TMDs in Parton Branching approach

Recap of Parton Branching approach

$$f(x,\mu^2) = f(x,\mu_0^2)\Delta_s(\mu^2) + \int^{z_M} \frac{dz}{z} \int \frac{d\mu'^2}{\mu'^2} \cdot \frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)} P^{(R)}(z) f\left(\frac{x}{z},\mu'^2\right)$$

- solve integral equation via iteration:

from μ' to μ w/o branching

branching at μ'

from μ to μ' w/o branching

$$f_0(x,\mu^2) = f(x,\mu_0^2)\Delta(\mu^2)$$

$$f_1(x,\mu^2) = f(x,\mu_0^2)\Delta(\mu^2) + \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta(\mu^2)}{\Delta(\mu'^2)} \int^{z_M} \frac{dz}{z} P^{(R)}(z) f(x/z,\mu_0^2)\Delta(\mu'^2)$$

  - with $P_{ab}{}^{(R)}(z)$ real emission probability (without virtual terms)
    - z_M introduced to separate real from virtual and non-emission probability
    - reproduces DGLAP up to $\mathcal{O}(1-z_M)$

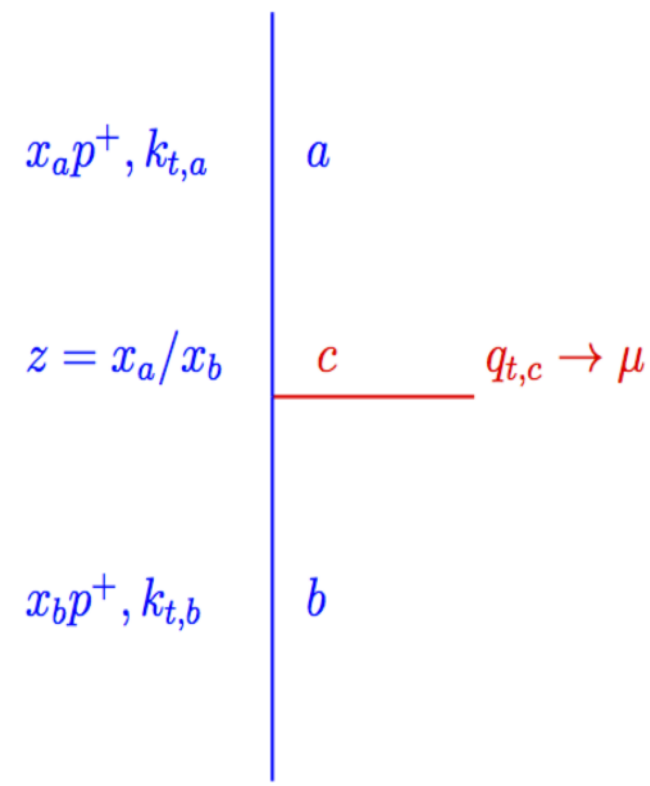
- make use of momentum sum rule to treat virtual corrections
  - use Sudakov form factor for non-resolvable and virtual corrections

$$\Delta_a(z_M,\mu^2,\mu_0^2) = \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} dz\ z\ P_{ba}^{(R)}(\alpha_s), z)\right)$$

Transverse Momentum Dependence

- Parton Branching evolution generates every single branching:
  - kinematics can be calculated at every step
- Give physics interpretation of evolution scale:
  - angular ordering:

    $\mu = q_T/(1-z)$

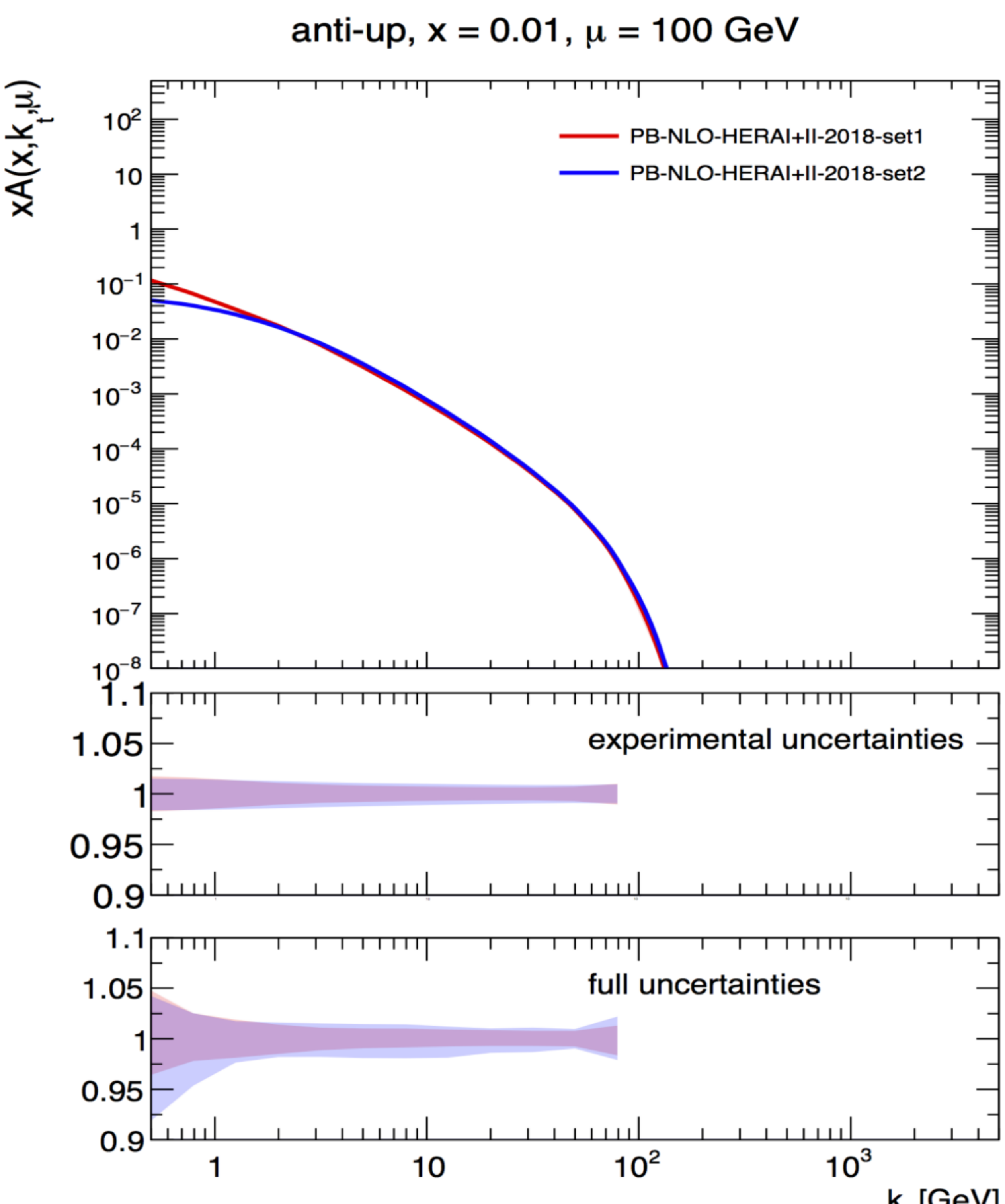


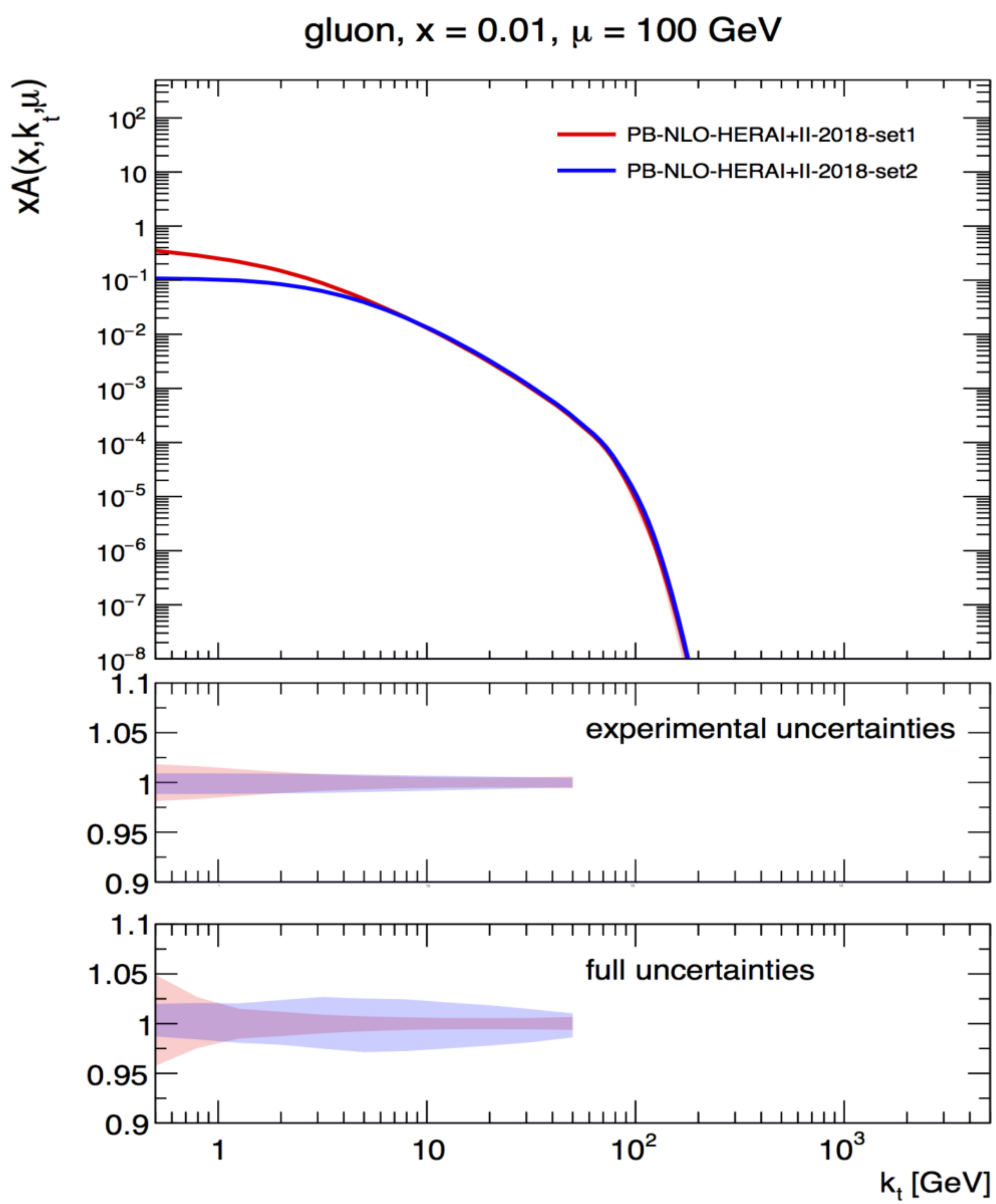
[1] F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Soft-gluon resolution scale in QCD evolution equations. Phys. Lett., B772:446–451, 2017.

[2] F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Collinear and TMD Quark and Gluon Densities from Parton Branching Solution of QCD Evolution Equations. JHEP, 01:070, 2018.

[3] A. Bermudez Martinez, P. Connor, F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Collinear and TMD parton densities from fits to precision DIS measurements in the parton branching method. DESY-18-042, arXiv 1804.11152

