Z+b production at NLO with the PB method

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together with
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- Recap of PB method
- Application of PB TMDs to
  - Z_0 production at the LHC
    (based on Phys Rev D.100.074027 (2019))
  - $Z_0 + b$ jet production at NLO
    - sensitivity to TMD
    - sensitivity to TMD initial state parton shower
    - $Z_0 + b$ and bb correlations

Recap of Parton Branching method

DGLAP evolution – solution with parton branching method

- differential form: $$\mu^2 \frac{\partial}{\partial \mu^2} f(x,\mu^2) = \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P_+(z)\, f\left(\frac{x}{z},\mu^2\right)$$

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$$\Delta_s(\mu^2) = \exp\left(- \int^{z_M} dz \int_{\mu_0^2}^{\mu^2} \frac{\alpha_s}{2\pi} \frac{d\mu'^2}{\mu'^2} P^{(R)}(z) \right)$$

- differential form using f/Δ_s with

$$\mu^2 \frac{\partial}{\partial \mu^2} \frac{f(x,\mu^2)}{\Delta_s(\mu^2)} = \int \frac{dz}{z} \frac{\alpha_s}{2\pi} \frac{P^{(R)}(z)}{\Delta_s(\mu^2)} f\left(\frac{x}{z},\mu^2\right)$$

DGLAP evolution – solution with parton branching method

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- integral form

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

no – branching probability from ${\mu^2}_0$ to μ^2

DGLAP evolution – solution with parton branching method

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

- solve integral equation via iteration:

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

DGLAP evolution – solution with parton branching method

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- solve integral equation via iteration:

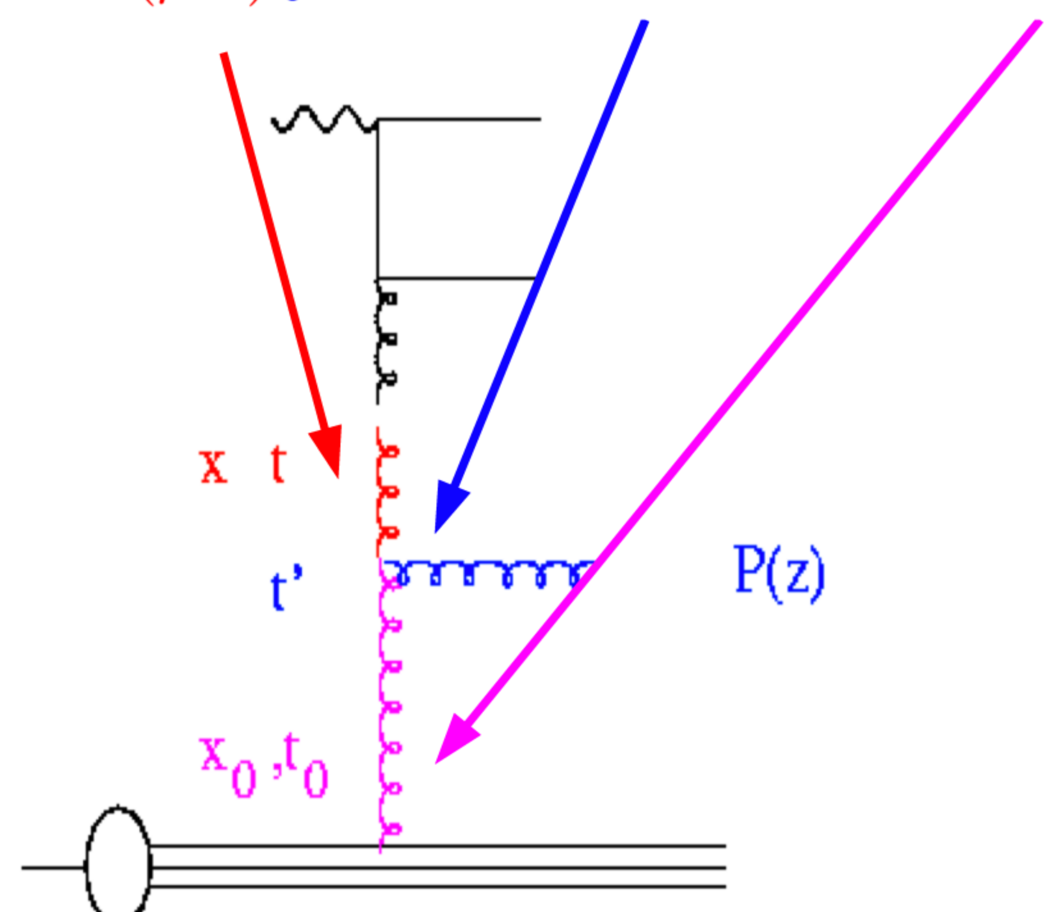
from μ' to μ w/o branching

branching at μ'

from μ to μ' w/o branching

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

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



DGLAP evolution – solution with parton branching method

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

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  - 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 $\mathcal{O}(1-z_M)$

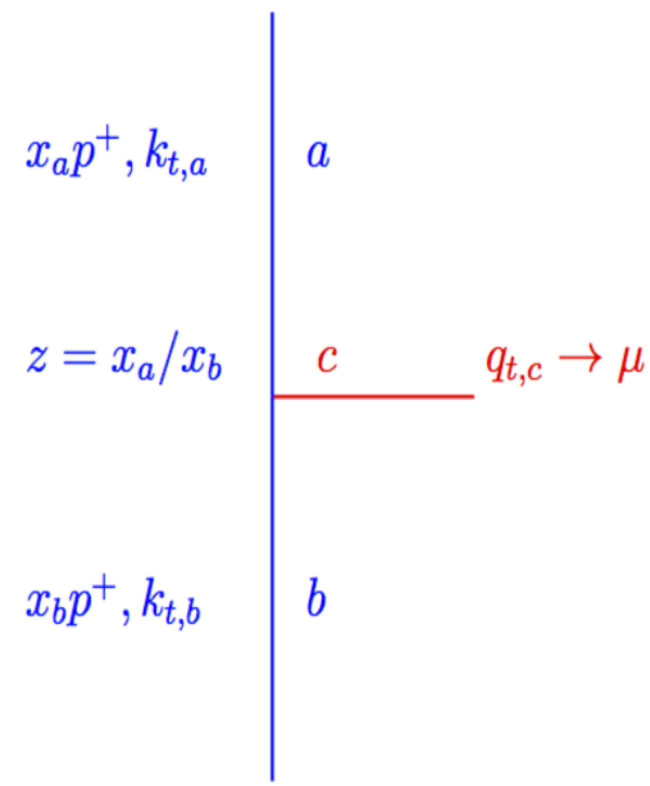
- make use of momentum sum rule to treat virtual corrections
  - use Sudakov form factor for non-resolvable and virtual corrections

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

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:

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



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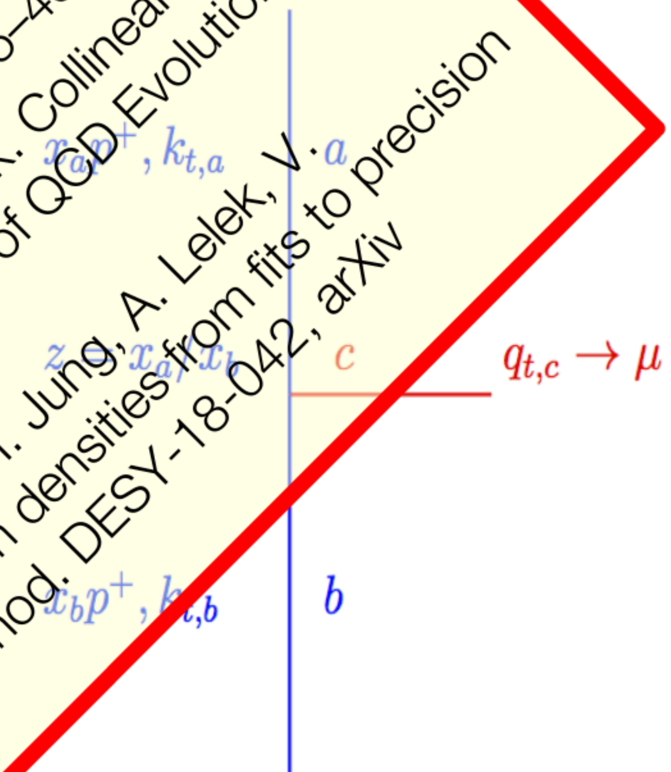


[1] F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Soft-gluon resolution scale in QCD evolution equations. Phys. Lett., B772:446–451, 2017.
[2] F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Collinear and TMD Quark and Gluon Densities from Parton Branching Solution of QCD Evolution 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

PDFs from Parton Branching method: fit to HERA data

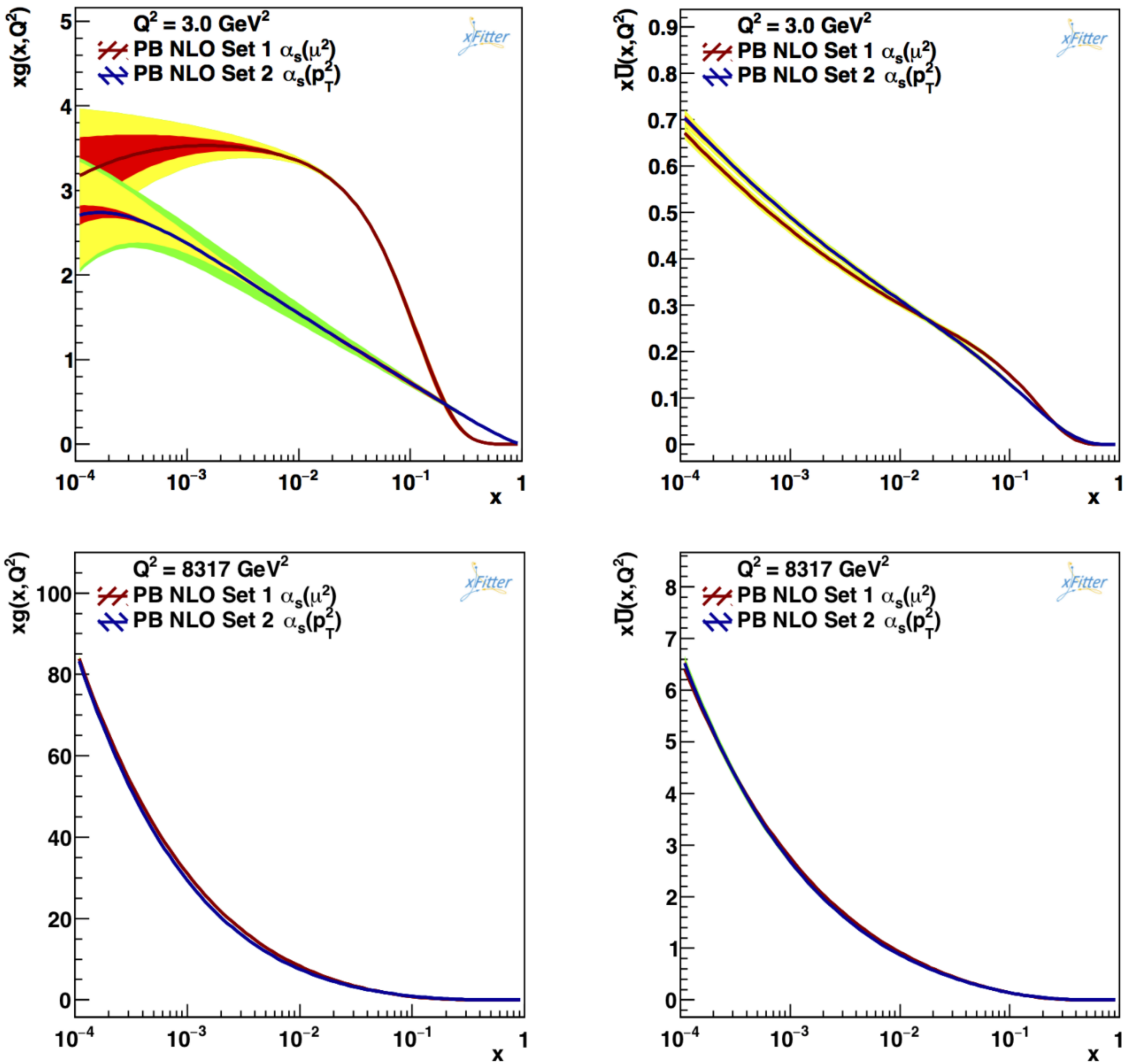
- Convolution of kernel with starting distribution

$$
\begin{aligned}
xf_a(x,\mu^2) &= x\int dx' \int dx'' \mathcal{A}_{0,b}(x') \tilde{\mathcal{A}}_a^b\left(x'',\mu^2\right) \delta(x'x''-x) \\
&= \int dx' \mathcal{A}_{0,b}(x') \cdot \frac{x}{x'}\ \tilde{\mathcal{A}}_a^b\left(\frac{x}{x'},\mu^2\right)
\end{aligned}
$$

- Fit performed using xFitter frame (with collinear Coefficient functions at NLO)
  - using full HERA 1+2 inclusive DIS (neutral current, charged current) data
    - in total 1145 data points
      - $3.5 < Q^2 < 50000\ \mathrm{GeV}^2$
      - $4 \cdot 10^{-5} < x < 0.65$
      - using starting distribution as in HERAPDF2.0
      - $\chi^2/ndf = 1.2$

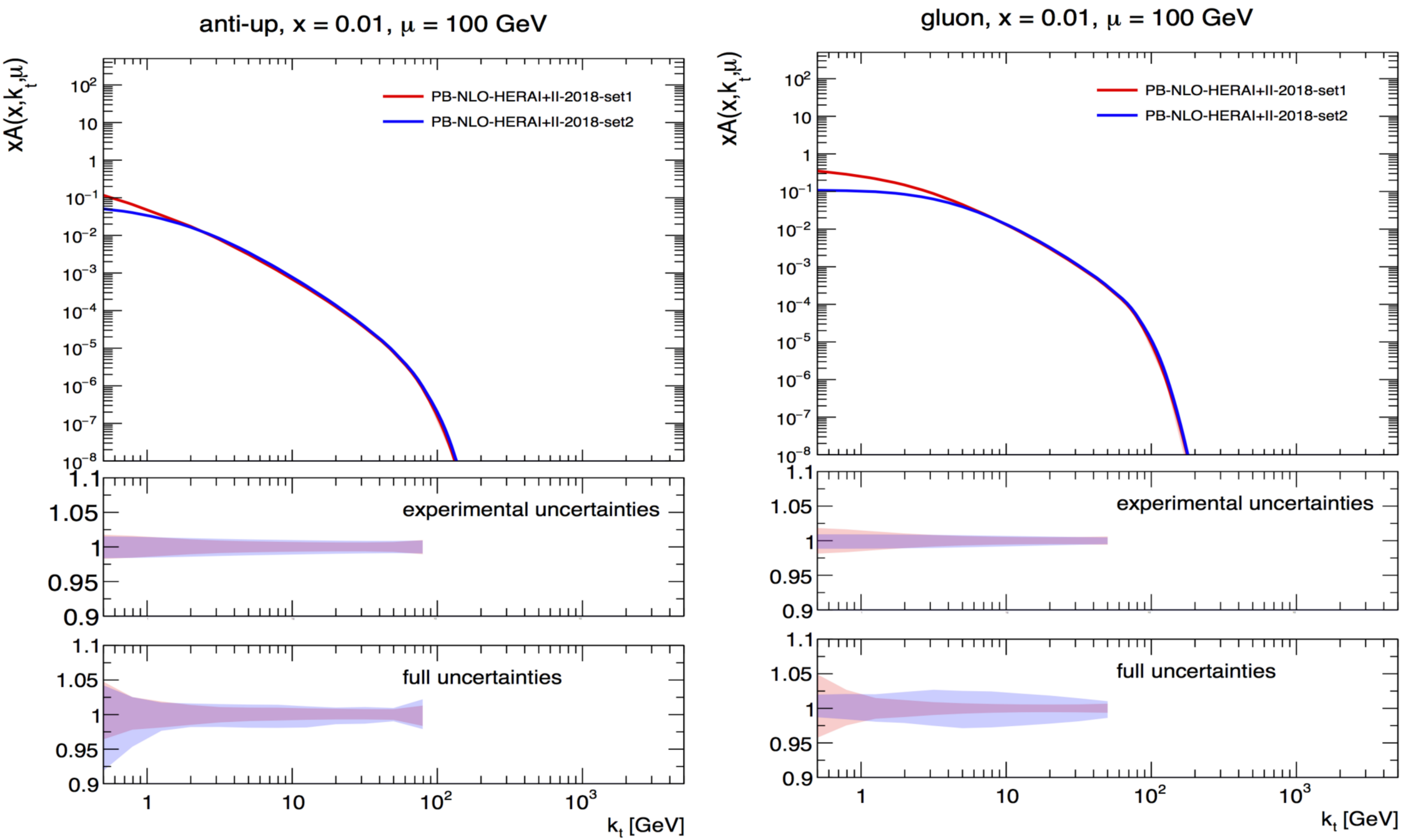
➔ Can be easily extended to include any other measurement for fit !

