Future ideas for jet substructure measurements

Some thoughts from an experimentalist

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Jet Quenching in the Quark-Gluon Plasma
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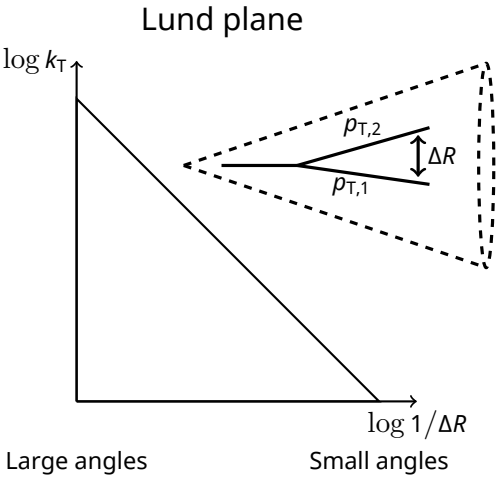
State of the art jet substructure

- **Large collection** of substructure measurements in recent years
  - Covered by Marta, Rey, Martin, Laura, ...
- **Great progress!**
- Improved understanding of splittings
- Improved control of backgrounds
- Grooming has broad impact on these efforts
  - Enabled unfolding broader collection of observables in some regions of phase space



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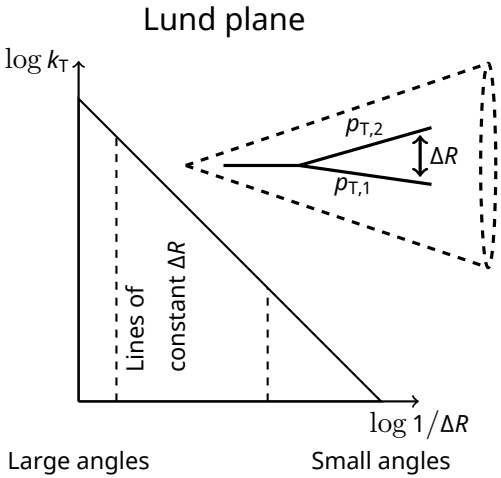

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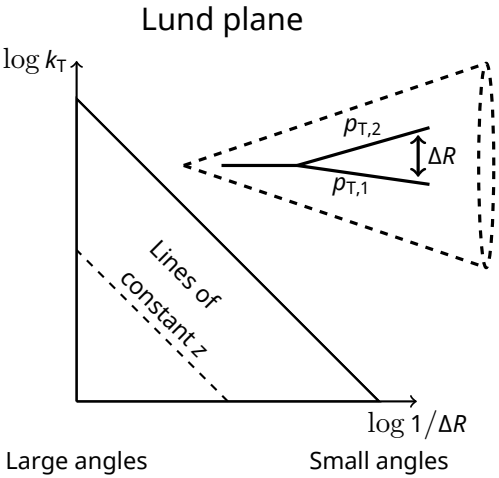

