Jet measurements with ALICE

James Mulligan
(UC Berkeley / LBNL)

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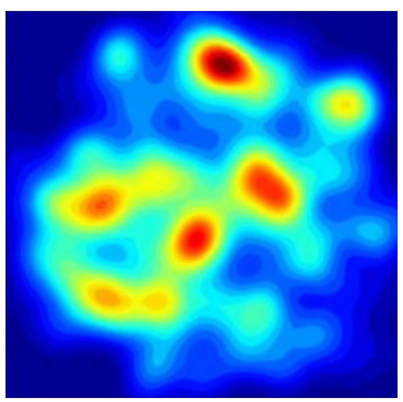
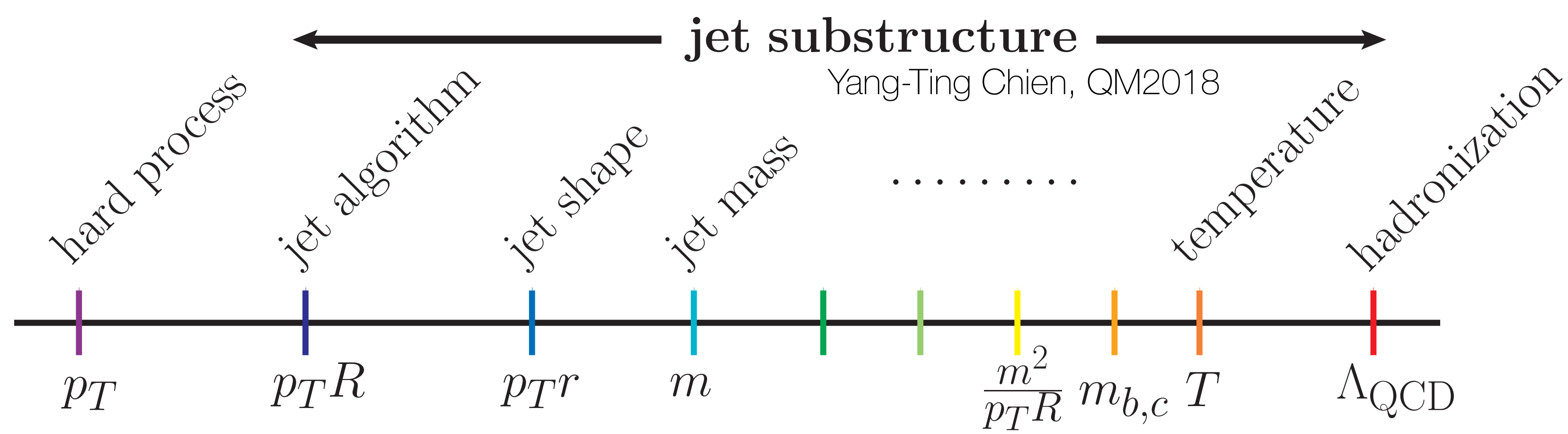
UT Knoxville

Jets to probe QCD matter

We want to answer **big** questions about QCD:

- What are the degrees of freedom of deconfined QCD?
- How do deconfined QCD transport properties arise?
- Does QCD factorization hold in AA?





Why do we think **jets** may eventually lead to some answers?

- Jets are calculable in pQCD
- Jets capture parton dynamics
- Jets probe a wide range of scales
- Jets have rich observables

There are a variety of directions to go…

Why is jet $R_{AA} < 1$ at $p_T = O(\text{TeV})$?

What is the relative suppression of g vs. q?

What is the parton flavor dependence at low p_T?

What is the source of the large-angle soft excess?

What causes jet v_2?

Are there really *no* cold nuclear matter effects for midrapidity jets?

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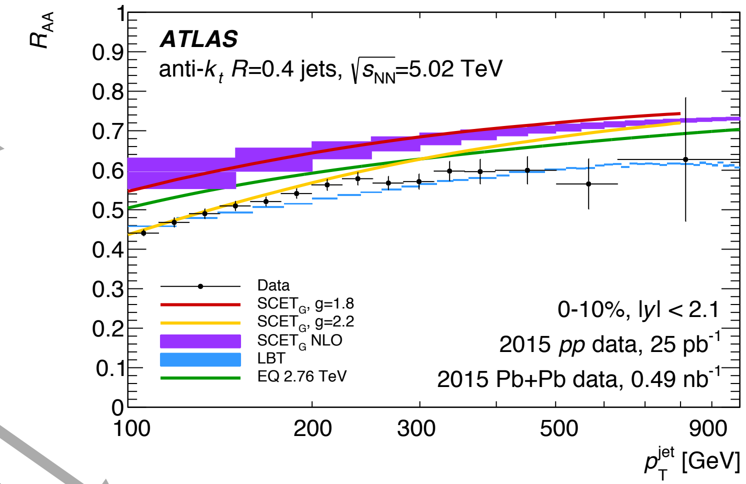
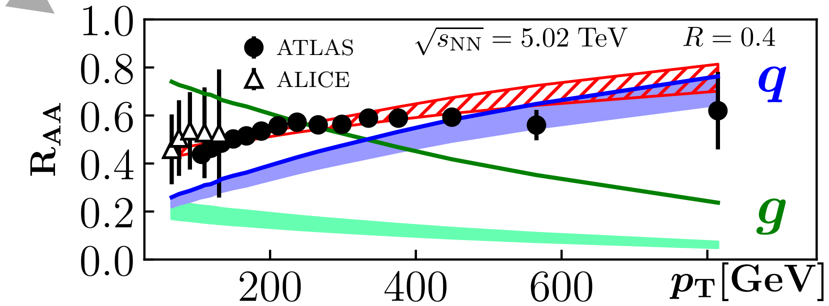
PLB 790 108-128 (2019)





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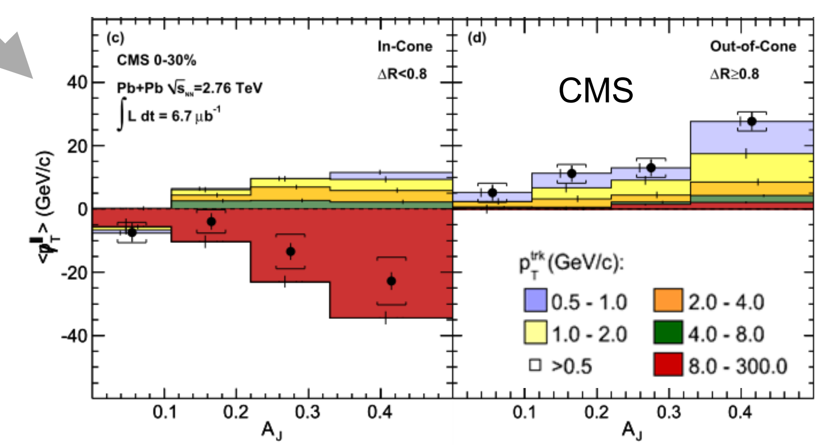
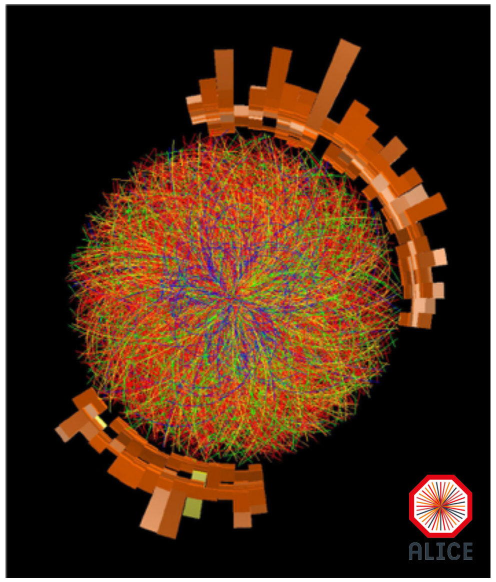


Phys. Rev. C 84 (024906)

Jets in ALICE

Charged particle jets (most ALICE measurements)

- Pro: Experimentally simpler
- Con: Additional modeling to compare to theory
- Well-resolved particles for substructure



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

- Pro: Direct comparison to theory
- Con: Significant experimental complication
- Limited EMCal coverage

ALICE is very good for:

- Jet substructure
- Particle Identification
- Low-p_T tracks: 150 MeV/c
  - Medium recoil particles

ALICE is not good for:

- High statistics
- High p_T > ~100 GeV
- Jets at forward/ backward rapidity

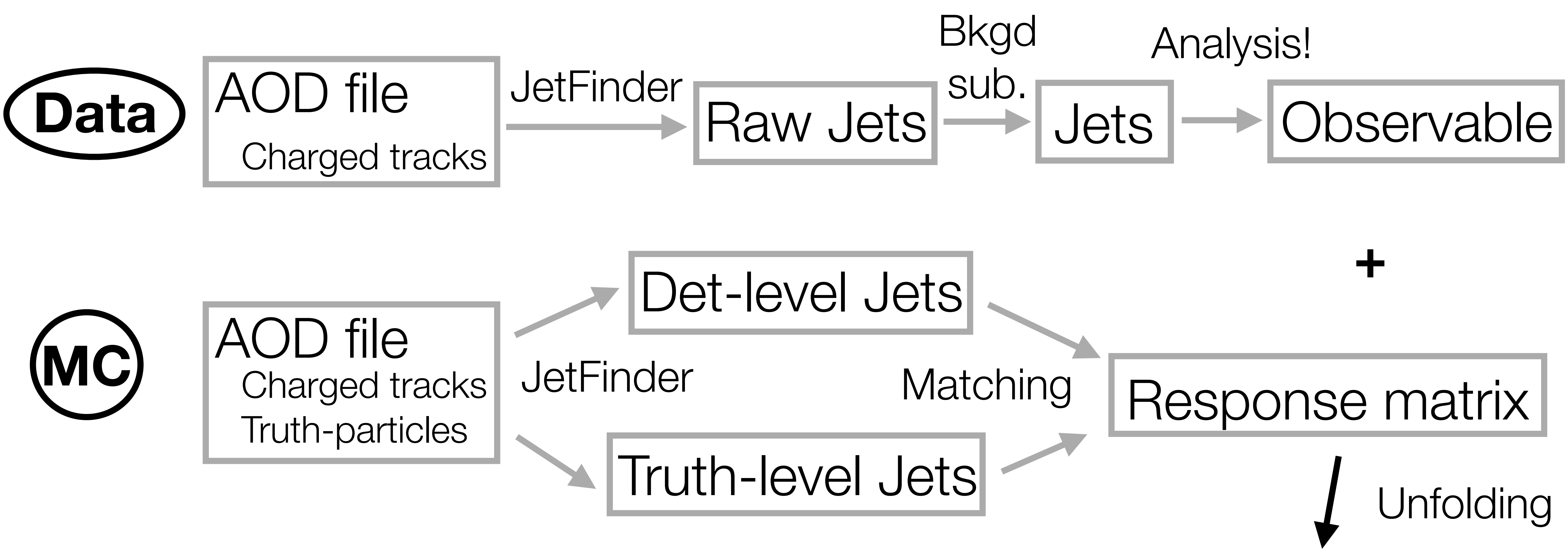
Jet analysis in ALICE: Practical information

Documentation: http://alidoc.cern.ch/AliPhysics/master/READMEjetfw.html

→ Includes examples that can form the basis for new analysis tasks

Note: The jet infrastructure is a community effort, please provide feedback and join the efforts!

