

# Jet substructure measurements probing the Lund radiation plane in pp and Pb–Pb collisions

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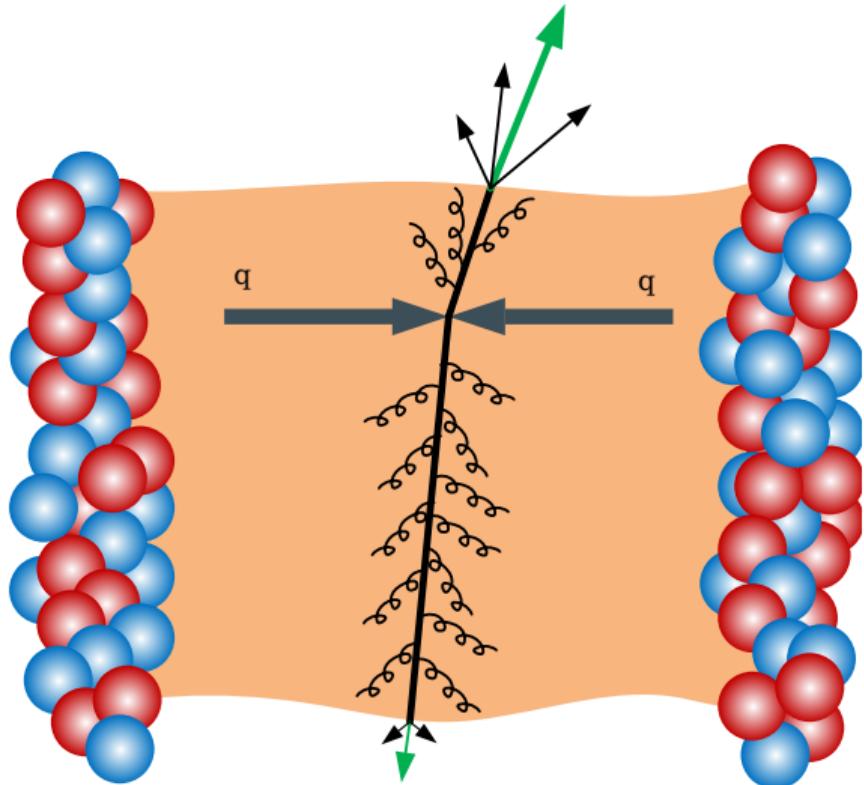
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# Heavy ion collisions and the quark-gluon plasma

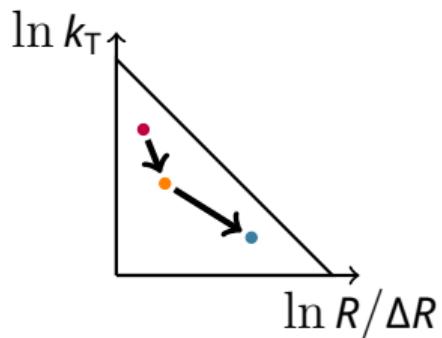
- The quark-gluon plasma (QGP) is formed in ultra-relativistic heavy-ion collisions
  - What can we learn about **QCD from this complex quantum matter?**
  - Is there **emergent structure, such as quasi-particles?**
  - What are the **relevant length scales and what can the QGP resolve?**
  - What can these studies say about **QCD in vacuum?**
- Today, utilize the **Lund Plane** to try to answer these questions



# Outline: Utilizing the Lund Plane in pp and Pb-Pb collisions

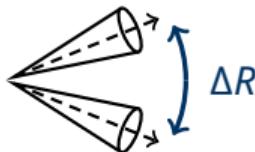
## 1. pp: Inclusive Lund Plane

- Test QCD models
- Baseline for Pb-Pb



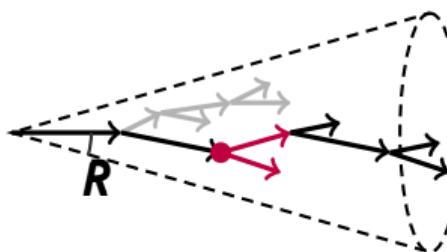
## 2. Pb-Pb: Groomed jet radius $R_g$

- What angular scale does the medium resolve?
- Projection of Lund Plane



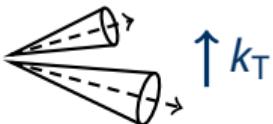
## 3. pp + Pb-Pb: Characterize grooming algorithms

- Selections in Lund Plane
- Optimally find hard splittings



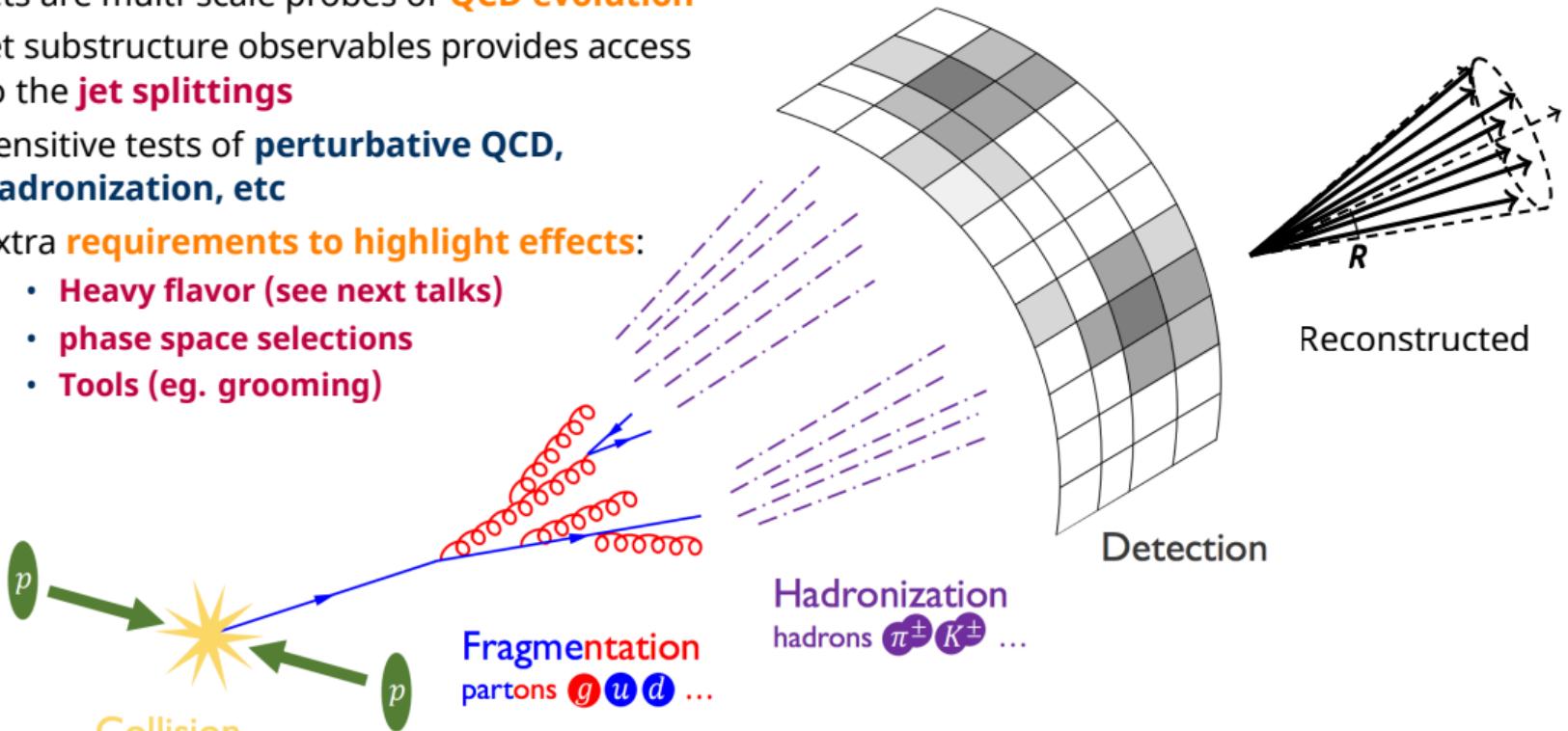
## 4. Pb-Pb: Groomed relative $k_{T,g}$

- Quasi-particle scattering in medium?
- Projection of Lund Plane



# Jets and their substructure in pp collisions

- Jets are multi-scale probes of **QCD evolution**
- Jet substructure observables provides access to the **jet splittings**
- Sensitive tests of **perturbative QCD, hadronization, etc**
- Extra **requirements to highlight effects:**
  - Heavy flavor (see next talks)
  - phase space selections
  - Tools (eg. grooming)



# Measuring the Lund Plane in pp collisions

- Test QCD description of the jet splittings via primary Lund Plane<sup>1</sup>

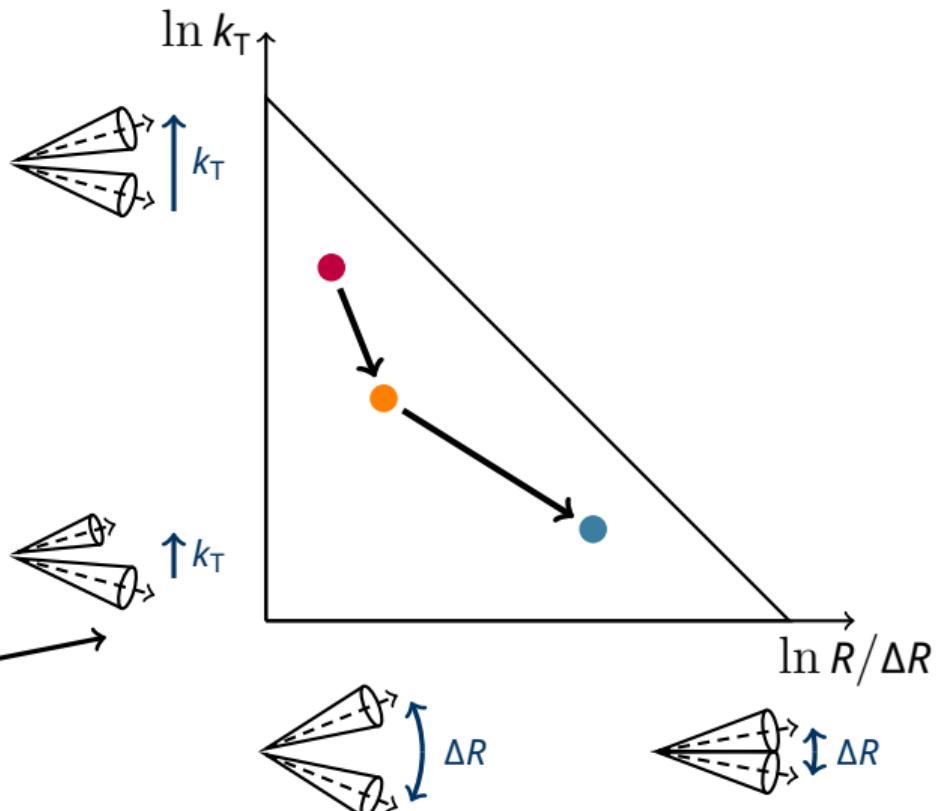
- Lund Plane density:

$$\rho(\theta, k_T) = \frac{1}{N_{\text{jets}}} \frac{d^2 n}{d \ln(R/\Delta R) d \ln k_T}$$

- pp @ 13 TeV,  $R = 0.4$  anti- $k_T$  ch-particle jets in  $20 < p_{T,\text{jet}}^{\text{ch}} < 120 \text{ GeV}/c$ 
  - Declustering via C/A
- Sensitive to effects from **hadronization and underlying event**

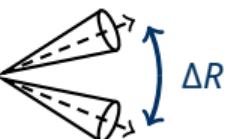
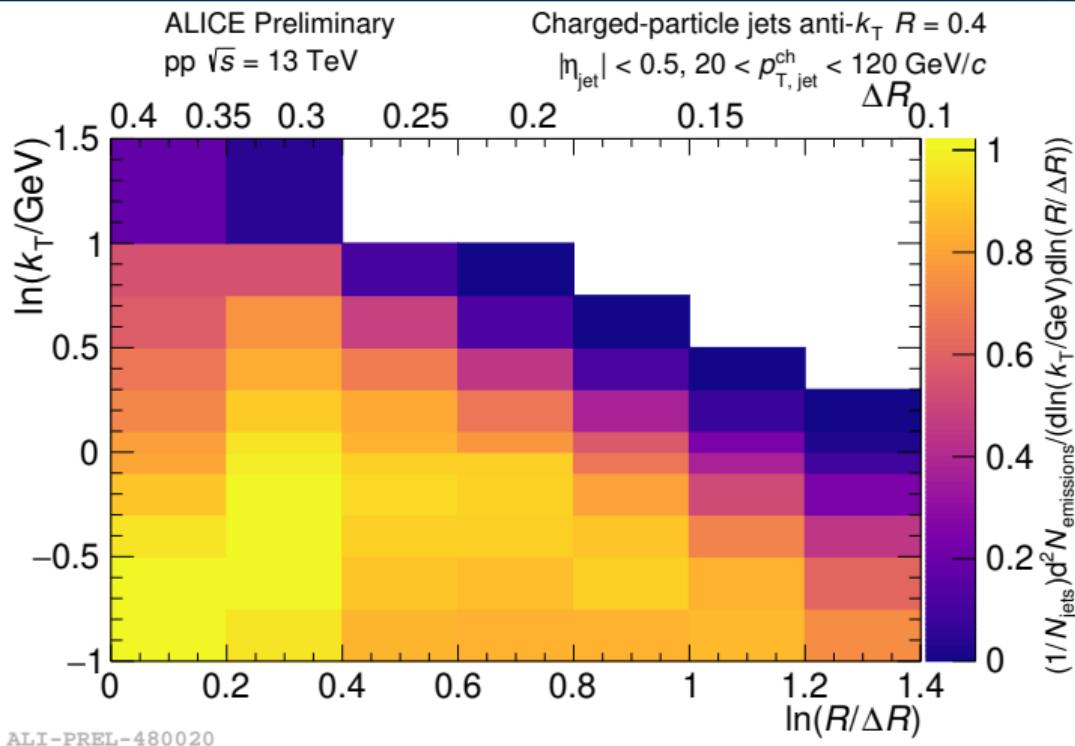


<sup>1</sup>Dreyer et al.,  
JHEP 12 (2018) 064



# Lund Plane density in pp collisions at 13 TeV

- Fully corrected Lund Plane density
- Utilize **3D unfolding** in  $(p_{T,\text{jet}}, \ln k_T, \ln R/\Delta R)$
- Unfolding effects  $\sim 20 - 30\%$
- Largest corrections in the steeply falling tails of  $k_T$
- $N_{\text{jets}}$  normalization from separate **1D unfolding**
- Make selections in phase space for model comparisons



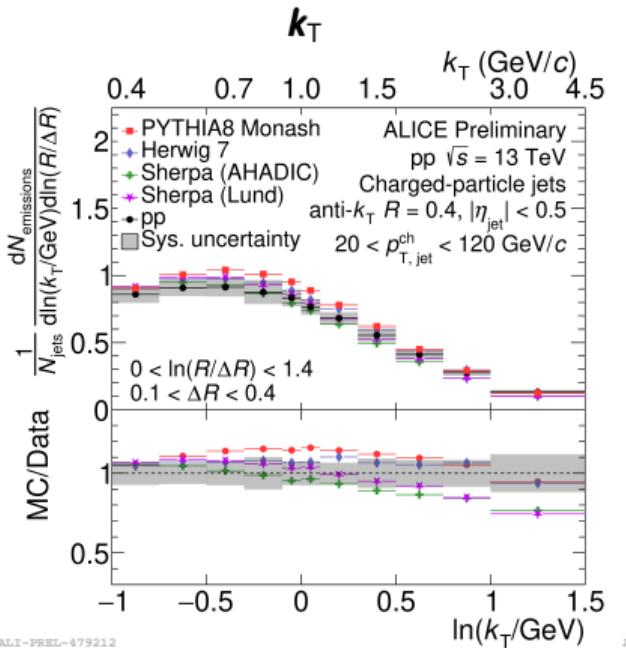
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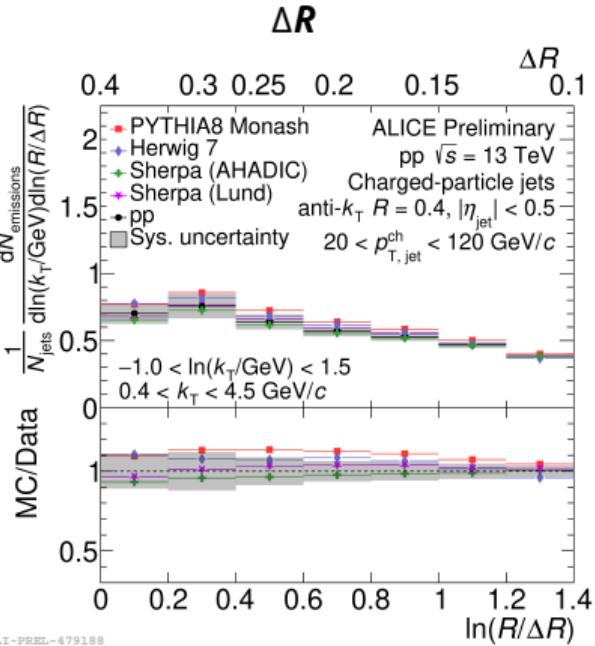
# Testing model comparisons: inclusive

Models for comparison:

- PYTHIA8 Monash 2013
- Sherpa 2.2.8 with cluster-like hadronization (AHADIC)
- Sherpa 2.2.8 with string-like hadronization (Lund)
- Herwig 7
- $\Delta R, k_T$  agree within  $\sim 10\%$  except SHERPA is low for  $k_T \gtrsim 2 \text{ GeV}/c$



