Collinear and TMD Parton densities from fits to DIS precision data at LO and NLO

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REF workshop 2019-Pavia

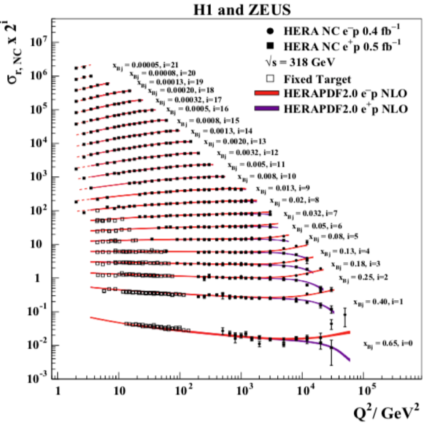
On be half of

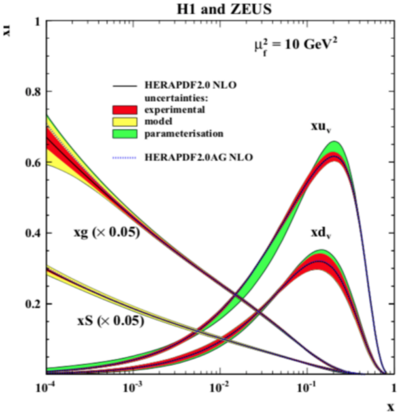
A. Bermudez Martinez, P. Connor, F. Hautmann, H. Jung, A. Lelek, V. Radescu, M. Schmitz and R. Žlebčík

Outline

1. **From inclusive to exclusive distributions**
2. **Parton Branching method**
3. **Determination of PDFs at LO and NLO**
4. **What is the gain with exclusive evolution?**

Inclusive cross section and inclusive PDFs





- **HERAPDF2.0**: available in LHAPDF for collinear calculations.

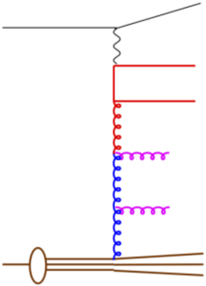
H. Abramowicz *et al.* [H1 and ZEUS Collaborations], Eur. Phys. J. C **75**, no. 12, 580 (2015) [arXiv:1506.06042 [hep-ex]].

From inclusive to exclusive PDFs

- standard parton density evolution is inclusive:
  - $f(x, \mu^2)$ gives probability to find parton at x and μ^2
  - no information about the history of evolution
  - no information about parton emissions at p_T and y
    - is enough for inclusive calculations not for exclusive processes.
- Our physics picture and intuition is not inclusive:
  - parton evolution proceeds via real parton emissions
- Formula exclusive evolution equation for parton densities :

new approach: Parton Branching Method

- $\rightarrow$ cover all transverse momenta from small k_t to large k_t as well as large range in x and μ^2.



TMDs- How to determine?

Transverse momentum effects are naturally coming from

- intrinsic k_t
- **parton shower**

Determine integrated PDFs from PB solution of evolution equation:

- check consistency with standard evolution on integrated PDFs
- at LO, NLO and NNLO
- advantages of PB method
  (full freedom of choosing renormalization/evolution scale ...)

Determine TMD:

- since each branching is generated explicitly, energy-momentum conservation is fulfilled and transverse momentum distributions can be obtained.

How to solve DGLAP evolution with PB method?

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

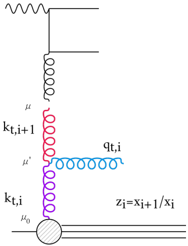
$$\mu^2 \frac{\partial}{\partial \mu^2} \frac{f(x,\mu^2)}{\Delta_s(\mu^2)} = \int \frac{dz}{z} \frac{\alpha_s}{2\pi} \frac{\mathcal{P}(z)}{\Delta_s(\mu^2)} f(\frac{x}{z},\mu^2)$$

- Integral form with a very simple physical interpretation:

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

- 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

Evolution equation and parton branching method

- use momentum weighted PDFs with real emission probability

$$
\begin{aligned}
xf_a(x,\mu^2) &= \Delta_a(\mu^2)xf_a(x,\mu_0^2) \\
&+ \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_s(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz\, P_{ab}^R(\alpha_a, z)\, \frac{x}{z}\, f_b(x/z,\mu^2)
\end{aligned}
$$

- due to step by step individual branchings, all kinematics can be calculated exactly.
- z_M introduced to separate real from virtual and non-resolvable branching
- reproduces DGLAP up to $\mathcal{O}(1 - z_M)$
- make use of momentum sum rule to treat virtual corrections
- use Sudakov form factor for non-resolvable and virtual corrections

$$
\Delta_a(z_M, \mu^2, \mu_0^2) = exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} dz\; z\; P_{ba}^R(\alpha_s, z) \right)
$$

Determination of PDFs

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

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

- 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.