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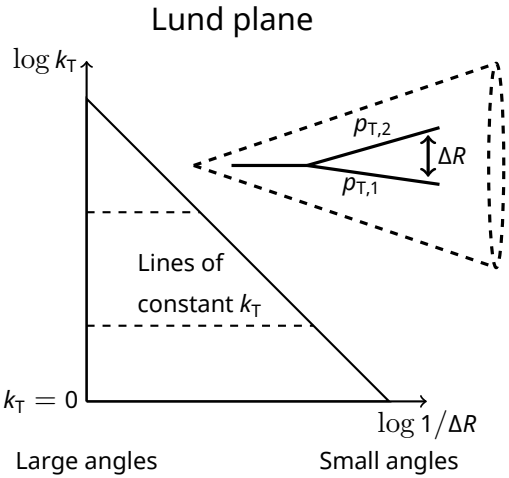
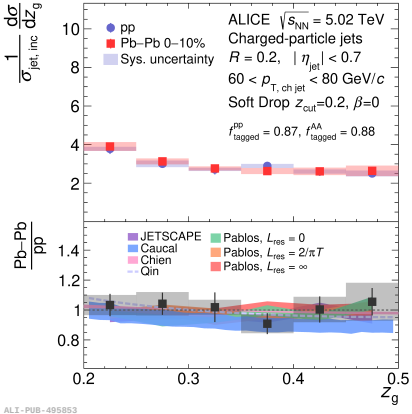
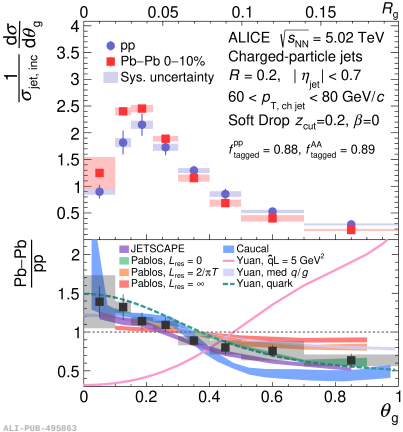
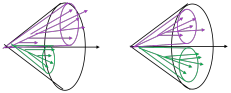


Interpreting existing jet substructure

- **Little modification** to splitting function
- **Narrowing effect** in observables that are sensitive to **angular scale**
  - Fairly well described by a number of models
- q/g fraction? decoherence?
- How to make a more complete picture?







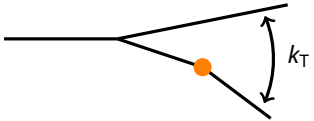
ALICE, PhysRevLett.128.102001

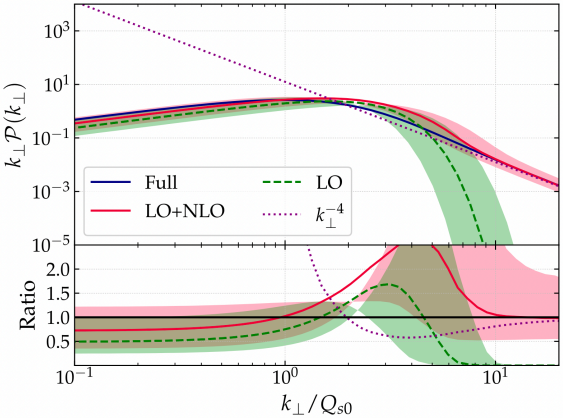
Where next?

1. A few selected recent measurements
2. Extensions of existing measurements
3. Some future directions

Constrain medium structure via jet substructure

- Can we detect high k_T emissions which are a **signature of point-like (Moliere) scattering** in the medium?
- Groomed jet substructure can **facilitate this search**
- **Complementary** to search via jet deflection



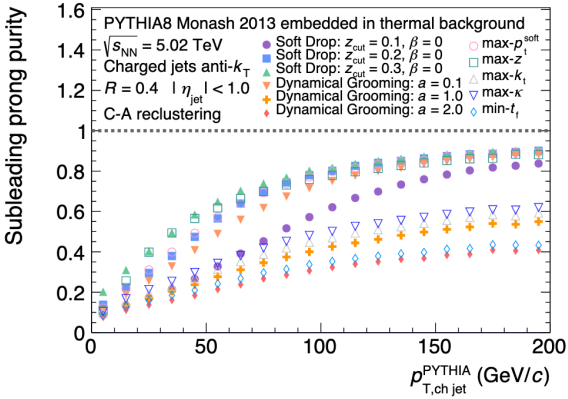


Barata et al, JHEP 09 (2021) 153

Extracting hardest $k_{T,g}$ splittings

- Attempt to select hardest k_T **directly** via Dynamical Grooming (DyG)
  - Grooming cutoff depends on jet properties
  - Can **change hardness measure** via parameter
  - $\kappa^a \propto \max_{i \in C/A}[z_i(1-z_i)p_{Ti}(\theta_i/R)^a]$
  - Use a = 0.5, 1 (k_T), 2 (t)
  - See Adam's talk
- Also measure with Soft Drop, $z_{cut} > 0.2$
- To measure $k_{T,g}$ (or other observables) in *AA*, need to deal with:

1. **Subleading** subjet purity
2. **Off-diagonal components** in the response



Mulligan, Ploskon, PhysRevC.102.044913

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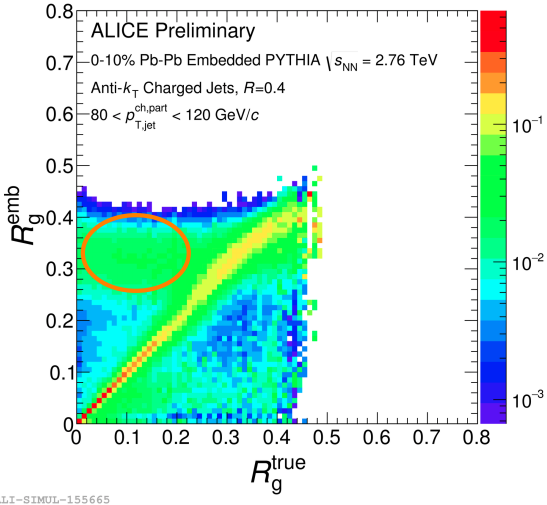
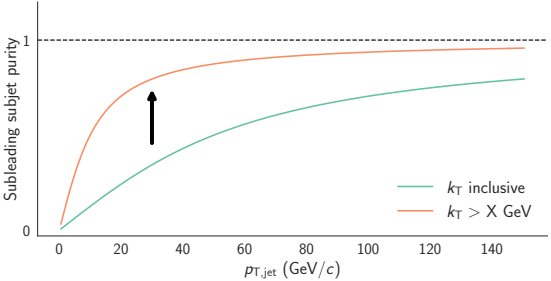
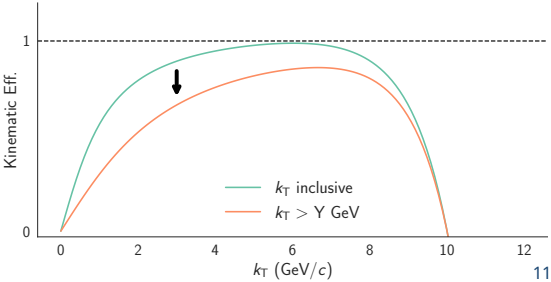


Using DyG for hardest $k_{T,g}$ splittings in Pb–Pb

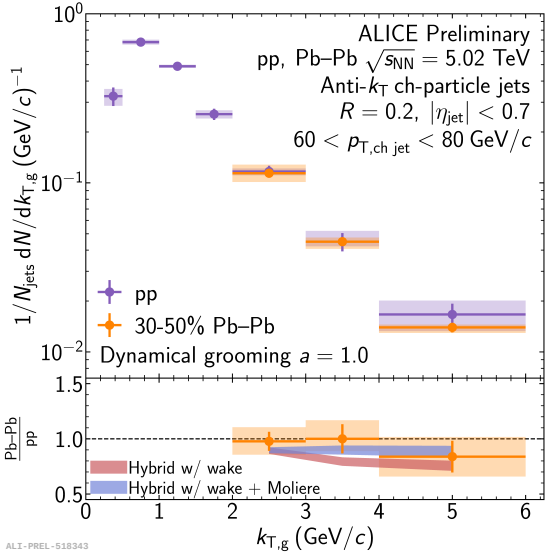
- Subleading subjet purity must be **sufficiently high** to unfold
- **Mismatched splittings** are major component of low k_T splittings
- **Minimum k_T** requirement increases purity
- Sketch illustrates effects on purity and kinematic efficiency
  - Optimization problem
- Off-diagonal response components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





Hardest $k_{T,g}$ splittings in Pb–Pb

- **First measurement of DyG in Pb–Pb**
- **Consistent set of splittings** selected at high $k_{T,g}$ by all DyG variations and SoftDrop
- SD $z_{cut} > 0.2$ removes soft component
- $\rightarrow$ Measurement over larger k_T range
- Convolved with the **narrowing effects**, as seen in R_g
- Measurement are **not yet sensitive** to impact of Moliere scattering



