

PB TMD fits at NLO with dynamical resolution scale

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Outline

2

- **Recap of Parton Branching method**
- **Fixed and Dynamical soft-gluon resolution scale z_M**
- **Fits with fixed z_M at NLO**
- **Fits with dynamical z_M at NLO**

Merged talk:

- **Z+b jet production in 4FL and 5FL**

Recap of PB TMDs

3

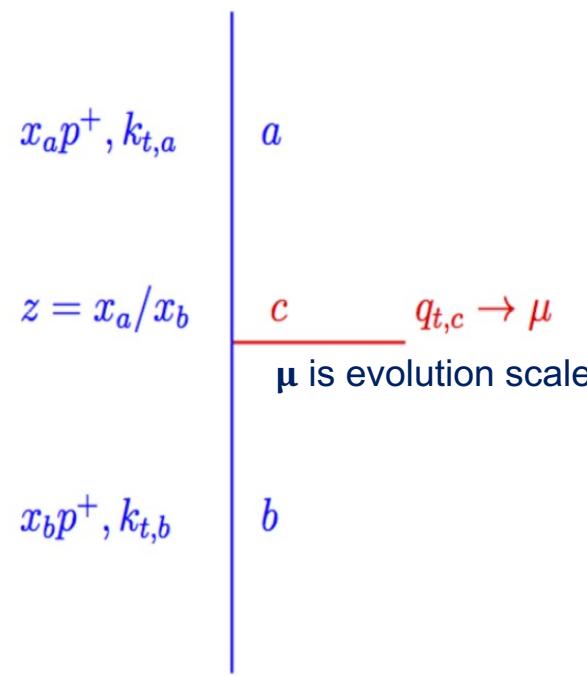
TMD evolution in the PB formalism:

$$\widetilde{A}_a(x, k_\perp, \mu^2) = \widetilde{A}_a(x, k_\perp, \mu_0^2) \Delta_a(\mu^2) + \sum_b \int \frac{d^2 \mu'_\perp}{\pi \mu'^2} \Theta(\mu^2 - \mu'^2) \Theta(\mu'^2 - \mu_0^2) \times \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz P_{ab}^R(z, \alpha_s(q_\perp)) \times \widetilde{A}_b\left(\frac{x}{z}, k_\perp + (1-z)\mu', \mu'^2\right)$$

- **z_M : Resolution scale :**  Resolvable branching : $z < z_M$
Non-resolvable branching : $z > z_M$

- **Splitting functions: $P_{ab}^R(z)$:** The real emission parts of the DGLAP splitting function:
Probability that a branching will happen

- **Sudakov form factor:** $\Delta_a = \exp\left(-\int_{\ln \mu_0^2}^{\ln \mu^2} d(\ln \mu'^2) \sum_b \int_0^{z_M} dz z P_{ba}^R(\alpha_s, z)\right)$
The probability of an evolution without any resolvable branching

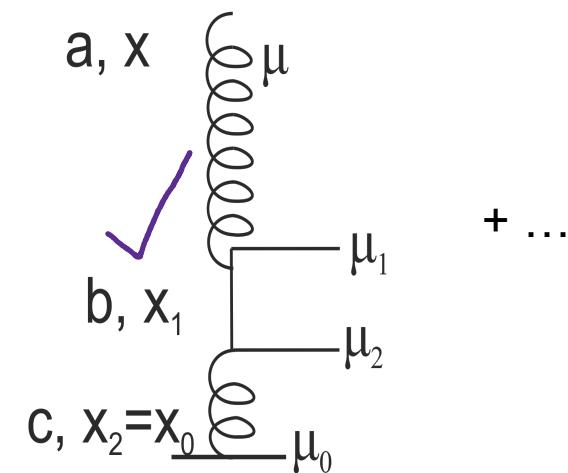
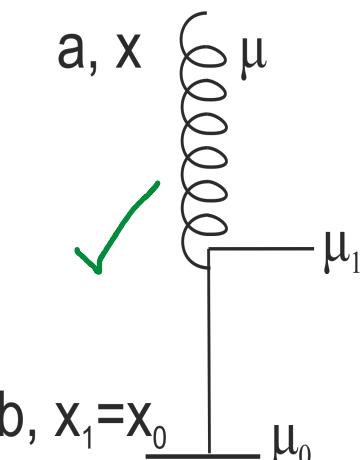
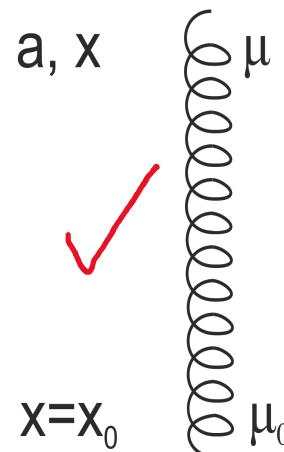


Recap of PB TMDs

4

Iterative form of the PB evolution equation:

$$\widetilde{A}_a(x, k_\perp, \mu^2) = \widetilde{A}_a(x, k_\perp, \mu_0^2) \Delta_a(\mu^2) + \sum_b \int_{\ln \mu_0^2}^{\ln \mu^2} d \ln \mu_1^2 \times \frac{\Delta_a(\mu^2)}{\Delta_a(\mu_1^2)} \int_x^{z_M} dz P_{ab}^R(z, \alpha_s(q_\perp)) \Delta_b(\mu_1^2) \times \widetilde{A}_b\left(\frac{x}{z}, k_\perp + (1-z)\mu_1, \mu_0^2\right) + \dots$$



Solvable by MC iterative technique:

- generated μ_1^2 : if $\mu_1^2 > \mu^2$ stop, otherwise splitting,
- generated the next scale μ_2^2 : if $\mu_2^2 > \mu^2$ stop, otherwise splitting,
- ...

Angular Ordering:

5

Color coherence phenomena:

- Angular ordering of the soft gluon emissions

$$|q_{\perp,i}| = (1 - z_i) |E_i| \sin \Theta_i$$

Associating " $|E_i| \sin \Theta_i$ " with μ'

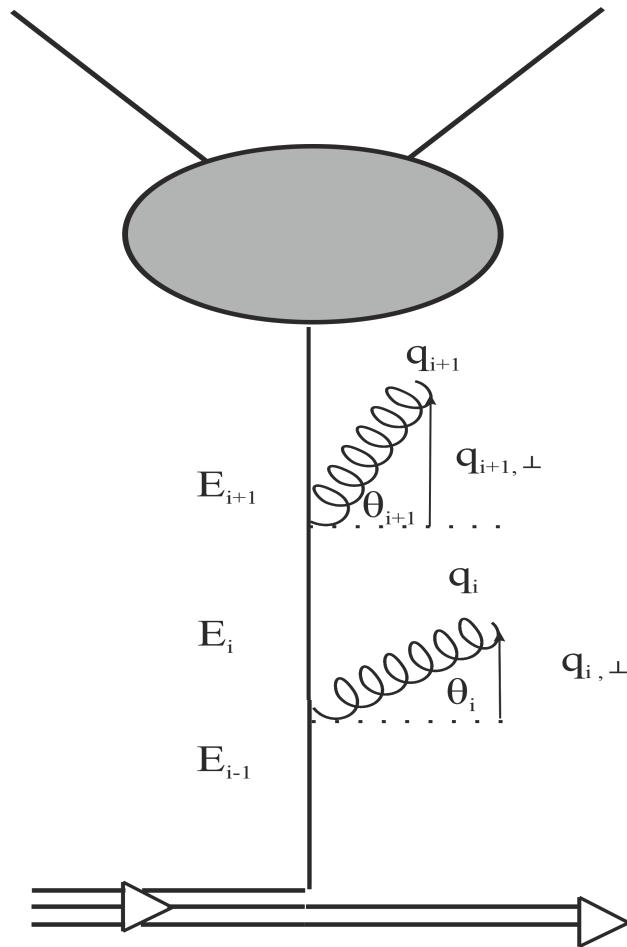
$$q_{\perp,i}^2 = (1 - z_i)^2 \mu'^2$$

- The argument of α_s should be q_{\perp}^2

$$\alpha_s(q_{\perp}^2) = \alpha_s((1 - z)^2 \mu'^2)$$

- resolvable & non-resolvable \rightarrow condition on $\min q_{\perp,i}^2 \rightarrow z_M$

