ECFA future e+e- BCFrag/GSplit topics

ECFA WG1-PREC conveners

Adrián Irles
Andreas Meyer
Ayres Freitas
Paolo Azurri
Fabio Maltoni (WG1 coordinator)

Expert team:

Eli Ben-Haim
Maria Ubiali
Andrzej Siodmok
Simon Plaetzer
Loukas Gouskos
Torbjörn Sjöstrand

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BCFrag: Measurement of b- and c-fragmentation functions and hadronisation rates

What?

- Insufficient knowledge of hadronisation and fragmentation of heavy quarks could introduce significant systematic uncertainties → for example in AFB (b/c) arXiv:2010.08604

Theory and pheno targets

- Are existing hadronization models (strong fragmentation, cluster fragmentation) flexible enough, or do we need new ideas?
- Identify calibration observables that are well understood theoretically and unaffected by BSM physics.
- See also https://indico.desy.de/event/33640/contributions/130328/attachments/77658/100472/ECFA22_Hadronization.pdf

Theory and pheno targets:

- Event shapes, angular distributions
- Fragmentation functions
- Specific observables, i,.e.
    - mW,
    - AFB(b,c) (at Z-pole and above)

Gsplit Measurement of gluon splitting to bb / cc, interplay with separating h → gluons from h → bb/cc

What?

- Insufficient knowledge of gluon splitting to heavy quarks could introduce significant systematic uncertainties in precision Higgs and electroweak measurement

Theory and pheno targets

- How to consistently implement gluon splitting in parton shower tools (modelling and free parameters

target physics observables

- 3/4-jet events with multiple heavy quark ids.
- Jet subtructure observables with hadron tags inside jet.

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Minutes of first meeting, 2023/08/31

Participants:

Eli Ben-Haim <benhaim@in2p3.fr>
Maria Ubiali <mu227@cam.ac.uk>
Andrzej Siodmok <a.siodmok@cern.ch>
simon.plaetzer@uni-graz.at <simon.plaetzer@uni-graz.at>
Loukas Gouskos <Loukas.Gouskos@cern.ch>
Torbjörn Sjöstrand <torbjorn.sjostrand@hep.lu.se>
&
Adrián Irles
Andreas Meyer
Ayres Freitas
Paolo Azurri
Fabio Maltoni

Notes:

Torbjorn - discussing slides 6/7 of his presentation: Fragmentation cannot be described as a convolution of a perturbative matrix element and a fragmentation function f(z) with $0<z<1$. In string fragmentation, color strings stretching between partons cause acceleration and produce a *hardening* of the hadron spectra at high energies.
Needs fragmentation model. There will still be free parameters, which we may have to determine ad hoc.

Ayres - Q: Are the currently used frameworks flexible enough (after adding more mesons than currently implemented in e.g. Pythia) to be precise/accurate enough for observables with sub-permille precision?
Simon: maybe rather ask can we reach accuracy ?

Ayres - Q: Are fragmentation functions universal, or do they depend on types of observables?
Eli: but parameters will not be universal.

Simon: modeling developments in disentangling hadronisation and fragmentation.
Cross-talk between parton shower and fragmentation. New work needed for NLL accurate showers.

Paolo - Q: Can the LHC data be used to test new and more accurate models in a way that help for the future e+e- measurements ?

Torbjorn: The environment is quite different. Charm and bottom production rates at LHC are not precisely known.
do we know the total c and production rate?
can we trust the extracted fragmentation functions ?
But something could maybe still be done (e.g. amount of non-B hadron activity in a cone around a B hadron).

Ayres -Q: is gluon splitting and quark fragmentation fundamentally different, conceptually ?
- Sjostrand:
Gluon splitting into cc/bb only in the perturbative (parton shower) region, not in the string/cluster fragmentation. But need to ask how to account for charm/bottom masses in the shower.
- in the string model, the nonpert. step does not add additional c or b.
everything is from pert. stage.
- one example of an uncertainty is alphas, where the in the limit of pt=0,
heavy quarks can still be treated, but for gluons everything is different.

Simon: Do we need to consider multi-parton fragmentation functions? It could be formulated in a theoretically rigorous framework, with factorization, but may be very complicated.
Useful data input: correlations among hadrons, Lund-plane observables
Transition shower to hadronization is a fuzzy one.
- we are at the start of exploring fragmentation/hadronisation, effect
- use LHC data, e.g. ALICE to test correlations between different heavy quarks.
(small-angle
Adrian:
- make a list of relevant observables (for the future ee collider) for which these things are relevant.

