Production of Z-boson in Parton branching method with TMD

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in collaboration with
A. Bermudez Martinez, P.Connor, D. Dominguez Damiani, L. Estevez Banos, F. Hautmann, H. Jung, J. Lidrych, M. Schmitz, S. Taheri Monfared, A. Lelek, V. Radescu, R. Zlebcik

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Ministry of Human Resources and Social Security
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

- TMDs and Parton Branching (PB) method
- Application in Drell-Yan (DY) production
  - DY production at 8 TeV
  - DY production at 13 TeV
- Conclusion

Part 1

TMDs and Parton Branching (PB) method

Introduction-TMD

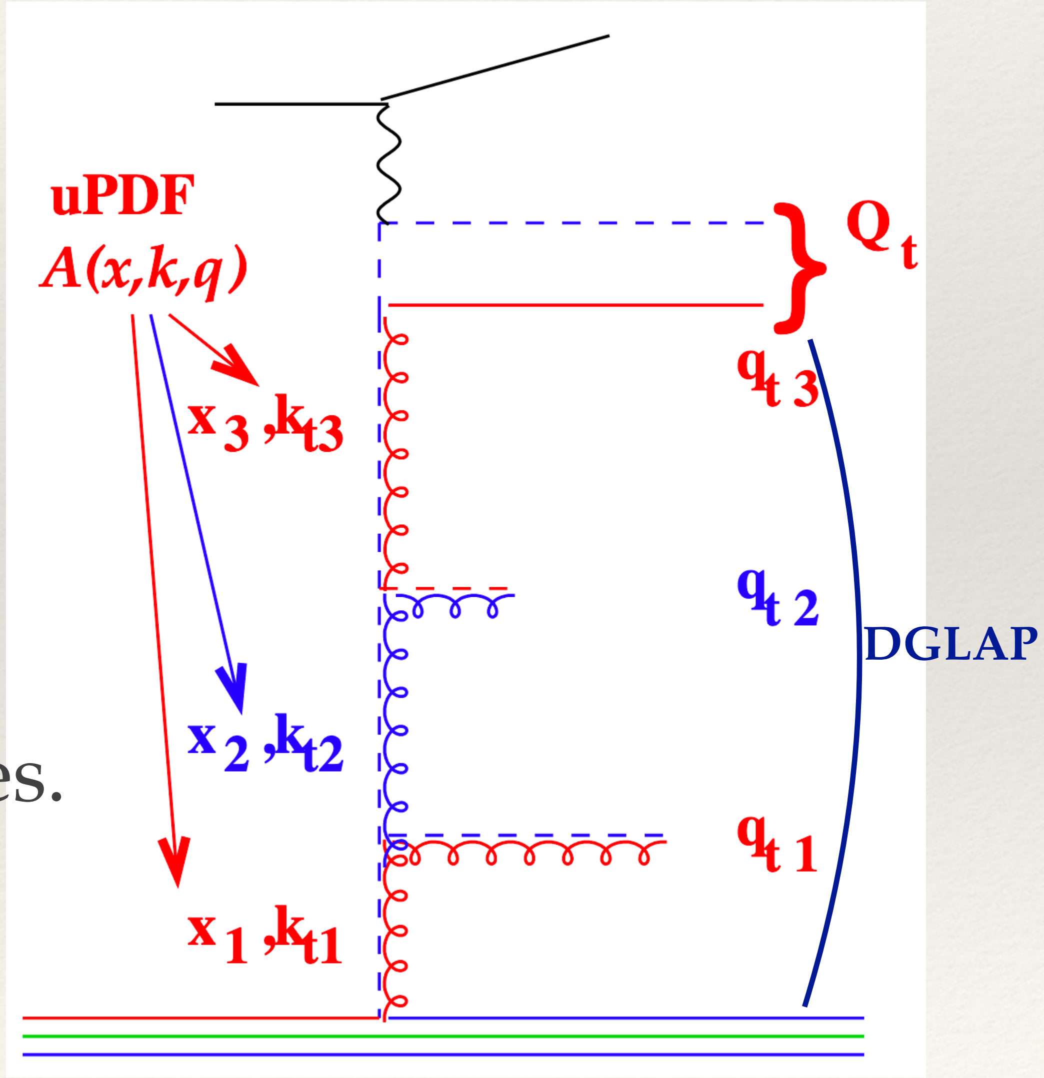
- TMDs (Transverse Momentum Dependent parton distributions)
  - at very small transverse momenta
    - typically for small q_t in DY production, or semi-inclusive DIS
  - at very small x - unintegrated PDFs
    - essentially only gluon densities (CCFM, BFKL etc)
  - New approach: Parton Branching method
    - Cover all transverse momenta from small k_t to large k_t as well a large range in x and μ^2
    - provide a novel method to solve evolution equations.

Parton Branching method: start with DGLAP evolution

- DGLAP evolution in differential form

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

  - describes the evolution from the proton to the hard process.



- Sudakov form factor:

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

  - describes the evolution between two scales.

Parton Branching method: integral form

- DGLAP evolution in differential form

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

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- introduce Sudakov form factor:

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

- Then one obtains its integral form:

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

No-branching probability from μ_0^2 to μ^2

PB: Iterative solution

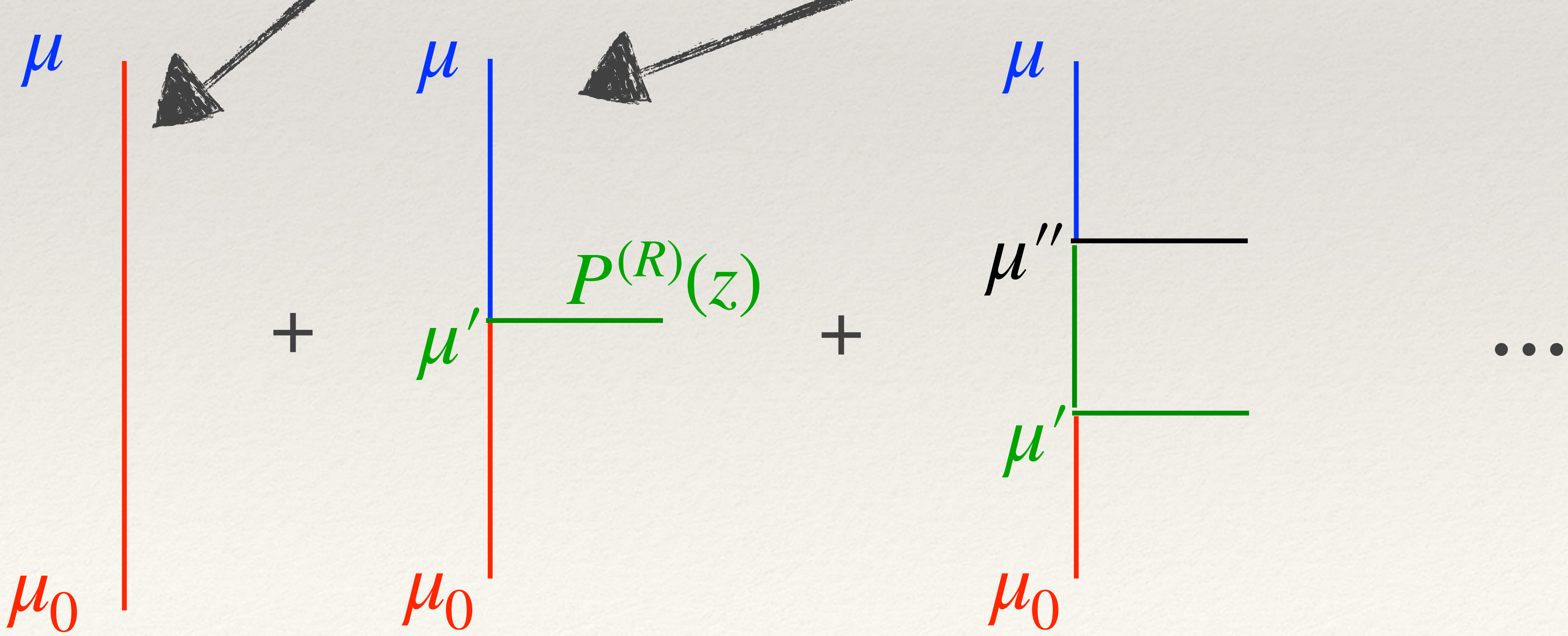
$$\mathbf{f}(\mathbf{x},\mu^2) = f(x,\mu_0^2)\Delta_s(\mu^2) + \int_x^{z_M}\frac{dz}{z}\int_{\mu_0^2}^{\mu^2}\frac{d\mu'^2}{\mu'^2}\frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)}P^{(R)}(z)\mathbf{f}\left(\frac{\mathbf{x}}{\mathbf{z}},\mu'^2\right)$$

- Solve integral equation via iteration:

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

$$\mathbf{f_1}(\mathbf{x},\mu^2) = f(x,\mu_0^2)\Delta(\mu^2) + \int_{\mu_0^2}^{\mu^2}\frac{d\mu'^2}{\mu'^2}\frac{\Delta(\mu^2)}{\Delta(\mu'^2)}\int_x^{z_M}\frac{dz}{z}P^{(R)}(z)\underbrace{\mathbf{f}\left(\frac{\mathbf{x}}{\mathbf{z}},\mu_0^2\right)\Delta(\mu'^2)}_{f_0}$$

$$\mathbf{f_2}(\mathbf{x},\mu^2) = \ldots$$



TMDs

- TMD parton densities:

$$A_a(x, \mathbf{k}, \mu^2) = A_a(x, \mathbf{k}, \mu_0^2)\Delta_a(\mu^2) + \sum_b \int \frac{d^2\mathbf{q}'}{\pi \mathbf{q}'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)} \Theta(\mu^2 - \mathbf{q}'^2)\Theta(\mathbf{q}'^2 - \mu_0^2)$$

$$\times \int_x^{z_M} \frac{dz}{z} P_{ab}^{(R)}(\alpha_s, z) A_b\left(\frac{x}{z}, \mathbf{k} + (1-z)\mathbf{q}', \mathbf{q}'^2\right)$$

  - Integrate TMD, one can obtain the collinear parton density $f_a(x, \mu^2)$

$$f_a(x, \mu^2) = \int A_a(x, \mathbf{k}, \mu^2)) \frac{d^2\mathbf{k}}{\pi}$$

- TMD parton densities distributions $xA_a(x, k_t^2, \mu^2)$ with $k_t^2 = \mathbf{k}^2$

$$xA_a(x, k_t^2, \mu^2) = \int dx' A_{0,b}(x', k_{t,0}^2, \mu_0^2) \frac{x}{x'} \; K_{ba}\left(\frac{x}{x'}, k_{t,0}^2, k_t^2, \mu_0^2, \mu^2\right)$$

the perturbative evolution kernal K, the non-perturbative starting distribution $A_{0,b}(x, k_{t,0}^2, \mu^2)$.

$$A_{0,b}(x, k_{t,0}^2, \mu^2) = f_{0,b}(x, \mu_0^2) \cdot \exp(-k_{t,0}^2/\sigma^2)$$

the intrinsic $k_{t,0}$ is a Gauss distribution with $\sigma^2 = q_0^2/2$, $q_0 = 0.5$ GeV .

Fit to HERA data

- Fit performed using xFitter ——Sara Taheri Monfared
  - DIS measurements from HERA I+II
  - Kinematic range:

    $$3.5 < Q^2 < 50000 \text{ GeV}^2,\ 4 \times 10^{-5} < x < 0.65$$

  - Using parametrization of starting distribution as in HERAPDF2.0
  - $\chi^2/ndf = 1.2$

Later, we will talk about two sets of renormalisation scale:

- **Set1:** $\alpha_s(\mu_i^2)$
- **Set2:** $\alpha_s(\mathbf{q}_{t,i}^2)$, with $\mathbf{q}_{t,i}^2 = (1 - z_i)^2 \mu_i^2$

[1]. F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. "Soft-gluon resolution scale in QCD evolution equations". Phys. Lett., B772:446451, 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 determined from fts to HERA DIS measurements", DESY-18-042

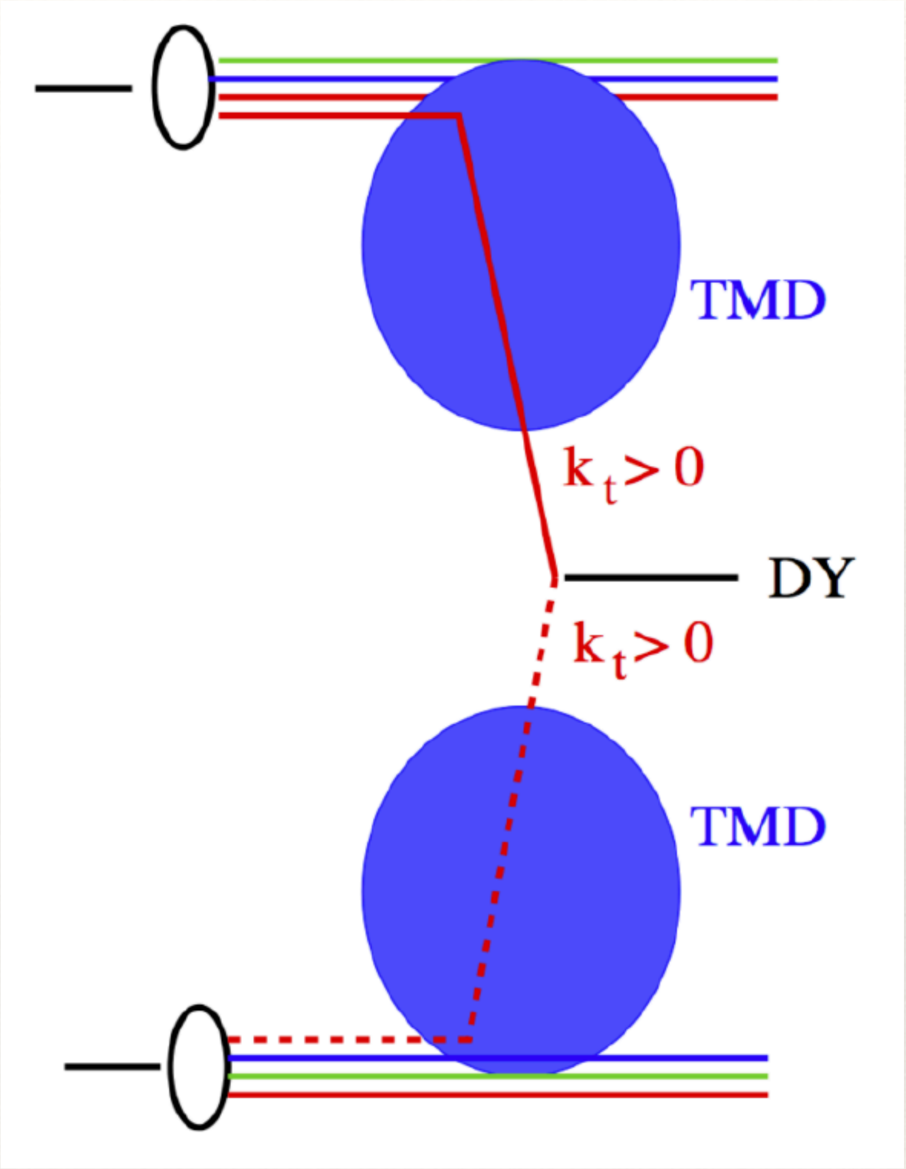
Part 2

Application in Drell-Yan (DY) production

Application to DY

- NLO calculations of DY production
  - Madgraph5_aMC@NLO (MC@NLO) for the hard process
  - PB-TMDs add k*T*, modify the kinematics of the initial state partons
  - the invariant mass and the rapidity of the partonic system are conserved.

