B-hadrons in top-quark pair production at NNLO QCD

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TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

in collaboration with: G. Corcella, T. Generet, A. Mitov and R. Poncelet

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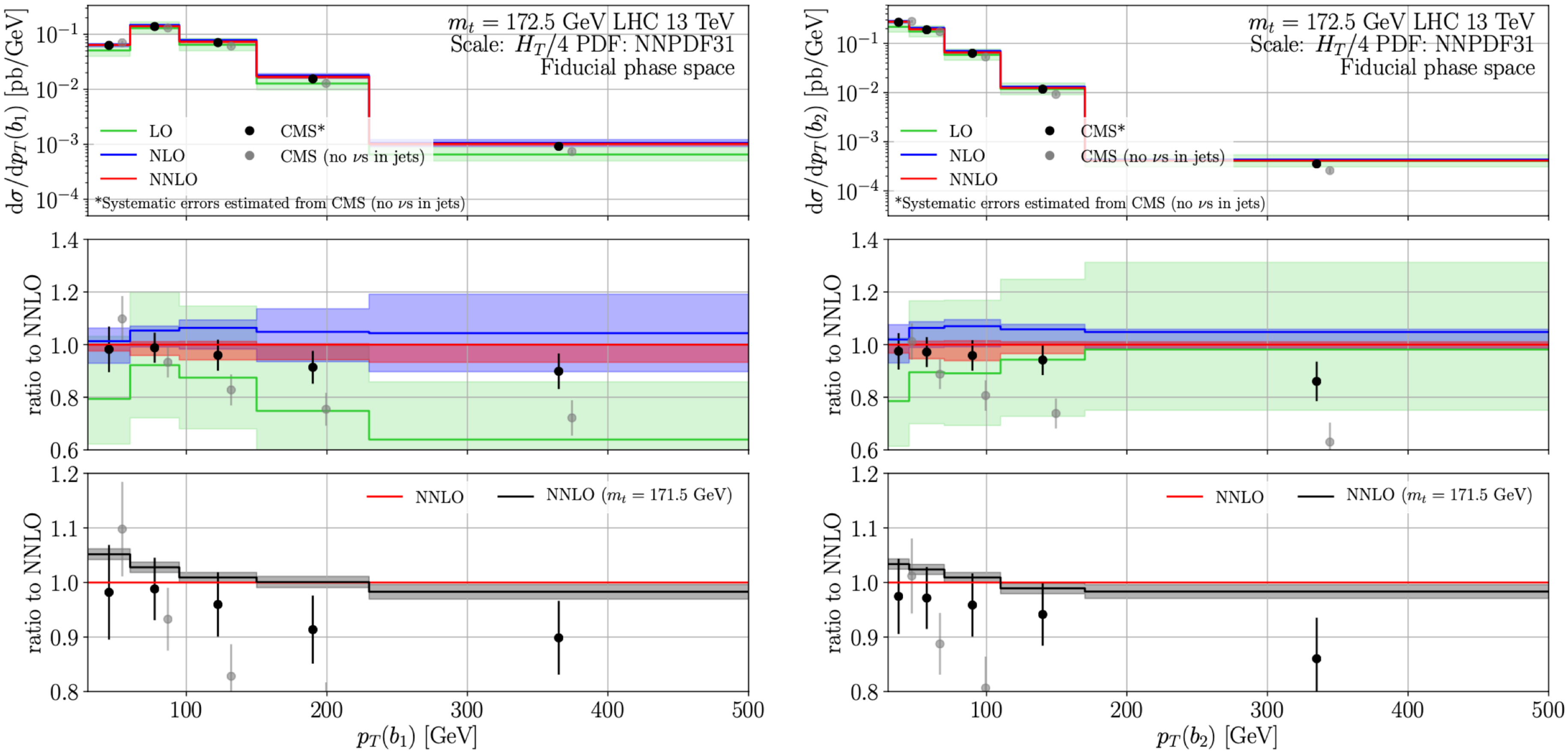
Main message

NNLO-QCD precise theory predictions for B-hadrons and their descendants

Top-quark pair production at the LHC is only one of many possible applications

b-jet definition non-trivial

Fixed order predictions require a different approach than event-generator simulations



[**MC**, Mitov, Poncelet, '20](#)
[Presented by Poncelet at TOP 2020](#)

