

Investigating Hard Splittings via Jet Substructure in pp and Pb–Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE

ORNL Nuclear Physics Seminar

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2020 October 01

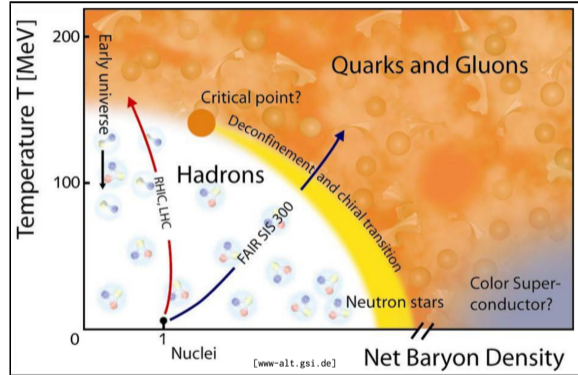
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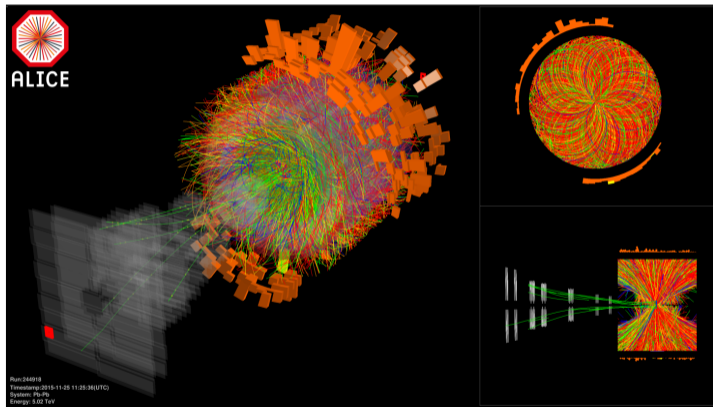
QCD Phase Diagram and the Quark Gluon Plasma (QGP)

- At high temperatures, hadrons melt into their constituent quarks and gluons.
- The quarks and gluons are deconfined in a strongly coupled state known as the **Quark Gluon Plasma (QGP)**.
- Phase transition occurs around a temperature of $T \sim 150$ MeV.
 - Smooth crossover phase transition near net baryon density of ~ 0 .
- Trajectories through the phase-space are experimentally accessible in heavy-ion collisions.



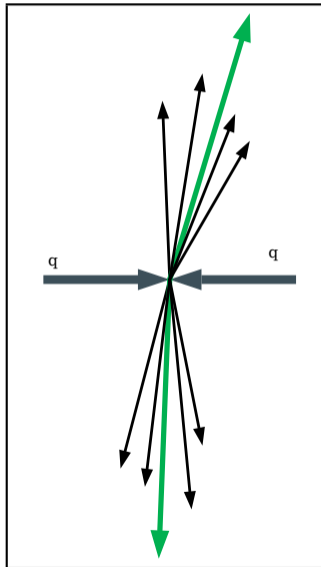
High Momentum Transfer Processes

- Heavy ion collisions involve a variety of physical processes.
 - → We need tools to isolate properties of interest.
- My focus: **High momentum transfer processes** which provide a built-in probe of the QGP.
- The experimental signature of high momentum transfer processes is known as a **jet**.



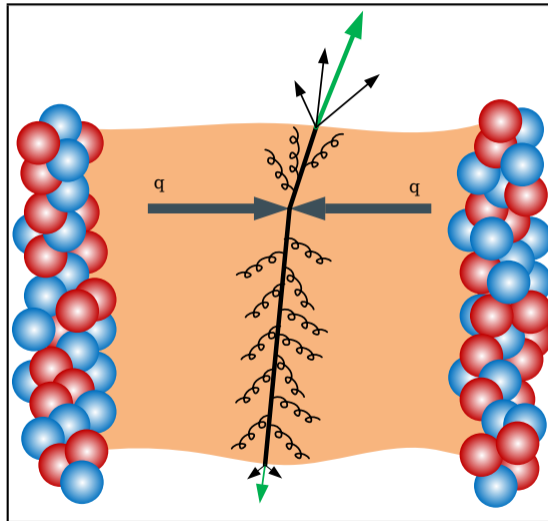
Jets and Jet Quenching

- Jets are collimated sprays of particles produced by the fragmentation of a parton from a high momentum transfer scattering.
 - Experimentally defined by a jet clustering algorithm with a resolution parameter, R .



Jets and Jet Quenching

- Jets are collimated sprays of particles produced by the fragmentation of a parton from a high momentum transfer scattering.
 - Experimentally defined by a jet clustering algorithm with a resolution parameter, R .
- In heavy-ion collisions, jets are produced before the QGP forms and then propagate through it, **losing energy**.
- Jet-medium interactions are expected to **modify the internal structure** of the jet.
 - Jets probe multiple scales during propagation.
- The impact of these interactions are collectively known as **jet quenching**.



How Do We Measure Jets in ALICE?

- ALICE performs two kinds of jet measurements:

- Charged-particle jets.
- Full jets.

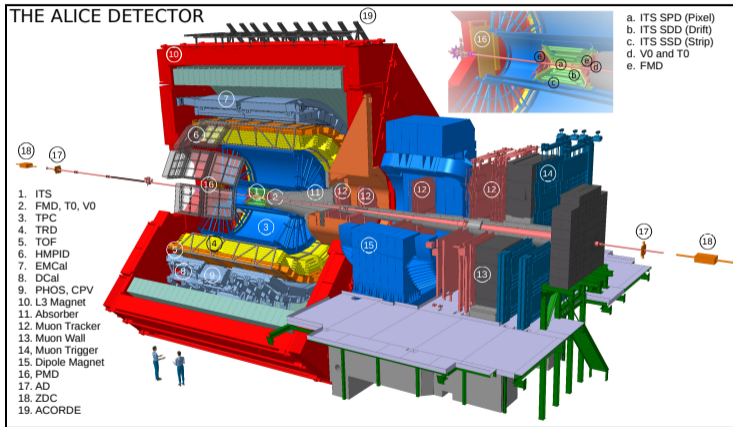
- Why charged-particle jets?

- ALICE central barrel tracking is based around the ITS and TPC.

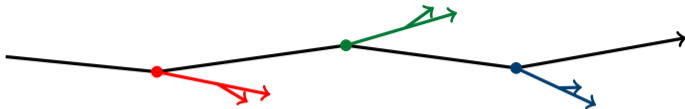
1. Measure charged particles with precise angular resolution down to $p_T > 150$ MeV/c.