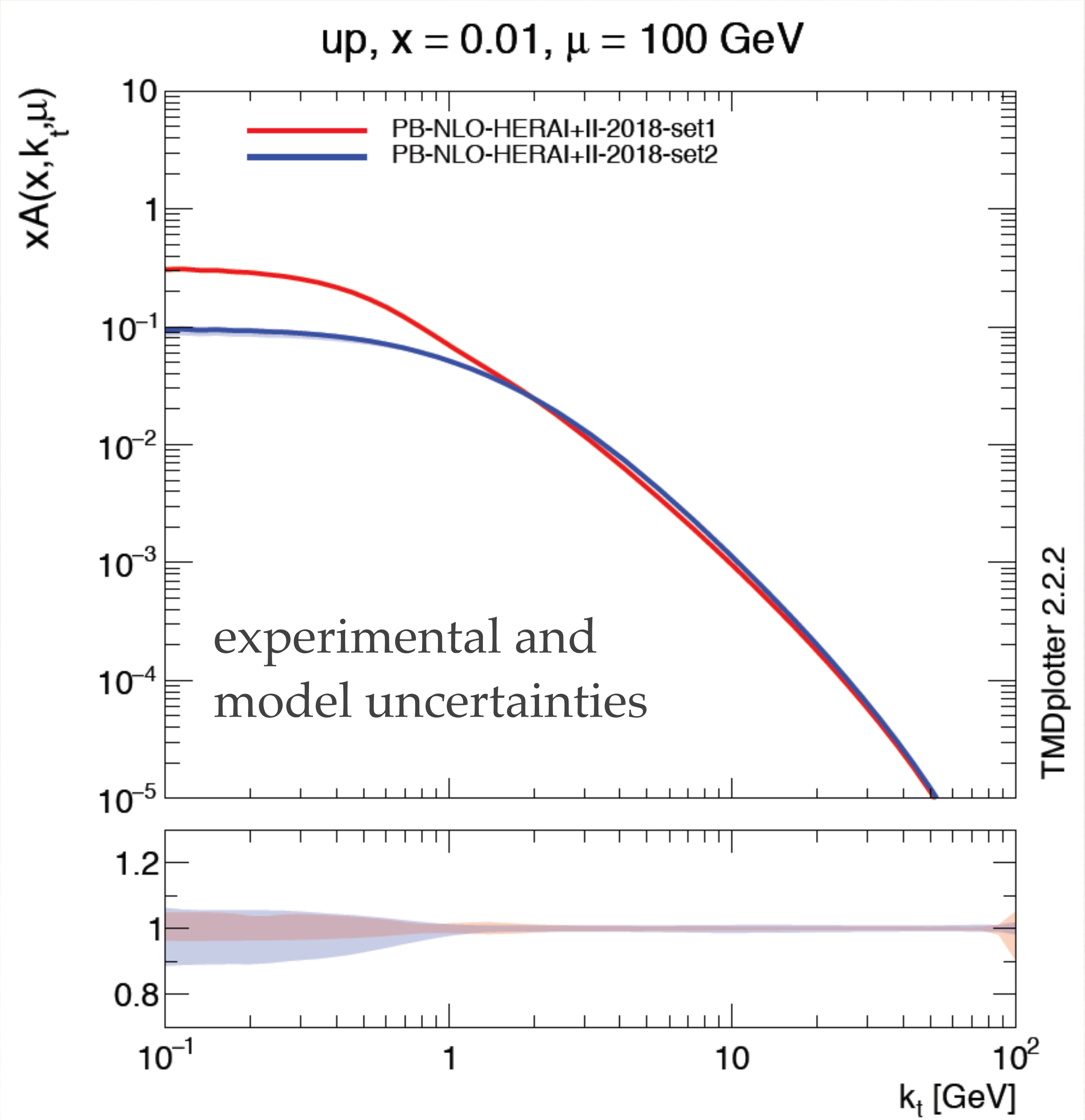
    —> x is changed accordingly

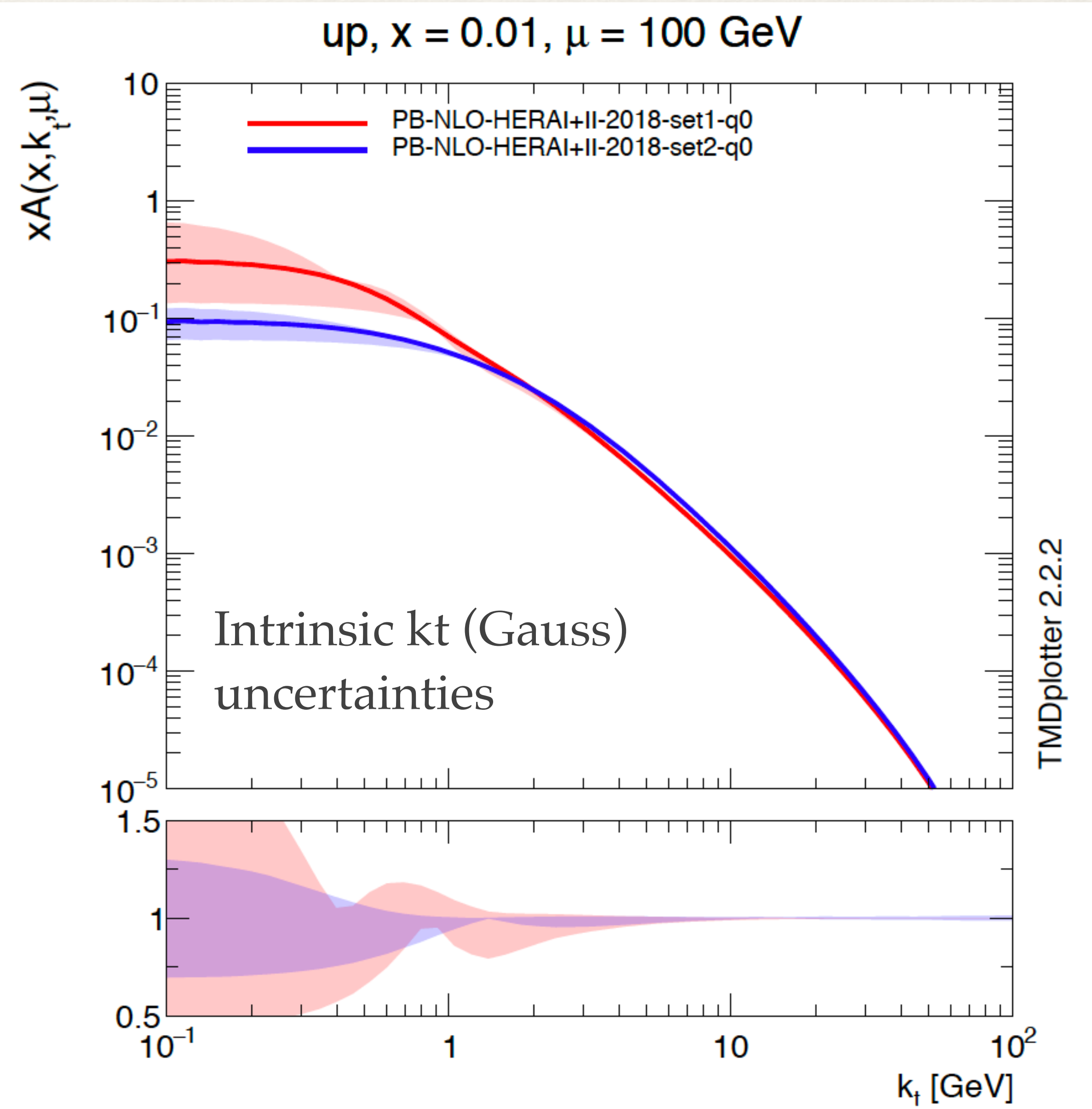


TMD distributions

- TMD distributions and its uncertainties
  - experimental and model uncertainties obtained from fit, small
  - uncertainties from intrinsic kt: change the width of the Gauss distribution q_0^2 by a factor of 2 up and down in the fit, sizable.

$$A_{0,b}(x, k_{t,0}^2, \mu^2) = f_{0,b}(x, \mu_0^2) \cdot \exp(-2 \cdot k_{t,0}^2 / q_0^2)$$



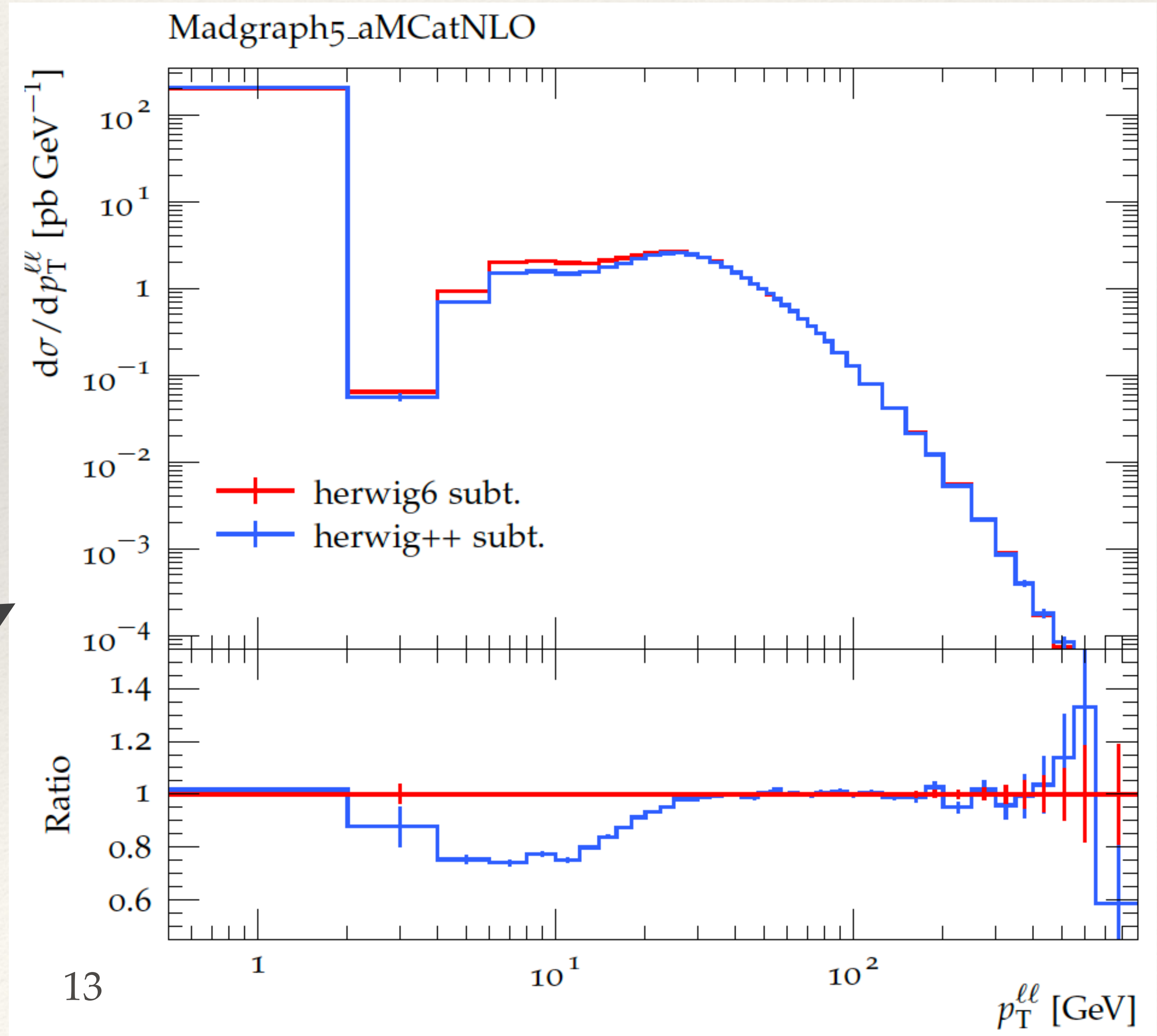


Matching to hard process: MC@NLO

- MC@NLO: soft and collinear parts from NLO are subtracted, that can be added back by TMD or parton shower later.
  - the subtraction terms of **Herwig** is used.
  - two choices, Herwig 6 and Herwig ++ , have been compared.
  - Low qT region affected
  - Some differences between

  two choices.