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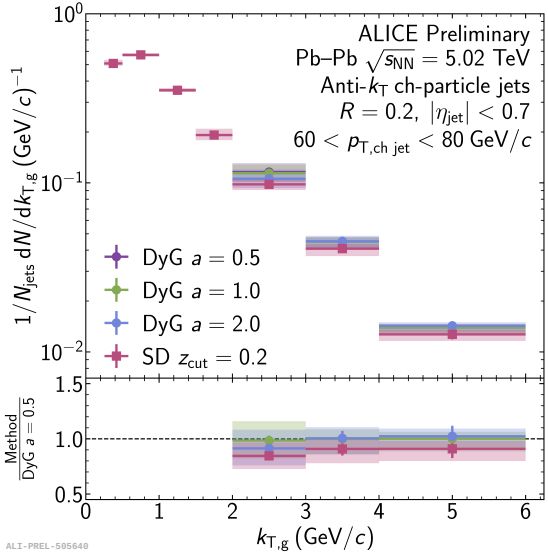

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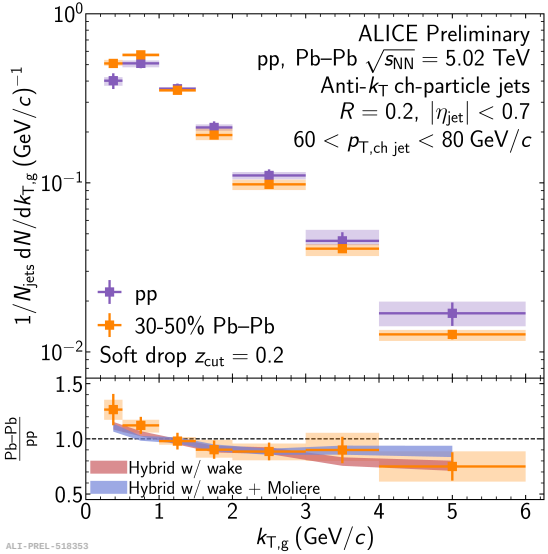
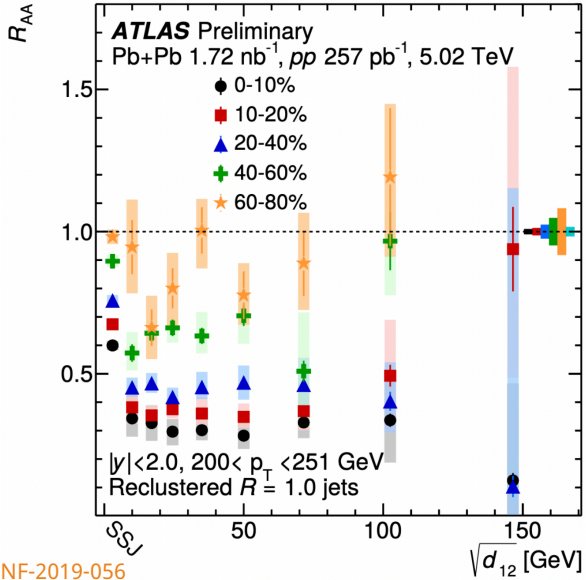


Further steps with $k_{T,g}$

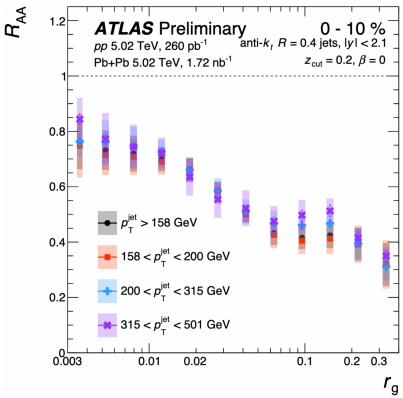
- Further modifications to DyG algorithm to enhance $k_{T,g}$ range?
  - Add z_{cut} to **reduce background** contamination?
- Going to **harder** k_T to move further into $1/k_T{}^4$ dominated region?
- ATLAS $\sqrt{d_{12}}$ sensitive to these effects?
  - Similar to SD $z_{cut} > 0.2$
  - **Different kinematics**