- Well suited for measurements I will discuss today.

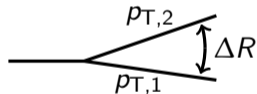
2. Larger acceptance.



Jet Splittings and Jet Substructure

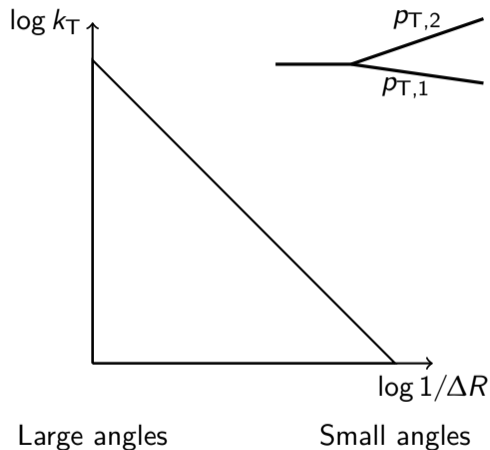


- Focus on the details of the jet evolution.
- As the parton propagates, it radiates and splits.
 - This leads to our collimated spray of particles which is identified as a jet.
- For each splitting, we have a leading and subleading subjet.
- Evolution of the jet is characterized by these jet splittings.
- To stay in the perturbative regime \rightarrow early, hard splittings.



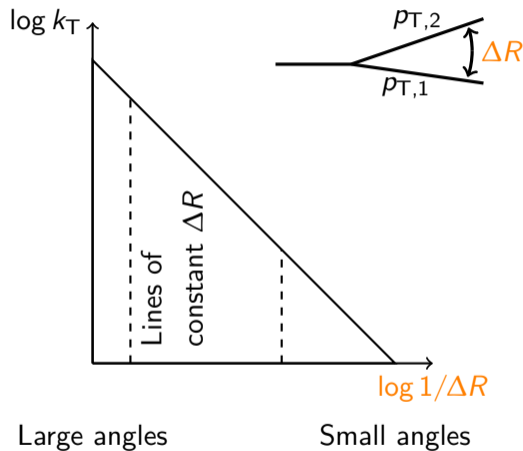
The Lund Plane

- Can visualize the splitting phase space with the Lund Plane.
- Three variables define our splittings via the leading (1) and subleading (2) subjects:
 - $\Delta R = \sqrt{(\varphi_1 - \varphi_2)^2 + (\eta_1 - \eta_2)^2}$
 - $k_T = p_T^{\text{sublead}} * \sin \Delta R$
 - $z = \frac{p_T^{\text{sublead}}}{p_T^{\text{lead}} + p_T^{\text{sublead}}}$
- For fixed α_s , splittings are uniformly distributed in the Lund Plane.
- Selecting on these variables provides a lever for exploring the phase space.



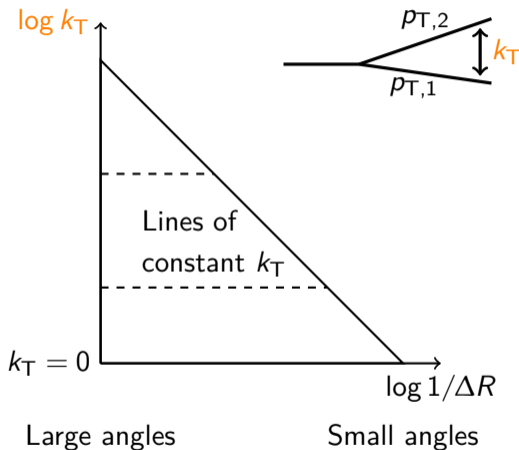
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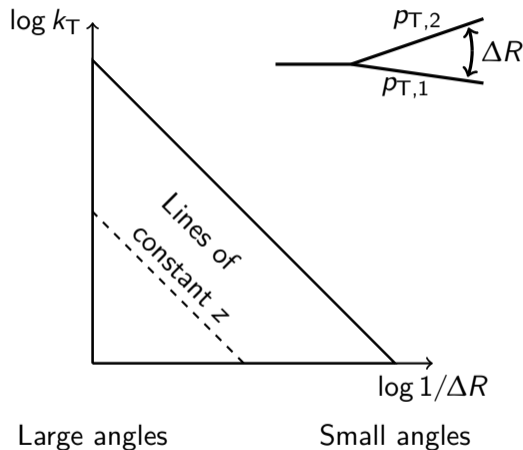
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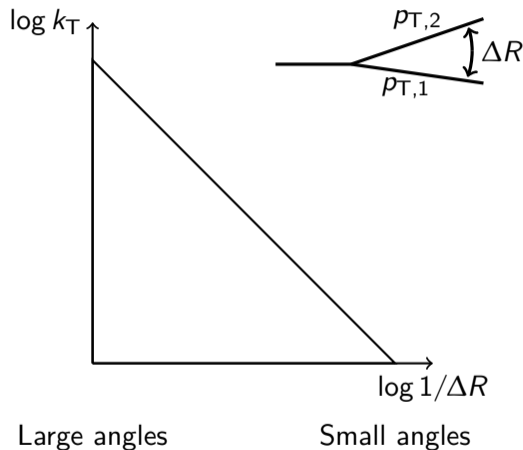
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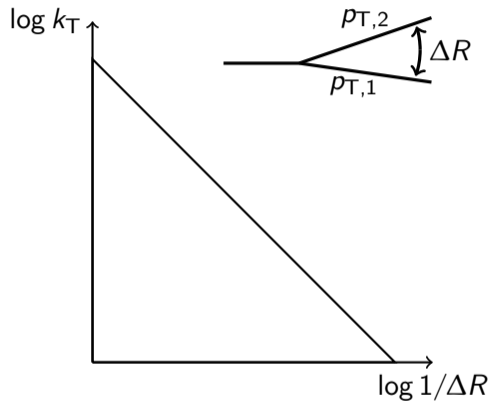
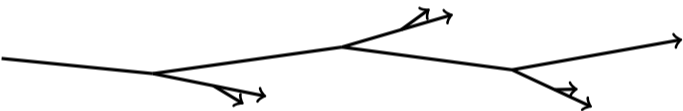


