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SEARCHING FOR THE Z' BOSON AT HADRON COLLIDERS

The Z' boson couplings to the Standard model fermions have been estimated with the 92% confidence level from the CMS data on the forward-backward asymmetry of the Drell-Yan process at 7 TeV in a model-independent approach. For doing that, in Wolfram Mathematica, a specific computer package is developed for calculation of the cross sections and forward-backward asymmetry of the Drell-Yan production at the LHC and TeVatron. In the present paper, the physical and mathematical principles of the developed package and its features are described. All the calculations are performed in the next-to-next-to-leading order in the QCD sector and next-to-leading order in the electroweak sector. The final state radiation can also be accounted for in terms of the Sudakov factor. Except the Standard model processes, the package accounts for the Z' effects. The output of the package is presented in the kinematic observables commonly used at the modern colliders. Also, all the typical phase space cuts are considered and may be applied.

Keywords: Wolfram Mathematica, Z', forward-backward asymmetry, Drell-Yan process, LHC.

У рамках модельно-незалежного підходу оцінені константи зв'язку Z' бозона з ферміонами Стандартної моделі на рівні довірчої ймовірності 92% за даними CMS з асиметрії вперед-назад у процесі Дрелла-Яна на 7 ТеВ. Для цього на базі системи Wolfram Mathematica розроблено комп'ютерний пакет для обчислення перерізу та асиметрії вперед – назад у процесі Дрелла-Яна на Великому гадронному колайдері та Теватроні. У даній роботі описані фізичні та математичні принципи та практичні можливості розробленого пакету. Усі обчислення виконані з точністю NNLO в QCD-секторі та з точністю NLO в електрослабкому секторі. Існує можливість врахування ефектів випромінювання в кінцевих станів у термінах судаковського фактора. Окрім стандартномодельних процесів, ураховуються прояви Z'-бозону. Результати роботи пакету представлені у стандартних кінематичних змінних, використовуваних на сучасних колайдерах. Реалізована можливість накладання усіх типових обмежень фазового простору.

Ключові слова: Wolfram Mathematica, Z', асиметрія вперед-назад, процес Дрелла – Яна, LHC.

В рамках модельно-независимого похода оценены константы связи Z' бозона с фермионами Стандартной модели на уровне доверительной вероятности 92% по данным CMS по асимметрии вперед-назад в процессе Дрелла-Яна на 7 ТэВ. На базе системы Wolfram Mathematica разработан компьютерный пакет для вычисления сечения и асимметрии вперед – назад в процессе Дрелла-Яна на Большом адронном коллайдере и Тэватроне. В данной работе описаны физические и математические принципы и практические возможности разработанного пакета. Все вычисления выполнены с точностью NNLO в QCD-секторе и с точностью NLO в электрослабом секторе. Существует возможность учета эффектов излучения в конечных состояниях в терминах судаковского фактора. Кроме стандартномодельных процессов, учитываются проявления Z'-бозона. Результаты работы пакета представлены в стандартных кинематических переменных, используемых на современных коллайдерах. Реализована возможность наложения всех типовых ограничений фазового пространства.

Ключевые слова: Wolfram Mathematica, Z', асимметрия вперед-назад, процесс Дрелла – Яна, LHC.

1. Introduction

Searching for new elementary particles is one of the main goals of modern physics. The Standard model has the well-known shortcomings, so it is important to understand how it may be extended. Existence of a new heavy neutral Z' boson is one of the most probable scenarios of this extension. During the recent time, there are numerous works where its direct search has been performed at the LHC. The current established limit on its mass is $m_{Z'} > 2.5$ TeV from the CMS data and $m_{Z'} > 2.9$ TeV from the ATLAS data at 95% confidence level (C.L.). At the same time a question arises which model the Z' belongs to. Currently there are more than hundred known models of the Z', such as LR, ALR, χ, ψ, $B-L$, and others. Taking into account that the Z' identification reach is about 5 TeV, it will be difficult to distinguish the basic Z' model even in the case if it is discovered explicitly in the LHC experiments. That is why model-independent approach to searching for the Z' may be more useful. This approach allows estimating not only the Z' mass but also its couplings with the Standard model fields.

Such a program has been implemented in our recent paper [1] basing on the CMS data on the forward-backward asymmetry A_{FB} in the Drell-Yan process. These data were analyzed in order to establish the Z' boson vector and axial-vector couplings to the Standard model fermions. That work required a large amount of the calculations of the cross sections and forward-backward asymmetry of the Drell-Yan production both in the Standard model (SM) and effective model SM + Z'. Also, the hardware peculiarities of the LHC apparatus had to be accounted for to make the results comparable with the experimental ones. A specific computer package was developed in Wolfram Mathematica [2] for these purposes. Then it was extended in order to make it usable for analyzing both the LHC and the TeVatron data. The present paper is devoted to description of the theoretical aspects and practical applications of the developed package.