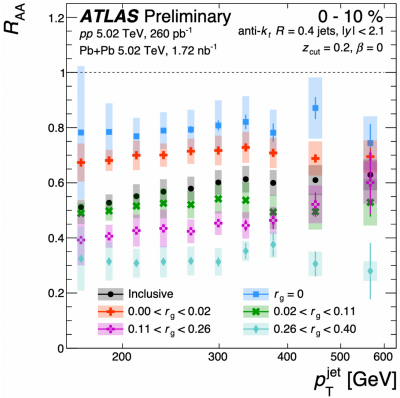


ATLAS-CONF-2019-056

Substructure dependent R_{AA} with ATLAS

- Add observables to substructure measurements to select jet populations
- Less quenching for more narrow R_g is **consistent** with expectations from coherence
- Well described by Caucal et al (see his talk)



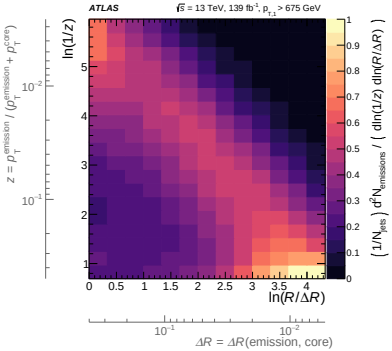


- **Additional statistics** enables more differential substructure measurements

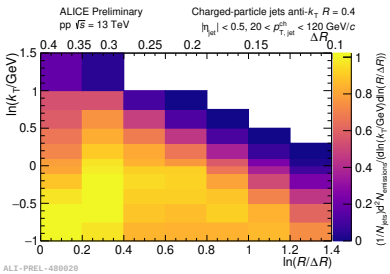
ATLAS-CONF-2022-026

Unfolding the Lund Plane in Pb–Pb

- Natural step from the perspective of more differential measurements
- Encodes substantial splitting information
- **3D unfolding** possible in pp collisions $(p_T, k_T, \Delta R)$
- Needs **explicit handling of misidentified subjets**, which become significant in Pb–Pb



PhysRevLett.124.222002



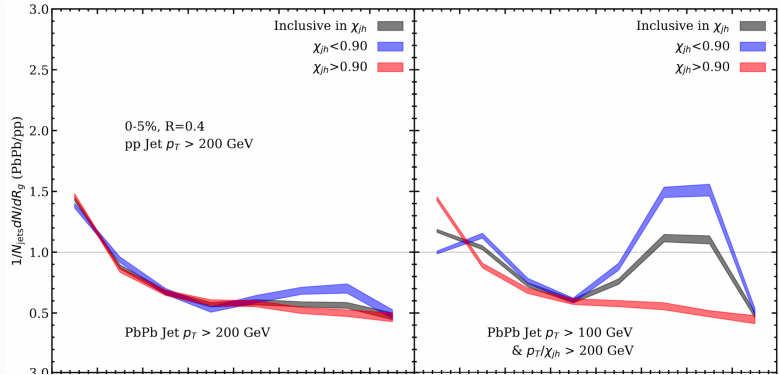
ALICE-PUBLIC-2021-002

- Most likely **require new approaches** for handling background
- If unfolding not possible: Bayesian Inference with 1D substructure observables
  - See Yi's talk

What jets are we actually measuring?

