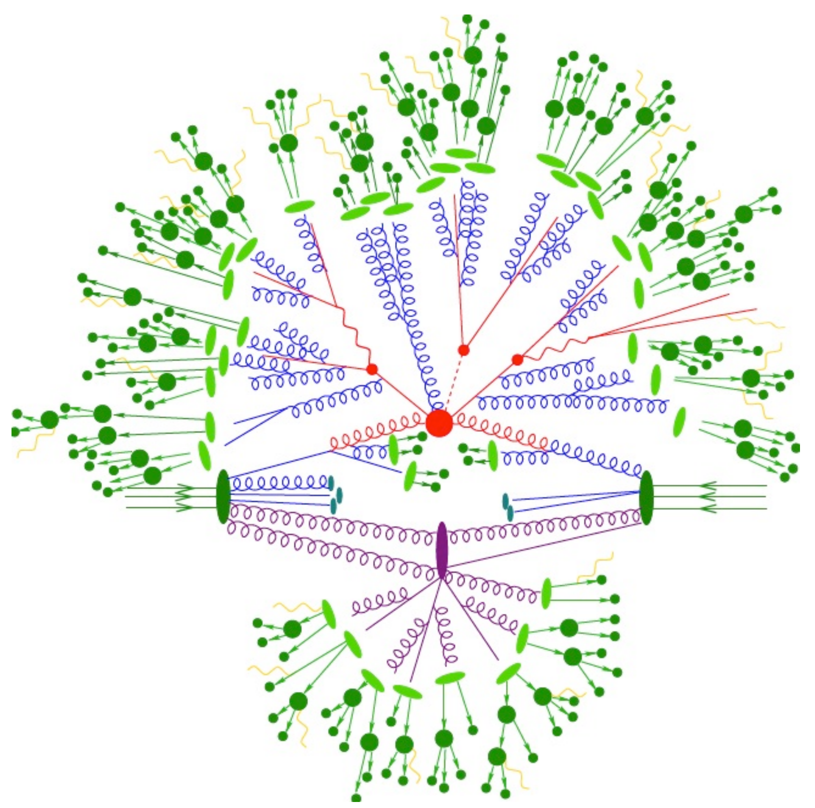
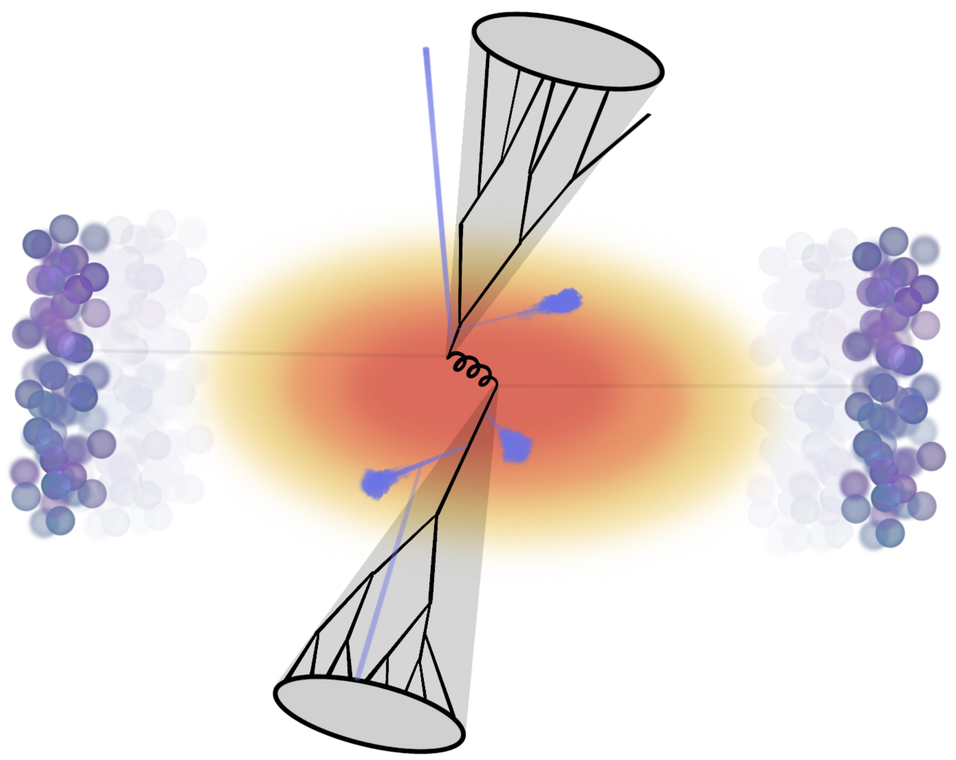
Jet substructure: from proton-proton to heavy-ion collisions with ALICE



James Mulligan

Lawrence Berkeley National Laboratory

on behalf of the ALICE Collaboration

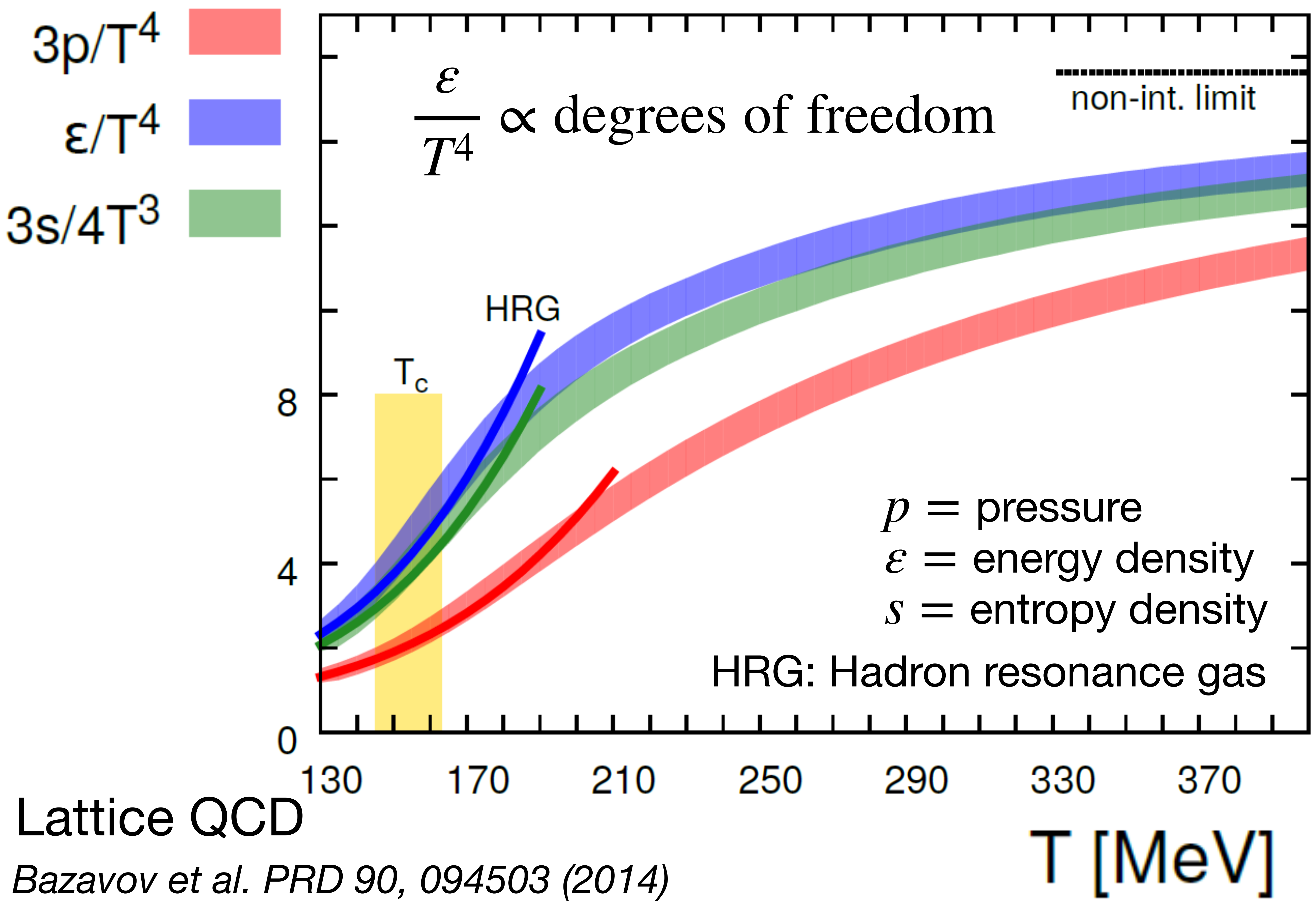


CERN LHC Seminar

Dec 7 2021

The quark-gluon plasma

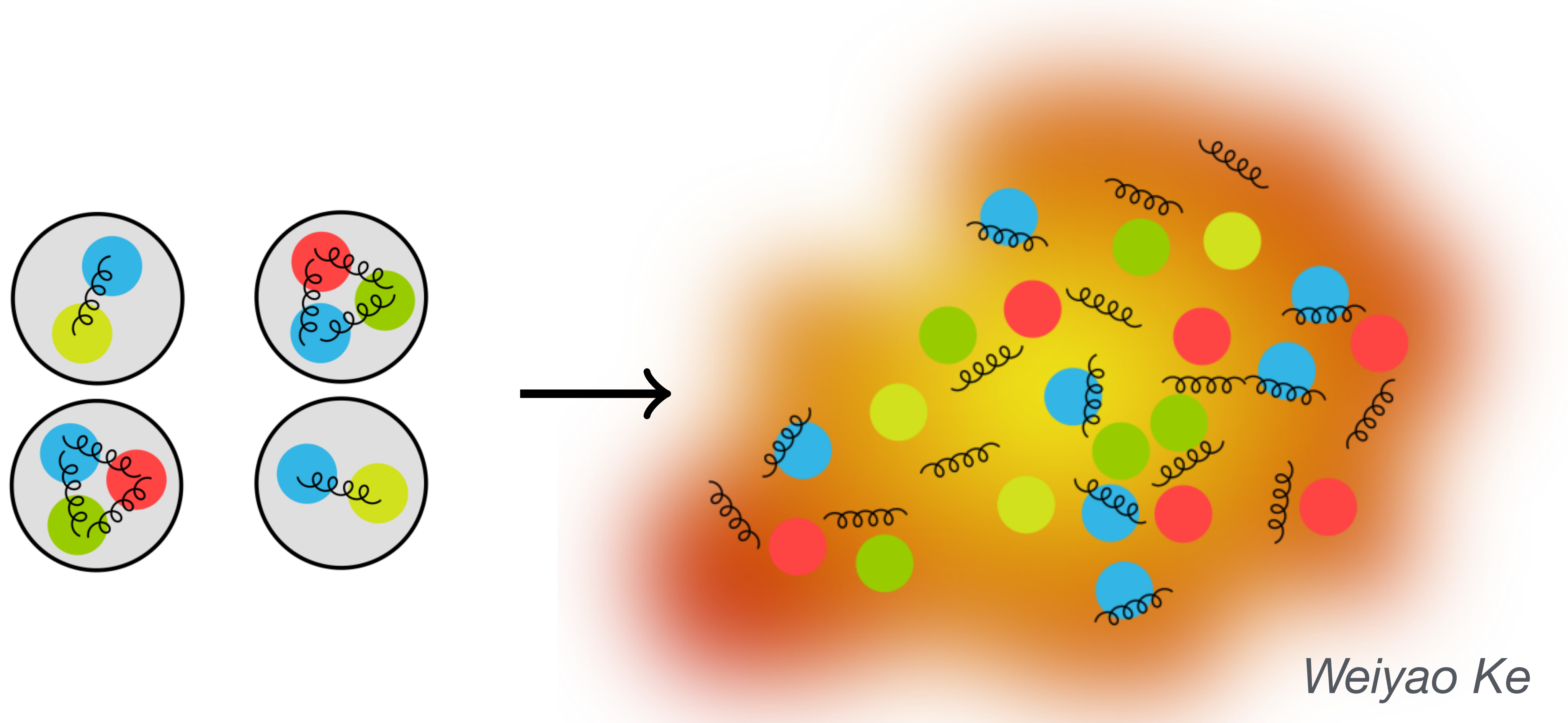
If we heat nuclear matter to $T = \mathcal{O}(100\ \mathrm{MeV})$, thermodynamic quantities exhibit a rapid rise near a crossover temperature T_c



Lattice QCD

Bazavov et al. PRD 90, 094503 (2014)

Deconfinement of quarks and gluons



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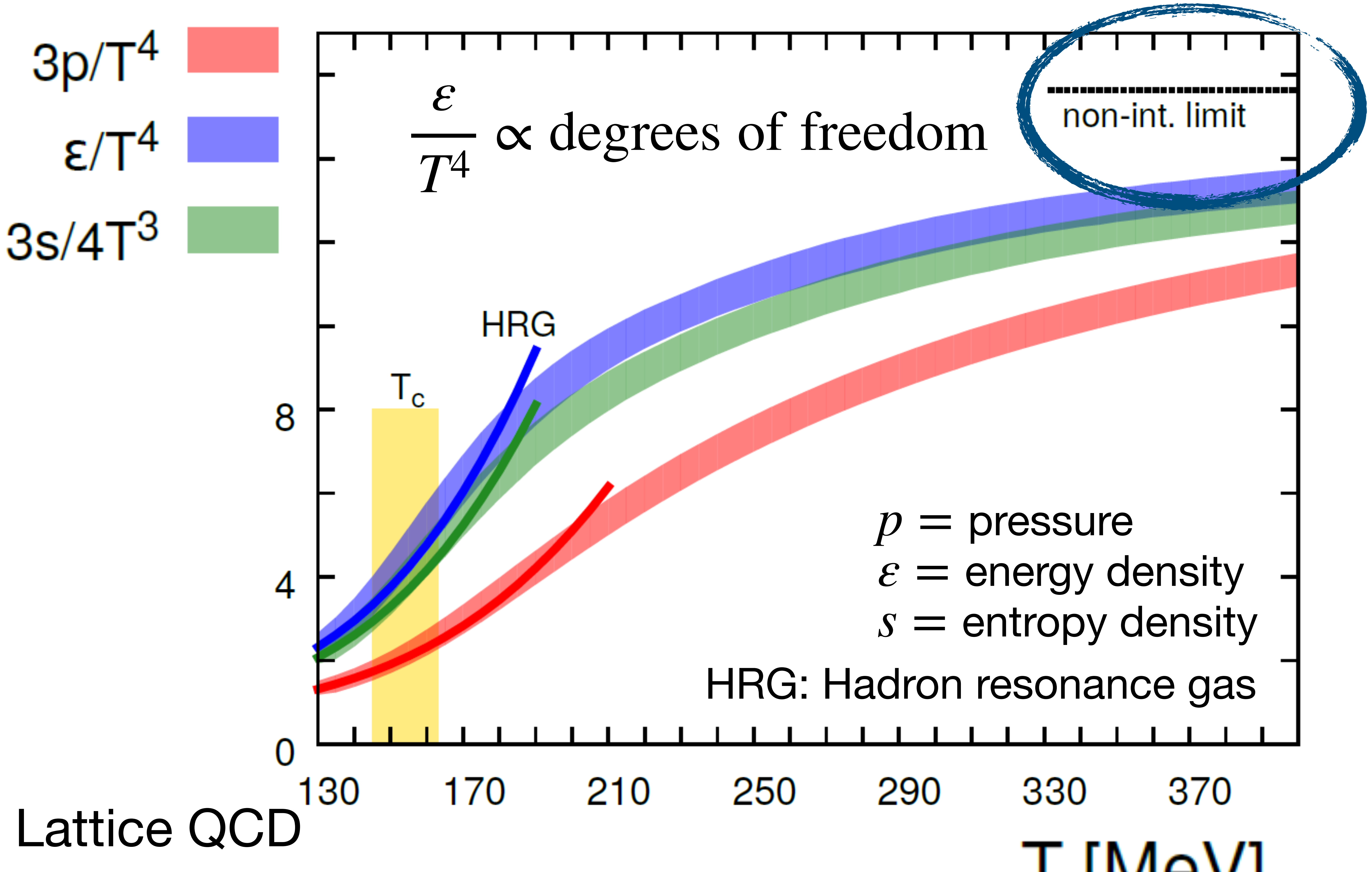
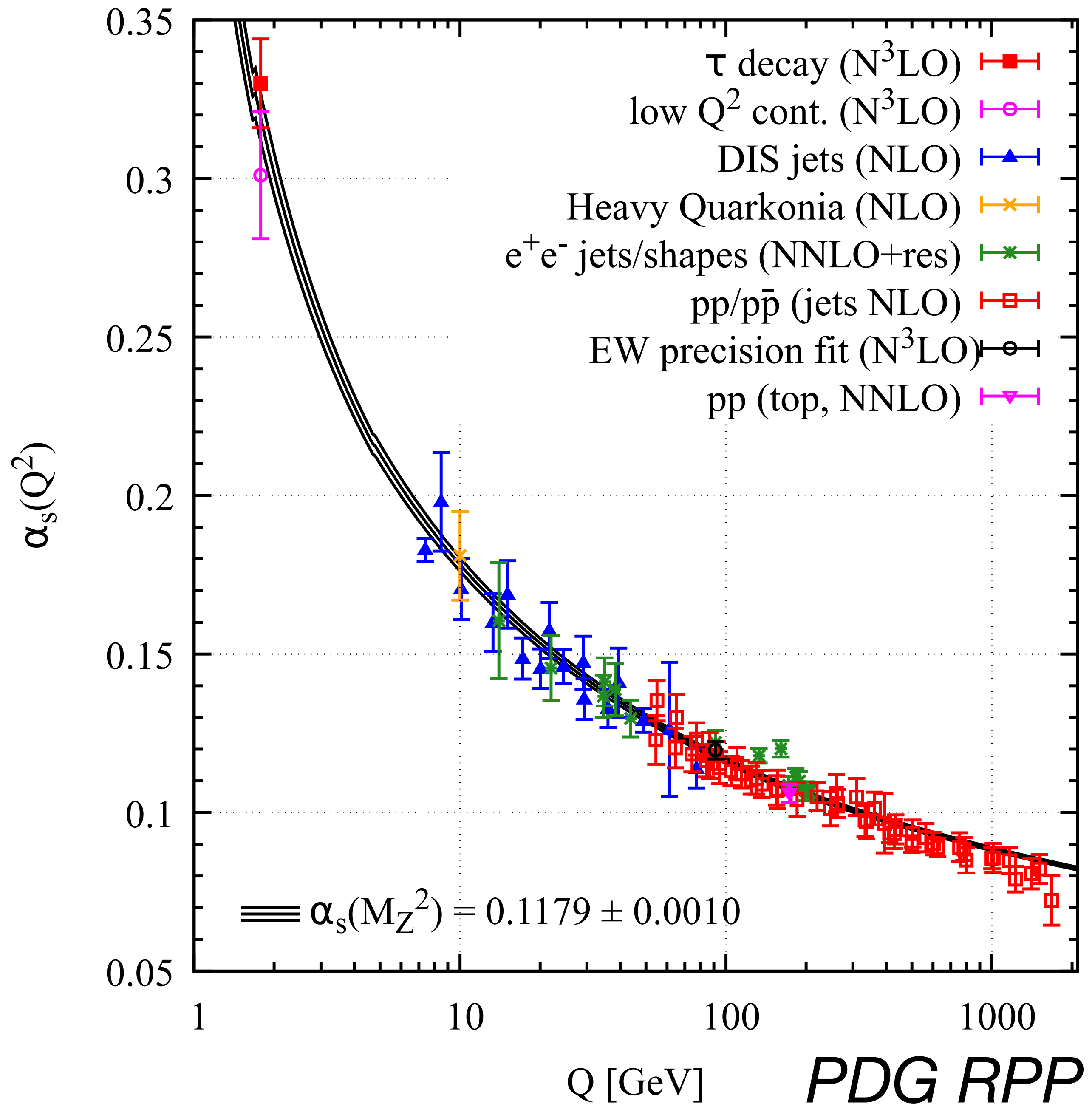


Lattice QCD

Bazavov et al. PRD 90, 094503 (2014)

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



PDG RPP (2019)

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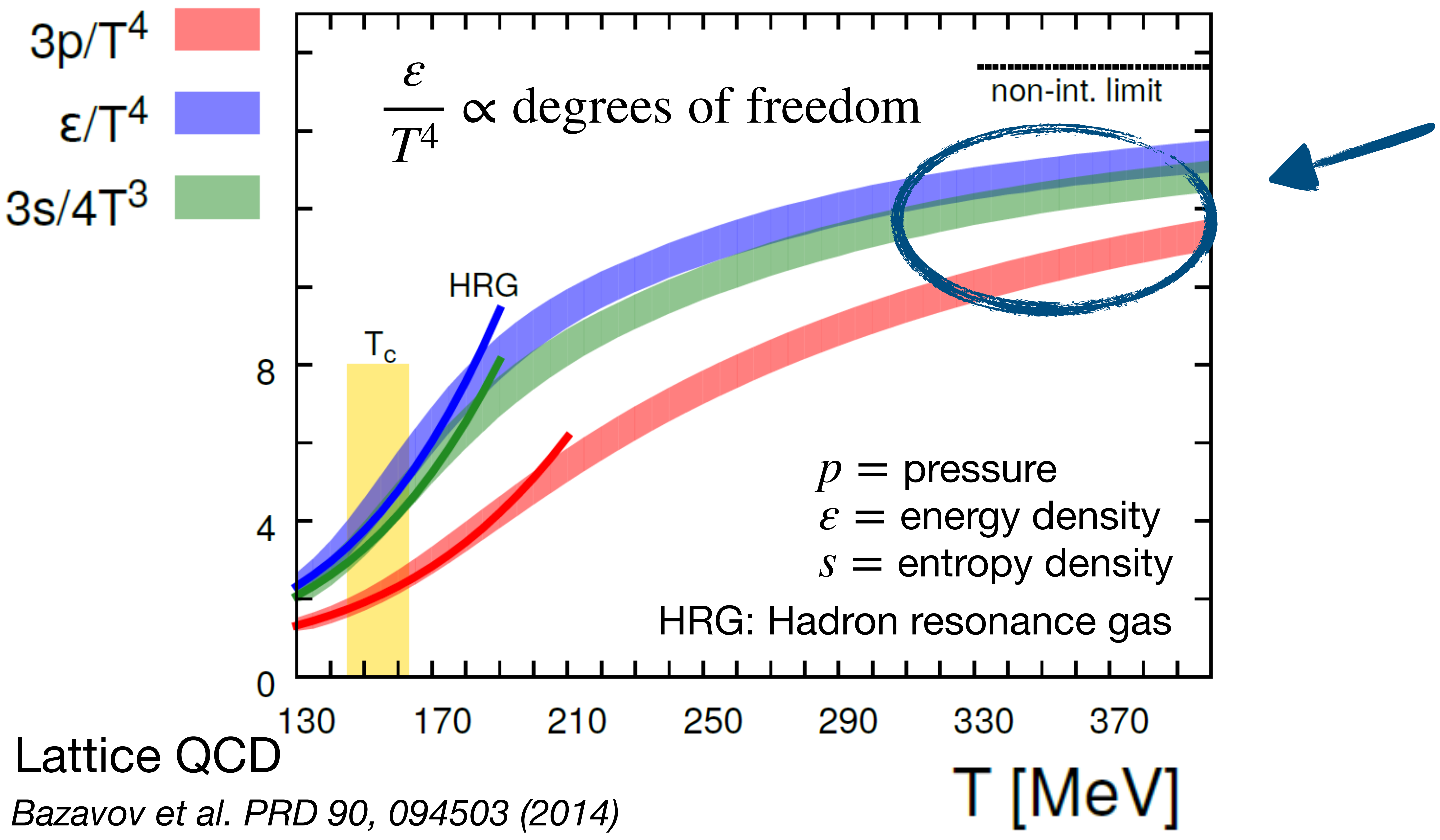
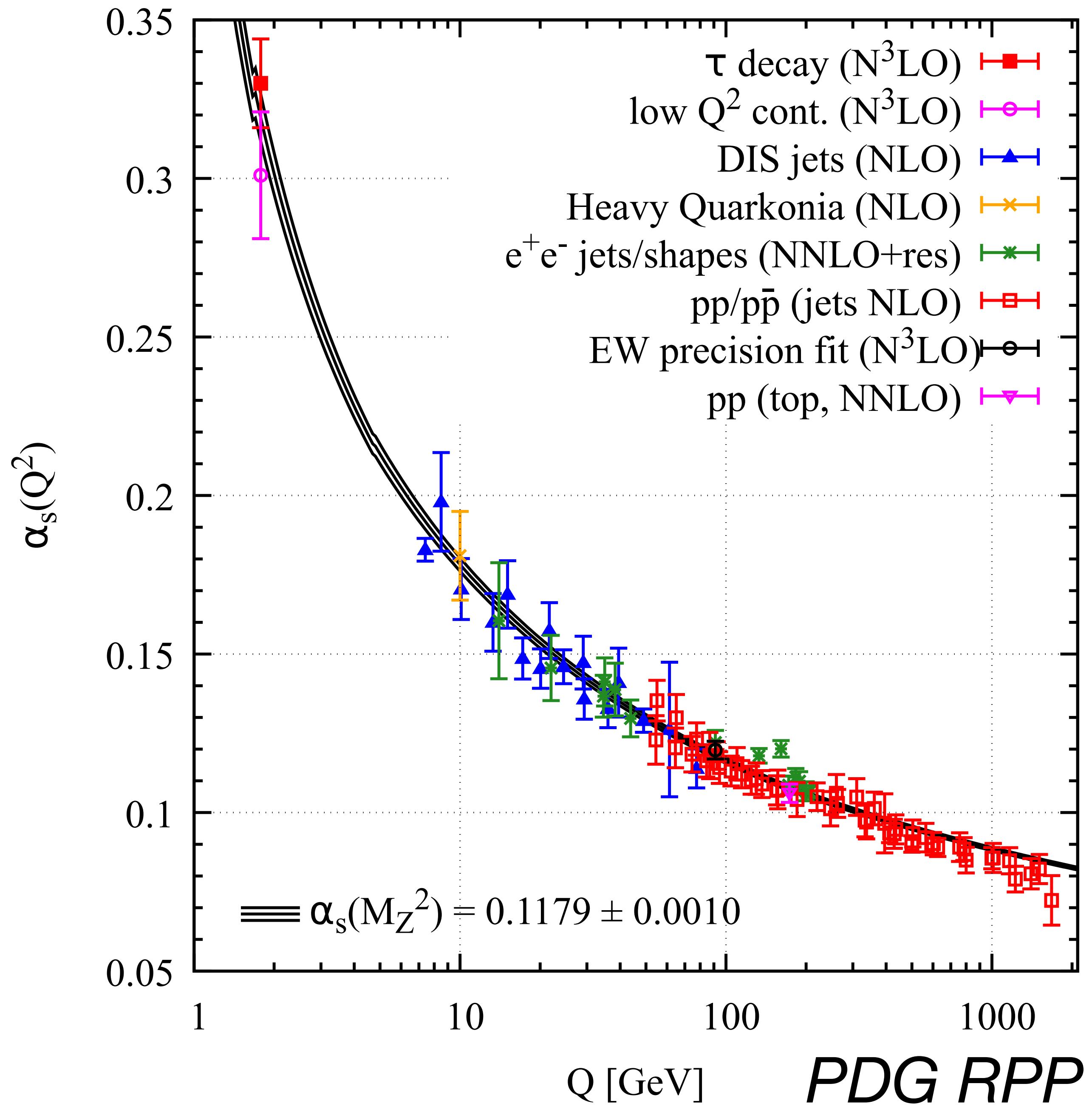


Lattice QCD

Bazavov et al. PRD 90, 094503 (2014)

What is the coupling here?