Basic analysis steps: Example



Running your analysis

- Locally (task development, testing): See documentation
- LEGO train (full analysis): https://twiki.cern.ch/twiki/bin/viewauth/ALICE/AnalysisTrains
  Send request to: alice-analysis-emcal-jet-train@cern.ch

Current activity in PWG-JE

Recent/ongoing analyses

- Inclusive jets
- Jet correlations
  - Jet-hadron correlations
  - Gamma/pi0-hadron/jet correlations
  - Hadron-jet recoil measurements
- Jet substructure
  - Groomed jet substructure
- Heavy flavor jets
- PID in jets

…

Lots of US involvement!

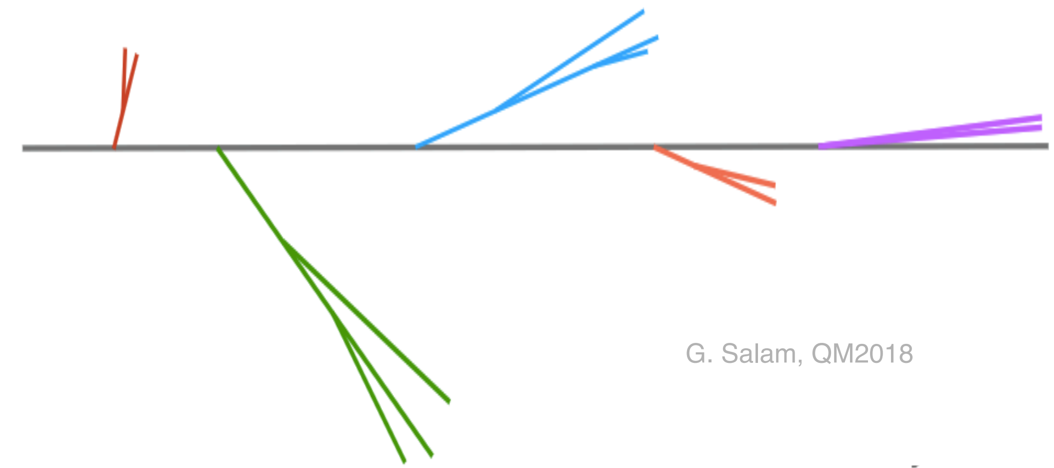
I will try to avoid talking about analyses that will be covered later today…

Groomed jet substructure

Soft Drop

M. Dasgupta et al. JHEP 1309 (2013) 029
A. Larkoski et al. JHEP 1405 (2014) 146

→ Approximately reconstruct the shower history of a jet

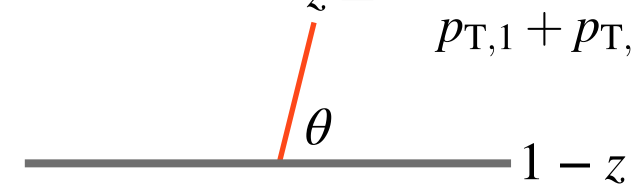


1. Cluster jets with the anti-k_T algorithm, then re-cluster each jet using the C/A algorithm
   - This produces an angularly ordered tree, similar to a parton shower
2. Unwind the last clustering step and check the Soft Drop condition: $z > z_{\mathrm{cut}} \left(\frac{\Delta R}{R_0}\right)^{\beta}$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

The resulting hard splittings are described by:

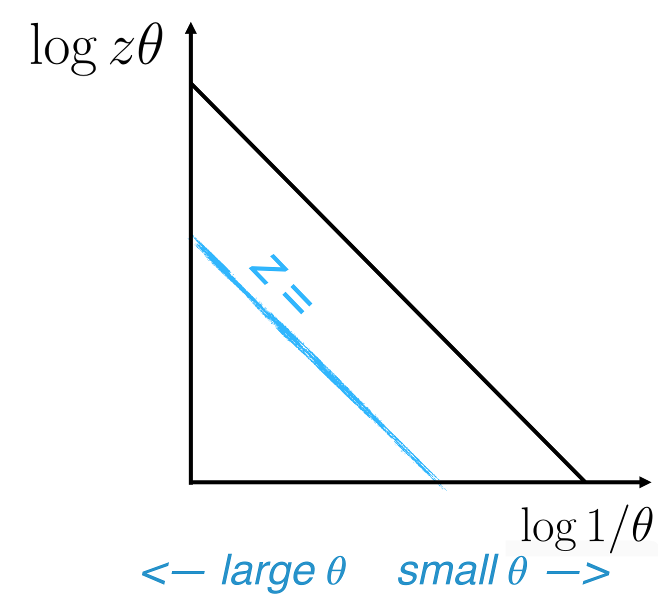
- z_g: momentum fraction of the first splitting
- R_g: angular separation of the first splitting

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



Lund diagram:

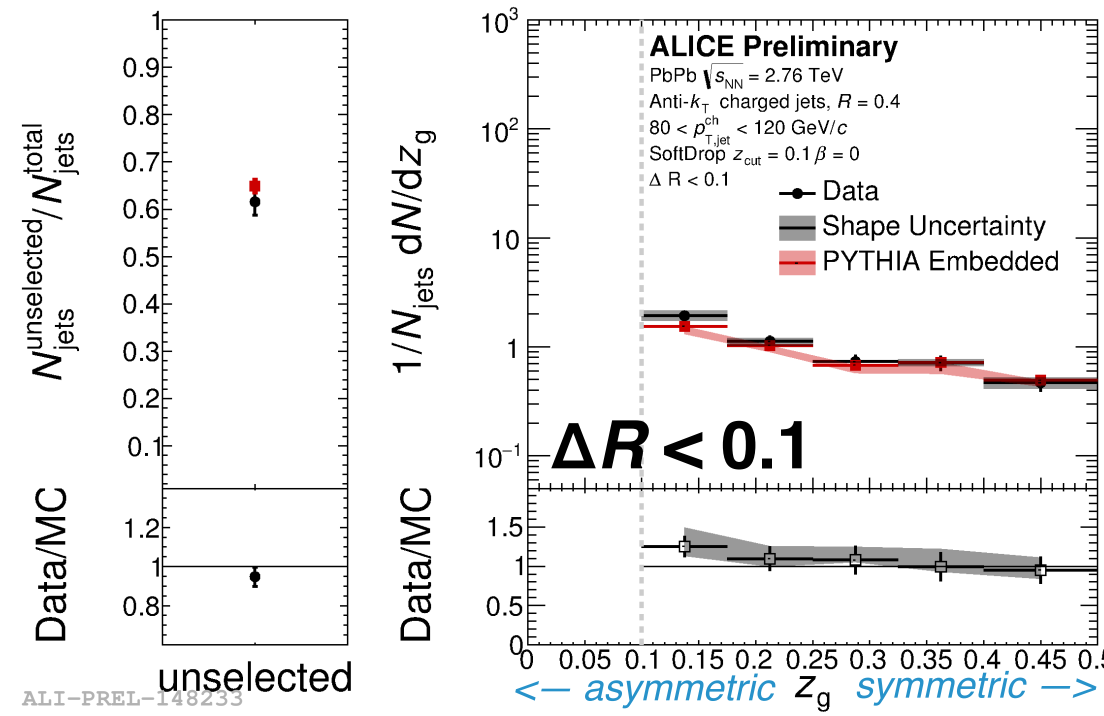
- Represents the phase-space density of 1—>2 splittings, described by (z,θ)

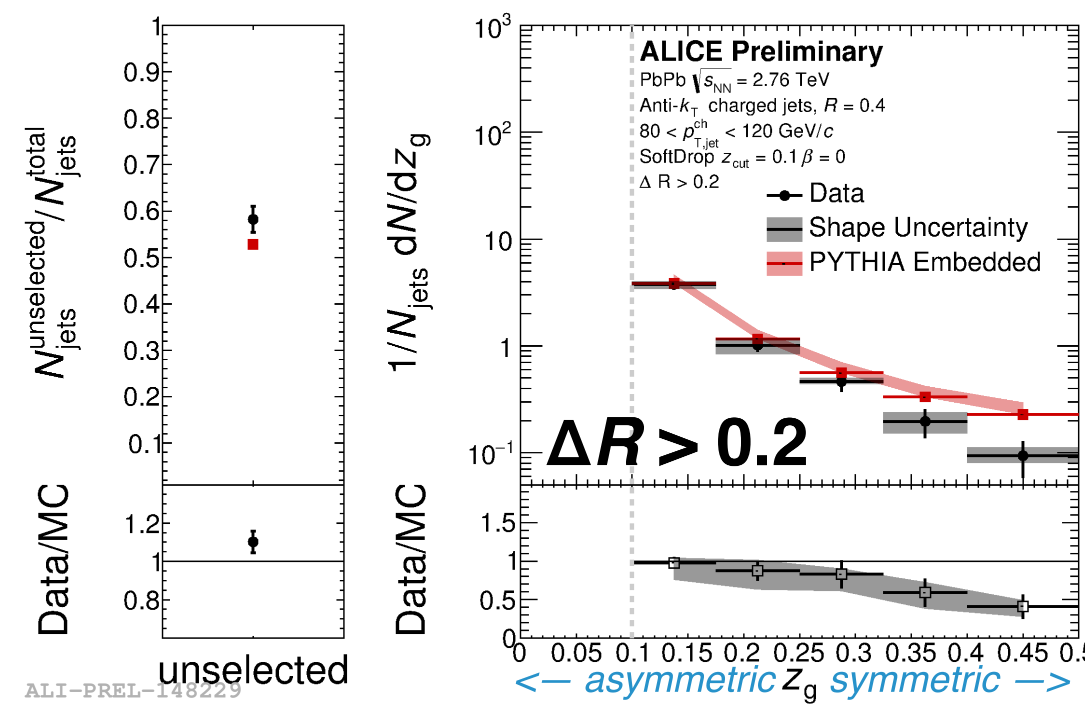


ALICE groomed jet substructure

- The groomed sub-jet sample is examined in two subsamples, depending on the ΔR between the two sub-jets
  - $\mathbf{\Delta \mathit{R} < 0.1}$: hint of enhancement of collinear splittings at small z_g
  - $\mathbf{\Delta \mathit{R} > 0.2}$: depletion of large-angle splittings at large z_g

→ Medium can resolve large-angle splittings?