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

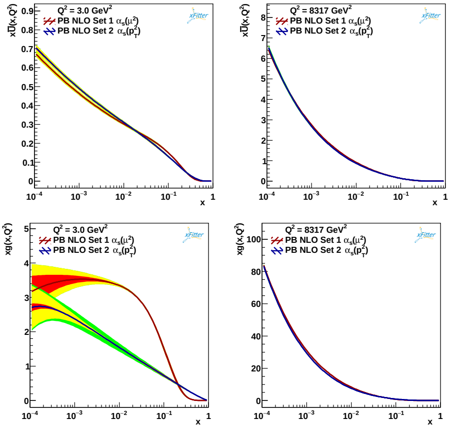
PDFs from PB method: fit to HERA data

- Two angular ordered sets with different argument in α_s (either μ or q_t)
- q_{cut} in, $\alpha_s(max(q_{cut}^2, |q_{t,i}^2|))$, to avoid the non-perturbative region, $|q_{t,i}^2| = (1 - z_i)^2 \mu_i^2$
- $\mu_0^2 = 1.9$ GeV^2 for set1 (as in HERAPDF)
- $\mu_0^2 = 1.4$ GeV^2 for set2 (the best χ^2/dof)
- 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

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

Standard NLO full fit with different scale in α_s



- Set1-$\alpha_s(\mu^2) \rightarrow \chi^2/dof = 1.2$
- Set2-$\alpha_s(p_T^2) \rightarrow \chi^2/dof = 1.21$

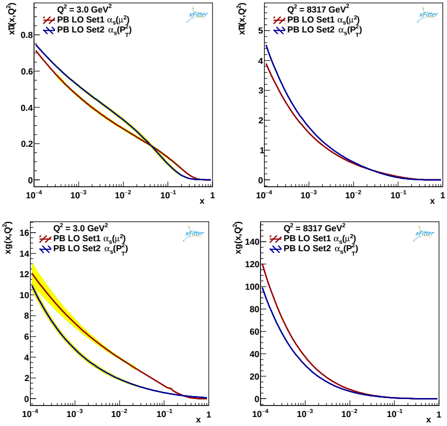
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x), \\
x\bar{D}(x)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

- 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).

Standard LO full fit with different scale in α_s

NEW!



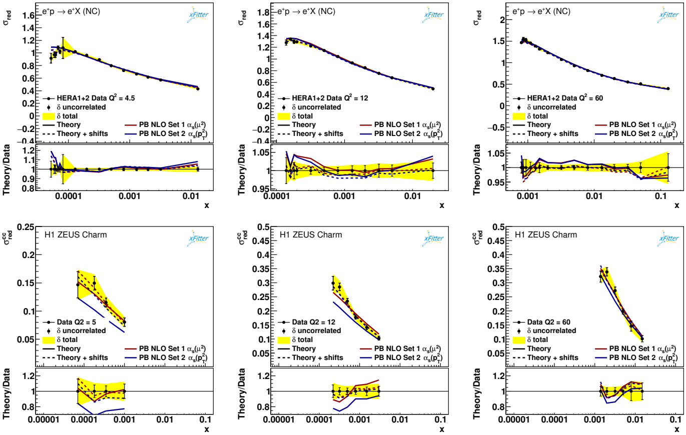
- Set1-$\alpha_s(\mu^2) \to \chi^2/dof = 1.24$
- Set2-$\alpha_s(p_T^2) \to \chi^2/dof = 1.37$

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} (1-x)^{C_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} \left(1 + E_{u_v} x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} \left(1 + D_{\bar{U}} x\right), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

- Very different gluon distribution obtained at small and large Q^2
- The differences exist at higher Q^2

Fit to DIS x-section at NLO: F_2 and F_2^c

How well can we describe inclusive DIS cross section and inclusive charm production with the two sets at NLO?

