Jet substructure for Standard Model measurements on ALICE

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on behalf of the ALICE collaboration

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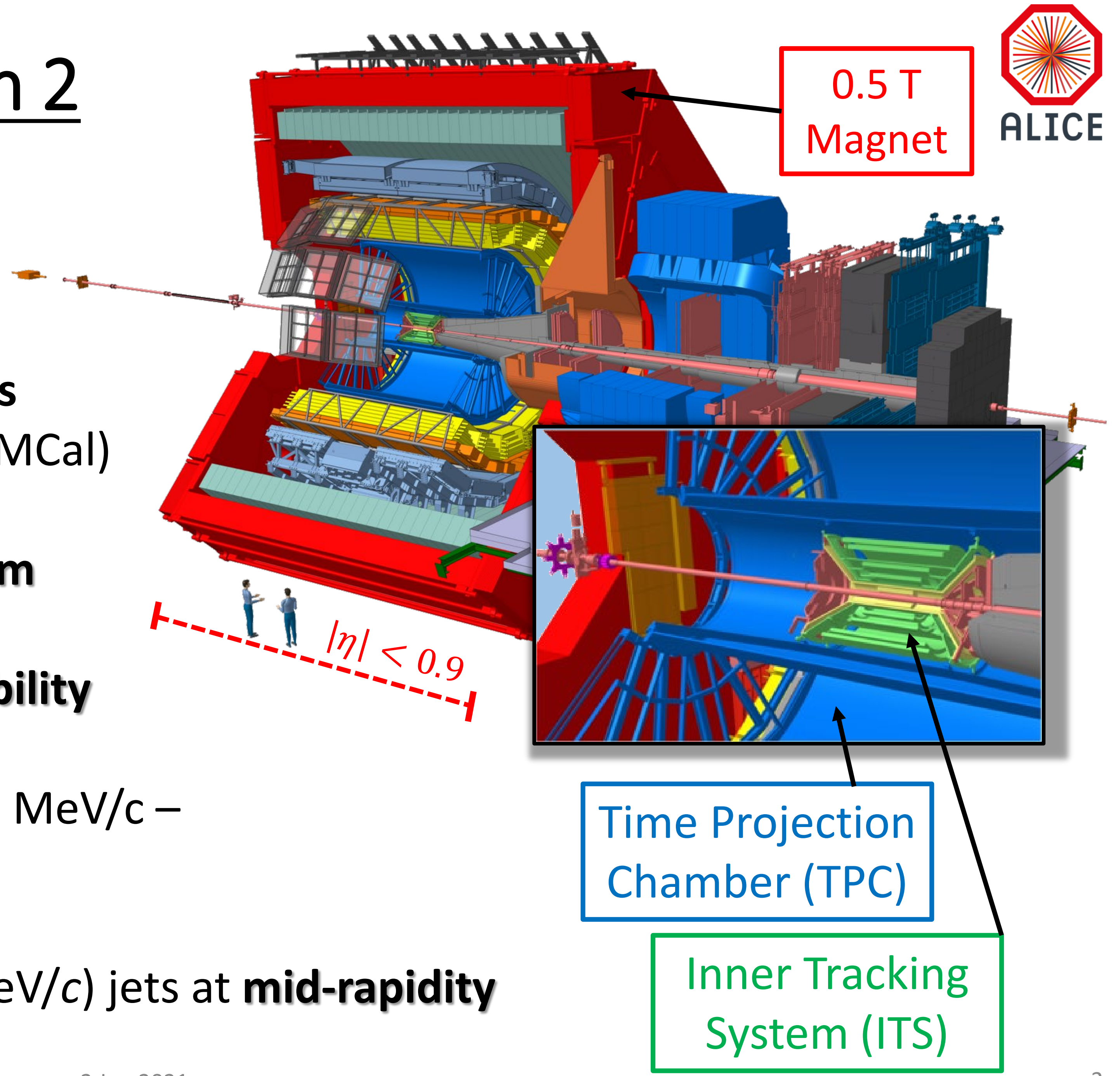
BERKELEY LAB

ALICE detector during Run 2

- **Central barrel**: silicon inner tracking system (ITS), gas TPC, EM calos.
- Measurement of **charged-particle jets** (ITS + TPC) and **full jets** (ITS + TPC + EMCal)
- **High-precision spatial and momentum resolution**, ideal for substructure measurements, plus **strong PID capability**
- Measurement of tracks with p_{T} > 150 MeV/c – study low-p_{T} tracks at LHC energies
- Great for **low/moderate-p_{T}** (< 150 GeV/c) jets at **mid-rapidity**



ALICE data (so far…)

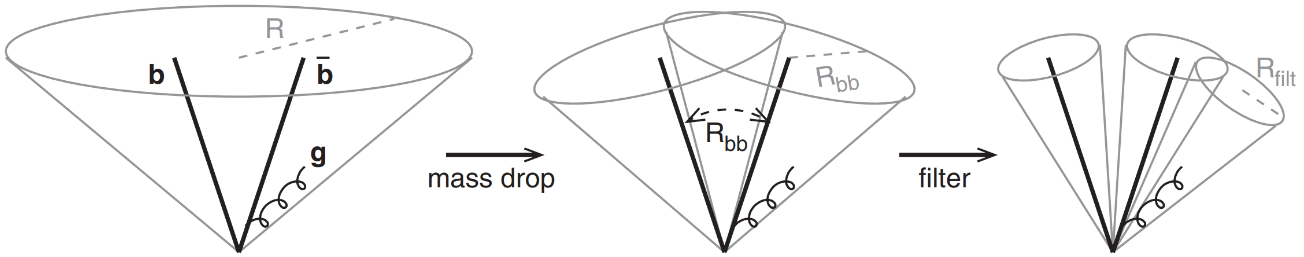
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2009-2013	0.9	200 μb^{-1}
		2.76	100 nb^{-1}
		7	1.5 pb^{-1}
		8	2.5 pb^{-1}
	2015, 2017	5.02	1.3 pb^{-1}
	2015-2018	13	36 pb^{-1}
pPb	2013	5.02	15 nb^{-1}
	2016	5.02	3 nb^{-1}
		8.16	25 nb^{-1}
Xe-Xe	2017	5.44	0.3 μb^{-1}
Pb-Pb	2010-2011	2.76	75 μb^{-1}
	2015, 2018	5.02	800 μb^{-1}

compiled by: Yaxian Mao, Hard Probes 2020

- As of May 2021, the ALICE Collaboration has 306 physics publications published in refereed journals
- Of those, 26 are published jet measurements (link)
- The large integrated luminosity in Run 2 allows precise new measurements and new observables

Jet substructure

- **Tagging jets** of particular origin
  - Boosted objects (Higgs/BSM searches: $H \to b\bar{b}$) [1]
  - Quark vs. gluon jets



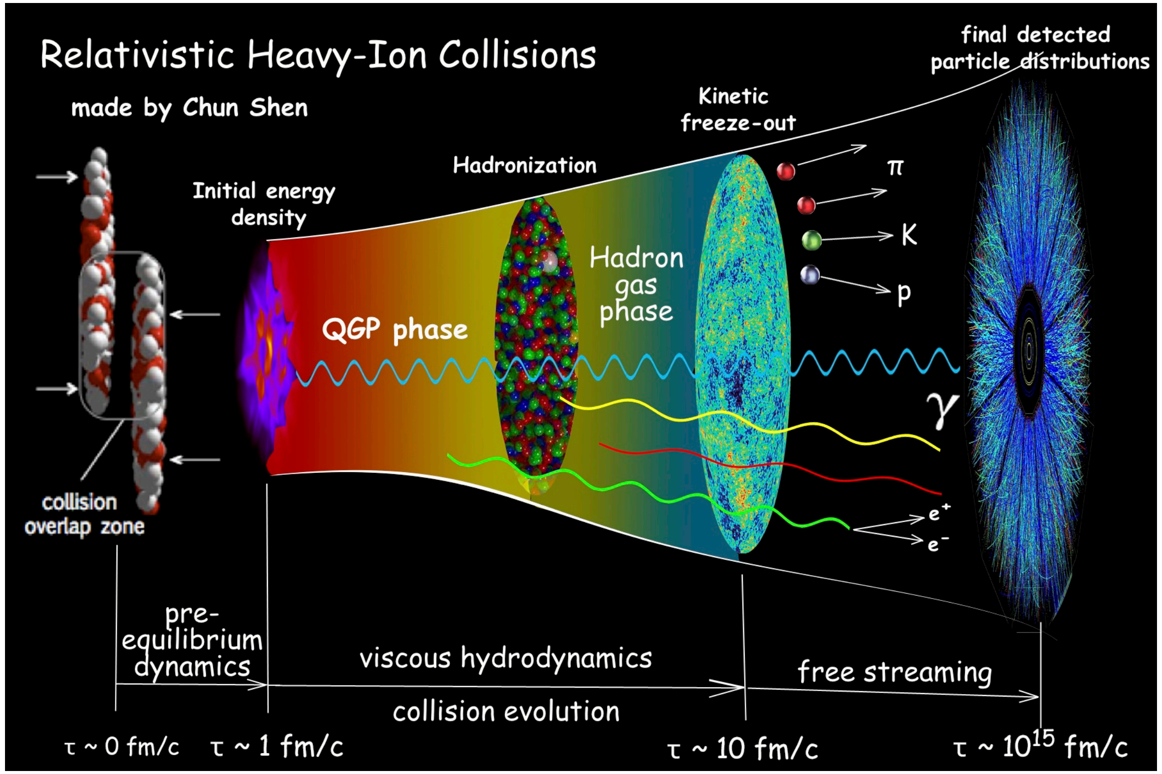
- Testing **fundamental QCD** (perturbative vs. nonperturbative)

- Probing the **quark-gluon plasma** in heavy-ion collisions

[1] *J. Butterworth, A. Davison, M. Rubin, G. Salam*
[Phys. Rev. Lett. 100, 242001 (2008)]

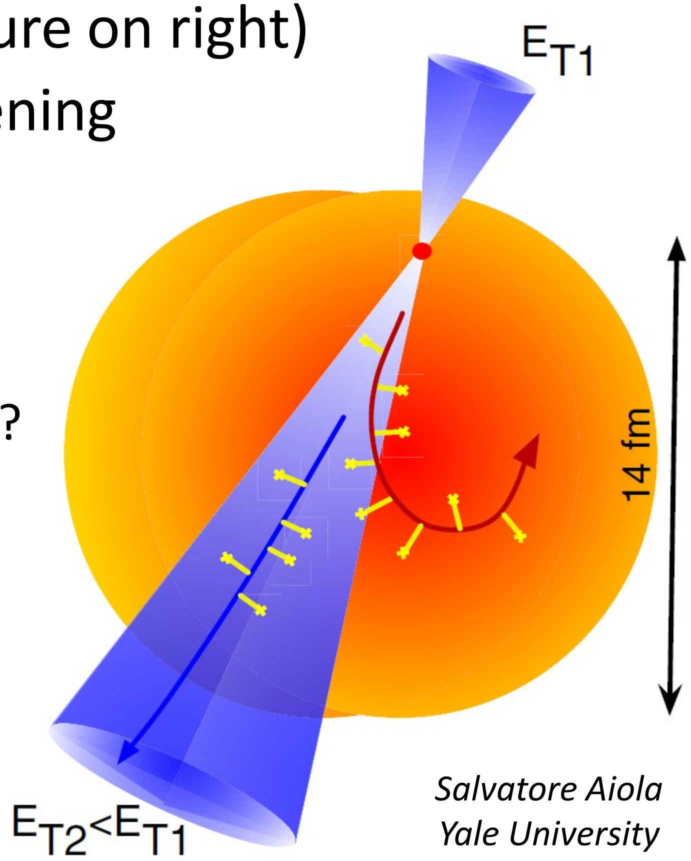
Pb-Pb collisions: Quark-Gluon Plasma (QGP)

- Strongly-interacting fluid believed to form in heavy-ion collisions
- Modifies jet interactions and reconstructed observables



- Jet quenching (picture on right)
- Momentum broadening

- Open questions:
  - Lumpy or smooth?
  - What are the d.o.f.?
  - q / g fraction?
  - Hadronization?
  - Factorization breaking?
  - …



Salvatore Aiola
Yale University

Recent ALICE pp jet substructure measurements

- Generalized jet angularities (with and without grooming)
- Inclusive jet Lund Plane: https://alice-figure.web.cern.ch/node/18640
- First direct observation of the dead-cone effect: Nucl. Phys. A (Jan 2021) 121905
- Groomed z_g and R_g (Soft Drop & dynamical grooming): ALICE-PUBLIC-2020-006
- First measurement of D^0-tagged Soft Drop $z_{\mathrm{g}}/R_{\mathrm{g}}/n_{\mathrm{SD}}$: ALICE-PUBLIC-2020-002
- Jet-axis differences: https://alice-figure.web.cern.ch/node/19522
- Fully-corrected N-subjettiness in pp and Pb-Pb: CERN-EP-2021-082
- Inclusive/leading subjet z_r: https://alice-figure.web.cern.ch/node/19990
- Using ML to reduce jet background: https://alice-figure.web.cern.ch/node/16909

We will overview a subset of these new studies

Generalized jet angularities

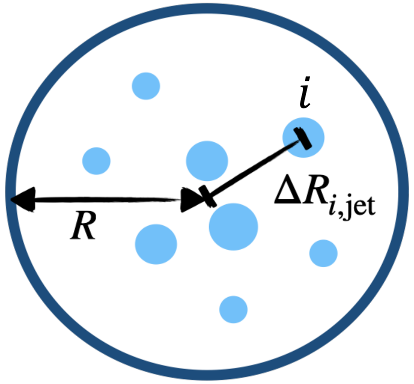
- **Substructure observable** dependent on $\boldsymbol{p}_{\mathbf{T}}$ and **angular** distributions of tracks within jets

$$\lambda_\beta^\kappa \equiv \sum_{i \in \text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T,jet}}}\right)^{\kappa} \left(\frac{\Delta R_{i,\text{jet}}}{R}\right)^{\beta}$$

Tunable, continuous parameters for relative weighting (κ, β)

Constituent angle in (η, ϕ) space

Constituent p_T

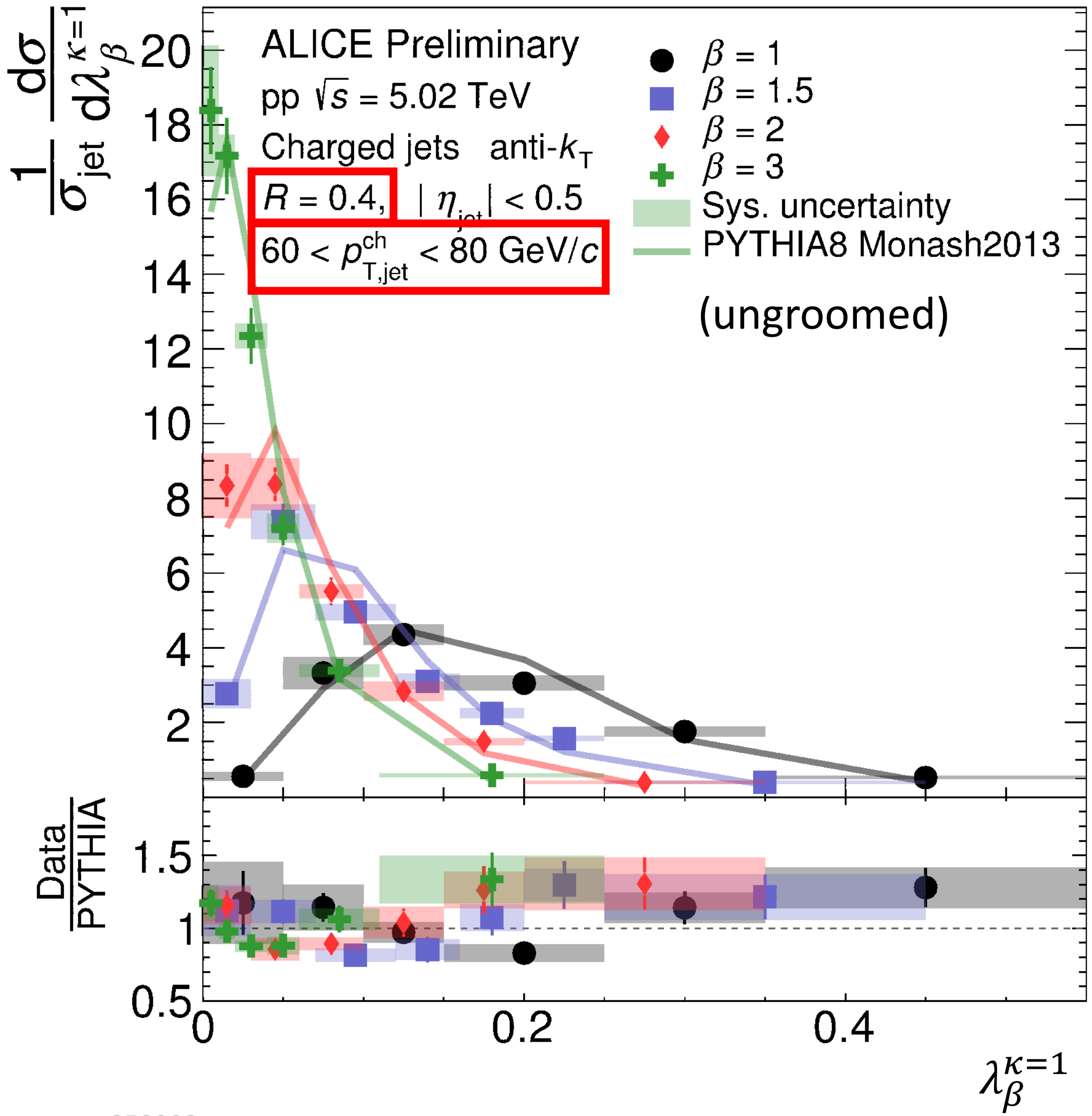


- IRC-safe observable for $\kappa = 1, \beta > 0$ → directly calculable from pQCD
- Each (κ, β) defines a different observable capable of probing jet structure and providing constraints on theory
- Can be further varied with jet resolution parameter R

