

Exploiting the Lund plane to study jet splitting kinematics at RHIC energies

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Physics in and around the Lund Jet Plane, CERN
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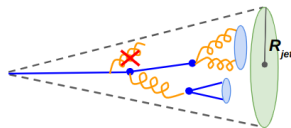


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SoftDrop and CollinearDrop

- Our goal is to access parton showers through experimental observables
- **SoftDrop**
 - Grooming technique called SoftDrop used to remove soft wide-angle radiation from the jet in order to mitigate non-perturbative (like hadronization and UE) and pileup effects
 - Connects parton shower and angular-ordered tree via Cambridge/Aachen (C/A) reclustering



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

$p_{T,1}, p_{T,2}$ - transverse momenta of the subjects
 z_{cut} - threshold (0.1)
 β - angular exponent (0)

ΔR_{12} - distance of subjects in the rapidity-azimuth plane

- **Iterative SoftDrop** used to study first, second, and third splits
- **CollinearDrop**
 - Probes the soft component of the jet
 - Difference of an observable with two different SoftDrop settings of parameters $(z_{cut,1}, \beta_1)$ and $(z_{cut,2}, \beta_2)$
 - Our case: $(z_{cut,1}, \beta_1) = (0, 0)$, $(z_{cut,2}, \beta_2) = (0.1, 0)$



Substructure observables

Momentum and angular observables

z_g	shared momentum fraction	$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$
R_g	groomed radius	first ΔR_{12} that satisfies SoftDrop condition
k_T	splitting scale	$k_T = z_g p_{T,\text{jet}} \sin R_g$

Mass observables

M	jet mass	$M = \sum_{i \in \text{jet}} p_i = \sqrt{E^2 - \vec{p} ^2}$
M_g	groomed jet mass	jet mass after grooming
μ	groomed mass fraction	$\mu \equiv \frac{\max(m_{j,1}, m_{j,2})}{M_g}$



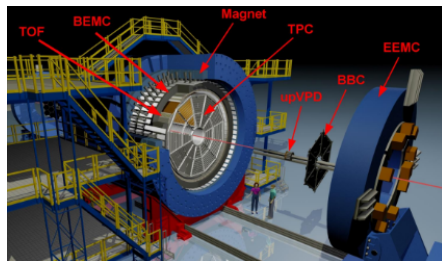
STAR experiment

TPC - Time Projection Chamber

- Detection of charged particles for jet reconstruction
- Transverse momenta of tracks:
 $0.2 < p_T < 30 \text{ GeV}/c$

BEMC - Barrel Electromagnetic Calorimeter

- Detection of neutral particles for jet reconstruction
- Granularity $(\Delta\eta \times \Delta\phi) = (0.05 \times 0.05)$
- Tower requirements:
 $0.2 < E_T < 30 \text{ GeV}$



Dataset:

$p+p$, $\sqrt{s} = 200 \text{ GeV}$, 2012

Algorithms:

anti- k_T , C/A

Jets:

Full jets, $20 < p_{T,\text{jet}} < 50 \text{ GeV}/c$

Full azimuthal angle, $|\eta| < 1$



Detector effects correction

- Measurement is affected by finite efficiency and resolution of the instrumentation
- Our goal is to deconvolve detector effects and obtain true distribution from measured one

(2+1)D unfolding (D'Agostini. arXiv:1010.0632(2010))

- 2D unfolding via Iterative Bayesian procedure
- Correction on ensemble level for the 3rd dimension

MultiFold (Andreassen et al. PRL 124, 182001 (2020))

- Machine learning method
- New tool at RHIC
- All observables are simultaneously unfolded in an unbinned way

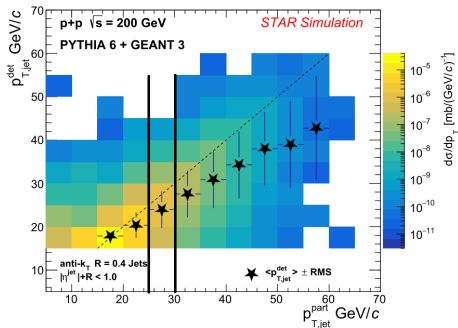
RooUnfold

The ROOT Unfolding Framework



RooUnfold (2+1)D method for z_g , R_g , and $p_{T,jet}$

- Results are in 3D $\rightarrow z_g$ vs. R_g is unfolded in 2D and correction for $p_{T,jet}$ in 1D is needed
 - For each particle-level $p_{T,jet}$ bin, we do projection of this bin into detector-level $p_{T,jet}$, and get the weights from detector-level $p_{T,jet}$ bins



