Heavy Flavours in Parton Showers

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Outline

- Introduction
- Heavy Flavour Evolution
- Heavy Flavour Production
- Hadronization and Decays
- Summary

Introduction

- There are two main processes with heavy flavours in parton showers:
  - the evolution via the parton shower of a heavy quark produced in the hard process;
  - the production in the parton shower via either forward of backward evolution of heavy quarks.

  There are then issues with the subsequent hadronization of the heavy quarks and the decay of the heavy flavour hadrons.

Evolution of Heavy Quarks

- The history of this goes back to Marchesini and Webber Nucl.Phys.B 330 (1990) 261-283

266 *G. Marchesini, B.R. Webber / QCD coherence*

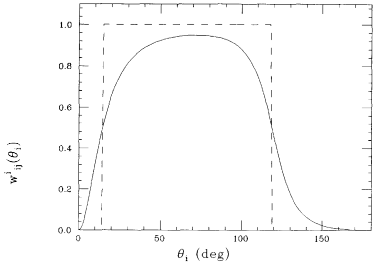


Fig. 2. Solid curve: coefficient function $w^i_{ij}(\theta_i)$ in eq. (11) for azimuthally averaged radiation pattern. Here $\gamma_i = \gamma_j = 4$, $\theta_{ij} = 120°$. Dashed: approximation (13), i.e., $w^i_{ij}(\theta_i) = \Theta(R^i_{ij})$.

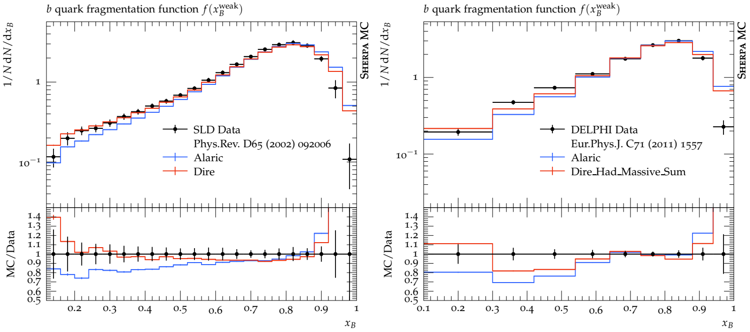
- Strict dead-cone and mass an after thought in the massless algorithm

Evolution of Heavy Quarks

Lot of developments in the 2000s.

- Use of either quasi-collinear or massive dipole functions instead of massless functions and mass as a cut-off.
- Allows simulation of the full soft radiation pattern in the small angle limit rather than the Θ function cut-off.
- Now we would expect to have a good simulation of the radiation from heavy quarks produced in the hard process.
- Still some issues about how we deal with cases where the parton shower has to evolve a massless heavy quark.
- and with the backward evolution of heavy quarks in the initial state.

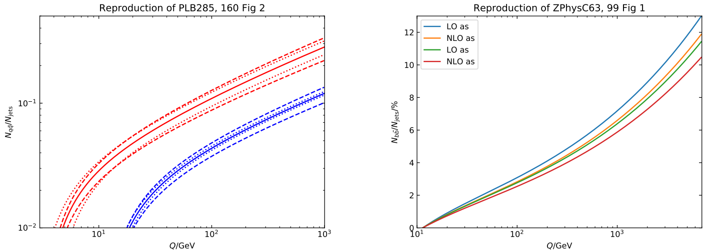
Evolution of Heavy Quarks



Assi and Höche, Phys.Rev.D 109 (2024) 11, 114008

Heavy Quark Production

- As the energy of a parton increases the probability that gluon radiation produces a heavy $Q\bar{Q}$ pair via $g \to Q\bar{Q}$ increases.



Reproduction of Figs from Nason and Mangano PLB 285 160 (1992) and Z.Phys.C63, 99 Seymour.

- Due to the increase of the number of radiated gluons, genuine log enhanced effect.
- Can't be solved with matching etc needs improvements in the parton shower.