- As mentioned in Laura's talk, the jet selection may be driven by a **survival bias**
- Narrower jets with a harder core are more likely to survive
- Selection of jets for comparison are not the same

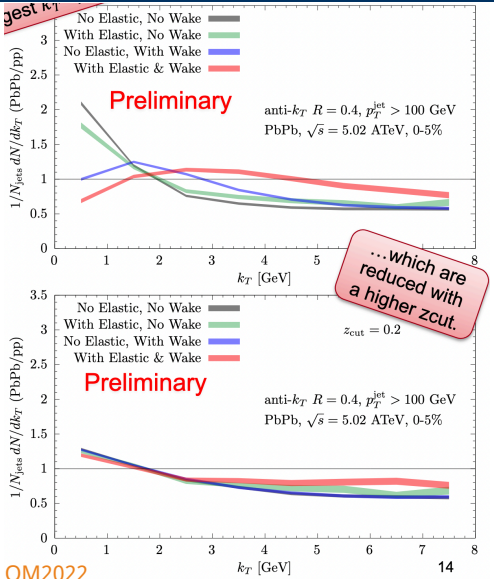
- Bias described by many different studies
- Selecting the **same initial energy** distribution shows:
  - Reduced narrowing for quenched jets
  - Larger modification at large R_g



Du et al, JHEP 03 (2021) 206

Where can we observe Moliere scattering effects?

- Hybrid model studies **with and without** Moliere scattering suggest that effects are observable via jet substructure
- Experimental search focused on high k_T tail
- However, most prominent Moliere effects show up at **low *z***
- Experimental requirements **cut into the phase space** of interest



Z. Hulcher et al @ QM2022

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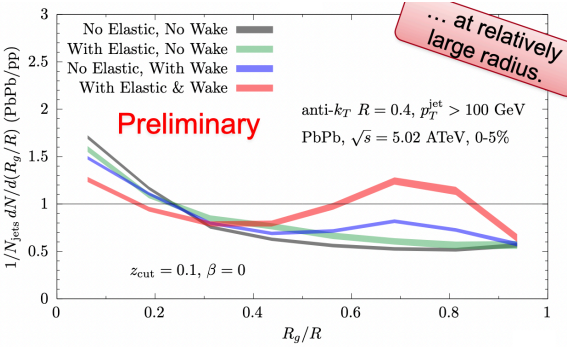


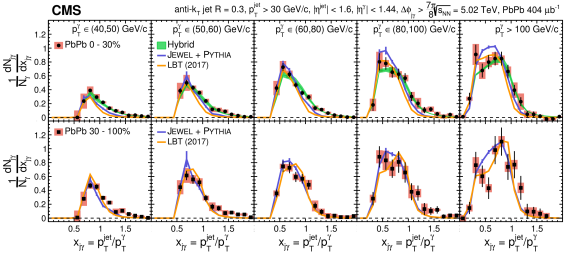
Z. Hulcher et al @ QM2022

Can we move into the lower z or k_T region to explore the full phase space?

- Together, we **may not have reached** all of the regions of interest in phase space
  - What have with missed in these regions that we do not see?
- Can we **relax the selections** on z, p_T, k_T, etc to add phase space and reduce jet selection bias?
- How can we do it such that the observable and background **stay under control?**
- **New techniques** to apply experimentally?
- **Additional ungroomed observables?**

γ/Z/hadron-jet and HF substructure

- Aim for **increased control** of observable properties via trigger or HF requirement
- Constraints on initial energy distribution via γ/Z-tagged jet substructure
- HF provides additional lever for controlling substructure observables
- Need to contend with **available statistics**



