

Novel jet substructure observables + techniques with ALICE

Raymond Ehlers¹ for the ALICE Collaboration

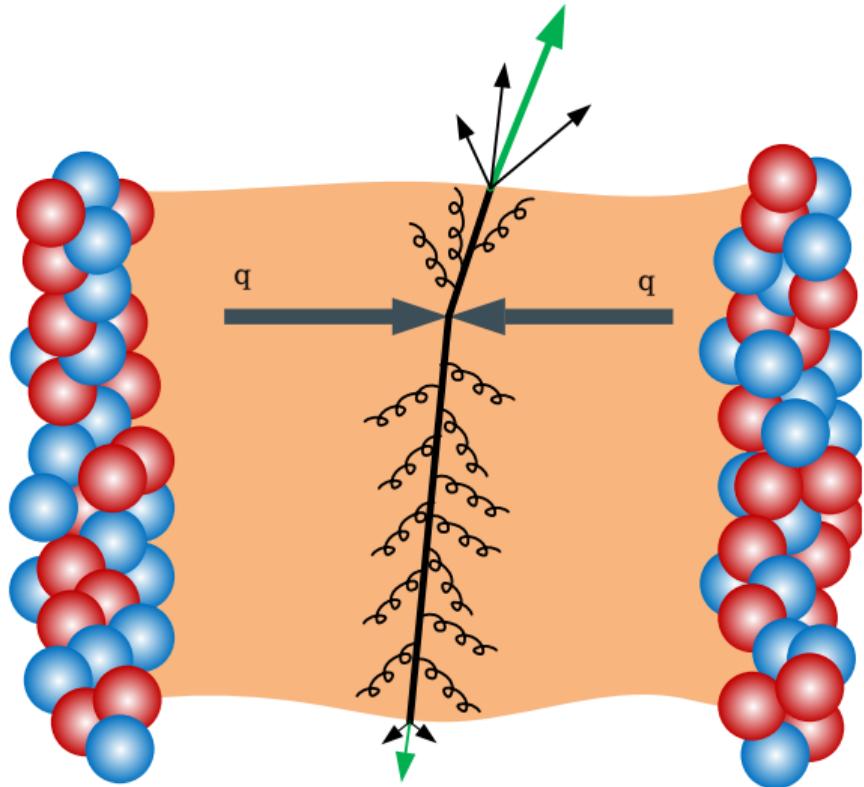
3 August 2023

¹Lawrence Berkeley National Lab/UC Berkeley
raymond.ehlers@cern.ch



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, **new observables and techniques** to try to answer these questions

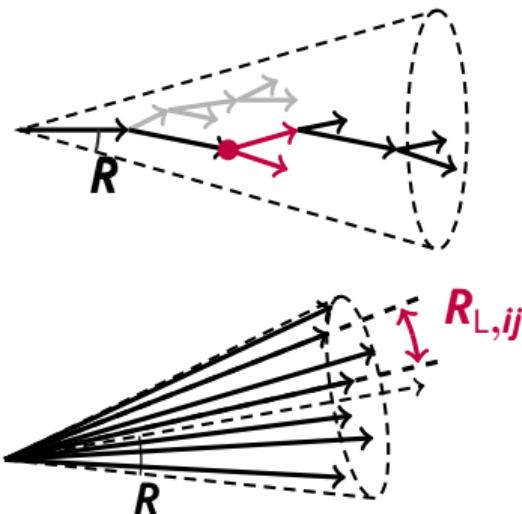


Outline: Thinking in angular scales

- Jets and their substructure are multi-scale probes of **QCD evolution**

1. Groomed jet substructure in Pb-Pb

- Isolate physical scales → resolve medium scales
- High $k_{T,g}$ emissions → Quasi-particle scattering in medium?
- Optimal approach to find hard splittings?



2. Energy-energy correlators (EECs) in pp

- Separate angular scales → isolate physical regimes
- Hadron-level correlations → pQCD, hadronization

More from ALICE:

Jet-medium interactions
Ezra Lesser, Today 11:00

HF jet-substructure
Preeti Dhankher, Today 11:40

Medium properties from jet substructure

Resolving medium scales

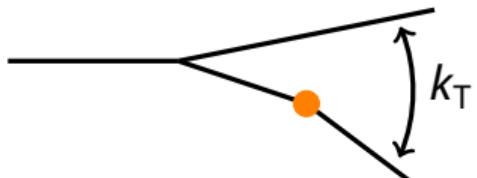
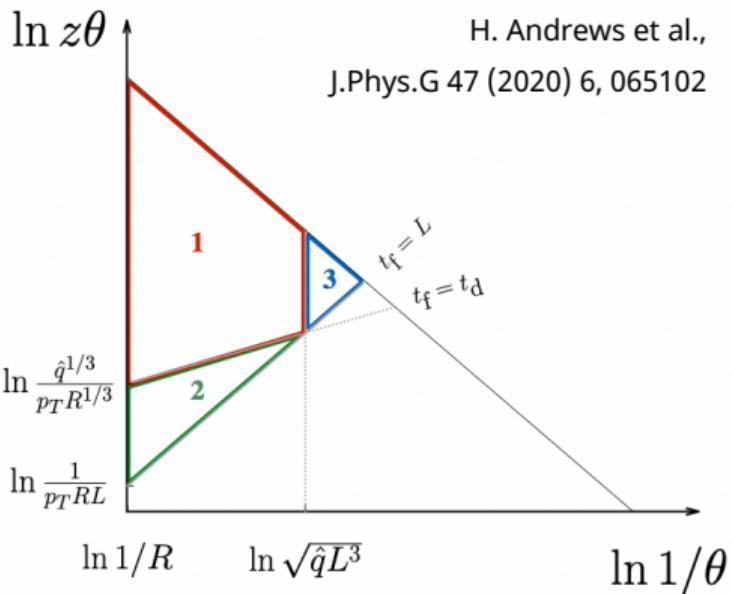
- Substructure observables sensitive to **which medium properties?**
- What are the **relevant length scales?**

e.g. Color coherence

- When do partons interact coherently?**
- Explored via **groomed jet radius (R_g)**:
Phys.Rev.Lett. 128 (2022) 10, 102001

Today: Grooming and 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?**



Identifying hard splittings: Soft Drop

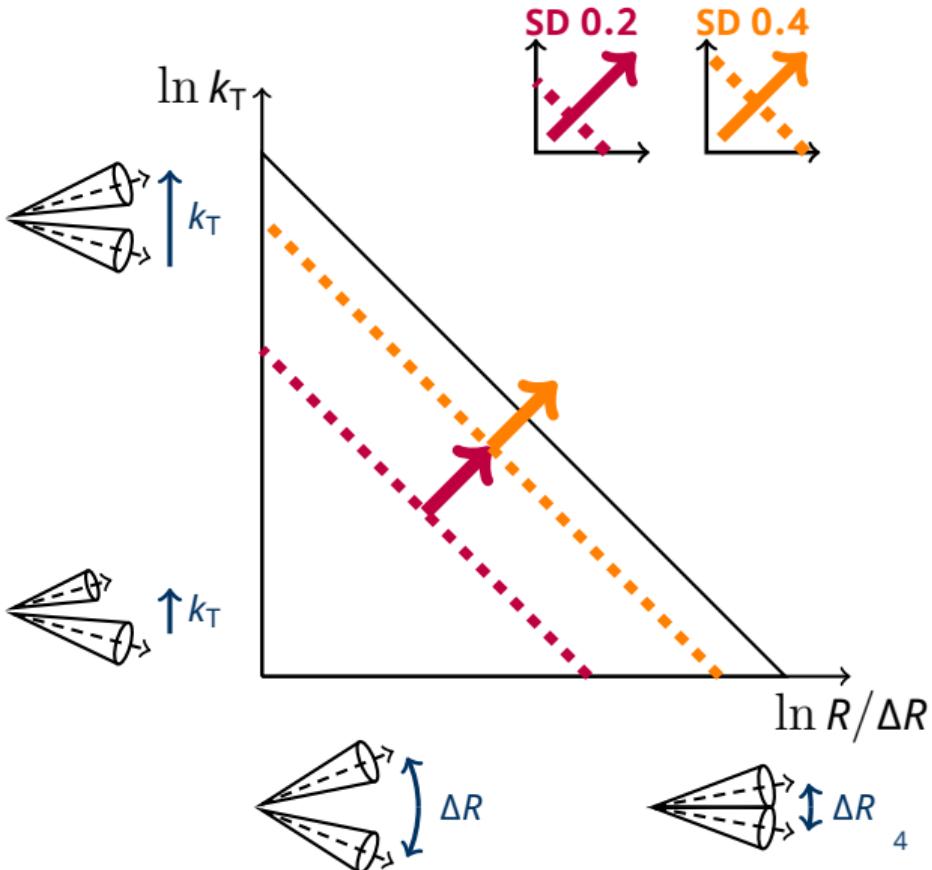
- $k_{T,g} = p_T^{\text{sublead}} \sin \Delta R$
- Iteratively follow splitting tree

Soft Drop

Larkoski et al., JHEP 05 (2014) 146

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

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



Identifying hard splittings: Dynamical Grooming

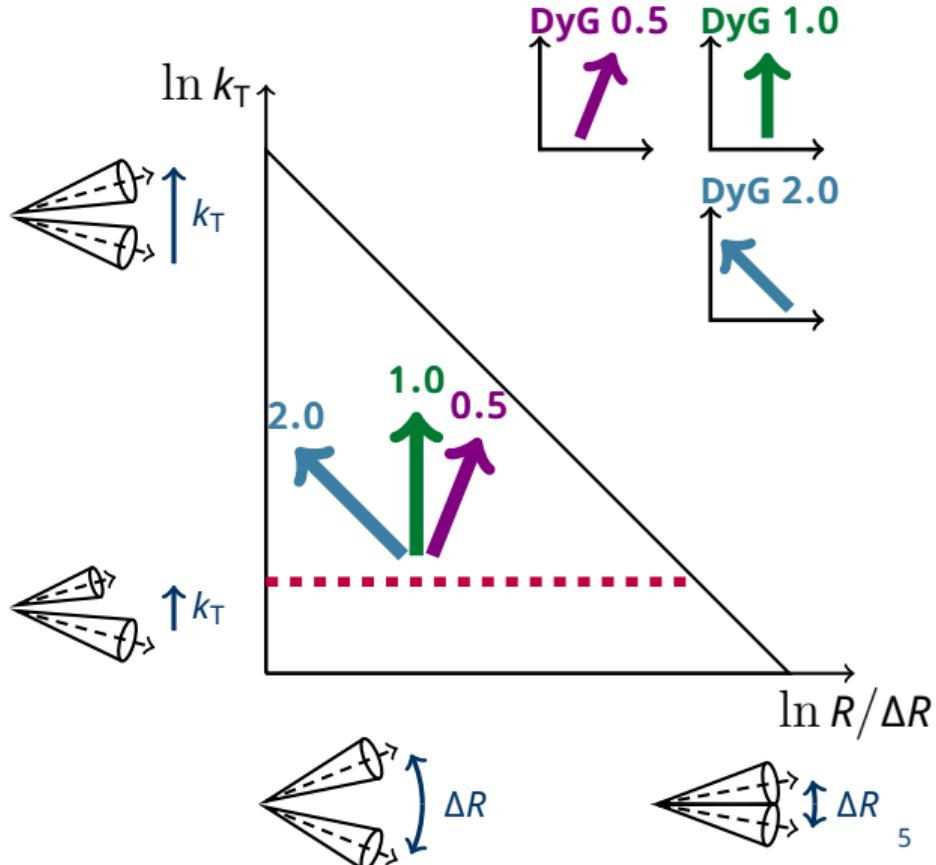
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Dynamical Grooming

Mehtar-Tani et al., PhysRevD.101.034004

$$\kappa^a \propto \max_{i \in C/A} [z_i(1 - z_i)p_{Ti}(\Delta R_i/R)^a]$$

- $a = 0.5$: "core" - more sym., narrow
- $a = 1$: " k_T " - largest $k_T \sim \kappa^1 p_T$
- $a = 2$: "time" - shortest splitting time $t_f^{-1} \sim \kappa^2 p_T$
- In practice, **further selections** needed for stable unfolding:
 1. **min k_T in Pb-Pb** (see backup)



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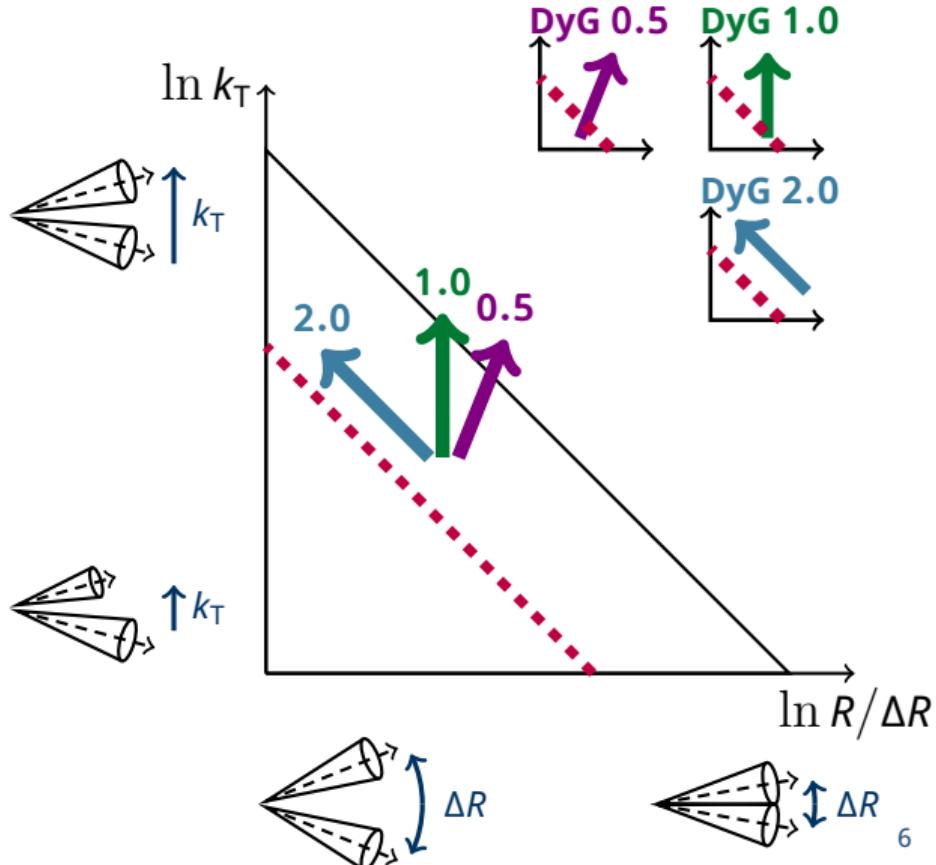
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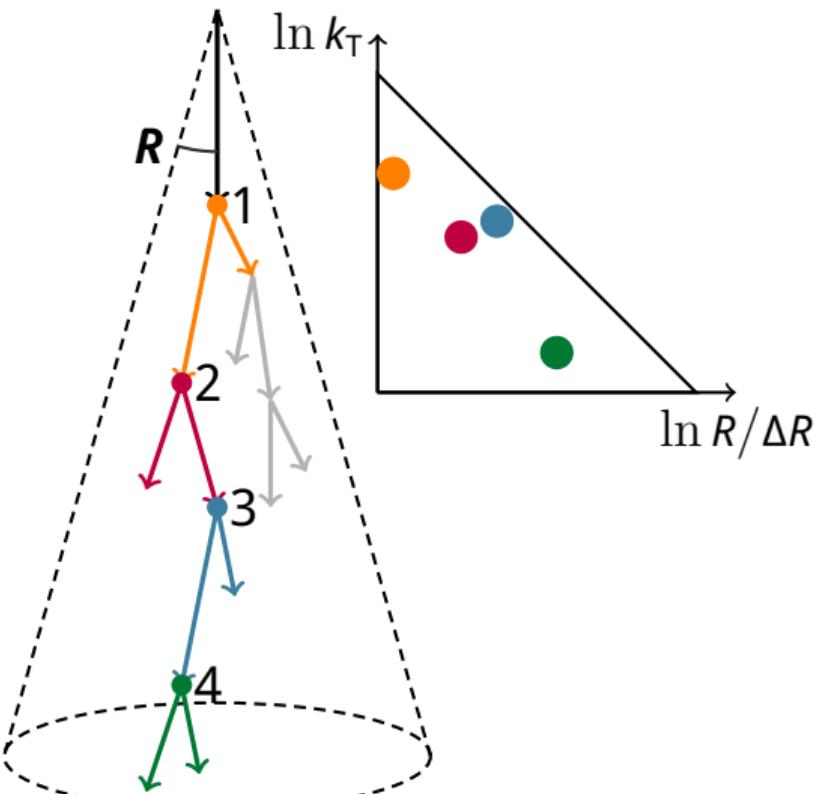
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- In practice, **further selections** needed for stable unfolding:
 1. **min k_T in Pb-Pb** (see backup)
 2. Alternatively, add **z requirement** (0.2)



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:
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?



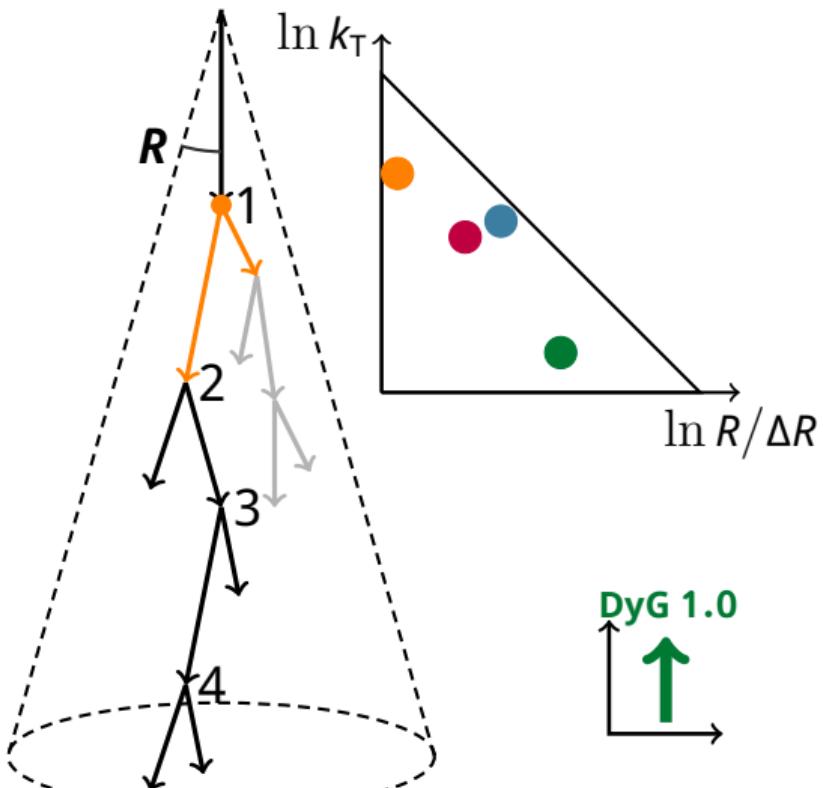
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→ Which method selects which splitting?

