What we can learn about the QGP dynamics from jets

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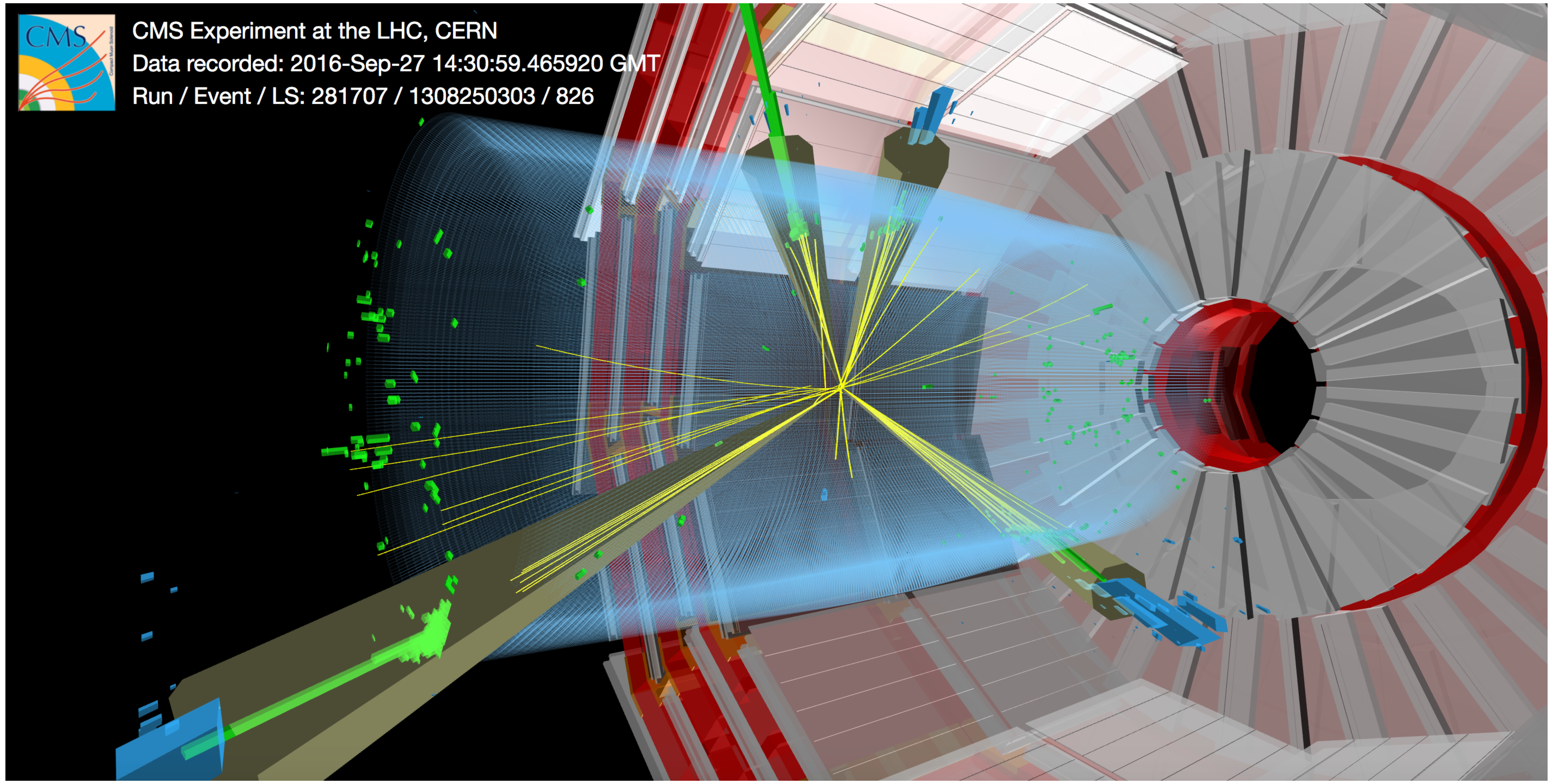
Brookhaven National Laboratory

