Deep Inelastic Scattering events for photon and heavy boson TMDs in the Parton Branching Method

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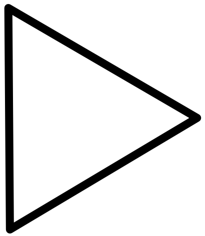
Agenda:

Introduction

Motivation



Methodology

Results

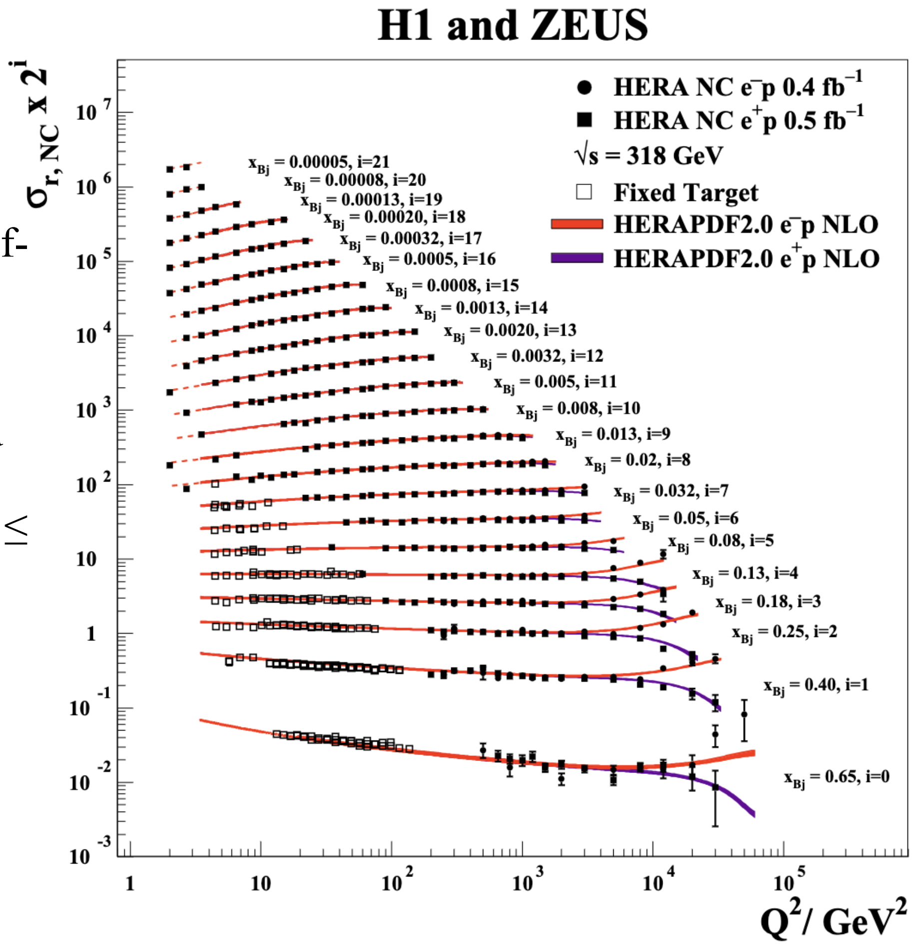
Conclusions & outlook

Introduction

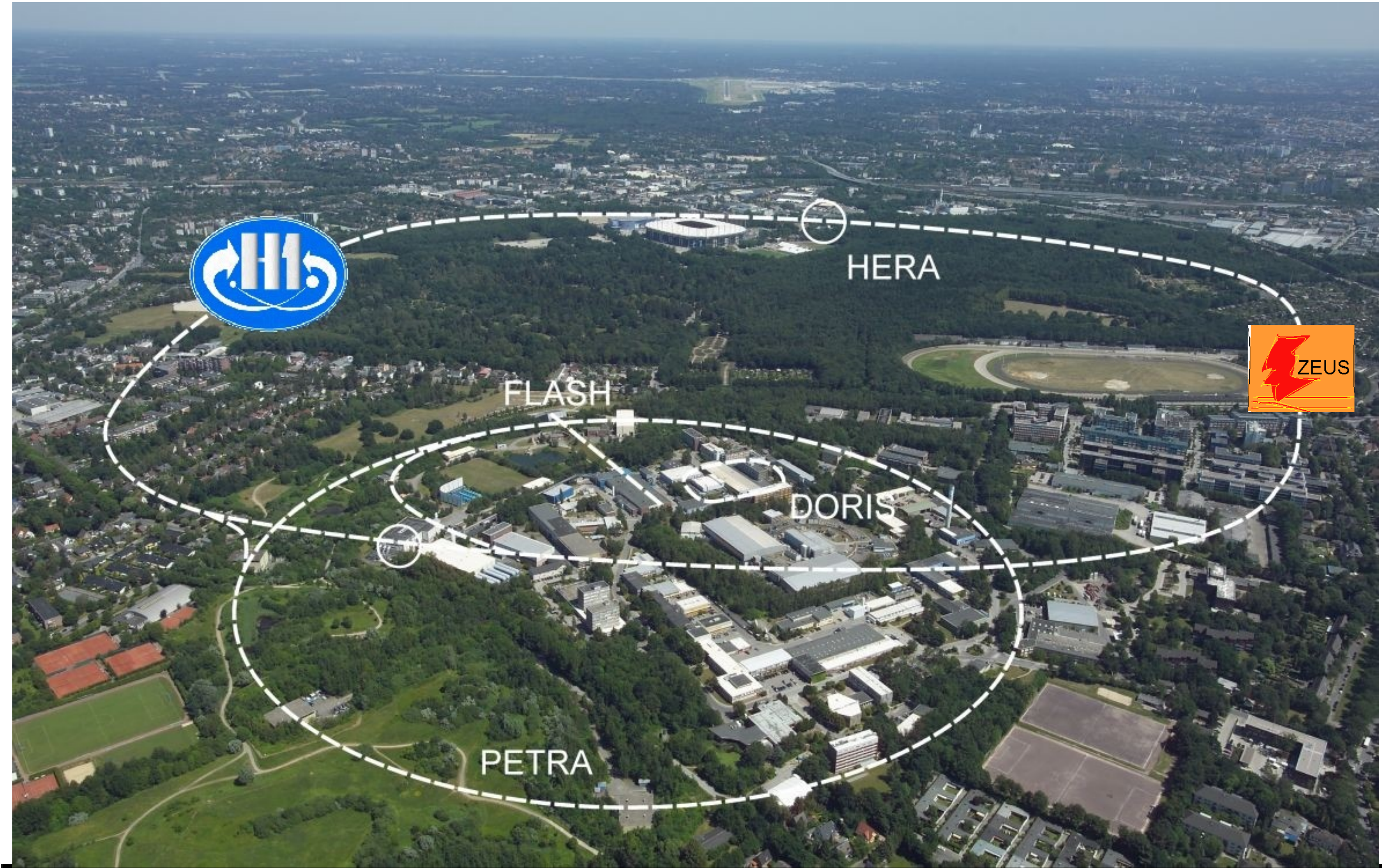
Deep inelastic scattering (DIS) of electrons on protons at centre-of-mass energies of up to √s ≃ 320 GeV at HERA covering:

- NC Cross sections for $0.045 \leq Q2 \leq 50000$ GeV2 and $6 \cdot 10{-}7 \leq xBj \leq 0.65$ at inelasticity, $y = Q2/(s \cdot xBj)$, between 0.005 and 0.95