A. Larkoski, J. Thaler, W. Waalewijn JHEP 11 (2014) 129

Angularities: Preliminary results

$$\lambda_\beta^{\kappa=1} \equiv \sum_{i \in \mathrm{jet}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}\right)\left(\frac{\Delta R_{\mathrm{jet},i}}{R}\right)^\beta$$



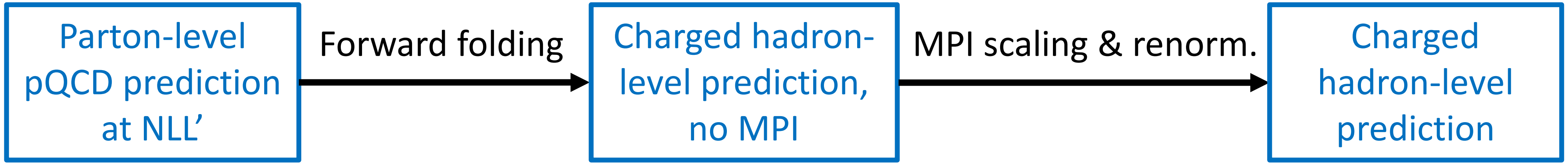
- Calculable way of **probing the p_T structure of jets**
- Distributions shift to the **left** for **higher β, $p_{\mathrm{T,jet}}^{\mathrm{ch}}$, and R**
- **Reasonable consistency is seen with MC predictions**
  - Residuals become even smaller with Soft Drop grooming
  - PYTHIA shower + fragmentation function model works in this regime

Preliminary figures are publicly available here:
https://alice-figure.web.cern.ch/node/18014

Comparing angularities to pQCD predictions with SCET

- Theoretical predictions for **parton** jets by F. Ringer & K. Lee (LBNL) [2] with Next-to-Leading Log (NLL’) resummation

- Apply a “forward folding” procedure to correct for multi-parton interactions (MPI), hadronization, and **charged** jets
  - 2D folding with $p_{\mathrm{T,jet}}$ and λ_β axes; followed by bin-by-bin scaling for MPI

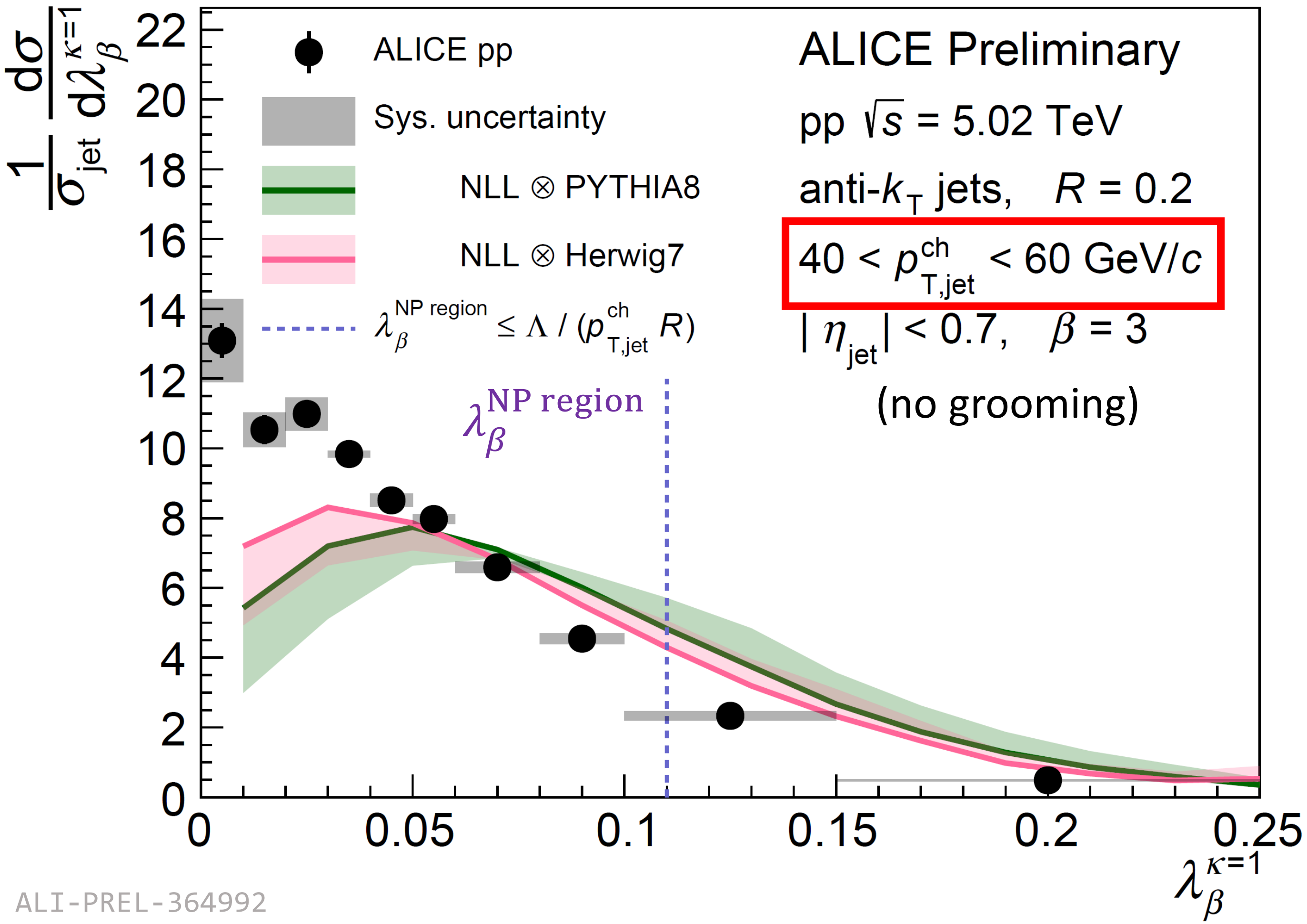


- There is additional model dependence introduced, which we address by repeating the folding procedure with both Herwig and PYTHIA

[2] Kang et al. JHEP 1804 (2018) 110

pQCD predictions with SCET ($R = 0.2, \beta = 3$)

ALICE



- Nonperturbative-dominated region is large for some distributions (skewed left at higher β)

(we use $\Lambda = 1$ GeV)

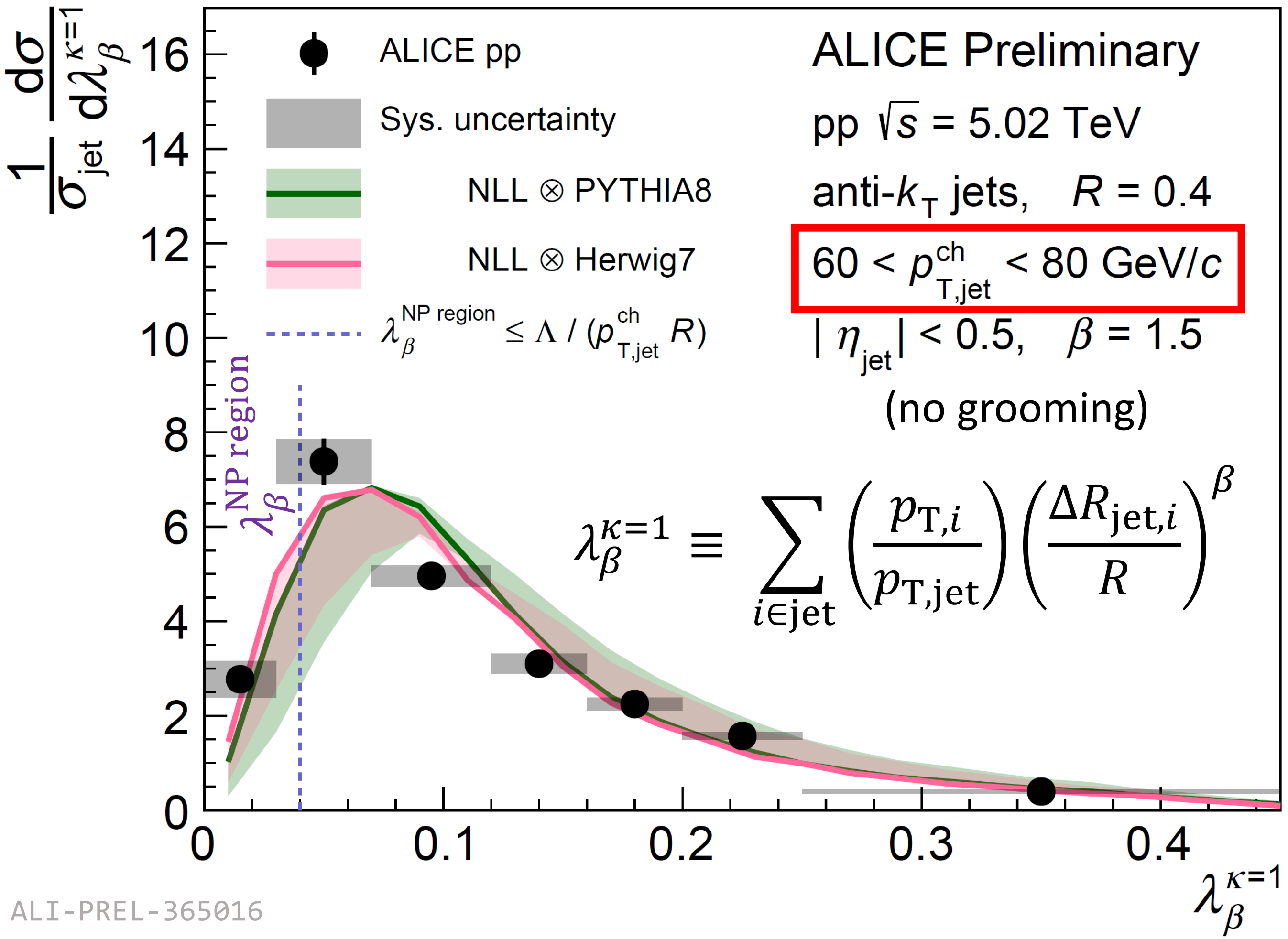
$$\lambda_\beta^{\text{NP region}} \sim \Lambda / (p_{\text{T,jet}} R)$$

- **Larger disagreements at low λ_β**
- Could be useful for tuning Monte Carlo generators

$$\lambda_\beta^{\kappa=1} \equiv \sum_{i \in \text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T,jet}}} \right) \left(\frac{\Delta R_{\text{jet},i}}{R} \right)^\beta$$

Smaller R, larger β, lower $p_{\text{T,jet}}^{\text{ch}}$ → nonperturbative-dominated regime

pQCD predictions with SCET $(R = 0.4, \beta = 1.5)$



- Nonperturbative region decreases at larger R and higher $p_{\text{T,jet}}^{\text{ch}}$
- Parton-to-hadron response becomes more diagonal → **less fragmentation model dependence**
- Consistency of the shape must be considered only in the **perturbative region**, where we find that agreement is good

Larger R, lower β, higher $p_{\text{T,jet}}^{\text{ch}}$ → perturbative-dominated regime

Inclusive jet (primary) Lund Plane

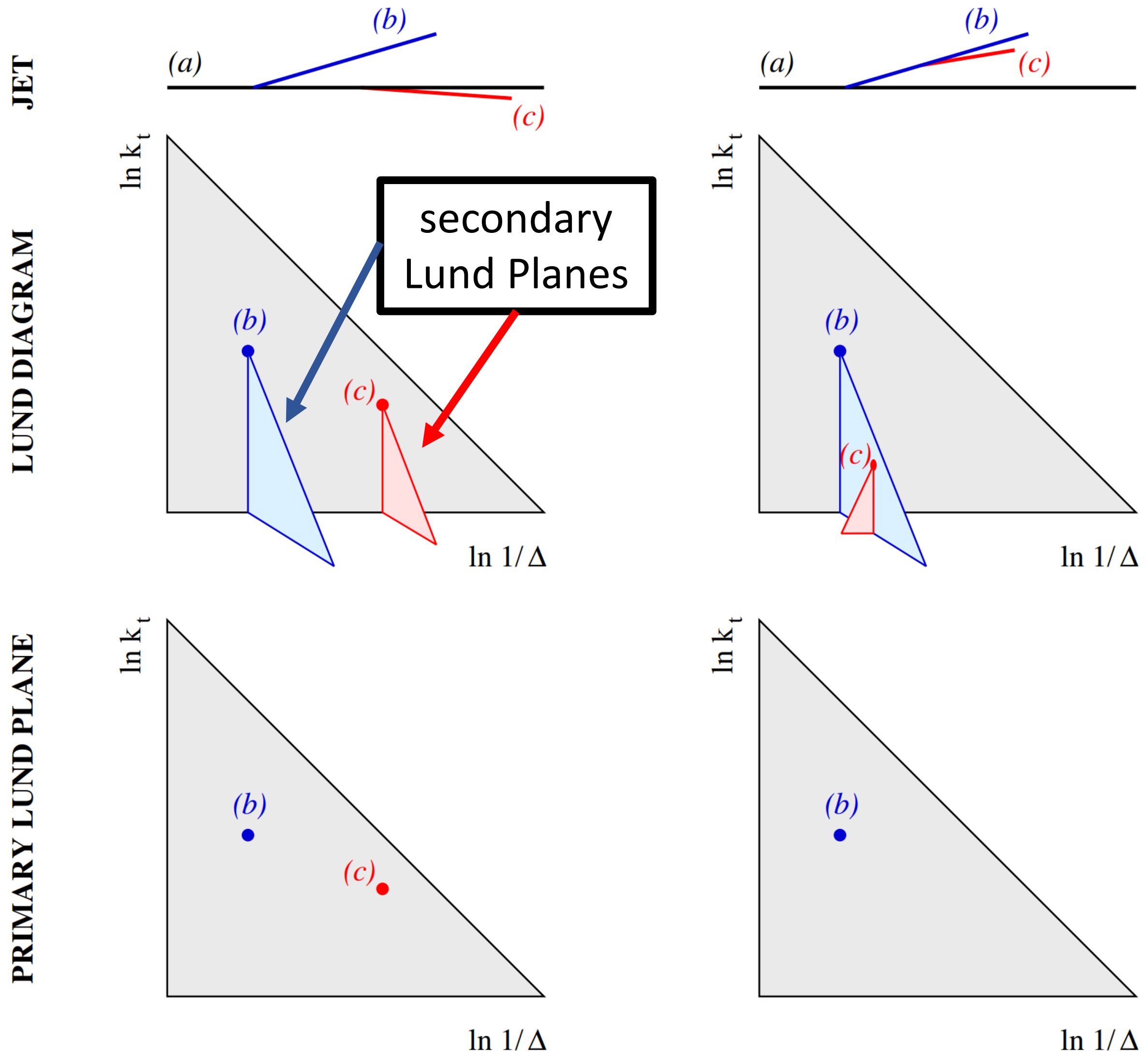
- Triangular diagram populated by each primary splitting after Cambridge-Aachen reclustering

