Exploring the QGP dynamics at colliders

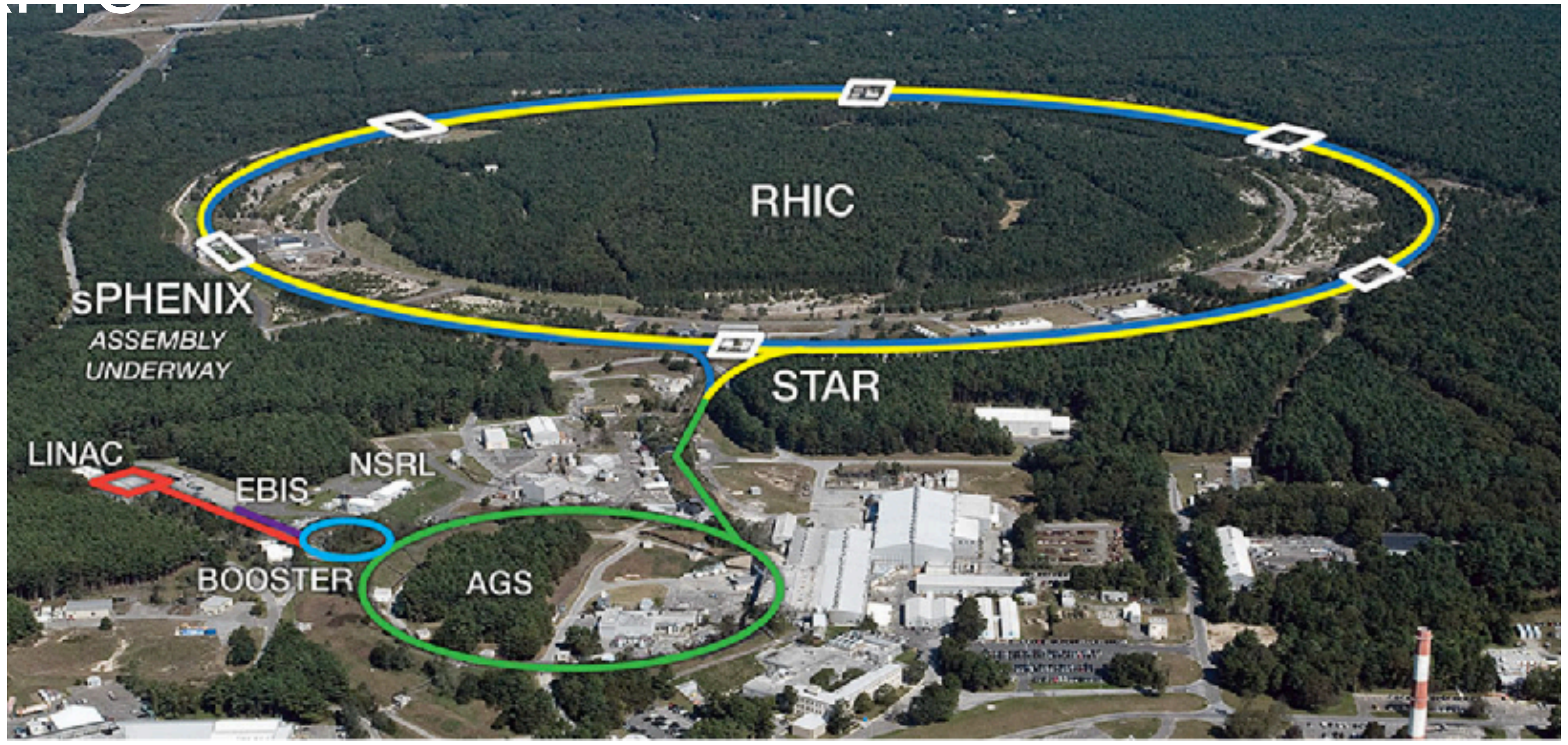
Yacine Mehtar-Tani (BNL & RBRC)

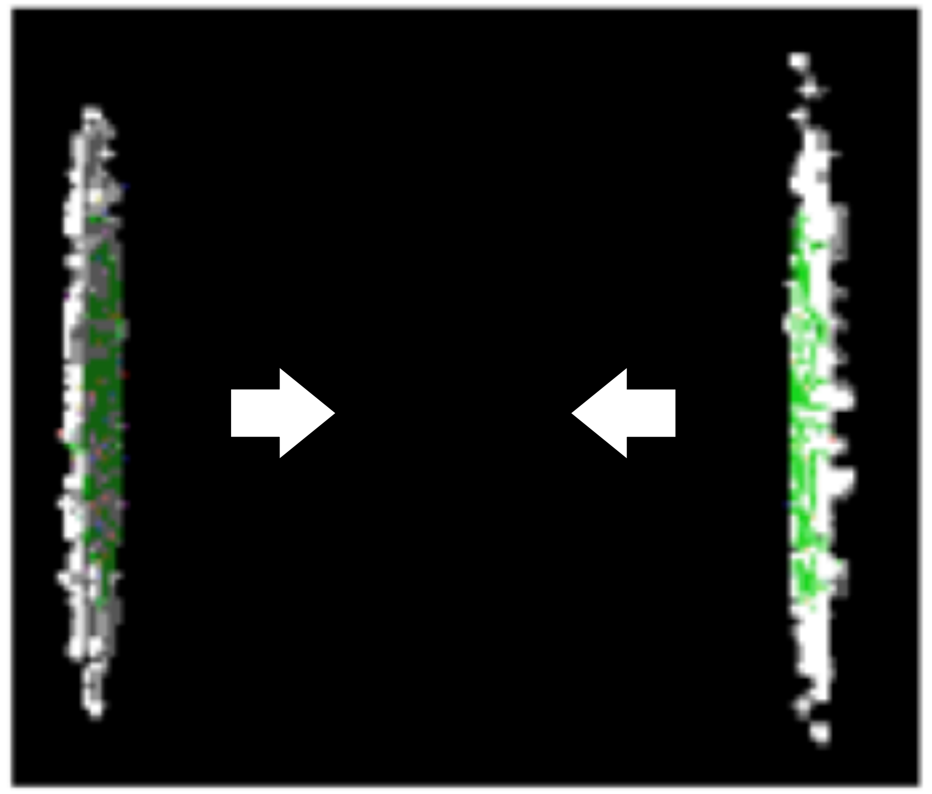
RHIC & AGS Users’ Meeting , August 1-4, 2023 @ BNL

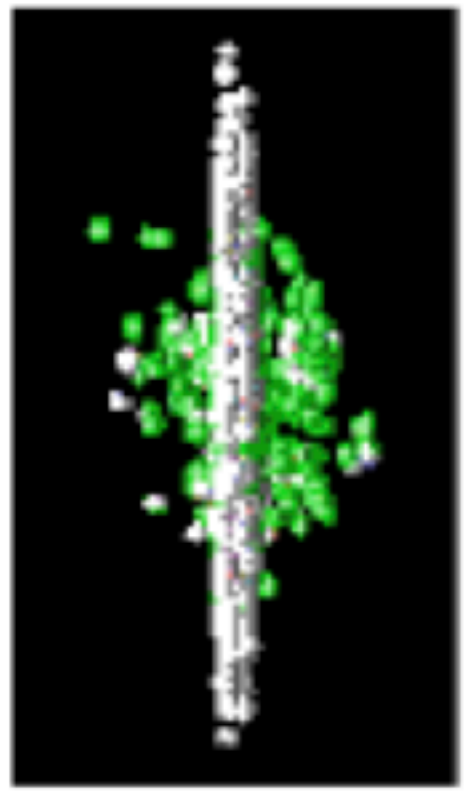
Outline

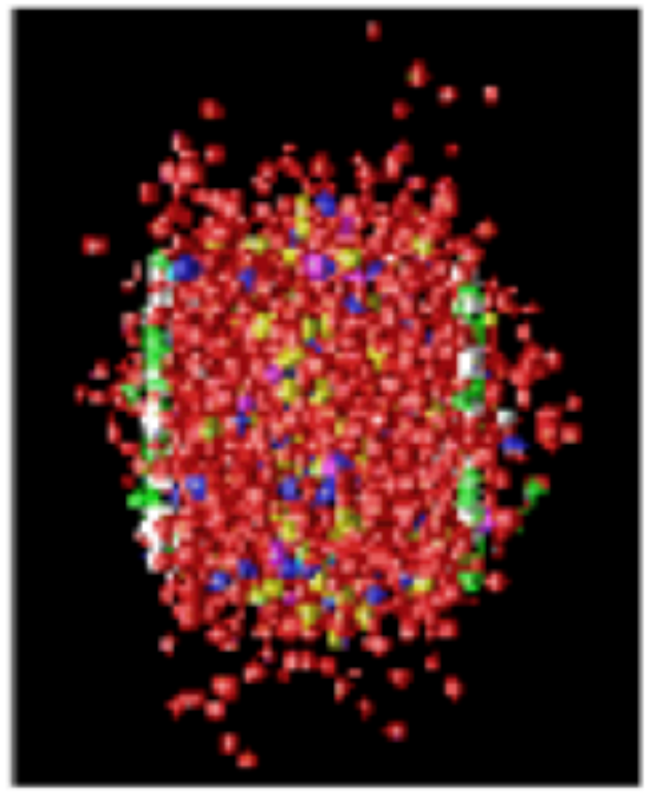
- Introduction: the QGP from large to short distance scales
- Emergent transport phenomena: anomalous diffusion, turbulent thermalization
- Toward precision phenomenology
- Conclusion

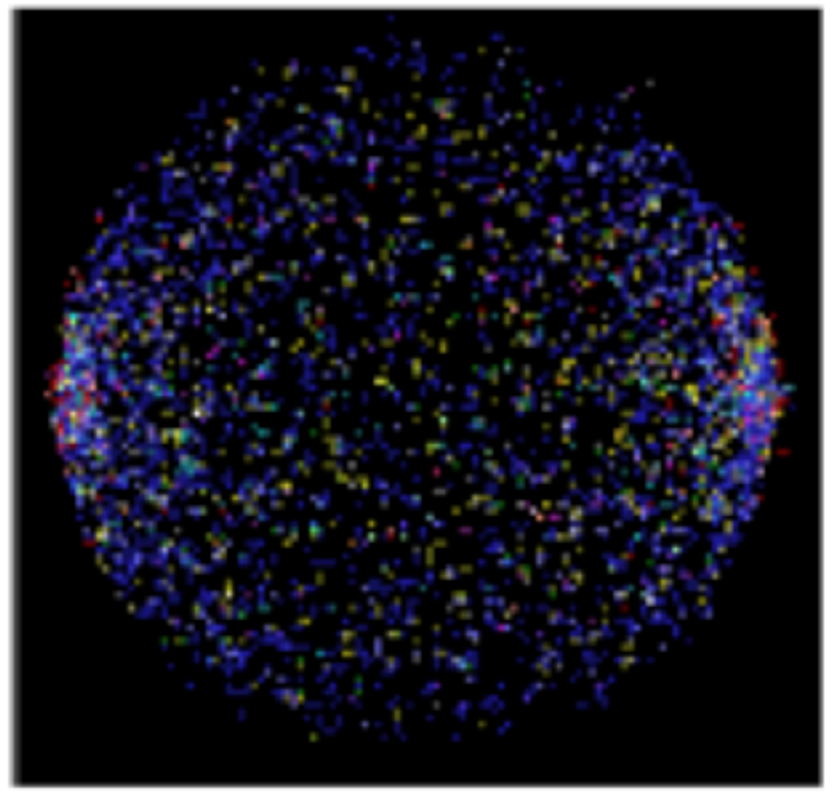
The little bang: producing deconfined hot QCD matter

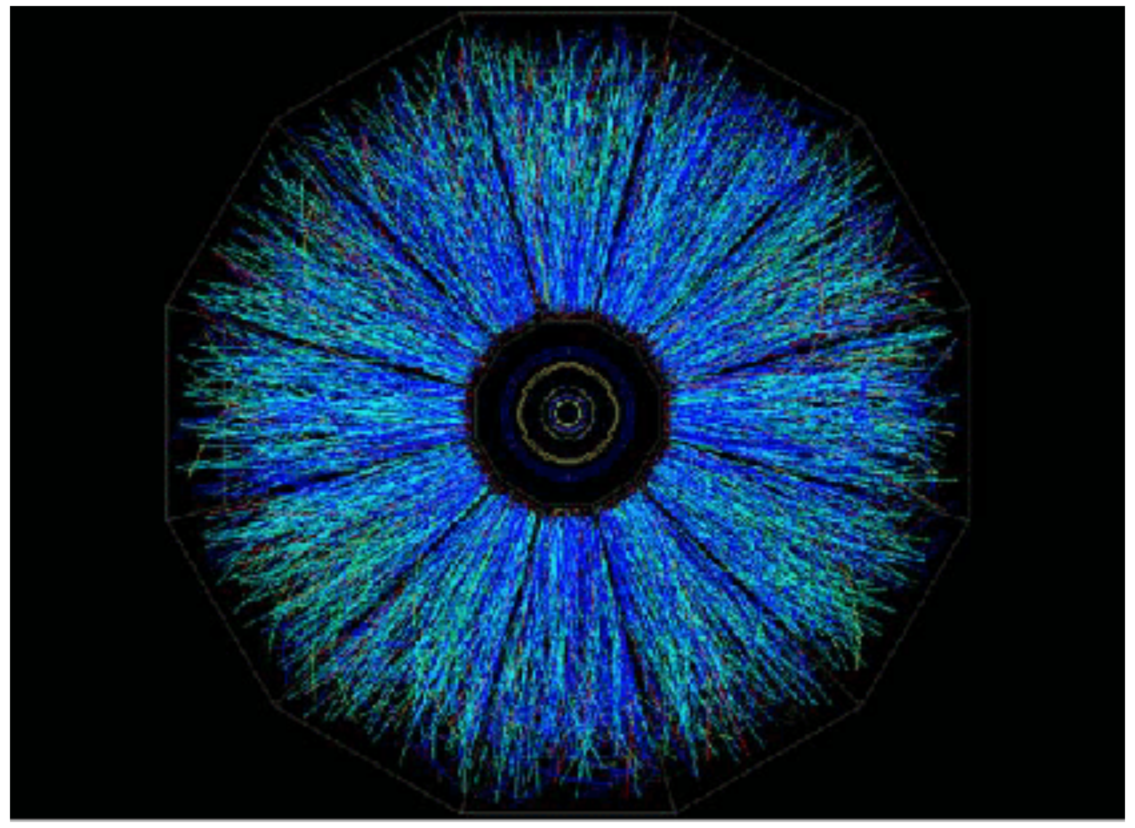






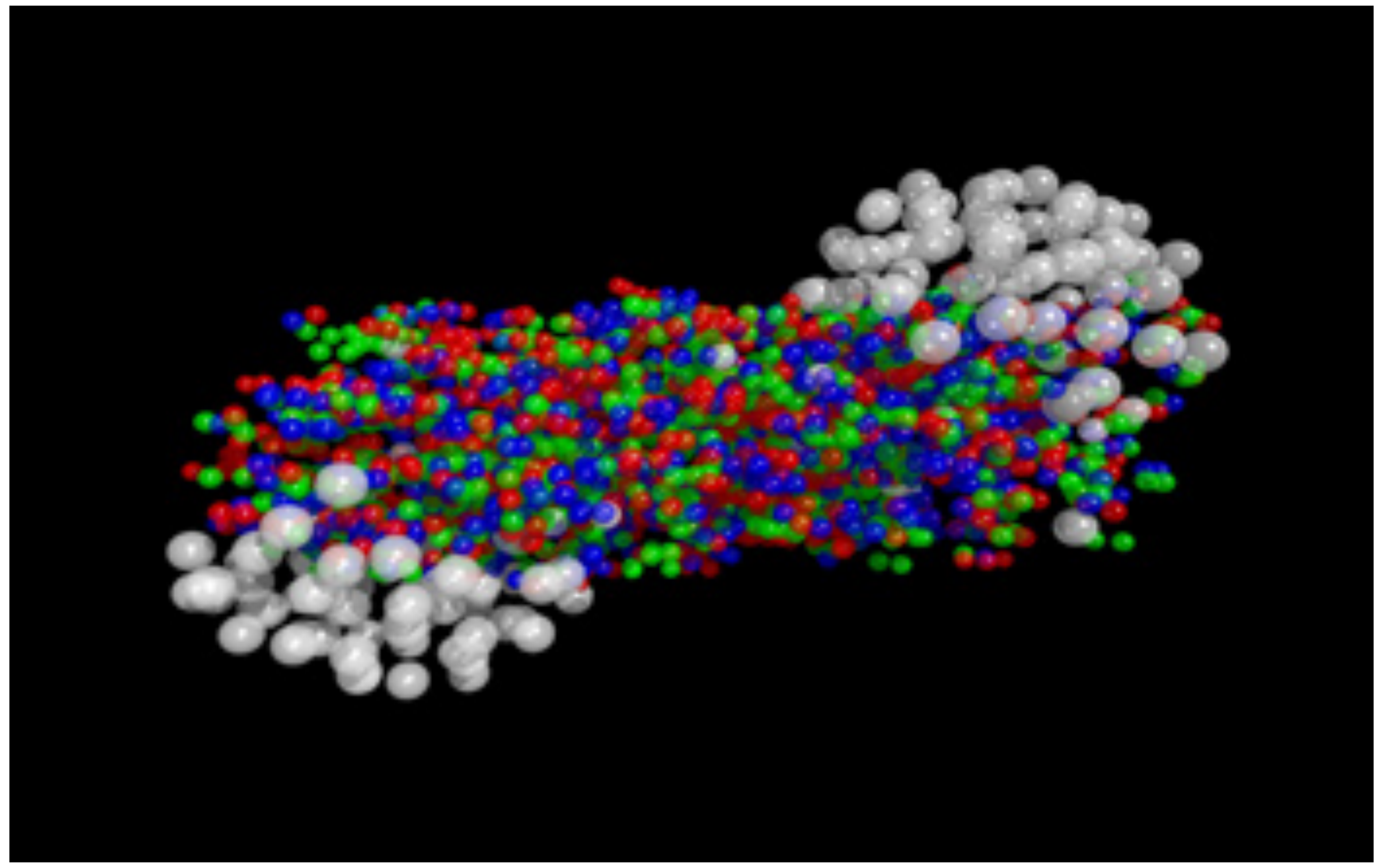


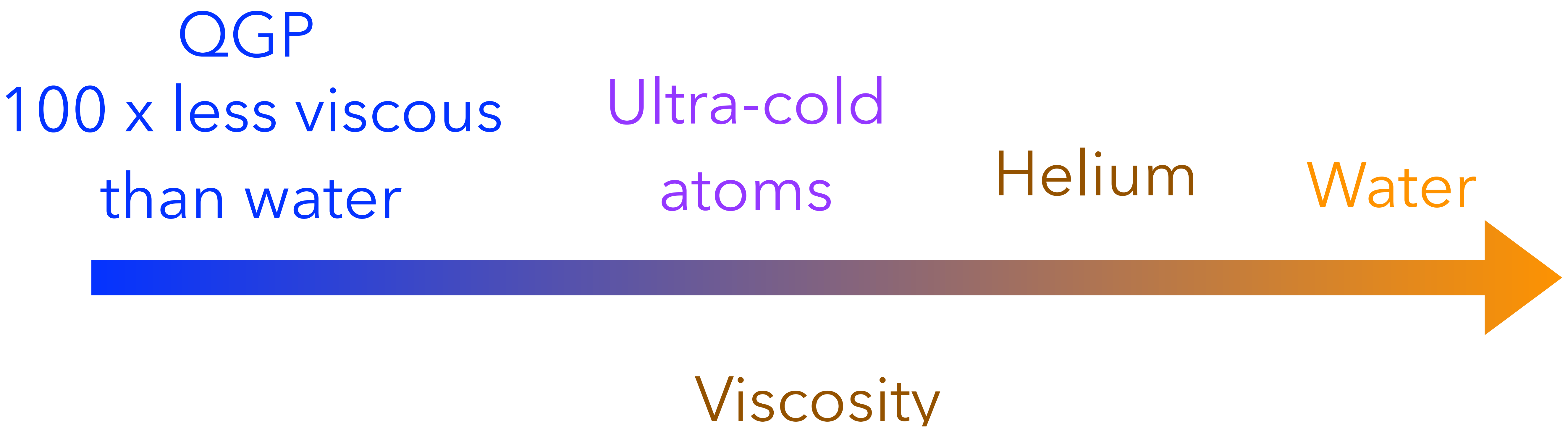




fast moving nuclei (gold nucleus) → nuclei collide → Quark gluon plasma forms → System expands and cools → experimental detection

