Transverse Momentum Dependent and collinear densities based on Parton Branching method

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- Phys. Lett. B **817** (2021), 136299 [arXiv:2102.01494]
- arXiv: 2106.09791

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ISMD2021

Outline

Preface: The ansatz

TMDs-what is it?

- TMDs : Transverse Momentum Dependent parton distributions
- extended collinear PDFs : transverse momentum effects from intrinsic k_t + evolution

Why TMD?

- small transverse momentum phenomena
- small-x phenomena

New approach: Parton Branching (PB) method

- evolution of TMDs and collinear PDFs at LO, NLO & NNLO
- automatically contain soft gluon resummation (at NLL identical to CSS approach)
- determination of TMDs from the fully exclusive solution
- unique feature : backward evolution fully determines the TMD shower

Today's plan

- How to obtain PB TMDs?
- How to use PB TMDs to obtain predictions?

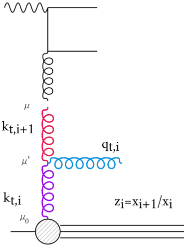
Phys. Lett. B **772** (2017), 446-451
JHEP **01** (2018), 070
CASCADE3 arXiv 2101.10221

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

$$f_a(x,\mu^2) = f_a(x,\mu_0^2)\Delta_s(\mu^2) + \sum_b \int_x^{z_M} \frac{dz}{z} \int_{\mu_0}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \cdot \frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)} P^{(R)}(z) f_b(\frac{x}{z},\mu'^2)$$

- the solution of the integral equation has the form of a Neumann series with the following terms:

$$f_0(x,\mu^2) = f(x,\mu_0^2)\ \Delta_s(\mu^2)$$
$$f_1(x,\mu^2) = f(x,\mu_0^2)\ \Delta_s(\mu^2)$$
$$+ \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)} \int \frac{dz}{z} P^R(z) f(x/z,\mu_0^2)\Delta(\mu'^2)$$



- iterating with second branching and so on to get the full solution
- PB evolution generates every single branching : all kinematic variables and combination between them can be calculated at every step

$$f_{0,b}(x,\mathbf{k}^2_{\mathbf{t},0},\mu_0^2) = f_{0,b}(x,\mu_0^2)\cdot \exp(-|k^2_{\mathrm{T},0}|/\sigma^2)\quad \sigma^2 = q_0^2/2\ \ \&\ q_0 = 0.5\ GeV$$

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

Convolution of kernel with starting distribution : a new kernel for the TMD distributions

$$xf_a(x,\mu^2) = \int dx' \, \mathcal{A}_{0,b}(x') \cdot \frac{x}{x'} \, \tilde{\mathcal{A}}_a^b(\frac{x}{x'},\mu^2)$$
$$xf_a(x,\mathbf{k_t^2},\mu^2) = \int dx' \, \mathcal{A}_{0,b}(x',\mathbf{k_{t,0}}) \cdot \frac{x}{x'} \, \tilde{\mathcal{A}}_a^b(\frac{x}{x'},\mathbf{k_t^2},\mu^2)$$

Fit performed using xFitter frame (with collinear coefficient functions at NLO)
Phys. Rev. D **99** (2019) no. 7, 074008

5FLNS:

- full coupled evolution with all flavors & $\alpha_s(M_Z^{n_f=5}) = 0.118$
- HERAPDF parametrization form
- using full HERAI+II inclusive DIS data $(3.5 < Q^2 < 50000 \text{ GeV}^2 \ \& \ 4.10^{-5} < x < 0.65)$
- χ^2/dof=1.21

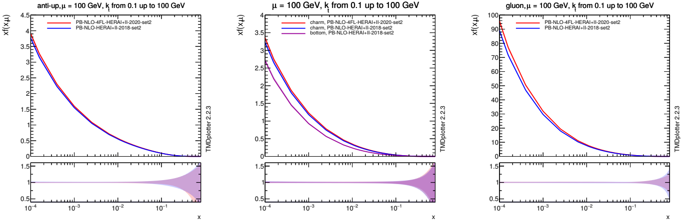
4FLNS:

- the same functional form & data as 5FL - parameters are re-fitted
- $m_b \to \infty$ & $\alpha_s(M_Z^{n_f=4}) = 0.1128$
- $\chi^2/dof = 1.25$

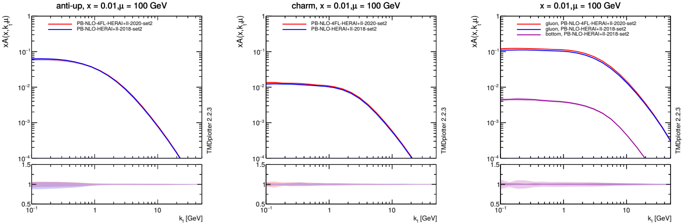
four- and five-flavour PB TMDs and corresponding parton showers

arXiv:2106.09791

The $\bar{u}$, charm & bottom and gluon 4FLVN and 5FLVN **collinear PDFs** versus x



The $\bar{u}$, charm, gluon & bottom 4FLVN and 5FLVN **TMDs** versus k_t



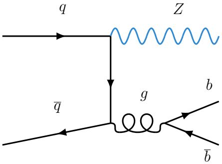
TMDs are plotted with TMDPLOTTER: arXiv:2103.09741

The hard processes calculation with the MADGRAPH5_aMC@NLO package :

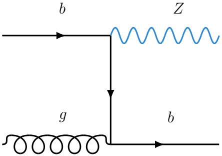
- 5FLVNS : Z + one parton process
  $pp \to l^+ \; l^- + \mathrm{j}, \; p = u, d, s, c, b, g, \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$
- 4FLVNS : $Z + q\bar{q}$ process
  $pp \to l^+ \; l^- + \; b\bar{b}, \; p = u, d, s, c, g, \bar{u}, \bar{d}, \bar{s}, \bar{c}$
- HERWIG6 subtraction terms

The PB-TMD parton shower implemented in CASCADE3 : *Eur. Phys. J. C* **81** (2021) 425

- the 5FLVNS and 4FLVNS PB-TMDs.

