

Reduction of the PDF Uncertainty in the High-Mass Drell-Yan Spectrum with ePump

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(Dated: September 26, 2018)

Abstract

Uncertainties in the parametrization of Parton Distribution Functions (PDFs) are becoming a serious limiting systematic uncertainty in Large Hadron Collider (LHC) searches for Beyond the Standard Model (BSM) physics. This is especially true for measurements at high scales induced by quark and anti-quark collisions, where Drell-Yan continuum backgrounds are dominant. Using ePump to emulate a candidate PDF global fitting strategy, it is shown that judicious selection of measurable kinematical quantities can reduce the assigned systematic PDF uncertainties by significant factors. This will be possible by the huge statistical precision of future LHC Standard Model datasets.

I. INTRODUCTION

Beyond the Standard Model (BSM) physics at the Large Hadron Collider (LHC) would be found as deviations from Standard Model (SM) expectations, possibly in rates, but more typically in the kinematic distributions of final state objects or their combinations—of jets, leptons, and missing energy. Therefore the importance of accurately and precisely modeling SM physics cannot be overstated. While the electroweak properties of the SM are very precisely known, precision knowledge of Parton Distributions Functions (PDFs) is becoming a limiting factor for many BSM searches.

As PDFs are not analytically calculable in the framework of perturbative Quantum Chromodynamics (QCD), their shapes must be modeled by globally fitting measured distributions from many combinations of varied experimental data. Most of these data come from legacy experiments, such as Deep Inelastic Scattering (DIS) experiments, various fixed target hadron experiments, and the Fermilab Tevatron. LHC experimental results are beginning to be used in global PDF fits, and in the coming decades new knowledge of PDFs will come from measurements at ATLAS, CMS, and LHCb. We suggest that new strategies are worth exploring and we present one here.

Constraining PDFs and their uncertainties is now an intense research program. The systematic uncertainty in the PDF models arises from the 1) experimental uncertainties of the input data used in a global fit, 2) any theoretical assumptions assumed by the fitting groups, and/or 3) the chosen parameterizations characterizing the functional forms of the PDFs themselves. All of the global PDF fitting groups (CTEQ-TEA [1], MMHT [2], and NNPDF [3]) characterize their fits with complex error matrices and so experiments can legitimately include PDF uncertainties as a component to any theoretical error for any measurement or limit.

In this paper we explore the PDF uncertainties as they apply to the BSM search for a resonant Z' gauge boson in the dilepton invariant mass spectrum. The dominant and irreducible background process to this search is the Drell-Yan (DY) process. Both ATLAS [4] and CMS [5] have recently completed their searches for new high-mass phenomena from the first $\sqrt{s} = 13$ TeV data-taking runs at the LHC. Both set comparable lower bounds on the mass of a hypothetical new vector boson and both publish extensive lists of their systematic uncertainties, including uncertainties attributed to our limited knowledge of PDF fitting.

To date, only 5% of the planned LHC data are in hand and yet these PDF uncertainties might already have limited future mass reaches for such searches. Not only are resonant Z' boson searches “at risk” but also W' boson searches and especially non-resonant (such as contact interactions) searches, which are very sensitive to sloped shape changes in the background. Therefore, it is critical that we improve our understanding of PDFs and their associated uncertainties. One way to do that in the short-term (on search timescales) is to explore the prospect of using the DY data collected at the LHC in a well-measured control region, to constrain the theoretical uncertainties in a kinematic region relevant to BSM searches.

The machinery of PDF global fitting groups is very complex and for physicists outside of the PDF groups, testing new PDF analysis strategies can be cumbersome. This will change with the recent development of tools like **ePump** [6] (the Error PDF Updating Method Package, see below for details), which makes it possible to explore the effects of new kinematic inputs to a global fit without requiring a full global analysis.

While other PDF profiling tools exist such as xFitter [7], in this paper we choose to use **ePump** which has been thoroughly tested [6] against the CT14 global fits.[8] The work in this paper is the first published use of this tool. Through its use, we demonstrate that new insight into kinematics of the DY process has emerged, and that considerable reduction in the quark and anti-quark PDF uncertainties is possible with new data inputs to PDF global fitting, and perhaps also a new analysis strategy.

A. Our Goals

Our goals in this paper are limited. **ePump** preserves all of the important features of a standard global fitting such as sum rules and full QCD evolution and we use it here as a tool to predict the influence of new data sources by “simulating” PDF global fitting. The result is an updated PDF set, augmented as if the new data were a regular input to a global fit. This pseudo-set includes the full complement of PDF uncertainties. We limit ourselves to the CT14HERA2 parameterization and do not attempt to explore the space of possible functional forms. We do not attempt to optimize theoretical uncertainties associated with any other theoretical considerations like the strong coupling constant, electroweak couplings, or higher order electroweak and QCD effects. We also make no effort to optimize or explore

the full set of possible experimental uncertainties. We simply ask the optimistic question: can qualitatively new data when combined with the current inputs of CT14HERA2 reduce future PDF uncertainties and if so, by how much?

Our *ansatz* is to treat BSM DY searches as consisting of a control region—from which we envision mining DY data for global fitting—and signal region to where those new global fits are extrapolated. Of course as in any control-signal region analysis, the assumption is that the control-region contains only SM physics. We specifically explore the possibility that LHC DY data in a safe control region might be useful to further constrain PDFs appropriate to high-mass BSM searches for which the continuum DY is the dominant background. Having determined that this is worth consideration, our ultimate proposal is that the LHC experiments and the PDF fitting teams work together to explore inclusion of LHC DY data into global fitting when prepared in a particularly useful way.

The paper is structured as follows. First, in Sec. II the current experimental results are briefly reviewed with an emphasis on the systematic uncertainties. Next, we review the kinematics of the DY process in Sec. III. Particular attention is paid to the role of the Collins-Soper (CS) angle (θ^*), as this variable will be shown to possess hitherto unemphasized discrimination power between up- and down-type quark flavors which varies as a function of the invariant mass of the DY pairs. Bearing this in mind, we then propose a new strategy for future PDF global fitting inspired by the use of **ePump** in Sec. IV. Here, the **ePump** package is described. Then, in Sec. V, the results of such a strategy are assessed, first on the high- x behavior of the post-fit CT14HERA2 PDFs, and then on the expected event yields of the high-mass dilepton spectrum. Finally, concluding remarks are given in Sec. VI.

II. CURRENT Z' BOSON SEARCH RESULTS

Both direct and indirect searches for Z' bosons have been conducted at several previous collider experiments. Early results were obtained from the LEP experiment at CERN, followed by the DØ and CDF experiments at the Tevatron, and more recently, the ATLAS and CMS experiments at the LHC. Examples of ATLAS and CMS limits on the Z' mass are shown in Table I.

The LHC currently holds the record as the highest energy particle collider, and as such, its ability to set Z' limits is vastly improved compared to what was achievable at LEP and the

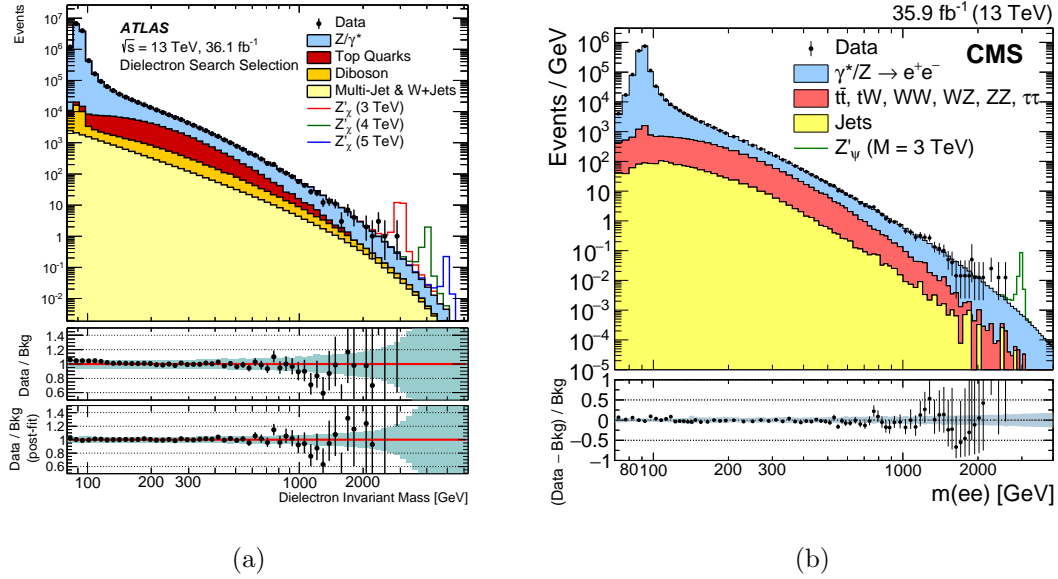


FIG. 1. Dielectron invariant mass search spectra in the ATLAS (a) and CMS (b) dilepton analyses at the LHC.

Collaboration	\sqrt{s} [TeV]	\mathcal{L} [fb $^{-1}$]	Channel	Lower Limit on $M_{Z'}$ [TeV]			Reference
				Z'_{SSM}	Z'_{ψ}	Z'_{χ}	
CMS	13	36	$\ell\ell$	4.5	3.9	-	[5]
ATLAS	13	36	$\ell\ell$	4.5	3.8	4.1	[4]

TABLE I. Observed limits at 95% C.L. on the mass of a Z' boson from the most recent LHC experimental searches. The CMS analyses listed do not provide limits on the Z'_{χ} , which would otherwise be slightly higher than what was obtained for the Z'_{ψ} . The integrated luminosity for each analysis is rounded to the nearest whole number. The $\ell\ell$ channel refers searches that combine individual electron and muon channels.

