Top-Pair Events with B-hadrons at the LHC

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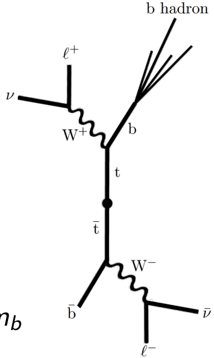
Top-pairs with B-Hadrons

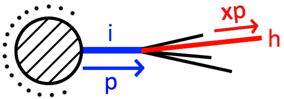
- Process considered:
  $p\,p \to t(\to B\ W^+ + X)\ \bar{t}(\to \bar{b}\ W^-)$
  $\quad\quad\quad\quad \hookrightarrow \ell^+\nu_\ell \quad\quad\quad \hookrightarrow \ell^-\bar{\nu}_\ell$

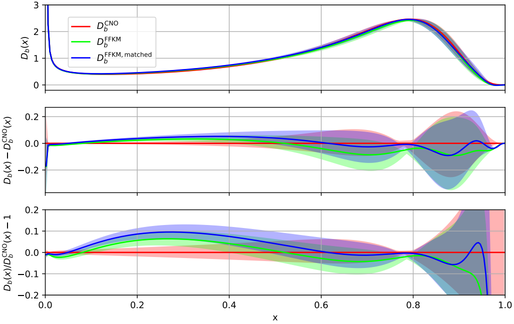


- Measurements of B-hadrons very precise
  $\Rightarrow$ high-precision top-mass determination
- High top mass $\Rightarrow$ small power corrections in m_b
- Production of hadrons is a non-perturbative effect

Fragmentation Functions

- Transition parton → hadron in the final state
- "Probability distribution" to find a hadron h with a fraction x of the parton i's momentum: $D_{i \to h}(x)$
- Only considers longitudinal kinematics; i, h massless
- Non-perturbative: fitted to data
- Scale dependent
- Analogous to PDFs

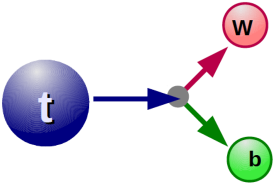


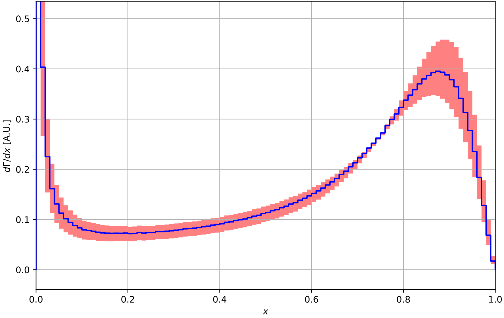


Example: Top-decay to a B-meson at LO

- $t \longrightarrow B\ W^{+} + X$

- Partonically at LO:
  $t \longrightarrow b\ W^{+}$



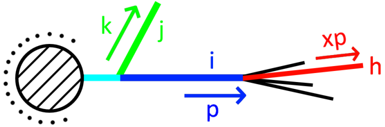


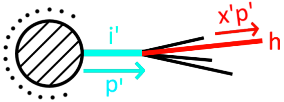
Introduction to Subtraction Schemes

- Strategy for numerical integration of cross sections
- Cross sections contain singularities in d=4 (soft, collinear)
- Idea: subtract divergences differentially (subtraction terms), add them in integrated form (integrated subtraction terms)
- Both value and kinematics of subtraction term must match cross section in singular limit
- Here: sector-improved residue subtraction scheme (previously implemented in C++ library STRIPPER)

Subtraction Schemes and Fragmentation

- Without fragmentation: cannot distinguish collinear quark-pair $q(p_1) + \overline{q}(p_2)$ from $g(p_1 + p_2)$
- With fragmentation: both momentum of fragmenting particle and flavour matter
  $\Rightarrow$ must store flavour and e.g. $p_1^0/(p_1^0 + p_2^0)$
- Introduce concept of reference observables: match reference observable for cross section and subtraction term by rescaling the momentum fraction





Subtraction Schemes and Fragmentation (Continued)

- Without fragmentation: cannot distinguish $q(p) + g(0)$ from $q(p)$
- With fragmentation: cannot remove gluon if it is the fragmenting particle
- Usually: have to recalculate integrated subtraction terms
- Important observation: not necessary if each subtraction term cancels only one singularity
- This is the case for STRIPPER $\Rightarrow$ major simplification