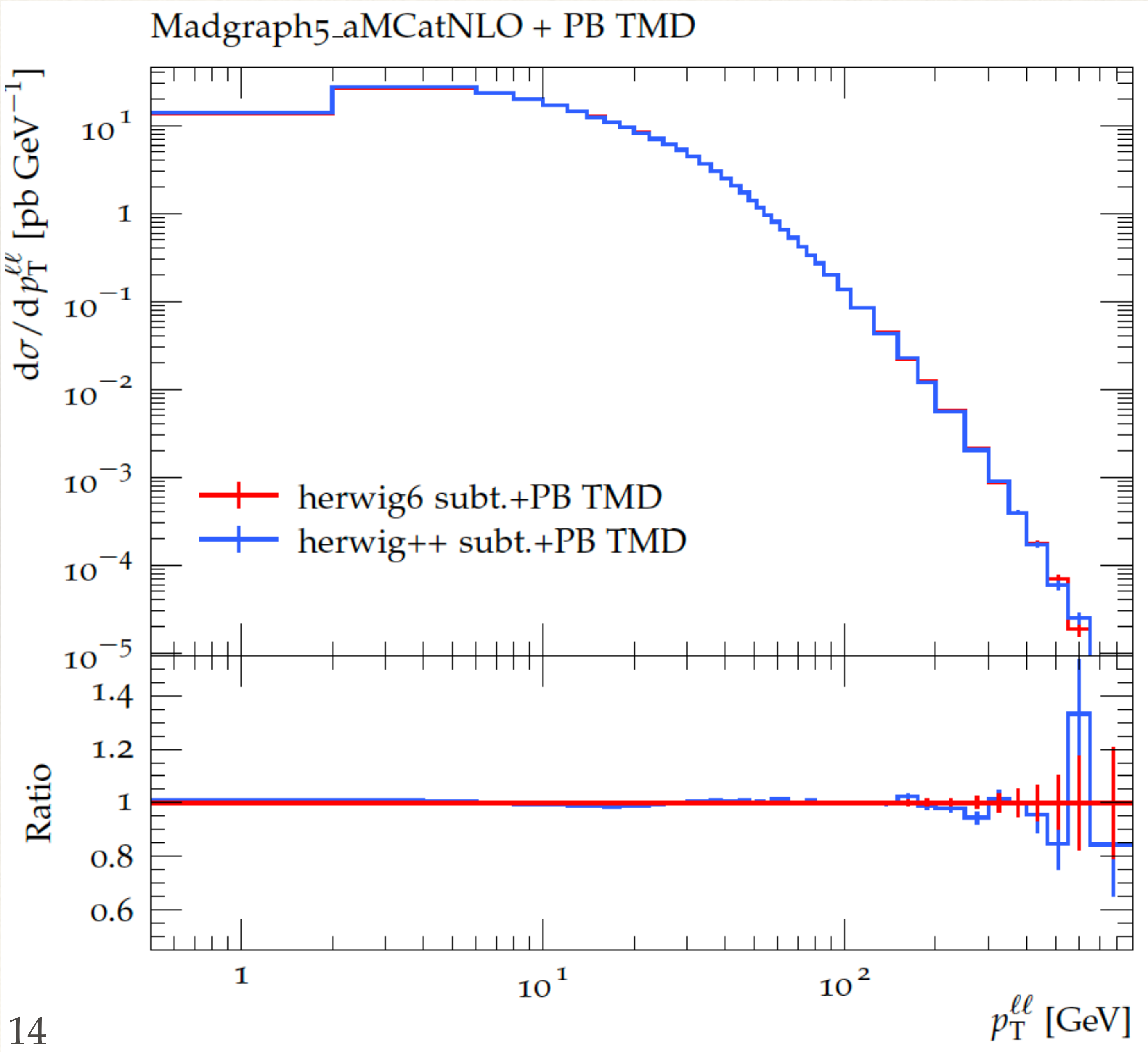
This is not physical.



Matching to hard process: MC@NLO

- MC@NLO subtracts soft and collinear parts from NLO with Herwig.
- apply PB TMD to add the soft and collinear parts back.

- low qT region affected
  —>filled by TMD
- no sensitivity to the subtraction terms is observed.

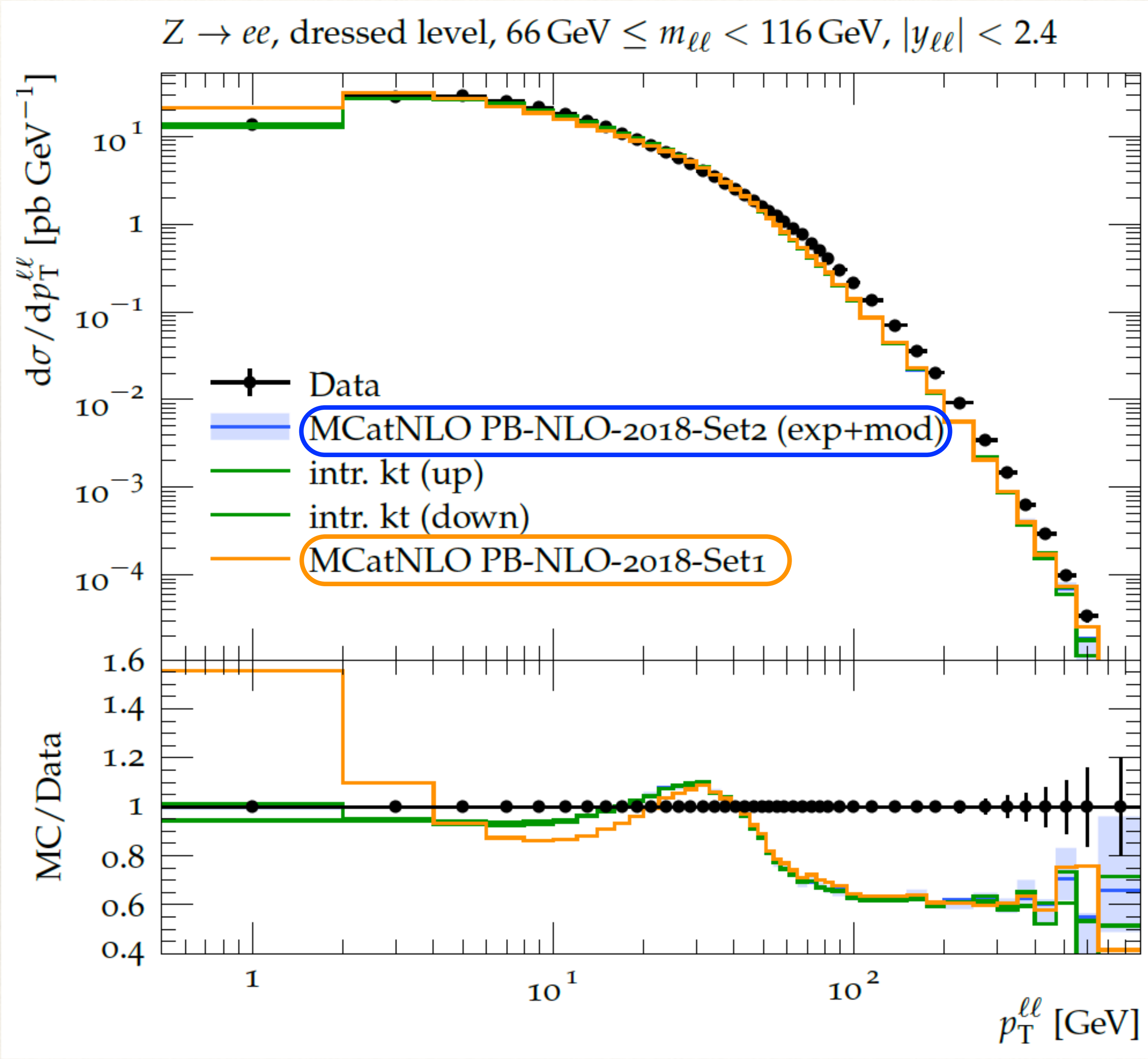


Z-boson production at 8TeV

- Z-boson production at **8 TeV ATLAS** is compared with prediction MC@NLO with PB-TMD.

- Predictions using PB-2018-Set1 ($\alpha_s(q)$) and Set2 ($\alpha_s(q(1-z))$) parton distributions:
  - Set1 overshoots the measurements at small qT.
  - Set2 agrees well with measurement.

- The deviation at higher qT comes from missing higher order contributions in the matrix element calculation.