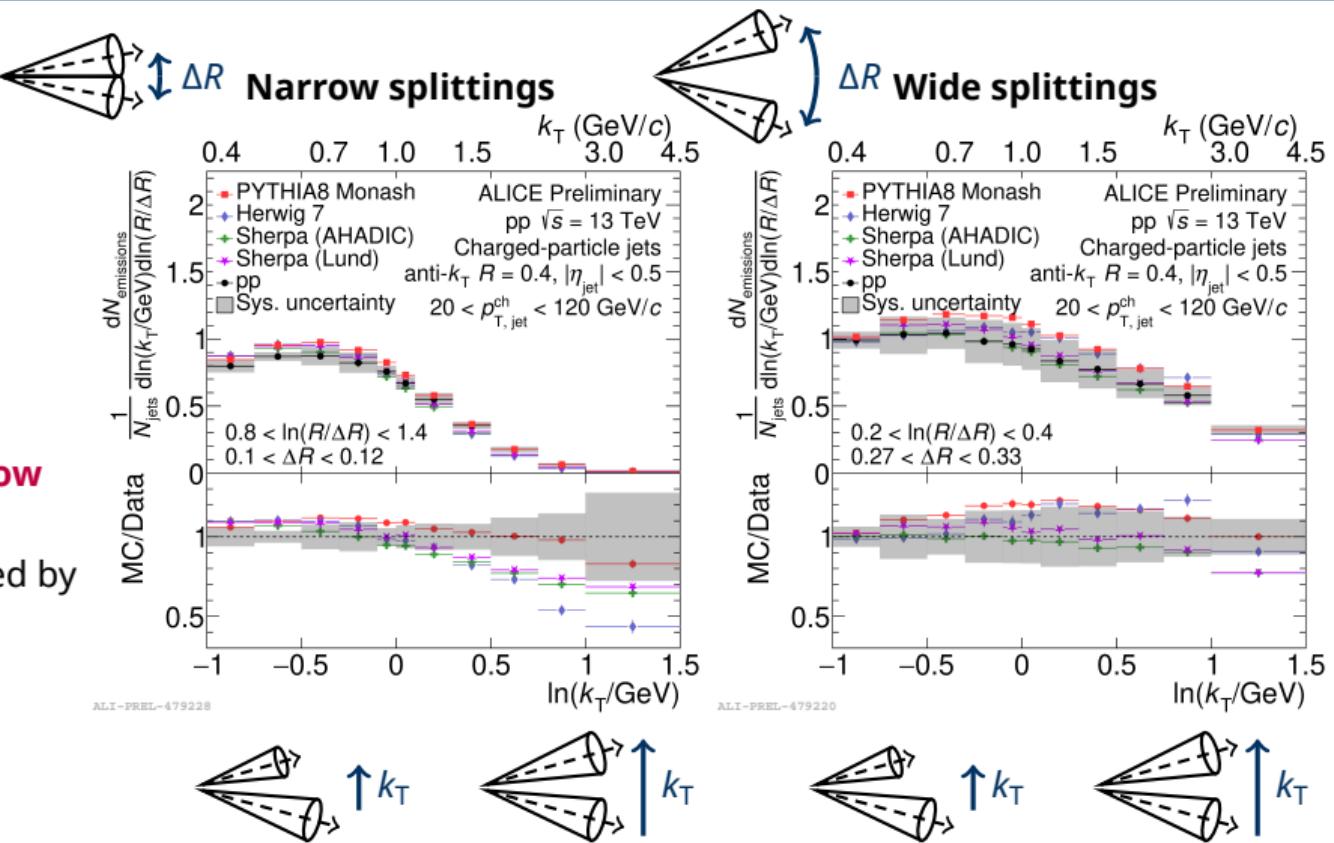
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# Testing model comparisons: narrow vs wide splittings

Models for comparison:

- PYTHIA8 Monash
- Sherpa (AHADIC)
- Sherpa (Lund)
- Herwig 7
- Disagreement for **narrow splittings at high  $k_T$**
- Wide splittings described by models **within 10-20%**



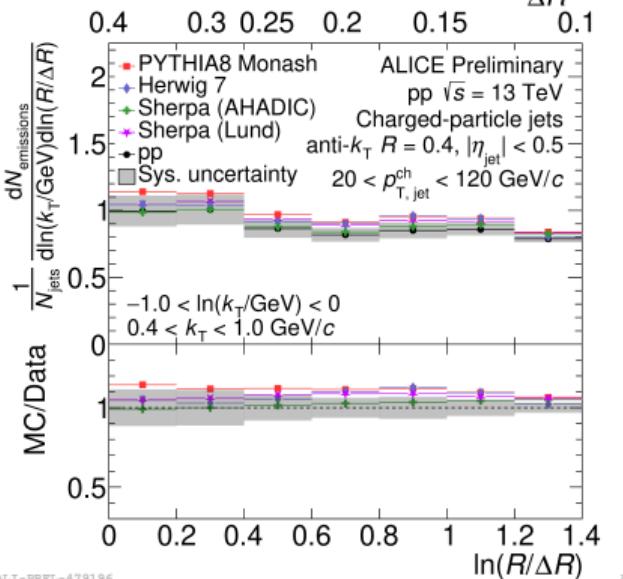
# Testing model comparisons: perturbative vs non-perturbative splittings

Models for comparison:

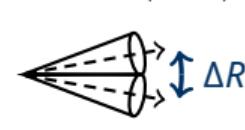
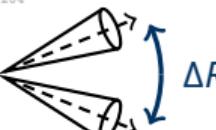
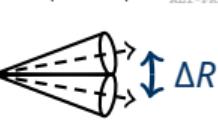
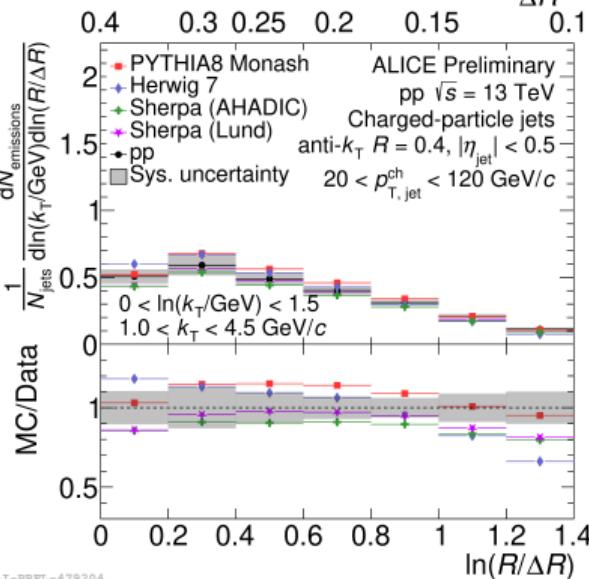
- PYTHIA8 Monash
- Herwig 7
- Sherpa (AHADIC)
- Sherpa (Lund)
- Non-perturb. region described **within 10-20%**
- Perturbative region described **within  $\sim 20\%$**



**Non-perturb. ( $k_T < 1$ )**



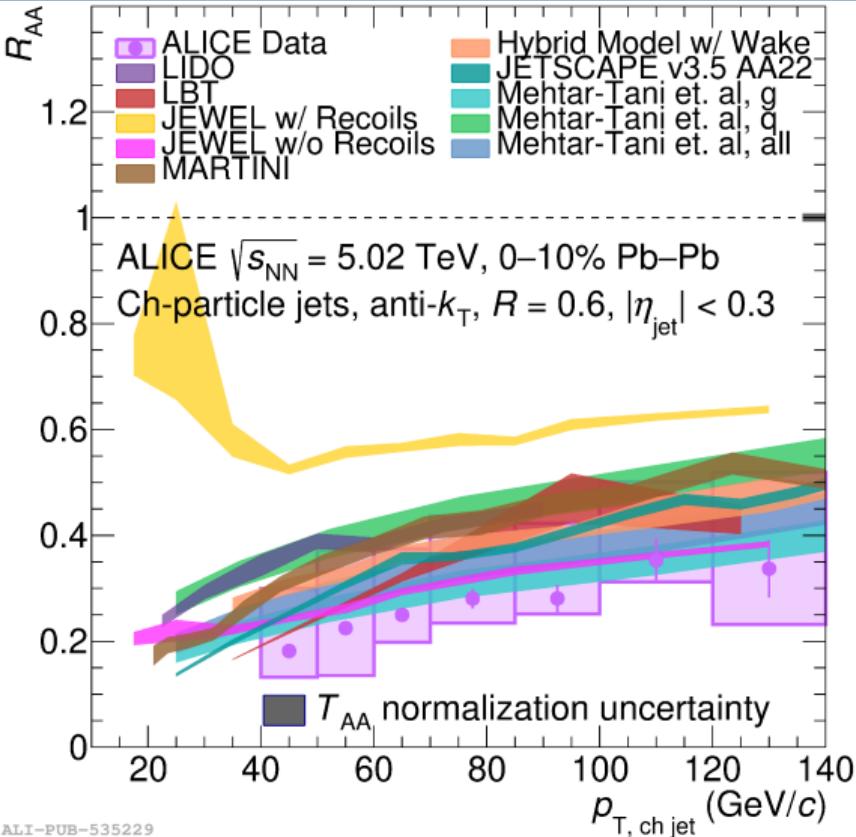
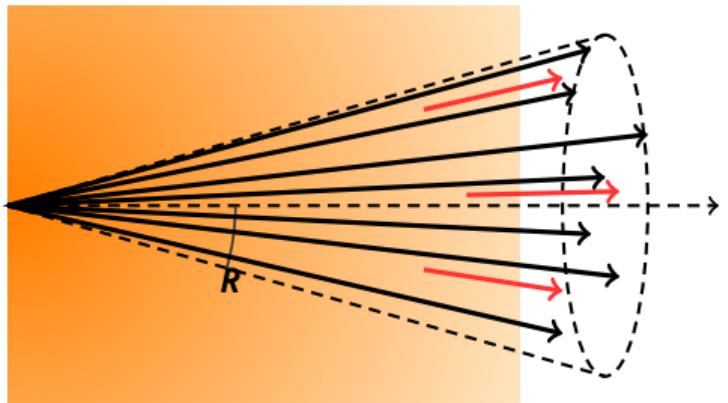
**Mostly perturb. ( $k_T > 1$ )**



# Jets and their substructure in Pb-Pb collisions



- Partons propagate and interact with medium, **modifying evolution** of parton shower
  - Jet-medium interactions modify the **jet properties and internal structure**
  - Medium properties encoded** into jet modification
- Jets are in-situ **probes of QGP dynamics**

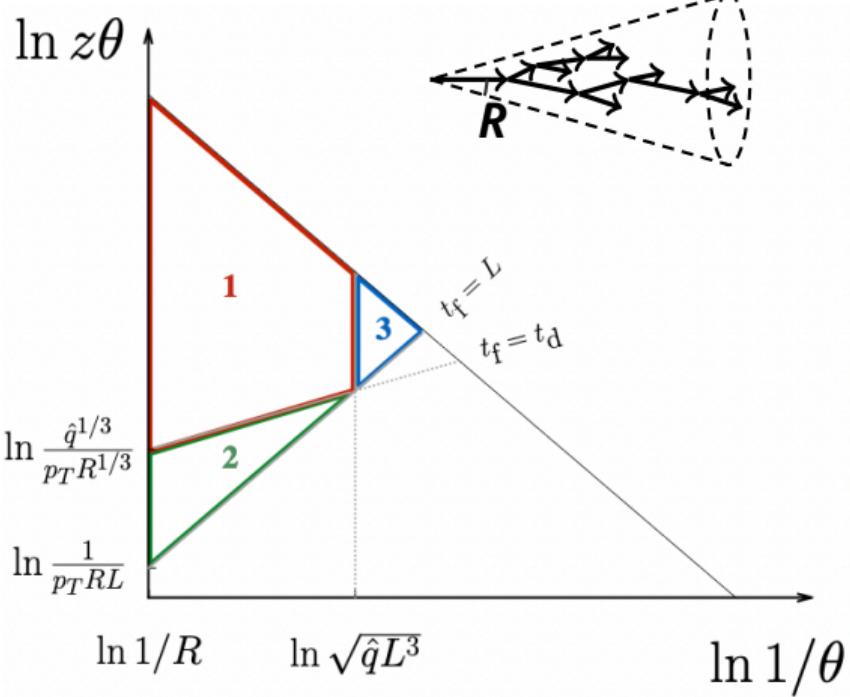
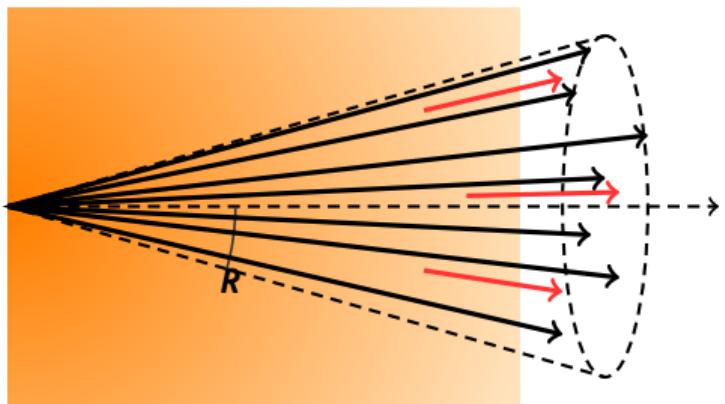


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H. Andrews et al., J.Phys.G 47 (2020) 6, 065102

# Medium properties from jet substructure

## Resolving medium scales

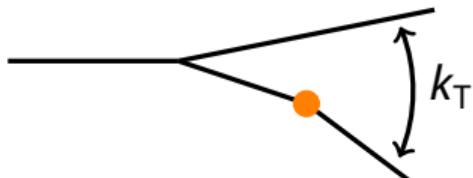
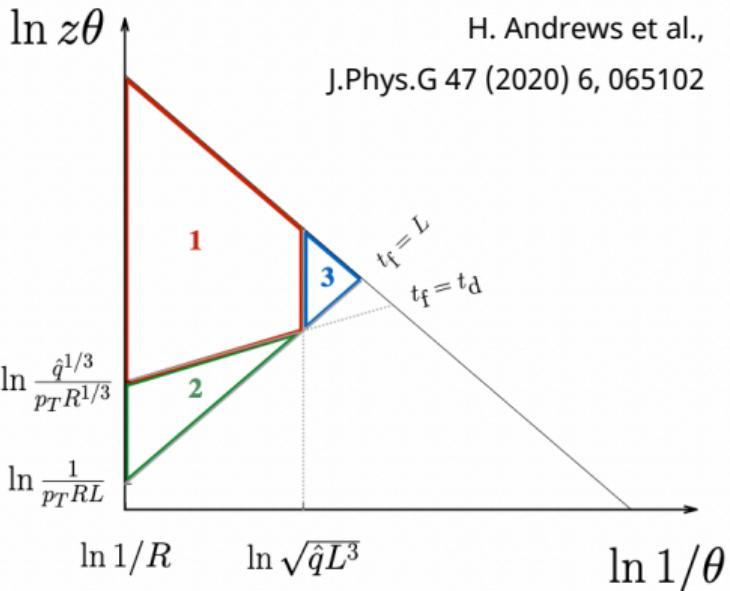
- Substructure observables sensitive to **which medium properties?**
- What are the **relevant length scales?**

### 1. Color coherence

- When do partons interact coherently?**  
→ Explore via **groomed jet radius ( $R_g$ )**

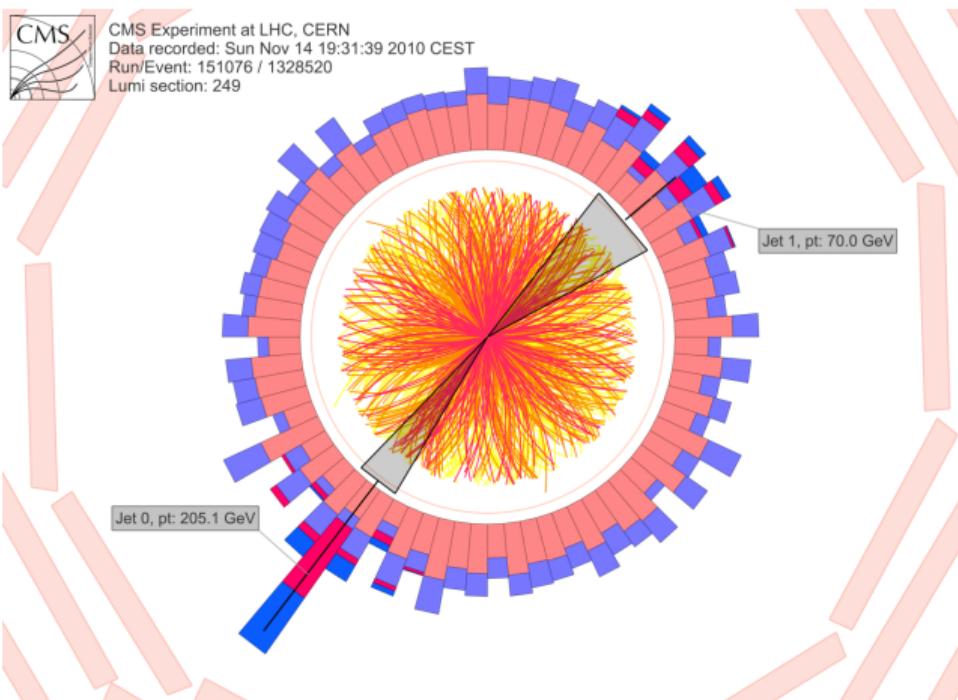
### 2. Medium scattering centers

- Is there **emergent structure, such as quasi-particles?**
  - Complementary searches via (sub)jet deflection
- Search for high  $k_T$  emissions via groomed substructure as **signature of point-like (Moliere) scattering**
- Optimal way to find the relevant splittings?**



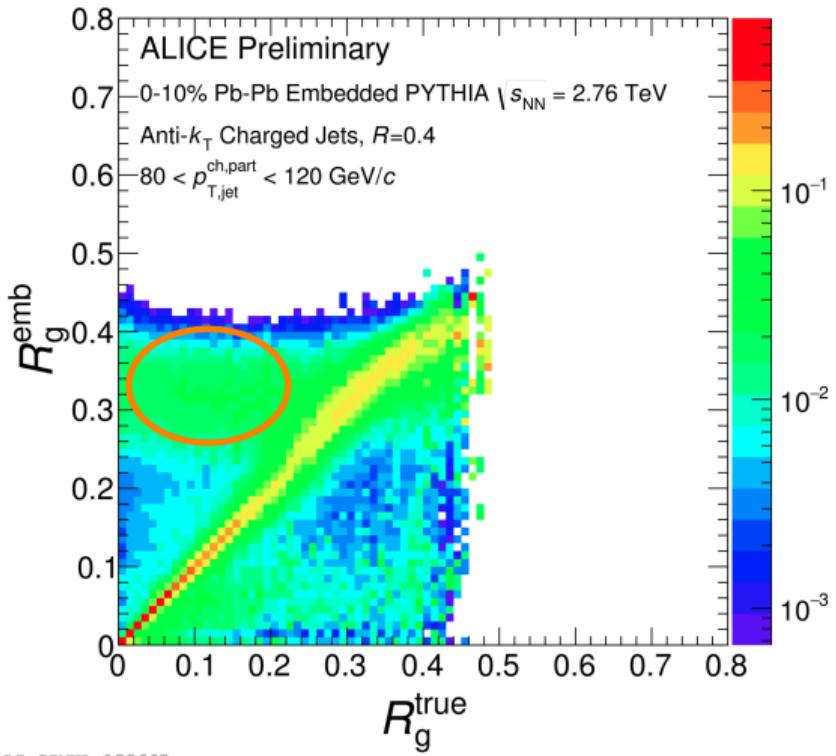
# Experimentally accessing jets in heavy-ion collisions

- Jets are **experimentally challenging** due to **large uncorrelated background** from underlying event
    - Fluctuations can be  $\sim p_{T,\text{jet}}$
  - Substructure **especially susceptible**
- Careful **bkg subtraction is critical!**
- Exp. approaches (not exclusive):
  - Subtract **event-by-event bkg**, unfold
    - Bkg fluc. limits accessible kinematics
  - Jet grooming** aims to removes uncorrelated bkg (contamination?)
  - Reduce bkg sensitivity or size**
  - Rethink problem: **statistical + correlation methods** remove bkg on ensemble level



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# Identifying hard splittings: Soft Drop