Fit with different scale in α_s



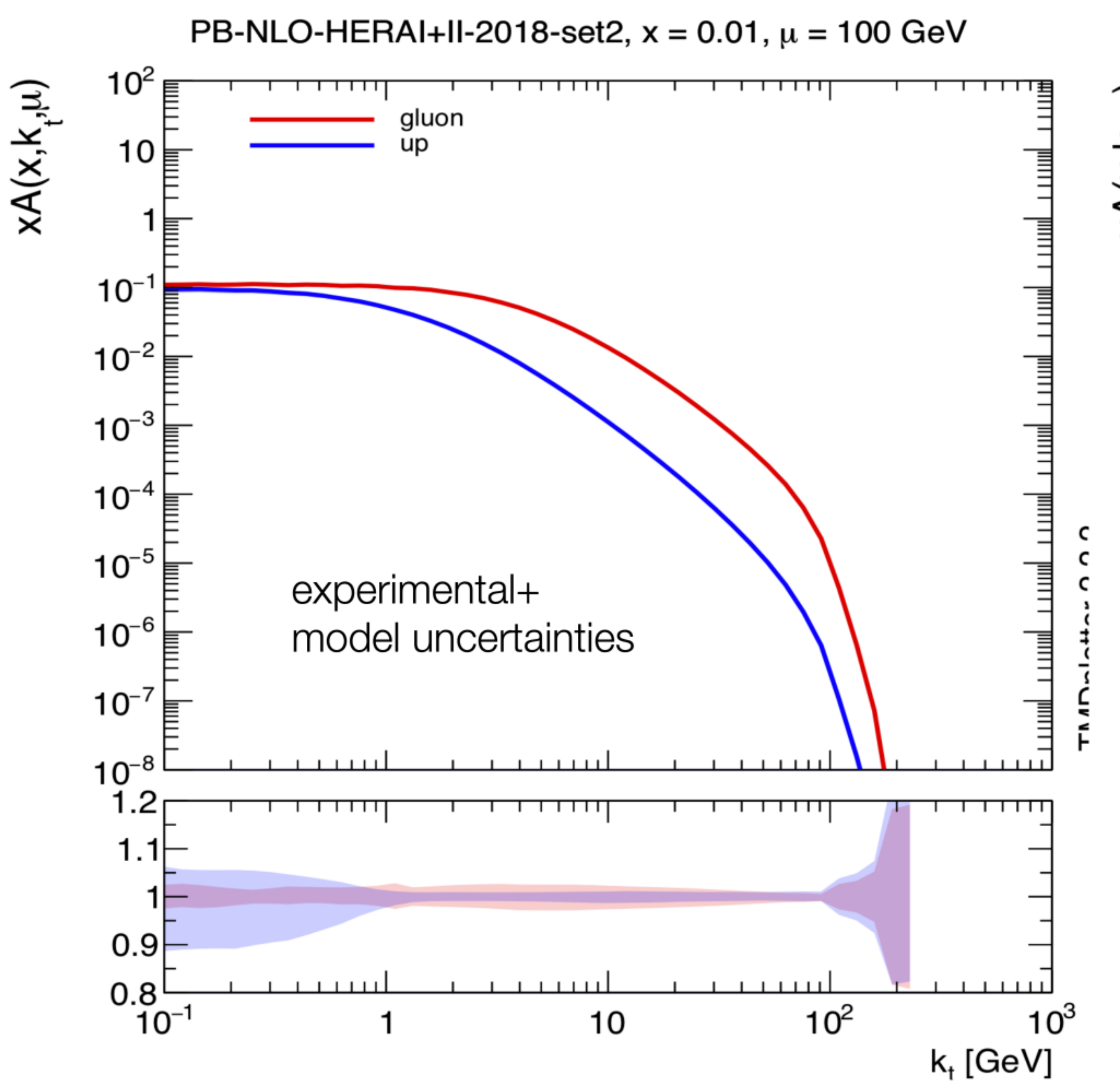
- fit 1 with $\alpha_s(q)$
  - as good as HERAPDF2.0 $\chi^2/ndf = 1.2$
- fit 2 with $\alpha_s(q(1-z))$
  - $\chi^2/ndf = 1.21$
- very different gluon distribution obtained at small Q^2

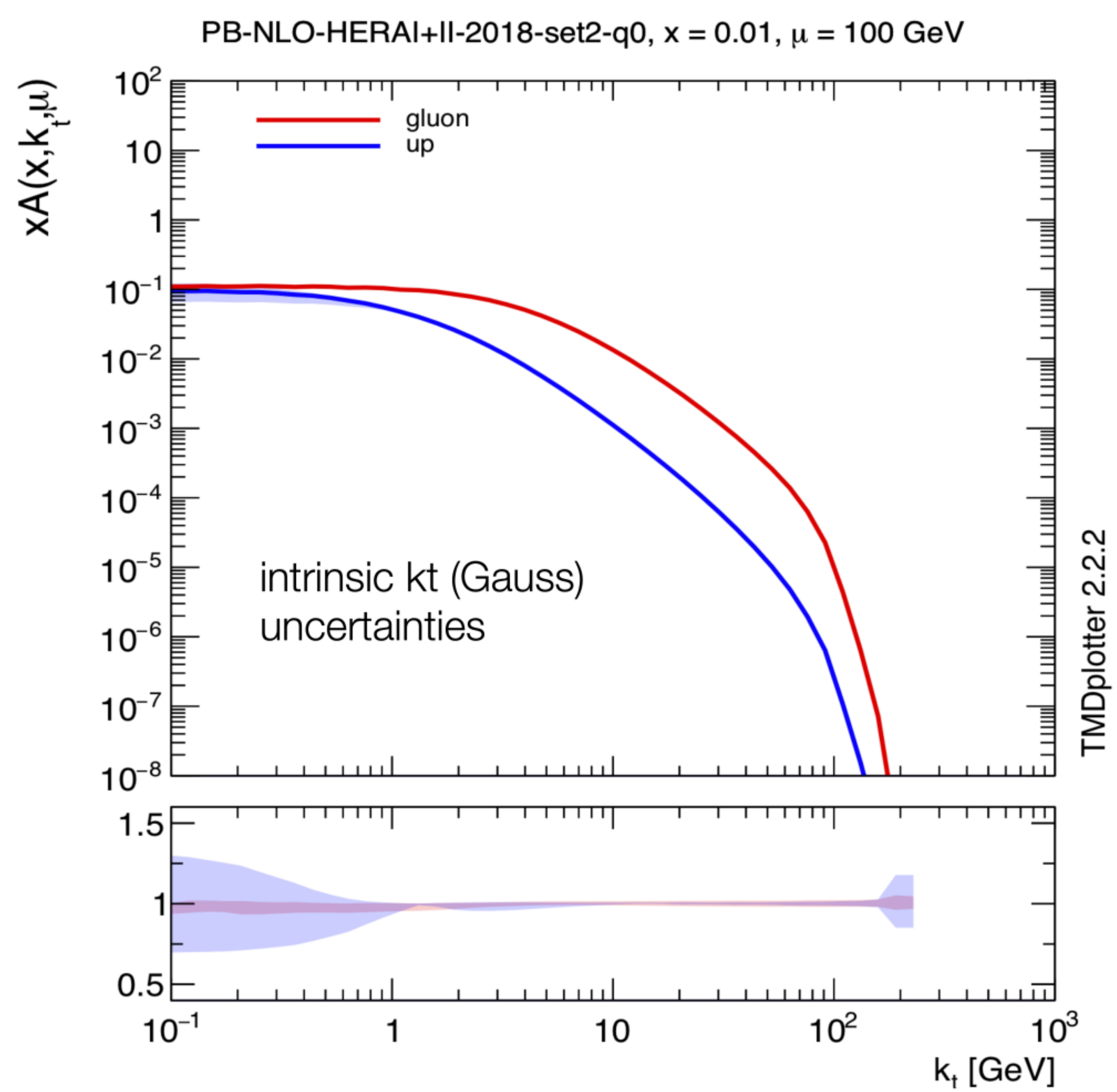
TMD distributions from fit to HERA data



- model dependence larger than experimental uncertainties

TMD distributions (light flavors)

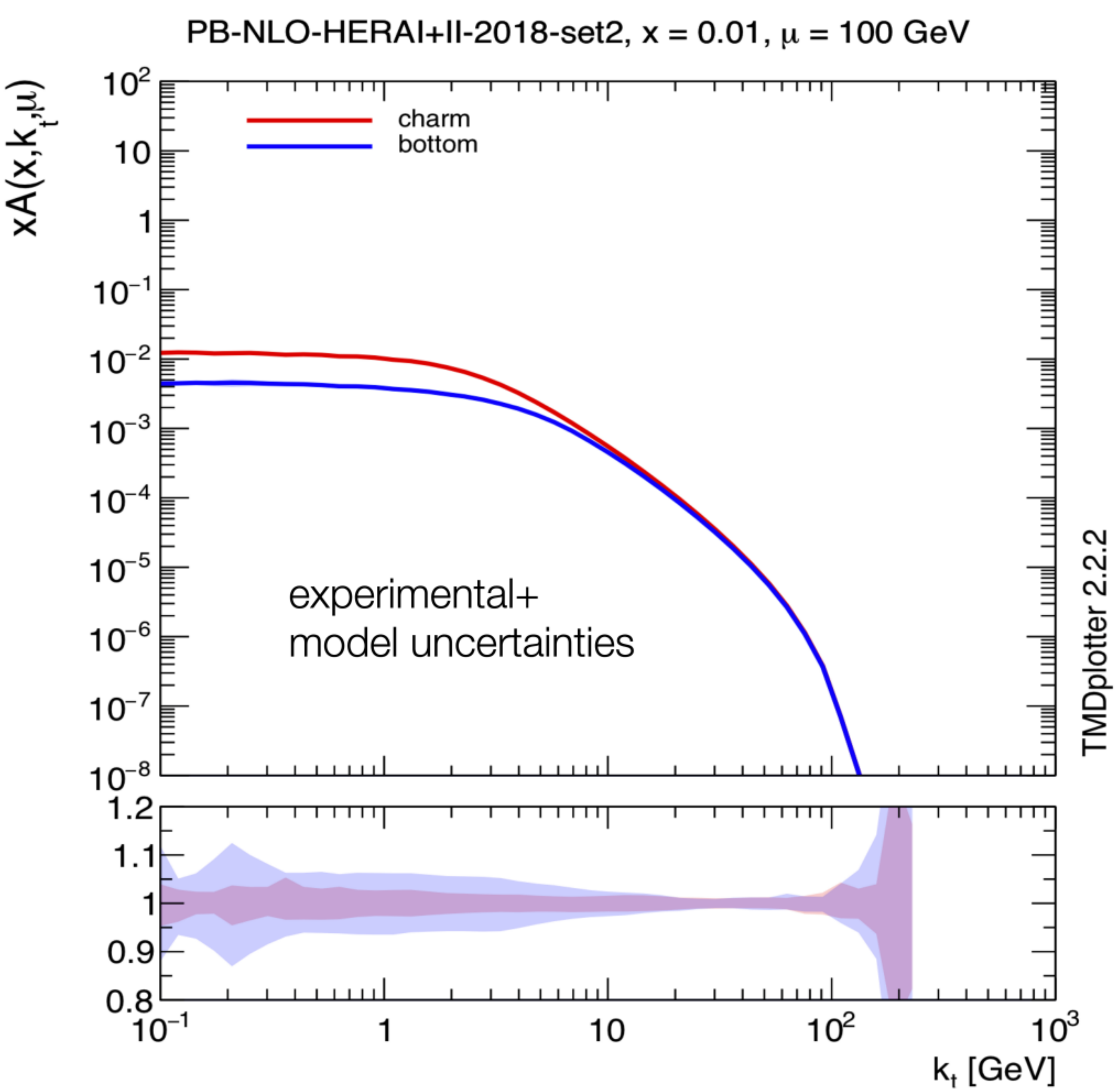


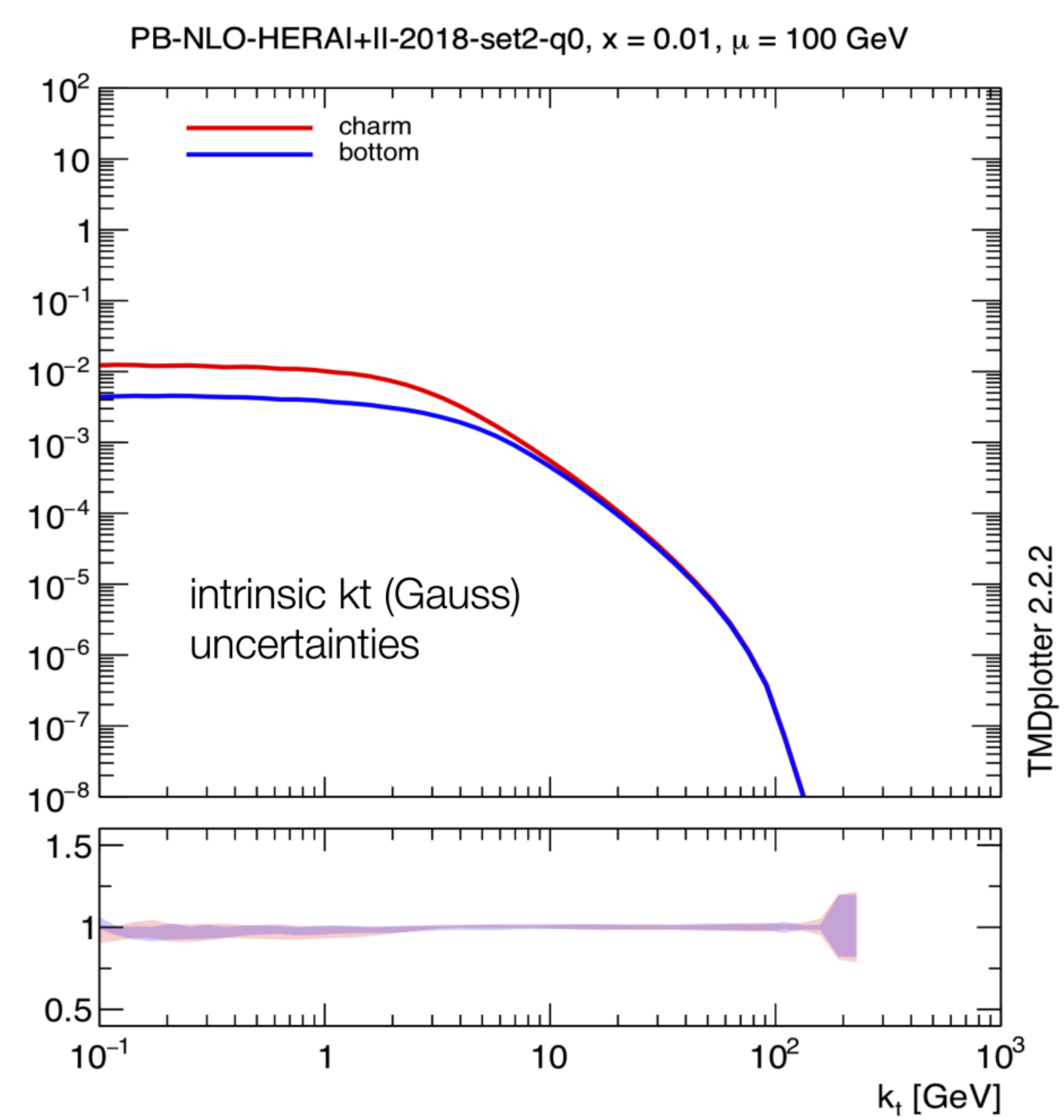


Differences essentially in low k_T region

- experimental+model uncertainties small
- uncertainties from intrinsic k_T sizable at very small k_T

TMD distributions (heavy flavors)





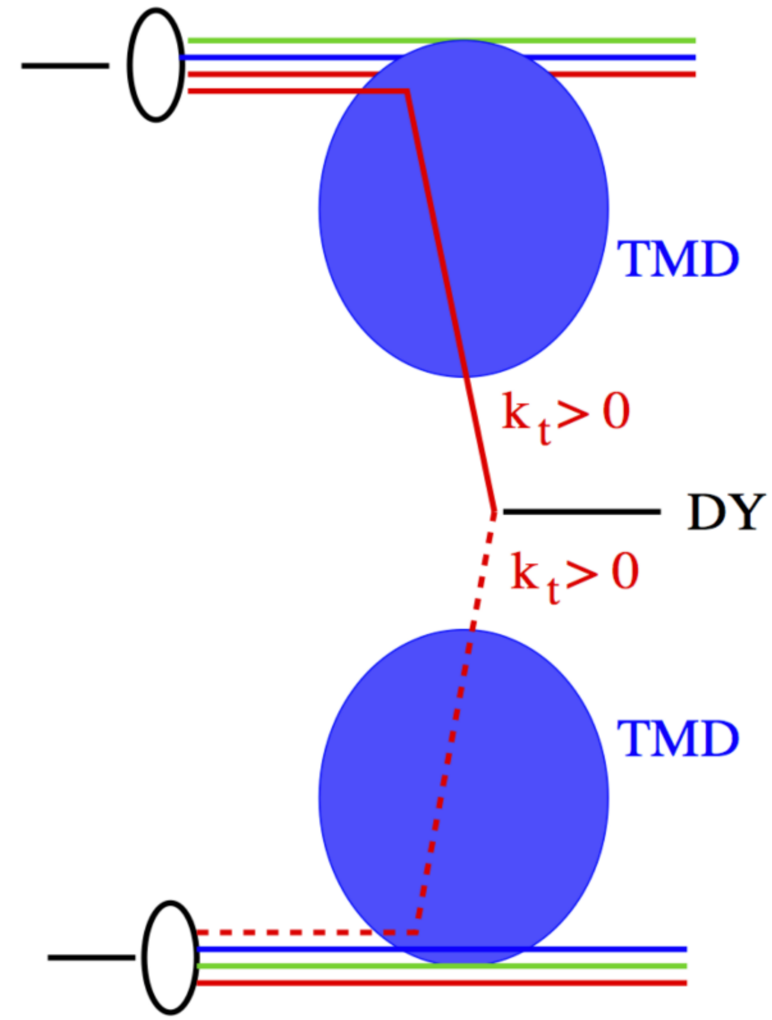
Differences essentially in low k_T region

- experimental+model uncertainties larger than for light flavors
- uncertainties from intrinsic k_T very small !