$$z_M = 1 - \left(\frac{q_0}{\mu'} \right)$$



Fixed and dynamical resolution scale

6

➤ **Fixed z_M :**

- μ independent

$$z_M = 1 - \epsilon$$

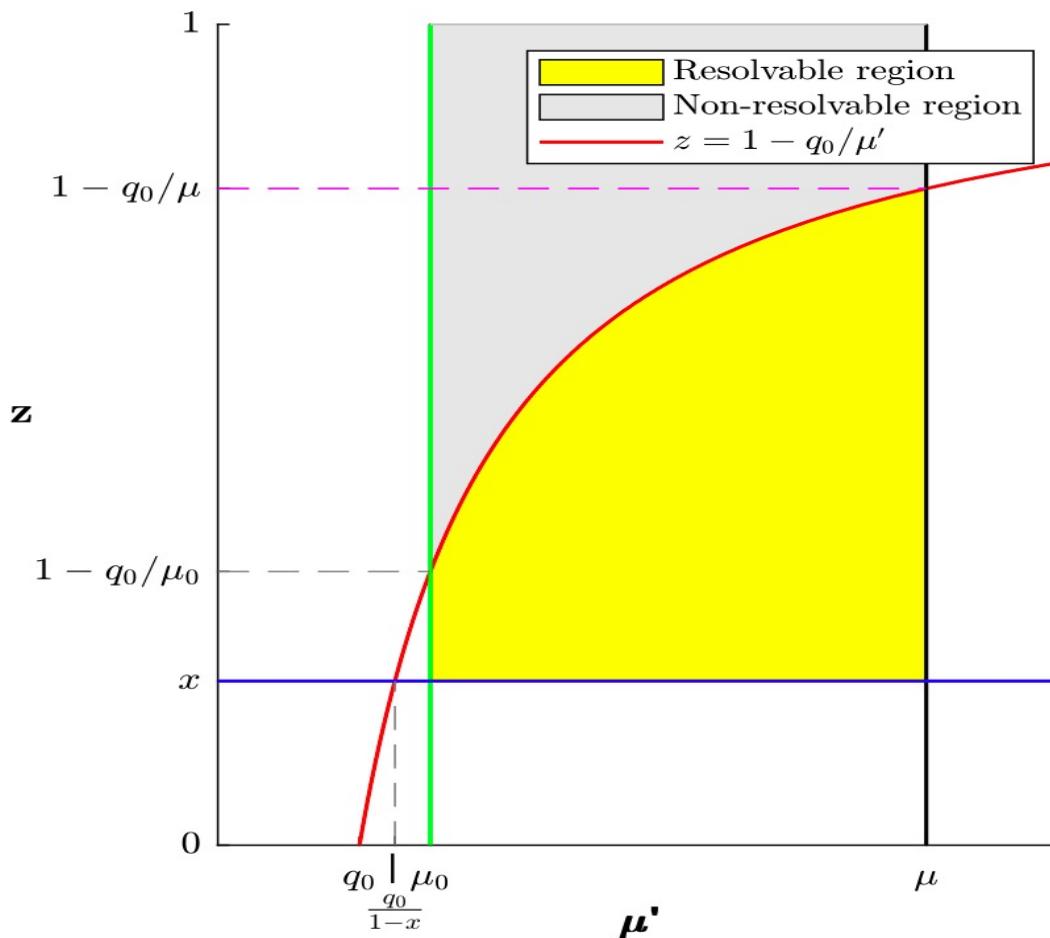
where ϵ is small: $10^{-3}, 10^{-4}, 10^{-5}, \dots$

➤ **Dynamical Resolution scale in Angular Ordering:**

$$z_M = 1 - \left(\frac{q_0}{\mu'} \right)$$

where q_0 is smallest emitted transverse momentum for resolvable partons

- Sudakov form factor Δ_a : non-resolvable region
- Splitting functions P_{ab}^R : resolvable region



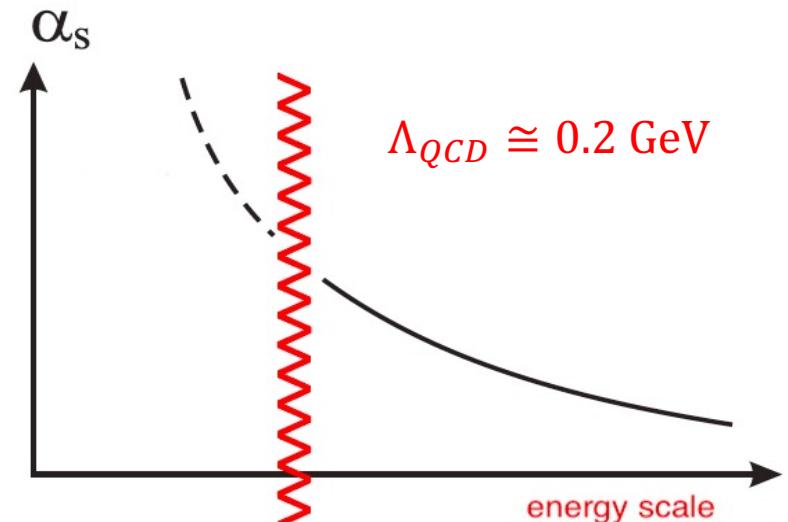
Dynamical resolution scale

7

The Condition on q_0 of

$$z_M = 1 - \left(\frac{q_0}{\mu'} \right)$$

- Scale of strong coupling: $\alpha_s(q_\perp^2) = \alpha_s((1-z)^2 \mu'^2)$
- Lowest scale in α_s corresponds to minimal q_\perp
- $q_{\perp,\min} = q_0 \text{ & } q_0 > \Lambda_{QCD} \Rightarrow \text{we stay in the weak coupling region!}$



PB TMD fits at NLO with fixed zmax

8

The Past PB TMD fits at NLO calculation using angular ordering : fixed z_M

"NLO DIS Matrix Element (ME) and NLO evolution kernel"

- Associating the evolution scale with some physical interpretation:

Two scenario

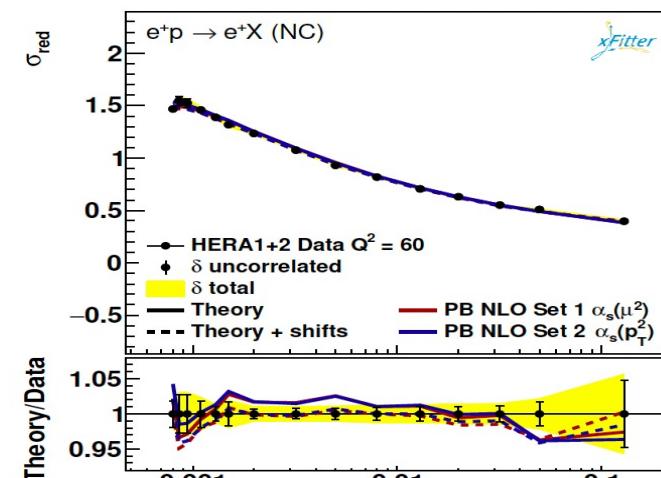
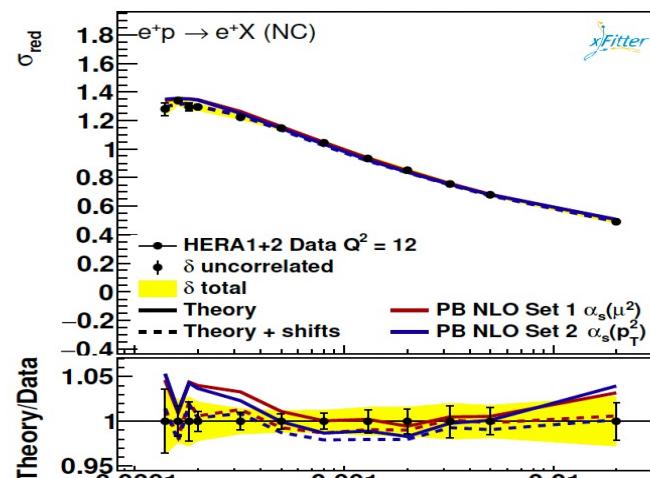
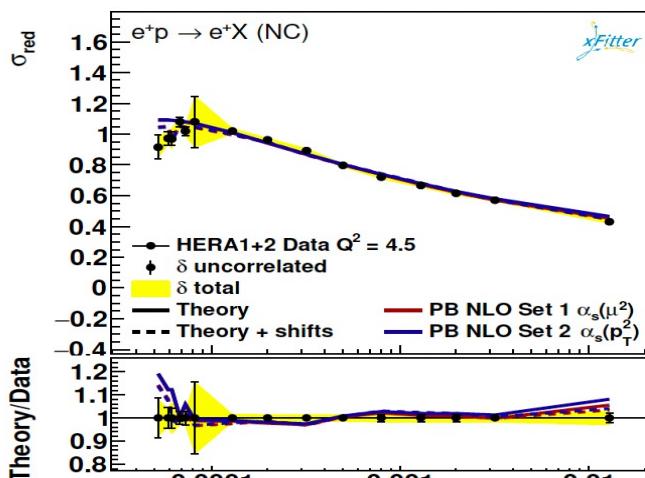
• Set 1
—————> $\alpha_s(\mu'^2)$
• Set 2
—————> $\alpha_s(q_\perp^2) = \alpha_s((1-z)^2 \mu'^2)$

- The resulting TMD parton densities, PB-NLO-2018-set1 and PB-NLO-2018-set2 are available in **TMDLIB2**: *The European Physical Journal C* 81.8 (2021): 1-10

- Data set: HERA 1+ 2 inclusive DIS data

PB NLO Set1 $\alpha_s(\mu_i^2)$			
	χ^2	d.o.f	$\chi^2/d.o.f$
$\mu_0^2 = 1.9 \text{ GeV}^2$	1363.37	1131	1.21
PB NLO Set 2 $\alpha_s(q_{ti}^2)$			
	χ^2	d.o.f	$\chi^2/d.o.f$
$\mu_0^2 = 1.4 \text{ GeV}^2$	1369.80	1131	1.21

.Phys Rev. D 99, 074008 (2019),



- ✓ Measurement of the inclusive DIS cross section obtained at HERA compared to predictions using Set 1 and Set 2