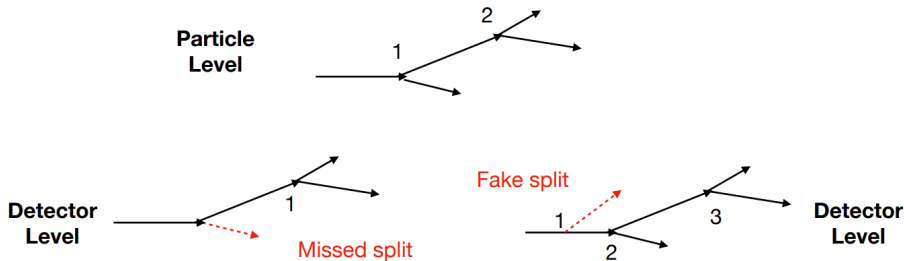
STAR, Phys. Lett. B 811 (2020) 135846

- We unfold z_g vs. R_g via iterative Bayesian unfolding in 2D using RooUnfold and unfolded spectra for each detector-level $p_{T,jet}$ bin are weighted and summed
- Additional corrections for trigger and jet finding efficiencies are applied



RooUnfold (2+1)D method for $p_{T,\text{jet/initiator}}$, z_g , R_g

- Splits can be affected by detector efficiency and resolution
- Observables at a given split are smeared
- Splitting hierarchy is modified going from particle level to detector level



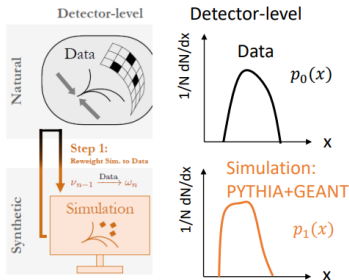
- z_g or R_g vs. $p_{T,\text{jet/initiator}}$ unfolded in 2D at each split, followed by a split-hierarchy correction



MultiFold

- Six observables are simultaneously unfolded in an unbinned way

$$p_T, Q^\kappa = \frac{1}{(p_{T,\text{jet}})^\kappa} \sum_{i \in \text{jet}} q_i \cdot (p_{T,i})^\kappa, M, R_g, z_g, M_g$$



E.g., Iteration 1, step 1:

Weights: $w(x) = p_0(x)/p_1(x)$ Ok for 1D

$$\approx f(x)/(1 - f(x))$$

([Andreassen and Nachman PRD 101, 091901 \(2020\)](#))

where $f(x)$ is a neural network and trained with the binary cross-entropy loss function

to distinguish jets coming from data vs from simulation

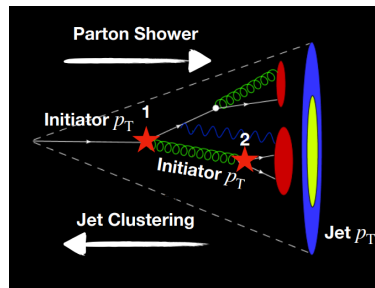
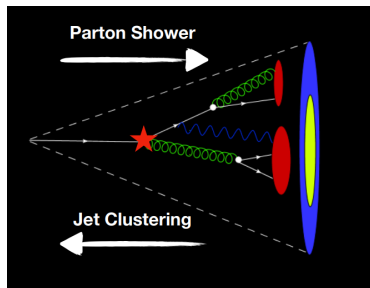
Unfolding \rightarrow Reweighting histograms
 \rightarrow Classification \rightarrow Neural network

Where does the machine learning part come in?