Isolated Top Decay: Setup

- Previously considered through NLO

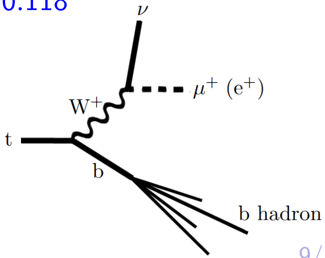
  S. Biswas, K. Melnikov and M. Schulze (2010)

- On-shell W^+ (narrow width approximation)

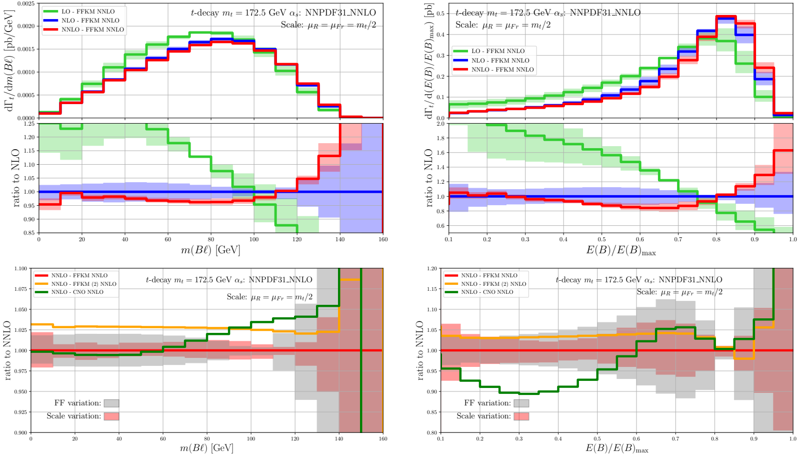
- Parameters:
  $m_t = 172.5$ GeV, $m_W = 80.385$ GeV, $\Gamma_W = 2.0928$ GeV,
  $m_b = (4.66$ GeV, 4.75 GeV$)$, $\alpha_s(M_Z) = 0.118$

- 7-point scale variation with
  central scales $\mu_R = \mu_{Fr} = m_t/2$

- Single cut: $E(B) > 5$ GeV



Isolated Top Decay: Plots



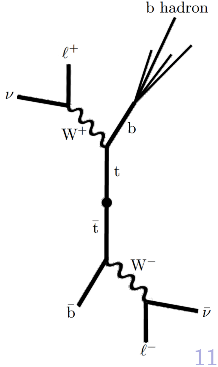
Top-Pair Events with B-hadrons at the LHC: Setup

- Previously studied at NLO

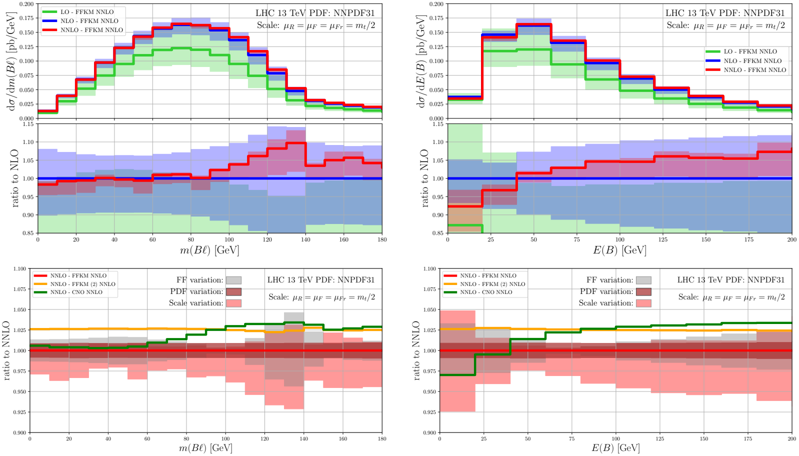
  A. Kharchilava (2000), S. Biswas, K. Melnikov and M. Schulze (2010)

  K. Agashe, R. Franceschini and D. Kim (2013), K. Agashe, R. Franceschini, D. Kim and M. Schulze (2016)

- On-shell W^+ (narrow width approximation)
- Parameters as before
- 15-point scale variation with central scales $\mu_R = \mu_F = \mu_{Fr} = m_t/2$ and $1/2 \leq \mu_i/\mu_j \leq 2$
- PDF set: NNPDF3.1
- $p_T(B) > 10$ GeV and $|\eta(B)| < 2.4$

