Searching for Moliere scattering with jet substructure observables

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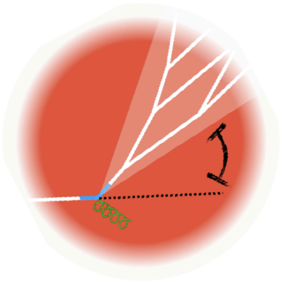
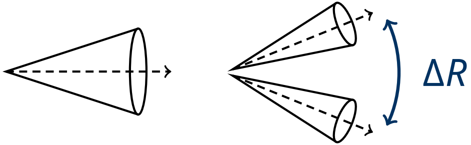
Resolving medium scales

- What are the **relevant length scales in the medium**?
- Which substructure observables sensitive to **which medium properties**?

Emergent structure, such as quasi-particles?



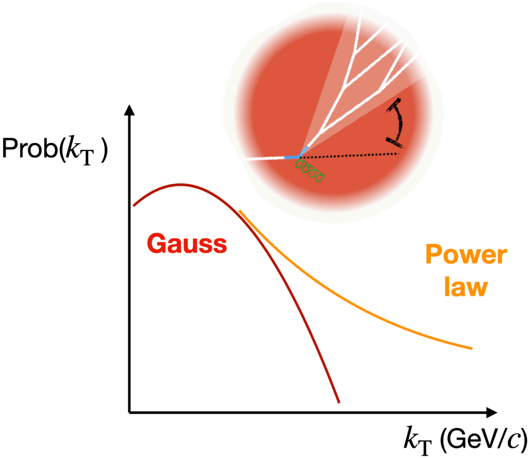
What can the medium resolve?



Moliere scattering and the quark-gluon plasma

- Search for **emergent medium structure** via **point-like single hard scattering**
- Concept: **Rutherford-like scattering exp.**
  - Broadening $\sim$ **Gaussian**
  - Single hard scattering: **power law tail** ($\sim 1/{k_T}^4$)
- Goal: **unambiguous experimental signal**
- In practice, models needed to interpret fully

Cartoon: R. Cruz-Torres, J. Norman

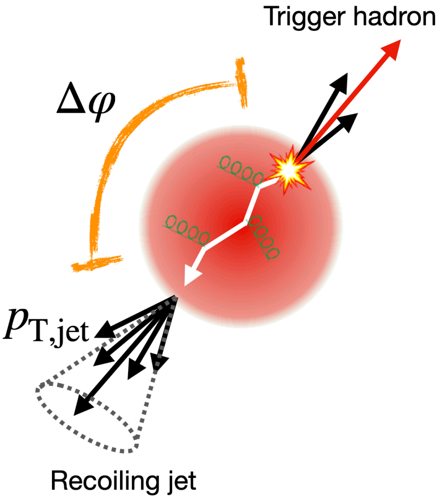


F. D'Eramo et al, JHEP 05 (2013) 031, JHEP 01 (2019) 172, etc

Caucal, Mehtar-Tani, PRD.106 (2022) 5, L051501, JHEP 09 (2022) 023, ...

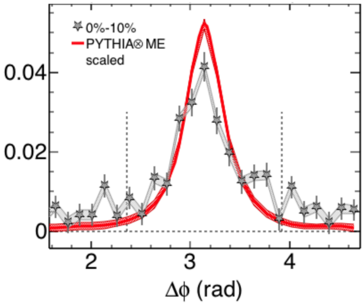
Searching via jet deflection

- Traditional approach: **jet acoplanarity**
- Search for **excess yield at large deflection**
- Can replace **trigger with *γ*, *Z***

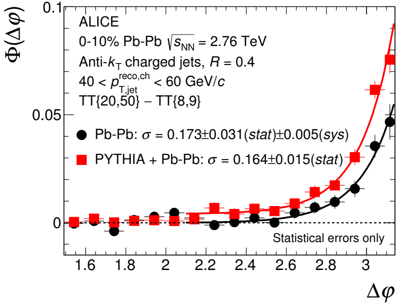


Experimental searches via jet deflection

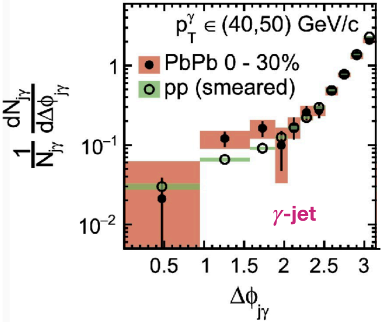
Traditional approach: **jet acoplanarity**



STAR: Phys.Rev.C 96 (2017) 2, 024905



ALICE: JHEP 09 (2015) 170

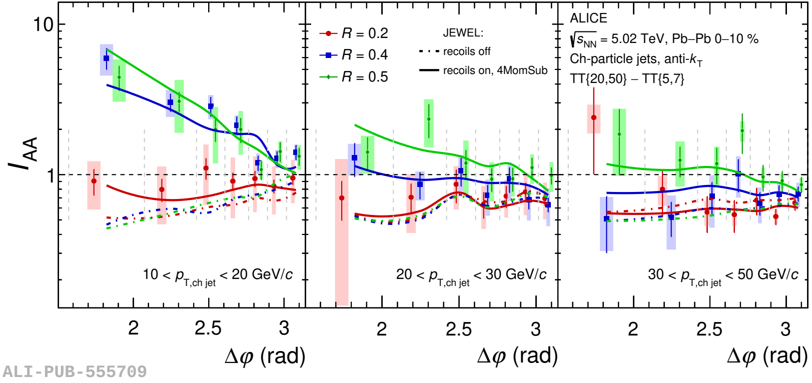


CMS: PRL 119, 082301 (2017)

No evidence for point-like scattering

Recent progress on jet deflection

- **Inconsistent with Moliere scattering**
- Consistent with **medium response**



ALICE: arXiv:2308.16131, arXiv:2308.16128

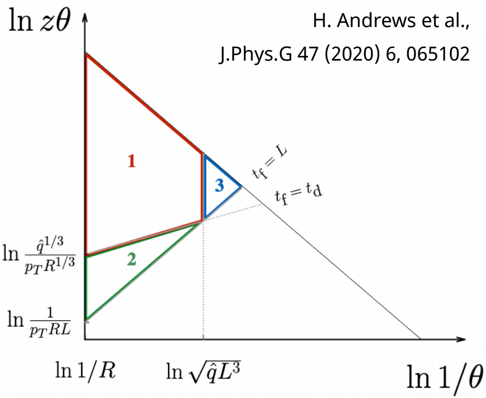
Recent CERN seminar, J. Norman

Alternative: searches via jet substructure

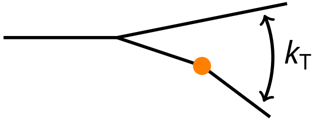
- Complementary search possible via **subjet deflection**
- Open questions:
  - Ideal observables?
  - Can be identified…?

