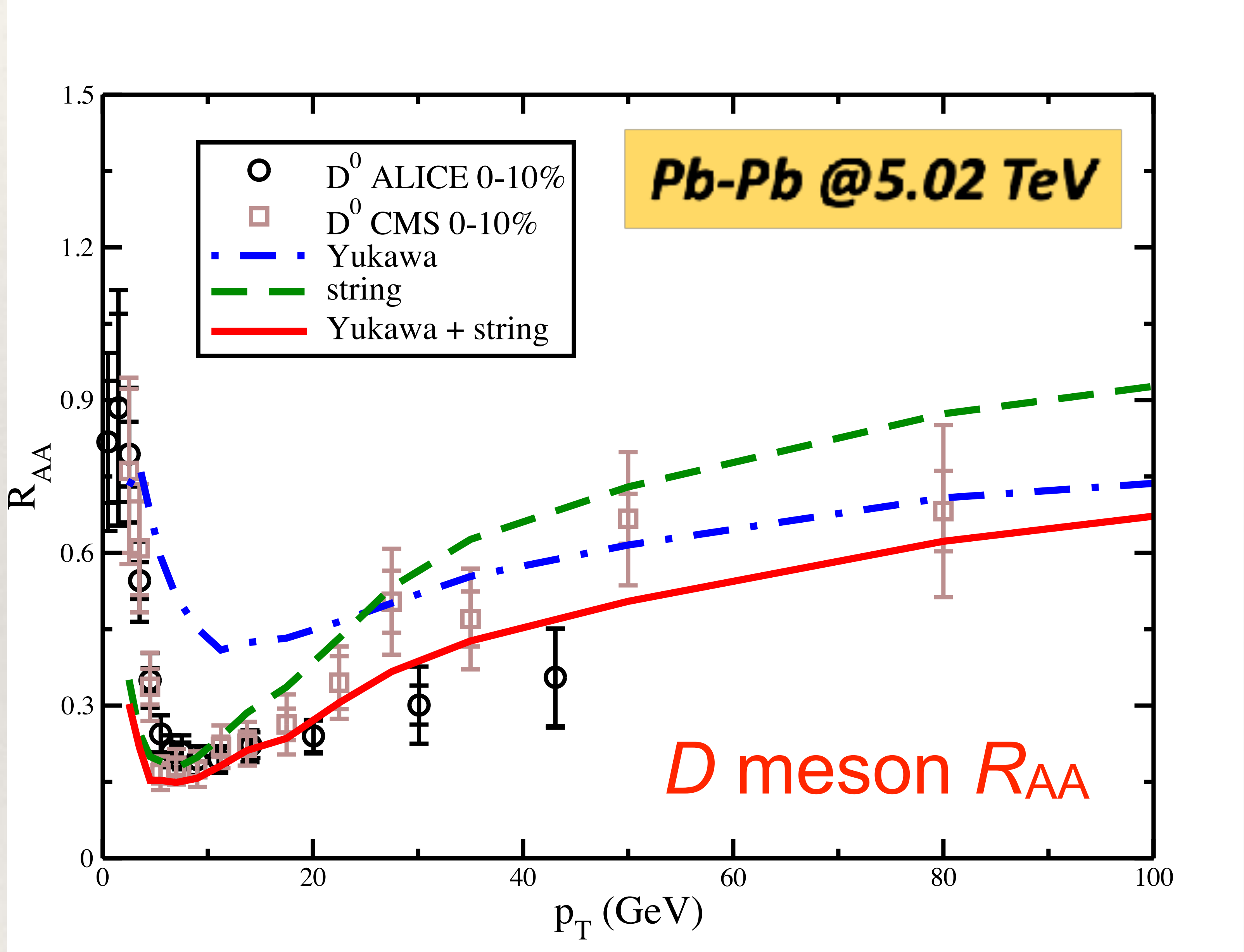
[Xing, SC, Qin, Xing, Phys. Lett. B 805 (2020) 135424]

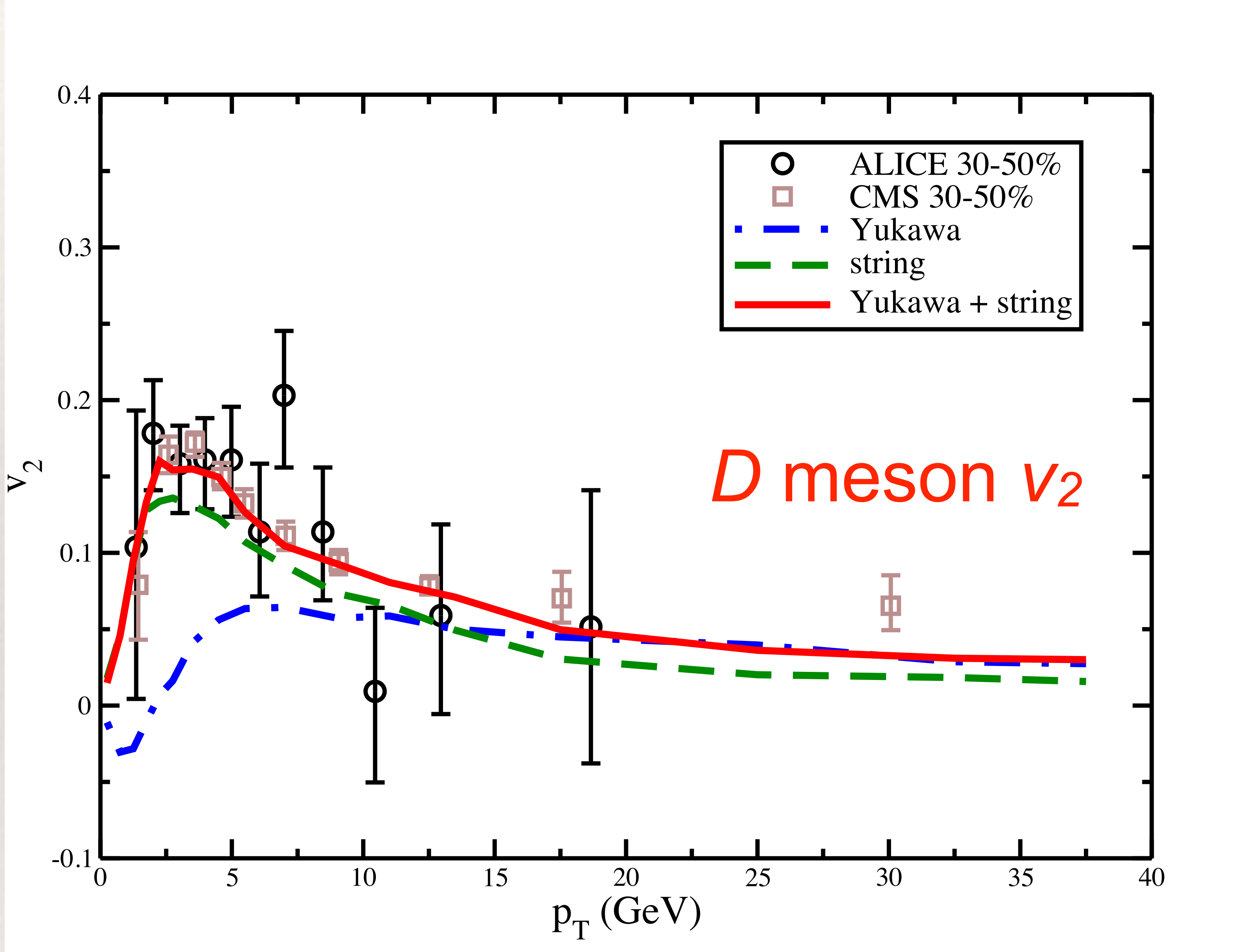
- A simultaneous description of charged hadron, *D* meson, *B* meson, *B*-decay *D* meson R_{AA}'s starting from p_T ~ 8 GeV
- Predict R_{AA} separation between *B* and *h* / *D* below 40 GeV, but similar values above – **wait for confirmation from future precision measurement**

