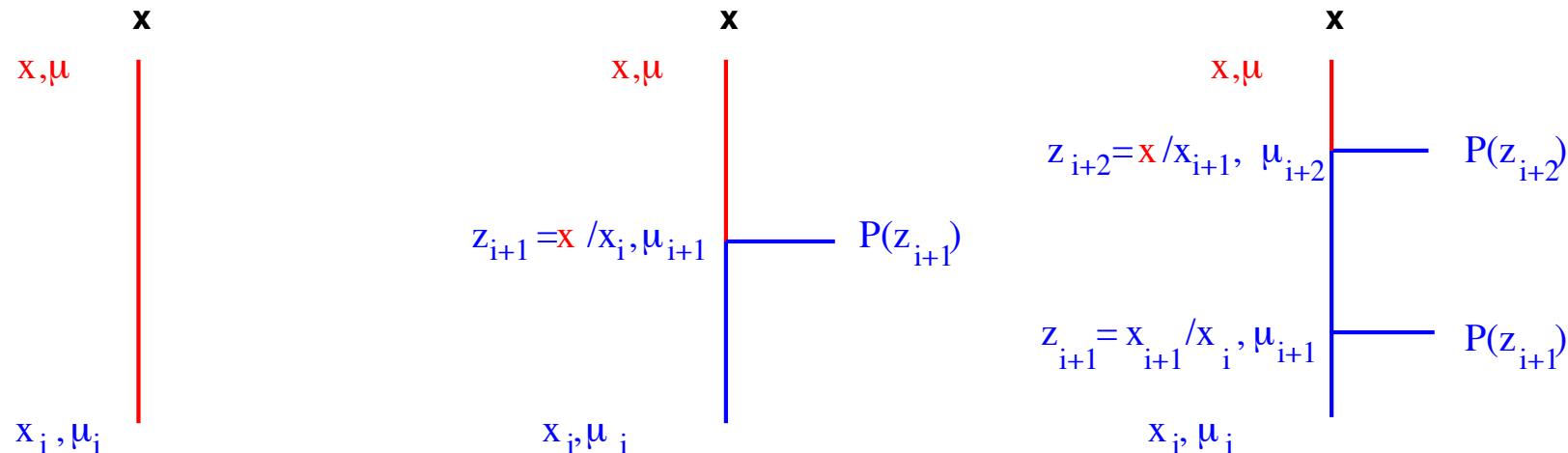


EVOLUTION EQUATION AND PARTON BRANCHING

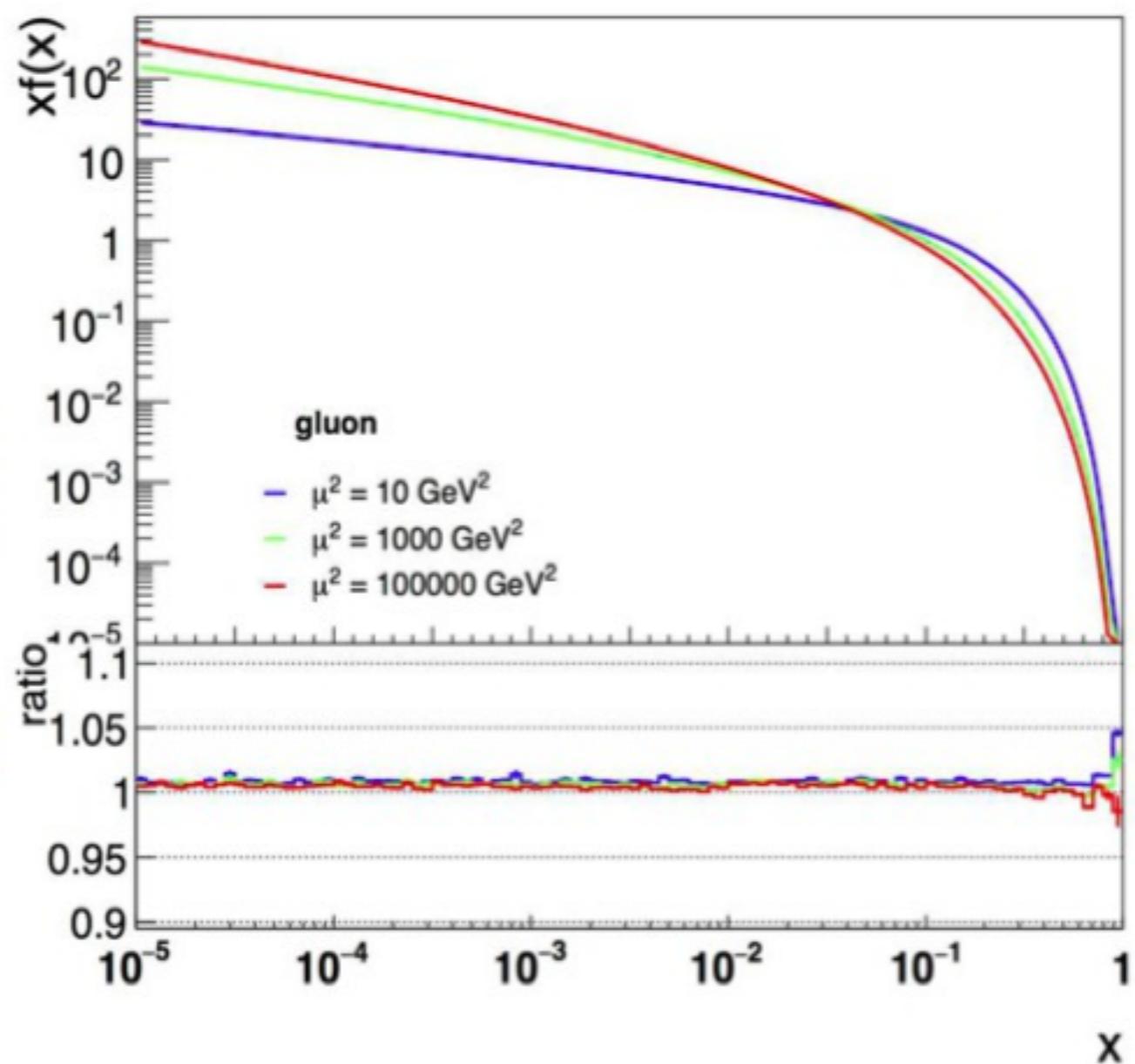
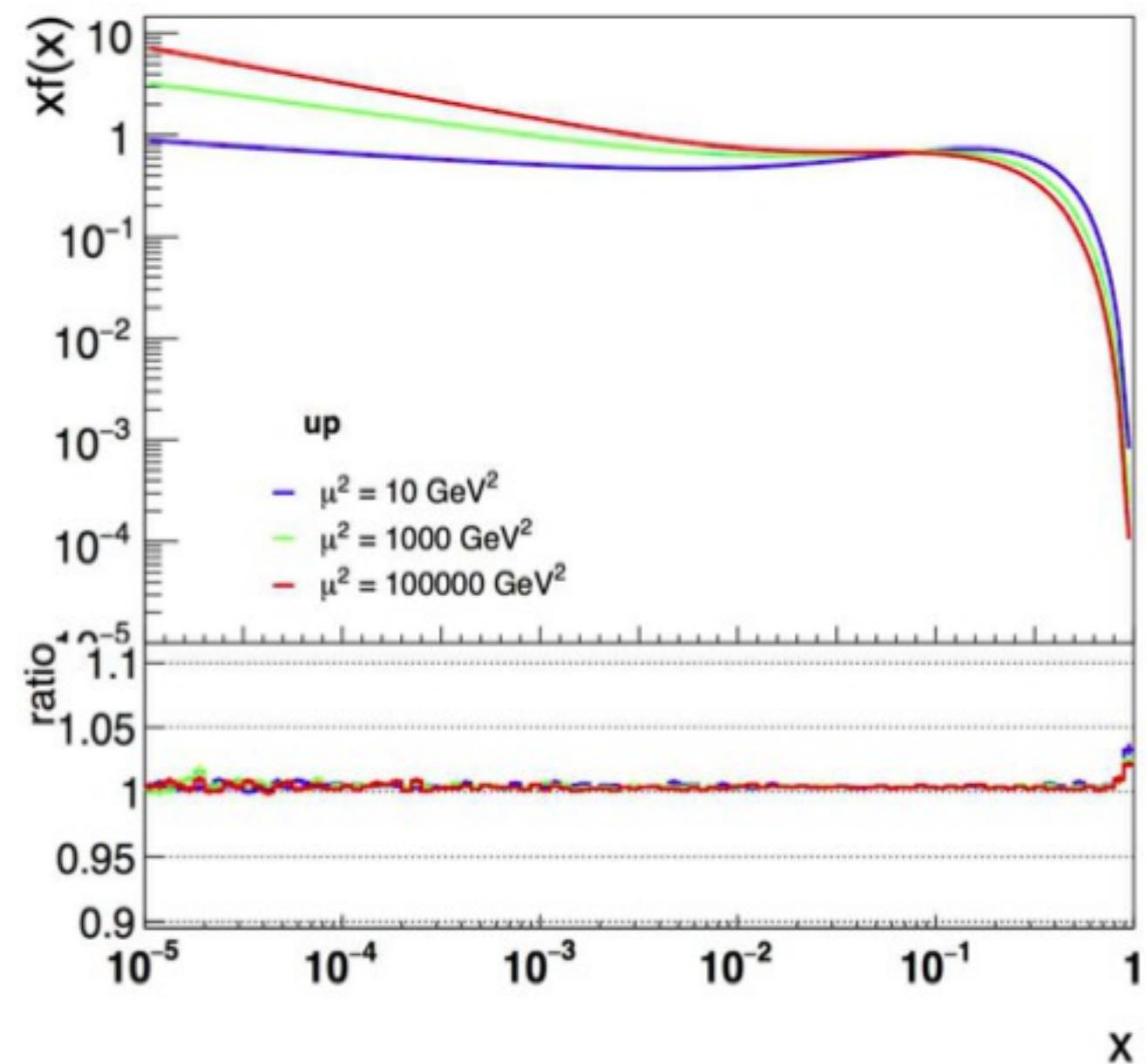
$$\tilde{f}_a(x, \mu^2) = \Delta_a(\mu^2) \tilde{f}_a(x, \mu_0^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz P_{ab}^{(R)}(\alpha_s(\mu'^2), z) \tilde{f}_b(x/z, \mu'^2)$$

