# Recent jet measurements from ALICE

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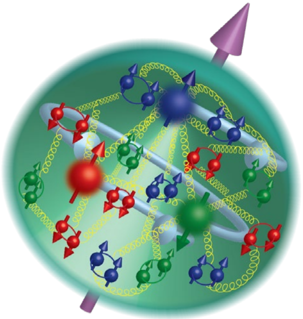
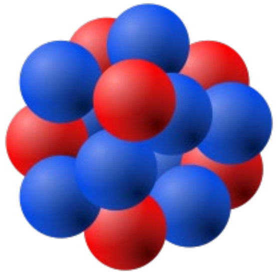
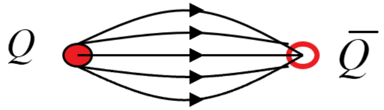
# Introduction

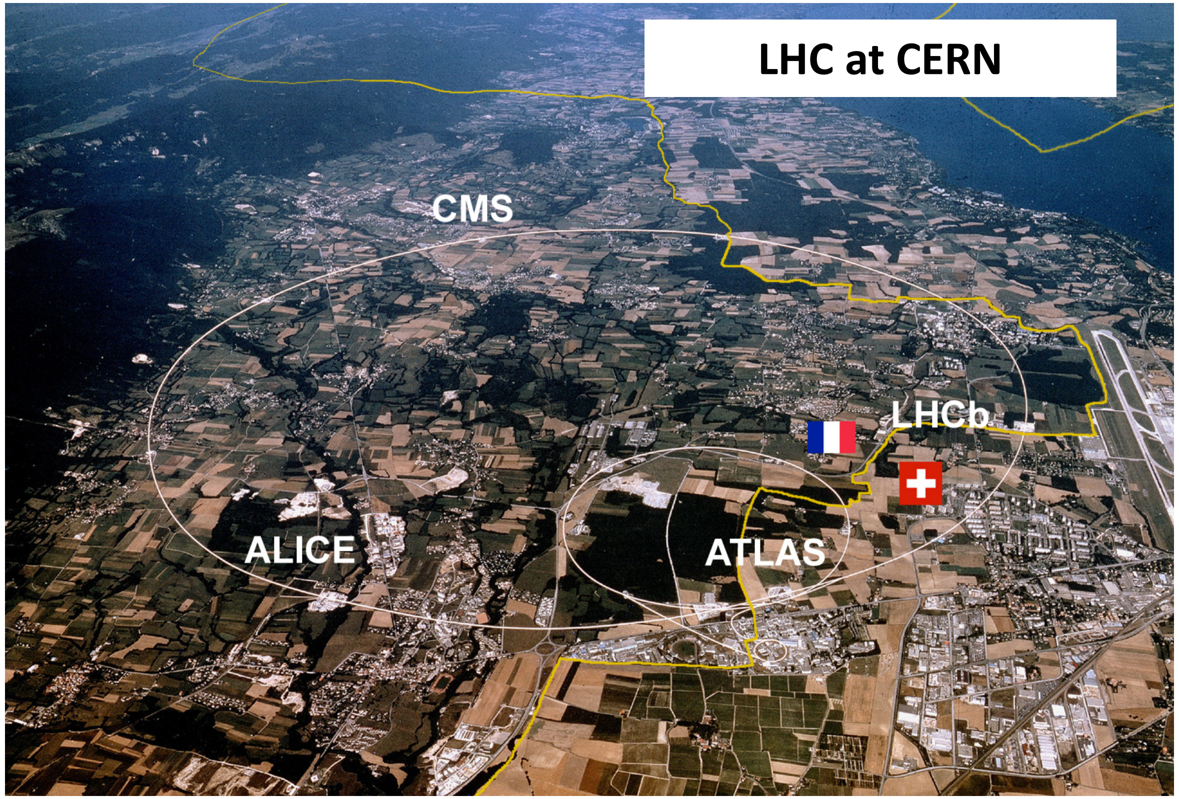




- **Quantum Chromodynamics (QCD)** is the theory of strong interactions

- We study high-energy QCD interactions using collider experiments
  - Small length scales ($\lambda \lesssim$ fm)
  - Color confinement 

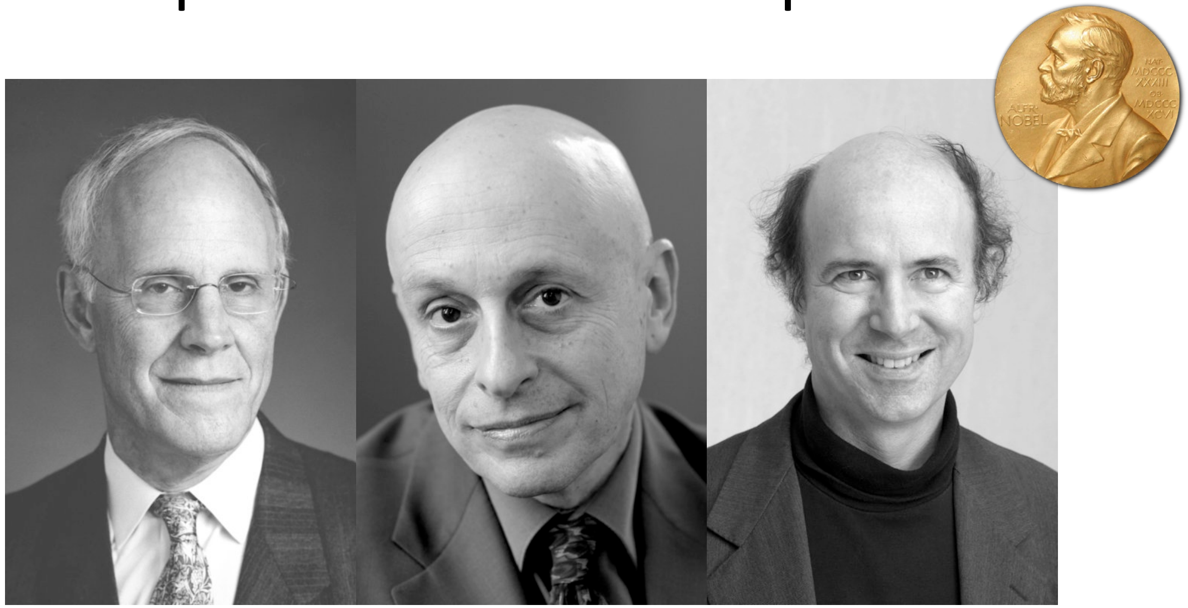
  - High temperature nuclear matter



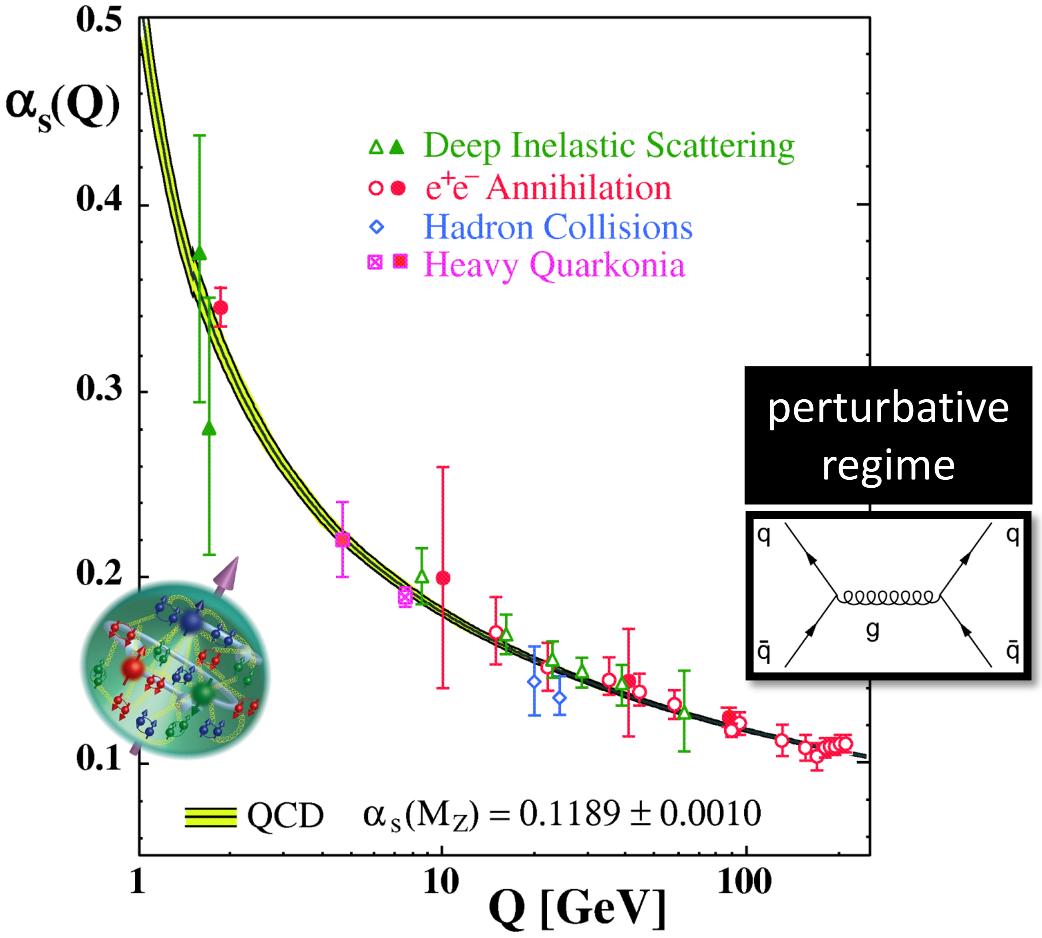
# Theoretical challenges

- $\alpha_S$ runs from divergence to $\Lambda_{\mathrm{QCD}} \approx 200$ MeV to **asymptotic freedom**

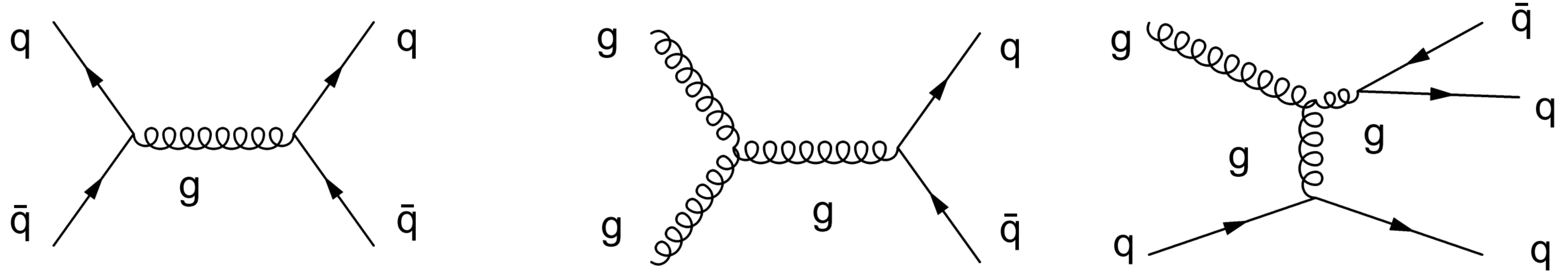
- Some physics cannot be calculated via perturbative techniques



*Gross/Politzer/Wilczek: 2004 Nobel Prize in Physics*



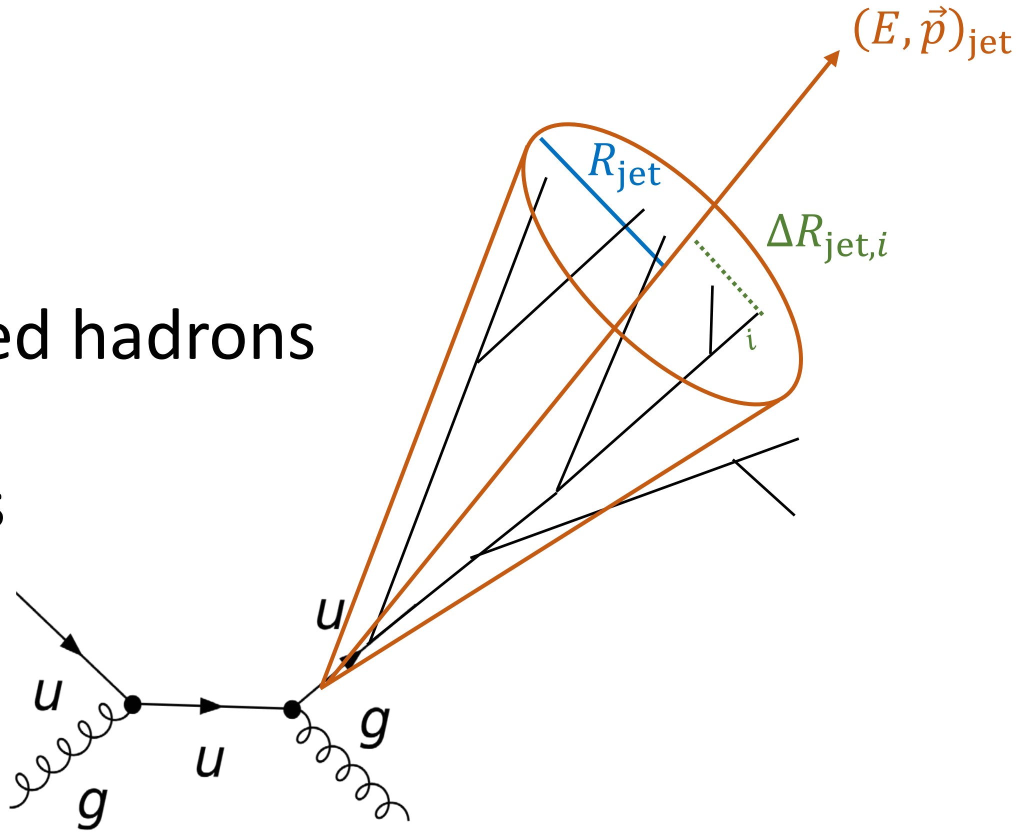
# QCD jets




- Interesting probe for various scales of strong interactions:
  - Initial, hard (high-$Q^2$) scattering
  - Parton shower
  - Fragmentation into hadrons

- Experimentally reconstructed from grouped hadrons

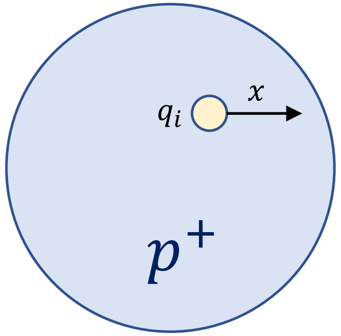
- **Dynamically recombined, tunable** objects which can be sensitive to either/both perturbative and nonperturbative physics



# Calculating jet observables

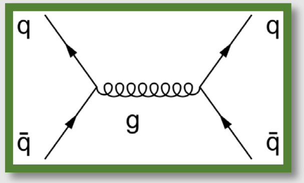
- Jet observables are useful because they can also be compared to first-principles QCD using **factorization theorems**
  - Ability to calculate physics at different scales separately, then combine

*Parton Distribution Functions (PDF)*




$\otimes$

*Hard scattering process*

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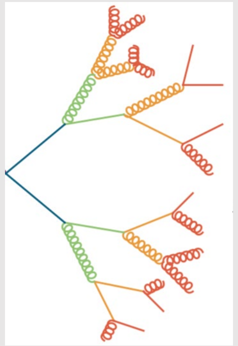
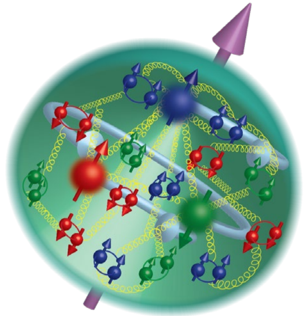


*"Parton shower"*

$\otimes$

*Hadronization*

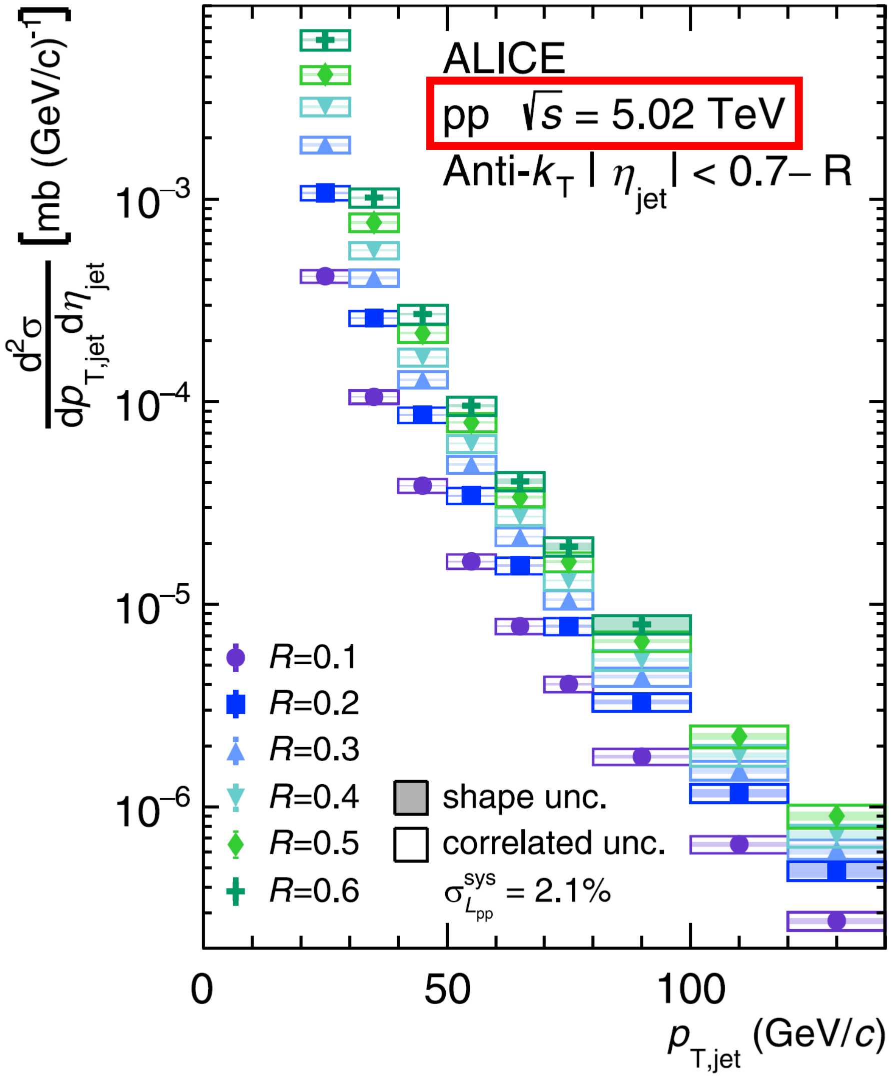


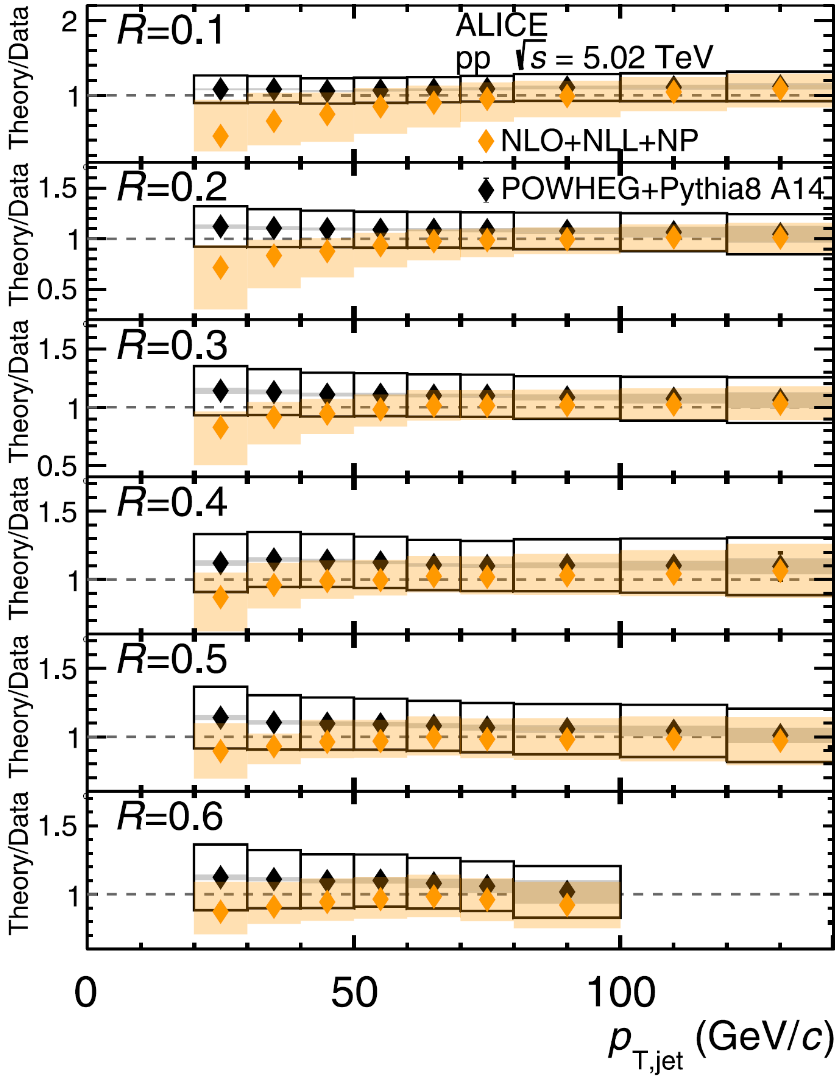
- Proven valid at leading power of $Q$ [1] and for leading power corrections
- Allows tests of **universal physics** throughout various measurements

- These steps can also be implemented into statistical generators for creating Monte Carlo simulations

[1] *J. Collins, D. Soper, G. Sterman* arXiv:hep-ph/0409313

# Measurements of the inclusive jet cross section



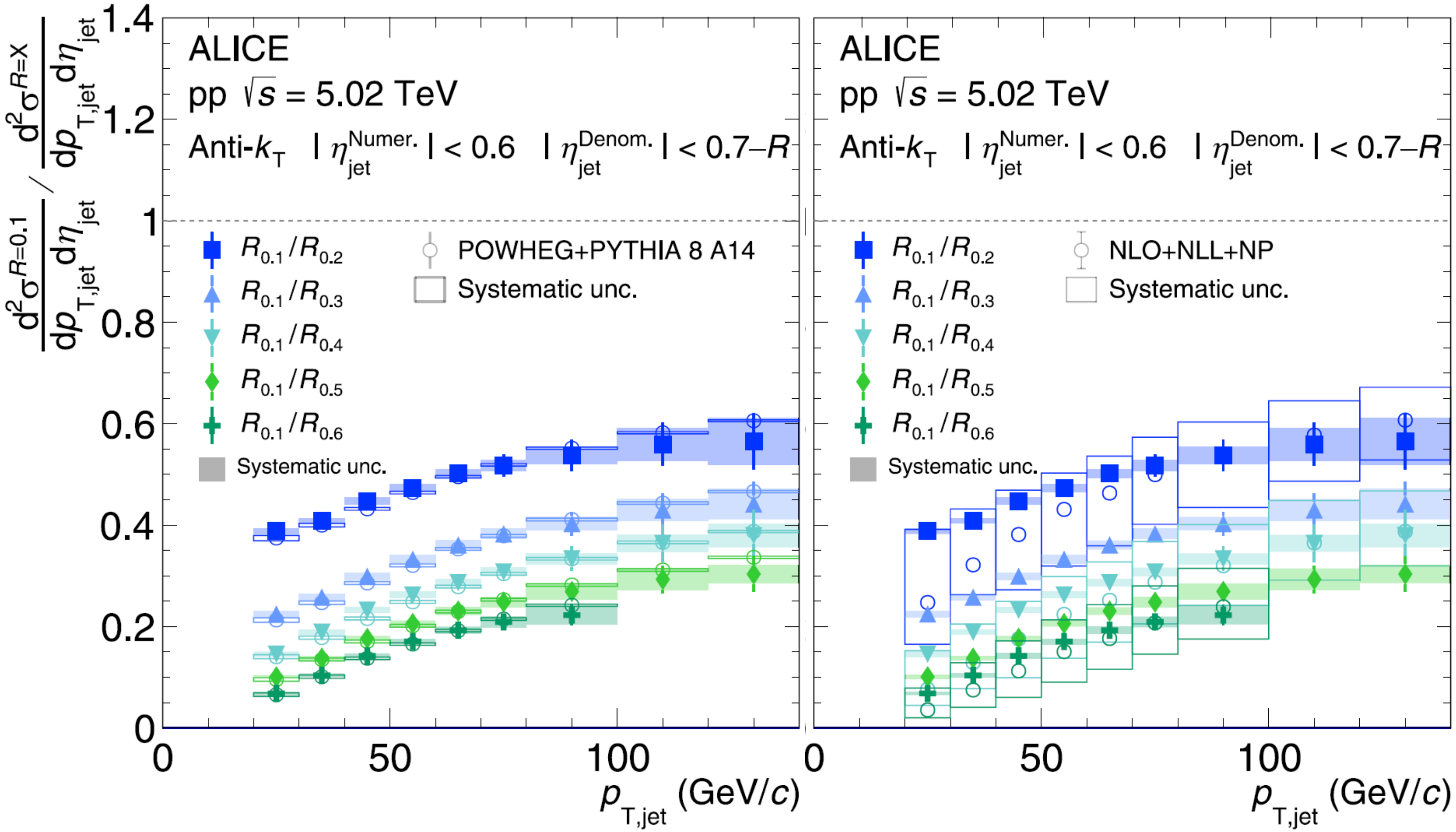

- Jets reconstructed with small to moderate jet radius $R$
- Increasing $R$ shifts spectrum to the right
- Slight tension at low $p_T$

**Higher-order theoretical predictions work well to describe the data over a range of $p_T$ and $R$**

*ALICE Collab.*: Phys. Rev. C 101 (2020) 034911

Theory: *X. Liu, S. Moch, F. Ringer* Phys. Rev. D 97 (2018) 056026

# Ratios of the inclusive jet cross section




- Taking ratios allows cancellation of most correlated systematic uncertainties [1]
- Large uncertainties on NLO+NLL+NP from scale variations

**Inclusive jet predictions agree well with experimental data within the given uncertainties**

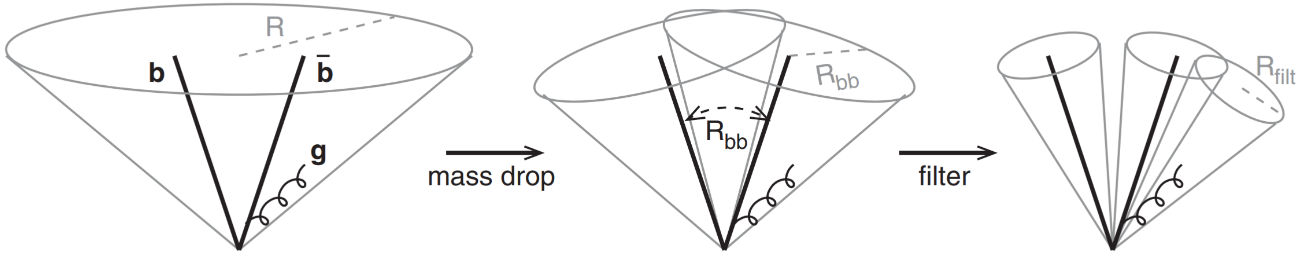
*Higher order calculations can lessen the systematic uncertainty on theory calculations*