The paper is organized as follows. In the next section, we introduce the kinematical variables used in particle physics. The special attention will be paid to a Collins-Soper reference frame that plays an essential role at the LHC. The third section describes a general structure of the developed package and the possible sources of appearing uncertainties. The fourth section contains a practical manual to the developed package. In the final section, some sample numerical results and their discussion are given. The Appendix contains a detailed description of all the functions implemented in the package.

2. The kinematic variables in particle physics

In high energy physics, the processes are usually described in the specific kinematic variables [3]. In this section, we introduce such variables for the Drell-Yan process ($pp(p\bar{p}) \to \gamma/Z(Z') \to l\bar{l}$) and discuss how the typical phase space cuts are applied. As usually, this process is discussed in a parton model, $q\bar{q} \to \gamma/Z(Z') \to l\bar{l}$. We use the following notation,

– s, t, u are the Mandelstam variables;
– the hatted letters ($\hat{\sigma}$, $\hat{s}$, …) stand for the parton-level quantities;
– the non-hatted letters σ, s, …) stand for the hadron-level quantities;
– the momenta with the asterisks (p_{q*}, p_{l*}, …) are calculated in the partons center-of-mass reference frame;
– the momenta without asterisks are calculated in the laboratory reference frame;
– (E, P) denote the energy and momentum of a hadron in the laboratory reference frame.

If the input hadrons move along the z axis, then

$$P_1^\mu = (E,0,0,E) \text{ and } P_2^\mu = (E,0,0,-E).$$

For the quarks, the transverse momenta are neglected, so

$$p_q^\mu = (x_1 E,0,0,x_1 E) \text{ and } p_{\bar{q}}^\mu = (x_2 E,0,0,-x_2 E)$$

where x_1 and x_2 are the Bjorken fractions. Further, the invariant mass M is introduced,

$$M^2 = (p_q + p_{\bar{q}})^2 = 4x_1x_2E^2,$$

and rapidity Y is defined by the relations

$$x_{1,2} = \frac{M}{\sqrt{s}}e^{\pm Y}.$$

Finally, pseudorapidity η is defined as

$$\eta = -\ln[\tan(\theta/2)]$$

where θ is an angle between the outgoing lepton and the ingoing quark.

Now let us consider the Collins-Soper reference frame that is commonly used at the LHC [4]. The direction of the z axes in this reference frame is given by the relation

$$\cos\theta_{CS} = \frac{Q_z}{|Q_z|}\frac{2\left(P_1^+P_2^- - P_2^+P_1^-\right)}{|Q|\sqrt{Q^2+Q_T^2}} \tag{1}$$

where $P_i^\pm = \left(p_i^0 \pm p_0^3\right)/\sqrt{2}$, $p_1(p_2)$ is the momentum of the lepton (antilepton), $Q^\mu = p_q^\mu + p_{\bar{q}}^\mu$ (so that $Q^2 = M^2$), and all the quantities are measured in the laboratory reference frame. First,

$$Q_z = (x_1 - x_2)E = \frac{ME}{\sqrt{s}}\left(e^Y - e^{-Y}\right) = M\sinh Y \Rightarrow \frac{Q_z}{|Q_z|} = \mathrm{sgn}(Y).$$

Further, as above, we neglect the transverse momentum, $Q_T = 0$. For the following, we move to the center-of-mass (CM) reference frame of the partons. Let us find the Lorentz transformation that gives $p_{q*}^3 + p_{\bar{q}*}^3 = 0$. The calculation yields that the Lorentz parameters of such a transformation are

$$\beta\gamma = \sinh Y \text{ and } \gamma = \cosh Y. \tag{2}$$

Expressing all the quantities in (1) through the corresponding quantities in a partons CM frame taking (2) into account, we obtain

$$\cos\theta_{CS} = \mathrm{sgn}(Y)\cos\theta_*$$

where θ_* is a scattering angle in a partons CM reference frame.