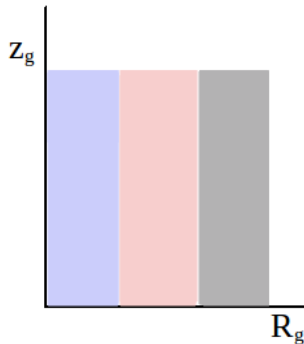
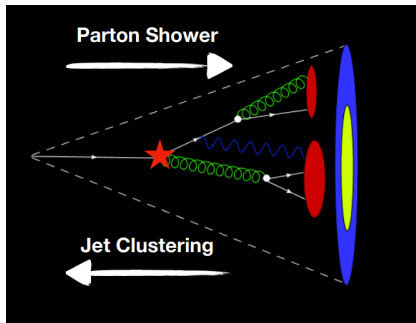


Motivation to study jet substructure at RHIC energies

- Two ways to study the parton shower:
 - Correlation between substructure observables at the first split
 - Evolution of the splitting kinematics as we travel along the jet shower



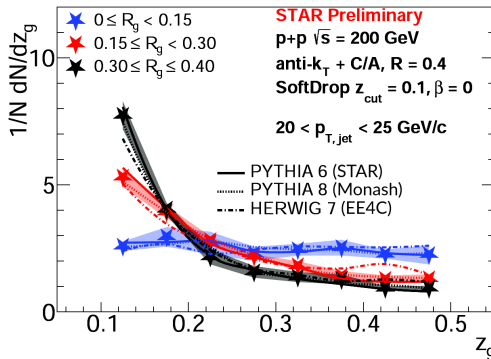
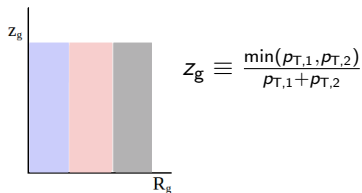
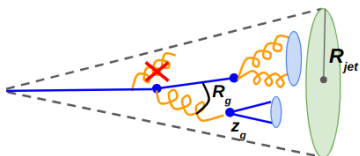
Correlation between substructure observables at the first split



z_g vs. R_g at the first split

RooUnfold

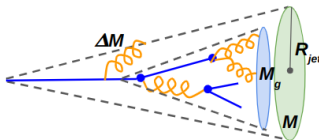
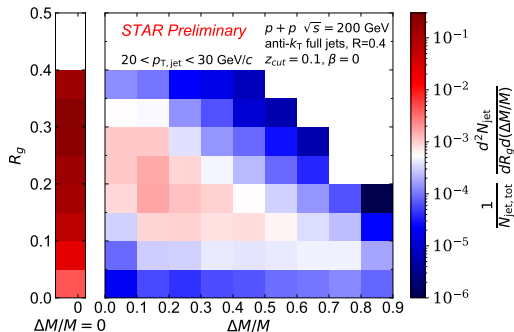
The ROOT Unfolding Framework



- When we move from collinear splitting to wide angle splitting, z_g distribution becomes **steeper** and more **perturbative** ($1/z$ trend of DGLAP)
- MC models describe the trend of the data



R_g vs. $\Delta M/M$ at the first split

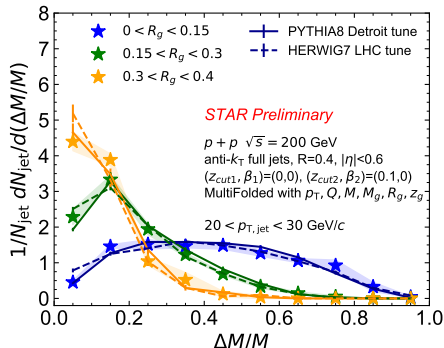
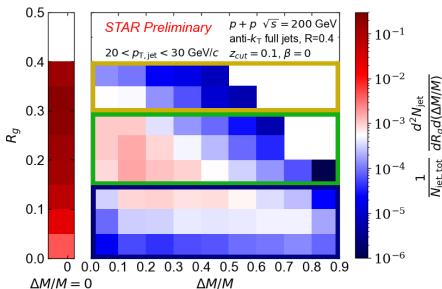


$$\Delta M = M - M_g \text{ [GeV]}$$

- CollinearDrop used to probe soft component of the jet
- Our parameters: $(z_{cut,1}, \beta_1) = (0, 0)$, $(z_{cut,2}, \beta_2) = (0.1, 0)$
- Unfolded with **MultiFold** method



