Electroweak corrections to parton distributions

Preliminary results using the NNPDF methodology

Stefano Carrazza

University & INFN Milan

Rencontres de Moriond, March 13, 2013

results presented on behalf of the NNPDF collaboration

Outline

1. Motivation
   - Why electroweak corrections?
2. PDF evolution
   - Solution & Benchmark
3. Observables
   - Introducing QED corrections to DIS processes
   - How do the observables change by fixing PDFs?
4. Extracting PDFs from real data
   - How do the PDFs change by fixing observables?
5. Preliminary results

Outline

1. Motivation
   - Why electroweak corrections?
2. PDF evolution
   - Solution & Benchmark
3. Observables
   - Introducing QED corrections to DIS processes
   - How do the observables change by fixing PDFs?
4. Extracting PDFs from real data
   - How do the PDFs change by fixing observables?
5. Preliminary results

Motivation

Why electroweak corrections?

- ***A naïve argument***:
  The QED coupling α can affects processes in which QCD DGLAP is computed at **NLO** and higher orders

$$\frac{\mathcal{O}(\alpha_s^2)}{\mathcal{O}(\alpha)} \to \frac{\alpha_s^2(M_Z^2)}{\alpha(M_Z^2)} = \frac{0.1184^2}{1/127} \sim 1.78$$

- Leading order QED effects are comparable to NLO QCD corrections.

- ***A naïve argument***:
  The QED coupling α can affects processes in which QCD DGLAP is computed at **NLO** and higher orders

$$\frac{\mathcal{O}(\alpha_s^2)}{\mathcal{O}(\alpha)} \to \frac{\alpha_s^2(M_Z^2)}{\alpha(M_Z^2)} = \frac{0.1184^2}{1/127} \sim 1.78$$

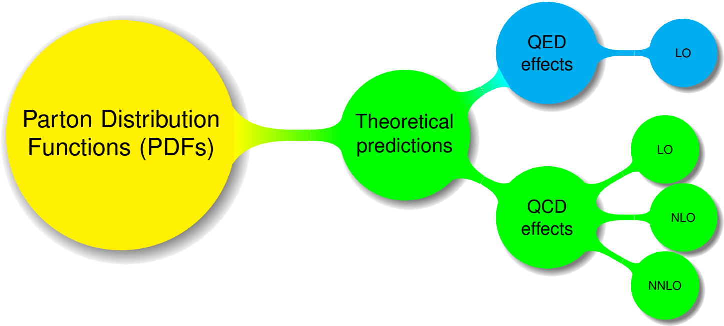
- Leading order QED effects are comparable to NLO QCD corrections.

- ***Main motivations:***
  1. Provide a first **unbiased determination** of the **photon PDF with faithful uncertainty**.
  2. Assessment of their impact on **theoretical predictions**:
     - ⋆ EW measurements at the LHC,
     - ⋆ High-mass Drell-Yan and related searches, m_W determination, etc...
  3. MRST2004QED is available but **old and based on model assumptions**.

Motivation

Why electroweak corrections?

- ***New Scenario:***



- The new scenario consists in the inclusion of QED effects to PDFs.

Technical aspects of QED corrections

Step by step: How to obtain the photon PDF.

- In order to achieve our goal we had to implement:

1. Modify **PDF evolution** (DGLAP)
   - ★ QCD (NLO/NNLO) + QED (LO)
2. Rewrite **observables** including the photon contribution
   - ★ Deep Inelastic Scattering, Drell-Yan and Jet
3. Add a new **PDF parametrization** for the **photon**
   - ★ $\gamma(x, Q^2)$ neural network, imposing PDF positivity
4. Perform a fit using the **NNPDF methodology**

Points (3) and (4) were completely written and optimized from scratch.