It turns out to still be quite strong



PDG RPP (2019)

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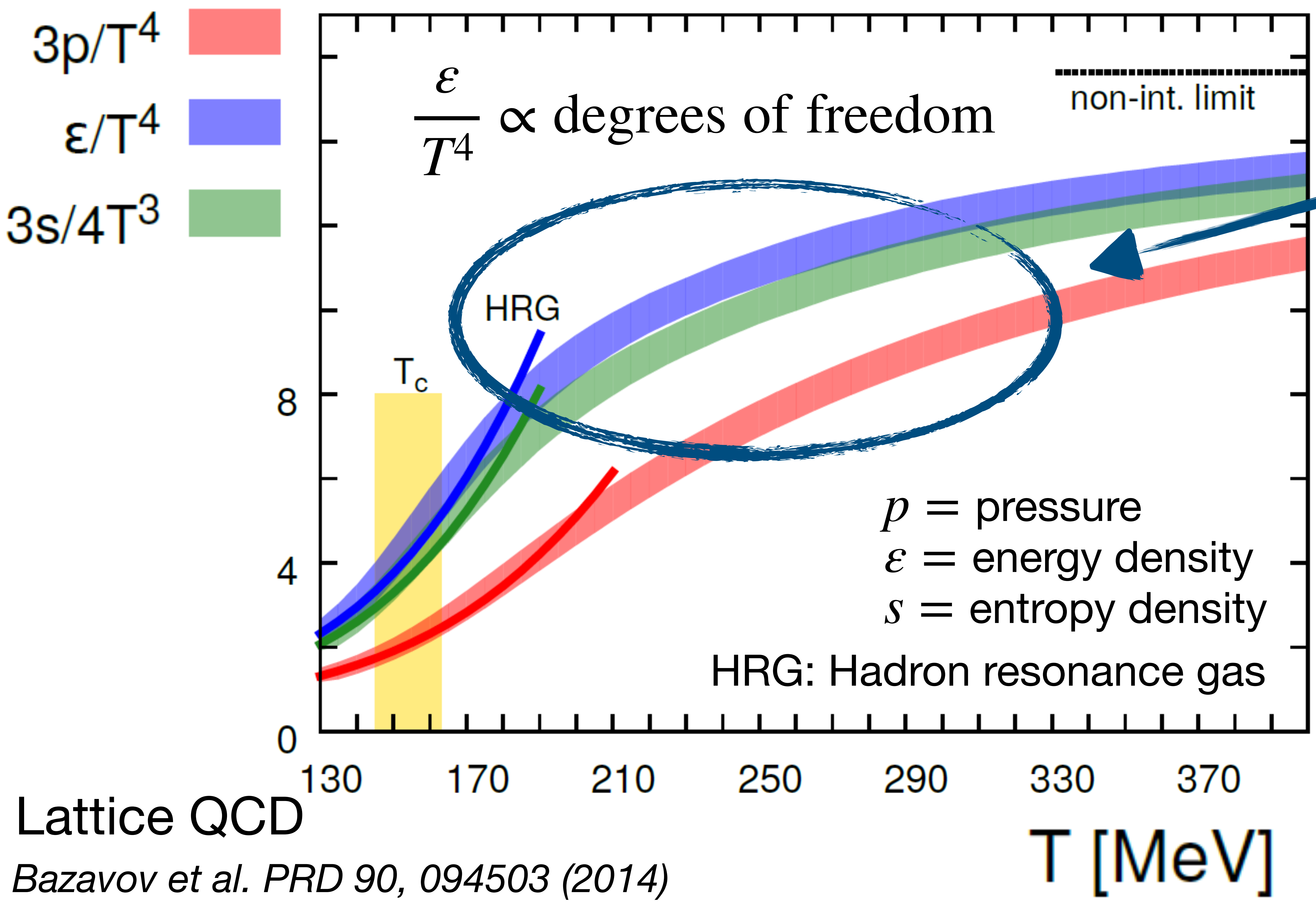
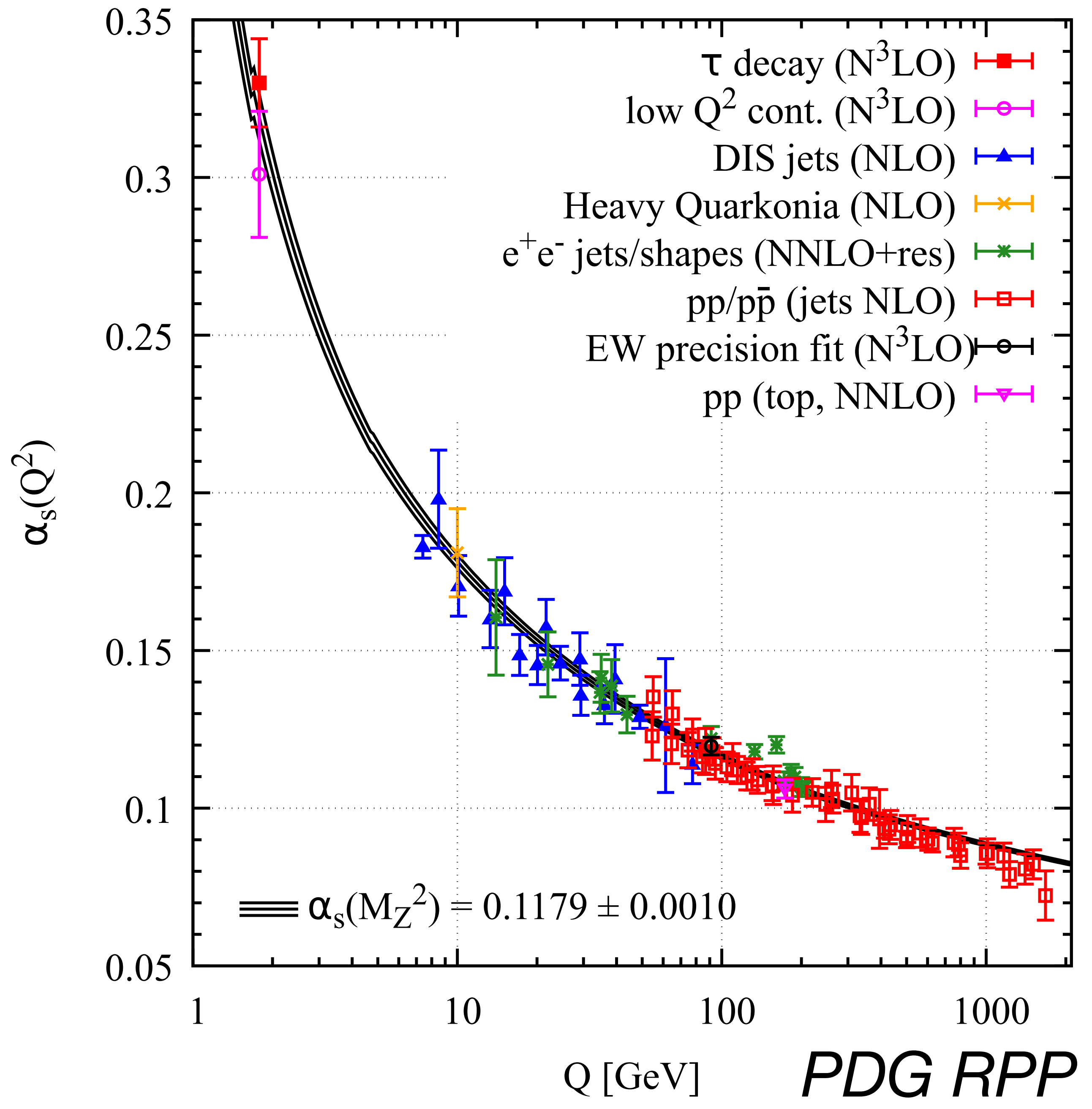


Lattice QCD

Bazavov et al. PRD 90, 094503 (2014)

What is the structure of QCD matter as a function of *T*?

We don't know!



PDG RPP (2019)

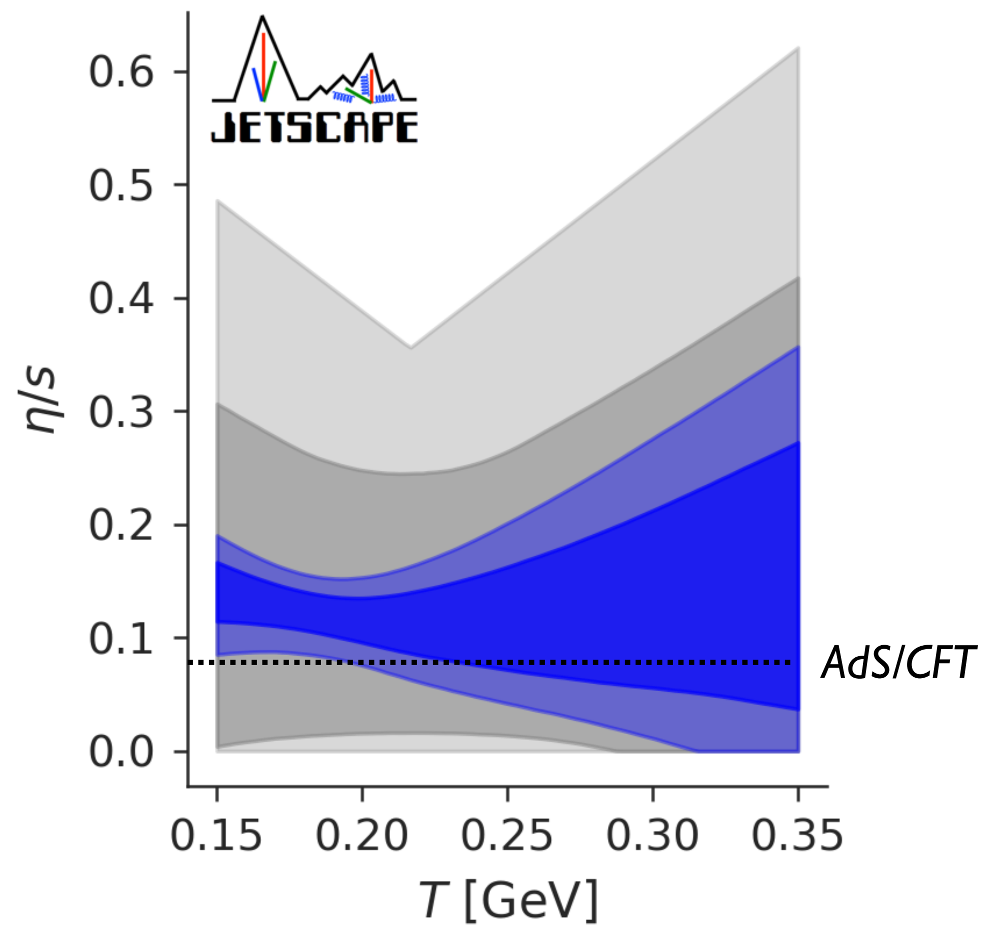
The quark-gluon plasma

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

- Deconfined
- Strongly-coupled

Example: Bayesian extraction of specific shear viscosity (η/s)

e.g. *JETSCAPE PRL 126, 242301 (2021)*



But much more to learn!

The quark-gluon plasma

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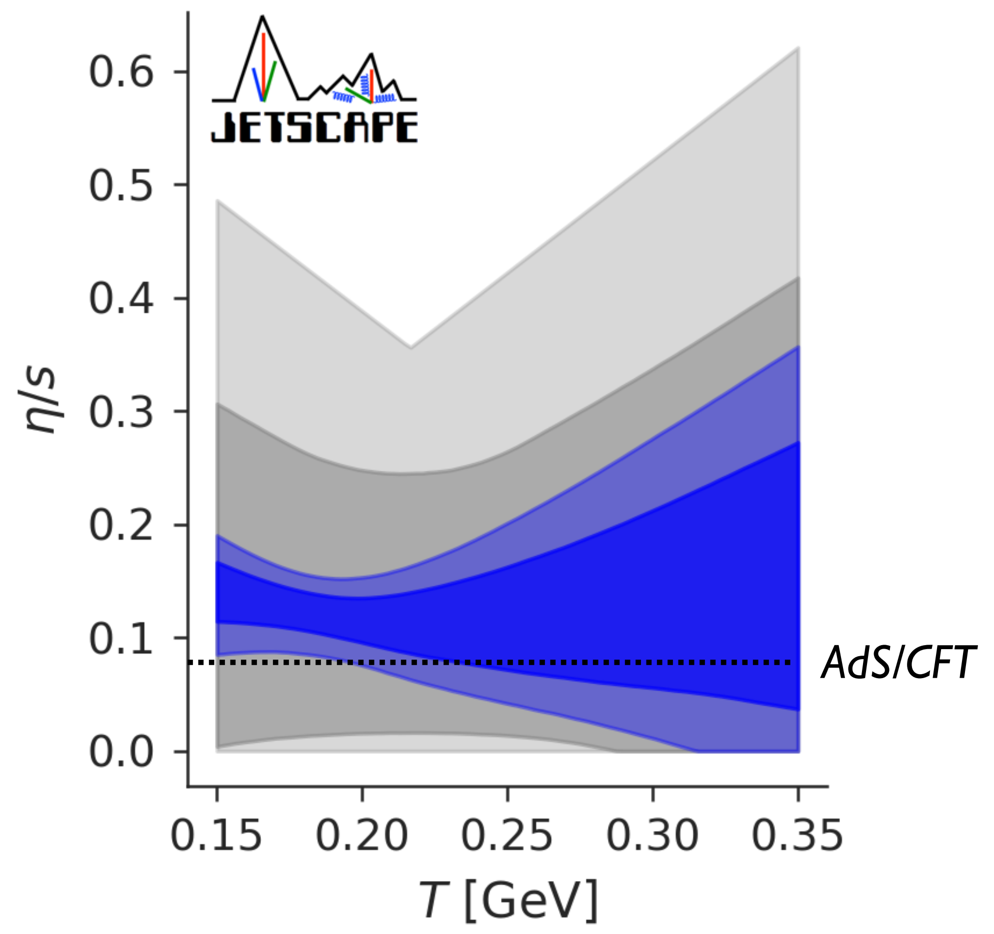


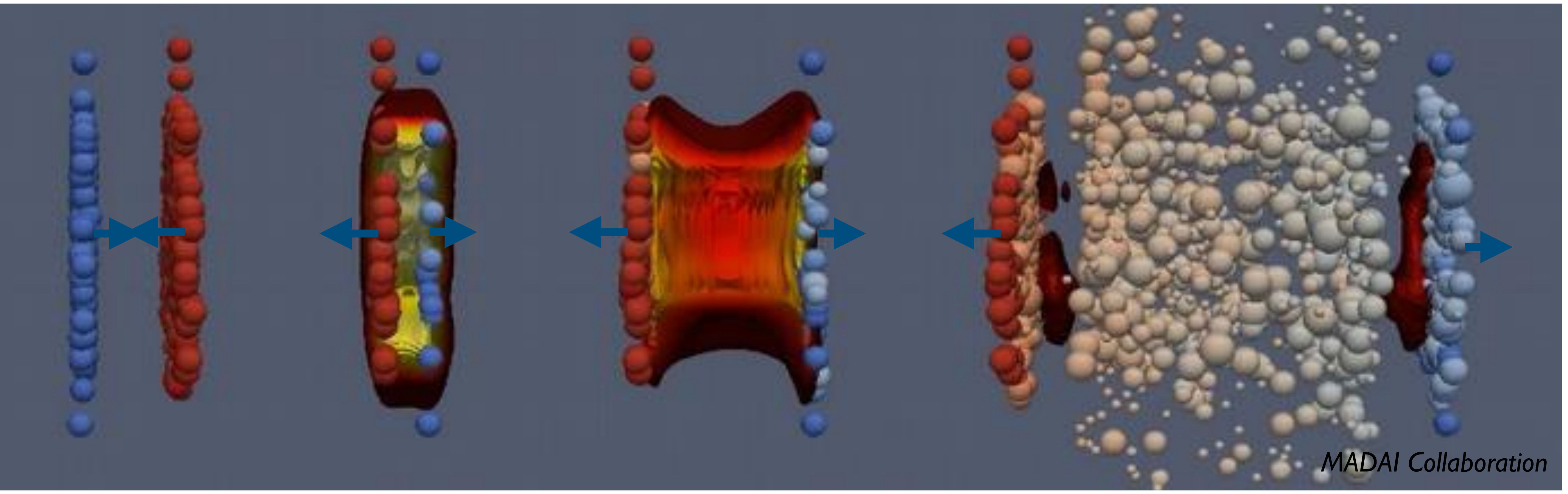
The quark-gluon plasma is a laboratory to study how complex properties emerge from the fundamental laws of quantum chromodynamics

How does this strongly-coupled fluid arise from the Lagrangian of QCD?

What are the relevant degrees of freedom of the QGP as a function of resolution scale?

How does color confinement emerge?

Heavy-ion collisions

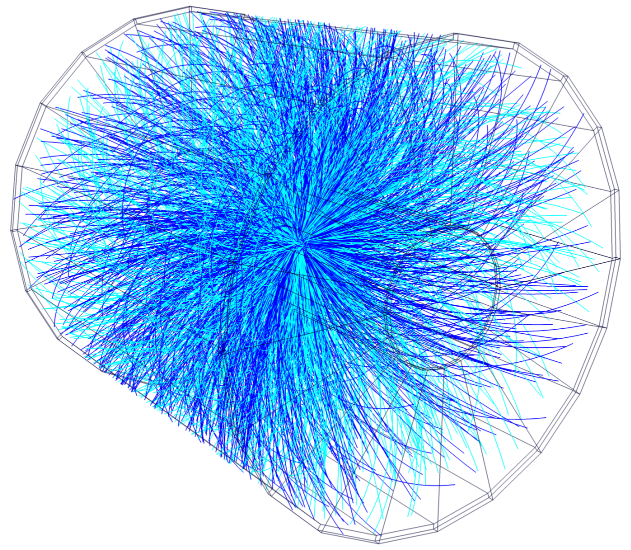


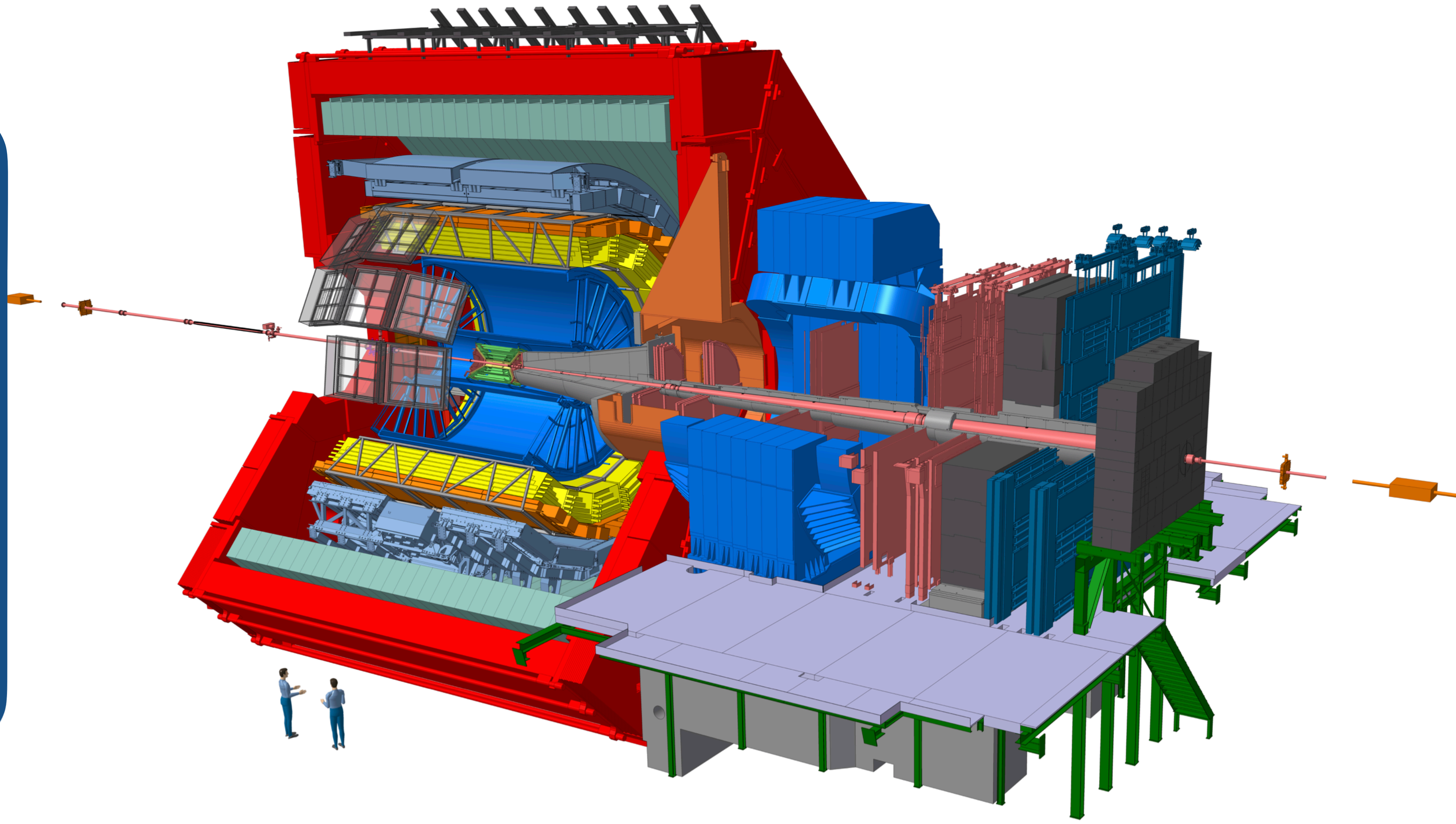
At the LHC, we collide nuclei to produce droplets of this hot, dense state of matter known as the quark-gluon plasma

$T \approx 150\text{-}500$ MeV $\qquad t \sim \mathcal{O}\left(10 \text{ fm}/c\right)$

The **ALICE detector** is designed for the high multiplicity environment of heavy-ion collisions

- High-precision tracking system
- Particle identification
- Forward muon arm
- Calorimetry

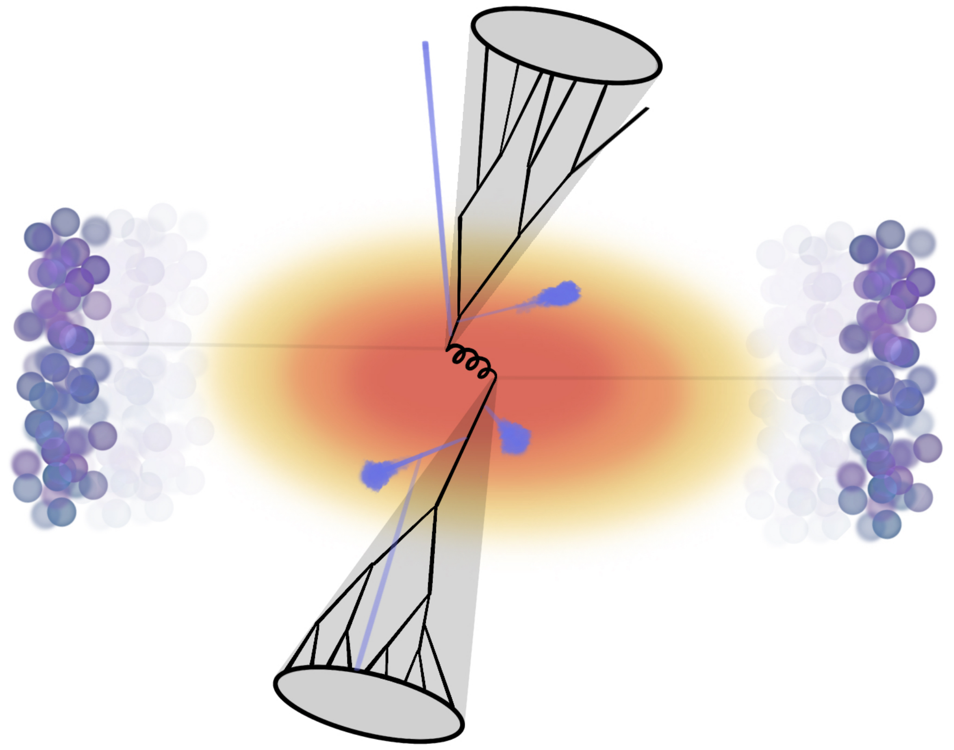




Jet quenching in the quark-gluon plasma

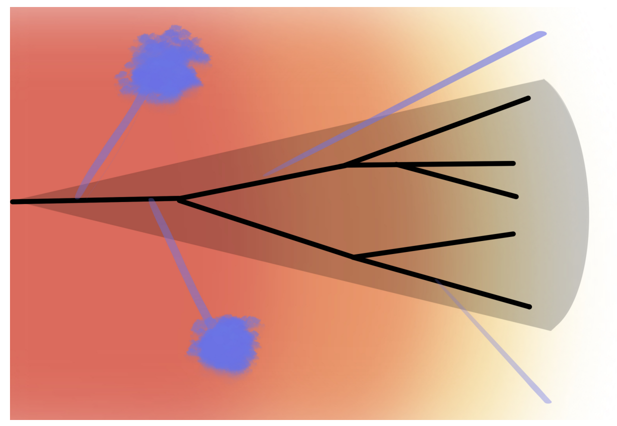
The QGP is too small and short-lived to be probed by traditional scattering beams

⟶ Use jets as probes



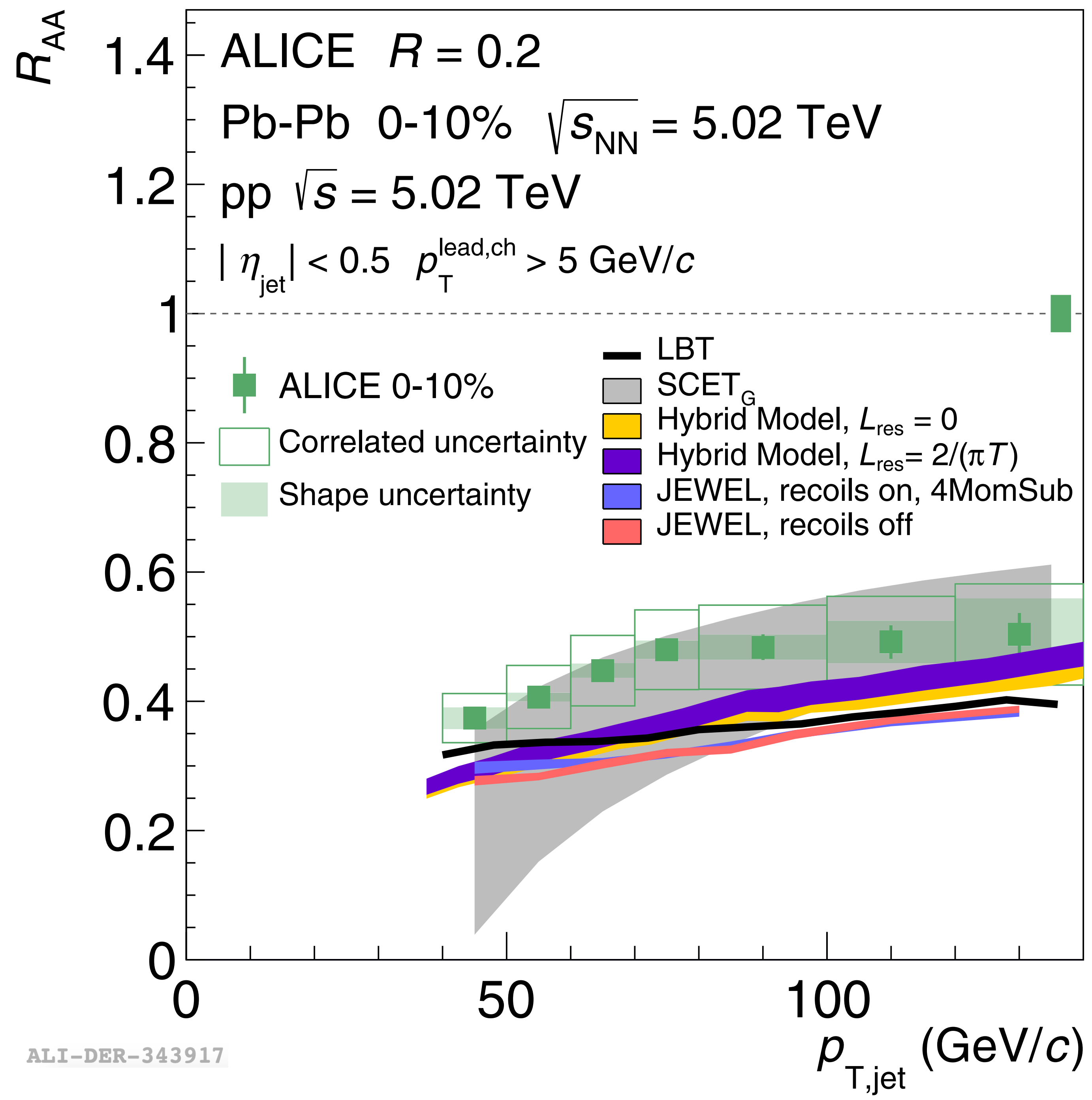
Jets interact with the quark-gluon plasma as they traverse it:

"Energy loss"



$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{PbPb}/dp_T}{dN^{pp}/dp_T}$$

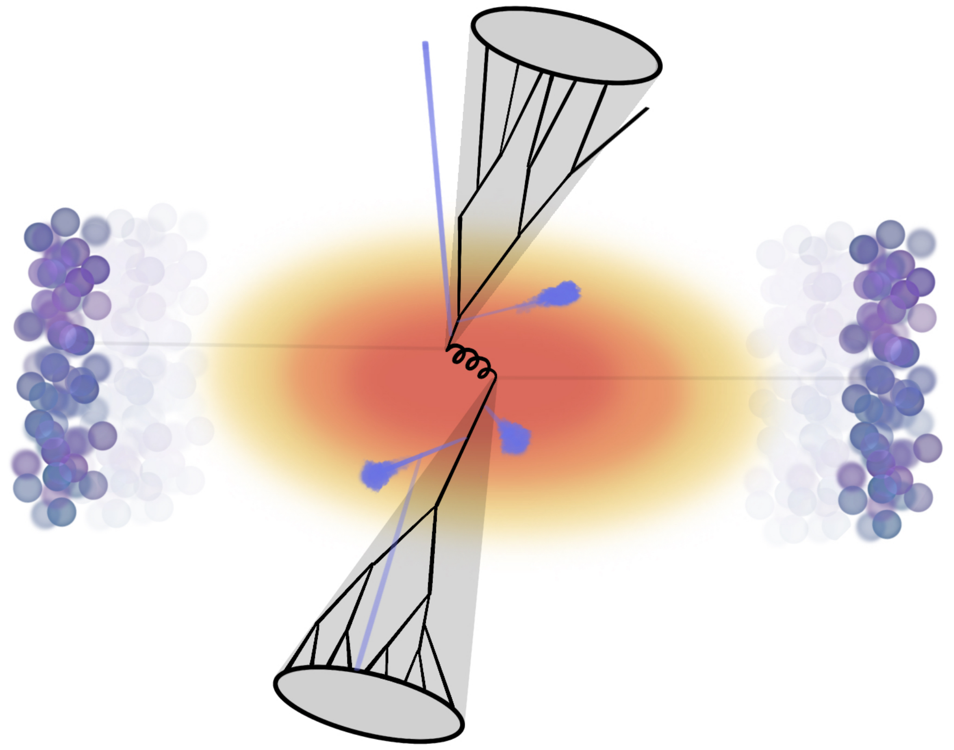
ALICE PRC 101 034911 (2020)
CMS JHEP 05 (2021) 284
ATLAS PLB 790 (2019) 108



Jet quenching in the quark-gluon plasma

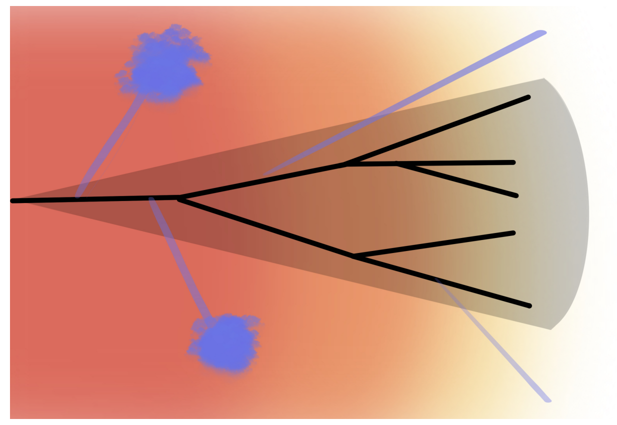
The QGP is too small and short-lived to be probed by traditional scattering beams

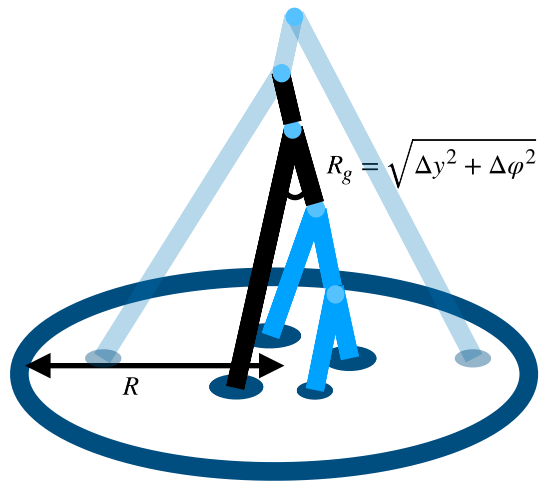
→ **Use jets as probes**

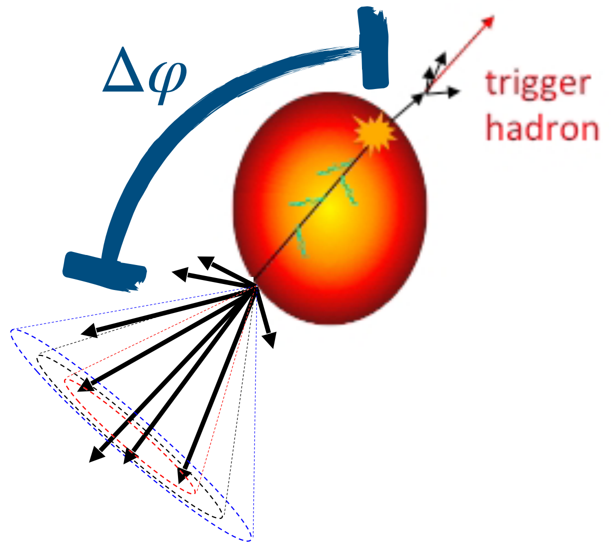


Jets interact with the quark-gluon plasma as they traverse it:

"Energy loss"	**Substructure modification**	**Deflection**





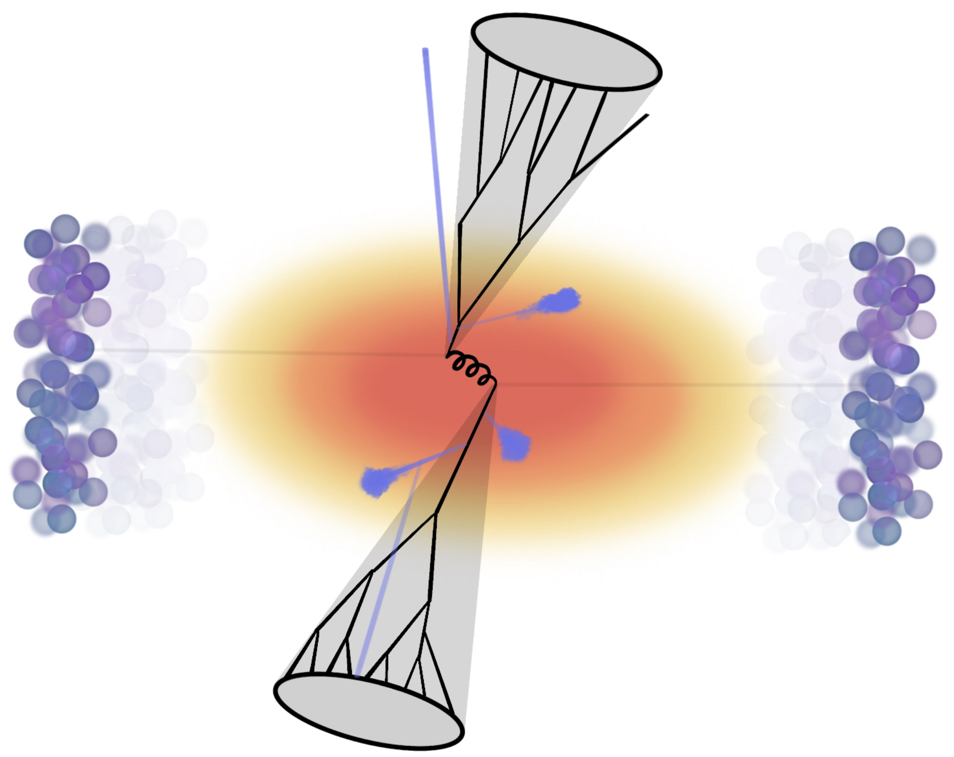


By modeling these interactions, we hope to determine the structure of the QGP

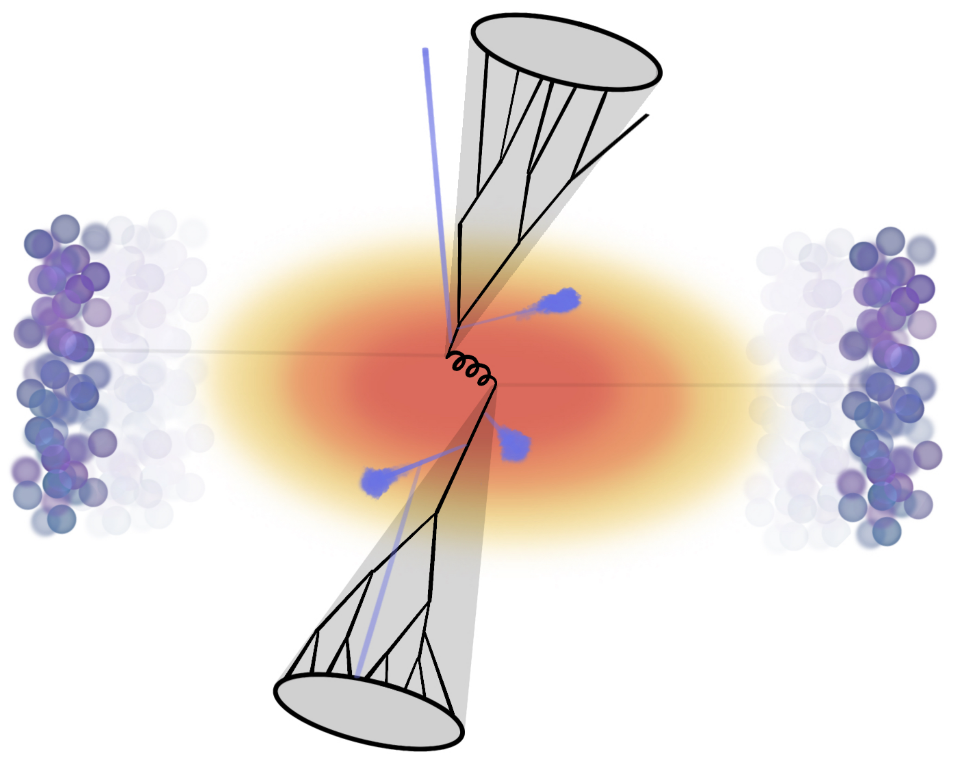
Jet quenching in the quark-gluon plasma

Theoretical challenges in AA

- Strongly-coupled vs. weakly coupled interaction?
- Factorization in AA?
- Spacetime picture of parton shower?
- …



Jet quenching in the quark-gluon plasma



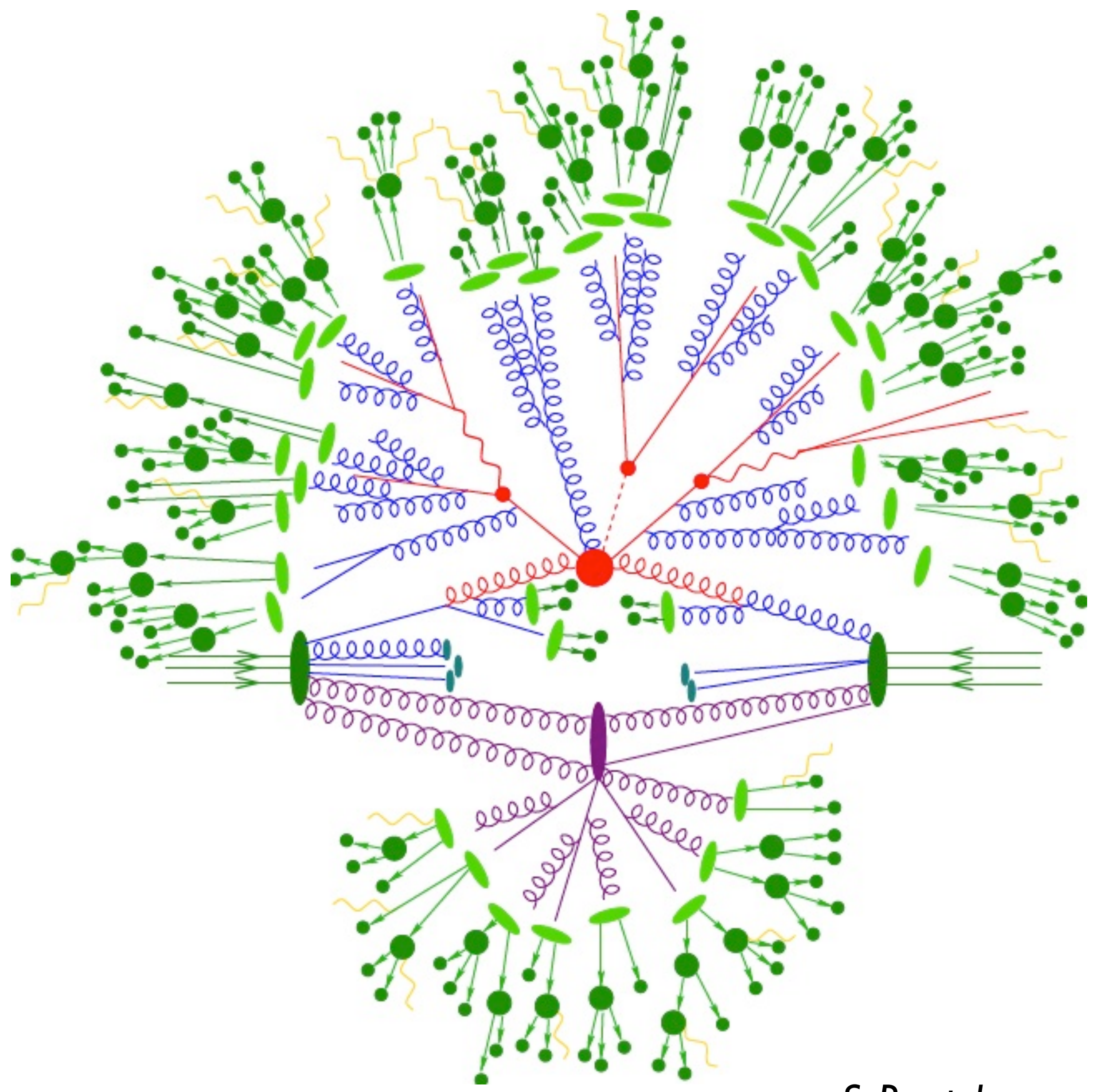
Theoretical challenges in AA

- Strongly-coupled vs. weakly coupled interaction?
- Factorization in AA?
- Spacetime picture of parton shower?
- …

But jet evolution is already quite complicated in pp!

- NLO, NNLO effects can be large
- Large logarithms in cross sections that contribute at all orders in α_s
- Non-perturbative effects: hadronization, underlying event
- …

Understanding jet quenching begins in proton-proton collisions



S. Prestel

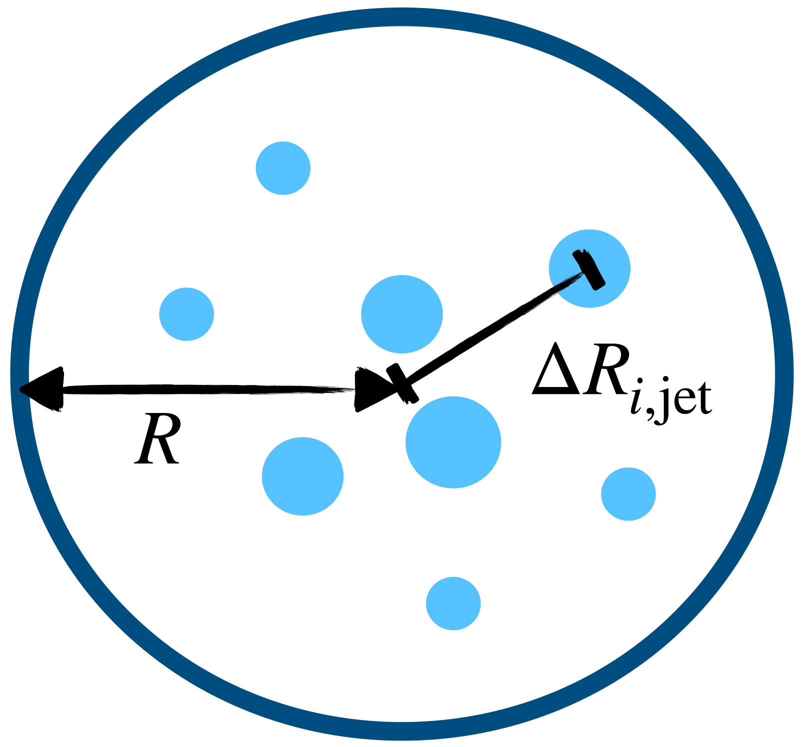
Jet substructure

First cluster a jet, then construct an observable from its constituents

Groomed observables

Recluster the jet constituents and identify a high-Q^2 splitting

Ungroomed observables



Sum a quantity over all jet constituents

e.g. jet mass: $m^2 = \left(\sum p_i\right)^2$

…

Jet substructure

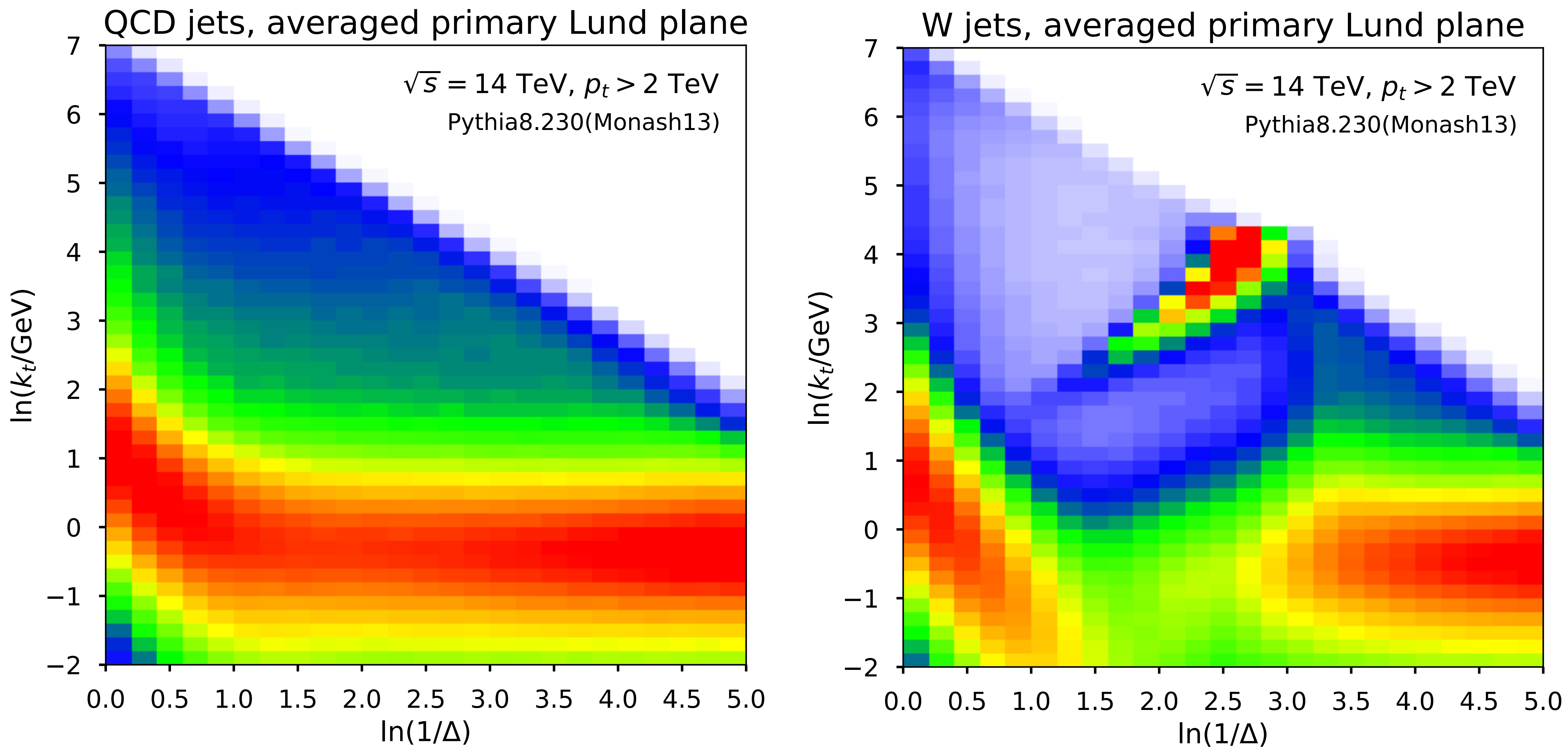
Tagging

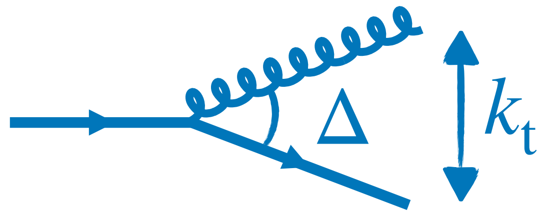
Fundamental QCD

Jet substructure

Tagging

- Boosted objects
- Quark vs. gluon jets





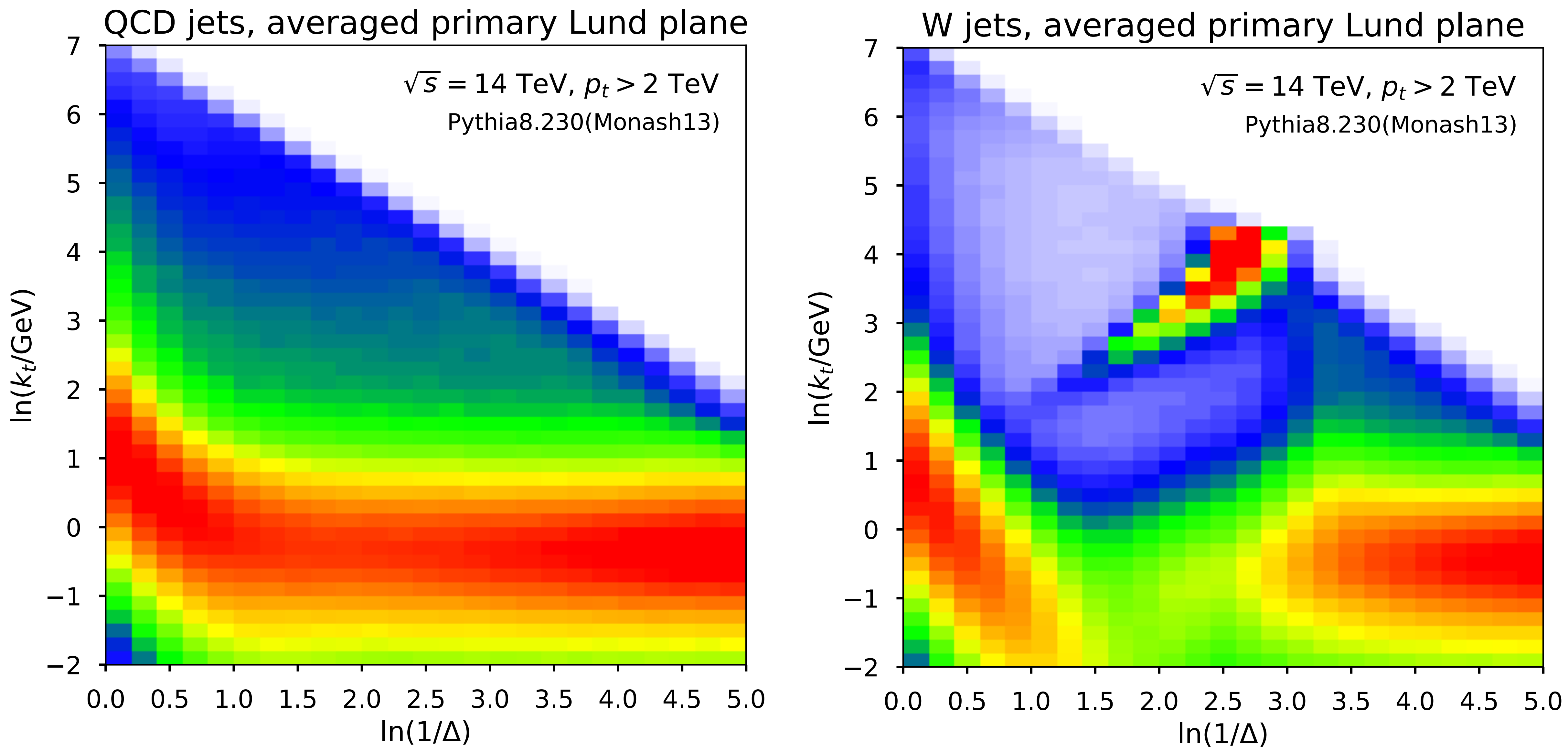
Dreyer, Salam, Soyez JHEP 12 (2018) 064

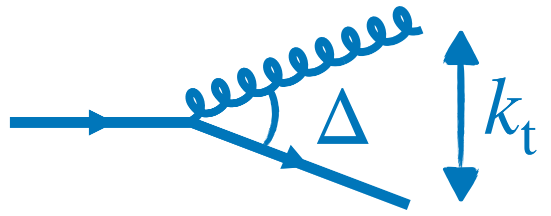
Fundamental QCD

Jet substructure

Tagging

- Boosted objects
- Quark vs. gluon jets

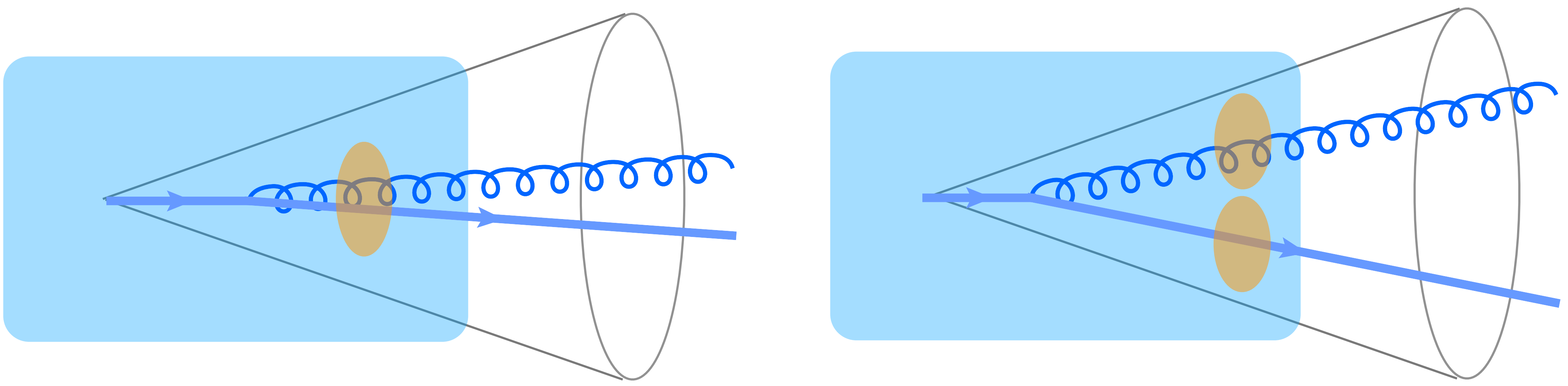




Dreyer, Salam, Soyez JHEP 12 (2018) 064

Fundamental QCD

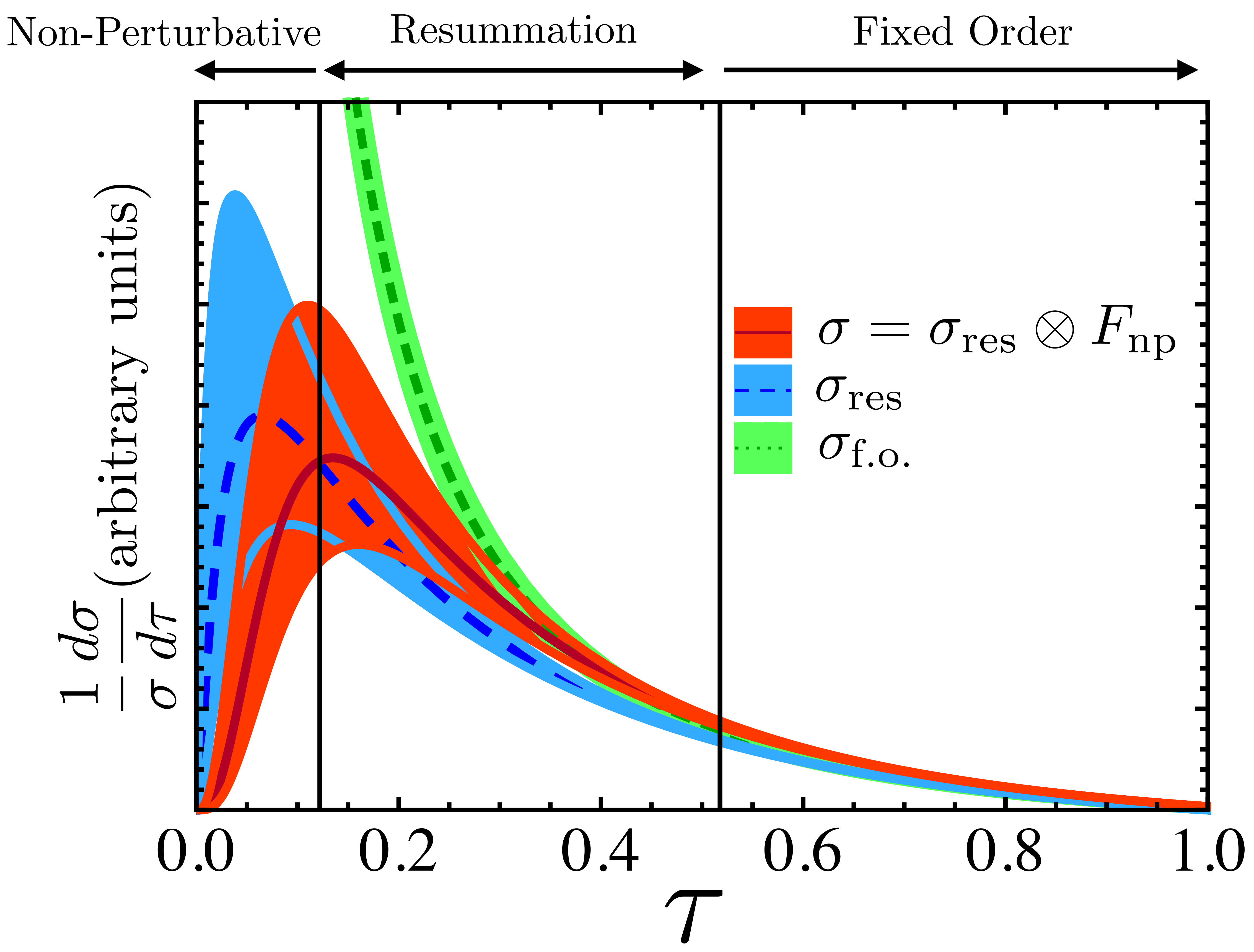
- Understanding validity of perturbative vs. non-perturbative physics
- Probes of quark-gluon plasma