PB TMD fits at NLO with **dynamical zmax**

9

New study

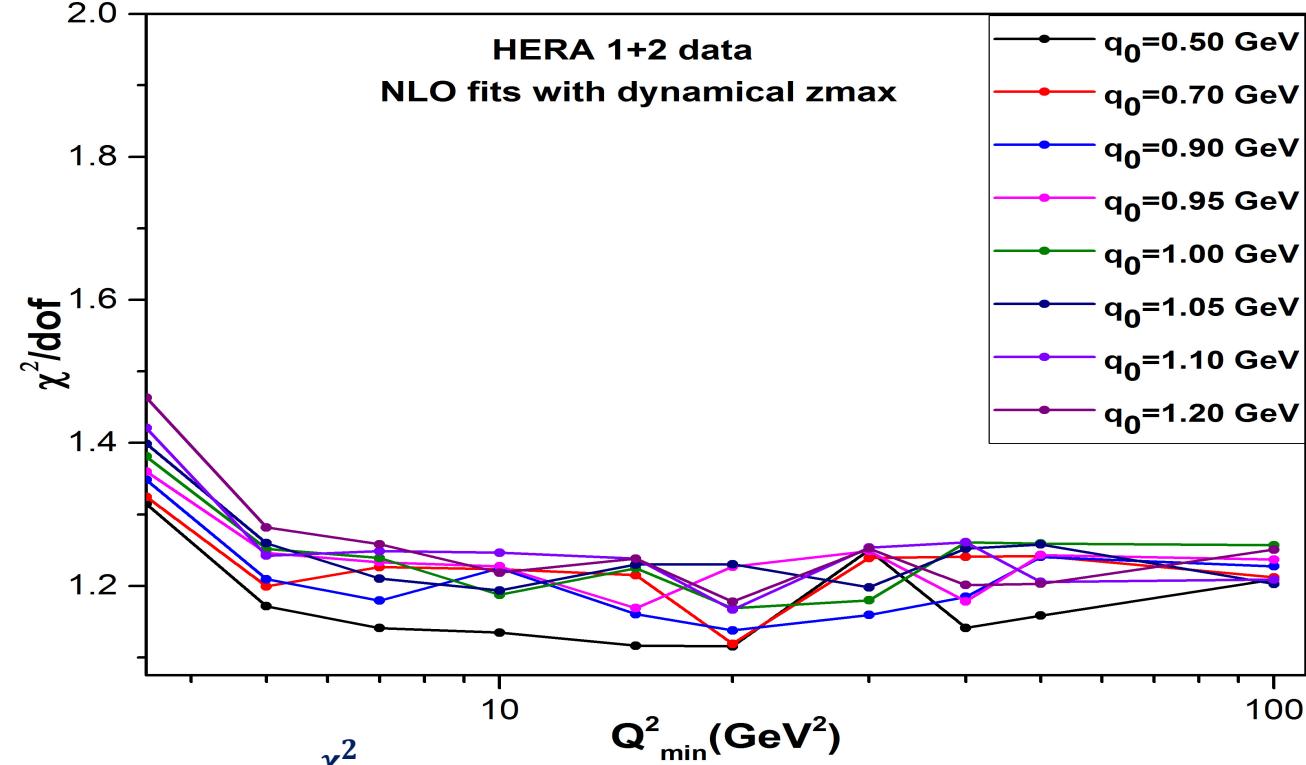
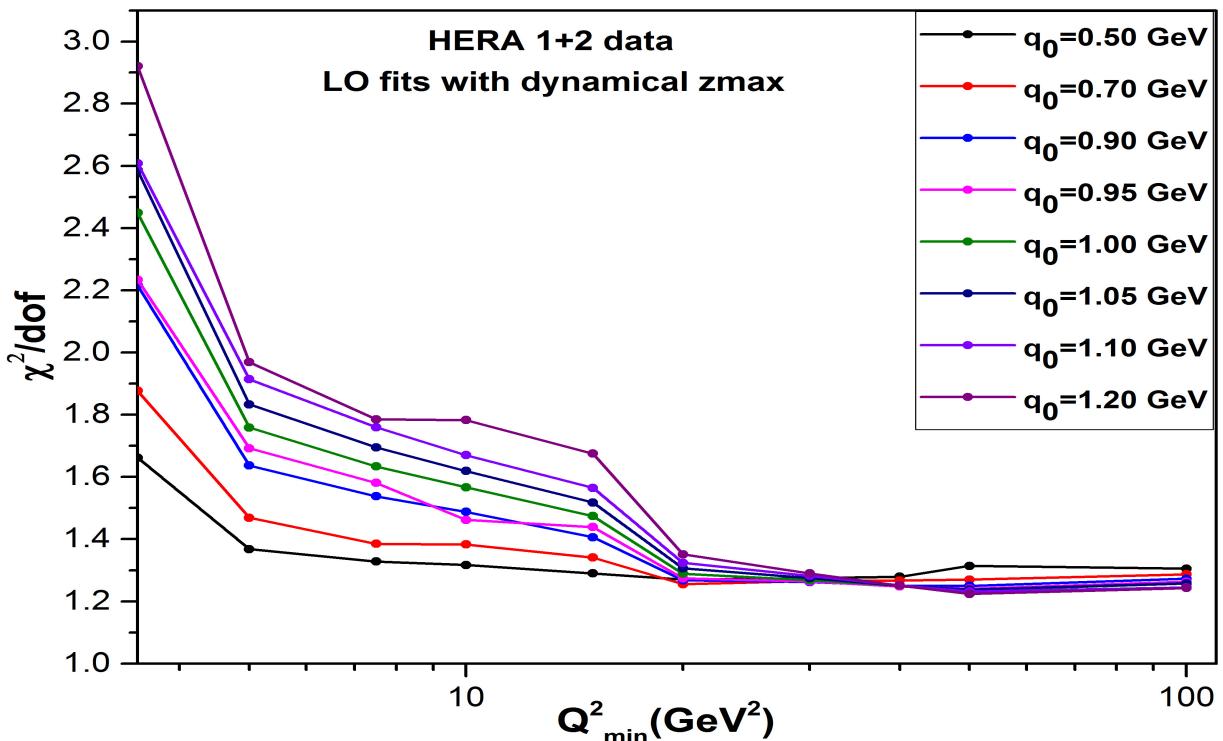
From **fixed resolution scale** to **dynamical resolution scale**

PB TMD fits at NLO with dynamical zmax: $z_M = 1 - \left(\frac{q_0}{\mu'}\right)$

10

New fits with dynamical zmax at LO and NLO with HERA 1 + 2 Data set: Using *xFitter* arXiv:1709.01151v1

- ✓ Performing different fits, each time by varying Q^2_{min} and on top of that with different q_0 values



- At LO , for small Q^2_{min} and $0.9 \text{ GeV} < q_0 < 1.2 \text{ GeV}$ $\longrightarrow 2.2 < \frac{\chi^2}{dof} < 3$
- AT NLO , for small Q^2_{min} and all values of q_0 , we have better fits with good $\frac{\chi^2}{dof}$!

The difference between LO and NLO

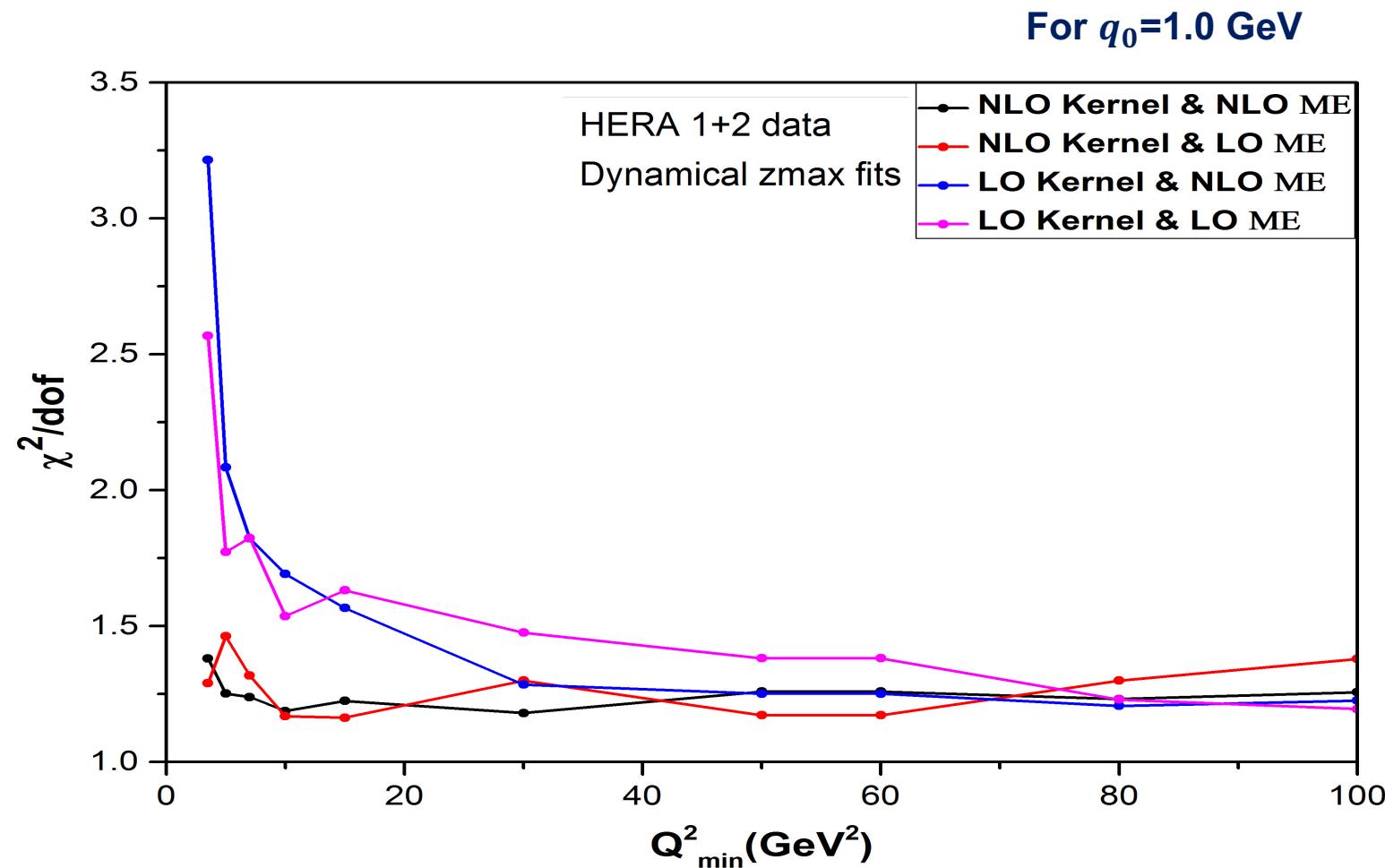
11

- Does the difference between LO and NLO come from the kernels? or ME?!

