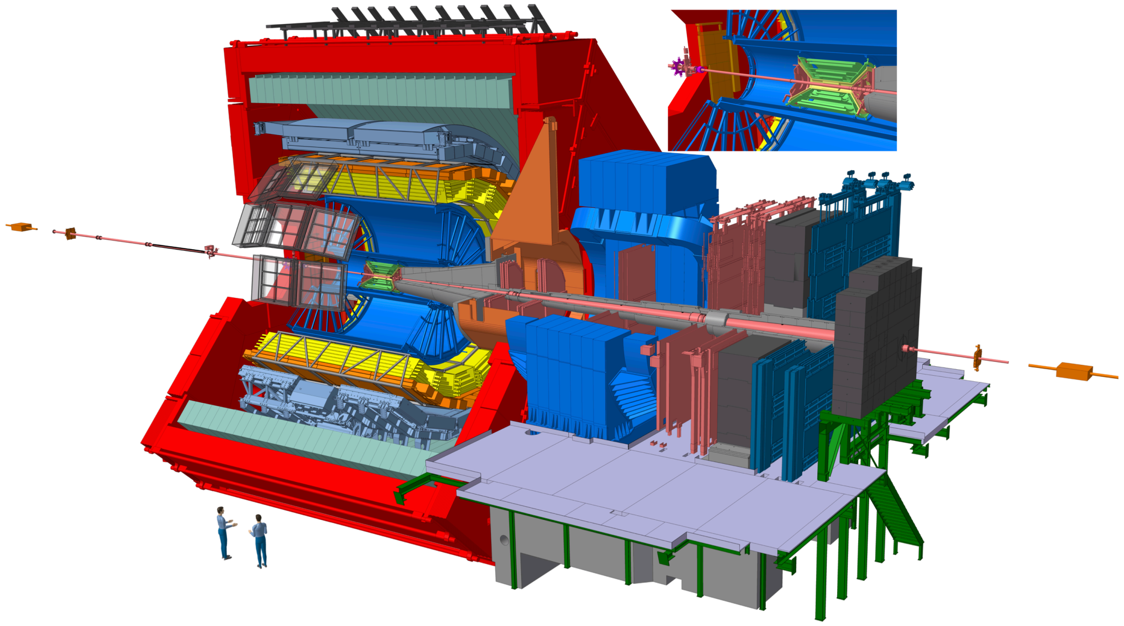
Inclusive jet measurements in Pb-Pb collisions with ALICE

James Mulligan
Yale University

Thesis Defense
Oct 9, 2018



PhD advisor: Professor John W. Harris

Thesis committee: Prof. Helen Caines, Prof. Karsten Heeger, Prof. Thomas Appelquist

QCD

We know some basic features of QCD

- *The Lagrangian*

$$\mathcal{L}_{QCD} = -\frac{1}{4g^2} F^a_{\mu\nu} F^{a\mu\nu} + \sum_{j=1}^{6} \bar{q}_j \left(i\gamma^\mu D_\mu - m_j \right) q_j$$

gluons

coupling

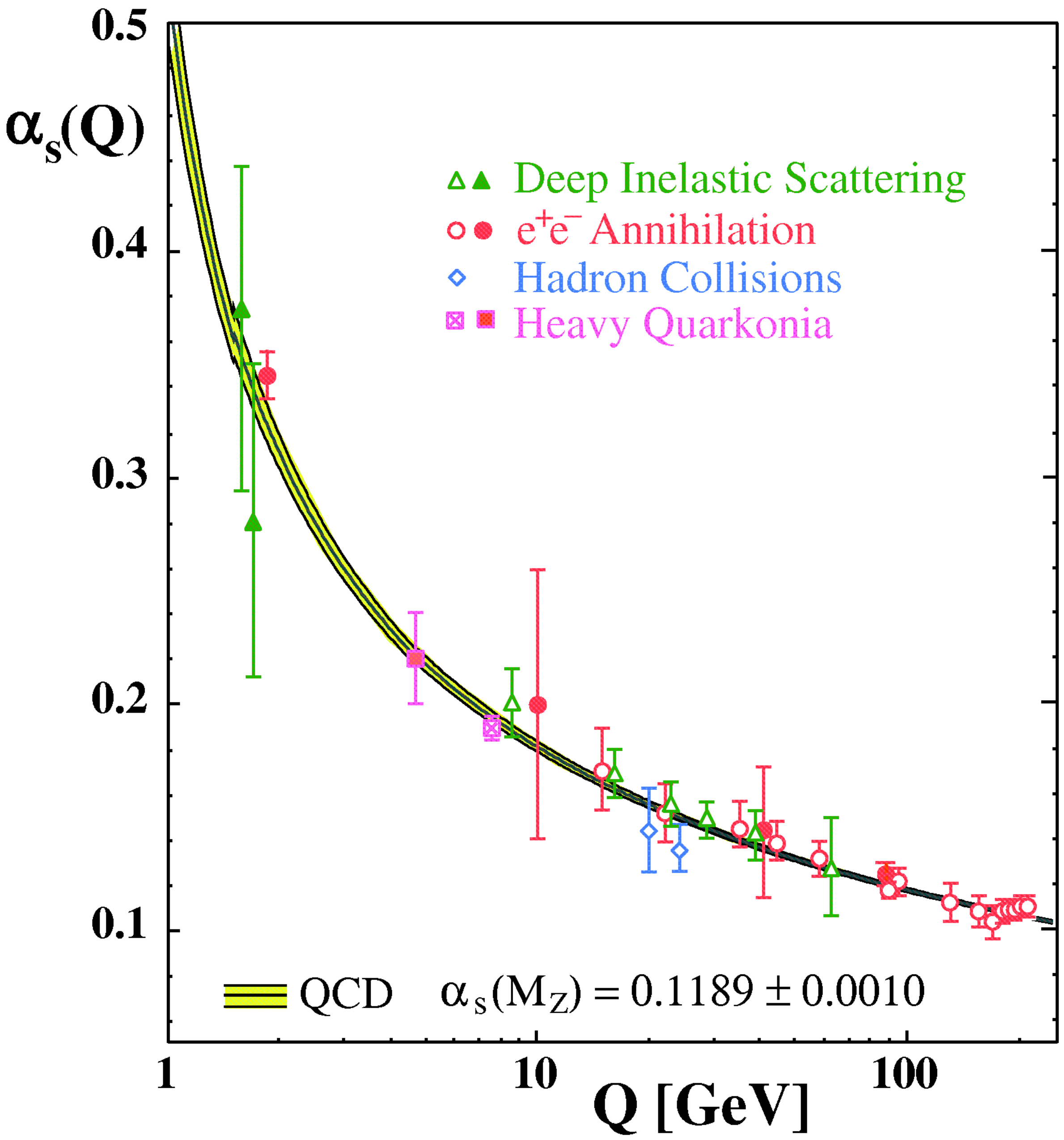
$\alpha_s(\mu) \equiv g(\mu)^2/4\pi$

6 quark flavors

QCD

We know some basic features of QCD

- *The Lagrangian*
- *The running of the coupling in the perturbative regime*



$$\mathcal{L}_{QCD} = -\frac{1}{4g^2} F^a_{\mu\nu} F^{a\mu\nu} + \sum_{j=1}^{6} \bar{q}_j \left(i\gamma^\mu D_\mu - m_j\right) q_j$$

gluons

coupling

$\alpha_s(\mu) \equiv g(\mu)^2/4\pi$

6 quark flavors

QCD

We know some basic features of QCD

- *The Lagrangian*
- *The running of the coupling in the perturbative regime*
- *Color confinement is observed*
- *Lattice QCD predicts the hadronic spectrum rather well*
- *…*

QCD

We know some basic features of QCD

- *The Lagrangian*
- *The running of the coupling in the perturbative regime*
- *Color confinement is observed*
- *Lattice QCD predicts the hadronic spectrum rather well*
- *…*

But most of the emergent behaviors of QCD are **not** understood

- *The origin of confinement*
- *The proton spin puzzle*
- *Certain bound states are unexpectedly observed / not observed*
- *Basic behaviors of de-confined QCD matter*
- …

“The strongest and least understood of the fundamental forces”

Outline

1. *Introduction:* The quark-gluon plasma

2. *Overview:* Using jets to study the quark-gluon plasma

3. *Results:* Inclusive jet measurements in Pb-Pb collisions with ALICE at $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$

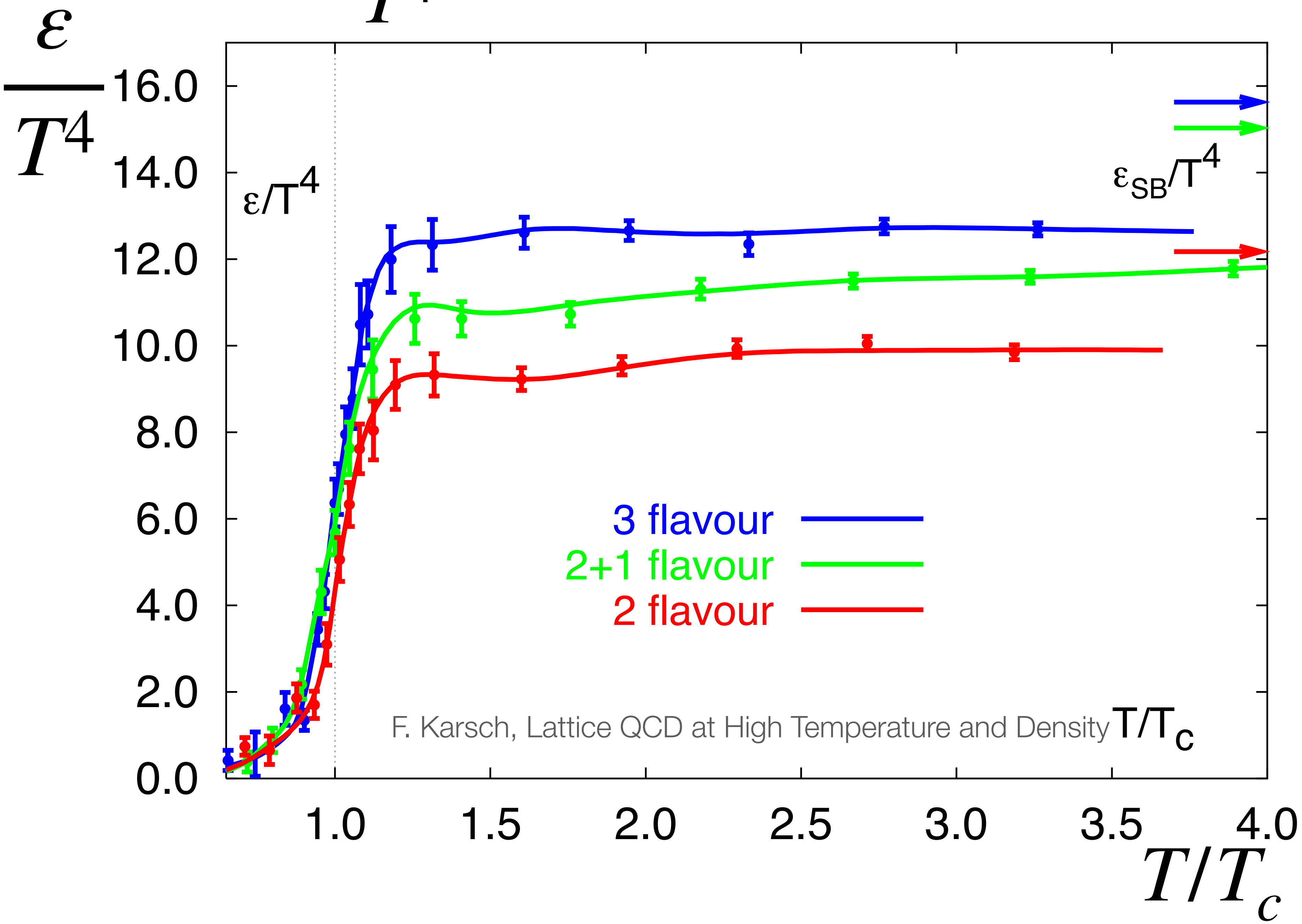
High-Temperature QCD

At high *T*, hadrons melt into quarks and gluons

High-Temperature QCD

At high *T*, hadrons melt into quarks and gluons

$$\frac{\varepsilon}{T^4} \propto \text{degrees of freedom}$$



F. Karsch, Lattice QCD at High Temperature and Density

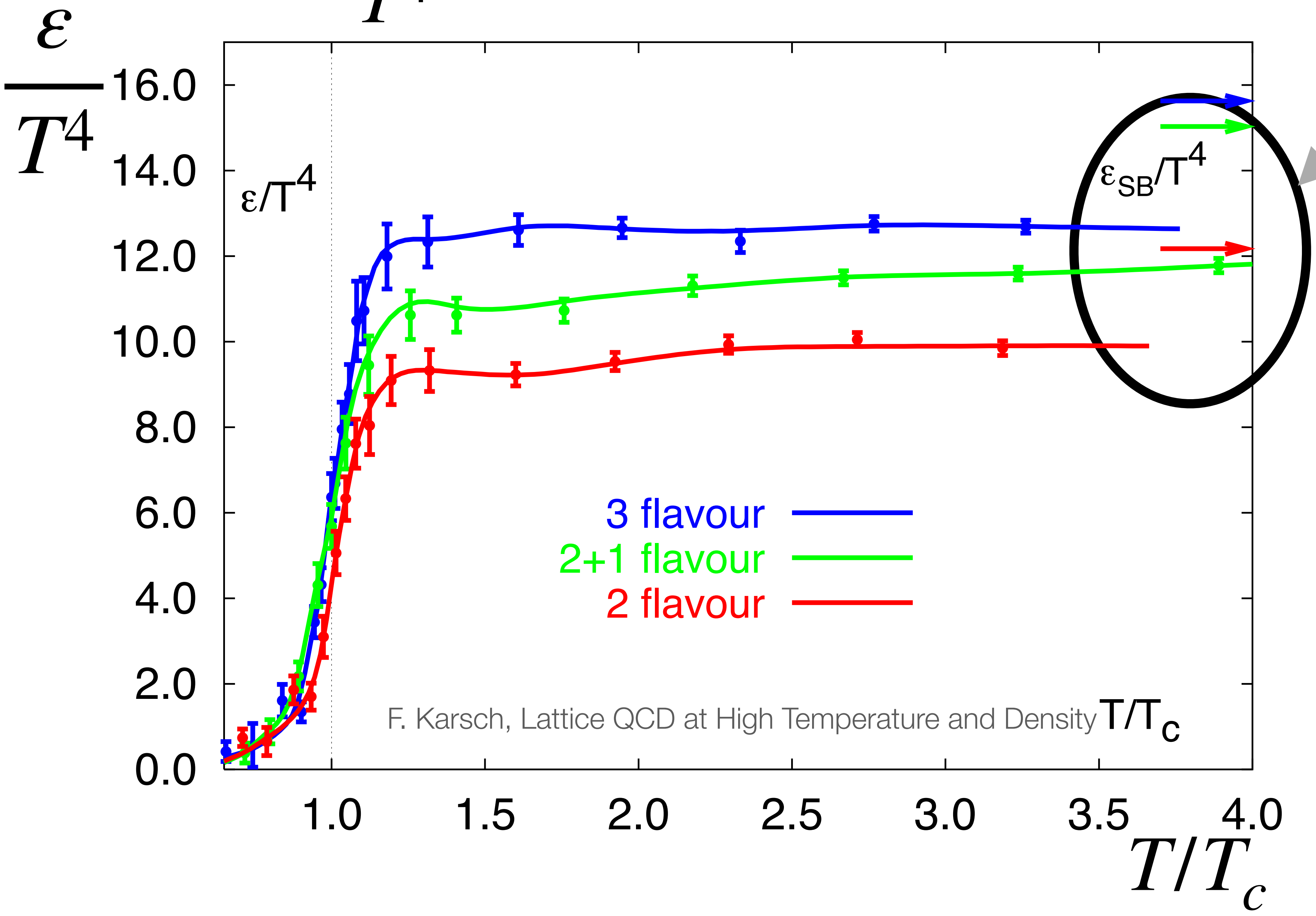
Lattice QCD predicts a transition to **deconfinement** at T_c ~ 165 MeV

"The quark-gluon plasma"

High-Temperature QCD

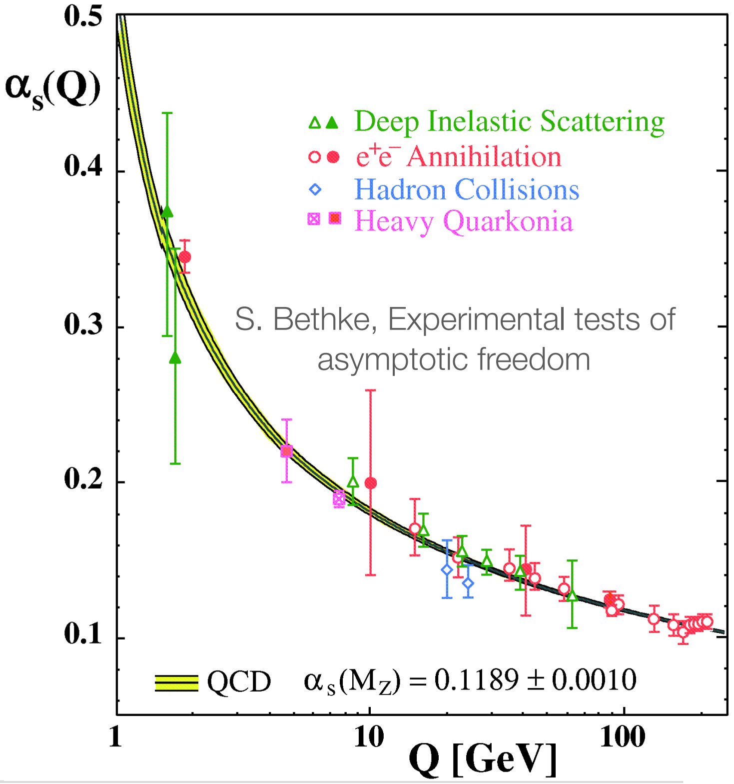
At high *T*, hadrons melt into quarks and gluons

$$\frac{\varepsilon}{T^4} \propto \text{degrees of freedom}$$



F. Karsch, Lattice QCD at High Temperature and Density

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

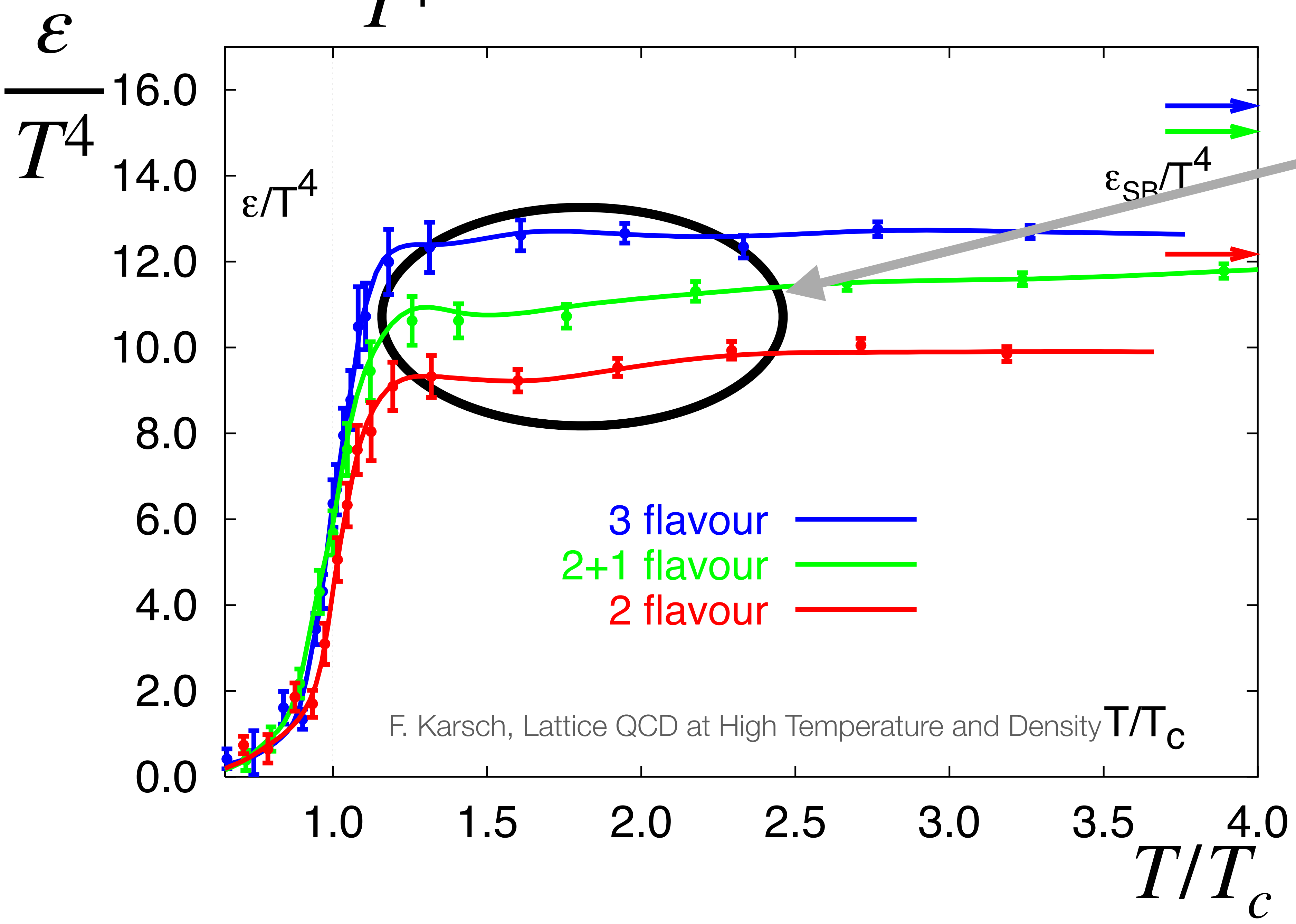


S. Bethke, Experimental tests of asymptotic freedom

High-Temperature QCD

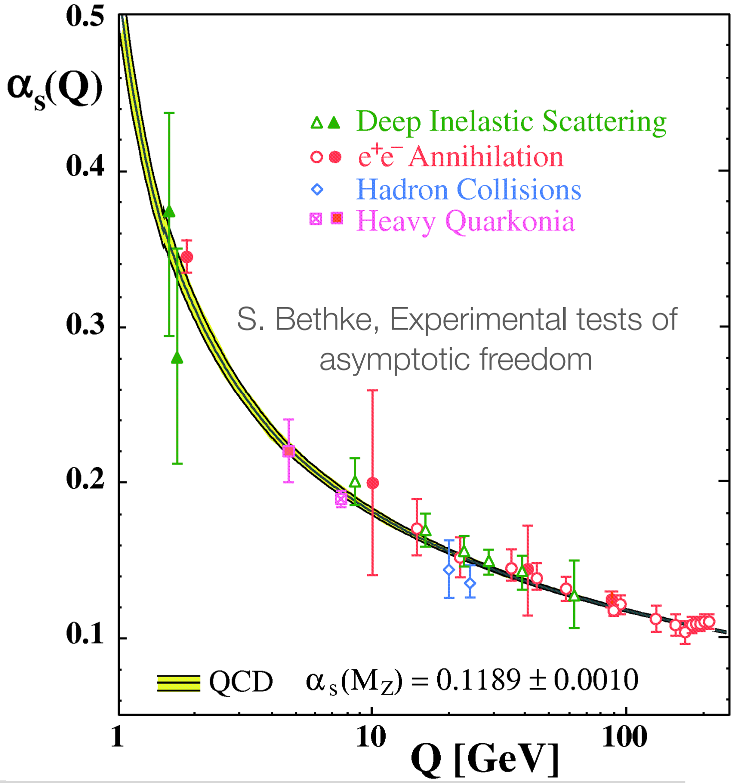
At high *T*, hadrons melt into quarks and gluons

$$\frac{\varepsilon}{T^4} \propto \text{degrees of freedom}$$



F. Karsch, Lattice QCD at High Temperature and Density

What is the coupling here?

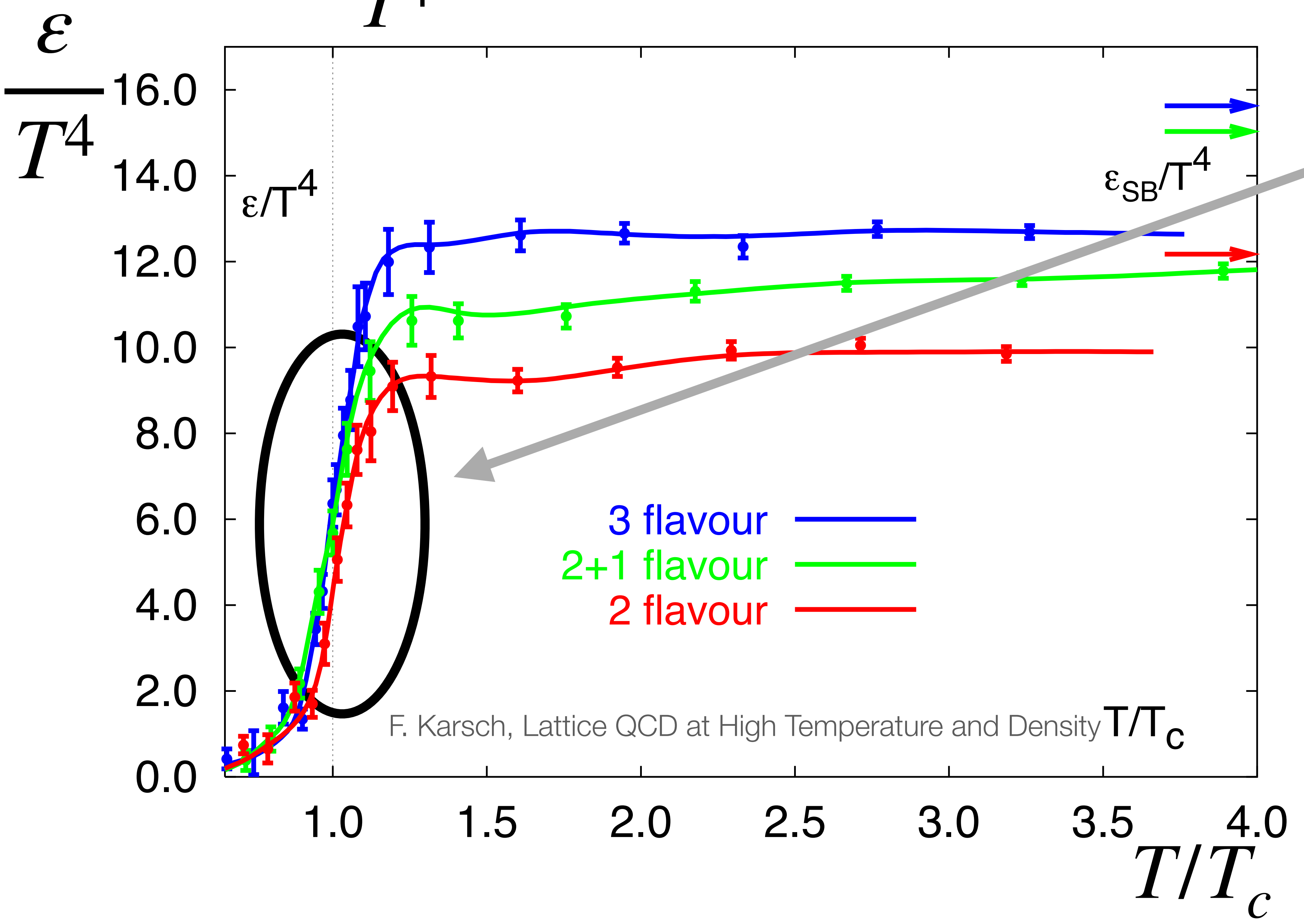


S. Bethke, Experimental tests of asymptotic freedom

High-Temperature QCD

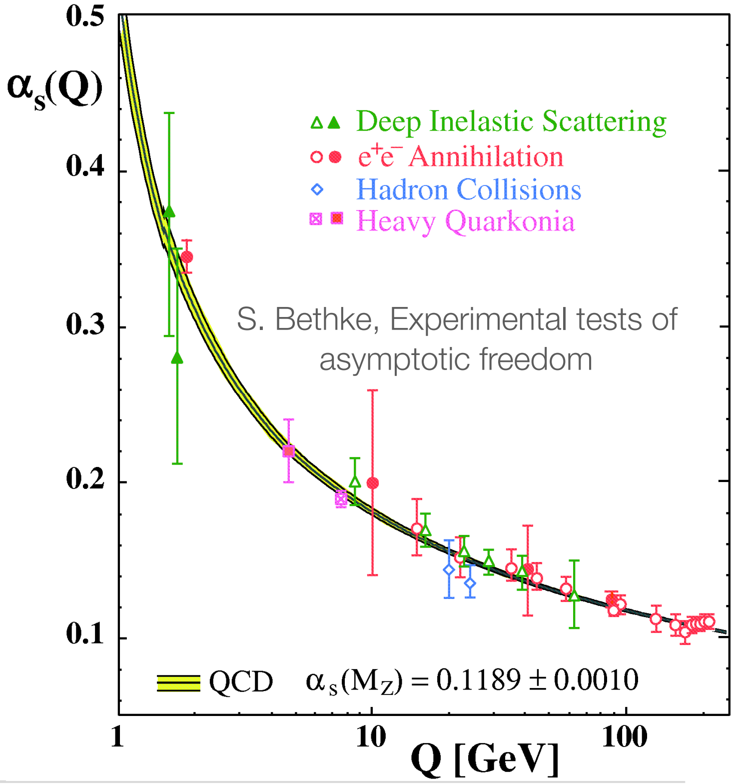
At high *T*, hadrons melt into quarks and gluons

$$\frac{\varepsilon}{T^4} \propto \text{degrees of freedom}$$



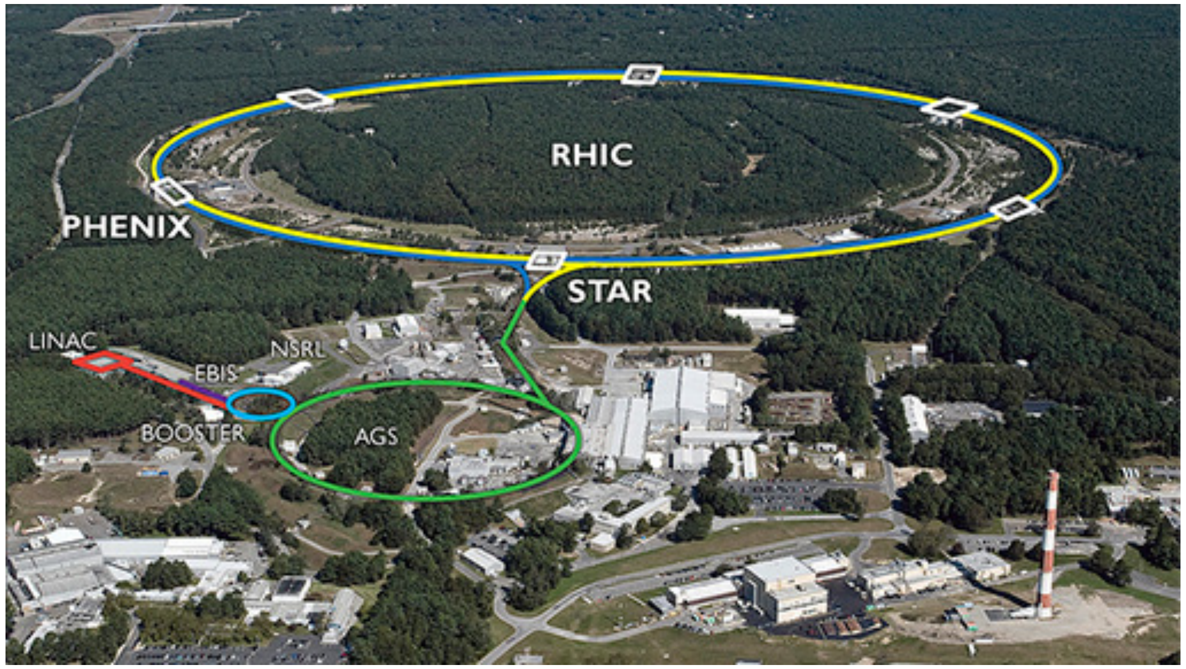
F. Karsch, Lattice QCD at High Temperature and Density

What is the structure of QCD matter here?