Paper in collaboration review

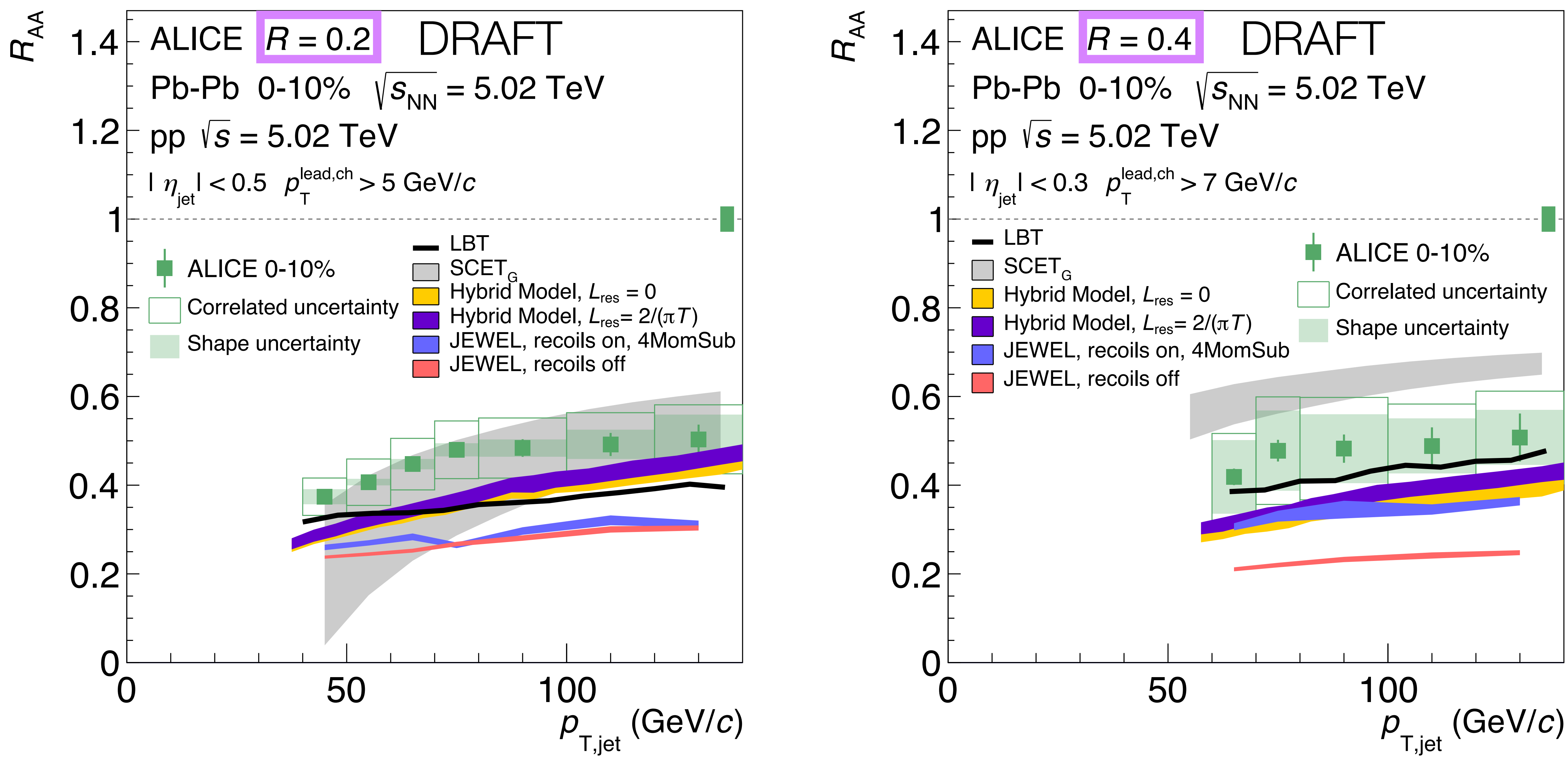
https://alice-publications.web.cern.ch/node/4745

Jet R_{AA}

Preliminary results: https://arxiv.org/abs/1812.07681
Paper in IRC review: https://alice-publications.web.cern.ch/node/4796

→ Low-p_T jet R_{AA} for multiple R

Similar suppression observed in R=0.2 and R=0.4

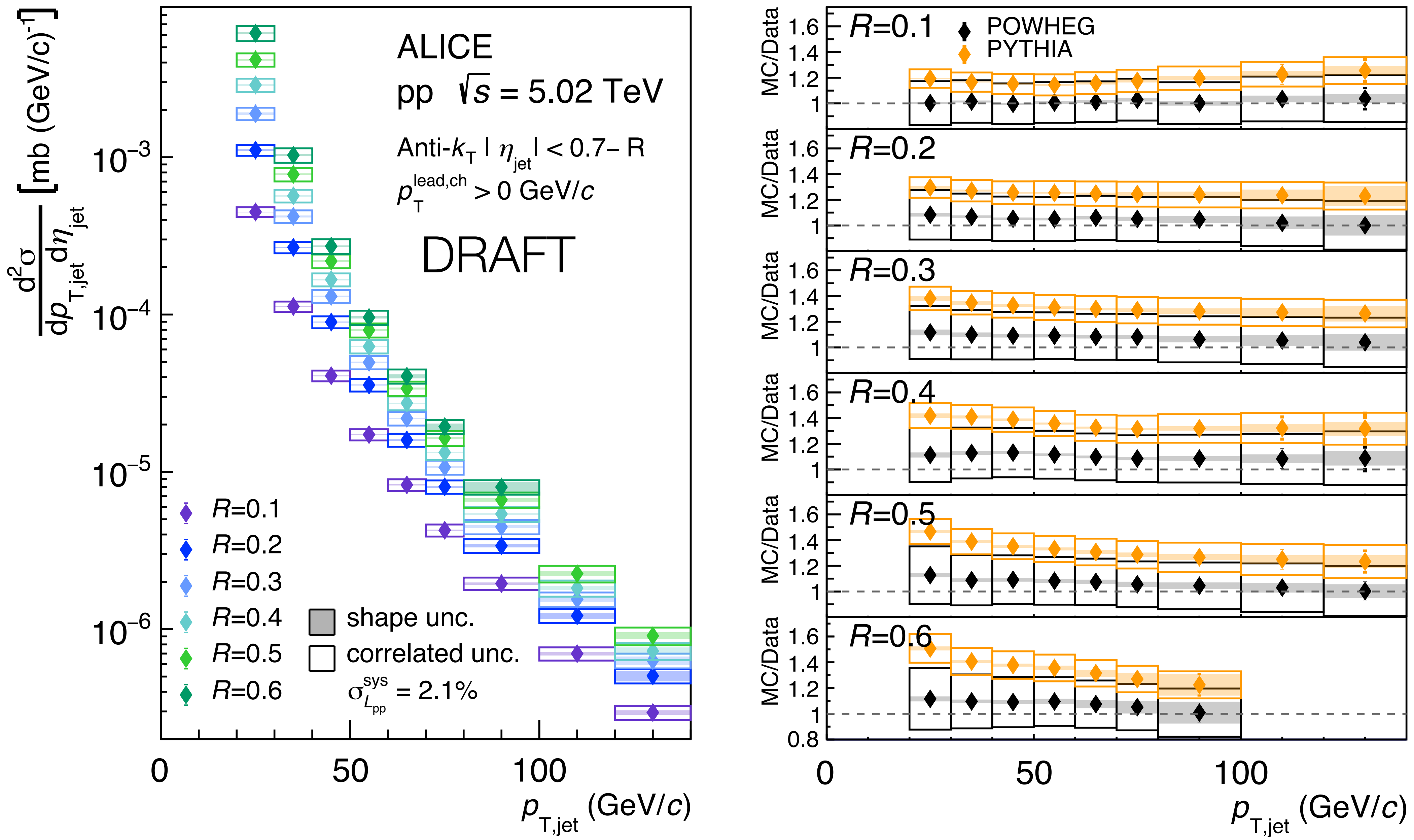


All models qualitatively describe the R_{AA}
But quantitatively, most models have slight tension with the data

pp jet cross-section

Preliminary results: https://arxiv.org/abs/1812.07681

Paper in IRC review: https://alice-publications.web.cern.ch/node/4796



Pythia: LO matrix element + LL parton shower

POWHEG + Pythia: NLO matrix element + Pythia shower

Predictions forthcoming from recent NNLO + resummation…

pp jet cross-section

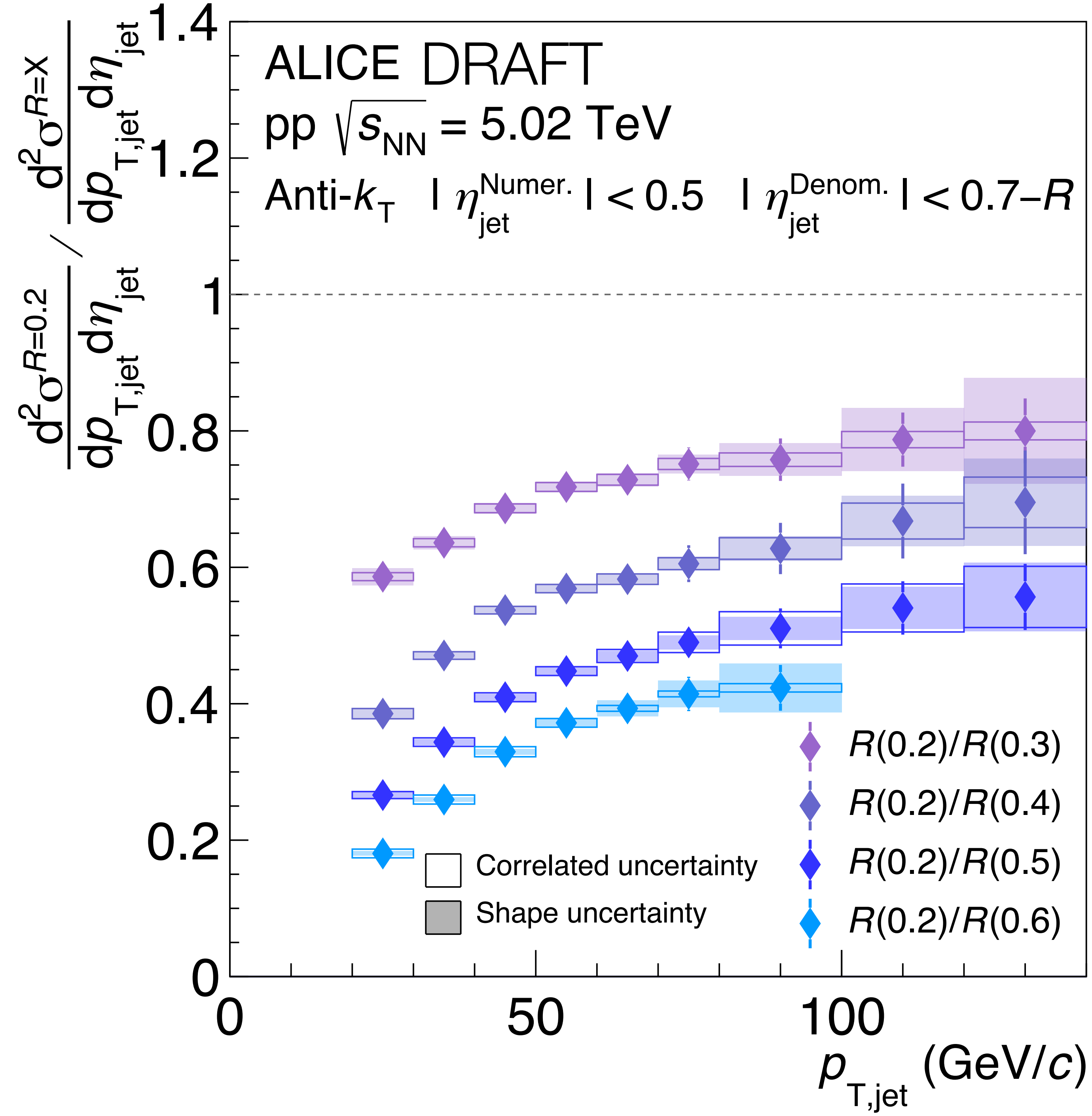
Preliminary results: https://arxiv.org/abs/1812.07681

Paper in IRC review: https://alice-publications.web.cern.ch/node/4796

The jet cross-section ratio of different R is useful to constrain the contributions to the observed cross-section from:

- pQCD
- hadronization
- underlying event

→ Precision QCD jet measurements

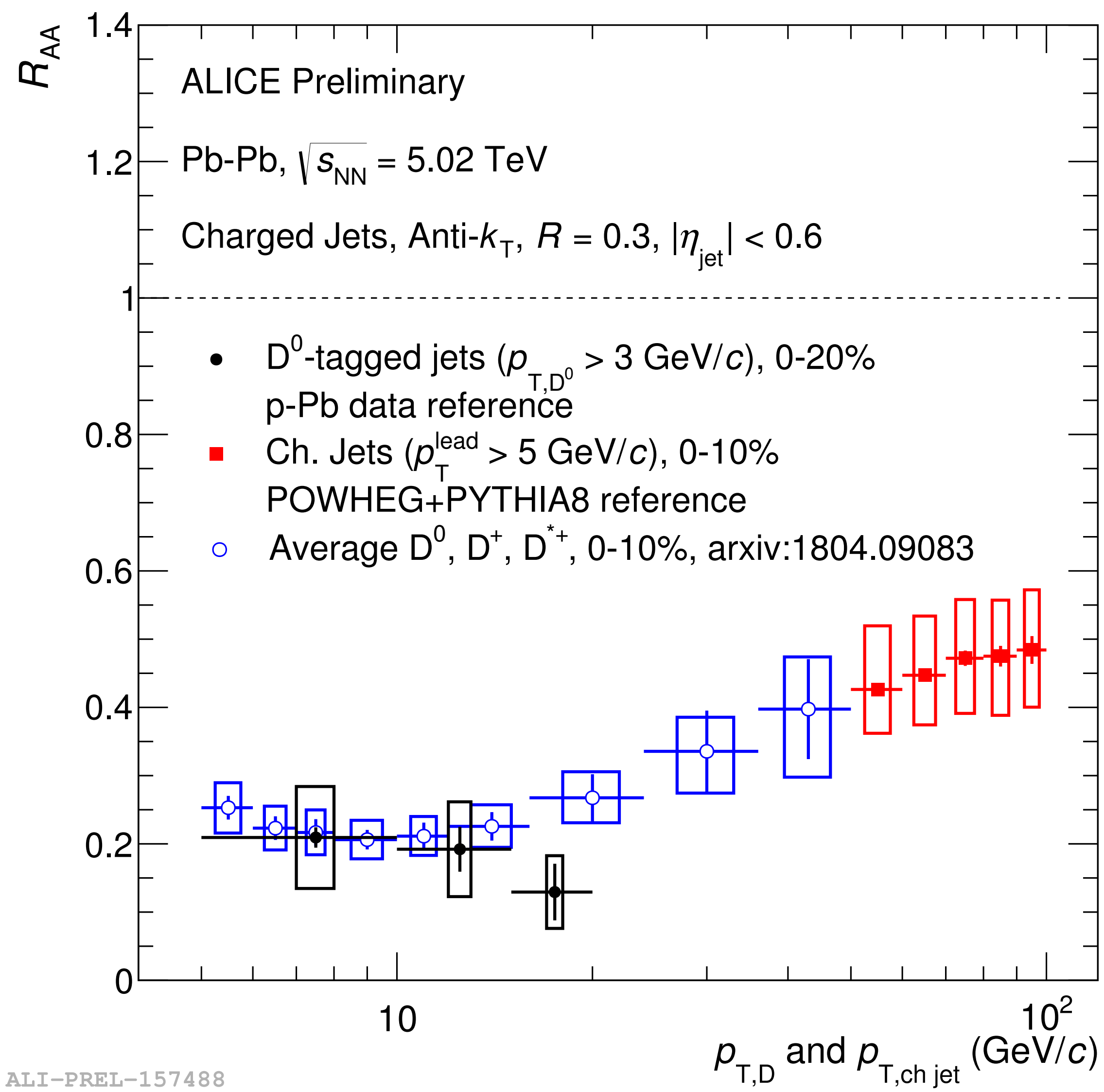


Heavy-flavor jet measurements

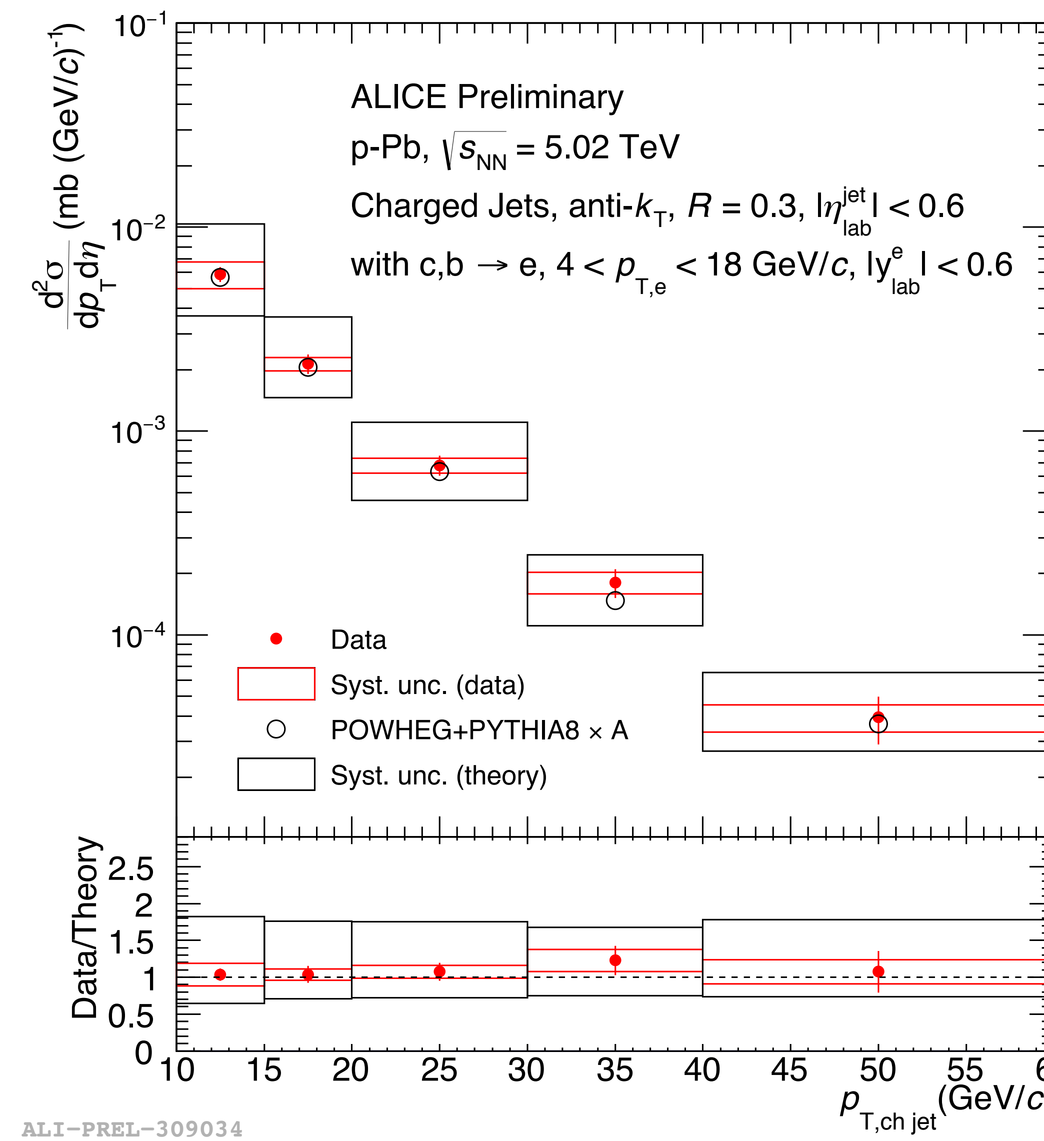
HF-tagged jets at low p_T

Work ongoing…

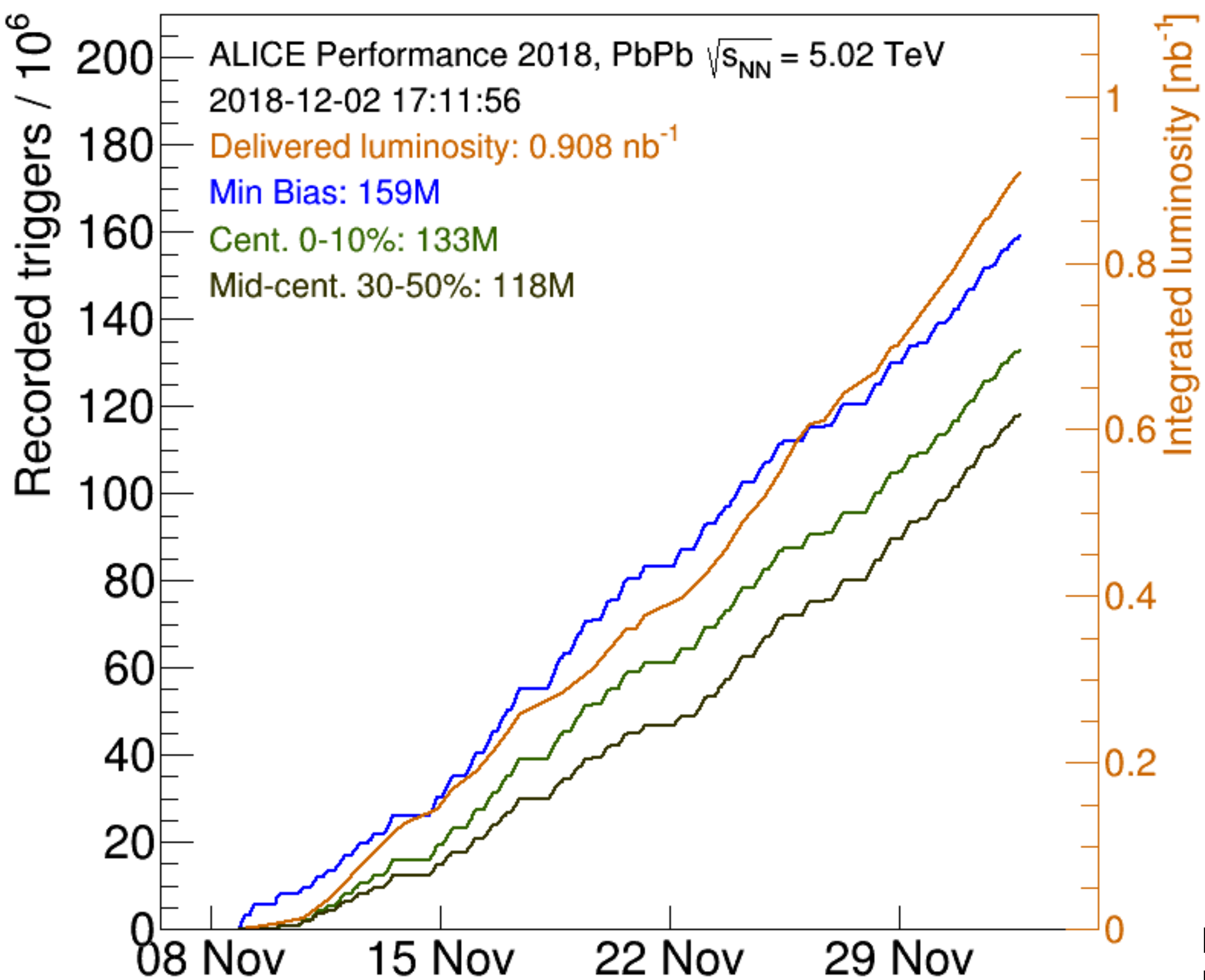
D0-tagged jets in Pb-Pb



HFe-jets in p-Pb



2018 Pb-Pb dataset



Pb-Pb run

- 0-10% ~ 9 x 2015
- 30-50% ~ 4 x 2015
- Minimum Bias = ~ 2015
- delivered lumi ~ 2 x 2015

Very impressive reduction of distortions

- **High IR** (~7.5 kHz): from up to ~4 cm, down to ~1 cm
- **Medium IR** (~4.5 kHz): from up to ~3 cm, down to ~0.3 cm

