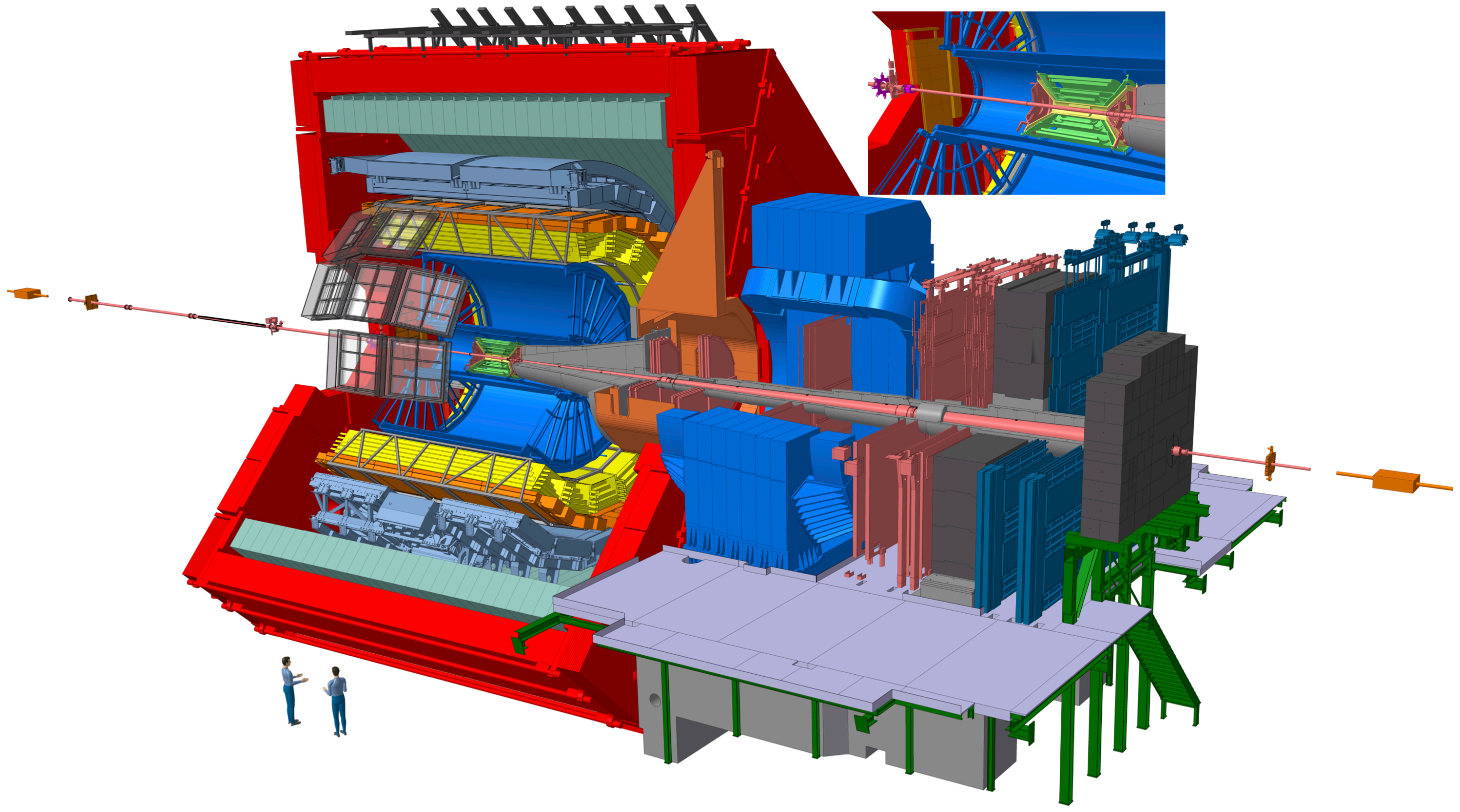
Recent results on jets from ALICE

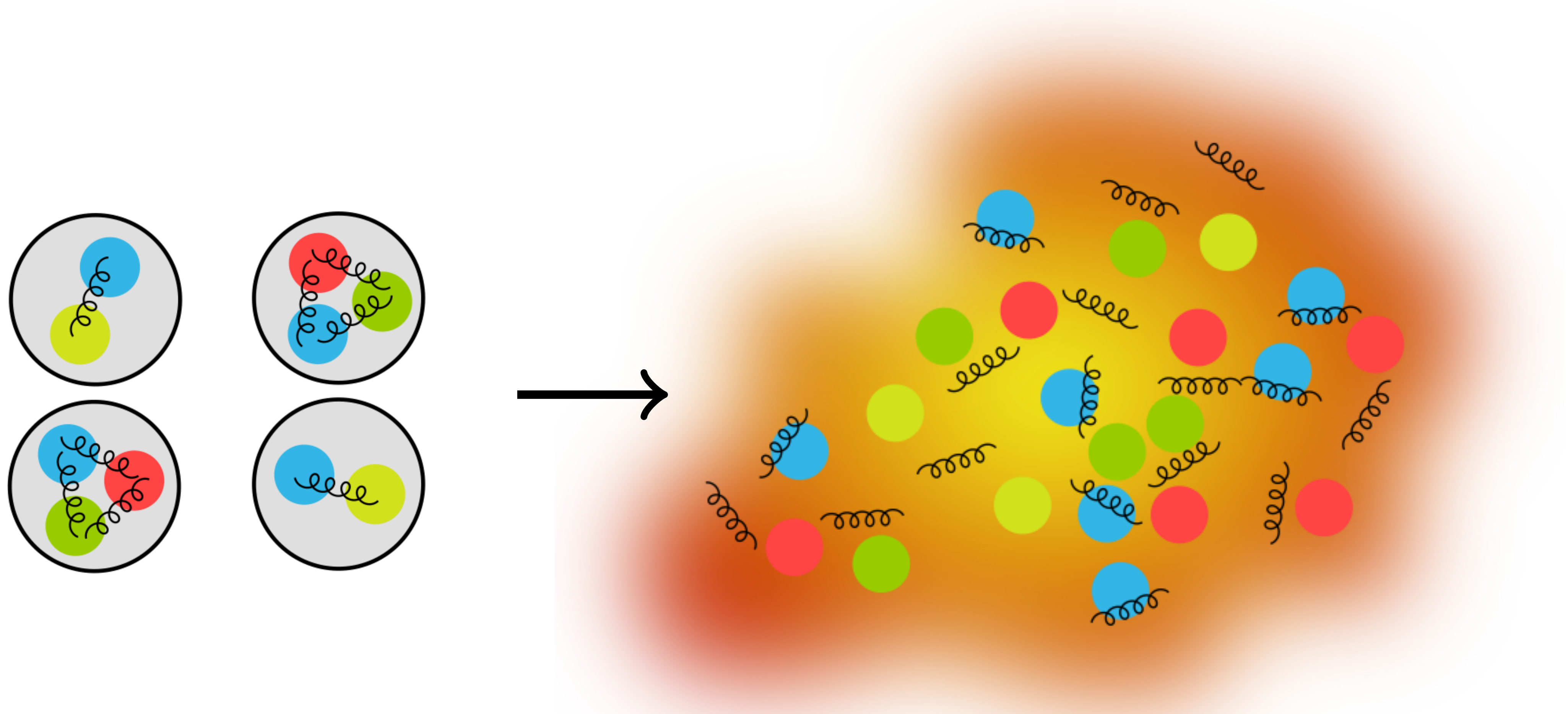
James Mulligan
Lawrence Berkeley National Lab



NSD staff meeting
Sep 8 2020

The quark-gluon plasma

What happens when we heat matter to extremely high temperature?



Weiyao Ke, NSD Staff Meeting, Aug 11 2020

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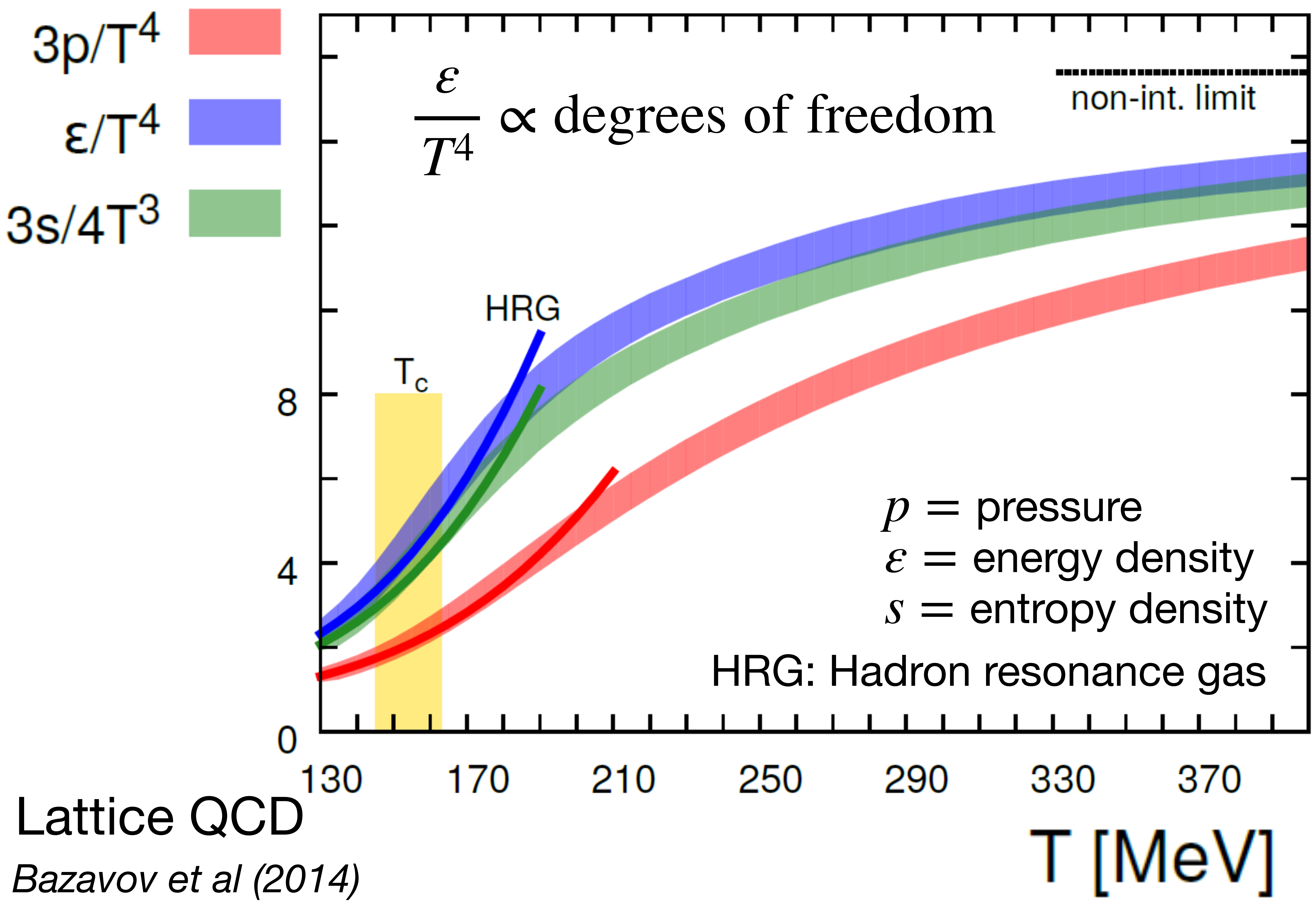
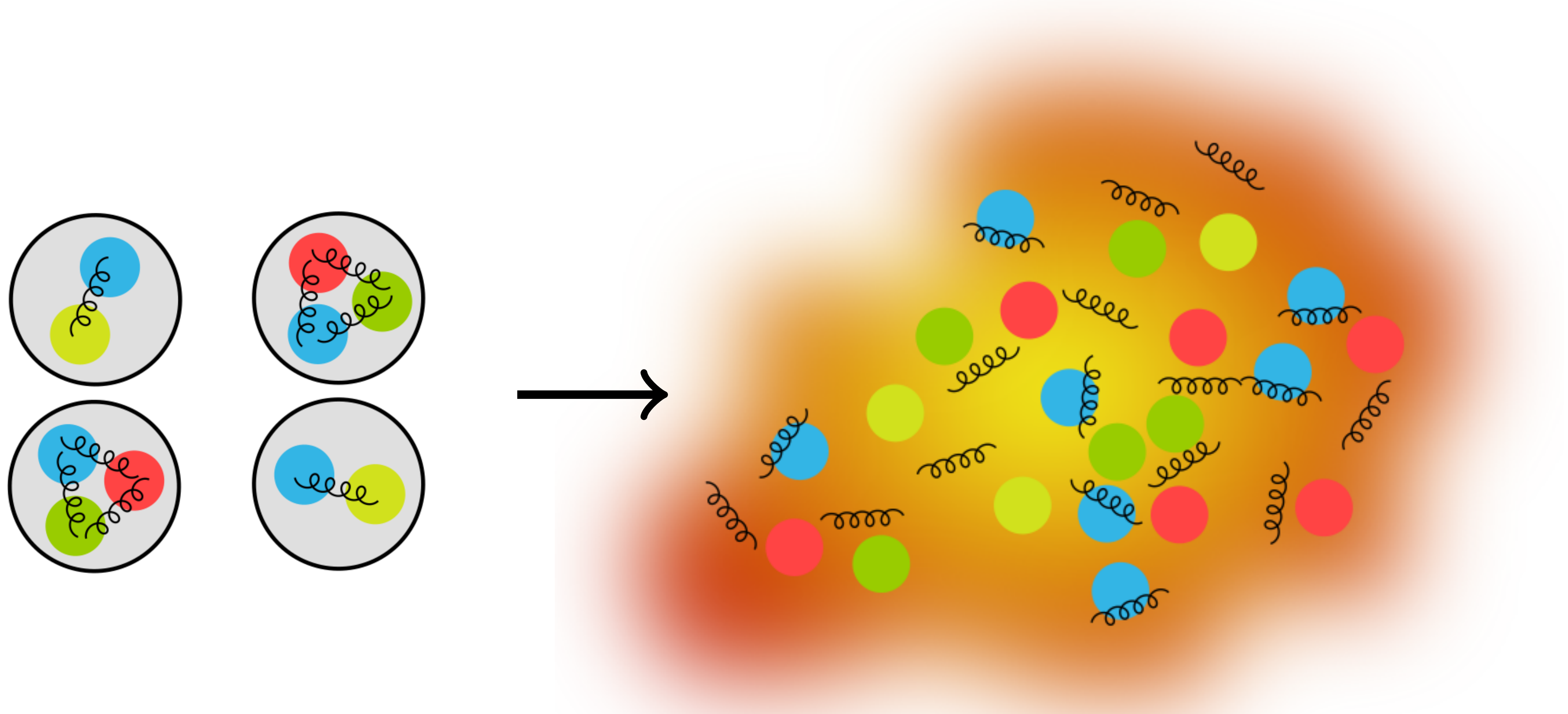


Lattice QCD

Bazavov et al (2014)



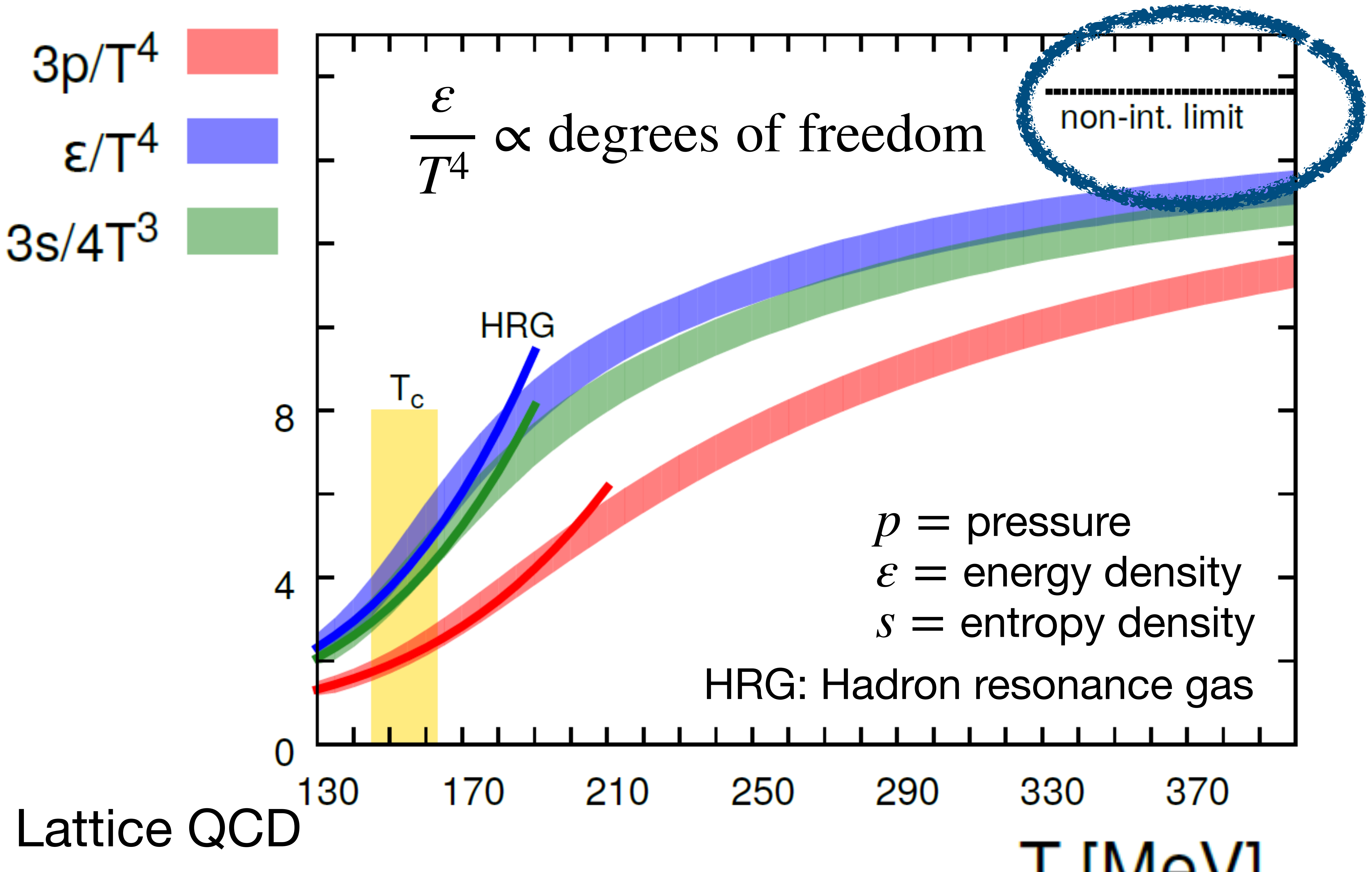
Weiyao Ke, NSD Staff Meeting, Aug 11 2020

If we heat nuclear matter to $T = \mathcal{O}(100\ \text{MeV})$, thermodynamic quantities exhibit a rapid rise in degrees of freedom near a crossover temperature T_c

Deconfinement of quarks and gluons

The quark-gluon plasma

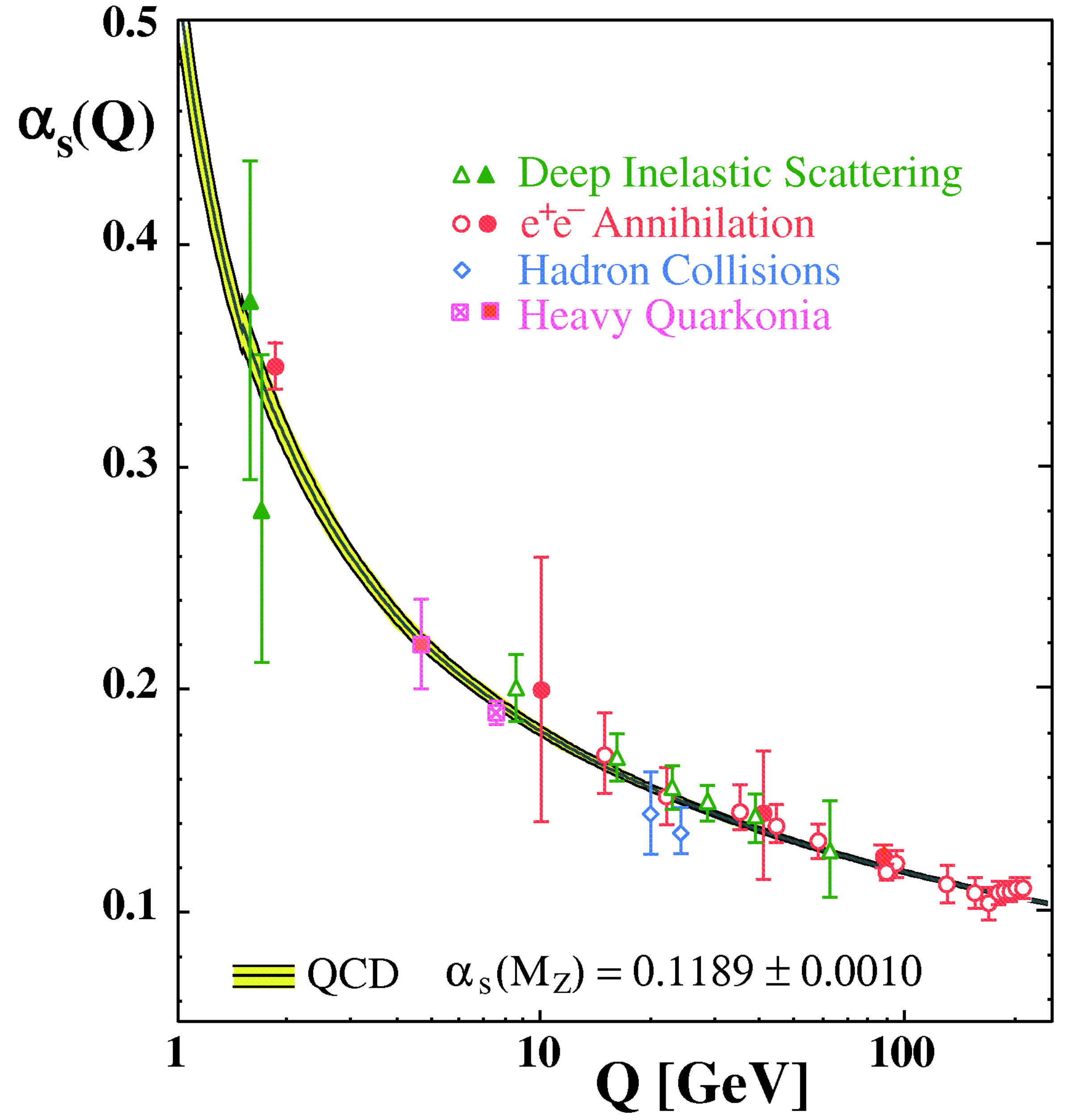
What happens when we heat matter to extremely high temperature?