S. Bethke, Experimental tests of asymptotic freedom

Ultra-relativistic heavy-ion collisions



$$\sqrt{s_{\mathrm{NN}}} = 200 \text{ GeV}$$

Relativistic Heavy-Ion Collider

Brookhaven National Lab

STAR PHENIX

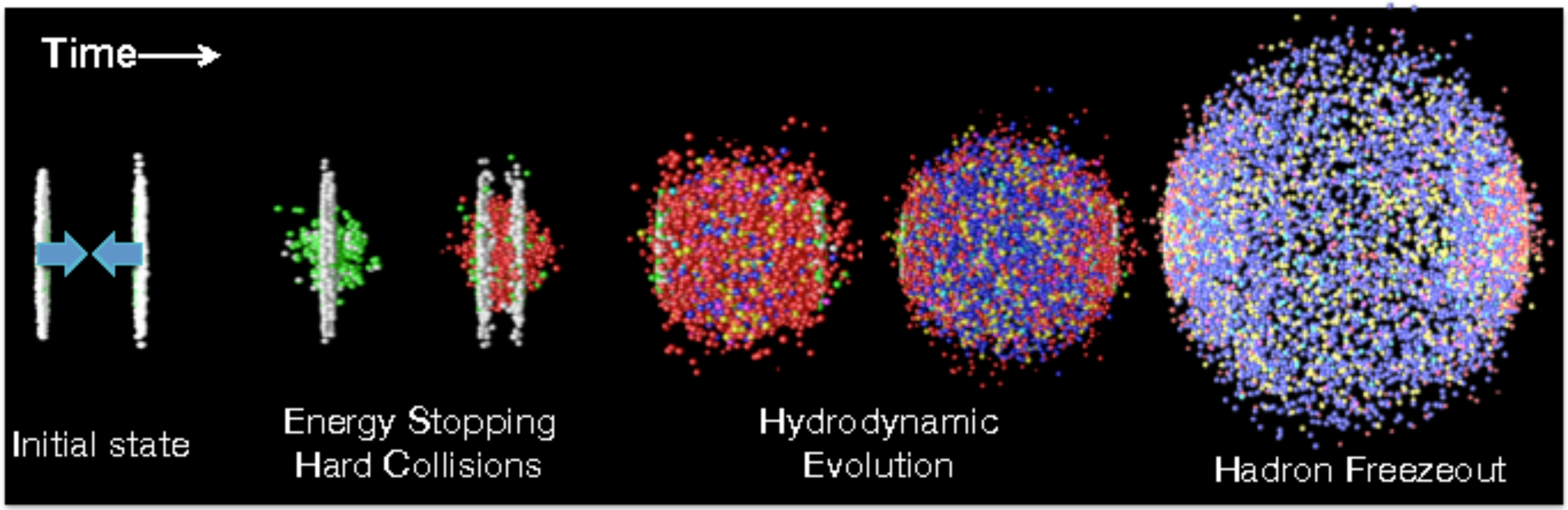
$$\sqrt{s_{\mathrm{NN}}} = 2.76, 5.02 \text{ TeV}$$

Large Hadron Collider

CERN

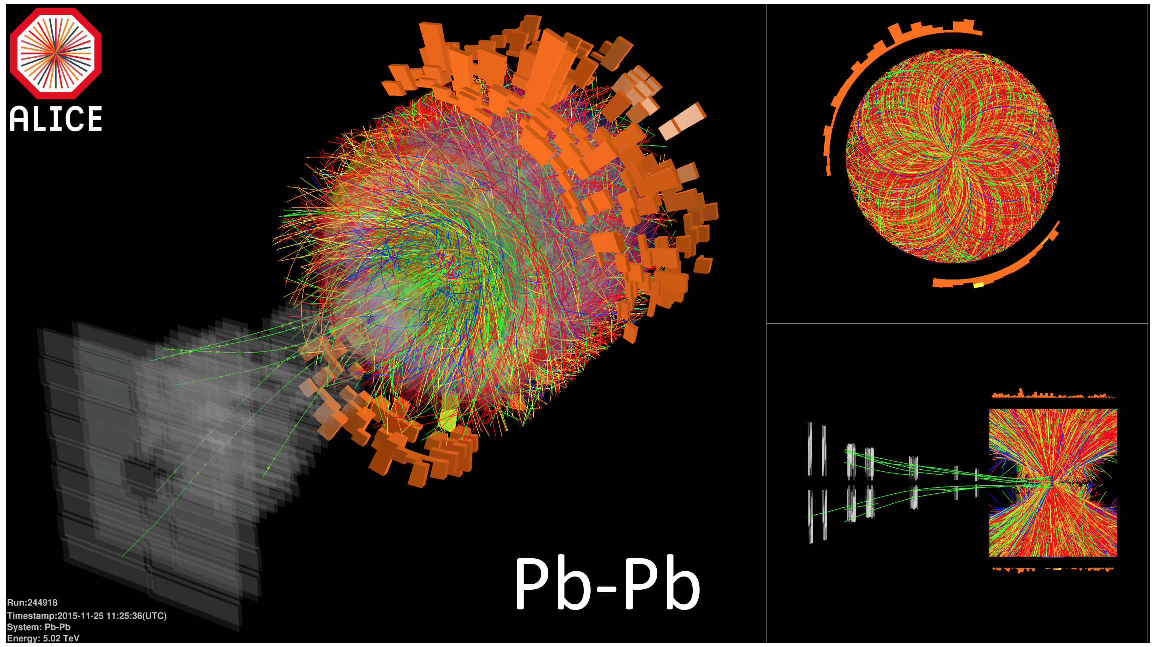
ALICE CMS Compact Muon Solenoid ATLAS EXPERIMENT

Ultra-relativistic heavy-ion collisions



Heavy-ion collisions create maximal energy density, and therefore allow us to create quark-gluon plasma experimentally

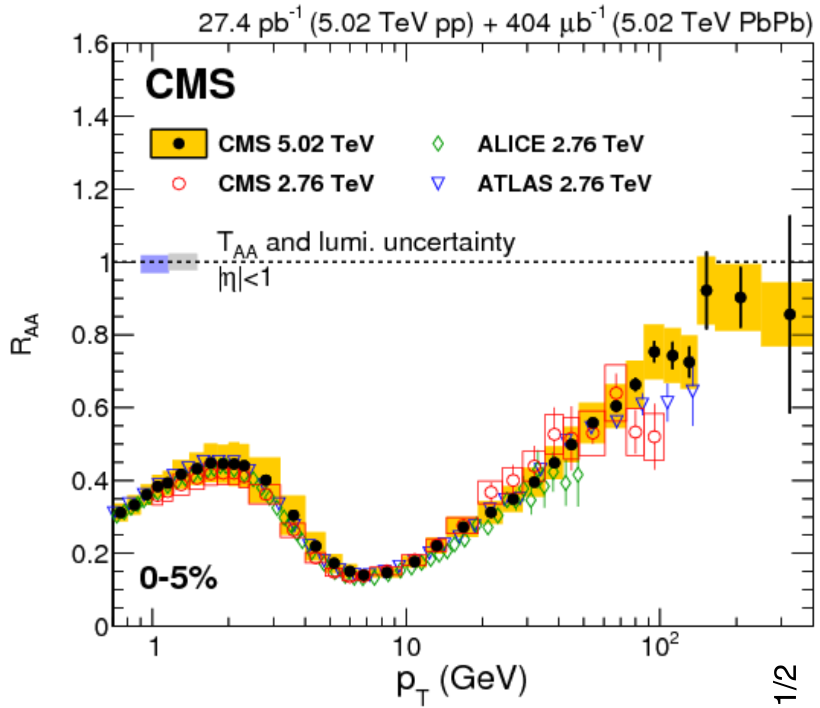
- The hottest matter created (T ~ 500 MeV)
- The most dense matter created ($\varepsilon \sim$ 1-10 $\varepsilon_{\mathrm{hadron}}$)



Signatures of the quark-gluon plasma

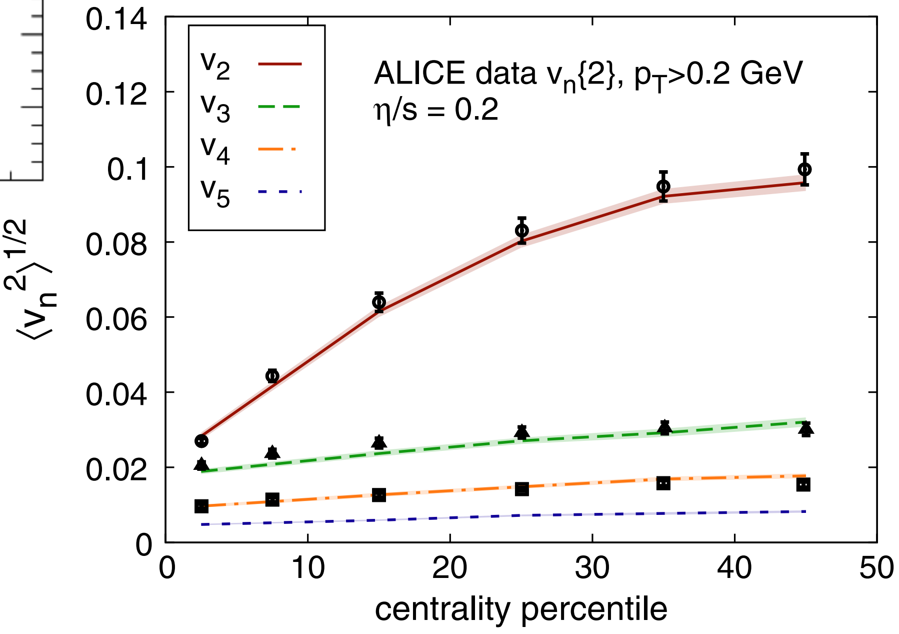
A variety of experimental signatures confirm that deconfined QCD matter is created in heavy-ion collisions

Suppression of high-p_T hadrons



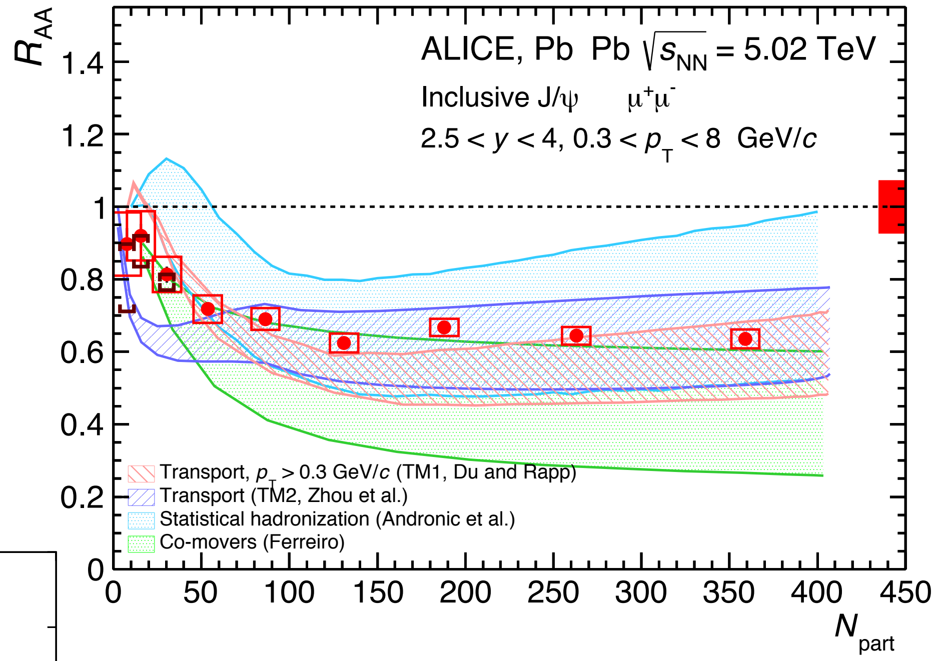
JHEP 1704 (2017) 039

Anisotropic flow



PRL 110 (2013) 012302

J/ψ suppression



PLB 766 (2017) 212-224

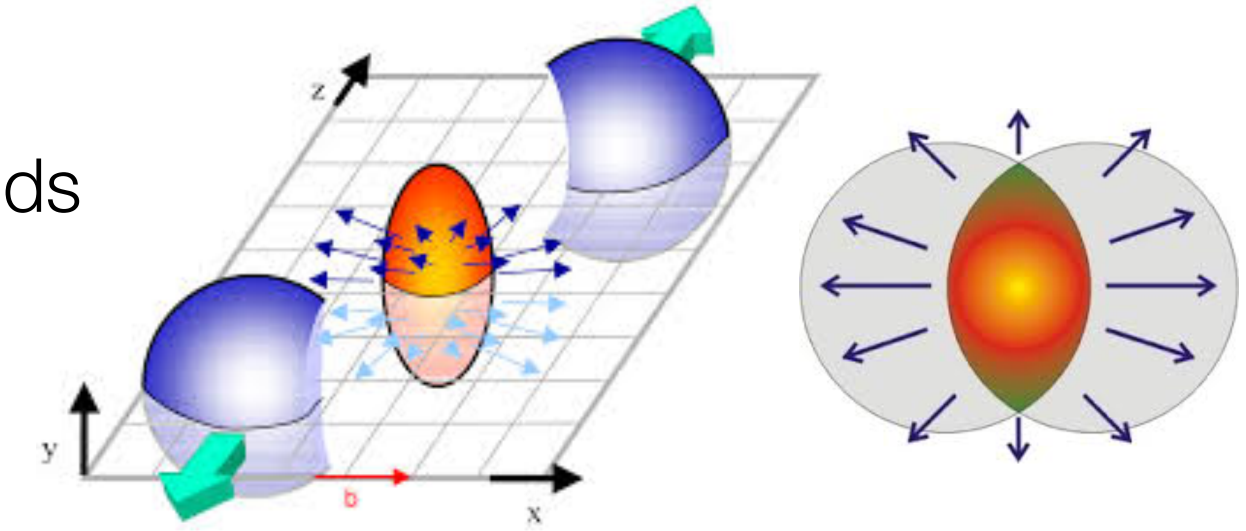
And more…

The strongly-coupled quark-gluon plasma

Elliptic flow: Back-to-back azimuthal correlation of soft particles

“Almond shape” is produced by collision overlap, and then hydrodynamically expands

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi$$

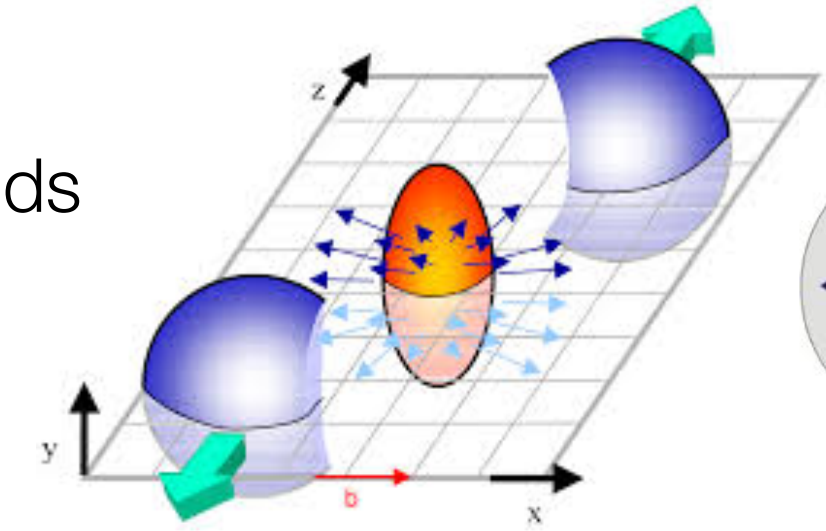


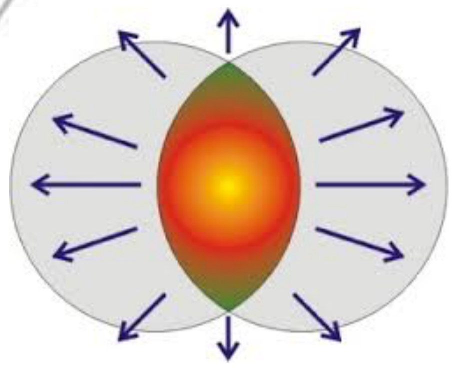
The strongly-coupled quark-gluon plasma

Elliptic flow: Back-to-back azimuthal correlation of soft particles

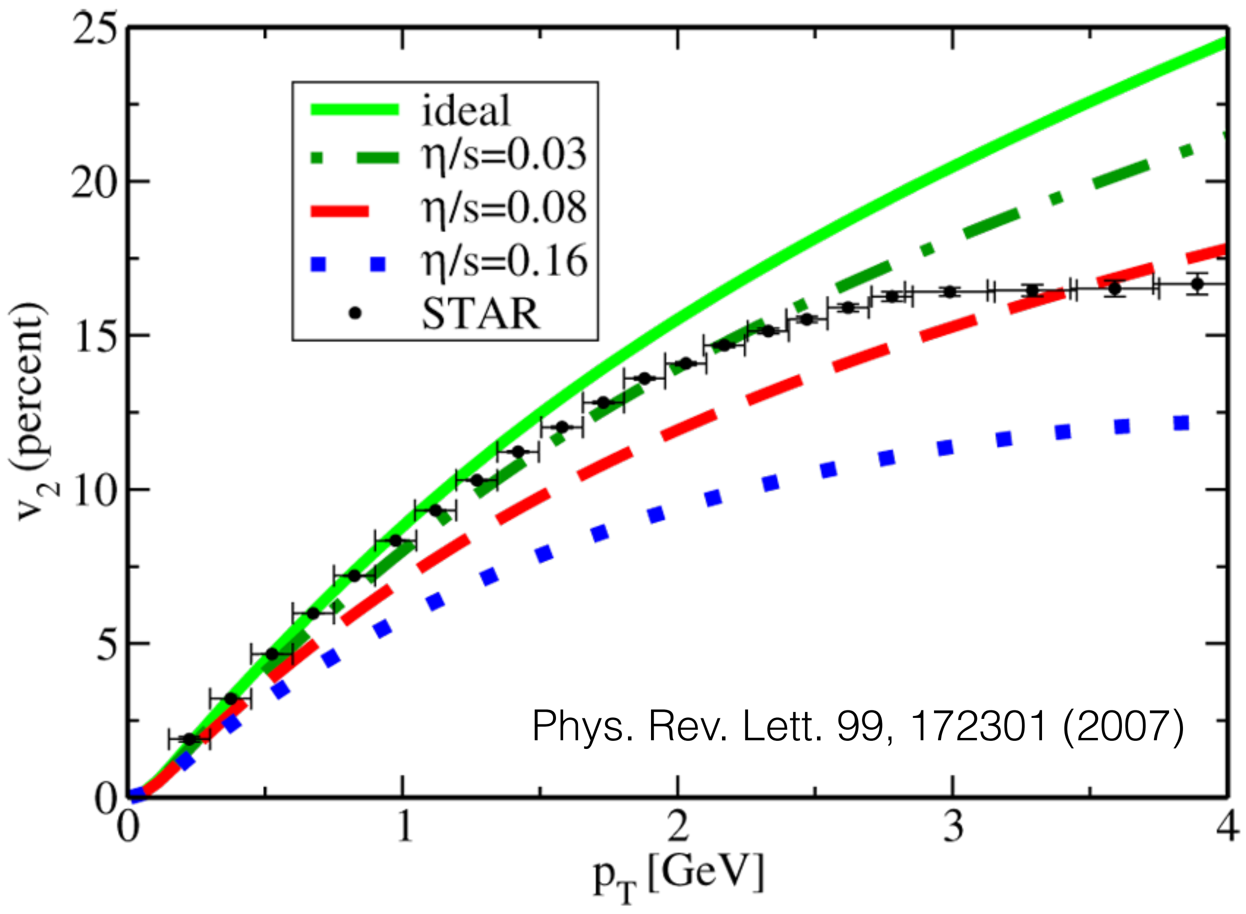
“Almond shape” is produced by collision overlap, and then hydrodynamically expands

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi$$





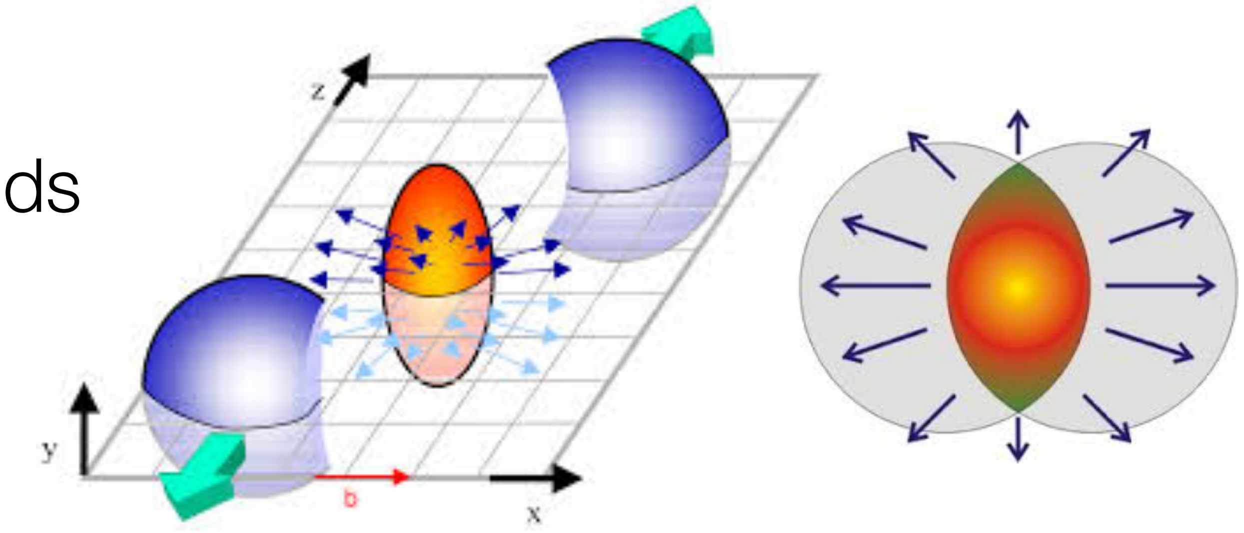
The strength of the back-to-back correlation, $\boldsymbol{v_2}$, is damped by the shear-viscosity to entropy-density ratio, $\boldsymbol{\eta/s}$



Phys. Rev. Lett. 99, 172301 (2007)

The strongly-coupled quark-gluon plasma

Elliptic flow: Back-to-back azimuthal correlation of soft particles



“Almond shape” is produced by collision overlap, and then hydrodynamically expands

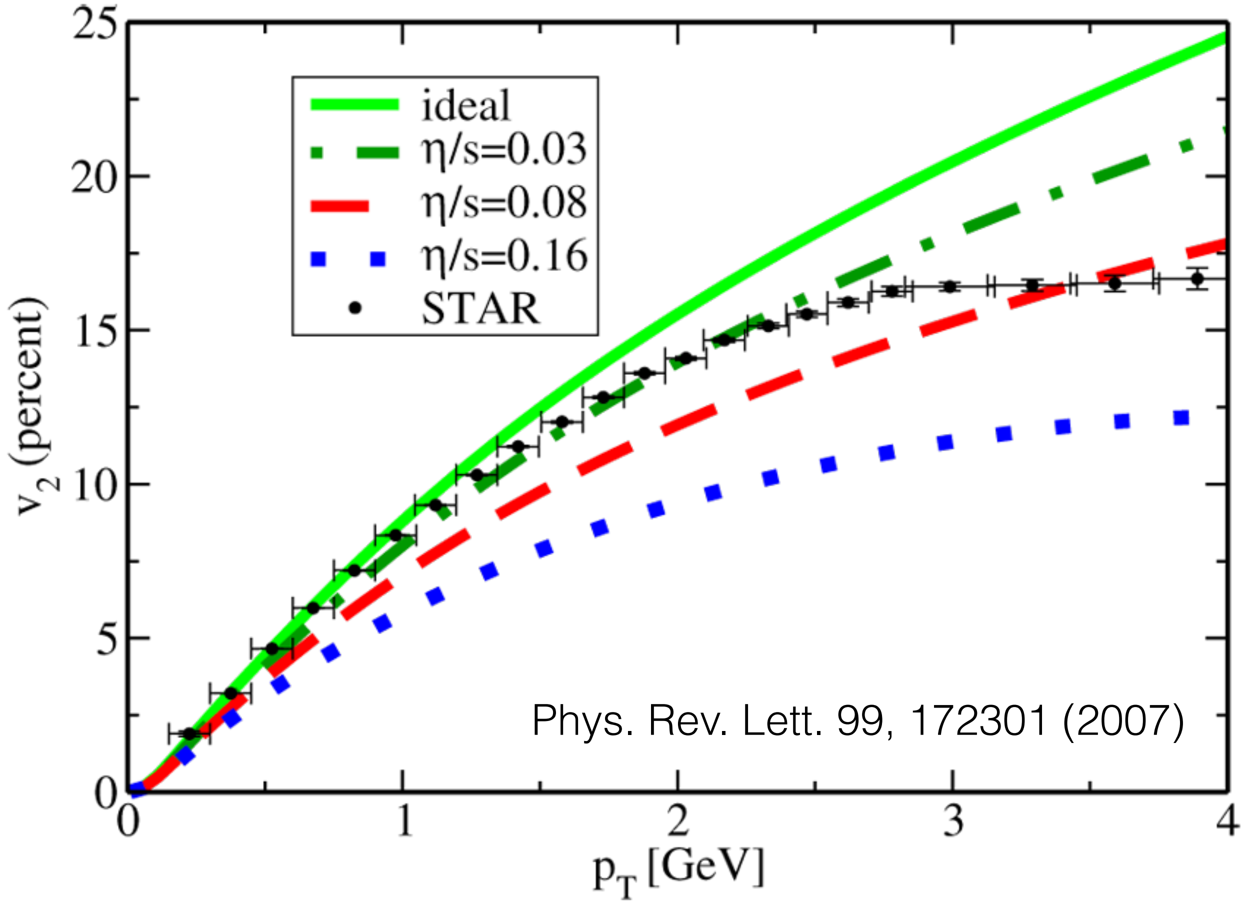
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi$$

The strength of the back-to-back correlation, ***v_2***, is damped by the shear-viscosity to entropy-density ratio, ***η/s***

The experimental data shows that η/s is near the conjectured lower quantum limit from the AdS/CFT correspondence

→ **“The perfect fluid”**

PRL 94 (2005) 111601

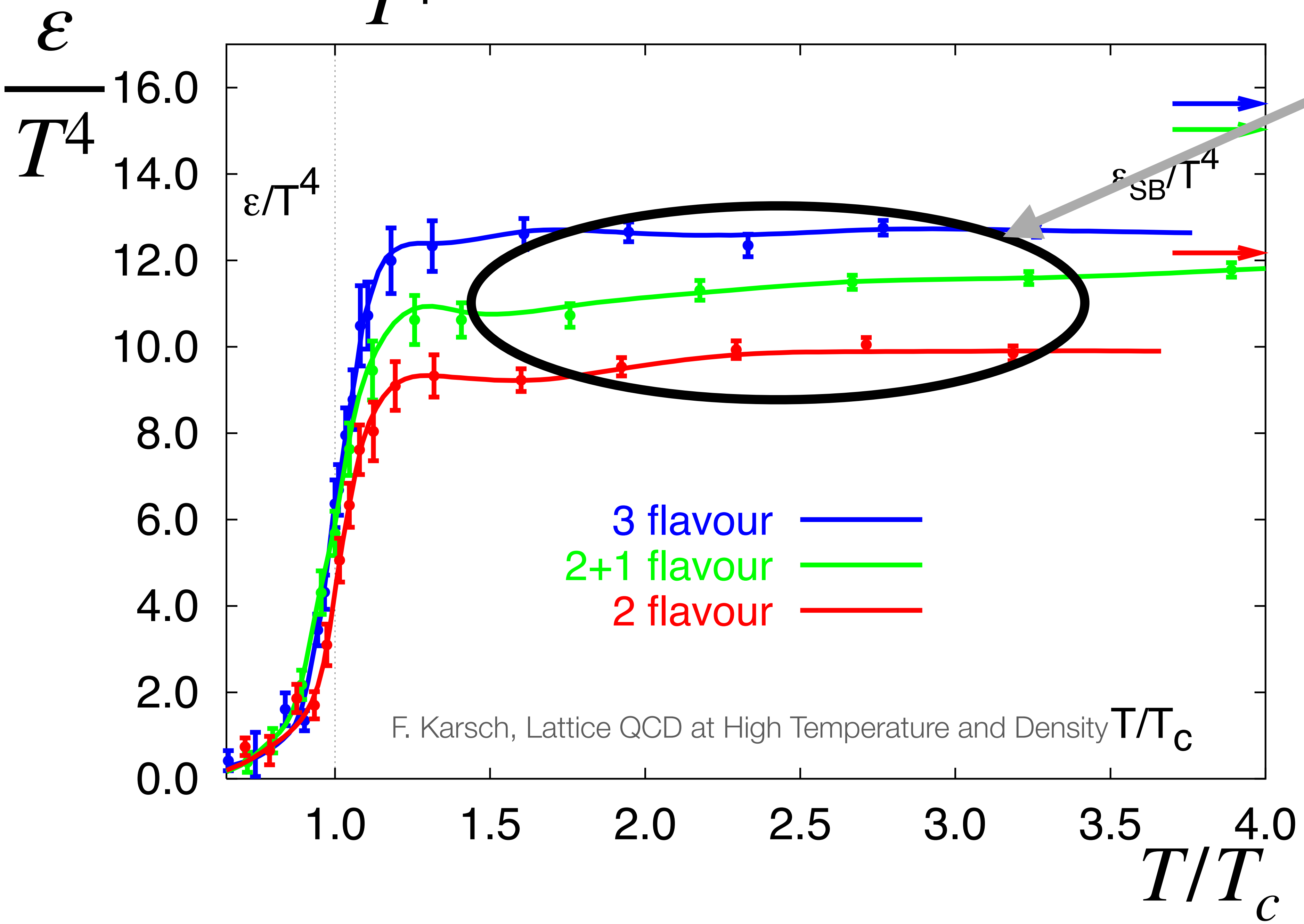


Phys. Rev. Lett. 99, 172301 (2007)

High-Temperature QCD

At high *T*, hadrons melt into quarks and gluons

$$\frac{\varepsilon}{T^4} \propto \text{degrees of freedom}$$



F. Karsch, Lattice QCD at High Temperature and Density

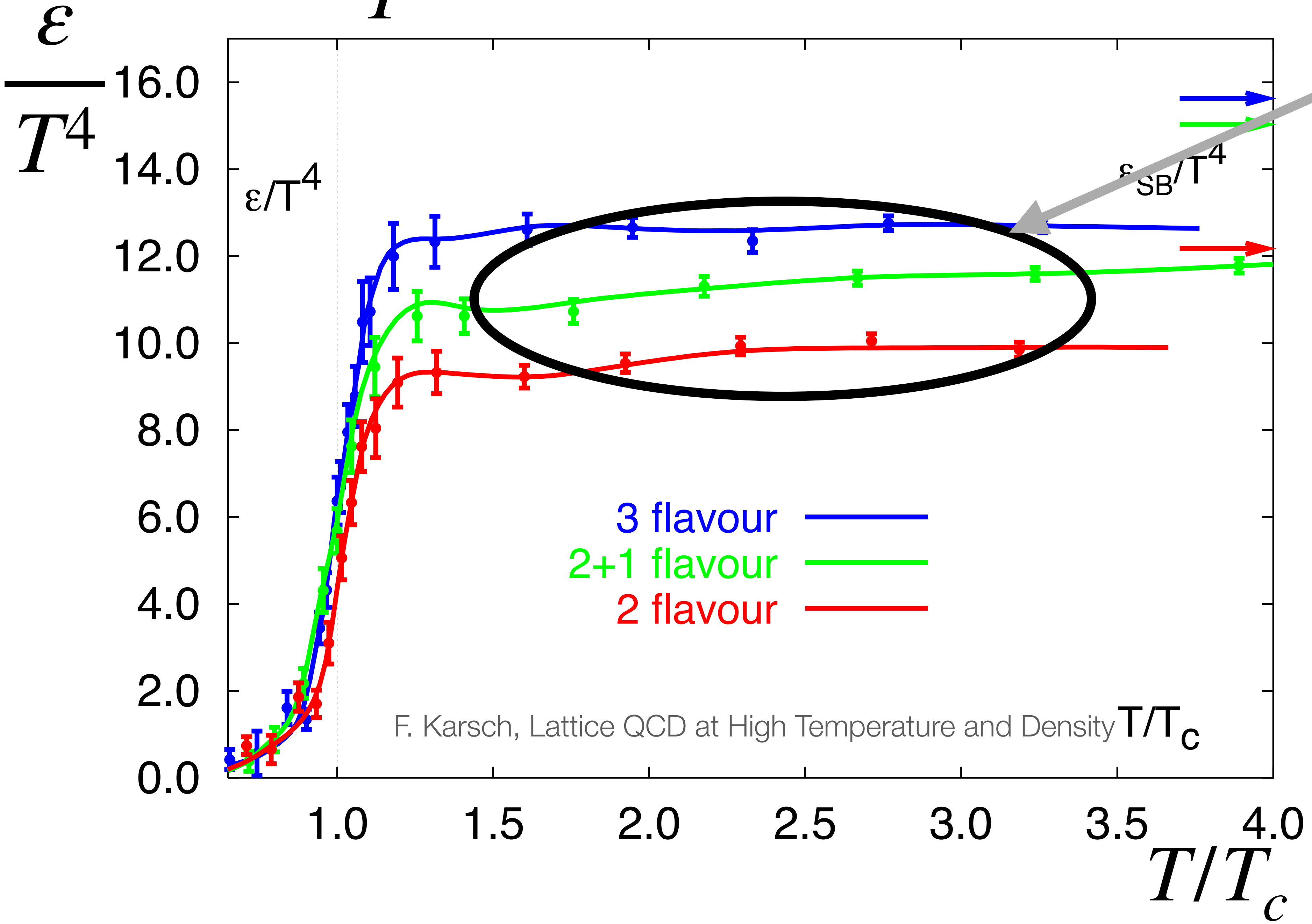
The coupling is still quite strong here!

Small *η*/s means that the coupling is strong

High-Temperature QCD

At high *T*, hadrons melt into quarks and gluons

$$\frac{\varepsilon}{T^4} \propto \text{degrees of freedom}$$



F. Karsch, Lattice QCD at High Temperature and Density

The coupling is still quite strong here!

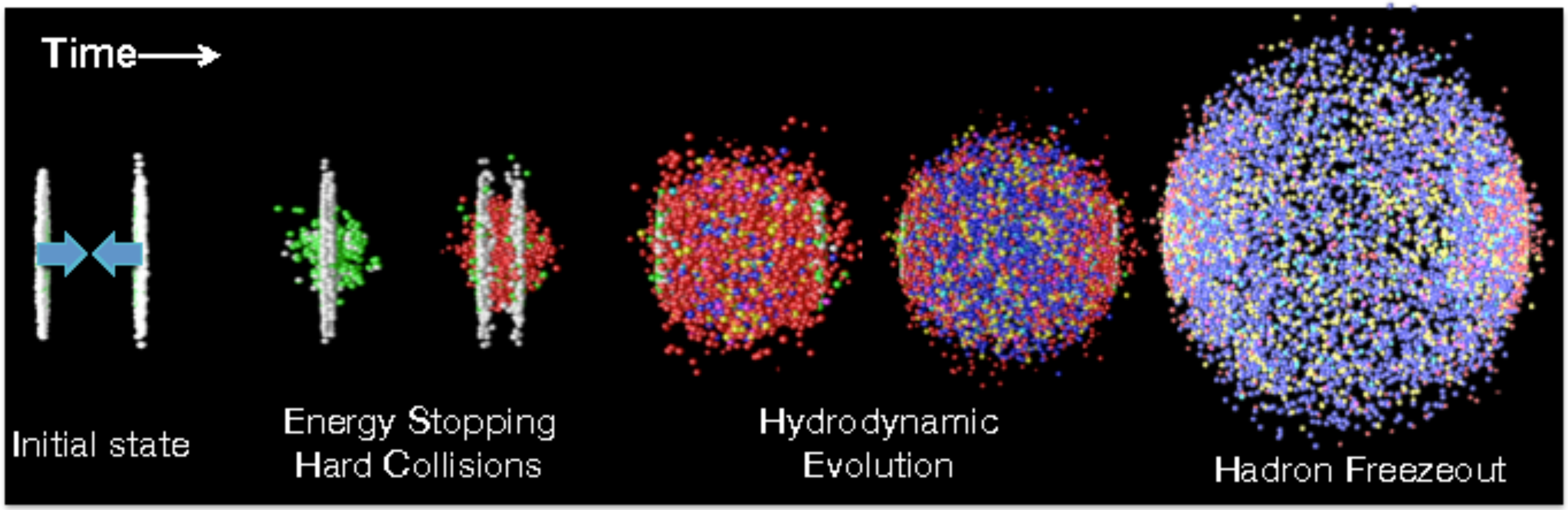
How does this strongly-coupled fluid emerge?

Does deconfined QCD have quasi-particle structure?

How does confinement emerge?

