Unveiling the Interplay of Multi-Partonic Structures and Strongly-Interacting Media via R-dependent Jet Modifications in Heavy-Ion Collisions

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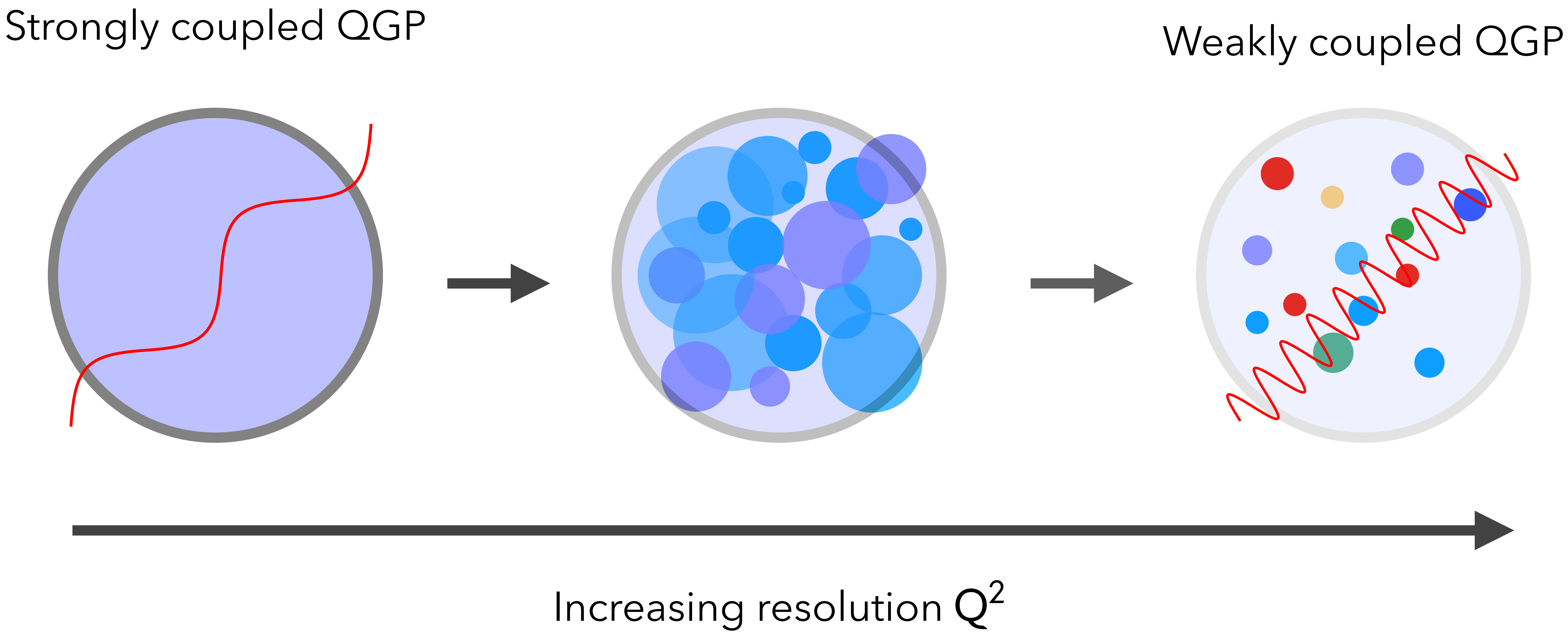
Brookhaven National Laboratory

Outline

- Introduction
- Dissecting jets in HIC
- R dependence of R_{AA}: Toward precision phenomenology?
- Jet v2 and some predictions for RHIC energies

How does the perfect liquid 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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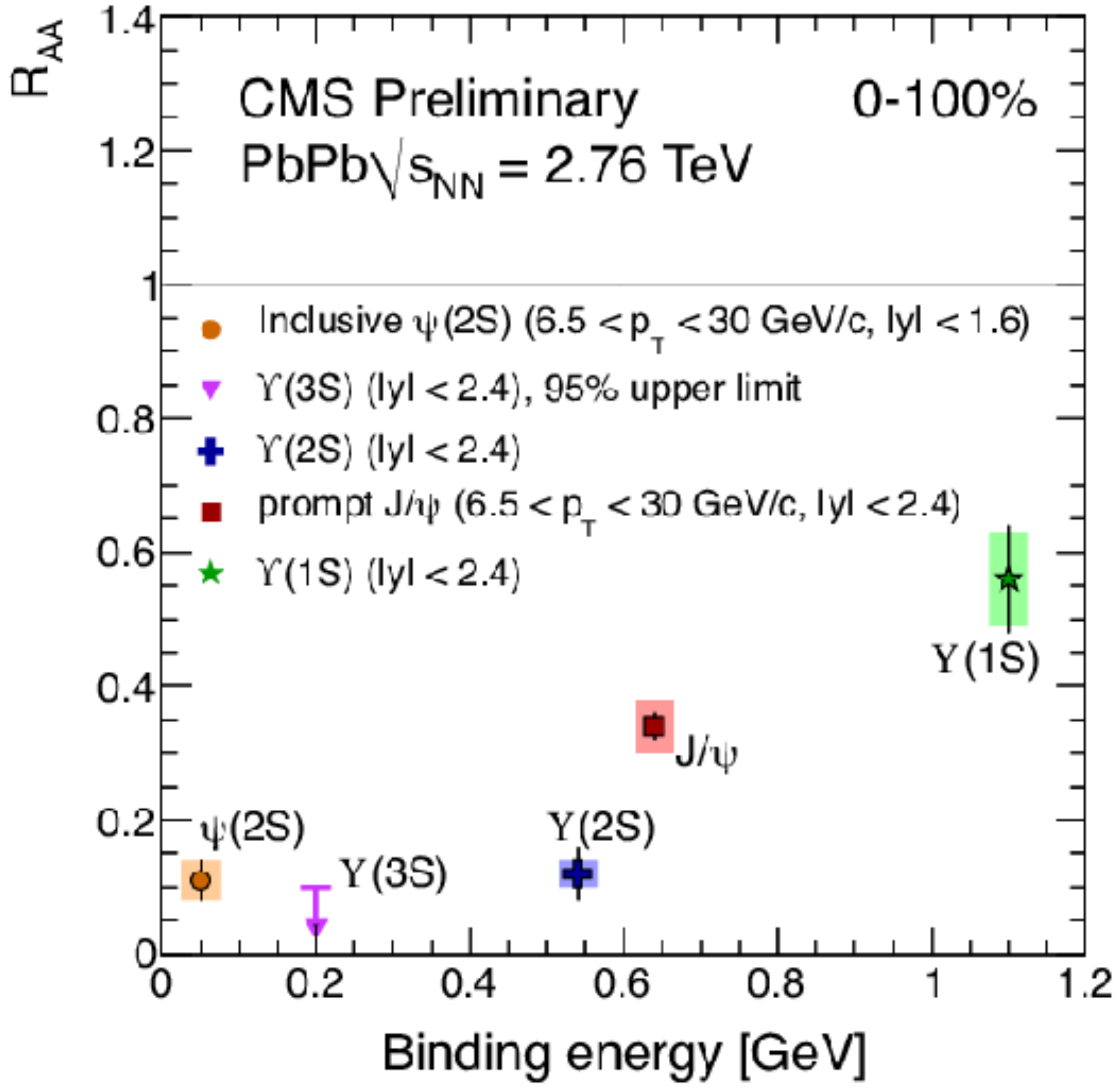
Hard probes to investigate the QGP dynamics at short distances

- Quarkonia, heavy flavor suppression



$p_T \gg 1$ GeV

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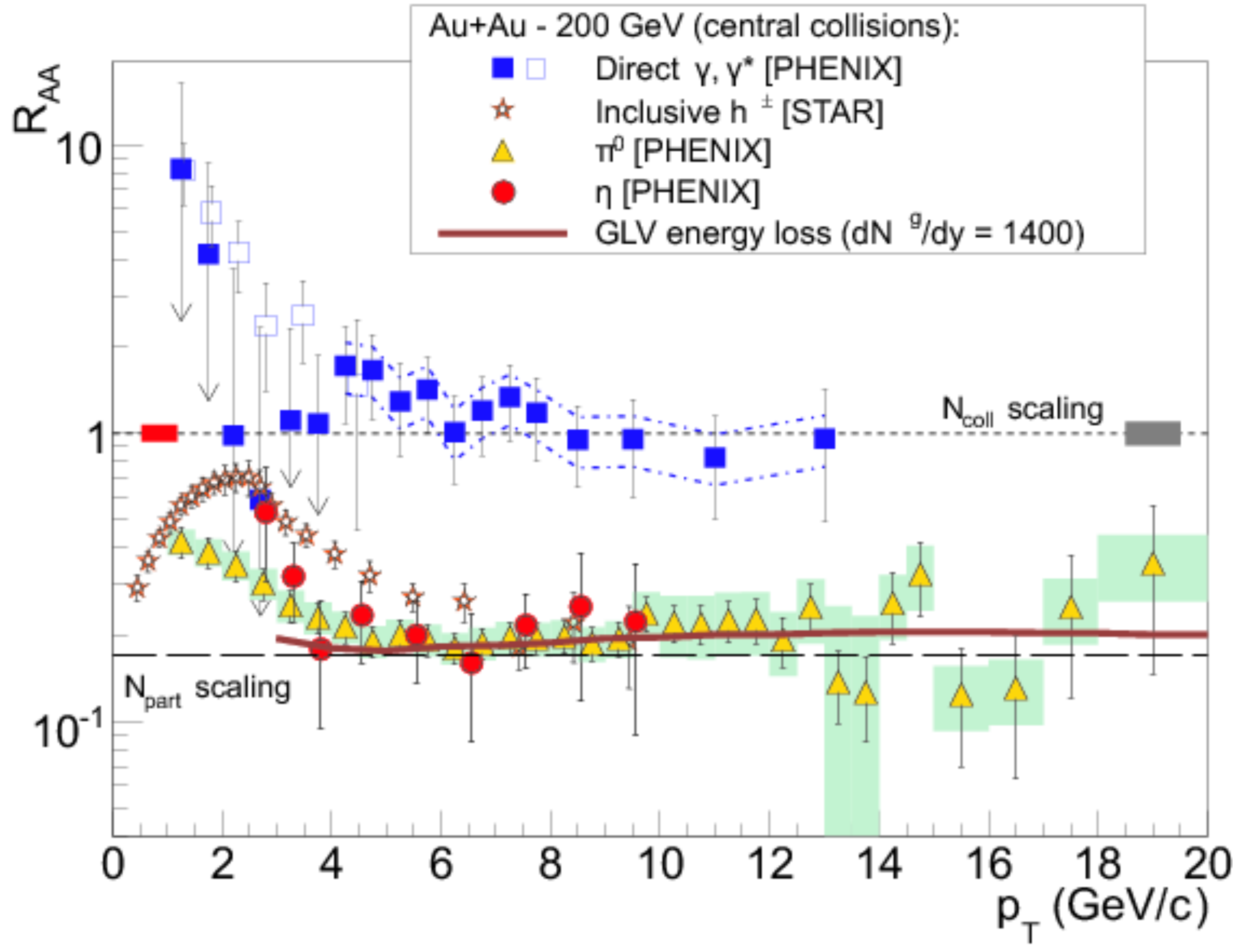