4 states for this purpose:

1. Fitting with NLO kernel & NLO ME
2. Fitting with NLO kernel & LO ME
3. Fitting with LO kernel & LO ME
4. Fitting with LO kernel & NLO ME

The difference is dominated by the kernel not ME!..



The difference between LO and NLO

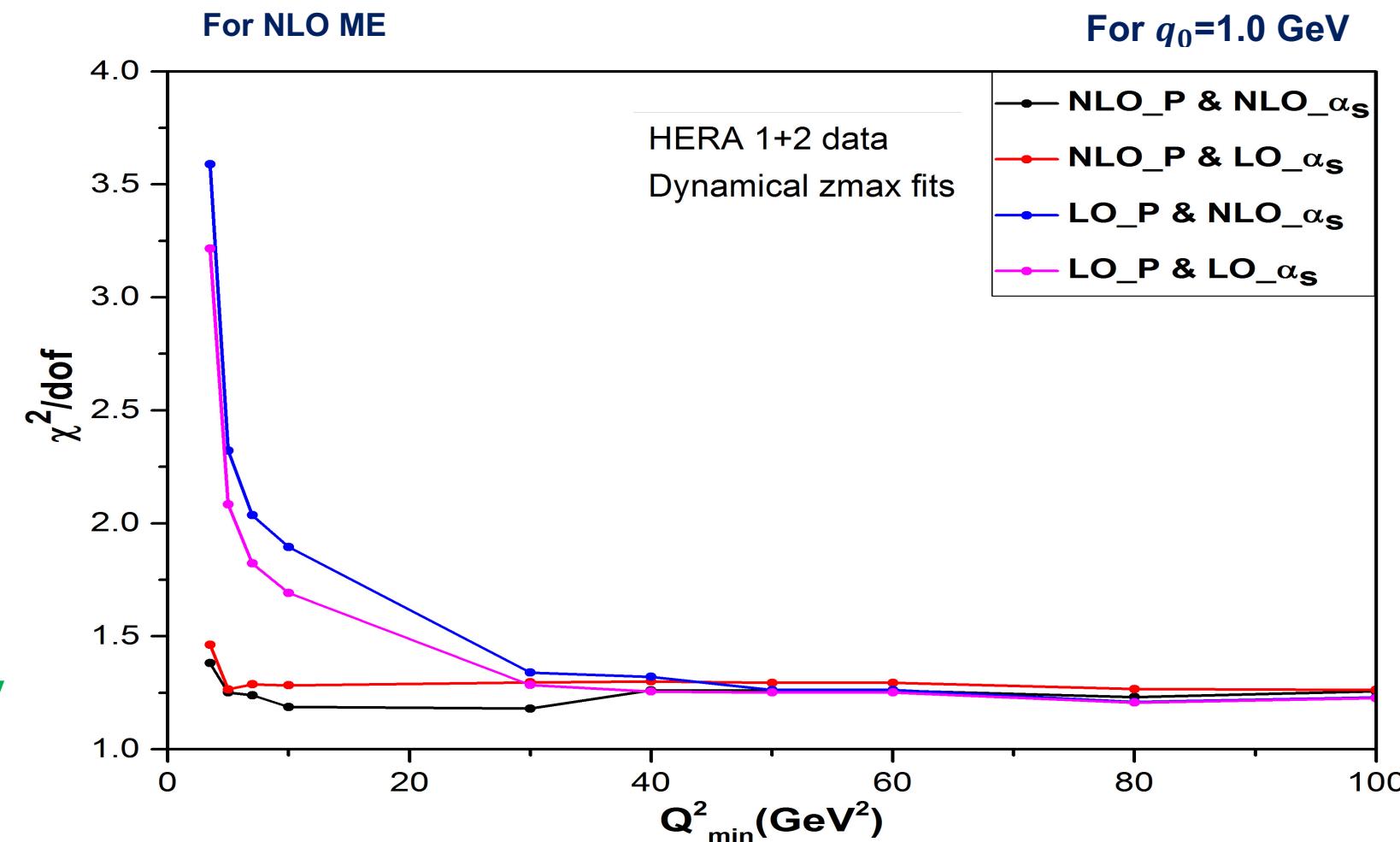
12

- Which part of the kernel is responsible?

$P_{ab}(z, \mu^2)$? or α_s ?

4 states for this purpose:

1. Fitting with NLO P_{ab} & NLO α_s
2. Fitting with NLO P_{ab} & LO α_s
3. Fitting with LO P_{ab} & LO α_s
4. Fitting with LO P_{ab} & NLO α_s



The difference is dominated by the splitting functions not α_s ..!

Which part of the splitting functions is responsible for the difference between LO and NLO?

13

- For high values of q_0 (e.g, [1.0 Gev, 1.2 Gev]) or low values of $z_M = 1 - \left(\frac{q_0}{\mu'}\right)$,
LO and NLO have different behavior.

The first piece for checking is $\frac{1}{z}$

- In the NLO, all the splitting functions have pieces with $(1/z)$ term :
 $P_{ab}(z, \mu^2) \sim P_{qq}(1/z, \mu^2), P_{qg}(1/z, \mu^2), P_{gg}(1/z, \mu^2), P_{gq}(1/z, \mu^2)$
 - In the LO, just the splitting functions with "gluon" in the final state have $(1/z)$ piece:
 $P_{gg}(z, \mu^2) = \frac{1}{1-z} + \frac{1}{z} - 2 + z(1-z),$
 $P_{gq}(z, \mu^2) = \frac{1+(1-z)^2}{z}$
 - And the splitting functions with "quark" in the final state don't have $(1/z)$ piece:
 $P_{qq}(z, \mu^2) = \frac{2}{1-z} - 1 - z,$
 $P_{qg}(z, \mu^2) = z^2 + (1-z)^2$
- Is the lack of $(1/z)$ piece in LO splitting function with quark in the final state responsible for this difference?

Let's check it!

Does the difference come from 1/z piece of NLO splitting function?

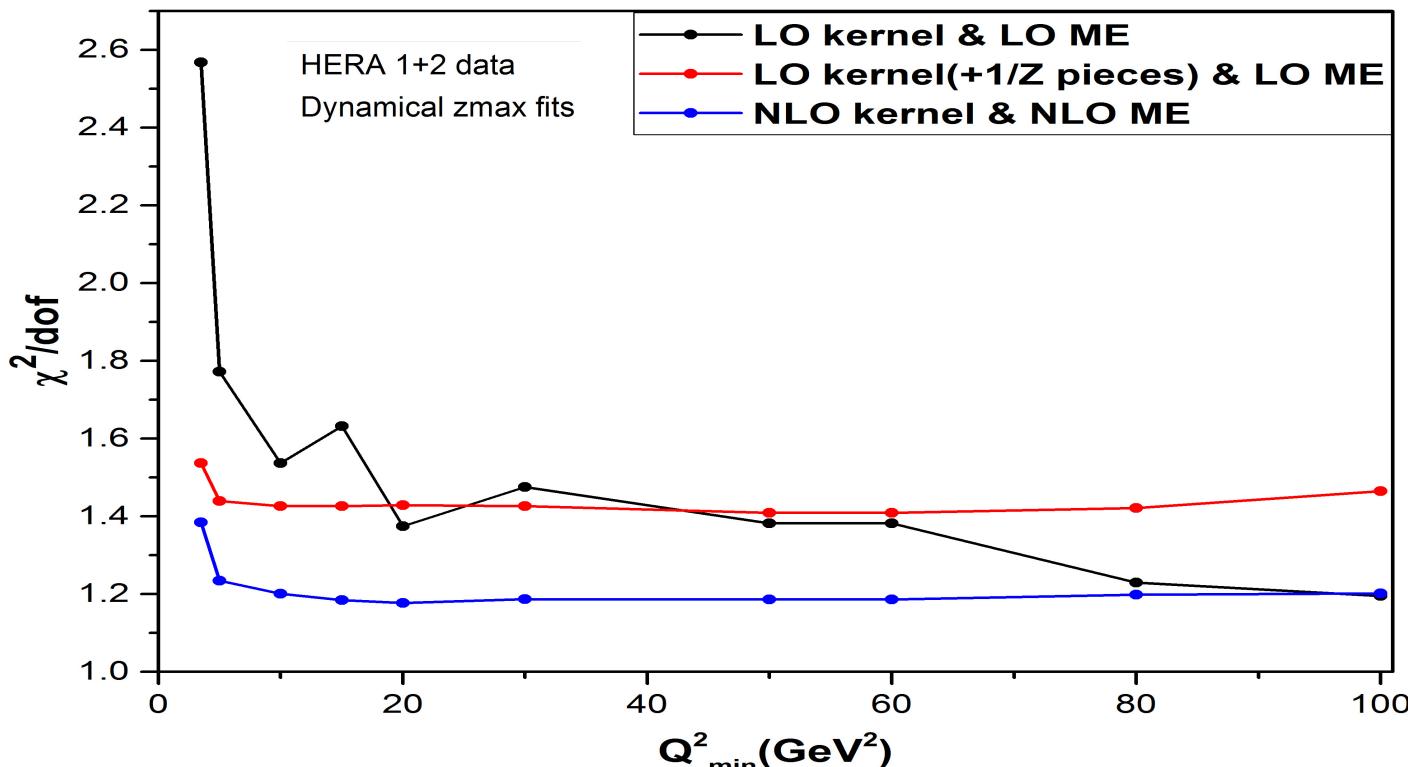
14

For better understanding: “**We added to the LO splitting functions(P_{qg} , P_{qq}) the 1/z pieces of NLO**”

✓ $P_{qq}(z, \mu^2) = \frac{2}{1-z} - 1 - z + \left(\frac{1}{z}\right)$ pieces of P_{qq} NLO

✓ $P_{qg}(z, \mu^2) = z^2 + (1-z)^2 + \left(\frac{1}{z}\right)$ pieces of P_{qg} NLO

For $q_0=1.0$ GeV



✓ In NLO we have an extra (1/z) pieces in the quark channels compared with LO which is responsible for this difference!