ATLAS (2016). DY at 8 TeV, EPJC 76, 291, 1512.02192

Z-boson production at 8TeV

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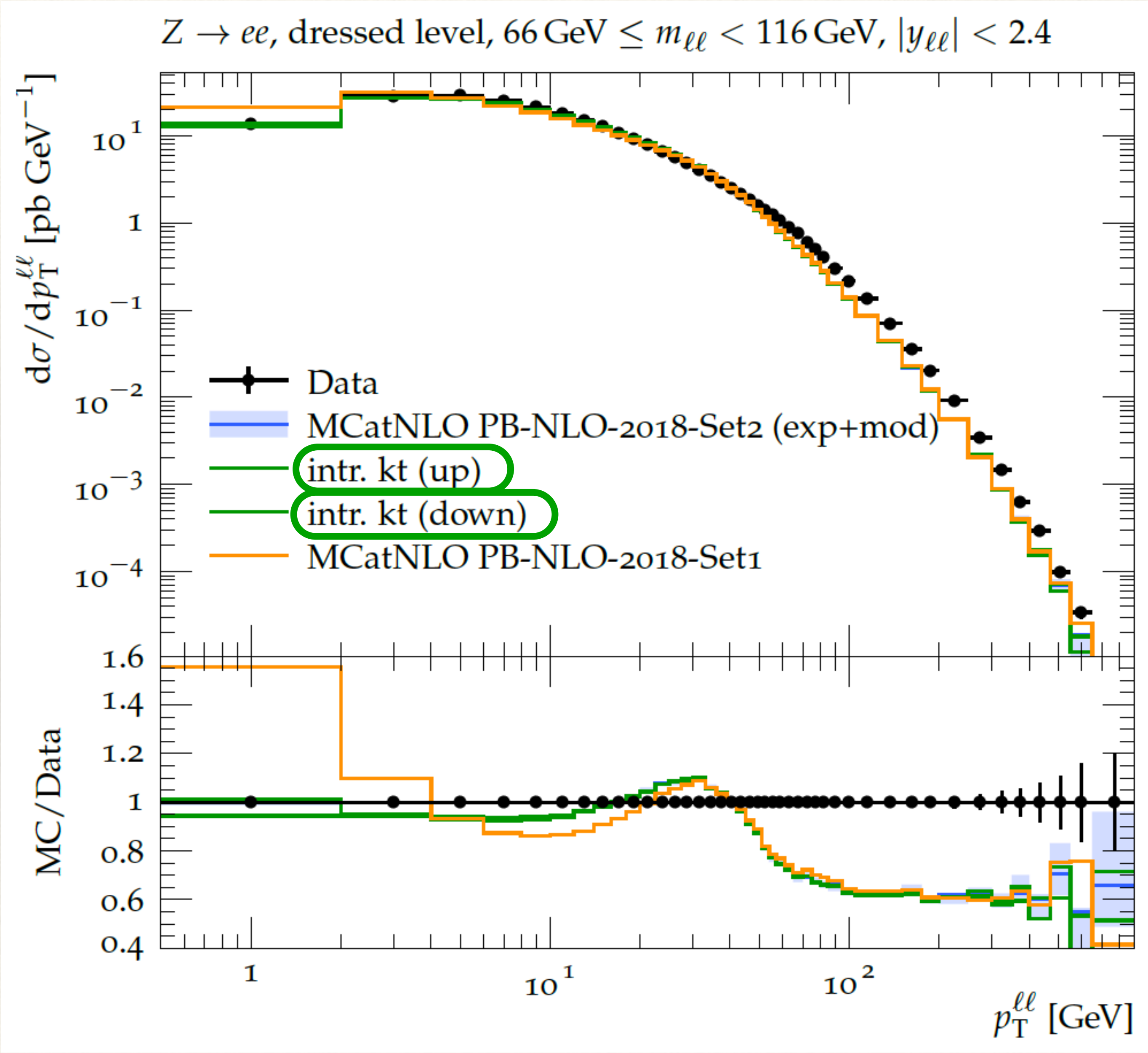
- Predictions using PB-2018-Set1 $(\alpha_s(q))$ and Set2 $(\alpha_s(q(1-z)))$ parton distributions.
  - Varying the mean of intrinsic kt distribution by factor 2, small



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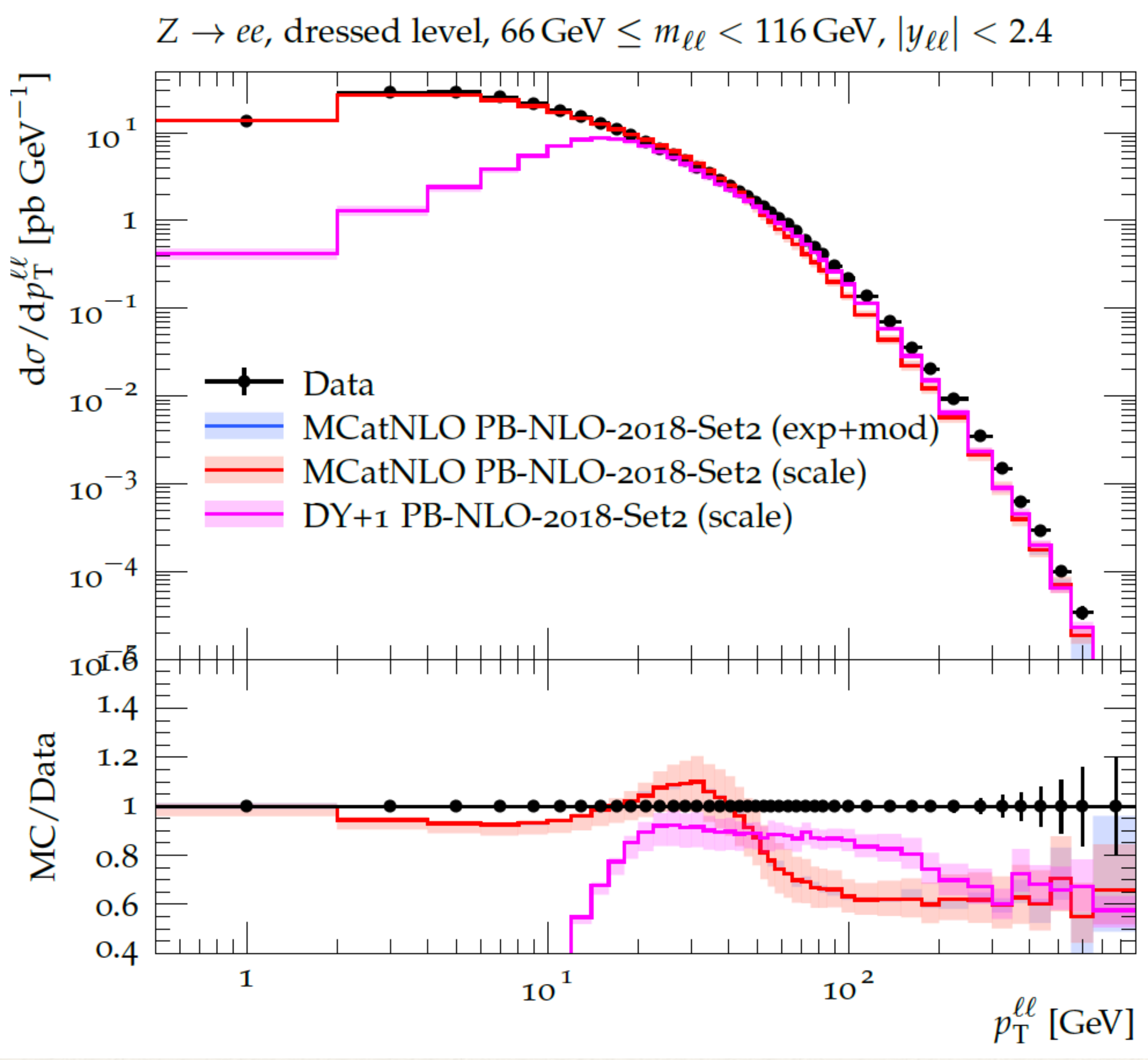
Z-boson production at 8 TeV

- Z-boson production at **8 TeV ATLAS** is compared with prediction MC@NLO with PB-TMD.

- TMD fills low qT part
  - TMD uncertainties is small.
  - scale uncertainties dominate, but small.

- DY+1 jet plays an important role and improves the description of the measurements at larger qT.

More details about merging DY and DY+1 jet calculation will be presented by A. Bermudez Martinez