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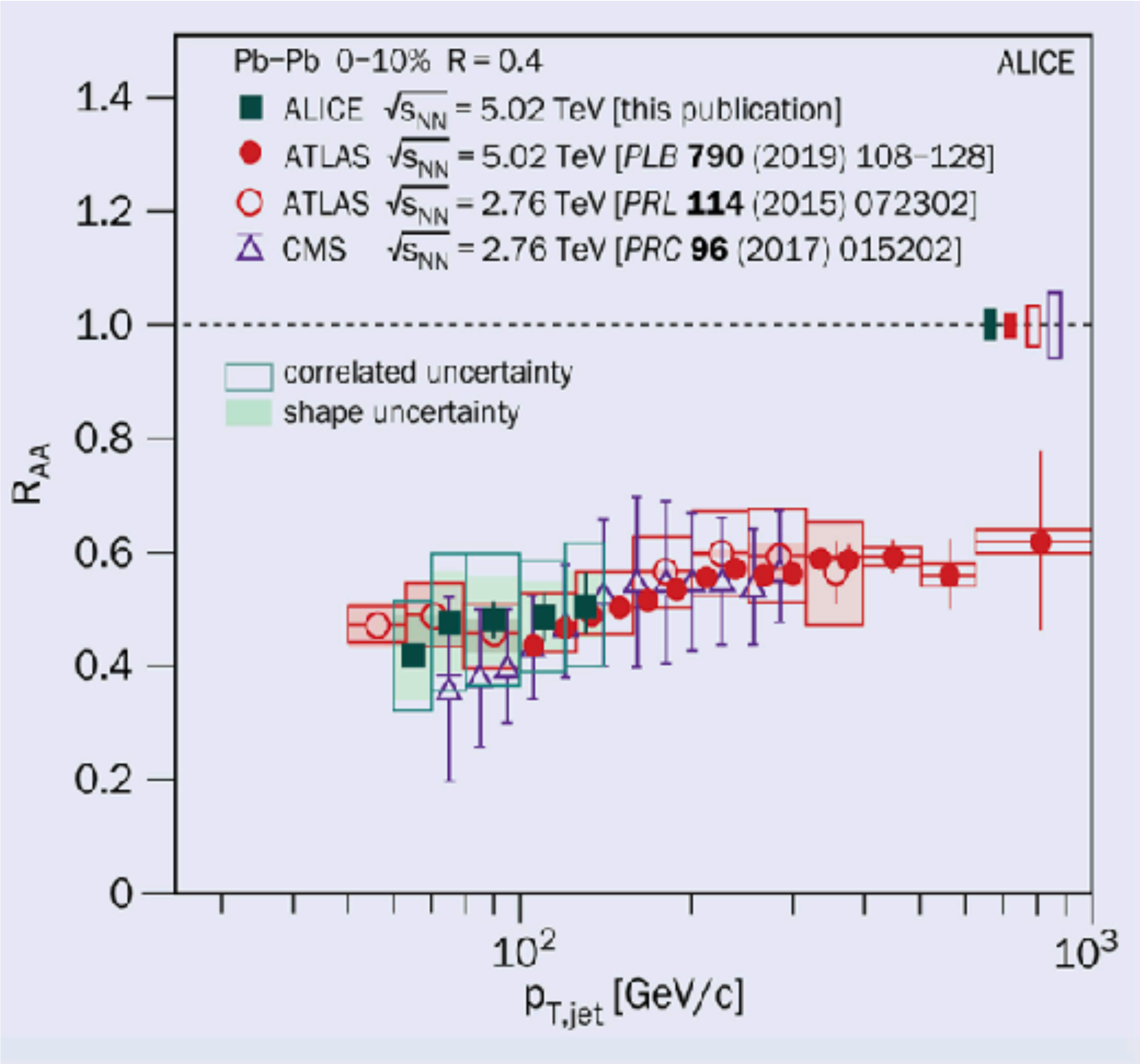
- Bulk observables: flow harmonics $p_T \sim T \sim 1$ GeV

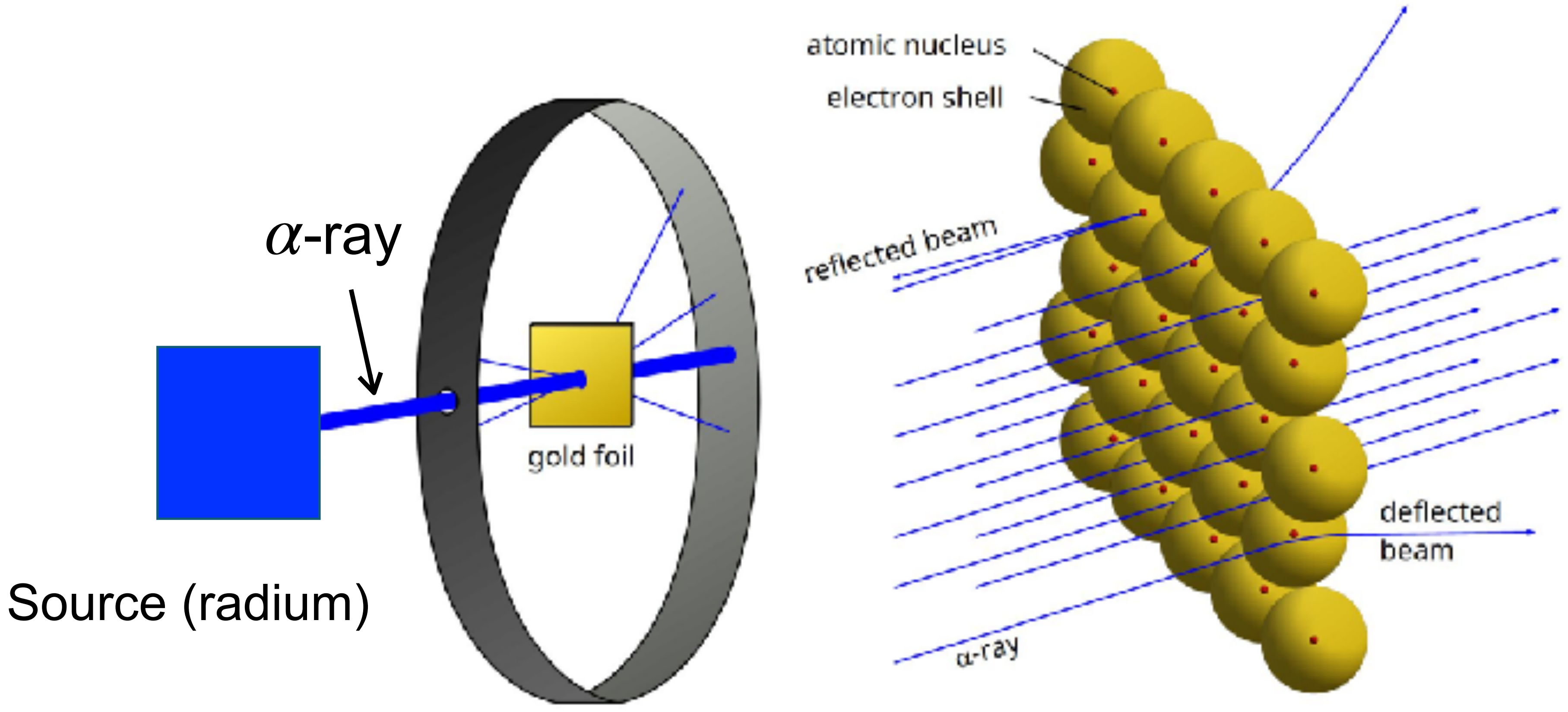
Hard probes to investigate the QGP dynamics at short distances