Outline

1. Motivation
   - Why electroweak corrections?
2. PDF evolution
   - Solution & Benchmark
3. Observables
   - Introducing QED corrections to DIS processes
   - How do the observables change by fixing PDFs?
4. Extracting PDFs from real data
   - How do the PDFs change by fixing observables?
5. Preliminary results

PDF evolution (DGLAP)

Solving the coupled evolution

- $\gamma(x, Q^2)$: photon PDF
  - **LO QED** evolution equations:

$$Q^2 \frac{\partial}{\partial Q^2} \gamma(x, Q^2) = \frac{\alpha(Q^2)}{2\pi} \left[P_{\gamma\gamma}(\xi) \otimes e_\Sigma^2 \gamma\left(\frac{x}{\xi}, Q^2\right) + P_{\gamma q}(\xi) \otimes \sum_j e_j^2 q_j \left(\frac{x}{\xi}, Q^2\right) \right]$$

$$Q^2 \frac{\partial}{\partial Q^2} q_i(x, Q^2) = \frac{\alpha(Q^2)}{2\pi} \left[P_{q\gamma}(\xi) \otimes e_i^2 \gamma\left(\frac{x}{\xi}, Q^2\right) + P_{qq}(\xi) \otimes e_i^2 q_i \left(\frac{x}{\xi}, Q^2\right) \right]$$

with $e_\Sigma^2 = \sum_f^{n_f} N_c^f e_{q_f}^2$ (charges), and the momentum sum rule becomes

$$\int_0^1 dx x \left\{ \sum_i q_i(x, Q^2) + g(x, Q^2) + \gamma(x, Q^2) \right\} = 1$$

PDF evolution (DGLAP)

Multiple methods to solve QCD+QED evolution:

- in a special evolution basis, e.g. in Mellin space:

$$Q^2 \frac{\partial}{\partial Q^2} \underline{f}(N, Q^2) = P(N) \cdot \underline{f}(N, Q^2)$$

where $P(N)$ is the splitting function matrix in N space

$$\begin{aligned} P(N) &= \alpha_s(Q^2) P_{\text{LO}}^{\text{QCD}} + \alpha_s^2(Q^2) P_{\text{NLO}}^{\text{QCD}} + \alpha(Q^2) P_{\text{LO}}^{\text{QED}} + \\ &+ \mathcal{O}(\alpha\alpha_s) + \mathcal{O}(\alpha_s^3) + \mathcal{O}(\alpha^2) \end{aligned}$$

e.g. Roth, Weinzierl (hep-ph/0403200)

PDF evolution (DGLAP)

Multiple methods to solve QCD+QED evolution:

- in a special evolution basis, e.g. in Mellin space:

$$Q^2 \frac{\partial}{\partial Q^2} \underline{f}(N, Q^2) = P(N) \cdot \underline{f}(N, Q^2)$$

where $P(N)$ is the splitting function matrix in N space

$$\begin{aligned} P(N) &= \alpha_s(Q^2) P_{\rm LO}^{\rm QCD} + \alpha_s^2(Q^2) P_{\rm NLO}^{\rm QCD} + \alpha(Q^2) P_{\rm LO}^{\rm QED} + \\ &+ \mathcal{O}(\alpha\alpha_s) + \mathcal{O}(\alpha_s^3) + \mathcal{O}(\alpha^2) \end{aligned}$$

e.g. Roth, Weinzierl (hep-ph/0403200)

- **our method:** combination of QCD and QED evolution solutions

$$f_i(N, Q^2) = \Gamma_{ik}^{\rm QCD}(Q^2, Q_0^2) \cdot \Gamma_{kj}^{\rm QED}(Q^2, Q_0^2) \cdot f_j(N, Q_0^2)$$

- Both methods treat the subleading terms in different ways.
- FastKernel implementation of DGLAP evolution.

Impact of QED corrections to evolution

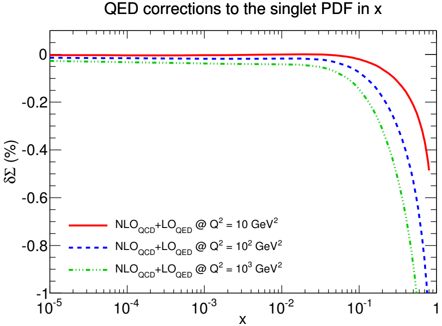
- Input PDF $\to$ Les Houches toy PDF +

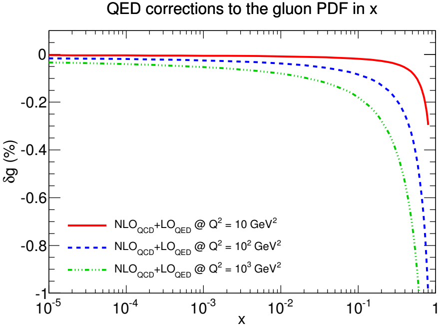
$$\hookrightarrow \boxed{x\gamma(x, Q_0^2 = 2\,\mathrm{GeV}^2) = 0}$$