Y. Mehtar-Tani

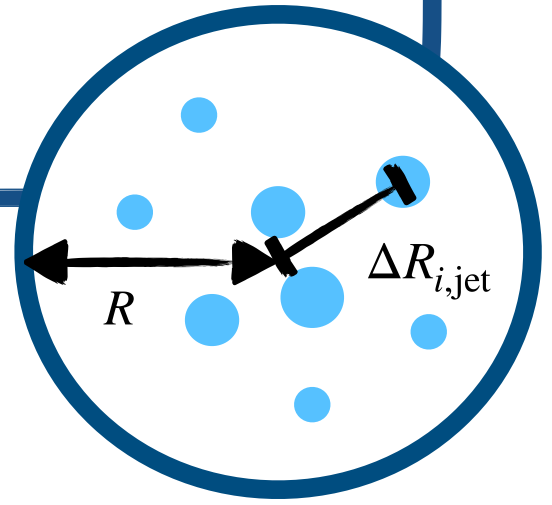
→ **This talk**

Jet substructure in proton-proton collisions



Larkoski, Moult, Nachman JPR 841 1 (2020)

Jet substructure observables are sensitive to **specific regions** of QCD radiation phase space



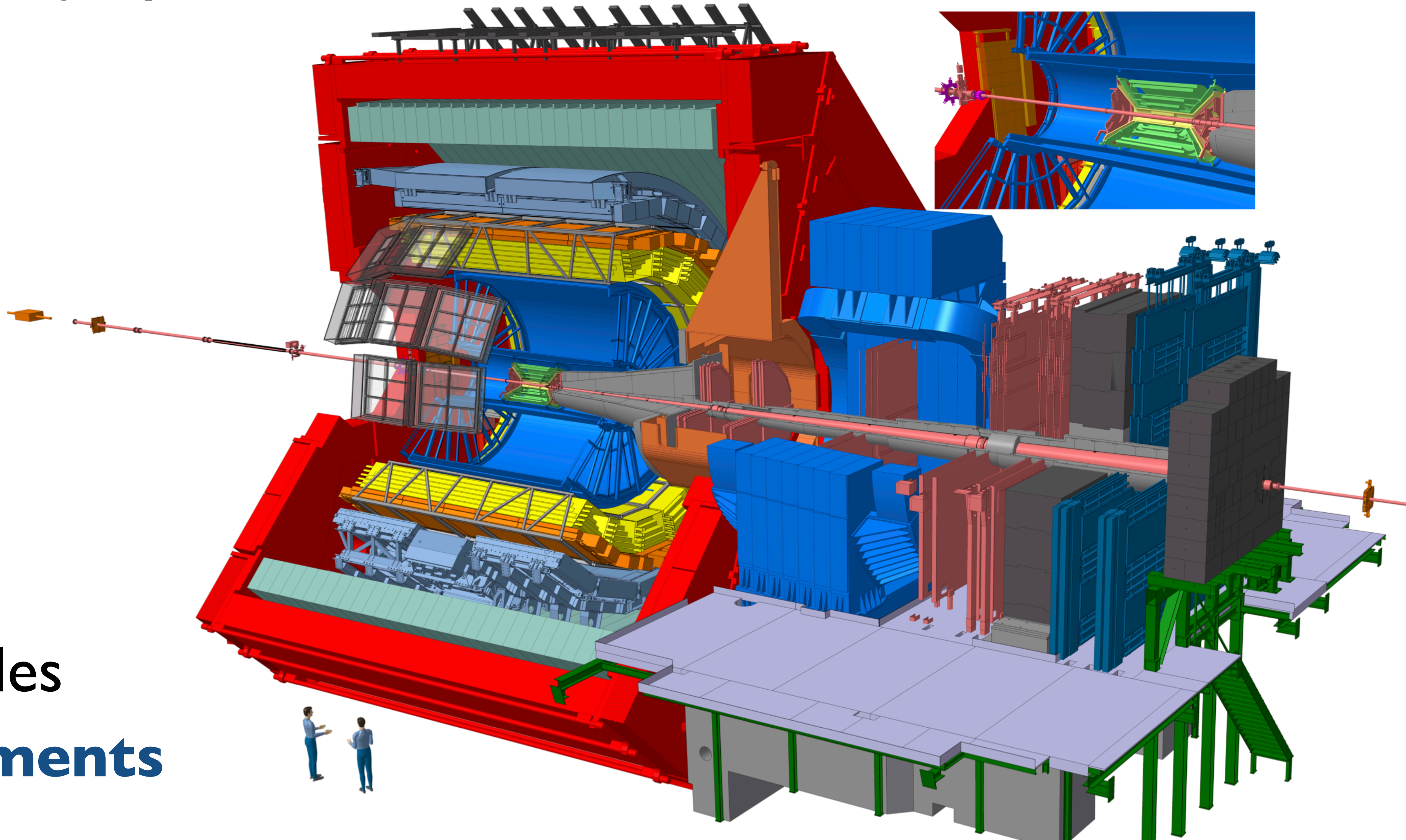
Each observable has:

- Fixed-order regime — $\mathcal{O}\left(\alpha_s^n\right)$
- Resummation regime — large logarithms to all orders in α_s
- Non-perturbative regime

Jets with ALICE

ALICE reconstructs jets at midrapidity with a high-precision tracking system (ITS+TPC) and EMCal

- $p_{\mathrm{T,jet}} \approx 20 - 200$ GeV/c
- $|\eta| < 0.9$



Charged particle jets

- High-precision spatial resolution to resolve particles

  → **Excellent for jet substructure measurements**

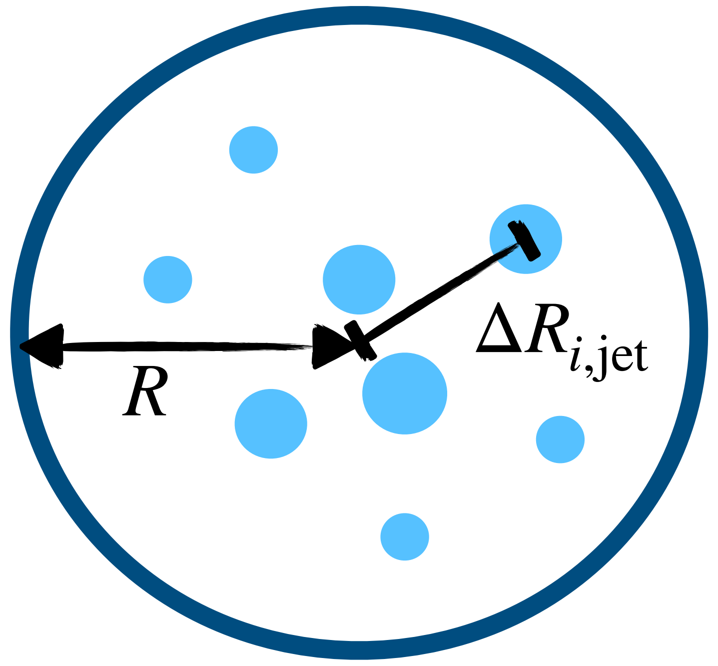
Full jets (charged tracks + EMCal π^0, γ)

- More direct comparison to theory

Jet angularities — pp

Class of IRC-safe observables:

$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha$$



$$z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}}$$

$$\theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}, \; \Delta R_{i,\text{jet}} = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

Continuous parameter $\alpha > 0$ systematically varies weight of collinear radiation

Almeida, Lee, Perez, Sterman, Sung, Virzi PRD 79 (2009) 074017
Larkoski, Thaler, Waalewijn JHEP 11 (2014) 129
…

Jet angularities — pp

ALICE arXiv 2107.11303 New

ALICE

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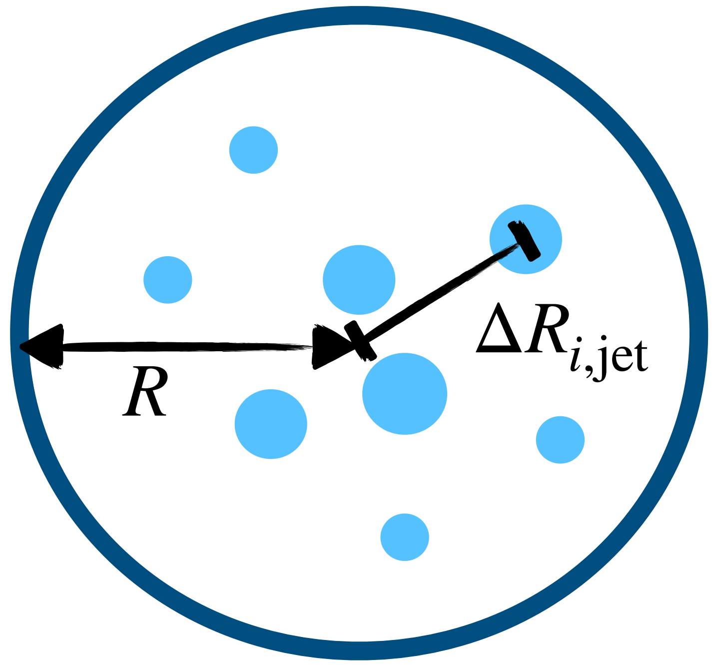

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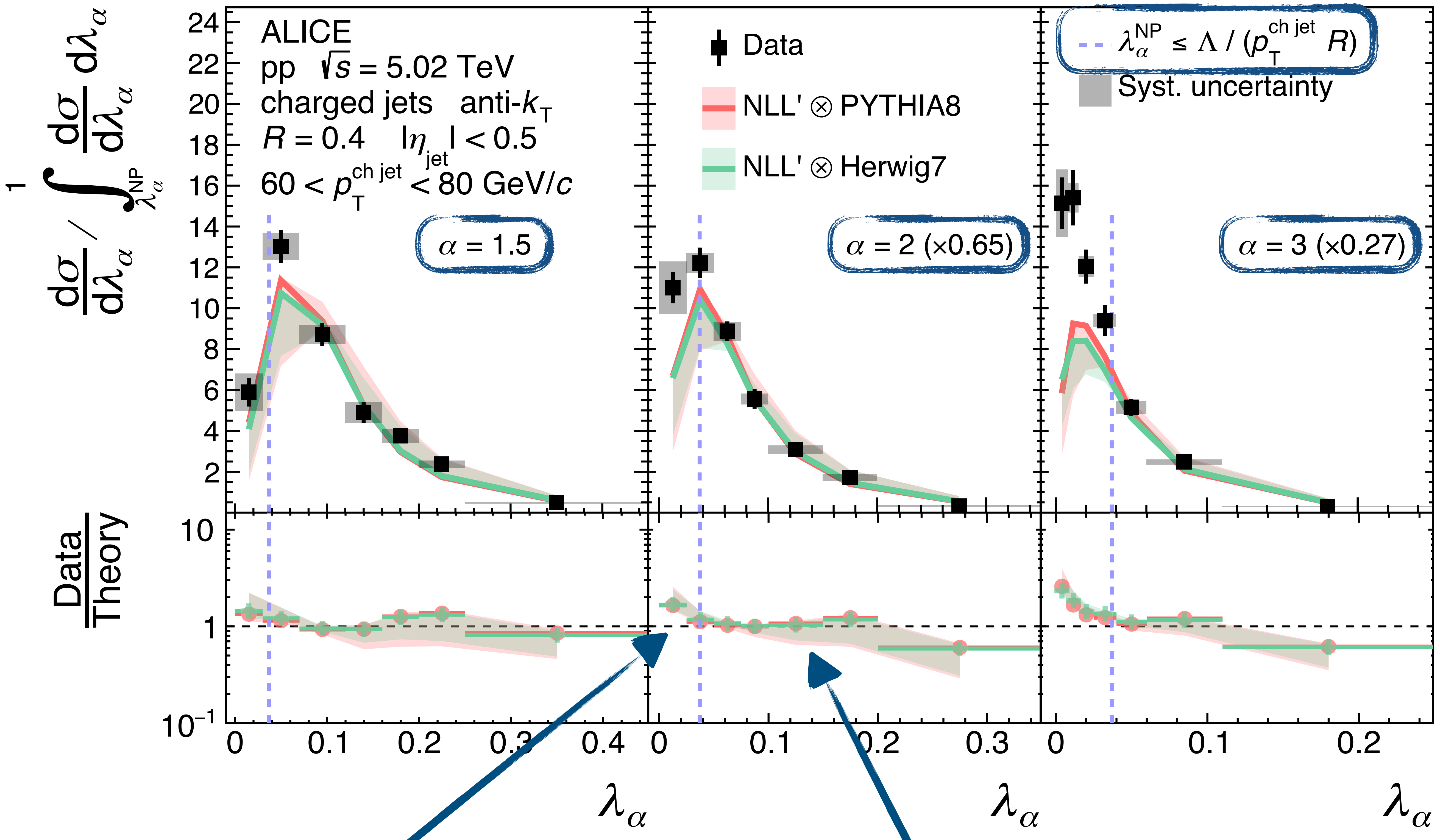
New measurement of jet angularities



Small λ_β: Non-perturbative

Larger λ_β: Good agreement with pQCD calculations

Kang, Lee, Ringer JHEP 04 (2018) 110

Jet angularities — pp

ALICE arXiv 2107.11303

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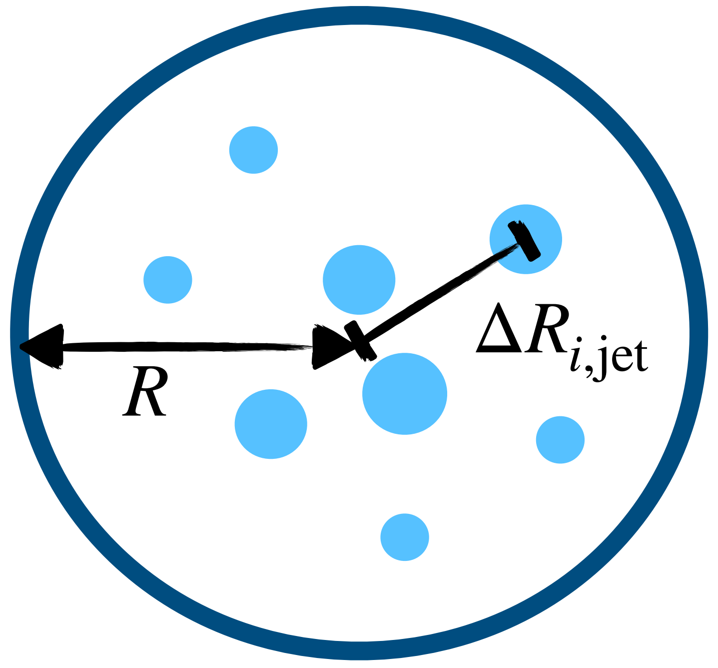

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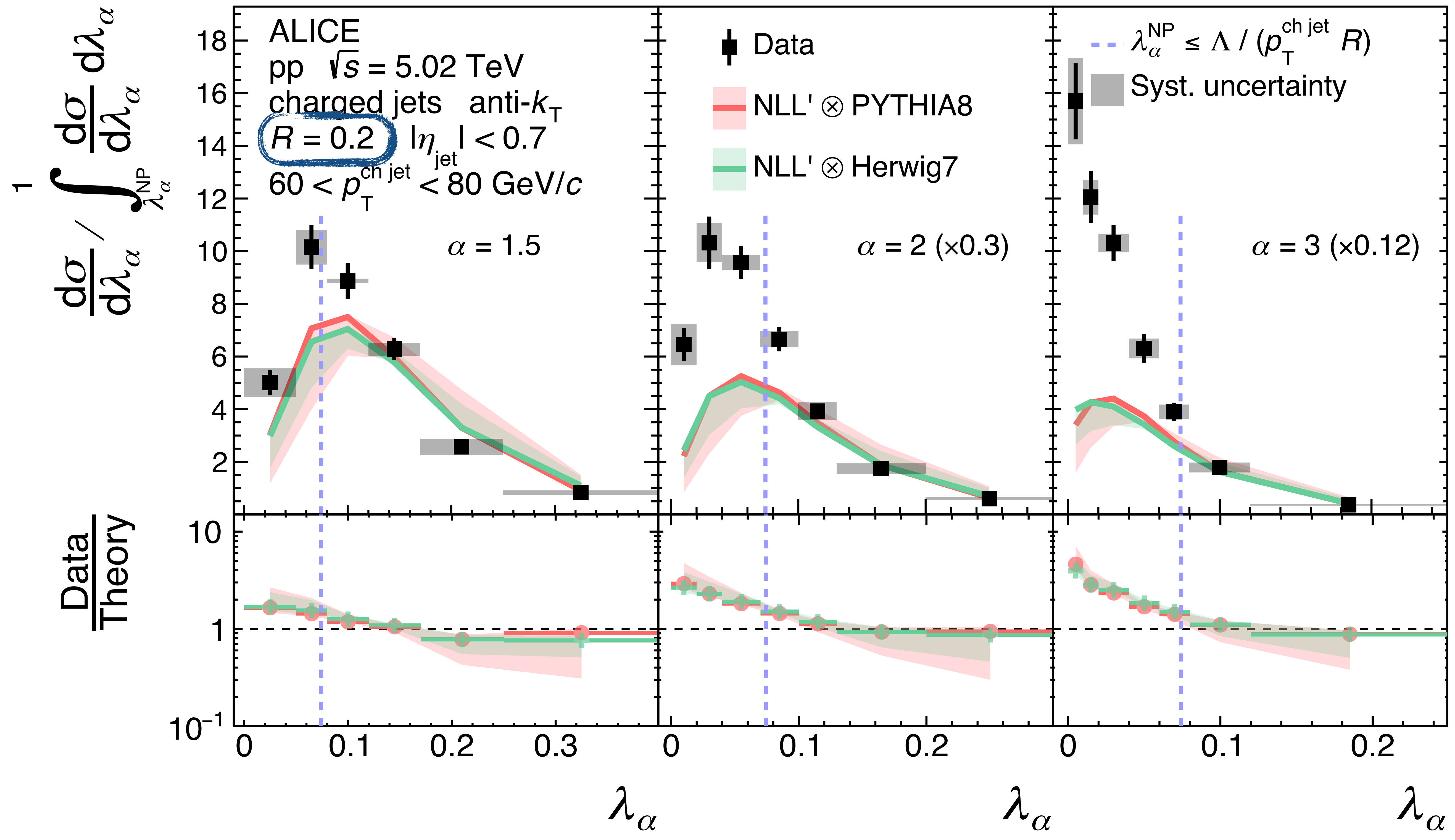
Continuous parameter $\alpha > 0$ systematically varies weight of collinear radiation

Smaller R ⟶ larger non-perturbative region



Most of the distribution can be non-perturbative — can spoil agreement in perturbative region due to self-normalization

Almeida, Lee, Perez, Sterman, Sung, Virzi PRD 79 (2009) 074017
Larkoski, Thaler, Waalewijn JHEP 11 (2014) 129
…

Jet angularities — pp

ALICE

Non-perturbative shape function $F(k)$ to describe hadronization and underlying event effects

$$\frac{d\sigma}{d\lambda_\alpha} = \int F(k) \frac{d\sigma^{\text{parton-level}}}{d\lambda_\alpha}\left(\lambda_\alpha - \frac{k}{p_T^{\text{jet}} R}\right) dk$$

$$F(k) = \frac{4k}{\Omega_\alpha^2} \exp\left(-\frac{2k}{\Omega_\alpha}\right)$$

Test predicted scaling of $F(k)$ with α

$$\Omega_\alpha = \Omega/(\alpha - 1)$$

Korchemsky, Sterman Nucl. Phys. B 555 1 (1999)
Stewart, Tackmann, Waalewijn PRL 114, 092001 (2015)
Kang, Lee, Ringer JHEP 04 (2018) 110
Kang, Lee, Liu, Ringer JHEP 10 (2018) 137

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ALICE arXiv 2107.11303 New

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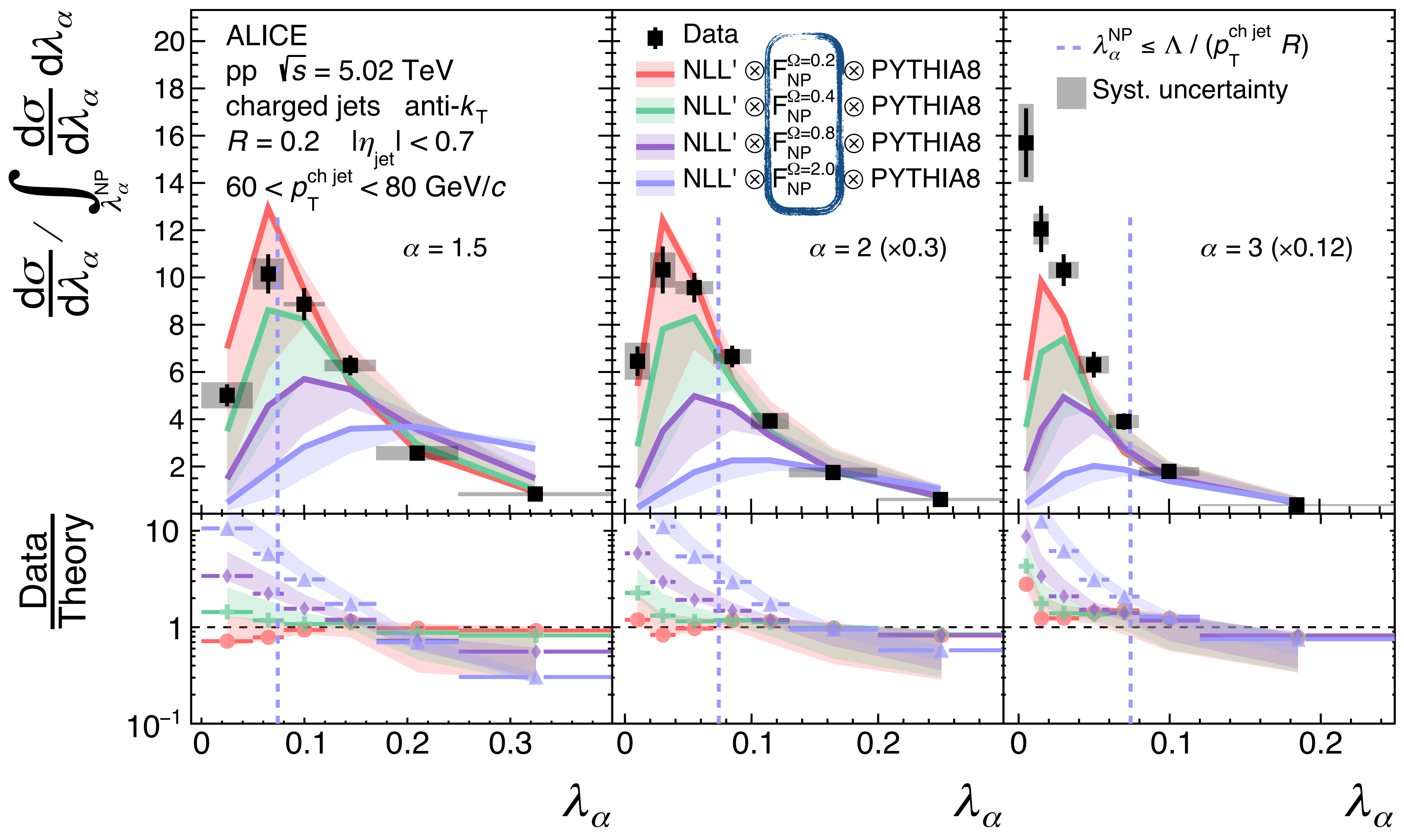

Universal description of data for $\Omega < 1$ GeV

See also: Kang, Lee, Liu, Ringer JHEP 10 (2018) 137

Jet angularities — pp

Groomed jet angularities:

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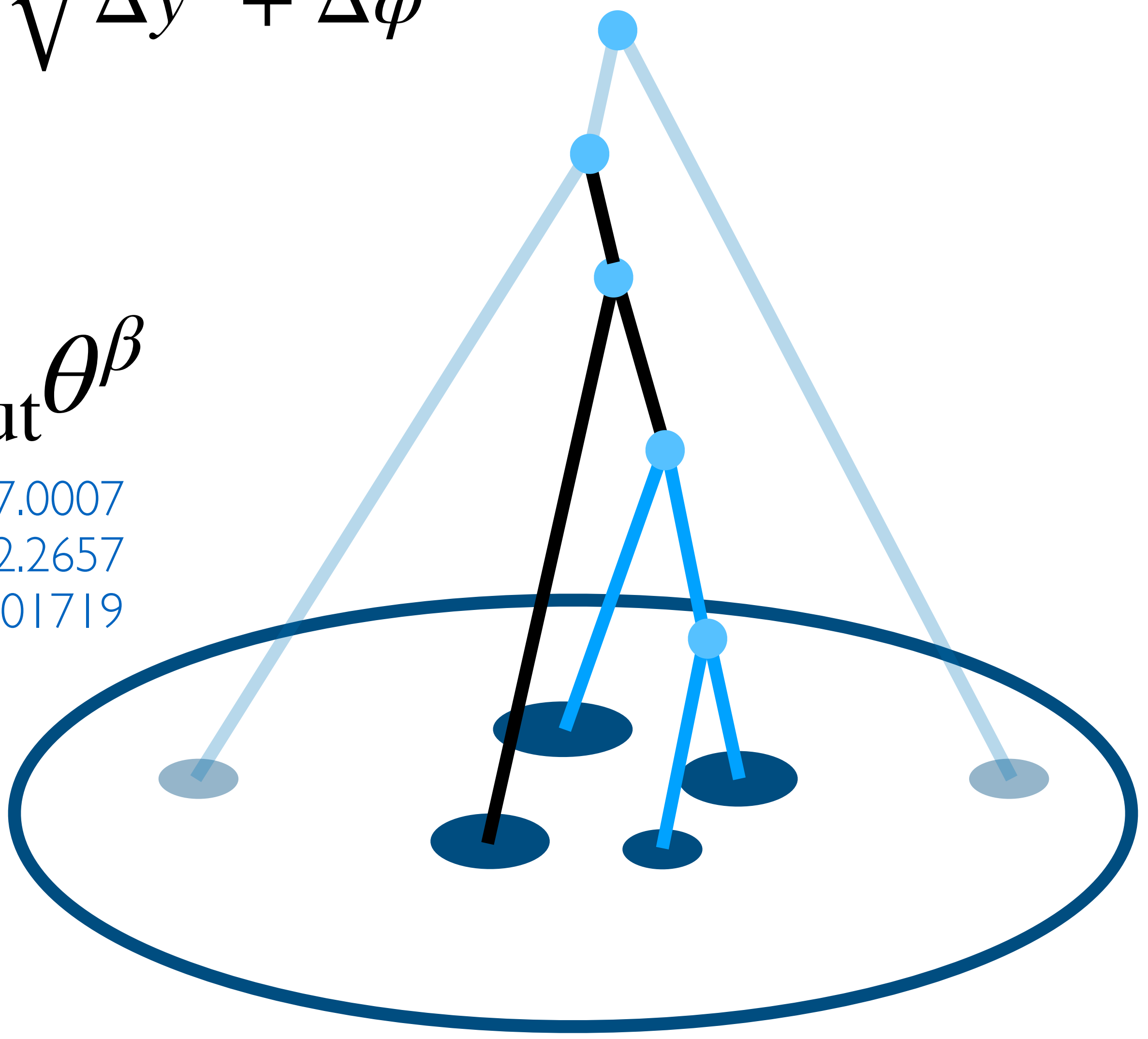
Soft Drop: $z < z_{\mathrm{cut}} \theta^{\beta}$

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



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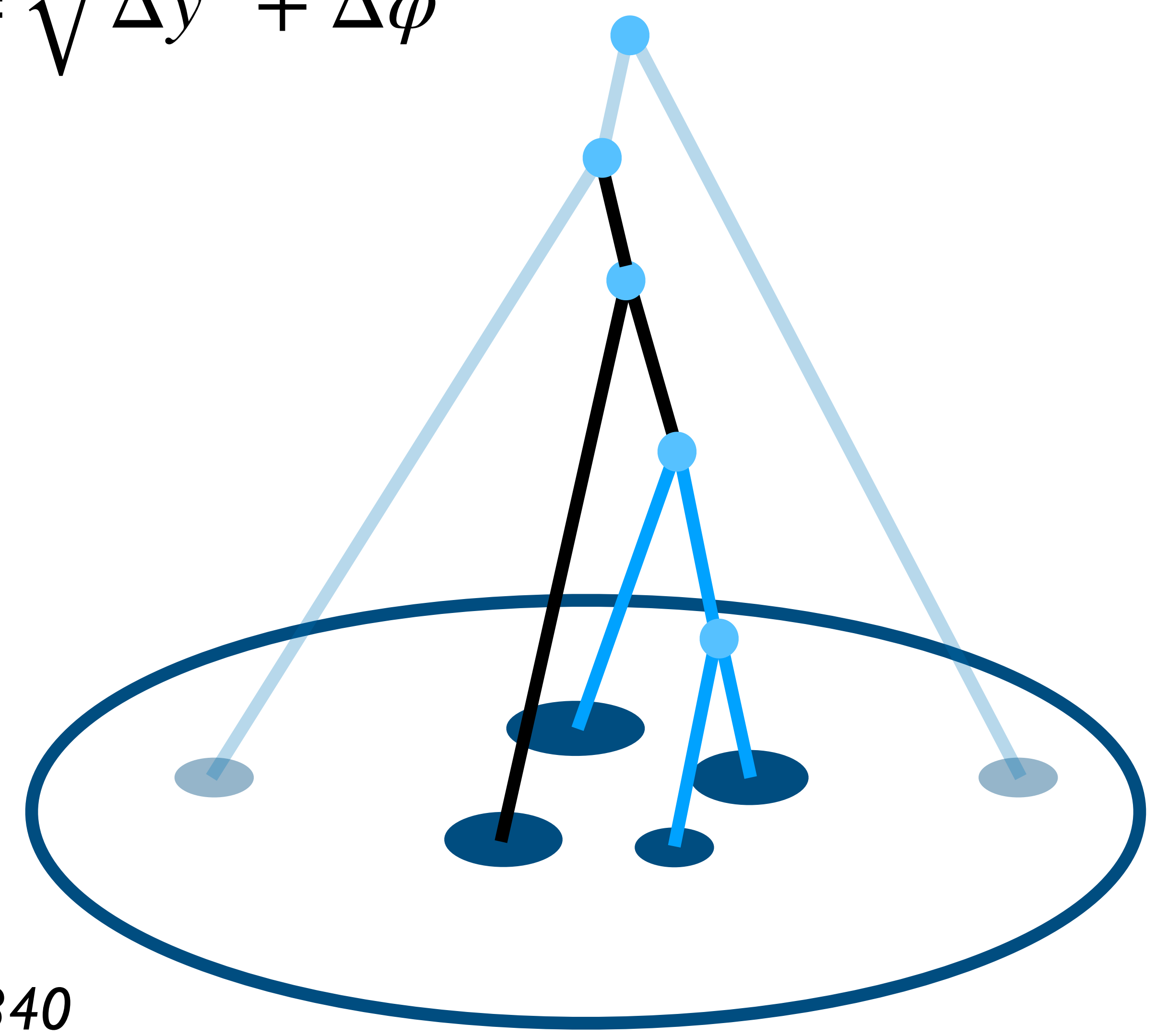
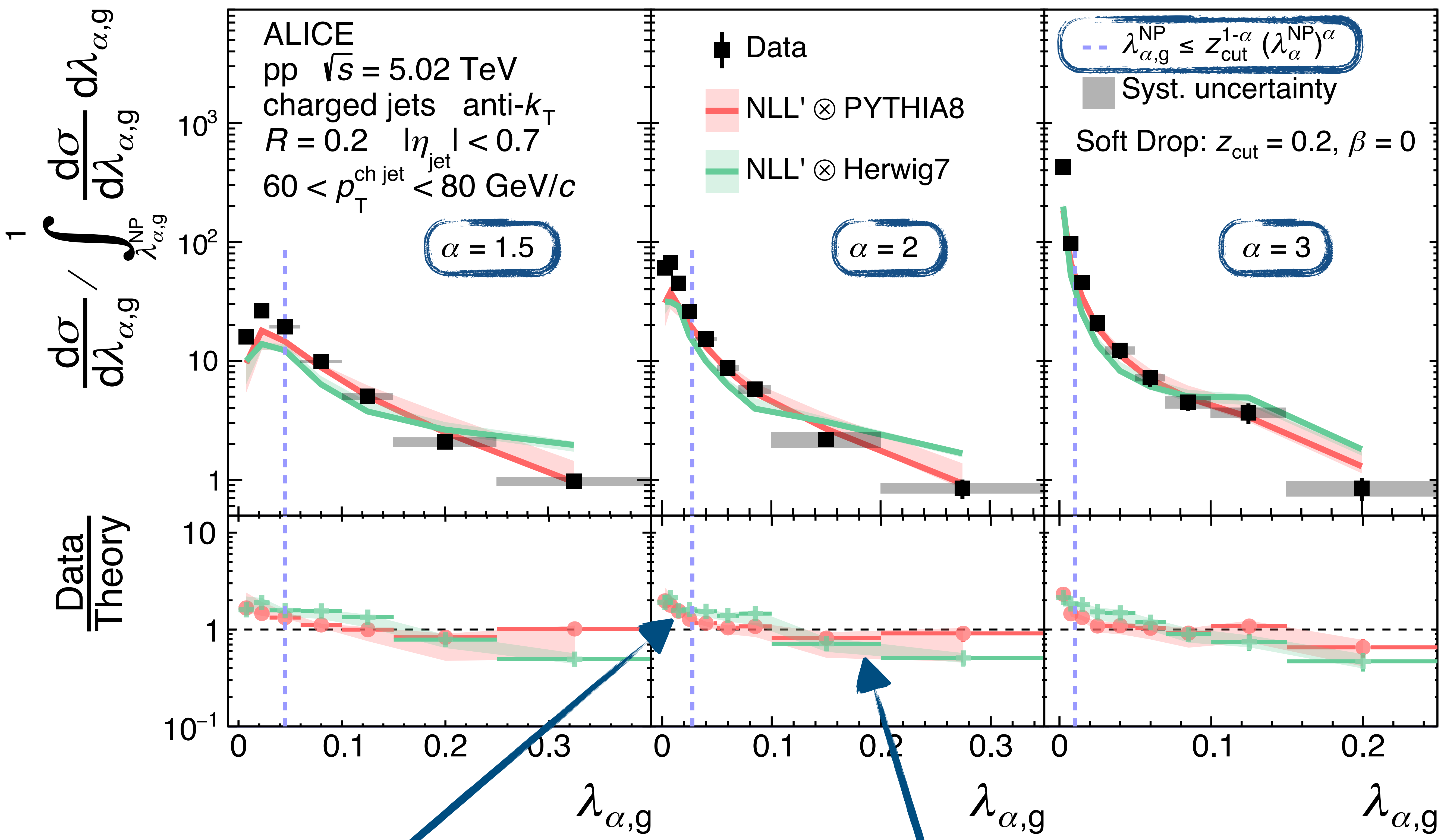


See also: CMS arXiv 2109.03340

Soft Drop grooming recovers perturbative physics



Small λ_β: Non-perturbative

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Kang, Lee, Liu, Ringer PLB 793 (2019) 41

Jet quenching in heavy-ion collisions

Theoretical challenges in AA

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- Factorization in AA?
- Spacetime picture of parton shower?
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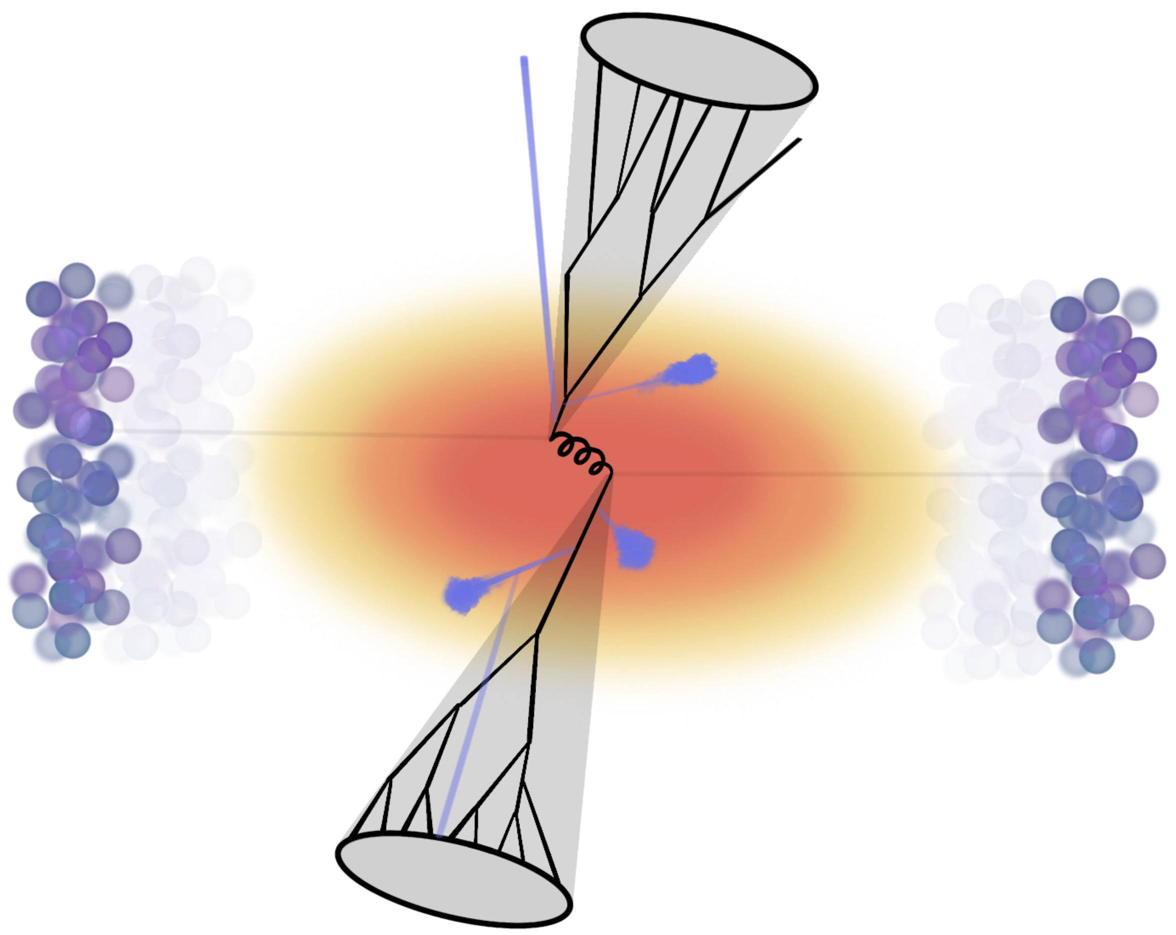
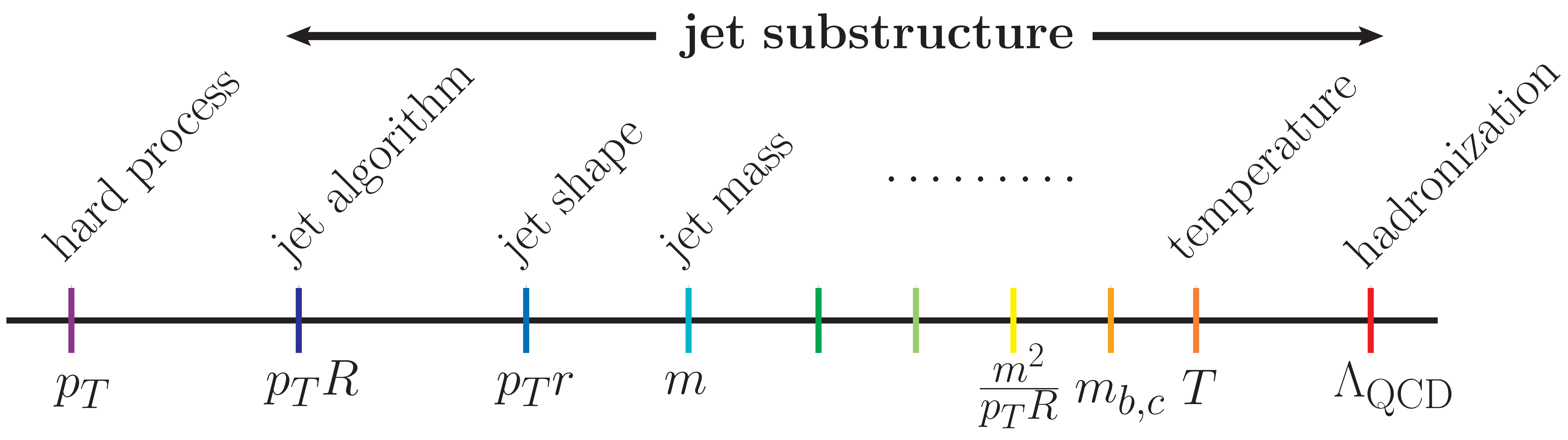
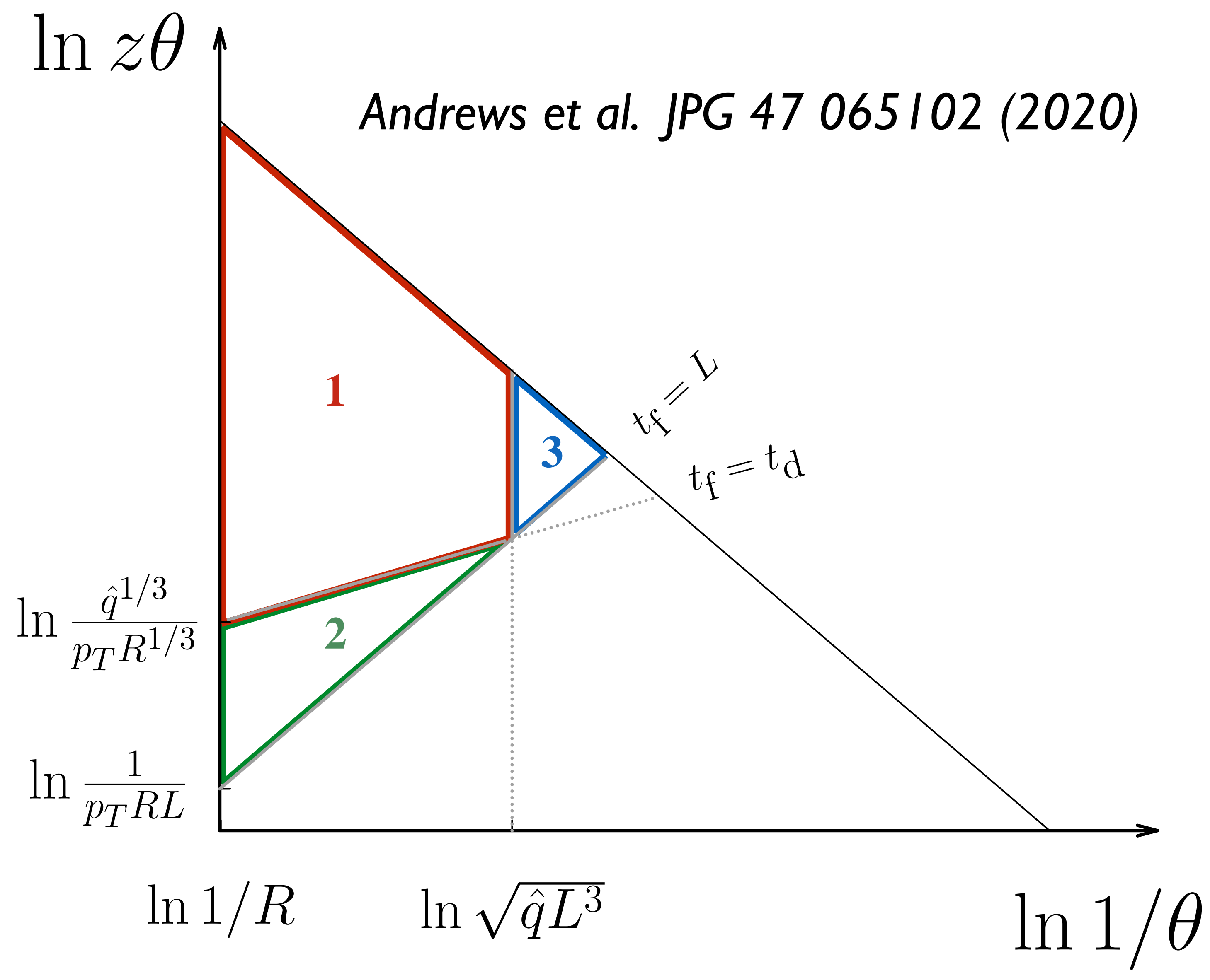


Jet substructure is an appealing tool to disentangle these

- Target specific regions of phase space



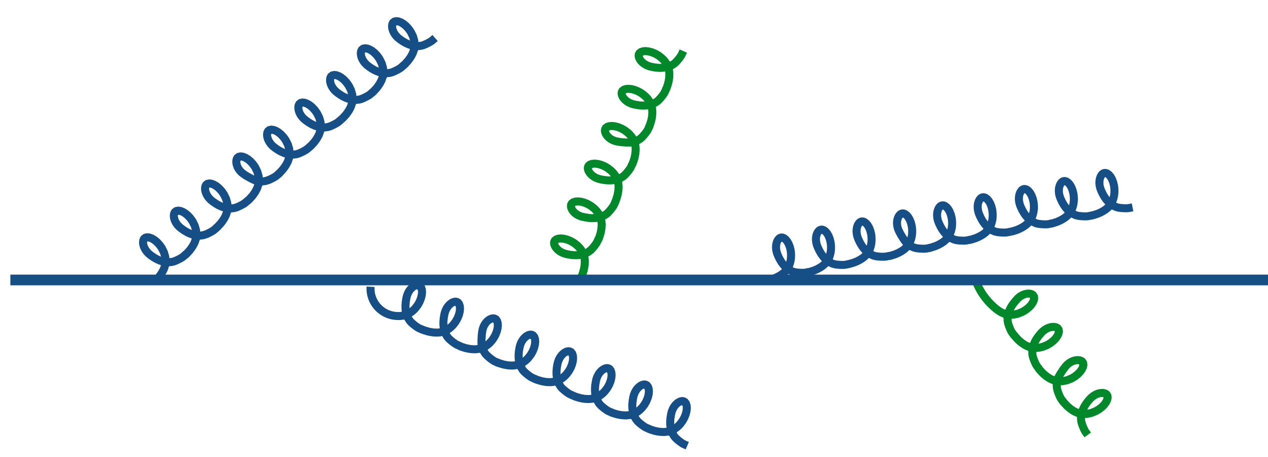
Yang-Ting Chien, QM2018



Jet quenching in heavy-ion collisions

State-of-the-art jet quenching models include:

- **Modified jet fragmentation**, such as:
  - Medium-induced soft gluon radiation *e.g. JEWEL JHEP 03 (2013) 080*
  - SCET-based factorization with modified jet function *e.g. Ringer et al. PRL 122 (2019) 25*
  - Strongly-coupled AdS/CFT-based drag *e.g. Hybrid Model JHEP 09 (2015) 175*
  - …

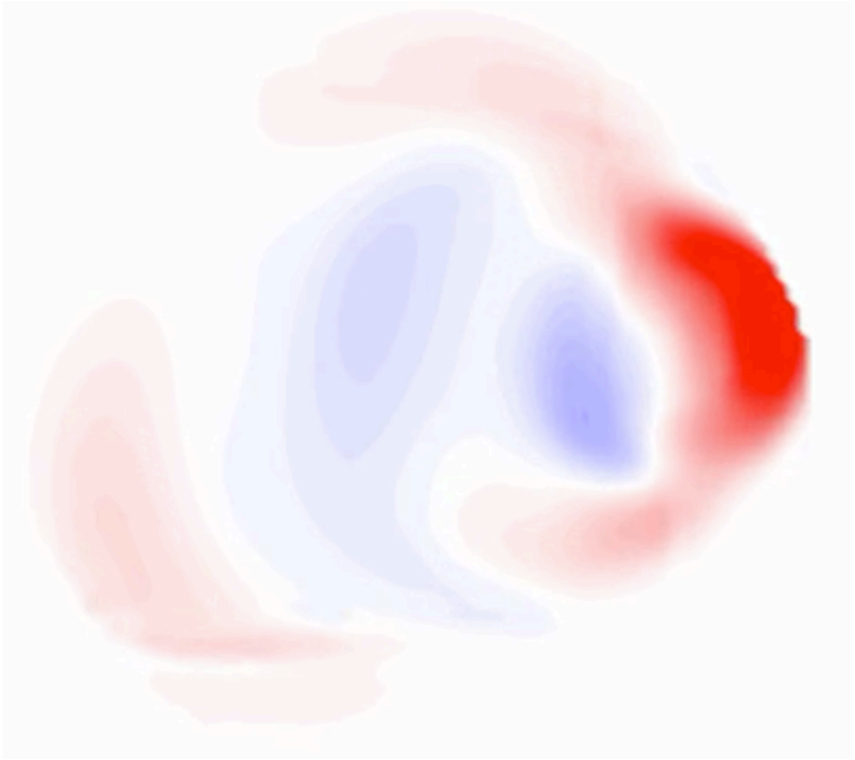


- **Expanding medium described by relativistic viscous hydrodynamics**
  - Tuned to measurements of soft observables

e.g. JETSCAPE PRC 103, 054904 (2021)

- **Medium response and transport**
  - Measurements include all energy flow correlated to hard jet

e.g. LBT PRC 91 (2015) 054908

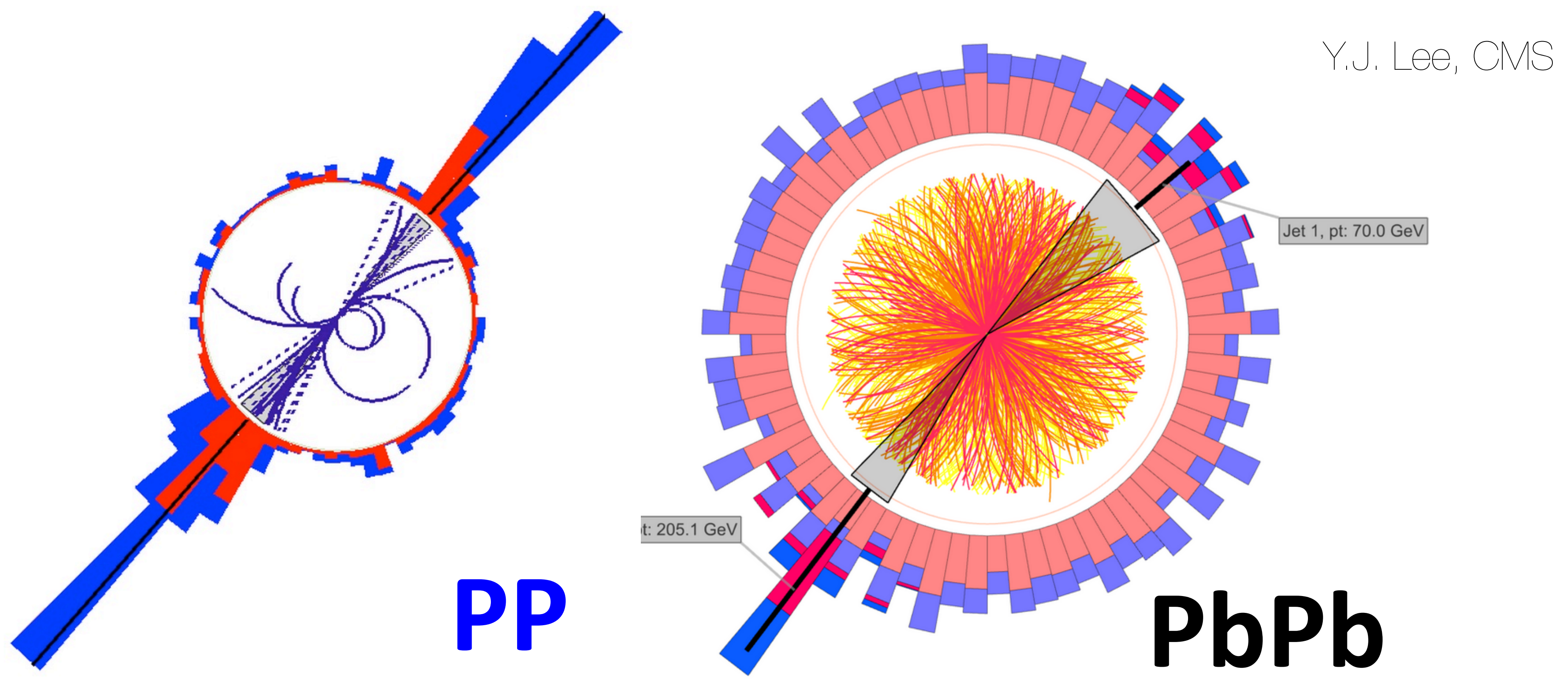


Major advances in last decade — but large landscape of models remain to be differentiated