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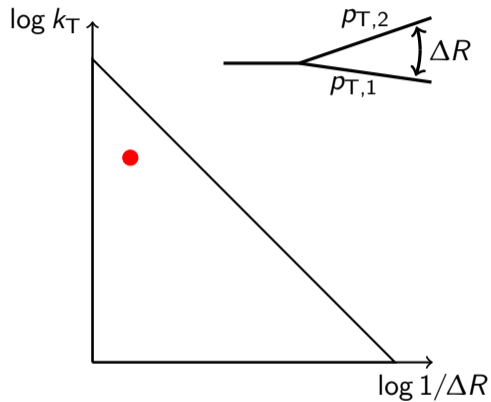
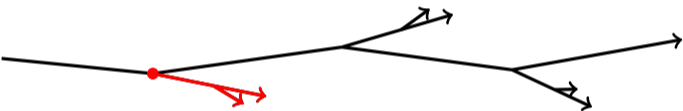
Splittings in the Lund Plane



Large angles

Small angles

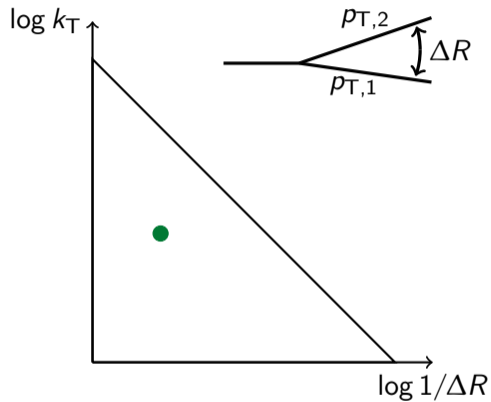
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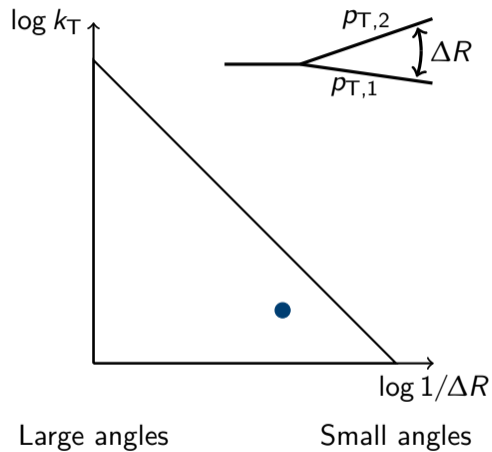
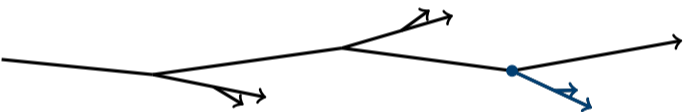
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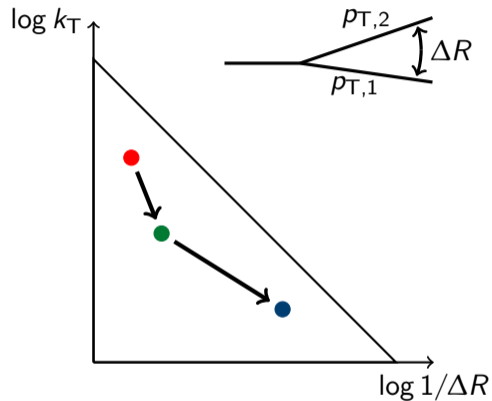
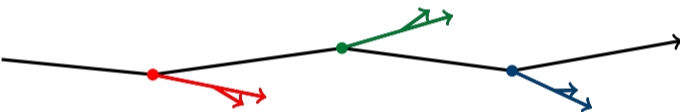
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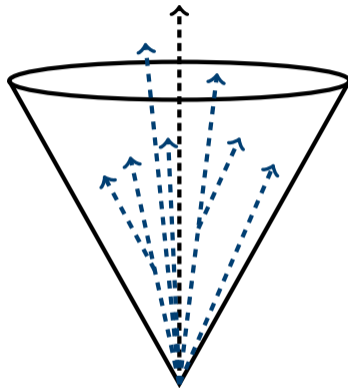


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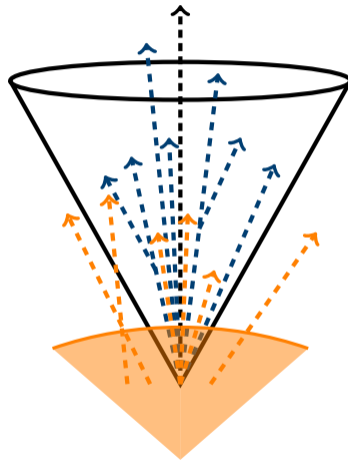
Measuring Jet Substructure

- We only measure final state hadrons.
 - → We don't have direct access to the jet splittings.
- How does our theory cartoon translate to an experimental measurement?
- How do we make meaningful measurements in the presence of the underlying background in heavy ion collisions?
- → **Jet substructure** measurements using **jet declustering** algorithms and **jet grooming**.



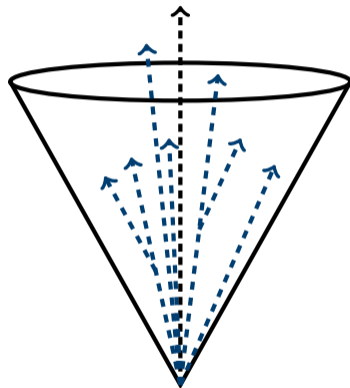
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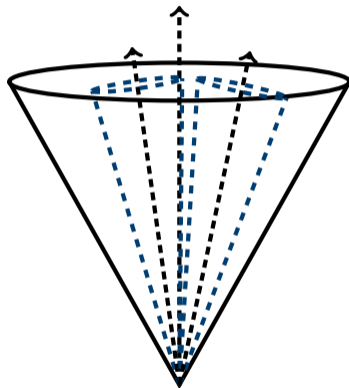
Jet Declustering

- Conceptually, jet declustering **undoes** the clustering algorithm used to find jets.
- **Iteratively group** jet constituents together based on their angular distance.
 - Closest constituents are paired together first.
- Continues until all constituents are clustered.
- By using angular distance, we impose angular ordering in the Lund Plane, mirroring QCD.
- Correlates with the splitting history.



