Hadronization Models and their Uncertainties

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- why should we care?
- hadronization models
- tuning & data
- summary

why should we care?

motivation: precision era at the LHC

- entering percent precision era at LHC:
  - huge phase-space coverage of large variety of observables
  - $\text{NNLO}_{(\text{QCD})}$, $\text{NLO}_{(\text{QCD})}\otimes\text{NLO}_{(EW)}$(approx) & $\text{NLO}_{(EW)}$ (exact) becoming the new baseline precision for many observables
  - rough estimate of uncertainities: $(\alpha_S/\pi)^2 \simeq 1\%$
- but how about sub-leading twist?
  - reminder: use collinear factorization, assume m_p/Q small
  - typical precision scale $Q \simeq M_Z$: $m_p/m_Z \simeq 1\%$
  - typical manifestations: MPI, hadronization, ...

soft physics effects may dominate theory uncertainties in (some) observables relevant to precision era at LHC

hadronization models:
a bird's eye view

underlying principles

- confinement through QCD linear potential:
  - known from lattice and fits to quarkonia masses
- local parton-hadron duality paradigm:
  - flow of hadronic quantum numbers (observable) $\simeq$ flow of partonic quantum numbers (calculable)
- space-time picture of strong interactions:
  - parton formation time vs. hadronization time
- common denominator: large N_c limit

i.e. for each color there is eactly one traceable anti-colour

introduce diquarks qq ($+q \to$ baryons) as colour anti-triplets

string fragmentation

- driver: linear QCD potential (flux-tube)
- produce colour singlet objects (strings): $\bar{q} - g - g - \cdots - g - g - q$
- iteratively split strings from their end: string $\to$ string + hadron
  - uniform kinematics
    $k_\perp \propto$ Gaussian: $\mathcal{P}(k_\perp) \propto \exp(-\pi k_\perp^2/\sigma^2)$
    $k_\| \propto$ string fragmentation function $f(z) \propto z^{-1}(1-z)^a \exp(-bm_\perp^2/z)$
    (can use other forms of $f(z)$ for heavy flavours)
  - select quark (diquark) according to “popping” probability
  - select hadron with wave functions and multiplet weights
- first wave of (unstable) hadrons will decay further
- implemented in PYTHIA, i.m.o. the best hadronization model

cluster fragmentation

- driver: local parton-hadron duality
- forcibly decay gluons $g \to q\bar{q}$ and form neutral clusters
- iteratively decay clusters into hadrons or clusters
  - kinematics may depend on decay mode (SHERPA)
    $k_\perp \propto$ of new quark pair according Gaussian
    $k_\parallel \propto$ fragmentation function $f(z)$ on "either" side

    (parametrization depends on light/heavy quark and mass)
  - select quark (diquark) according to "popping" probability
  - select hadron with wave functions and multiplet weights
- first wave of (unstable) hadrons will decay further
- implemented in two different versions in HERWIG and SHERPA

tuning & data

tuning framework

- (semi-)automated tuning with **PROFESSOR**
- based on analyses **available in RIVET**
- in principle multi-step process:
  - dynamics of string/cluster break-up
  - "popping" probabilities/pop-corn
  - multiplet weights (like vector vs. pseudoscalars)
- user selects relevant data/bins
- possible extraction of uncertainties from "eigen"-tunes

practical realization

- **hadronization tuning** entirely **dominated by LEP I** (and to a very little amount, SLD)
- typical observables:
  - event shapes ⟶ dynamics
    (trust, major, minor, . . .)
  - (differential) jet multiplicities ⟶ dynamics
    (differential jet multis, . . .)
  - single-particle distributions ⟶ dynamics, popping
    (x_P for charged/hadron species, dependent on primary quarks. . .)
  - fragmentation functions ⟶ dynamics
    (especially B fragmentation (from SLD))
  - (PDG) hadron multiplicities ⟶ popping & multiplets
    (especially K, p, . . . ; possibly also ratios w.r.t. $\pi^\pm$)

practical limitations

- only one $E_{\rm cms}$ in e^+e^-:
  $\longrightarrow$ no significant handle on energy extrapolation
  (only very few measurements from, e.g., JADE, TASSO available in RIVET, with limited reach and statistics)
  $\longrightarrow$ data from BELLE 2 would help a lot!!!
- LEP dominated by quark jets:
  $\longrightarrow$ questionable handle on details of gluon fragmentation
  (examples: enhanced diquark-popping? (leading) baryons? realisation of LPHD in gluons?)
  $\longrightarrow$ hadron "chemistry" of jets at TEVATRON/LHC?
  (maybe use low-lumi runs and known q/g ratio in inclusive jets, tops, W/Z + jet?)
- LEP has no initial hadrons:
  $\longrightarrow$ no handle on beam fragmentation
  (also: impact of energetic source of colour on energy/particle flows)
  $\longrightarrow$ use data from HERA/LHCf for tune
  (but: existing analyses need to be put into RIVET— and used by "tuners")

one more limitation

- impact of HI environment a hard problem
  - notable absence of models
    exception: rope model in DIPSY (see T.S. talk yesterday)
  - tricky interplay with a lot of other physics effects
    (not sure how to define a strategy for systematic extraction)
  - data situation is critical

(it seems there is not a big repository like HEPDATA/RIVET for collaborations beyond ALICE)

consequences

- for ongoing *pp* analyses we need to discuss uncertainties
    - all hadronization models tuned to same data, often with the same tools, typically aiming to reproduce them
    - so: how do we assess uncertainties?
      current: run a handful of PYTHIA tunes or PYTHIA vs. HERWIG
    - I am not sure that this is very systematic
- for *AA* collisions
    - define a program of critical measurements
      (e.g. ratios of particle correlations, w.r.t. *pA*, *pp*)
    - combine with RHIC/HERMES/fixed target(?)/... data?
      (and discuss impact on EIC/LHeC etc.)

summary

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- hadronization is (still) an unsolved problem (no surprise)
- there is a good chance that it will become a limiting factor for the analysis and interpretation of precise data and their uncertainties
- while I have focused on hadronization, this is certainly also true for MPI, interplay with diffraction, colour reconnections . . .