Top-pair events with B-hadrons at the LHC

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Based on arXiv:2102.08267 and preliminary results

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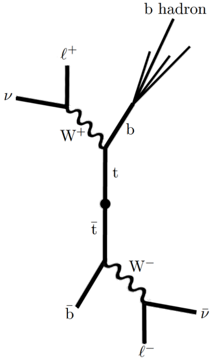
Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Top-pairs with B-hadrons

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



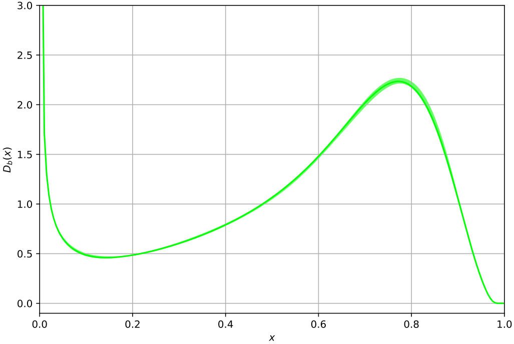
- Measurements involving *b*-jets suffer from large jet energy scale uncertainties

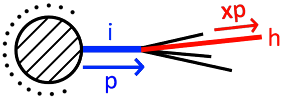
- Measurements of B-hadrons very precise
  $\Rightarrow$ high-precision top-mass determination

- Production of hadrons is a non-perturbative effect

Fragmentation functions

- "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
- No parton showers used





The software

- Calculations were performed using C++ library STRIPPER
- Many NNLO firsts over the years. Recently:
  - Three-jet production at the LHC *Czakon, Mitov, Poncelet (2021)*
  - Diphoton + jet at the LHC *Chawdhry, Czakon, Mitov, Poncelet (2021)*
  - Exact top-mass effects in Higgs production at the LHC *Czakon, Harlander, Klappert, Niggetiedt (2021)*
  - Top-pairs with B-hadrons at the LHC *Czakon, TG, Mitov, Poncelet (2021)*
  - W + c-jet at the LHC *Czakon, Mitov, Pellen, Poncelet (2020)*
  - ...
- First implementation of fragmentation in a general code for NNLO cross sections
- Fully general implementation; not limited to cases presented in this talk

First application: LHC top-pair events with B-hadrons

- Previously studied at NLO

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

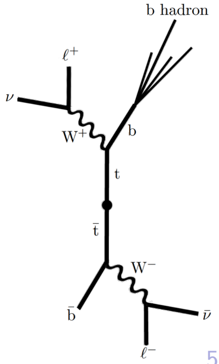
  K. Agashe, R. Franceschini and D. Kim (2013), K. Agashe, R. Franceschini, D. Kim and M. Schulze (2016)

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

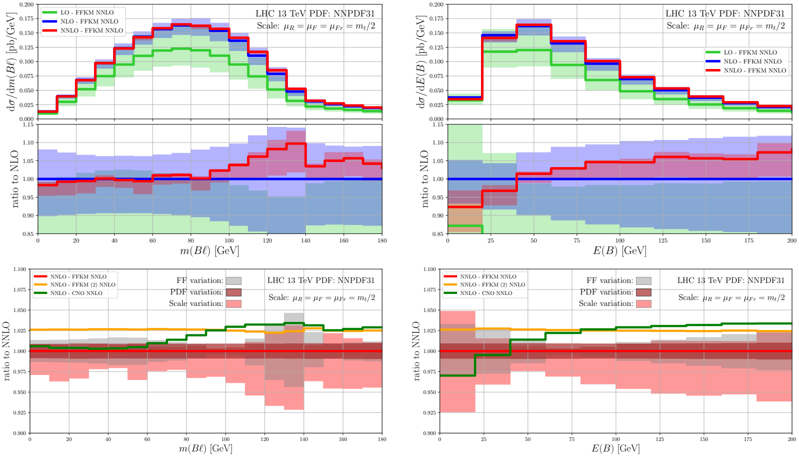
- 15-point scale variation with central scales $\mu_R = \mu_F = \mu_{Fr} = m_t/2$ and $1/2 \leq \mu_i/\mu_j \leq 2$

