PB TMD fits at NLO with dynamical resolution scale

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Outline

- 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

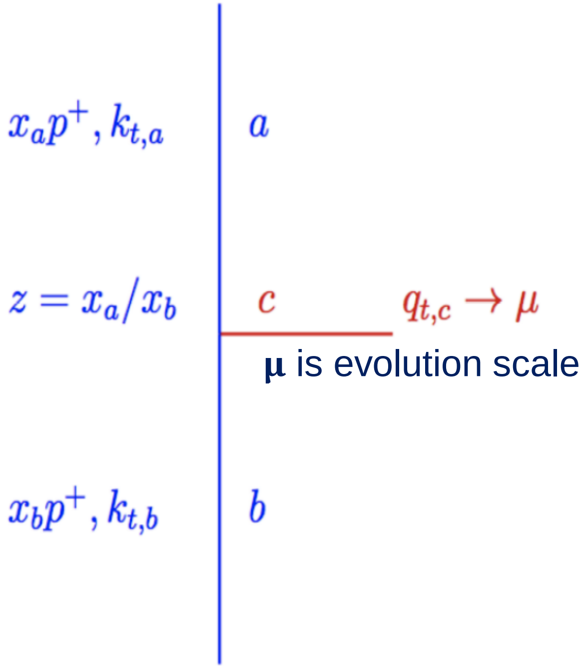
TMD evolution in the PB formalism:

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

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

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

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



At every step kinematics can be calculated!

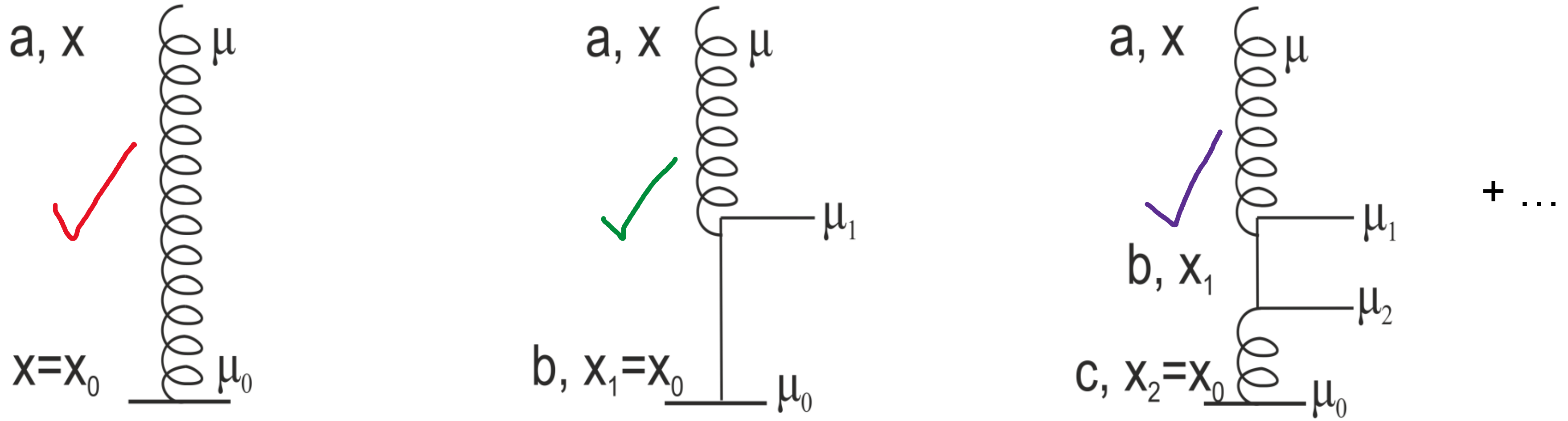
[Hautmann et all., JHEP 01 (2018) 070, 1708.03279]

Recap of PB TMDs

Iterative form of the PB evolution equation:

$$\widetilde{\mathbf{A}_\mathbf{a}}(\mathbf{x}, \mathbf{k}_\perp, \boldsymbol{\mu}^2) =$$

$$\widetilde{\mathbf{A}_\mathbf{a}}(\mathbf{x}, \mathbf{k}_\perp, \boldsymbol{\mu}_0^2)\, \Delta_\mathrm{a}(\boldsymbol{\mu}^2) + \sum_\mathrm{b} \int_{ln\mu_0^2}^{ln\mu^2} d \ln \boldsymbol{\mu}_1{}^2 \times \frac{\Delta_\mathrm{a}(\boldsymbol{\mu}^2)}{\Delta_\mathrm{a}(\boldsymbol{\mu}_1{}^2)} \int_\mathbf{x}^{\mathbf{z}_\mathbf{M}} \mathbf{dz}\, \mathbf{P}_{\mathbf{ab}}^{\mathbf{R}}(\, \mathbf{z}, \boldsymbol{\alpha}_\mathbf{s}(\boldsymbol{q}_\perp))\Delta_{\boldsymbol{b}}(\boldsymbol{\mu}_1{}^2) \times \widetilde{\mathbf{A}_\mathbf{b}}\left(\frac{\mathbf{x}}{\mathbf{z}}, \mathbf{k}_\perp + (\mathbf{1} - \boldsymbol{z})\boldsymbol{\mu}_1, \boldsymbol{\mu}_0{}^2\right) + \ldots$$



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:

Color coherence phenomena:

- Angular ordering of the soft gluon emissions

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

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

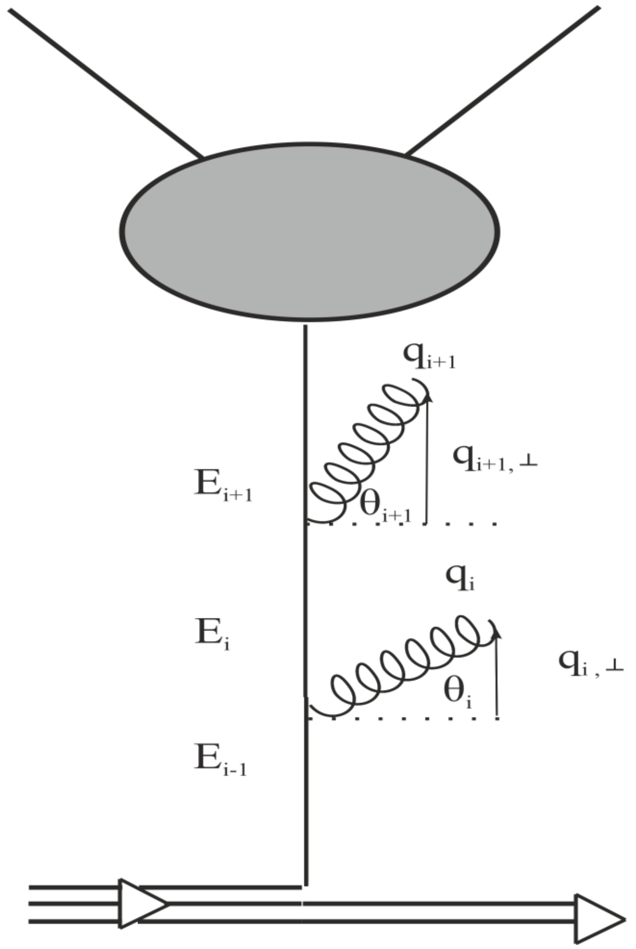
$$q_{\perp,i}^2 = (1 - z_i)^2\ \mu_i'^2$$

