Developing the Parton Branching TMD Evolution: heavy quark thresholds and QED interactions

Sara Taheri Monfared

Deutsches Elektronen-Synchrotron (DESY)

REF 2020

On behalf of
F. Hautmann, H. Jung, T. Wening

Outline

1. **Recap of Parton Branching method**
2. **Determination of 4FL NLO PDFs and its application**
3. **Determination of Photon TMD and its application**

Recap of Parton Branching method

- Including the Δ_s in to the differential form of the DGLAP eq.

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

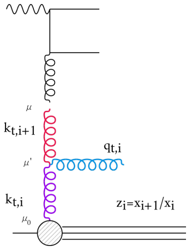
- Integral form with a very simple physical interpretation:

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

- Solve integral equation via iteration:

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

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



- iterating with second branching and so on to get the full solution

PDFs from PB method: fit to HERA data

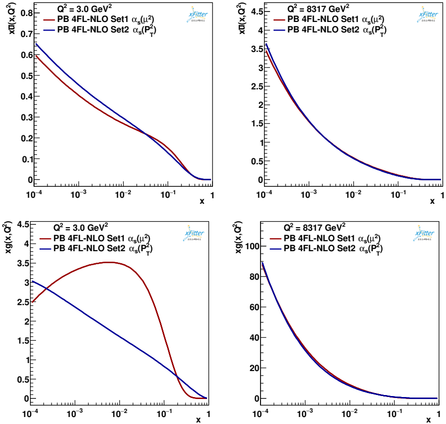
- A kernel obtained from the MC solution of the evolution equation for any initial parton
- Kernel is folded with the non-perturbative starting distribution

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

- Fit performed using xFitter frame (with collinear Coefficient functions at both **LO & NLO**)
- LO PDFs are of especial interest for MC event generators, based on LO ME + PS.
  - full coupled-evolution with all flavors
  - using full HERA I+II inclusive DIS (neutral current, charged current) data
  - $3.5 < Q^2 < 50000$ GeV^2 & $4.10^{-5} < x < 0.65$
- Can be easily extended to include any other measurement for fit.

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

Standard 4FL-NLO full fit with different scale in α_s



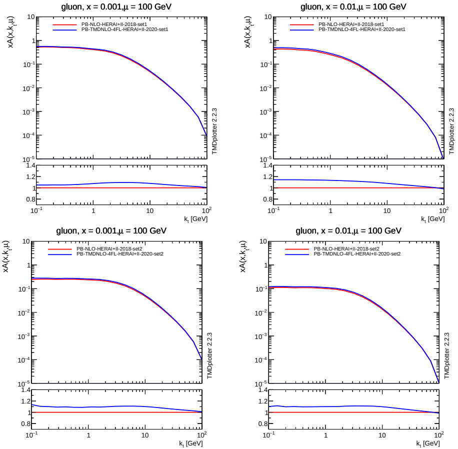
- very different gluon distribution at small Q^2
- the differences are washed out at higher Q^2

- Set1-$\alpha_s(\mu^2) \rightarrow \chi^2/dof = 1.26$
- Set2-$\alpha_s(p_T^2) \rightarrow \chi^2/dof = 1.25$

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right),$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},$$
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1 + D_{\bar{U}}x),$$
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.$$

- no b quark in the evolution
- $\alpha_s(m_Z)$ adjusted
- mass threshold for charm
- m_c=1.47 GeV

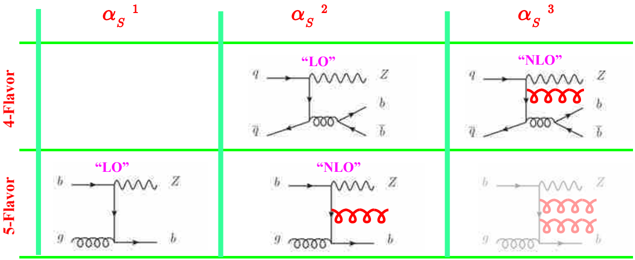
k_t behavior at 4FL-NLO and 5FL-NLO



- 4-FL gluon is larger than 5-FL gluon at small kt region.
- at small k_t $\rightarrow$ starting distribution
- at large k_t $\rightarrow$ the differences are washed out due to having more splittings.

The basic contribution to Bottom Flavor Production

Fred Olness's talk-U Manchester-22 April 2016



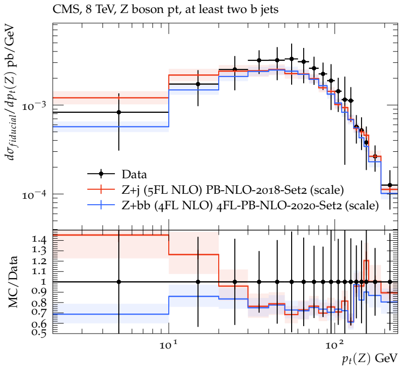
- data in the Z+ $\geq$ 1 b-jet and Z+ $\geq$ 2 b-jets cases are better described by 5FL prediction and 4FL prediction, respectively.

application: PB-TMD shower & MC@NLO : 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