TMD distributions from fit to HERA data



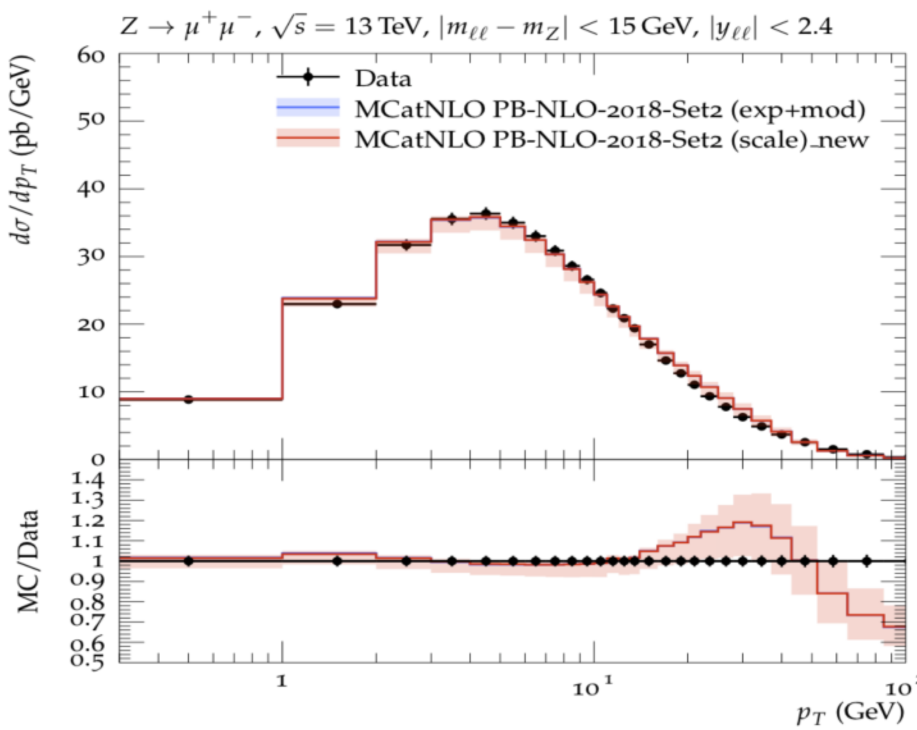


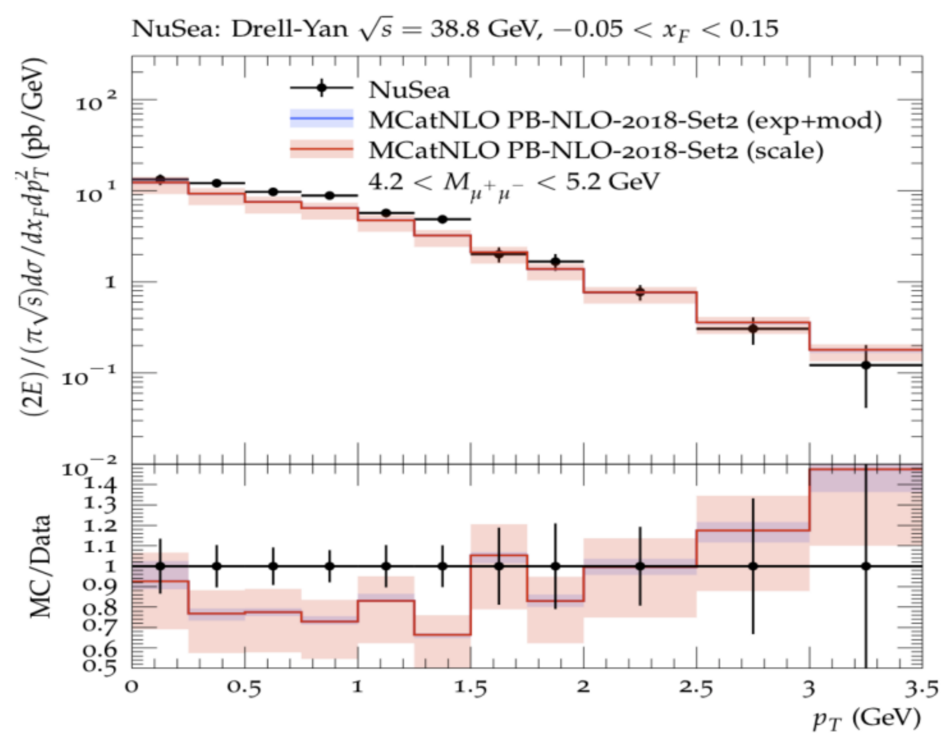
- model dependence larger than experimental uncertainties

What will be known about the TMD structure of hadrons in 5, 10, and 15 years from now?

- TMD densities from a global fit
  - PB TMD approach is implemented in xfitter
    - allows for precision determination – PB determination from inclusive HERA
  - Need: DY transverse momentum spectra for fits
- TMD densities applicable to low and high k_T and to all $\sqrt{s}$
  - PB approach for low and high mass DY

Bermudez Martinez, A. et al The transverse momentum spectrum of low mass Drell--Yan production at next-to-leading order in the parton branching method, Eur. Phys. J. C, 80(7), 598





