ECFA Focus Topics: BCFrag/Gsplit

Adrián Irles

***AITANA group at IFIC – CSIC/UV**

AGENCIA ESTATAL DE INVESTIGACIÓN
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
GENERALITAT VALENCIANA Conselleria de Educación, Universidades y Empleo
Gen-T
AITANA

BCFrag/GSplit

IFIC INSTITUT DE FÍSICA CORPUSCULAR

14 BCfrag and Gsplit — Heavy quark fragmentation and hadronisation, gluon splitting and quark-gluon separation

Expert Team: Paolo Azzurri, Eli Ben Haim, Loukas Gouskos, Ayres Freitas, Adrián Irles, Andreas B. Meyer, Simon Plätzer, Andrzej Siodmok, Torbjörn Sjöstrand, Maria Ubiali

- Coordinated by the WG1-PREC
  - Paolo Azurri (INFN Pisa), Ayres Freitas (Pittsburg U.), A. I. (IFIC – CSIC/Valencia U.), Andreas B. Meyer (DESY)
  - https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/WG1-PREC
- Expert team:
  - Eli Ben Haim (LPNHE), Loukas Gouskos (Brown U.), Simon Plätzer (Wien U., Graz U.), Andrzej Siodmok (Jagiellonian U.), Torbjörn Sjöstrand (Lund U.), Maria Ubiali (Cambridge U.)
- https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics/BCfrag

BCFrag/GSplit

IFIC INSTITUT DE FÍSICA CORPUSCULAR

14 BCfrag and Gsplit — Heavy quark fragmentation and hadronisation, gluon splitting and quark-gluon separation

Expert Team: Paolo Azzurri, Eli Ben Haim, Loukas Gouskos, Ayres Freitas, Adrián Irles, Andreas B. Meyer, Simon Plätzer, Andrzej Siodmok, Torbjörn Sjöstrand, Maria Ubiali

https://arxiv.org/pdf/2401.07564.pdf

- key ingredients to the precision modeling of physics processes.
- The two issues are entangled, and their systematic uncertainties are expected to be limiting factors in precision Higgs and electroweak measurements at the Higgs factory.
  - Specially in the ultra-high precision limit
- In this document we tried to:
  - Identify channels/topics which require deeper understanding of these uncertainties
  - Make a snapshot of the state of the art in theory but also on experimental studies
  - Identify challenges / open points
  - Provide a list of physics observables of high interest

BCFrag/GSplit

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

- In the high-precision limit, fragmentation functions (FF) will not be universal
  - → observables and initial states dependent.
- It is argued that the factorisation of the perturbative and non-perturbative parts of the problem is not possible without dedicated tuning of free parameters in the required fragmentation model used.
  - There are ongoing developments in disentangling hadronisation and fragmentation, specifically the cross-talk between parton shower and fragmentation.
  - New work is needed for NLL-accurate showers.

- The splitting of $g \to b\bar{b}$ / $c\bar{c}$ is only modelled in the perturbative step of the process
  - but still, charm and bottom masses are parameters in the shower (non perturbative step)
- Other relevant differences may be in the treatment of the strong coupling differently for heavy quarks or (massless) gluons in the limit of pT = 0.
  - Separation of h → gluons from h → $b\bar{b}$ or $c\bar{c}$ ($\sqrt{s}$ = MZ and beyond) is affected.

Relevance for the physics Higgs/Top/EW factory

IFIC INSTITUT DE FÍSICA CORPUSCULAR

Precise study of $h \to gg/b\bar{b}/c\bar{c}$: (HtoSS, Sec. 1, and ZHang, Sec 2). Future Higgs Factories will provide sensitivity to these topologies providing capabilities to fully explore the second generation of Yukawa couplings, which is out of reach at the LHC. However, current uncertainties in gluon splitting into heavy quarks would introduce large systematic uncertainties in the measurements. The questions arising are: how to consistently implement gluon splitting in parton shower tools (modelling and free parameters)? and how to evaluate the impact of incomplete modelling of the gluon splitting when determining the $h \to gg/b\bar{b}/c\bar{c}$ couplings? This issue is discussed in the **HtoSS** focus topic (Sec. 1).

Precise determination of W-mass and cross section: (Wmass, Sec. 4, Wdiff, Sec. 5, and CKMWW, Sec. 11). W mass measurements at future Higgs factories are expected to deliver statistical accuracies at the MeV level [87, 89]. To match this unprecedented precision, the control of systematic uncertainties is crucial. At LEP2, the modelling of non-perturbative QCD effects in W boson hadronic decays was a dominant source of systematic uncertainties. Further theoretical and experimental studies are required to estimate the size of such uncertainties at future colliders. This issue is discussed in the **Wmass** focus topic.

***Z*-*b*/*c* couplings: (TwoF, Sec. 13).** What would be the impact of these uncertainties on the extraction of Z-b/c couplings at the Z-pole? In Ref. [257] it is demonstrated that hadronisation uncertainties have a significant impact on determinations of the partial widths normalised to total hadronic width ($R_{b,c}$), the forward-backward asymmetries ($A_{\mathrm{FB}}^{b,c}$) (or left-right asymmetries) at e^+e^- colliders, even after application of cuts to reduce their impact. The size of these uncertainties could be a limiting factor when operating at the Z-pole in the high luminosity scenarios of FCC-ee. This issue is discussed in the **TwoF** focus topic.