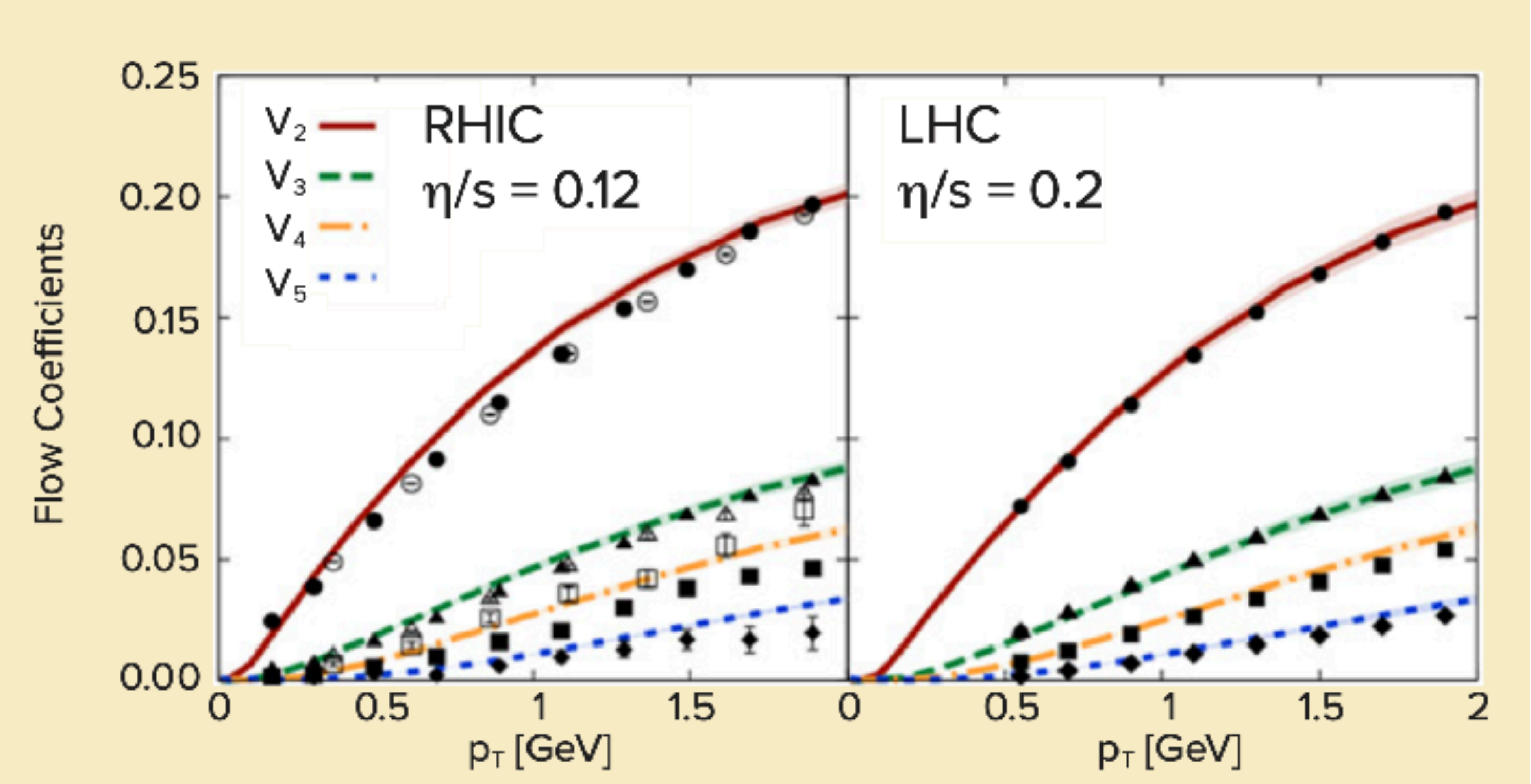
The QGP: the most perfect liquid





- Collective behavior in heavy ion collisions: Viscous hydrodynamic simulations point to low shear viscosity to entropy ratio (near the Gauge/Gravity Duality Kovtun, Son and Starinet Bound from (2001)

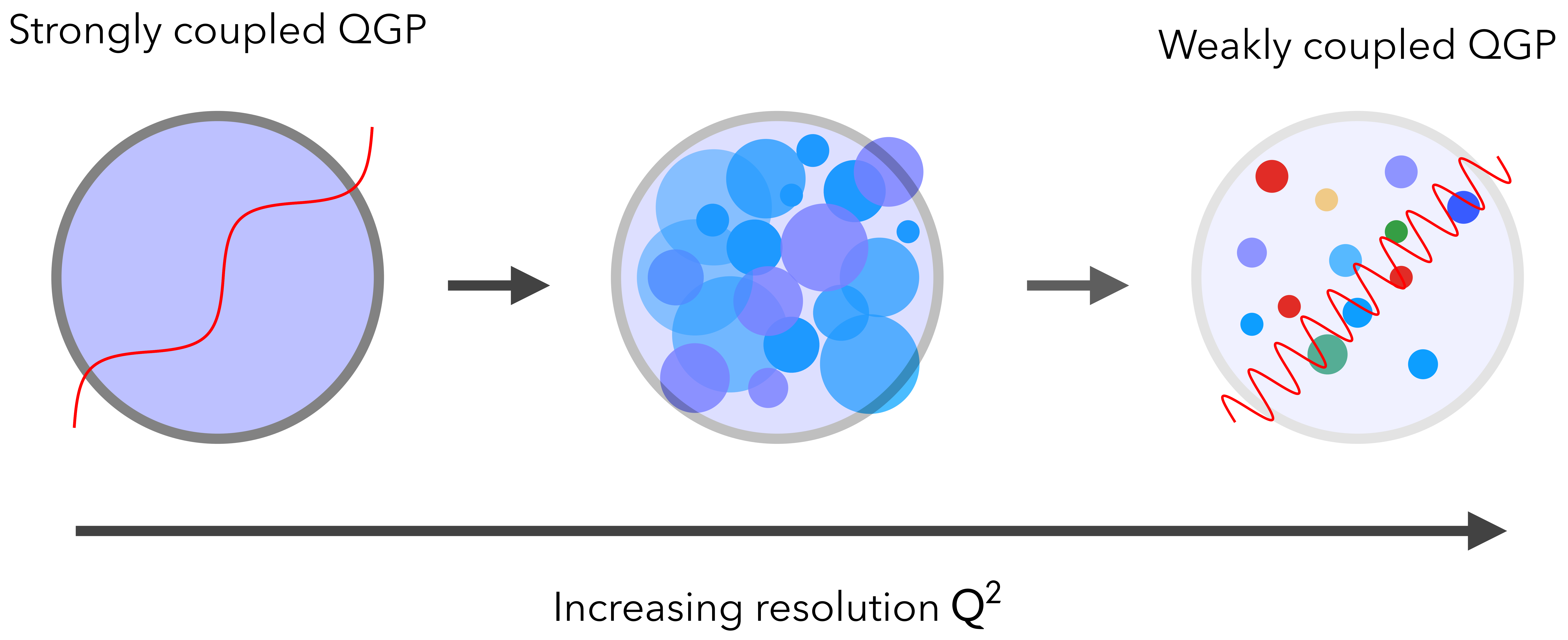
$$\frac{\eta}{s} > \frac{1}{4\pi} \sim 0.08$$



From 2015 Long Range Plan for Nuclear Science

Flow harmonic coefficients

How does this behavior emerge from QCD as a function of distance scale ?



Multi-messenger HI physics

In addition to soft probes

- Bulk observables: flow harmonics $p_T \sim T \sim 1\ \mathrm{GeV}$

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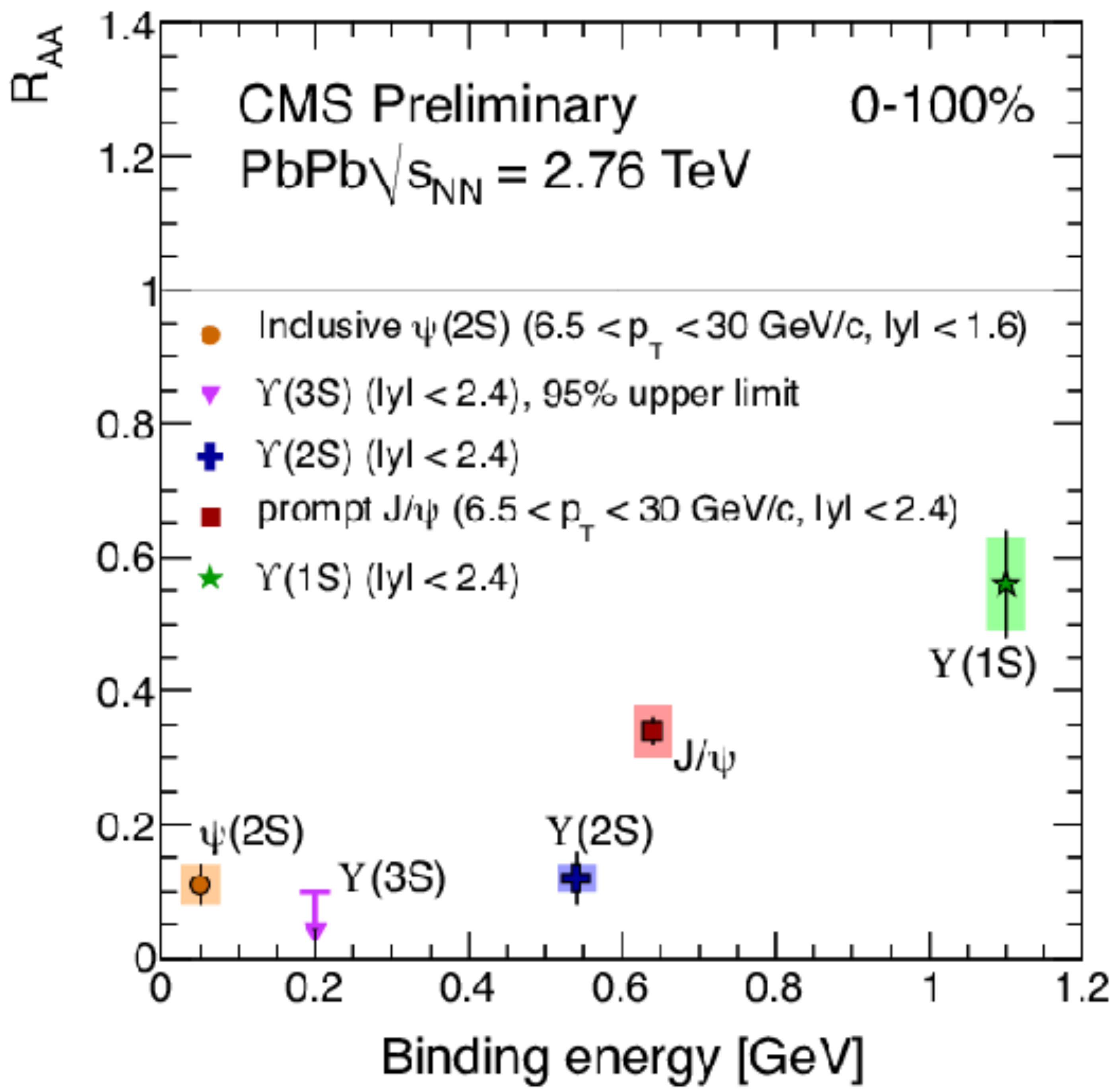
Hard probes to investigate the QGP dynamics at short distances

- Quarkonia, heavy flavor suppression

$p_T \gg 1$ GeV



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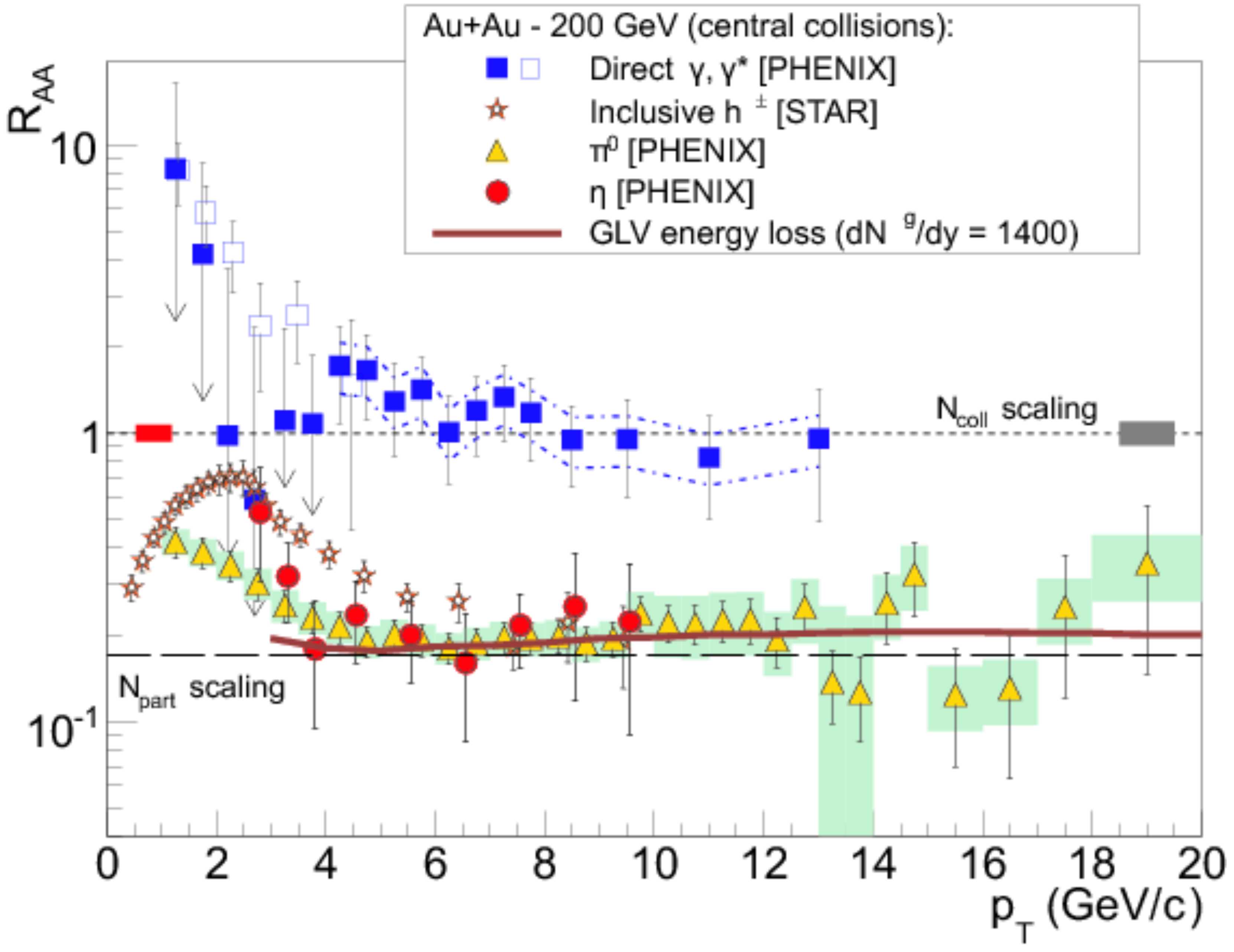