 - DyG $\alpha = 1.0$: #1



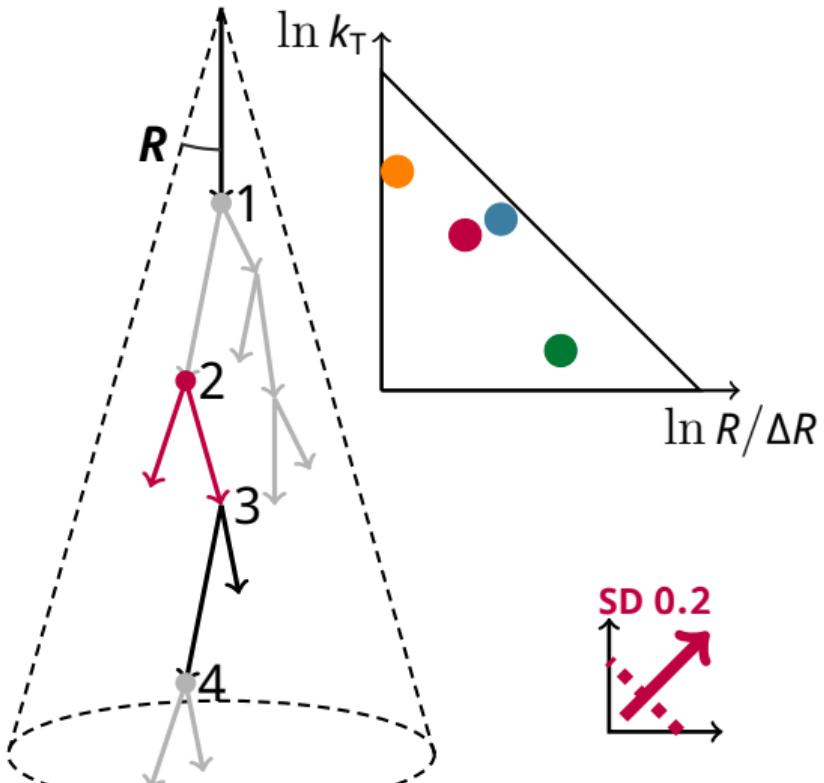
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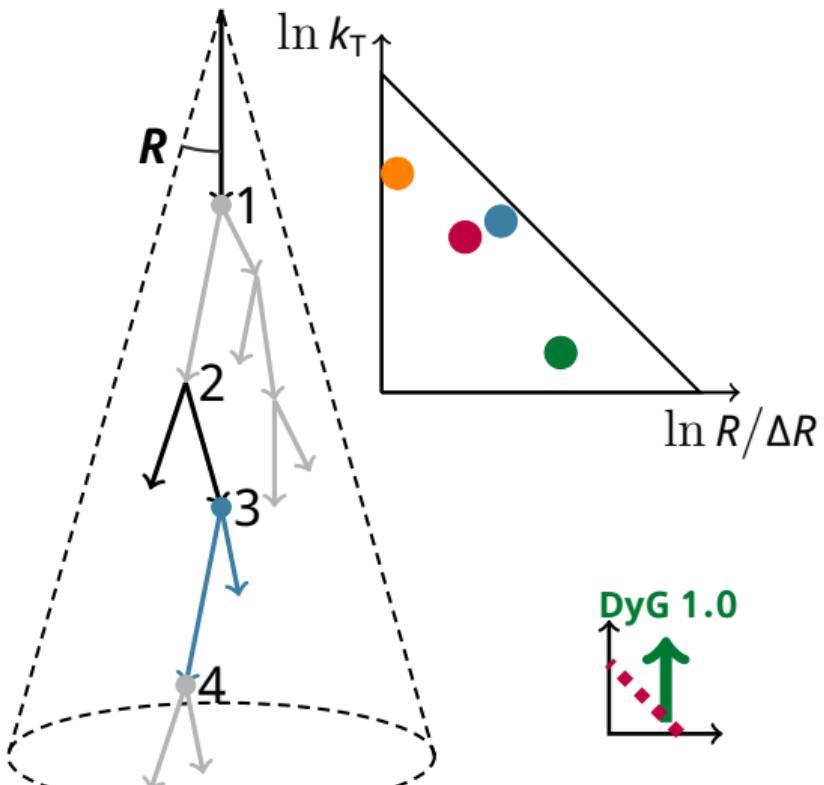
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 - DyG $\alpha = 1.0$: #1
 - SD $z_{\text{cut}} = 0.2$: #2



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



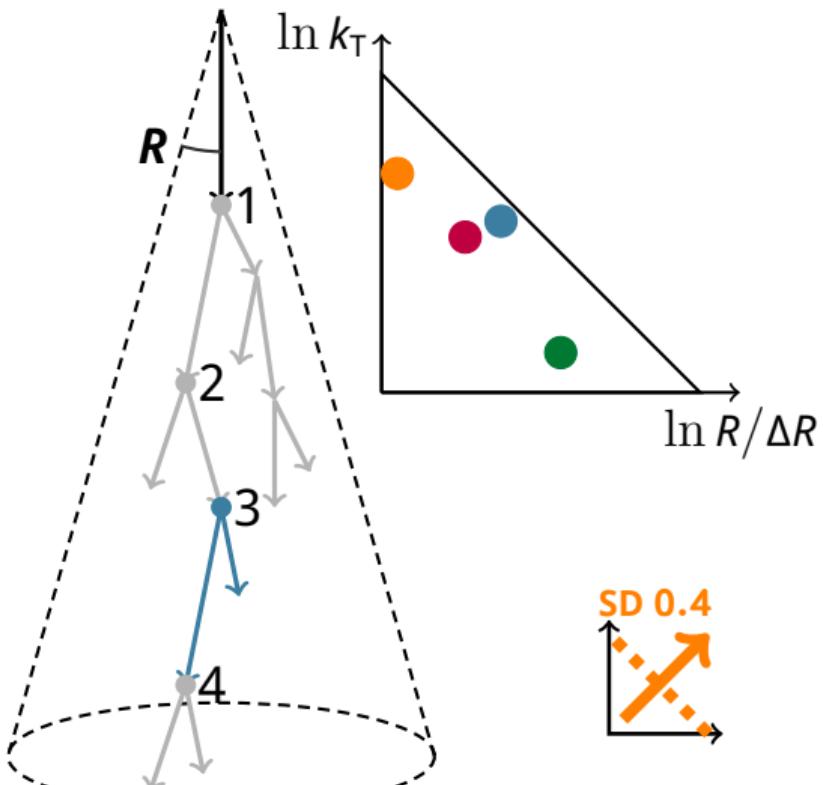
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- DyG $\alpha = 1.0$: #1
- SD $z_{\text{cut}} = 0.2$: #2
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- SD $z_{\text{cut}} = 0.4$: #3

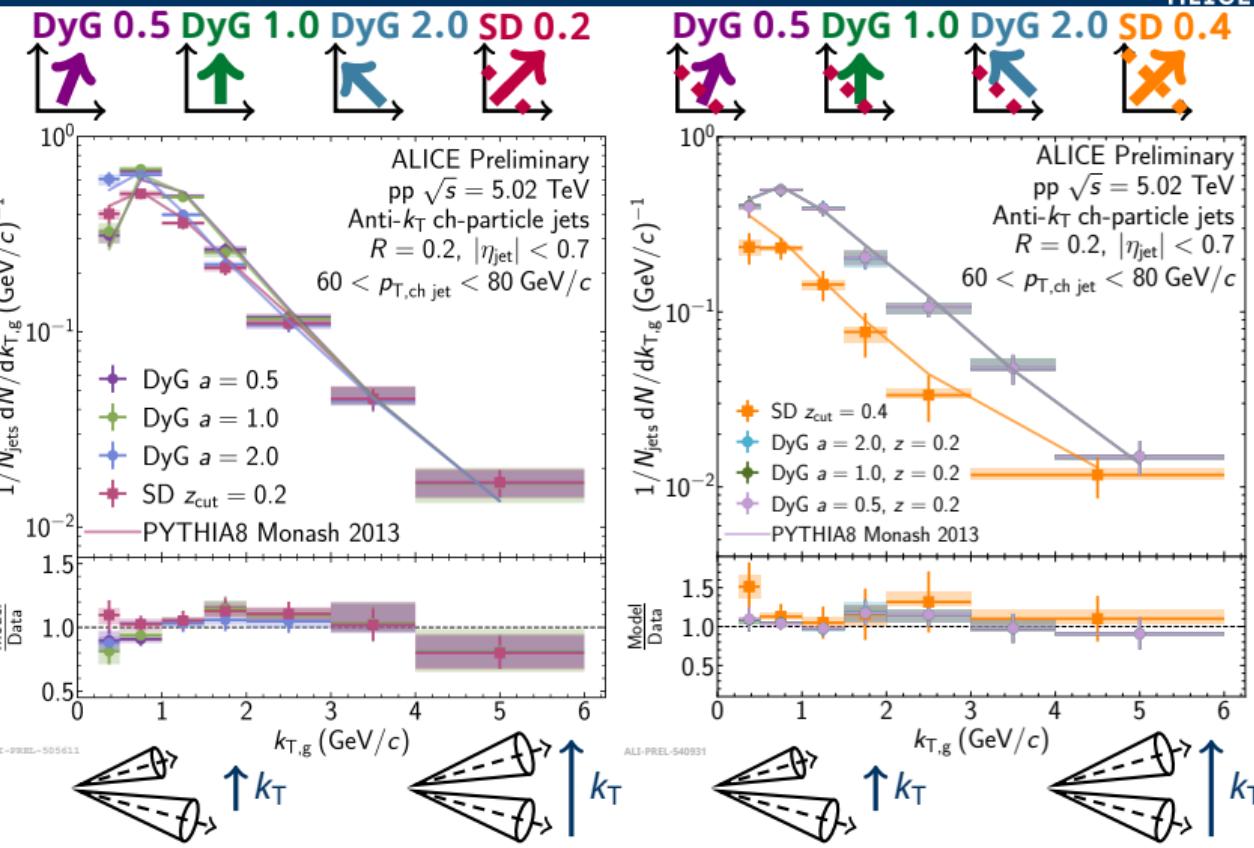


Comparing grooming methods in pp



- 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
- Additional R + further models in backup

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

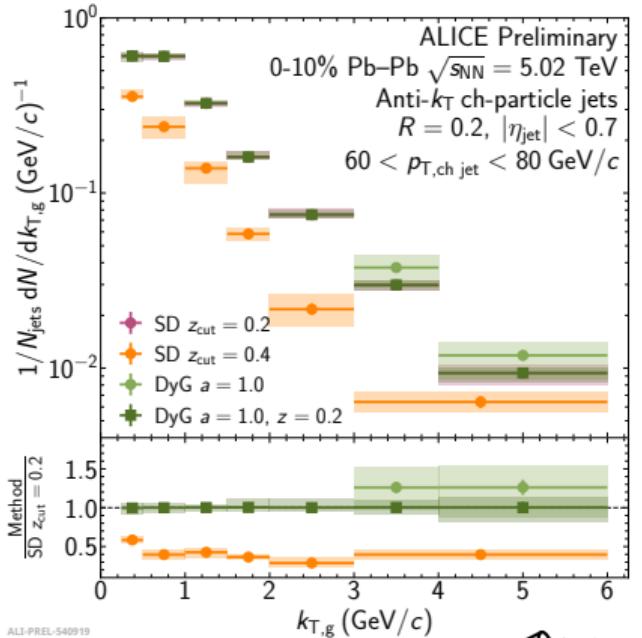


Comparing grooming methods in Pb-Pb

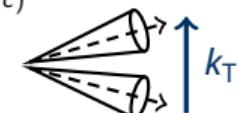
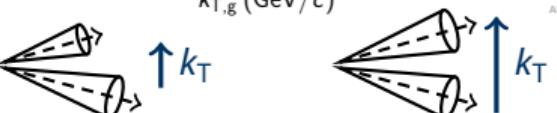
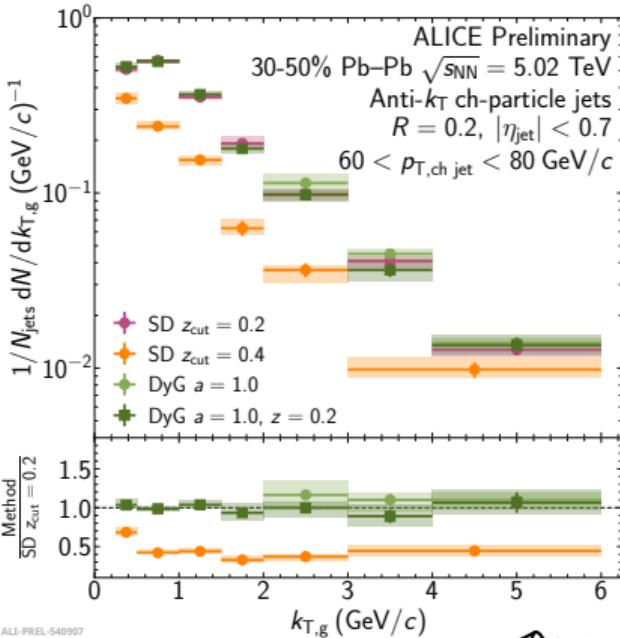


- First DyG in Pb-Pb
 - Similar trends in 0-10% and 30-50%
 - Reduced SD $z_{\text{cut}} = 0.4$ yield due to phase space
 - Consistent set of splittings from all DyG $a = 1.0$, SD $z_{\text{cut}} = 0.2$
- Suggests few hard splits further into tree

0-10% central



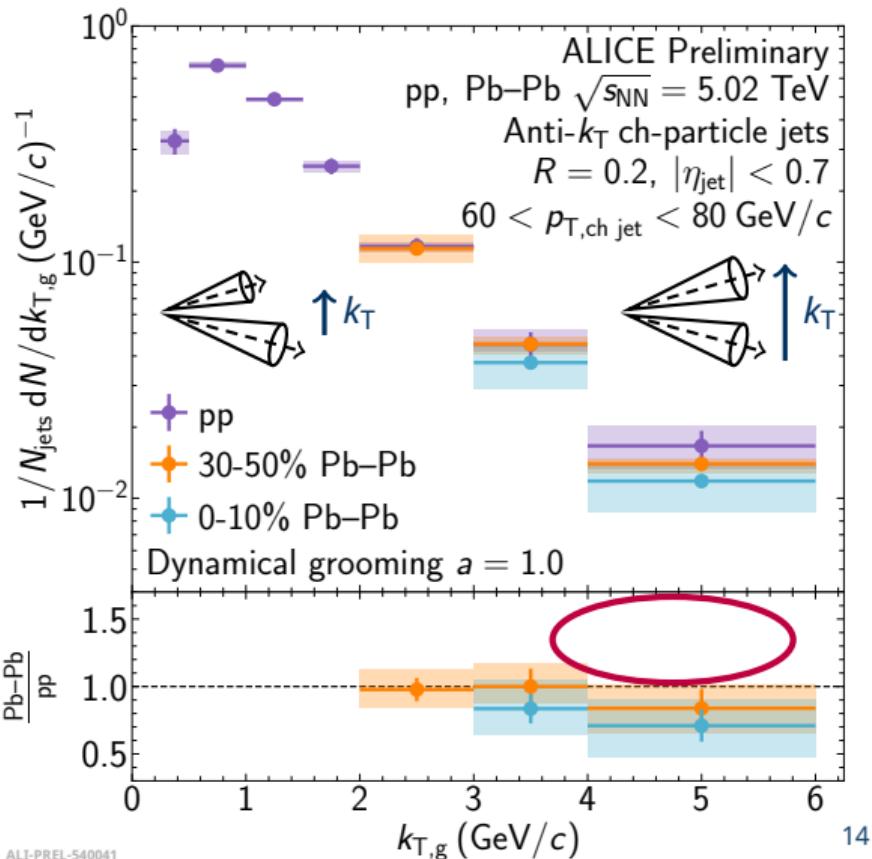
30-50% semi-central



Searching for modification

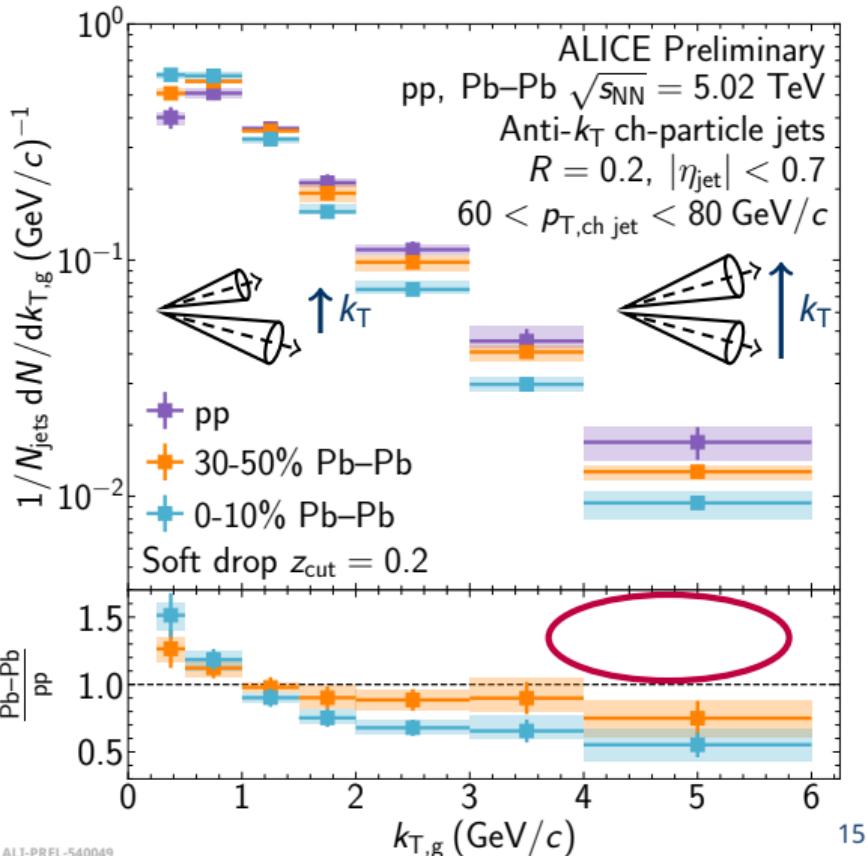
- **No enhancement** at high $k_{T,g}$
- Standard DyG shows **little modification**