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

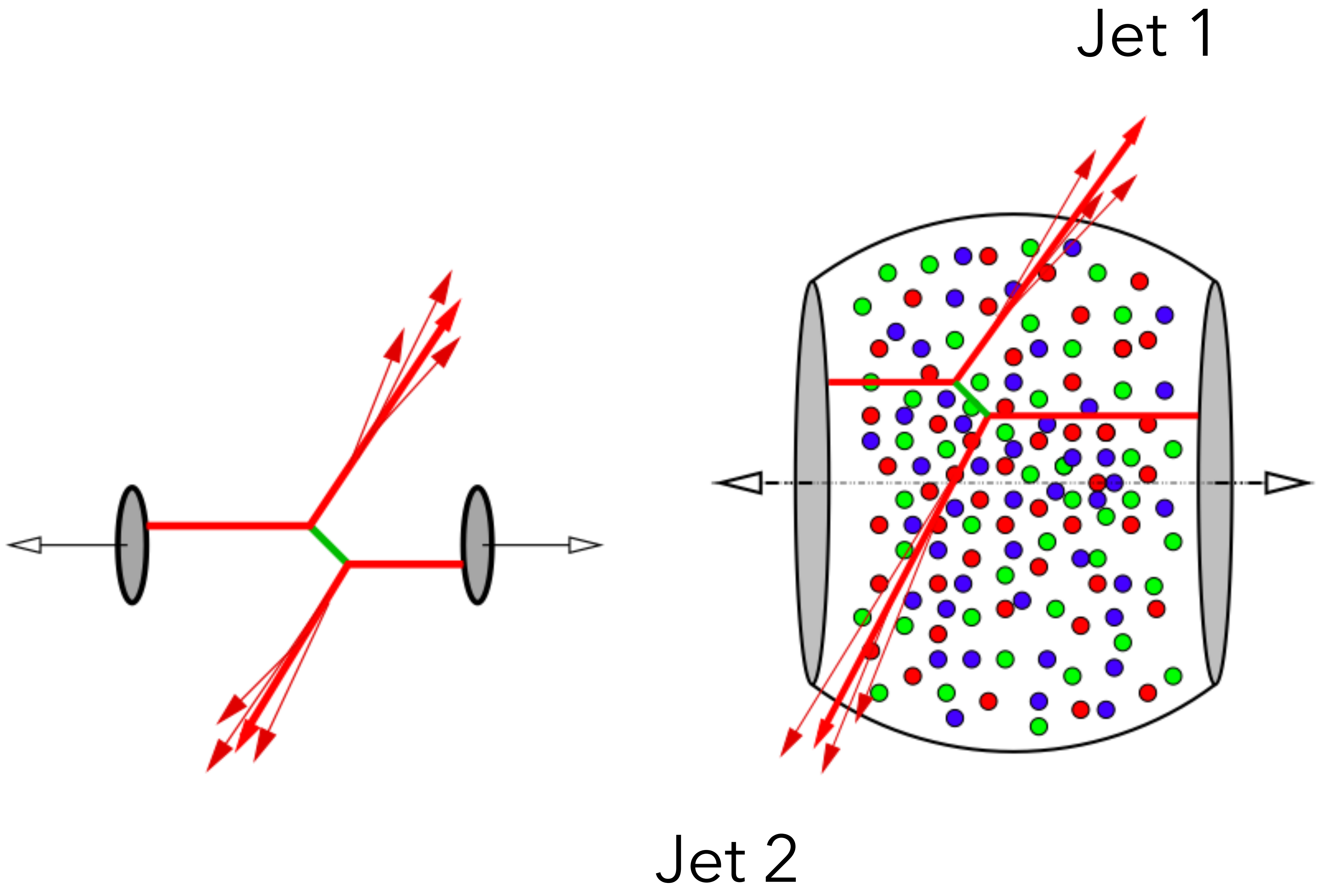
$p_T \gg 1$ GeV



A Rutherford-like experiment - Jets in HIC



Discovery of the atomic nucleus



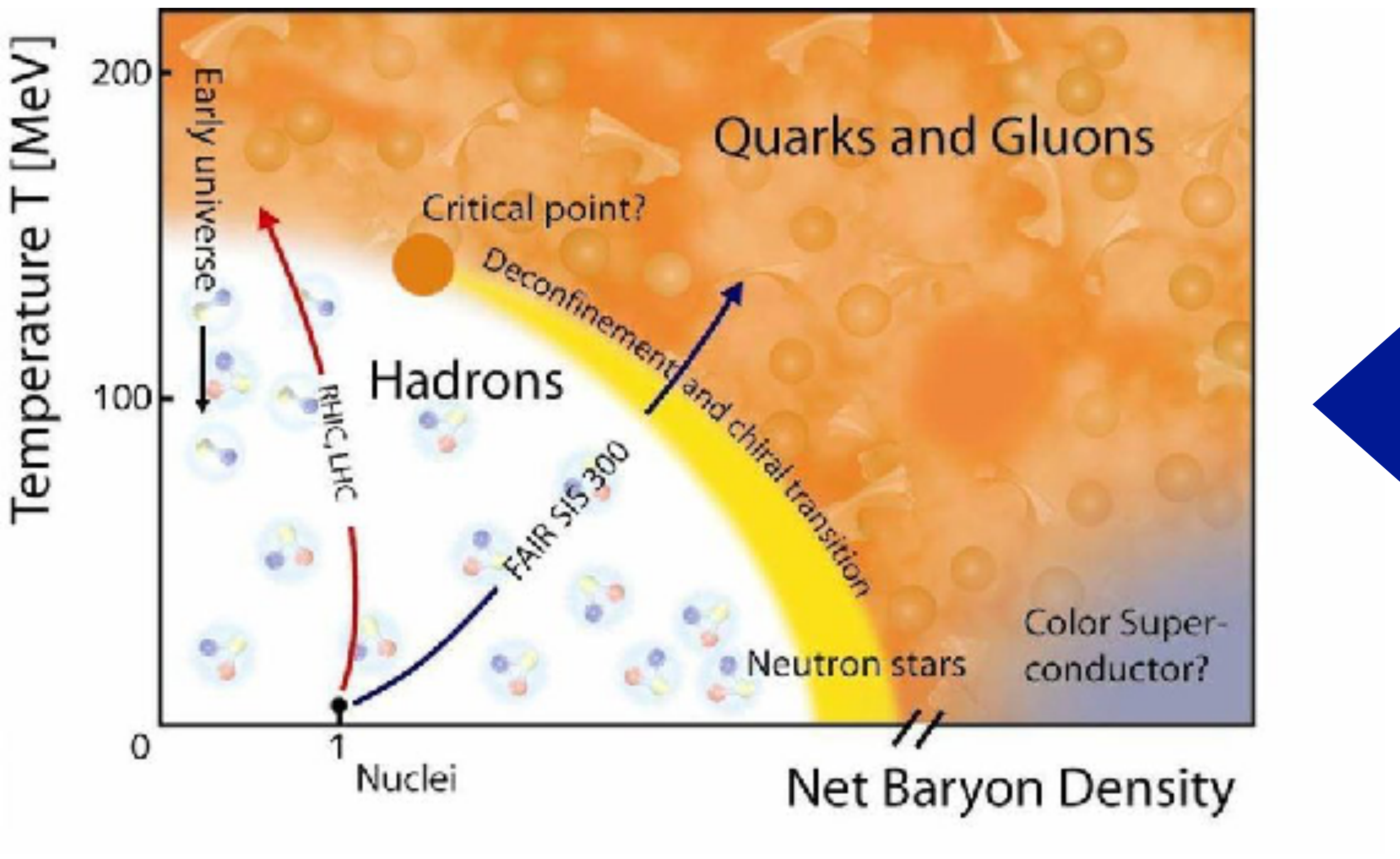
Probing the microscopic properties of the QGP with jets

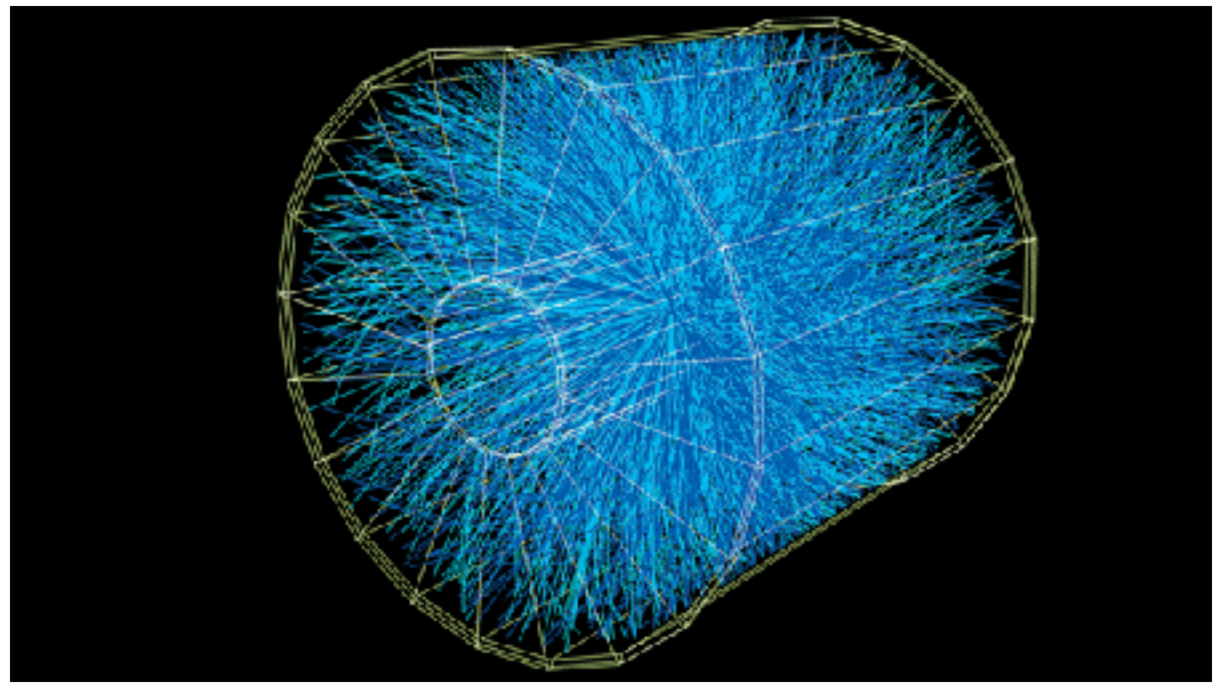
Multiscale dynamics

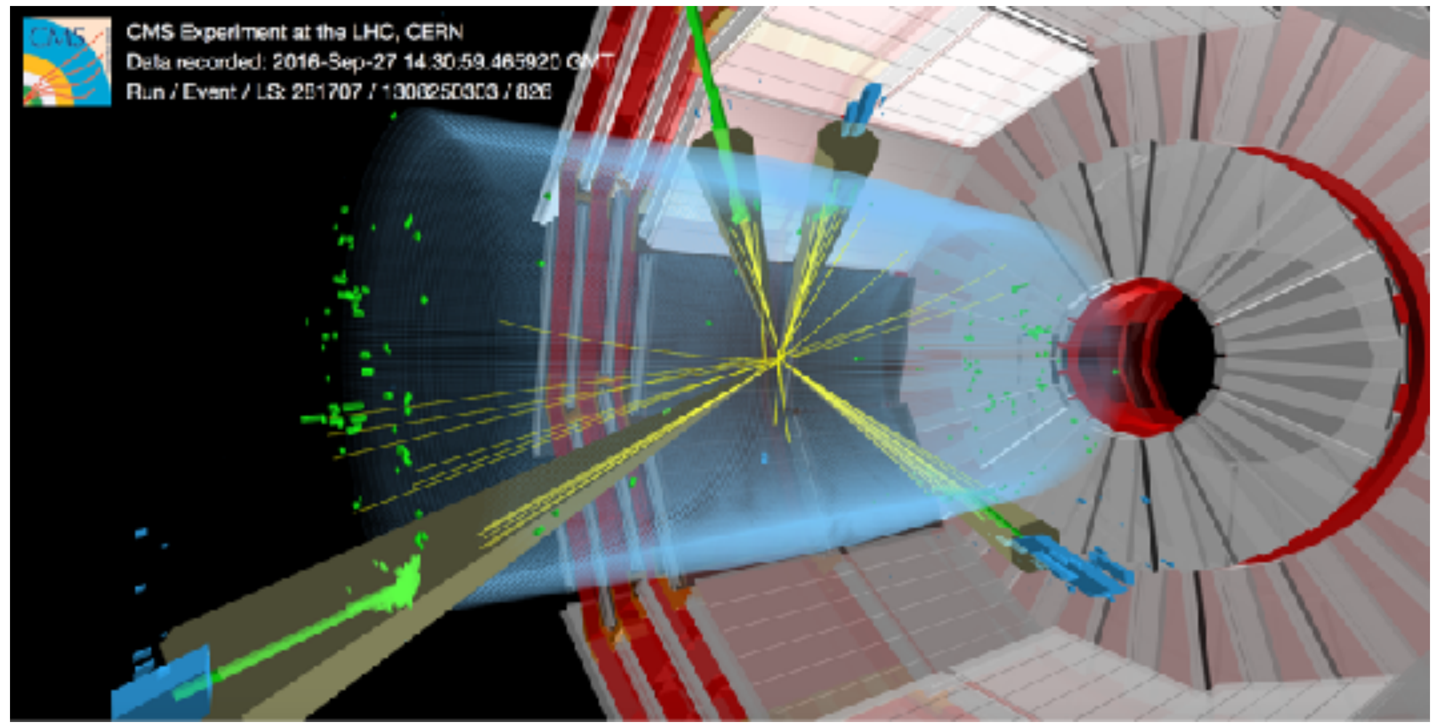
Thermal equilibrium (T≠ 0)