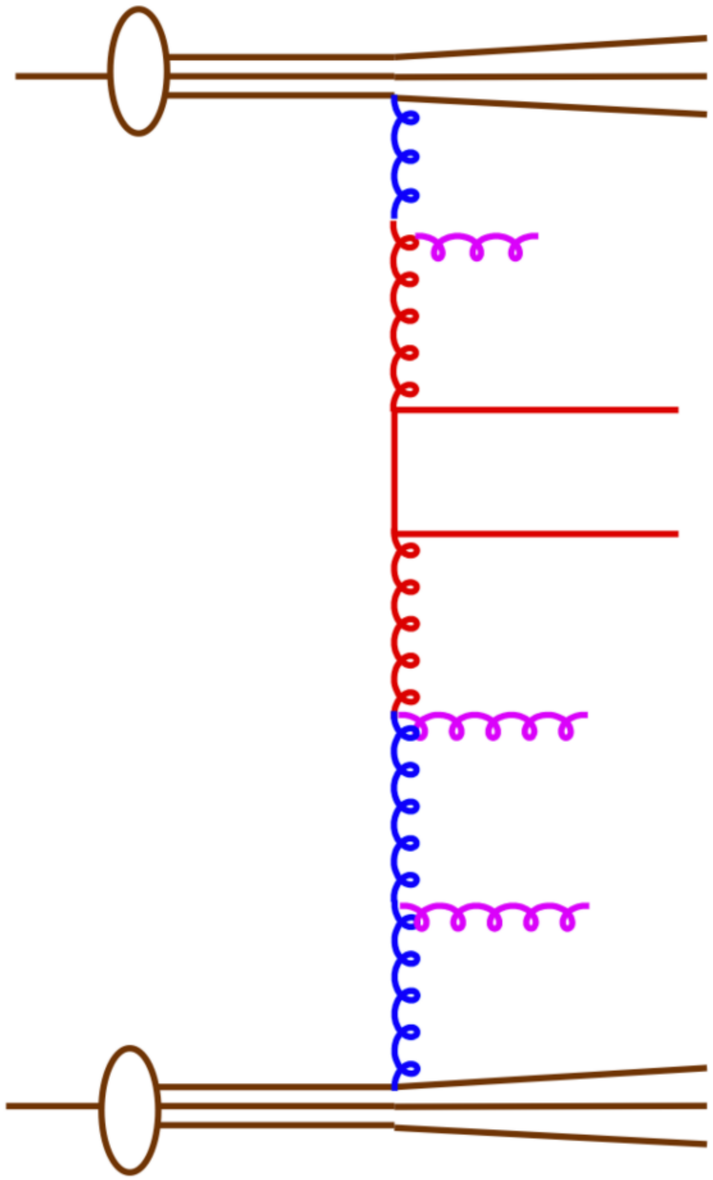
How will your own research contribute to the progress in understanding of TMD's?

- Further development of PB TMDs and PB TMD fits
  - fit collinear and TMD distributions not only to HERA data
    - include DY pt measurements at high and low masses
      - determination of non-perturbative (intrinsic) k_T distribution
    - obtain 3, 4 flavor TMDs
  - obtain nuclear TMDs (some available in PB approach)
  - obtain γ , W, Z TMD densities
  - extension to NNLO in VFNS

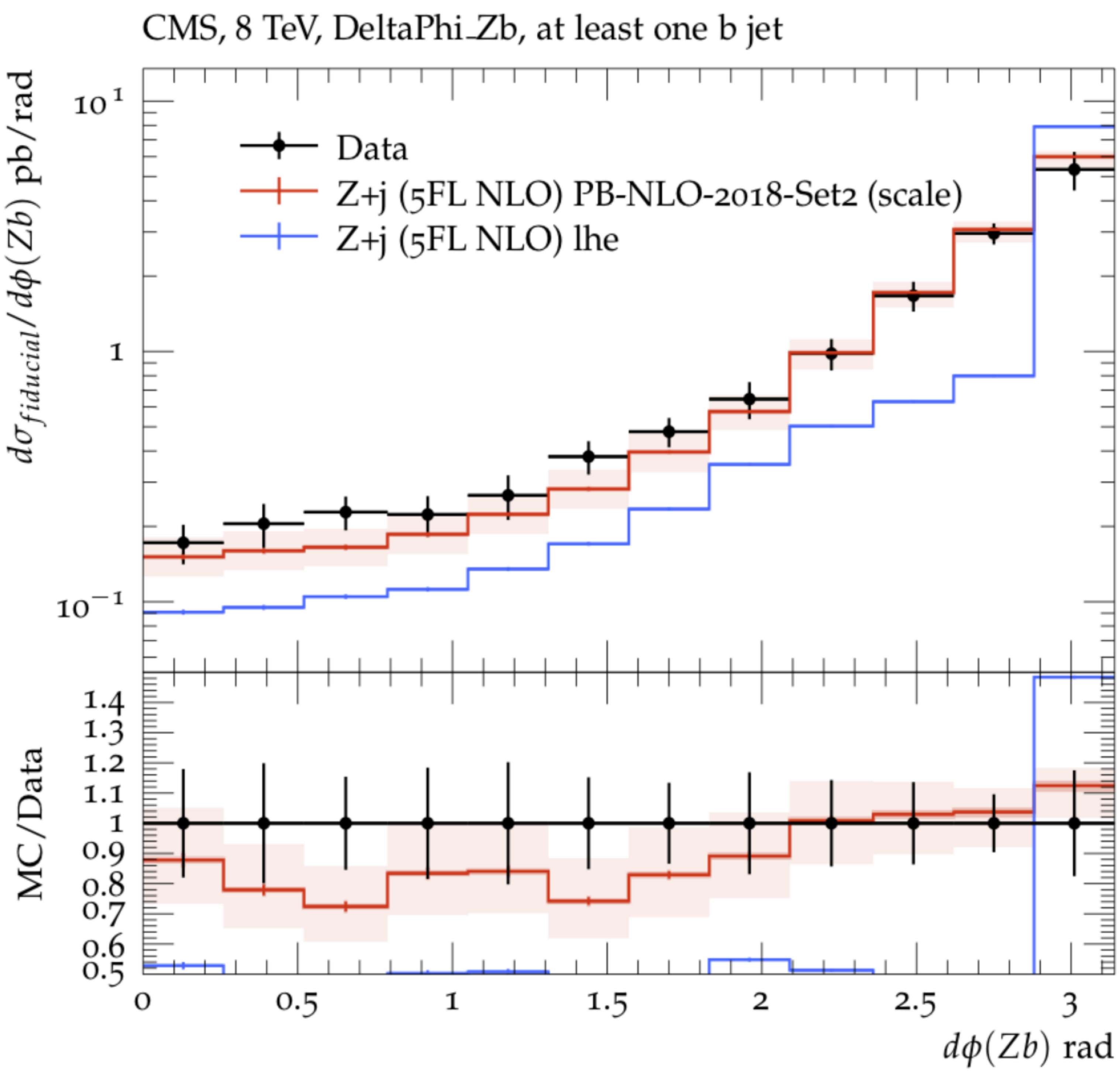
- Relation of TMD pdfs and TMD parton shower
  - essential for full hadron level Monte Carlo event generator
  - first and only full hadron level TMD MCEG, CASCADE3, existing

