Recent theory developments on jet substructure

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Overview

"event built from jets" $\Rightarrow$ "jet built from constituents"

"cluster the event into jets"
$\rightarrow$ "cluster jet into subjets"

- tagging
- trimming
- soft-drop
  - + recursive
  - + dynamical
  - includes modified mass-drop
- collinear-drop
- ...

"observables from jets"
$\rightarrow$ "observables from constituents"

- jet mass
- angularities
- energy correlation functions
- jet pull
- Lund plane
- ...

* disclaimer: this is a non-exhaustive and biased list of examples

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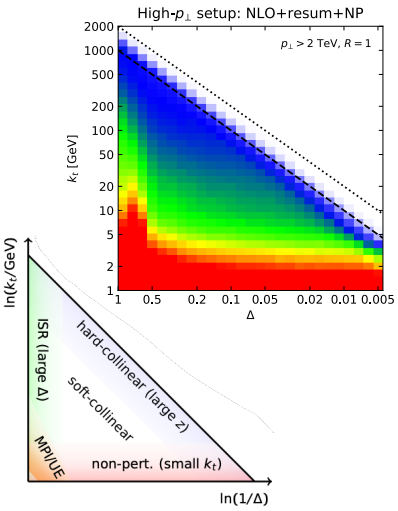
Observables I: The Lund Plane

[Andersson, Gustafson, Lönnblad, Petterson '88]
[Dreyer, Salam, Soyez '18] [Lifson, Salam, Soyez '20]



representation of single emission phase space

→ at LL uniform ⇒ predicted deviations

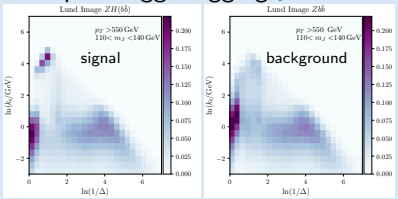
uses:

1. forward: resummed calculations / parton shower building

   e.g. [Gustafson '92] [Hamilton, Medves, Salam, Scyboz, Soyez '20]

2. backwards: map cluster steps of final jets to Lund plane
   ⇒ physics insights to build optimal observables

Example: Higgs tagging [Khosa, Marzani '21]



Similarly:

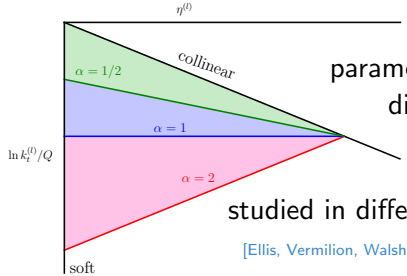
- ▷ quark-gluon jets [Dreyer, Soyez, Takacs '21]
- ▷ b-jets [Fedkevych, Khosa, Marzani, Sforza '22]

Observables II: Jet Angularities

study family of observables

$$\lambda_\alpha^\kappa = \sum_{i \in J} \left(\frac{p_{T,i}}{p_{T,J}} \right)^\kappa \left(\frac{\Delta R_i}{R} \right)^\alpha$$

here: calculations need IRC safety, so $\kappa = 1$



parameter $\alpha \Rightarrow$ probe different kinematic regimes

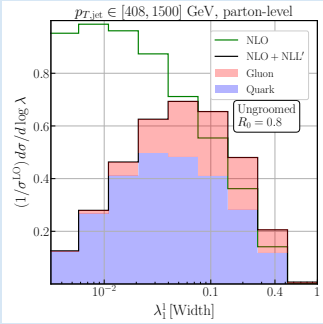
studied in different frameworks

[Ellis, Vermilion, Walsh, Hornig, Lee '10] [Hornig, Makris, Mehen '16]

[Kang, Lee, Ringer '18] [DR, Caletti, Fedkevych, Marzani, Schumann, Soyez → see later]

reuse energy-correlations @ NLL [Larkoski, Salam, Thaler '13] [Larkoski, Neill, Thaler '14] [Banfi, Salam, Zanderighi '04]

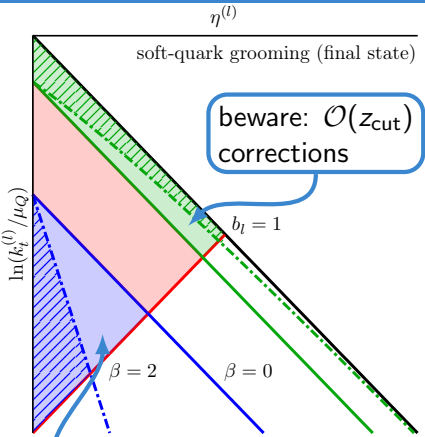
context: [Les Houches 15/17/19] [Larkoski, Thaler, Waalewijn '14]
quark-gluon tagging



Zj @ 13 TeV from [Caletti, Fedkevych, Marzani, DR, Schumann, Soyez, Theeuwes '20]

