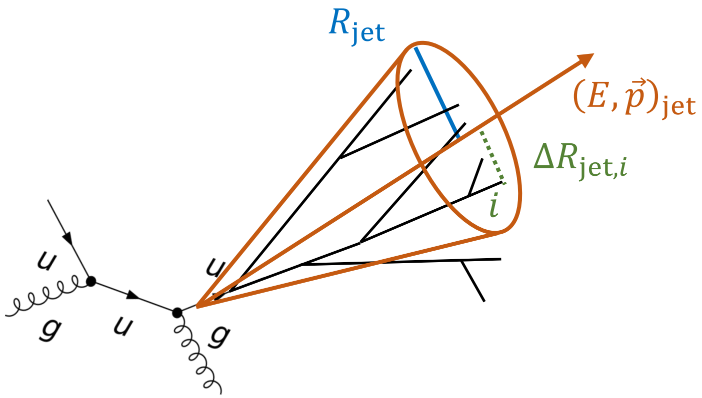
Exploring medium modifications to jet substructure in heavy-ion collisions



Ezra D. Lesser (CERN)
on behalf of the ALICE collaboration

14th International Workshop on MPI@LHC
22 November 2023
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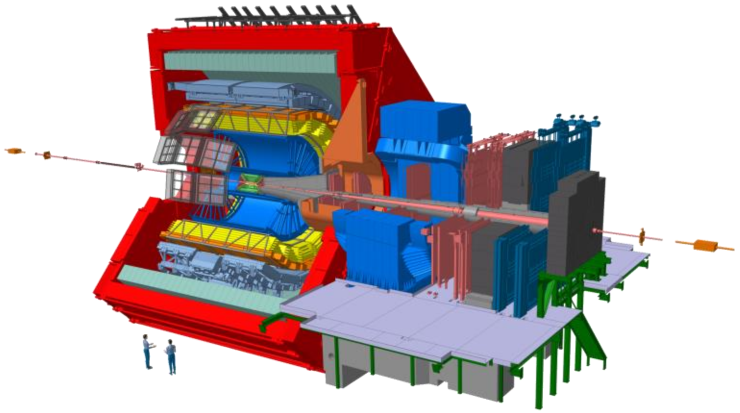
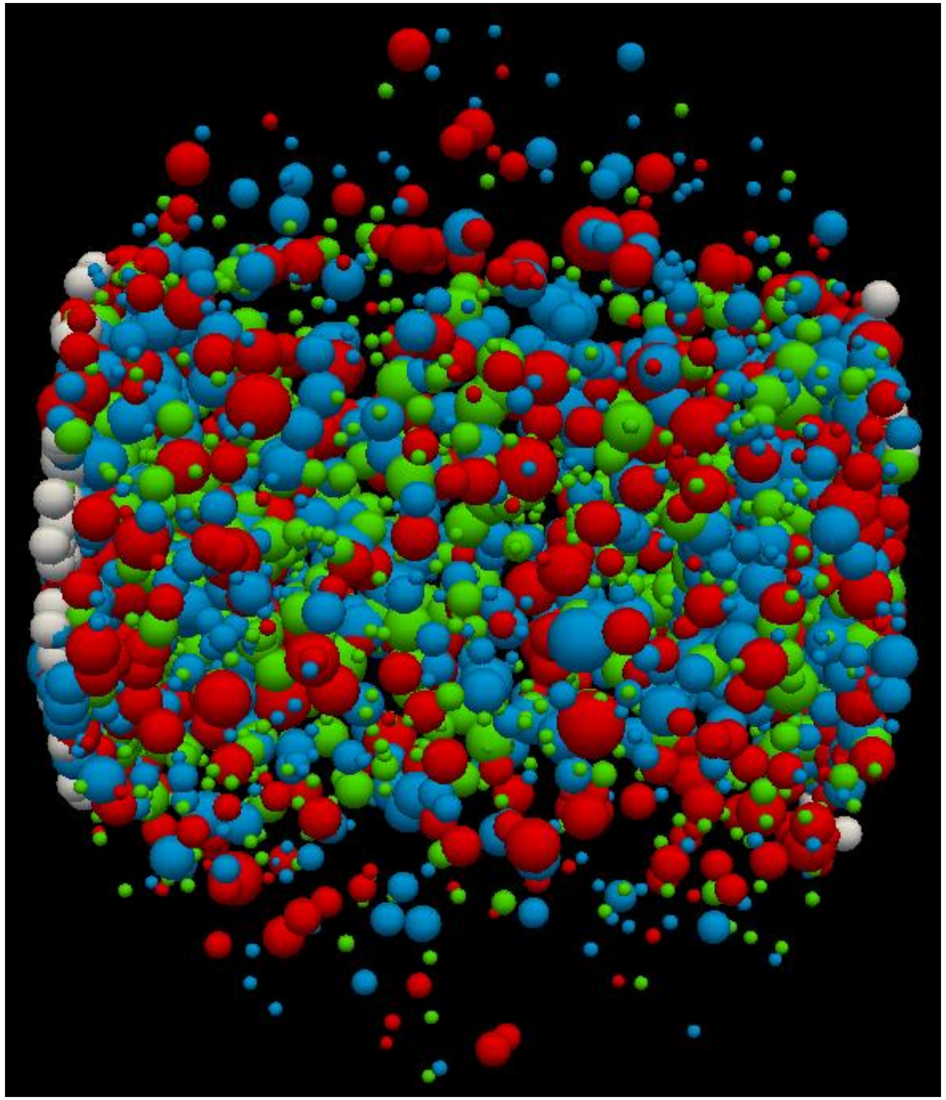
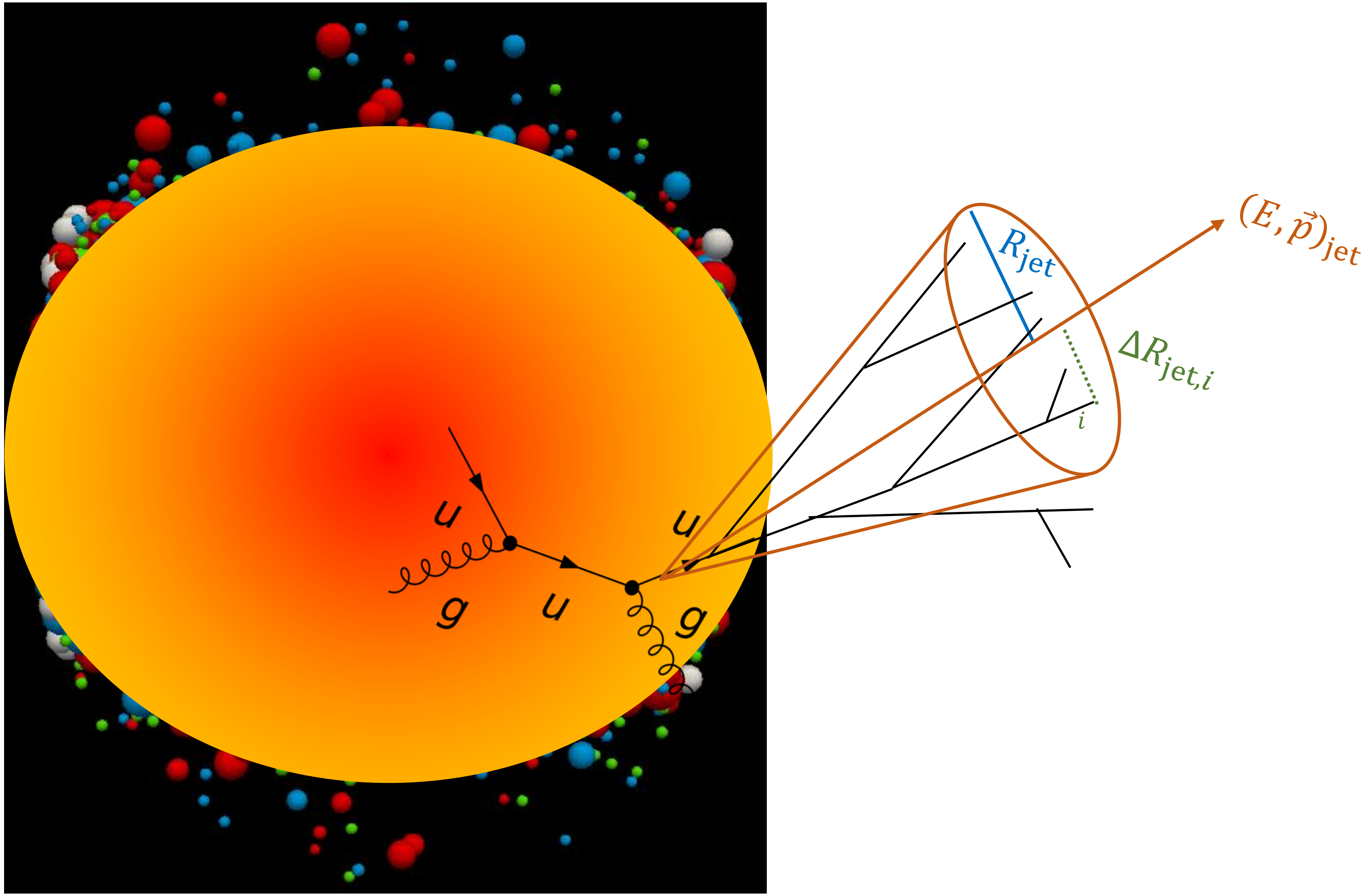
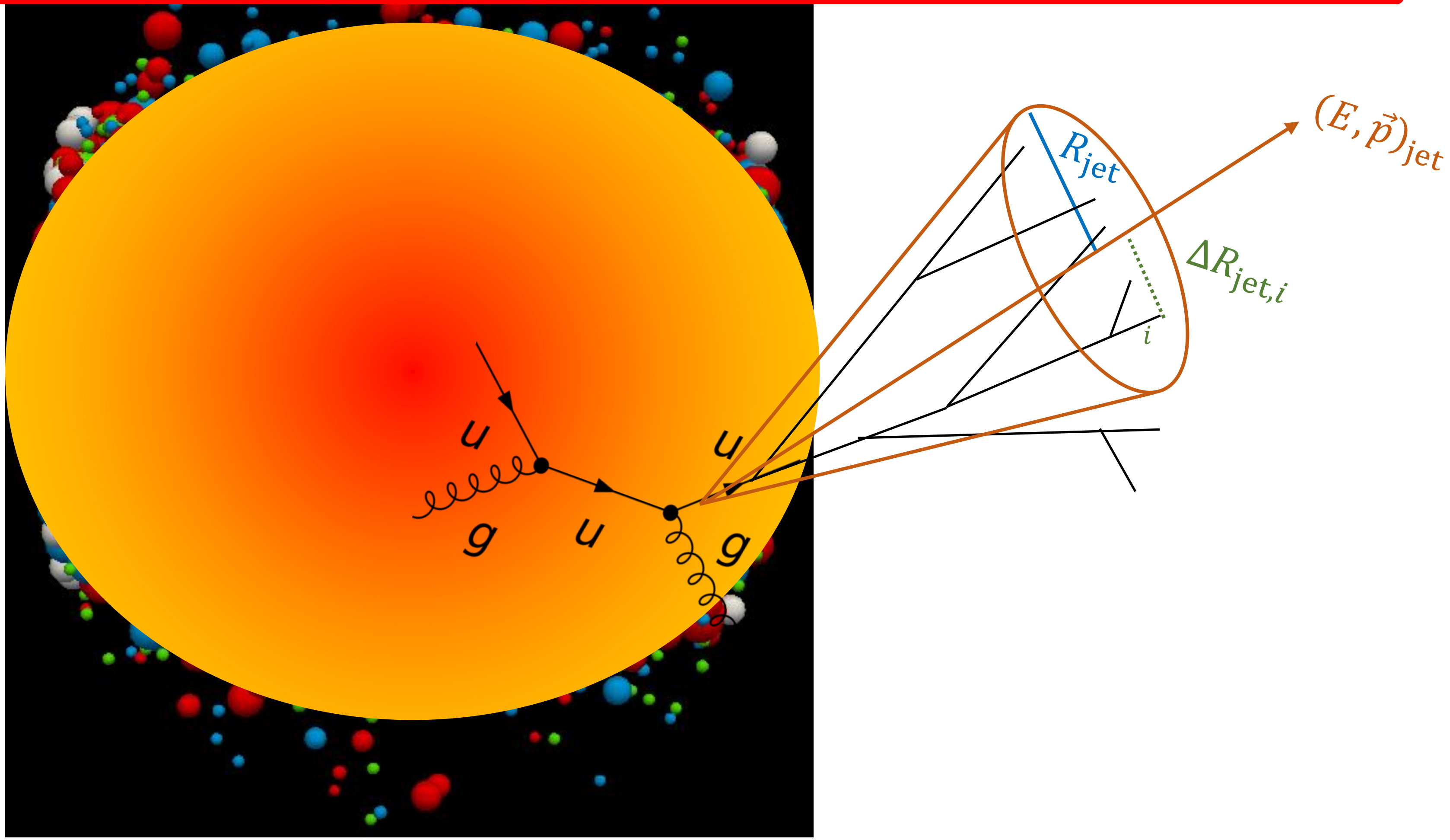




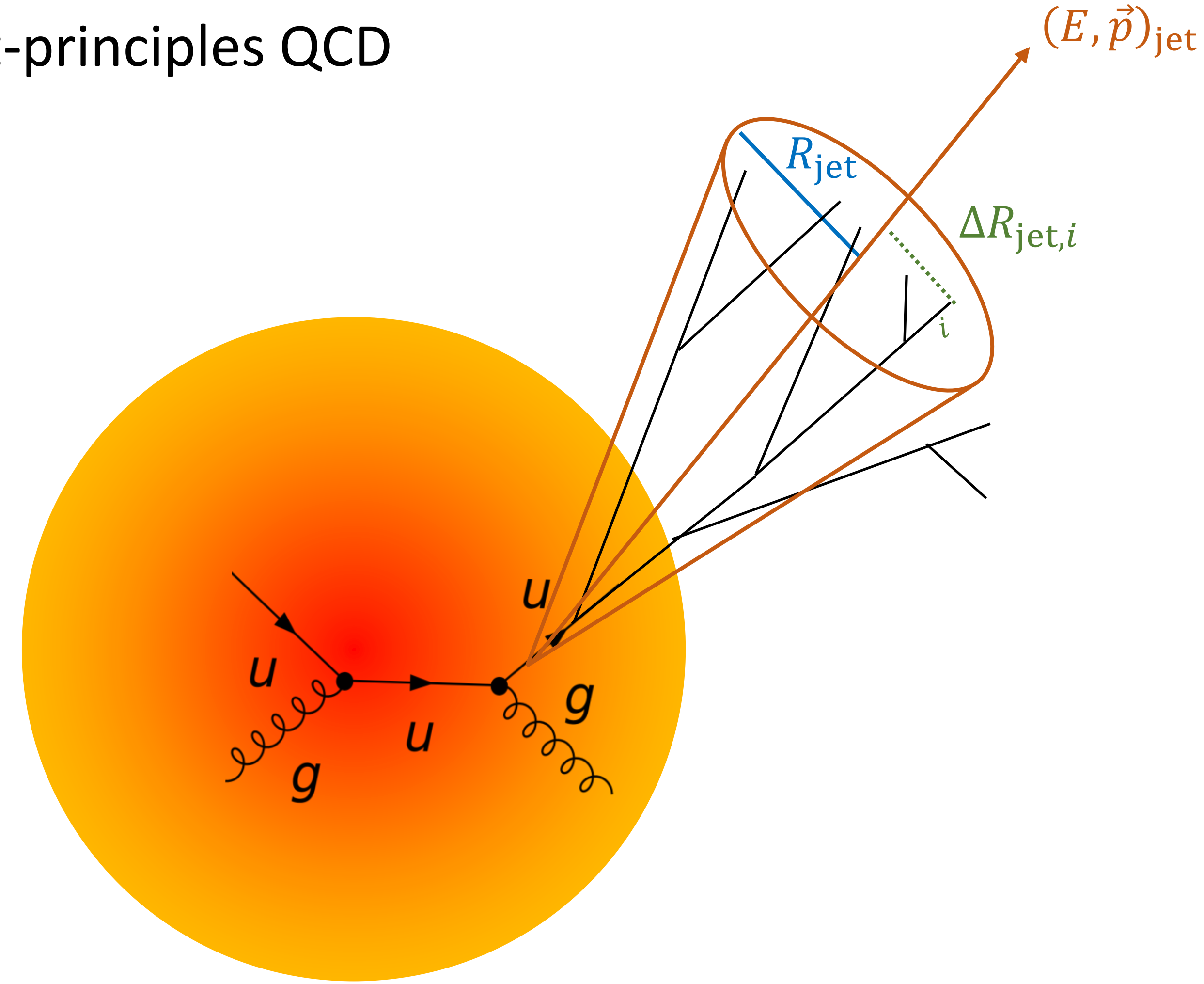

u
g
u
u
g
R_{jet}
$(E, \vec{p})_{jet}$
$\Delta R_{jet,i}$
i

What can we learn about QCD from the jets produced in heavy-ion collisions?



Many-body QCD with jet-medium interactions

- **Very challenging to study!**
  - Dynamics never (yet) derived from first-principles QCD
  - Competing phenomenological effects



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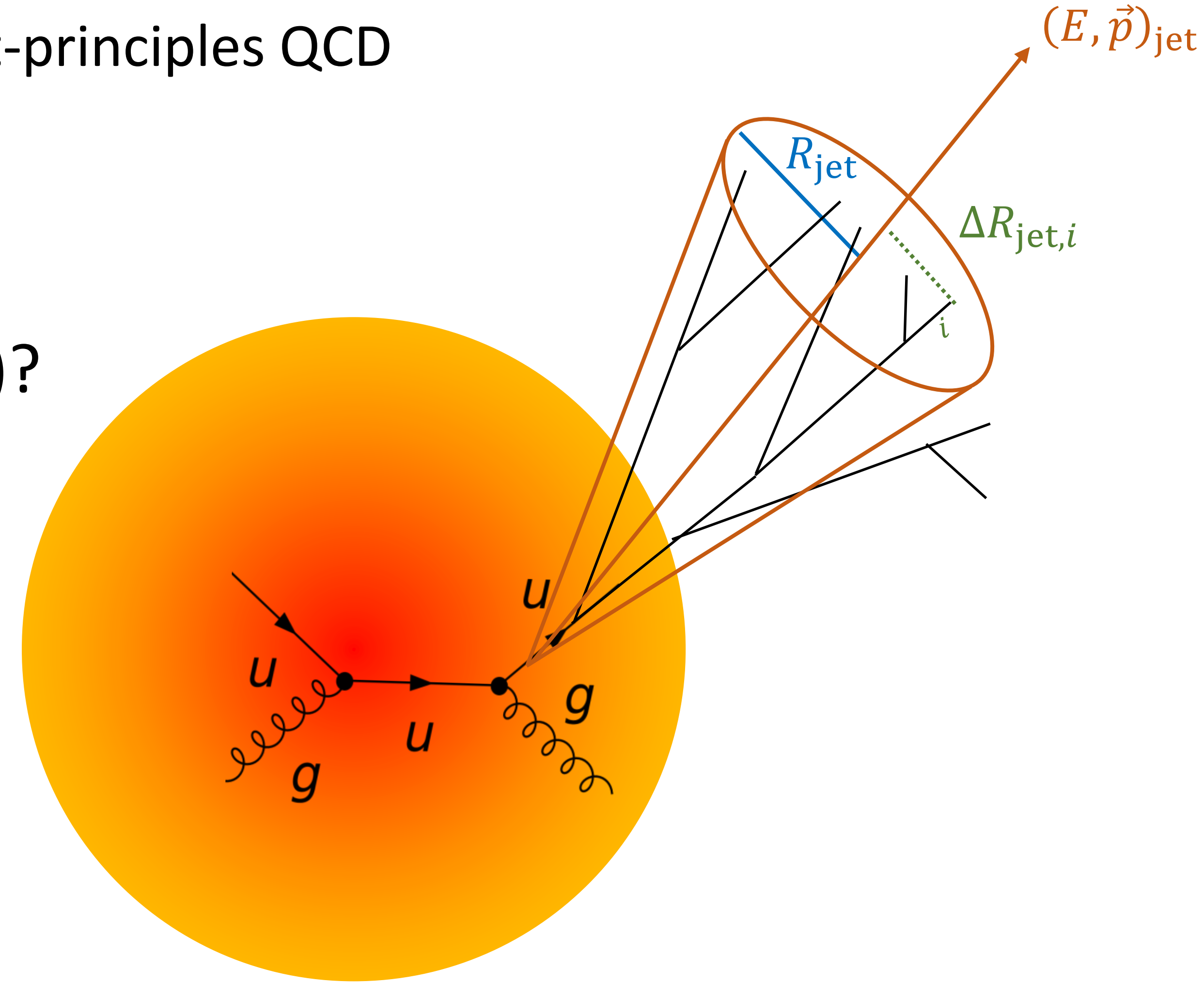

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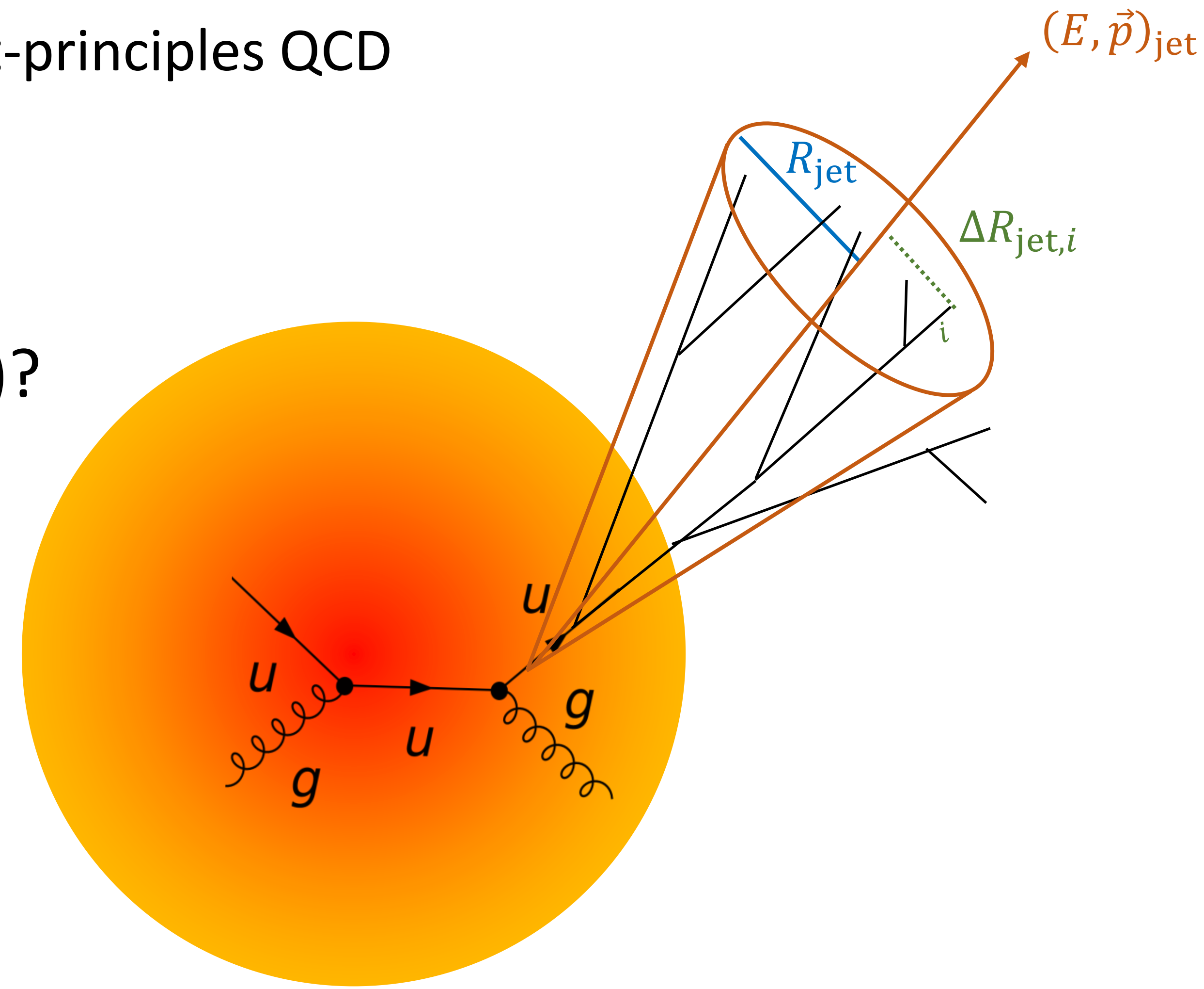

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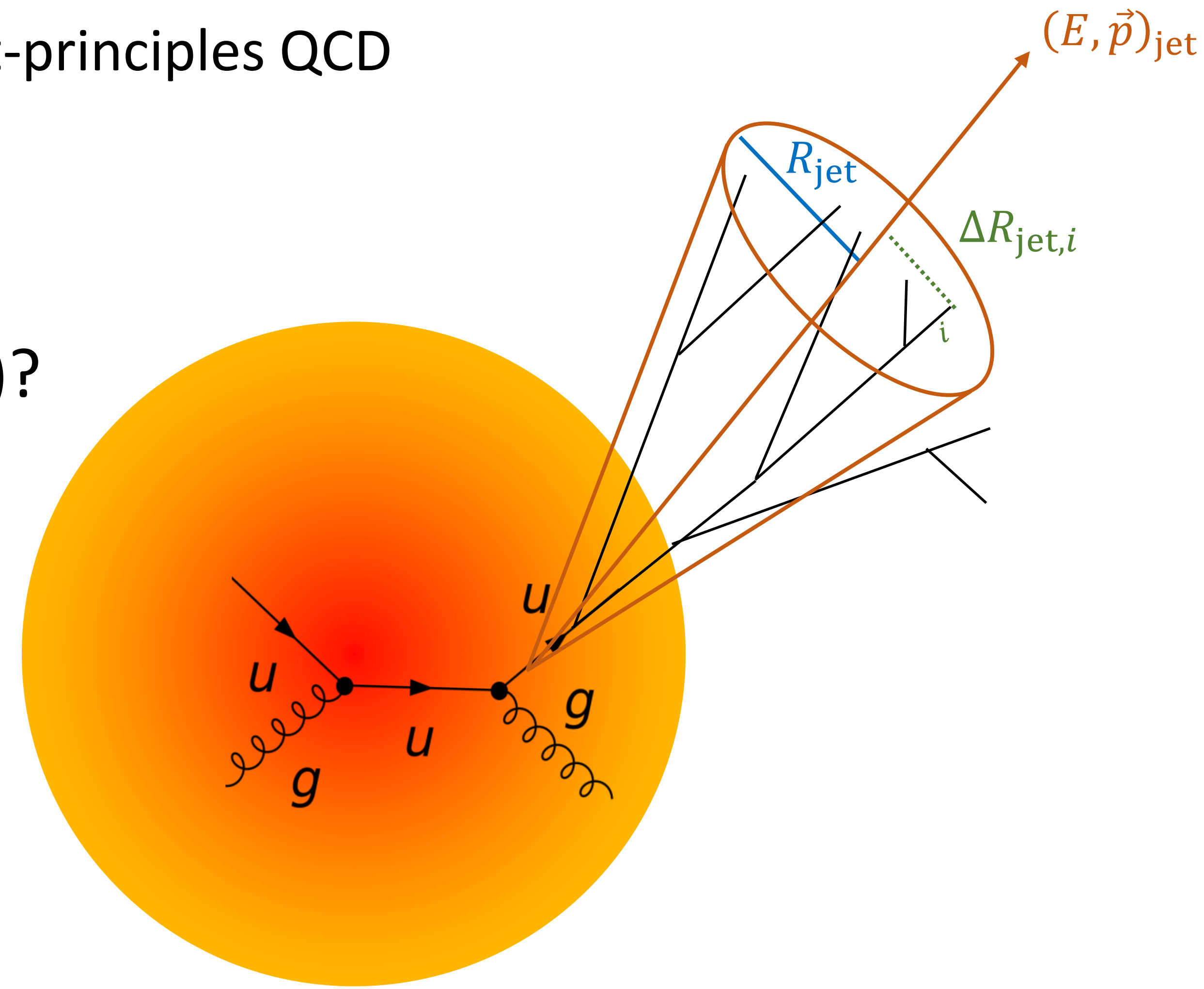

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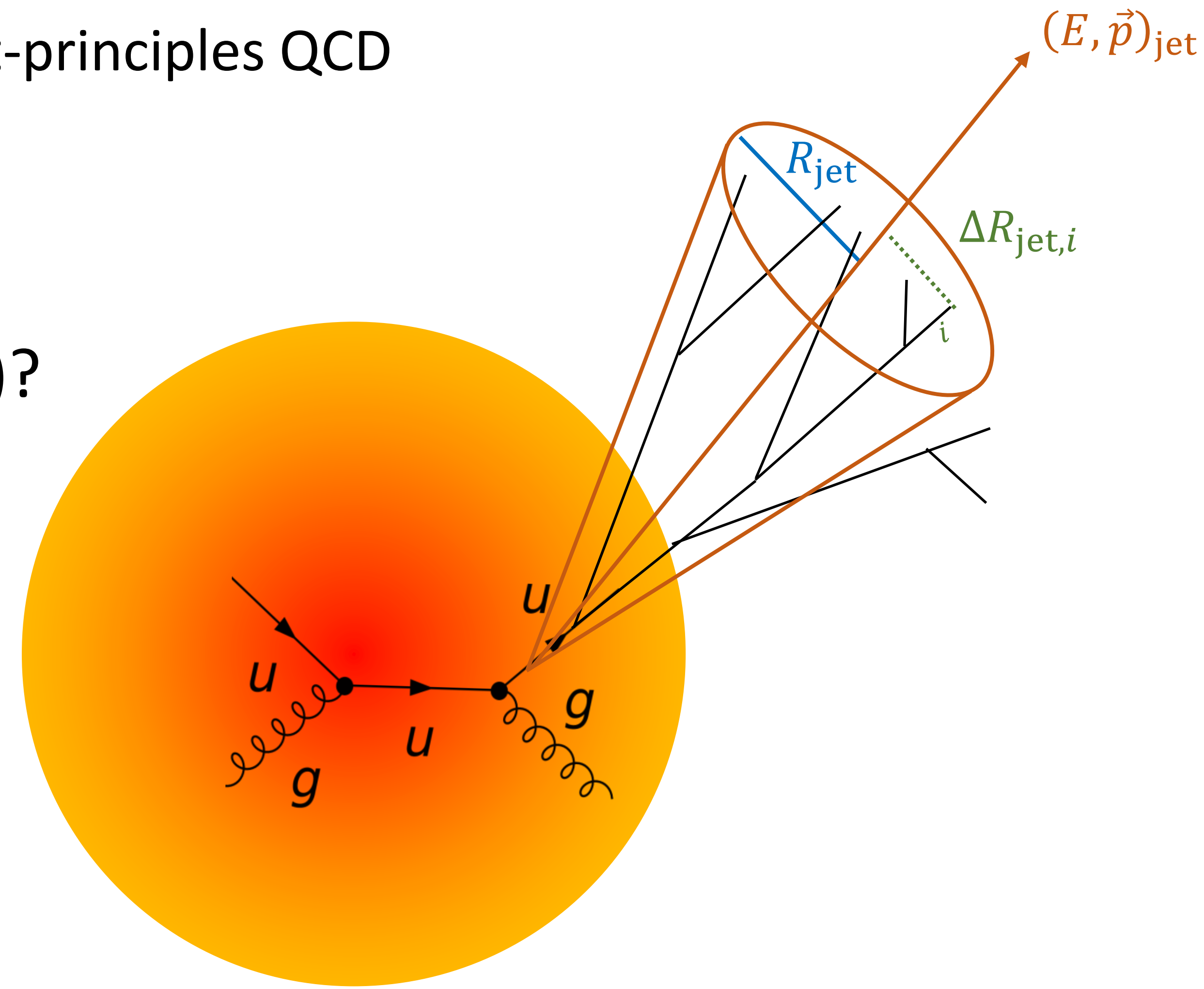

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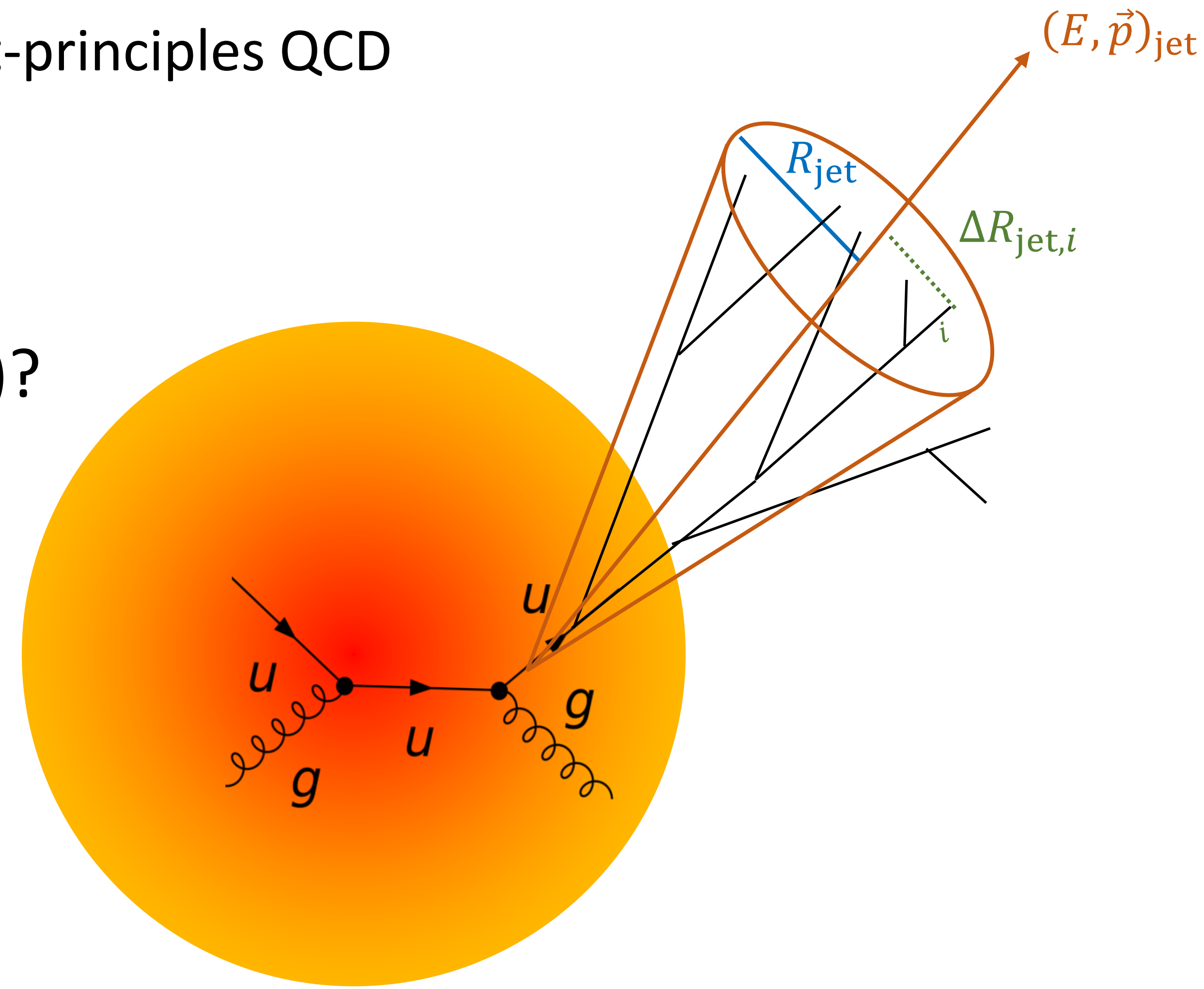

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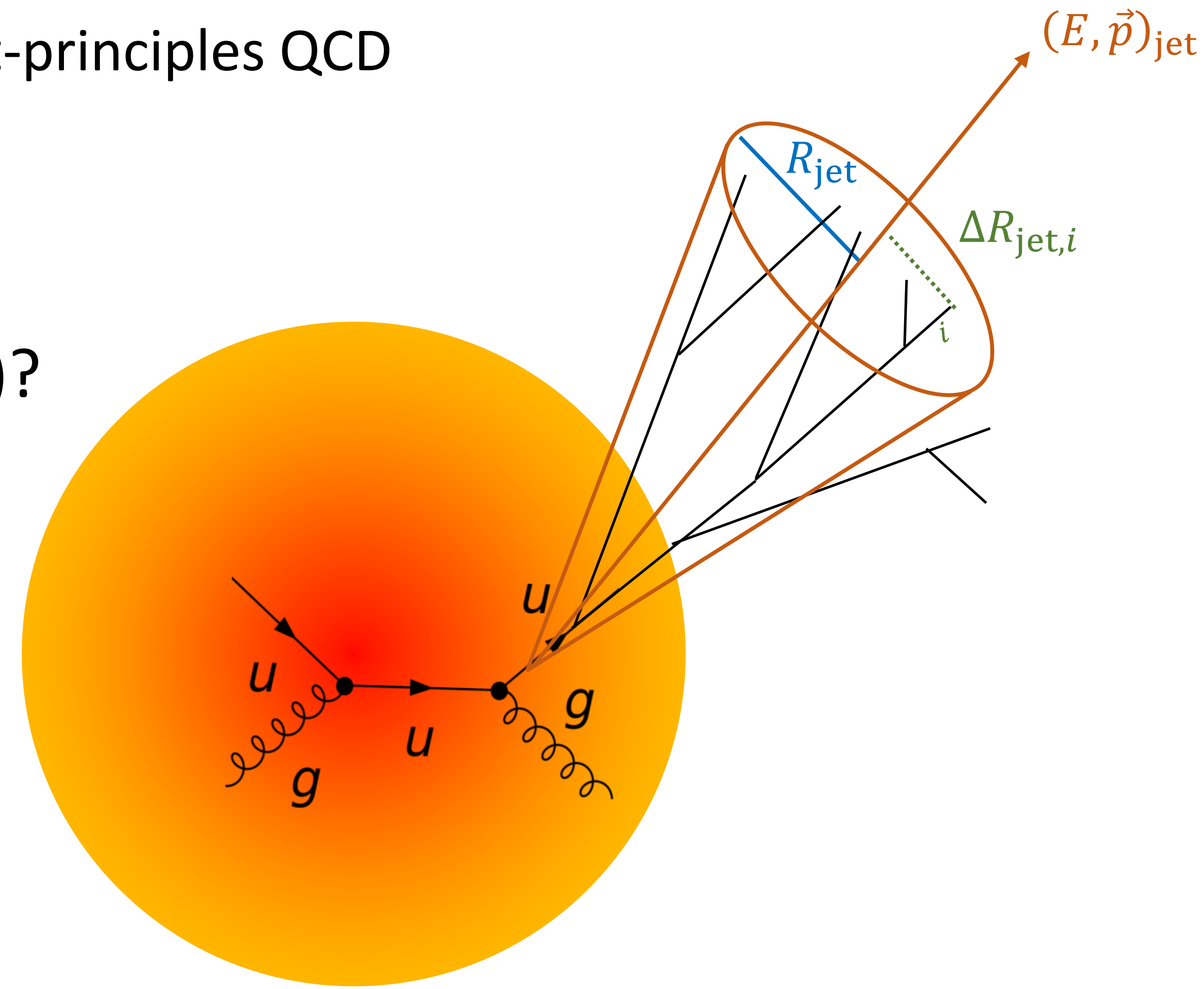

In-medium jet modification

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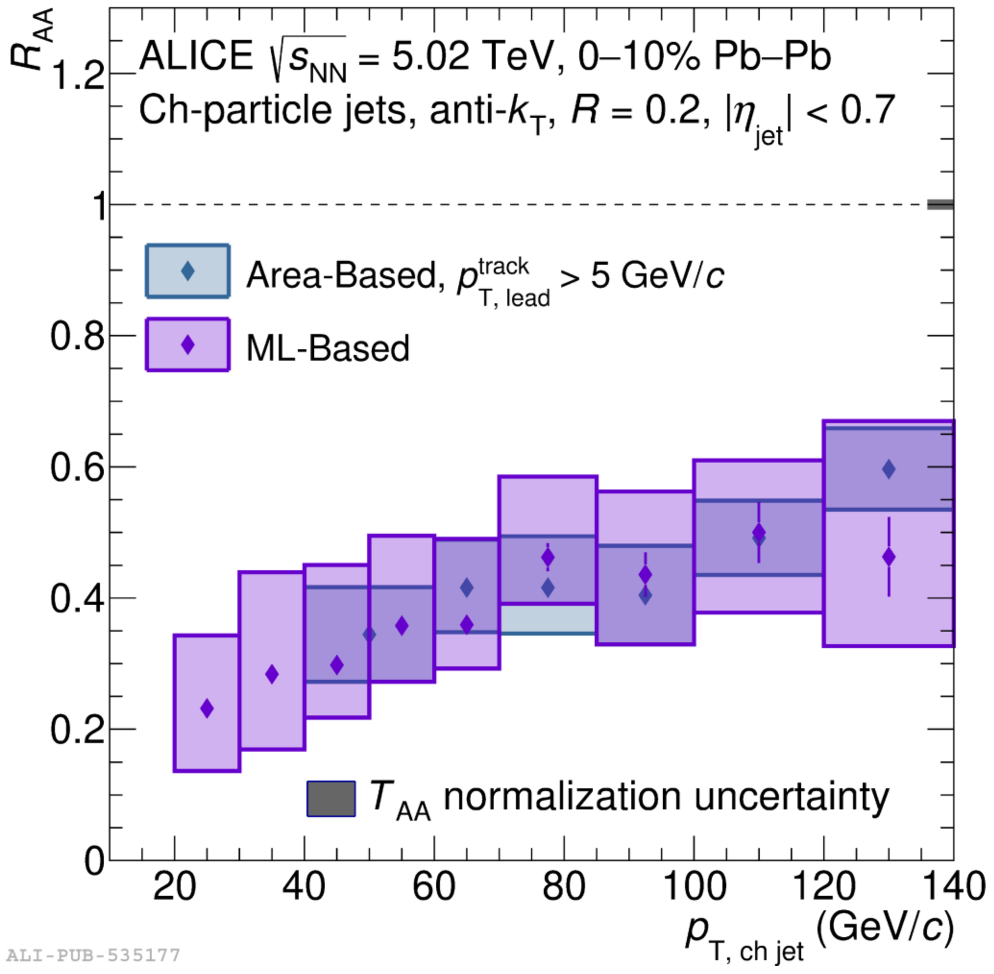

ALICE Collaboration
arXiv:2303.00592 [nucl-ex]

$$R_{AA} \sim \frac{\text{jet yield in AA}}{\text{jet yield in pp}}$$

- $R_{AA} < 1 \quad \rightarrow \quad$ **jets are "quenched"**

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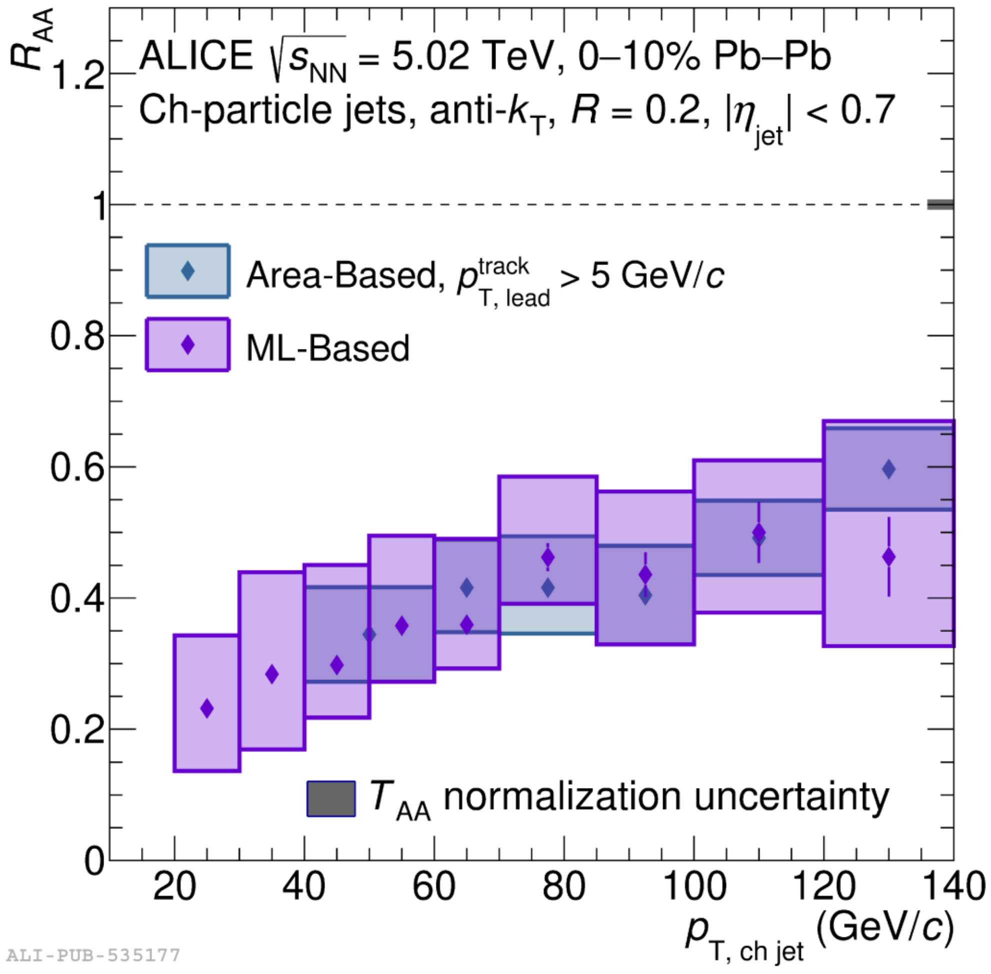

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- How does jet quenching affect **jet fragmentation** inside the plasma?

In-medium jet modification

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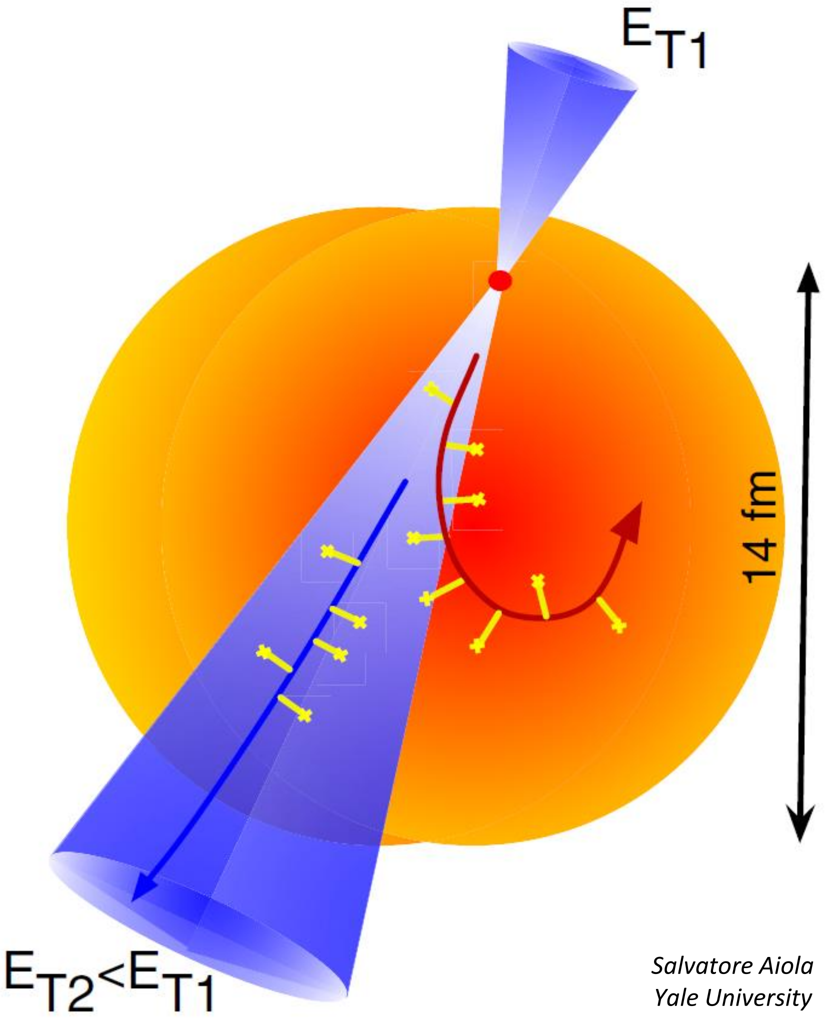

Salvatore Aiola
Yale University

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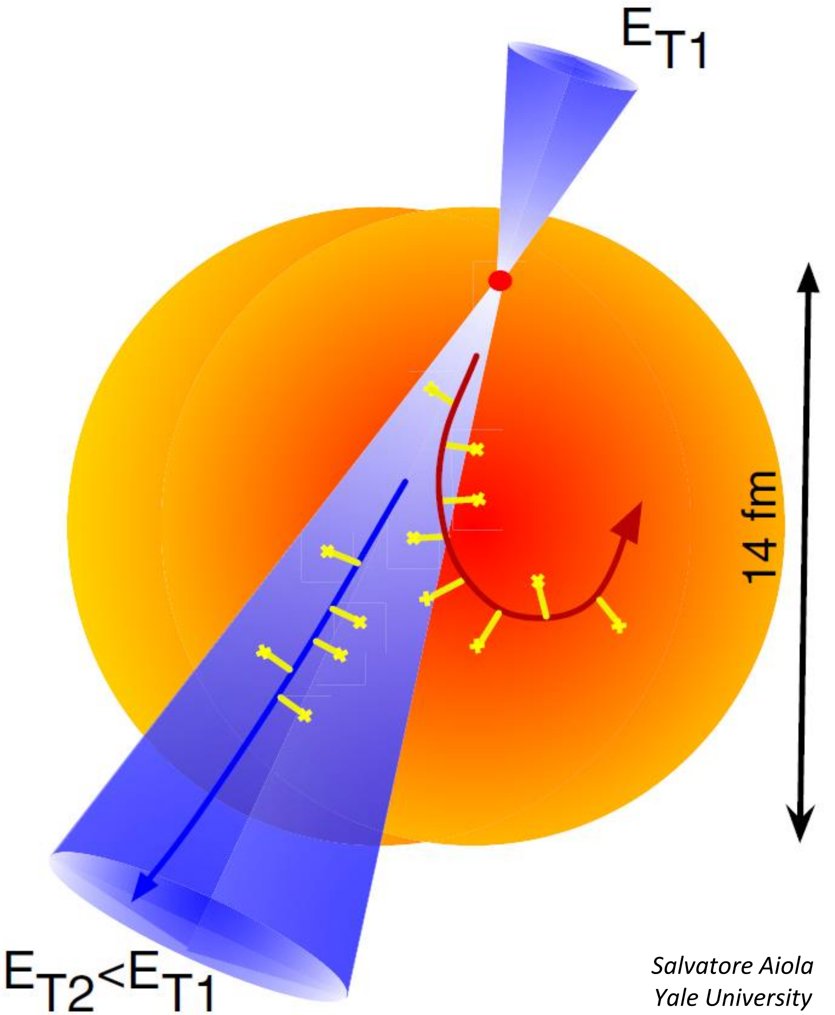

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- **Jet substructure** gives insight into the microscopic modification

- Choose observables based on desired probe

Generalized jet angularities ($\lambda_{\alpha}^{\kappa}$)

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

- **Class of substructure observables** dependent on $\boldsymbol{p}_{\mathbf{T}}$ and **angular** distributions of jet constituents

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

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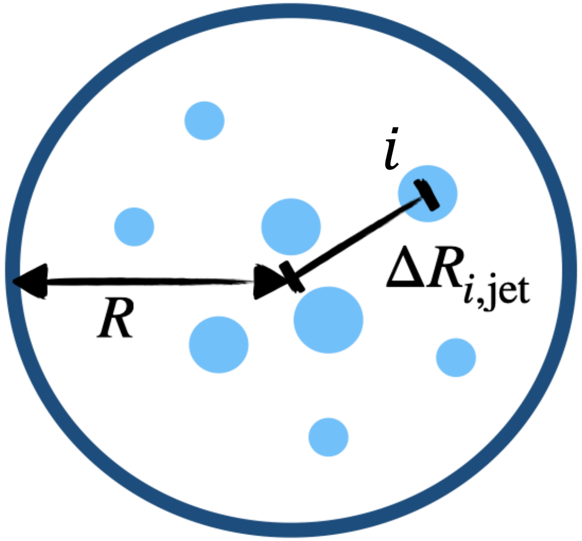
Constituent p_T



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Tunable, continuous parameters for relative weighting

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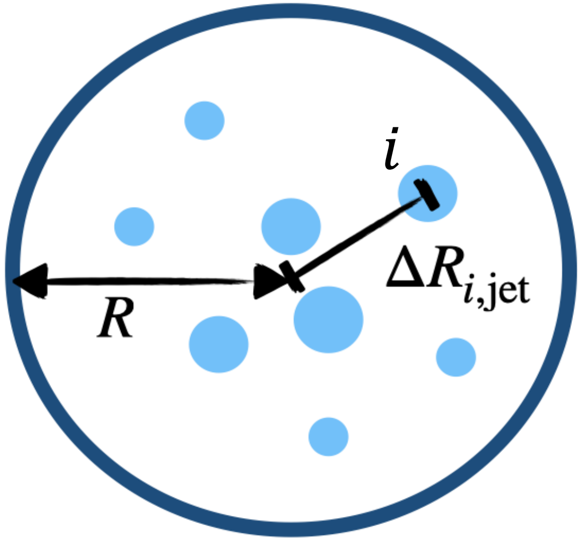

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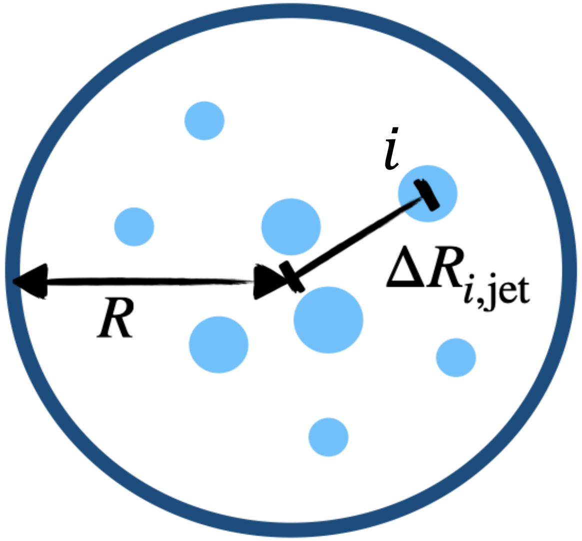
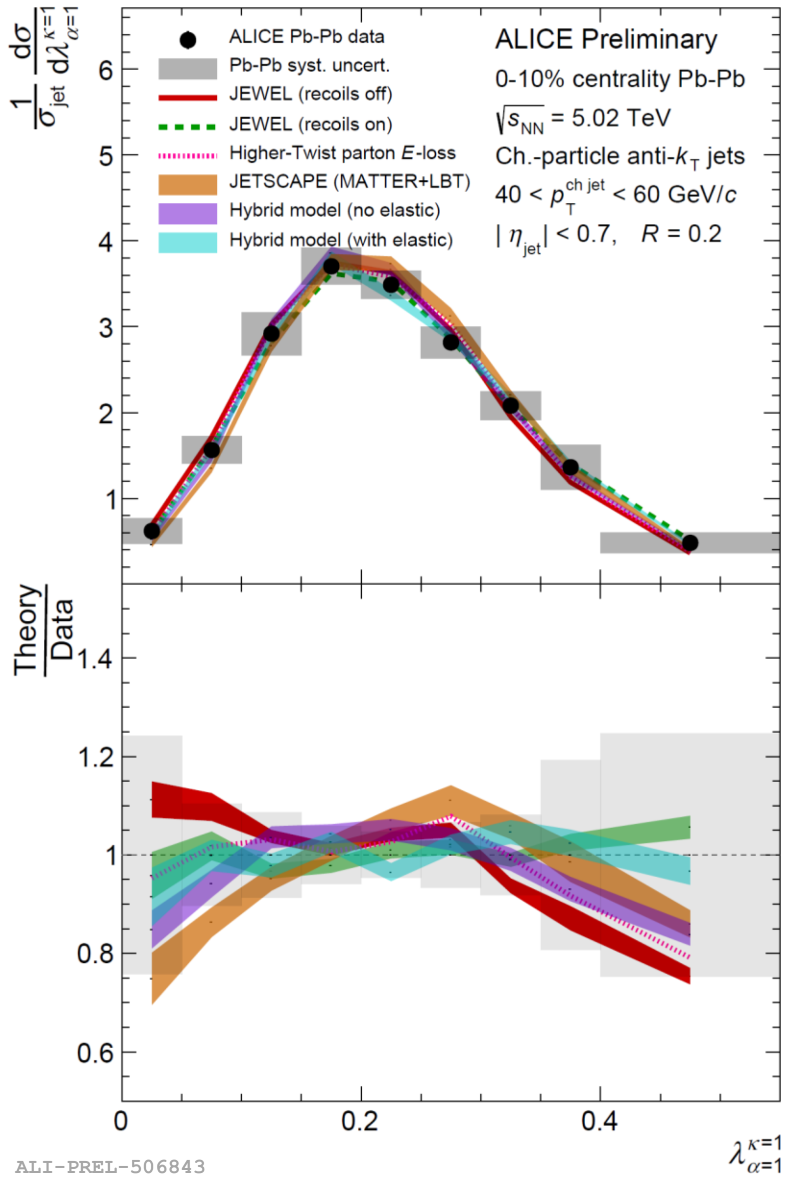


- IRC-safe* observable for $\kappa = 1$, $\alpha > 0$ → vacuum is calculable from pQCD
- Each (κ, α), R defines a different observable capable of probing jet structure and providing systematic constraints on theory
- Generalizes other observables: **jet girth** $g = \lambda_1^1$; **jet thrust** $= \lambda_2^1$; …

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

Pb-Pb angularities compared with models

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



https://alice-figure.web.cern.ch/node/21570

- **JEWEL** with recoils off / on
  - "Recoils on" uses negative energy recombiner scheme

  K. Zapp, JHEP 1804 (2018) 110

- **JETSCAPE (MATTER + LBT)**

  arXiv:2204.01163 [hep-ph]

- **Higher-Twist partonic energy loss**

  S.-Y. Chen, B.-W. Zhang, et al., CPC 45 (2021) 2, 024102

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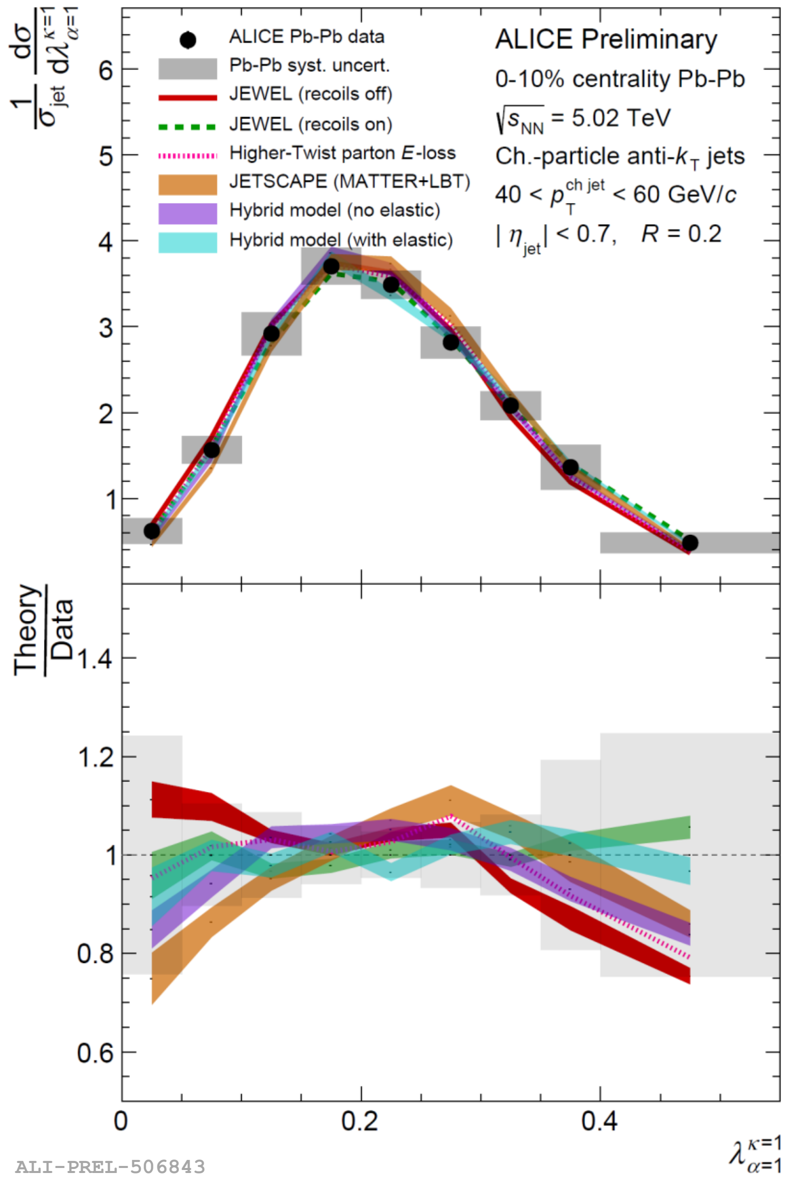

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- **Models are within uncertainties on Pb-Pb data…**

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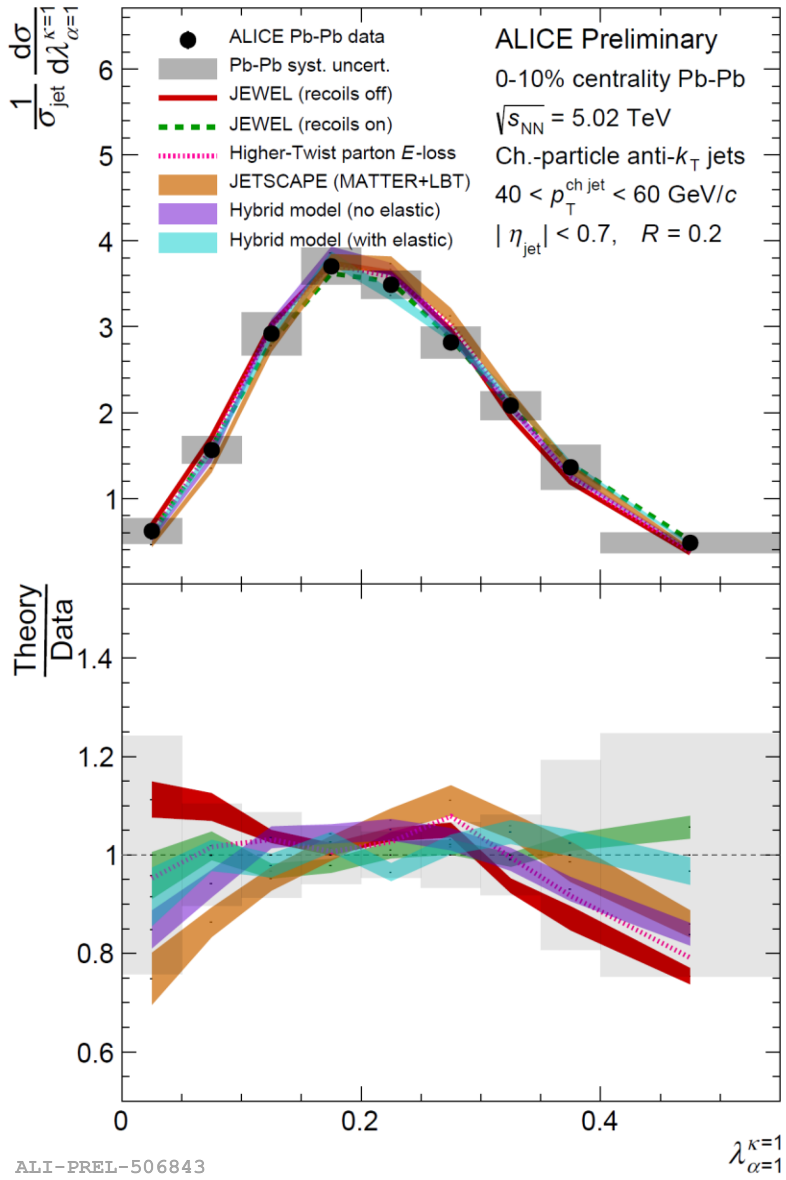

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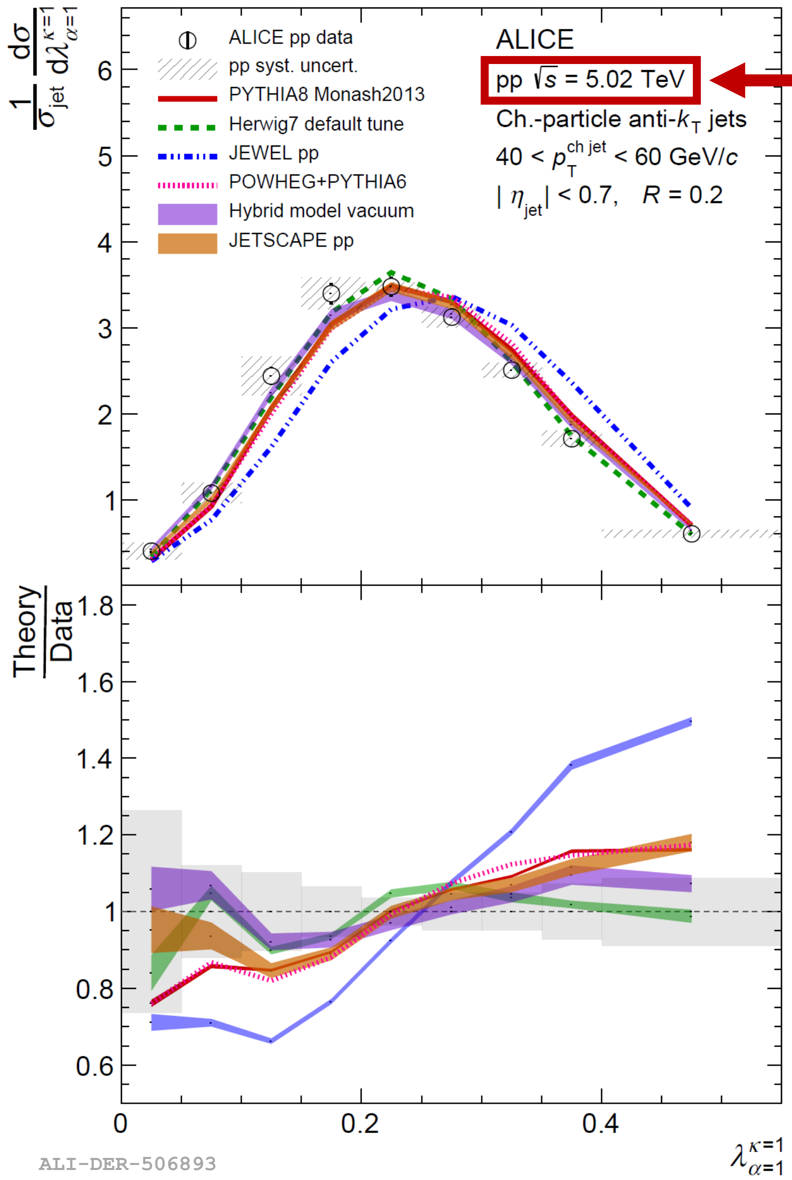

Run 2 pp baseline for AA quenching

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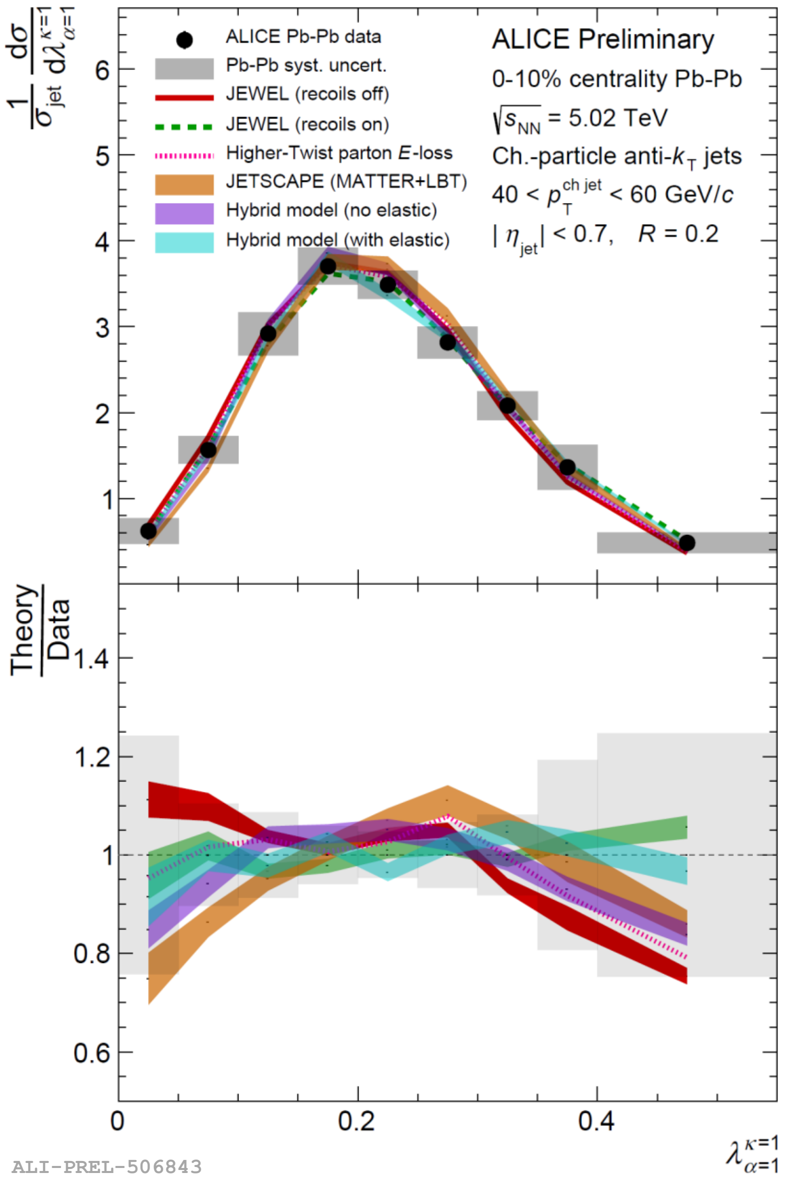

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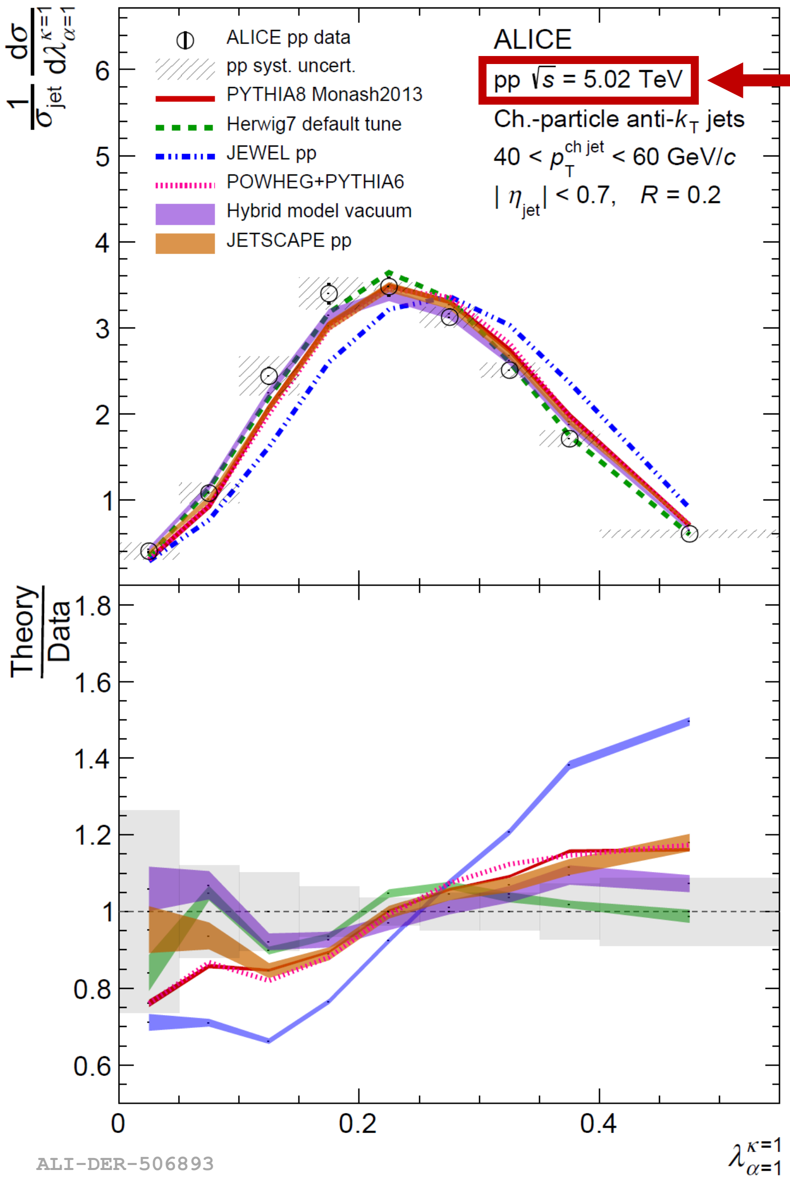

Run 2 pp baseline for AA quenching

Some models exhibit more tension in pp baseline than in AA

Pb-Pb angularities compared with models

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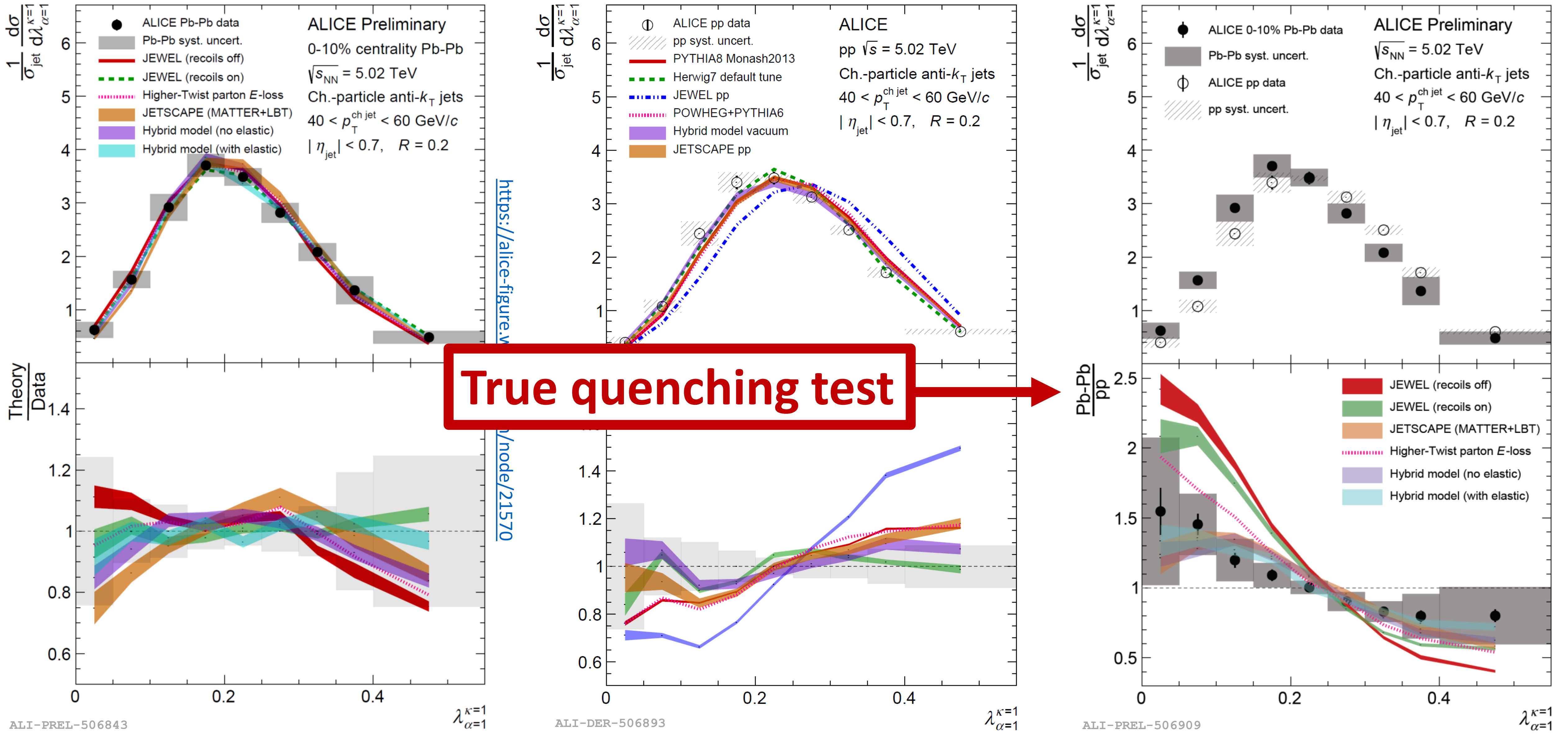

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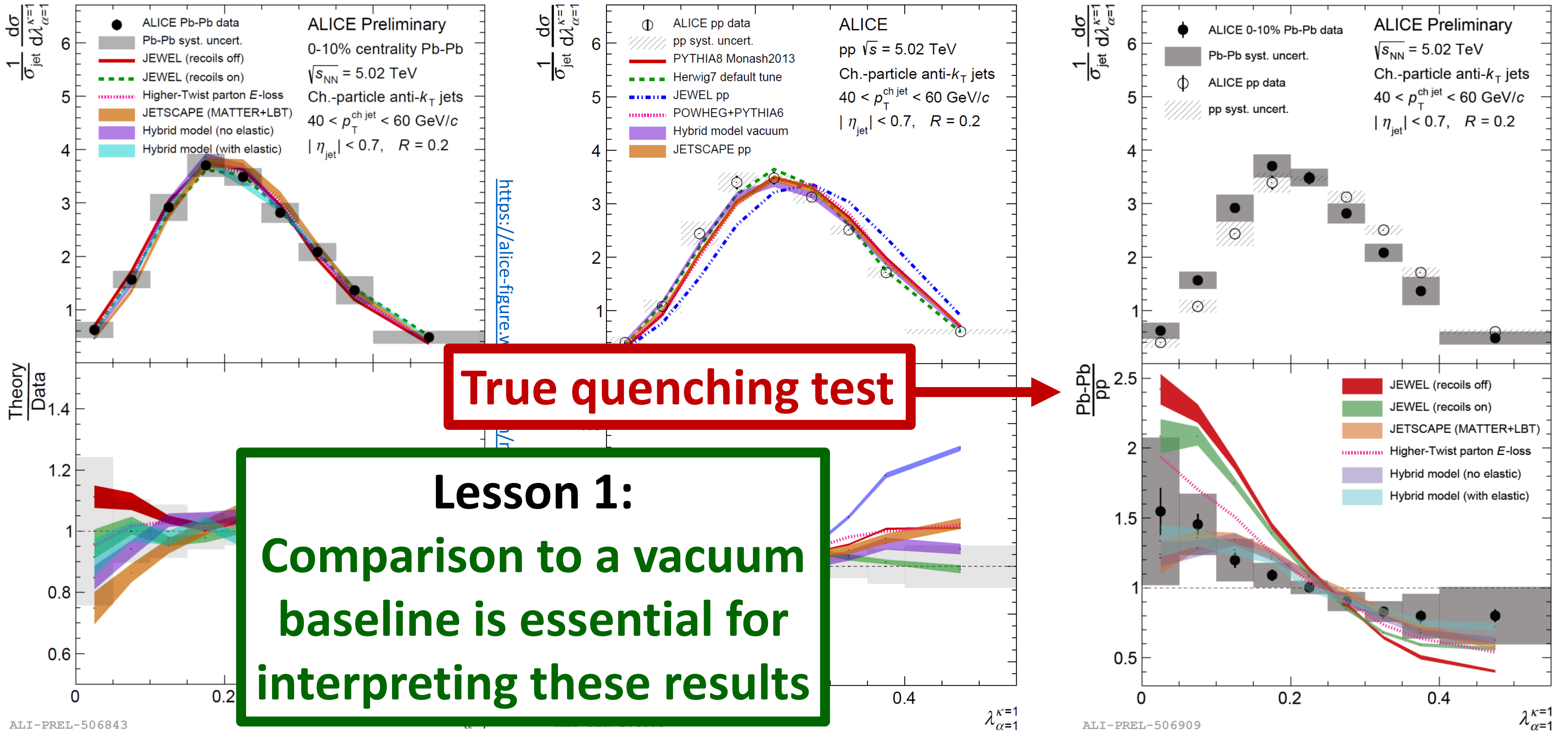


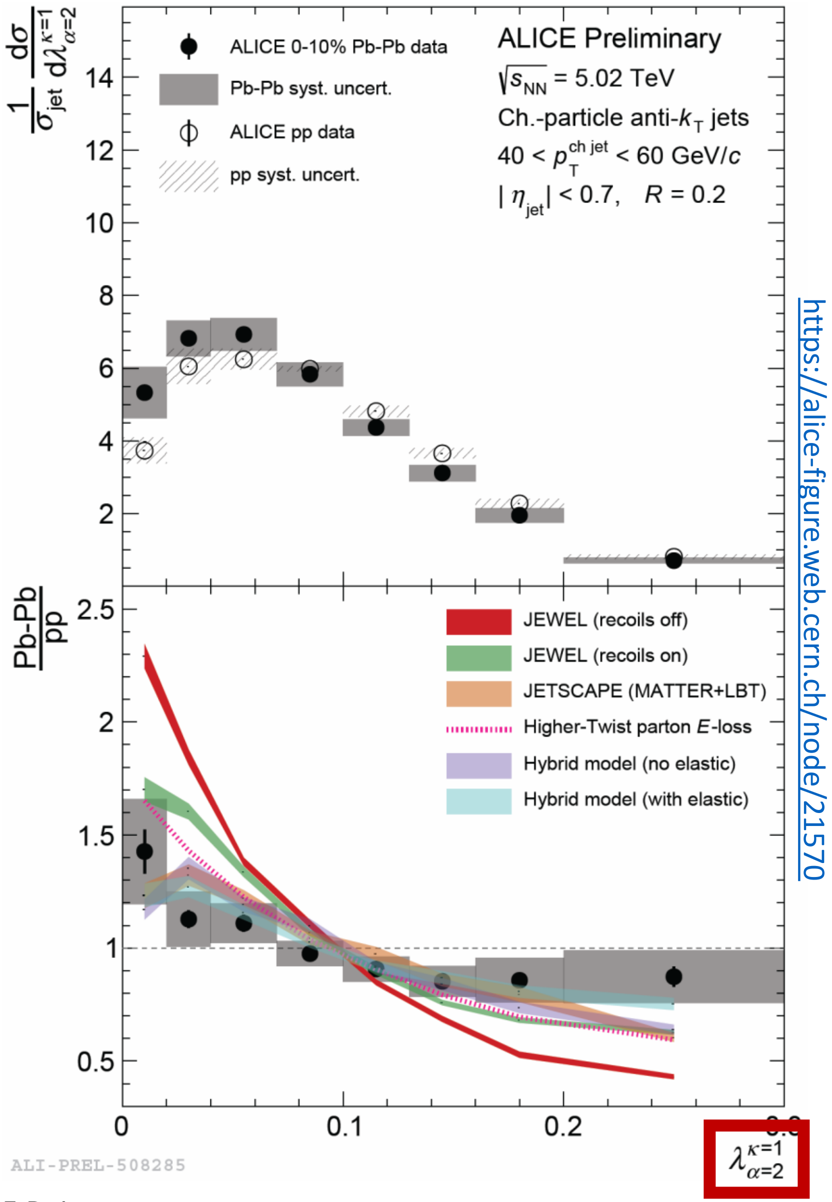
True quenching test

Lesson 1:

Comparison to a vacuum baseline is essential for interpreting these results

Pb-Pb thrust ($\alpha = 2$)

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



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Pb-Pb thrust ($\alpha = 2$) vs. jet mass

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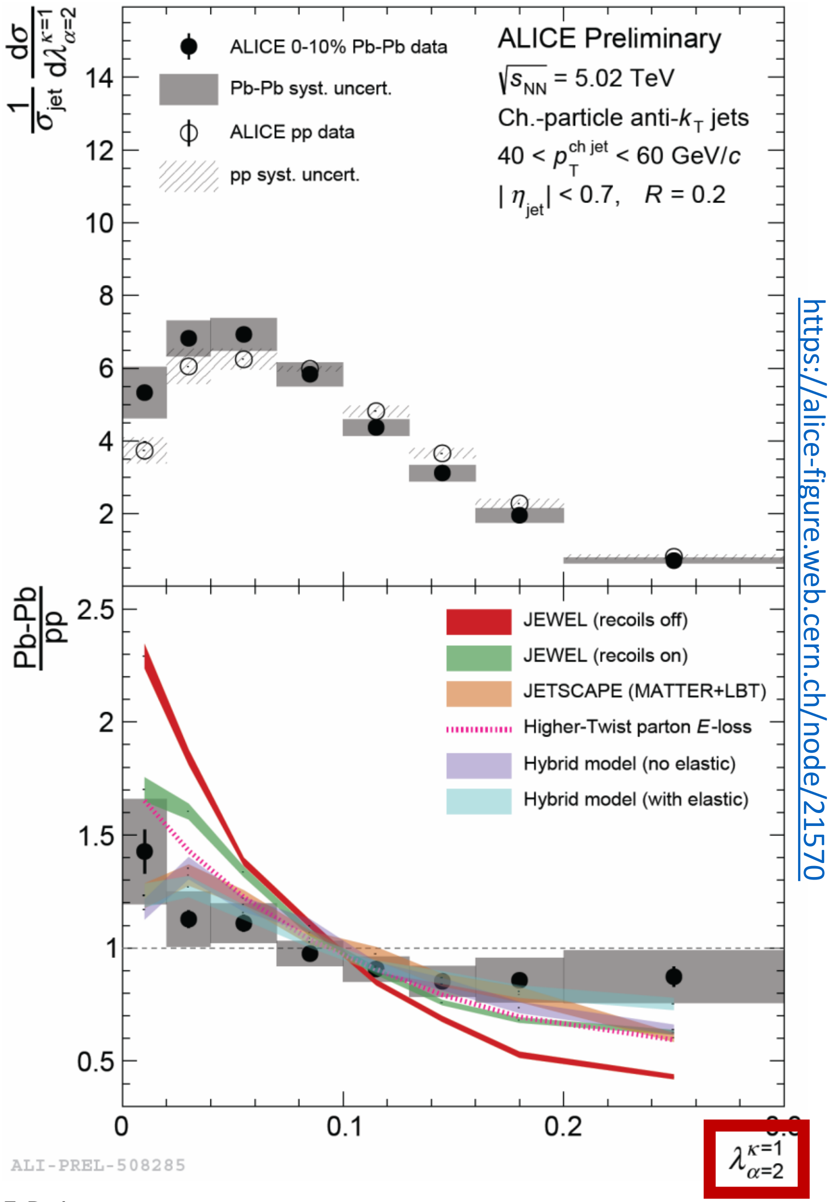

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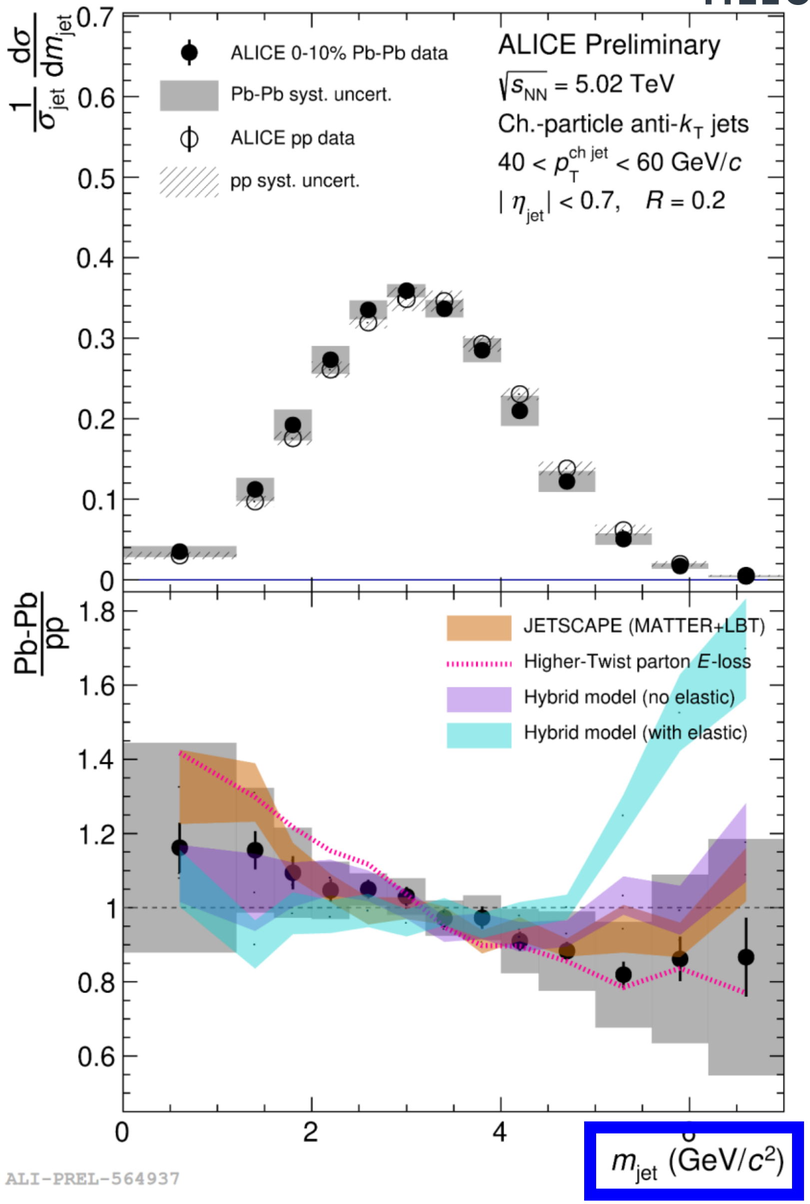

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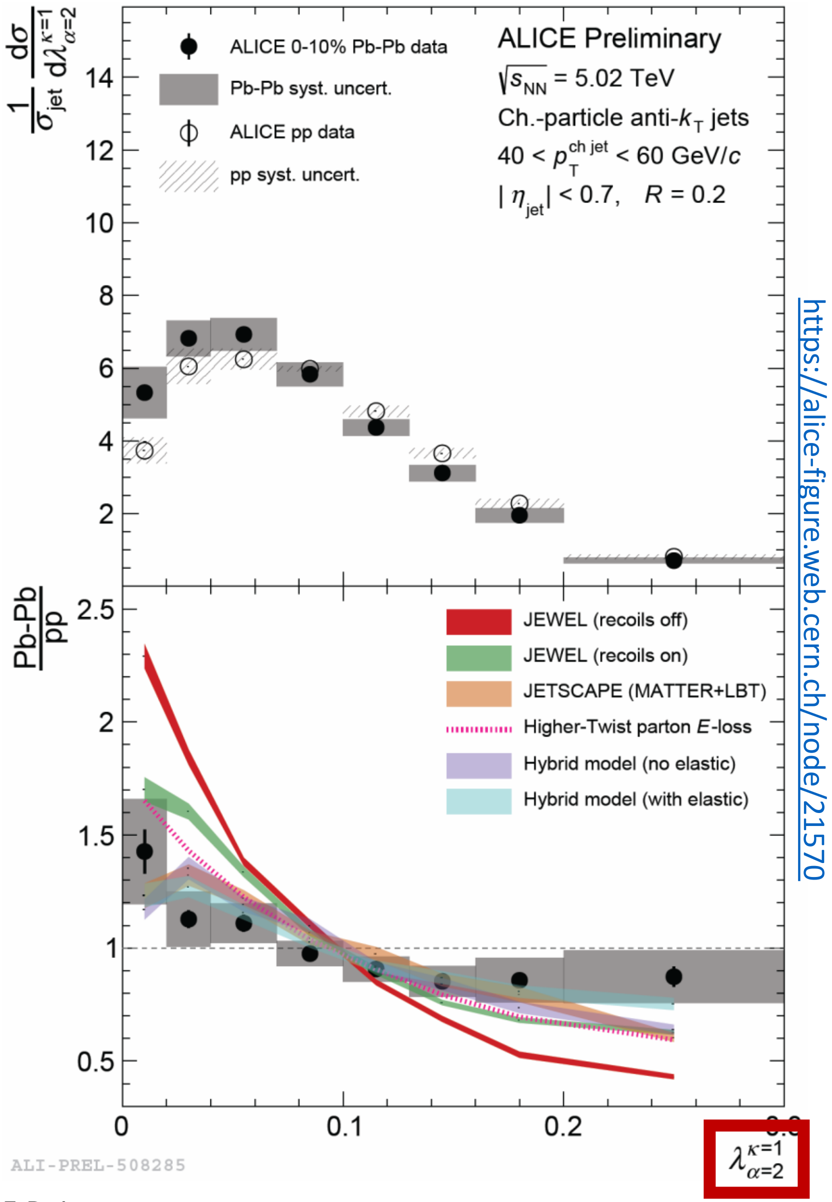

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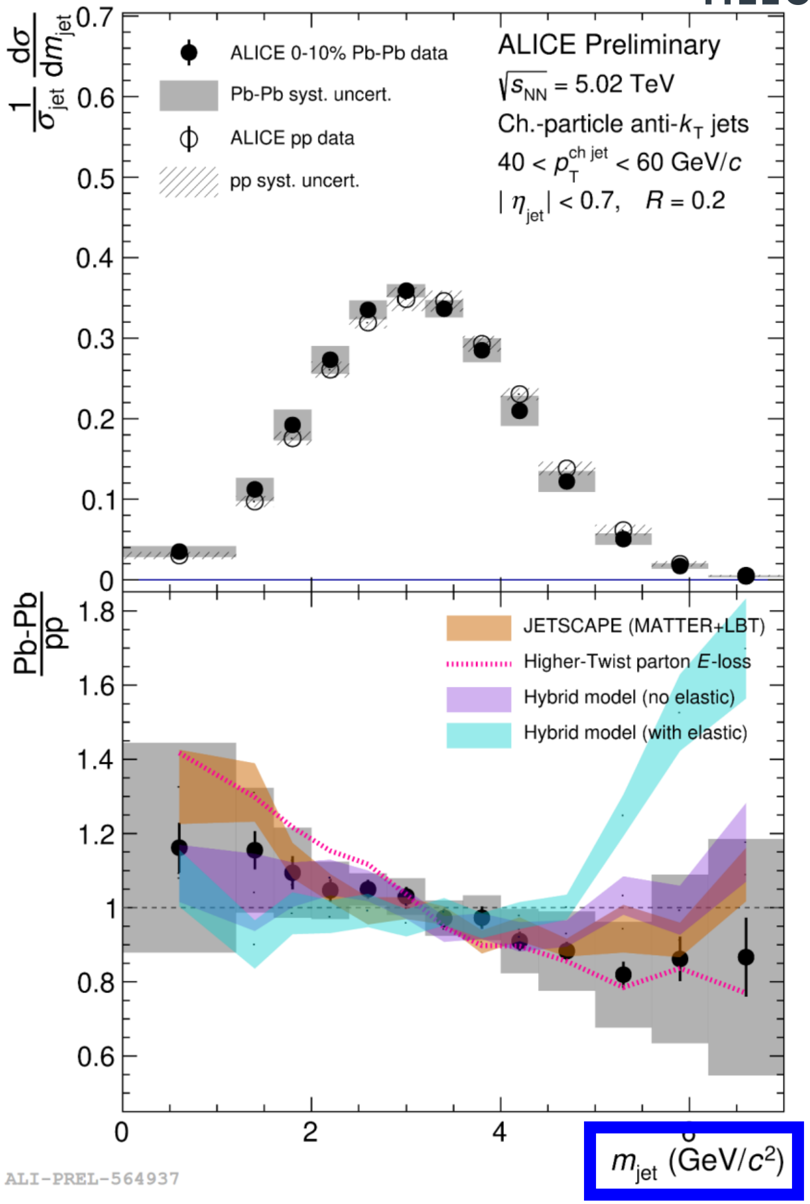
- **Differing behavior:** some models show **enhancement in $\bar{m}_\mathrm{jet}$** despite **suppression in λ_2**



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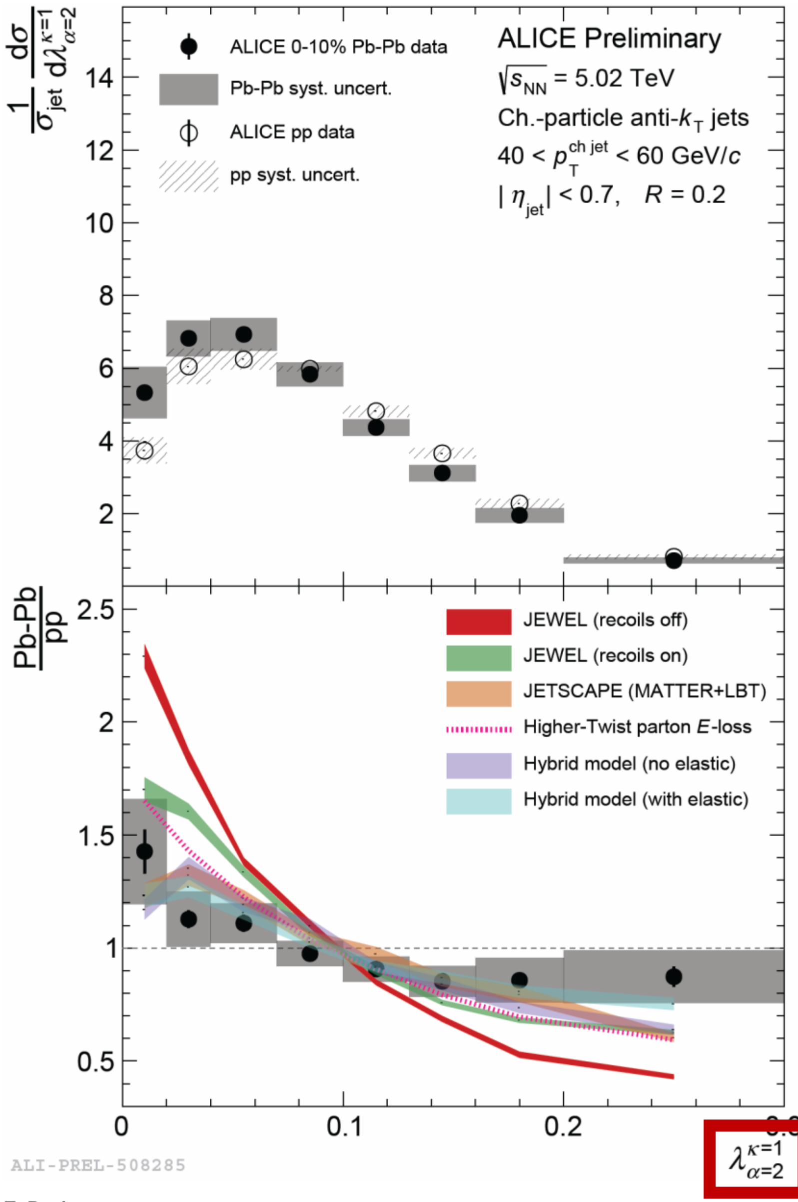

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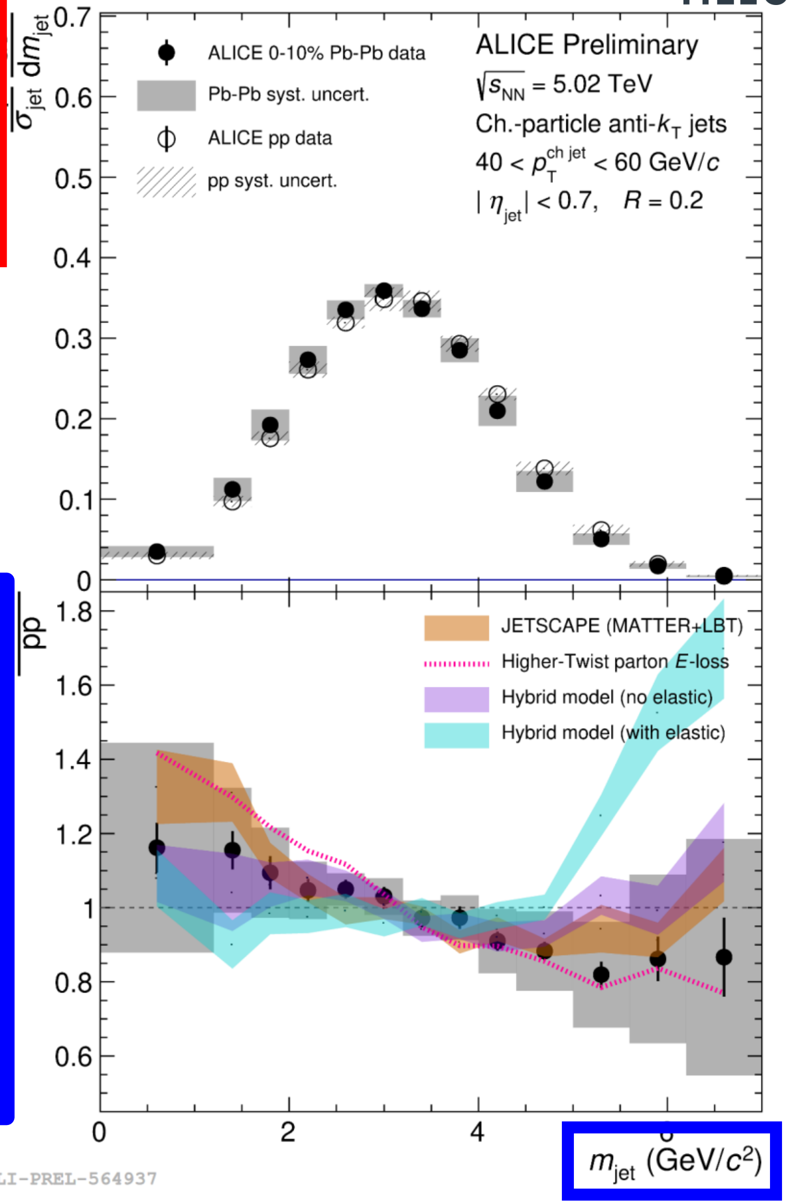
Not useful for low-p_T jets

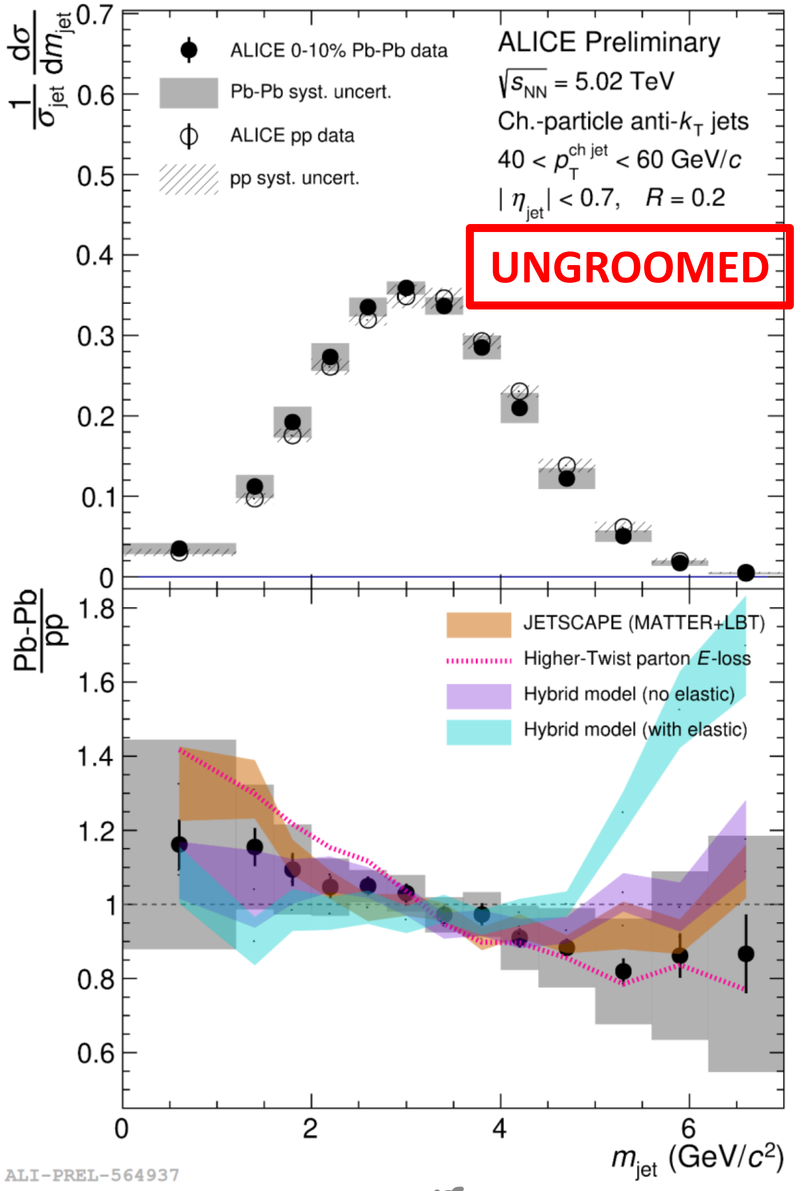
- **Resolves the girth-mass difference found in Run 1**

Lesson 2:

Closely related observables can have very different physics sensitivities

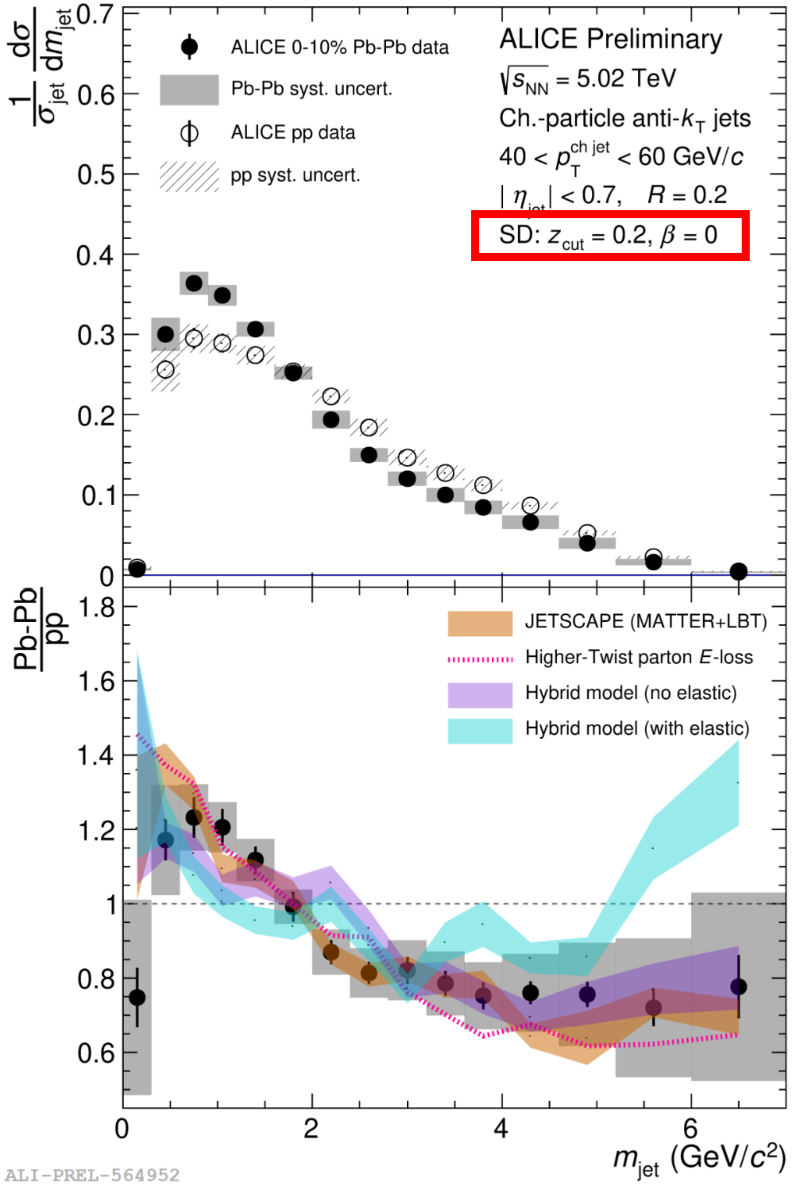


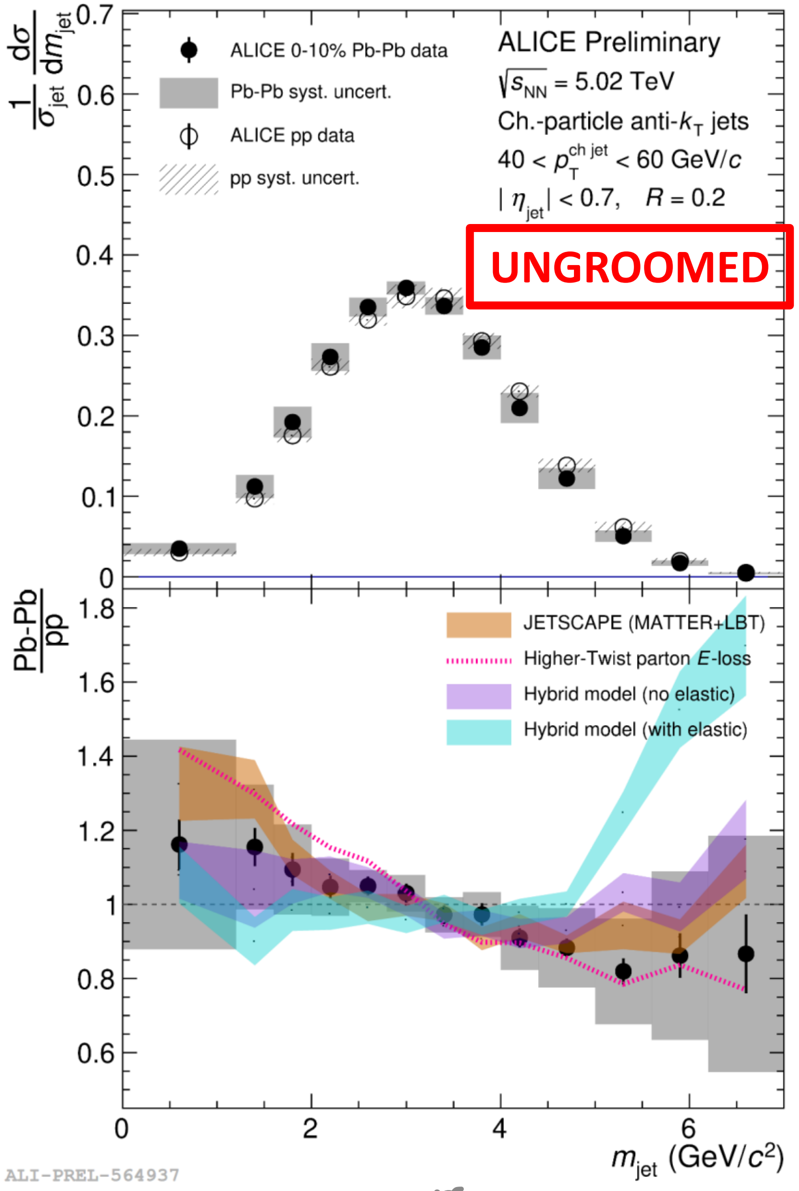
Quenched jet mass



- **What about the effects of jet grooming?**
  - Employ Soft Drop to remove soft, wide-angle radiation
  - Calculate mass using remaining constituents

Quenched jet mass





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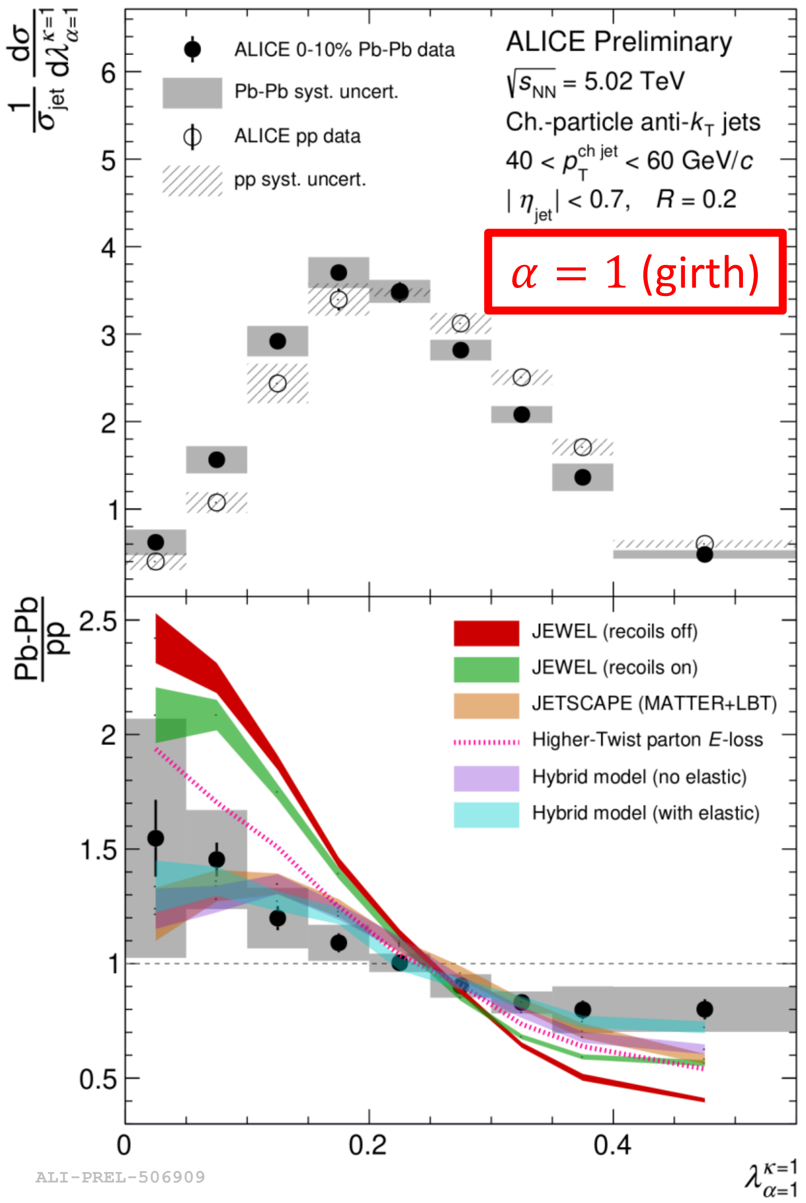
Lesson 3:

- **Hard jet core is strongly quenched**

- Possible interpretations:
  - Quark vs. gluon jets
  - SD removes soft background from jet

Angular dependence of jet quenching

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



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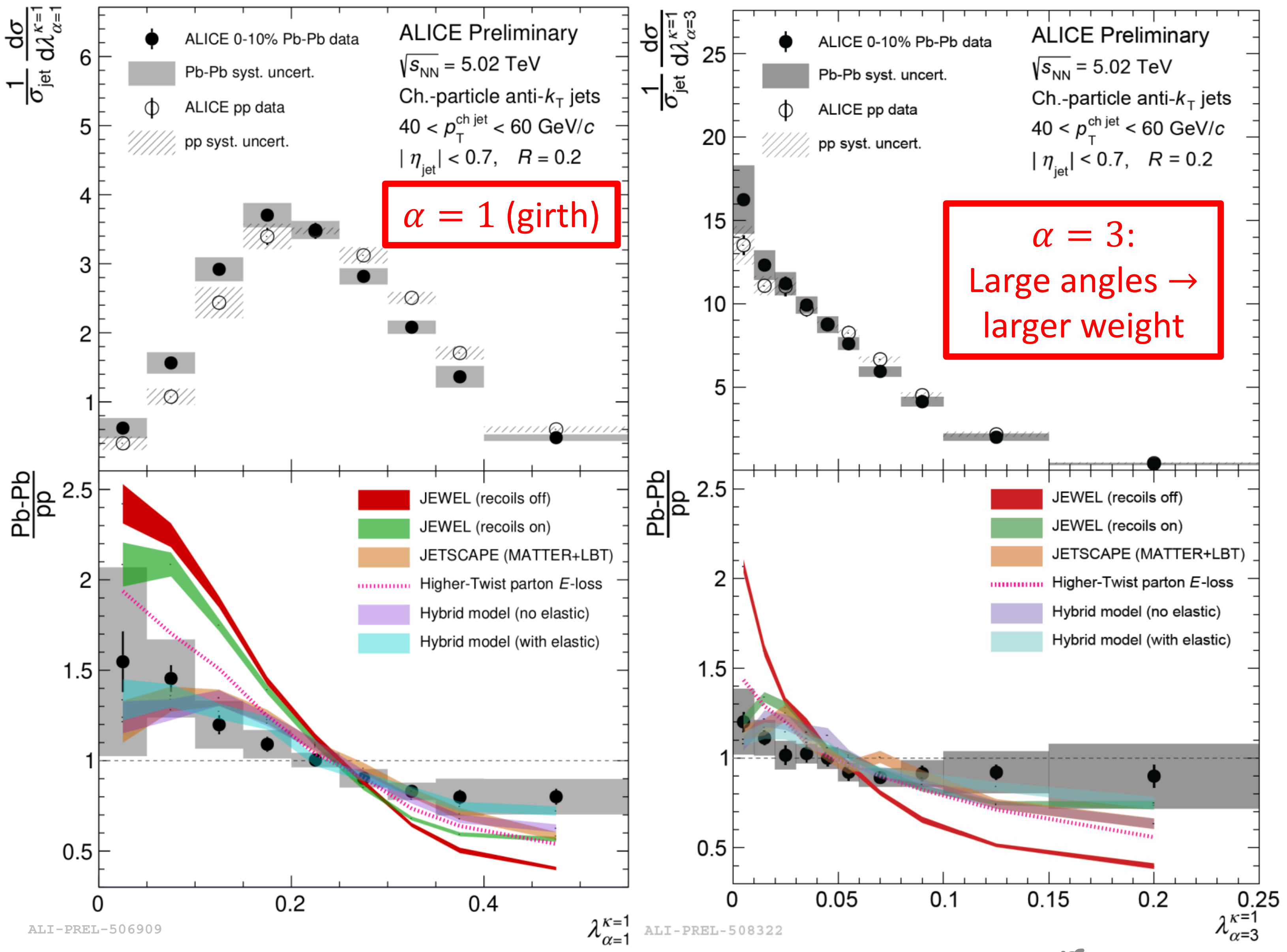
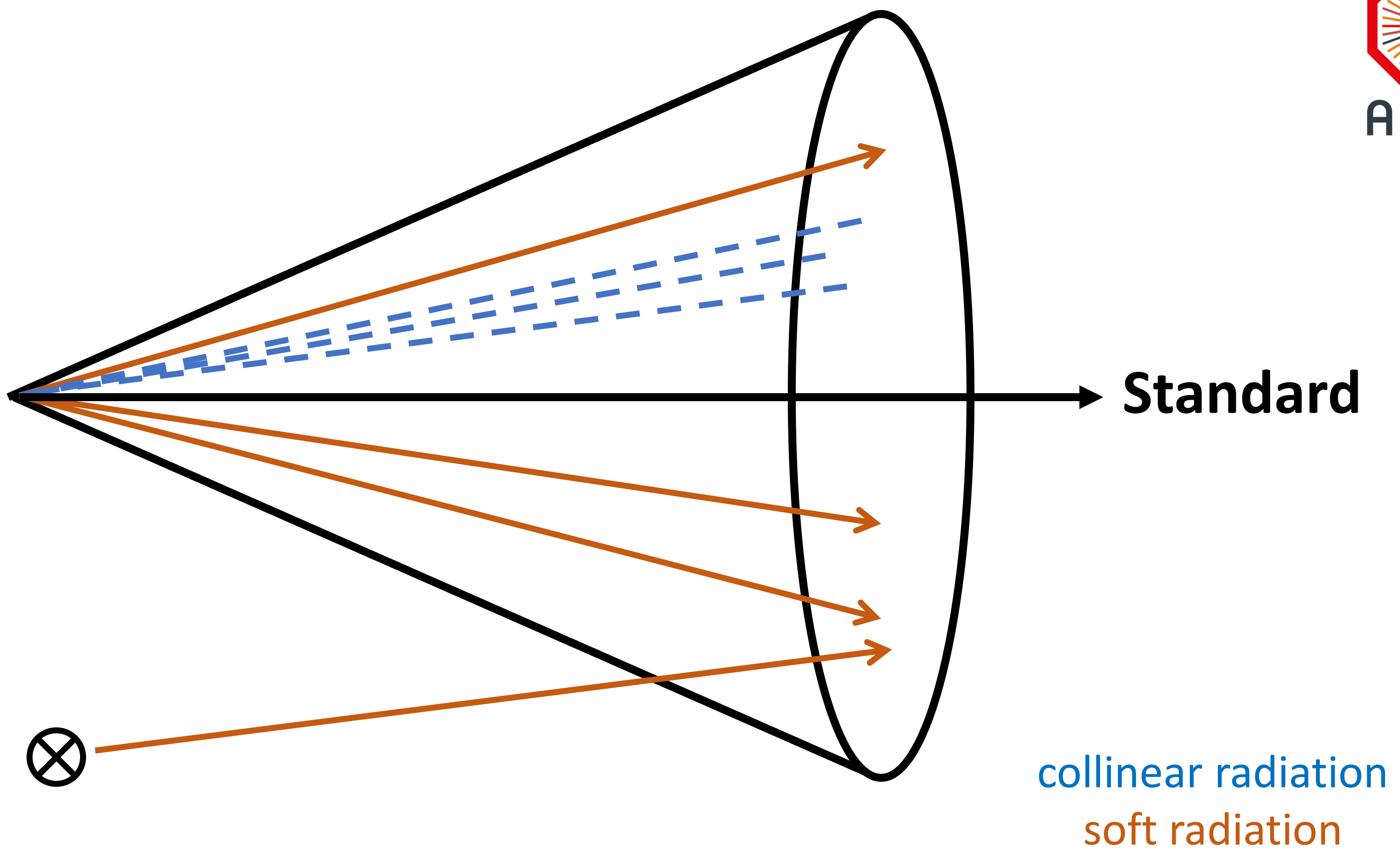


- Higher α → higher sensitivity to recoil effects *Larkoski, Salam, Thaler* [JHEP 06 (2013) 108]
- **Jet core is more significantly modified than wide-angle radiations**
- Models mostly overestimate large-angle quenching effects

Jet-axis differences

- **Standard**: anti-k_{T} jet with E-scheme recombination



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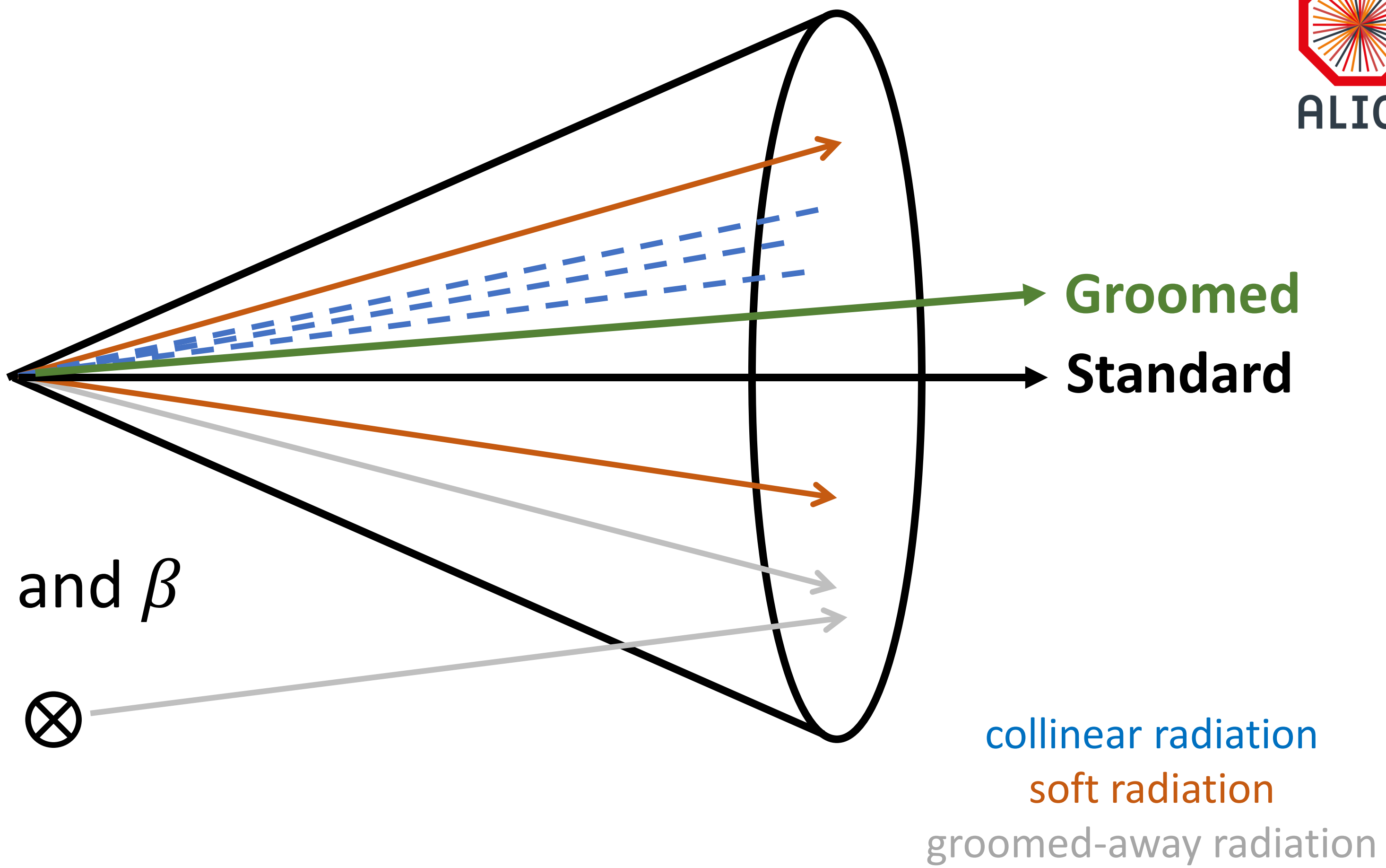

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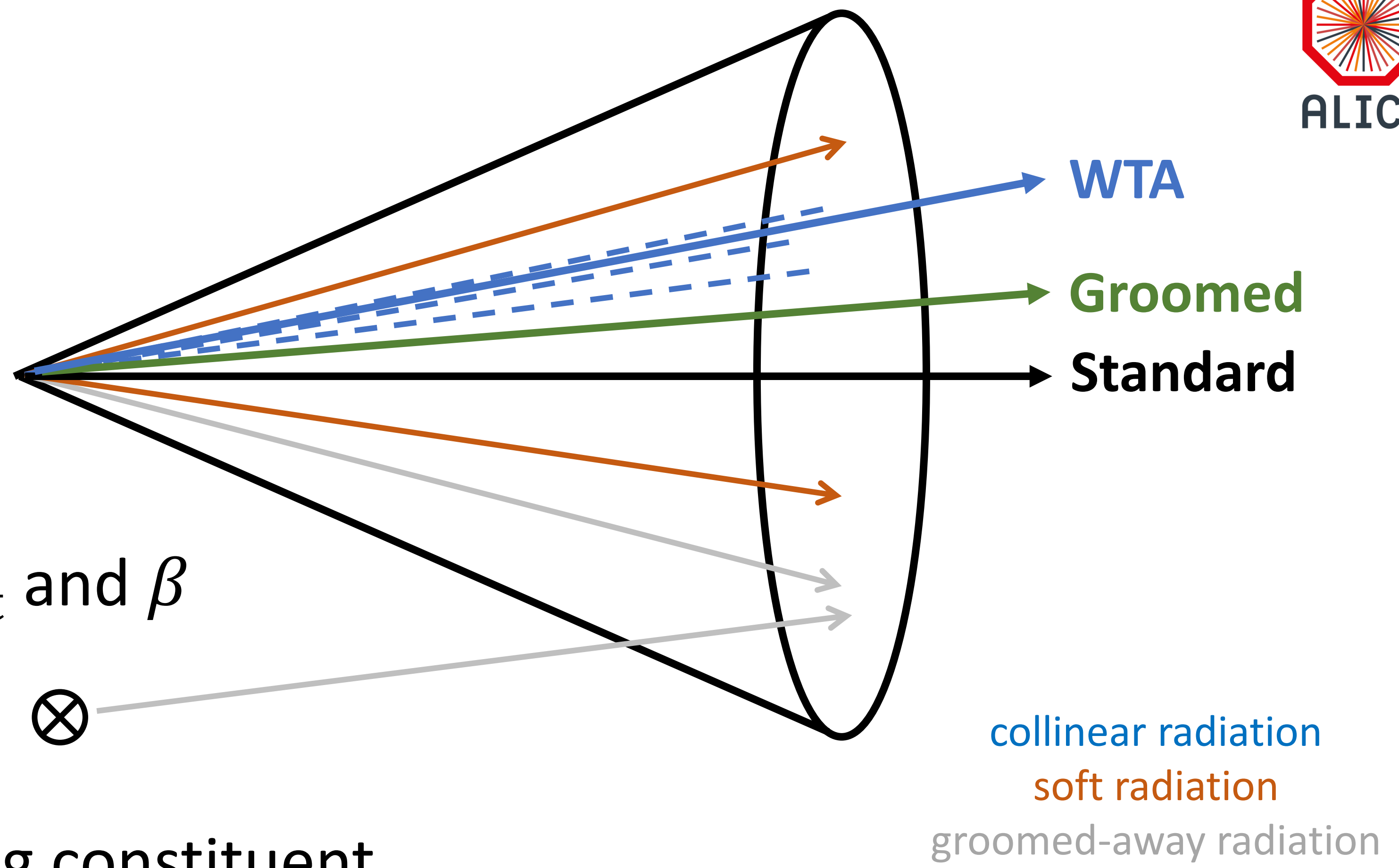

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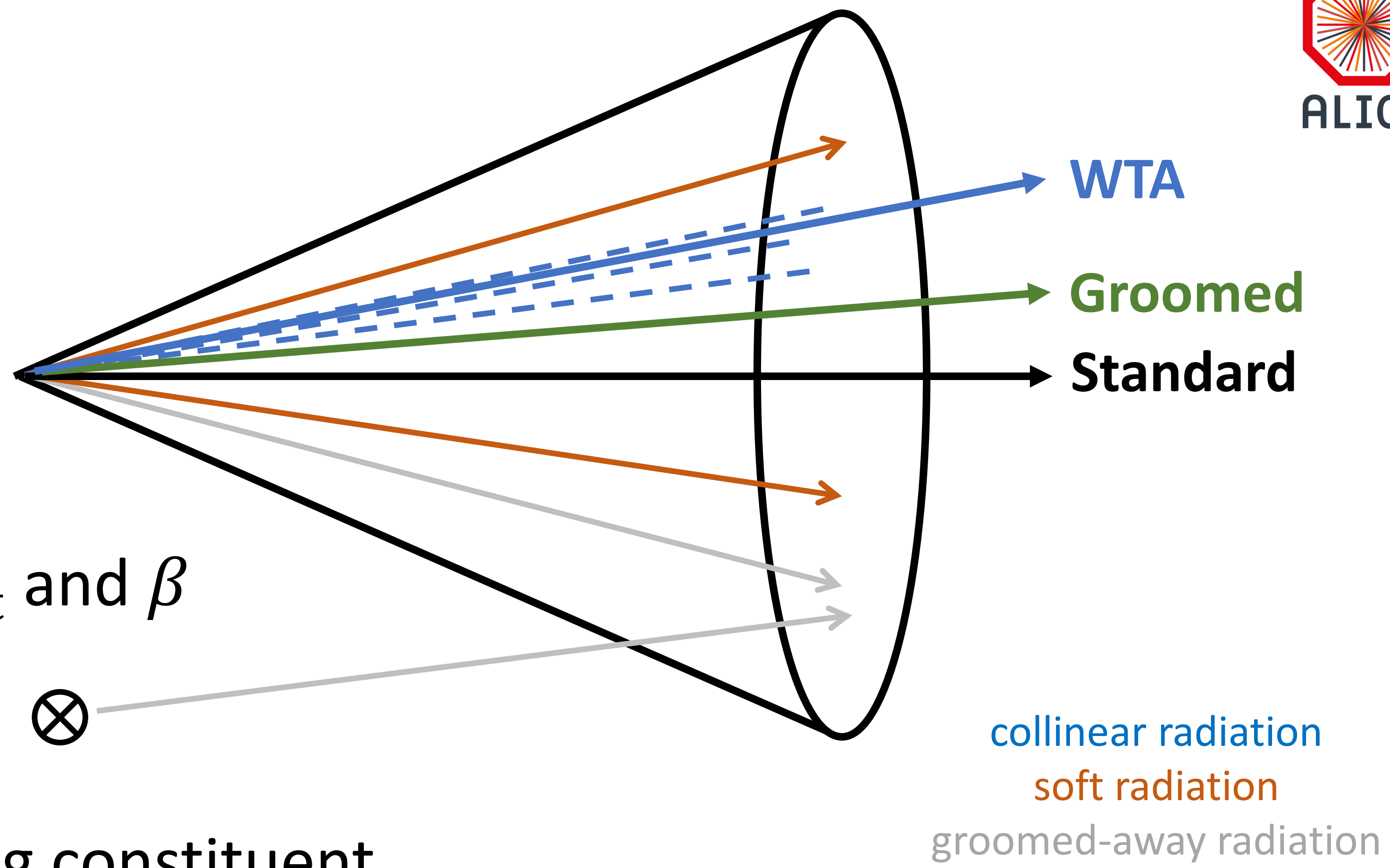
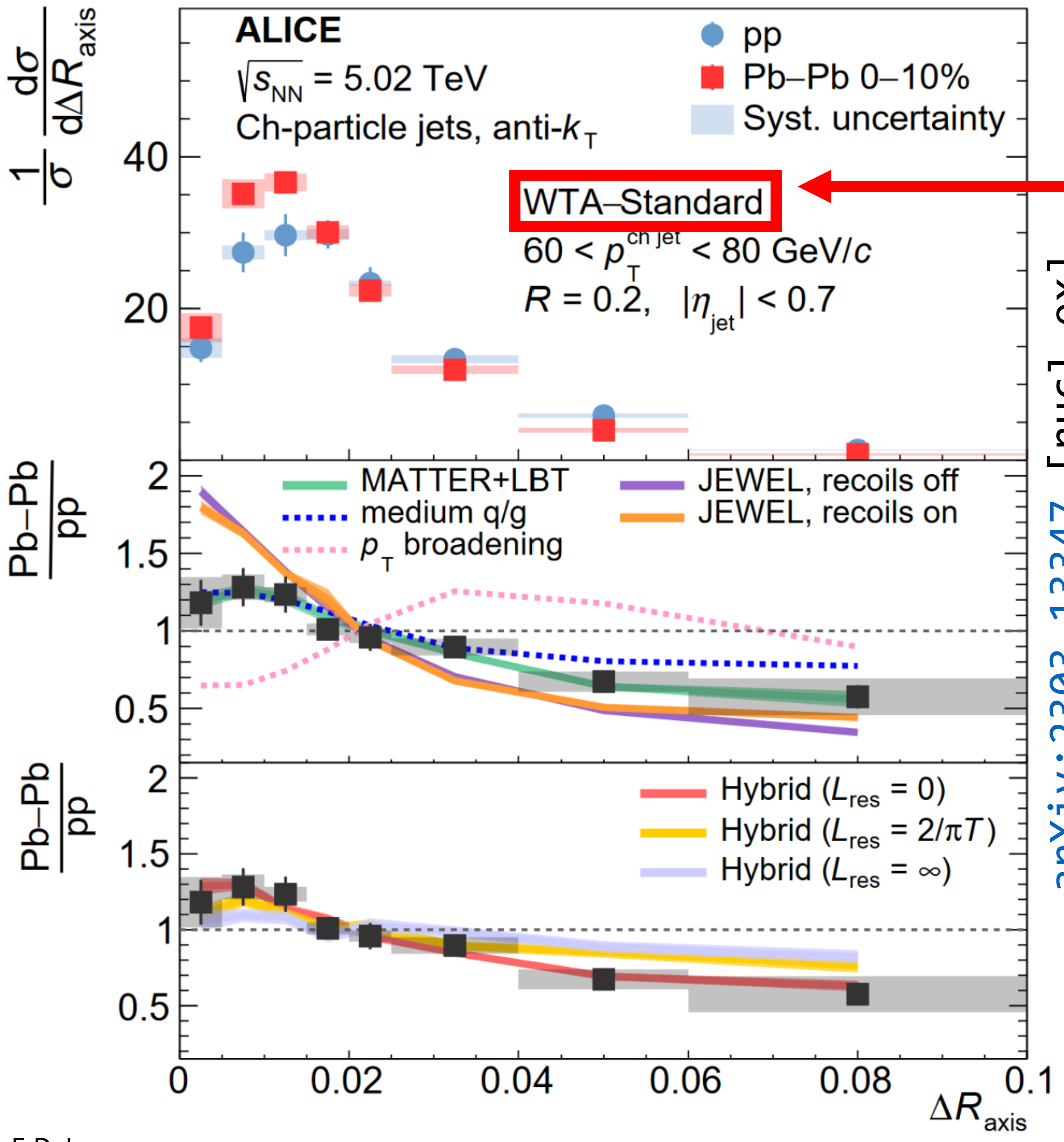


- Calculate the angular separation: $\Delta R_{\mathrm{axis}} = \sqrt{\Delta y^2 + \Delta \phi^2}$
- IRC-safe observable sensitive to **soft radiation, TMDs, and PDFs**

Cal, Neill, Ringer, Waalewijn JHEP 04 (2020) 211

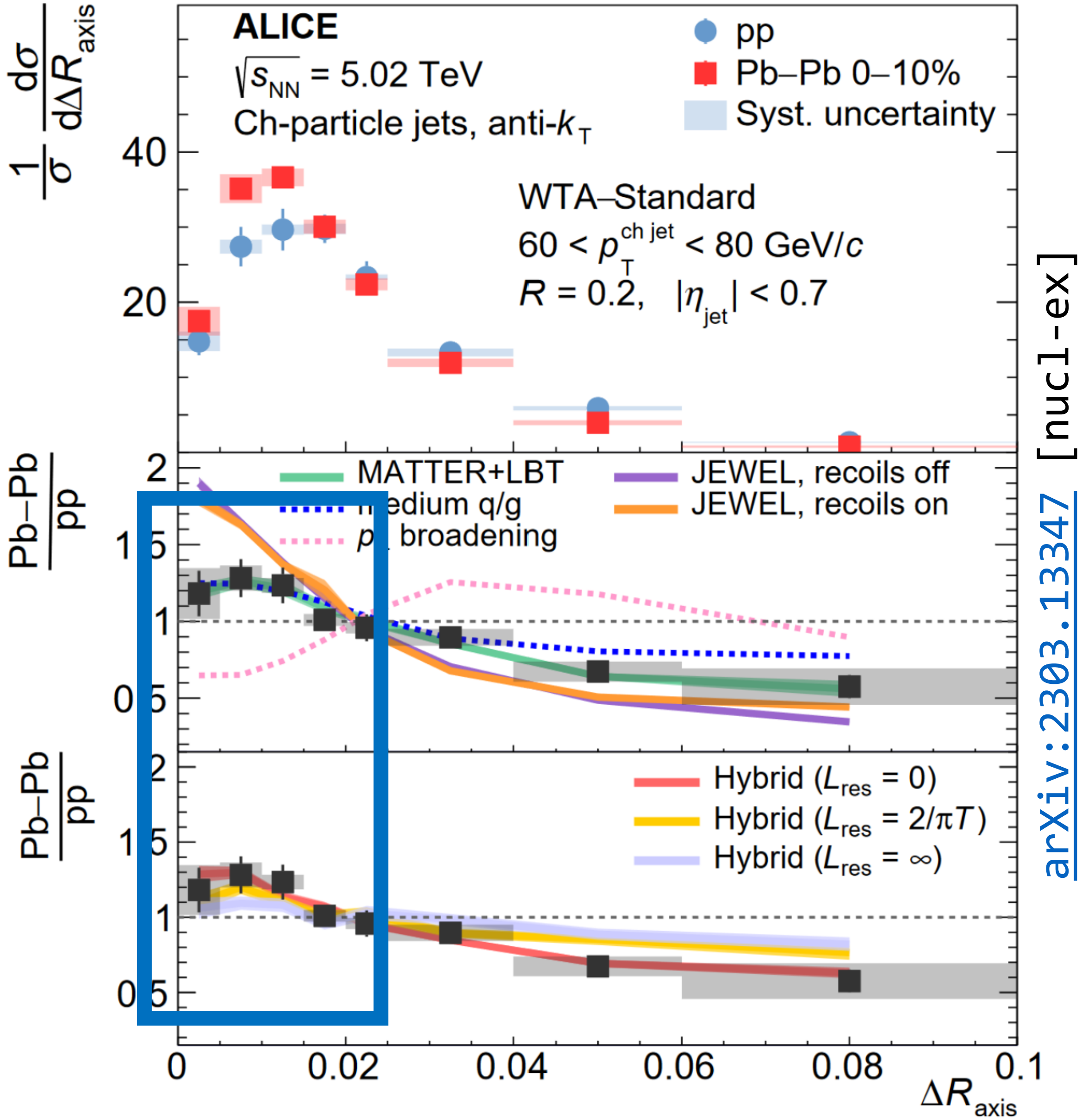
Jet axis differences in Pb-Pb vs. pp



[nucl-ex] arXiv:2303.13347

Standard (E-scheme)
vs.
Winner-Take-All

Jet axis differences in Pb-Pb vs. pp



- **Quenched jet axes are more similar** than vacuum jets
  - *Consistent with "narrowing"*

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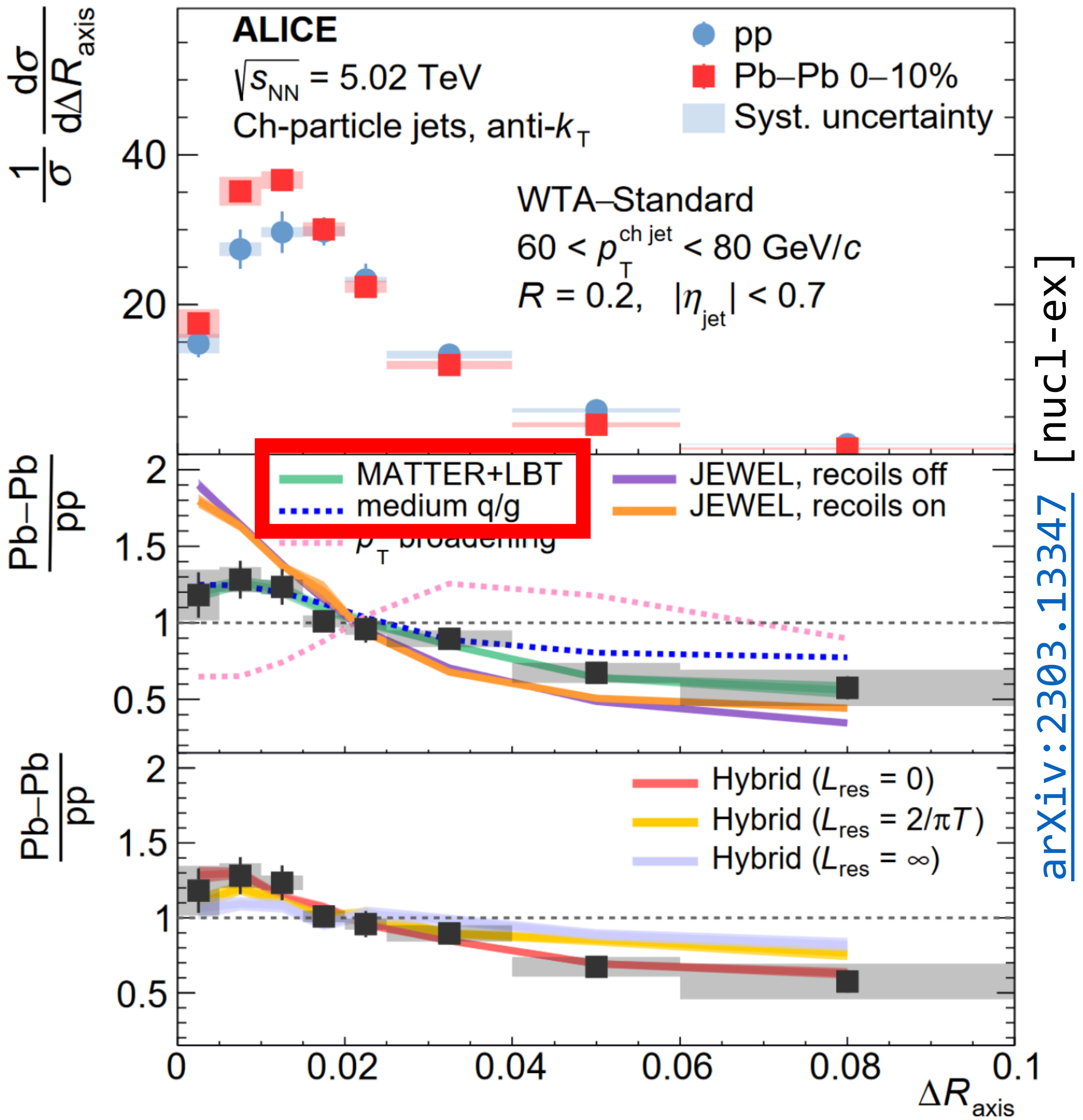

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- Agreement with JETSCAPE (MATTER+LBT) and medium q/g modification calculations

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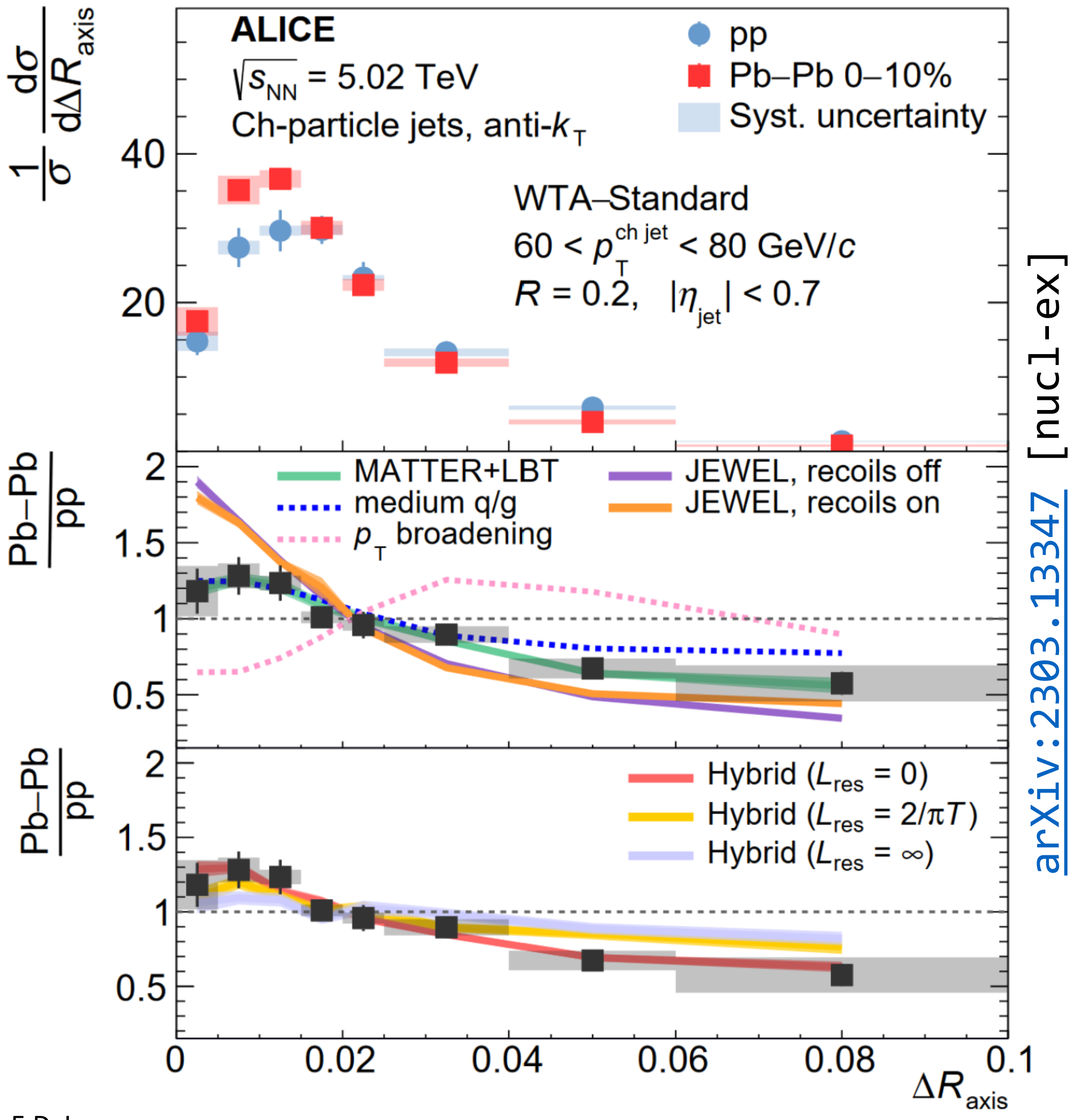


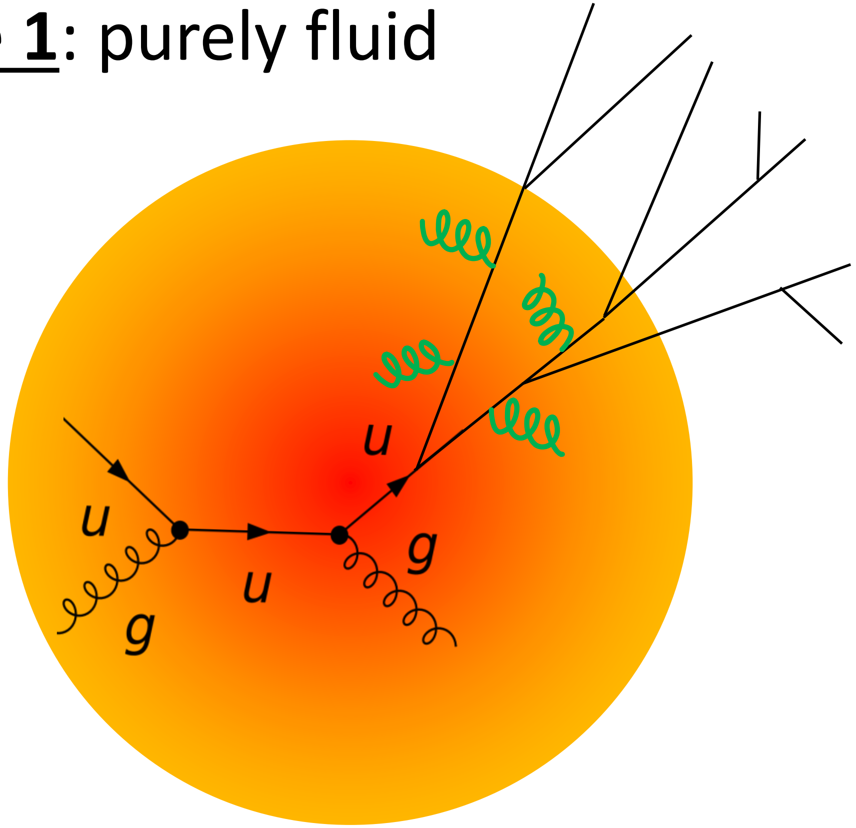
- **Quenched jet axes are more similar** than vacuum jets
  - *Consistent with "narrowing"*
- Agreement with JETSCAPE (MATTER+LBT) and medium q/g modification calculations
- Preference towards **zero resolution length of the medium** in Hybrid model

→ **fully incoherent energy loss**

Multiple (hard) interactions in the medium?

D'Eramo, Rajagopal, Yin
[JHEP 01 (2019) 172]

Picture 1: purely fluid



Jet fragmentation
+ medium-induced emissions

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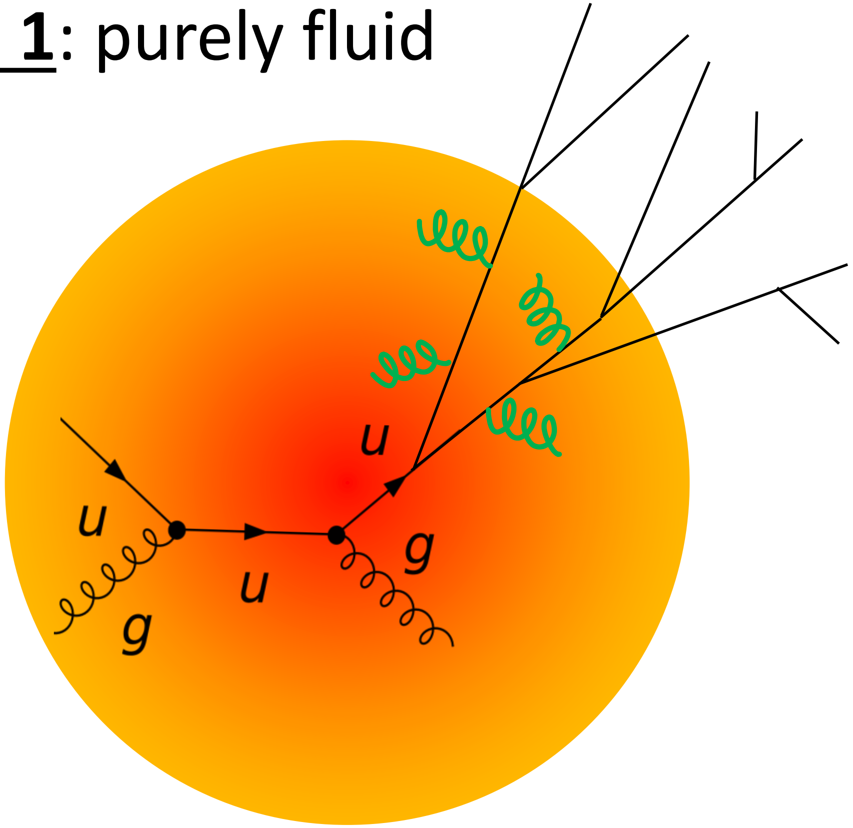
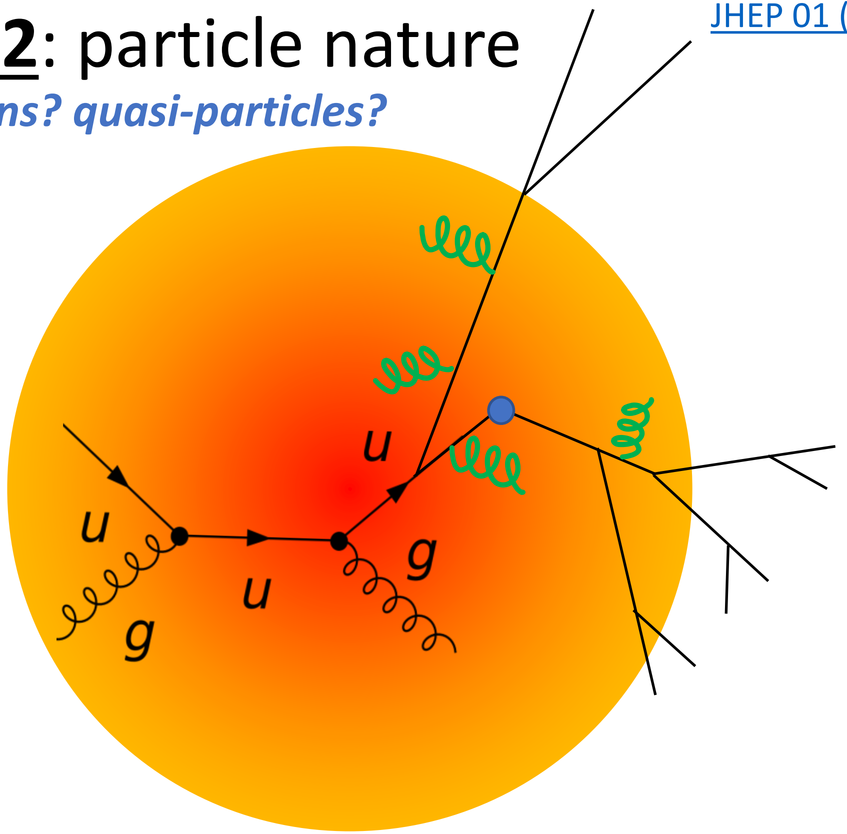


Jet fragmentation
+ medium-induced emissions

Picture 2: particle nature
partons? quasi-particles?



Jet fragmentation
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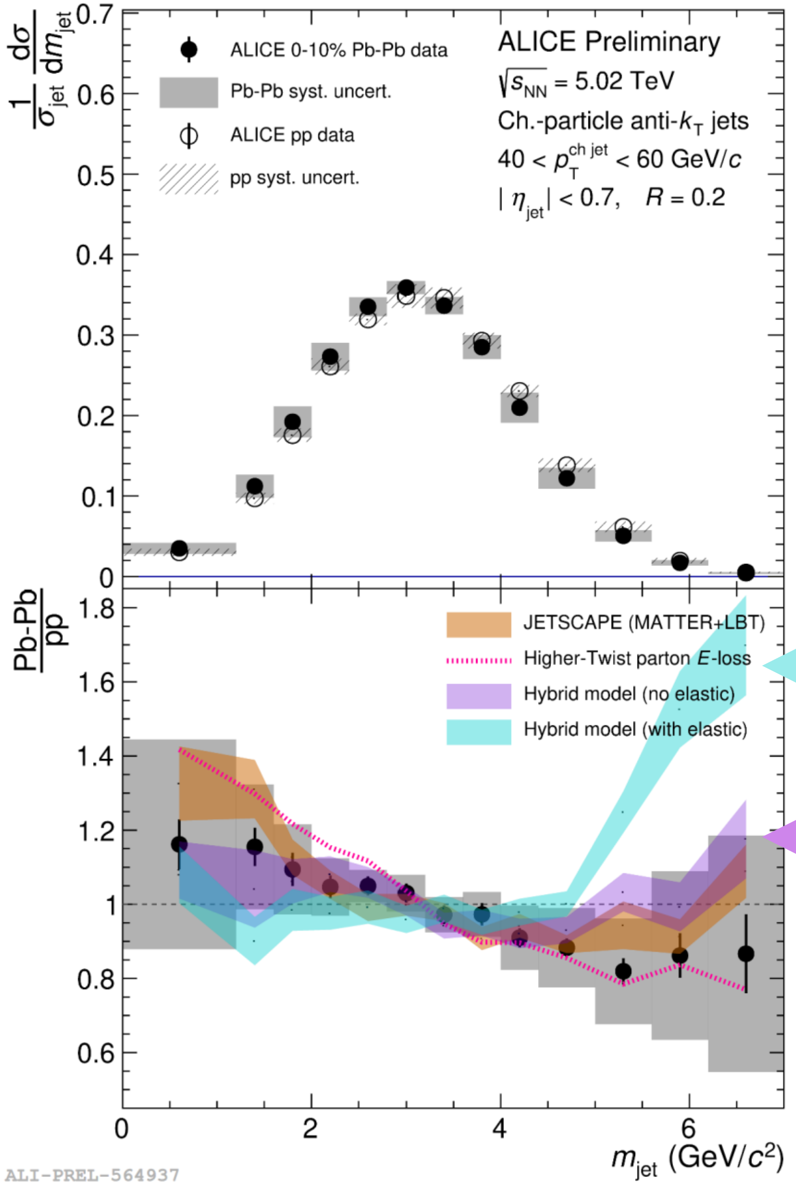
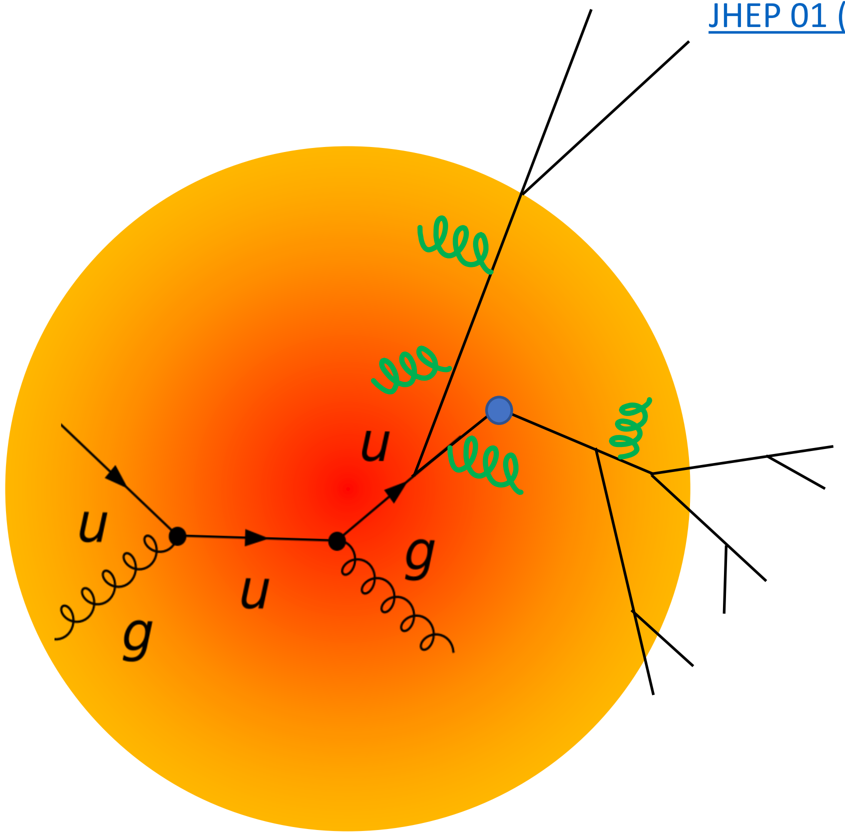


With Molière

No Molière

D'Eramo, Rajagopal, Yin
JHEP 01 (2019) 172



Jet fragmentation
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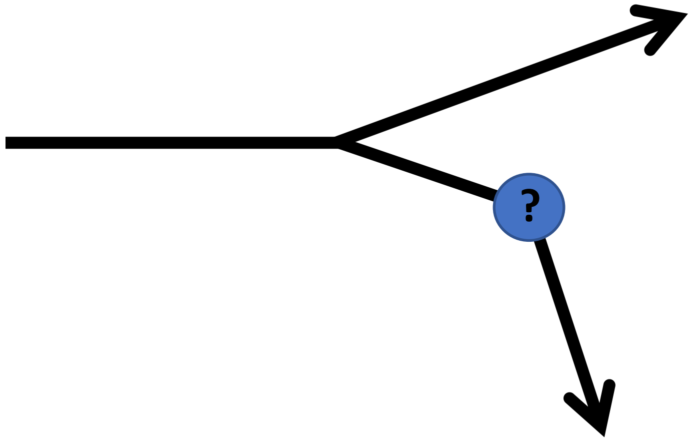
Direct search: use jet reclustering



Select individual splitting using:

1. **Soft drop grooming**

   Larkoski, Marzani, Soyez, Thaler
   JHEP 1405 (2014) 146

2. **Dynamical grooming**

   Mehtar-Tani, Soto-Ontoso, Tywoniuk
   Phys. Rev. D 101, 034004 (2020)

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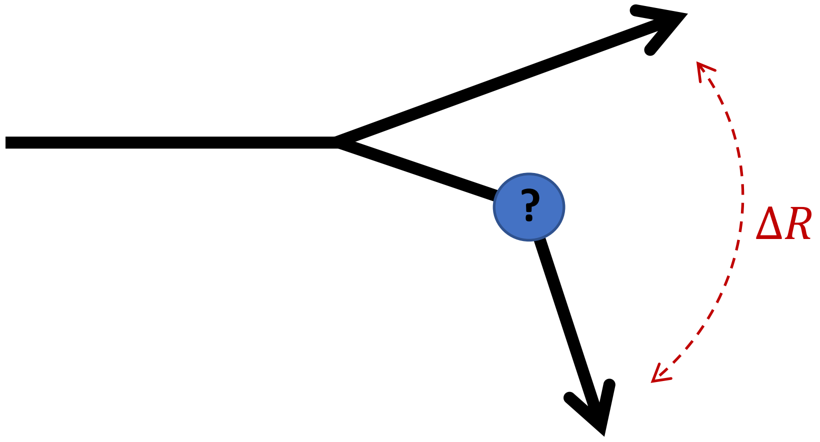

$$k_{\mathrm{T},g} = p_{\mathrm{T}}^{\mathrm{subleading}} * \Delta R$$

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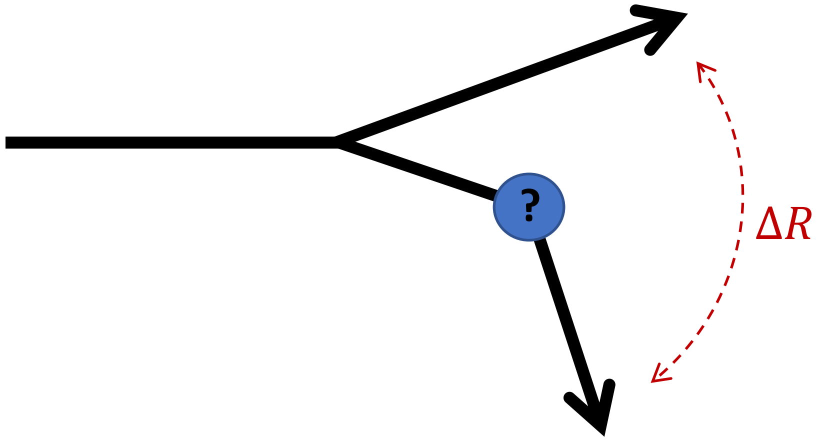

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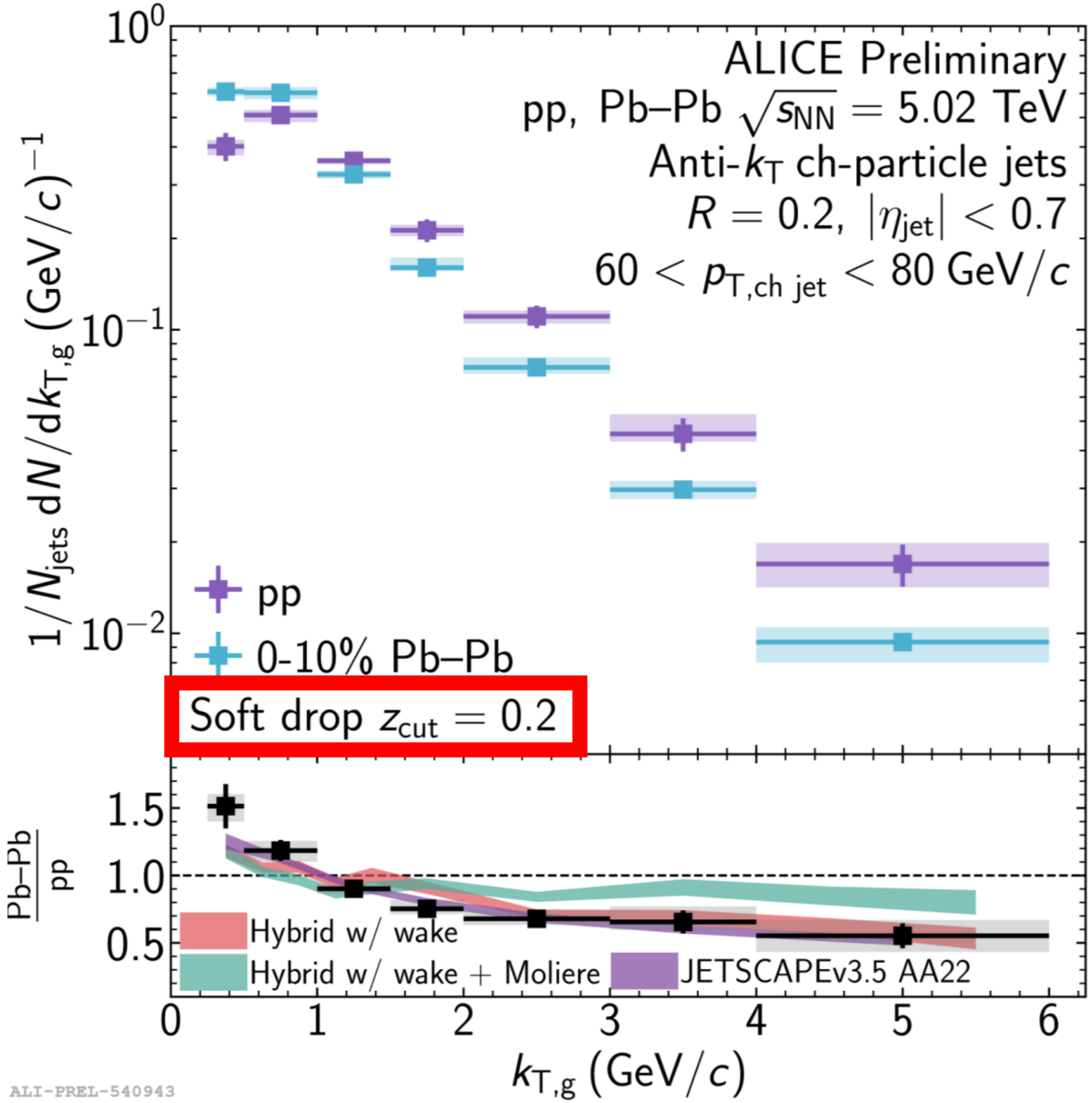
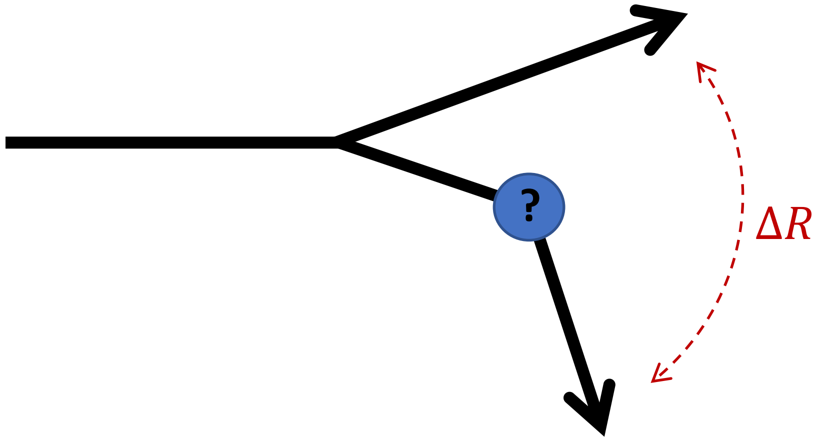


https://alice-figure.web.cern.ch/node/18030

Direct search: use jet reclustering



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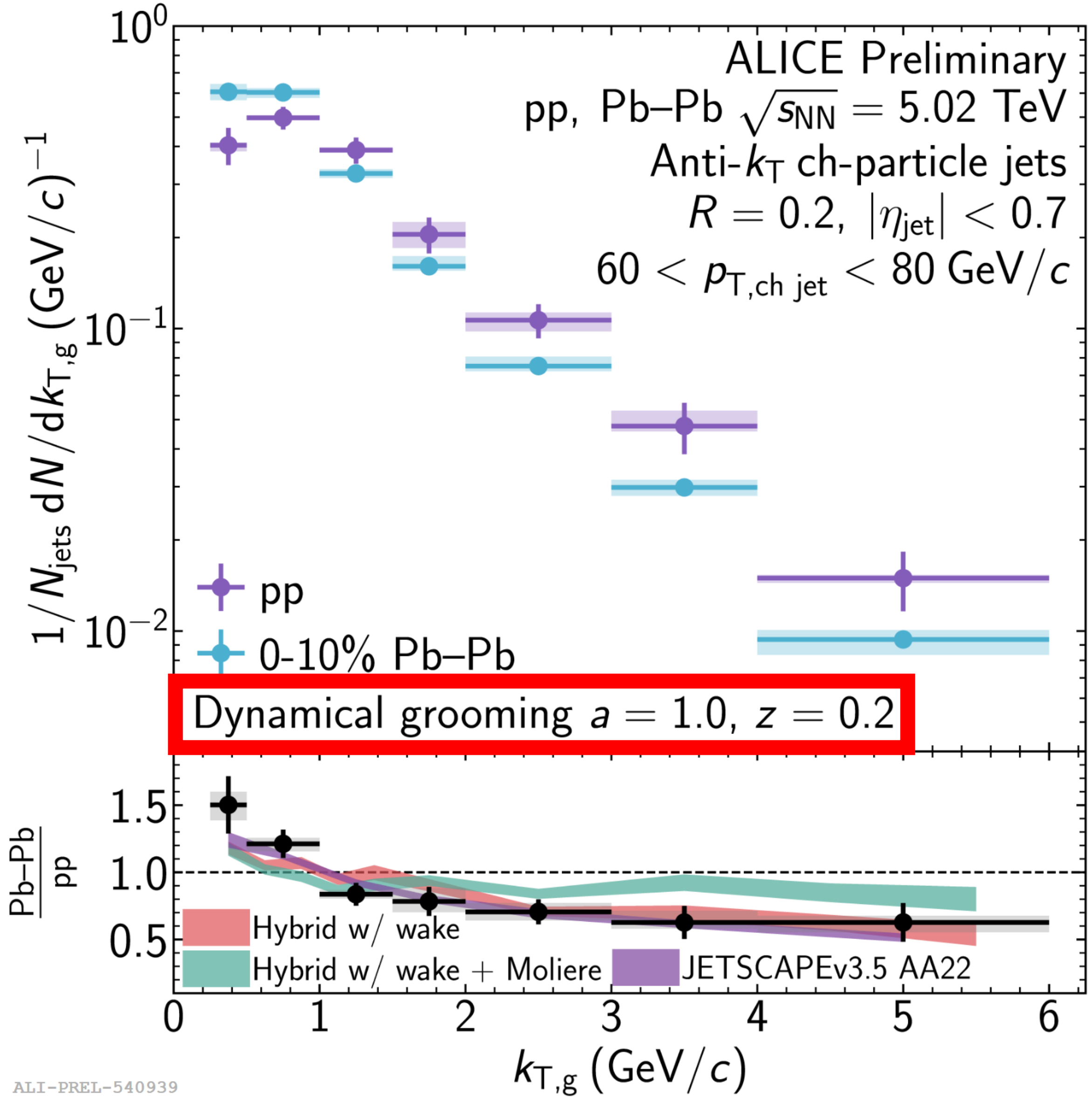

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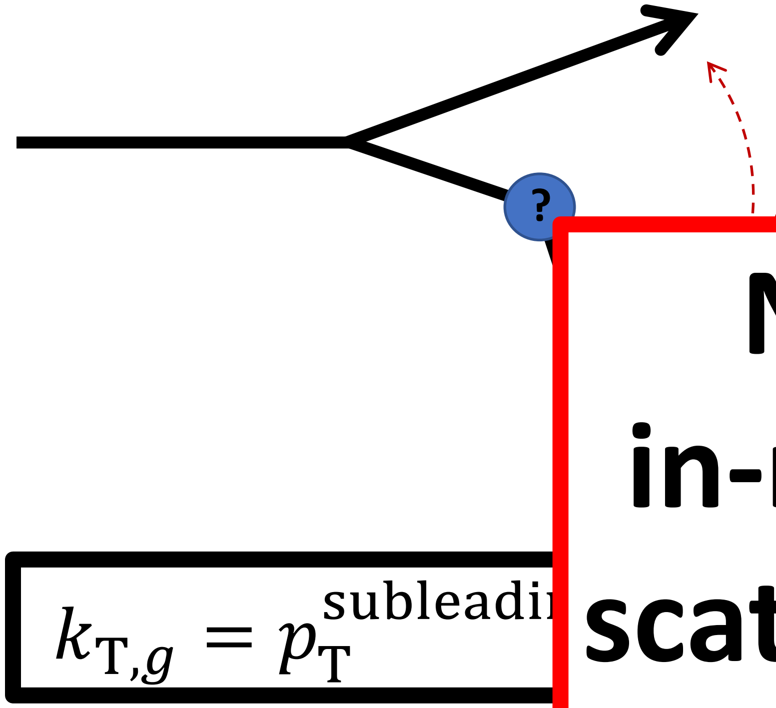

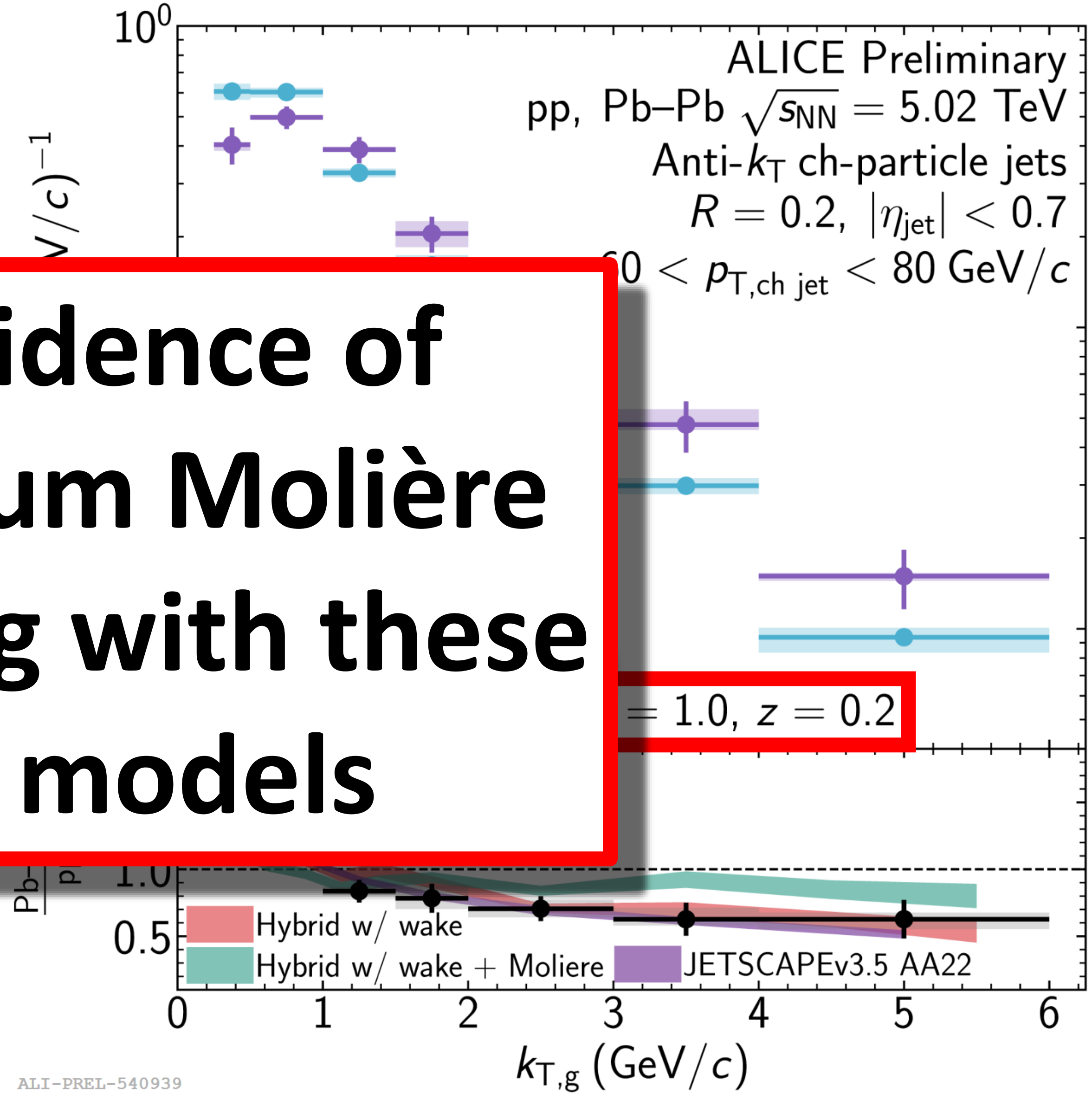

No evidence of in-medium Molière scattering with these QGP models

https://alice-figure.web.cern.ch/node/18030

There's much to learn from Pb-Pb substructure…

ALICE

- Jet angularity & mass measurements:
  1. **Comparison to a vacuum baseline is essential for interpreting these results**

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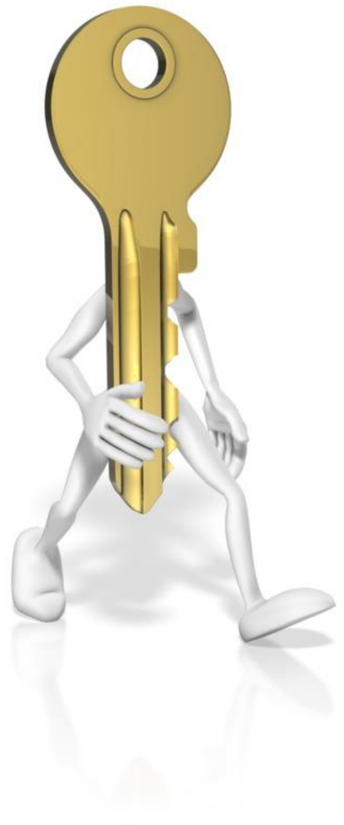
- ALICE presents several substructure observables to constrain models
    - **Improving models' pp baselines will improve AA predictive power**

Closing riddle…

- **What key has legs and can’t open a door?**



Closing riddle…

- **What key has legs and can't open a door?**

a tur-key

Happy Thanksgiving!

Bad joke credit: https://www.thedodo.com/dodowell/turkey-jokes

Backup

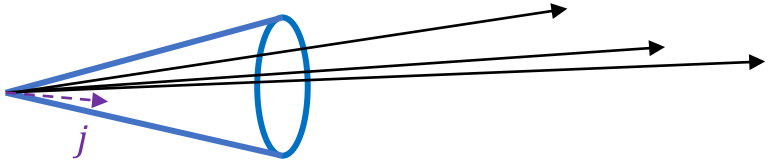
What is IRC safety?

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

- 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



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

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

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

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

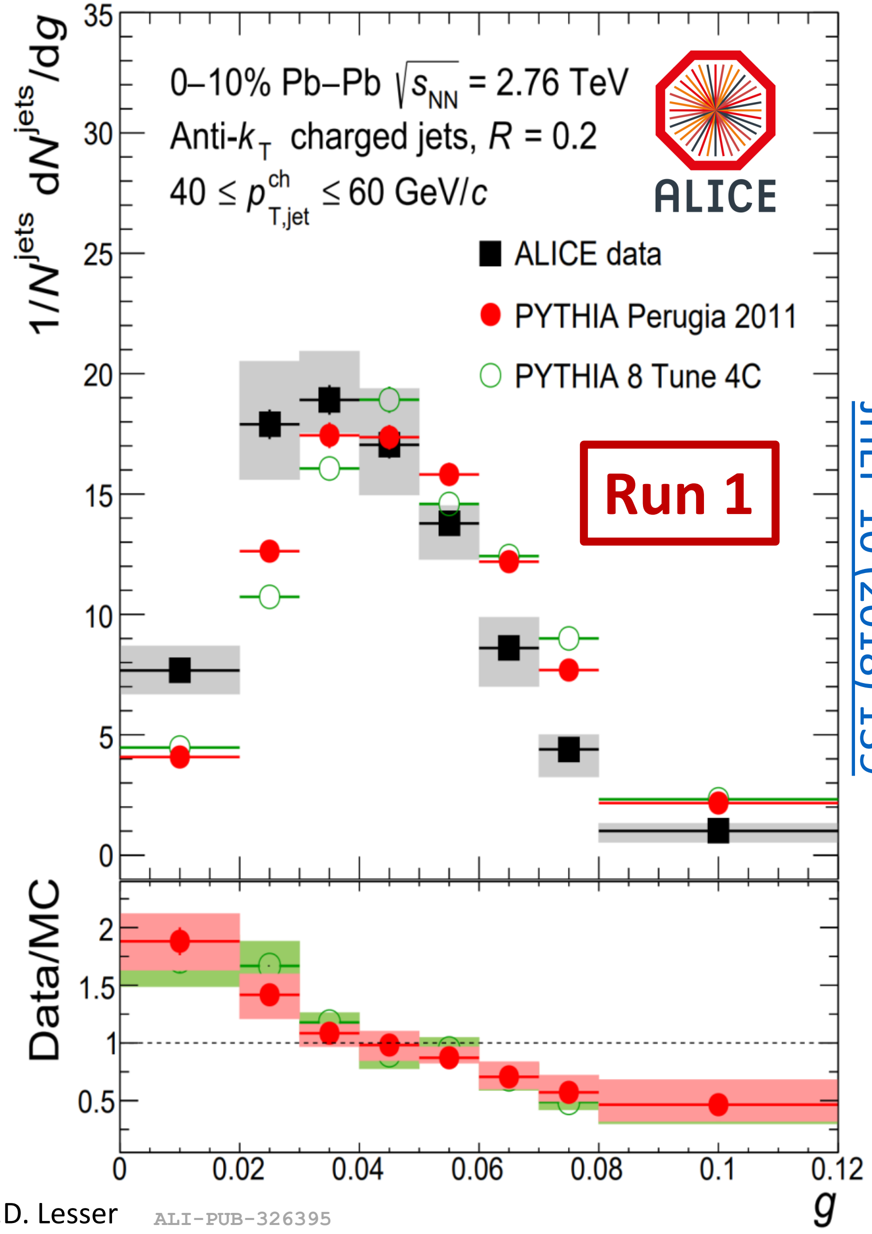
$$\theta_j = 0 \rightarrow z_j^\kappa \theta_j^\alpha = 0 \quad (\alpha > 0)$$

Charged-particle jet observables

- 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**†
- Currently we use the IRC-safe observables to motivate our measurements, and then apply nonperturbative corrections using different methods

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

Run 2 improved girth study



JHEP 10 (2018) 139

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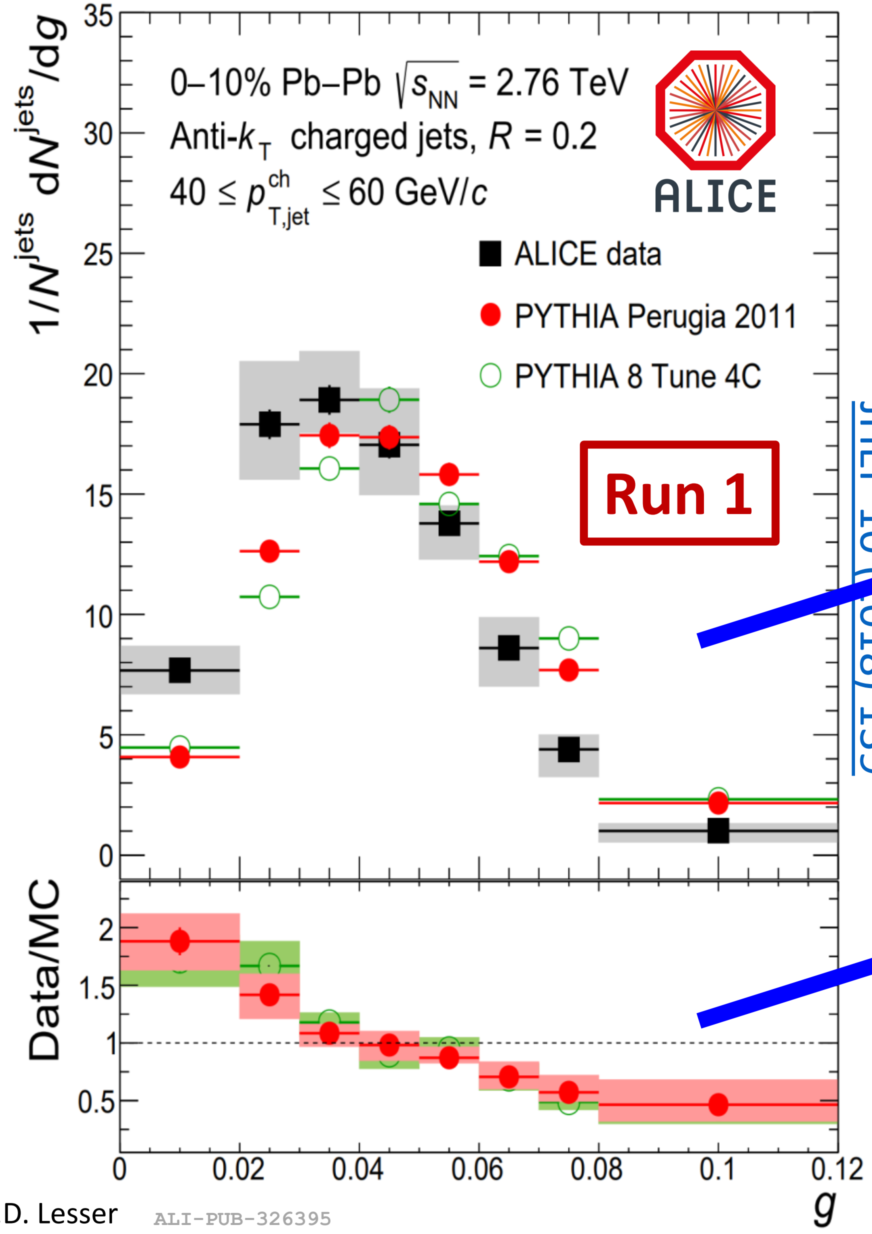
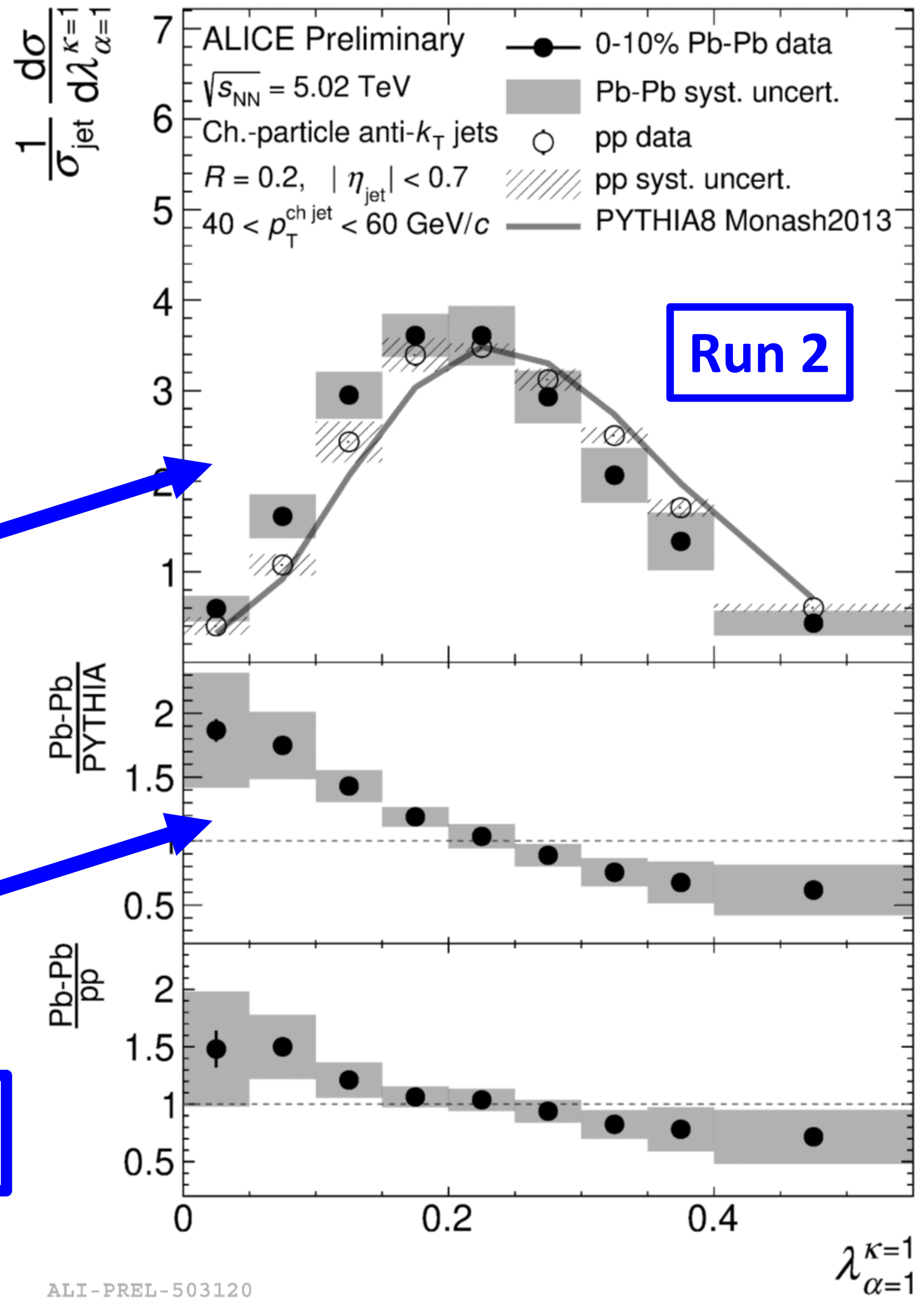


JHEP 10 (2018) 139

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

$$g = \lambda_1 * R$$



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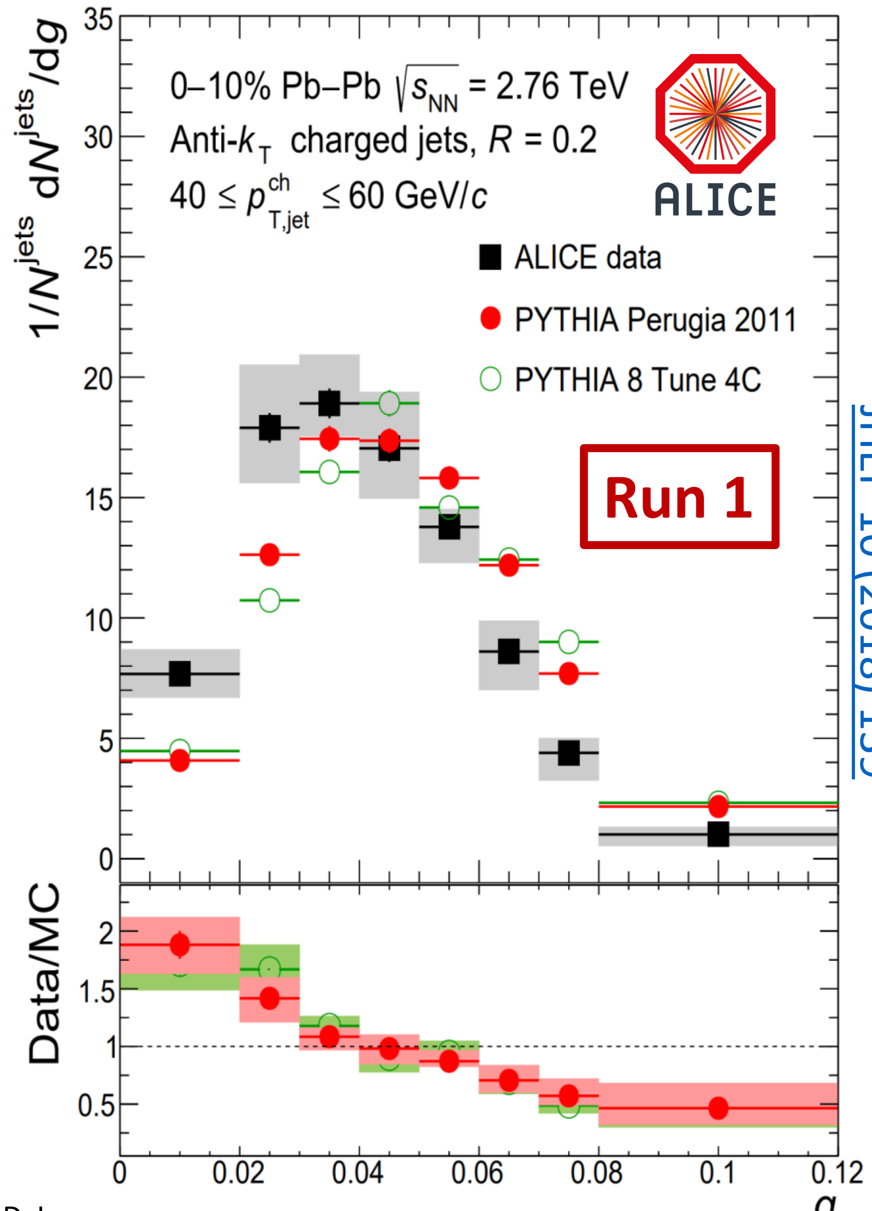

JHEP 10 (2018) 139

ALI-PUB-326395

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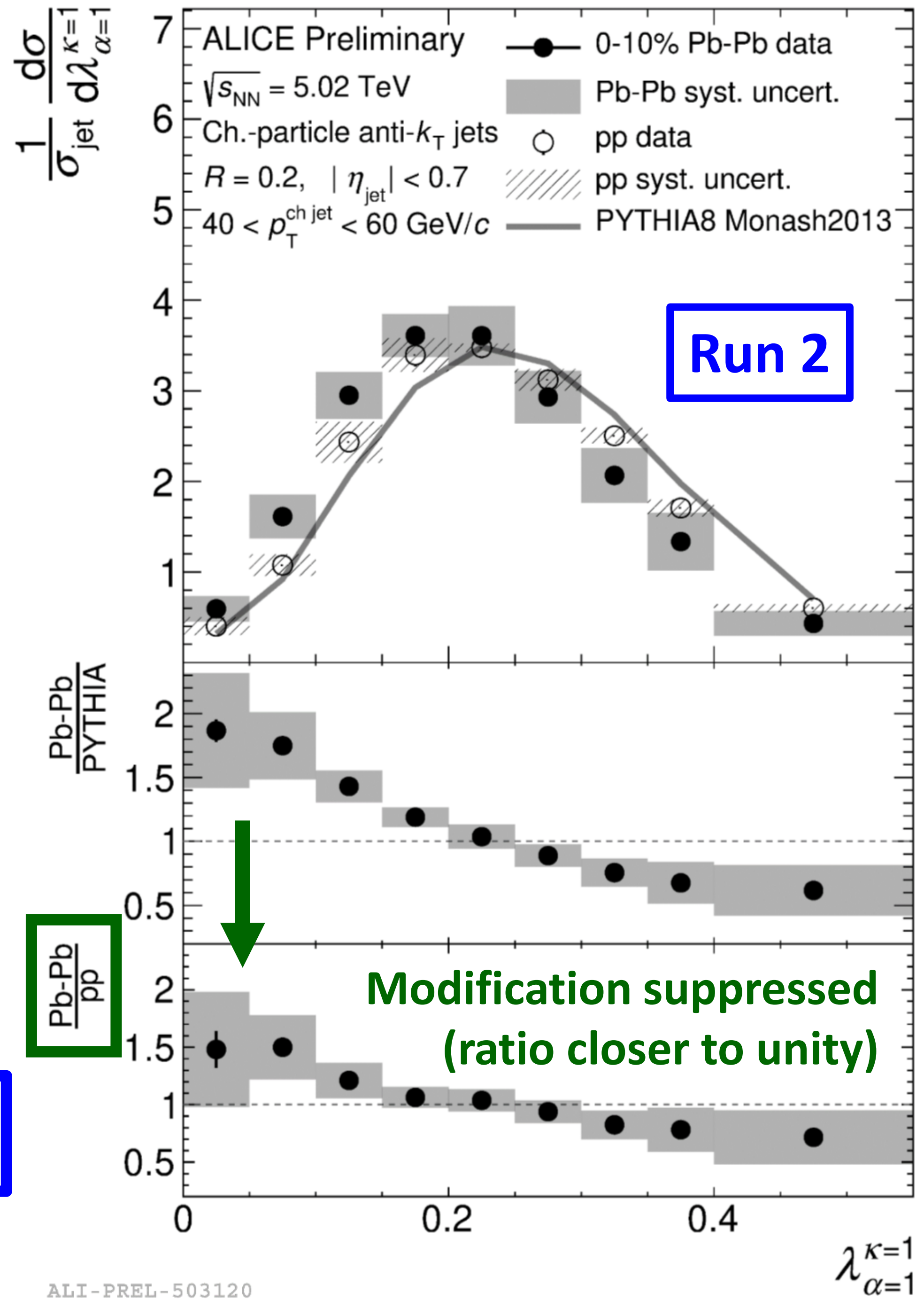

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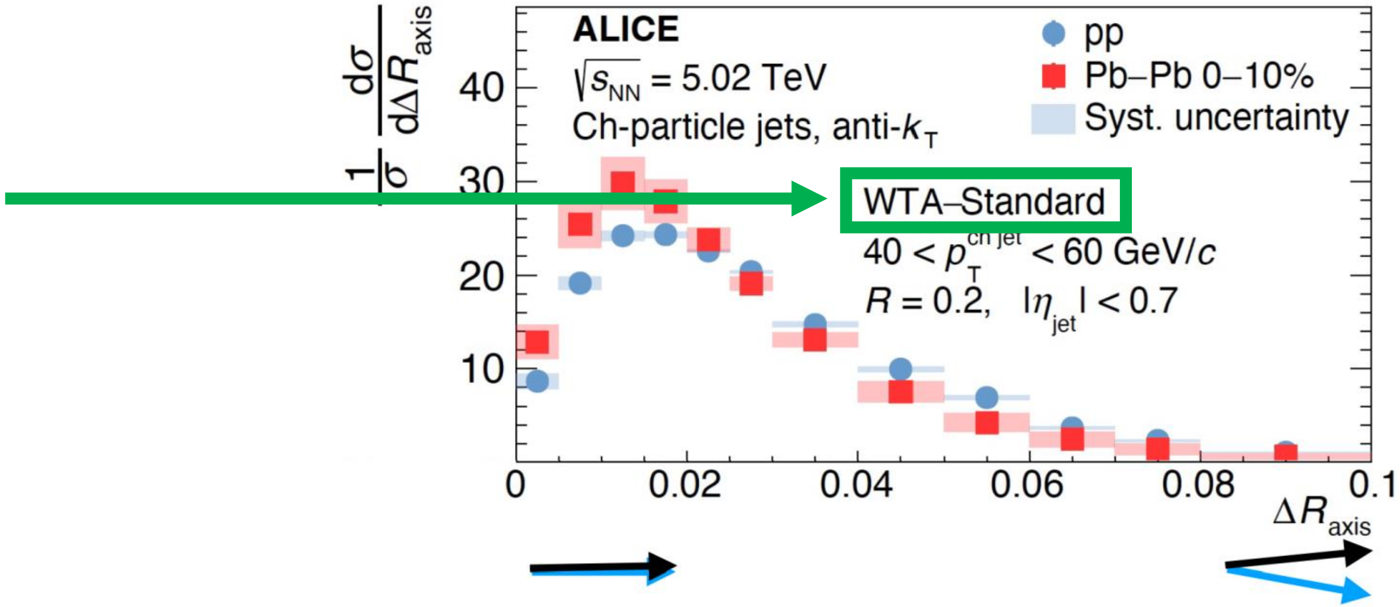
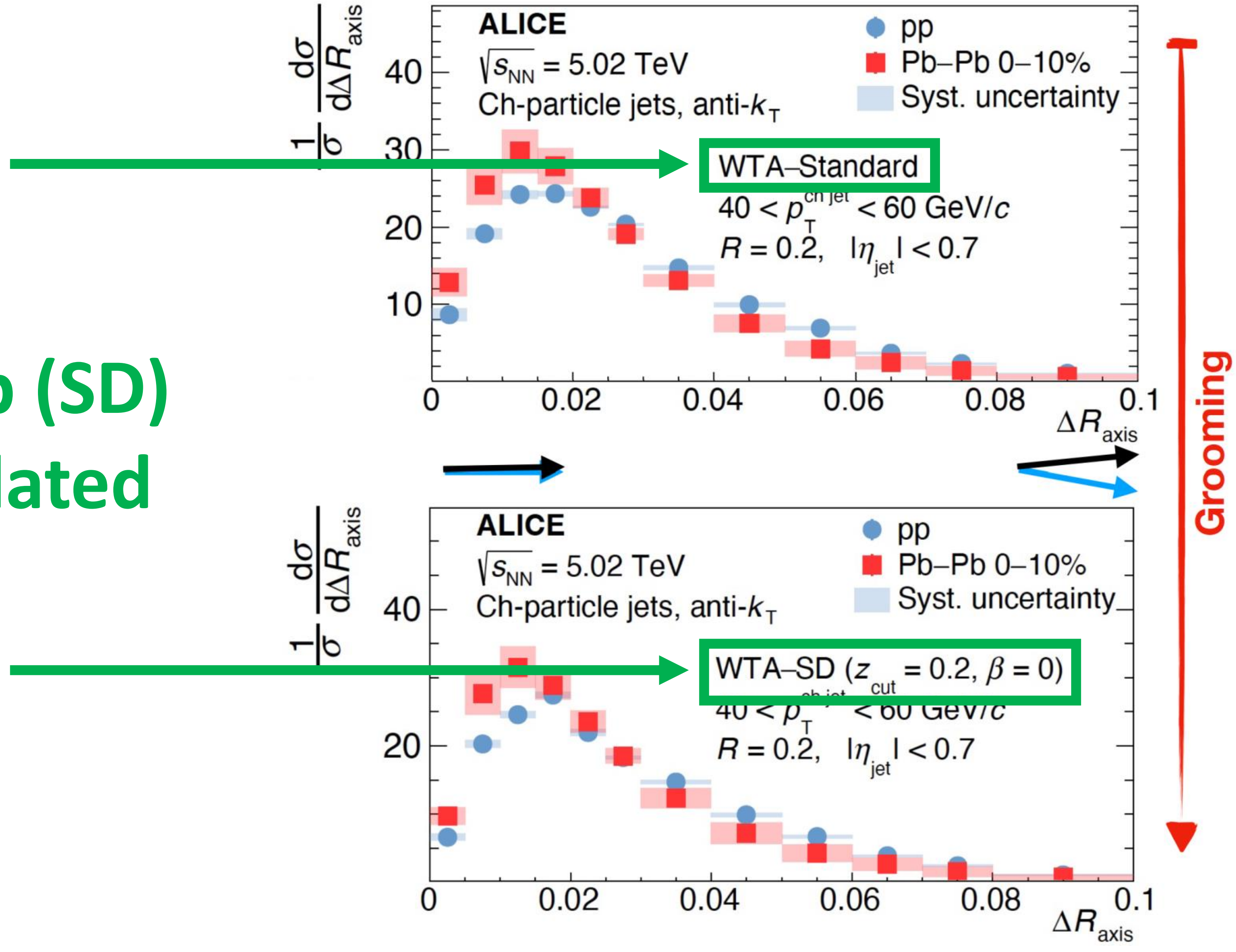
Jet axis differences in Pb-Pb vs. pp



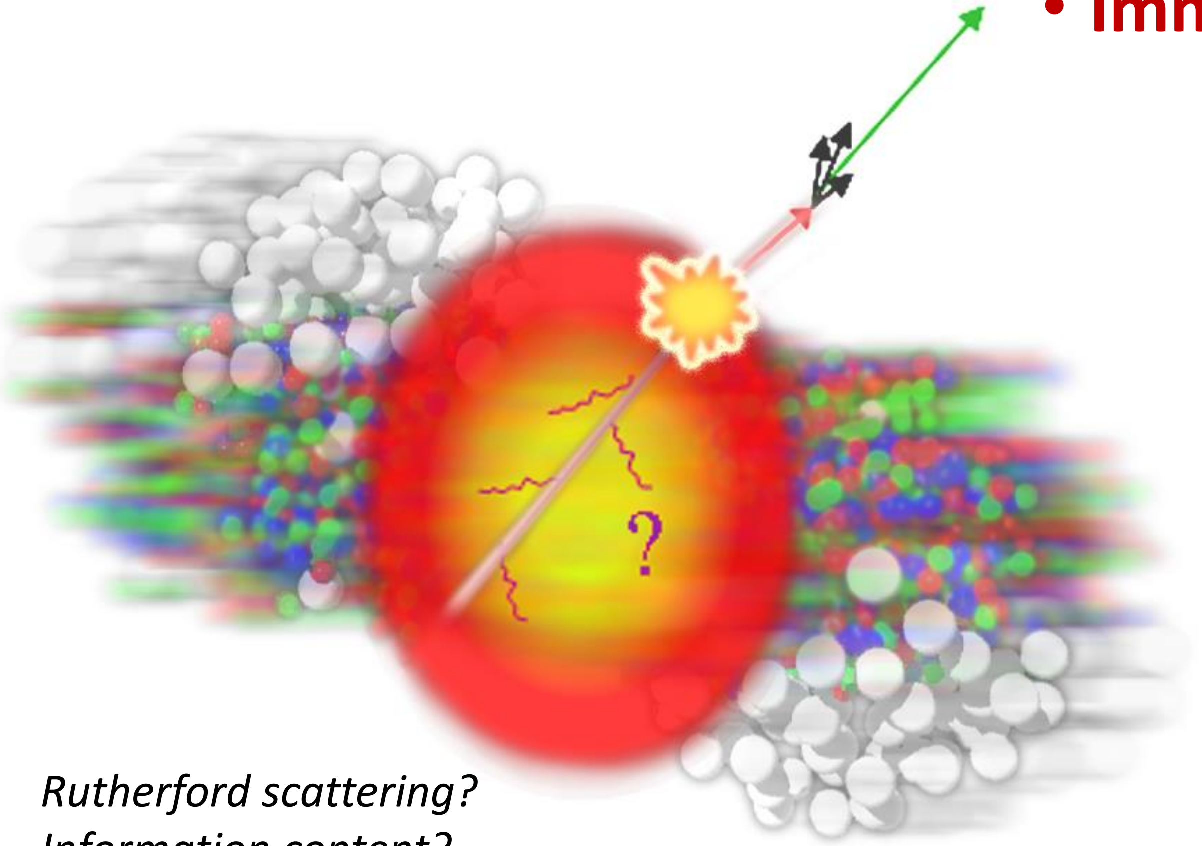
Jet axis differences in Pb-Pb vs. pp

Standard and Soft Drop (SD) axes are strongly correlated



Probing the QGP with low-momentum jets

- Low-p_{T} jets (< 40 GeV/c) **challenging in QGP**
  - **Immense uncorrelated background**