RBRC
RIKEN BNL Research Center

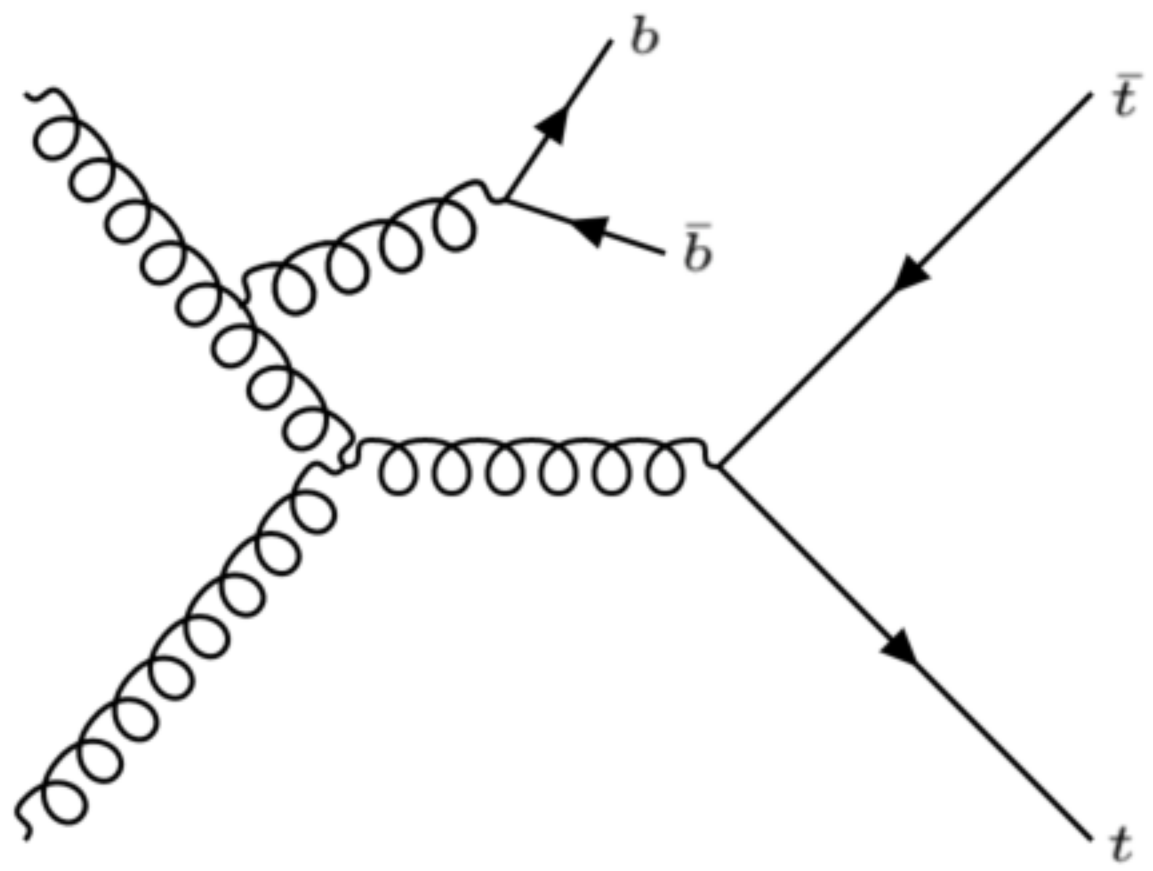
Introduction

Jets at Colliders

- QCD Jets are a direct manifestation of high energy quarks and gluons

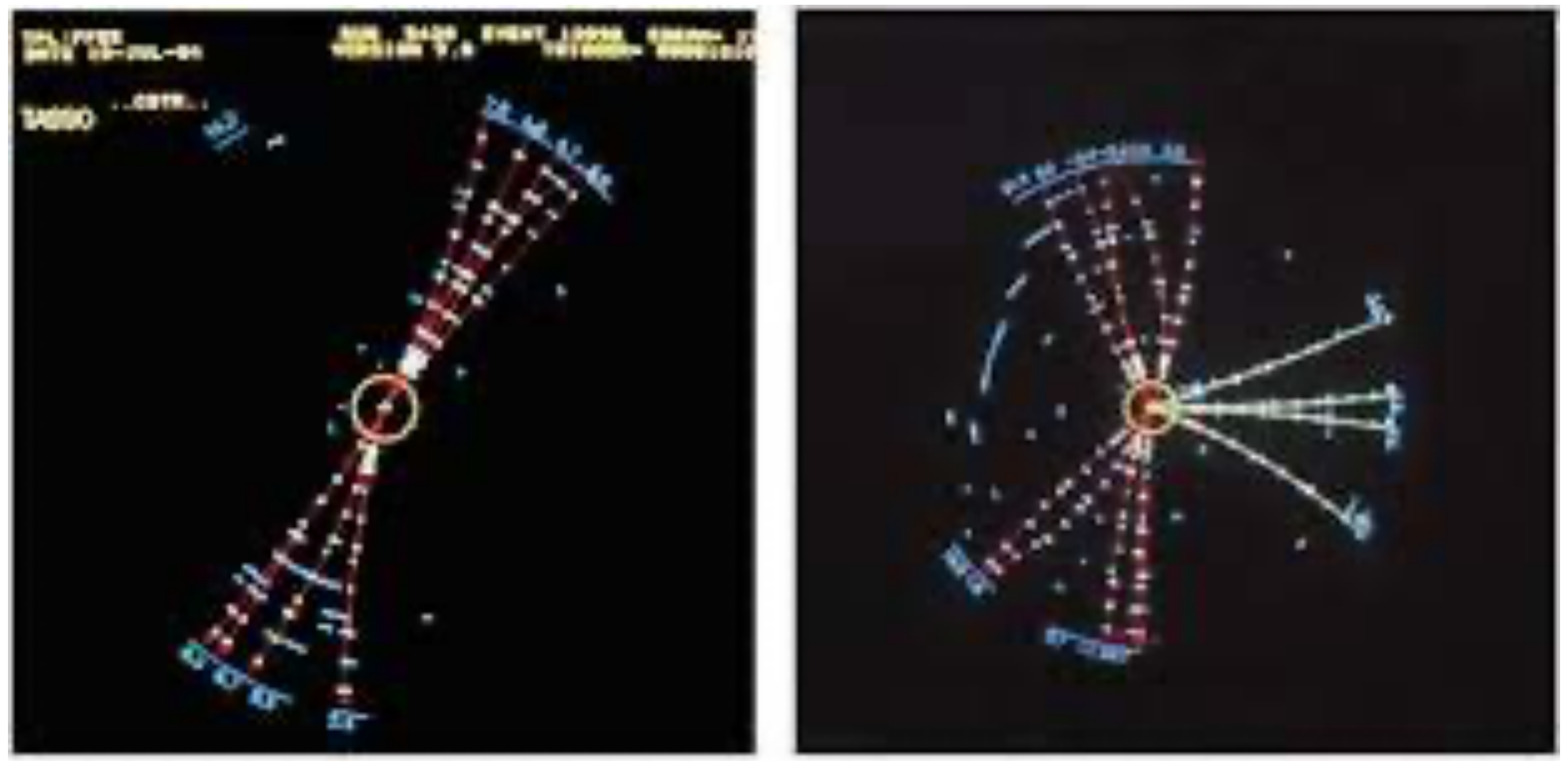


Multi-jet event at LHC

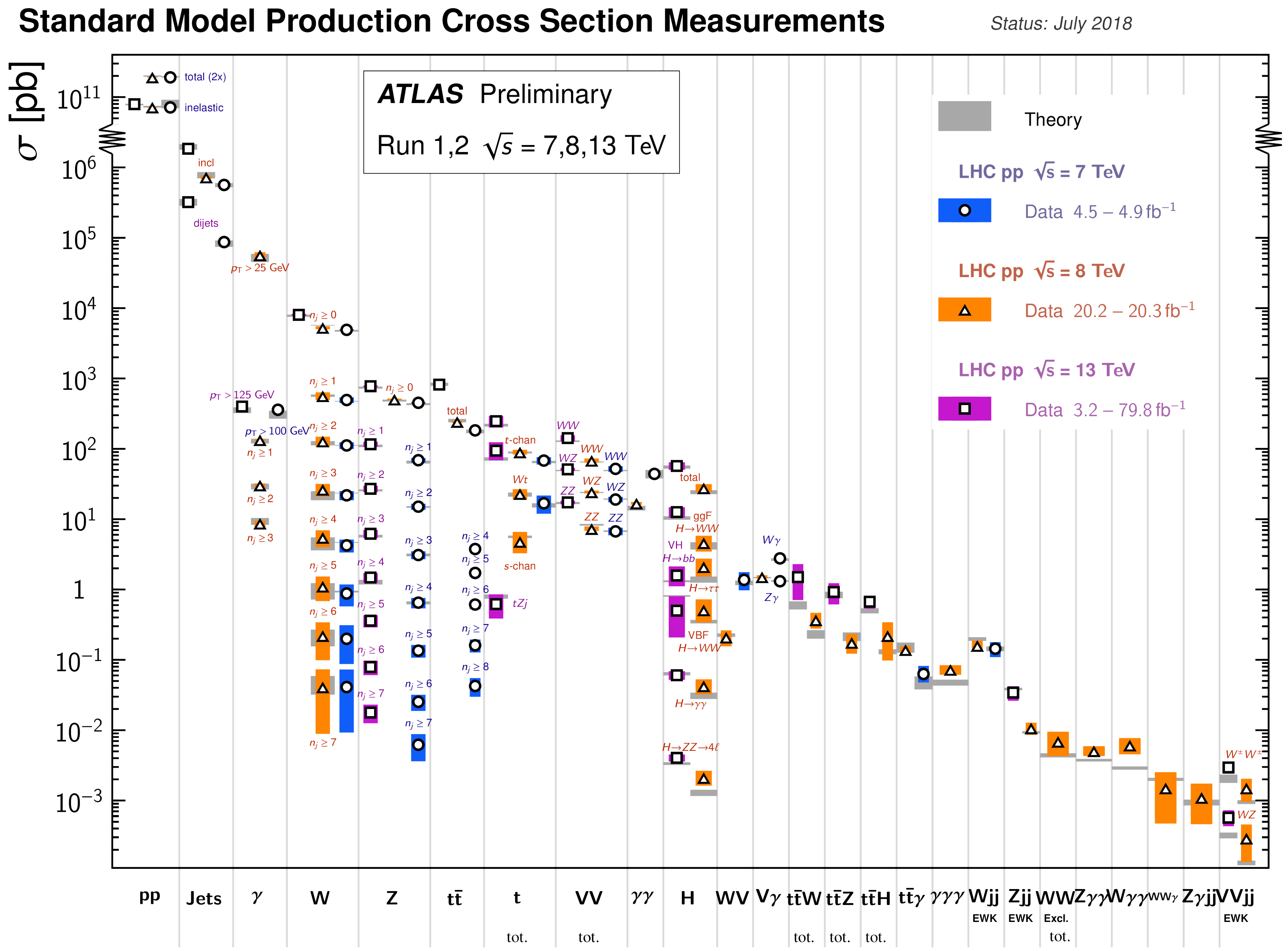


- Extensively studied: from the discovery of the gluon to precision tests of QCD

DESY 1979 - electron positron collisions



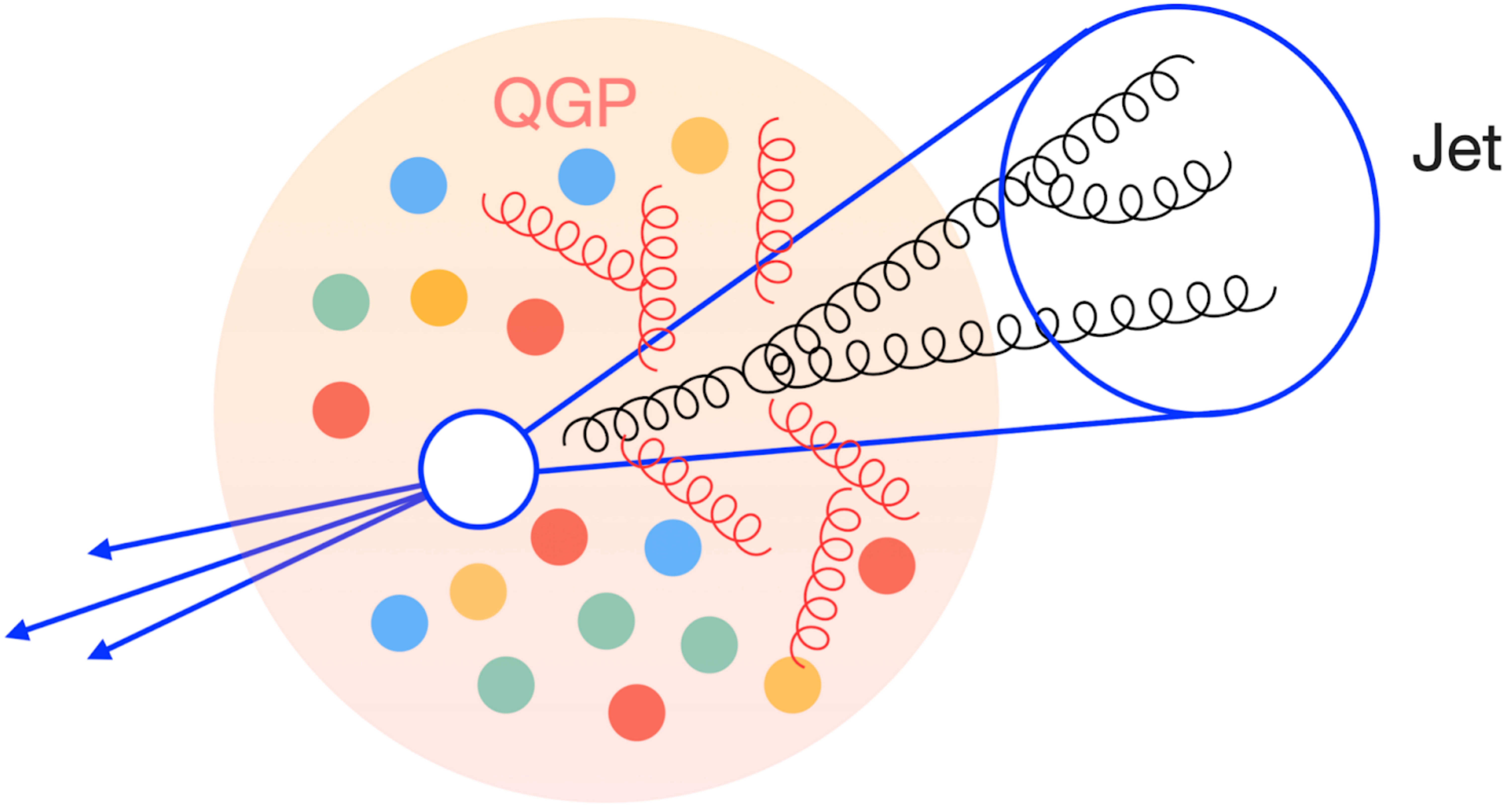
Early tests of QCD



Today's theory accuracy $\gtrsim 5\,\%$

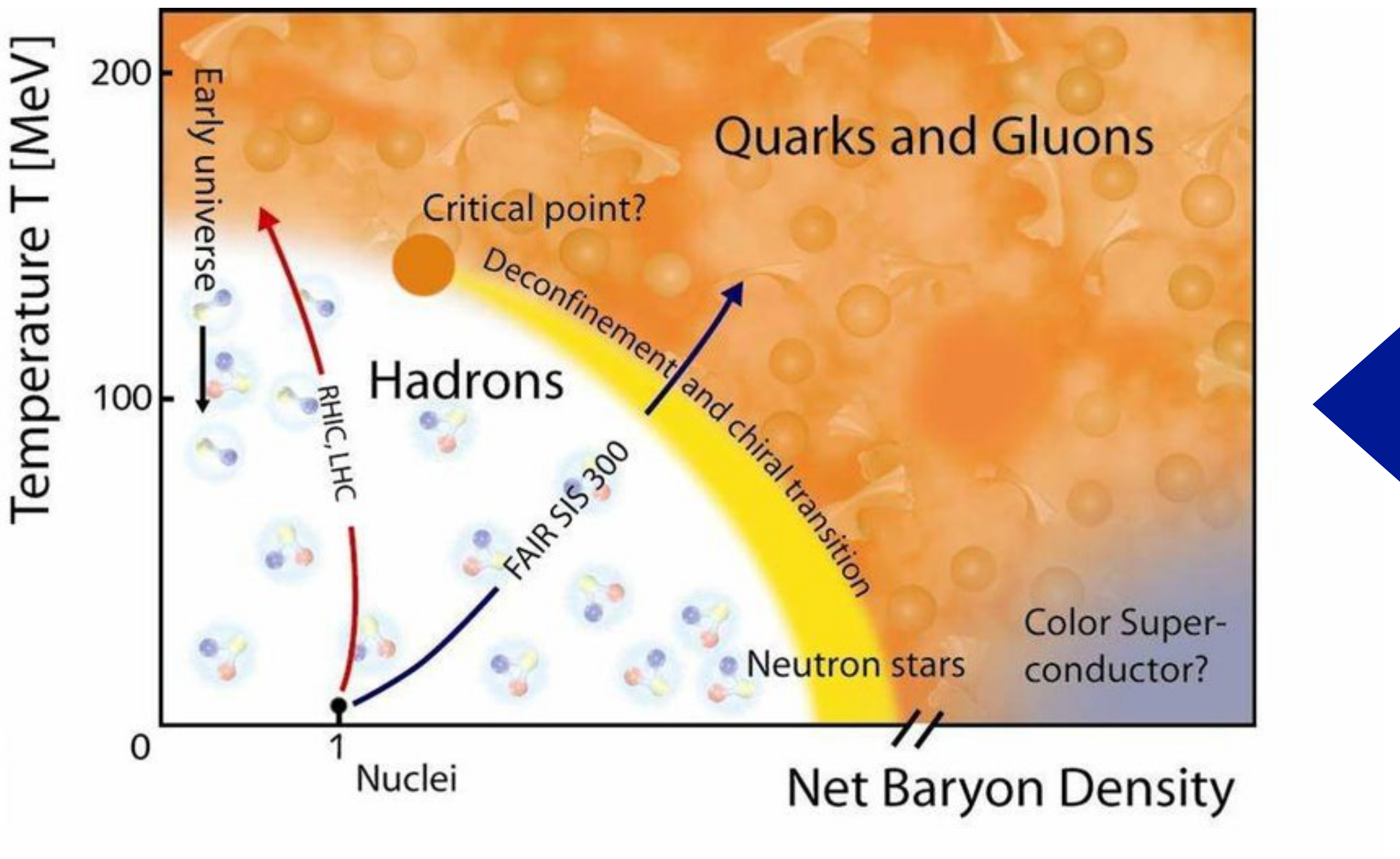
- Paramount for Higgs discovery and new physics searches

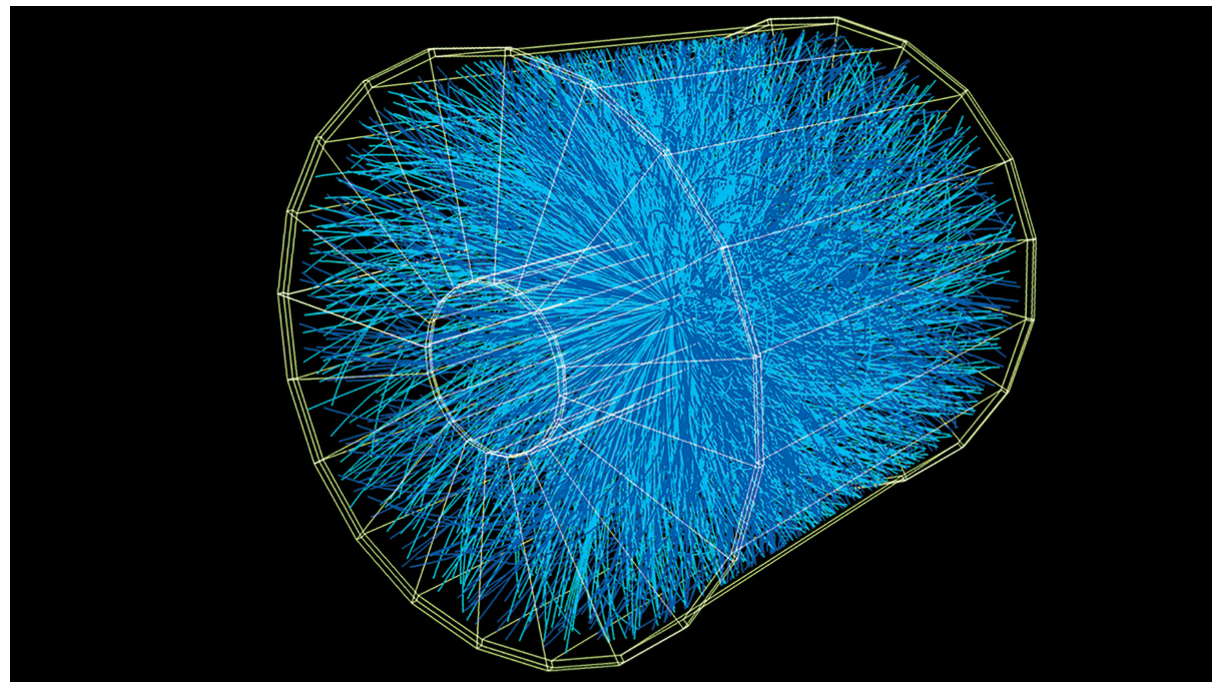
Jets in heavy ion collisions: The new pQCD frontier



Multiscale dynamics

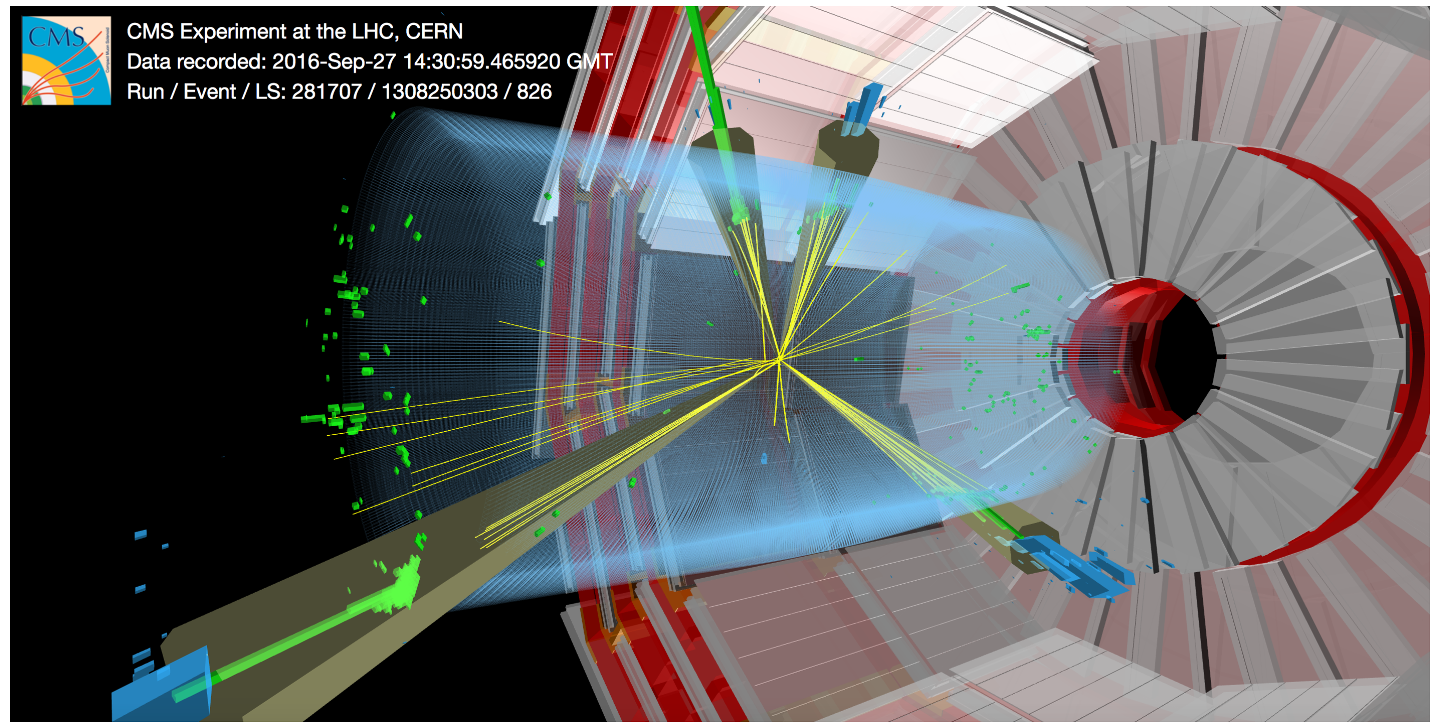
Thermal equilibrium (T≠ 0) | Non-equilibrium | T=0