Tevatron. The most stringent direct limits come from the ATLAS and CMS experiments where searches have been conducted at $\sqrt{s} = 7, 8$ and 13 TeV, with varying amounts of integrated luminosity. The most recent results for the combined electron and muon pair invariant mass are shown in Fig. 1 for ATLAS and CMS.

Of particular interest are the systematic errors due to PDF fitting uncertainties. The two LHC experiments treat these quite differently. Table II illustrates their assignments from CMS ([5]) and ATLAS ([4]). ATLAS assigns a large uncertainty derived from a sophisticated

Collaboration (nominal PDF)	$m_{Z'}$	Channel	Assigned uncertainty	Uncertainty source
CMS (NNPDF2.3)	~ 4 TeV	ee	7%	PDF variation & choice
	~ 4 TeV	$\mu\mu$	7%	PDF variation & choice
ATLAS (CT14NNLO)	~ 4 TeV	ee	19%	PDF variation
	~ 4 TeV	$\mu\mu$	1.9%	PDF variation
	~ 4 TeV	ee	8.4%	PDF choice
	~ 4 TeV	$\mu\mu$	13%	PDF choice

TABLE II. Published uncertainties due to the lack of PDF knowledge on the DY backgrounds for CMS and ATLAS for the 13 TeV LHC running. Each experiment determines PDF uncertainties from a common nominal PDF choice which is parenthetically indicated. The uncertainties have a scale dependence and can differ according to the di-lepton channel. The results quoted here are evaluated at a mass of approximately 4 TeV. PDF “choice” for ATLAS results refers to the PDF4LHC forum recommendations [9] to account for differences among the PDF fitting groups’ predictions as excursions from the nominal choice and its full error matrix. PDF variation is the results from the full error matrix for the nominal PDF set.

treatment and it is this large uncertainty that we address in this work. The combined ATLAS PDF errors of 20.8% are to be compared with the other uncertainties of 9.9% for non-PDF theory, 13% for the total experimental, and 26% for the total. This PDF uncertainty is large at this point in time and potentially irreducible absent new data of a qualitatively different sort (new DIS experiments?) or new ideas. We propose new ideas to address this using LHC data itself.

III. THE DRELL-YAN PROCESS

The general Drell-Yan process [11] of $pp \rightarrow \ell^+ \ell^- + X$ at leading order originates from an s -channel exchange of an electroweak boson

$$q\bar{q} \rightarrow \gamma^*/Z \rightarrow \ell^+ \ell^-. \quad (1)$$

Here, X denotes any additional final-state particles (radiated partons, the underlying event, multi-parton interactions, etc.). At next-to-leading order, the real corrections introduce

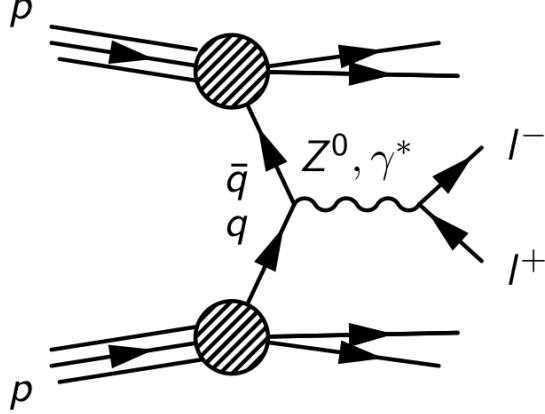


FIG. 2. The DY process initiated by a quark-antiquark pair as observed at the LHC [10].

three t -channel processes, listed in order of decreasing cross section at LHC energies,

$$qg \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^- + q \quad (2)$$

$$\bar{q}g \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^- + q \quad (3)$$

$$q\bar{q} \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^- + g. \quad (4)$$

The leading order process is depicted in Fig. 2.

In each case, the vector boson decays into a pair of same-flavor, oppositely-charged leptons. For simplicity, our discussion will center on the leading order process, but our simulations and results are based on the calculations using the RESBOS [12–14] package which resums effects of multiple soft-gluon radiation to all order at the next-to-next-to-leading-log (NNLL) accuracy with Wilson coefficients calculated at next-to-leading-order (NLO) in the CSS transverse momentum resummation formalism.

The DY triple-differential cross section can be represented as a function of the dilepton invariant mass $m_{\ell\ell}$, the dilepton rapidity $y_{\ell\ell}$, and the cosine of the lepton polar angle in the Collins-Soper rest frame $\cos\theta^*$. For the LO s -channel process, this is

$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s} \sum_q P_q [f_{q/P_1}(x_1, Q^2)f_{\bar{q}/P_2}(x_2, Q^2) + (q \leftrightarrow \bar{q})]. \quad (5)$$

Here \sqrt{s} is the CM energy of the LHC, and P_1 and P_2 are the 4-momenta of protons 1 and 2. In the standard fashion, x_1 and x_2 are the incoming parton momentum fractions such that $p_1 = x_1P_1$ and $p_2 = x_2P_2$.

The functions $f_{q/P_1}(x_1, Q^2)$ and $f_{\bar{q}/P_2}(x_2, Q^2)$ are the PDFs for quark flavors q and \bar{q} ,

respectively. The term $(q \leftrightarrow \bar{q})$ accounts for the fact that either proton can carry a sea quark, as the LHC is a proton-proton collider.

Finally, the quantity P_q accounts for the parton-level dynamics in terms of important electroweak parameters, and exhibits dependencies on both dilepton mass and $\cos\theta^*$. We will be concerned with each factor in this formula, and it is discussed in detail in Sec. III C.

The energy scale of the collision is set by the transferred four-momentum squared Q^2 , which can be identified with the square of the dilepton invariant mass $m_{\ell\ell}^2$. Well-known kinematic definitions include

$$Q^2 = (p_1 + p_2)^2 = x_1 x_2 s, \quad (6)$$

and,

$$y_{\ell\ell} = \frac{1}{2} \ln \left(\frac{x_1}{x_2} \right), \quad (7)$$

which parametrizes the dilepton rapidity in terms of the x fractions of the initial-state partons at LO. From these, the variables are related, also at LO, by

$$x_1 = \frac{m_{\ell\ell}}{\sqrt{s}} e^{+y_{\ell\ell}}, \quad x_2 = \frac{m_{\ell\ell}}{\sqrt{s}} e^{-y_{\ell\ell}}. \quad (8)$$

Eq. (8) provides the first hint to the source of the large PDF uncertainty in high-mass DY production. The $\sqrt{s} = 13$ TeV LHC is now probing extremely large values of $m_{\ell\ell}$, beyond a few TeV. As such, a central dilepton event with an invariant mass of $m_{\ell\ell} = 3$ TeV and rapidity of $y_{\ell\ell} = 0$ requires x fractions beyond $x \simeq 0.2$. This is beginning to probe regions of sea and even valence quark momentum fractions which are not well constrained by mostly DIS inputs. Figure 3 shows current quark and gluon momentum fractions from the CT14NNLO PDF set evaluated at two scales Q^2 .

A. Behavior of PDFs at high parton x

The reason for this inherent high- x uncertainty in the quark and anti-quark PDFs is due to the need to extrapolate experimental data—especially for quark and anti-quark fitting—as seen in Fig. 4. The only data which directly probe quark and anti-quark PDFs for $x \gtrsim 0.2$ come from legacy deep-inelastic scattering experiments and HERA measurements. PDFs relevant for current and future LHC DY production scales of interest require an extrapolation

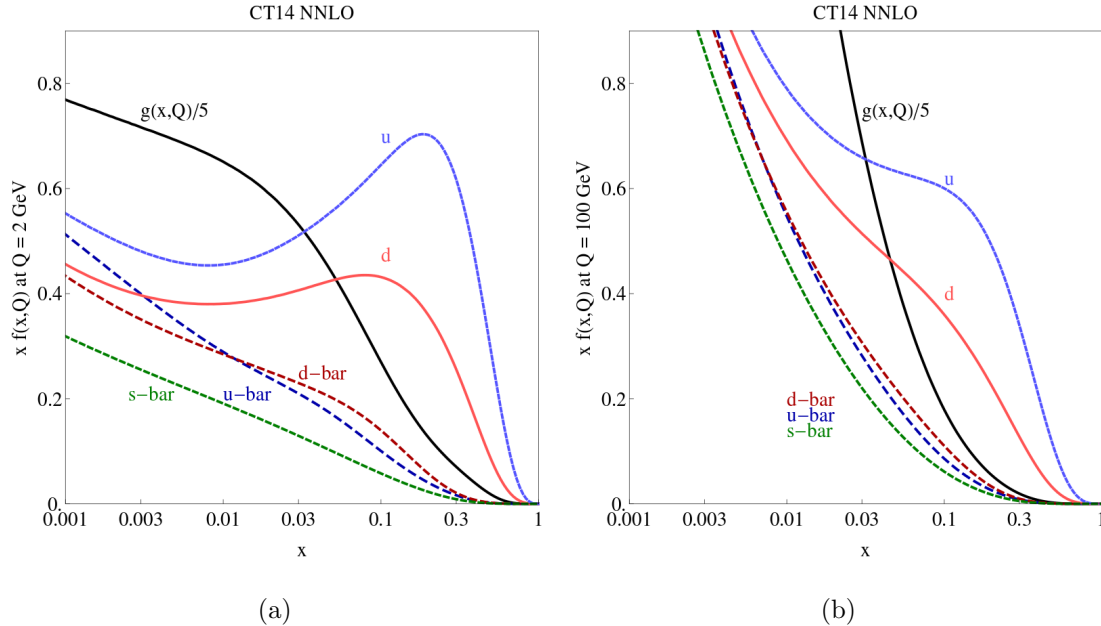


FIG. 3. The CT14NNLO PDFs of the CTEQ collaboration. Depicted are gluon, quark, and anti-quark PDFs as a function of x , evaluated at a scale of $Q = 2$ GeV (a) and $Q = 100$ GeV (b) [1].

of almost three orders of magnitude in mass and this proves difficult to do precisely with the current world data.