MCEG: TMDs and parton shower - CASCADE3

- basic elements are:
  - Matrix Elements:
    - ➔ MC@NLO or POWHEG
  - PDFs
    - ➔TMDs
  - Parton Shower
    - ➔ following TMDs for initial state !
- Proton remnant and hadronization handled by standard hadronization program



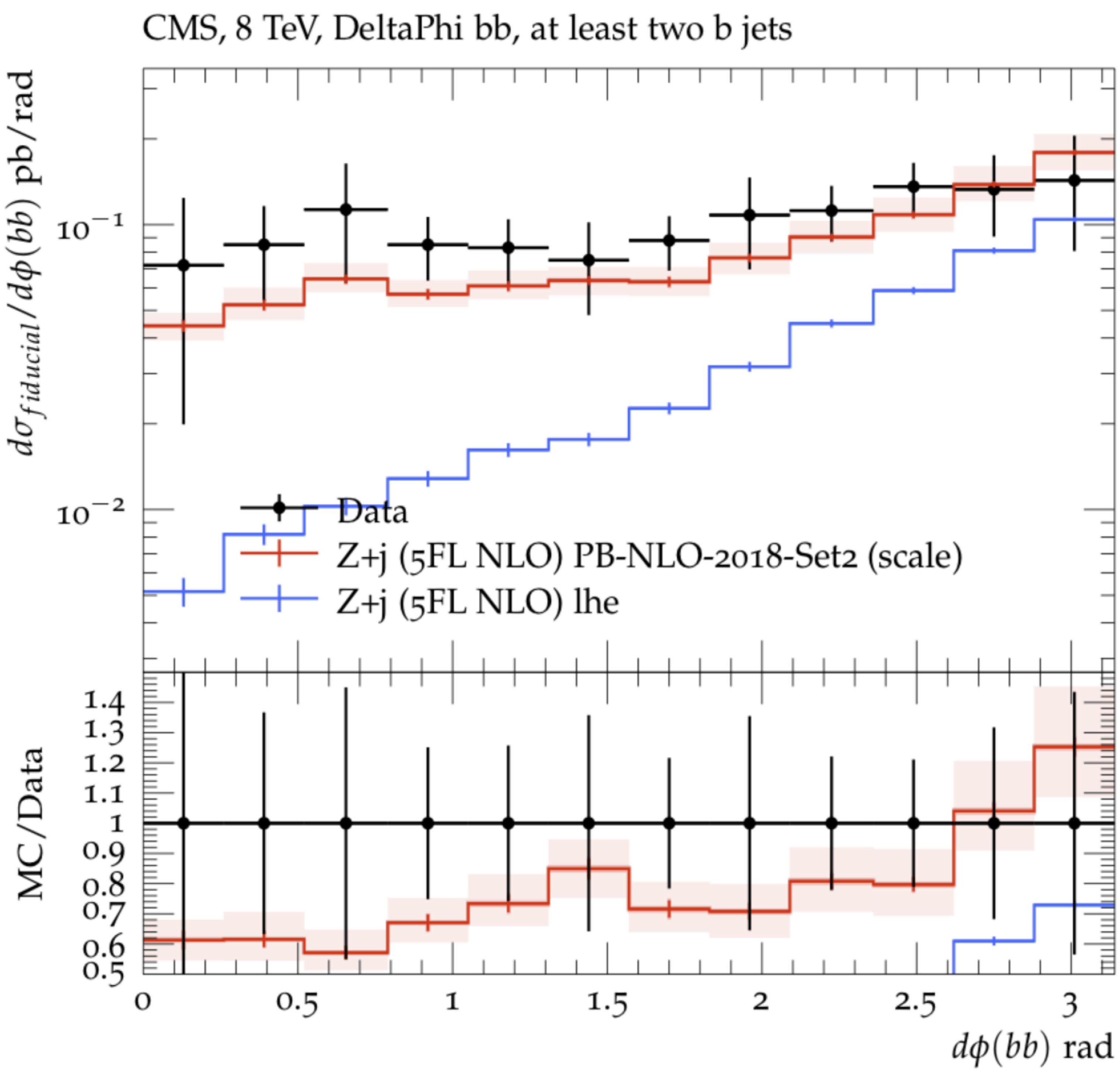
Z+b-jets: $\Delta\phi(Zb)$ - comparison to measurement



