# Jet substructure measurements with ALICE

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Probing QCD at High Energy and Density with Jets
Jet Probes of Hot and Cold Nuclear Matter Workshop
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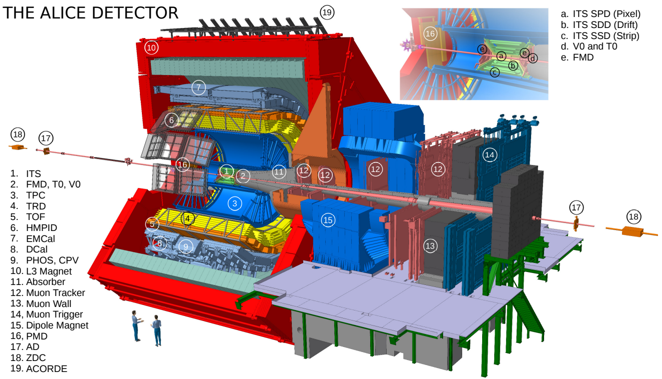
# Jets and their substructure in ALICE

- Jets probe properties of the QGP
- Substructure provides access to the evolution of jet splittings
- Explore via a variety of strategies:
  - Inclusive jet $\mathbf{R_{AA}}$
  - Groomed **jet radius and momentum sharing**
  - **N-subjettiness**
  - **Subjet fragmentation**
- ALICE is well suited for measuring:
  - Low $p_{\mathrm{T}}$ jets
  - Small splitting angles at high efficiency
- Anti-$k_{\mathrm{T}}$ jets measured in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76,\ 5.02$ TeV
  - Charged-particle jets, with larger acceptance
  - Full jets, capturing more $p_{\mathrm{T,jet}}$ with the EMCal



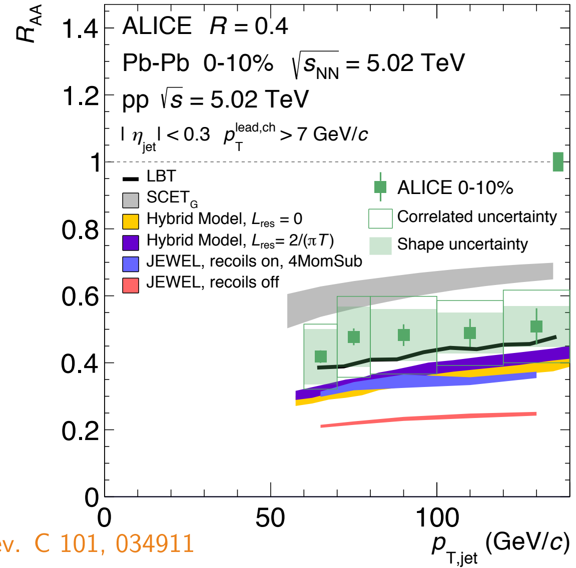
# Inclusive Jet $R_{AA}$

- Inclusive jet $R_{AA}$ is one of the basic measurements for characterizing jet suppression:

$$R_{AA} = \frac{\frac{1}{N_{\mathrm{event}}} \frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\eta_{\mathrm{jet}}}\Big|_{\mathrm{PbPb}}}{\langle T_{AA}\rangle \frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\eta_{\mathrm{jet}}}\Big|_{\mathrm{pp}}}$$

- Measured $R = 0.2$ and 0.4 full jets
- Focus on measuring down to low jet $p_T$
- Most models are able to describe reasonably well, with some slight tension

$\rightarrow$ Need more differential measurements to disentangle effects




Phys. Rev. C 101, 034911

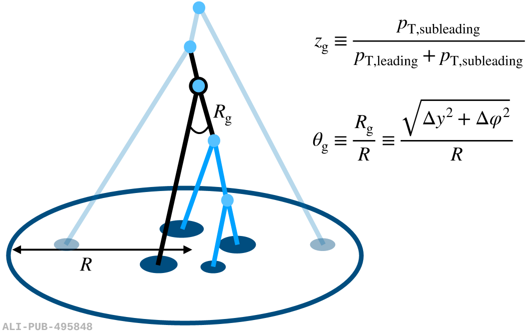
# Groomed Jet Substructure

[1]Larkoski et al., JHEP 05 (2014) 146

- Selecting on substructure variables provides a lever for exploring the splitting phase space.
- Such selections performed with jet grooming
- Often via SoftDrop[1]:

$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R}{R}\right)^{\beta}$$

- pp: Limit contamination of QCD background
- Pb–Pb: Select hard component of quenched jets
- Combinatorial background introduces off diagonal components in response of substructure variables
- How to handle the background?






arXiv:2107.12984

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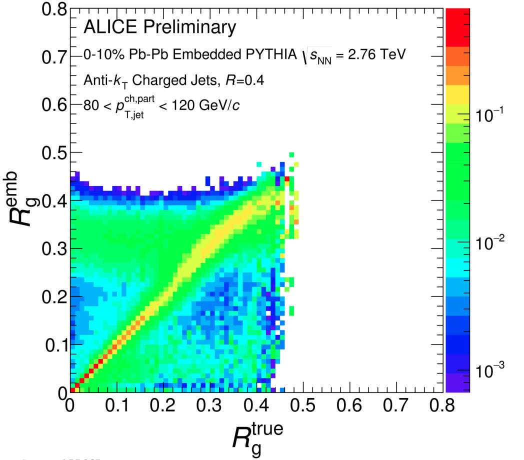


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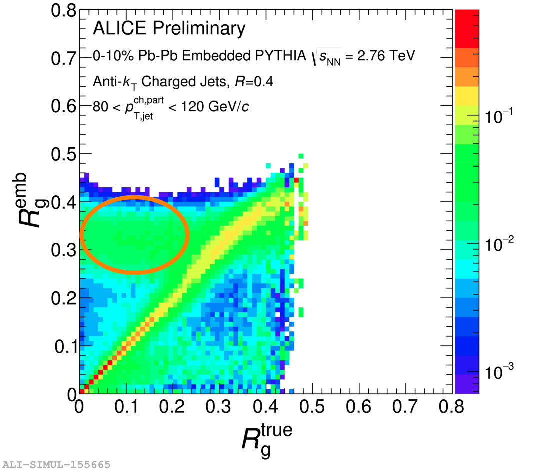
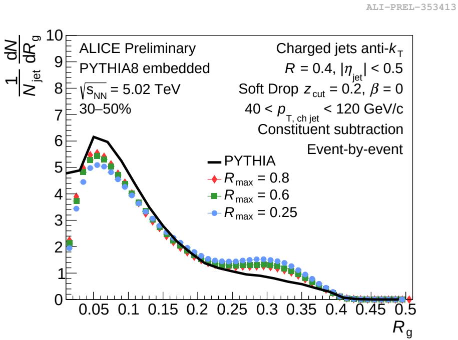
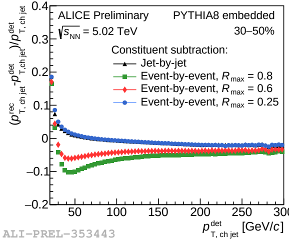
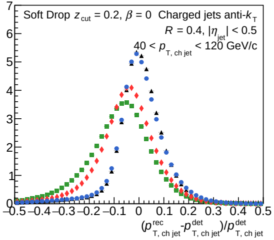


# Understanding Background Contributions

- Different strategies used by ALICE to suppress combinatorial background:
  - Measure small $R$ jets
  - Increase $z_{\mathrm{cut}}$
  - Measure in semi-central collisions
    - Reduces jet quenching relative to central, but combinatorial background is heavily suppressed
- Strategies selected based on constraints of observable
- Utilize event-wise constituent subtraction JHEP 08 (2019) 175.
  - Parameters optimized for Pb–Pb collisions