Federico Antinori, ALICE Week Dec 2018
Marco van Leeuwen, ALICE Week Dec 2018

Most of data reconstruction is complete
LHC18q, LHC18r preliminary runlists available
https://twiki.cern.ch/twiki/bin/view/ALICE/DPGDataProcessing2018Progress

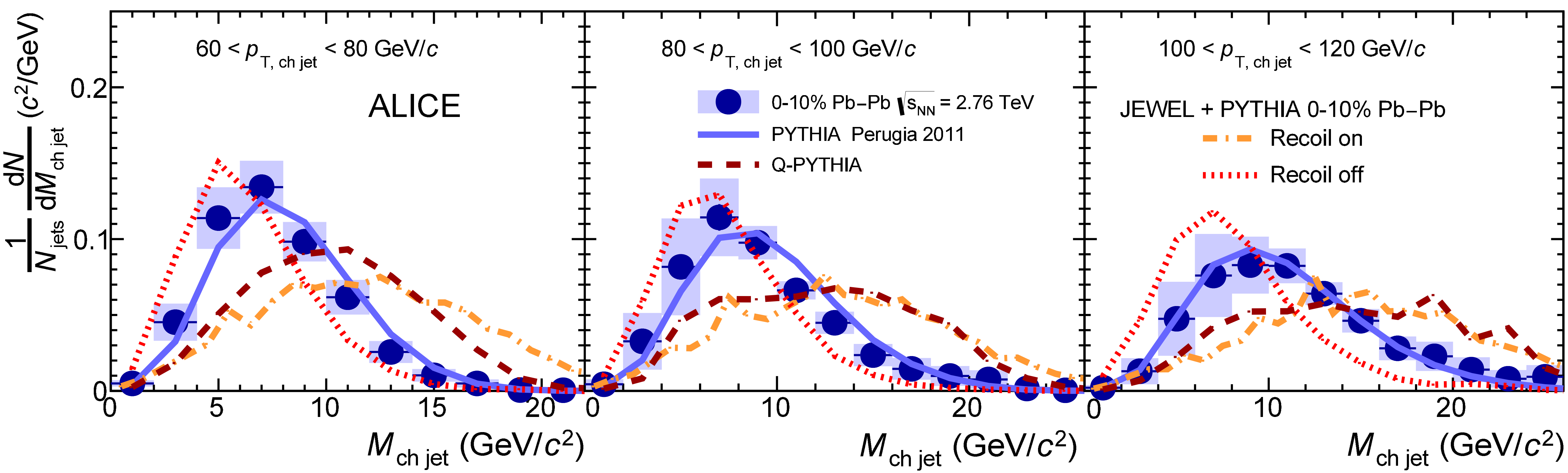
Many jet analyses have improved prospects — I will only discuss a few

What should we measure next?

1 Jet mass at different R

Jet mass shows little modification, which models badly mis-predict

Phys. Lett. B776(2018) 249-264



But jet mass is a balance of (i) particles flowing outside the jet cone, and (ii) particles flowing to larger angle but within the jet cone (both radiated energy and medium recoil).

→ Perform R-dependent measurement (and low p_T)

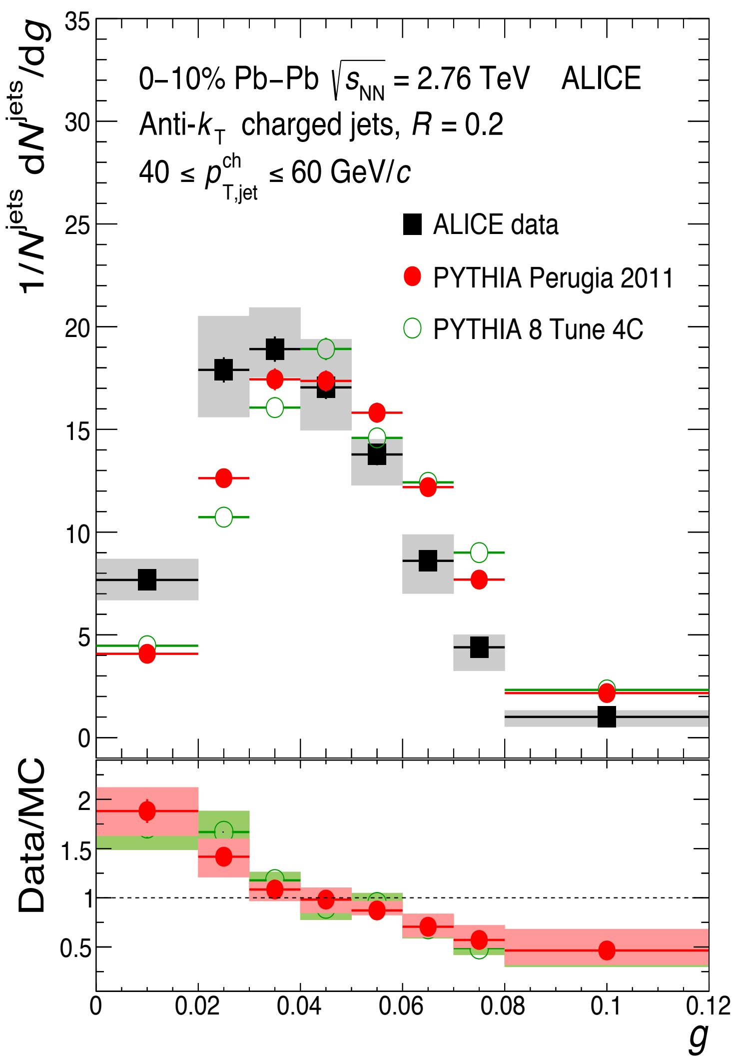
What should we measure next?

2 **Generalized angularities** $e_\beta \equiv \sum_{i \in jet} z_i \theta_i^\beta$

$\beta = 1$ Radial moment → Significant modification

$\beta = 2$ Jet mass → No significant modification

(The R was also different)



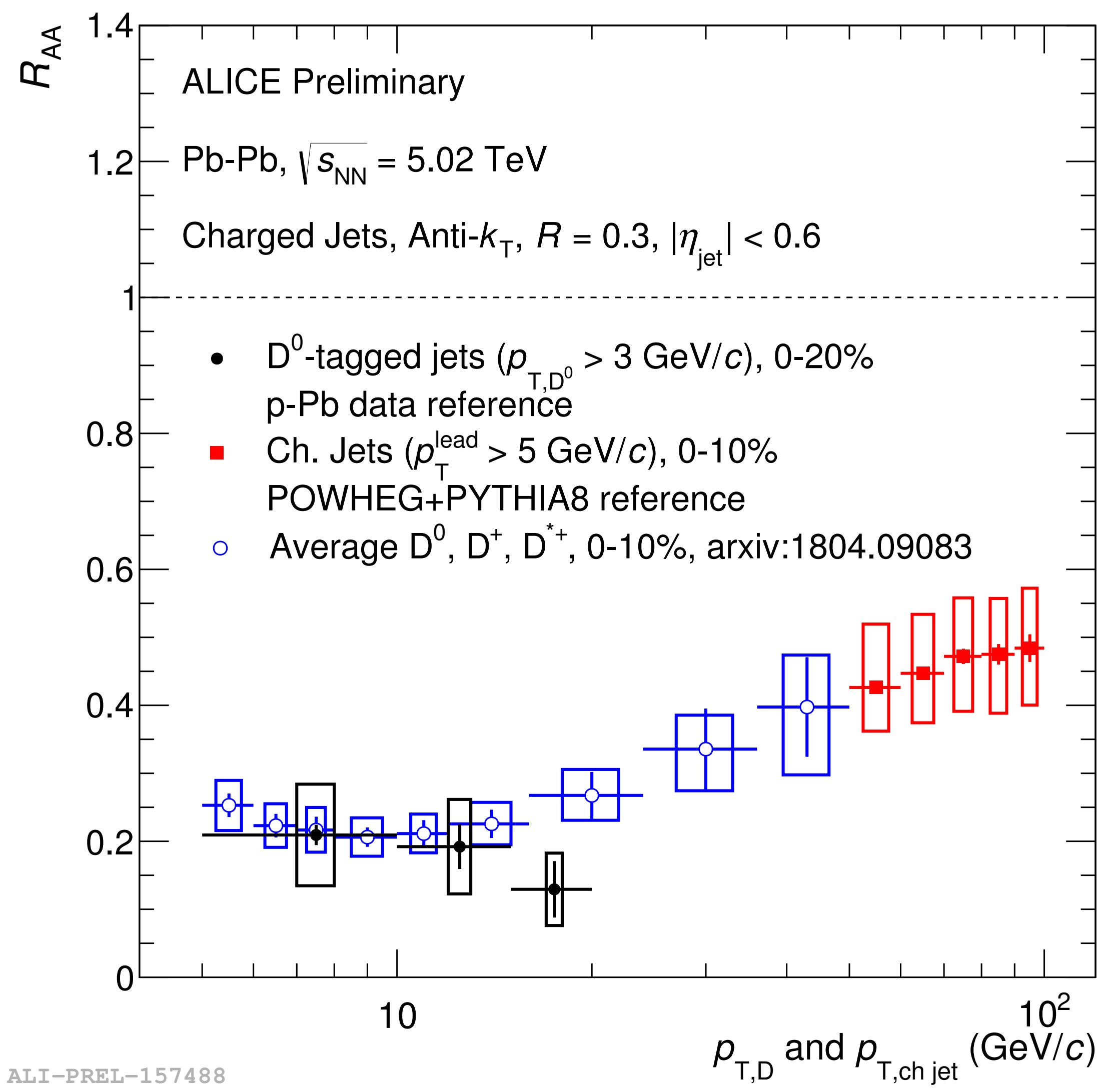
We should measure multiple angularities, including an intermediate value (e.g. $\beta = 1.5$)

Ability to do more differential jet shapes

What should we measure next?