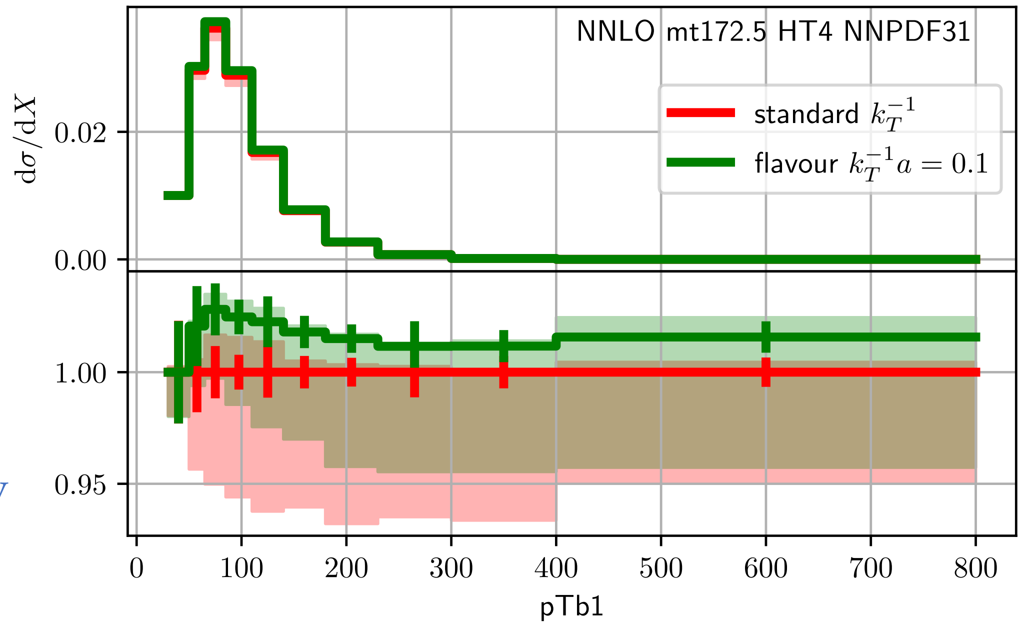
Flavor anti-k_T algorithm for top pairs

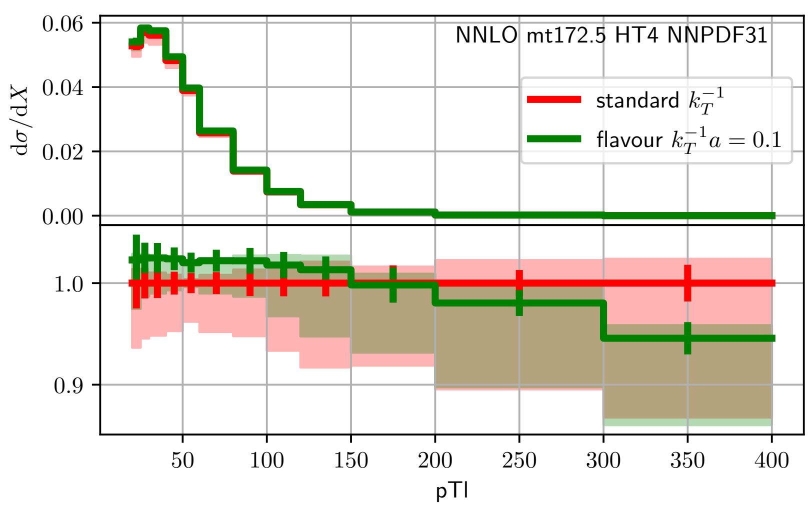
Problem led to a new proposal of a flavor-sensitive jet algorithm

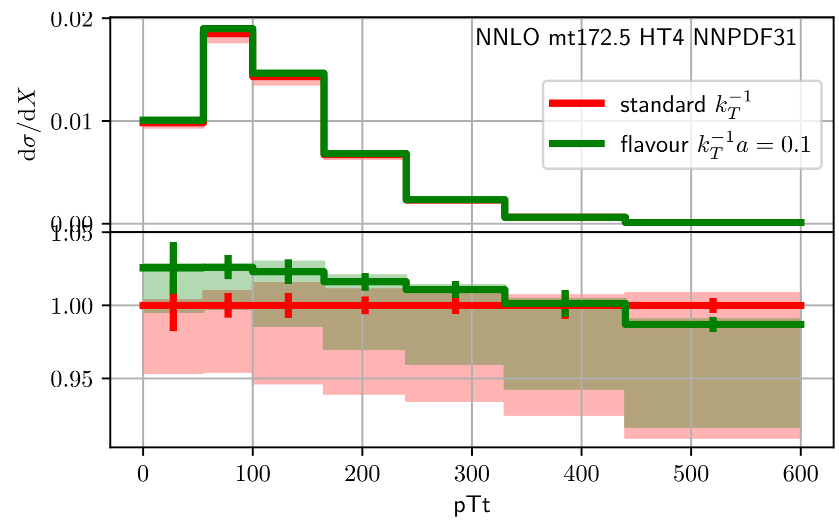
$$pp \to t\bar{t}b\bar{b} \to b\bar{\ell}\nu\bar{b}\ell\bar{\nu}b\bar{b}$$

NNLO production and decays

MC, A. Mitov, R. Poncelet, preliminary







Flavor and jet algorithms

- Flavor k_T algorithm Banfi, Salam, Zanderighi, '06

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}, k_{tj})^{\alpha} \min(k_{ti}, k_{tj})^{2-\alpha} & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}, k_{tj})^{\alpha} & \text{softer of } i,j \text{ is unflavoured} \end{cases}$$

$0 < \alpha \leq 2$
typically
$\alpha = 2$

$$d_{i\overset{(-)}{B}} = \begin{cases} \max(k_{ti}, k_{t\overset{(-)}{B}}(y_i))^{\alpha} \min(k_{ti}, k_{t\overset{(-)}{B}}(y_i))^{2-\alpha} & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}, k_{t\overset{(-)}{B}}(y_i))^{\alpha} & \text{softer of } i,j \text{ is unflavoured} \end{cases}$$

$$k_{tB}(y) = \sum_i k_{ti} \left(\Theta(y_i - y) + \Theta(y - y_i)\, e^{y_i - y}\right)$$

$$k_{t\bar{B}}(y) = \sum k_{ti} \left(\Theta(y - y_i) + \Theta(y_i - y)\, e^{y - y_i}\right)$$

jet flavor = net flavor or net flavor modulo 2, with flavor of relevant quarks +1 or -1

- Flavor anti-k_T algorithm proposal **MC,** A. Mitov, R. Poncelet

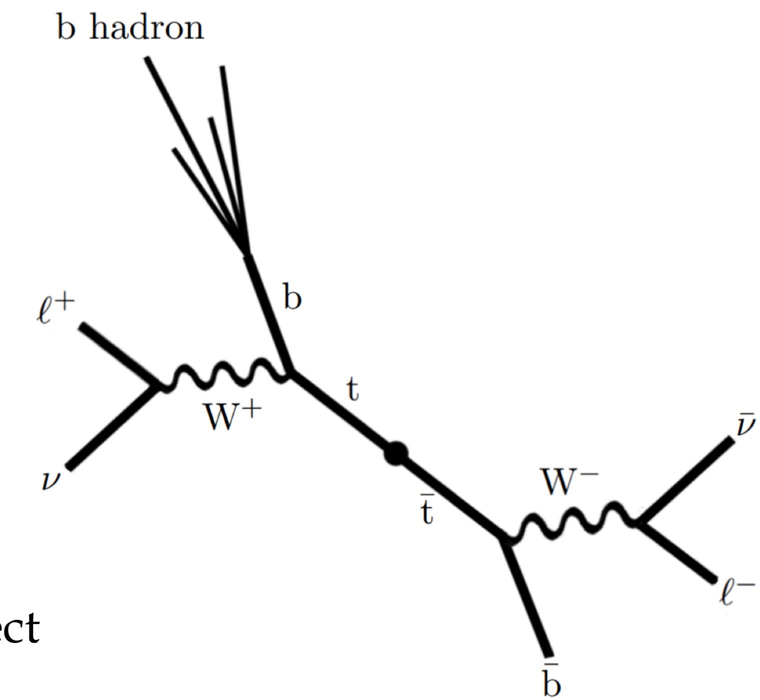
$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{if } i,j \text{ is a flavoured pair} \\ 1 & \text{else} \end{cases}$$

$$\mathcal{S}_{q\bar{q}}^{a} = 1 - \theta\,(1-x) \cos\left(\frac{\pi}{2} x\right) \quad \text{with} \quad x = \frac{k_T(q)^2 + k_T(\bar{q})^2}{a 2 k_{T,\max}^2}$$

Alternative: B-hadron observables

Process considered

$$pp \to t(\to BW^+(\to l^+\nu_l) + X)\ \bar{t}(\to \bar{b}W^-(\to l^-\bar{\nu}_l))$$