Non-perturbative interactions at low p_T

Heavy quark interaction with **quasi-particles** → with a **general potential**

$$V(r,T) = -\frac{4}{3}\alpha_s \frac{e^{-m_d r}}{r} - \frac{\sigma}{m_s} e^{-m_s r}$$ (Yukawa + string, fit to the lattice data)



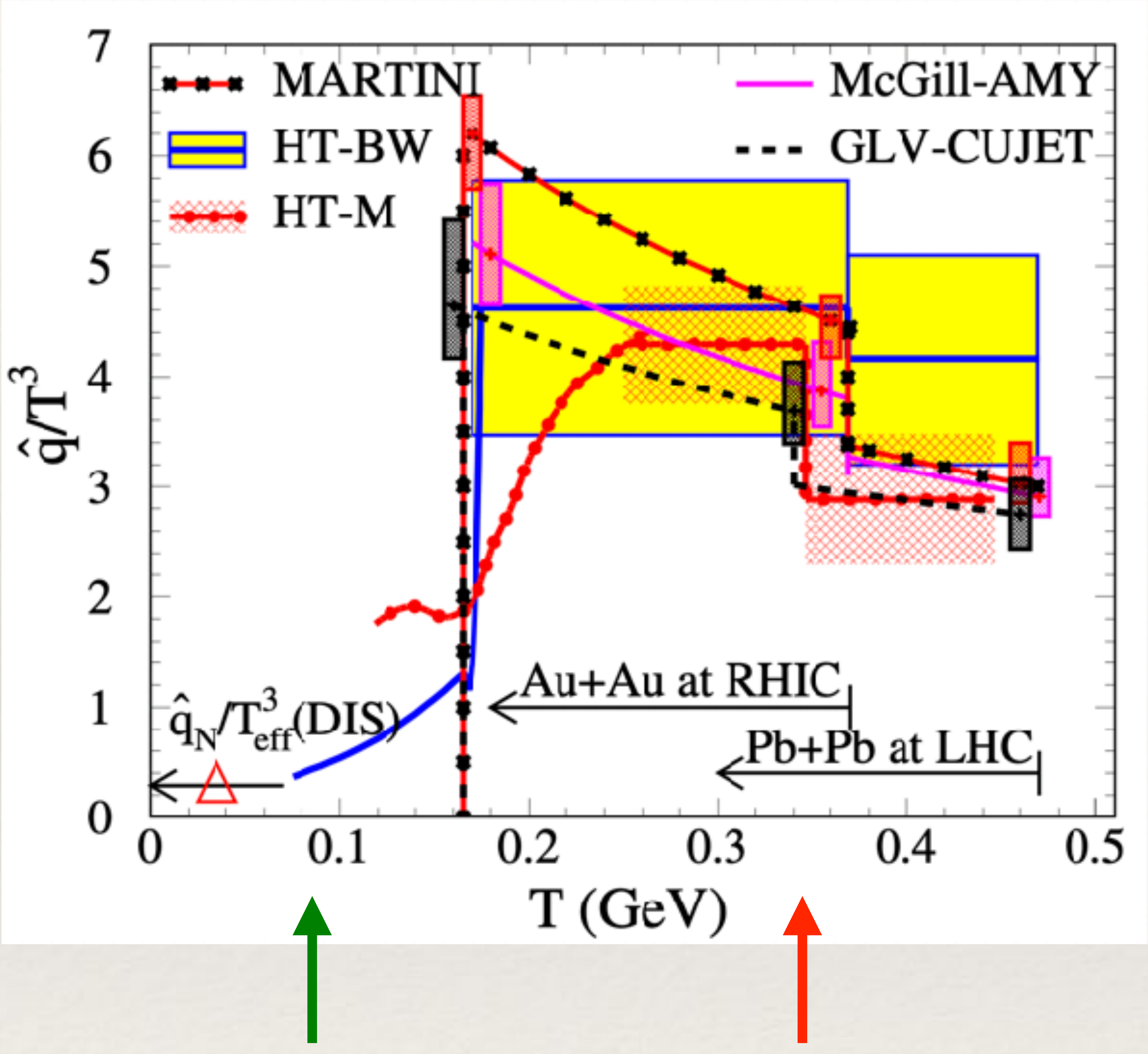


[Xing, Qin, SC, Phys. Lett. B 838 (2023) 137733]

- At **high p_T**, the **Yukawa** interaction dominates heavy-quark-medium interaction
- At **low to intermediate p_T**, the **string** interaction dominates

Constraints on jet transport coefficient inside the QGP

$$\hat{q} \equiv d\langle k_\perp^2\rangle/dt \sim \langle F^{ai+}(0)F_i^{a+}(y^-)\rangle$$



nucleus $\ll$ QGP

[JET, Phys. Rev.C 90 (2014) 1, 014909]

- QGP is much more opaque than cold nuclear matter to jet propagation

- Recent developments on $\hat{q}$ extraction:

  Multistage jet evolution model with Bayesian analysis

  [JETSCAPE, Phys. Rev. C 104 (2021) 1, 024905]

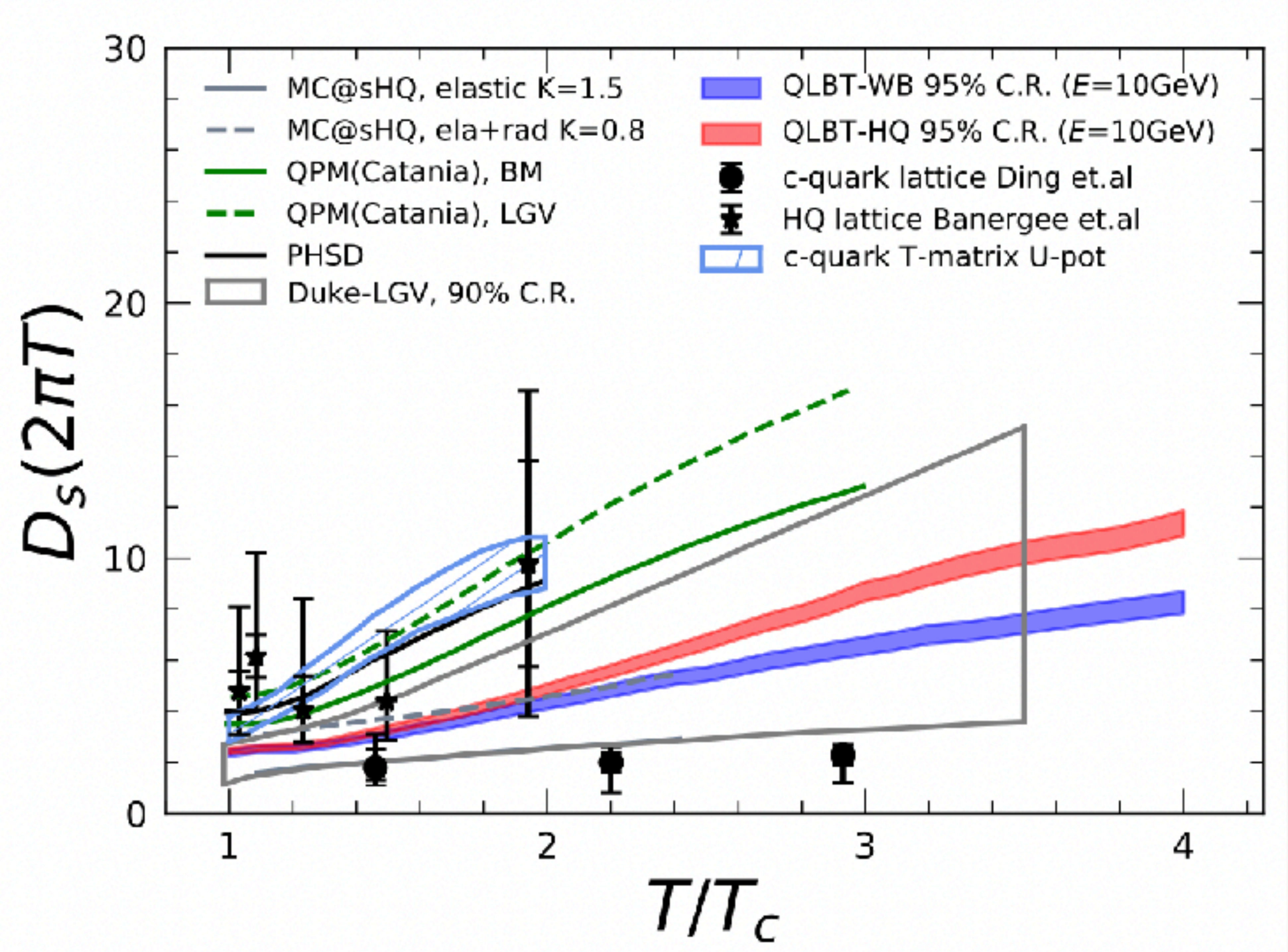
  Information field based global interference