$g \to Q\bar{Q}$

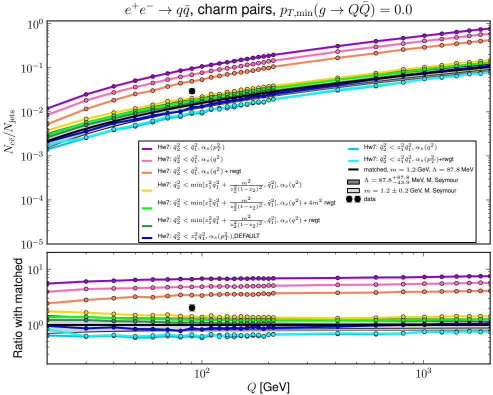
- The rate of $Q\bar{Q}$ production depends on
  - The number of gluons which can branch into a $Q\bar{Q}$ pair
  - The calculation of the $g \to Q\bar{Q}$ branching probability
- The first is a basic prediction of a given parton shower algorithm and the parameters are tuned to range of data.
- There can be then some freedom in description of the $g \to Q\bar{Q}$ splitting.

$g \to Q\bar{Q}$

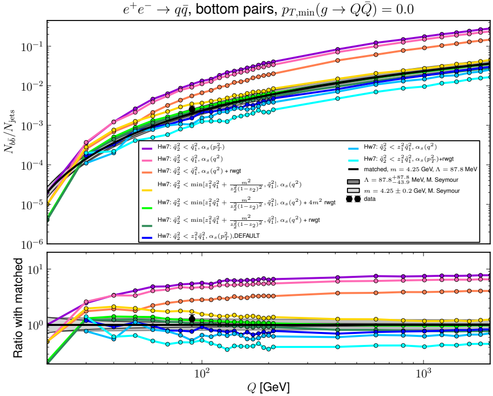
- In $1 \to 2$ branching parton shower algorithms the branching is naturally included but there are issues about the description of the branching
  - In angular-ordered parton showers while the emission has to be ordered in the ordering variable as it is not soft the angular-ordering restriction does not have to apply but is normally imposed.
  - The arguments to use $p_\perp$ as the scale for α_S no longer apply and other scales such as $\tilde{q}$ or even Q can be used.
- In $2 \to 3$ branching parton shower algorithms the branching is not so naturally included
  - Often the branching is split into 2 dipoles
  - Same issues with the scale of α_S

$g \to Q\bar{Q}$

I'm not aware of much recent work on $g \to Q\bar{Q}$ so I'll show some preliminary results of work on this with Herwig (Bewick, Ferrario Ravasio, Richardson, Seymour) that ground to halt during COVID.