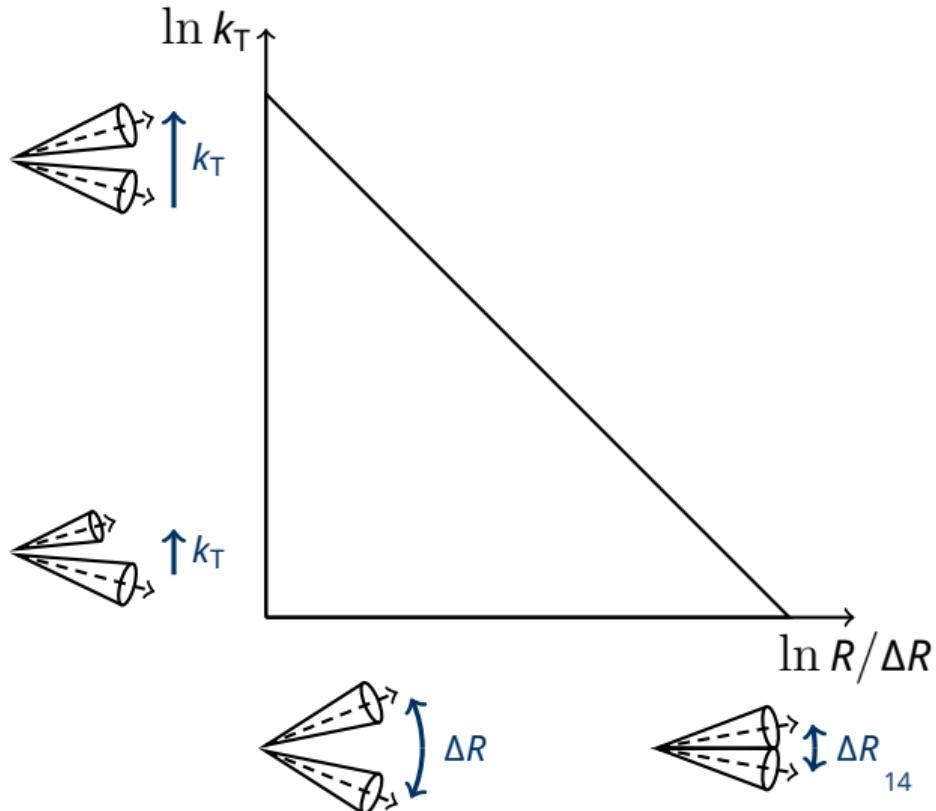
- $\theta_g = R_g/R = \frac{\sqrt{\Delta\phi^2 + \Delta y^2}}{R}$
- $k_T = p_T^{\text{sublead}} \sin \Delta R$
- Iteratively follow splitting tree

## Soft Drop

Larkoski et al., JHEP 05 (2014) 146

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

- $z_{\text{cut}} = 0.2$
- $\beta = 0$



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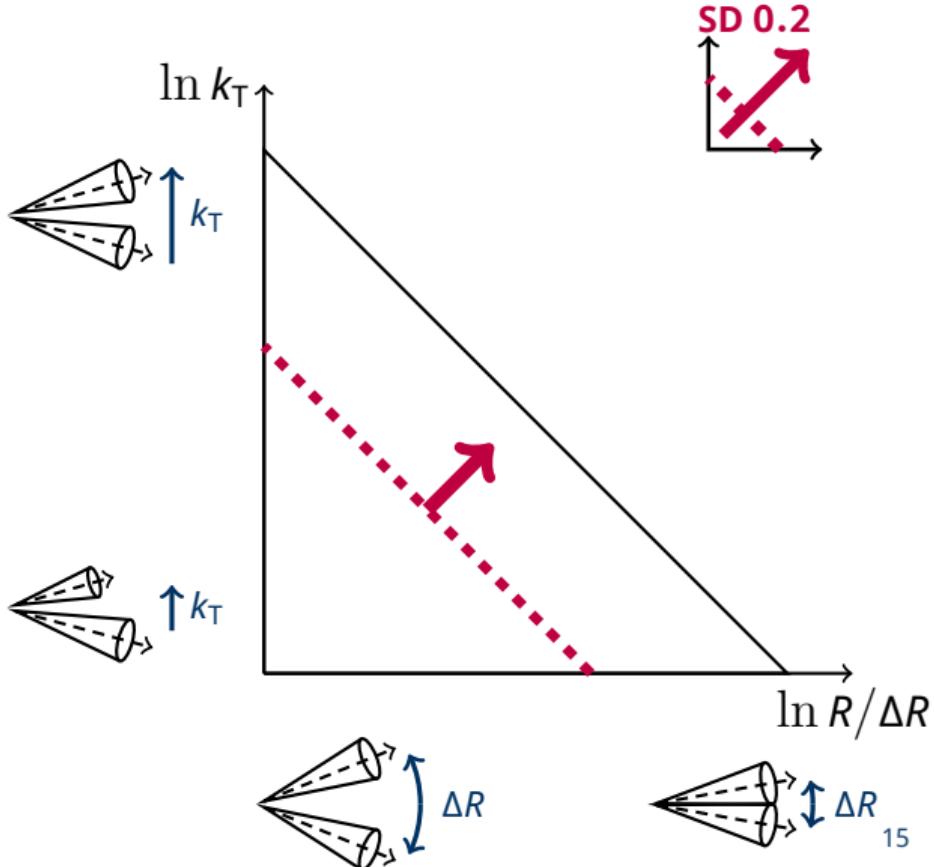
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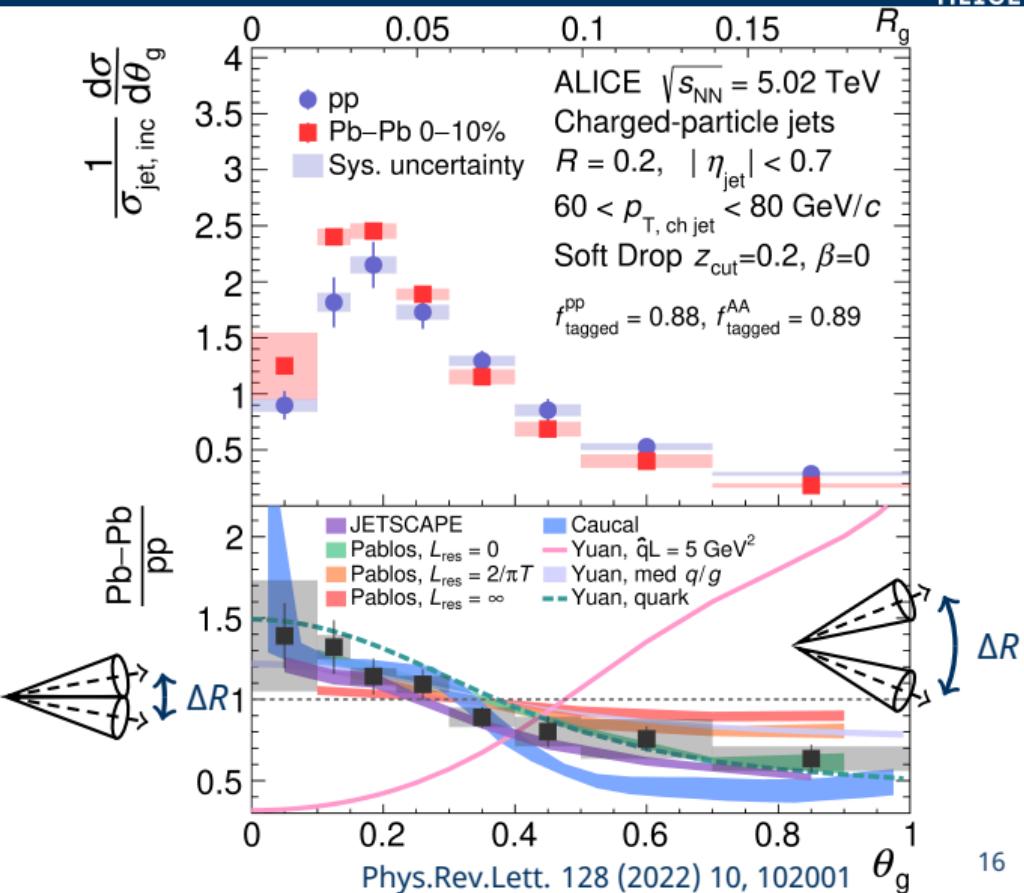
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# Exploring angular dependence via groomed substructure

- Characterize **QGP resolution scale** via **angular dependence** of hard splittings
- Relative **suppression of large angles** and **enhancement of small angles**
- **Promotes narrow** or **filters out wider** subjets
- **Well described** by most models
- Incoherent energy loss effects may indicate **medium resolving the splittings?**  
Or **changing q/g fraction?**  
Or **"survival bias"?**



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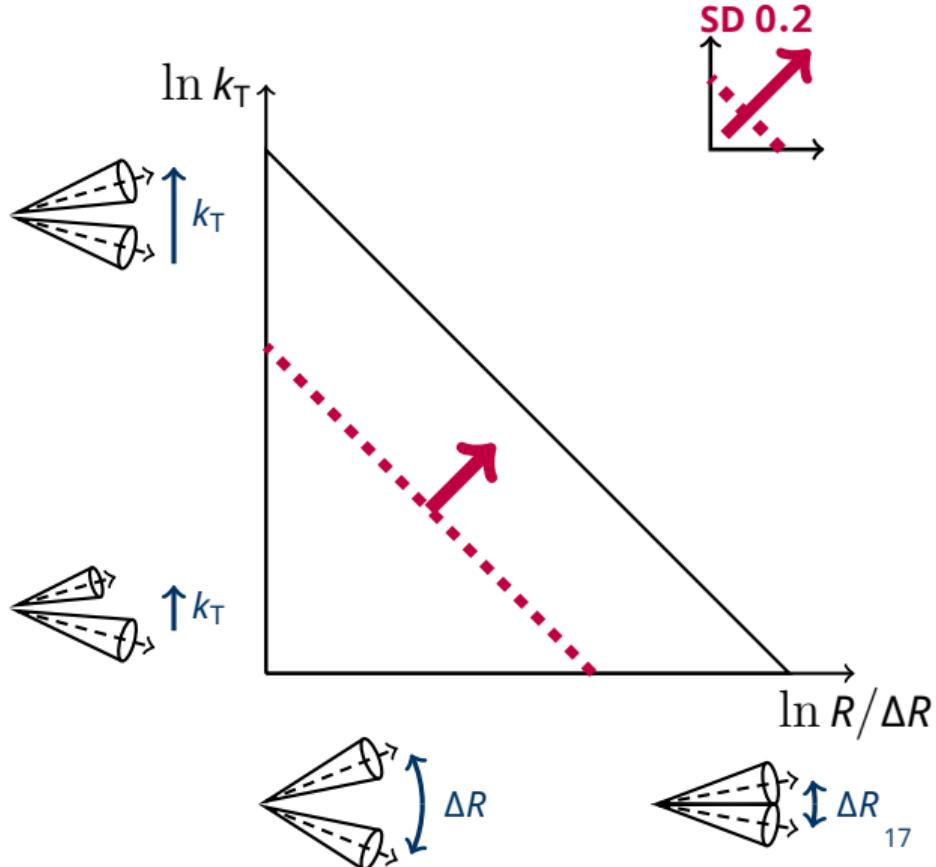
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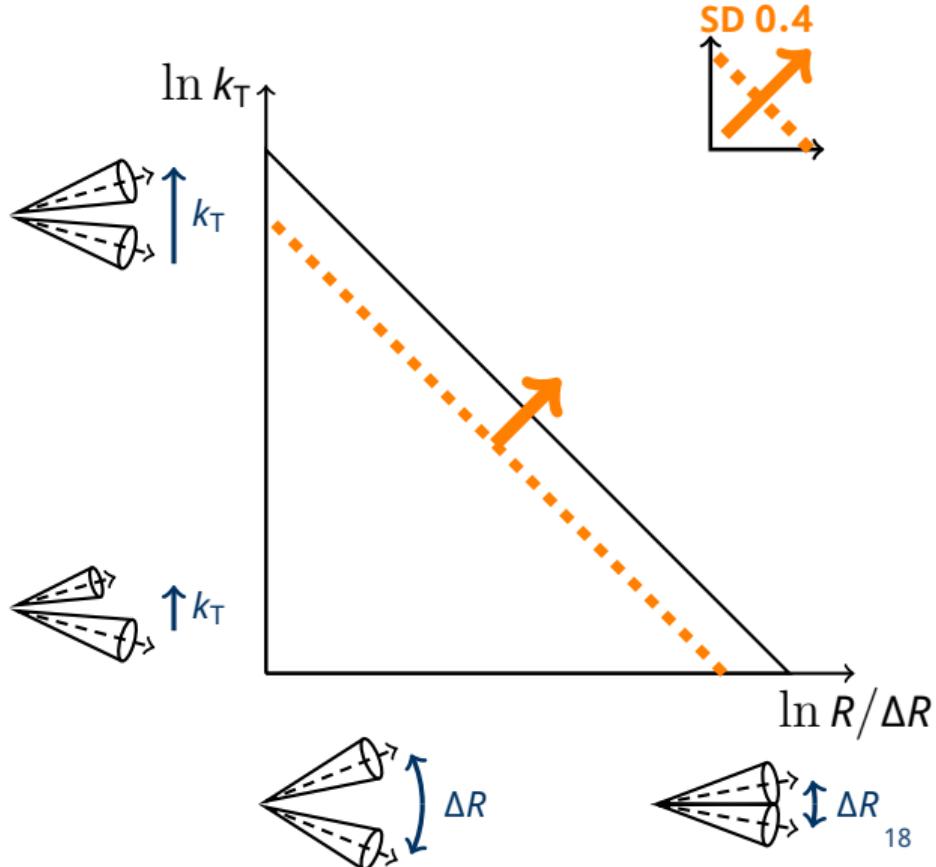
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- $z_{\text{cut}} = 0.2, 0.4$
- $\beta = 0$
- $z_{\text{cut}} = 0.4$  trades phase space to focus on **angular dependence**



# Identifying hard splittings: Dynamical Grooming

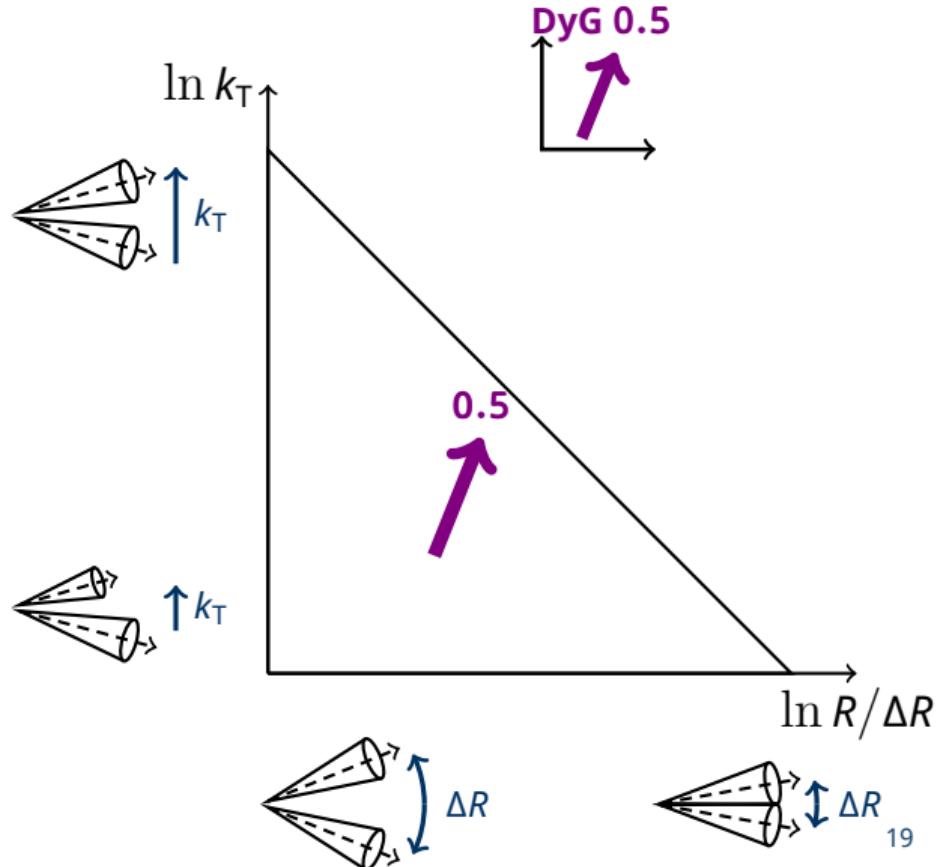
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## Dynamical Grooming

Mehtar-Tani et al., PhysRevD.101.034004

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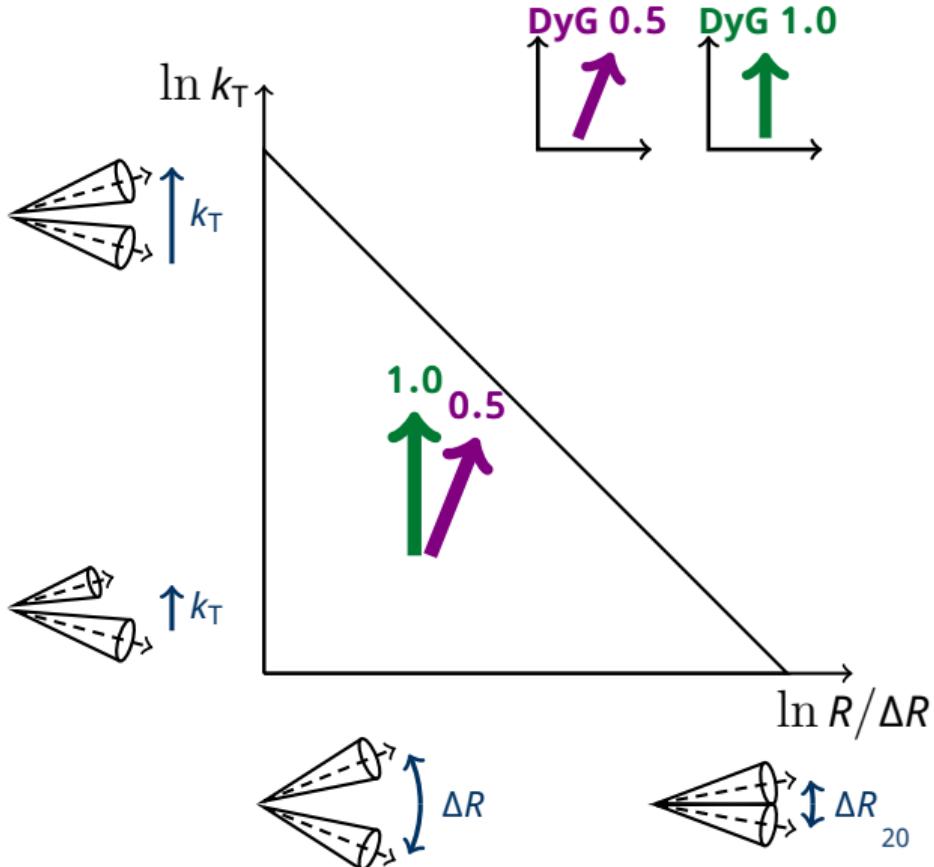
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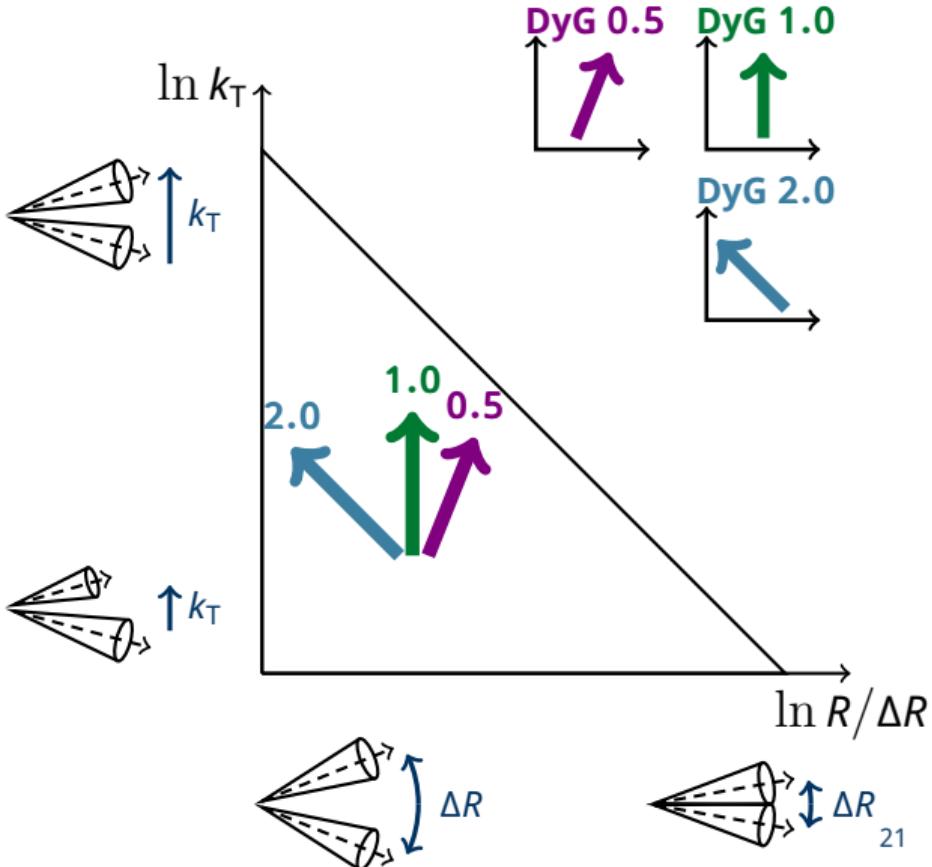
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- $a = 2$ : "time" - shortest splitting time  
 $t_f^{-1} \sim \kappa^2 p_T$