- Good description in large $\Delta\phi$ region where TMD effects are relevant
  - decorrelation comes essentially from k_T from initial evolution
    - details of shower are less important
  - distribution essentially determined by TMD distribution
  - uncertainties only from TMD

➔ Z+b correlation tests TMD

Z+2b-jets: $\Delta\,\phi\,(bb)$ - comparison to measurement



- Good description
  - decorrelation comes essentially from k_T from initial evolution
    - Space shower is important
    - Time shower only at small $\Delta\,\phi(bb)$
    - sensitive to b-quark TMD density AND b-quark TMD-shower

➔ bb correlation tests space shower

What will be necessary to extend TMD formalisms to new scattering processes?

- PB TMDs are easily applicable
  - to NLO matrix elements within collinear factorization
    - apply also parton shower and multi-jet merging

- further developments
  - application to off-shell processes (initial and final legs off shell)
    - needed for proper treatment of kinematics
  - NLO calculation for off-shell processes
  - TMD parton shower at higher orders fully consistent with TMD parton densities
    - full NLO and NNLO parton showers

Conclusion - outlook

- PB TMD has high potential for applications
  - at highest energies (LHC etc)
  - at low energies (see DY at low energies)

- PB TMDs are best suitable for full Monte Carlo event generators
  - including initial and final state parton shower (which follow TMDs)

- precision determination of TMDs from precision measurements
  - consistent with collinear PDFs

- determination of nuclear TMDs

- PB TMDs obtained within xfitter
  - easily extendable

- TMDlib is the tool – this is the repository for TMDs

Appendix

What critical physics questions must be solved to make progress?

- TMD physics implies proper treatment of kinematics
  - need to include x^+ and x^- components (virtuality in addition to k_T)
  - need approach with off-shell kinematics → off-shell matrix elements
    - for initial legs
    - for final legs

- On a different scope: TMD and small x issues
  - inclusion of small x dynamics

What experimental measurements can provide incisive information?

- Low mass DY q_T measurements at different energies
  - to measure non-pert k_T distribution of quarks as function of x