DyG 1.0
↑



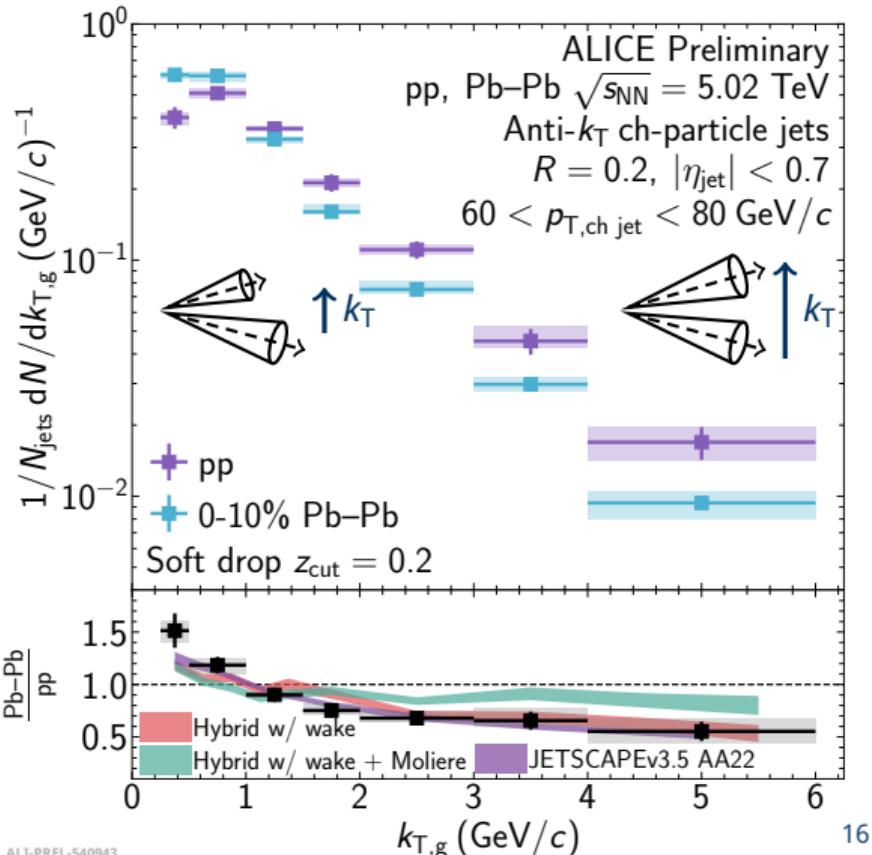
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- **Modification** in methods with $z > 0.2$
 - Larger modification in 0-10%
- **Consistent with narrowing picture** seen in many substructure analyses.
 - eg. R_g , jet axis difference, angularities, etc
- **No clear evidence of Moliere scattering**



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 - eg. R_g , jet axis difference, angularities, etc
- **No clear evidence of Moliere scattering**
- 0-10% data described by **JETSCAPEv3.5 AA22¹** and **Hybrid model²** w/out Moliere
- **Caveat: pp baseline**



1: JETSCAPE arXiv:2301.02485

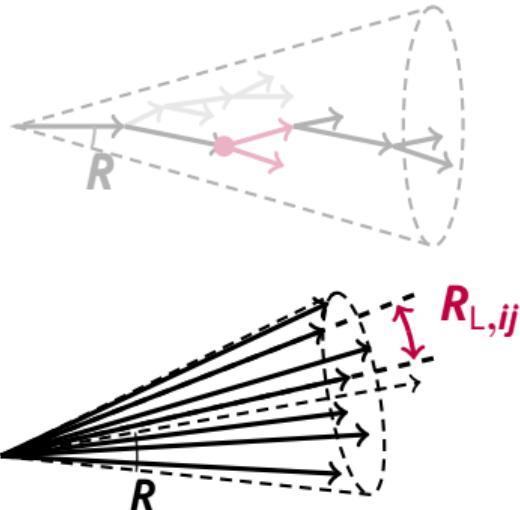
2: D'Eramo et al. JHEP 01 (2019) 172, Hulcher et al. QM 22

Outline: Thinking in angular scales

- Jets and their substructure are multi-scale probes of **QCD evolution**

1. Groomed jet substructure in Pb-Pb

- Isolate physical scales → resolve medium scales
- High $k_{T,g}$ emissions → quasi-particle scattering in medium?
- How to find hard splittings?



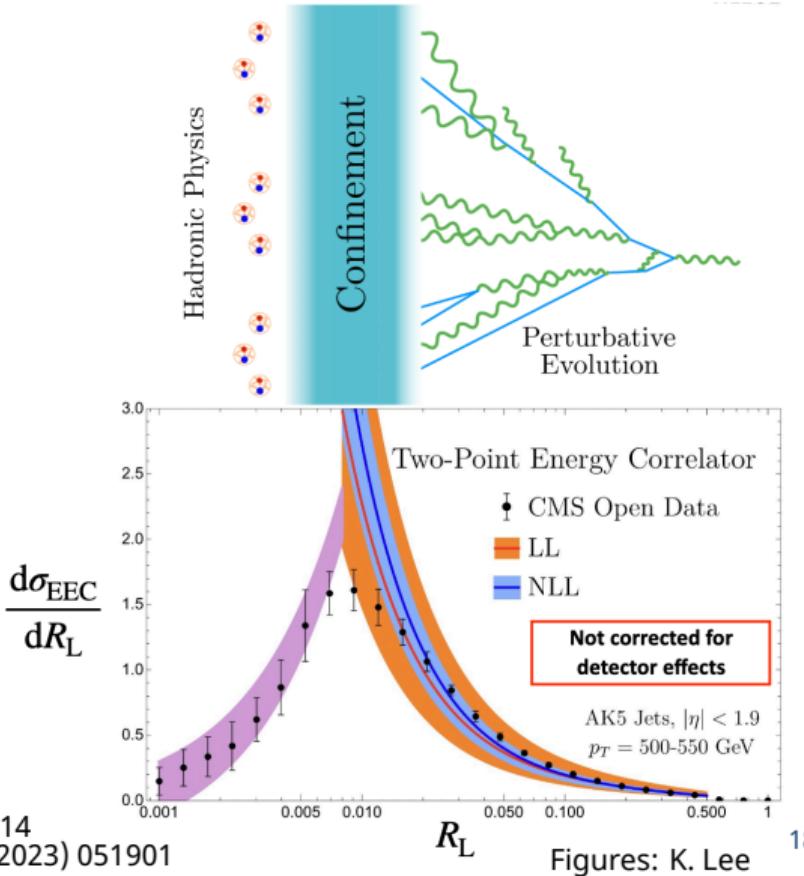
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- Separate angular scales → isolate physical regimes
- Hadron-level correlations → pQCD, hadronization

Energy-energy correlators

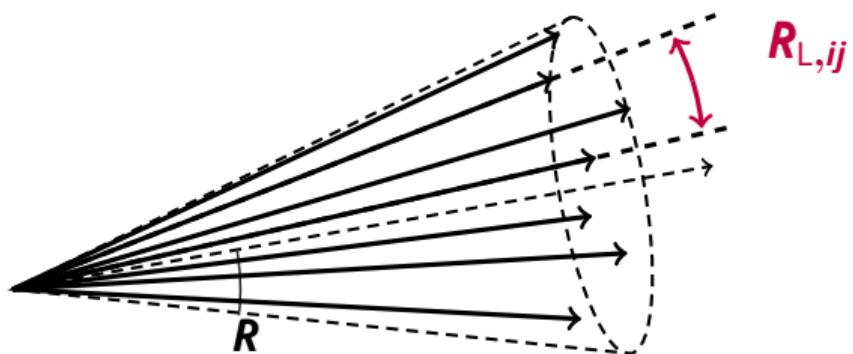
- Energy flow via class of **p_T -weighted cross sections**: **Energy-energy correlators (EECs)**
- Angular dependence **isolates hadronic** → **partonic dominated dynamics**

$$\frac{d\sigma_{\text{EEC}}}{dR_L} = \sum_{i,j} \int d\sigma(R'_L) \frac{p_{T,i} p_{T,j}}{p_{T,\text{jet}}^2} \delta(R'_L - R_L)$$



Energy-energy correlators

- Energy flow via class of **p_T -weighted cross sections**: Energy-energy correlators (EECs)
- Angular dependence isolates hadronic → partonic dominated dynamics
- p_T -weighted angular correlation of all jet constituent pairs
- Pair weighted by jet and constit. p_T
- Reduced sensitivity to soft emissions
→ No need for grooming algorithms

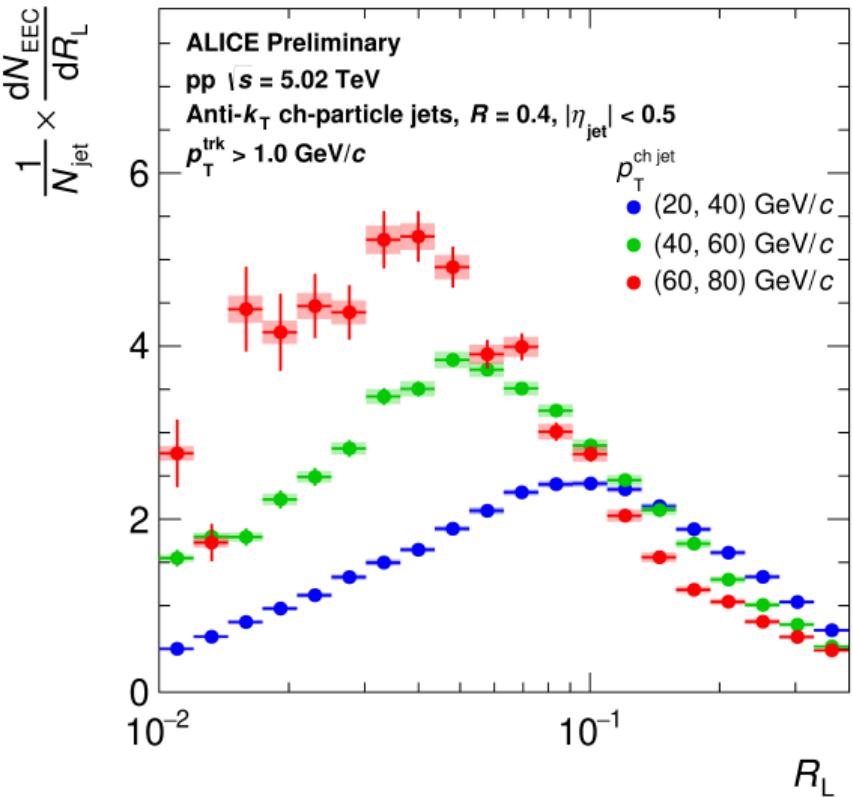


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$$R_L = \sqrt{\Delta\phi^2 + \Delta\eta^2} \quad \text{Weight: } \frac{p_{T,i} p_{T,j}}{p_{T,\text{jet}}^2}$$

Energy-energy correlators in pp collisions

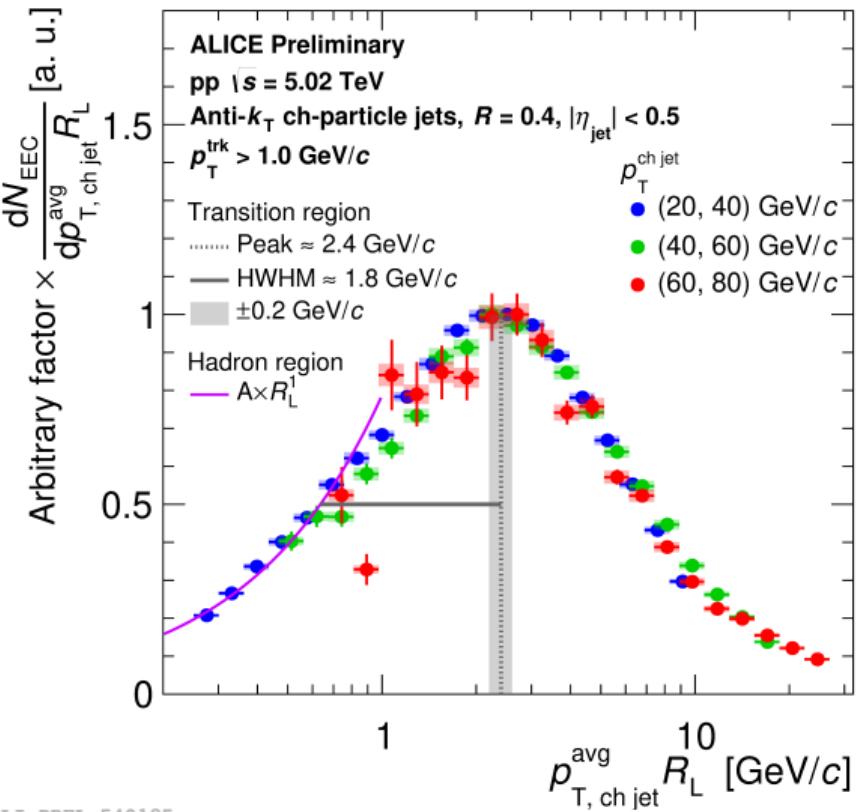
- **2-point correlator** measured in $R = 0.4$ charged-particle jets $20 < p_{T,jet} < 80 \text{ GeV}/c$
- Use jet **constituents with $p_T > 1 \text{ GeV}/c$**
- Detector effects corrected with **bin-by-bin correction**:
 - small overall correction factor
 - weak MC generator dependence
 - weak dep. on systematic variations
- Peak shifts **left with increasing $p_{T,jet}$**
- Transition region **occurs at similar relative scale**



ALI-PREL-540213

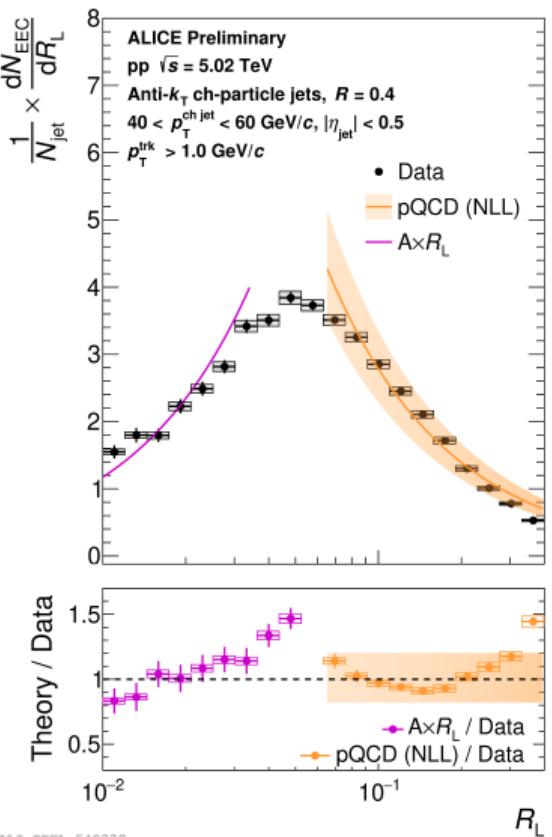
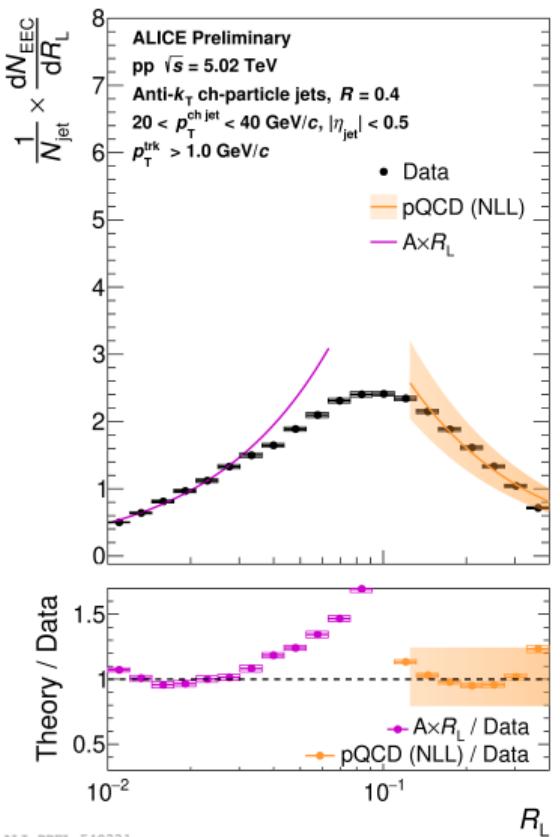
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Comparing to pQCD calculations

- **NLL calculations** from K. Lee et al., arXiv:2205.03414
- Full jet calculation **normalized to pertub. region**
- Broadly describes data **shape within theory uncertainties**
 - **Hints of tension**, needs further investigation
- Deviation from calculation **due to non-pertub. effects**
- **Free hadron like behavior** at small angles



