Transverse Momentum Dependence of Parton Density for Vector Boson Scattering

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Abstract

Little is known about the effect of the fractional momentum in the hardest sub-process in Multi Parton Radiation. The following study tries to determine the transverse momentum dependence of different parton distribution functions in a proton-proton interaction, using a Monte Carlo simulation Phytia for the event generation, and a Rivet routine for the data analysis. This is made by comparing fractional momentum histograms subject to different parton distribution functions and scales.

Contents

1 Introduction

In the QCD parton model each hadron is described as a set of free elementary constituents. It is the interaction of said constituents that lead to the complex events observed in HEP detectors. At fixed mass final states, partons with low momentum fraction, x, are probed.

1.1 PDFs and TMDs

The parton distribution function $f_i(x, \mu^2)$ is the probability density of finding a parton carrying a certain fraction x of the proton momentum with μ being the energy scale (resolution) of the hard interaction[1]. The importance of Transverse Momentum Dependent (TMD) parton distributios lies in the fact that they bring essential information about the structure of the protons.

Commonly, fixed-order QCD calculations only take into account the first couple orders of perturbation. Nevertheless, there are regions of phase space in which higher-order terms are enhanced and cannot be neglected.[4] Such terms should be considered when trying to get an approximate result. It has been noted that important contributions appear when a gluon is emitted, or when a gluon splits into two partons.

1.2 Fractional Momentum Evolution

Multiple branching is an effect involved in the evolution of QCD events and it refers to the higher-order contributions of multiple parton emission.

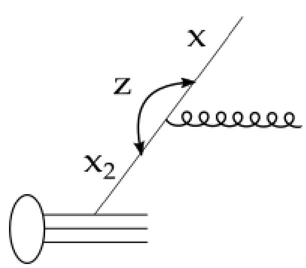


Figure 1: Momentum fraction evolution with the emission of a gluon.

An incoming quark carries a fraction x_2 of the initial hadron's momentum and moves to a lower momentum fraction by emitting a gluon. This emission can go on successively. The gluon in question is generated with a certain momentum fraction $(1-z)$, leaving a reminder in the quark of x.

$$x = z \cdot x_2 \tag{1}$$

One can observe that if $z = 1$ there is no emission.

It follows that the cross section, σ, for the hard-scattering depends on the scale μ^2 and the momentum fraction distribution of the parton, $f(x, \mu^2)$.

$$\sigma = f(x_1, \mu^2) \otimes \hat{\sigma}(x_1, x_2, \mu^2) \otimes f(x_2, \mu^2) \tag{2}$$

The Total Cross-section is factorized into a hard part, $\hat{\sigma}(x_1, x_2, \mu^2)$ and the parton distribution functions. The following figure shows an example diagram of a the production of a boson with parton showers indicating the *pdf* we are interested in.

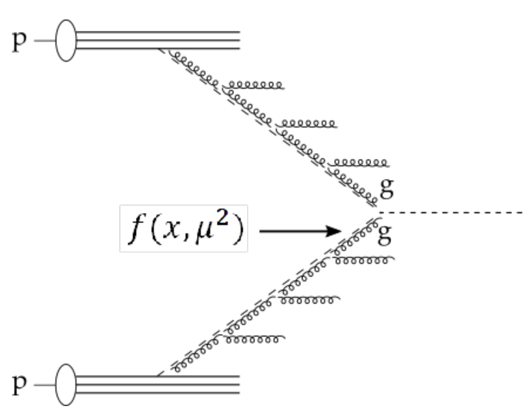


Figure 2: Gluon emission in DY scattering from two incoming protons.

This structure was chosen based on its convenience when studying the kinematics involved in the transverse momentum dependence. It is also worth mentioning that for small x it is more likely to find gluon radiation, therefore the gluon density is very high.

2 Techniques

2.1 MC Event Generation with Pythia

The events analyzed were generated through the Monte Carlo method using the *PYTHIA* program, a tool for the generation of events in high-energy collisions of elementary particles.[2] It makes use of basic physics models in order to display the evolution of a hard process into its final state.