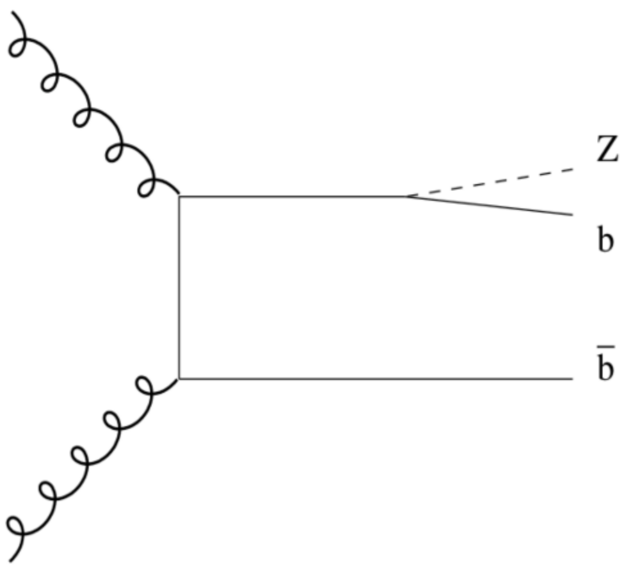
- bbar production

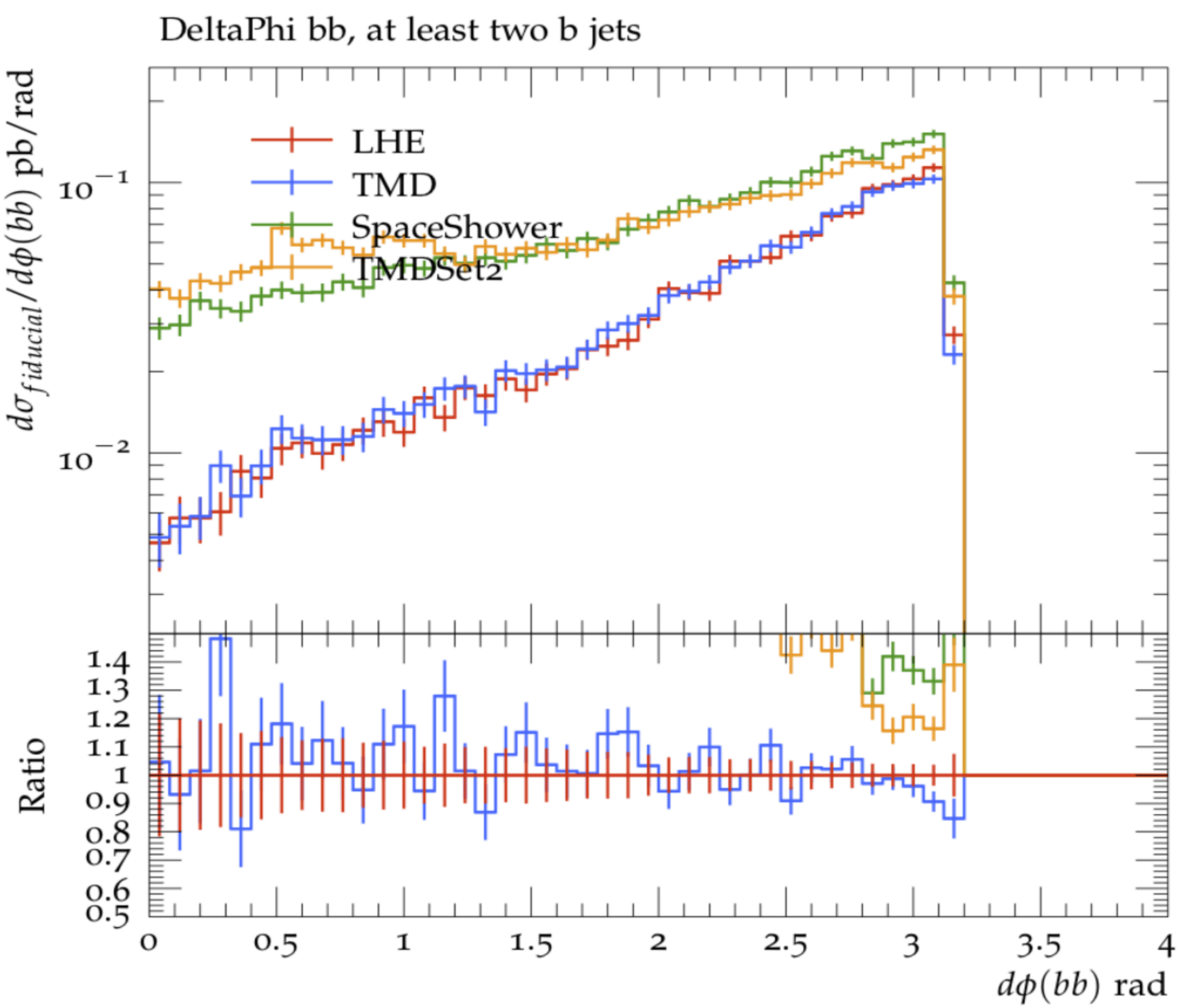
  Baranov, S. P., Jung, H., Lipatov, A. V., and Malyshev, M. A. (2017). Testing the parton evolution with the use of two-body final states, Eur. Phys. J., C77(1), 2

  - to measure k_T distribution of gluons as function of x

- q_T measurement in VBS
  - to measure perturbative k_T distribution of W,Z at large k_T

$Z+2$ jets: sensitivity to initial state TMD shower





- TMD has little impact
- initial state PS large small effect (on top of TMD)
- FSR significant only at small $\Delta\phi$: $g \rightarrow bb$