- CC Cross sections for $200 \leq Q2 \leq 50000$ GeV2 and $1.3 \cdot 10{-}2 \leq xBj \leq 0.40$ at y between 0.037 and 0.76

Since H1 and ZEUS employed different experimental techniques, (detectors, kinematic reconstruction…) → Reduced systematic uncertainty.



Combined HERA data for the inclusive NC e+ p and e− p reduced cross sections together with fixed-target data and the predictions of HERAPDF2.0 NLO. The bands represent the total uncertainties on the predictions [1] [2] [3].



Aerial view of the DESY accelerators.

Image credit: DESY

Motivation

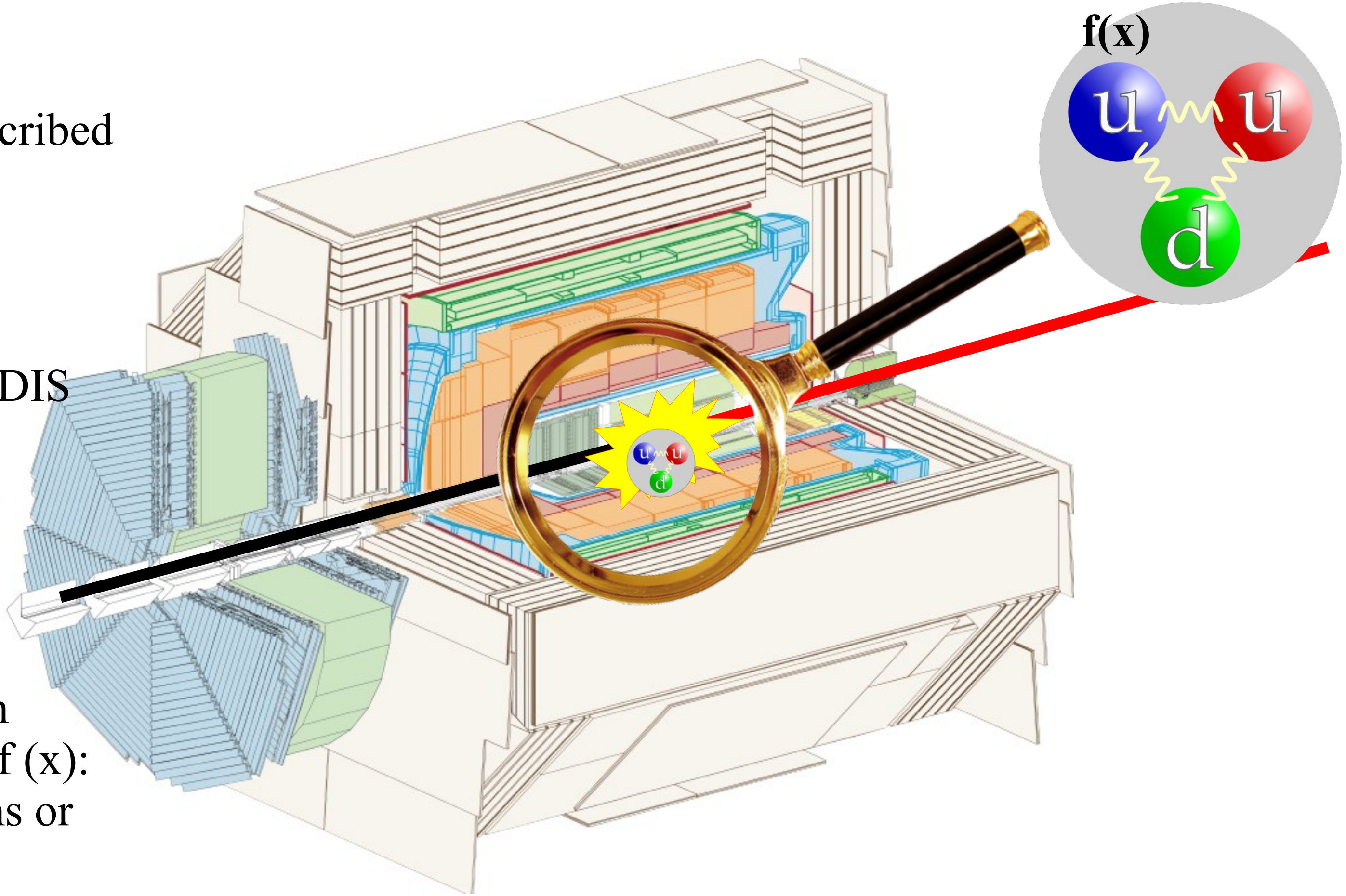
In pQCD the proton is described in terms of parton density functions f(x).

