Top-pair events with B-hadrons at the LHC

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Based on arXiv:2102.08267 and arXiv:2210.06078

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Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

Research Training Group Physics of the Heaviest Particles at the LHC

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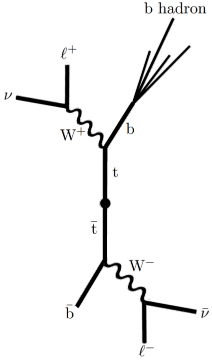
Top-pairs with B-hadrons

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

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

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

- Production of hadrons is a non-perturbative effect

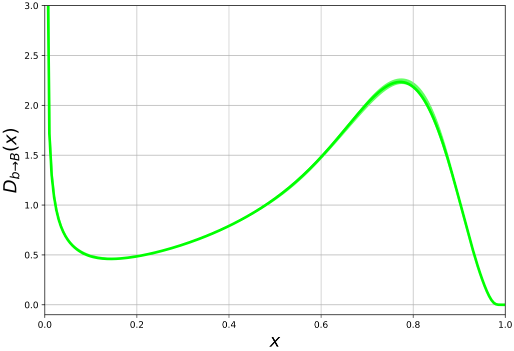


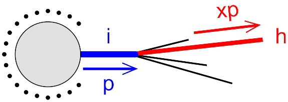
Introduction to fragmentation

- 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→hadron in the final state
- Mathematically similar to transition hadron→parton in the initial state
- Factorisation accurate up to $\mathcal{O}\left(\frac{m_h}{Q}\right)$

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:
  - Isolated photon + dijet production at the LHC
    Badger, Czakon, Hartanto, Moodie, Peraro, Poncelet, Zoia (2023)
  - Event shapes at the LHC
    Alvarez, Cantero, Czakon, Llorente, Mitov, Poncelet (2023)
  - $Wb\bar{b}$ production at the LHC *Hartanto, Poncelet, Popescu, Zoia (2022)*
  - 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)
  - ...
- First implementation of fragmentation in a general code for NNLO cross sections
- Fully general implementation; not limited to cases presented in this talk

New fragmentation function fits

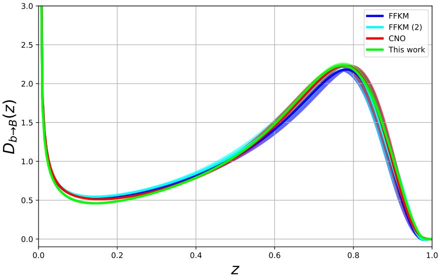
- No fits based on PFF approach available at NNLO
- Required for fully consistent results
- First paper: FF sets based on three different compromises
- Two based on NNLO calculation within SCET/HQET

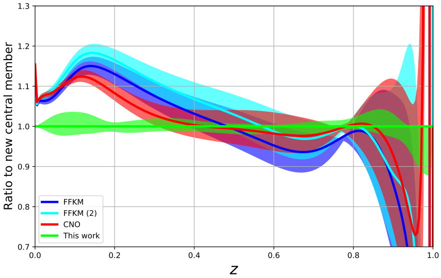
  Fickinger, Fleming, Kim, Mereghetti (2016)
- One based on NLO calculation within PFF approach

  Cacciari, Nason, Oleari (2006)
- Different compromises consistent within uncertainties
- Nonetheless better to use a consistent fit

First NNLO fit within the PFF approach

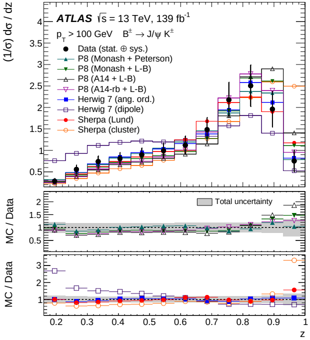
- Based on data from ALEPH, DELPHI, OPAL and SLD.
- Blue/cyan: based on Fickinger, Fleming, Kim, Mereghetti (2016)
- Red: based on Cacciari, Nason, Oleari (2006)
- Green: Czakon, TG, Mitov, Poncelet (2022)
- First NNLO PFF with NNLL soft-gluon resummation