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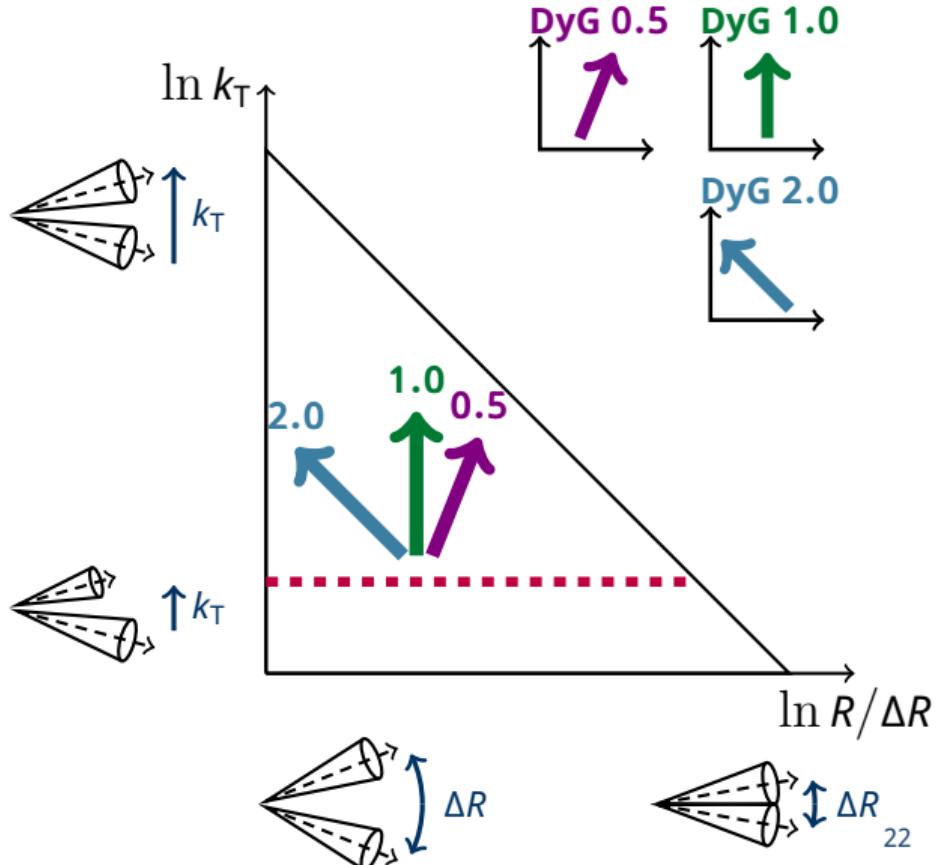
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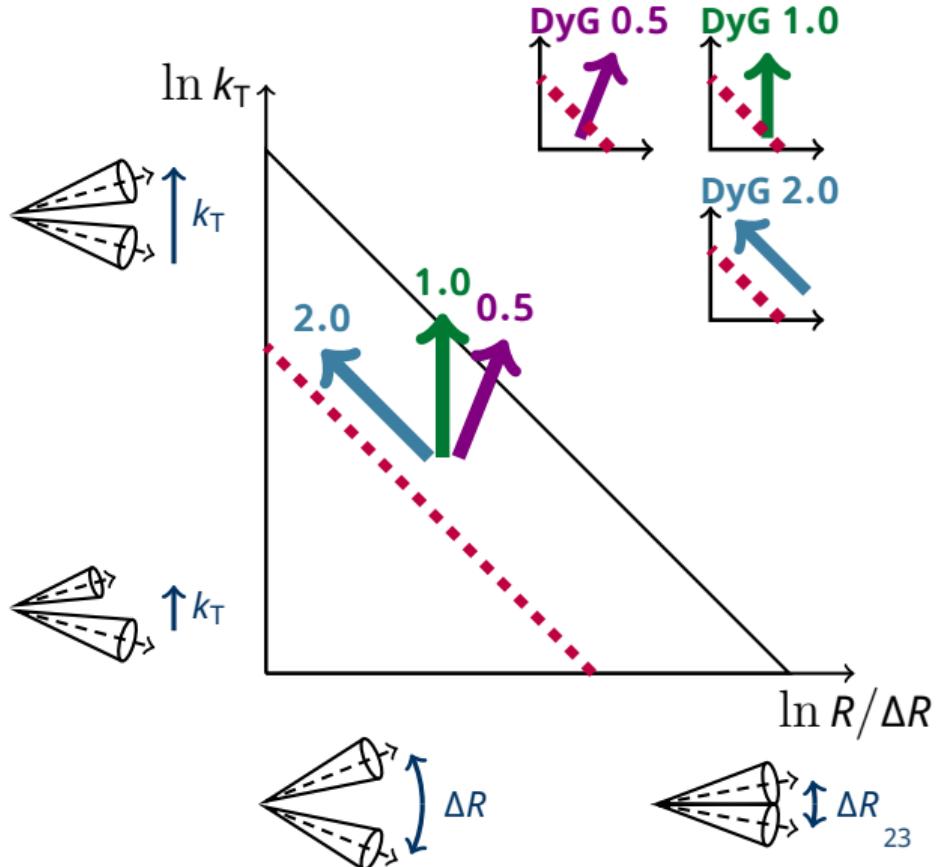
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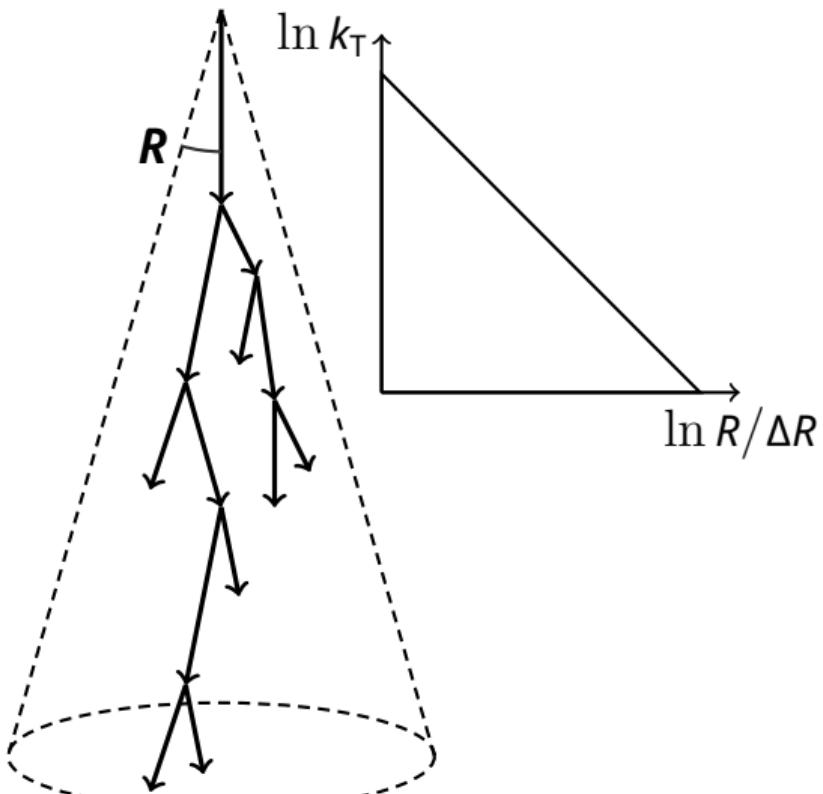
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 $t_f^{-1} \sim \kappa^2 p_T$
- In practice, need **min  $k_T$  in Pb-Pb**
- Alternatively, add  **$z$  requirement** (0.2)



# Employing the grooming methods

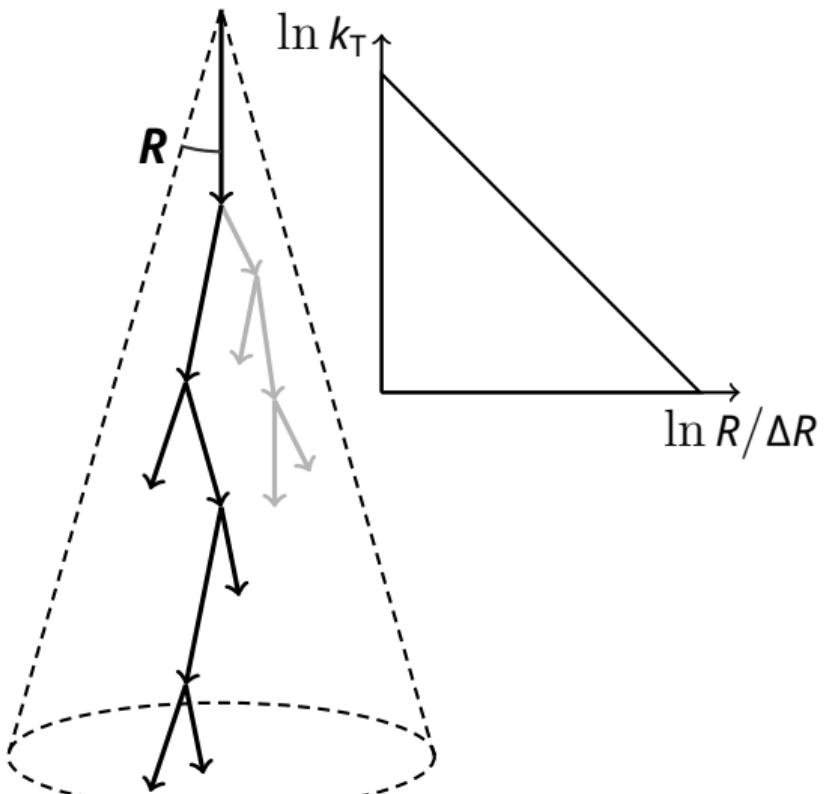
- Consider  $p_{T,\text{jet}}^{\text{ch}} = 60 \text{ GeV}/c$   $R = 0.2$  jet
- Decluster with C/A, select iterative splittings:



# Employing the grooming methods

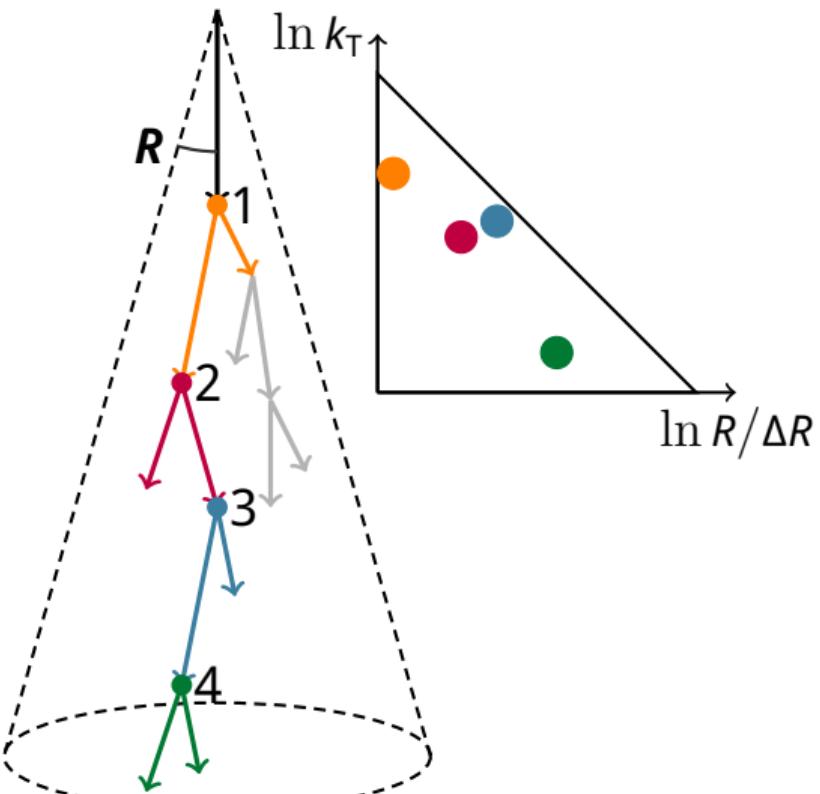
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  1.  $z = 0.175, \Delta R = 0.4, k_T = 4.09 \text{ GeV}/c$
  2.  $z = 0.2, \Delta R = 0.3, k_T = 2.93 \text{ GeV}/c$
  3.  $z = 0.4, \Delta R = 0.2, k_T = 3.15 \text{ GeV}/c$
  4.  $z = 0.1, \Delta R = 0.1, k_T = 0.24 \text{ GeV}/c$



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- Which method selects which splitting?



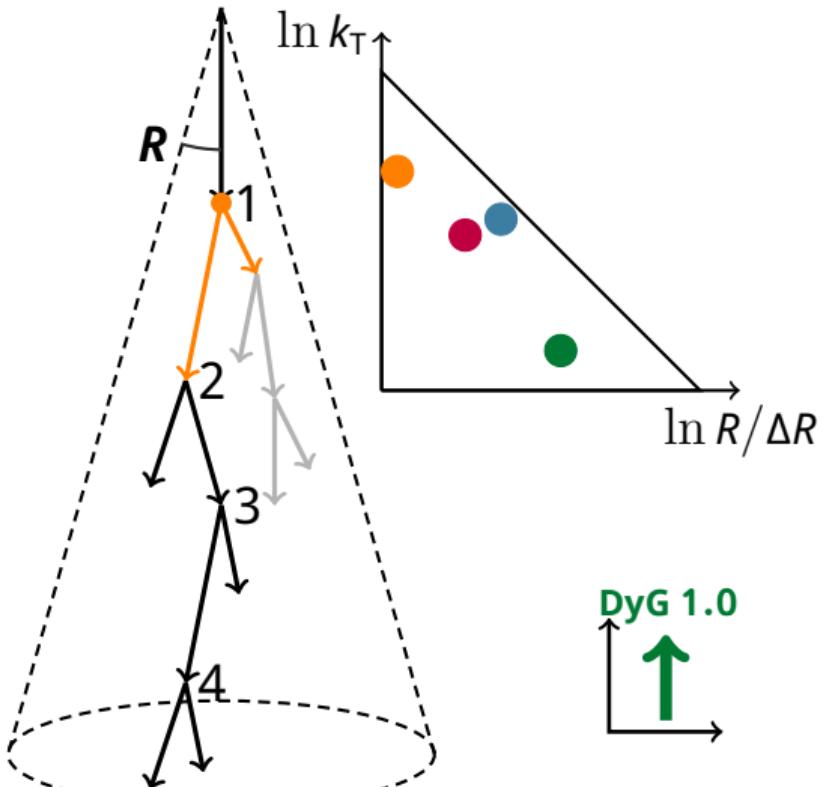
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→ Which method selects which splitting?

  - DyG  $\alpha = 1.0$ : #1



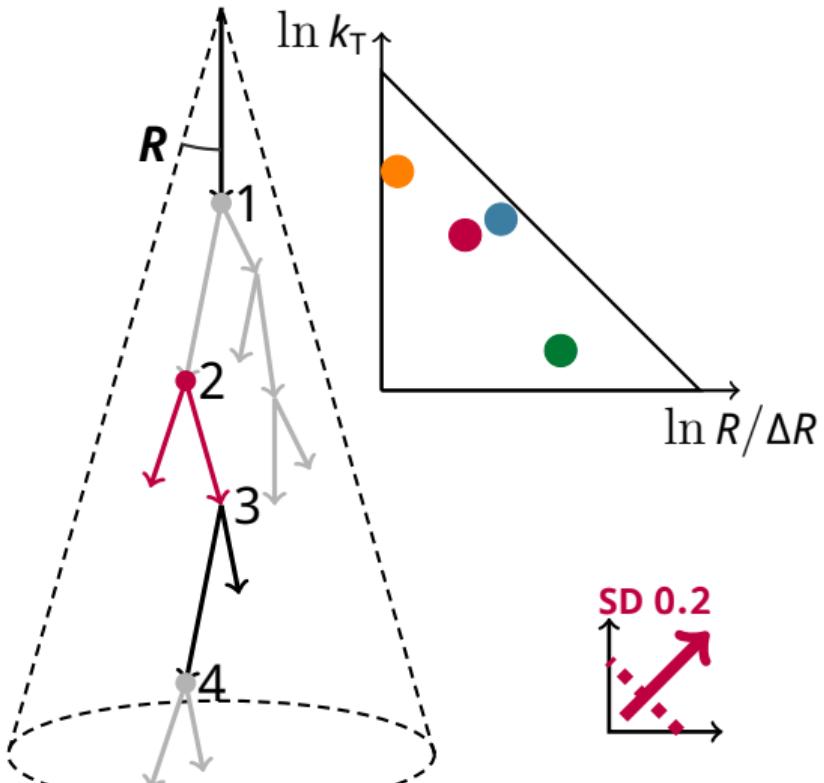
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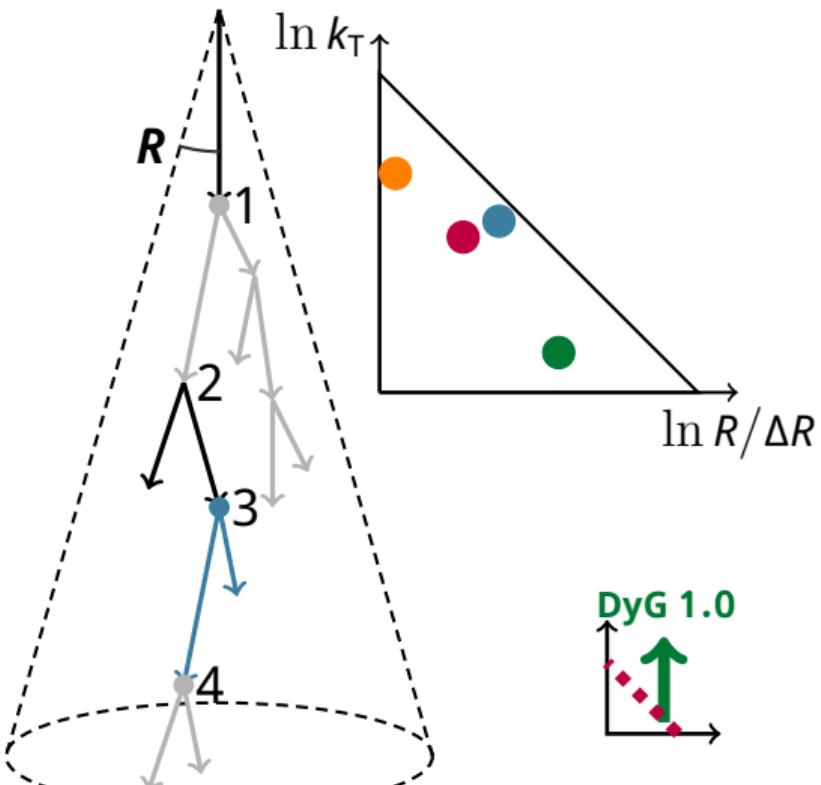
→ Which method selects which splitting?