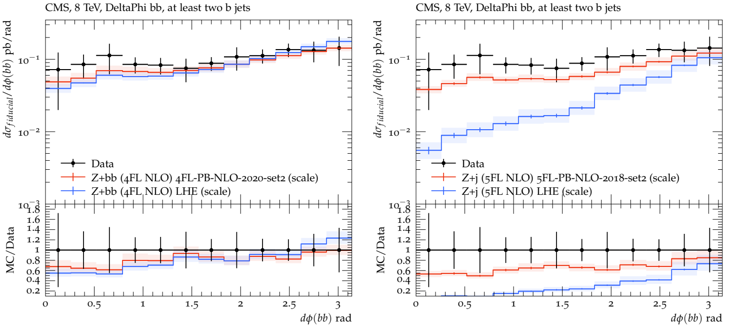


(a) $Z + b\bar{b}$ 4FLNS



(b) $Z + b$ 5FLNS

Differential cross section for $Z + b\bar{b}$ as a function of $\Delta\phi_{b\bar{b}}$ by CMS *Eur. Phys. J. C* **77** (2017) 751



- **4FL** : weakly depends on PB-TMD and parton shower
- **5FL** : significant contribution coming from parton shower

Very good consistency of both approaches

First determination of TMD photon densities

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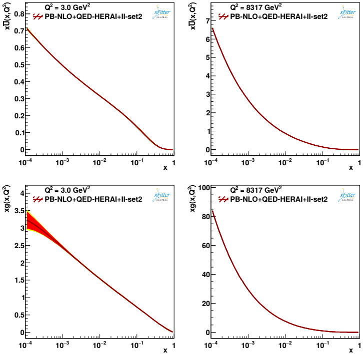
complete set of TMD and collinear photon densities over full phase space

- photon density appears when evolving parton distributions with QED corrections ($\alpha \sim \alpha_s^2$)
- photons generated by **perturbative** radiation using Parton Branching method
- QCD partons constrained by fit to HERA data



$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g},$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} \left(1 + E_{u_v} x^2\right),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}},$$

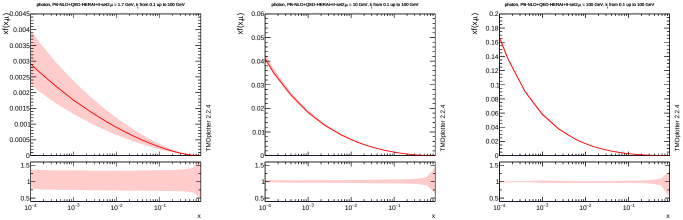
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x),$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}.$$

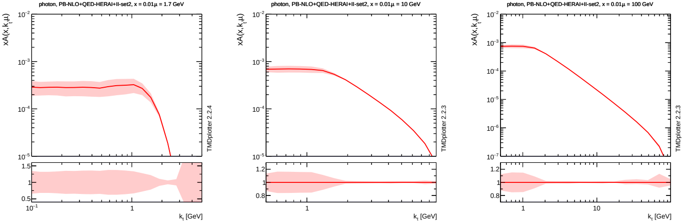
- fit is as good as QCD NLO $\chi^2/dof = 1.21$

Collinear and TMD photon density

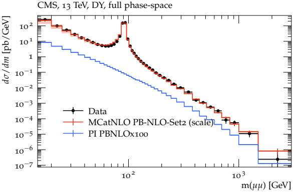
collinear photon PDF extracted from fit to HERA data

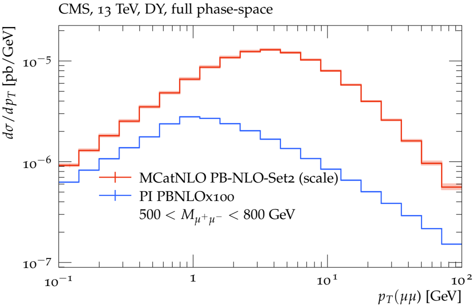


TMD parton densities can be obtained within the PB method



Measurement of the differential Drell-Yan cross section in proton-proton collisions at 13 TeV (CMS-2018-I1711625) JHEP **12** (2019), 059





Matrix Elements: MC@NLO

- Standard Drell-Yan : $qq \rightarrow l^+ l^-$
- PI process : $\gamma\gamma \rightarrow l^+ l^-$

calculation with CASCADE3

Eur. Phys. J. C **81** (2021) no.5, 425

Phys. Lett. B **817** (2021), 136299 presented at Moriond'21 and DIS,21

Conclusion

- PB method to solve DGLAP equation at LO, NLO, NNLO.
- New PDF sets determined within the PB approach:
  1. **4FL collinear and TMD** PDF
  2. **photon collinear and TMD** PDF
- Application of new PB-TMD sets:
  1. 4FL and 5FL PB-TMD distributions used to calculate $Z + b\bar{b}$ production : the evolution of the PB-TMD parton densities as well as in the PB-TMD parton shower is checked.
  2. photon PB-TMD densities used to predict the transverse momentum spectra of very high mass lepton pairs from both Drell-Yan production and Photon-Initiated lepton processes.
- Outlook:
  - PDFs for heavy gauge bosons
  - PB-TMD determination from global fit

Thank you