- The **argument of $\boldsymbol{\alpha_s}$** should be $\boldsymbol{q_\perp^2}$

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

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

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



Fixed and dynamical resolution scale

- **Fixed z_M:**
  - μ independent

$$z_M = 1 - \epsilon$$

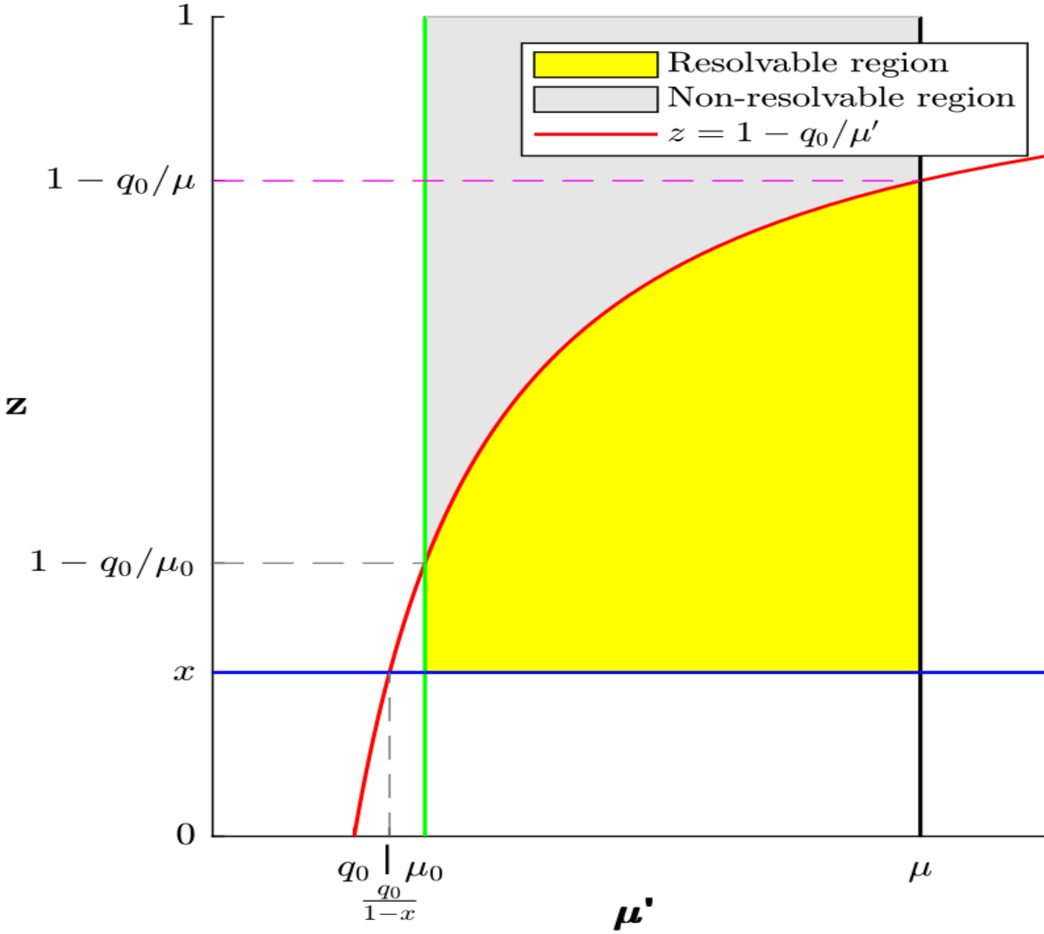
where ϵ is small: 10^{-3}, 10^{-4}, 10^{-5},...

- **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^R_{ab}: resolvable region

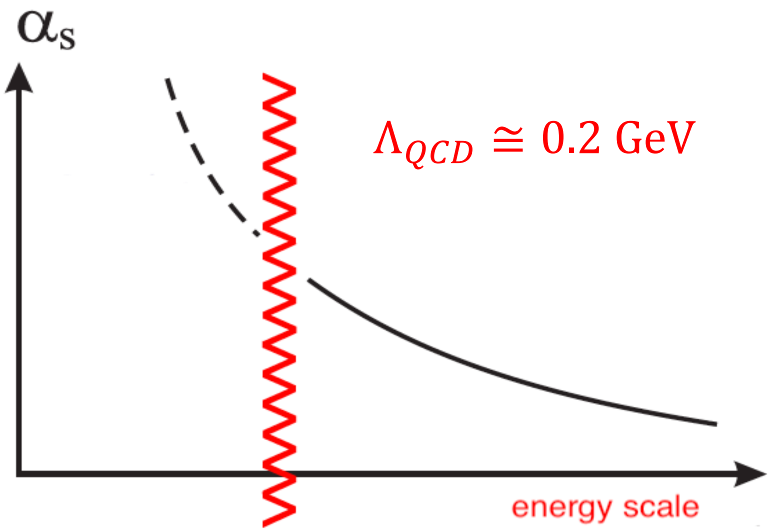


[Hautmann, Keersmaekers, Lelek, van Kampen NuclPhysB (2019) 114795,1908.08524]

Dynamical resolution scale

The Condition on q_0 of $$\mathbf{z_M = 1 - \left(\frac{q_0}{\mu'}\right)}$$

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



PB TMD fits at NLO with fixed zmax

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:

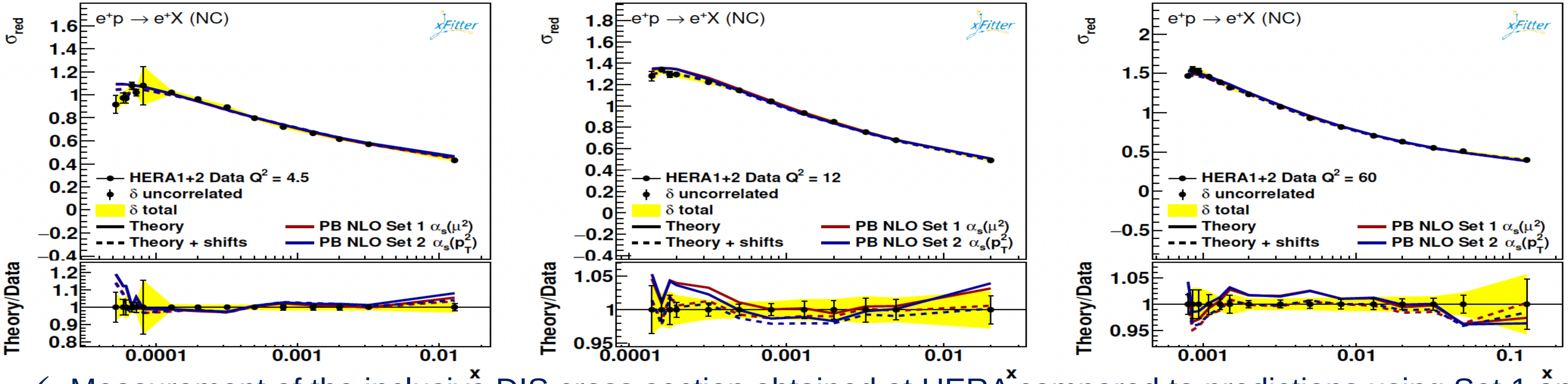
Two scenario
- Set 1 ⟶ $\alpha_s(\mu'^2)$
- Set 2 ⟶ $\alpha_s(q_\perp^2) = \alpha_s((1-z)^2\mu'^2)$

- **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	χ^2/d.o.f
$\mu_0^2 = 1.9$ GeV^2	1363.37	1131	1.21
PB NLO Set 2 $\alpha_s(q_{t\,i}^2)$			
	χ^2	d.o.f	χ^2/d.o.f
$\mu_0^2 = 1.4$ 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