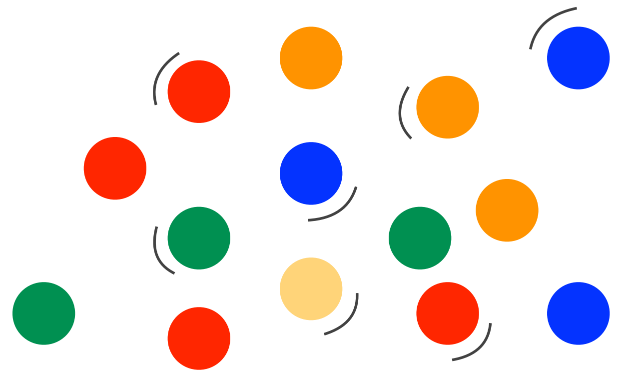


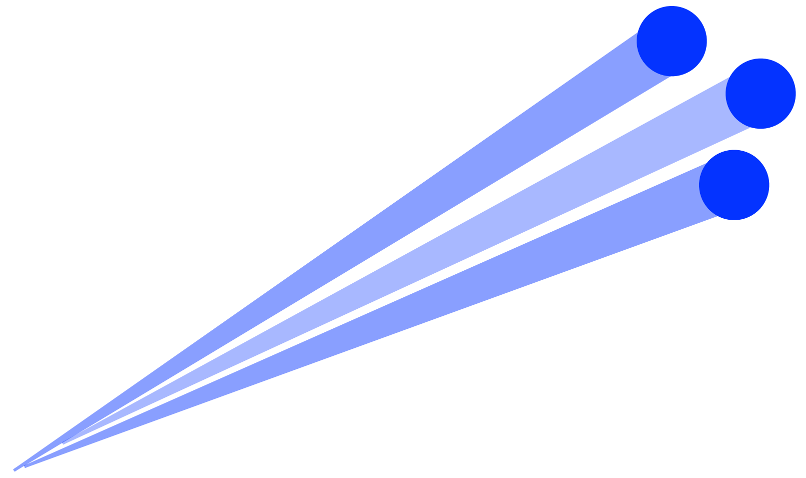
Heavy ion event

~ 1000's particles



Jets in pp



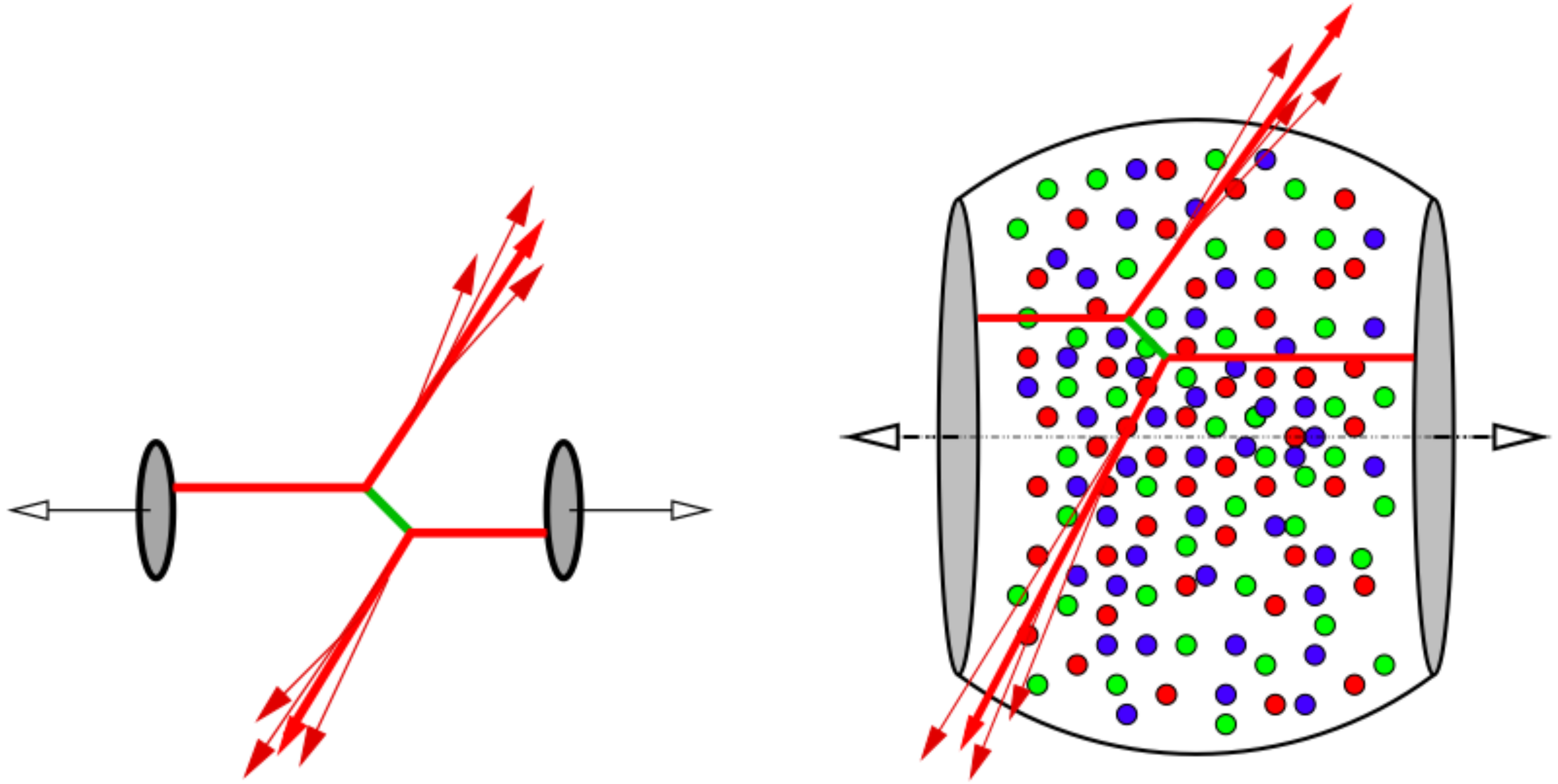


Energy

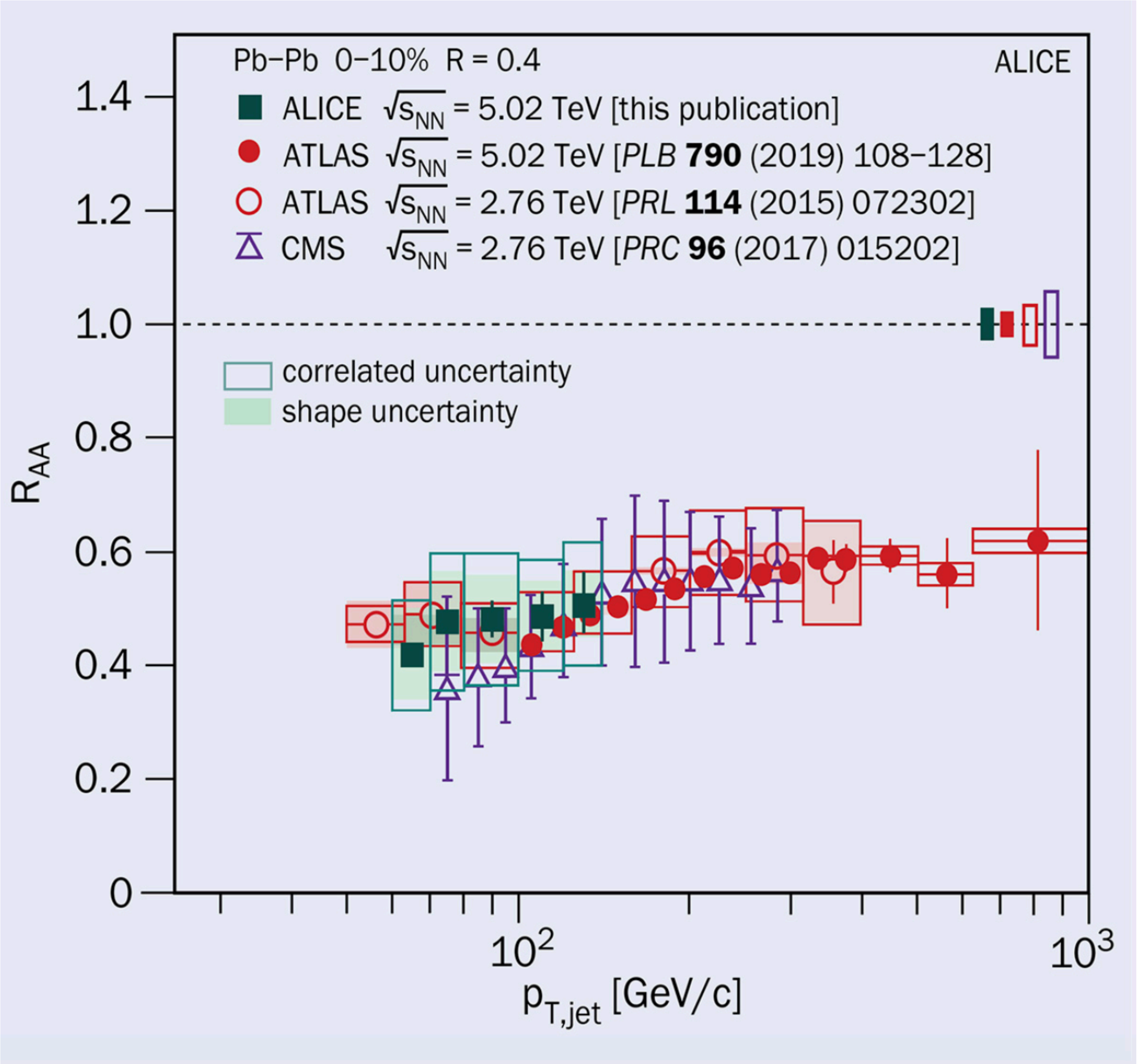
$T \sim 1$ GeV

$p_T \sim 1$ TeV

Discovery of the QGP (from RHIC to LHC)



Nuclear modification factor

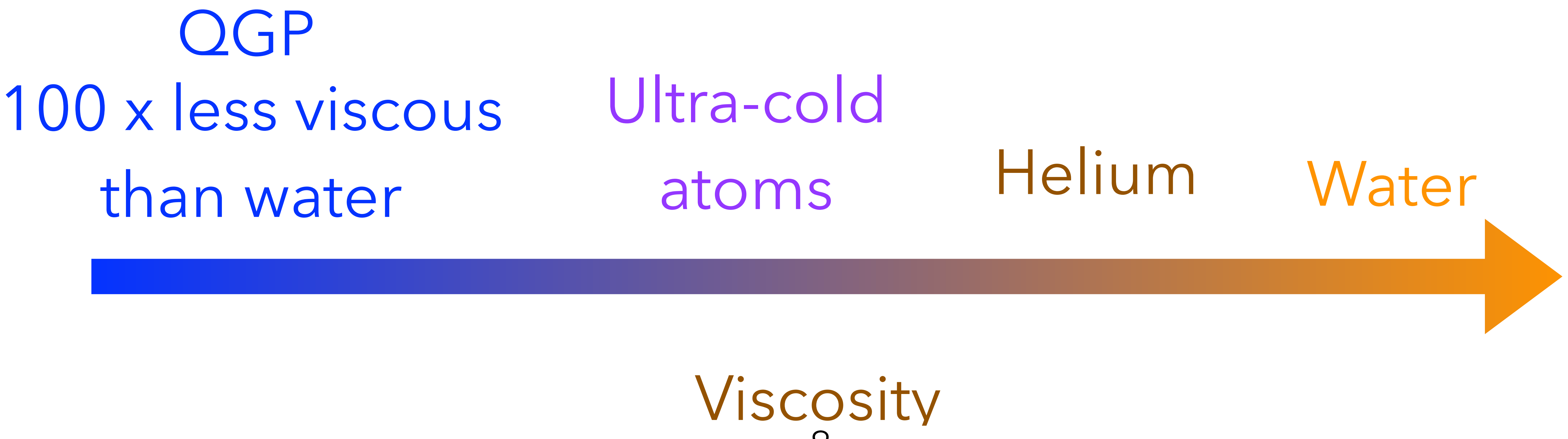


- Strong suppression of jets in ultra-relativistic heavy ion collisions: evidence of the formation of the quark gluon plasma
- Jet quenching mechanisms: radiative and collisional parton energy loss

$$R_{AA} = \frac{dN_{AA}}{N_{coll}\, dN_{pp}}$$

What can we learn by studying jets?

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



A challenging problem

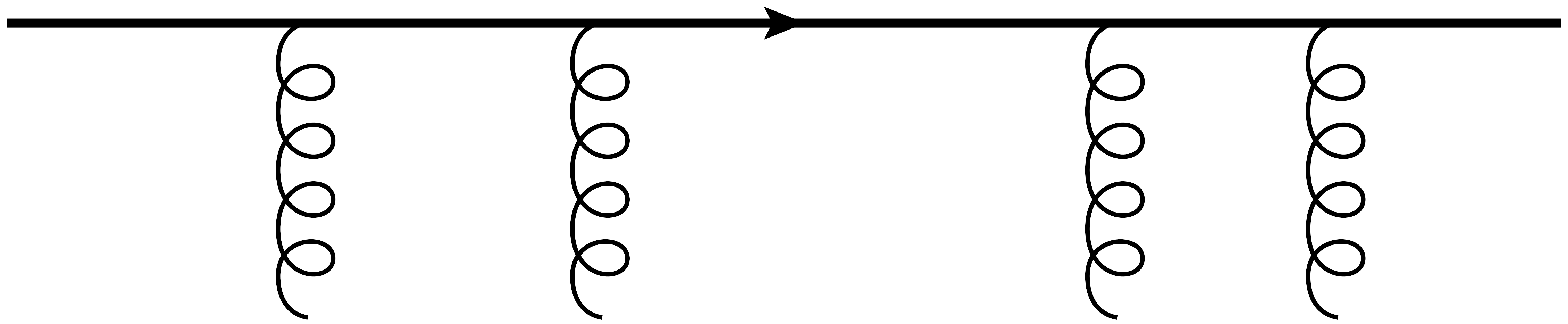
- Theory:
    - Rich physics, new emergent phenomena,… 🙂
    - lack of a comprehensive framework ☹️
- Phenomenology/Experiement:
    - Versatile tools: dijet, R dependence, substructure, … 🙂
    - Convolved processes, large soft background (semi-soft scale contamination) ☹️

Elements of jet quenching theory

Transverse momentum broadening

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996)