  - DyG  $\alpha = 1.0$ : #1
  - SD  $z_{\text{cut}} = 0.2$ : #2



# Employing the grooming methods

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    2.  $z = 0.2, \Delta R = 0.3, k_T = 2.93 \text{ GeV}/c$
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    4.  $z = 0.1, \Delta R = 0.1, k_T = 0.24 \text{ GeV}/c$
- Which method selects which splitting?
- DyG  $\alpha = 1.0$ : #1
  - SD  $z_{\text{cut}} = 0.2$ : #2
  - DyG  $\alpha = 1.0, z > 0.2$ : #3



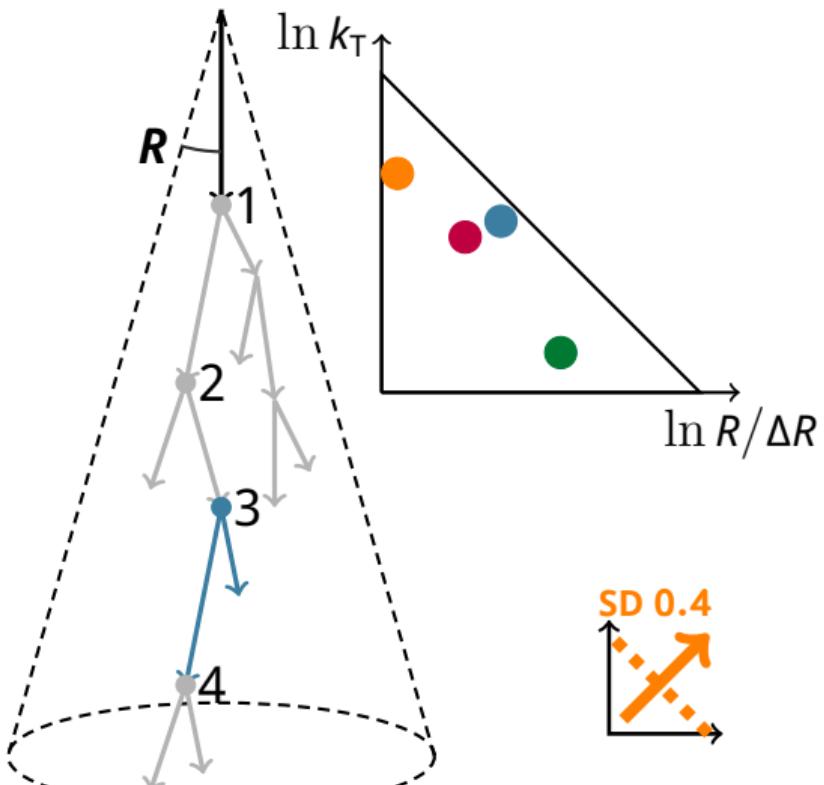
# Employing the grooming methods

- Consider  $p_{T,\text{jet}}^{\text{ch}} = 60 \text{ GeV}/c$   $R = 0.2$  jet
- Decluster with C/A, select iterative splittings:

  1.  $z = 0.175, \Delta R = 0.4, k_T = 4.09 \text{ GeV}/c$
  2.  $z = 0.2, \Delta R = 0.3, k_T = 2.93 \text{ GeV}/c$
  3.  $z = 0.4, \Delta R = 0.2, k_T = 3.15 \text{ GeV}/c$
  4.  $z = 0.1, \Delta R = 0.1, k_T = 0.24 \text{ GeV}/c$

→ Which method selects which splitting?

- DyG  $\alpha = 1.0$ : #1
- SD  $z_{\text{cut}} = 0.2$ : #2
- DyG  $\alpha = 1.0, z > 0.2$ : #3
- SD  $z_{\text{cut}} = 0.4$ : #3



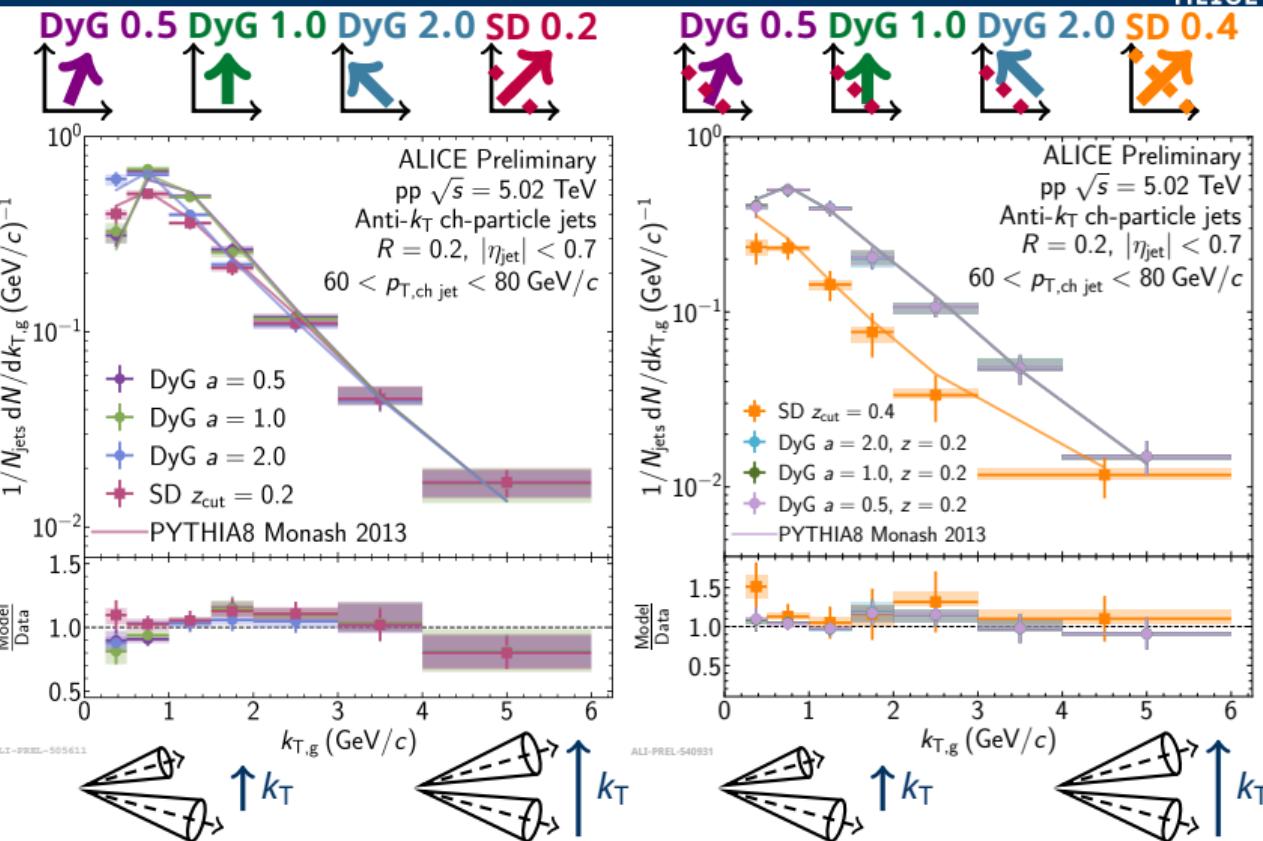
# Comparing grooming methods in pp

New



- Shape variations at low  $k_T$
- Grooming methods **converge at high  $k_{T,g}$**
- **$z$  requirement dominates** over grooming method
- PYTHIA in broad agreement with data

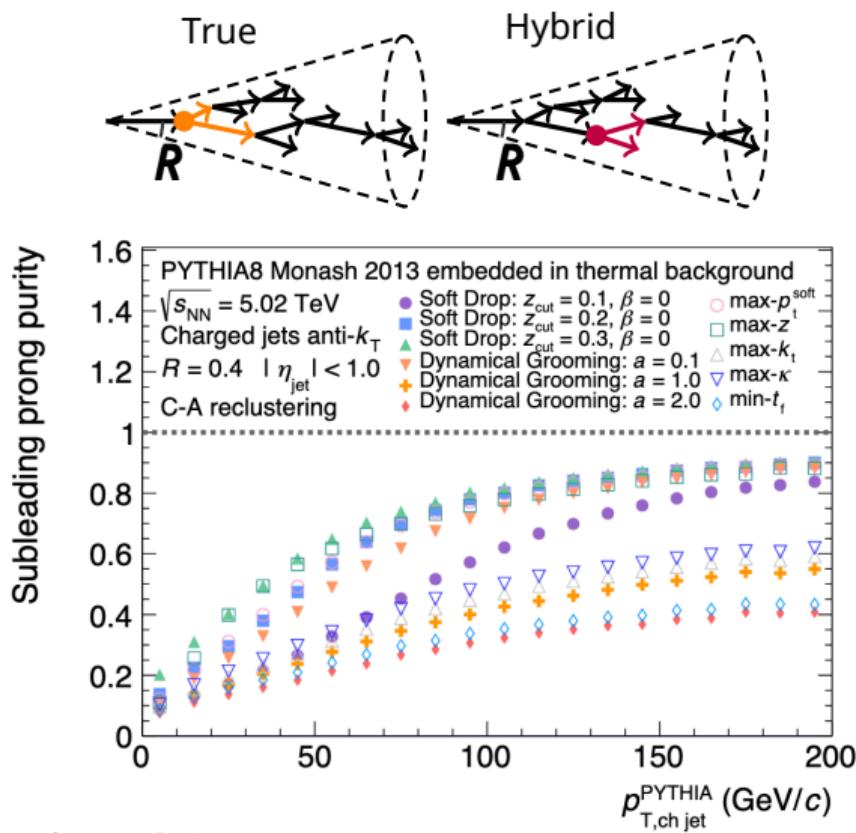
See also:  $R_g + z_g$  with DyG:  
arXiv:2204.10246



# Unfolding Dynamical Grooming in Pb-Pb



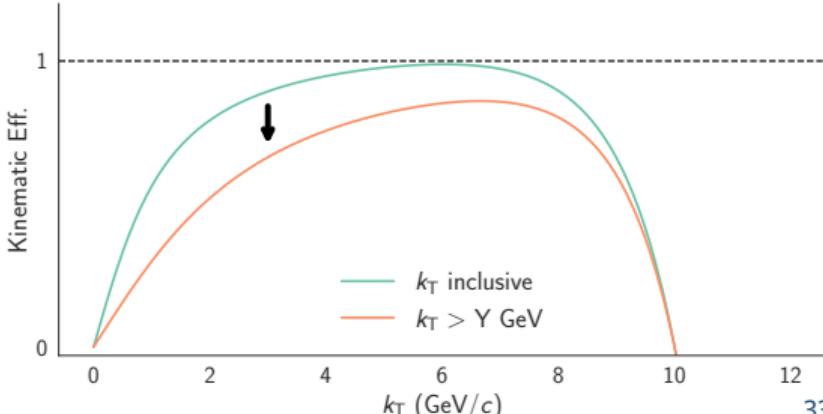
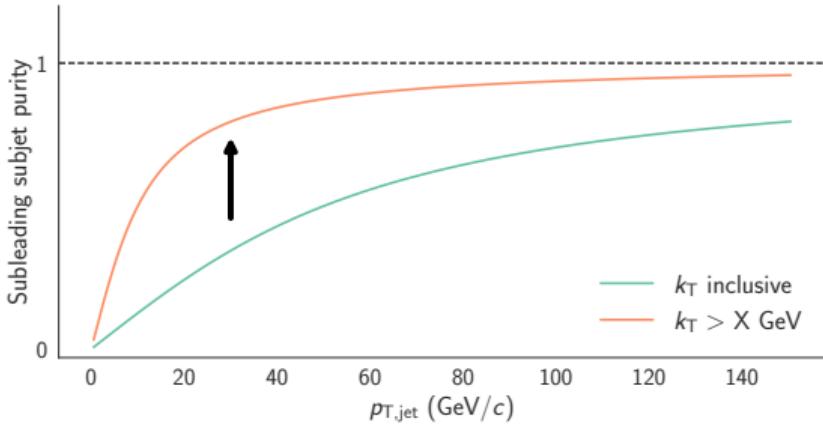
- Dynamical Grooming exhibits **reduced subleading subjet purity** in Pb-Pb
  - Off-diagonal mismatched splittings** are major component at low  $k_T$
- **Problematic for unfolding**
- Caused by **requirement to always select a splitting**
  - Address by minimum measured  $k_T$**  requirement
  - Trade **improved purity** for reduced dynamic **range** and kinematic efficiency
  - Minimum z** has similar impact



# Unfolding Dynamical Grooming in Pb-Pb

- Dynamical Grooming exhibits **reduced subleading subjet purity** in Pb-Pb
  - Off-diagonal mismatched splittings** are major component at low  $k_T$
- **Problematic for unfolding**

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- Address by minimum measured  $k_T$**  requirement
- Trade **improved purity** for **reduced dynamic range** and kinematic efficiency
- Minimum  $z$**  has similar impact



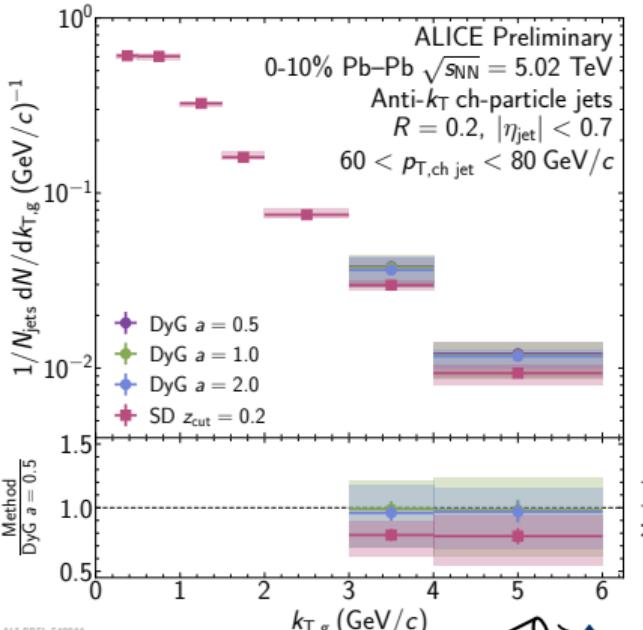
# Dynamical Grooming in Pb-Pb

New

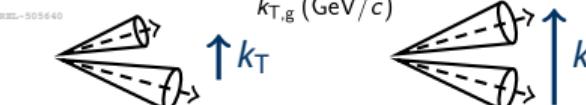
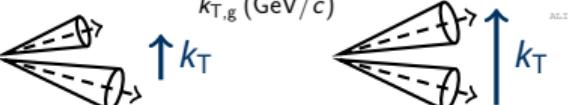
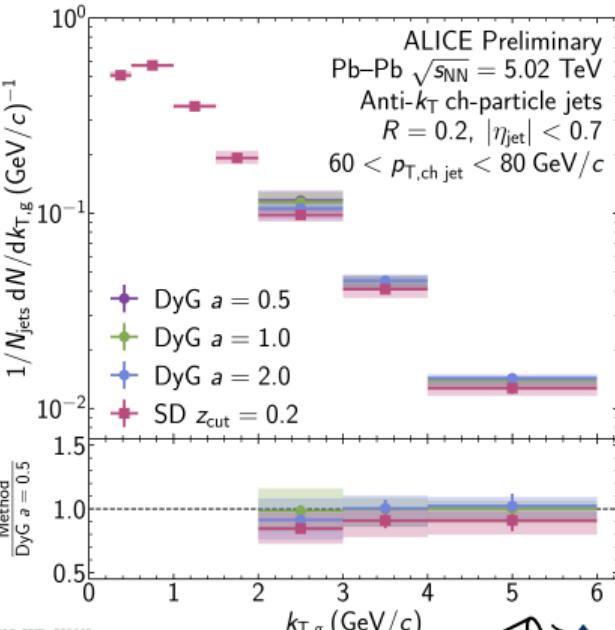


- First measurements of Dynamical Grooming in Pb-Pb
- Grooming methods converge at high  $k_{T,g}$
- Smaller bkg extends  $k_{T,g}$  range in semi-central

0-10% central



30-50% semi-central



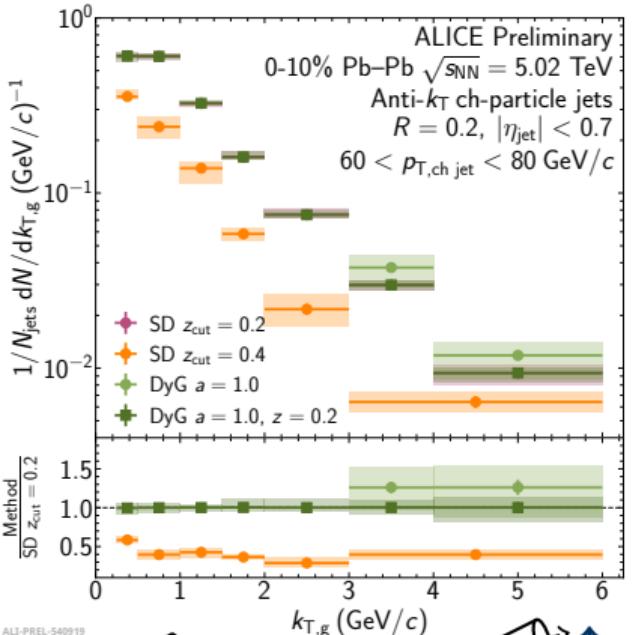
# Comparing grooming methods in Pb-Pb

New

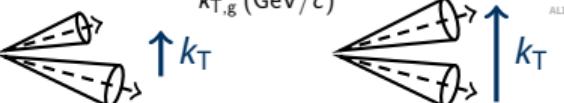
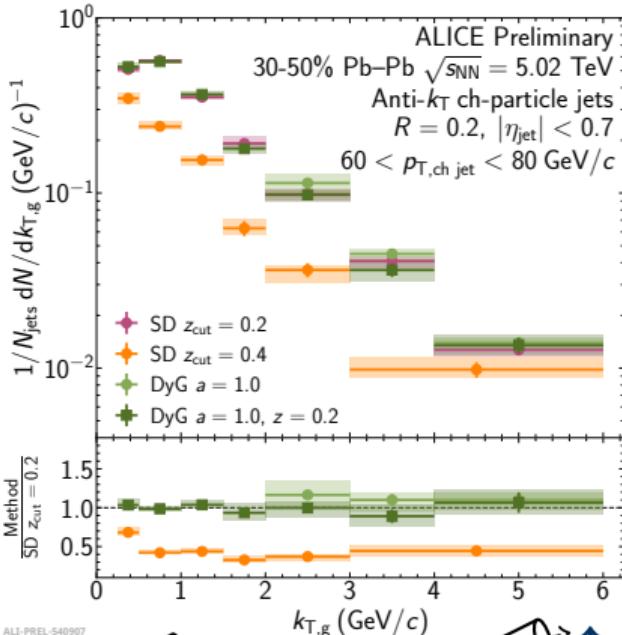