+

These depend on the factorisation scale, μ^2 (for DIS usually Q^2).

↓

Usually presented as parton momentum distributions, xf (x): parton distribution functions or **PDFs**.



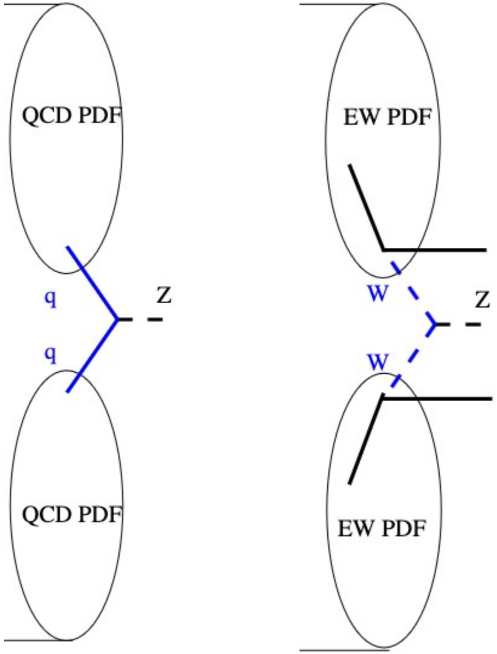
The H1 detector. Image credit: DESY

The **PDFs** are convoluted with the fundamental point-like scattering cross sections for partons to calculate **cross sections → 2 way road!**

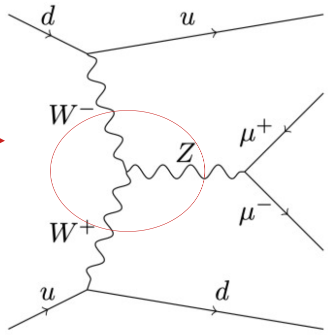
We can extrapolate this!

What if heavy bosons and photons were considered to be inside the proton as well?

Momentum dependent parton distribution functions for heavy bosons and **photons**



Diagrams for production of Z bosons:
left: standard qqbar → Z, right: VBF with Z boson.



We can **validate** this!

Photon "PDFs"

Methodology

The photon parton distribution of photons carrying a fraction z of the proton's light-cone momentum, obeys the DGLAP equation [4] .

$$\frac{d\gamma(z,Q^2)}{d\log Q^2} = \frac{\alpha_{\rm em}}{2\pi}\sum_f e_f^2 \int_z^1 \frac{dx}{x} P_{\gamma\leftarrow q}\left(\frac{z}{x}\right)\left[q_f(x,Q^2)+\bar{q}_f(x,Q^2)\right]$$

$$z\,\frac{d\gamma(z,Q^2)}{d\log Q^2} = \frac{\alpha_{\rm em}}{2\pi}\sum_f e_f^2 \int_z^1 \frac{dx}{x} P_{\gamma\leftarrow q}\left(\frac{z}{x}\right)\left[q_f(x,Q^2)+\bar{q}_f(x,Q^2)\right] z = \frac{\alpha_{\rm em}}{2\pi}\sum_f e_f^2 \int_z^1 \frac{dx}{x} P_{\gamma\leftarrow q}\left(\frac{z}{x}\right)\left[q_f(x,Q^2)+\bar{q}_f(x,Q^2)\right] x \cdot (z/x)$$

$$z\,\gamma(z,Q^2) = \frac{\alpha_{\rm em}}{2\pi}\int_{Q_0^2}^{Q^2}\frac{d\mu^2}{\mu^2}\int_z^1 \frac{dx}{x} P_{\gamma\leftarrow q}\left(\frac{z}{x}\right) F_2(x,\mu^2)\ z/x$$