- Relative difference due to QED corrections at $Q^2 = 10, 10^2, 10^3\,\mathrm{GeV}^2$:

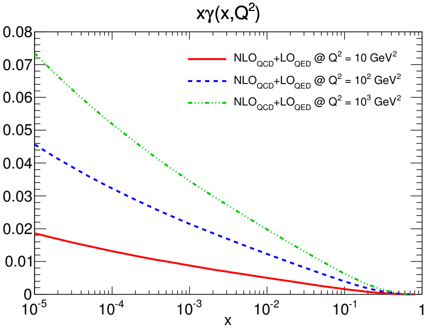
$$\delta f(x, Q^2) = \frac{f_{\text{with QED}}(x, Q^2) - f_{\text{QCD only}}(x, Q^2)}{f_{\text{with QED}}(x, Q^2)}$$

- **Singlet** and **Gluon PDFs**





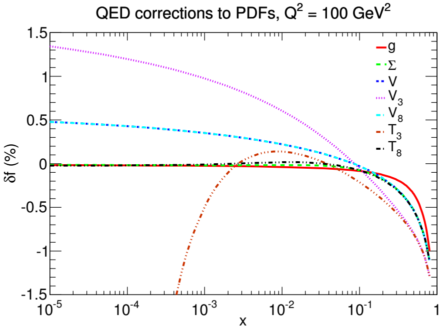
- Also for the **photon PDF!**

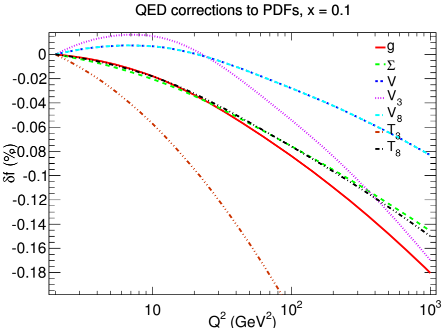


... obtained **dynamically**. $\gamma(x, Q^2)$ is minimally affected by the evolution.

Impact of QED corrections to evolution

- Finally, in the **evolution basis**:



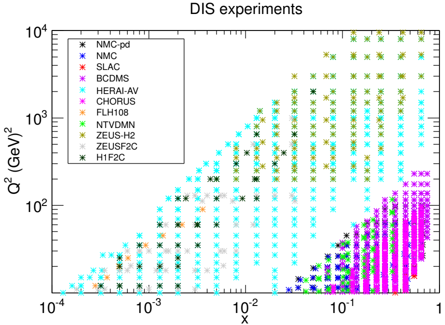


$$
\begin{array}{lcl|lcl}
\Sigma & = & u^+ + d^+ + s^+ & V & = & u^- + d^- + s^- \\
T_3 & = & u^+ - d^+ & V_3 & = & u^- - d^- \\
T_8 & = & u^+ + d^+ - 2s^+ & V_8 & = & u^- + d^- - 2s^-
\end{array}
$$

Outline

Observables, current state of the art

- Observables including photon contribution due to evolution:
  - **2767 DIS data points**: e.g. $F_2^{\gamma,p}$, $F_2^{\gamma,d}$, Dimuon CC cross-section



Isospin symmetry breaking:

When activating QED corrections

$$u^p \neq d^n,\ d^p \neq u^n$$

so, e.g. $T_3^p(x, Q^2) \neq T_3^n(x, Q^2)$

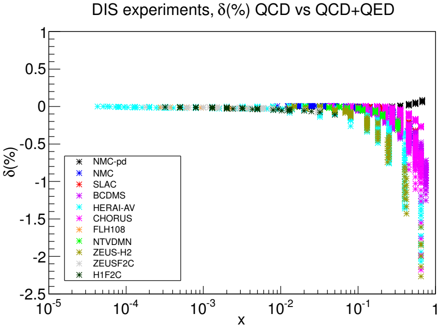
- At initial scale there is **no isospin symmetry breaking**

