Focus Topic BCfrag – Gsplit

ECFA Higgs/Top/EW Study WG1-PREC conveners:

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The topic(s)

- BCFrag:
  - Measurement of b- and c-fragmentation functions and hadronization rates (√s =MZ and beyond)
- Gsplit:
  - Measurement of gluon splitting to bb / cc, interplay with separating h → gluons from h → bb/cc (√s = MZ and beyond)

The expert team

- Eli Ben-Haim (LPNHE-IN2P3 France),
- Loukas Gouskos (CERN),
- Simon Plaetzer (Graz University, Austria)
- Andrzej Siodmok (CERN)
- Torbjorn Sjostrand (Lund University, Sweden)
- Maria Ubiali (Cambridge Universty, UK)
- Manqui Ruan (IHEP, China)
- +WG1-PREC conveners

Our meetings

- BCFrag / GSplit Expert Team, 1st meeting, 31 August 2023
  - https://indico.cern.ch/event/1318673/
- BCFrag / GSplit Expert Team, 2nd meeting, 3 October 2023
  - https://indico.cern.ch/event/1332815/

Relation with others focus topics: TwoF

- Z to b/c (and all fermion) couplings
  - Via AFB (and variants as ALR, AFBLR, etc), Rb,Rc… observables
- FC runs at the Z-pole with high statistics (order of magnitude better than at LEP/SLC)
  - Could be a limiting factor at TeraZ luminosities ?

- The TwoF discussion has been scheduled just before this one
  - Organized by ECFA-WHF-WG1-HTE-conveners@cern.ch

Relation with others focus topics: Wmass

- Precise determination of W -mass and cross section:
  - Precisions at the MeV level are expected
- At LEP2, the modelling of non-perturbative QCD effects in the W boson hadronic decays was a dominant source of systematic uncertainties.
  - Newer theory and experimental studies are required to estimate the size of such uncertainties in future colliders
- This issue is discussed in the W mass focus topic
  - Organized by ECFA-WHF-WG1-PREC-conveners@cern.ch

Relation with others focus topics: HtoSS

- Precise study of $h \rightarrow gg/b\bar{b}/c\bar{c}$: Future Higgs Factories will enable the exploration of the second generation of Yukawa couplings and the highest precision
  - However, current uncertainties on gluon splitting into heavy quarks would introduce large systematic uncertainties in the measurements.
- How to estimate them?
- How to minimize them?

- This issue is discussed in the HtoSS focus topic
  - Organized by ECFA-WHF-WG1-HTE-conveners@cern.ch

Overview -1

BCFrag & GSplit are key topics on the physics modelling of many processes (source of systematic uncertainties on some measurements)

- Revision of the state of the art
- What theory developments are needed (and/or envisioned) to further reduce these uncertainties ?
  - At future but also current experiments (and past ones!)
- **FC will push the precision boundaries**
  - Fragmentation functions may not be universal but observable dependent

Overview -2

- It is argued that factorization of perturbative and non-perturbative parts of the process is not possible without dedicated tunning of free parameters of the fragmentation→ precision limitation??-
  - Ongoing developments in disentangling hadronization&fragmentation → new work in NLL accurate showers is needed
- Special challenges with heavy quarks (b/c)
  - The splitting of gluons into $b\bar{b}/c\bar{c}$ is only modelled in the perturbative step of the process (not in the string/cluster fragmentation) but still, charm and bottom masses are parameters in the shower.

