Exploring the quark-gluon plasma with jet measurements at ALICE

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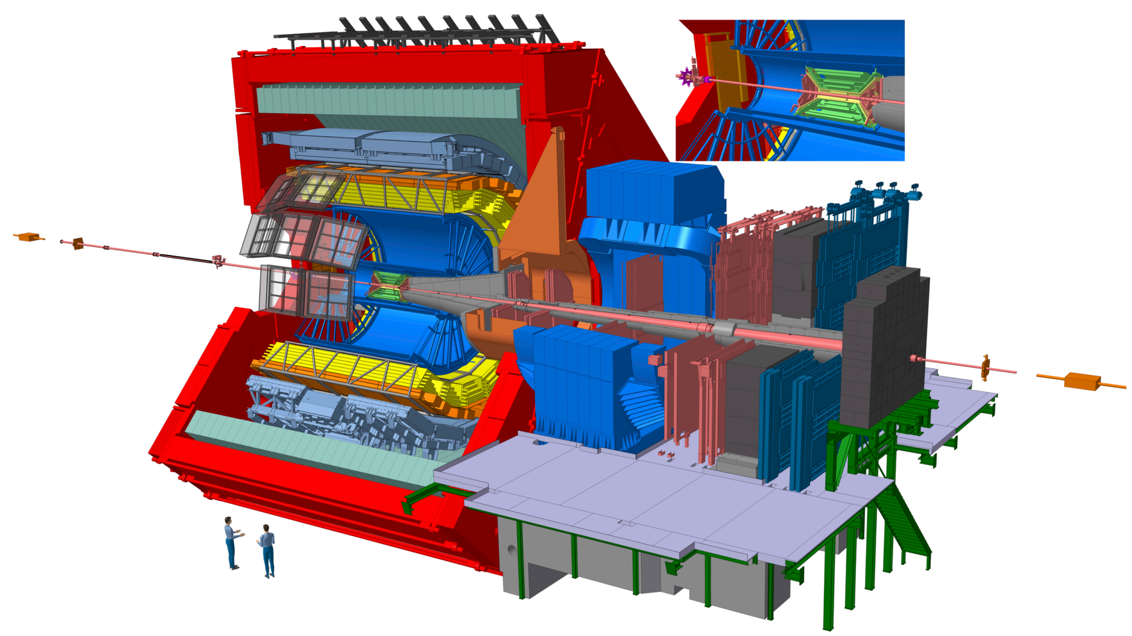
UCSB
Sep 5, 2018



Wright Laboratory
Yale
ALICE

QCD

We know some basic features of QCD

- *The Lagrangian*
- *The running of the coupling (confinement, asymptotic freedom)*
- *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 pp, 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

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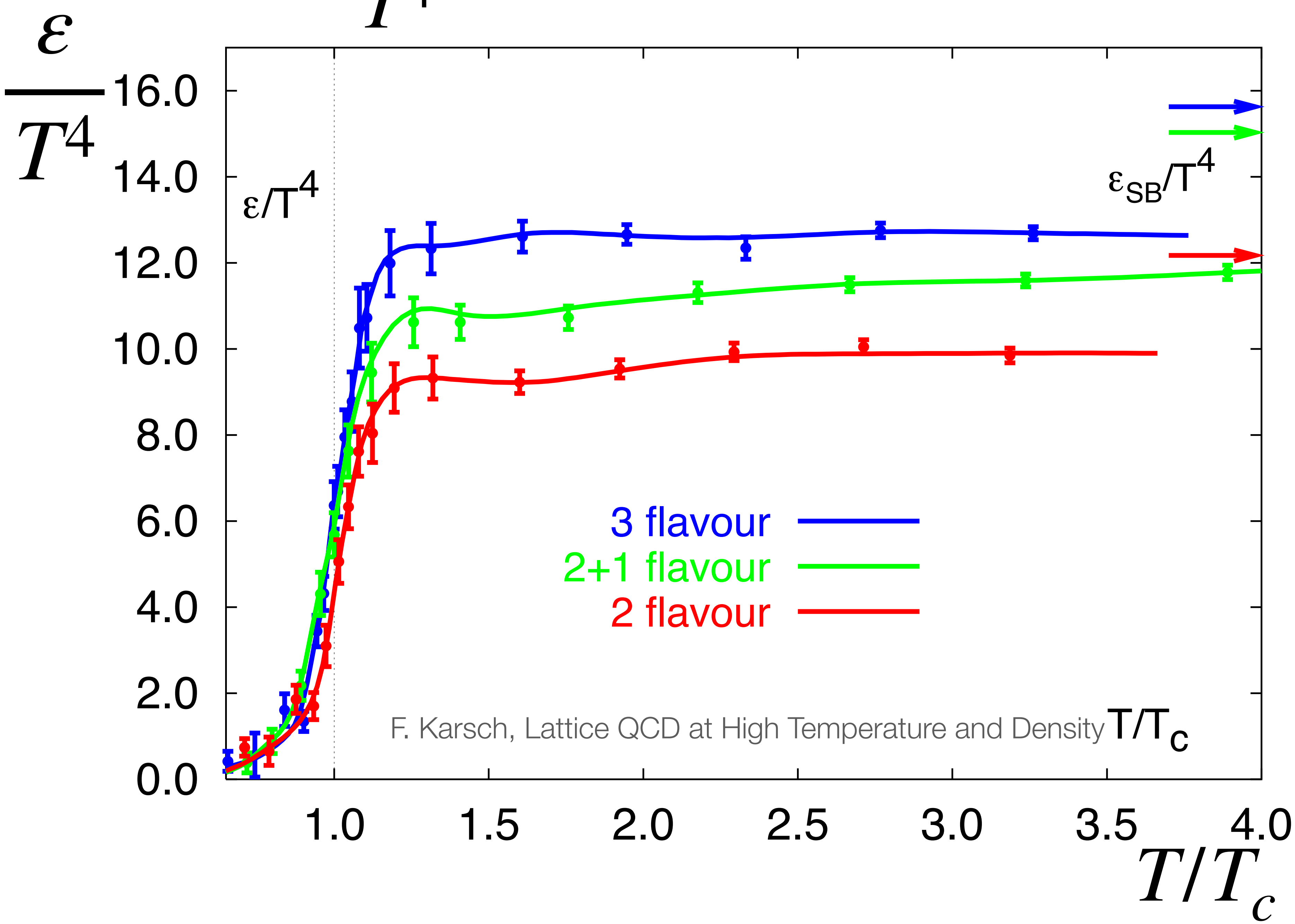
$$\frac{\varepsilon}{T^4} \propto \text{degrees of freedom}$$



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

"The quark-gluon plasma"

High-Temperature QCD

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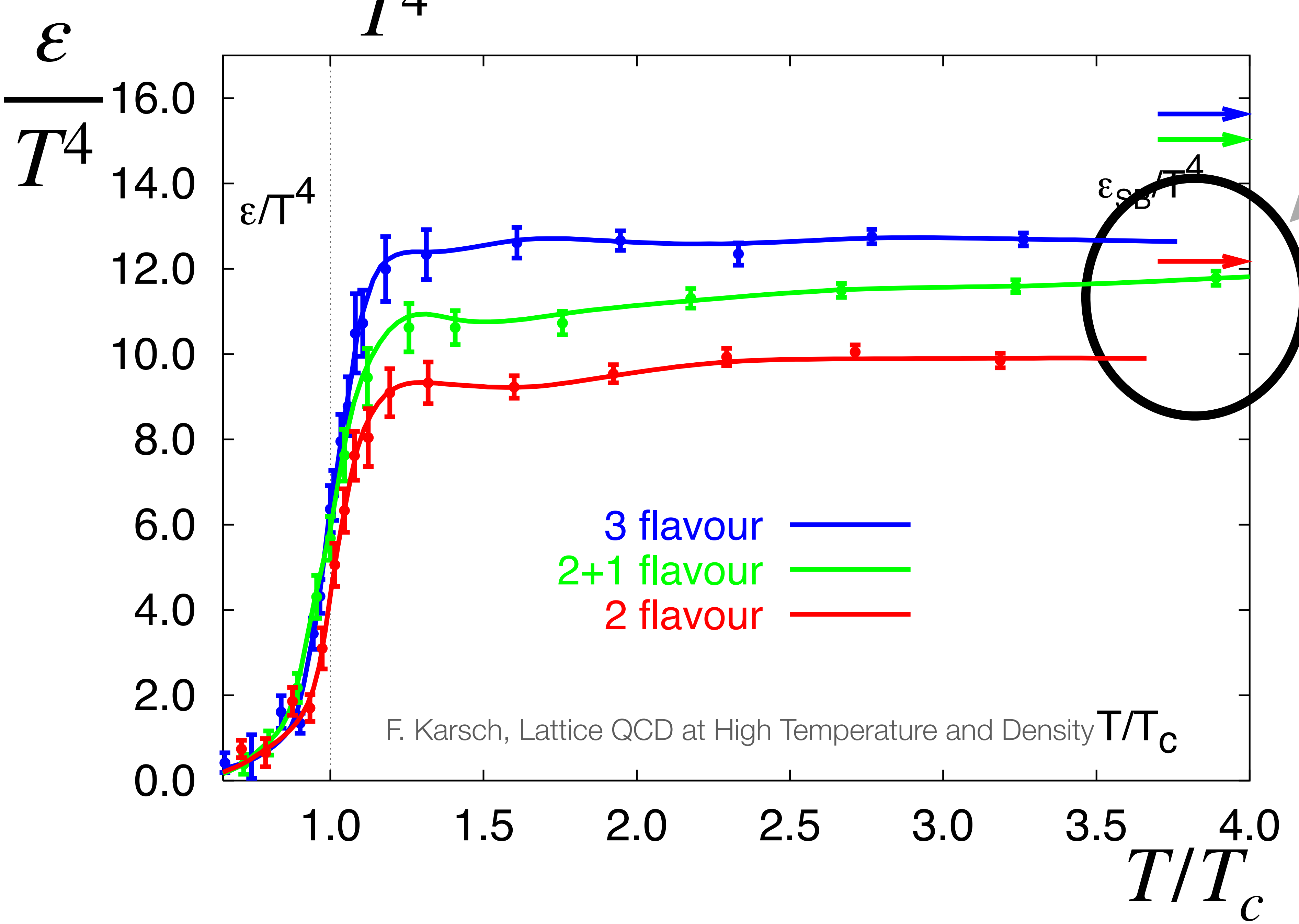
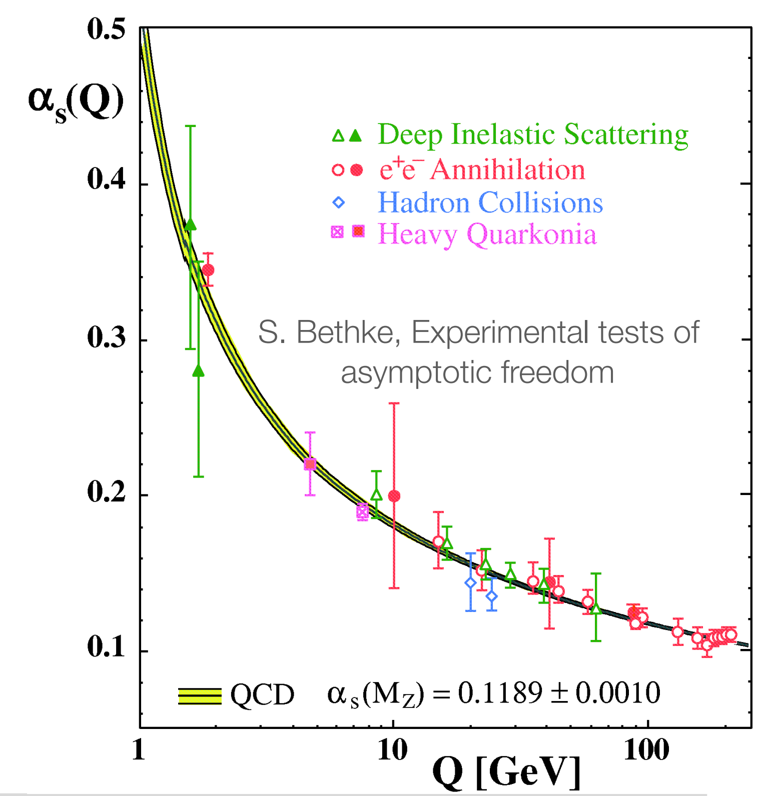


For very large T, we expect this deconfined matter to be **asymptotically free**



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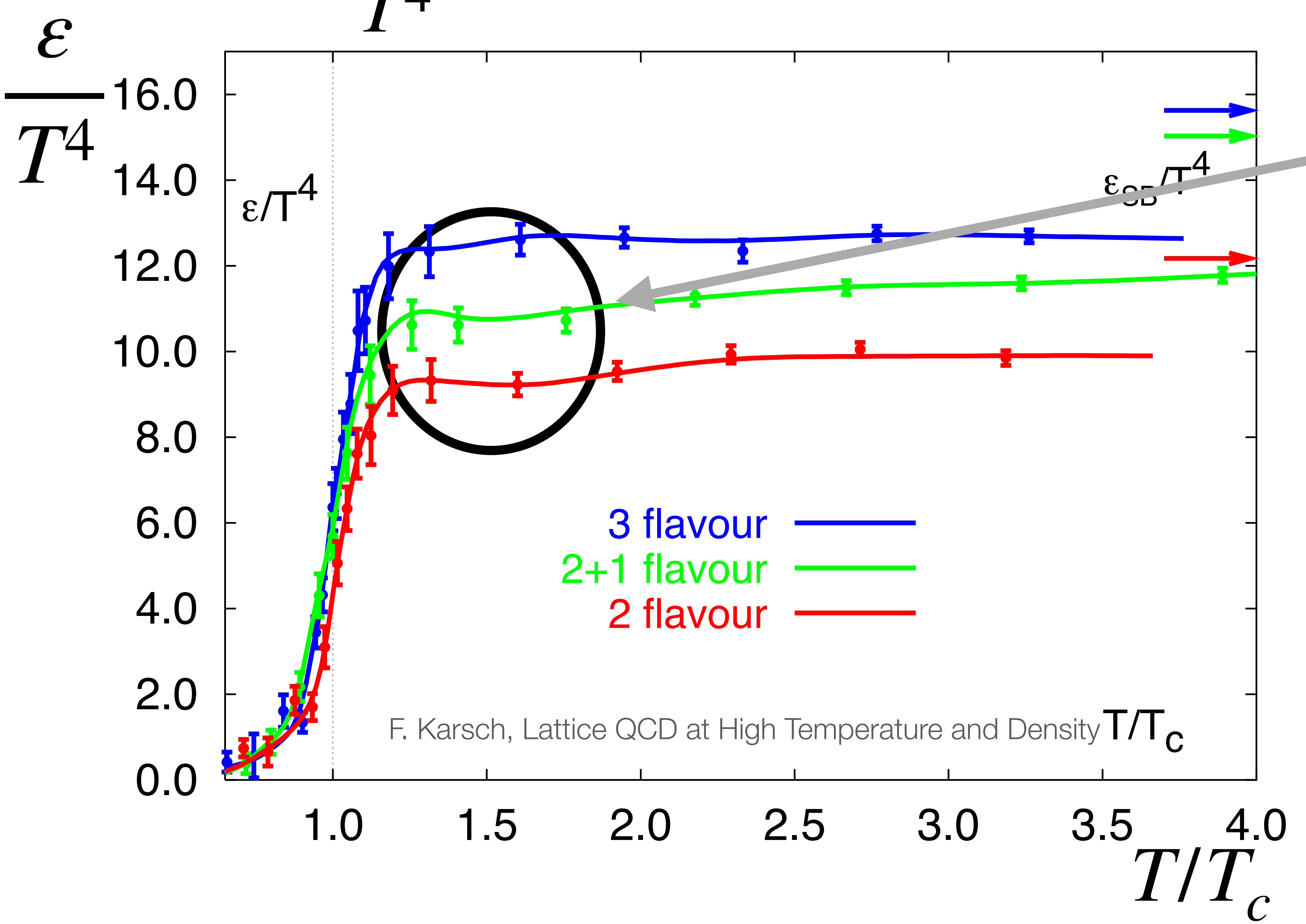
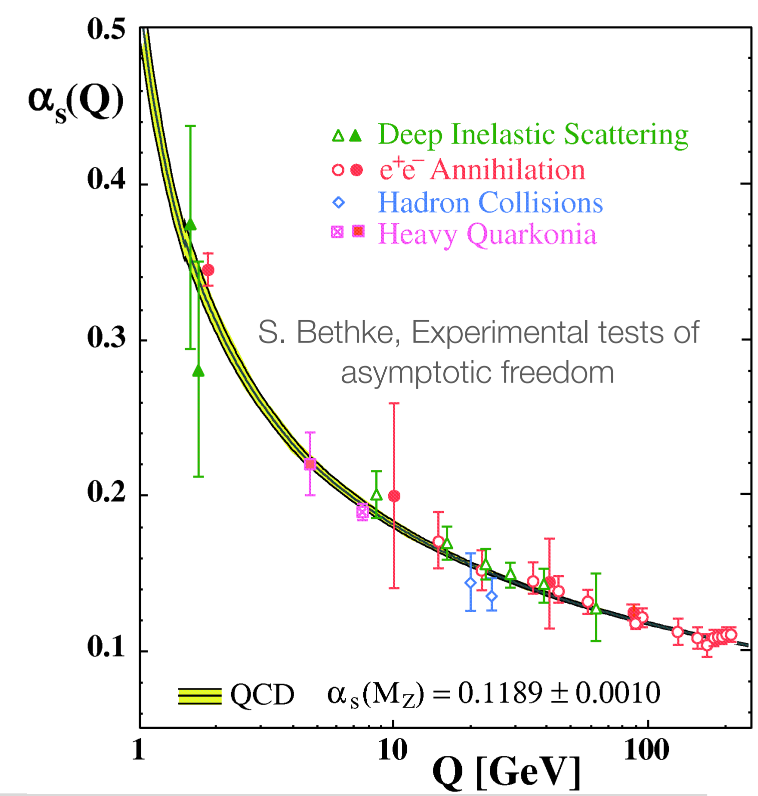


What is the coupling here?



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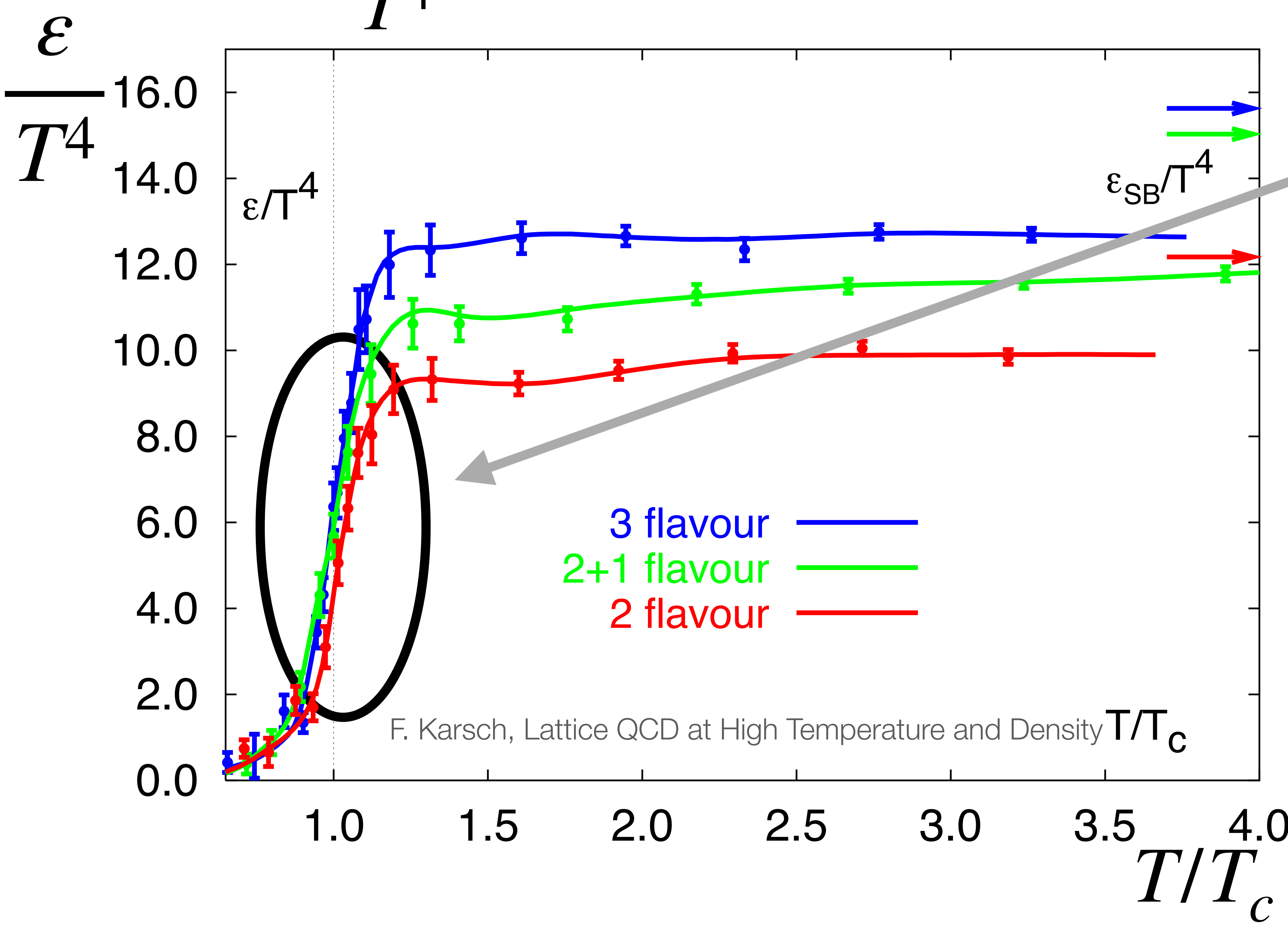
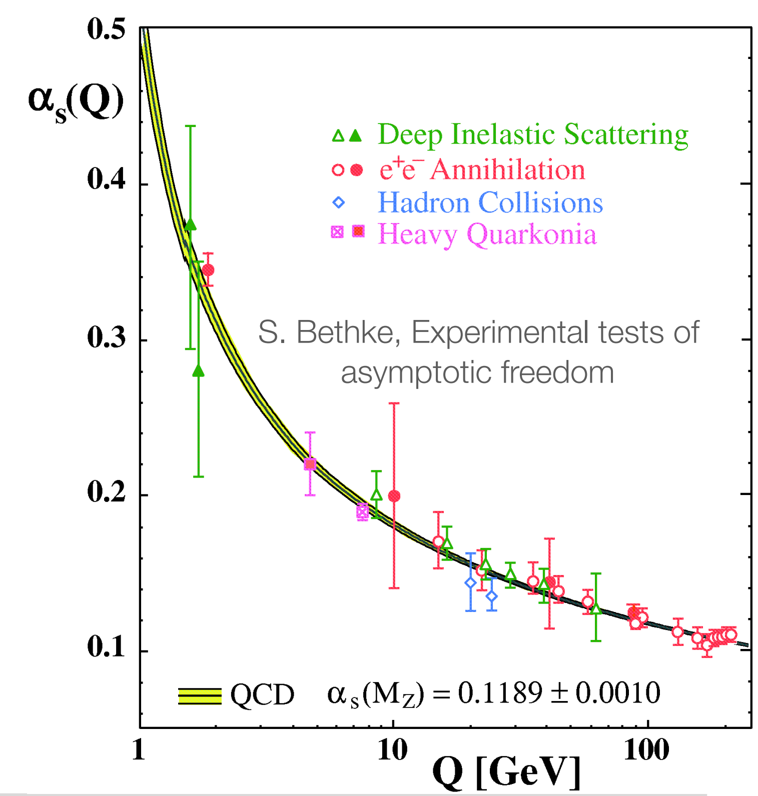
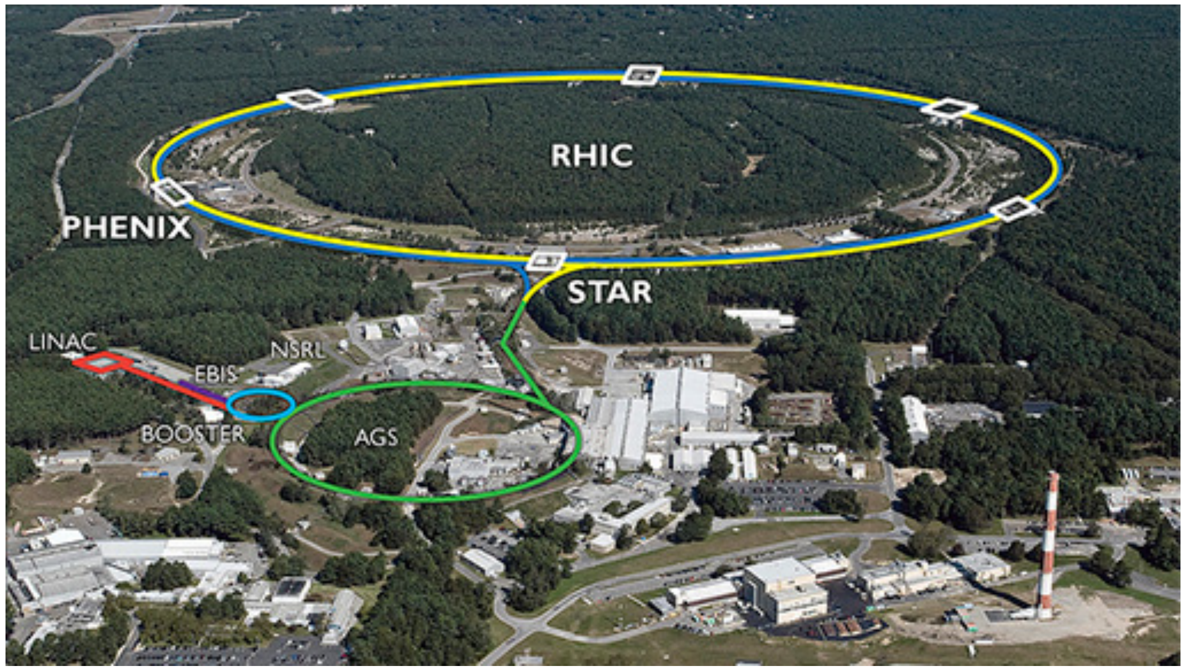


What is the structure of QCD matter here?



Ultra-relativistic heavy-ion collisions



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

Relativistic Heavy-Ion Collider

Brookhaven National Lab

STAR PHENIX

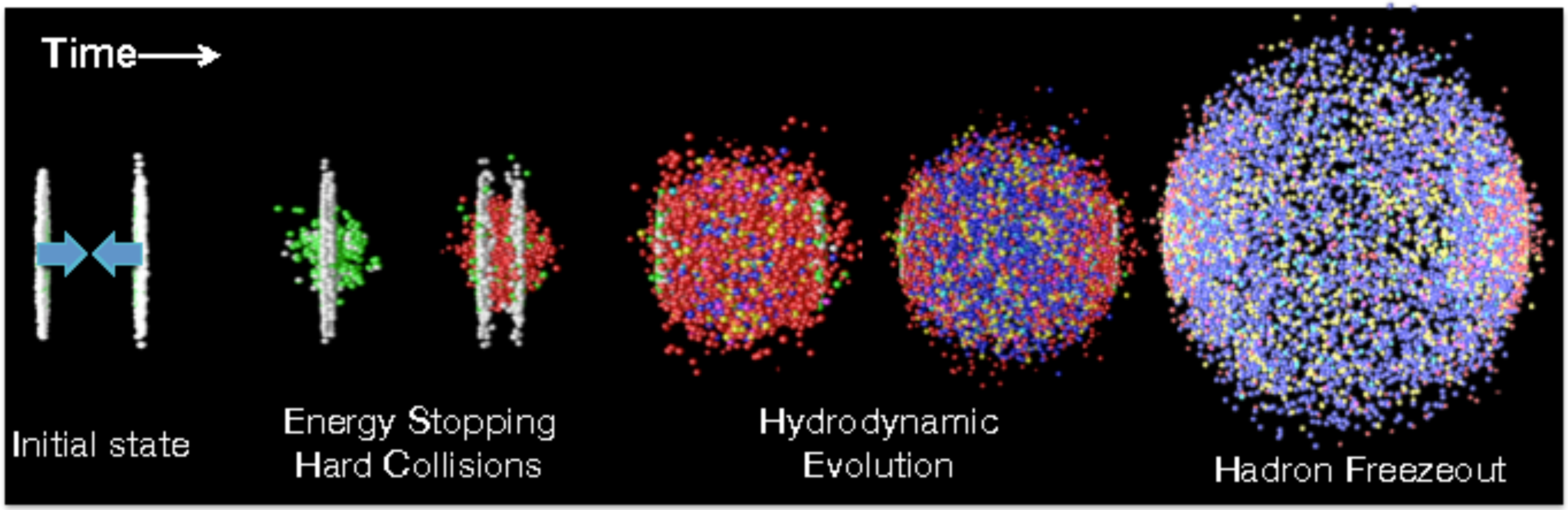
$$\sqrt{s_{\mathrm{NN}}} = 2.76,\ 5.02\ \mathrm{TeV}$$

Large Hadron Collider

CERN

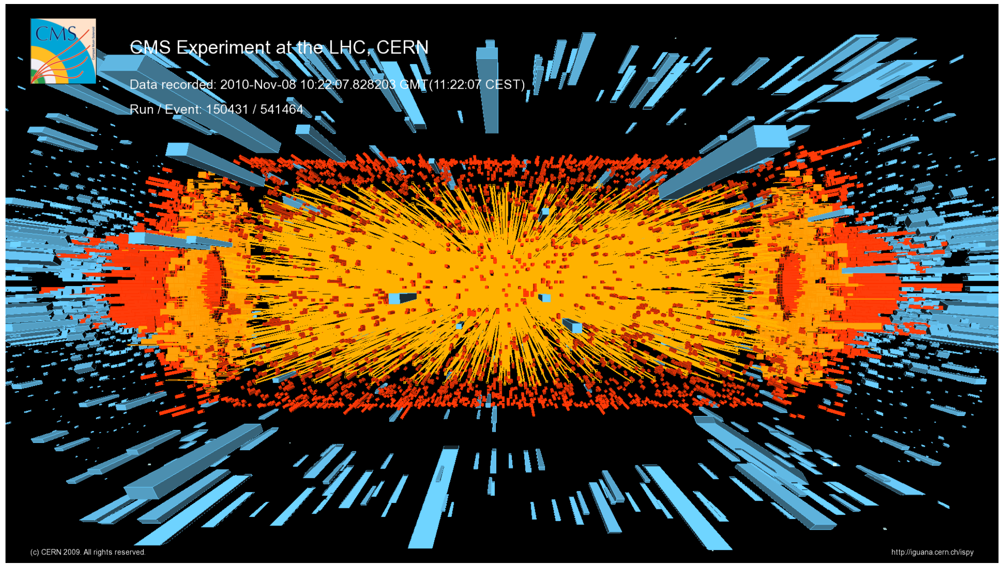
ALICE CMS ATLAS EXPERIMENT

Ultra-relativistic heavy-ion collisions



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

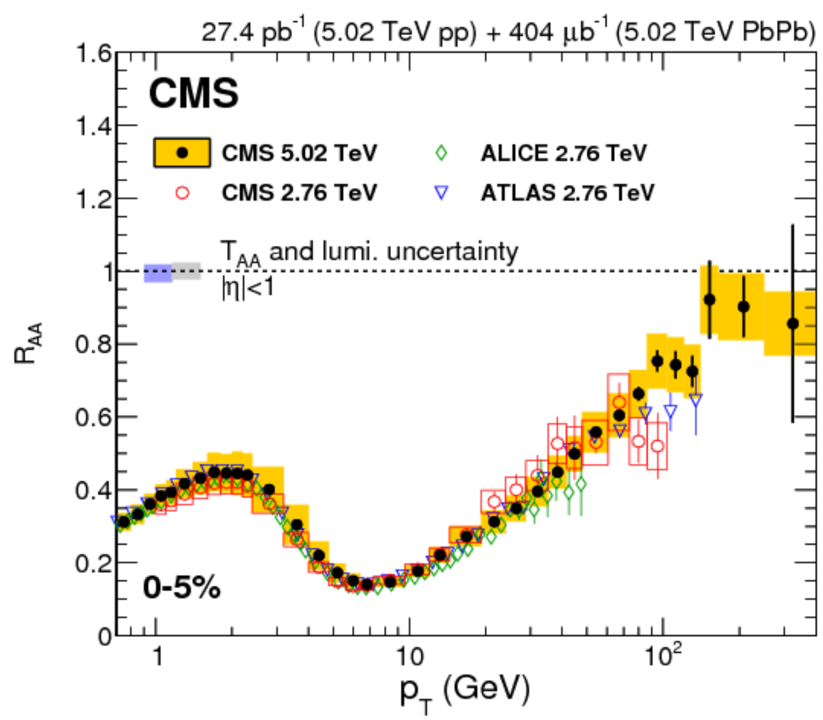
- The hottest matter created (T ~ 500 MeV)
- The most dense matter created (ε ~ 1-10 $\varepsilon_{\mathrm{hadron}}$)