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



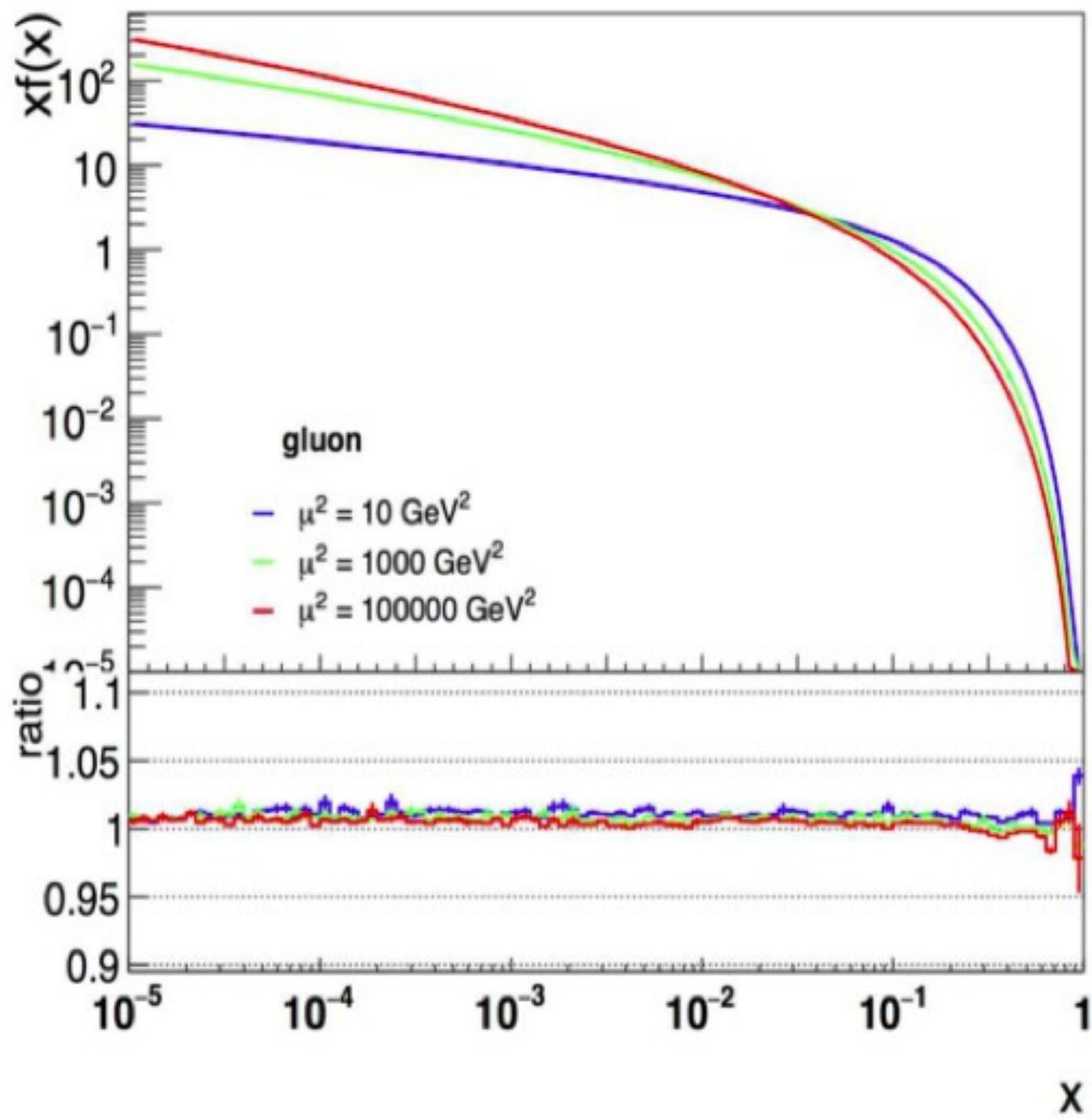
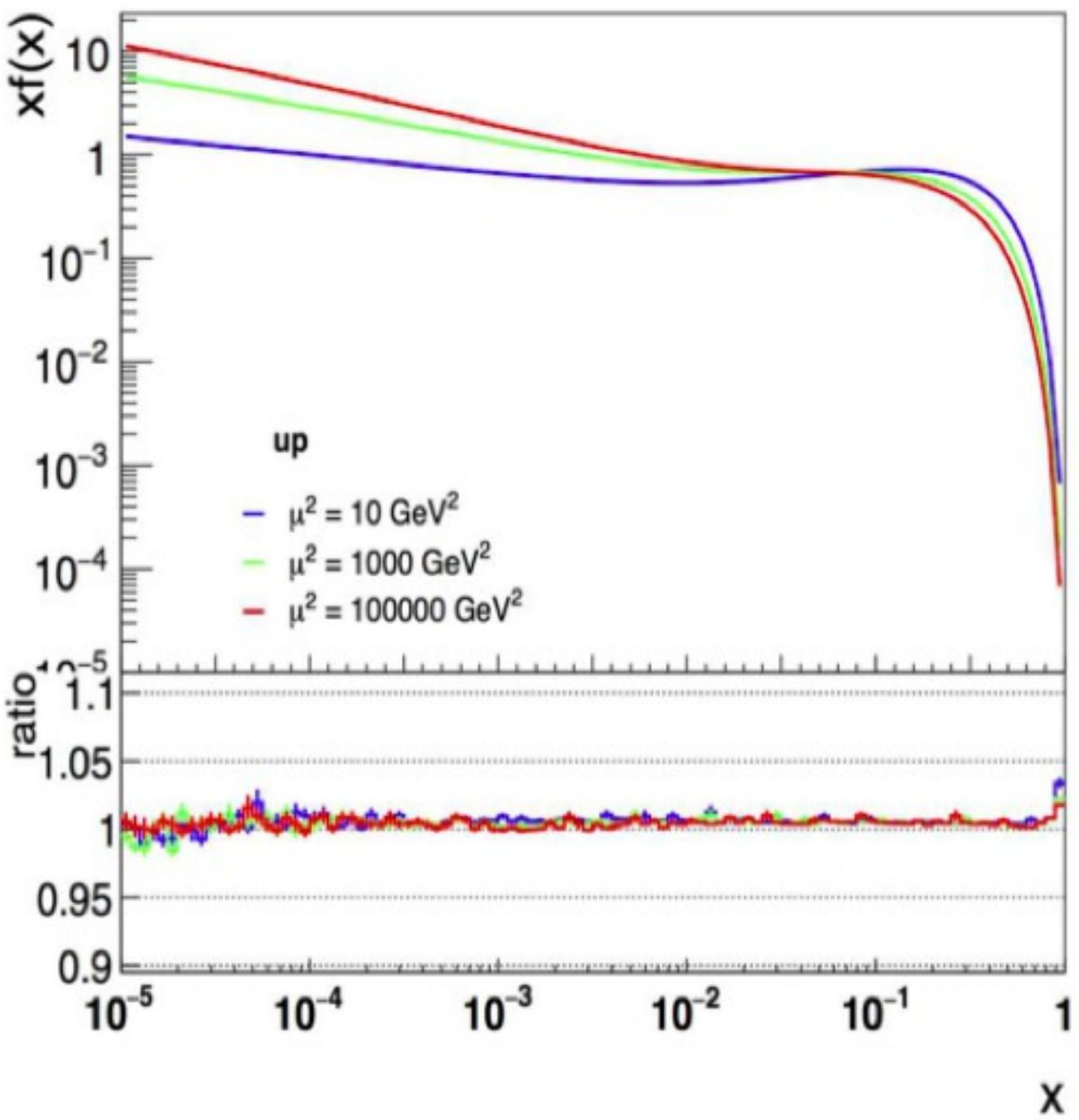
- ▷ soft-gluon resolution parameter z_M separates resolvable and nonresolvable branchings
- ▷ no-branching probability Δ ; real-emission probability $P^{(R)}$