Measurements of B-hadrons very precise
⇒ high-precision top-mass determination

High top mass
⇒ small power corrections in m_b

Production of hadrons is a non-perturbative effect

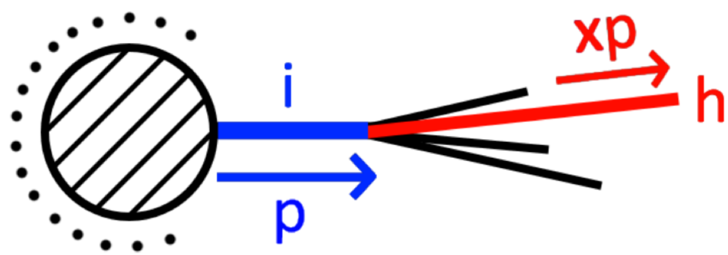
Idea: describe production of hadrons using two steps

1. production of partons (gluon and quarks) using perturbation theory
2. (non-perturbative) fragmentation of partons into the observed hadrons

Alternative: B-hadron observables

Transition parton → hadron in the final state
Hadron's momentum is measurable (parton's is not)
Mathematically similar to transition hadron → parton in the initial state

"Probability distribution" to find a hadron h with a fraction x
of the parton i's momentum: $D_{i \to h}(x)$



Formalism used here: collinear fragmentation from QCD factorisation

Only considers longitudinal kinematics; i, h massless
No need to rely on parton showers

Production of heavy-flavoured hadrons only requires
a single non-perturbative function

Alternative: B-hadron observables

Calculations were performed using C++ library Stripper

Many NNLO firsts over the years, e.g.:

Three-jet production at the LHC
MC, Mitov, Poncelet `21

Diphoton + jet at the LHC
Chawdhry, MC, Mitov, Poncelet `21

Exact top-mass effects in Higgs production at the LHC
MC, Harlander, Klappert, Niggetiedt `21

Top-pairs with B-hadrons at the LHC
MC, Generet, Mitov, Poncelet `21

W + c-jet at the LHC MC, Mitov, Pellen, Poncelet `20

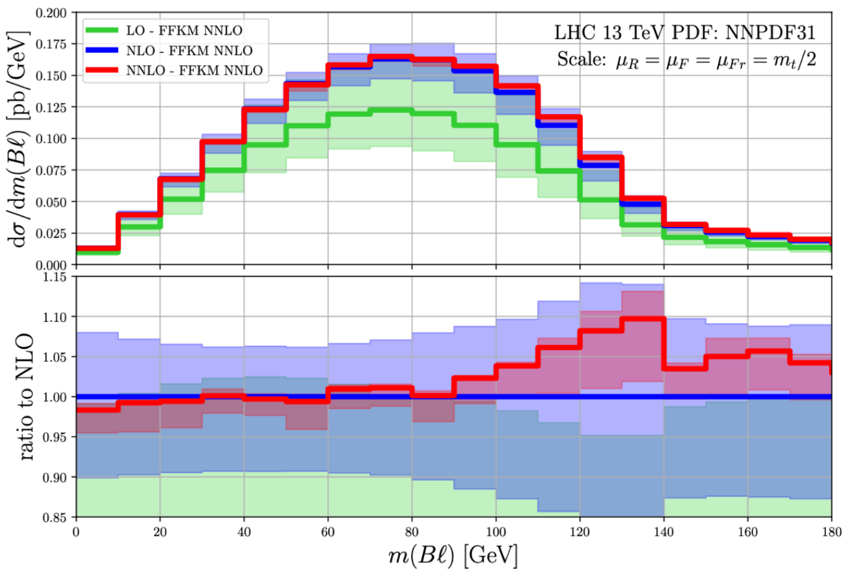
Here: first implementation of fragmentation in a general code for NNLO cross sections
Fully general; not limited to cases presented in this talk

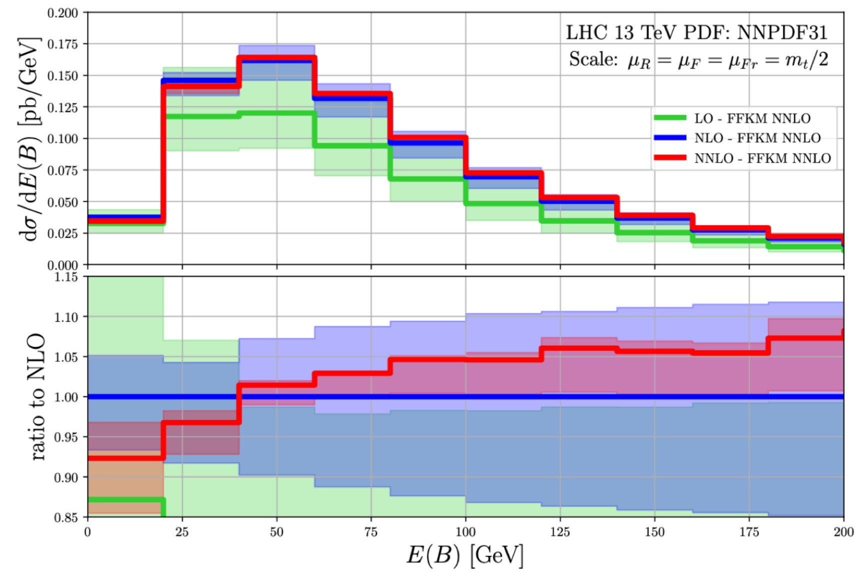
First study at NNLO QCD

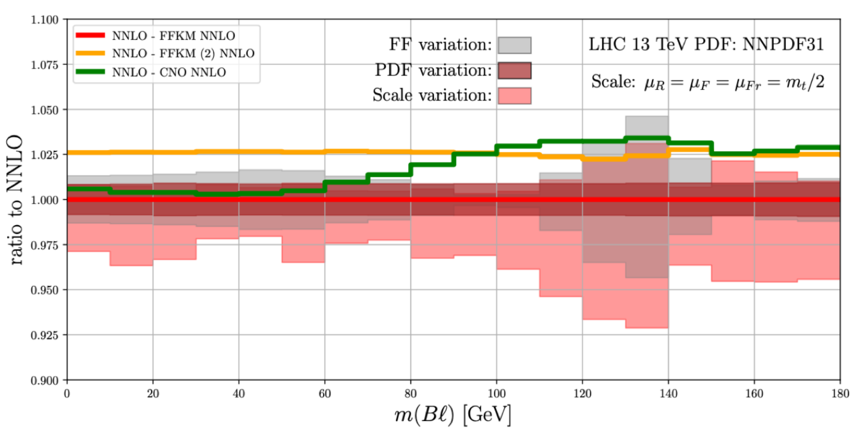
Previously studied at NLO QCD

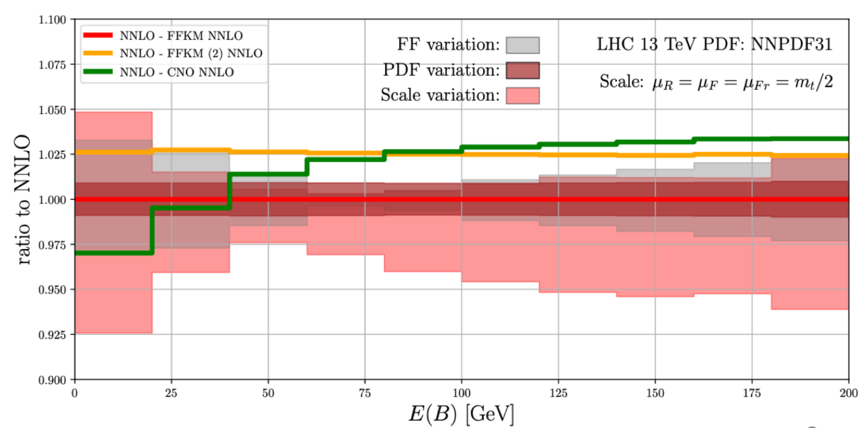
Kharchilava `00, Biswas, Melnikov and Schulze `10