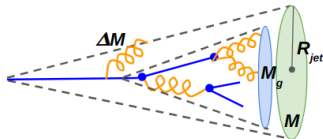
R_g vs. $\Delta M/M$ at the first split



- The $\Delta M/M$ distribution is **anti-correlated** with R_g , which is consistent with angular ordering of the parton shower
- Large groomed jet radius \rightarrow little/no soft wide angle radiation (small $\Delta M/M$) in the shower
- MC models describe the trend of the data

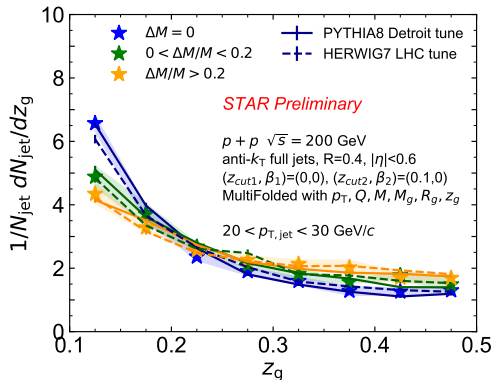


z_g vs. $\Delta M/M$ at the first split



$$\Delta M = M - M_g \text{ [GeV]}$$

- The more mass that is groomed away relative to the ungroomed mass, the **flatter** and more **non-perturbative** the z_g distribution is
- The first splitting that passes SoftDrop can be non-perturbative \rightarrow application of the $\Delta M = 0$ selection can filter out the jets with large non-perturbative contribution

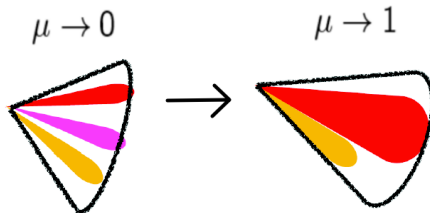
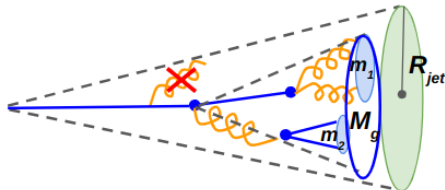


μ vs. R_g at the first split

RooUnfold

The ROOT Unfolding Framework

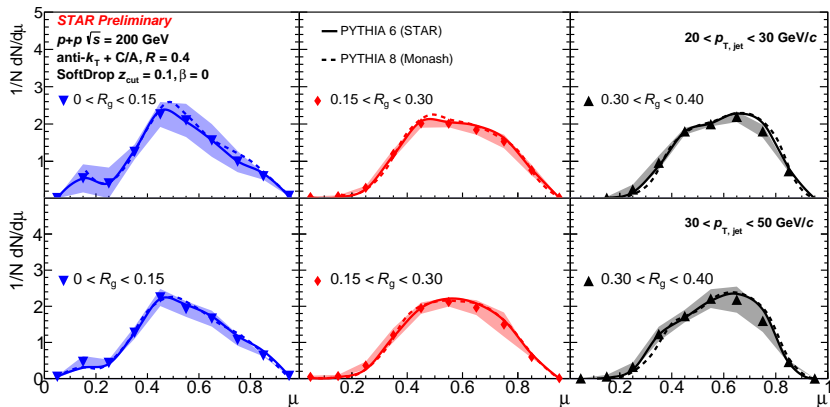
$$\mu \equiv \frac{\max(m_{j,1}, m_{j,2})}{M_g}$$



μ allows us to study mass sharing of the hard splitting



μ vs. R_g at the first split for two different $p_{T,jet}$ bins



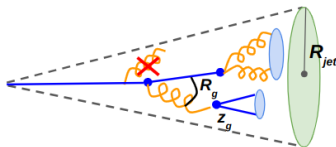
- Dependence on R_g much **weaker** than $\Delta M/M$, largely independent of $p_{T,jet}$, MC models agree with data
- Narrow splits lead to smaller transfer of virtuality or mass