  [Xie et al., arXiv:2206.01340]

Constraints on heavy quark diffusion coefficient

Low energy heavy quark inside the QGP: diffusion (Brownian motion)

Spatial diffusion coefficient: $D_s \equiv \langle |\vec{x}|^2 \rangle / (2dt)$

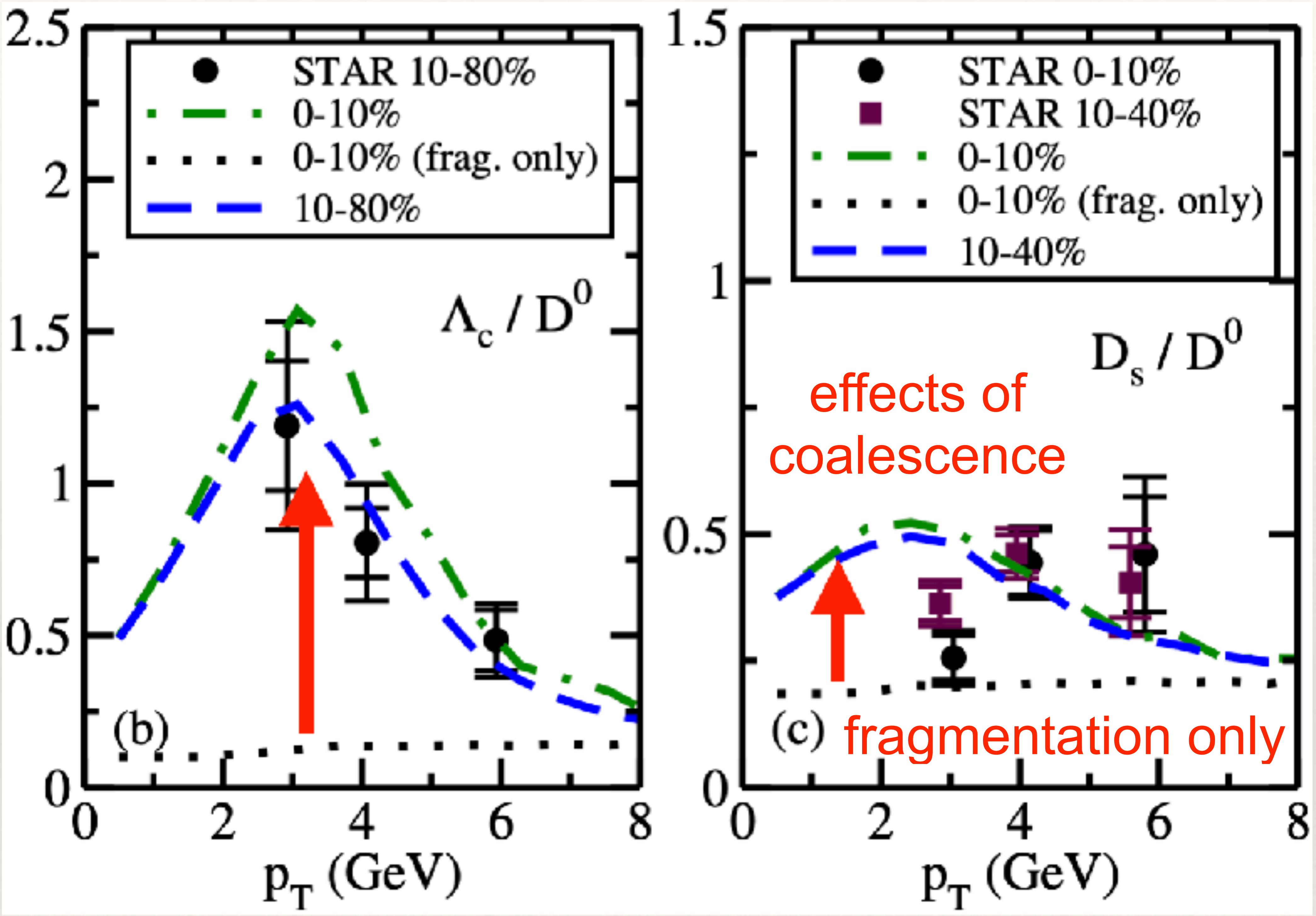


- $D_s(2\pi T) = 2 \sim 6$ extracted from model-to-data comparison
- An order of magnitude smaller than pQCD, close to the strongly coupled limit
- Strongly coupling between low energy heavy quarks and the QGP
- Consistent with the lattice QCD results

[Liu, Xing, Wu, Qin, SC, Wang, Eur. Phys. J. C 82 (2022) 4, 350]

Constraints on hadron formation and structure

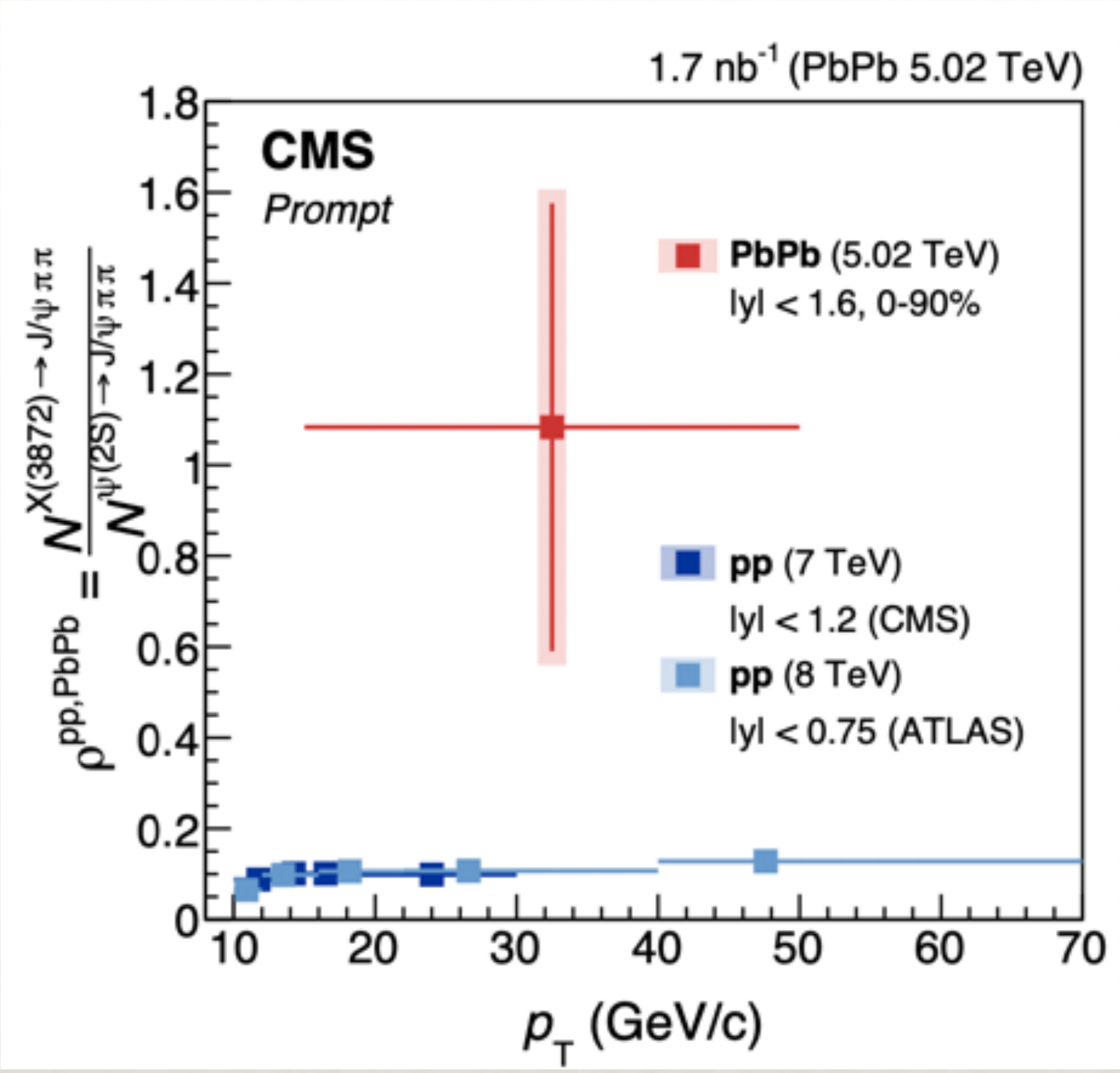
Charmed hadron chemistry



[SC *et al.*, Phys. Lett. B 807 (2020) 135561]