- **For today:**

1. **Optimal way to find the relevant splittings?**
2. Search for **high k_T emissions** via groomed substructure as **signature of point-like scattering**
3. **Next generation** of groomed substructure measurements: γ-tagged R_g



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



Identifying hard splittings: Soft Drop

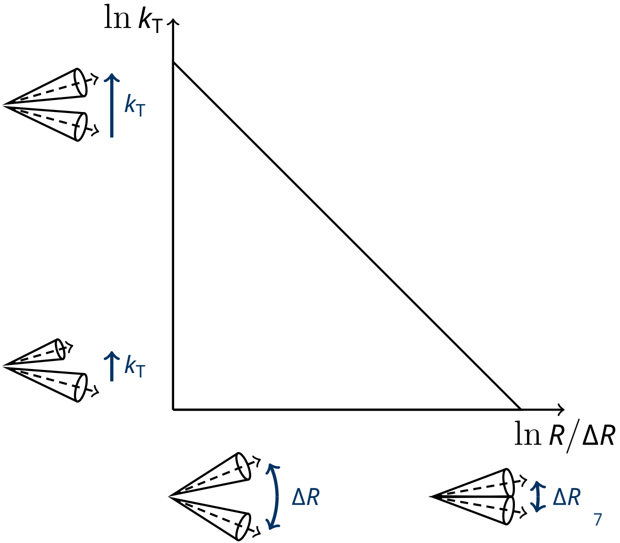
- $k_{\mathrm{T}} = p_{\mathrm{T}}^{\text{sublead}} \sin \Delta R$
- Iteratively follow splitting tree

Soft Drop

Larkoski et al., JHEP 05 (2014) 146

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

- $z_{\mathrm{cut}} = \mathbf{0.2}$
- $\beta = 0$



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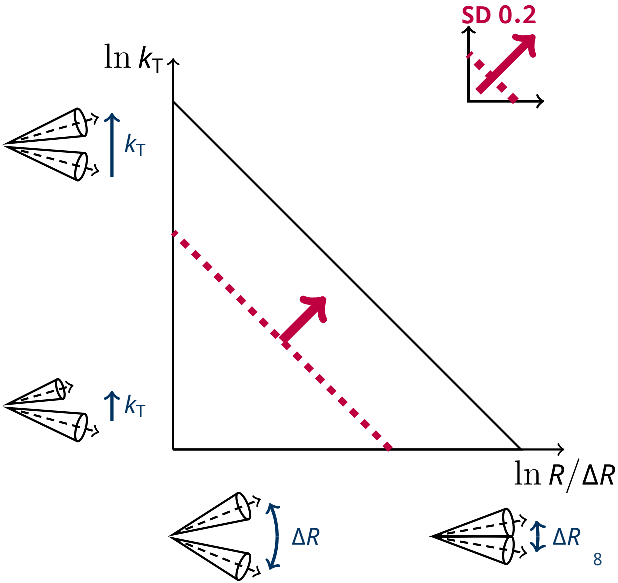

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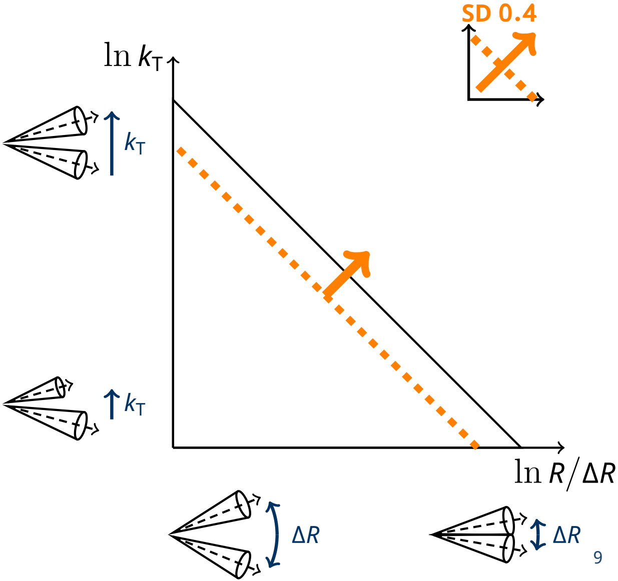
- $z_{\mathrm{cut}} = $ **0.2**, **0.4**
- $\beta = 0$
- $z_{\mathrm{cut}} = $ **0.4** trades phase space to focus on **angular dependence**



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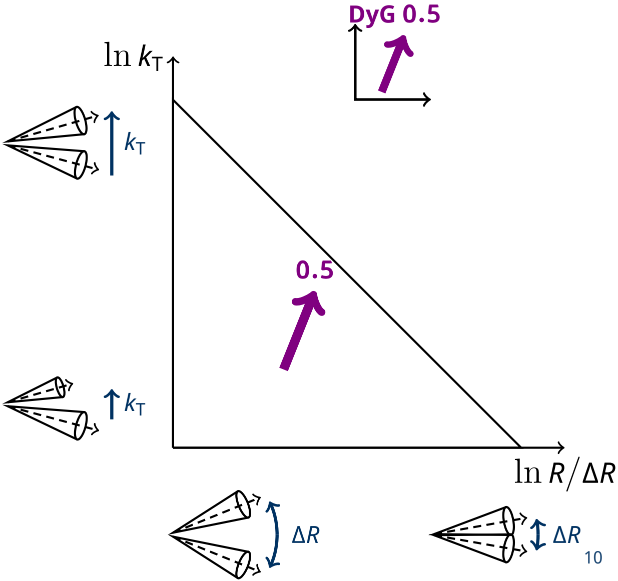
Dynamical Grooming

Mehtar-Tani et al., PRD.101.034004

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

- $a = 0.5$: **"core"** - more sym., narrow



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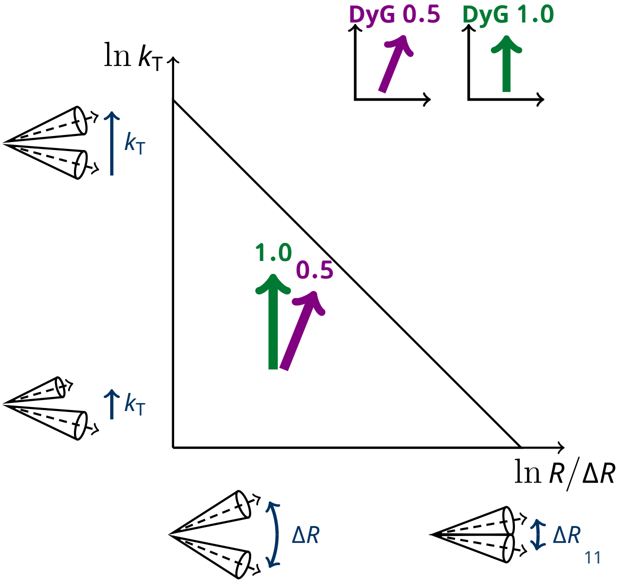

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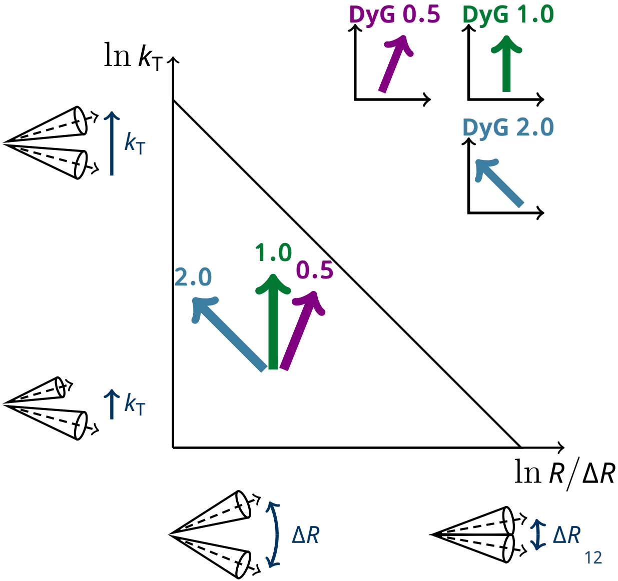

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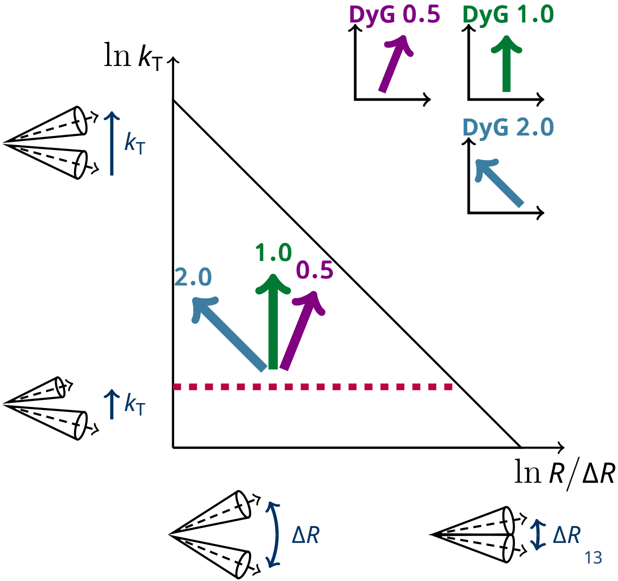