$\log(k_T)$ vs. R_g at the first split

RooUnfold

The ROOT Unfolding Framework



$$k_T = z_g p_{T,jet} \sin R_g$$

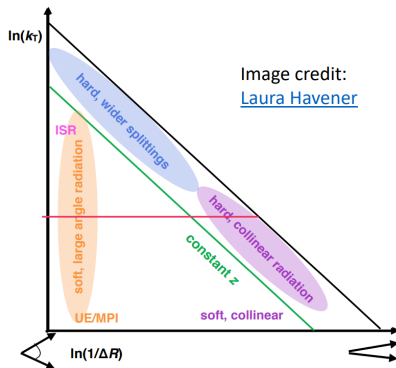


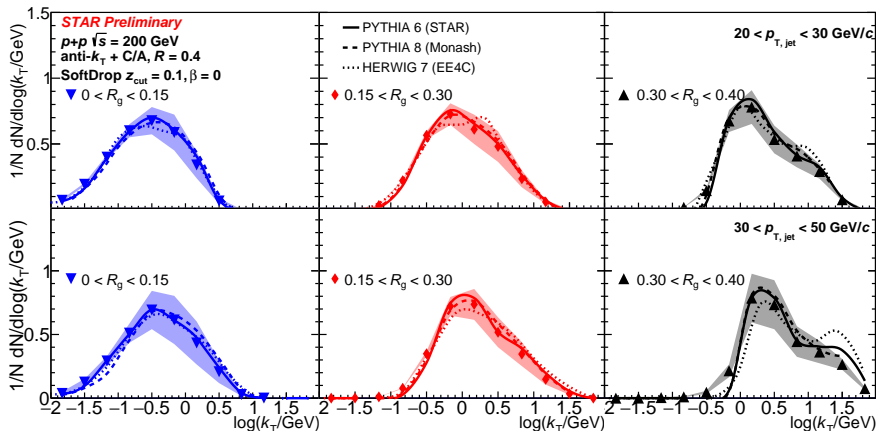
Image credit:
[Laura Havener](#)

ΔR - distance of subjects in the rapidity-azimuth plane
 R_g - first ΔR that satisfies SoftDrop condition

Cutting on R_g moves us to different $k_T \rightarrow$ we are probing different parts of the Lund Plane



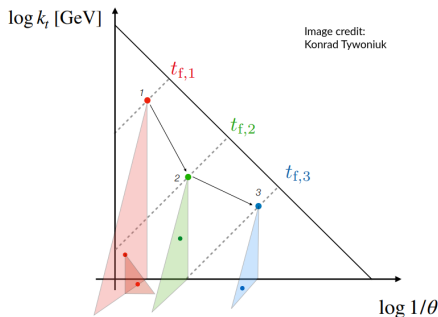
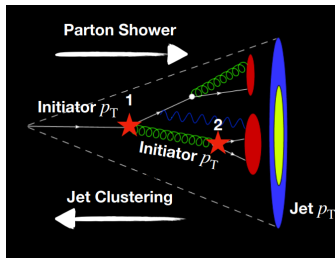
$\log(k_T)$ vs. R_g at the first split for two different $p_{T,jet}$ bins



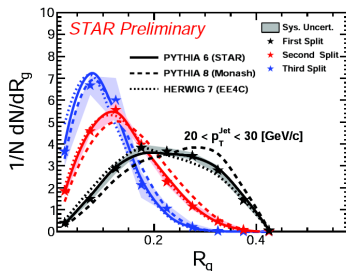
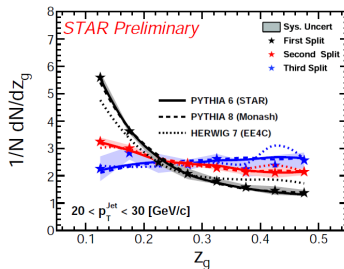
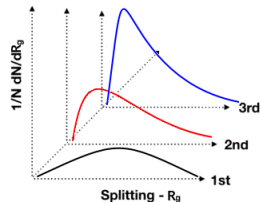
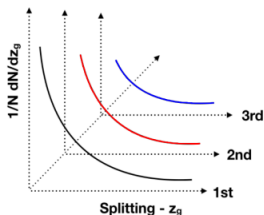
- $\log(k_T)$ has a **strong** dependence on R_g and **weak** dependence on $p_{T,jet}$, MC models describe the trend of the data
- 0 value corresponds to 1 GeV \rightarrow we move from **non-perturbative** to **perturbative** region