Neutral current (NC)

$$\sigma^{\pm}_{r,\rm NC} = \frac{d^2\sigma^{e^\pm p}_{\rm NC}}{dx_{\rm Bj}\,dQ^2}\cdot\frac{Q^4 x_{\rm Bj}}{2\pi\alpha^2 Y_+}$$

At low Q2, i.e. Q2 ≪ M^2_Z , the contribution of Z exchange is negligible

$$\sigma^{\pm}_{r,\rm NC} = F_2 - \frac{y^2}{Y_+}F_L$$

The contribution of the term containing F_L is negligible at small y

$$\sigma^{\pm}_{r,\rm NC} \approx F_2$$

Since $Y_+ = 1+(1-y)^2$ and $P_{\gamma\leftarrow q}\left(\frac{z}{x}\right) = \frac{(1 + (1- (z/x)^2))}{(z/x)}$:

$$z\gamma(z,Q^2) = \frac{\alpha_{em}}{2\pi}\int_{Q_0^2}^{Q^2}\frac{d\mu^2}{\mu^2}\int_z^1\frac{dx}{x}\,\frac{(1 + (1- (z/x)^2))}{z/x}\,\frac{d^2\sigma_{NC}^{e^\pm p}}{dx_{Bj}dQ^2}\cdot\frac{Q^4\, x}{2\pi\alpha^2}\,\frac{1}{1+(1-y)^2}\; z/x$$

1. Numerical integration

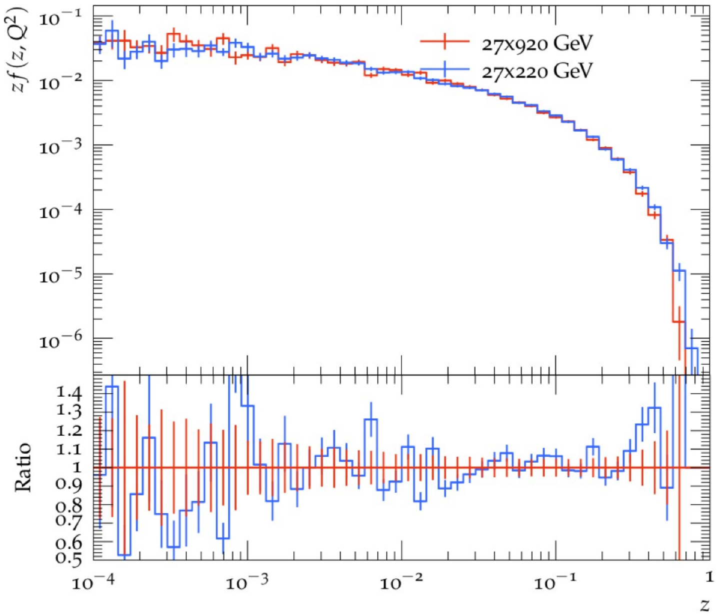
2. DIS kinematics
z/x = y
Veto event if:
(x or y < z)
$z < Q^2/s$
$y > 1$

Results

1. Numerical integration

$$z\gamma(z,Q^2) = \frac{\alpha_{em}}{2\pi}\int_{Q_0^2}^{Q^2}\frac{d\mu^2}{\mu^2}\int_z^1\frac{dx}{x}\,\frac{(1+(1-(z/x)^2))}{z/x}\,\frac{d^2\sigma_{NC}^{e^\pm p}}{dx_{Bj}dQ^2}\cdot\frac{Q^4\,x}{2\pi\alpha^2}\,\frac{1}{1+(1-y)^2}\,z/x$$

μ = 10 GeV



Photon PDF at energy scale μ = 10 GeV with numerical integration

Results

2. DIS kinematics

$$z\gamma(z,Q^2) = \frac{\alpha_{em}}{2\pi}\int_{Q_0^2}^{Q^2}\frac{d\mu^2}{\mu^2}\int_z^1 \frac{dx}{\cancel{x}}\,\frac{(1+(1-(z/x)^2))}{\cancel{z/x}}\,\frac{d^2\sigma_{NC}^{e^\pm p}}{dx_{Bj}dQ^2}\cdot\frac{Q^4\,\cancel{x}}{2\pi\alpha^2}\,\frac{1}{1+(1-y)^2}\,\cancel{z/x}$$