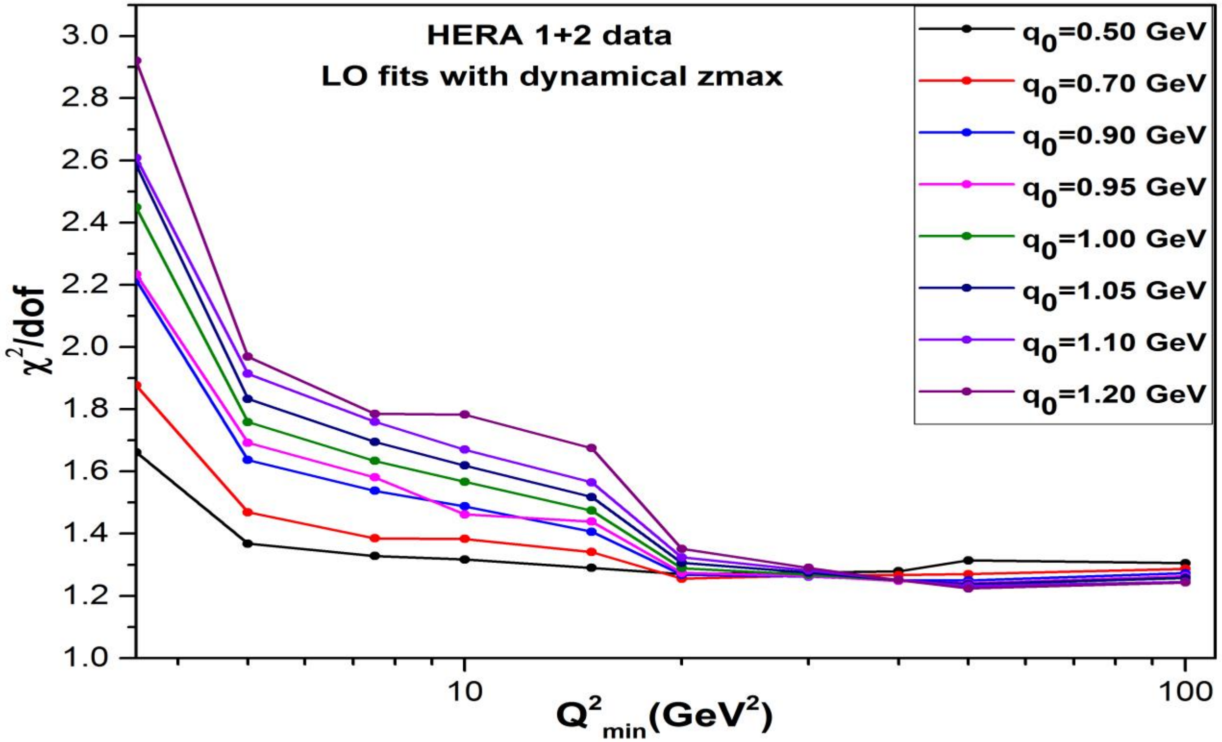
New study

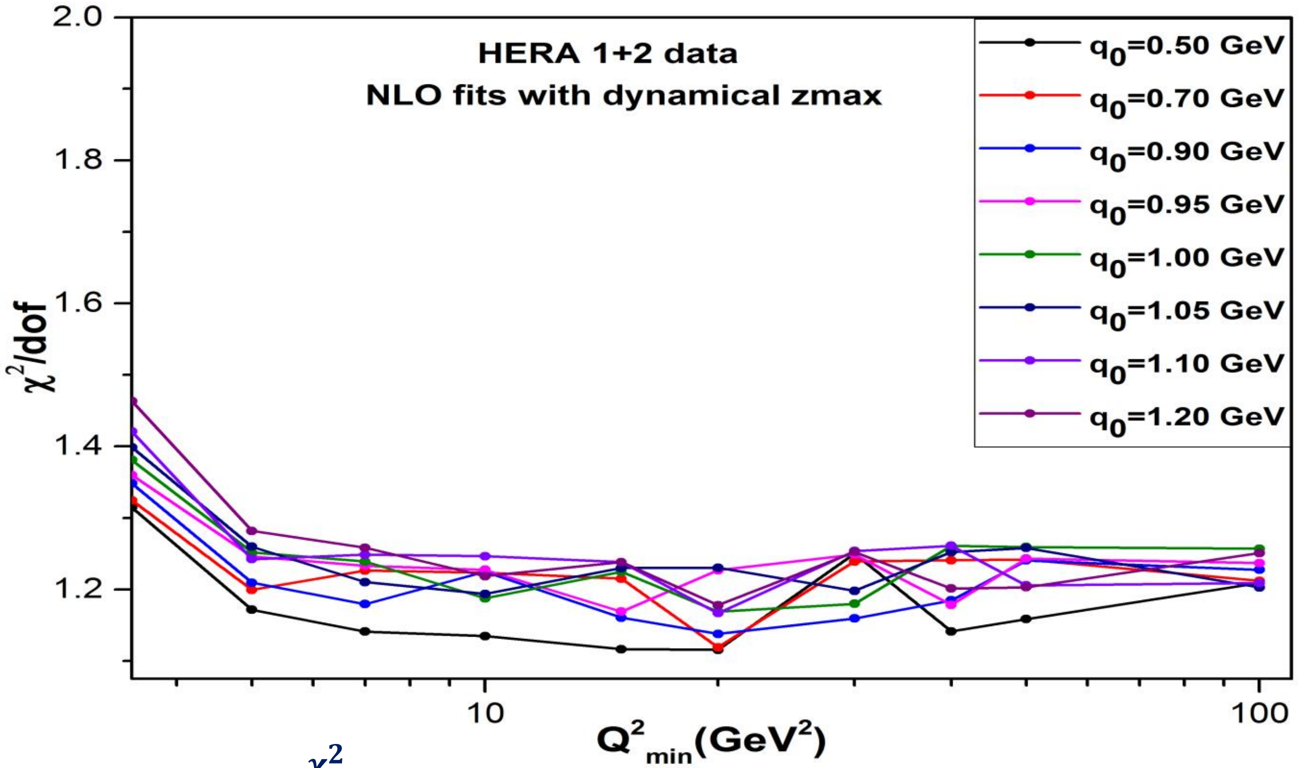
From fixed resolution scale to dynamical resolution scale

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

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 $\mathbf{q_0}$ values





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

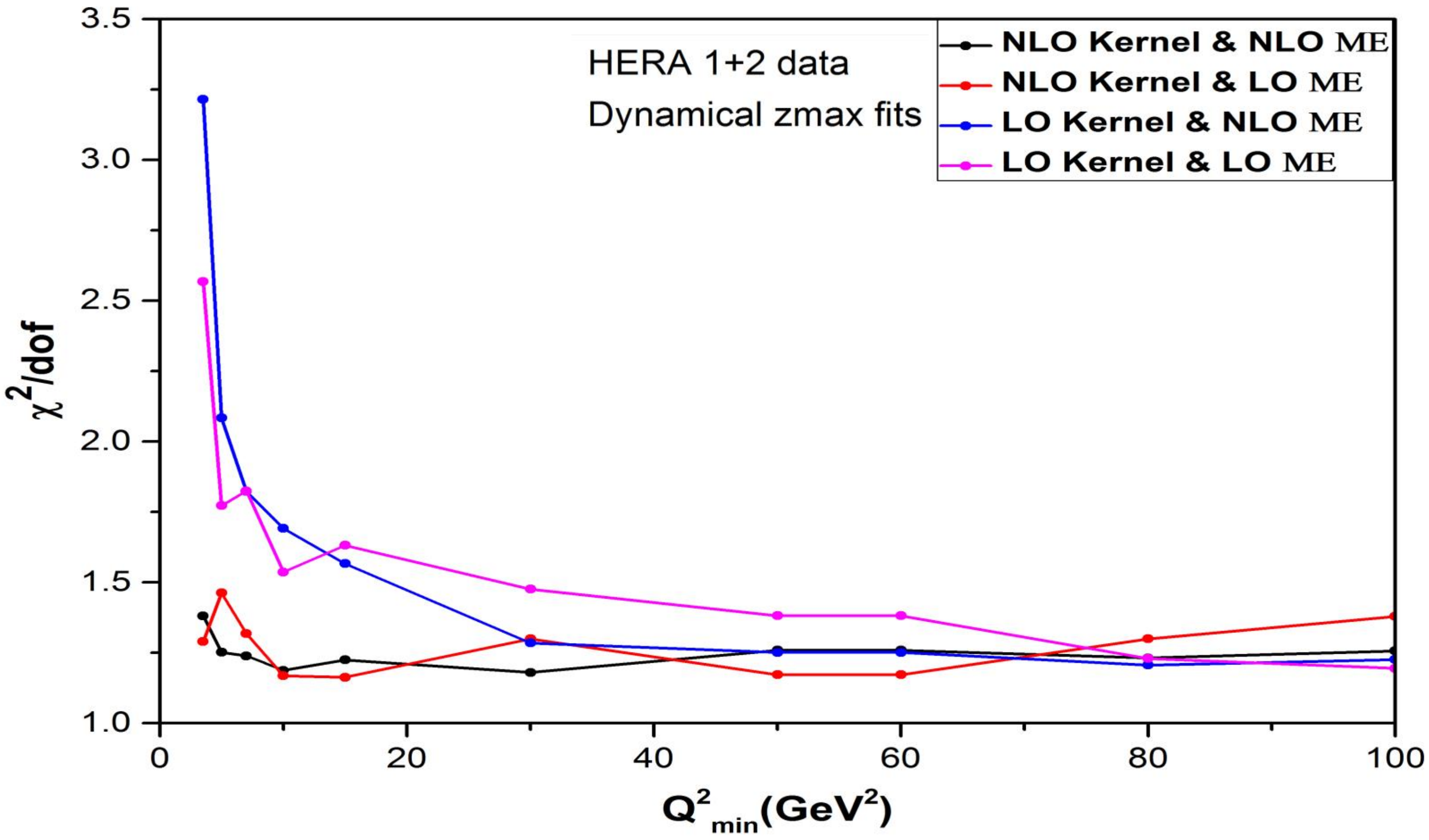
The difference between LO and NLO

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

For q_0=1.0 GeV

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

- Which part of the kernel is responsible?