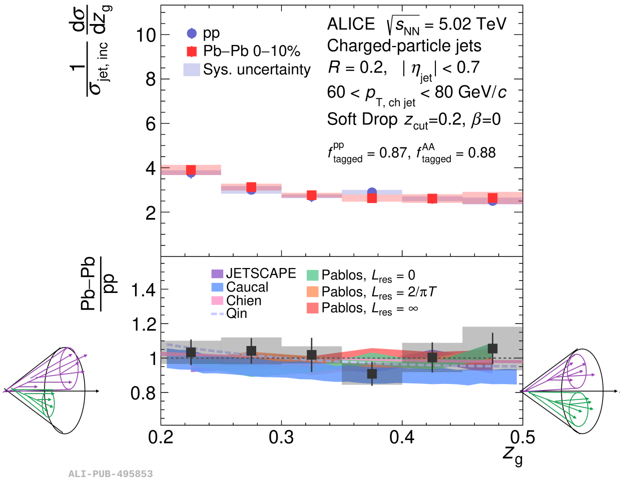


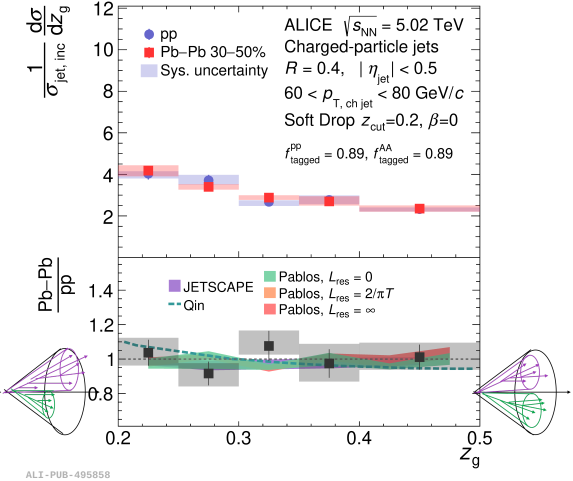



# Fully Unfolded $z_g$ in 0–10%, 30–50% Pb–Pb Collisions

0–10% $R = 0.2$




30–50% $R = 0.4$

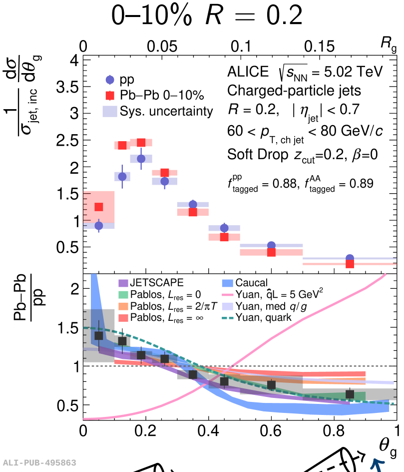


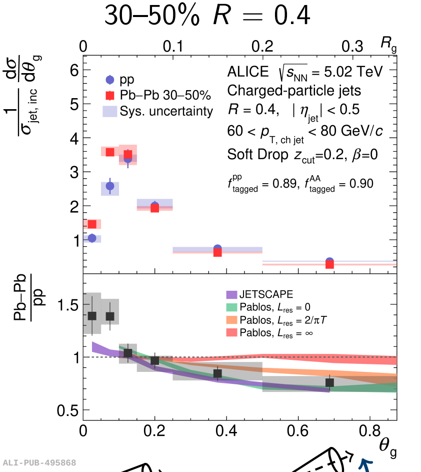

Consistent with **no modification**

arXiv:2107.12984

# Fully Unfolded $R_g$ in 0–10%, 30–50% Pb–Pb Collisions

- Suppression of large angles and enhancement of small angles.
- Qualitative description by most of the models
- Medium has resolving power for splittings
- Promotes narrow or filters out wider subjets





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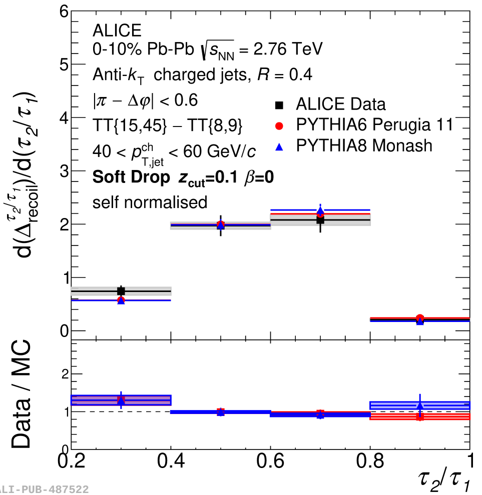
# Exploring radiation patterns with N-subjettiness