- Charm coalescence with thermal partons in QGP results in the large Λ_c/D^0, B_s/B^+, D_s/D^0 observed at RHIC and LHC

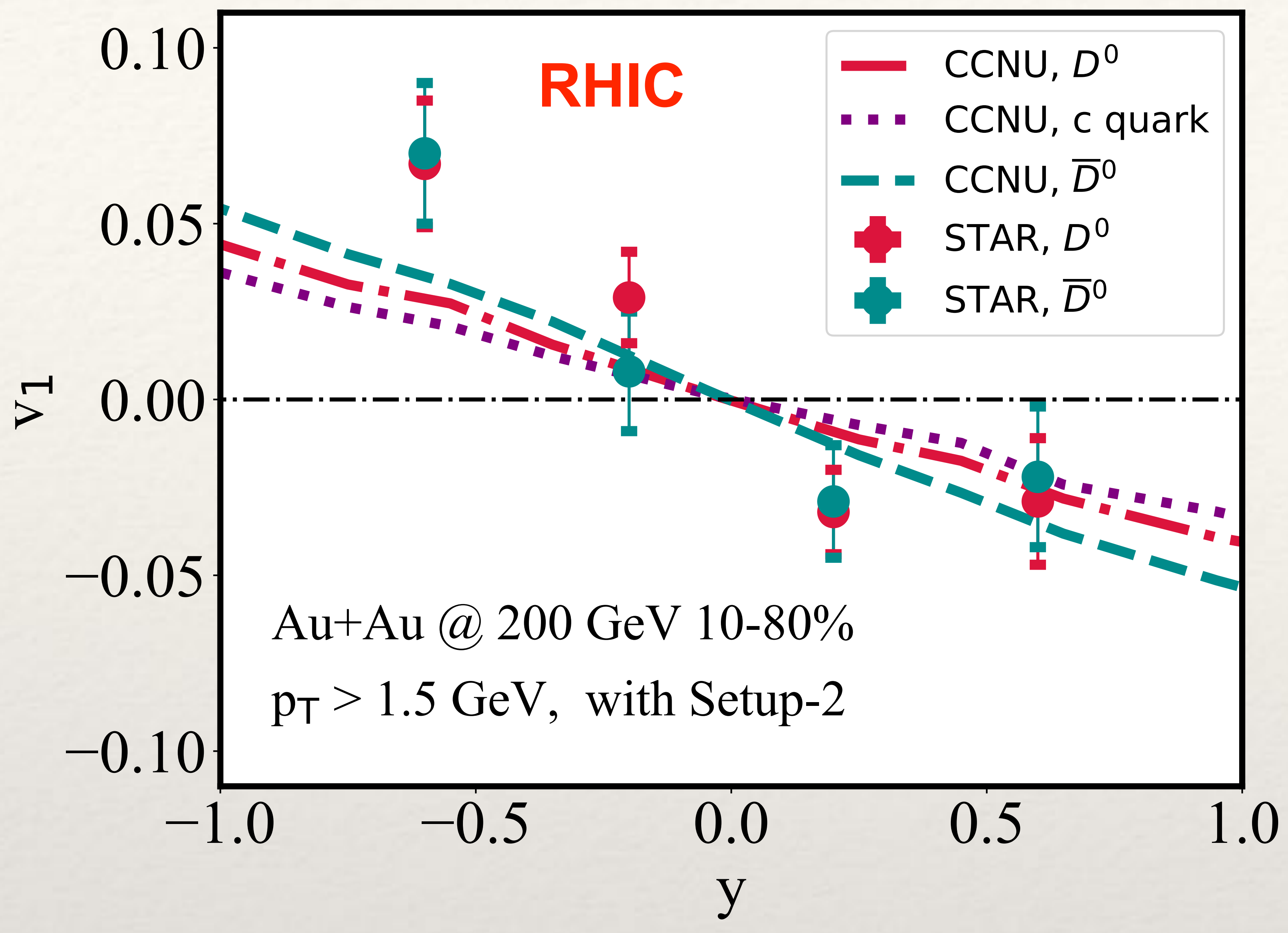
X(3872) in heavy-ion collisions

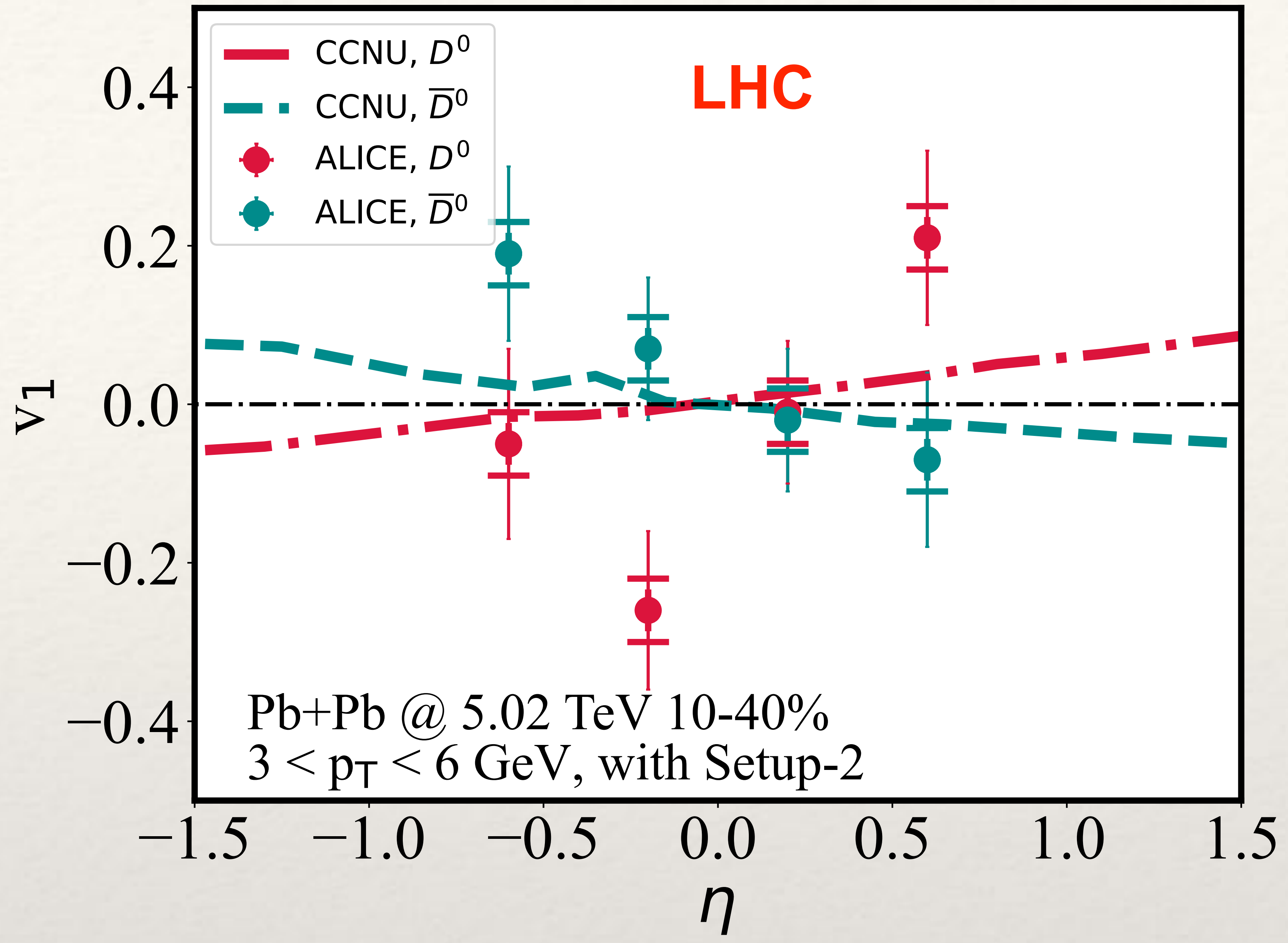


[Phys. Rev. Lett. 128 (2022) 3, 032001]

