Measurements to Improve Hadronization Models

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

why should we care?

motivation: it's all about precision

- anticipated (perturbative) theory precision: $\leq 1\%$ (personal take!)
    - at least $\mathcal{O}(\alpha_S^3)$ corrections for QCD event shapes
    - at least $\mathcal{O}(\alpha_S^2)$ corrections for QCD final states with up to four jets

      (I think we'll see the first of such calculations in the next 2-3 years)
    - systematic inclusion of $\mathcal{O}(\alpha_{EW})$ in a multiplicative scheme and a lot of mixed $\mathcal{O}(\alpha_S\alpha_{EW})$ corrections
    - NNLL parton shower matched to NNLO QCD
- bottlenecks (if any):
    - treatment of massive particles in parton shower
    - Bhabha scattering at $\mathcal{O}(\alpha^3)\otimes$ resummation for $m_e \neq 0$ (luminosity)
    - photon-photon physics (PDFs, underlying event)

soft physics effects may dominate theory uncertainties:
no first-principles theory $\longrightarrow$ must measure!

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 $d_{qq'}$ $(+q \to$ baryons) as colour anti-triplets
- $\mathcal{O}(10)$ parameters to be fitted to (mainly LEP) data:
  - event shapes, jet rates, fragmentation functions, particle yields, ...

string fragmentation

- driver: linear QCD potential (flux-tube)
- implemented in PYTHIA, i.m.o. the best hadronization model
- 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

cluster fragmentation

- driver: local parton-hadron duality
- implemented in two different versions in HERWIG and SHERPA
- forcibly decay gluons $g \to q\bar{q}$ and form neutral clusters

  (in SHERPA: also $g \longrightarrow d_{qq'}\bar{d}_{\bar{q}\bar{q}'}$)
- iteratively decay clusters into hadrons or clusters
  - kinematics may depend on decay mode (SHERPA)
    $k_\perp \propto$ of new quark pair according Gaussian
    $k_{||} \propto$ 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

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

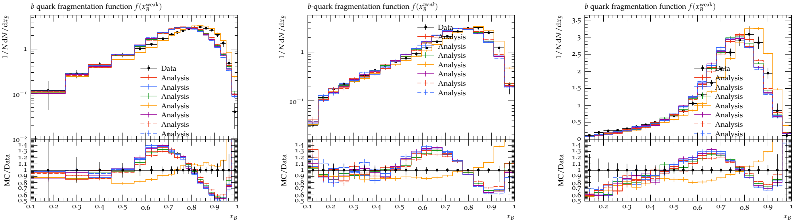
practical realization

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

a data issue

- disagreement in *b*-quark fragmentation measurements

(look at results from ALEPH, OPAL, SLD ⟶ need to chose one!)



“missing” pieces: gluon fragmentation (1)

- $g \to Q\bar{Q}$ splitting tricky in parton showers

  (no soft enhancement, coll. divergence shielded by masses)

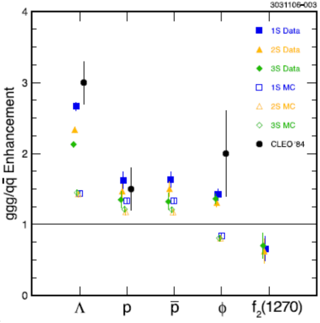
  - HF production is perturbative process
  - analyse $4b$ and $2b2c$ final states
    combine two softest equal flavour HFs into “gluon” and measure the $g \to Q\bar{Q}$ splitting function
    will yield information about shower evolution parameter and correct scale definition for α_S

“missing” pieces: gluon fragmentation (2)

- e^-e^+ (like LEP) dominated by quark jets:
  $\longrightarrow$ questionable handle on details of gluon fragmentation

(examples: enhanced diquark-popping? (leading) baryons? realisation of LPHD in gluons?)

- measurement strategy:
  - “Mercedes star” with two id’d heavy quark jets
    $\longrightarrow$ third jet is gluon jet
  - jet-shape measurements: sub-jettiness & friends
  - hadron yields inside jet
  - leading hadron identity/x_p
  - di-baryon/di-strange correlations inside jet

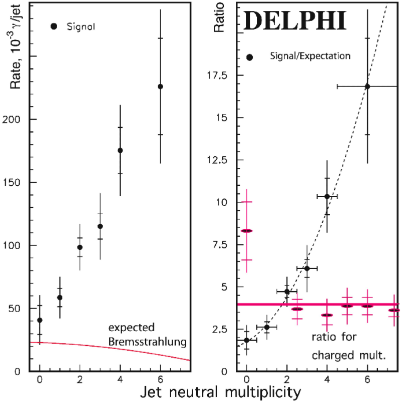


“missing” pieces: the riddle of the soft photons

- expect 0.02 photons/jet using isolation cuts

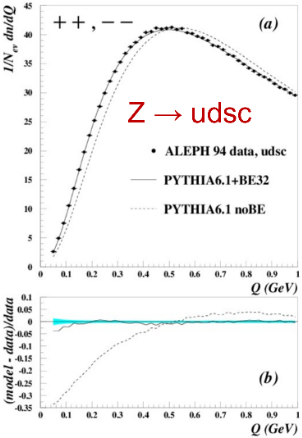
  (from Bremsstrahlung)

- but: multiplicity # of neutral hadrons
  - dipole emissions?
  - radiation off quarks during hadronization?



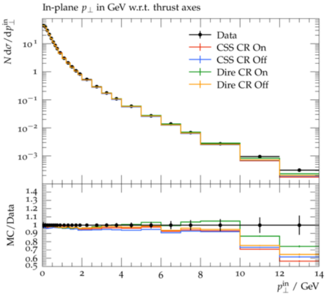
"missing" pieces: BE effects

- quantum statistics of identical particles
  (produced at same point)
- so far only implemented in PYTHIA
  (model dates back to 80's or so)
  - implemented as classical shift
  - four-momentum conservation (?)
- results ($Q^2 = -(p_i - p_j)^2$)



"missing" pieces: colour reconnections

- source of uncertainty in W-mass measurements at LEP in fully hadronic events
- various implementations in HERWIG, PYTHIA, SHERPA, but: no idea how to systematically test it in $Z/\gamma^* \to q\bar{q}$



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
- necessitates a dedicated QCD programme at a future e^-e^+ collider