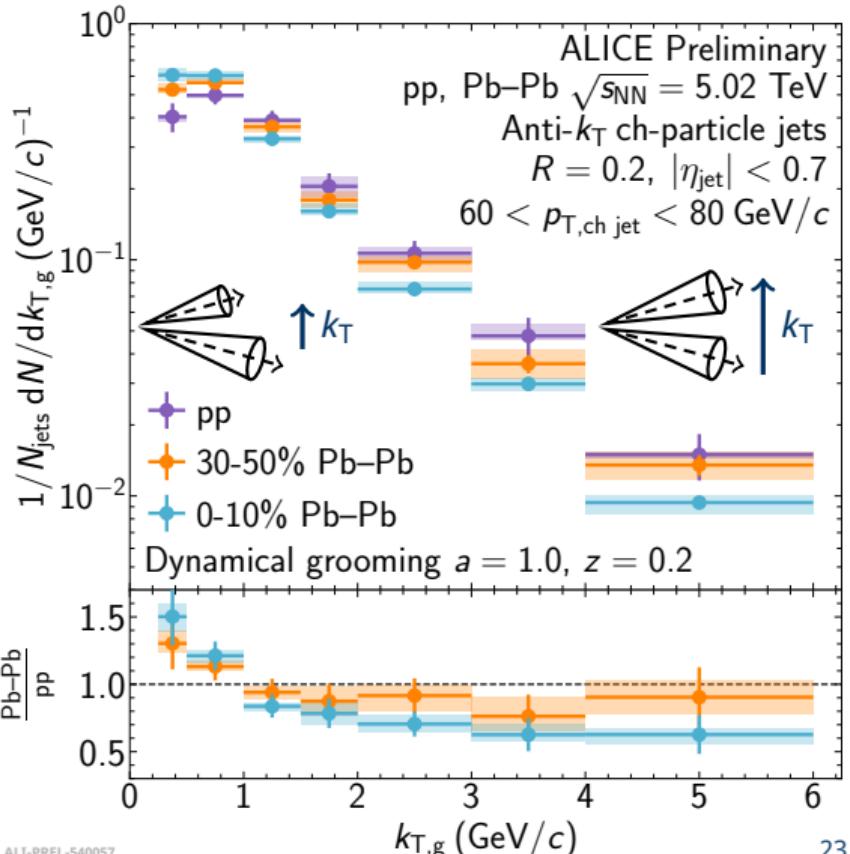
Summary

1. Grooming studies + medium scattering centers

- First measurement of DyG in Pb-Pb
- z_{cut} dominates over grooming method details
- Suggests minimal impact of splittings far into splitting tree
- No clear evidence of Moliere scattering

2. Energy-energy correlators

- First corrected EEC measurement at LHC
- Shape changes corresponding to QCD regimes
- Observe universality of transition region
- Roughly described by calculations



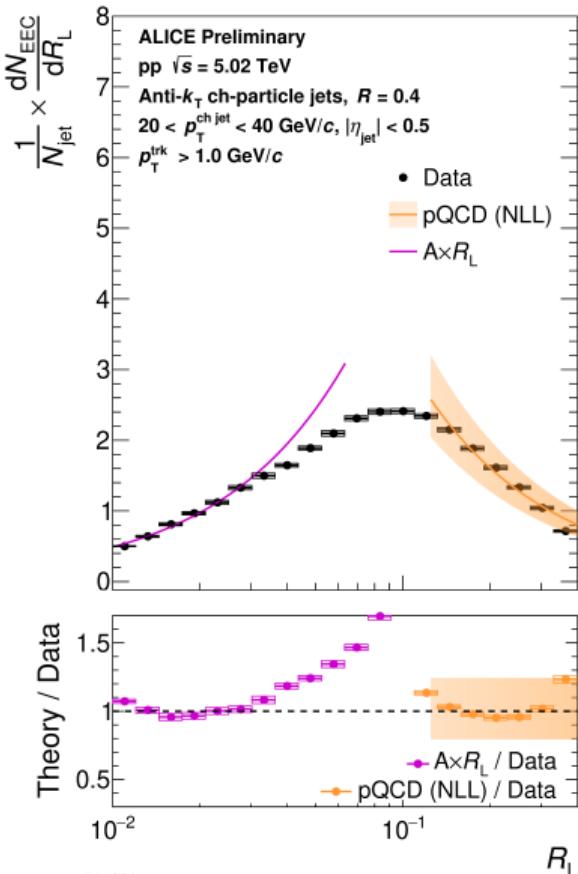
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Outlook

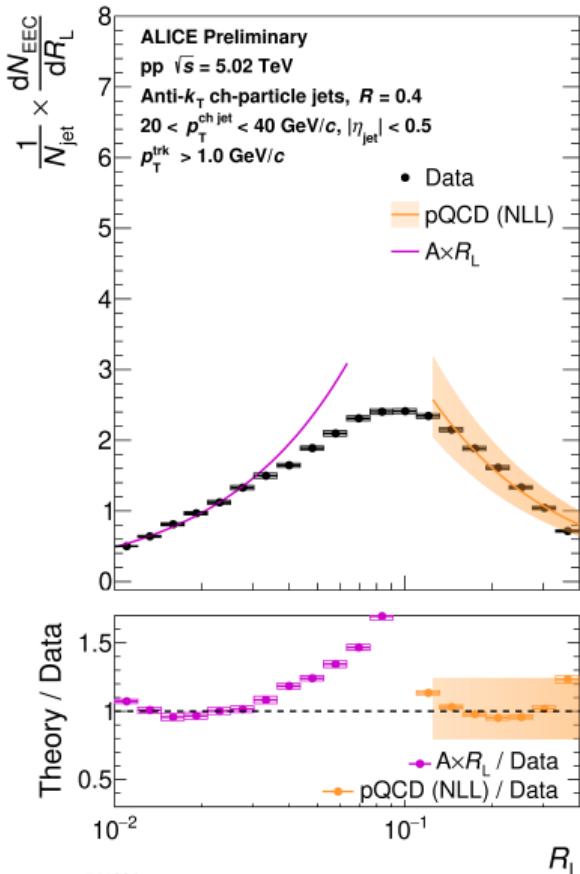
- **Much to explore** in medium and in vacuum!

New techniques

- **Statistical methods?**
- Applications of **machine learning?**

New observables and applications

- **Full Lund Plane in Pb-Pb?**
 - Relax grooming requirements? Heavy flavor?
- **Energy correlators in Pb-Pb?** Higher-point energy correlators?
 - **What information do we learn** from EECs compared to other substructure observables?



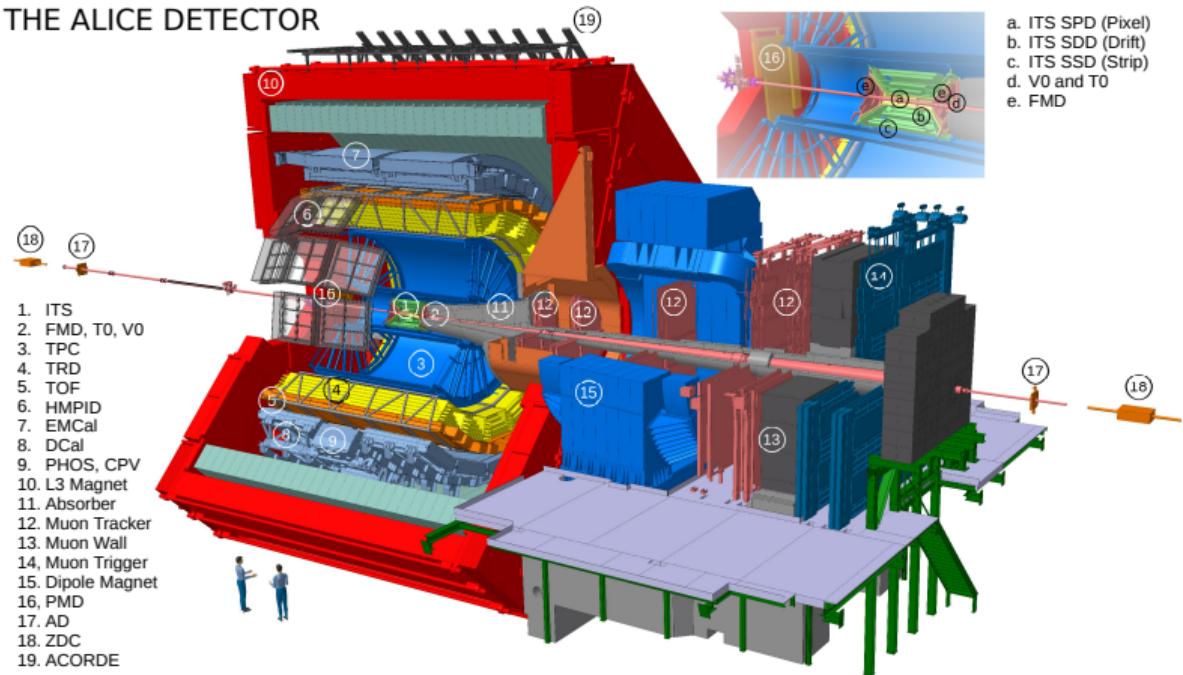
Backup

Jets and their substructure in ALICE



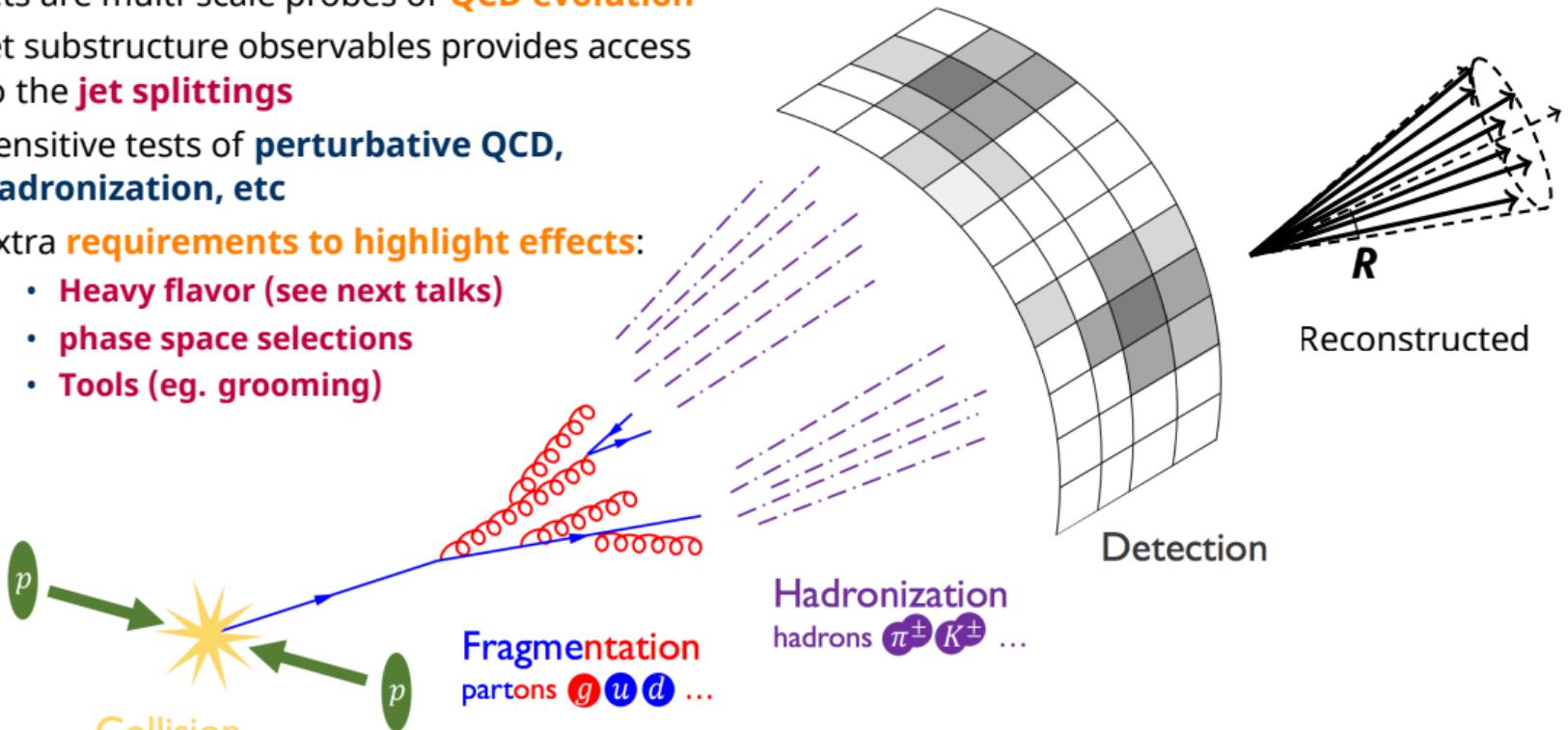
- ALICE well suited for measuring:
 - **Low p_T** jets
 - **Small splitting angles** at high efficiency
- Enables **strong substructure program**
- Anti- k_T charged-particle jets measured in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

THE ALICE DETECTOR



Jets and their substructure in pp collisions

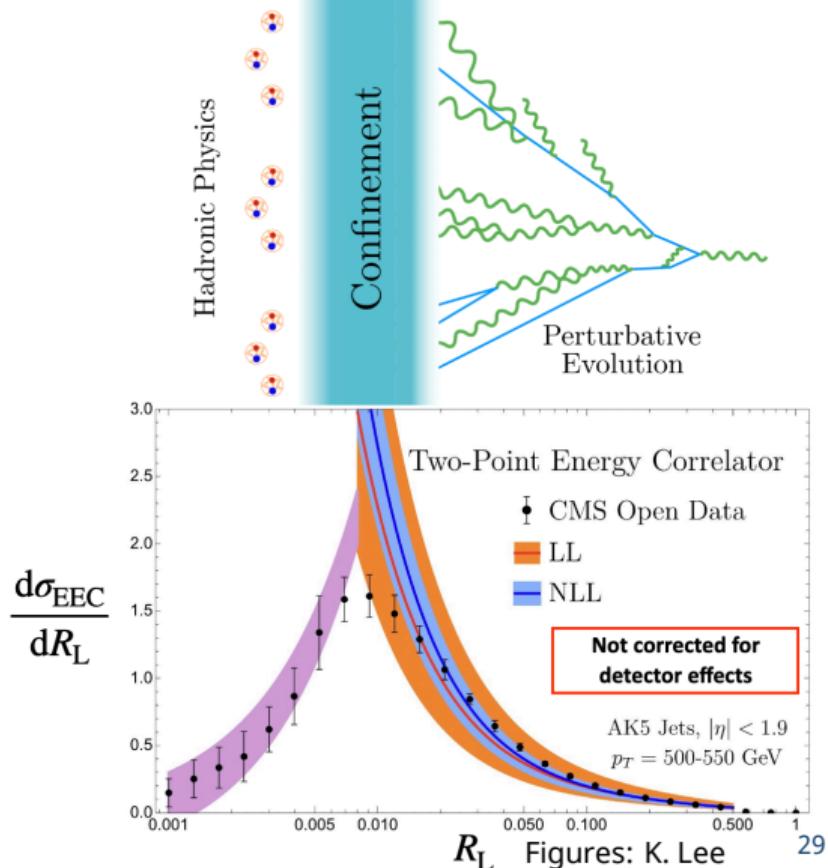
- Jets are multi-scale probes of **QCD evolution**
- Jet substructure observables provides access to the **jet splittings**
- Sensitive tests of **perturbative QCD, hadronization, etc**
- Extra **requirements to highlight effects:**
 - Heavy flavor (see next talks)
 - phase space selections
 - Tools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



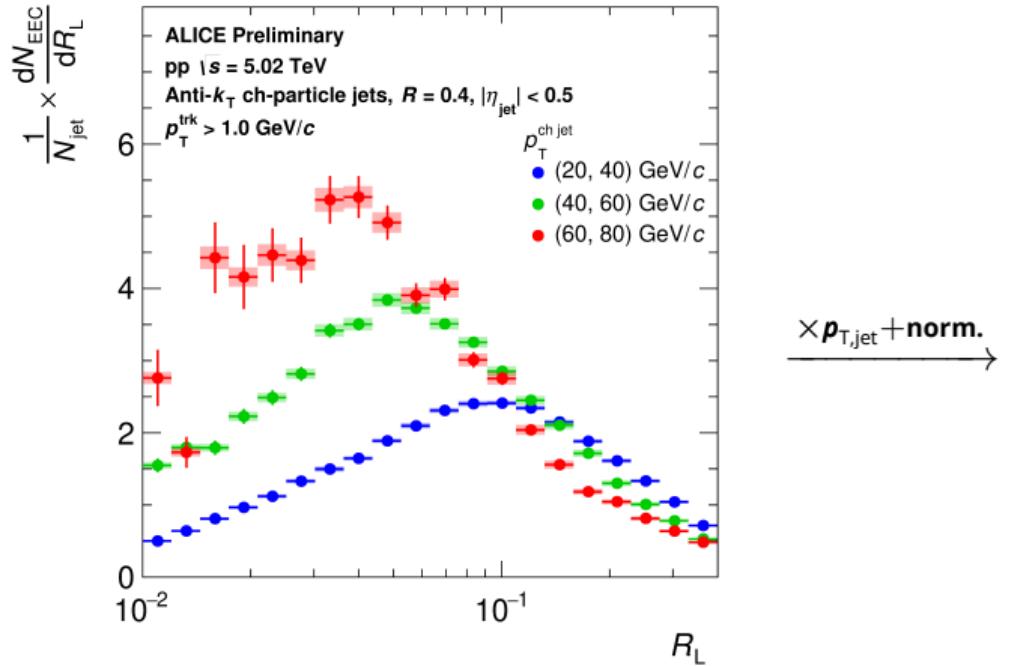
Energy-energy correlators/2

- Spans **hadronic → partonic dominated dynamics**
 - Large angle → **perturbative QCD**
 - Intermediate → **confinement**
 - Small angle → **free hadron like**
 - Large angles **calculable in pQCD**
- $Q \sim p_T R_L, \tau \sim 1/(p_T R_L^2)$