$P_{ab}(z,\mu^2)$? or α_s?

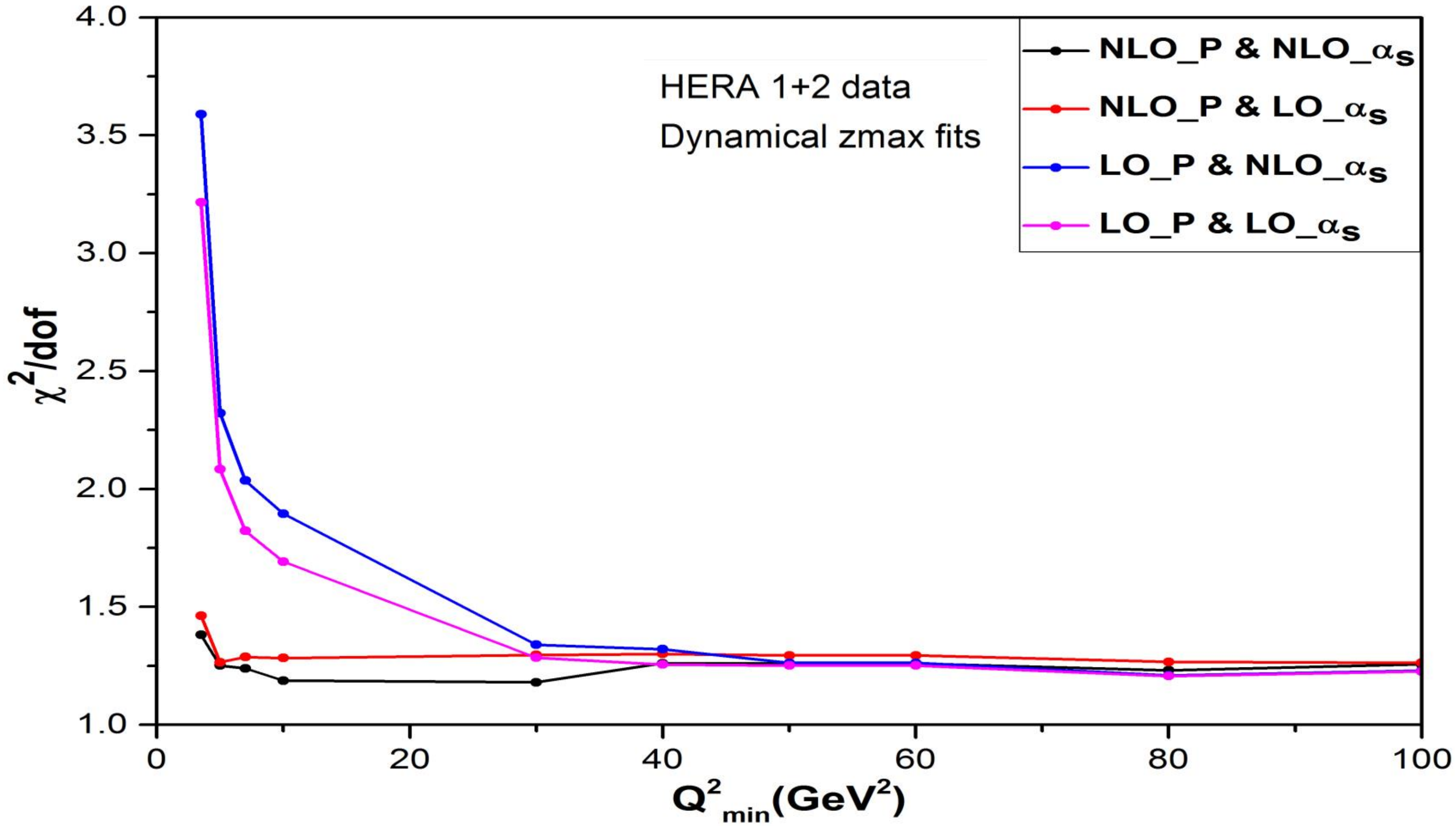
4 states for this purpose:

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..!

For NLO ME

For q_0=1.0 GeV



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

- **For high values of q_0(e.g, $[1.0\ \mathrm{Gev}, 1.2\ \mathrm{Gev}]$) 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?

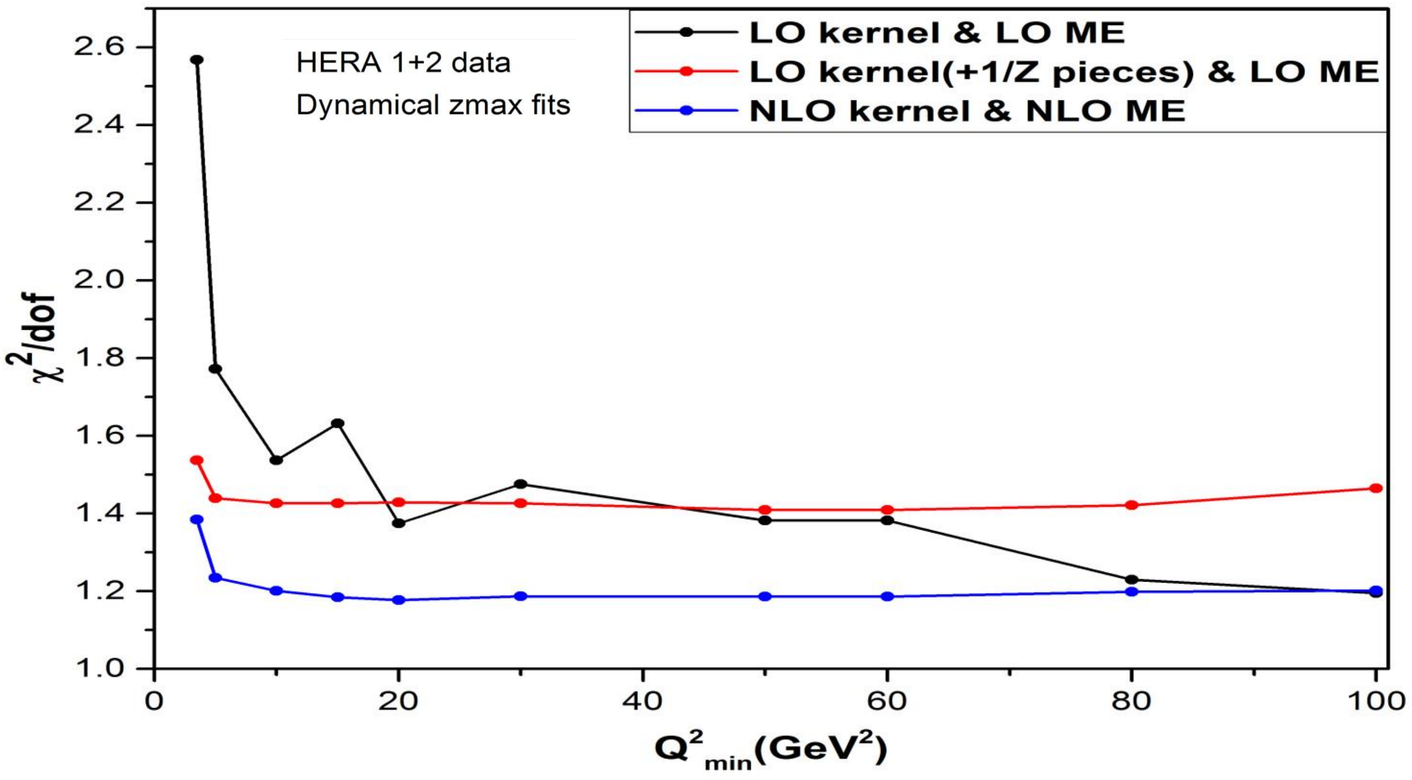
Let's check it!