Application to Drell – Yan production

Drell -Yan production: q_T - spectrum

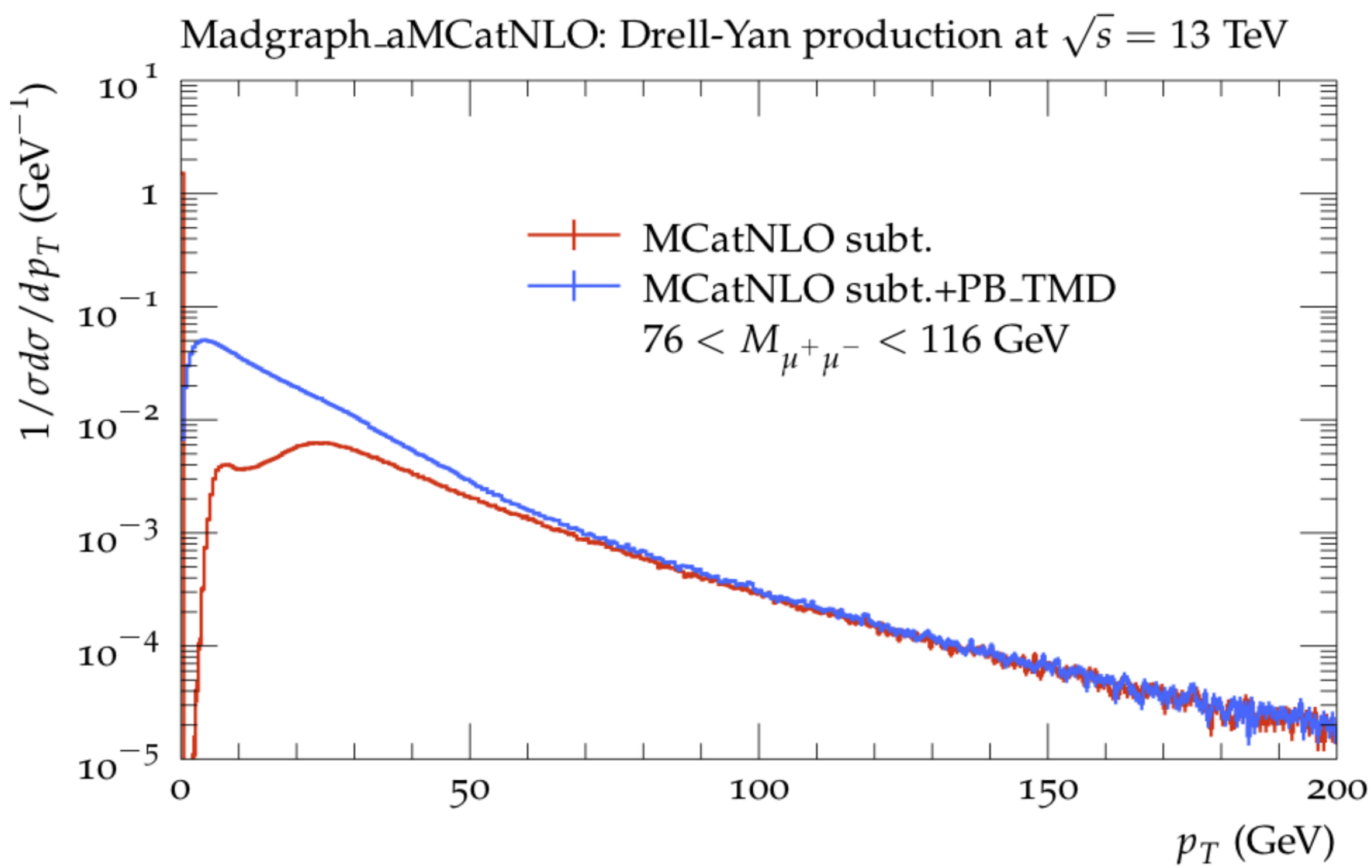
- DY production
  - $q\bar{q} \rightarrow Z_0$
  - add k_t for each parton as function of x and μ according to TMD
  - keep final state mass fixed:
    - x_1 and x_2 (light-cone fraction) are different after adding k_t
  - use NLO calculations: MC@NLO



Matching to hard process: MC@NLO method

The transverse momentum spectrum of low mass Drell-Yan production at next-to-leading order in the parton branching method
Bermudez Martinez, A. et al, arXiv 2001.06488

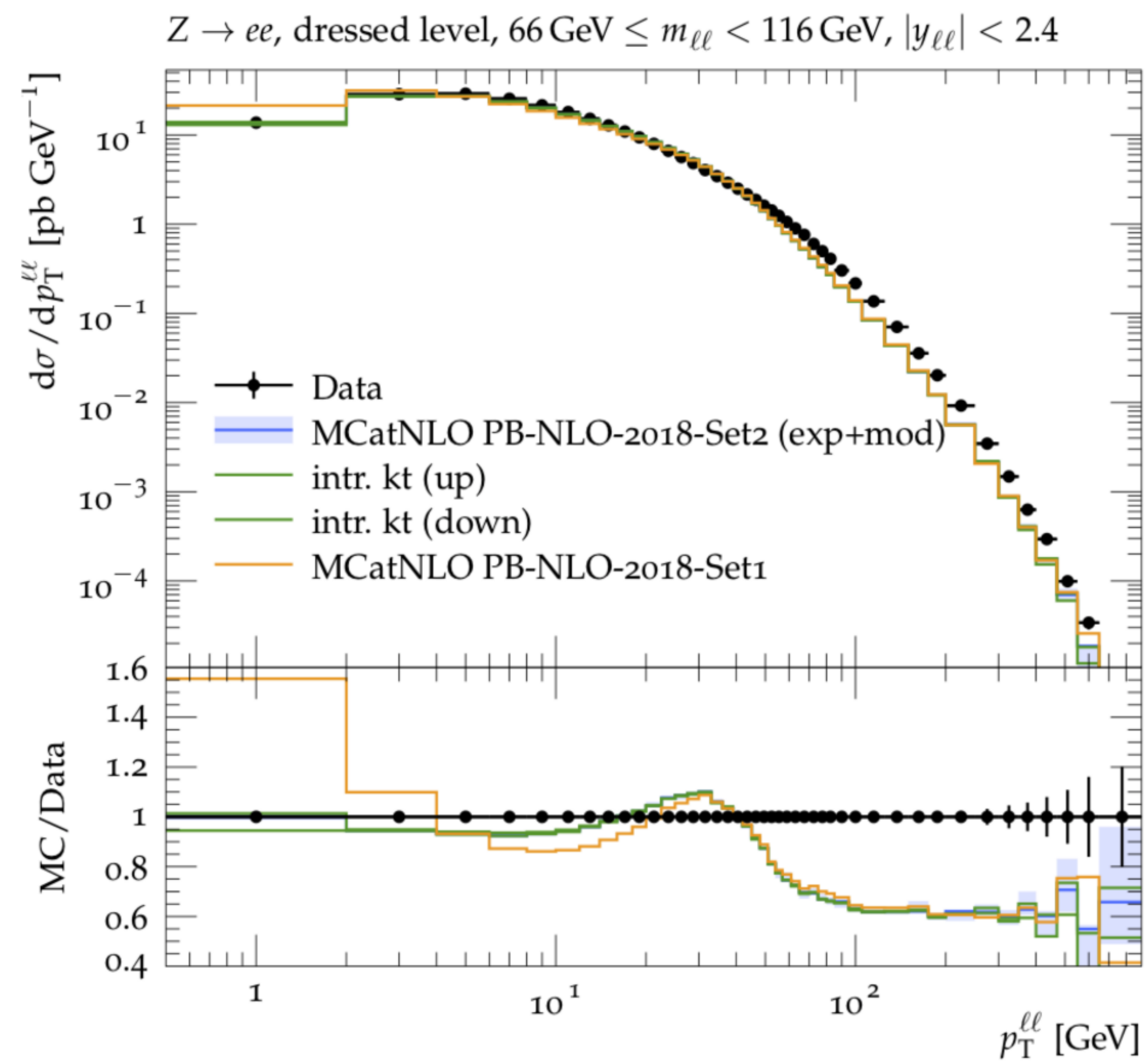
- MC@NLO subtracts soft & collinear parts from NLO (added back by TMD and/or parton shower)
  - MC@NLO without shower and/or TMD unphysical
    - use herwig6 subtraction terms



Matching to hard process: MC@NLO method

- MC@NLO subtracts soft & collinear parts from NLO (added back by TMD and shower)
- low q_T region affected by subtraction of soft & collinear parts
  - filled by TMD (+ PS)
- DY production very well described by TMD with MC@NLO
  - TMD fills low q_T part
    - angular ordering with $\alpha_s(q(1-z))$ is best
    - intrinsic Gauss plays little role

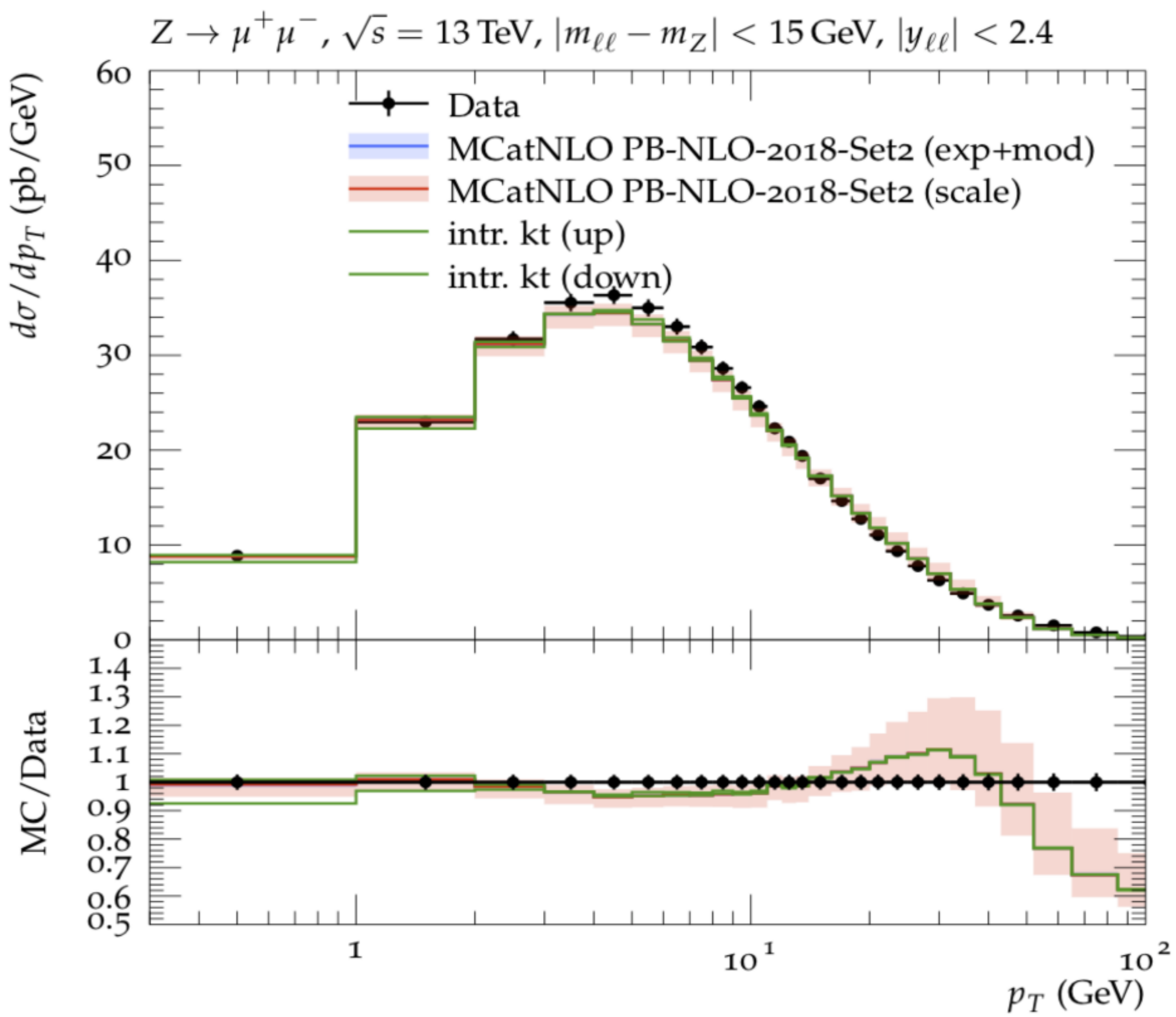
DY with PB TMDs: Bermudez Martinez, A. et al, arXiv 1906.00919, PhysRevD.100.074027



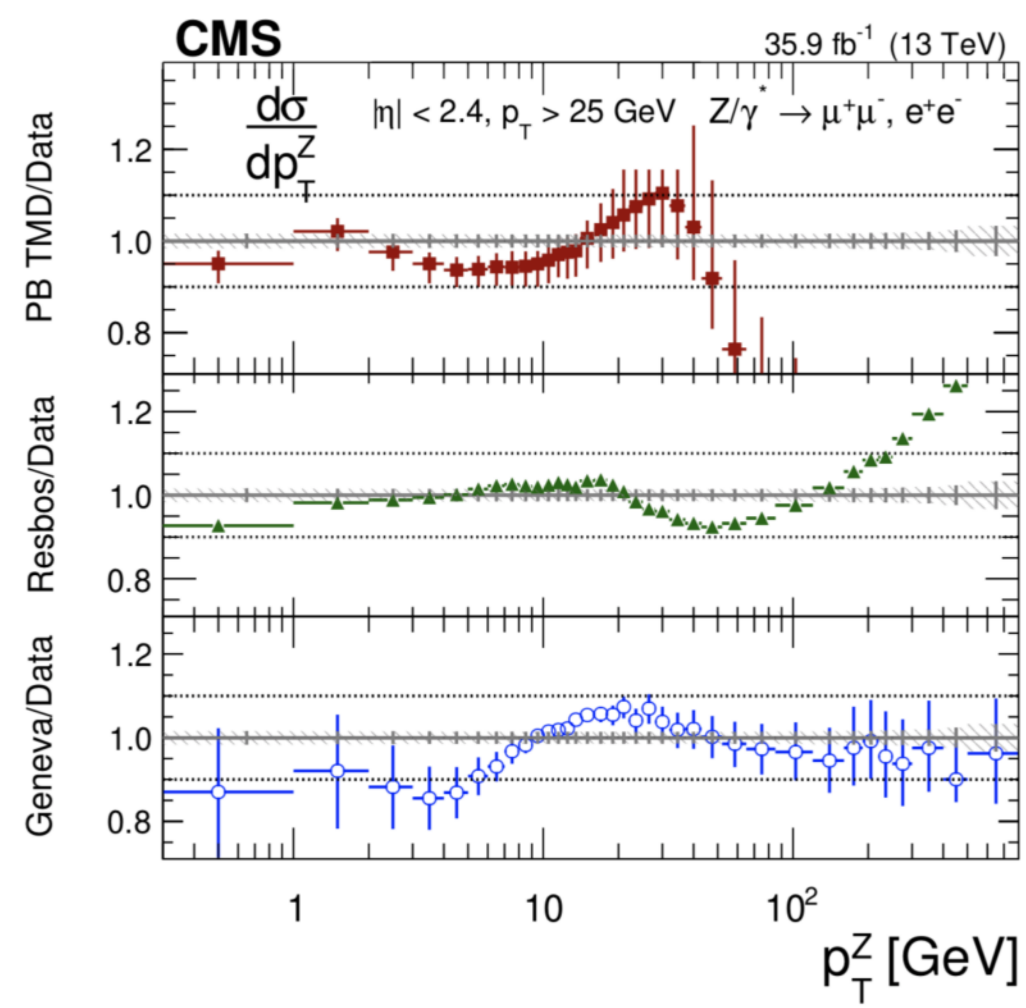
ATLAS (2016). DY at 8 TeV, EPJC76, 291, 1512.02192

Z - production at 13 TeV (CMS)

Bermudez Martinez, A. et al, arXiv 2001.06488



SMP-17-010, JHEP12 (2019) 061



- very good description of low p_T region
  - at larger p_T contribution from higher order matrix elements important
- Uncertainties in PB method mainly from scale of MC@NLO matrix element
- intrinsic k_T distribution only small effect at very small p_T

so far …

- p_T spectrum of DY production very well described with PB -TMDs and NLO calculation a la MCatNLO
  - PB – TMDs obtained from NLO fit to inclusive HERA data
    - parameters of collinear initial distribution obtained
    - intrinsic Gauss distribution with: (Bermudez Martinez, A. et al, arXiv 2001.06488)

$$\mathcal{A}_{0,b}(x, k_T^2, \mu_0^2) = f_{0,b}(x, \mu_0^2) \cdot \exp\left(-|k_T^2|/2\sigma^2\right)/(2\pi\sigma^2)$$

constrained width $\sigma^2 = q^2{}_s/2$ of Gauss distribution (default $q_s = 0.5\, GeV$)

    - association of evolution scale with q_T

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

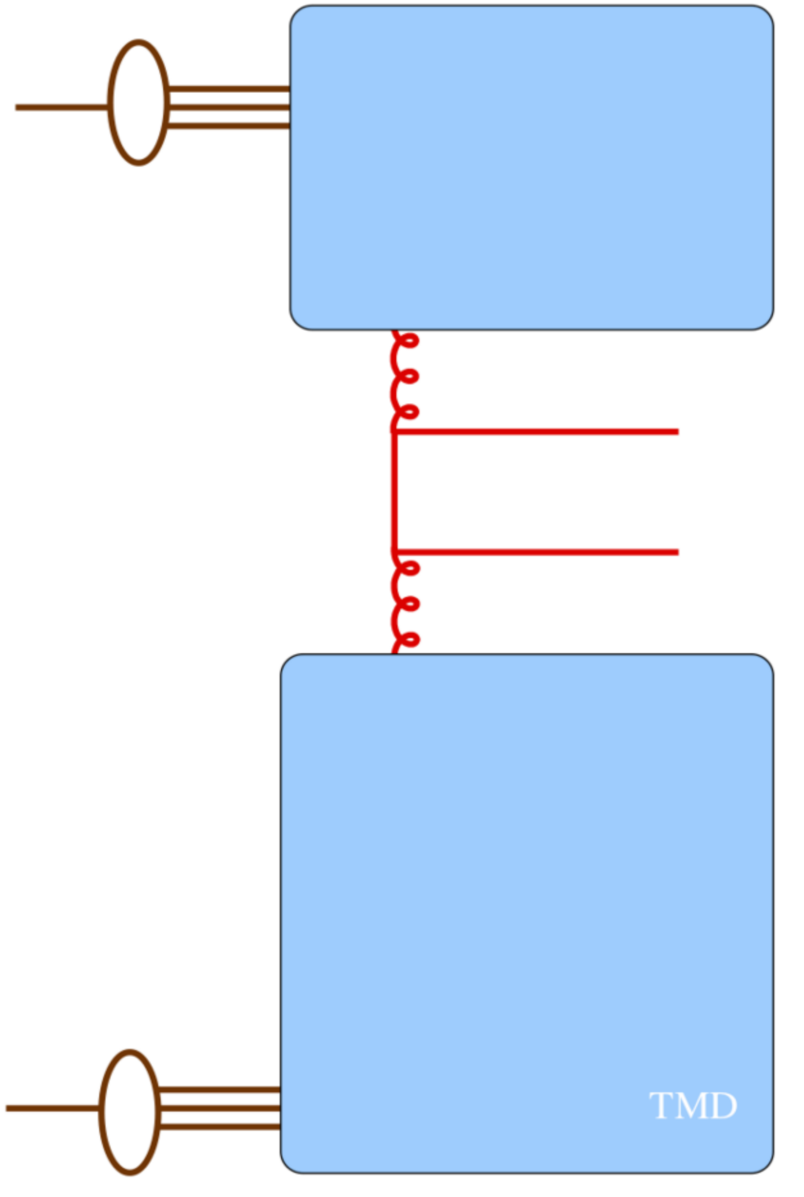
    - no further free parameters !

➔ Can this method be applied to other processes involving multi-partonic final states ?

➔ Is there a PB-TMD initial state parton shower ?