Figure 5 shows the PDF uncertainties for several individual parton flavors in the CT14NNLO and CT14HERA2 PDF sets. It's not surprising that the $\bar{u}(x)$ and $\bar{d}(x)$ distributions are least precisely known at moderate-to-high x where input data are difficult to obtain and where their magnitudes have fallen to small fractions of their valence counterparts. But even the $u_V(x)$ and $d_V(x)$ distributions are poorly constrained in this region, although the up quark is much better determined than the down. Each of these distributions plays an important role in the initial-state quark-antiquark annihilation that results in the DY process.

This significant lack of precision is the source of the large systematic uncertainties required in a high mass, dilepton Z' search. Figure 6 shows the iconic invariant mass distribution of dilepton pairs calculated using the RESBOS [12–14] Monte Carlo (MC) generator and the CT14HERA2 PDF. The ratio band is the quoted CT14HERA2 [16] PDF uncertainties of about 18% at $m_{\ell\ell} = 4$ TeV consistent with that quoted in the ATLAS result of 19% at $m_{ee} = 4$ TeV.

As DY data inputs are the only way to constrain high- x PDFs, a strategy is explored here that turns this lack of sensitivity into an opportunity. The DY continuum is well-

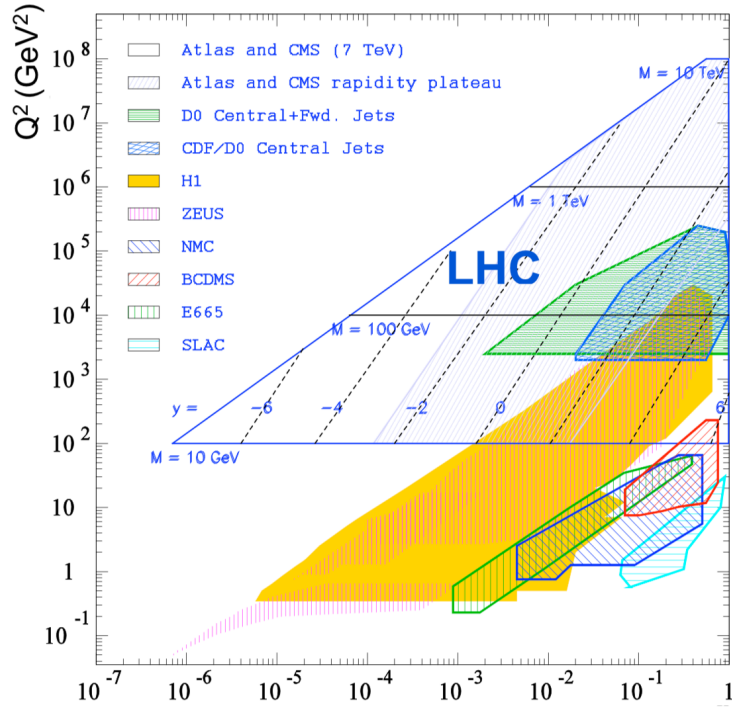


FIG. 4. The transferred momentum squared Q^2 versus the parton momentum fraction x at $\sqrt{s} = 7$ TeV. The regions probed by previous DIS, fixed-target, and collider-based experiments are labeled [15].

measured and reliably SM physics. If PDF global fits were to include LHC DY data well below any search region, but high enough in invariant mass to better constrain the fits, this uncertainty could be reduced. Moreover, the amount of LHC data that will become available in the coming years will be staggering, so we've decided to explore DY kinematics further in hopes of finding/discovering sensitivities that would help to enhance the potential of high- x PDF fits.

We will show that there are DY observables, such as $\cos\theta^*$, that could in principle be incorporated in PDF global fitting, and the use of **ePump** tells us approximately how much reduction in PDF uncertainty is possible, as well as how much smaller the PDF systematic uncertainty might become in the DY differential mass spectrum. Due to the importance of $\cos\theta^*$, and the role it plays in our fitting strategy, a brief review is given in the next section.

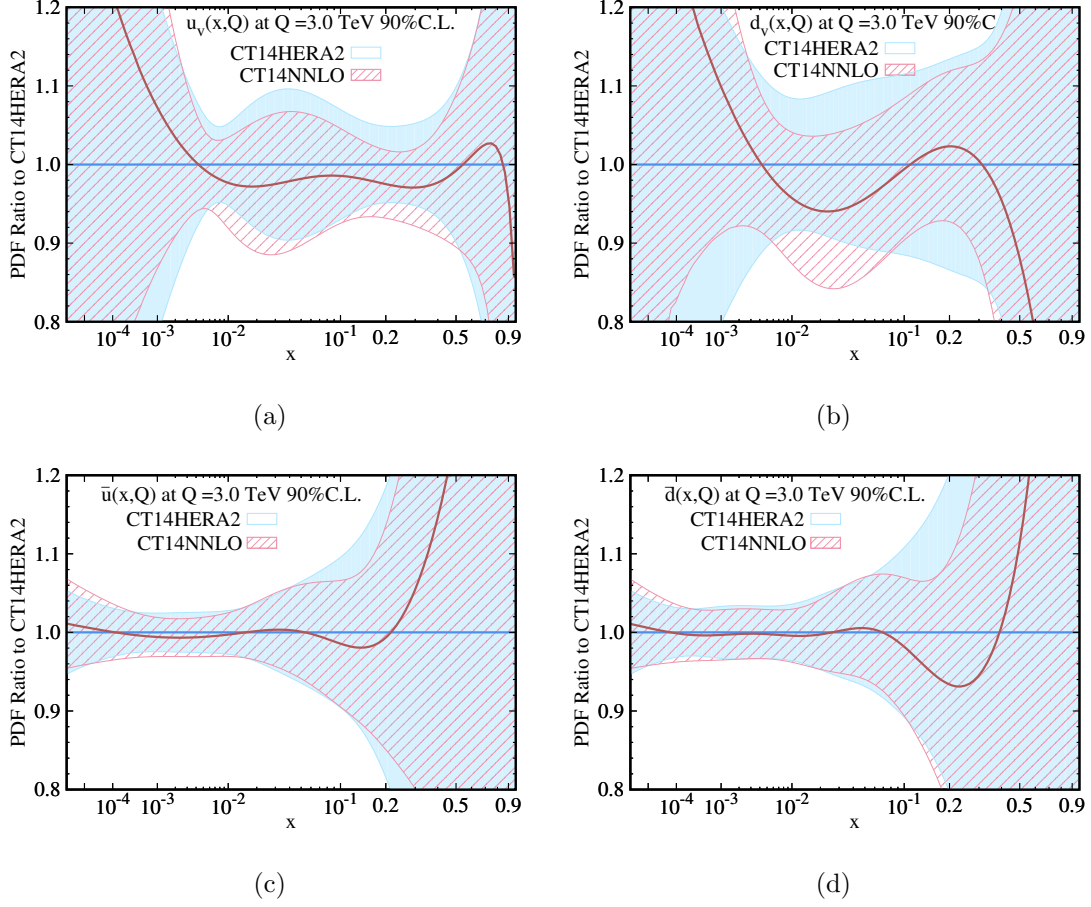


FIG. 5. PDF uncertainties associated with the (a) $u_v(x)$, (b) $d_v(x)$, (c) $\bar{u}(x)$, and (d) $\bar{d}(x)$ distributions in the CT14NNLO and CT14HERA2 PDF sets evaluated at a scale of $Q = 3$ TeV. At high values of x , such as $x \gtrsim 0.1$ relevant for high-mass DY production, the PDF uncertainties begin to diverge.

B. The Collins-Soper Polar Angle

We have found particular power in $\cos \theta^*$ in Eq. (5). This angle is defined in the Collins-Soper (CS) [17] rest frame of the lepton-pair with the polar and azimuthal angles defined relative to the two proton directions. The z axis is defined in the Z boson rest frame so that it bisects the angle formed by the momentum of one of the incoming protons and the negative of the momentum of the other incoming proton. The y is constructed to be normal to the plane of the two proton momenta and the x axis which is chosen in order to create a right-handed Cartesian coordinate system.

The cosine of the polar angle θ^* defines the direction of the outgoing lepton ℓ^- relative

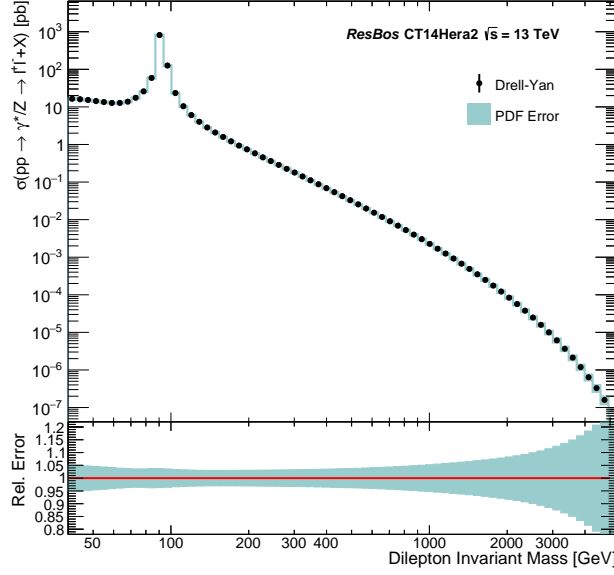


FIG. 6. The dilepton invariant mass spectrum, generated with the RESBos MC generator and the CT14HERA2 PDF set.

to \hat{z} in the CS frame and can be calculated directly from lab frame lepton quantities with

$$\cos \theta^* = \frac{P_z}{|P_z|} \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{M_{\ell\ell} \sqrt{M_{\ell\ell}^2 + P_T^2}}. \quad (9)$$

The sign of the z axis is defined on an event-by-event basis as the sign of the lepton pair momentum with respect to the z axis in the laboratory frame. Here, P_T and P_z are the transverse and longitudinal momentum of the dilepton system, respectively, and,

$$p_i^\pm = \frac{1}{\sqrt{2}} (E_i \pm p_{z,i}), \quad i = 1, 2, \quad (10)$$

where the lepton (anti-lepton) energy and longitudinal momentum are E_1 and $p_{z,1}$ (E_2 and $p_{z,2}$), respectively. This definition requires the electric charge identification of each lepton. We define DY events as forward ($\cos \theta^* > 0$) or backward ($\cos \theta^* < 0$) according to the direction of the outgoing lepton in this frame of reference.