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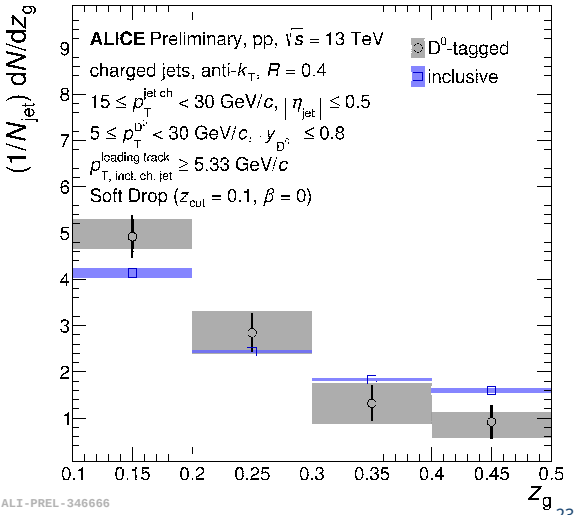
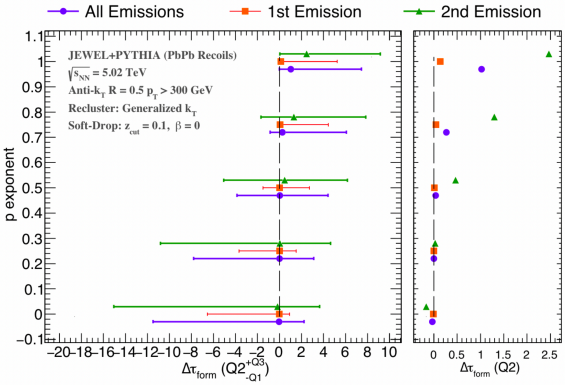


Time reclustering

- Angular ordering of emissions may not be preserved in medium
- Can we **account for this in the reclustering?**
  - Do we need to?
- $\rightarrow$ Reclustering based on formation time (generalized k_T with p = 0.5)
- First splitting found for time, groomed C/A
  - Broader asymmetric dist. for groomed C/A

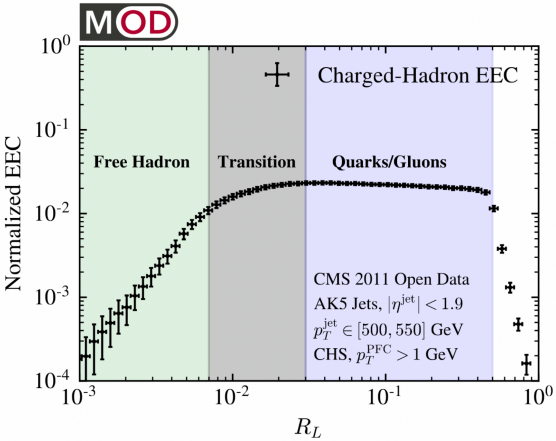


- Grooming **greatly improves** prob. of finding earliest splitting with time reclustering
- However, grooming is less critical for time reclustering
  - Reduce selections to move into broader phase space by focusing on formation time?
- See Liliana's talk

Apolinário et al, Eur. Phys. J. C 81, 561 (2021)

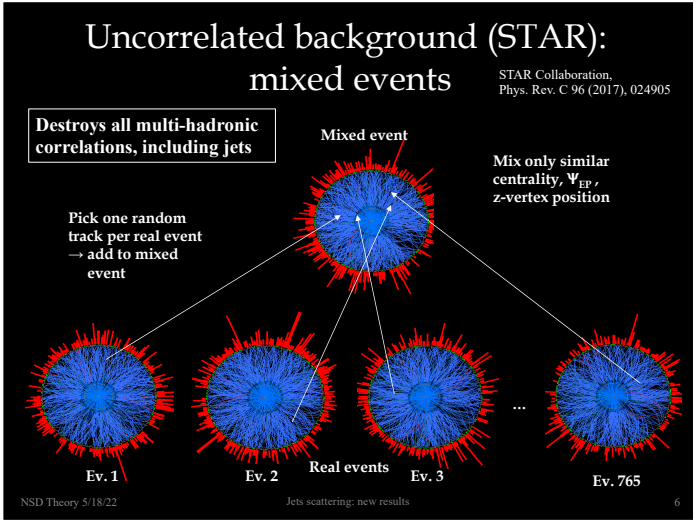
Energy-energy correlators

- **Reframing** of jet substructure in terms of correlation functions
  - Different approach to accessing the splitting information
- Simplest is a 2-point correlator **characterizing ΔR between constituents**
  - Probes jet substructure **as a function of angular scale**
- Ungroomed observable, so needs appropriate handling of the background
- Correlations weighted by energy
  - Focus in on hard contributions
- First look in pp via CMS open data
- Feasibility in HI **still to be assessed**