*ALICE Collab.*: Phys. Rev. C 101 (2020) 034911

[1] *ALICE Collab.*: Phys. Lett. B 722 (2013) 262

# Going deeper using jet substructure

- **Tagging jets** of particular origin
  - Boosted objects (Higgs/BSM searches: $H \to b\bar{b}$) [2]
  - Quark vs. gluon jets

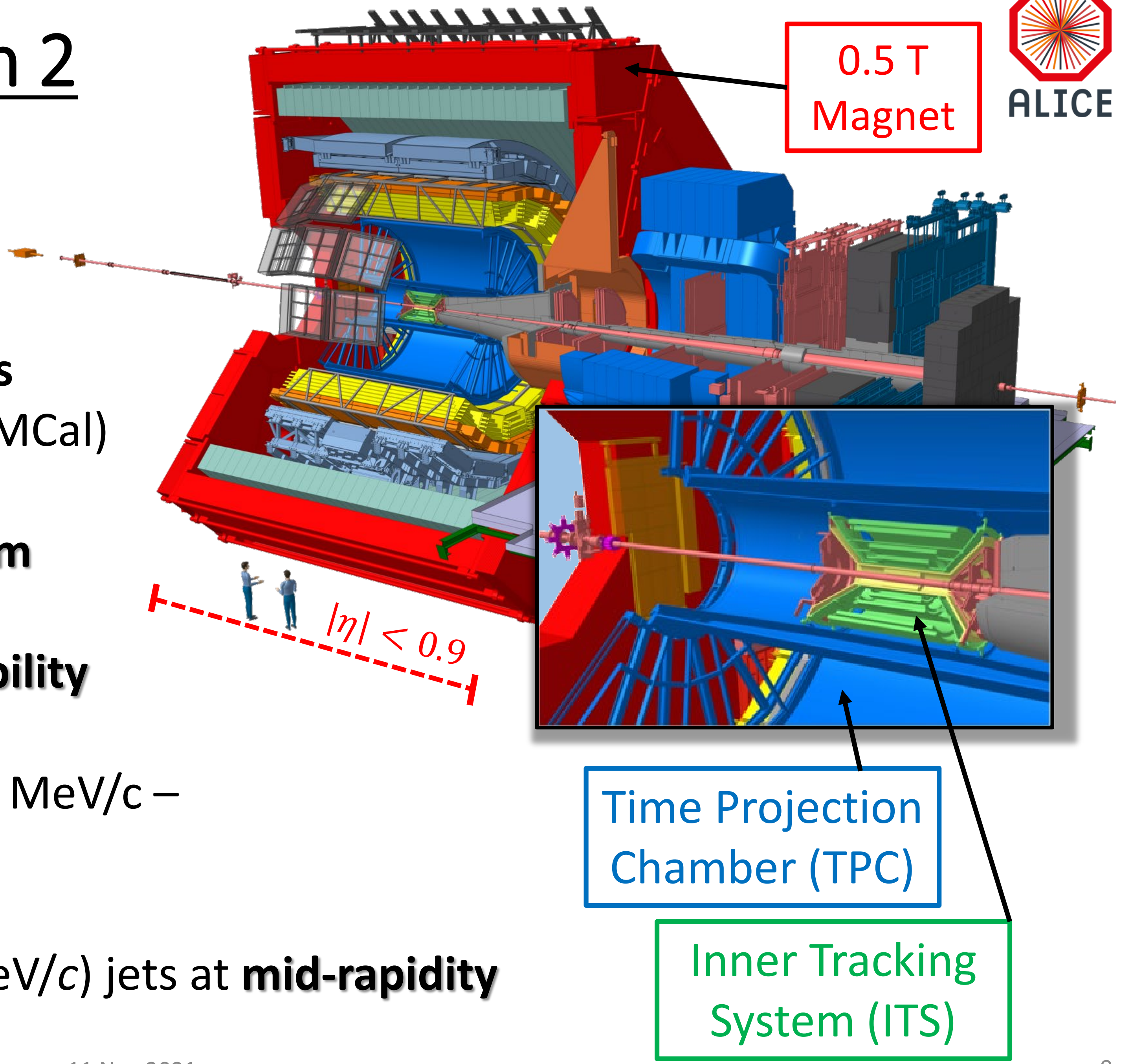



- Precision **tests of perturbative QCD** and factorization
  - We will discuss this first
- Probing the **quark-gluon plasma** in heavy-ion collisions
  - We will discuss this later

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

# 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**, excellent for substructure measurements, plus **strong PID capability**
- Measurement of tracks with $p_{\mathrm{T}}$ > 150 MeV/c – study low-$p_{\mathrm{T}}$ tracks at LHC energies
- Great for **low/moderate-$p_{\mathrm{T}}$** (< 150 GeV/*c*) jets at **mid-rapidity**



# Generalized jet angularities

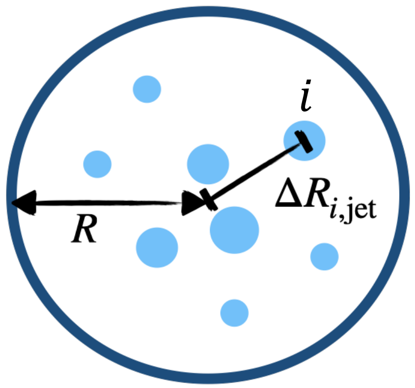
- **Class of substructure observables** dependent on $p_{\mathbf{T}}$ and **angular** distributions of tracks within jets

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

*Tunable, continuous parameters for relative weighting* ($\kappa$, $\alpha$)

*Constituent angle in $(\eta, \phi)$ space* ($\Delta R_{i,\text{jet}}/R$)

*Constituent $p_T$* ($p_{\mathrm{T},i}/p_{\mathrm{T,jet}}$)




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

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

** track-based observables IRC-unsafe (see backup)*

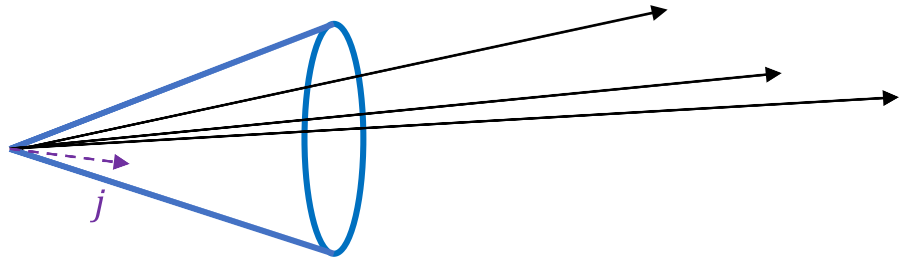
# What is IRC safety?

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

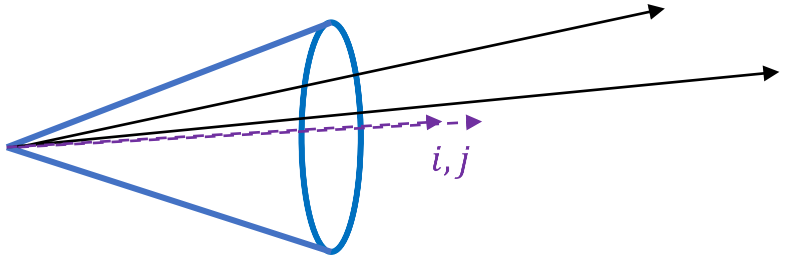
- Stands for Infra-Red and Collinear (IRC) safety

- Class of reconstruction algorithms & observables which satisfy certain conditions in order to avoid singularities from appearing in a well-defined path towards theoretical calculation

**Infra-Red safety**: the observable should not change if an infinitely-low-momentum particle is added to the event/jet

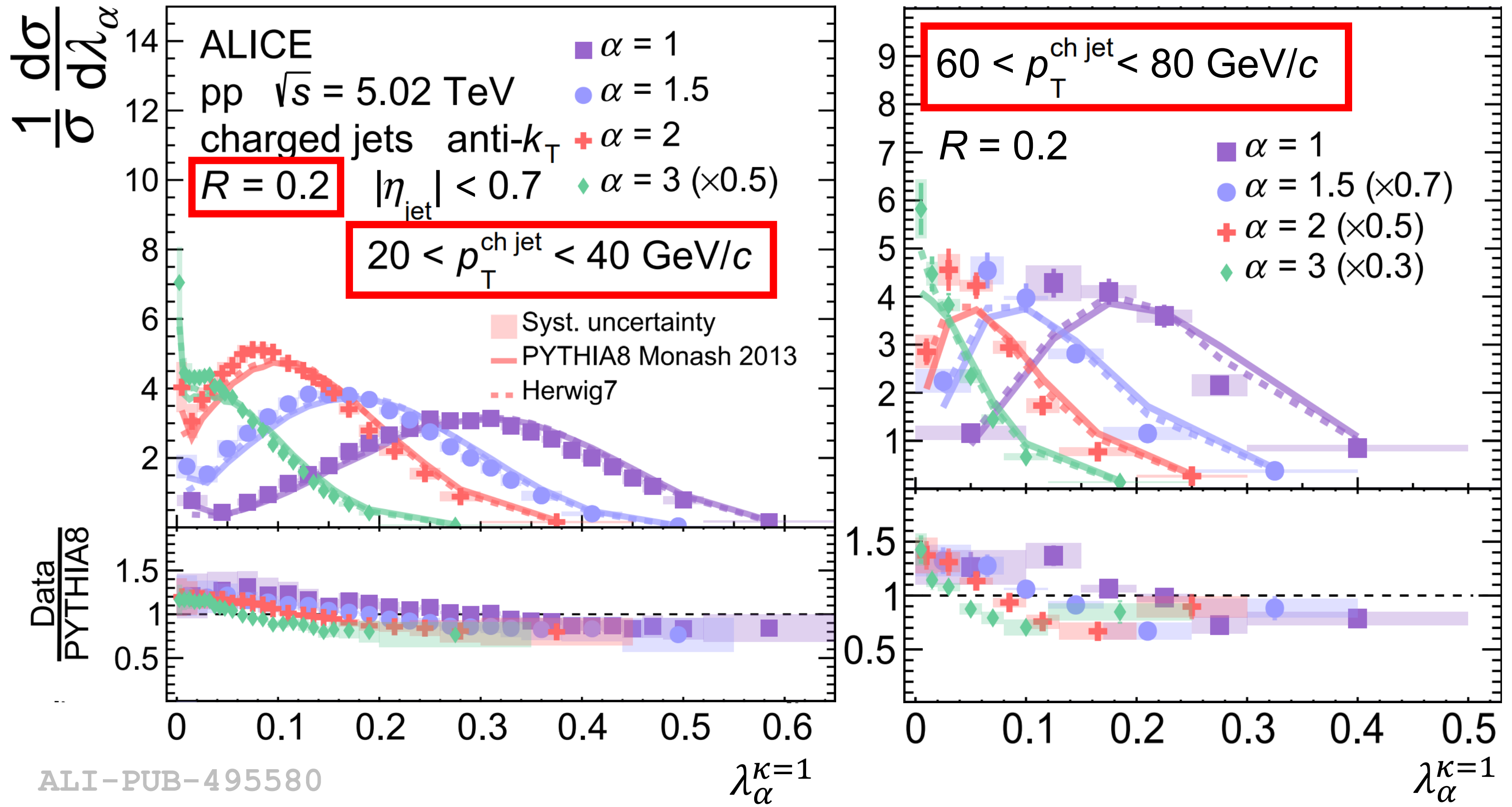



**Collinear safety**: the observable should not change if one particle splits into two collinear particles



# Some jet angularity measurements

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

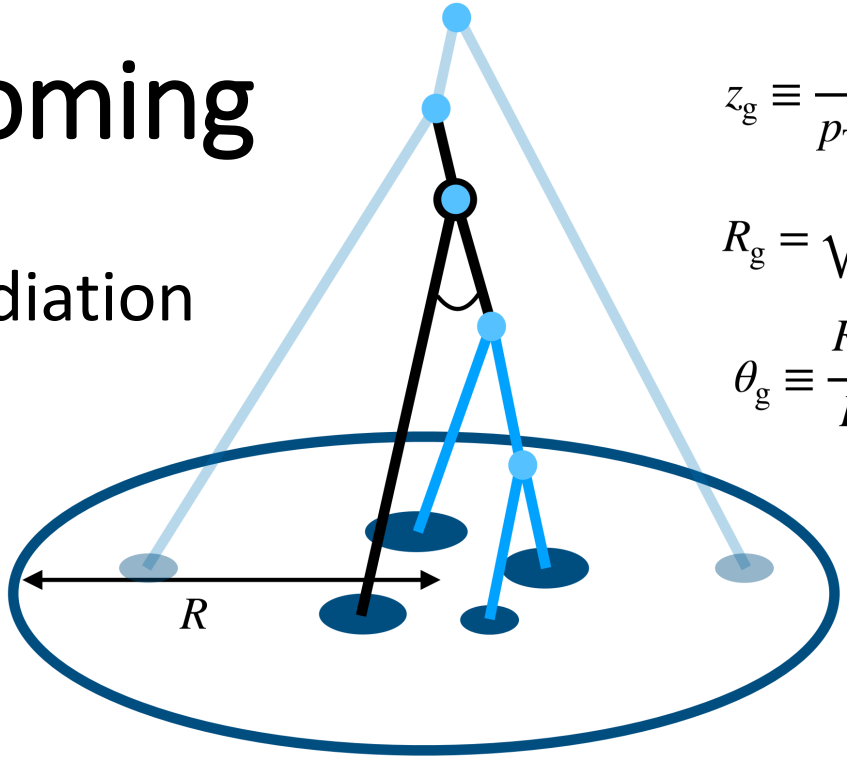



*all figures available from*: ALICE Collab. arXiv:2107.11303 [nucl-ex]

- Calculable way of **probing the $p_{\mathrm{T}}$ structure of jets**

- Distributions shift to the **left** for **higher** $\alpha$, $p_{\mathrm{T,jet}}^{\mathrm{ch}}$, **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

# Going deeper: jet grooming




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

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

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

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- Removal of soft, wide-angle radiation to enhance the influence of perturbative effects

- One popular algorithm is **Soft Drop grooming** [3]

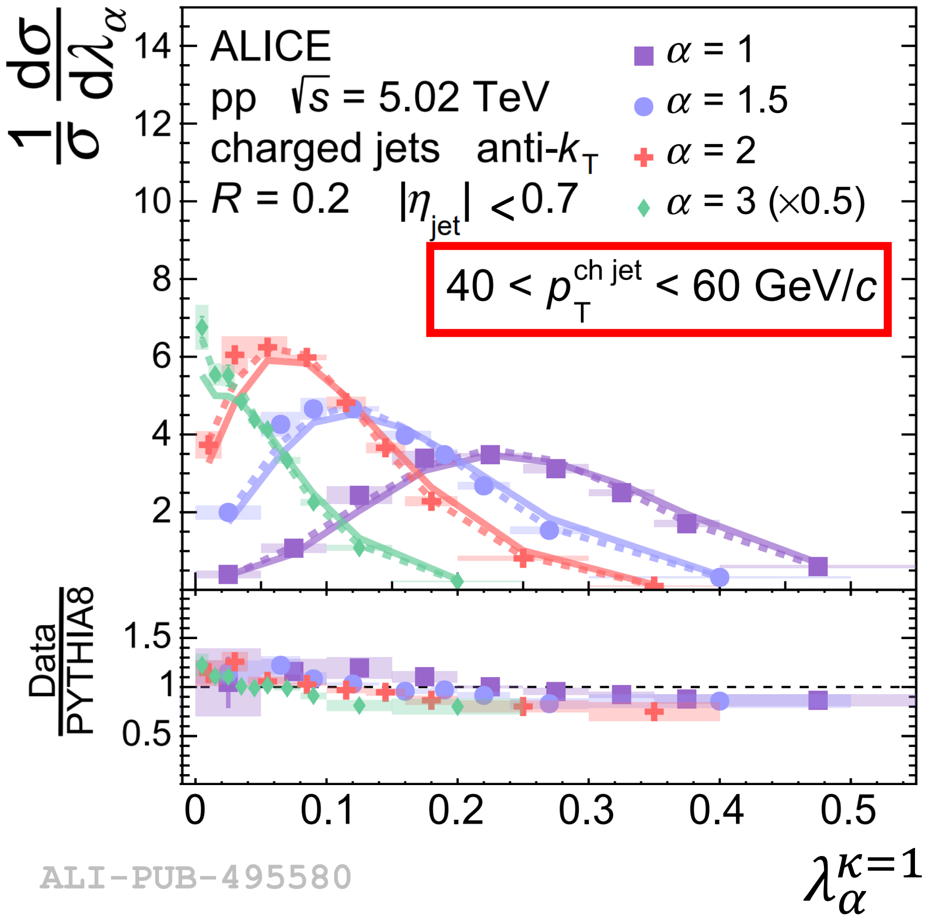
Soft Drop Condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$

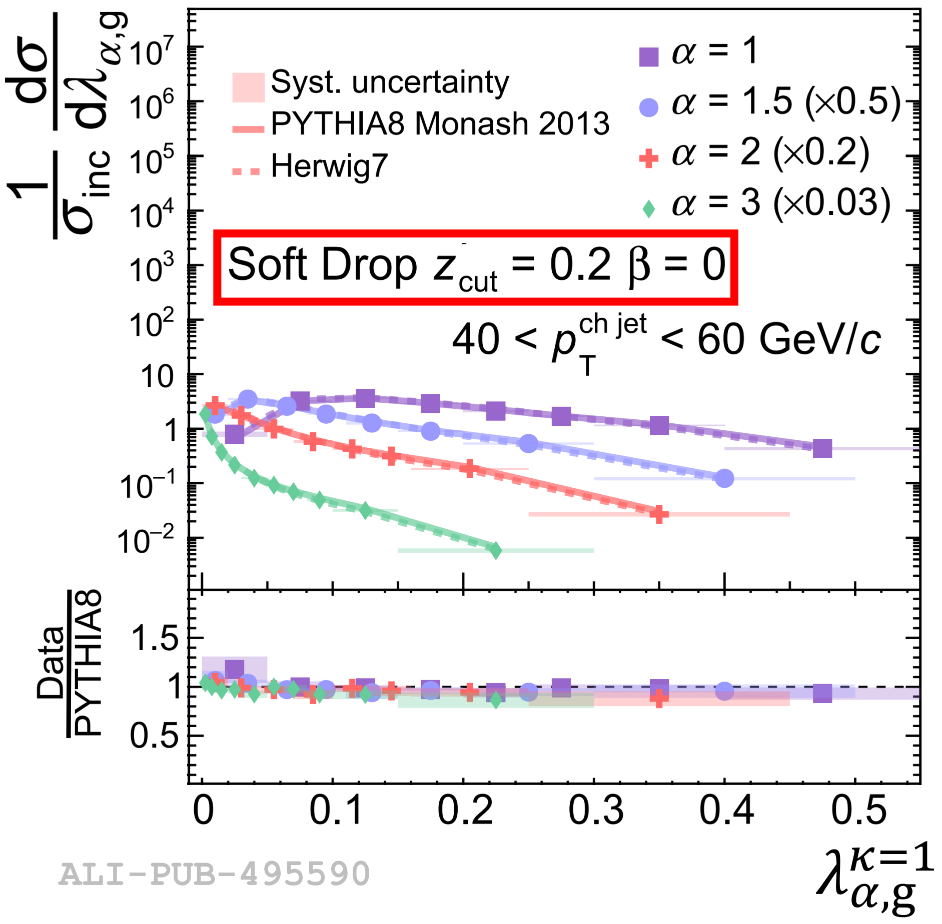
- Recluster jet into ordered tree using Cambridge-Aachen algorithm and then trim branches until the Soft Drop condition is satisfied

- IRC-safe → **repeatable on theoretical predictions**

[3] *A. Larkoski, S. Marzani, G. Soyez, J. Thaler* JHEP 1405 (2014) 146

# Ungroomed vs. Groomed angularities ($R = 0.2$)




**Better agreement seen after grooming**

- Removing some nonperturbative effects from data and models increases the agreement, as would be expected

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

- Similar improvement in agreement is seen for all $\alpha$, $R$, and $p_{\mathrm{T}}^{\text{ch jet}}$ bins

# Theoretical calculations

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

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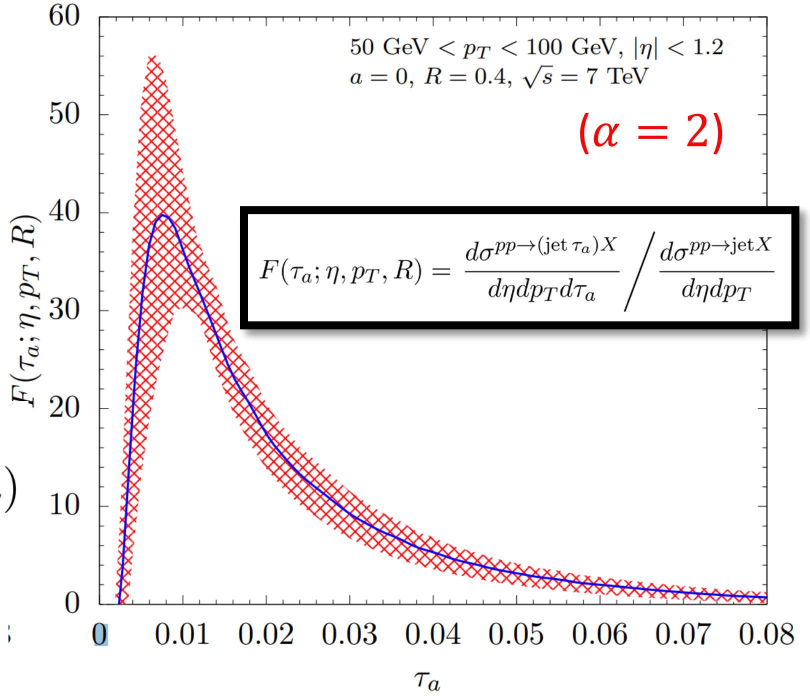
- We use theoretical predictions for inclusive **parton** jets [6] calculated at Next-to-Leading Log (NLL') perturbative accuracy
  - *New calculations also exist for Z+jets* [7]

INFN GENOVA

- Carried out in **Soft Collinear Effective Theory**

*C. W. Bauer, S. Fleming, M. Luke* Phys. Rev. D 63 (2000) 014006

$$\frac{d\sigma^{pp\to(\text{jet}\,\tau_a)X}}{d\eta\, dp_T\, d\tau_a} = \sum_{abc} \underbrace{f_a(x_a,\mu)\otimes f_b(x_b,\mu)}_{\text{PDFs }(NP)} \otimes \underbrace{H_{ab}^c(x_a,x_b,\eta,p_T/z,\mu)}_{\text{Hard Function }(P)} \otimes \underbrace{\mathcal{G}_c(z,p_T,R,\tau_a,\mu)}_{\text{siAJFs }(P\,/\,NP)}$$




***Definitional difference:***

$$\tau_a \equiv \tau_a^{pp} \equiv \frac{1}{p_T}\sum_{i\in J} p_T^i \left(\Delta\mathcal{R}_{iJ}\right)^{2-a} \equiv \lambda_{\beta=2-a}^{\kappa=1} * R^{2-a}$$

**We can compare ALICE data to first-principles predictions from theory**

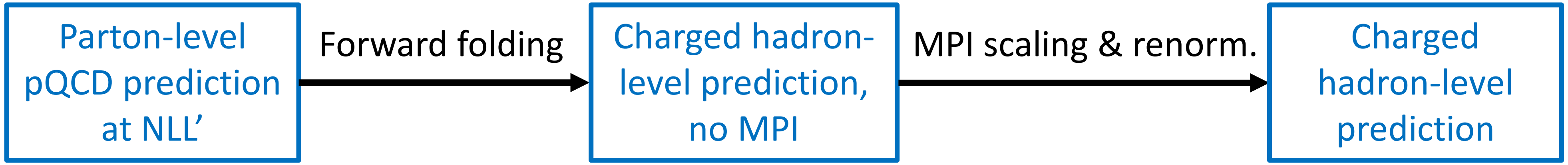
[6] *Z. Kang, K. Lee, F. Ringer* JHEP 1804 (2018) 110

BERKELEY LAB

[7] *S. Caletti, O. Fedkevych, S. Marzani, D. Reichelt, S. Schumann, G. Soyez, V. Theeuwes* JHEP 07 (2021) 076

# Comparing to pQCD predictions with SCET

- **Parton** jet calculations cannot be directly matched to experimental data
- Must apply a “forward folding” procedure to correct for multi-parton interactions (MPI), hadronization, and **charged-particle** jets




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

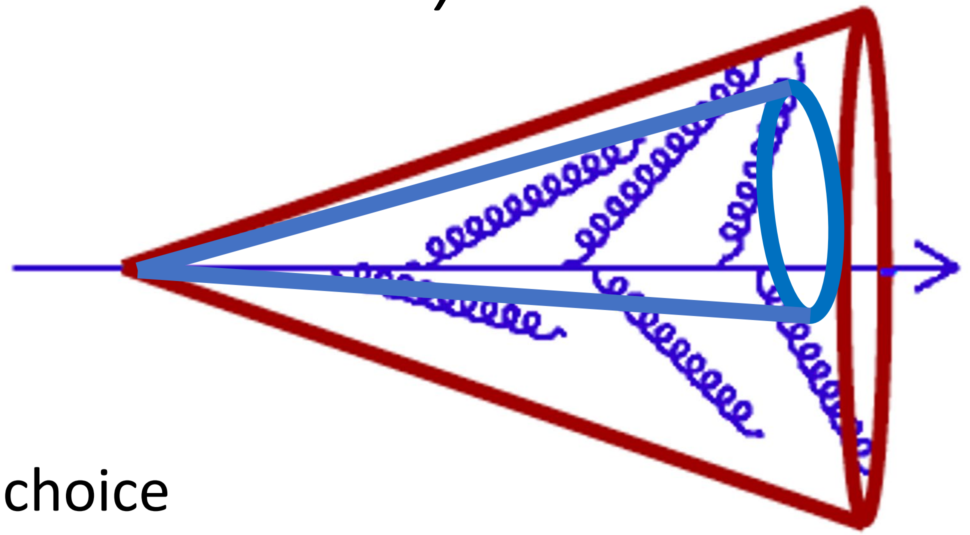
# Determining regions of interest

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

- Nonperturbative effects in the calculation are larger at low $p_\mathrm{T}^\mathrm{jet}$ and small $R$
  - Become dominant when soft-collinear scale becomes small:

$$\lambda_\alpha^{\mathrm{NP\ region}} \lesssim \Lambda/(p_\mathrm{T}^\mathrm{jet} R) \quad \textit{(we use } \Lambda = 1 \text{ GeV)}$$