Energetic quark



$k_\perp \ll E$

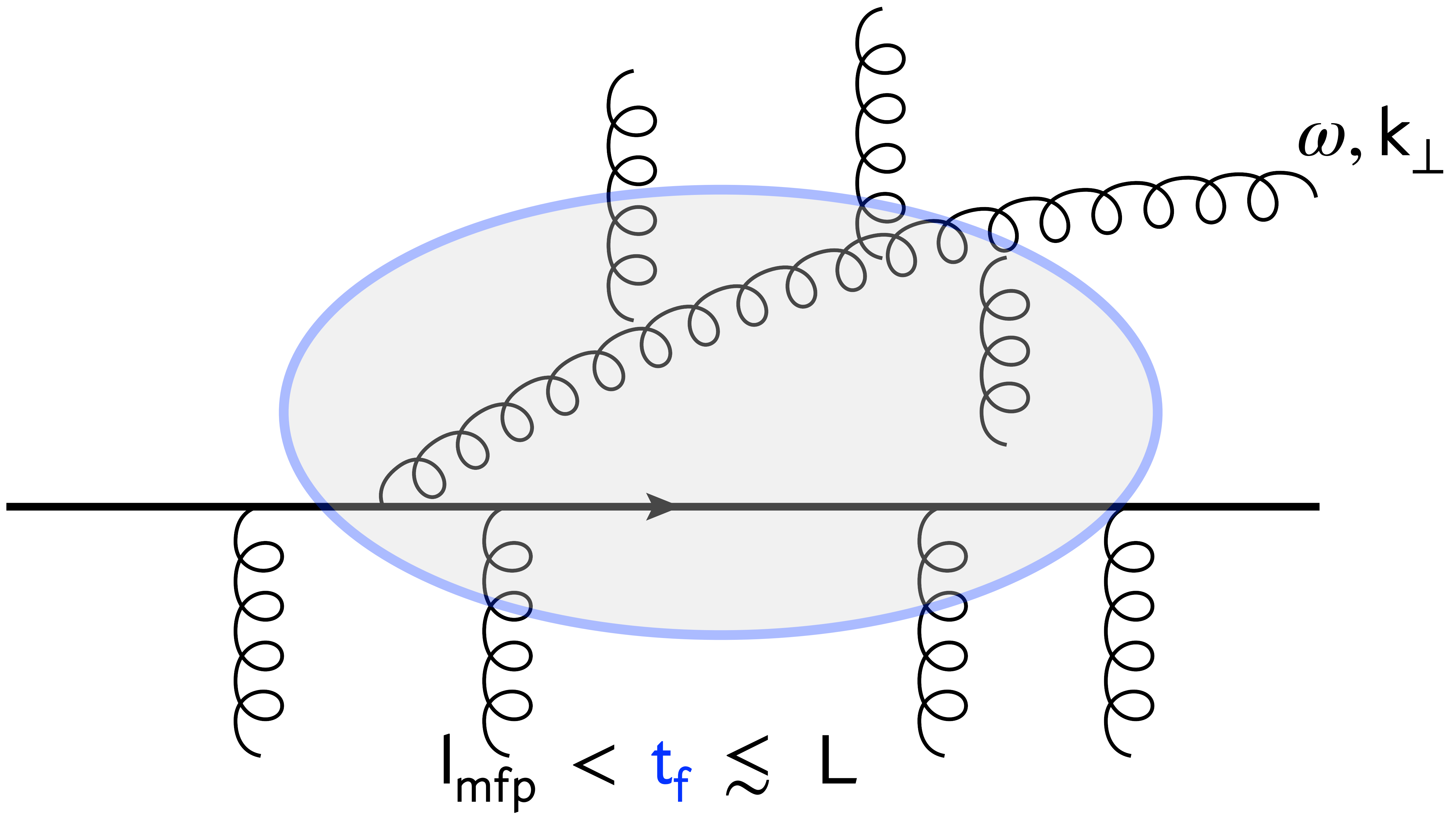
- Multiple scattering cause transverse momentum diffusion

$$\langle k_\perp^2 \rangle \sim \hat{q}\, t$$

Brownian motion in k_T

- Diffusion coefficient $\hat{q} \sim m_D^2 / l_{mfp} \sim g^4 T^3$ probes medium properties

Laudau-Pomeranchuk-Migdal effect



Baier, Dokshitzer, Mueller, Peigné, Schiff (1996)
Zakharov (1996)
Wiedemann, Gyulassy, Levai, Vitev (2001)
Arnold, Moore, Yaffe (2002)

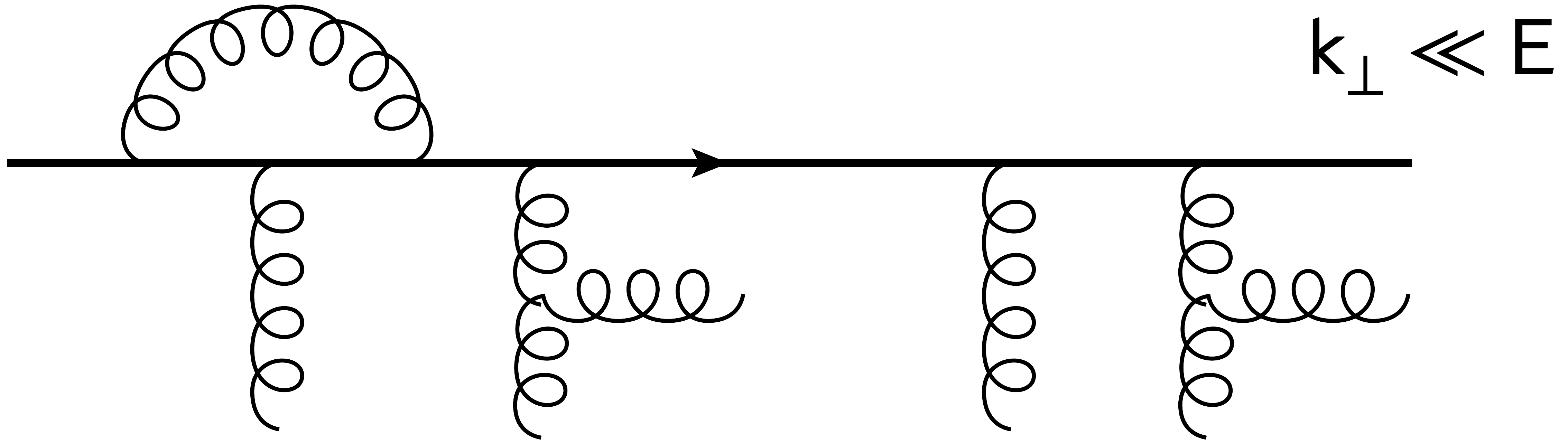
Gluon coherent/formation time:

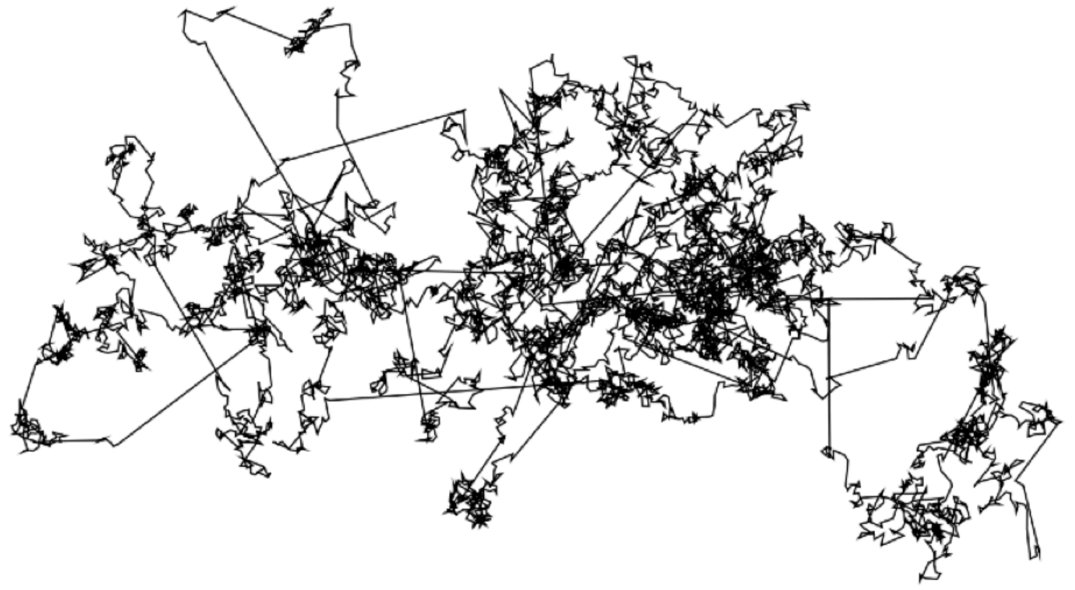
$$t_f \sim \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}} \qquad (k_\perp^2 \sim \hat{q}\, t_f)$$

- Medium induced gluon radiation: Multiple scattering act coherently during t_f to produce the gluon

Radiative corrections to transverse momentum diffusion

Energetic quark



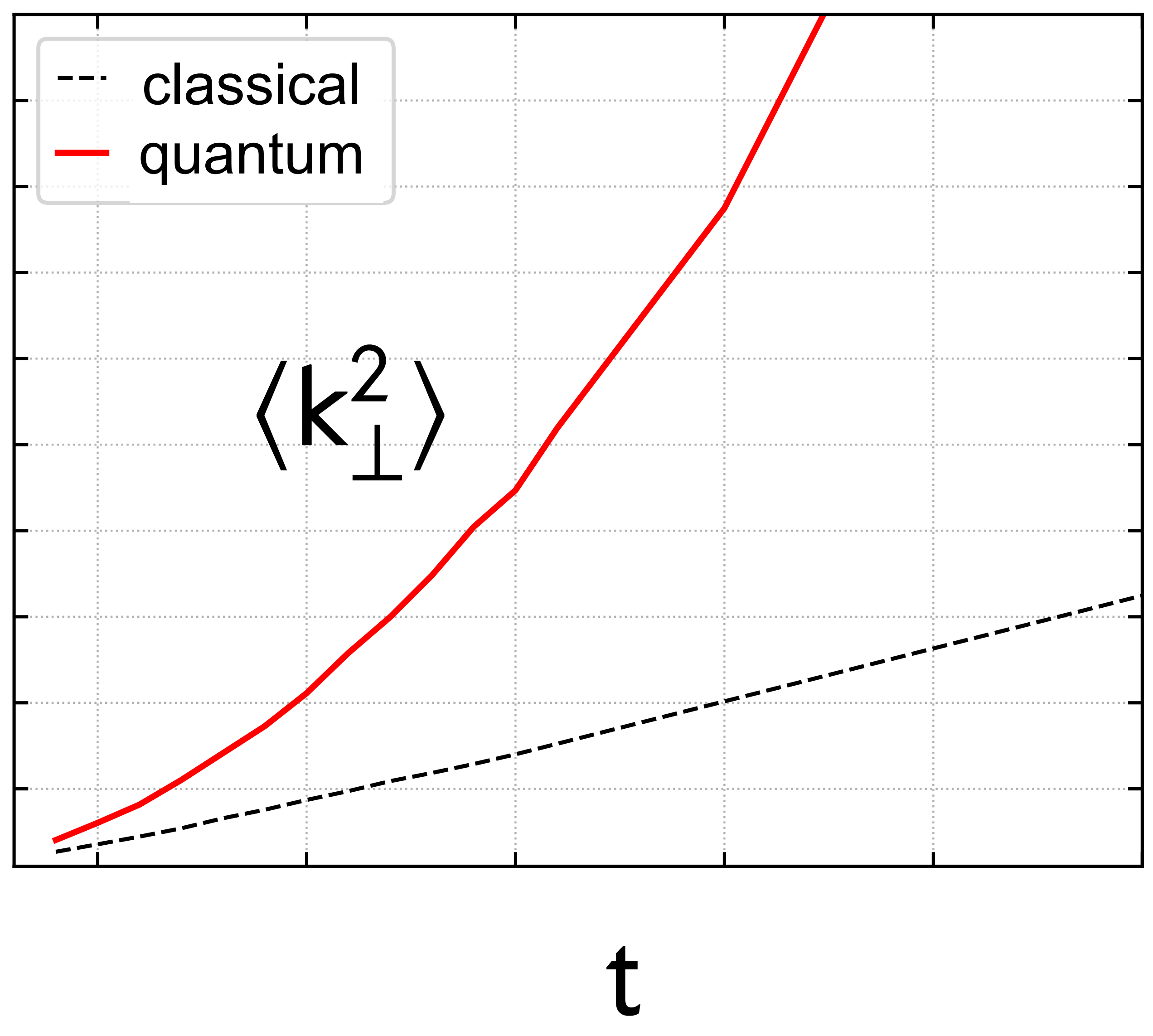


Lévy flight

- Quantum corrections to momentum broadening:

Normal diffusion → Anomalous (super) diffusion

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



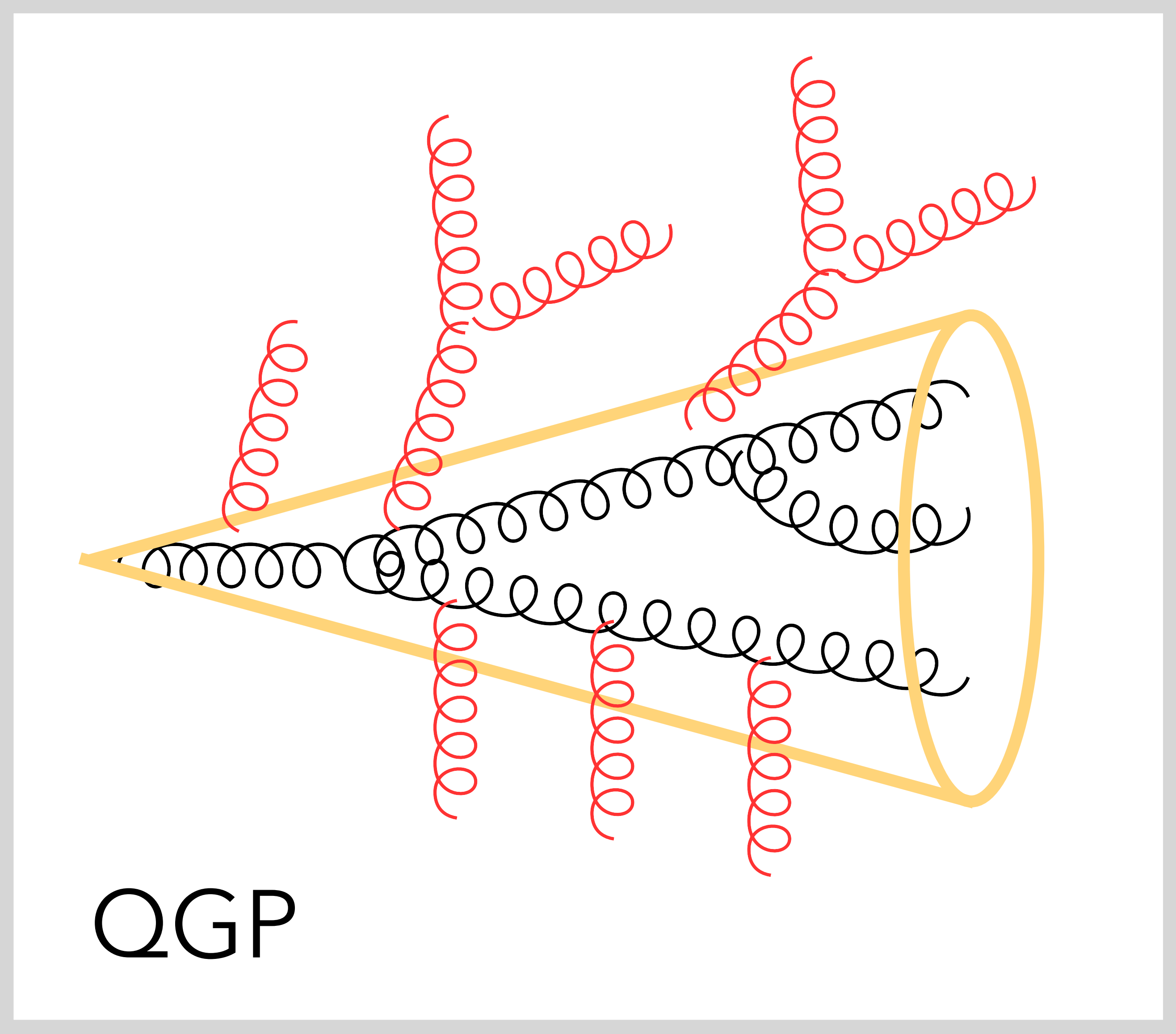
Resummations of perturbative series (multiple scattering and large logarithms): emergent phenomena

- Energy loss/thermalization via large angle turbulent medium-induced cascade
  [Baier, Mueller, Schiff, Son (2001) Jeon, Moore (2003) Blaizot, Dominguez, Iancu, MT (2014)]