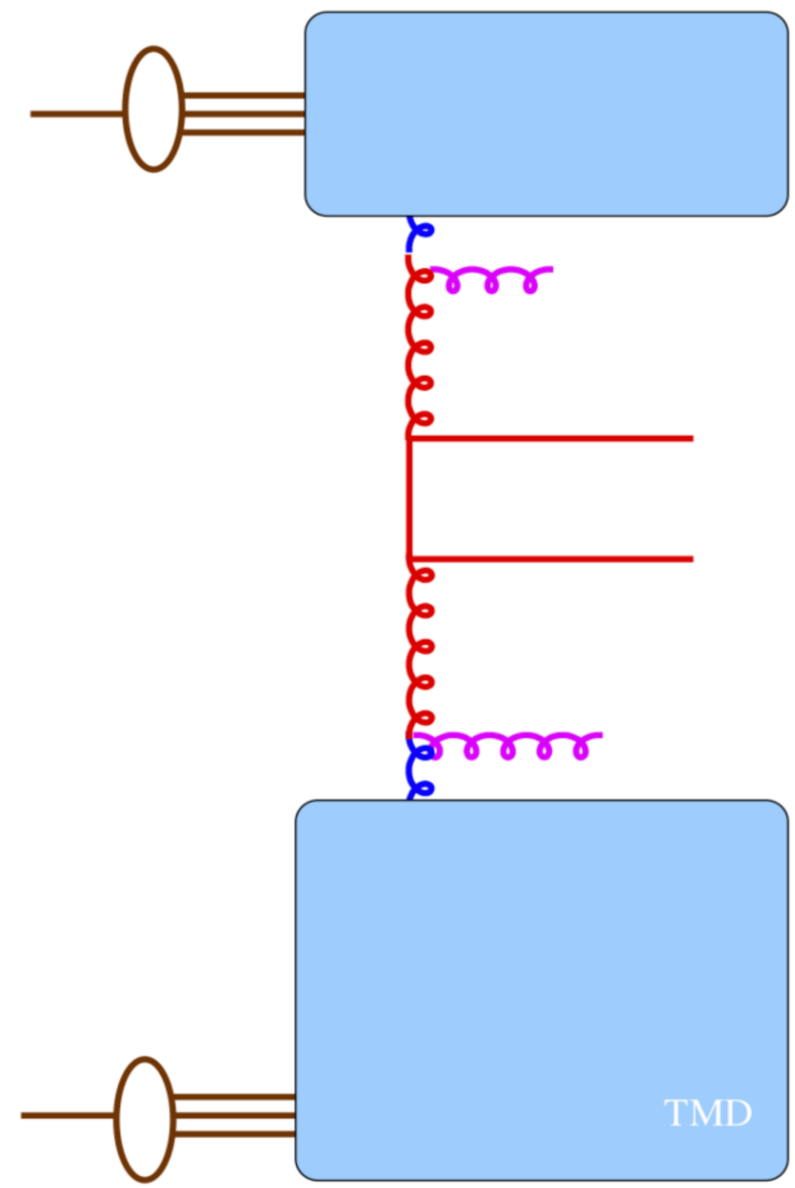
MCEG: TMDs and parton shower - CASCADE3

- basic elements are:
  - Matrix Elements:
    - ➔ MC@NLO or POWHEG
  - PDFs
    - ➔TMDs
    - ➔ enough for inclusive distributions, i.e. DY q_T spectrum



MCEG: TMDs and parton shower - CASCADE3

- basic elements are:
  - Matrix Elements:
    - ➔ MC@NLO or POWHEG
  - PDFs
    - ➔TMDs
  - Parton Shower
    - ➔ following TMDs for initial state !



MCEG: TMDs and parton shower - CASCADE3

- basic elements are:
  - Matrix Elements:
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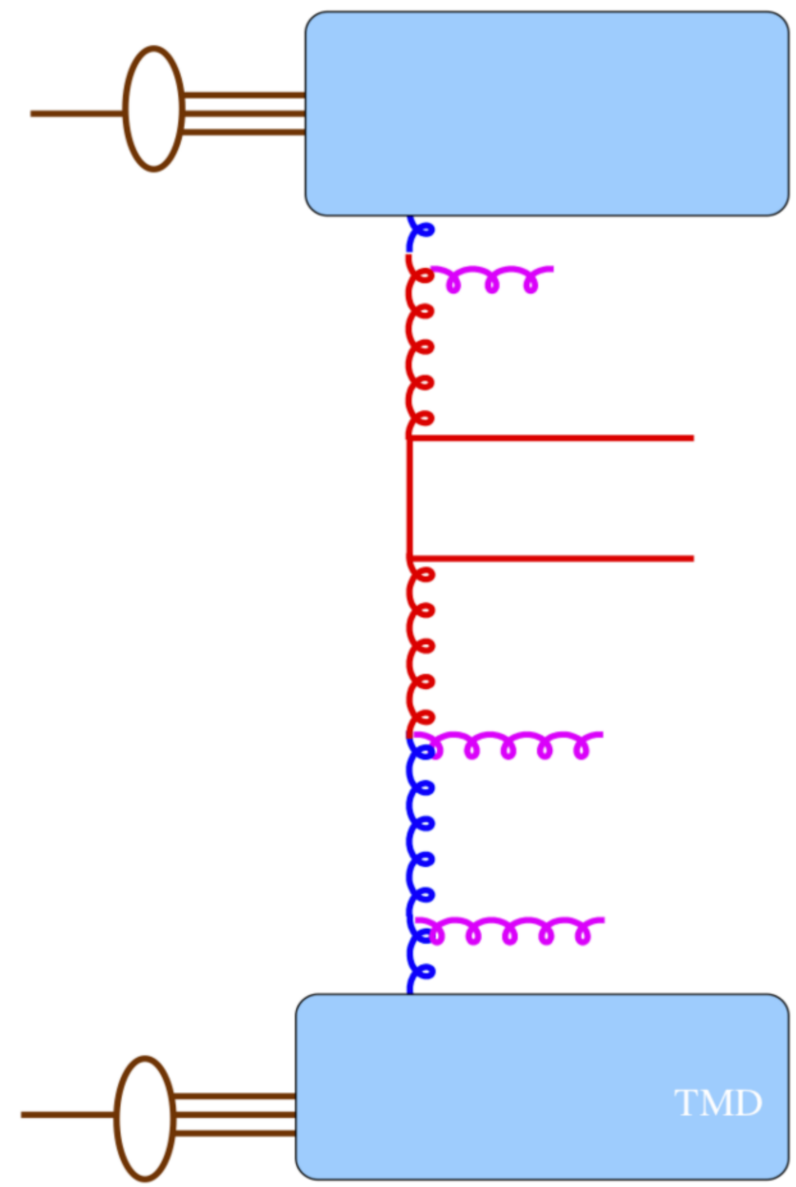
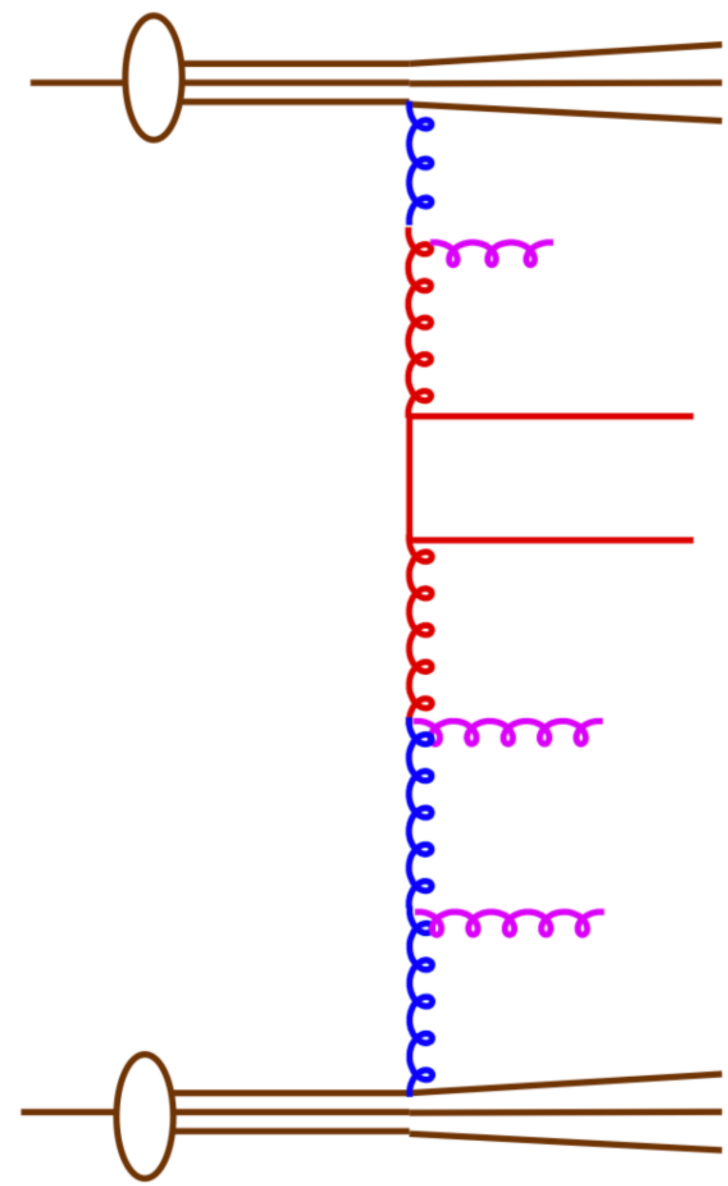


MCEG: TMDs and parton shower - CASCADE3

- 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



PB-TMD, PB-TMD shower & MCatNLO: $Z{+}b$ jets

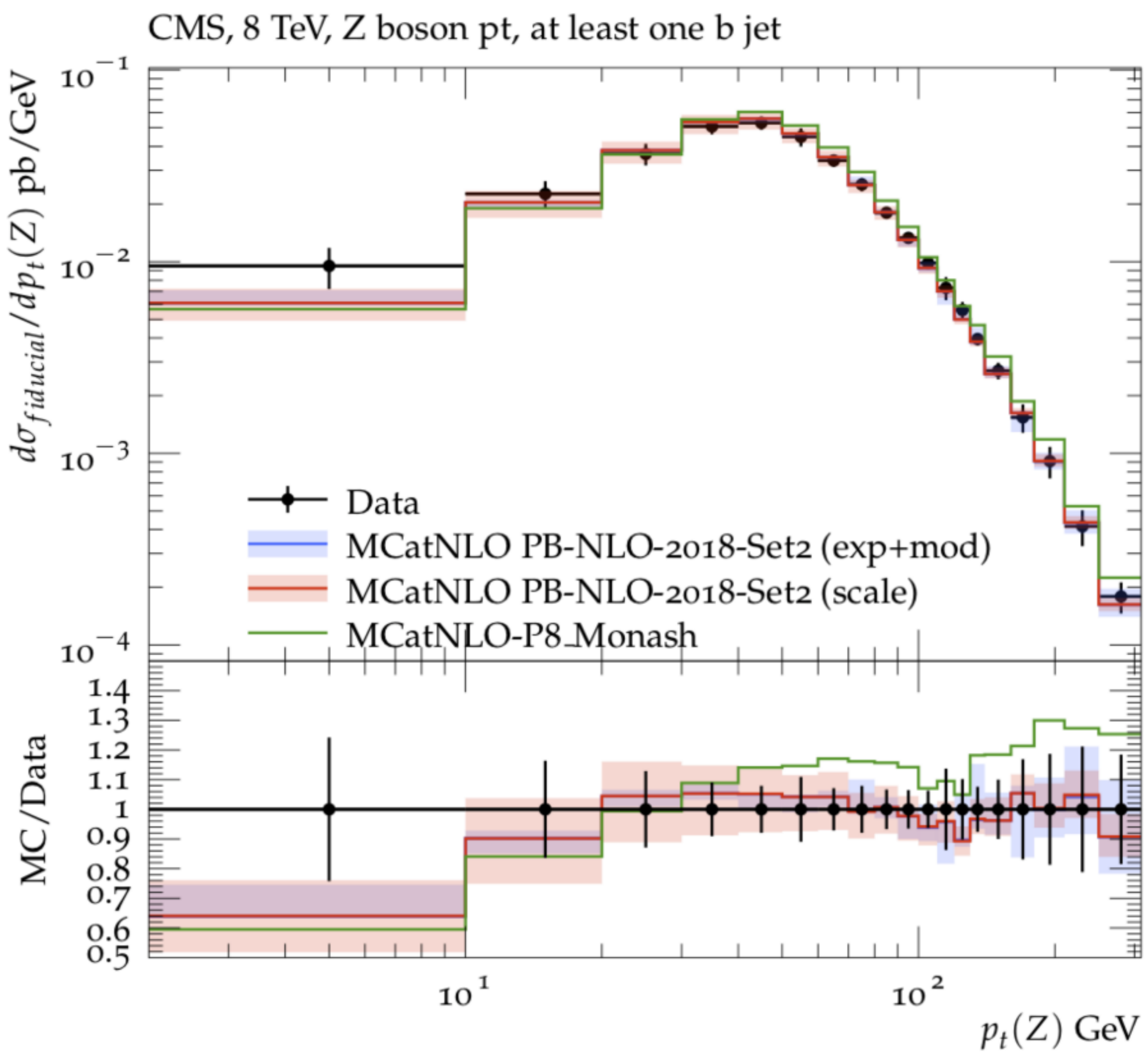
- MCatNLO for Z+b: (5-flavor scheme, since PB TMD in 5-flavor)
  - using herwig6 subtraction terms
  - PB-TMD to generate initial state k_T
  - initial state parton shower following PB TMD (same α_s, same NLO splitting functions(!), same cut-off params)

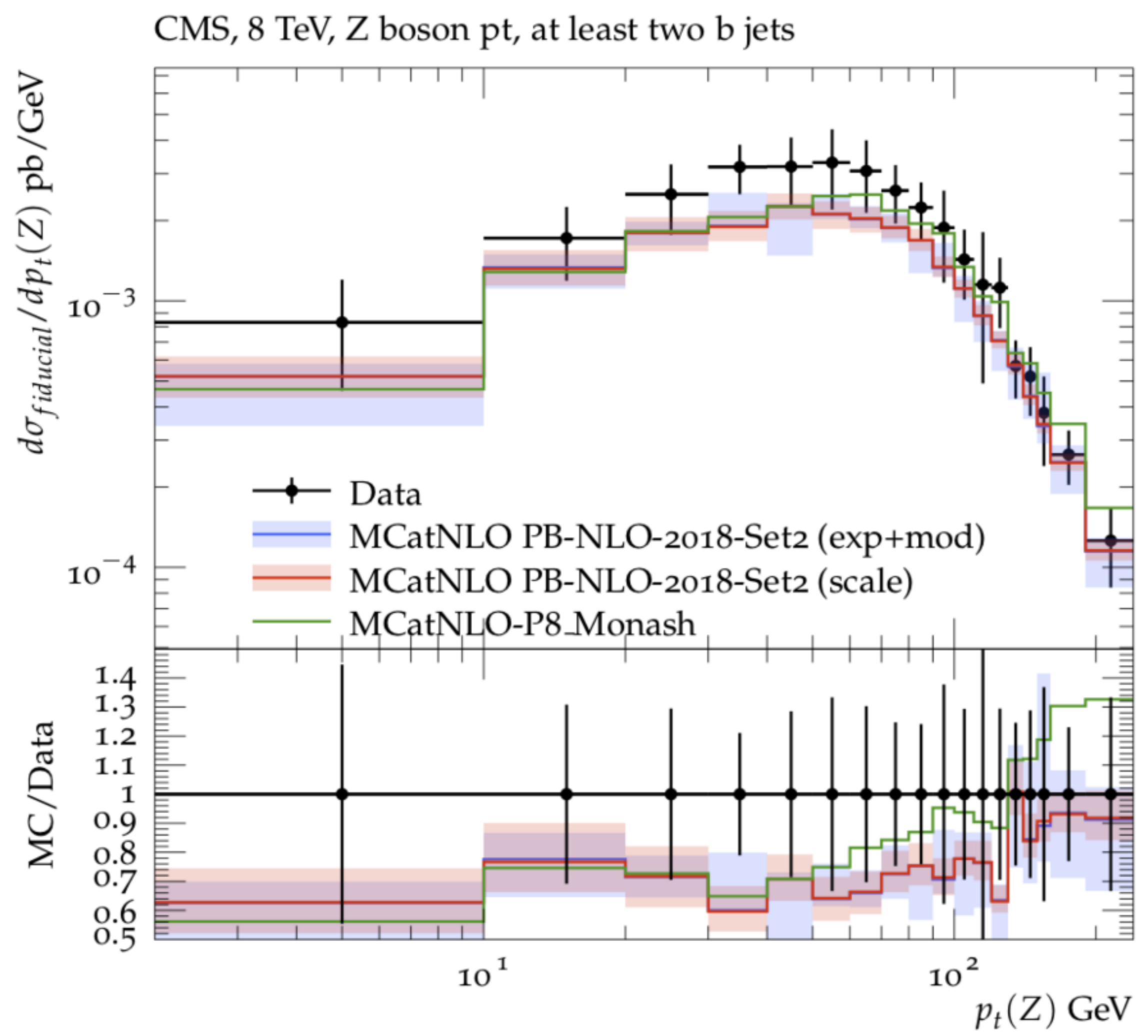
  - uncertainties:
    - NLO scale uncertainties
    - PDF (TMD) uncertainties
    - fixed order – TMD/parton shower matching scale
    - BUT NO further parton shower or intrinsic k_T uncertainties

PB-TMD, PB-TMD shower & MCatNLO: $Z+b$ jets

CMS Measurements of the associated production of a Z boson and b jets in pp collisions at 8 TeV, Eur. Phys. J., C77(11), 751, CMS-SMP-14-010, arXiv:1611.06507

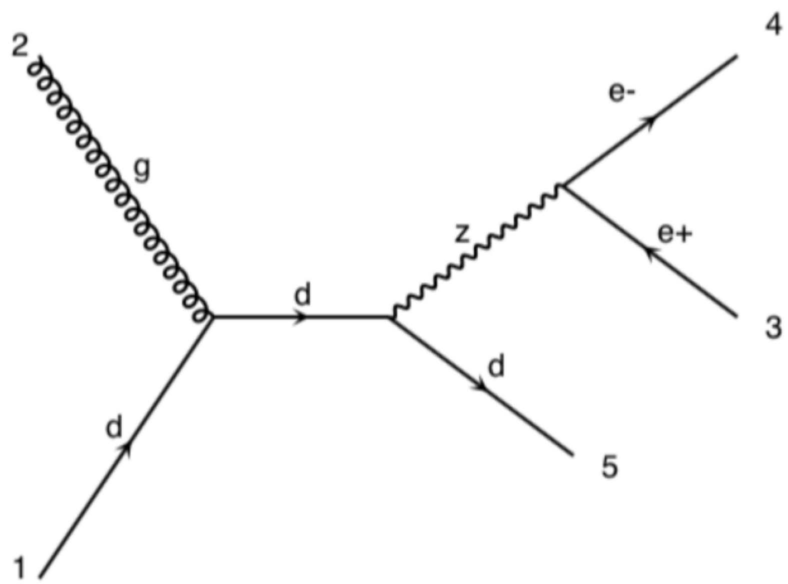
- Cuts:
  - leptons: $|\eta| < 2.,4$ p_T> 20 GeV, 71 GeV < m_{ll} <111 GeV
  - Jets: anti-k_T , R=0.5, $|\eta| < 2.4$, p_T > 30 GeV, b-Hadron





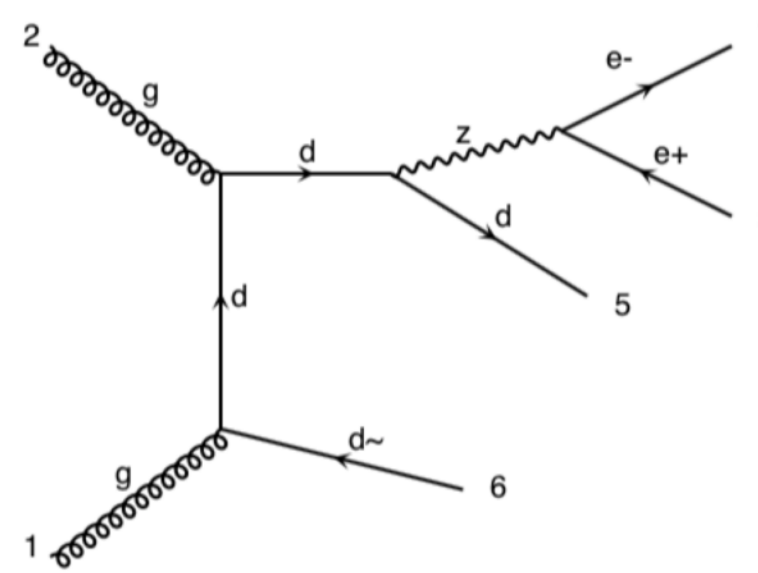
- comparison PB-TMD and P8 shower shows good agreement,
  - differences in details :)