- Similar trends in 0-10% and 30-50%
- Reduced SD  $z_{\text{cut}} = 0.4$  yield due to **phase space**
- Consistent set of splittings from all DyG  $a = 1.0$ , SD  $z_{\text{cut}} = 0.2$
- Suggests **few hard splits further into tree**

## 0-10% central



## 30-50% semi-central



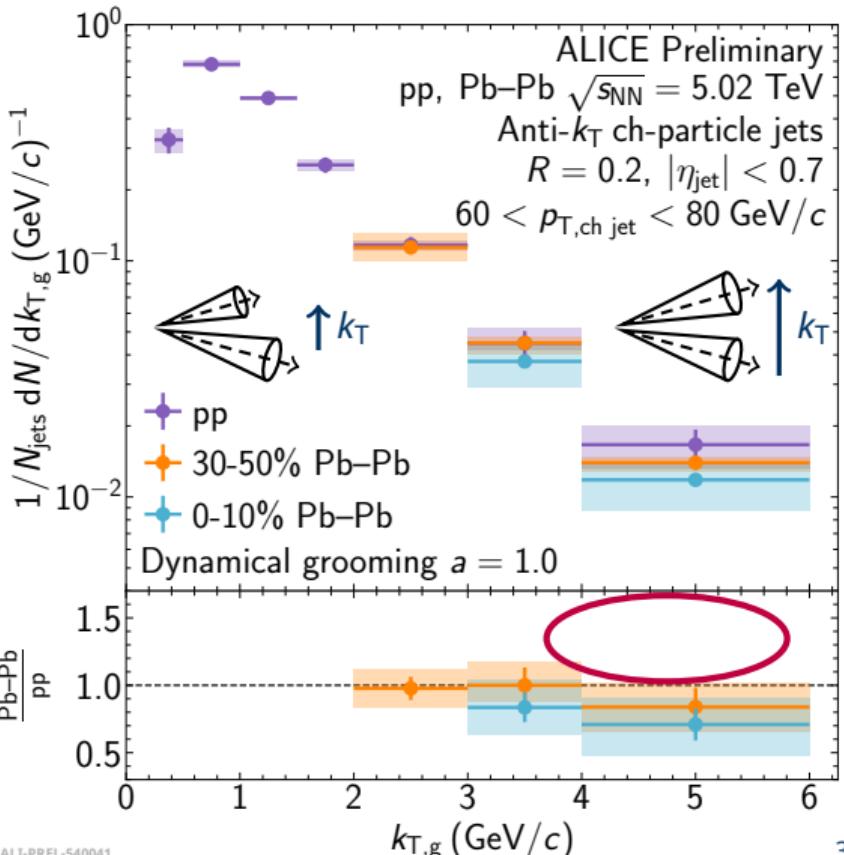
# Searching for modification

New



- No enhancement at high  $k_{T,g}$
- Standard DyG shows little modification

DyG 1.0  
↑

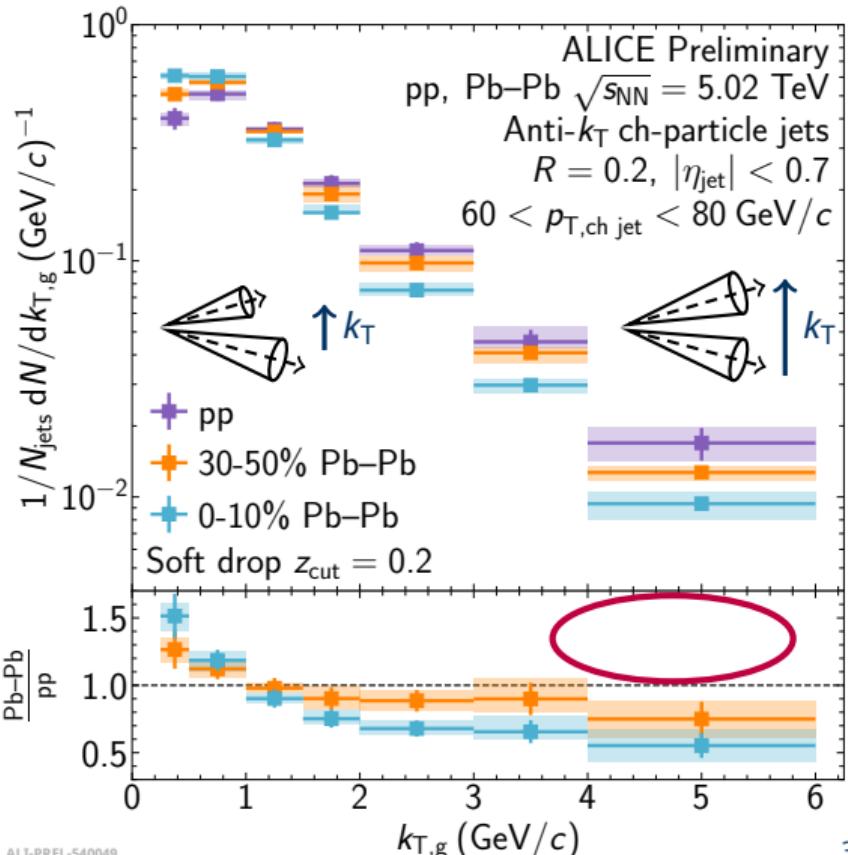


# Searching for modification

New



- **No enhancement** at high  $k_{T,g}$
- Standard DyG shows **little modification**
- **Modification** in methods with  $z > 0.2$ 
  - Larger modification in 0-10%
- **Consistent with narrowing picture** seen in many substructure analyses.
  - e.g.  $R_g$ , jet axis difference, angularities, etc
- **No clear evidence of Moliere scattering**

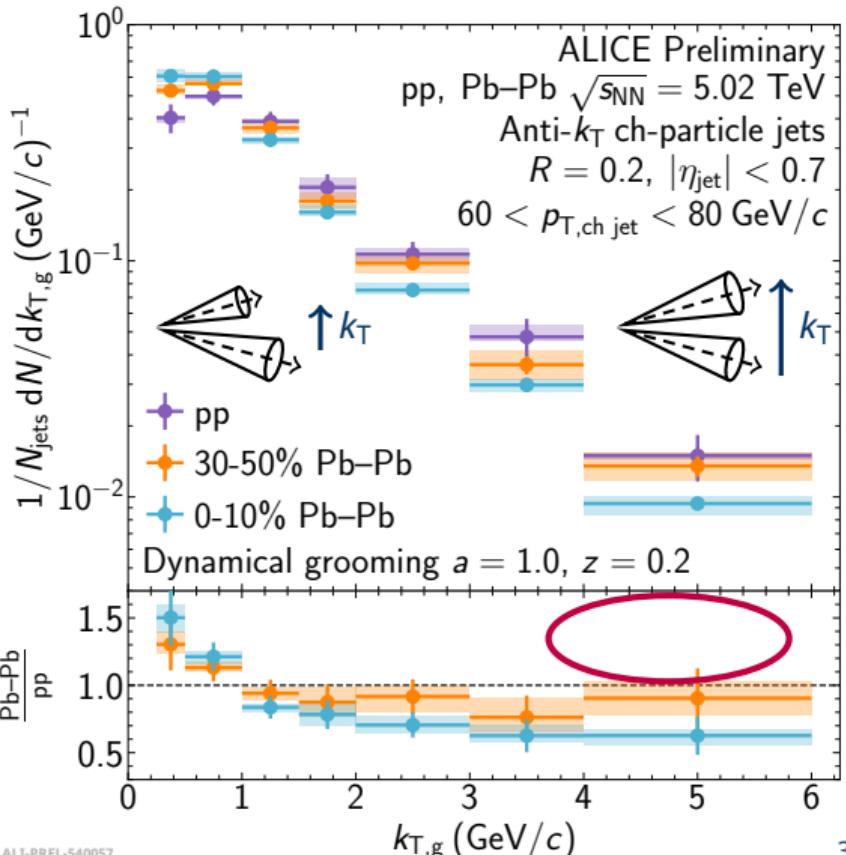


# Searching for modification

New



- **No enhancement** at high  $k_{T,g}$
- Standard DyG shows **little modification**
- **Modification** in methods with  $z > 0.2$ 
  - Larger modification in 0-10%
- **Consistent with narrowing picture** seen in many substructure analyses.
  - e.g.  $R_g$ , jet axis difference, angularities, etc
- **No clear evidence of Moliere scattering**



# How do models fare?

New



## JETSCAPEv3.5 AA22 tune

JETSCAPE arXiv:2301.02485

- MATTER+LBT
- Describes data well

## Hybrid model

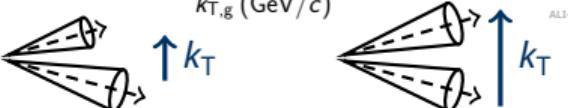
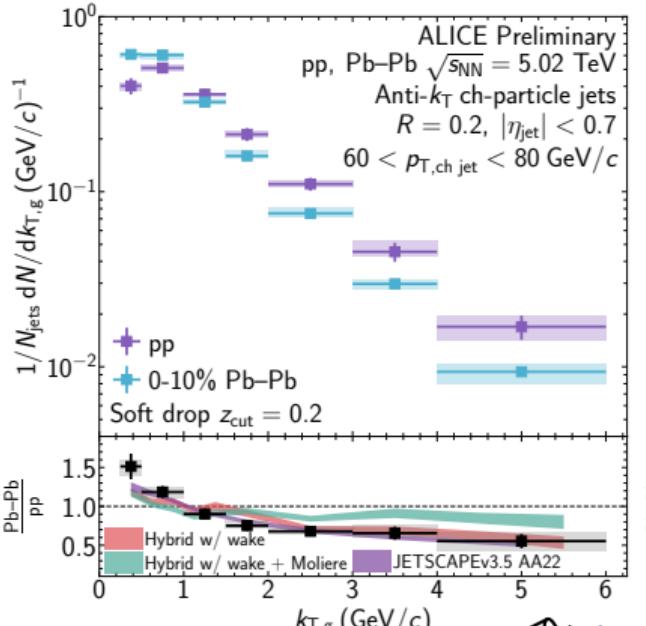
D'Eramo et al. JHEP 01 (2019) 172

Hulcher et al. QM 22

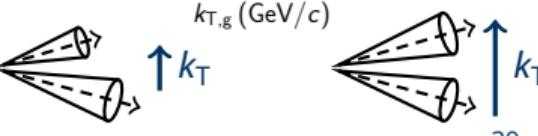
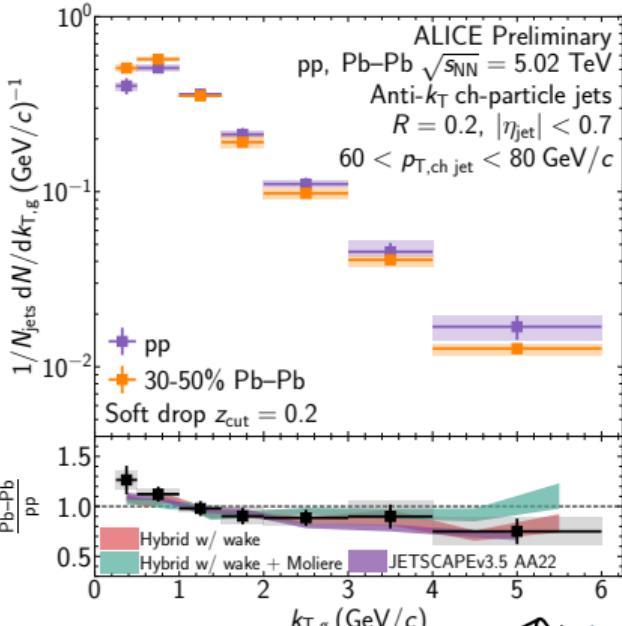
- With, w/out Moliere
- w/out Moliere **describe 0-10% data better**

## Caveat: pp baseline

### 0-10% central

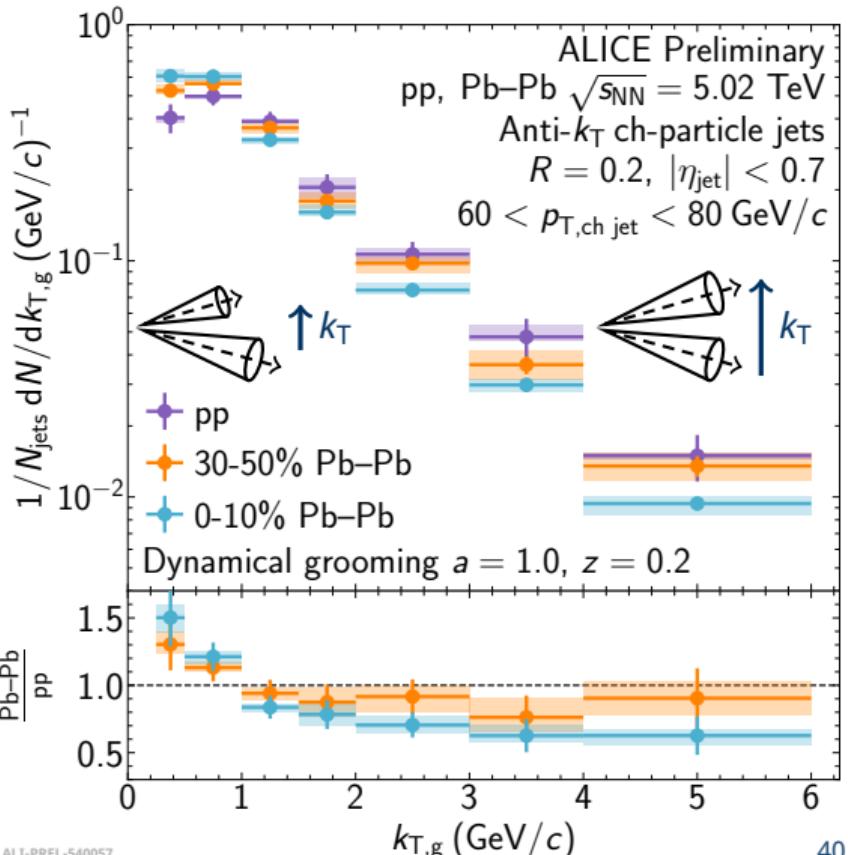


### 30-50% central



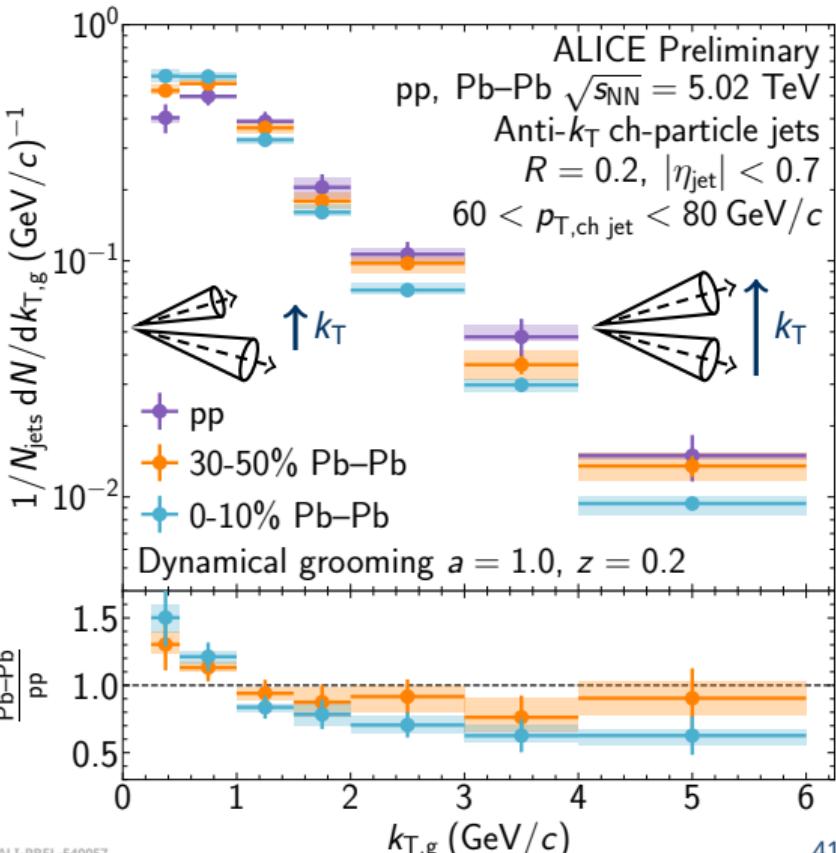
# Summary + Outlook/1

- Lund Plane is **useful approach for understanding QCD and QGP properties**
- 1. Low  $p_{T,\text{jet}}$  **inclusive pp Lund Plane to test QCD**
- 2. **Modification of angular-dep. substructure in Pb-Pb** w/ similar narrowing in many observables ( $R_g$ ,  $k_{T,g}$ , jet-axis, angularities, etc)
- 3. Comprehensive grooming method study:
  - First measurement of DyG** in Pb-Pb
  - $z_{\text{cut}}$  **dominates** over grooming method details
  - Suggests minimal impact** of splittings far into splitting tree
- 4. **No clear evidence of Moliere scattering**



# Summary + Outlook/2

- Much more to explore!
- Full Lund Plane in Pb-Pb?
  - Can we relax our grooming requirements?
- New approaches: Statistical? ML?
- Heavy flavor (see next talks)



