Developing the Parton Branching TMD Evolution: QED interactions

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Outline

Recap of Parton Branching method

- Including the Δ_s in 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:

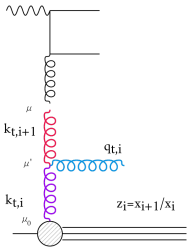
$$f(x,\mu^2) = f(x,\mu_0^2)\Delta_s(\mu^2) + \int \frac{dz}{z} \frac{d\mu'^2}{\mu'^2} \cdot \frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)} P^R(z) f(\frac{x}{z},\mu'^2)$$

- 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

PDFs from PB method: QCD fit to HERA data

Convolution of kernel with 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 NLO)
Phys. Rev. D **99** (2019) no. 7, 074008

- Full coupled evolution with all flavors
- using full HERAI+II inclusive DIS (neutral current, charged current) data
- in total 1145 data points
- $3.5 < Q^2 < 50000$ GeV^2 & $4.10^{-5} < x < 0.65$
- χ^2/dof=1.21

Can be easily extended to include any other measurement for fit.

Recap of application of PB-TMD densities

So far ...

- PB-TMDs obtained from QCD NLO fit to inclusive HERA data
- parameters of collinear initial distribution obtained
- intrinsic Gauss distribution with Phys. Rev. D **99** (2019) no. 7, 074008
  - $\mathcal{A}_a(x, k_t^2, \mu_0^2) = f_a(x, \mu_0^2) \cdot \exp(-|k_t^2|/\sigma^2)$
  - constrained with $\sigma^2 = q_s^2/2$ of Gauss distribution $q_s = 0.5$ GeV
- association of evolution scale with q_t
  - $\mu = q_t/(1-z)$
- no further free parameter!

Very successful for description of inclusive processes

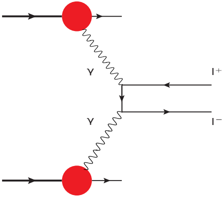
Phys. Rev. D **100** (2019) no.7, 074027, Eur. Phys. J. C **80** (2020) no.7, 598 $\rightarrow$ talk by Aleksandra Lelek

- without any adjustment of parameters : high energy/mass as well as low energy/mass DY production are reasonably well described by PB method.

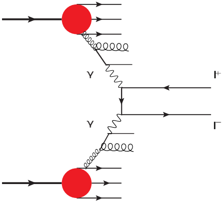
QED corrections

- LO QED splitting functions are included: P^{γ}_{qq}, $P_{q\gamma}$, $P_{\gamma q}$
- running LO-QED coupling with matching at quark-mass thresholds
- since $\alpha \sim \alpha_s^2$: NLO QCD splitting kernels are used
- fitting PB PDFs with QED corrections to HERA data

- photon density is generated perturbatively
    - simplicity
    - check contribution from just perturbatively generated photons in both collinear and TMD photon density



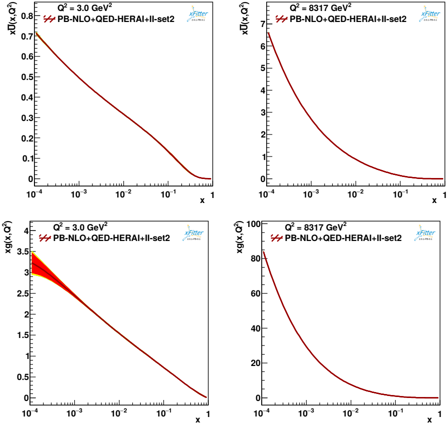
elastic photon (not considered here)



pertubatively generated photon

NLO QCD+QED fit

The first determination of the PB PDFs using LO QED + NLO QCD evolution



- $\chi^2/dof = 1.21$

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

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

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

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

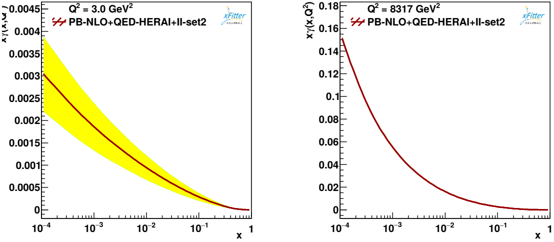
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}.$$

- fit is as good as QCD NLO
- inclusion of a photon PDF has a negligible impact on the other PDF sets
- all PDFs were benchmarked against ones produced in 1509.00209 [S. Carrazza PhD theis] - excellent agreement is achieved.