Lattice QCD

Bazavov et al (2014)

For very large T, we expect this deconfined matter to be **asymptotically free**



The quark-gluon plasma

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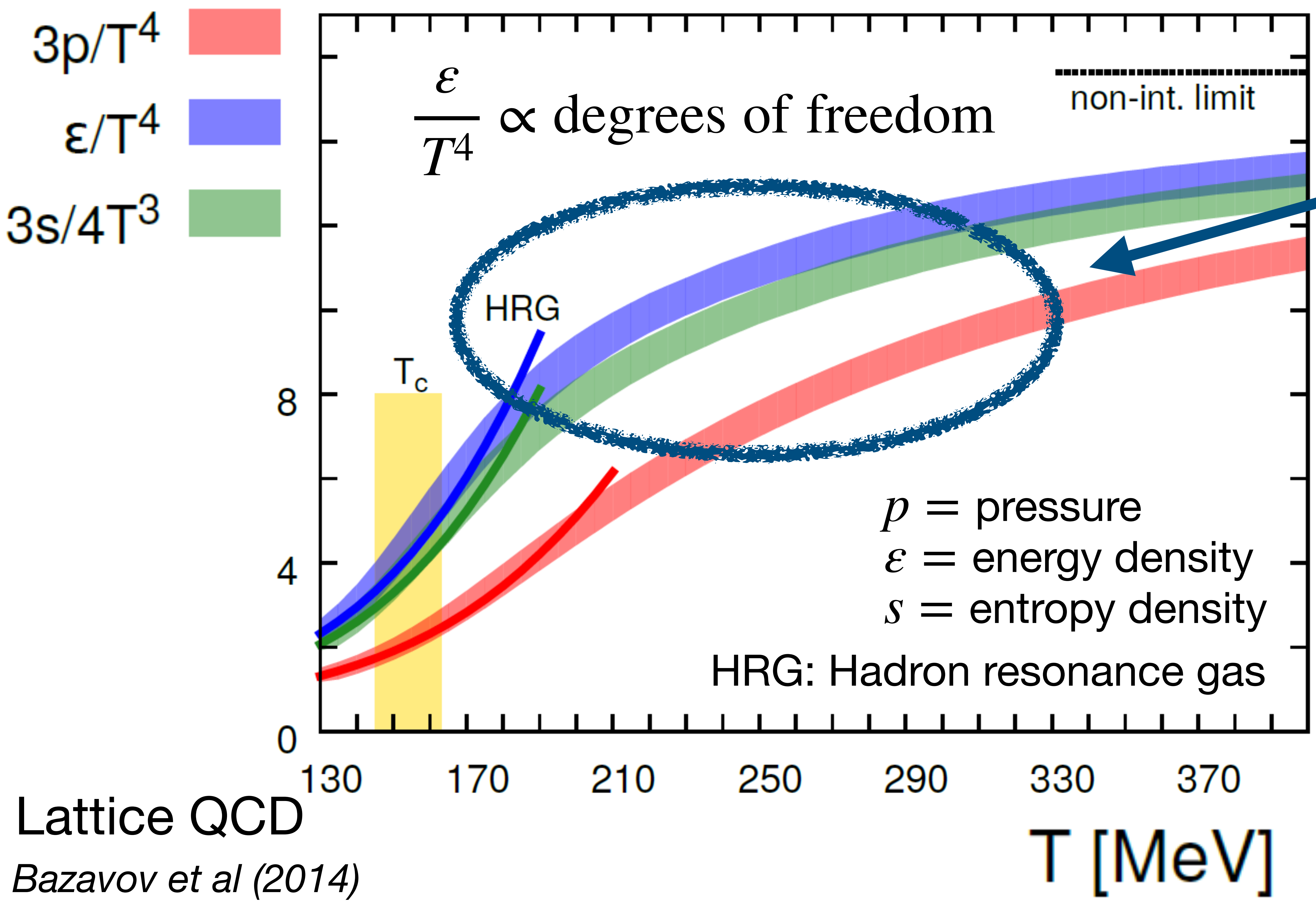
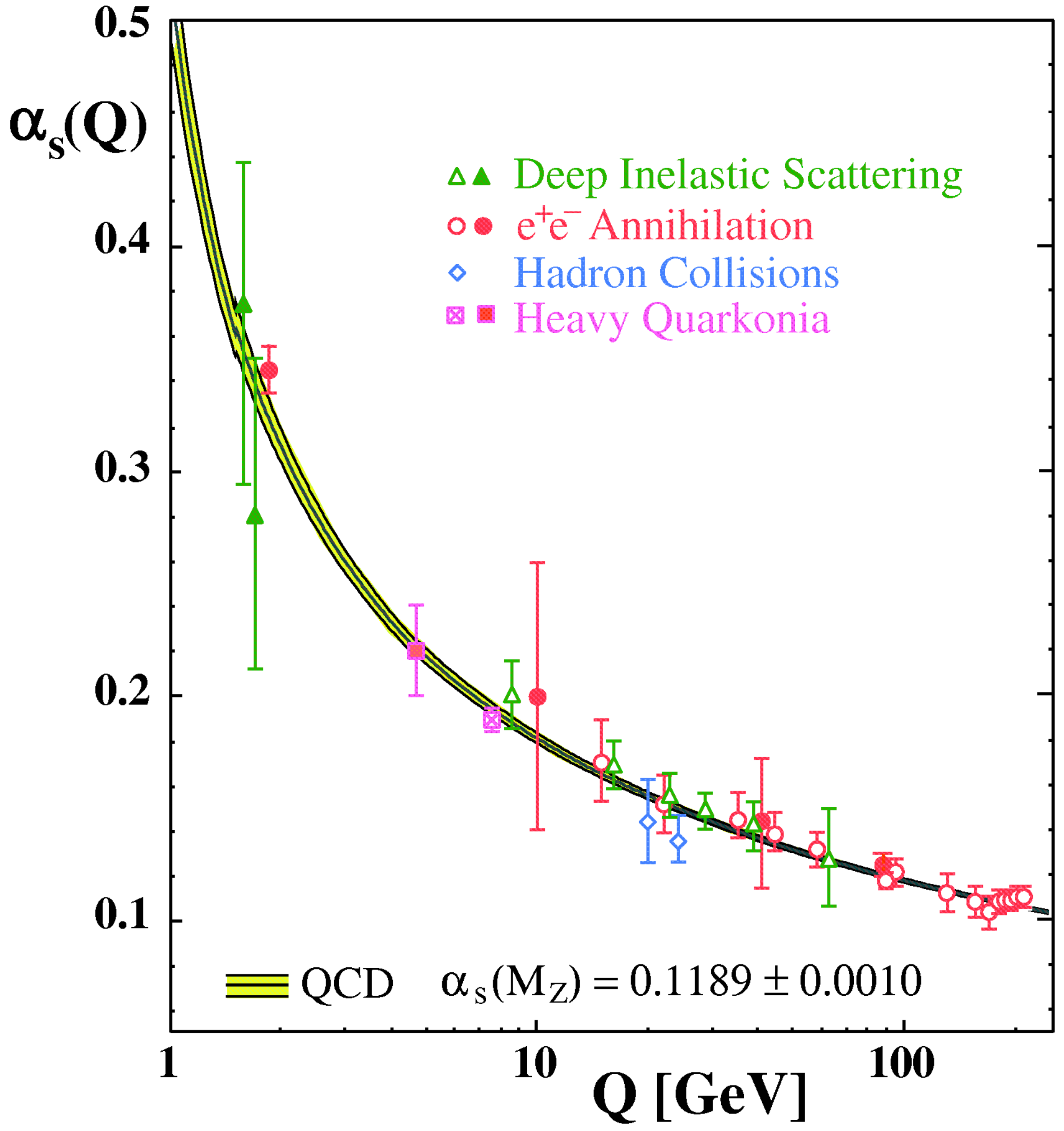


Lattice QCD

Bazavov et al (2014)

What is the coupling here?

It turns out to still be quite strong



The quark-gluon plasma

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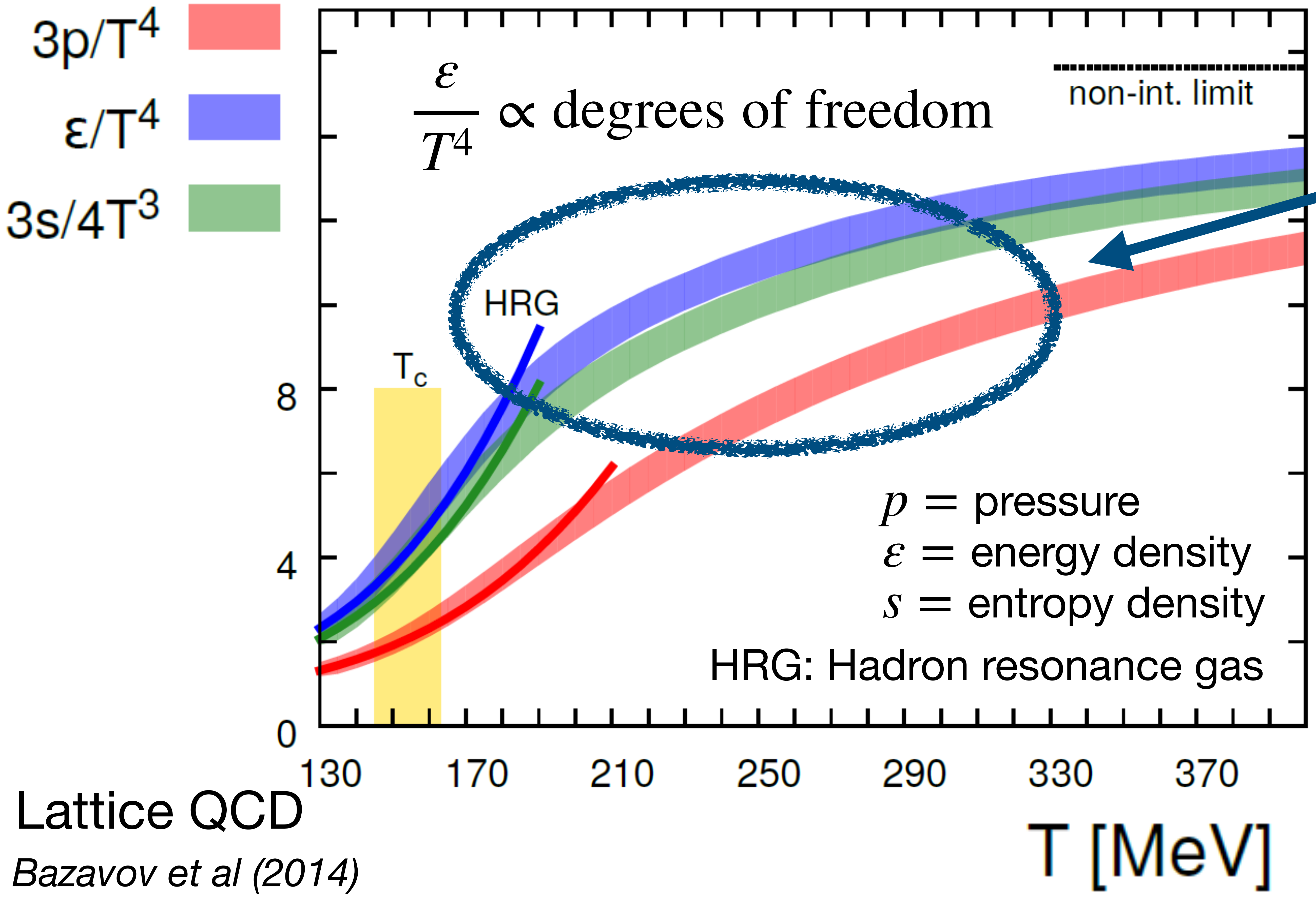
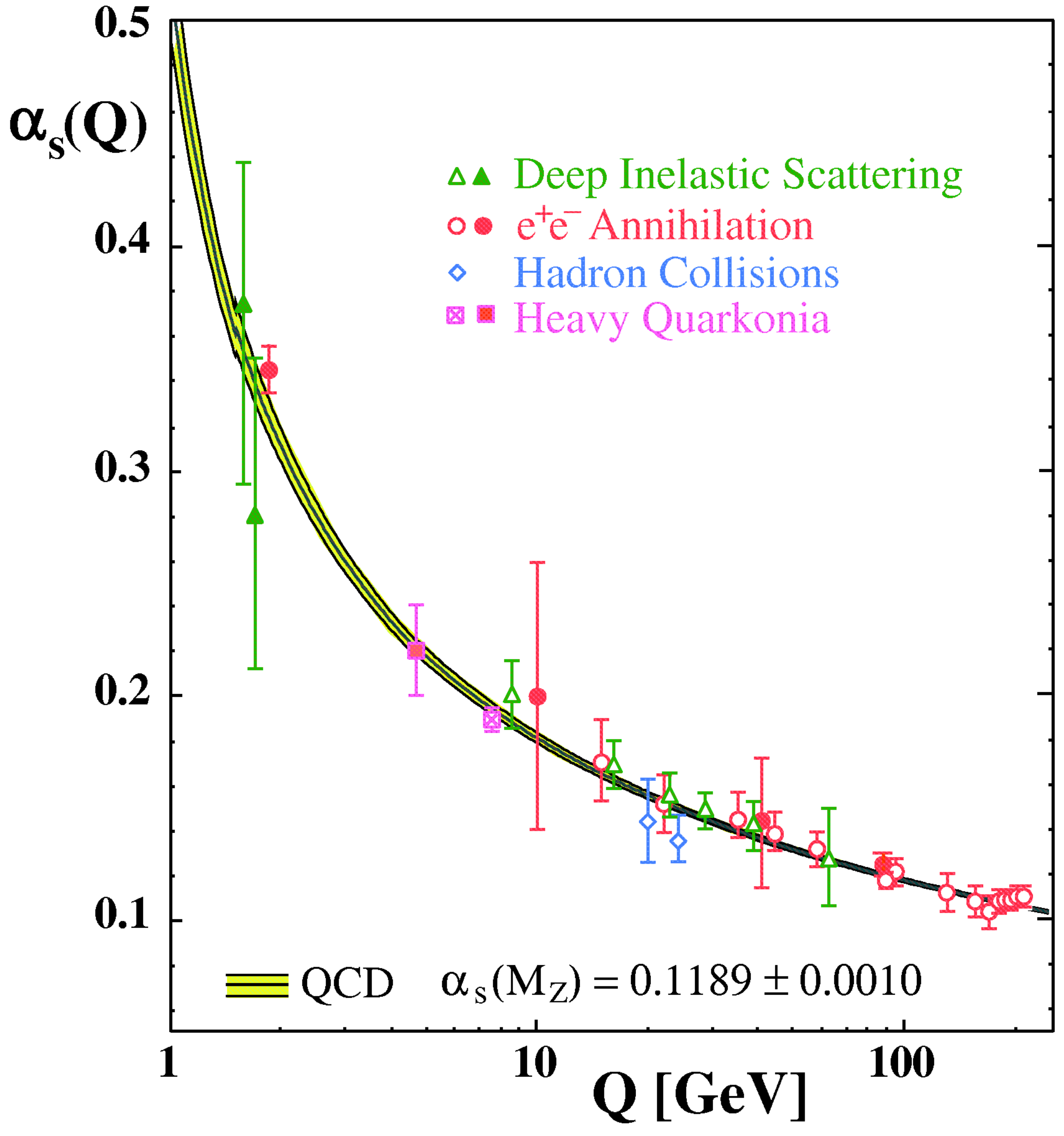


Lattice QCD

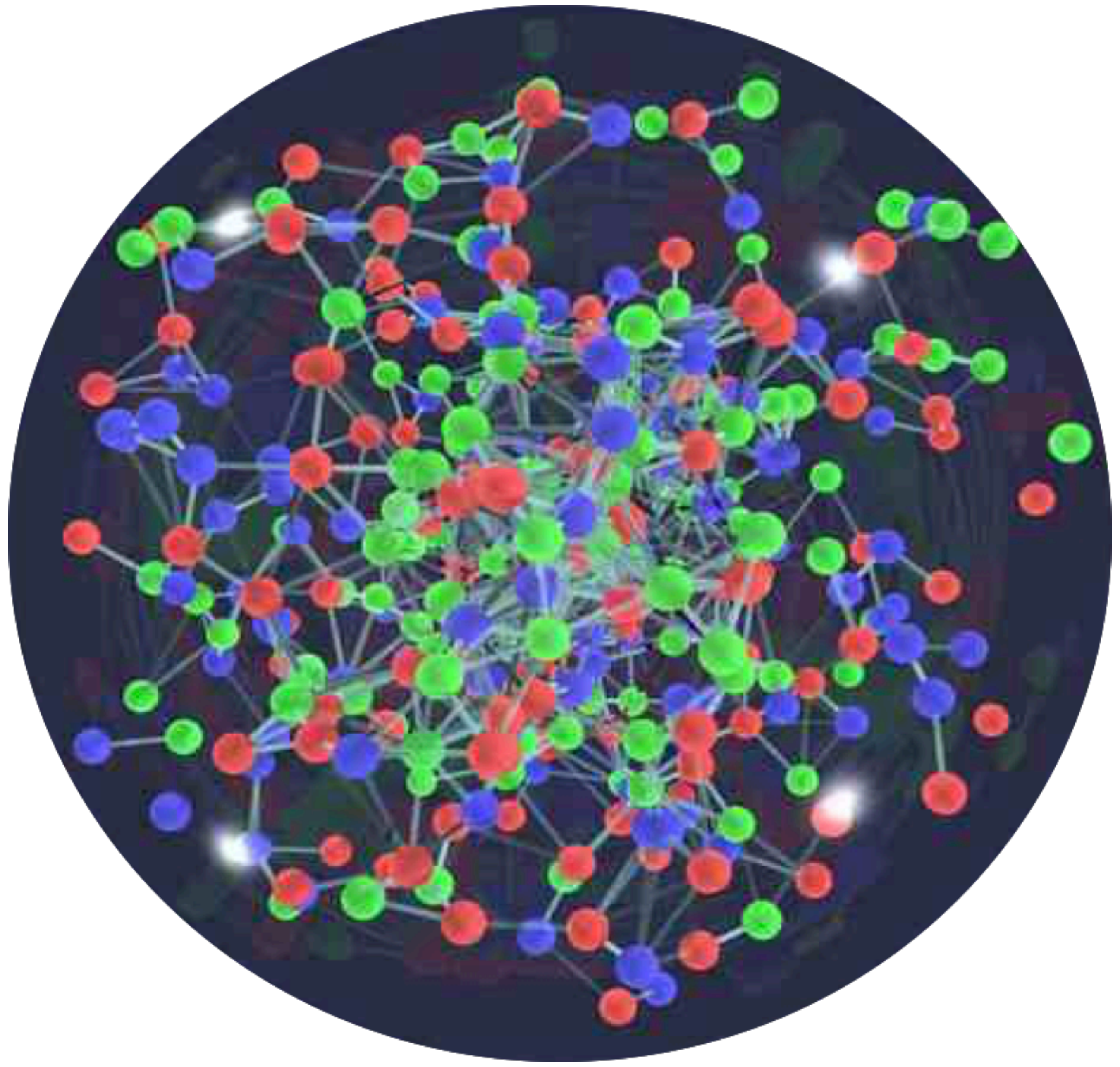
Bazavov et al (2014)

What is the structure of QCD matter here?

We don't know!



The quark-gluon plasma



In the last two decades it has been established that hot QCD matter is:

Deconfined
Strongly-coupled

But we do not understand much more than that!

How do complex properties arise from QCD?

Does deconfined QCD have quasi-particle structure?

How does this strongly-coupled fluid emerge?

How does confinement emerge?

Transition from discovery phase to a more quantitative phase

Heavy-ion collisions

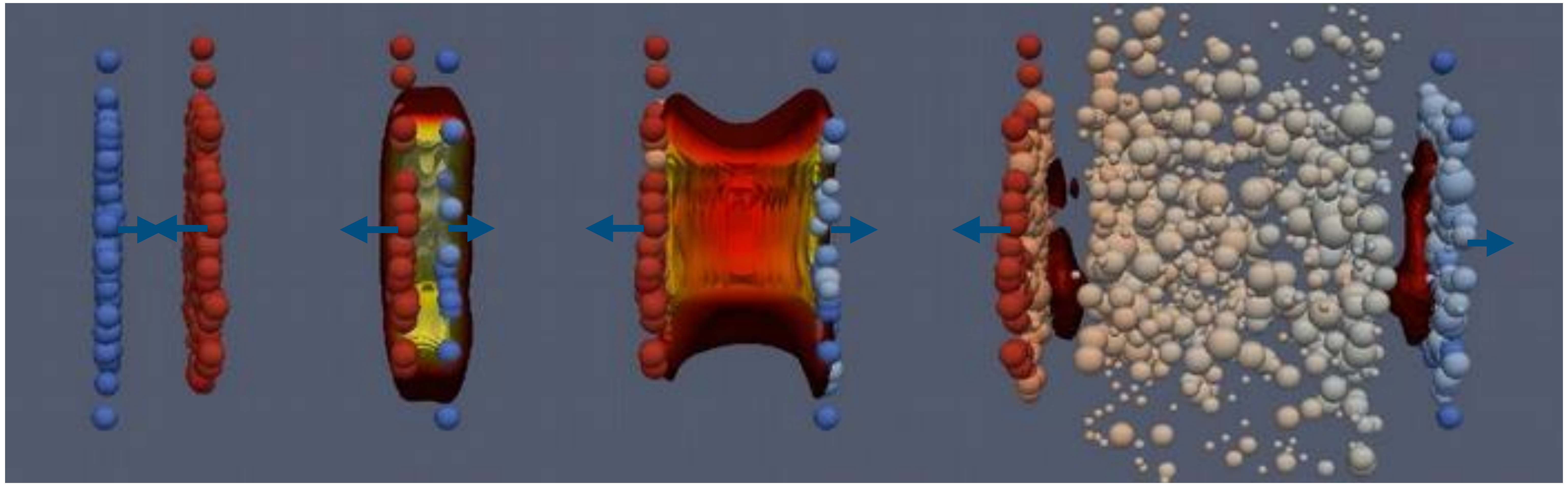
ALICE

We collide nuclei together at

Large Hadron Collider (LHC)

Relativistic Heavy Ion Collider (RHIC)

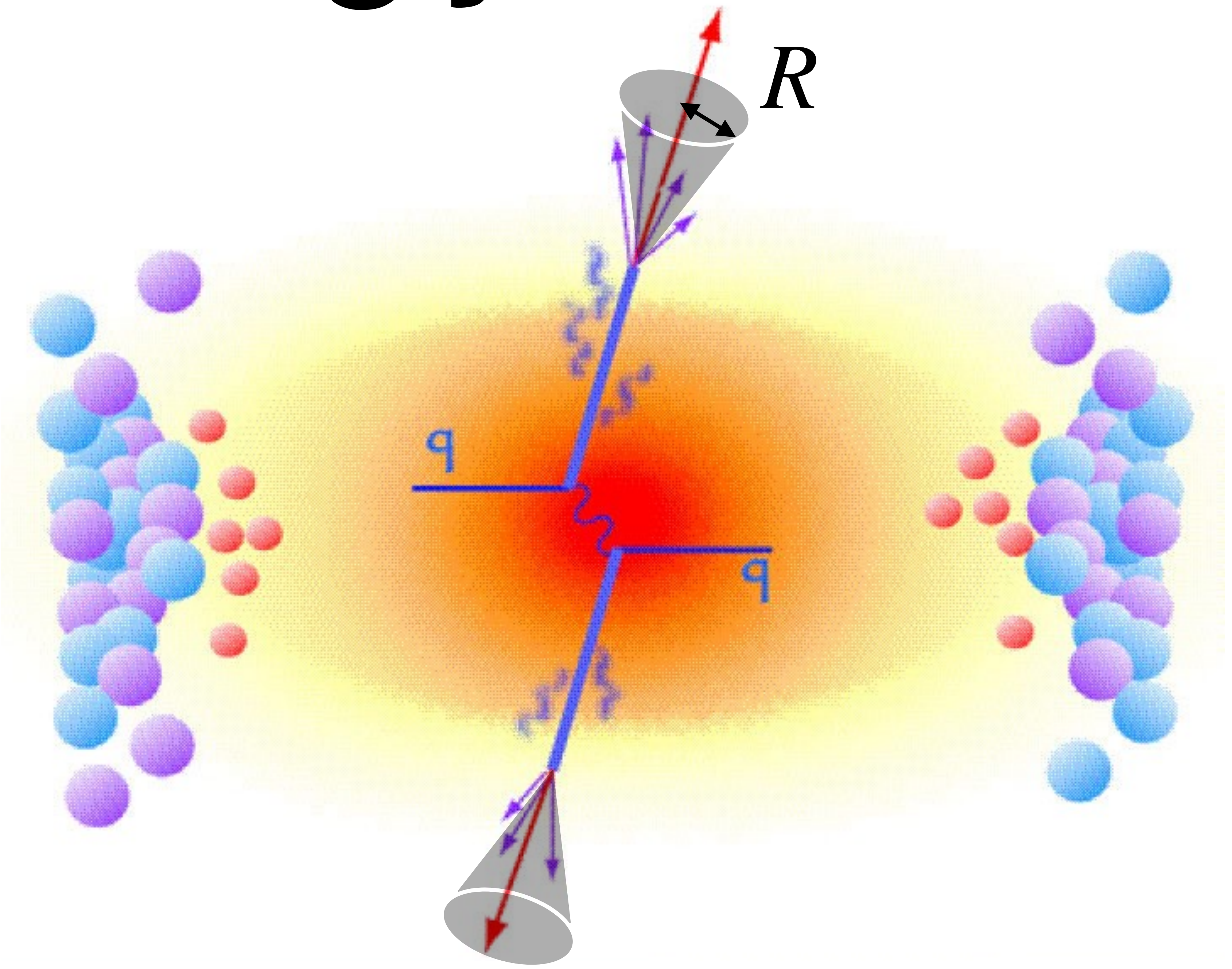
to produce a hot, dense state of matter known as the quark-gluon plasma