Now, let us re-write the standard expression for the Drell-Yan cross section known in the parton model through the new kinematic variables M, Y, and $z = \cos\theta$. Doing some transformations, we come to the formula

$$\sigma = \sum_q \int_{(M)} dM\, M \int_{(Y)} dY \left[F_q\left(\frac{M}{\sqrt{s}} e^{Y}\right) F_{\bar{q}}\left(\frac{M}{\sqrt{s}} e^{-Y}\right) + \right.$$

$$\left. + F_q\left(\frac{M}{\sqrt{s}} e^{-Y}\right) F_{\bar{q}}\left(\frac{M}{\sqrt{s}} e^{Y}\right)\right] \int_{(z)} dz\, \hat{\sigma}_{q\bar{q}\to l\bar{l}}(M, z) \qquad (3)$$

in the partons CM reference frame and

$$\sigma = \sum_q \int_{(M)} dM\, M \left[\int_{(Y>0)} dY F_q\left(\frac{M}{\sqrt{s}} e^{Y}\right) F_{\bar{q}}\left(\frac{M}{\sqrt{s}} e^{-Y}\right) \int_{(z)} dz \hat{\sigma}_{q\bar{q}\to l\bar{l}}(M, z) + \right.$$

$$\left. + \int_{(Y<0)} F_q\left(\frac{M}{\sqrt{s}} e^{-Y}\right) F_{\bar{q}}\left(\frac{M}{\sqrt{s}} e^{Y}\right)\right] \int_{(z)} dz\, \hat{\sigma}_{q\bar{q}\to l\bar{l}}(M, -z) \qquad (4)$$

in the Collins-Sopper reference frame, where $F_q(x) \equiv x f_q(x, M^2)$ and $f_q(x, M^2)$ is a PDF calculated at the Bjorken fraction x and factorization scale M.

Finally, let us consider some typical cuts on the phase space [7].

1. $M_1 < M < M_2$ and/or $Y_1 < |Y| < Y_2$. These cuts are implemented directly by constraining an integration region in (3), (4).
2. $p_T^l > p_0$. It can be shown easily that this cut yields a restriction $|z| < \sqrt{1 - 4p_0^2/M^2}$.
3. $|\eta_l| < \eta_0$. Using the definition of η, we obtain that in this case $|z| < \tanh \eta_0$.

3. The general structure of the *DrellYan* package

The *DrellYan* package bases completely on formulae (3), (4). At the first step it loads the parton-level cross sections $\hat{\sigma}_{q\bar{q}\to l\bar{l}}$ calculated previously with the FeynArts and FormCalc [5] packages. Then it convolutes them with the selected PDFs and performs a numerical integration taking the applied phase space cuts into account. As a result, the inclusive Drell-Yan cross sections are obtained. The forward-backward asymmetry is calculated by the standard formula

$$A_{FB} = \frac{\int_0^{z_0} (d\sigma/dz) dz - \int_{-z_0}^{0} (d\sigma/dz) dz}{\int_0^{z_0} (d\sigma/dz) dz + \int_{-z_0}^{0} (d\sigma/dz) dz}$$

where z_0 is defined by p_T^l and η_l cuts. If the latter are absent, then $z_0 = 1$.

Let us consider accuracy of the *DrellYan* package output separately. In what follows we discuss the A_{FB} uncertainties only because precise calculation of the cross section requires including the *K*-factor which is out of the *DrellYan* package scope.

The QCD sector accuracy is defined by the order of the selected PDFs by α_s. A possibility exists to select the leading order (LO), next-to-leading order (NLO, and next-to-next-to-leading (NNLO) order PDF set. The electroweak sector is calculated in an improved Born approximation which corresponds to the NLO accuracy with not more than 1-2% error [6]. Here we use the running coupling $\alpha_{em} = 1/128$ and the effective

Weinberg mixing angle $\sin^2\theta_W = 0.2312$ which account for the one-loop radiative corrections. Also, it is possible to account for the real final-state photon radiation explicitly by turning on a contribution from the Sudakov factor (switched off by default)

$$d\sigma_{WithSudakov} = d\sigma_0 \times \exp\left(-\frac{\alpha_{em}}{2\pi}\ln\left(\frac{M^2}{m_l^2}\right)\ln\left(\frac{M^2}{E_0^2}\right)\right),$$

where M is an invariant mass, m_l is a mass of a final-state lepton, and E_0 is a hardware energy threshold of soft photons. We use the value $E_0 = 20$ GeV basing on [8].