C. Relearning Drell-Yan Kinematics

We will exploit a novel feature of the DY subprocess cross section from Eq. (5) and the definition of $\cos \theta^*$ of Eq. (9), to form the basis of the PDF update with **ePump** in Sec. IV.

	v_f	a_f
u	$+\frac{1}{4} - \frac{2}{3}x_W$	$-\frac{1}{4}$
d	$-\frac{1}{4} + \frac{1}{3}x_W$	$+\frac{1}{4}$
ν_ℓ	$+\frac{1}{4}$	$-\frac{1}{4}$
ℓ	$-\frac{1}{4} + x_W$	$+\frac{1}{4}$

TABLE III. Vector and axial-vector couplings of the SM fermions. Rows specify couplings within each respective fermion generation.

The function P_q of Eq. (5) encodes the parton-level dynamics with

$$P_q = C_q^0 (1 + \cos^2 \theta^*) + C_q^1 \cos \theta^*, \quad (11)$$

which is a weighted sum of an even function $(1 + \cos^2 \theta^*)$ and an odd function $\cos \theta^*$. In the calculation of the total inclusive cross section, the odd term integrates to zero, but is responsible for inducing the well-known γ^*/Z forward-backward asymmetry A_{FB} .

The asymmetry coefficients C_q^0 and C_q^1 of Eq. (11) include the electroweak couplings of the initial-state quarks and final-state leptons, and describe the $m_{\ell\ell}$ spectrum as

$$\begin{aligned} C_q^0(m_{\ell\ell}) &= Q_\ell^2 Q_q^2 + 2Q_\ell Q_q v_\ell v_q \chi_1(m_{\ell\ell}) + (a_\ell^2 + v_\ell^2) (a_q^2 + v_q^2) \chi_2(m_{\ell\ell}) \\ C_q^1(m_{\ell\ell}) &= 4Q_\ell Q_q a_\ell a_q \chi_1(m_{\ell\ell}) + 8a_\ell v_\ell a_q v_q \chi_2(m_{\ell\ell}). \end{aligned} \quad (12)$$

Where

$$\begin{aligned} \chi_1(m_{\ell\ell}) &= \frac{1}{\sin \theta_W \cos \theta_W} \frac{m_{\ell\ell}^2 (m_{\ell\ell}^2 - m_Z^2)}{(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2}, \\ \chi_2(m_{\ell\ell}) &= \frac{1}{\sin^2 \theta_W \cos^2 \theta_W} \frac{m_{\ell\ell}^4}{(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2}. \end{aligned} \quad (13)$$

Here m_Z and Γ_Z are the mass and decay width of the SM Z boson, and Q_f , v_f , and a_f are the electric charge, and the electroweak vector and axial-vector couplings of each fermion, whose values are shown in Table III. The function χ_1 results from γ^*/Z interference, while χ_2 arises from pure Z boson exchange.

Our strategy was to explore the DY cross section with the goal of finding global PDF fitting inputs tailored specifically to DY physics. To that end we used the RESBOS MC (and the MADGRAPH generator as a check), configured with the CT14HERA2 PDF set to study several kinematic distributions.

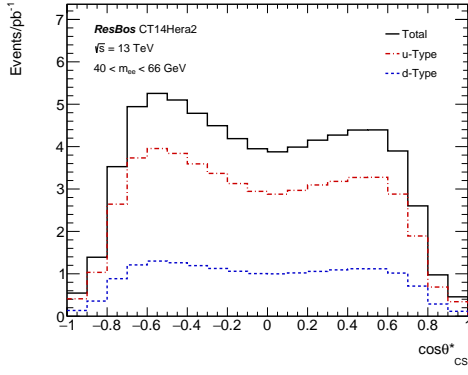
All simulation samples are produced in bins of true dilepton invariant mass in the range $m_{\ell\ell} = 40$ GeV to $m_{\ell\ell} = 1$ TeV at $\sqrt{s} = 13$ TeV. In order to roughly correspond to ATLAS, CMS, and/or LHCb acceptances, the lepton pseudo-rapidities were restricted. Central-central (CC) events are required to have both leptons with $|y_\ell| < 2.47$, and the dilepton rapidity, $|y_{\ell\ell}| < 2.47$. Central-forward (CF) events are required to have one lepton with $|y_\ell| < 2.47$, and the other with $2.47 < |y_\ell| < 3.6$, where the dilepton rapidity can extend out to $|y_{\ell\ell}| < 3.6$, which allows access to a much broader range in x , c.f. Eq. (16).

We found particular practical significance in focusing on the polar angle. Figure 7 shows several $\cos\theta^*$ distributions of Eq. (9) in discrete slices of dilepton invariant mass. Each mass-slice is further decomposed into sub-processes that consist distinctly of up-type or down-type initial-state quarks. The up-type sub-processes include initial-states of $u\bar{u}$, ug , and $\bar{u}g$, where u is the up quark or charm quark and g is the gluon. A similar definition applies to the d -type (down, strange, bottom) sub-processes, with u replaced by d . This is in accordance with the four DY reactions in Eqs. (1) and (4).

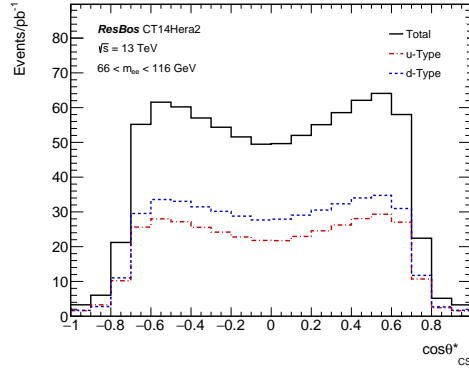
Intriguingly, the relative up-type and down-type sub-processes are highly dependent on both mass and polar angle θ^* . This is especially true above the Z boson mass peak, in which the forward region ($\cos\theta^* > 0$) shows an increasing degree of separation between the rates associated with the up-type and down-type DY sub-processes. Indeed, in this region the contribution to the total cross section is due almost entirely to the up-type sub-process by itself. *At high mass and high polar angle, the LHC DY process proceeds almost entirely through the $u\bar{u}$ sub-process, effectively making the LHC a $u\bar{u}$ collider.*

Why is this the case? Figure 7(f) shows that as $\cos\theta^*$ nears +1, the up quark dominates DY production by almost a factor of four over that of the down quark. Taking apart Eqs. (5), (11), (12), and (13) explains this observation. Figure 8 shows the quantities P_u and P_d evaluated at $\cos\theta^* = \pm 1$. The closed (open) circles tag P_u (P_d) at a $\sqrt{\hat{s}} = 1$ TeV for the $\cos\theta^* = 1.0$ curves. The ratio of P_u/P_d is about 2. Figure 9 shows the separate parton luminosity functions $\mathcal{L}_{u\bar{u}}$ and $\mathcal{L}_{d\bar{d}}$ for the leading order $u\bar{u}$ and $d\bar{d}$ sub-processes in accordance with the CT14HERA2 PDF set. Here too, the closed and open circles refer to the up-quark and down-quark parton luminosity functions and again, the ratio of $\mathcal{L}_{u\bar{u}}/\mathcal{L}_{d\bar{d}}$ is approximately 1.5. The product of these contributions (i.e., $P_u/P_d \times (\mathcal{L}_{u\bar{u}}/\mathcal{L}_{d\bar{d}})$) to the rates confirms the near factor of 4 ratio observed in Fig. 7 at $\cos\theta^*$ near 1.

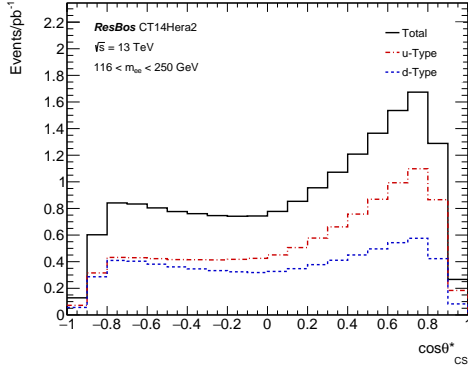
Notice that we've not really learned anything new! DY kinematics is an old subject but



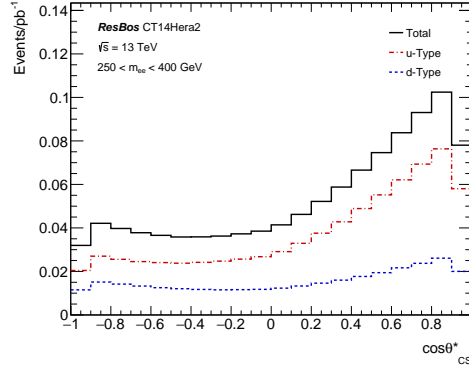
(a)



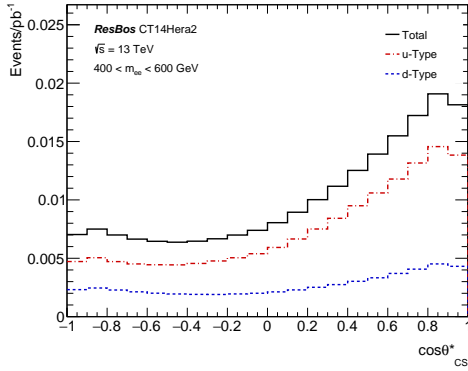
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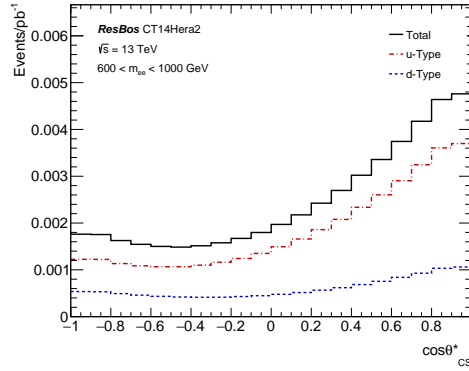
(c)