Soft collisions transform kinetic energy of nuclei into region of large energy density for $t \sim \mathcal{O}(10\ \mathrm{fm}/c)$

$T \approx 150 - 500\ \mathrm{MeV}$

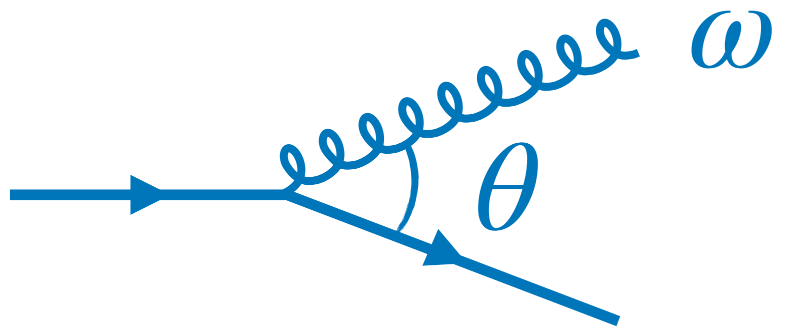
Using jets to learn about the QGP



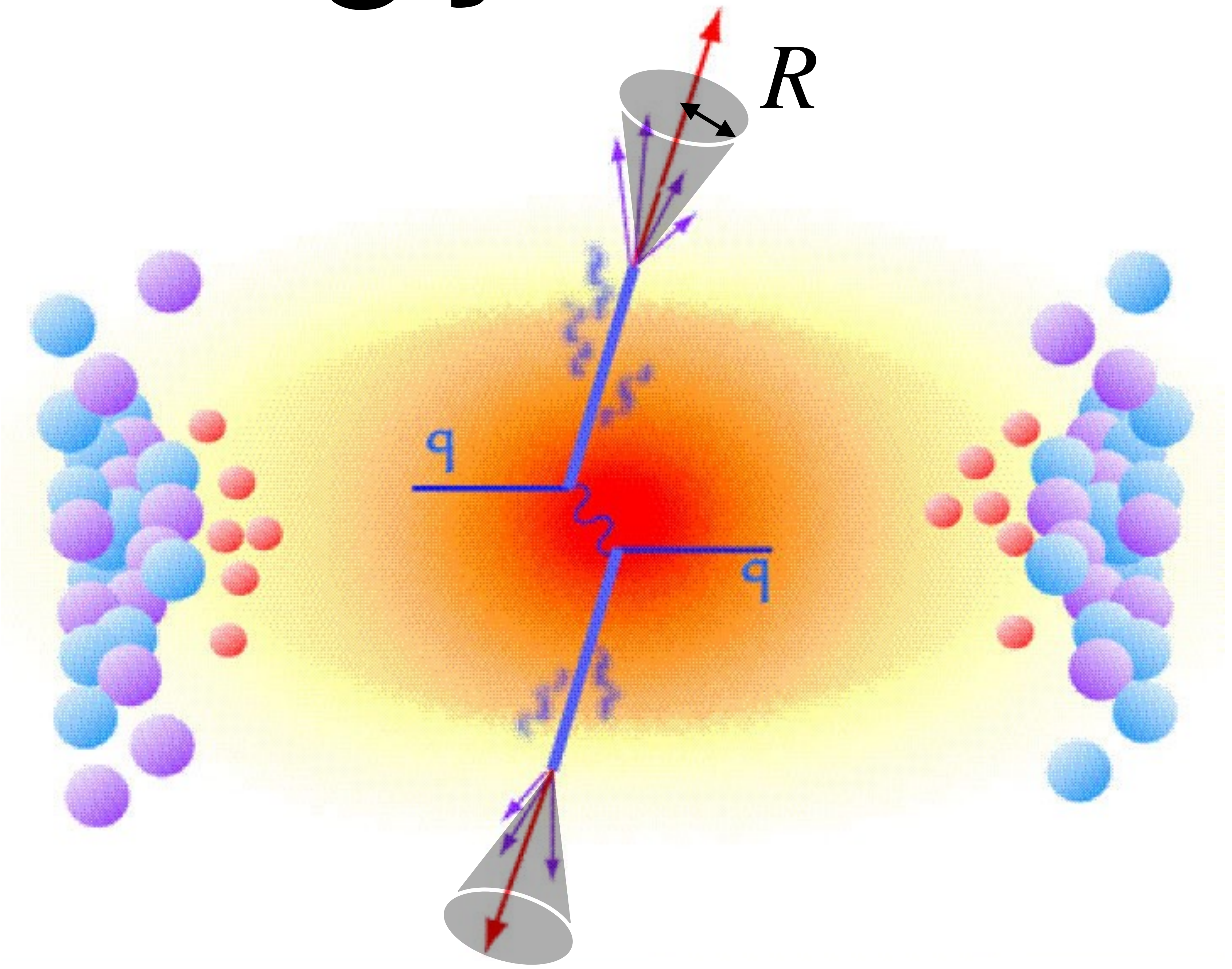
In addition to soft scatterings, there are occasional hard (large-Q^2) scatterings early in the collision

High energy partons radiate a soft and collinear "shower" before they hadronize

$$dP \sim \alpha_s C_R \frac{d\theta}{\theta} \frac{d\omega}{\omega}$$



Using jets to learn about the QGP



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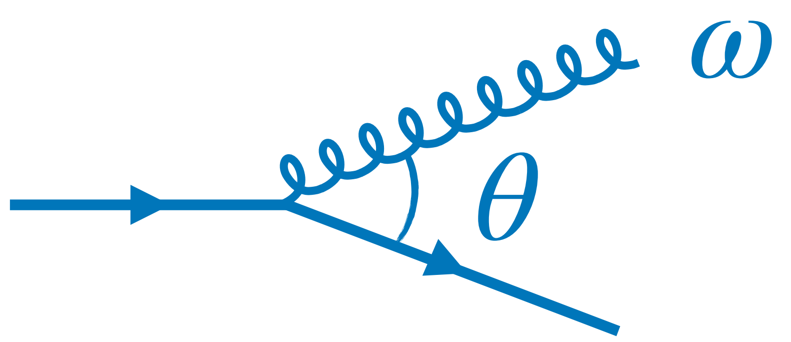
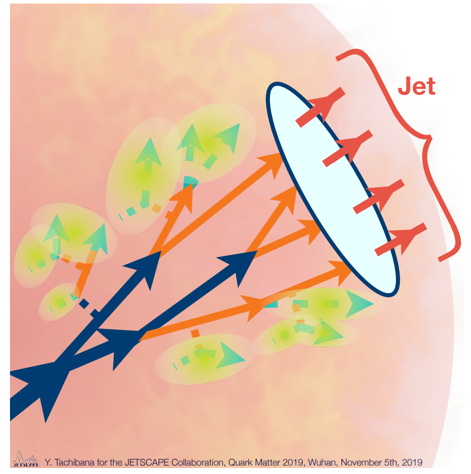
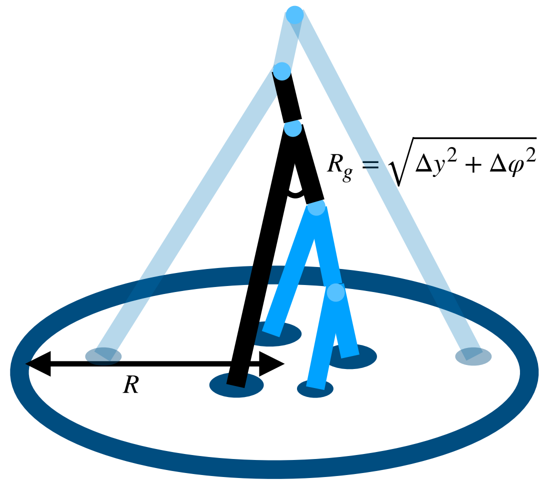


These jets interact with the quark-gluon plasma as they traverse it:

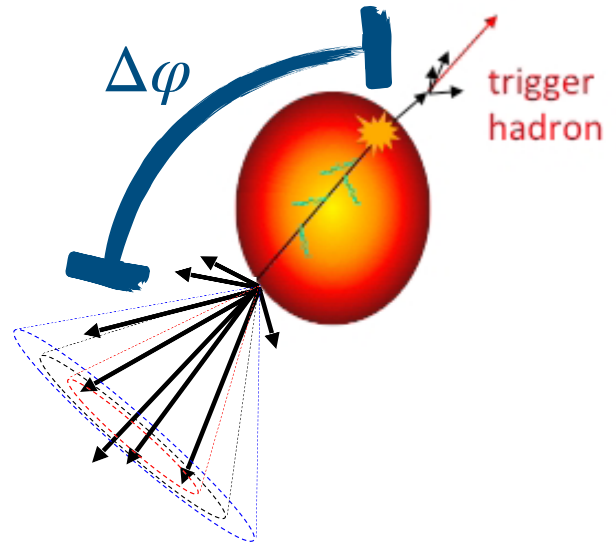
"Energy loss"



Substructure modification



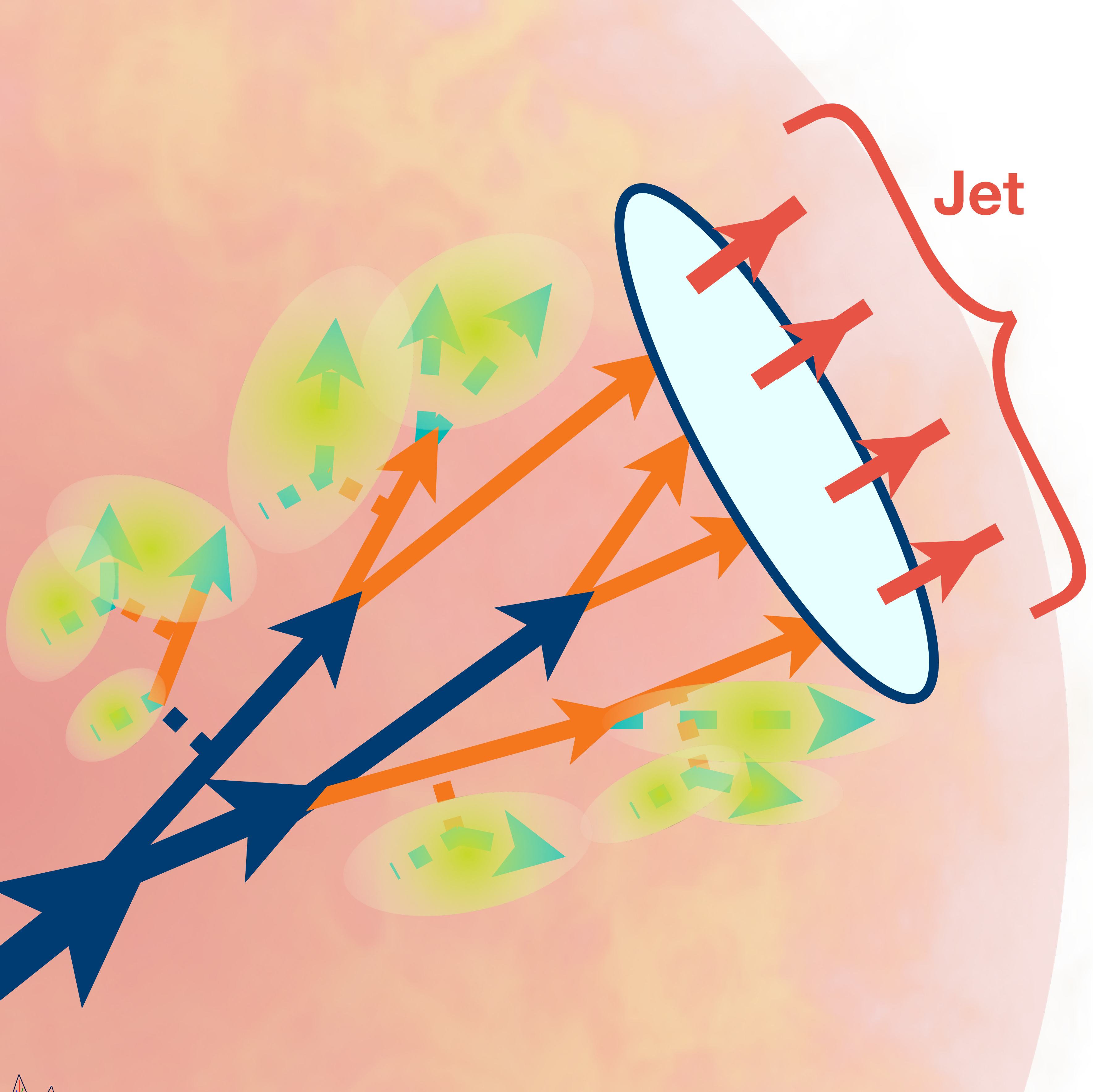
Deflection



By modeling these interactions, we hope to determine the structure of the QGP

Using jets to learn about the QGP

Jets are appealing probes for several reasons



Y. Tachibana for the JETSCAPE Collaboration, Quark Matter 2019, Wuhan, November 5th, 2019

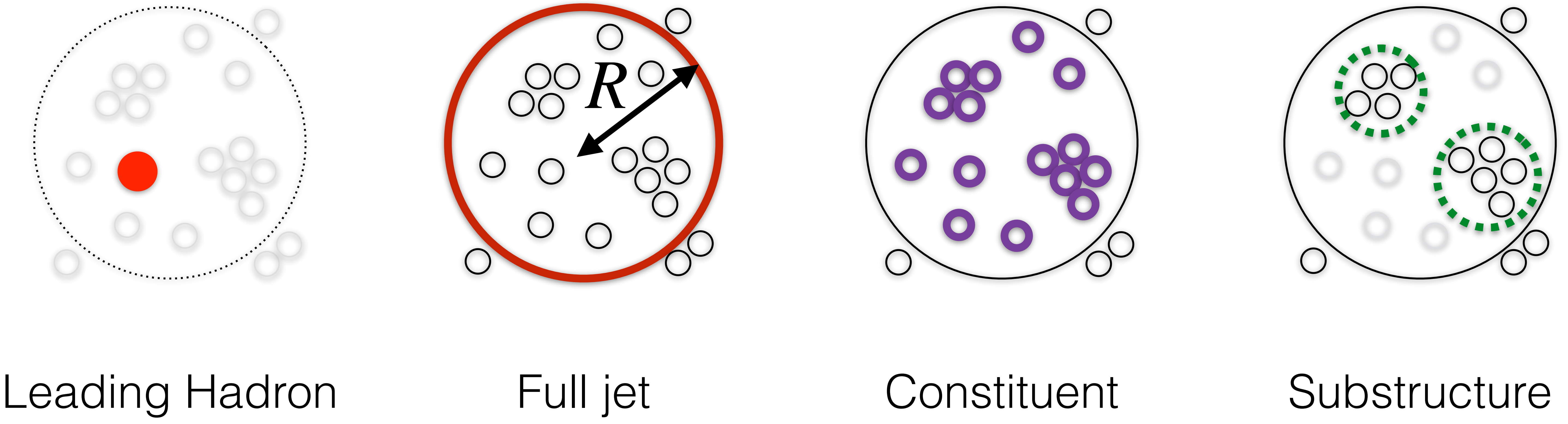
Calculable in pQCD from first principles

Can probe down to the smallest distance scales

Since jets are composite objects, can construct a rich set of complementary observables

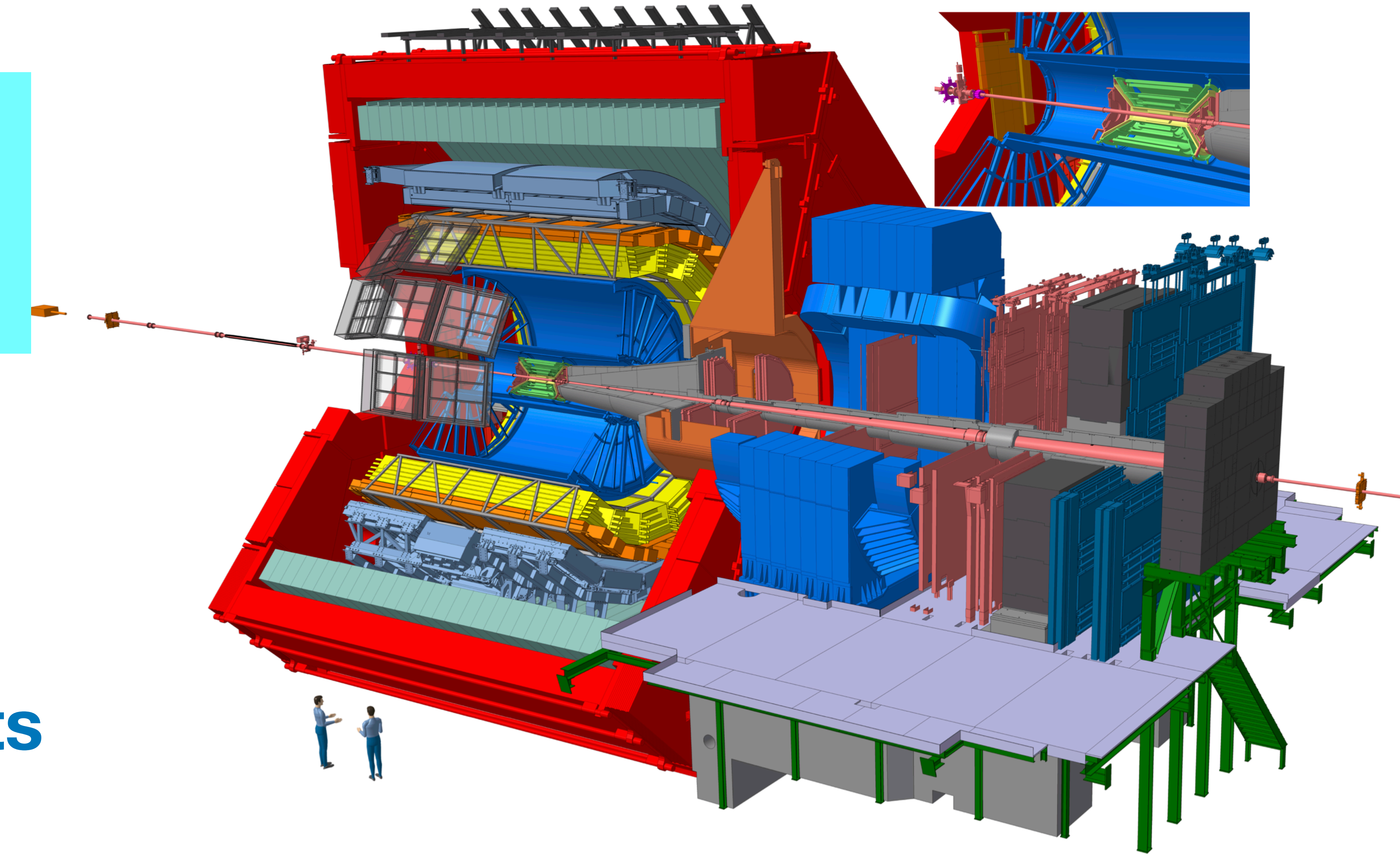
Different sensitivities to: pQCD, hadronization, medium interactions

from Yi Chen



Jets in ALICE

ALICE reconstructs jets at mid-rapidity $(|\eta| < 0.9)$ with a high-precision tracking system (ITS+TPC) and EMCal

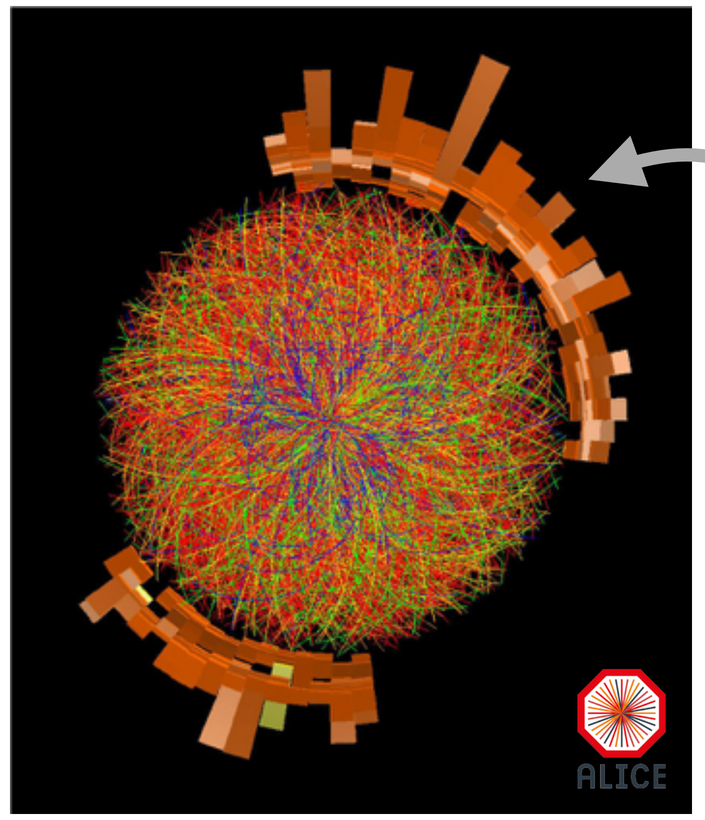


Charged particle jets

- High-precision spatial resolution to resolve particles
  - → **Ideal for precise jet substructure measurements**
- Requires additional modeling to compare to theory

Full jets (charged tracks + EMCal π^0, γ)

- Direct comparison to theory



EMCal φ acceptance: 107°

ALICE measures jets at "intermediate" $p_{\mathrm{T}} \approx 20 - 150$ GeV

Complementary to STAR and ATLAS/CMS

Fundamental QCD with Jets

ALICE

proton-proton collisions

Test pQCD techniques: Parton showers, resummations, power corrections, …

Constrain non-perturbative effects: Hadronization, underlying event

Constrain PDFs, α_s

Reference for heavy-ion collisions: Which observables are under theoretical control?