$g \to Q\bar{Q}$

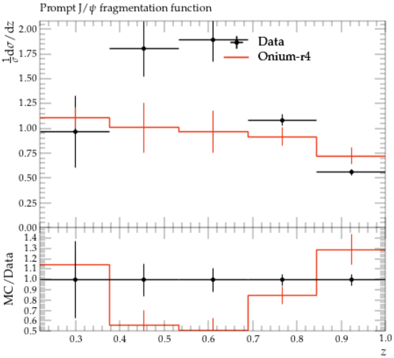

$e^+e^- \to q\bar{q}$, bottom pairs, $p_{T,\min}(g \to Q\bar{Q}) = 0.0$
$N_{b\bar{b}}/N_{\rm jets}$
Ratio with matched
Q [GeV]
Hw7: $\tilde{q}_2^2 < \tilde{q}_1^2, \alpha_s(p_T^2)$
Hw7: $\tilde{q}_2^2 < \tilde{q}_1^2, \alpha_s(q^2)$
Hw7: $\tilde{q}_2^2 < \tilde{q}_1^2, \alpha_s(q^2)$ + rwgt
Hw7: $\tilde{q}_2^2 < \min[z_1^2\tilde{q}_1^2 + \frac{m^2}{z_2^2(1-z_2)^2}, \tilde{q}_1^2], \alpha_s(q^2)$
Hw7: $\tilde{q}_2^2 < \min[z_1^2\tilde{q}_1^2 + \frac{m^2}{z_2^2(1-z_2)^2}, \tilde{q}_1^2], \alpha_s(q^2) + 4m^2$ rwgt
Hw7: $\tilde{q}_2^2 < \min[z_1^2\tilde{q}_1^2 + \frac{m^2}{z_2^2(1-z_2)^2}, \tilde{q}_1^2], \alpha_s(q^2)$ + rwgt
Hw7: $\tilde{q}_2^2 < z_1^2\tilde{q}_1^2, \alpha_s(p_T^2)$,DEFAULT
Hw7: $\tilde{q}_2^2 < z_1^2\tilde{q}_1^2, \alpha_s(q^2)$
Hw7: $\tilde{q}_2^2 < z_1^2\tilde{q}_1^2, \alpha_s(p_T^2)$+rwgt
matched, $m = 4.25$ GeV, $\Lambda = 87.8$ MeV
$\Lambda = 87.8^{+87.8}_{-43.9}$ MeV, M. Seymour
$m = 4.25 \pm 0.2$ GeV, M. Seymour
data

$g \to Q\bar{Q}$

- In all cases issues with the efficiency of event generation.
- Need to run the parton shower and see what you get.
- Modern tools allow weighting of emissions in the shower.

Quarkonium in Jets

- Can describe quarkonium production in the parton shower using splitting functions based on NRQCD.
- Issues with handling the colour-octet term where a $g \to J/\psi+$ infinitesimally soft gluon



Herwig 7 preliminary vs

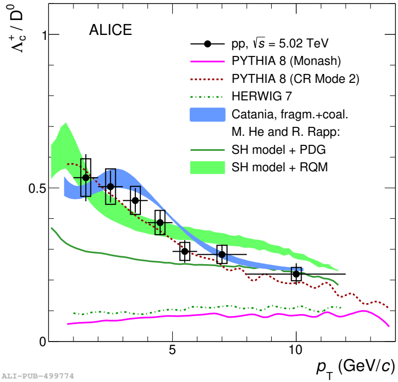
CMS Phys.Lett.B 825 (2022) 136842

Aside: Comparisons with data

- If an experimental analysis is implemented in Rivet the event generator collaborations (at least some of them) will make comparisons with the result to new models/tunes where relevant.
- If the unfolded data is in HEPDATA but not Rivet and its really usefully for some new development we may implement a Rivet analysis and look at it. ($\sim$ 100 times less likely)
- If the data is not in HEPDATA extremely unlikely we will look at it and certainly if the tabulated values aren't available its unlikely to ever be used.

Heavy Quark hadronization

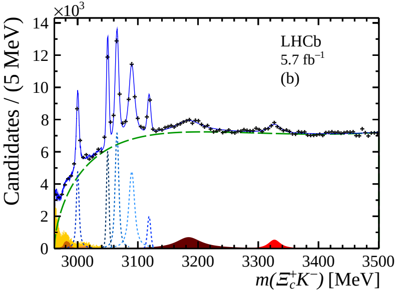
- There are unresolved issues in heavy quark hadronization.
- Observation that heavy baryon production is enhanced at low $p_\perp$



ALICE Phys.Rev.Lett. 127 (2021) 20, 202301

Heavy Quark hadronization

- Properties of many heavy flavour hadrons are not well known.
- Still reliant on partonic models for the decays of bottom and charm baryons (less so for mesons)
- Uncertainties in the hadronization over including excited states.



Ω_c^* states LHCb Phys. Rev. Lett. 131 (2023) 131902

Summary

- There has been a lot of progress in including masses for the simulation of radiation from heavy quarks.
- New more accurate parton shower algorithms should give better estimates of the rate of $g \to Q\bar{Q}$
- More study needed of the simulation of the $g \to Q\bar{Q}$ branching itself.