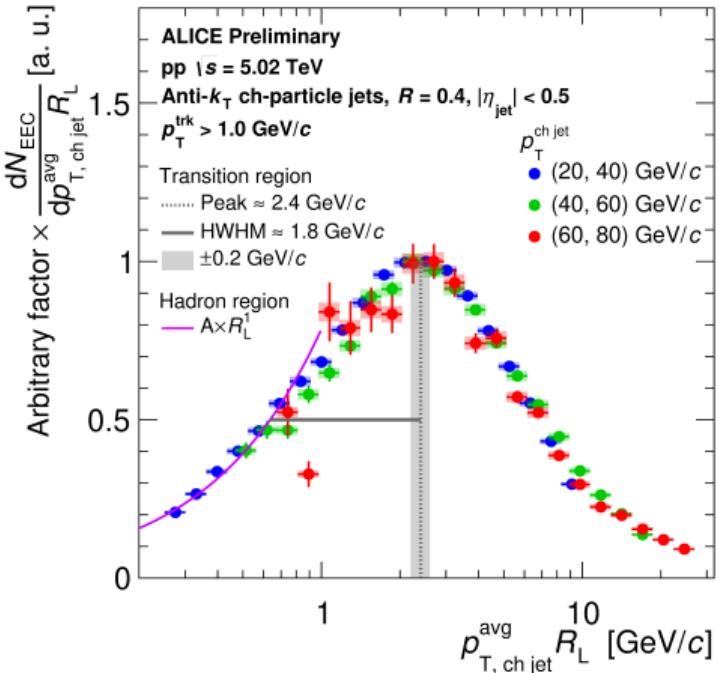
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Universality of transition region

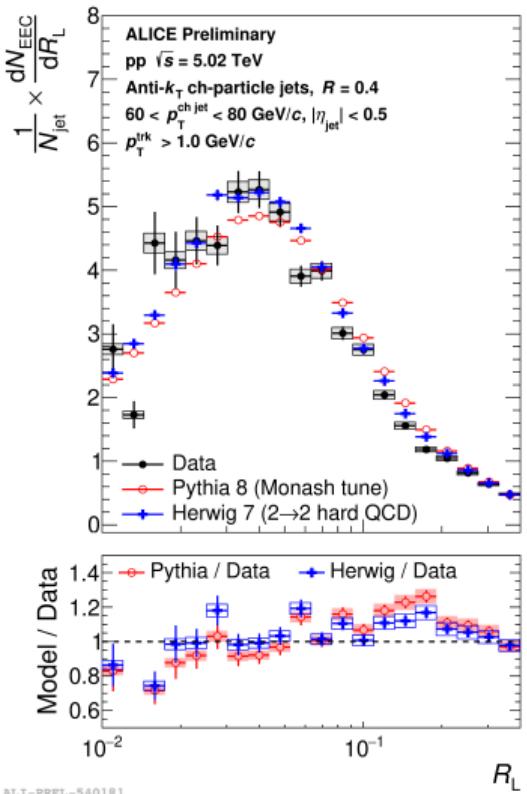
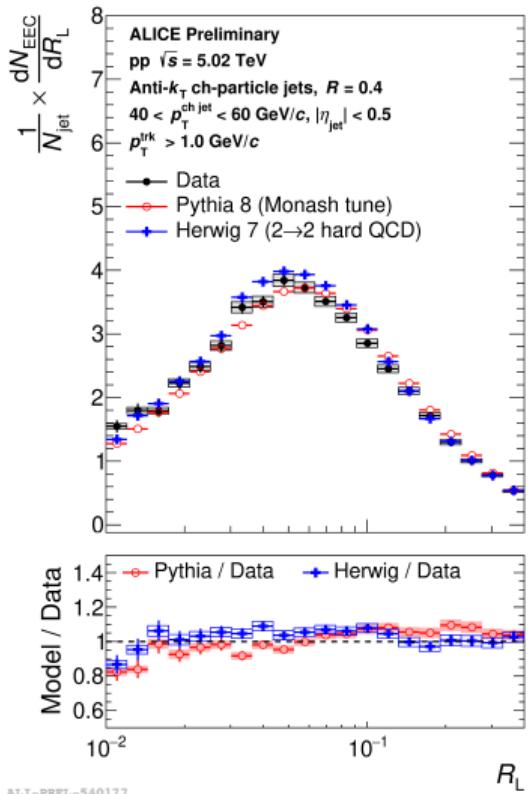
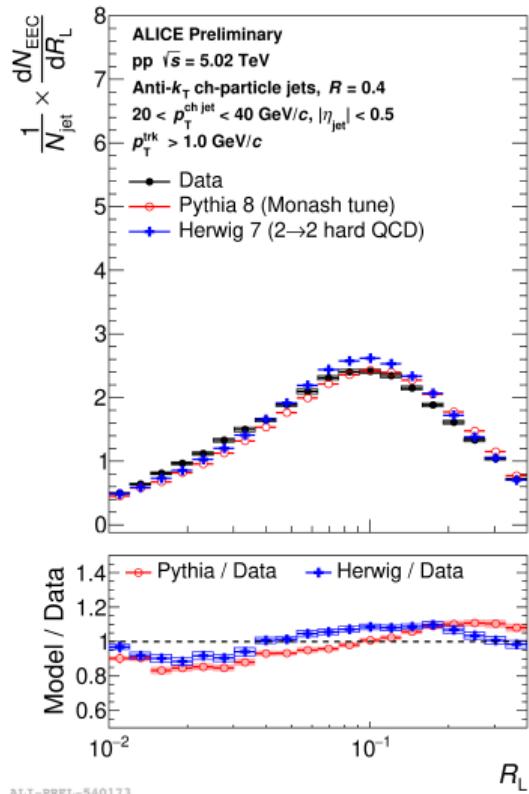


$\times p_{T,\text{jet}} + \text{norm.}$



Transition region **occurs at similar relative scale**

EEC model comparisons

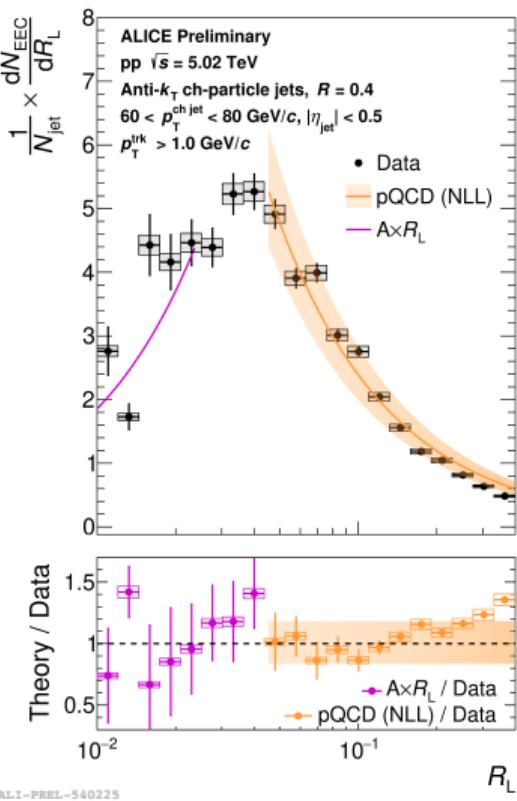
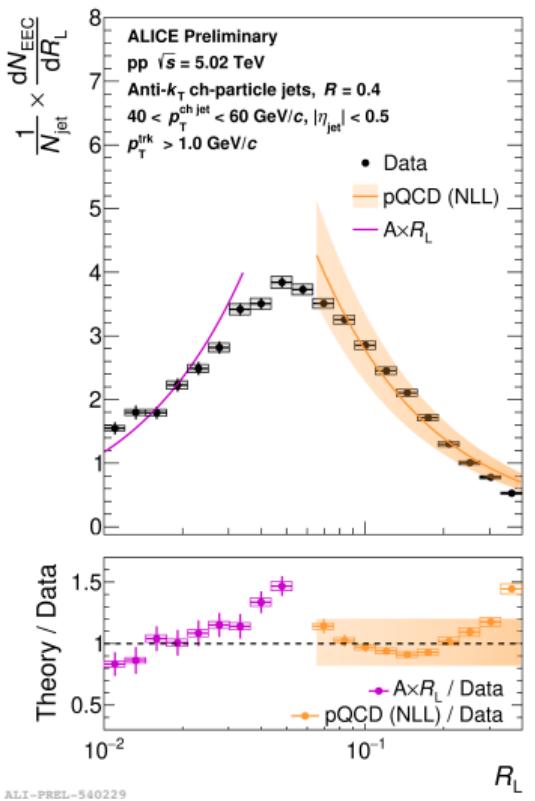
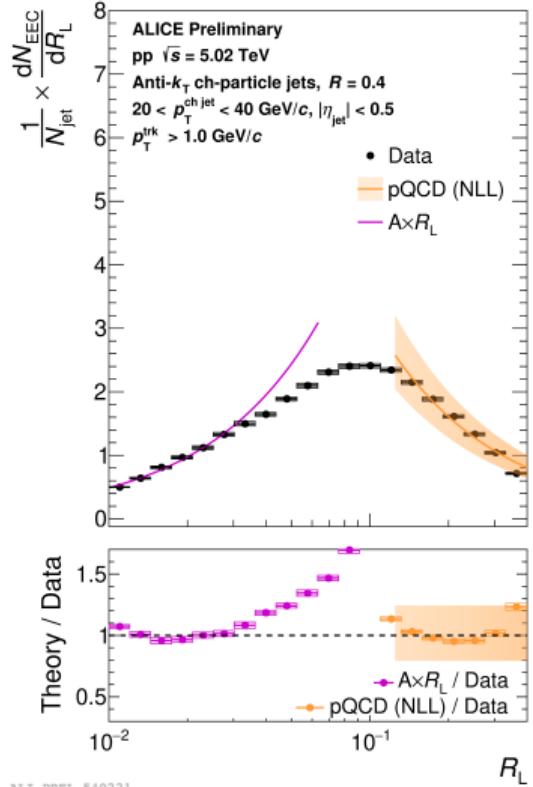


ALI-PREL-540173

Raymond Ehlers (LBNL/UCB) - 3 August 2023

Herwig, PYTHIA show similar level of agreement

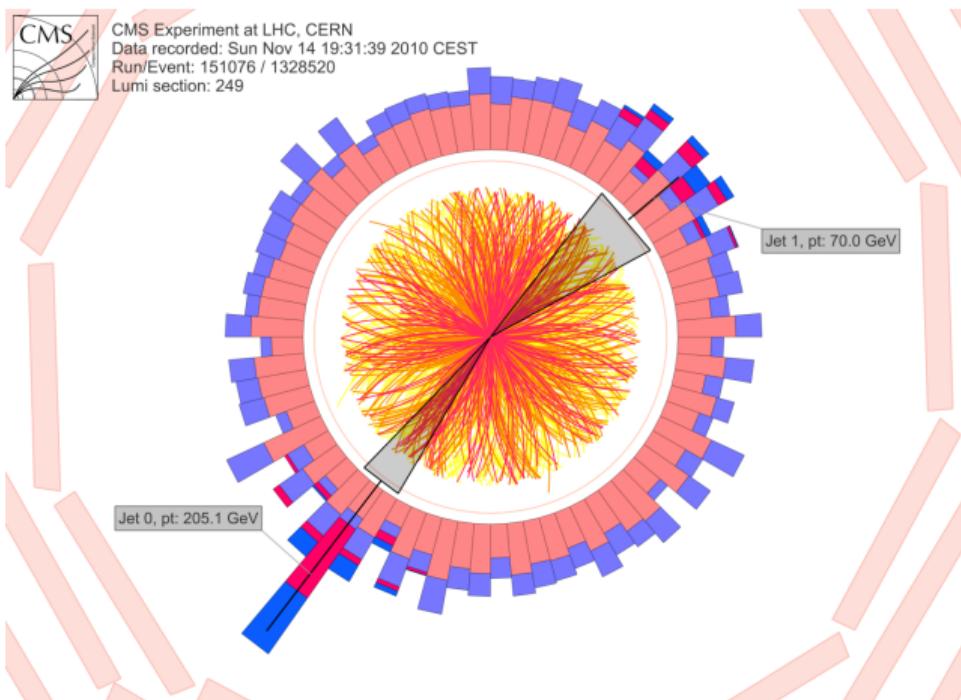
Comparing to pQCD calculations



ALI-PREL-540221

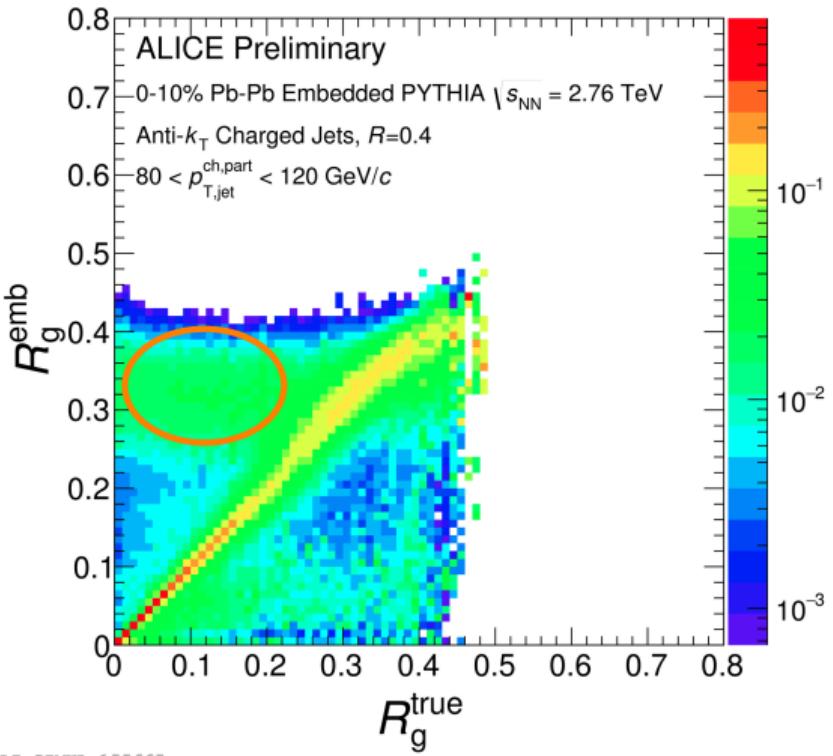
Experimentally accessing jets in heavy-ion collisions

- 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



Experimentally accessing jets in heavy-ion collisions

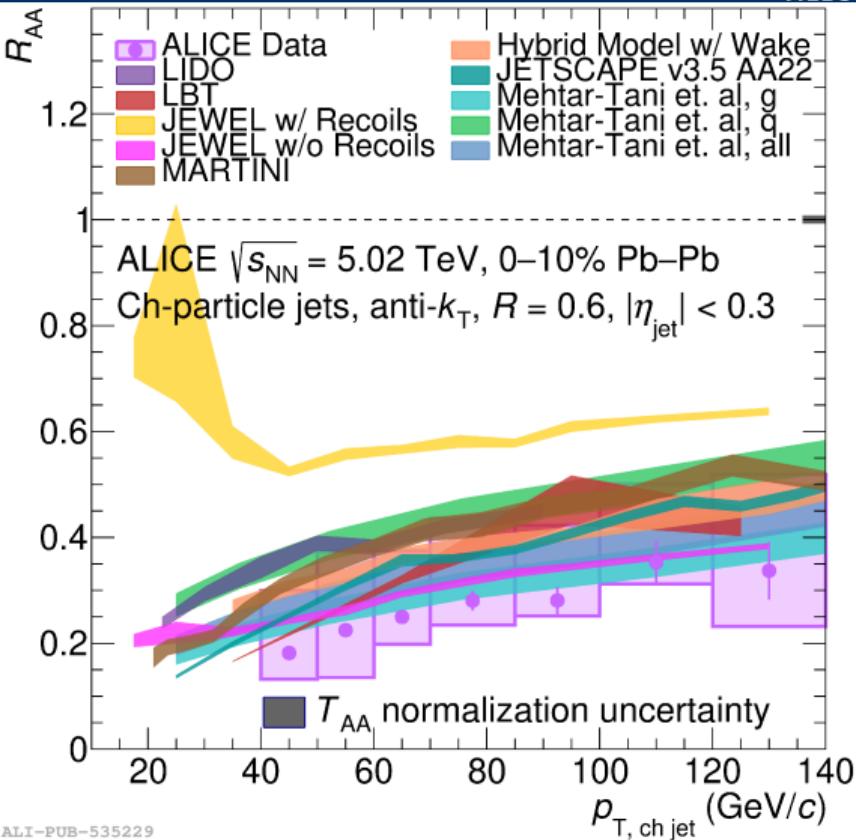
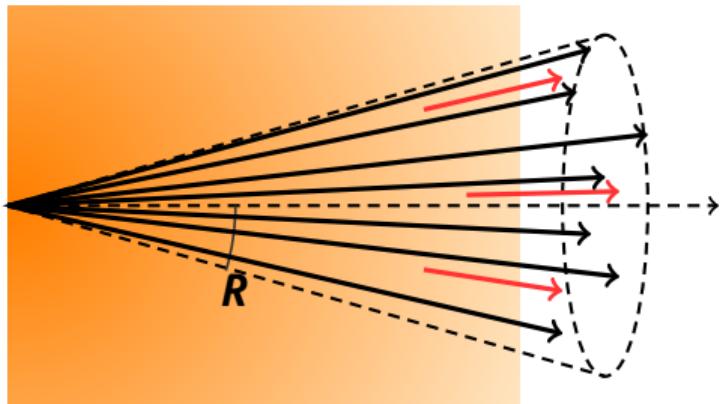
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Jets and their substructure in Pb-Pb collisions



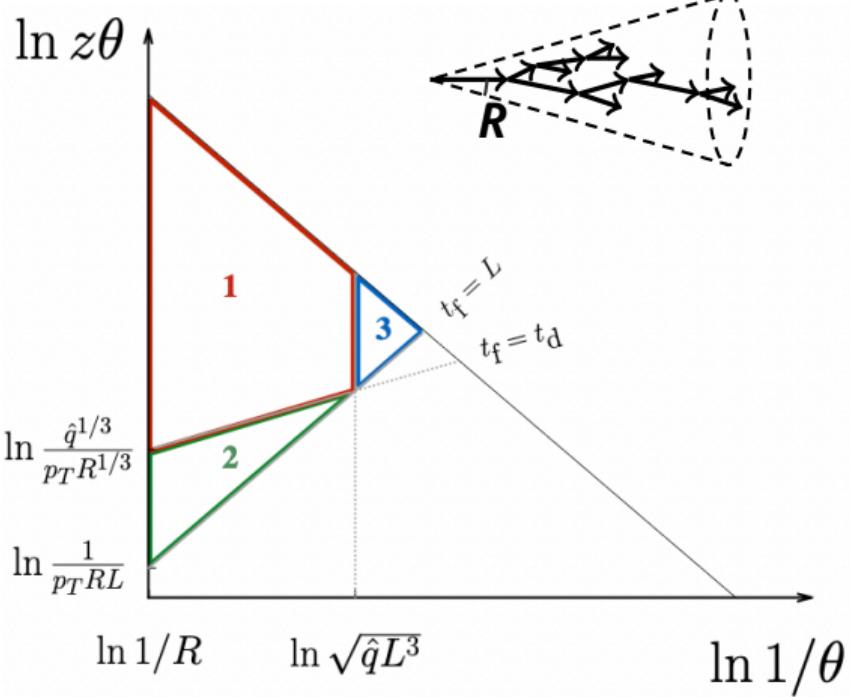
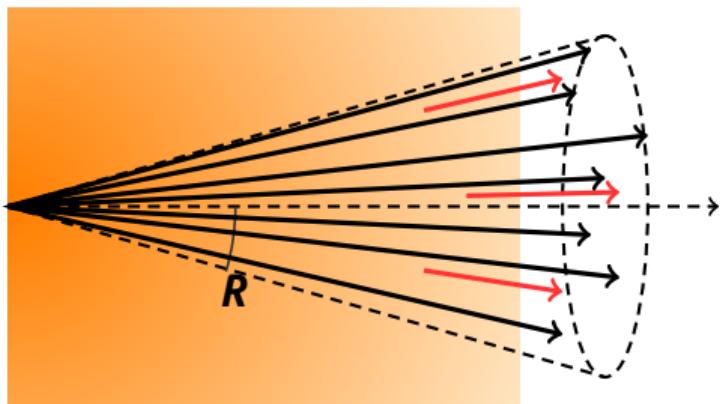
- Partons propagate and interact with medium, **modifying evolution** of parton shower
 - Jet-medium interactions modify the **jet properties and internal structure**
 - Medium properties encoded** into jet modification
- Jets are in-situ **probes of QGP dynamics**



ALI-PUB-535229

Jets and their substructure in Pb-Pb collisions

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- Jets are in-situ **probes of QGP dynamics**



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

How do models fare?