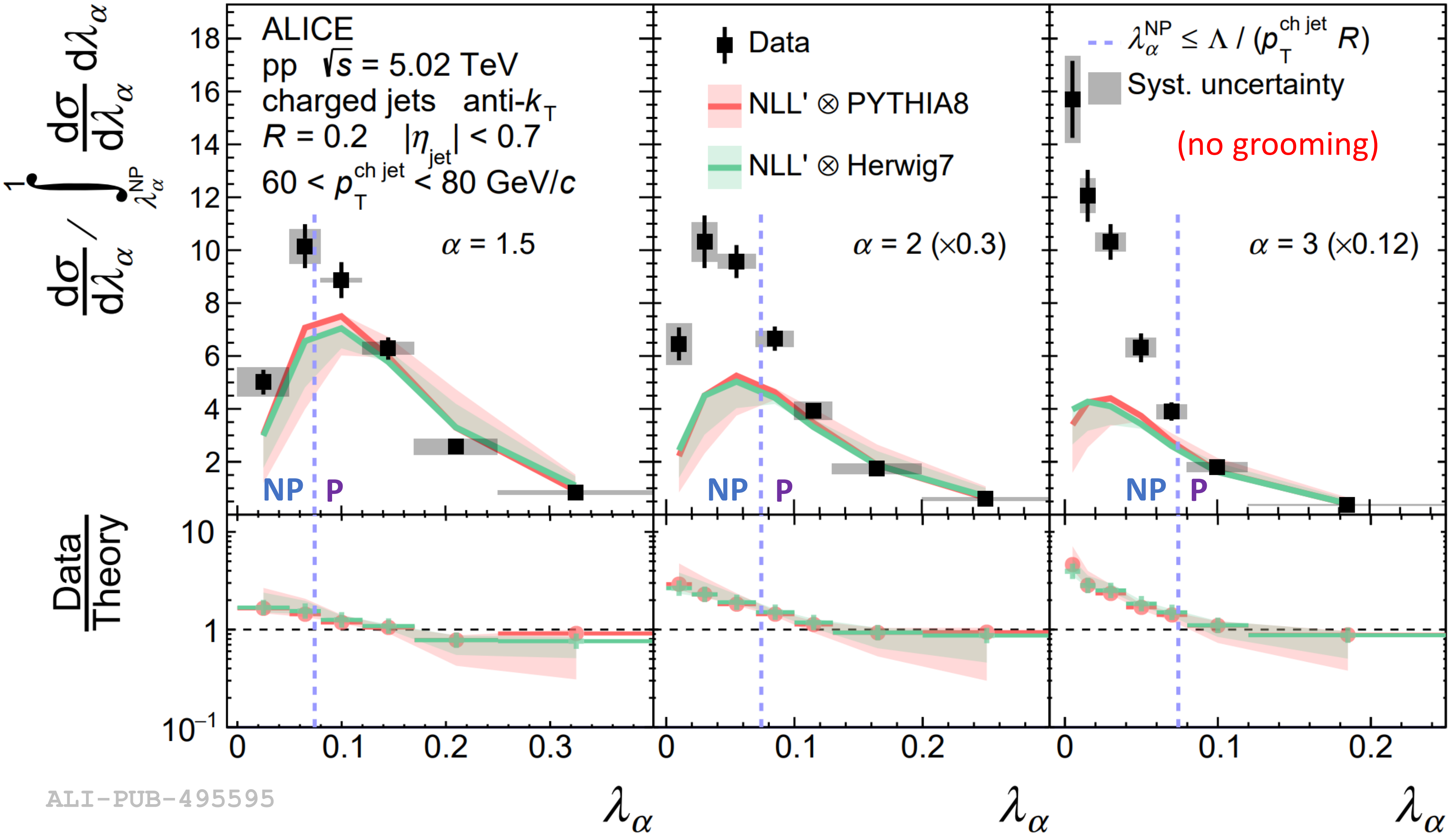
- Parton-to-charged response is largely non-diagonal for small $R$, low $p_\mathrm{T}^\mathrm{jet}$
  - Due primarily to hadronization
  - Corresponds to an increased dependence on the choice of hadronization model and tuning
  - These regions can be used for testing & tuning MC models



***small R is more susceptible to boundary effects***

# pQCD predictions with SCET ($R = 0.2$)

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

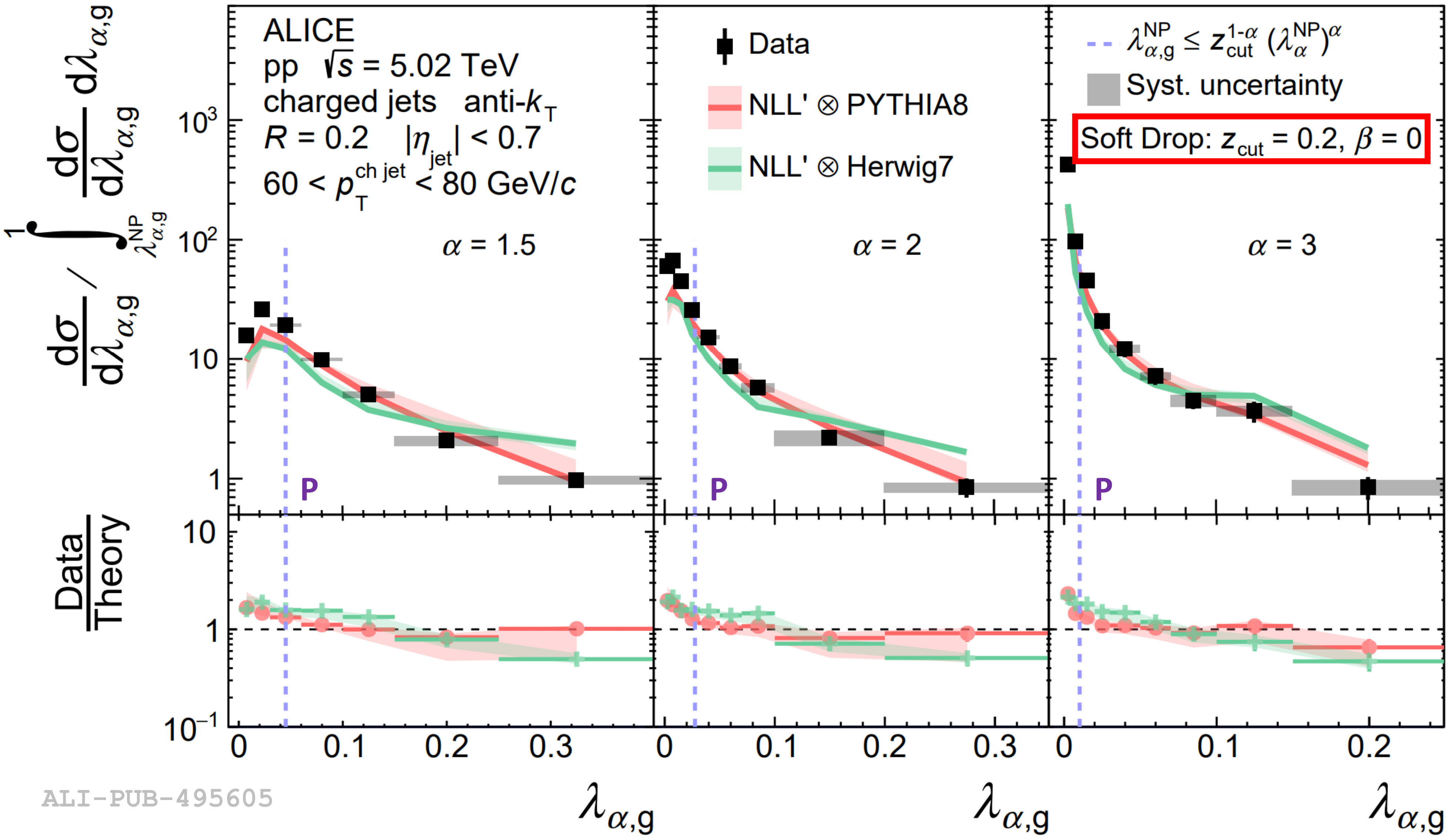



Distributions dominated by nonperturbative effects at large $\alpha$

Agreement within perturbative region is reasonable

# pQCD predictions with SCET ($R = 0.2$)

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




SD grooming greatly increases the perturbative region for predictions

Reasonable agreement still seen within uncertainties

# Alternate hadronization correction

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

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- Comparisons to Monte Carlo predictions are limited in interpretation
  - Highly-tuned phenomenological models
- Apply nonperturbative shape function $F$ [8,9] from first principles: $\Omega_\alpha = \frac{\Omega}{\alpha - 1}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}\lambda_\alpha} = \int \mathrm{d}k\, F(k) \frac{\mathrm{d}\sigma^{\text{pert}}}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}\lambda_\alpha}\left(\lambda_\alpha - \frac{k}{p_T R}\right) \sim \boxed{\left(F * \frac{\mathrm{d}\sigma^{\text{pert}}}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}\lambda_\alpha}\right)(\lambda_\alpha)} \quad \text{where} \quad \boxed{F(k) = \frac{4k}{\Omega_\alpha^2}\exp\left(-\frac{2k}{\Omega_\alpha}\right)}$$

  - Single-parameter ($\Omega$) function: hadronization effects should be described by one (unknown to pQCD) parameter, containing universal effects
  - Still requires folding to charged level, which is mostly well-described $p_\mathrm{T}$ shift

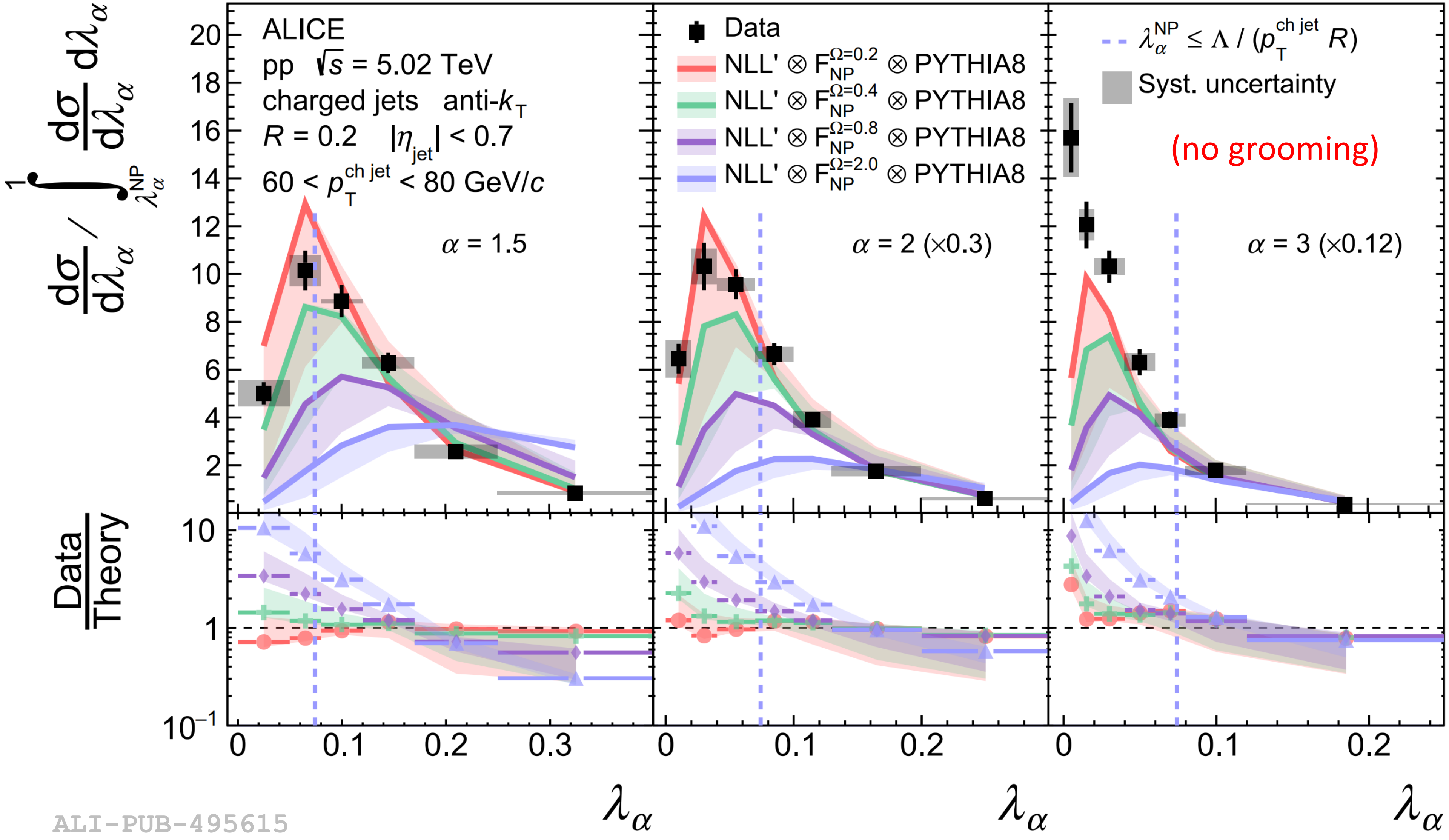
Parton-level pQCD prediction at NLL' → $\otimes F_\mathrm{NP}$ → Hadron-level prediction, including MPI → Forward folding → Charged hadron-level prediction

[8] *G. Korchemsky, G. Sterman*
Nuc. Phys. B 555 (1999) 335-351

[9] *E. Aschenaur, K. Lee, B. Page, F. Ringer*
Phys. Rev. D 101, 054028 (2020)

# pQCD predictions with SCET ($R = 0.2$)

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




Best agreement seen with smaller values of $\Omega = 0.2$ or 0.4 GeV/$c$

Tension with previous result of $\Omega = 3.5$ GeV/$c$ ($R = 0.4$ full jets, higher $p_{\mathrm{T}}^{\mathrm{jet}}$, and for jet mass) [10]

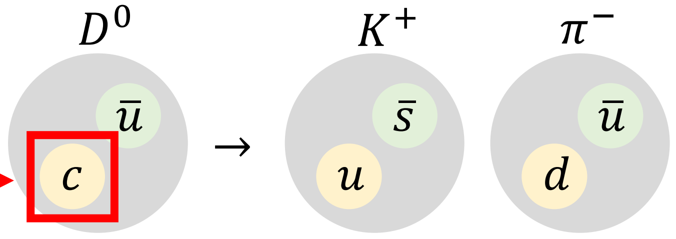
$\left(\lambda_{\alpha=2}^{\kappa=1} \sim \frac{m_{\text{jet}}^2}{p_{\mathrm{T,jet}}^2}\right)$

[10] *Z. Kang, K. Lee, F. Ringer* JHEP 1810 (2018) 137

# Substructure of "heavy-flavor jets"

- Jets from **quarks of heavy flavor** (e.g. charm, bottom)
  - Much higher mass ($m_c = 1.3$ GeV/$c^2$, $m_b = 4.2$ GeV/$c^2$ $\gg m_{u,d} \sim$ few MeV/$c^2$)
- Primarily created from an initial hard scattering
  - Can be used to probe long timescales in the QGP
- Can be used to **boost the proportion of quark jets** over gluon jets
- Candidate jets are "tagged" based on decays and vertexing
  - Nontrivial corrections (efficiency, purity) are often required

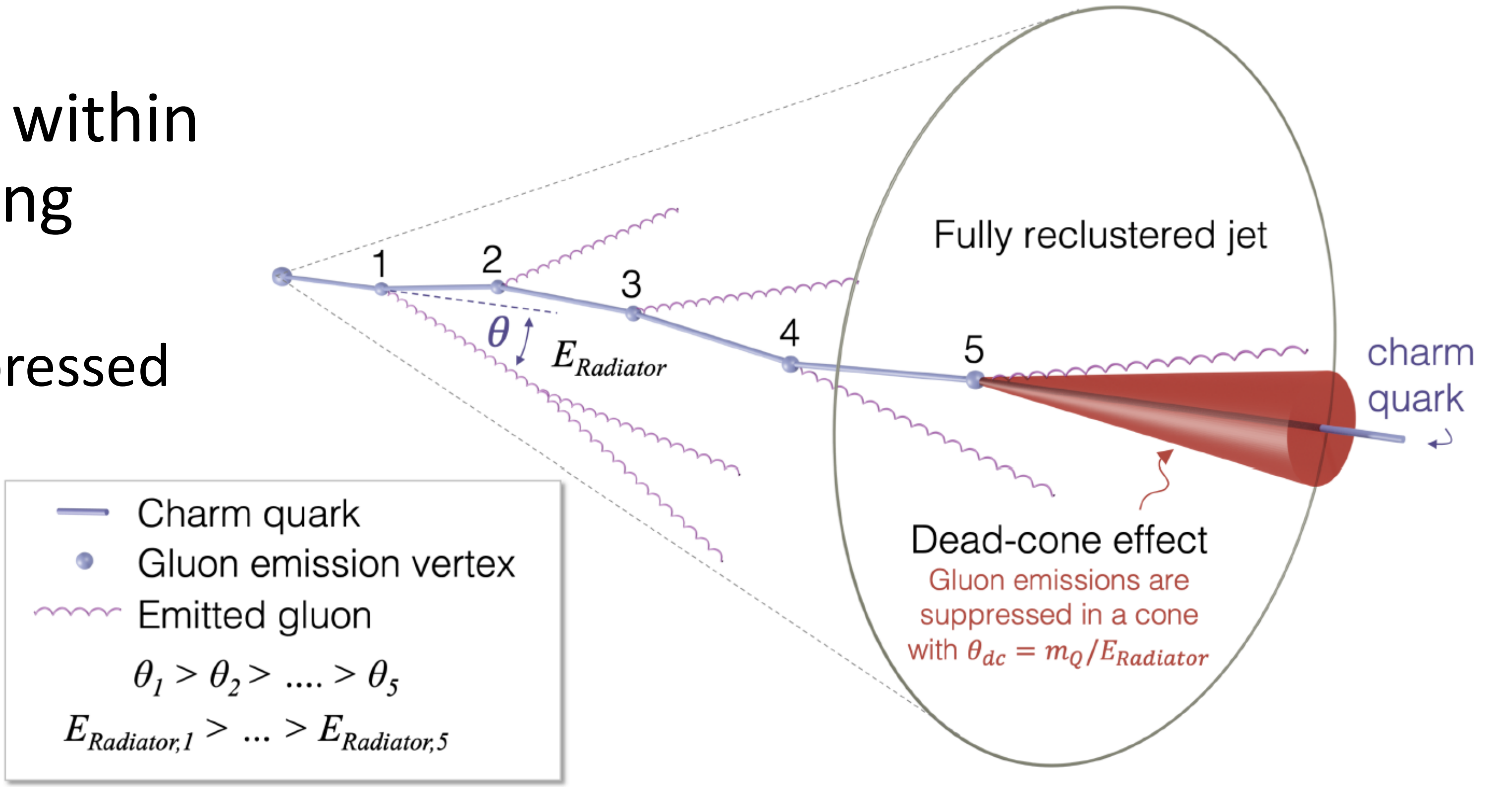
$c$ and $b$ hadronize, then quickly decay into more stable particles →




*(weak decay via $W^{*-}$)*

# Measuring the dead-cone effect in QCD

- Gluon radiation is suppressed within an angle $m/E$ from the emitting particle [11]
  - Radiation should be more suppressed for heavy flavor quarks




*ALICE Collab.*: arXiv:2106.05713 [nucl-ex]

- Challenges of measurement:
  - 1) Identifying gluon radiation
    - Background contributions from hadronization, heavy hadron decays, …
  - 2) Determining dynamic direction of heavy quark throughout the shower

**Solution: use declustering procedure with Cambridge/Aachen algorithm**

*L. Cunqueiro, M. Płoskoń* Phys. Rev. D 99 (2019) 074027

[11] *Y. Dokshitzer, V. Khoze, S. Troyan* J. Phys. G17 (1991) 1602

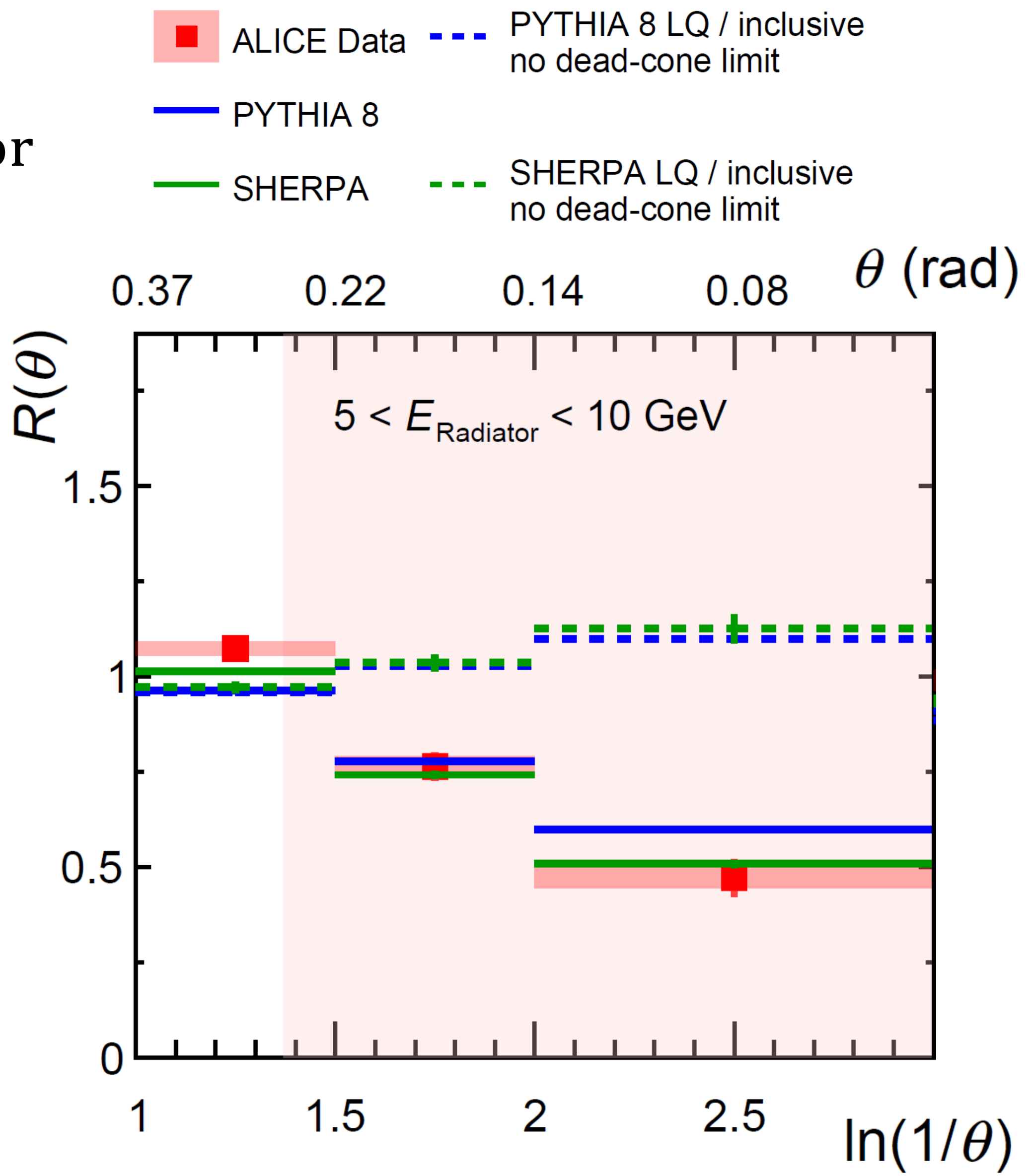
# First direct observation of dead-cone effect

- Calculate ratio of the splitting angle ($\theta$) for $D^0$-tagged vs. inclusive jets, vs. $E_{\text{radiator}}$

$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_\mathrm{T}, E_\mathrm{Radiator}}$$

- 1) Reconstruct Lund Plane for **inclusive** and $D^0$**-tagged jets**
- 2) Project onto the angular axis, and take the ratio $D^0$**-tagged / inclusive**

- Significant suppression is seen, and is enhanced at lower $E_{\text{radiator}}$




ALICE Collab.: arXiv:2106.05713 [nucl-ex]

# Motivation for Pb-Pb studies

- **Quark-Gluon Plasma (QGP)** believed to form in heavy ion collisions

- Modifies jet interactions:
  - Jet quenching (see figure on right)
  - Momentum broadening

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

- How else does the QGP modify the jets we observe?
  - → how can we study the QGP using jet observables?

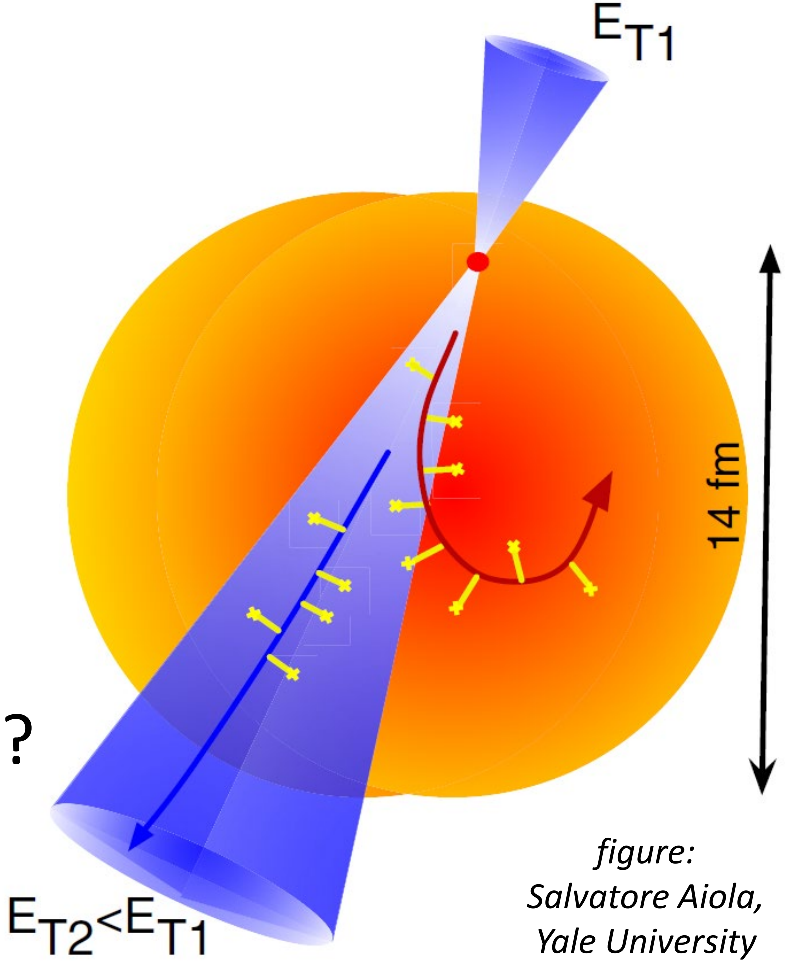
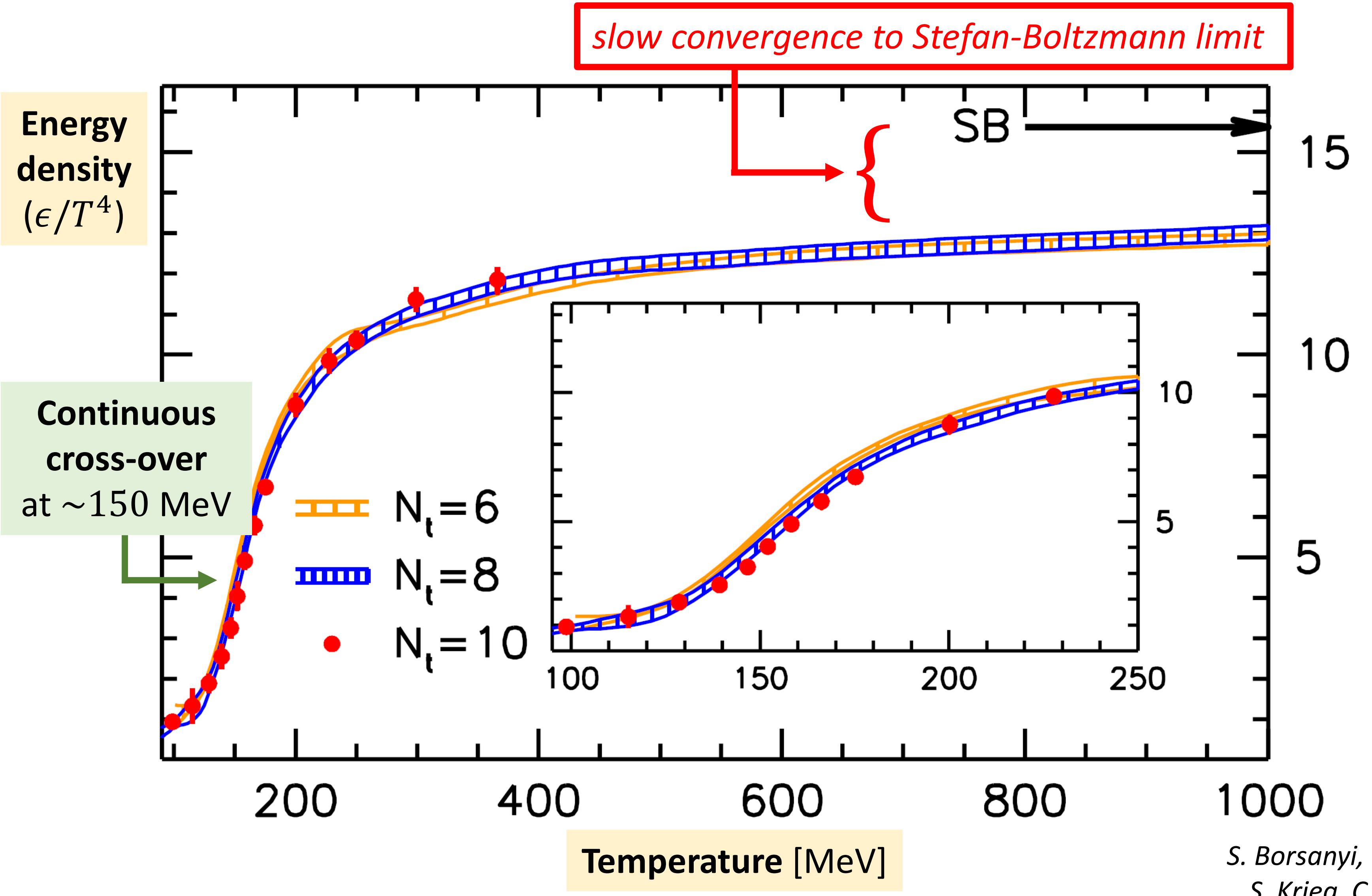



*figure: Salvatore Aiola, Yale University*

# Finite temperature QCD on the lattice




- **Lack of sharp phase transition**
  - e.g. ionization of an atomic plasma
- **What carries the extra energy?**
  - Complex $q$+$g$ states?
  - "Strongly coupled" plasma effects?