S. Carrazza, Parton distribution functions with QED corrections [arXiv:1509.00209 [hep-ph]]

Collinear photon density

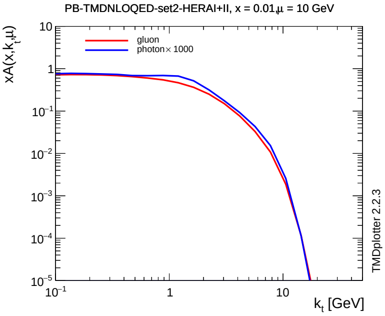
- the collinear photon PDF extracted from fit to HERA data arXiv:2102.01494 [hep-ph]
- photon PDF has large experimental uncertainty coming from valence quark distribution

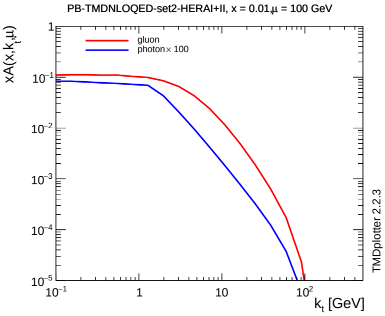


TMD photon and gluon

TMD parton densities can be obtained within the PB method. arXiv:2102.01494 [hep-ph]

TMDs are plotted with TMDplotter arXiv:2103.09741 [hep-ph]

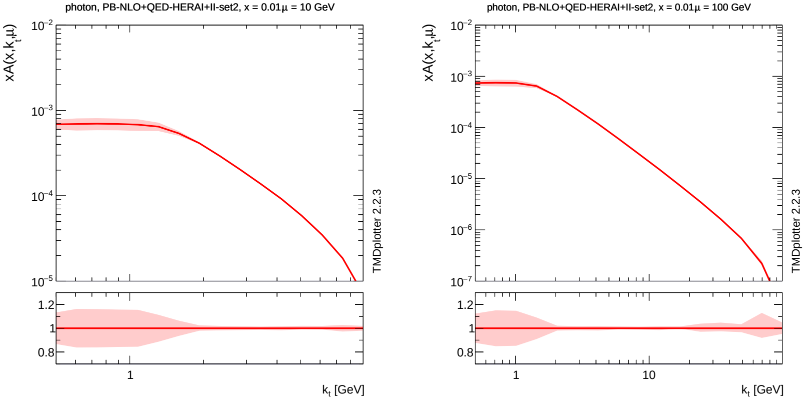




the shape of photon and gluon distributions

- at low k_t is the same.
- at large k_t is different: gluon-gluon splitting

TMD photon uncertainty



- k_t-dependent uncertainty distribution
- large uncertainty at small k_t comes from valence quark distribution at small k_t

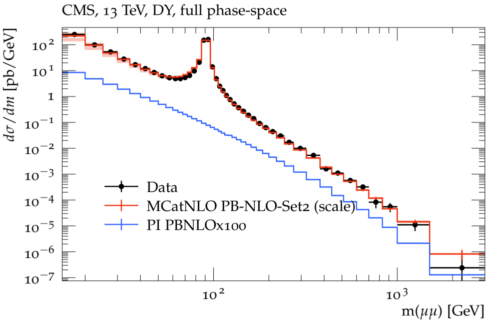
TMD photon application: high mass DY spectrum

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 : $pp \to l^+ l^-$
- PI process : $\gamma\gamma \to l^+ l^-$