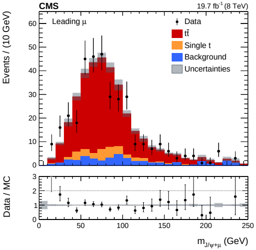
Incorporating *B*-hadron decays

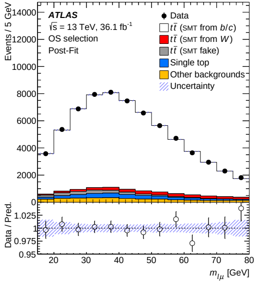
- First paper: predictions for fully reconstructed *B*-hadrons only
- Full reconstruction of *B*-hadrons difficult in practice
- Not enough $t\bar{t}$ events for distributions
  $\Rightarrow$ Cannot compare first results to experiment at present
- Could compare to data if process changed to $p\,p \rightarrow B + X$
- Fully reconstructed *B*-hadrons in arXiv:2108.11650 (ATLAS)
- Not a problem for the software, but process lacks information on m_t



Incorporating B-hadron decays

- Solution: incorporate B-hadron decays
- Only reconstruct some decay products
  $\Rightarrow$ Significantly boost statistics
- Examples:
  CMS: arXiv:1608.03560 ($B \longrightarrow J/\psi + X$)
  ATLAS: arXiv:2209.00583 ($B \longrightarrow \mu + X$)
- Still considering top-pair production,
  but comparison with experiment now possible

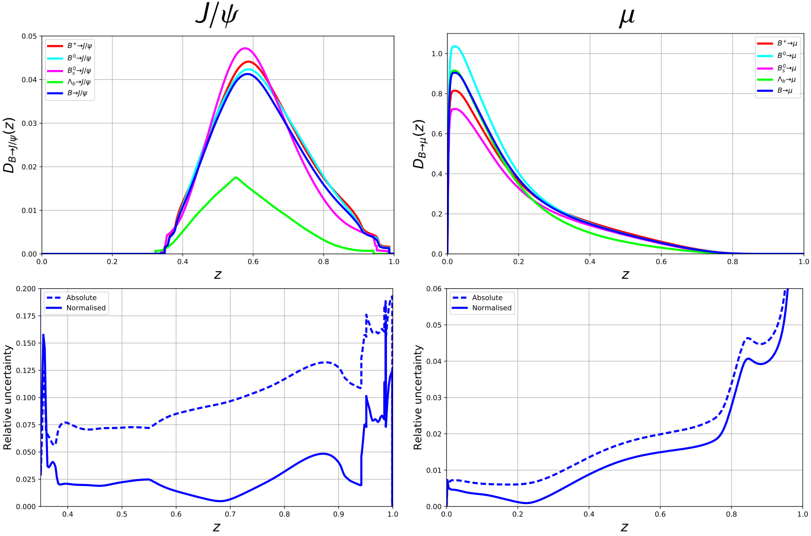




Including B-hadron decays in theory predictions

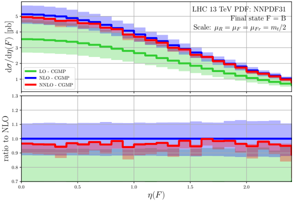
- B-hadron treated as massless $\Rightarrow$ cannot decay
- Most obvious solution:
  1. Map massless B-hadron momentum to massive one
  2. Decay massive B-hadron using external package
- Not ideal:
  - Momentum remapping ambiguous
  - Need to interface to external package (e.g. EvtGen)
- Easier and more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

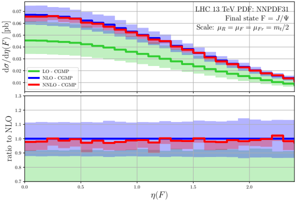
B-hadron decay fragmentation functions

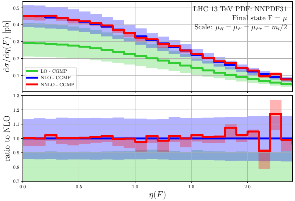


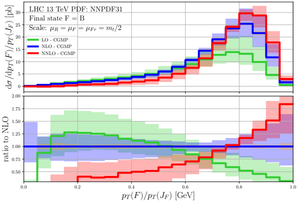
Results: pseudorapidity and jet-ratio spectra