Random numbers were used to generate the momentum fraction x from the parton distribution function and then the event. These were based on a function:

$$f(x) \propto \frac{1}{x} \tag{3}$$

The x values from the probability function $f(x)$ were obtained from

$$u(x) = \frac{1}{x - x_{min}} \int_{x_{min}}^{x} f(t)dt = \frac{1}{x - x_{min}} \int_{x_{min}}^{x} \frac{1}{t}dt \tag{4}$$

And integrating Eq. 4 leads to

$$x_j = x_{min}(\frac{x_{max}}{x_{min}})^{u_j} \tag{5}$$

Moreover, the usual QCD event generator, which provides a model for a process involving the interaction of hadrons, was modified for this study so that it would show the information needed. First of all, the momentum fraction of one of the incoming gluons had to be fixed while the other one remained variable (so it could be kinematically reconstructed later from the generated particles). Second, in contrast to the general way, the events had to be generated not according to the cross-section, but to the parton density function. All these with the purpose of extracting said parton density after the shower simulation. Lastly, another reason for using this special code is the fact that one can easily switch the incoming particles from quarks to gluons. The latter were used in this particular case since the purpose of the study lies on the kinematics and the TMD parton density.

In the framework of this program, the random x described above is inserted into the parton distribution density for its further analysis.

$$x = x_{min}(\frac{x_{max}}{x_{min}})^R \tag{6}$$

with $x_{min} = 10^{-6}$, $x_{max} = 1$ and R a random number from a flat distribution.

2.2 Data Analysis Using Rivet

Rivet provides a convenient infrastructure for the analysis, reproduction and display of high-energy events generated with MC. It is a tool for the reproduction and display of the data generated by Pythia. In this particular program, the kinematical quantities of interest of the incoming proton p and the outgoing boson are used to calculate:

$$p_{g_2} = p_B - x_1 \cdot p_p \tag{7}$$

where p_{g_2}, p_B and p_p indicate the four-momentum of the scattered gluon, the boson and the proton respectively. $x_1 = 0.99$ corresponds to the momentum fraction (fixed in pythia) of the other gluon generated by the proton. Figure 3 shows a simplified version of Figure 2, portraying only the particles in the main focus.

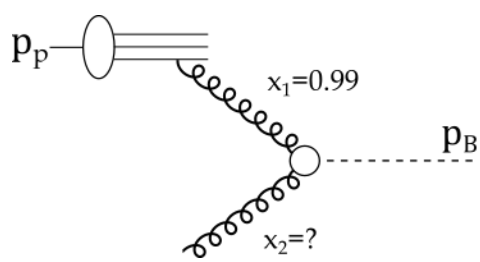


Figure 3: Incoming gluons and outgoing boson in the hard-process.

Using this information is then possible to calculate x_2 according to the equation:

$$x_2 = \frac{(E + p_z)_g}{(E + p_z)_p} \tag{8}$$

where E is the energy of the particle and p_z its momentum in the z direction.

Afterwards, the plotting information is stored in a YODA (Yet more Objects for Data Analysis) file and transformed into histograms using the *rivet-mkhtml command*.

3 Results

Two different *pdfs* were used for the comparison of data. The first one, a *simple pdf* of the form

$$g(x) = \frac{3(1-x)^5}{x} \tag{9}$$

represents a simple gluon leading to a constant total cross-section for increasing energies. Although, this is actually not the case since the total cross-section does rise slowly with the energy. Therefore a second, and more realistic, pdf was employed in the Pythia code. It is a pdf from the cteq collaboration including pp data which has a scale dependence and includes the QCD evolution.

Three cases were analyzed through the use of histograms, as seen in Table 1: the first makes use of the simple pdf in the hard process and takes a default pdf in the parton shower. The second and third use the real pdf in the hard process, but the third one also uses that same real pdf in the parton shower generation.

Hard Process	Parton Shower
Simple *pdf*	Pythia Default
Real *pdf* + QCD evolution	Pythia Default
Real *pdf* + QCD evolution	

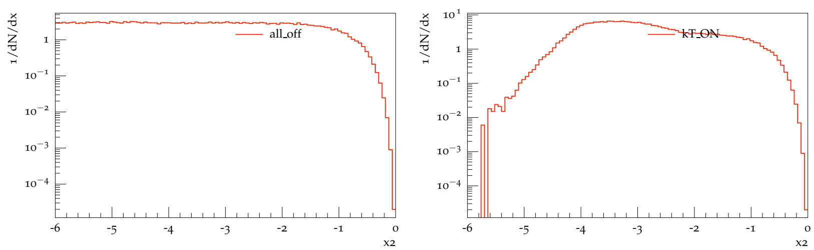
Table 1: Description of the *pdfs* employed in the different cases.