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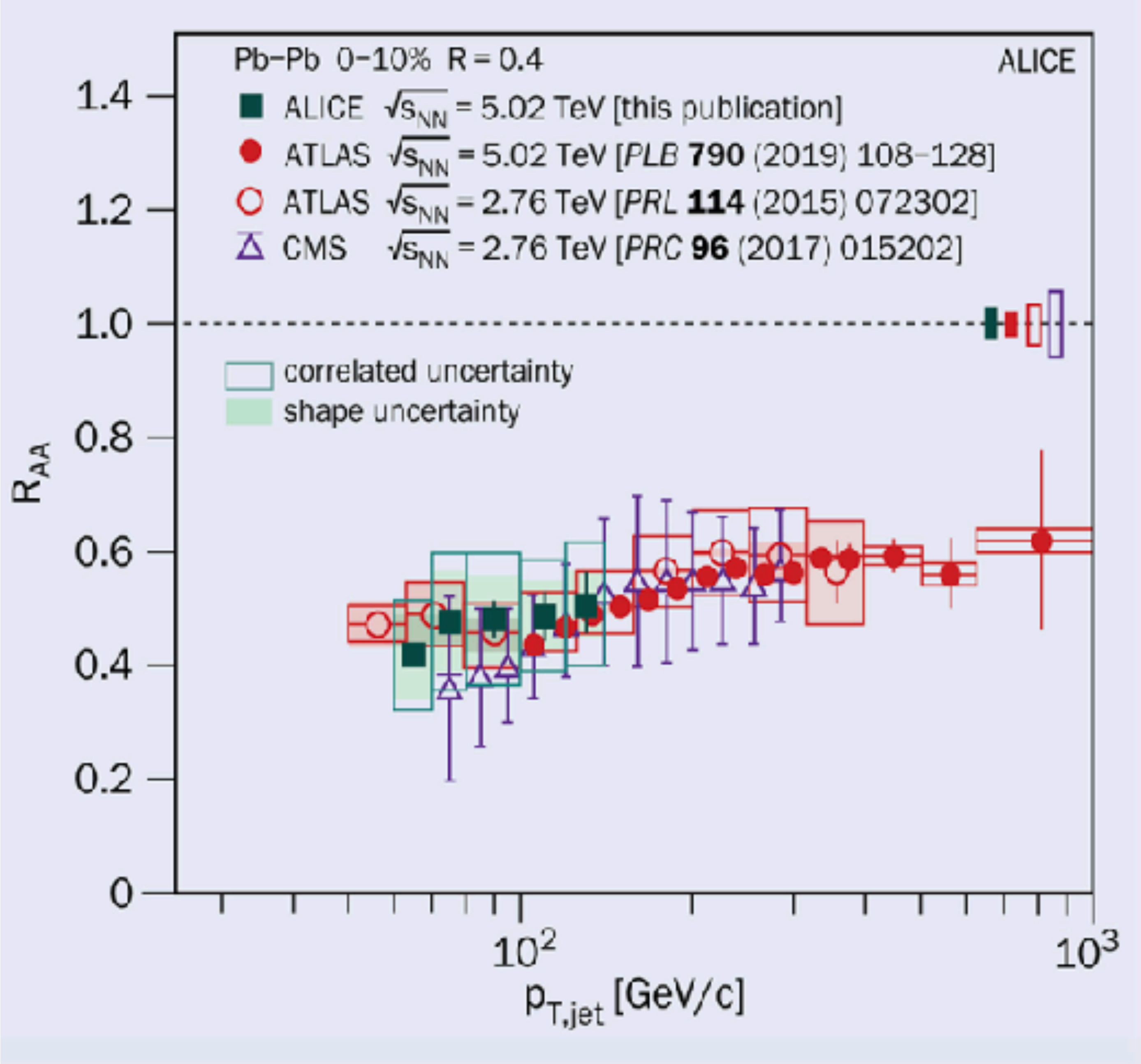
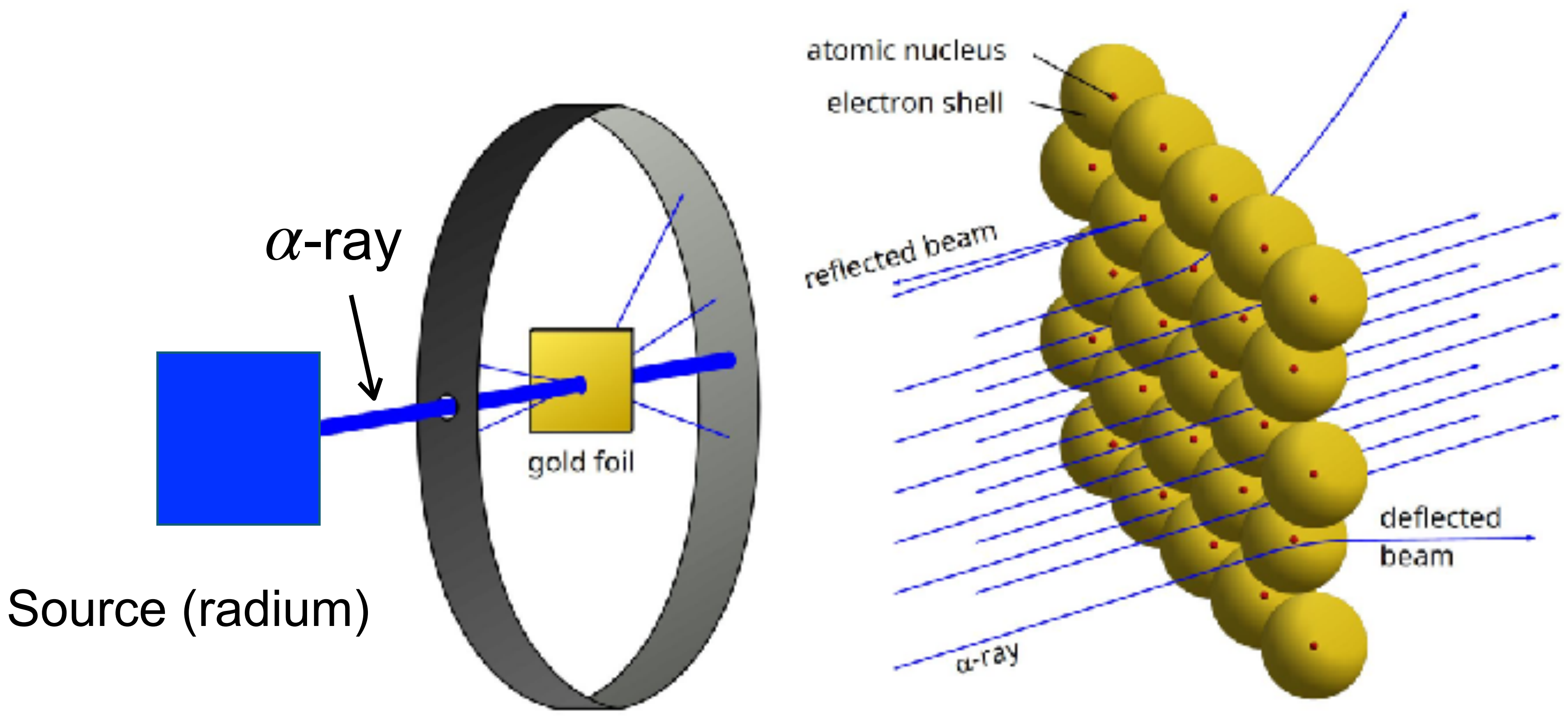
Hard probes to investigate the QGP dynamics at short distances

- Quarkonia, heavy flavor suppression
- High pt hadrons, direct γ
- Fully reconstructed jets

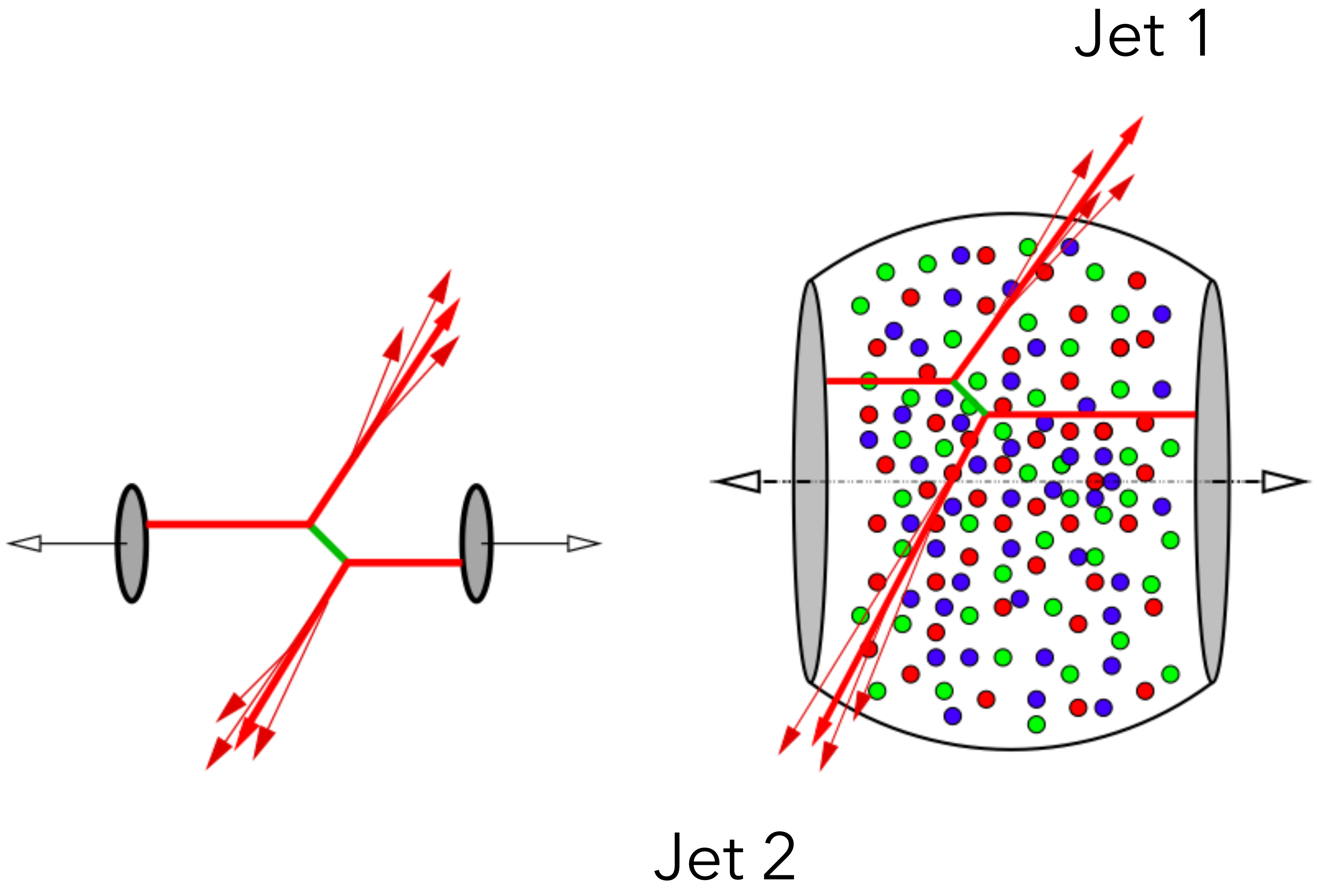


$p_T \gg 1$ GeV

A Rutherford-like experiment - Jets in HIC

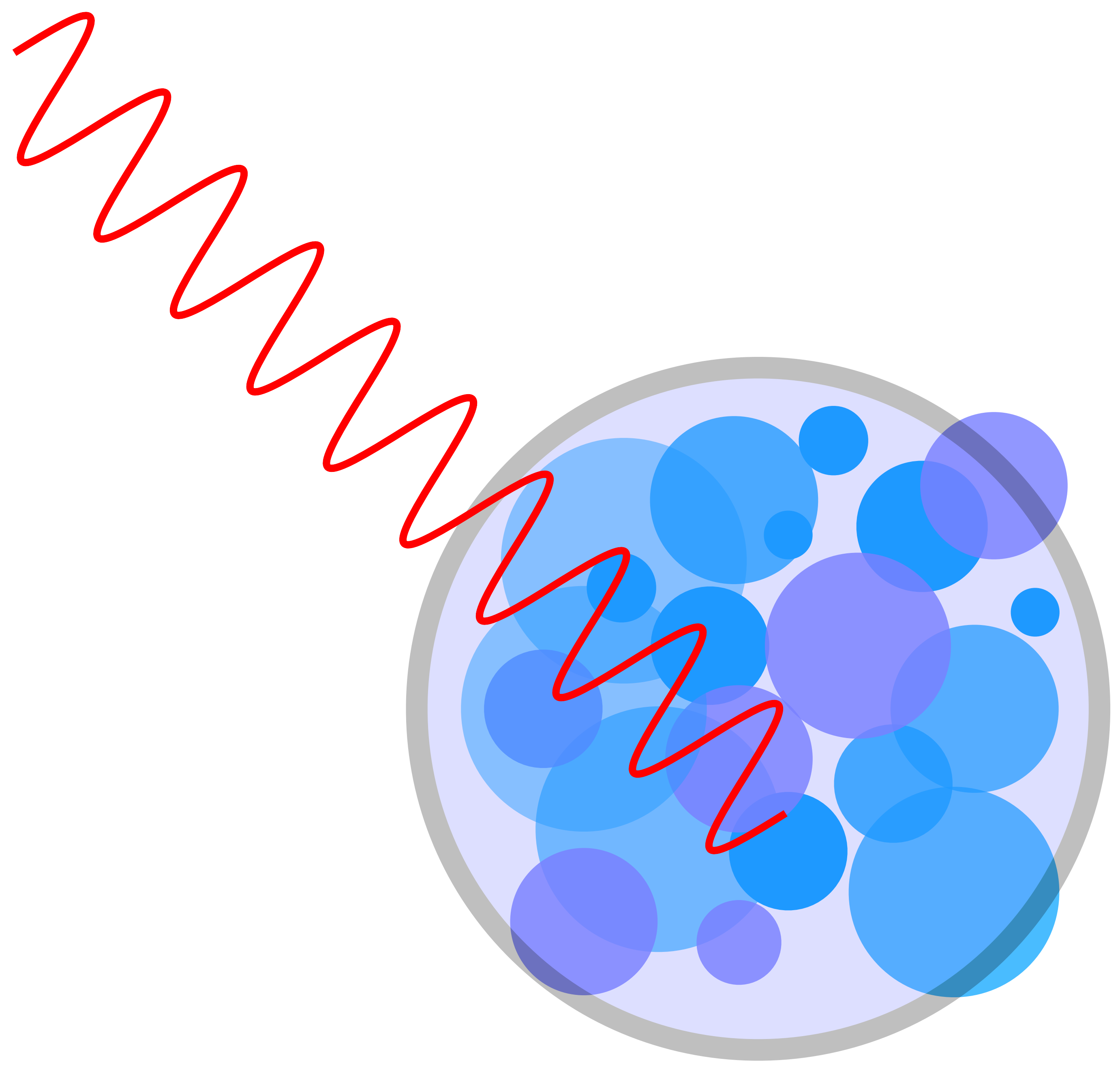


Discovery of the atomic nucleus



Probing the microscopic properties of the QGP with jets

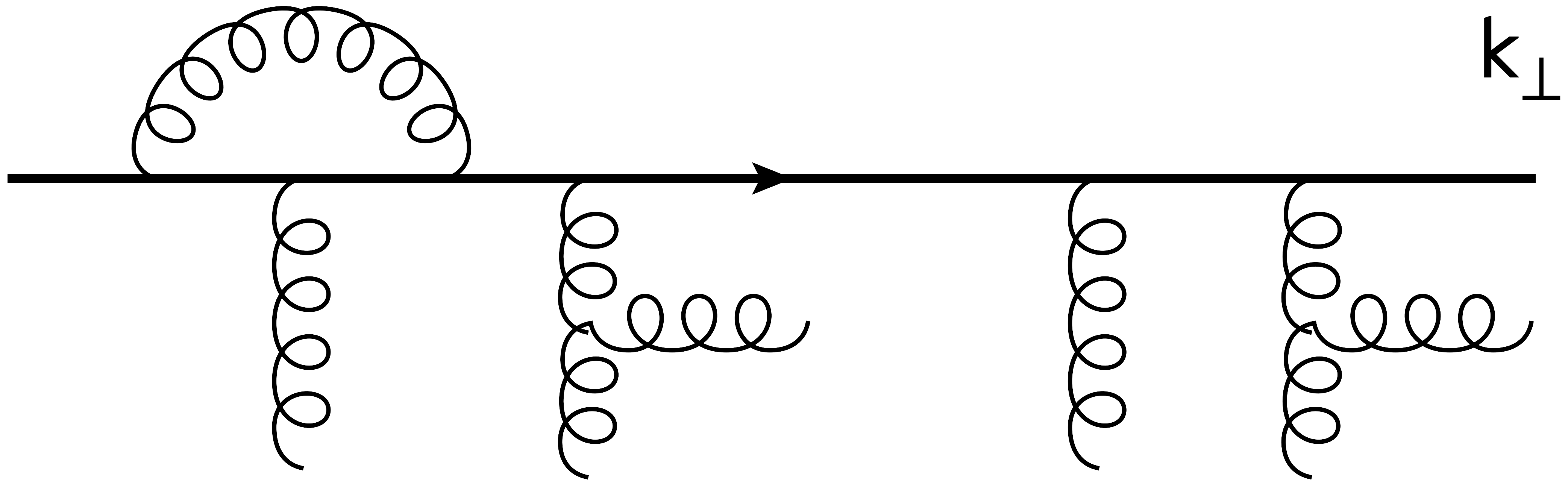
Do jets scatter off point-like color charges?



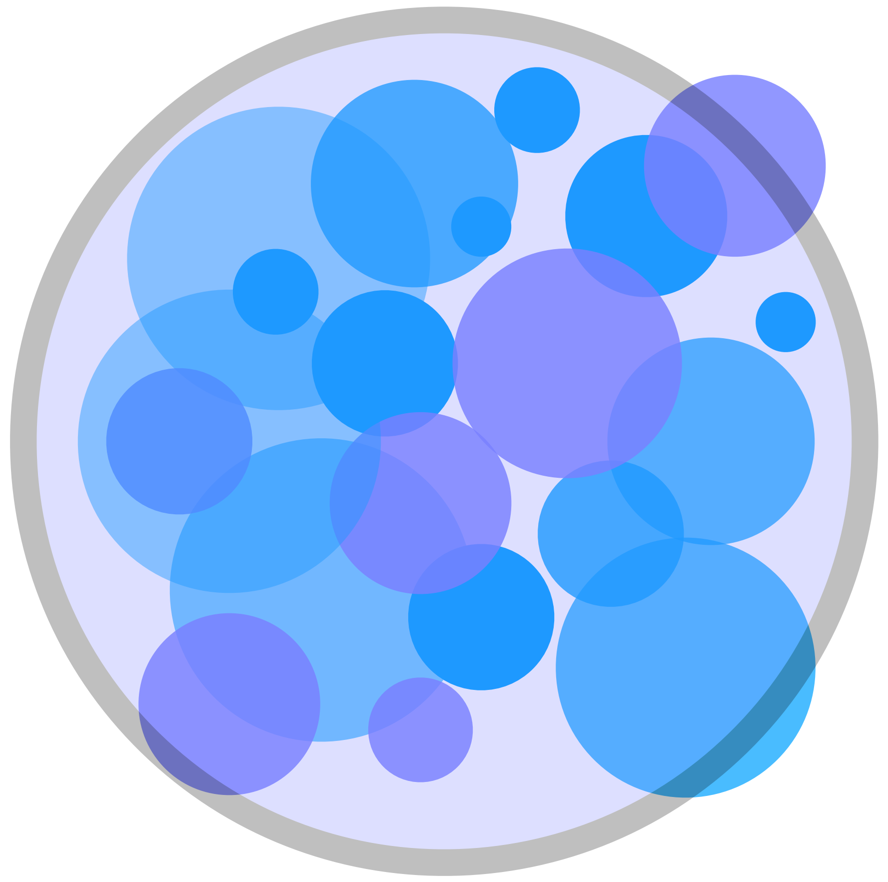
Anomalous Diffusion in the QGP

Liou, Mueller, Wu, Iancu, MT, Blaizot (2014) MT, Caucal (2021), Arnold (2021) Ghilieri, Weitz (2022)