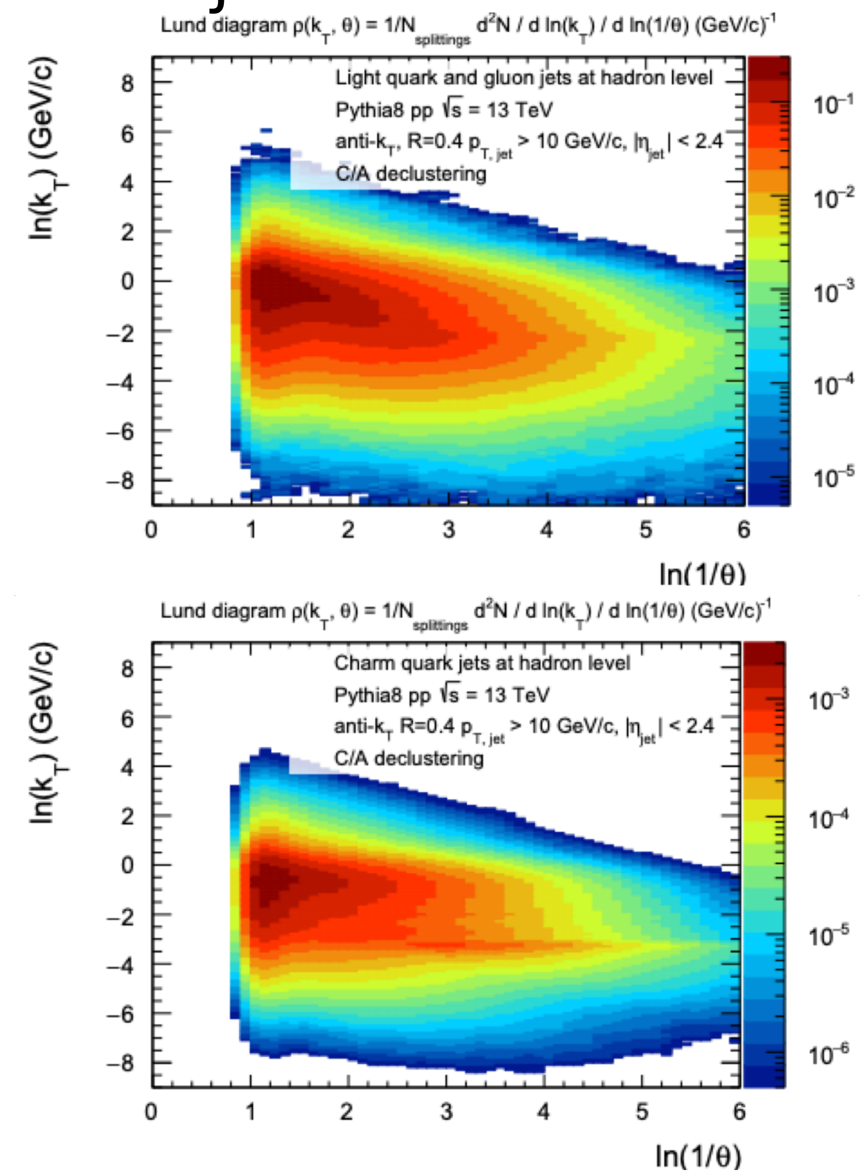
3 Heavy flavor jets at low-p_T

HF-tagged jet R_{AA}



Should see significant improvement!

HF-jet substructure



L. Cunqueiro, M. Ploskon arXiv:1812.00102

New observables!

What should we measure next?

4 Jet acoplanarity

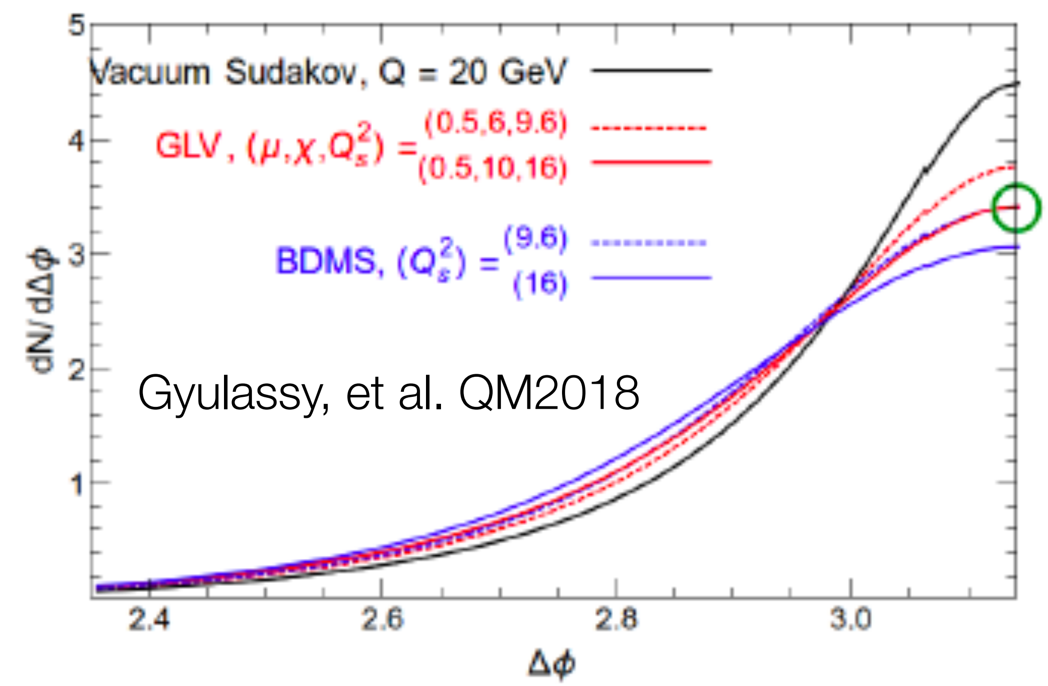
Look at angular distribution between trigger hadron and recoil jet

Biggest deflection at low/intermediate p_T

(i) Search for large-angle Moliere scattering

(ii) Search for angular broadening near jet axis

Example:



Phase 1: Achieve sufficient precision to distinguish AA from pp

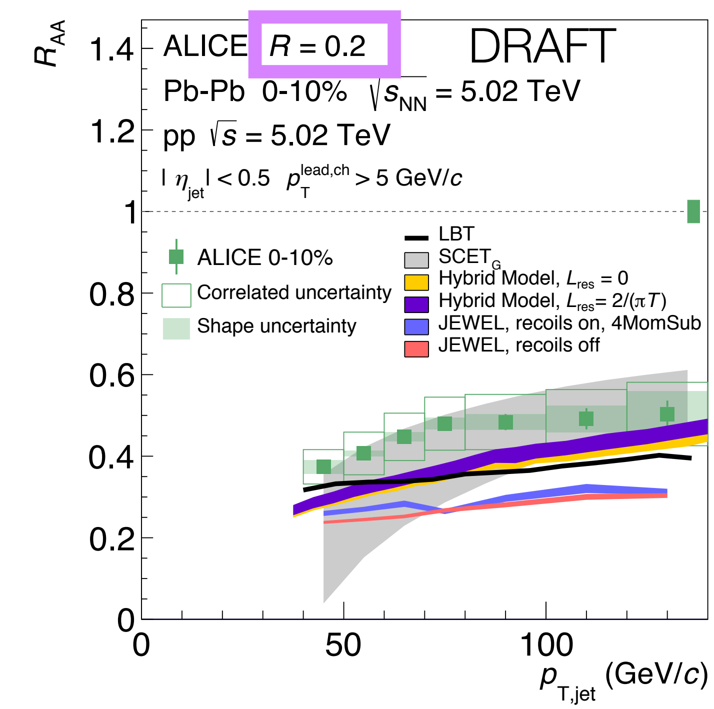
Phase 2: Achieve sufficient precision to distinguish AA models

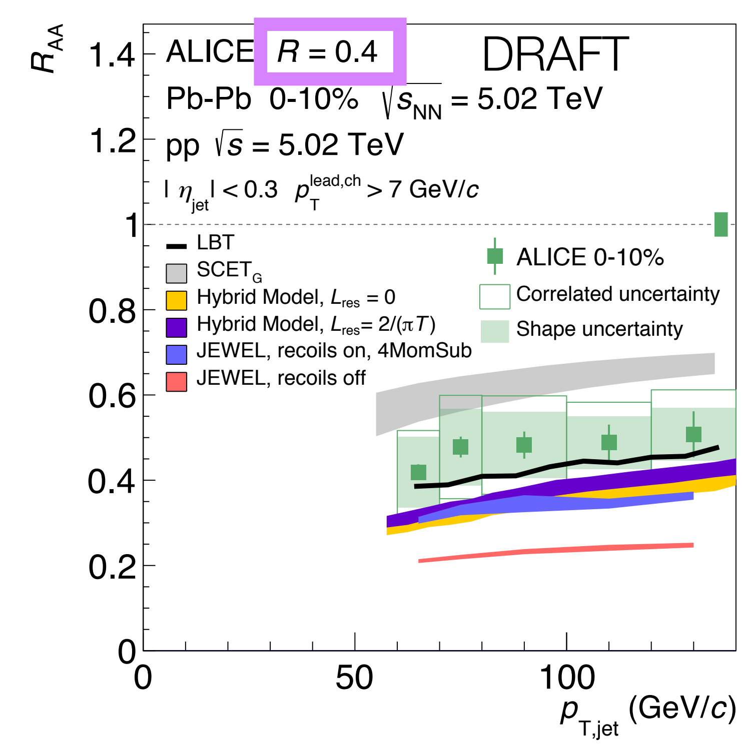
What should we measure next?

5 Next-generation Jet R_{AA}

Many possible improvements:

- Push to lower p_T and larger R
  - ML? Mixed events? Improve unfolding?
- Reduce size of error bars
  - Control unfolding? Detector systematics?
  - Can we measure the R-dependence?
- Centrality-dependence
  - Useful for HF-jet R_{AA} comparison
- Extend to higher p_T?
  - Limitations: Tracking, EMCal non-linearity, pp reference
- Push also to *smaller* R? to test theoretical understanding of R-dependence. Do we start to recover the hadron R_{AA}?





What should we measure next?

6 Next-generation Groomed jet substructure

Measure z_g modification:

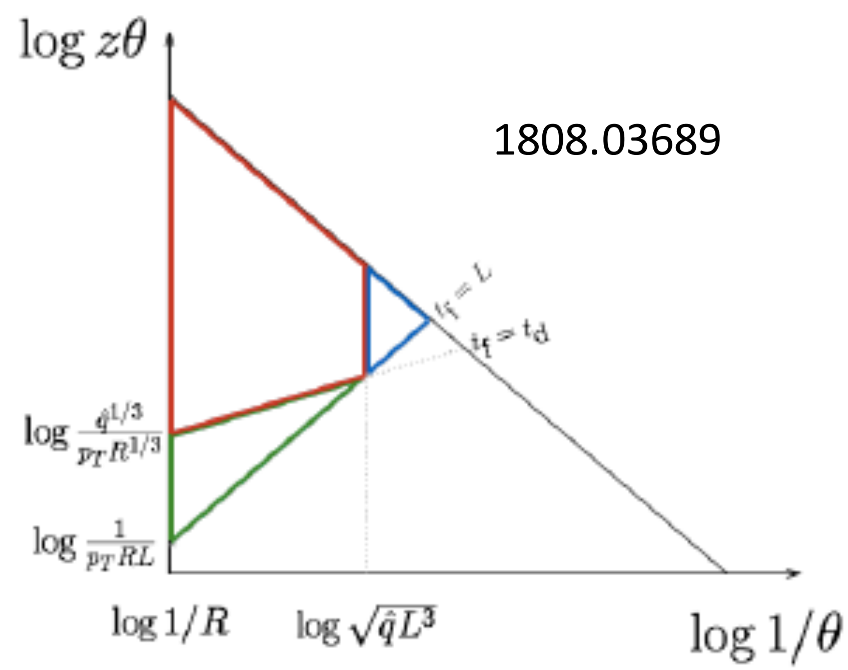
- p_T-dependence
- Centrality-dependence

Are there better groomed substructure observables?

How to interpret grooming in PbPb?

Can we figure out how to unfold z_g?

→ Scanning of the Lund plane



What else should we think about?

Limited pp reference data

- pp reference dataset $O(1\%)$ N_{coll} of Pb-Pb dataset
  - O(10/nb) pp, O(1/nb) Pb-Pb

High-p_{T} tracking

- Is this something we want to spend effort to pursue?