All this was done in order to study separately the effect of the pdf in the hard process and in the parton shower.

3.1 Gluons

3.1.1 Simple PDF

As ground for comparison, starting with the *simple pdf*, the following histograms display the difference between activating the primordial k_T for the x distribution and not activating it. There is a clear difference in the kinematics of the distribution since x must balance the added momentum.



(a) (b)

Figure 4: x distributions for the primordial k_T (a) on and (b) off.

On the other hand, when turning on the parton showers added to k_T (Fig. 5) the effects are more significant when looking at the k_T distribution.

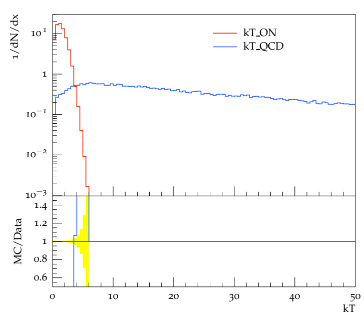
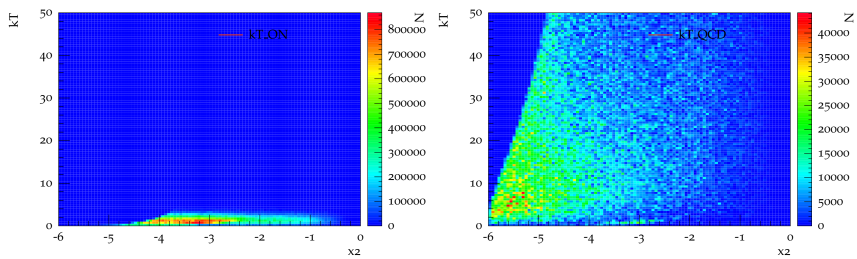


Figure 5: k_T distribution primordial k_T and parton showers activated.

When QCD showers are activated, the distribution becomes larger and flatter than its counterpart, which falls quite fast. This evidently huge change in k_T is due to gluon splitting caused by the radiation. There is also a new dependence between k_T and x as can be seen in Fig. 6:



(a) (b)

Figure 6: $x$vs.k_T plots when the showers are (a) desactivated and (b) activated.

3.1.2 Real PDF in the Hard Process and in the Parton Shower

The same analysis applied to the simple pdf was used with the real one in both cases, Hard Process and Hard Process + Parton Shower as explained in the beginning of this section. To summarize the results, Fig. 7 portraits a comparison of the x and k_T distributions for each one of the studied cases.

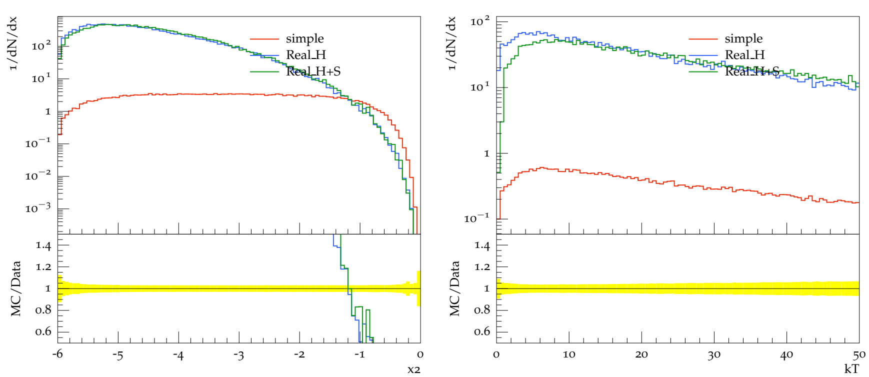


Figure 7: $x$and k_T distributions for three cases analyzed. Red: Simple pdf. Blue: Real pdf in Hard Process. Green: Real pdf in Hard Process and Parton Shower.

3.2 Quarks

All the process described above was analyzed using incoming quarks instead of gluons. Results from both versions are shown in Fig. 8, where the plot in red corresponds to the gluons case and blue to the quarks.