Non-equilibrium

T=0

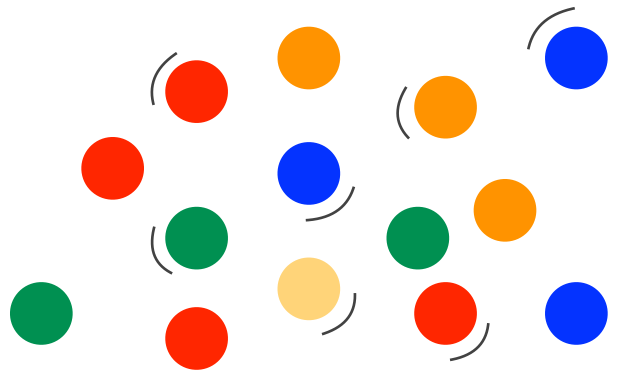


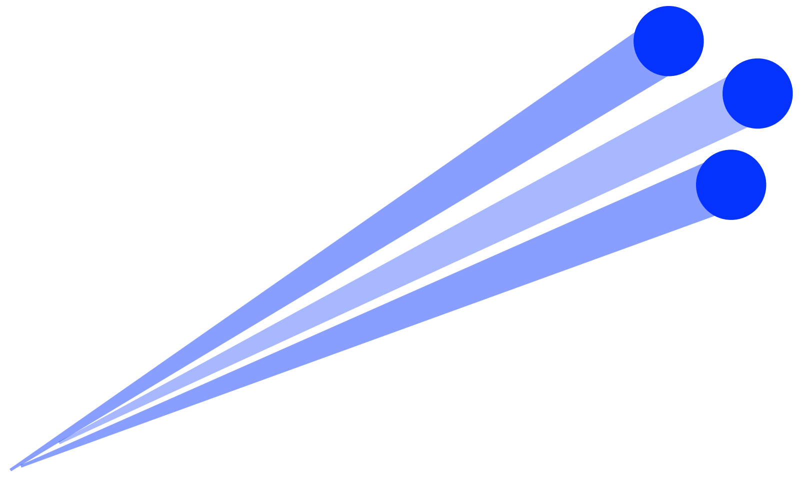




Heavy ion event
~ 1000's particles

Jets in pp





How is energy transported and dissipated?

Energy

T ~ 1 GeV

p_T ~ 1 TeV

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

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) ☹️

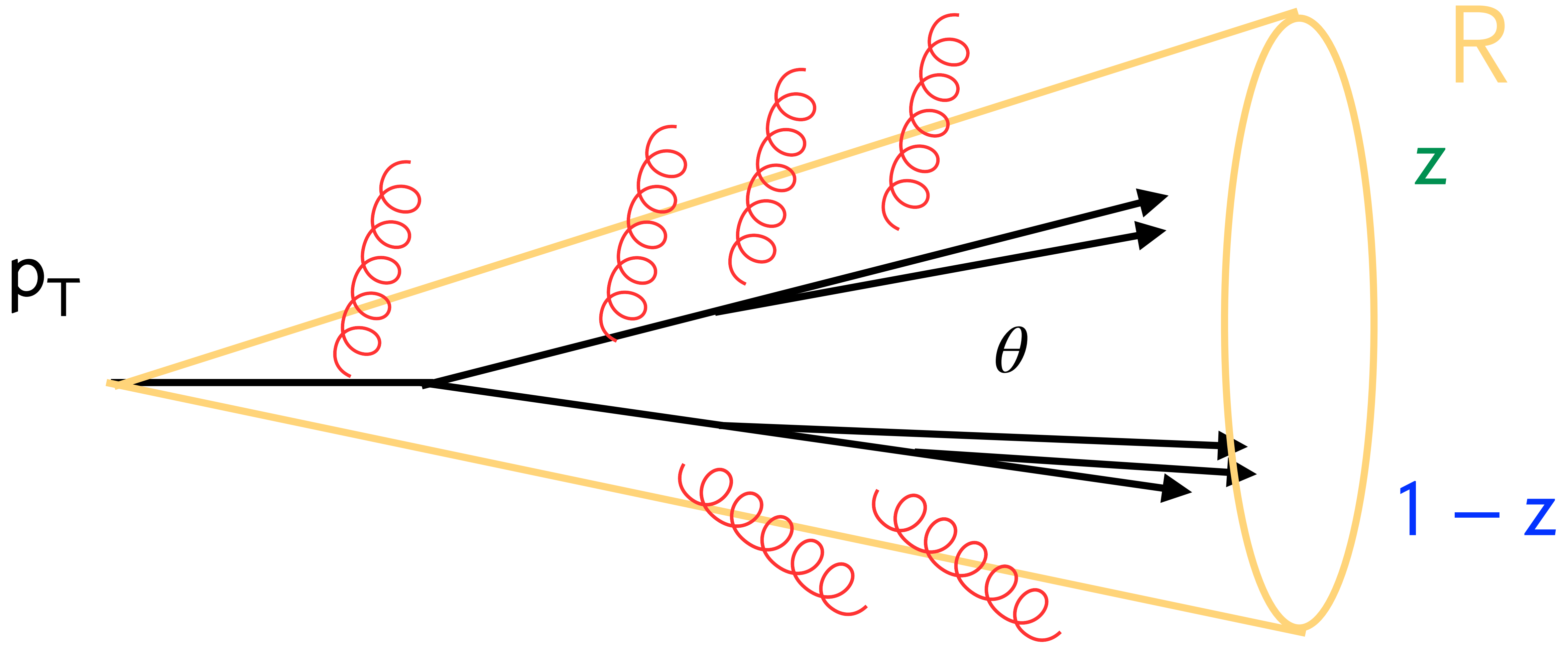
Phenomenology:
where do we stand?

- 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? 🙂

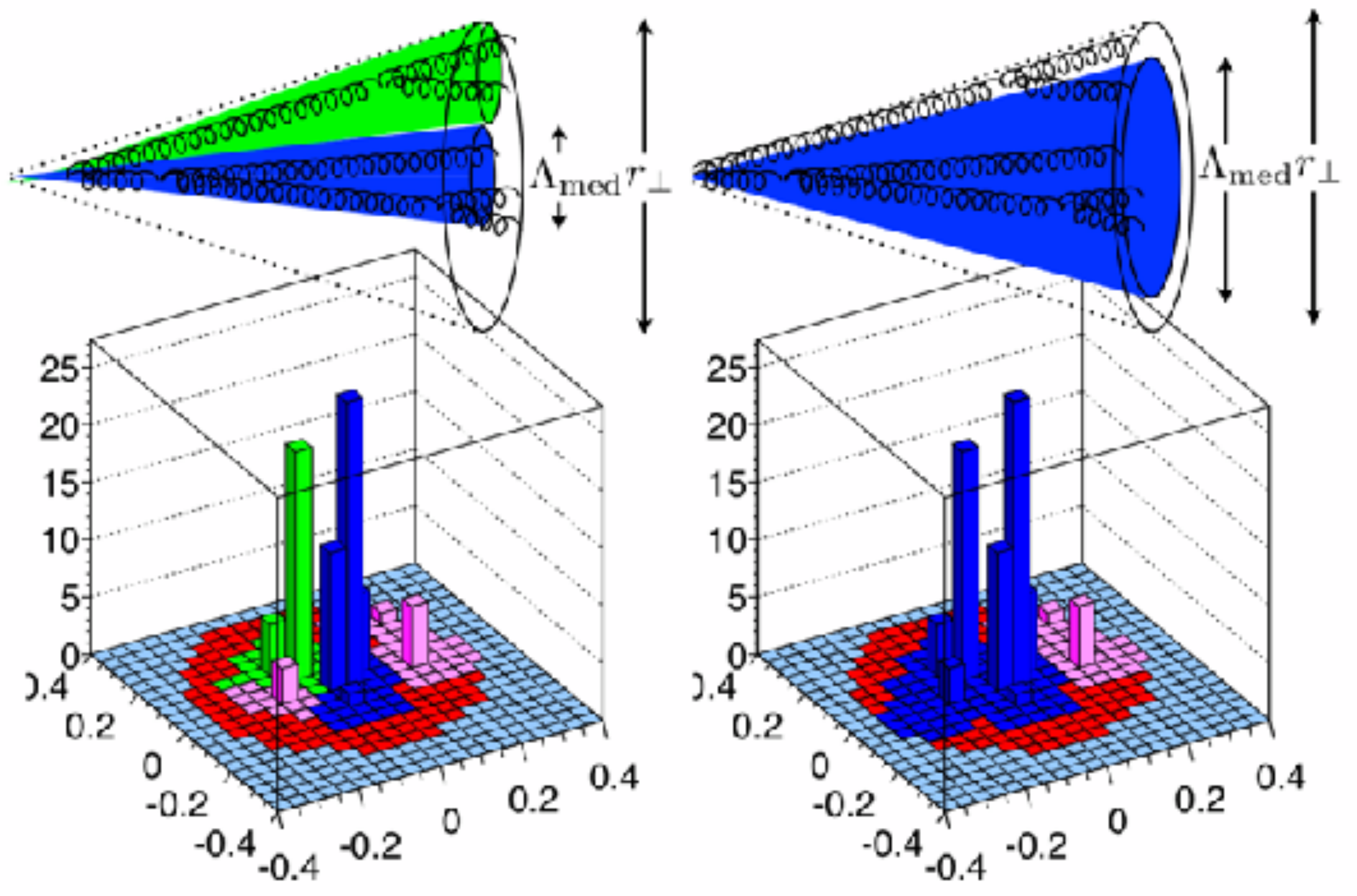
Toward precision phenomenology?