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

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

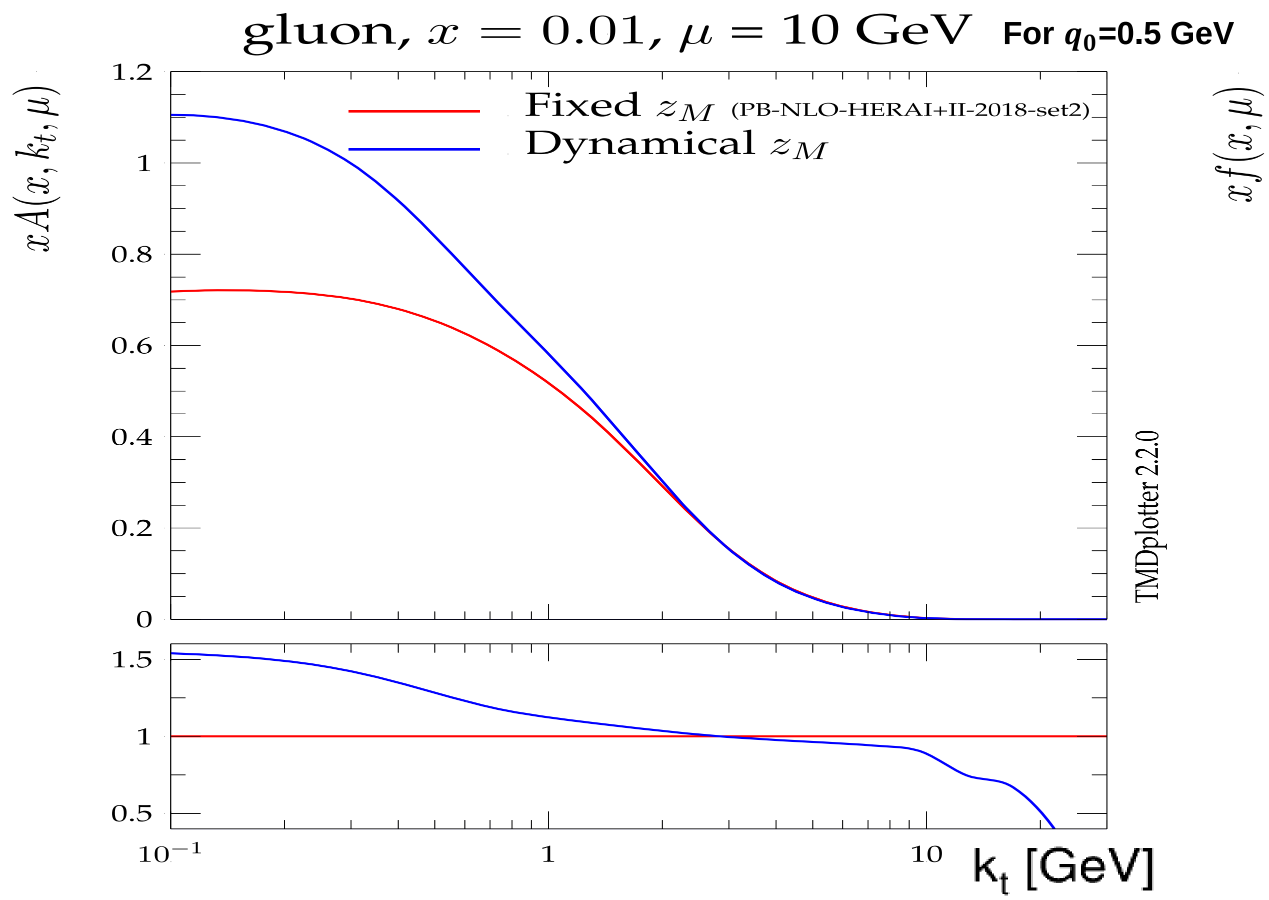


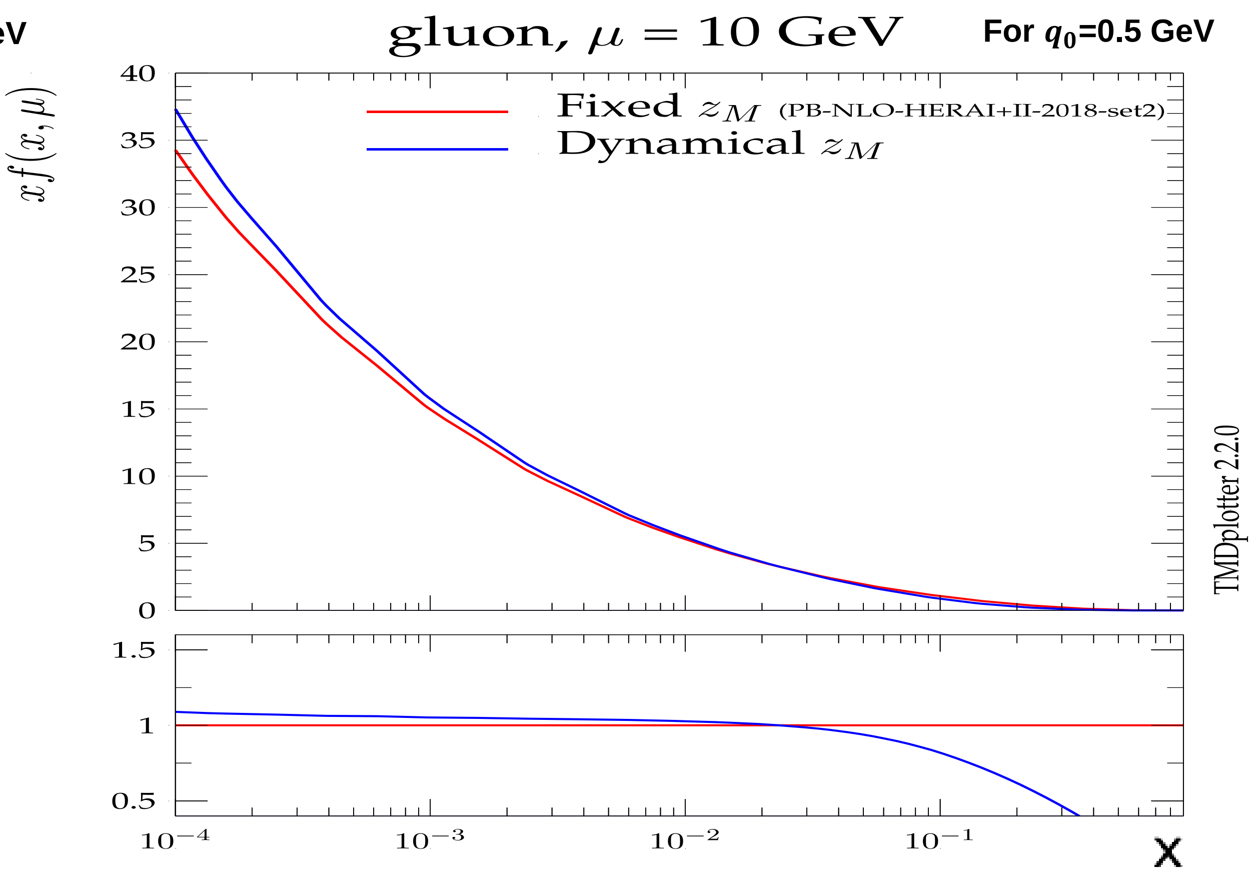
- ✓ In NLO we have an extra (1/z) pieces in the quark channels compared with LO which is responsible for this difference!
- ✓ With this piece we are describing data well! Amount of $\frac{\chi^2}{\mathrm{dof}}$ is reasonably good!