Signatures of the quark-gluon plasma

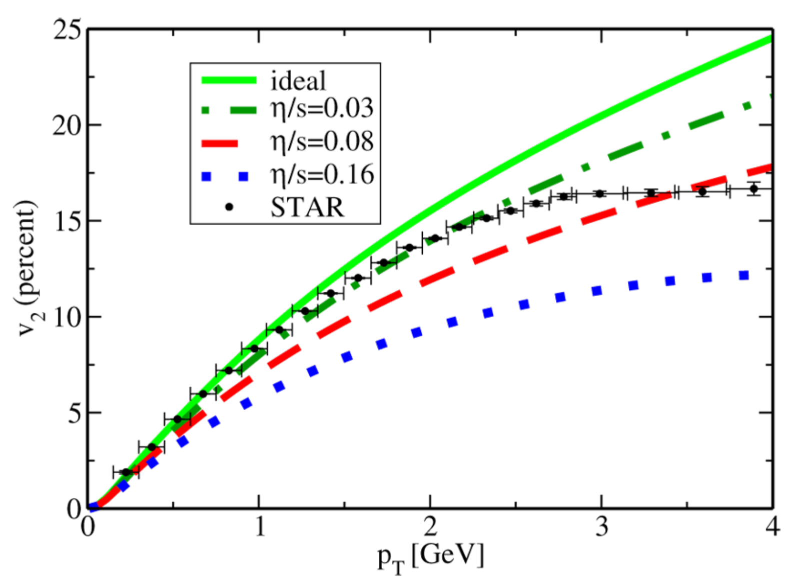
A variety of experimental signatures confirm that deconfined QCD matter is created in heavy-ion collisions

Suppression of high-p_T hadrons



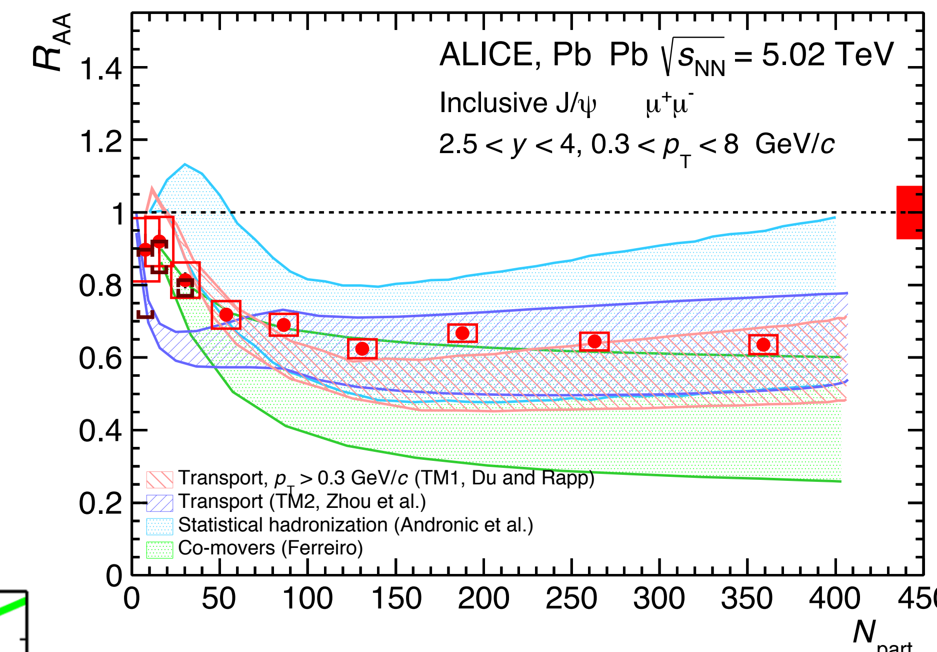
JHEP 1704 (2017) 039

Elliptic flow



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

J/ψ suppression



PLB 766 (2017) 212-224

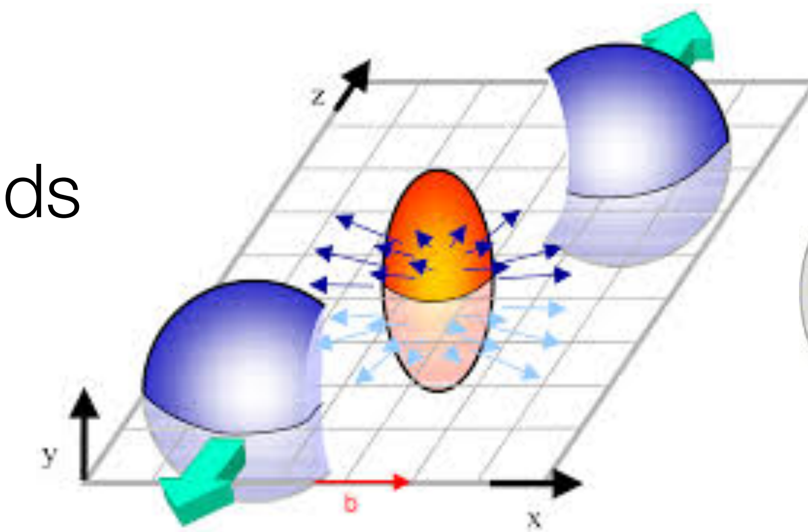
And more…

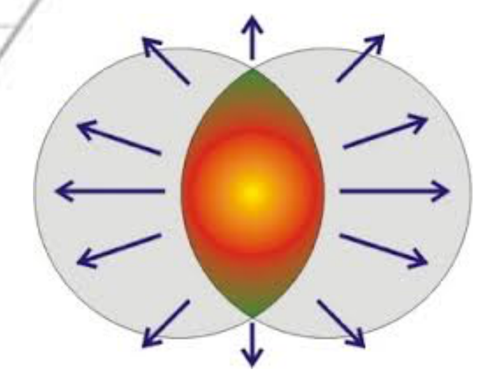
The strongly-coupled quark-gluon plasma

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

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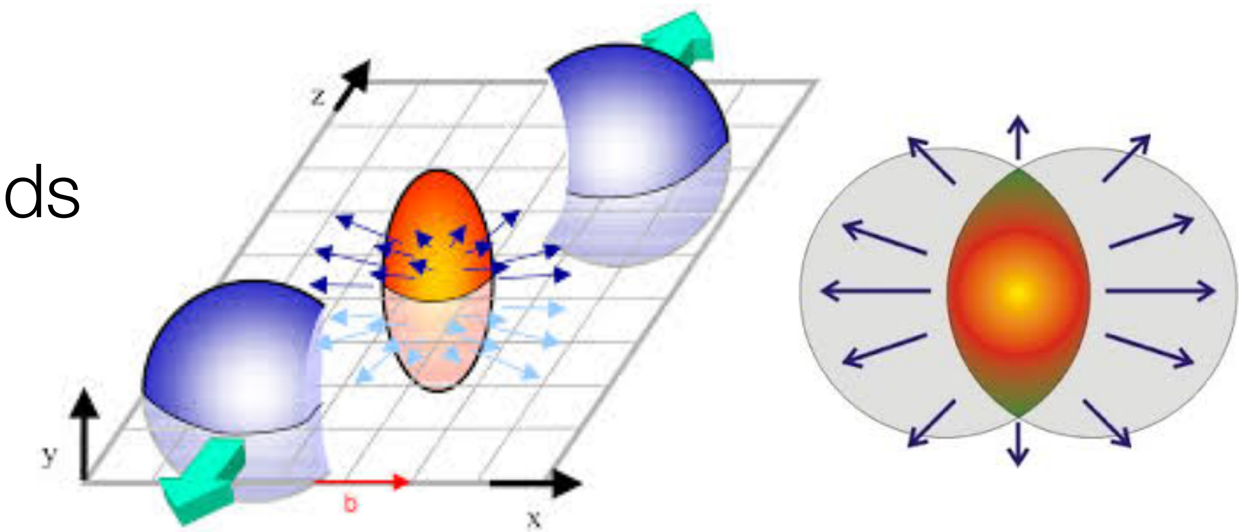
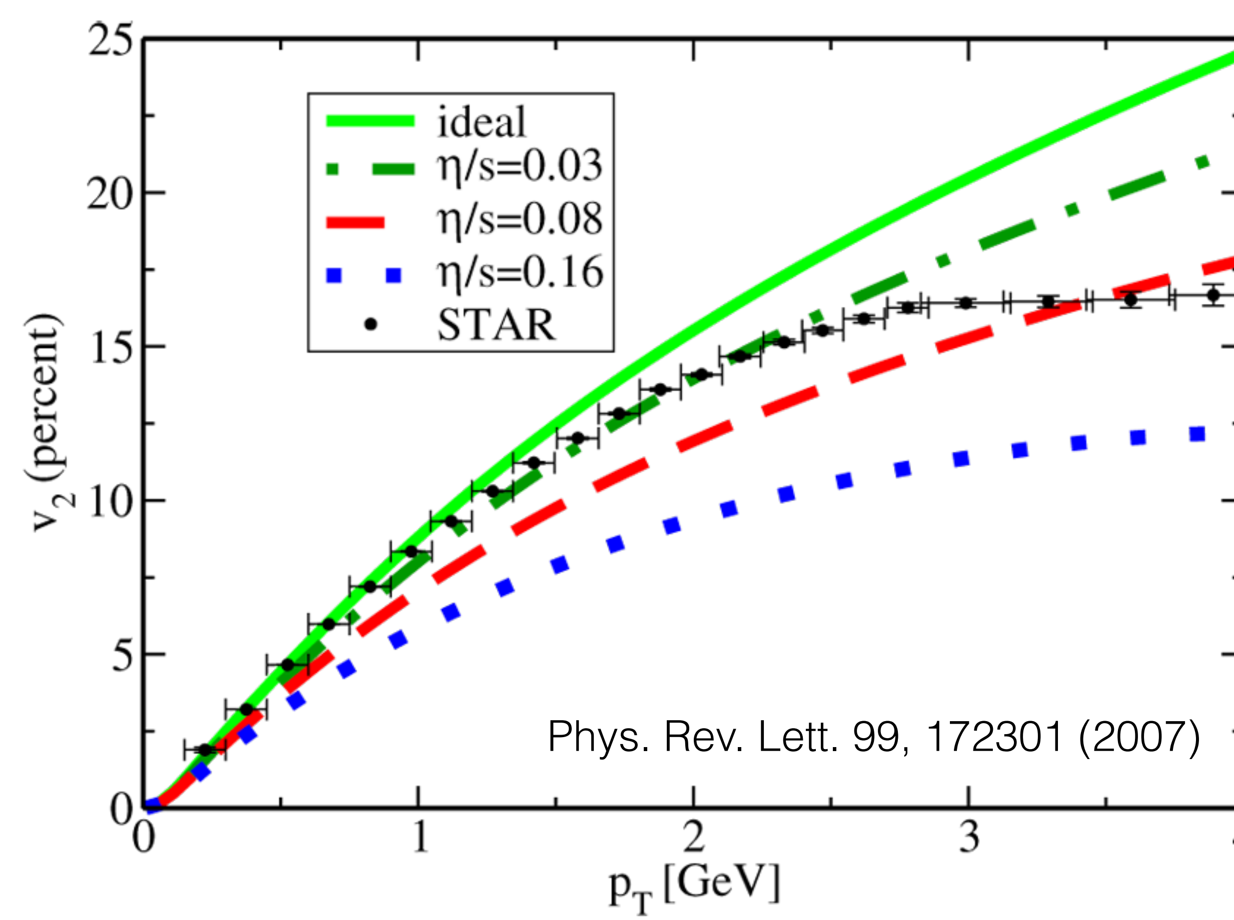


The strength of the back-to-back correlation, $\boldsymbol{v_2}$, is damped by the shear-viscosity to entropy-density ratio, $\boldsymbol{\eta/s}$



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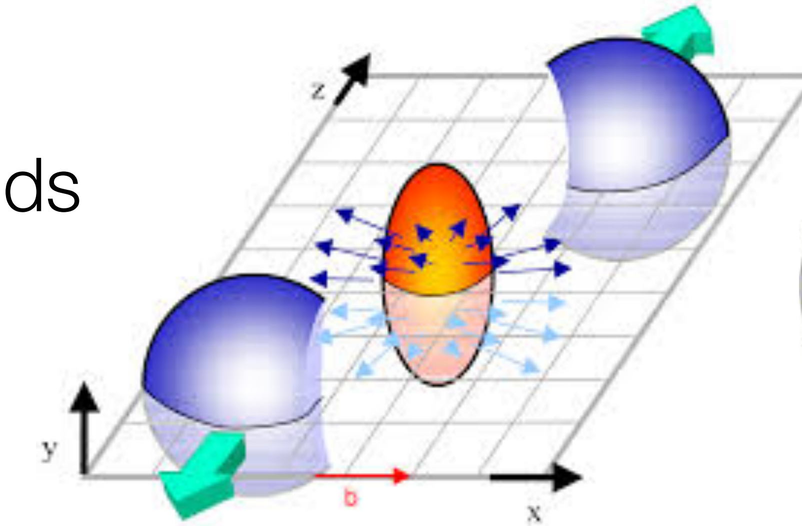
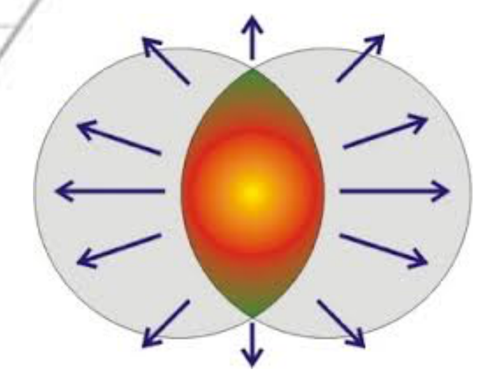




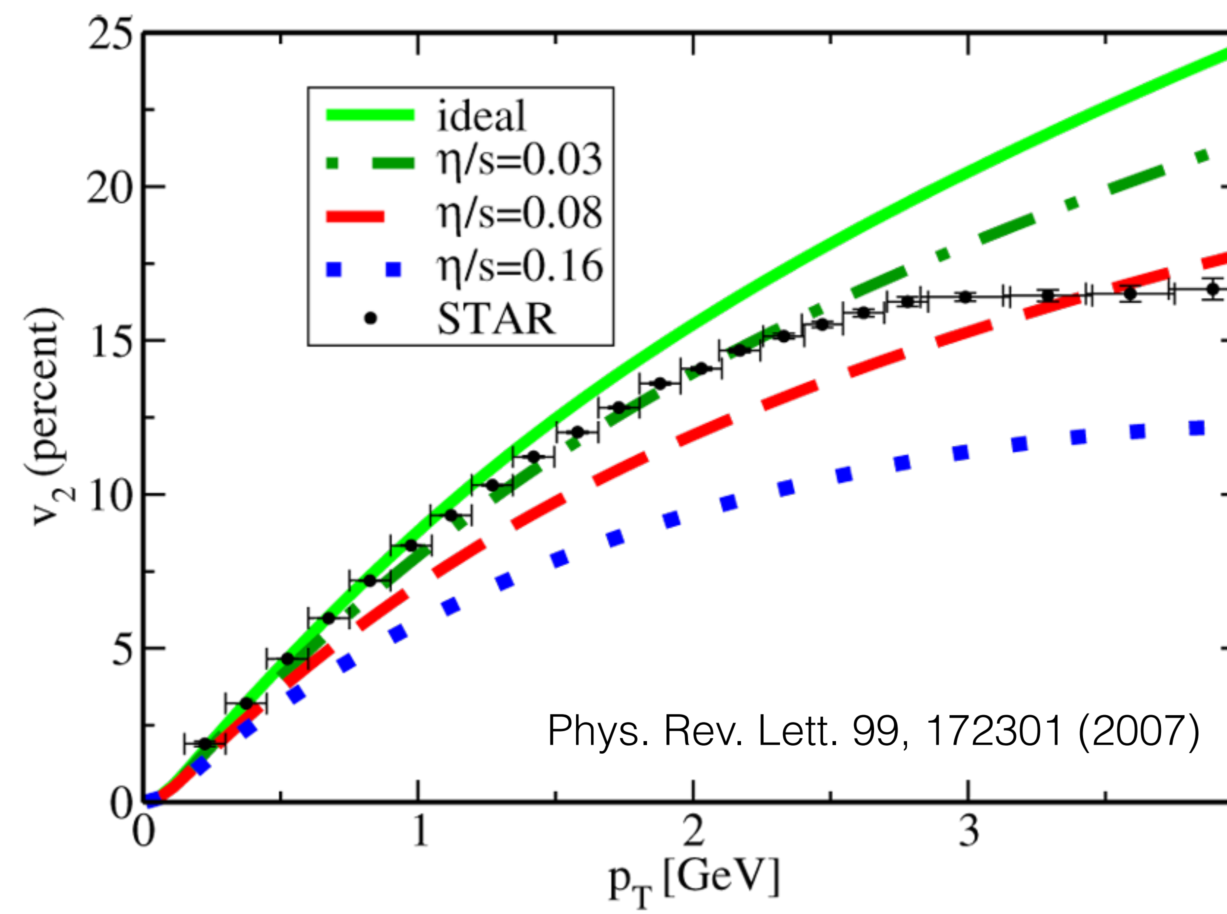
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi$$

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



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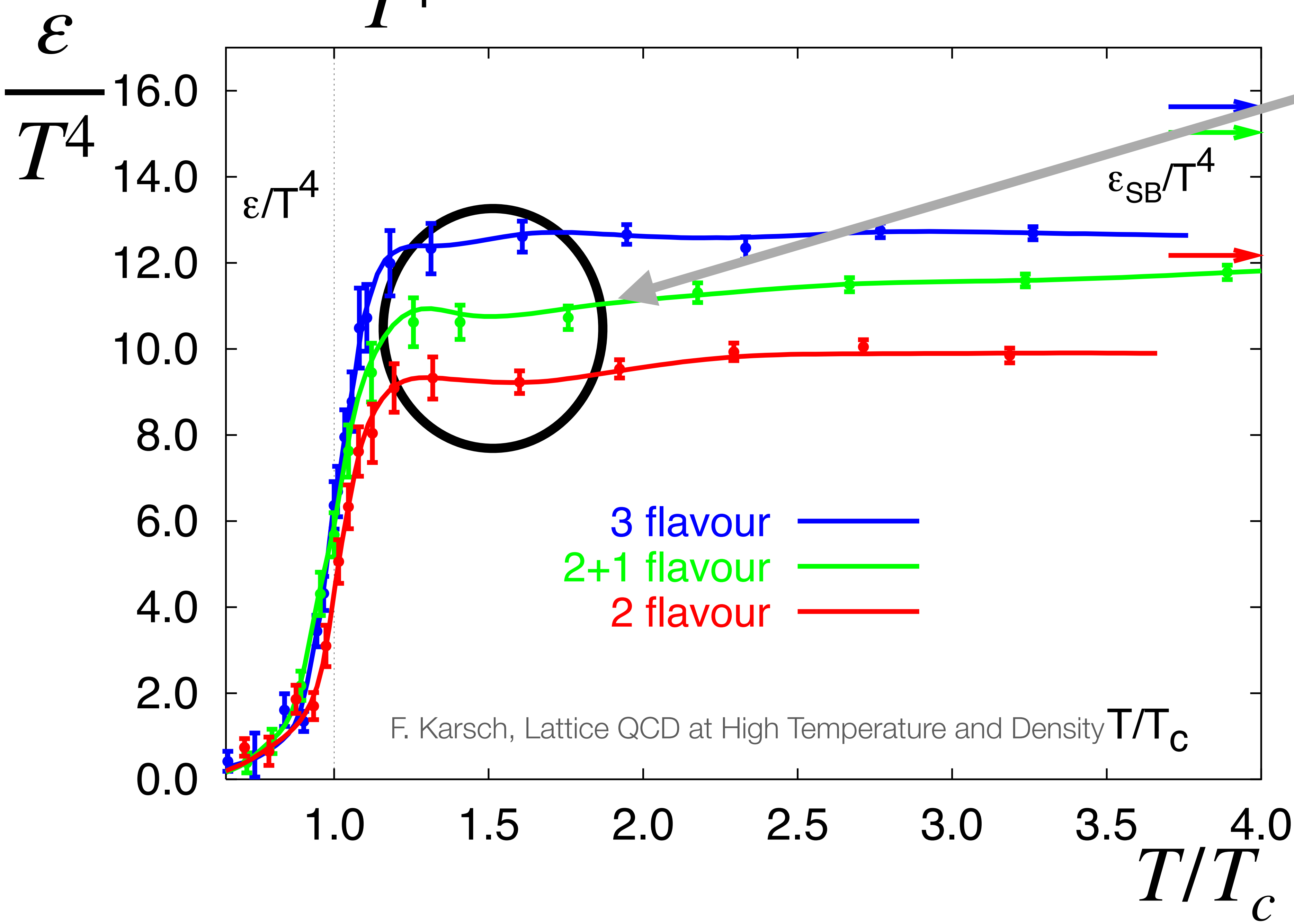

The coupling is still quite strong here!

Small η/s means that the coupling is strong

High-Temperature QCD

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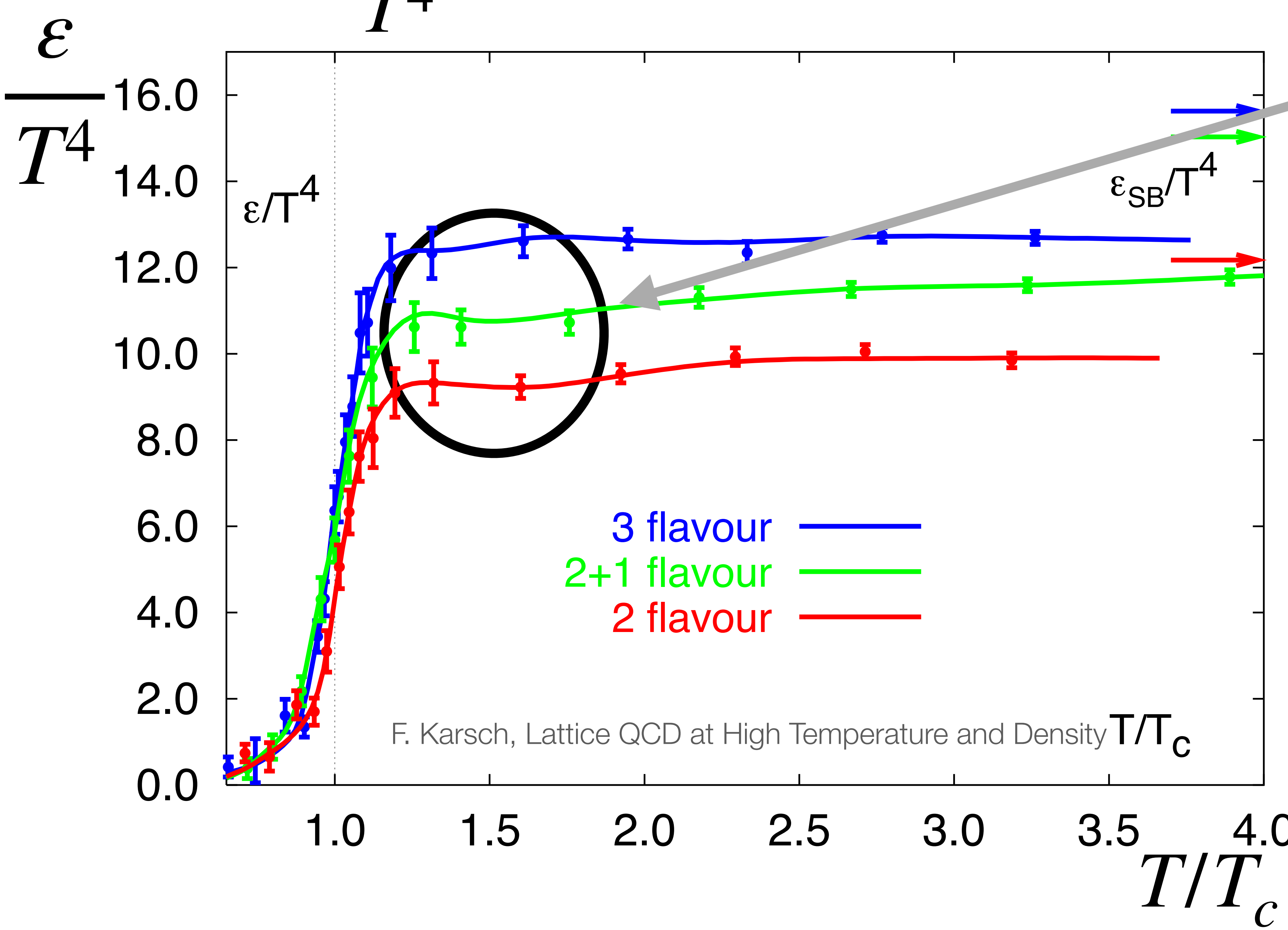


The coupling is still quite strong here!

How does this strongly-coupled fluid emerge?

Does deconfined QCD have quasi-particle structure?

How does confinement emerge?

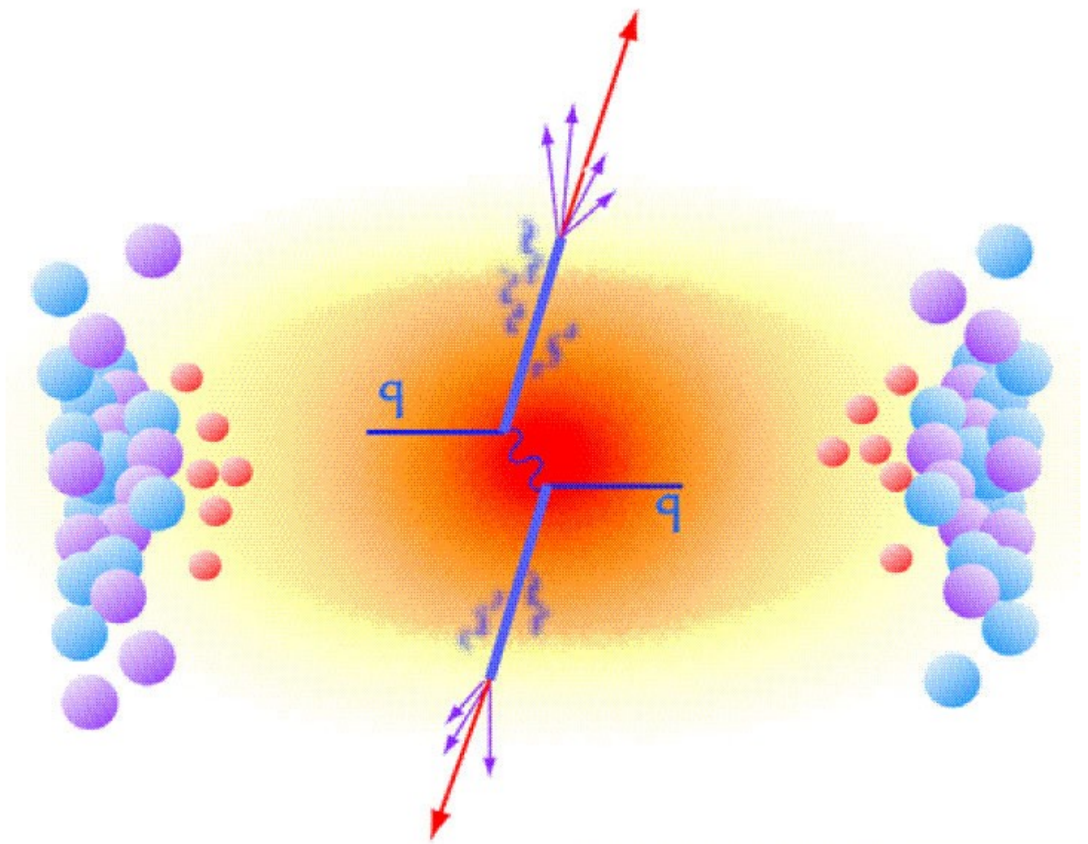
De-confined QCD matter

Use jet physics to answer these questions

- 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

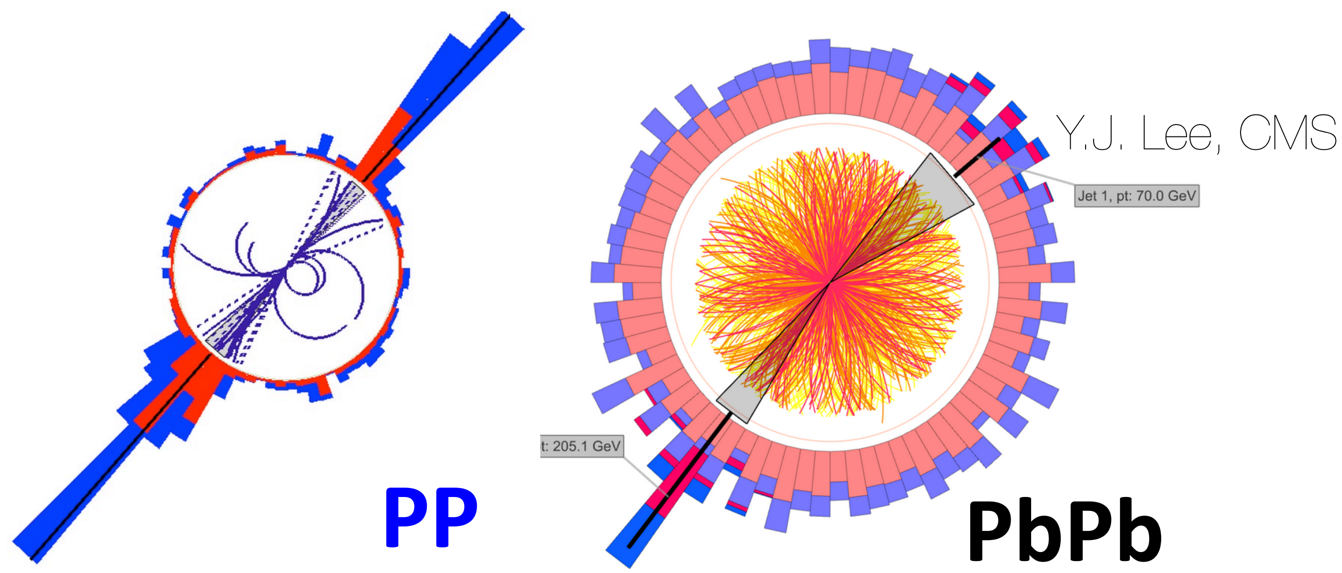
Jets are produced early in the heavy-ion collision, and propagate through the QGP

Jets allow a rich set of observables!