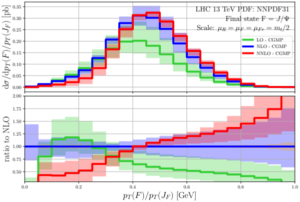
B | J/ψ | μ

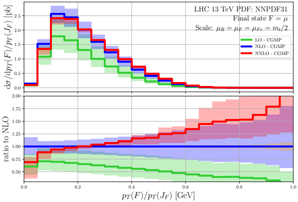






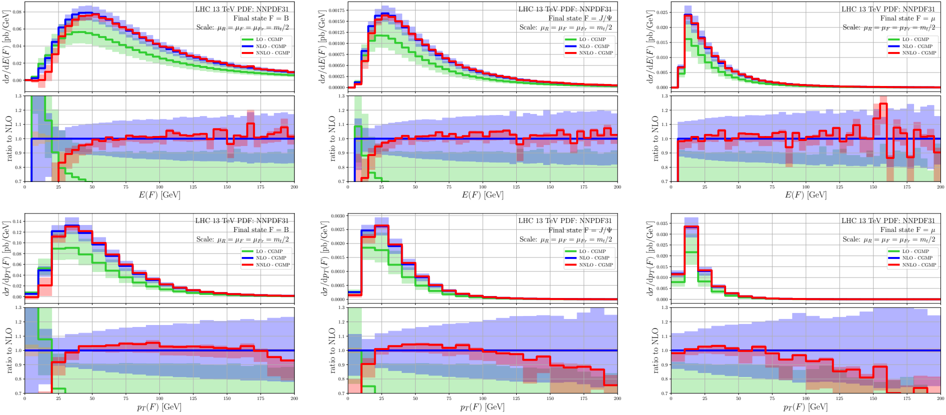






Results: energy and transverse momentum spectra

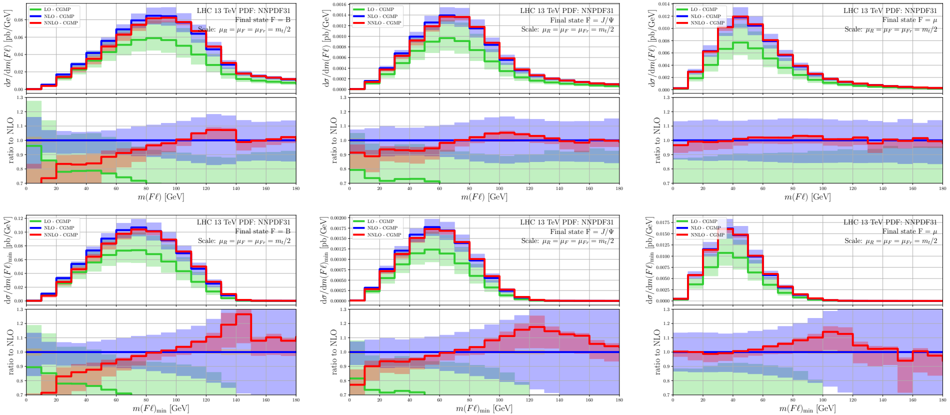
B | J/ψ | μ



Results: invariant mass spectra

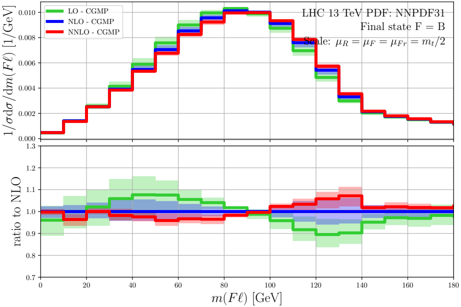
Two versions: $m(F\ell) \equiv m(F\ell^+)$ and $m(F\ell)_{\text{min}} \equiv \min(m(F\ell^+), m(F\ell^-))$