- Novel way of exploring molecule *vs.* tetraquark states of exotic particles [Cho and Lee, PRC 101 (2020), 2, 024902; Zhang, *et al.*, PRL, 126 (2021) 1, 012301; Wu *et al.*, EPJA, 57 (2021) 4, 122.]
- Need more precise data for conclusion

Constraints on the E&M field with the *D* meson v_1





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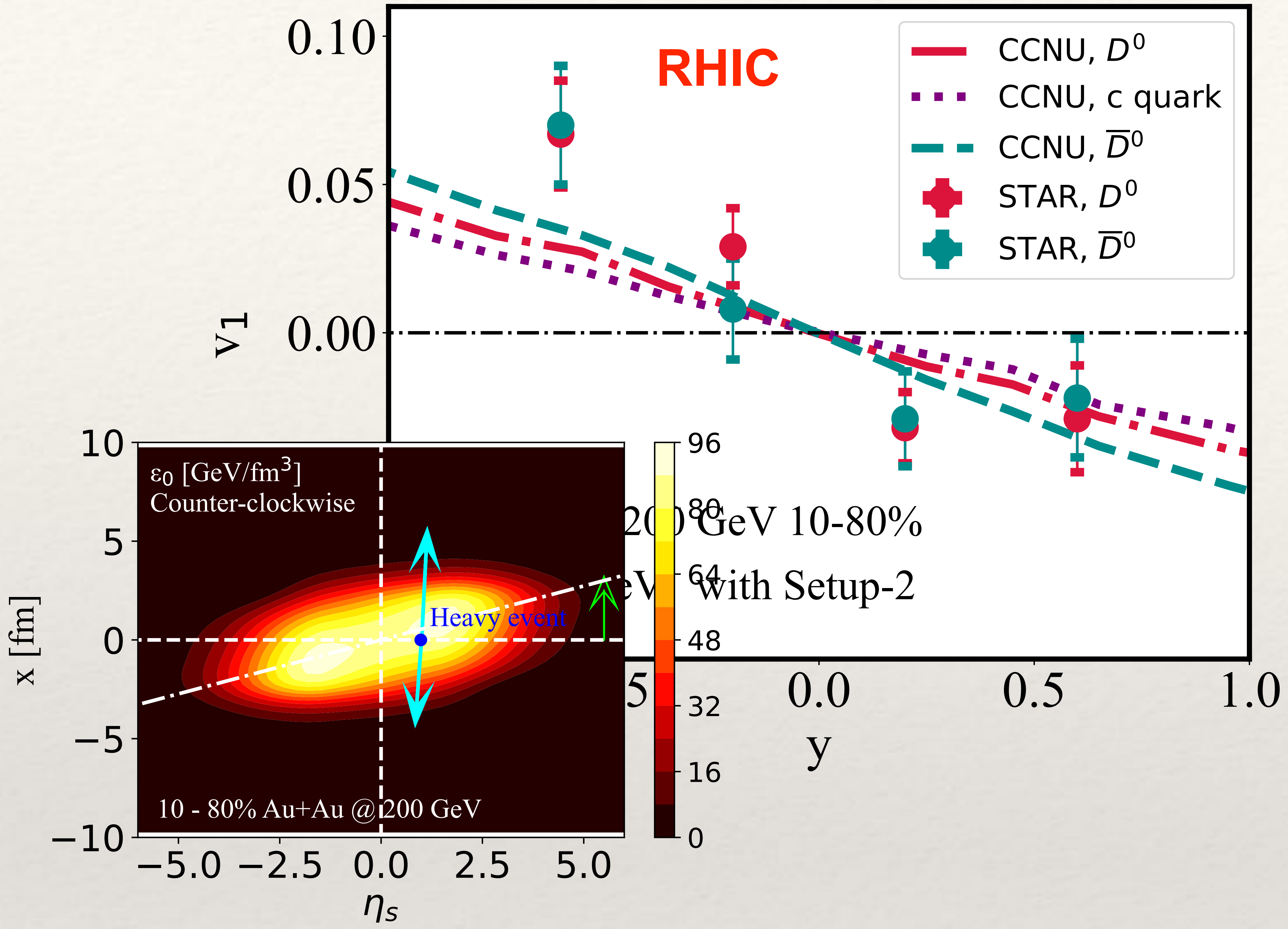
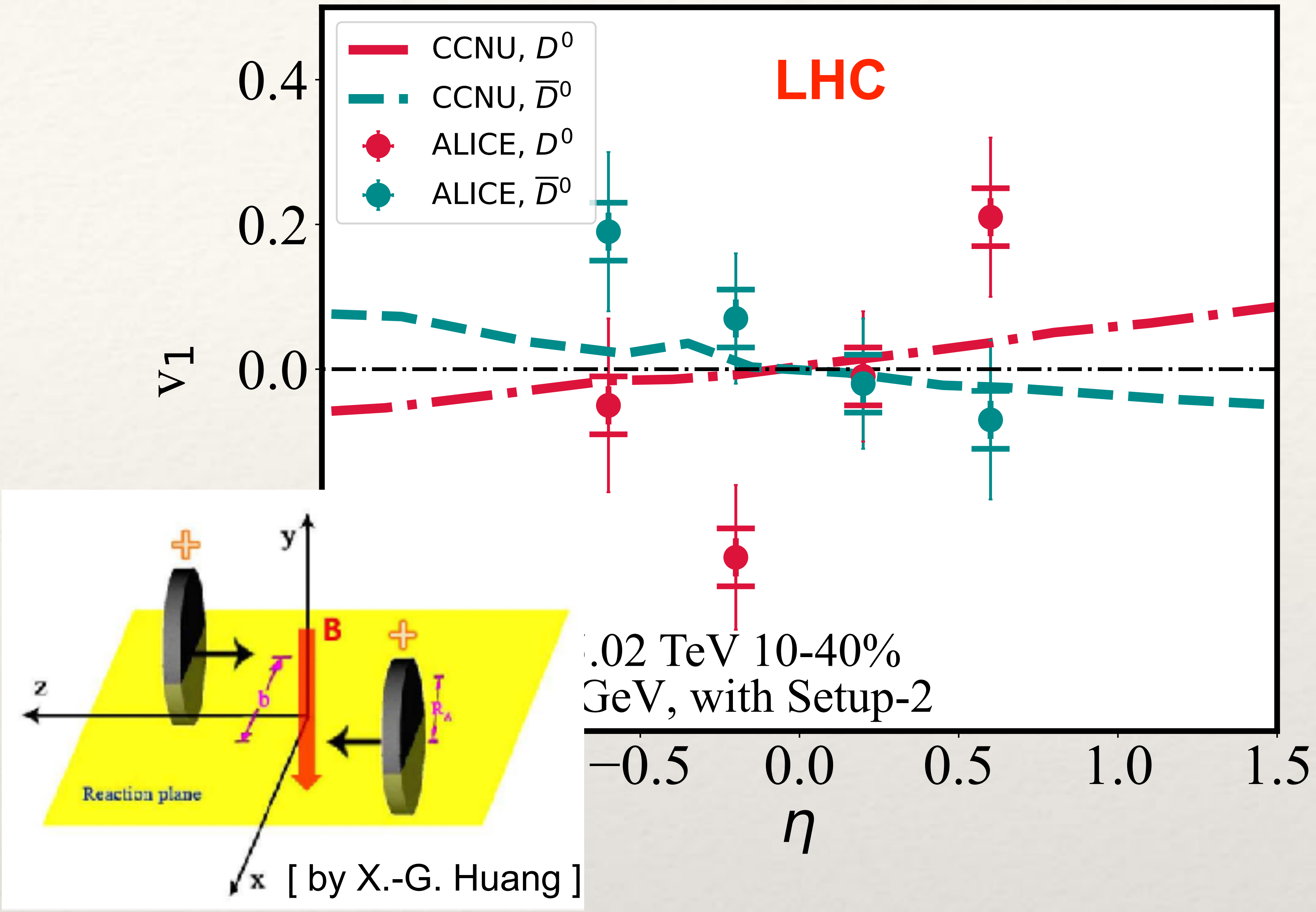
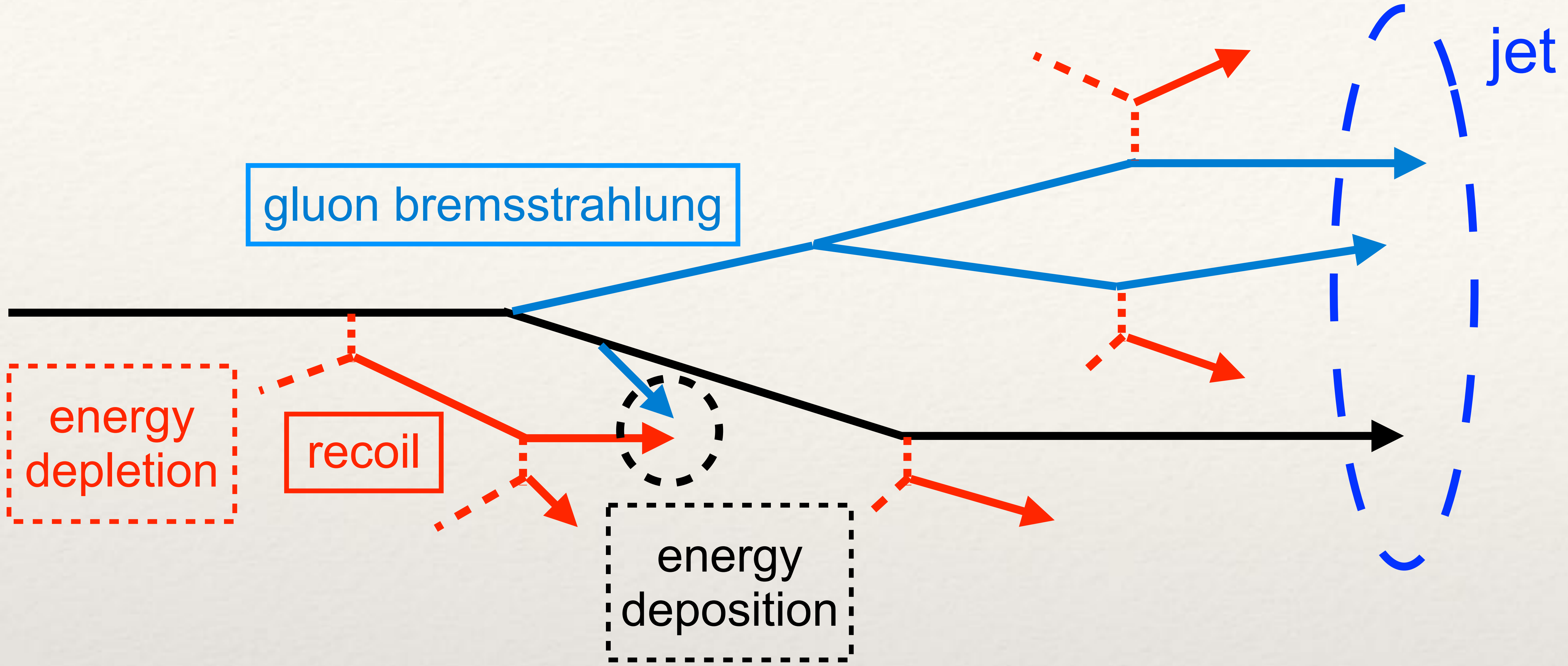