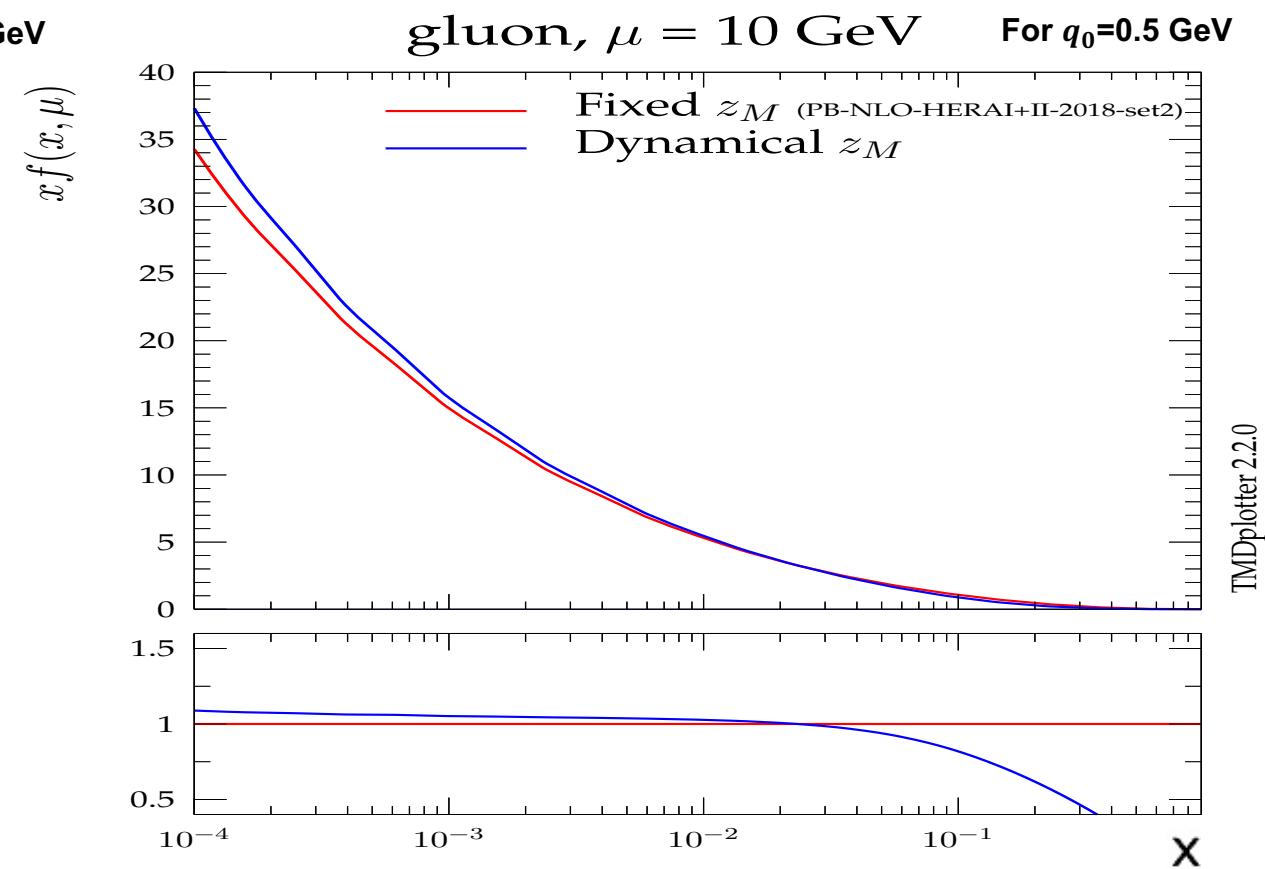
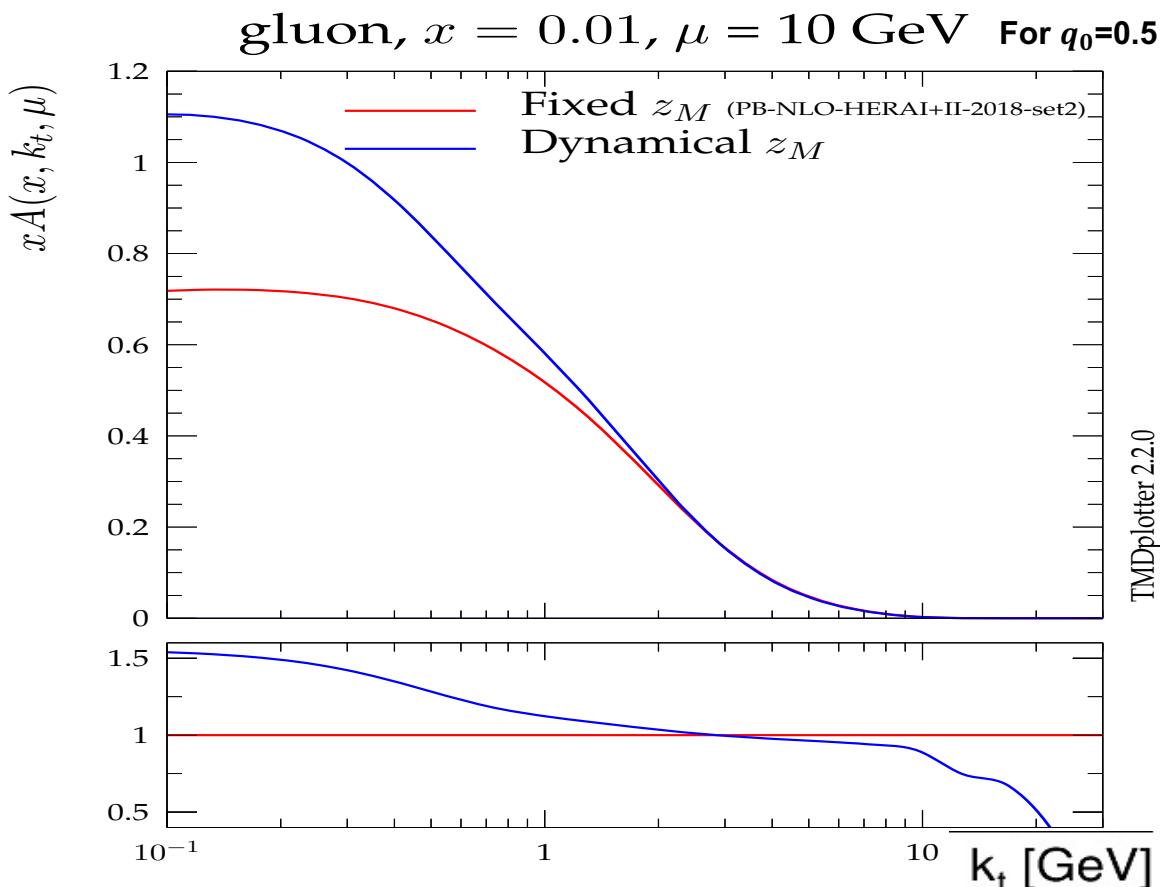
✓ With this piece we are describing data well! Amount of $\frac{\chi^2}{\text{dof}}$ is reasonably good!

** For PB-TMD fit with dynamical zmax we obtain a reasonably good $\frac{\chi^2}{\text{dof}}$ at NLO! **

How does dynamical zmax affect the fitted TMD (iTMD)?