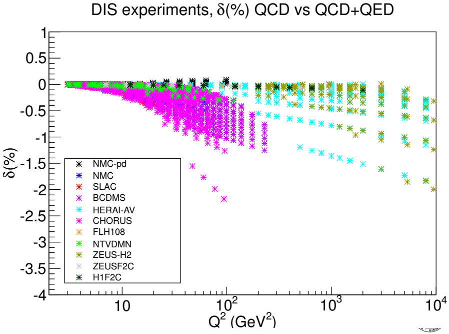
$$T_3^p(x, Q_0^2) = -T_3^n(x, Q_0^2), \quad V_3^p(x, Q_0^2) = -V_3^n(x, Q_0^2)$$

- Isospin is **broken dynamically** by DGLAP evolution.

Observables, current state of the art

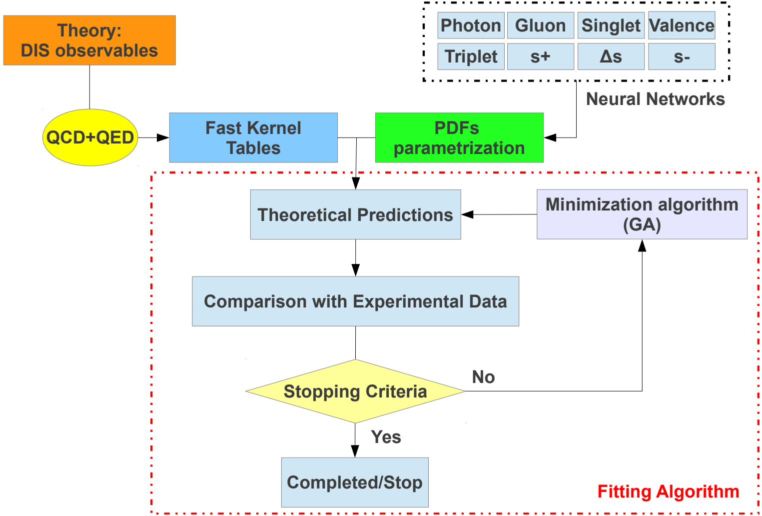
- Observables are codified in Fast Kernel grids
  - measure the impact on DIS data using NNPDF2.3 NLO
  - set $\gamma(x, Q^2) = 0$
- General behavior very similar to PDFs comparison:
  - relative differences around -1% for $x \to 1$





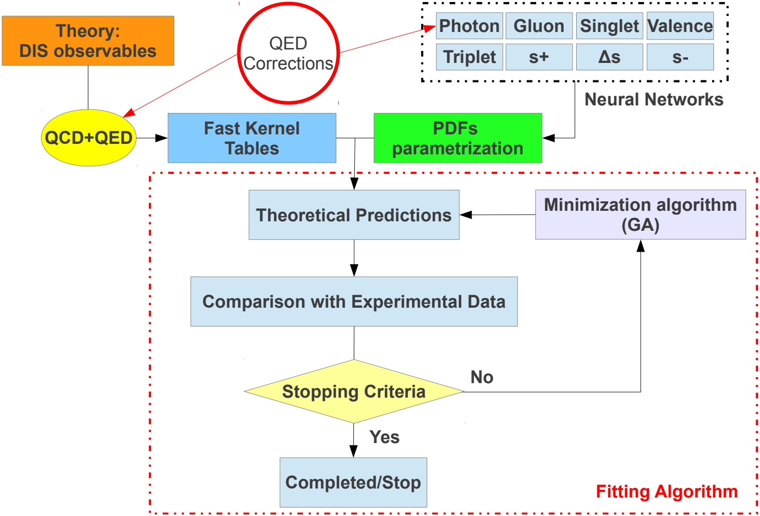
Outline

Fitting algorithm overview



- Fit mechanism also includes momentum sum rule and positivity.