Heavy-ion collisions: Background

Heavy-ion collisions produce a large underlying event due to the hadronization of the QGP

$p_{\mathrm{T}}^{\mathrm{UE}} \approx 100\ \mathrm{GeV}/c$ for $R = 0.4$ jet



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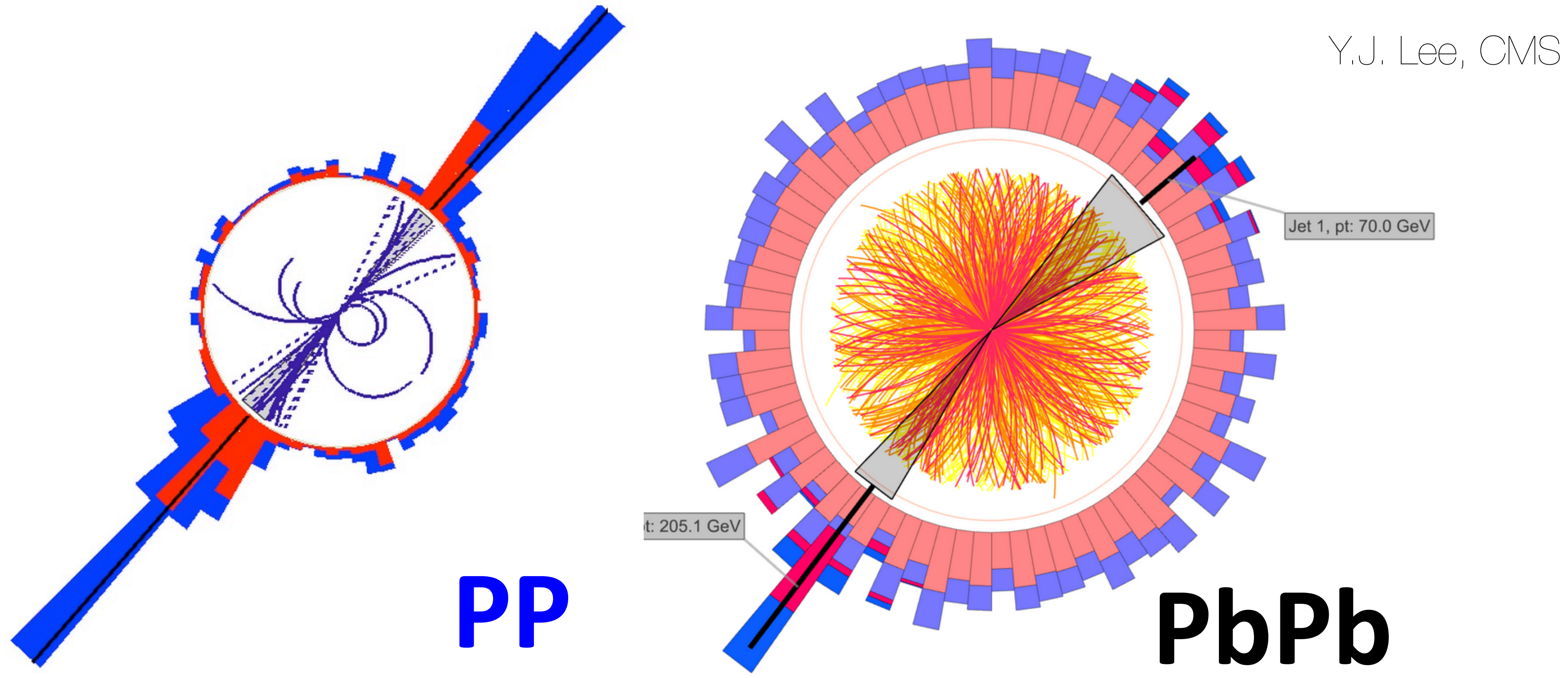


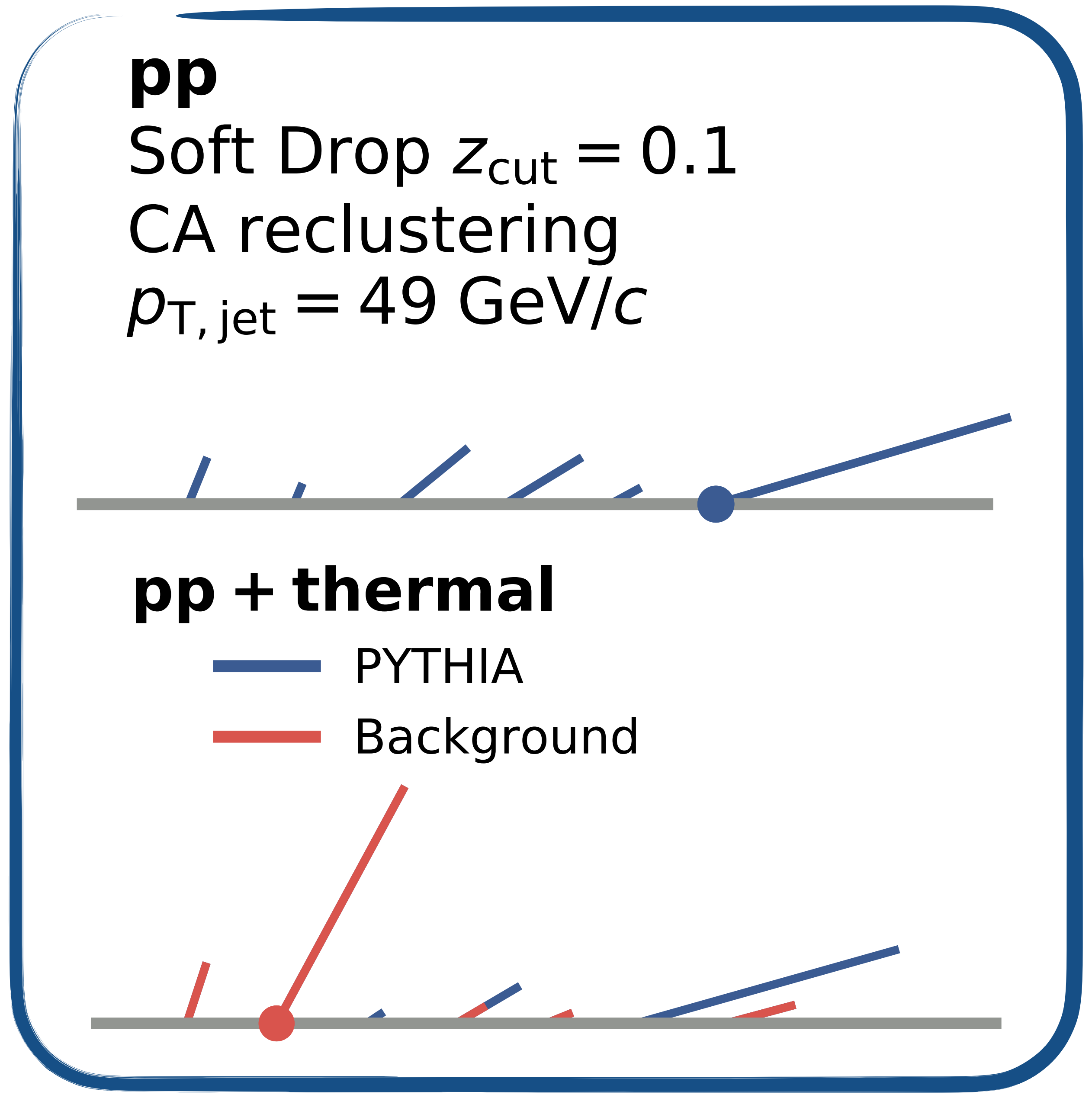
Background effects must be corrected for, in addition to detector effects

- Measurements challenging at low-p_{T}, large-R

  ALICE JHEP 09 (2015) 170
  CMS JHEP 05 (2021) 284
  …

- Mis-tagging of substructure objects: groomed splittings, leading subjets

  JM, Ploskon PRC 102 (2020) 044913

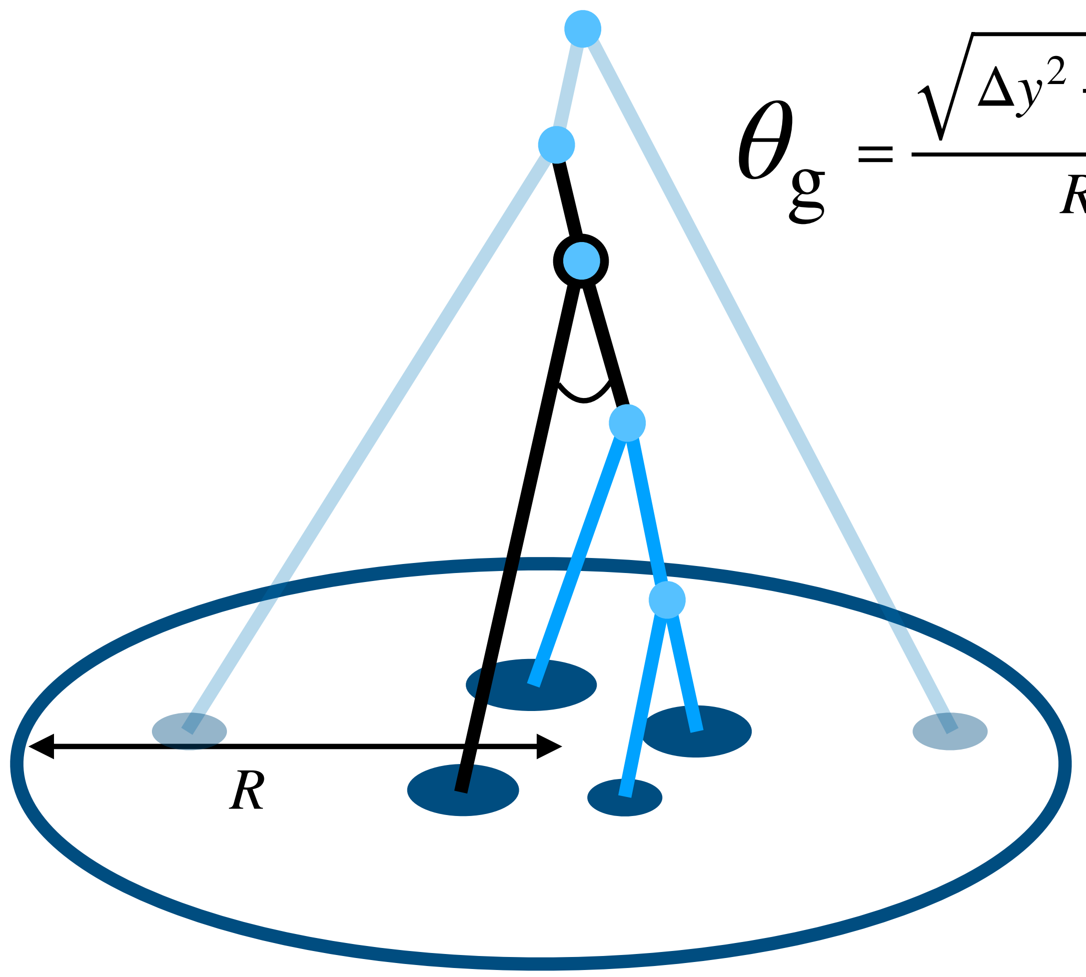


Groomed substructure — Pb-Pb

How is the hard jet substructure modified in heavy-ion collisions?

$$z_{\mathrm{g}} \equiv \frac{p_{\mathrm{T,subleading}}}{p_{\mathrm{T,leading}} + p_{\mathrm{T,subleading}}}$$

$$\theta_{\mathrm{g}} = \frac{\sqrt{\Delta y^2 + \Delta \varphi^2}}{R}$$



Grooming condition: $z > z_{\mathrm{cut}} = 0.2$

Groomed substructure — Pb-Pb

ALICE arXiv 2107.12984

New

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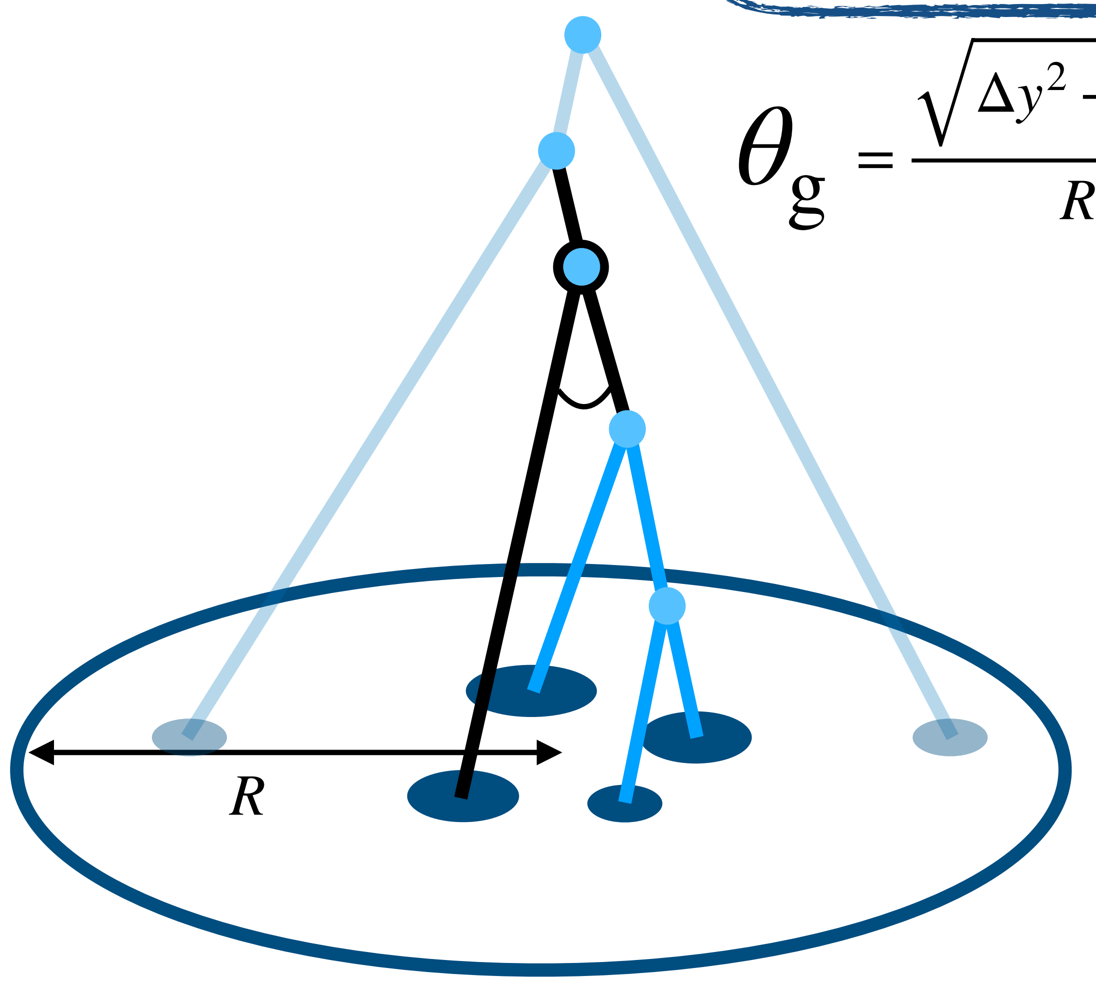

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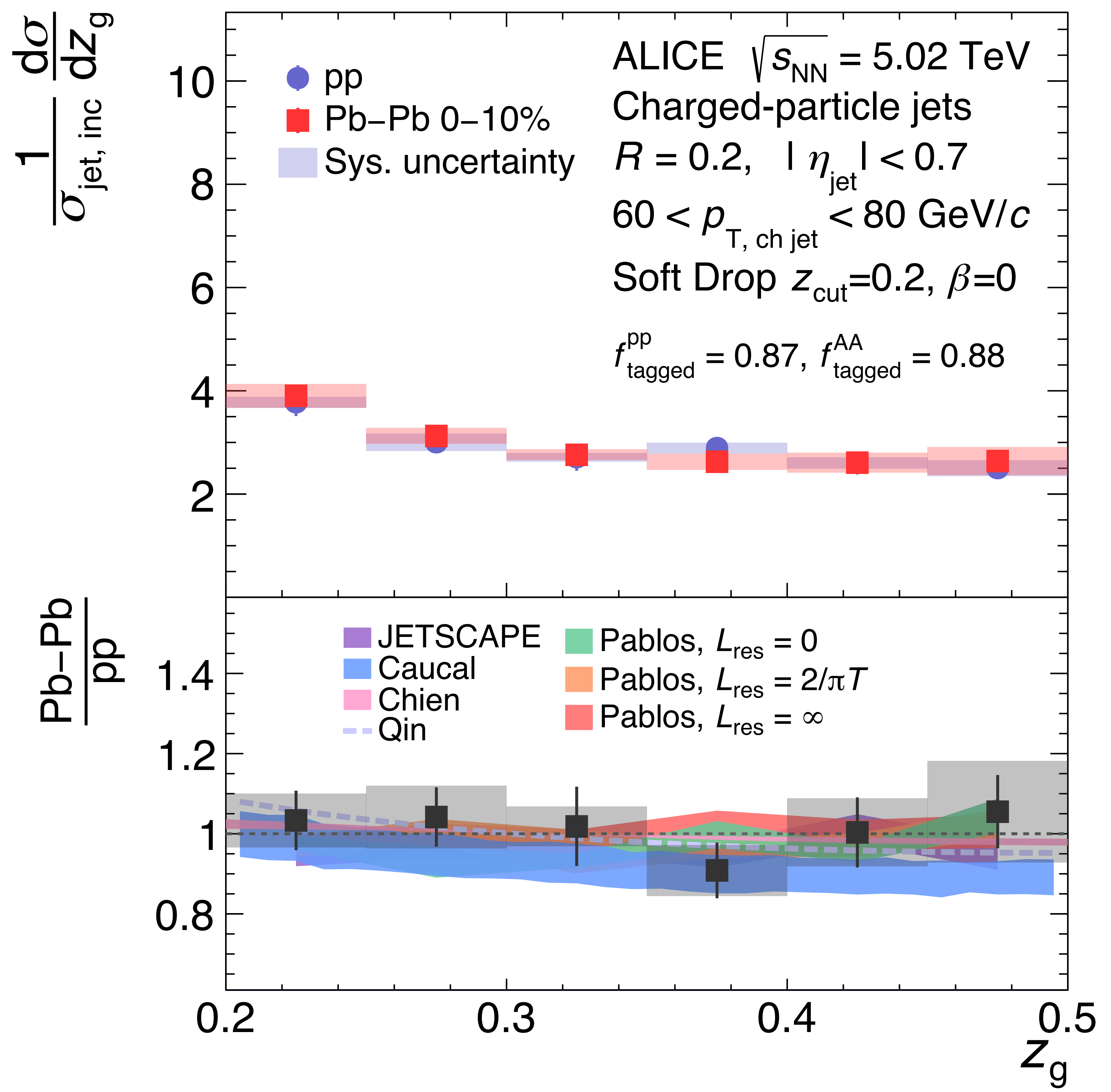

No significant modification in z_g distribution

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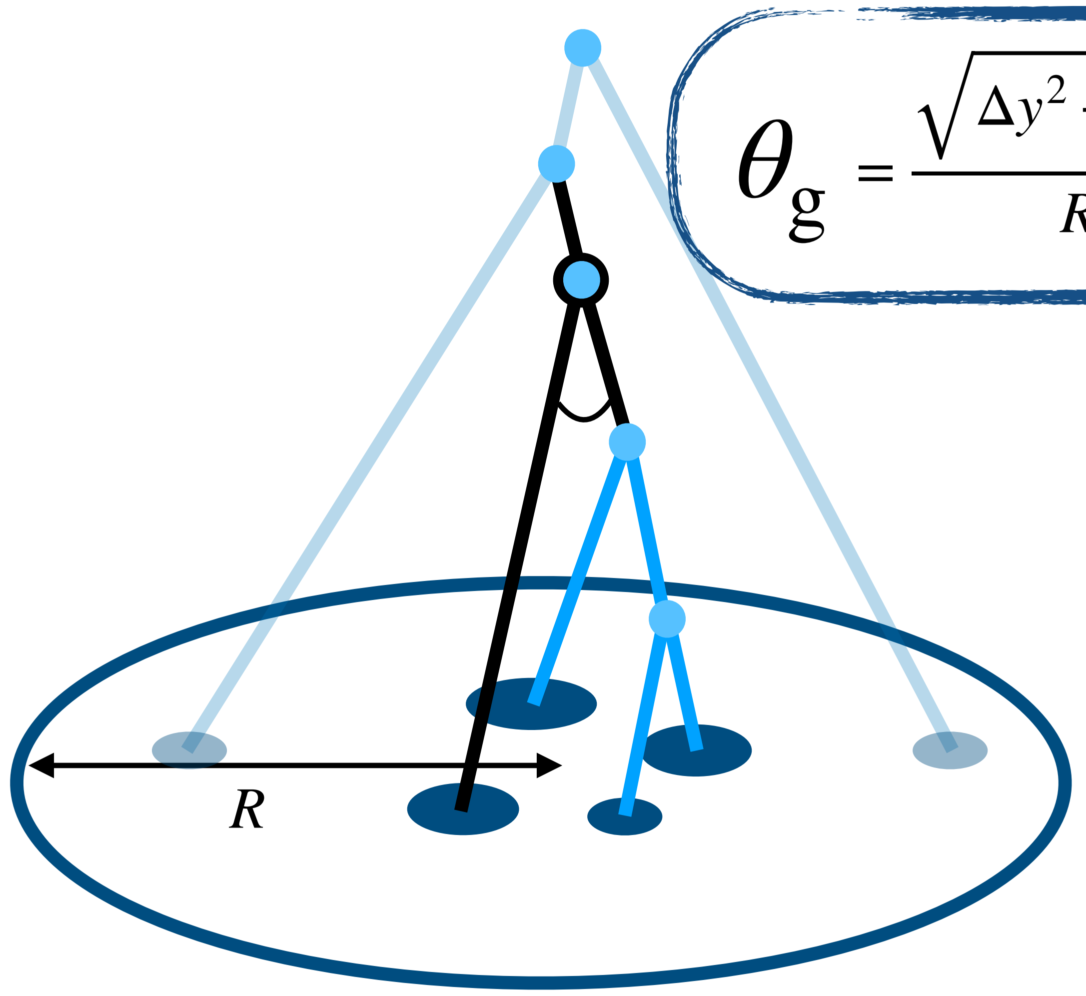

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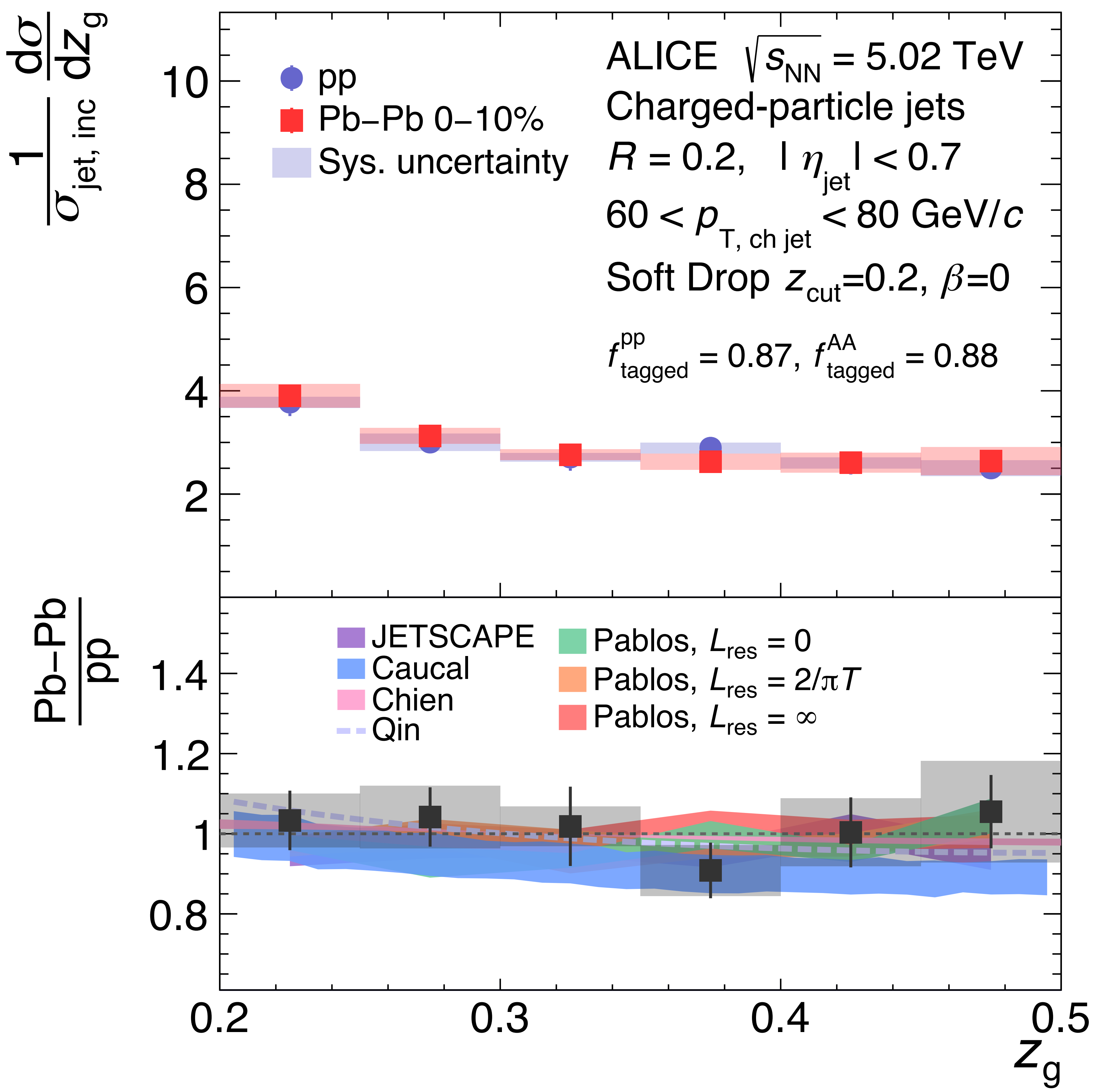