…

Ultra-relativistic heavy-ion collisions



Heavy-ion collisions provide a rich laboratory for physics

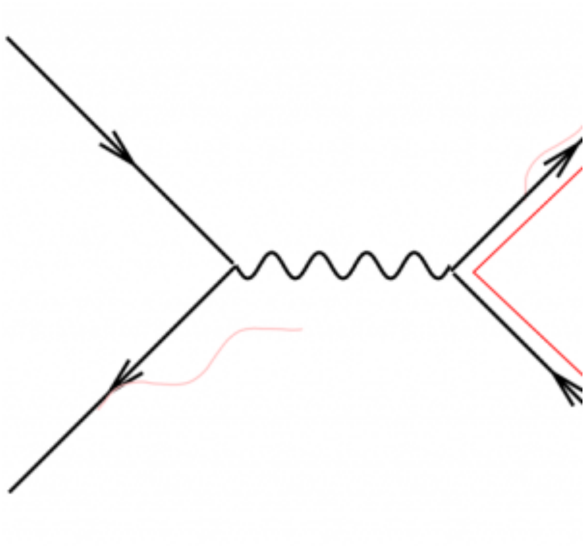
Hadronization and confinement
Relativistic fluid properties
The AdS/CFT correspondence
Chiral symmetry restoration

…

Unforeseen physics that we may learn in such a rich system

Jets in heavy-ion physics

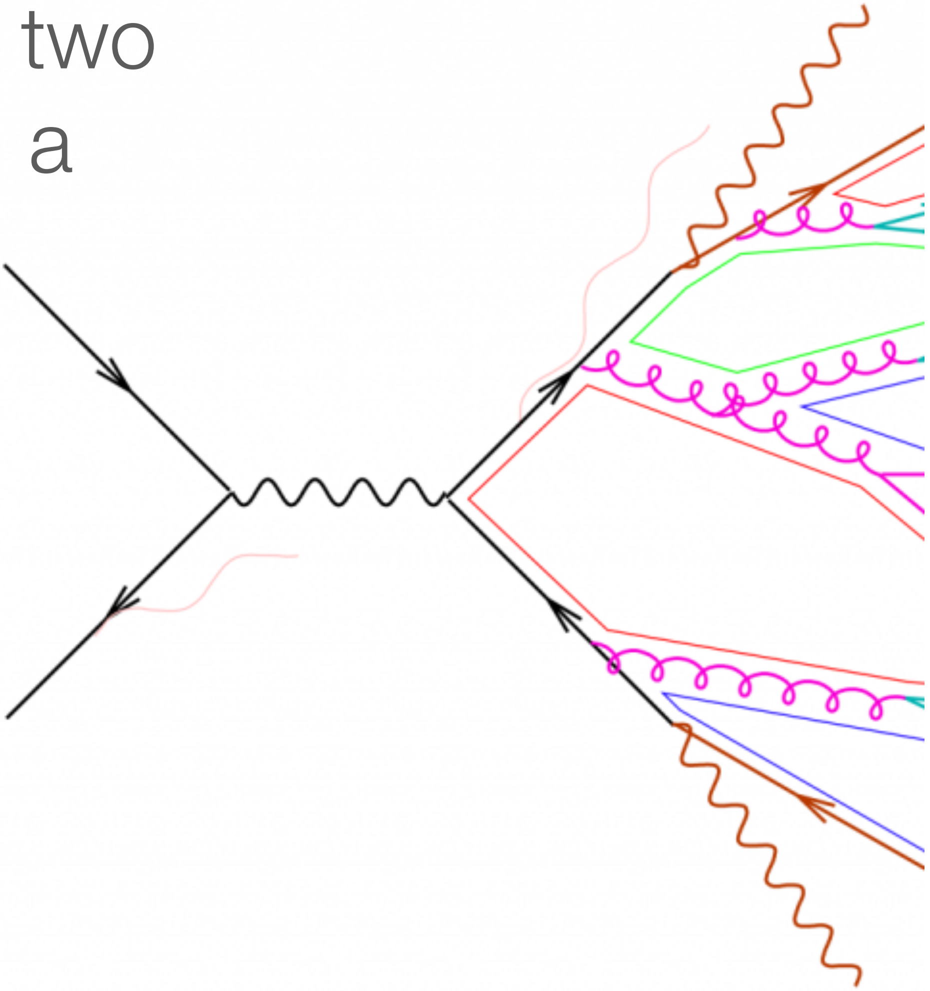
A rare, high-Q^2 scattering between two partons can produce a parton with a large transverse momentum, p_T



Jets in heavy-ion physics

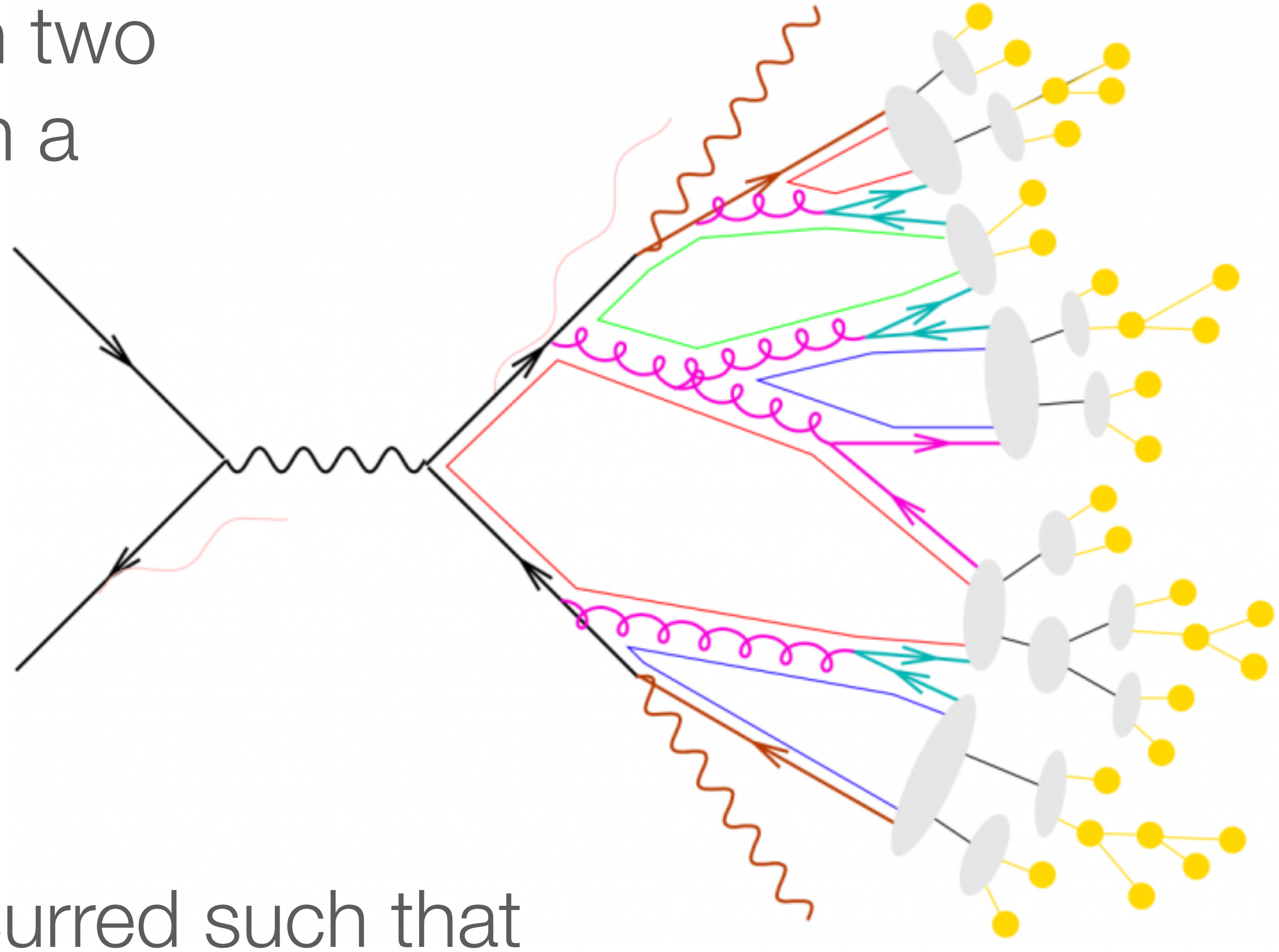
A rare, high-Q^2 scattering between two partons can produce a parton with a large transverse momentum, p_T

As they propagate, the high-p_T partons will fragment into a shower of partons, mostly via collinear gluon radiation



Jets in heavy-ion physics

A rare, high-Q^2 scattering between two partons can produce a parton with a large transverse momentum, p_T

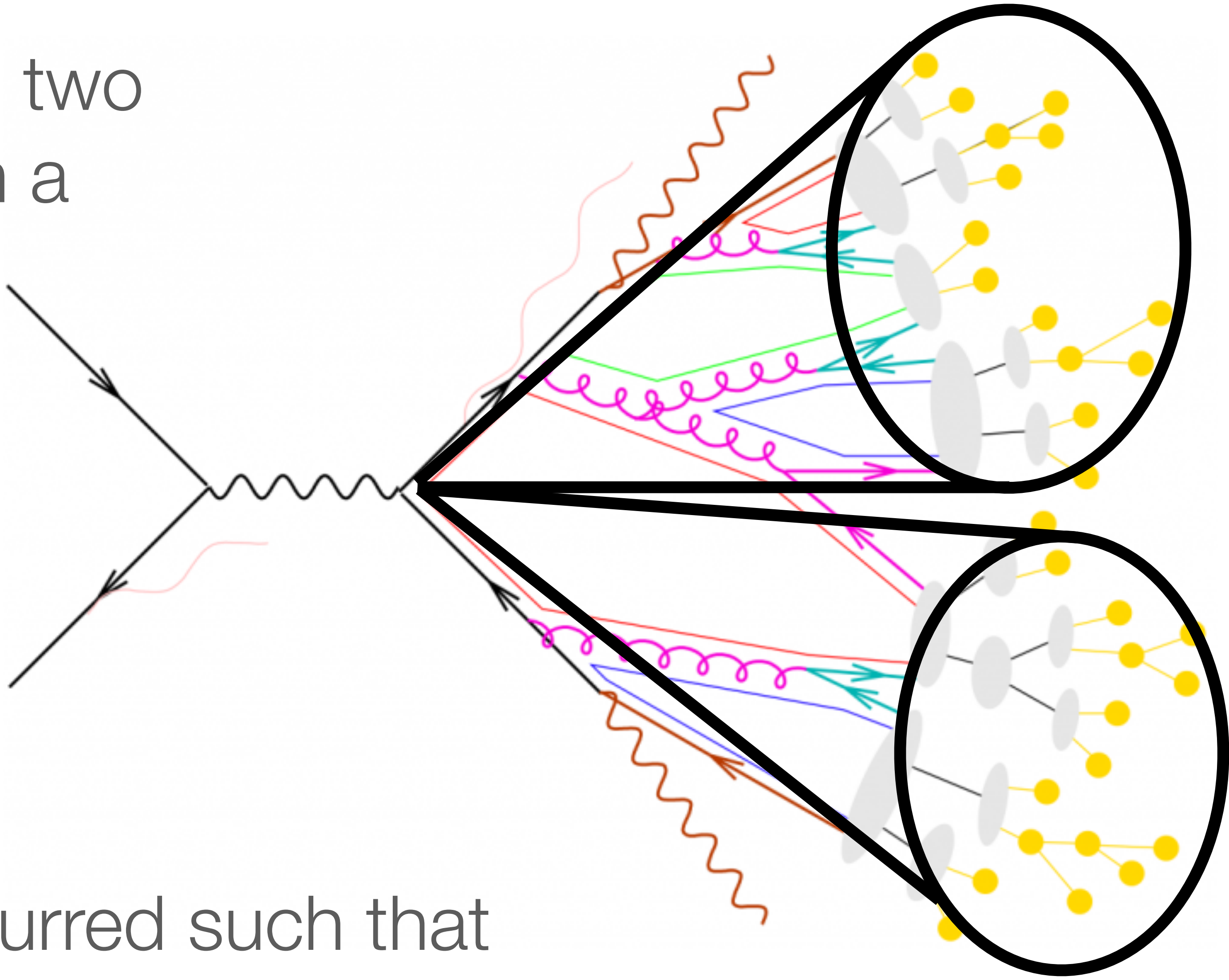


As they propagate, the high-p_T partons will fragment into a shower of partons, mostly via collinear gluon radiation

When sufficient splittings have occurred such that the shower partons reach low enough energy, the coupling becomes large and the partons hadronize

Jets in heavy-ion physics

A rare, high-Q^2 scattering between two partons can produce a parton with a large transverse momentum, p_T



As they propagate, the high-p_T partons will fragment into a shower of partons, mostly via collinear gluon radiation

When sufficient splittings have occurred such that the shower partons reach low enough energy, the coupling becomes large and the partons hadronize

This collimated collection of final state particles, grouped according to a chosen jet clustering algorithm, is referred to as a **jet**

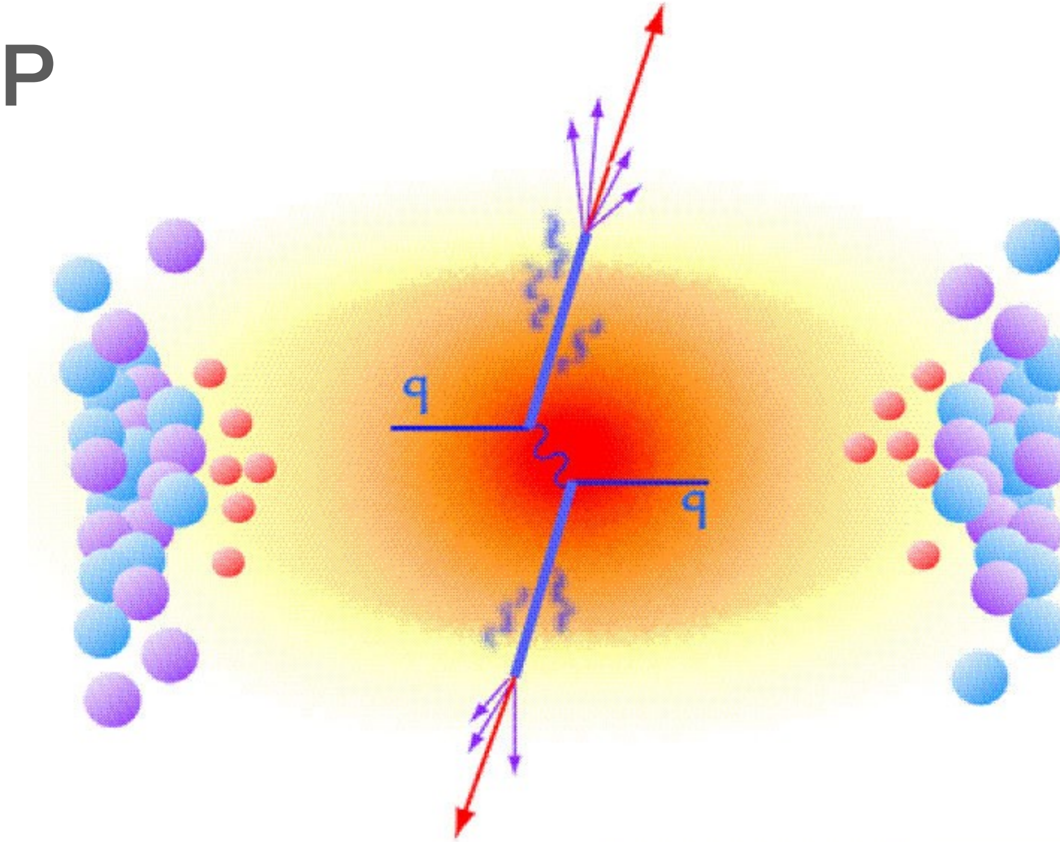
Jets in heavy-ion physics

Jets are produced early in the heavy-ion collision, and propagate through the QGP

Jet production is calculable in pQCD

Jets are sensitive to a wide range of scales

Jets allow a rich set of observables to be constructed

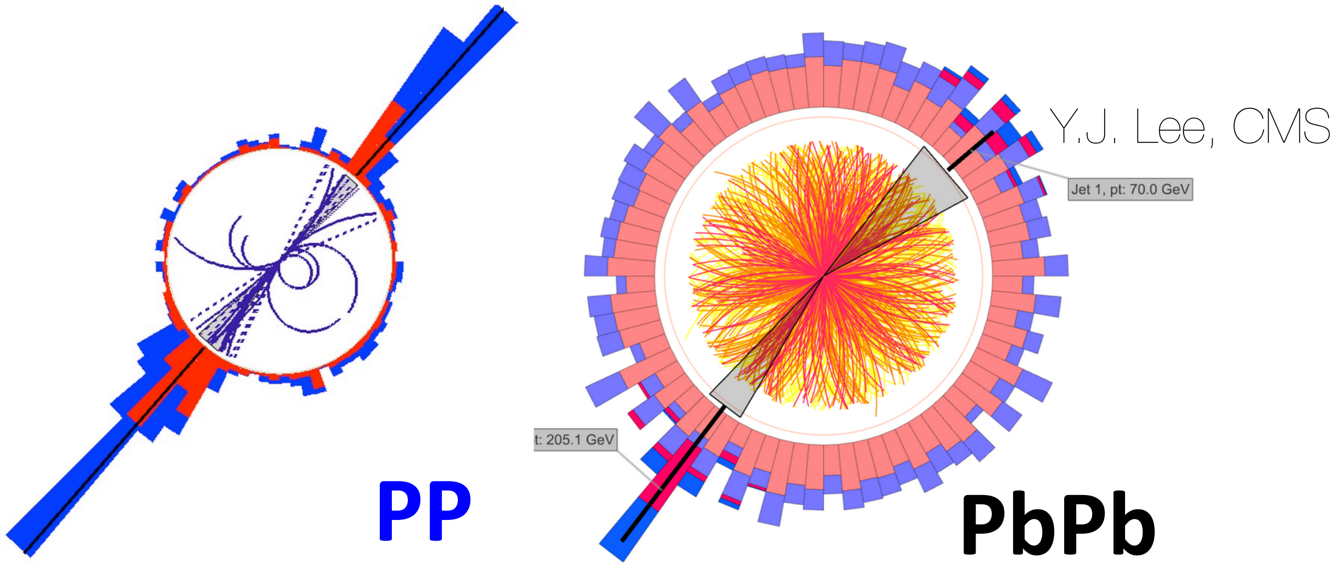


Use jets to study the quark-gluon plasma

- The past: Jet suppression as proof of the QGP
- The goal: Learn about the structure of the hot QCD medium by understanding how jets interact with it

Jets in heavy-ion physics

The basic idea is simple: Compare jet observables in heavy-ion collisions to those in proton-proton collisions



Y.J. Lee, CMS

In practice:

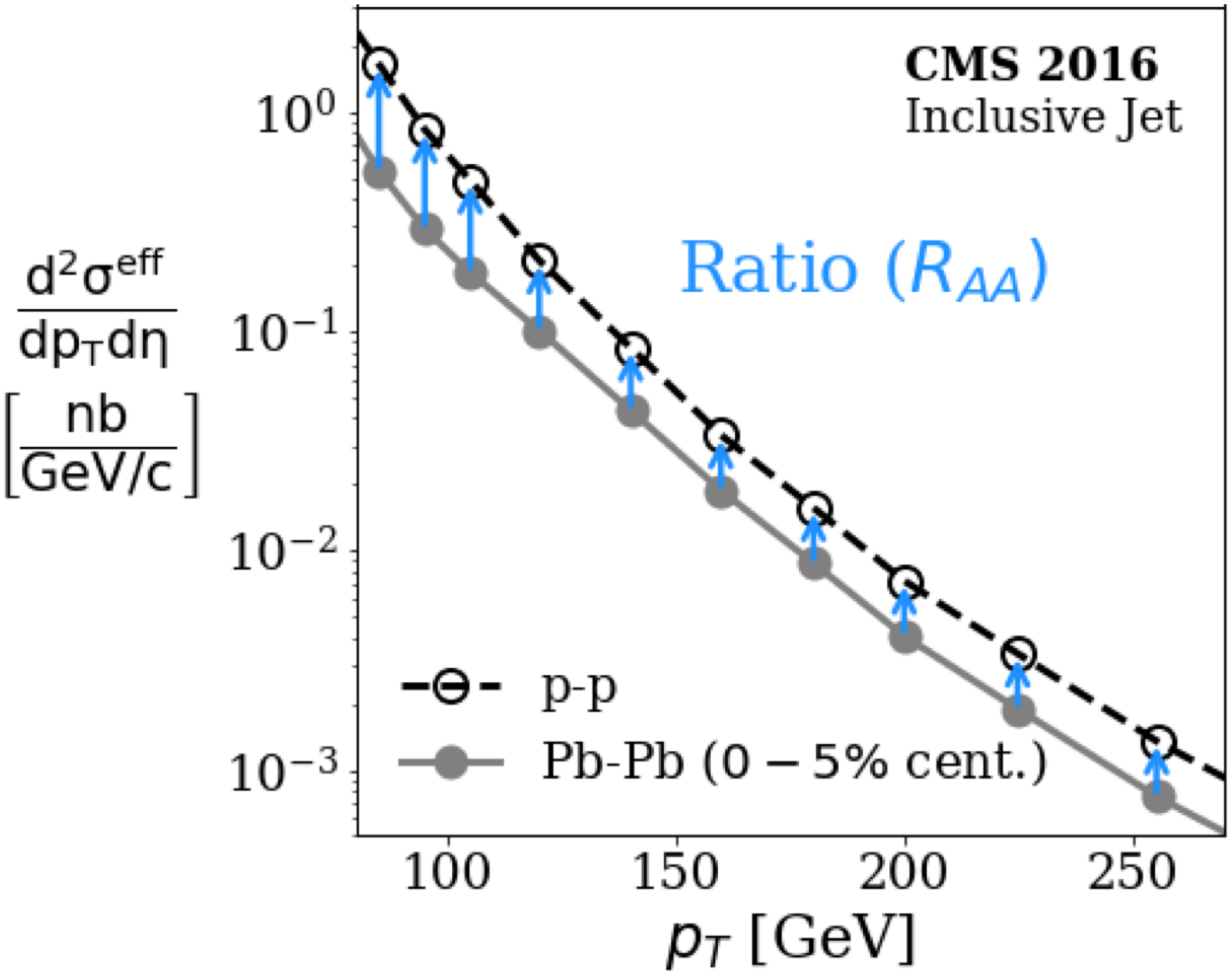
- *Which observables?*
- *How to disentangle background?*
- *How to address multi-stage and multi-scale evolution?*
- *How to compare experiment to theory?*
- *…*

What have we learned about jet modification?

1. Jet yields are suppressed

$$R_{\mathrm{AA}} = \frac{\left.\frac{1}{\langle T_{\mathrm{AA}}\rangle}\frac{1}{N_{\mathrm{event}}}\frac{d^2N}{dp_{\mathrm{T}}d\eta}\right|_{\mathrm{AA}}}{\left.\frac{d^2\sigma}{dp_{\mathrm{T}}d\eta}\right|_{\mathrm{pp}}}$$

Inclusive jet measurements show that jets in central Pb-Pb collisions lose on average ~10-20% of their energy, depending on $p_{\mathrm{T,jet}}$



Jasmine Brewer, HP2018

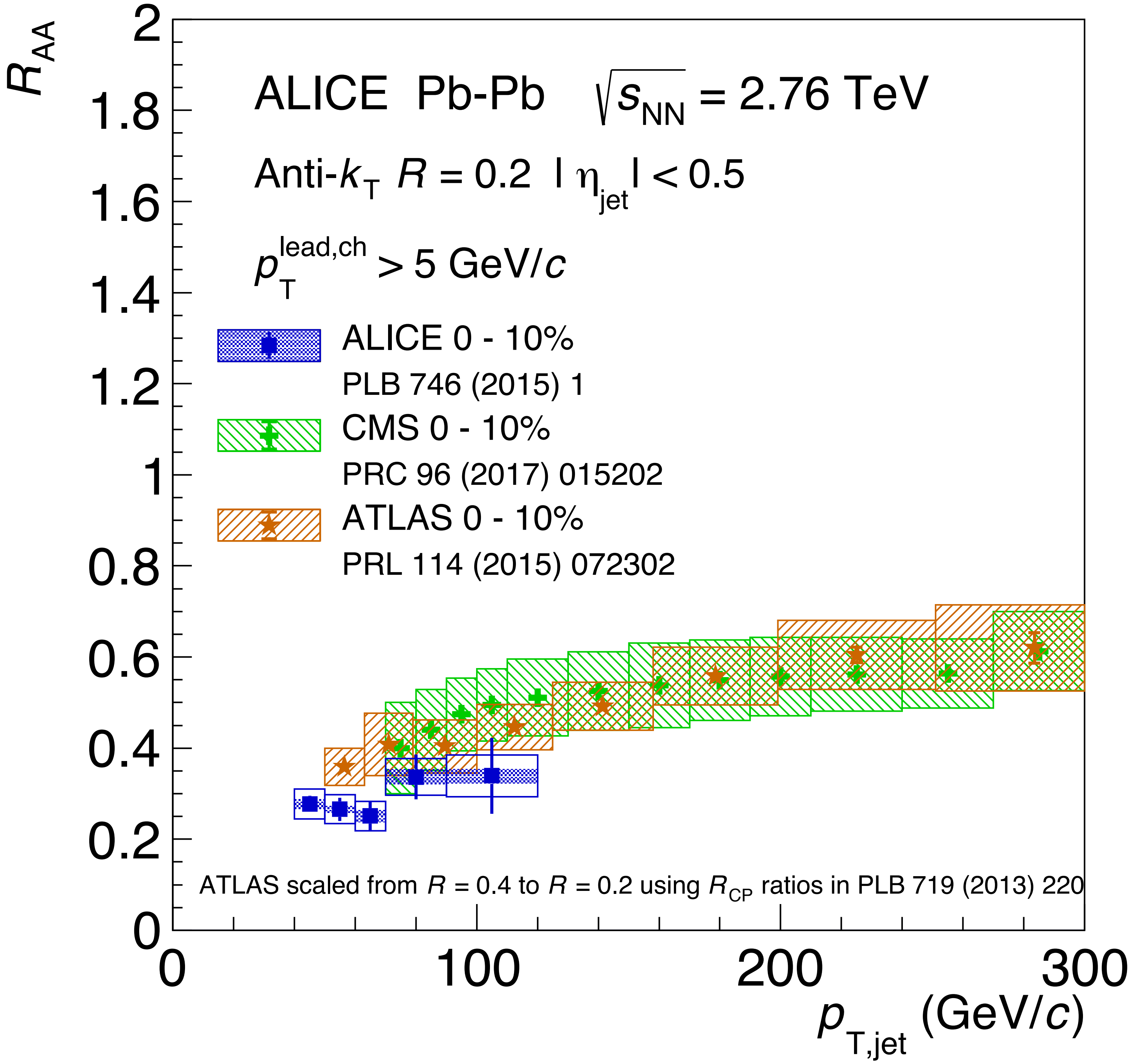
What have we learned about jet modification?

1. Jet yields are suppressed

$$R_{AA} = \frac{\frac{1}{\langle T_{AA}\rangle}\frac{1}{N_{\mathrm{event}}}\frac{d^2N}{dp_{\mathrm{T}}d\eta}\Big|_{\mathrm{AA}}}{\frac{d^2\sigma}{dp_{\mathrm{T}}d\eta}\Big|_{\mathrm{pp}}}$$

Inclusive jet measurements show that jets in central Pb-Pb collisions lose on average ~10-20% of their energy, depending on $p_{\mathrm{T,jet}}$

The energy loss fraction gradually decreases as $p_{\mathrm{T,jet}}$ increases



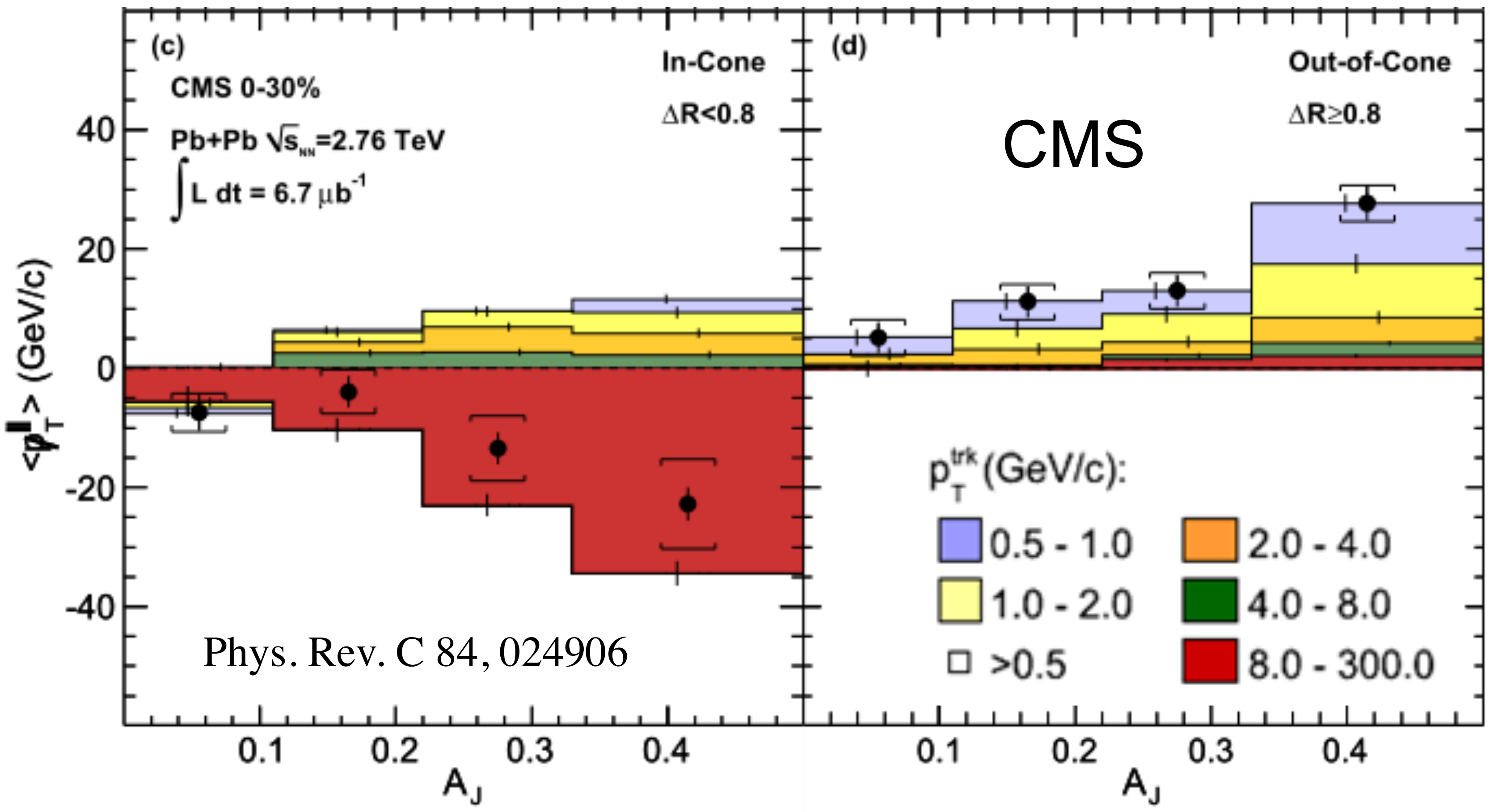
ALI-DER-310487

What have we learned about jet modification?

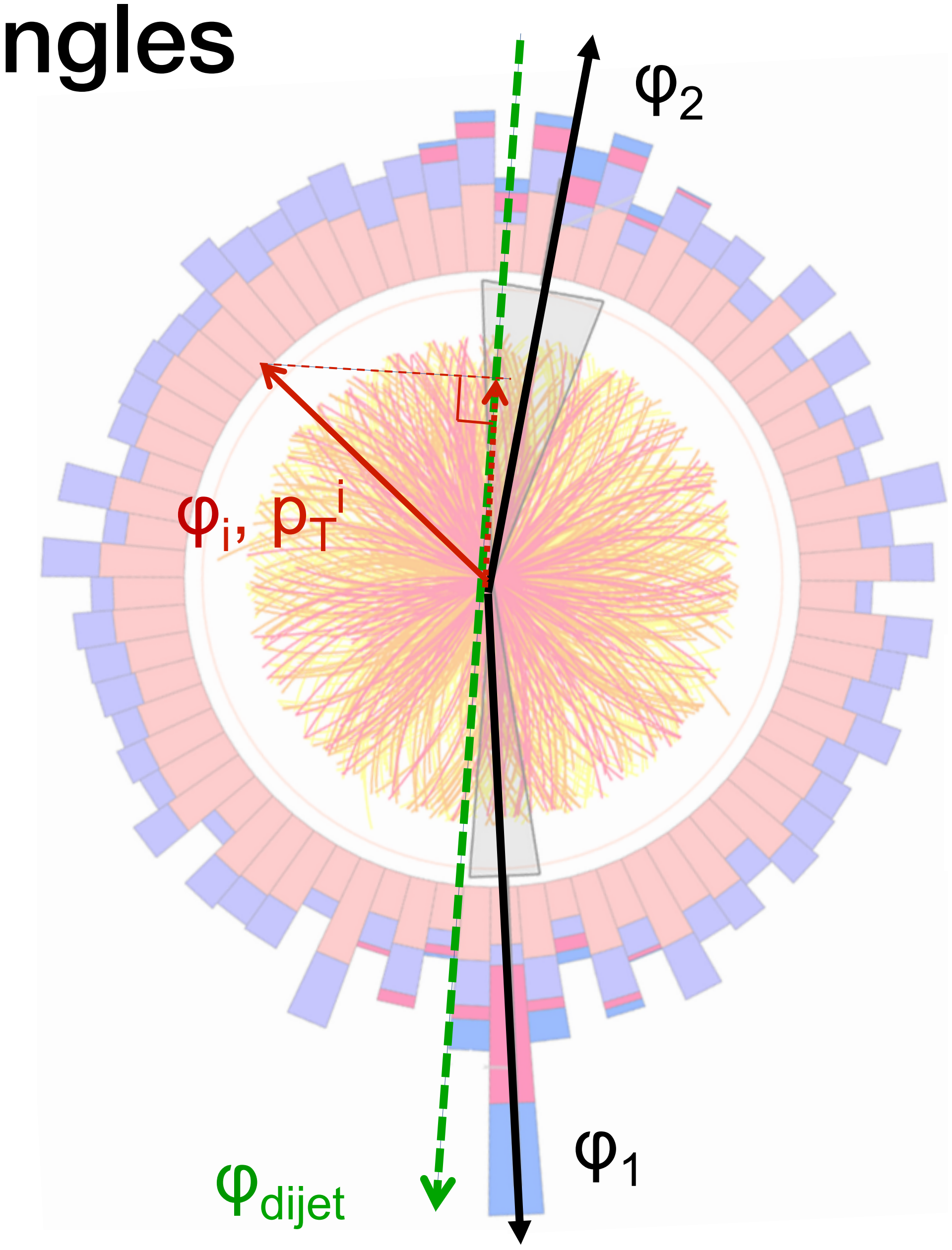
2. Soft energy is distributed to large angles

Di-jets with large p_T imbalance have an excess of soft particles at large angle

The origin of this effect remains debated



Phys. Rev. C 84, 024906



$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

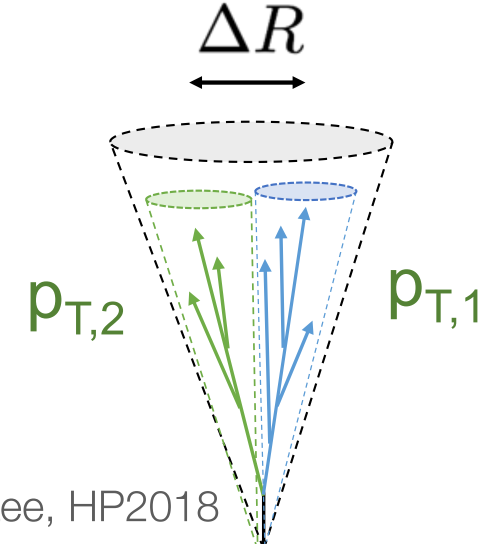
What have we learned about jet modification?