B J/ψ μ

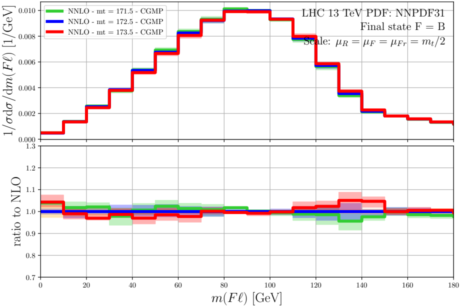


Measuring m_t using the $m(B\ell)$ spectrum

LO, NLO, NNLO for fixed m_t

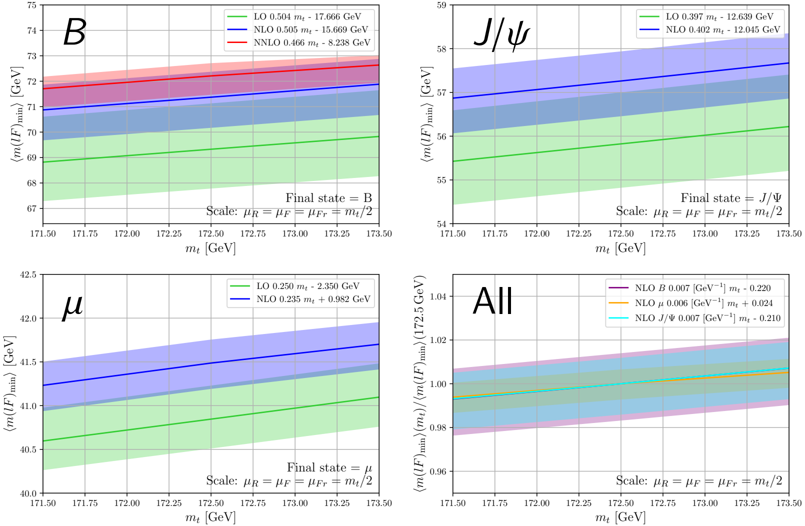


NNLO, varying m_t by 1 GeV



- Note: NNLO effects almost identical to a $\sim$1 GeV shift in m_t

Measuring m_t using $\langle m(F\ell)_{\min}\rangle$



Conclusion & outlook

- First NNLO+NNLL B-hadron FF fit within PFF approach
- Introduced novel method of integrating decays into FFs
- First application: top-quark pairs at the LHC
- Much smaller uncertainties at NNLO than at NLO
  $\Rightarrow$ Reduction of theory uncertainties on extracted m_t
- Framework completely general: any process, any hadron, any decay

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

Backup slides

Phase-space cuts

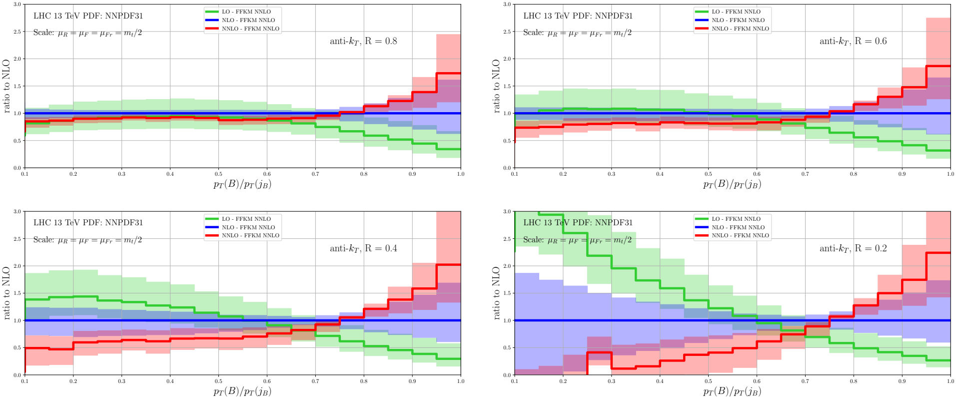
Differential distributions:

- $p_T(\ell) > 25$ GeV, $|\eta(\ell)| < 2.5$
- at least 2 anti-k_T jets $(R = 0.4)$ with $p_T(j) > 25$ GeV and $|\eta(j)| < 2.5$
- $\Delta R(\ell, j) > 0.4$
- $p_T(F) > 8$ GeV and $|\eta(F)| < 2.5$, F must be part of one jet

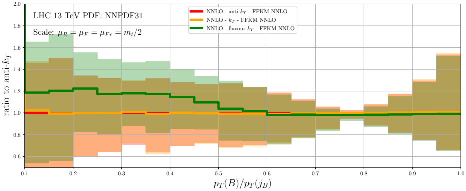
Top-quark-mass extraction:

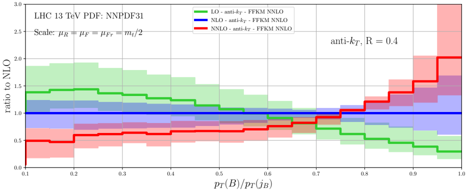
- $p_T(\ell) > 25$ GeV, $|\eta(\ell)| < 2.5$
- $p_T(F) > 8$ GeV and $|\eta(F)| < 2.5$