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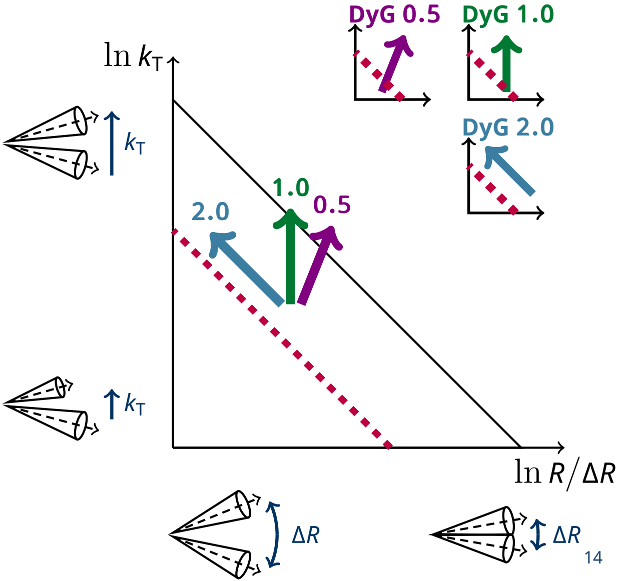
- Alternatively, add **z requirement** (0.2)



Employing the grooming methods

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

1. $z = 0.175$, $\Delta R = 0.4$, $k_{\mathrm{T}} = 4.09\ \mathrm{GeV}/c$
2. $z = 0.2$, $\Delta R = 0.3$, $k_{\mathrm{T}} = 2.93\ \mathrm{GeV}/c$
3. $z = 0.4$, $\Delta R = 0.2$, $k_{\mathrm{T}} = 3.15\ \mathrm{GeV}/c$
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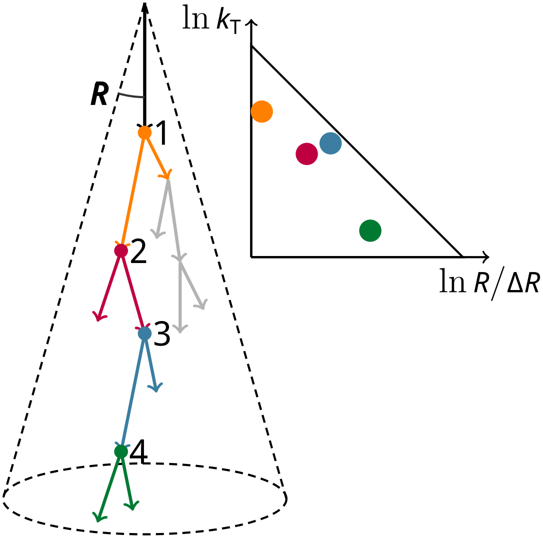
$\rightarrow$ Which method selects which splitting?



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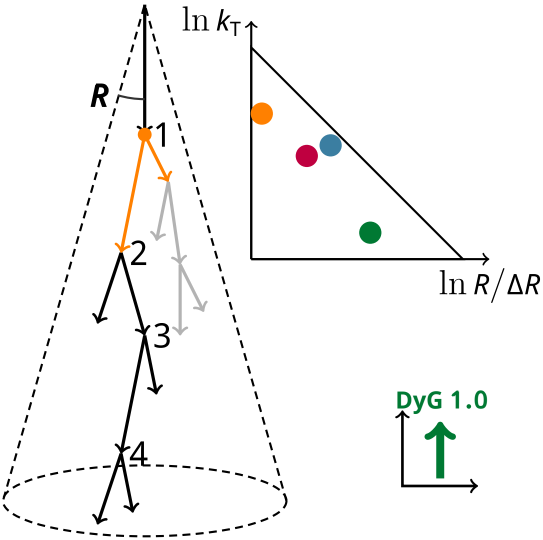
- DyG $a = 1.0$: **#1**



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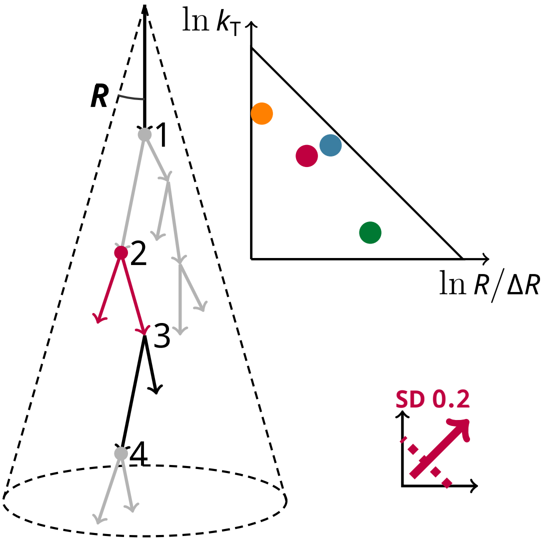
- SD $z_{\mathrm{cut}} = 0.2$: **#2**



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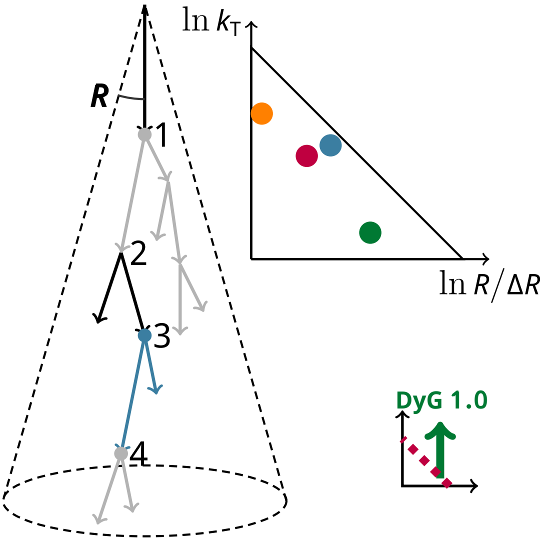
- DyG $a = 1.0, z > 0.2$: **#3**



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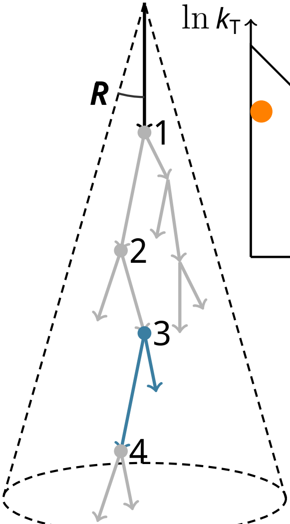
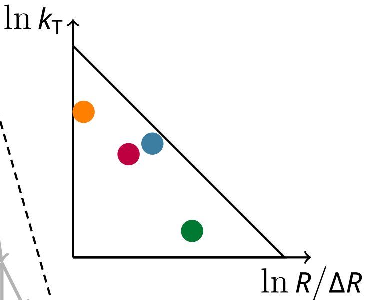
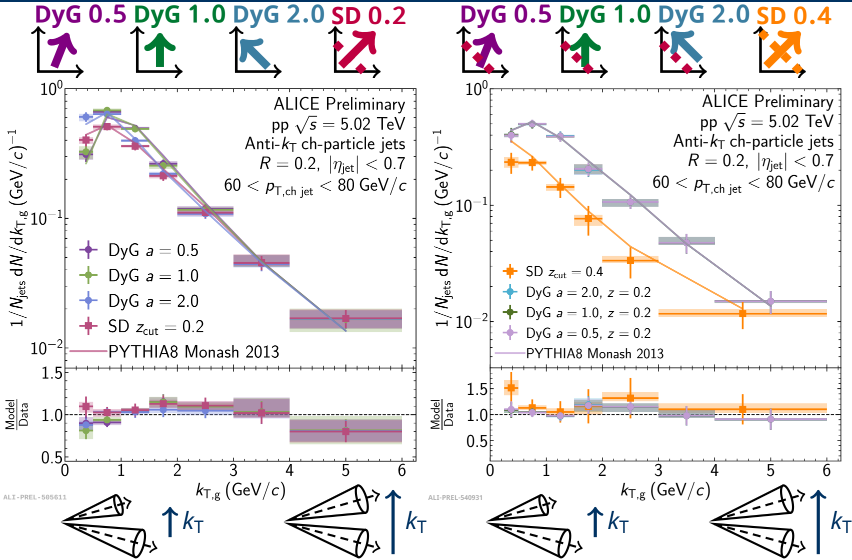
- SD $z_{cut} = 0.4$: **#3**