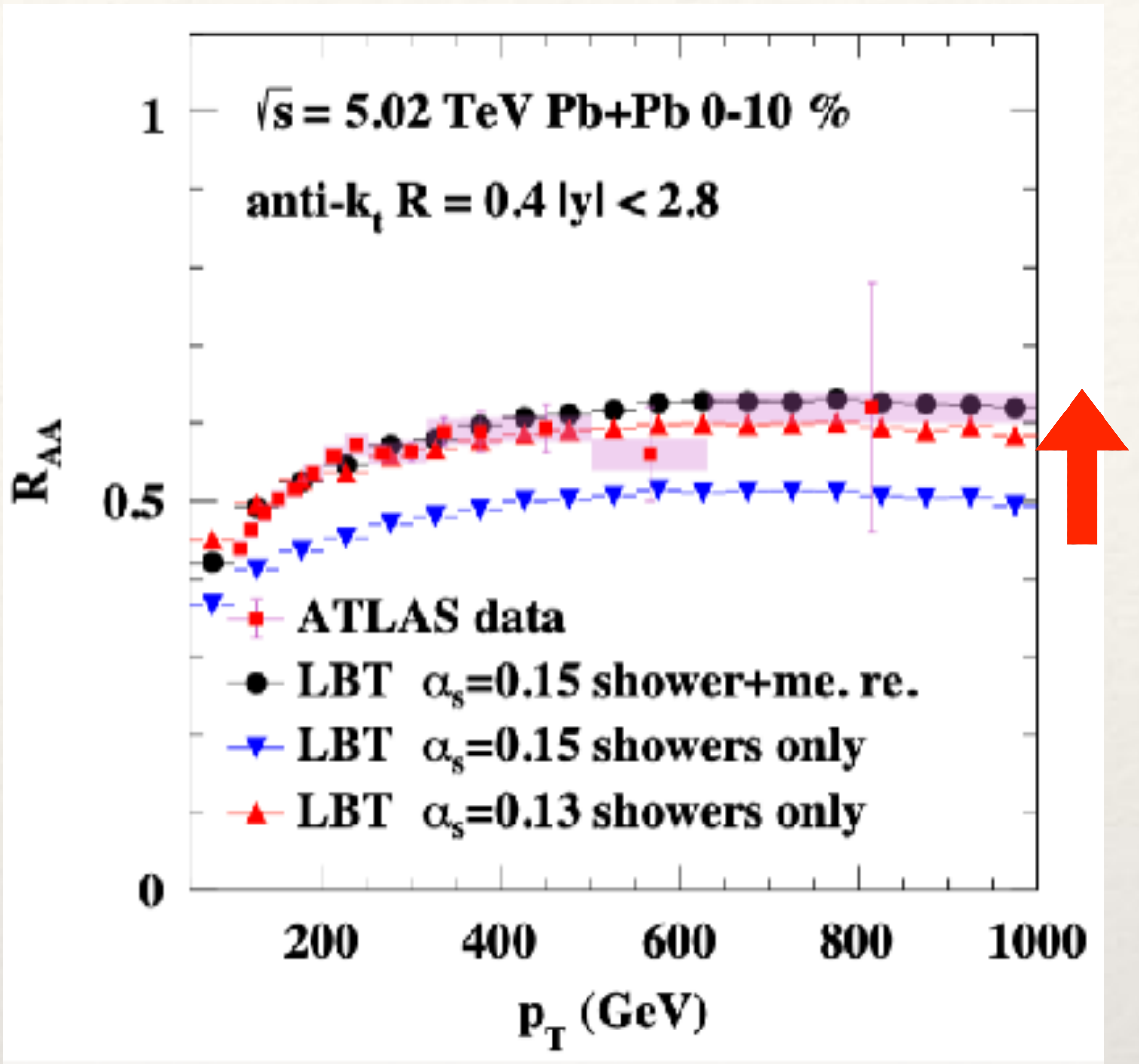


- Tilted geometry w.r.t. the beam direction dominates at the RHIC energy
- Strong E&M field dominates at the LHC energy
- Sensitivity of the *D* meson v_1 to different E&M evolution profiles at the LHC