→ see talk by Luis Ignacio Estevez (DESY) : 8th Dec; Breakout Room 7

- 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



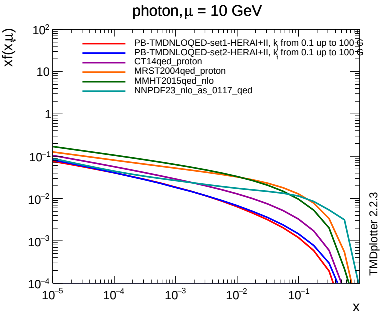
- p_t spectrum of Z boson is nicely described with both 4FL and 5FL schemes

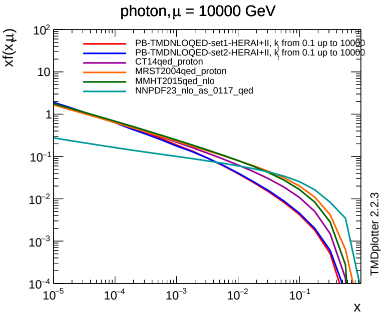
Is it possible to generate photon TMDs using the parton branching method?

The Transverse Momentum Dependent PDF of the Photon

We generated photon TMDs using the parton branching method

- since $\alpha \sim \alpha_s^2$: NLO QCD splitting are used
- no intrinsic photon density
- running LO-QED coupling with matching at quark-mass thresholds
- fit to HERA data

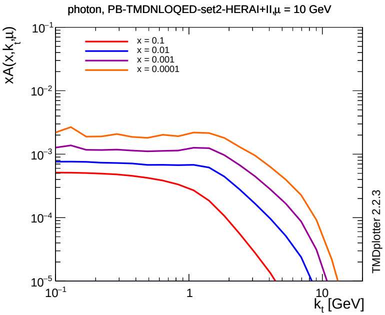


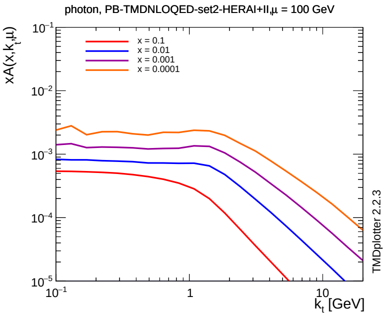


Thomas Wening master thesis, TMD PDF for the Photon, https://bib-pubdb1.desy.de/record/449805

Photon TMD

Parton Branching can be used to generate photon TMDs.

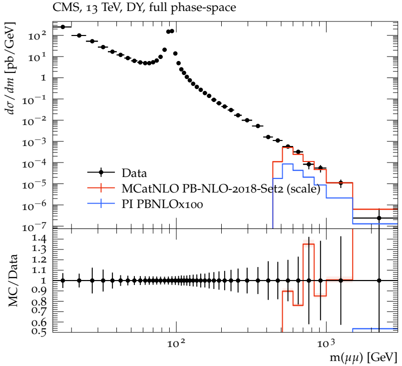




- fluctuation at low k_t: To generate small k_t, no branching at high t (unlikely) $\Rightarrow$ statistical fluctuations
- Increasing x $\Rightarrow$ decreases TMD photon density: Region for a resolvable branching $z \in [x, z_m]$

Photon TMD application: high mass DY spectrum

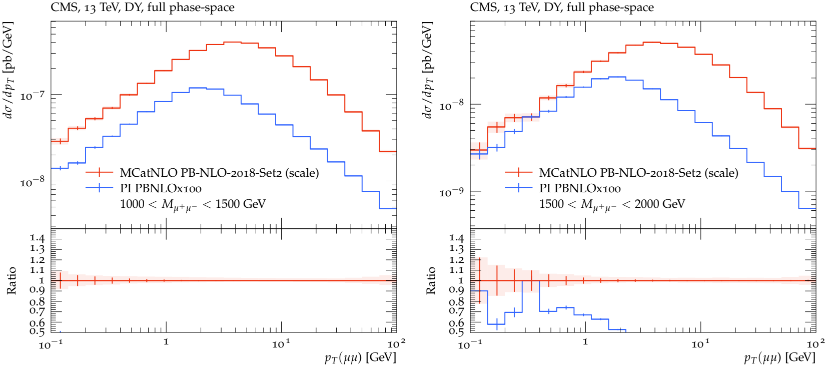
Measurement of the differential Drell-Yan cross section in proton-proton collisions at 13 TeV (CMS-2018-I1711625)



- PI is multiplied by 100.
- large mass region is well described by PB method.
- The fraction of PI process is generally less than 1%.

Photon TMD application: p_T spectrum at large DY mass

Measurement of the differential Drell-Yan cross section in proton-proton collisions at 13 TeV (CMS-2018-I1711625)



- The mass spectrum is reasonable.
- The p_T spectrum of PI process is different from standard DY.