- PDF set: NNPDF3.1

- $p_T(B) > 10$ GeV and $|\eta(B)| < 2.4$

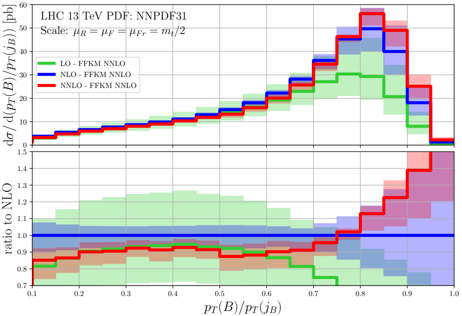


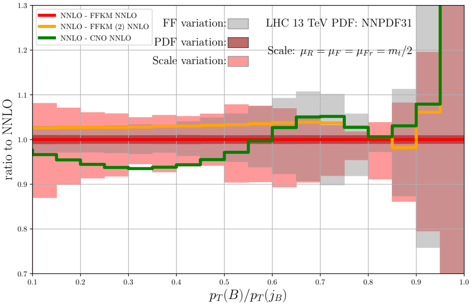
Top-pair events with B-hadrons at the LHC: plots



Top-pair events with B-hadrons at the LHC: jet ratio

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





First improvement: fragmentation function fits

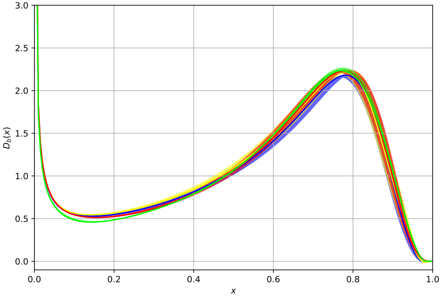
- At the time: no fits based on PFF approach available at NNLO
- Required for fully consistent results
- Three different FF sets based on three different compromises
- Two based on NNLO calculation within SCET/HQET

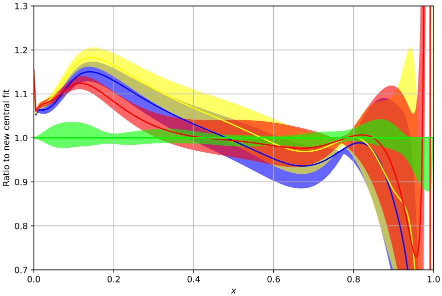
  M. Fickinger, S. Fleming, C. Kim and E. Mereghetti (2016)
- One based on NLO calculation within PFF approach

  M. Cacciari, P. Nason and C. Oleari (2006)
- Different compromises consistent within uncertainties
- Nonetheless better to use a consistent fit

First NNLO fit within the PFF approach

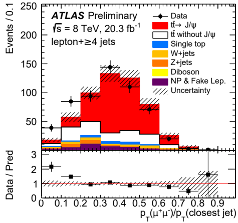
- Based on data from ALEPH, DELPHI, OPAL and SLD.
- Blue/Yellow: based on Fickinger, Fleming, Kim, Mereghetti (2016)
- Red: based on Cacciari, Nason, Oleari (2006)
- Green: Corcella, Czakon, TG, Mitov, Poncelet (preliminary)

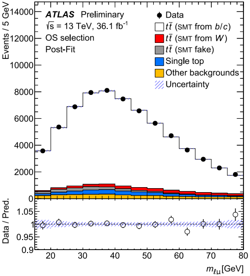




Second improvement: B-hadron decays

- Full reconstruction of B-hadrons difficult
- Not enough $t\bar{t}$ events for distributions
  $\Rightarrow$ Cannot compare first results to experiment
- Solution: incorporate B-hadron decays
- Only reconstruct some decay products
  $\Rightarrow$ Significantly boost statistics
- Examples:
  ATLAS-CONF-2015-040 ($B \rightarrow J/\psi + X$)
  ATLAS-CONF-2019-046 ($B \rightarrow \mu + X$)