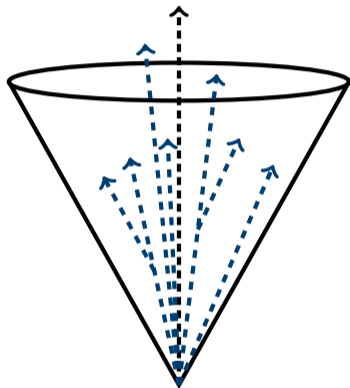
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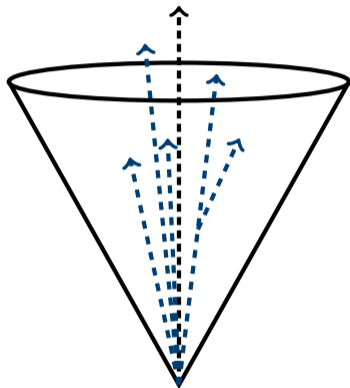
Jet Grooming Algorithms

- Even in vacuum, soft QCD splittings can distort this process.
 - Even more problematic in heavy ion collisions.
- → Employ **jet grooming** algorithms to require sufficiently hard splittings.
- Benefits depend on the collision system:
- pp: Limit contamination of soft QCD background.
- Pb–Pb: Select hard component of quenched jets.
- I will focus on **SoftDrop** to start.
 - There are a wide variety of grooming algorithms.



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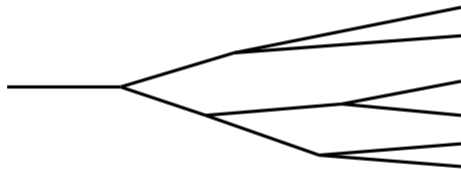


Jet Grooming: Soft Drop

- Recluster the jet using Cambridge/Aachen algorithm (geometric).
- Undo the last clustering step to get two branches with $p_{T,1}$ and $p_{T,2}$
- Check whether the two branches pass the SoftDrop condition:

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \theta^\beta = z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^\beta$$

- If condition passed, record subjet properties.
 - Often labeled with “g”, such as z_g .
- If failed, take the harder branch and continue by to the next splitting of that branch.

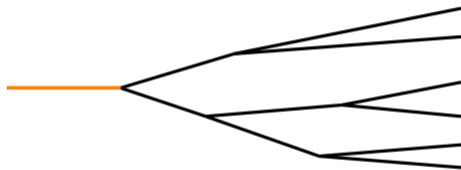


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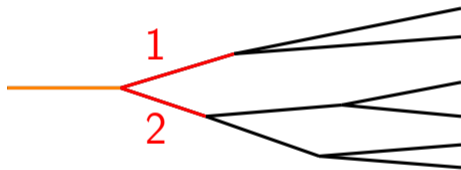


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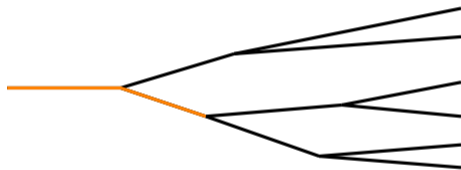


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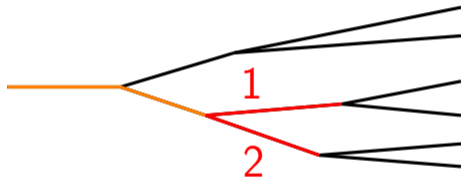


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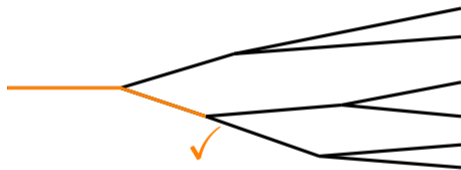


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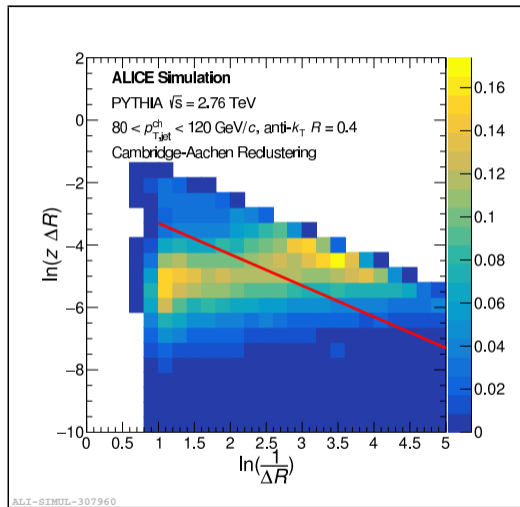
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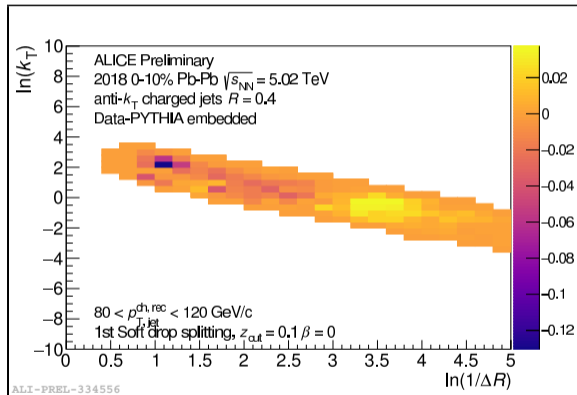
Soft Drop Characteristics

- SoftDrop is often employed with $z_{\text{cut}} = 0.1, 0.2, 0.4$ and $\beta = 0$.
- Lund Plane shown for PYTHIA, with no grooming cut applied.
- Characteristic behavior of SoftDrop is shown with the red line.
 - Only keep the first splitting above that line.
- Differences become apparent by **subtracting** embedded PYTHIA from Pb–Pb.
- Significant off-diagonal for response matrix.
 - → Difficult to unfold.