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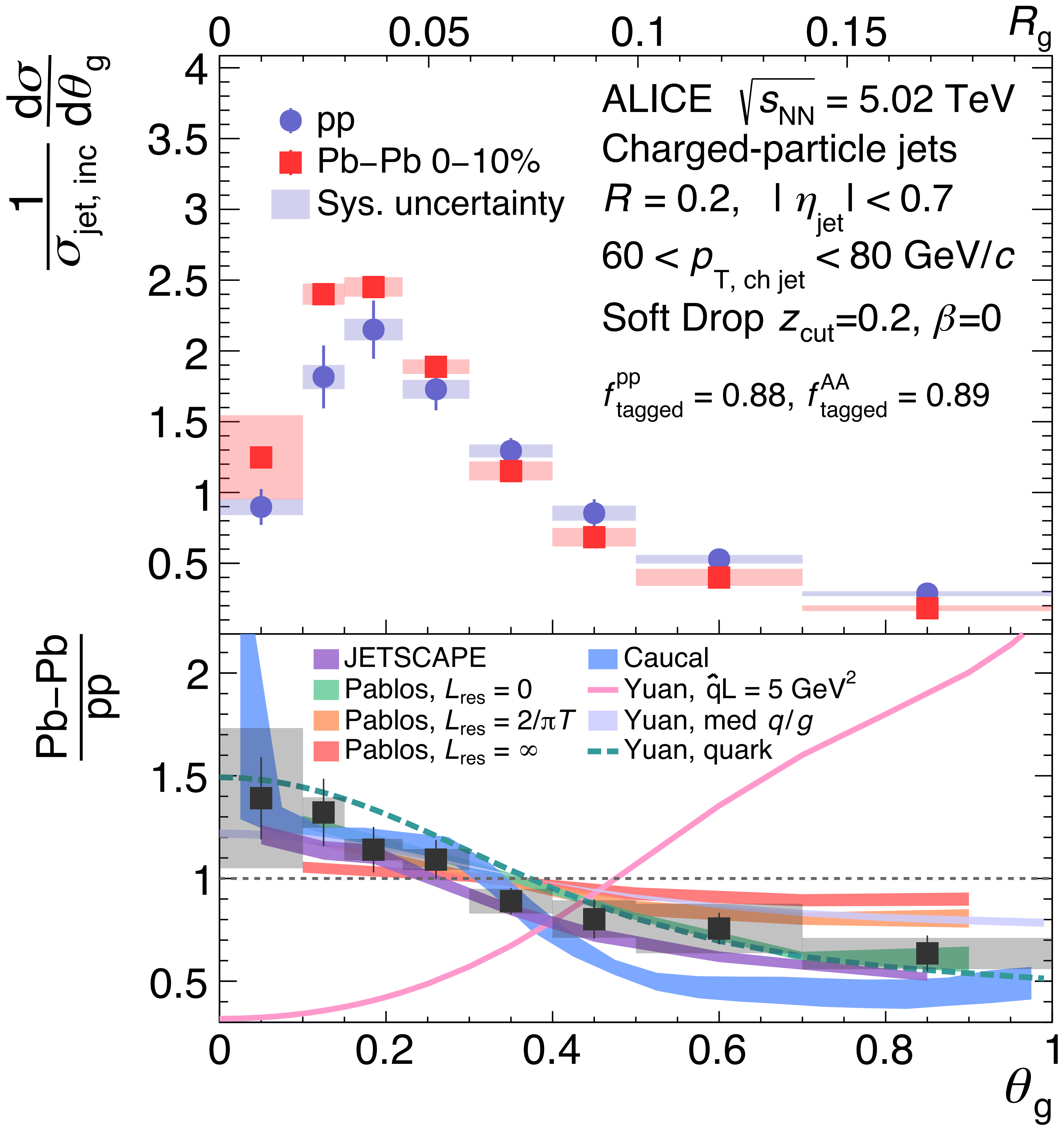


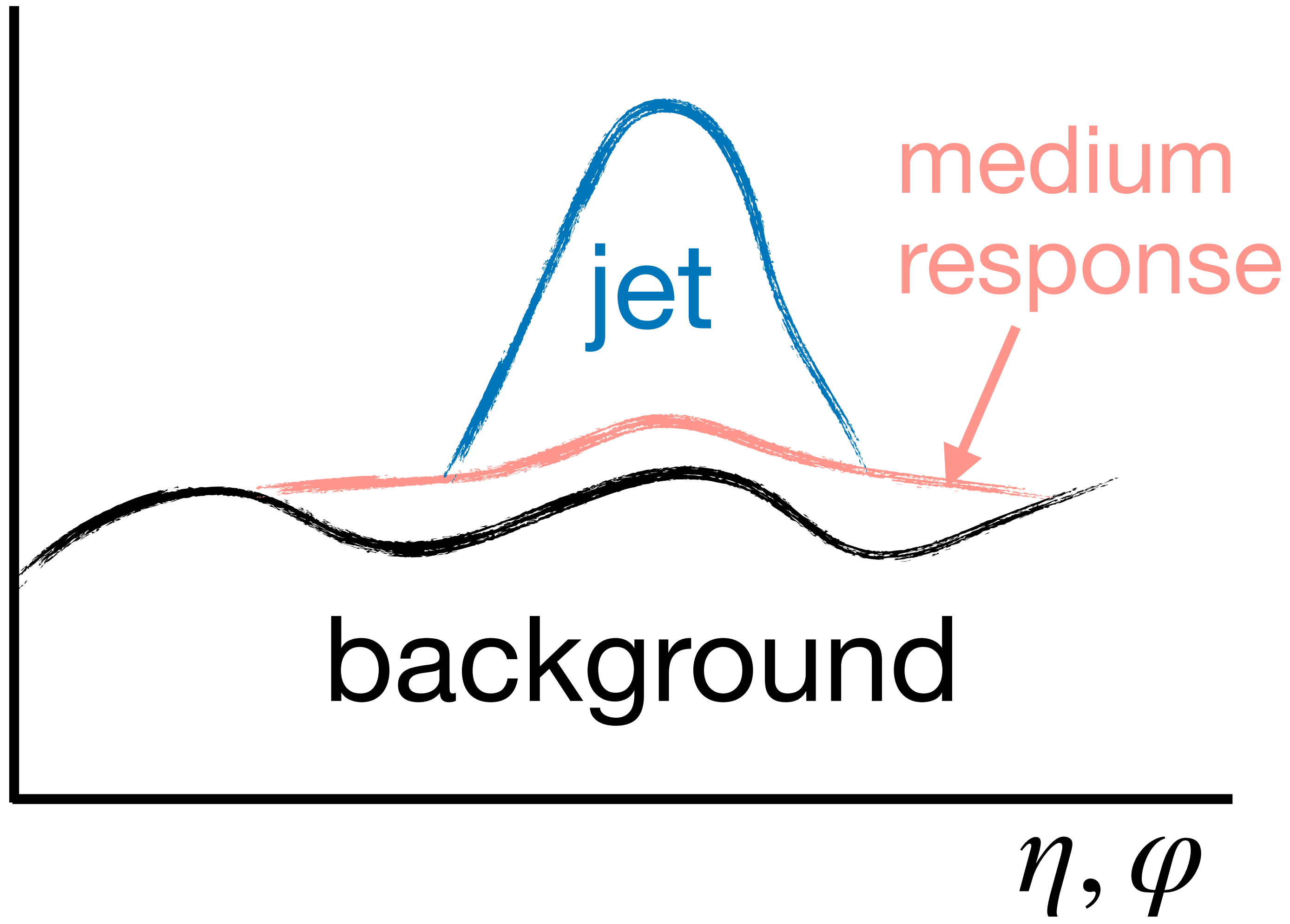
The cores of jets are narrower in Pb-Pb compared to pp collisions

Sensitive to QGP resolution length

→ **Microscopic structure of QGP**

Ungroomed jet substructure

How is the soft jet substructure modified in heavy-ion collisions?



Ungroomed jet substructure

ALICE PLB 776 (2018)

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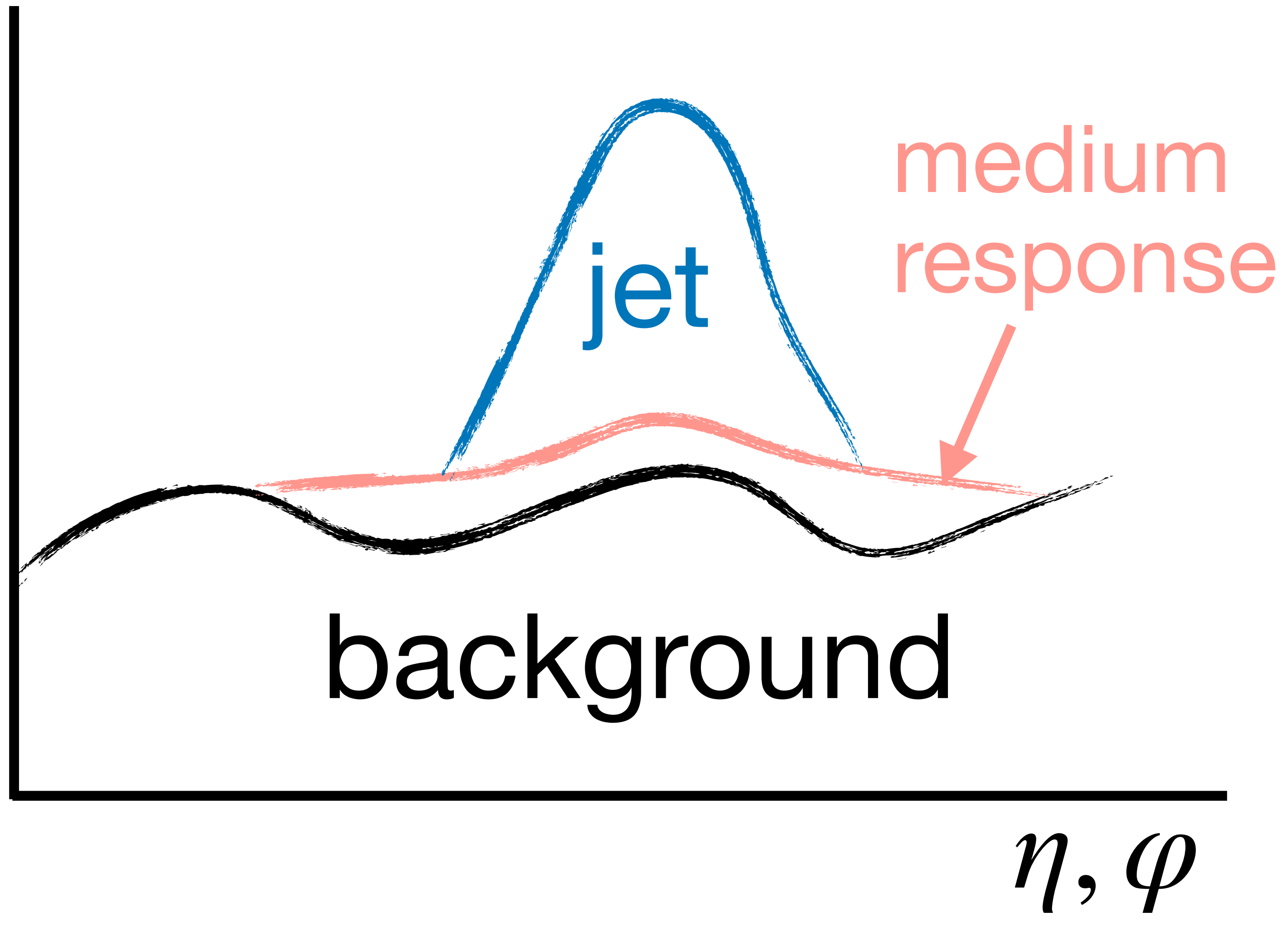
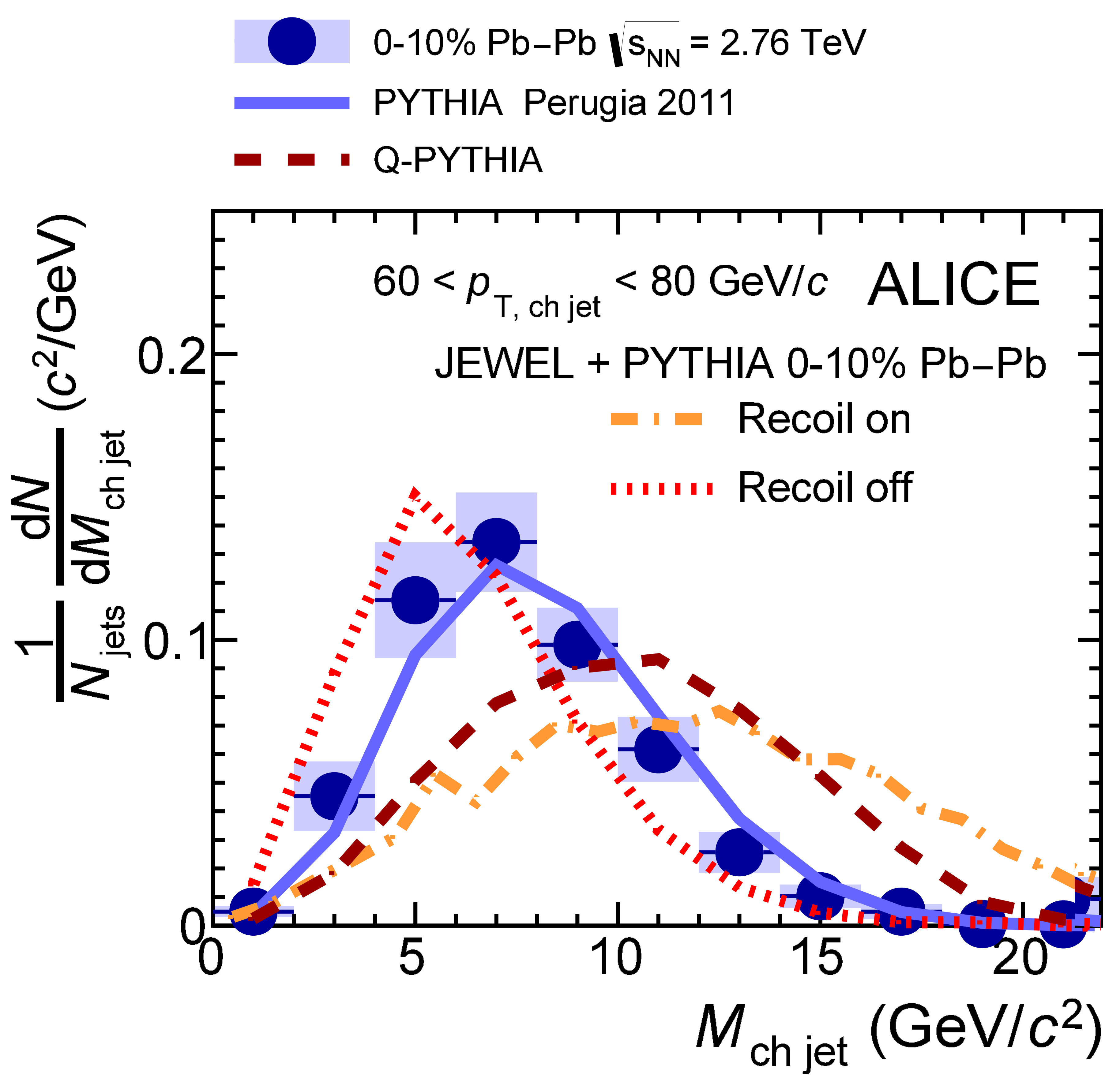


Jet mass $M = \sqrt{E^2 - p_{\mathrm{T}}^2 - p_{\mathrm{z}}^2}$



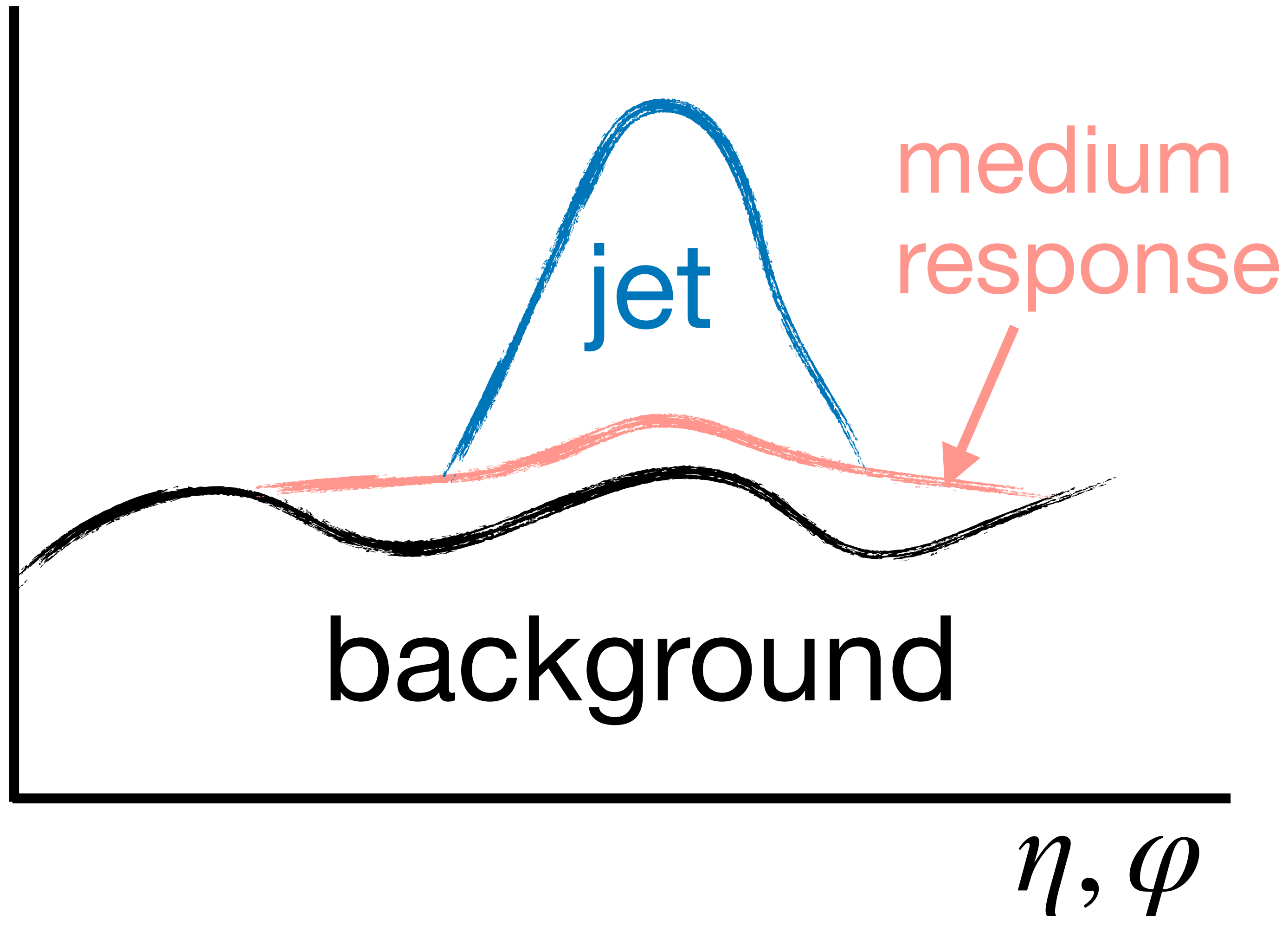
Poor description by jet quenching models

Large impact of medium response

Ungroomed jet substructure

ATLAS PRL 123 042001 (2019)

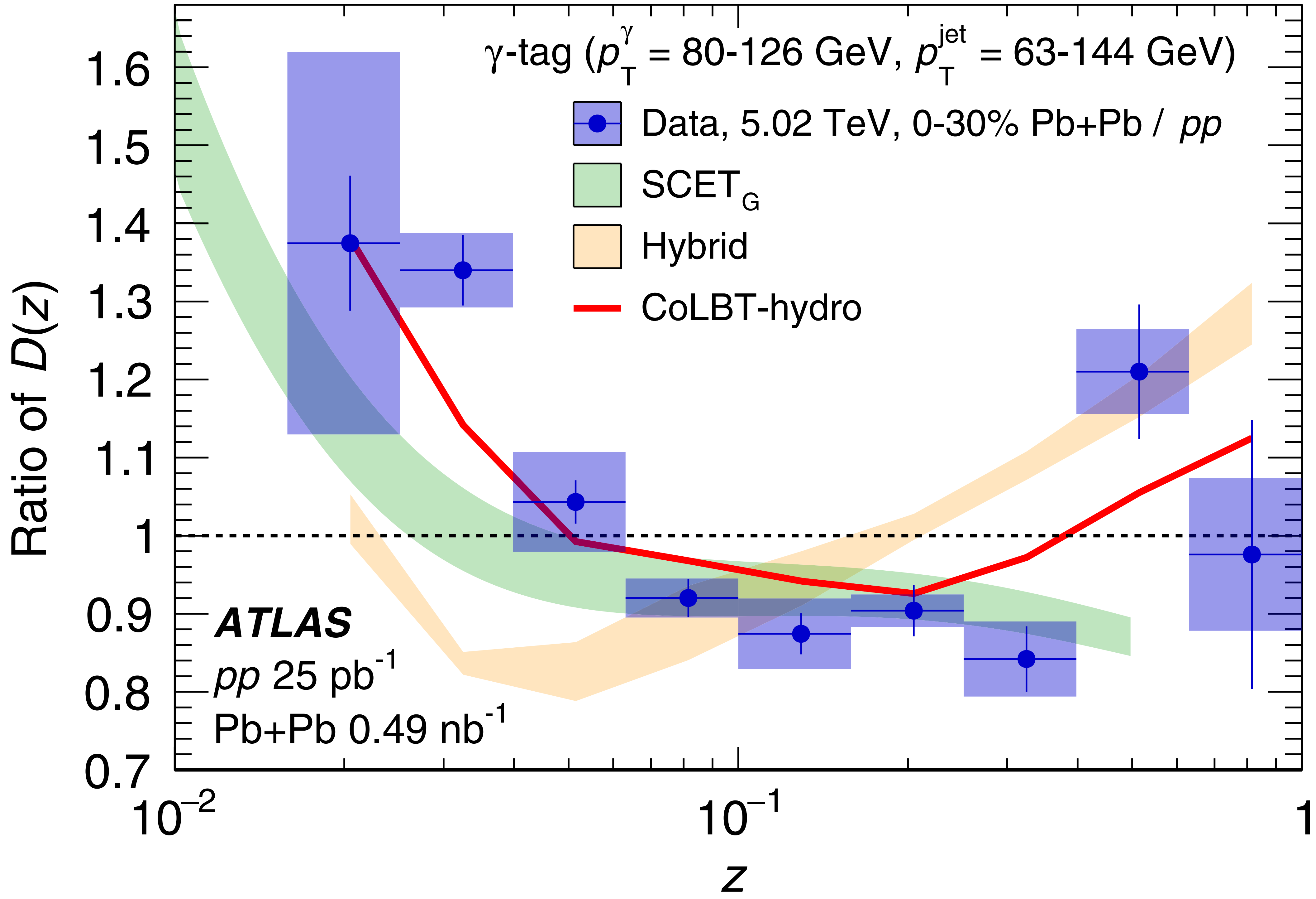
How is the soft jet substructure modified in heavy-ion collisions?



Longitudinal momentum fraction of hadrons in jets

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{dn_{\mathrm{ch}}}{dz}$$

$$z \equiv p_{\mathrm{T}} \cos \Delta R \; / \; p_{\mathrm{T}}^{\mathrm{jet}}$$



Simultaneous description of high-z and low-z is an open question

See also: CMS PRC 90, 024908 (2014)

Subjet fragmentation

Cluster inclusive jets with radius R, then recluster with anti-k_t with radius r

Neill, Ringer, Sato JHEP 07 (2021) 041
Kang, Ringer, Waalewijn JHEP 07 (2017) 064

$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$

Measure subjets to probe jet quenching

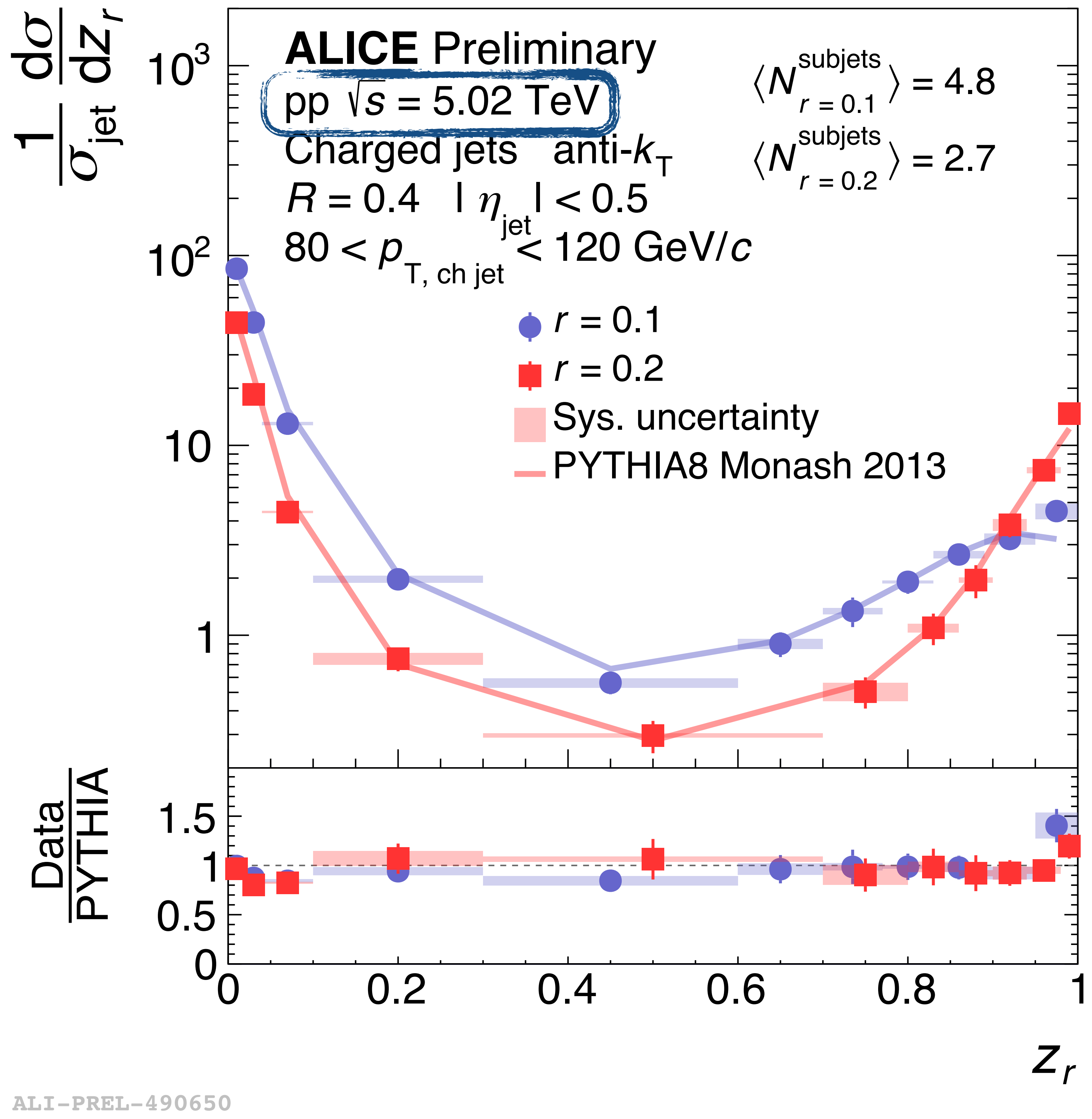
- Probe higher z than hadron fragmentation measurements   *CMS PRC 90 (2014) 2 024908; ATLAS PRL 123 (2019) 4 042001*
- Opportunity to test universality of jet fragmentation functions   *Qiu, Ringer, Sato, Zurita PRL 122 (2019) 25*