Many recent measurements from ALICE…but I will focus on heavy-ion collisions

Dynamical grooming: z_g, θ_g, k_T

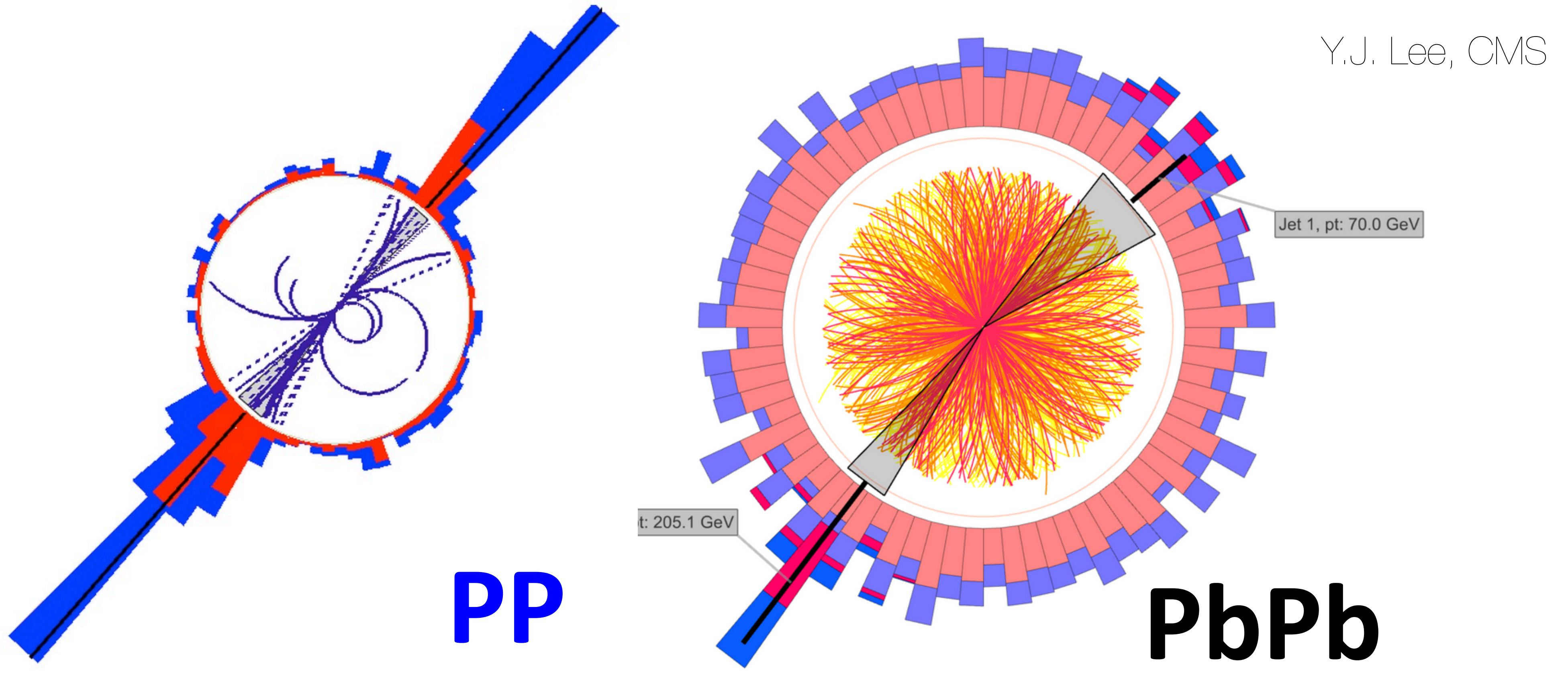
Jet angularities: λ_β

D^0**-tagged jets:** z_g, θ_g

Dead cone

Measuring jets in heavy-ion collisions

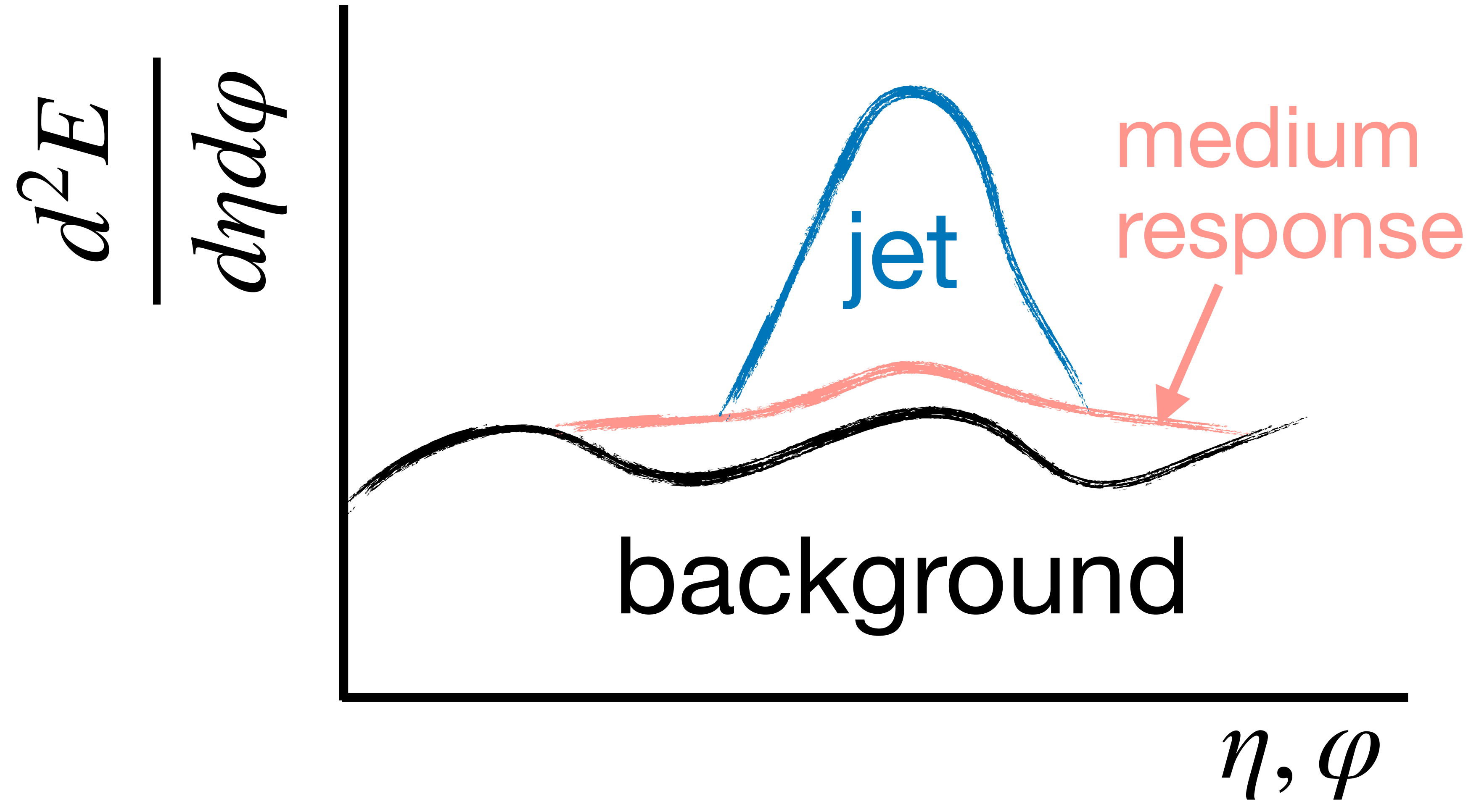
The soft collisions in a heavy-ion event produce a large, fluctuating background



Measurements challenging at low-p_T, large-R

$R = 0.4$ jet has $p_T \approx 100$ GeV of background

We correct for this using both event-by-event and statistical procedures



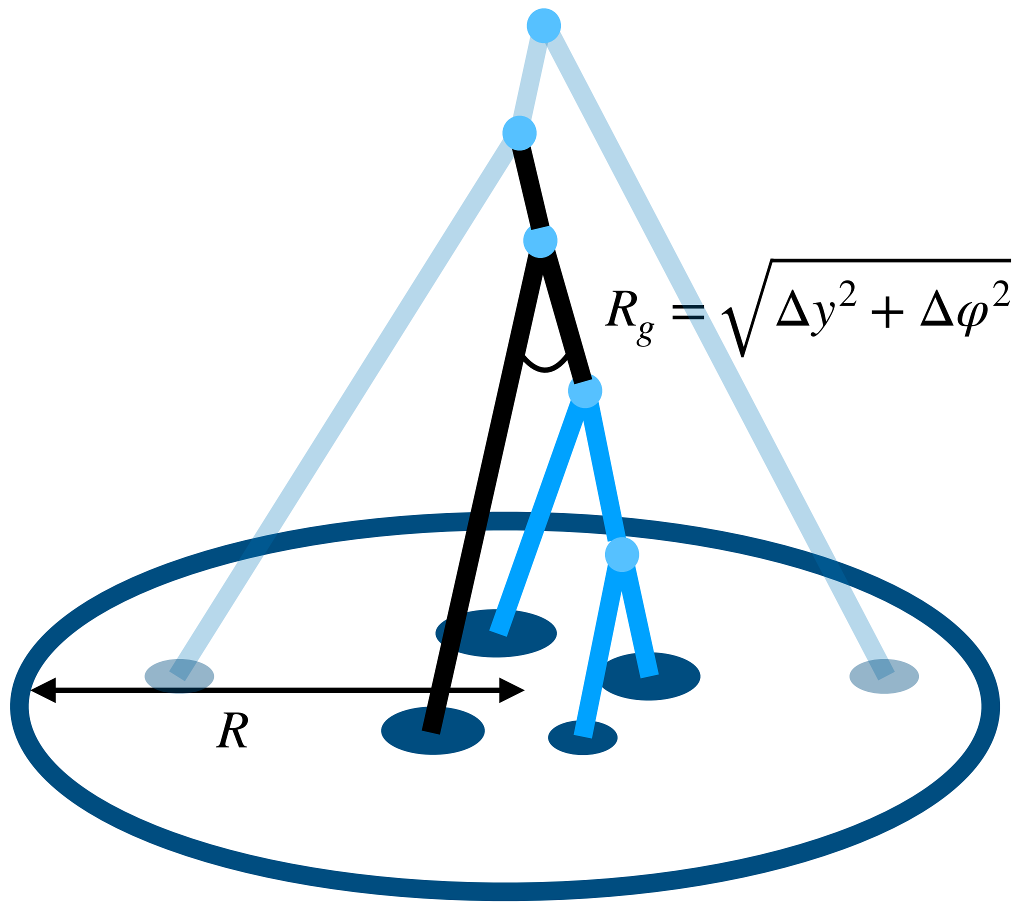
We measure everything "correlated" to the jet

Measuring jets in heavy-ion collisions

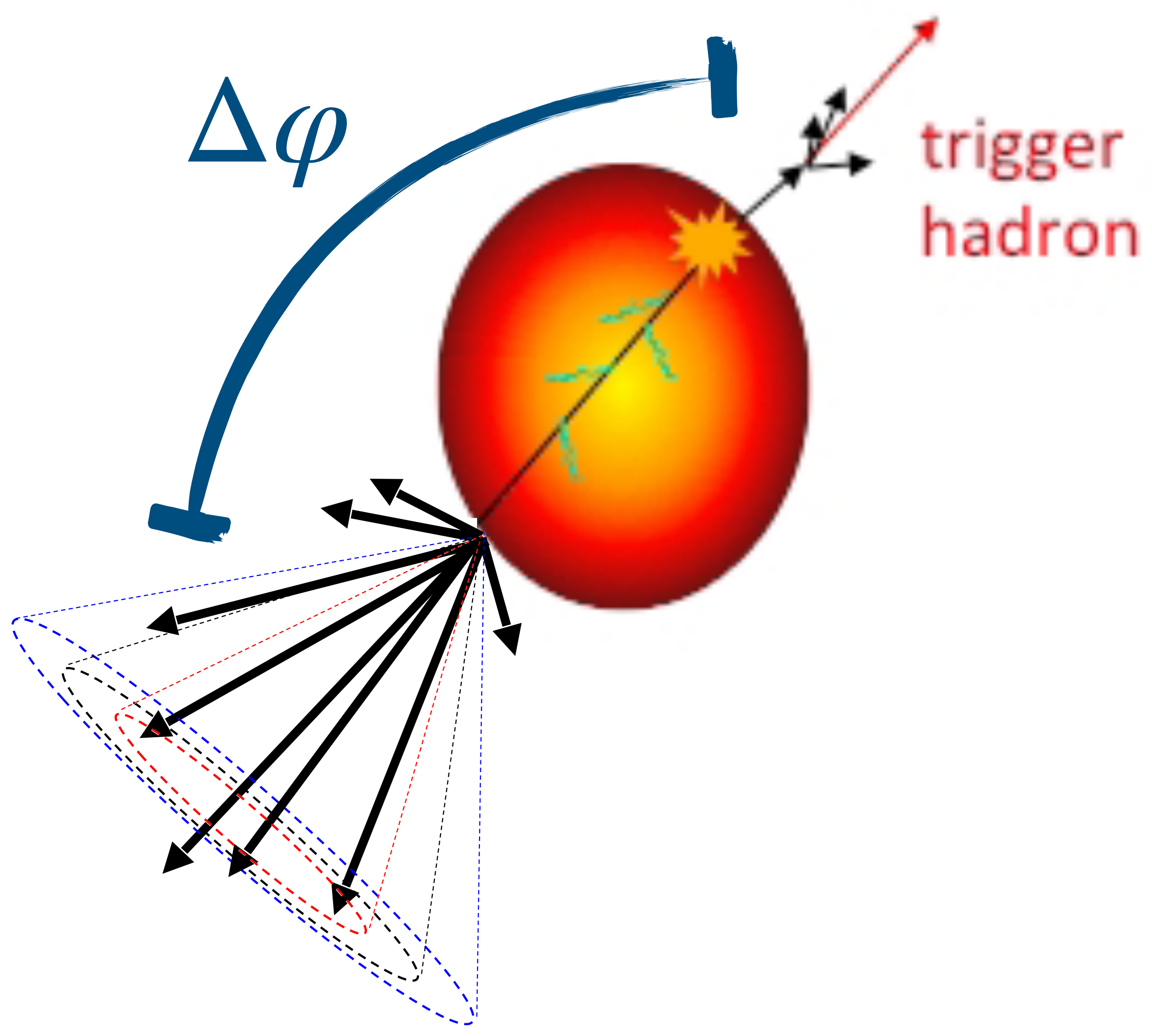
ALICE

I will describe two recent measurements:

Jet substructure



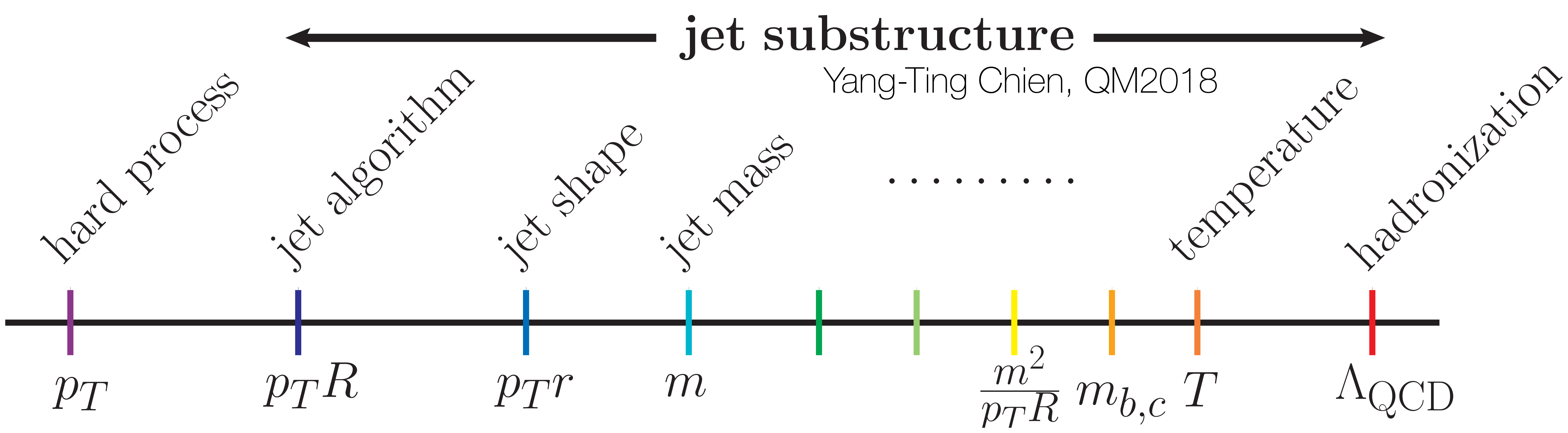
Hadron-jet coincidences



Jet substructure

A powerful class of observables

- Sensitive to a wide span of scales
  - Provide complementary information to disentangle multiple QCD effects
- Many are analytically calculable from pQCD



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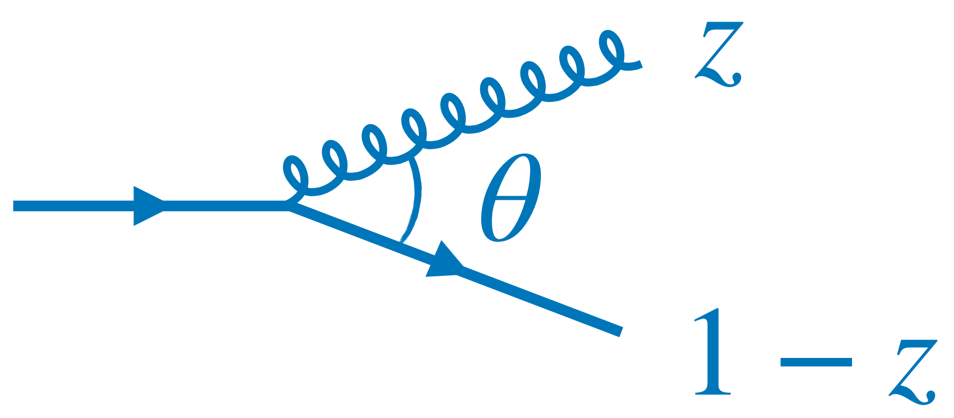
Groomed jet substructure

Recluster the jet constituents and "groom" the jet to **identify the first hard splitting**

Soft Drop: $z < z_{\mathrm{cut}}\theta^{\beta}$

Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657
Larkoski, Marzani, Thaler 1502.01719



A theoretically well-controlled way to ask: **Does the medium modify the hard substructure of jets, or only the soft substructure?**

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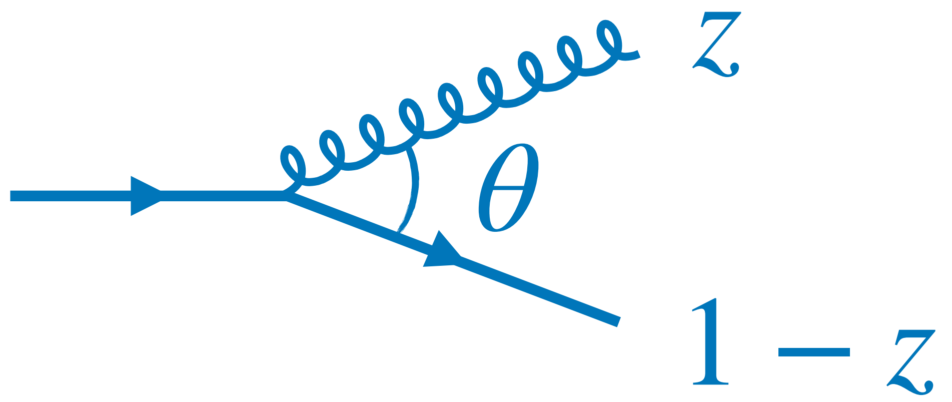

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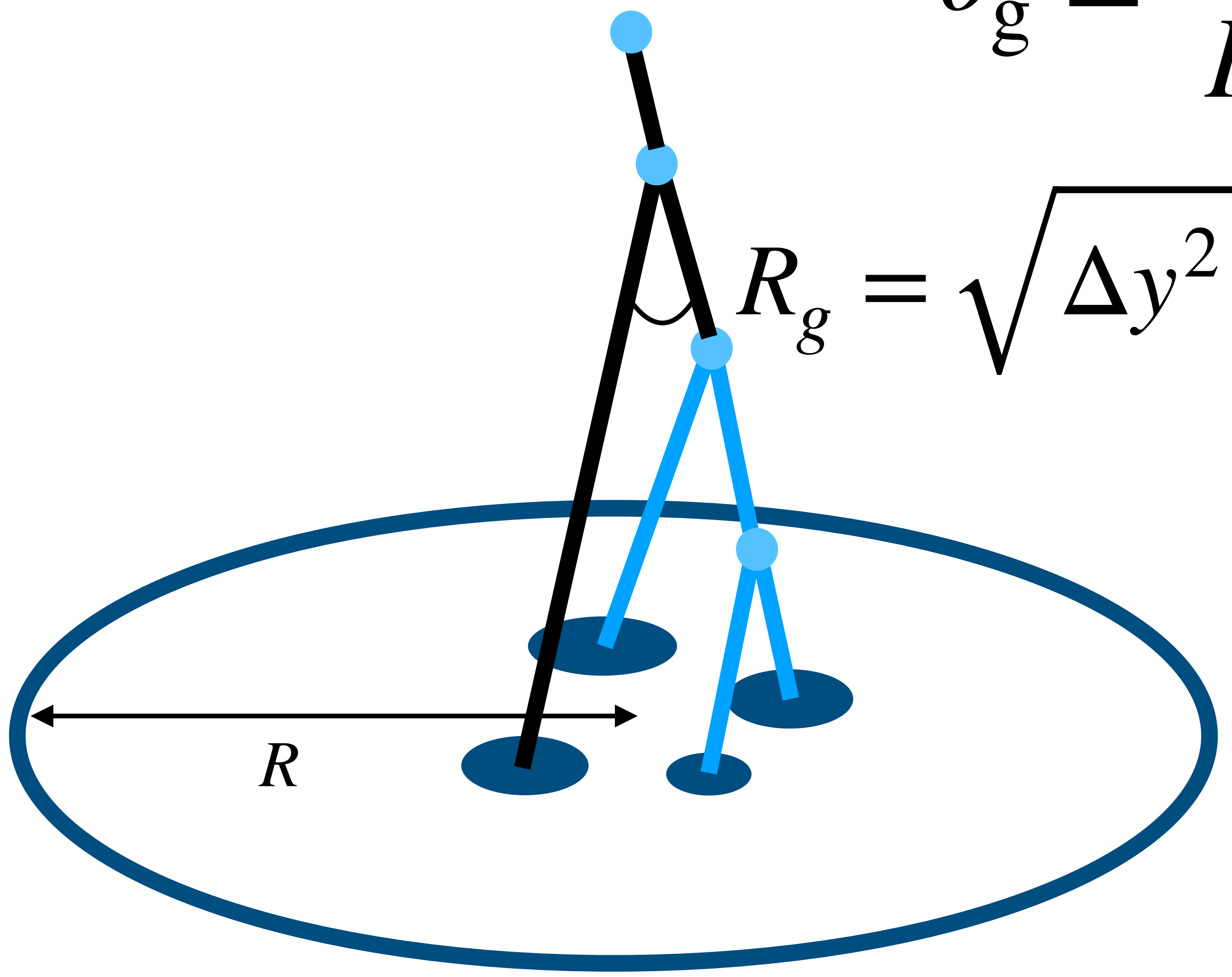
$$\theta_{\mathrm{g}} \equiv \frac{R_{\mathrm{g}}}{R}$$