Jets in heavy-ion physics

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



In practice:

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

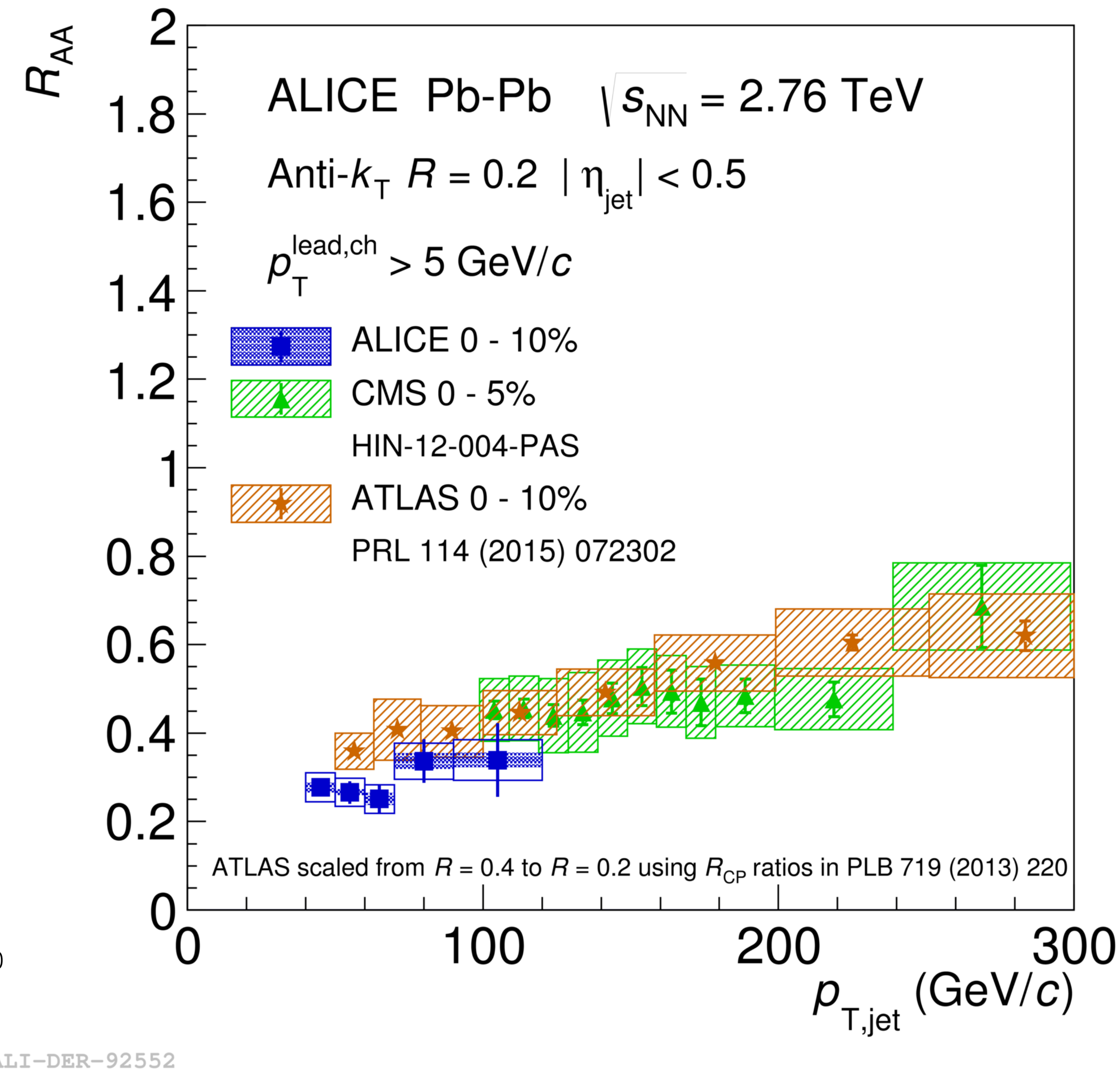
What have we learned about jet modification?

1. Jet yields are suppressed

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

Inclusive jet measurements show that jets in central Pb-Pb collisions lose on average ~10-20% of their energy, increasing roughly as $\sim\sqrt{p_T}$

Spousta & Cole, EPJ C (2016) 76:50



What have we learned about jet modification?

2. The fragmentation pattern of a jet impacts modification

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

B. Gluon jets lose more energy than quark jets

What have we learned about jet modification?

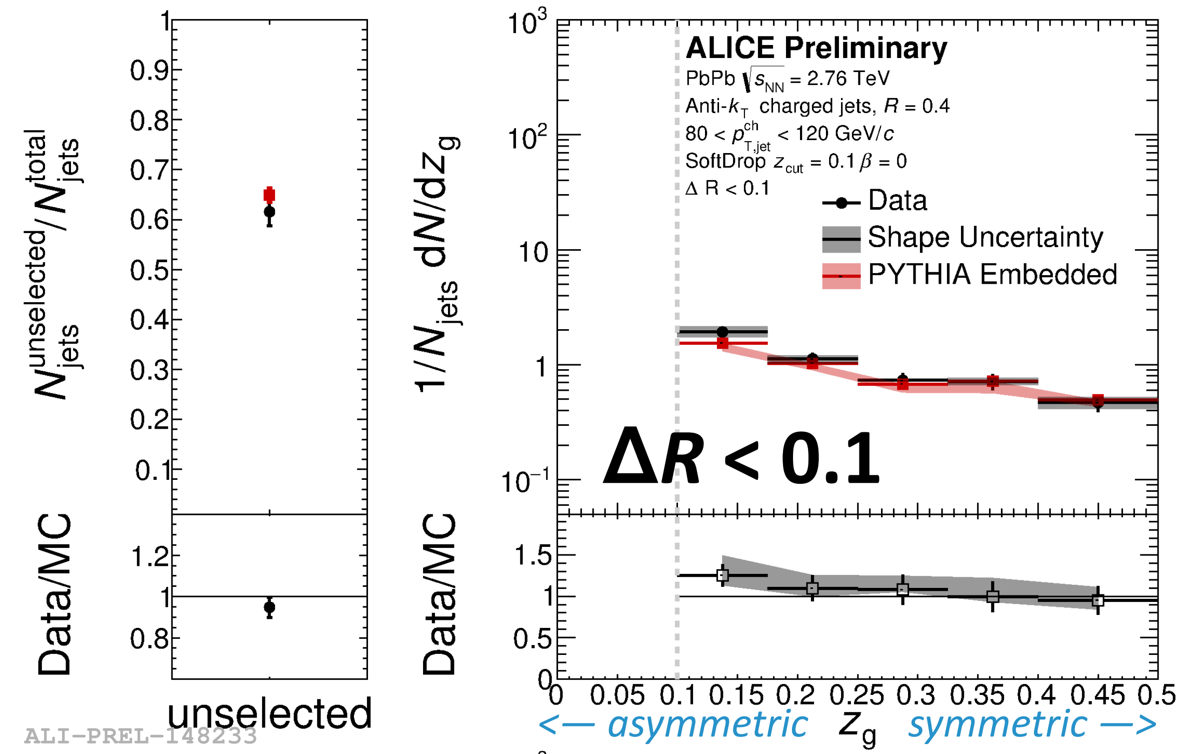
A. Jets with wide-angle hard splittings lose more energy than jets with collinear hard splittings

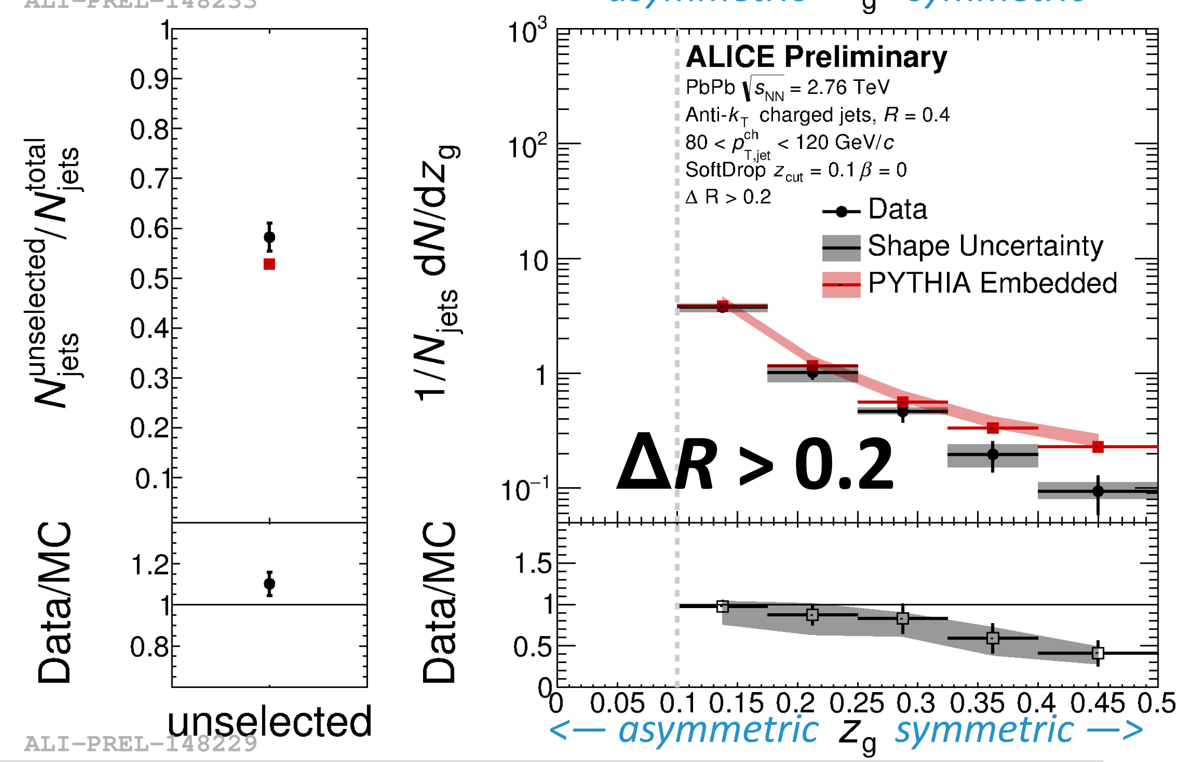
Find a jet, then groom and re-cluster the jet into two sub-jets

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

The sub-jets are then examined in two subsamples, depending on the ΔR between the two sub-jets

- **ΔR < 0.1**: small enhancement of collinear splittings at small z_g
- **ΔR > 0.2**: depletion of wide-angle, symmetric splittings at large z_g





What have we learned about jet modification?

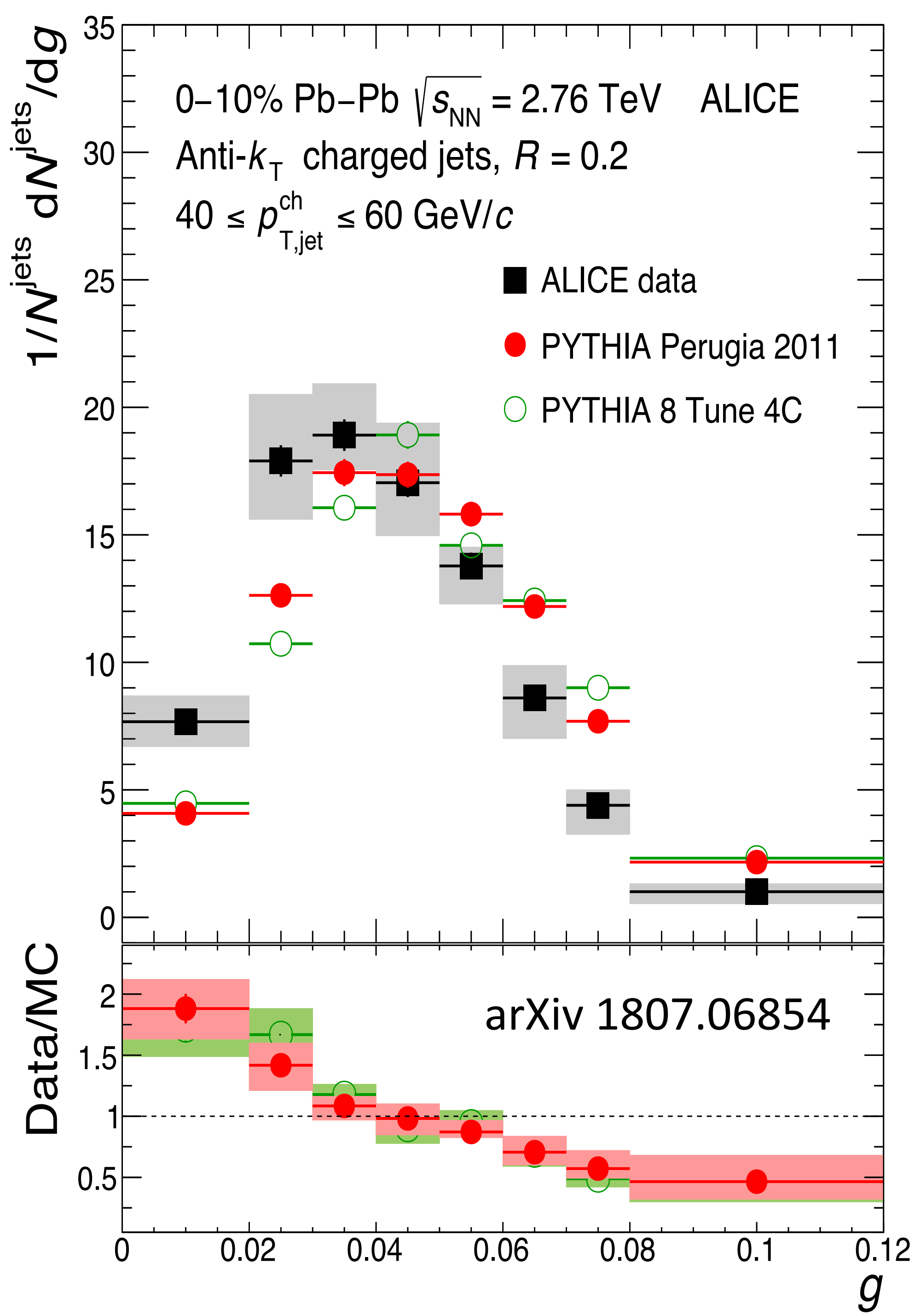
B. Gluon jets lose more energy than quark jets

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

Measures a jet's radial momentum profile

In Pb-Pb, the radial moment for R=0.2 small-radius jets is shifted to lower values.
—> Jet cores are more collimated!

The modification of the radial moment, as well as several other observables, suggest that in Pb-Pb, the **jet core becomes more collimated and harder-fragmenting — more quark-like**

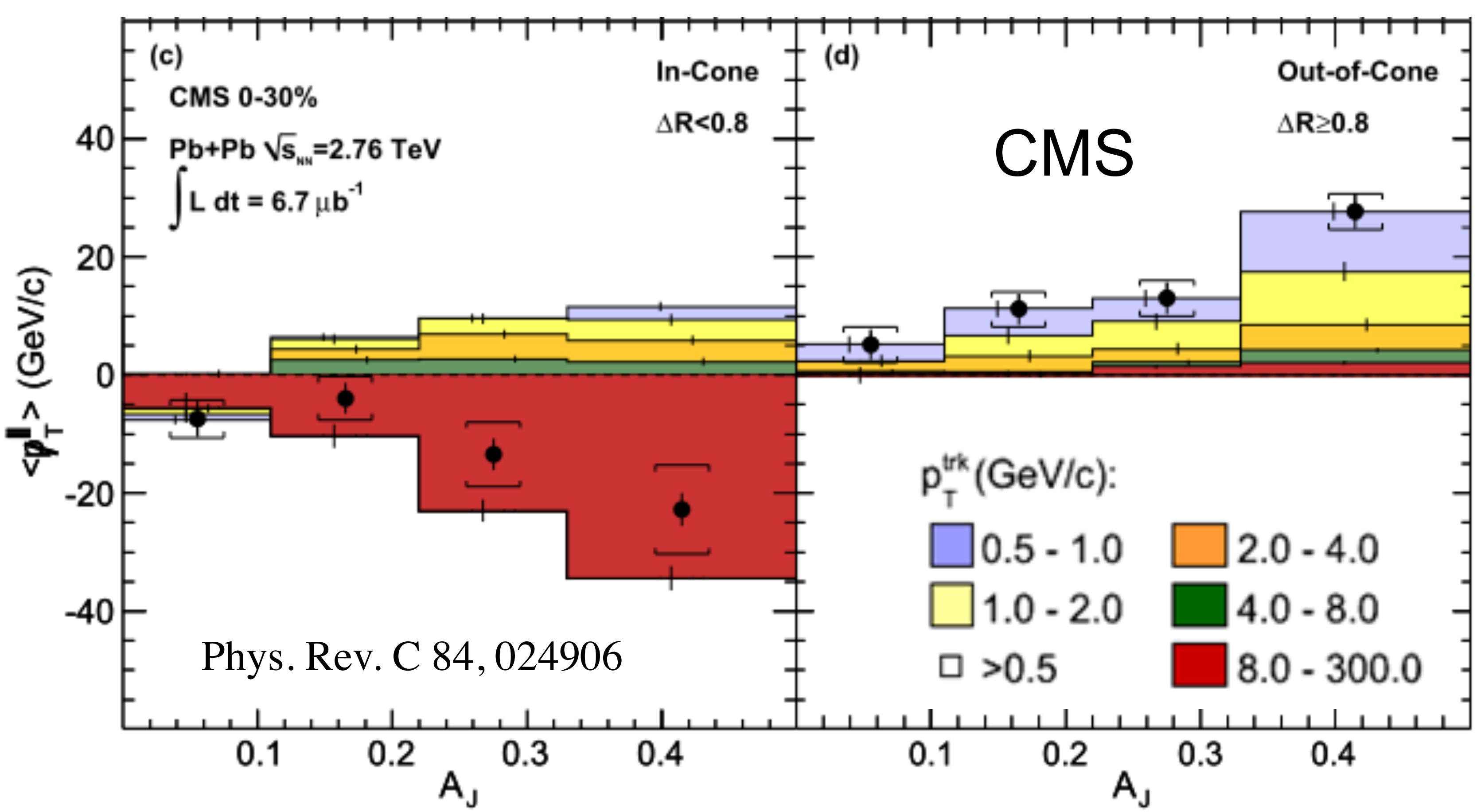


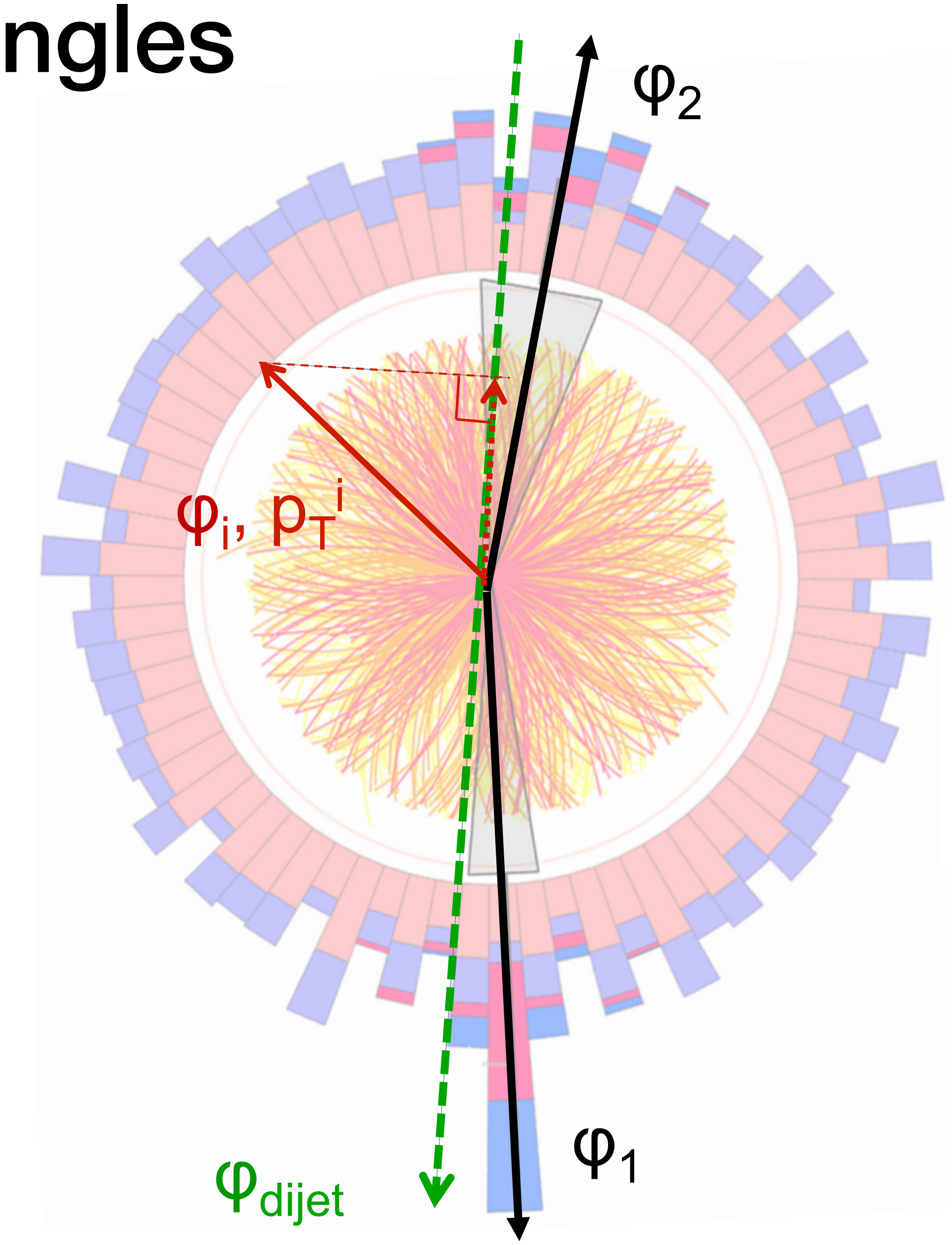
What have we learned about jet modification?

3. 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





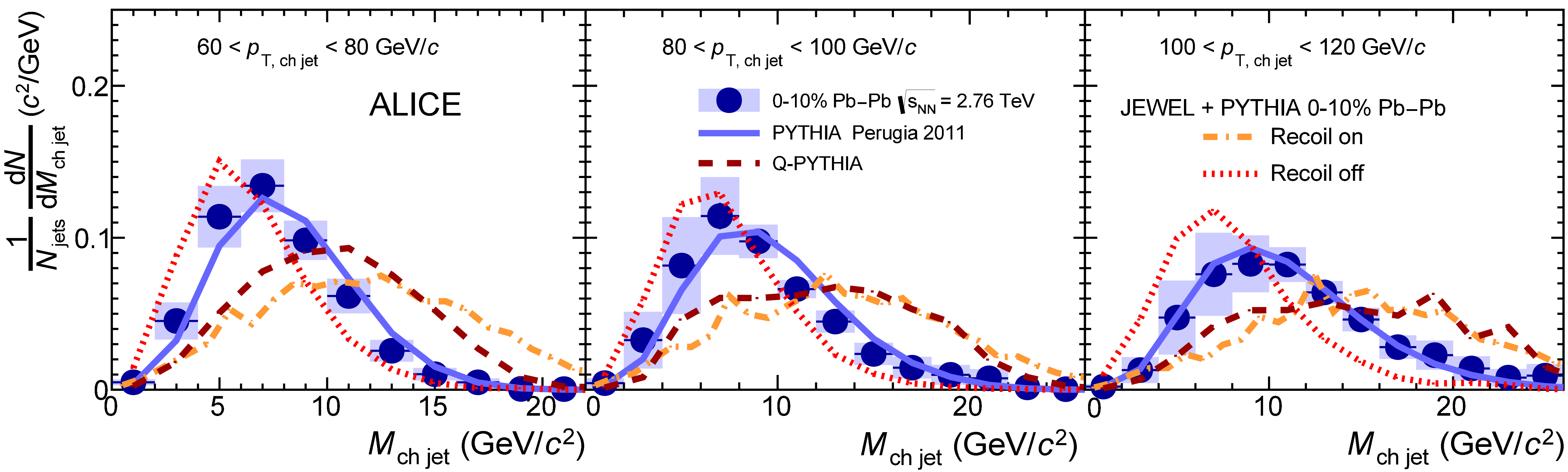
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

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

What have we **not** learned?

We do not know the cause of the large-angle soft excess: medium recoil vs. large-angle radiation

We have not distinguished between various pQCD-based energy loss models, or the role of strongly-coupled energy loss

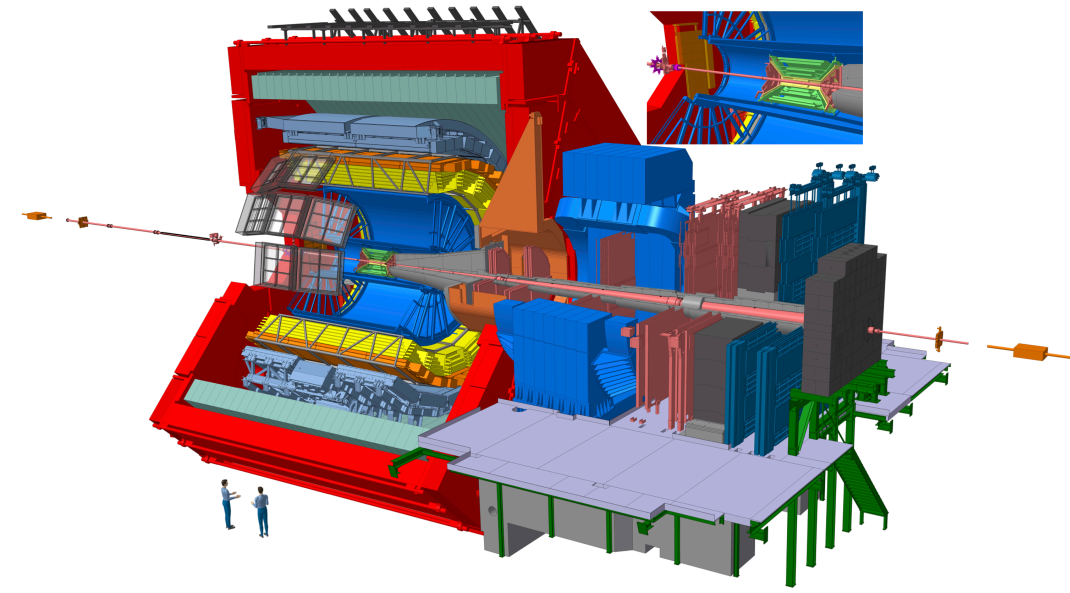
We often do not have apples-to-apples comparisons of theory to experiment

- Biases in the measurements due to background
- Multi-stage evolution of medium
- Hadronization effects

We need further constraints of models, for observables which can be meaningfully compared to theory

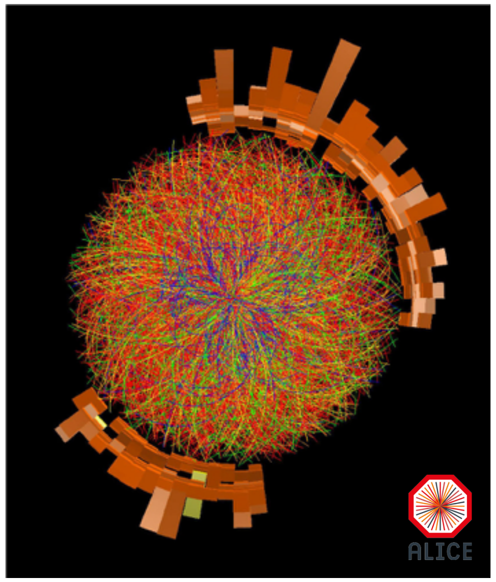
Measuring jets in ALICE

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



Charged particle jets (*charged jets*)

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

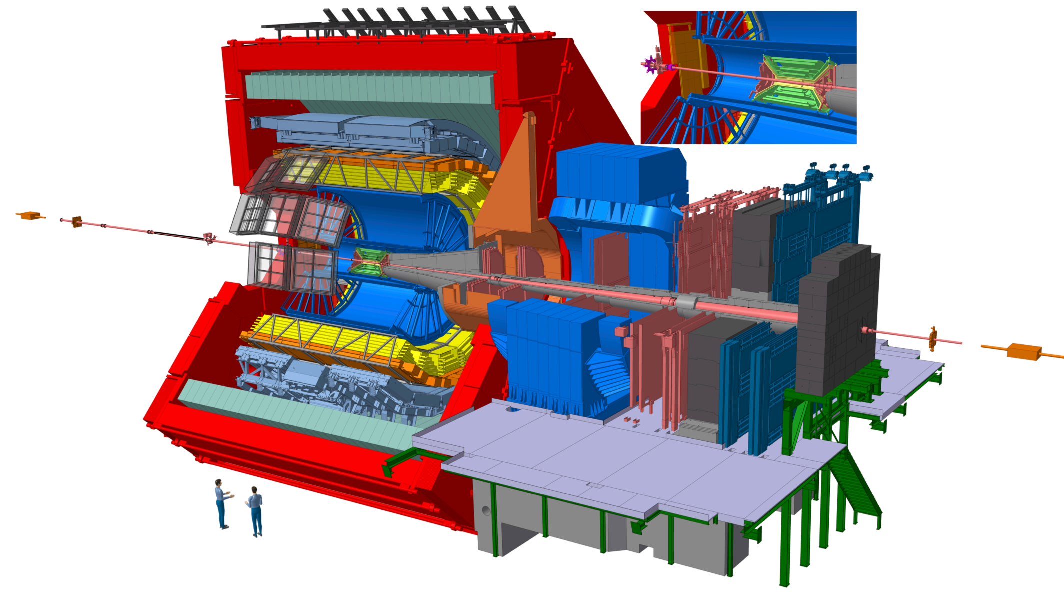


Jets (*full jets*)

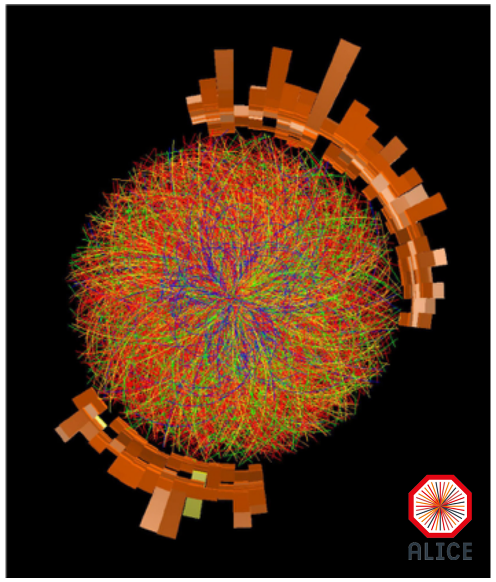
- Addition of particle information from the EM calorimeter down to $p_{\rm T,cluster} = 300$ MeV/c

Measuring jets in ALICE

Strengths of ALICE



- Low-momentum constituent thresholds allows to measure softest components of jet
- High-precision spatial resolution of tracking system allows precise jet substructure measurements
- Particle identification in jets



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 meaningful 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 meaningful comparison to theory**
- But significant experimental complication!
    - And reduced statistics due to limited coverage

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

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

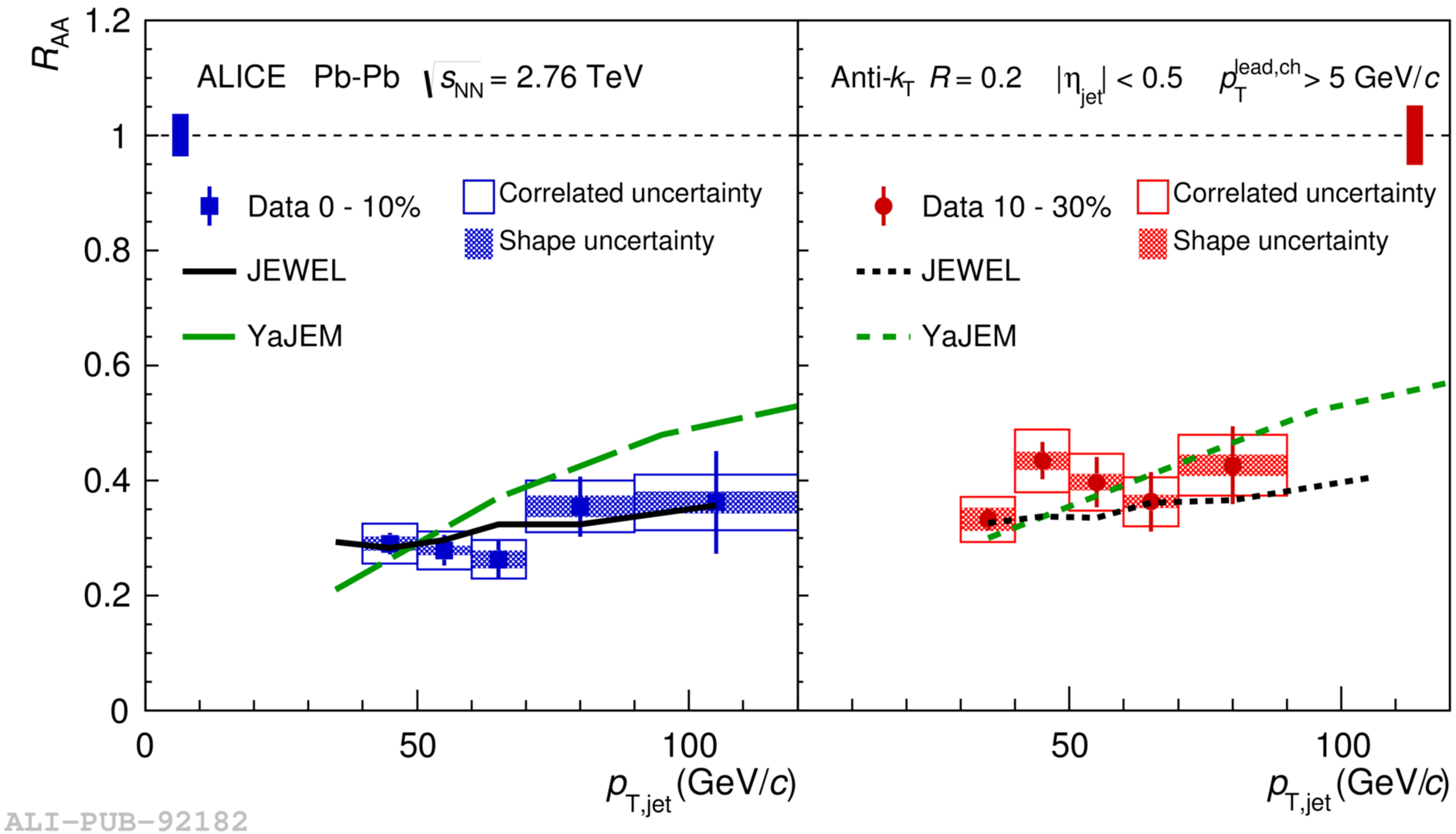
(1) Jet R_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV

Goals:

- Constrain energy loss models by providing the first full jet measurements at low transverse jet momentum at 5.02 TeV
- Measure R-dependence of jet R_{AA}
    - Is energy recovered as we increase R?