- Axes are related to angle and p_{T}:

$$\Delta \equiv \Delta_{ab} = \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2}$$

$$k_t \equiv p_{\mathrm{T},b}\Delta_{ab}$$

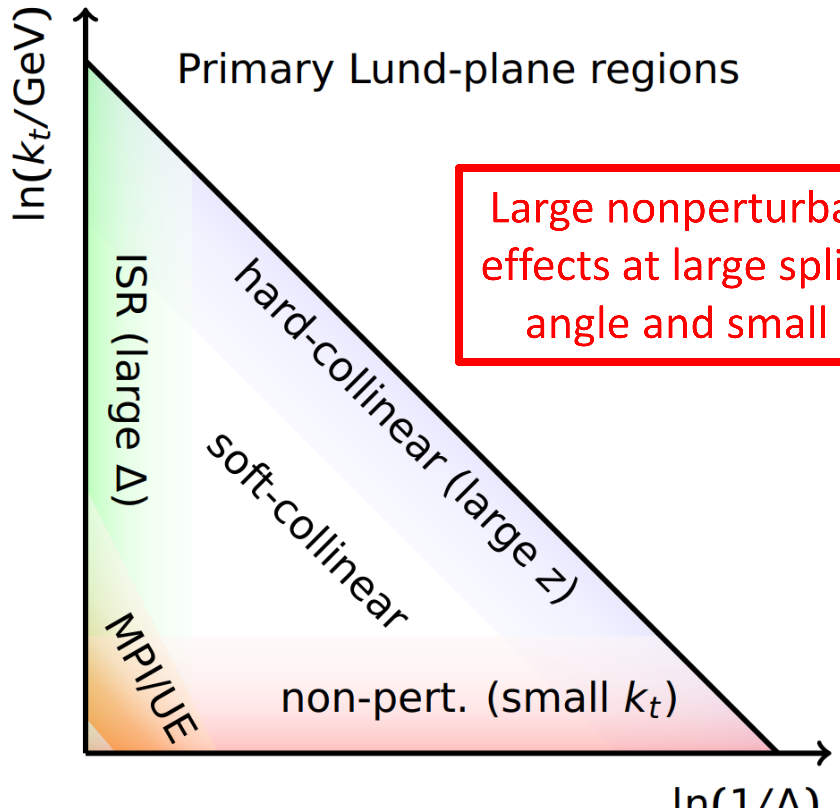
- Not generally IRC-safe; perturbatively amenable for $k_t \gg \Lambda_{\mathrm{QCD}}$



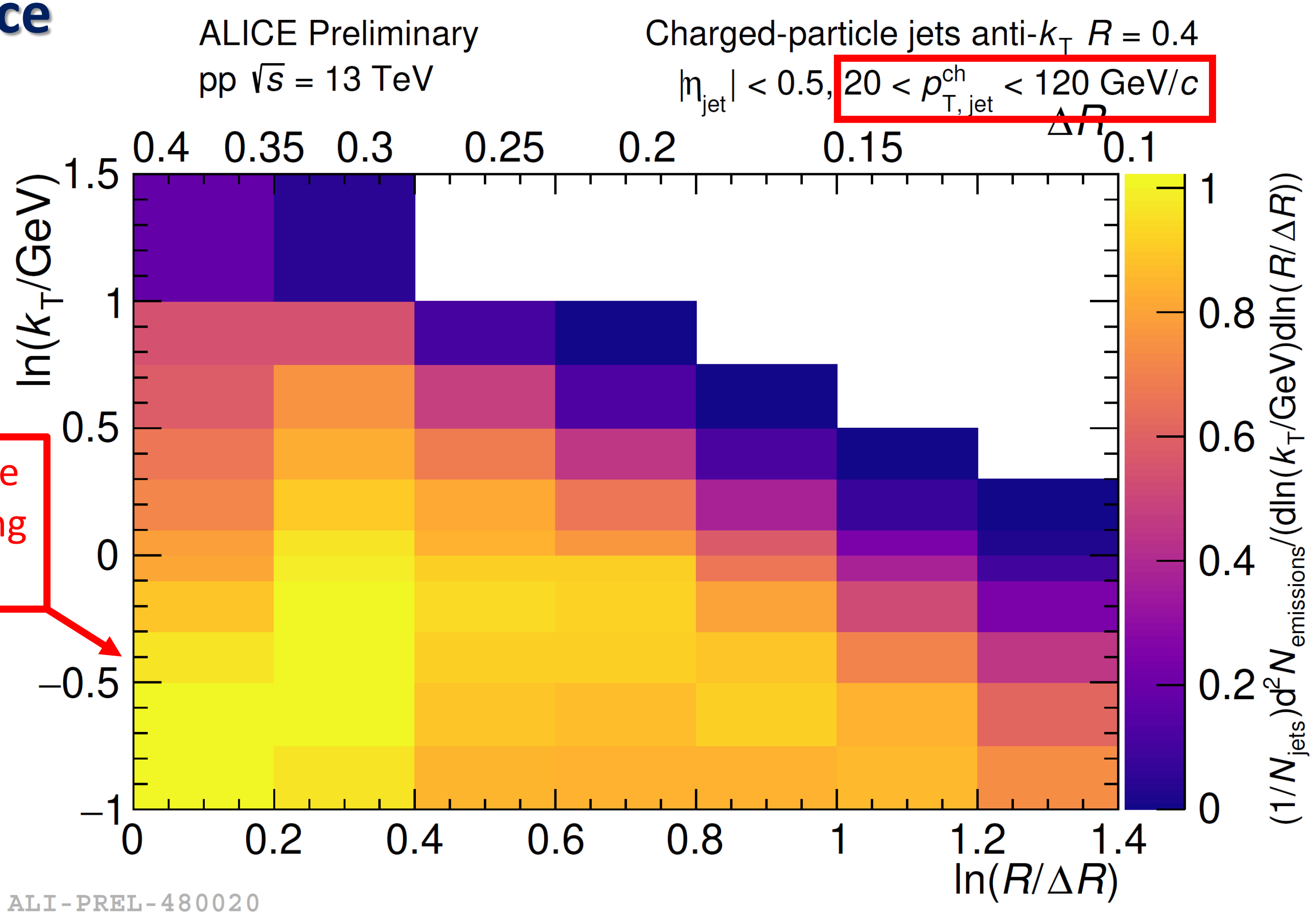
Dreyer, Salam, Soyez JHEP 12 (2018) 064

Inclusive jet (primary) Lund Plane

- Illustrates **branching phase space**
- Has been also measured by ATLAS [7] at higher jet p_T ($>$ 675 GeV/c)



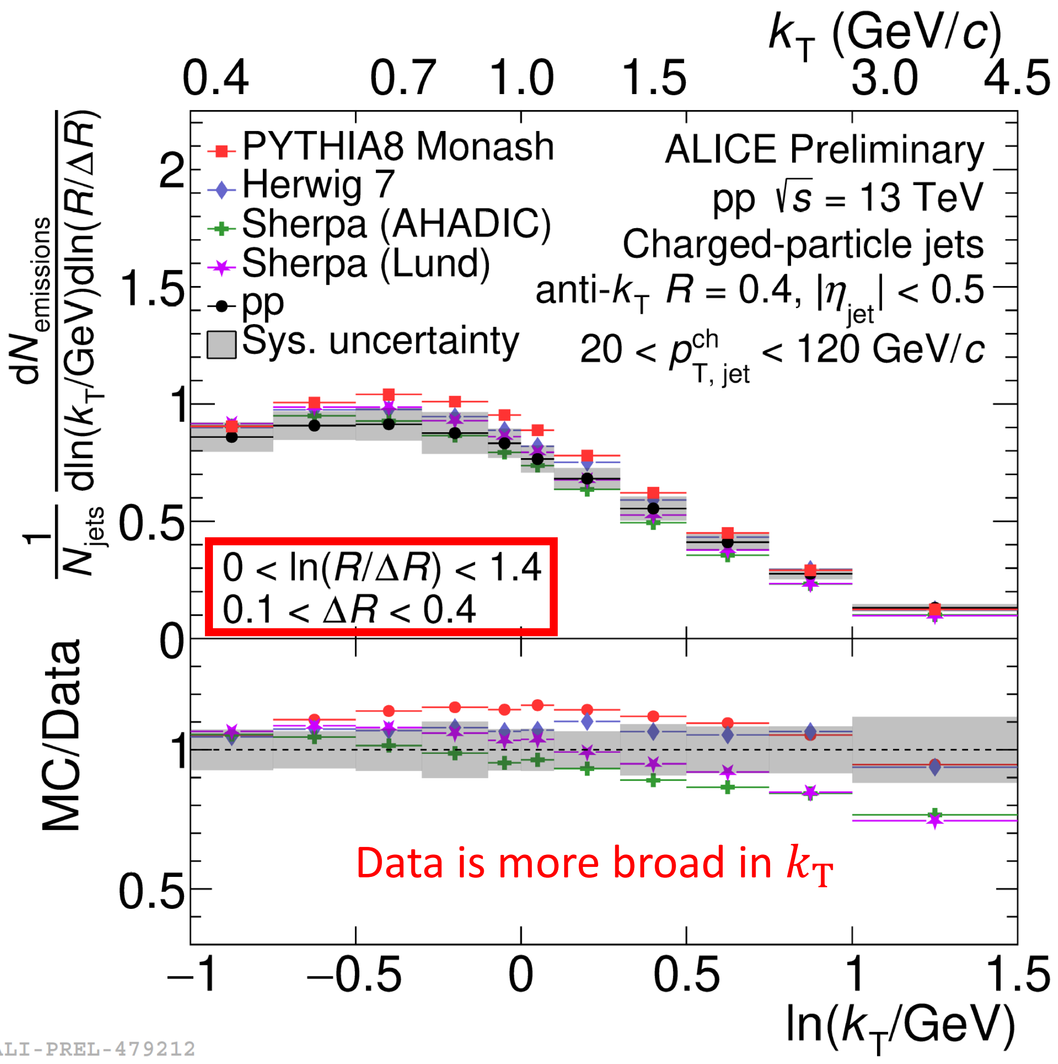
Large nonperturbative effects at large splitting angle and small k_T

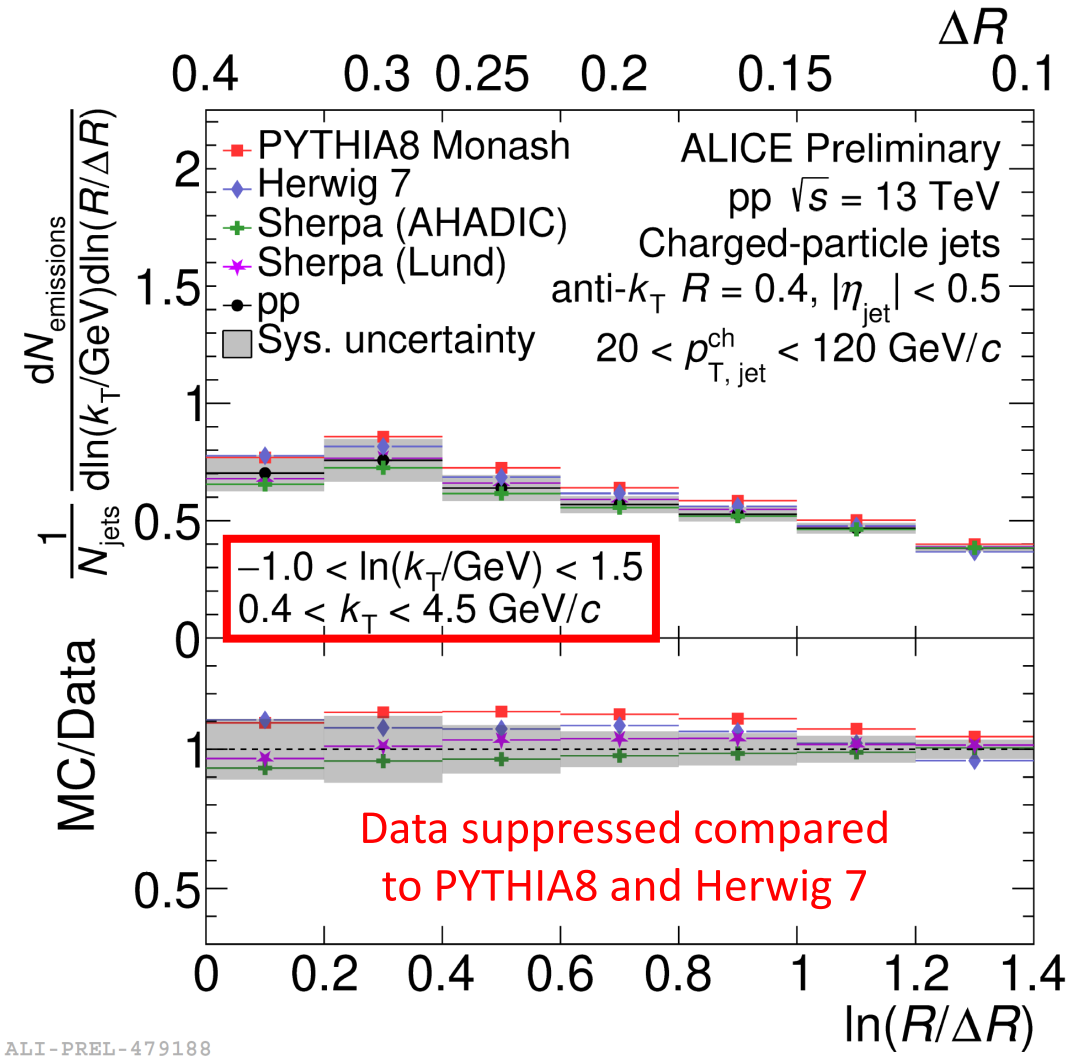


[7] Phys. Rev. Lett. 124, 222002 (2020)

Comparing Lund Plane projections to models

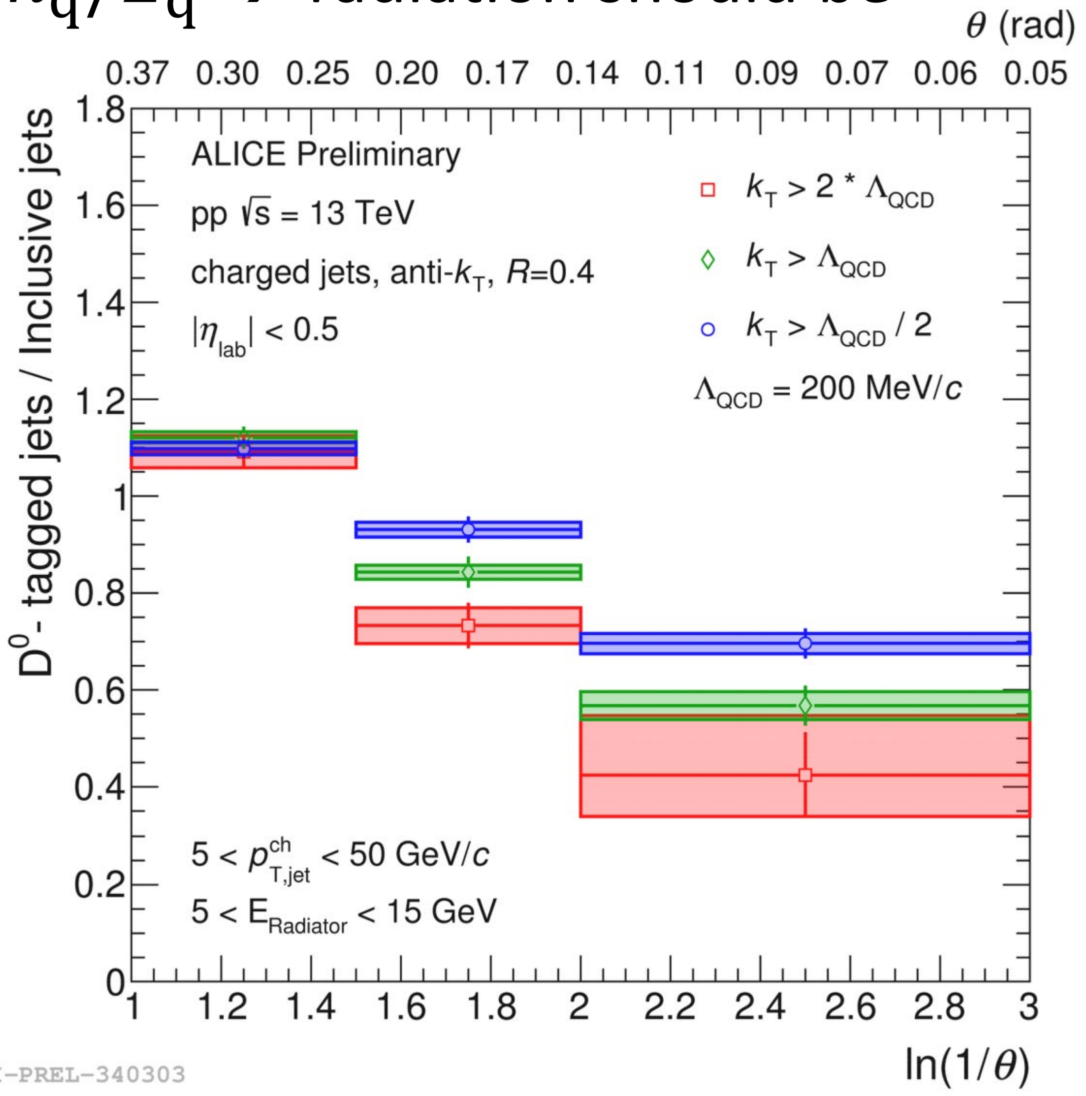
- Slight tension seen with some models in different regions of phase space