$Z{+}b$ jets: sensitivity to initial state k_T



born diagram 2 QCD=1, QED=2

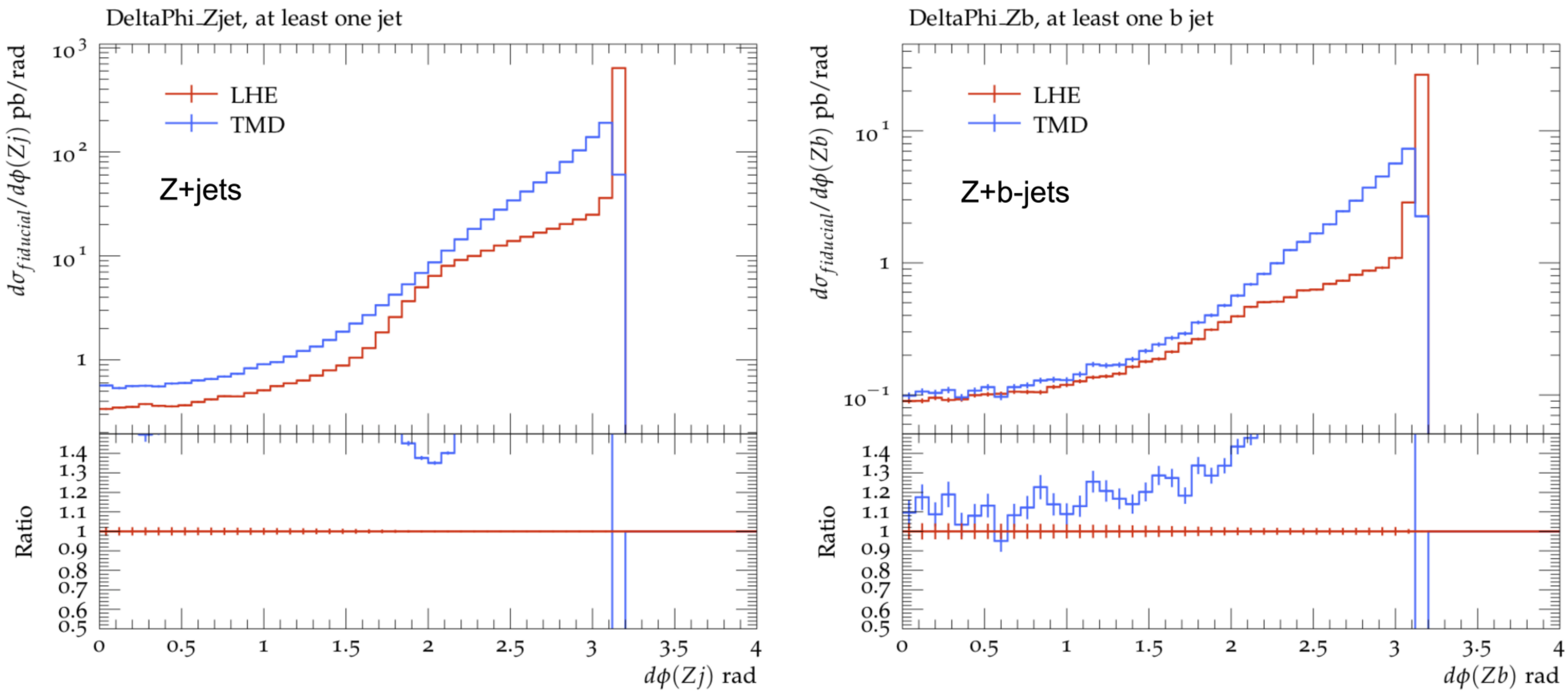
d-type = b



real diagram 12 QCD=2, QED=2

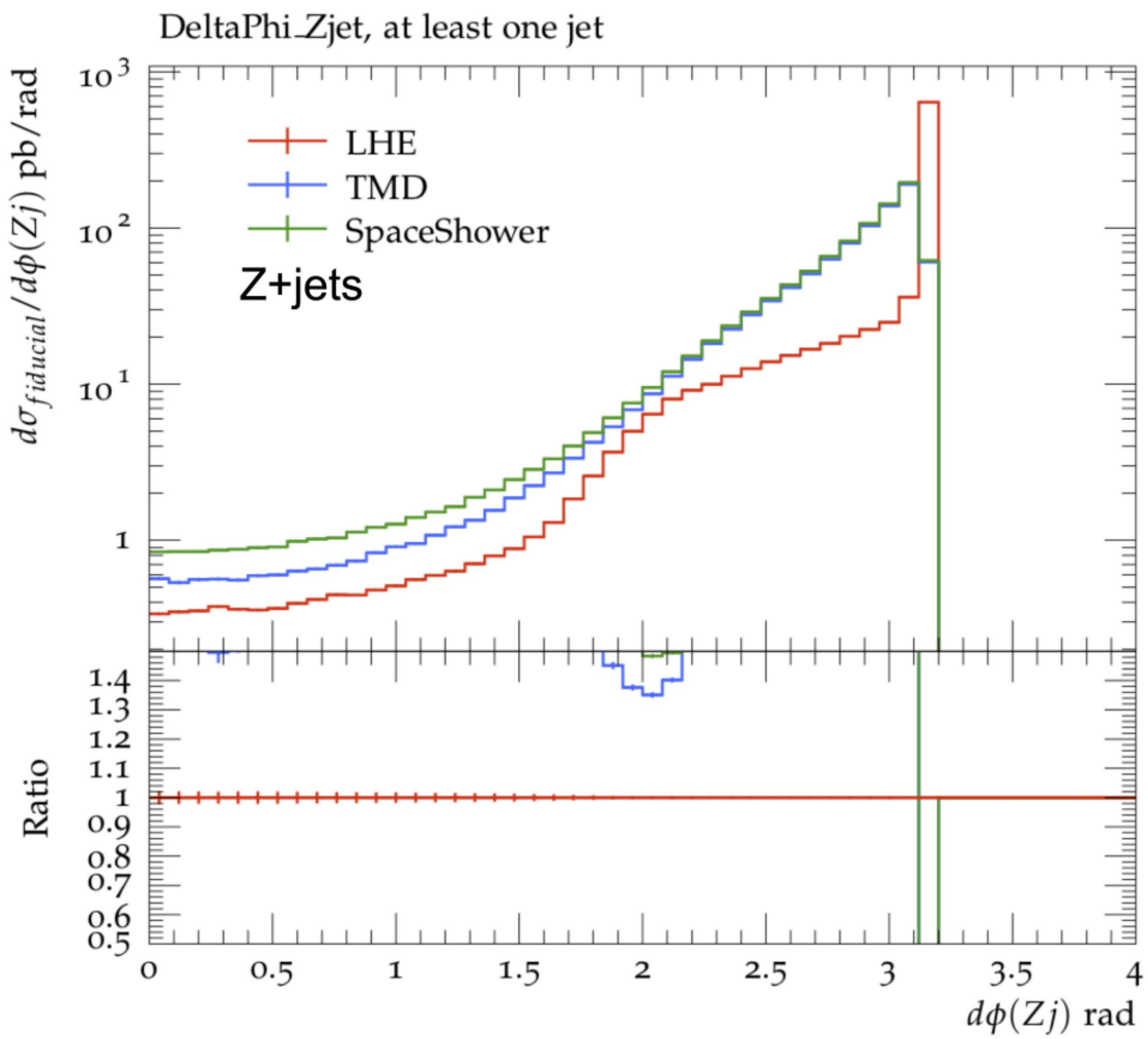
- in LO: $\Delta\,\phi\,(Z{,}b) = \pi$
  - TMD introduces k_T on g and b → deviation from $\Delta\,\phi\,(Z{,}b) = \pi$
- real NLO correction: $\Delta\,\phi\,(Z{,}b) \leqslant \pi$
  - TMD introduces k_T on g
    → additional decorrelation $\Delta\,\phi\,(Z{,}b)$

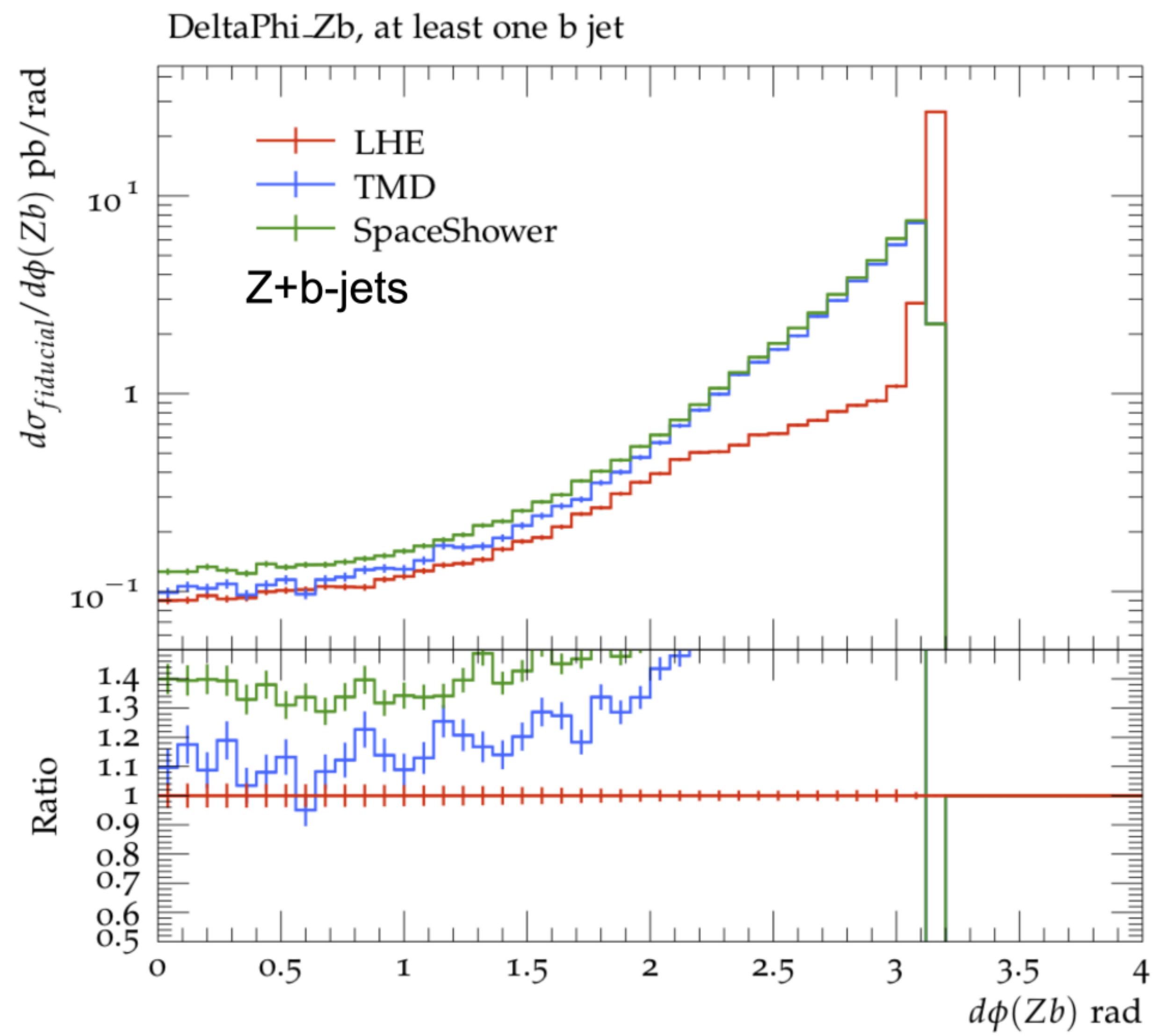
$Z+$ jets: sensitivity to initial state k_T



- TMD important at large and small $\Delta\,\phi$
- TMD important at large $\Delta\,\phi$

$Z+$ jets: sensitivity to initial state k_T

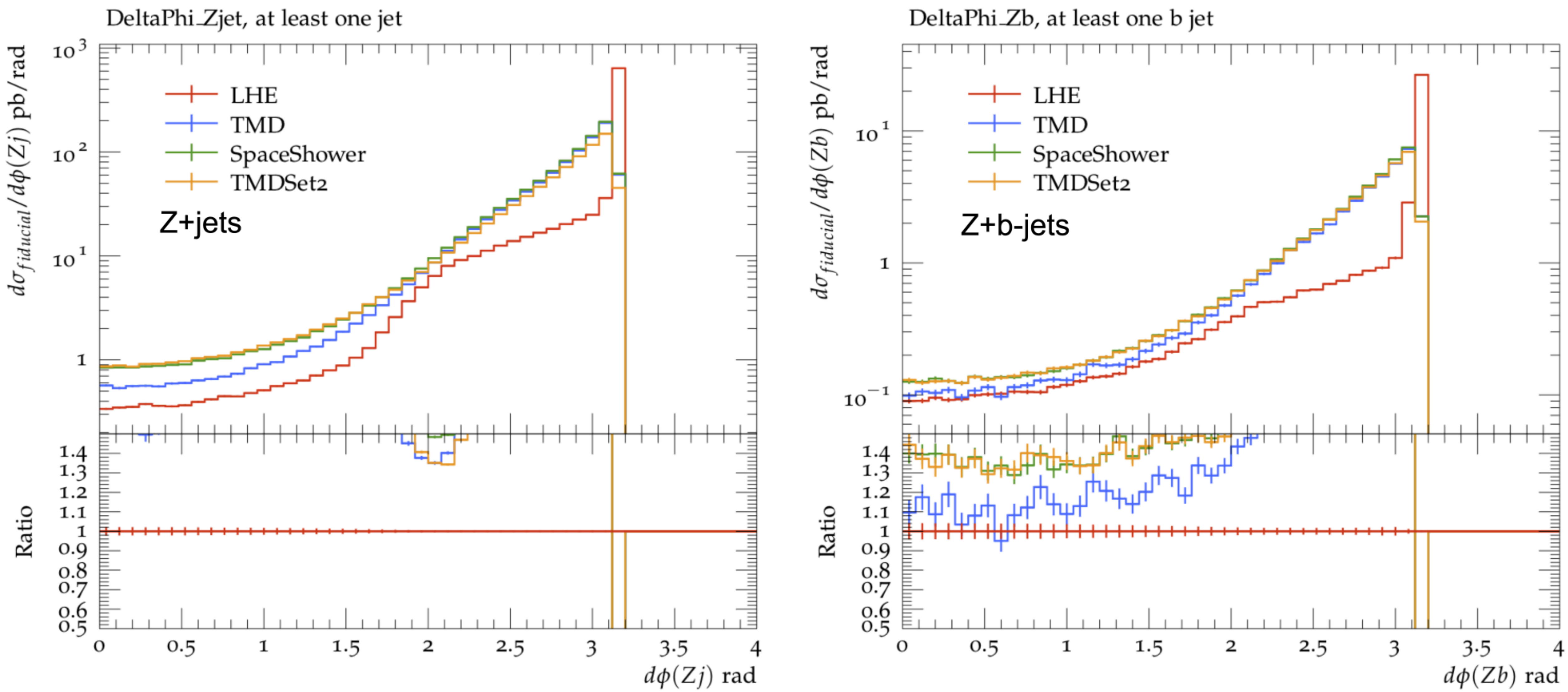




- TMD important at large and small $\Delta\,\phi$
- initial state PS at small $\Delta\,\phi$

- TMD important at large $\Delta\,\phi$
- initial state PS only small effect (on top of TMD)

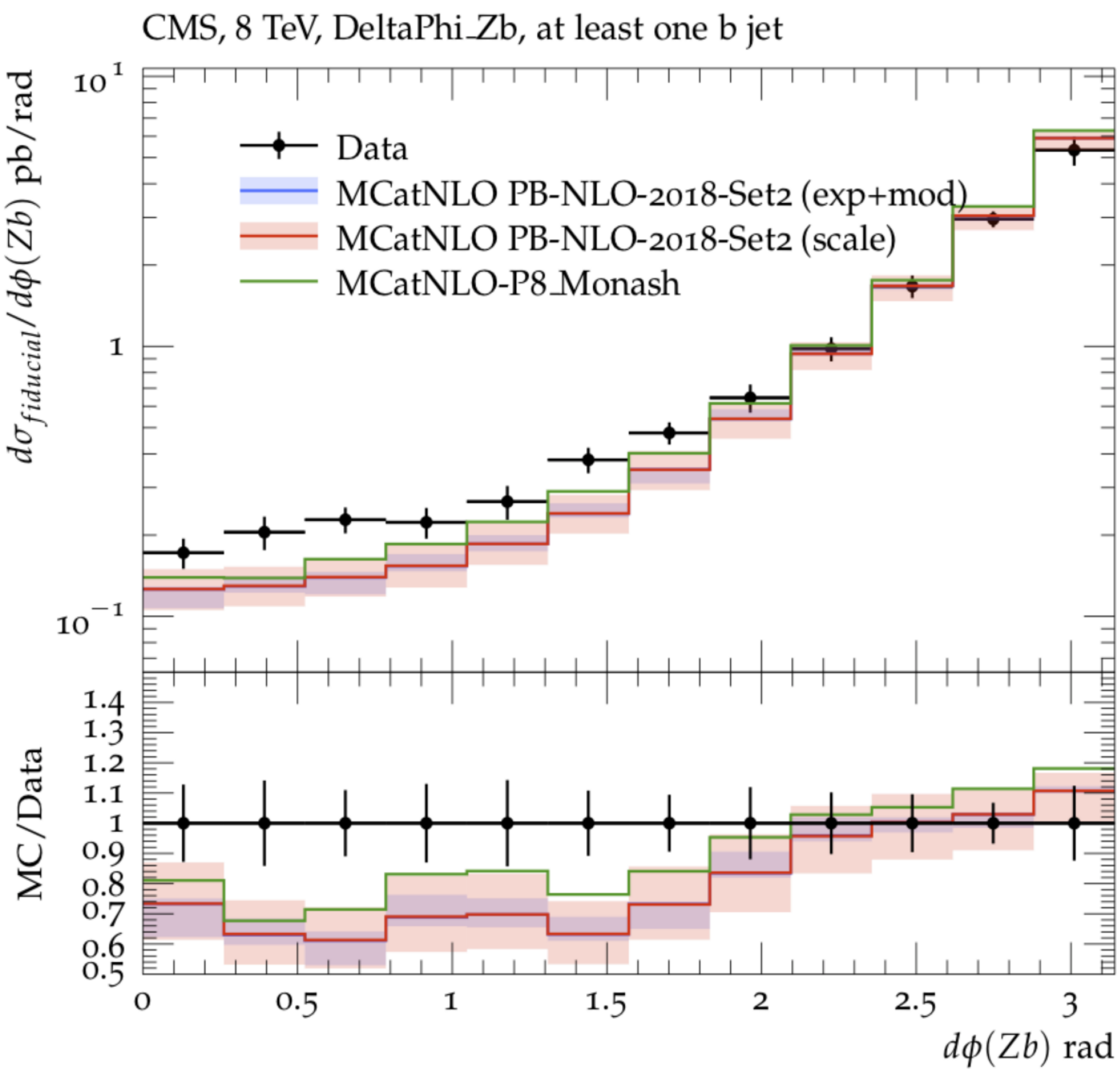
$Z+$ jets: sensitivity to initial state k_{T}