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

ALICE previously published full jet R_{AA} for R=0.2 down to $p_T = 40$ GeV/c at 2.76 TeV



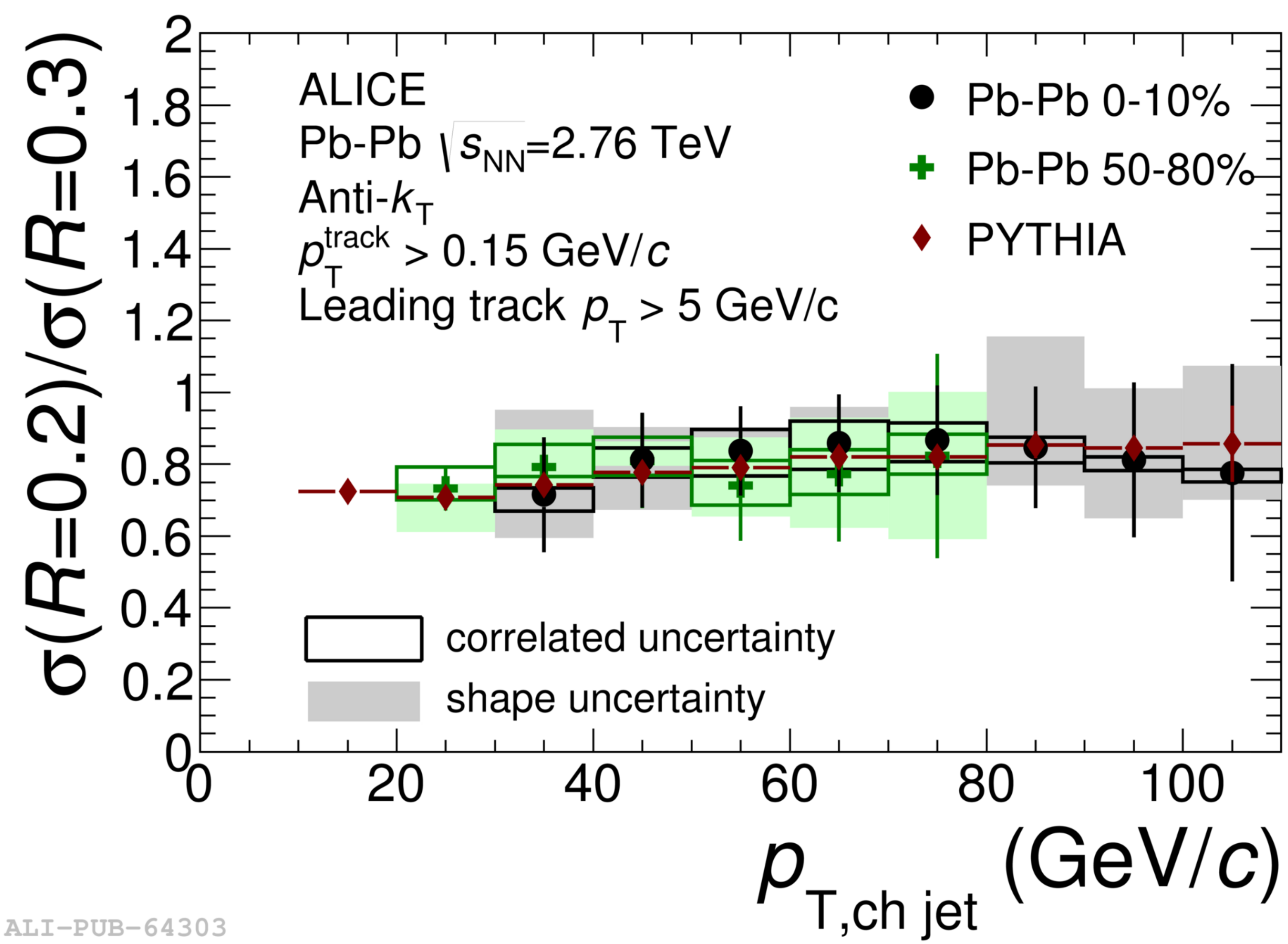
(2) Pb-Pb jet cross-section ratio R=0.2/R=0.4

The ratio of jet cross-sections at different R is an inclusive jet shape observable, sensitive to the R-dependence of jet energy loss

- We expect collimation of the jet core, but also energy flowing to larger angles — what is the net result for R=0.2 —> R=0.4?

ALICE has published the charged jet cross-section ratio R=0.2/R=0.3 at 2.76 TeV

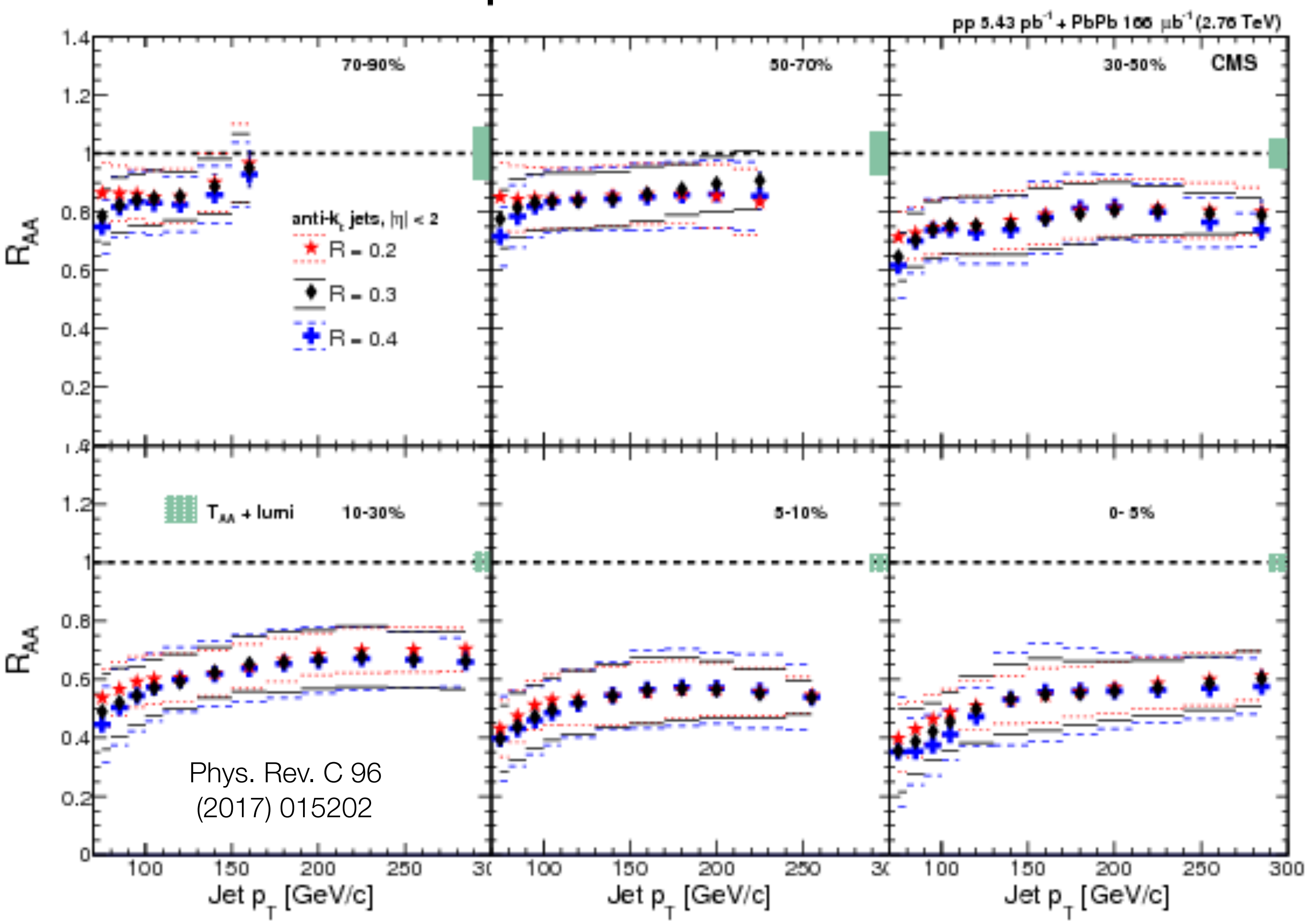
- Consistent with Pythia



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

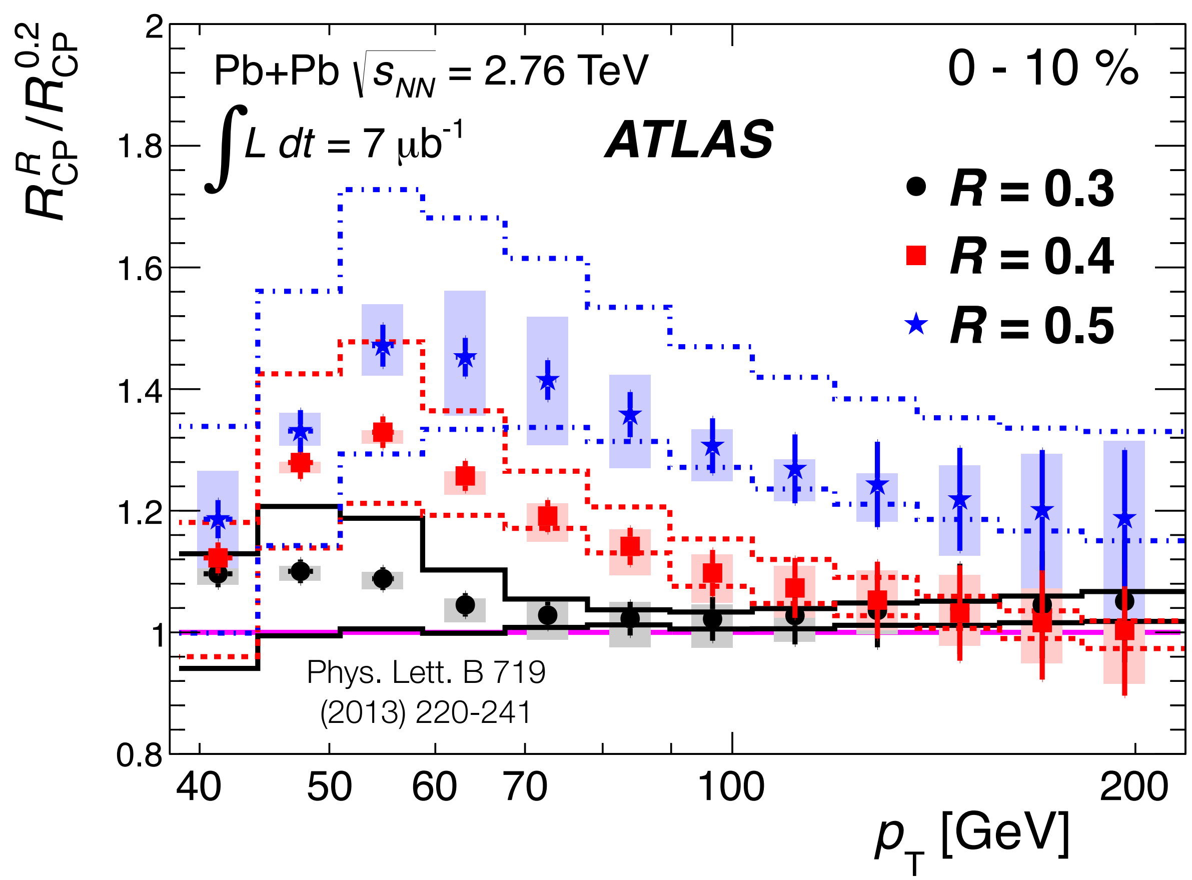
CMS

R-dependence of R_{AA}



ATLAS

R-dependence of R_{CP}



Measurements do not provide a clear picture

There is no measurement of R-dependence at 5.02 TeV

Analysis strategy

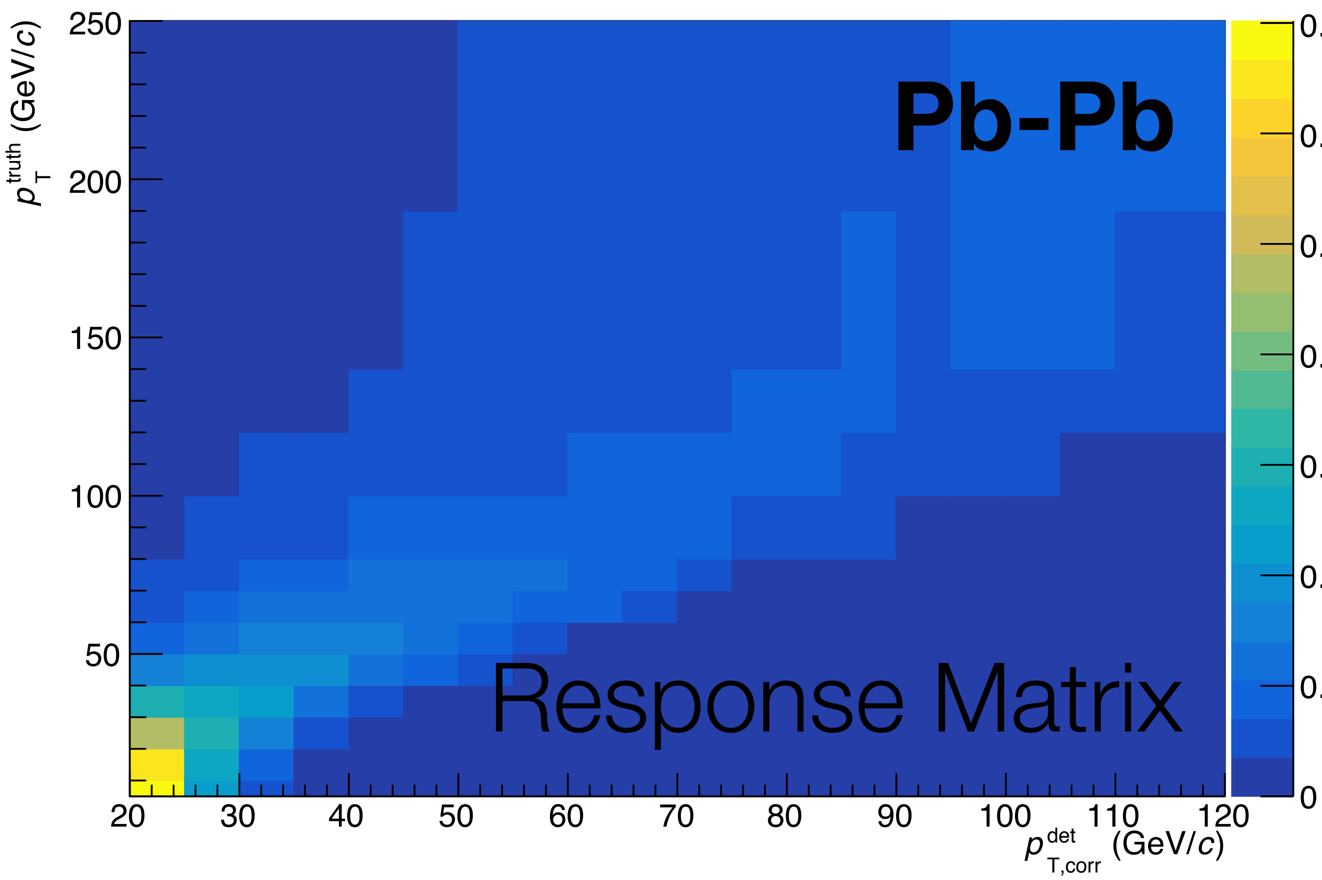
- **Three main pieces to the analysis:**
  - Measure the jet p_T — combine track p_T and EMCal p_T
  - Deal with the large combinatorial background
  - Correct the jet p_T for detector and resolution effects

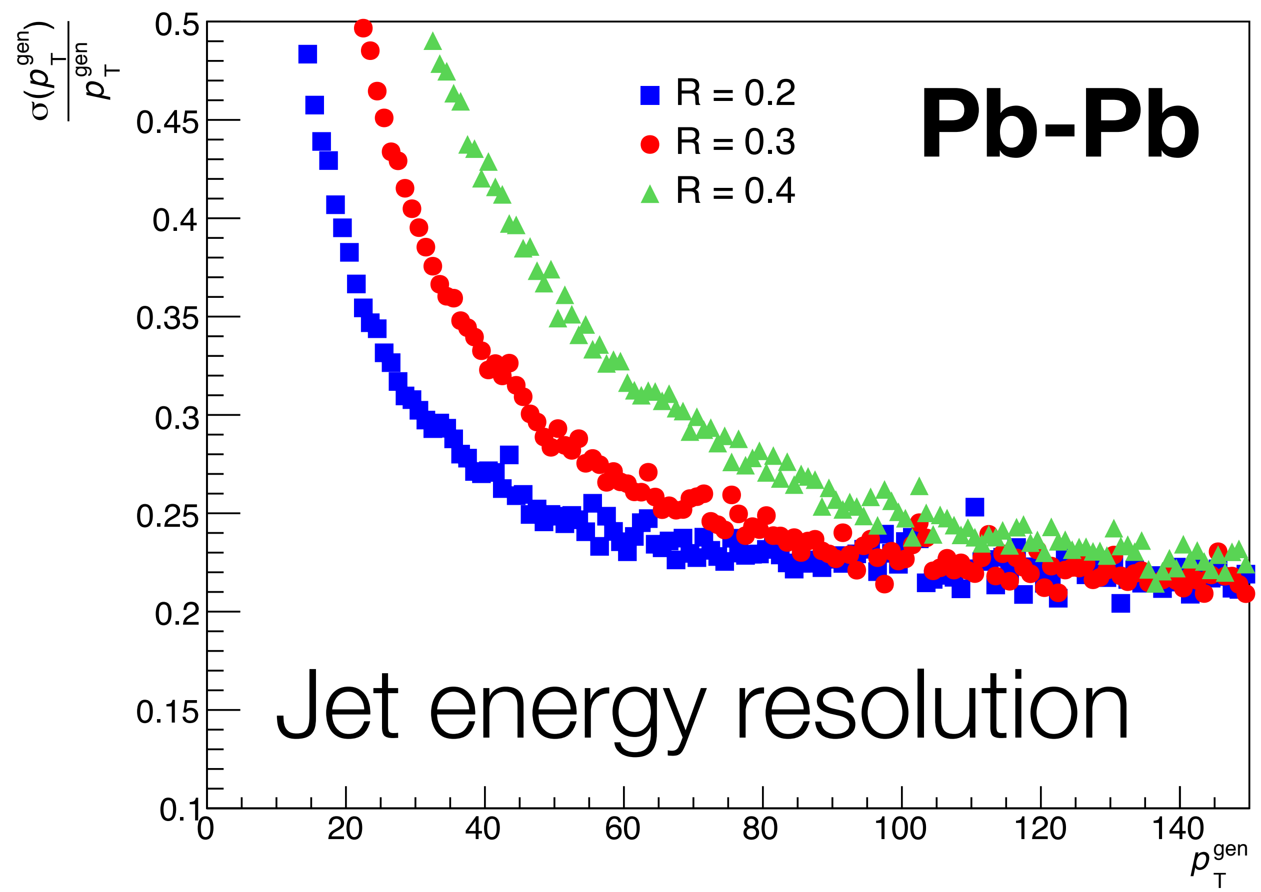
- **Improvements relative to the 2.76 TeV analysis**
  - Extend to R=0.3, R=0.4
    - Allows examination of modification to jet shape
  - Refine analysis technique
    - Better understanding of our tracking and calorimetry
    - Utilization of embedding-based jet p_T correction

Analysis strategy — jet p_T correction

Unfold the jet p_T spectrum for detector response and background fluctuations

- Build a response matrix by **embedding** Pythia8 events into Pb-Pb data
  - Properly accounts for centrality-dependent detector effects
  - Corrects for any residual background contribution

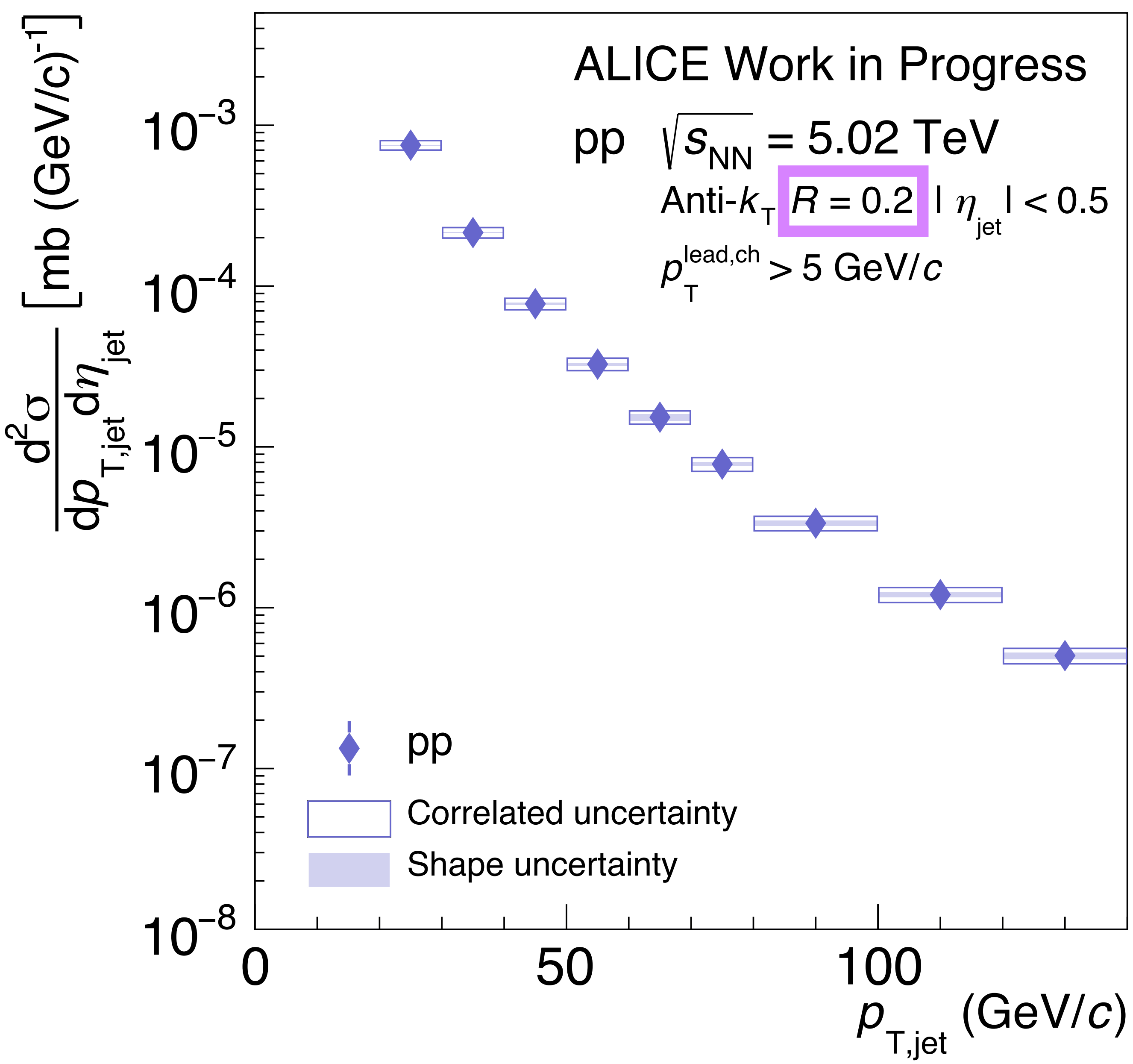


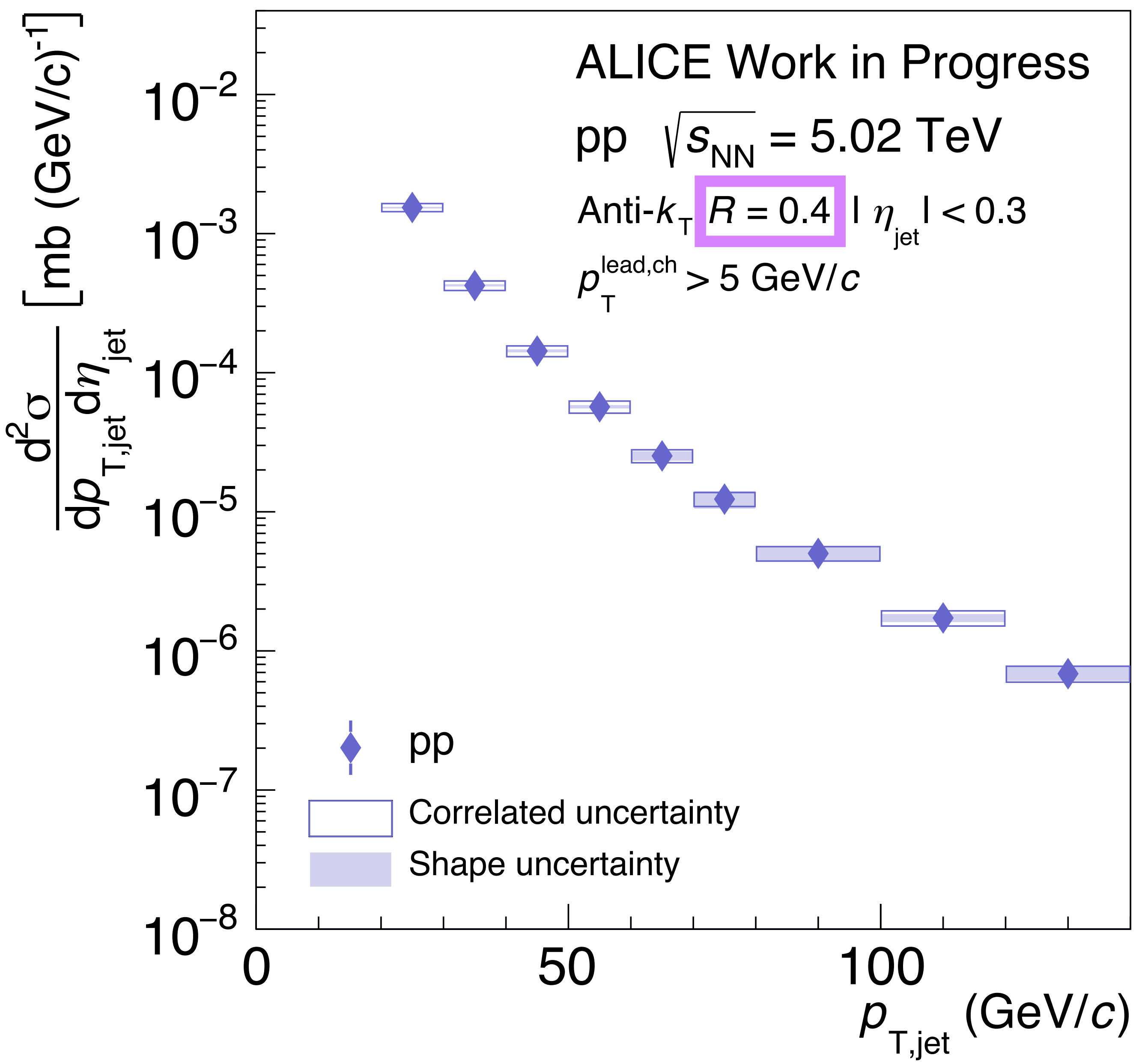


Results — pp jet cross-section

Publication in preparation

We measure the inclusive pp jet cross-section at 5.02 TeV as a reference for jet R_{AA}