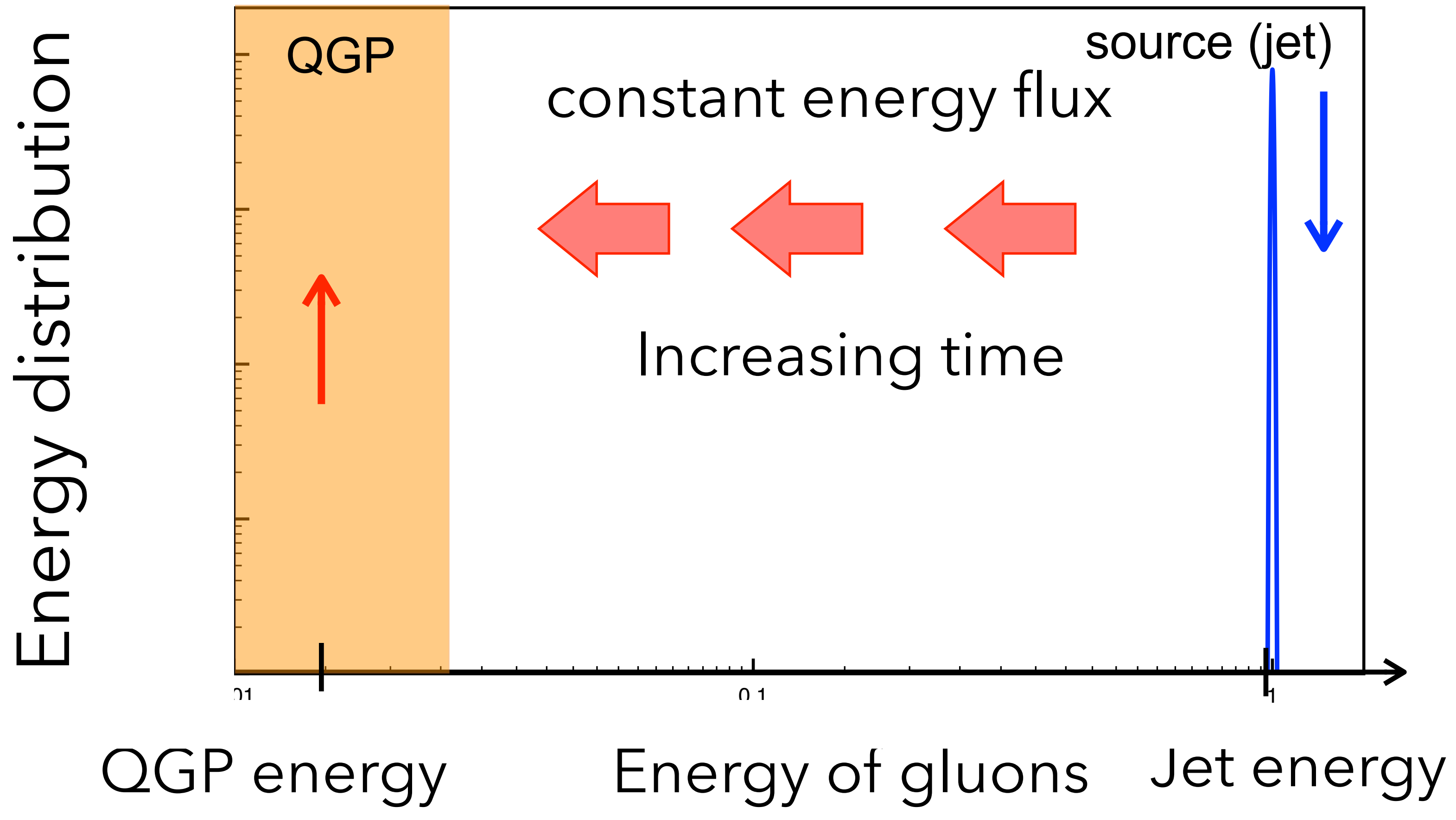
- Normal diffusion ⤳ anomalous (super)-diffusion
  [Liou, Mueller, Wu, Blaizot, MT, Iancu (2014) Caucal, MT (2021)]

- Color coherence ⤳ unresolved multi-partonic state lose energy as a single color charge
  [MT, Salgado, Tywoniuk, Casalderrey-Solana, Iancu (2011-2013)]

- Open quantum system formulation (see J- P- Blaizot's talk)



MT, Schilchting, Soudi (2022)



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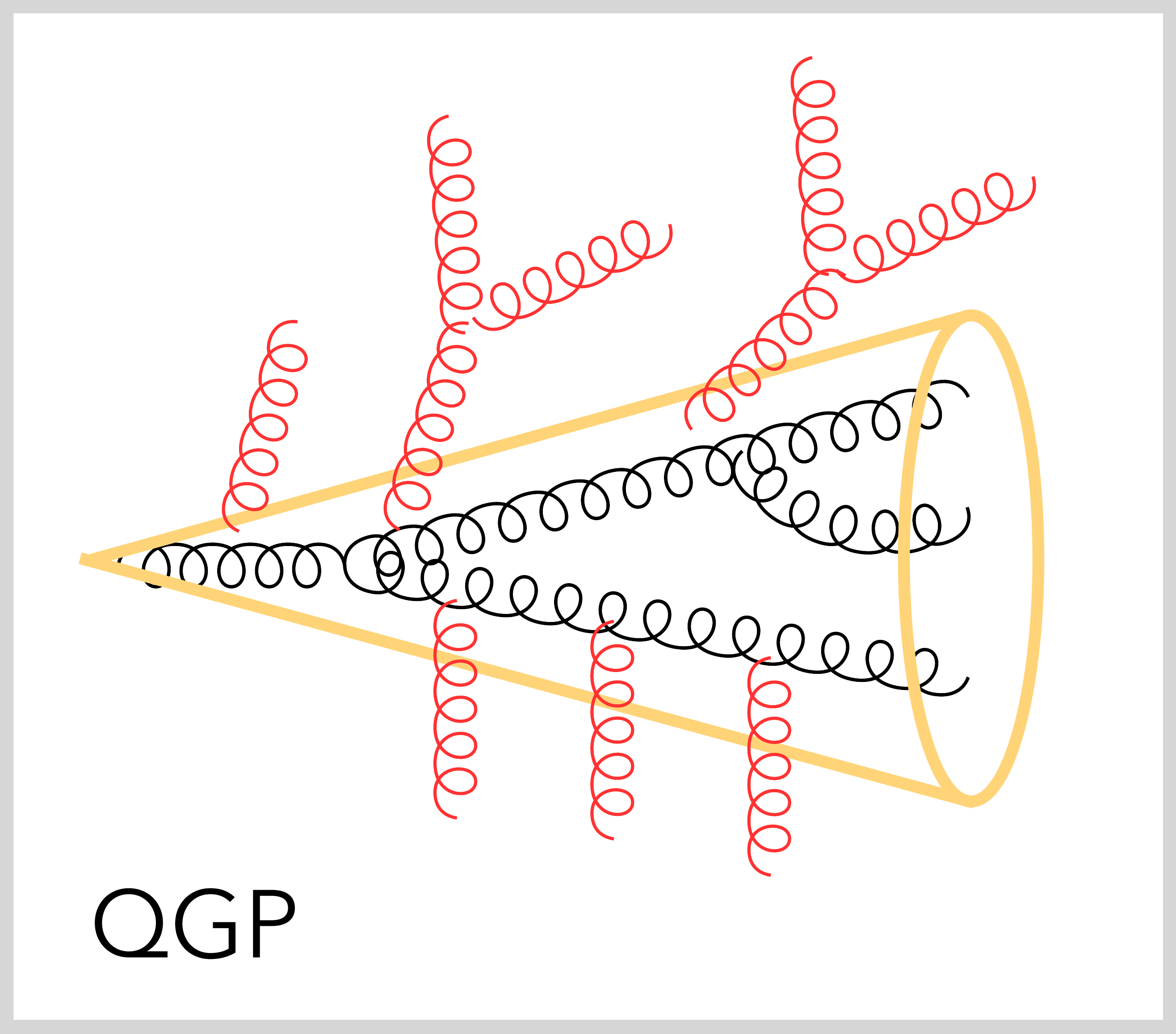

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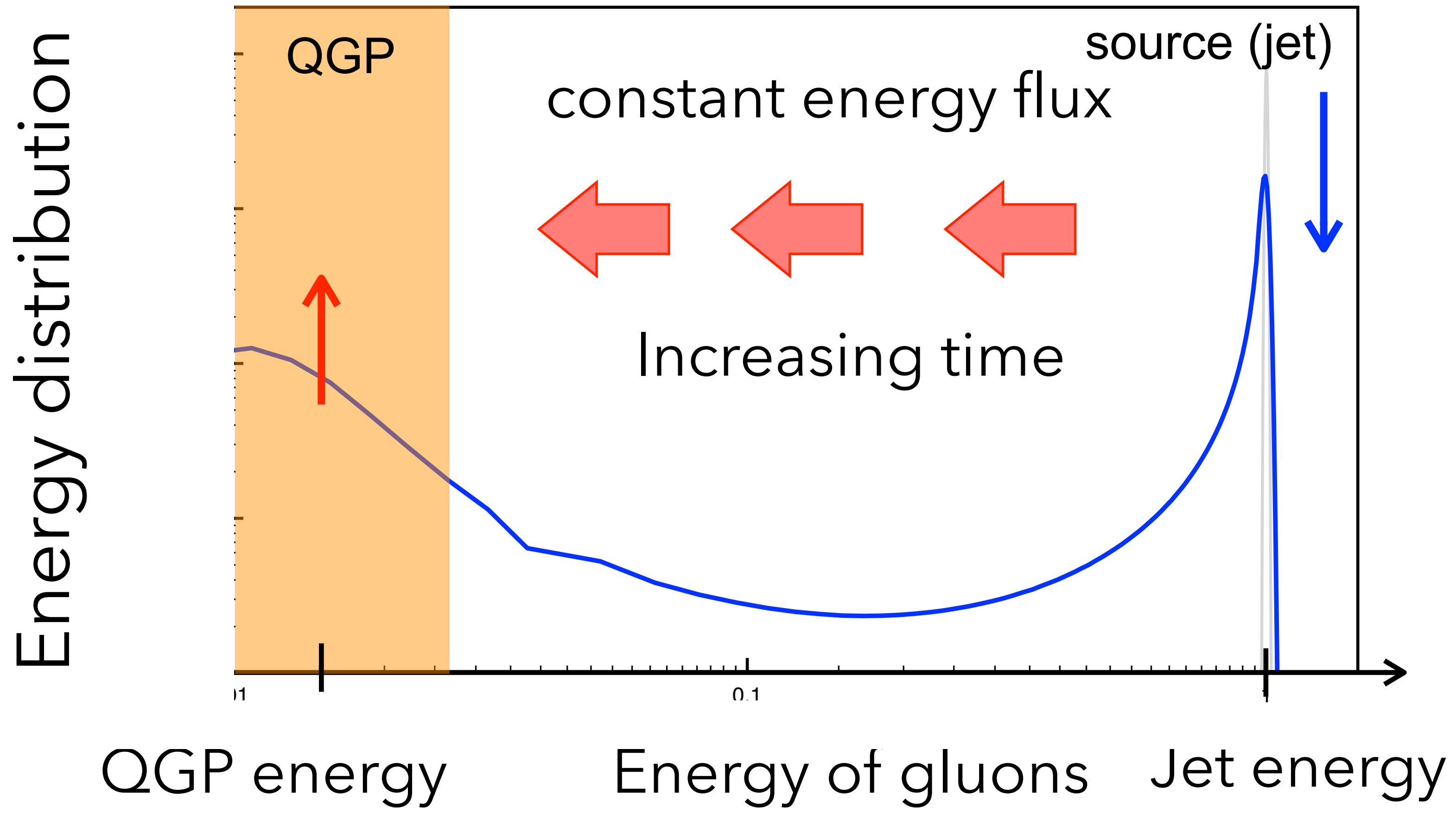

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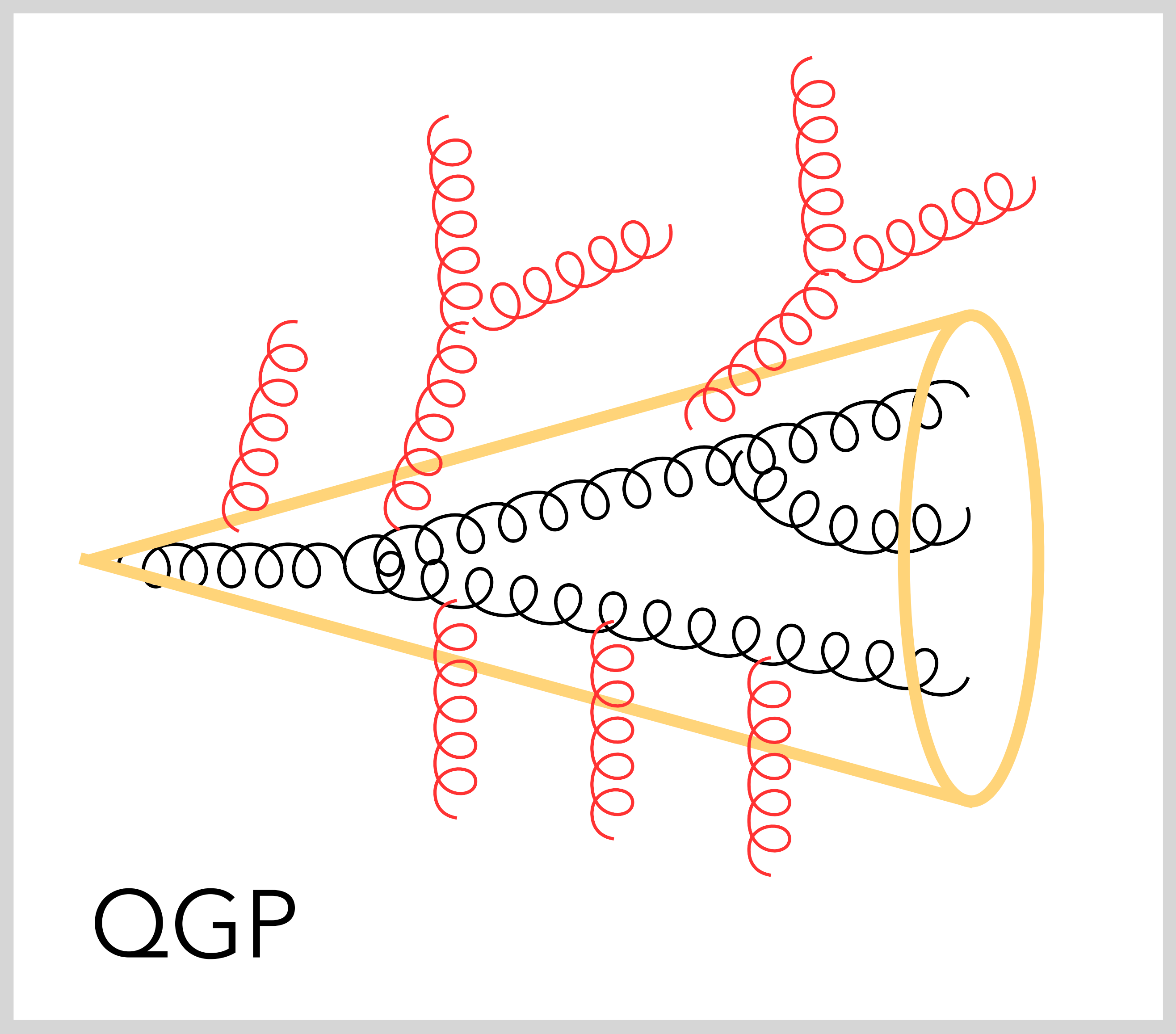