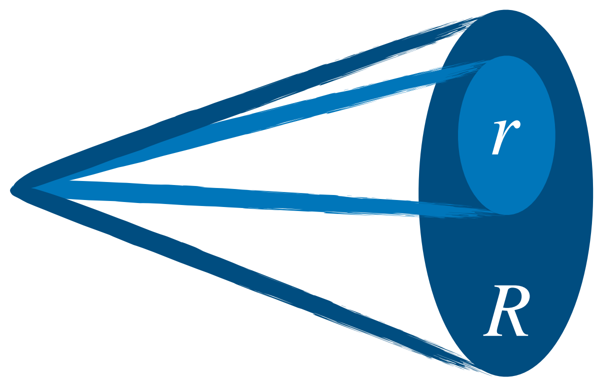
$$J_{r,\text{med}}(z) = J_{\text{med}}(z)$$

parton → subjet   parton → jet

Inclusive subjets

ISMD arXiv 2110.15467

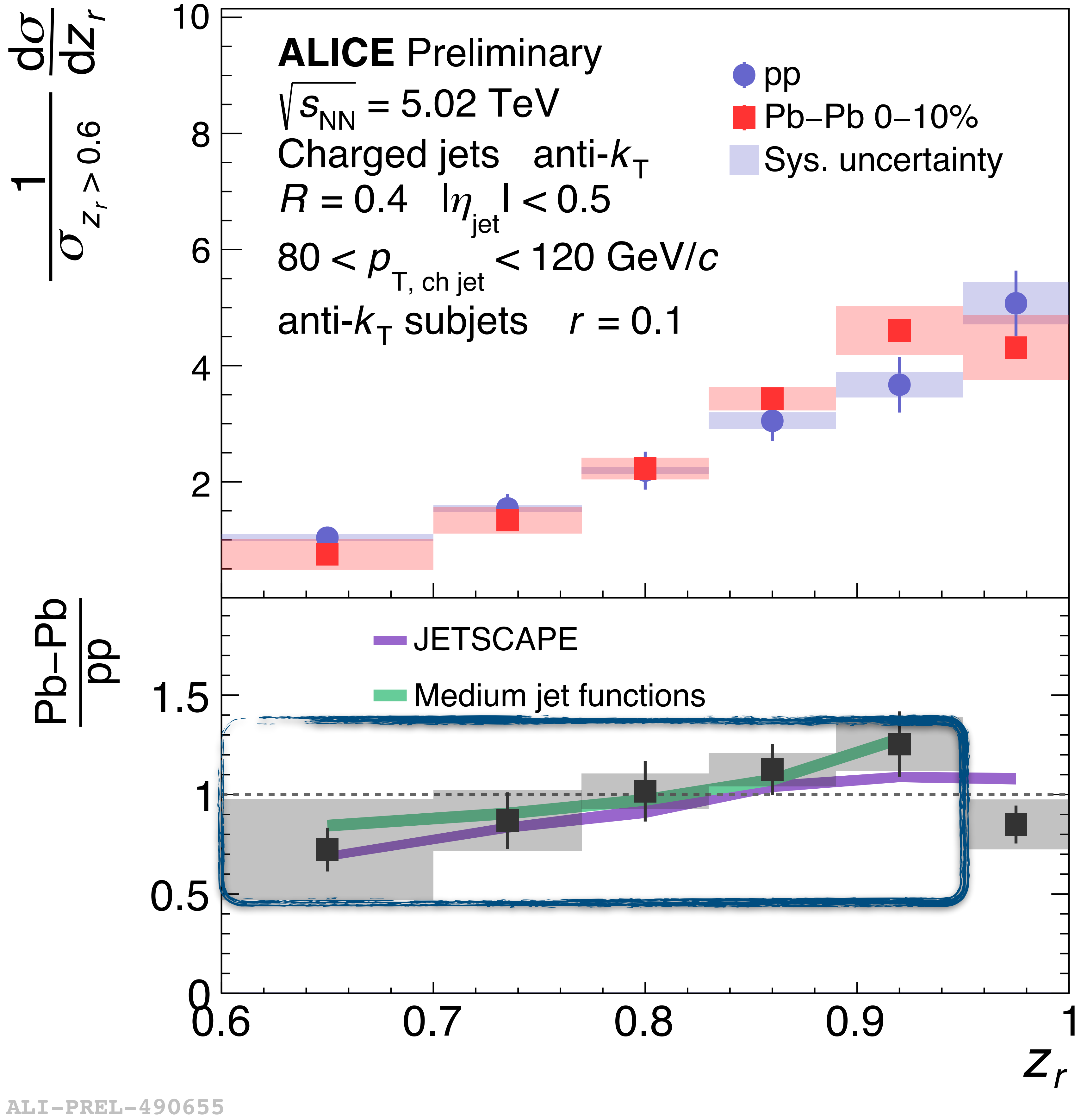




Subjet fragmentation — Pb-Pb

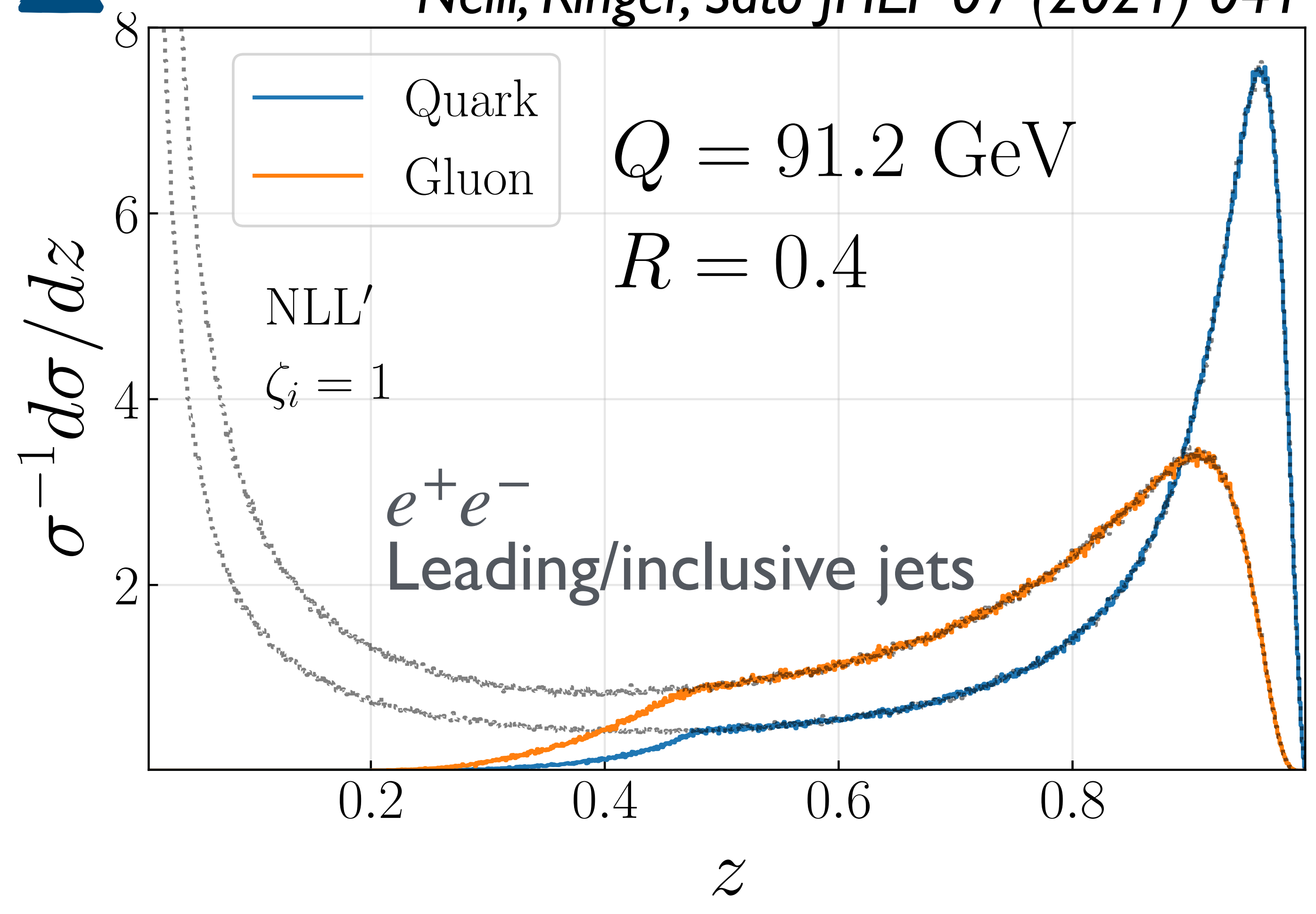
Leading subjets

ISMD arXiv 2110.15467



Hardening distribution at intermediate z_r
- Large quark-gluon differences in vacuum
- Competing effects
  - Gluon suppression → larger z_r
  - Soft radiation → smaller z_r

Neill, Ringer, Sato JHEP 07 (2021) 041



Well-described by theoretical predictions

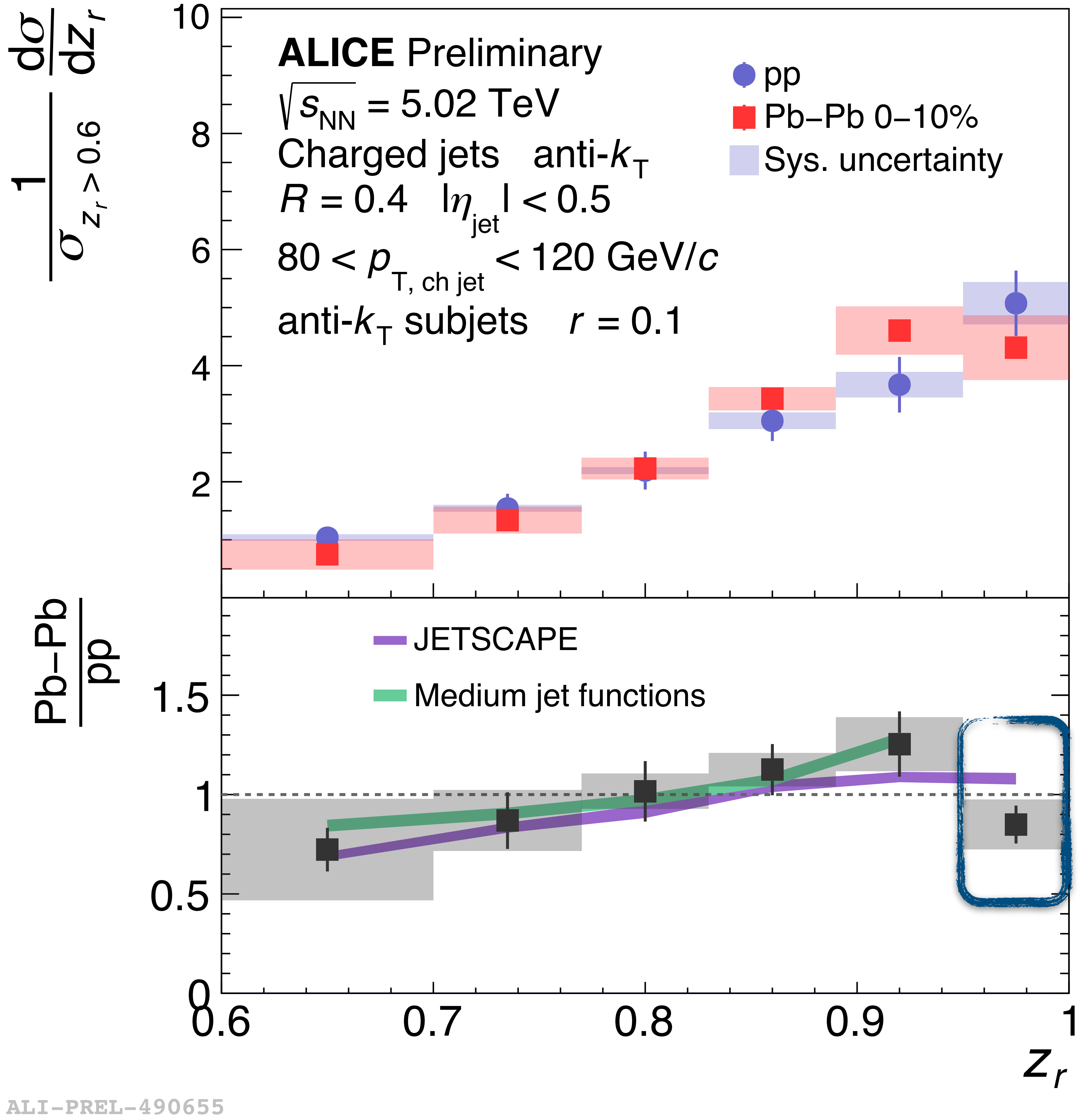
→ Consistent with universality of jet fragmentation in QGP

Qiu, Ringer, Sato, Zurita PRL 122 (2019) 25

Subjet fragmentation — Pb-Pb

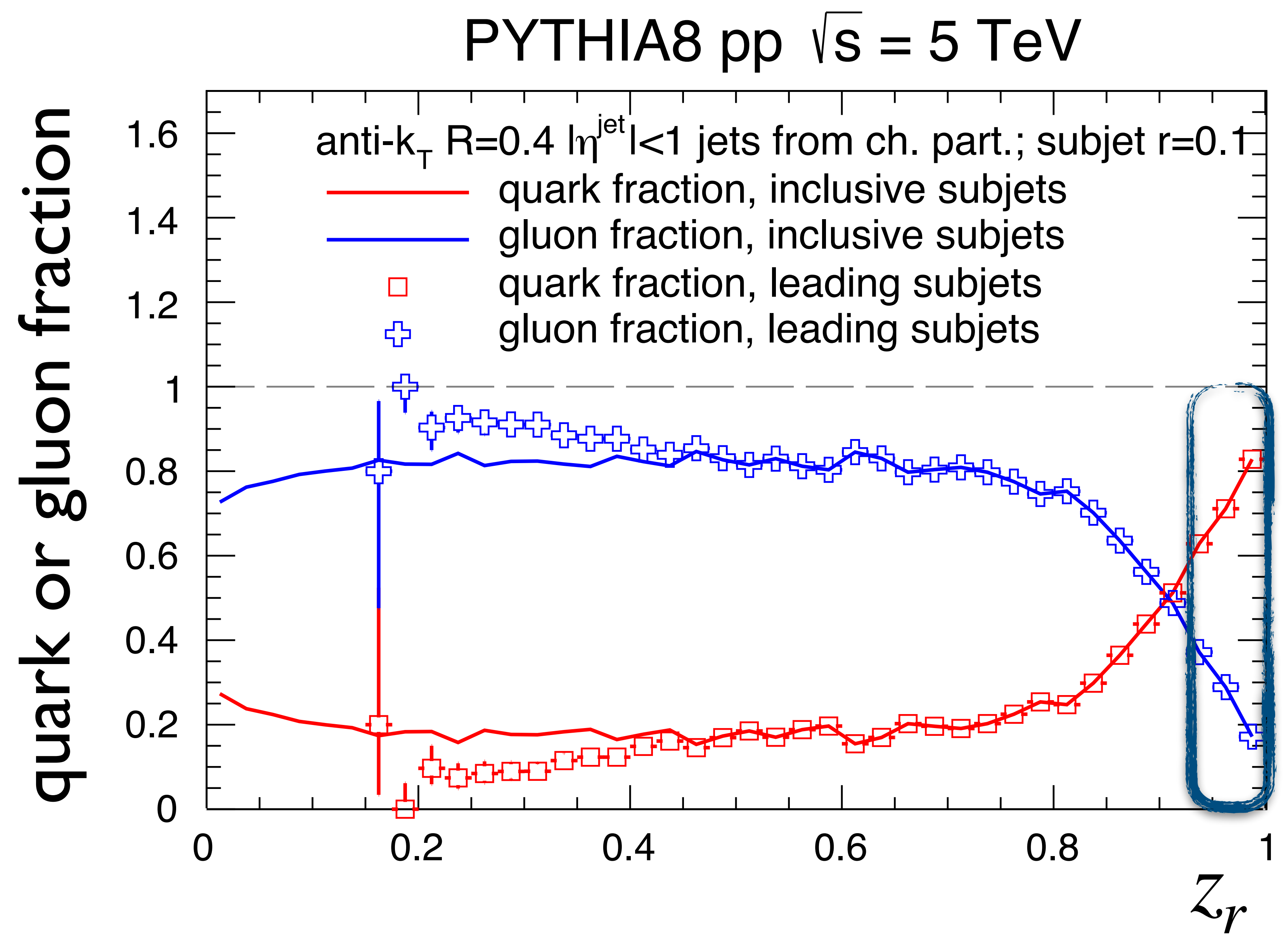
Leading subjets

ISMD arXiv 2110.15467



Hint of suppression as $z_r \to 1$

- At $z_r \to 1$, the sample becomes closer to purely quark jets!
- **Expose region depleted by soft medium induced emissions**



New path to disentangle quenching effects

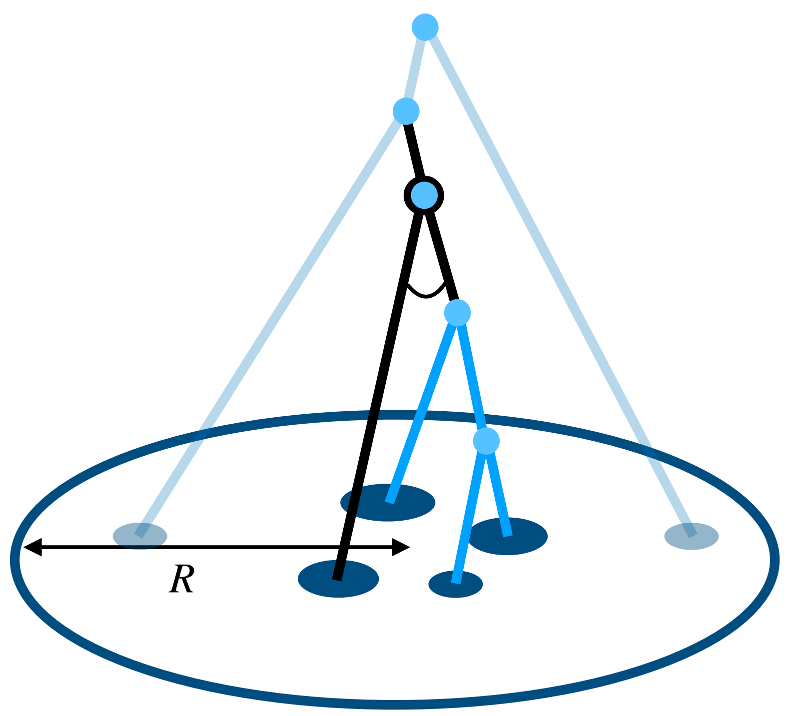
Outlook — jet substructure in heavy-ion collisions

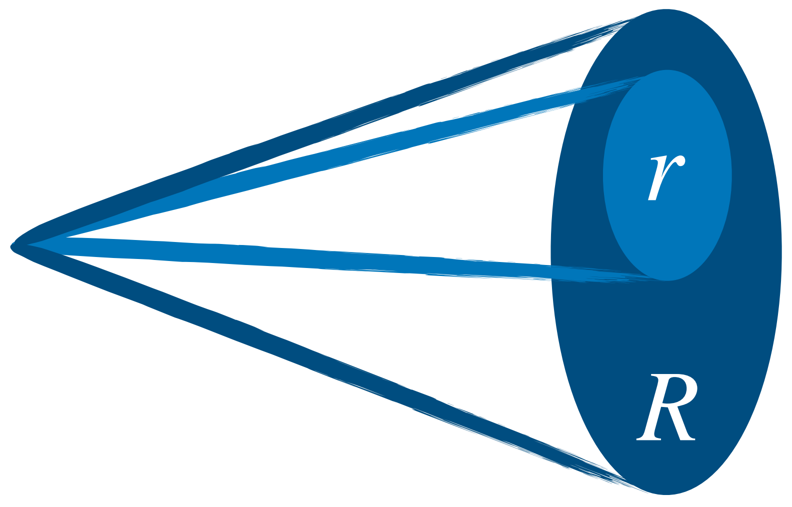
By measuring carefully chosen observables…

- Calculable in proton-proton collisions
- Corrected for background and detector effects

…we are producing an emerging picture of jet quenching phenomenology

- Hard splitting momentum distribution not strongly modified — z_g
- Collimation/filtering of wide jets — θ_g
- Medium-induced soft splitting can be exposed in region dominated by quark jets — z_r

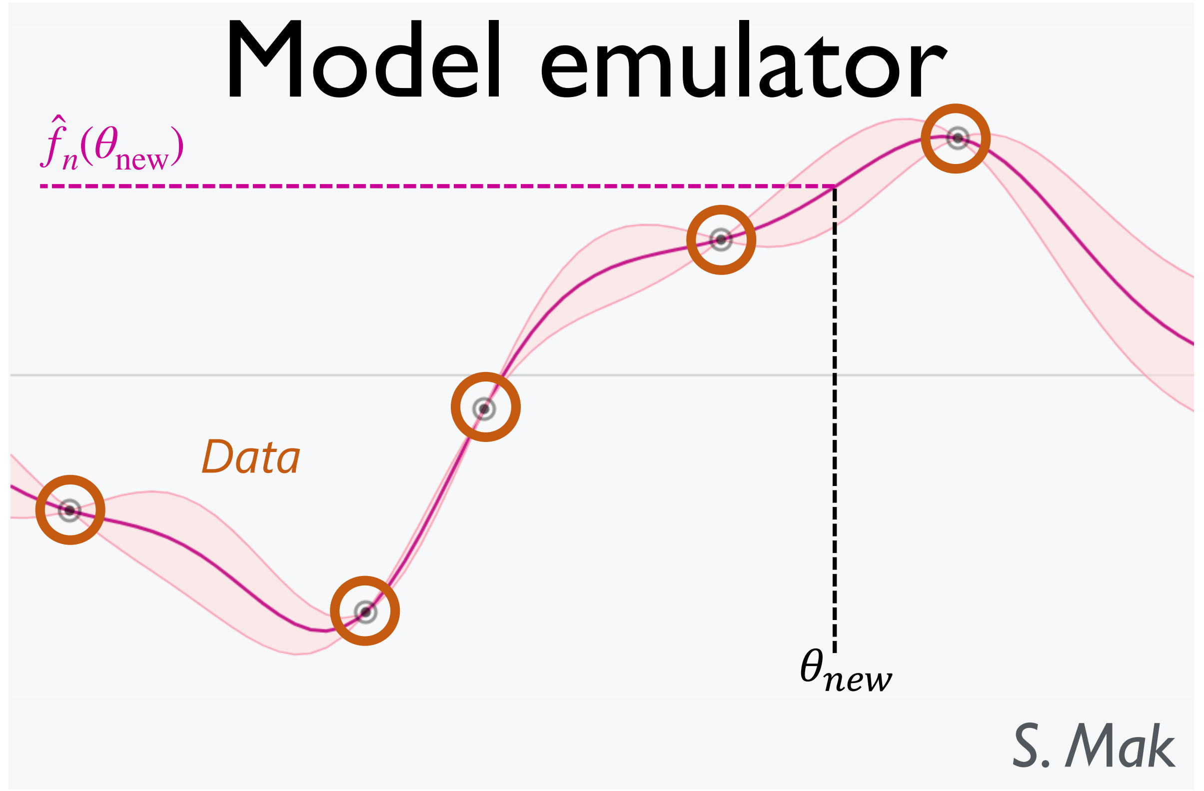


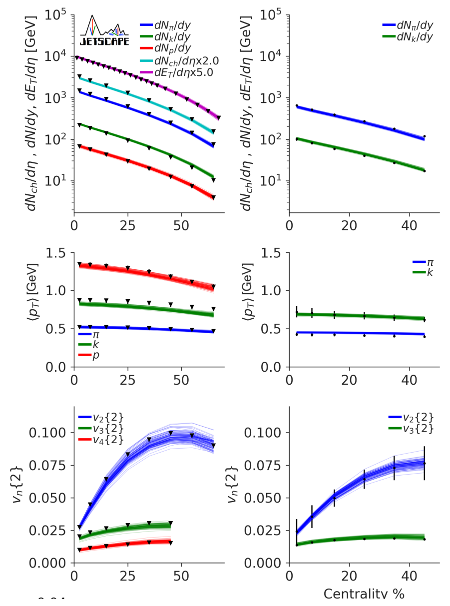


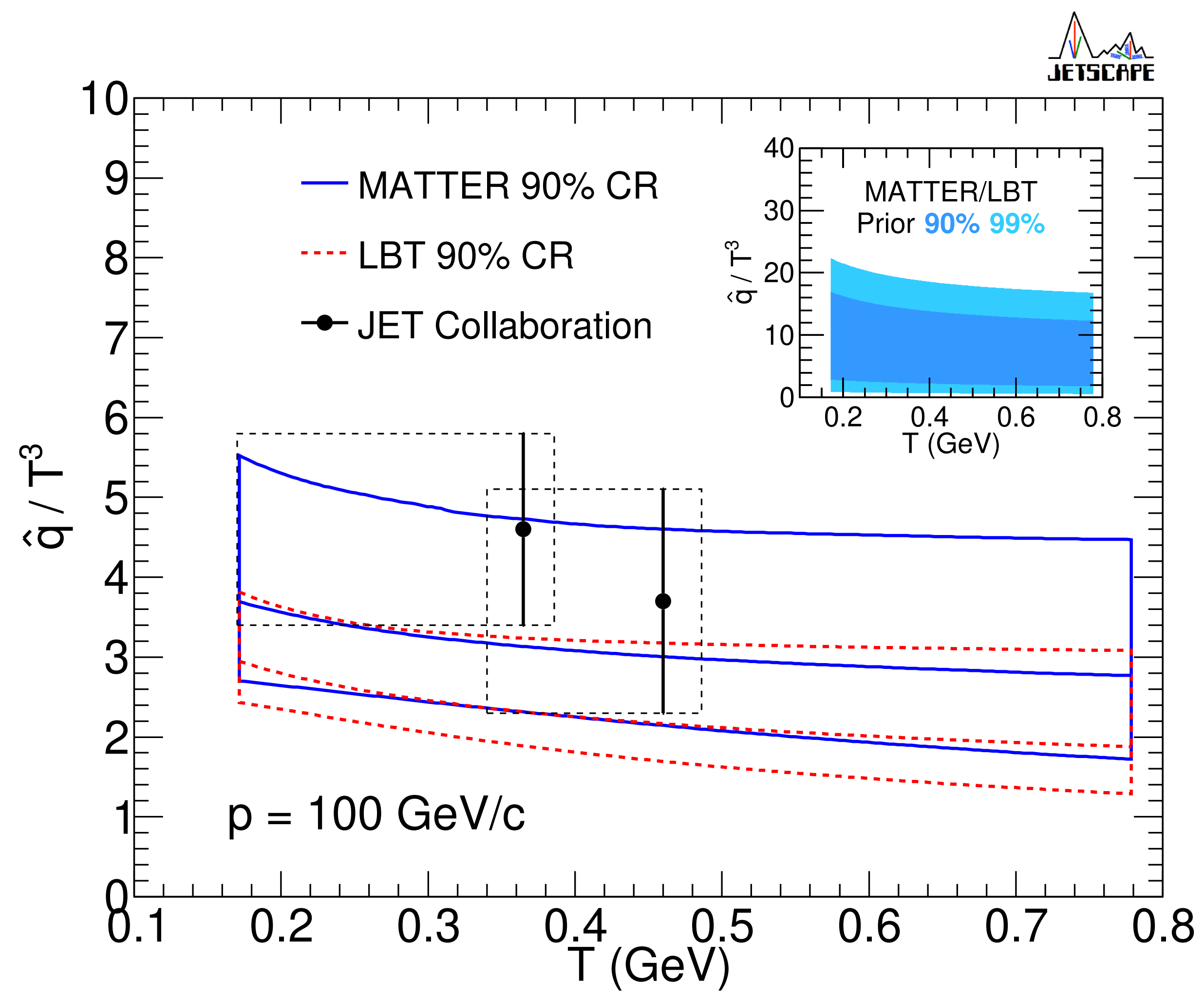
Where do we go from here?

Bayesian inference to extract QGP properties using multiple jet observables

- Controlled comparisons of specific aspects within model (q vs. g, medium response, …)







JETSCAPE PRC 104, 024905 (2021)

See also:
Ke, Wang JHEP 05 041 (2021)
Andrés et al. EPJC 76 475 (2016)
JET PRC 90, 014909 (2014)

Observable design to add new information to these global extractions

- Model sensitivity — *JETSCAPE PRC 103, 054904 (2021)*; *Lai arXiv 1810.00835*; *Sangaline, Pratt PRC 93, 024908 (2016)*
- Information content distinguishing pp from AA jets — *Lai, JM, Płoskoń, Ringer arXiv 2111.14589*

Summary

ALICE measurements of jet substructure in proton-proton collisions are providing new tests of our first-principles understanding of QCD

- Explore the transition from the perturbative to non-perturbative regimes
- More results not shown here: dead cone, Lund plane, axis differences, Dynamical grooming, …

New measurements of jet substructure in heavy-ion collisions are producing an emerging picture of jet quenching and starting to connect to QGP properties

- Emphasis on observables that can be directly compared to theoretical calculations

ALICE jet capabilities in LHC Runs 3+4 will enable new extractions of QGP properties

- Increased statistics by 50-100x, improved tracking — HF-jet, γ-jet, larger p_{T}