Energetic quark



$k_\perp \ll E$



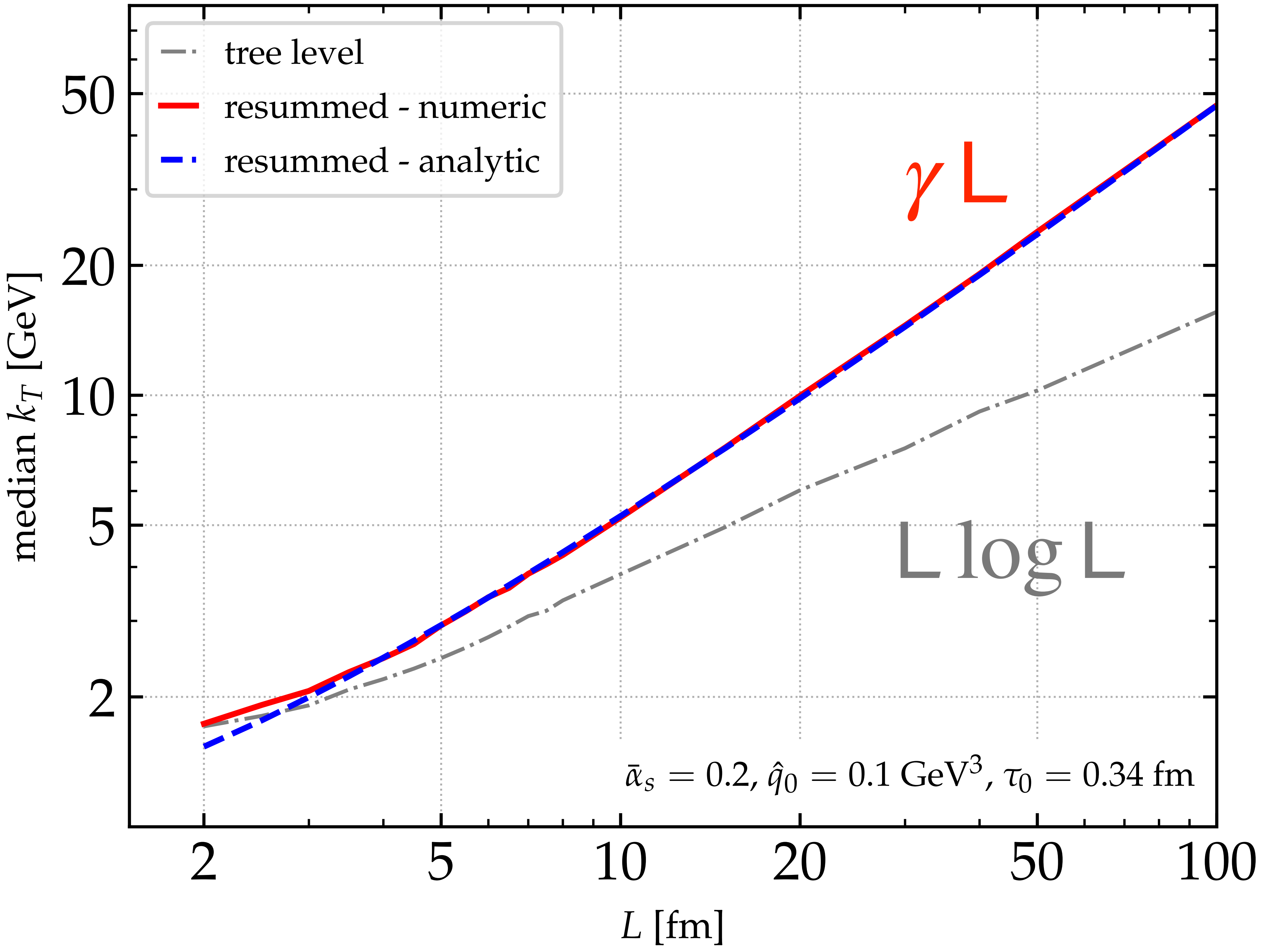
- Nonlocal quantum corrections to all orders in perturbation theory to leading log
- Normal diffusion → Anomalous (super) diffusion

$$\langle k_\perp^2 \rangle \sim t^{\gamma} \qquad\qquad \gamma \sim 1 + 2\sqrt{N_c \alpha_s / \pi} > 1$$

t

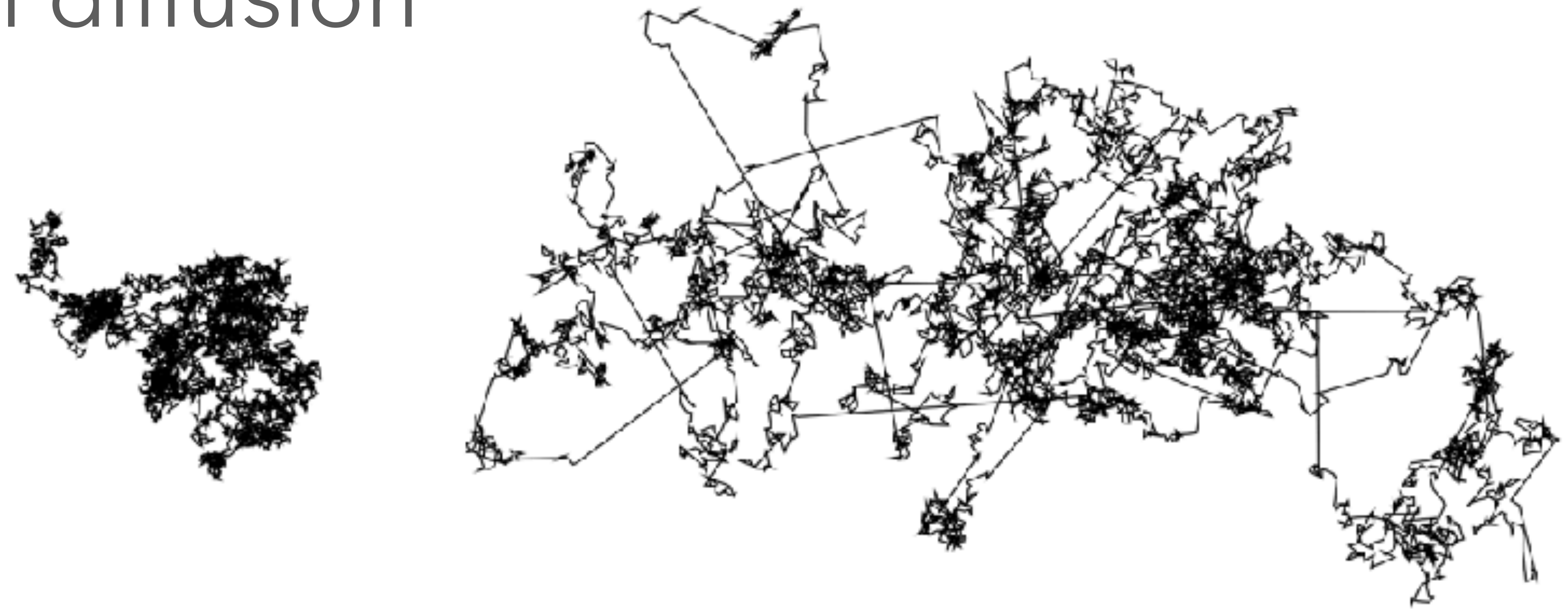
Quantum induced super-diffusion in the QGP

MT, Caucal PRD (2021)



Super diffusion

Normal diffusion



Brownian motion

$\gamma = 1$

Lévy flight

$\gamma > 1$

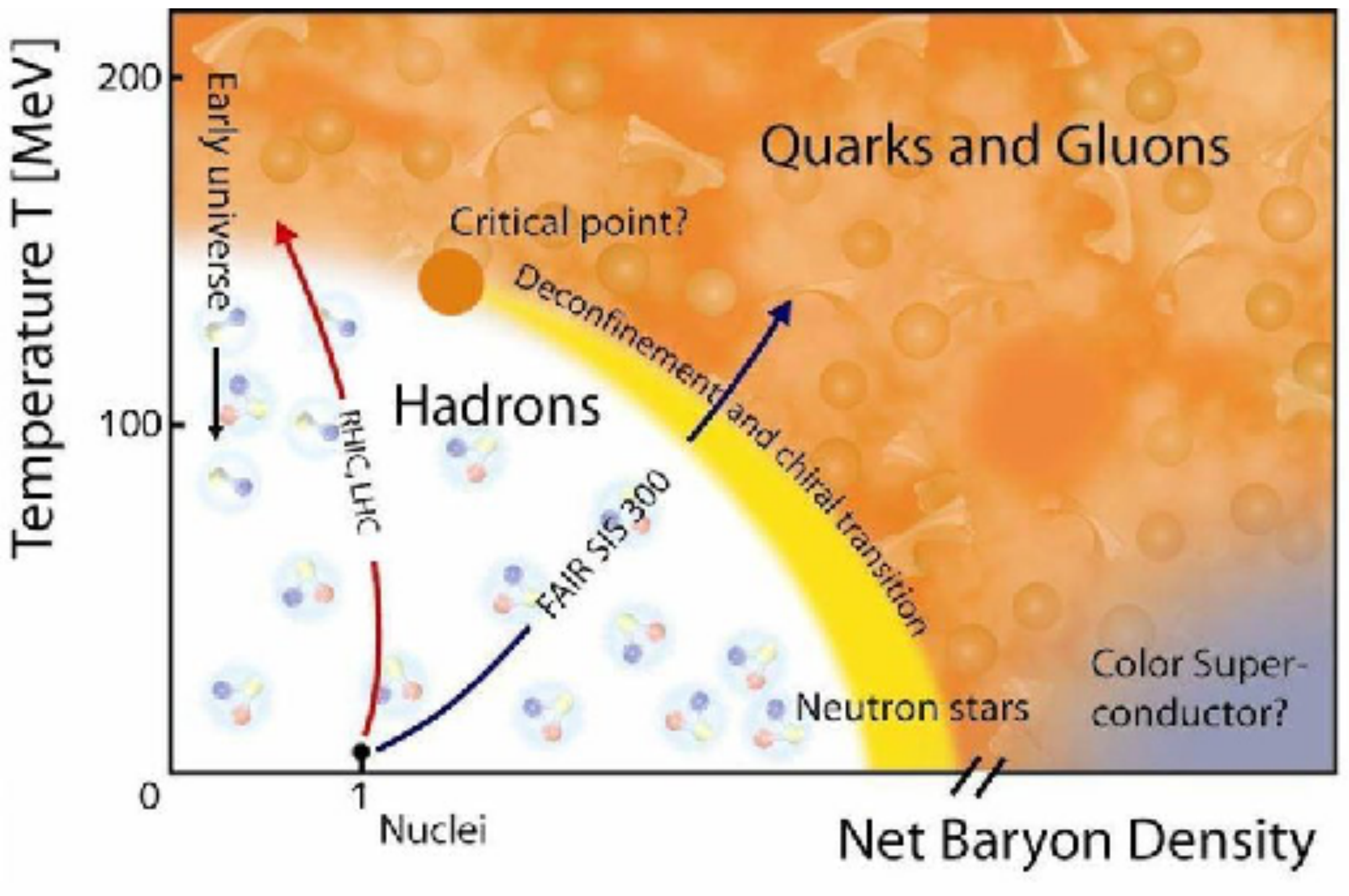
- (Non)perturbative physics of the plasma encoded in diffusion coefficient $\hat{q}(Q^2, t)$

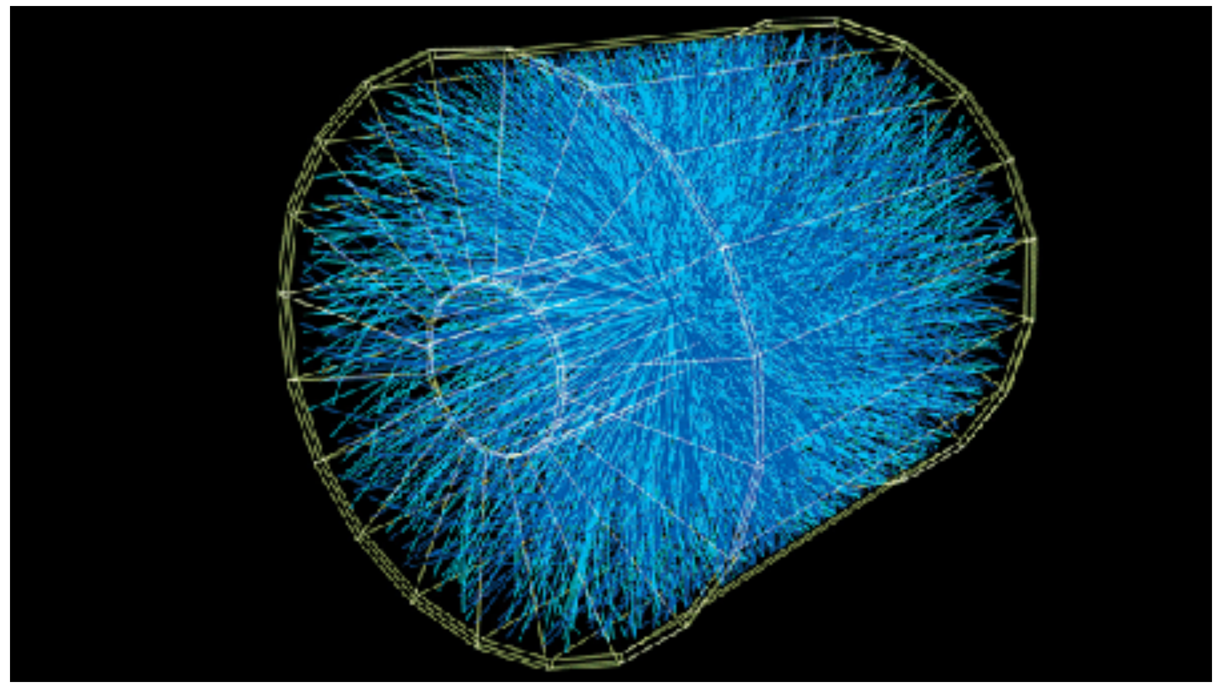
What can we learn by studying jets?

- QCD dynamics at high energy and high partons density
- Mechanisms of thermalization
- Transport properties of the QGP: $\hat{q}\,,\ \hat{e}\,,\ \eta/s\,,\ \ldots$
- Emergence of the nearly perfect liquid behavior

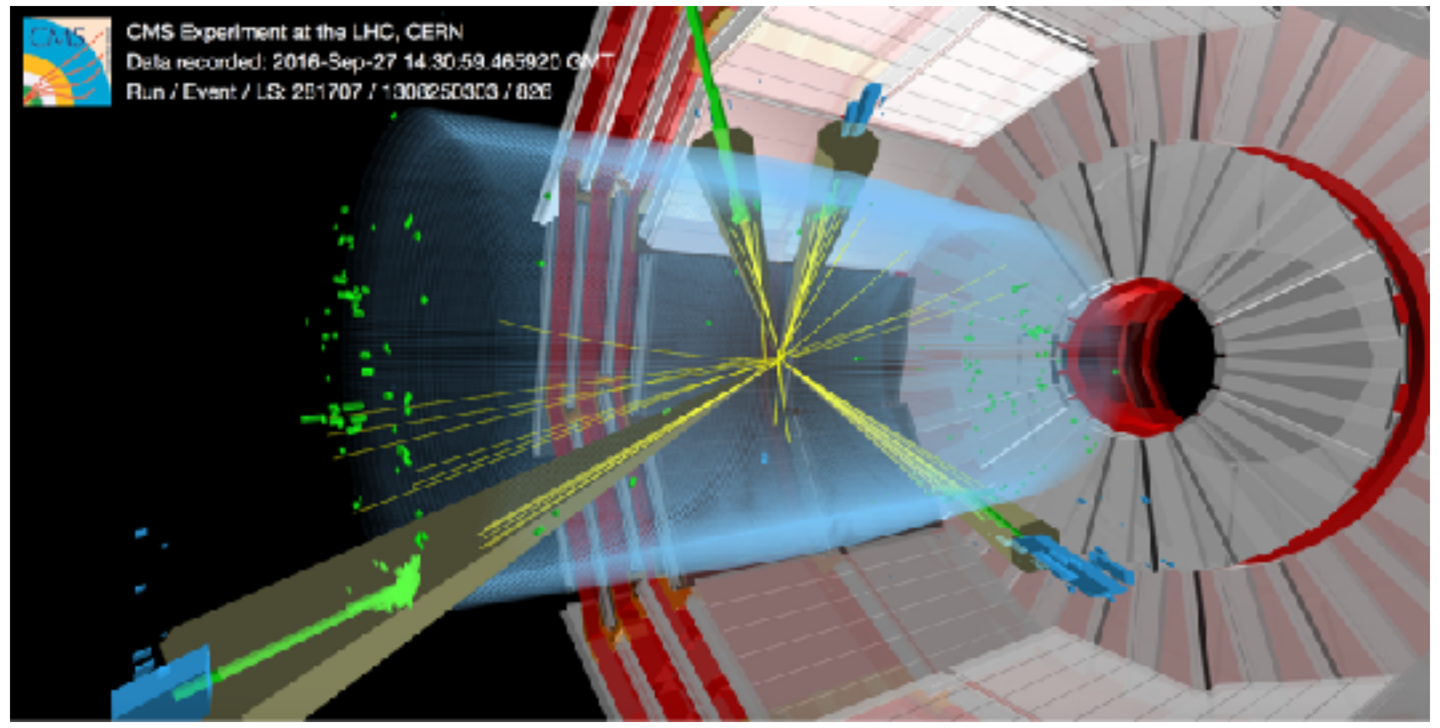
Multiscale dynamics

Thermal equilibrium (T≠ 0) | Non-equilibrium | T=0

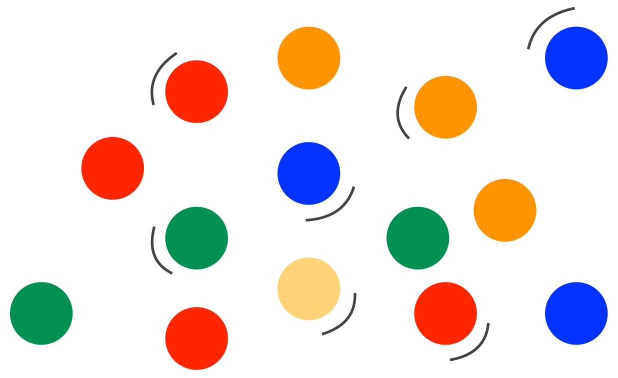


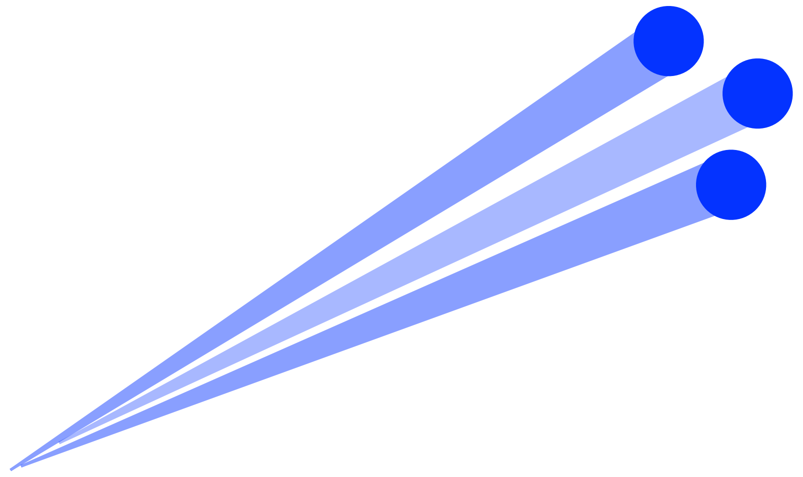


Heavy ion event
~ 1000's particles



Jets in pp





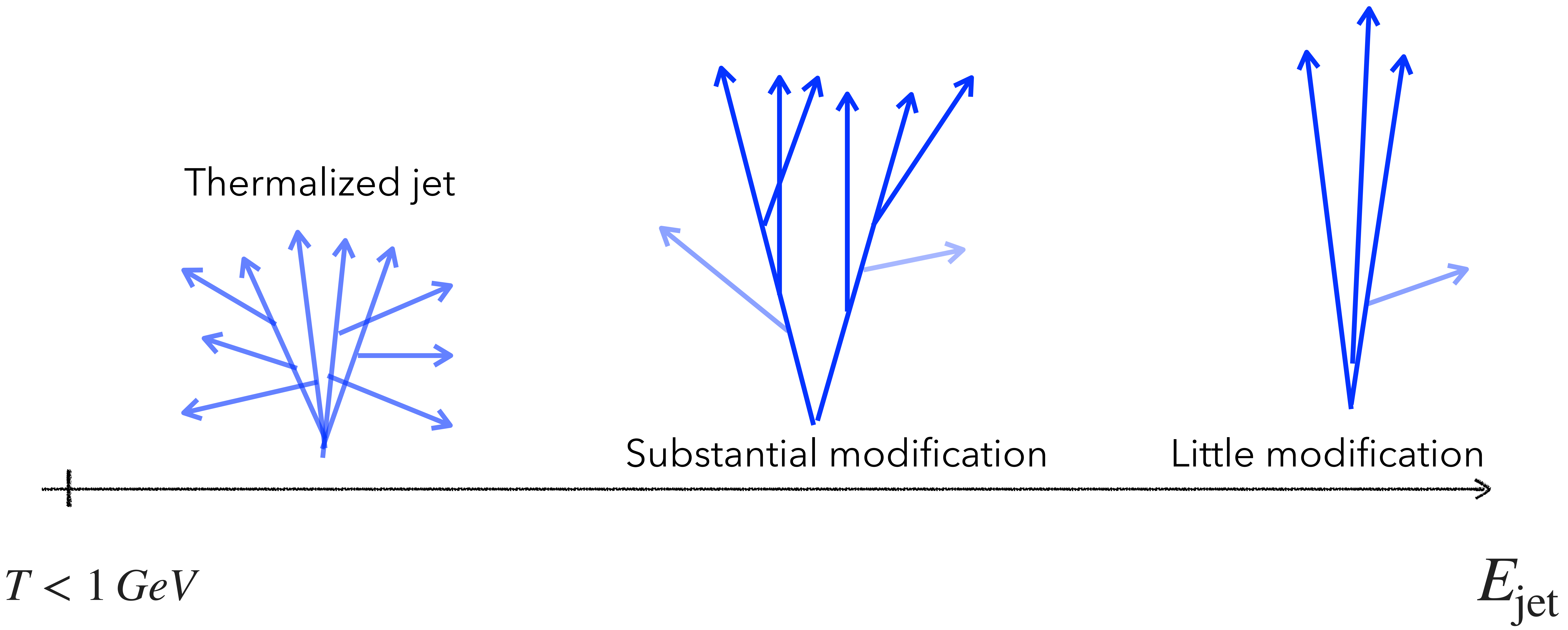
How is energy transported and dissipated?