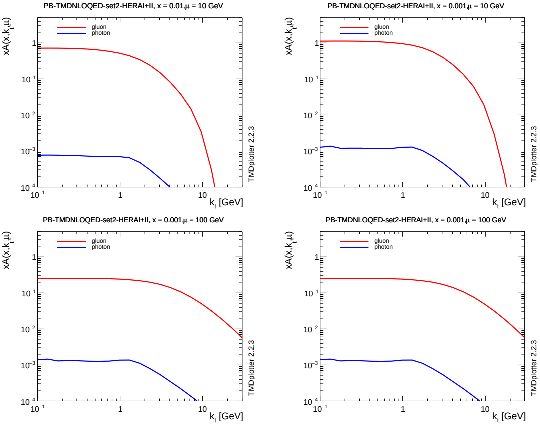
Conclusion

- PB method to solve DGLAP equation at LO, NLO, NNLO.
  - advantages of PB method (angular ordering)
- method directly applicable to determine k_t distribution (as would be done in PS)
  - TMD distributions for all flavors determined at NLO for 4FL and 5FL
  - application to pp processes: Z+b-jets measurement is used to study TMD and TMD showers in details. 4FL & 5FL results including TMD+IPS+FSP do agree.
- NEW: collinear and TMD photon
  - The photon density is a necessary step to also implement the W,Z density.
  - application to pp processes: mass and p_T of high mass DY pairs

Thank you

Backup

k_t behavior of gluon & photon



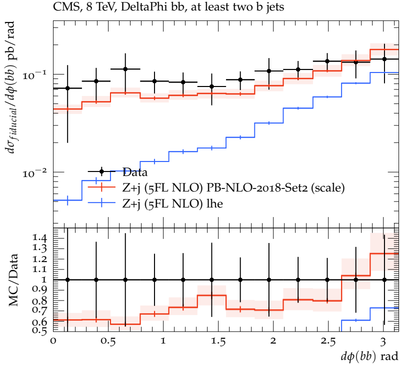
- gluon TMD is higher than photon TMD:
- gluon TMD and photon TMD are similar at high k_t and not at small k_t

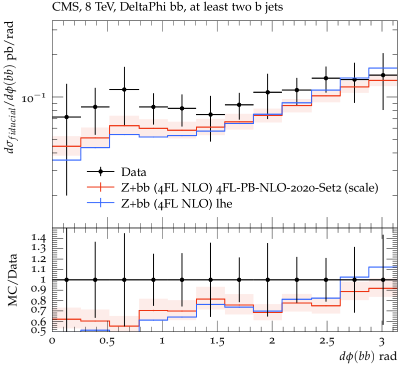
PDFs from PB method: fit to HERA data

- two angular ordered sets with different argument in α_s (either μ or q_t)
- q_{cut} in, $\alpha_s(max(q^2_{cut}, |q^2_{t,i}|))$, to avoid the non-perturbative region, $|q^2_{t,i}| = (1 - z_i)^2 \mu_i^2$
- for both LO & NLO:
  - $\mu_0^2 = 1.9$ GeV^2 for set1 (as in HERAPDF)
  - $\mu_0^2 = 1.4$ GeV^2 for set2 (the best χ^2/dof)
- fits to HERA measurements performed using χ^2/dof minimization
- the experimental uncertainties defined with the Hessian method with $\Delta\chi^2 = 1$.
- the model dependence obtained by varying charm and bottom masses and μ_0^2.
- the uncertainty coming from the q_{cut} in set2

	Central value	Lower value	Upper value
PB Set1 μ_0^2 (GeV^2)	1.9	1.6	2.2
PB Set 2 μ_0^2 (GeV^2)	1.4	1.1	1.7
PB Set 2 q_{cut} (GeV)	1.0	0.9	1.1
m_c (GeV)	1.47	1.41	1.53
m_b (GeV)	4.5	4.25	4.75

Z+2b jets: comparison between 5FL & 4FL

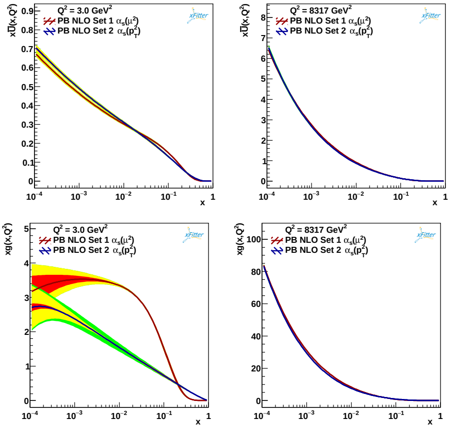




- ME calculation at 5FL is Z+1jet NLO
- PS is important in the 5-FL scheme

- ME calculation at 4FL is Z+2jet NLO
- PS and TMD has very little impact in 4-FL scheme

Standard 5FL-NLO full fit with different scale in α_s



- Set1-$\alpha_s(\mu^2) \rightarrow \chi^2/dof = 1.21$
- Set2-$\alpha_s(p_T^2) \rightarrow \chi^2/dof = 1.21$

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right),$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},$$
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1 + D_{\bar{U}}x),$$
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.$$

- fits are as good as HERAPDF2.0.
- very different gluon distribution obtained at small Q^2
- the differences are washed out at higher Q^2

A. Martinez, P. Connor, H. Jung, A. Lelek, R. Žlebčík, F. Hautmann and V. Radescu, Phys. Rev. D **99**, no. 7, 074008 (2019).