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

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

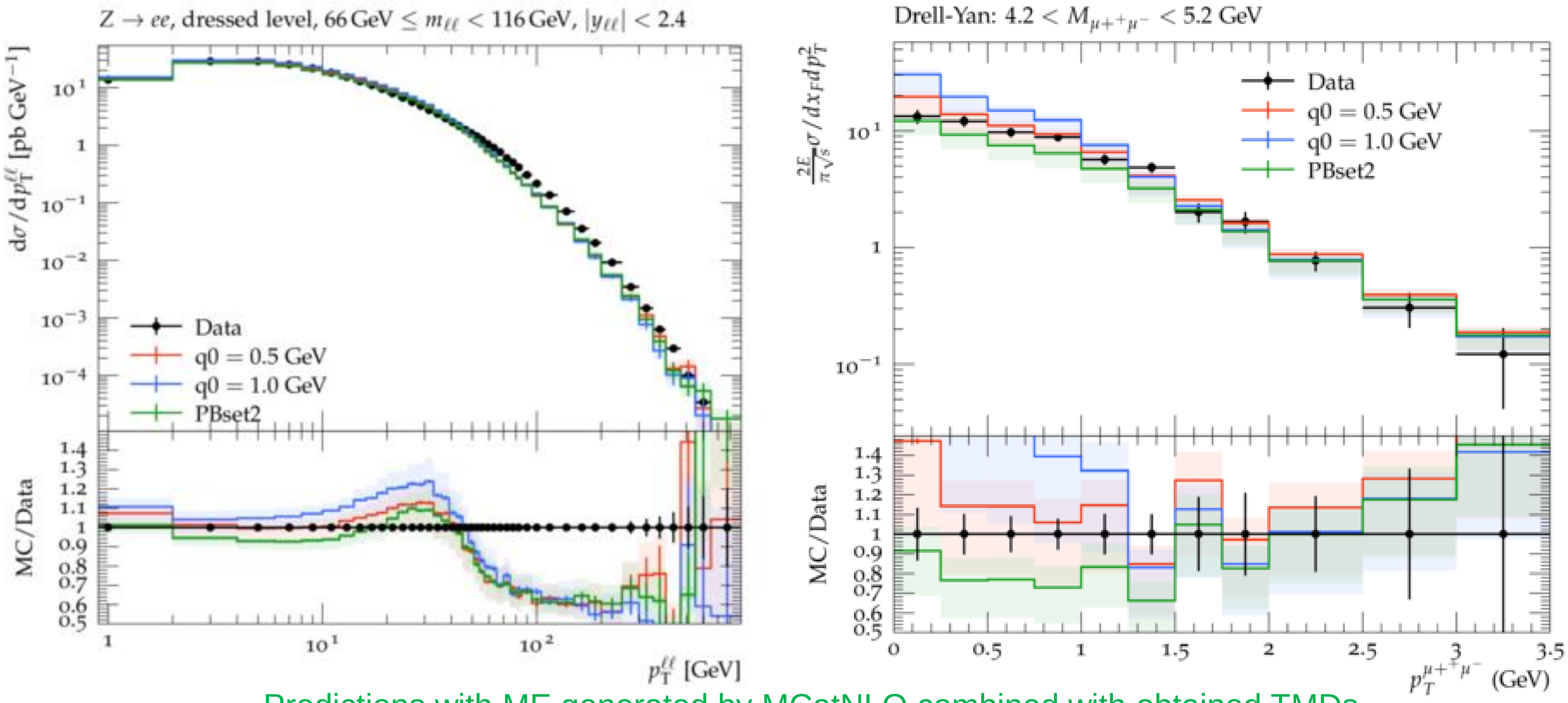
Set 2: fixed zmax & $\alpha_s(q_\perp^2) = \alpha_s((1-z)^2\mu'^2)$





✓ 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



Predictions with ME generated by MCatNLO combined with obtained TMDs.

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

5 FLNS

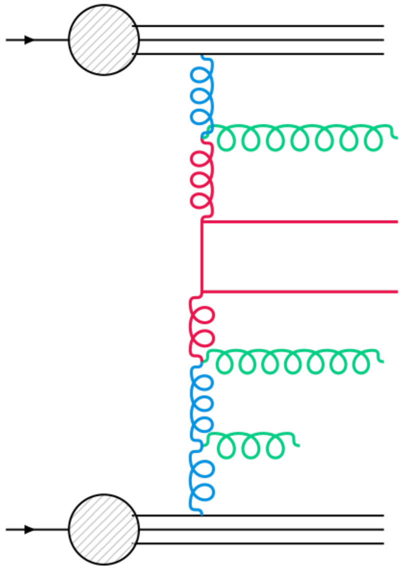
- Full coupled evolution with all flavours & $\alpha(M_Z^{nf=5})$=0.118
- HERAPDF parametrization form
- Using full HERAI+II inclusive DIS data
- chi2/dof=1.21

[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

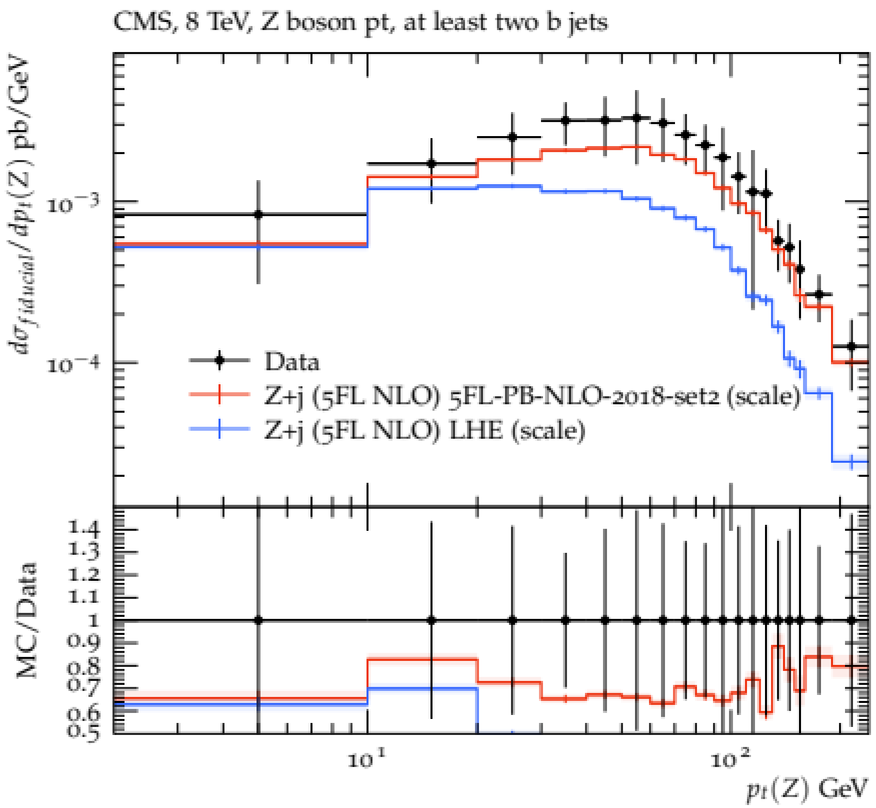
Parton shower following TMDs for intial state
- 5FL & 4FL PB-TMDs included in the Cascade3

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

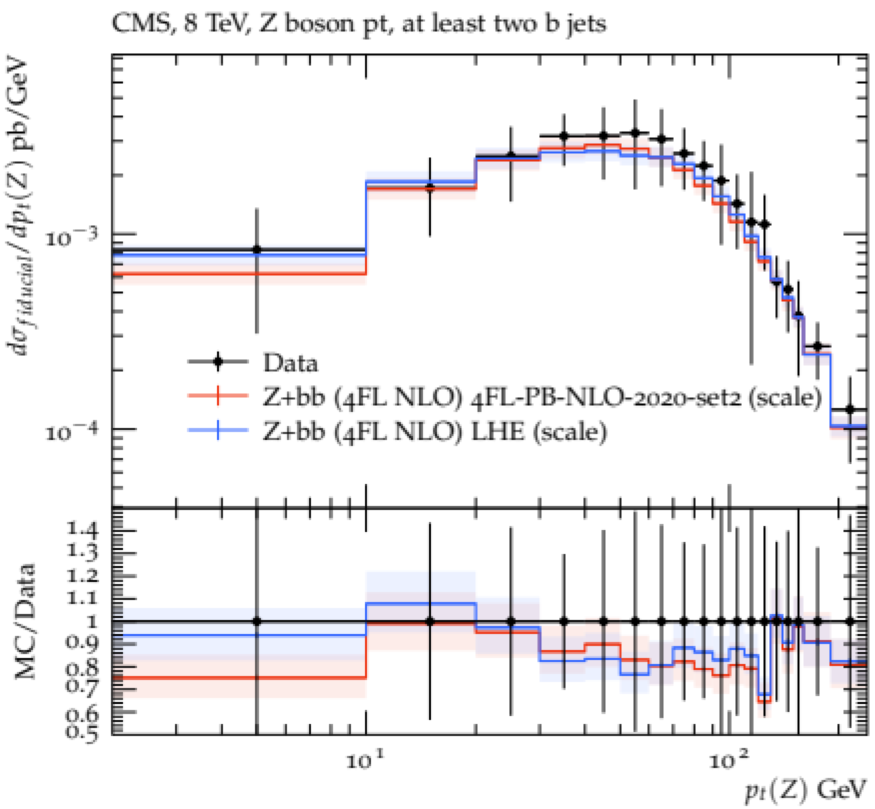
Z+ $b\bar{b}$ as a function of p_t (Z)