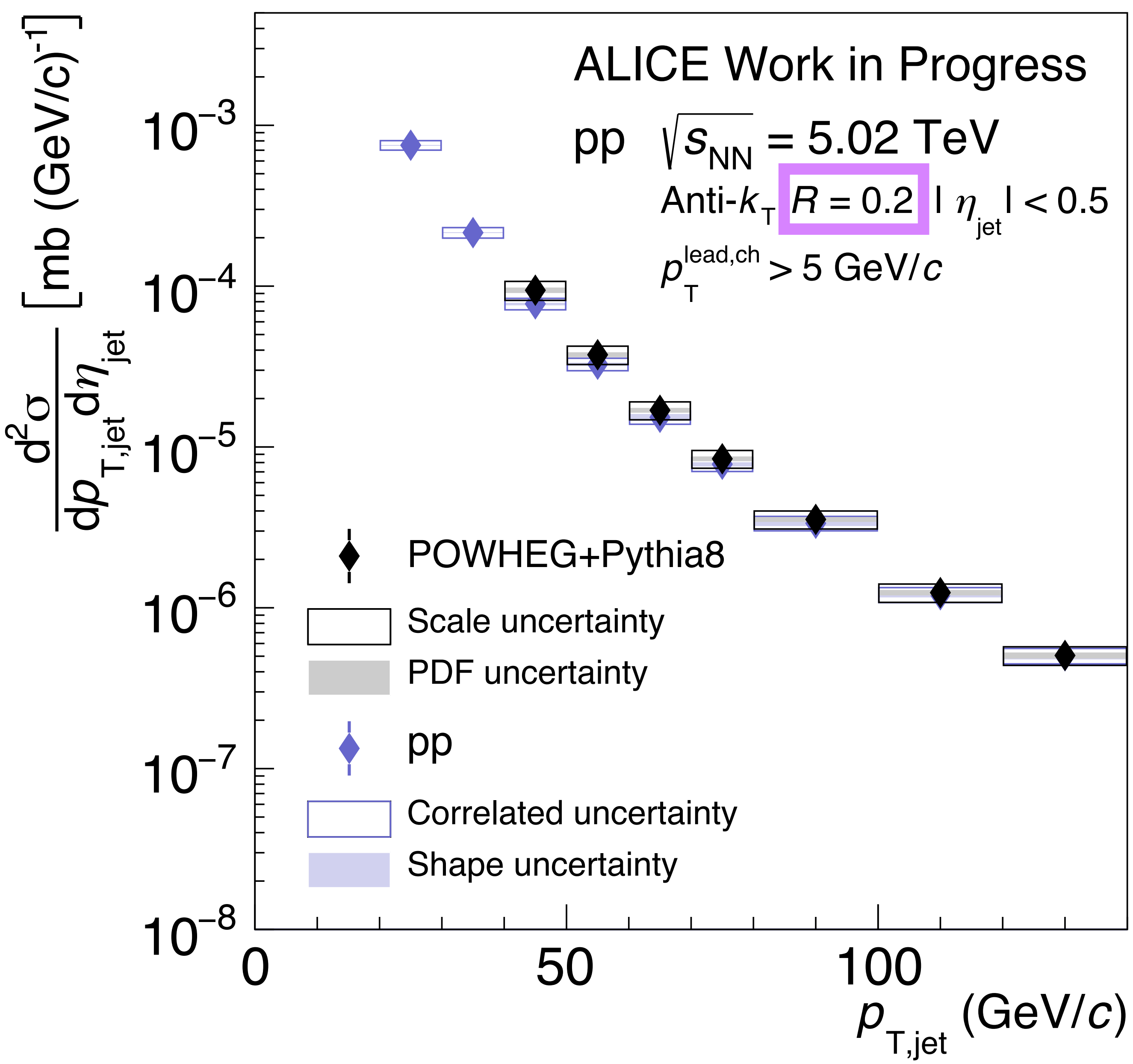


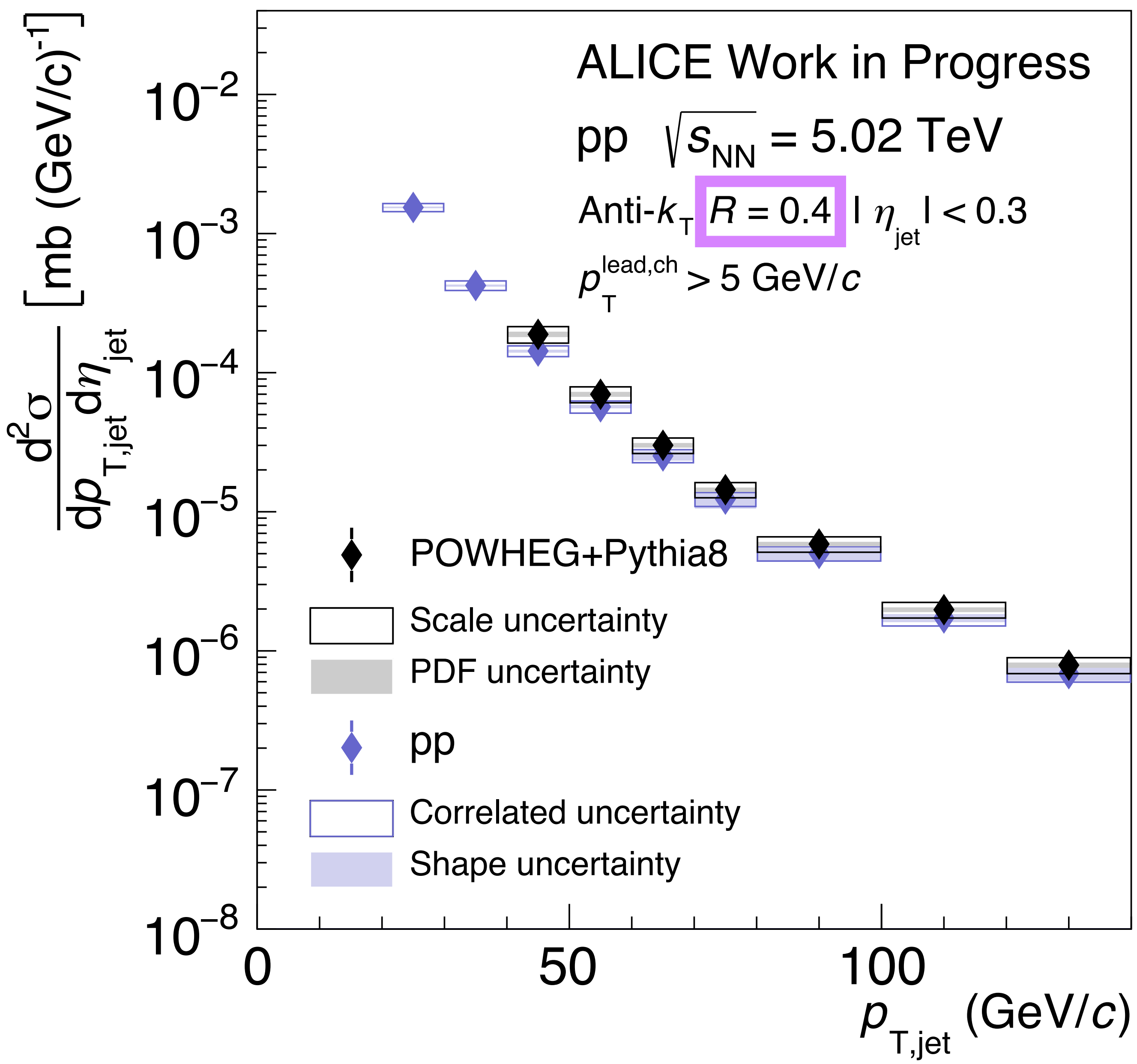


Results — pp jet cross-section

Publication in preparation

The measurement is consistent with POWHEG + Pythia8

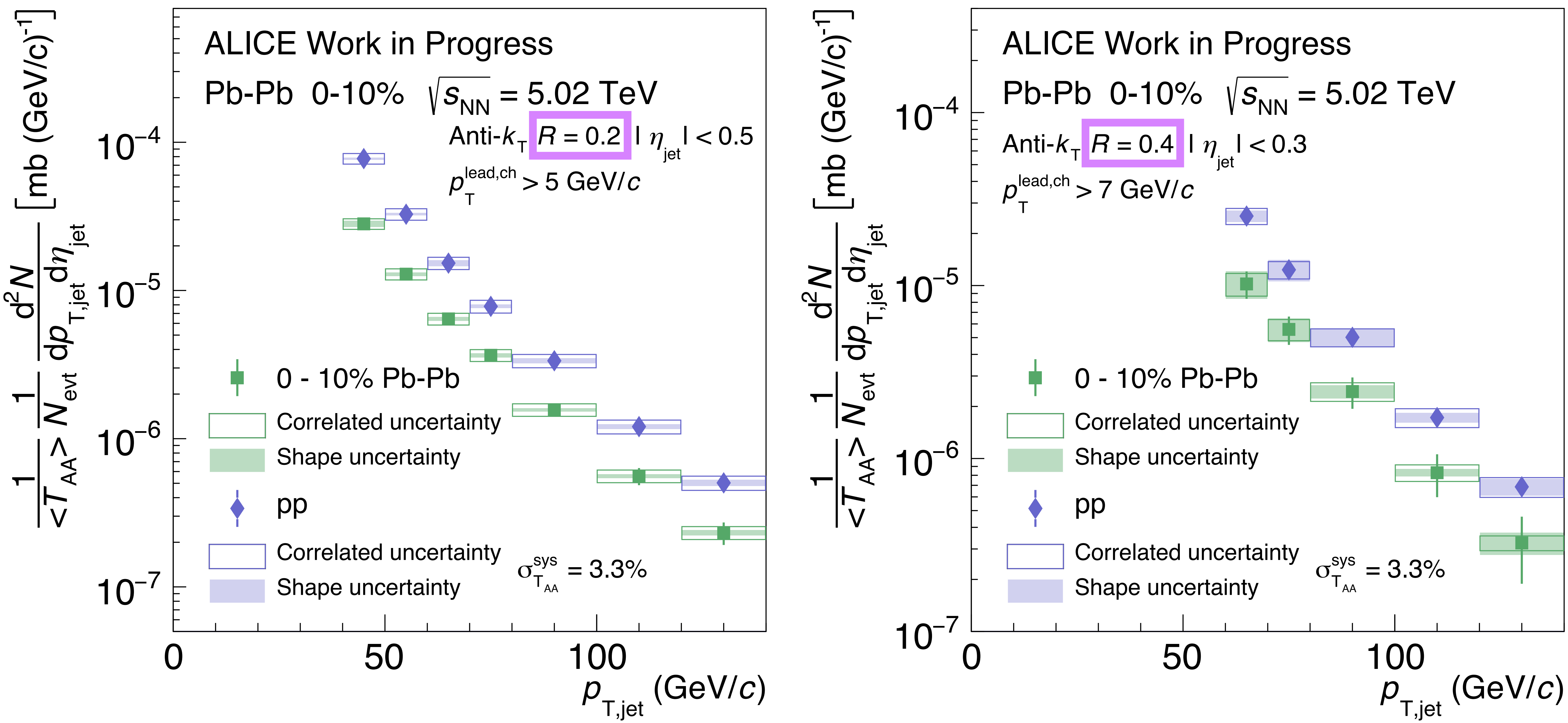




Results — Pb-Pb jet spectra

Publication in preparation

We measure the Pb-Pb jet spectrum for $p_{T,jet}$ = 40-140 GeV/c

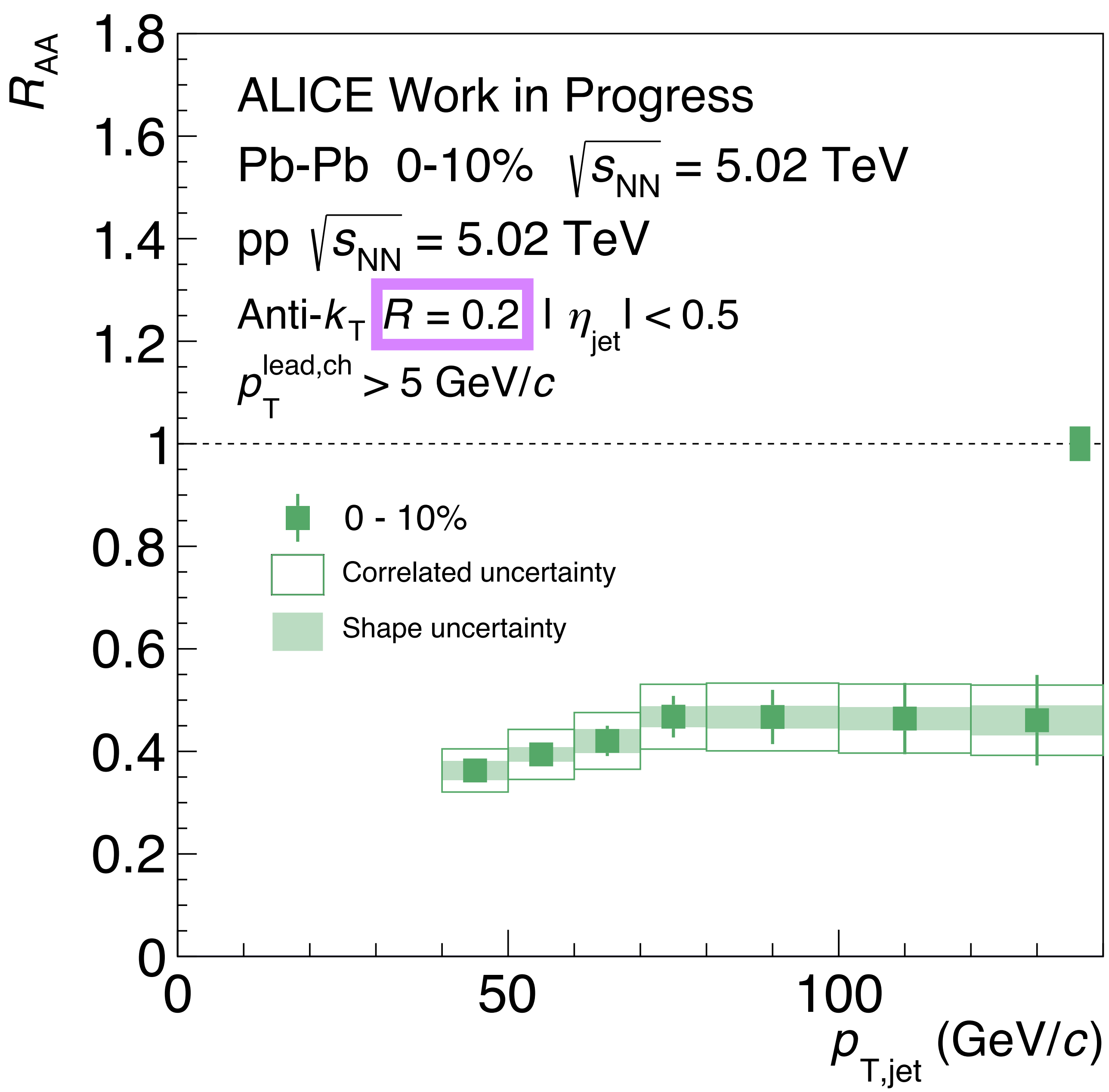


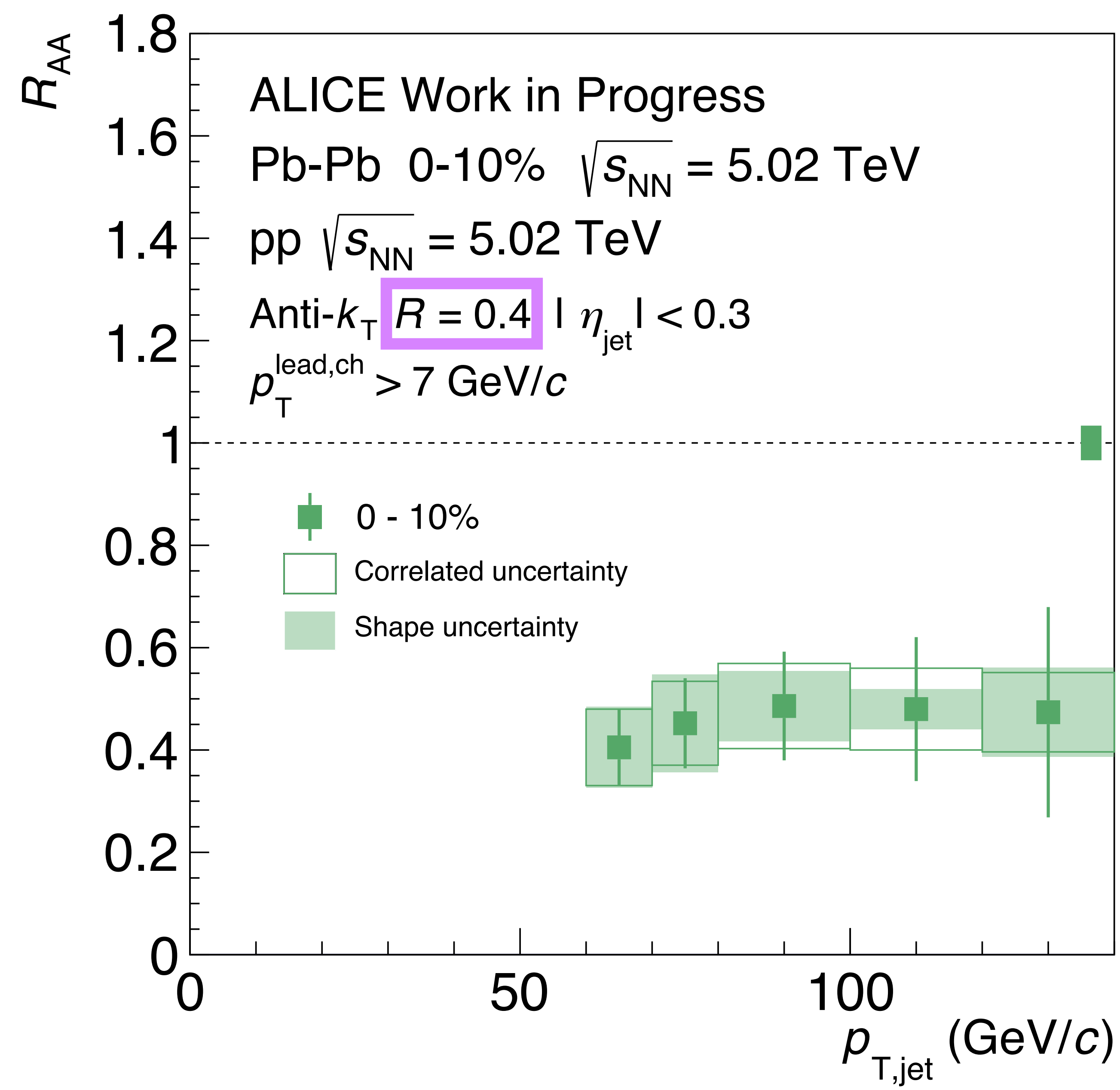
Results — Jet R_{AA}

Publication in preparation

The first Pb-Pb full jet measurement at **low $p_{T,jet}$** at 5.02 TeV

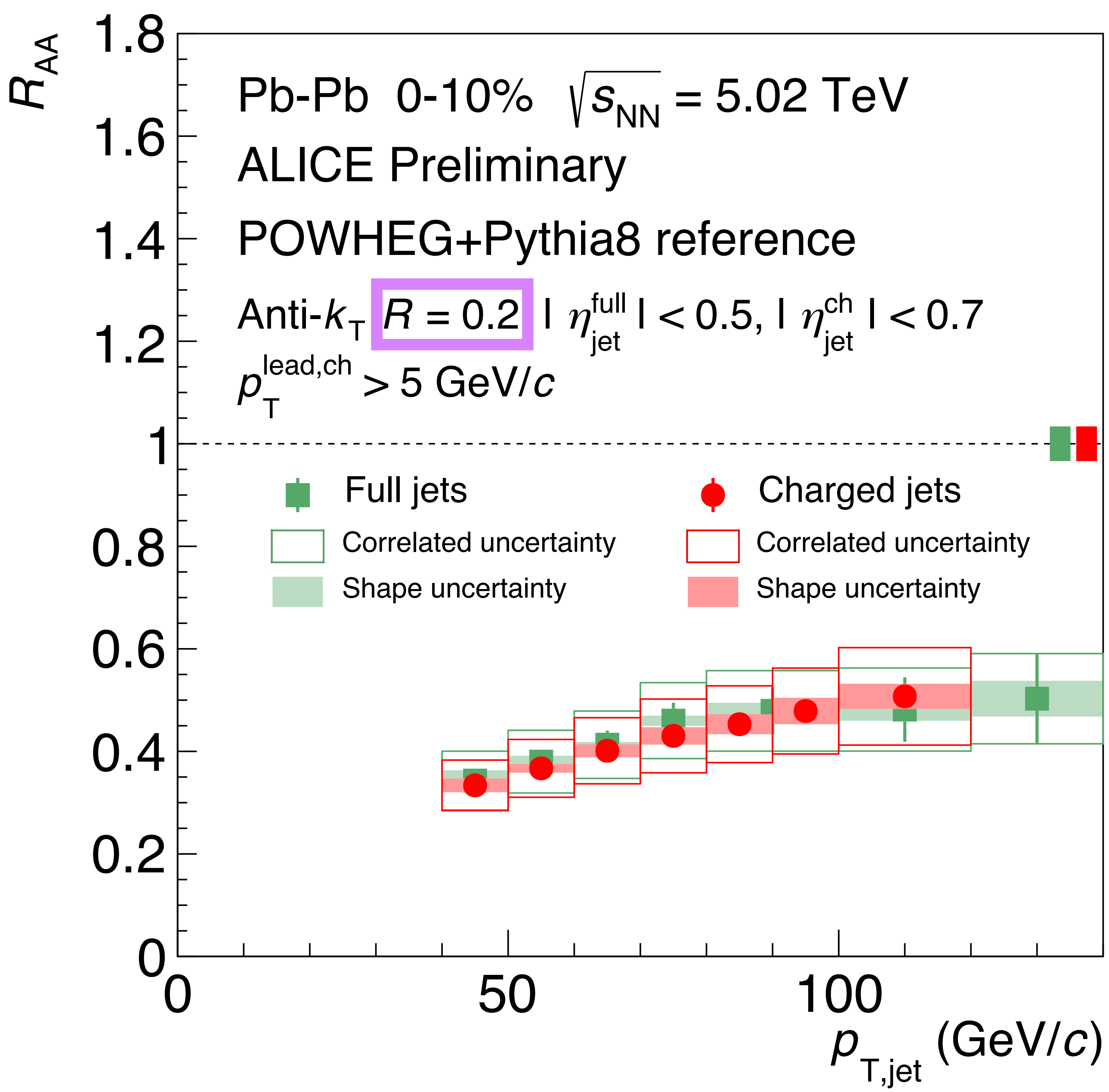
Similar suppression observed in R=0.2 and R=0.4

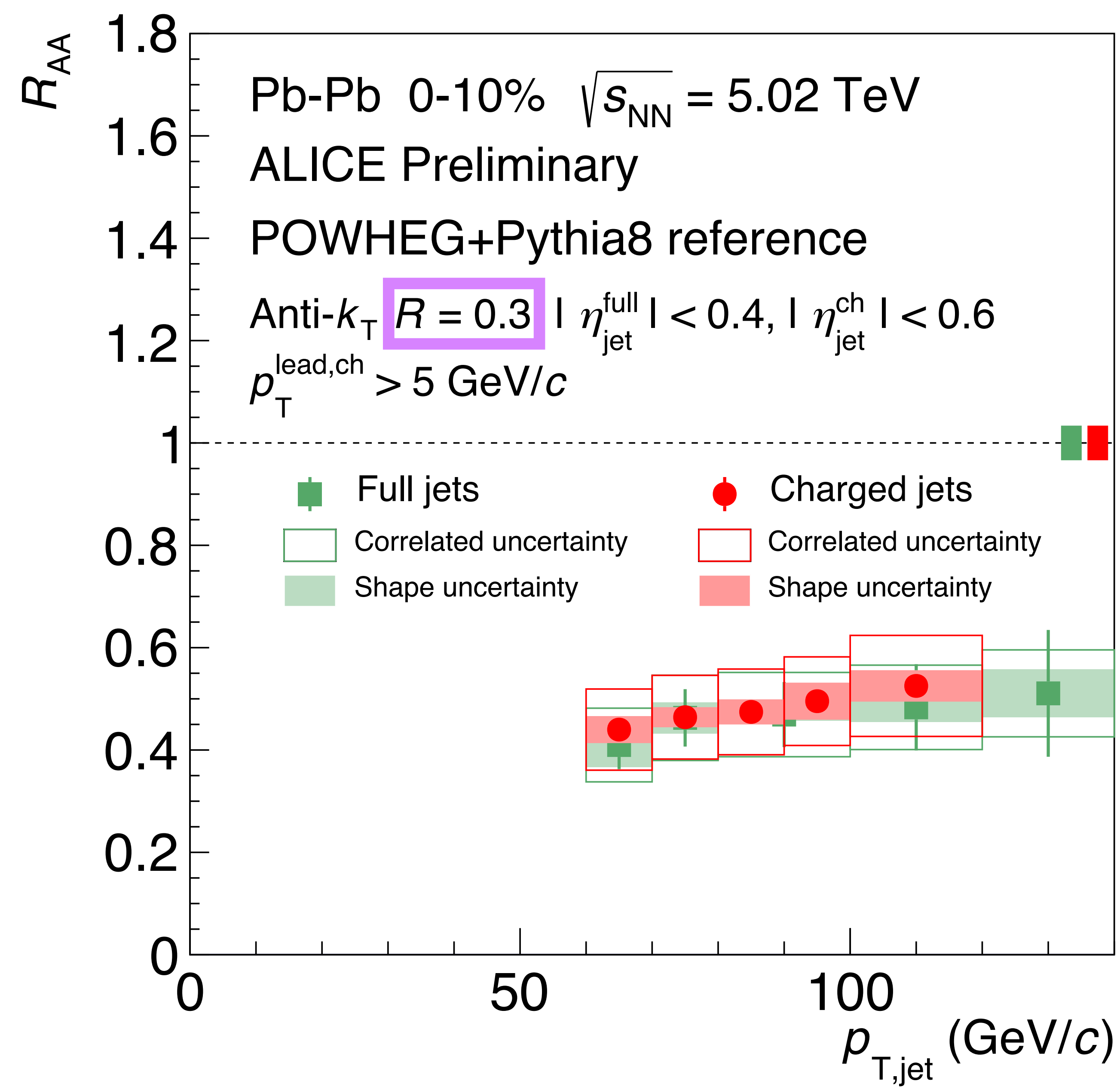




Results — Jet R_{AA}

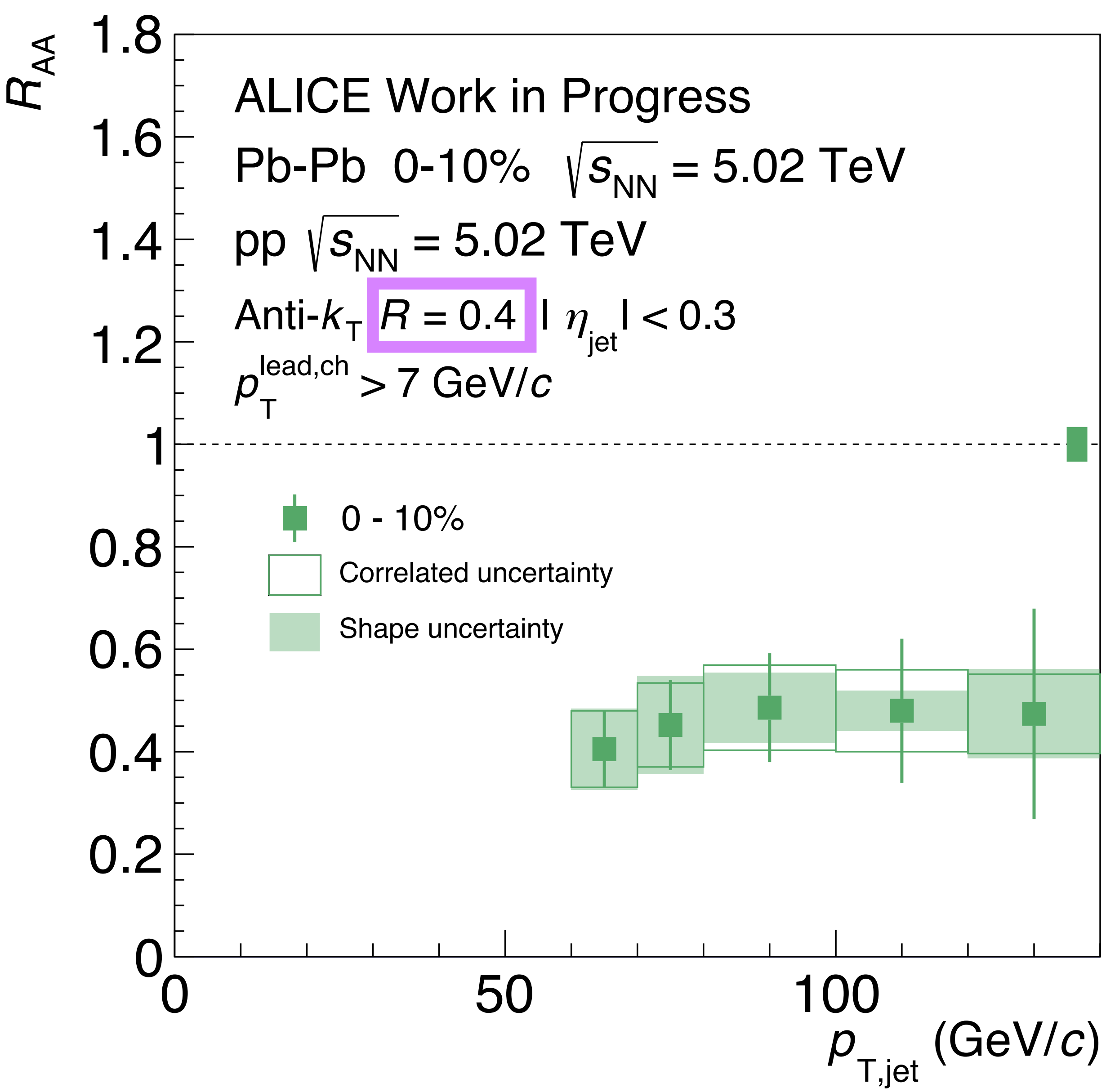
Charged particle jets and full jets are consistent