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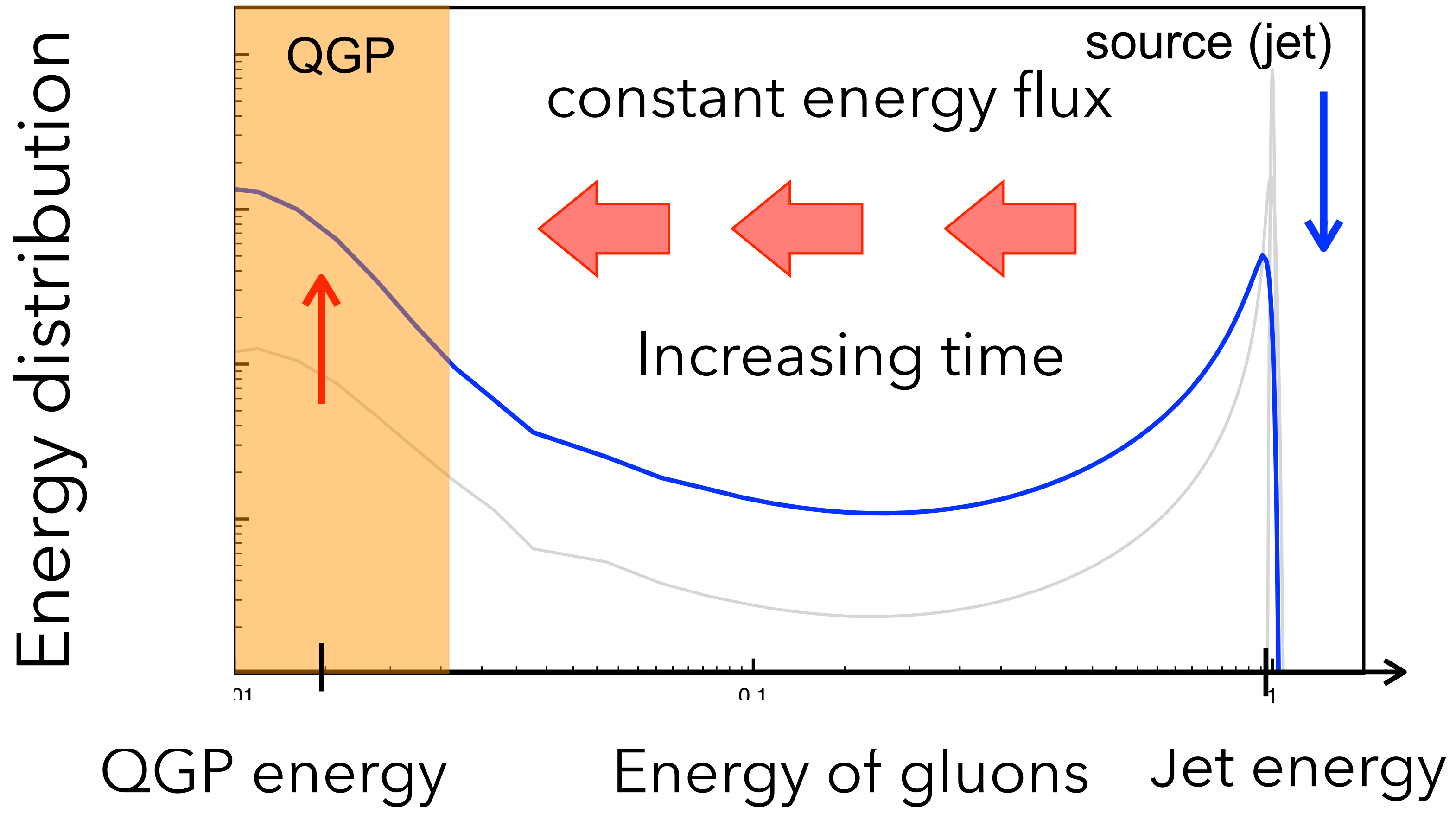

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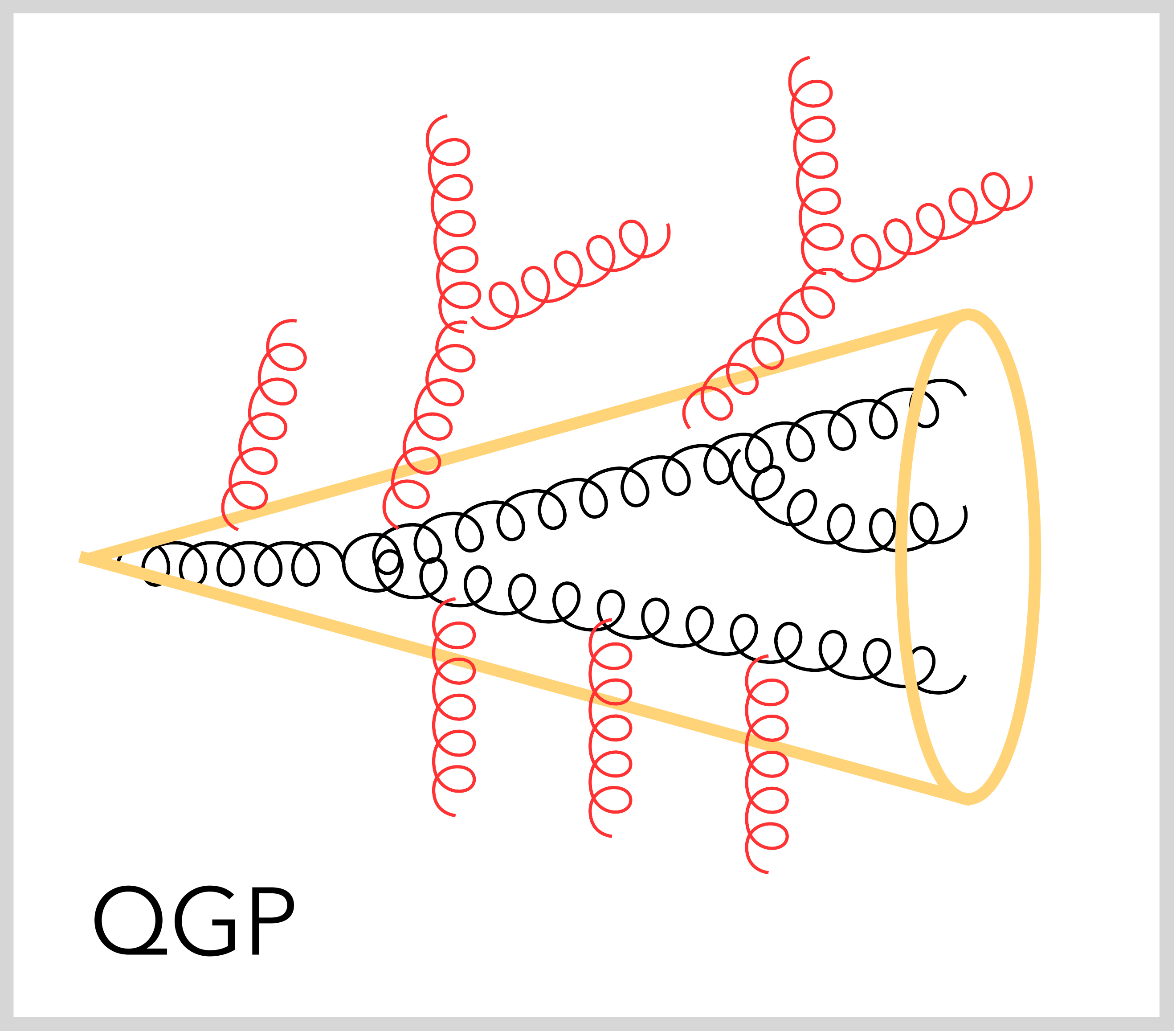

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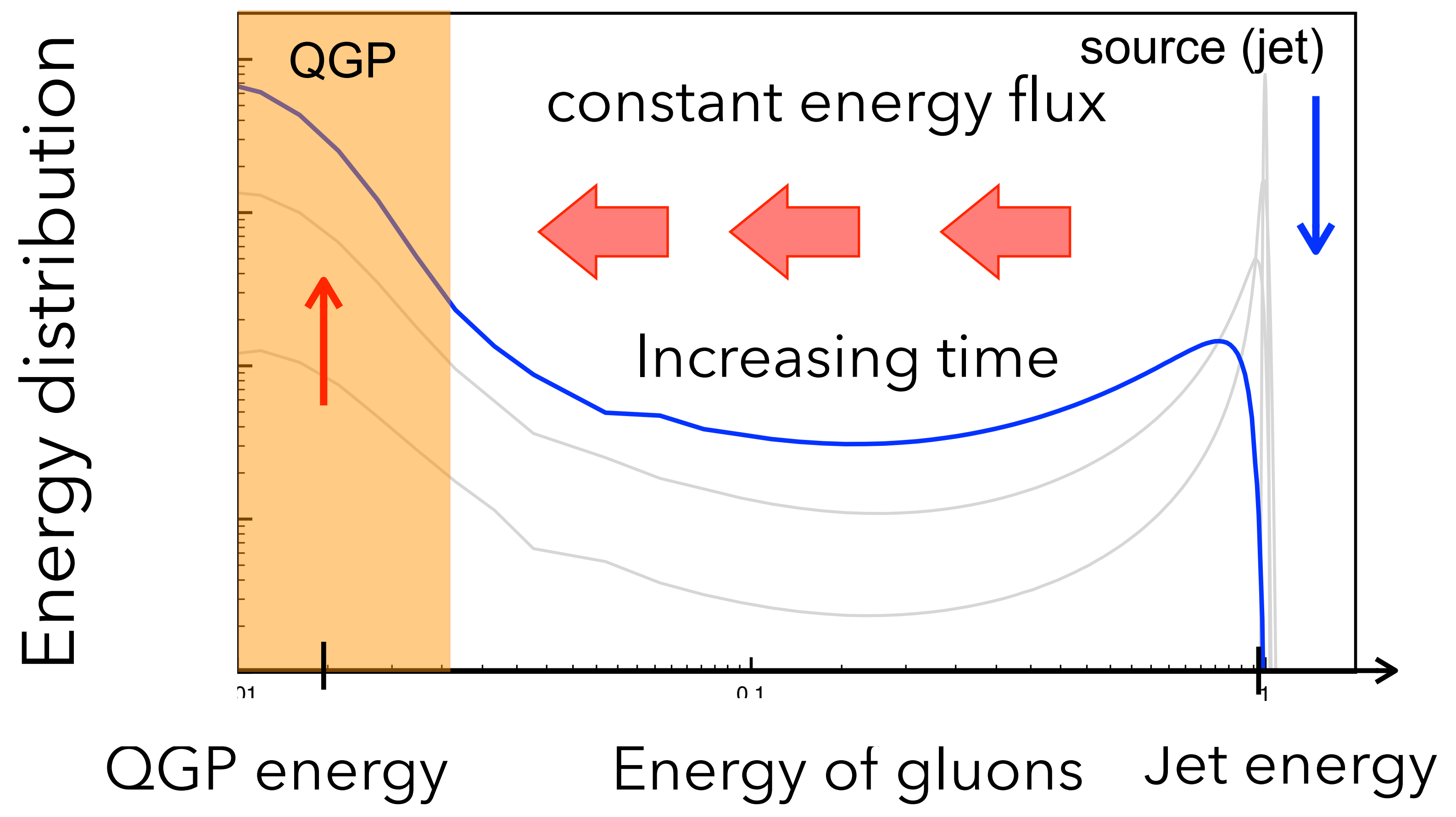

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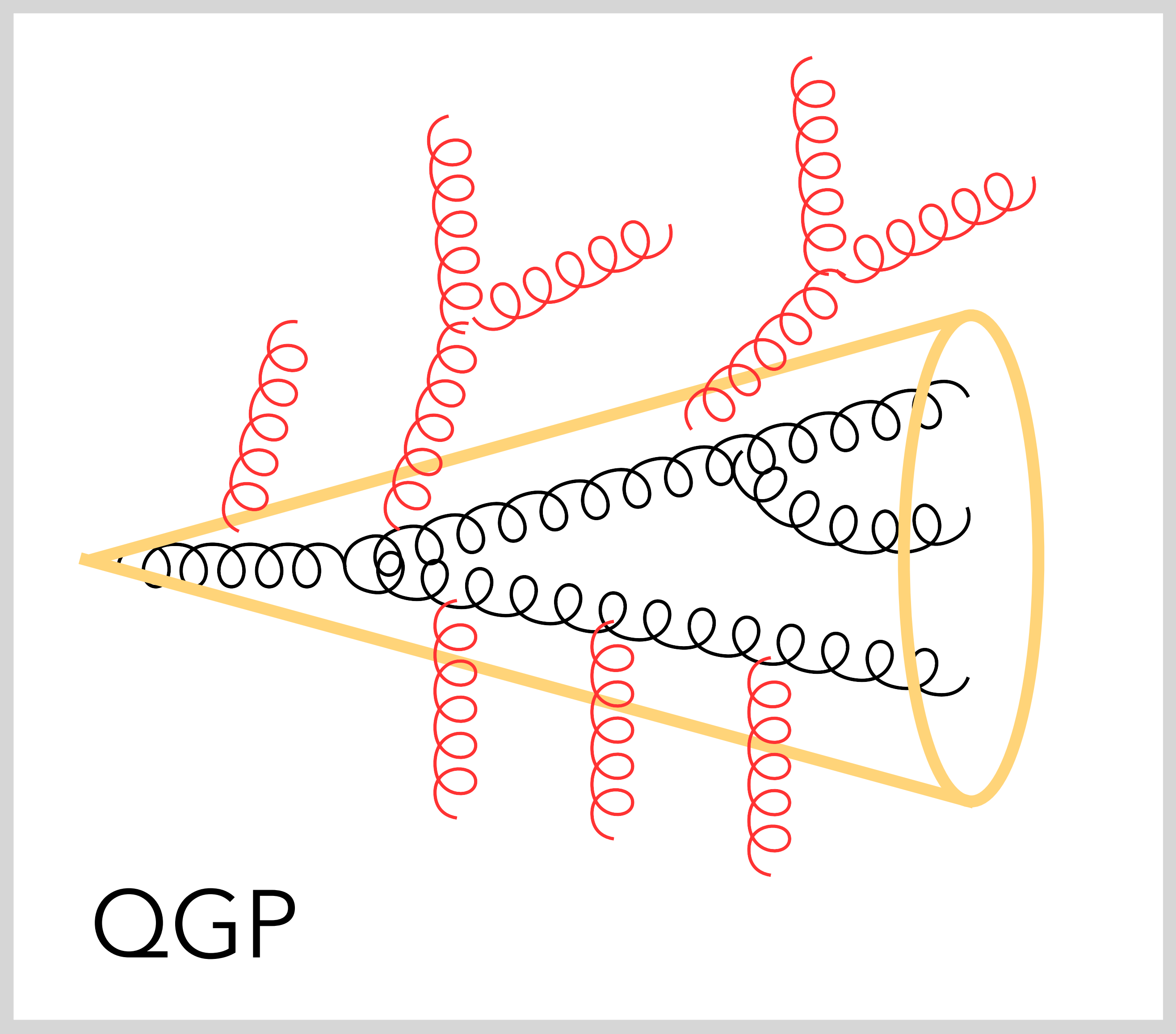