Evolution of the splitting observables as we travel along the jet shower



z_g and R_g distributions at 1st, 2nd, and 3rd splits



RooUnfold
The ROOT Unfolding Framework

- Going from 1st → 3rd split
 - z_g distribution becomes **flatter**
 - R_g distribution becomes **narrower**
- Collinear emissions are enhanced when going from 1st to 3rd split



Summary

Correlation at the first split

- New methods for the unfolding were applied (MultiFold, (2+1)D unfolding)
- z_g , $\Delta M/M$, $\log(k_T)$ have a **weak** dependence on $p_{T,\text{jet}}$ and a **strong** dependence on R_g
- Selecting on jet substructure observables and correlations between them allows us to access different regions of the Lund Plane

Splits along the shower

- Observed significantly harder/symmetric splitting at the third/narrow split compared to the first and second splits

Selecting on the split number along the jet clustering tree results in similar change in z_g distributions as selecting on R_g or $\Delta M/M$ at the first split

Jet substructure measurements at RHIC energies allow to disentangle perturbative (early, wide splits) and mostly non-perturbative dynamics (late, narrow splits) within jet showers, and test validity of MC models



Thank you for your attention!



Backup



Jet clustering algorithms

- Jets are defined using algorithms

Anti- k_T algorithm

- $d_{ij} = \frac{\min(1/p_{Ti}^2, 1/p_{Tj}^2)\Delta R_{ij}^2}{R}$, $d_{iB} = 1/p_{Ti}^2$
- Clustering starts from the particles with the highest transverse momentum

Cambridge/Aachen (C/A) algorithm

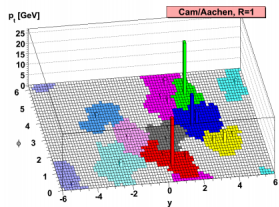
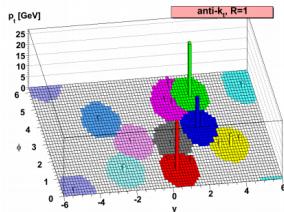
- $d_{ij} = \Delta R_{ij}^2/R^2$, $d_{iB} = 1$
- Particles are clustered exclusively based on angular separation, ideal to be used to resolve jet sub-structure

d_{iB} - distance of the particle i from the beam

p_T - transverse momentum

ΔR_{ij} - distance between the particle i and j

R - jet resolution parameter



Cacciari, Salam, Soyez,
JHEP 0804:063 (2008)



- Grooming technique used to remove soft wide-angle radiation from the jet
- Connects parton shower and angular tree

- 1 Jets are first found using the anti- k_T algorithm
- 2 Recluster jet constituents using the C/A algorithm
- 3 Jet j is broken into two sub-jets j_1 and j_2 by undoing the last stage of C/A clustering
- 4 Jet j is final SoftDrop jet, if sub-jets pass the condition on the right, otherwise the process is repeated



Larkoski, Marzani, Thaler, Tripathee, Xue,
Phys. Rev. Lett. 119, 132003 (2017)

- **Shared momentum fraction z_g**

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \theta^\beta,$$

$$\text{where } \theta = \frac{\Delta R_{12}}{R}$$

- **Groomed radius R_g** - first ΔR_{12} that satisfies SoftDrop condition

$p_{T,1}, p_{T,2}$ - transverse momenta of the subjets

z_{cut} - threshold (0.1)

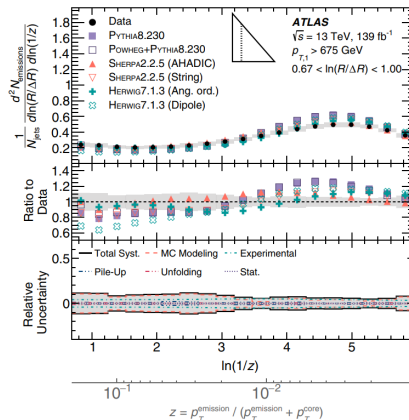
β - angular exponent (0)

ΔR_{12} - distance of subjets in the rapidity-azimuth plane



Lund Plane measurement

- Previous ATLAS measurement uses Lund jet plane
- Significant differences in varying hadronization models at high $p_{T,\text{jet}}$ at the LHC \rightarrow we want to study this at lower $p_{T,\text{jet}}$, where non-perturbative effects are expected to be larger
- While Lund jet plane integrates over all splits, we focus on the first split