JETSCAPEv3.5 AA22 tune

JETSCAPE arXiv:2301.02485

- MATTER+LBT
- Describes data well

Hybrid model

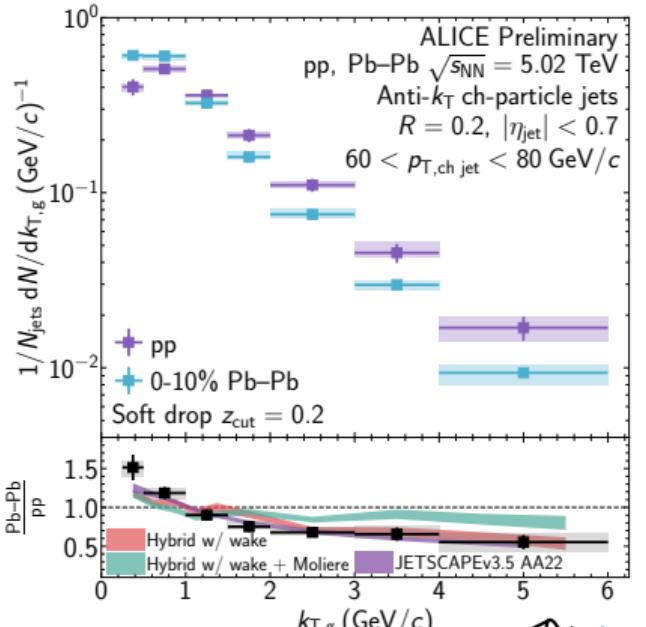
D'Eramo et al. JHEP 01 (2019) 172

Hulcher et al. QM 22

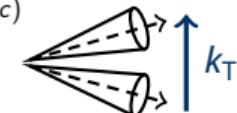
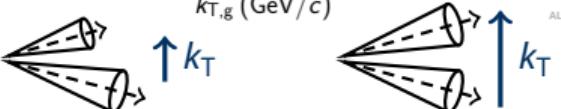
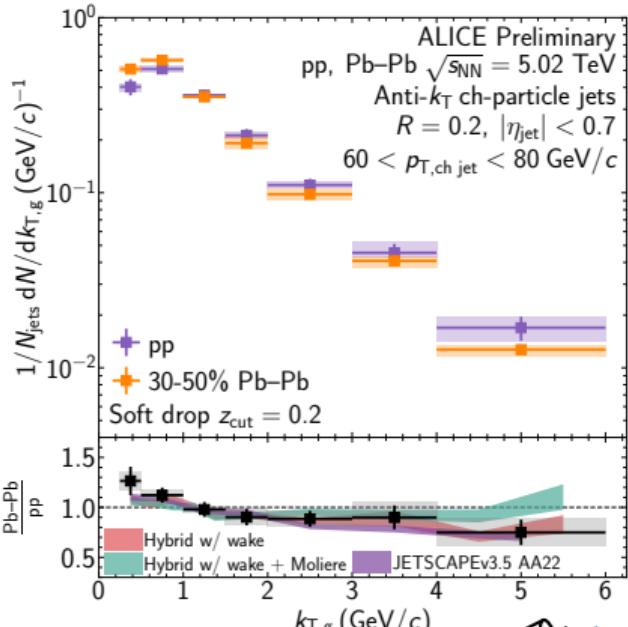
- With, w/out Moliere
- w/out Moliere **describe 0-10% data better**

Caveat: pp baseline

0-10% central

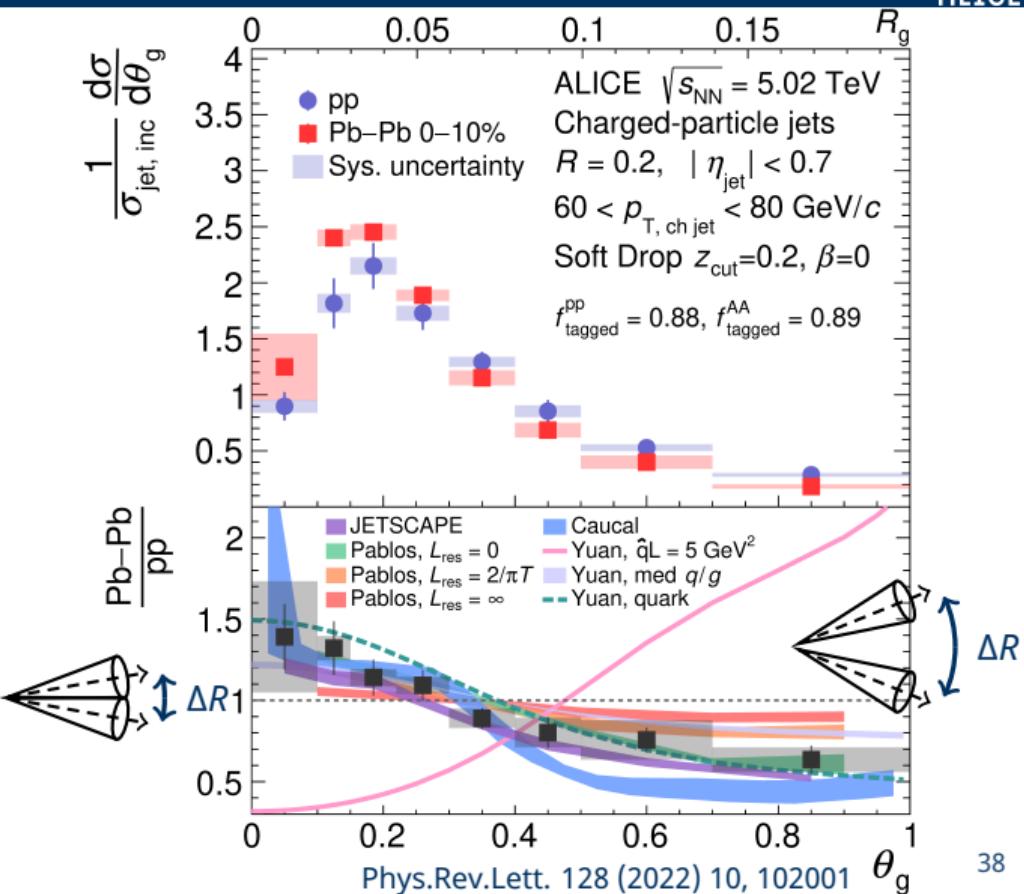


30-50% central

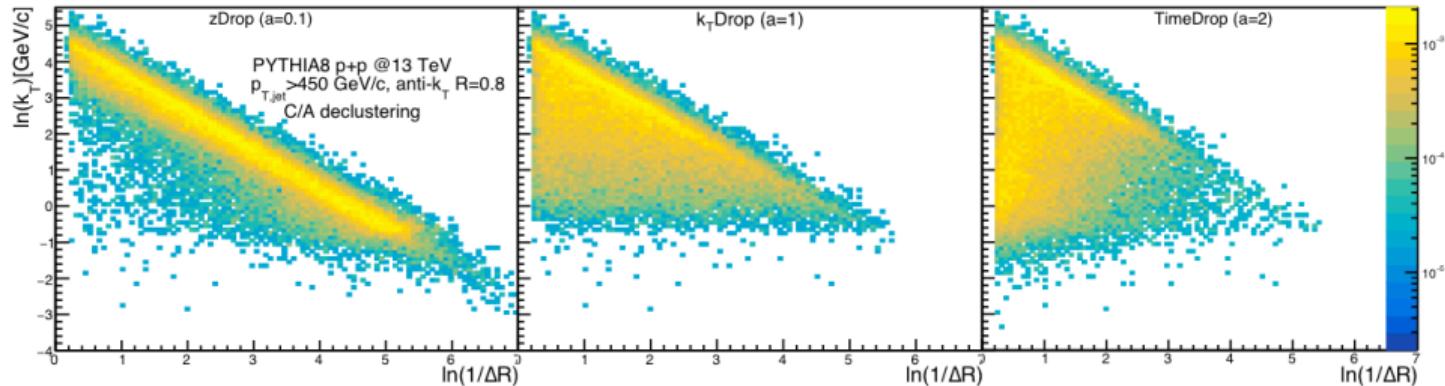


Exploring angular dependence via groomed substructure

- 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"?**

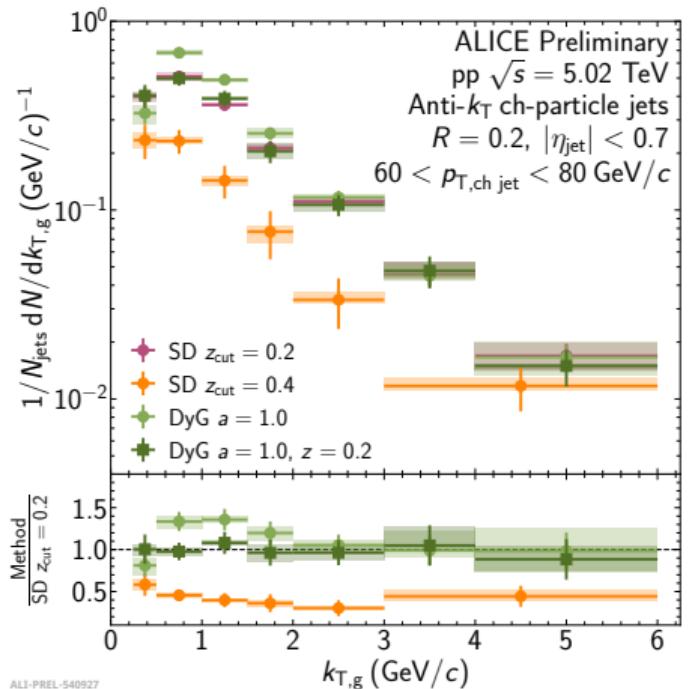


Dynamical Grooming: Lund Planes

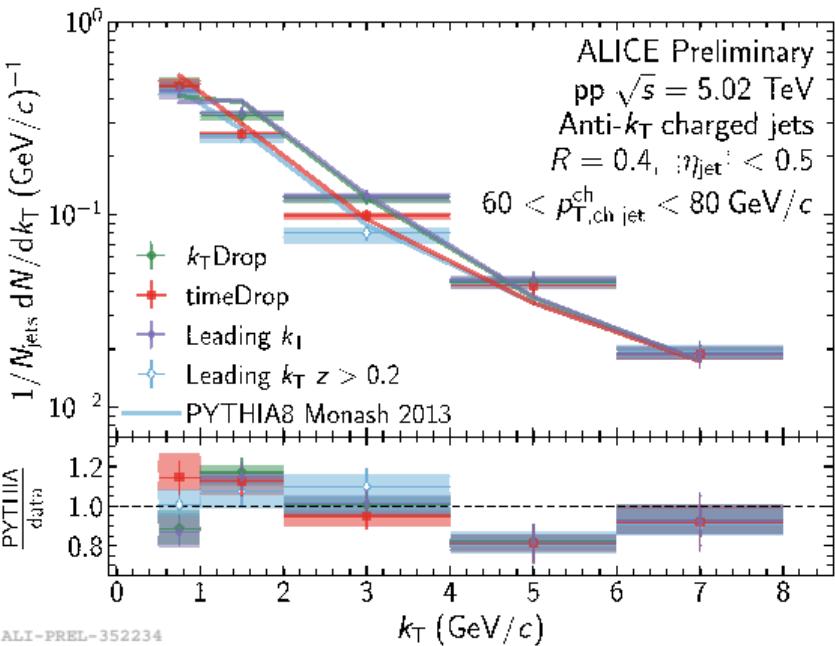


Mehtar-Tani et al., PhysRevD.101.034004

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

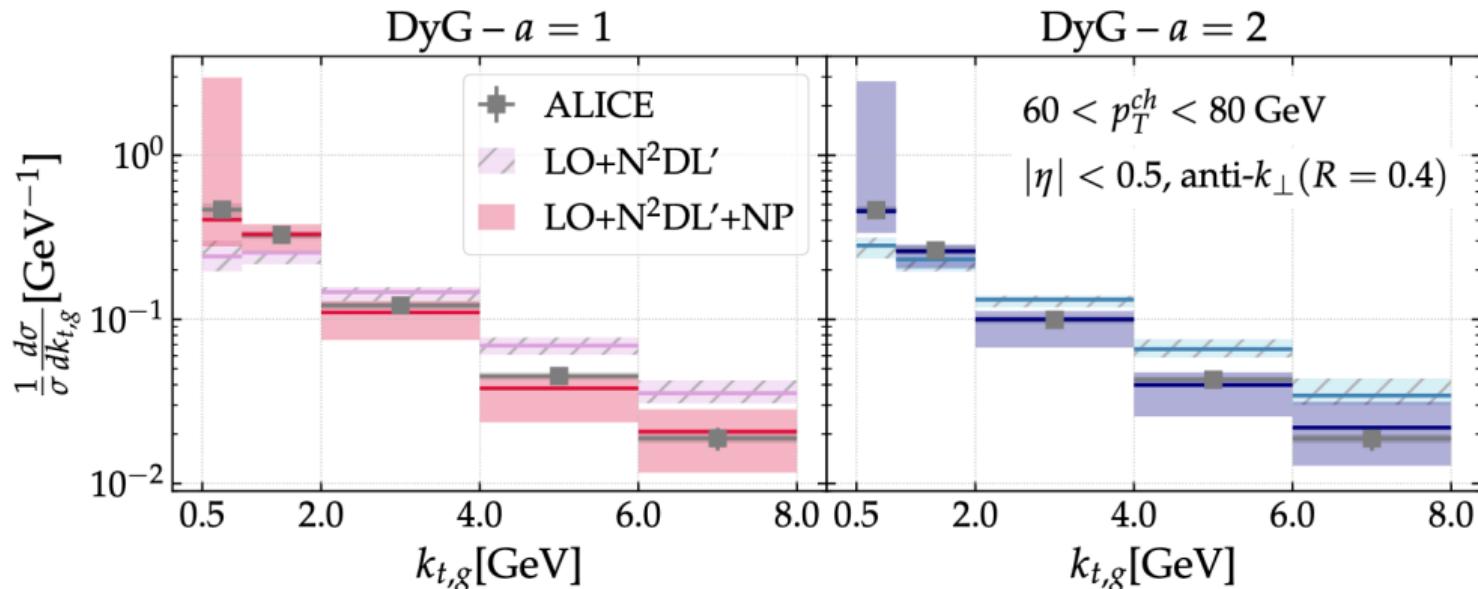


ALI-PREL-540527



ALI-PREL-352234

Dynamical Grooming: analytical calculations pp



Unfolding Dynamical Grooming in Pb-Pb

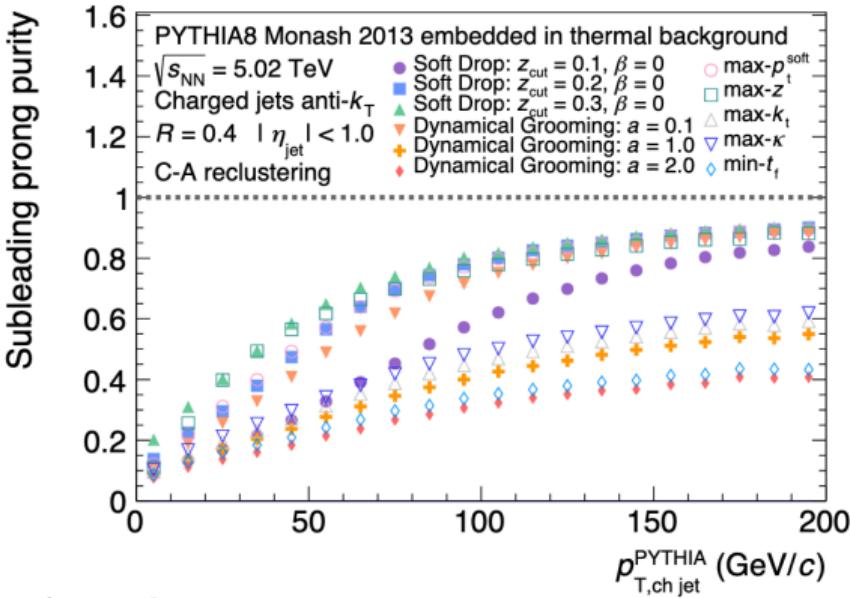
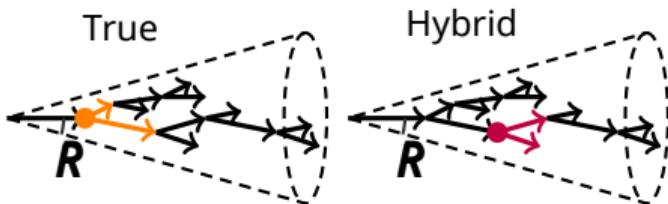