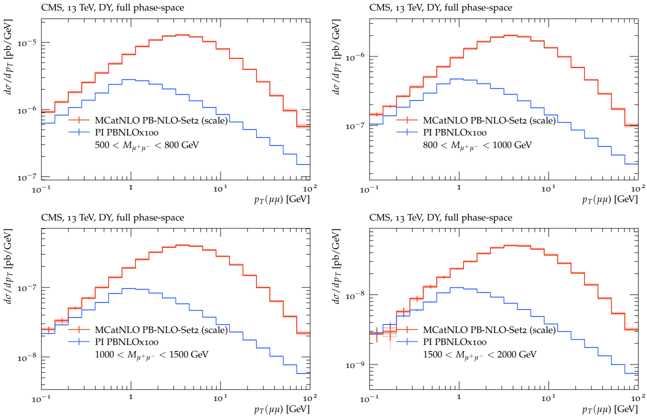
PDFs



- whole mass region is well described by collinear PB-QED (SET2)
- the fraction of PI process is generally less than 1%
- our PI prediction is 1% of the other approaches with intrinsic photon distribution - For the integrated photon density the perturbative piece is 10%
- special feature of PB method: the transverse momentum spectrum of DY and PI process can be predicted for high mass DY pairs

TMD photon application: p_t spectrum at large DY mass

- p_t-distribution of high mass DY pair at different energies CASCADE3 [arXiv:2101.10221 [hep-ph]]



- huge difference in the scale from high mass DY pair down to few GeV is predicted by PB formalism with no tuning
- the transverse momentum contribution of PI processes predicted with a TMD photon density
- non-zero p_t of lepton pair can come only from perturbatively generated photon
- the p_t-spectrum of PI process is different from standard DY

Conclusion

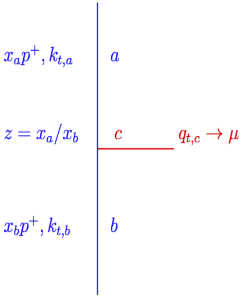
- PB method to solve DGLAP equation at LO, NLO, NNLO.
  - advantages of PB method (angular ordering)
  - method directly applicable to determine k_t-distribution
  - **collinear and TMD photon** density recently determined with the PB method
- TMD densities are used to predict the mass and **transverse momentum** spectra of very high mass lepton pairs from both **Drell-Yan production and Photon-Initiated lepton processes** at the LHC
  - dilepton mass measurements well described in the range 15 to 3000 GeV at $\sqrt{s} = 13$ TeV - there is no significant contribution from perturbatively generated photon
  - a measurement can be made to constrain the photon TMD distribution
- outlook:
  - PDFs for heavy gauge bosons

Thank you

Backup

Transverse Momentum Dependence

- Parton Branching evolution generates every single branching:
  - kinematics can be calculated at every step
- give physics interpretation of evolution scale:
  - in high energy limit: p_T-ordering: $\mu = q_T$
  - angular ordering: $\mu = q_T/(1-z)$

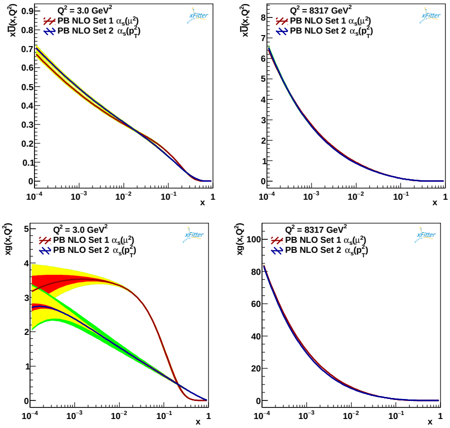


PDFs from PB method: fit to HERA data

- 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

Standard 5FL-NLO full fit



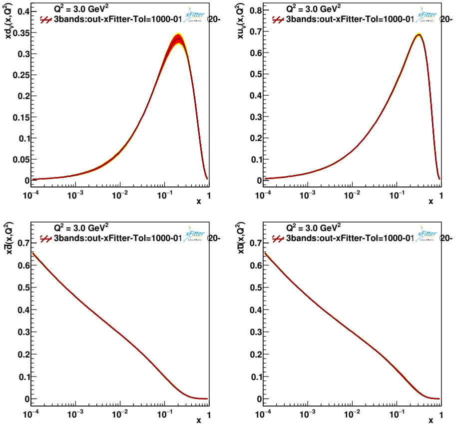
- Set1-$\alpha_s(\mu^2) \rightarrow \chi^2/dof = 1.21$
- Set2-$\alpha_s(p_T^2) \rightarrow \chi^2/dof = 1.21$