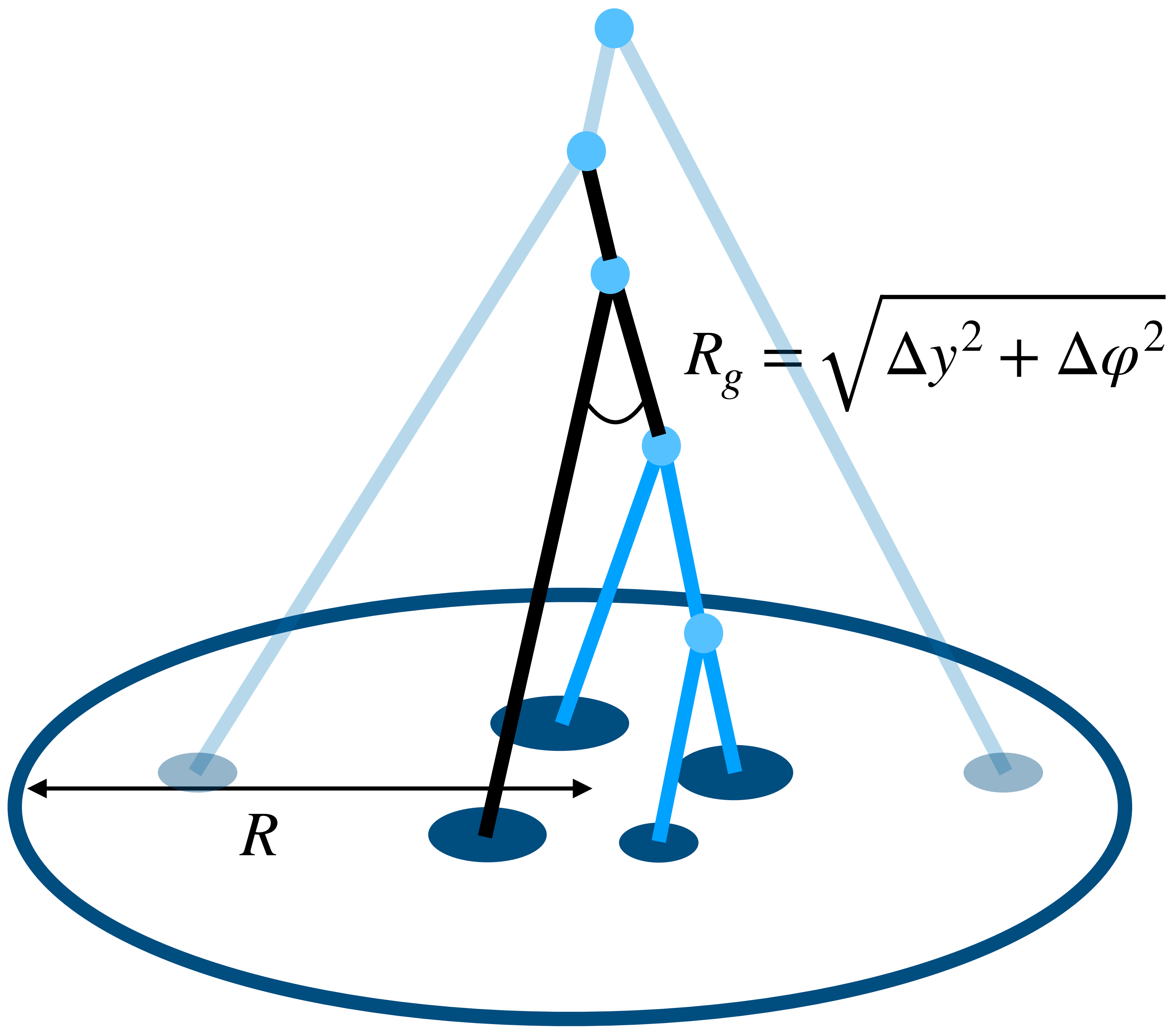
$$R_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$



Groomed jet substructure in Pb-Pb

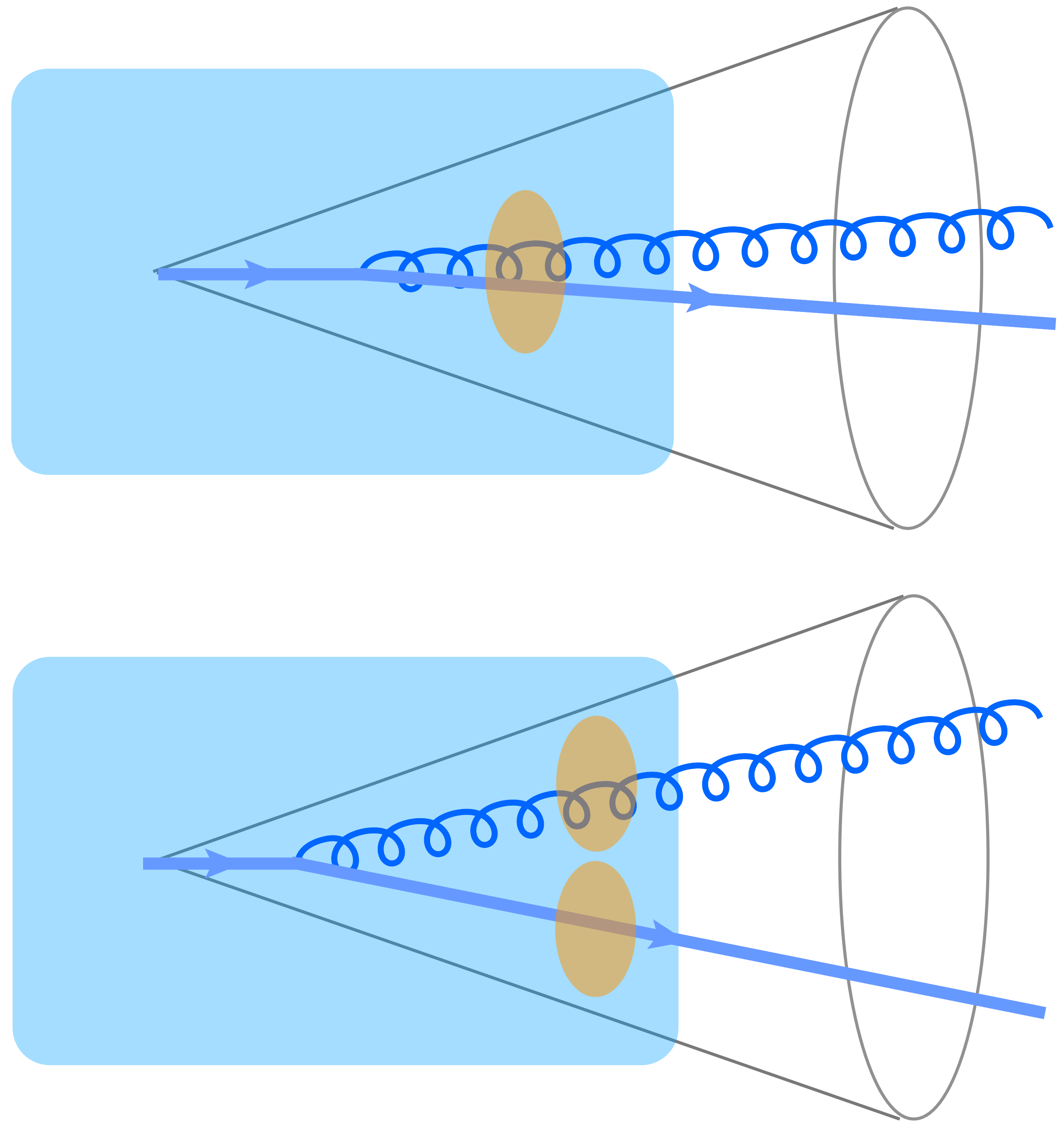
Groomed jet radius, θ_g

We can measure the **angular distribution** of the hard splitting:



$$\theta_g \equiv \frac{R_g}{R}$$

What is the transverse resolution length of the medium?



Y. Mehtar-Tani

Never measured in heavy-ion collisions

Groomed jet substructure in Pb-Pb

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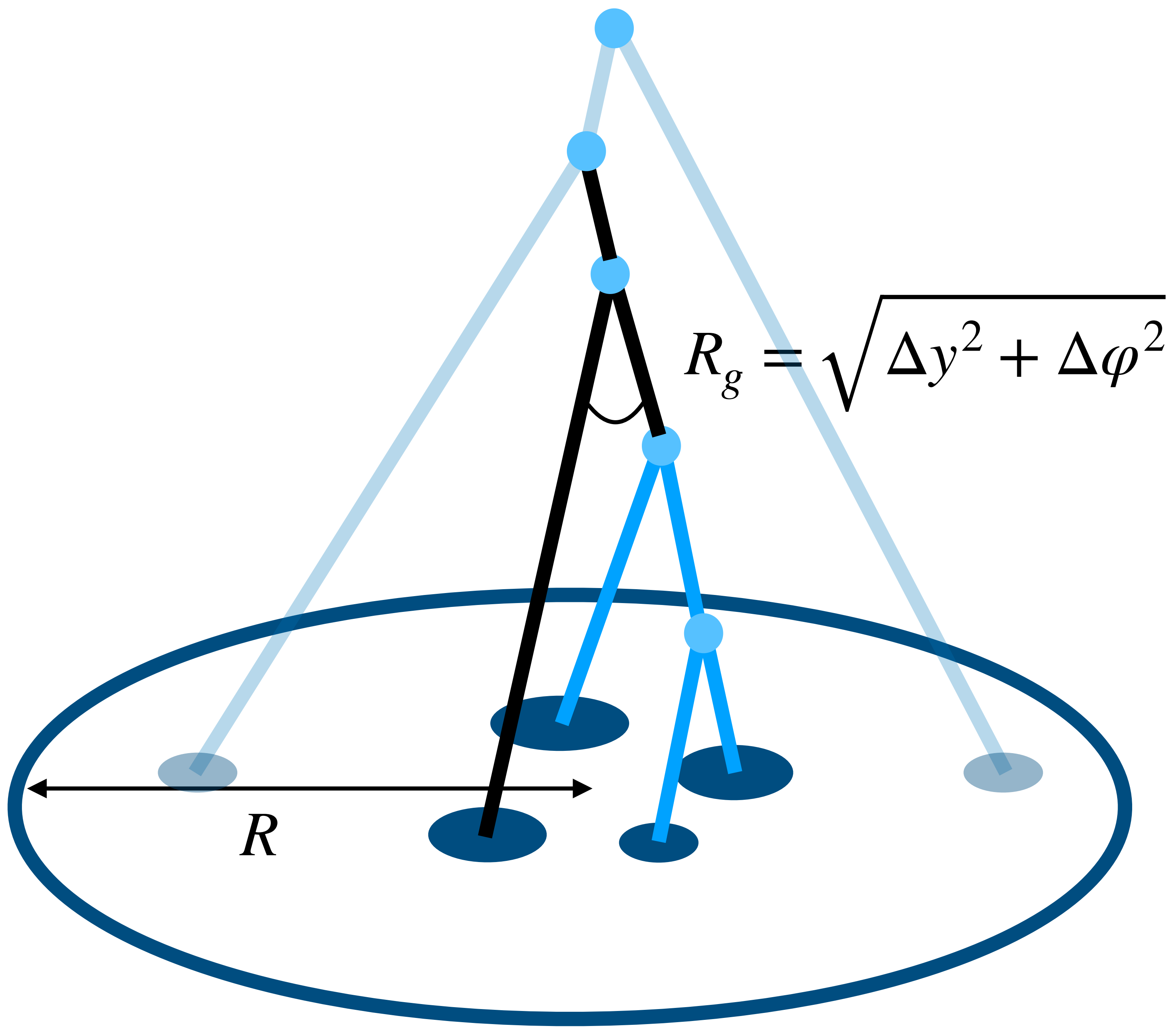
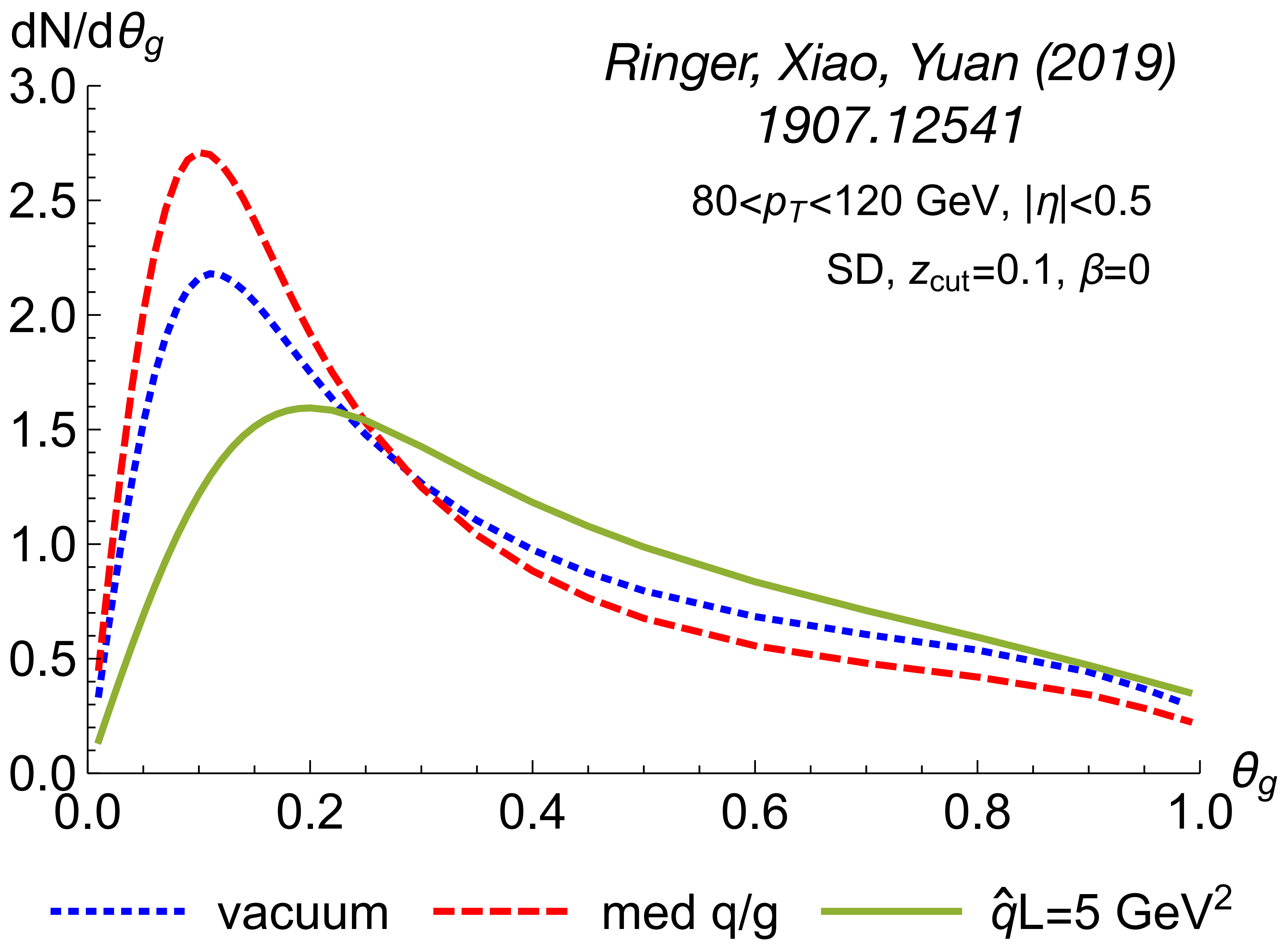


$$\theta_g \equiv \frac{R_g}{R}$$

Medium-induced emissions may narrow or broaden the splitting angle

Medium-induced gluon radiation broadens jets

Energy loss selects narrow jets



Never measured in heavy-ion collisions

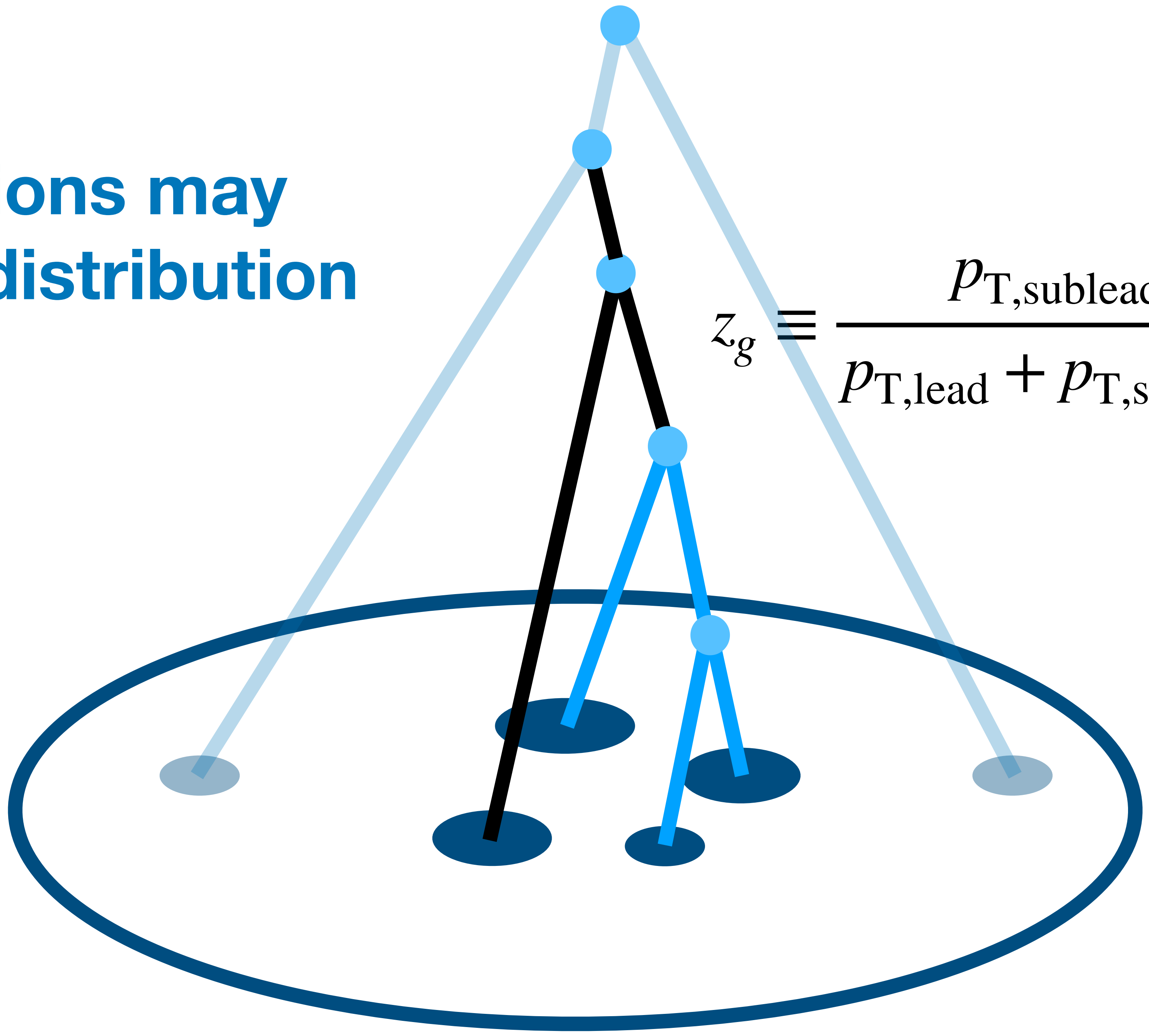
Groomed jet substructure in Pb-Pb

Groomed jet momentum fraction, z_g

We can measure how symmetric **in momentum** the hard splitting is:

Medium-induced emissions may modify the momentum distribution

- Semi-hard gluon radiation
- Energy loss effects
- Medium response
- Color coherence



$$z_g \equiv \frac{p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

Groomed jet substructure in Pb-Pb

Groomed jet momentum fraction, z_g

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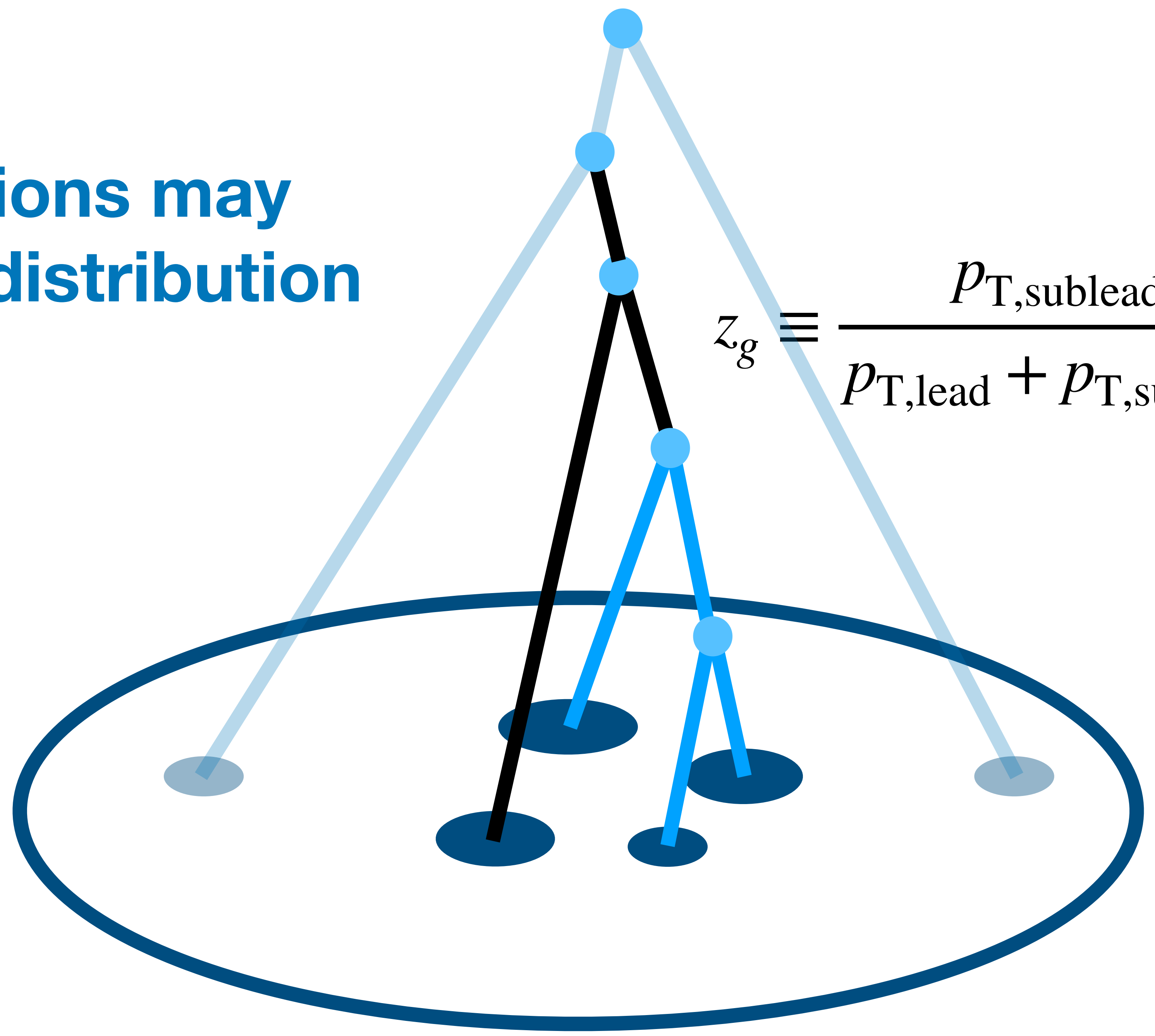
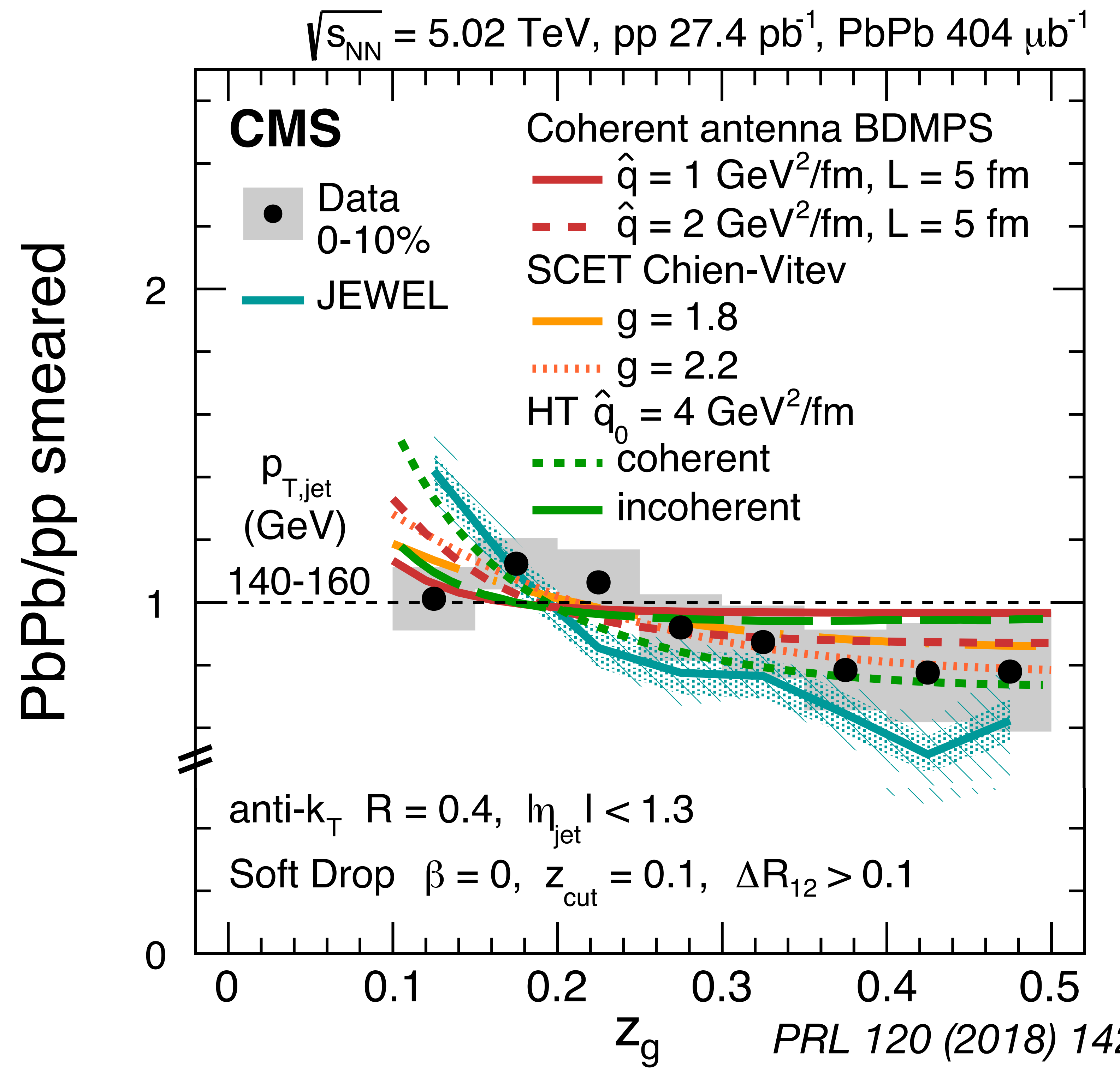