DIS: z/x = y

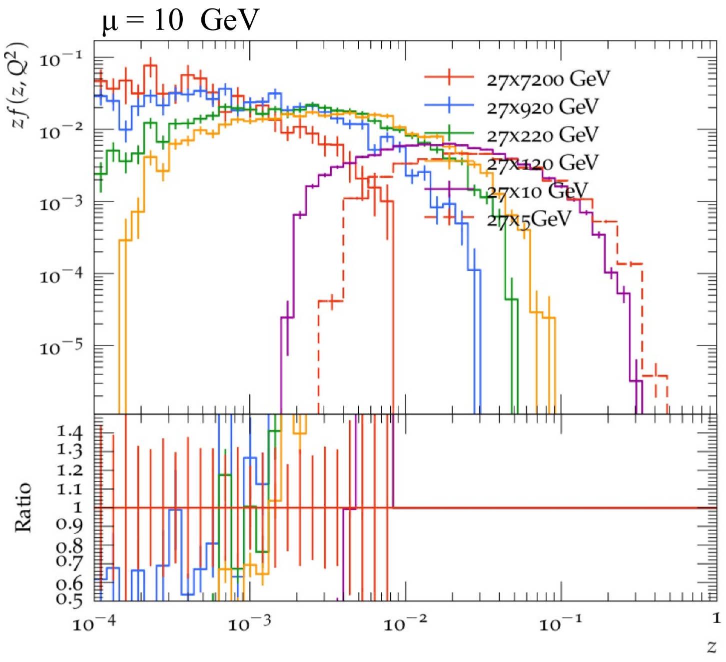
Veto event if:

(x or y < z)

$z < Q^2/s$

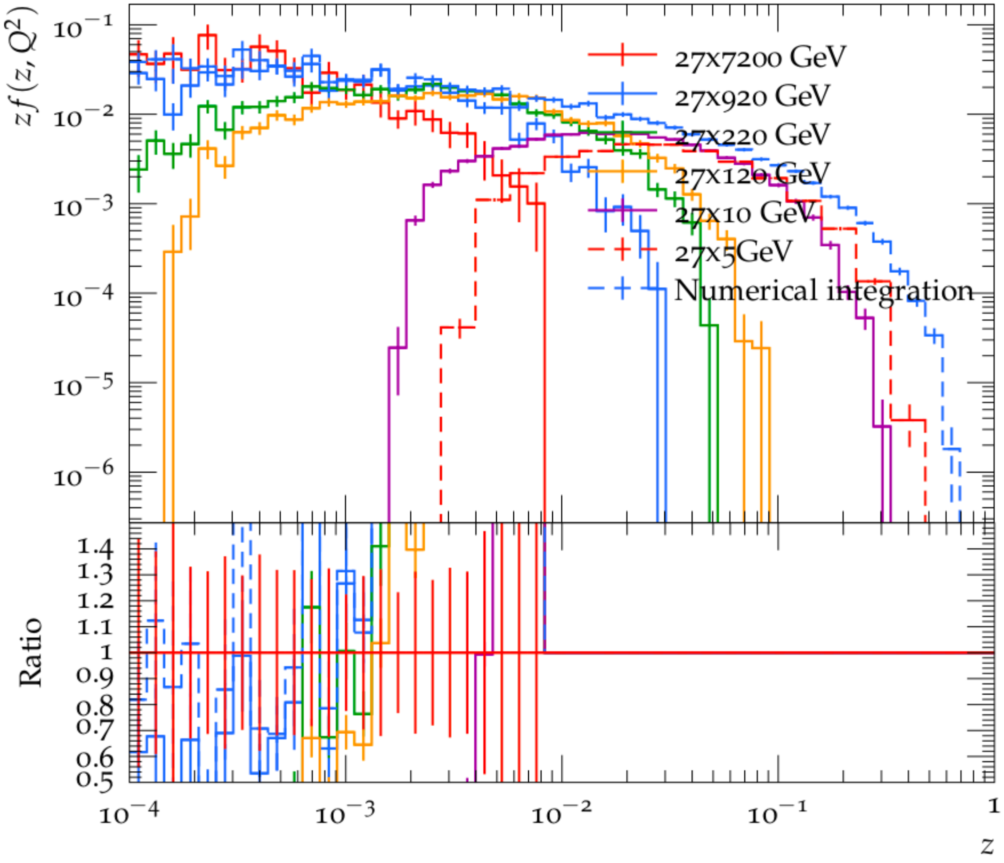
$y > 1$

$$z\,\gamma(z,Q^2) = \frac{\alpha_{em}}{2\pi}\int_{Q_0^2}^{Q^2}\frac{d\mu^2}{\mu^2}\int_z^1 \frac{dx}{\cancel{x}}\,\frac{\cancel{1+(1-y)^2}}{\cancel{y}}\,\frac{d^2\sigma_{NC}^{e^\pm p}}{dx_{Bj}dQ^2}\cdot\frac{Q^4\,\cancel{x}}{2\pi\alpha^2}\,\frac{1}{\cancel{1+(1-y)^2}}\,\cancel{y}$$