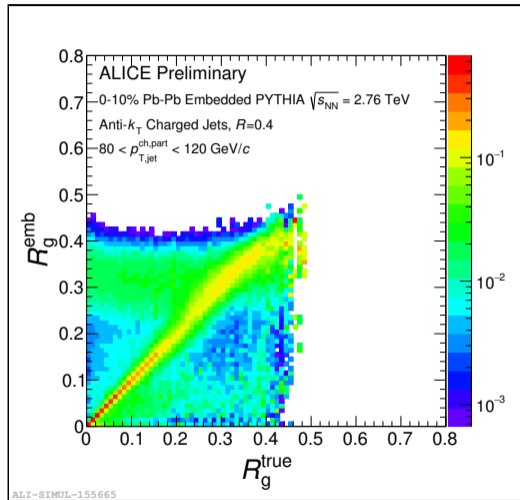
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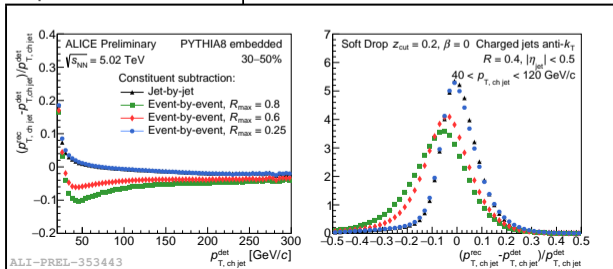
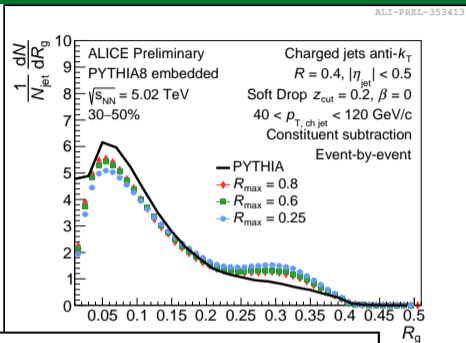
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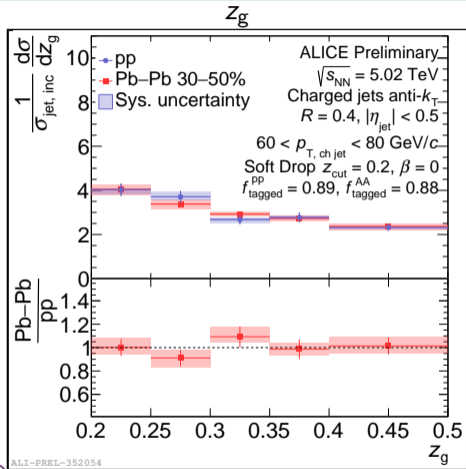
Background Contributions to Substructure in Pb–Pb

- Although grooming helps to select the quenched hard splitting, combinatorial background is still present.
- Standard $p_{T,jet}$ correction doesn't correct the jet constituents which form the subjets.
- Correct for this with event-wise constituent subtraction [JHEP 08 \(2019\) 175](#).
 - Distributes background energy throughout the event, and subtracts that energy from close particles.
- Parameters optimized for Pb–Pb collisions to reduce background but minimally impact the signal.
 - Comparison for R_g on the right.
- Unfold in background free region.

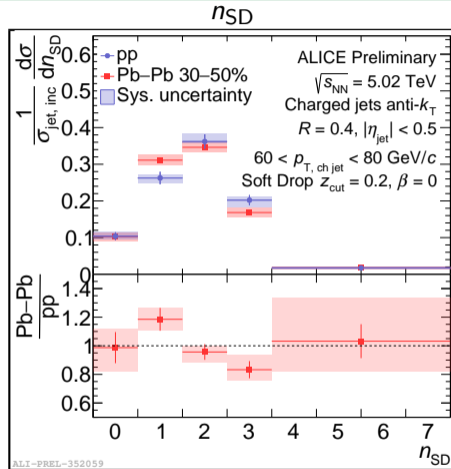


Fully Unfolded z_g , n_{SD} in 30–50% Pb–Pb Collisions

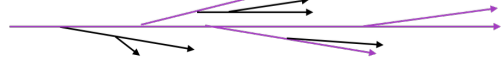
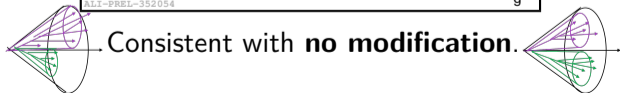
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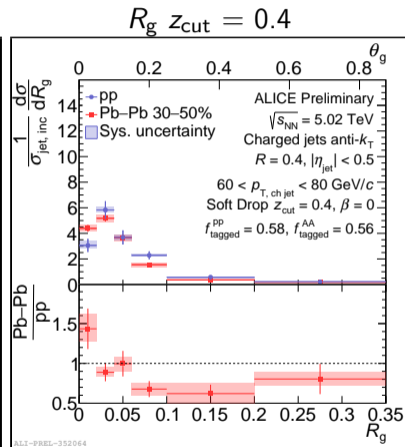
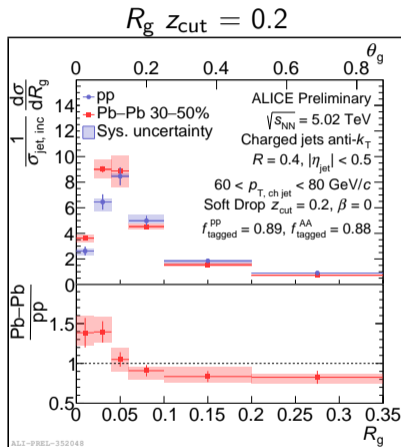
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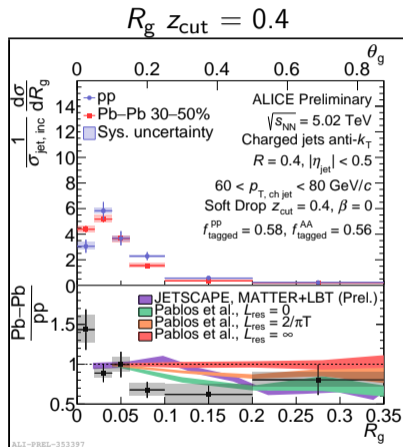
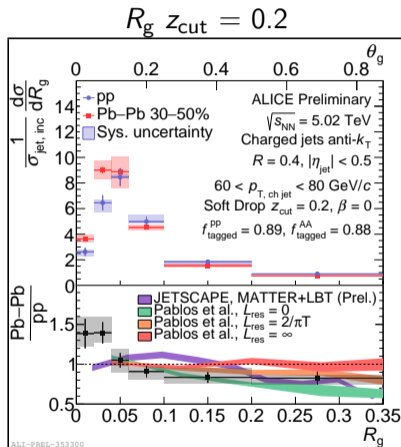


- Suppression of large angles and enhancement of small angles for both z_{cut} .
- Tested for consistency with unity, as determined by χ^2 CDF for sys + stat in quadrature.
 - $z_{\text{cut}} = 0.2$: $p=0.03$
 - $z_{\text{cut}} = 0.4$: $p=0.029$