*S. Borsanyi, G. Endrodi, Z. Fodor, A. Jakovac, S. Katz, S. Krieg, C. Ratti, K. Szabo* JHEP 1011 (2010) 077

# Modification of jet cross section in Pb-Pb

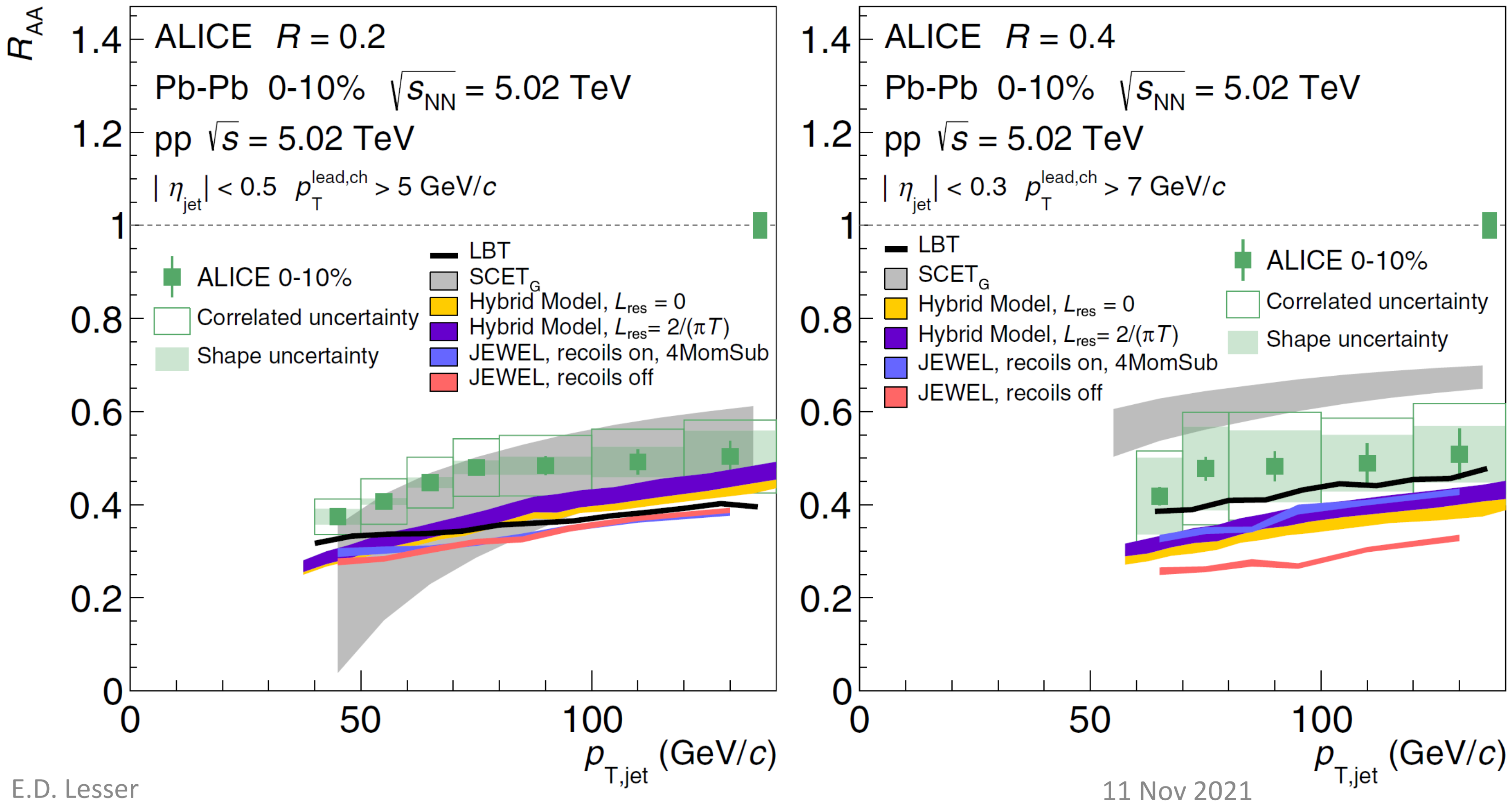
$$R^i_{AA}(p_T) = \frac{d^2N^i_{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma^i_{NN}/dp_T d\eta}$$

Jet yield in *AA* (here Pb-Pb) collisions

Jet cross section in pp collisions

Geometry → # NN collisions

***No modification*** **↔ $R_{AA} = 1$**



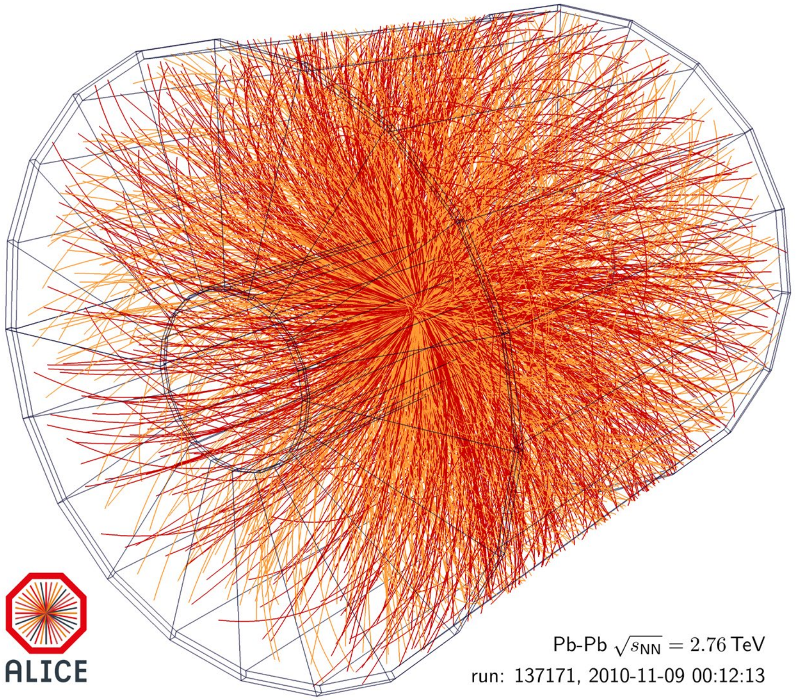

- **Strong suppression** of jet yield emulated by all of the quenching models
- Hints of disagreement with some models
  - Can we use **substructure measurements** to place stronger limits on some?

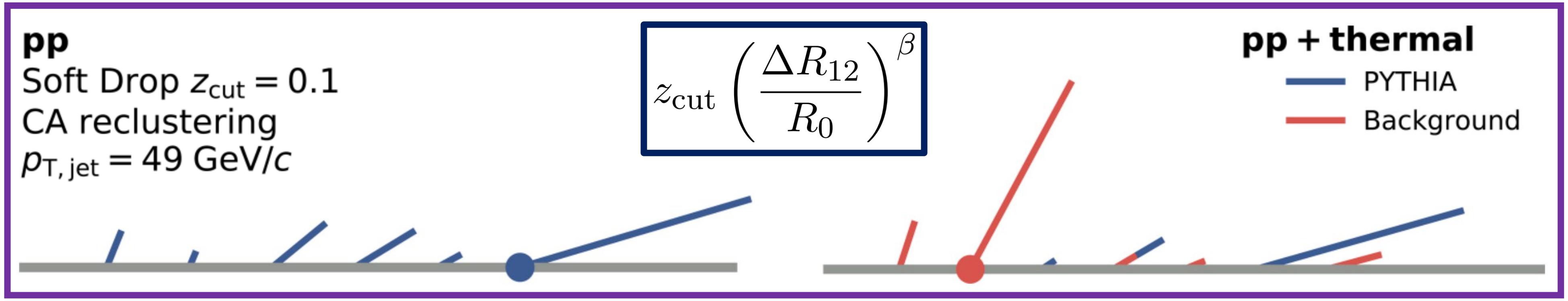
*ALICE Collab.*: Phys. Rev. C 101 (2020) 034911

# Grooming settings in Pb-Pb

- Mistagging of the primary splitting occurs in jets in heavy-ion collisions due to the increased background

- Higher values of $z_{cut} \geq 0.2$ (Soft Drop) increase the tagging purity in high-background environments [12]

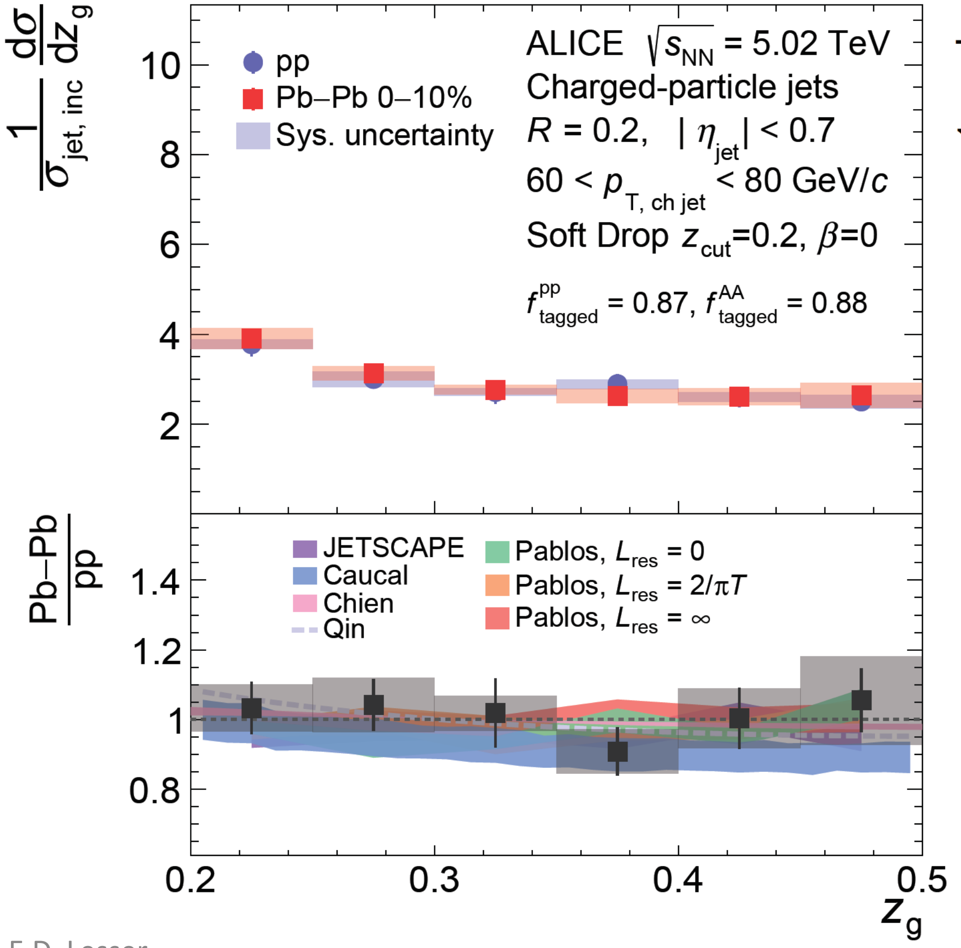


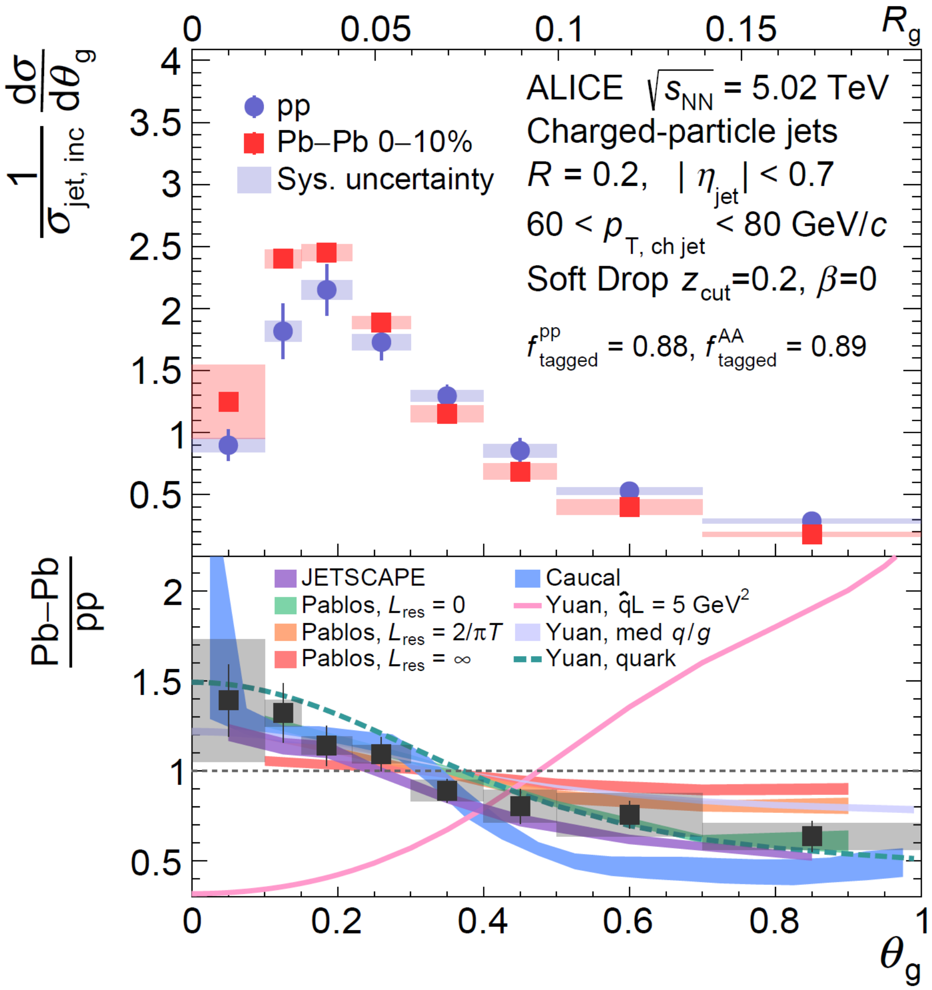




[12] *J. Mulligan, M. Płoskoń* Phys. Rev. C 102, 044913 (2020)

# $z_g$ and $R_g$ in pp compared to Pb-Pb

- Stronger grooming conditions ($z_{cut} = 0.2$) allows fully-corrected groomed jet observables, and enabled the first measurement of $\theta_g$ in Pb-Pb data

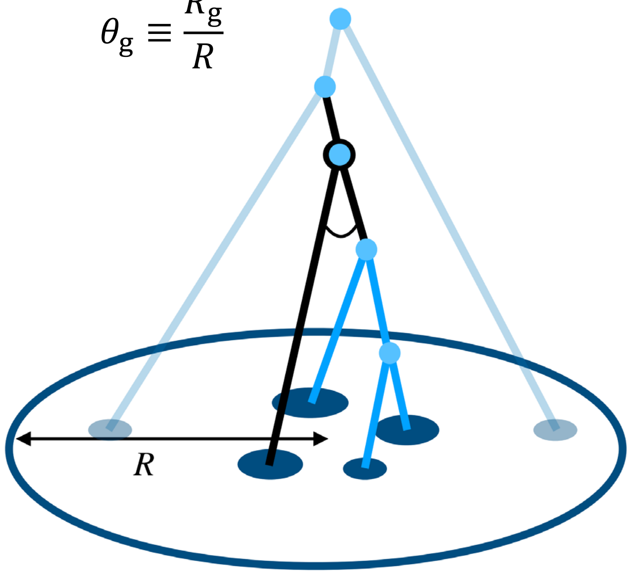



$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

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

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




*ALICE Collab.*: arXiv:2107.12984 [nucl-ex]

# Conclusions

- ALICE has many **new and developing analyses** with novel comparisons to first-principles pQCD predictions
  - Stay tuned for new upcoming results!
- **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

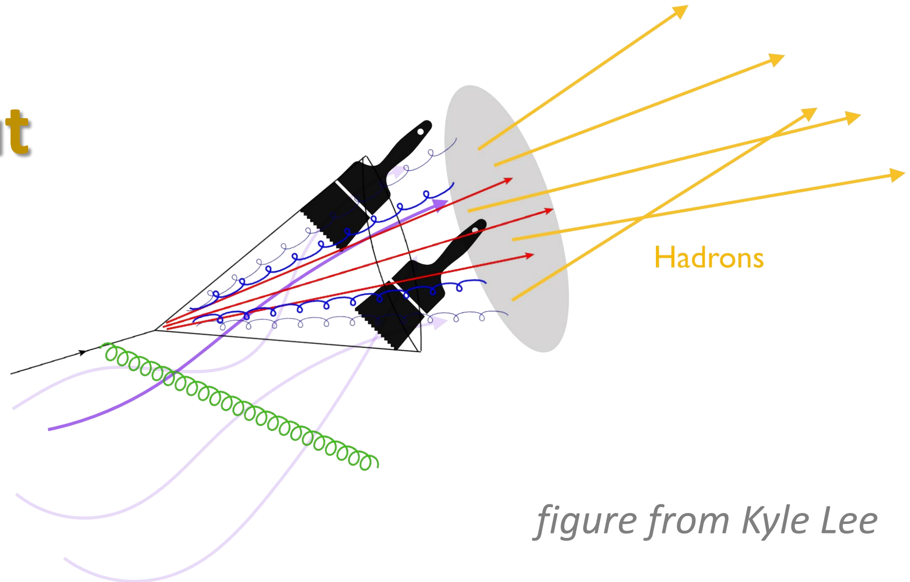


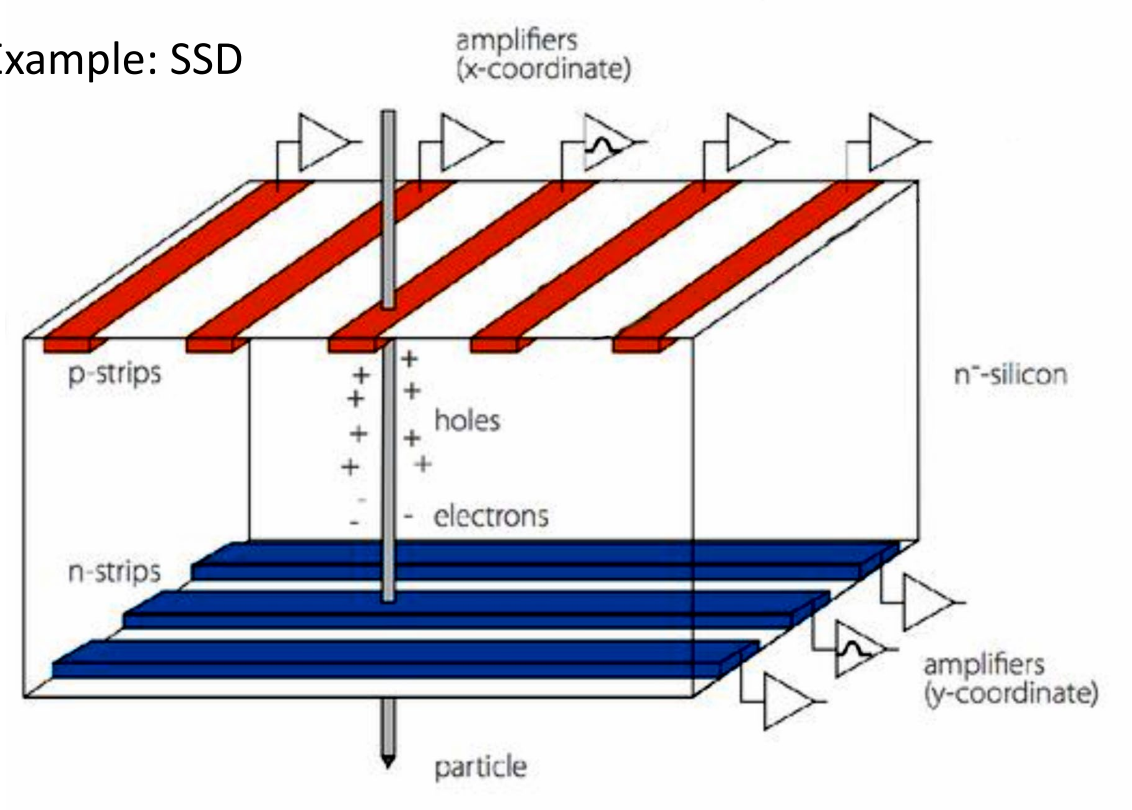

*figure from Kyle Lee*

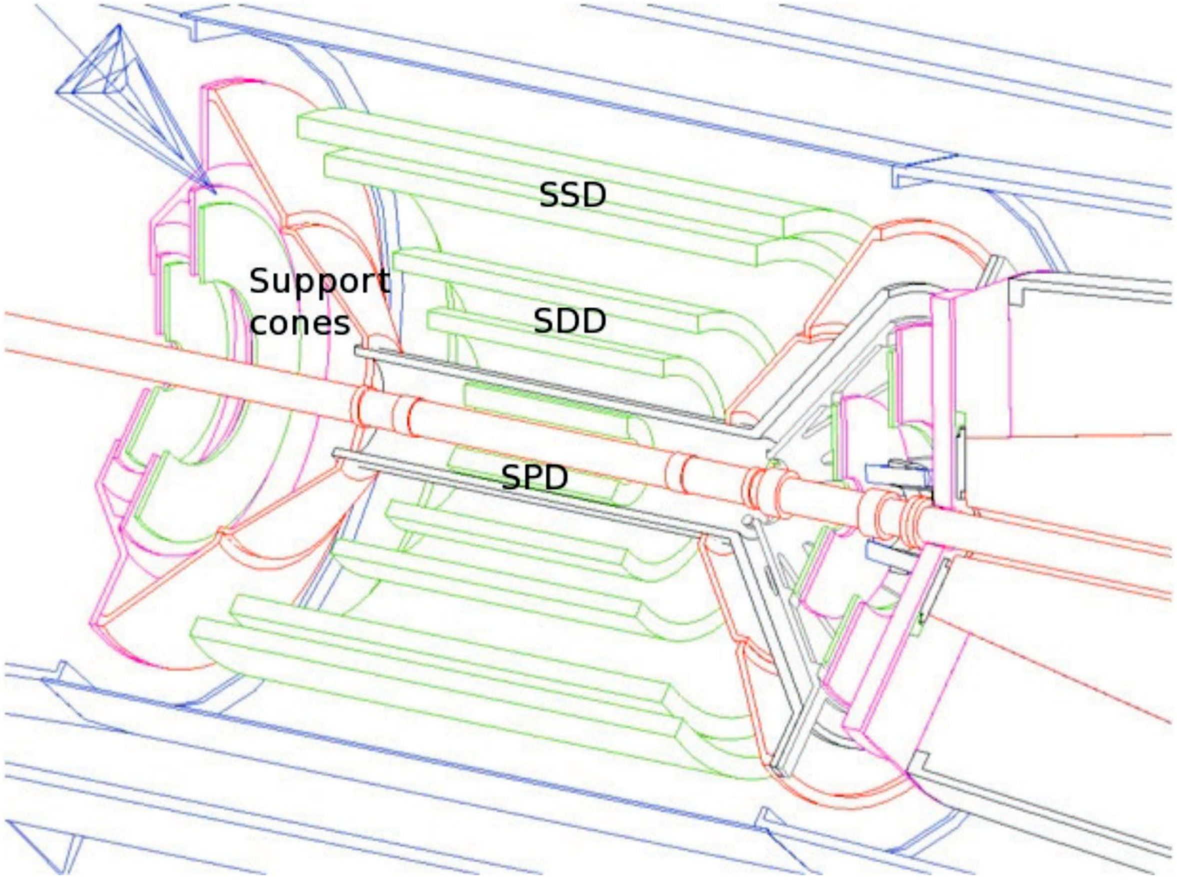
# Backup

# ALICE Inner Tracking System (ITS)

- 6 layers (two each of pixel, drift, and strip detectors)
- SSD & SDD can measure charge → $\frac{\mathrm{d}E}{\mathrm{d}x}$