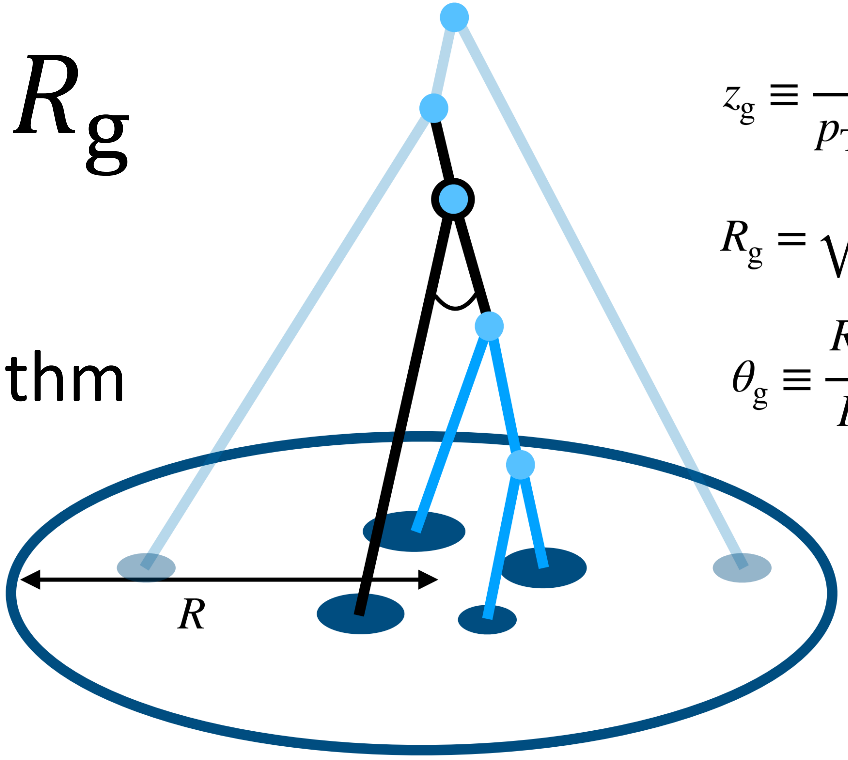
First direct observation of dead-cone effect

- Radiation is suppressed within an angle m_q/E_q → radiation should be suppressed for heavy flavor quarks
- Reconstruct Lund Plane for **inclusive** and D^0**-tagged jets**
- Project onto the angular axis, and take the ratio D^0**-tagged** / **inclusive**
- Significant suppression is seen, and is enhanced at lower E_{radiator}



Nucl. Phys. A (Jan 2021) 121905

Groomed jet z_g and R_g



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

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

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

ALICE

- Recluster jet into ordered tree using Cambridge-Aachen algorithm
- Trim branches, using one of two different algorithms:
  - **Soft Drop grooming** [3]
    - Removes soft, wide-angle radiation
  - **Dynamical grooming** [4]
    - Identifies the "hardest" splitting
- IRC or Sudakov safe

Soft Drop Condition: $$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

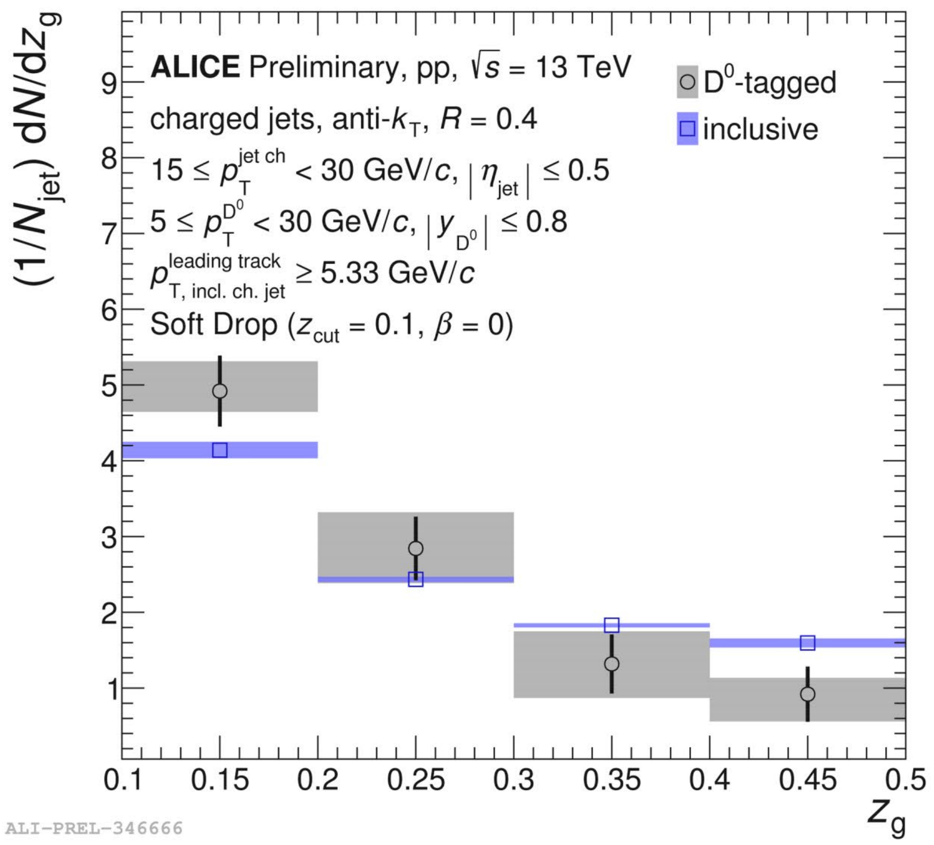
"Hardness": $$\kappa^{(a)} = \frac{1}{p_{\mathrm{T}}} \max_{i \in \mathrm{C/A\ seq.}} \left[z_i (1 - z_i)\, p_{\mathrm{T},i} \left(\frac{\theta_i}{R} \right)^{a} \right]$$

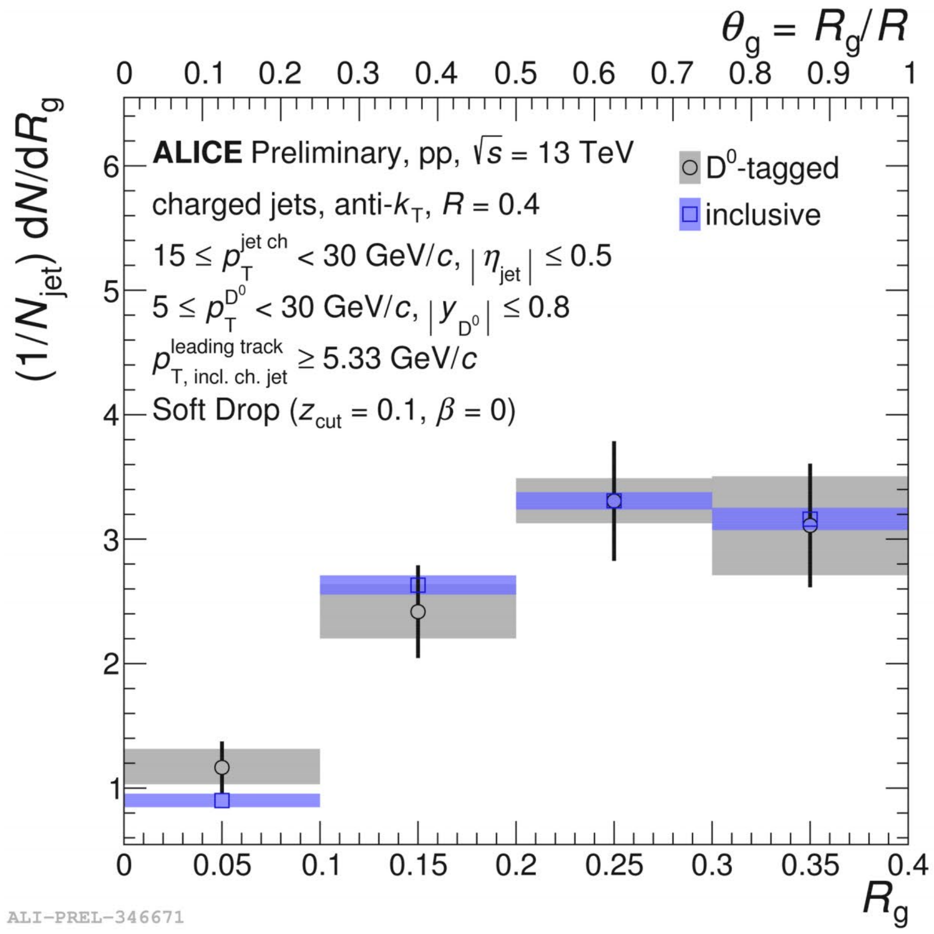
[3] Larkoski et al. JHEP 1405 (2014) 146

[4] Mehtar-Tani et al. Phys. Rev. D 101, 034004 (2020)

First measurement of $z_g/R_g/n_{SD}$ in D^0-tagged jets

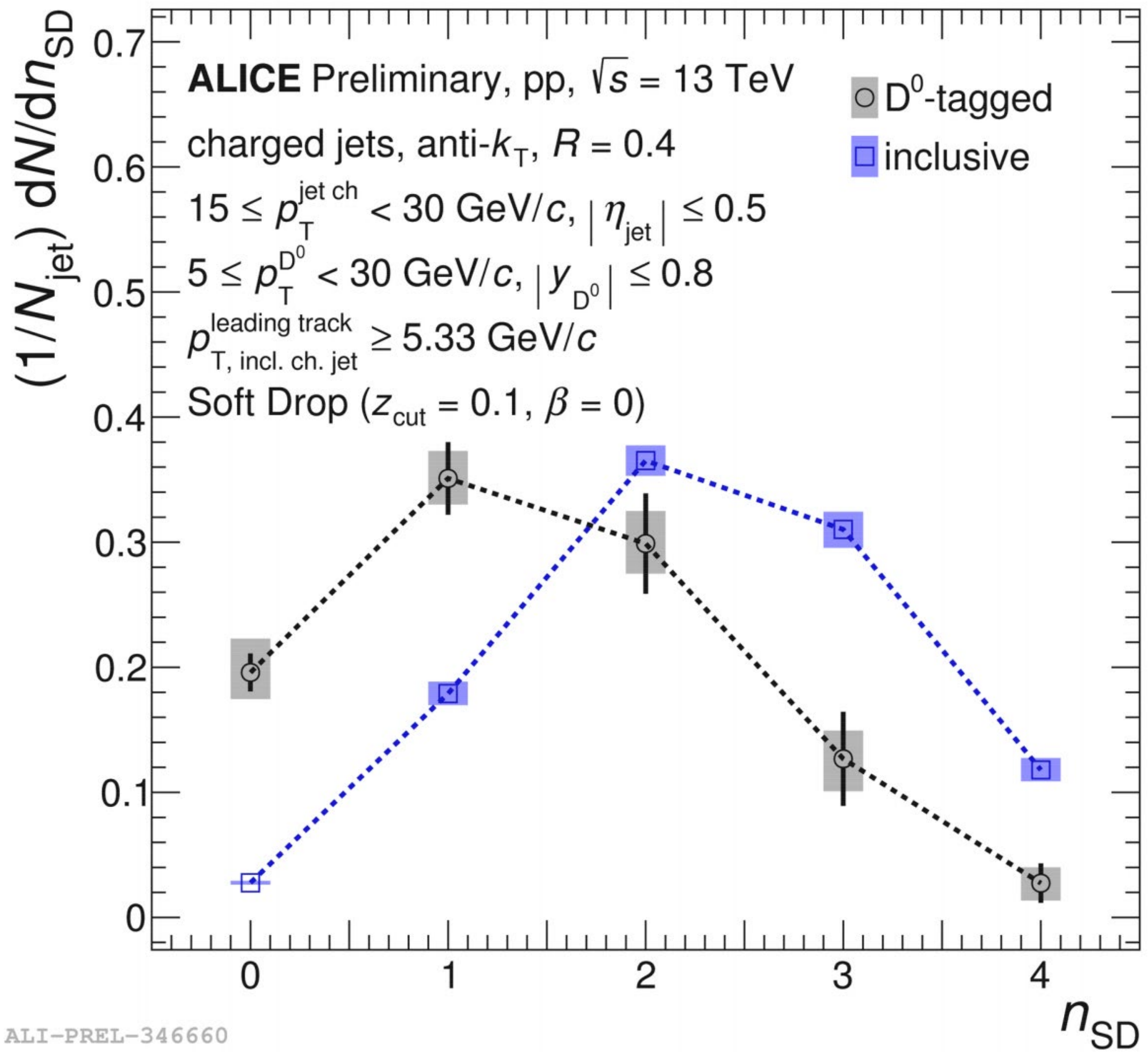
- Reconstruct D^0 mesons through $D^0 \to K^-\pi^+$ decay channel
- Calculate substructure observable in signal and both sideband regions





- Apply **statistical subtraction** to obtain the measurement for “pure” signal
- Any differences probe influence of **heavy quark mass** and **parton flavor** of the jet

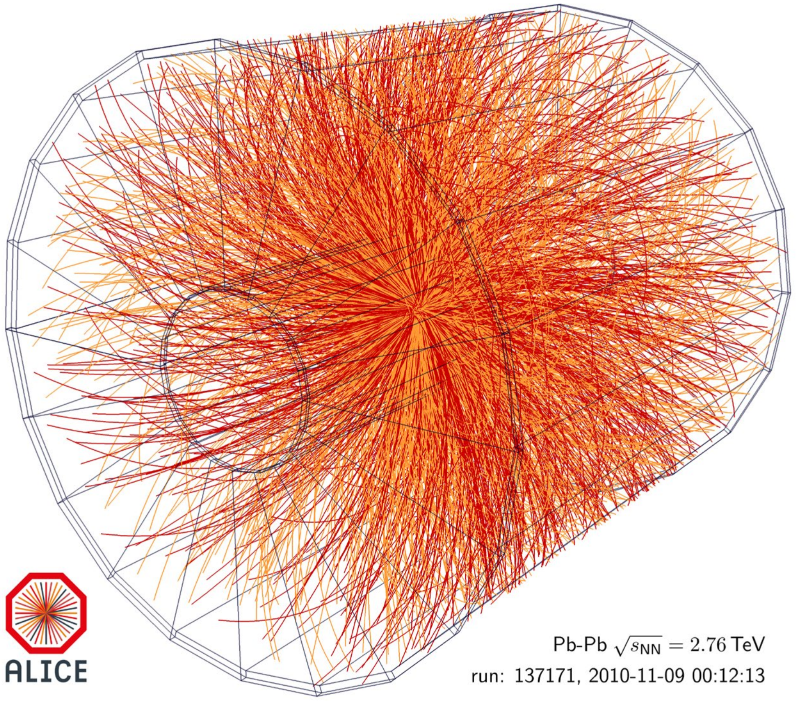
First measurement of $z_g/R_g/n_{SD}$ in D^0-tagged jets

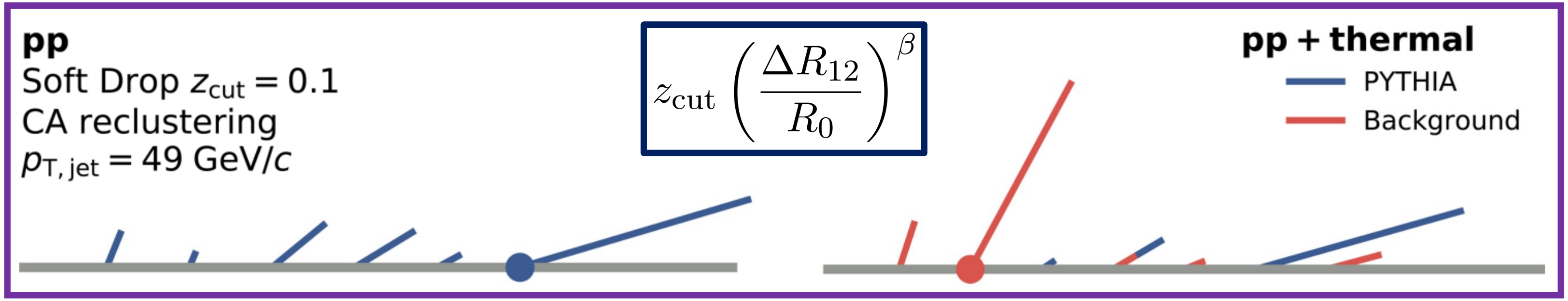


- n_{SD} is the number of splittings which pass the Soft Drop grooming condition
  - Follows the hardest branch
- ***D^0*-tagged jets have fewer splittings** than inclusive jets
- Consistent with quark jets being **harder with fewer emissions** than gluon jets

Choosing grooming settings

- Mistagging of the primary splitting occurs in jets in heavy-ion collisions due to the increased background
- Higher values of $z_{\text{cut}} \geq 0.2$ (Soft Drop) and $a \to 0$ (Dynamical Grooming) increase the tagging purity in high-background environments [5]