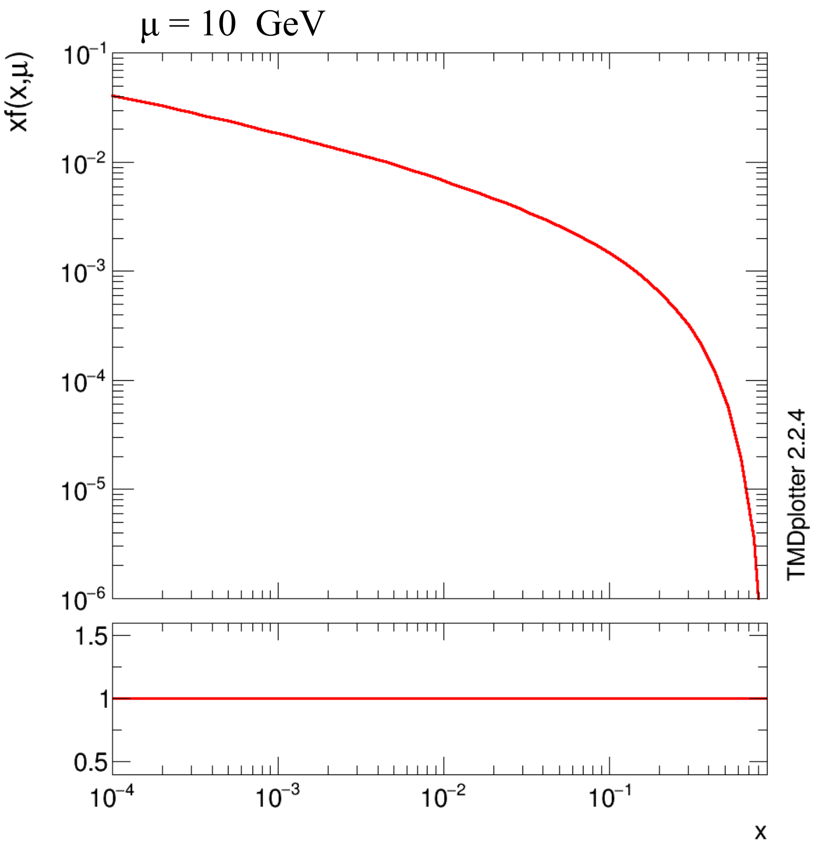


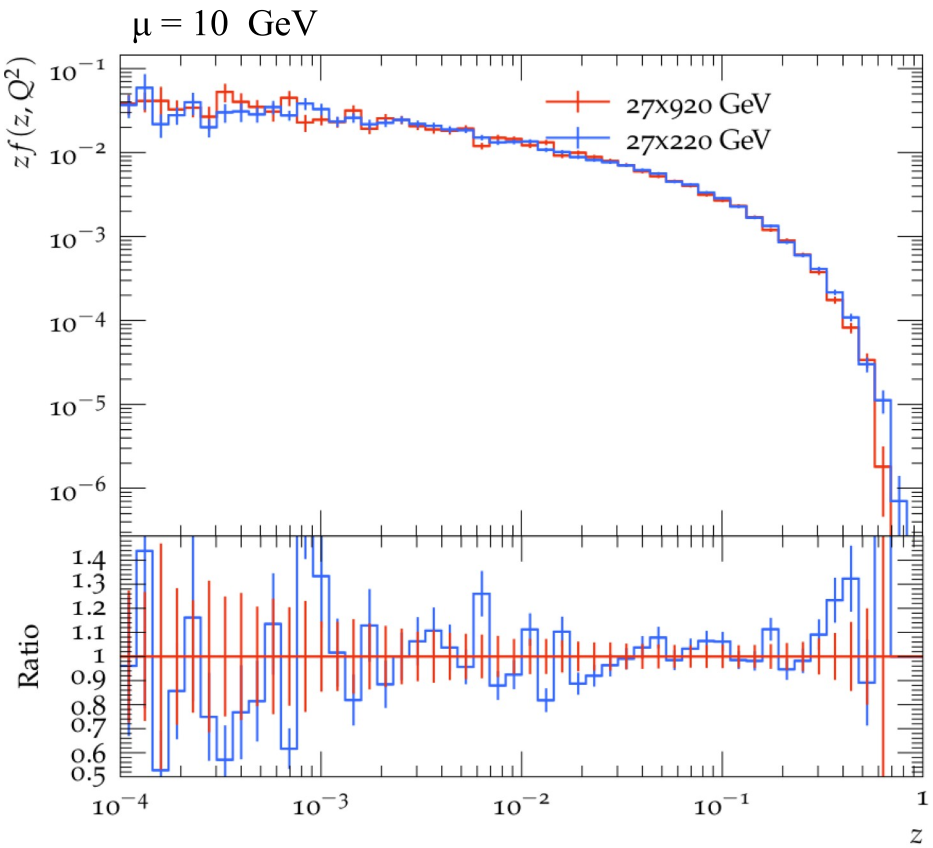
Photon PDF at energy scale μ = 10 GeV with different proton energy beams (right.)