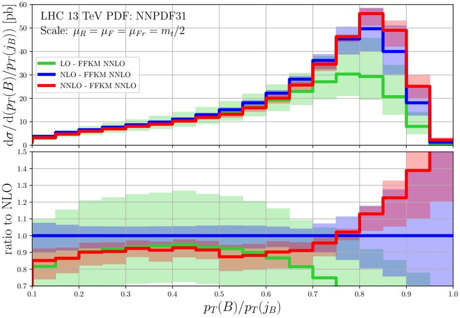


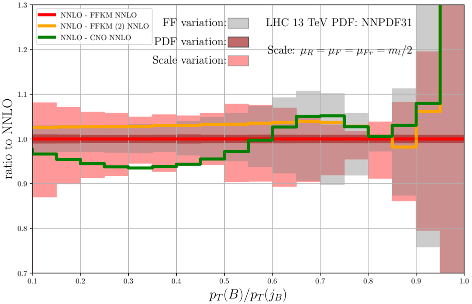
Top-Pair Events with B-hadrons at the LHC: Plots



Top-Pair Events with B-hadrons at the LHC: Jet Ratio

- Jet algorithm: anti-k_T with $R = 0.8$





Conclusion and Outlook

- Fragmentation has been implemented in STRIPPER
- First application: top-quark pairs at the LHC
- Big reduction in scale uncertainties from NLO to NNLO
- $\Rightarrow$ potential for more accurate top-mass determination
- PDF-insensitive extraction of FFs at LHC plausible
- Framework completely general: can describe the production of any hadron in any process at NNLO

Perturbative Vs. Non-perturbative

- Production of b-quarks is perturbative
  $\Rightarrow$ Can separate perturbative and non-perturbative parts

- Perturbative part: previously calculated through NNLO

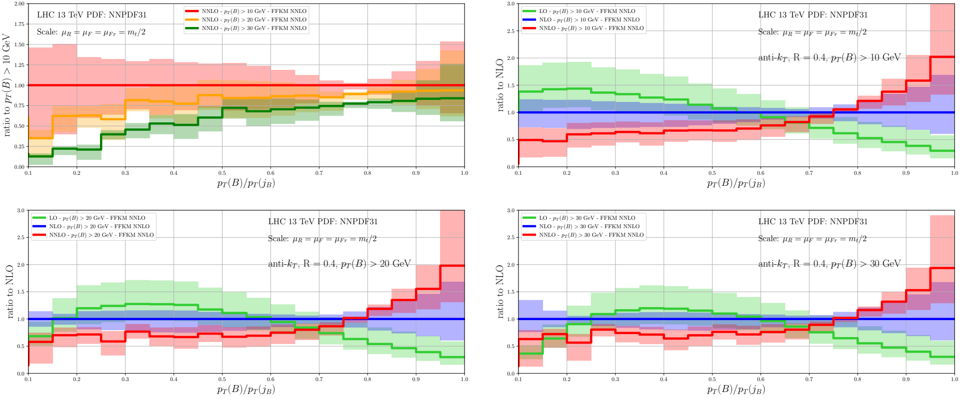
  K. Melnikov and A. Mitov (2004), A. Mitov (2005)

- Non-perturbative part: a single function fitted to data

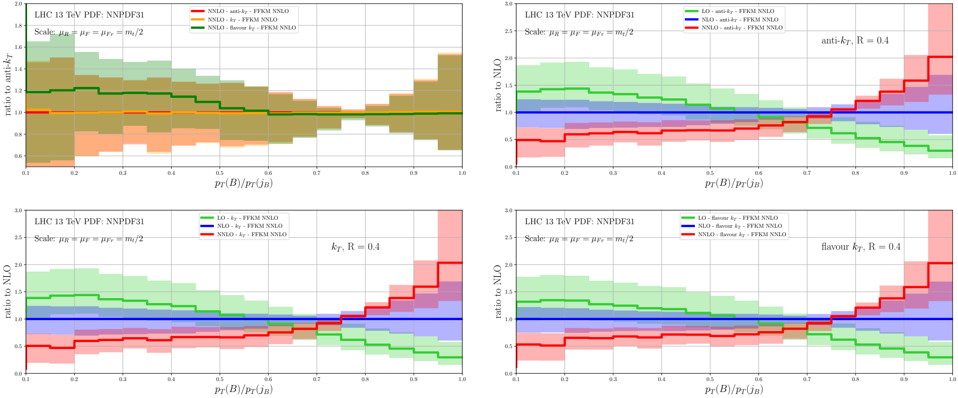
  M. Cacciari, P. Nason and C. Oleari (2006)