ATLAS, Phys. Rev. Lett. **124**, 222002 (2020)



Data analysis

- $p + p$ collisions at $\sqrt{s} = 200$ GeV, 2012
- ~ 11 million events analyzed

Event and track selection

- Transverse momenta of tracks: $0.2 < p_T < 30$ GeV/c
- Tower requirements: $0.2 < E_T < 30$ GeV

Jet reconstruction

- Jets reconstructed with anti- k_T algorithm, reclustered with the C/A algorithm
- Transverse momenta of jets: $15 < p_{T,\text{jet}} < 40$ GeV/c
- Resolution parameters: $R = 0.4, R = 0.6$
- SoftDrop parameters: $z_{\text{cut}} = 0.1, \beta = 0$

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

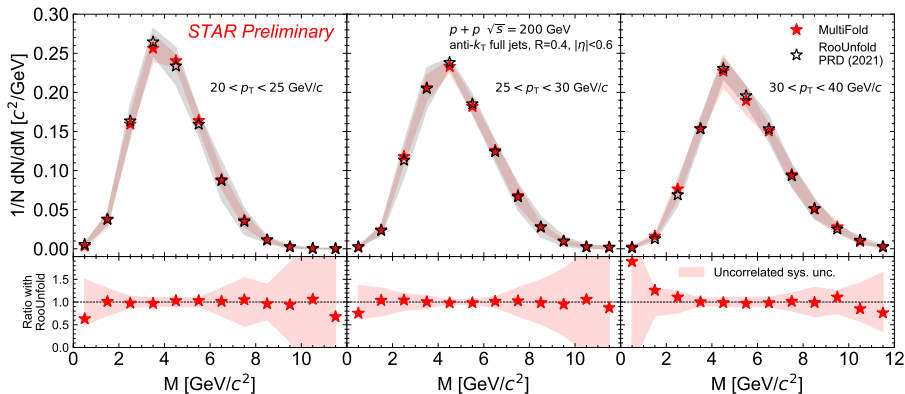


2D Bayesian Unfolding

- 2D iterative Bayesian method implemented in the RooUnfold
- Procedure has following steps:
 - 1 The jets at the detector and particle level are reconstructed separately
 - 2 Jets are matched based on $\Delta R < 0.6$
 - 3 Jets without match - missed jet (particle level) and fake jets (detector level)
 - 4 Response between detector level and particle level for observables is constructed
- We use RooUnfold response which contains Matches and Fakes
 - Unfolding is done separately for p_T^{det} intervals 15-20, 20-25, 25-30, 30-40 GeV/c
- Then unfolded spectra are weighted with values from our projection and put together
- Together with trigger missed and unmatched weighted spectra we get our fully unfolded spectrum



Multifold method for fully corrected jet M

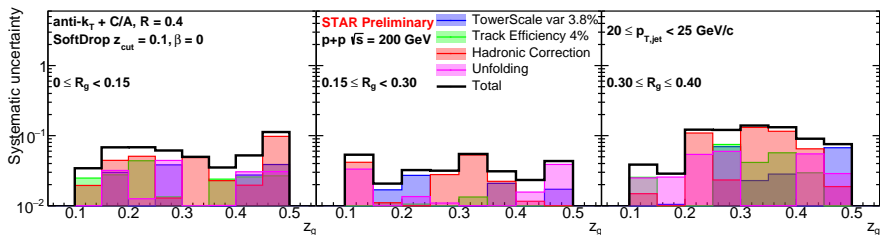


- **Multifold** results agree with **RooUnfold** results (STAR Collaboration. PRD 104, 052007(2021))



Systematic uncertainties

- Systematic uncertainties estimated by varying the detector response
 - Hadronic correction - fraction of track momentum subtracted is varied
 - Tower scale variation - tower gain is varied by 3.8%
 - Tracking efficiency - efficiency is varied by 4%
 - Unfolding - iterative parameter is varied from 4 to 6
- Systematics due to prior shape variation will be included in the final publication



$0 \leq R_g < 0.15$

$0.15 \leq R_g < 0.30$

$0.30 \leq R_g \leq 0.40$