3. The fragmentation pattern of a jet impacts modification

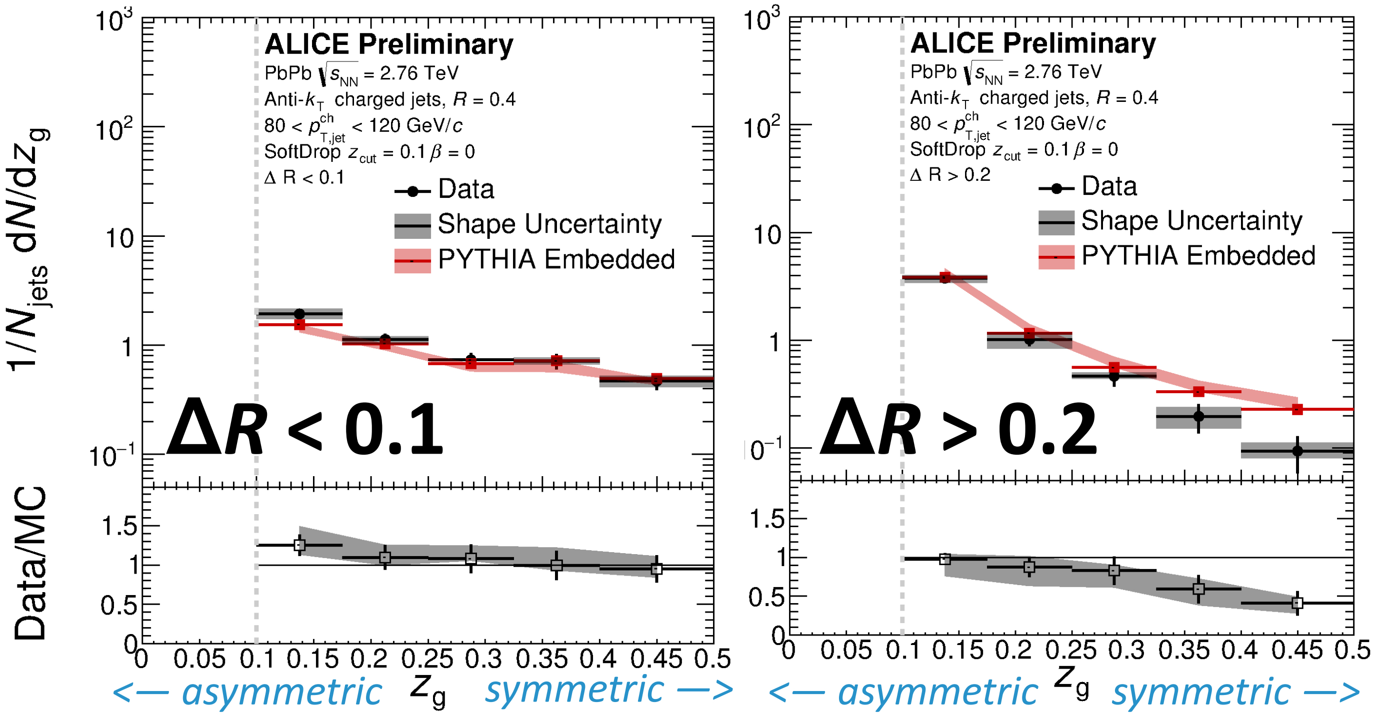
A. Jets with wide-angle hard splittings lose more energy than jets with collinear hard splittings

Re-cluster a jet into two sub-jets, and examine their momentum share

$$z = \frac{min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}}$$



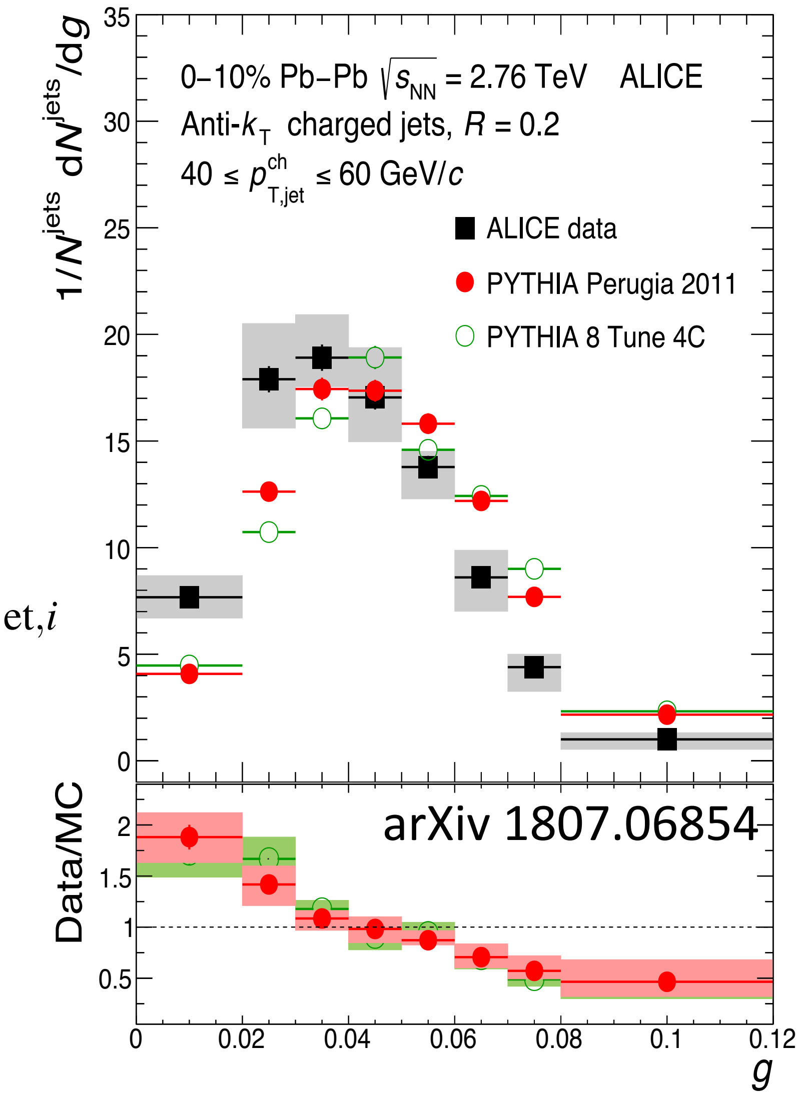
YJ Lee, HP2018



B. Gluon-like jets lose more energy than quark-like jets

Radial moment

$$g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \Delta R_{\mathrm{jet},i}$$



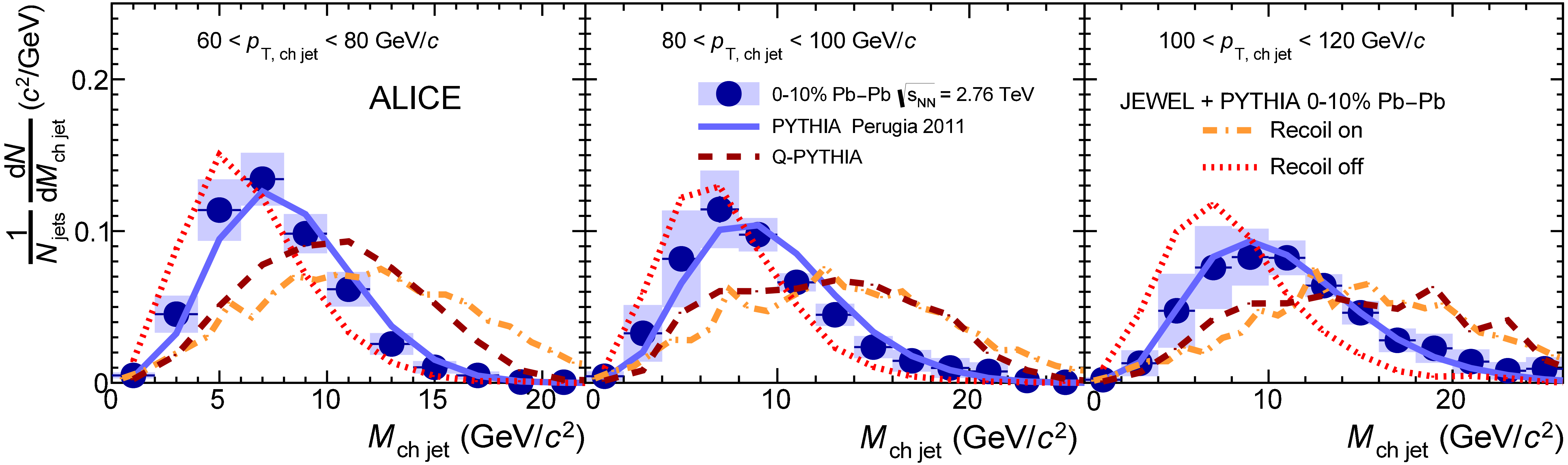
The **jet core** becomes **more collimated and harder-fragmenting**

What have we learned about jet modification?

4. Medium recoil is important to understand

As a jet propagates through the medium, it induces medium particles to flow in the direction of the jet

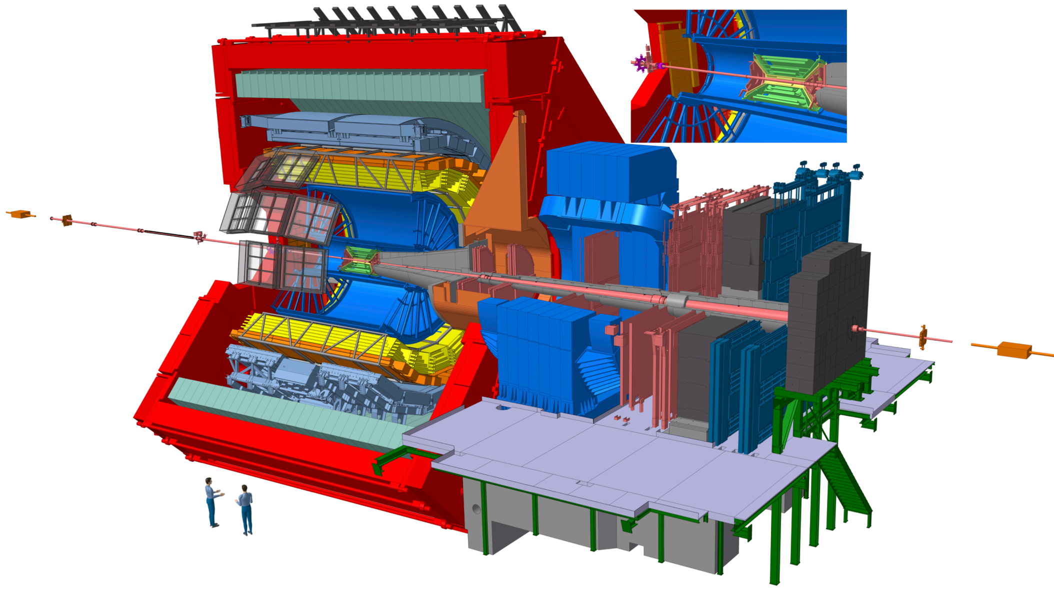
The **jet mass** in Pb-Pb for ***R* = 0.4** measured by ALICE may be highly sensitive to medium recoil



Phys. Lett. B776 (2018) 249-264

Measuring jets in ALICE

ALICE reconstructs jets at mid-rapidity ($\eta < 0.7$) in pp, p-Pb, Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76 - 13\ \mathrm{TeV}$

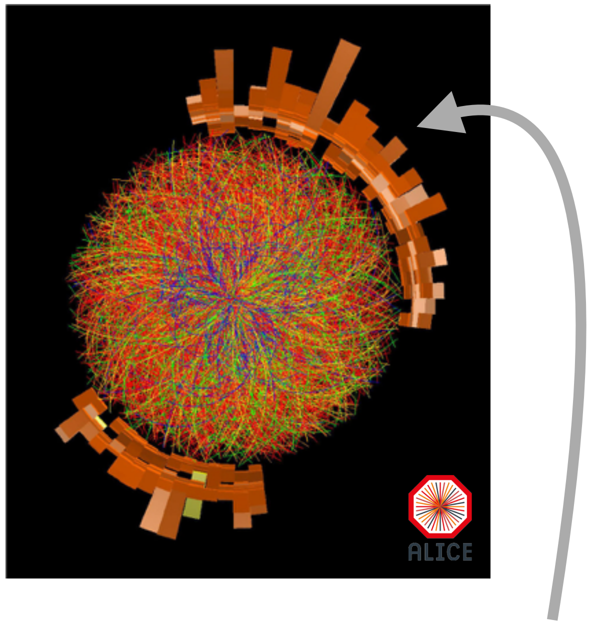


Charged particle jets (*charged jets*)

- High-precision tracking down to $p_{\mathrm{T,track}} = 150\ \mathrm{MeV}/c$

Jets (*full jets*)

- Addition of particle information from the EM calorimeter down to $p_{\mathrm{T,cluster}} = 300\ \mathrm{MeV}/c$



EMCal φ acceptance: 108°

Measuring jets in ALICE

Most ALICE jet measurements use charged particle jets

Today, I will focus on ***full jets*** (charged + neutral)

- **Full jets allow a direct comparison to theory**
- But significant experimental complication!
  - And reduced statistics due to limited coverage

Measuring jets in ALICE

Most ALICE jet measurements use charged particle jets

Today, I will focus on ***full jets*** (charged + neutral)

- **Full jets allow a direct comparison to theory**
- But significant experimental complication!
  - And reduced statistics due to limited coverage

Inclusive jet measurement in pp, Pb-Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

1. Measure jet R_{AA} for R=0.2-0.4
2. Measure Pb-Pb jet cross-section ratio

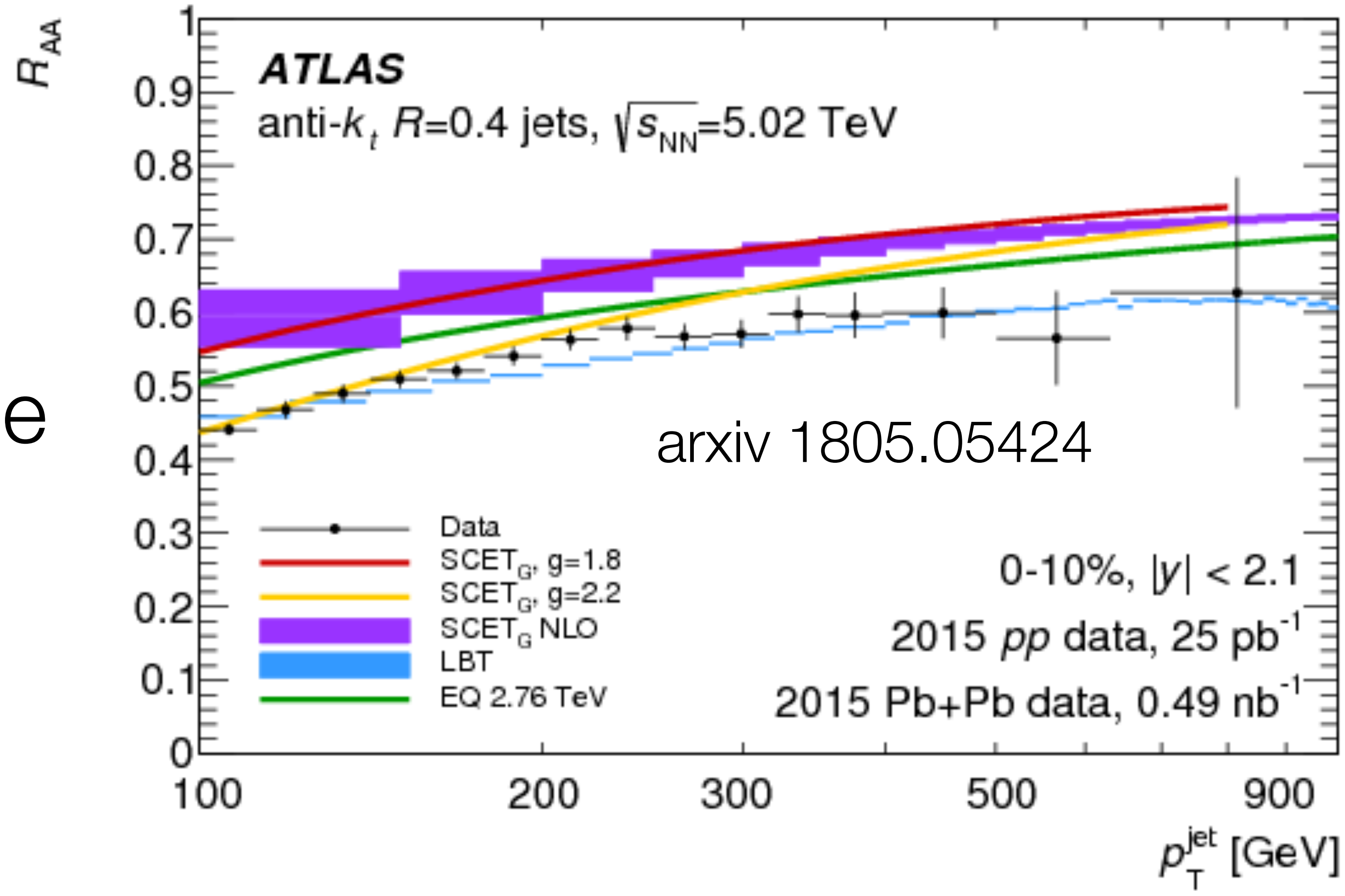
How well do we understand jet R_{AA}?

Can we distinguish jet energy loss models using jet R_{AA}?

- All models have strong quenching, decreasing with p_T
- There are slight differences in the absolute level of quenching, and the p_T-dependence of quenching

ATLAS jet R_{AA} measurement at 5.02 TeV from p_T = 100-1000 GeV

High precision!



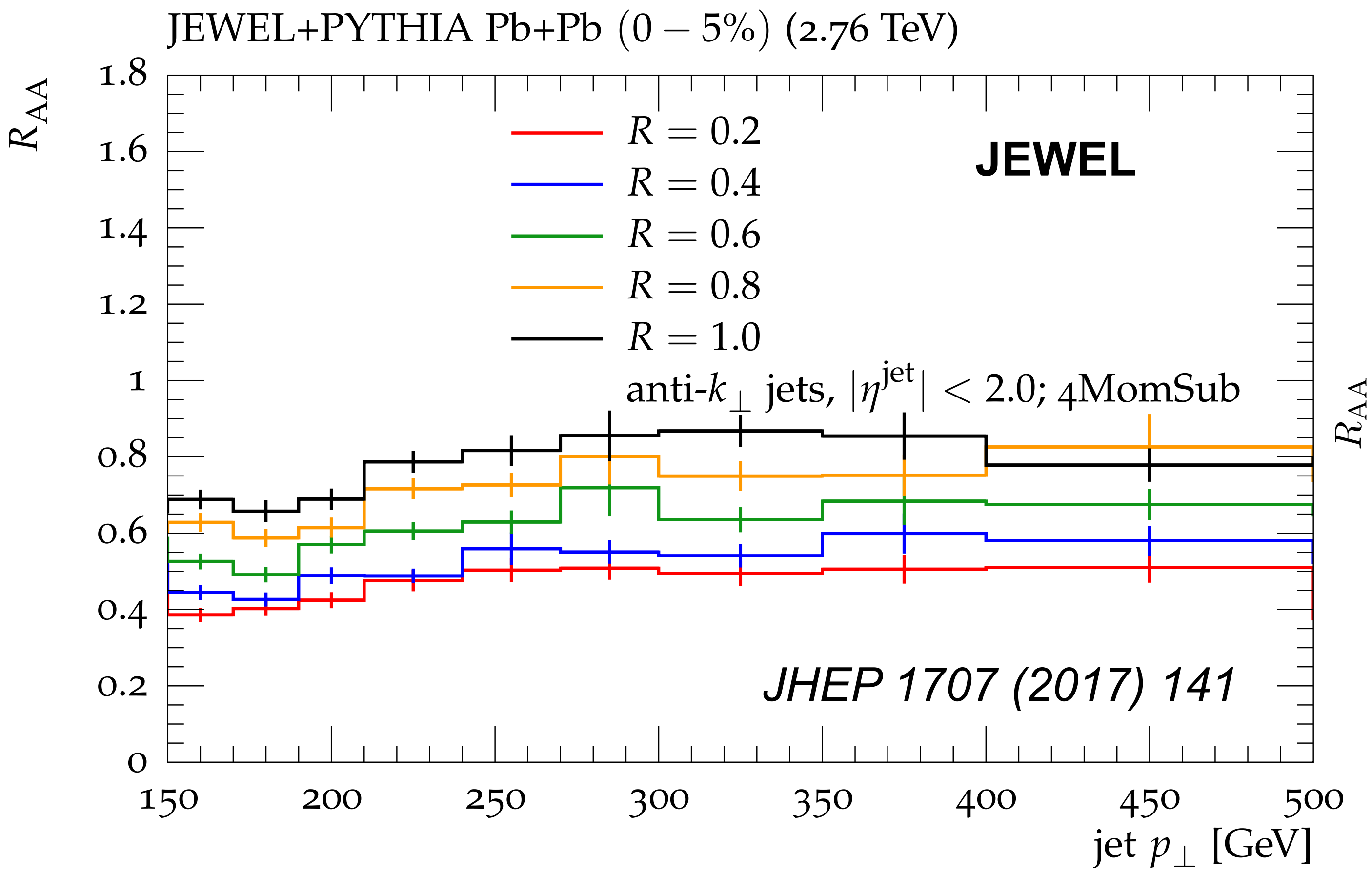
arxiv 1805.05424

What about at low p_T? → Strongest p_T-dependence

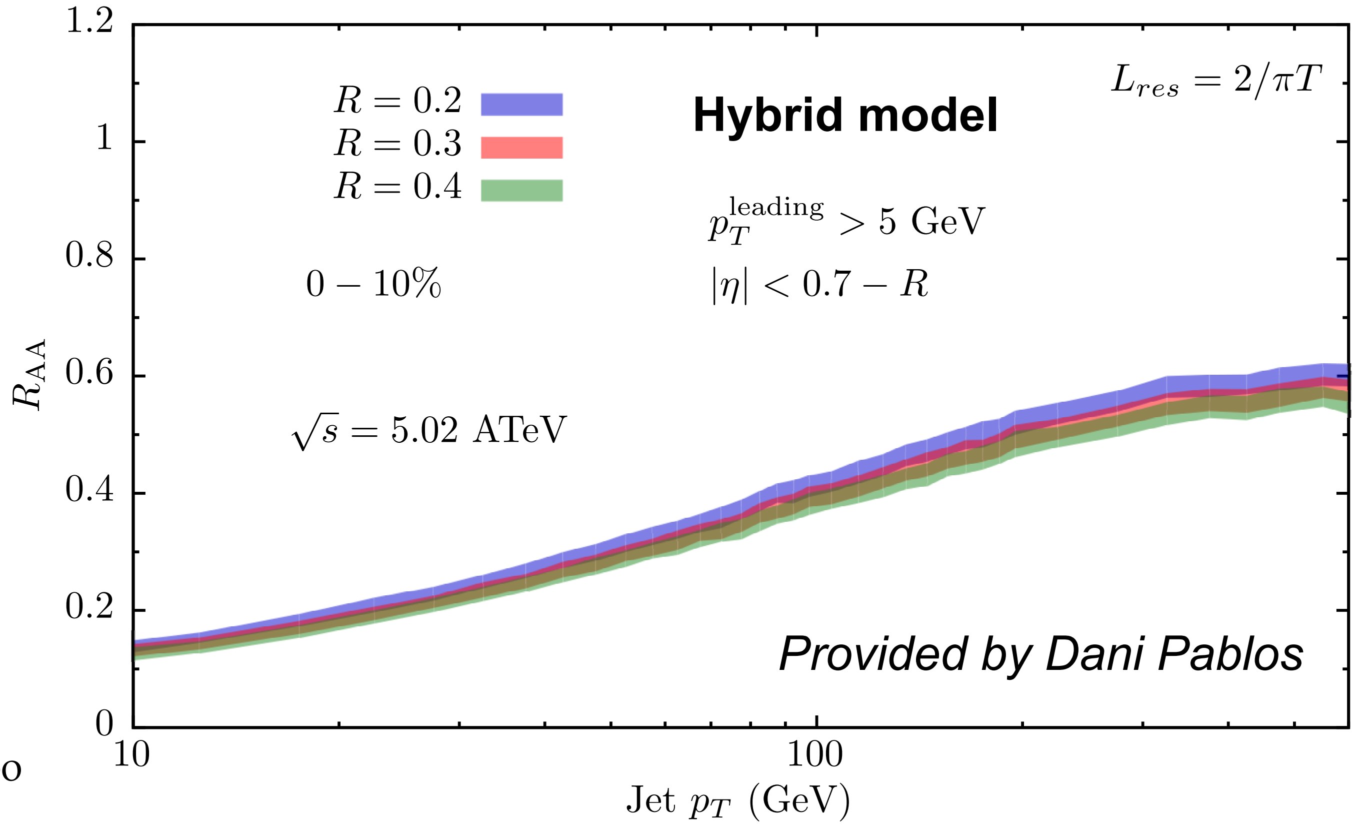
How well do we understand jet R_{AA}?

Can we distinguish the *R*-dependence of jet energy loss?

- *Do we recover induced gluon radiation and/or medium recoil? (Less suppression as R increases)*
- *Or do smaller R jets tend to be more collimated, and therefore less quenched? (More suppression as R increases)*


JEWEL+PYTHIA Pb+Pb $(0-5\%)$ (2.76 TeV)

JHEP 1707 (2017) 141

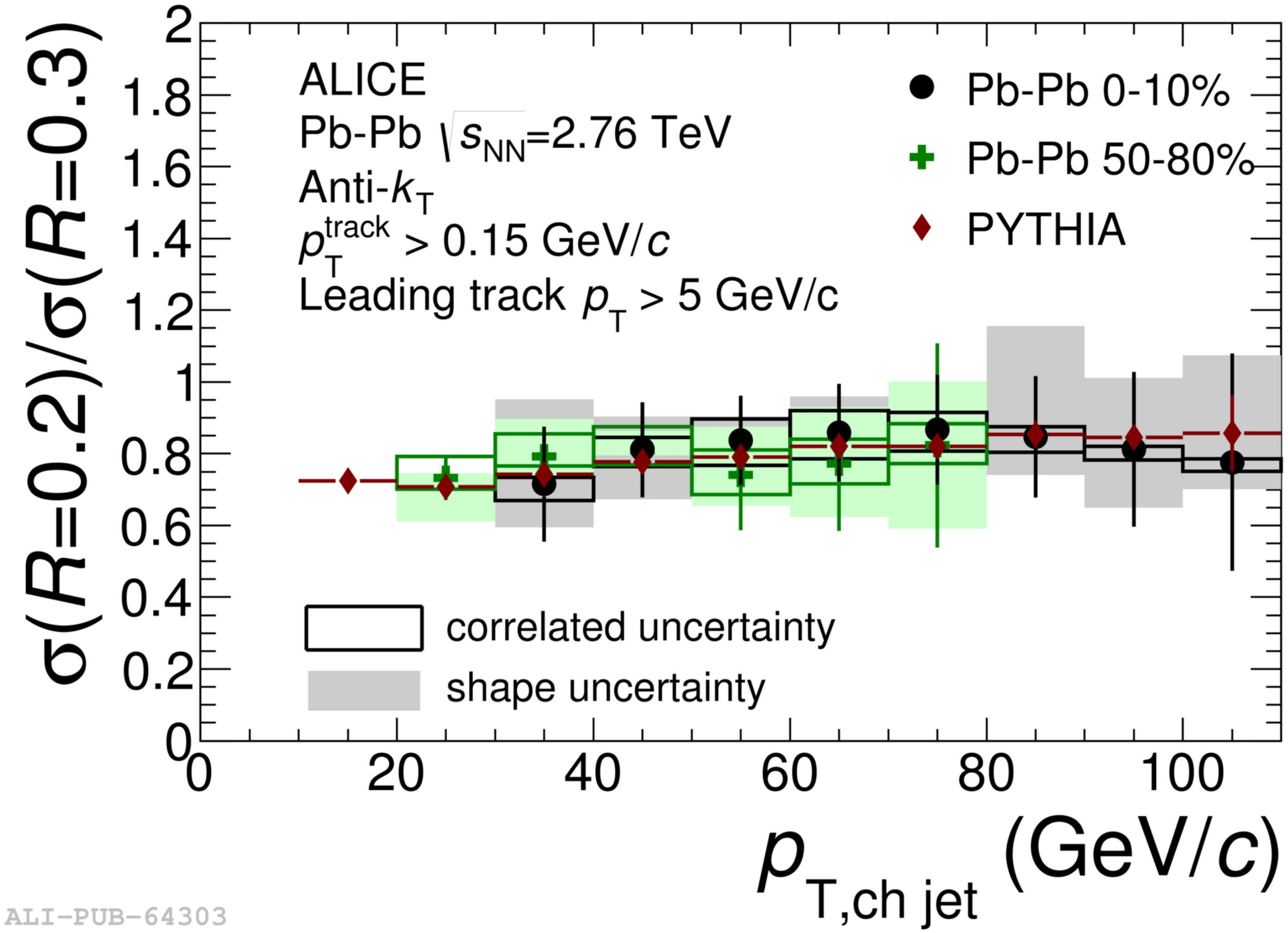

Provided by Dani Pablos

→ Can we achieve sufficient experimental precision to distinguish whether jet R_{AA} increases or decreases with jet *R*?

Do measurements show an *R*-dependence?

- **ALICE charged jets**
  - **No modification in ratio *R*=0.2/*R*=0.3**
- CMS jet R_{AA}
  - No significant modification *R*=0.2-0.4
- ATLAS R_{CP}
  - Significant modification for *R*=0.2-0.5
- Jet shapes (ALICE, CMS) show modification, hadron-jet coincidence measurement (ALICE) shows no significant intra-jet broadening from *R*=0.2-0.5, …

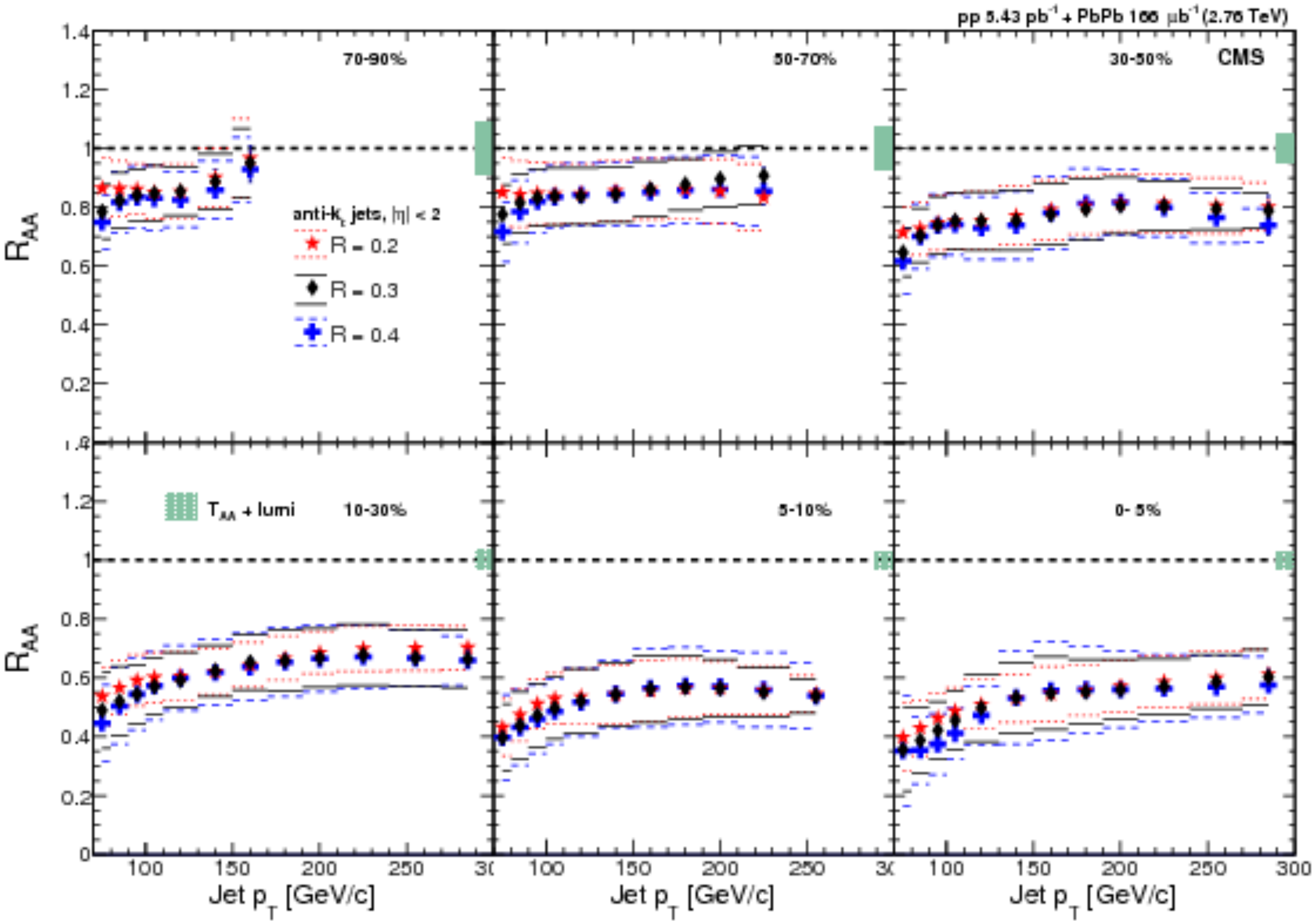
JHEP 03 (2014) 013



Do measurements show an *R*-dependence?

- ALICE charged jets
  - No significant modification *R*=0.2/*R*=0.3
- **CMS jet R_{AA}**
  - **No significant modification *R*=0.2-0.4**
- ATLAS R_{CP}
  - Significant modification for *R*=0.2-0.5
- Jet shapes (ALICE, CMS) show modification, hadron-jet coincidence measurement (ALICE) shows no significant intra-jet broadening from *R*=0.2-0.5, …

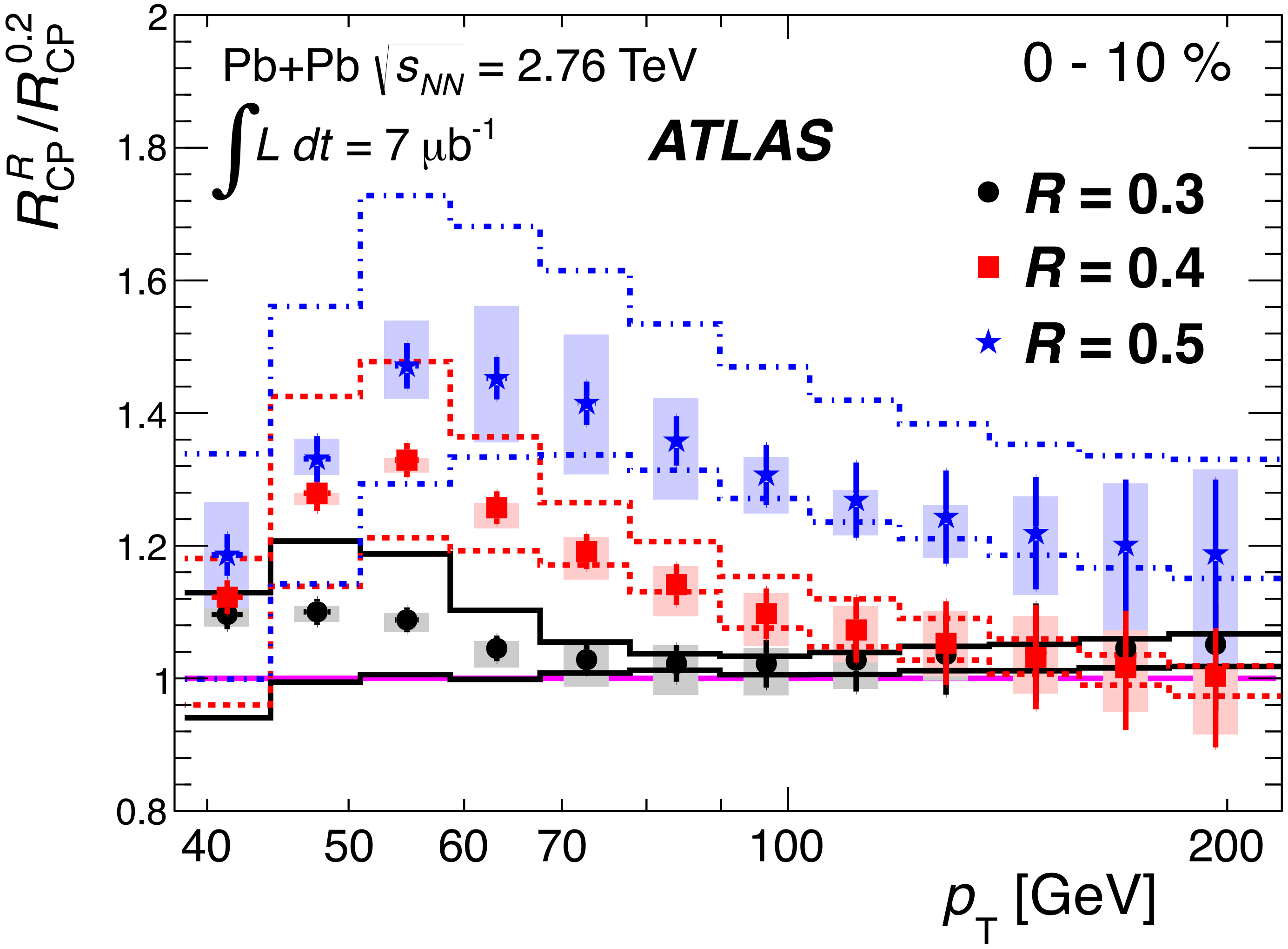
Phys. Rev. C 96 (2017) 015202



Do measurements show an *R*-dependence?