  M. Fickinger, S. Fleming, C. Kim and E. Mereghetti (2016)

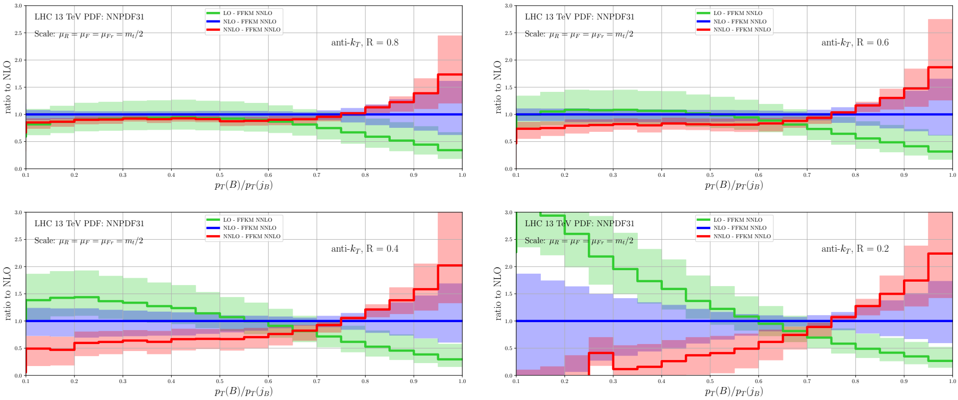
Jet Ratio: p_T-Cut-Dependence



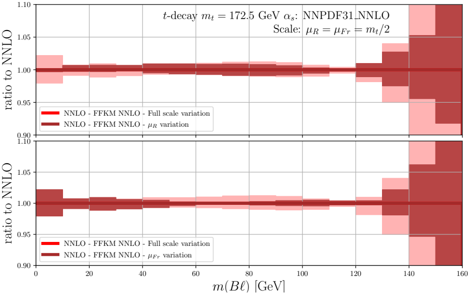
Jet Ratio: Jet-Algorithm-Dependence

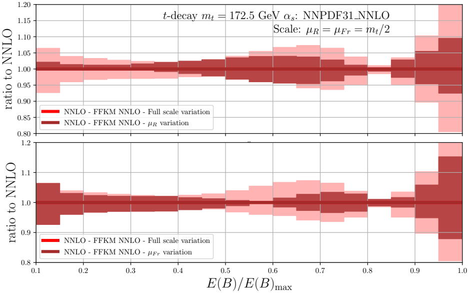


Jet Ratio: R-Dependence

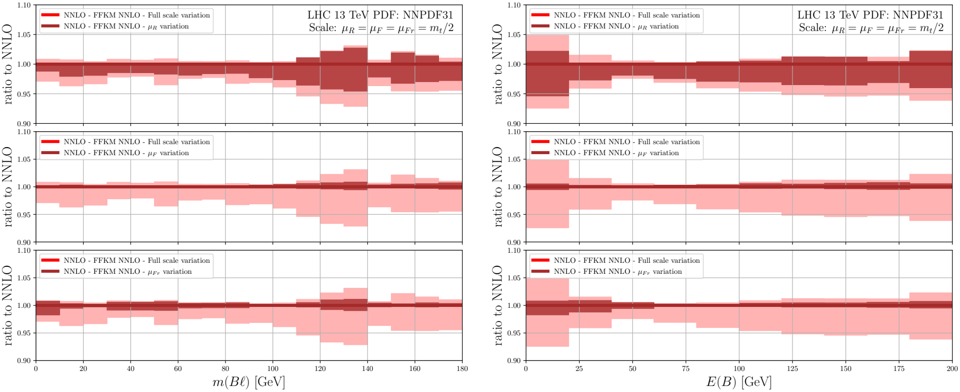


Isolated Top Decay: Separated Scale Dependence

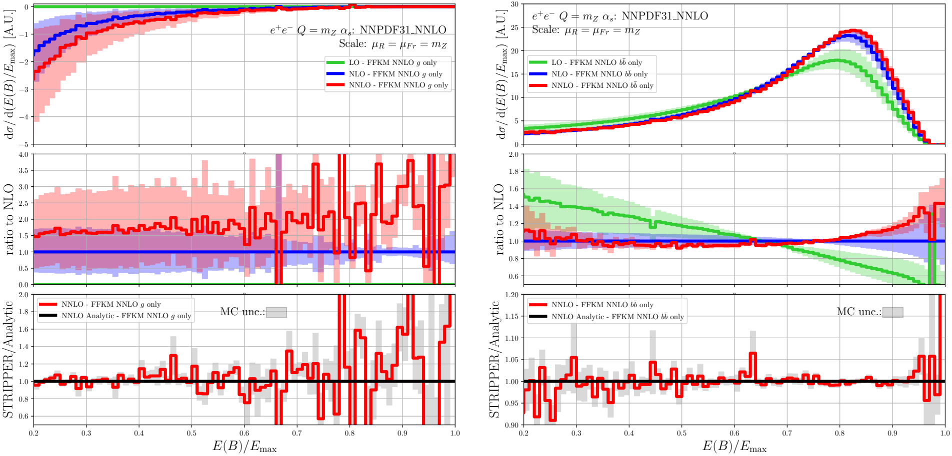




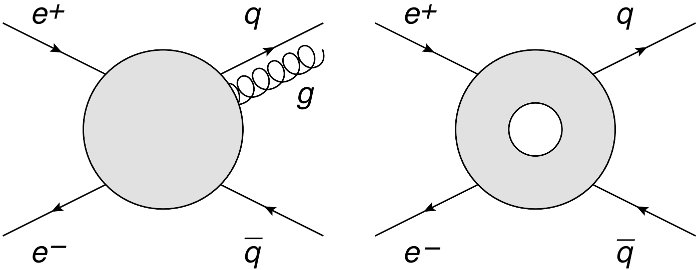
Top-Pair Events with B-hadrons at the LHC: Separated Scale Dependence



Cross-Check: B-Hadrons at LEP



Collinear Renormalisation



Collinear Renormalisation

$$D_i^B(x) = \sum_j \left(Z_{ij} \otimes D_j\right)(x)\,, \quad (f \otimes g)(x) = \int_x^1 \frac{dz}{z} f\left(\frac{x}{z}\right) g(z)$$

$$\begin{aligned} Z_{ij}(x) = {} & \delta_{ij}\delta(1-x) + \frac{1}{\epsilon}\left(\frac{\mu_R^2}{\mu_{Fr}^2}\right)^{\epsilon} \frac{\alpha_s}{2\pi} P_{ij}^{(0)\mathrm{T}}(x) \\ & + \left(\frac{\alpha_s}{2\pi}\right)^2 \left[\frac{1}{2\epsilon}\left(\frac{\mu_R^2}{\mu_{Fr}^2}\right)^{2\epsilon} P_{ij}^{(1)\mathrm{T}}(x) \right. \\ & \qquad + \frac{1}{2\epsilon^2}\left(\frac{\mu_R^2}{\mu_{Fr}^2}\right)^{2\epsilon} \sum_k (P_{ik}^{(0)\mathrm{T}} \otimes