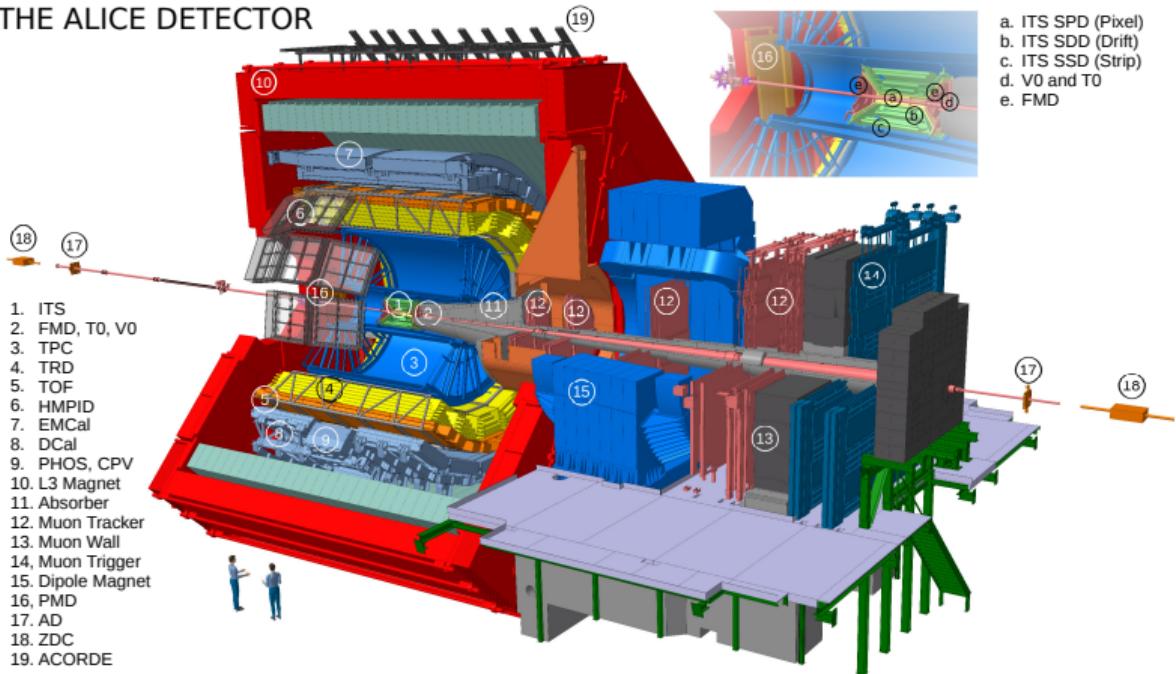
# Backup

# Jets and their substructure in ALICE

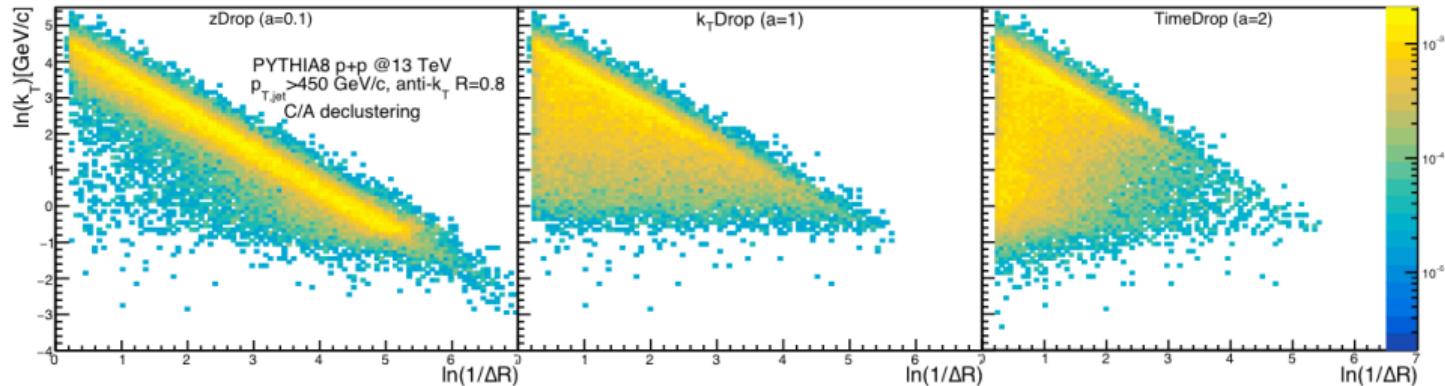


- ALICE well suited for measuring:
  - **Low  $p_T$**  jets
  - **Small splitting angles** at high efficiency
- Enables **strong substructure program**
- Anti- $k_T$  charged-particle jets measured in pp and Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

THE ALICE DETECTOR

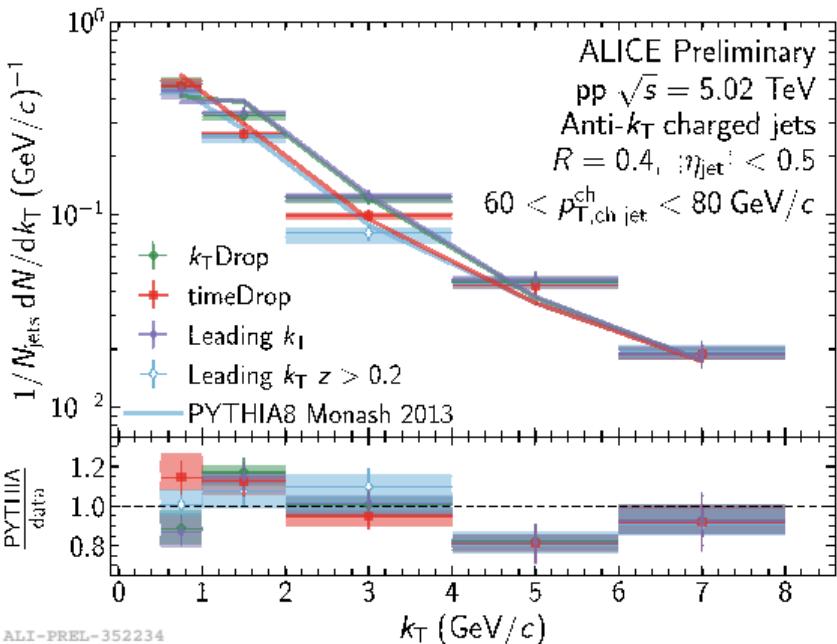
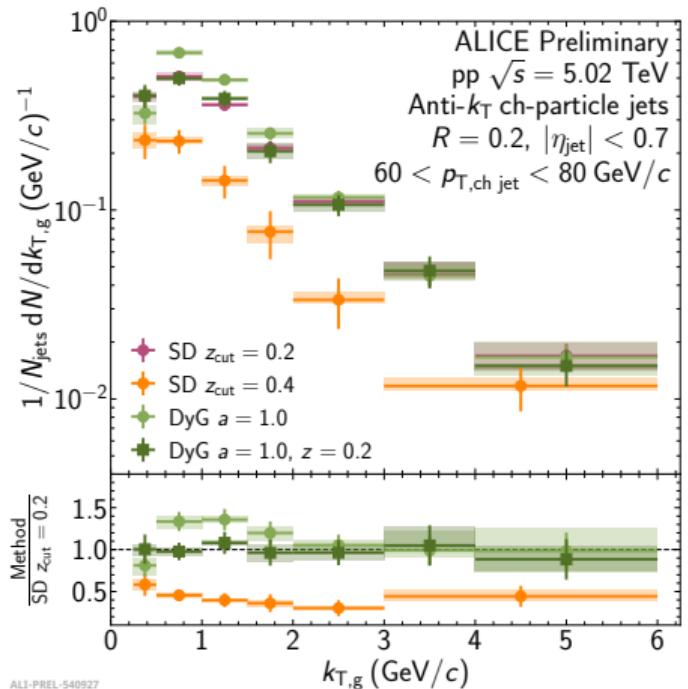


# Dynamical Grooming: Lund Planes

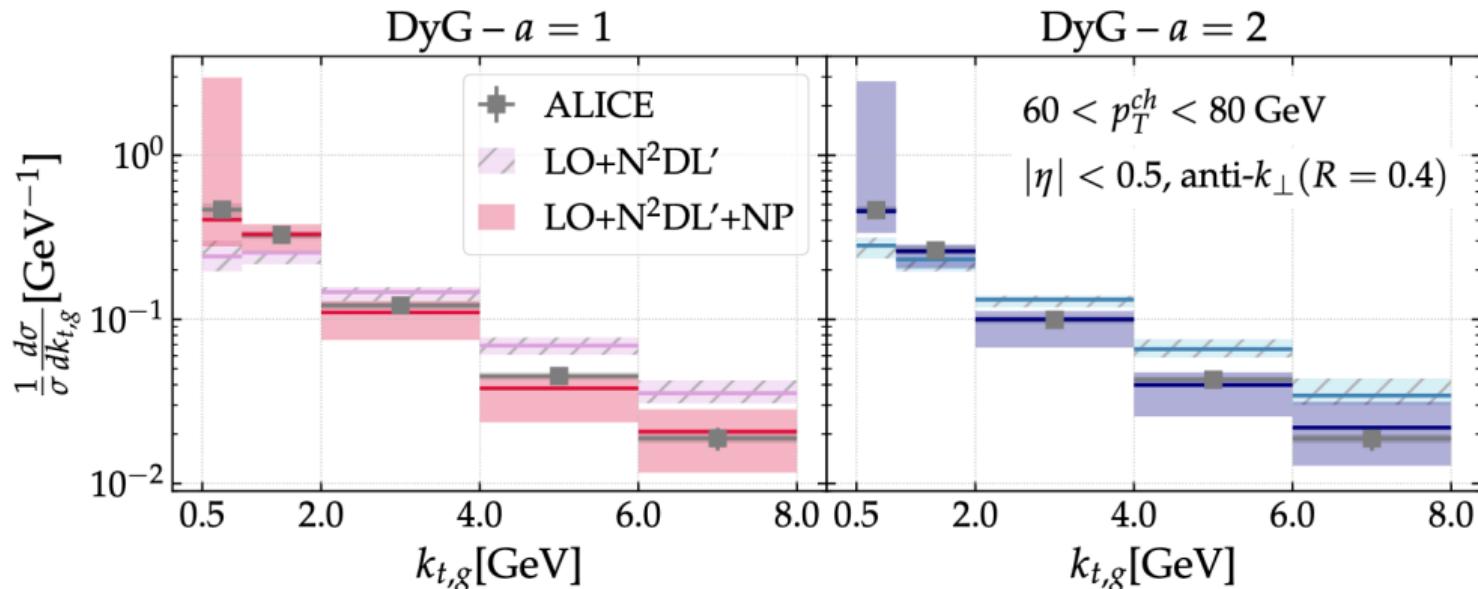


Mehtar-Tani et al., PhysRevD.101.034004

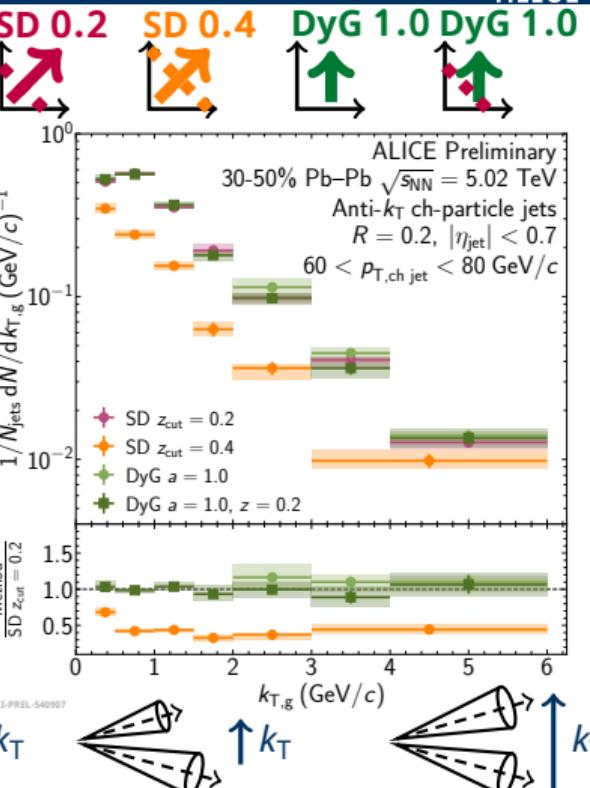
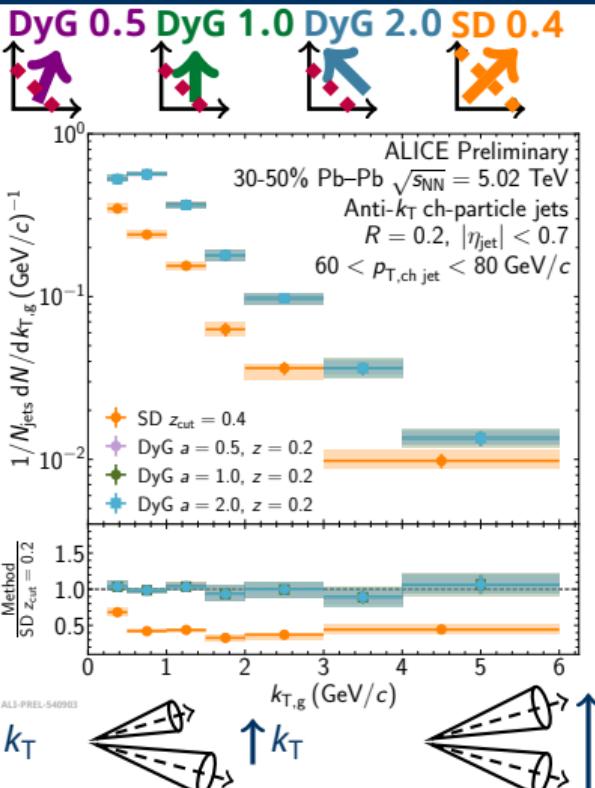
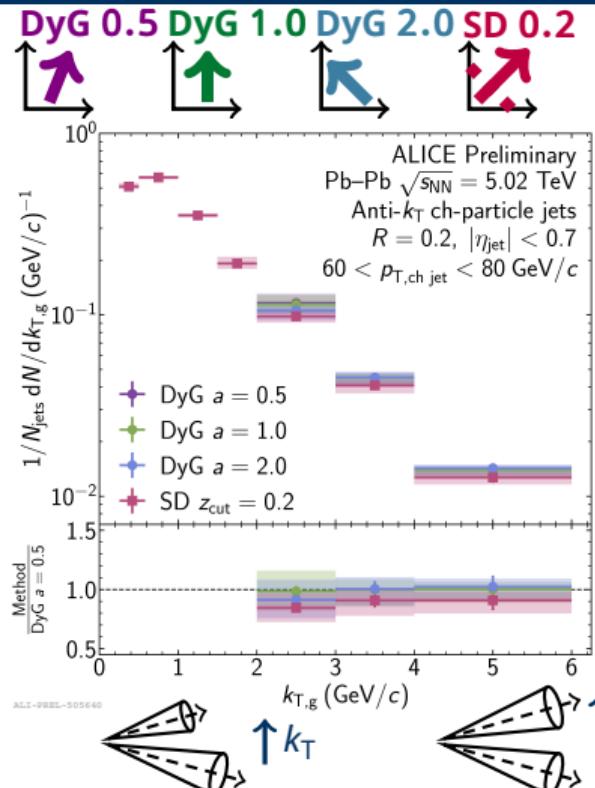
# Comparing grooming methods in pp: mixed methods, $R = 0.4$



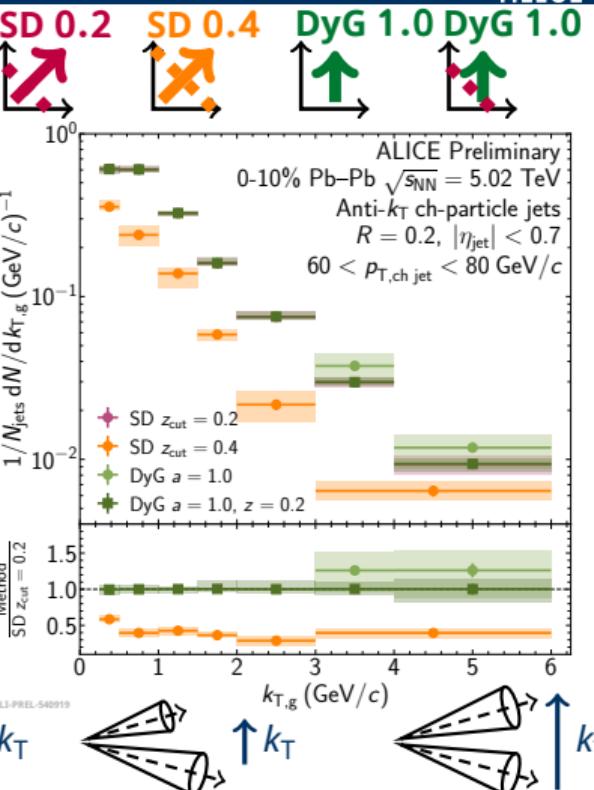
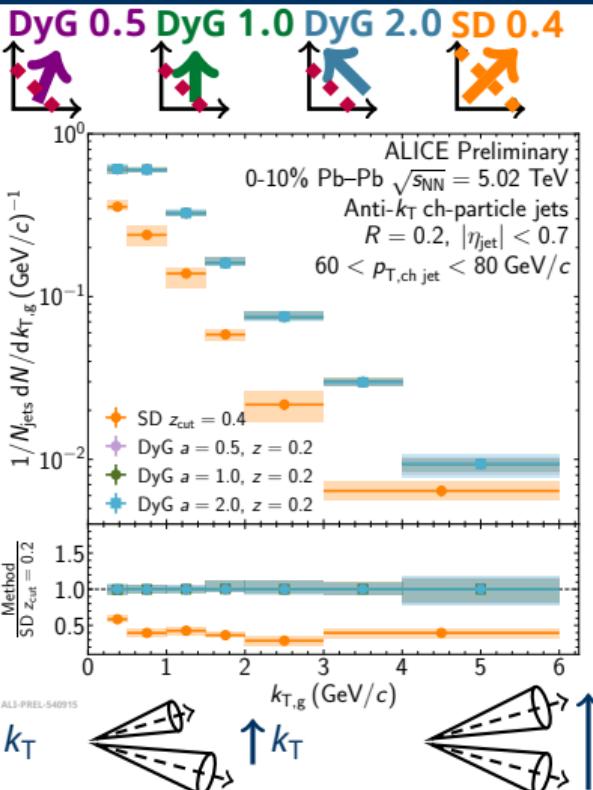
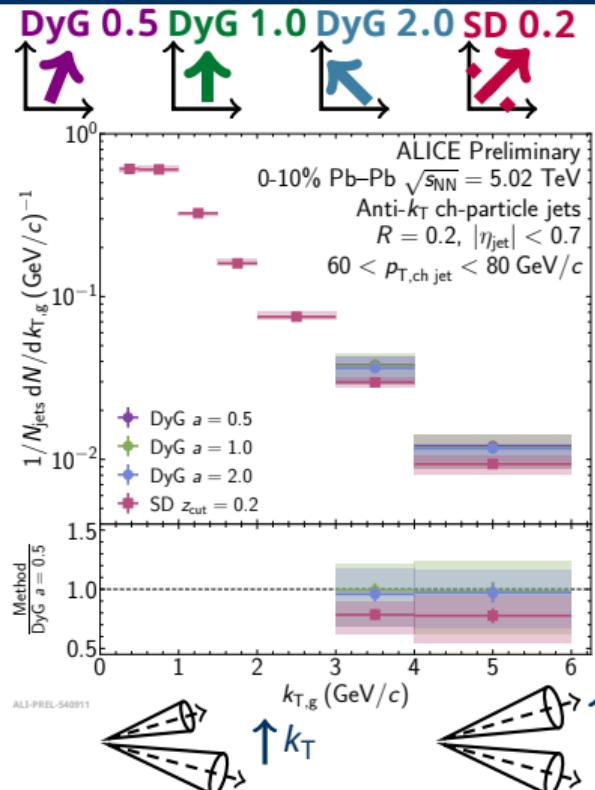
# Dynamical Grooming: analytical calculations pp