15

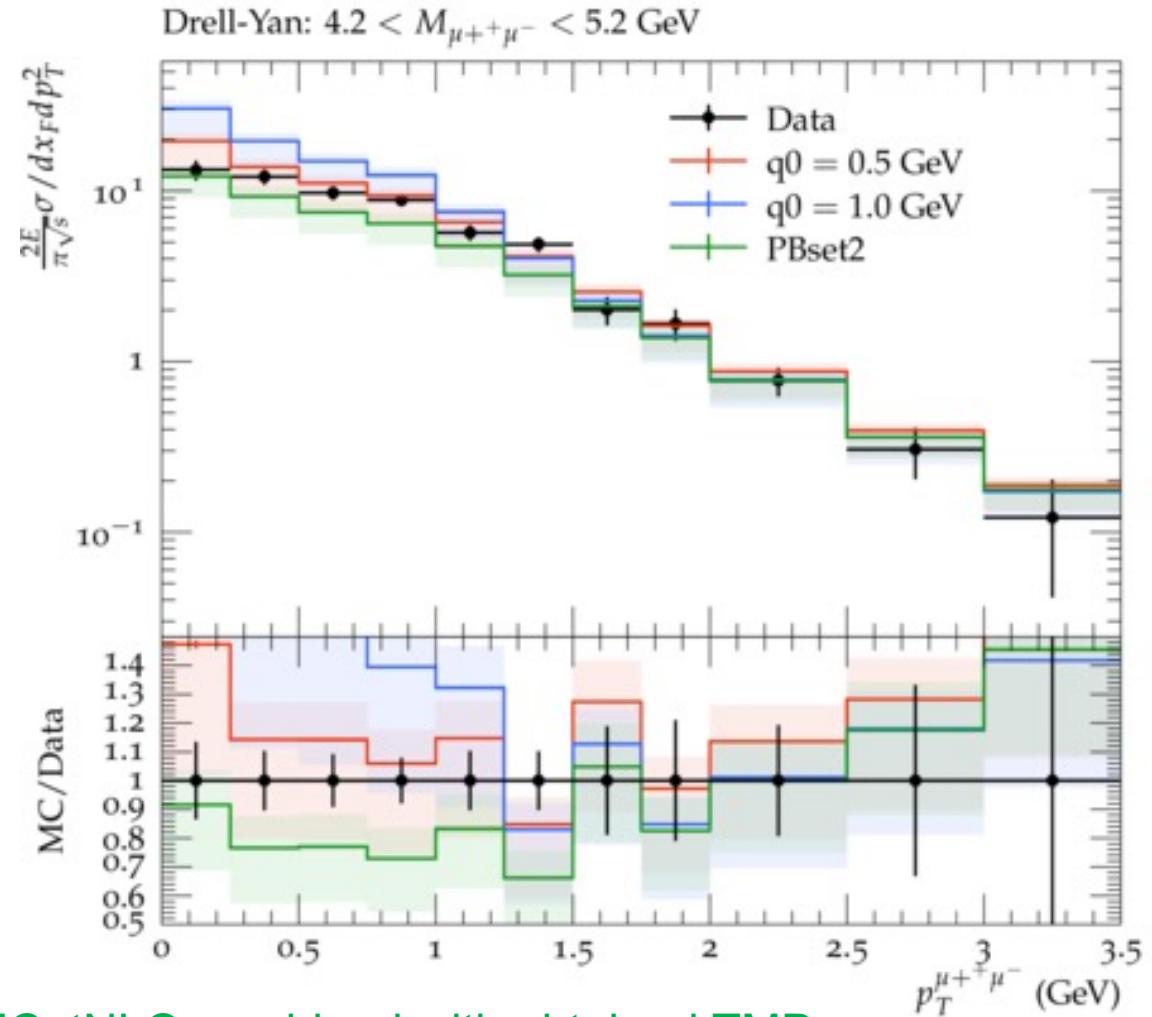
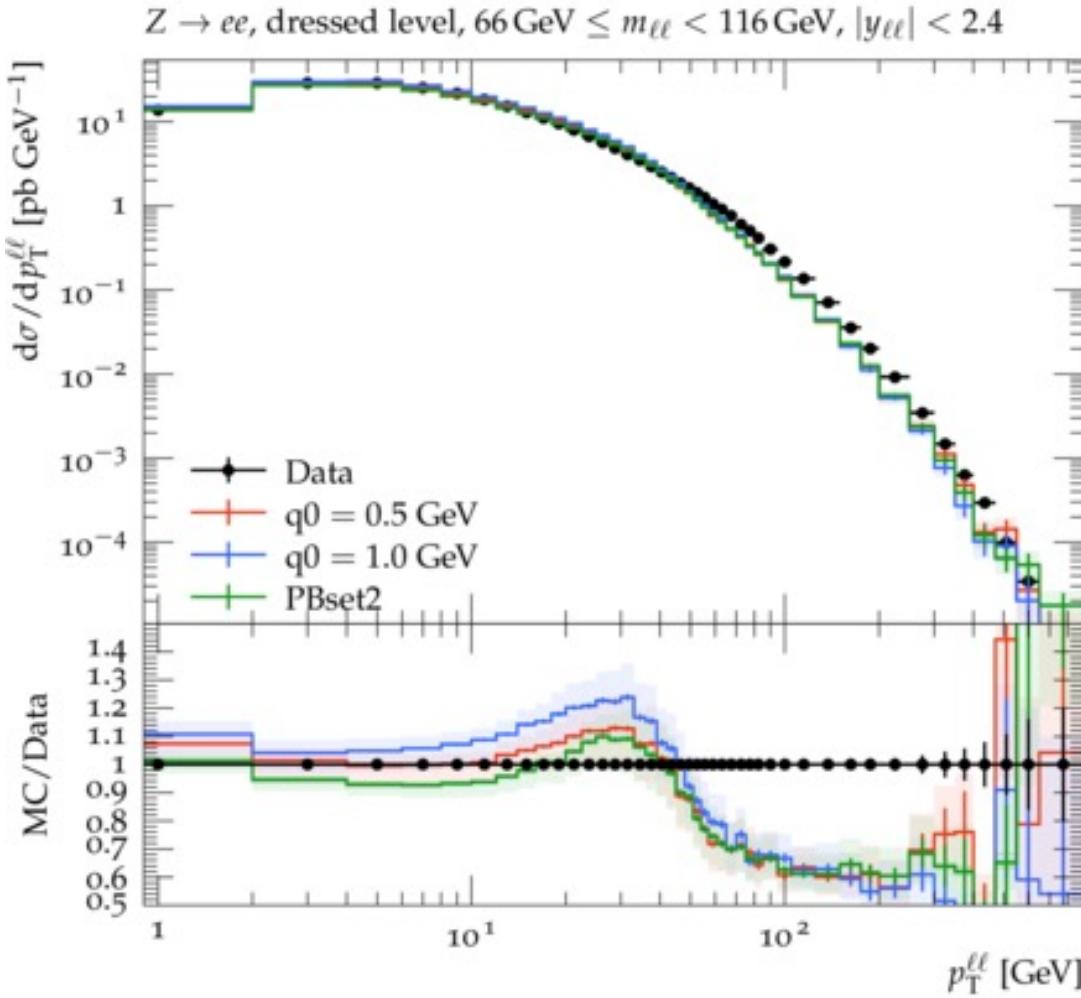
Set 2: fixed zmax & $\alpha_s(q_\perp^2) = \alpha_s((1-z)^2\mu'^2)$



✓ The dynamical zmax fit implies an effect not only in the k_T dependence but also in the x dependence!

The predictions in dynamical zmax frame

16



Predictions with ME generated by MCatNLO combined with obtained TMDs.

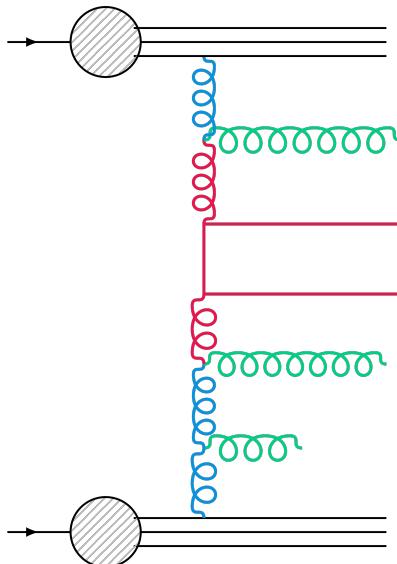
The merged talk: Z+b jet production in 4FL and 5FL

17

5 FLNS

- Full coupled evolution with all flavours & $\alpha(M_Z^{nf=5})=0.118$
- HERAPDF parametrization form
- Using full HERAI+II inclusive DIS data
- chi²/dof=1.21

[Phys. Rev. D 99 (2019) no. 7, 074008]



4 FLNS

- The same functional form and data as 5FL-parameters re-fitted
- $M_b \rightarrow \infty$ & $\alpha(M_Z^{nf=4})=0.1128$
- chi²/dof=1.25

[arXiv:2106.09791]

Matrix elements from MC@NLO (HERWIG6 subtraction)

- 5FLVNS : Z + one parton process
- 4FLVNS : Z + bb process

PDFs : TMDs (4FL & 5FL)

- 5FLVNS : b-quark is treated as a light quark
- 4FLVNS : no b-quark in the parton density

Parton shower following TMDs for initial state

- 5FL & 4FL PB-TMDs included in the Cascade3

Eur. Phys. J. C 81 (2021) 425

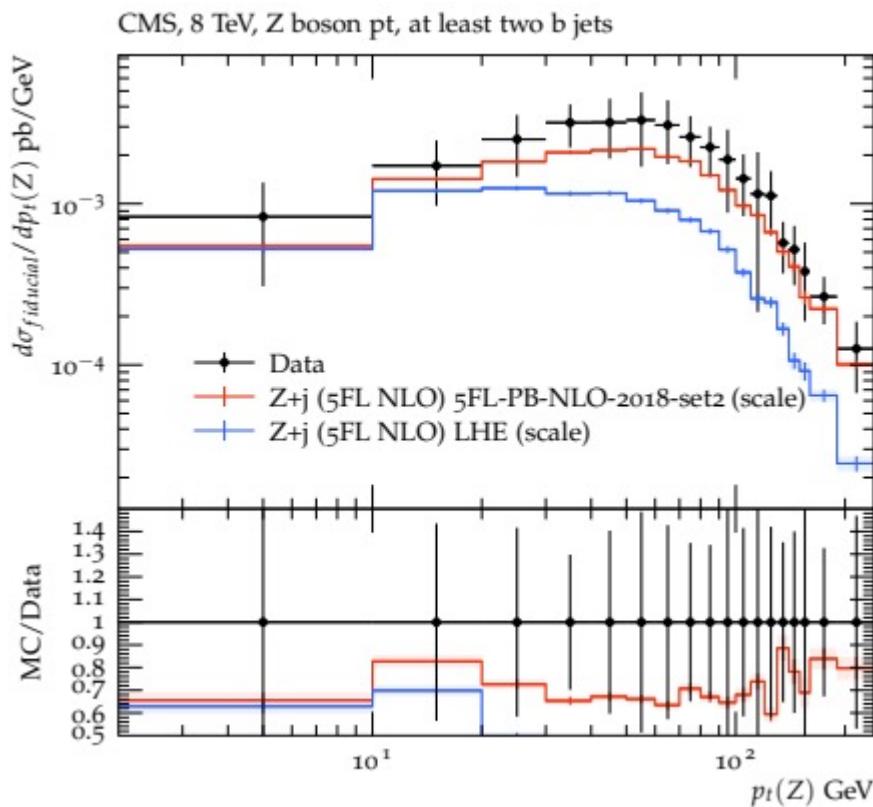
$Z + b\bar{b}$ as a function of $p_t(Z)$