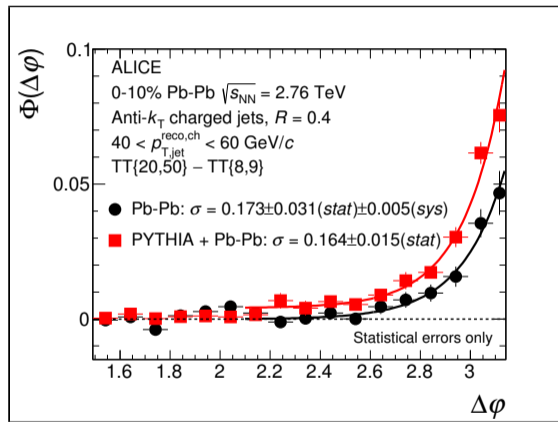
Model Comparisons for R_g in 30–50% Pb–Pb Collisions

- JETSCAPE:
MATTER+LBT
[arxiv:1903.07706](https://arxiv.org/abs/1903.07706)
- Pablos et al. Hybrid model
[JHEP 01 \(2020\) 044](https://arxiv.org/abs/1903.07706)
 - $L = 0, 2/\pi T, \infty$
- Perhaps sensitive to coherence in the medium.



Jet Substructure as a Tool to Study Medium Structure?/1

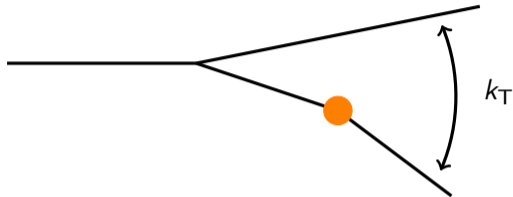
- ALICE is searching for the signature of point-like (Moliere) scattering centers in the medium.
- Up to now, ALICE has measured large-angle recoil jet deflections in $\sqrt{s_{NN}} = 2.76$ TeV.
 - Consistent with no acoplanarity of recoil jets within uncertainties.
- What is the impact of the medium on jet substructure?
- Would it be sensitive to such scattering centers?



JHEP 09 (2015) 170

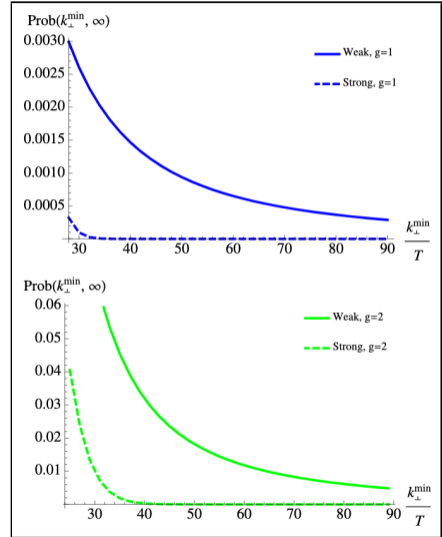
Jet Substructure as a Tool to Study Medium Structure?/2

- If a subjet is deflected at a large angle by a scattering center, it will increase the k_T of that splitting [JHEP 05 \(2013\) 031](#), [JHEP 01 \(2019\) 172](#)
 - Point-like scatterers in the medium would appear as an excess of large k_T emissions in Pb–Pb collisions relative to pp collisions.
- Can we detect with jet substructure observables high- k_T emissions which are signature of point-like (Moliere) scatterers in the medium?
- Alternative approach to access the same physics as investigated via hadron-jet decorrelations.



Jet Substructure as a Tool to Study Medium Structure?/2

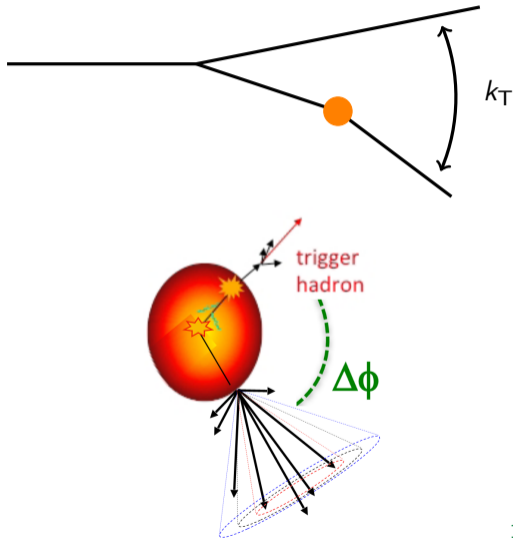
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[JHEP 05 \(2013\) 031](#)

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Methods for Extracting Hardest k_T

- Use grooming methods to identify the hardest k_T splitting in a jet:

- For each considered splitting i ,

$$k_{Ti} = p_{Ti}^{\text{sublead}} \sin \Delta R_i$$

- We compare eight grooming methods:

- Leading k_T : $\max_{i \in C/A} k_{Ti}$
- Leading k_T for all $z > 0.2$ splittings.
- Dynamical grooming ([PhysRevD.101.034004](#)):

$$\kappa^a = \frac{1}{p_T} \max_{i \in C/A} [z_i(1 - z_i)p_{Ti}(\theta_i/R)^a]$$

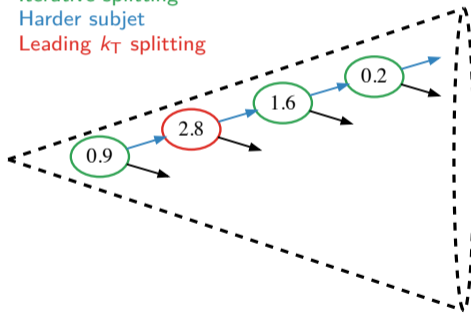
- $a = 0.1$ - Most symmetric z : “zDrop”.
- $a = 1$ - Largest $k_T \sim \kappa^1 p_T$: “ k_T Drop”.
- $a = 2$ - Shortest splitting time $t_f^{-1} \sim \kappa^2 p_T$: “TimeDrop”.

PYTHIA8 Particle Level: Jet $p_T = 83.3$ GeV/c
 k_T in node (GeV/c)

Iterative splitting

Harder subjet

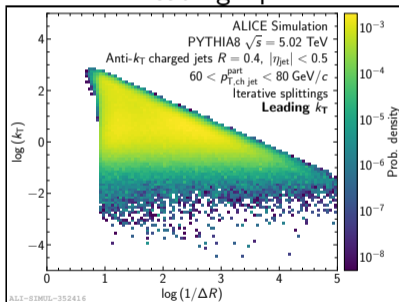
Leading k_T splitting



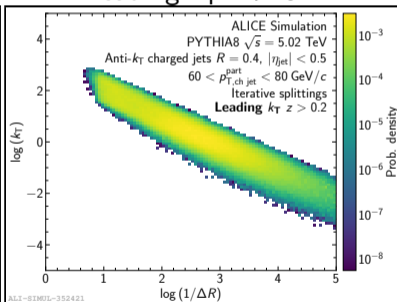
Grooming Method Characteristics/1

Each grooming method has different characteristic behavior in the Lund Plane.