- ALICE charged jets
  - No significant modification *R*=0.2/*R*=0.3
- CMS jet R_{AA}
  - No significant modification *R*=0.2-0.4
- **ATLAS R_{CP}**
  - **Significant modification for *R*=0.2-0.5**
- Jet shapes (ALICE, CMS) show modification, hadron-jet coincidence measurement (ALICE) shows no significant intra-jet broadening from *R*=0.2-0.5, …

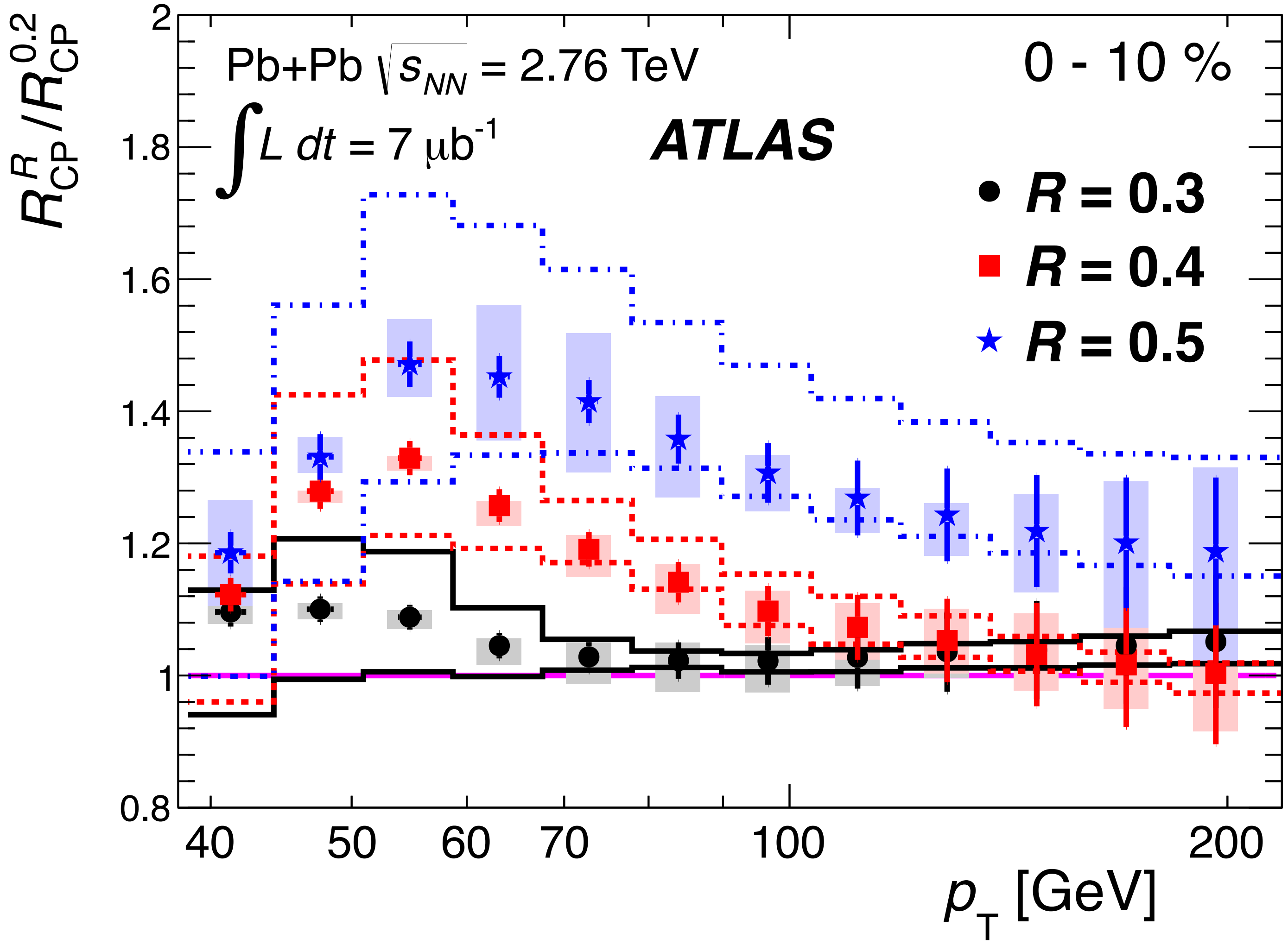
Phys. Lett. B 719 (2013) 220-241



Do measurements show an *R*-dependence?

- ALICE charged jets
  - No significant modification *R*=0.2/*R*=0.3
- CMS jet R_{AA}
  - No significant modification *R*=0.2-0.4
- ATLAS R_{CP}
  - Significant modification for *R*=0.2-0.5
- Jet shapes (ALICE, CMS) show modification, hadron-jet coincidence measurement (ALICE) shows no significant intra-jet broadening from *R*=0.2-0.5, …

Phys. Lett. B 719 (2013) 220-241



Measurements do not provide a clear picture

There is no measurement of *R*-dependence at 5.02 TeV

Analysis strategy

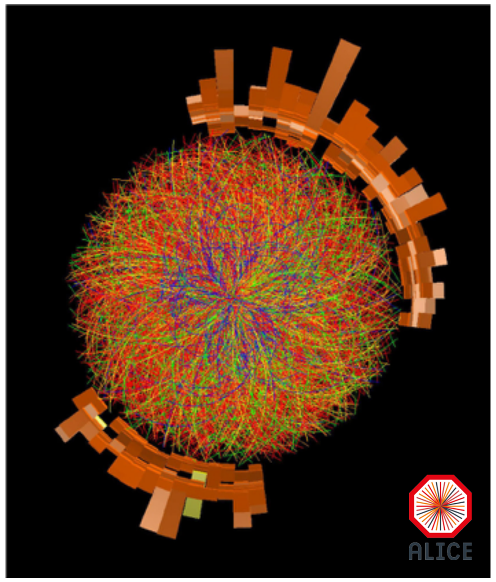
- **Four main pieces to the analysis:**
    - Reconstruct the jet p_{T} from tracks and EMCal clusters
    - Reject the combinatorial background
    - Correct the jet p_{T} for detector and resolution effects
    - Correct for the jet reconstruction efficiency and kinematic efficiency

- **Improvements relative to the 2.76 TeV ALICE analysis**
    - Extend to R=0.4
        - Allows examination of modification to jet shape
    - Refine analysis technique
        - Better understanding of our tracking and calorimetry
        - Utilization of embedding-based jet p_{T} correction

Analysis strategy — jet reconstruction

First, we reconstruct charged tracks and EMCal clusters

- A variety of calibrations and cuts are performed on these objects: track fitting requirements, EMCal energy calibrations, …



We then propagate reconstructed tracks to the EMCal, and if they overlap geometrically with a cluster, the track p_T is subtracted from the cluster p_T

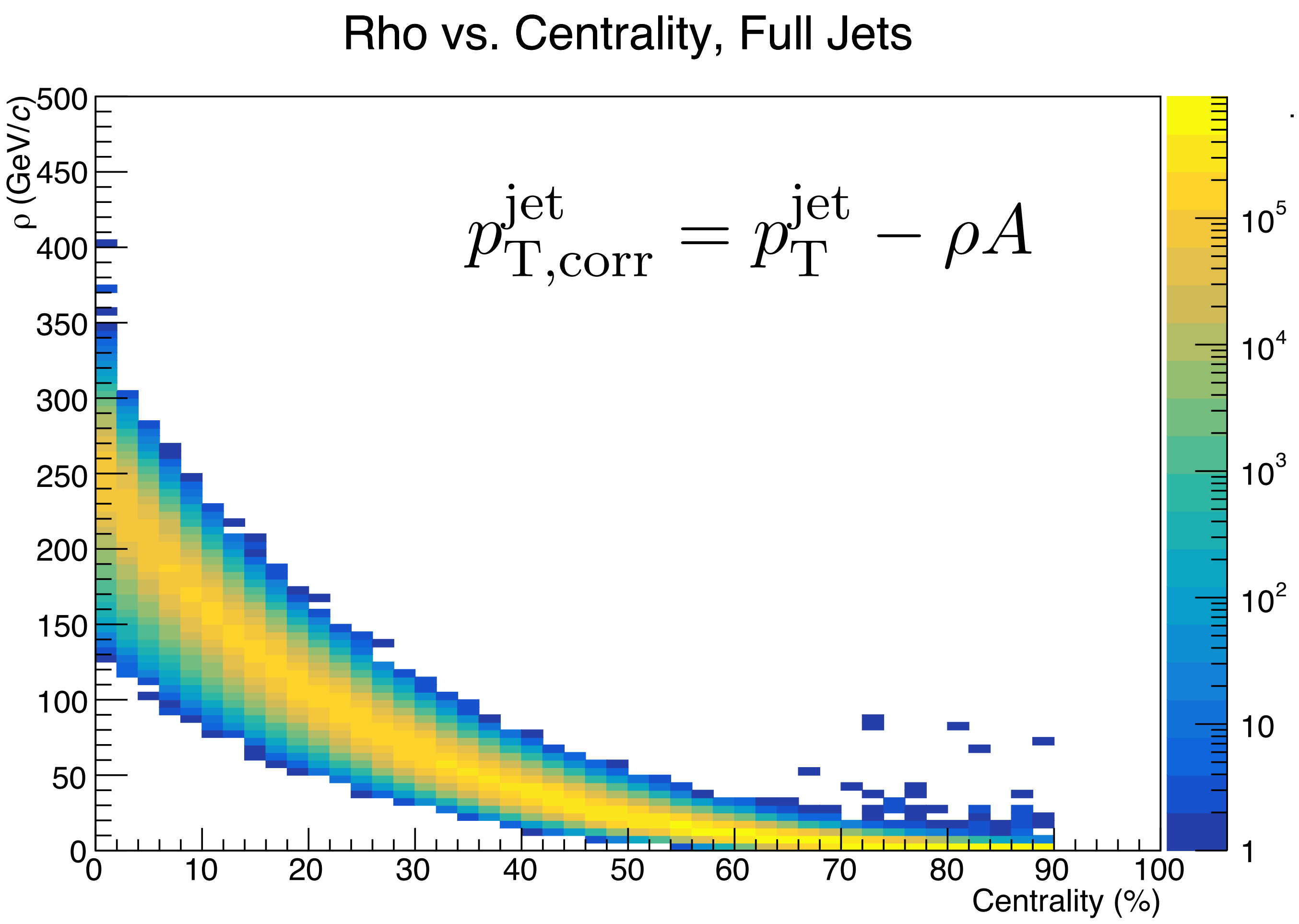
Finally, we reconstruct jets with the anti-k_T jet clustering algorithm with $R = 0.2, 0.4$

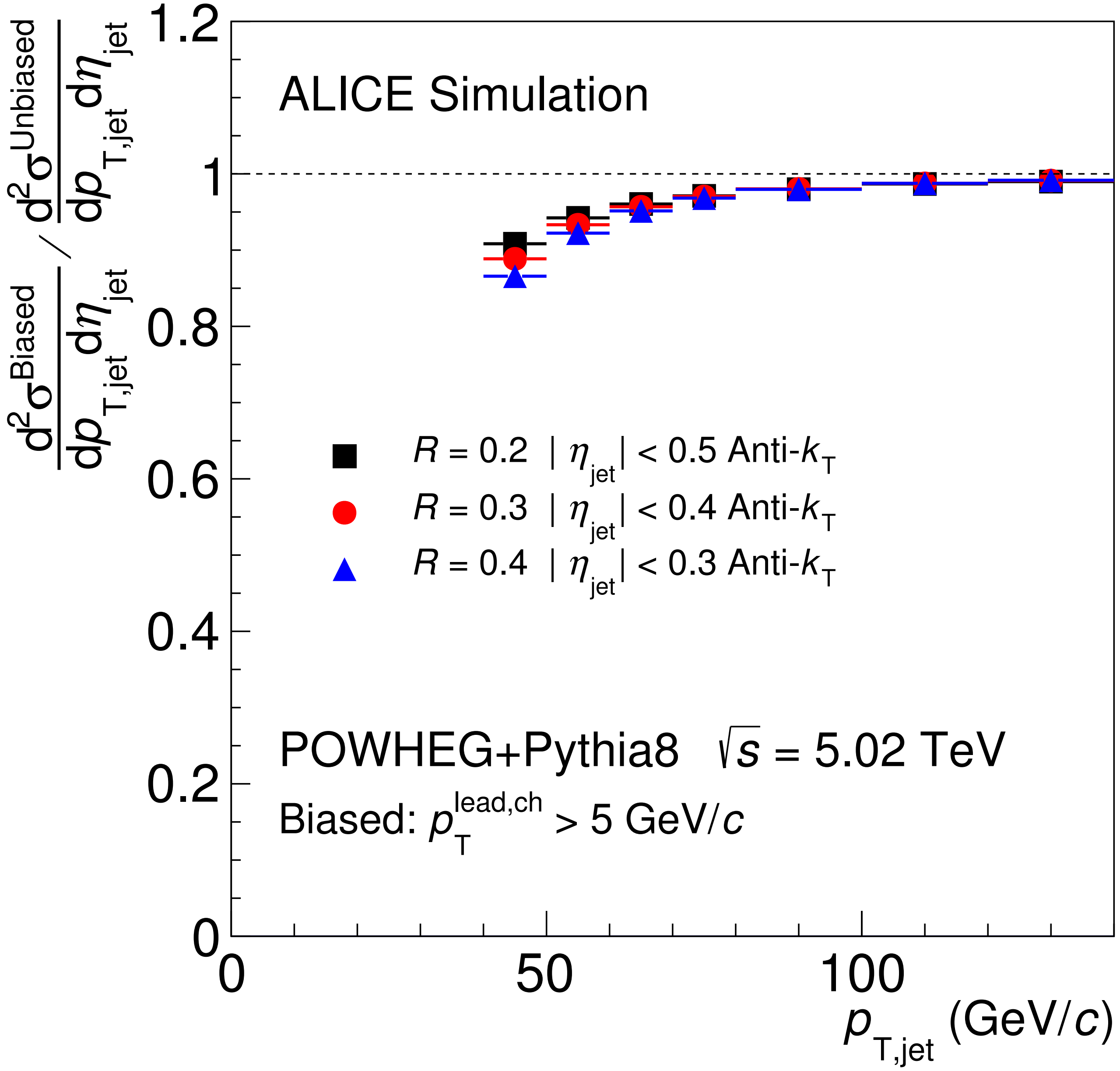
$$p_{\mathrm{T}}^{\mathrm{jet}} = \sum_i p_{\mathrm{T,i}}^{\mathrm{track}} + \sum_j p_{\mathrm{T,j}}^{\mathrm{cluster}}$$

Analysis strategy — background

The average combinatorial background is subtracted from each jet event-by-event using the event-averaged background density

Suppress combinatorial jets by requiring jets to contain a 5 GeV/*c* charged track





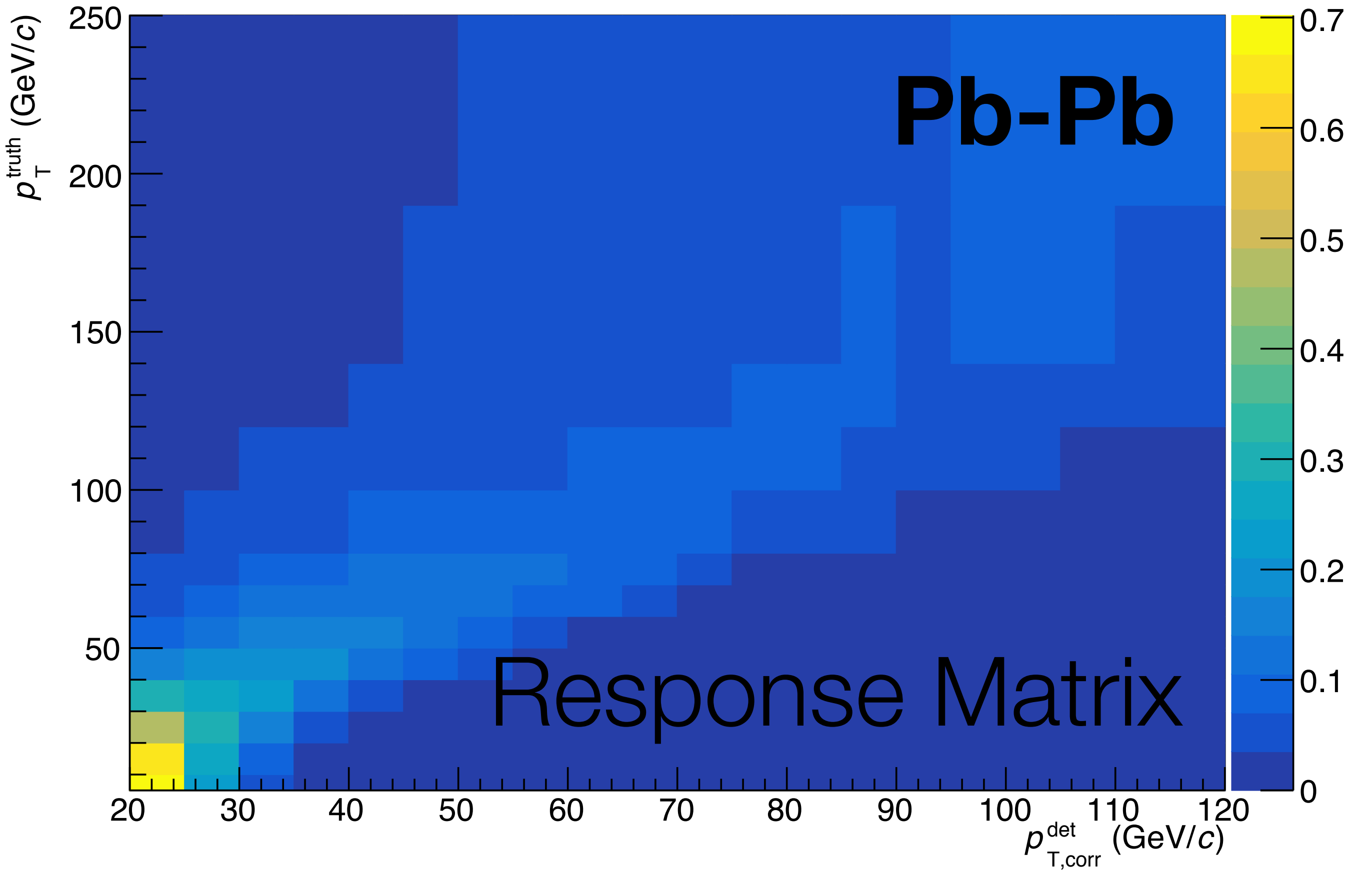
ALI-SIMUL-148684

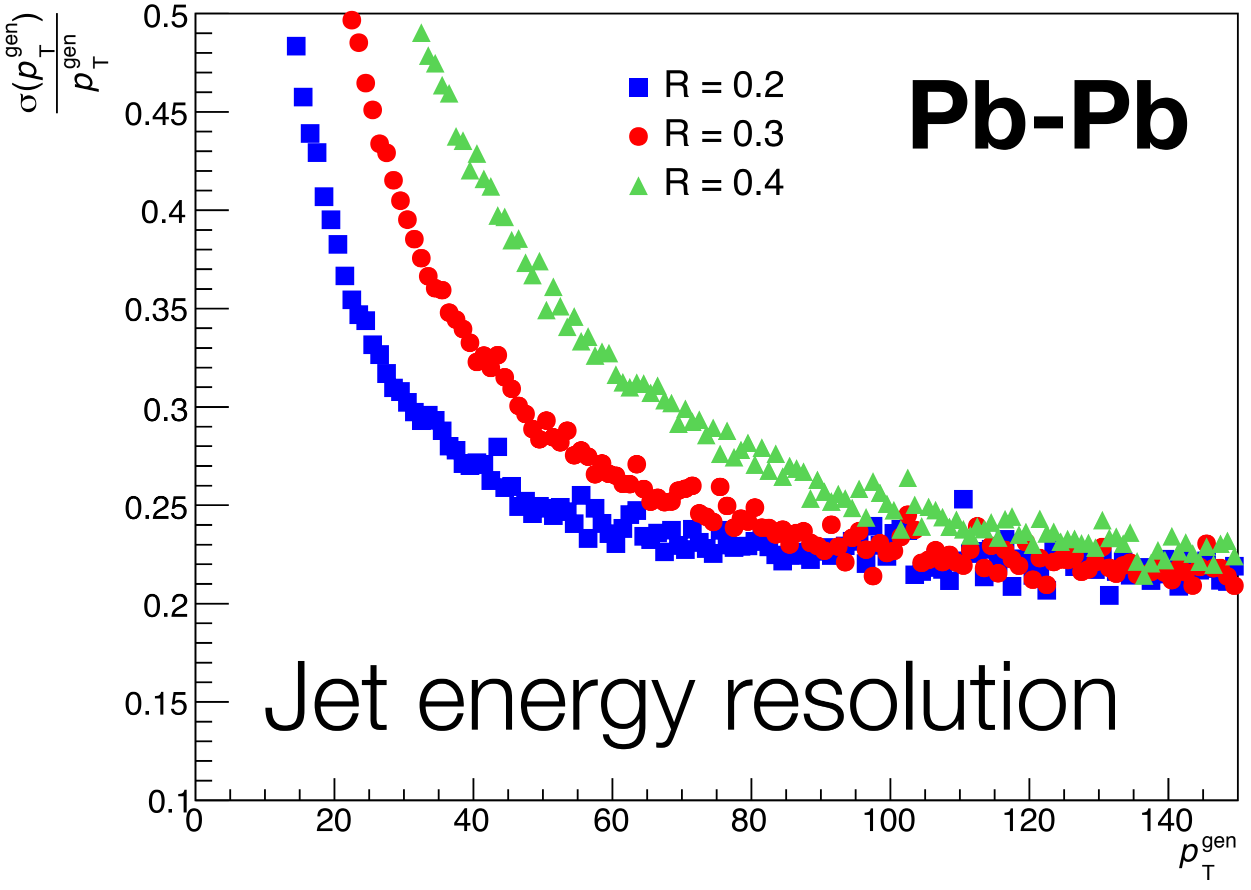
Analysis strategy — jet p_T correction

The measured jet p_T must be corrected for detector effects (tracking efficiency, bad channels, …) and smearing by background fluctuations

We deconvolute or “unfold” the jet p_T spectrum for the detector response and background fluctuations by building a response matrix **embedding** Pythia8 events into Pb-Pb data

- Properly accounts for centrality-dependent detector effects
- Corrects for any residual background contribution



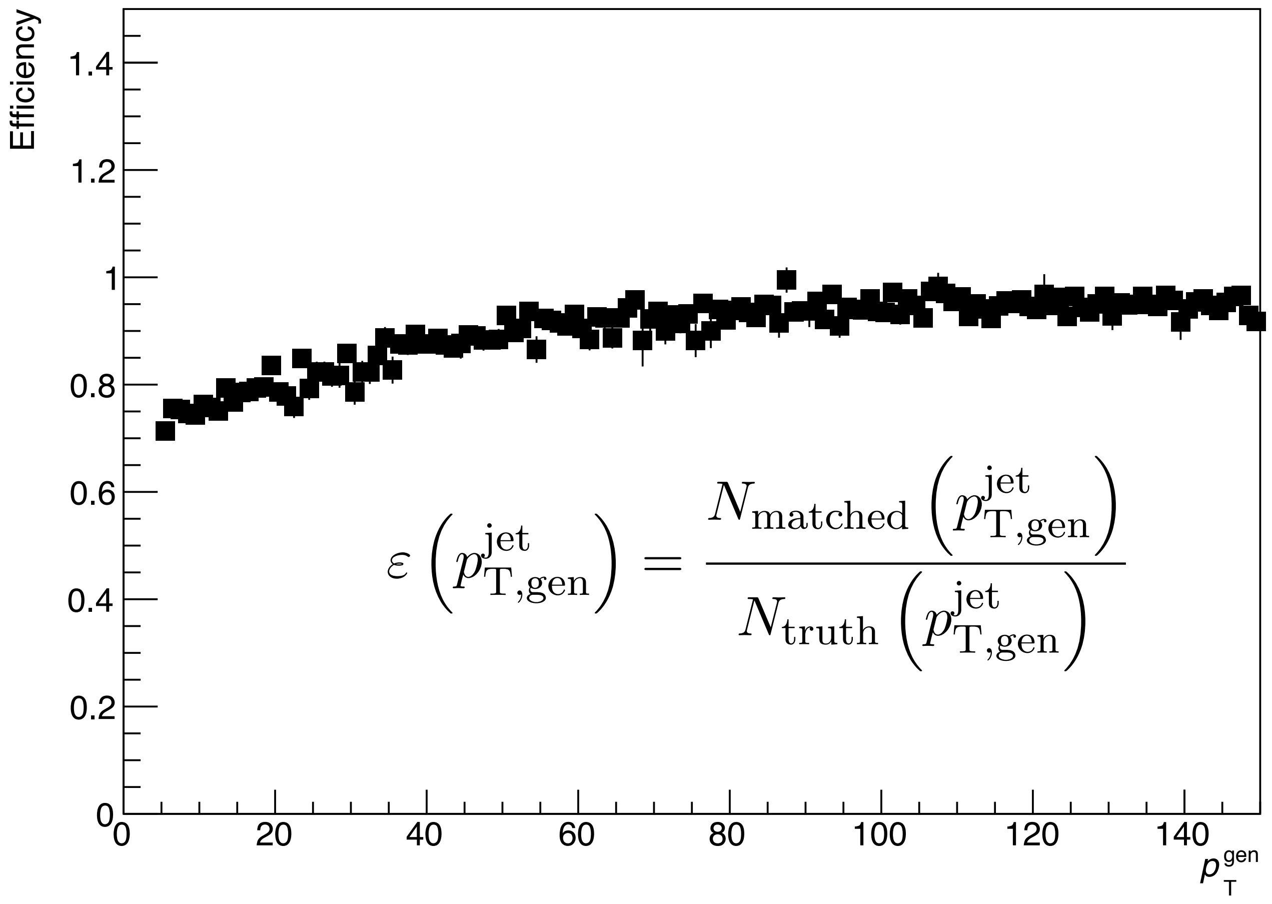


Analysis strategy — efficiency corrections

There are two further efficiency corrections we must apply:

Jet reconstruction efficiency

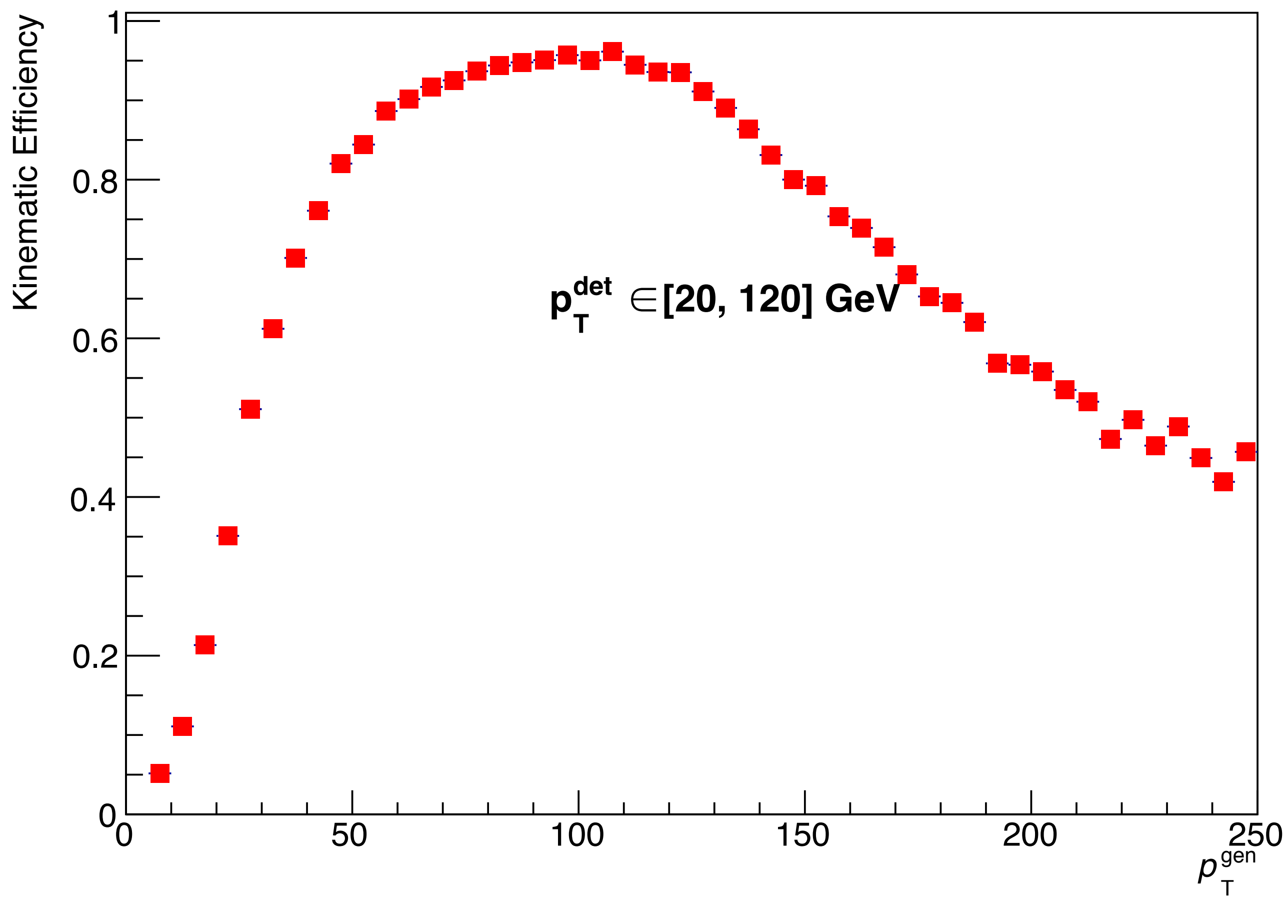
Probability to successfully reconstruct a jet at detector-level (including leading track requirement), given a truth-level jet



$$\varepsilon\left(p_{\mathrm{T,gen}}^{\mathrm{jet}}\right) = \frac{N_{\mathrm{matched}}\left(p_{\mathrm{T,gen}}^{\mathrm{jet}}\right)}{N_{\mathrm{truth}}\left(p_{\mathrm{T,gen}}^{\mathrm{jet}}\right)}$$

Kinematic efficiency

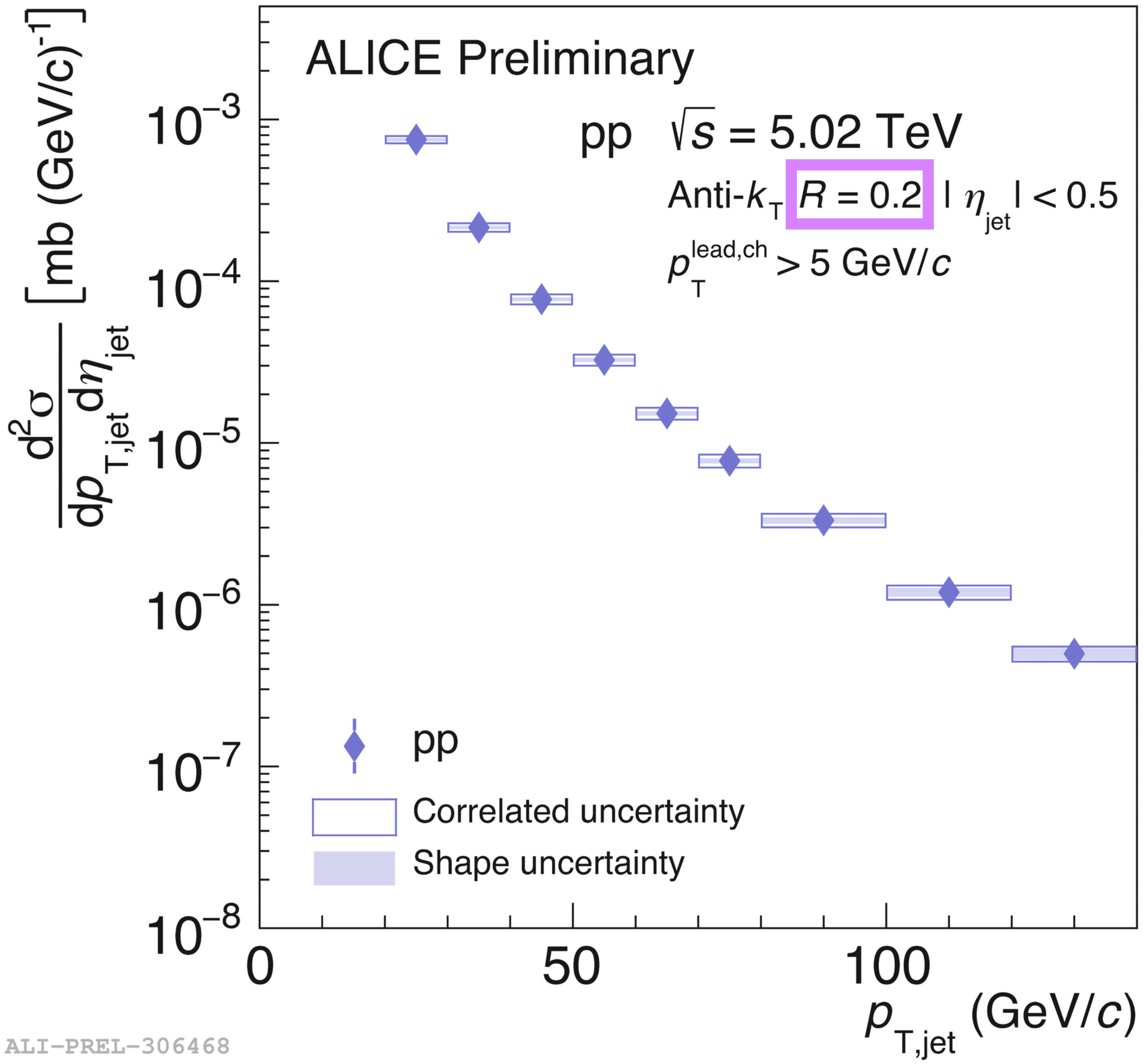
Probability to successfully reconstruct a jet within the measured detector-level p_T range, given a truth-level jet at a given p_T