- Dynamical Grooming exhibits **reduced subleading subjet purity** in Pb-Pb

- Off-diagonal mismatched splittings** are major component at low k_T

→ **Problematic for unfolding**

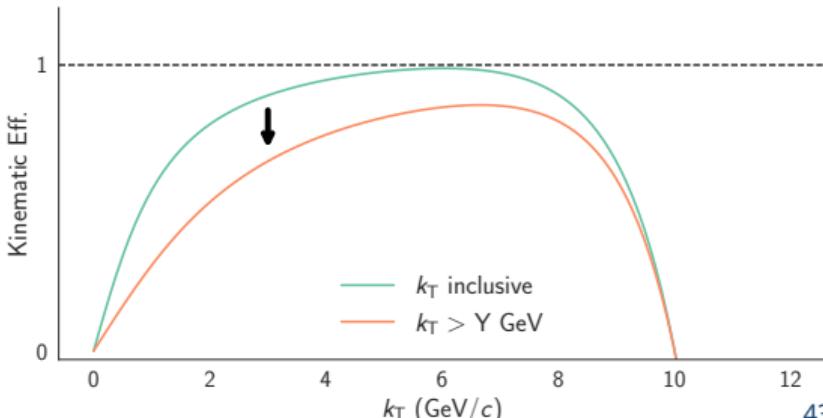
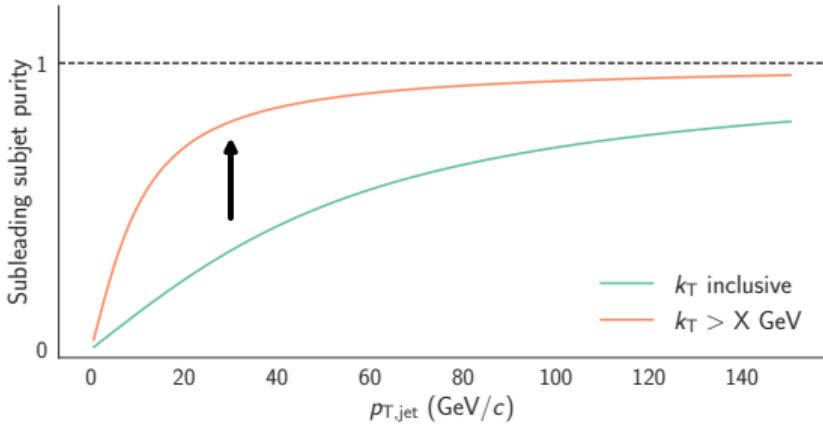
- Caused by **requirement to always select a splitting**
- Address by minimum measured k_T** requirement
- Trade **improved purity** for reduced dynamic **range** and kinematic efficiency
- Minimum z** has similar impact



Unfolding Dynamical Grooming in Pb-Pb

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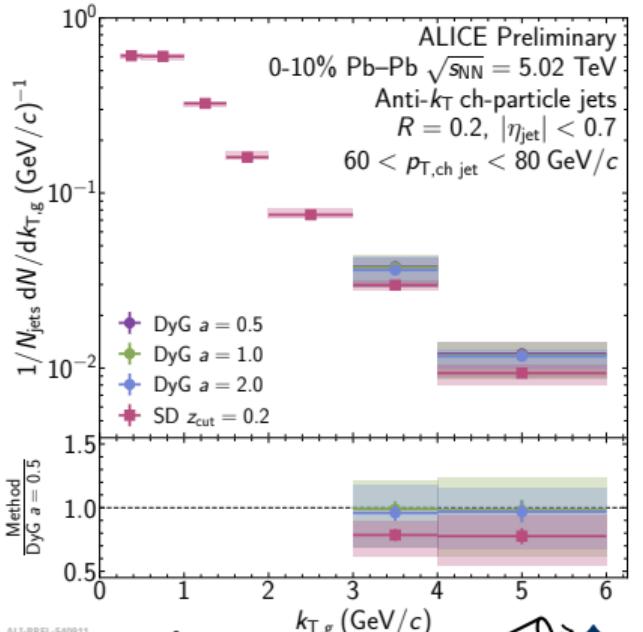


Dynamical Grooming in Pb-Pb

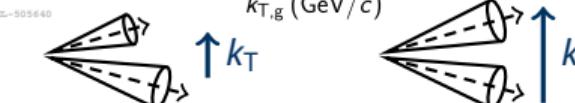
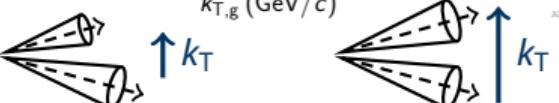
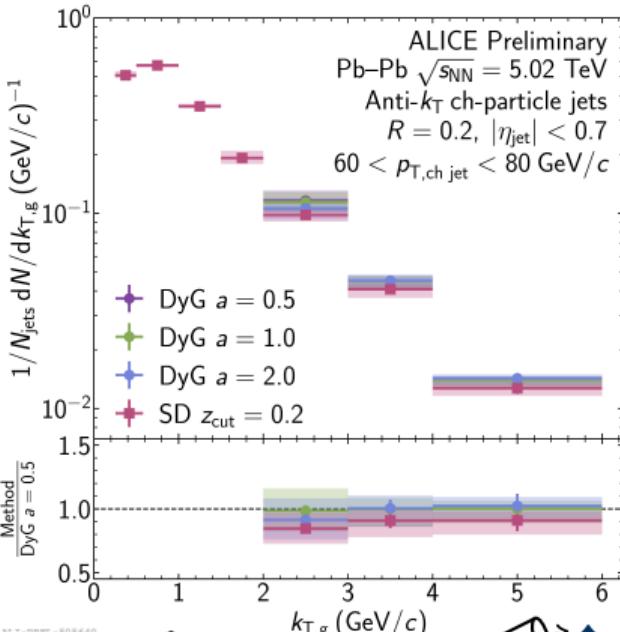


- First measurements of Dynamical Grooming in Pb-Pb
- Grooming methods converge at high $k_{T,g}$
- Smaller bkg extends $k_{T,g}$ range in semi-central

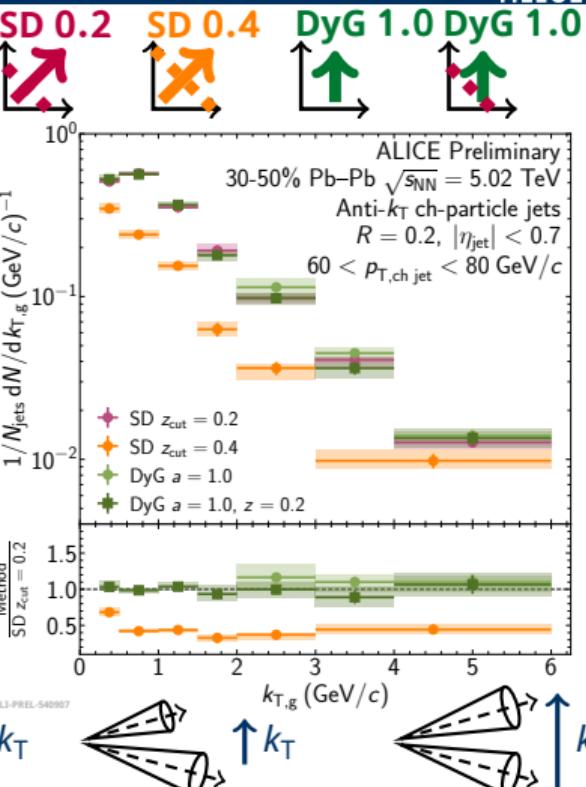
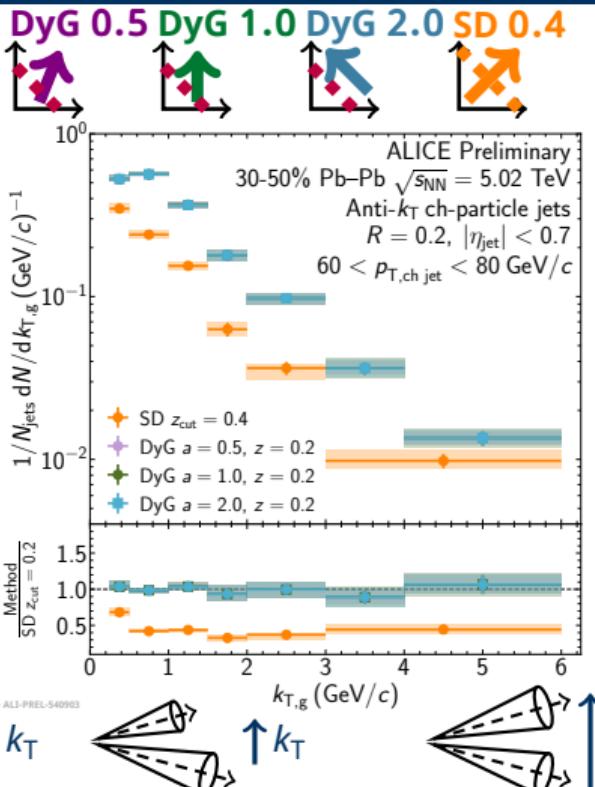
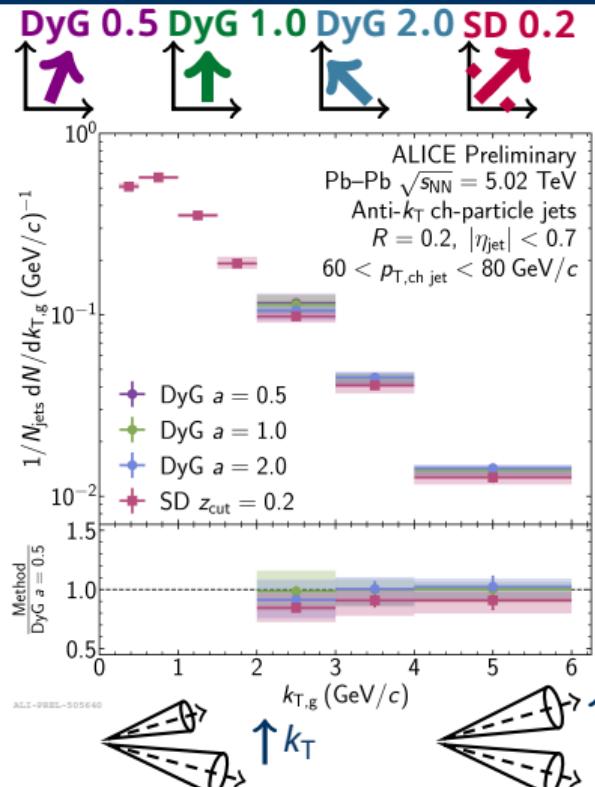
0-10% central



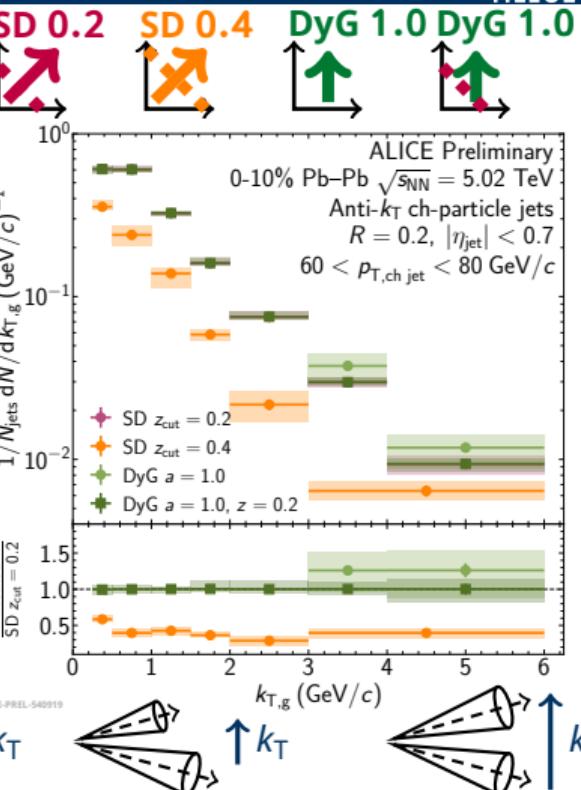
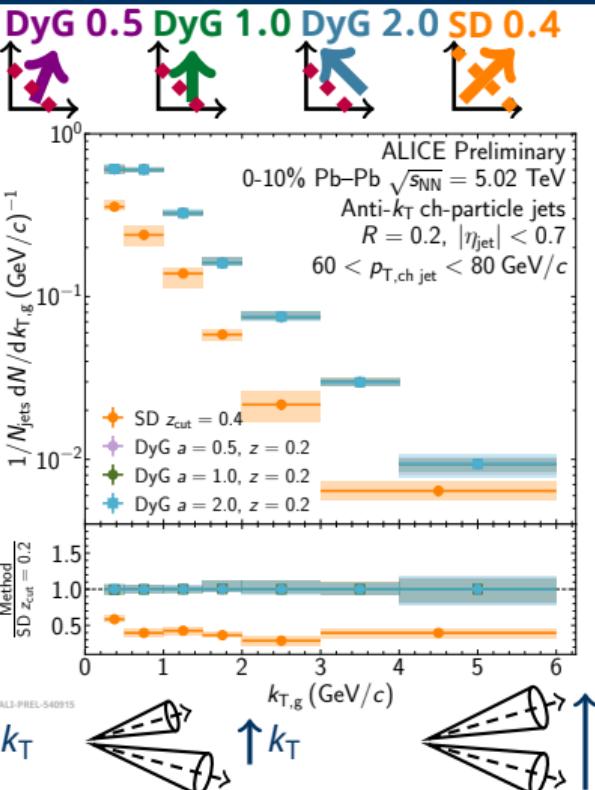
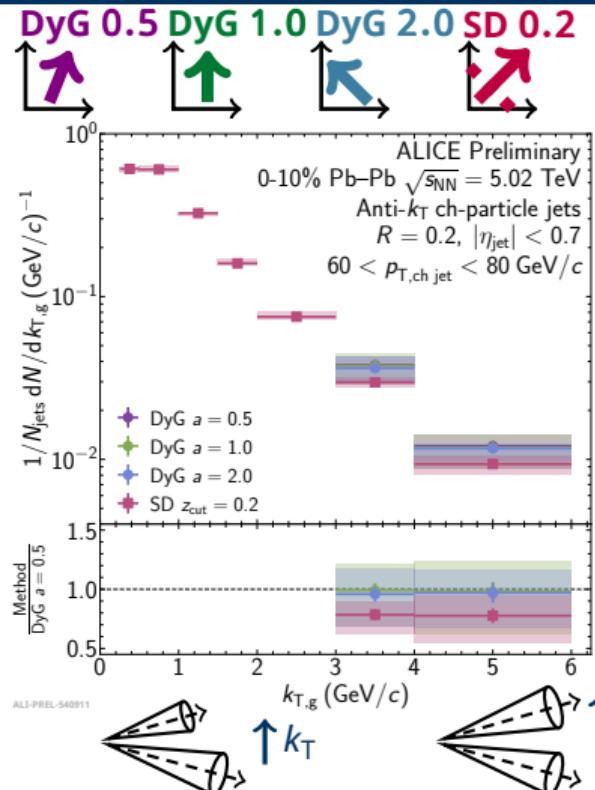
30-50% semi-central