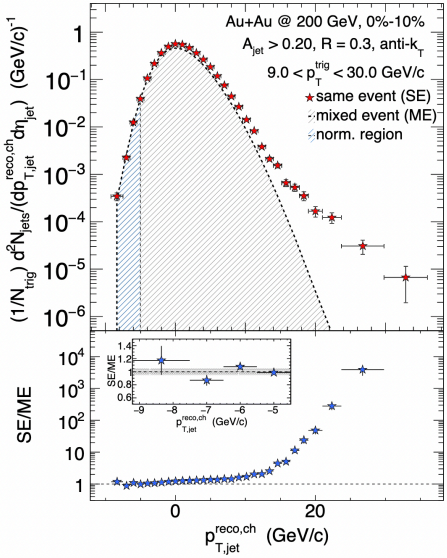
- Unfolding needs **careful consideration**

Mixed event techniques



Further possibilities

- **Statistical methods** another promising option for characterizing background
  - See Peter's talk
  - May be especially useful for ungroomed observables
  - Require carefully constructed observables
- Extend **ML based background subtraction** for jet substructure?
  - Needs extremely careful examination of biases
- ML assisted **observable design?**
  - Maximize the differences between pp and AA
  - See Mateusz's talk



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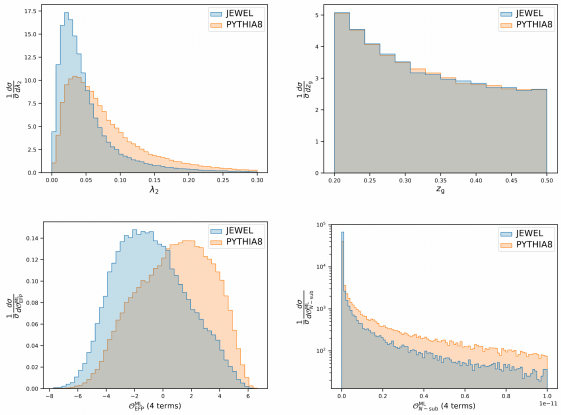


Summary and Outlook

- **Great progress** in recent years on jet substructure measurements
- **Comprehensively measuring groomed substructure** and soon more differential
- Important ungroomed observables such as jet shapes, FF, angularities, jet axis, etc were not covered here

- Relaxing selections may **reduce jet survival bias** and open regions of interest
- Many interesting **new techniques and observables**
  - DyG, time reclustering, EEC, mixed events and statistical methods, ML, etc

- Important to continue **exploring and filling splitting phase space!**
- High statistics future is nearly upon us:
  - sPHENIX and STAR will (continue to) further constrain our picture
  - As will LHC in Run 3-5 (see Chris' talk)

Backup

Grooming methods for extracting $k_{\mathrm{T,g}}$

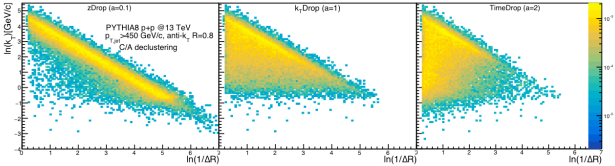
For each considered splitting i, $k_{\mathrm{T}i} = p_{\mathrm{T}i}^{\mathrm{sublead}} \sin \Delta R_i$

Dynamical Grooming (DyG)

Mehtar-Tani et al., PhysRevD.101.034004

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

- $a = 0.5$: "core" - more symmetric, narrow
- $a = 1$: "k_{T}" - largest $k_{\mathrm{T}} \sim \kappa^1 p_{\mathrm{T}}$
- $a = 2$: "time" - shortest splitting time $t_f^{-1} \sim \kappa^2 p_{\mathrm{T}}$



Soft Drop (SD)

Larkoski et al., JHEP 05 (2014) 146

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

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