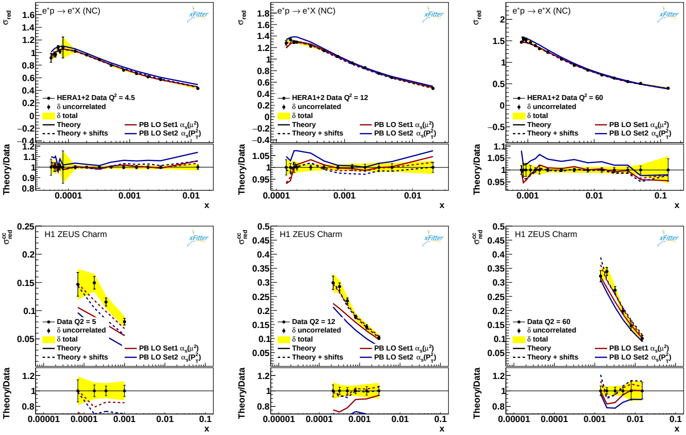


A. Martinez, P. Connor, H. Jung, A. Lelek, R. Žlebčík, F. Hautmann and V. Radescu, Phys. Rev. D **99**, no. 7, 074008 (2019).

Fit to DIS x-section at LO: F_2 and F_2^c

How well can we describe inclusive DIS cross section and inclusive charm production with the two sets at LO?

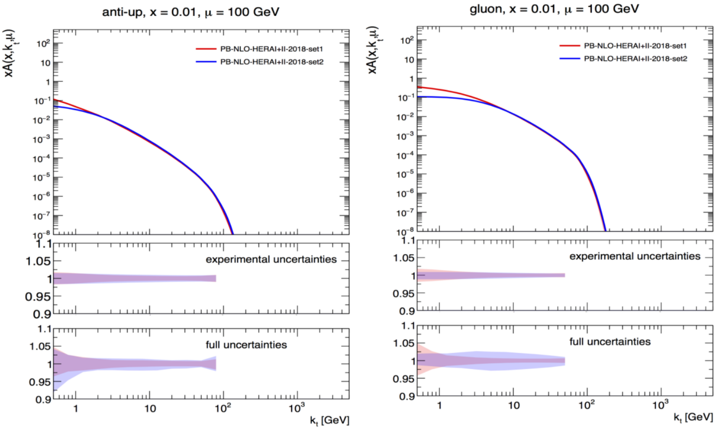
NEW!



On the inclusive level, DIS cross section and charm production are well described.

What is the gain with exclusive evolution?

TMD distributions from fit to HERA data

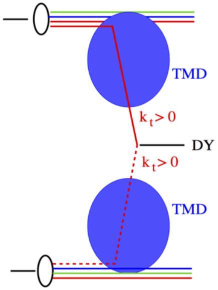


- Different shape and dependence of the uncertainty as a function of k_t.
- Model dependence larger than experimental uncertainties.
- Difference essentially in low k_t region.
- Introducing p_T instead of μ suppresses further soft gluons at low k_t.

Application to DY q_T- spectrum

- fixed-order purturbative calculations cannot describe transverse momentum spectrum of Z bosons in DY at small q_T .

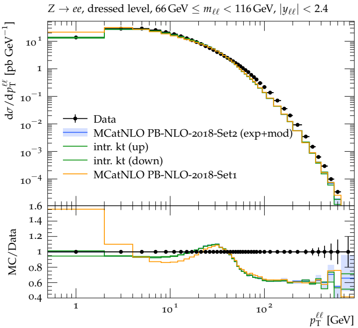
- Use LO ME $q\bar{q} \to z_0$
- add k_t for each parton as function of x and μ according to TMD
- keep final state mass fixed:
  - x_1 and x_2 are different after adding k_t



Application to DY q_T- spectrum

Transverse momentum spectrum of Z-bosons obtained from two **NLO** and **LO** TMDs, compared with ATLAS measurements. :

- TMD with angular ordering including $\alpha_s(\mu^2)$
- TMD with angular ordering including $\alpha_s(p_T^2)$ $\rightarrow$ Qun's talk for NLO DY spectrum



ATLAS Collaboration Eur. Phys. J. C76 (2016),291, arXiv:1512.02192 [hep-ph].
A. Martinez, P. Connor, H. Jung, A. Lelek, R. Žlebčík, F. Hautmann and V. Radescu, Phys. Rev. D **99**, no. 7, 074008 (2019).
A. Bermudez Martinez *et al.*, Phys. Rev. D **100**, no. 7, 074027 (2019).