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

- 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

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

Collinear PDF at $Q^2 = 3$ Gev^2



$$P_{qq} = e_q^2 \; \frac{1+z^2}{[1-z]_+} + \frac{3}{2} \; e_q^2 \; \delta(1-z)$$

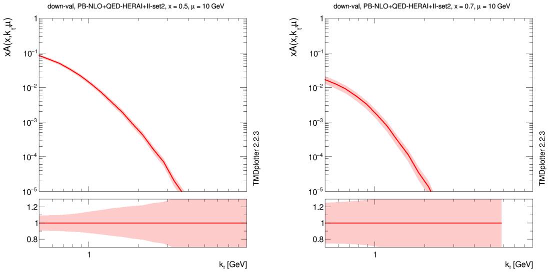
$$P_{q\gamma} = N \; e_q^2 \; (z^2 \; + \; (1-z)^2)$$

$$P_{\gamma q} = e_q^2 \; \frac{1+(1-z)^2}{z}$$

$$P_{\gamma\gamma} = -\frac{N}{3} \; \sum_q \; e_q^2 \; \delta(1-z)$$

- the probability to radiate a photon off quark is large at small z
- $\rightarrow$ small-x photon is radiated from large-x values of quarks, where the probability of valence quarks is large
- $\Rightarrow$ the valence quark uncertainty is reflected to photon uncertainty

Valence TMD



- the uncertainty of valence quark at small-k_t is large

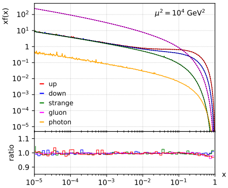
$$\mathcal{A}_a(x,\mathbf{k},\mu^2) = \Delta_a(\mu^2)\,\mathcal{A}_a(x,\mathbf{k},\mu_0^2) + \sum_b \int \frac{d^2\mathbf{q}'}{\pi \mathbf{q}'^2}\,\frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)}\,\Theta(\mu^2-\mathbf{q}'^2)\,\Theta(\mathbf{q}'^2-\mu_0^2)$$

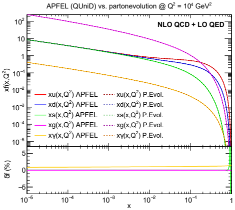
$$\times \int_x^{z_M} dz z\, P_{ab}^{(R)}(\alpha_s,z)\,\mathcal{A}_b\left(\frac{x}{z},\mathbf{k}+(1-z)\mathbf{q}',\mathbf{q}'^2\right)$$

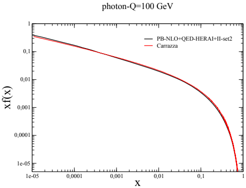
- at small k_t $\rightarrow$ the uncertainty comes from the starting distribution at x
- at large k_t $\rightarrow$ the uncertainty comes from the starting distribution at $x/z \gg x$

a benchmark test

- a benchmark test by taking the same parametrization and initial scale in the FFN scheme with only four active quarks is performed.
- with the same assumption of $\gamma(x, Q^2) = 0$, an excellent agreement is achieved for all flavors, photon and gluon PDFs.





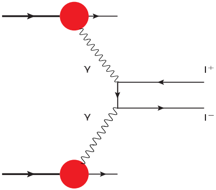


S. Carrazza, [arXiv:1509.00209 [hep-ph]].

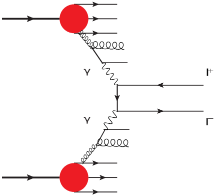
Photon TMD application: DY production

lepton pair p_t can come from two PI processes:

- elastic $\rightarrow$ rapidity gap + lepton pair (can be distinguished experimentally)
- inelastic $\rightarrow$ hadronic activity + lepton pair (More similar to normal DY production)



a) elastic photon (not considered here)



b) pertubatively generated photon