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Parton Distributions at a 100 TeV Hadron Collider

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The determination of the parton distribution functions (PDFs) of the proton will be an essential input for the physics program of a future 100 TeV hadron collider. The unprecedent center-of-mass energy will require knowledge of PDFs in currently unexplored kinematical regions such as the ultra low-x region or the region of multi-TeV momentum transfers Q^2. In this contribution we briefly summarize the studies presented in the PDF section of the upcoming report on *"Physics at a 100 TeV pp collider: Standard Model processes"*. First we map the PDF kinematical coverage in the (x, Q^2) plane, quantify PDF uncertainties, and compute ratios of PDF luminosities between 100 TeV and 14 TeV. Then we show how the extreme kinematics of such collider lead to a number of remarkable PDF-related phenomena such as the top quark as a massless parton, an increased role of photon-initiated processes and the possible need of PDFs with high-energy resummation.

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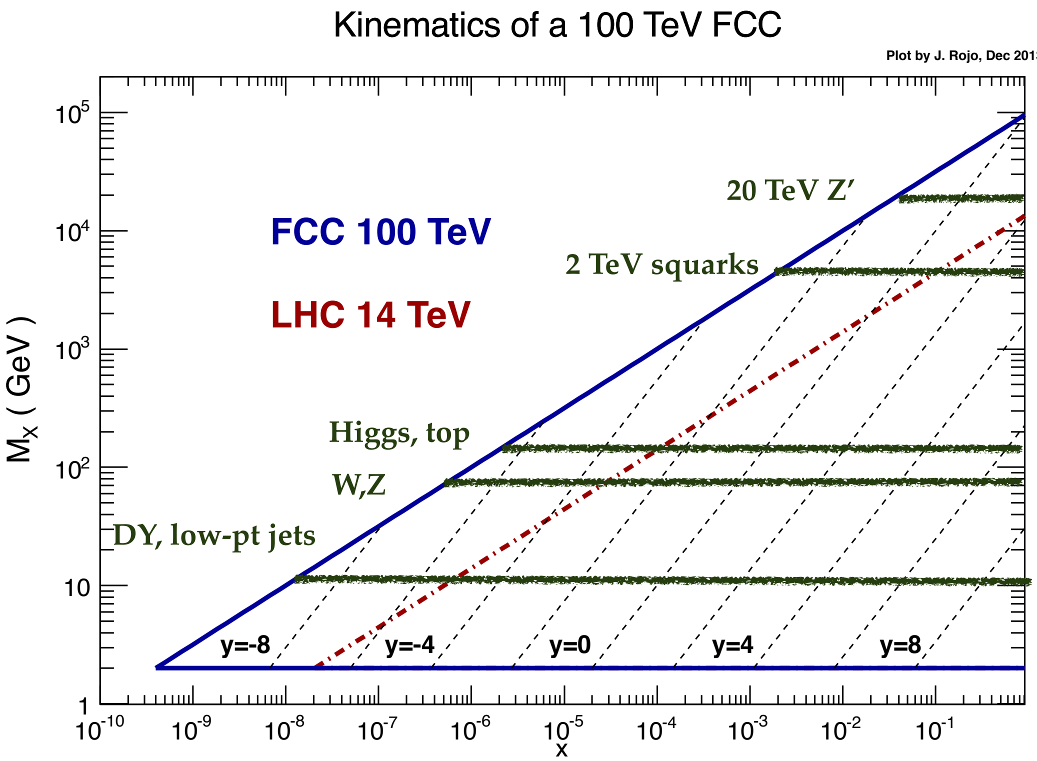

Figure 1: Kinematical coverage in the (x,M_X) plane of a $\sqrt{s}=100$ TeV hadron collider (solid blue line), compared with the corresponding coverage of the LHC at $\sqrt{s}=14$ TeV (dot-dashed red line). The dotted lines indicate the lines of constant rapidity y at the FCC. We also indicate the relevant M_X regions for phenomenologically important processes, from low masses (Drell-Yan, low p_T jets), electroweak scale processes (Higgs, W,Z, top), and possible new high-mass particles (squarks, Z').

The structure of the proton at a 100 TeV collider. The accurate determination of the parton distribution functions (PDFs) of the proton is an essential ingredient of the LHC physics program [1–7], and will be even more so at any future higher-energy hadron collider. In particular, a new collider with center-of-mass energy of $\sqrt{s}=100$ TeV, dubbed the Future Circular Collider (FCC), would probe PDFs in currently unexplored kinematical regions, such as the ultra low-x region, $x\lesssim 10^{-5}$, or the region of very large momentum transfers, $Q^2\geq(10\ \text{TeV})^2$.

In this contribution we summarize the studies presented in the PDF section of the report on *"Physics at a 100 TeV pp collider: Standard Model processes"* [8]. On the one hand, we quantify in various ways PDF uncertainties at a 100 TeV hadron collider, map their kinematical coverage in the (x,Q^2) plane, and compute ratios of PDF luminosities between 100 and 14 TeV. On the other hand, we show how the extreme kinematics of such collider lead to a number of new phenomena related to PDFs such as the top quark as a massless parton, an increased role of photon-initiated processes and the need for PDFs with high-energy resummation.

In Fig. 1 we represent the kinematical coverage in the (x,M_X) plane, where M_X is the invariant mass of the produced final state, for a $\sqrt{s}=100$ TeV hadron collider, compared with the corresponding coverage of the LHC at $\sqrt{s}=14$ TeV. We also indicate the coverage in M_X for phenomenologically important processes at the FCC, from low masses (such as Drell-Yan or low p_T

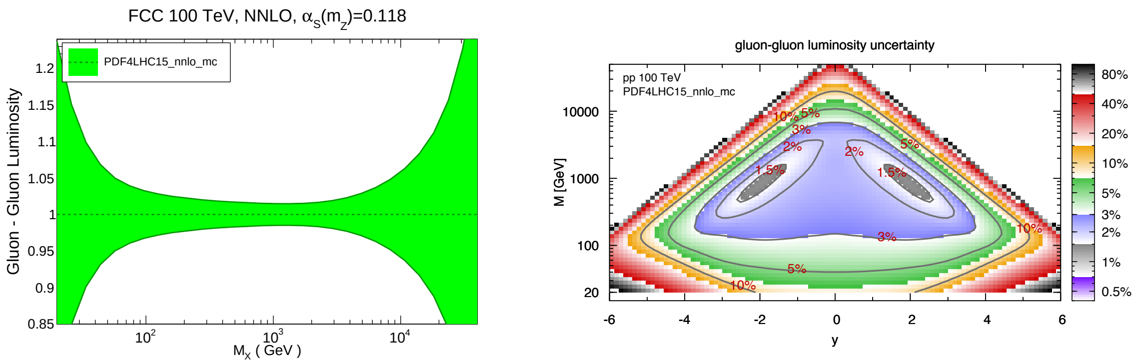

Figure 2: The PDF uncertainties in the gluon-gluon luminosity at the FCC with $\sqrt{s} = 100$ TeV computed with the `PDF4LHC15_nnlo_mc` set. Left plot: the rapidity-integrated luminosity $\mathscr{L}_{gg}(M_X)$. Right plot: the double-differential luminosity $\widetilde{\mathscr{L}}_{gg}(M_X, y)$.

jets), electroweak scale processes (such as Higgs, W, Z, or top production), and hypothetical new high-mass particles (such as a 2 TeV squark or a 20 TeV Z').

In Fig. 2 we show the PDF uncertainties in the gluon-gluon luminosity at the FCC with $\sqrt{s} =$ 100 TeV computed with the `PDF4LHC15_nnlo_mc` set [2, 9], both for the rapidity-integrated PDF luminosity $\mathscr{L}_{gg}(M_X)$ and for the corresponding double-differential luminosity $\widetilde{\mathscr{L}}_{gg}(M_X, y)$ [8]. PDF uncertainties are at the few-percent level for 100 GeV $\lesssim M_X \lesssim$ 5 TeV, increasing for larger values of M_X, relevant for heavy particle searches, and for smaller values of x, relevant for electroweak physics and semi-hard QCD. The same qualitative behaviour is observed for other initial-state partonic combinations.

Next we compute the ratio of the rapidity-integrated PDF luminosities between 100 TeV and 14 TeV, for different initial-state partonic channels, $\mathscr{L}_{ij}^{(100)}(M_X)/\mathscr{L}_{ij}^{(14)}(M_X)$. These ratios provide a direct method to rescale production cross-sections between 14 and 100 TeV for processes dominated by a single initial-state luminosity. In Fig. 3 we show the ratio of PDF luminosities between 100 TeV and 14 TeV for different initial-state channels, using as input `PDF4LHC15_nnlo_mc`, with the corresponding 68% CL PDF uncertainties. We observe that for low invariant masses, $M_x \lesssim 100$ GeV, the increase in parton luminosities when going from the LHC to the FCC is moderate, a factor 10 at most. On the other hand, the luminosity ratio increases rapidly as we move away from the electroweak scale, since these the increase in energy of the FCC dramatically dominates over the large-x fall-off of the PDFs at the LHC. For invariant masses around $M_X \simeq 1$ TeV, for instance, the gg, qg, $q\bar{q}$ and qq luminosity ratios are $\simeq 100, 50, 20$ and 10, respectively. In general, gluon-initiated processes are those that will benefit more from the increase in center-of-mass energy due to the rapid rise of the gluon PDF at medium- and small-x from DGLAP evolution.

Photon-initiated processes at 100 TeV. Consistent evaluation of electroweak corrections require PDFs with QED effects including a determination of the photon PDF $\gamma(x, Q)$. A number of QED PDF sets are available: MRST2004QED [10], NNPDF2.3QED [11] and the recent CT14QED [12], and PDF evolution with QED effects has been implemented in the `APFEL` public PDF evolution program [13]. Remarkable, already at the LHC, photon-initiated diagrams can be comparable to quark-initiated ones, and this trend continues at the FCC energies, and to illustrate this now we

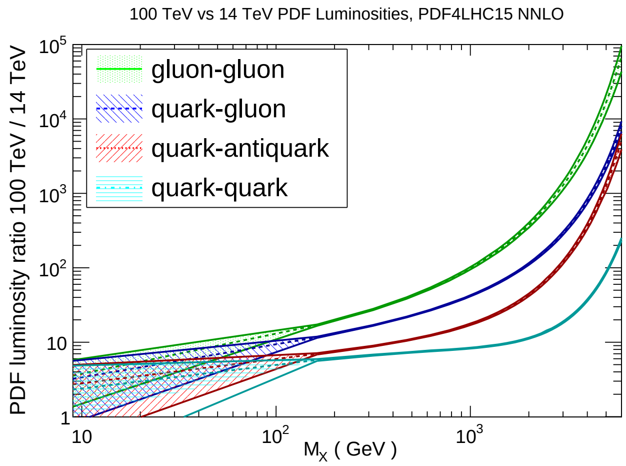

Figure 3: The ratio of PDF luminosities between $\sqrt{s_1} = 100$ TeV and $\sqrt{s_2} = 14$ TeV for different initial-state channels, computed with the PDF4LHC15 NNLO set.

provide predictions for electroweak production processes at $\sqrt{s} = 100$ TeV. The results have been obtained with `aMC@NLO` [14] using the `apfel_nn23qednlo0118_lept` PDF set [15].

In Fig. 4 we show the invariant mass distribution of lepton pairs in neutral-current Drell-Yan production at $\sqrt{s} = 100$ TeV for $m_{e^+e^-} \geq 5$ TeV, separated in the different initial-state contributions, where the leptons must satisfy acceptance cuts of $p_T^{e^\pm} \geq 100$ GeV and $|\eta_{e^\pm}| \leq 4$. The lower panel shows the corresponding PDF uncertainties. We find that the photon-initiated contribution is $\geq 10\%$ for all the invariant mass range, although with large associated uncertainties. One of the reasons for this is that in the DY process the $q\bar{q}$-channel receives an additional kinematic suppression due to s-channel diagrams that are absent in the $\gamma\gamma$-channel. In Fig. 4 we also show the differential distributions for the invariant mass of the di-boson pair $m_{W^+W^-}$ in W^+W^- production. We find that the photon-initiated contribution dominates over the quark-antiquark annihilation for $m_{W^+W^-} \geq 7.5$ TeV, also here with substantial PDF uncertainties. The results of Fig. 4 highlight the importance of photon-initiated processes at high-energy hadron colliders, and the need to reduce the theoretical uncertainties that currently affect determinations of the photon PDF.

Top as a massless parton. At a 100 TeV hadron collider, for some processes the top quark mass can be much smaller than the typical hard-scattering collision energy. For $Q \sim 10$ TeV, for instance, $\alpha_s(Q)\log(Q^2/m_t^2) \sim 0.6$, which makes a perturbative expansion of the hard process questionable. Therefore, one might wonder if the concept of top quark PDF is relevant at the FCC, just as charm and bottom PDFs are commonly used in LHC calculations. As with charm and bottom, introducing a PDF for the top quark allows to resum potentially large collinear logarithms of the form $\alpha_s^n(Q)\log^n(Q^2/m_t^2)$ to all orders in perturbation theory. The generalization of the DGLAP evolution equations to include a top PDF up to NNLO is straightforward, and indeed most modern PDF sets provide variants where the maximum number of light quarks in the PDF evolution is set to $n_f = 6$. In Fig. 5 we show the top quark PDF, evaluated at $Q = 10$ TeV, together with the other light partons, for the NNPDF2.3NNLO $n_f = 6$ PDF set [17]. We observe that the top quark PDF can be of a similar size as the light quark PDFs, in particular at medium and small-x.

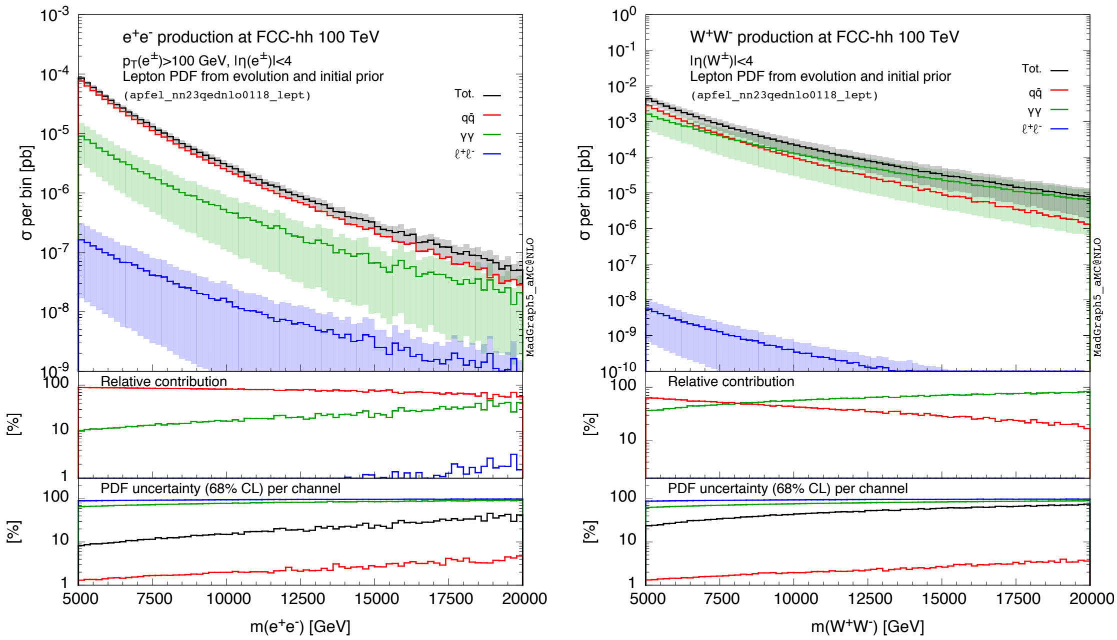

Figure 4: The invariant mass distribution of dileptons in e^+e^- (Drell-Yan) production (left) and for W^+W^- pairs (right) at a 100 TeV hadron collider, separating the contribution from each initial state.

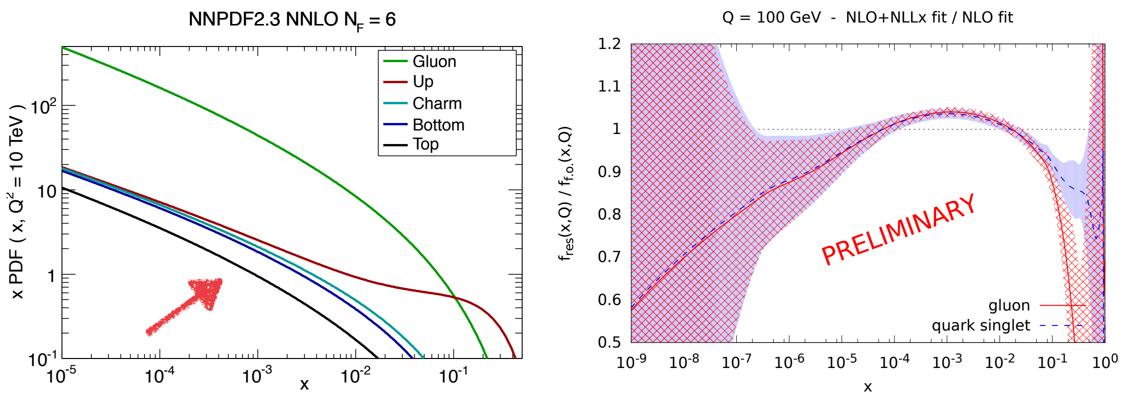

Figure 5: Left plot: the NNPDF2.3 NNLO $n_f = 6$ PDF set at $Q = 10$ TeV including the top quark PDF. Right plot: the gluon and quark single PDFs obtained from a preliminary DIS-only fit with NLO+NLLx DGLAP evolution, compared to a baseline fit with NLO evolution.

So while technically generating a top quark PDF is straightforward, it still needs to be demonstrated if it provides any calculational advantage over using the standard FFN scheme, where the top quark is treated as massive, even for the extreme energies of a 100 TeV collider. This issue has been recently studied in [18, 19], as well as the SM FCC report [8], reaching similar conclusions: a purely massless treatment of top quarks is unreliable even at 100 TeV, but the concept of a top quark PDF is still relevant in the context of matched calculations of heavy quark production such as FONLL [20].

High-energy resummation at 100 TeV. When Bjorken-x is small enough, logarithms of the form $\ln^k 1/x$ in the DGLAP splitting functions and in partonic matrix elements become large, and might hamper the standard perturbative expansion. These logarithms can be resummed to all orders by means of the k_t factorization theorem. Ongoing work [21] aims at providing resummed anomalous dimensions and coefficient functions through a fast `C++` code named `HELL` interfaced to `APFEL` [13], able to perform DGLAP evolution with NLLx small-x resummation matched to the fixed order up to NLO. Using this code, preliminary DIS-only NNPDF fits with NLLx evolution have been performed. In Fig. 5 we show the ratio of the gluon and quark singlet PDFs obtained from a DIS-only fit with NLO+NLLx DGLAP evolution to the corresponding fit with NLO evolution at $Q = 100$ GeV. In this comparison, NLO coefficient functions are used in both fits. As compared to the fixed-order NLO fit, including NLLx small-x effects in the PDF evolution leads to a suppression of the gluon and quark singlet for $x \lesssim 10^{-4}$, which reaches 20% at $x \simeq 10^{-7}$, and moderate few-percent enhancement of the PDFs at intermediate x. The further suppression at large-x is related to the lack of hadronic data. This preliminary results indicate that small-x resummation effects should be relevant for precision physics at a 100 TeV collider, and thus deserve further investigation in this context.

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