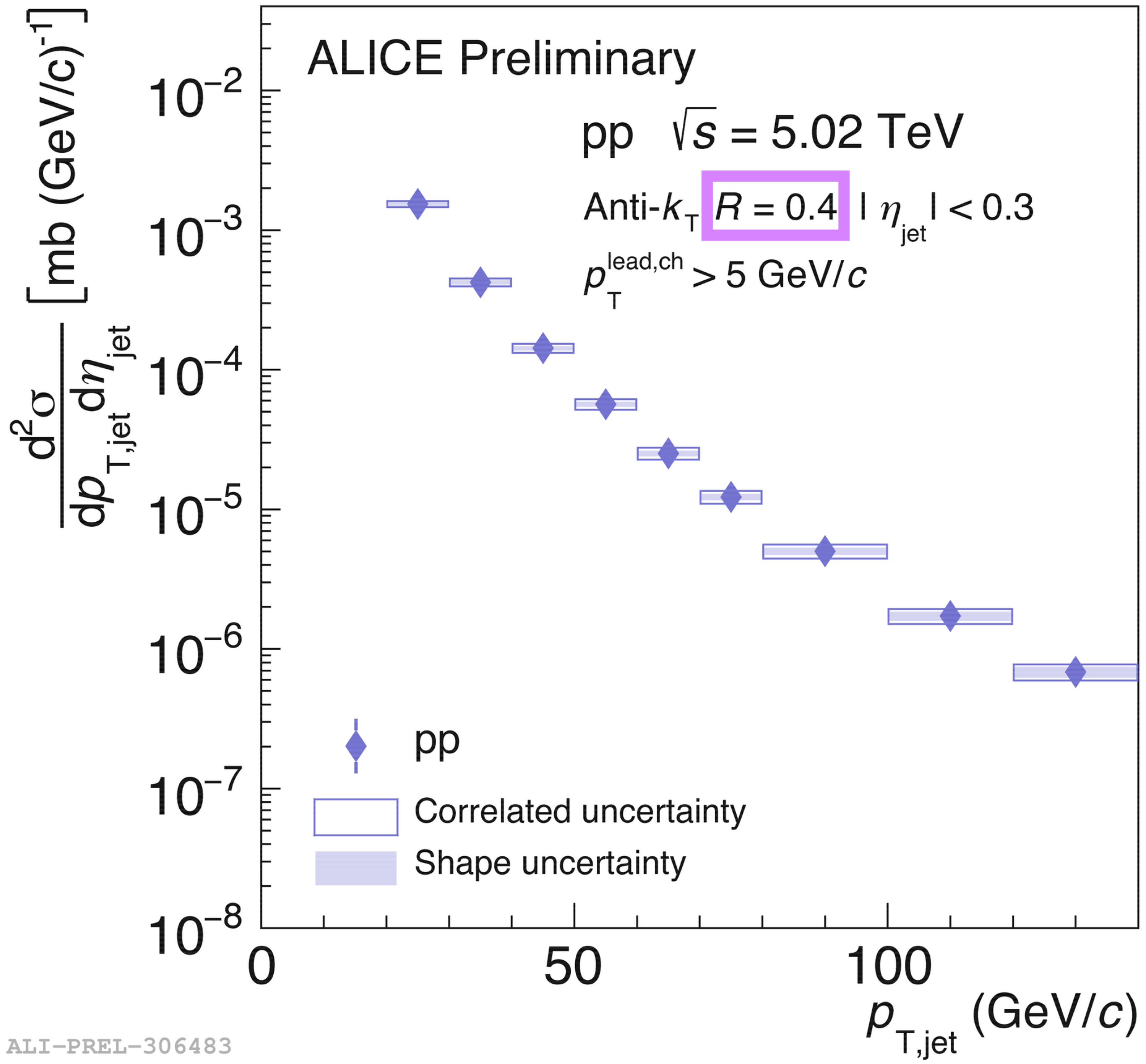
Results — pp jet cross-section

Eliane Epple + JM

We measure the inclusive pp jet cross-section for $p_{\mathrm{T,jet}}$ = 20-140 GeV/c at 5.02 TeV as a reference for jet R_{AA}



ALI-PREL-306468

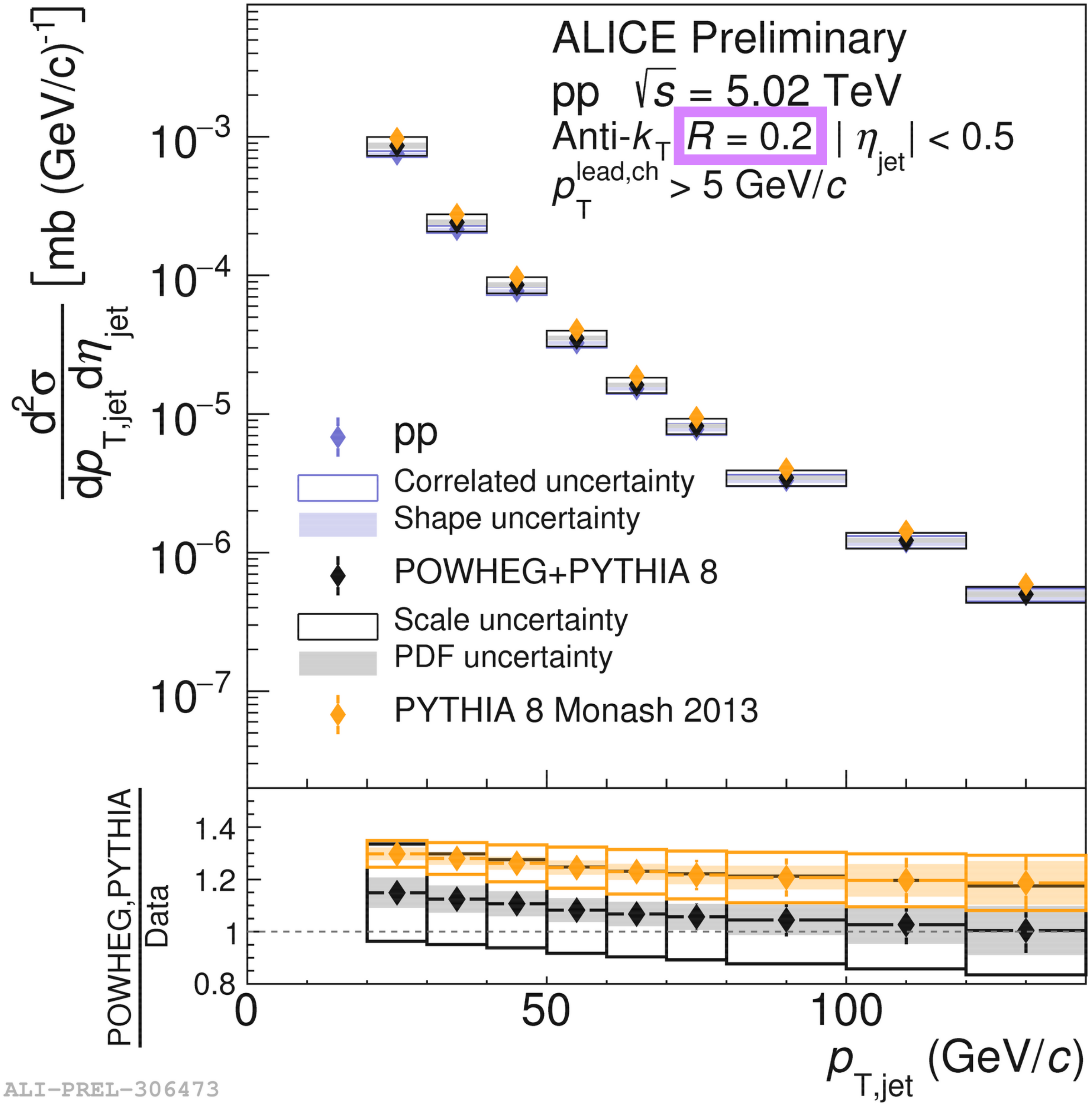


ALI-PREL-306483

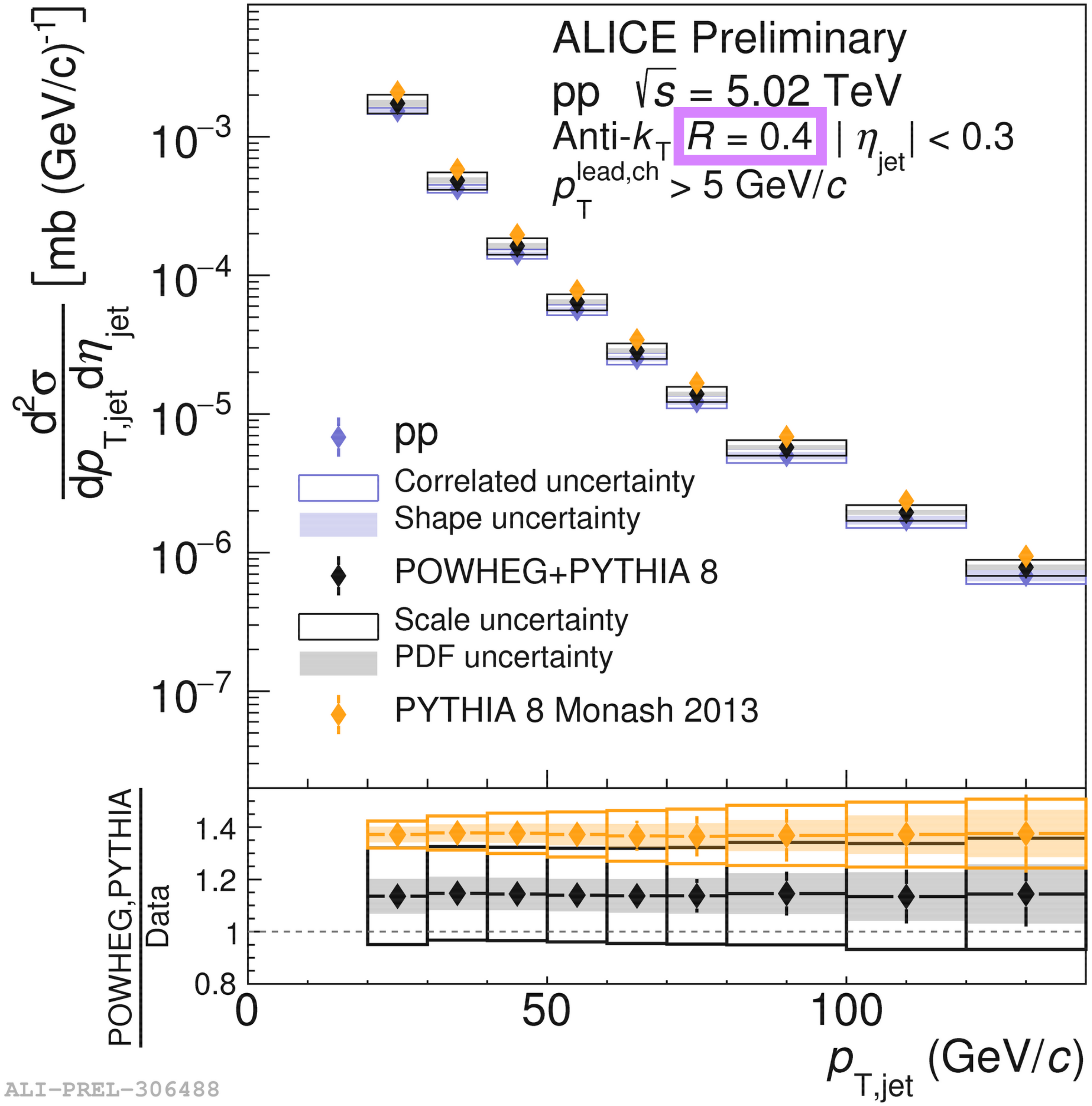
Results — pp jet cross-section

Eliane Epple + JM

The measurement is consistent with POWHEG + Pythia8



ALI-PREL-306473

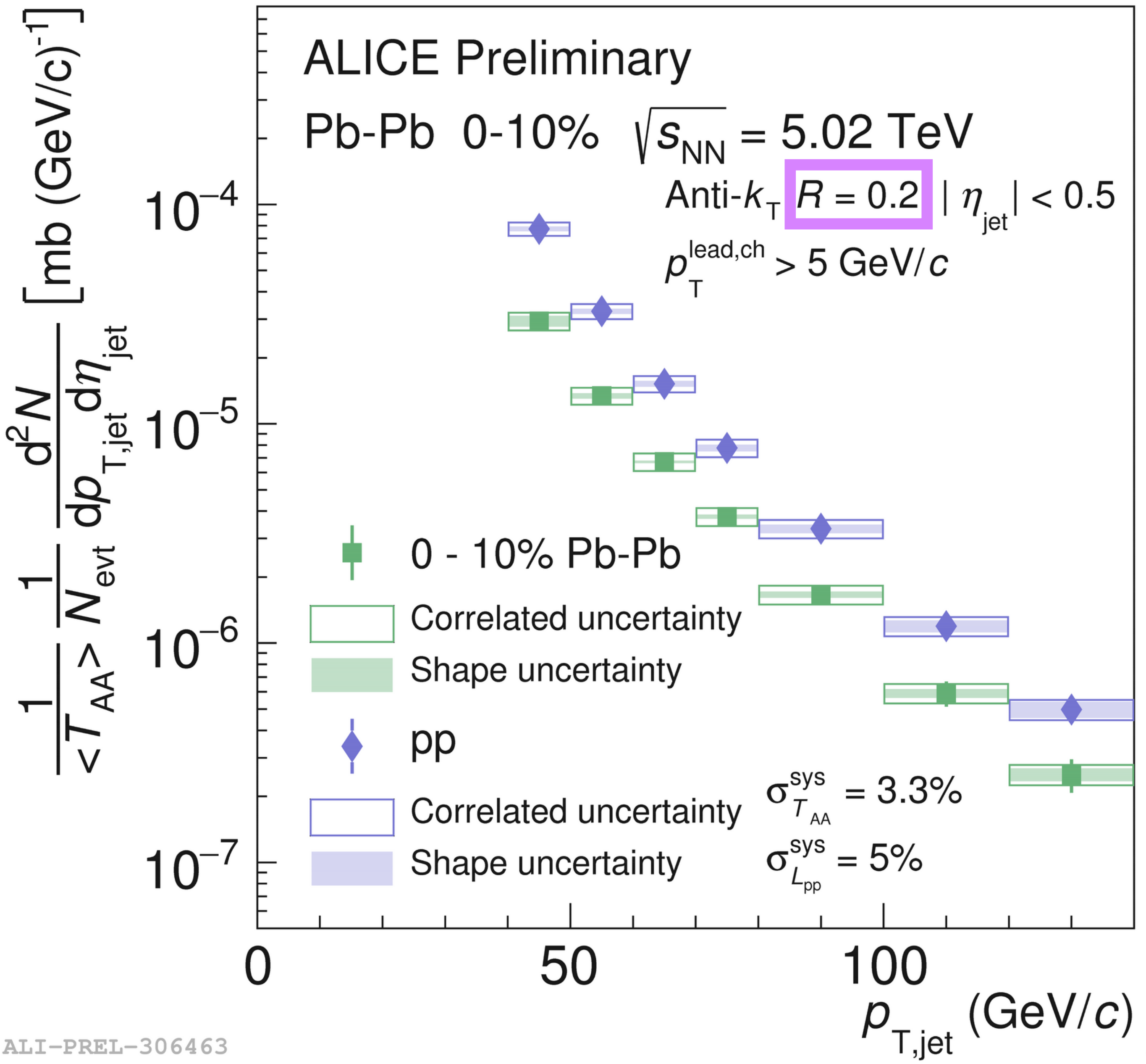


ALI-PREL-306488

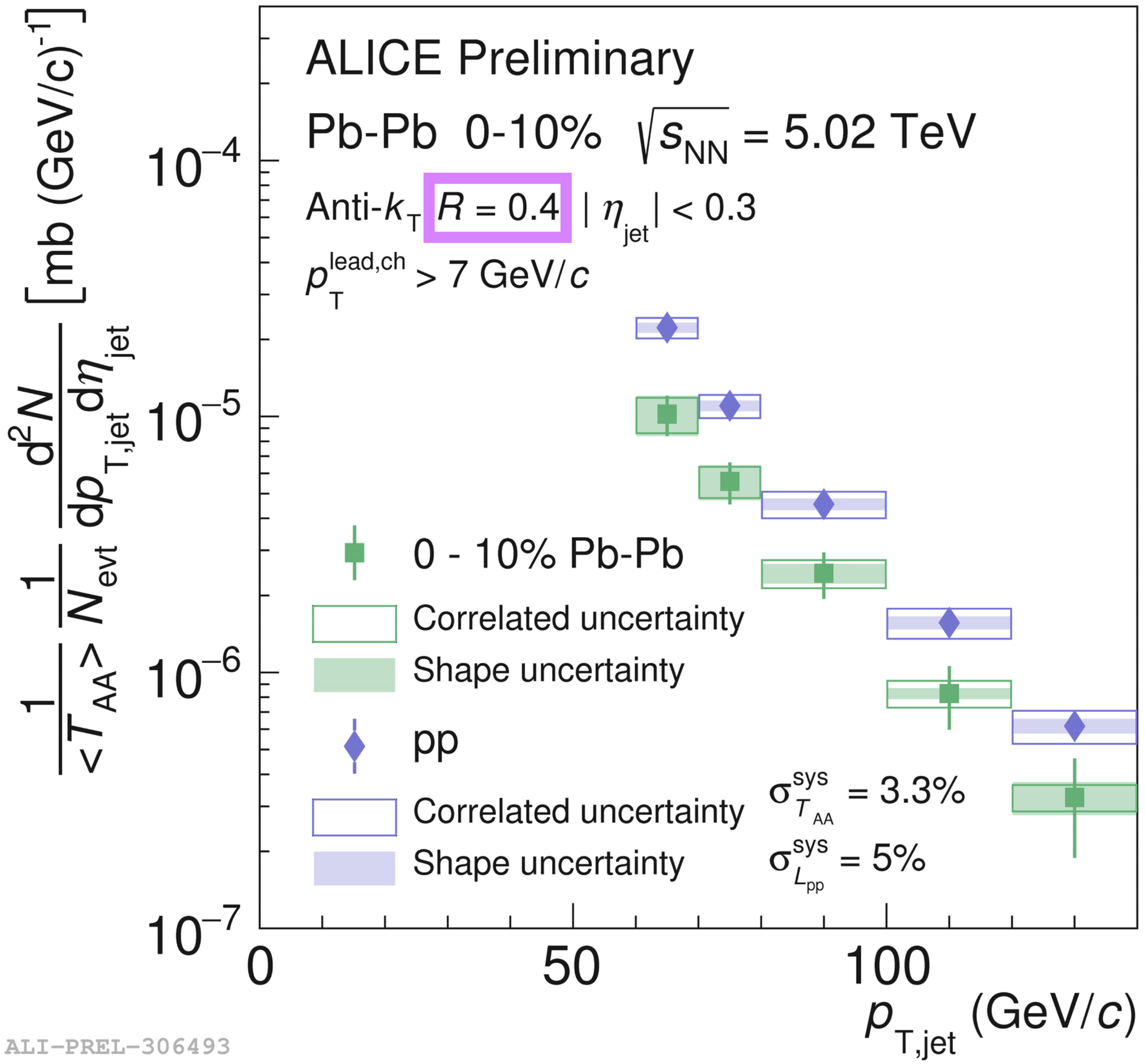
Results — Pb-Pb jet spectra

Publication in preparation

We measure the Pb-Pb jet spectrum in 0-10% centrality for $p_{\mathrm{T,jet}}$ = 40-140 GeV/c



ALI-PREL-306463



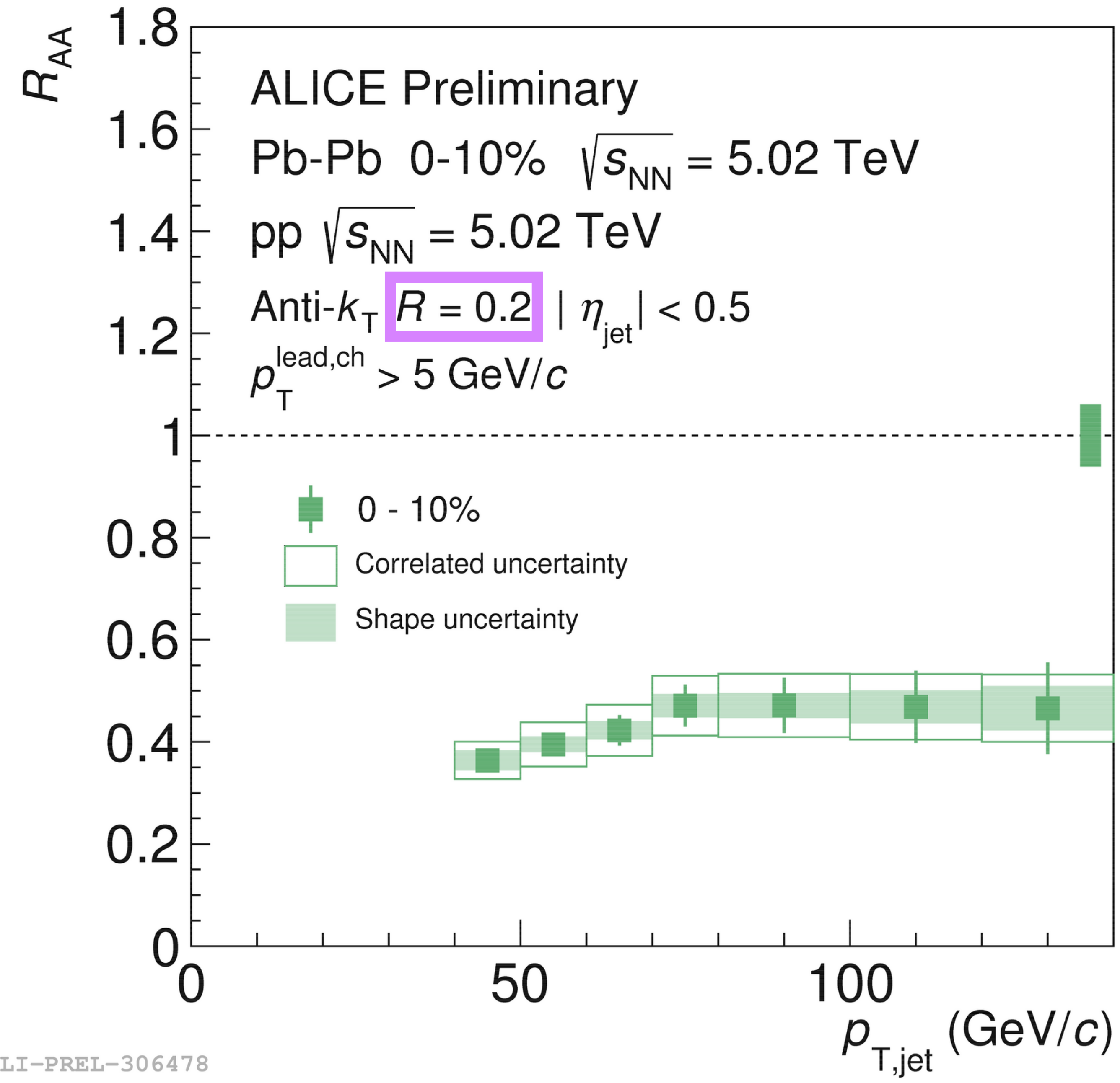
ALI-PREL-306493

Results — Jet R_{AA}

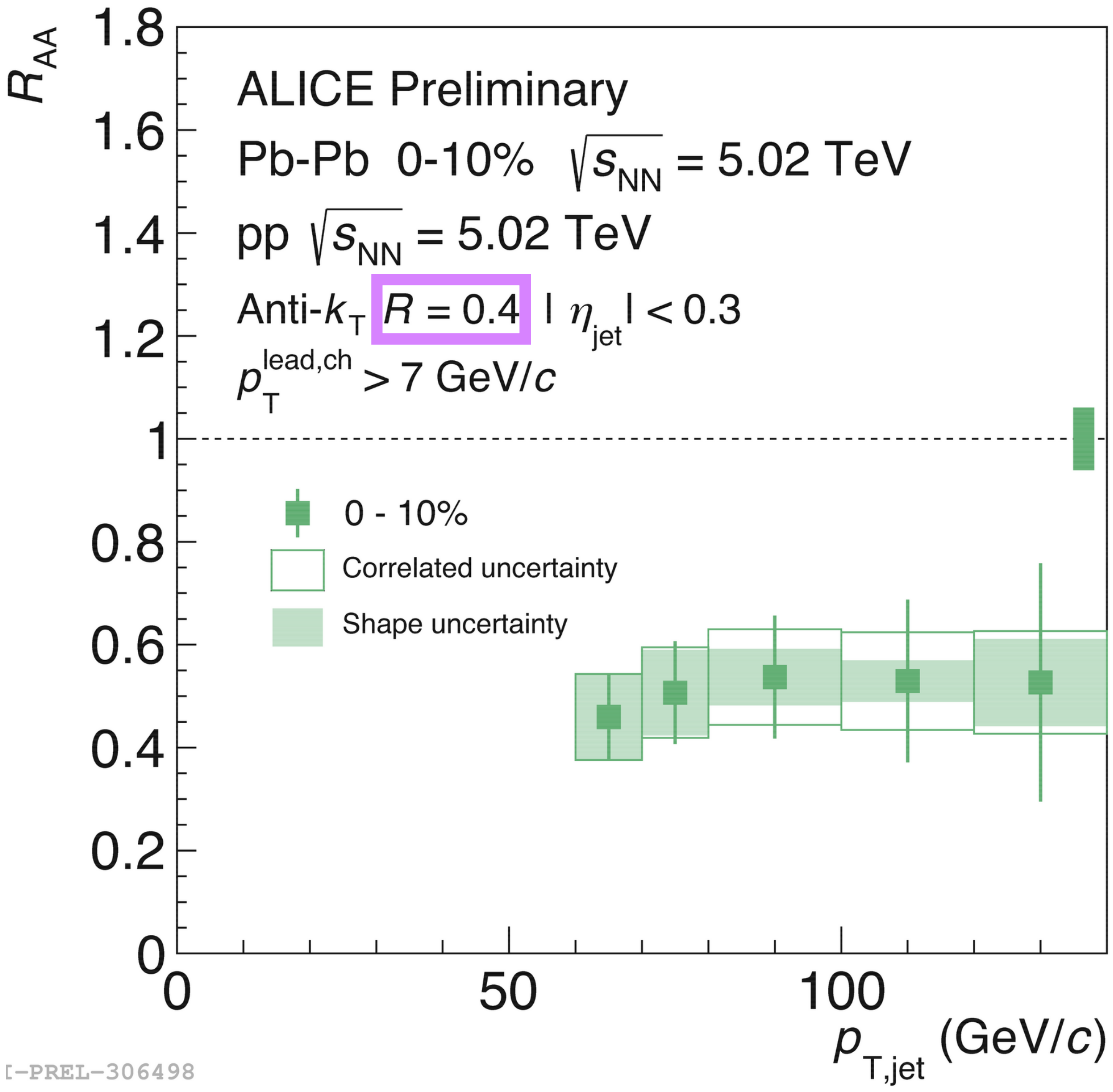
Publication in preparation

The first full jet R_{AA} measurement at $\boldsymbol{p_{T,jet} < 100}$ **GeV/*c*** at 5.02 TeV

Similar suppression observed in R=0.2 and R=0.4



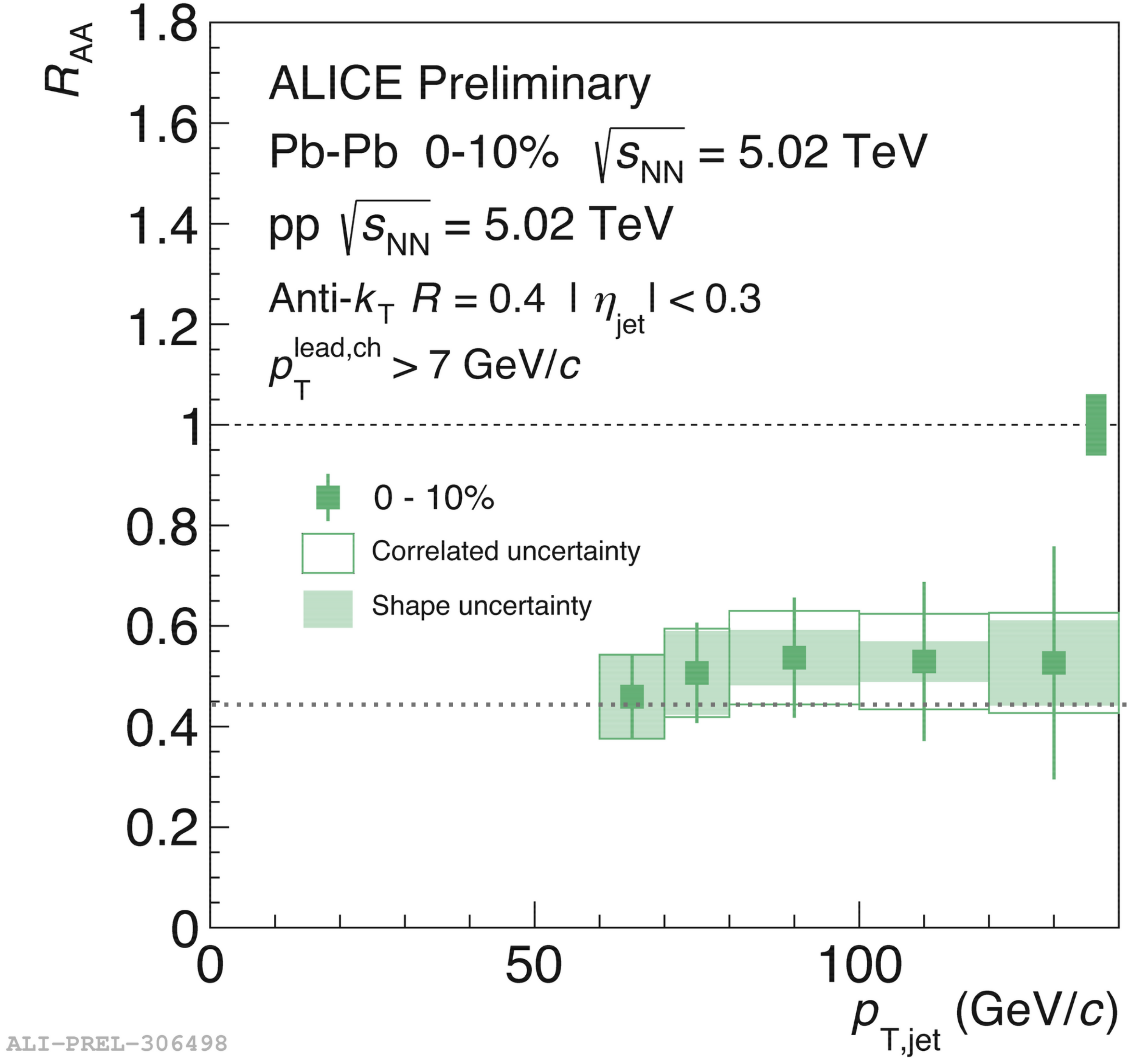
ALI-PREL-306478



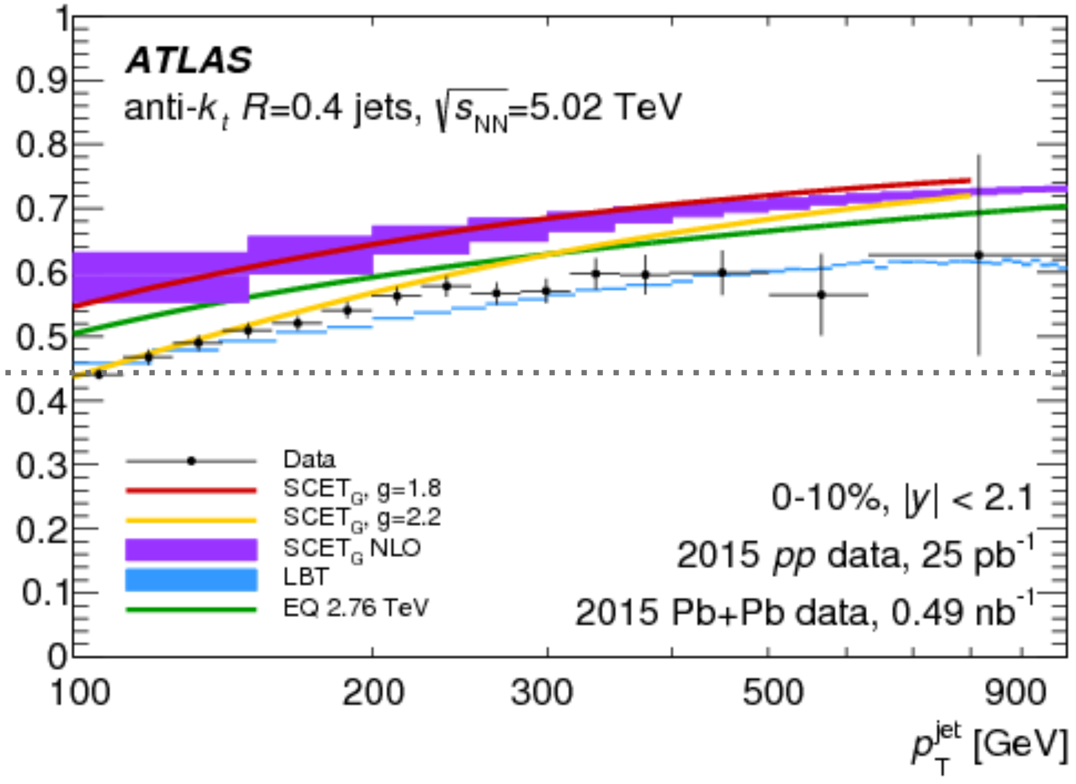
-PREL-306498

Results — Jet R_{AA}

ALICE R=0.4 jet R_{AA} is consistent with ATLAS R=0.4 jet R_{AA}

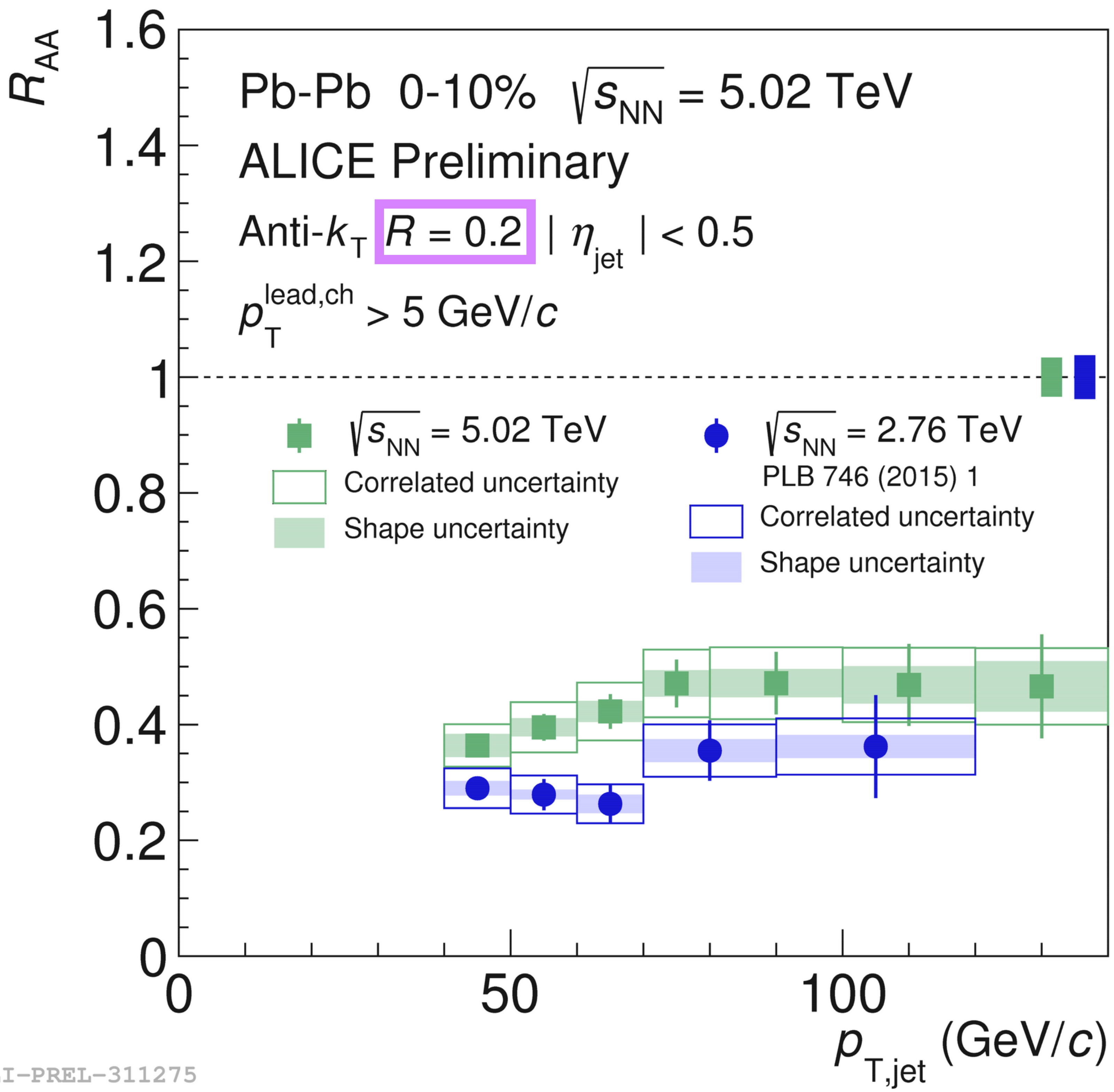


arxiv 1805.05424



Results — Jet R_{AA}

ALICE full jet R_{AA} at 5.02 TeV is similar to 2.76 TeV for R=0.2, with hint of increase