Role of EMCal in jet measurements

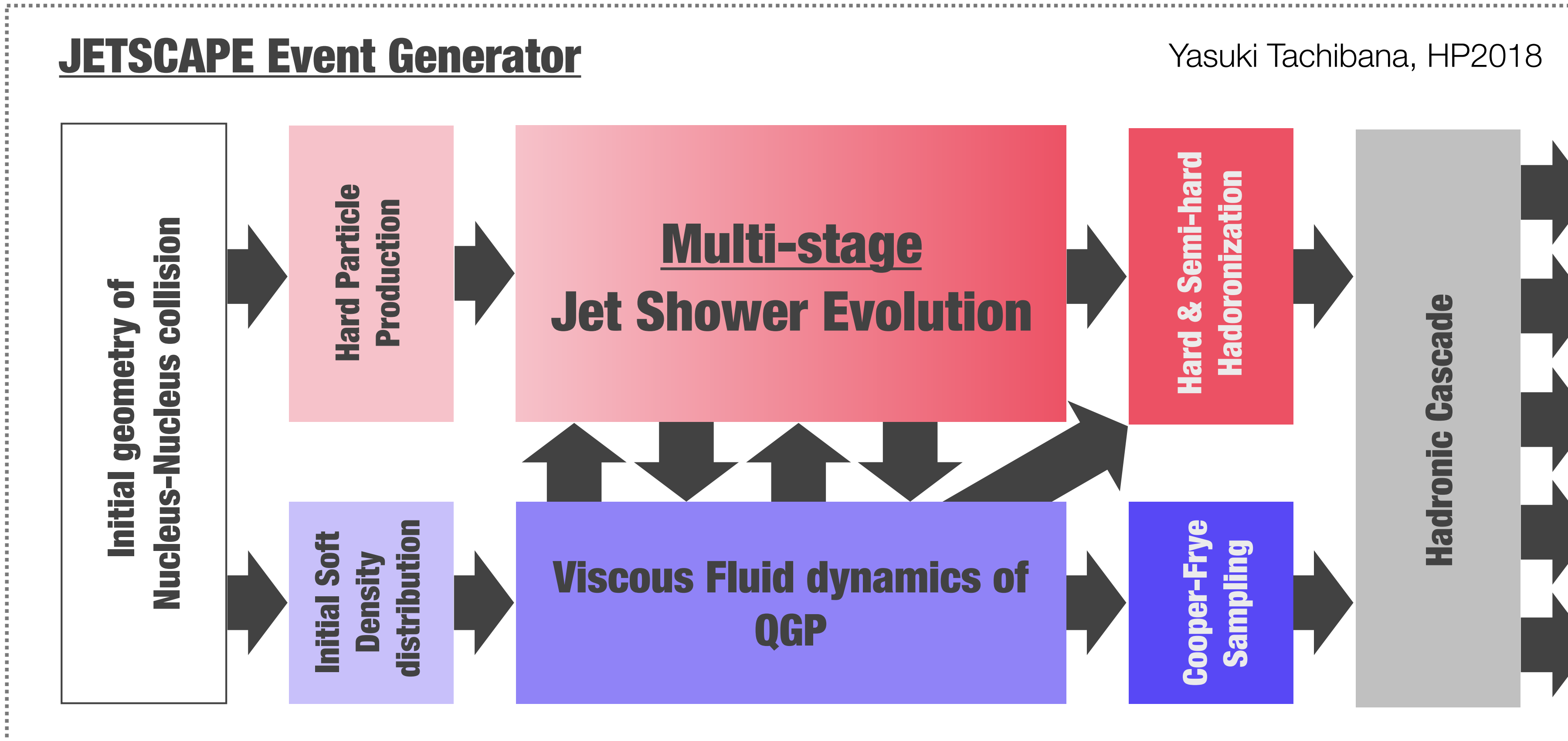
- Difficult to do substructure — Important for p_{T} scale
- Triggered data — pp reference with jet trigger?

New substructure ideas!

Comparing to theory

Our goal is not to measure observables and compare them to an MC generator. Our goal is to learn fundamental physics.

A ***modular*** heavy-ion event generator



Crucial to **systematically study jet energy loss models in a controlled way**, and try to extract real understanding of the physics.

Several ALICE members involved!

https://github.com/JETSCAPE/JETSCAPE

Summary

Jets are a promising tool to understand deconfined QCD matter

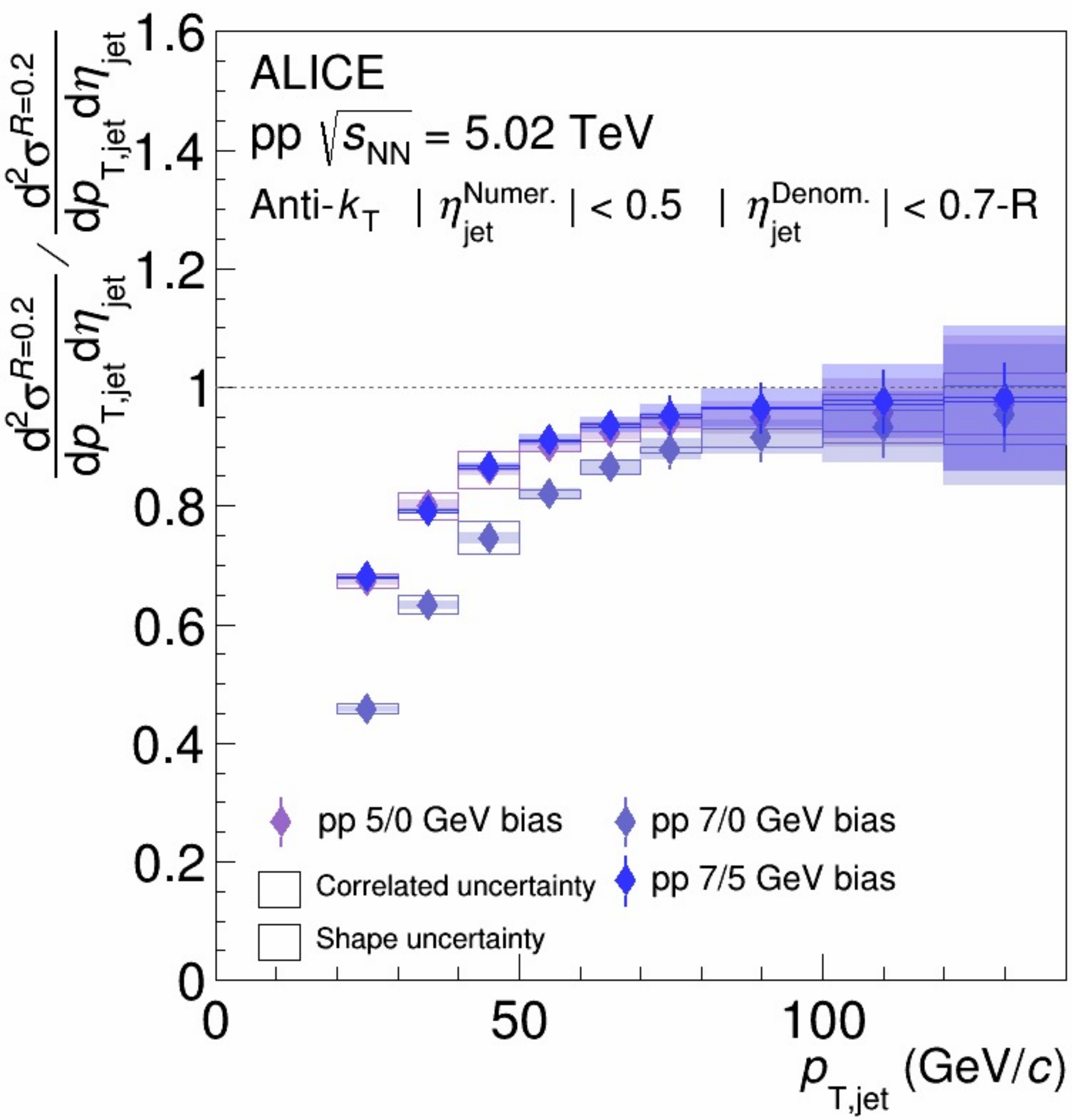
We have learned a lot about jets, and are using that knowledge to choose our next measurements

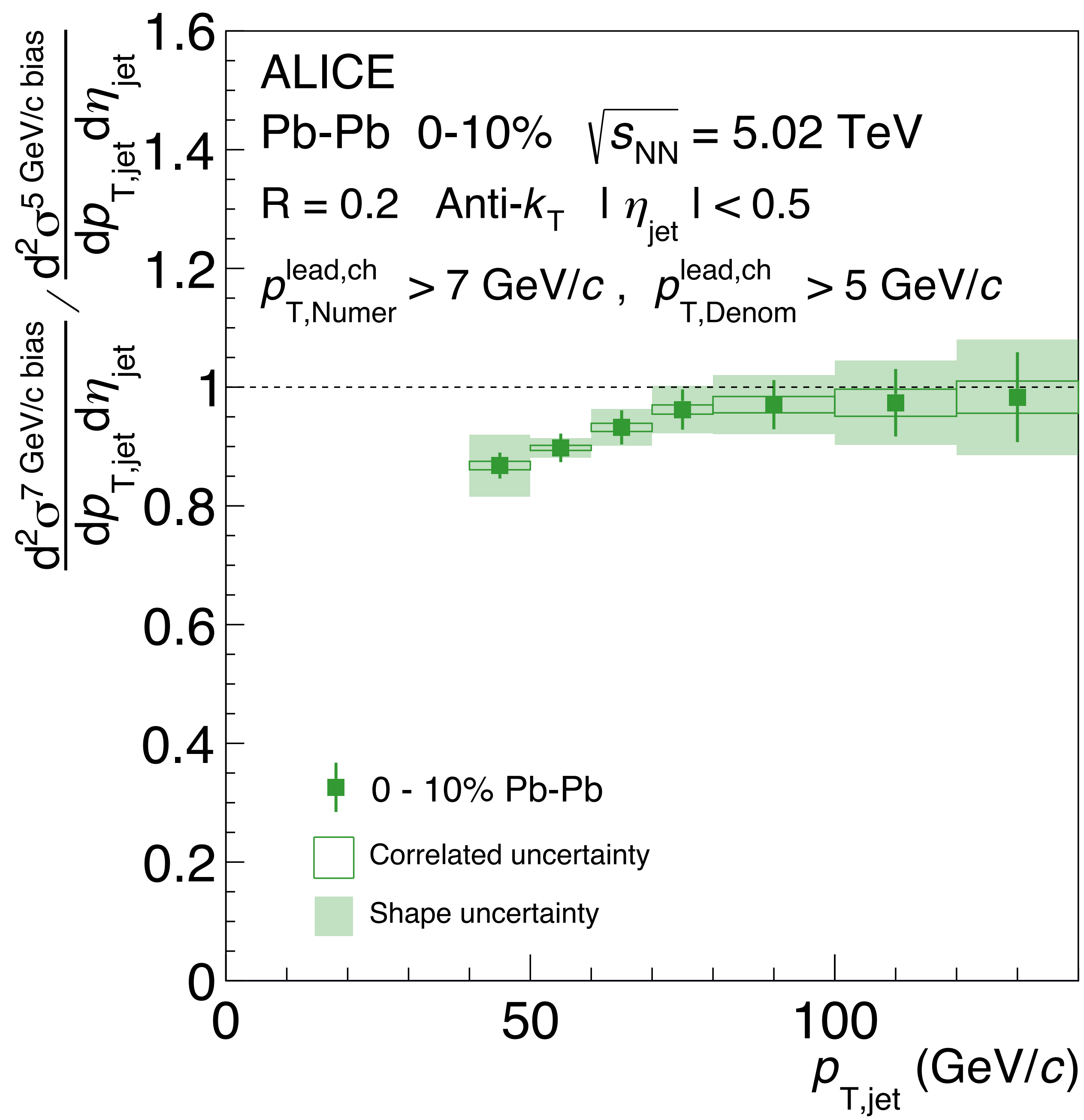
The ALICE 2018 Pb-Pb dataset gives us a substantial boost in statistics:

- More precision
- More differential
- New observables

Thank you!