Validation of method with semi-analytic QCDNUM result at LO



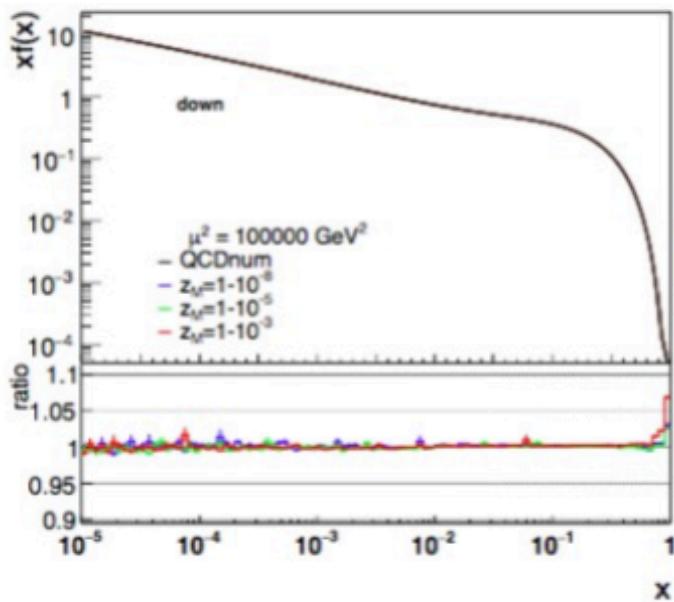
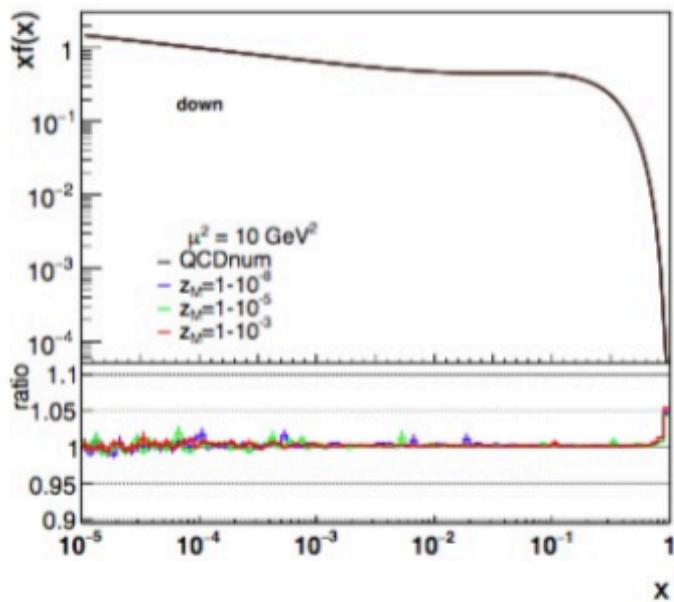
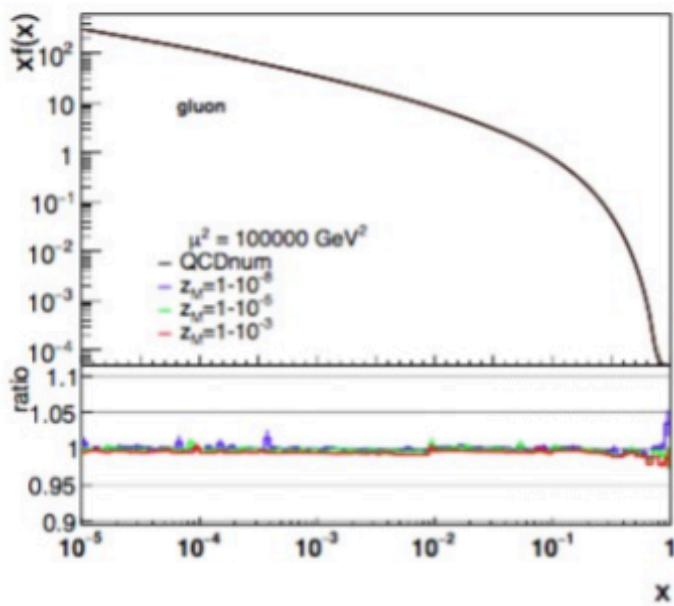
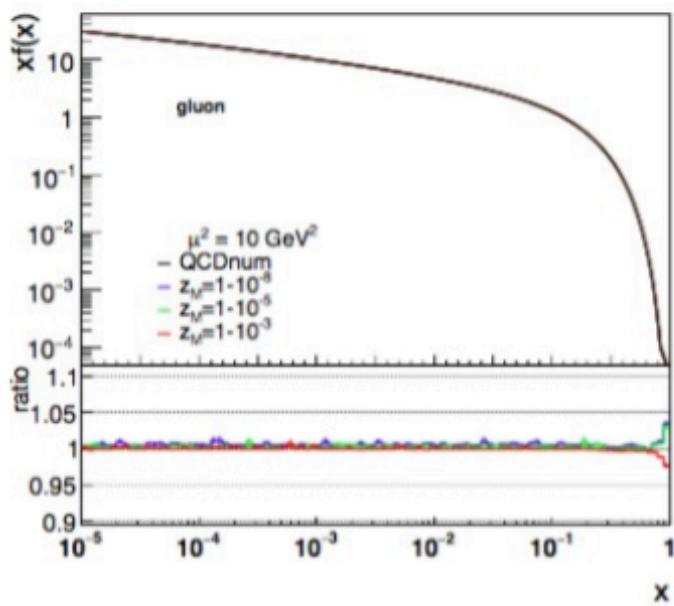
Agreement to better than 1 % over several orders of magnitude in x and mu