Agashe, Franceschini and Kim `13, Agashe, Franceschini, Kim and Schulze `16



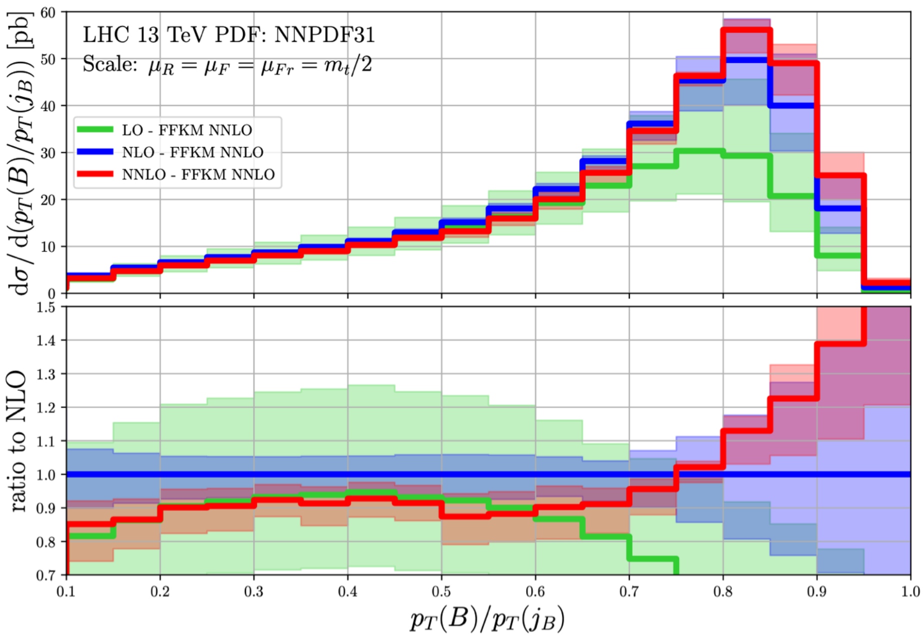


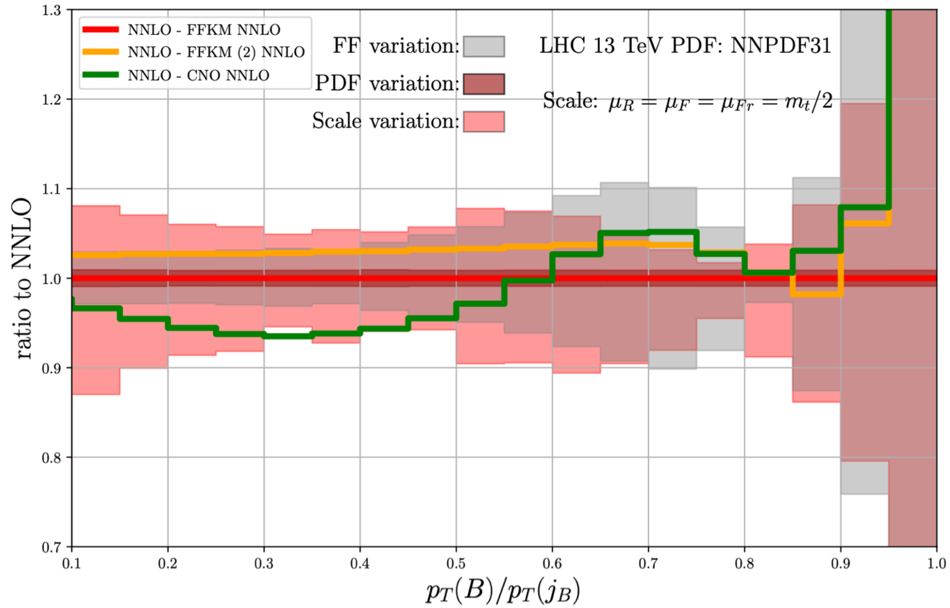




First study at NNLO QCD

Direct measurement of the fragmentation function in principle possible through a jet-ratio observable (here anti-k_T algorithm)