- *N*-subjettiness describes the number of subjet prongs in a jet:

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

- Describe how 2-pronged the jet appears via $\tau_2/\tau_1$
  - Insight into radiation patterns
- Measured using recoil jets in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - Measure unbiased jets to lower $p_{T,jet}$
- Subjet axes determined via SoftDrop
- In-medium interactions could shift up or down
- Consistent with **no modification** relative to PYTHIA



ALI-PUB-487522

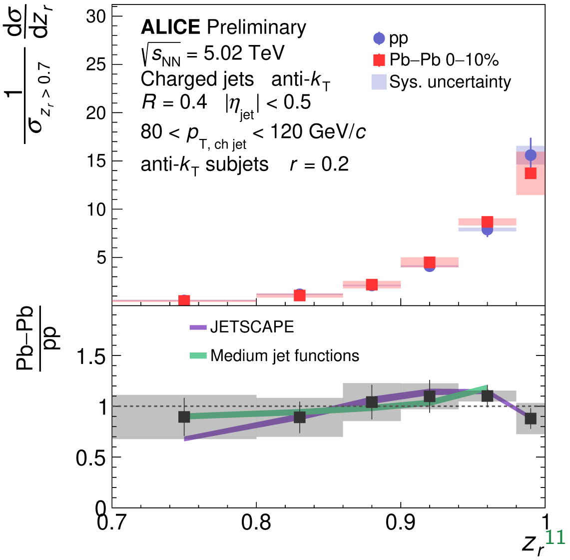
arXiv:2105.04936

# Subjet fragmentation

- Recluster inclusive jets using anti-$k_T$ with resolution parameter $r < R$
- Characterize the subjet fragmentation via:

$$z_r = \frac{p_T^{\text{ch,subjet}}}{p_{T,\text{jet}}^{\text{ch}}}$$

- Leading subjets are measured for pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Consistent with no modification for $r = 0.2$
- **Hints of modification** for $r = 0.1$
  - May be related to **quark/gluon** differences
- Well described by model predictions



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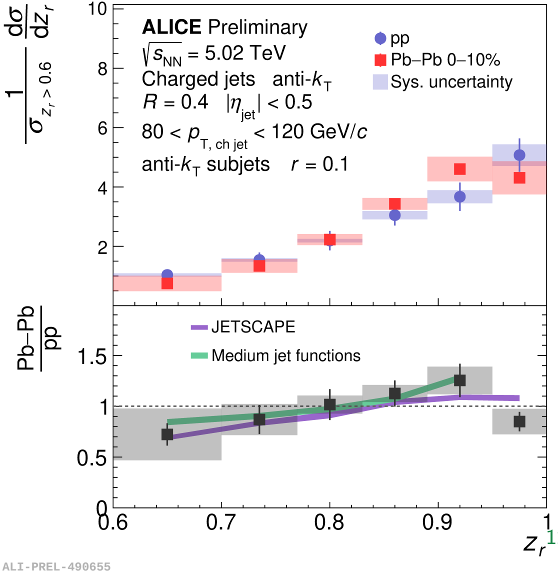
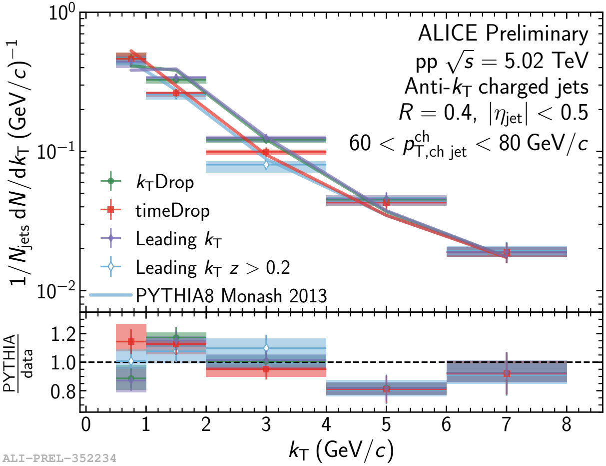


Where else can we look for further modification?