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:

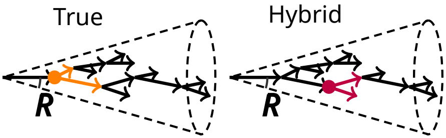
ALICE, JHEP 05 (2023) 244

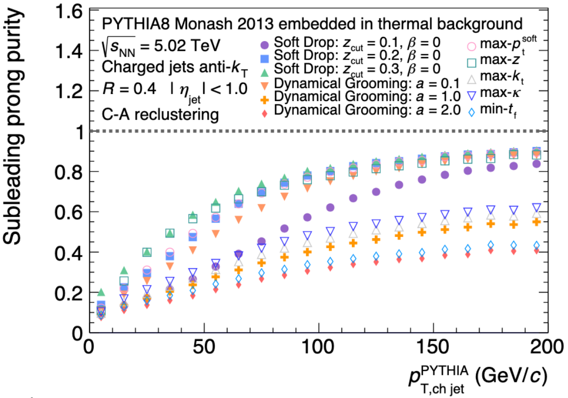
Unfolding Dynamical Grooming in Pb–Pb

- 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





Mulligan, Ploskon, PhysRevC.102.044913

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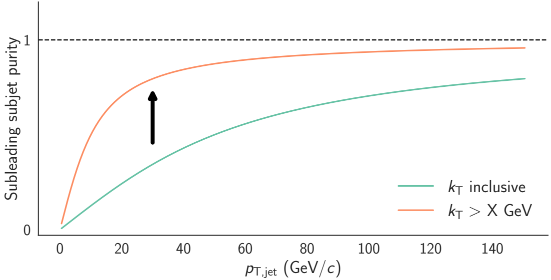

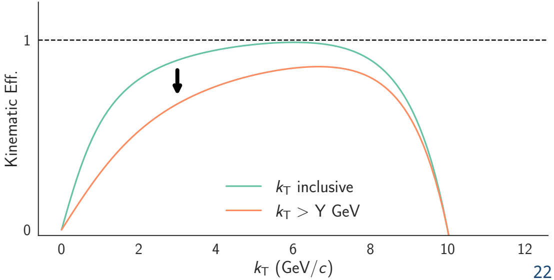

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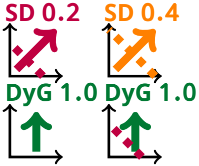
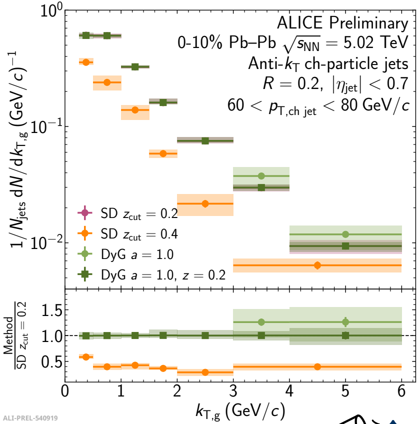
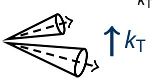


- **First DyG in Pb–Pb**
- **Similar trends** in 0-10% and 30-50%
- Reduced SD $z_{cut} = 0.4$ yield due to **phase space**
- **Consistent set of splittings** from all DyG $a = 1.0$, SD $z_{cut} = 0.2$

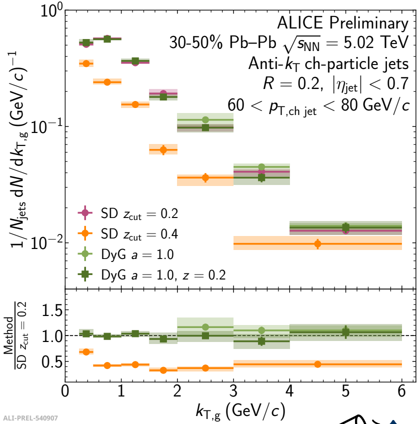
→ Suggests **few hard splits further into tree**

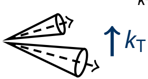
0-10% central

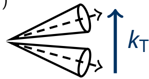




30-50% semi-central







Searching for modification

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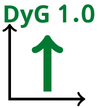
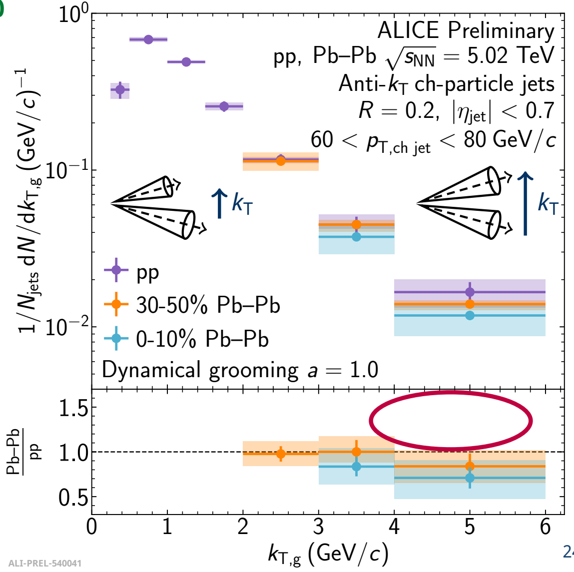
- Standard DyG shows **little modification**





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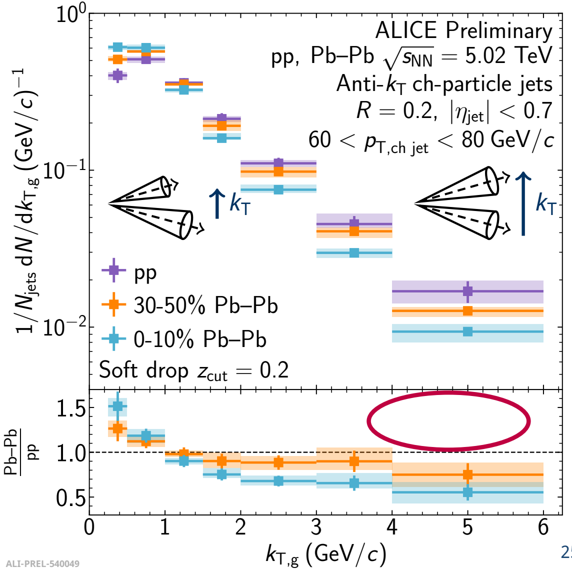
- **No clear evidence of Moliere scattering**