18

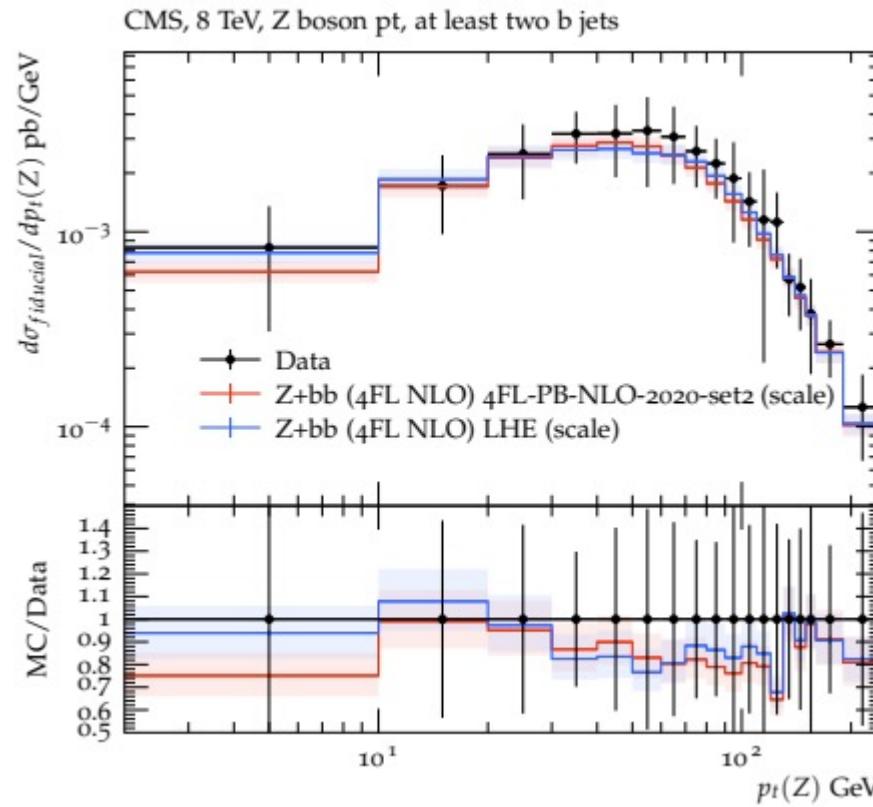
Differential cross section for $Z + b\bar{b}$ as a function of $p_t(Z)$ as measured by CMS collaboration

[Eur. Phys. J. C 77 (2017) 751]

5 FLNS



4 FLNS

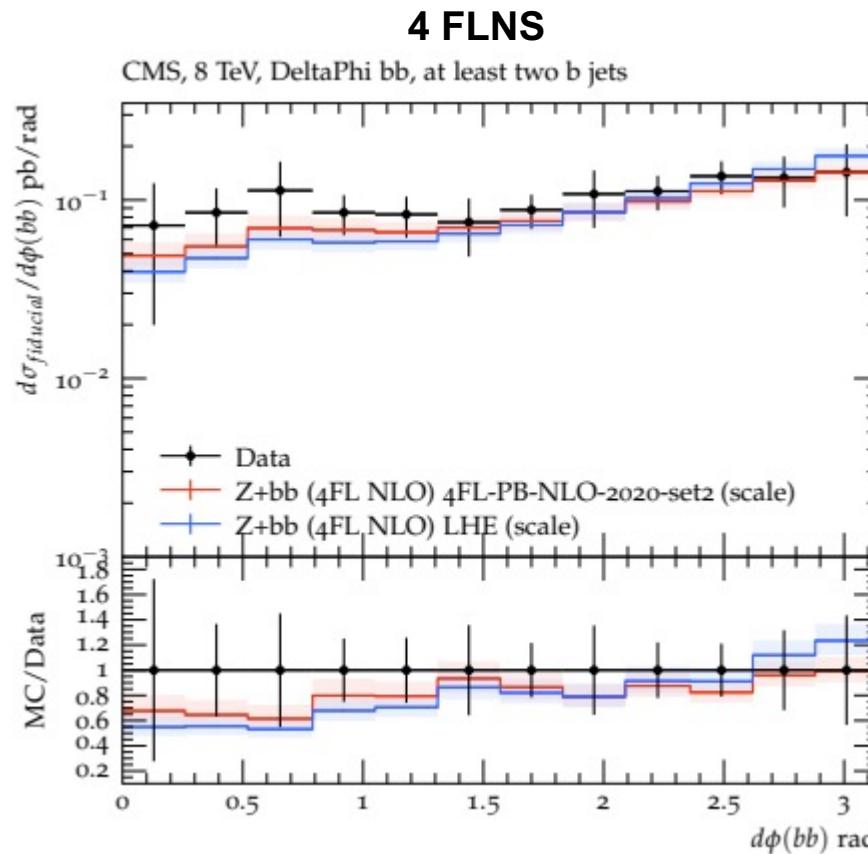
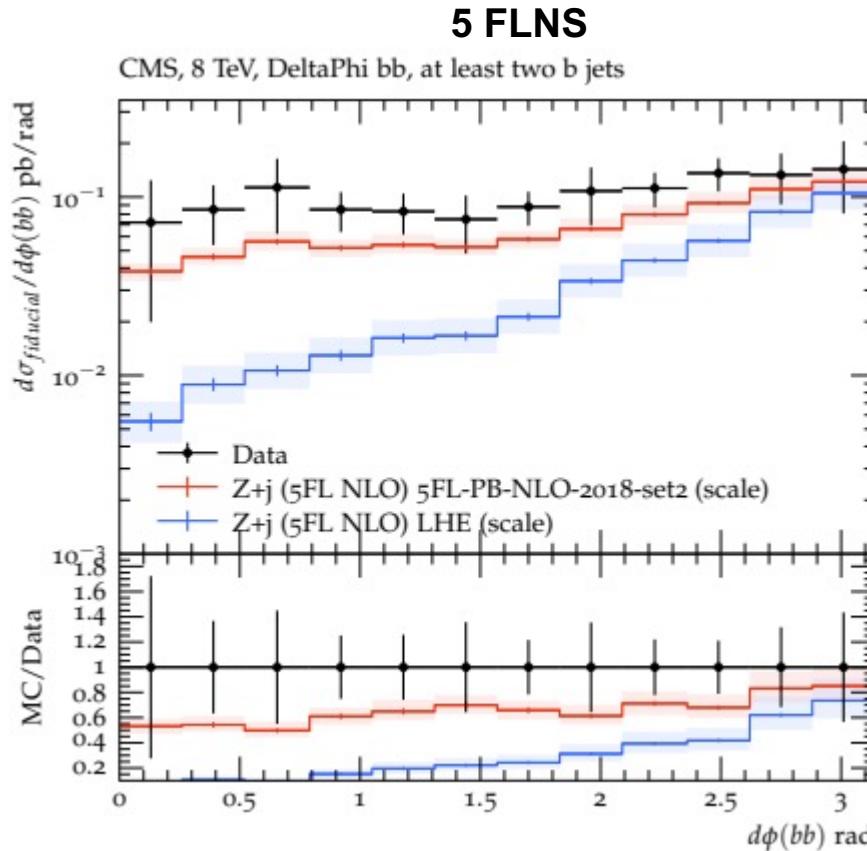


the full prediction + the result of using only the LHE files are shown.

Z+bb as a function of $\Delta\phi(b\bar{b})$

19

Differential cross section for Z + $b\bar{b}$ as a function of $\Delta\phi(b\bar{b})$ as measured by CMS collaboration

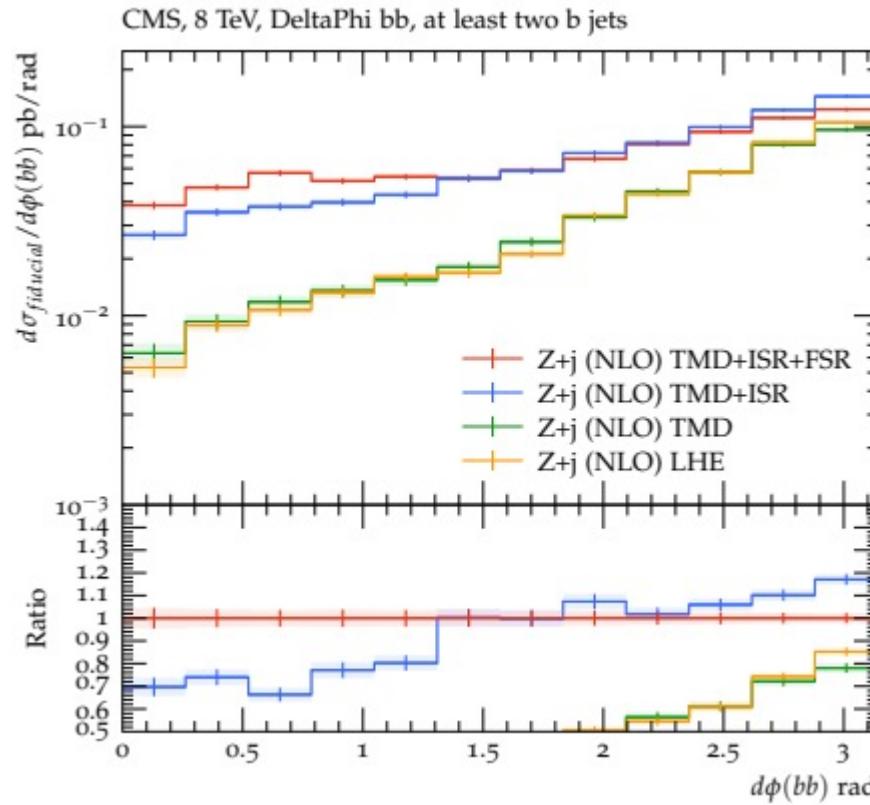


4FL : both b partons are already produced at the ME level
5FL : $b\bar{b}$ must be simulated in the parton shower.