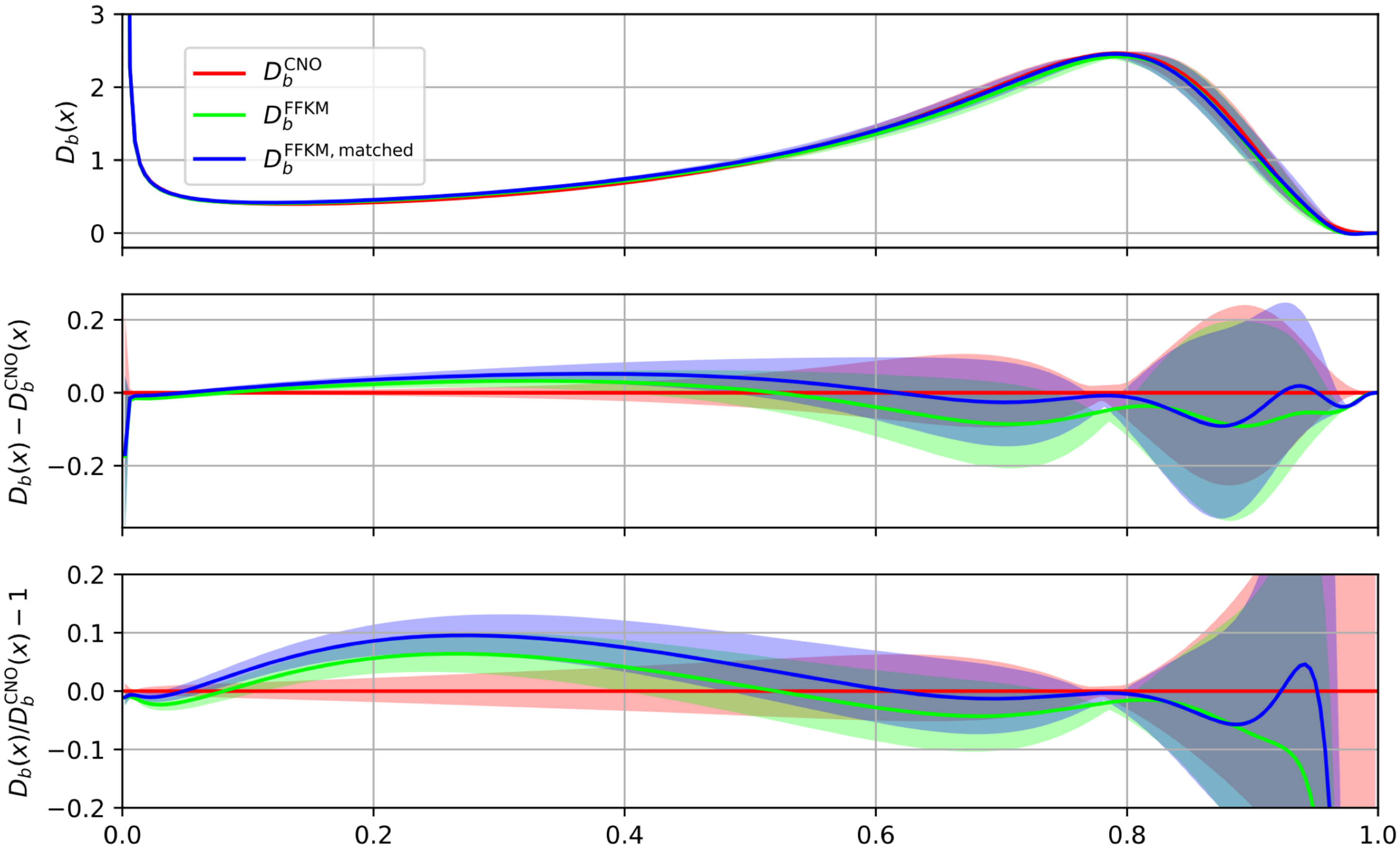




Analysis uses previously determined fragmentation functions
⇒ (minor) inconsistency of the (first) analysis

Fragmentation functions

Published analysis uses previously determined fragmentation functions
⇒ (minor) inconsistency of the (first) analysis