(d)



(e)



(f)

FIG. 7. The lepton angular distribution $\cos \theta^*$ in slices of dilepton invariant mass $m_{\ell\ell}$ ranging from 40 GeV to 1 TeV (a)-(f). The up-type and down-type DY sub-processes are shown as well, which exhibit a strong angular dependence, especially at high mass. The CT14HERA2 fits are used.

the high-mass behavior is revealing and the question is whether $\cos \theta^*$ behavior as a function

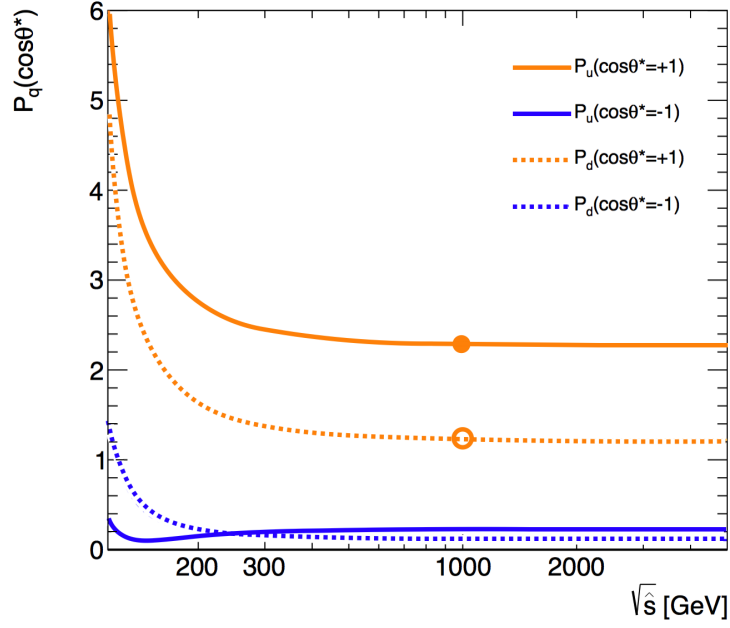


FIG. 8. The DY parton-level kinematics as described Eq. (11). The function P_q is evaluated at values of $\cos \theta^* = \pm 1$ for both up (solid)- and down (dashed)-type quarks. The dots indicate the values the P_u and P_d functions at $\cos \theta^* = 1.0$ and $\sqrt{\hat{s}} = 1$ TeV.

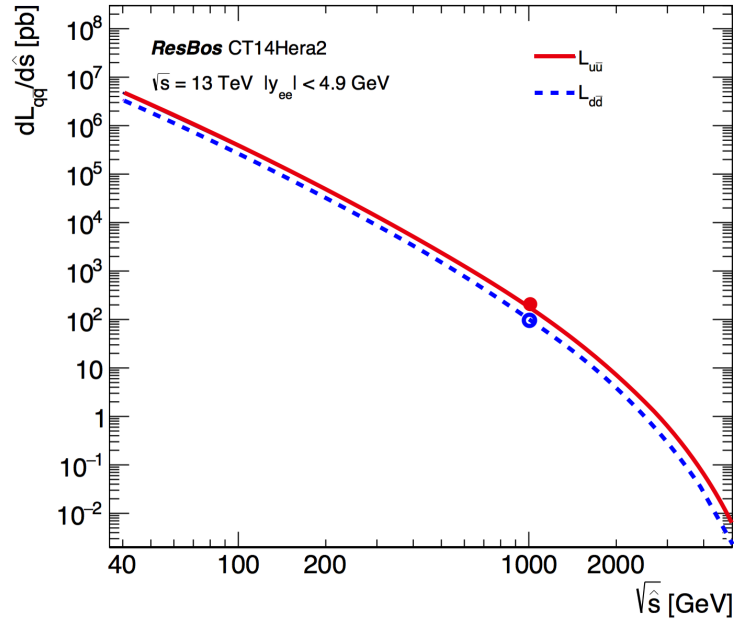


FIG. 9. Parton luminosities for $u\bar{u}$ and $d\bar{d}$ DY sub-processes. The dots indicate the values of the luminosity functions at $\sqrt{\hat{s}} = 1$ TeV.

of mass should be an important discrimination as an input to global PDF fitting. This is

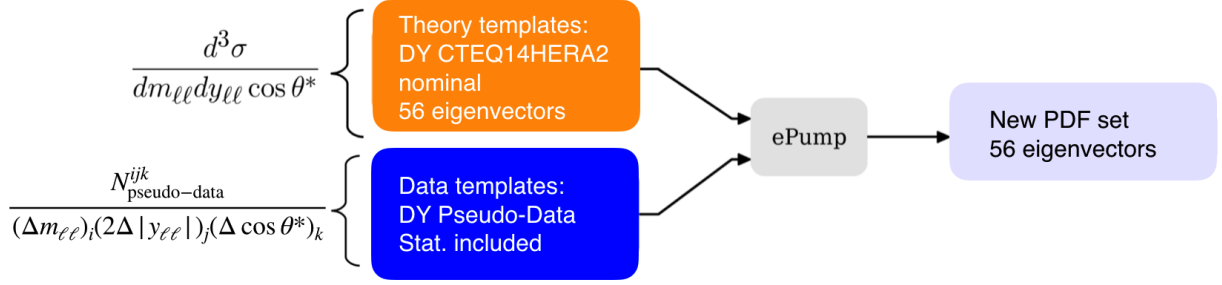


FIG. 10. The **ePump** package requires two inputs to generate an updated PDF set: an existing Theory template of a PDF set (parameters + uncertainties) and binned Data template of (pseudo-) data, including statistical uncertainties from integrated luminosity assumptions.

where **ePump** comes in.

IV. A PROPOSED STRATEGY TO PDF ERROR REDUCTION FOR DY

We attempt to shed light on two questions:

1. If $\cos \theta^*$ data were incorporated in global fitting, how significant might the reduction in PDF uncertainties be?
2. Would those decreased errors be a significant reduction in the overall theoretical uncertainties in future BSM, high-mass DY searches?

In order to answer Question 1, **ePump** was used, which can update an existing PDF set with new experimental data (or pseudo-data) in order to produce an improved best-fit and Hessian Error PDFs. The **ePump** workflow can be seen in Fig. 10.

For this analysis, “pseudo-data” are used to mimic a possible future LHC dataset for PDF fitting. As any dataset has finite statistics, the resulting uncertainties in the new PDFs will reflect whatever statistical precision is modeled in the pseudo-data. The effects of new PDFs and uncertainties can then be used to re-evaluate the PDF systematic uncertainty on the high-mass dilepton event yield.

Furthermore, we imagine a Signal Region (SR) as $m_{\ell\ell} > 1$ TeV and a Control Region (CR) to be for $0.04 < m_{\ell\ell} < 1$ TeV. Since new physics should lie above the current limits of approximately $m_{\ell\ell} \sim 3$ TeV (as in Sec. II), it would be “fair” to use low-mass DY data to constrain the high-mass DY spectrum.

A. The ePump Package

In a standard PDF global fit, the PDFs are determined by minimizing the function,

$$\chi_{\text{global}}^2 = \sum_{n=1}^{N_{\text{exp}}} \chi_n^2, \quad (14)$$

which consists of contributions from N_{exp} fitted experiments, χ_n^2 . In the simplest case with no correlations between data points, the contribution from an experiment can be written

$$\chi_n^2 = \sum_{i=1}^{N_n} \frac{(T_{ni}(\mathbf{z}) - D_{ni})^2}{\sigma_{ni}^2}, \quad (15)$$

where D_{ni} is the experimental data value, σ_{ni} is the experimental error (combined systematic and statistical), and $T_{ni}(\mathbf{z})$ is the theory prediction, which depends on the PDFs, which in turn are described by a finite number of parameters, \mathbf{z} . In practice, the χ_n^2 for modern experiments will include correlated errors among data points, and there may be additional terms added to impose constraints on the theoretical parameters, but the general procedure is unchanged. The central or best-fit PDFs are obtained by minimizing χ_{global}^2 with respect to \mathbf{z} . In addition, χ_{global}^2 is, to a good approximation, a quadratic function of the parameters around the minimum. This is the basis for the Hessian approximation for PDF errors, which utilize PDF eigenvector sets, two for each PDF parameter, to evaluate the uncertainty due to the PDFs for any physical observable. Each PDF eigenvector set corresponds to a movement in the parameter space along the eigenvector directions of the Hessian error matrix around the global minimum of χ_{global}^2 at a defined confidence level (C.L.). For CT14HERA2 PDFs there are 56 eigenvector sets defined at the 90% C.L.

If the contribution from a new experiment, $\chi_{N_{\text{exp}}+1}^2$, is added to the global analysis, the exact solution of the problem would require finding the new minimum of Eq. (14), as well as diagonalizing the new Hessian matrix. Since this requires the full data sets from all experiments in the global analysis, as well as the theory calculations for every data point evaluated at many parameter values, it is an onerous and time-consuming task even for the global analysis teams that specialize in this endeavor.

This is where a tool such as ePump is advantageous. ePump works by using the fact that the original χ_{global}^2 is well-approximated by the known quadratic function and the fact that the theory predictions for the new observables, $T_{N_{\text{exp}}+1,i}(\mathbf{z})$, can be approximated using the original Hessian error PDFs. Under these approximations, the minimization and Hessian

diagonalization can be performed algebraically [6, 18], with the numerical computations taking seconds, rather than hours or days.