Validation of method with semi-analytic QCDNUM result at NLO



Very good agreement at NLO over all x and μ .
NB: the same approach is designed to work at NNLO.

Stability with respect to resolution scale z_M

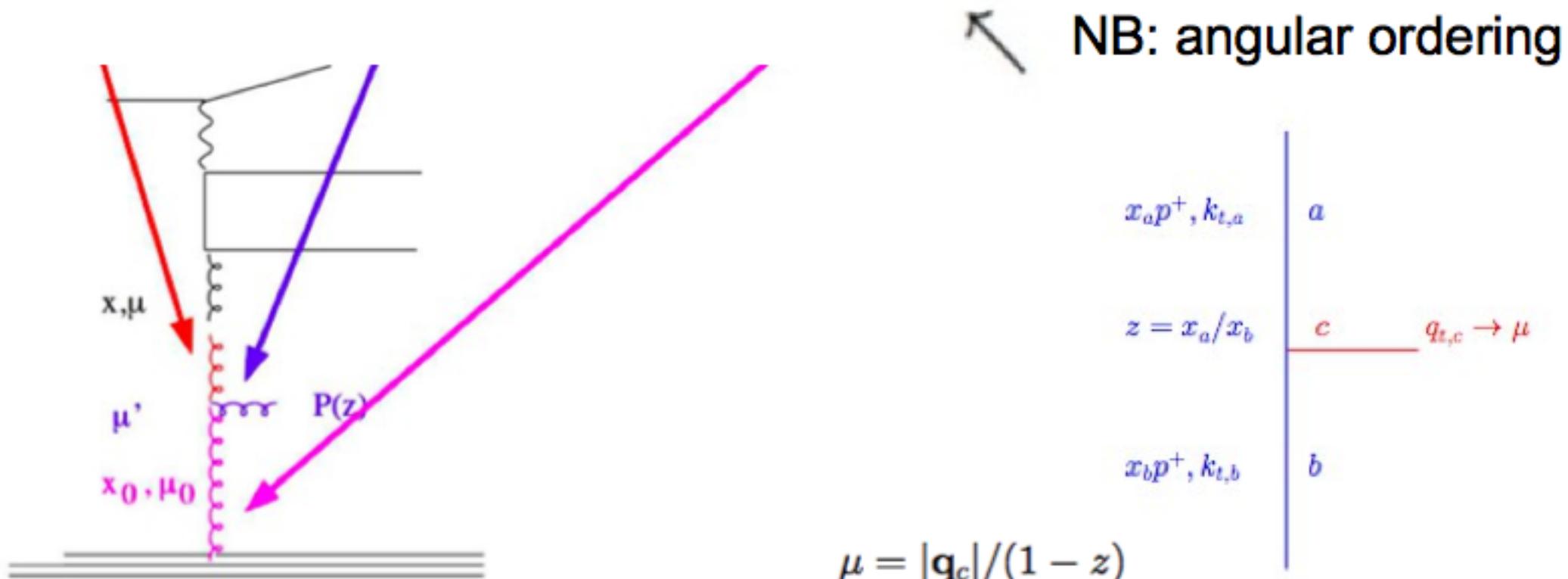


TMDs from parton branching method

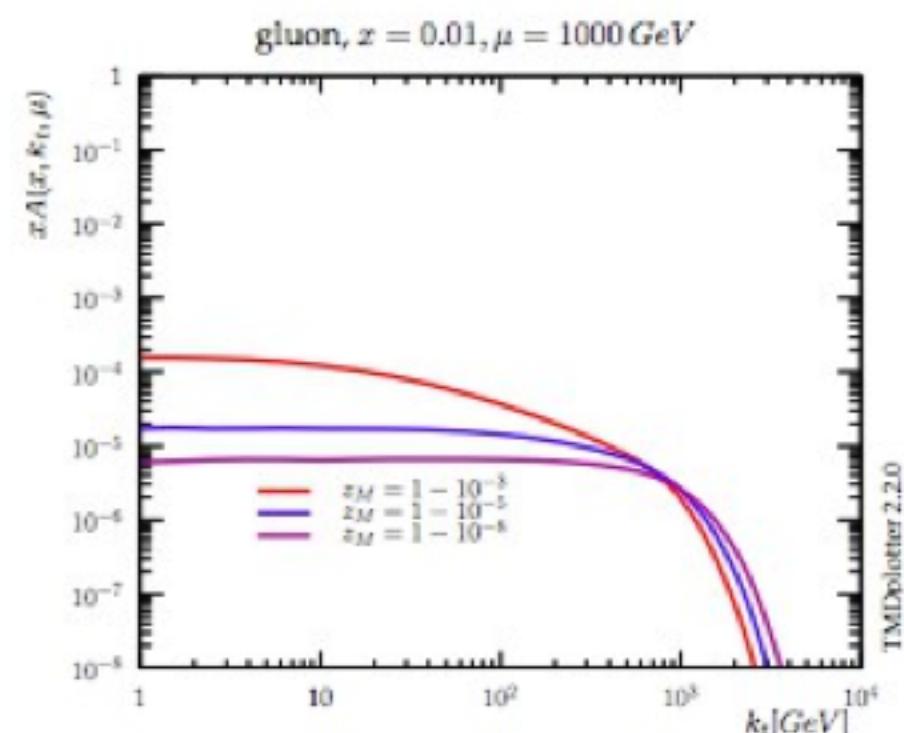
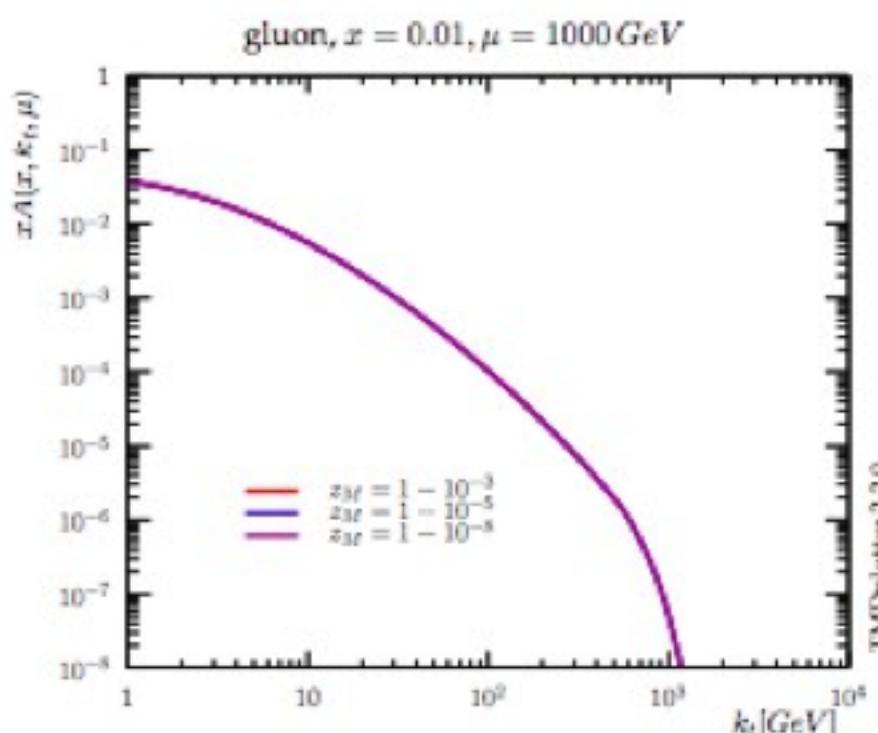
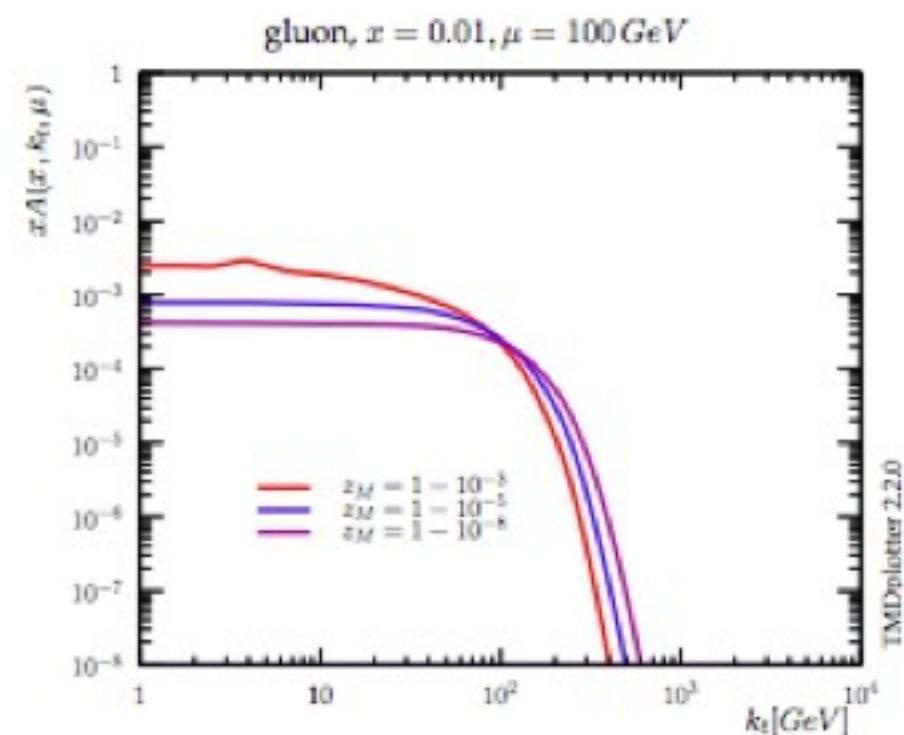
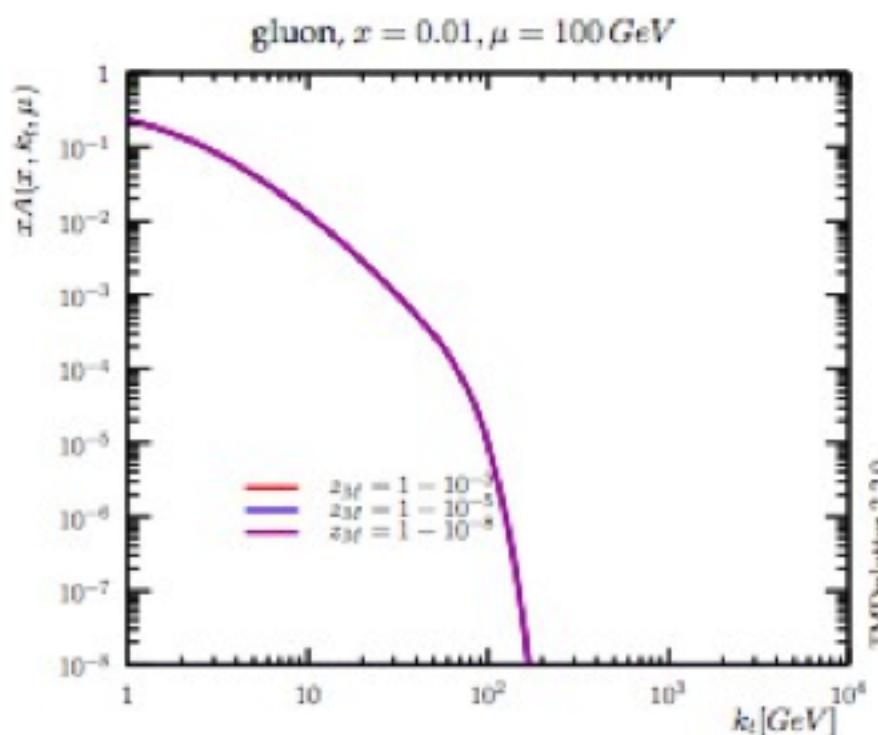
$$\begin{aligned}\tilde{\mathcal{A}}_a(x, \mathbf{k}, \mu^2) &= \Delta_a(\mu^2) \tilde{\mathcal{A}}_a(x, \mathbf{k}, \mu_0^2) + \sum_b \int \frac{d^2 \mathbf{q}'}{\pi \mathbf{q}'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)} \Theta(\mu^2 - \mathbf{q}'^2) \Theta(\mathbf{q}'^2 - \mu_0^2) \\ &\times \int_x^{z_M} dz P_{ab}^{(R)}(\alpha_s(\mathbf{q}'^2), z) \tilde{\mathcal{A}}_b(x/z, \mathbf{k} + (1-z)\mathbf{q}', \mathbf{q}'^2)\end{aligned}$$