# Selecting specific splitting with Dynamical Grooming

- Focus on subset of splittings via alternative grooming methods
- First measurements of $k_{\mathrm{T,g}}$, $R_{\mathrm{g}}$, and $z_{\mathrm{g}}$ in pp with **Dynamical Grooming**[1]
- Hardest $k_{\mathrm{T}}$ splittings shown for a variety of grooming methods
  - All methods consistent at high $k_{\mathrm{T}}$
- PYTHIA **broadly** reproduces data within stat. and sys. uncertainties
- Recent analytical calculations[2] show **good agreement**
  - Large uncertainties due to non-perturbative effects




[1]Mehtar-Tani et al., Phys. Rev. D 101, 034004
[2]Caucal et al., arxiv:2103.06566

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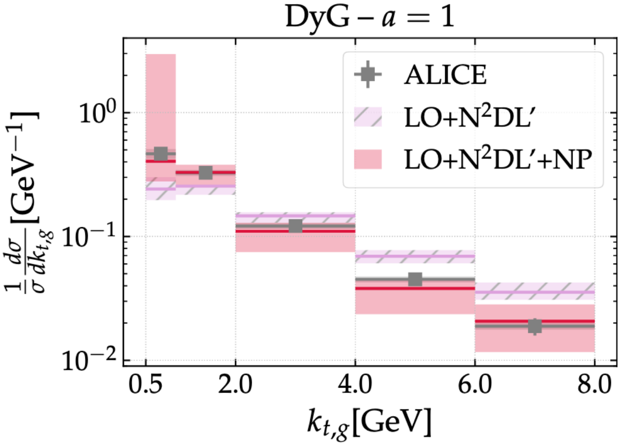


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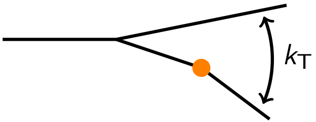
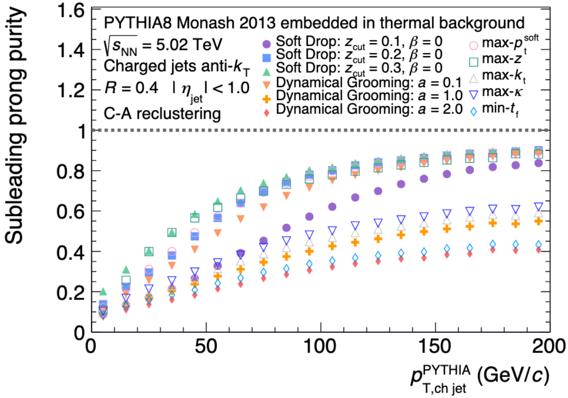
# Extending the hardest $k_T$ splittings to Pb–Pb

- Can we detect high $k_T$ emissions which are a signature of point-like (Moliere) scattering in the medium?
- Groomed jet substructure can facilitate this search
  - Complementary to ALICE large angle recoil jet deflection searches: JHEP 09 (2015) 170
- Two major difficulties in Pb–Pb:
  - Decreased subleading subjet purity for Dynamical Grooming
  - Off-diagonal components in the response