Energy

$T \sim 1$ GeV

$p_T \sim 1$ TeV

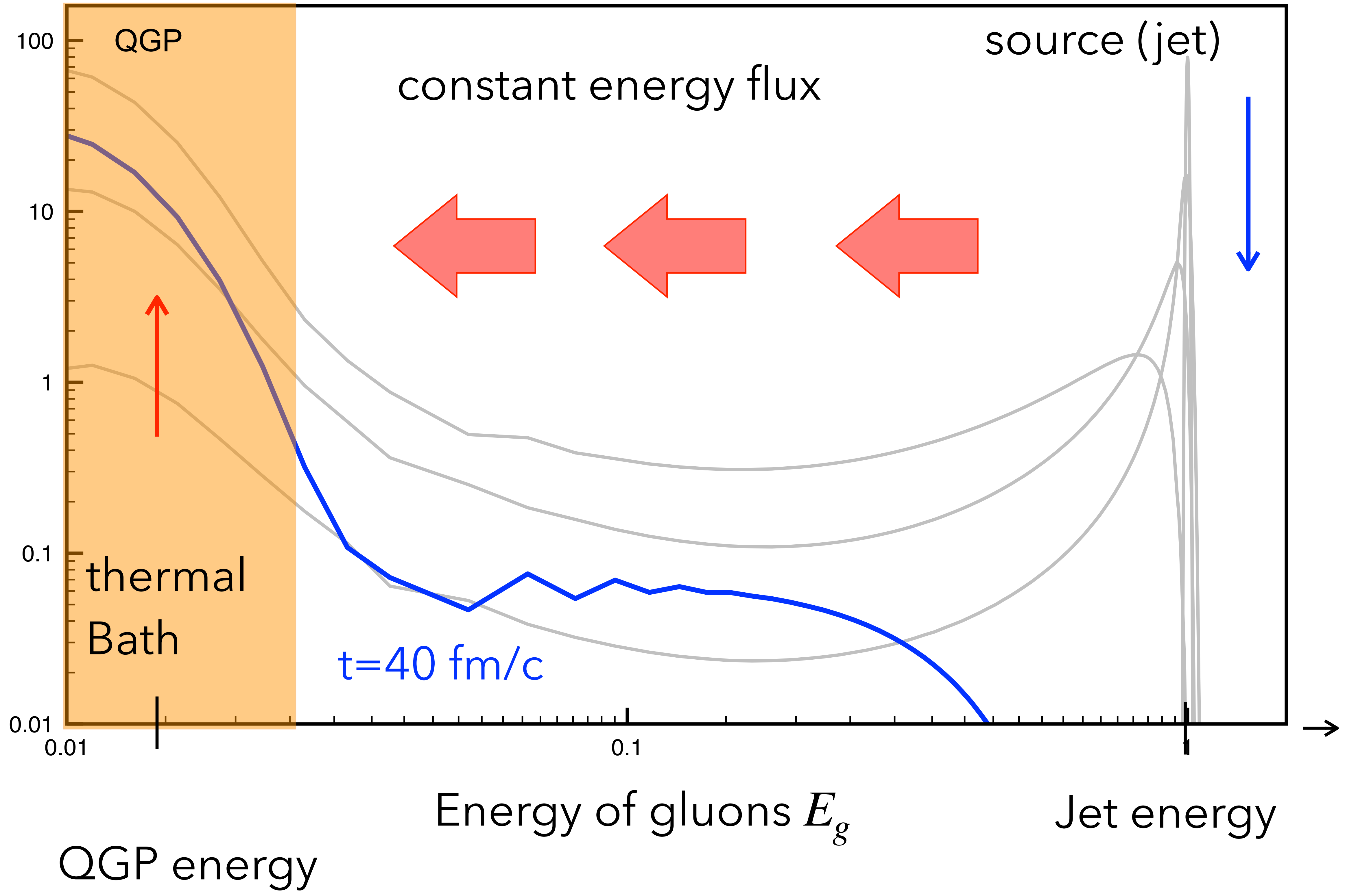
Understanding thermalization of the QGP

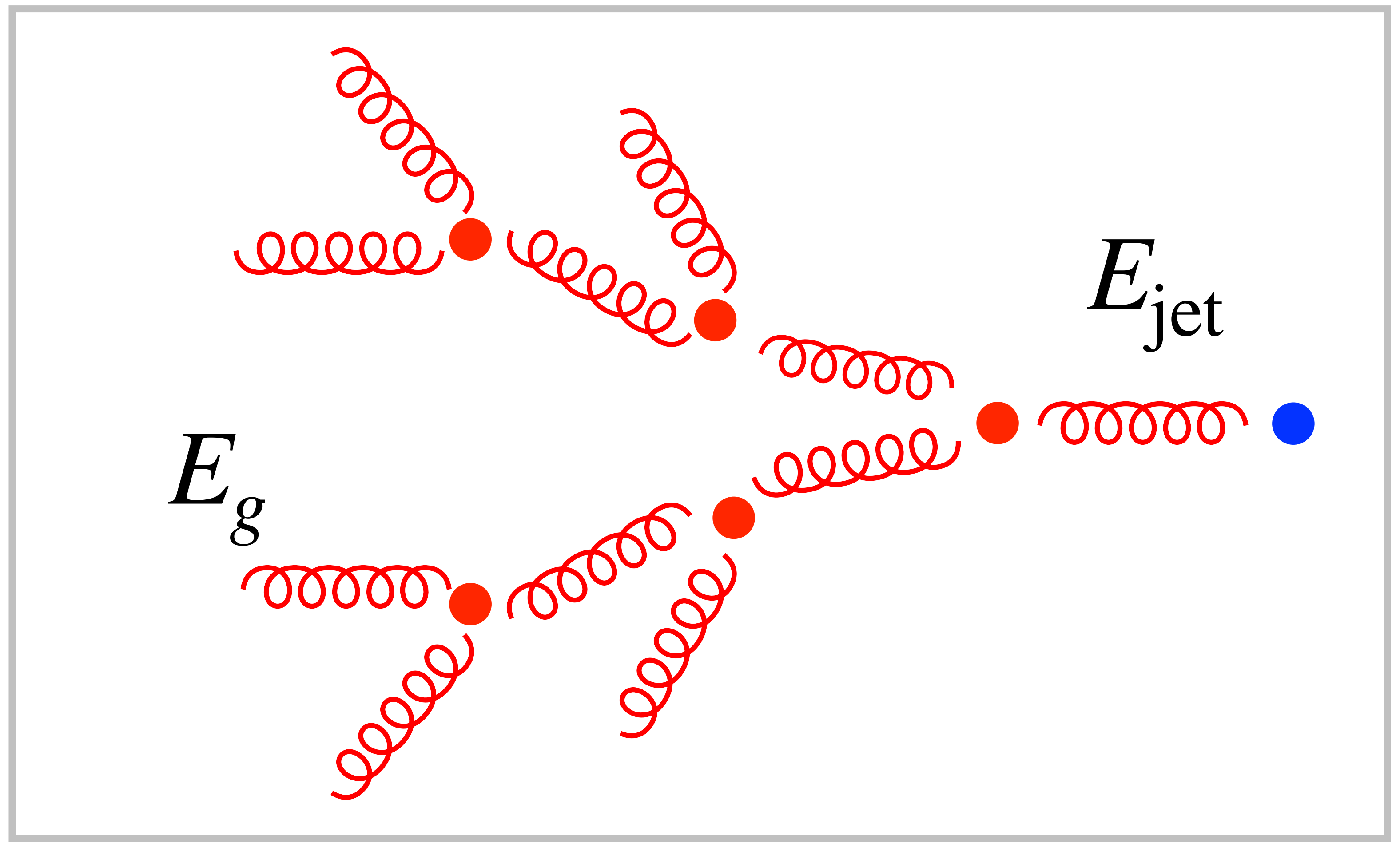


Melting jets at sPHENIX: lower pt jets thermalize faster in the QGP

Turbulent thermalization: Kinetic theory simulation

Distribution of fragments (gluons)





Jeon, Moore (2002) Blaizot, Iancu, MT (2013)
MT, S. Schlichting, I. Soudi, (2022)

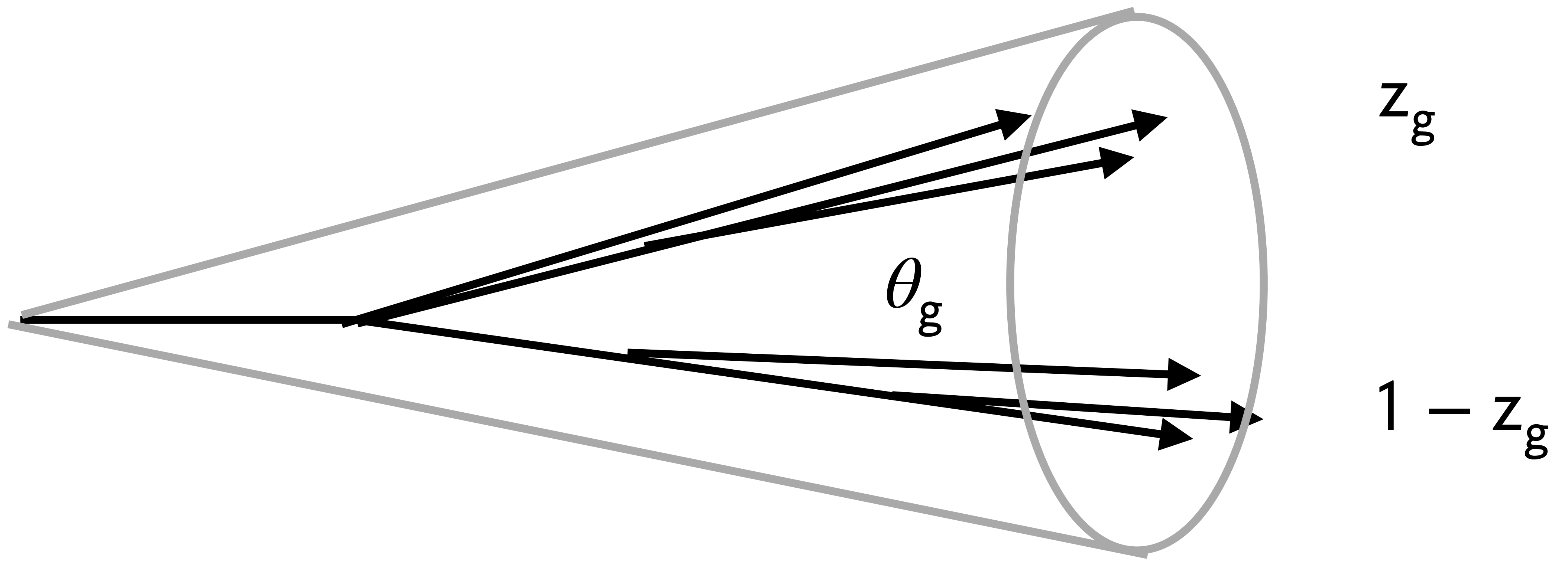
A challenging problem

- Theory:
  - Rich physics, new emergent phenomena,… 🙂
  - lack of a comprehensive framework ☹️
- Phenomenology/Experiment:
  - Versatile tools: dijet, R dependence, substructure, … 🙂
  - Convolved processes, large soft background (semi-soft scale contamination) ☹️

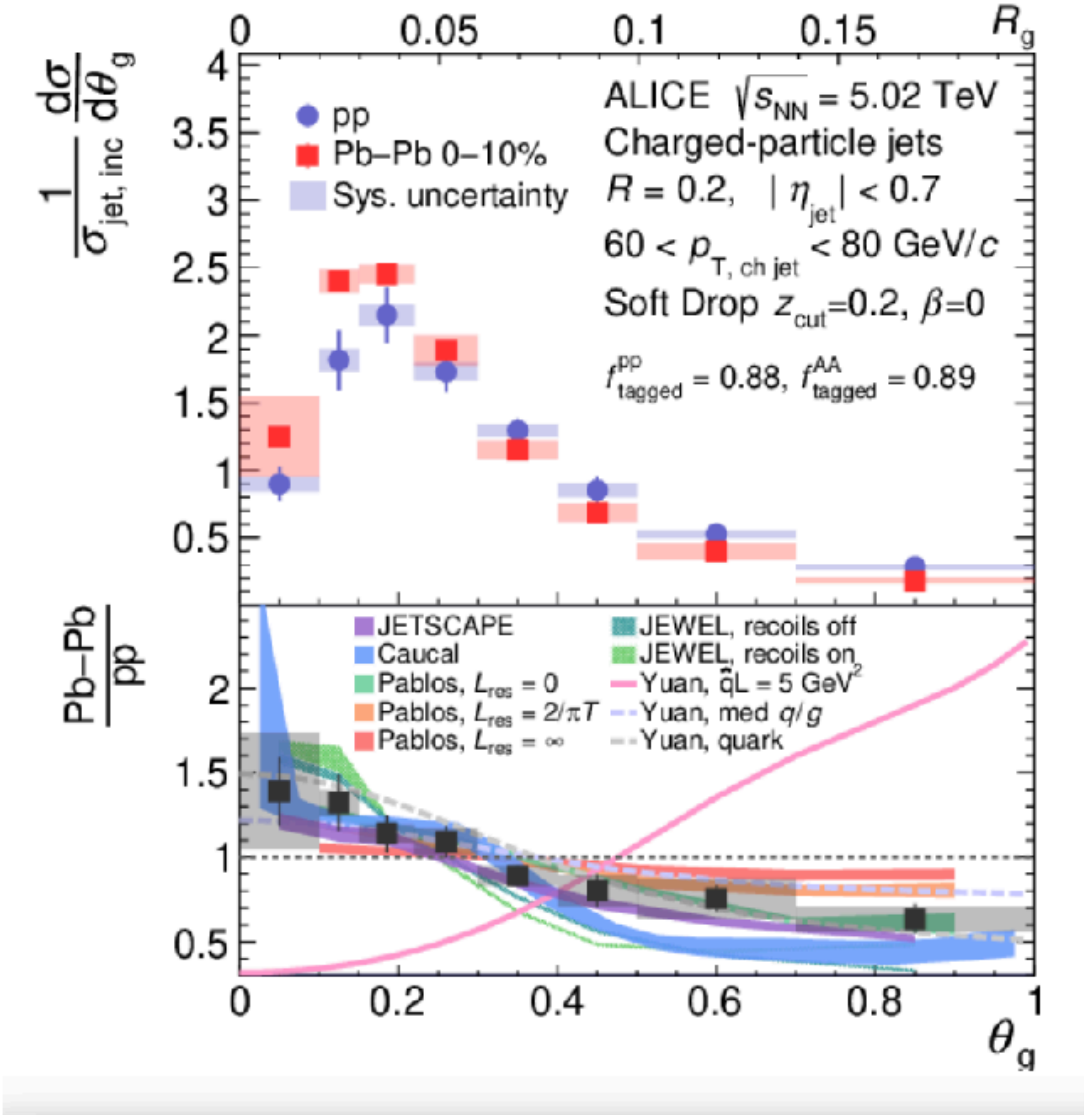
Phenomenology:
where do we stand?

- Thrust 1: General-purpose Monte Carlo event generator (CoLBT, Hybrid, JEWEL, MARTINI, JetMed, Q-Pythia, JETSCAPE, …)
    - Observables are easy to compute 🙂
    - Extensive modeling of perturbative and non-perturbative physics ☹️
- Thrust 2: first principle analytic approaches - limited in phase space and observables ☹️ - better control on theoretical uncertainties? 🙂

Jet substrucure observables



- Access the hard components of the jet by reducing soft contamination with Groomed jet observables: jet mass, θ_g, z_g → jet collimation observed
- Also: Jet mass, jet shape, fragmentation function, angularities, …
- Promising new observable: Energy-Energy Correlator (EEC) (Andres et al (2021))



ALICE Collaboration (2021)

Toward precision phenomenology?