Fitting algorithm overview

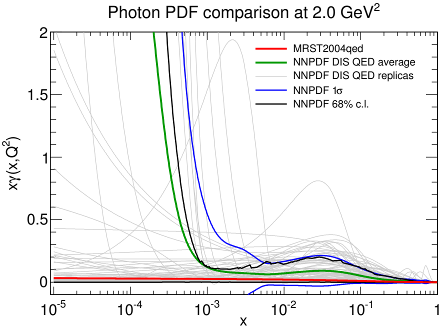


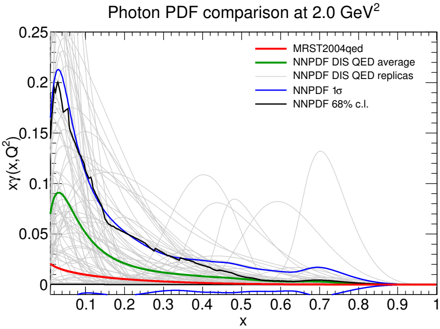
- Fit mechanism also includes momentum sum rule and positivity.

Outline

Photon PDF (preliminary)

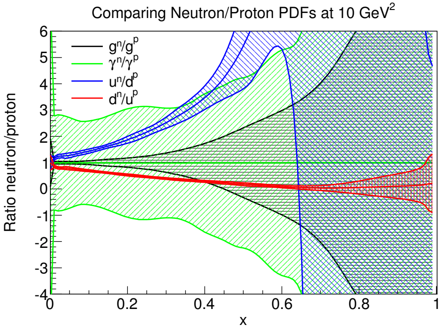
- Performing a **preliminary** **DIS fit** we obtain
  - the photon PDF **extracted from data** (no toy model)
- A small photon was preannounced by the QED corrected observables





Isospin (preliminary)

- We are able to build a **neutron PDF set** for $Q^2 > 2\,\mathrm{GeV}^2$
  - modify evolution basis $u^p \to d^n$, $d^p \to u^n$
- The ratio Neutron/Proton PDFs
  - **isospin symmetry breaking on quarks distributions**



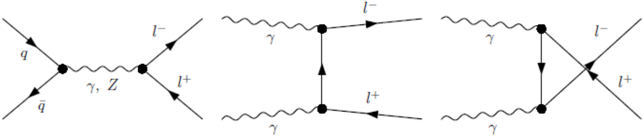
HORACE (preliminary)

- Photon PDF: impact on Z production
  - **HORACE**: Drell-Yan EW $\mathcal{O}(\alpha)$, pp @ $\sqrt{s} = 14\,\text{TeV}$
  - cuts: $|\eta^l| \leq 2.5$, $p_T^l \geq 20\,\mathrm{GeV}$

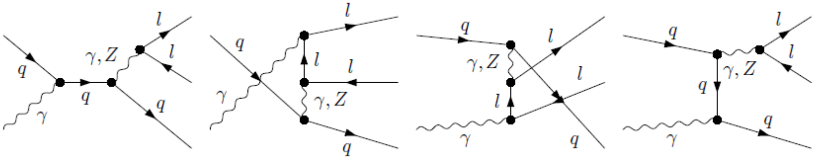
HORACE (preliminary)

- Photon PDF: impact on Z production
  - **HORACE**: Drell-Yan EW $\mathcal{O}(\alpha)$, pp @ $\sqrt{s} = 14\,\text{TeV}$
  - cuts: $|\eta^l| \leq 2.5$, $p_T^l \geq 20\,\mathrm{GeV}$

- **Born** diagrams (from arXiv:0710.1722):

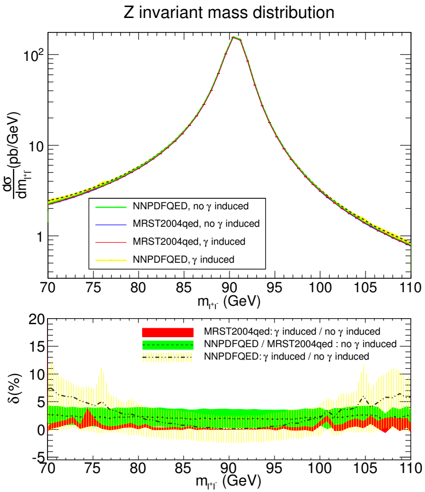


- **Photon-induced** NLO-EW process diagrams:



HORACE (preliminary)

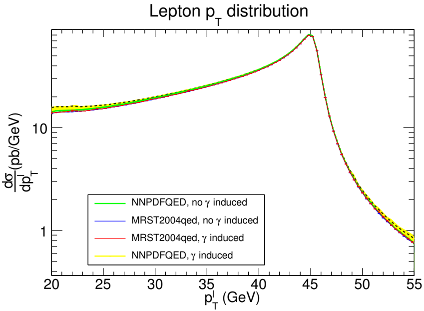
- **Example:** $Z \to l^+ l^-$ invariant mass (**very preliminary**)

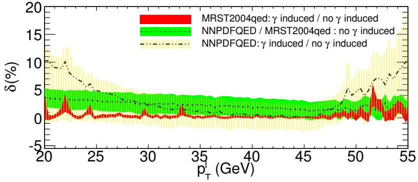


- Effect of photon PDF from DIS data
  - moderate in the region of the peak
  - rapidly increases away from the peak
- Potentially huge contribution due to lack of constraints from DIS on small-x
  - ruins predictions for high m_Z/p_T^l!
- **Next step:** use W/Z production data to constraint photon PDF → use for e.g.
  - predictions for jets & Z' production

HORACE (preliminary)

- **Example:** $Z \to l^+ l^-$ lepton p_T distribution (**very preliminary**)





- Effect of photon PDF from DIS data
  - moderate in the region of the peak
  - rapidly increases away from the peak
- Potentially huge contribution due to lack of constraints from DIS on small-x
  - ruins predictions for high m_Z/p_T^l!
- **Next step:** use W/Z production data to constraint photon PDF $\to$ use for e.g.
  - predictions for jets & Z' production

Outlook

- **Conclusion**
  - Extraction of a preliminary photon PDF from DIS data
  - Study the impact of photon PDF to Z production (HORACE)
- **Outlook**
  - Include Drell-Yan and Jet data (NNPDF2.3 QED)
  - Build a NNLO QCD + LO QED fit
- **Release**
  - Release a set with QED corrections before summer
    - ⋆ NNPDF2.3 + photon

Les Houches Toy PDF

- For the benchmark we have used hep-ph/0204316

$$xu_v(x, Q_0^2) = 5.10720 \cdot x^{0.8}(1-x)^3$$

$$xd_v(x, Q_0^2) = 3.06432 \cdot x^{0.8}(1-x)^4$$

$$xg(x, Q_0^2) = 1.70000 \cdot x^{-0.1}(1-x)^5$$

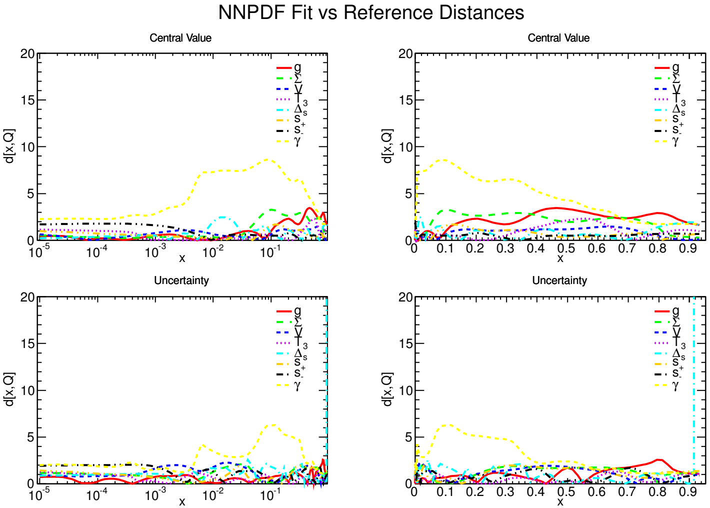
$$x\bar{d}(x, Q_0^2) = .1939875 \cdot x^{-0.1}(1-x)^6$$

$$x\bar{u}(x, Q_0^2) = (1-x)x\bar{d}(x, Q_0^2)$$

$$xs(x, Q_0^2) = x\bar{s}(x, Q_0^2) = 0.2 \cdot x(\bar{u}+\bar{d})(x, Q_0^2)$$

Photon PDF (preliminary)

- Distances between a pure QCD NLO DIS fit and the respective QED corrected fit.