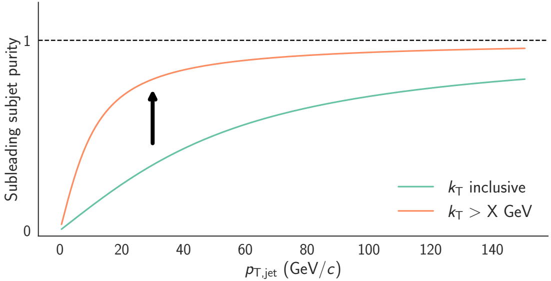


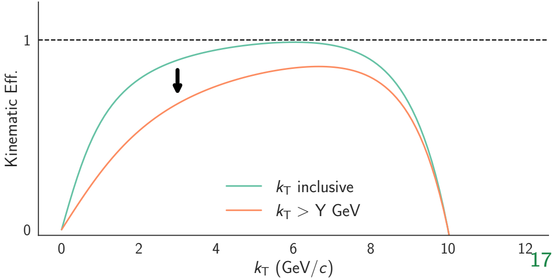




Mulligan, Ploskon, PhysRevC.102.044913

# Extending the hardest $k_T$ splittings to Pb–Pb

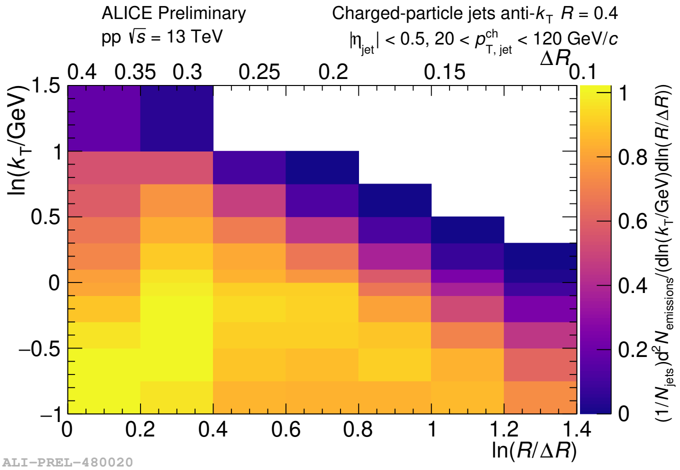
- Subleading subjet purity must be sufficiently high to unfold
- Mismatched splittings are major component of low $k_T$ splittings
- **Minimum $\mathbf{k_T}$** requirement increases purity
- Sketch illustrates effects on purity and kinematic efficiency
  - Optimization problem
- Off-diagonal response components are driven by mismatch of subjet to low $k_T$
  - **Reduced** via minimum $k_T$ requirement
- Minimum $z$ has similar impact for sufficiently small background (eg. smaller $R$)



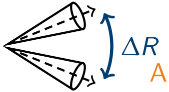



# Further splitting information via the Lund Plane

- The Lund Plane[1] can be used to describes the full set of jet splittings
- ALICE recently measured the fully unfolded primary Lund Plane in pp collisions at $\sqrt{s} = 13$ TeV
- Selections in phase space illustrate some **tensions** with model predictions
- Substantial experimental challenges for measuring in Pb–Pb, but contains wealth of information




[1]Dreyer et al., JHEP 12 (2018) 064

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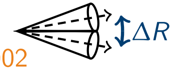

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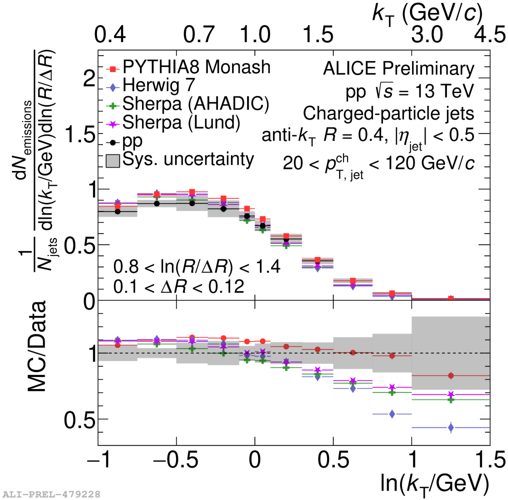


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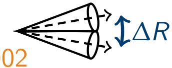


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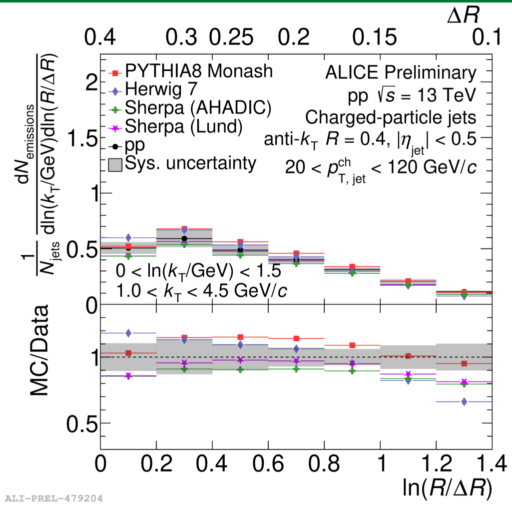