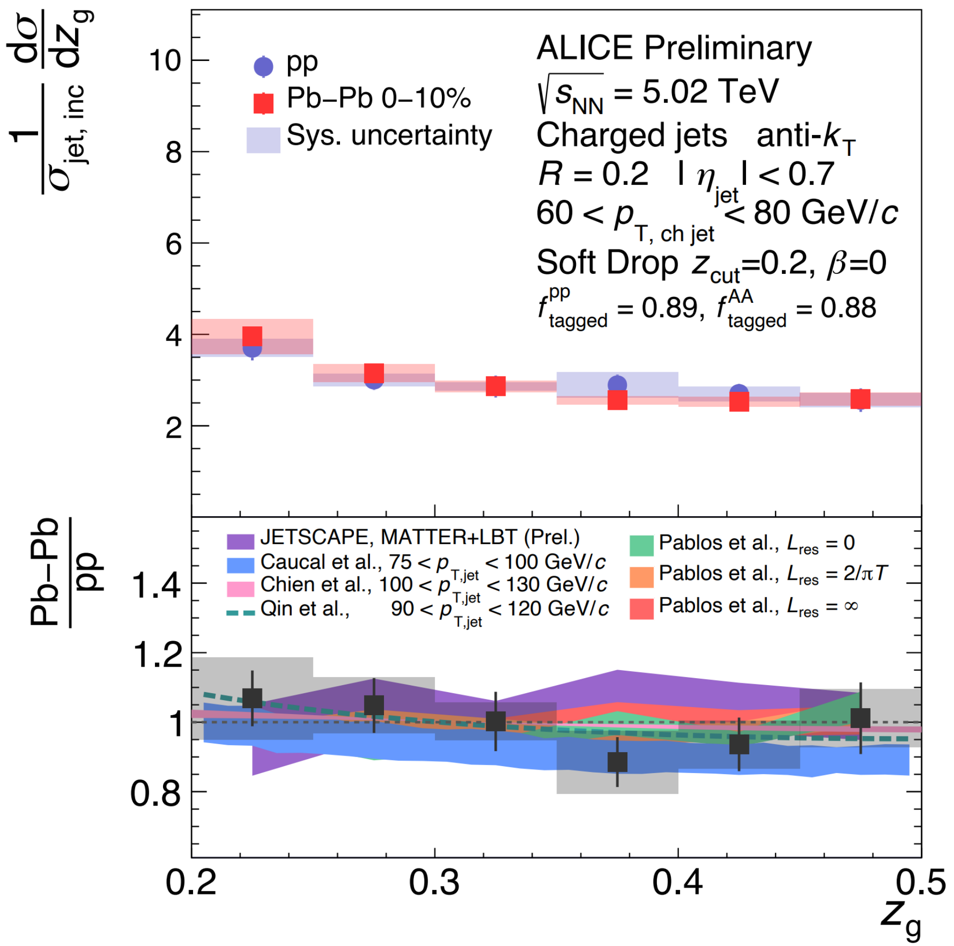


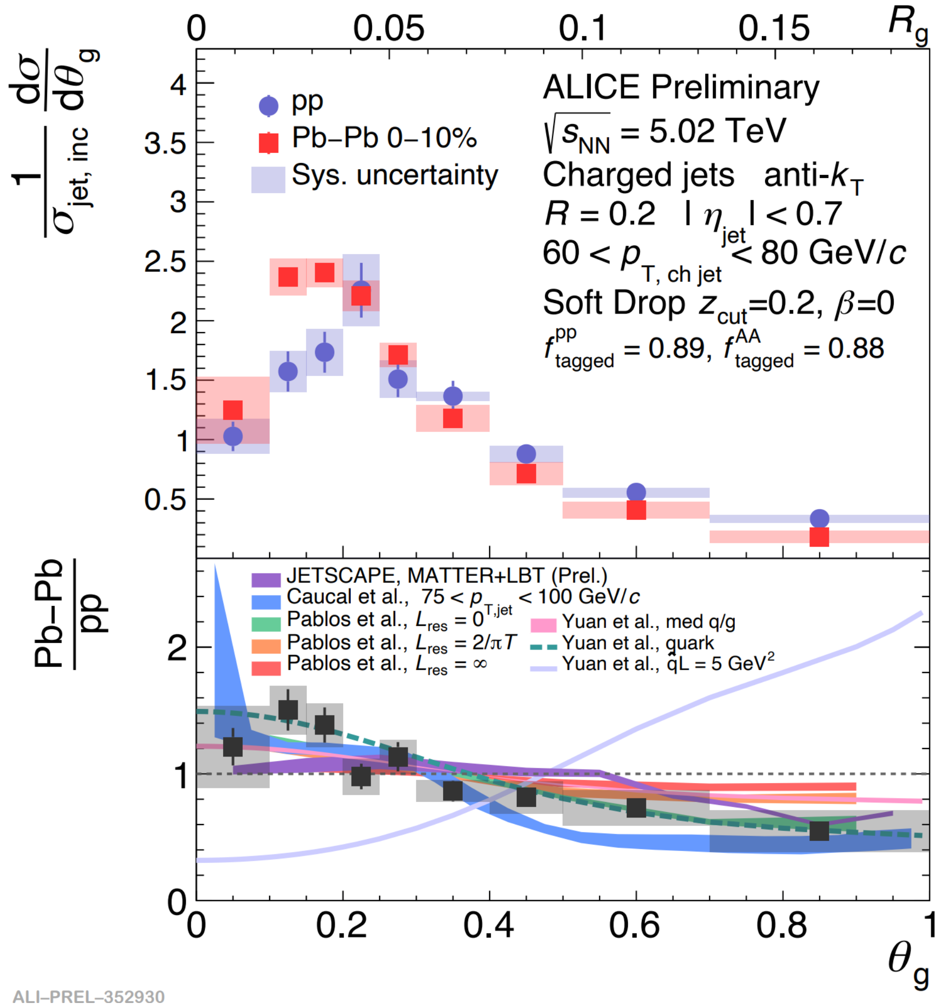


[5] Mulligan, Płoskoń Phys. Rev. C 102, 044913 (2020)

z_{g} and R_{g} in pp compared to Pb-Pb

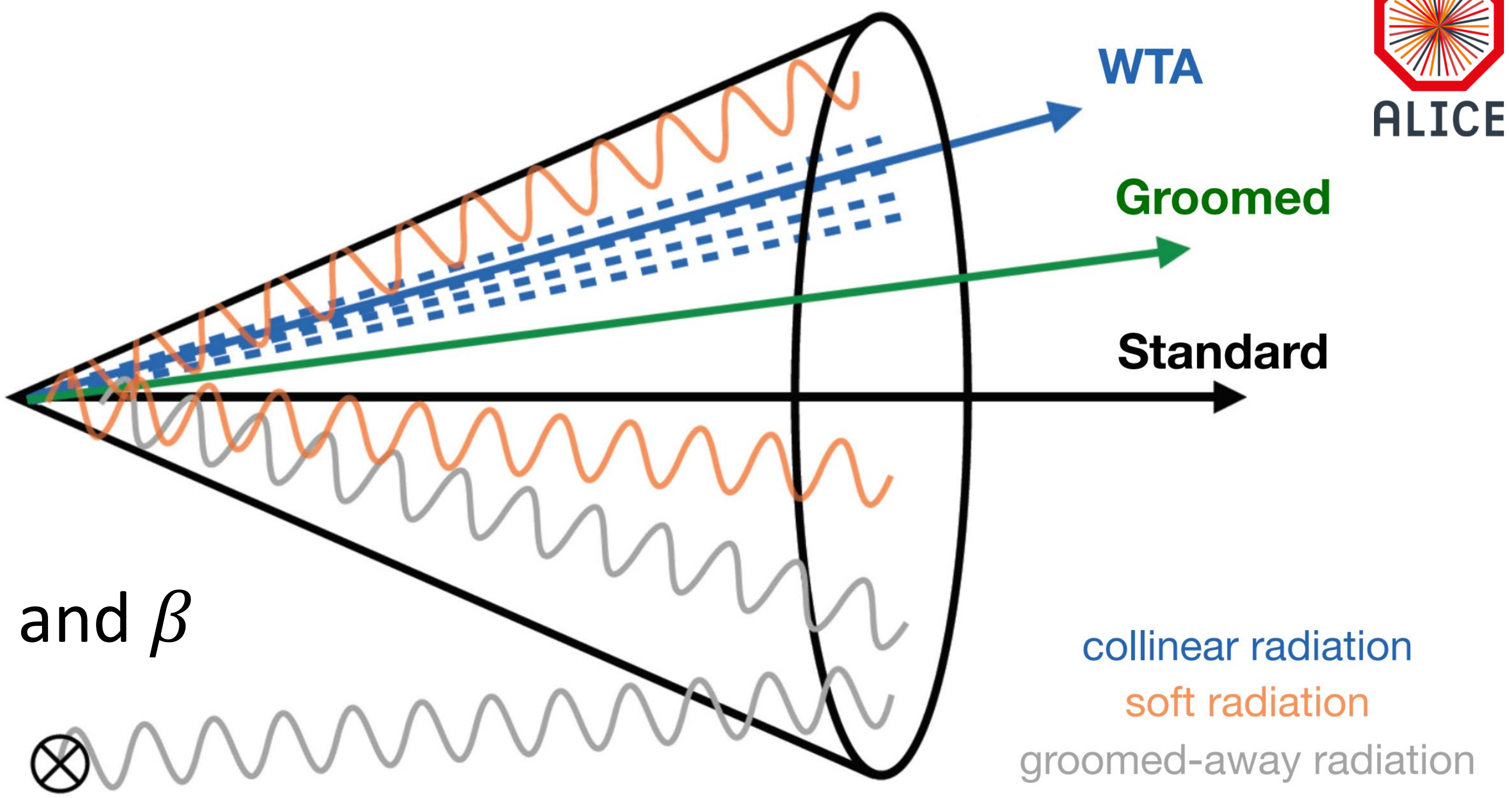
- By using stronger grooming conditions ($z_{\mathrm{cut}} = 0.2$), ALICE measured fully-corrected groomed jet observables, and enabled the first measurement of θ_{g} in Pb-Pb data





Jet-axis differences

- **Standard**: anti-k_{T} jet with E-scheme recombination
- **Groomed**: apply Soft Drop with different values of z_{cut} and β
- **Winner-Take-All (WTA)**: jet axis is given by its leading constituent

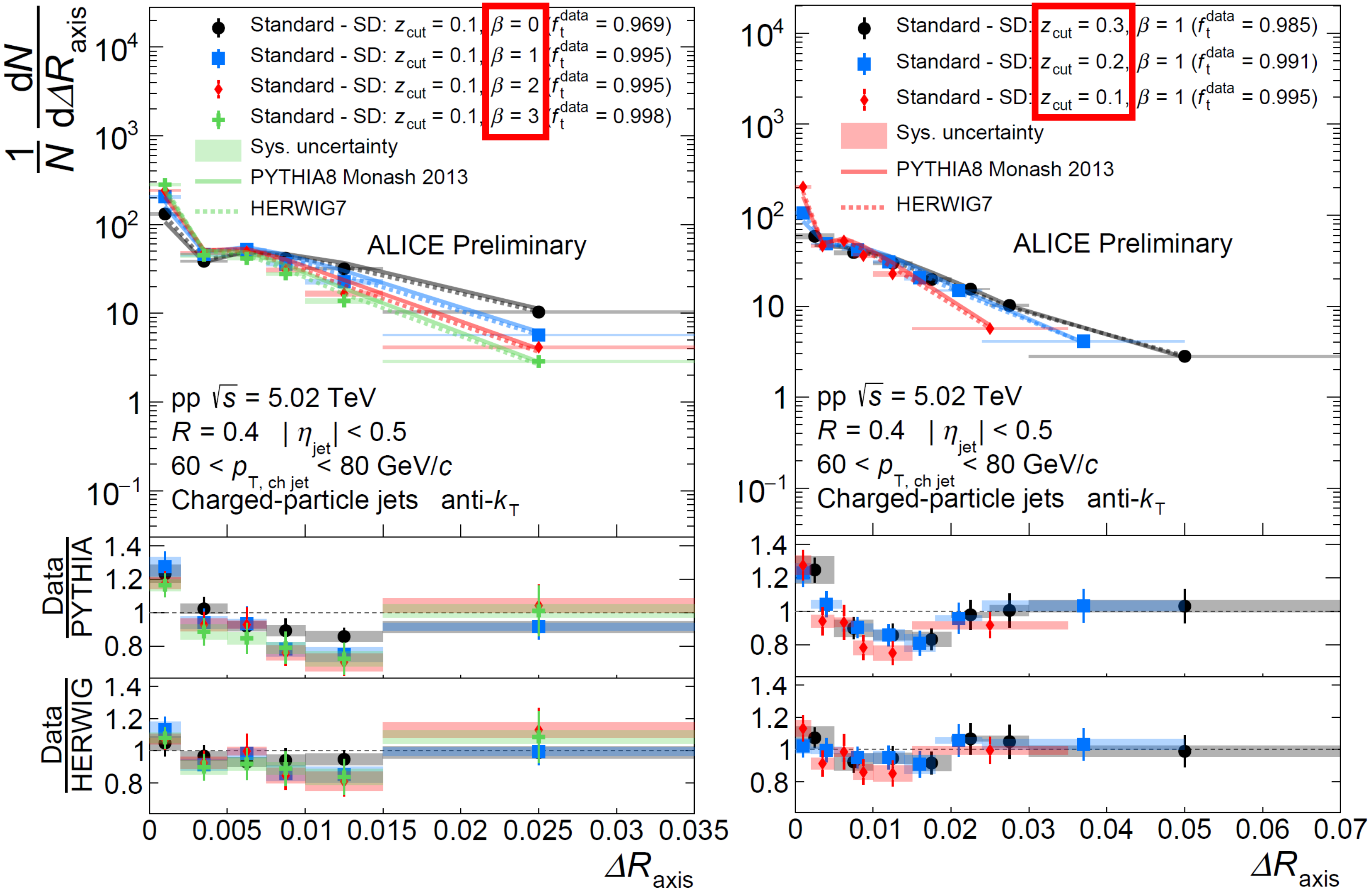


- Calculate the angular separation: $\Delta R_{\mathrm{axis}} = \sqrt{\Delta y^2 + \Delta\phi^2}$
- IRC-safe observable sensitive to **soft radiation, TMDs, and PDFs** [6]

[6] Cal, Neill, Ringer, Waalewijn JHEP 04 (2020) 211

First measurement of the jet-axis differences

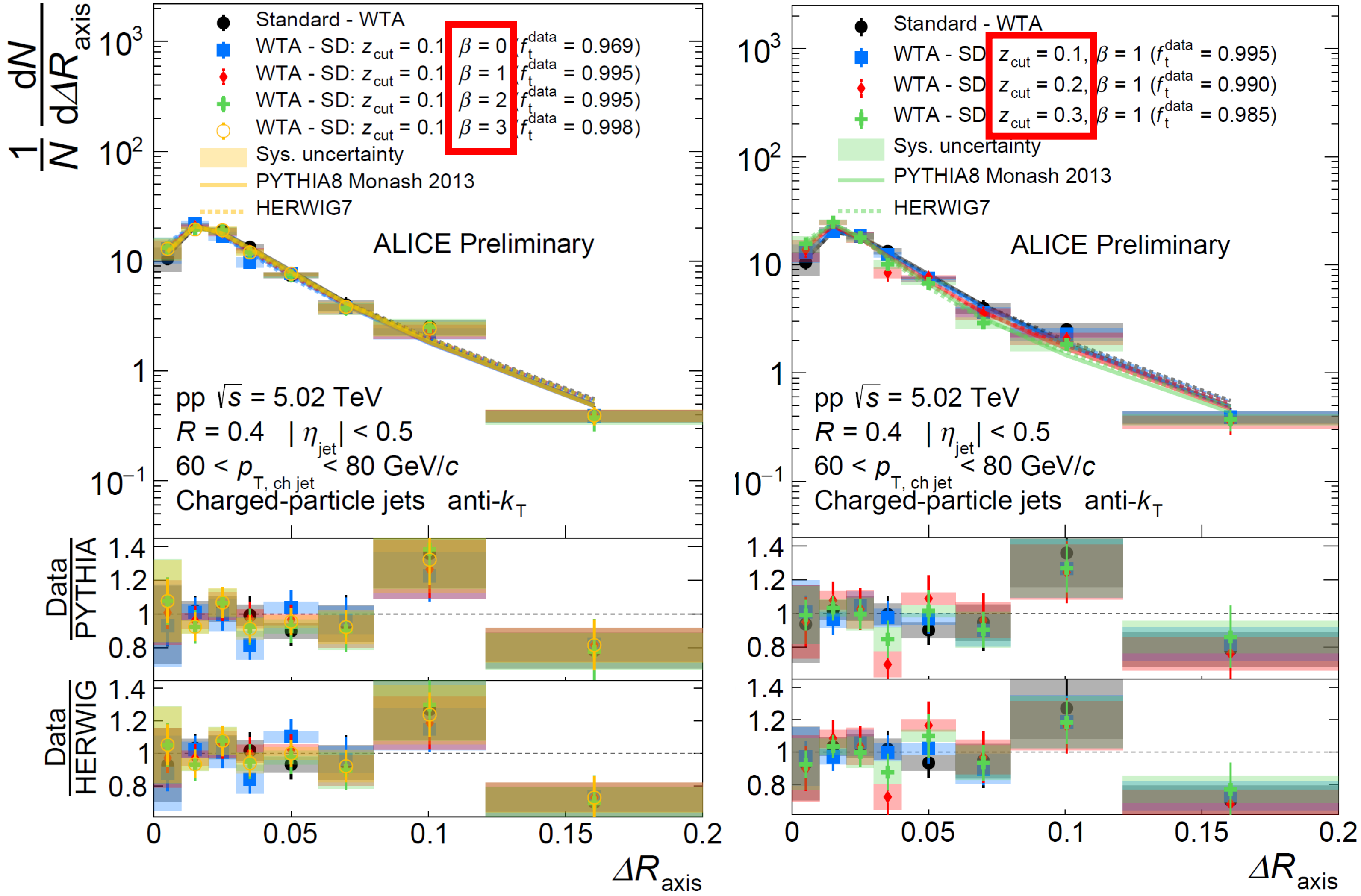
- Slight tension seen between data and MC for standard versus SD axis



- **Standard and SD axes are strongly correlated**
- Seems mostly independent of grooming parameters
- Will be useful for tuning MC generators
- pQCD comparisons are coming soon!