Conclusion

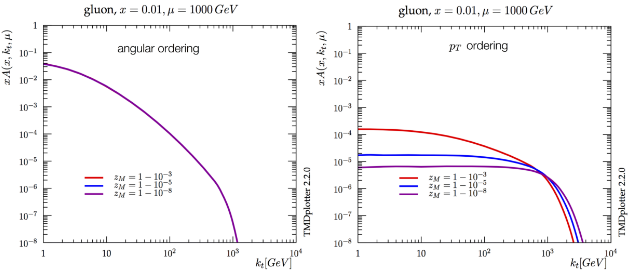
- PB method to solve DGLAP equation at LO, NLO, NNLO.
  - consistent for collinear (integrated) PDFs shown
  - advantages of PB method (angular ordering)
- method directly applicable to determine k_t distribution (as would be done in PS)
  - TMD distributions for all flavors determined at LO & NLO
  - TMD evolution implemented in xFitter -fits to processes at the moment
- Application to pp processes:
  - DY q_T-spectrum without new parameters

Thank you for your attention

Backup

Transverse Momentum Dependence

- Parton Branching evolutions generates every single branching. Kinematics can be calculated at every step.
- Give physics interpretation of evolution scale:
  - p_T-ordering : $\mu = q_T$
  - angular ordering : $\mu = q_T/(1-z)$



- p_T-ordering shows significant dependence on Z_M: Unstable results because of soft gluon contribution.
- angular ordering is independent of Z_M: stable results since soft gluons are suppressed.

intrinsic $k_{t,0}$ distribution

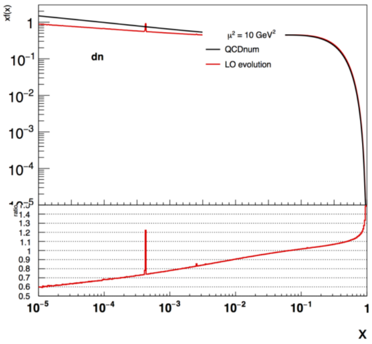
$$
\begin{aligned}
xf_a(x,\mu^2) &= x\int dx' \int dx'' \mathcal{A}_{0,b}(x')\, \tilde{\mathcal{A}}_a^b(x'',\mu^2)\, \delta(x'x''-x) \\
&= \int dx'\, \mathcal{A}_{0,b}(x')\, .\, \frac{x}{x'}\, \tilde{\mathcal{A}}_a^b(\frac{x}{x'},\mu^2)
\end{aligned}
$$

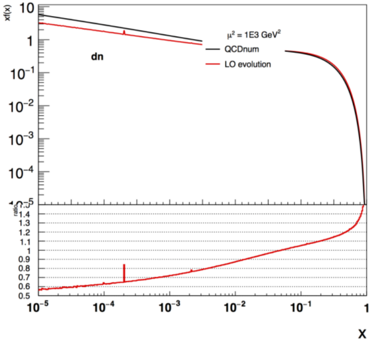
$$
\mathcal{A}_{0,b}(x,k_{t,0}^2) = f_{0,b}(x)\cdot \exp(-|k_{t,0}^2|/\sigma^2)
$$

where the intrinsic $k_{t,0}$ distribution is given by a Gauss distribution with $\sigma^2 = q_0^2/2$ for all flavors and all x with a constant value $q_0 = 0.5$ GeV.

Effect of LO vrs NLO evolution

Using the same starting distribution, but LO or NLO splitting functions

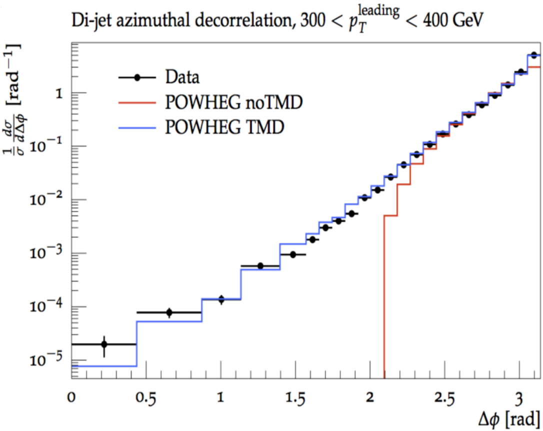


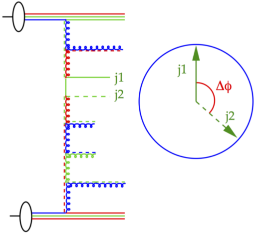


- effect of NLO evolution (α_s and P_{ij}) is very large:$\sim$ 50% for quarks

NB: spikes in plots come from fluctuations in MC solution.

Why TMDs?





- NLO-dijet with collinear POWHEG cannot describe small $\Delta\phi$
- NLO-dijet with TMD POWHEG describes spectrum at small and large $\Delta\phi$
- Region of higher order emissions described by TMDs. This approach improves the description of jet production.