- TMD important at large and small $\Delta\phi$
- initial state PS at small $\Delta\phi$
- FSR only small effect at large $\Delta\phi$

- TMD important at large $\Delta\phi$
- initial state PS only small effect (on top of TMD)
- FSR only small effect at large $\Delta\phi$

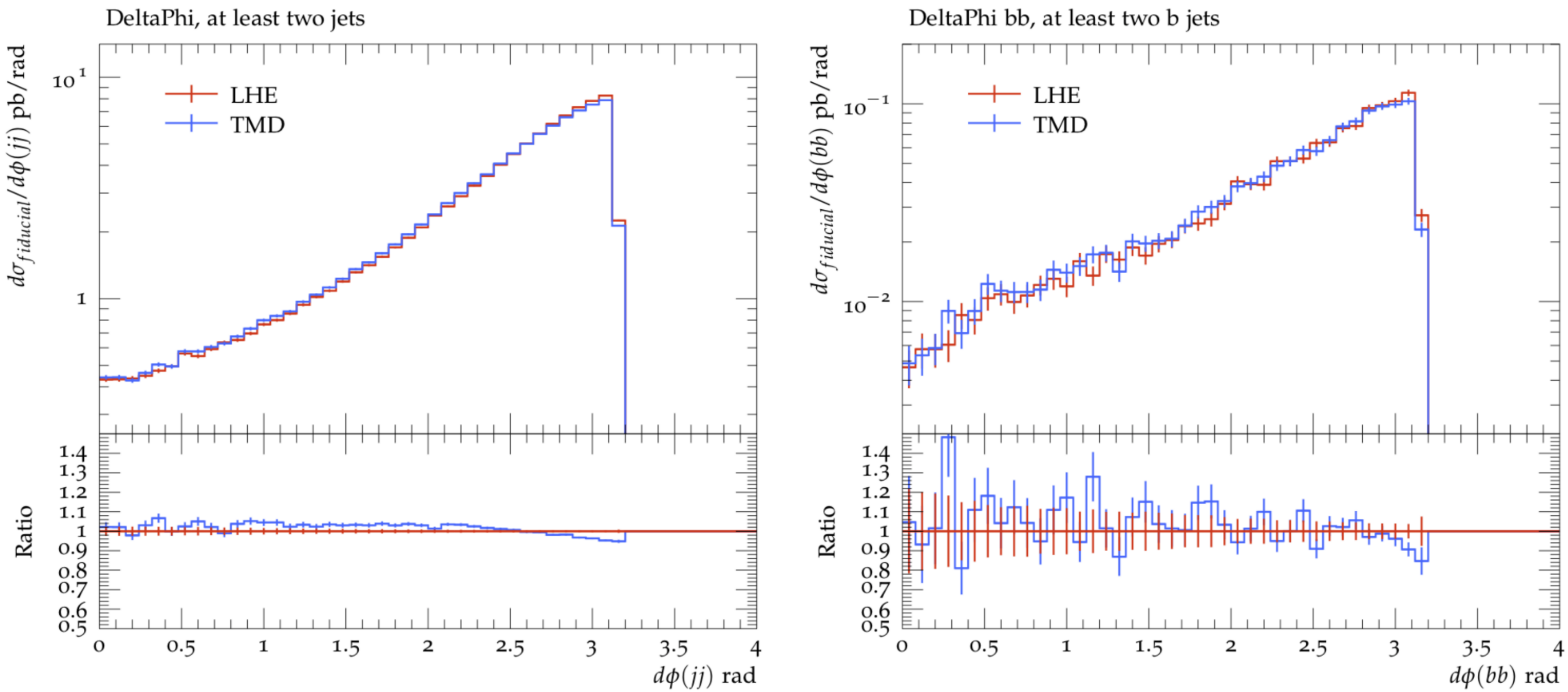
Z+b-jets: $\Delta\,\phi\,(Zb)$ - comparison to measurement



- 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 (see slides before)
  - distribution essentially determined by TMD distribution
  - uncertainties only from TMD

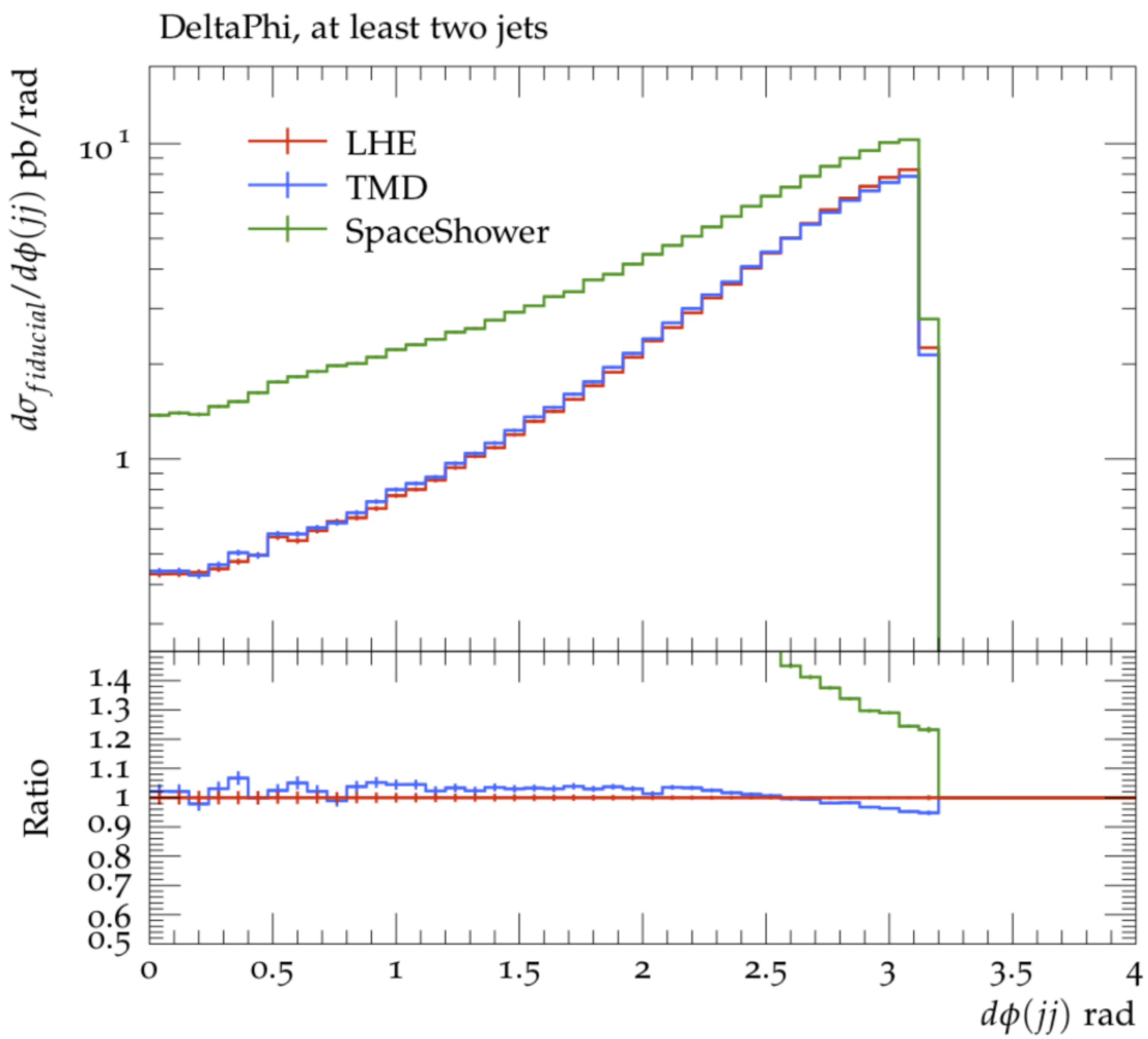
➔ Z+b correlation tests TMD

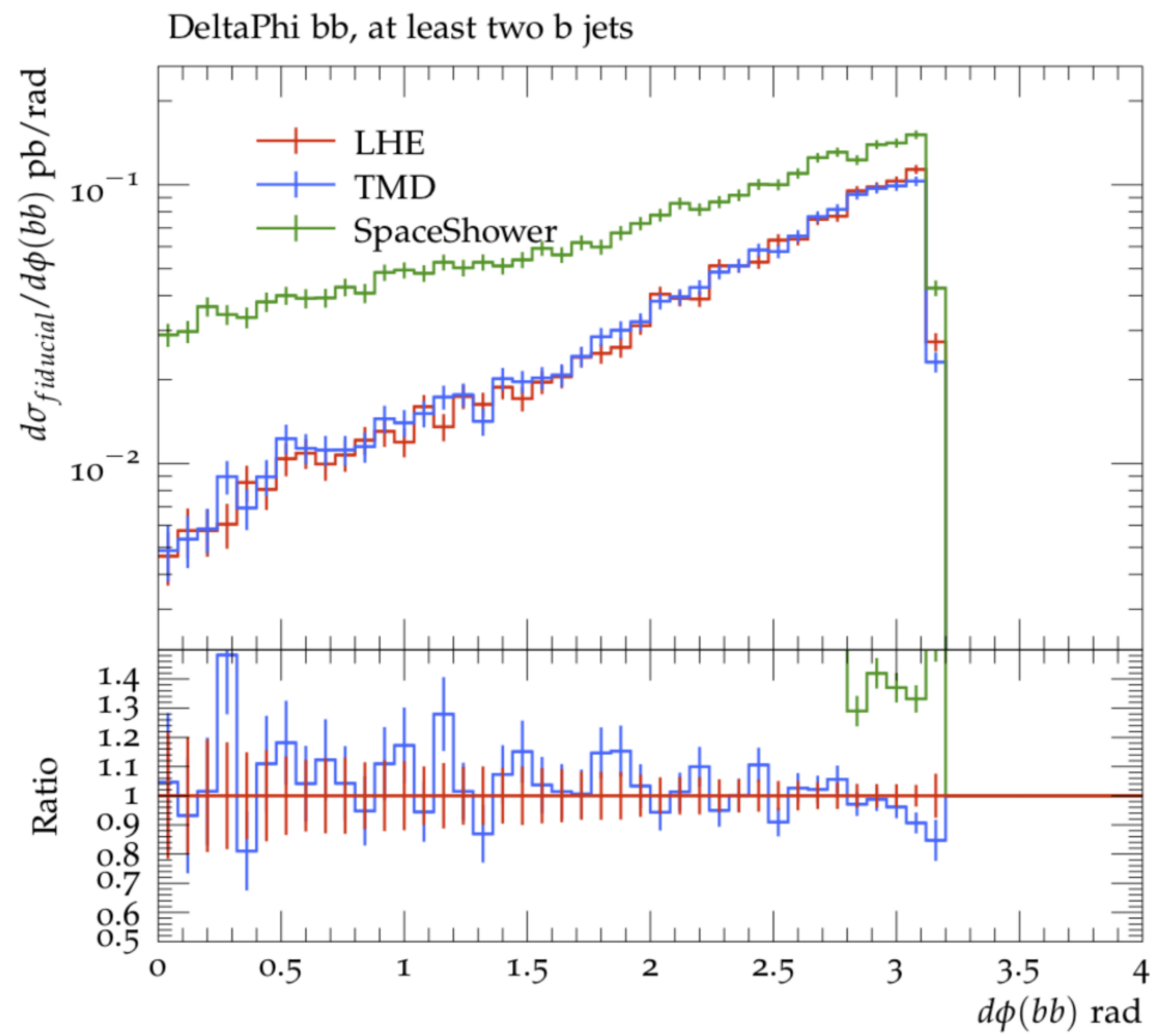
$Z+$ 2 jets: sensitivity to initial state shower



- TMD has little impact

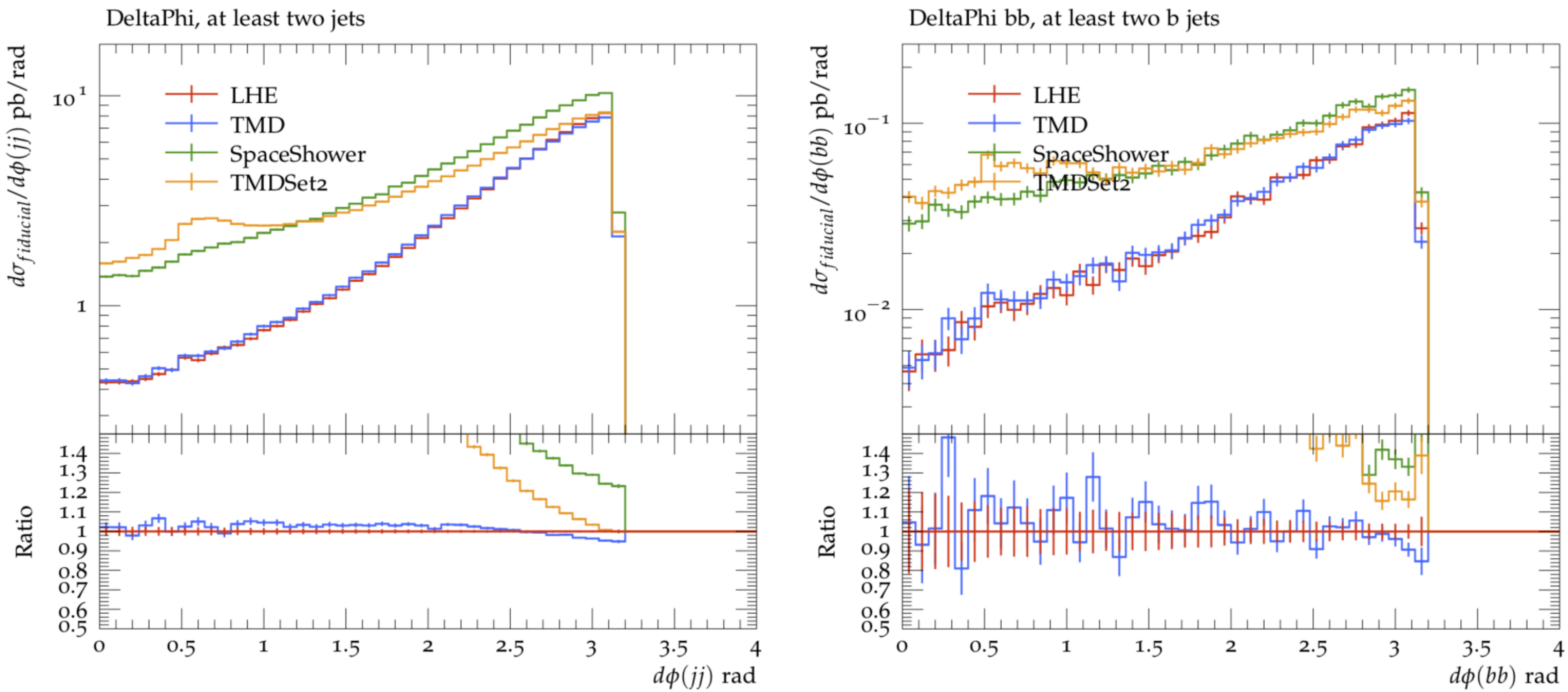
$Z+$ 2 jets: sensitivity to initial state shower





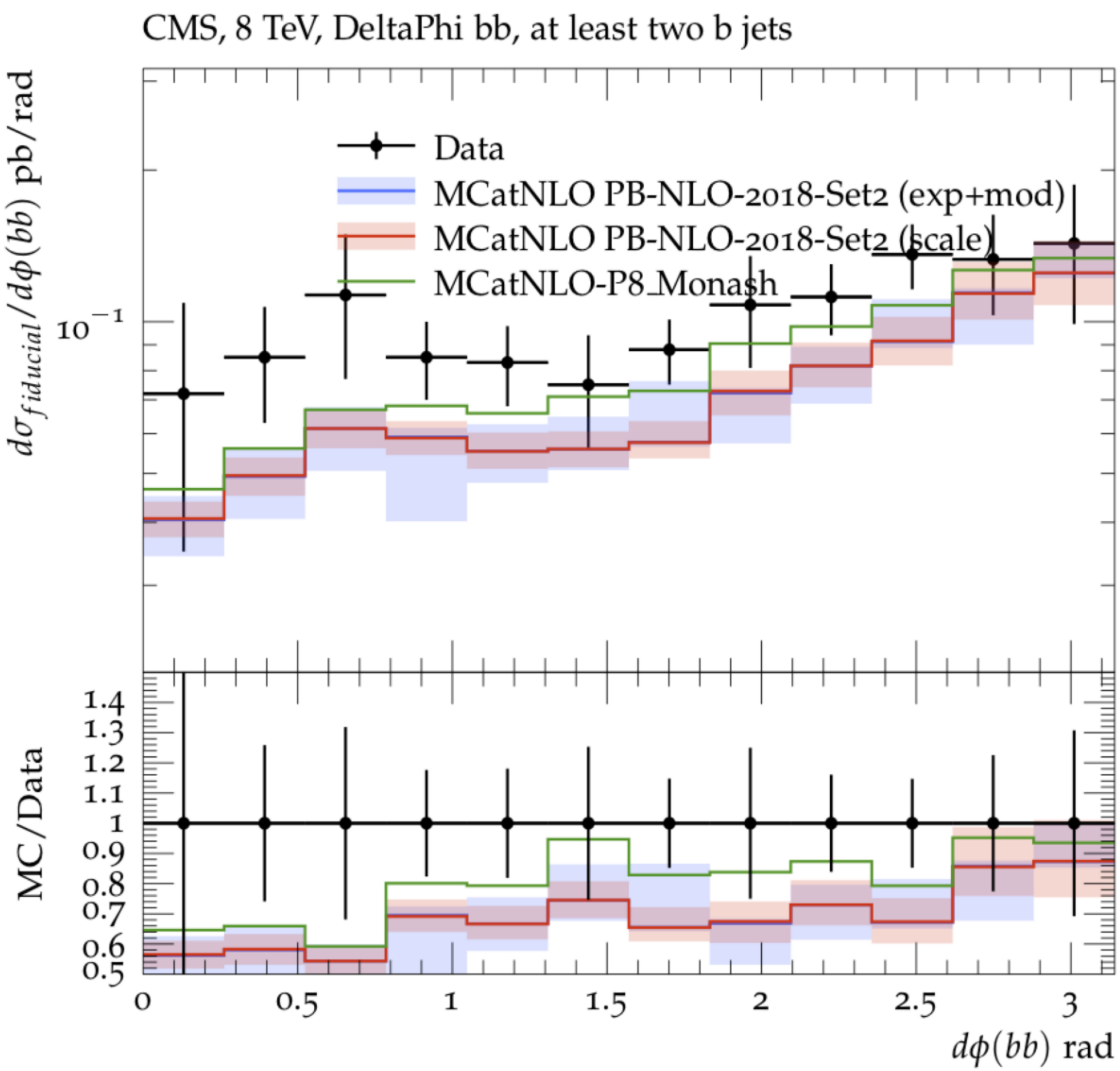
- TMD has little impact
- initial state PS large small effect (on top of TMD)