First measurement of the jet-axis differences

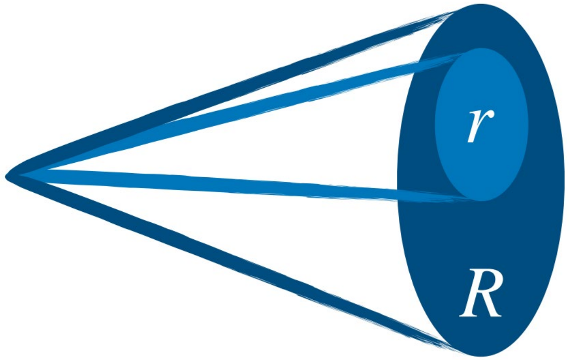
- Good agreement seen with MC for a wide range of SD parameters



- **WTA and standard/SD axes are less strongly aligned/correlated**
  - p_T is distributed more broadly within the jet, rather than collimated along a single axis
  - PYTHIA and Herwig reproduce this trend
- Note: every curve uses the same sample of jets

Measurement of subjets

- Reconstruct inclusive jets with radius R, then recluster using anti-k_{T} with smaller radius r



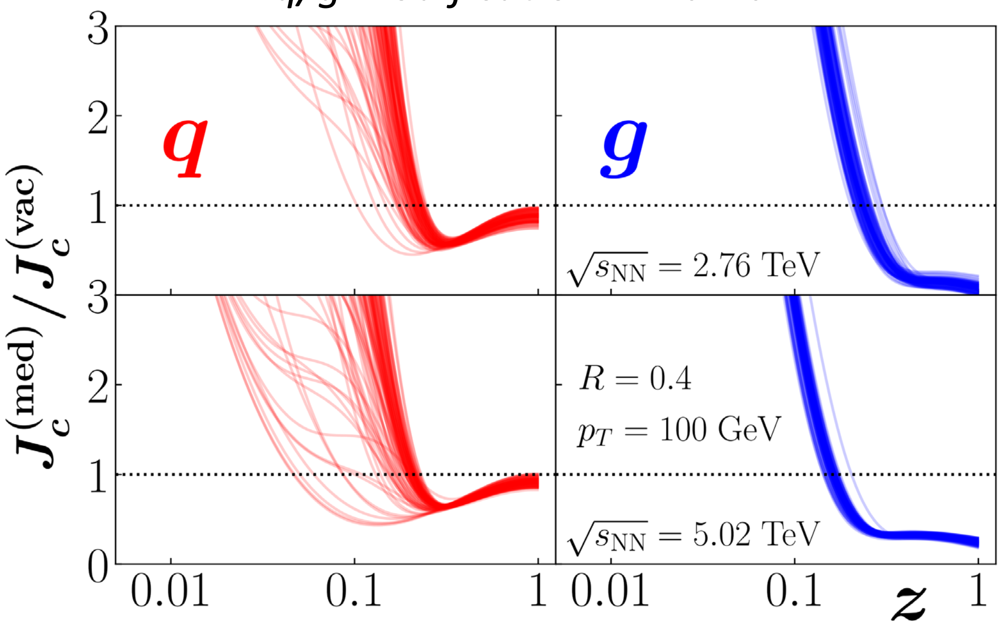
$$z_{\mathrm{r}} = \frac{p_{\mathrm{T}}^{\mathrm{ch\ subjet}}}{p_{\mathrm{T}}^{\mathrm{ch\ jet}}}$$

- Can either study **inclusive** or **leading** subjets

- Sensitive to jet quenching effects from the hot, dense QCD medium formed in heavy-ion collisions

- Test of **universality of jet functions**: compare extraction of $J_{r,\mathrm{med}}(z)$ to $J_{\mathrm{med}}(z)$ from R_{AA} [8]

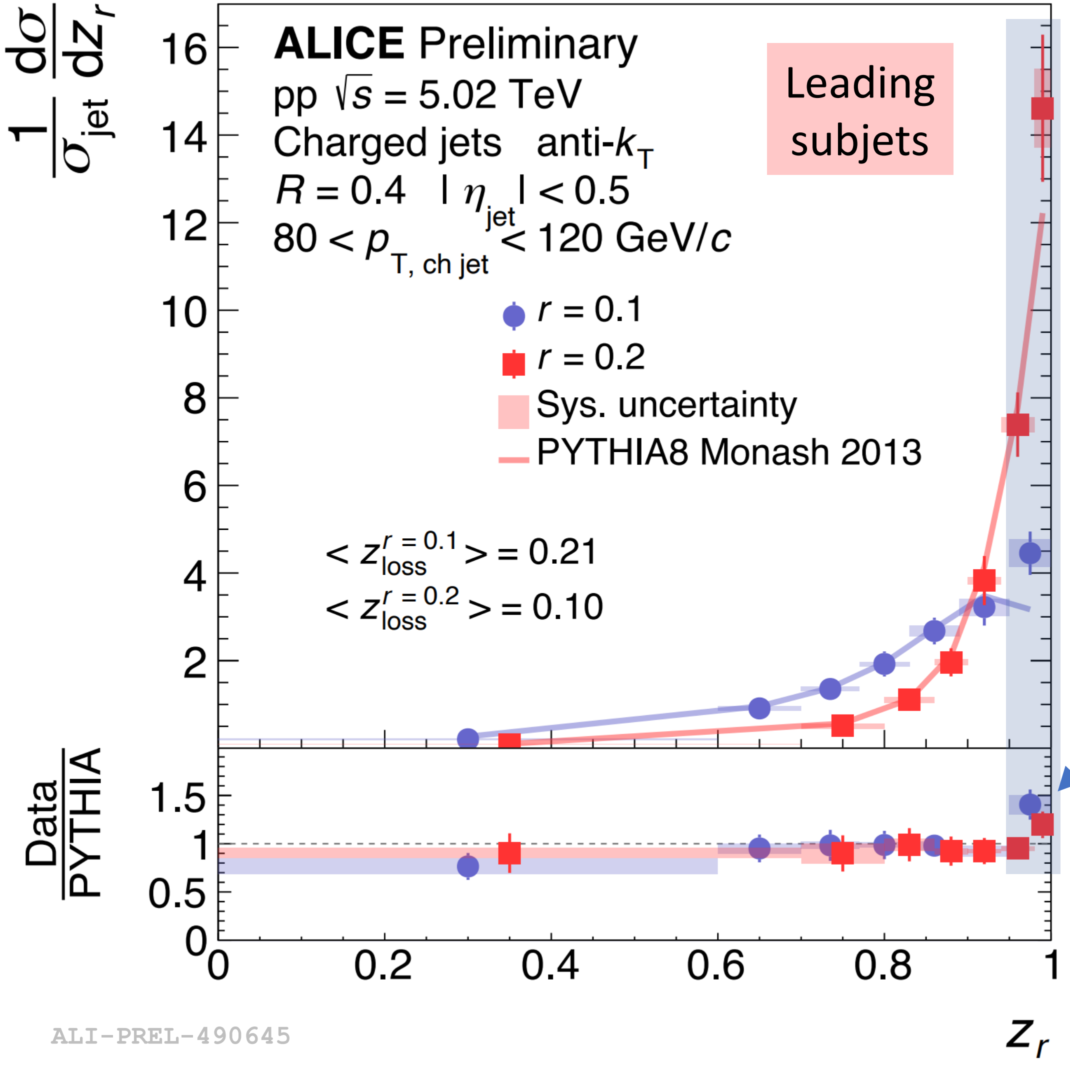
q/g modification in Pb-Pb?



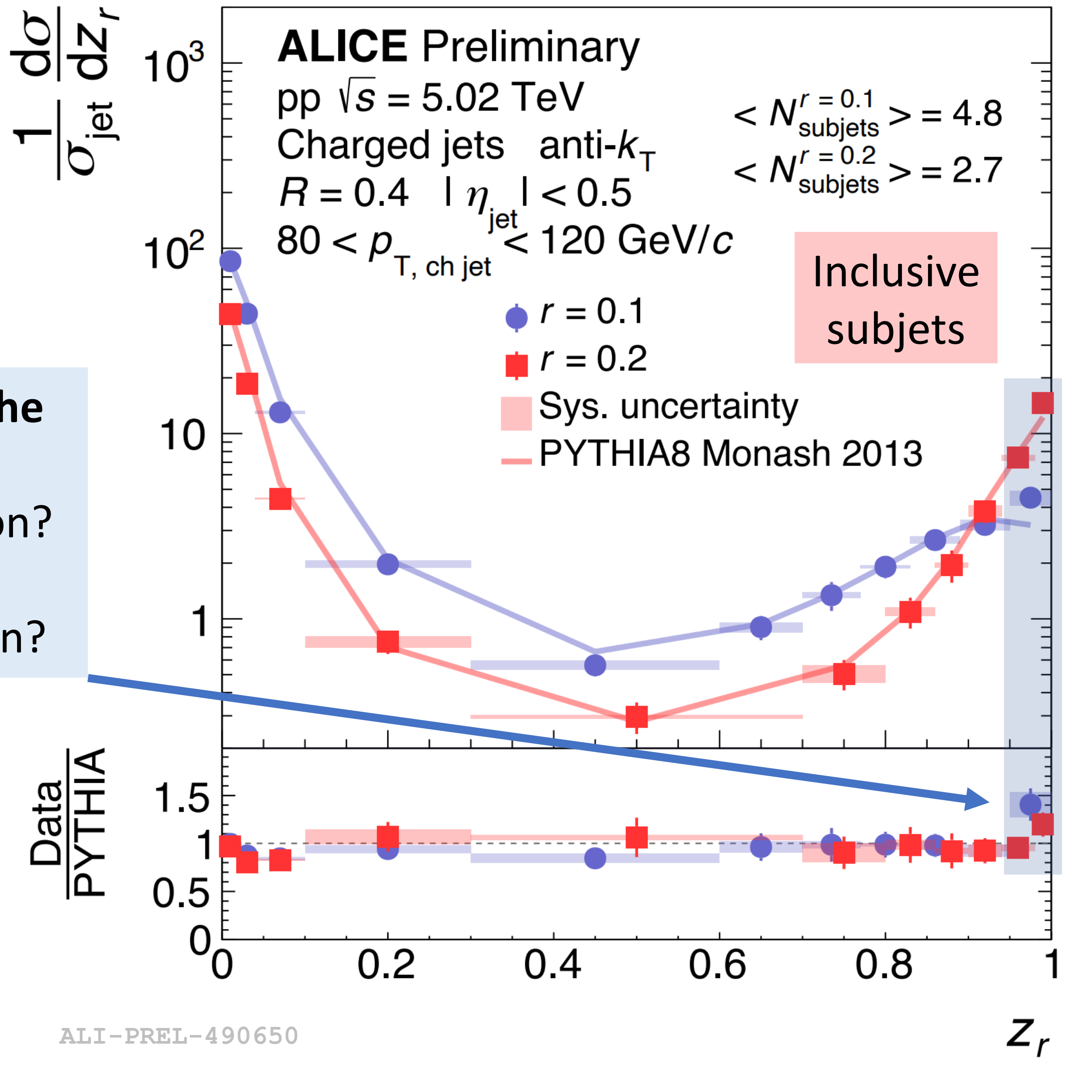
[8] Qiu, Ringer, Sato, Zurita PRL 122 (2019) 25

New subjet measurements in pp

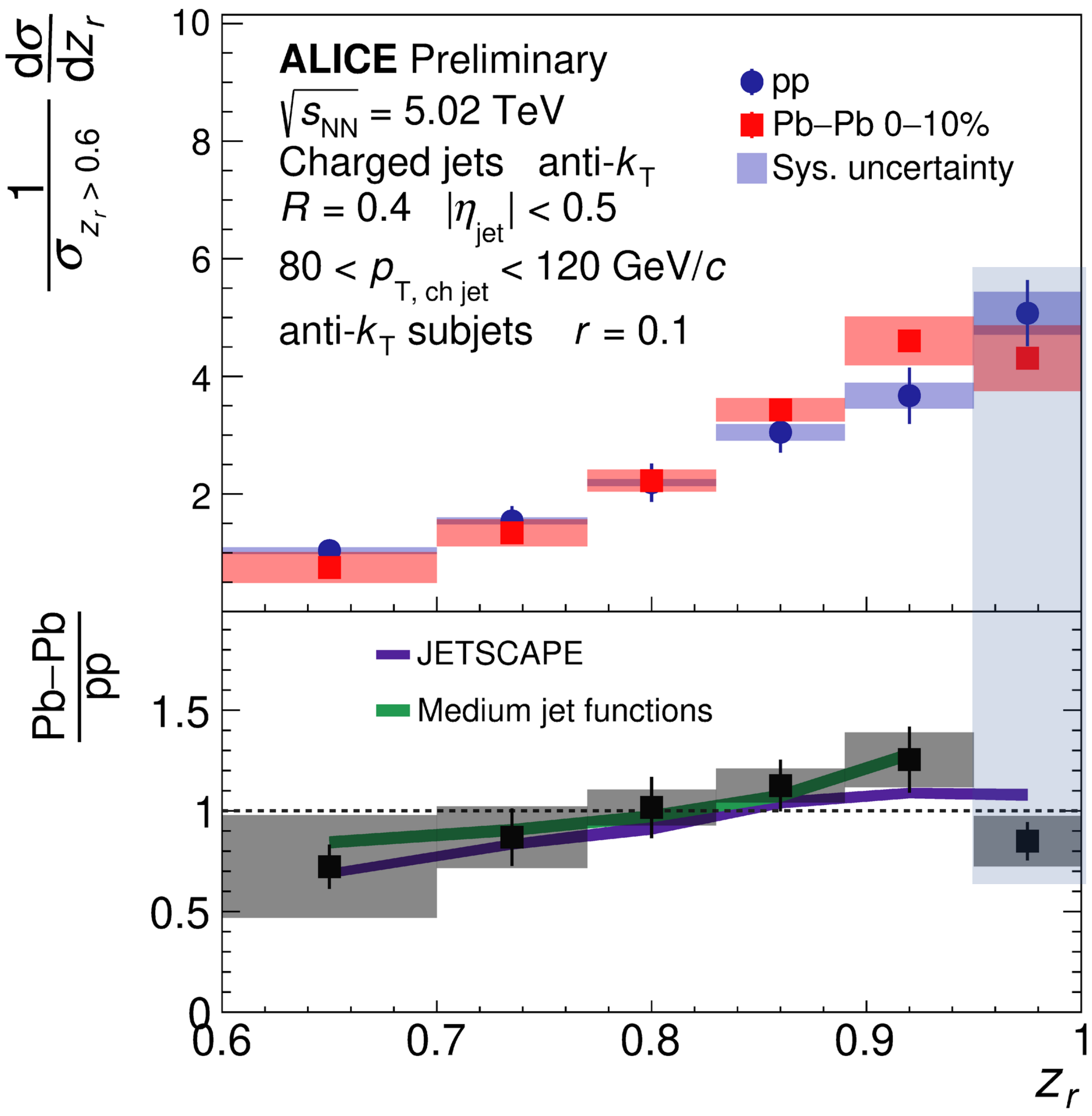
- Reasonable agreement is observed with respect to MC generators



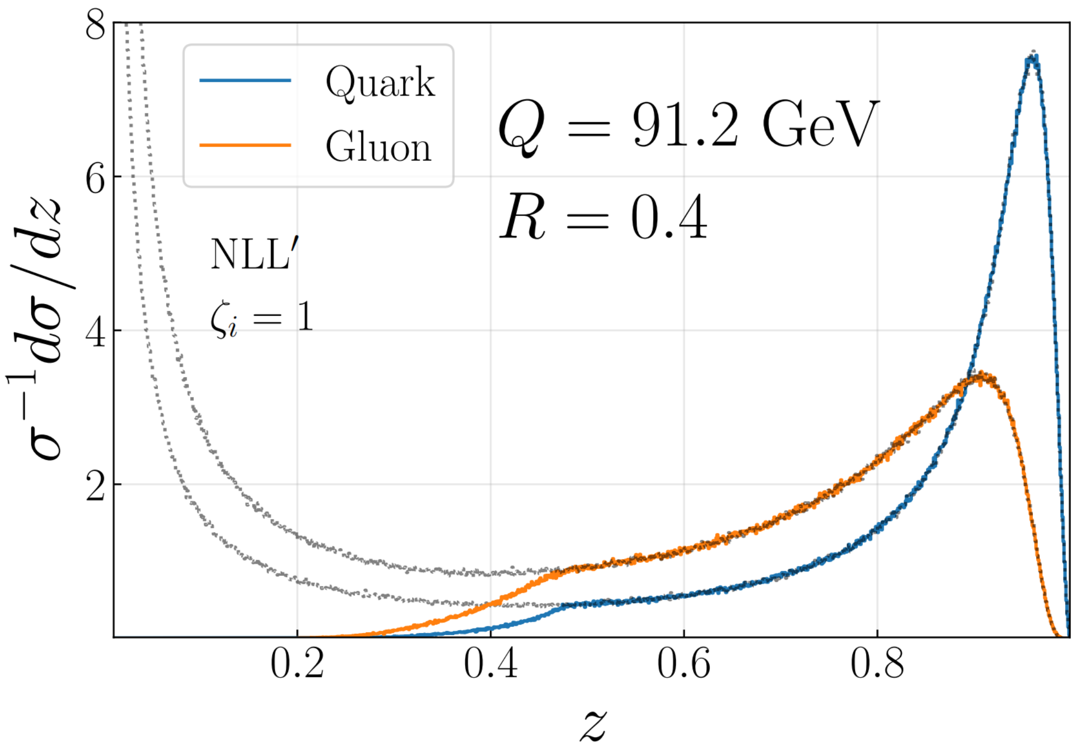
Tension in the last bin:
Hadronization?
Threshold resummation?