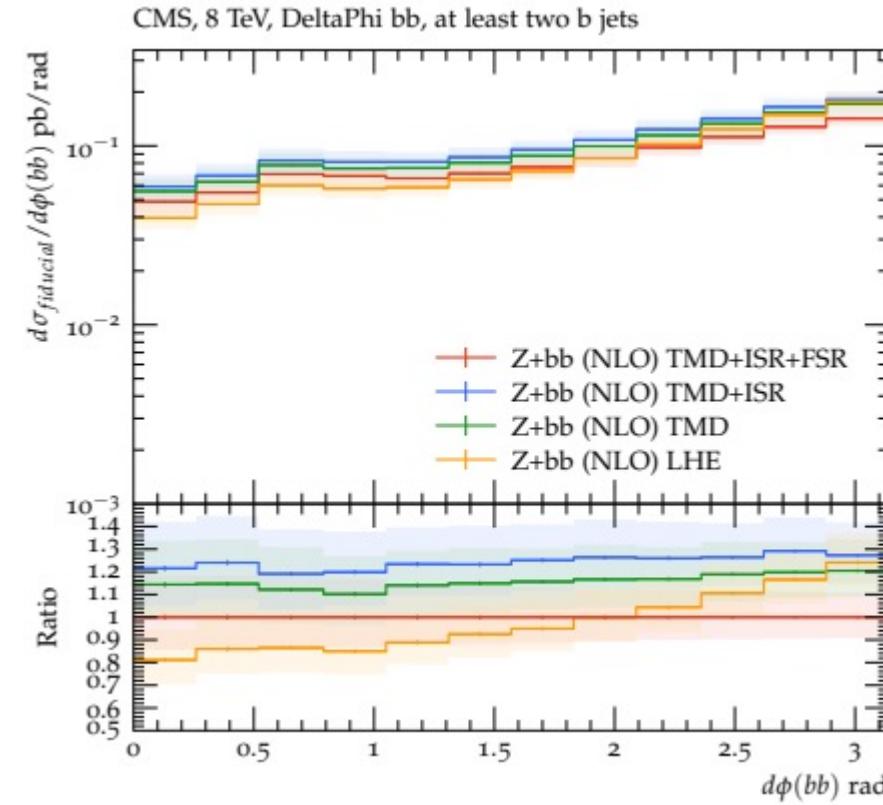
Breakdown of the different contributions to quantify their roles

20

5 FLNS



4 FLNS



4FL: weakly depends on PB-TMD/parton shower

5FL: significant contribution from TMD parton shower

Summary

21

- PB TMD fits at NLO with dynamical zmax for the first time!
- For PB-TMD fit to HERA data with dynamical zmax, we obtain a reasonably good $\frac{\chi^2}{dof}$ at NLO!
- The difference between LO and NLO fits is mostly due to (1/z) pieces in quark channel in NLO splitting functions!
- The dynamical zmax impacts both the k_T dependence and the x dependence of the fitted parton distribution!
- The next step: Using the PB TMD with dynamical zmax in phenomenology of LHC and lower energy colliders!
- The 4FL and 5FL PB-TMD distributions used to calculate Z + bb production
 - Good agreement with measurements obtained by the CMS collaboration
 - The evolution of the PB-TMD parton densities as well as in the PB-TMD parton shower is checked.

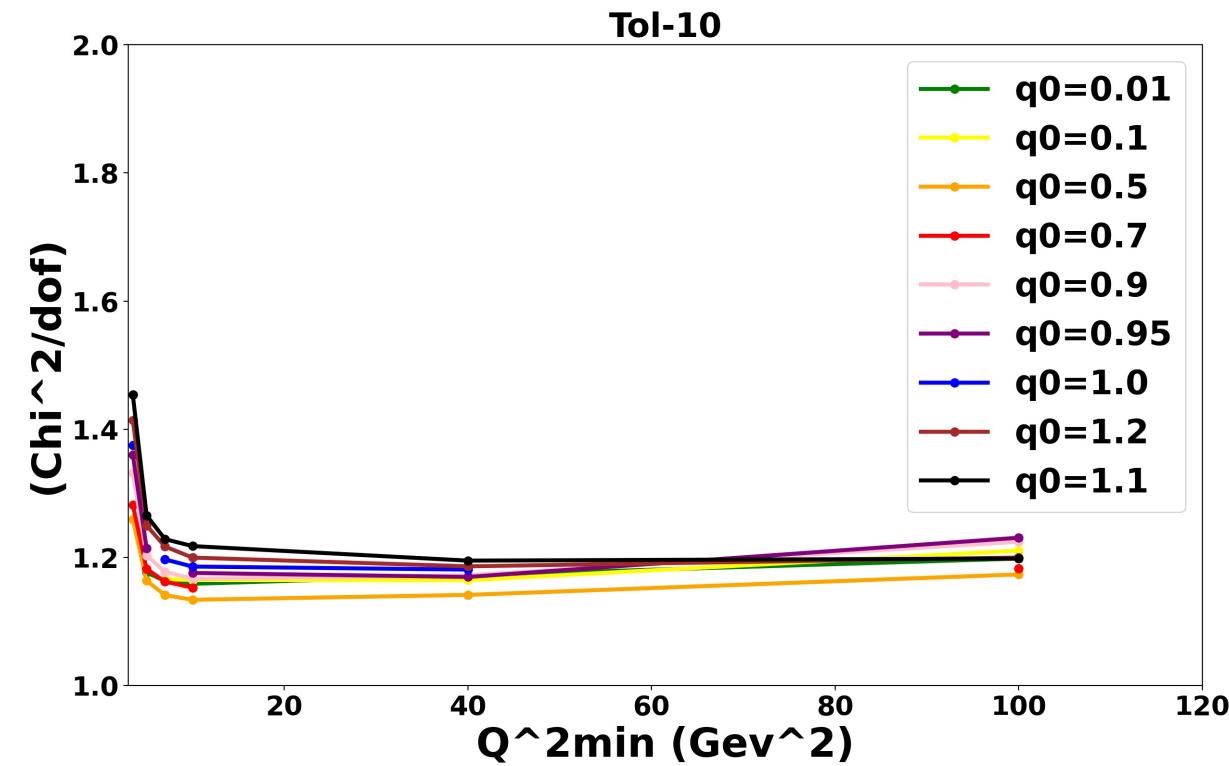
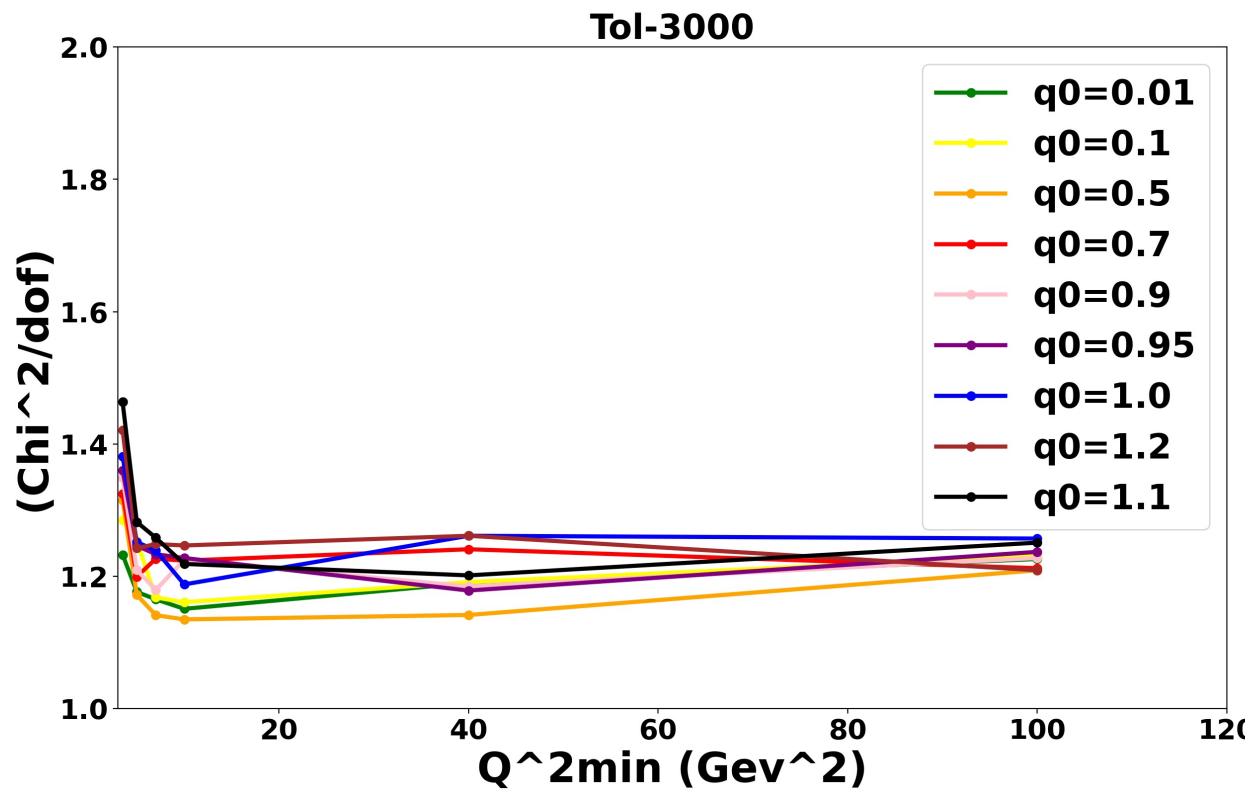
Thank you ...

BACK UP ...



Back up...

23



PB TMD fits at NLO with dynamical zmax:

24