$$z_g \equiv \frac{p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$

Previous measurements: Slight suppression of symmetric splittings?

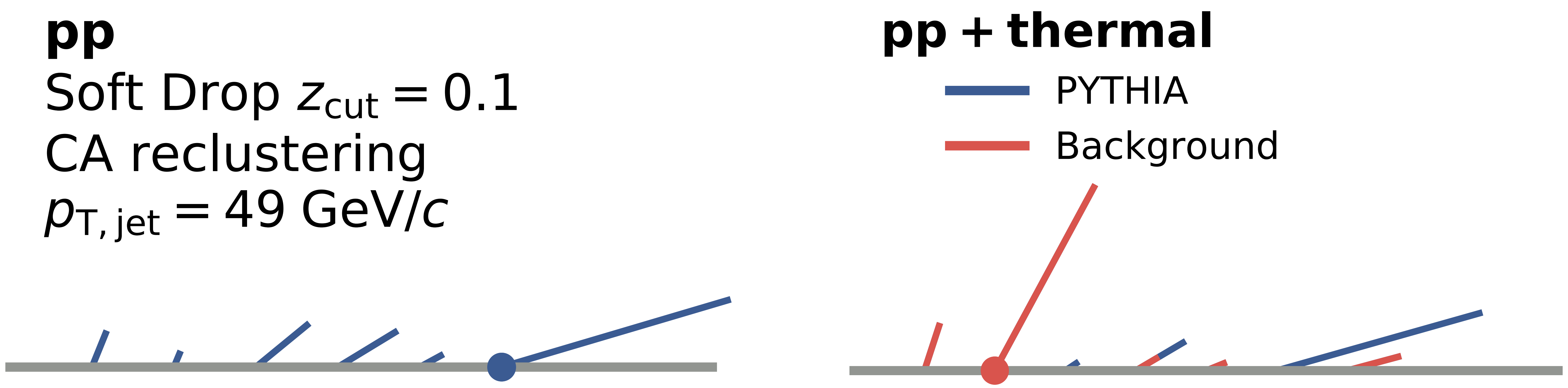


PRL 120 (2018) 142302

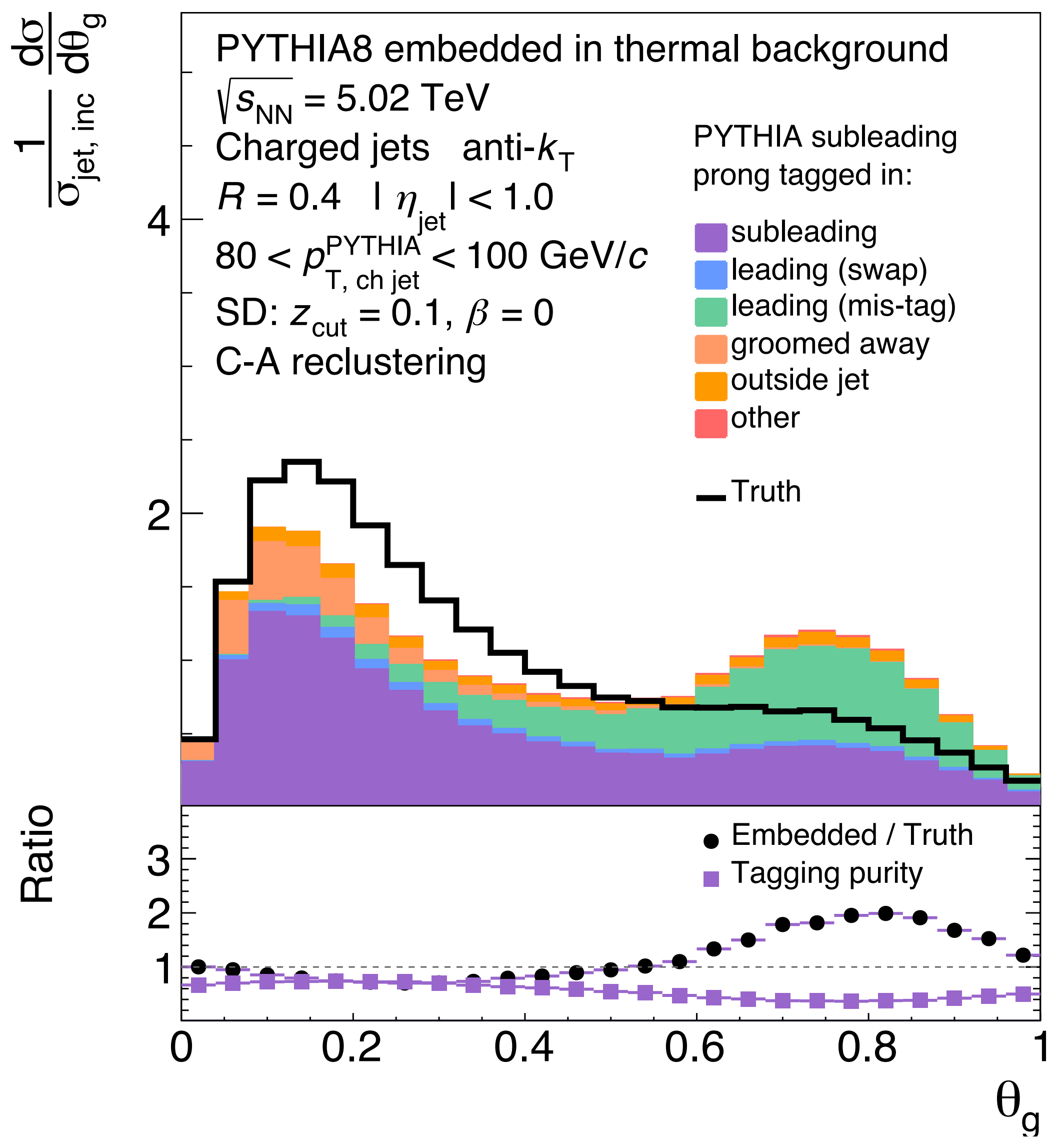
Measurements not corrected for background fluctuations in heavy-ion collisions

Identifying groomed jet splittings in Pb-Pb

The heavy-ion background can cause an entirely wrong splitting to be identified



JM, M. Ploskon 2006.01812

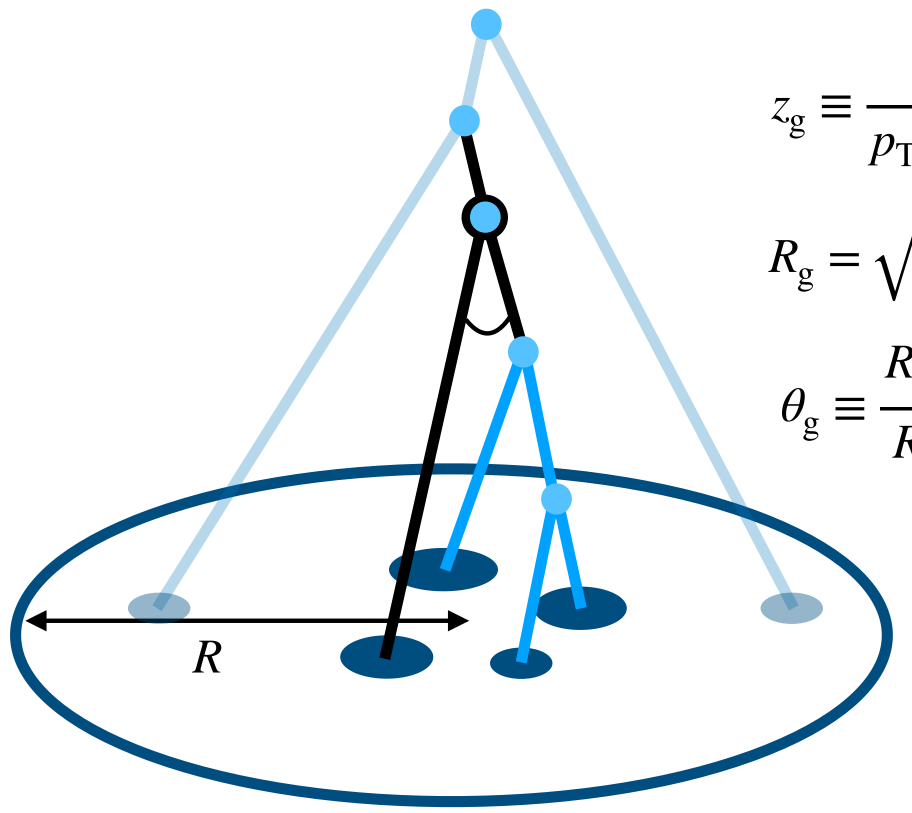


Typical grooming settings for proton-proton collisions (used in previous heavy-ion measurements) misidentify background fluctuations as jet splittings

The grooming algorithm must be appropriately designed for heavy-ion collisions

Results — Soft Drop z_g, θ_g

Pb-Pb



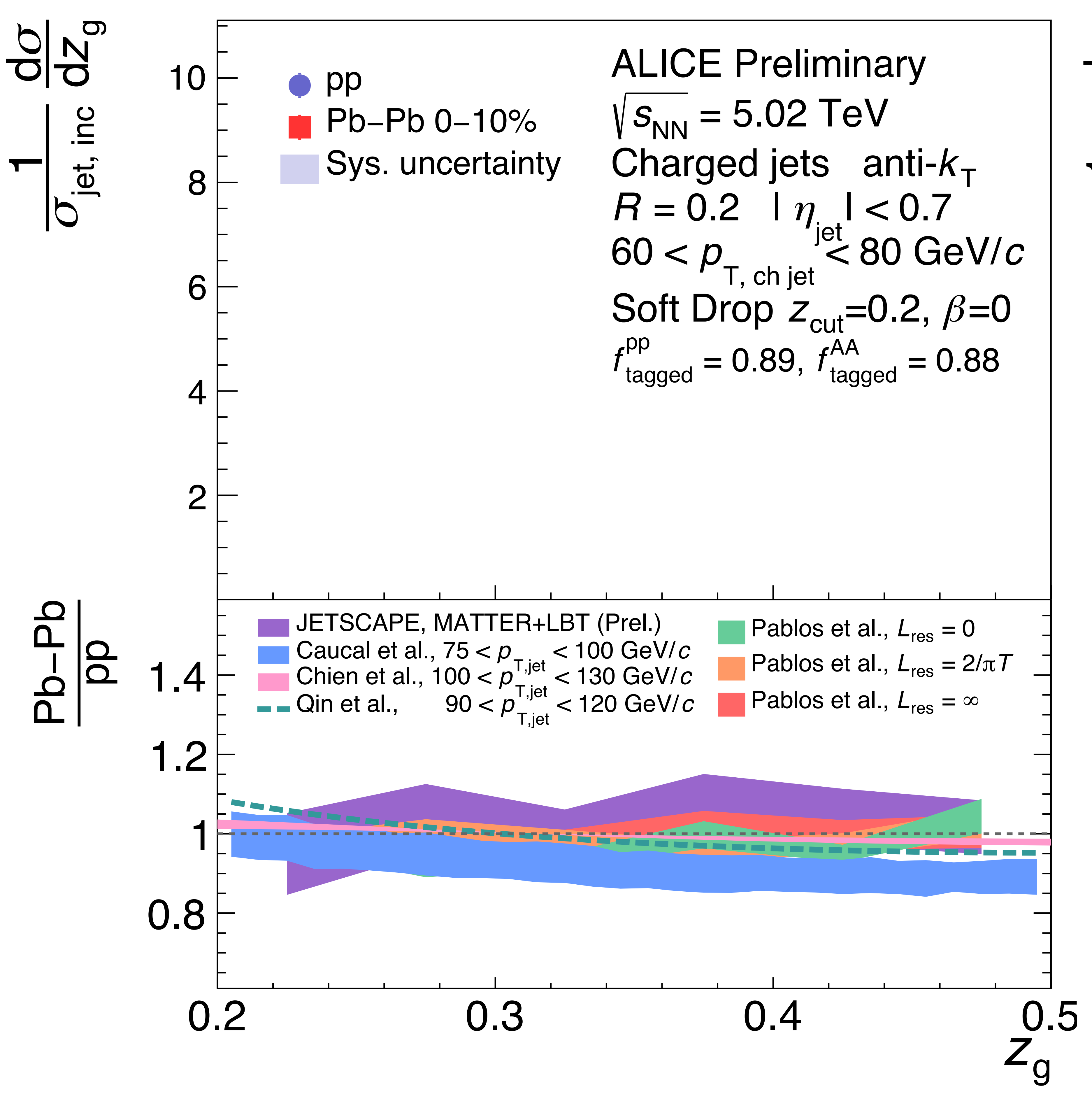
$$z_g \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}} + p_{T,\text{subleading}}}$$

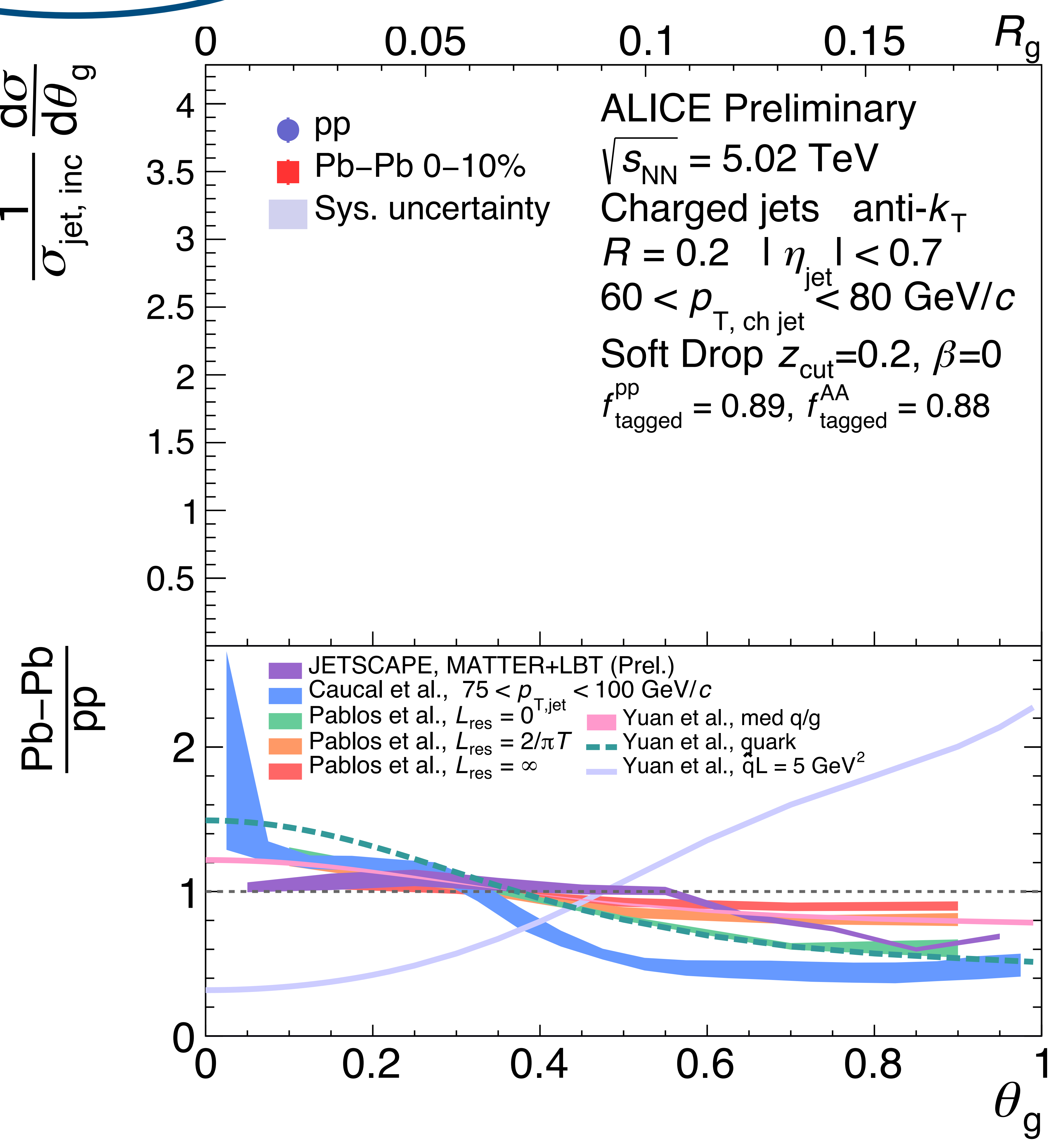
$$R_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

$$\theta_g \equiv \frac{R_g}{R}$$

Variety of theoretical models

- Strongly-coupled vs. weakly-coupled jet-medium interaction
- Coherent vs. incoherent interactions
- ...