Theory: state of the art

IFIC INSTITUT DE FÍSICA CORPUSCULAR

- Heavy quark FFs can be computed in perturbation theory in QCD, starting from initial conditions at a reference scale $\mu_0 \sim m_0$ + timelike DGLAP evolution
- Initial conditions for gluon- and heavy-quark-initiated fragmentation into heavy quark are
  - known at order α_s [1990, 91: B. Mele and P. Nason]
  - Calculated at order α_s^2 [2004 K. Melkinov, A. Mitov, 2005, A. Mitov]

  NLO FF (α_s^2) of the FF at the initial scale matched with soft-emission logarithm resummation to NNLL
- Timelike DGLAP evolution eq. Is implemented in public codes up to NNLL
  - QCDNUM [2011 M. Botje] FFEVOL [2012 M. Hirai, S. Kumano] APFEL [2014 V. Bertone, S. Carrazza, J. Rojo] MELA [2015 V. Bertone, S. Carrazza, E. R. Nocera]
- Studies of the role of gluon-initiated fragmentation to heavy quarks and the coupled timelike evolution of bottom quarks and gluons [2020 G. Ridolfi, M. Ubiali, M. Zaro]
  - Subdominant effect at LEP2/Tevatron → not at LHC (neither at the high precision limit)
- The perturbative component of the fragmentation function of the b quark to the best of the present theoretical knowledge (resummation effects) [2022 F. Malltoni, G. Ridolfi, M. Ubiali, M. Zaro]
- b/c-quark fragmentation at NNLO+NNLL supplemented by fits to non-perturbative component of b→B (c→ D) hadrons [2021 M. L. Czakon, T. Generet, A. Mitov] [2023 L. Bonino, M. Cacciari, and G. Stagnitto]

Theory: state of the art

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

- Important progresses in the Perturbative FF framework, supplemented by fits of the non-perturbative component.
- However, the exclusive nature of the fragmentation process is not addressed in such approach → the modifications under experimental cuts / selection is undefined
  - Therefore parton showers are needed for the perturbative step, and fragmentation models for the non-perturbative one.
  -
- **How can this progress in the Perturbative FF + non-pert. fits could be implemented in PS MonteCarlo??**
  - are existing hadronisation models (strong fragmentation, cluster fragmentation) flexible enough,

  or do we need new ideas like for example ML hadronisation models ?

Summary of reccommended measurements and simulation studies

Table 3: Target physics observables at e^+e^- and pp.

Observable	e^+e^-	pp
Event shapes and angular distributions		
Inclusive B/D production cross section	primary production is well known from theory, so any "excess" is from gluon splitting	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)	we do not expect sizeable momentum dependence, but interesting to contrast mesons and baryons for smaller ones	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	none expected, except tiny from CP-violation in oscillations	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	dn/dx_E with $x_E = 2E_{\mathrm{had}}/E_{\mathrm{cm}}$; basic distribution for tuning of "fragmentation function"	dn/dp_{T} and dn/dy give basic production kinematics, but the many production channels give less easy interpretation
Energy flow around B/D hadrons, excluding the hadron itself, as a test that dead cone effects are correctly described	$dE/d\theta$ where θ is the distance from B/D on the sphere	dp_{T}/dR where R is the distance in (η, ϕ) or (y, ϕ) space, only applied for B/D above some p_{T} threshold
B/D hadron momentum fraction of total E or p_{T} in a jet, with $x = p_{\mathrm{T}}^{\mathrm{had}}/p_{\mathrm{T}}^{\mathrm{jet}}$, 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)	draw a jet cone in θ around B/D and measure x	draw a jet cone in R around B/D and measure x
B/D hadron multiplicity, 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	separation in θ	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, $\Delta = (p_{\mathrm{T}}^{\mathrm{max}} - p_{\mathrm{T}}^{\mathrm{min}})/(p_{\mathrm{T}}^{\mathrm{max}} + p_{\mathrm{T}}^{\mathrm{min}})$, where for gluon splitting $x^2+(1-x)^2$ translates to $1+\Delta^2$	separately for small or large θ	separately for large or small ϕ

More in https://arxiv.org/pdf/2401.07564.pdf

Target Observables & ILD activities

IFIC INSTITUT DE FÍSICA CORPUSCULAR

Table of observables proposed:

- a) crosscheck model performance
- b) revisit models/tunning using LEP/SLC data
- **c) study full simulation and detector performance**

▷**Open (detector) points**

- Tracker acceptance impact.
- Kaon ID.
- Jet charge measurements → hadronization is a source of uncertainty if not double tagging Is used

▷**ILD recent progresses** on adapting the generation chain

- to use **Pythia8** (facilitating playing with tunning parameters)
- To use **QCD NLO** ee-→qq calculations in Whizard (with PS matching).
- Zhijie Zhao, J. List, M. Berggren https://agenda.infn.it/event/34841/contributions/208079/attachments/111374/158899/ECFA2023-zzi.pdf

Person power, short term activities

IFIC INSTITUT DE FÍSICA CORPUSCULAR

Sample production?