[Sun, Plumari, Greco, Phys. Lett. B, 816 (2021) 136271]
[Jiang, SC, Xing, Wu, Yang, Zhang, Phys. Rev. C 105 (2022) 5, 054907]

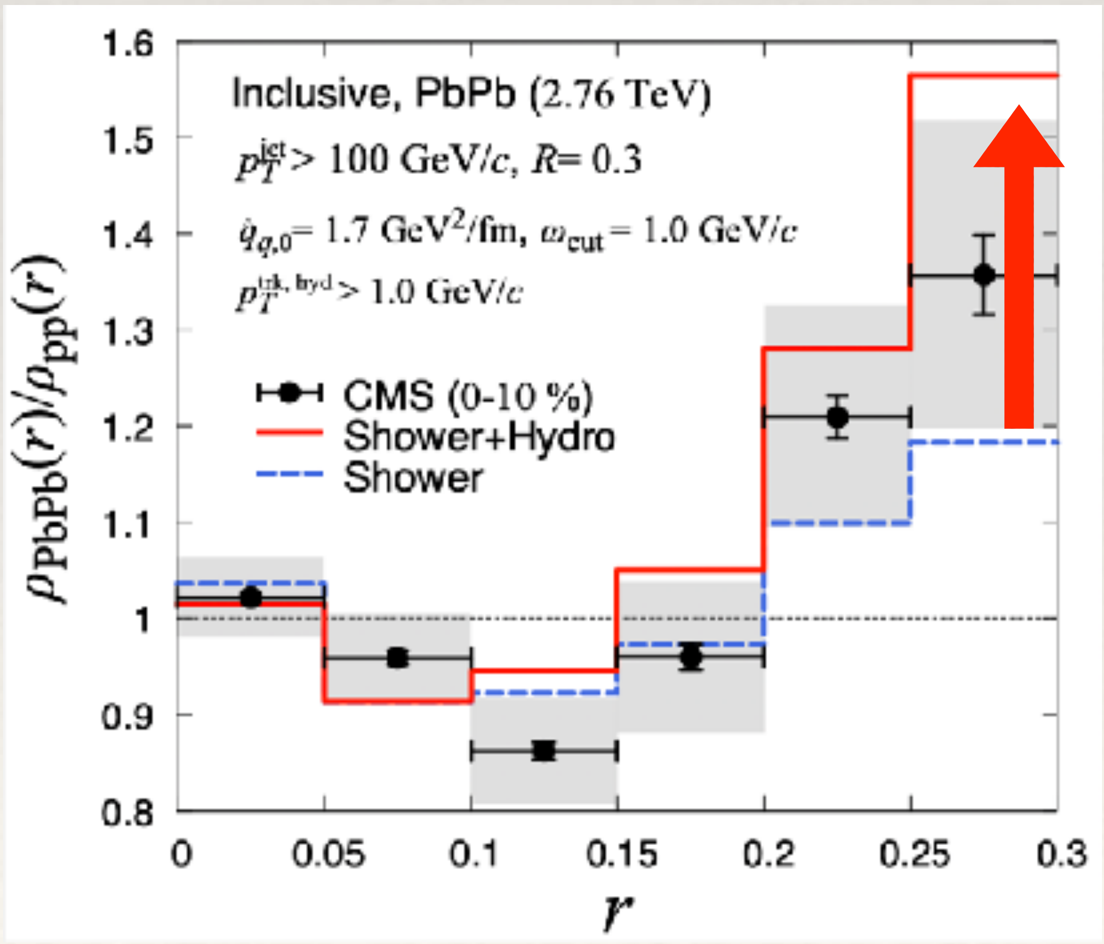
Fully reconstructed jets





Increase jet R_{AA}

[He *et al.*, PRC 99 (2019), 054911]



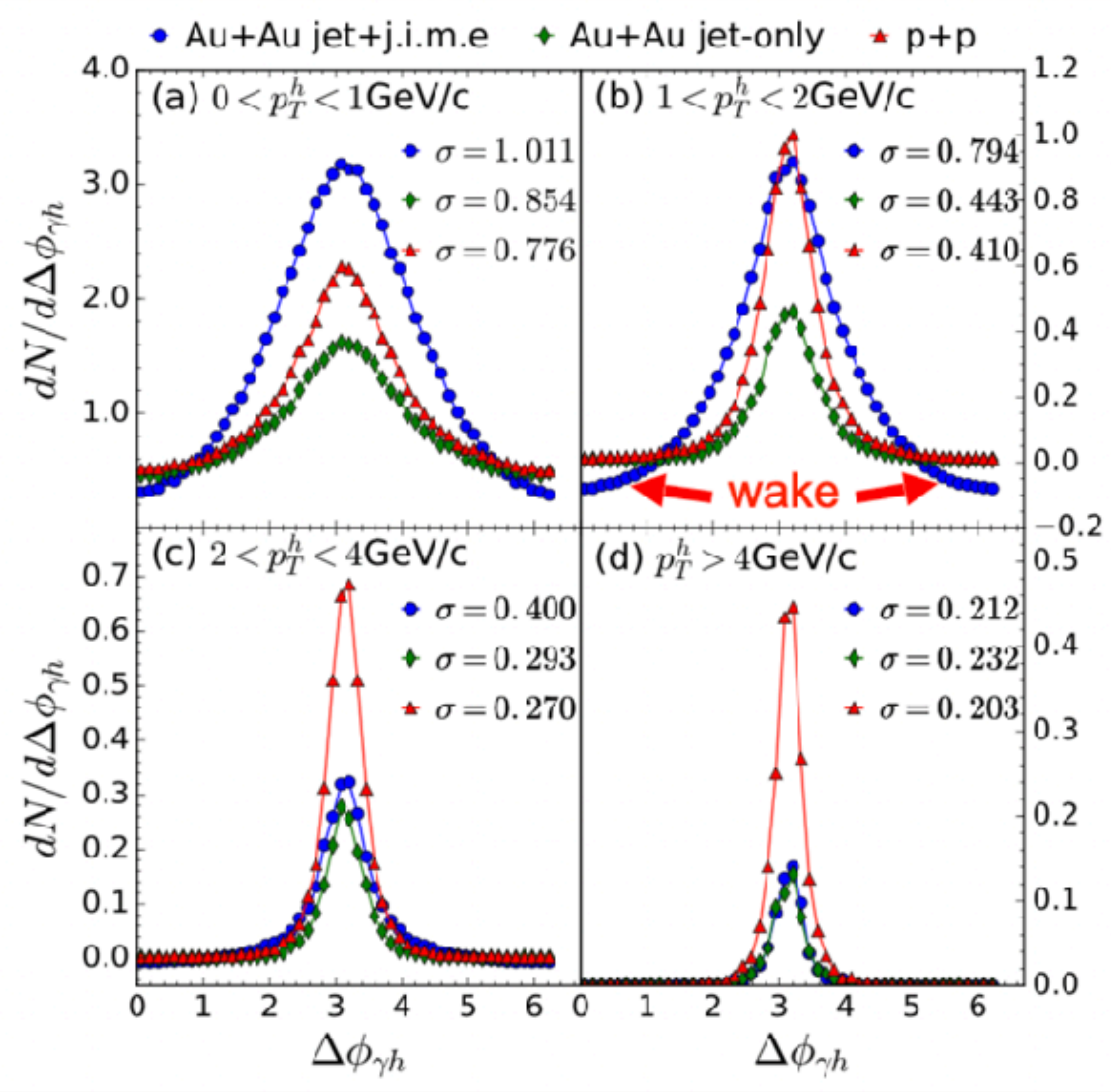
Enhancement of jet energy at large radius