Soft-Drop: Intro

[Larkoski, Marzani, Soyez, Thaler '14]



method: decluster w/ C/A, remove softer branch if

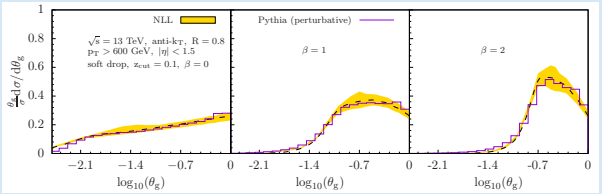
$$\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i}+p_{T,j}} < z_{\text{cut}} \left(\frac{\Delta R}{R}\right)^{\beta}$$

analytical understanding: [Larkoski, Marzani, Thaler '15]

p_T fraction z_g, separation $\theta_g = R_g/R$ of splitting

$\Rightarrow$ using concept of Sudakov safety

calculations available at NLL, NLL′ [Kang, Lee, Liu, Neill, Ringer '19] [Cal, Lee, Ringer, Waalewijn '21]



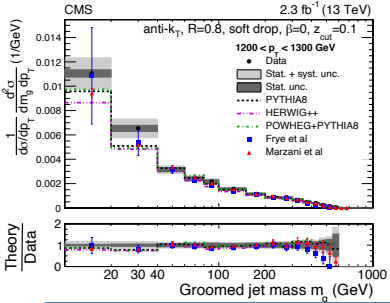
Soft Drop: Application

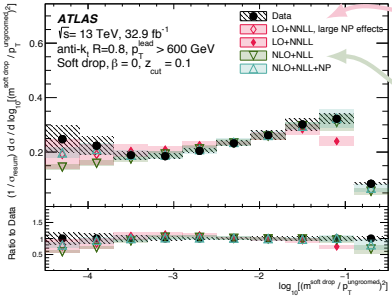
[CMS '18] [ATLAS '17]

procedure:

1. soft-drop groom jet constituents
2. calc standard observable "after grooming"

example: jet mass after grooming





[Frye, Larkoski, Schwartz, Yan '16]

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[Marzani, Schunk, Soyez '17]

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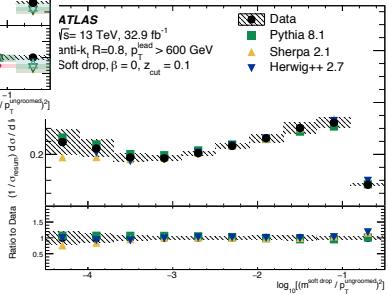


side note: also applicable to global event shapes

[Baron, Marzani, Theeuwes '18], [Marzani, DR, Schumann, Soyez, Theeuwes '19],

even in pp [Baron, DR, Schumann, Schwanemann, Theeuwes '20]

Automated calculations (in the SHERPA framework)

[Gerwick, Höche, Marzani, Schumann '15]
[Baberuxki, Preuss, DR, Schumann '19]

Basic soft gluon resummation

- use well known CAESAR formalism
  [Banfi, Salam, Zanderighi '04]
- master formula for NLL resummation of rIRC safe global observables

Note: similar work in MadGraph using SCET
[Farhi, Feige, Freytsis, Schwartz '15] [Balsinger, Becher, Shao '18]

Jet observable specifics

- modified wide angle behaviour
  [Dasgupta, Khelifa-Kerfa, Marzani, Spannowski '12]
  [Caletti, Fedkevych, Marzani, DR, Schumann '21]
- non-global logs [Dasgupta, Salam, '01]

Automation in SHERPA

- use available technology (PS integration, PDF evaluation etc.)
- interface to COMIX for colour exact insertions in mulit-jet MEs
- final state fully differential in kin. and flavour $\rightarrow$ useful in matching
  [Banfi, Salam, Zanderighi '06] [Banfi, Salam, Zanderighi '10]

Soft Drop grooming effects

- well known in $v \ll z_{\text{cut}} \ll 1$ limit
- CAESAR-style formulas available
  [Baron, DR, Schumann, Schwanemann, Theeuwes '20]

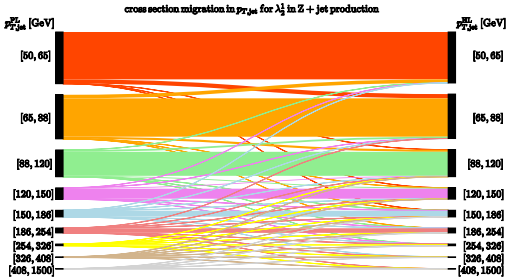
Non-perturbative corrections

[DR, Caletti, Fedkevych, Marzani, Schumann, Soyez '21]

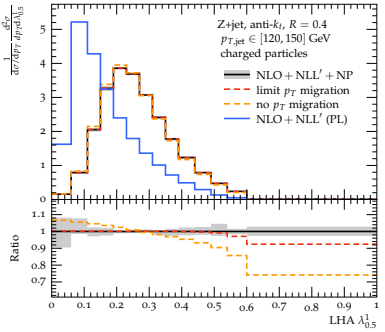
Setup for measurements: (i.e. CMS analysis in JHEP 01 (2022) 188)