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



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

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

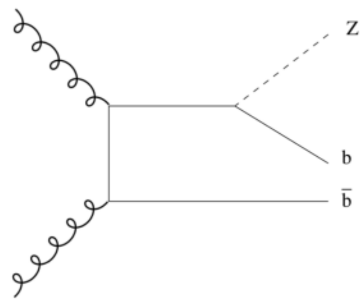


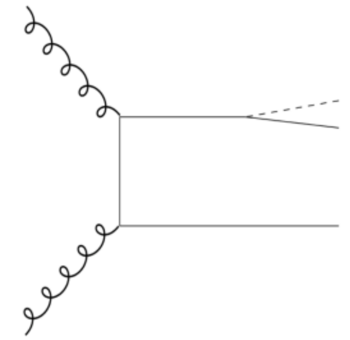
- Good description
  - decorrelation comes essentially from k_T from initial evolution
    - Space shower is important
    - Time shower only at small $\Delta\,\phi(bb)$
    - sensitive to b-quark TMD density AND b-quark TMD-shower

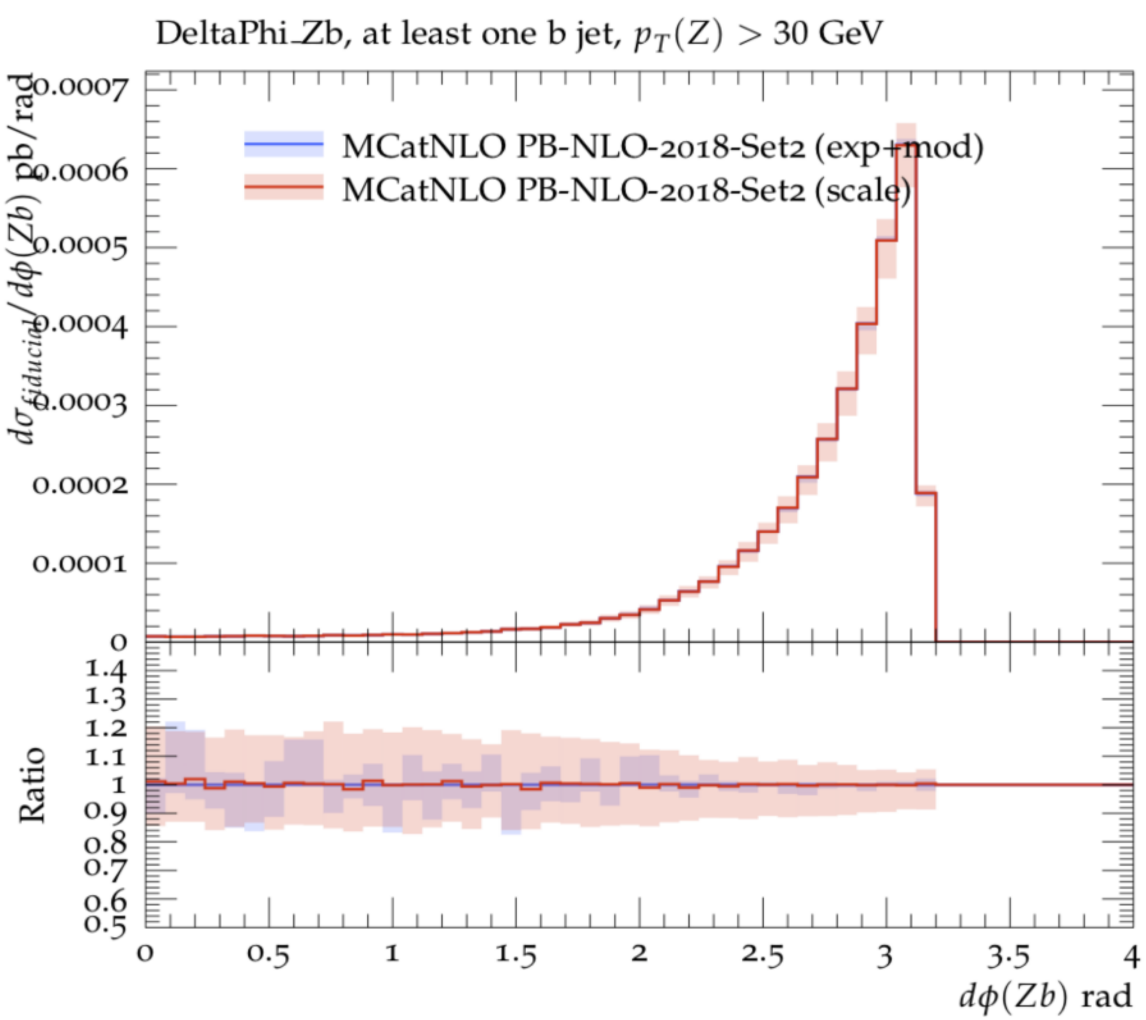
➔ bb correlation tests space shower

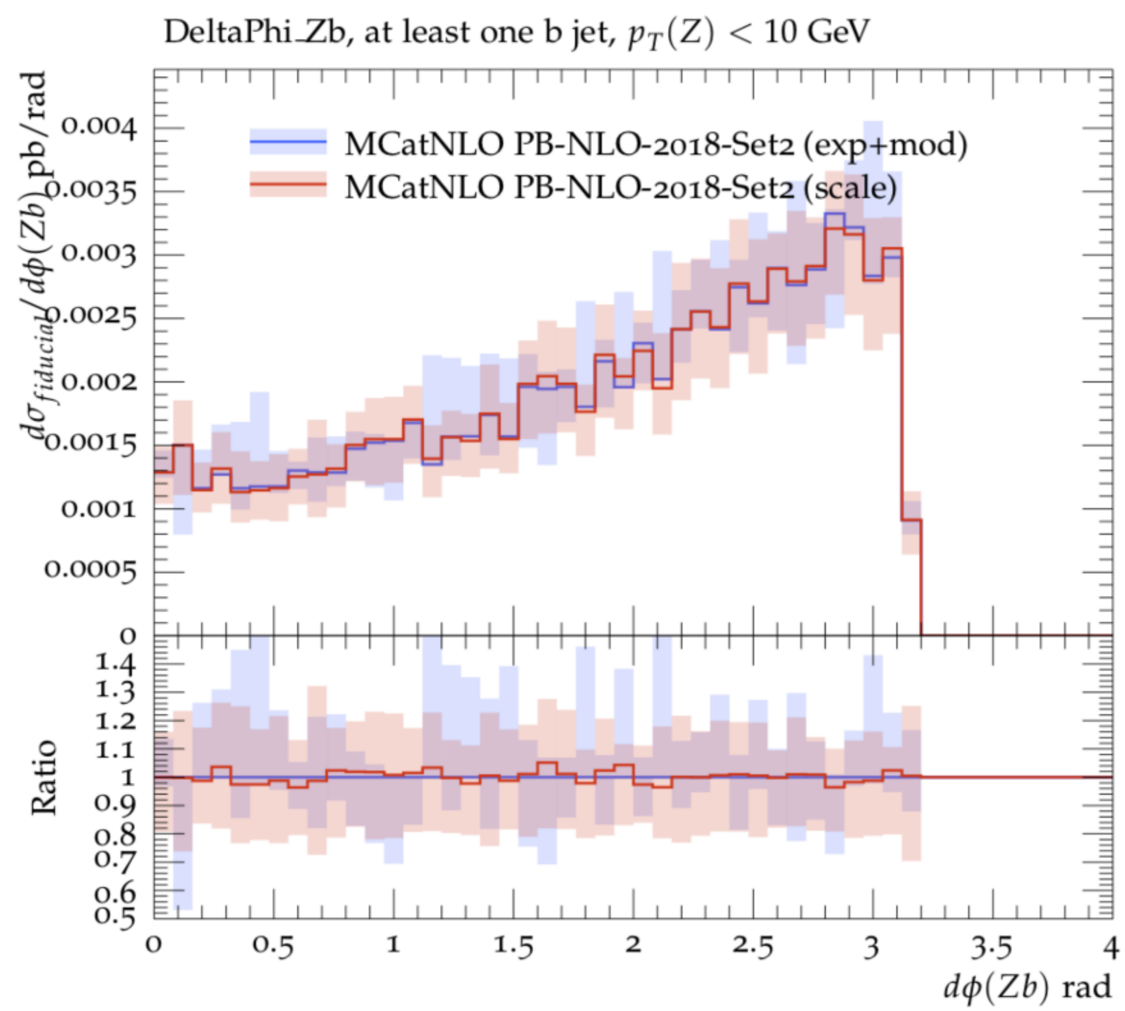
Correlations: Z and b-jet

- $p_T(Z)$ dependence of Zb correlation





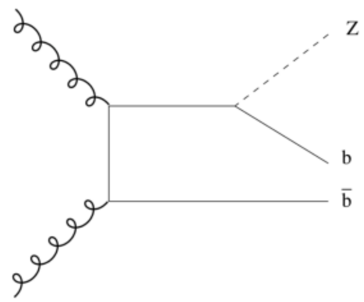


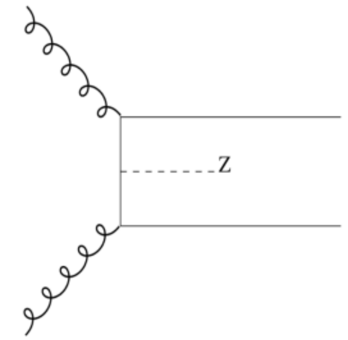


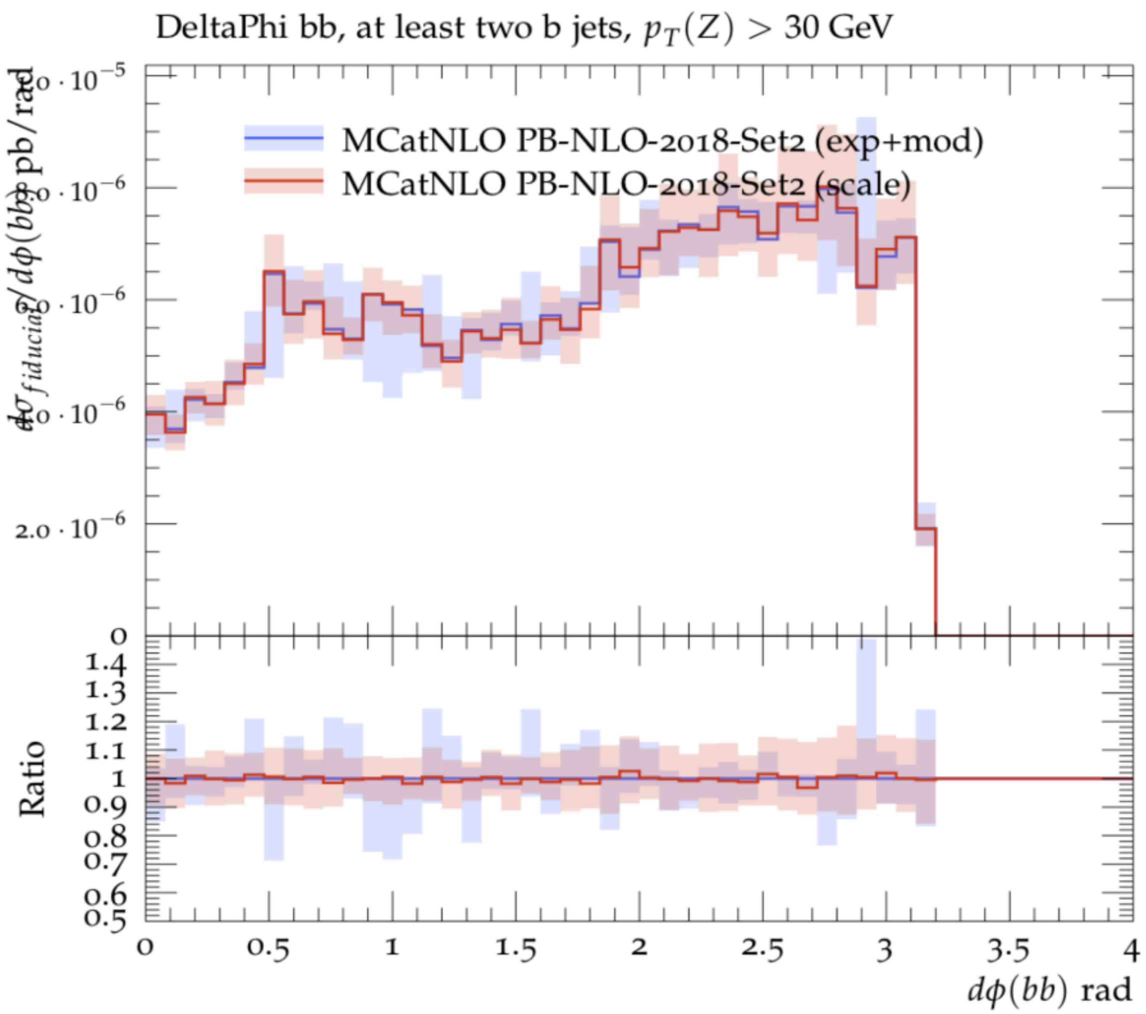
- large $p_T(Z)$: correlation between Z+b-jets

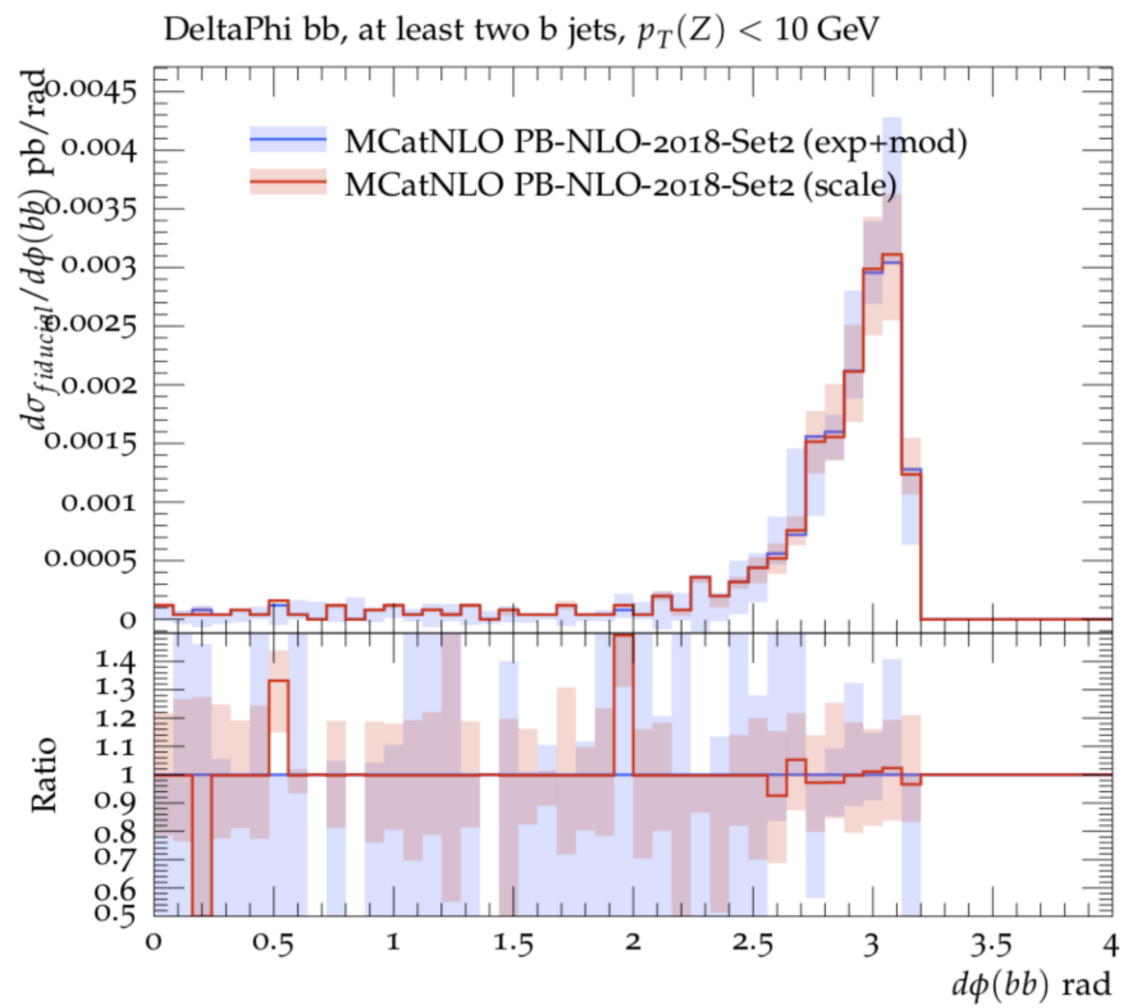
Correlations: bb-jets

- $p_T(Z)$ dependence of bb correlation









- small $p_T(Z)$: correlation between bb-jets

Conclusion

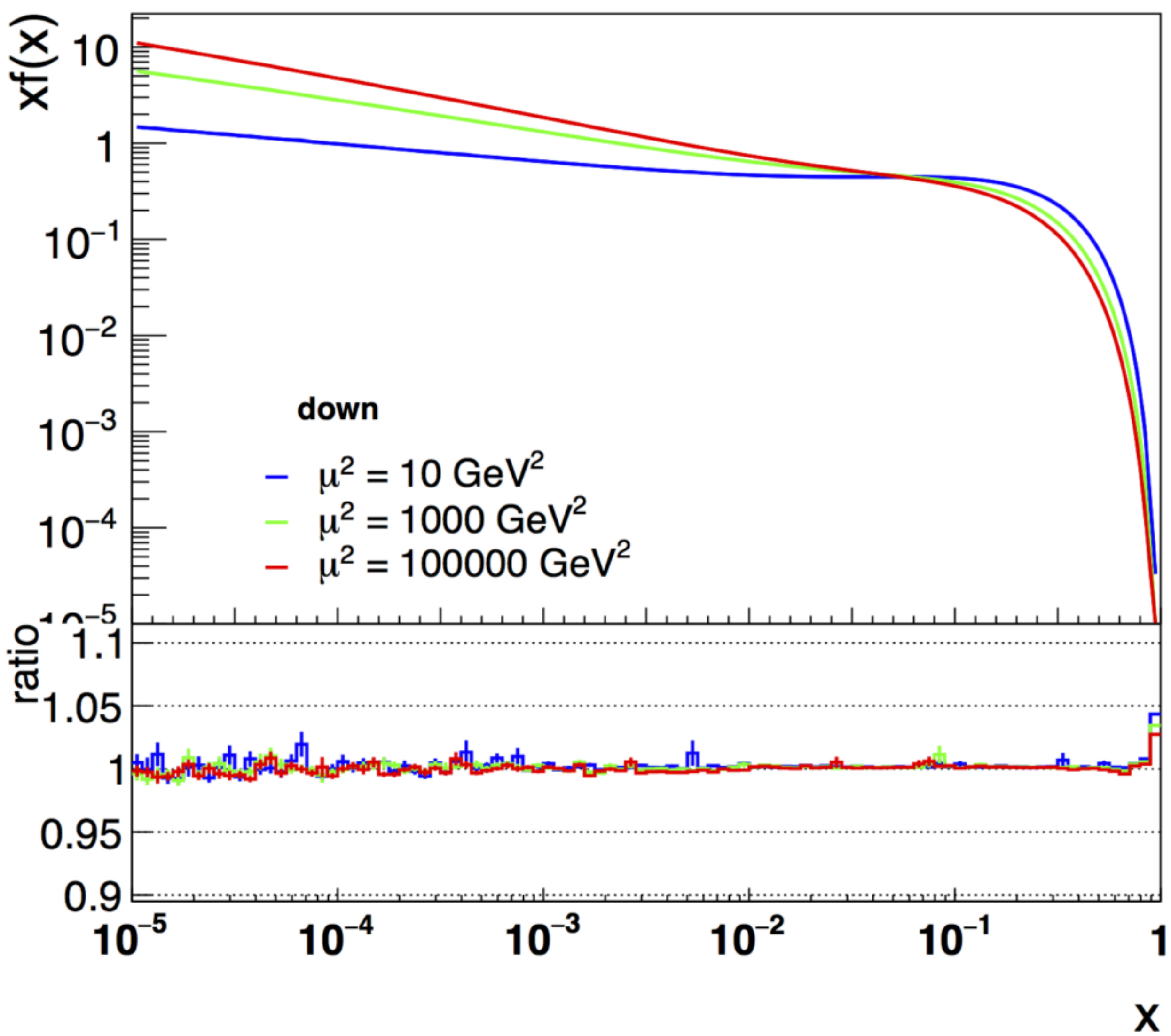
- Parton Branching method to solve DGLAP equation at LO, NLO and NNLO
  - method directly applicable to determine k_t distribution (as would be done in PS)
  - ➔ TMD distributions for all flavors determined at LO and NLO
  - ➔ TMD evolution implemented in xFitter – fits to DIS processes at the moment

