QCD for Lepton Colliders

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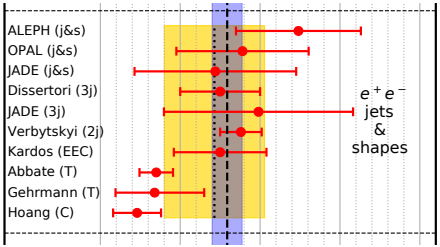
This talk...

- motivation & examples physics cases
- QCD calculations toolkit - analytic resummation and parton showers
- recent developments in parton showers

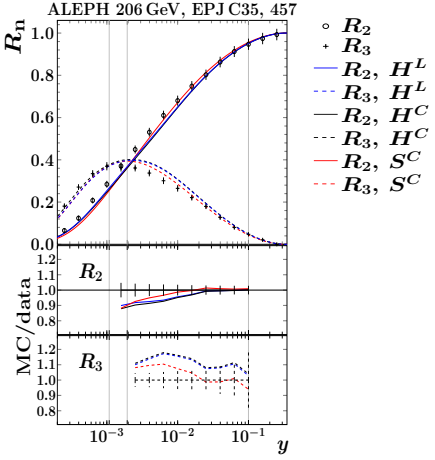
Disclaimer: this will be a biased selection of topics and results

Motivation - Physics - precision α_s



from [PDG '19]

- measurements based on ...
  - ... jet rates and shapes (j& s)
  - ... jet rates (3j)
  - ... resummed Thrust (T)



from [Verbytskyi *et.al.* '19]

- measure α_s from $2-, 3-$ jet rates
- $N^3LO+NNLL$ for 2 jets
- correlations provide additional constraint

Motivation - Physics - fragmentation and tuning

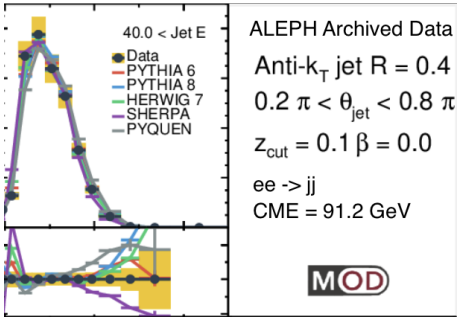
- tuning of hadronisation corrections in MC
  - currently against LEP data (+ UE/MPI tunes w/ Tevatron/LHC data)
  - new precise measurements at Z-pole would naturally complement/replace those
  - possibly feed into next-gen hadron collider (like LEP and LHC)
- Measure fragmentation functions as fundamental quantity

See also Frank Krauss's talk tomorrow

Motivation - Physics - substructure and tagging

- even if no direct QCD study:
  - backgrounds might involve QCD
  - decays might be hadronic
    e.g. $h \to gg$, $h \to b\bar{b}$
- study QCD objects like top quarks
  b-tagging, hadronic W decay channels
- work with jet substructure / tagging techniques
- a lot to learn from LHC

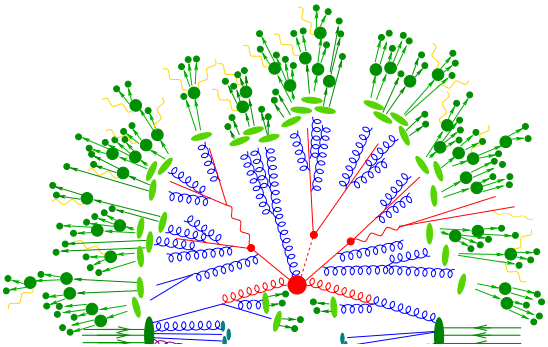
Re-analysis of LEP data [Chen *et.al.* '21]
⇒ possible to validate LHC methods in lepton collider environment



groomed jet mass measurement

QCD - structure of calculation

- Hard process
- QCD radiation
- Non-perturbative
  - hadronisation
  - hadron decays



Factorisation:

$$\frac{d\sigma}{dv} \sim \frac{d}{dv}\,\sigma_{\text{hard}} \otimes e^{-R} \otimes \mathcal{P}(\text{PL} \to \text{HL})$$

Analytic Resummation

Fixed order calculation

- up to NLO fully automated (e.g. CS subtraction)
  NNLO in specialised codes
- progress towards NNLO automation