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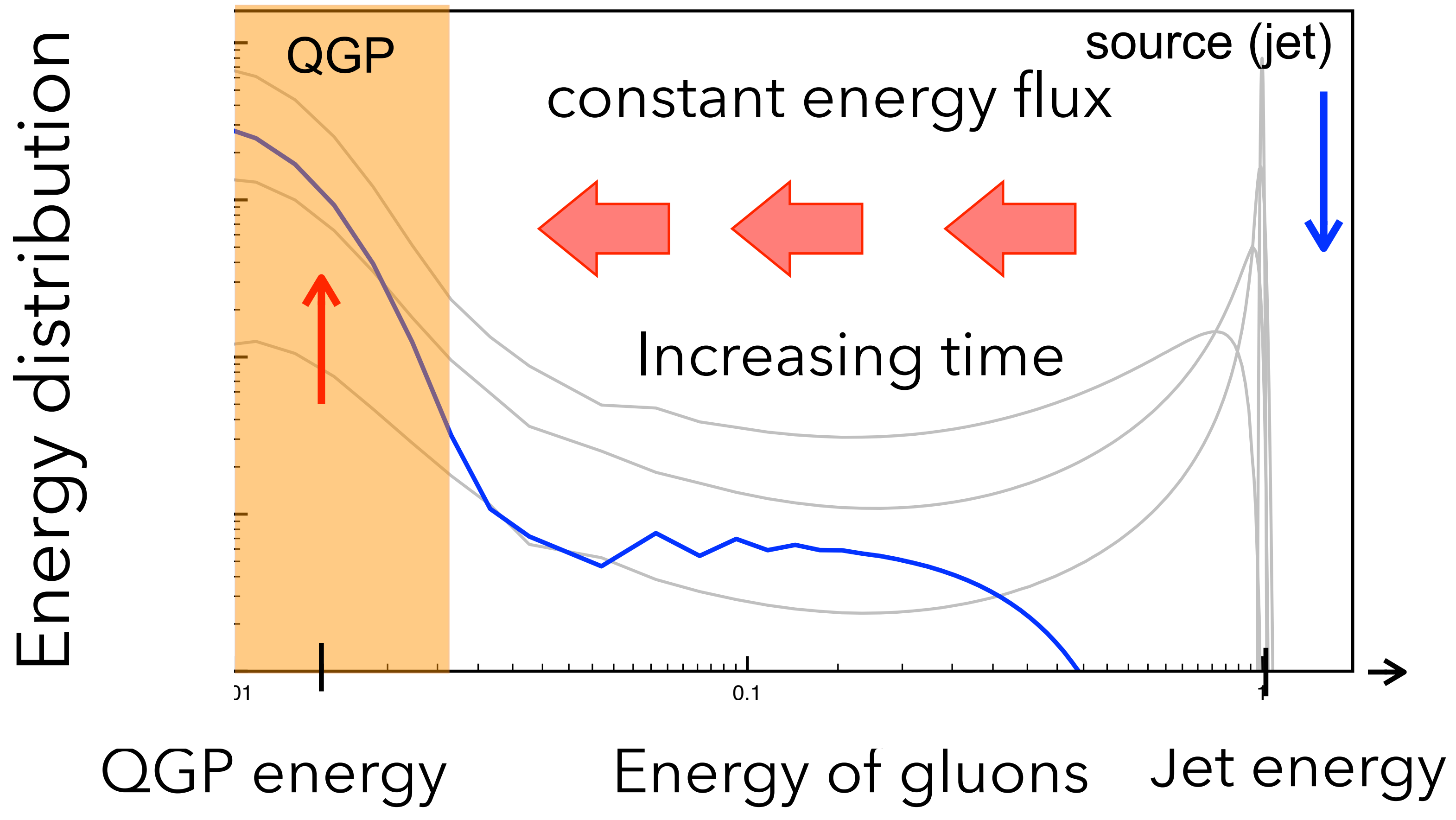
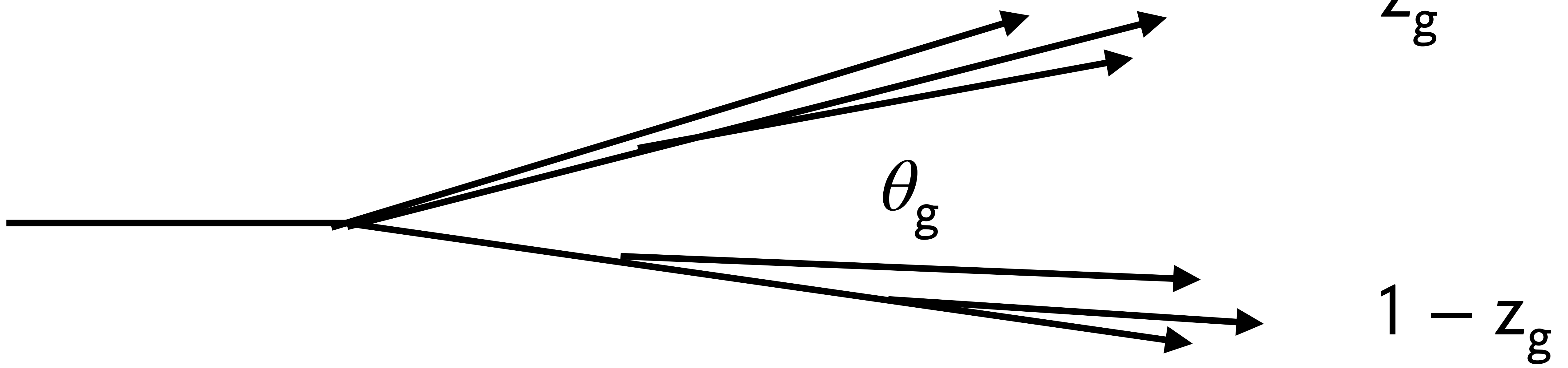


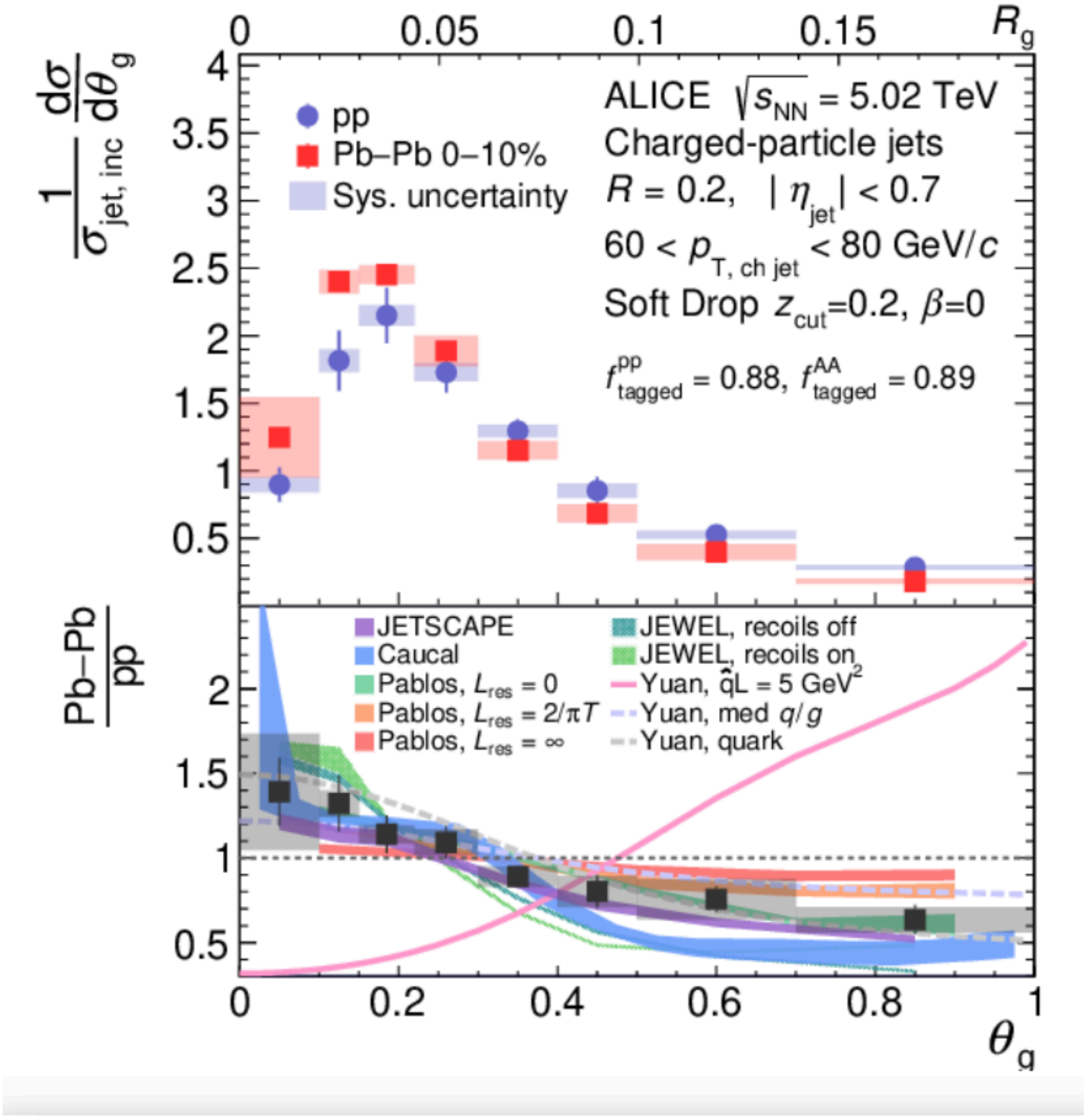
Phenomenology:
where do we stand?

- Thrust 1: All 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) (see Carlota Andres' talk)





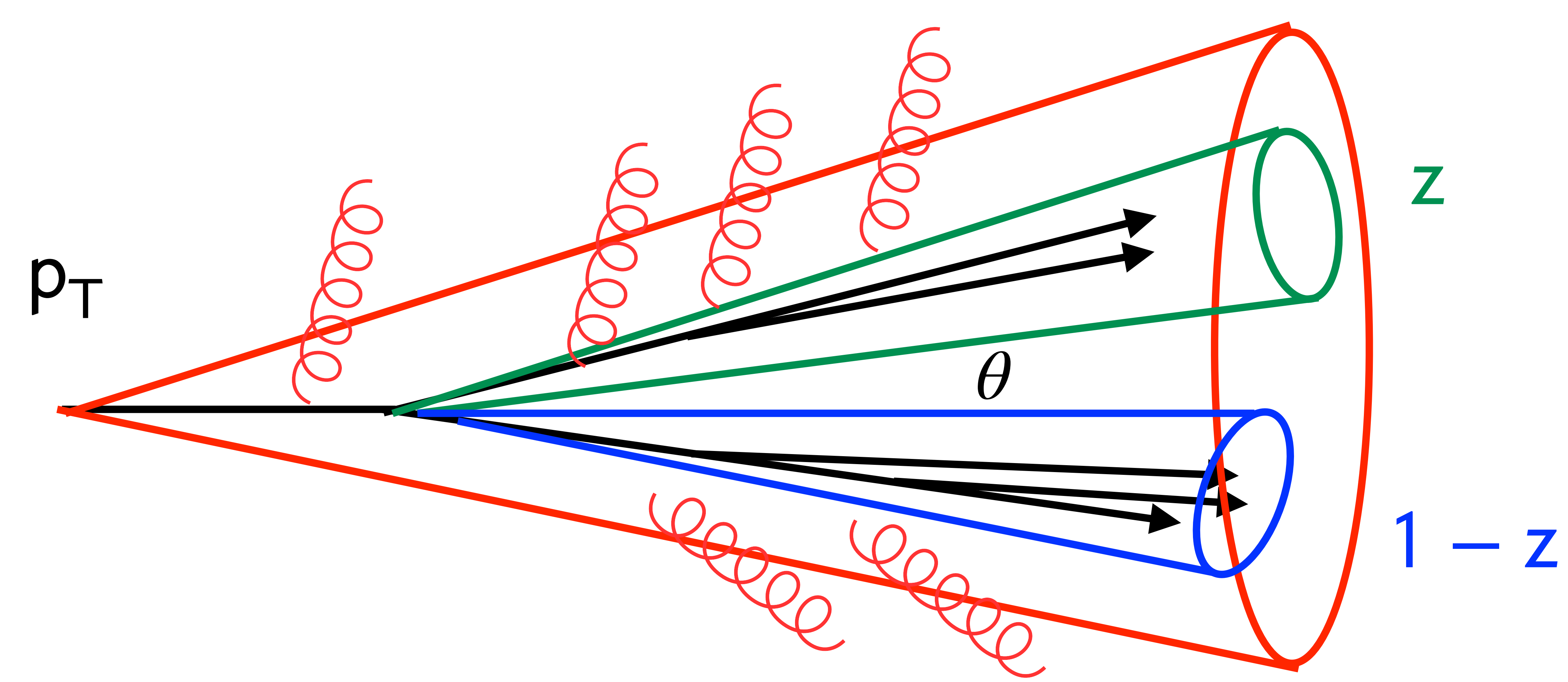
ALICE Collaboration (2021)