Jet nuclear modification factor

- Analytic calculation includes: multiple gluon radiation, color coherence, collinear shower, collision geometry

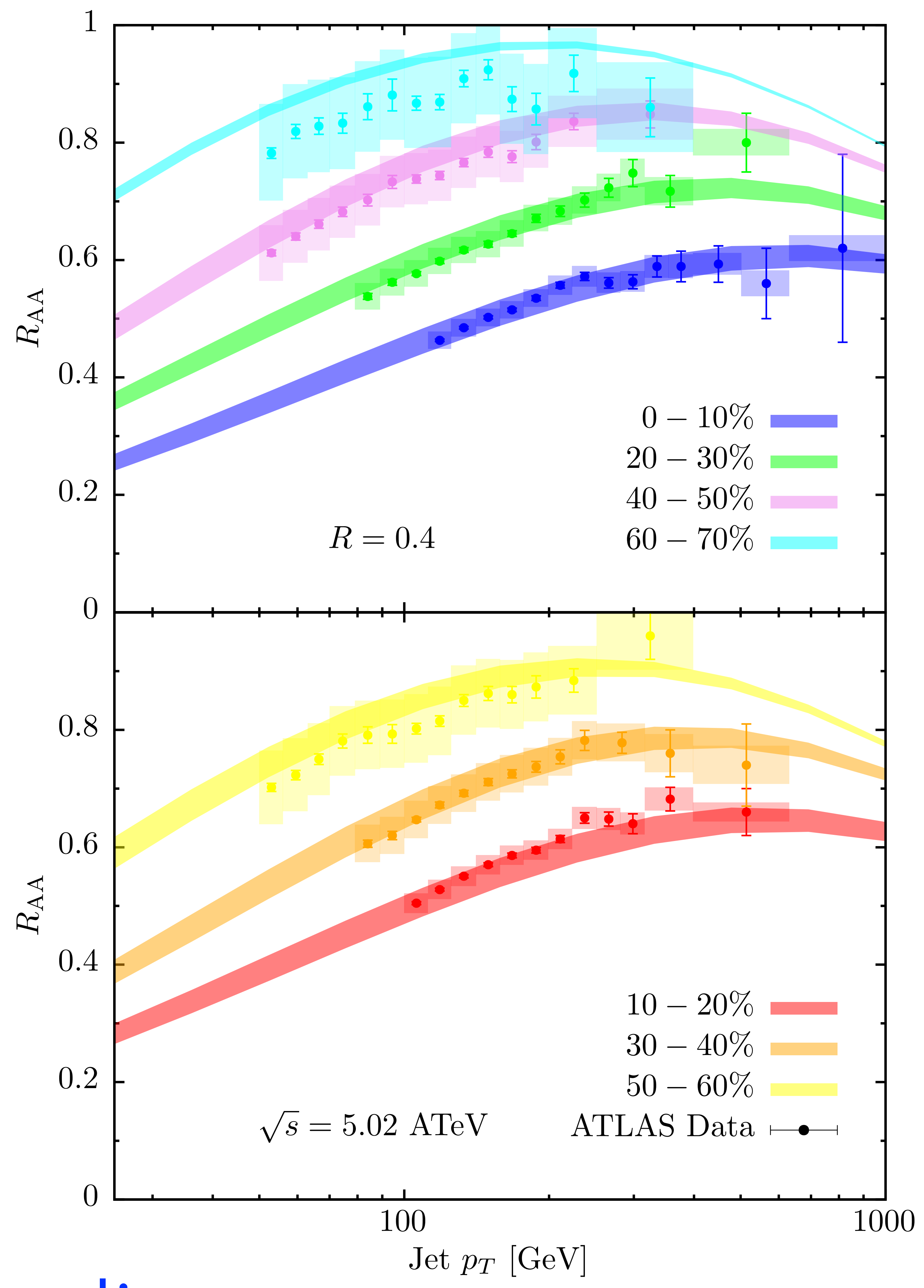
- Medium coupling constant $g_{med} \sim 2.2 - 2.3$

- Toward precision phenomenology: uncertainties dominated by parton shower at leading log accuracy, up to $\sim 20\,\%$

- Extracted transport coefficient:

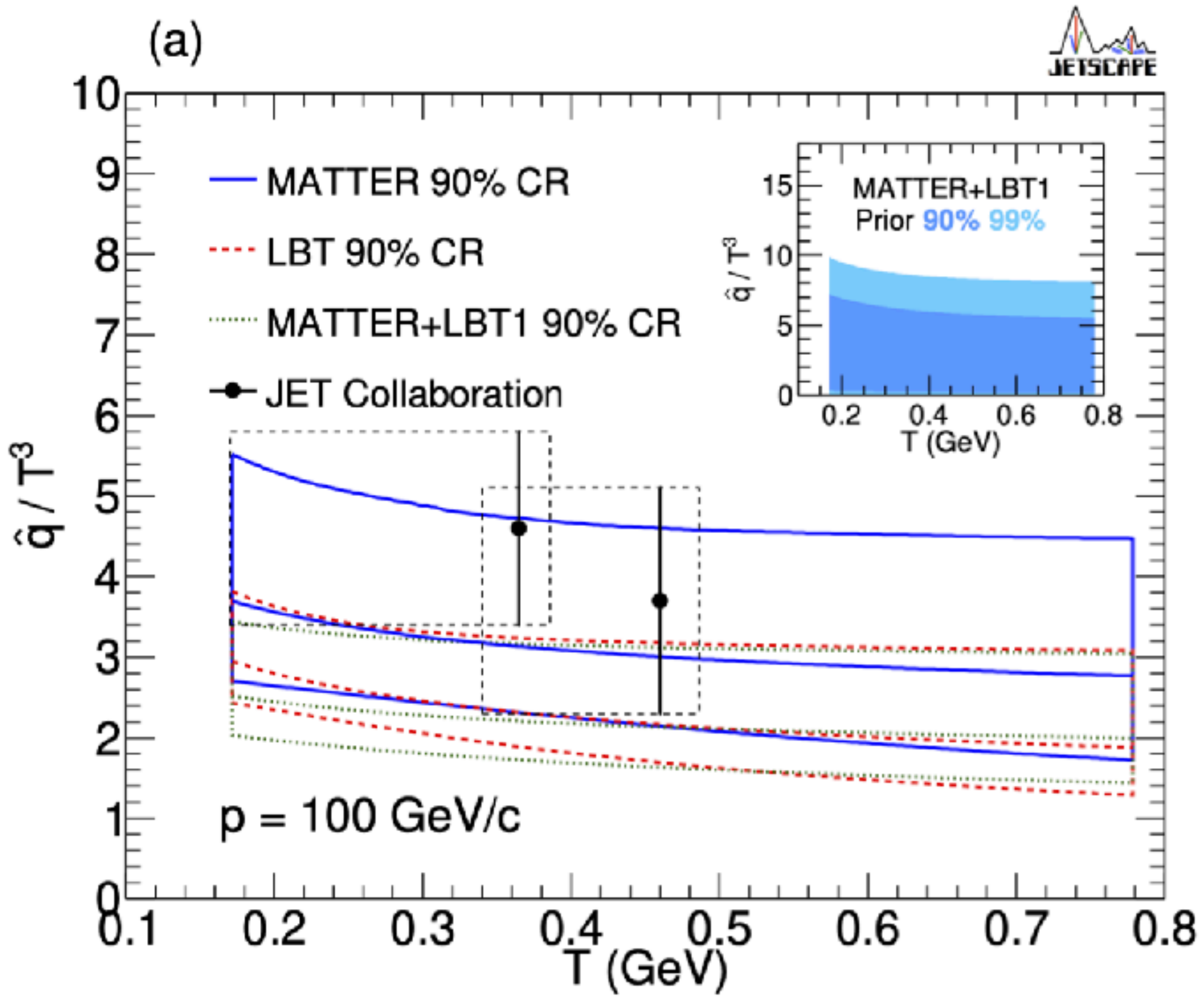
$$\hat{q} = 2.46 \ \text{GeV}^2/\text{fm} \ \text{at} \ Q^2 = 14.2 \ \text{GeV}^2$$

MT, Pablos, Tywoniuk (2021)



→ Good agreement with ATLAS data as function of pT and centrality

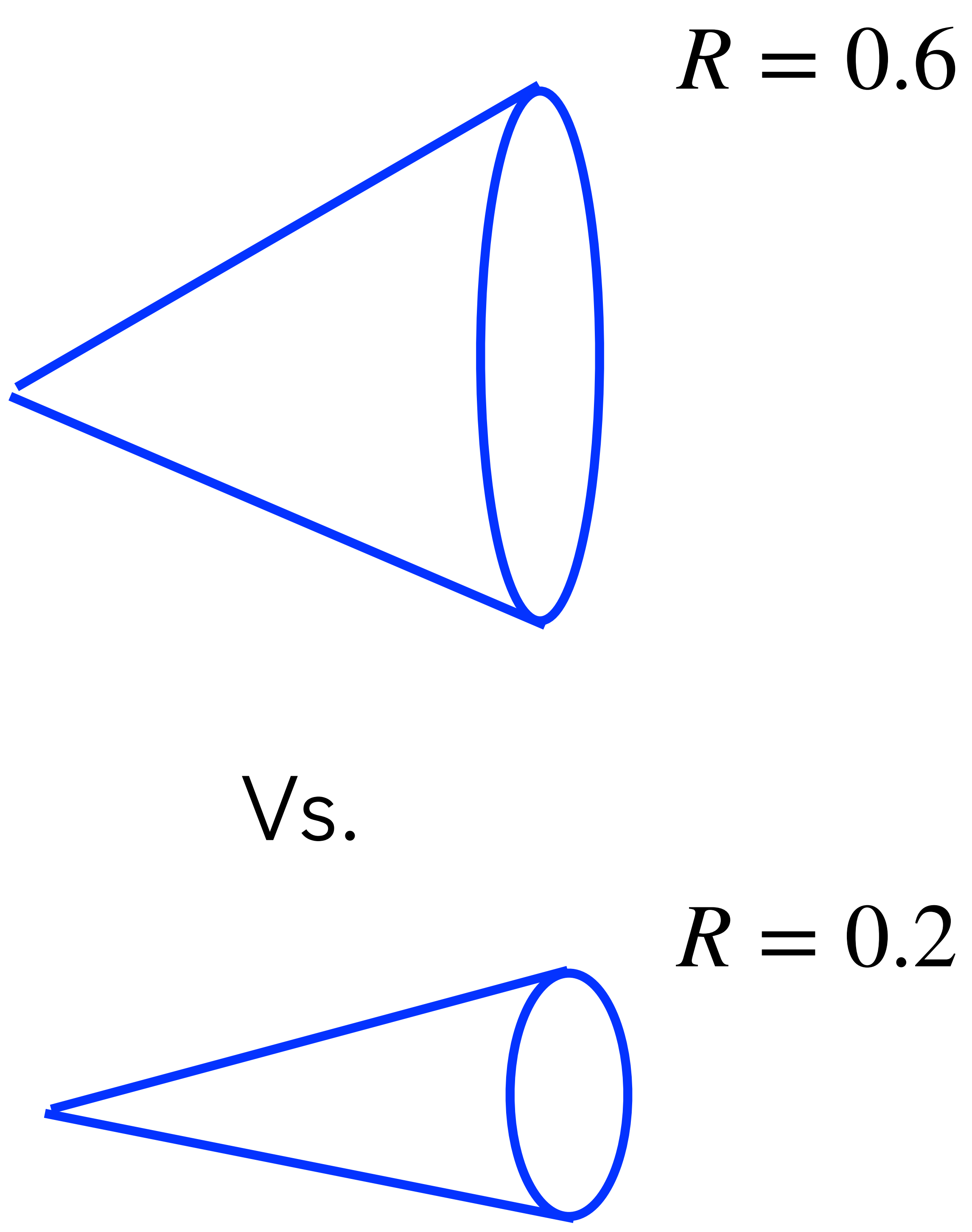
Extraction of q̂ using Bayesian parameter estimation

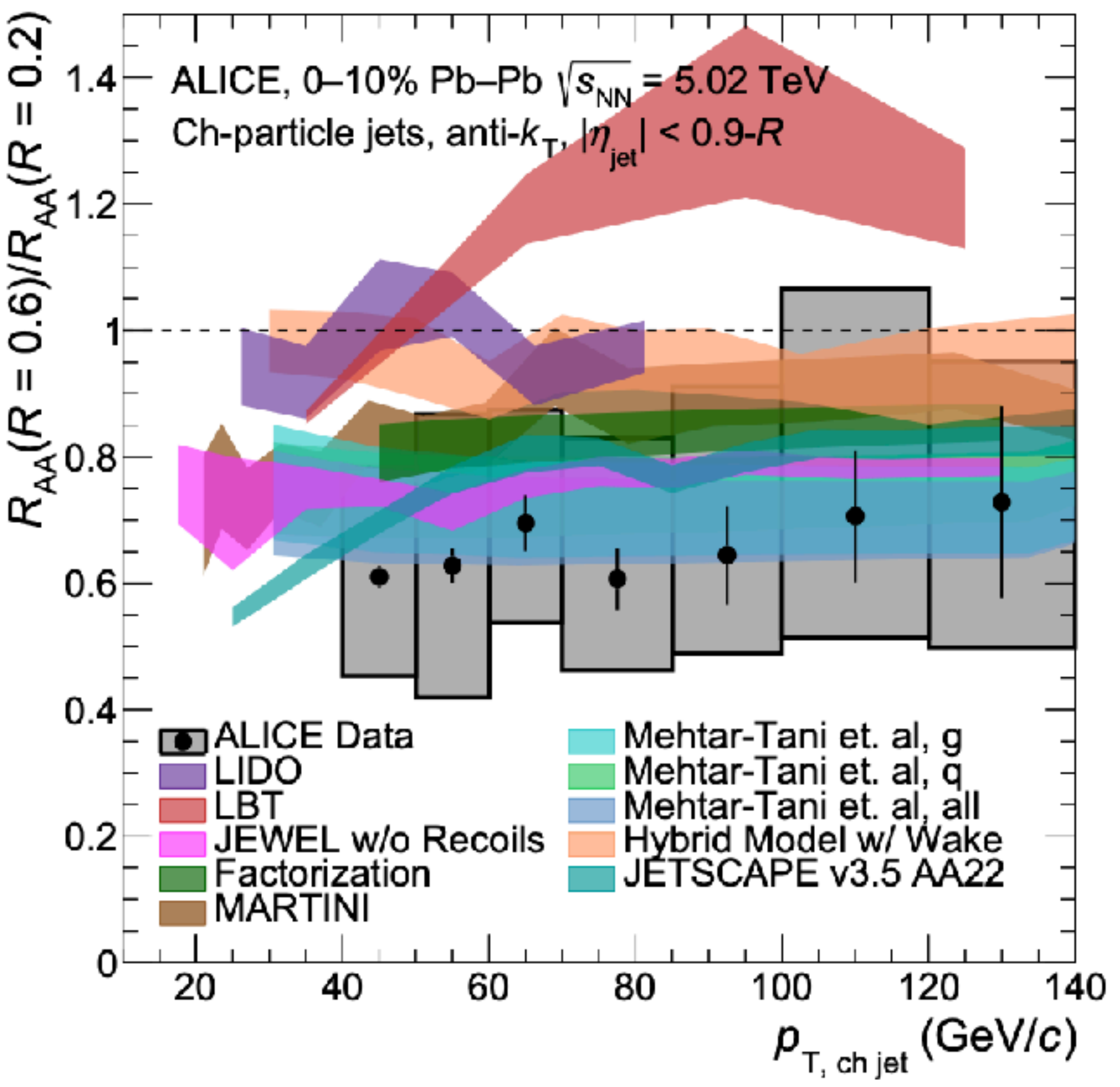


JETSCAPE Collaboration (2021)

Predictions for R dependence in ALICE

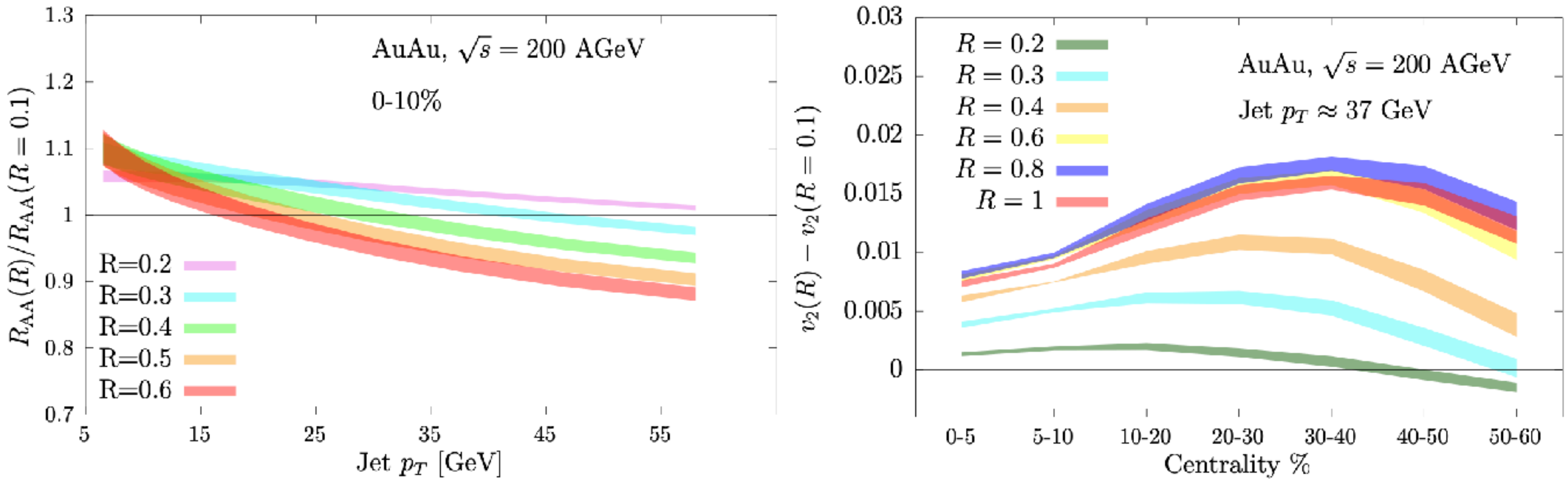
- R dependence encodes color coherence effects





→ Good agreement with 2023 ALICE data as function of pT and jet cone size

Predictions for R dependence for sPHENIX



- Strong R dependence of Jet v_2 : larger sensitivity to jet substructure modification and color coherence

Predictions for the sPHENIX physics program (RBRC workshop, July 2022)

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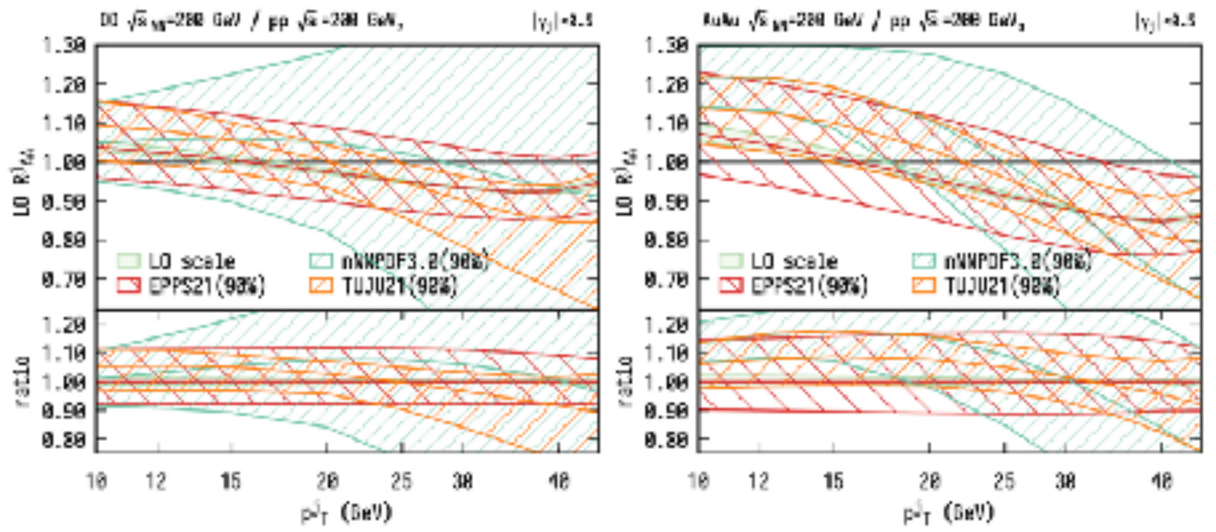