Resummation

- "direct" e.g. CAESAR (NLL), ARES (NNLL)
- SCET, typically highest accuracy

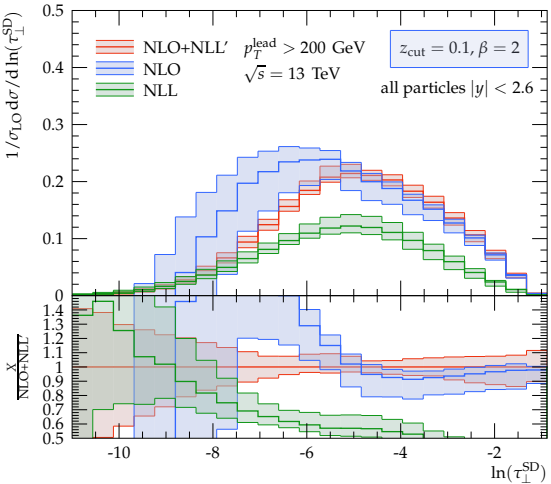
Matching

- $\Sigma_{\text{match}} = \Sigma_{\text{fo}} \oplus \Sigma_{\text{res}} \ominus \Sigma_{\text{res}}|_{\text{fo}}$
- several schemes, "additive", "multiplicative", "logarithmic" may achieve different accuracy

Hadronisation

- Shape functions
- MC based hadronisation

Resummation - Example



Parton Showers

Hard process

- up to NLO fully automated
  (e.g. CS subtraction)
  NNLO in specialised codes
- first approaches for N^3LO

Resummation

- Parton showers
  - angular ordered
  - dipole / antenna
- NLL (?!) accurate
- progress towards NNLL

Matching

- $\Sigma_{\text{match}} = \Sigma_{\text{fo}} \oplus \Sigma_{\text{shower}} \ominus \Sigma_{\text{shower}}|_{\text{fo}}$
- Powheg, MC@NLO, KrkNLO

Merging

- include higher multiplicities

Hadronisation

- Lund String Model
- Cluster Model

Parton Showers - LHC work horses

- Herwig 7
  - angular ordered and dipole parton shower
  - internal matching
- Pythia 8
  - p_T ordered shower, DIRE and VINCIA showers
  - matching via externally, e.g. via MadGraph/Powheg
- Sherpa
  - CSShower, DIRE, Alaric
  - internal MC@NLO style matching
- See also [Buckley *et. al.* '19]
- General purpose tools, should be ready for lepton collider physics

Parton Showers - current accuracy

- naive expectation: α_s in CMW scheme $\Rightarrow$ NLL accuracy
  (at leading color / neglecting spin correlations)
- correct for global observables in angular ordered shower
- most recoil schemes in dipole showers violate this

  [Dasgupta, Dreyer, Hamilton, Monni, Salam '18]
- developments in the major shower programs to address this:

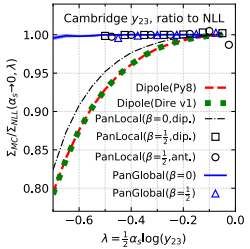
  [Bewick, Ferrario-Ravasio, Richardson, Seymour '19]

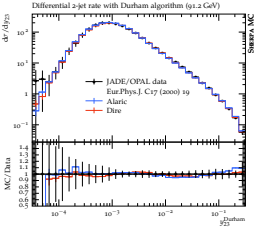
  [Dasgupta, Dreyer, Hamilton, Monni, Salam '20]

  [Forshaw, Holguin, Plätzer '20]

  [Herren, Höche, Krauss, DR, Schönherr '22]
- + residual effects at physical working point

  [Höche, DR, Siegert '17]





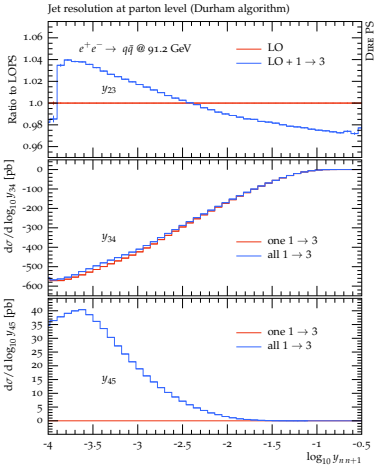
Parton Showers - towards NNLL

- include NLO splitting kernels / understand structure and relation to NNLL resummation
- efforts in several collaborations to...
  - ...implement triple collinear splitting functions

    [Höche, Prestel '17] [Höche, Krauss, Prestel '16] [Gellersen, Höche, Prestel '21]
  - ...study structure and relation to analytic results

    [Dasgupta, El-Menoufi '21] [Braun-White, Glover '22]
  - ...rethink existing structures

    [Löschner, Plätzer, Simpson Dore '21]



from [Gellersen, Höche, Prestel '21]

Summary

- QCD aspects relevant at lepton colliders
- analysis techniques: learn from LHC
- standard: NLO+NLL
  + critical evaluation of PS logarithms
- steps towards NNLL accurate showers
- some things not covered:
  - progress in fixed order calculations, automation of NNLO subtraction and PS matching to NNLO, N^3LO
    $\Rightarrow$ NNLO+NNLL probable standard on time scale of future colliders
  - significant amount of work on colour accuracy and spin correlations in parton showers

Backup