# Comparing grooming methods in 30-50% semi-central Pb-Pb

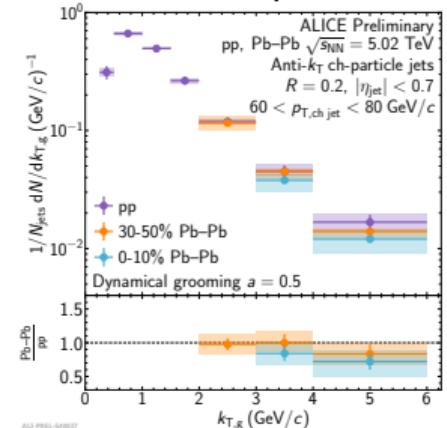


# Comparing grooming methods in 0-10% central Pb-Pb

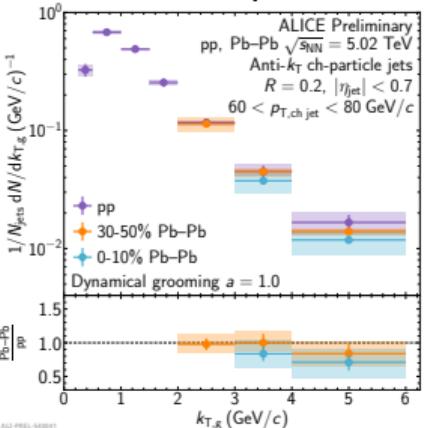


# Searching for modification (with more methods)/1

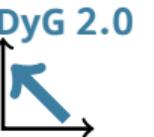
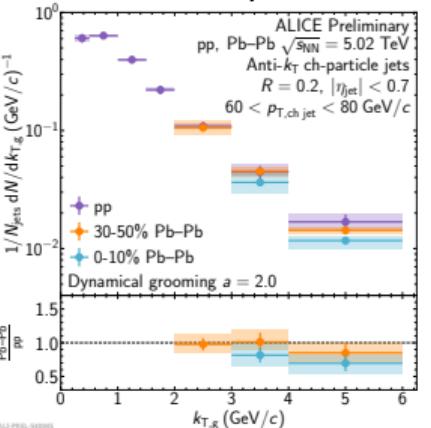
DyG 0.5

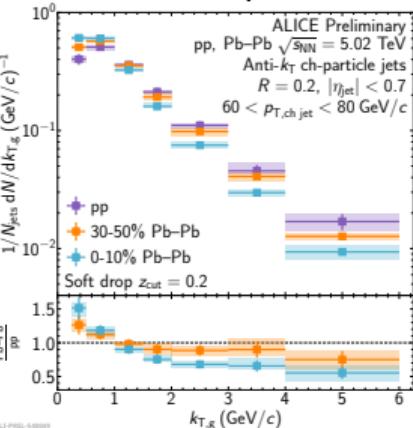
DyG 1.0

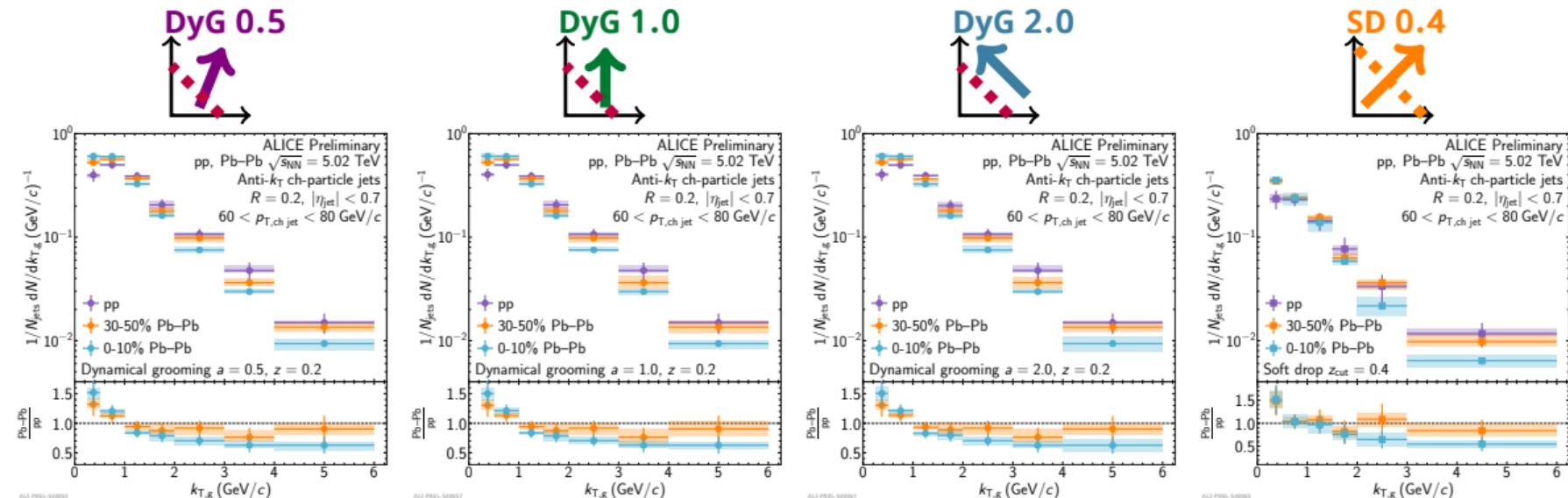
DyG 2.0

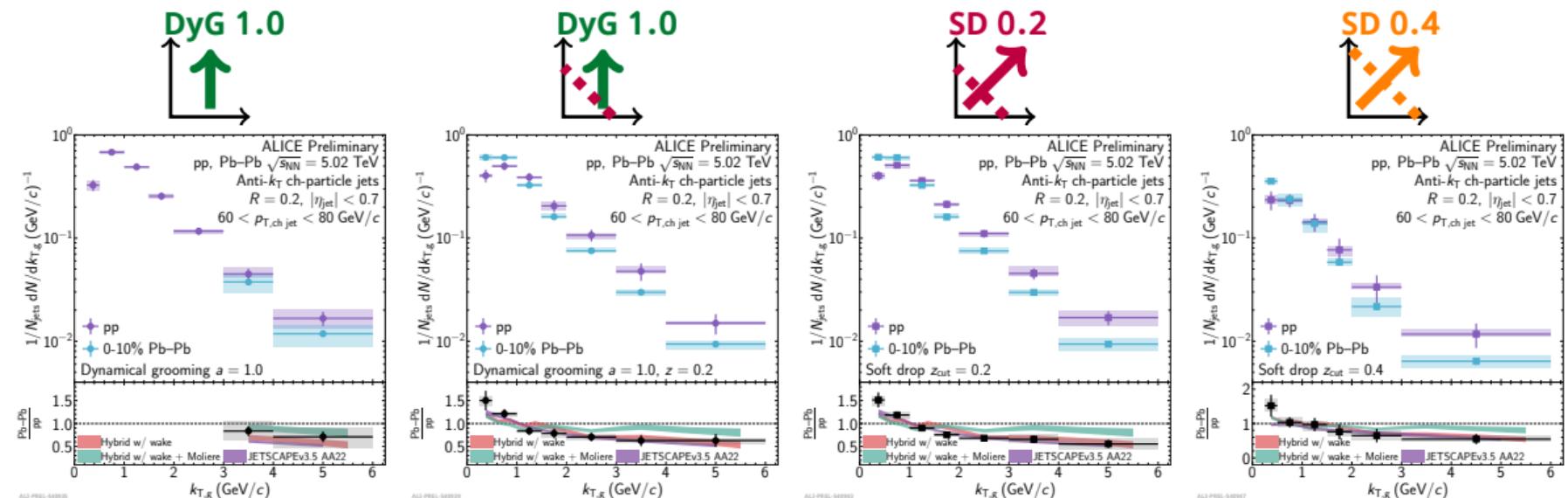
SD 0.2

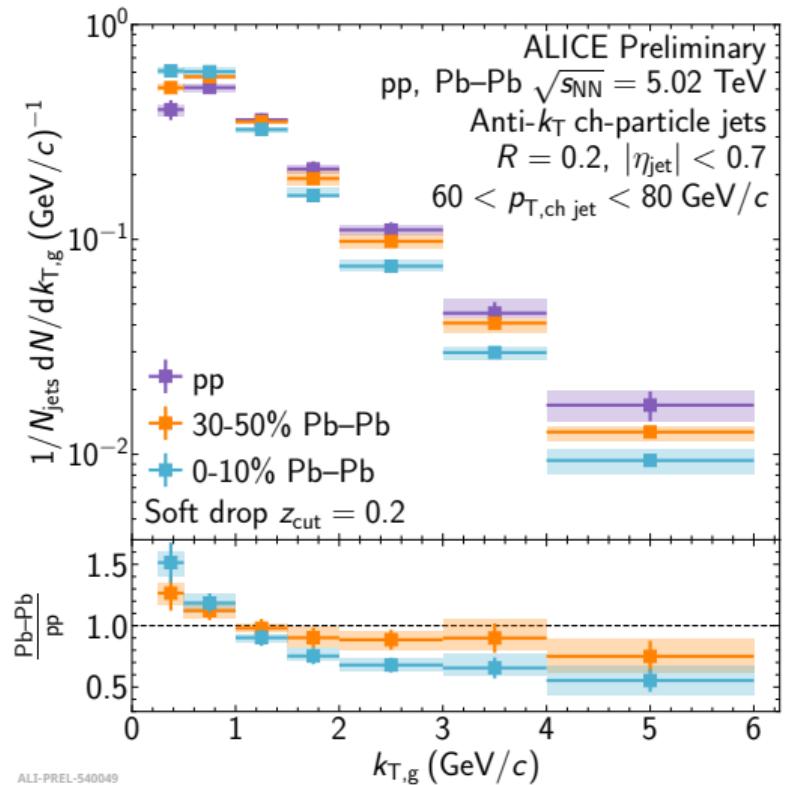
# Searching for modification (with more methods)/2



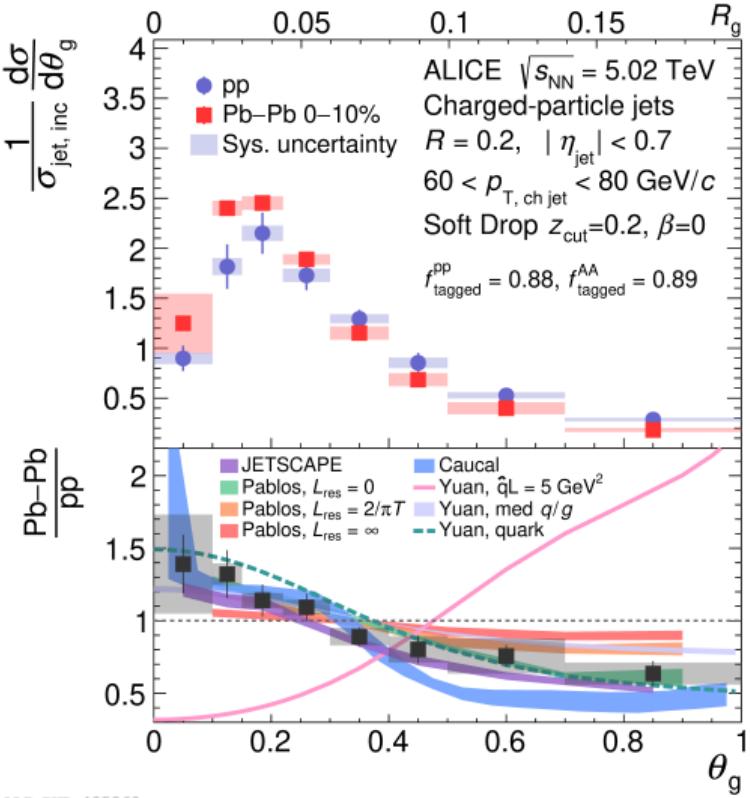
# Comparing with models in 0-10% central Pb-Pb



# Narrowing in $k_{T,g}$ vs $R_g$

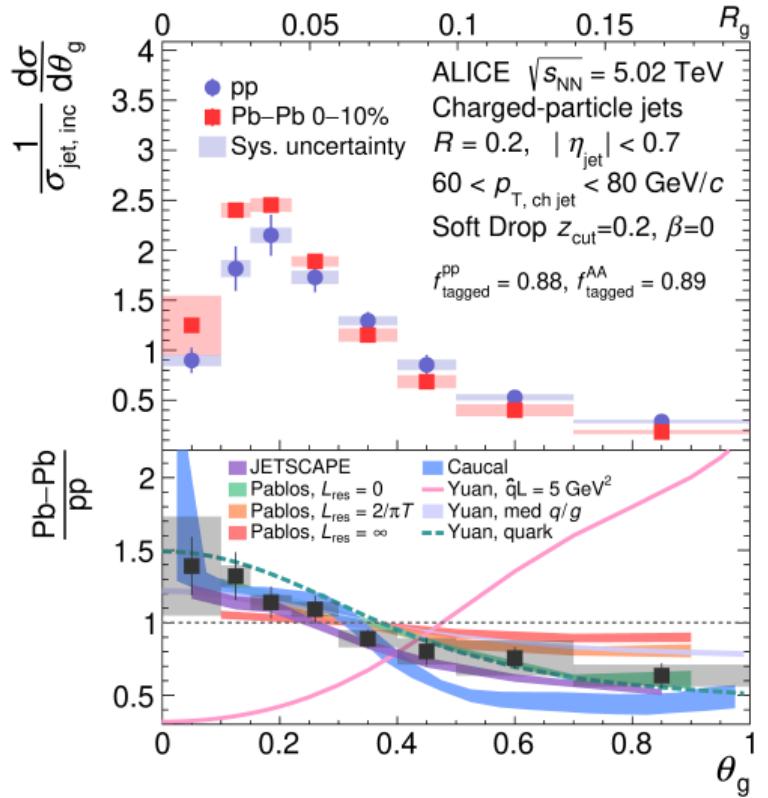


ALI-PREL-540049



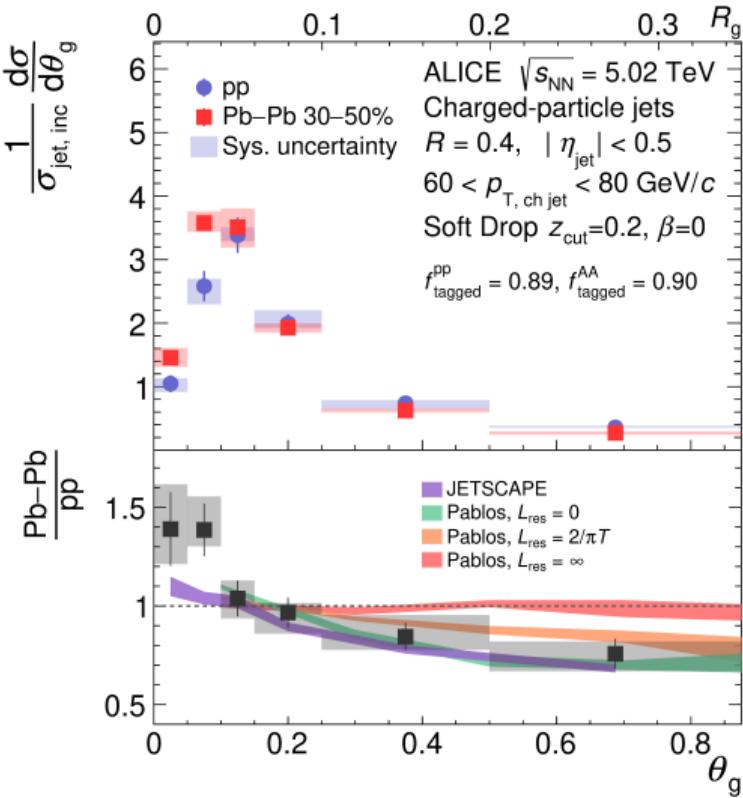
ALI-PUB-495863

# Groomed jet radius $\theta_g$



ALI-PUB-495863

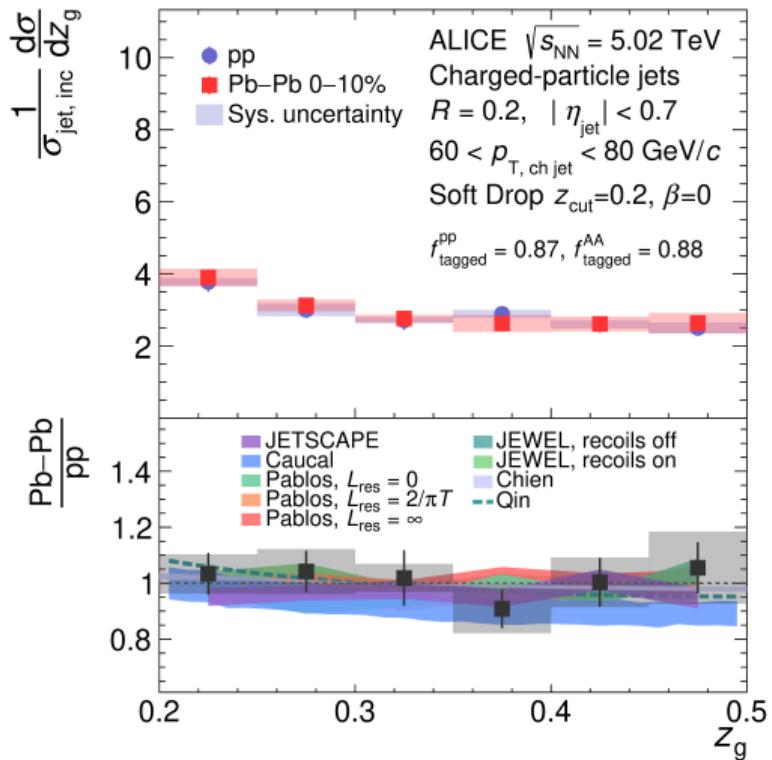
Raymond Ehlers (LBNL/UCB) - 4 July 2023



ALI-PUB-521487

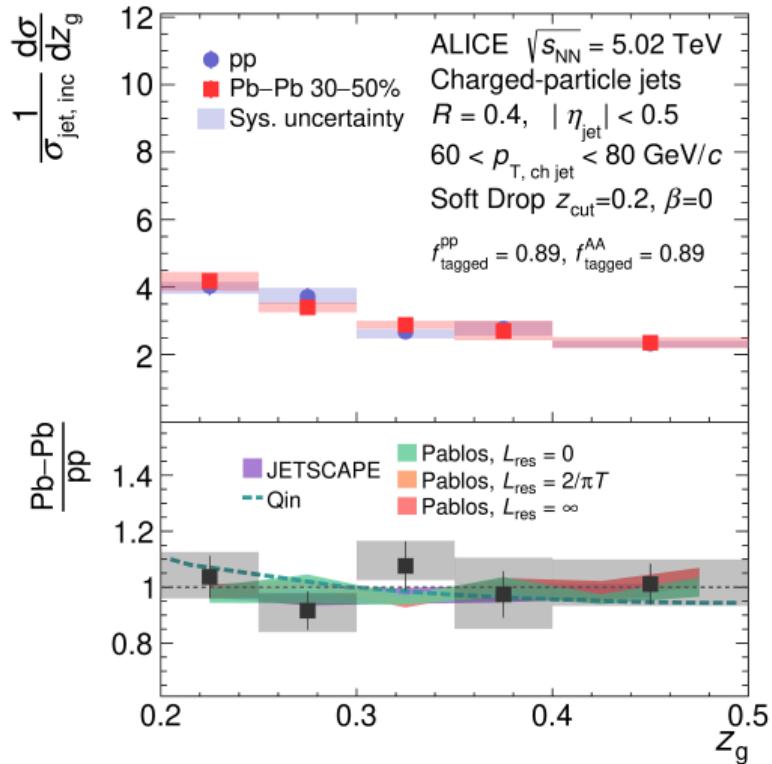
Phys.Rev.Lett. 128 (2022) 10, 102001

# Groomed shared momentum fraction $z_g$



ALI-PUB-521472

Raymond Ehlers (LBNL/UCB) - 4 July 2023



ALI-PUB-521477

Phys.Rev.Lett. 128 (2022) 10, 102001

# Jet mass: model baseline in pp

→ Model baseline is important for many observables!