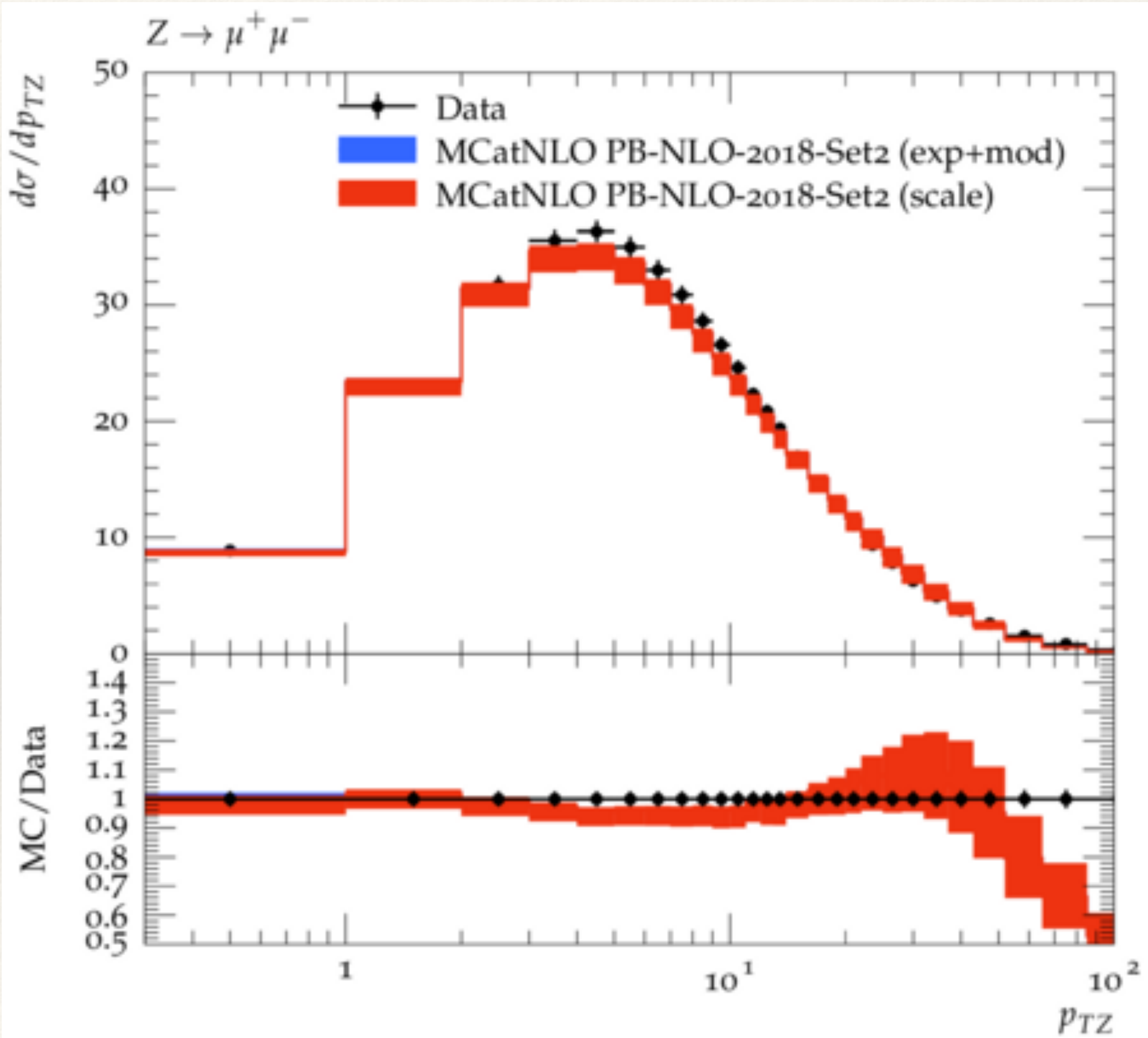
ATLAS (2016). DY at 8 TeV, EPJC 76, 291, 1512.02192

Z-boson production at 13 TeV

- Z-boson production at **13 TeV CMS** is compared with prediction MC@NLO with PB-TMD.

- The prediction agrees well with the measurement in the low pT region,
- but deviates at high pT because of missing Z+jets matrix element calculation.

- The dominate theory uncertainties are from scale of MC@NLO matrix element.



CMS (2016). DY at 13 TeV, submitted, 1909.04133

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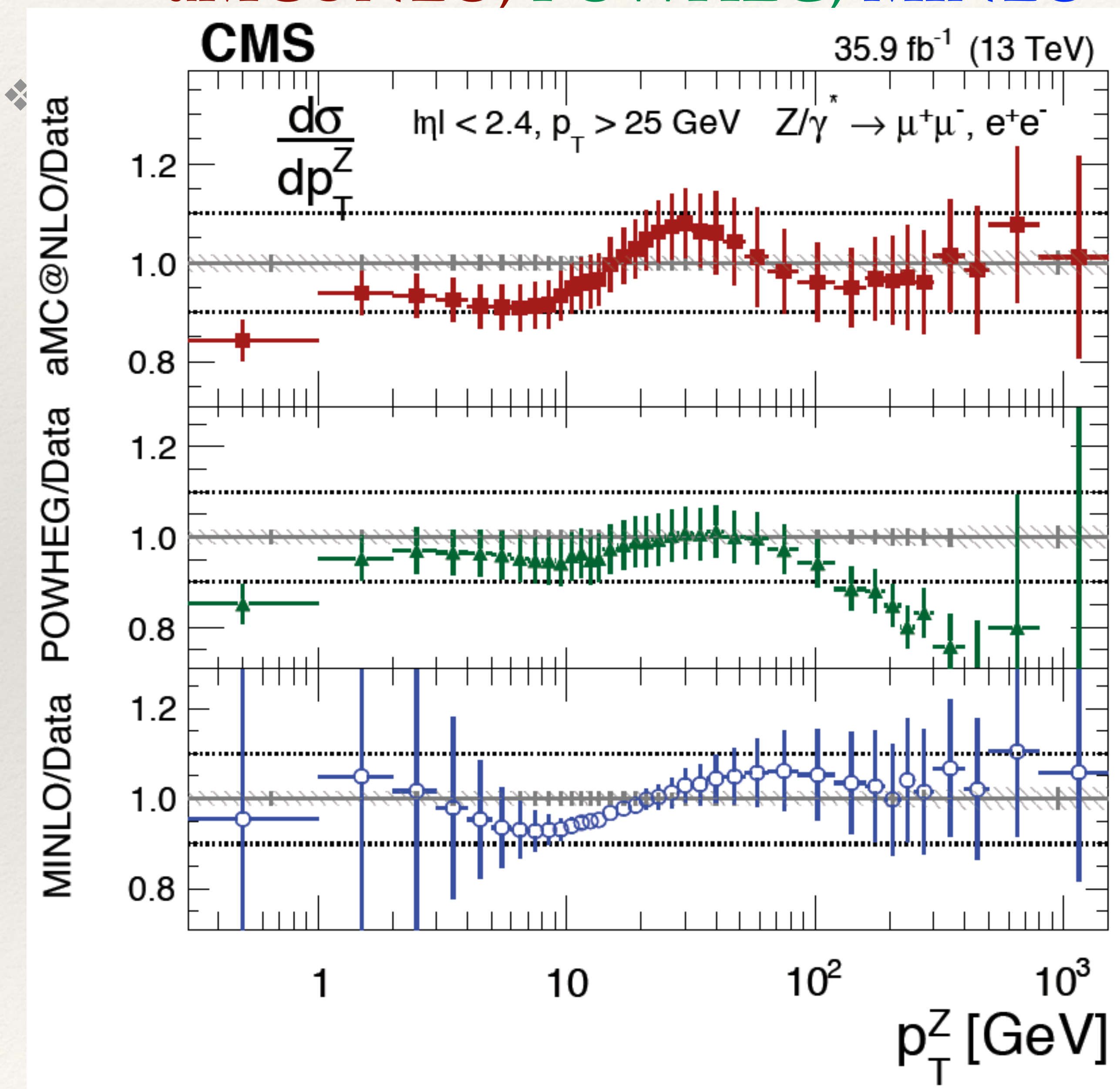
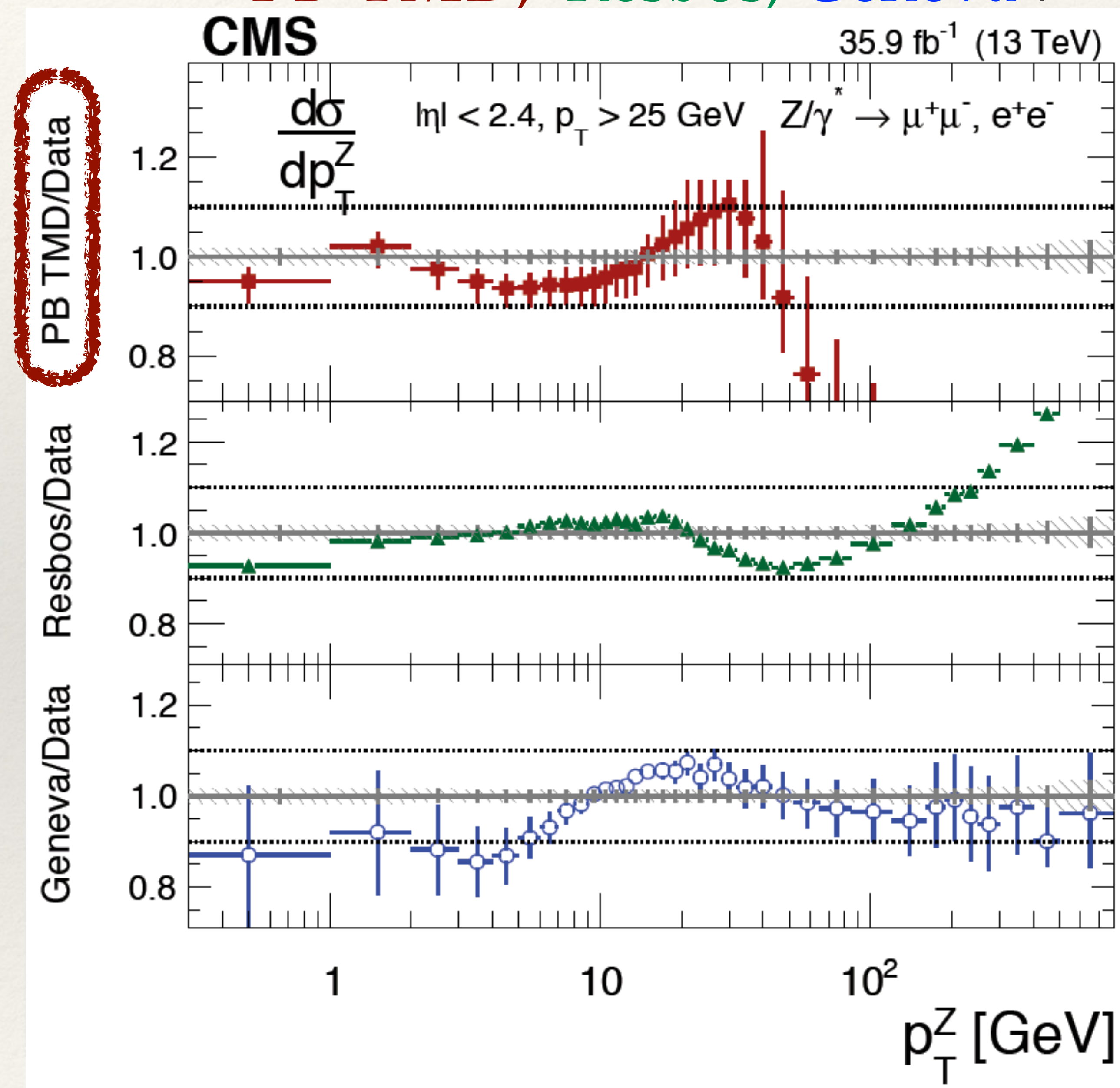
aMC@NLO, POWHEG, MINLO



PB-TMD, Resbos, Geneva .