The uncertainties of the calculation results consist of two ingredients. The PDF uncertainty $(\Delta A_{FB})_{PDF}$ gives the most significant contribution. It may be evaluated by the standard formula (for example, [9])

$$(\Delta A_{FB})_{PDF} = \frac{1}{2}\sqrt{\sum_k \left[A_{FB}\left(S_k^+\right) - A_{FB}\left(S_k^-\right)\right]^2},$$

where S_k are the eigenvectors of the given PDF set, and summation is performed over all the eigenvectors. In our calculations, we obtained that $(\Delta A_{FB})_{PDF} < 5\%$. The next uncertainty source is the deviation $(\Delta A_{FB})_{IBA}$ of the improved Born approximation from exact NLO. As mentioned above, $(\Delta A_{FB})_{IBA} < 2\%$. So, finally

$$\Delta A_{FB} = \sqrt{(\Delta A_{FB})^2_{PDF} + (\Delta A_{FB})^2_{IBA}} < 6\%.$$

4. Getting started with the *DrellYan* package

The package consists of the module file “drell-yan.m” and the parton-level Drell-Yan cross sections placed in the same directory in folders “Sigmas” and “Factors”. In order to make the module work properly, the folders “NNPDF” and “mstw2008code” containing the NNPDF and MSTW2008 PDF sets must be also located in the same directory. Working with the package requires several steps.

1. Open an instance of Wolfram Mathematica and create a new notebook.
2. Set the directory where “drell-yan.m” is located as a working directory,

SetDirectory[“Path/To/Folder/With/drell-yan.m”];

3. Configure the PDFs properly. For that, open “drell-yan.m” in any text editor and set the needed values of the variables $PDFSetToUse, $PDFOrder, and $PDFCL accordingly to their description in the file.

3. Load the *DrellYan* module with a command

<< “drell-yan.m”

This operation loads also the selected PDF set, so it takes several minutes.

4. Set the needed kinematic parameters and cuts with the help of commands

SetColliderType[…];	(* 0 – pp or 1 – $p\bar{p}$)
SetSqrtS[…];	(* center-of-mass energy, $\sqrt{s}$, in GeV *)
SetSW2[…];	(* $\sin^2\theta_W$ *)
SetFrameType[…];	(* 0 – partons CM frame or 1 – Collins-Soper frame *)
SetPTCut[…];	(* p_T^l cut in GeV *)
SetEtaCut[…];	(* η_l cut *)
SetSudakovOn[…];	(* True or False; whether to account for the FSR *)

5. The package is ready to work. Now it is possible to perform the by use of the functions described in Appendix.

5. The results and discussion

In this section, we show the forward-backward asymmetry calculated for the LHC and the TeVatron in the same bins as measured. The tables below demonstrate all the main features of the *DrellYan* package.

In Table 1, the simulated data on A_{FB} at the CMS detector at 7 TeV are presented. The cuts applied are 40 GeV < M < 400 GeV, $0<|Y|<1.5$, $p_T^l > 20$ GeV. It can be seen that in all the bins, the deviation between the simulated and experimental data do not exceed several percent. In Table 2, the TeVatron data are simulated and the contribution of the FSR to A_{FB} accounted for by the Sudakov factor is shown. The results show that this contribution does not exceed 1%, as it is known from the literature [6].

Table 1

The simulation of the CMS data on A_{FB} at 7 TeV

A_{FB}, the CMS data	Simulation, IBA	A_{FB}, the CMS data	Simulation, IBA
–0.0167±0.0067	–0.0105	0.1655±0.0105	0.1883
–0.0225±0.0142	–0.0258	0.1663±0.0174	0.1937
–0.0355±0.0052	–0.0254	0.2485±0.0187	0.2442
–0.1122±0.0125	–0.0804	0.0905±0.0108	0.0955
–0.0415±0.0045	–0.0427	0.2191±0.0195	0.2233
–0.0999±0.0084	–0.1038	0.2576±0.0287	0.2796
–0.1293±0.0086	–0.1340	0.1020±0.0128	0.1080
–0.0221±0.0029	–0.0232	0.2903±0.0279	0.3104
–0.0468±0.0064	–0.0566	0.1251±0.0194	0.1209
–0.0700±0.0065	–0.0732	0.2401±0.0308	0.2763
0.0157±0.0011	0.0188	0.3209±0.0335	0.3400
0.0249±0.0013	0.0238	0.3245±0.0282	0.3224
0.0747±0.0063	0.0827	0.3752±0.0308	0.3887
0.1012±0.0067	0.1055	0.1541±0.0331	0.1908

Table 2

Contribution of the final-state radiation to A_{FB} at the TeVatron at 1.96 TeV

A_{FB}, IBA	A_{FB}, IBA+FSR	A_{FB}, IBA	A_{FB}, IBA+FSR
–0.3792	–0.3785	0.3971	0.3970
–0.5226	–0.5226	–0.1583	–0.1583
–0.4255	–0.4256	–0.0773	–0.0773
–0.2678	–0.2679	0.0035	0.0034
0.1307	0.1307	0.0713	0.0713
0.1977	0.1976	0.5268	0.5267