Results — Soft Drop z_g, θ_g

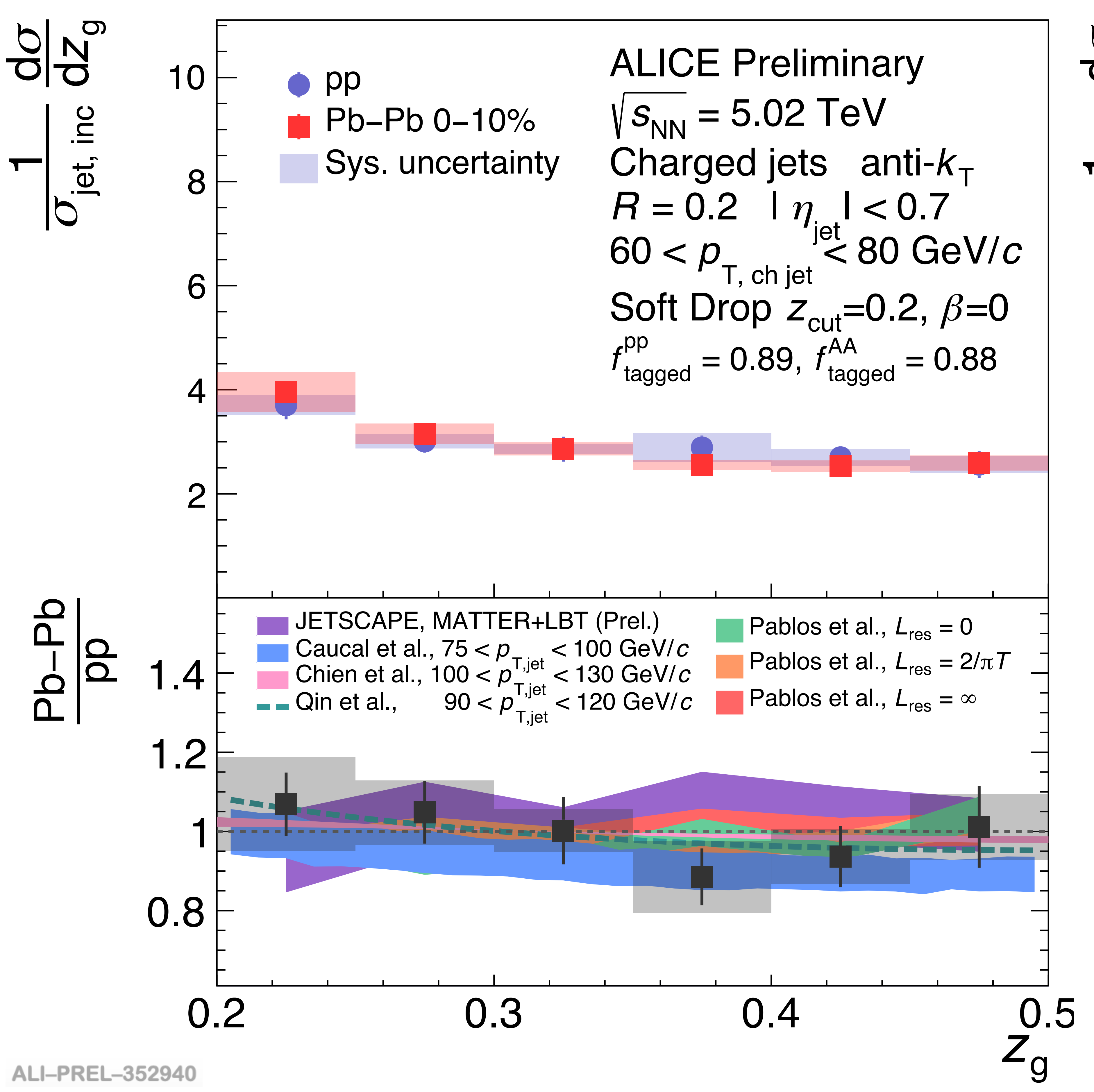
ALICE-PUBLIC-2020-006

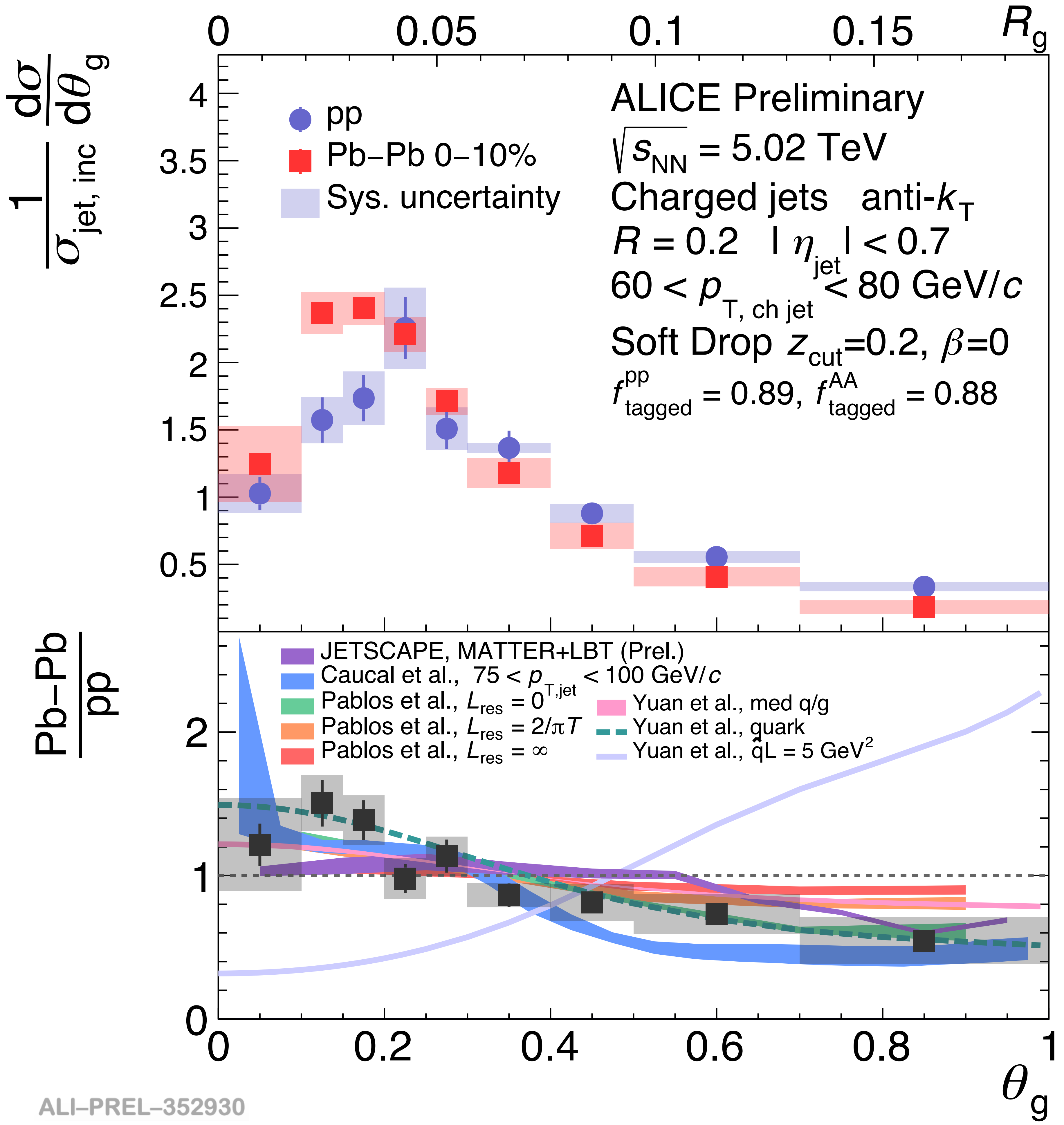
Pb-Pb

Fully corrected for background and detector effects

No significant modification of z_g distribution

Modification of θ_g: Collimation / Narrowing





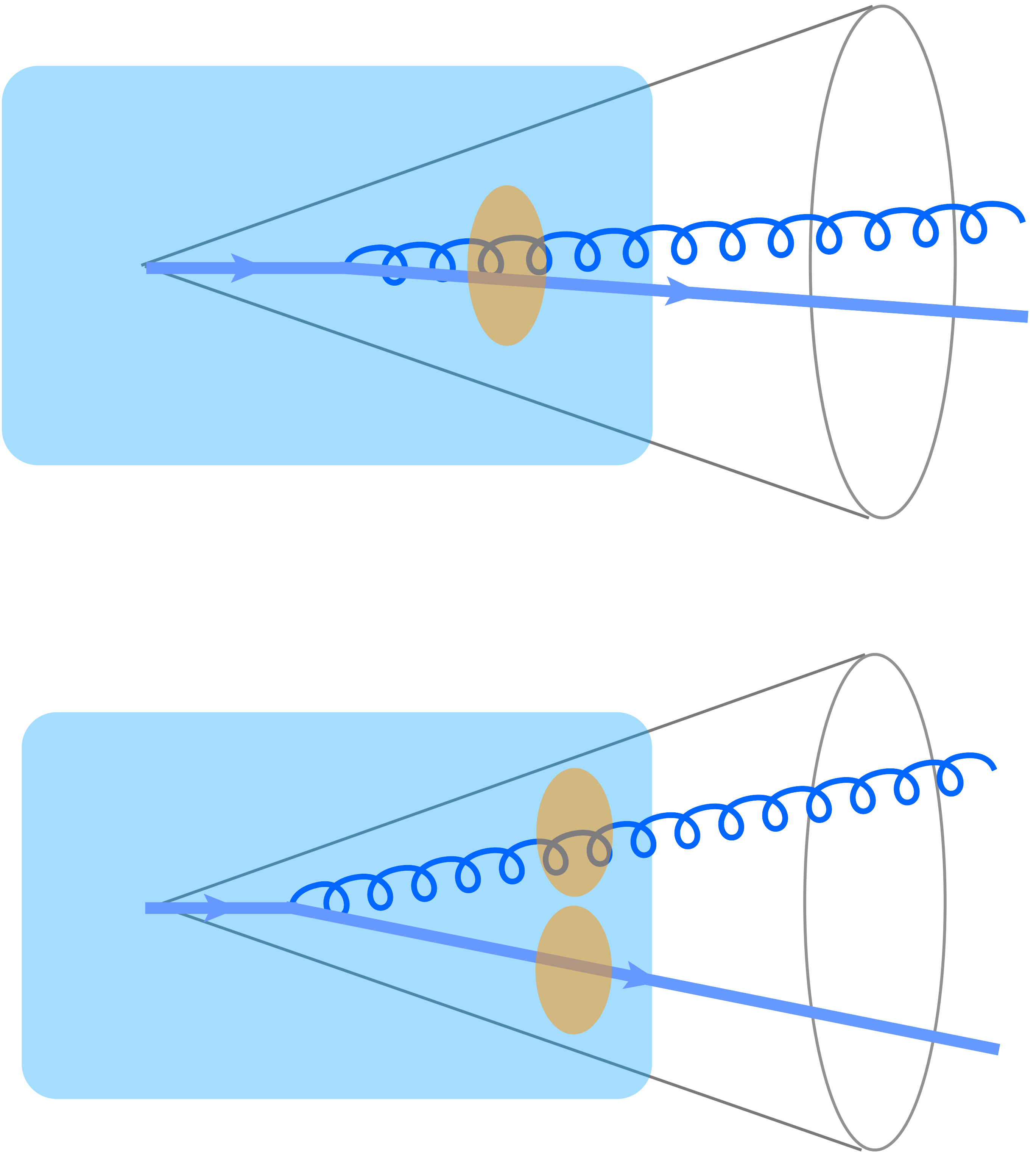
Results — Soft Drop z_g, θ_g

Pb-Pb

ALICE-PUBLIC-2020-006

Fully corrected for background and detector effects

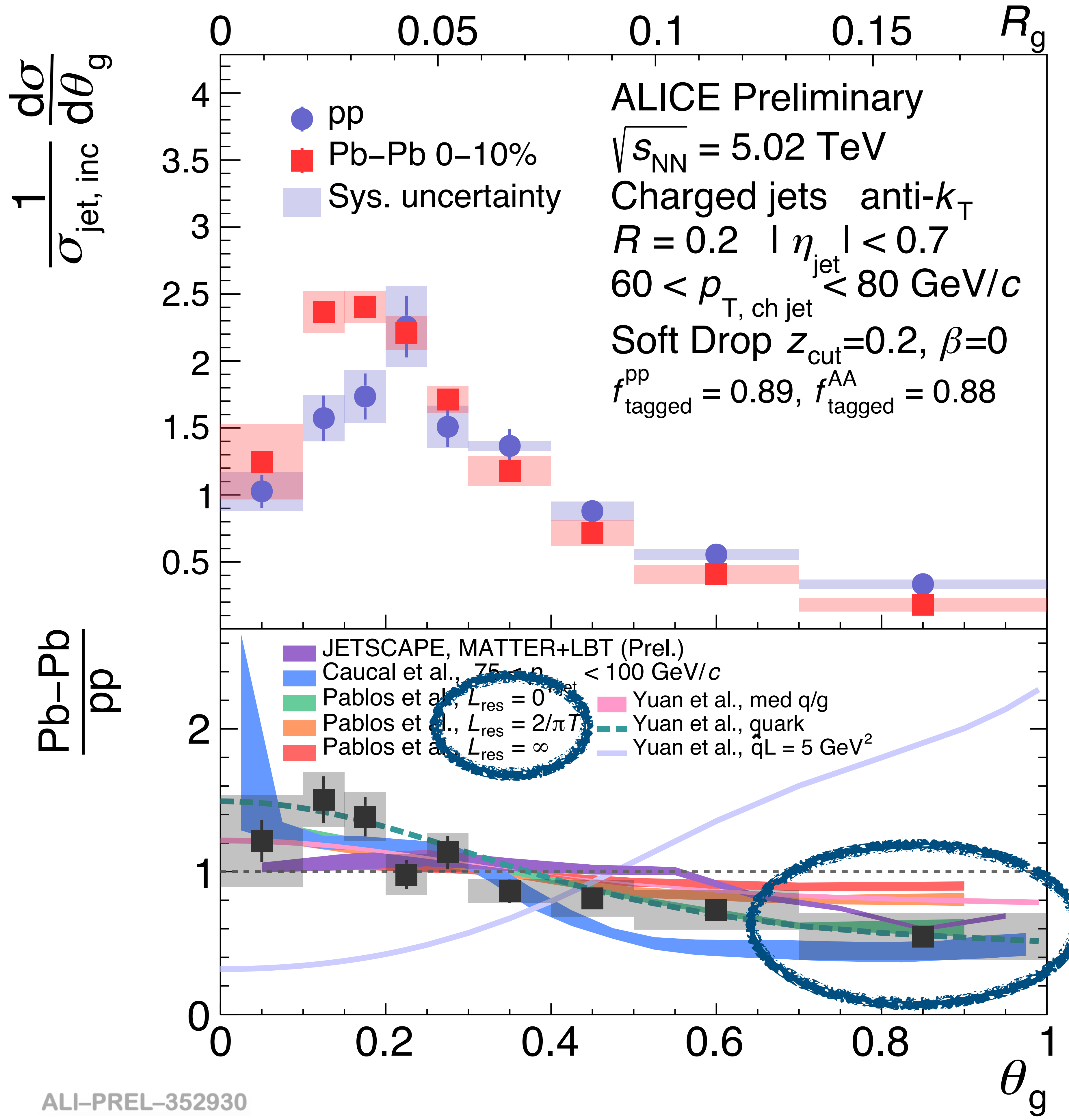
Data seem to favor incoherent energy loss and/or large q/g suppression



Y. Mehtar-Tani

ALI–PREL–352940

Modification of θ_g: Collimation / Narrowing



ALI–PREL–352930

Results — Soft Drop z_g, θ_g

ALICE-PUBLIC-2020-006

Pb-Pb

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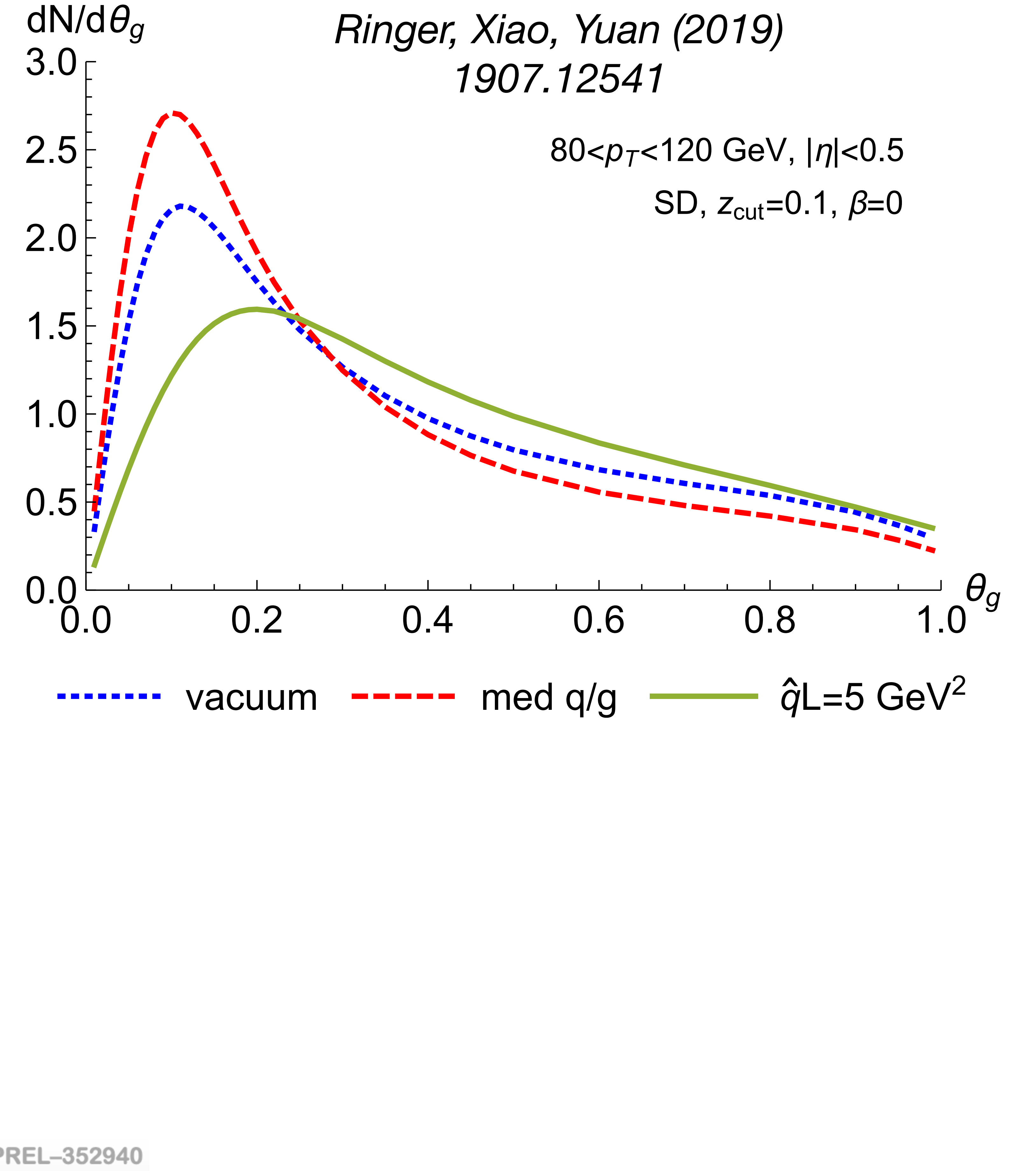

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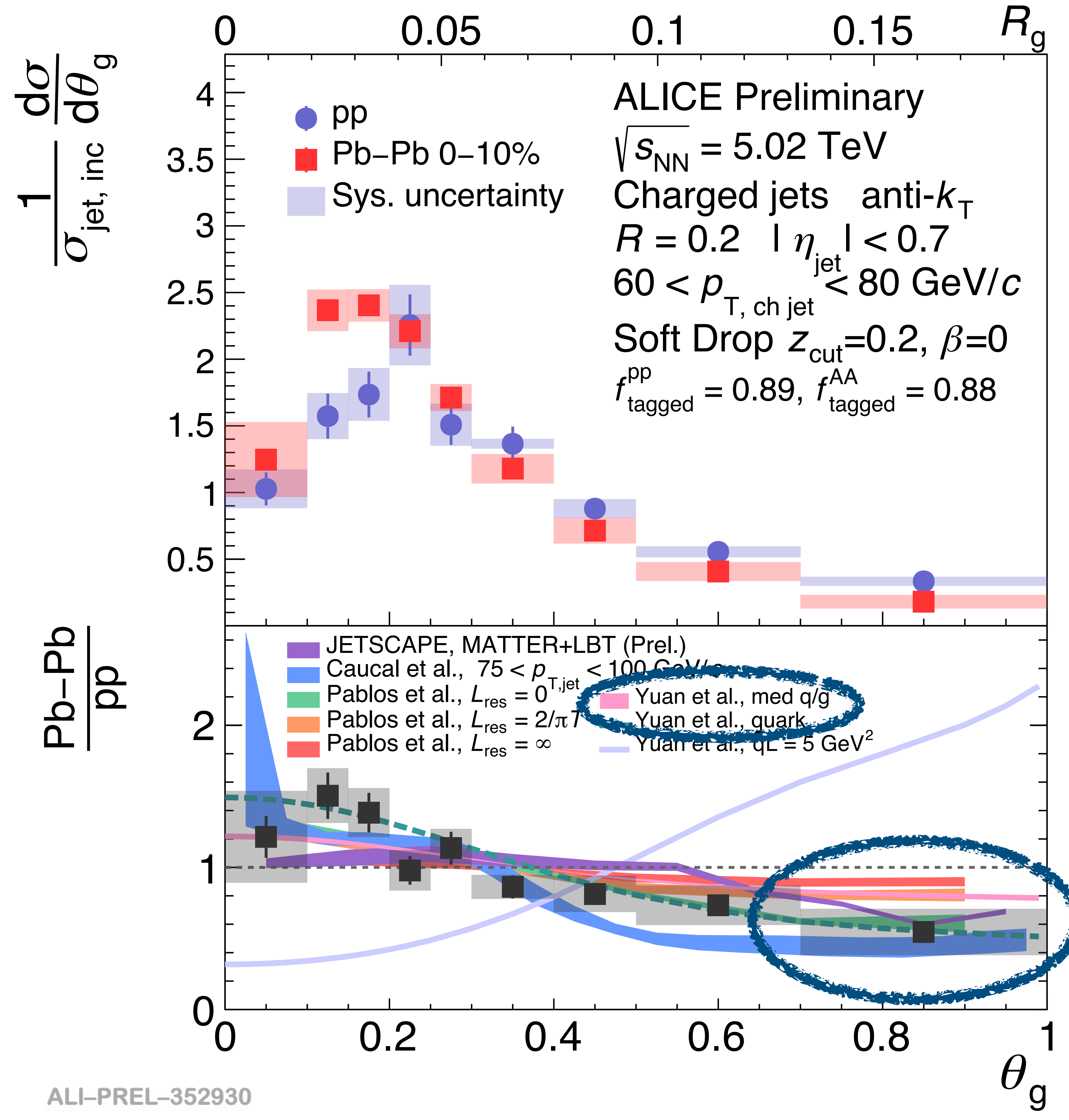
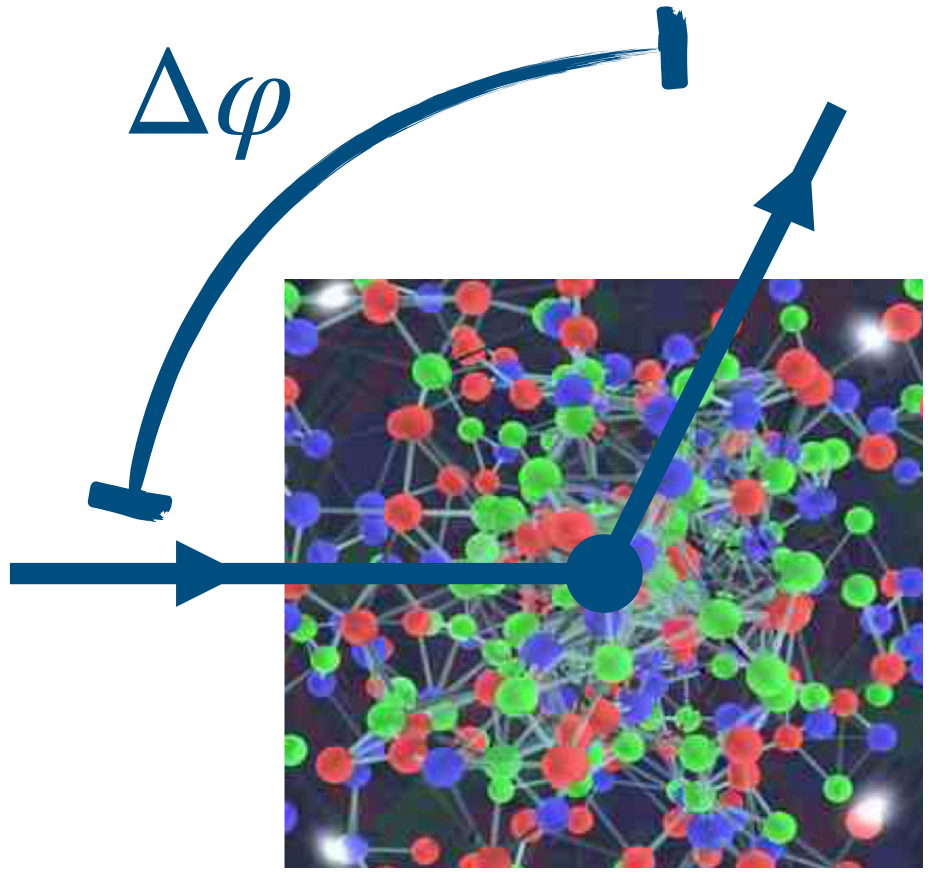