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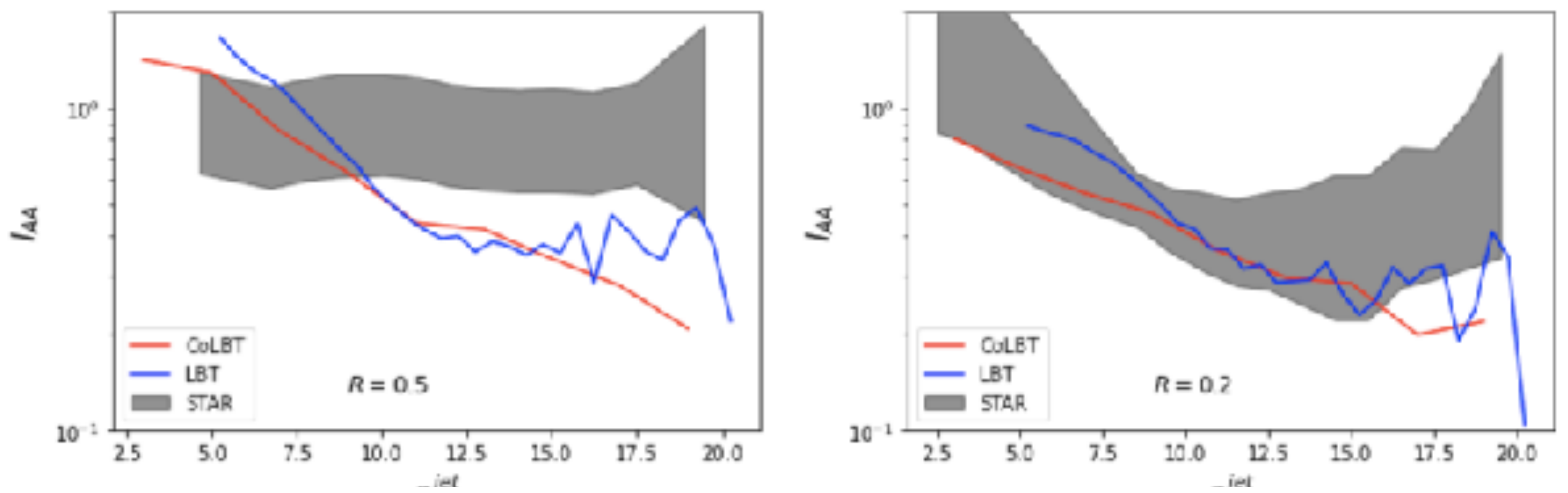
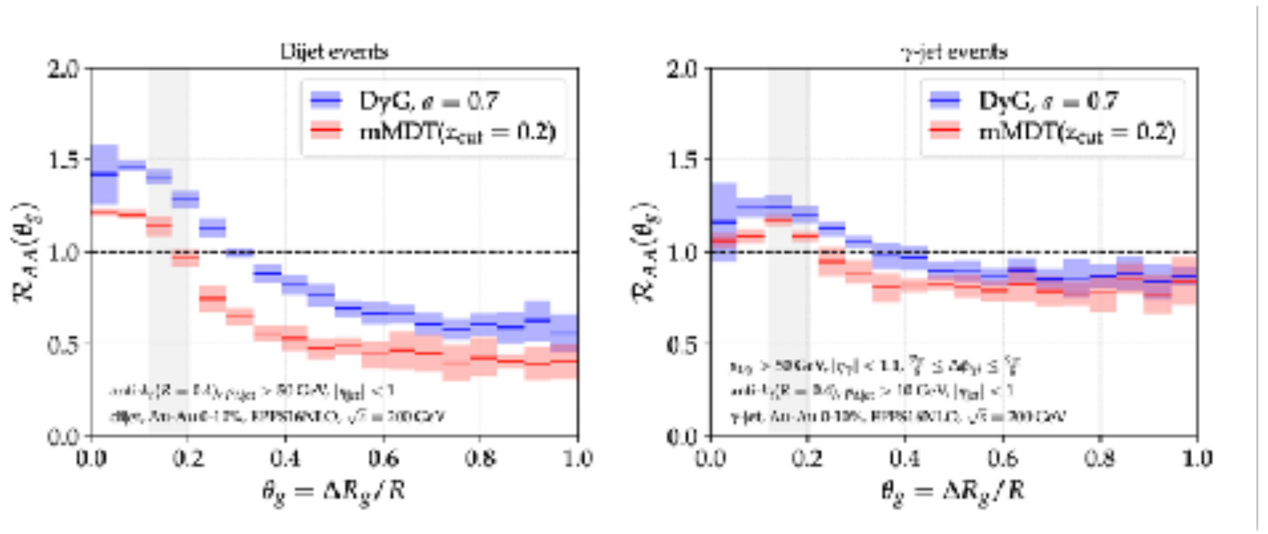
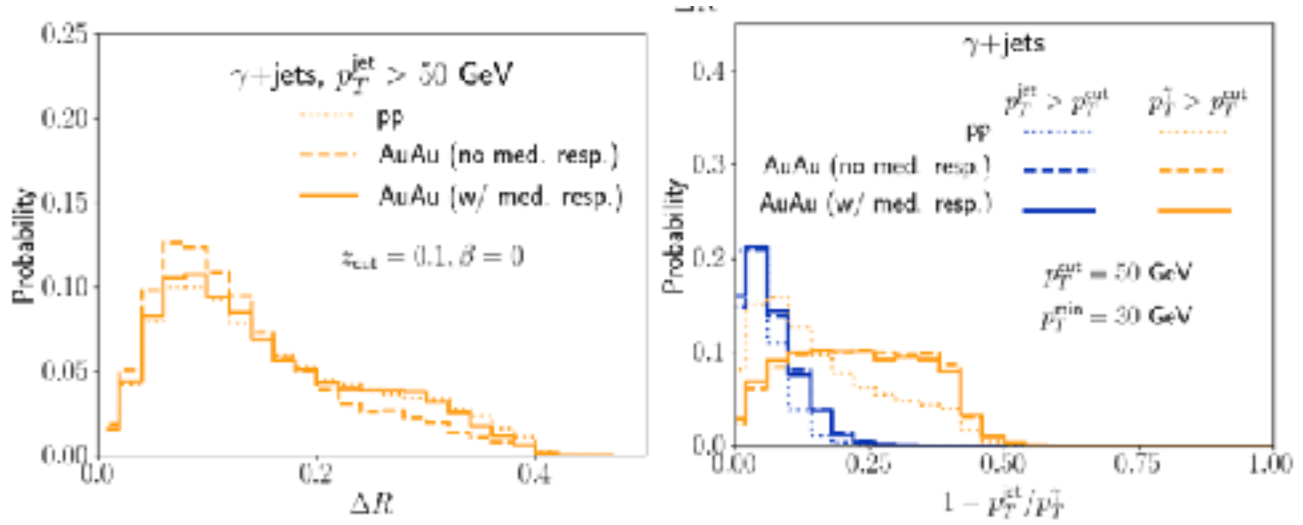
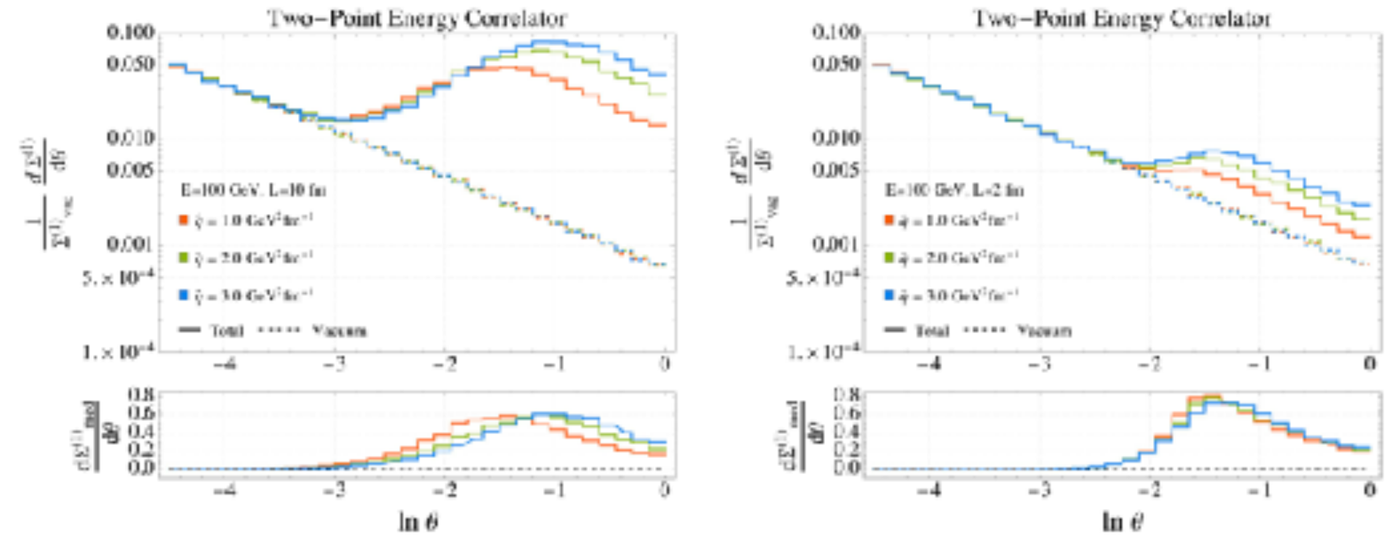
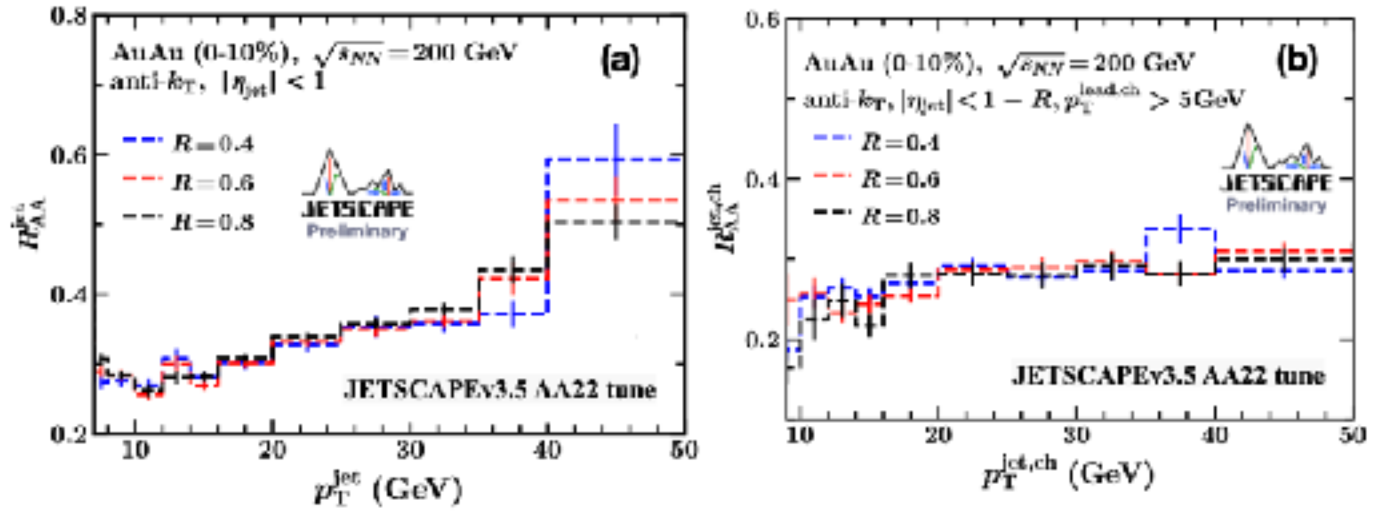