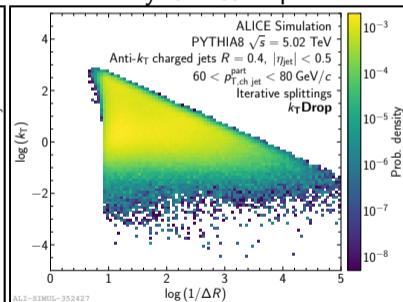
Leading k_T



Leading k_T $z > 0.2$



Dynamical k_T

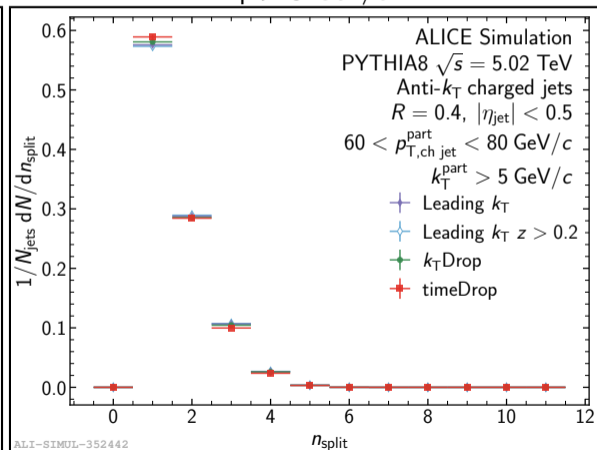
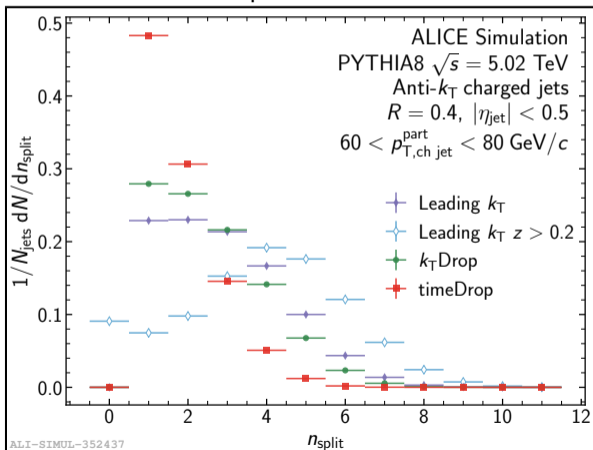


Grooming Method Characteristics/2

Number of splittings until the selected splitting converges at high k_T .

k_T inclusive

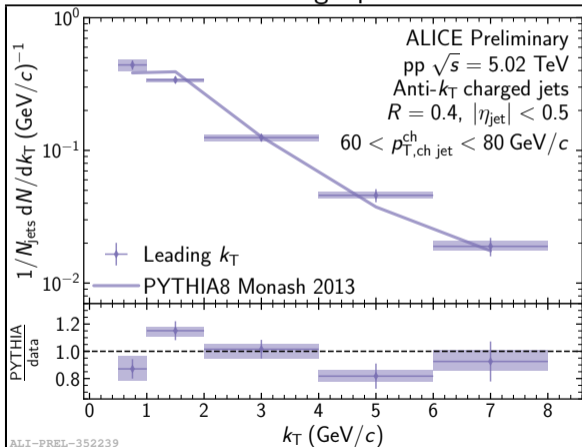
$k_T > 5$ GeV/c



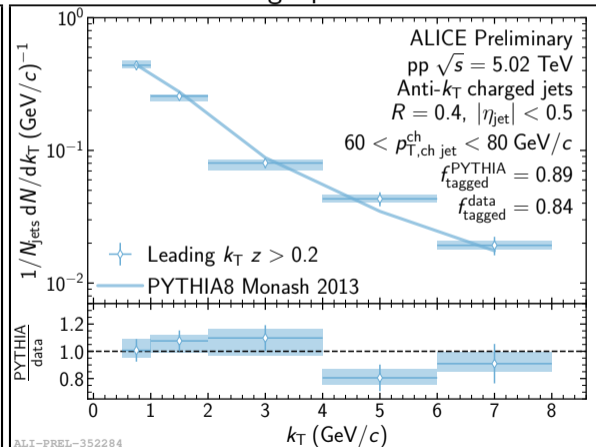
Hardest k_T Measured in pp Collisions

- k_T follows characteristic steeply falling shape.
- PYTHIA in broad agreement with the data.

Leading k_T



Leading k_T $z > 0.2$



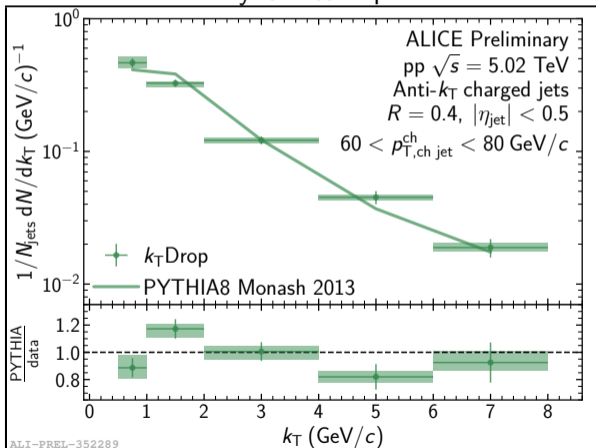
ALI-PREL-352239

ALI-PREL-352284

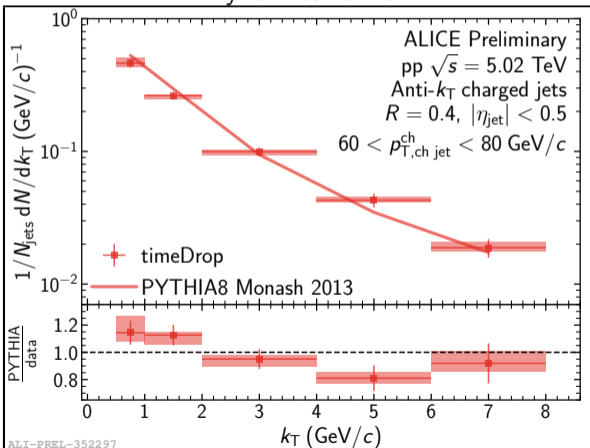
Hardest k_T Measured in pp Collisions

- Dynamical grooming methods show same trends.
- PYTHIA in broad agreement with the data.