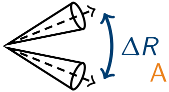


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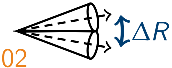


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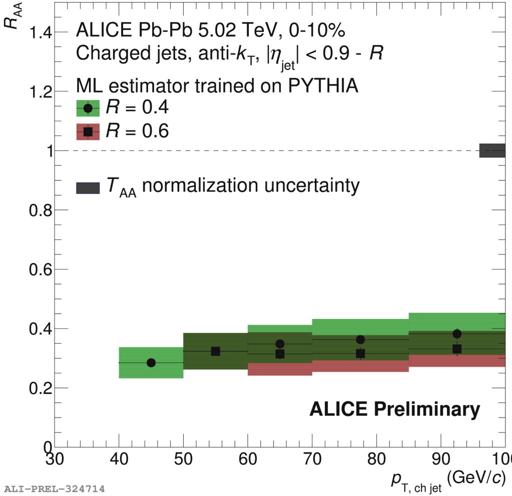
# Inclusive jet $R_{AA}$ via Machine Learning

- Utilize shallow neural network to expand measurements to larger $R$, lower $p_{T,jet}$[1]
- Uses jet properties ($p_{T,jet}$, $\rho$, constituent $p_T$, angularity) to help characterize background contributions
- Measured for $R = 0.4$ and 0.6 charged jets, $R = 0.4$ full jets at $\sqrt{s_{NN}} = 5.02$ TeV
- **Consistent** with area based methods in overlapping regions
- Some dependence on fragmentation patterns
    - Impact on other jet observables to be investigated




[1] Haake, Loizides, arXiv:1810.06324

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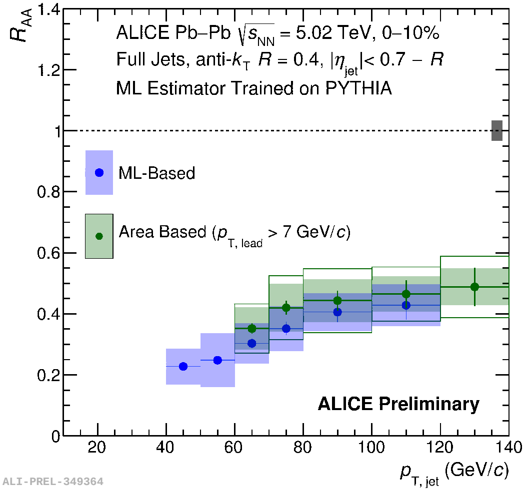
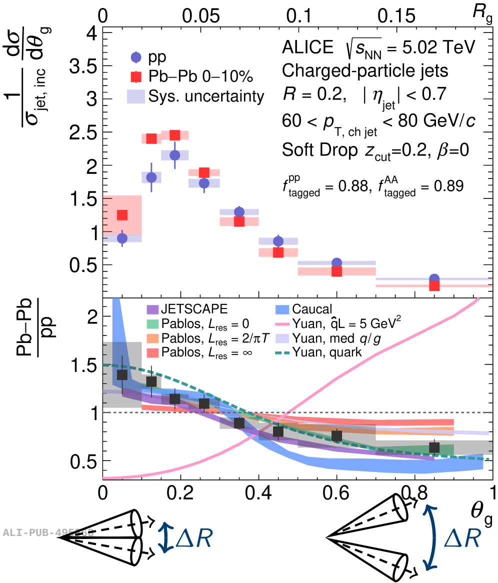


ALI-PREL-349364

[1] Haake, Loizides, arXiv:1810.06324

# Summary and Outlook

- ALICE has measured a diverse collection of jet substructure observables in Pb–Pb collisions:
  - Groomed **jet radius and momentum sharing**
  - **N-subjettiness**
  - **Subjet fragmentation**
- Visible modifications in groomed observables and subjet fragmentation, but not in N-subjettiness
- Variety of observables and tools are upcoming
  - Hardest $k_{T,g}$ with DyG
  - Utilizing the Lund Plane
  - Machine Learning techniques
- Continue to focus on increasing precision
- Stay tuned!



# Backup