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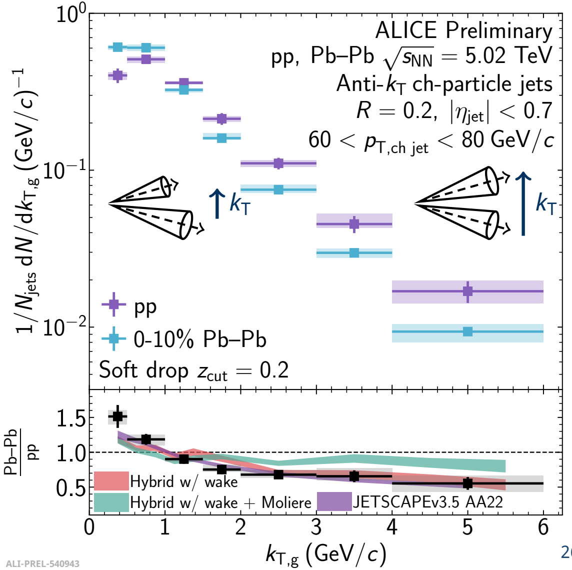
- 0–10% data described by **JETSCAPEv3.5 AA22**[1] and **Hybrid model**[2] **w/out Moliere**

1: JETSCAPE arXiv:2301.02485
2: D'Eramo et al. JHEP 01 (2019) 172, Hulcher et al. QM 22

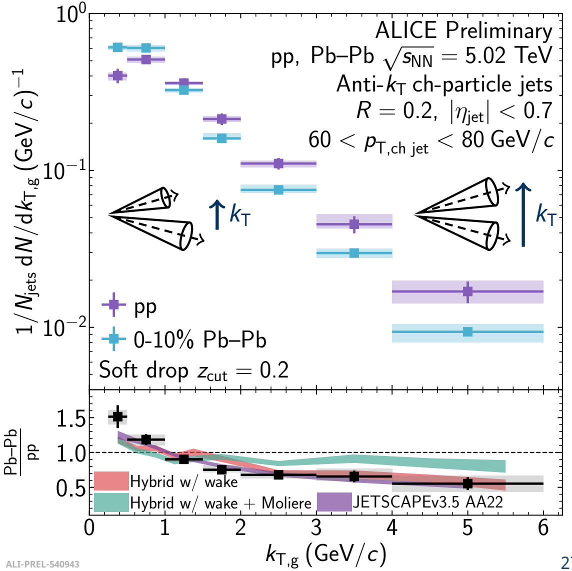


Interpreting modification

- No clear modification → **No evidence for point-like single hard scattering**
  - Possible **competing effects**: signal on top of energy loss
- **JETSCAPE (inc. Moliere)** and **Hybrid w/o Moliere** both describe data.
- **Caveat: pp baseline**

- Now what…?

→ Look to **other substructure observables**



1: JETSCAPE arXiv:2301.02485
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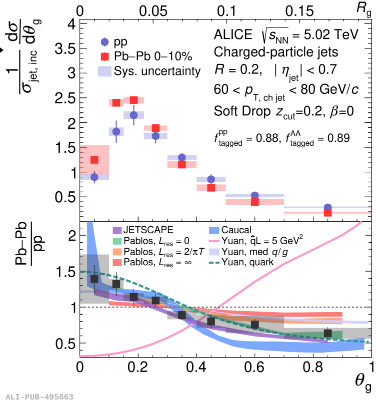
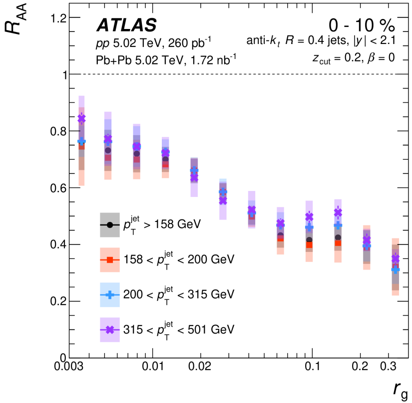
Inclusive groomed jet radius, R_g

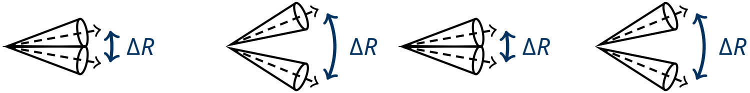
- Characterize **QGP resolution scale** via **angular dependence** of hard splittings
- **Consistent picture** for ALICE + ATLAS
- **Promotes narrow** or **filters out wider** subjets
- Incoherent energy loss effects may indicate **medium resolving the splittings**?
  Or **changing q/g fraction**?
  Or **"survival bias"**?

ALICE, PRL.128.102001



ATLAS, PRC.107.054909

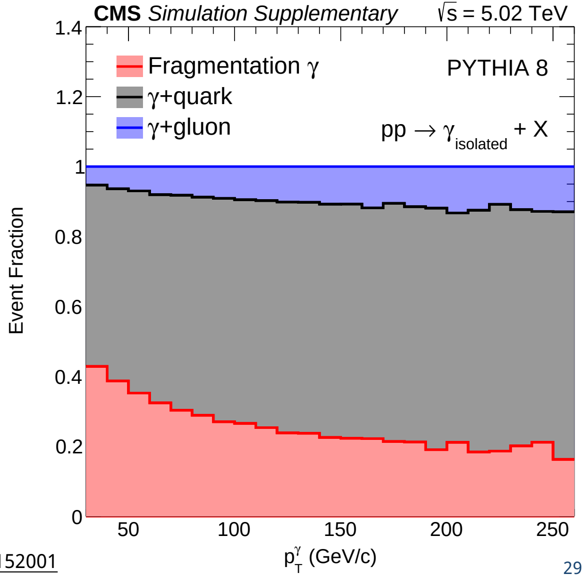




γ-tagged angular substructure

- Disentangle via **γ-tagged substructure**
1. **Quark enhanced sample**
2. Access **initial hard scattering momentum** (eg. $\sim$ unquenched $p_{\mathrm{T,jet}}$)

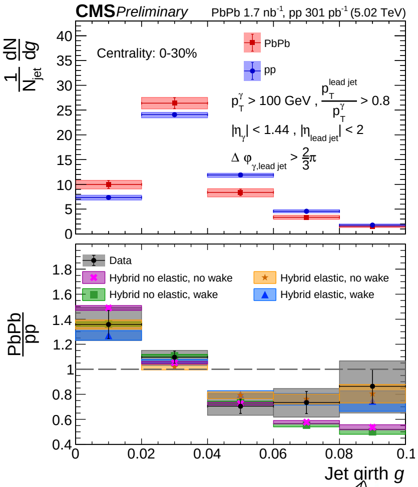
- CMS recently measured angular-dependent observables, CMS-PAS-HIN-23-001:
  - R_{g} with SD $z_{\mathrm{cut}} = 0.2$
  - Jet girth: $g = 1/p_{\mathrm{T,jet}} \sum_i p_{\mathrm{T}}^i \Delta R_{i,\mathrm{jet}}$
- $p_{\mathrm{T}}^{\gamma} > 100$ GeV$/c$, $R = 0.2$
- Selection two regions in $x_{\mathrm{j}\gamma}$:
1. **More quenched**: $x_{\mathrm{j}\gamma} = p_{\mathrm{T,jet}}/p_{\mathrm{T}\gamma} > 0.4$
2. **Less quenched**: $x_{\mathrm{j}\gamma} > 0.8$

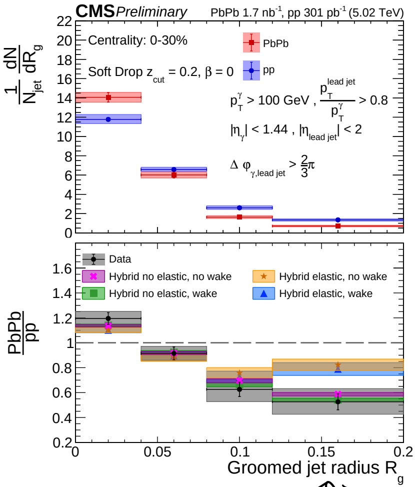


CMS, PRL.122.152001

Studying less quenched jets

- Less quenched jets ($x_{j\gamma} > 0.8$) show **similar behavior as inclusive jets**
- Suggests **consistent selection bias** in both measurements
- **Mixed description** by Hybrid model
- **Moliere preferred for g, w/o preferred for R_g**