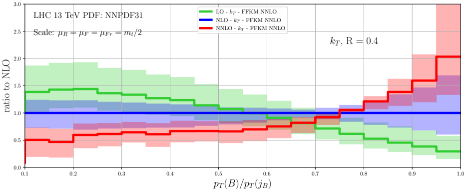
Jet ratio: R-dependence

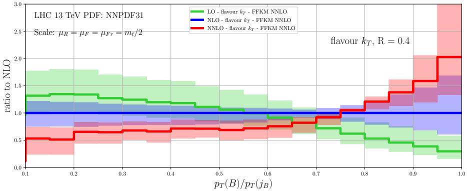


Jet ratio: jet-algorithm-dependence

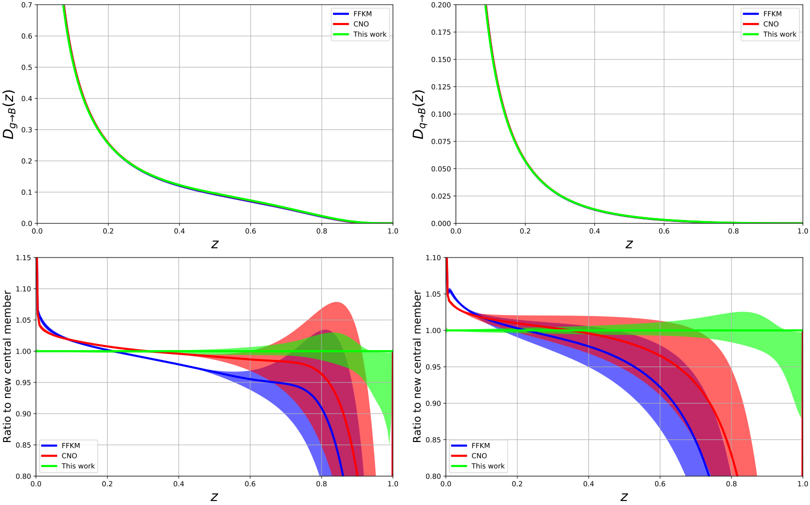








First NNLO fit within the PFF approach



Including B-hadron decays in theory predictions

- 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 $z = E_\mu / E_B$

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

- $D_{B\to\mu}$ is the 'fragmentation function' for transition $B \to \mu$

Including B-hadron decays in theory predictions

- Can calculate $D_{B\to\mu}$ once and for all
- $D_{B\to\mu}$ combines with known $D_{i\to B}$ via convolution
- 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 $D_{i\to B}$

Decay fragmentation function derivation

$$d\Gamma(B \longrightarrow d + X) = \frac{1}{4\pi} f(E_d^{\text{rest}})\, dE_d^{\text{rest}}\, d\cos(\theta)\, d\phi \overset{y=\frac{E_d^{\text{rest}}}{m_B}}{=} \frac{m_B}{4\pi} f(y\, m_B)\, dy\, d\cos(\theta)\, d\phi$$

Boost to $E_B \gg m_B$ along the z-axis and fix $z = \frac{E_d}{E_B}$ using

$$\delta\left(z - \frac{E_d}{E_B}\right) = \delta\left(z - \gamma_B \frac{E_d^{\text{rest}} + \beta_B \cos(\theta)\sqrt{(E_d^{\text{rest}})^2 - m_d^2}}{E_B}\right)$$

$$\approx \delta\left(z - \frac{E_d^{\text{rest}} + \cos(\theta)\sqrt{(E_d^{\text{rest}})^2 - m_d^2}}{m_B}\right)$$

$$= \delta\left(z - y - \cos(\theta)\sqrt{y^2 - \frac{m_d^2}{m_B^2}}\right)$$

Decay fragmentation function derivation

Integrating over the angles and y yields

$$\frac{d\Gamma(B \to d + X)}{dz}$$

$$= \int_0^{2\pi} \int_{-1}^{1} \int_0^{1} \frac{m_B}{4\pi} f(y\, m_B) \delta\left(z - y - \cos(\theta) \sqrt{y^2 - \frac{m_d^2}{m_B^2}} \right) dy\, d\cos(\theta)\, d\phi$$

$$= \int_0^{1} \frac{m_B}{2\sqrt{y^2 - \frac{m_d^2}{m_B^2}}} f(y\, m_B) \theta\left(1 - \frac{(z-y)^2}{y^2 - \frac{m_d^2}{m_B^2}} \right) dy$$

$$= \int_{\frac{z}{2} + \frac{m_d^2}{2z\, m_B^2}}^{1} \frac{m_B}{2\sqrt{y^2 - \frac{m_d^2}{m_B^2}}} f(y\, m_B)\, dy \equiv \Gamma_B\, D_{B \to d}(z)$$