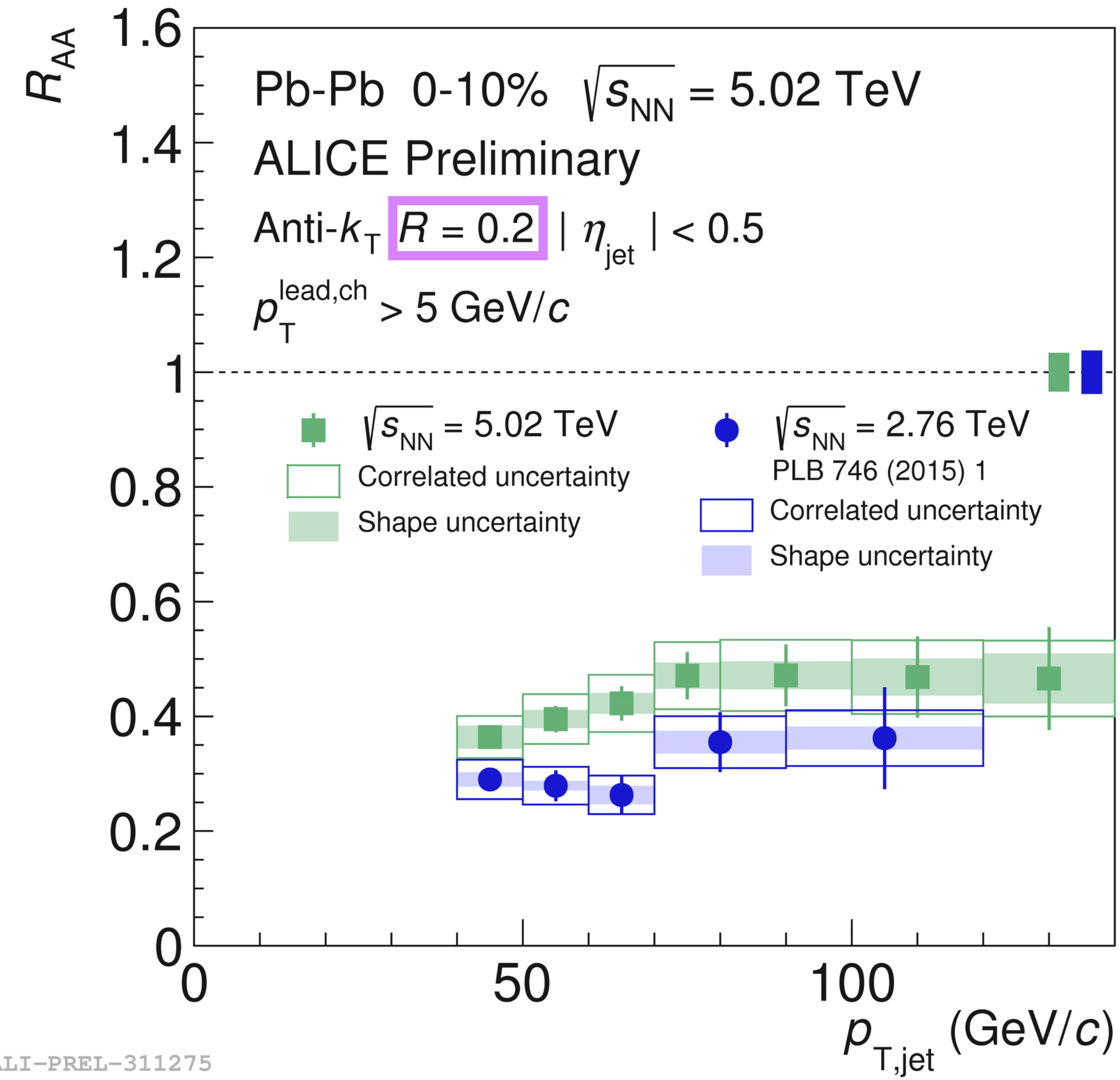
Leading track bias





Results — Jet R_{AA}

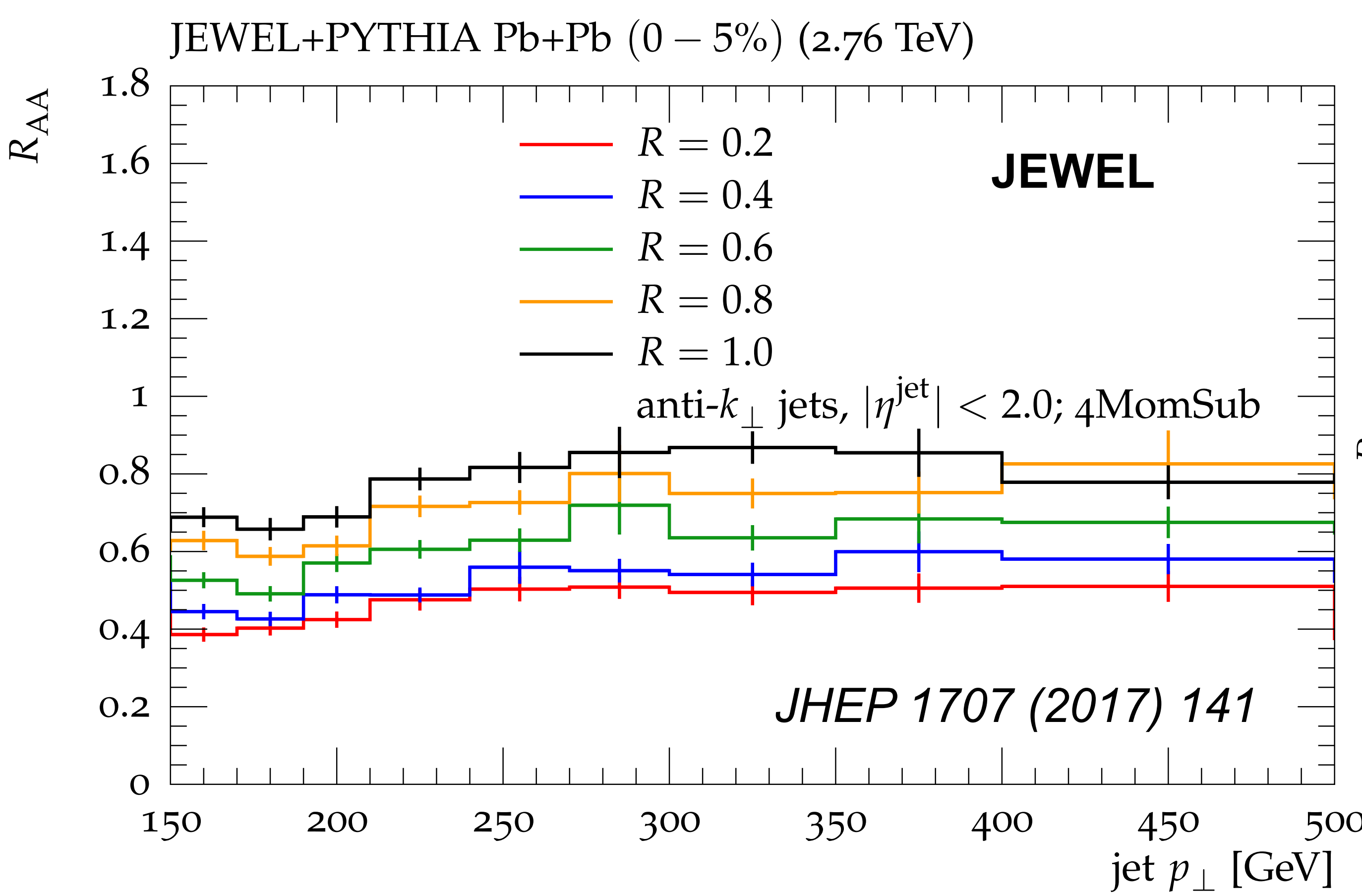
ALICE full jet R_{AA} at 5.02 TeV is similar to 2.76 TeV for R=0.2, with hint of increase

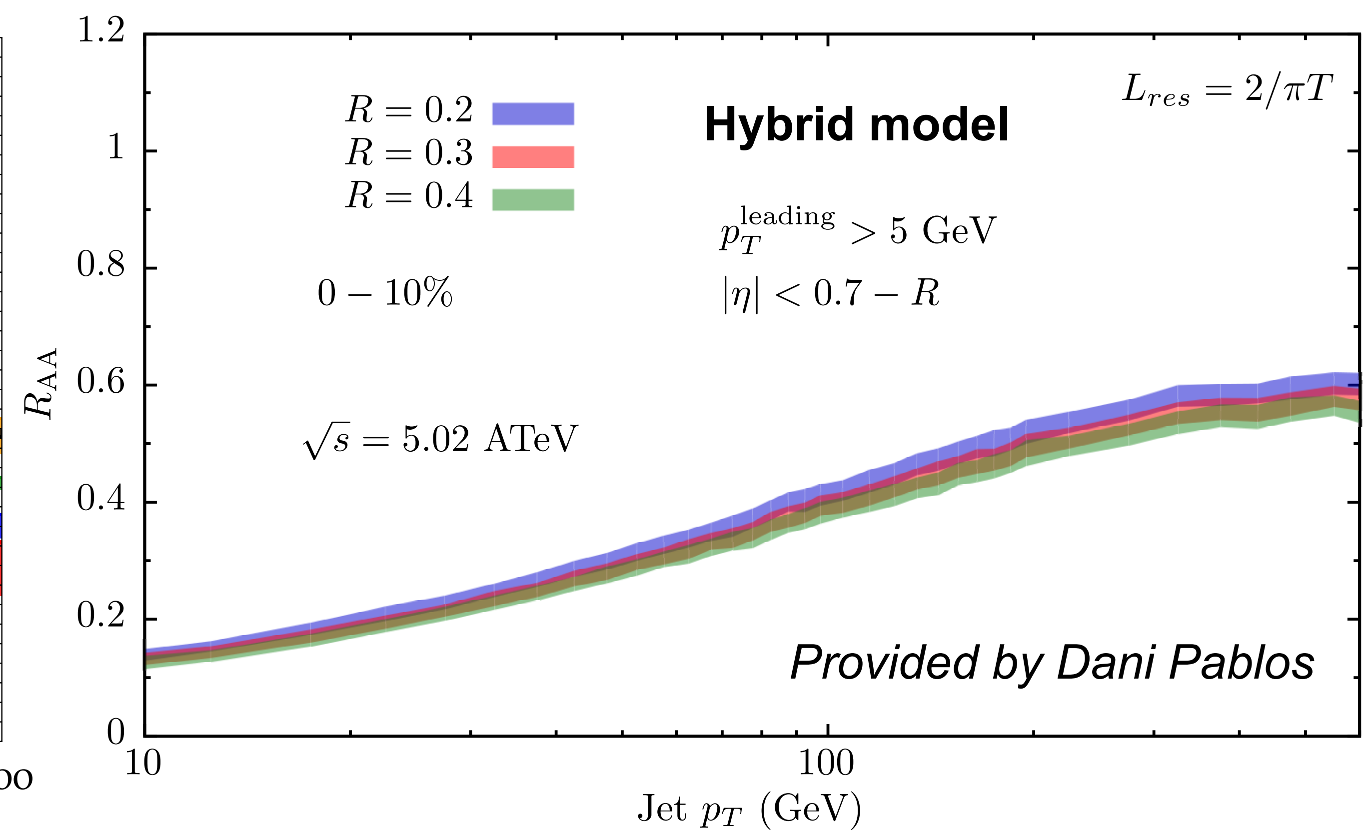


How well do we understand jet R_{AA}?

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)*





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