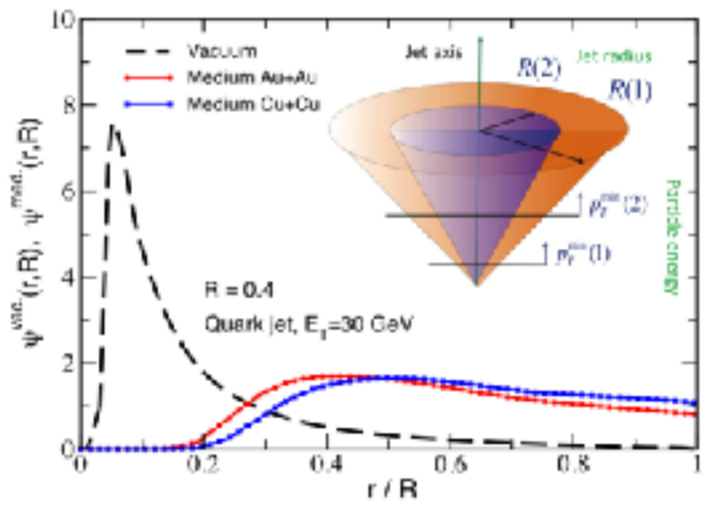
Jet probes

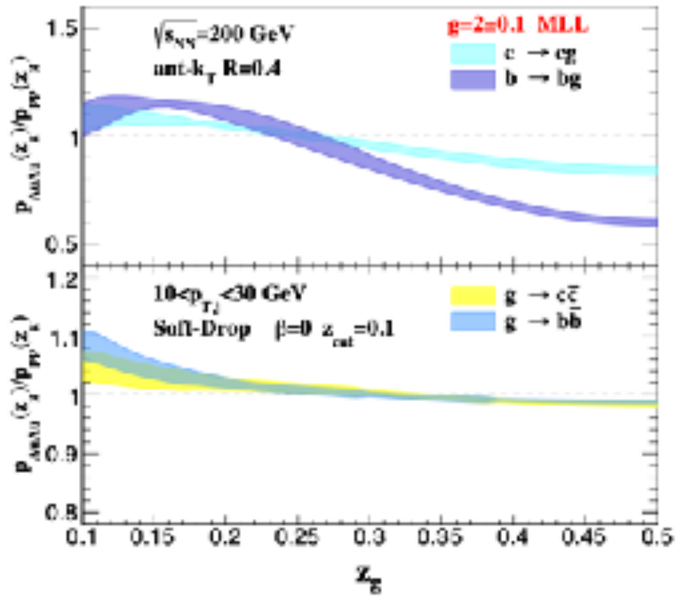


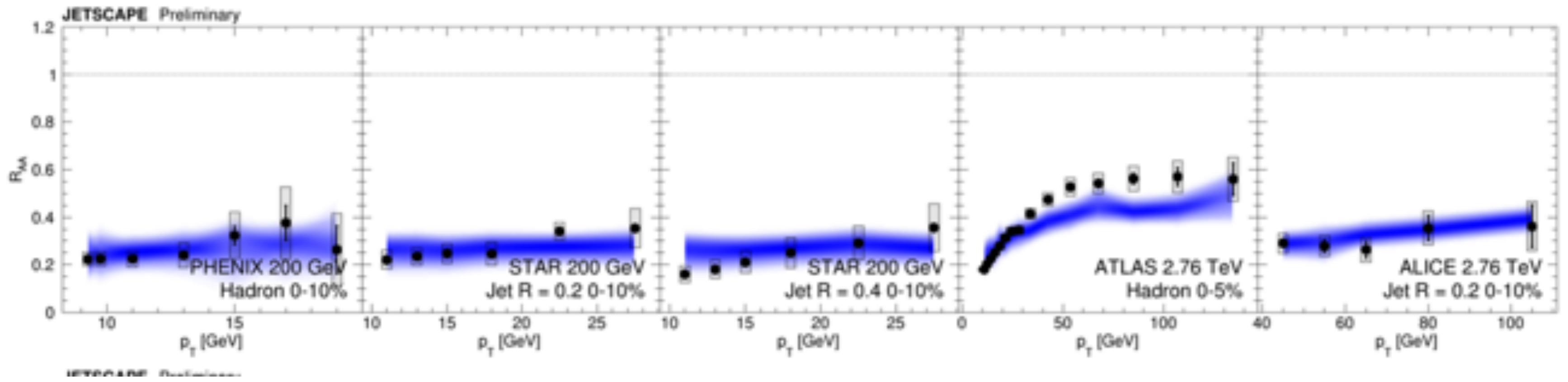












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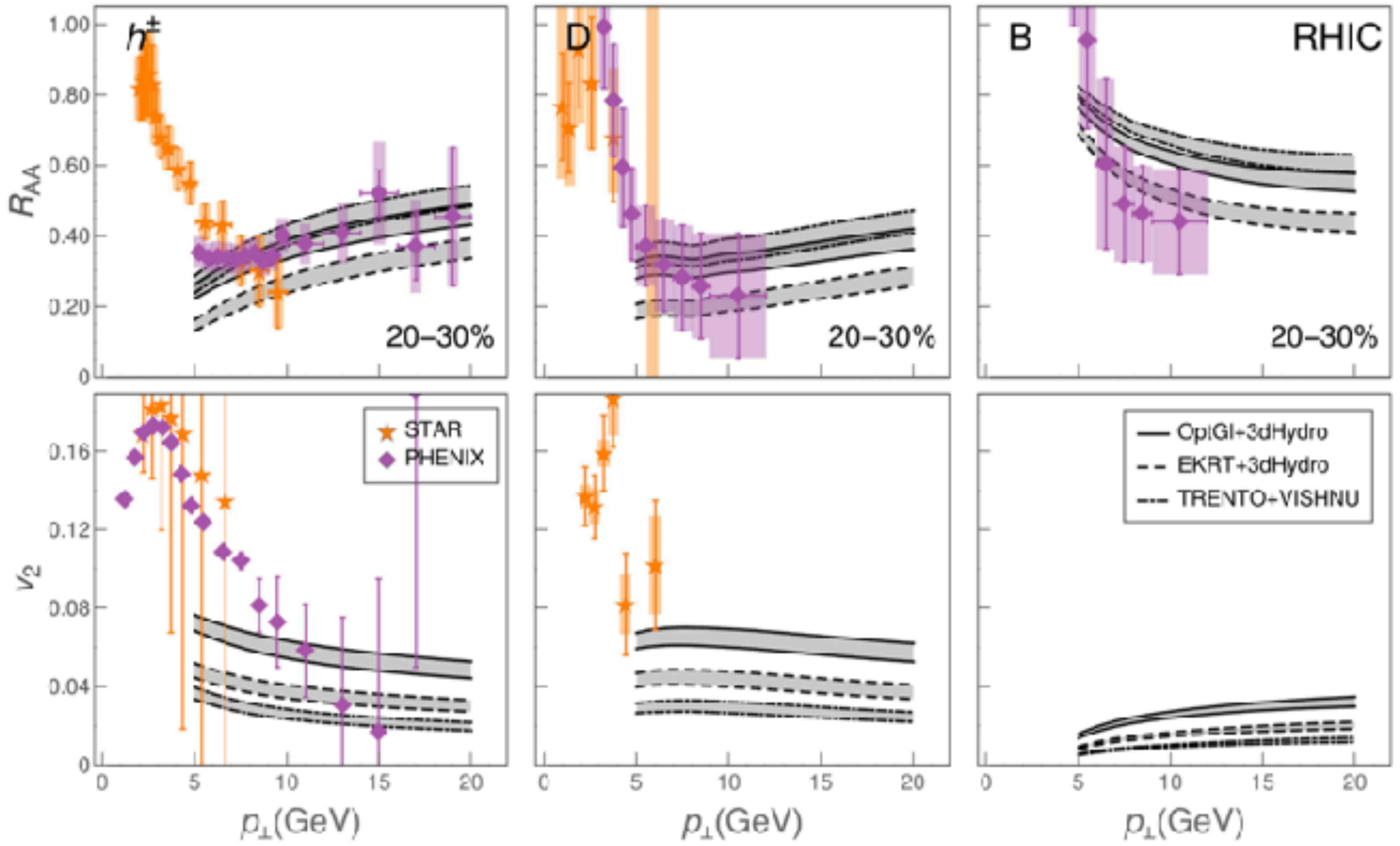
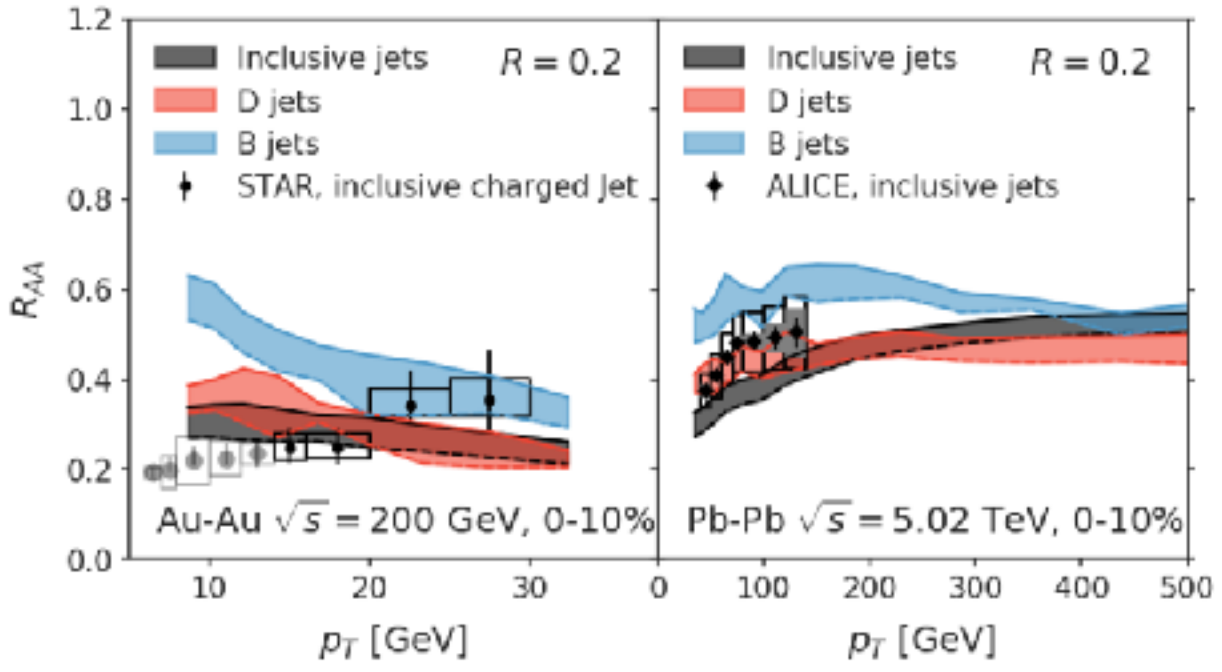
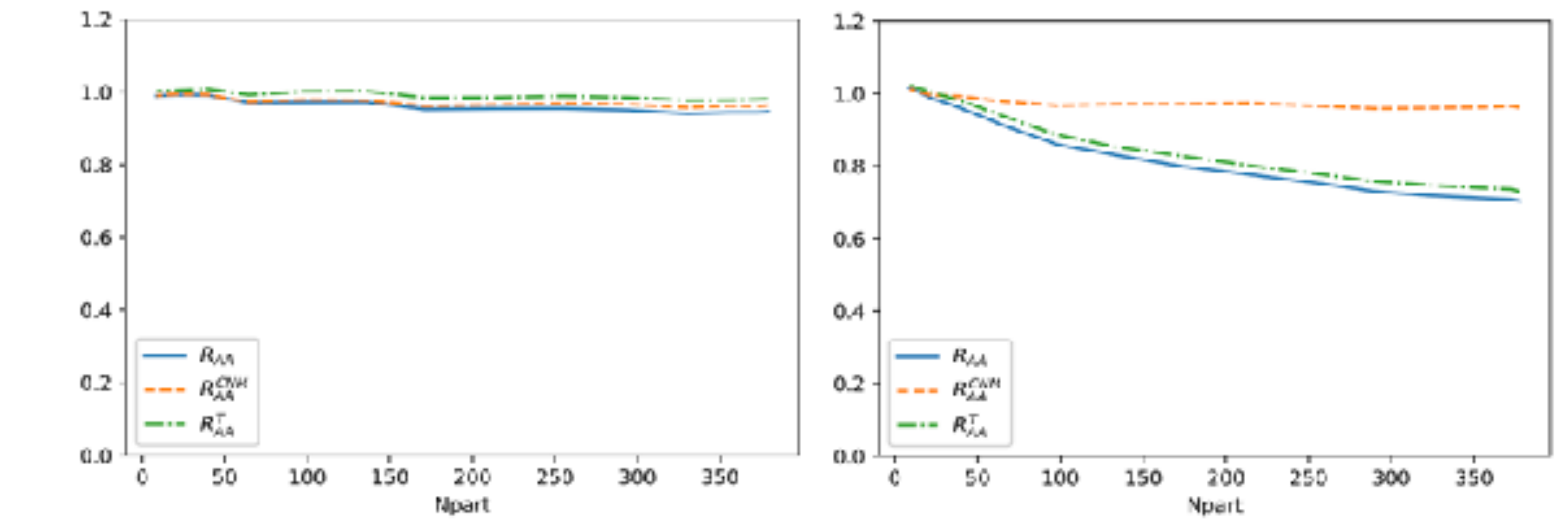
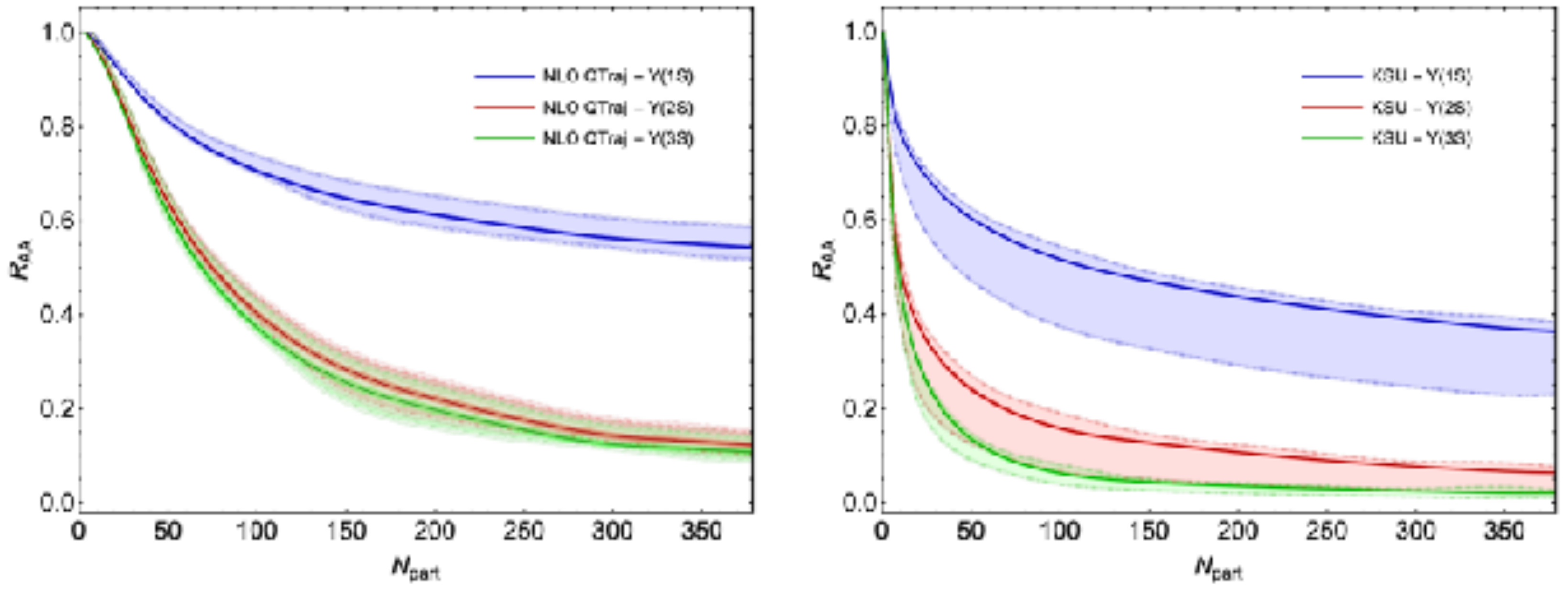
Heavy Flavor









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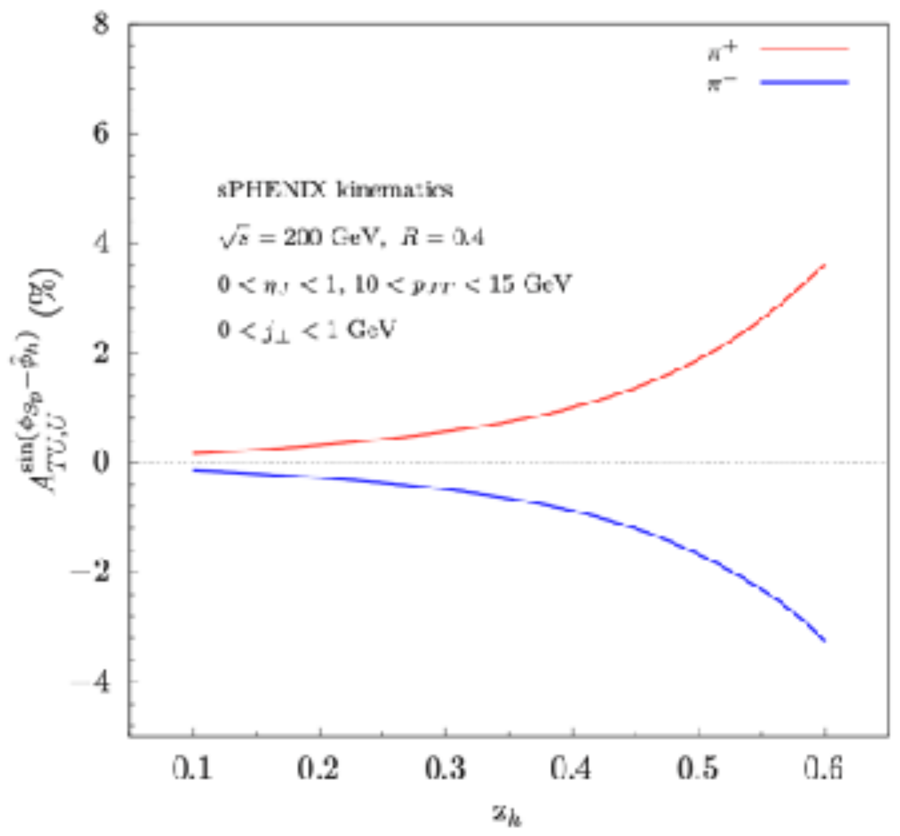
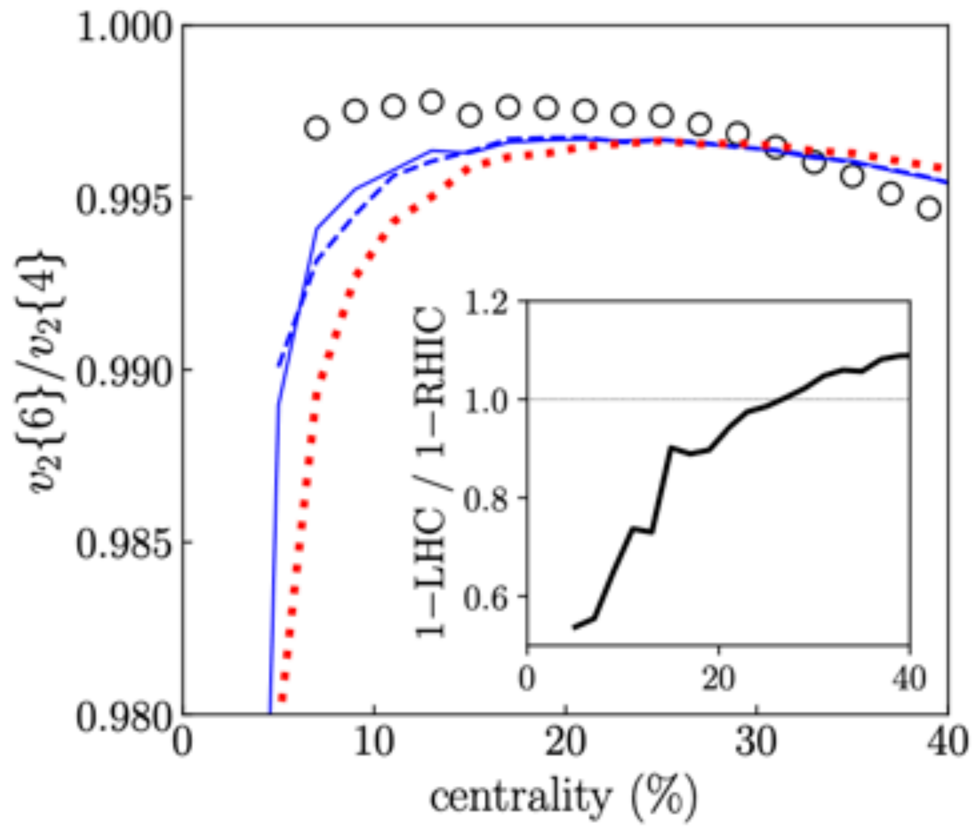
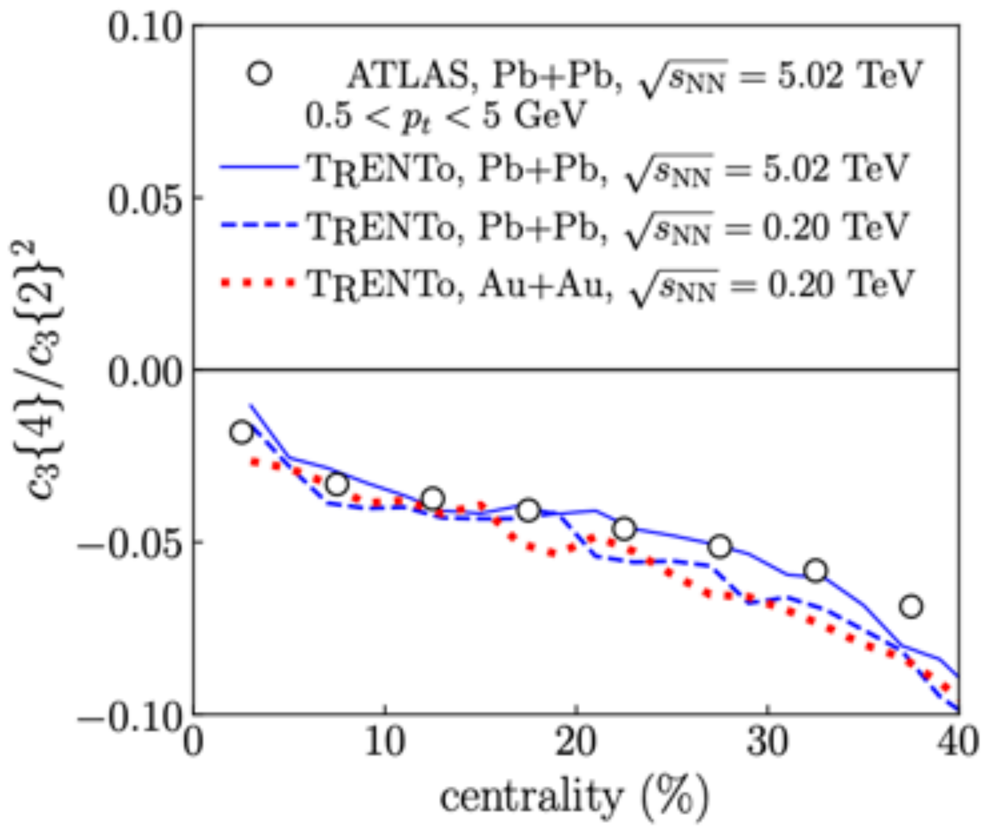
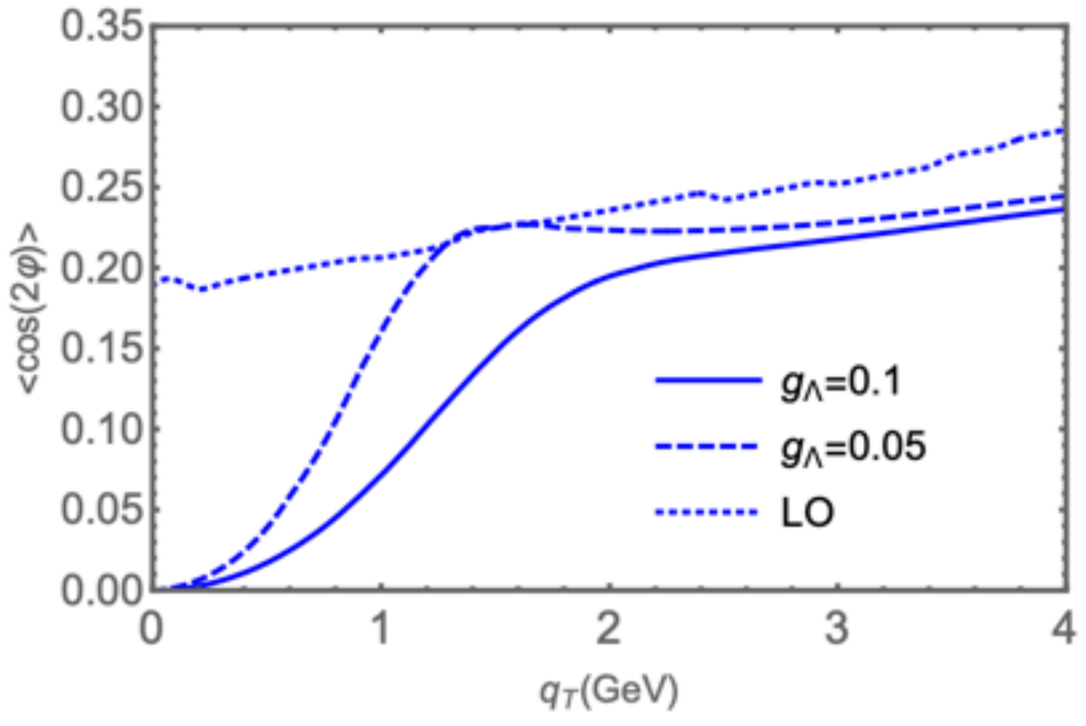
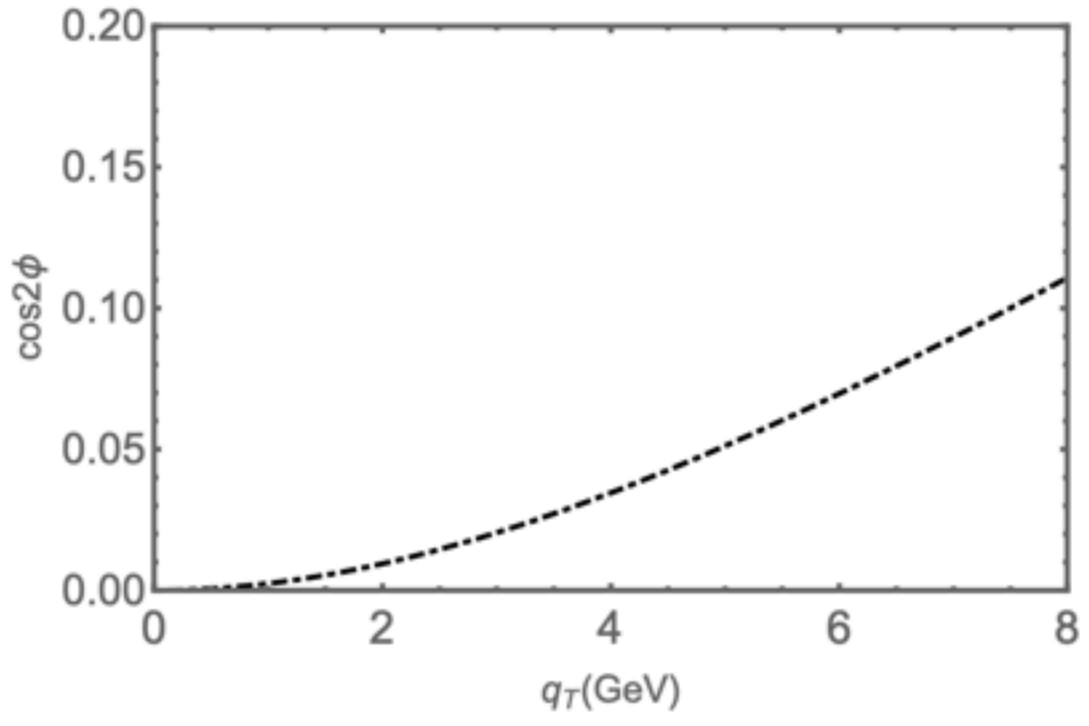


Bulk probes









Summary

- Heavy Ion collisions provide a unique laboratory to study the QGP
- Rich QCD dynamics uncovered in a large range of scales: perfect fluid, turbulent energy loss, anomalous diffusion, etc
- Remaining challenge 1: smooth description of the QGP dynamics from soft to hard scales
- Remaining challenge 2: precision phenomenology and extraction of transport coefficients

Thank you!