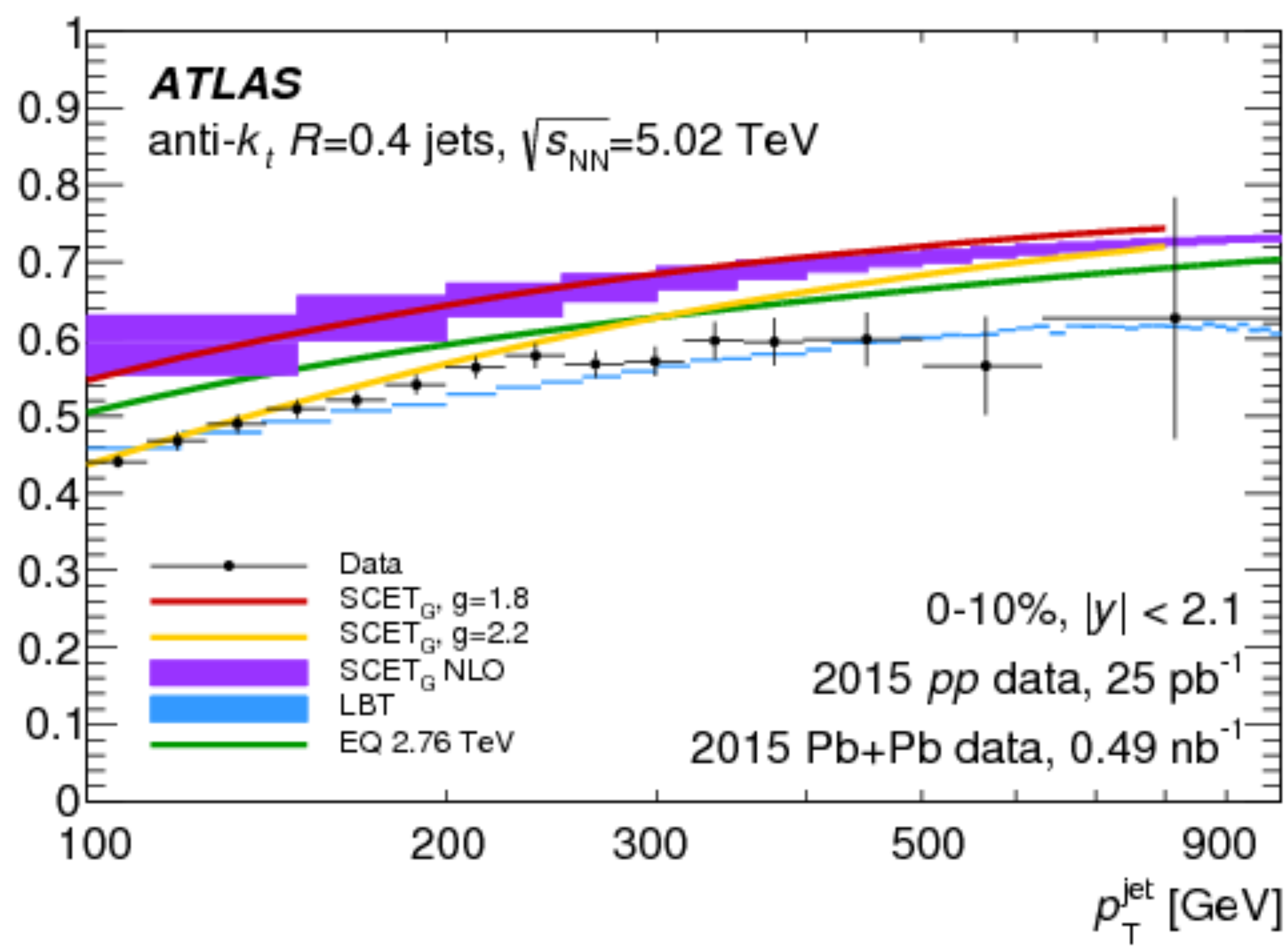


Results — Jet R_{AA}

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



arxiv 1805.05424

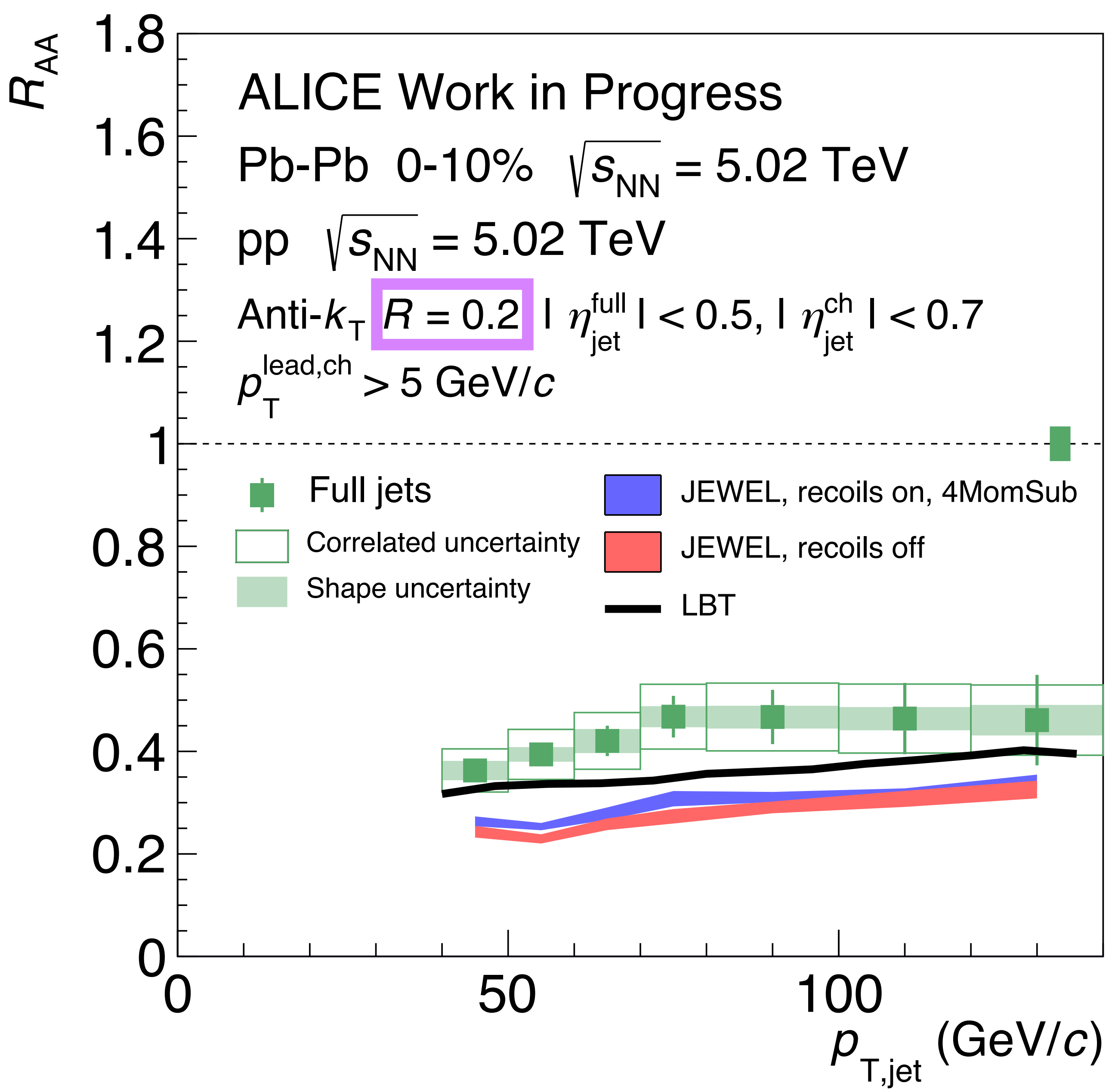


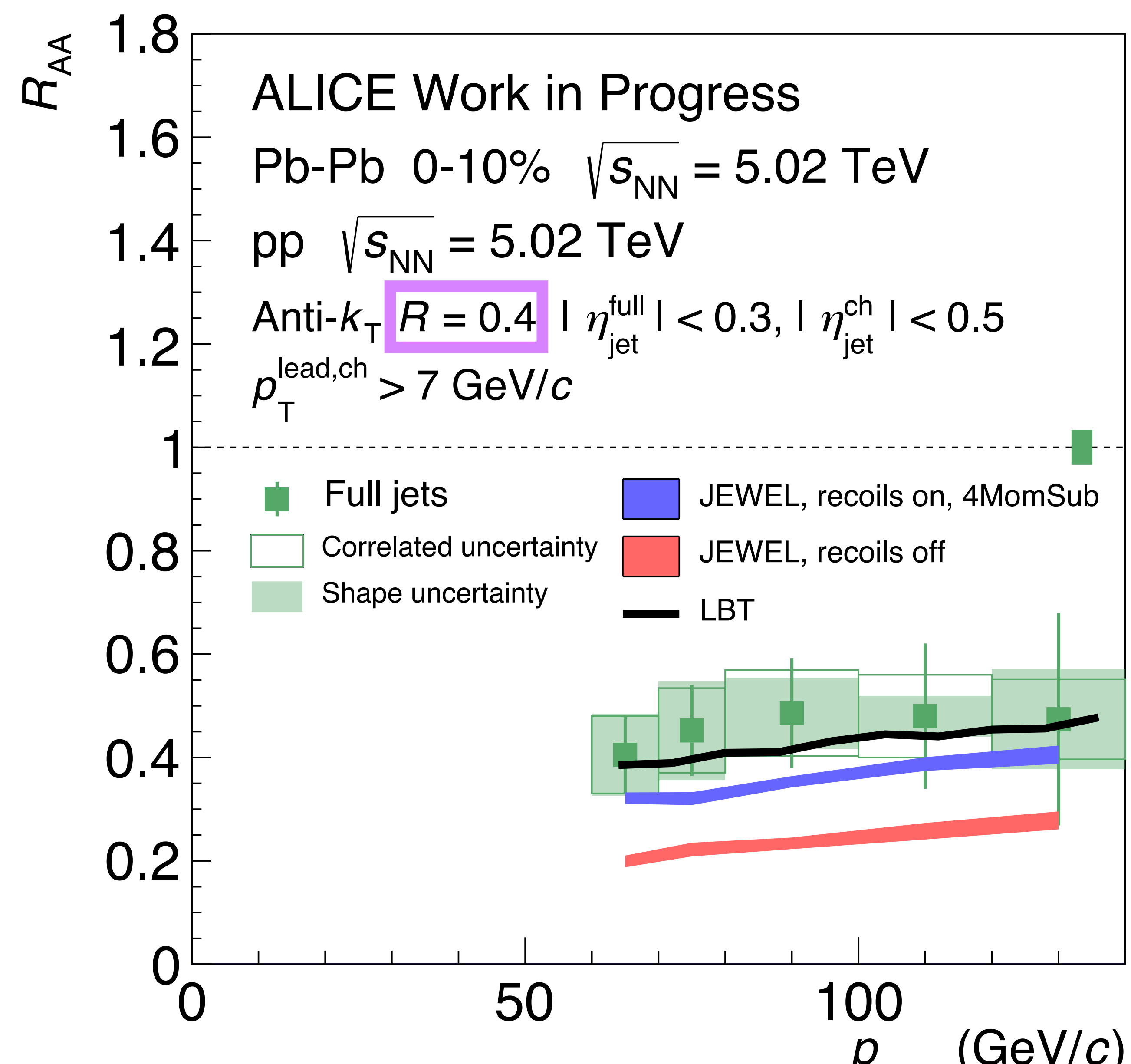
Results — Jet R_{AA}

Publication in preparation

JEWEL model under-predicts the jet R_{AA} at 5.02 TeV

Linear Boltzmann Transport model does better…





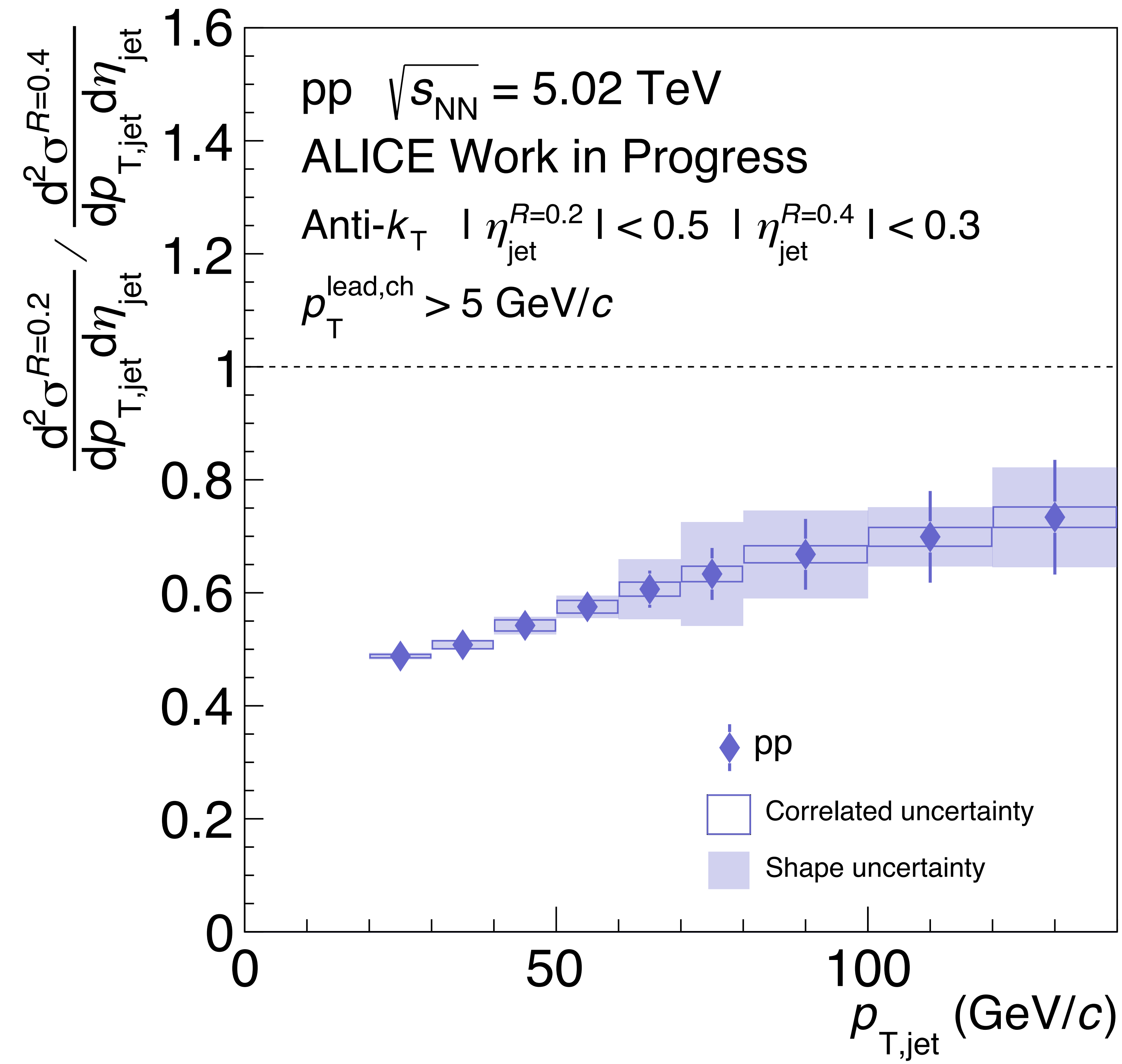
JEWEL provided by Ritsuya Hosokawa

Results: Jet cross-section ratio

Publication in preparation

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

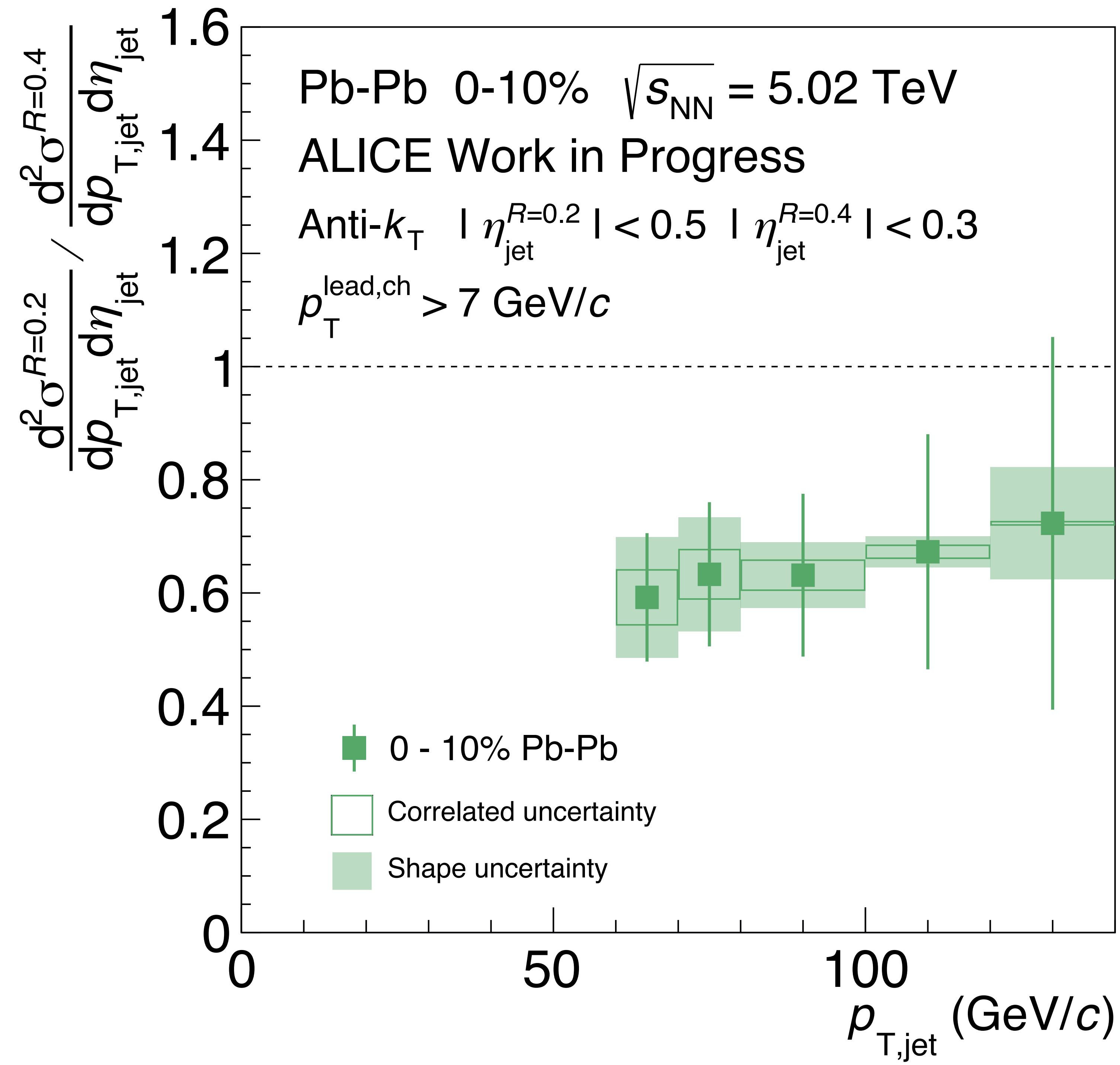
In pp, the jet cross-section ratio is also useful to disentangle hadronization and underlying event effects



Results: Jet cross-section ratio

Publication in preparation

The ratio of jet cross-sections *R*=0.2 / *R*=0.4 in Pb-Pb is an inclusive jet shape observable

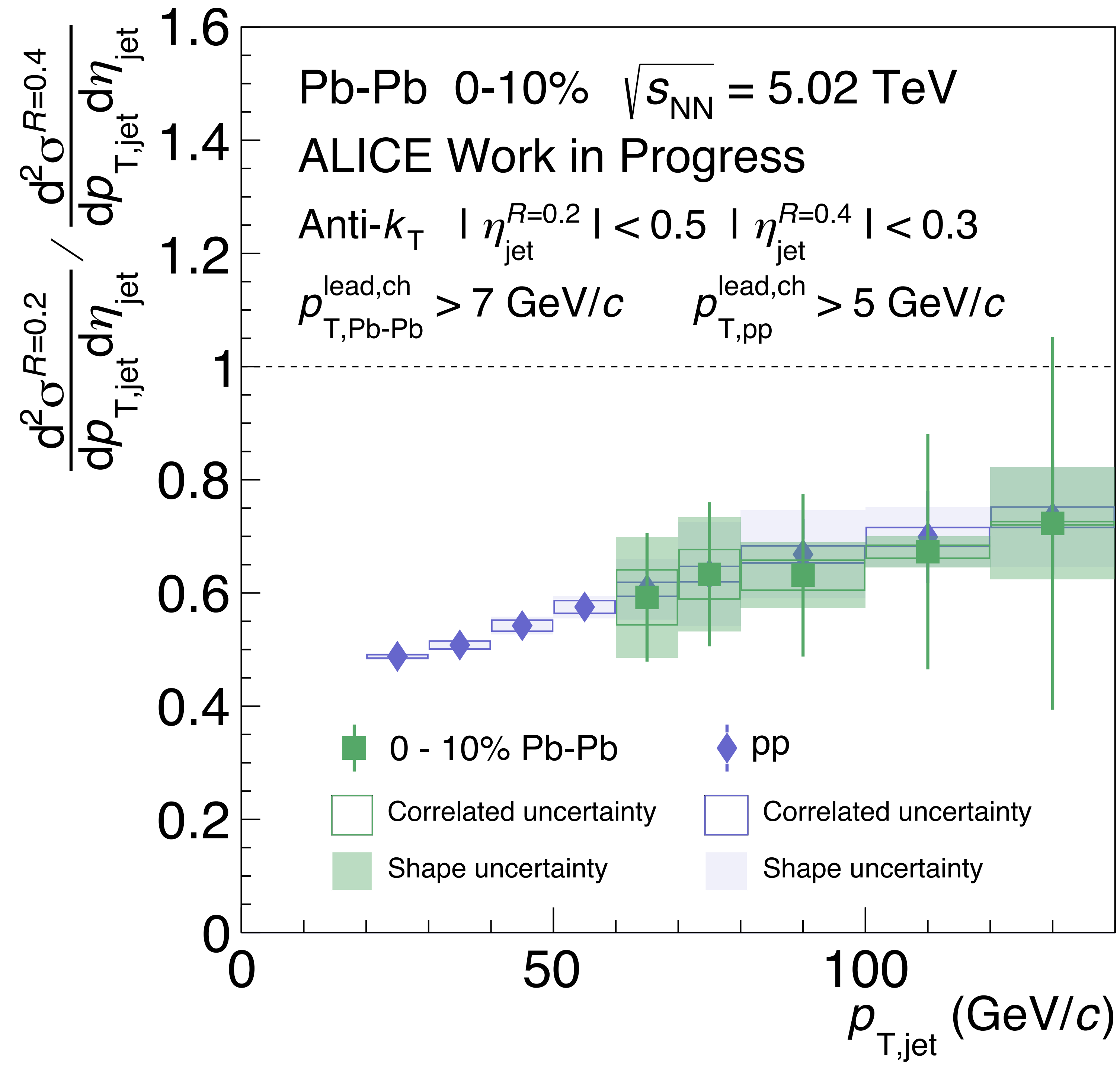


Results: Jet cross-section ratio

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

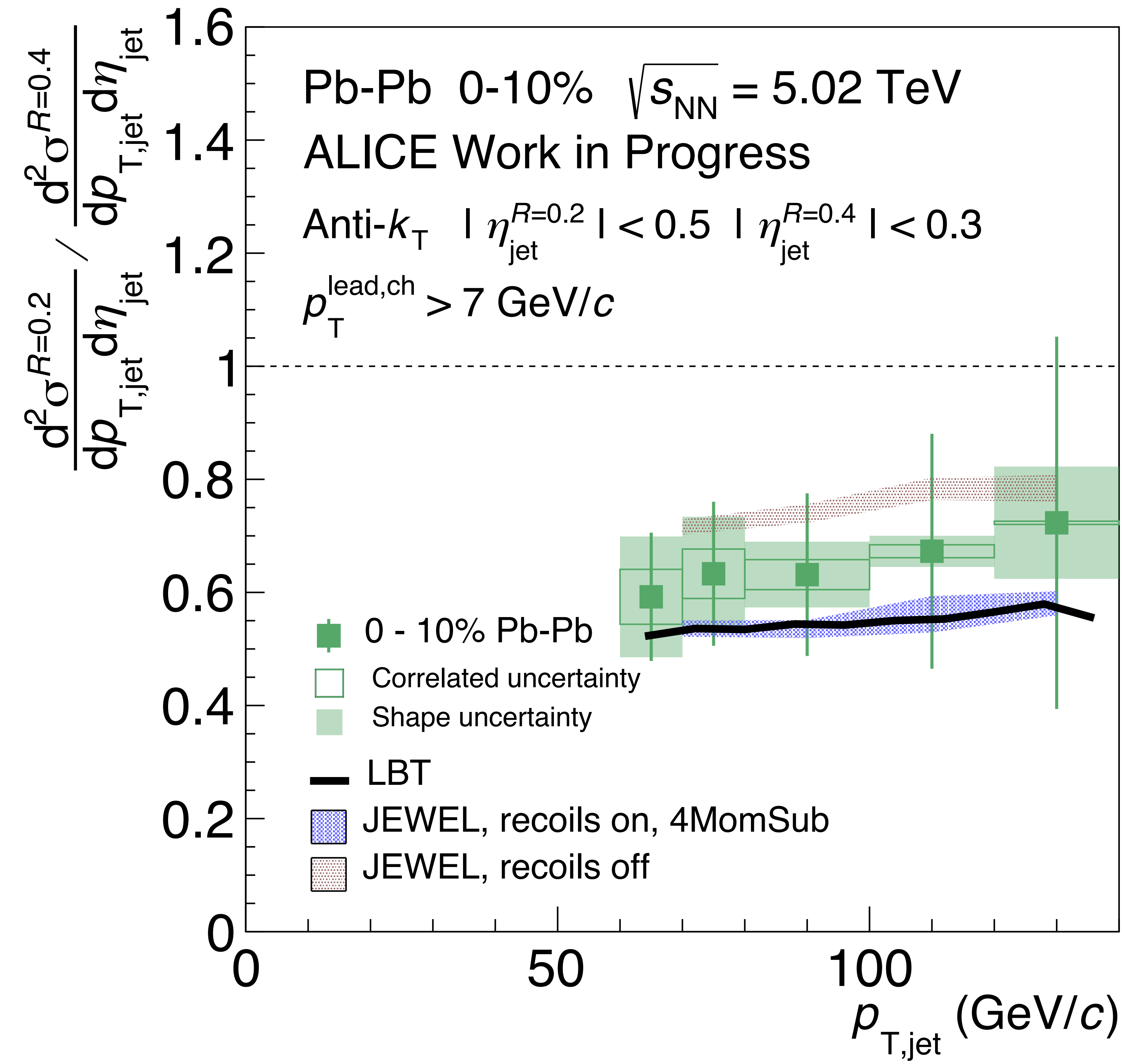


Results: Jet cross-section ratio

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



Outlook

We have placed constraints both on jet observables that are modified by the quark-gluon plasma and observables that are not modified

- Jet R_{AA} shows strong suppression and p_T-dependence at low p_T
- Jet R_{AA} is approximately independent of R for R=0.2-0.4
- Jet cross-section ratio R=0.2/R=0.4 shows no significant modification

Big picture questions remain:

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?*

Outlook

The LHC will run Pb-Pb collisions later this year

- ALICE anticipates a large gain ~10x statistics

Rich program ahead for heavy-ion jet physics

- 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 in 2018!

Thank you!

Backup

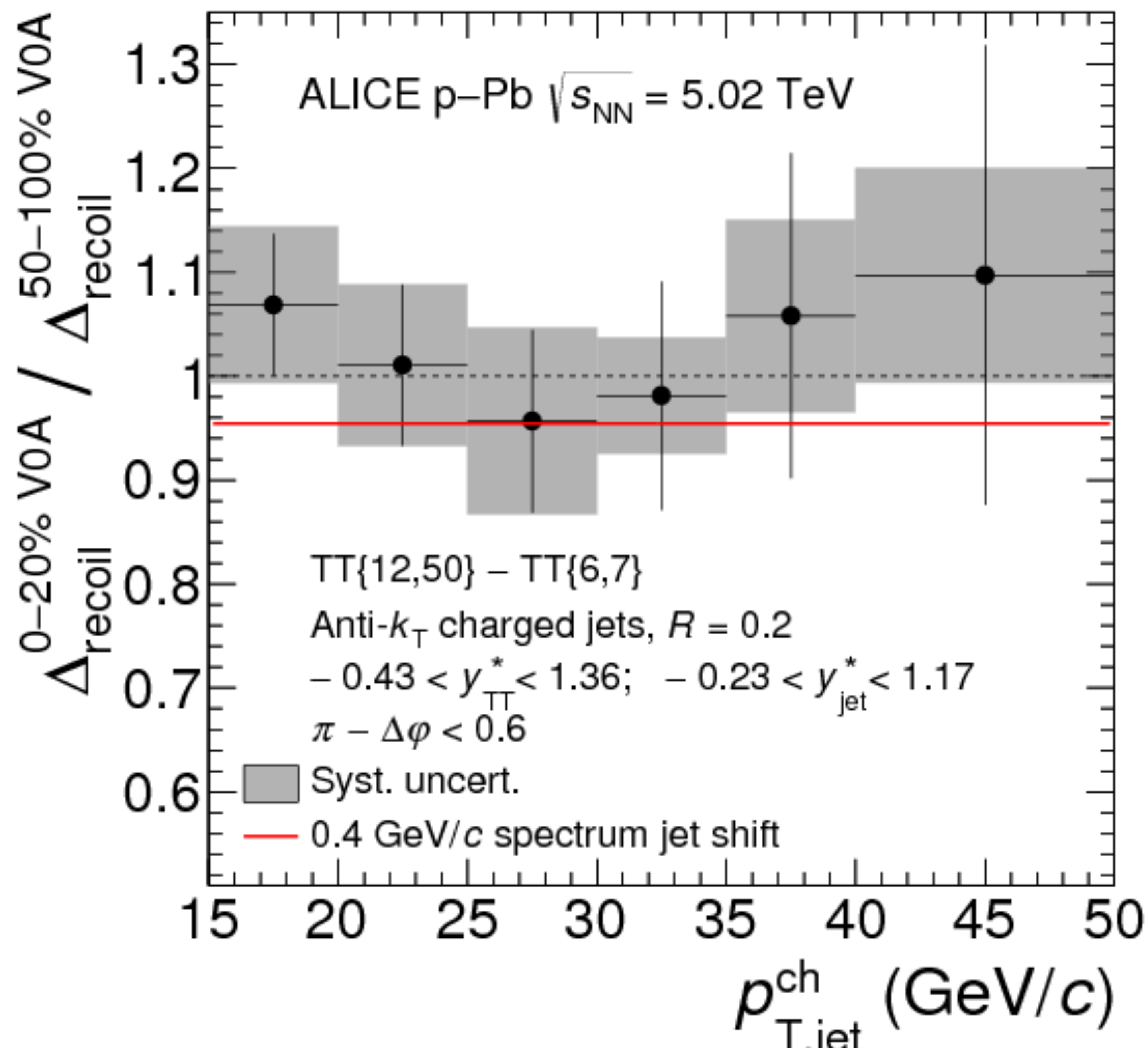
What have we learned about jet modification?

1. Jet yields are suppressed

Phys.Lett. B783 (2018) 95-11

No jet suppression is observed in p-Pb

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

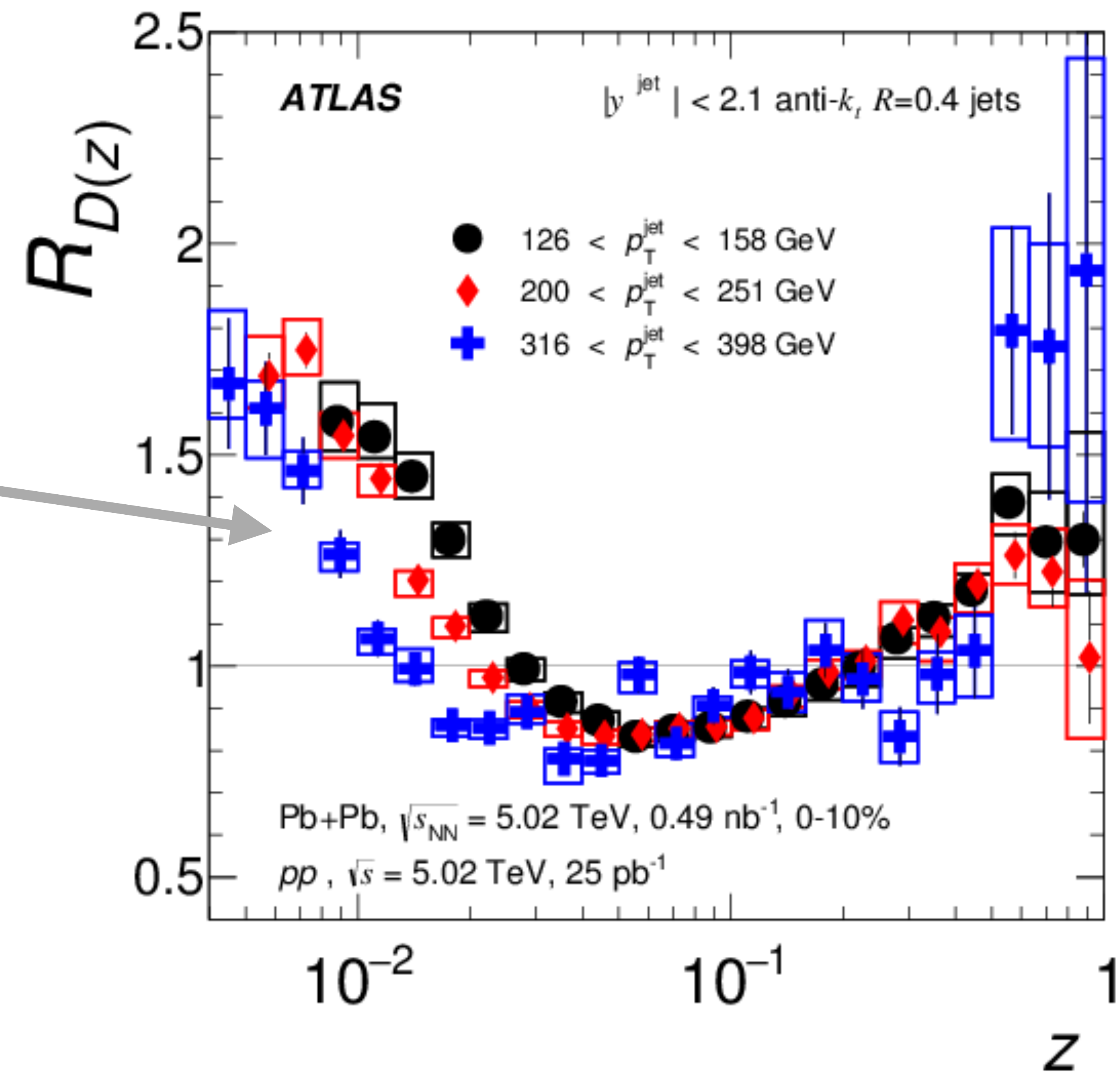


What have we learned about jet modification?