Results — Jet R_{AA}

Measurements compared to theoretical predictions:

LBT provided in arxiv:1809.02525

PRC 91 (0549098)

Hybrid model provided by Daniel Pablos

JHEP 10 (2014) 19

JHEP 03 (2016) 53

JHEP 03 (2017) 135

JHEP 03 (2018) 10

SCET$_G$ provided by Haitao Li

arxiv:1801.00008

PLB 769 (242)

JEWEL (generated internally)

JHEP 03 (2013) 80

JHEP 07 (2017) 141

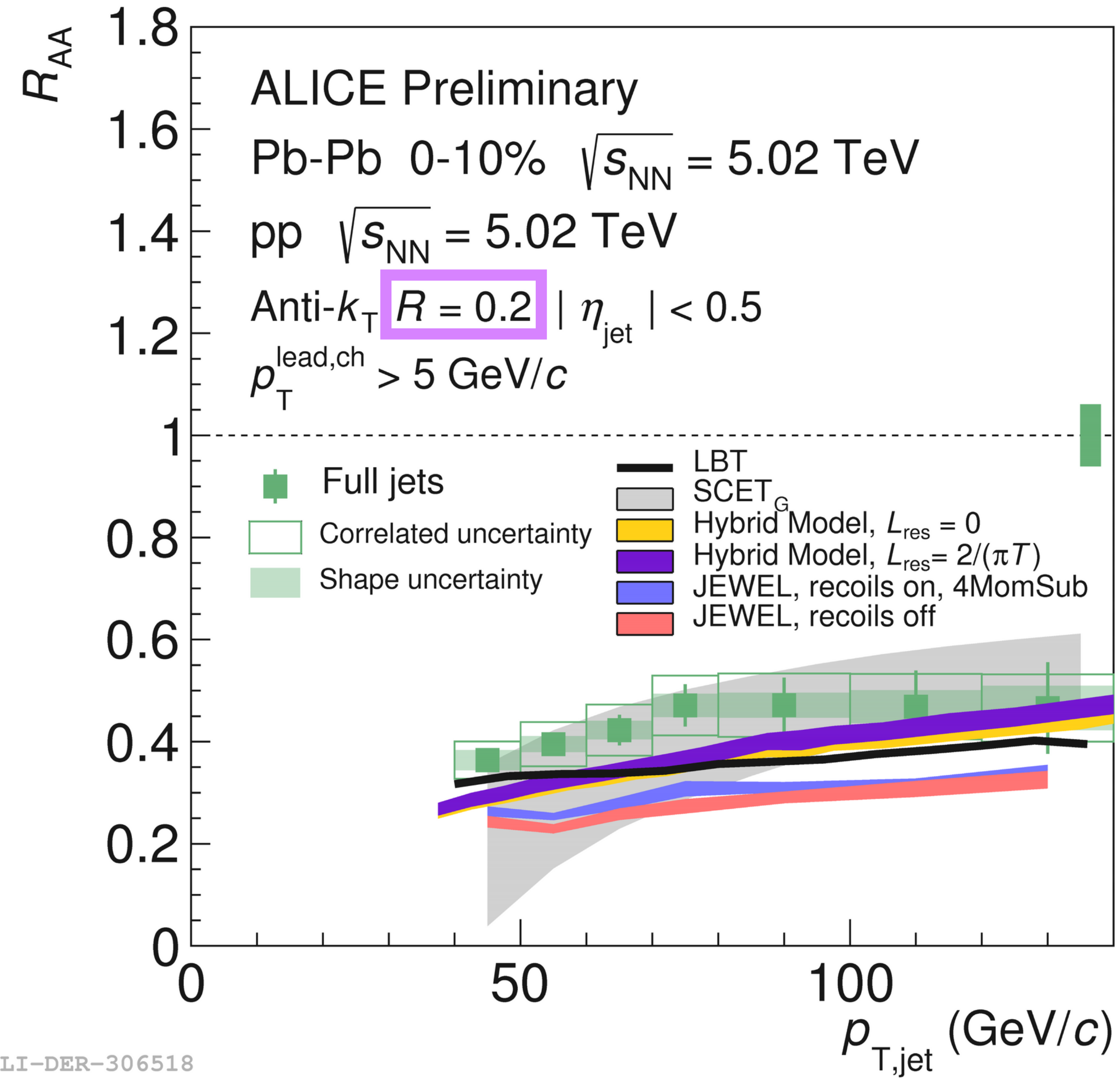
EPJ C (2016) 76:695

Results — Jet R_{AA}

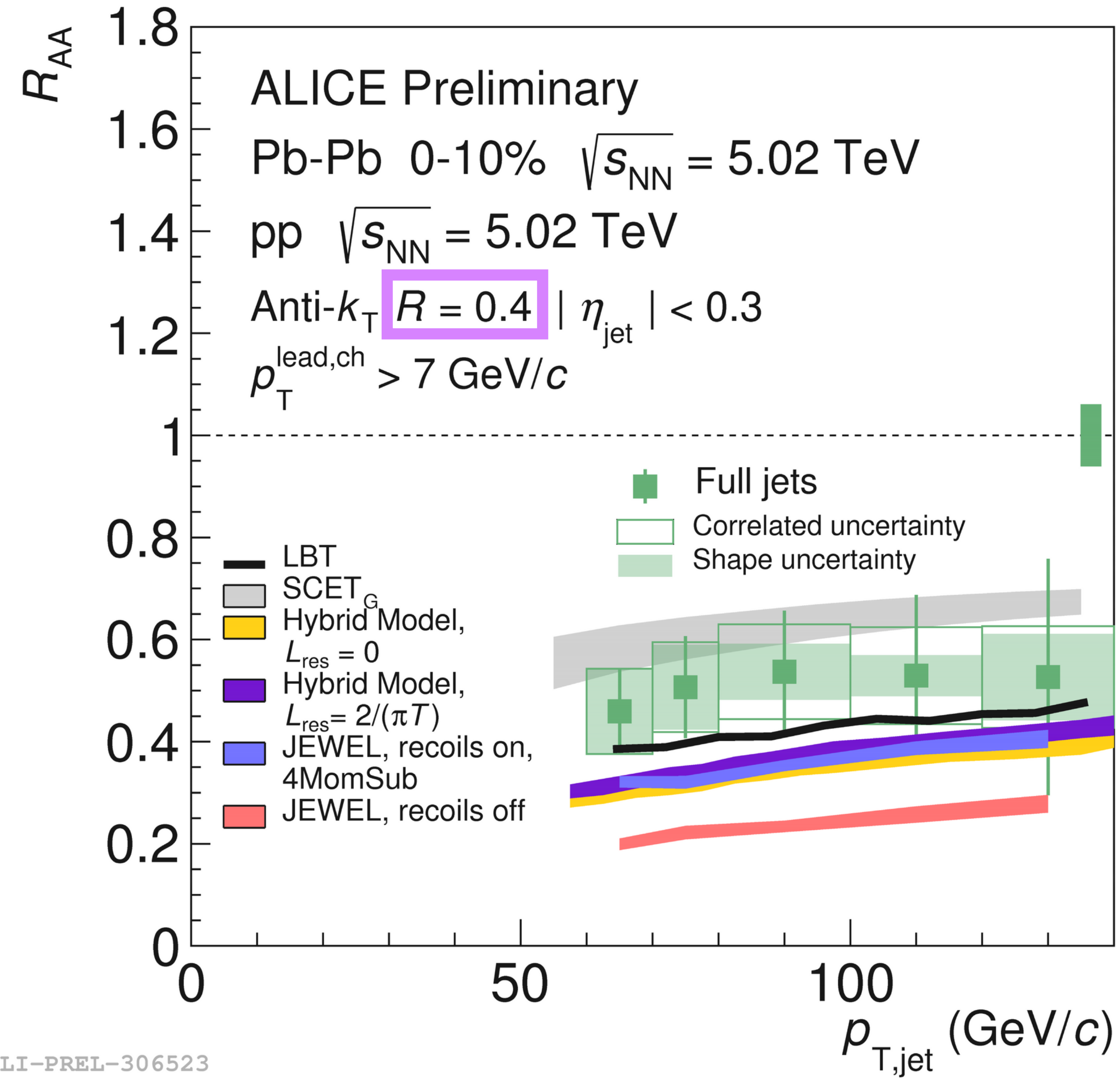
Publication in preparation

All models qualitatively describe the R_{AA}

But quantitatively, most models have slight tension with the data



ALI-DER-306518



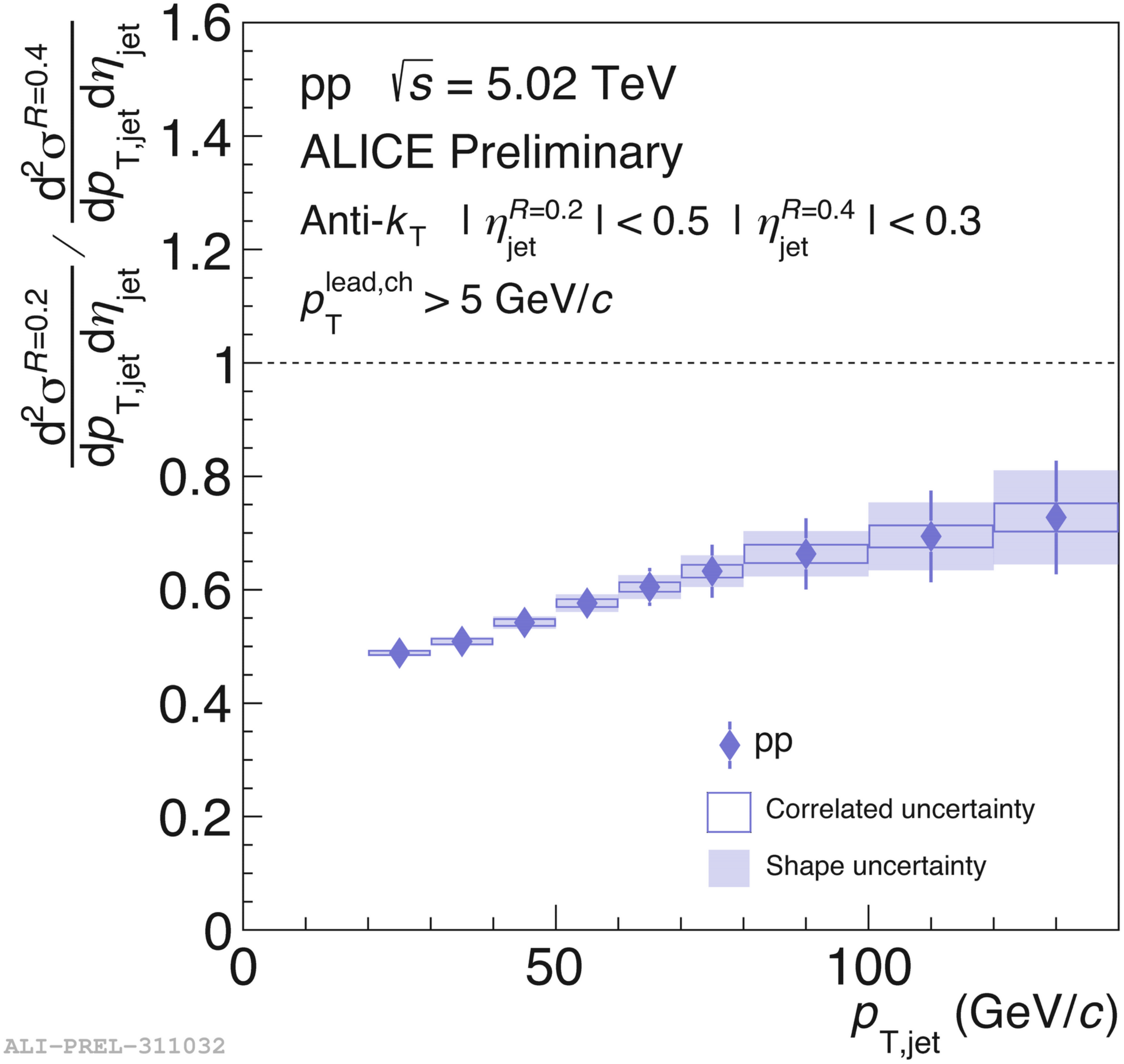
ALI-PREL-306523

Results: Jet cross-section ratio

Eliane Epple + JM

The ratio of jet cross-sections R=0.2 / R=0.4 in pp provides a baseline for Pb-Pb

In pp, the jet cross-section ratio is also useful to disentangle hadronization and underlying event effects

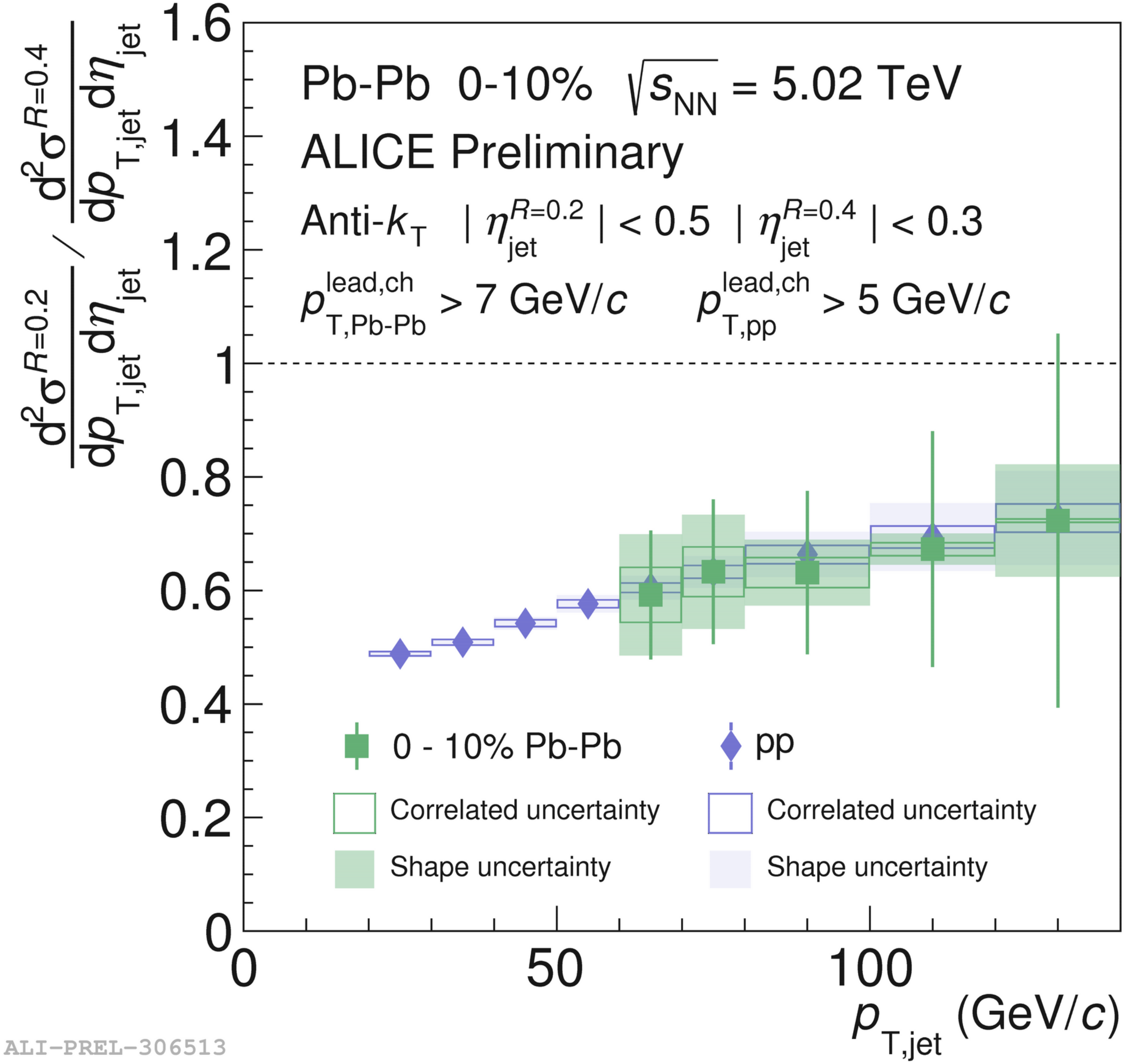


Results: Jet cross-section ratio

Publication in preparation

No modification in Pb-Pb is observed compared to pp

Generally consistent with previous measurements at 2.76 TeV showing no significant modification in *R*~0.2-0.4

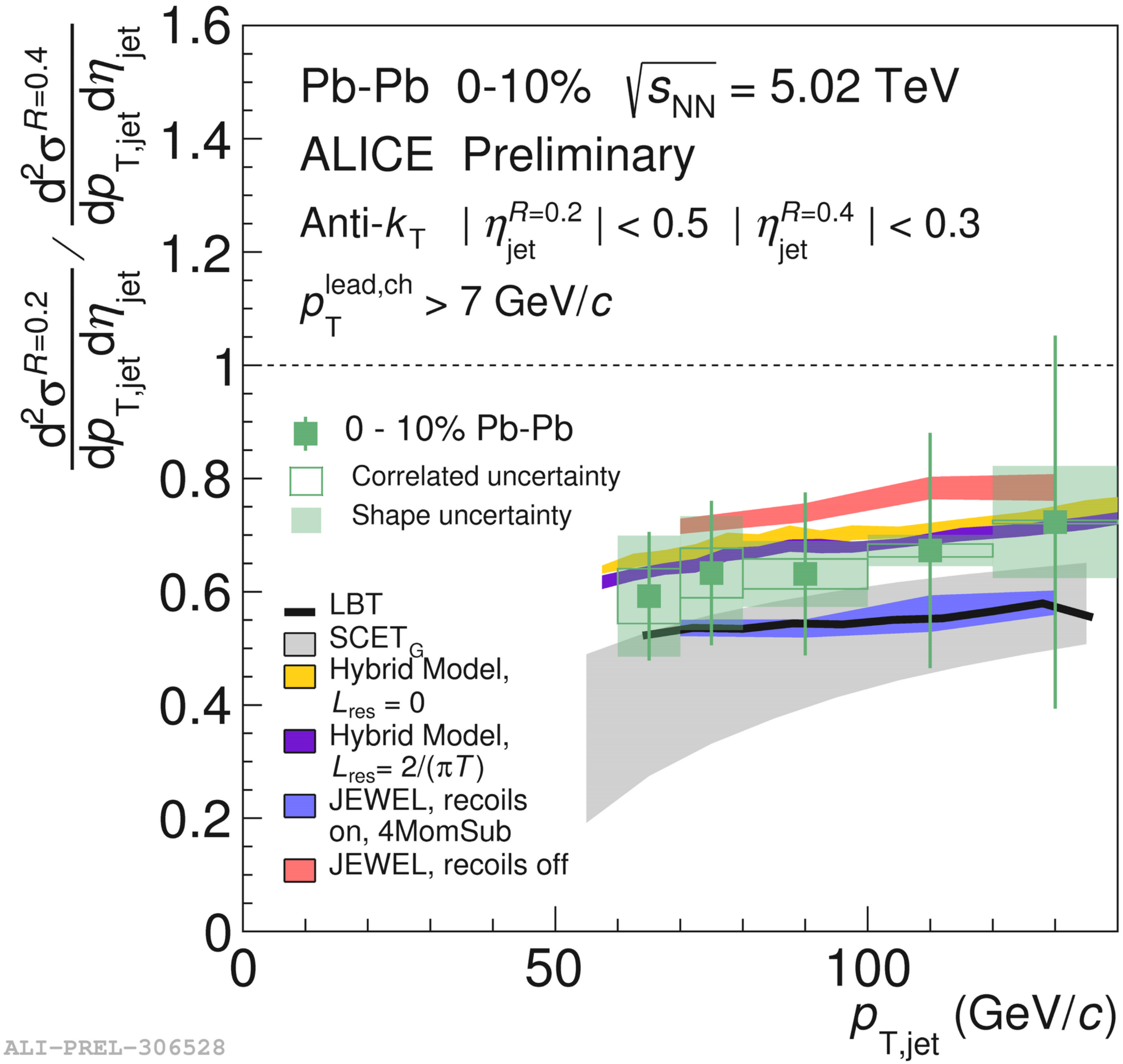


Results: Jet cross-section ratio

Publication in preparation

No modification in Pb-Pb is observed compared to pp

Models predict some modification, but our resolution is not good enough to distinguish them



Summary

We have measured the level of inclusive full jet suppression in heavy-ion collisions at low-p_{T} for $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, as well as the *R*-dependence of the suppression

- *Jet R_{AA} shows strong suppression and significant p_T-dependence at low p_T*
- *Jet R_{AA} and the jet cross-section ratio show no significant dependence on R for R=0.2-0.4*

Several models exhibit slight tension with the jet R_{AA}

- *However, the models use different input spectra, different medium evolution, different hadronization, different leading track biases, and different ways of fixing model parameters…*
- *What does it mean for a model to be "consistent" or "inconsistent" with measured R_{AA}?*

Outlook

Big picture questions remain in heavy-ion jet physics:

1. *Can we converge on a description of jet energy loss in deconfined QCD matter?*
2. *Does deconfined QCD matter contain quasiparticles? If so what are they?*

Rich program ahead as we try to answer these questions:

- *Search for quasiparticles with large-angle scatterings*
- *Jet substructure*
- *Heavy-flavor jets*
- *…*

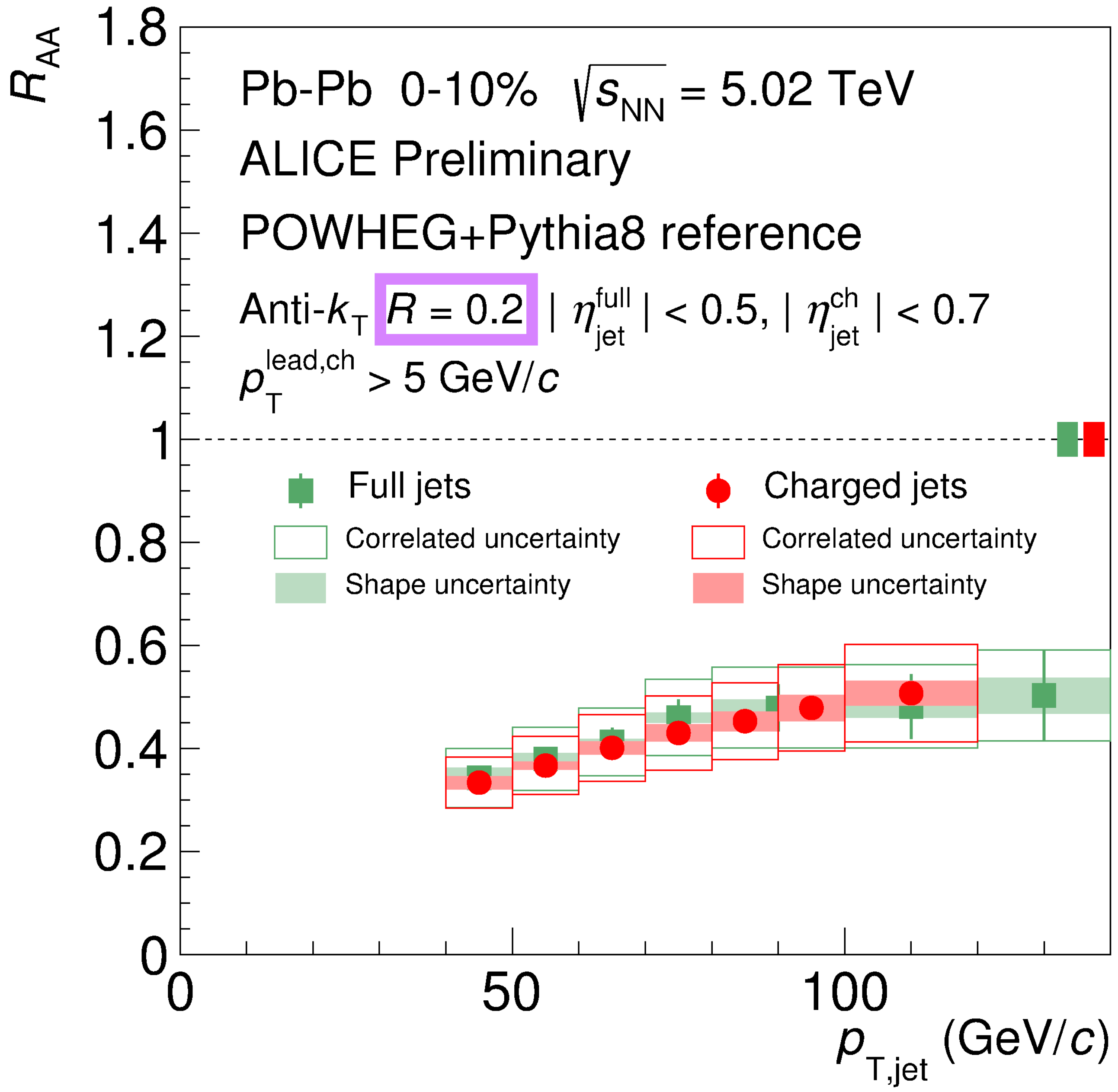
Multiple avenues to explore jet modification in new ways and greater detail, and a big boost in Pb-Pb statistics coming by the end of 2018!

Thank you!

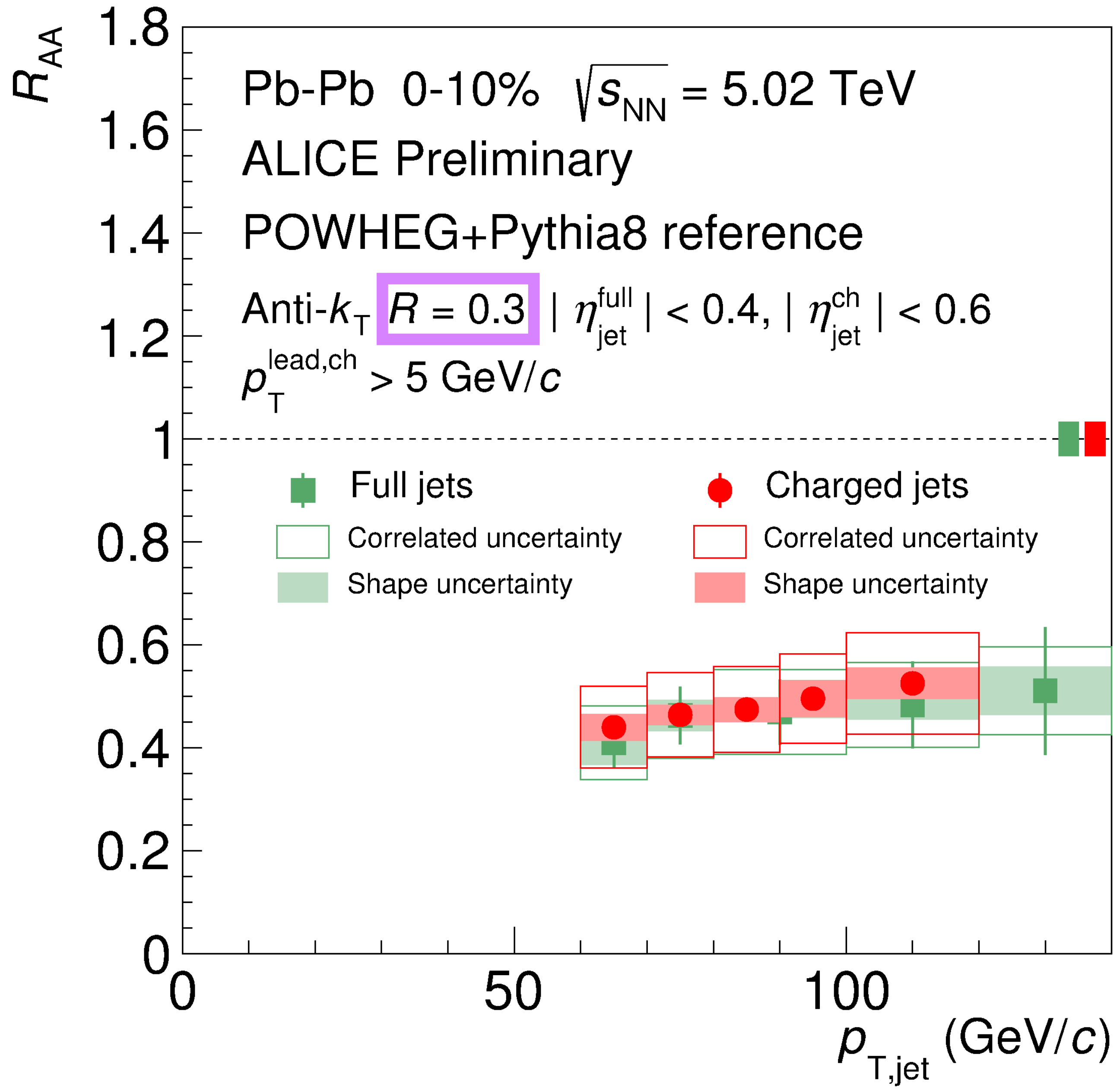
Backup

Results — Jet R_{AA}

Charged particle jets and full jets are consistent

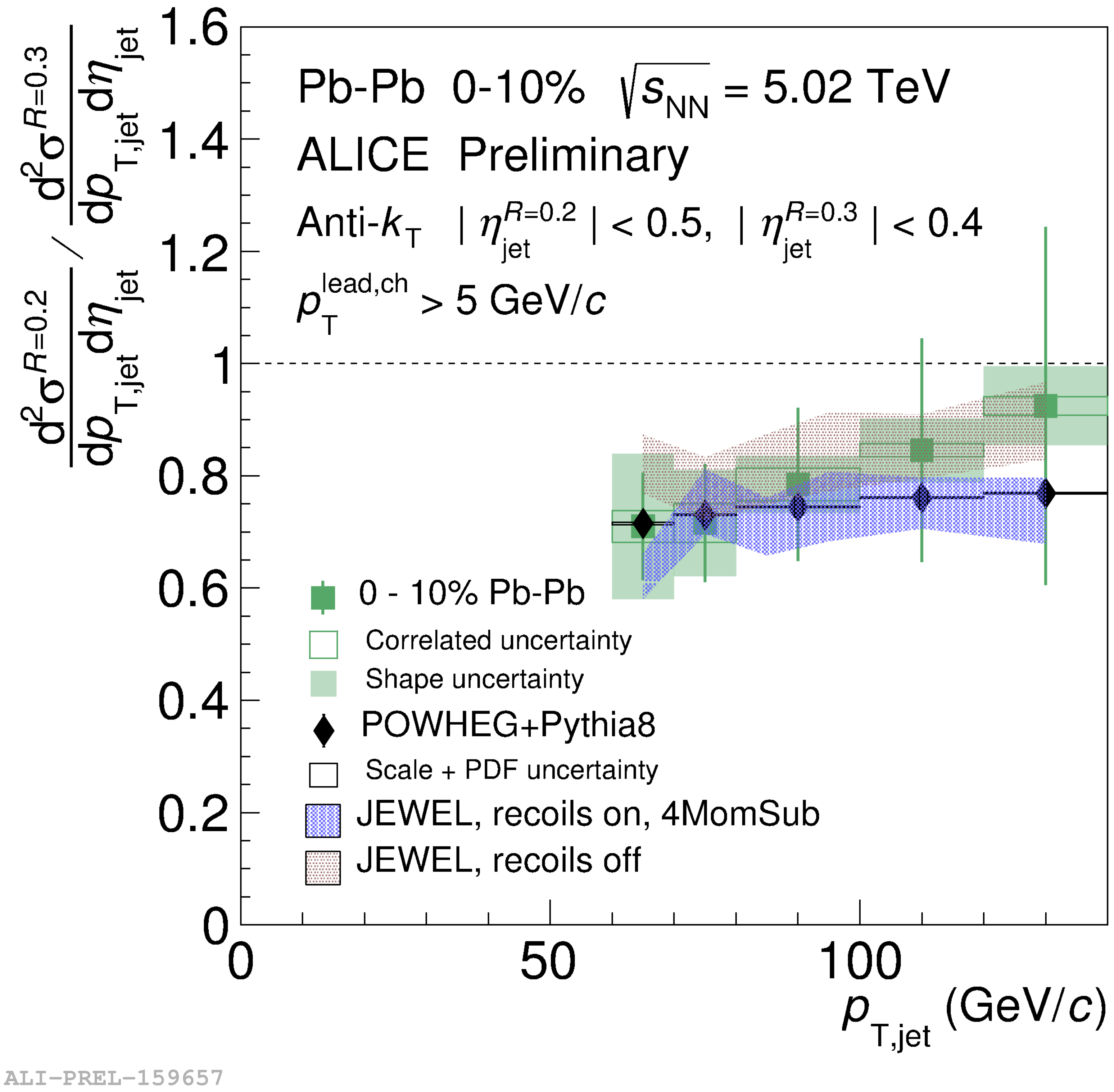


ALI-PREL-159649



ALI-PREL-159653

R=0.2 / R=0.3 jet cross-section ratio



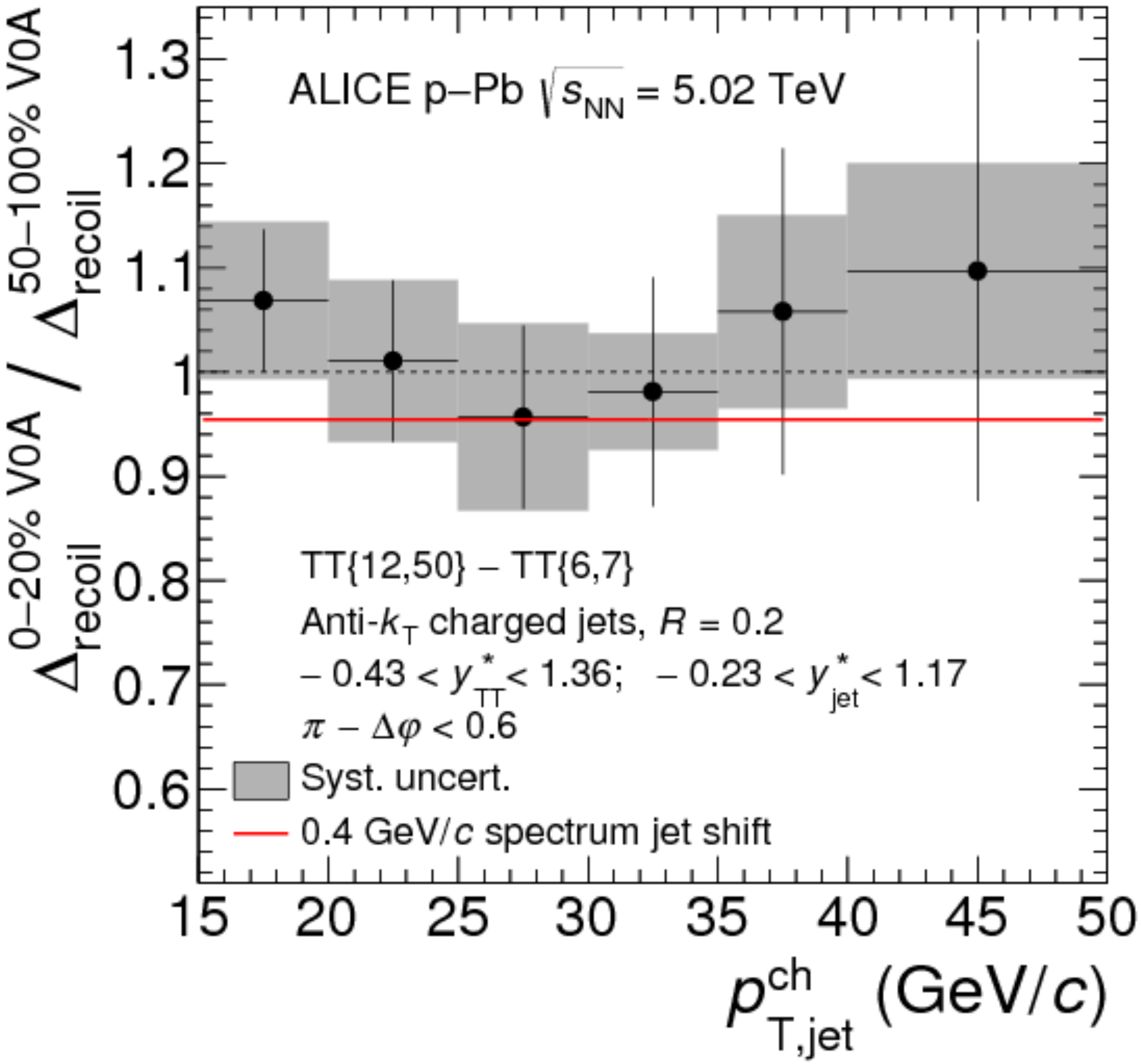
What have we learned about jet modification?