Jet deflection

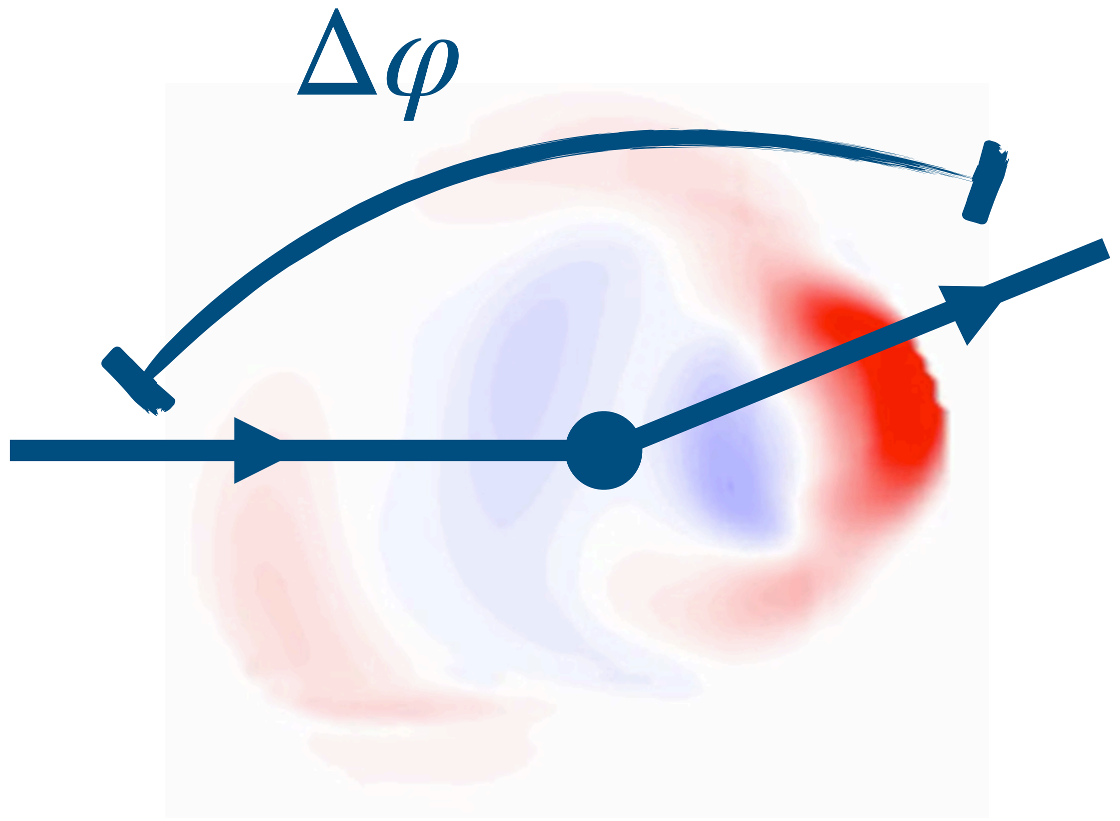
Discrete medium



Large-angle scattering:

$P \sim 1/k_T^4$

Smooth medium



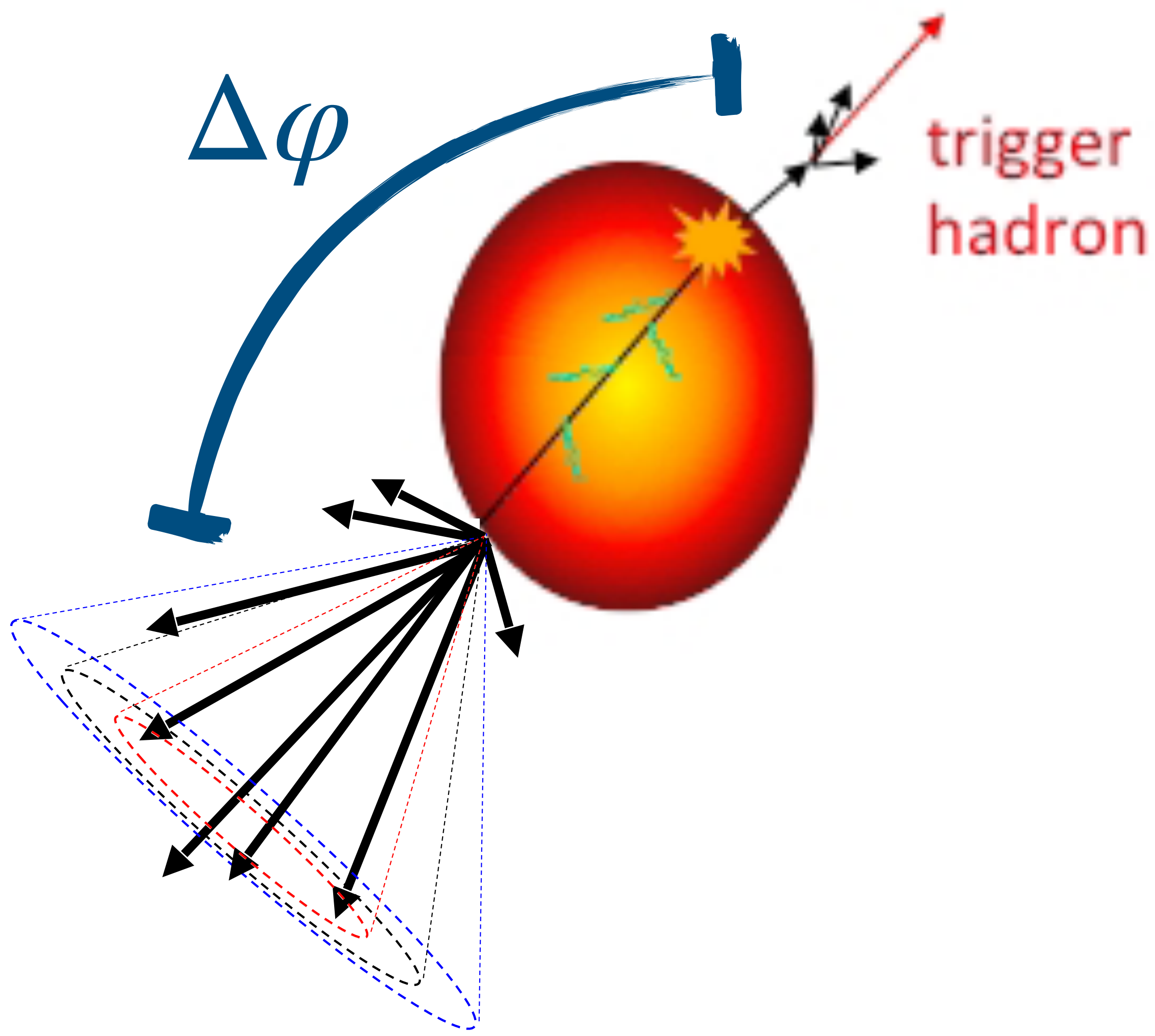
Large-angle scattering:

$P \sim \exp\left(-Ak_T^2\right)$

Search for large-angle scattering — direct probe of microscopic structure

Semi-inclusive hadron-jet correlations

ALICE JHEP 2015 9 (2015) 170
STAR PRC 96 (2017) 024905



Measure semi-inclusive yield of jets recoiling from a trigger hadron:

$$\frac{1}{\mathrm{N}_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^2\mathrm{N}_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{AA}\rightarrow\mathrm{h+X}}} \cdot \frac{\mathrm{d}^2\sigma^{\mathrm{AA}\rightarrow\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\mathrm{d}\eta_{\mathrm{jet}}}\right)\Bigg|_{p_{\mathrm{T,h}}\in\mathrm{TT}}$$

Well-suited to statistical background subtraction procedure in heavy-ion collisions

Allows low-p_{T}, large-*R* measurements

Semi-inclusive hadron-jet correlations

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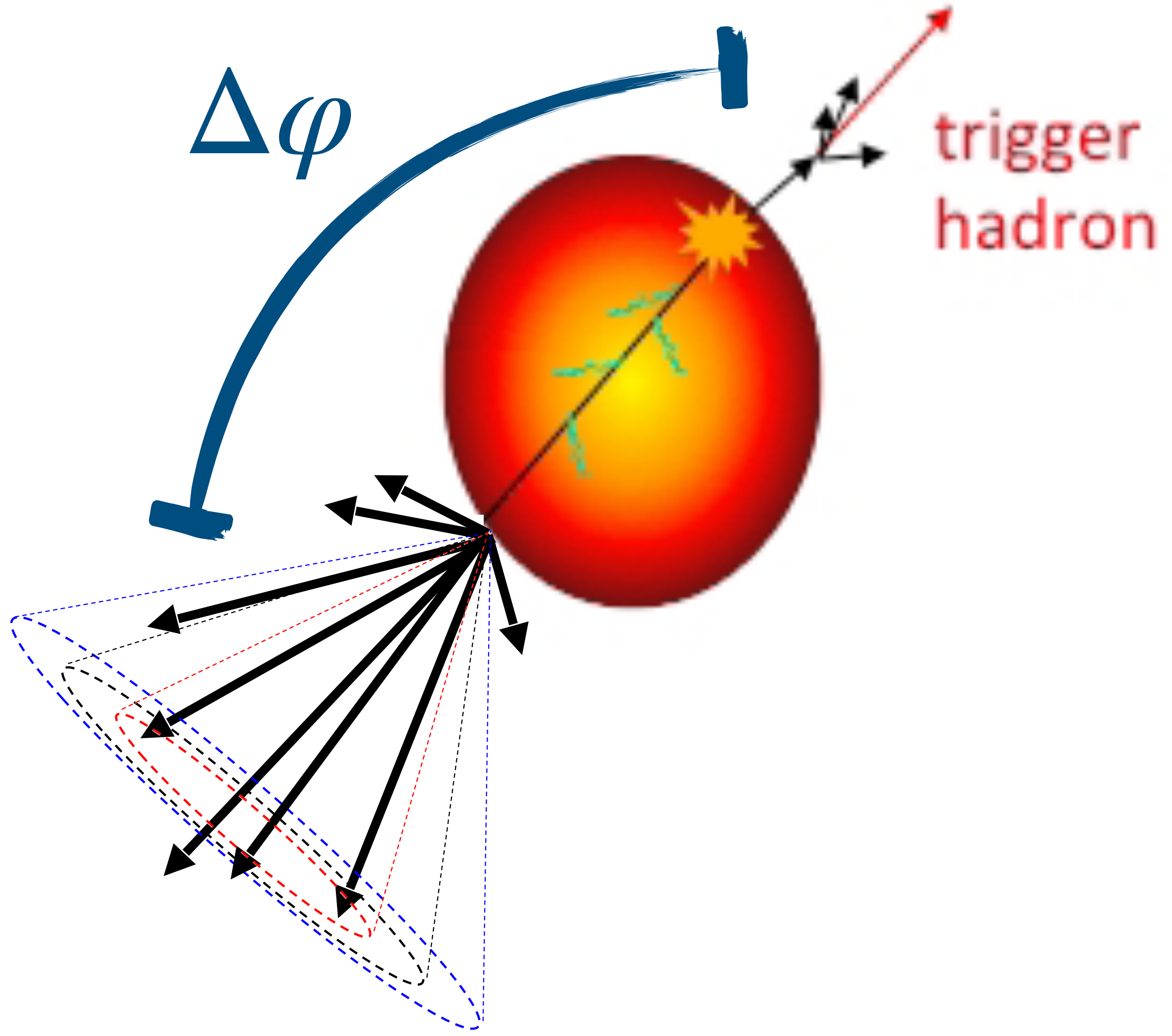
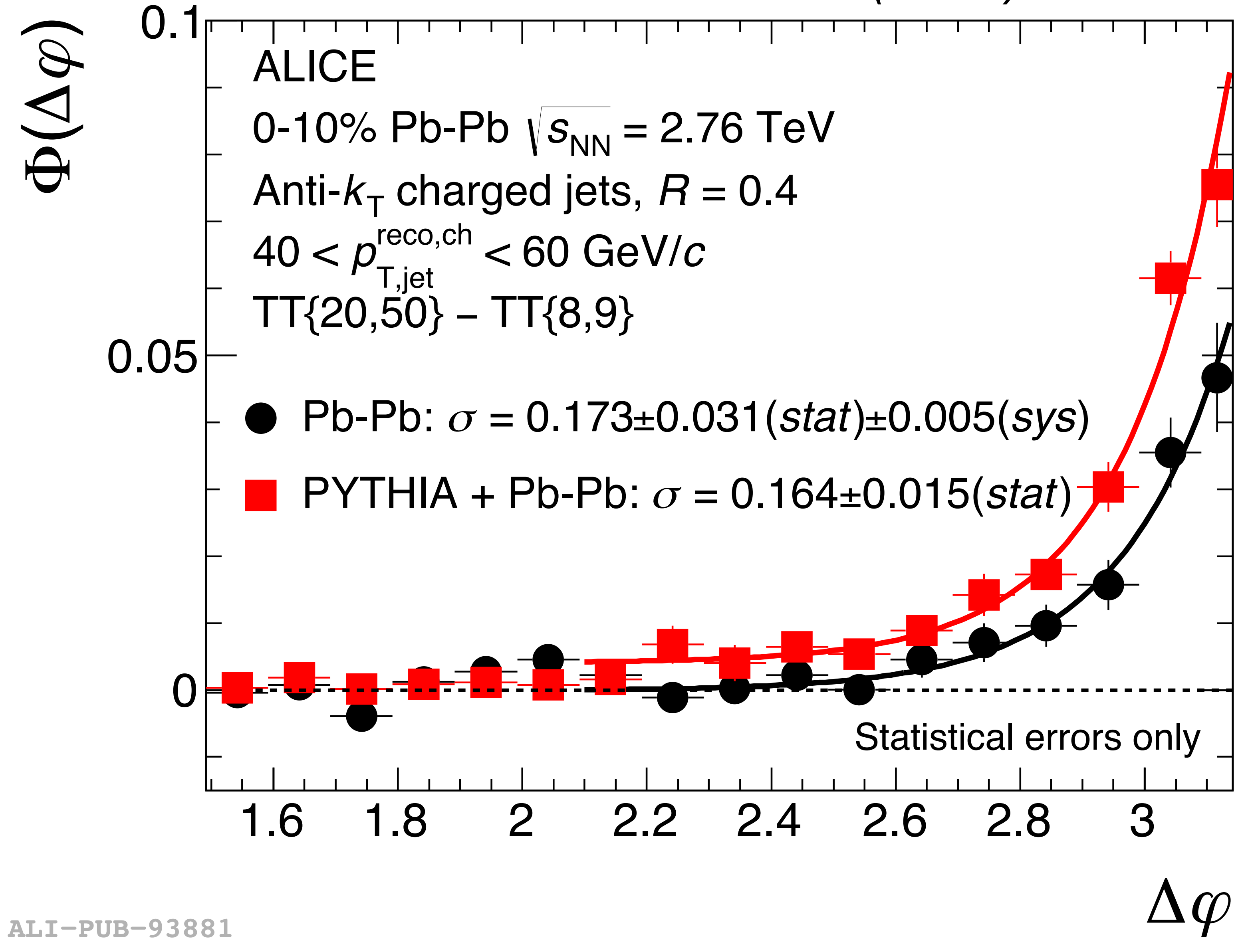


Measure semi-inclusive yield of jets recoiling from a trigger hadron:

$$\frac{1}{N_{\text{trig}}^{\text{AA}}}\frac{d^2N_{\text{jet}}^{\text{AA}}}{dp_{\text{T,jet}}^{\text{ch}}d\eta_{\text{jet}}}\Bigg|_{p_{\text{T,trig}}\in\text{TT}} = \left(\frac{1}{\sigma^{\text{AA}\rightarrow\text{h+X}}}\cdot\frac{d^2\sigma^{\text{AA}\rightarrow\text{h+jet+X}}}{dp_{\text{T,jet}}^{\text{ch}}d\eta_{\text{jet}}}\right)\Bigg|_{p_{\text{T,h}}\in\text{TT}}$$

JHEP (2015) 9 170



Well-suited to statistical background subtraction procedure in heavy-ion collisions

Allows low-p_T, large-*R* measurements

Angular distribution may be sensitive to:

Large-angle deflection

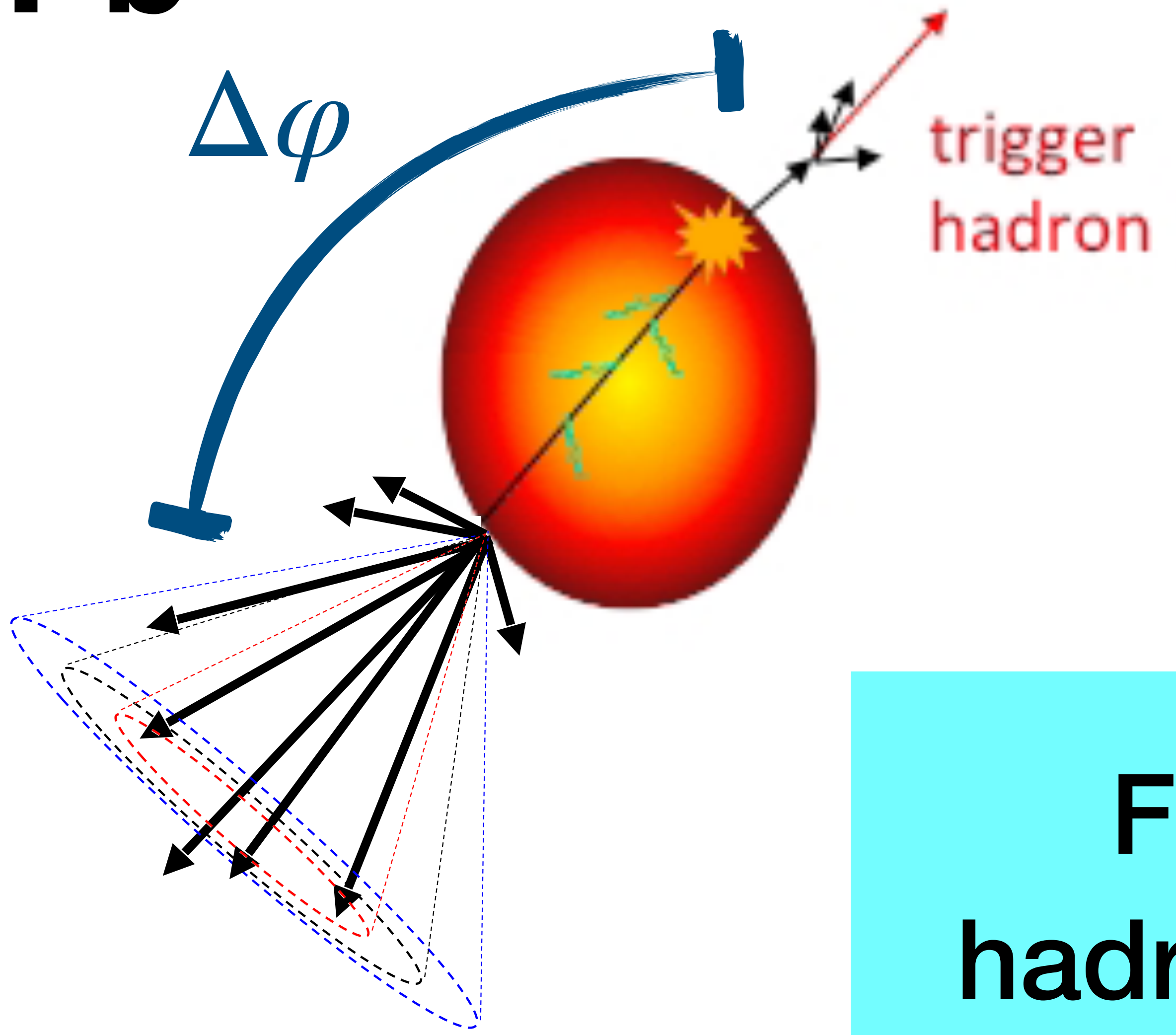
D'Eramo, Rajagopal, Yin JHEP 01 (2019) 172

Jet broadening: $\hat{q}$

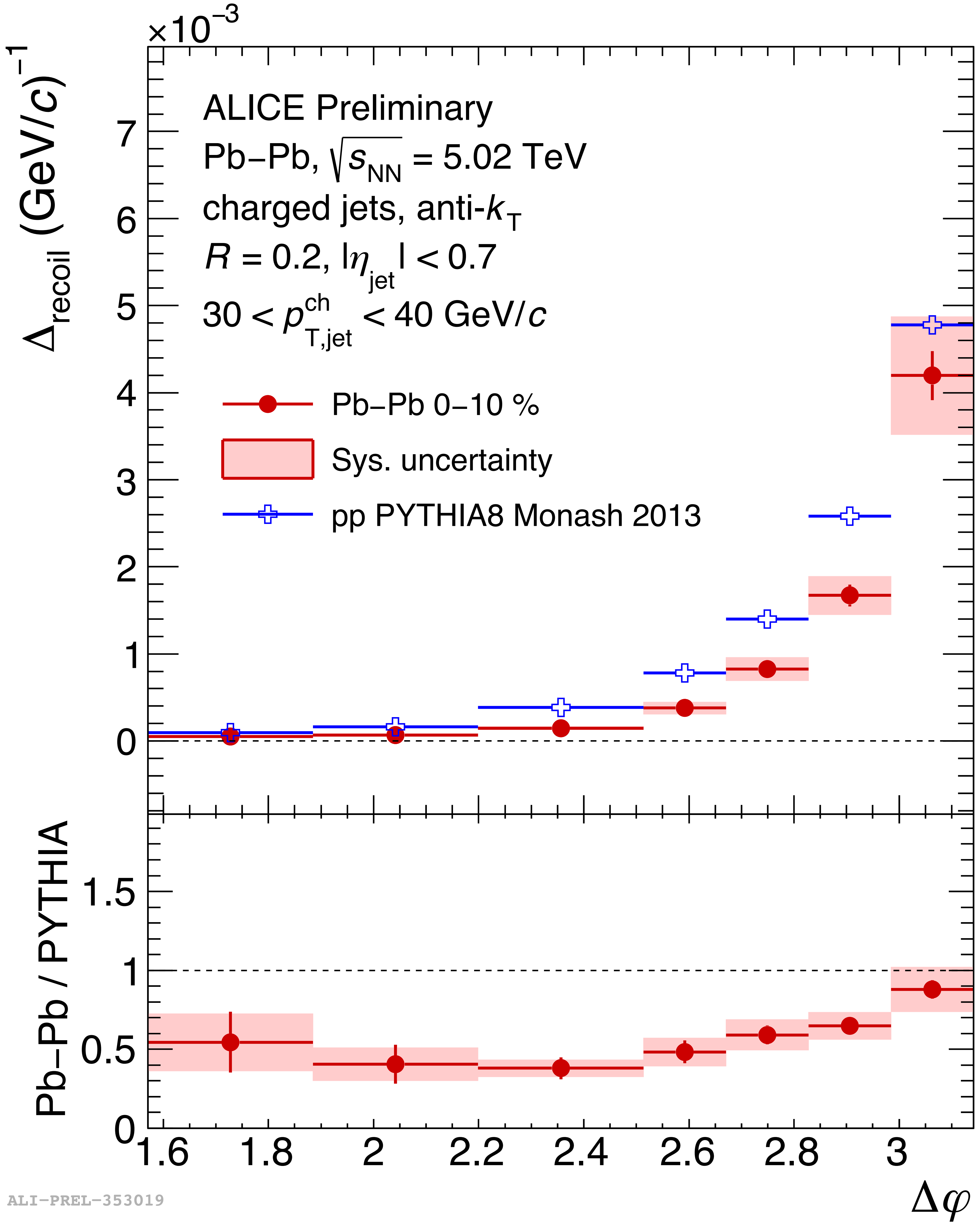
Chen et al., PLB 772 (2017) 672
Gyulassy et al., 1808.03238
Zakharov, 2003.10182

Semi-inclusive hadron-jet correlations

Pb-Pb



First fully-corrected hadron-jet $\Delta\varphi$ distibution



Suppression of Pb-Pb yields relative to pp — but no modification to shape of large-angle tail

Need higher statistics for stronger constraint

Summary

ALICE

ALICE has a rich QCD jet program in both pp and Pb-Pb collisions

Jet substructure, semi-inclusive measurements, and more not covered

Experimental techniques are advancing — corrections for large background

New observables — targeted to **constrain specific physics mechanisms of jet-medium interactions**

The future

Higher luminosities will open higher precision and new probes

LHC Run 3 RHIC (STAR+SPHENIX)

Global analyses — a complex environment demands complementary constraints

JETSCAPE collaboration

Need for theoretical innovation — **how to learn about the medium structure**