Solve iteratively : $\tilde{\mathcal{A}}_a^{(0)}(x, \mathbf{k}, \mu^2) = \Delta_a(\mu^2) \tilde{\mathcal{A}}_a(x, \mathbf{k}, \mu_0^2)$,

$$\begin{aligned}\tilde{\mathcal{A}}_a^{(1)}(x, \mathbf{k}, \mu^2) &= \sum_b \int \frac{d^2 \mathbf{q}'}{\pi \mathbf{q}'^2} \Theta(\mu^2 - \mathbf{q}'^2) \Theta(\mathbf{q}'^2 - \mu_0^2) \\ &\times \frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)} \int_x^{z_M} dz P_{ab}^{(R)}(\alpha_s(\mathbf{q}'^2), z) \tilde{\mathcal{A}}_b(x/z, \mathbf{k} + (1-z)\mathbf{q}', \mu_0^2) \Delta_b(\mathbf{q}'^2)\end{aligned}$$



TMDs and soft-gluon resolution effects



angular ordering

transverse momentum ordering

Well-defined TMDs require appropriate ordering condition

Flavor decomposition at TMD level

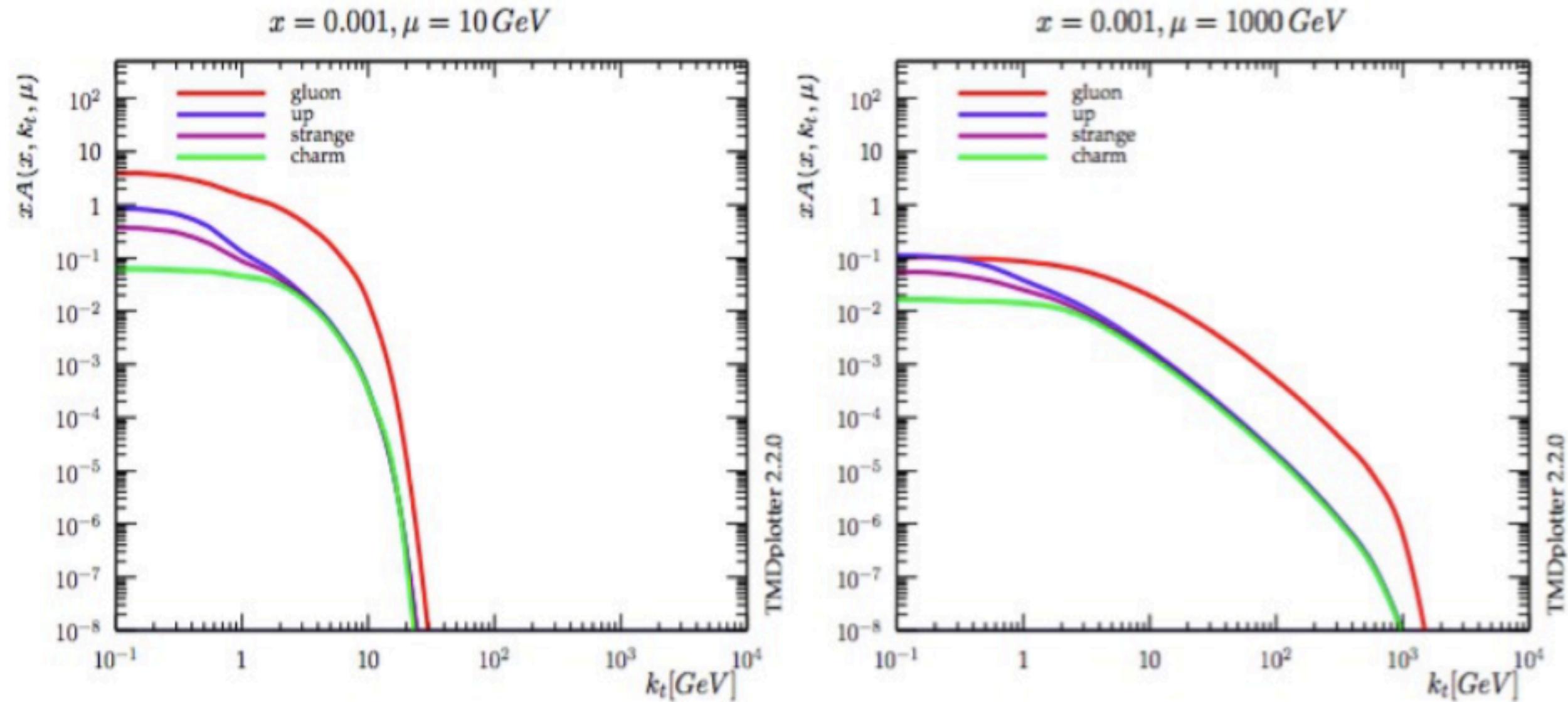


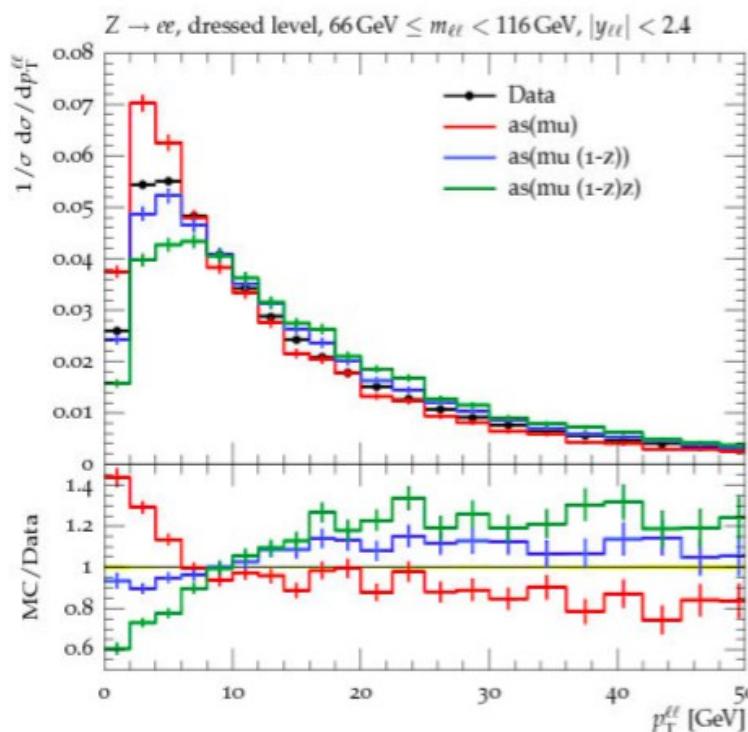
Figure 8: Transverse momentum distributions at $x = 0.001$ and evolution scales $\mu = 10 \text{ GeV}$ (left), $\mu = 1000 \text{ GeV}$ (right) for different flavors.