- observables (i.e. jet angularities) measured on selected jet (leading p_T, y range etc.)
- In different energy-scale bins (i.e. p_T bin of selected jet)

Physical effects:



shift between p_T bins



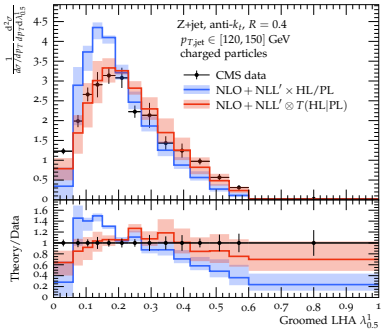
shift in observable

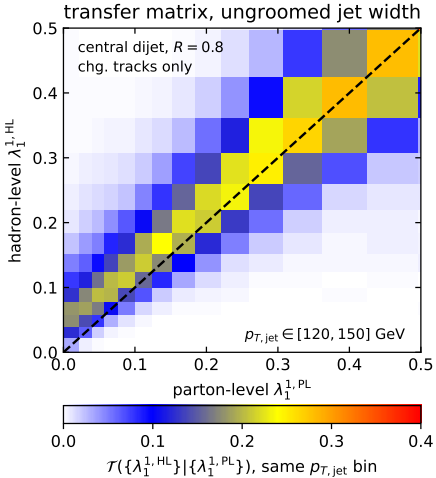
Non-perturbative corrections

[DR, Caletti, Fedkevych, Marzani, Schumann, Soyez '21]

approach:

- define "transfer matrix" according to conditional probabilities
$$\mathcal{T}(v^{\mathrm{HL}}, p_T^{\mathrm{HL}} | v^{\mathrm{PL}}, p_T^{\mathrm{PL}})$$
- easily extracted from MC (here: SHERPA)

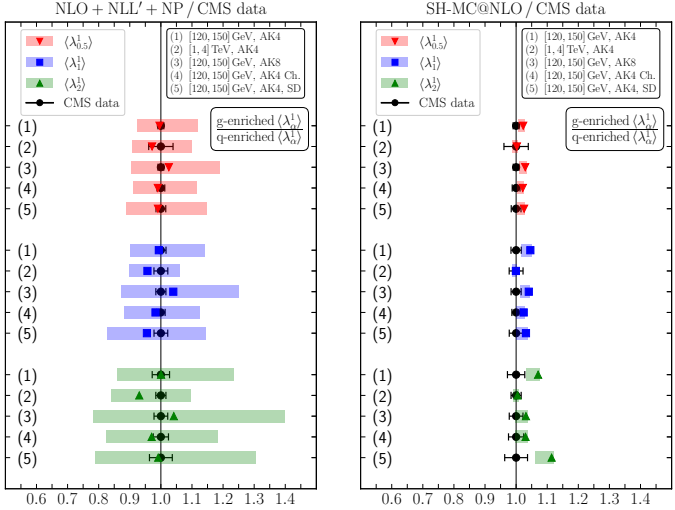




Results

[CMS '21] [DR, Caletti, Fedkevych, Marzani, Schumann, Soyez '21]

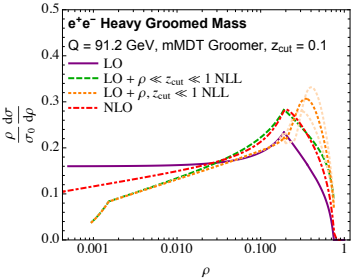
- Z+jet $\sim$ quark jets
- dijet $\sim$ gluon jets
- ratio $\frac{\text{gluon}}{\text{quark}}$ of distribution means
- data well described by MC@NLO and NLO+NLL′+NP
  $\Rightarrow$ challenges traditional "quarks are better understood than gluons"



What next?

Better understanding of soft drop grooming

- resummation around transition point $\rho \sim z_{\text{cut}}$
  [Benkendorfer, Larkoski, '21]
- relax strict $v \ll z_{\text{cut}} \ll 1$ assumption $\Rightarrow$ $v, z_{\text{cut}} \ll 1$
- towards full consistent resummation across full observable range



Non-global logarithms at NLL

- first calculations in [Banfi, Dreyer, Monni '21] [Banfi, Dreyer, Monni '21]
- often neglected piece in NNLL efforts, but last missing piece for automated calculations? (for example in a framework like [Banfi, McAslan, Monni, Zanderight '15])

Summary

- jet substructure as a rapidly growing field
  with close interplay between
  - experiment
  - theory
  - construction of methods
  - Monte Carlo / parton shower development
- examples:
  - jet angularities w/ different parameters as playground
  - soft-drop grooming to eliminate UE/NP corrections $\rightarrow$ increase resummation regime
- Outlook:
  - automated NNLL?
  - range of groomed calculations?
  - NGLs?

Backup