$\mu = 10$ GeV



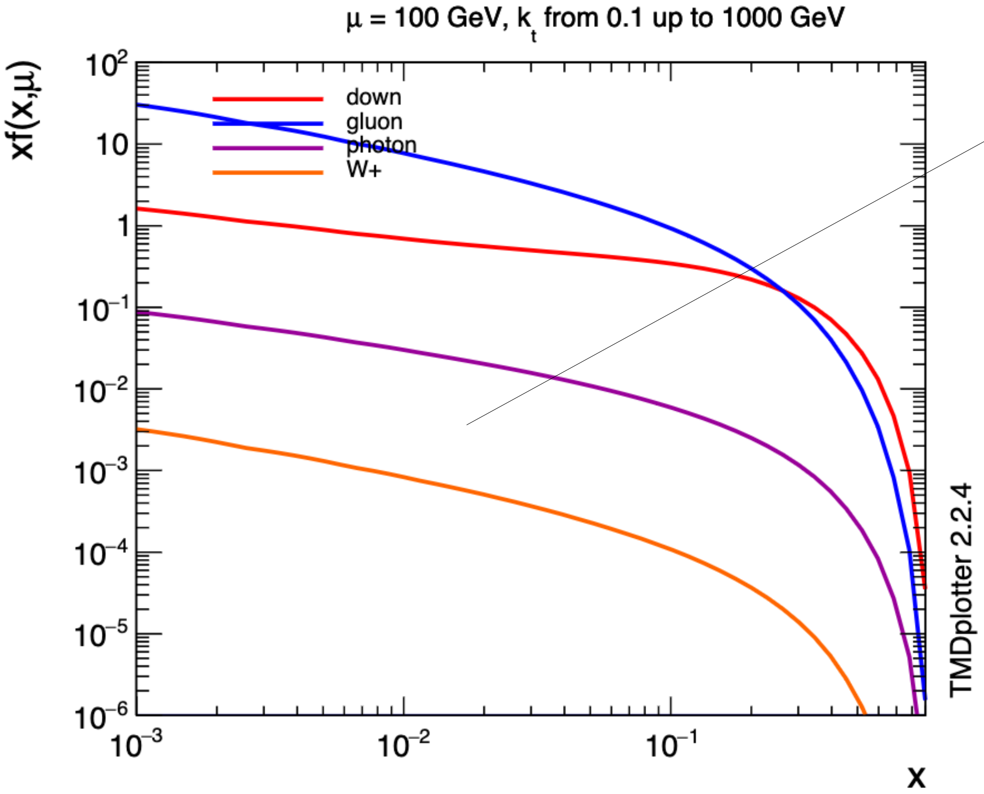
Photon PDF at energy scale $\mu = 10$ GeV with different proton energy beams and numerical integration (dashed blue line)





Photon PDF at energy scale μ = 10 GeV (left) and photon PDF at energy scale μ = 10 GeV with numerical integration (right)

Outlook



Charged current (CC)

$$\sigma^{\pm}_{r,\mathrm{CC}} = \frac{2\pi x_{\mathrm{Bj}}}{G_F^2}\left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{\mathrm{d}^2\sigma^{e^\pm p}_{\mathrm{CC}}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2}$$

$$\sigma^{\pm}_{r,\mathrm{CC}} = \frac{Y_+}{2} W_2^{\pm} \mp \frac{Y_-}{2} x W_3^{\pm} - \frac{y^2}{2} W_{\mathrm{L}}^{\pm}$$

$$\sigma^{+}_{r,\mathrm{CC}} \approx (x\bar{U} + (1-y)^2 xD)\,, \qquad \sigma^{-}_{r,\mathrm{CC}} \approx (xU + (1-y)^2 x\bar{D})$$

W PDF (orange), down quark PDF (red), gluon PDF (blue) and photon PDF (violet) energy scale 100 GeV (left).

Conclusions

Conclusions:

- The photon PDF in the neutral current channel has been obtained and validated.
- First tests for heavy boson PDFs have been performed.
- Operative framework.

Outlook:

- Charged current W PDF.
- Perform the photon PDF fit to the available DIS data.
- Heavy bosons PDFs, heavy bosons and photon TMDs.

- This study motivates the extraction of W PDF from charged current DIS. Then one can use it to compare it with the measurement of the VBF cross-section.

Backup

The Parton Branching Method

Parton Branching (PB) a method to obtain collinear PDFs and (transverse momentum dependent parton density functions) TMDs.

It is based on introducing a soft-gluon resolution scale z_M into the QCD evolution equations to separate

resolvable and **non-resolvable** emissions

splitting probabilities

Sudakov form factors ($P_{ba}(\alpha_s,z)$):

PB evolution Equation for TMDs densities

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

$\in [0,1] \rightarrow z \rightarrow \boldsymbol{\mu^2}$”

$\mu^2 < \mu$

∃ Splitting in $[\mu_0, \mu]$

$\mu^2 > \mu$

No splitting in $[\mu_0, \mu]$

The Parton Branching Method & TMDs

PB evolution Equation for TMDs Densities:

Starting energy scale: μ0

μ

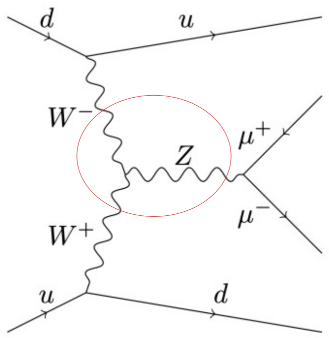
$$\tilde{\mathcal{A}}_a(x, k_{\perp,0}^2, \mu_0^2) = x f_a(x, \mu_0^2) \cdot \frac{1}{q_s^2} \exp\left(-\frac{k_{\perp,0}^2}{q_s^2}\right)$$