3. Soft energy is distributed to large angles

arXiv 1805.05424

The soft excess is also observed in the fragmentation function



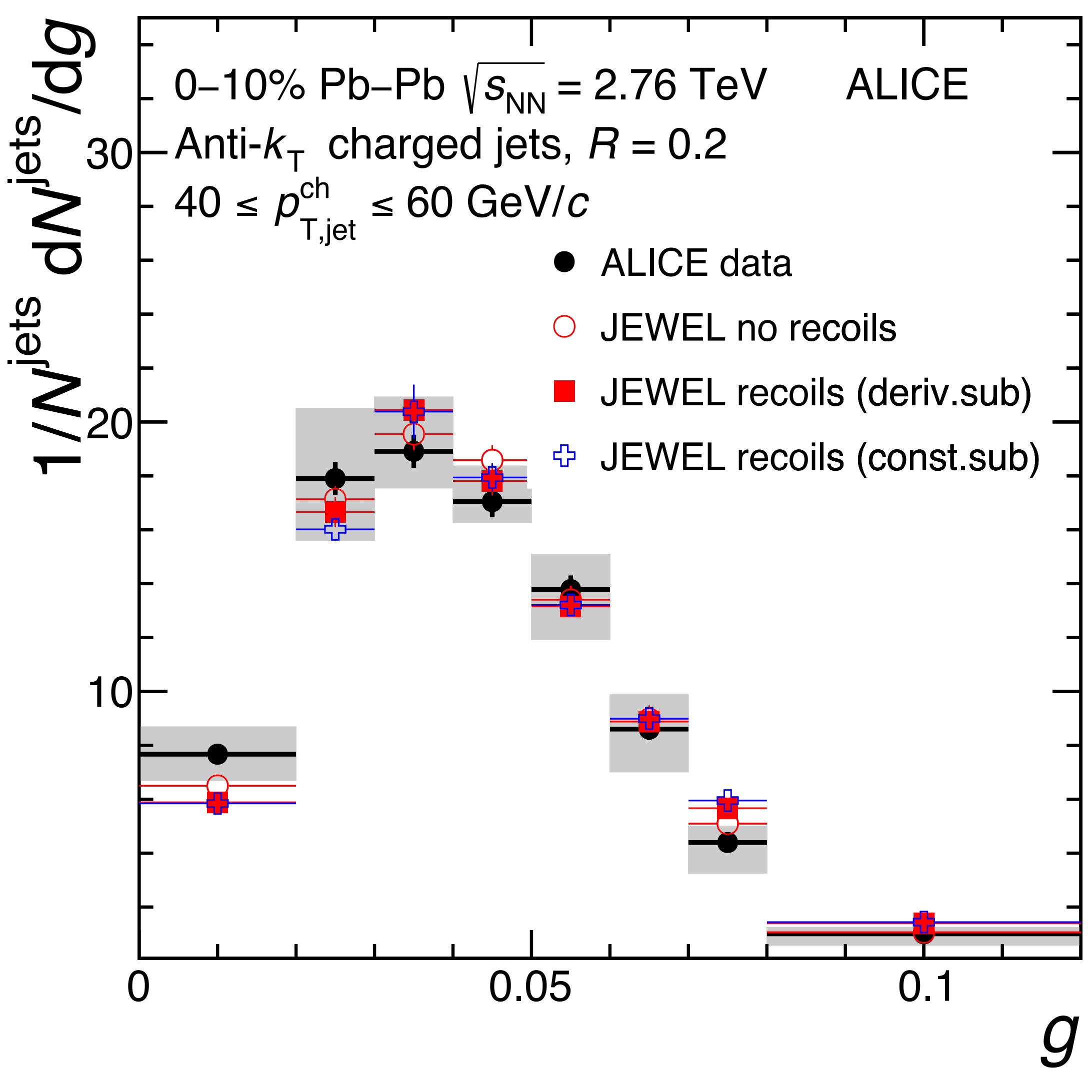
$$R_{D(z)} \equiv \frac{D(z)_{\text{PbPb}}}{D(z)_{pp}}$$

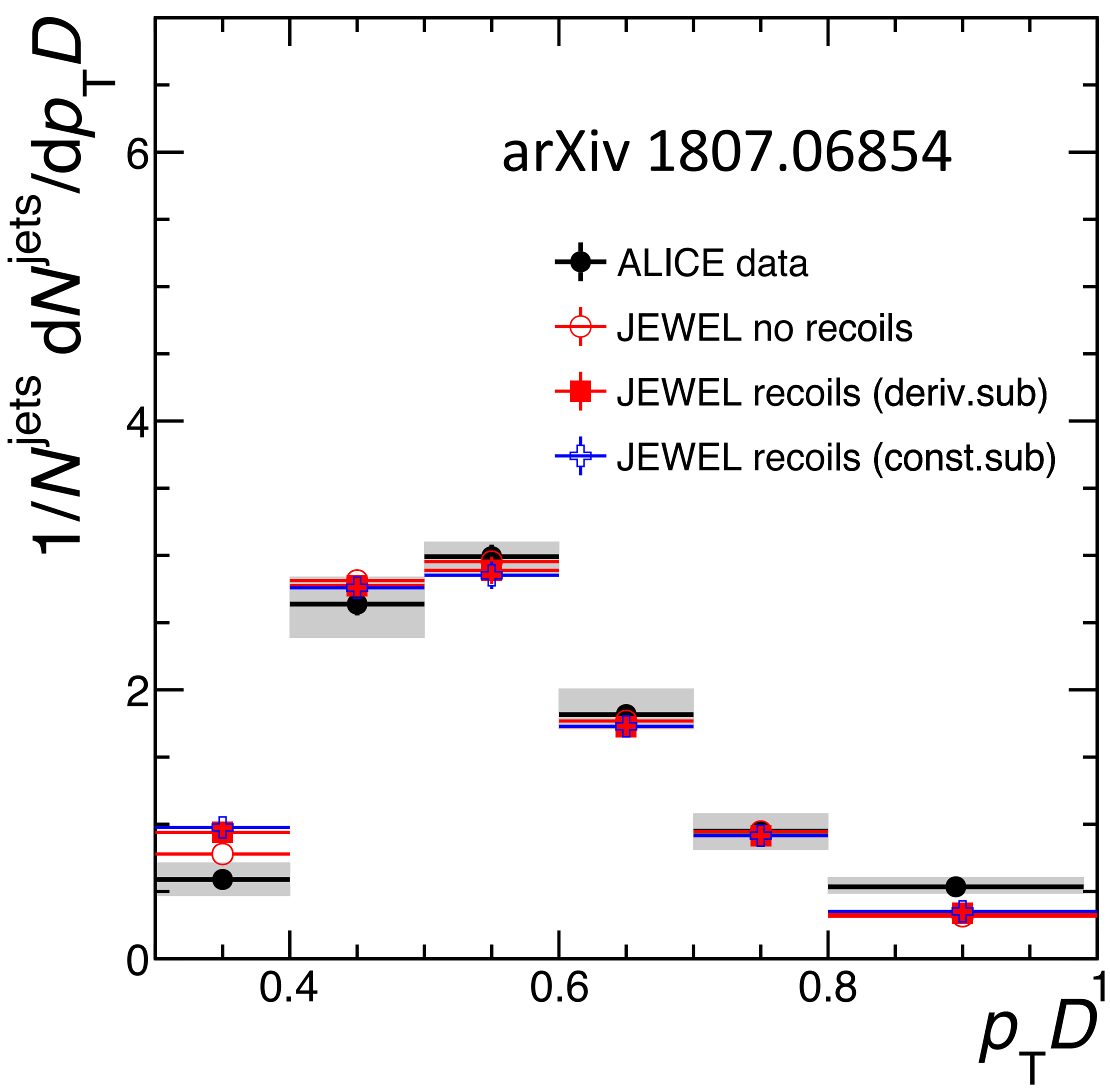
$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dn_{\text{ch}}}{dz}$$

What have we learned about jet modification?

4. Medium recoil is important to understand

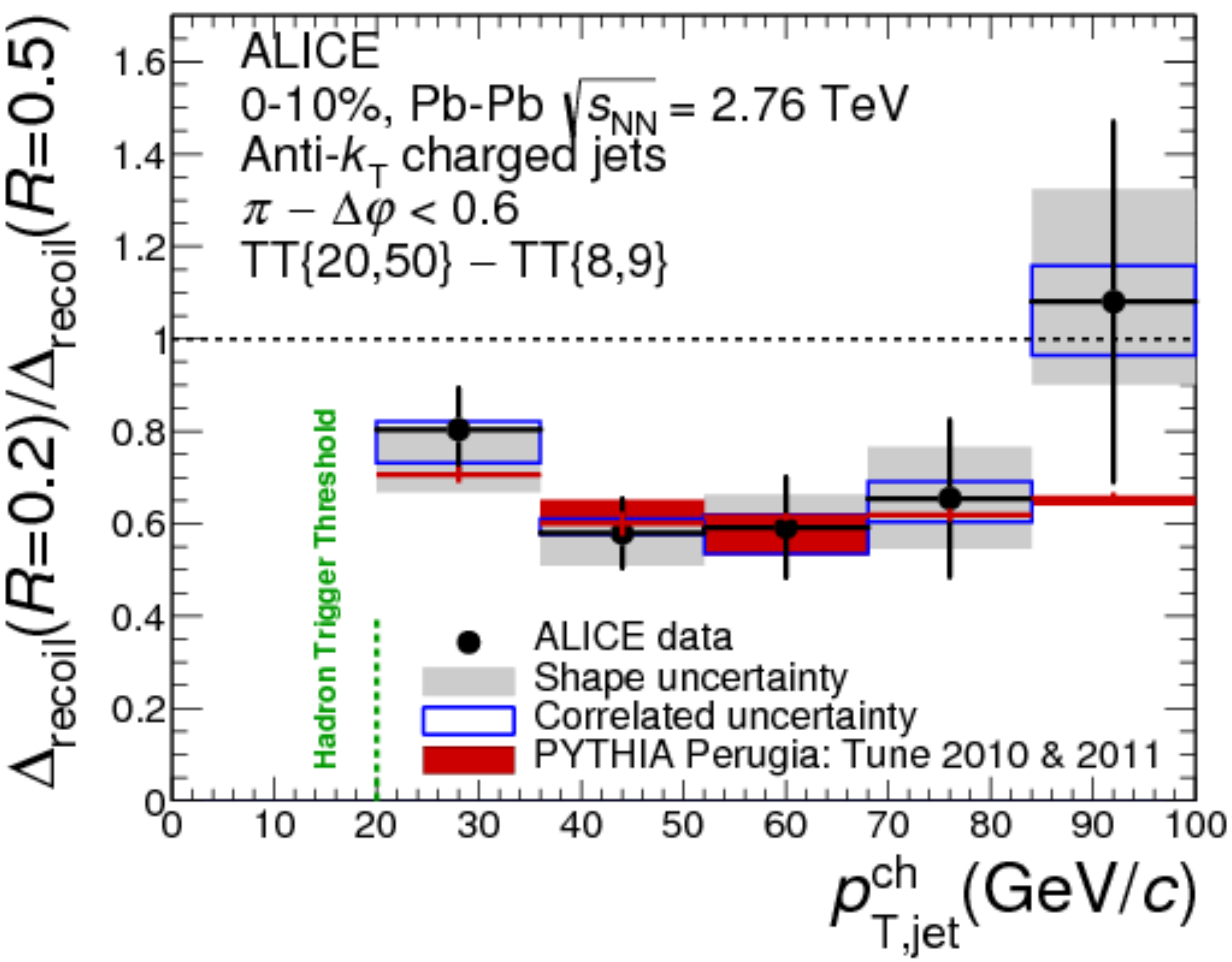
However the radial moment and momentum dispersion for ***R*=0.2** jets in Pb-Pb does not appear to be sensitive to medium recoil





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

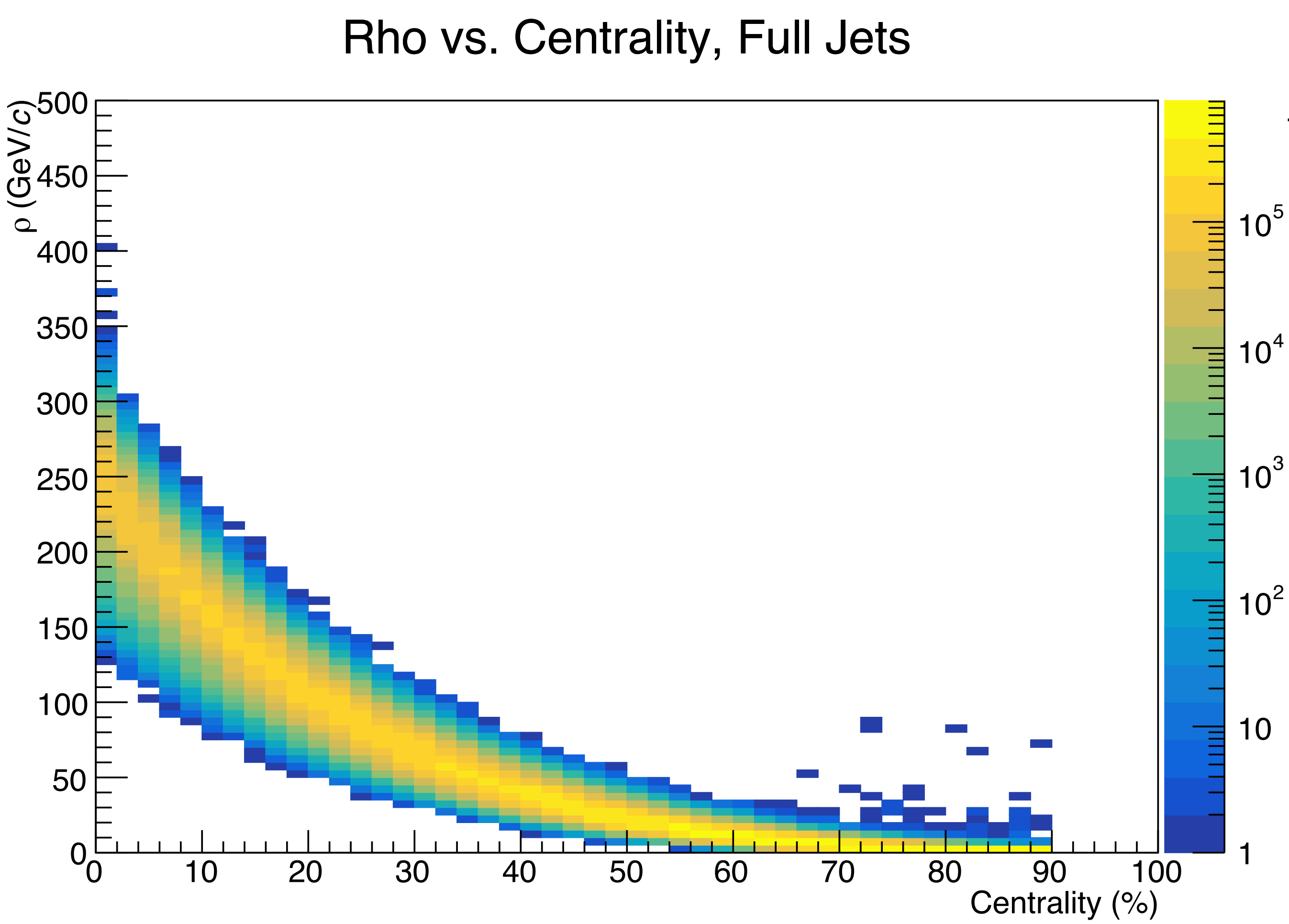
JHEP 09 (2015) 170



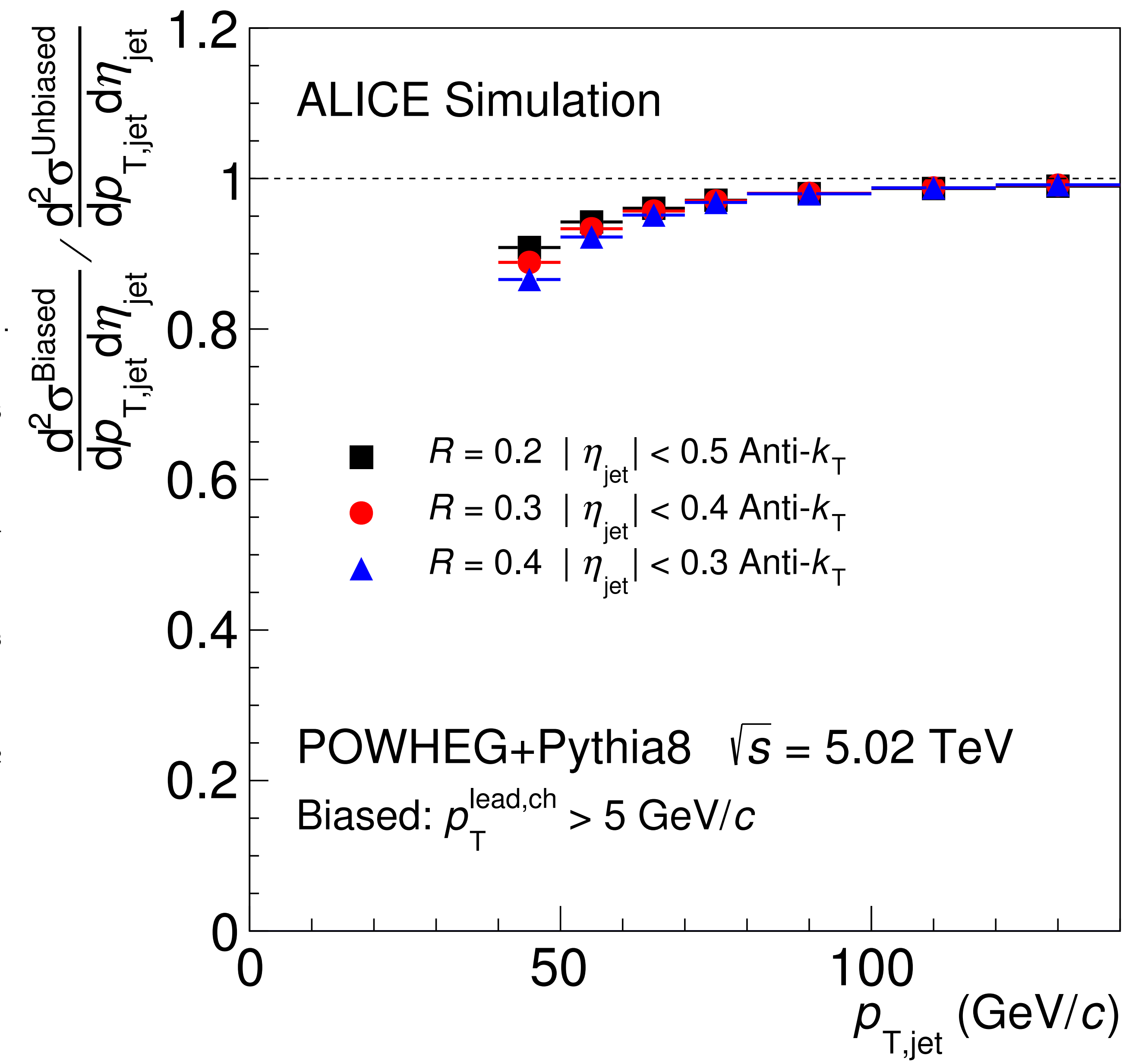
ALICE hadron-jet coincidence measurement shows no significant intra-jet broadening from R=0.2 to R=0.5

Analysis strategy — background

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

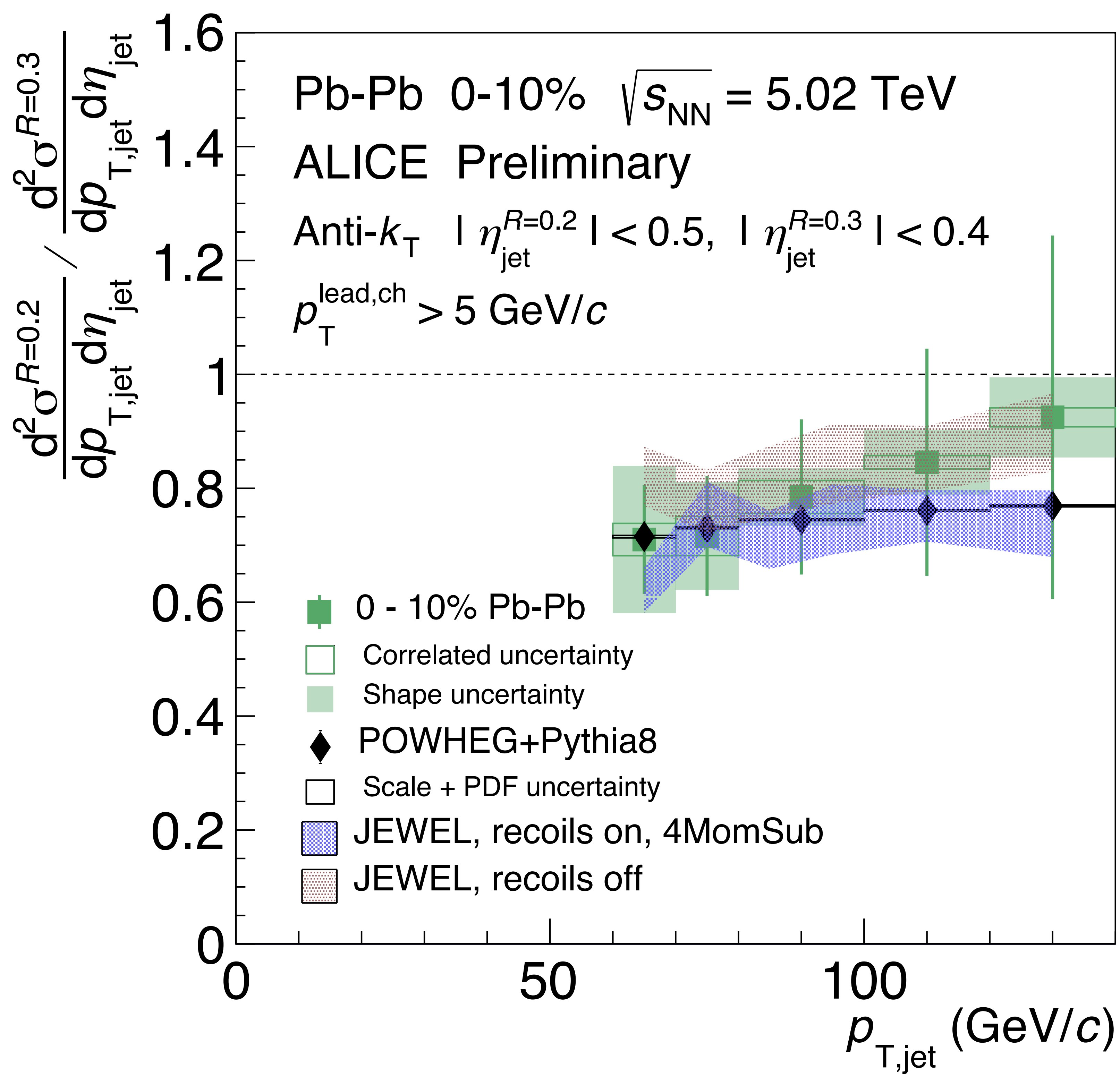


Suppress combinatorial jets by requiring jets to contain a 5 GeV/*c* charged track



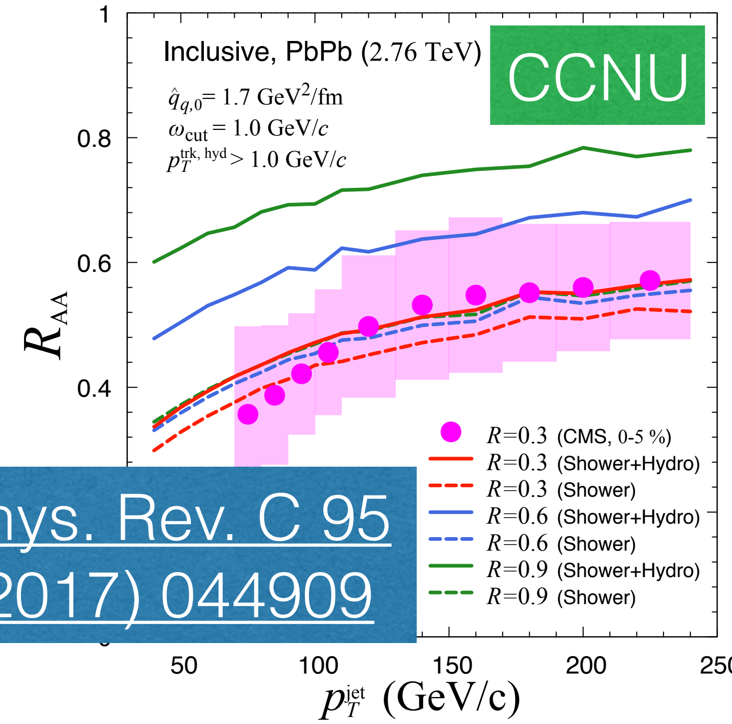
ALI-SIMUL-148684

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

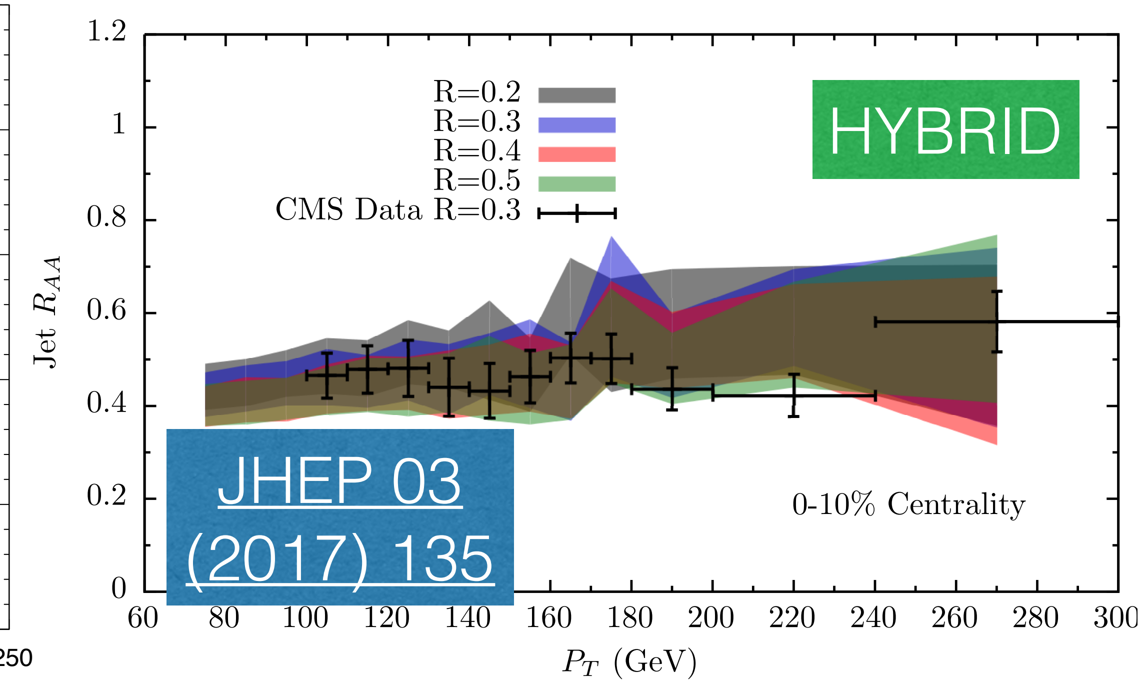


Scanning Jet Radius to Study Quenching

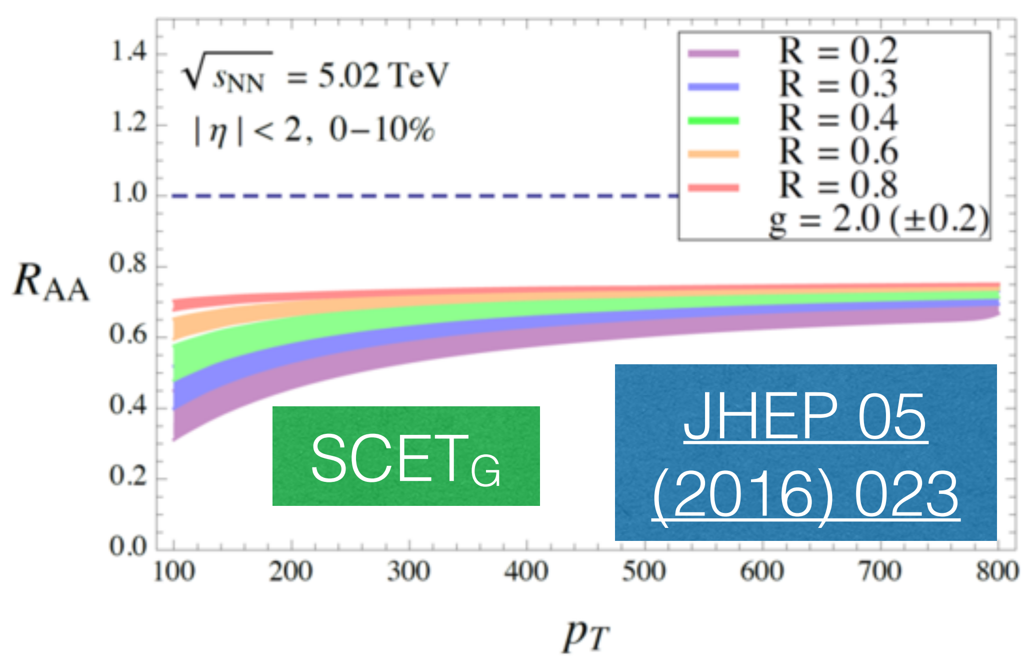
- **THEORY**
- More ambitious than experiments
- Scanning R=0.2 thru R=1.0
- Magnitude of R dependence varies with model
- Sensitive to:
  - Angular redistribution of energy
  - Medium Response