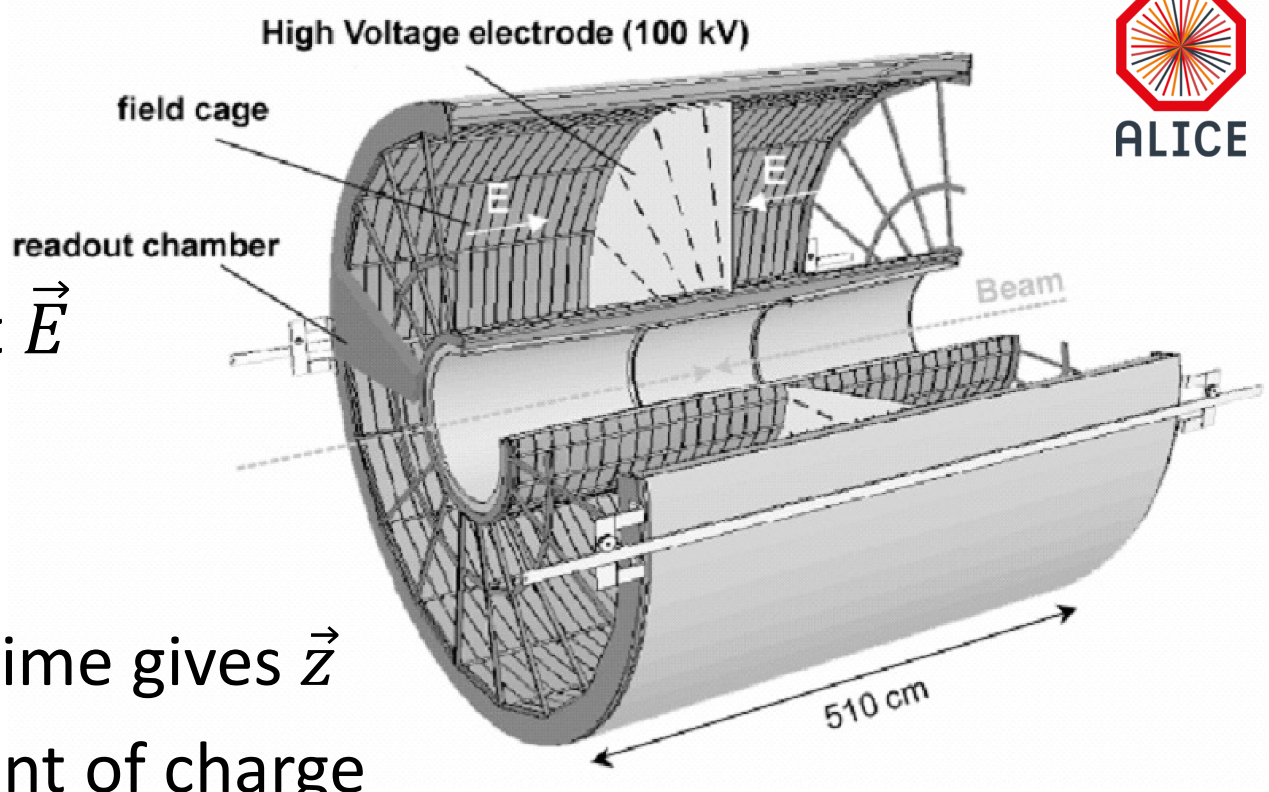
Example: SSD

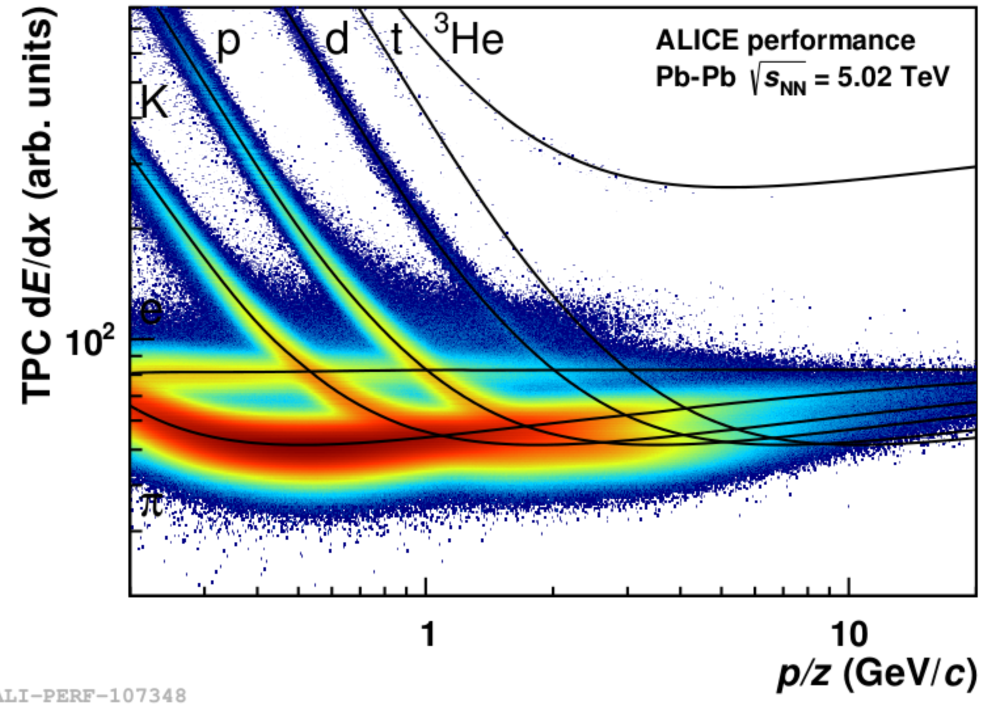


# ALICE TPC

- HV electrode creates high-gradient $\vec{E}$
- Ionization electrons drift to wire chamber readout




ALI-PERF-107348

- Drift time gives $\vec{z}$
- Amount of charge (pulse height) correlates to the energy

- The first TPC was invented by David Nygren at LBNL

*David Nygren*

# ALICE data (so far)

| System | Year(s) | $\sqrt{s_{NN}}$ (TeV) | $L_{int}$ |
|---|---|---|---|
| pp | 2009-2013 | 0.9 | 200 $\mu b^{-1}$ |
| | | 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 $\mu b^{-1}$ |
| Pb-Pb | 2010-2011 | 2.76 | 75 $\mu b^{-1}$ |
| | 2015, 2018 | 5.02 | 800 $\mu b^{-1}$ |

*compiled by: Yaxian Mao, Hard Probes 2020*

- As of November 2021, the ALICE Collaboration has 322 physics publications published in refereed journals
- Of those, 29 are published jet measurements (link)
- The large integrated luminosity in Run 2 allows precise new measurements and new observables

# 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

# Jet reconstruction

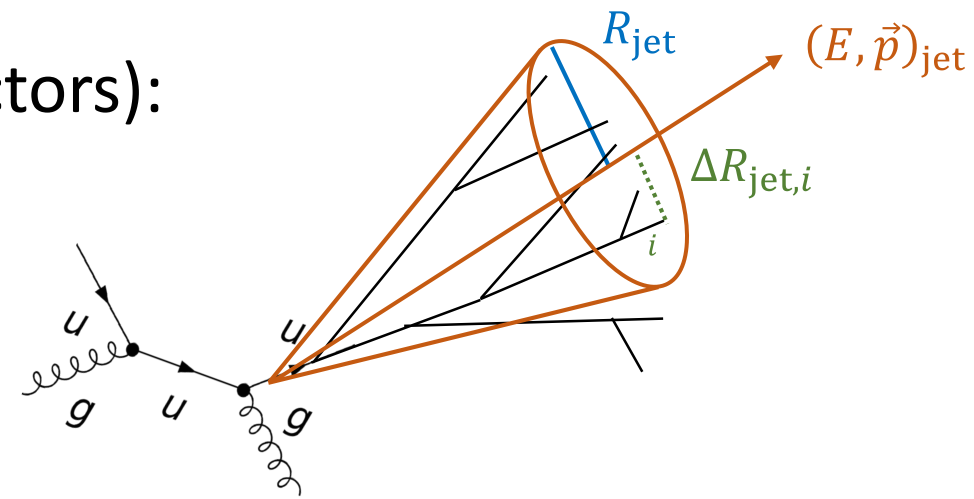
- Jets are reconstructed from charged particle tracks using the **anti-$k_T$** sequential recombination algorithm [5]
  - From an **IRC-safe** class of algorithms
  - **Soft-resilient**: shape is not strongly affected by soft, wide-angle radiation

$$d_{ij} = \min\left(k_{Ti}^{2p}, k_{Tj}^{2p}\right)\frac{\Delta_{ij}^2}{R^2}$$
$$d_{iB} = k_{Ti}^{2p}$$

$$p = \begin{cases} 1, & (\text{"inclusive"})\ k_T \\ 0, & \text{Cambridge/Aachen} \\ -1, & \text{anti } k_T \end{cases}$$

- ***E*-scheme** recombination (adding four vectors):

$$(E,\vec{p})_{\text{jet}} = \sum_{i\in\text{jet}} (E,\vec{p})_i$$



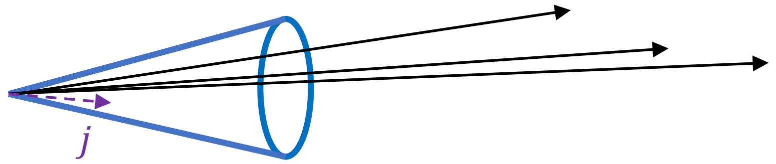

[5] JHEP 0804:063,2008

# What is IRC safety?

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

- Stands for Infra-Red and Collinear (IRC) safety
- Class of reconstruction algorithms & observables which satisfy certain conditions in order to avoid singularities from appearing in a well-defined path towards theoretical calculation

**Infra-Red safety**: the observable should not change if an infinitely-low-momentum particle is added to the event/jet




$$\lambda_{\alpha,\text{new}}^{\kappa} = \sum_{i \in \text{jet}} z_i^{\kappa} \theta_i^{\alpha} + z_j^{\kappa} \theta_j^{\alpha}$$

$$z_j = 0 \rightarrow z_j^{\kappa} \theta_j^{\alpha} = 0 \quad (\kappa > 0)$$

$$\lambda_{\alpha,\text{new}}^{\kappa} = \lambda_{\alpha,\text{old}}^{\kappa}$$

**Collinear safety**: the observable should not change if one particle splits into two collinear particles

$$\lambda_{\alpha,\text{new}}^{\kappa} = \sum_{(i \neq j) \in \text{jet}} z_i^{\kappa} \theta_i^{\alpha} + (\lambda z_j)^{\kappa} \theta_j^{\alpha} + [(1-\lambda) z_j]^{\kappa} \theta_j^{\alpha}$$

Need $\lambda^{\kappa} + (1-\lambda)^{\kappa} = 1 \ \ \forall \{\lambda \in [0,1]\} \ \rightarrow \ \kappa = 1$

Consider 1-particle jet: $\lambda_{\alpha,\text{new}}^{\kappa} = (\lambda z_j)^{\kappa} \theta_j^{\alpha} + [(1-\lambda) z_j]^{\kappa} \theta_j^{\alpha}$

$$\theta_j = 0 \rightarrow z_j^{\kappa} \theta_j^{\alpha} = 0 \quad (\alpha > 0)$$

# Charged-particle jet observables

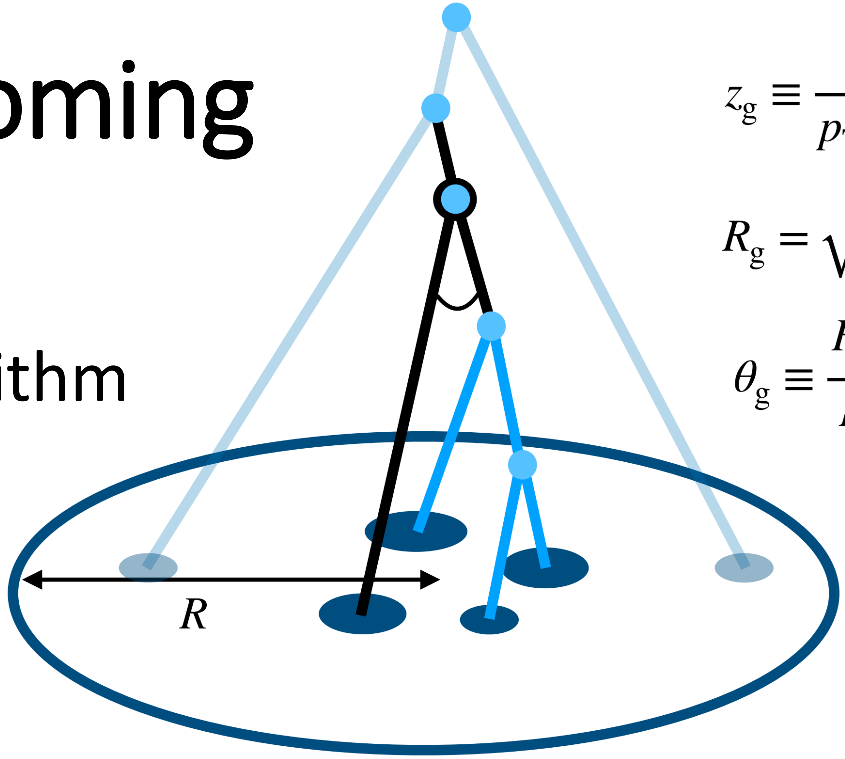
ALICE

- Charged-particle jets are useful for substructure observables since tracking detectors give **enhanced spatial precision**
- However, track-based observables are IRC-unsafe
- Formalism to calculate these observables using **track functions** [5]
- Currently we use the IRC-safe observables to motivate our measurements, and then apply nonperturbative corrections using different methods

[5] *H. Chang, M. Procura, J. Thaler, W. Waalewijn*
Phys. Rev. Lett. 111 (2013) 102002

# Going deeper: jet grooming

- 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 [5]
  - Repeatable on theoretical predictions




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

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

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

ALICE

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

[3] *A. Larkoski, S. Marzani, G. Soyez, J. Thaler* JHEP 1405 (2014) 146

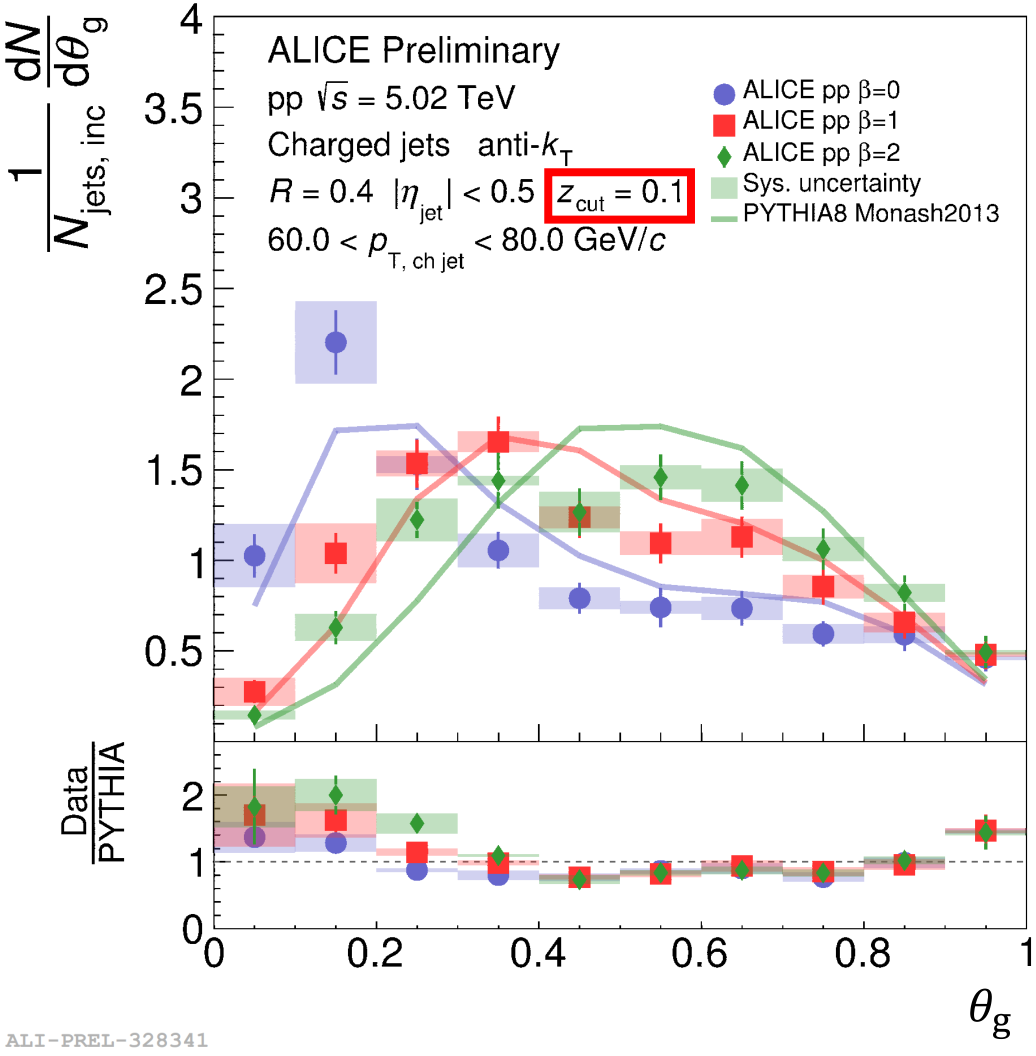
"Hardness": $\kappa^{(a)} = \dfrac{1}{p_T} \max_{i \in \text{C/A seq.}} \left[ z_i (1 - z_i)\, p_{T,i} \left(\dfrac{\theta_i}{R}\right)^{a} \right]$

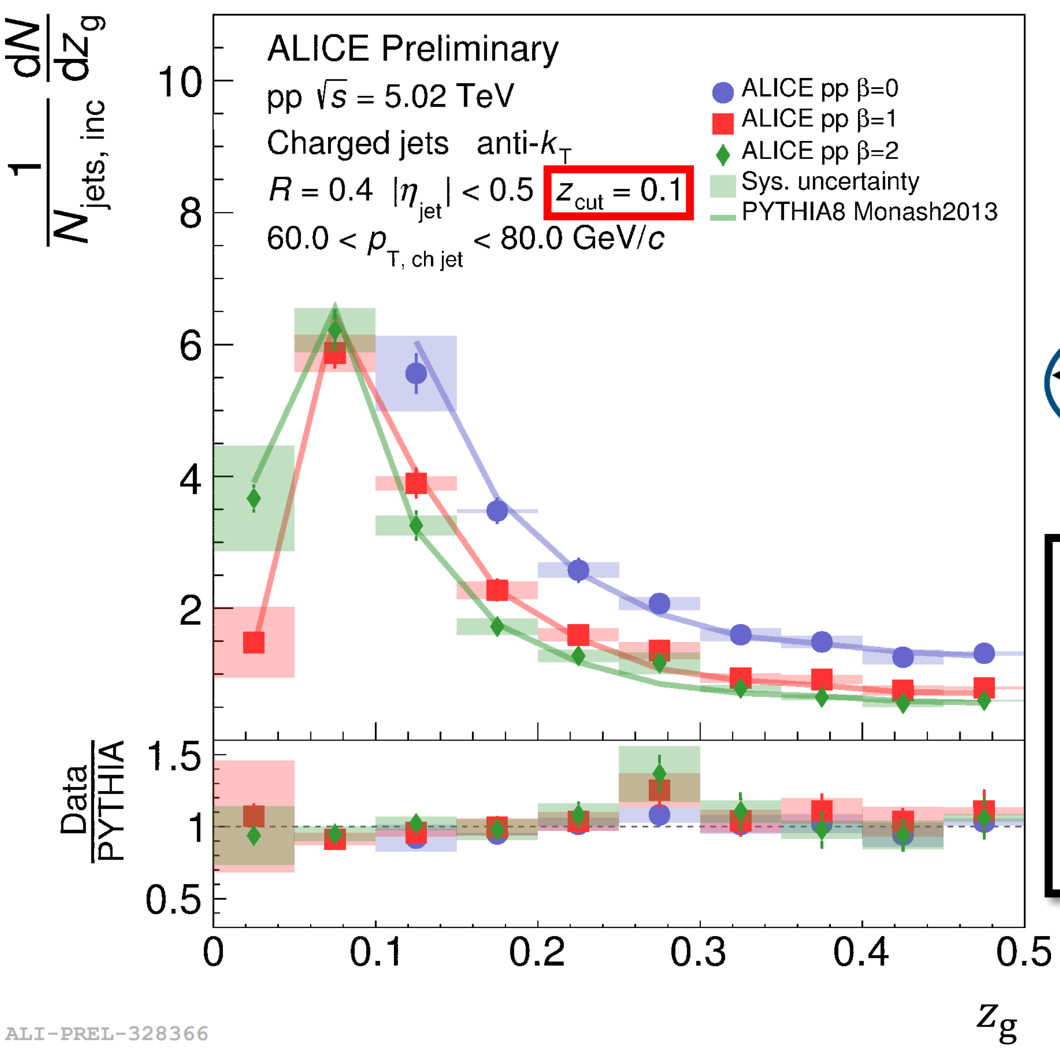
[4] *Y. Mehtar-Tani, A. Soto-Ontoso, K. Tywoniuk* Phys. Rev. D 101 (2020) 034004

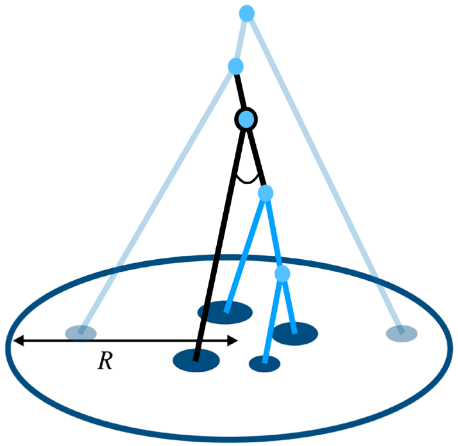
[5] *A. Larkoski, S. Marzani, J. Thaler* Phys. Rev. D 91 (2015) 111501

# $z_g$ and $R_g$ with Soft Drop grooming

- Comparisons to PYTHIA show stronger modification with larger $\beta$



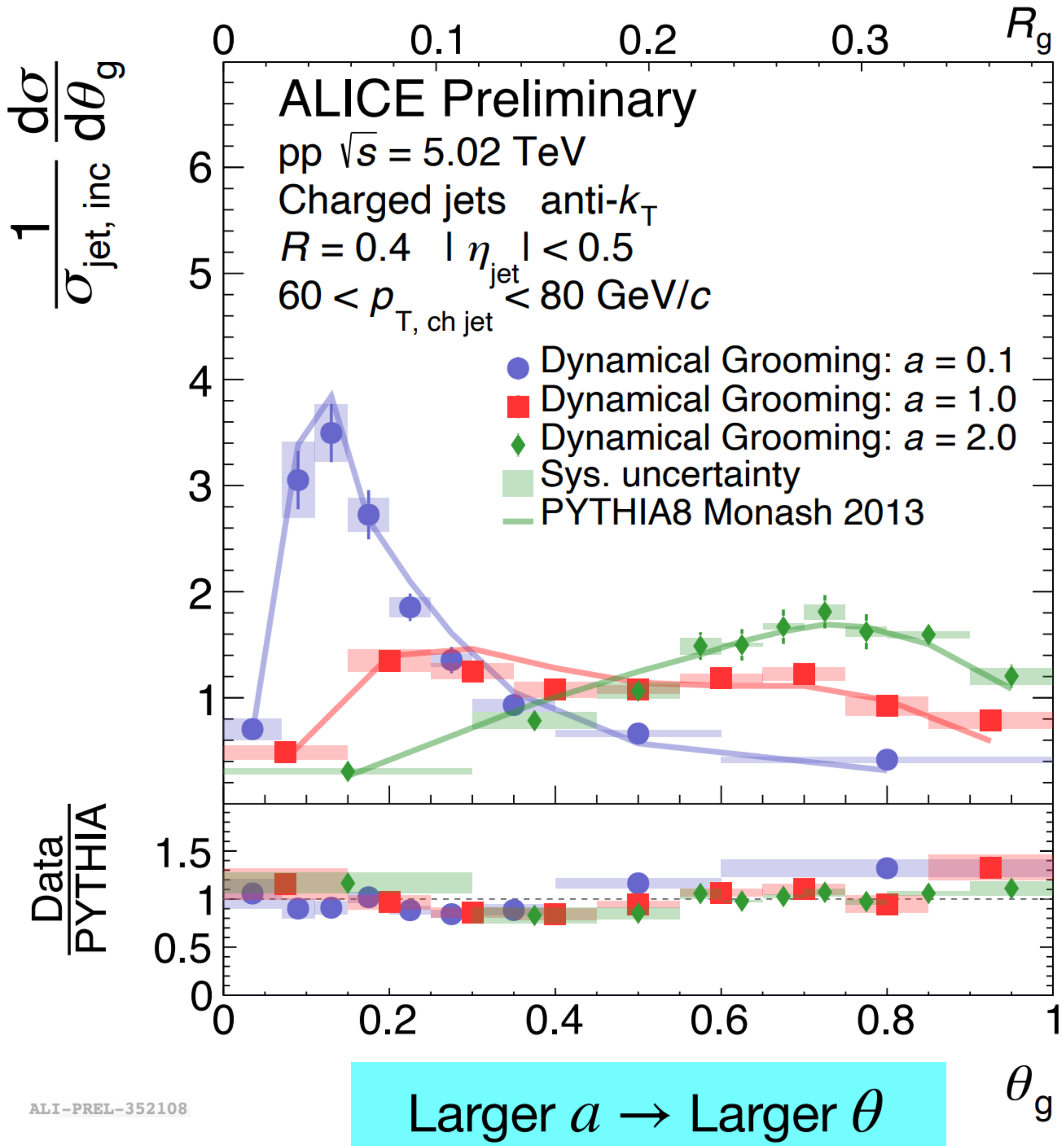




$$z_g \equiv \frac{p_{T,\mathrm{subleading}}}{p_{T,\mathrm{leading}} + p_{T,\mathrm{subleading}}}$$