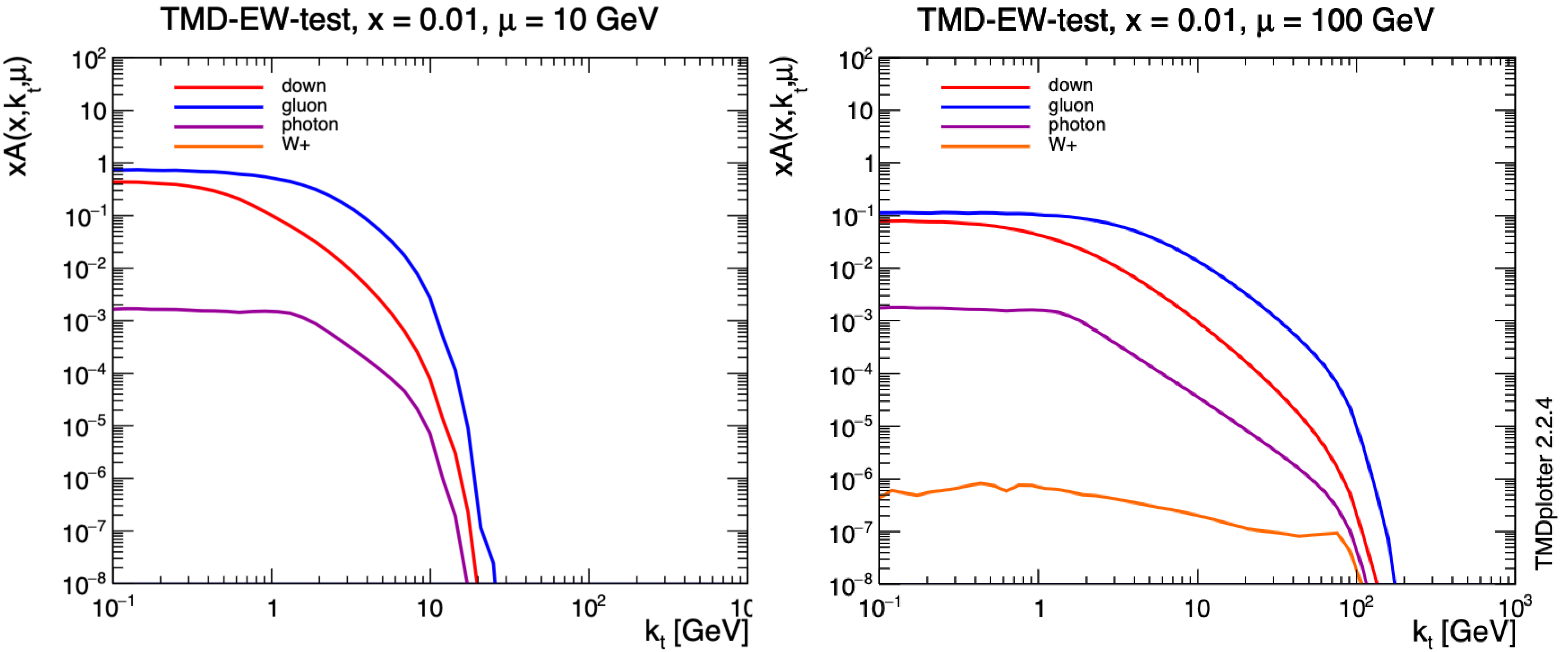
$$\mathcal{A}_a(x, \mathbf{k}, \mu^2) = \Delta_a(\mu^2)\, \mathcal{A}_a(x, \mathbf{k}, \mu_0^2) + \sum_b \int \frac{d^2\mathbf{q}'}{\pi \mathbf{q}'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)} \Theta(\mu^2 - \mathbf{q}'^2)\, \Theta(\mathbf{q}'^2 - \mu_0^2)$$
$$\times \int_x^{z_M} \frac{dz}{z} P_{ab}^{(R)}(\alpha_s, z)\, \mathcal{A}_b\left(\frac{x}{z}, \mathbf{k} + (1-z)\mathbf{q}', \mathbf{q}'^2\right) \quad ,$$

Where the TMDs are linked to the collinear parton densities (also called ”integrated TMDs“ (iTMDs):

$$\widetilde{f}_a(x, \mu^2) = \Delta_a(\mu^2)\, \widetilde{f}_a(x, \mu_0^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz\, P_{ab}^{(R)}(\alpha_s(\mu'^2), z)\, \widetilde{f}_b(x/z, \mu'^2)$$

$$f_a(x, \mu^2) = \int \mathcal{A}_a(x, \mathbf{k}, \mu^2) \frac{d^2\mathbf{k}}{\pi}$$





W TMD (orange), down quark TMD (red), gluon TMD (blue) and photon TMD (violet) (with Parton Branching Method) for energy scale 10 GeV (left) and energy scale 100 GeV (right)

References

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