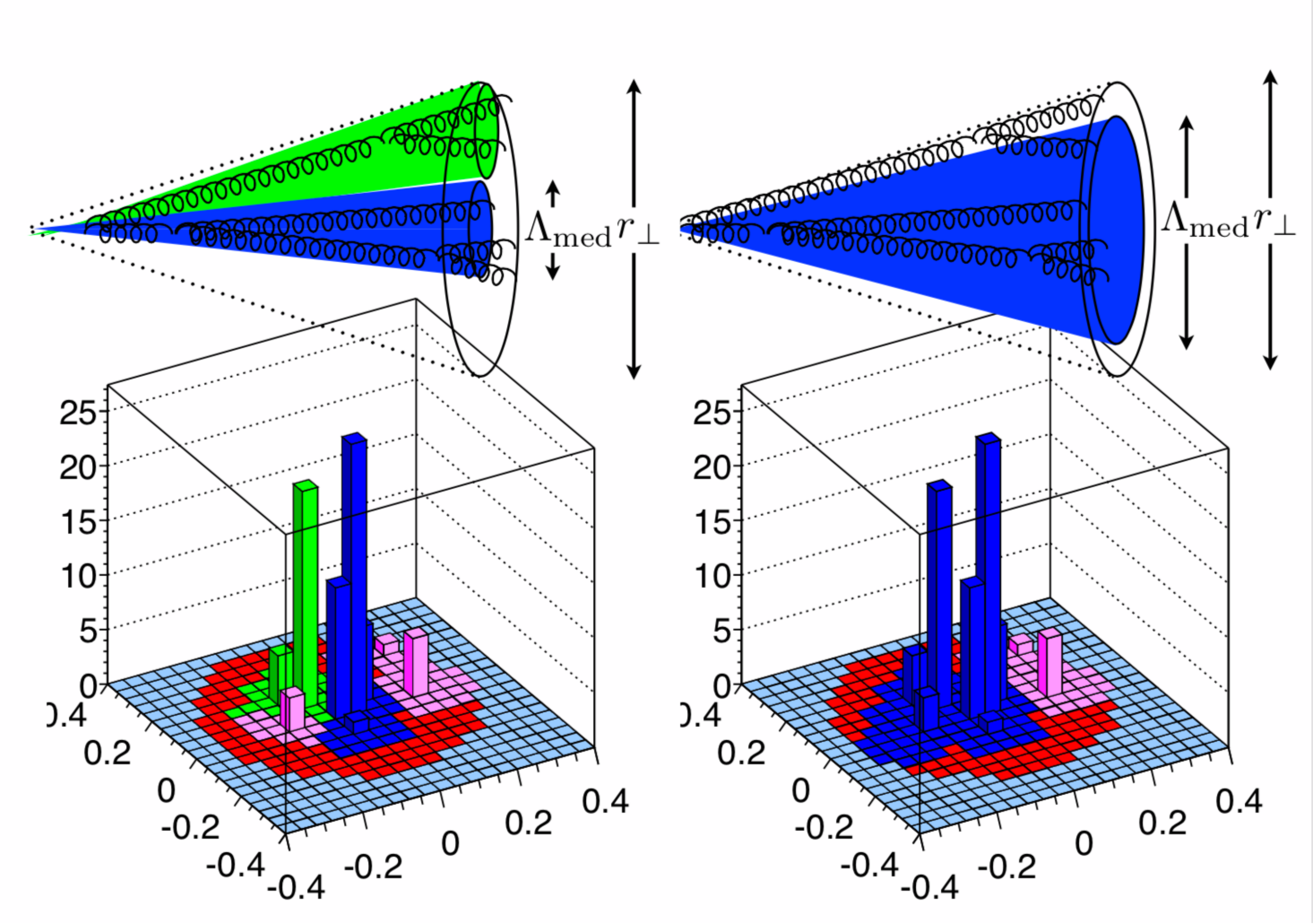
Inclusive jet spectra

A substructure observable in disguise

Non-linear evolution of jet quenching

- Energy loss of a muti-parton system is sensitive to coherence effects: resolution angle $\theta_c = (\hat{q}L^3)^{1/2}$
- Quenching factor: $Q \sim R_{AA} < 1$





Two effective color charges

One effective color charge

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

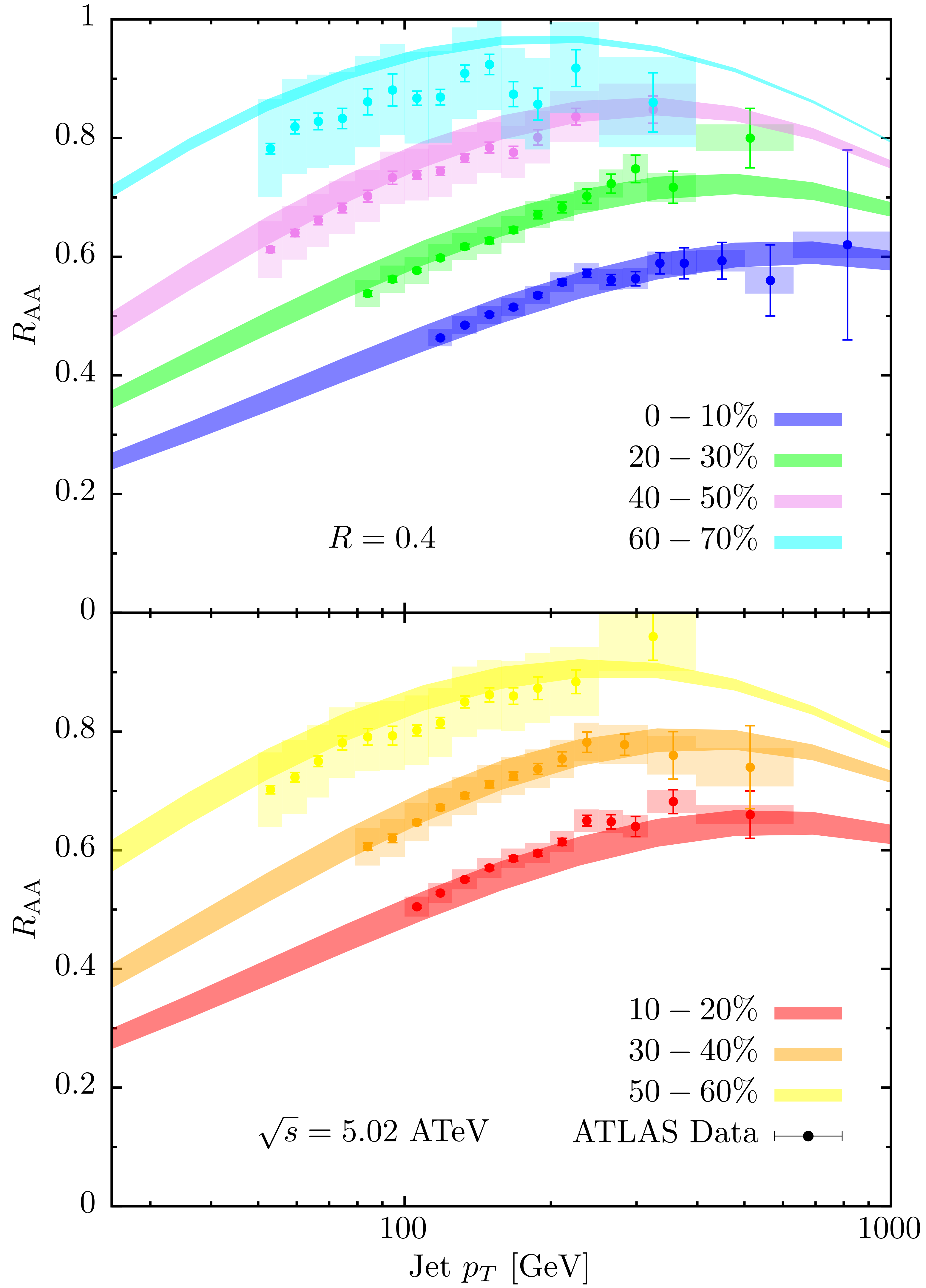
MT, Tywoniuk (2017)

Jet nuclear modification factor

- Theory calculation includes: multiple gluon radiation, color coherence, collinear shower, collision geometry
- Free parameter: medium coupling constant $g_{\rm med} \sim 2.2 - 2.3$
- Theory uncertainties dominated by parton shower at leading log accuracy, up to $\sim 20\,\%$

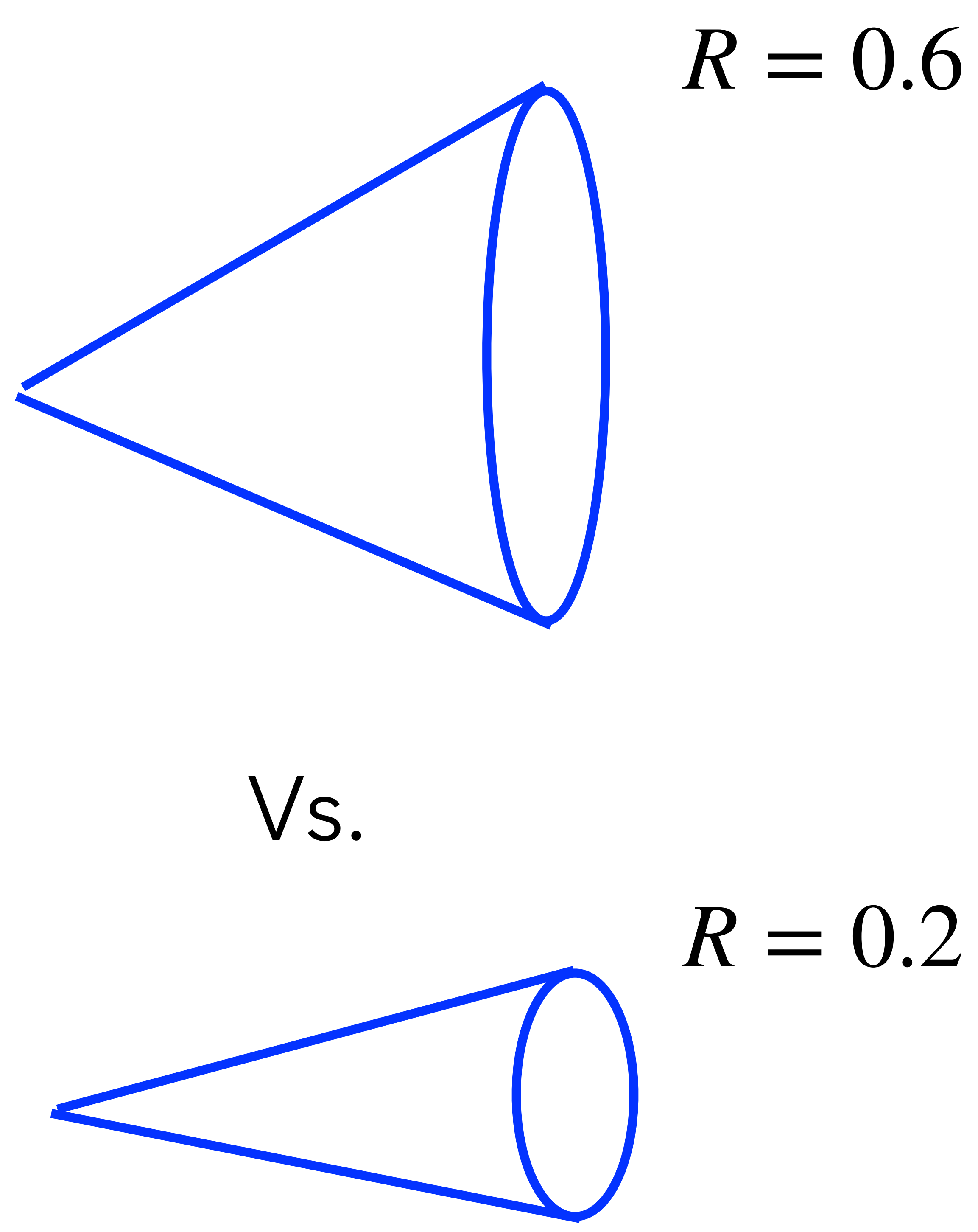
→ Good agreement with ATLAS data as function of pT and centrality

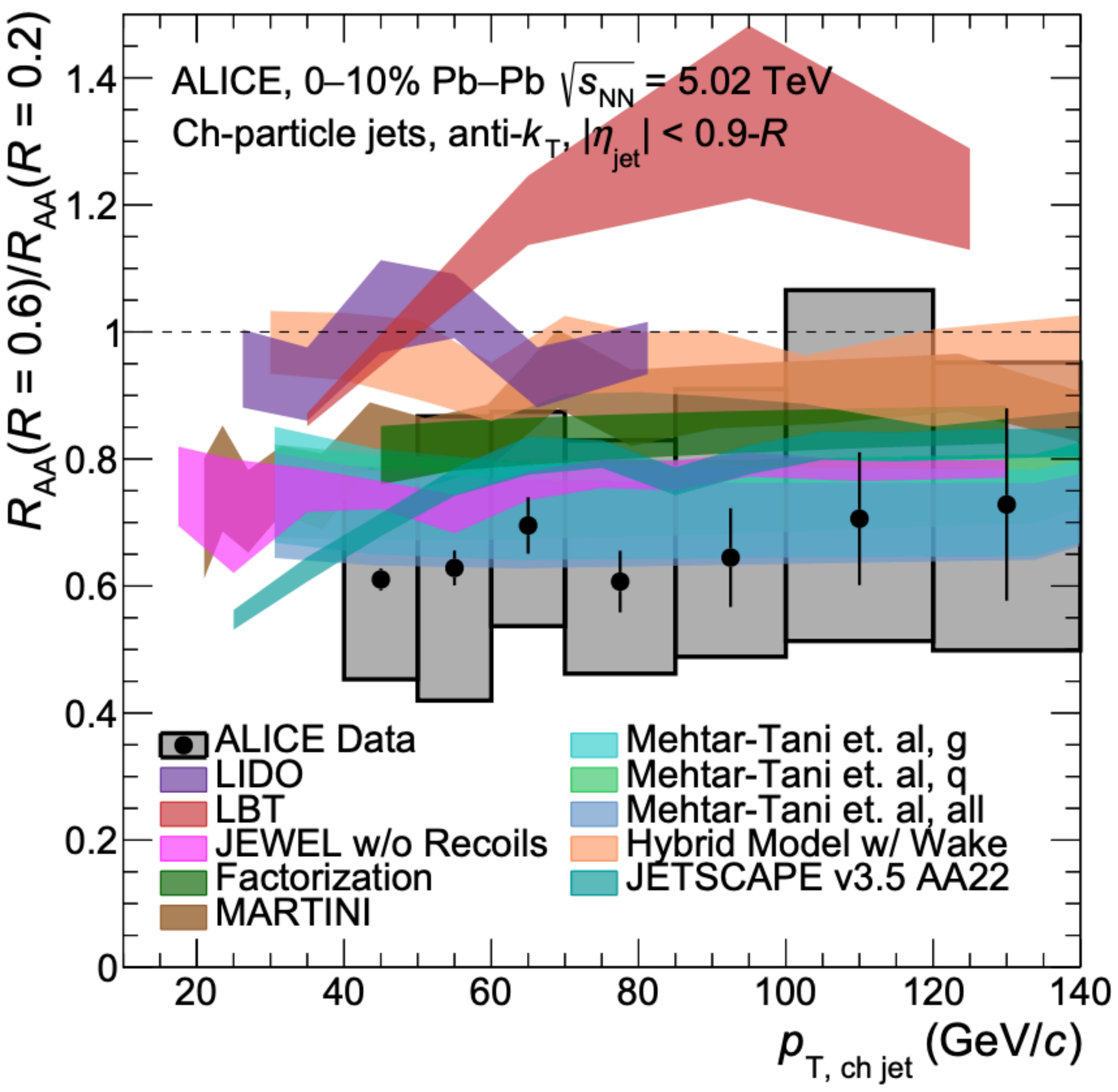
MT, Pablos, Tywoniuk (2021)



Predictions for R dependence

- R dependence encodes color coherence effects





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

Conclusion

- Jets constitue unique tools to advance our understanding of QCD dynamics at high density
- Despite the complexity of the topic a lot of progress has been achieved on the theory front: LPM effect, turbulent thermalization, anomalous diffusion, color decoherence, medium response, …
- Probing these emergent phenomena in experiment proves to be challenging but tailored observables are being developed
- Outlook: higher order analytic computations and state-of-the-art MC implementation theory → towards high precision phenomenology