List of observables

- A list of observables it is been collected (some listed in the back-up) and will be added to the Focus-Topic document.
  - Want to contribute? Contact-us

These should be applied to test

- new fragmentation models
  - Using old data from LEP/SLC? Usage of such data for new analysis is always challenging… It will require new efforts on “translation” of data to newer formats/frameworks/environments such that are usable for Key4HEP users
- Detector models/analysis methods tools
  - Large tracker acceptance is needed as well as very good vertexing and flavour tagging capabilities (including light quark s and gluon quarks)
  - Jet charge measurements including charge hadron identification capabilities (see above).
  - Samples for hadronic observables using different hadronization models and parameters. Full simulation required to understand flavour tagging capabilities.
  - Existing tools are e.g. the generators Pythia, Herwig, Sherpa and the tuning tools Professor, Rivet

- Event shapes, angular distributions
- Inclusive B/D particle (mesons + baryons) production cross section
  - ee: primary production is well known from theory, so the "excess" is from gluon splitting
  - pp: combines primary production, gluon splitting, and MPI (multiparton interactions) contributions, each with significant theoretical uncertainties
- Flavour composition, as far back in decay chains as can be traced (even equal D^{*0} and D^{*+} rates gives unequal D^0 and D^+ ones)
  - ee: we do not expect sizeable momentum dependence, but interesting to contrast mesons and baryons for smaller ones
  - pp: significant p_T dependence observed and to be studied further, also high- vs. low-multiplicity events, rapidity, ..., which is important for development/tuning of colour reconnection models
- Particle-antiparticle production asymmetries
  - ee: none expected, except tiny from CP-violation in oscillations
  - pp: asymmetries expected and observed from p flavour content, increasing at larger rapidities; relates to how string (and cluster?) fragmentation connects central rapidities to beam remnants

- Momentum spectra
  - ee: dn/dx_E where $x_E = 2E_{had}/E_{cm}$; basic distribution for tuning of "fragmentation function"
  - pp: dn/dp_T and dn/dy give basic production kinematics, but the many production channels gives less easy interpretation
- Energy flow around B/D hadron, excluding this hadron itself, as a test that dead cone effects are correctly described
  - ee: $dE/d\theta$ where theta is distance from B/D on the sphere
  - pp: dp_T/dR where R is distance in (η, ϕ) or (y, ϕ) space, only applied for B/D above some p_T threshold
- B/D hadron fraction of total E or p_T in a jet, with $x = p_T^{had}/p_T^{jet}$, as a test of the fragmentation function combined with almost collinear radiation, suitably for some slices of p_T (and in addition with a veto that no other B/D should be inside the jet cone, so as to suppress the gluon splitting contribution).

- Distribution in number of reconstructed B/D hadrons, as a measure of how often several pairs are produced
- Separation inside B/D pairs, where large separation suggests back-to-back primary production, while small separation suggests gluon splitting
  - ee: separation in θ
  - pp: separation both in ϕ and in R, since for primary production $\phi = \pi$ is hallmark with η/y separation less interesting, while gluon splitting means R is small while ϕ and y/η individually are less interesting
- Hardness difference within (reasonably hard) pairs, $\Delta = (p_T^{max} - p_T^{min})/(p_T^{max} + p_T^{min})$, where for gluon splitting $x^2 + (1-x)^2$ translates to $1 + \Delta^2$
  - ee: separately for small or large θ
  - pp: separately for large or small ϕ
- For a pair with small separation, say $\theta/R < 0.7$, draw a cone around the midpoint of the two, say again $\theta/R = 0.7$, and find the fraction $x = (p_T^{had,1} + p_T^{had,2})/p_T^{jet}$, to quantify loss to showers and hadronization. This loss would be reduced if colour reconnection often would make the $b\bar{b}$ or $c\bar{c}$ into a singlet, rather than the default octet where the two fragment separately.

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– In events with two B/D pairs, many observables become possible. There are four possible particle-antiparticle pairs (more if $B\bar{B}$ mixing is taken into account), each of which can be studied according to the two points above. In addition, a pair with a small separation would suggest a gluon splitting, while one with a large ditto a primary production. For pp, two back-to-back pairs would suggest MPI. One can try to classify events into most likely history and study relative composition of (a) two separate hard processes (MPIs, pp only); (b) one hard process and one gluon split; (c) two gluon splits on same side of the event; and (d) two gluon splits on opposite sides.

– Even if one B/D is missed in pp, so that only three B/D are observed, one can study the three pairings, and see whether either pair has a small R or a large ϕ. Again relative rates will provide info on the composition of production mechanisms.