Dynamical k_T



Dynamical time

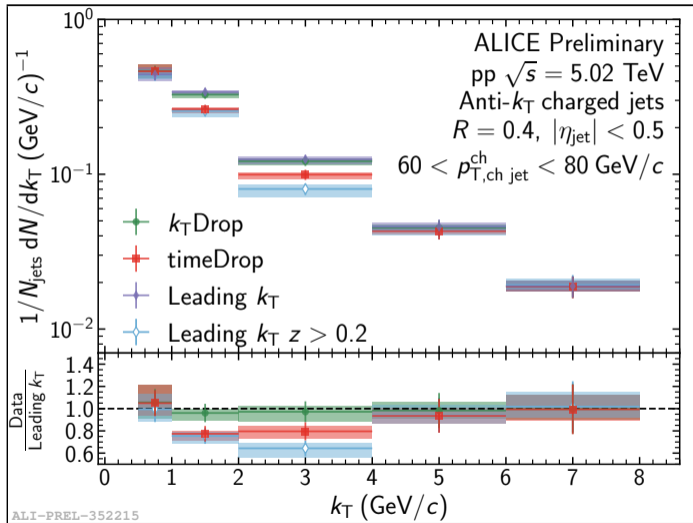


ALI-PREL-352289

ALI-PREL-352297

Comparison Between Grooming Methods

- Comparison of the different grooming methods in pp collisions.
- Ratio is relative to leading k_T .
- At low-mid k_T there is some divergence between the methods.
- All grooming methods converge at high k_T .
- The exact same splitting is selected by all methods at very high k_T .

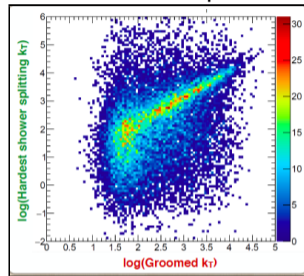


Toward Hardest k_T in Pb–Pb

- To access feasibility in Pb–Pb, study the correlation between the hardest k_T splitting in the parton graph and from declustering at particle level.
 - Identified the hardest k_T graph, and then performed declustering for $R = 0.8$ jets.
- Compare pythia graph vs:
 - Particle level PYTHIA (as crosscheck).
 - Particle level PYTHIA + thermal background.
- **Strong correlation** between the hardest emission and the hardest splitting at large k_T .
- Studied at **EMMI RRTF Workshop** on the space-time structure of jet quenching.
- Difficulty of unfolding that was found in SoftDrop substructure **persists** for the hardest k_T .

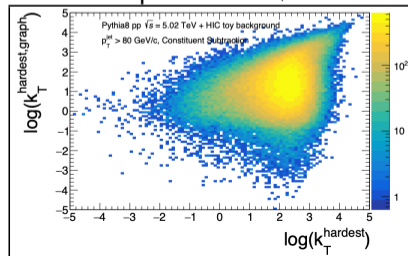
Raymond Ehlers (ORNL) - 2020 October 01

PYTHIA part. level



Y. Chen
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PYTHIA part. level + thermal

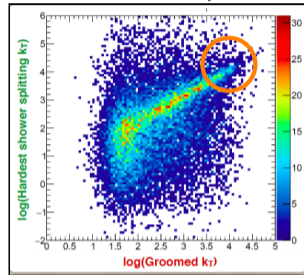


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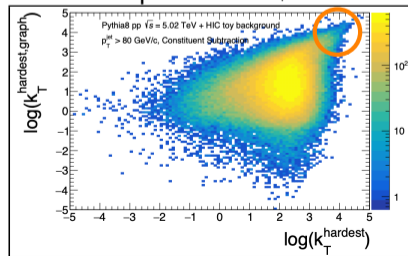
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© EMMI

PYTHIA part. level + thermal

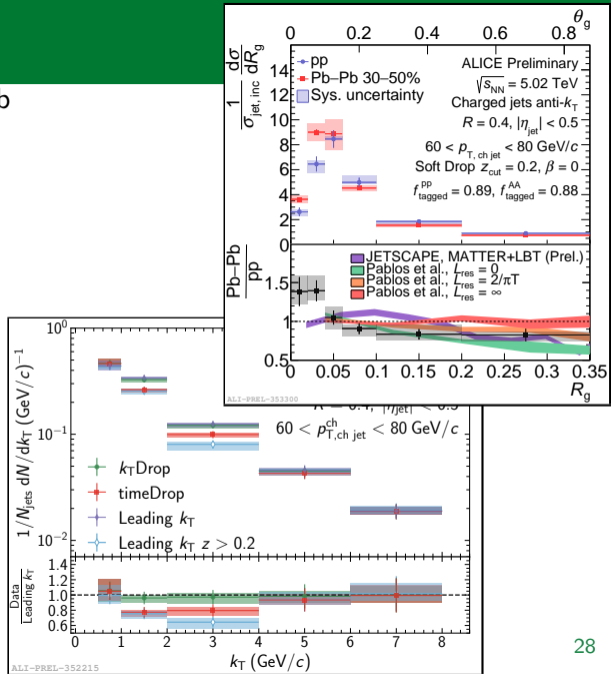


Sneak Peak: Prong Matching: Subleading Purity

Not available...

Summary and Outlook

- Measured z_g , R_g , and n_{SD} in 30–50% Pb–Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
 - z_g , n_{SD} consistent with no modification.
 - R_g shows **enhancement at small angles** and **suppression at large angles**.
 - Both for $z_{cut} = 0.2$ and 0.4 .
- Measured hardest k_T splittings in pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
 - Grooming methods **converge** at high k_T .
 - PYTHIA broadly consistent with data.
- Hardest k_T in Pb–Pb is **converging** and **looks promising**.
- Further exploration of larger R jets, jet splitting structure, and grooming methods.



Backup

Groomed Jet Substructure at $\sqrt{s_{NN}} = 2.76$ TeV

More symmetric splittings seem to be more suppressed in agreement with detector level measurements in the $\sqrt{s_{NN}} = 2.76$ TeV data (PLB 2020.135227).