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

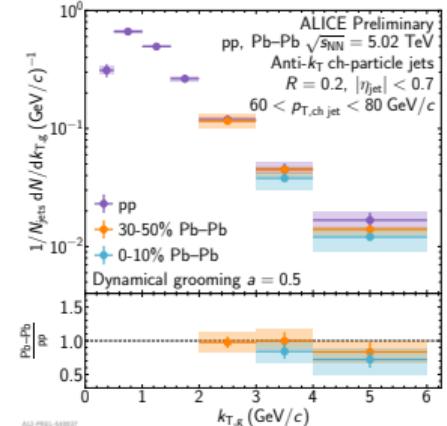


Comparing grooming methods in 0-10% central Pb-Pb

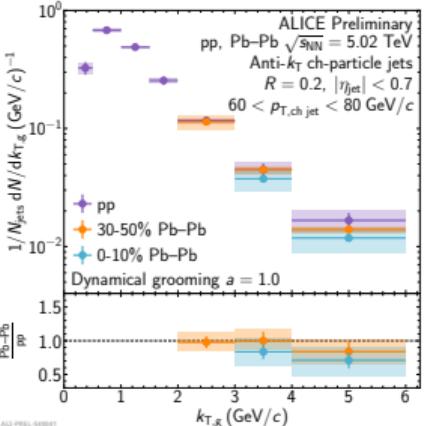


Searching for modification (with more methods)/1

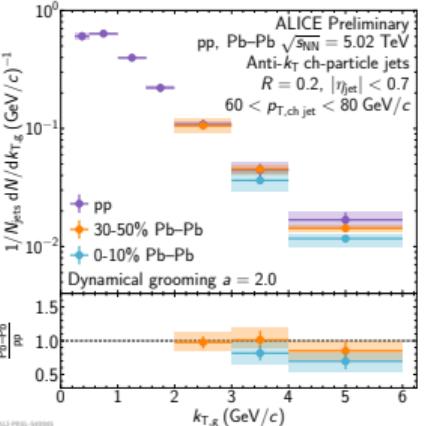
DyG 0.5

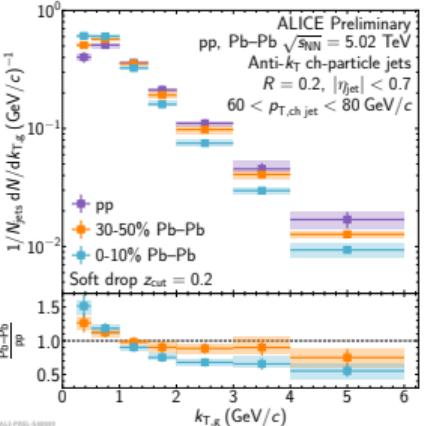
DyG 1.0

DyG 2.0

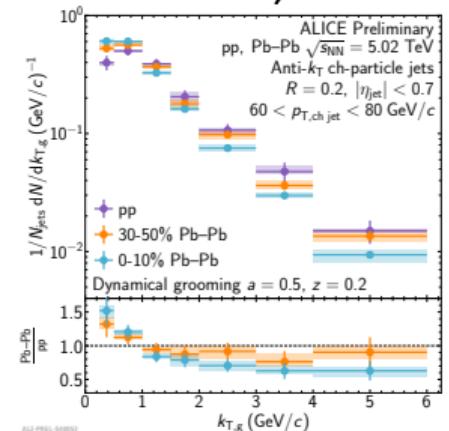



SD 0.2

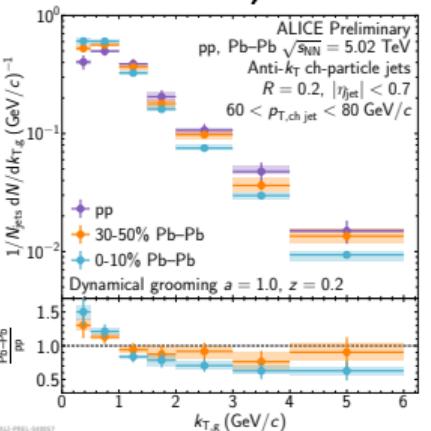



Searching for modification (with more methods)/2

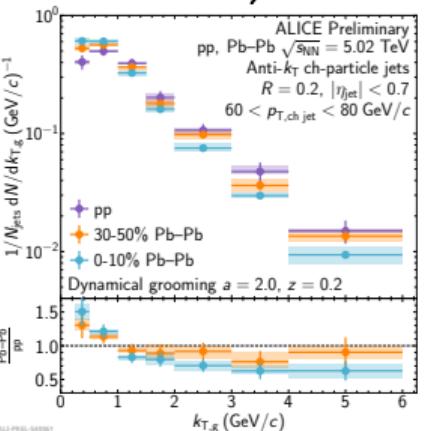
DyG 0.5



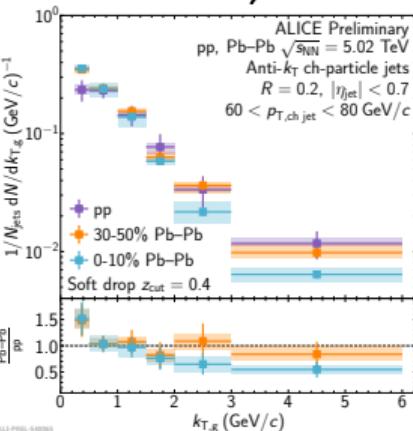
DyG 1.0



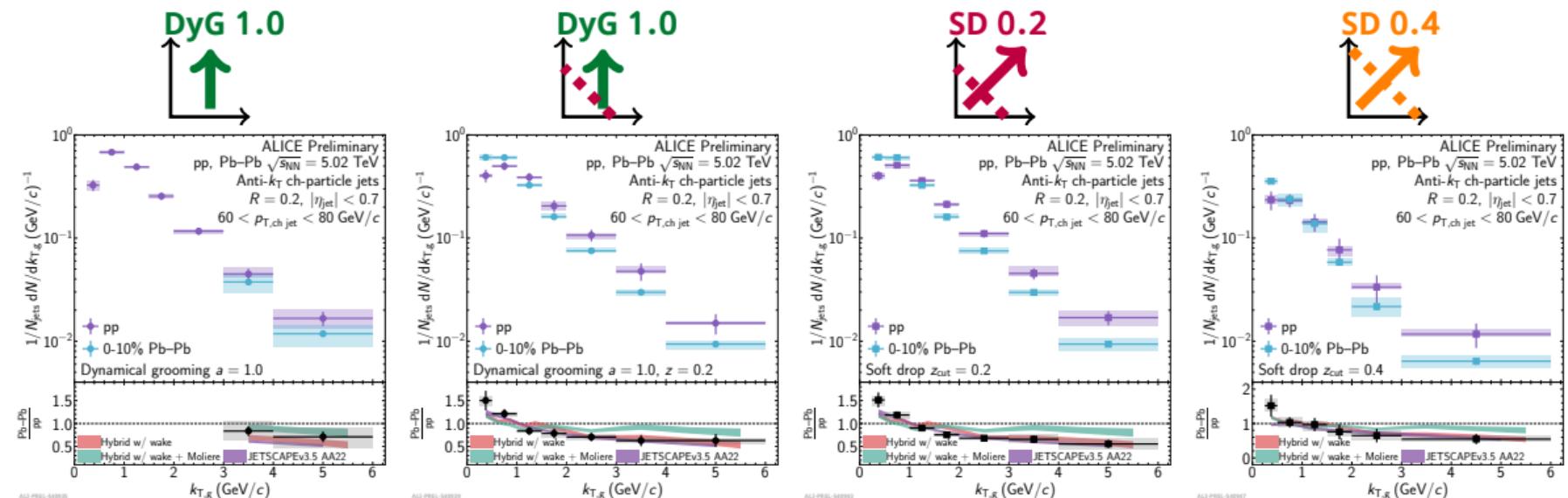
DyG 2.0



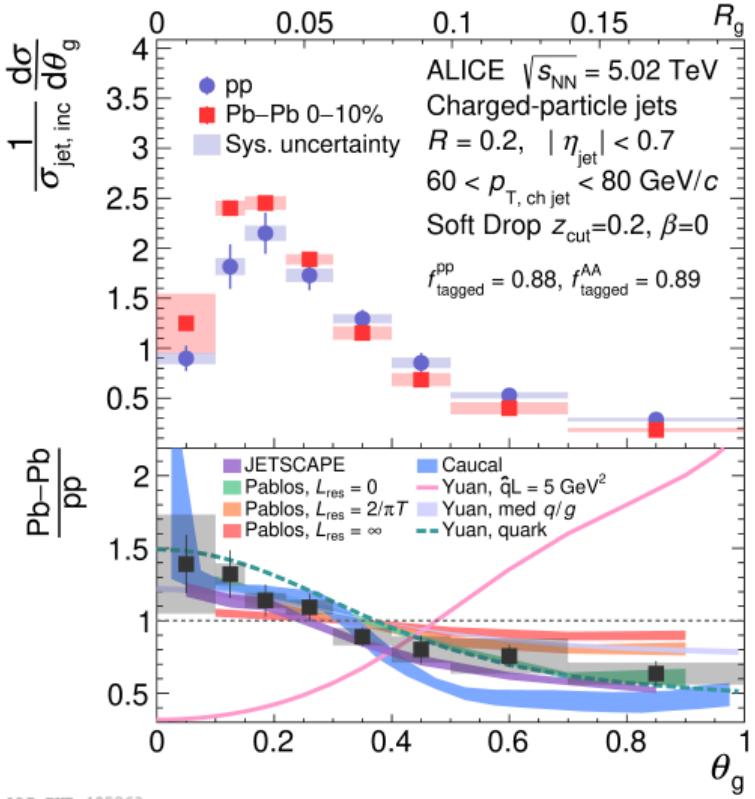
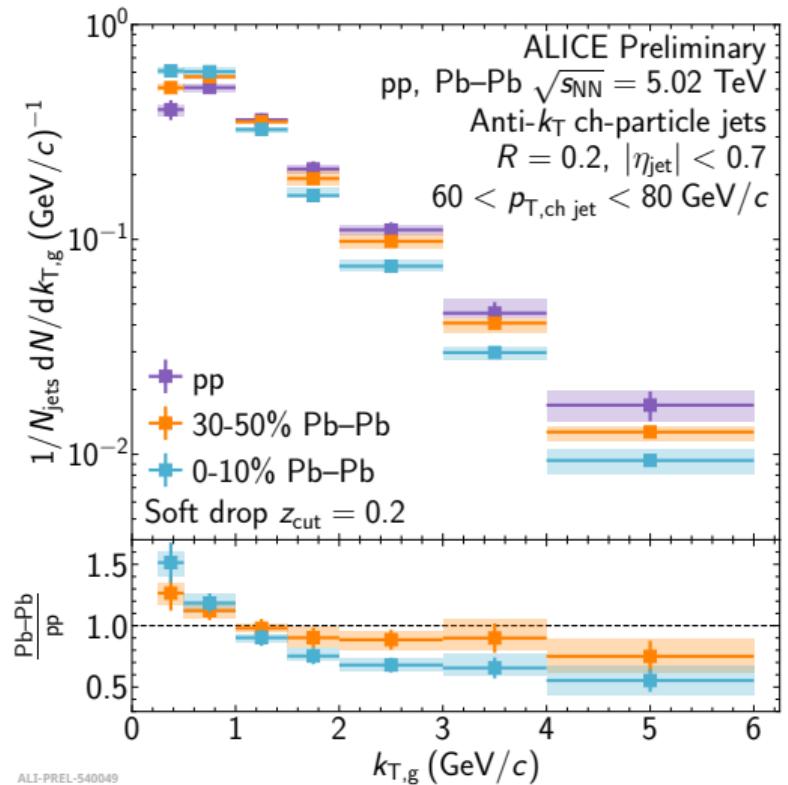
SD 0.4



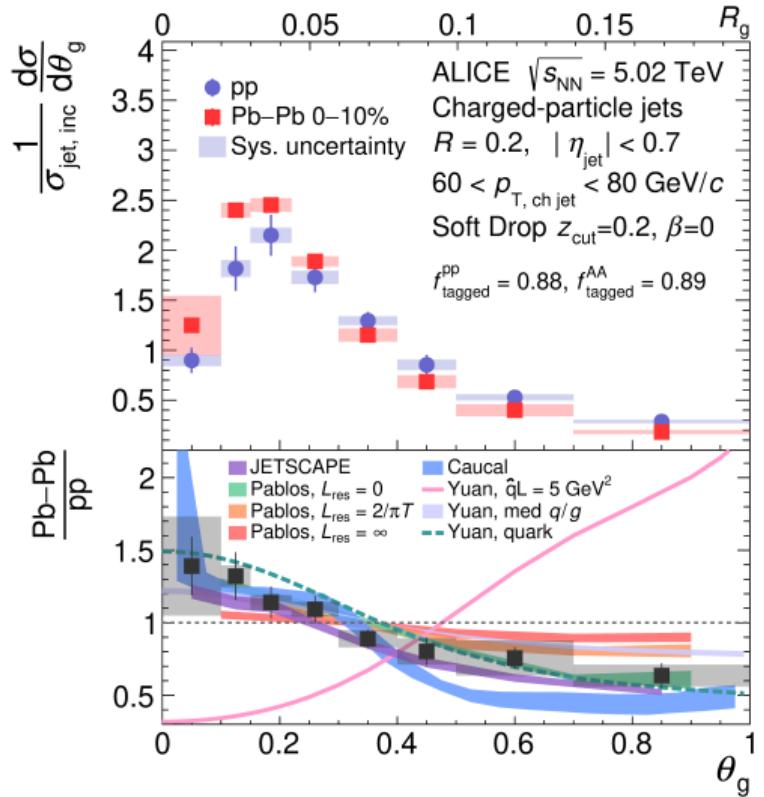
Comparing with models in 0-10% central Pb-Pb



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

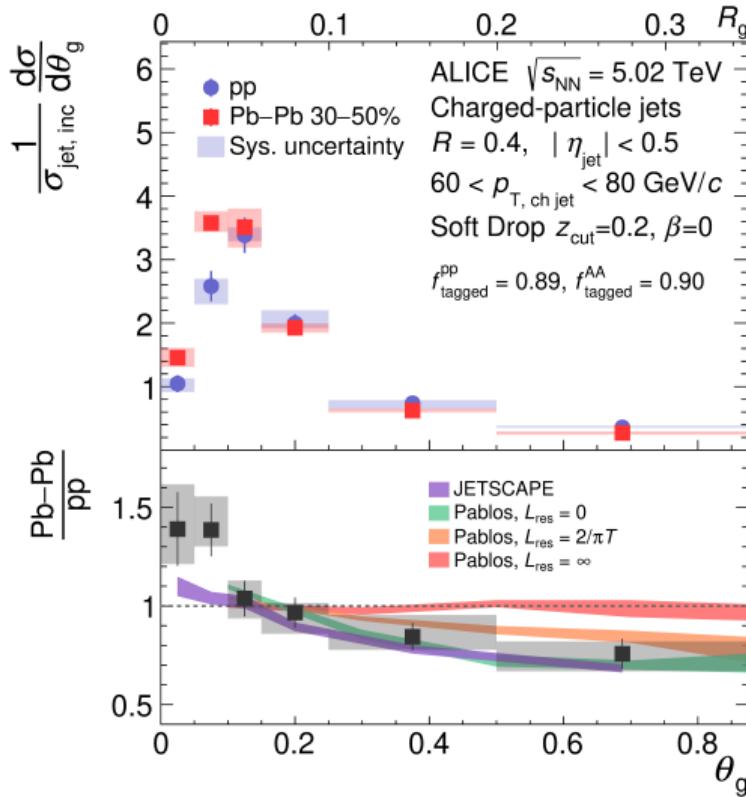


Groomed jet radius θ_g



ALI-PUB-495863

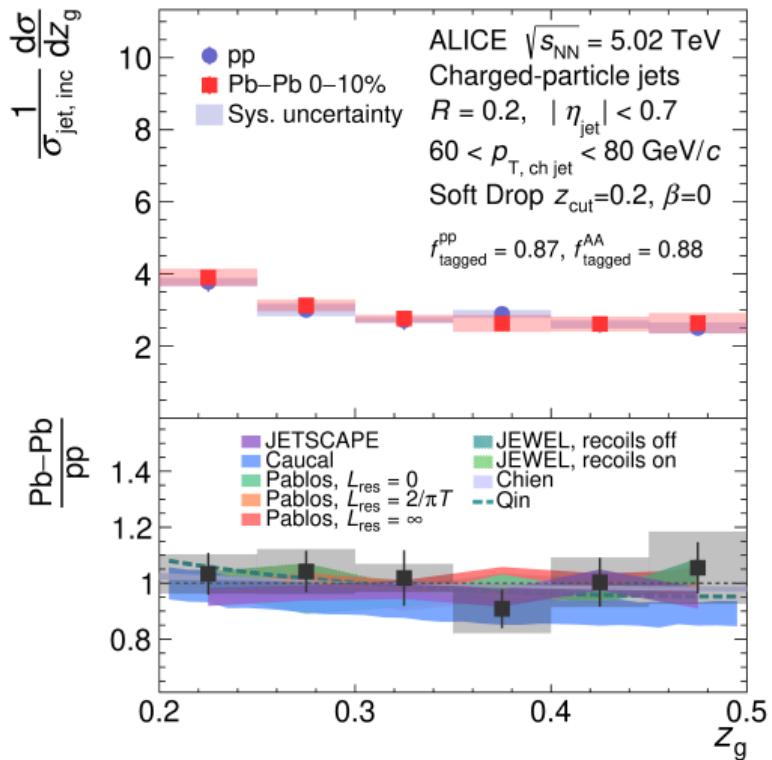
Raymond Ehlers (LBNL/UCB) - 3 August 2023



ALI-PUB-521487

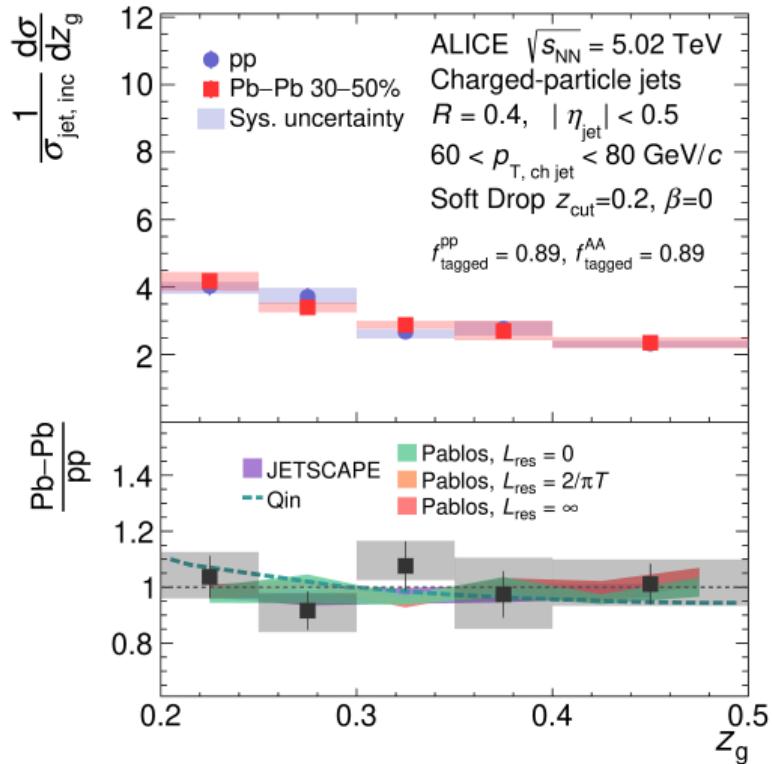
Phys.Rev.Lett. 128 (2022) 10, 102001

Groomed shared momentum fraction z_g



ALI-PUB-521472

Raymond Ehlers (LBNL/UCB) - 3 August 2023



ALI-PUB-521477

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

Jet mass: model baseline in pp

→ Model baseline is important for many observables!