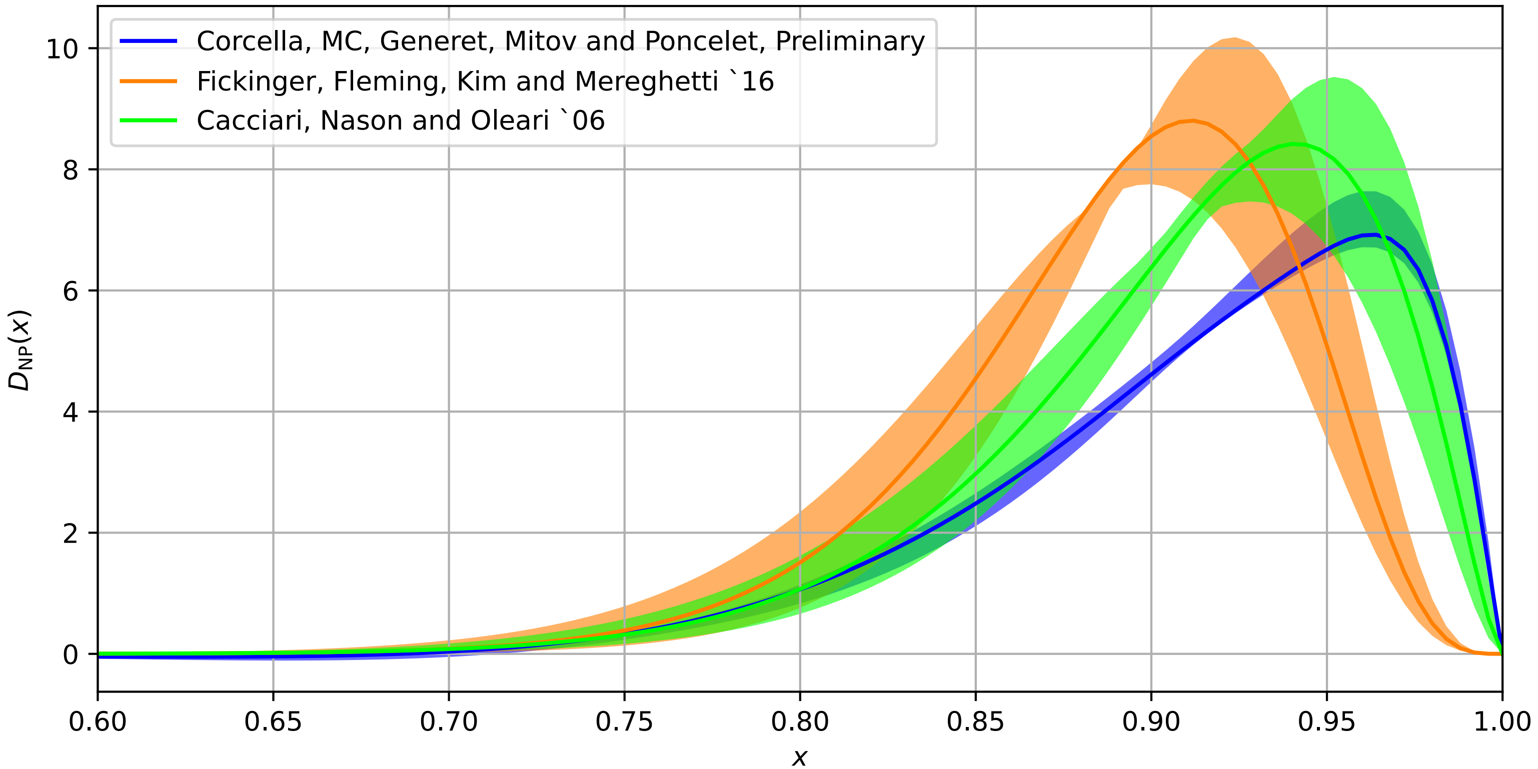


Fragmentation functions

New, consistent, determination of fragmentation functions

Dataset	ALEPH	DELPHI	OPAL	SLD
# of bins	19	9	20	22

Non-perturbative fragmentation function



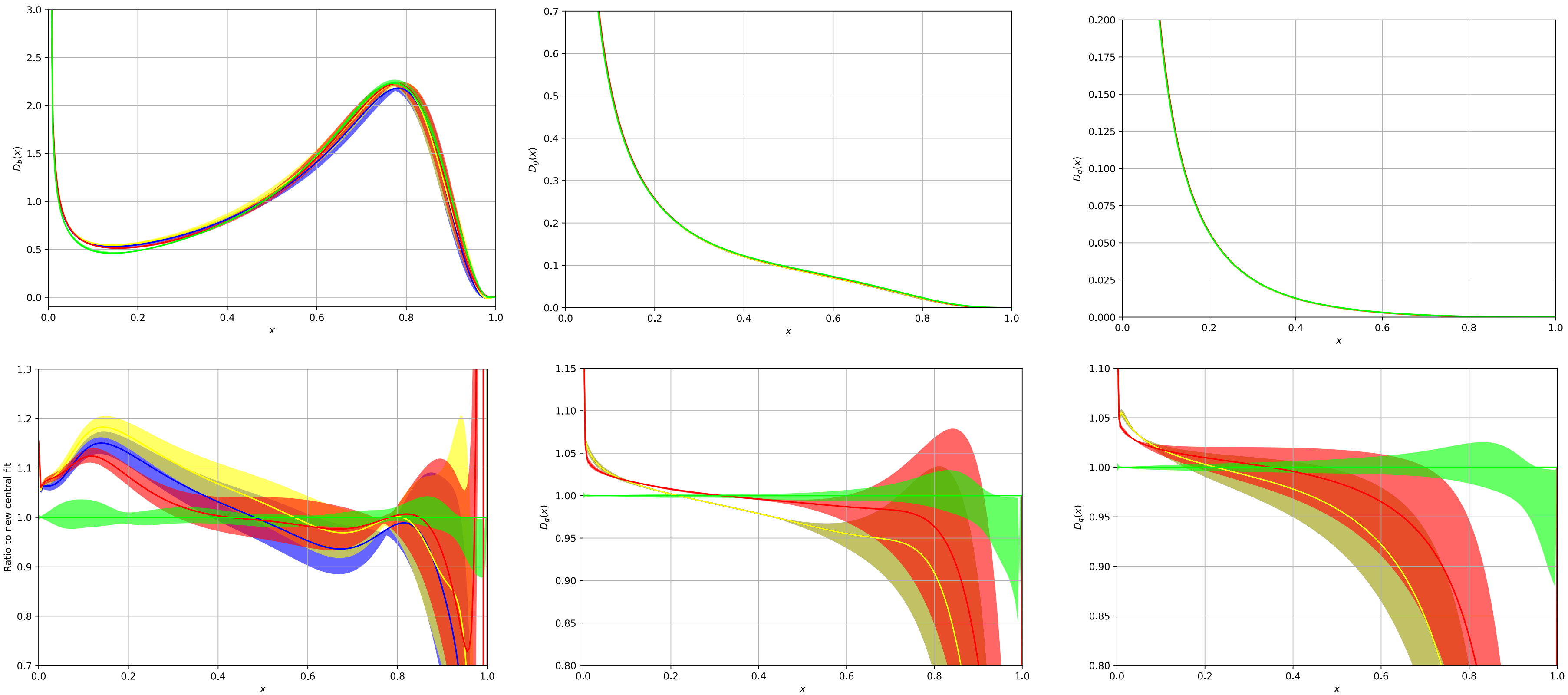
Fragmentation functions

Parton fragmentation function (convolution of perturbative and non-perturbative FFs)

Fickinger, Fleming, Kim and Mereghetti `16
Fickinger, Fleming, Kim and Mereghetti `16

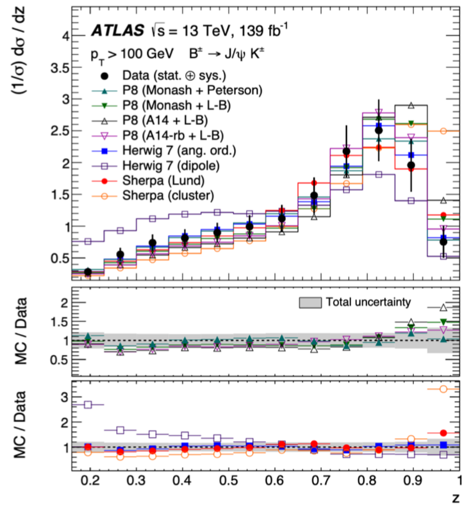
Corcella, MC, Generet, Mitov and Poncelet, Preliminary

Cacciari, Nason and Oleari `06

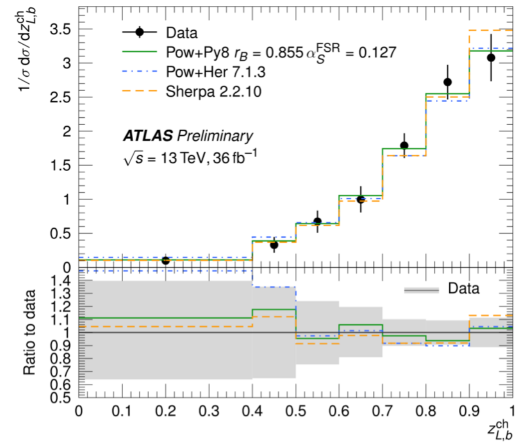


b-quark gluon light-quark

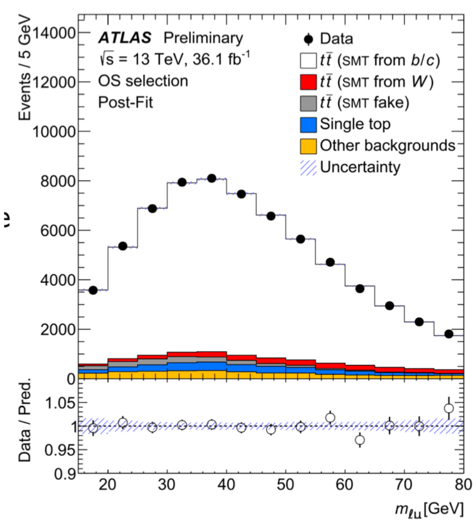
Example experimental studies



arXiv:2108.11650



ATLAS-CONF-2020-050



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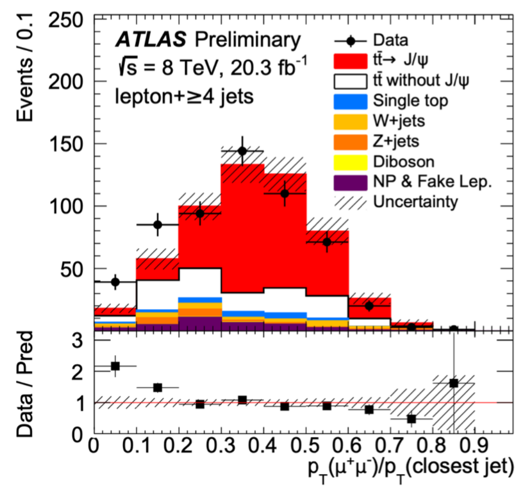


ATLAS-CONF-2015-040

Inclusion of B-hadron decays

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:

1. Momentum remapping ambiguous
2. 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

How can the decay be included in the fragmentation?