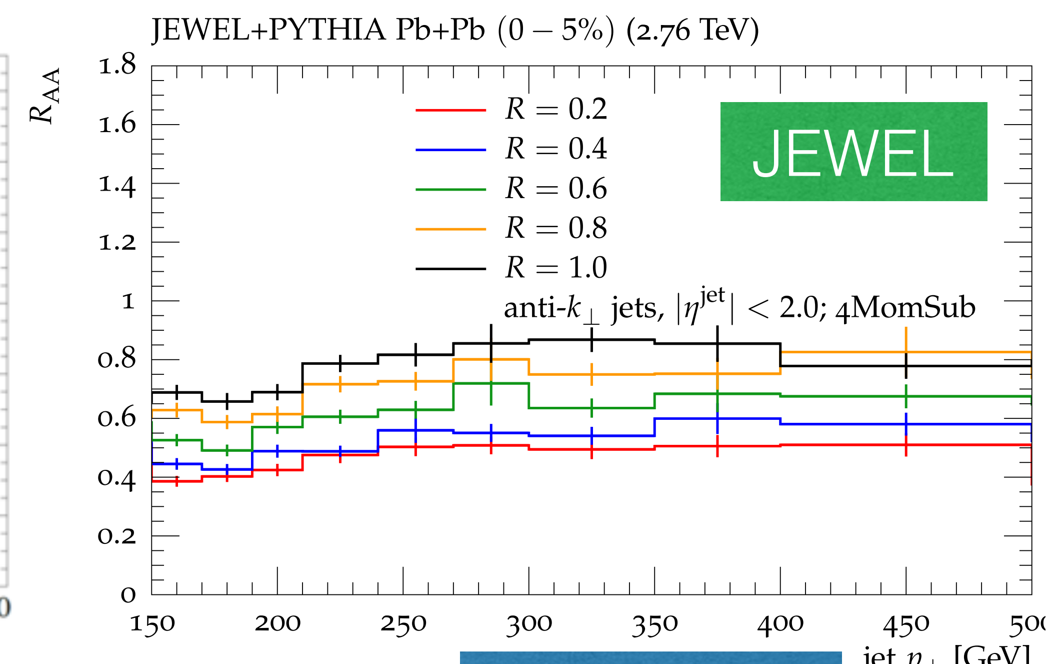
Phys. Rev. C 95 (2017) 044909



JHEP 03 (2017) 135



JHEP 05 (2016) 023

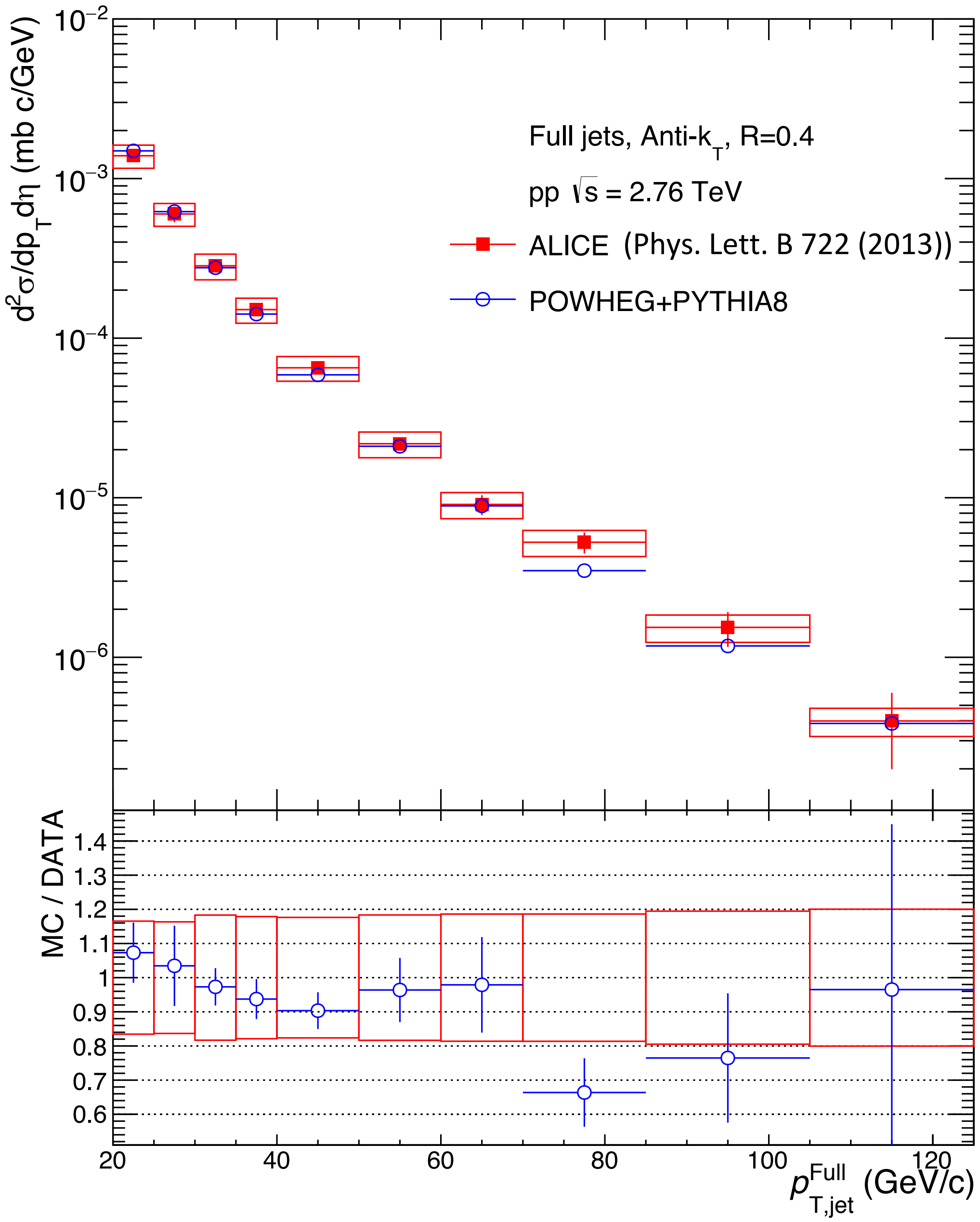


JHEP 1707 (2017) 141

2.76 TeV pp comparison

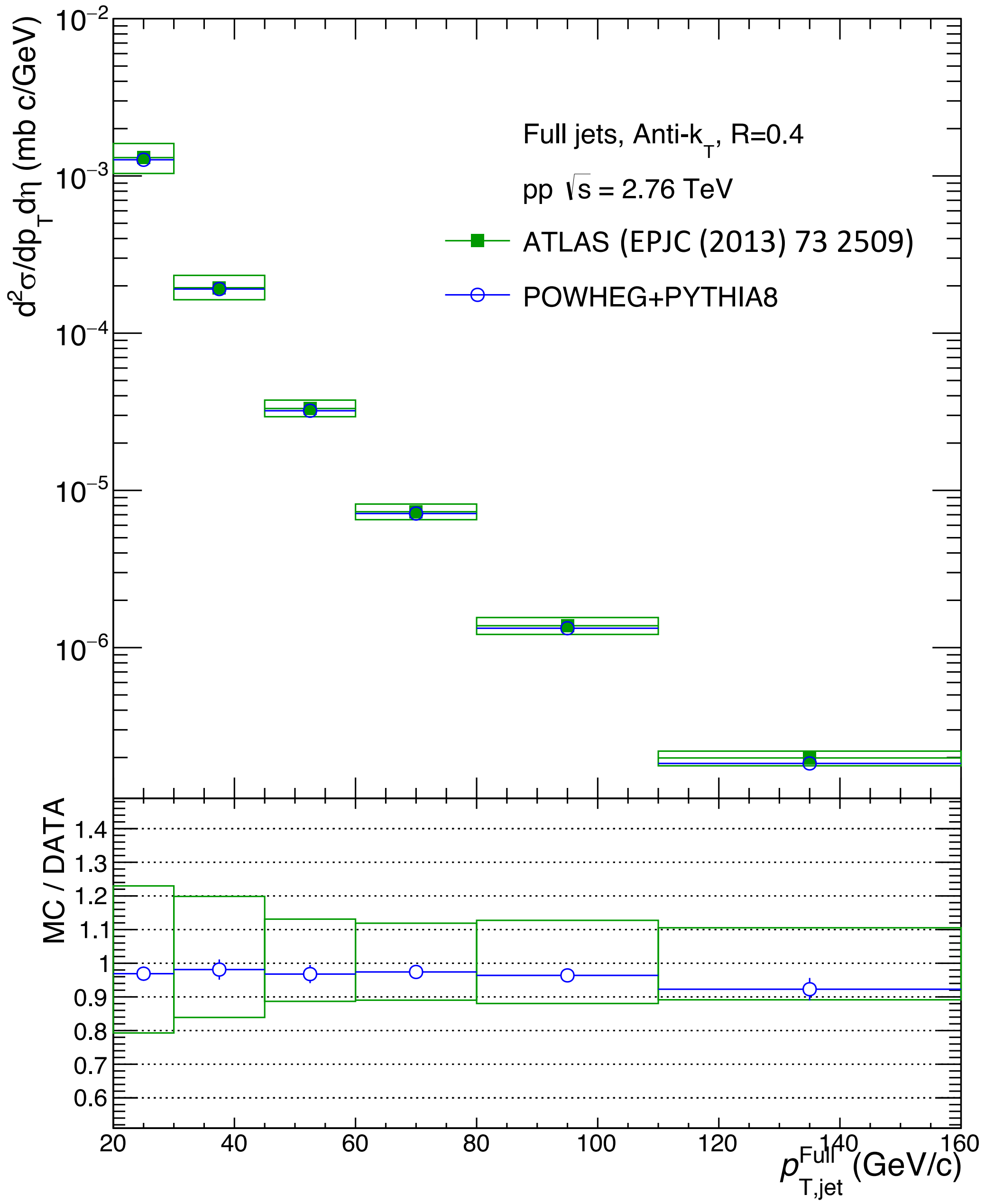
Courtesy of Ritsuya Hosokawa

- ALICE vs POWHEG



- Good agreement within ~10% except at few bins

- ATLAS vs POWHEG



- Good agreement within ~8%

Quark-gluon ratio

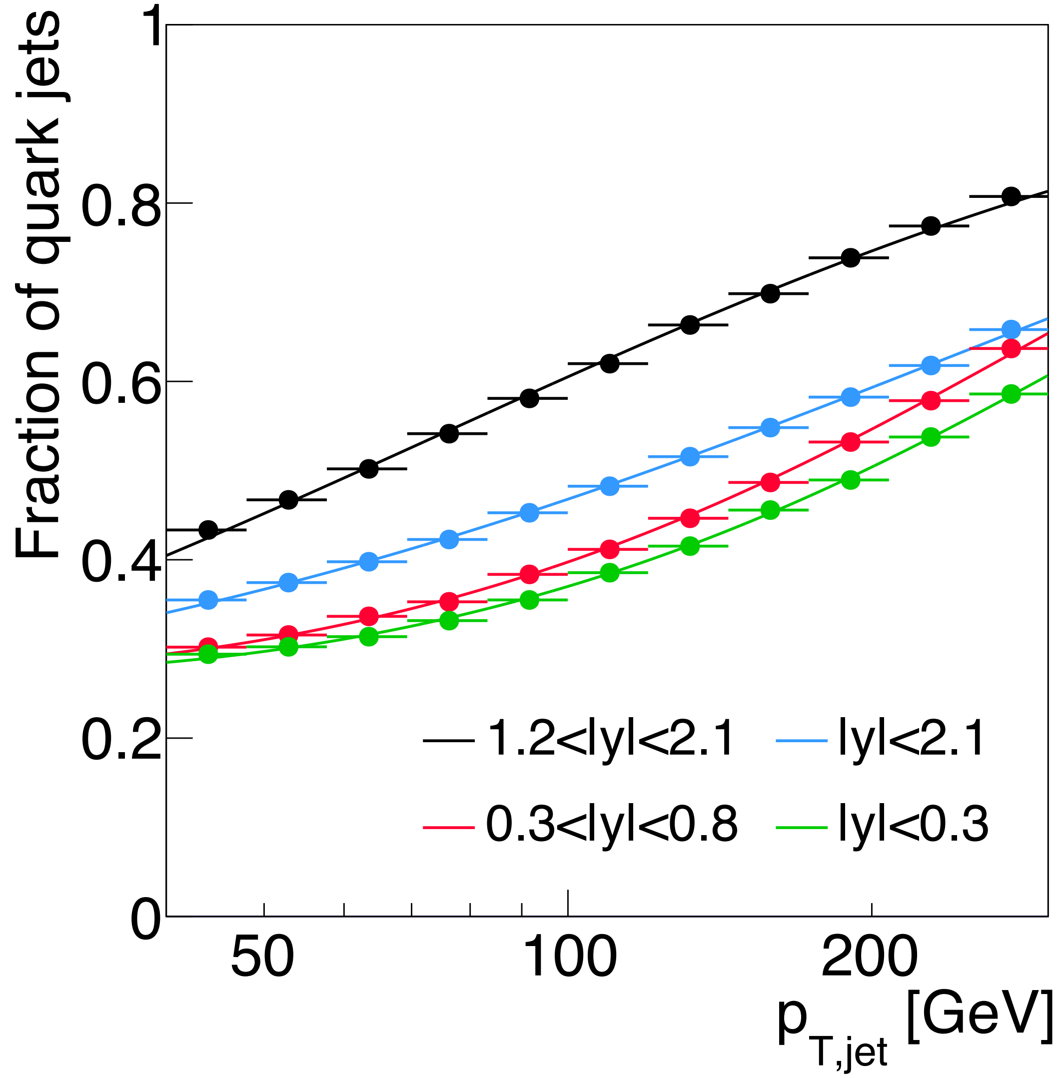
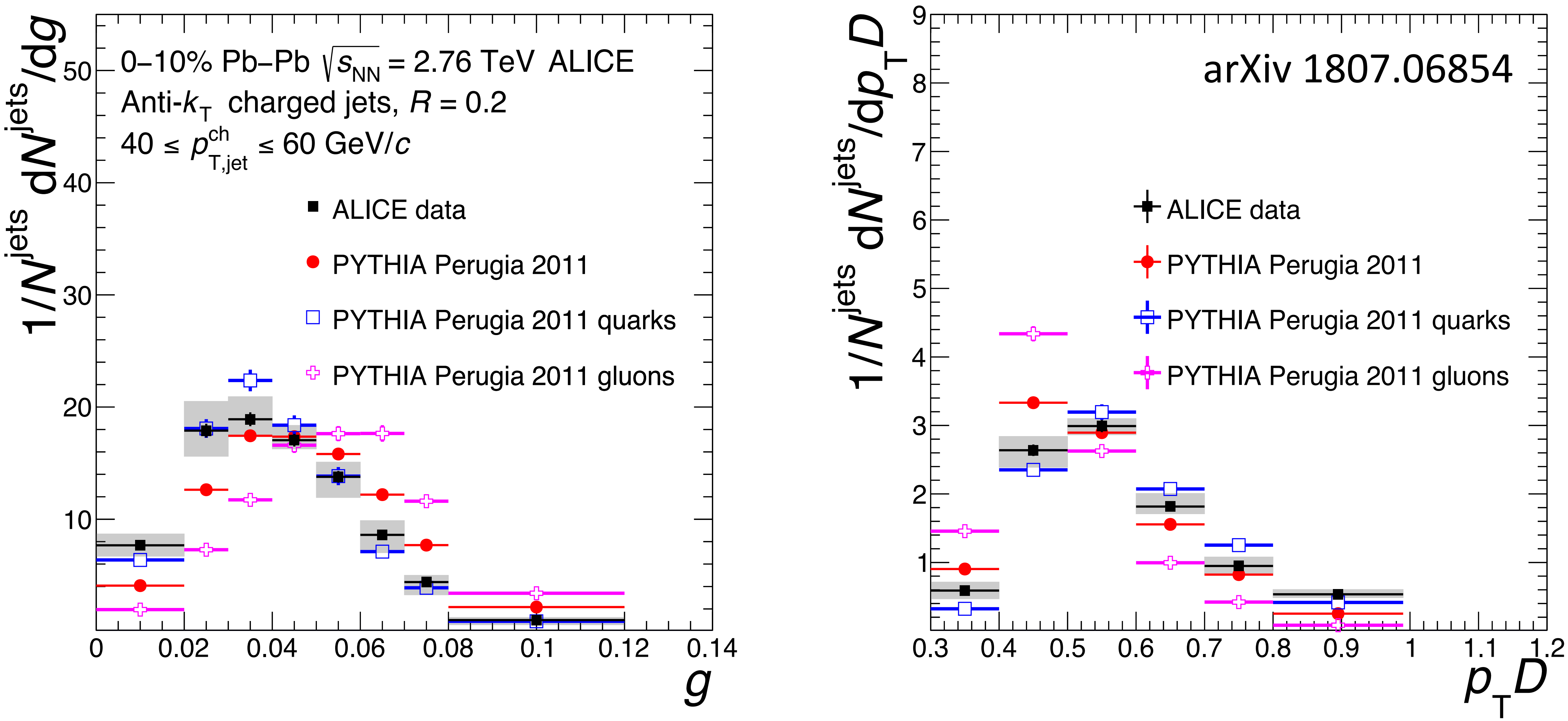


Figure 2: Jet quark fraction as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$ in the different jet rapidity intervals used in this study. The points show results obtained from PYTHIA8 simulations, the solid lines represent results obtained from extended power-law fits with the parameters shown in Table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

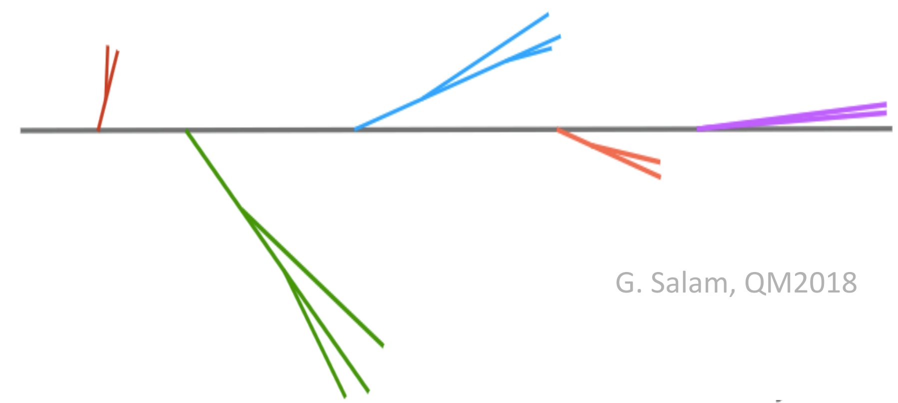
How is the jet core modified?

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



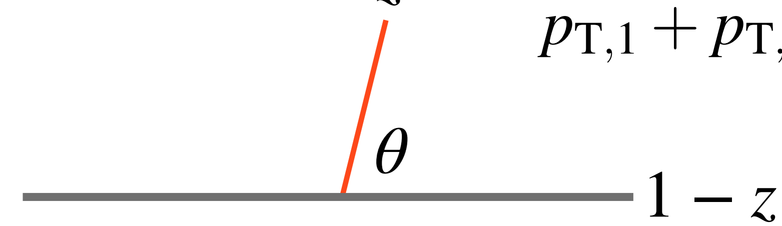
Groomed jet substructure

- 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



G. Salam, QM2018

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

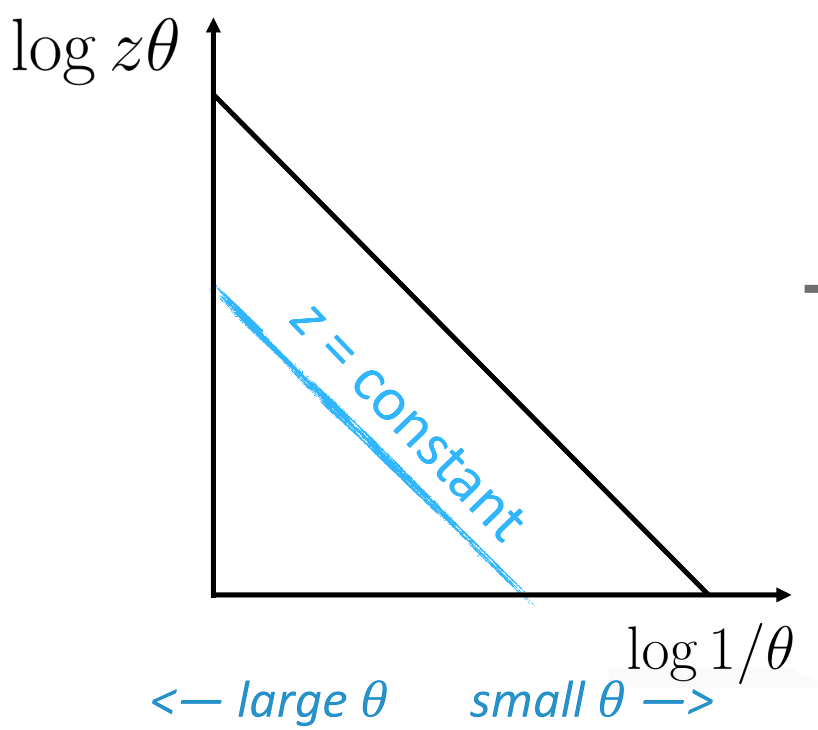


- The resulting hard splittings are described by:
  - n_{SD} is the number of splittings that pass the Soft Drop condition
  - z_g, R_g describe the momentum fraction and angular separation of the **first** splitting

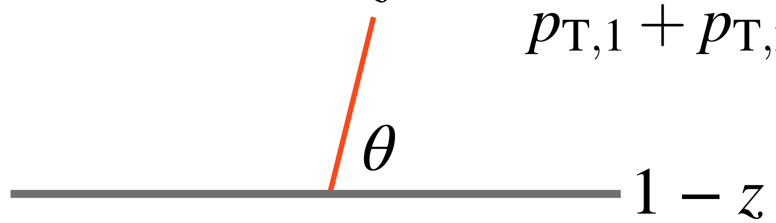
We use
$(z_{\text{cut}}, \beta) = (0.1, 0)$

Groomed jet substructure

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



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

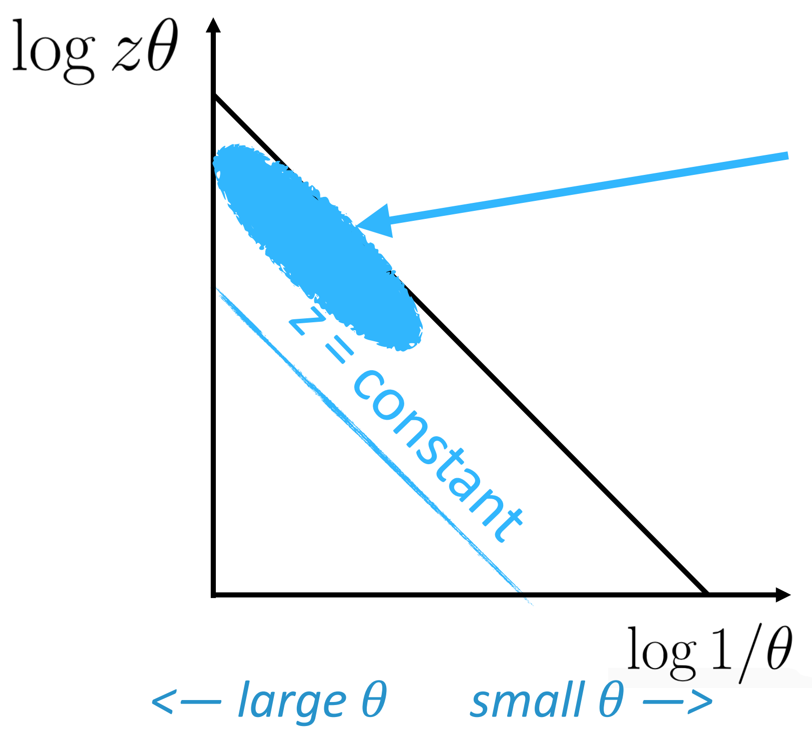


- By varying the Soft Drop parameters z_{cut}, β one can vary the phase space populated in the Lund diagram

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

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

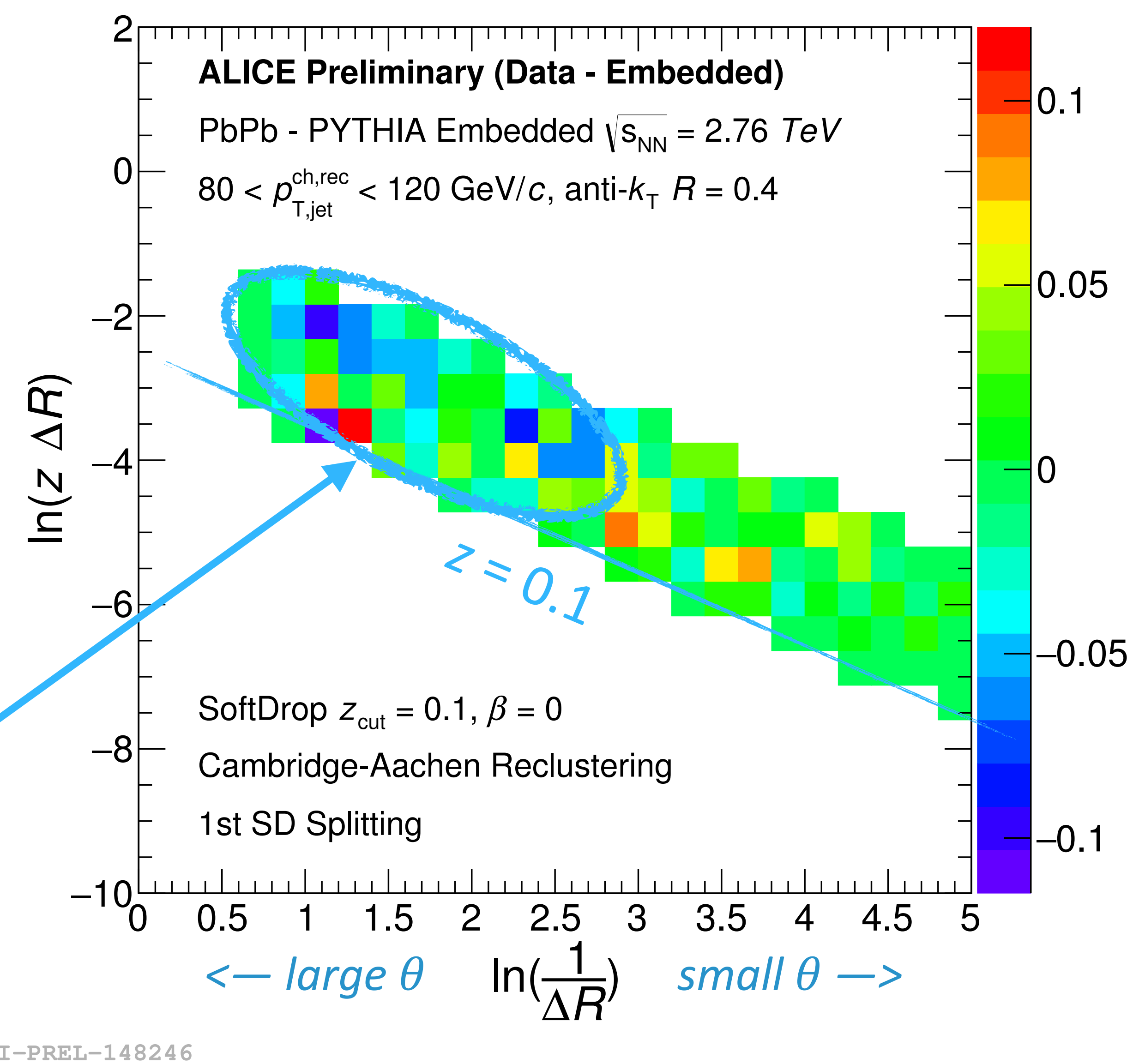
$$z > z_{\mathrm{cut}} \left(\frac{\Delta R}{R_0}\right)^{\beta}$$

Groomed jet substructure – Pb-Pb

- Pb-Pb measurement at $\sqrt{s_{\rm NN}} = 2.76$ TeV
  - R = 0.4, $p_{\rm T}$ = 80-120 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!

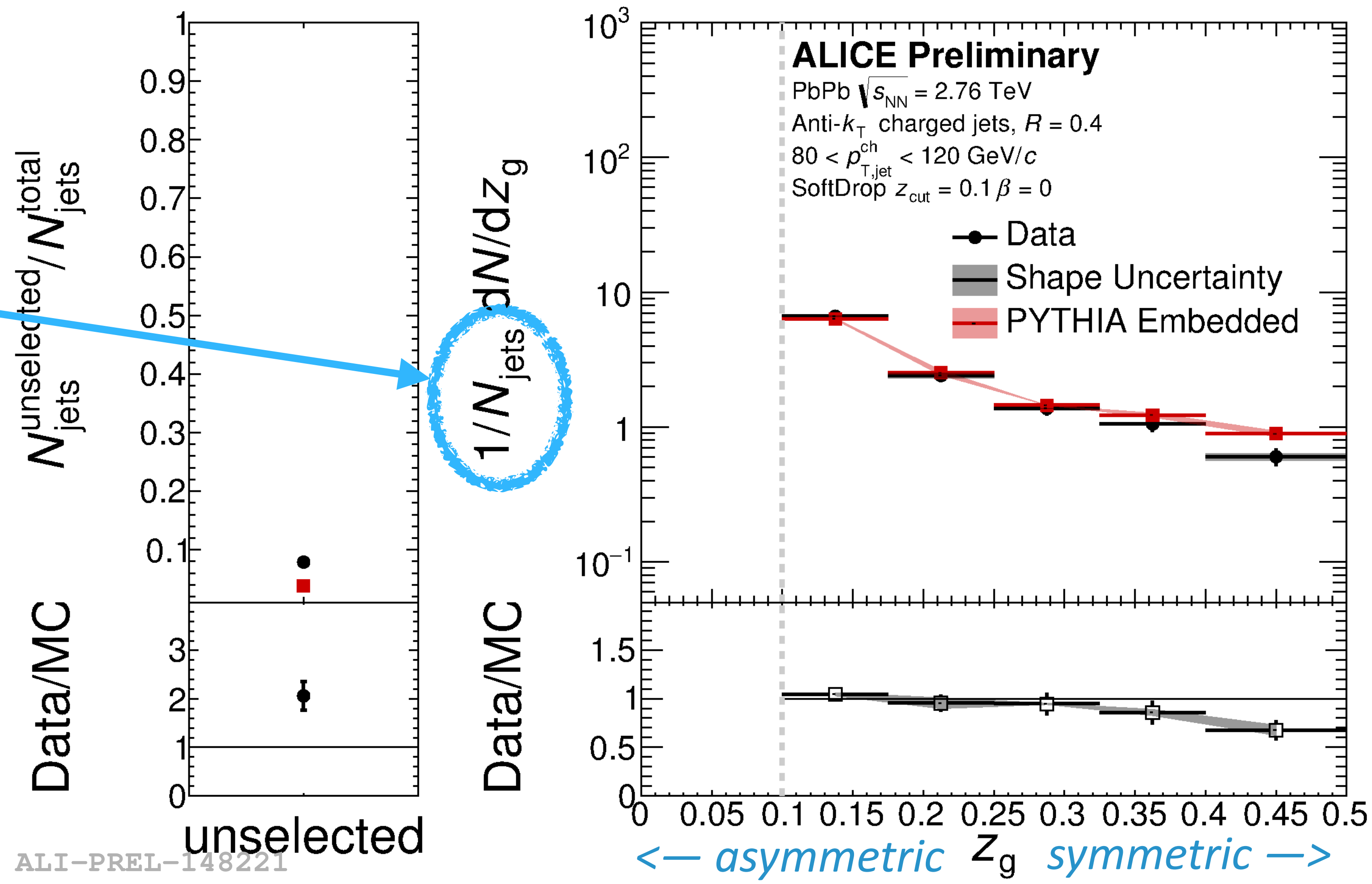


Groomed jet substructure – Pb-Pb

- 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

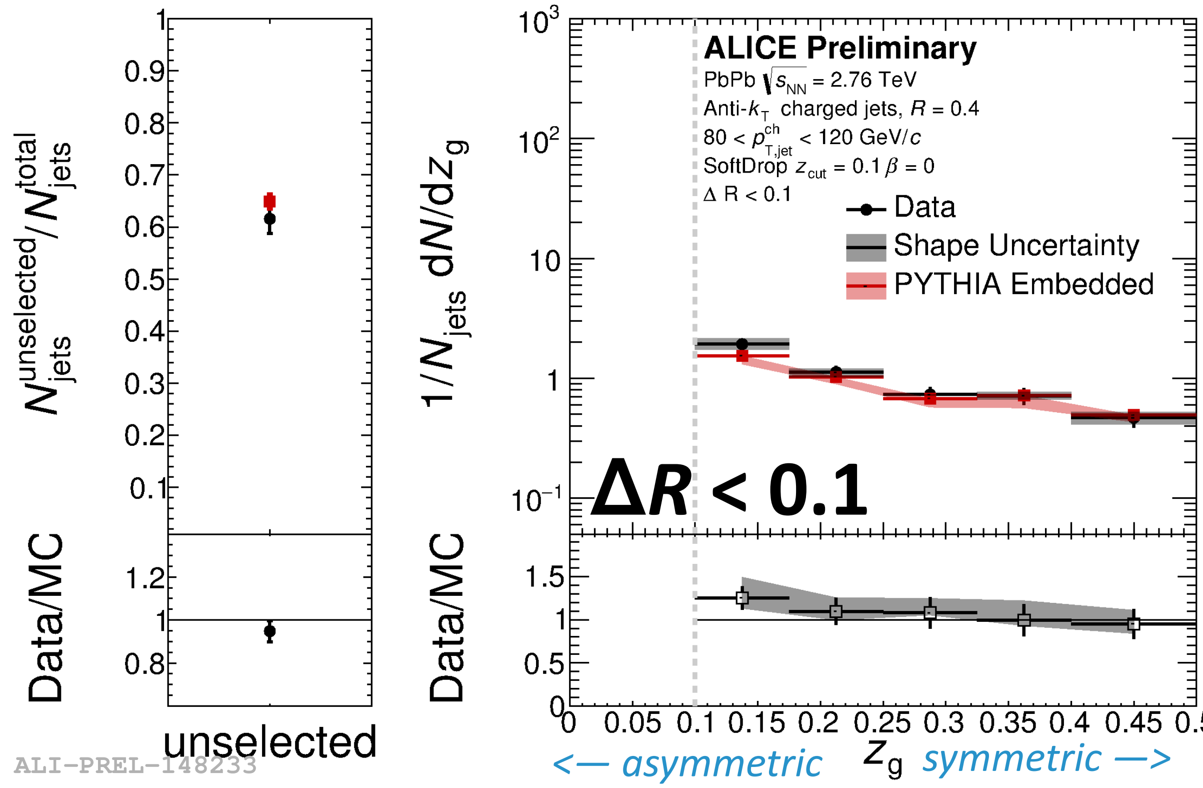
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

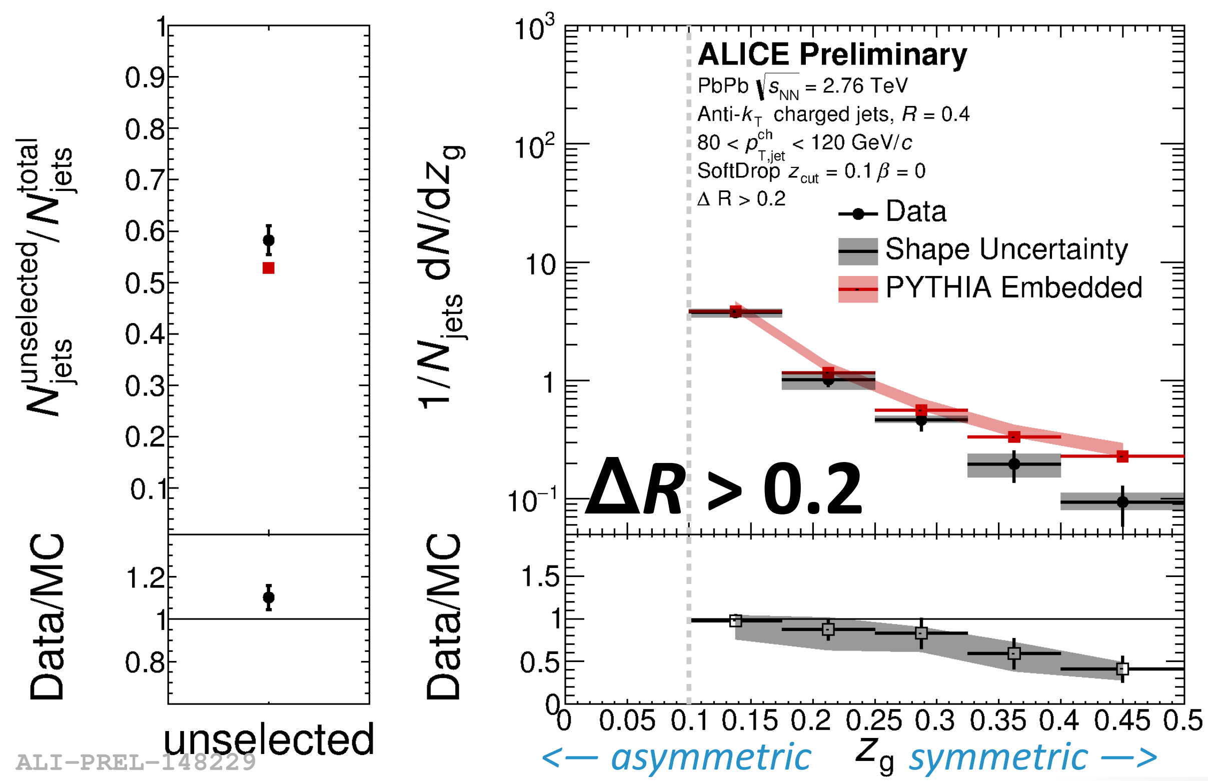
In order to interpret the results as absolute suppression/ enhancement, **must normalize by the number of inclusive jets**, including those that do not pass the Soft Drop condition



Groomed jet substructure – Pb-Pb

- The groomed sub-jet sample is then examined in two subsamples, depending on the ΔR between the two sub-jets
  - **ΔR < 0.1**: small enhancement of collinear splittings at small z_g
  - **ΔR > 0.2**: depletion of large-angle splittings at large z_g





Groomed jet substructure – Pb-Pb

- n_{SD} is the number of splittings that satisfy the Soft Drop condition
- For $1 \leq n_{SD} \leq 7$, there is no significant modification in Pb-Pb compared to embedded Pythia
- For $n_{SD} = 0$, there is slight enhancement in the number of jets that fail the Soft Drop condition