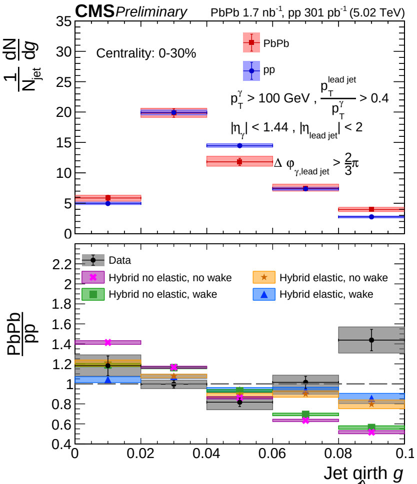


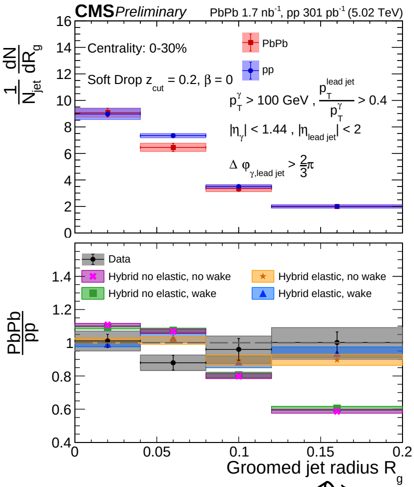


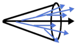
CMS-PAS-HIN-23-001

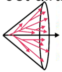
And more quenched jets?

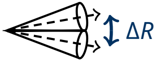
- More quenched jets ($x_{j\gamma} > 0.4$): **no narrowing**
- **w/ Moliere preferred**
    - Tension at large g
- **No sensitivity to wake**
- **Strongly suggests narrowing due to survival bias**

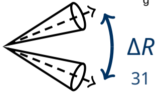






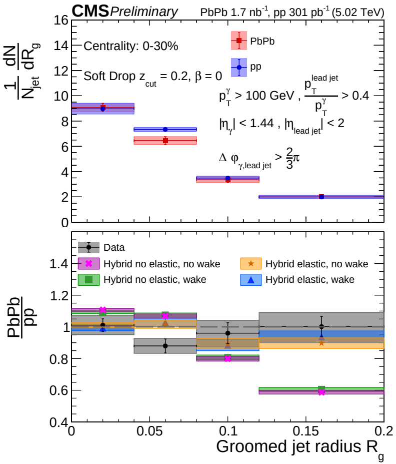


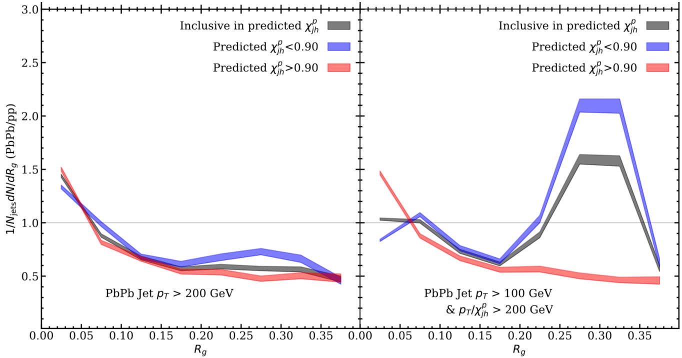




CMS-PAS-HIN-23-001

Interpreting more quenched jets





Du et al, JHEP 03 (2021) 206

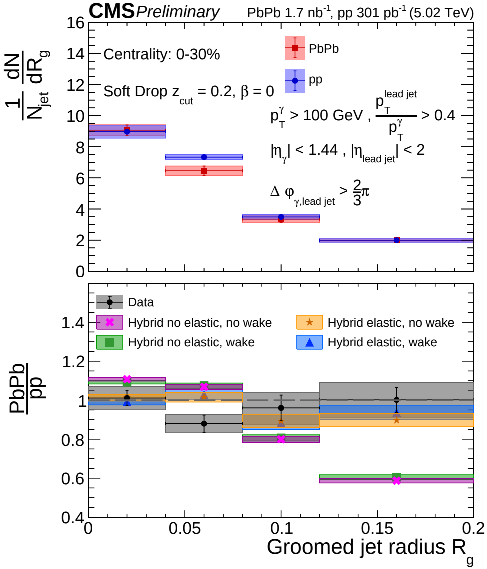
- Disappearance of narrowing as anticipated
- What **remains in $x_{j\gamma}$ dist.**?
- **Disentangle energy loss and rare point-like scattering in R_g?** Next to $k_{T,g}$?

Where are we and what's next?

- **What can serve as an unambiguous signal?**
  - Preferred model between $k_{T,g}$ and γ-tagged R_g highlights difficulty
- **Bayesian inference** w/ Hybrid model?
  - Model dependence caveats, etc
- **Overly simple mental model?**
- Not sensitive enough? Wrong region of phase space?

Next steps

- Low p_T signal may be clearer. **Mixed events? ML?**
- ***γ*-tagged $k_{T,g}$?**
- **New unambiguous observables** sensitive to Moliere?

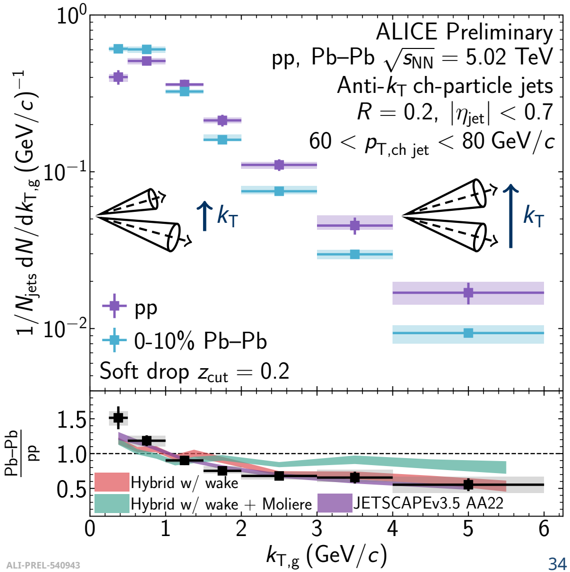


Summary

- **Comprehensive studies** searching for Moliere scattering via jet substructure

1. **Modification of $k_{T,g}$**, similar to narrowing seen in other substructure observables
2. **No clear evidence of Moliere scattering in inclusive jets**
3. **Narrowing disappears for γ-tagged jets**
    - Suggests **survival bias** in inclusive jets case leads to narrowing
4. **Model dependent Moliere signal in γ-tagged R_g**
    - **Not unambiguous + tension with $k_{T,g}$**

Careful choice of next steps is critical



ALI-PREL-540943

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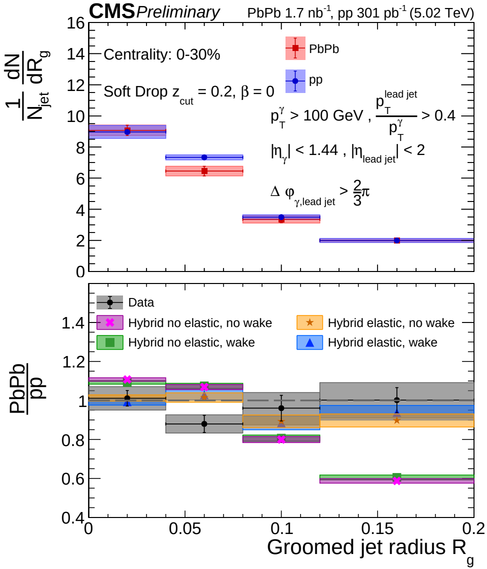