Sensitivity to substructure via R dependence

- Open quantum system: Jets are multi-parton quantum system in contact with a thermal bath [J. Barata's talk on Tuesday]
- Color/quantum decoherence in addition to energy loss and pt broadening



Casalderrey-Solana, Iancu, MT, Tywoniuk, Salgado, (2011-2013)



- coherence effects: resolution angle $\theta_c = (\hat{q}L^3)^{1/2}$

Resolution angle θ_c vs. centrality

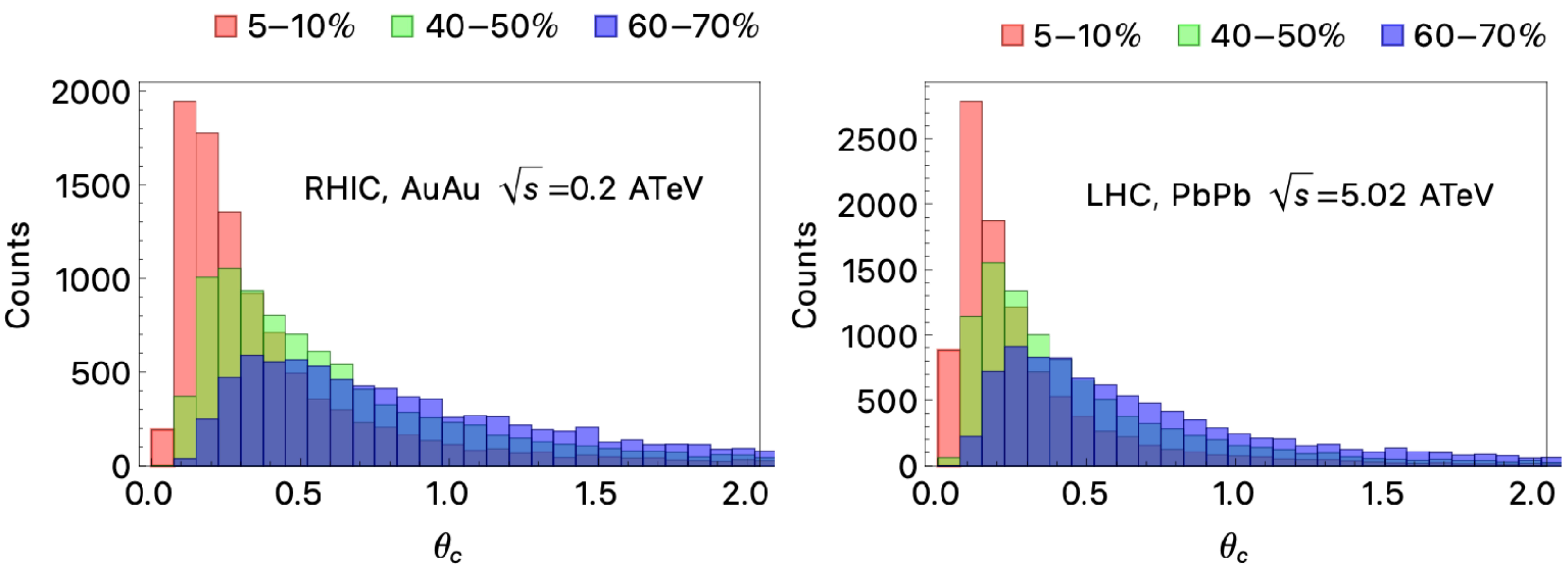
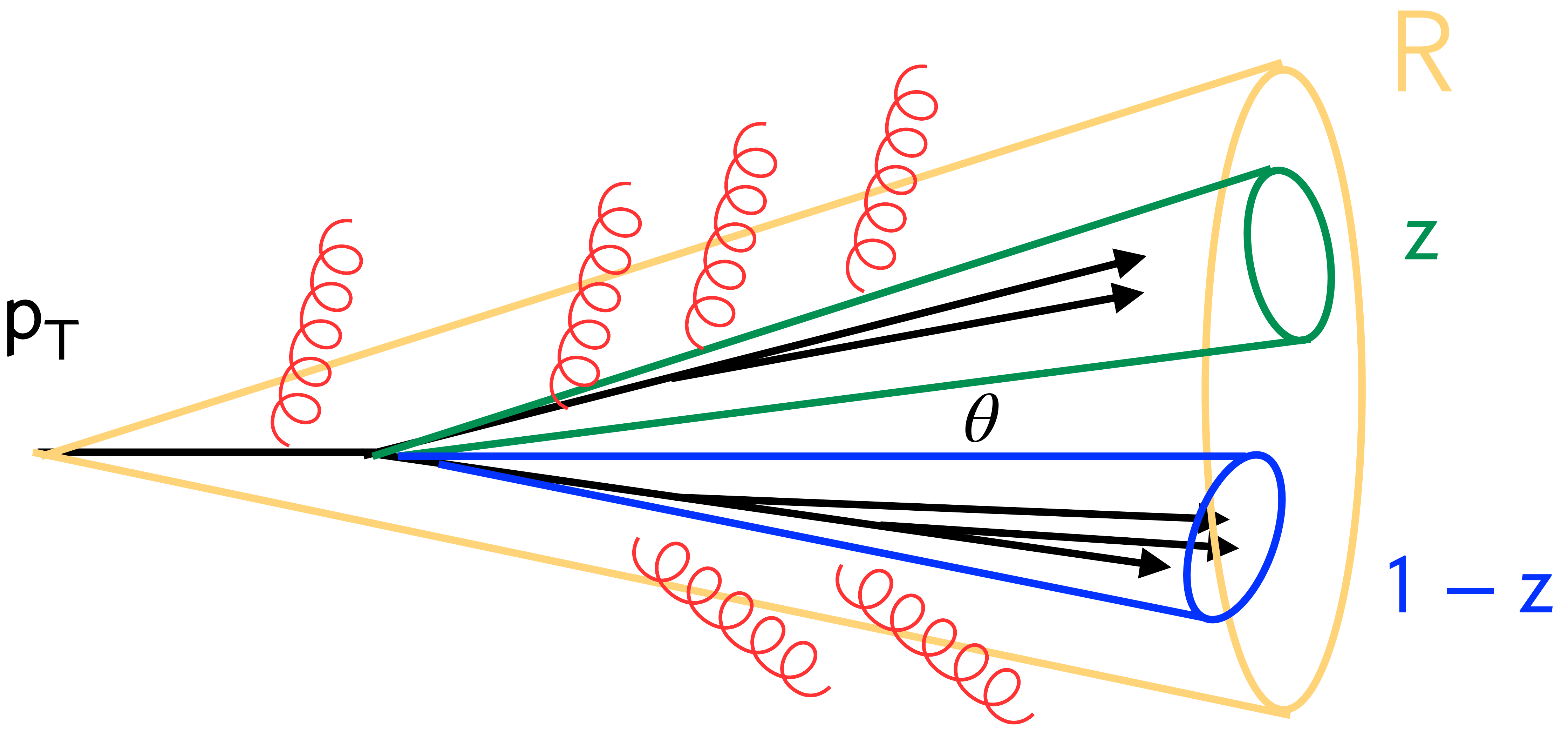


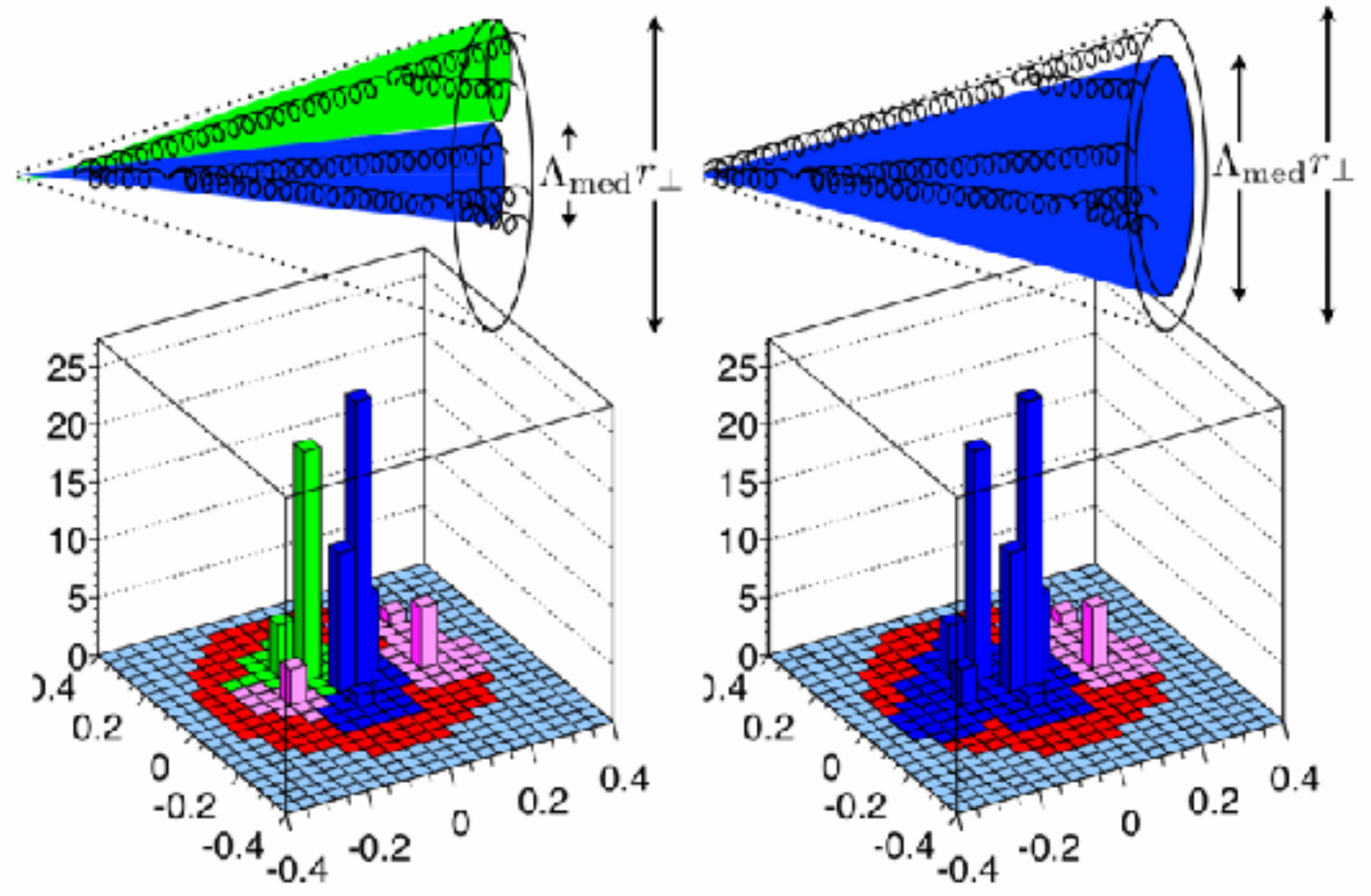
FIG. 2. Distribution of the value of θ_c determined by the possible different jet in-medium histories, for three different centralities, for RHIC energies in the left panel and LHC energies in the right panel.