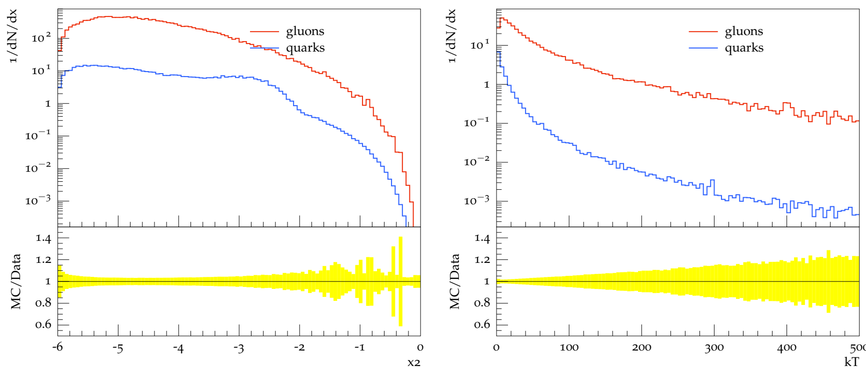


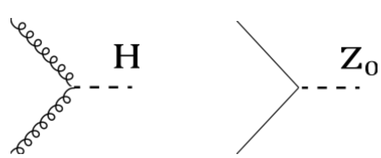
Figure 8: Gluons vs. Quarks: $x$and k_T distributions for incoming gluons and incoming quarks.

Even though both plots have a different normalization and apparently comparable sizes, there is however a considerable difference between their x and k_T values.

4 Conclusions

When comparing the histograms obtained from either gluons or quarks, there is a clear difference in the transverse momentum when the parton showers are activated — the distribution becomes somewhat flat, resulting in a tail at large k_T.

Regarding the differences between quarks and gluons, it should me mentioned that this two cases can be compared to Higgs production ($gg \longrightarrow H$) and Drell-Yan pairs ($q\bar{q} \longrightarrow Z_0$), and thus account for the difference in k_T spectra of Z and H production (Fig. 10).



(a) (b)

Figure 9: (a) Higgs boson pairs and (b) Drell-Yan scattering.

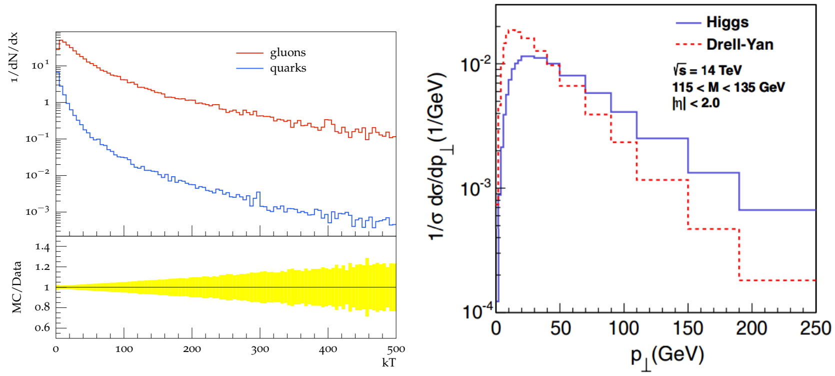


Figure 10: Normalized transverse momentum spectra for Higgs bosons and for Drell-Yan pairs.[7]

5 Aknowledgements

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References

[1] Transverse Momentum Dependent (TMD) Parton Distribution Functions: status and prospects. Ángeles-Martínez, R. *et al.* arXiv: 1507.052267v1 2015

[2] An Introduction to Pythia 8.2 T. Sjöstrand *et al.* Comput.Phys.Commun. 191 (2015) 159-177 arXiv:1410.3012a 2014

[3] Light-cone Variables, Rapidity and All That. J C Collins arXiv: hep-ph/970539v1 1997

[4] QCD and Collider Physics R K Ellis, W J Stirling, B R Webber Cambridge University Press 1996

[5] Parton Distribution Functions Placakyte, Ringaile arXiv:1111.5452 2011

[6] Multi-Parton Interactions at the LHC P. Bartalini *et al.* arXiv:1111.5452 2011

[7] Higgs boson as a Gluon Trigger P. Cipriano *et al* DOI: 10.1103/PhysRevD.88.097501 2013