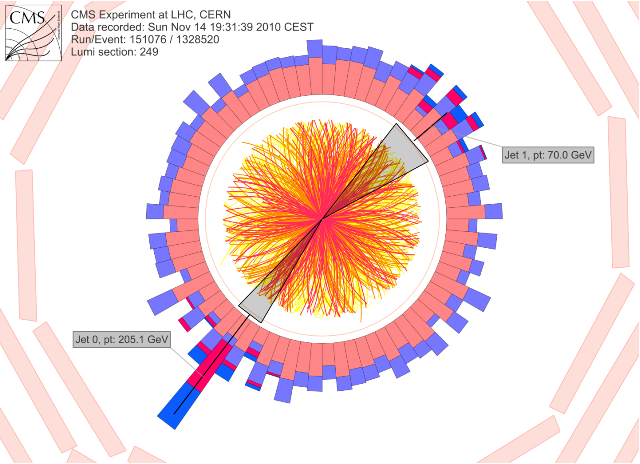
Backup

Experimentally accessing jets in heavy-ion collisions

- Jets are **experimentally challenging** due to **large uncorrelated background** from underlying event
  - Fluctuations can be $\sim p_{\mathrm{T,jet}}$
- 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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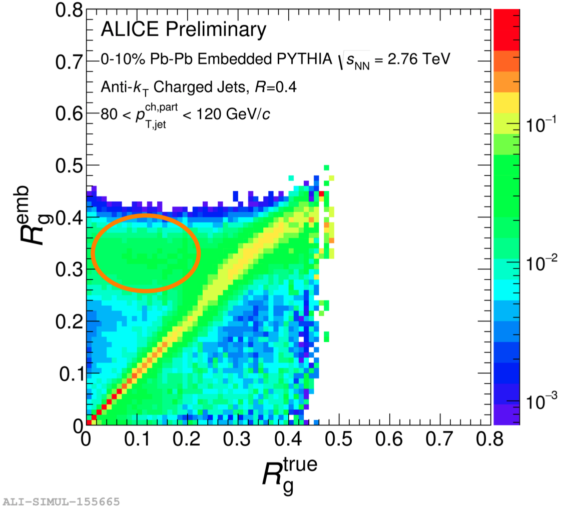
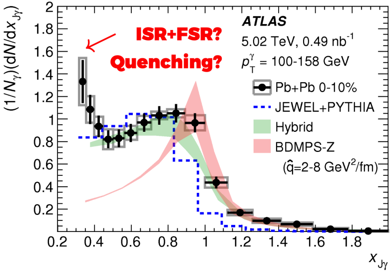
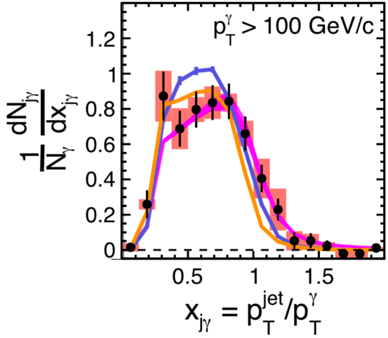