- The PB TMD prediction describes data well at low pT.

Conclusion

- Parton Branching method can be used to solve DGLAP equation.
- PB TMD fit with HERA data, and works out very nice when applied to pp collision.
- Application to pp processes, DY:
  - DY qT-spectrum
  - NLO TMD with MC@NLO works well for both 8 and 13 TeV.
  - The dominant uncertainties are scale uncertainties, but quite small.

Prospects:

- PB TMD application in multijets/ HF jets productions.
- Parton shower based on PB TMD.

Backup

Thank you for your attention!

TMDs

- TMDs extend collinear PDFs by taking into account the transverse momentum of the parton:

$$f(x,\mu^2) = \int \frac{d^2k_t}{2\pi}\mathcal{A}(x,k_t,\mu^2)$$

In the context of PB method, we adopt the simplified form of starting distribution:

$$\mathcal{A}_0(x,k_t,\mu^2) = f_0(x,\mu^2)\cdot\exp(-k_t^2/\sigma^2)$$

Collinear PDF

Intrinsic kt

TMDs & Fit to HERA data

- The starting distribution:

$$A_{0,b}(x, k_{t,0}^2, \mu^2) = f_{0,b}(x, \mu_0^2) \cdot \exp(-k_{t,0}^2/\sigma^2)$$

the intrinsic $k_{t,0}$ is a Gauss distribution with $\sigma^2 = q_0^2/2,\ q_0 = 0.5$ GeV .

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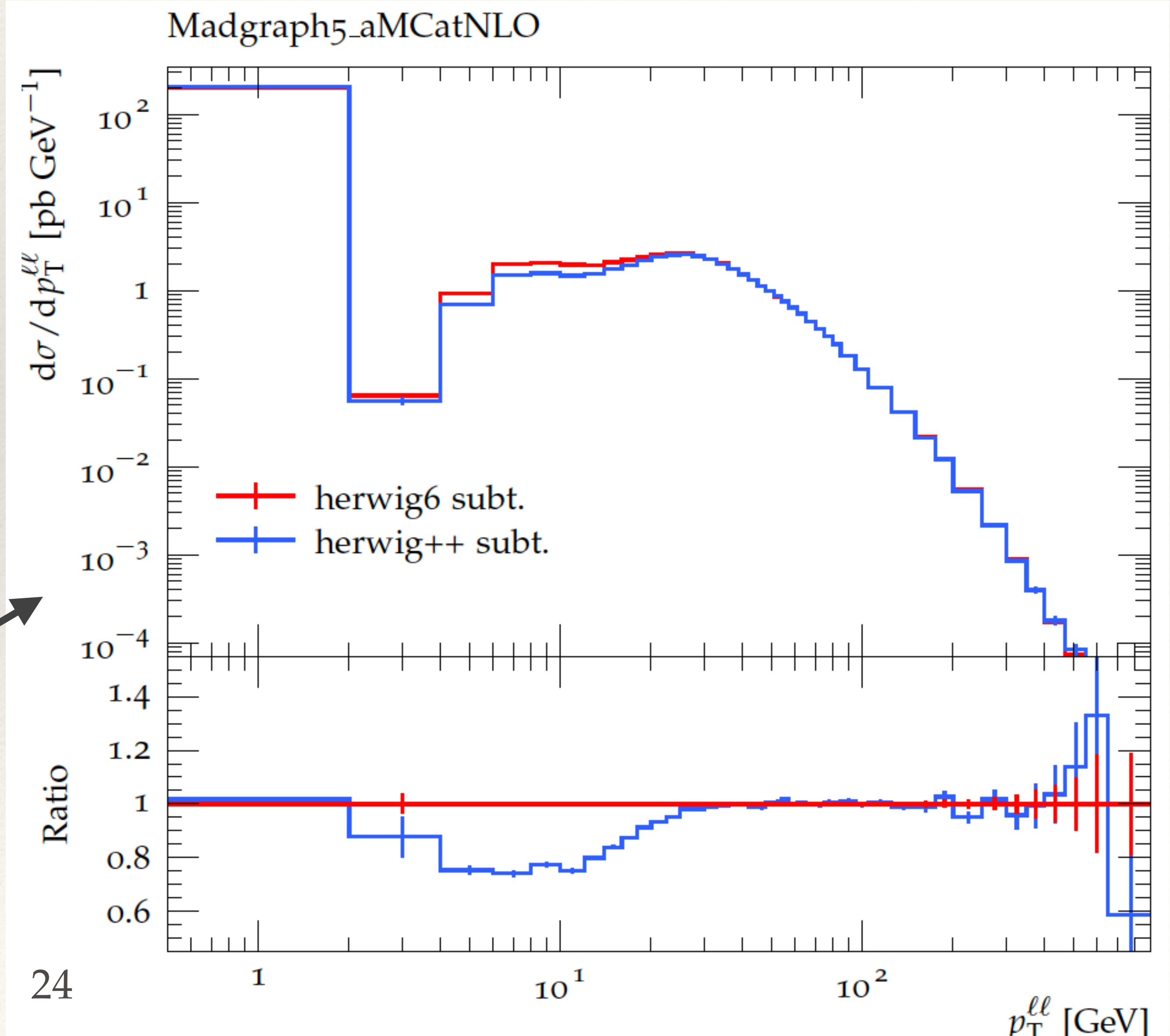
Matching to hard process: MC@NLO

- MC@NLO: subtracts soft and collinear parts from NLO
- (added back by TMD and parton shower)
  - Since the PB-method allows angular ordering, the hard process with the subtraction terms of **Herwig** is used.
  - Herwig 6 and Herwig ++



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Z-boson production at 8 TeV

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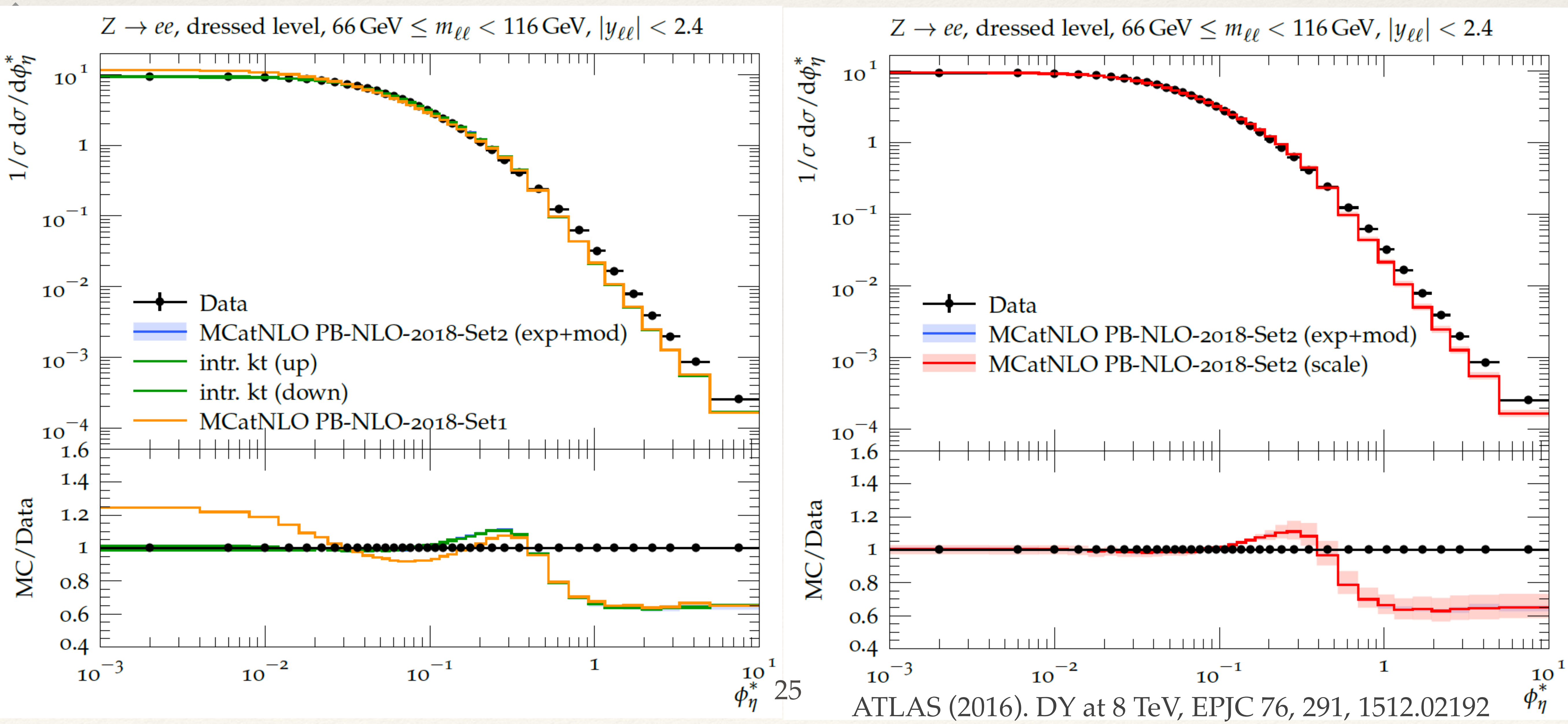
- The $\phi*$ distribution are compared also.