- At 250GeV and higher energy, BCFrag/Gsplit is not the main concern for 2f studies → less urgent to have newer samples, although the QCD NLO would be interesting to be studied (to address QCD correlation uncertainties in AFB)
- Priority? for H→ssbar → Samples with different tunes ?
- Z-pole? WW?

Person power

- **DESY** → Pythia8, NLO QCD
- TwoF groups
- Wmass studies
- Higgs studies

Revisiting LEP data ?

IFIC INSTITUT DE FÍSICA CORPUSCULAR

– Access to LEP Archived Data. LEP data (and simulations) have been partially archived to allow their use for physics analyses after the closure of the collaboration. The use of archived data is authorised to former members of the collaboration and collaborators. However, the understanding and reprocessing of analysis is still challenging and depends on the safeguarding of the different collaboration's analysis frameworks and mini-data at CERN. Recent efforts [269] have been driven to re-analyse these data by exporting the data and simulations to more modern and accessible formats, for instance, the MIT Open Data format. A systematic approach for the exportation of such archived data and software tools to the KEY4HEP environment should be considered by the Higgs Factory community. This would allow the validation of newer calculations and MC tools with existing data.

Summary + open questions

- How can the recent progress in the Perturbative FF framework, supplemented by the fits of the non-perturbative component, be implemented and used in practice, e.g. in PS Monte Carlo?
- What is the quantitative impact of uncertainties from parton-shower, fragmentation and hadronisation on flagship Higgs/Top/EW measurements - and which level of precision will be required?
- Which measurements of particle rates, species, distributions are needed in order to constrain fragmentation and hadronisation models to the required level of precision?
- Which detector capabilities are required and to which extend do the proposed detector concepts provide these?
- To which extend could LEP data be useful and how could they be made accessible to test new calculations and MC tools?

Contact and more info

IFIC INSTITUT DE FÍSICA CORPUSCULAR

- Gitlab wiki:
  - https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/
- FocusTopics/BCFRAG
  - Sign up for egroup: ECFA-WHF-FT-BCFRAG@cern.ch via http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=ecfa-whf-ft-bcfrag
  - and/or email the conveners of ECFA WG1 PRECision group:

    ecfa-whf-wg1-prec-conveners@cern.ch

https://arxiv.org/pdf/2401.07564.pdf

13 TwoF — EW precision: 2-fermion final states ($\sqrt{s} = M_Z$ and beyond)

Expert Team: Emanuele Bagnaschi, Adrián Irles, Daniel Jeans, Alessandro Vicini

- The unprecedented statistical power provided by future colliders will require a large effort on the control and understanding of systematic uncertainties from theory and experiment. Indeed, the run at the Z pole foreseen by FCC-ee will offer 500 times smaller statistical uncertainties than those of previous measurements [14]. A significant improvement in precision could also be reached at the ILC [20].

- Very challenging measurements at Z-pole, dominated by systematics
  - Polarization (or non-polarization) measurements
  - Luminosity
  - Fragmentation
  - Detector acceptance, flavour tagging, PID performance

ILD activities

IFIC INSTITUT DE FÍSICA CORPUSCULAR

- **e+e- → tautau**
  - D. Jeans et al (IDR, 500GeV, 250GeV in the pipeline)
- **ee→qqbar at 250 GeV (and above). Focus on AFB measurements**
  - T. Suehara et al https://agenda.infn.it/event/34841/contributions/208275/attachments/111331/158807/231011-2f-ecfa-nagae-suehara.pdf
  - R. Poeschl, F.Richard, A.I, J.. Márquez (see Jesus talk tomorrow, ILD paper on its way) ,Okugawa et al
  - Full simulations studies (mu/b/c/s) Focus on flavour tagging, PID, jet-charge measurement
  - Precision physics for indirect BSM searches
  - Assume a revisited precision on Z-couplings to fermions (via GigaZ or RadReturn measurements).
  - Exploiting the ILC/ILD characteristic features: beam polarization, high energy reach, PID, etc
- **PID, flavour tagging**
  - See yesterday session https://agenda.linearcollider.org/event/10211/contributions/53835/
  - And U. Einhaus talk https://agenda.linearcollider.org/event/10211/contributions/53839/

- No current efforts on Full Simulation at **GigaZ**.

Person power, short term activities

Sample production?

- Newer samples using NLO QCD events and/or with different PS tunes (see next topic)
- What about GigaZ samples?

Further detector optimization?

- Acceptance (forward region)
- PID detectors / reconstruction techniques ?
- Person power for physics benchmark analysis?

New topics/analysis opportunities

- Light-quark AFB (thanks to more powerful flavour tagging using PID)

▷**Person power**

- **Tokyo/KEK** → flavour tagging, tau
- **IJCLAB →** squark
- **IFIC** → b/c quark (BSM searches)