The Drell-Yan production is a very essential process for modern high energy physics. In particular, it is used as a benchmark in many investigations, such as measurement of the effective electroweak mixing angle, fitting the parton distribution functions, probing the flavor asymmetry of the proton and others. Our *DrellYan* package is a powerful tool that may obtain different applications. Certainly, generally speaking, it is not the only way to calculate the differential cross section of the Drell-Yan process. The existing Monte-Carlo generators can solve this problem. But the developed package has two advantages. First, it is an analytical tool, in contrary to any Monte-Carlo generator. ZFITTER [10] is the only known analytical instrument that can be used for the similar purposes. But it is much more bulky in exploitation. Besides, it does not do the same as the *DrellYan*, so it cannot be considered an adequate replacement. Secondly, the

Monte-Carlo generators hardly can be extended with the Z' sector in a model-independent approach as it is implemented in the developed package. Some of them do not include the Z' at all while other ones support only a narrow class of the Z' models. For example, the PYTHIA [11] provides the Z' without its mixing with the standard Z. However, it is clear that since the Higgs field exists, the $Z-Z'$ mixing is unavoidable.

In our recent paper [1], with the help of the *DrellYan* package we have managed to estimate the Z' couplings to the Standard model fermions from the CMS data on A_{FB} at 7 TeV. It is worth noting that it is the first calculation of these parameters known in the literature. The works exist where the model-dependent constraints on the Z' mass are established. But its couplings have been never estimated till now from the experimental data directly. We have obtained that these couplings are nonzero at ~ 92% C.L. In fact, it means the existence of the Z' hint at almost 2σ level. This statement agrees with the results obtained earlier from the LEP [12] and TeVatron [13] data.

Further results are expected from the measurements within run 2 of the LHC. The developed method allows its application to the new data without significant changes. Also, it is of interest to study the Z production in order to estimate the $Z-Z'$ mixing angle that has be never calculated directly before. We left these problems for the future.

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Appendix. The functions of the *DrellYan* module

Function name	Description	Example
SigmaSMCV	The cross section of the Drell-Yan process in the Standard model in a given $(M,\|Y\|)$ bin, calculated with the central PDF value	SigmaSMCV[40, 50, 0, 1]
SigmaSMRep	The cross section of the Drell-Yan process in the Standard model in a given $(M,\|Y\|)$ bin, calculated with the central PDF value Yan process in the Standard model, calculated with the i-th PDF eigenvector	SigmaSMRep[40, 50, 0, 1, 5]
AsymSMCV	The forward-backward asymmetry of the Drell-Yan process in the Standard model in a given $(M,\|Y\|)$ bin, calculated with the central PDF value	AsymSMCV[40, 50, 0, 1]
AsymSMRep	The forward-backward asymmetry of the Drell-Yan process in the Standard model in a given $(M,\|Y\|)$ bin, calculated with the i-th PDF eigenvector	AsymSMRep[40, 50, 0, 1]
SigmaA2SeriesCV	The coefficients of the expansion of the Z' factor at a^2 into a series by $\zeta = m_Z/m_{Z'}$ up to $O(\zeta^6)$ in a given $(M,\|Y\|)$ bin, calculated with the central PDF value	SigmaA2SeriesCV[40, 50, 0, 1]
SigmaA2SeriesRep	The coefficients of the expansion of the Z' factor at a^2 into a series	SigmaA2SeriesRep[40, 50, 0, 1, 5]

	by $\zeta = m_Z / m_{Z'}$ up to $O(\zeta^6)$ in a given $(M, \lvert Y \rvert)$ bin, calculated with the i-th PDF eigenvector	
SigmaAVlSeriesCV	The same as SigmaA2SeriesCV, but for the Z' at av_l	SigmaAVlSeriesCV[40, 50, 0, 1]
SigmaAVlSeriesRep	The same as SigmaA2SeriesRep, but for the Z' at av_l	SigmaAVlSeriesRep[40, 50, 0, 1, 5]
SigmaAVqSeriesCV	The same as SigmaA2SeriesCV, but for the Z' at av_q	SigmaAVqSeriesCV[40, 50, 0, 1]
SigmaAVqSeriesRep	The same as SigmaA2SeriesRep, but for the Z' at av_q	SigmaAVqSeriesRep[40, 50, 0, 1, 5]
SigmaVqVlSeriesCV	The same as SigmaA2SeriesCV, but for the Z' at $v_l v_q$	SigmaVqVlSeriesCV[40, 50, 0, 1]
SigmaVqVlSeriesRep	The same as SigmaA2SeriesRep, but for the Z' at $v_l v_q$	SigmaVqVlSeriesRep[40, 50, 0, 1, 5]

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