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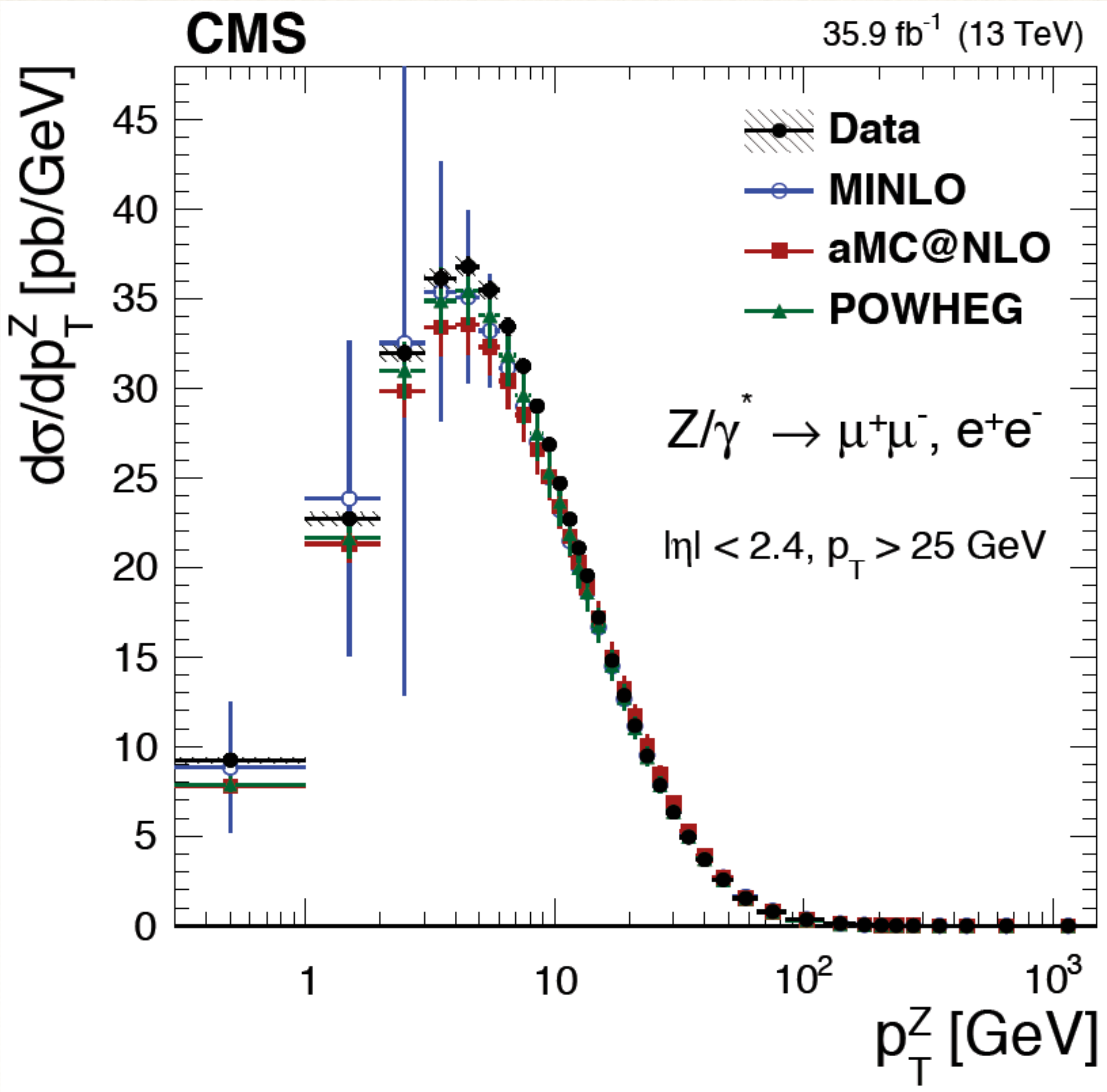
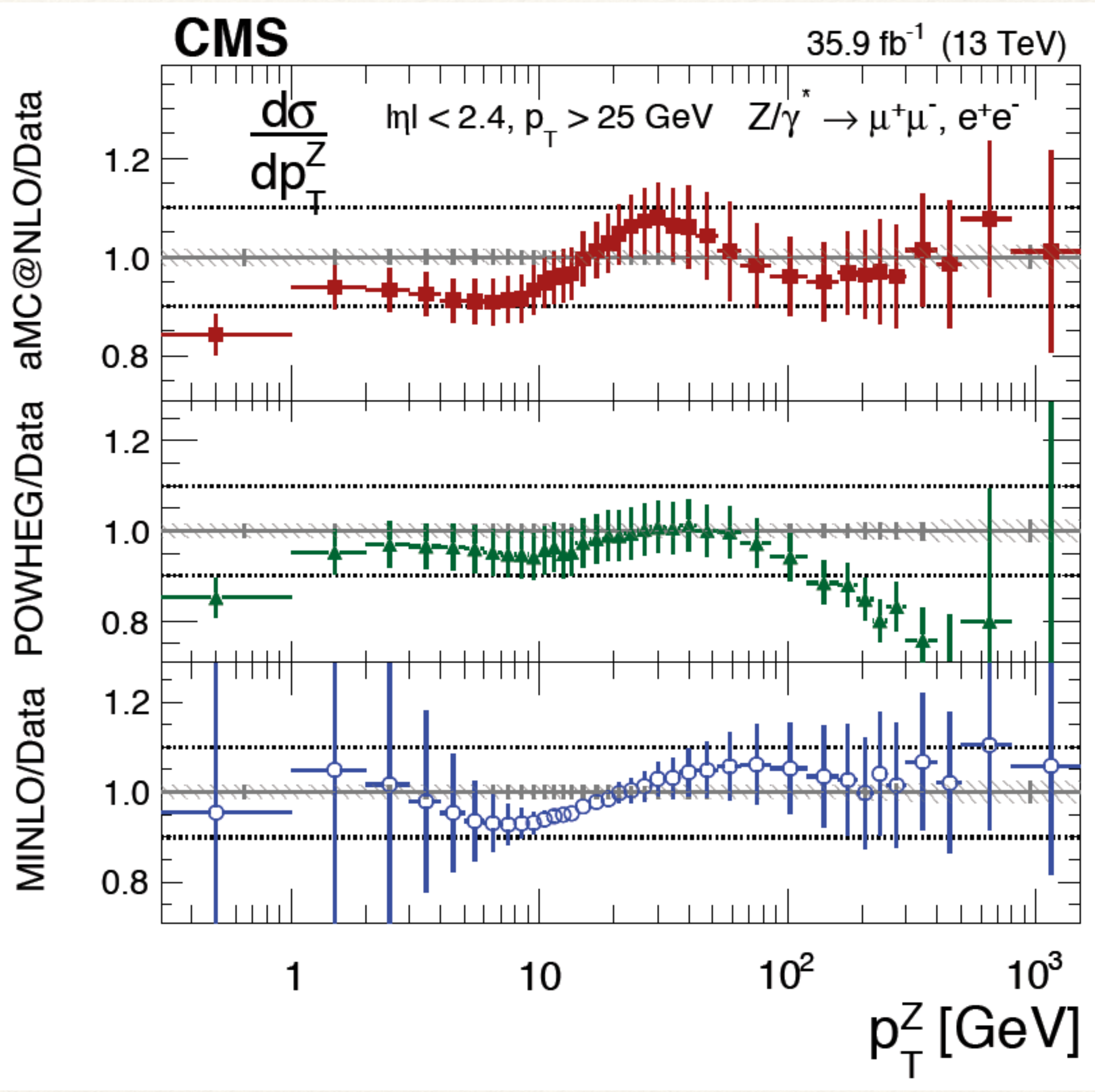
Introduction-TMD

- Transverse momentum effects are naturally coming from intrinsic k_t and parton showers.
- Now approach: Parton branching method
  - determine integrated PDF from parton branching solution of evolution eq.
    - Check consistency with standard evolution on integrated PDFs at LO, NLO and NLO.
  - determine TMD:
    - Since each branching is generated explicitly, energy-momentum conservation is fulfilled and transverse momentum distributions can be obtained.

Z-boson production at 13 TeV

- Z-boson production at 13 TeV CMS.





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Z-boson production at 13 TeV

- Z-boson production at 13 TeV CMS is compared with prediction MC@NLO with PB-TMD.
- Uncertainties in PB method mainly from scale of MC@NLO matrix element.