- *Rutherford scattering?*
- *Information content?*

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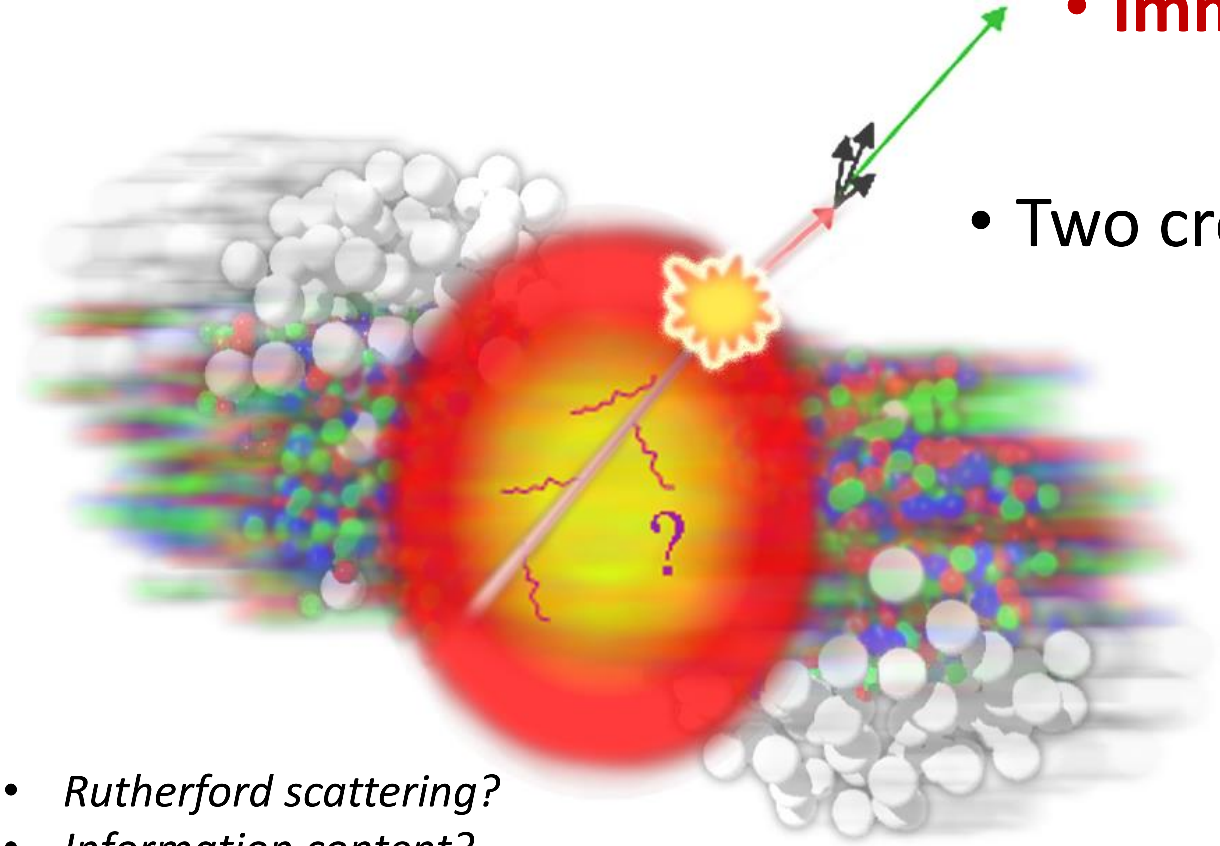

- *Rutherford scattering?*
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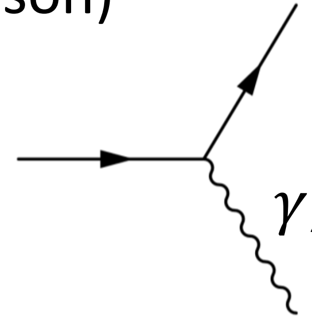
- Two creative solutions:
  1. Tagging jets using a transverse probe (e.g. EW boson)

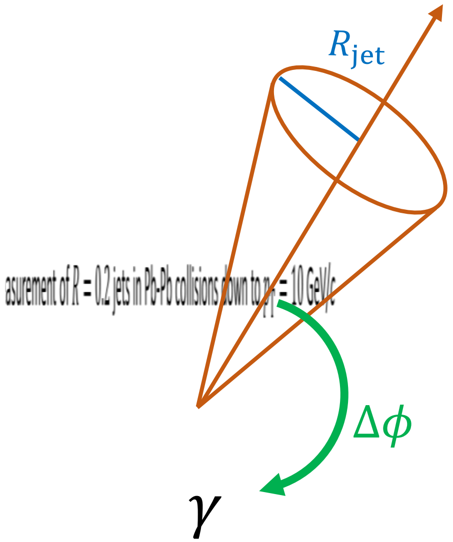


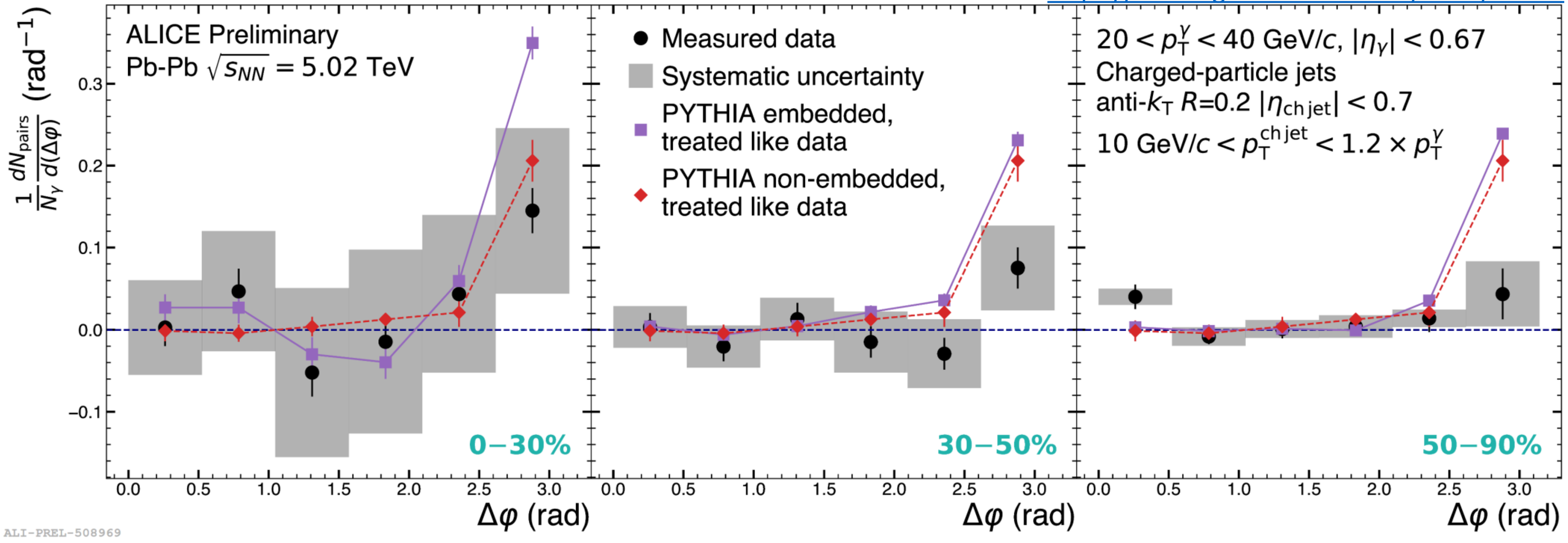
  2. Requiring semi-hard probe inside jet

- *adds some bias to jet substructure*

Photon-tagged jet correlations

https://alice-figure.web.cern.ch/node/21910

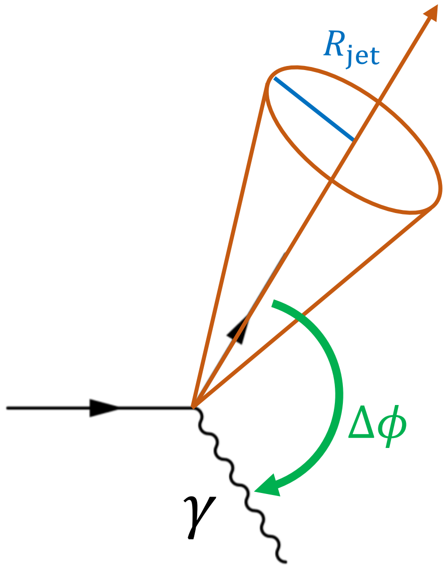


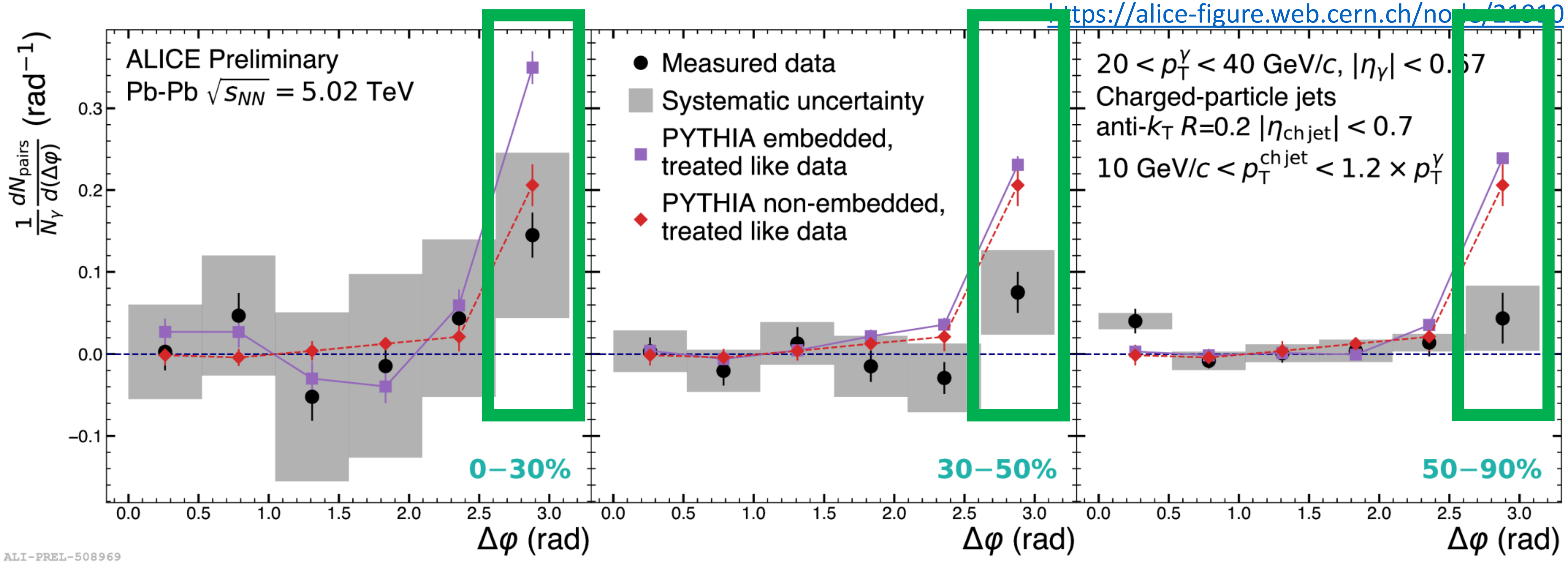


- Measurement of $R = 0.2$ jets in Pb-Pb collisions down to $p_{\mathrm{T}} = 10$ GeV/c

Photon-tagged jet correlations

https://alice-figure.web.cern.ch/node/21010

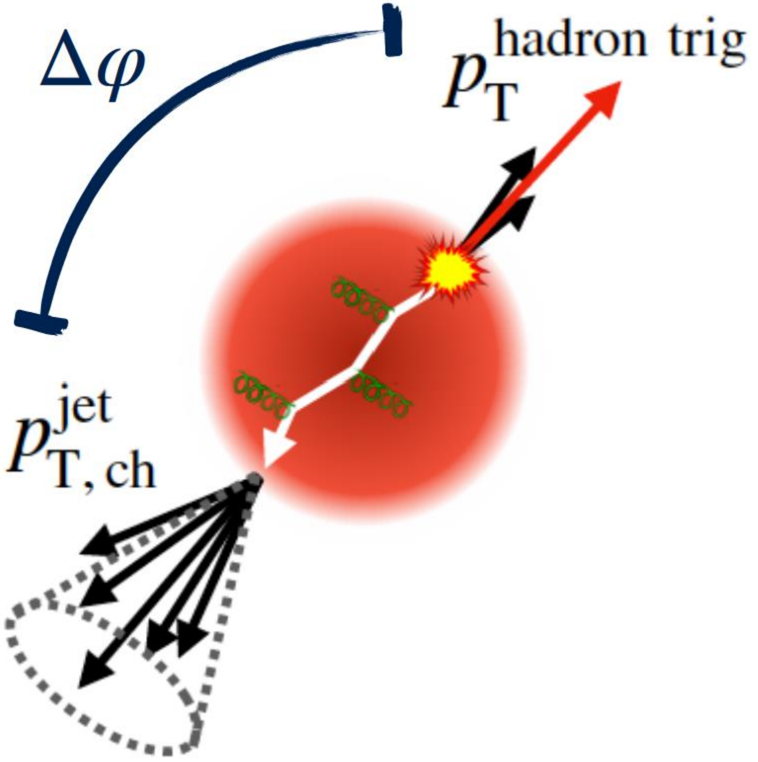


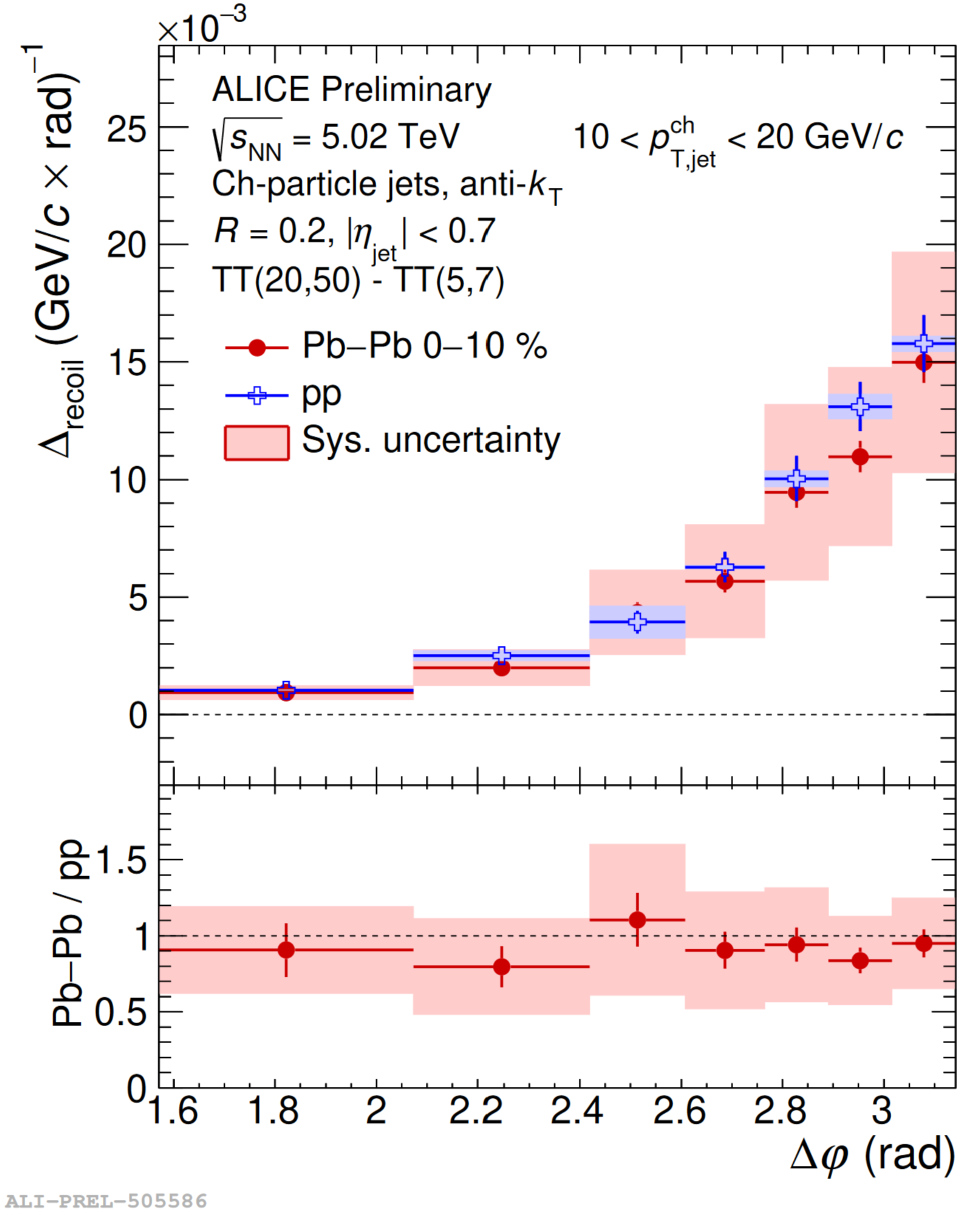


- Measurement of $R = 0.2$ jets in Pb-Pb collisions down to $p_T = 10$ GeV/c
- **Jets back-to-back with photon = no observed Rutherford effect?**
- Tension with PYTHIA vacuum jets → quenching effect?

see also: **CMS Collab.** PLB 785 (2018) 14-39

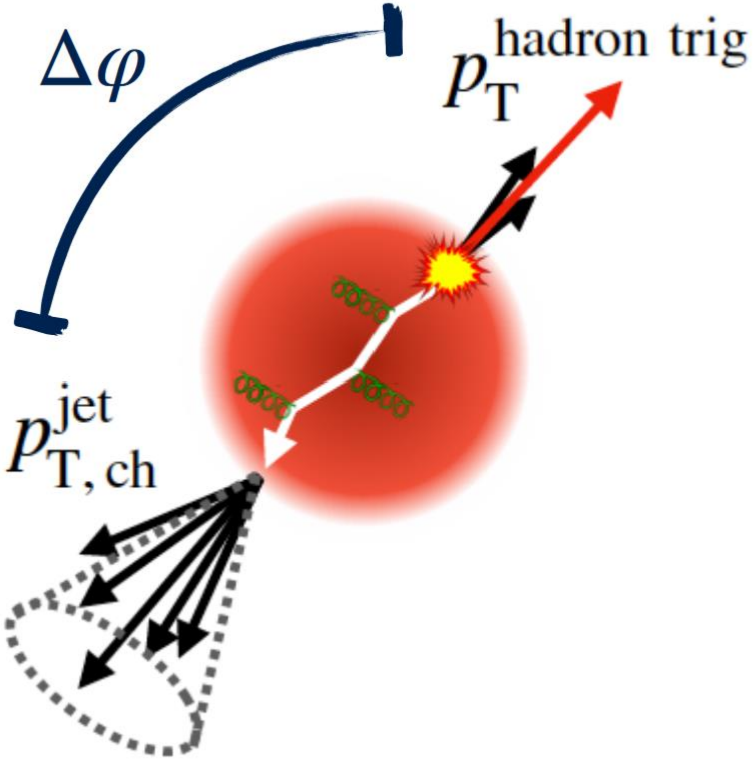
Hadron-jet acoplanarity

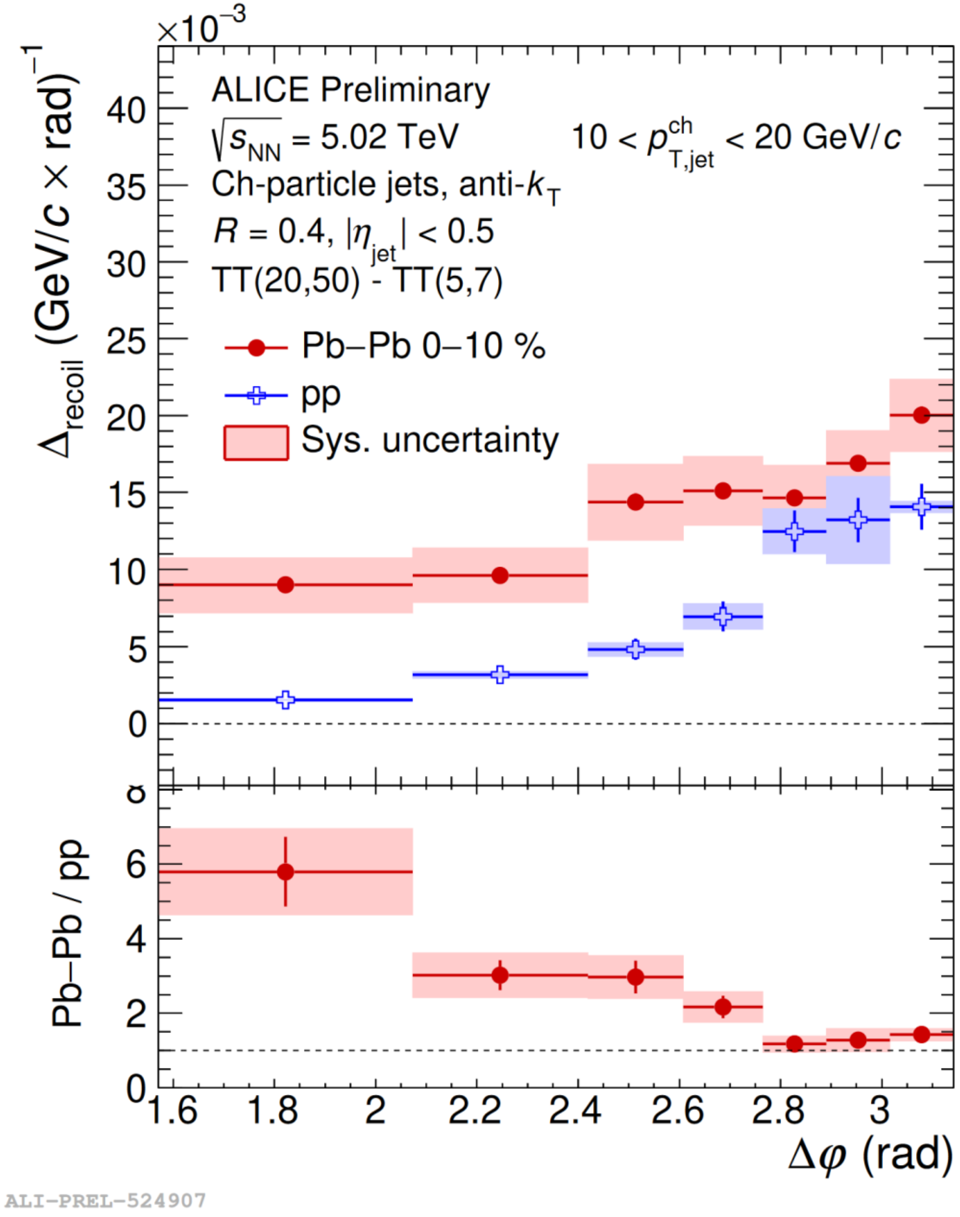




- No broadening for small R…

Hadron-jet acoplanarity





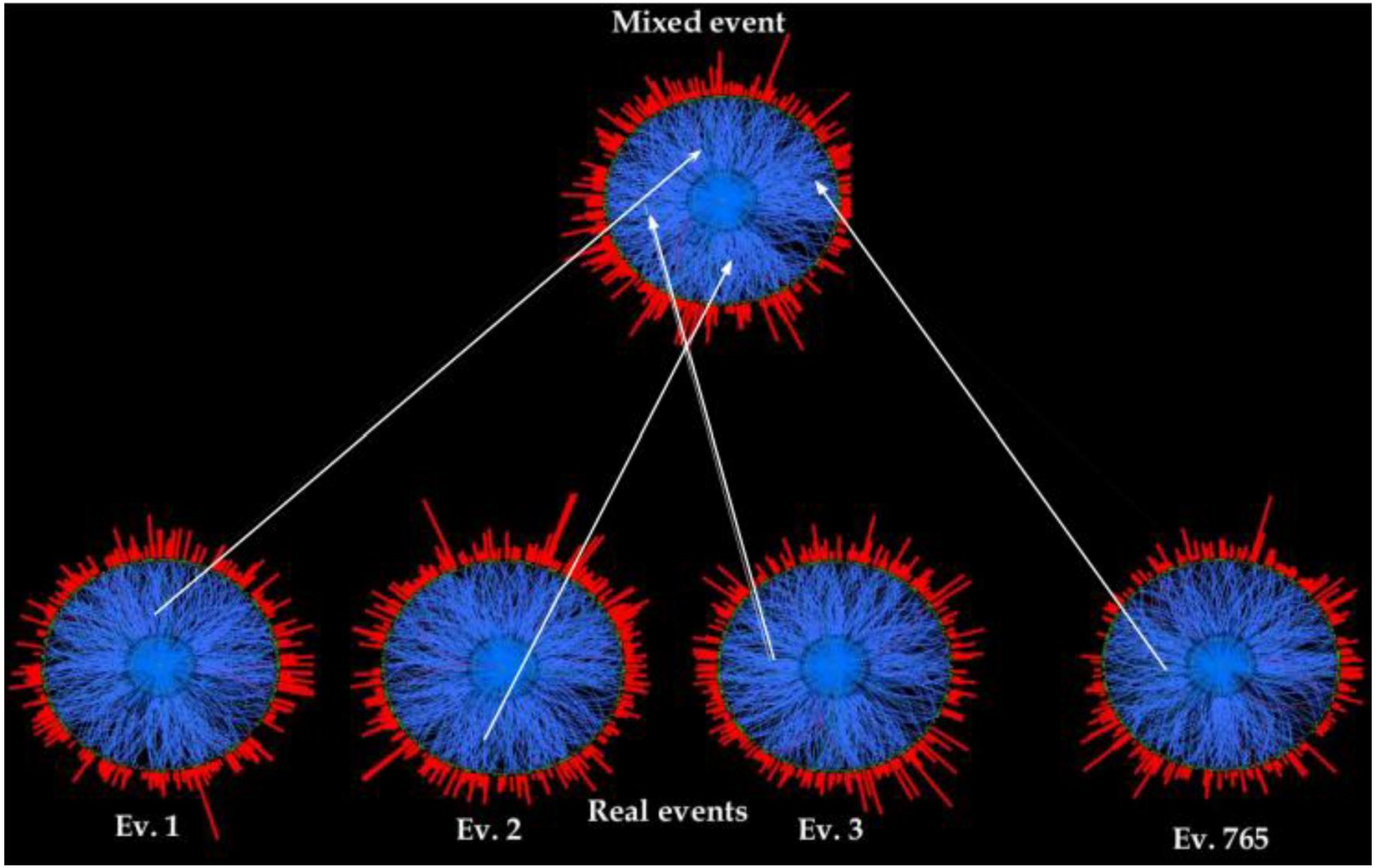
- No broadening for small R…
- **Rutherford effects observed with larger R?**
- Further study needed

Mixed-event (ME) technique

- Randomly mix tracks from similar events together to create **uncorrelated fake ("mixed") events**

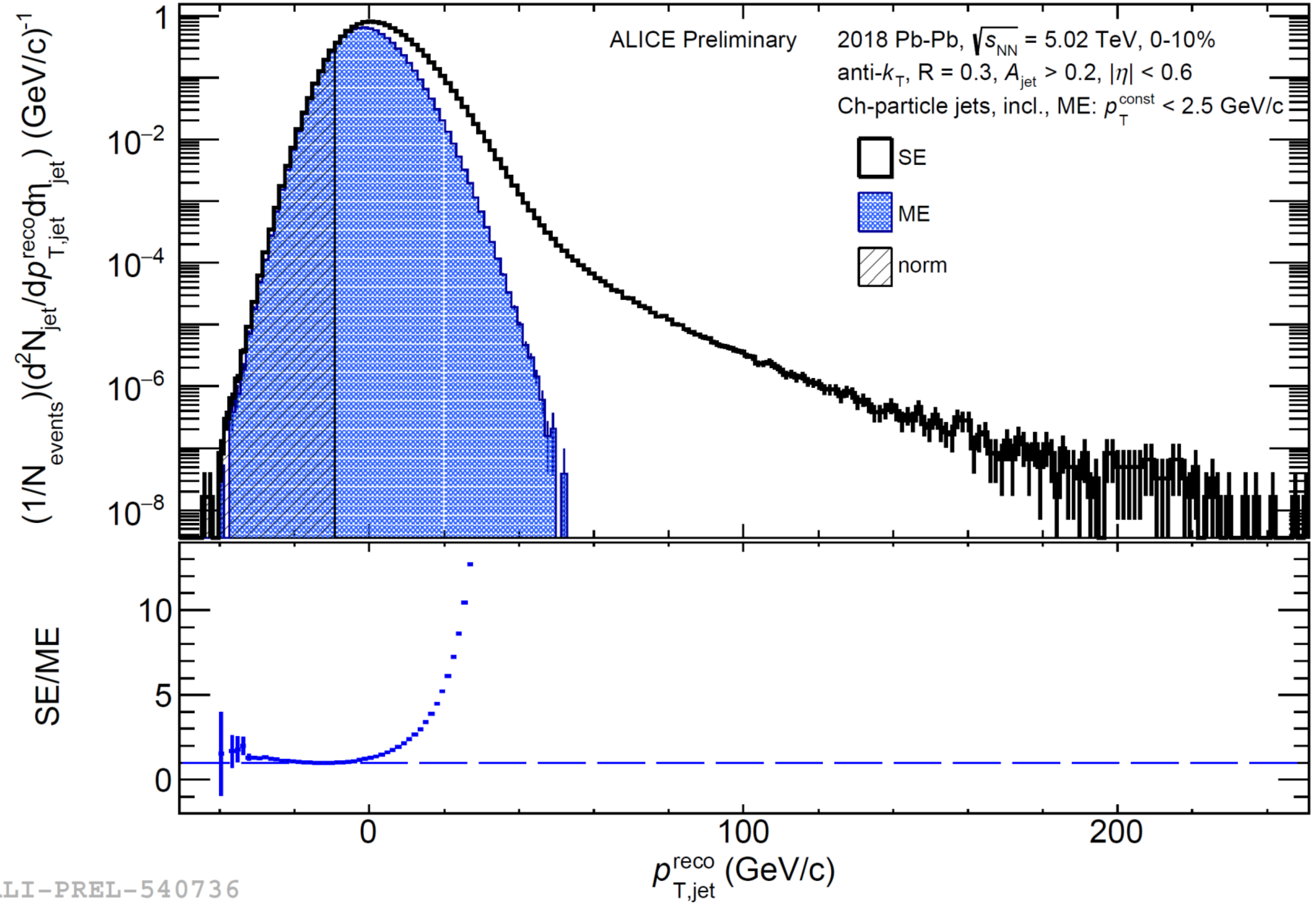
- Classified into one of into 9600 categories based on multiplicity, z-vertex, event plane ϕ

- Require jets to have one track with $p_{\mathrm{T}} > 5$ GeV/c
  - ***Specific jet population***



Using ME technique to correct for fake jets

- Area-based correction (subtraction) for jet p_{T}
- Normalize ME to "same event" (SE) in the uncorrelated region
- **Subtract ME from SE**



Fully unfolded result – jets down to 5 GeV/c

- **Uncorrelated background fully removed!**
- Need to explore selection bias based on leading track selection