Figure 10 illustrates the use of **ePump**. In order to perform the PDF update, **ePump** requires two sets of inputs: data templates and theory templates. The data templates consist of the new experimental data values and their statistical and systematic uncertainties, including correlations, exactly as would be included in a standard global analysis. In the case of our present study these are the event counts of the new pseudo-data, along with their associated statistical uncertainties. The theory templates consist of the corresponding theory predictions for the same observables, evaluated using the central PDF and each of the Hessian eigenvector PDFs. Note that any number of new data sets can be included in the update by **ePump**, with any number of data points per new data set.

The output of **ePump** is an updated central and Hessian eigenvector PDFs, which approximate the result that would be obtained from a full global re-analysis that includes the new data. As an additional benefit, **ePump** can also directly output the updated predictions and uncertainties for any other observables of interest (such as the cross section in the signal region), without the necessity to recalculate using the updated PDFs. For more details about the use of **ePump**, see Ref. [6]. The code for **ePump** and more specific details of its usage can be obtained at the website <http://hep.pa.msu.edu/epump/>.

B. PDF Update Strategy

ePump requires standard inputs to emulate the global fit—the templates in Fig. 10. We describe our strategy here. The analysis was performed at “truth level,” such that the acceptance and efficiency effects associated with the reconstruction and identification of prompt, high- p_T leptons in an LHC detector are neglected. However, leptons are well measured at the LHC, so this is an acceptable first look at this technique. Additional dilepton backgrounds were neglected, but are well understood by the LHC experiments as can be seen in Fig. 1. These backgrounds include $t\bar{t}$ production, Wt Single Top production, WW , WZ , and ZZ Diboson production, and W +jets & Multi-jet production in the electron channel.

C. ePump Template Construction

Naively, one might imagine only using $m_{\ell\ell}$ in the CR to predict the improvement in the SR, but our awareness of the significant differential quark sensitivities to $\cos\theta^*$ (and moderate sensitivity to $y_{\ell\ell}$) plus the knowledge that future LHC running will provide enormous continuum DY datasets led us to explore dividing pseudo-data into many bins of dilepton mass $m_{\ell\ell}$, as well as $y_{\ell\ell}$ and $\cos\theta^*$.

The fiducial region considered for our analysis is designed explicitly to probe the PDFs at high x , and is defined by

$$40 \text{ GeV} < m_{\ell\ell} < 1000 \text{ GeV}, \quad |y_{\ell\ell}| < 3.6, \quad -1 < \cos\theta^* < 1. \quad (16)$$

DY samples were generated using the RESBOS MC generator with the CT14HERA2 PDF set for the $\sqrt{s} = 13$ TeV LHC. Events were further required to pass a loose event selection in order to construct the finalized Data templates. Dilepton events with an invariant mass of $m_{\ell\ell} > 80$ GeV were required to satisfy $p_T > 30$ GeV, while low-mass events in the interval of $40 < m_{\ell\ell} < 80$ must satisfy $p_T > 15$ GeV. In addition, events must consist of leptons which are distributed as central-central or central-forward.

Events passing these selections were binned in **ePump** template histograms, which parametrize the triple-differential cross section of Eq. (5), according to

$$\mathcal{L}_{\text{int}} \left(\frac{d^3\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*} \right)_{ijk} = \frac{N_{\text{pseudo-data}}^{ijk}}{(\Delta m_{\ell\ell})_i (2\Delta|y_{\ell\ell}|)_j (\Delta\cos\theta^*)_k}, \quad (17)$$

where i , j , and k correspond to the bin indices of each distribution of interest.

The total number of pseudo-data events are given by $N_{\text{pseudo-data}}^{ijk}$, the integrated luminosity of the pseudo-dataset is \mathcal{L}_{int} , and $(\Delta m_{\ell\ell})_i$, $(2\Delta|y_{\ell\ell}|)_j$, and $(\Delta\cos\theta^*)_k$ are the corresponding bin widths.[19] The factor of two in the denominator accounts for the modulus in the rapidity bin width. The bins used to parametrize Eq. (17) are

- $40 < m_{\ell\ell} < 1000 : \{40, 66, 80, 91, 102, 116, 145, 200, 275, 381, 525, 725, 1000\} \text{ GeV}$
- $0 < |y_{\ell\ell}| < 2.4 : \{0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4\}$
- $2.4 < |y_{\ell\ell}| < 3.6 : \{2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 3.6\}$
- $-1 < \cos\theta^* < 1 : \{-1.0, -0.7, -0.4, 0.0, 0.4, 0.7, 1.0\}.$

where the C and F regions are explicitly called out for the CC and CF selections. The total number of measurement bins is $N_{\text{bins}} = 12 \times 18 \times 6 = 1296$ for the fiducial region considered and they define the N_{new} data points that supplement Eq. (14).

Events were generated as if they came from a future integrated luminosity and so uncertainties in the **ePump** results are scattered according to the statistics of such a hypothetical LHC input dataset. For each bin the DY cross section estimate $\sigma_{\text{Drell-Yan}}^{ijk}$ was scaled by a characteristic integrated luminosity \mathcal{L}_{int} to arrive at a definite DY event yield $N_{\text{Drell-Yan}}^{ijk}$. The resulting yield was assumed to be the mean of a Poisson distribution, which was then used to throw a random number according to Poisson statistics, thereby populating the bin with $N_{\text{pseudo-data}}^{ijk}$ pseudo-data events. Note that the pseudo-data were treated as those of one “experiment,” but in practice ATLAS, CMS, and LHCb would all be sources of fitting input data. For illustration we chose two future LHC scenarios for integrated luminosities: $\mathcal{L}_{\text{int}} = 300 \text{ fb}^{-1}$ approximating the data set for one experiment following Run-3 of the LHC, and $\mathcal{L}_{\text{int}} = 3000 \text{ fb}^{-1}$, approximating that of the final dataset for one experiment of the HL-LHC.

V. PDF UPDATE RESULTS

We can answer Question 1 by re-evaluating the effect of the 3000 fb^{-1} DY pseudo-dataset on the CT14HERA2 PDFs, as well as Question 2 by assessing the reduction of the PDF systematic uncertainty in the high-mass dilepton spectrum.

A. Impact on CT14HERA2 PDFs

Question 1 asked whether explicit inclusion of $\cos \theta^*$ data might have a useful effect in reducing the uncertainties in the parton fits. The answer can be seen in the following four plots in Figs. 11 and 12. In order to see the effect of each of the quantities in the **ePump**-simulated refitting, there are four sets of results in each plot:

- The shaded background shows the uncertainties resulting from the current CT14HERA2 uncertainties.
- The dotted curve labeled “mass” corresponds to the error reduction by sending only binned $(\Delta m_{\ell\ell})$ to **ePump**; i.e., integrated over the $y_{\ell\ell}$ and $\cos \theta^*$ dimensions.

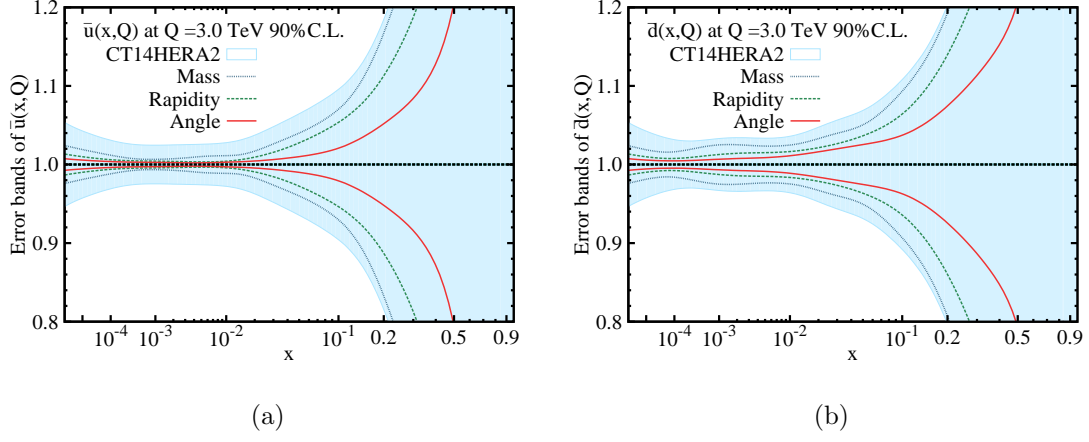


FIG. 11. Impact of the 3000 fb^{-1} update on the (a) CT14HERA2 $\bar{u}(x)$ and (b) $\bar{d}(x)$. The curves are explained in the text.

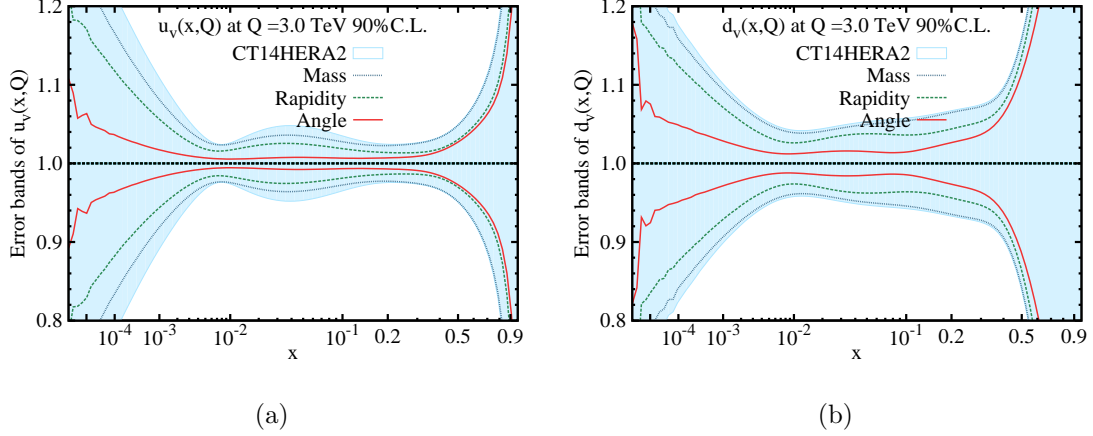


FIG. 12. Impact of the 3000 fb^{-1} update on the (a) CT14HERA2 $u_v(x)$ and (b) $d_v(x)$. The curves are explained in the text.