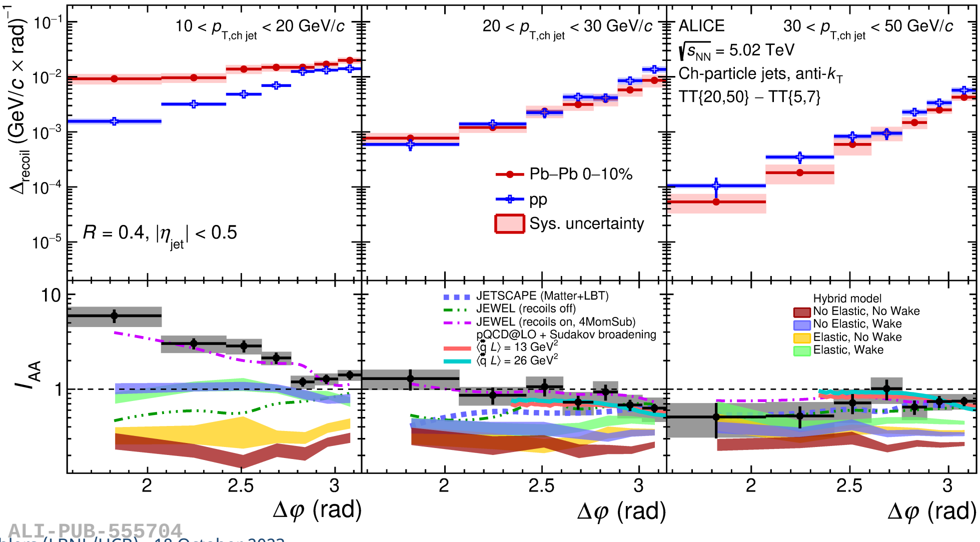
$x_{j\gamma}$ distributions

NOTE: **Selections are a bit different**, **unfolded vs smeared**

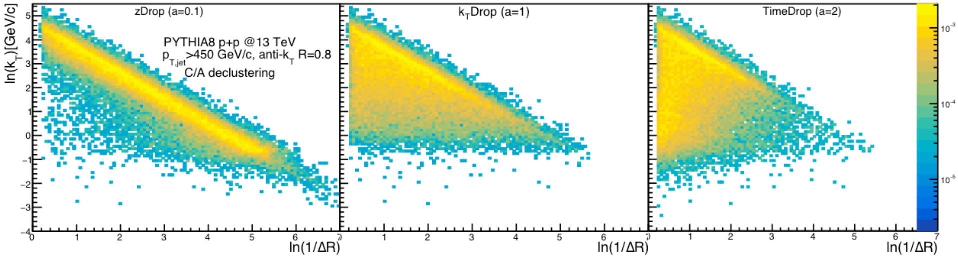




ALICE jet deflection R = 0.4

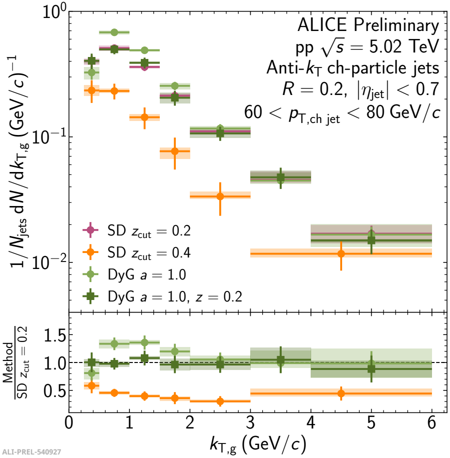


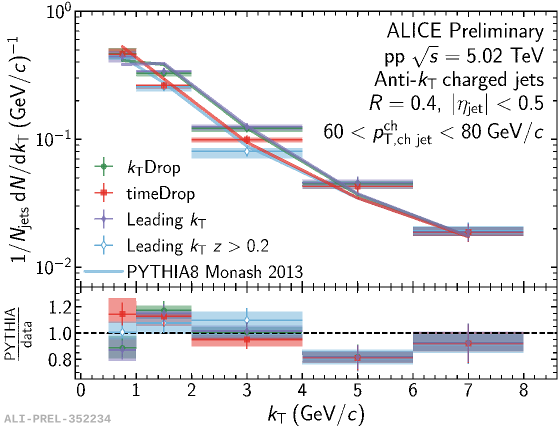
Dynamical Grooming: Lund Planes



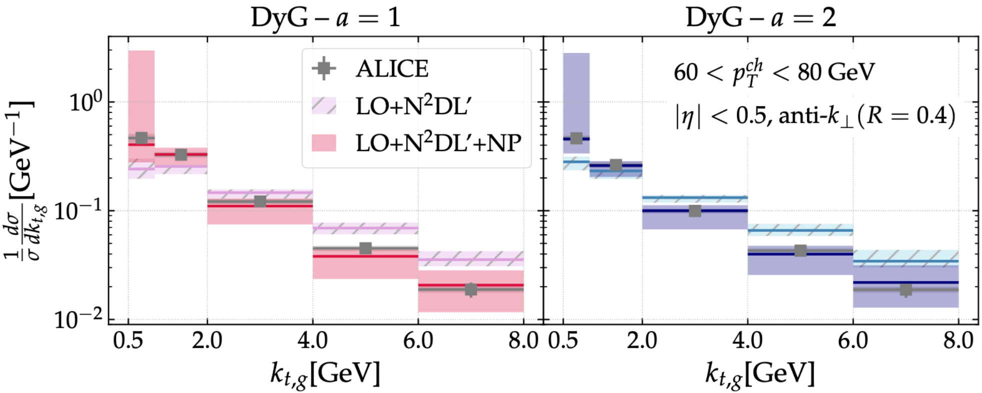
Mehtar-Tani et al., PhysRevD.101.034004

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



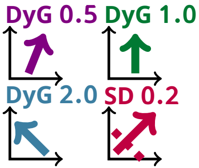


Dynamical Grooming: analytical calculations pp



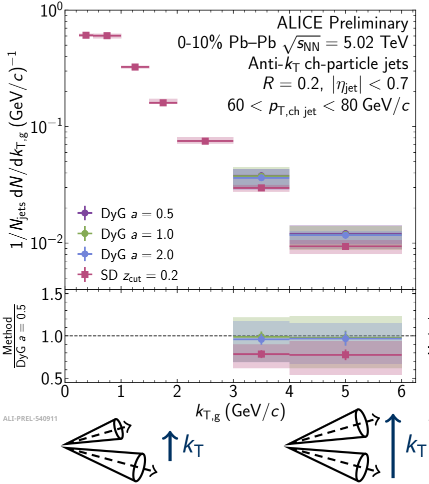
[1] Mehtar-Tani et al., Phys. Rev. D 101, 034004
[2] Caucal et al., JHEP 07 (2021) 020

Dynamical Grooming in Pb–Pb

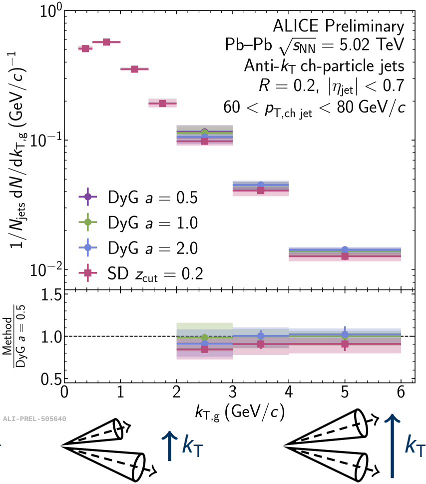


- **First measurements** of Dynamical Grooming in Pb–Pb
- Grooming methods **converge at high $k_{T,g}$**
- **Smaller bkg extends $k_{T,g}$ range** in semi-central

0-10% central



30-50% semi-central



How do models fare?

SD 0.2

JETSCAPEv3.5 AA22 tune

JETSCAPE arXiv:2301.02485

- **MATTER+LBT**
- **Describes data well**

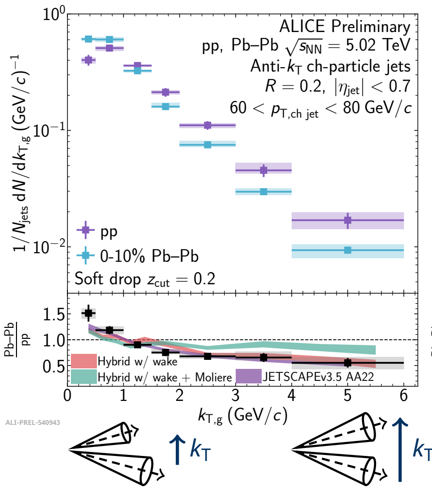
Hybrid model

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**

0-10% central



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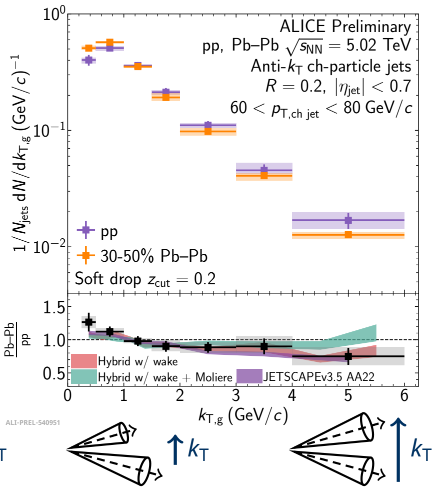
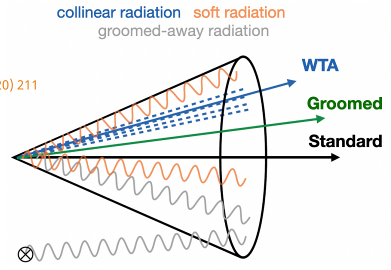


Caveat: pp baseline

Angle between jet axes

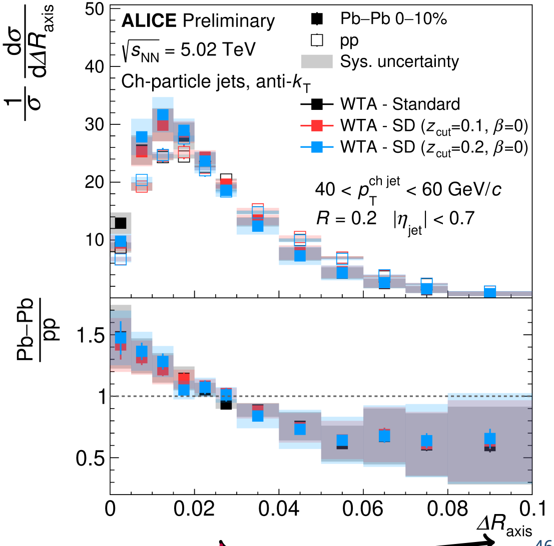


$$\Delta R_{\text{axis}} = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}$$

- Jet quenching **disrupts transverse jet structure**

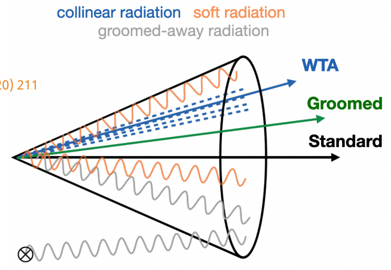
→ Weight contributions to **resolve angular scales**, inc. effect of soft radiation

- **Narrower jets** found in Pb–Pb relative to pp
- Jet axis **insensitive to grooming**
- **Qualitatively describe by most models**
- **Similar conclusion** as R_g



ALICE arXiv:2303.13347

Angle between jet axes



P. Cal et al., JHEP 04 (2020) 211

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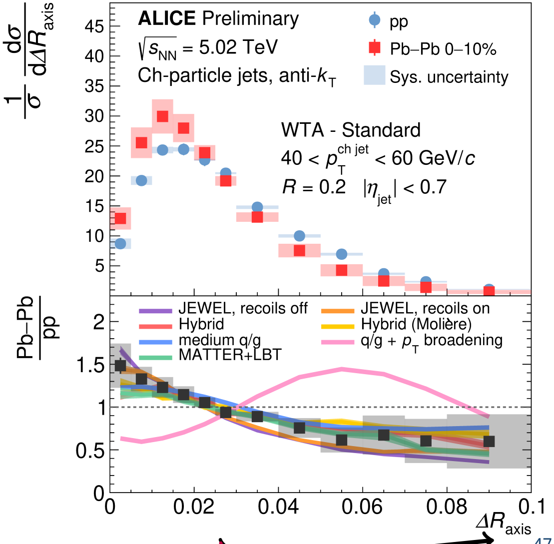

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