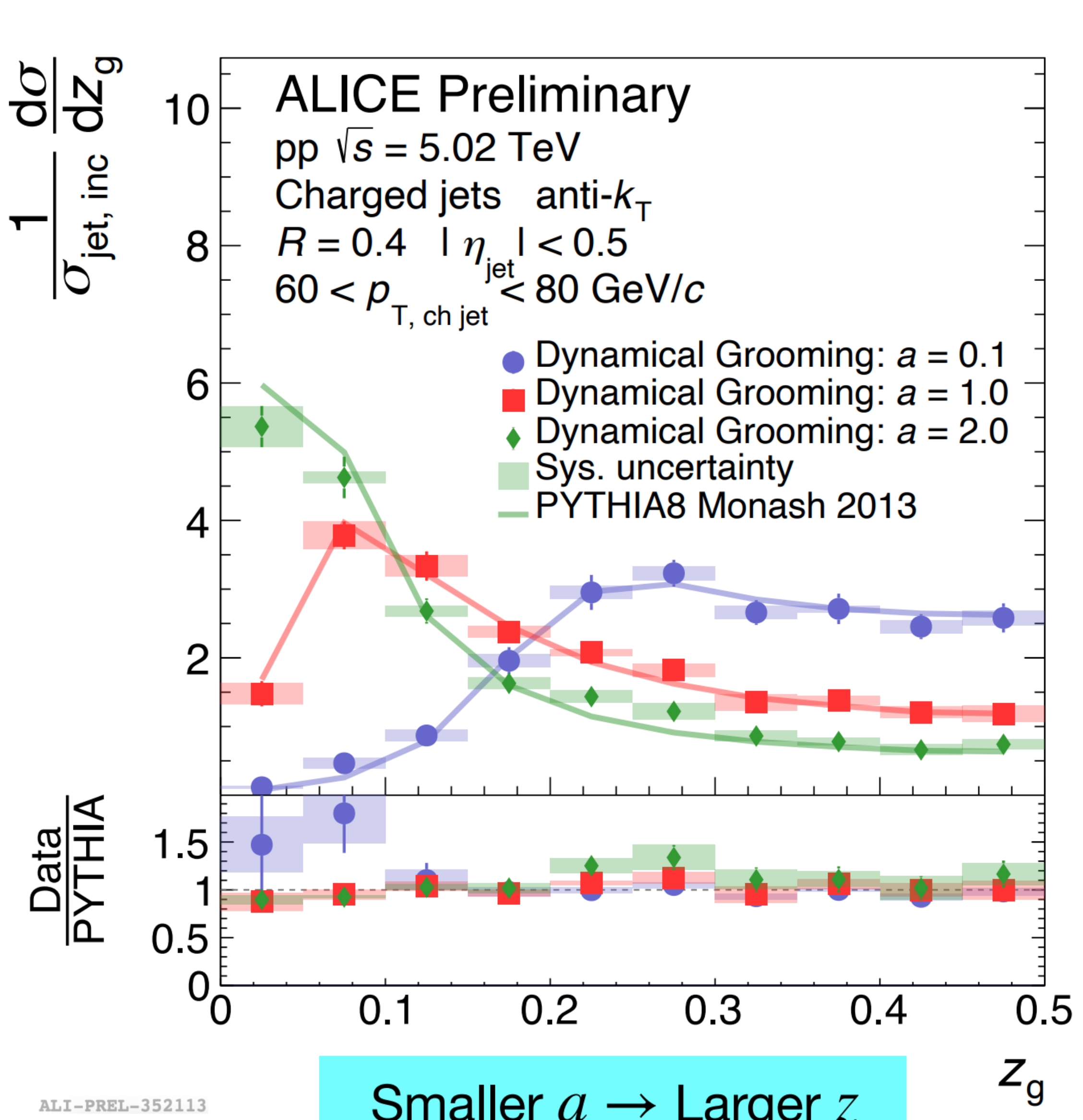
$$R_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

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

# First measurement with Dynamical Grooming

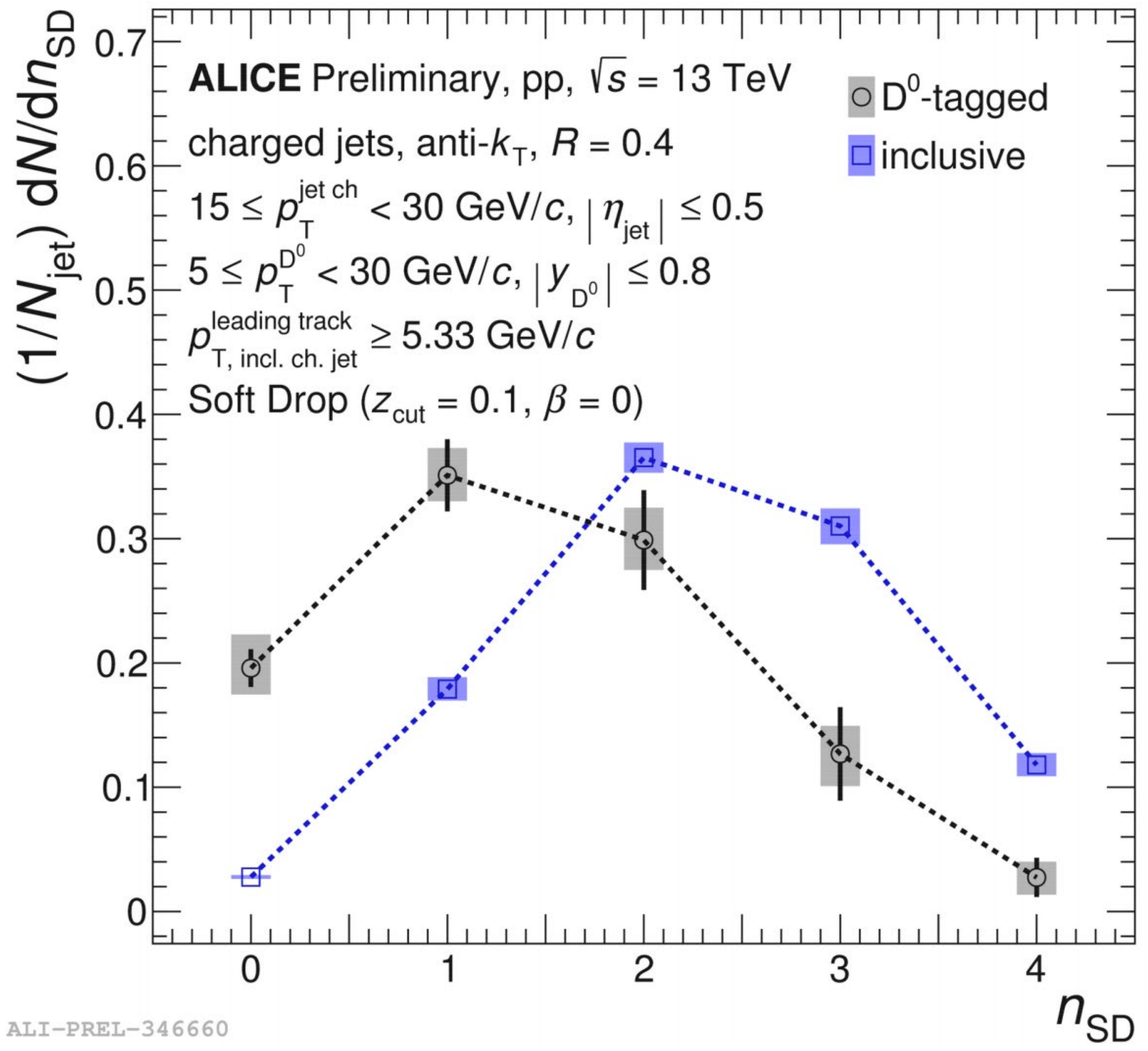



Larger $a$ → Larger $\theta$




Smaller $a$ → Larger $z$

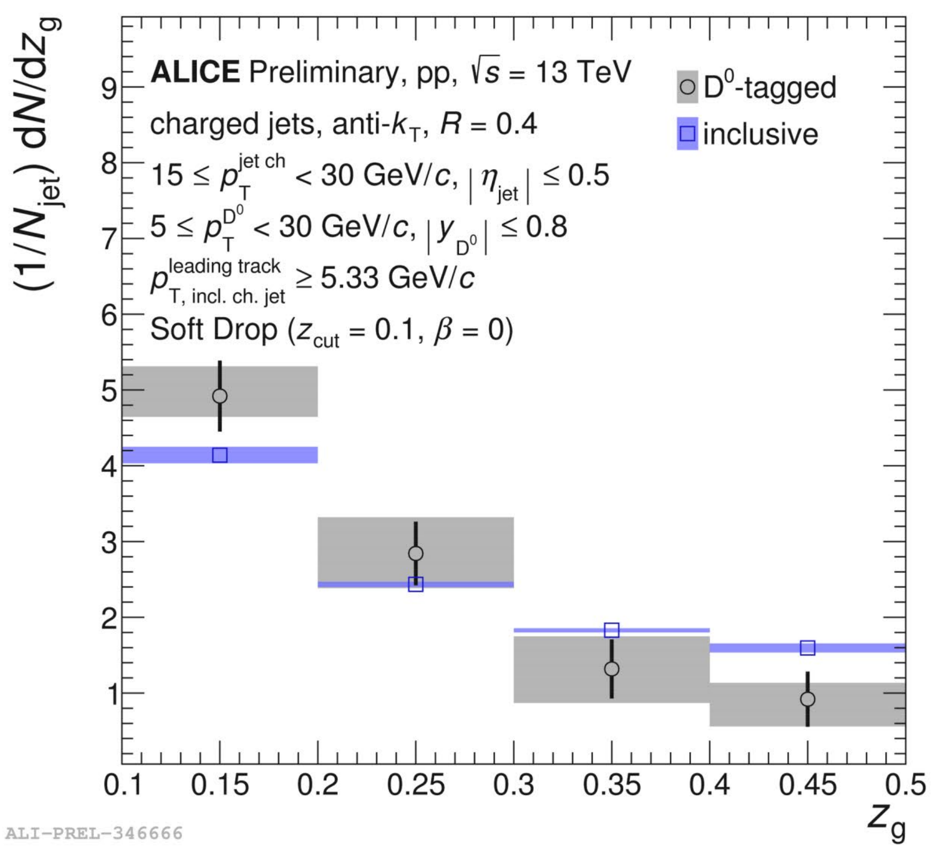
# First measurement of $z_g/R_g/n_{SD}$ in $D^0$-tagged jets

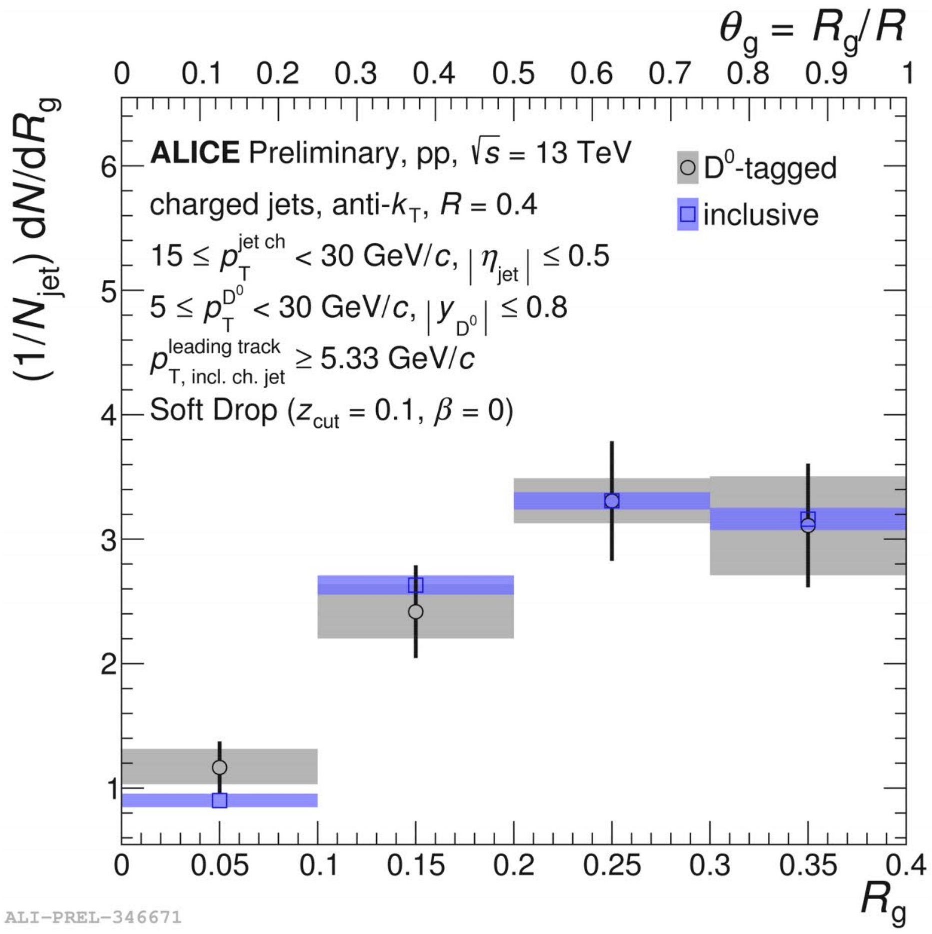



- $n_{SD}$ is the number of splittings which pass the Soft Drop grooming condition
  - Follows the hardest branch
- ***$D^0$*-tagged jets have fewer splittings** than inclusive jets
- Consistent with quark jets being **harder with fewer emissions** than gluon jets

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

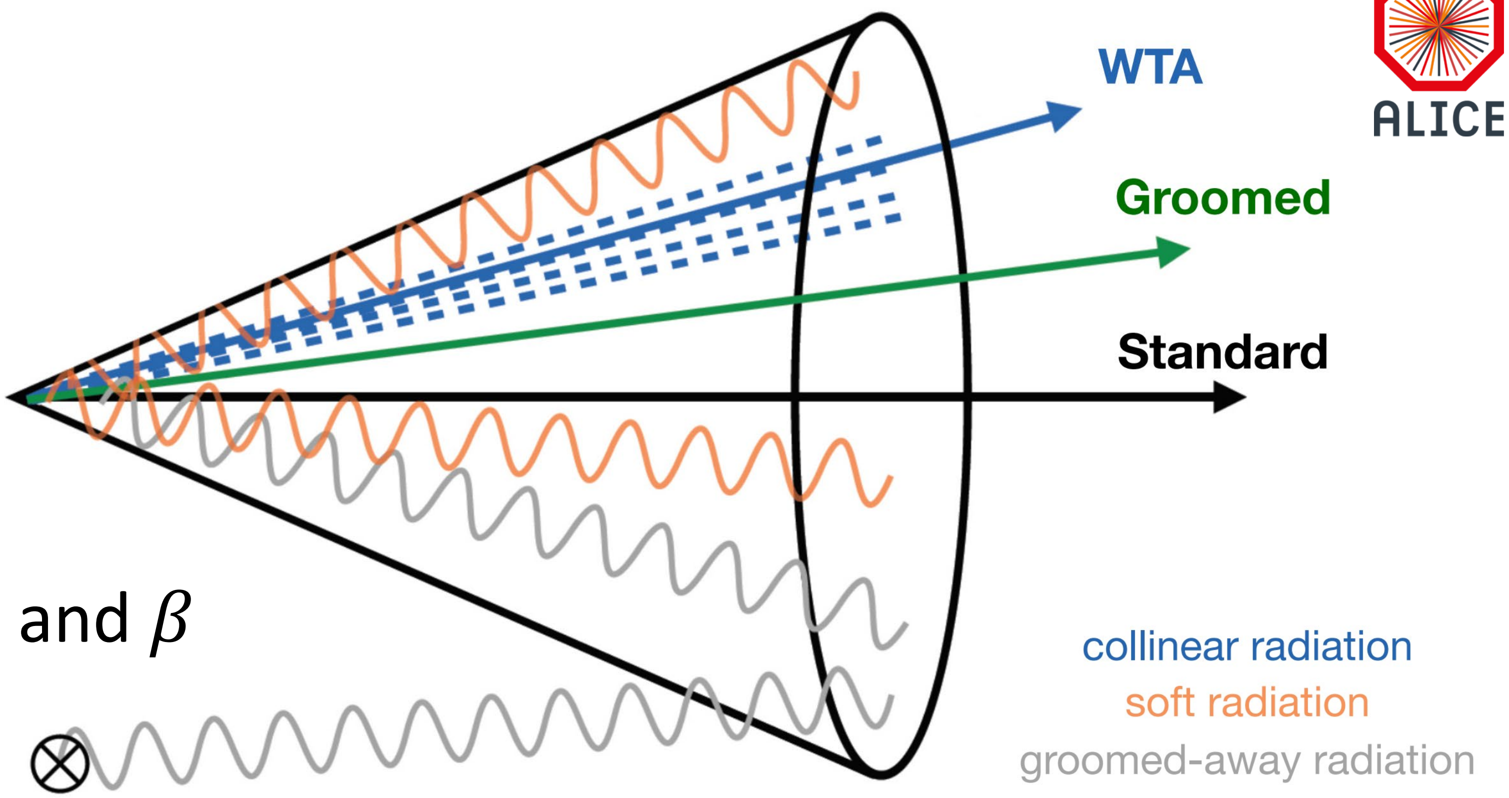
- Reconstruct $D^0$ mesons through $D^0 \rightarrow K^-\pi^+$ decay channel
- Calculate substructure observable in signal and both sideband regions




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

# Jet-axis differences

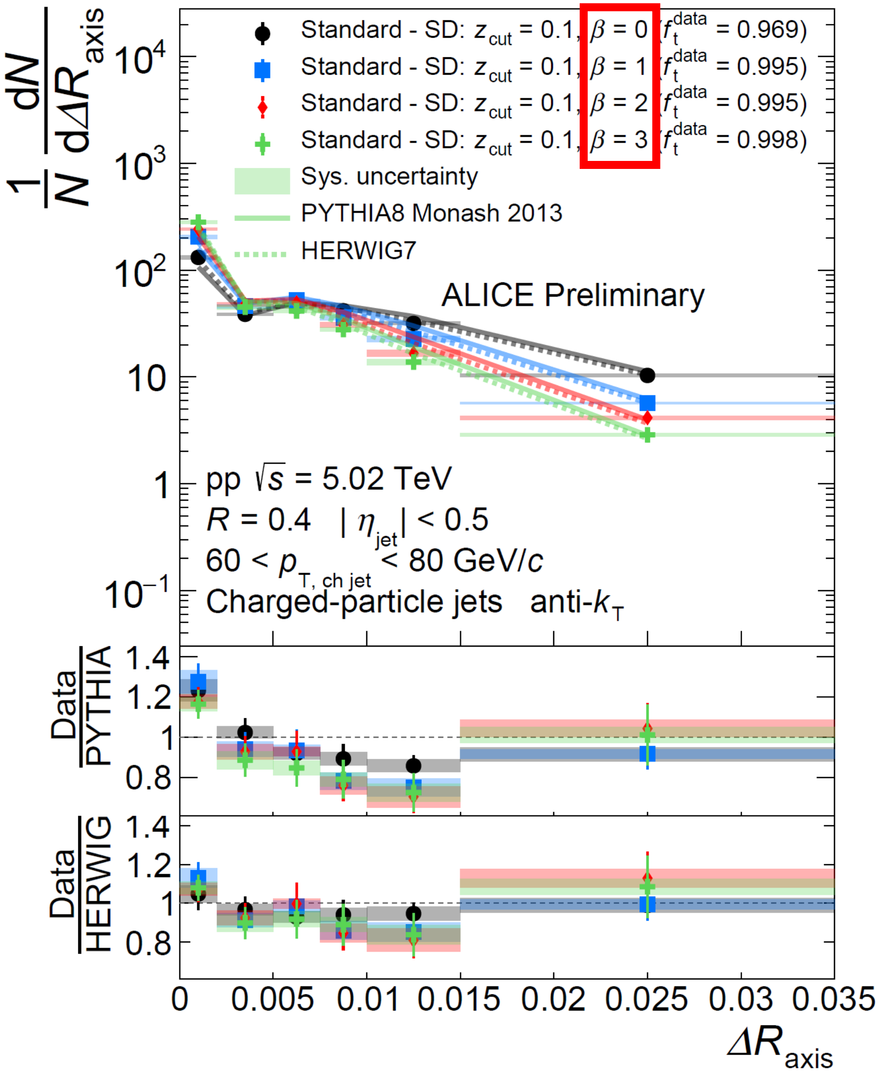


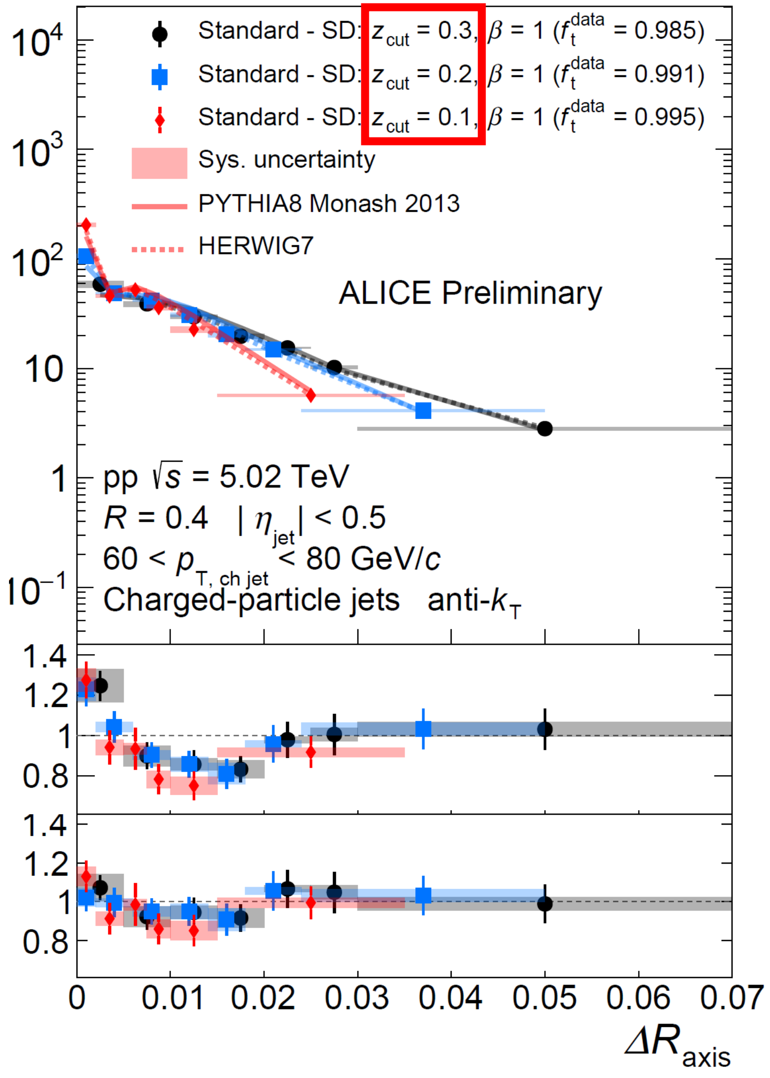

- **Standard**: anti-$k_T$ jet with $E$-scheme recombination
- **Groomed**: apply Soft Drop with different values of $z_{\text{cut}}$ and $\beta$
- **Winner-Take-All (WTA)**: jet axis is given by its leading constituent
- Calculate the angular separation: $\Delta R_{\text{axis}} = \sqrt{\Delta y^2 + \Delta\phi^2}$
- IRC-safe observable sensitive to **soft radiation, TMDs, and PDFs** [5]

[5] 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

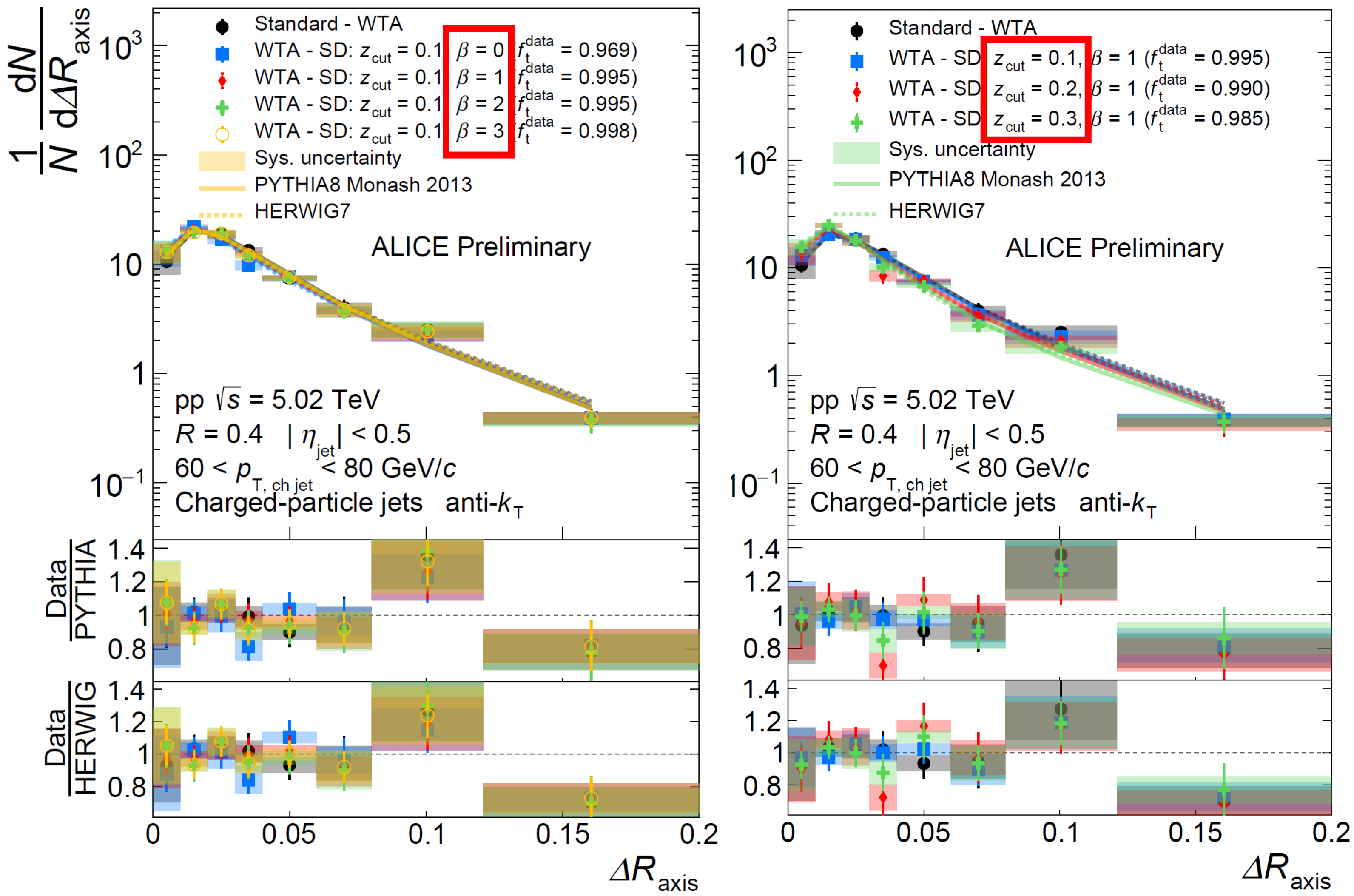



- **Standard and SD axes are strongly correlated**
- Seems mostly independent of grooming parameters
- Will be useful for tuning MC generators
- pQCD comparisons are coming soon!

# First measurement of the jet-axis differences

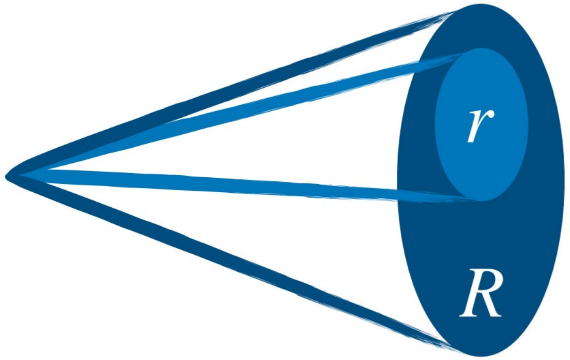
- Good agreement seen with MC for a wide range of SD parameters




- **WTA and standard/SD axes are less strongly aligned/correlated**
  - $p_{\mathrm{T}}$ 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-$k_{\mathrm{T}}$ with smaller radius $r$



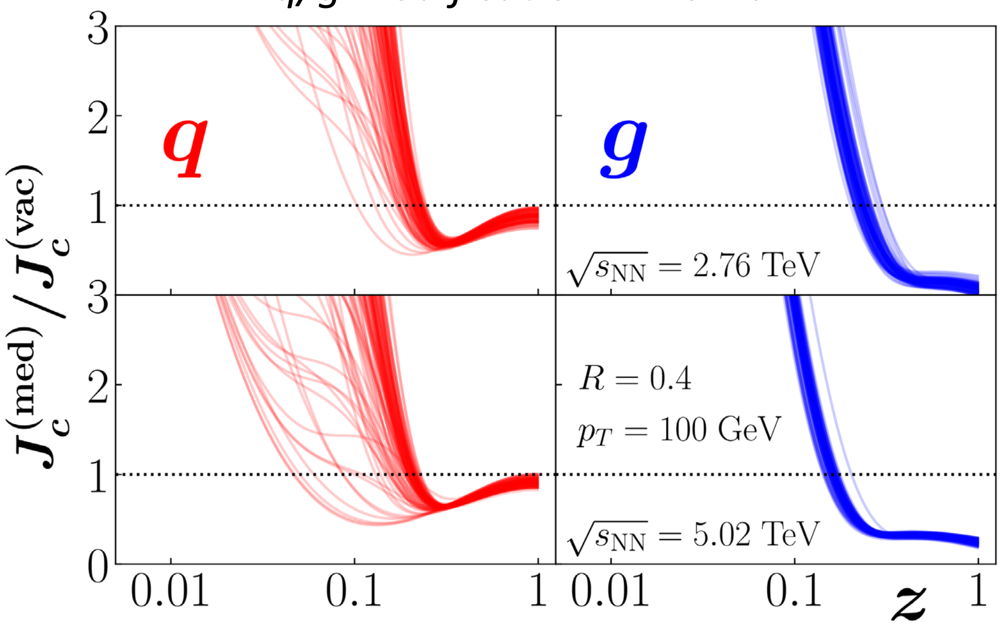

$$z_{\mathrm{r}} = \frac{p_{\mathrm{T}}^{\text{ch subjet}}}{p_{\mathrm{T}}^{\text{ch jet}}}$$

- 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 $R_{\mathrm{AA}}$ [6]

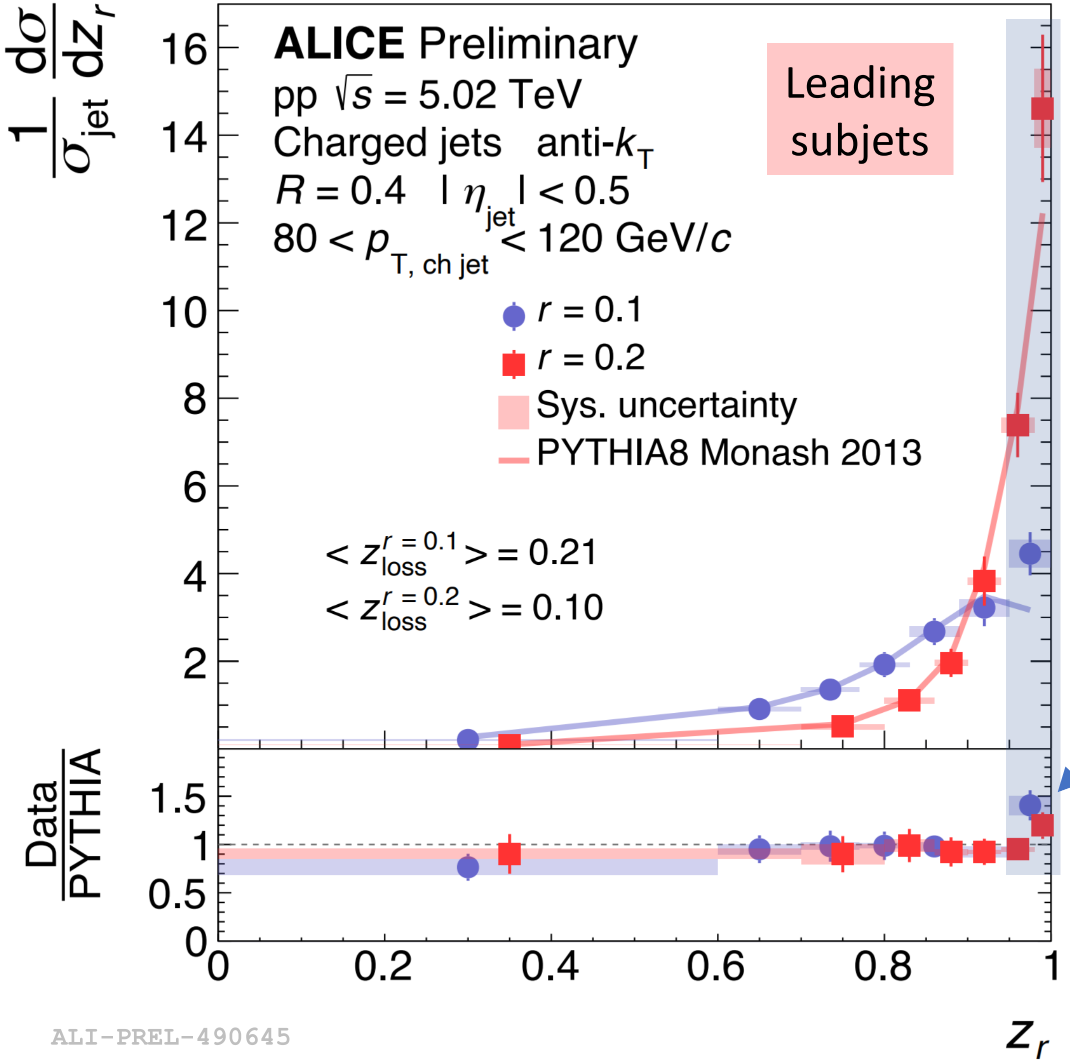
*q/g modification in Pb-Pb?*



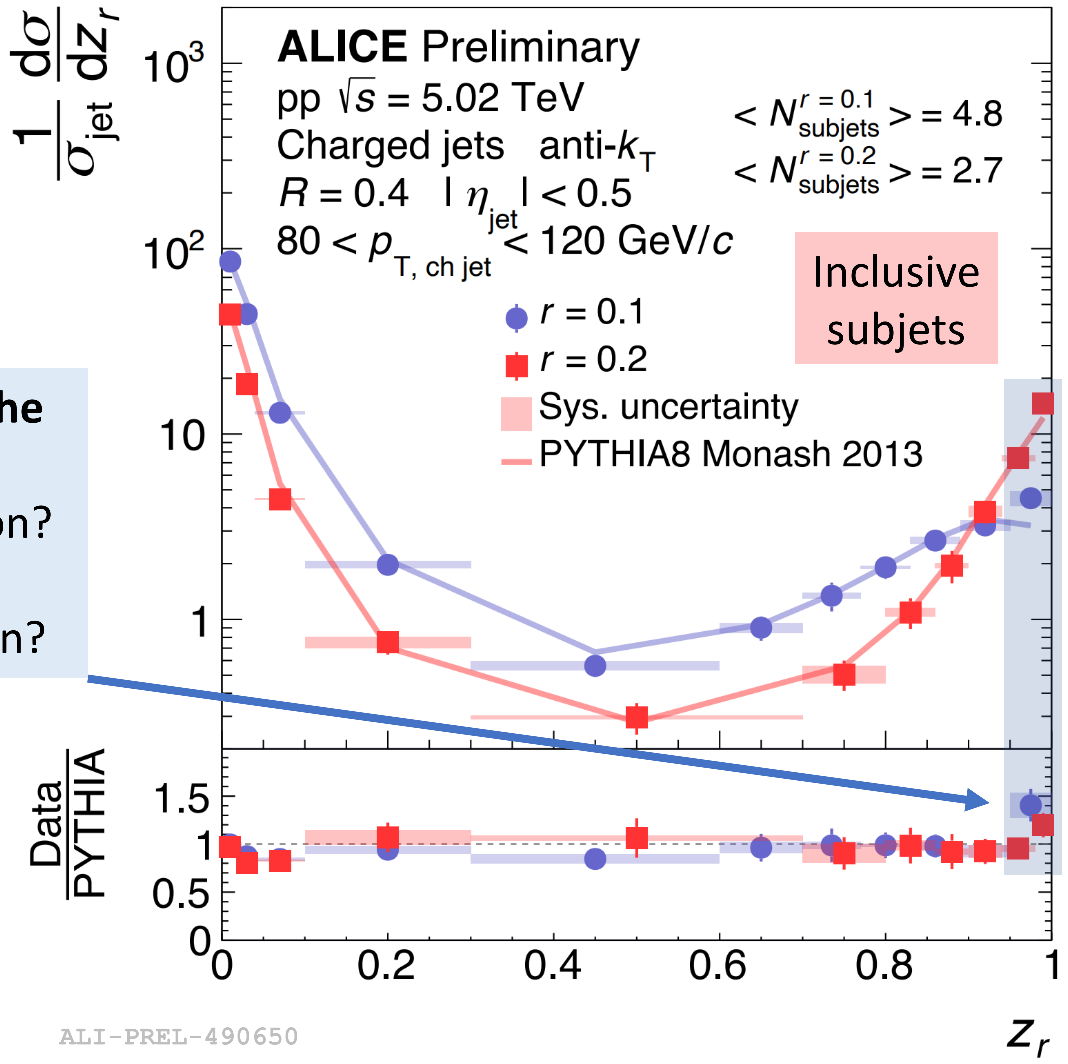

[6] Qiu, Ringer, Sato, Zurita PRL 122 (2019) 25

# New subjet measurements in pp

- Reasonable agreement is observed with respect to MC generators




**Tension in the last bin:**
Hadronization?
Threshold resummation?



# Inclusive jet (primary) Lund Plane

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

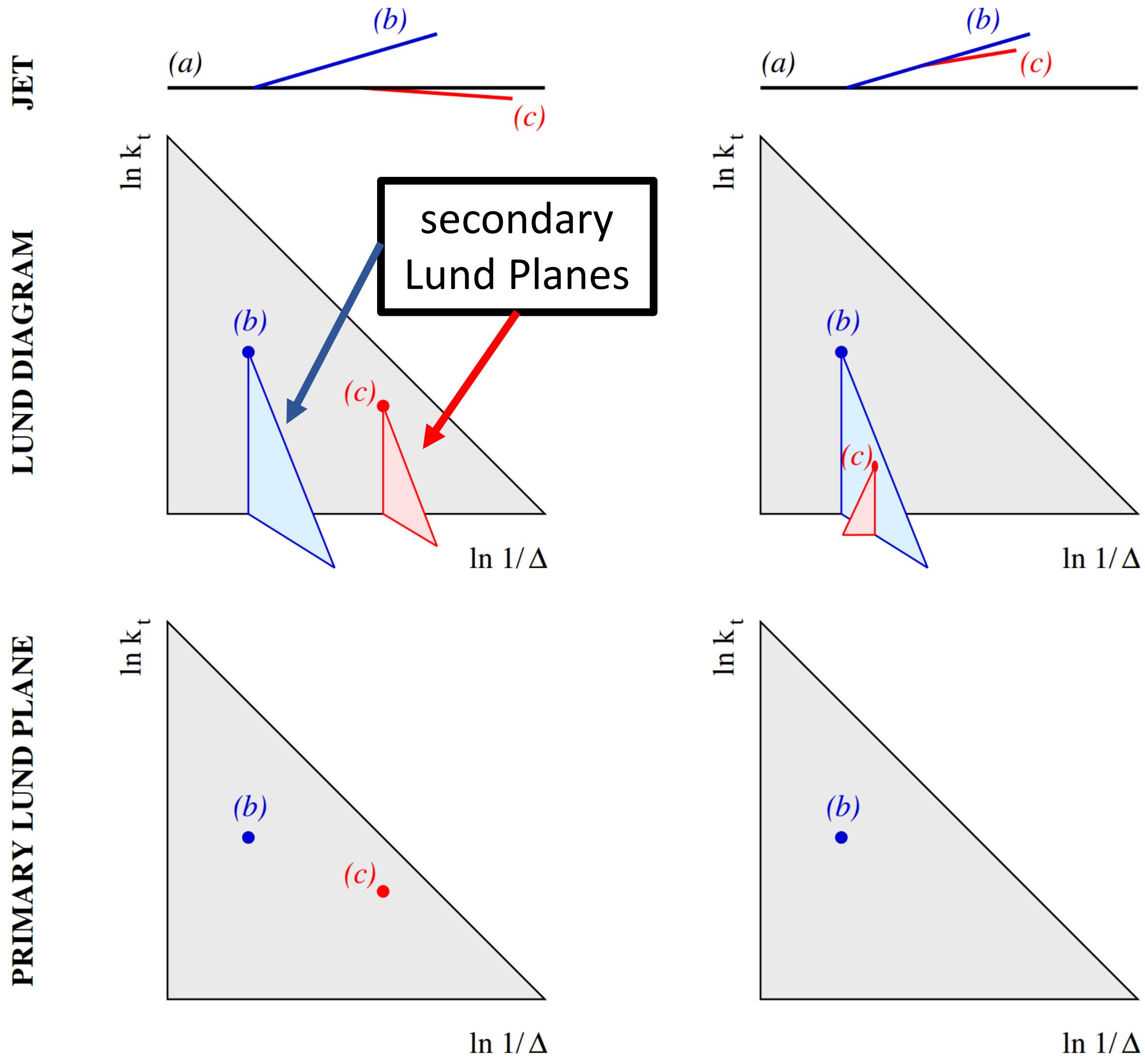
- Axes are related to angle and $p_{\mathrm{T}}$:

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

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

- Not generally IRC-safe; perturbatively amenable for

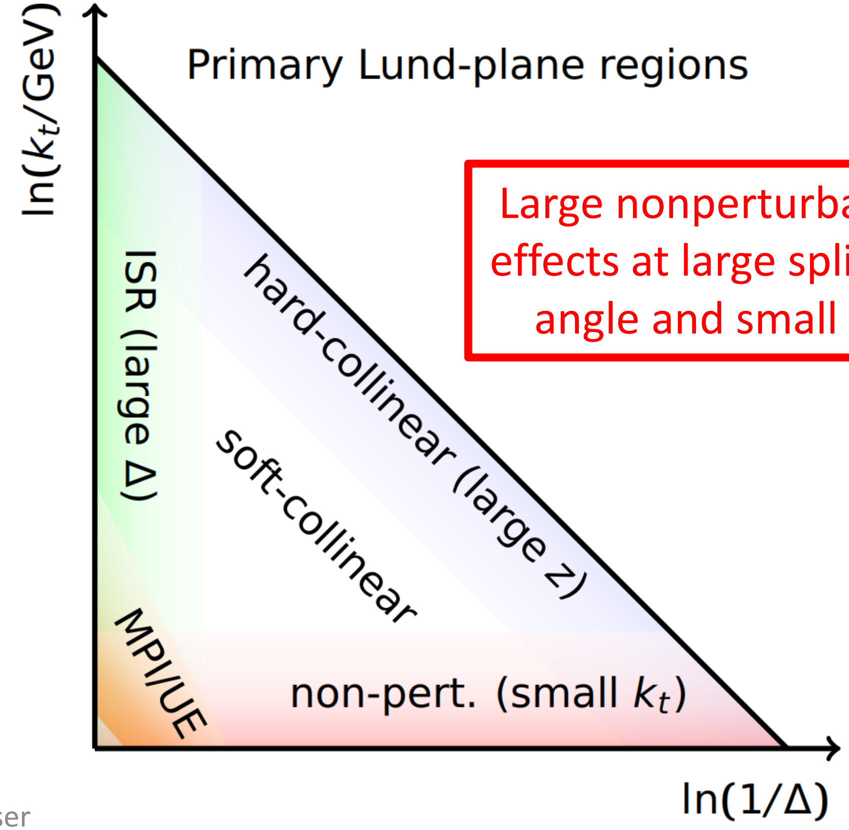
$$k_t \gg \Lambda_{\mathrm{QCD}}$$



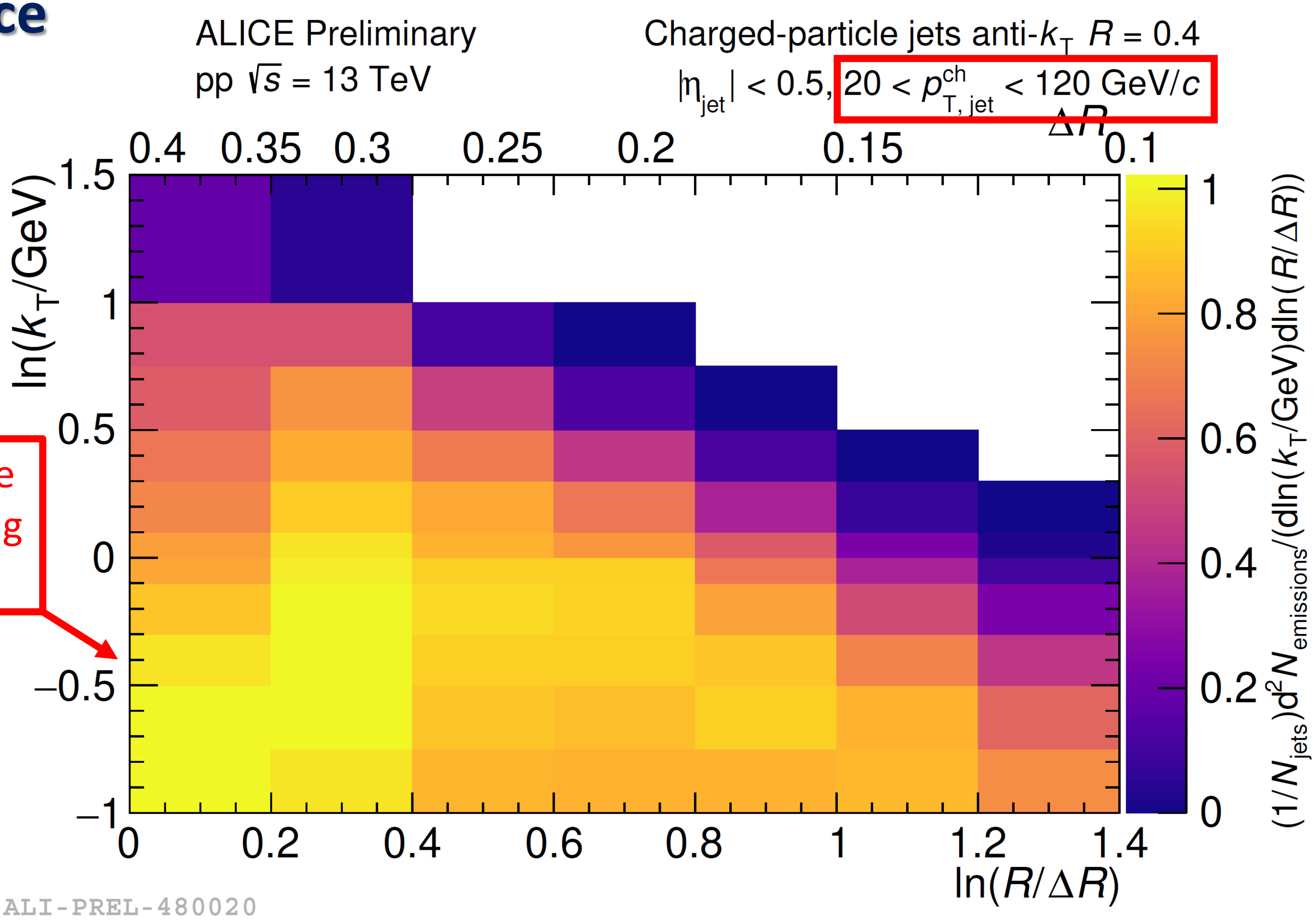

F. Dreyer, G. Salam, G. Soyez JHEP 12 (2018) 064

# Inclusive jet (primary) Lund Plane

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



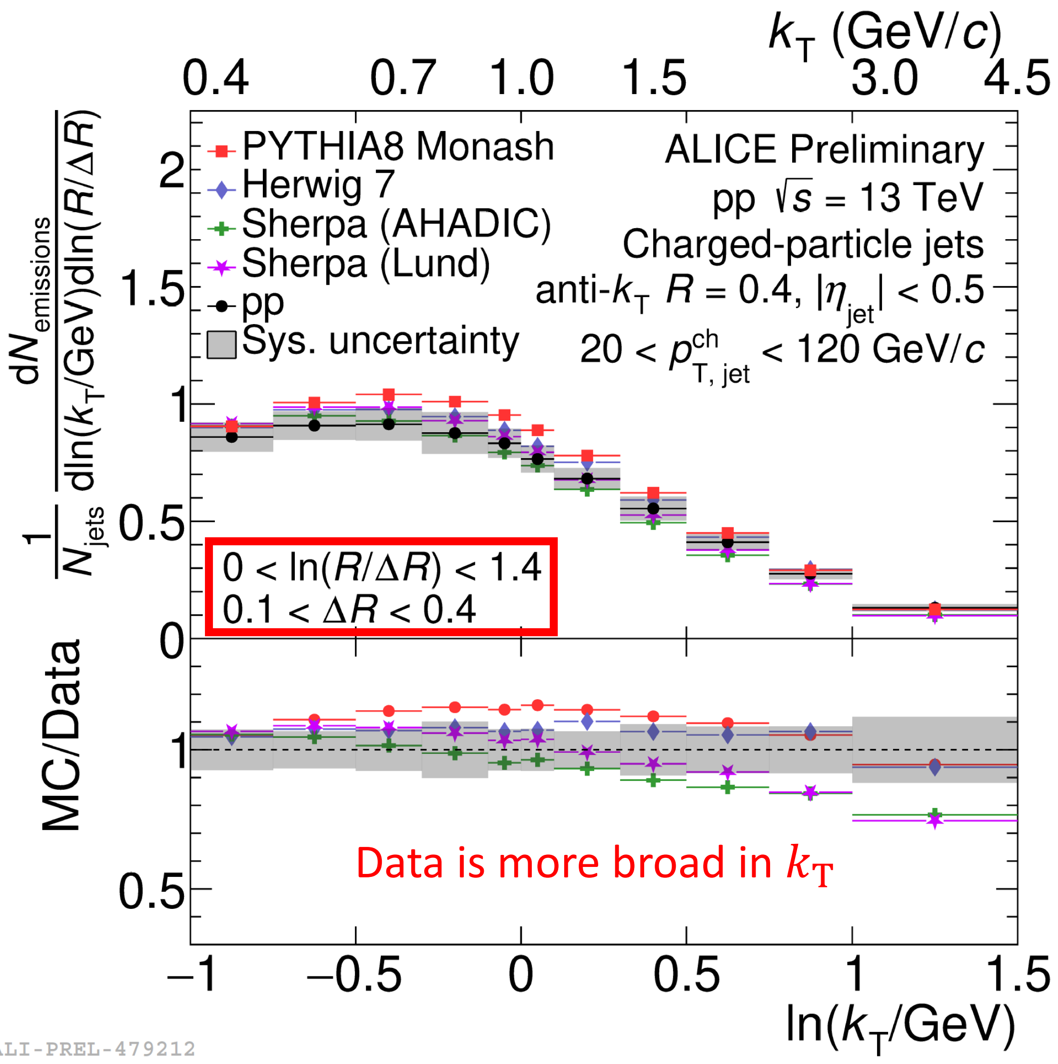

Large nonperturbative effects at large splitting angle and small $k_T$

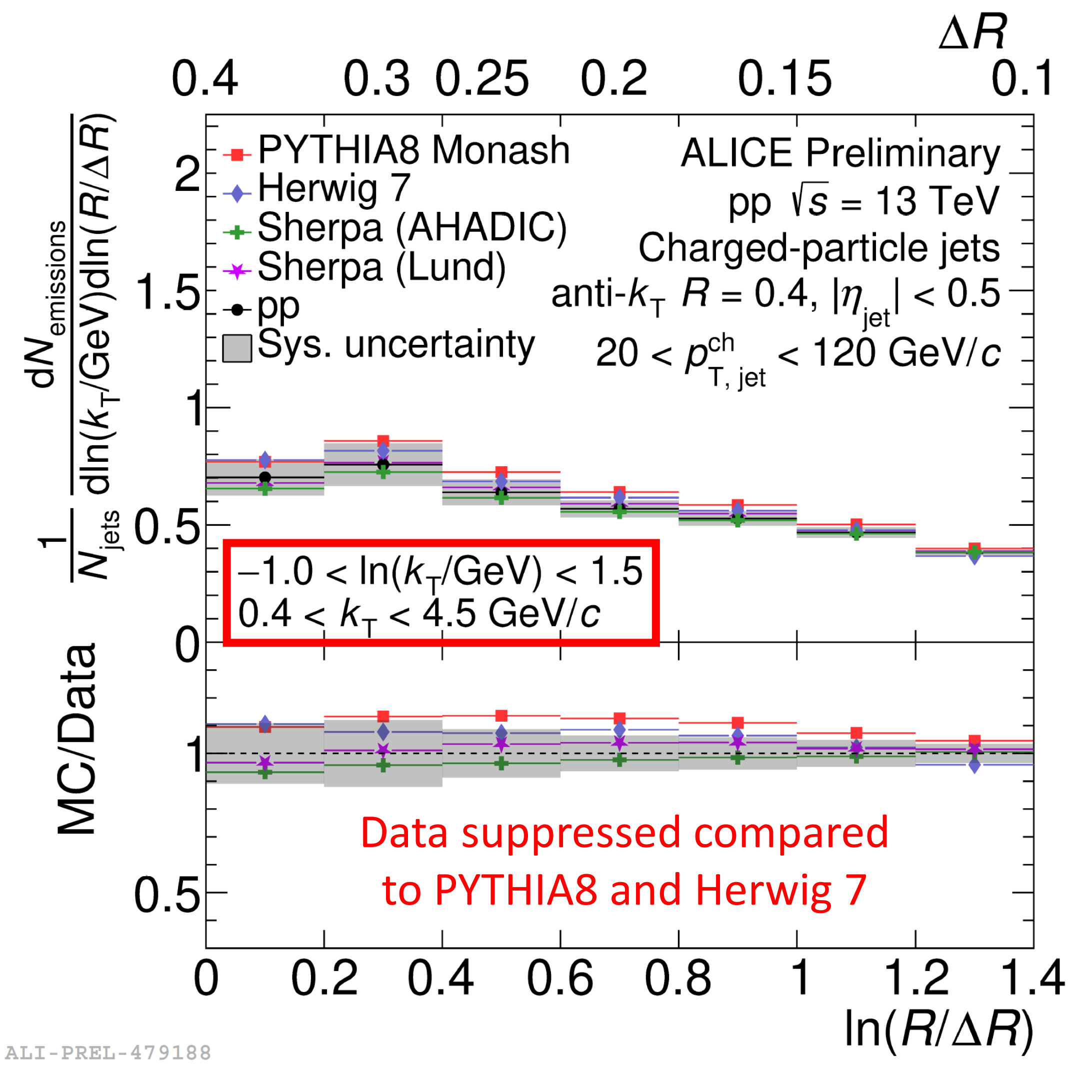



[7] ATLAS Collab.: Phys. Rev. Lett. 124 (2020) 222002

# Comparing Lund Plane projections to models

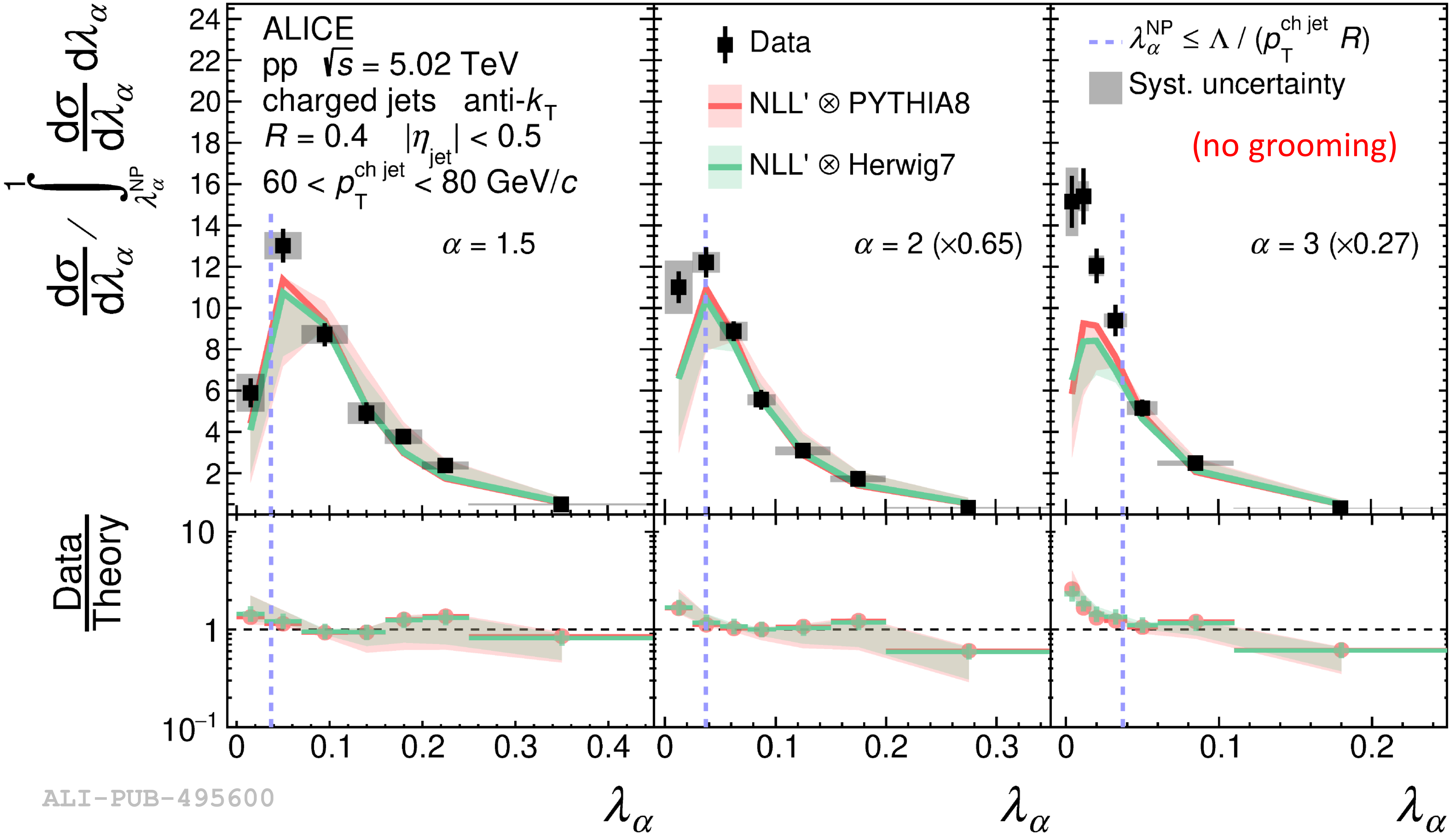
- Slight tension seen with some models in different regions of phase space



# pQCD predictions with SCET ($R = 0.4$)

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




For larger $R$ we see increased tension at large values of $\lambda_\alpha$

This could hint at the importance of higher-order terms (for example, power corrections in $\lambda_\alpha$)

# 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]

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

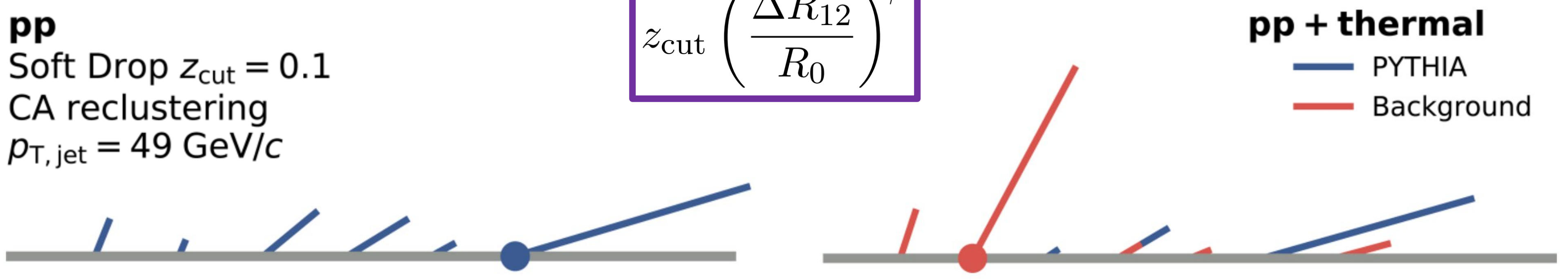



*figure: J. Mulligan, LBNL*

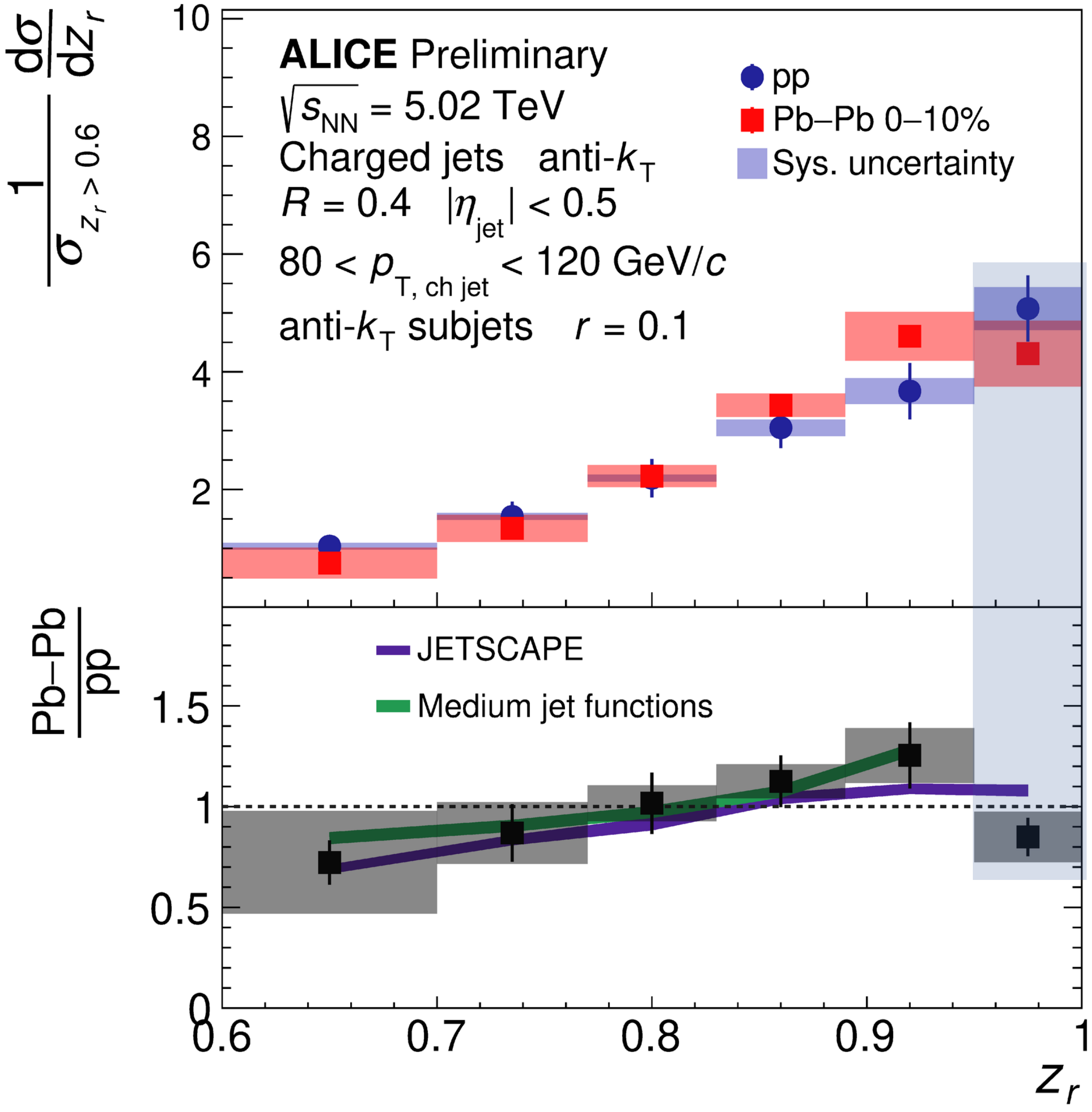
- **Dynamical**: same is true for lower $a \to 0$

| | | |
|---|---|---|
| $a \to 0$ | 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 $t_f$ | $\ln k_t(R_{\mathrm{jet}}) \approx -\sqrt{a}$ |

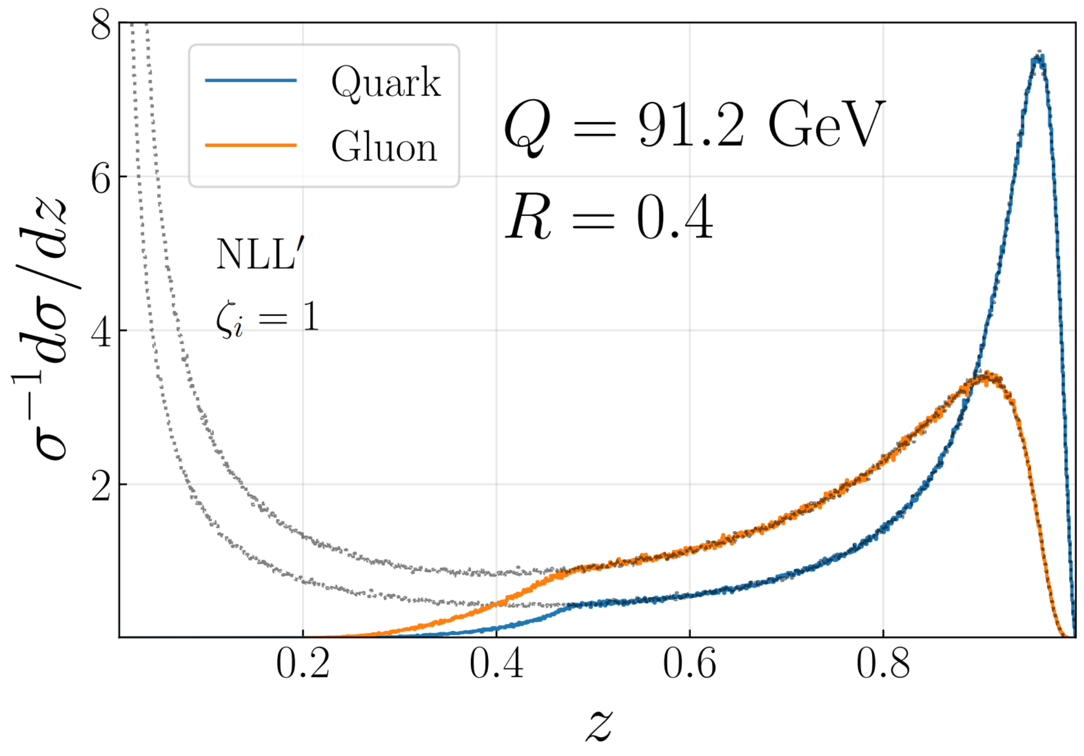
$$z_i (1 - z_i)\, p_{\mathrm{T},i} \left( \frac{\theta_i}{R} \right)^{a}$$

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

# 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

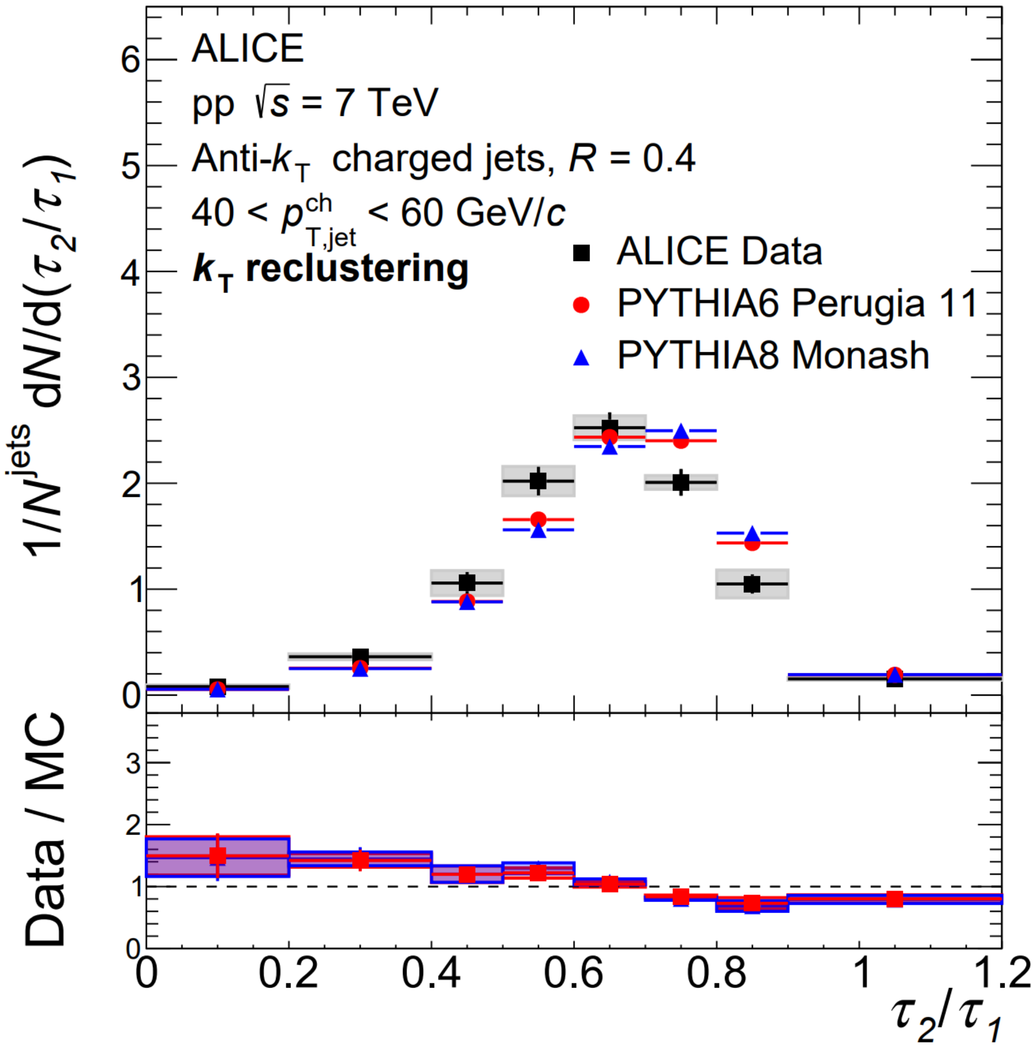



D. Neill, F. Ringer, N. Sato arXiv:2103.16573

# Measuring the $N$-subjettiness in pp

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

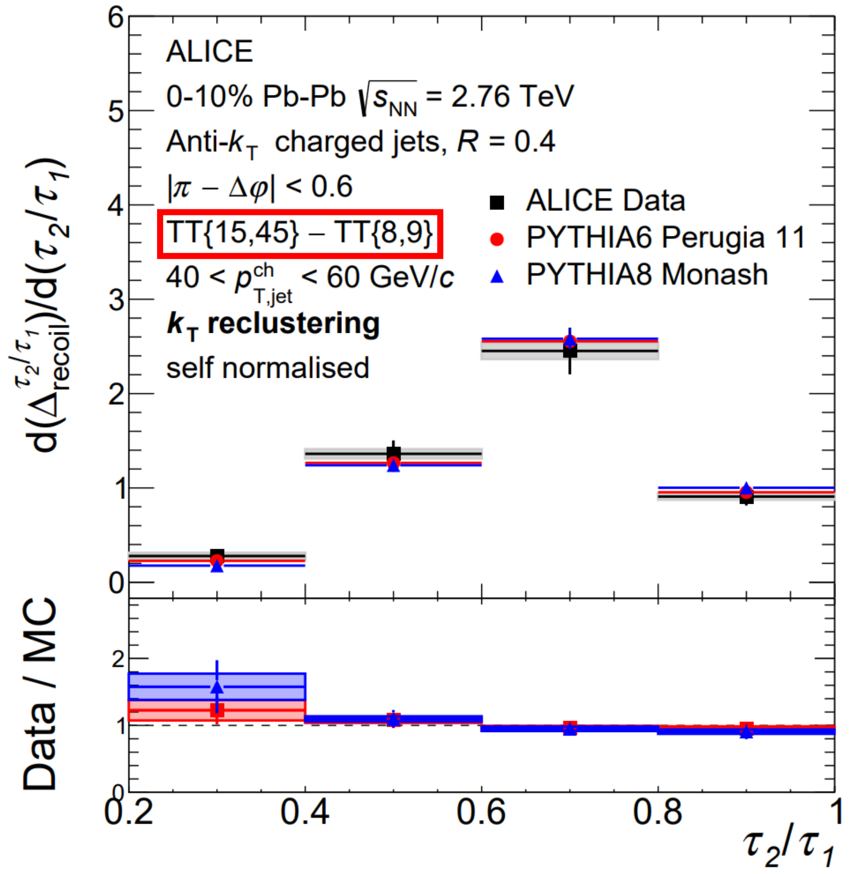
- Used for **tagging 1- or 2-pronged jets**
  - Originally designed to tag boosted decays such as $W^{\pm} \to \bar{q}q$ or $t \to W^{+}b$
- $\tau_N \to 0$ means correlation to $N$ subjets; $\tau_N \to 1$ means no strong correlation and suggests at least $N+1$ subjets
- Low values of $\tau_N/\tau_{N-1}$ are used to **discriminate $N$-prongness**
- $\tau_2/\tau_1$ is peaked at intermediate values $\to$ pp jets are found to be **mostly single-cored**, as two hard substructures are not well-separated and defined

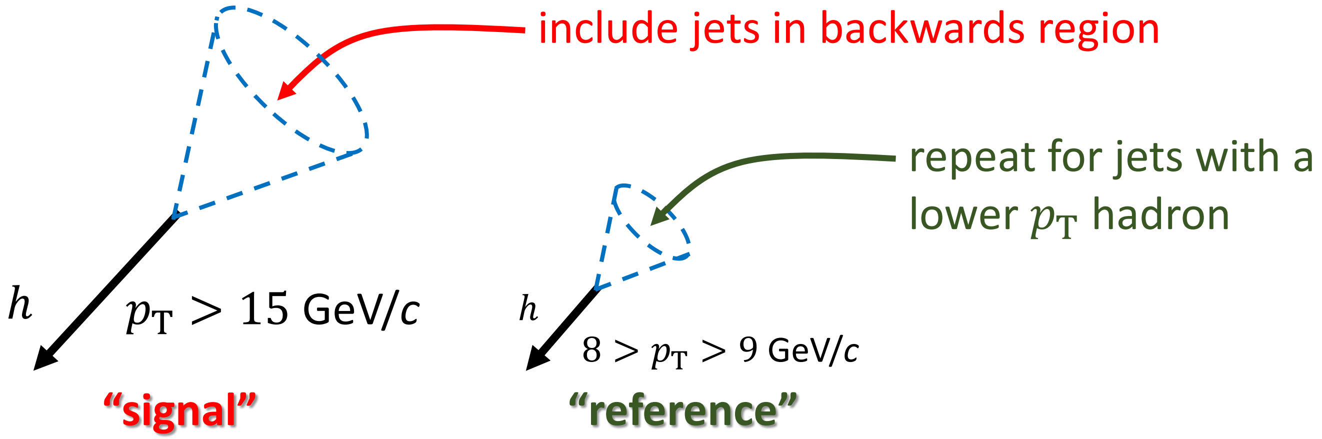



arXiv:2105.04936 [nucl-ex]

# 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)



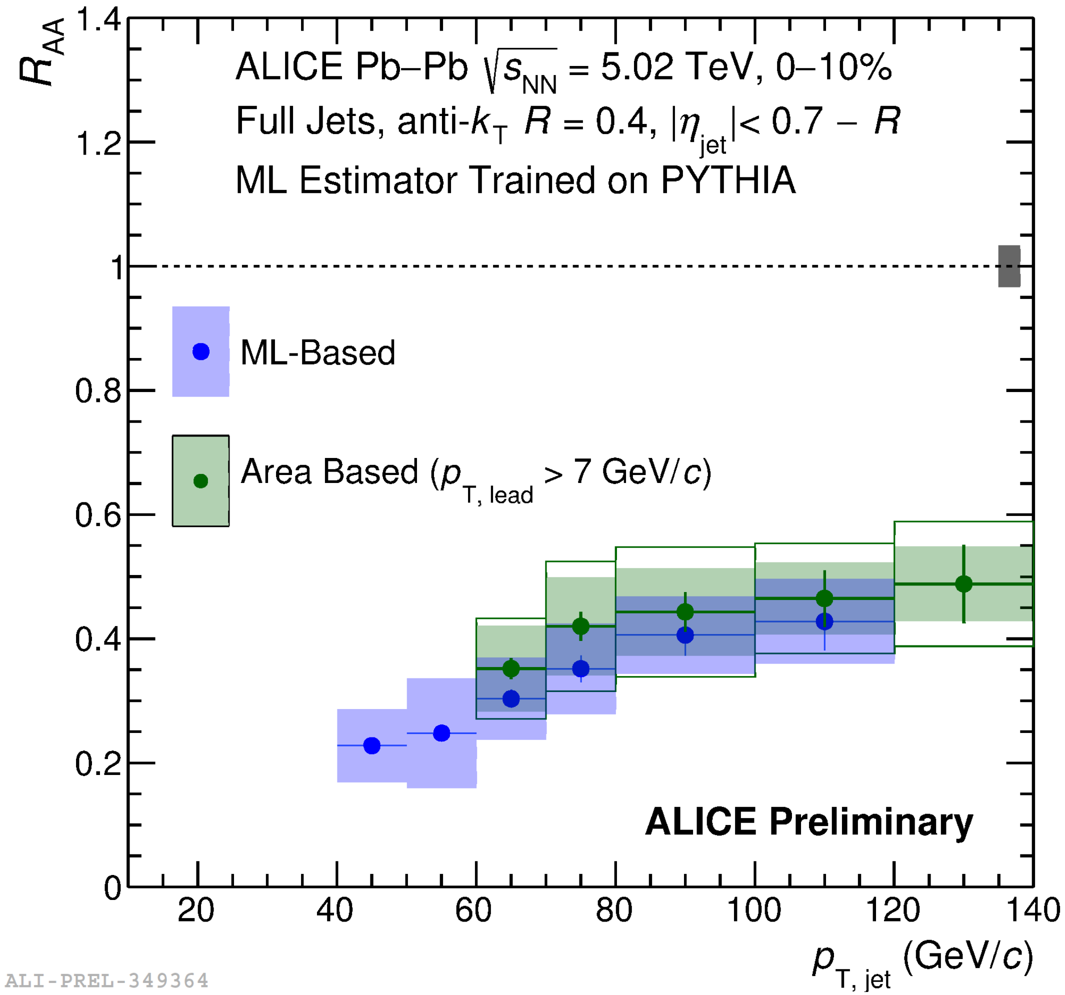




- Reduce contamination from combinatorial jets via requirement of a back-to-back high-$p_T$ hadron, then subtracting the observable shape from a reference Trigger Track (**TT**) bin

[9] ALICE Collab. JHEP 09 (2015) 170

# Using ML to reduce jet background [10]

- May allow studying jets with lower jet $p_{\mathrm{T}}$ and larger $R$ than before



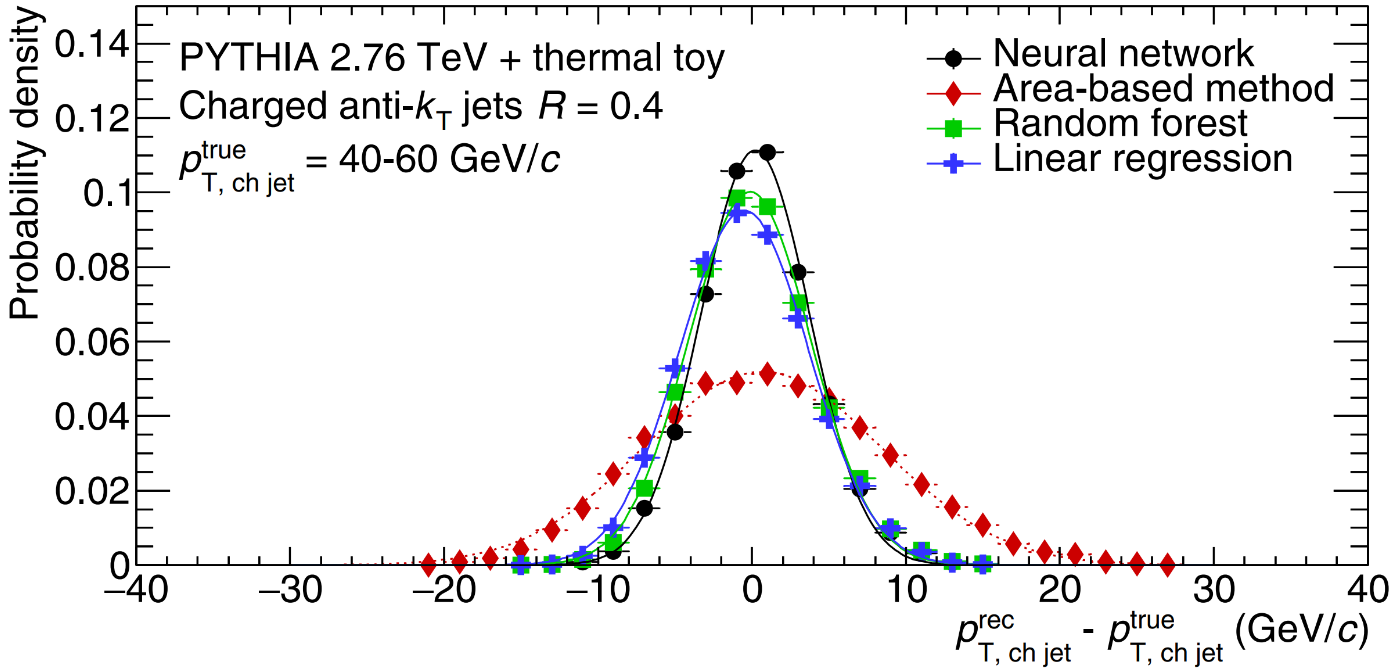




FIG. 2. Residual distributions for several background estimators in $40 \leqslant p^{\mathrm{true}}_{\mathrm{T,\,ch\,jet}} < 60$ GeV/$c$.

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