1. Jet yields are suppressed

Phys.Lett. B783 (2018) 95-11

No jet suppression is observed in p-Pb

$$\Delta_{\text{recoil}}\left(p_{\text{T,jet}}^{\text{ch}}\right) = \frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2 N_{\text{jets}}}{\mathrm{d}p_{\text{T,jet}}^{\text{ch}}}\bigg|_{p_{\text{T,trig}}\in \text{TT}_{\text{Sig}}} - c_{\text{Ref}}\cdot\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2 N_{\text{jets}}}{\mathrm{d}p_{\text{T,jet}}^{\text{ch}}}\bigg|_{p_{\text{T,trig}}\in \text{TT}_{\text{Ref}}}$$



What have we learned about jet modification?

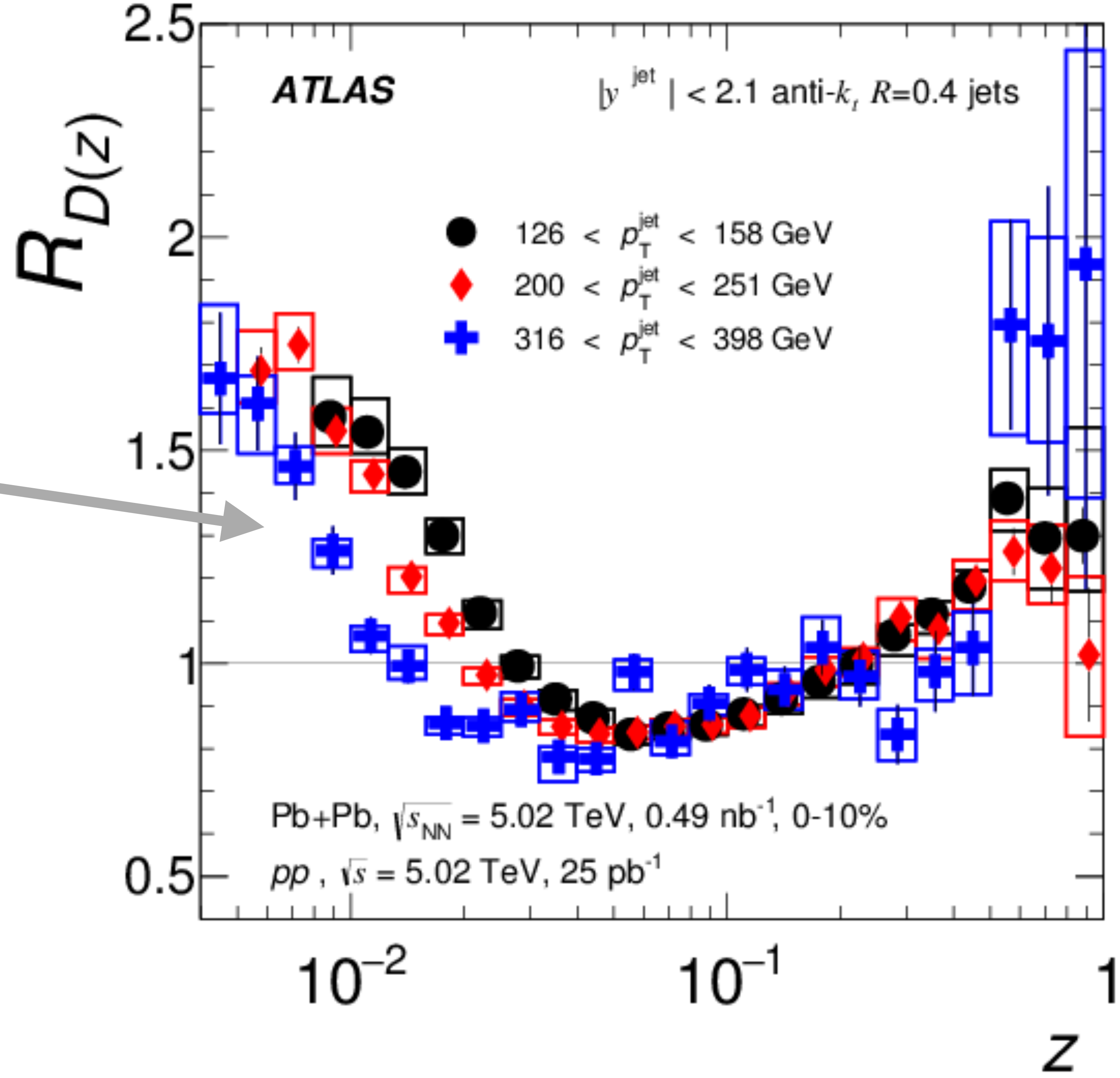
3. Soft energy is distributed to large angles

The soft excess is also observed in the fragmentation function

$$R_{D(z)} \equiv \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{pp}}$$

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

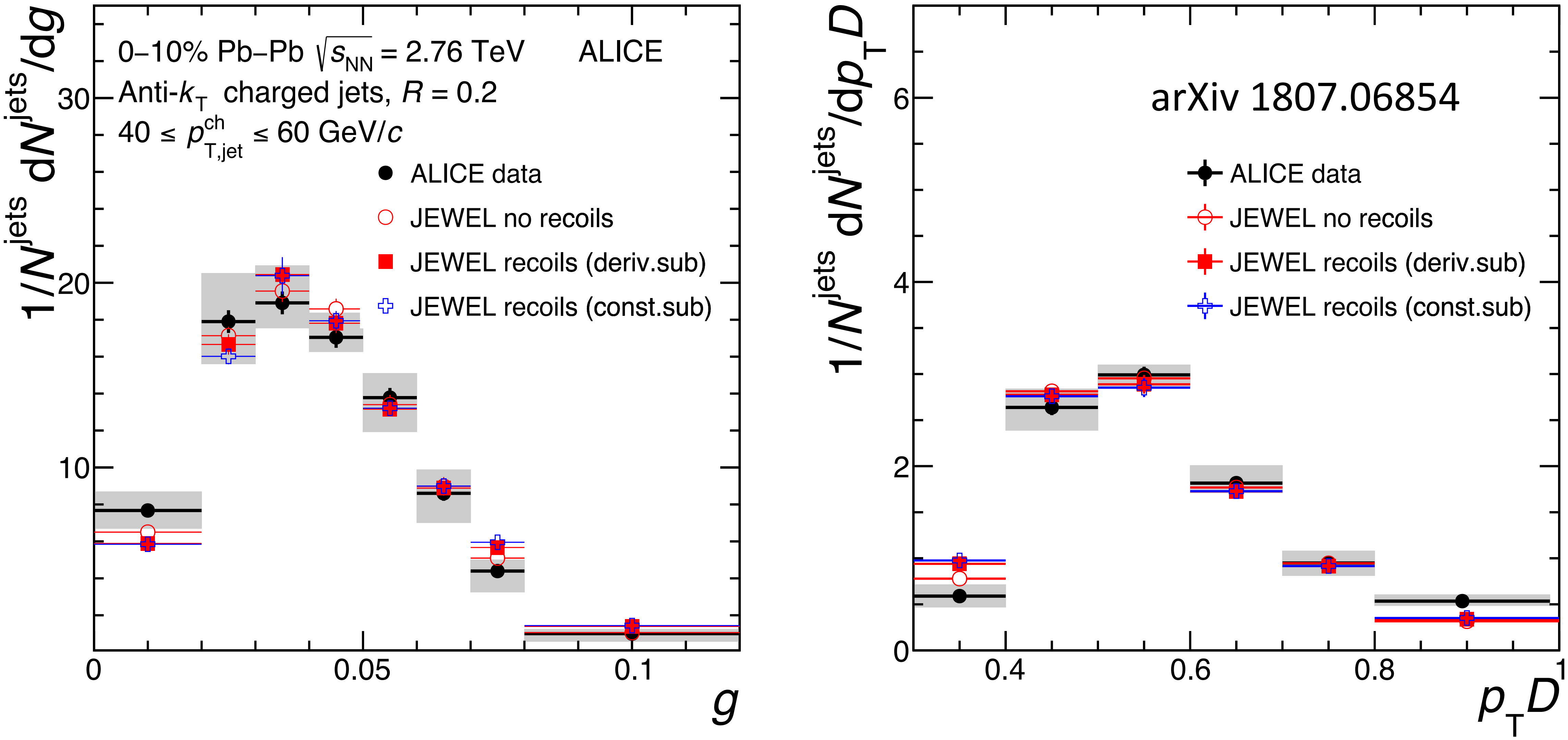
arXiv 1805.05424



What have we learned about jet modification?

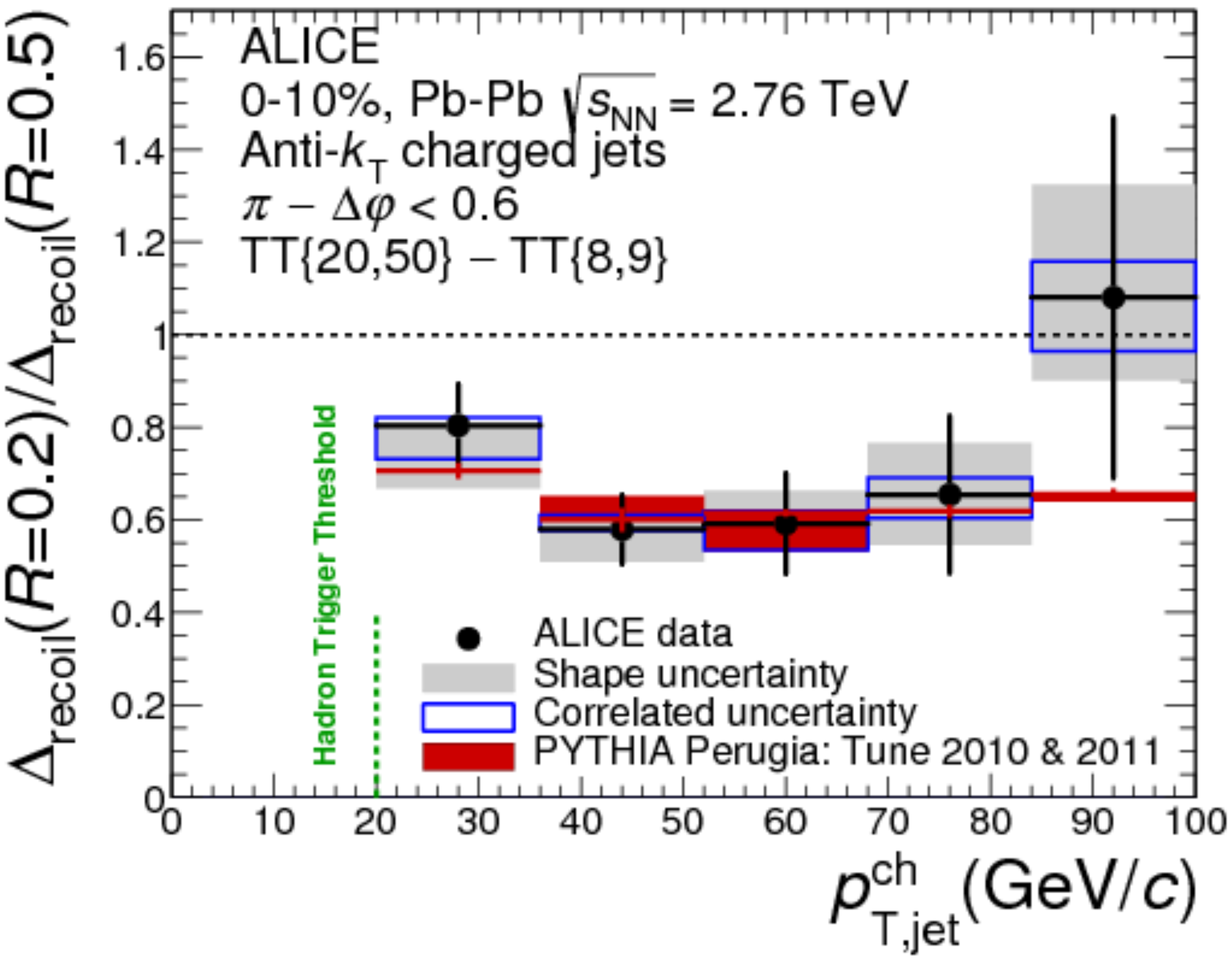
4. Medium recoil is important to understand

However the radial moment and momentum dispersion for ***R*=0.2** jets in Pb-Pb does not appear to be sensitive to medium recoil



R-dependence of jet suppression at $\sqrt{s_{NN}} = 2.76$ TeV

JHEP 09 (2015) 170



ALICE hadron-jet coincidence measurement shows no significant intra-jet broadening from *R*=0.2 to *R*=0.5

Quark-gluon ratio

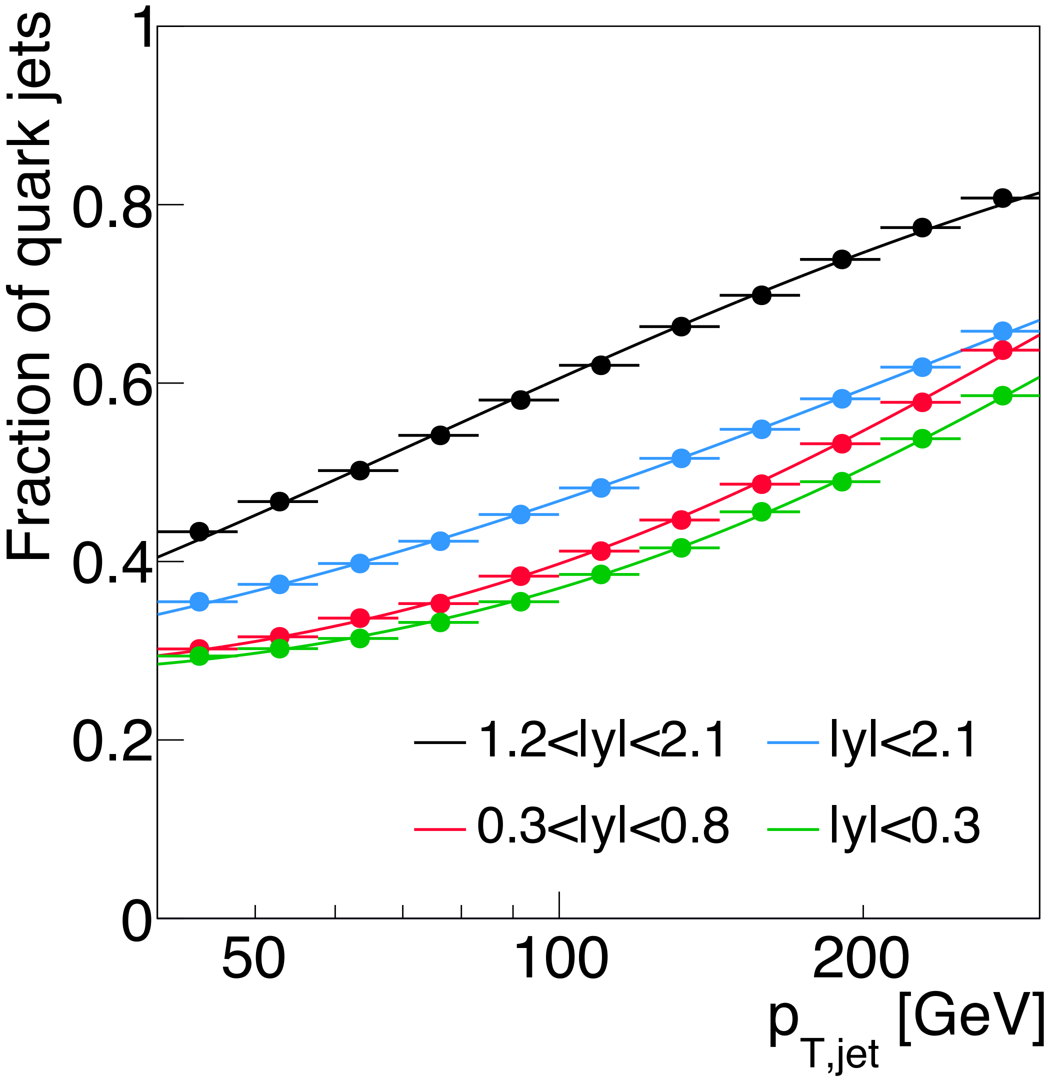
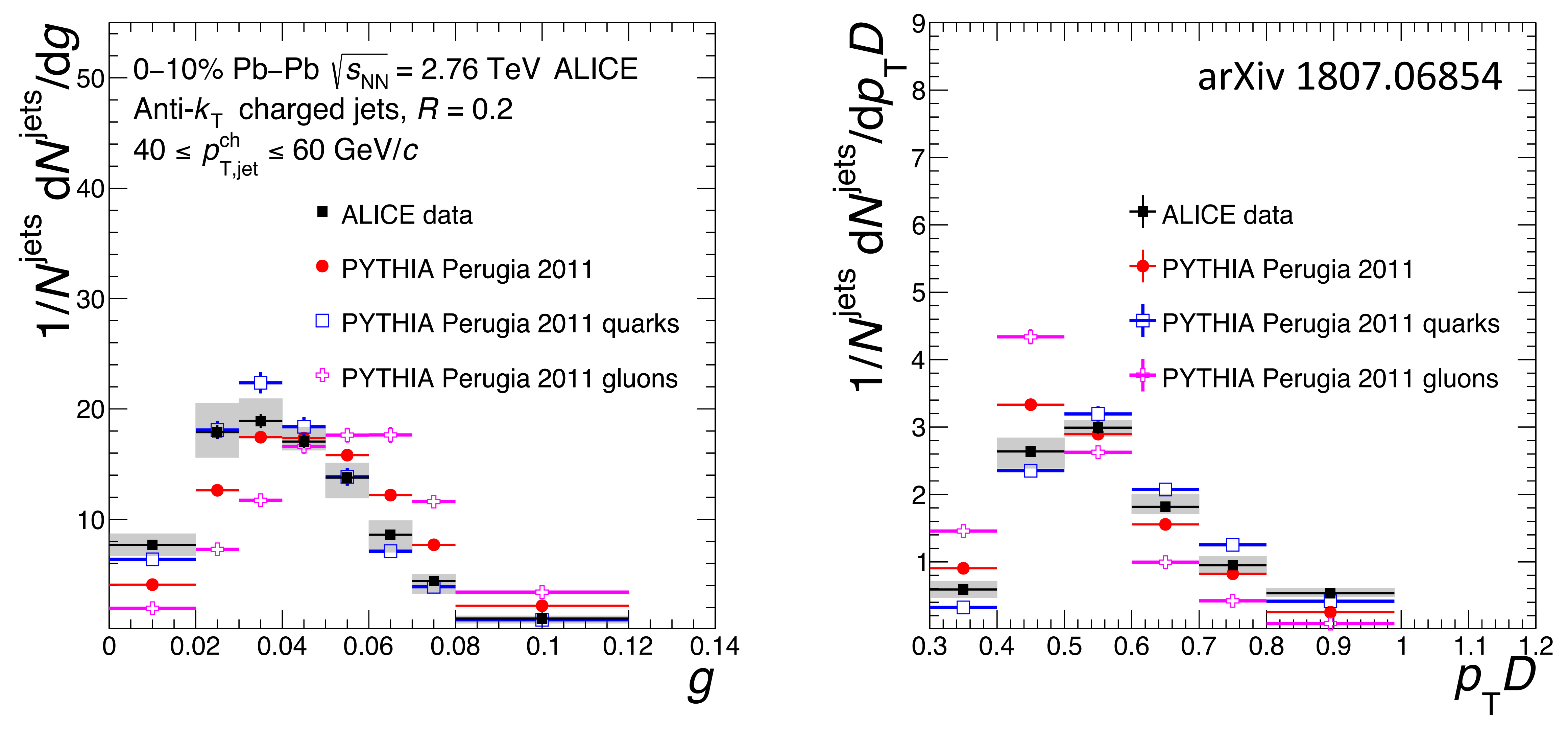


Figure 2: Jet quark fraction as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$ in the different jet rapidity intervals used in this study. The points show results obtained from PYTHIA8 simulations, the solid lines represent results obtained from extended power-law fits with the parameters shown in Table 1.

How is the jet core modified?

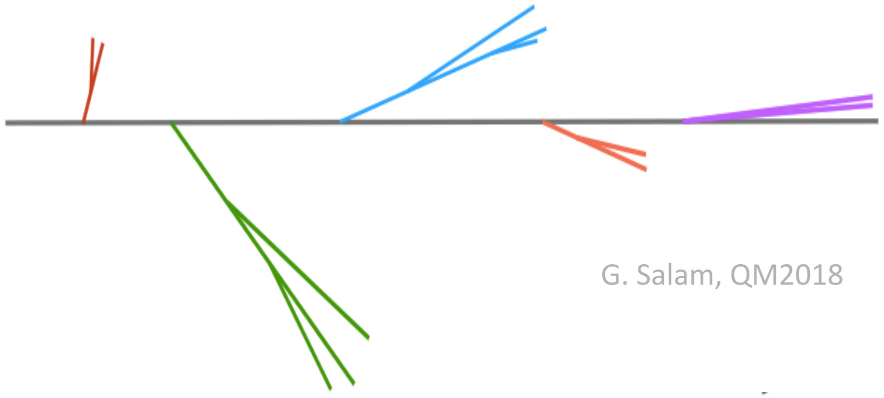
The Pb-Pb results agree fairly well with Pythia quark jets


arXiv 1807.06854

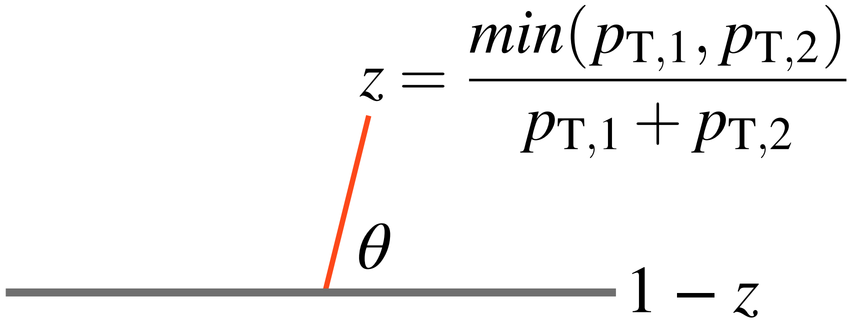
Groomed jet substructure

- Measurement procedure
  1. Cluster jets with the anti-k_T algorithm, then re-cluster each jet using the C/A algorithm
     - This produces an angularly ordered tree, similar to a parton shower
  2. Unwind the last clustering step and check the Soft Drop condition: $z > z_{\text{cut}}\left(\frac{\Delta R}{R_0}\right)^{\beta}$
  3. Discard the softer sub-jet and repeat

- The resulting hard splittings are described by:
  - n_{SD} is the number of splittings that pass the Soft Drop condition
  - z_{g}, R_{g} describe the momentum fraction and angular separation of the **first** splitting



G. Salam, QM2018

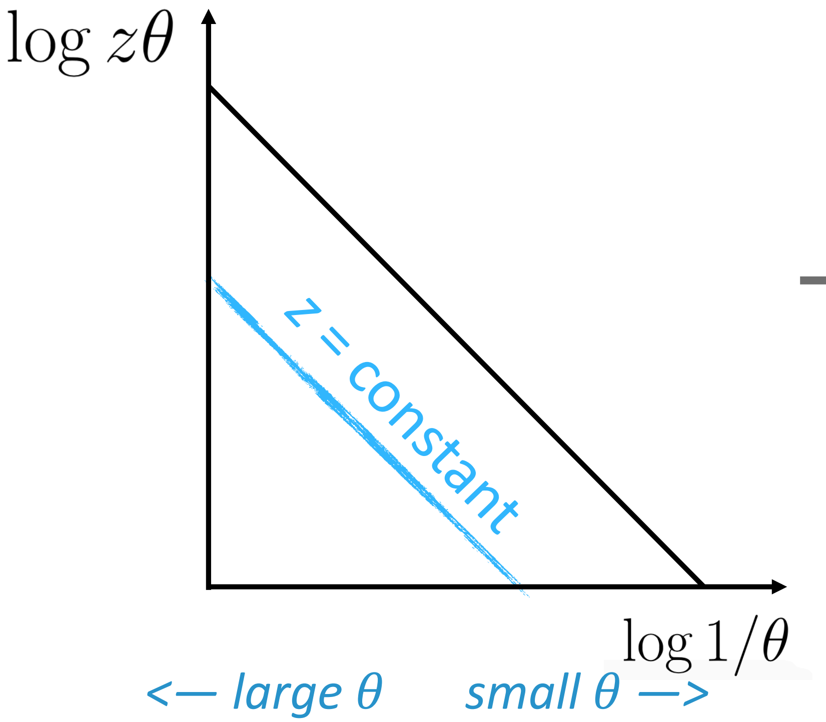


$$z = \frac{min(p_{\text{T},1}, p_{\text{T},2})}{p_{\text{T},1} + p_{\text{T},2}}$$

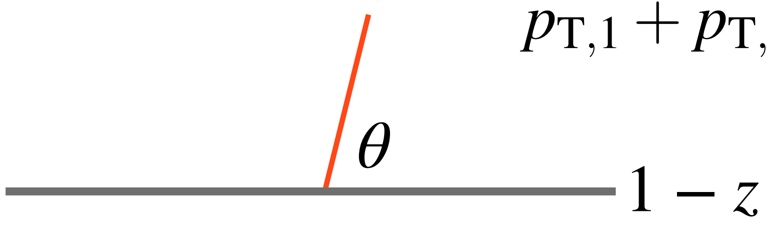
We use
$(z_{\text{cut}}, \beta) = (0.1, 0)$

Groomed jet substructure

- Lund diagram:
  - Represents the phase-space density of 1 —>2 splittings, described by (z,θ)



$$z = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

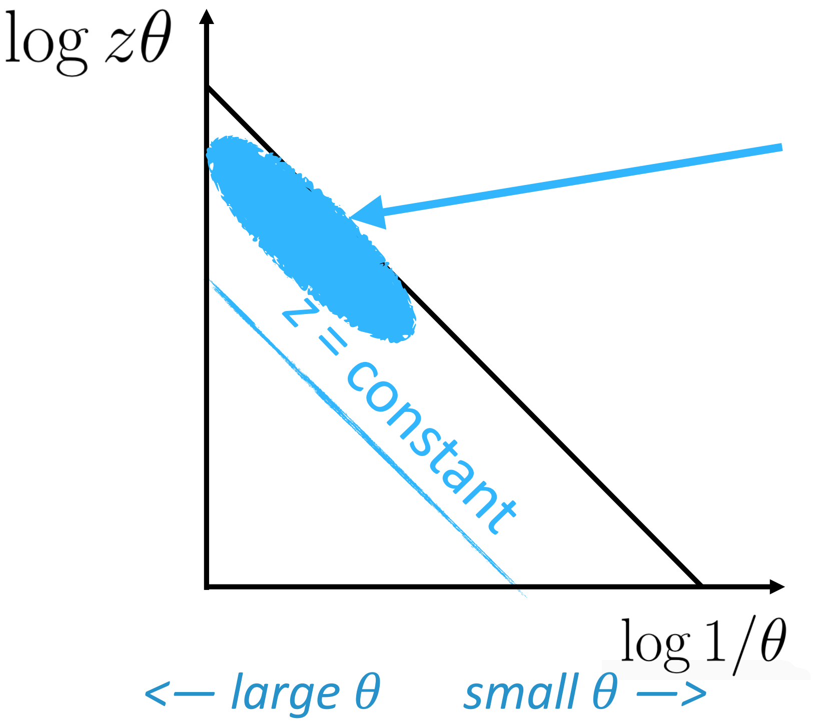


- By varying the Soft Drop parameters z_{cut}, β one can vary the phase space populated in the Lund diagram

$$z > z_{\mathrm{cut}} \left(\frac{\Delta R}{R_0}\right)^{\beta}$$

Groomed jet substructure

- Lund diagram:
  - Represents the phase-space density of 1 —>2 splittings, described by (z,θ)



Large θ hard splittings are predicted to be resolved by the medium and suppressed

- By varying the Soft Drop parameters z_{cut}, β one can vary the phase space populated in the Lund diagram

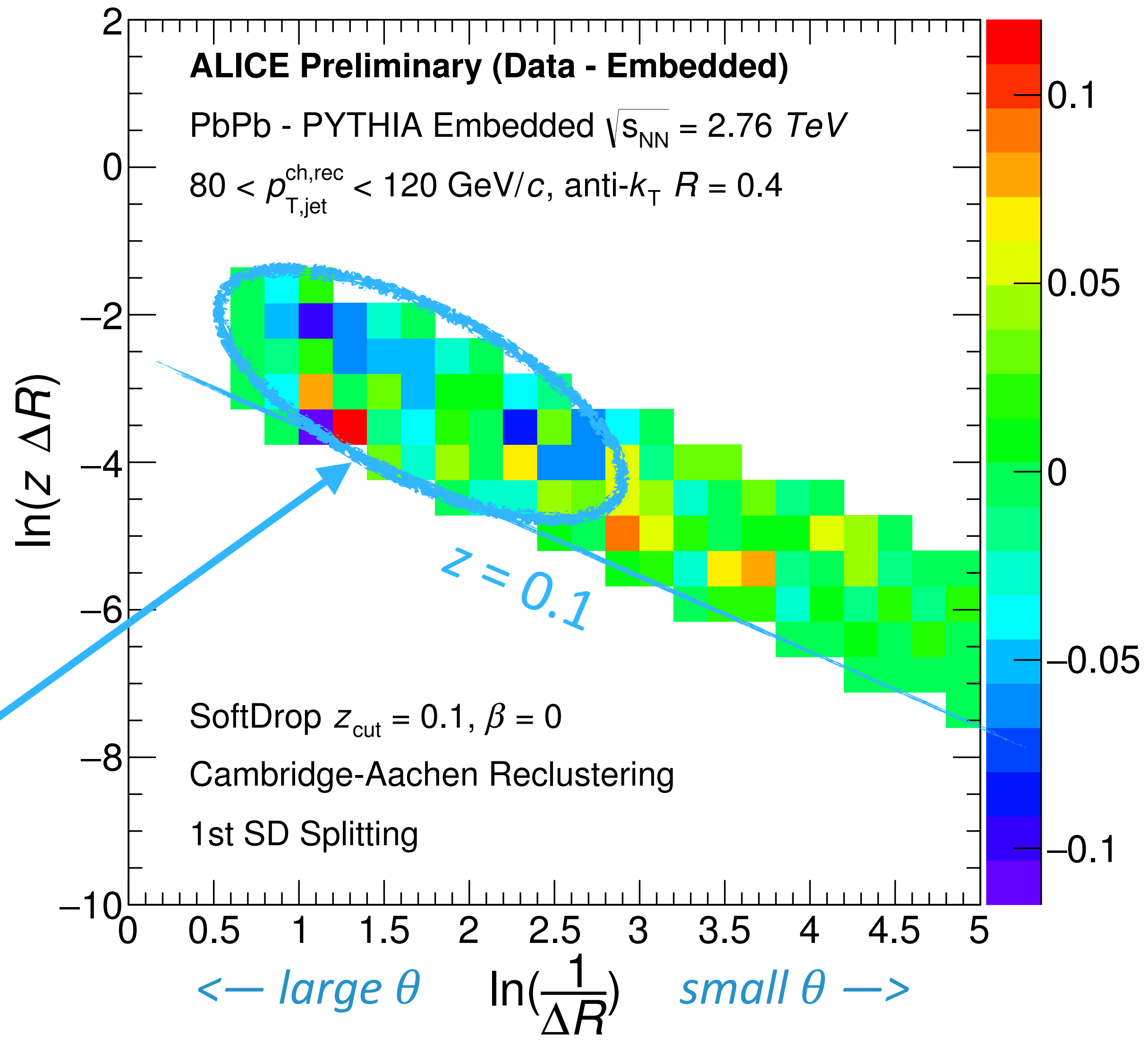
$$z > z_{\text{cut}} \left(\frac{\Delta R}{R_0}\right)^{\beta}$$

Groomed jet substructure – Pb-Pb

- Pb-Pb measurement at $\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}$
  - $R = 0.4$, $p_{\mathrm{T}} = 80\text{-}120\ \mathrm{GeV}/c$, $|\eta| < 0.5$
  - Detector-level measurement, compared to Pythia embedded

Note: Soft Drop grooming removes below the constant diagonal line $z = 0.1$

- There is a depletion of the large-angle splittings in Pb-Pb!



ALI-PREL-148246

Groomed jet substructure – Pb-Pb

- The z_g distribution shows suppression at high z_g
    - That is, the hardest splittings are suppressed in Pb-Pb
- No enhancement at small z_g

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

In order to interpret the results as absolute suppression/ enhancement, **must normalize by the number of inclusive jets**, including those that do not pass the Soft Drop condition