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Examples of observables (list made by Torbjörn Sjöstrand)

Examples of Bfrag/Gsplit observables:

Approximately ordered in terms of increasing differentiation,
as viewed by a theorist, disregarding experimental complications.
In reality, several measurements would be intertwined.

"EpT" will be used as shorthand for E or pT hardness variable of
particle, the former normally for e+e- and the latter for pp.

*** Inclusive B/D particle (mesons + baryons) production cross section**
- e+e-: primary production well known from theory,
  so "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 D0 and D+ ones)
- e+e-: we do not expect sizeable momentum dependence, but
  interesting to contrast mesons and baryons for smaller ones
- pp: significant pT 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**
- e+e-: 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**
- e+e-: dn/dx_E where x_E = 2E_had / E_cm;
  basic distribution for tuning of "fragmentation function"
- pp: dn/dpT 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**
  - e+e-: dE/dtheta where theta is distance from B/D on the sphere
  - pp: dpT/dR where R is distance in (eta, phi) or (y, phi) space,
    only applied for B/D above some pT threshold

* **B/D hadron fraction of total E or pT in a jet, with**
  x = EpT_had / EpT_jet, as a test of the fragmentation function combined with almost collinear radiation, suitably for some slices of EpT
  - e+e-: draw a jet cone in theta around B/D and measure x
  - pp: draw a jet cone in R around B/D and measure x

* **As above, but 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
  - e+e-: separation in theta
  - pp: separation both in phi and in R, since for primary production
    phi = pi is hallmark with eta/y separation less interesting,
    while gluon splitting means R is small while phi and y/eta
    individually are less interesting

* Hardness difference within (reasonably hard) pairs,
  Delta = (EpT_max - EpT_min) / (EpT_max + EpT_min),
  where for gluon splitting $x^{\wedge 2} + (1 - x)^{\wedge 2}$ translates to $1 + \mathrm{Delta}^{\wedge 2}$
  - e+e-: separately for small or large theta
  - pp: separately for large or small phi

* 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 = (EpT_had1 + EpT_had2) / EpT_jet, to quantify loss to showers and hadronization. This loss would be reduced if colour reconnection often would make the b-bbar or c-cbar into a singlet, rather than the default octet where the two fragment separately.

* In events with two B/D pairs, many observables become possible. There are four possible particle-antiparticle pairs (more if

B-Bbar 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,
(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 phi. Again relative rates will provide info on the composition of production mechanisms.

##
Minutes of second meeting, 2023/10/03

Private overleaf document to be filled

→ Link in the agenda of the event. Please read it and add suggestions/corrections wherever needed.

First draft of the document started. Current approach:

- identify the main analysis/physics cases that will suffer the most from uncertainties on BCFrag/GSplit.
- Describe the existing tools (experimental and theory)
- Find a set of observables that could be used as entry point for
    - experimentalists to study new detector models/reconstruction tools
    - Theorists to test new models
    - Use LEP data to validate these new models?

Discussion

- **Ubiali/Platzer discussion** (sorry, I missed most of it due to unexpected construction works for ~5minutes…)
- Definition of observables
    - Should start with a short list for the ECFA-Paestum workshop timescale in mind.
    - Further in time, ideally, we find people who are interested in reproducing these observables and study them for different models/tunes.

        - Theory and/or full simulation studies? LEP data?
- Using LEP data:
    - Simon has some experience: it is very useful but very techncially challenging. It requires an expert from LEP to understand the data and how to use it.
    - Loukas CERN team will hire a technical student to look into that together with ALEPH physicists. The idea would be to migrate these data to the Key4HEP (or similar) format.
        - Comment: it could be interesting to do the same for other experiments.
- ECFA-Paestum meeting
    - We will share the zoom link.
    - Overlap with the TwoF focus topic.. Which is highly correlated with this one. We will contact the conveners and try not to make them overlap.

June 19, 2024: Conveners meeting
Simon P.:

- Whole program, can not look at parton shower and hadronization in a coherent framework.
- Solving evolution equations in color space, at amplitude level (name?)
- Measurements observables: hadron correlations, angularities
- Generalizing CR observables at LEP.

Could be interesting to also use data from b-factories (Belle II).

Les Houches workshop: flavor-tagged study, uncertainties due to cross-talk between PS and hadronization. => plan document on the arXiv in Fall ‘24.

Chris Hayes: bring in people from the LHC that do relevant work on BCFrag

- CMS tagging,
- How much can LHC work trans