Scale in α_s

- Up to now the scale in α_s in was the scale of a branching μ^2 . But the angular ordering suggests to use $\alpha_s(\mu^2(1-z)^2)$

We compare:

- $\alpha_s(\mu^2)$
- $\alpha_s(\mu^2(1-z)^2)$
- $\alpha_s(\mu^2(1-z)^2z^2)$



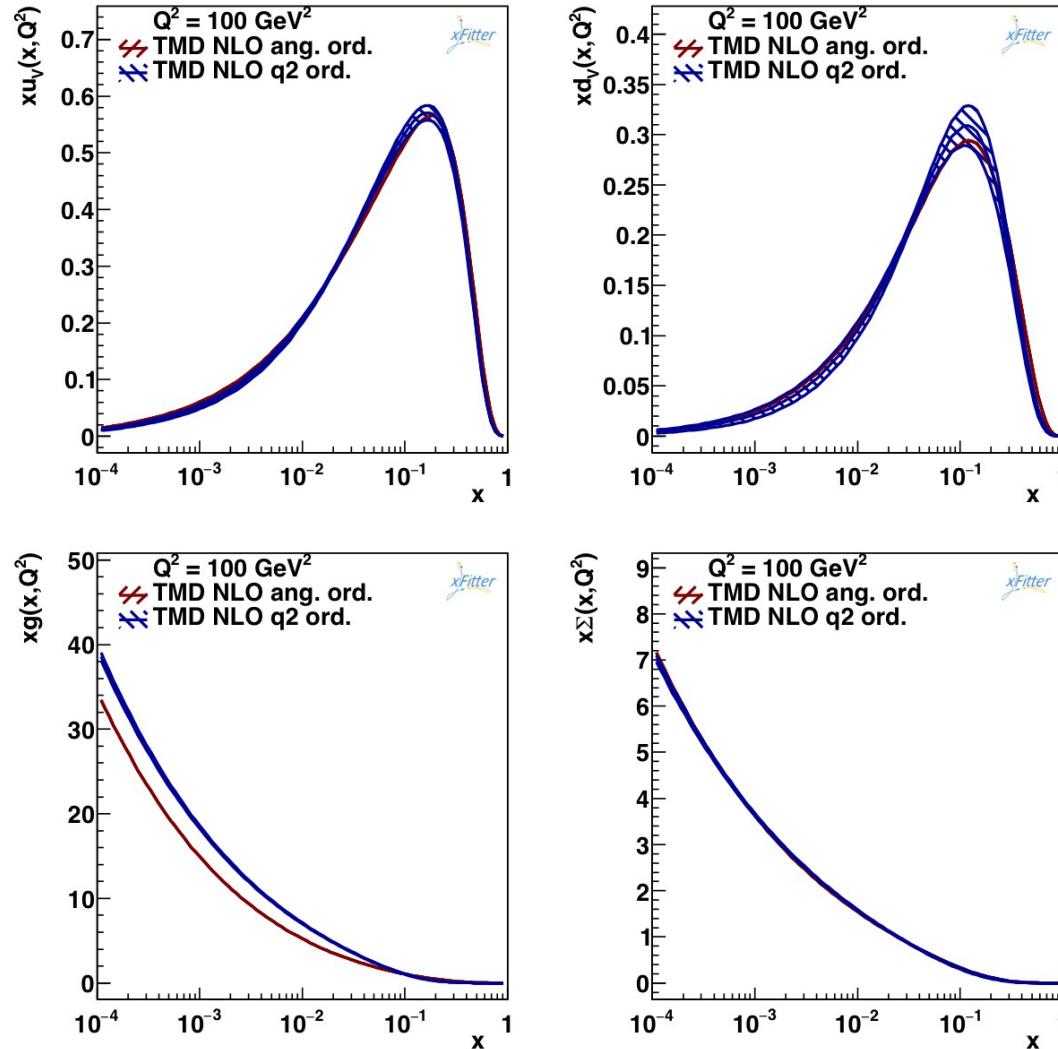
The scale suggested by angular ordering give a very good description of the $Z p_T$ spectrum.

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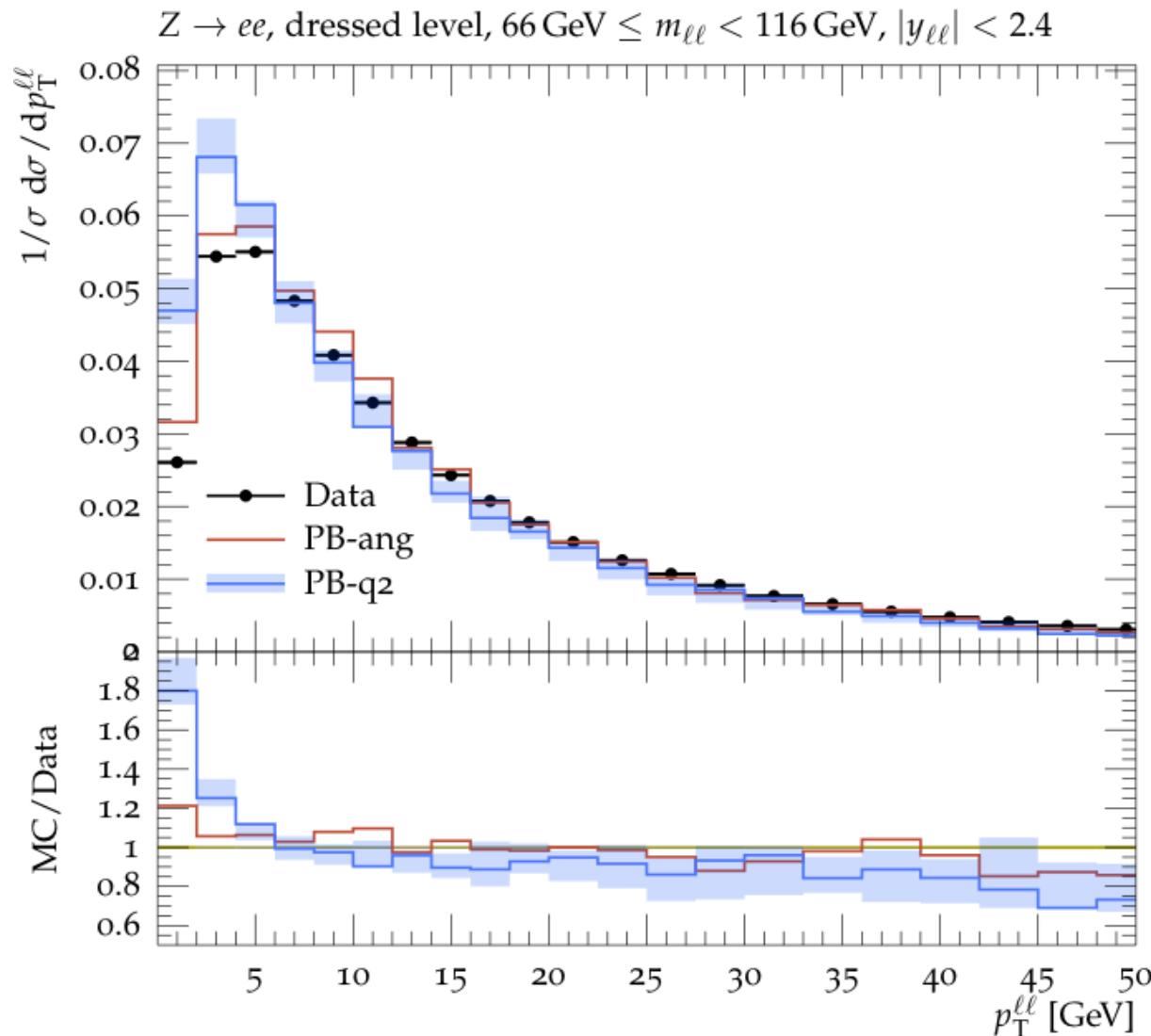
Note: no tuning of free parameters here!