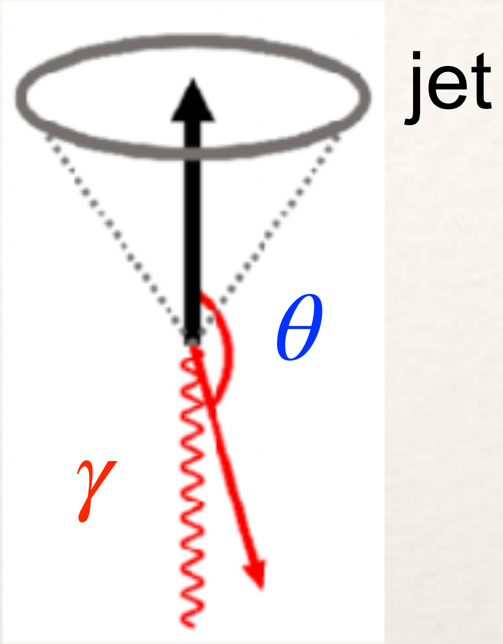
[Tachibana *et al.*, PRC 95 (2017), 044909]

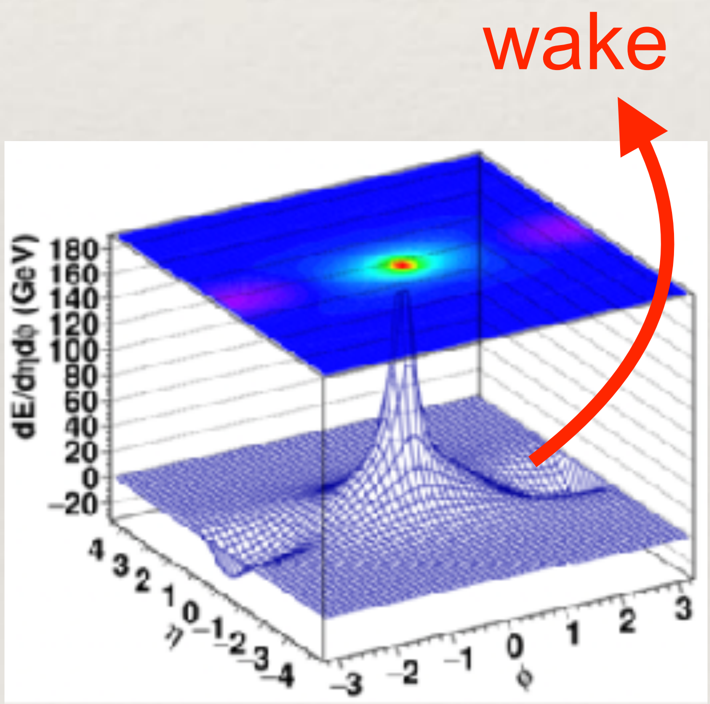
- Jet partons and medium background cannot be cleanly separated in reality
- Medium response (energy deposition + depletion) is naturally included in all jet observables
- Jet-medium interactions: medium modification of jets + medium response

Search for unique signatures of medium response

Diffusion wake (energy depletion)



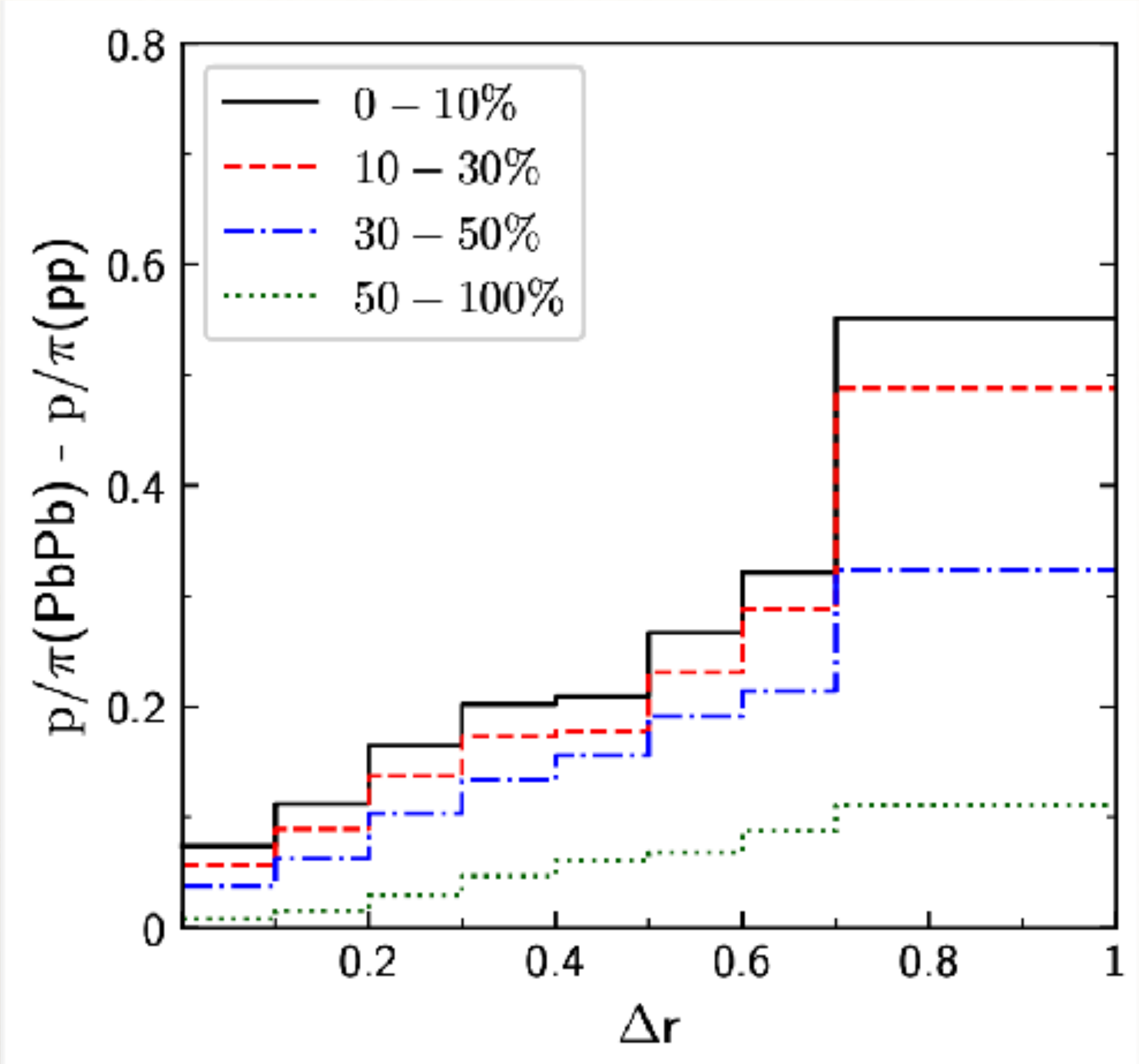




- Diffusion wake predicted in the backward direction of γ/Z at $1 < p_T^h < 2$ GeV

[Chen, SC, Luo, Pang, Wang, PLB 777 (2018) 86]
[Yang, Luo, Chen, Pang, Wang, PRL 130 (2023) 052301]

Hadron chemistry inside jets



- Richer baryons inside the QGP than inside a vacuum jet
- Enhanced baryon-to-meson ratio in *AA vs. pp* collisions

[Luo, Mao, Qin, Wang, Zhang, PLB 837 (2023) 137638]
[Chen, SC, Luo, Pang, Wang, NPA 1005 (2021) 121934]

Summary

- Overview of soft and hard probe theories in relativistic heavy-ion collisions
- Soft hadrons probe the initial geometry and fluctuation, thermal properties, transport coefficients and EoS of the QGP
- Heavy quarks and jets probe the perturbative and non-perturbative interactions, hadronization mechanism, transport coefficient inside the QGP
- More accurate understanding of nuclear matter under extreme conditions with more precise data from future LHC runs, e.g., nucleus geometry, parton energy loss, hadron structure, strong E&M field, …

Thank you!