Modification in Pb-Pb collisions?



- Hardening at mid-z_r could point to quark/gluon fraction modification
- Soft radiation enhanced at small z_r → competing normalization effect

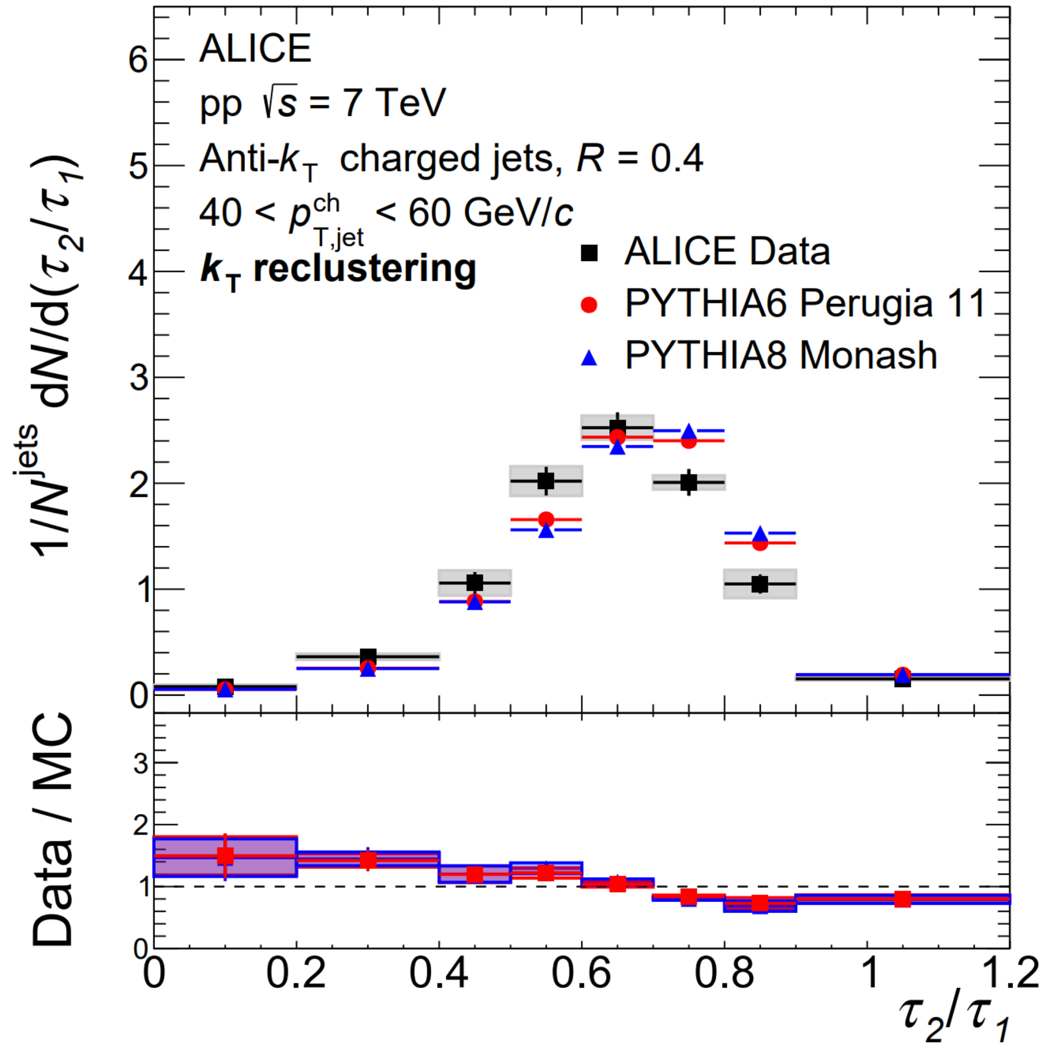


Neill, Ringer, Sato arXiv:2103.16573

Measuring the N-subjettiness in pp

$$\tau_N = \frac{1}{p_{\mathrm{T,jet}} \times R} \sum_k p_{\mathrm{T},k} \,\mathrm{minimum}(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{\mathrm{N},k})$$

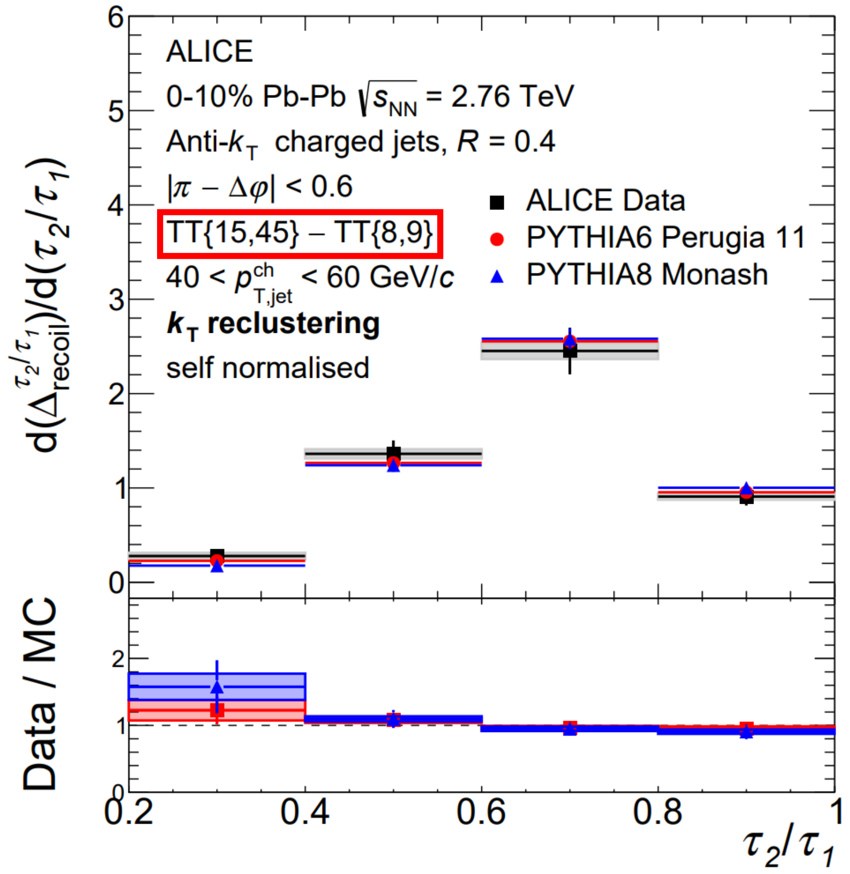
- Used for **tagging 1- or 2-pronged jets**
  - Originally designed to tag boosted decays such as $W^{\pm} \rightarrow \bar{q}q$ or $t \rightarrow W^{+}b$
- $\tau_N \rightarrow 0$ means correlation to N subjets; $\tau_N \rightarrow 1$ means no strong correlation and suggests at least $N+1$ subjets
- Low values of τ_N/τ_{N-1} are used to **discriminate N-prongness**
- τ_2/τ_1 is peaked at intermediate values → pp jets are found to be **mostly single-cored**, as two hard substructures are not well-separated and defined

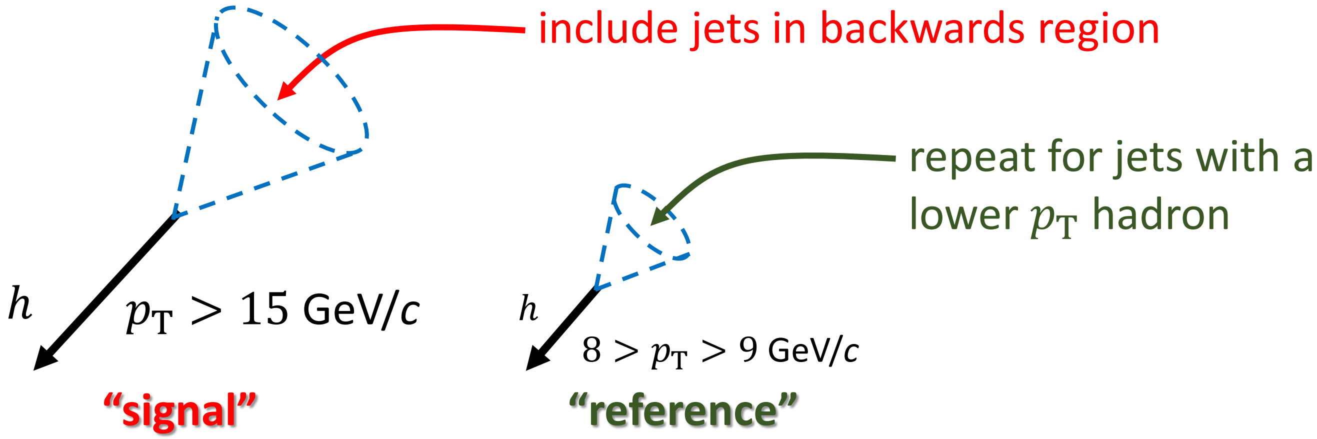


arXiv:2105.04936 [nucl-ex]

Fully corrected N-subjettiness in Pb-Pb

- Using the **semi-inclusive hadron-jet recoil technique** [9] for the first time in a substructure measurement (CERN-EP-2021-082)





- Reduce contamination from combinatorial jets via requirement of a back-to-back high-p_T hadron, then subtracting the observable shape from a reference Trigger Track (**TT**) bin

[9] JHEP 09 (2015) 170

Conclusions

- ALICE has many **new and developing analyses** with novel comparisons to first-principles pQCD predictions
  - Stay tuned for new upcoming articles on the arXiv!
- **Folding approach to nonperturbative corrections** can be used to constrain theory and Monte Carlo hadronization models
- Some new approaches to **mitigating large backgrounds** which appear in heavy-ion collisions
- Comparing measurements **with and without grooming** allows an approach to study soft effects
  - Grooming settings must be chosen in pp to maximize calculability and Pb-Pb comparisons

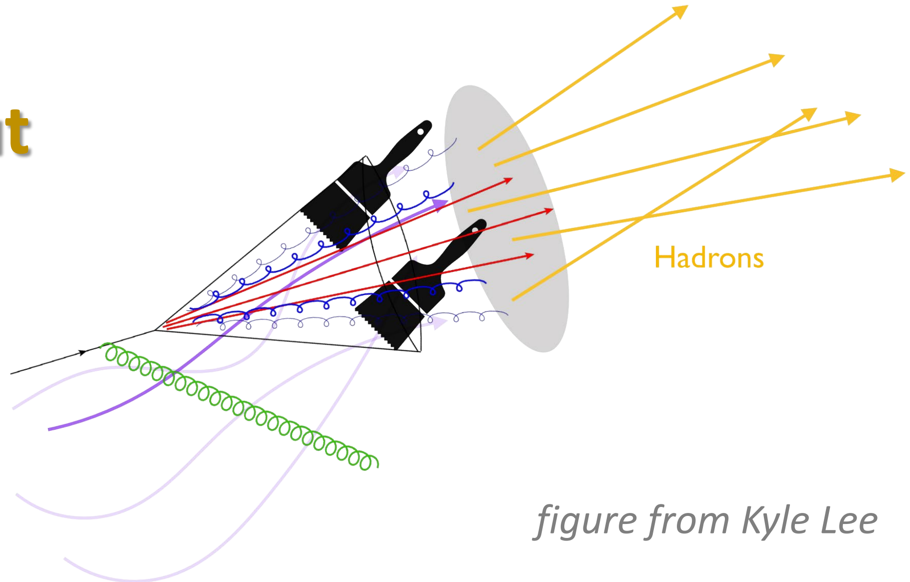
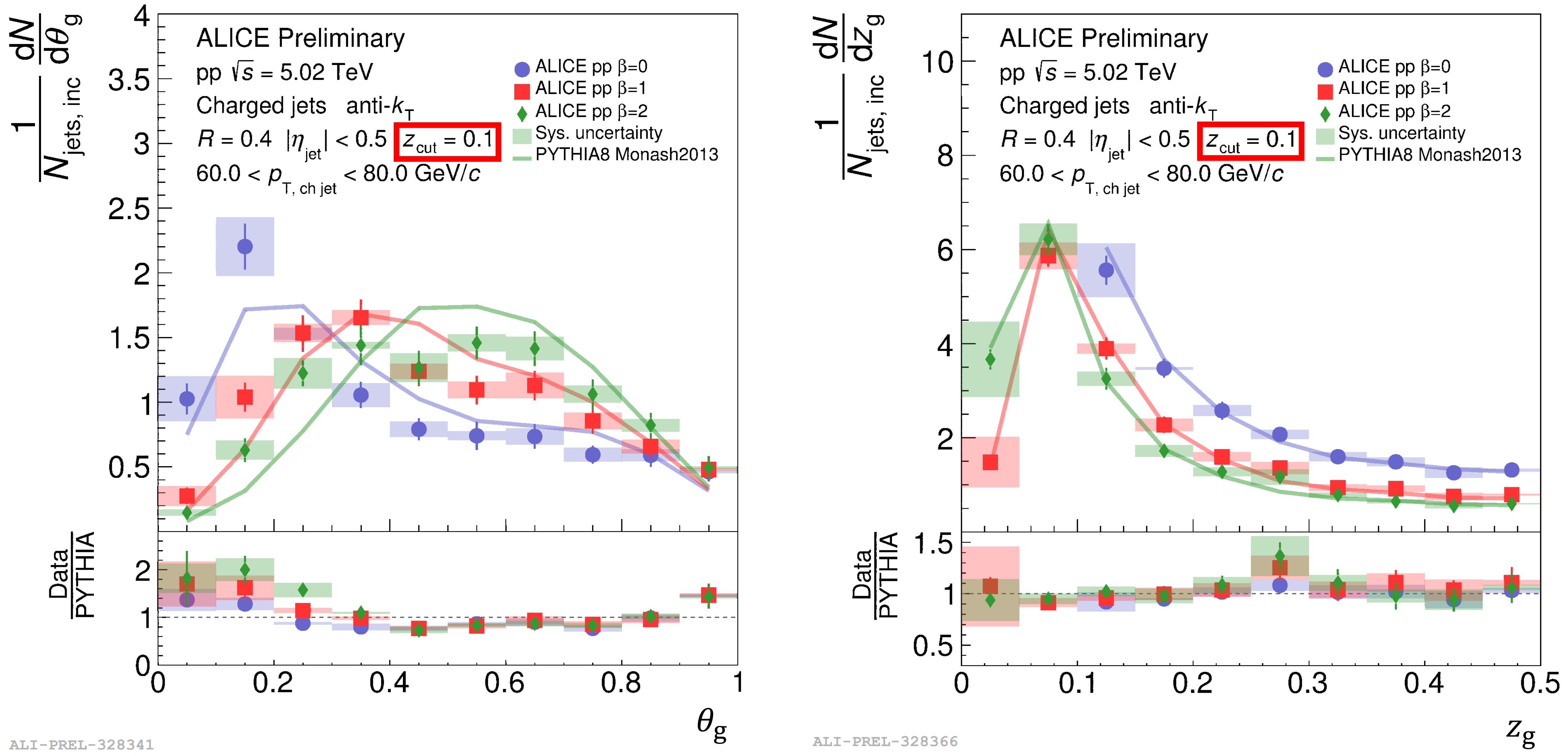