A. Lelek, talk at REF 2017

Effects of the coupling's scale and angular ordering in integrated parton distributions



Drell-Yan pT spectrum from parton branching method including TMD uncertainties

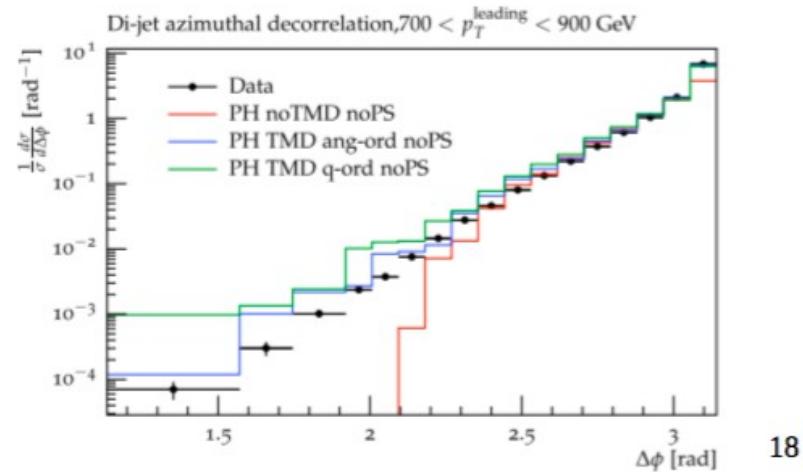
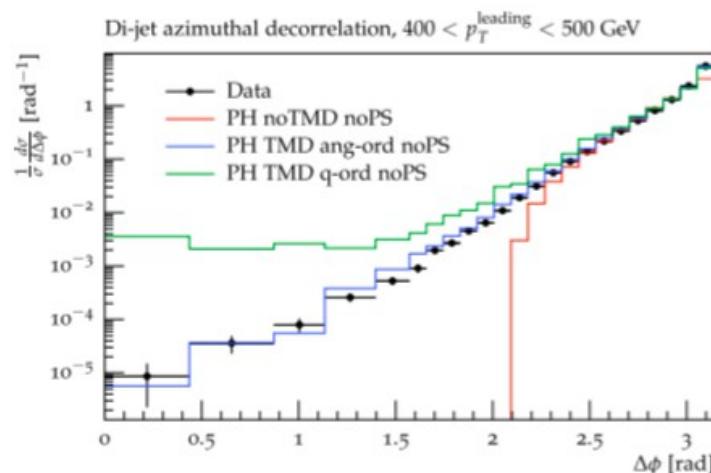


Application: Dijet production - $\Delta\phi$

- 1) Events generated by **POWHEG** 2jets, without including the parton shower
- 2) The transverse momentum from TMD added to the original POWHEG sample
- 3) Events analyzed by RIVET

The CMS collaboration: Measurement of dijet azimuthal decorrelation in pp collisions at $\sqrt{s} = 8$ TeV
[arXiv:1602.04384]

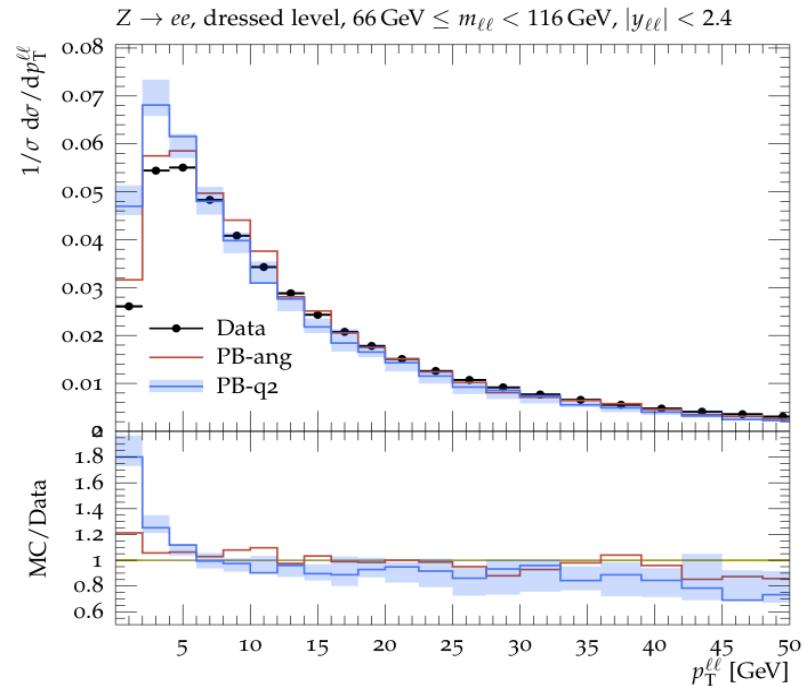
$$\sigma = A(x_1, k_{T1}, \mu^2) \otimes \hat{\sigma} \otimes A(x_2, k_{T2}, \mu^2)$$



R. Zlebcik, talk at REF 2017, November 2017

Prospects for measuring TMDs from pT spectra and angular asymmetries

- Parton branching method applicable from low to high energies, and from low to high pT
- LHC, Tevatron and fixed-target measurements in Drell-Yan production – and possibly colored probes, e.g. pT spectra and angular correlations in heavy quark pair and jet production



- Method implemented in xFitter – ready to use for HERA measurements and future lepton-hadron collider studies.