- The dashed curve labeled “rapidity” adds the cumulative effect of binned $(\Delta|y_{\ell\ell}|)$ and $(\Delta m_{\ell\ell})$ to ePump.
- Finally, the solid curve labeled “angle” adds the cumulative effect of binned $(\Delta \cos \theta^*)$, $(\Delta|y_{\ell\ell}|)$, and $(\Delta m_{\ell\ell})$ to ePump.

Figure 11 shows the impact of the ePump update with the 3000 fb^{-1} scenario on the $\bar{u}(x)$ and $\bar{d}(x)$ sea distributions and Fig. 12, the impact on the $u_v(x)$ and $d_v(x)$ valence distributions.

The sea distributions show a considerable reduction in uncertainty at high x . For example, in both the $\bar{u}(x)$ and $\bar{d}(x)$ distributions, the PDF uncertainty is reduced from its pre-update

x	$u_v(x)$		$d_v(x)$		$\bar{u}(x)$		$\bar{d}(x)$	
	δ_{pre} [%]	δ_{post} [%]	δ_{pre} [%]	δ_{post} [%]	δ_{pre} [%]	δ_{post} [%]	δ_{pre} [%]	δ_{post} [%]
0.1	3.4	0.7	5.8	1.5	9.8	2.2	11	3.8
0.3	2.6	0.9	7.5	3.6	30	8.3	32	11
0.5	4.8	2.6	16	11	71	20	69	20
0.7	12	7.0	45	30	280	77	250	67

TABLE IV. Impact of 3000 fb^{-1} update on the CT14HERA2 $u_v(x)$ and $d_v(x)$ valence and $\bar{u}(x)$ and $\bar{d}(x)$ sea distributions for several values of x using the standard triple-differential templates at $Q = 3 \text{ TeV}$. To be compared with the “Angle” curves of Figs. 11 and 12.

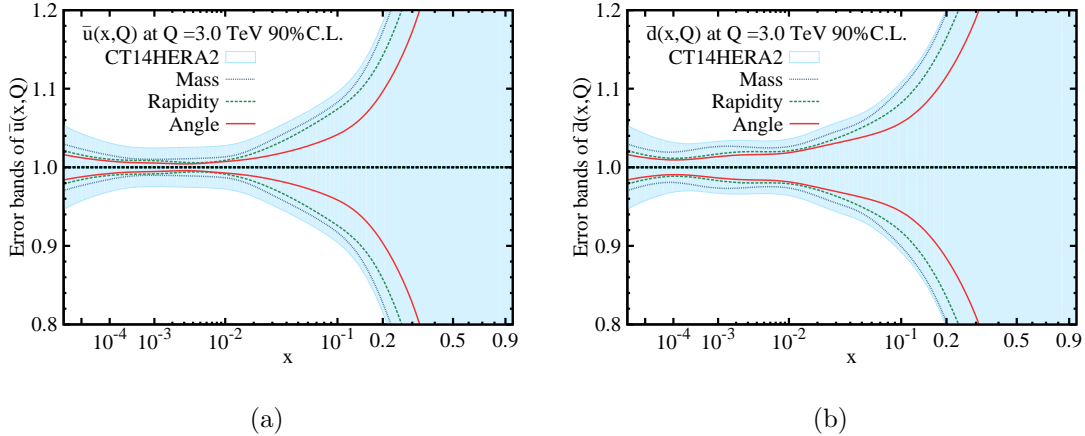


FIG. 13. Impact of the 300 fb^{-1} update on the (a) CT14HERA2 $\bar{u}(x)$ and (b) $\bar{d}(x)$. The curves are explained in the text.

value of approximately 70% to 20% at $x = 0.5$. The improvement in the valence distributions at $x \gtrsim 0.5$ is less dramatic, but substantial improvement is observed in the ranges of $x \lesssim 0.5$. The post-update $u_v(x)$ distribution remains better constrained than $d_v(x)$ at high x , where the uncertainty measures 2.6% as compared to 11% at $x = 0.5$, respectively. Table IV lists the pre- and post-update uncertainties for several parton flavors and values of x explicitly.

Figures 13 and 14 show the reduction in uncertainties for the 300 fb^{-1} scenario and Table V is the corresponding comparison for the 300 fb^{-1} scenario.

The answer to Question 1 is that a global PDF fit which includes DY LHC data below 1 TeV in mass, and binned in rapidity and $\cos \theta^*$, would dramatically improve the precision

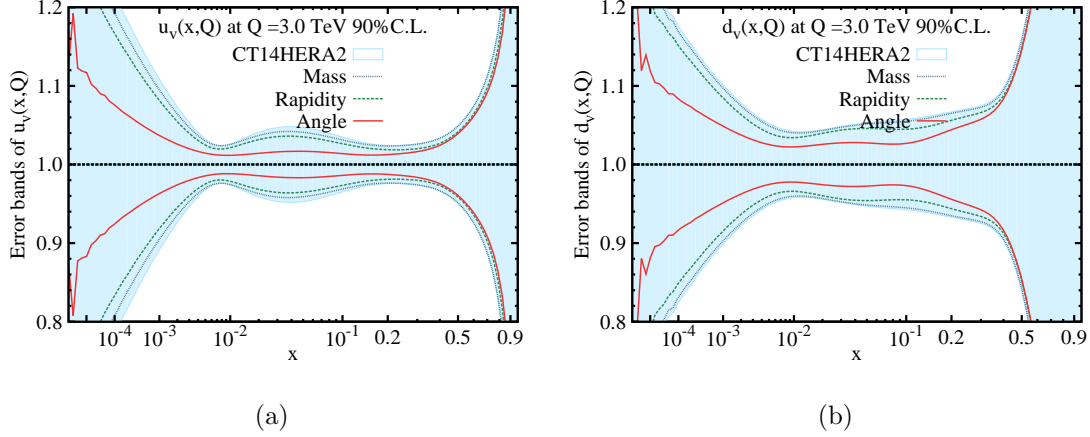


FIG. 14. Impact of the 300 fb^{-1} update on the (a) CT14HERA2 $u_v(x)$ and (b) $d_v(x)$. The curves are explained in the text.

x	$u_v(x)$		$d_v(x)$		$\bar{u}(x)$		$\bar{d}(x)$	
	$\delta_{pre} [\%]$	$\delta_{post} [\%]$	$\delta_{pre} [\%]$	$\delta_{post} [\%]$	$\delta_{pre} [\%]$	$\delta_{post} [\%]$	$\delta_{pre} [\%]$	$\delta_{post} [\%]$
0.1	3.4	1.4	5.8	2.7	9.8	4.3	11	6.0
0.3	2.6	1.6	7.5	5.7	30	17	32	19
0.5	4.8	3.9	16	14	71	43	69	41
0.7	12	9.7	45	41	280	180	250	160

TABLE V. Impact of 300 fb^{-1} update on the CT14HERA2 $u_v(x)$ and $d_v(x)$ valence and $\bar{u}(x)$ and $\bar{d}(x)$ sea distributions for several values of x using the standard triple-differential templates at $Q = 3 \text{ TeV}$. To be compared with the “Angle” curves of Figs. 13 and 14.

in our knowledge of the up and down PDFs. During the LHC era DY measurements of this kind are likely the only way to reduce uncertainties on the PDFs at high x ; no other input data are capable of achieving this improvement.

B. Impact on the High-Mass Drell-Yan Spectrum

With an updated set of PDFs, we can answer Question 2: the effect of new PDFs on the systematic uncertainty on high-mass DY cross section. Rather than the enormous extrapolation required of current-day PDFs, the extrapolation from our CR to our SR is modest

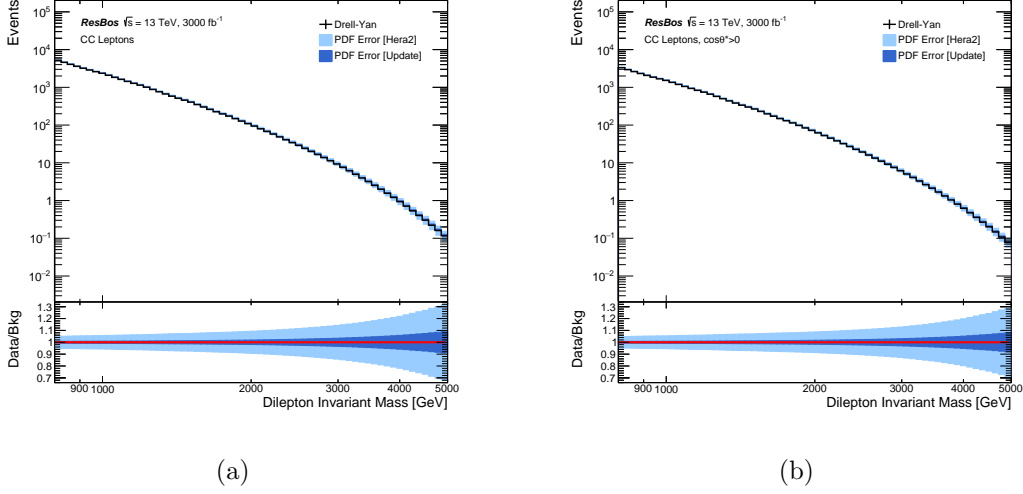


FIG. 15. The dilepton invariant mass distribution for (a) central-central dilepton events, and (b) with an additional $\cos \theta^* > 0$ requirement added to the selection. The ratio sub-plot depicts the CT14HERA2 PDF uncertainty before and after the 3000 fb^{-1} update.

and impactful. In order to make contact with primarily the ATLAS dilepton analysis, the invariant mass distribution assessed here utilizes leptons that originate in the central-central final state only.

The results are presented in Fig. 15, which shows the impact of the 3000 fb^{-1} pseudo-dataset on the high-mass PDF systematic uncertainty. The PDF uncertainty is evaluated at several characteristic values of dilepton mass, which are listed in Table VI. At $m_{\ell\ell} = 5 \text{ TeV}$, the PDF systematic uncertainty is reduced from 31% to 8.9%, a reduction of roughly a factor of 3.5. Similarly, at $m_{\ell\ell} = 3 \text{ TeV}$, the uncertainty is reduced from 15% to 3.7%, roughly a factor of 4. In each case, a substantial improvement is obtained compared to the current state-of-the-art predictions (as depicted in Fig. 7). The PDF uncertainty assessed in the ATLAS dilepton analysis is, for example, 13% and 29% at $m_{\ell\ell} = 3$ and $m_{\ell\ell} = 5 \text{ TeV}$, respectively.

C. Additional Analysis Strategies

Remembering that positive $\cos \theta^*$ is essentially all up-quark collisions, an additional analysis strategy might be to only analyze data from specific regions of $\cos \theta^*$. Figure 15(b) displays the dilepton invariant mass with the selection requirement of limiting data to

$m_{\ell\ell}$ [TeV]	CC Selection		CC+cos θ^* Selection	
	δ_{pre}^{PDF} [%]	δ_{post}^{PDF} [%]	δ_{pre}^{PDF} [%]	δ_{post}^{PDF} [%]
1	5.9	1.0	5.6	0.9
2	9.6	2.0	8.9	1.7
3	15	3.7	13	3.2
4	22	6.0	20	5.3
5	31	8.9	28	8.0

TABLE VI. The estimated PDF uncertainty in several invariant mass bins for the distributions shown in Fig. 15. Two selections are tested: firstly the central-central selection, and secondly for the central-central selection with an additional $\cos \theta^* > 0$ requirement. For each selection, the current CT14Hera2 uncertainty estimates are shown in the first column, and the result of the 3000 fb1 update is shown in the second. The pre-update values for the central-central selection are consistent with those assessed in the ATLAS dilepton analysis.

$\cos \theta^* > 0$, where the error is assessed with the updated PDFs. Such a combination provides for a marginal, but non-trivial further reduction in the PDF uncertainty at high-mass at the expense of a reduction in statistics. Table VI quantifies the PDF uncertainty before and after the update in several high-mass bins of interest for each of these selections.

For the 300 fb⁻¹ scenario, the results are shown in Fig. 16 and Table VII. While not as dramatic, this is an un-tuned effort and Run-3 LHC data will benefit significantly from the analysis approach we outlined here. Statistical precision can be enhanced by judiciously choosing the pseudo-data granularity.

The answer to Question 2 is that with the triply differential global fitting and analysis strategies suggested here, true global fitting that includes inputs from CR DY data in bins of $m_{\ell\ell}$, $y_{\ell\ell}$, and $\cos \theta^*$ should extend search limits dramatically. By this approach the now dominant PDF uncertainties in DY backgrounded searches can be reduced to be comparable or smaller than published experimental uncertainties.

Finally, further improvement at high-mass could be obtained by extending the nominal 1 TeV control region if, for example, the signal region in which no new physics was observed reached to even higher masses than current analyses. The bottom line is this: the heretofore

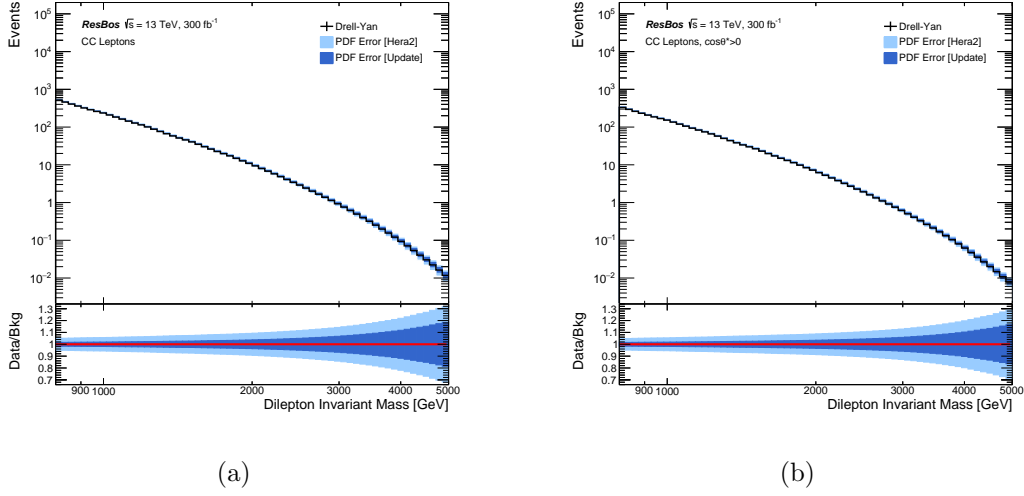


FIG. 16. The dilepton invariant mass distribution for (a) central-central dilepton events, and (b) with an additional $\cos \theta^* > 0$ requirement added to the selection. The ratio sub-plot depicts the CT14HERA2 PDF uncertainty before and after the 300 fb^{-1} update.

$m_{\ell\ell}$ [TeV]	Central-Central Selection		CC+ $\cos \theta^*$ Selection	
	δ_{pre}^{PDF} [%]	δ_{post}^{PDF} [%]	δ_{pre}^{PDF} [%]	δ_{post}^{PDF} [%]
1	5.8	1.9	5.5	1.7
2	9.4	3.8	8.8	3.5
3	15	7.1	13	6.1
4	23	13	21	11
5	32	19	29	16

TABLE VII. The estimated PDF uncertainty in several invariant mass bins for the distributions shown in Fig. 16. The current CT14HERA2 uncertainty estimates are shown in the first column, the result of the 300 fb^{-1} update is shown next, and the 300 fb^{-1} update with an additional $\cos \theta^* > 0$ requirement on the dilepton selection is shown last.

enormous PDF uncertainties in any BSM search at high mass can be significantly reduced *below* the current experimental uncertainties by including DY data in bins of $m_{\ell\ell}$, $y_{\ell\ell}$, and $\cos \theta^*$ in future global PDF fitting.

$m_{\ell\ell}$ [TeV]	CC Selection	ATLAS Dilepton Analysis				
	δ_{post}^{PDF} [%]	δ^{PDF} [%]	δ^{Choice} [%]	δ^{Theory} [%]	δ^{Exp} [%]	δ^{Total} [%]
2	2.0	8.7	0.0	9.8	11	15
4	6.0	19	8.4	23	13	26

TABLE VIII. The post-update PDF uncertainty as compared to the experimental and dominant theoretical uncertainties in the electron channel of the dilepton analysis. As the PDF uncertainty will be reduced well below the current experimental uncertainty, attention will be shifted to the reduction of others, such as the “PDFChoice” uncertainty, improving the discovery potential of future iterations of the dilepton analysis.

VI. OUTLOOK

The impact of a future DY cross section measurement on the CT14HERA2 PDF uncertainty was assessed using the **ePump** package at the $\sqrt{s} = 13$ TeV LHC with 300 fb^{-1} and 3000 fb^{-1} of DY pseudo-data. The fiducial region considered for the PDF update was based on three variables: the dilepton mass ($m_{\ell\ell}$), the dilepton rapidity ($y_{\ell\ell}$), and the cosine of the polar angle in the CS-frame ($\cos \theta^*$). This region was divided into 1296 histogram bins and used to construct **ePump** pseudo-data and signal templates, which were designed to probe the PDFs in the extreme kinematic regions of (x, Q^2) only accessible at the LHC.

The CT14HERA2 PDF set was used for the update, but similar effects would be observed in other PDF sets. The results showed a significant reduction in the uncertainties associated with all parton flavors, especially $\bar{u}(x)$ and $\bar{d}(x)$ sea distribution at high x . Likewise, these reduced PDF uncertainties, when propagated to the dilepton invariant mass spectrum, lead to a significantly improved description at high mass.

These proof-of-concept results indicate a great deal of improvement can still be obtained from precision PDF measurements at LHC. The use of $\cos \theta^*$ as an additional dimension in future PDF global fits is absolutely crucial, as it supplements the more standard double-differential measurements in invariant mass and rapidity; when used in conjunction, as was done here, the reduction in uncertainty can be dramatic.

For these reasons, DY cross section measurements could be vital to the success of future searches and measurements at the LHC. Not only will the PDF uncertainty that affects

the high-mass dilepton analysis be reduced, improving the discovery potential of many non-resonant new physics models, but also the inclusion of new and robust data into the modern PDF global fits might even bring the uncertainty estimates of the various global fitting groups into better agreement.

Such an opportunity might result in a reduction of the “PDF choice” uncertainty when all PDF groups include triply differential DY data as discussed here. Obviously the goal would be to reach a stage in which the largest uncertainty would cease to be due to the PDFs. Table VIII compares these uncertainties explicitly.[20] Therefore, for the reasons outlined in this paper, experiments at the LHC and global fitting groups should seriously consider the inclusion of precision measurements of the DY triple-differential cross section in order to further constrain the PDF uncertainties in future PDF global fits. In the short term the methodology described here could also be used by experiments when judiciously choosing careful control regions to update current PDF uncertainties, perhaps vastly improving search sensitivity at high mass.

ACKNOWLEDGMENTS

We thank our CTEQ-TEA colleagues for support and discussions. This work was supported by the U.S. National Science Foundation under Grants No. PHY-1719914 and PHY-1707812. C.-P. Yuan is also grateful for the support from the Wu-Ki Tung endowed chair in particle physics. This work was also supported by Fermi Research Alliance, LLC, under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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