P_{kj}^{(0)\mathrm{T}})(x) \\ & \qquad \left. + \frac{\beta_0}{4\epsilon^2}\left\{\left(\frac{\mu_R^2}{\mu_{Fr}^2}\right)^{2\epsilon} - 2\left(\frac{\mu_R^2}{\mu_{Fr}^2}\right)^{\epsilon}\right\} P_{ij}^{(0)\mathrm{T}}(x)\right] \end{aligned}$$

DGLAP Scale Evolution

- Collinear renormalisation of fragmentation functions
- $\Rightarrow$ 'RGEs' for fragmentation functions
- $\Rightarrow$ DGLAP evolution equations:

$$\mu_{Fr}^2 \frac{d}{d\mu_{Fr}^2} D_i = \sum_j P_{ij}^{\mathrm{T}} \otimes D_j \equiv \sum_j \sum_n \left(\frac{\alpha_s}{2\pi} \right)^{n+1} P_{ij}^{(n)\mathrm{T}} \otimes D_j$$

- Scale dependence predicted by theory, need only x-dependence

Fragmentation and Subtraction Schemes

- IR singularities at higher orders (soft/collinear)
- Subtraction schemes:
  $d\sigma = d\sigma_0 + \sum_{j=1}^{n} \sum_{m=0}^{n} \int_m \left\{ \left(d\sigma_j^m - \sum_i d\sigma_{j,i}^m \right) + \sum_i d\sigma_{j,i}^m \right\}$
- Lower-order matrix elements with factors to match singular behaviour
- Without fragmentation: kinematics match at jet-level in singular limits
- With fragmentation: kinematics mismatch
- $\Rightarrow$ Use full kinematics in singular limit in subtraction terms

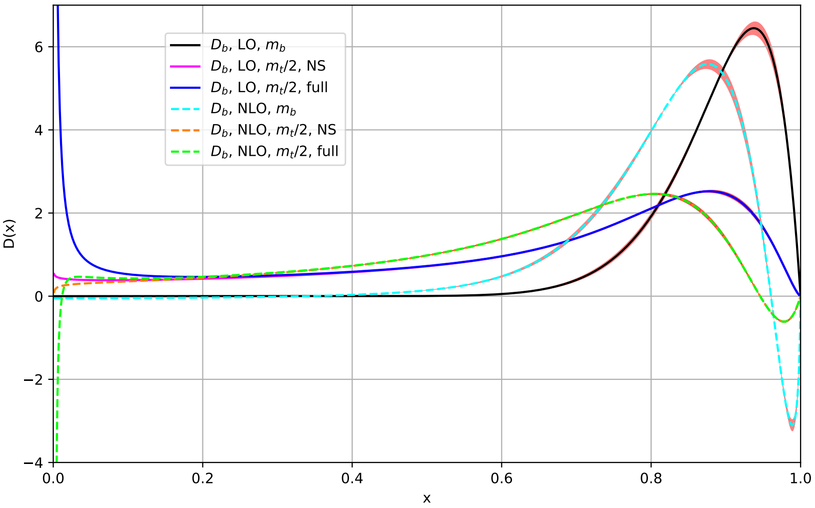
Subtraction Terms

- Singular factors can be reused from case without fragmentation
- Integrated subtraction terms usually cannot be reused
- Calculation often assumes independence of observables w.r.t. collinear kinematics
- Especially when one subtraction term regulates multiple singularity types (e.g. CS dipoles)
- $\Rightarrow$ Need to redo integration
- Leads to left-over convolution with fragmentation function
- Convenient: in STRIPPER only one singularity is regulated per subtraction term

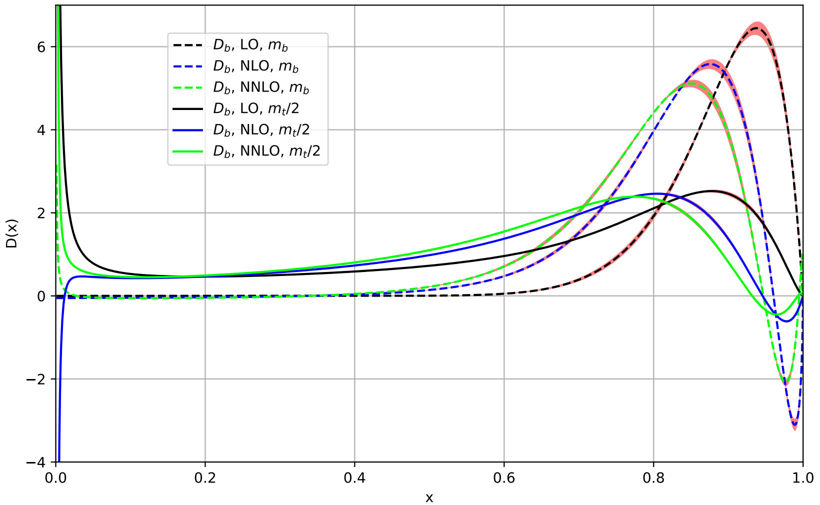
Reference Observables

- Momentum fraction of subtraction terms not fully constrained
- Must be the same distribution for full/integrated subtraction terms
- Must match fraction of real contribution in relevant singular limit
- $\Rightarrow$ Can use freedom to improve numerical convergence
- Idea: rescale fractions per event to make all terms land in the same histogram bin
- Significantly reduce poor convergence due to "missed binning"
- Process requires "reference observable"

Full Vs. Non-Singlet Scale Evolution



A Fragmentation Function Through NNLO



Fragmentation Functions of Different Flavours

- Three different fragmentation functions with large-x resummation
- D^{CNO} resums large logarithms through NLL.

  M. Cacciari, P. Nason and C. Oleari (2006)

- D^{FFKM} and $D^{\text{FFKM,matched}}$ resum through N^3LL.

  M. Fickinger, S. Fleming, C. Kim and E. Mereghetti (2016)

- Definition of FFs of type FFKM does not match the one used here.
- Ambiguity resolved in two different ways.