Inclusion of B-hadron decays

Assume isotropic decay $\mathrm{d}\Gamma(B \to \mu + X) = f(E_\mu)\mathrm{d}E_\mu \mathrm{d}\cos\theta_\mu \mathrm{d}\phi_\mu$
Valid for spin-0 particles (e.g. weakly-decaying B-mesons)

Normalize E_μ using m_B ⇒ $f(E_\mu)\mathrm{d}E_\mu \;\to\; f(y)\mathrm{d}y$

Boost from B-hadron rest frame to $E_B \gg m_B$
and integrate over the angles and y, fixing $x = E_\mu/E_B$

$D_{B\to\mu}$ is the „fragmentation function" for transition $B \to \mu$

$$\frac{\mathrm{d}\Gamma(B \to \mu + X)}{\mathrm{d}y} \;\to\; D_{B\to\mu}(x)$$

$D_{B\to\mu}$ combines with known $D_{i\to B}$ via convolution

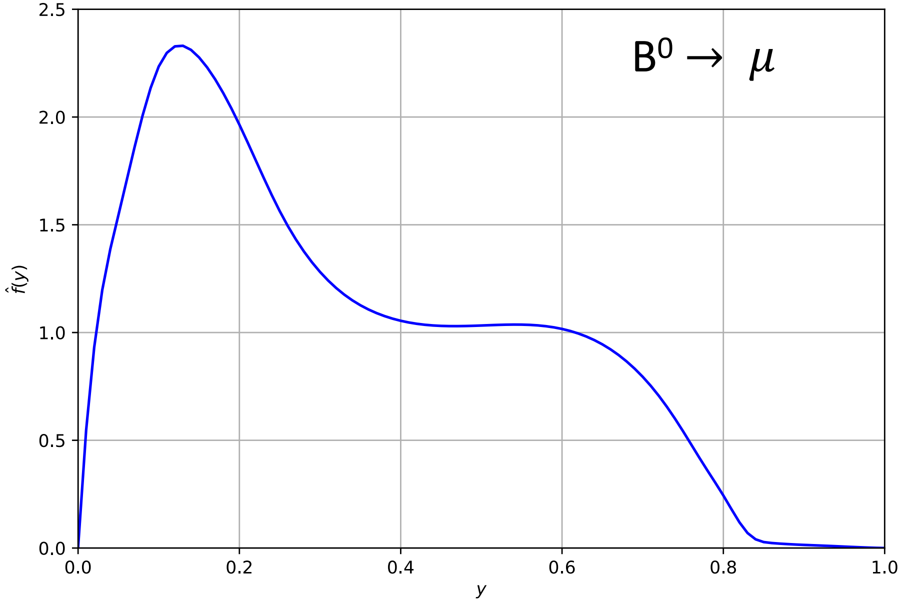
Only requirement: must know f (E_μ) can be obtained using e.g. EvtGen

Works for any descendant, not just muons

Vast amount of data from B-factories ⇒ f (E_μ) expected to be more precise than $D_{i\to B}$