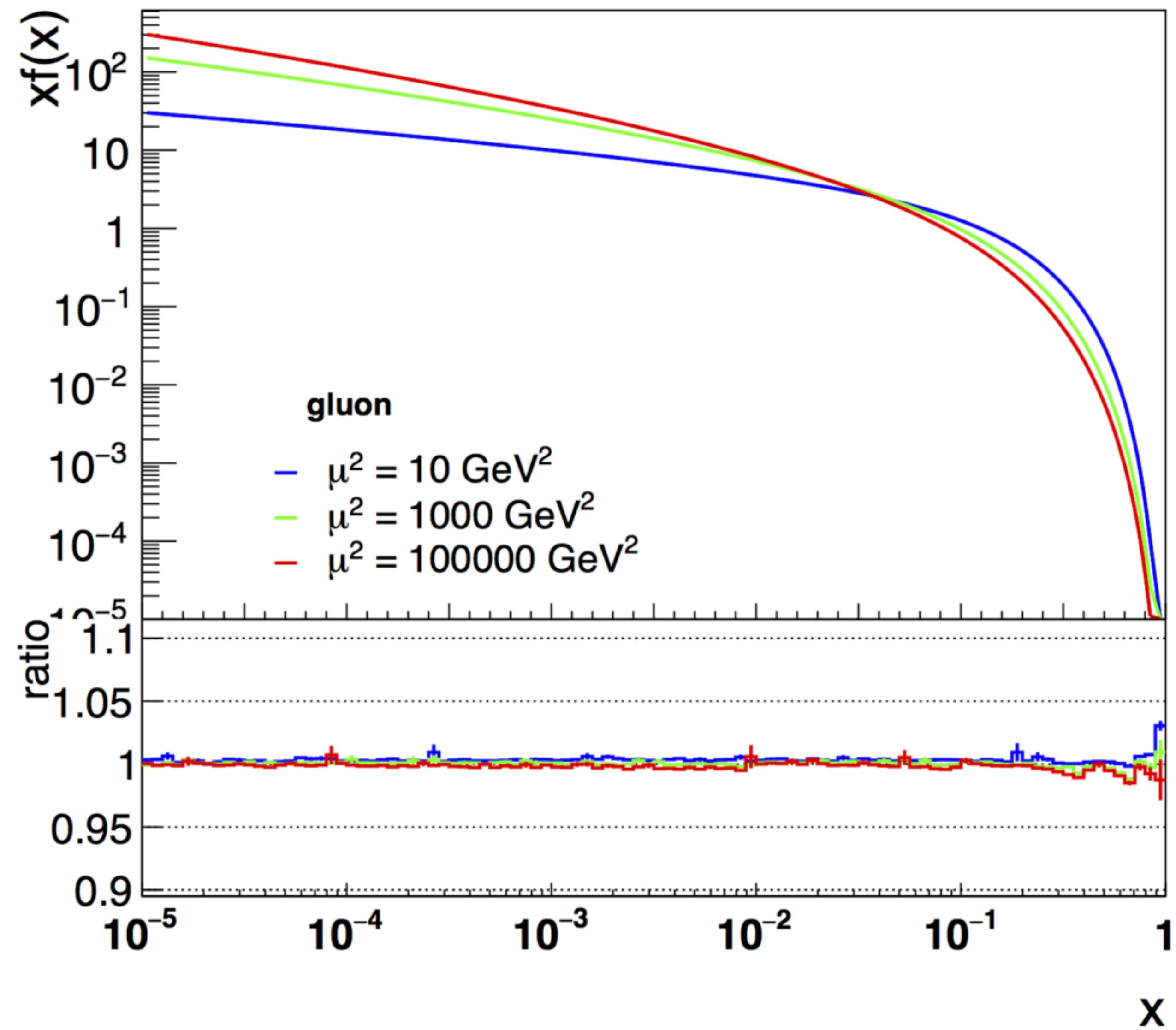
- Application to DY processes in pp:
  - ➔ DY q_T - spectrum without new parameters for Z and low mass DY
    - ➔ matching TMD with MC@NLO
  - NEW: application to Z + b-jets
    - distributions well described – no additional uncertainties from shower
    - Regions of sensitivity to TMD and space shower identified:
      - ➔ b-quark TMD density AND b-quark TMD shower !

➔ Z + b-jets interesting tool for studying initial state parton radiation in very detail: TMDs and TMD showers

Appendix

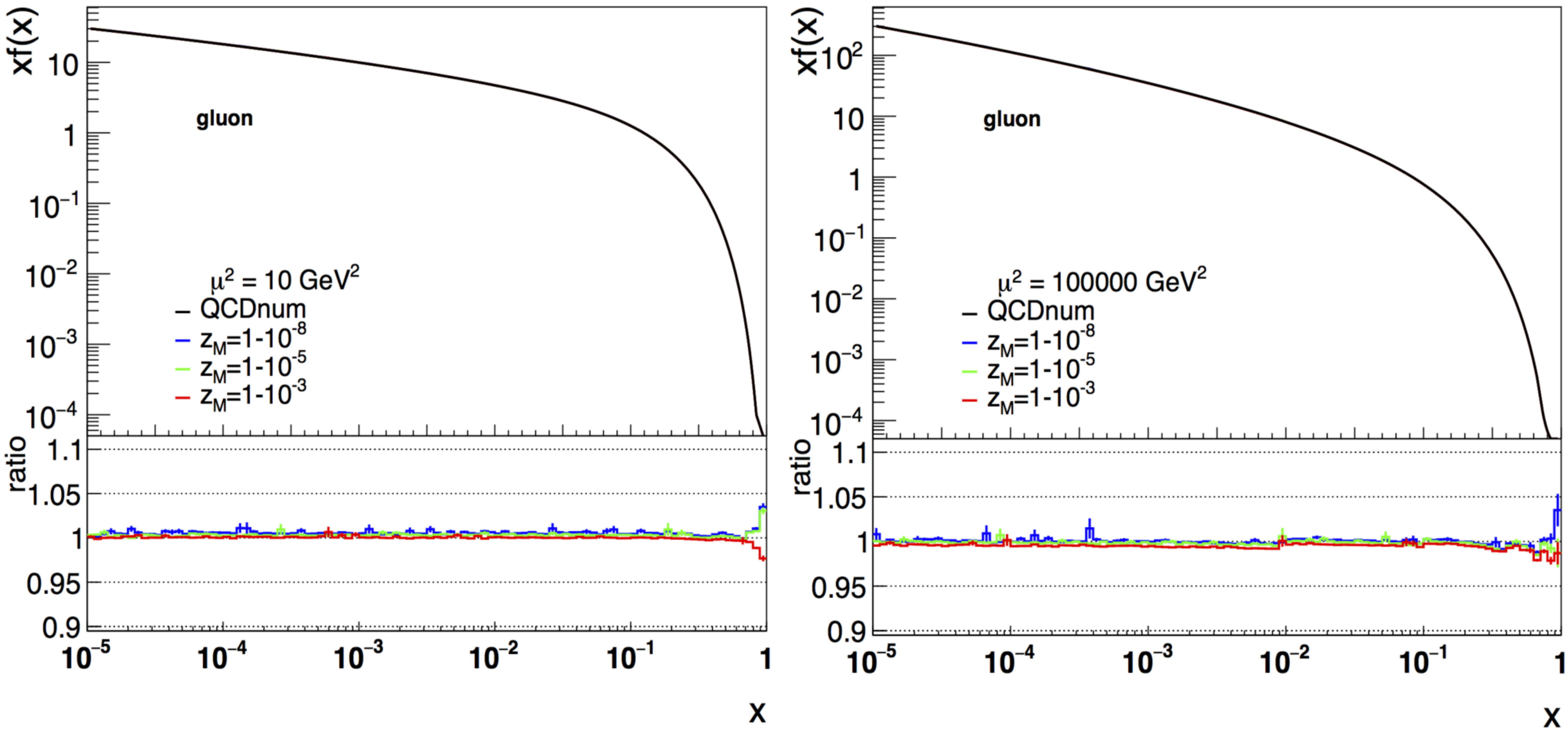
Validation of method with QCDnum at NLO





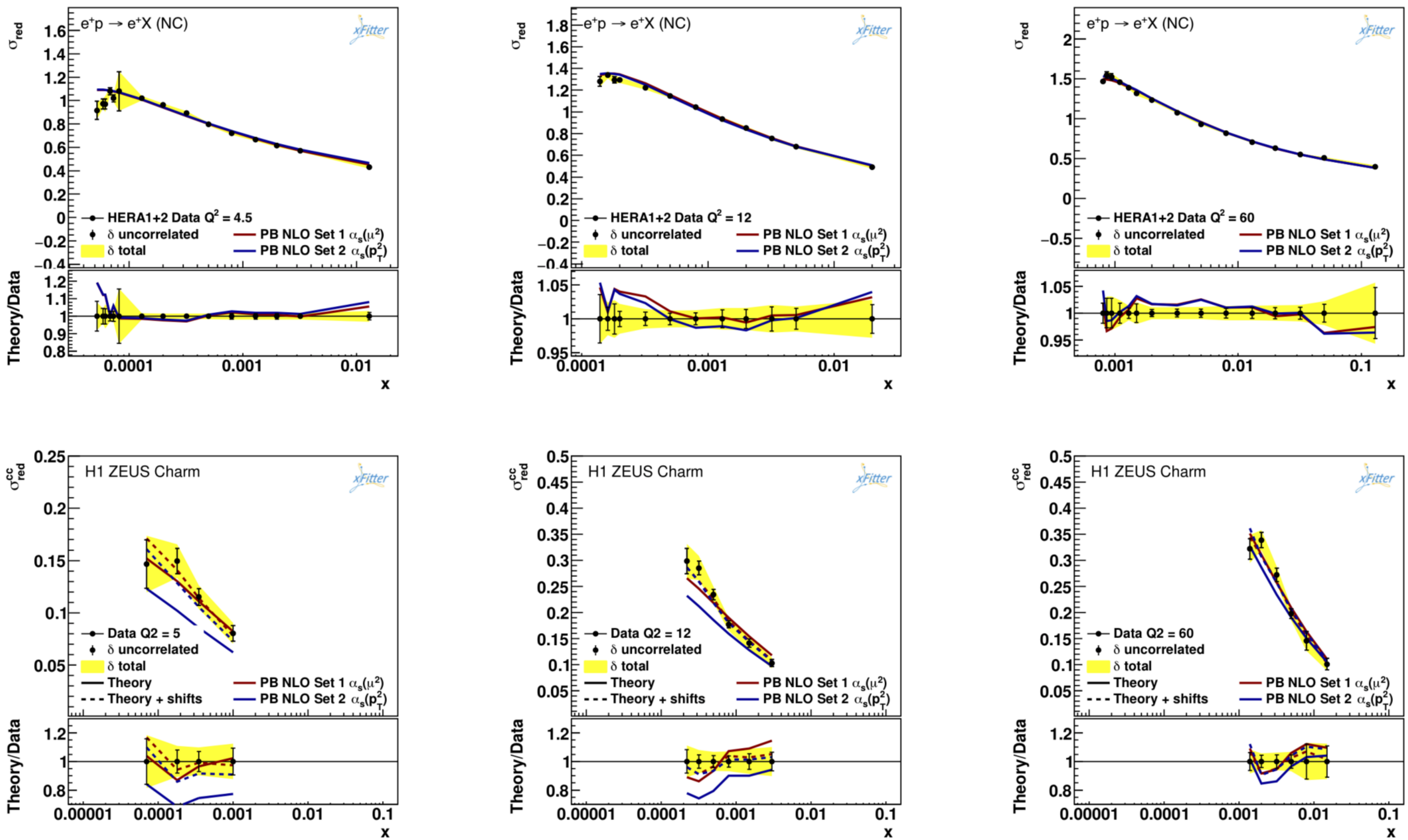
- Very good agreement with NLO - QCDnum over all x and μ^2
  - the same approach works also at NNLO !

Validation of method at NLO: z_M - dependence



- No dependence on z_M if z_M is large enough:
  - approximation is of $\mathcal{O}(1 - z_M)$
- Very good agreement with NLO - QCDnum

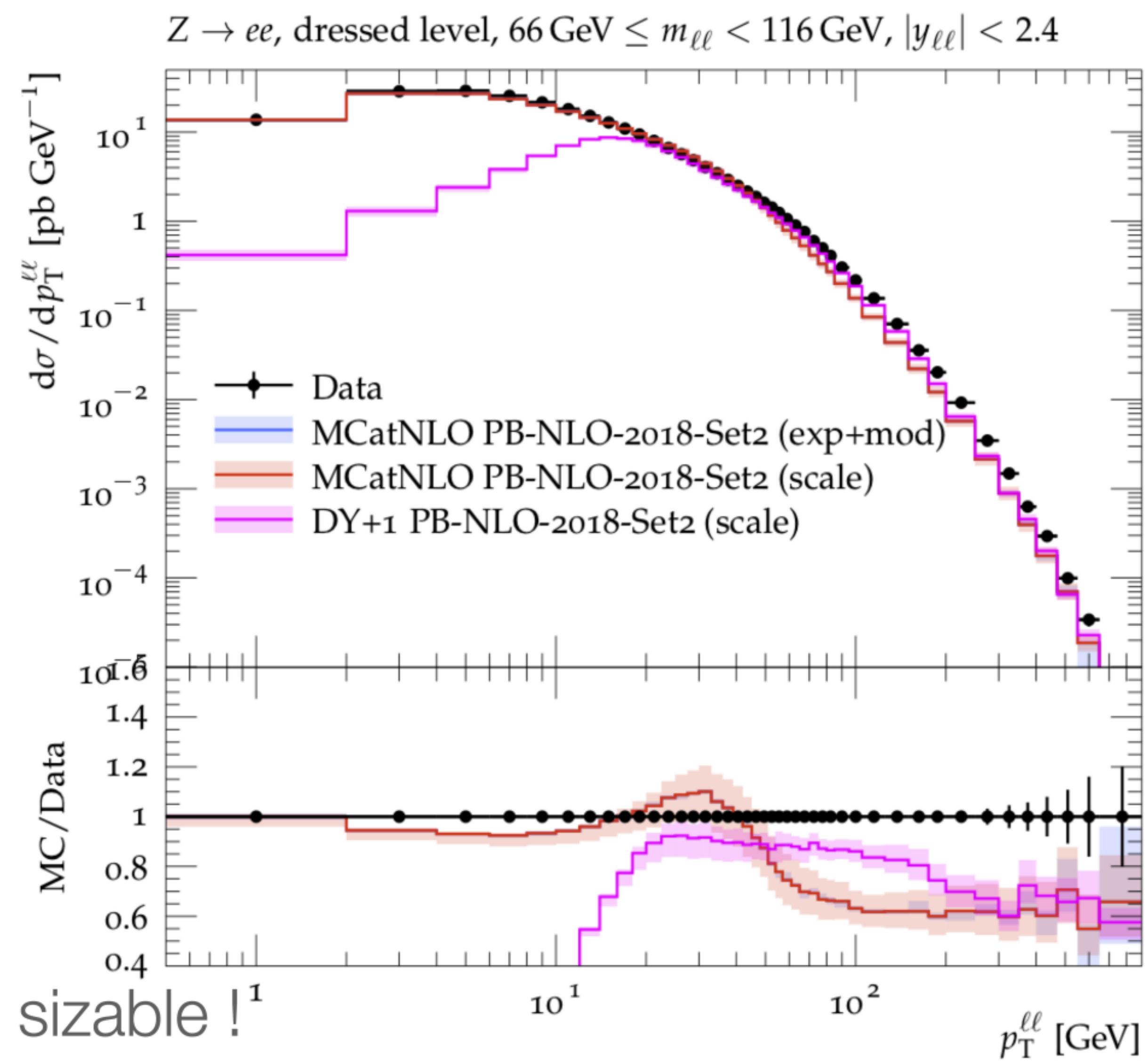
Fits to DIS x-section at NLO: F_2 and F_2^c



Matching to hard process: MC@NLO method

DY with PB TMDs: Bermudez Martinez, A. et al, arXiv 1906.00919, PhysRevD.100.074027

- MC@NLO subtracts soft & collinear parts from NLO (added back by TMD and shower)
- low q_T region affected by subtraction of soft & collinear parts
  - filled by TMD (+ PS)
- DY production very well described by TMD with MC@NLO
  - TMD fills low q_T part
    - small uncertainties in small p_t region
    - scale uncertainties from hard process sizable !
  - at large q_T contribution from DY+1 jet significant



ATLAS (2016). DY at 8 TeV, EPJC76, 291, 1512.02192