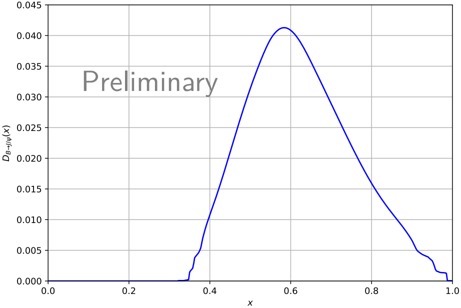


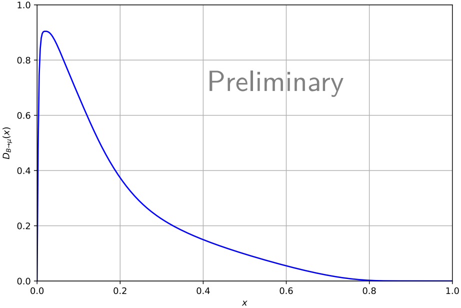


Including B-hadron decays in theory predictions

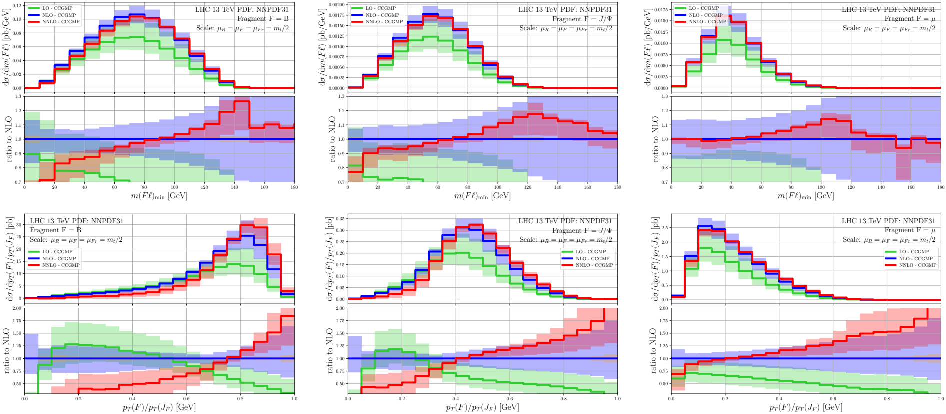
- B-hadron treated as massless ⇒ cannot decay
- Most obvious solution:
  1. Map massless B-hadron momentum to massive one
  2. Decay massive B-hadron using external package
- Not ideal:
  - Momentum remapping ambiguous
  - Need to interface to external package (e.g. EvtGen)
- Easier and more consistent solution:
  1. Modify fragmentation function to incorporate the decay
  2. Run the program as usual, no modifications required
- Fragmentation function $D_{B\to d}$ for the decay $B \to d + X$

Including B-hadron decays in theory predictions





Preliminary results



Conclusion and outlook

- Can now describe the production of any hadron in any process at NNLO
- First application: top-quark pairs at the LHC
- Much smaller uncertainties at NNLO than at NLO
- Fitted a new NNLO B-hadron FF consistent with our approach
- Calculation can now include B-hadron decays

We are very interested in comparing to data in dedicated studies!

Fragmentation functions for B-hadron decays

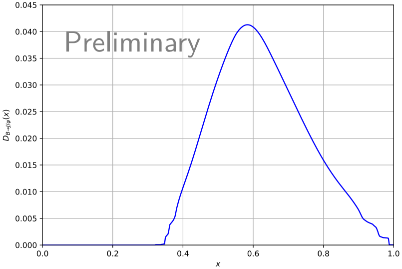
- Assume isotropic decay: $d\Gamma(B \to \mu + X) = f(E_\mu) dE_\mu d\cos\theta_\mu d\phi_\mu$
- Valid for spin-0 particles (e.g. weakly-decaying B-mesons)
- Normalize E_μ using $m_B \Rightarrow f(E_\mu)dE_\mu \to f(y)dy$
- Boost from B-hadron rest frame to $E_B \gg m_B$ and integrate over the angles and y, fixing $x = E_\mu / E_B$

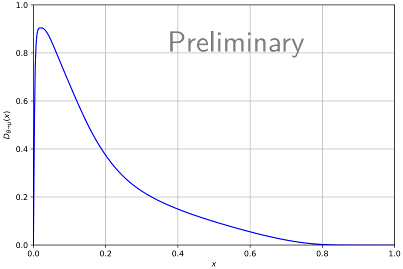
$$\Rightarrow \frac{d\Gamma(B \to \mu + X)}{dy} \to D_{B\to\mu}(x)$$

- $D_{B\to\mu}$ is the ‘fragmentation function’ for transition $B \to \mu$
- Can calculate $D_{B\to\mu}$ once and for all
- $D_{B\to\mu}$ combines with known $D_{i\to B}$ via convolution

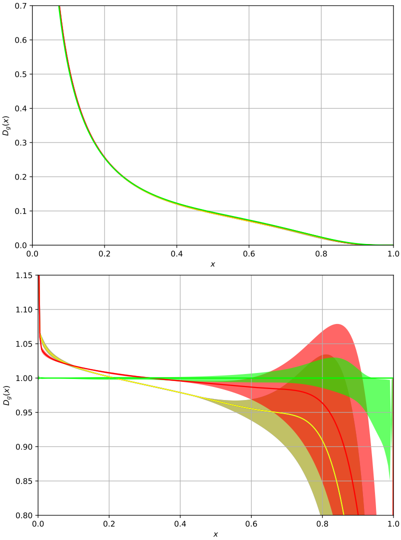
Fragmentation functions for B-hadron decays

- Only requirement: must know $f(E_\mu)$
- Can be obtained using e.g. EvtGen
- Works for any descendant, not just muons
- Vast amount of data from B-factories
  $\Rightarrow f(E_\mu)$ expected to be more precise than $D_{i\to B}$

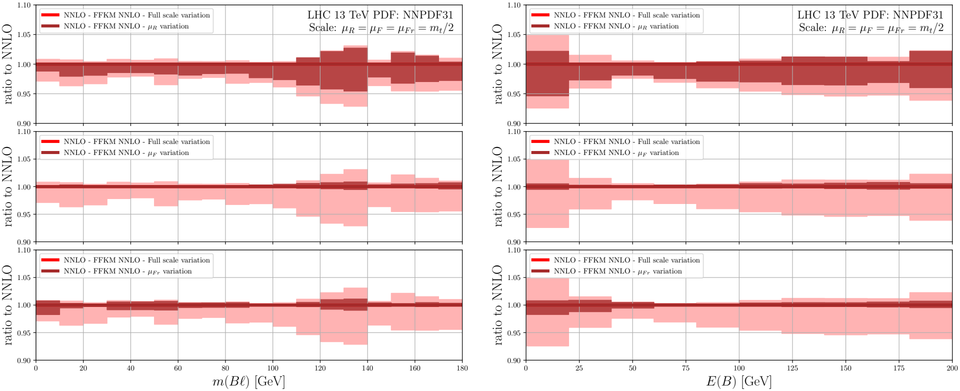




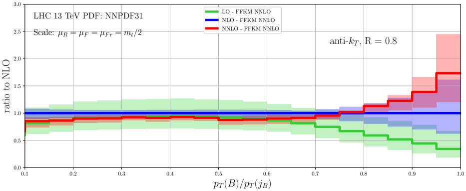
Gluon and light-quark to B-hadron FFs (preliminary)

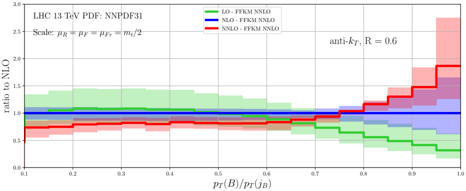


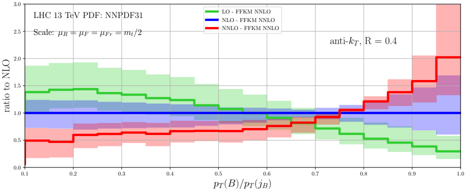
Top-pair events with B-hadrons at the LHC: separated scale dependence

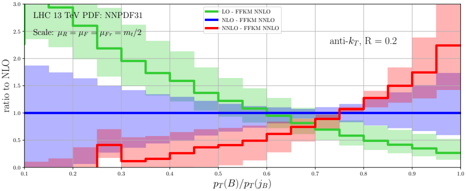


Jet ratio: R-dependence

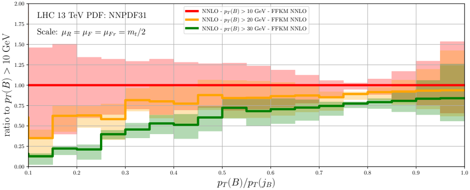


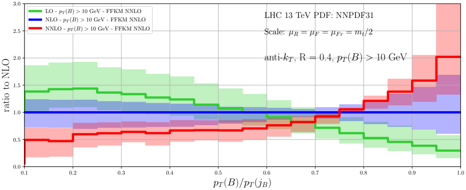


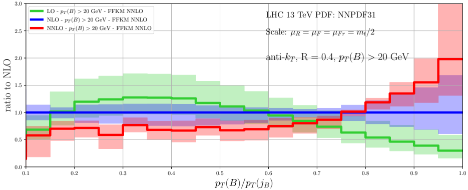


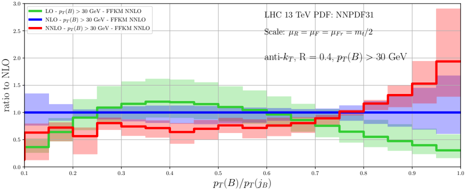


Jet ratio: p_T-cut-dependence

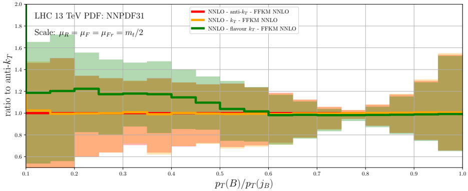


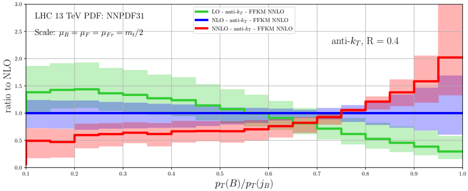


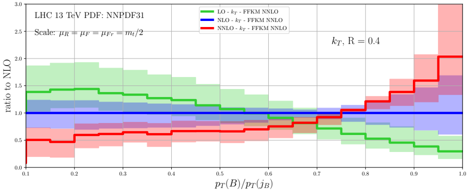


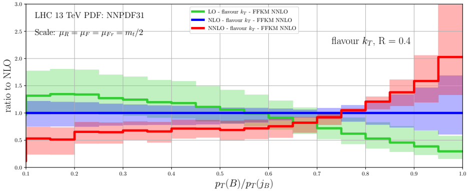


Jet ratio: jet-algorithm-dependence









Introduction to fragmentation

- Idea: describe production of hadrons using two steps
  1. The production of partons using perturbation theory
  2. The (non-perturbative) fragmentation of these partons into the observed hadrons
- Transition parton $\longrightarrow$ hadron in the final state
- Hadron's momentum is measurable (parton's is not)
- Mathematically similar to transition hadron $\longrightarrow$ parton in the initial state

Perturbative fragmentation functions: introduction

- Need to fit many parameters (one function per parton)
- Reduction possible for heavy flavours using perturbative fragmentation functions (PFFs) *Mele and Nason (1991)*
- Heavy-flavoured hadrons contain heavy quarks
- The heavy-quark mass satisfies $m_Q \gg \Lambda_{\text{QCD}}$
- $\Rightarrow$ Production of heavy quarks can be described perturbatively
- $\Rightarrow$ Split fragmentation into production of heavy quark and fragmentation of heavy quark into hadron

Reduction of non-perturbative parameters

- Split fragmentation function into a non-perturbative FF (NPFF) and PFFs:

$$D_{i\to h} = D_{i\to Q} \otimes D_{Q\to h}$$

- $D_{i\to Q}$ calculable $\Rightarrow$ only need to fit $D_{Q\to h}$ (single function)
- Without PFFs: gluon FF poorly constrained by e^+e^--colliders
- $\Rightarrow$ Large uncertainties at the LHC