PDF evolution (DGLAP)

Multiple methods to solve QCD+QED evolution:

- **(1)** in a special evolution basis, e.g. in Mellin space:

$$Q^2 \frac{\partial}{\partial Q^2} \underline{f}(N, Q^2) = P(N) \cdot \underline{f}(N, Q^2)$$

where $P(N)$ is the splitting function matrix in N space

$$P(N) \quad = \quad \alpha_s(Q^2) P_{\text{LO}}^{\text{QCD}} + \alpha_s^2(Q^2) P_{\text{NLO}}^{\text{QCD}} + \alpha(Q^2) P_{\text{LO}}^{\text{QED}} + \mathcal{O}(\alpha\alpha_s) + \cdots$$

e.g. Roth, Weinzierl (hep-ph/0403200)

- **(2) our method:** combination of QCD and QED evolution solutions

$$f_i(N, Q^2) = \Gamma_{ik}^{\text{QCD}}(Q^2, Q_0^2) \cdot \Gamma_{kj}^{\text{QED}}(Q^2, Q_0^2) \cdot f_j(N, Q_0^2)$$

Schematically $\Rightarrow$
$$\begin{cases} \textbf{Method (1):} \quad f(N, Q^2) = \exp\,[\text{QCD} + \text{QED}] \cdot f(N, Q_0^2) \\ \textbf{Method (2):} \quad f(N, Q^2) = \exp\,[\text{QCD}] \cdot \exp[\text{QED}] \cdot f(N, Q_0^2) \end{cases}$$

- Methods differ by subleading terms $\mathcal{O}(\alpha\alpha_s)$ (Baker-Campbell-Hausdorff)

Current PDF evolution (DGLAP)

- Our DGLAP properties: possibility to switch between **fixed** and **variable** flavor number schemes (**FFNS/VFNS**), running $\alpha(Q^2)$.
- **Fast Kernel** implementation in **x-space**, building the interpolation grid.

$$xN_j(x;\mu^2,\nu^2) = \sum_{k=1}^{N_{pdf}} \sum_{\alpha=1}^{N_x} \Gamma_{jk}^{\text{QCD}}(x, x_\alpha|\mu^2,\mu_0^2)\left[x_\alpha N_k(x_\alpha;\mu_0^2,\nu^2)\right],$$

$$x_\alpha N_k(x_\alpha;\mu_0^2,\nu^2) = \sum_{l=1}^{N_{pdf}} \sum_{\beta=1}^{N_x} \Gamma_{kl}^{\text{QED}}(x_\alpha, x_\beta|\nu^2,\nu_0^2)\left[x_\beta N_l(x_\beta;\mu_0^2,\nu_0^2)\right],$$

combining both kernels and setting $\mu = \nu = Q$ we obtain the final expression

$$xN_j(x;Q^2) = \sum_{l=1}^{N_{pdf}} \sum_{\beta=1}^{N_x} \underbrace{\Gamma_{jl}^{\text{QCD}\cdot\text{QED}}(x, x_\beta|Q^2,Q_0^2)}_{\text{Fast Kernel}}\left[\underbrace{x_\beta N_l(x_\beta;Q_0^2)}_{\text{Input PDF}}\right]$$

where $\Gamma_{jl}^{\text{QCD}\cdot\text{QED}}(x, x_\beta|Q^2,Q_0^2) = \sum_{k=1}^{N_{pdf}} \sum_{\alpha=1}^{N_x} \Gamma_{jk}^{\text{QCD}}(x, x_\alpha|Q^2,Q_0^2)\Gamma_{kl}^{\text{QED}}(x_\alpha, x_\beta|Q^2,Q_0^2)$