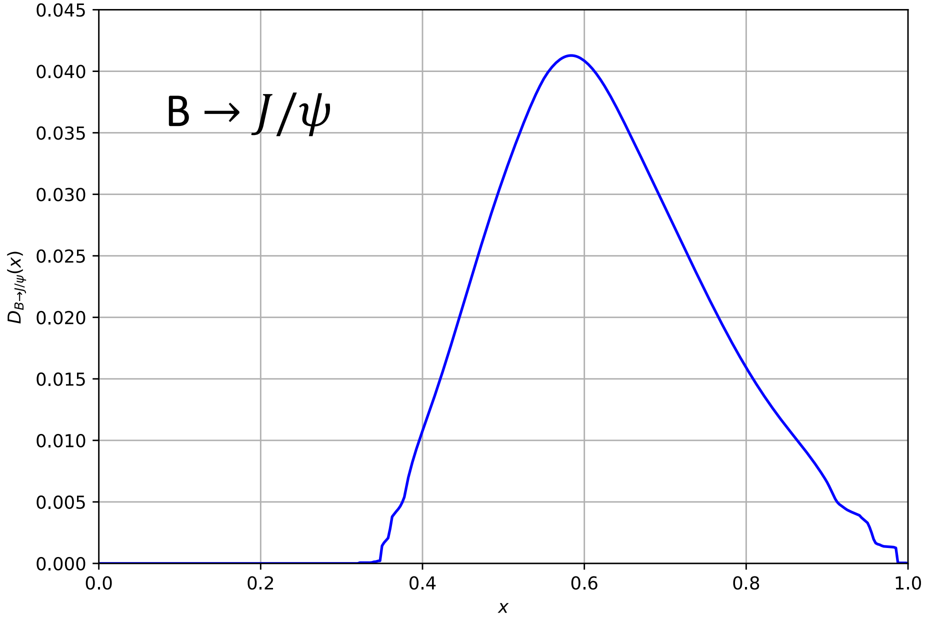
Inclusion of B-hadron decays

Example spectrum

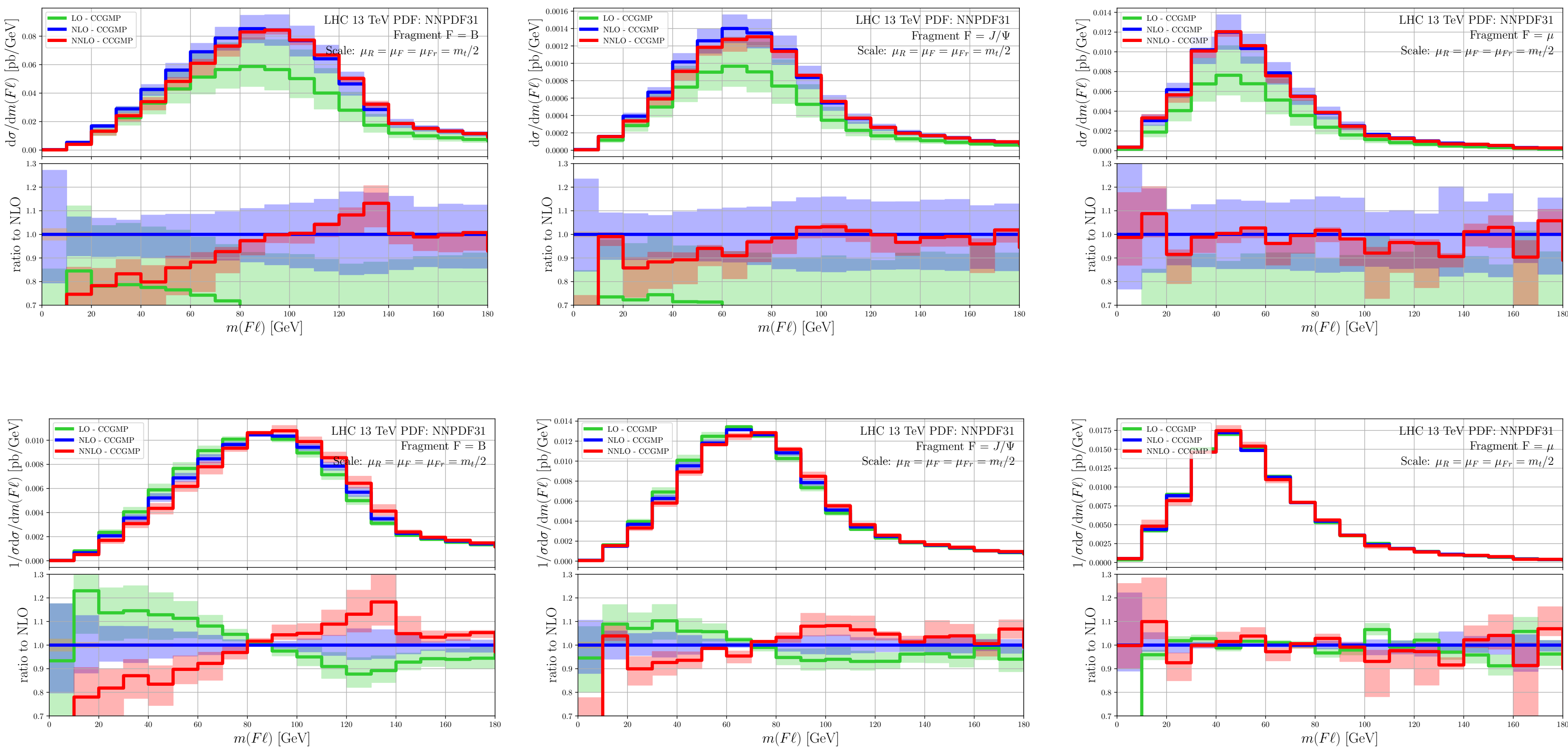


Corcella, MC, Generet, Mitov and Poncelet, Preliminary

Example fragmentation function

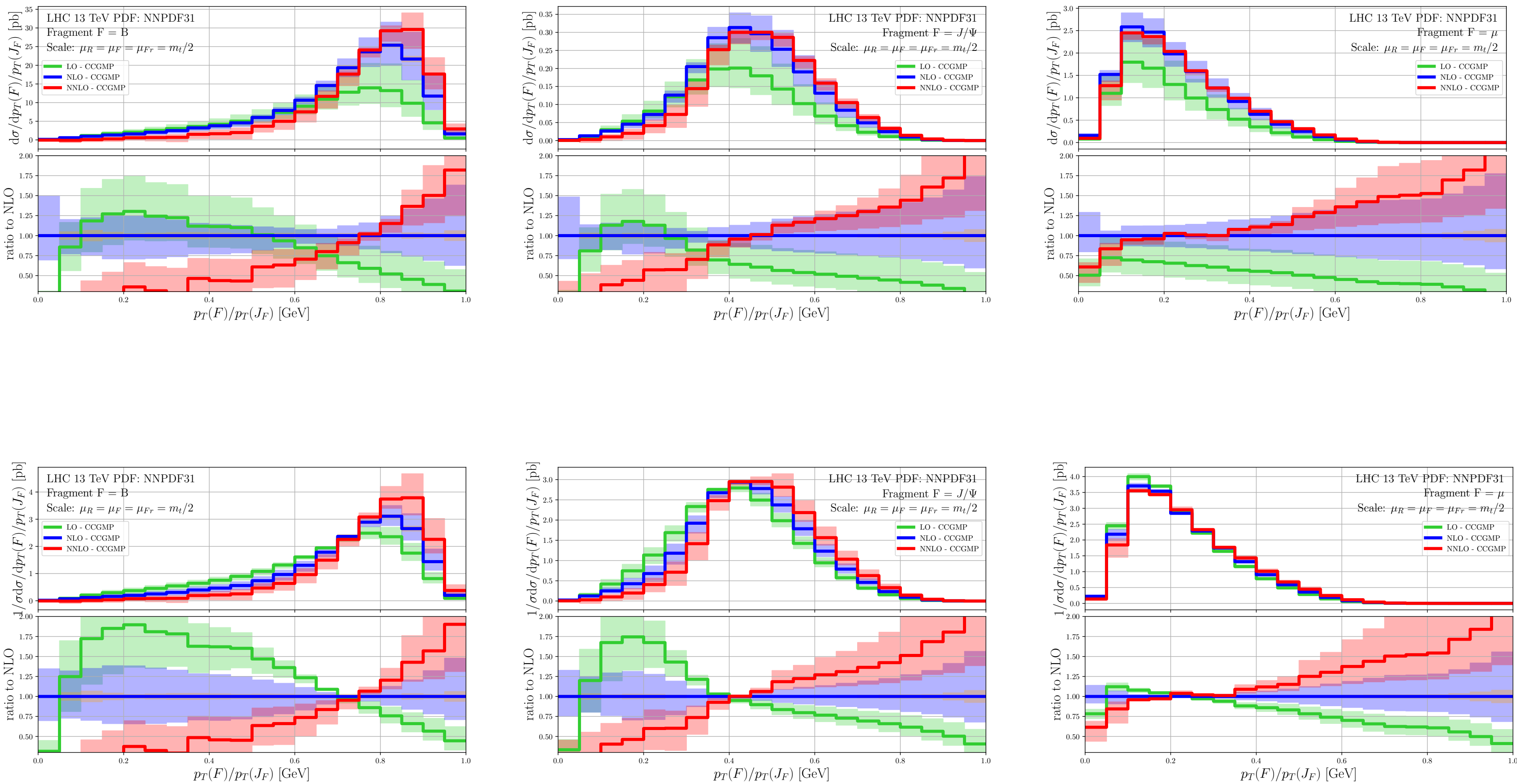


Application to top-pair production



Corcella, MC, Generet, Mitov and Poncelet, Preliminary

Application to top-pair production



Corcella, MC, Generet, Mitov and Poncelet, Preliminary

Conclusions

Can now describe any process involving fragmentation at NNLO QCD

First published application: top-quark pairs with B-hadrons at the LHC

Experiment: not enough statistics for fully reconstructed B-hadrons

Theory: cannot describe spectra involving charged tracks only
⇒ Must resort to studying B-hadron descendants

Included B-hadron decays to muons and J/ψ through convolutions of fragmentation functions

First application to top-quark pair-production at LHC presented, but more is possible

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