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

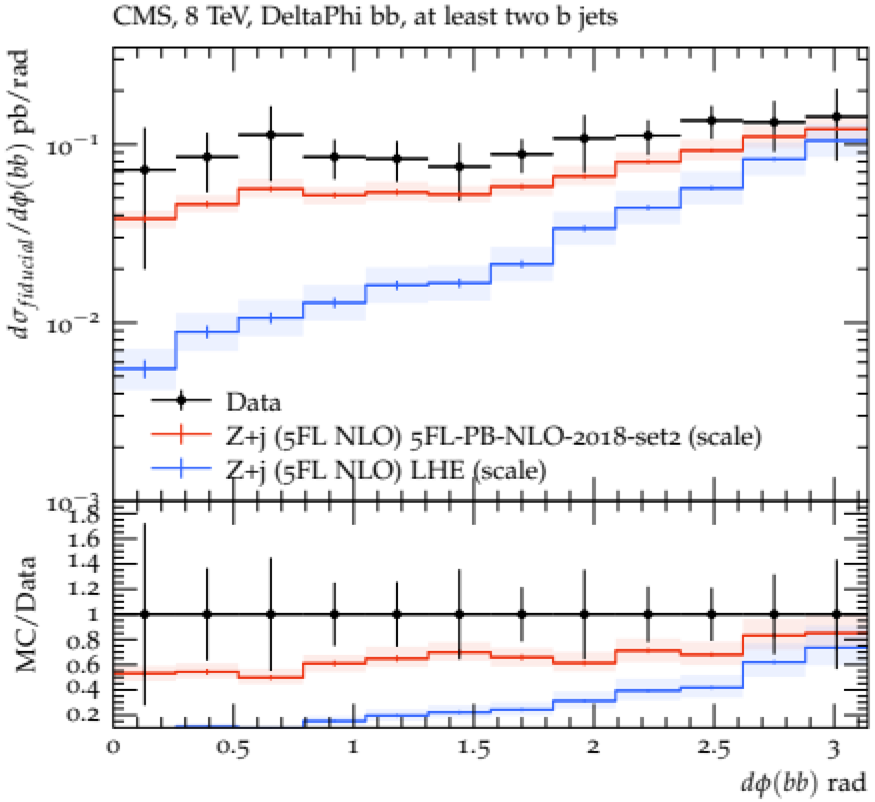


the full prediction + the result of using only the LHE files are shown.

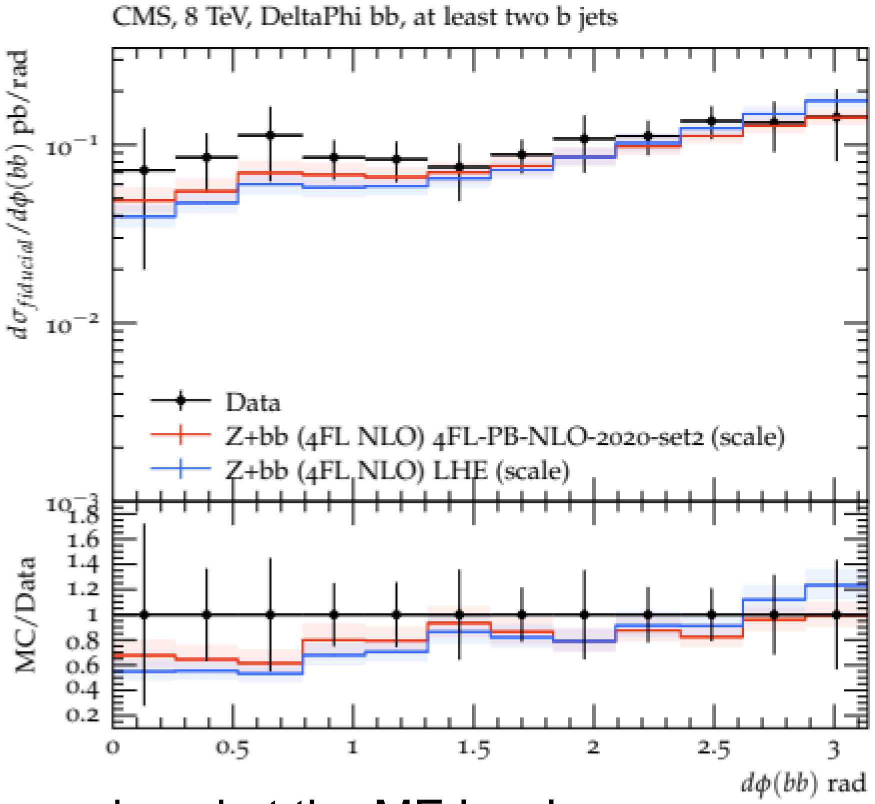
Z+bb as a function of Δφ ($b\bar{b}$)

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

5 FLNS



4 FLNS

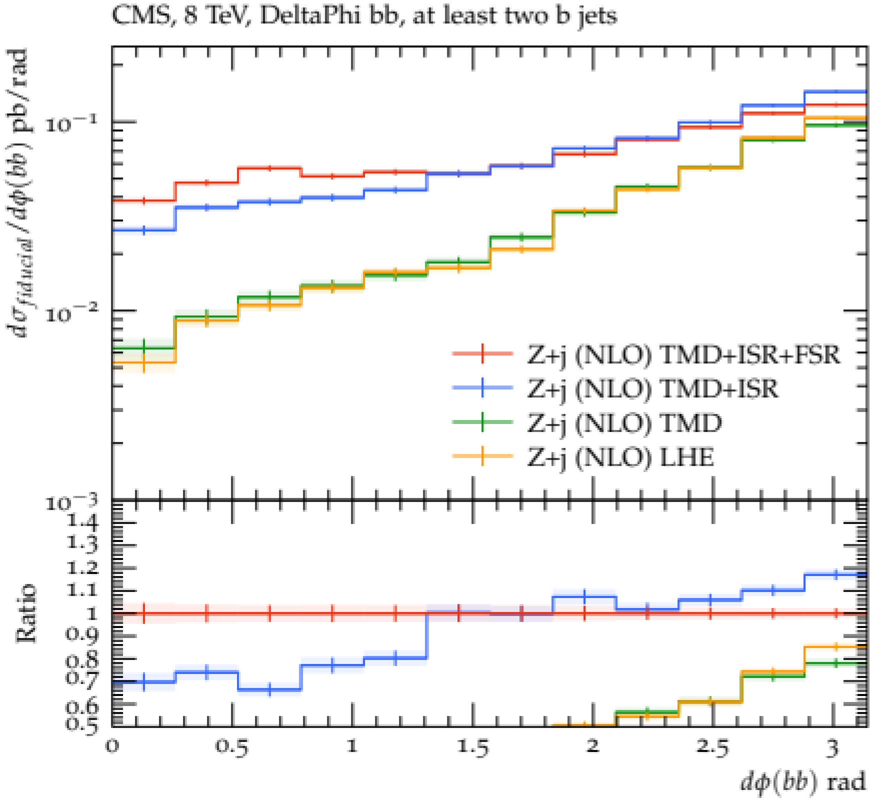


4FL : both b partons are already produced at the ME level

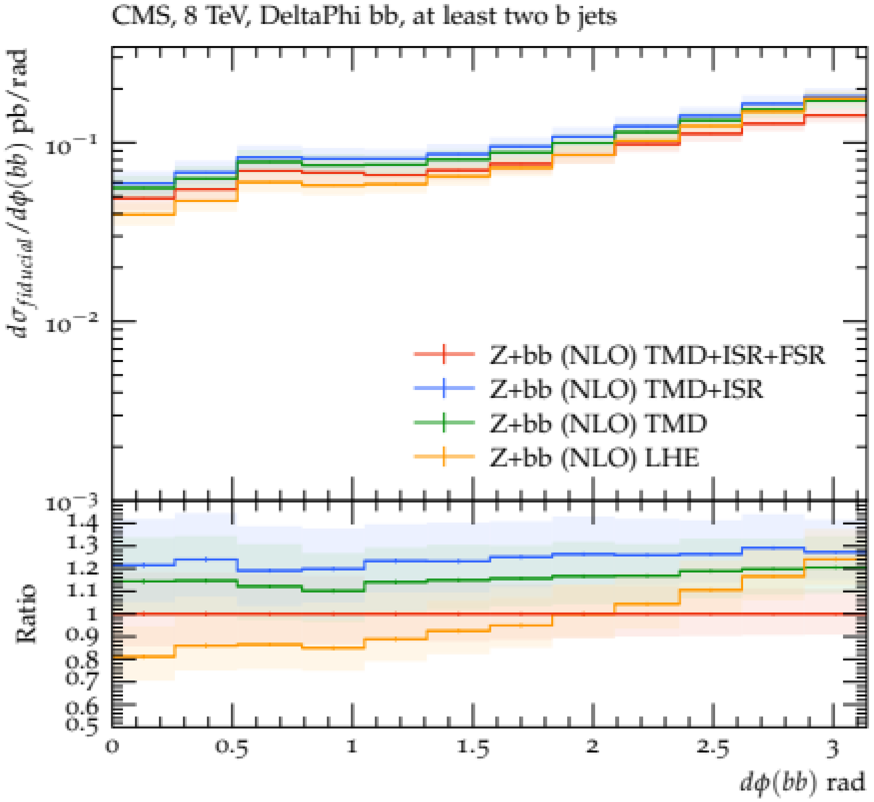
5FL : $b\bar{b}$ must be simulated in the parton shower.