MT, Tywoniuk (2017)

Nonlinear evolution evolution of energy loss

- Quenching factor: $Q \sim R_{AA} < 1$





Two effective color charges

One effective color charge

$$\frac{\partial}{\partial \ln\theta} Q_a(\theta, p_T) = \bar{\alpha} \int dz\, p^a_{bc}(z)\, \Theta_{res}(z,\theta) \left[Q_b(\theta, z p_T)\, Q_c(\theta, (1-z)p_T) - Q_a(\theta, p_T) \right]$$

$\theta > \theta_c$ $\qquad$ $k_\perp^2 > \sqrt{z(1-z)p_T \hat{q}}$

MT, Tywoniuk (2017)

Jet nuclear modification factor

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

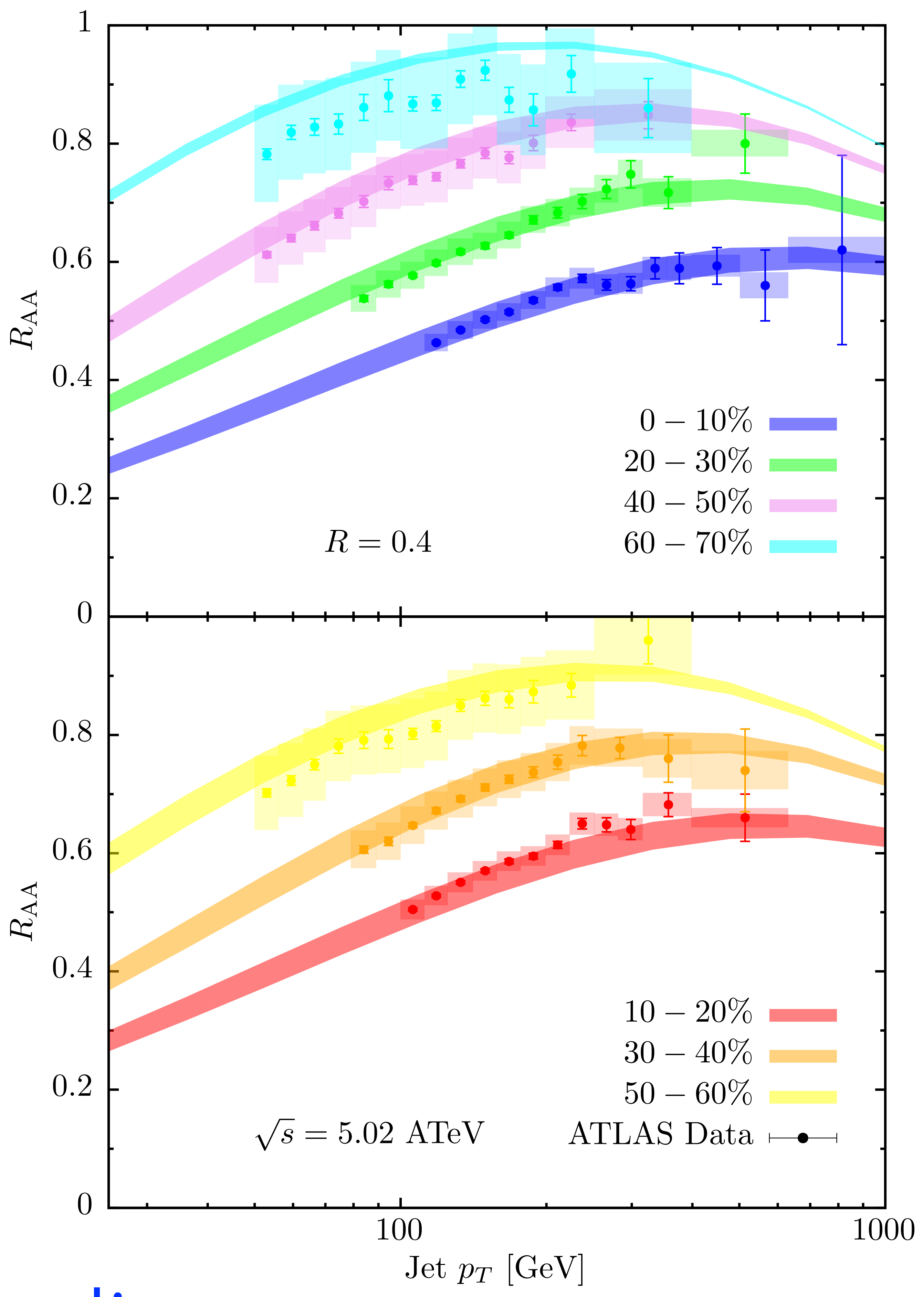
- Medium coupling constant $g_{\text{med}} \sim 2.2 - 2.3$

- 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 PRL (2021)



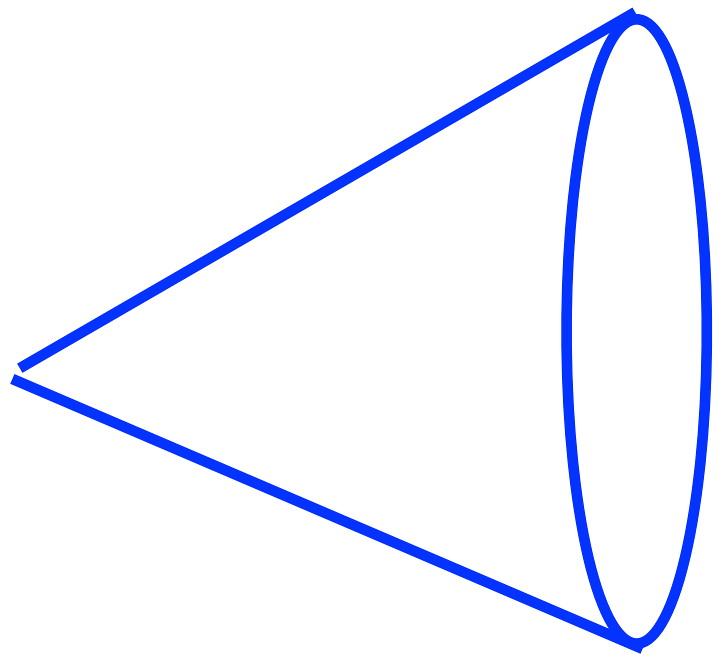
→ Good agreement with ATLAS data as function of pT and centrality

Data: arXiv:1805.05635

Predictions for R dependence in ALICE

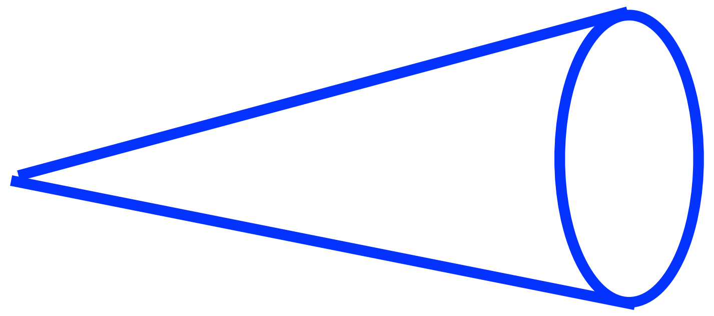
- R dependence encodes color coherence effects

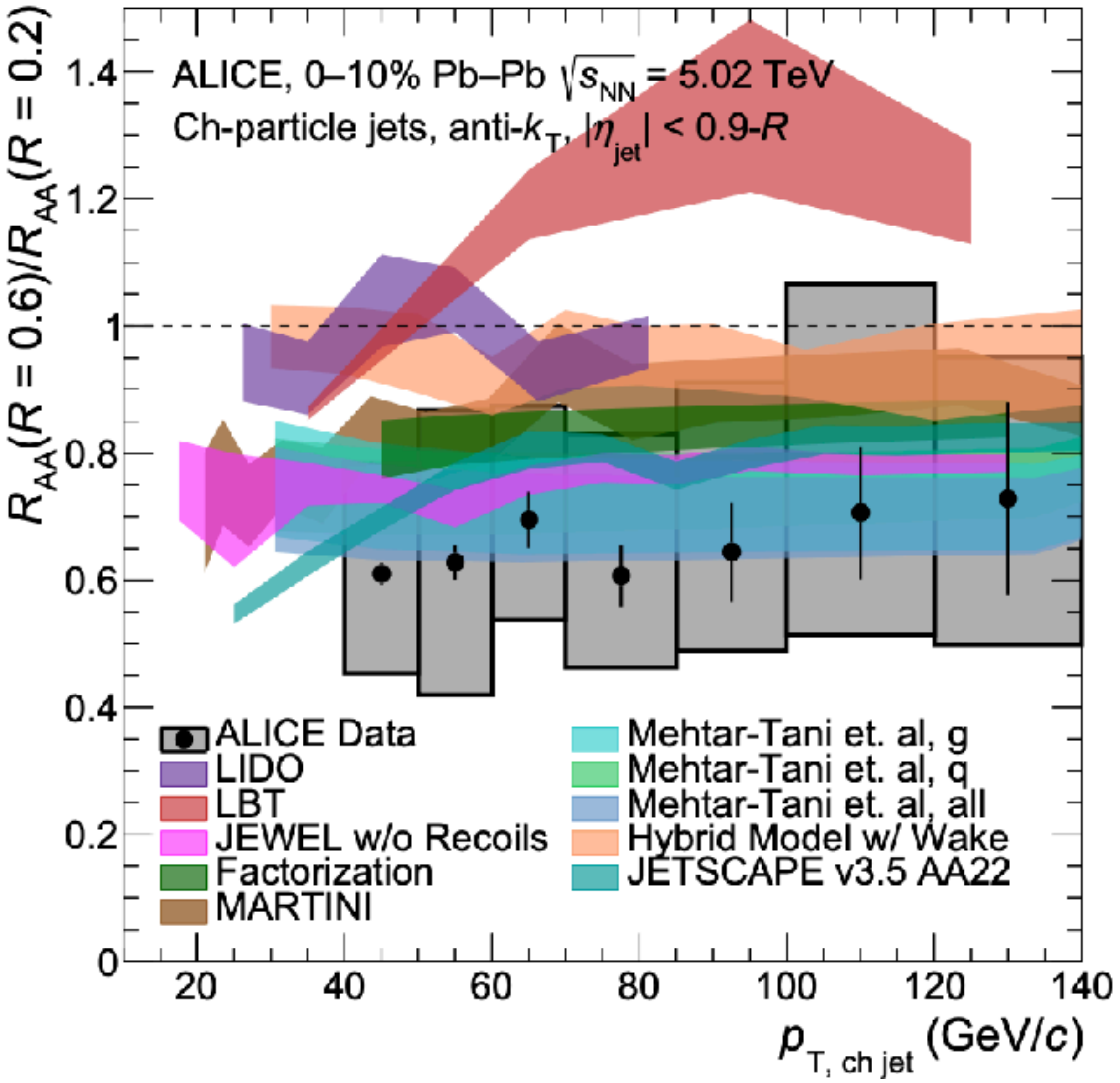
$R = 0.6$



Vs.

$R = 0.2$





Data: arXiv:2303.00592

← Our prediction

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

R dependence in ALICE and ATLAS

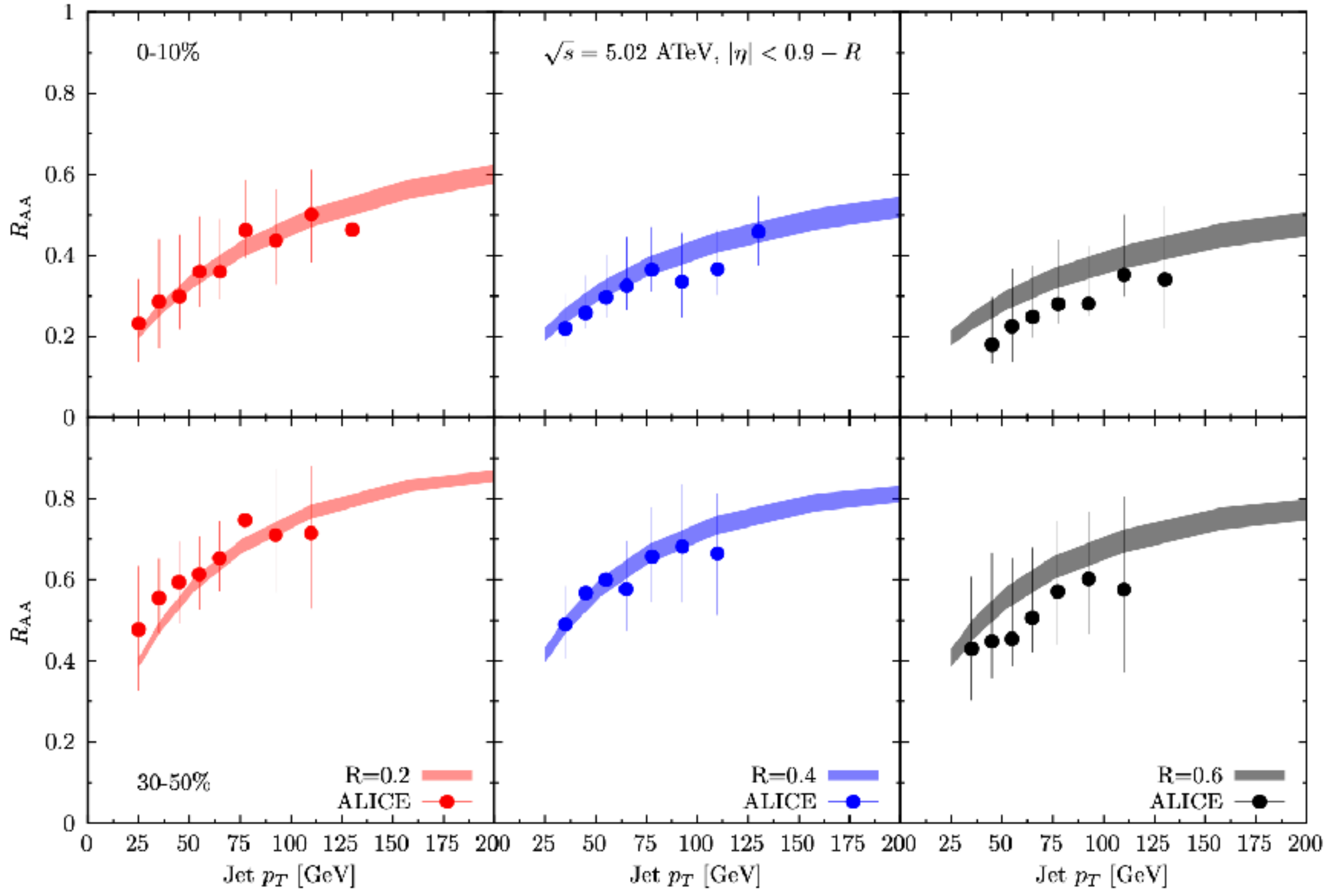


FIG. 6. Comparison of R_{AA} at LHC for $\sqrt{s} = 5.02$ ATeV.

Data: arXiv:2303.00592

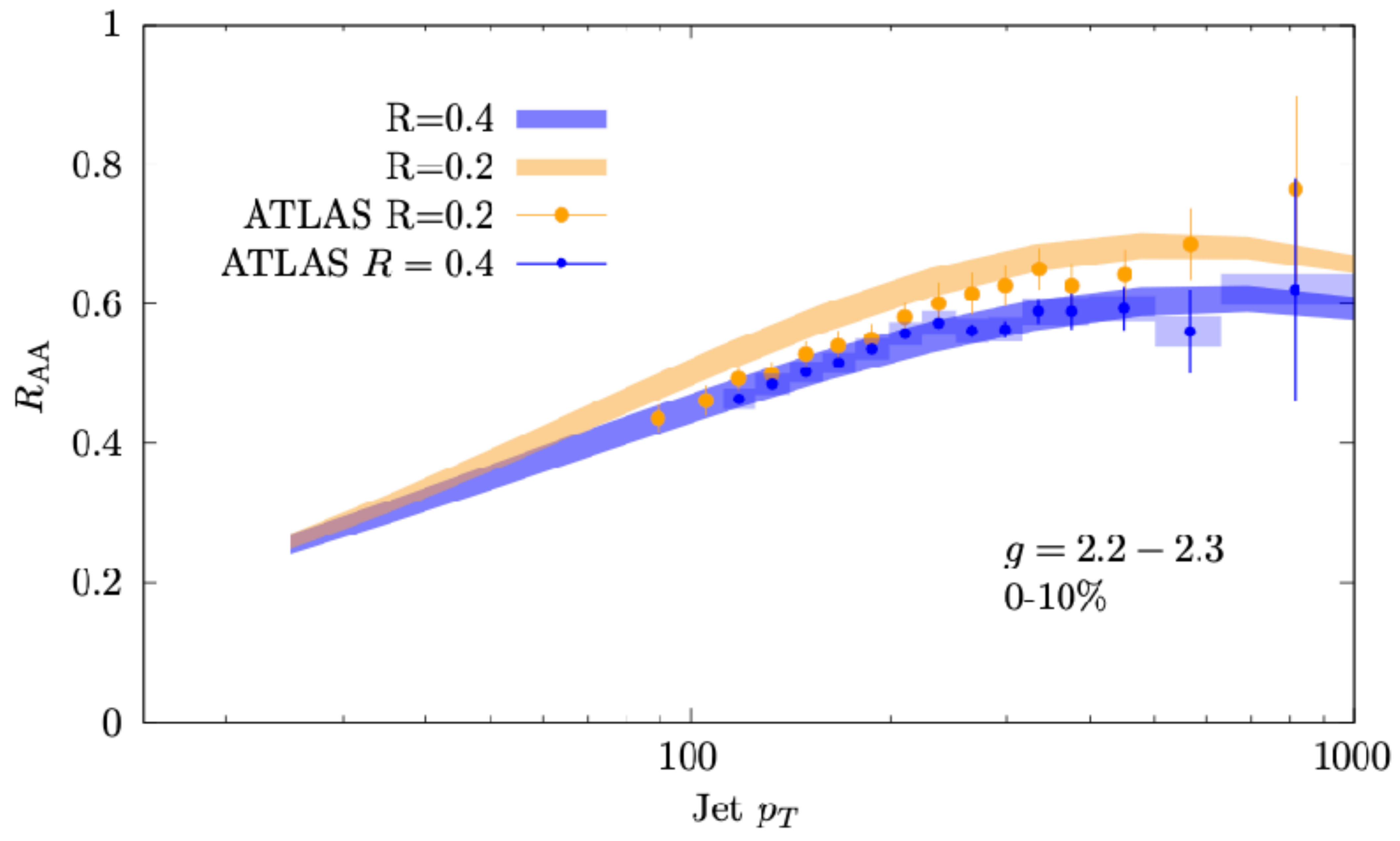


FIG. 7. Comparison of R_{AA} at LHC for $\sqrt{s} = 5.02$ ATeV.

Data: arXiv:2301.05606

- weak R dependence: interplay of energy recovery and enhanced phase space for vacuum splitting

Testing multi-parton dynamics with jet v_2

Approximation: $$v_2 \simeq \frac{1}{2}\frac{R_{AA}(L_{in}) - R_{AA}(L_{out})}{R_{AA}(L_{in}) + R_{AA}(L_{out})},$$

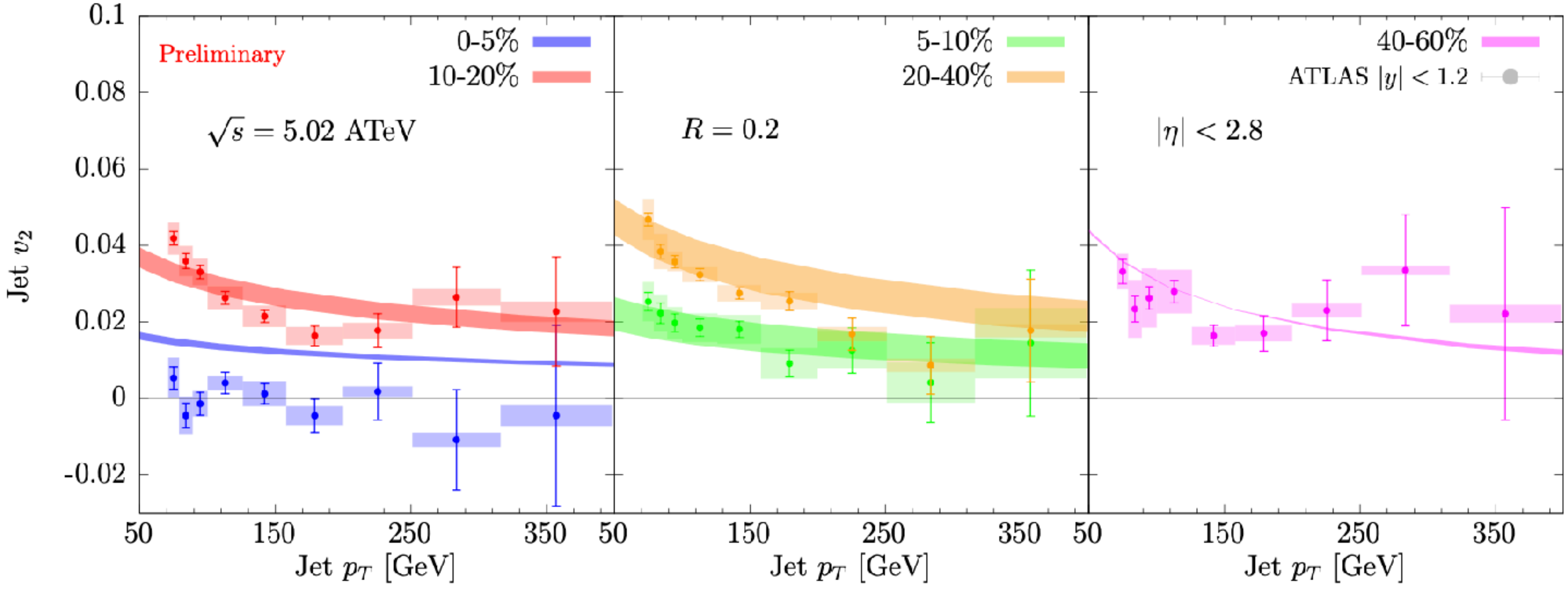
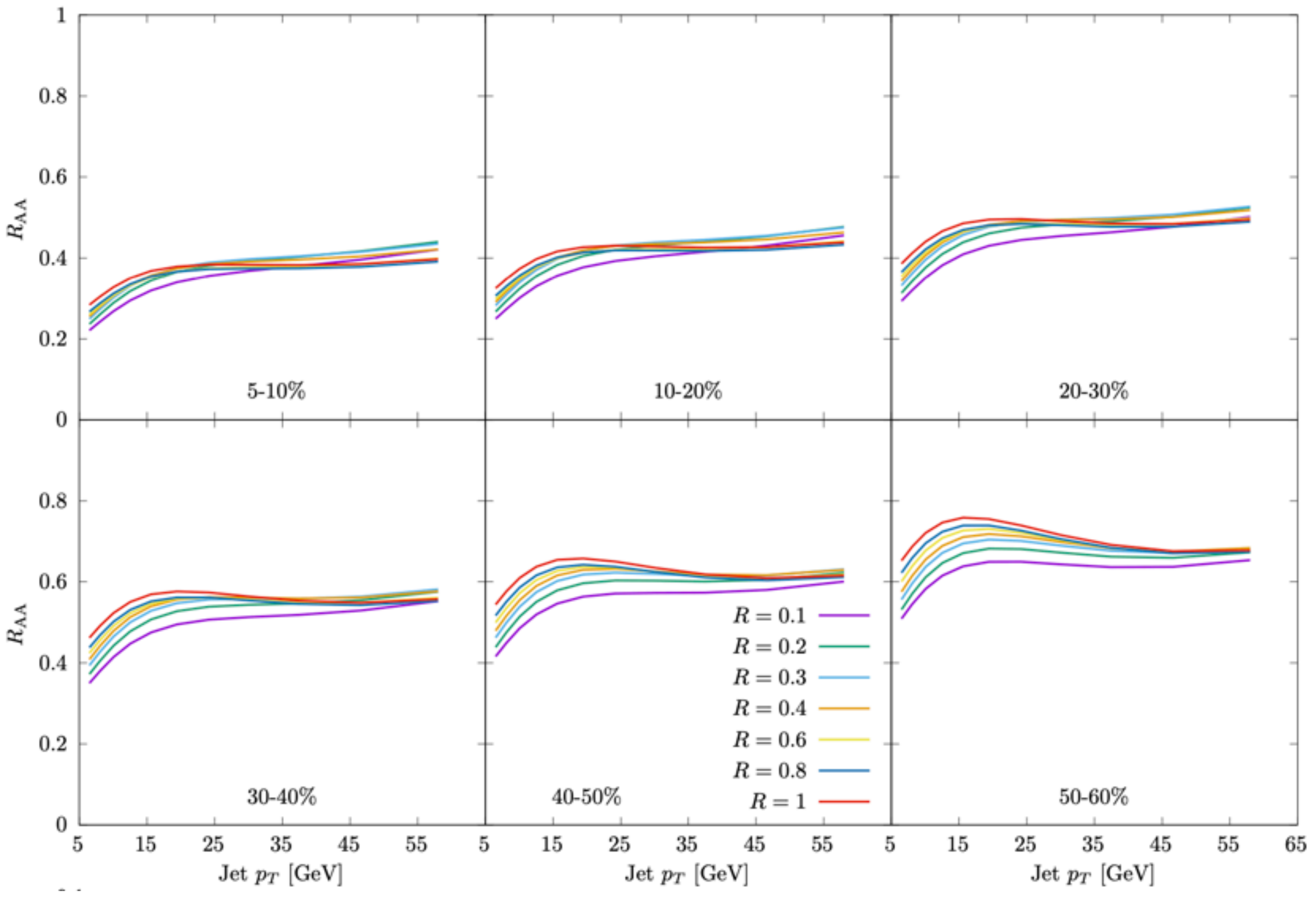
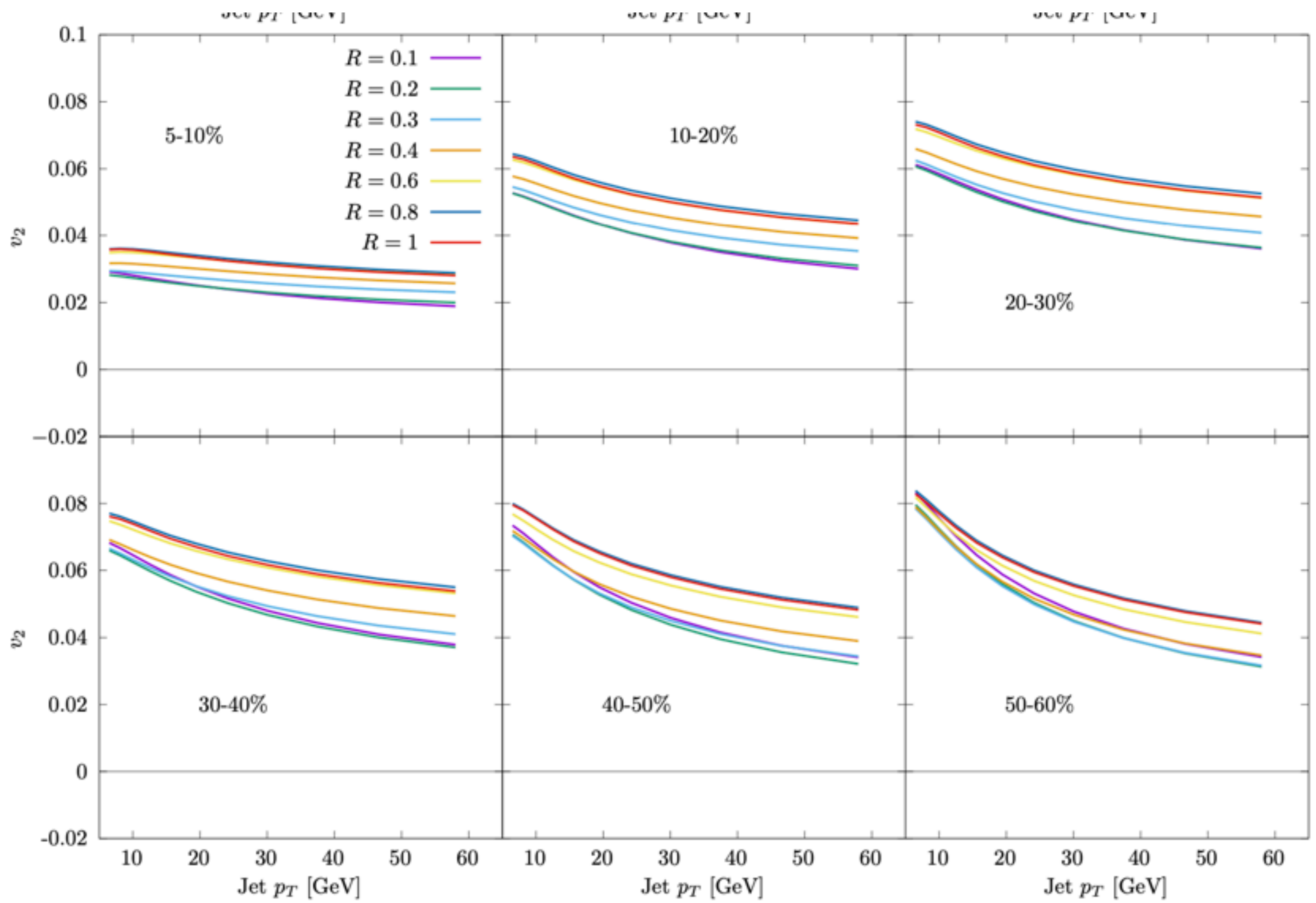


FIG. 8. Comparison of jet v_2 for LHC at $\sqrt{s} = 5.02$ ATeV.

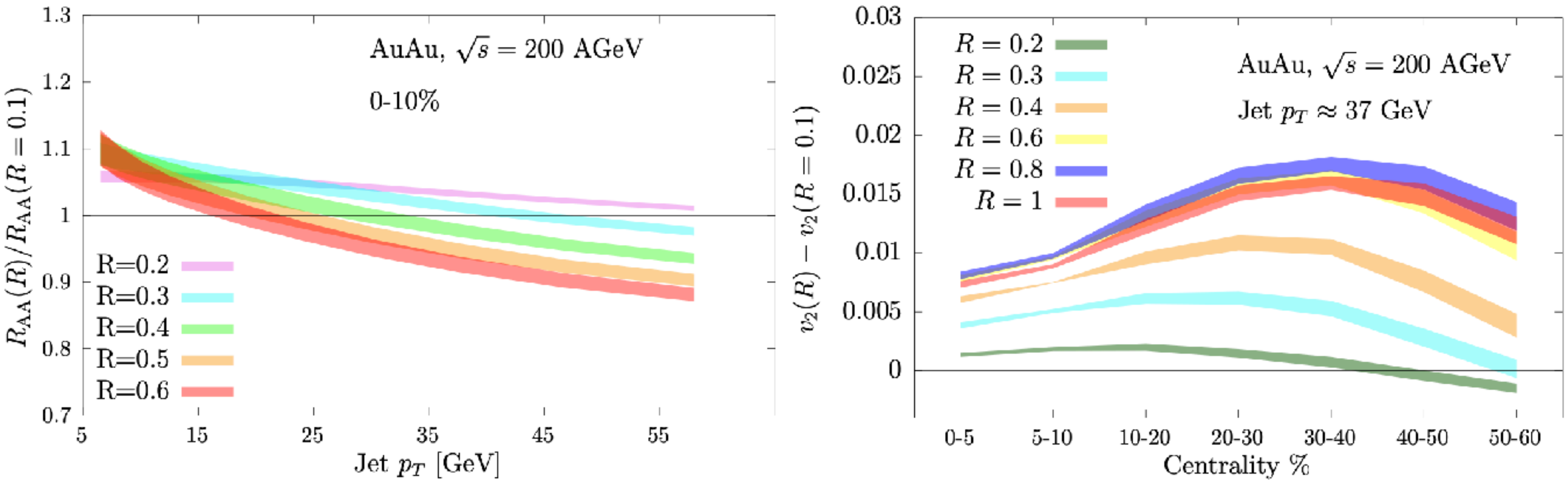
Predictions for R dependence for sPHENIX





- Relatively weak R dependence in R_{AA} and v_2

Predictions for R dependence for sPHENIX



- R dependence of Jet v_2 : sensitivity to jet substructure modification and color coherence angle θ_c

Conclusion

- Jets in HIC are open quantum systems probed by the medium!
  Medium resolution scale plays a crucial role in jet energy loss
- This talk: analytic approach to R_{AA} and jet v_2 as testing ground of the theory and its uncertainties
- Progress: Smooth description of the QGP dynamics from soft to hard scales. Towards precision phenomenology and extraction of transport coefficients

Thank you!