figure from Kyle Lee

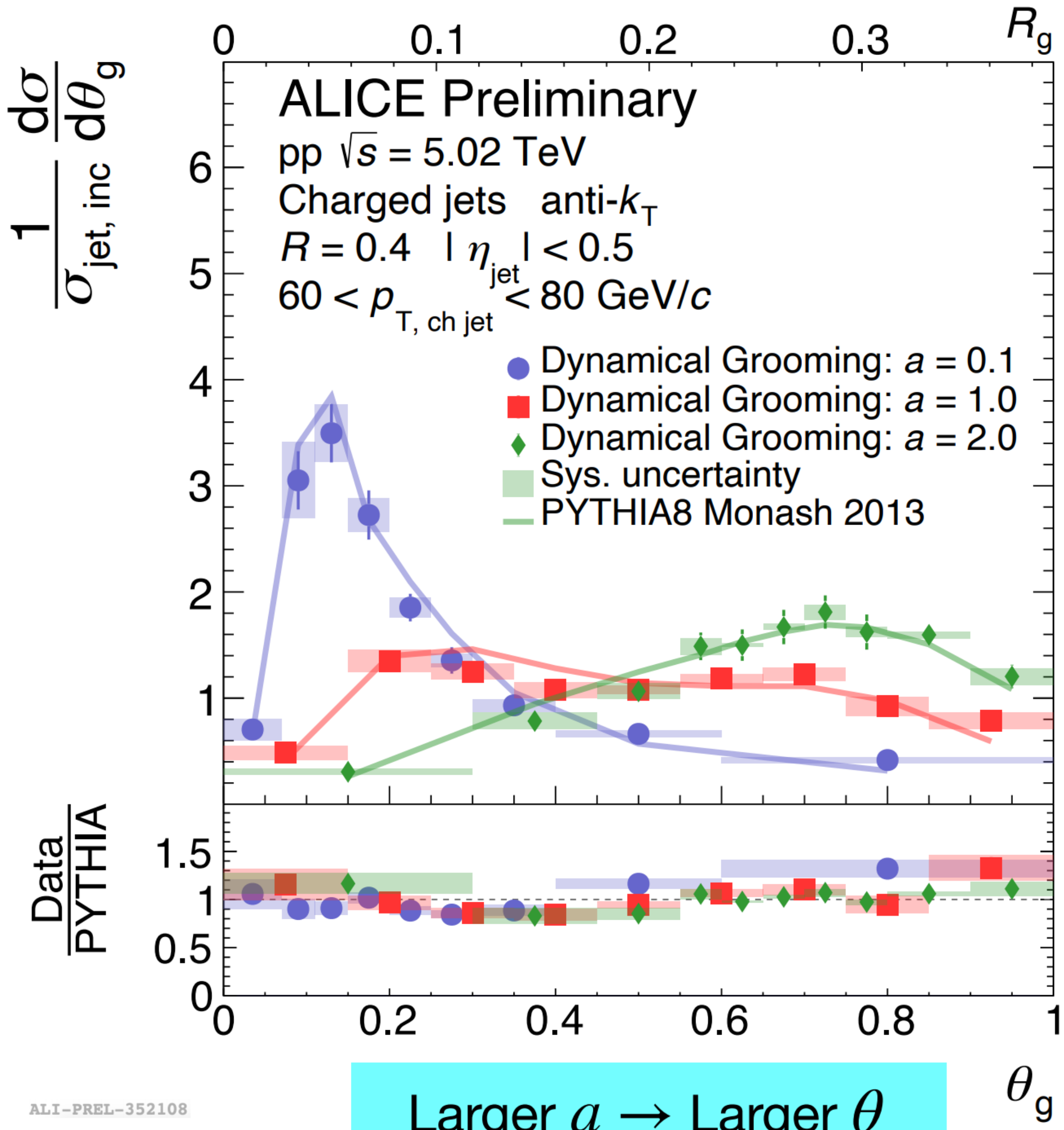
Backup

z_g and R_g with Soft Drop grooming

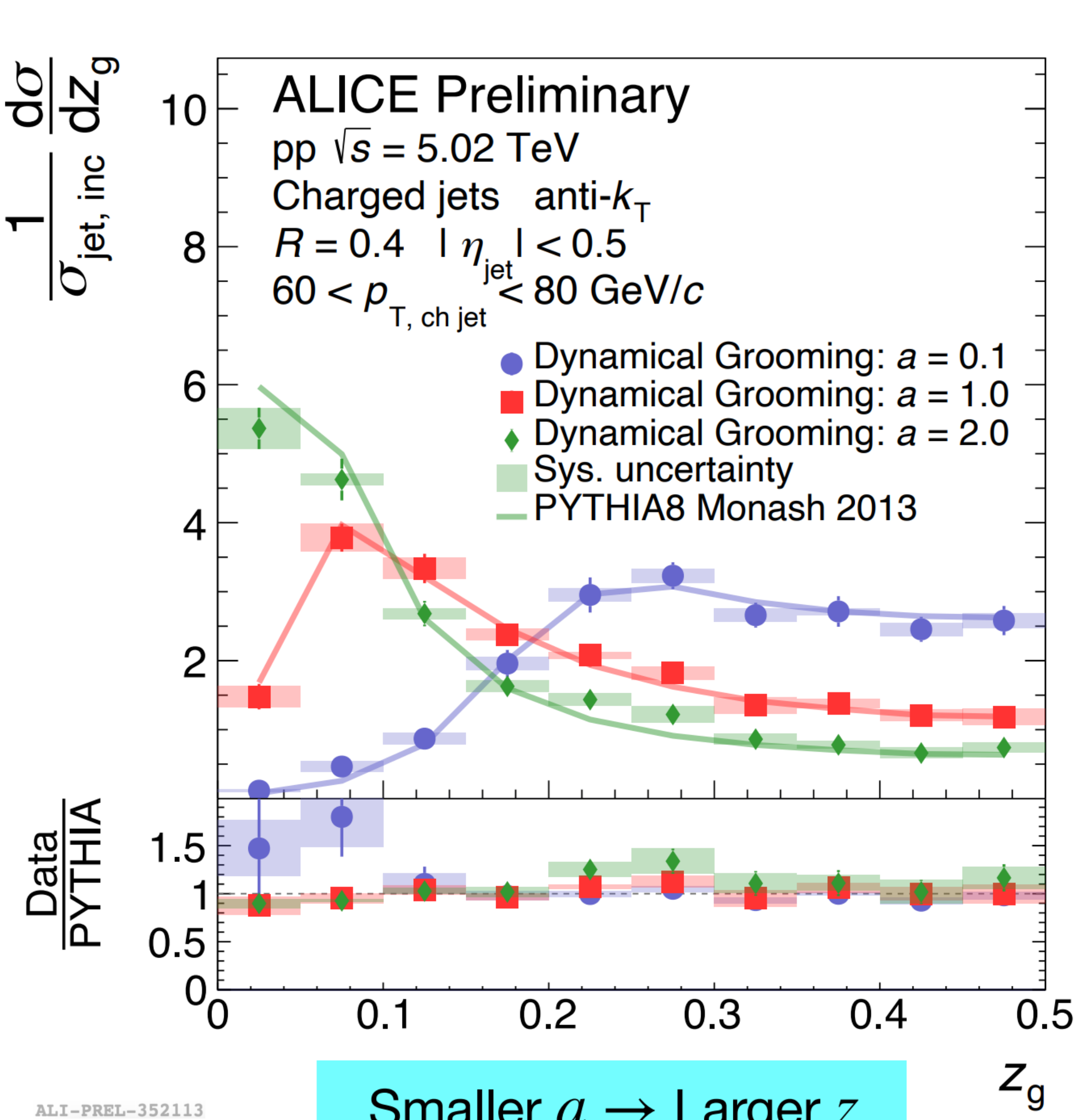
- Comparisons to PYTHIA show stronger modification with larger β



First-ever measurement with Dynamical Grooming



Larger a → Larger θ



Smaller a → Larger z

Choosing grooming settings

- **Soft Drop**: higher values of $z_{\mathrm{cut}} \geq 0.2$ increase the leading branch tagging purity in high-background environments [5]

$$z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

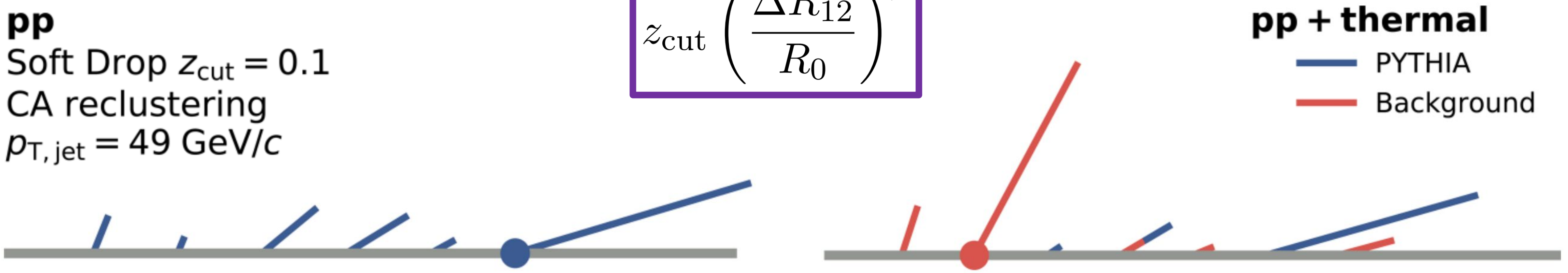


figure: J. Mulligan, LBNL

- **Dynamical**: same is true for lower $a \to 0$

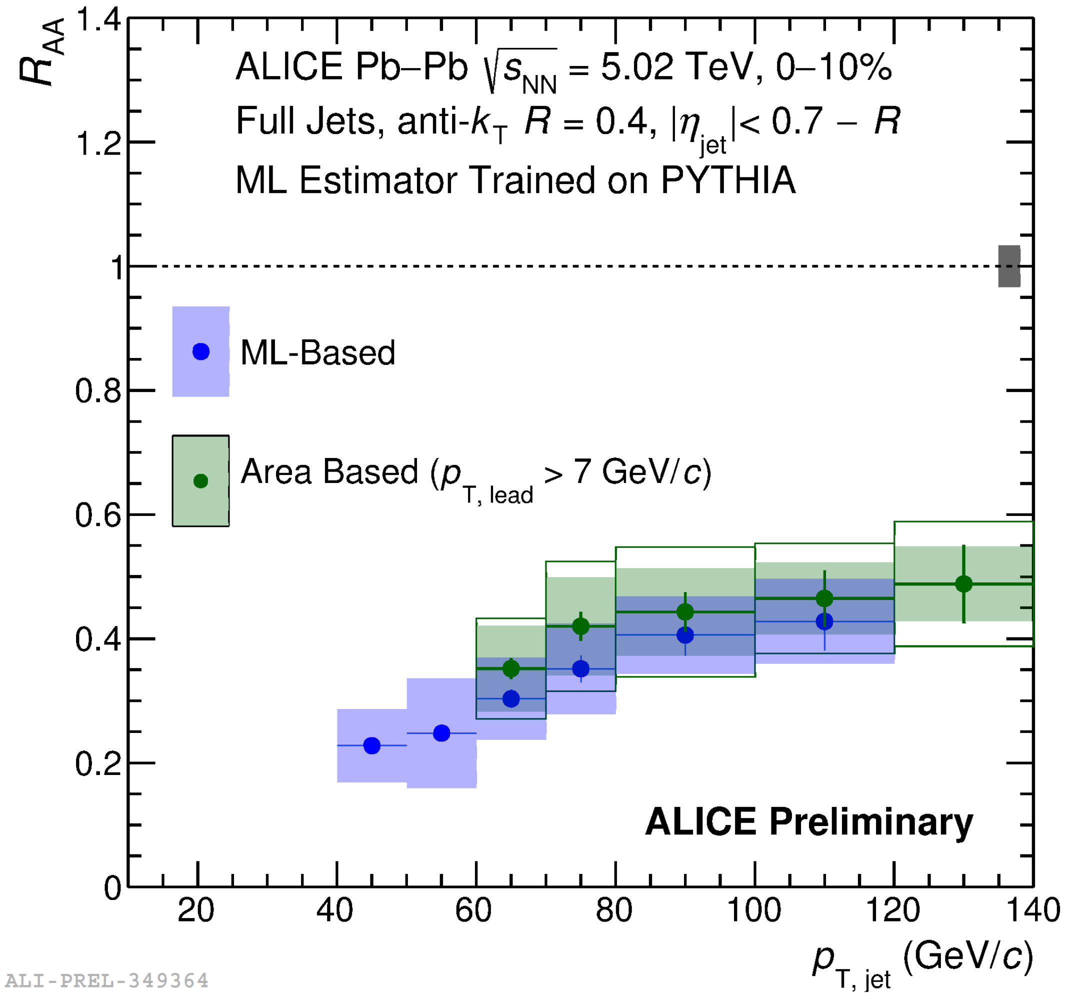
$a \to 0$	hardest z	$z_{cut} \approx e^{-a\pi/\alpha_s C_F}$
$a = 1$	hardest k_T	$\ln k_t \approx -\sqrt{a}$
$a = 2$	smallest t_f	$\ln k_t(R_{\mathrm{jet}}) \approx -\sqrt{a}$

$$z_i(1 - z_i)\, p_{\mathrm{T},i} \left(\frac{\theta_i}{R} \right)^{a}$$

[5] Mulligan, Płoskoń Phys. Rev. C 102, 044913 (2020)

Using ML to reduce jet background [10]

- May allow studying jets with lower jet p_T and larger R than before



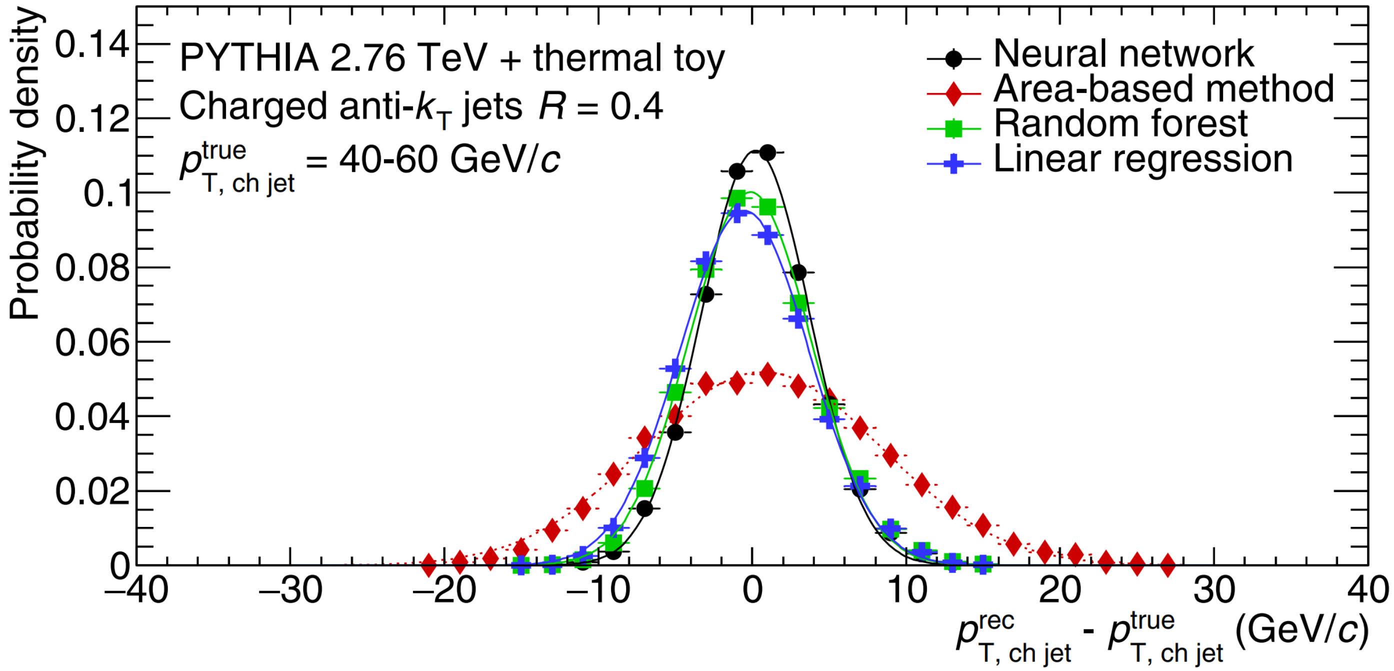


FIG. 2. Residual distributions for several background estimators in $40 \leqslant p^{true}_{T, ch jet} < 60$ GeV/c.

Talk tomorrow:
Hannah Bossi,
Yale University

[10] Haake, Loizides Phys. Rev. C 99, 064904 (2019)