Breakdown of the different contributions to quantify their roles

5 FLNS



4 FLNS



4FL: weakly depends on PB-TMD/parton shower
5FL: significant contribution from TMD parton shower

Summary

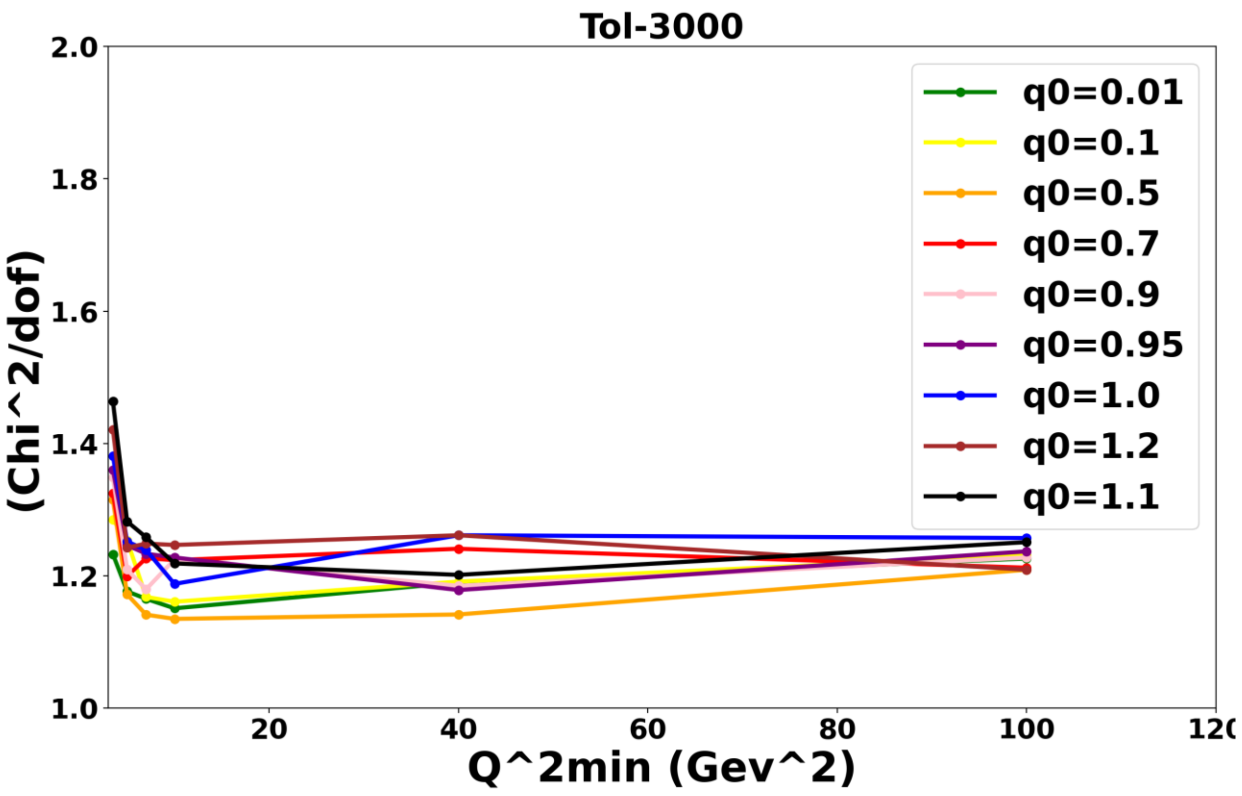
- **PB TMD fits at NLO with dynamical zmax for the first time!**
- **For PB-TMD fit to HERA data with dynamical zmax, we obtain a reasonably good $\frac{\chi^2}{dof}$ at NLO!**
- **The difference between LO and NLO fits is mostly due to (1/z) pieces in quark channel in NLO splitting functions!**
- **The 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!**

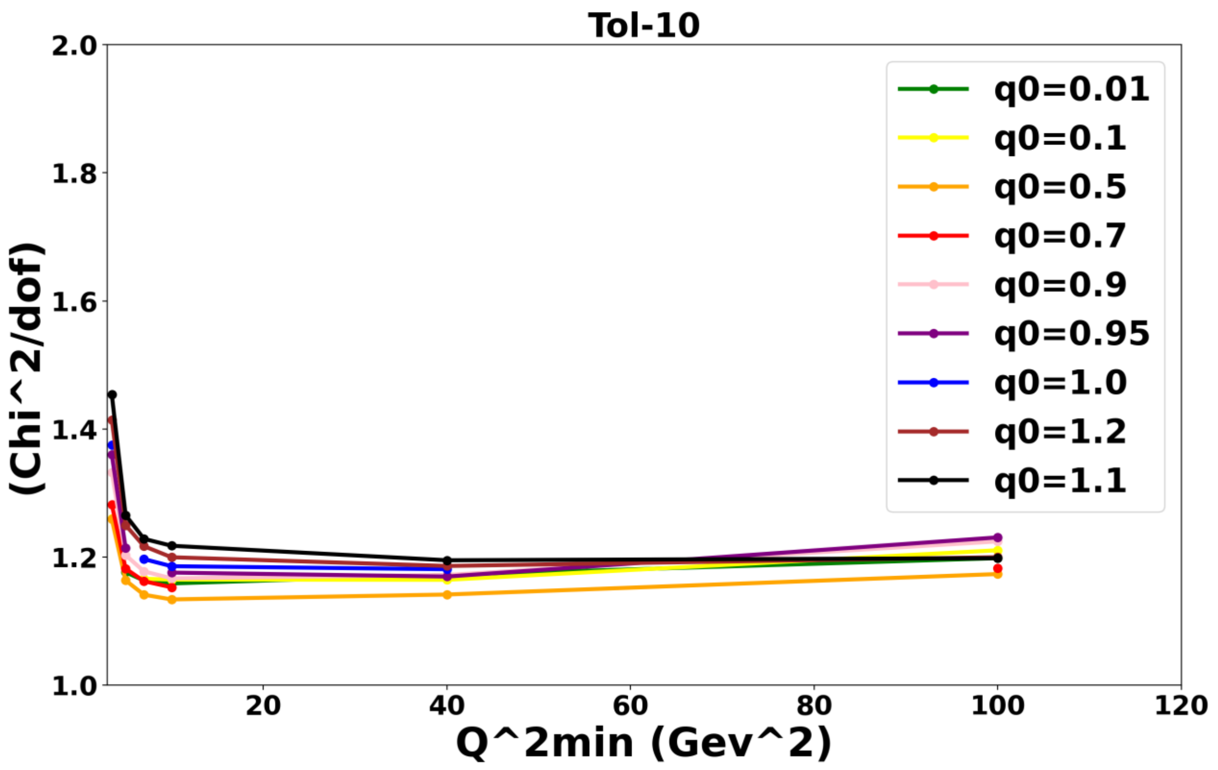
- **The 4FL and 5FL PB-TMD distributions used to calculate Z + bb production**
  - Good agreement with measurements obtained by the CMS collaboration
  - The evolution of the PB-TMD parton densities as well as in the PB-TMD parton shower is checked.

Thank you …

BACK UP …

Back up…


Tol-3000
(Chi^2/dof)
Q^2min (Gev^2)
2.0
1.8
1.6
1.4
1.2
1.0
20
40
60
80
100
120
q0=0.01
q0=0.1
q0=0.5
q0=0.7
q0=0.9
q0=0.95
q0=1.0
q0=1.2
q0=1.1


Tol-10
(Chi^2/dof)
Q^2min (Gev^2)
2.0
1.8
1.6
1.4
1.2
1.0
20
40
60
80
100
120
q0=0.01
q0=0.1
q0=0.5
q0=0.7
q0=0.9
q0=0.95
q0=1.0
q0=1.2
q0=1.1

PB TMD fits at NLO with dynamical zmax: