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ESTIMATES FOR AXIAL-VECTOR COUPLING OF AN ABELIAN Z' BOSON FROM MODERN COLLIDER DATA

In the present paper we derive upper boundaries for Z' boson axial-vector coupling to Standard Model fermions. We use all currently-available data on Z' boson searches in the narrow-resonance approximation at the LHC at 7 TeV, 8 TeV, and 13 TeV, and Tevatron. The Z' boson is described using an effective low-energy Lagrangain in a model-independent parameterization. The cross section is computed in the narrow width approximation. We compare the calculated cross section to experimental upper boundaries for deviations from the Standard Model at 95% confidence level. These boundaries are transformed into limits for the axial-vector coupling at different Z' mass values. The presented values are consistent with a fit of LHC forward-backward asymmetry data recently obtained in the literature. We conclude that the Z- Z' mixing angle cannot be higher than $2{\sim}4\times10^{-4}$. We also see that while the latest 13 TeV data provides higher energy reach, more strict coupling bounds arise from the 8 TeV data. At the same time, Tevatron data still posesses accuracy comparable to the LHC data at resonance energies up to 1 TeV.

Keywords: gauge bosons, Tevatron, LHC, model-independent searches.

У даній статті отримано обмеження зверху на аксіально-векторні константи взаємодії Z'-бозона з ферміонами Стандартної моделі. Для цього використовуються всі доступні на даний момент дані з пошуків Z'-бозона в наближенні вузького резонансу в експериментах на LHC за енергій 7 ТеВ, 8 ТеВ і 13 ТеВ, а також на Теватроні. Z'-бозон параметризується за допомогою ефективного низкоенергетичного лагранжіану в модельно-незалежній параметризації. Переріз обчислюється в наближенні малої ширини. Це значення порівнюється з експериментально встановленими верхніми границями відхилень від Стандартної моделі з рівнем довіри 95%. Ми перетворюємо ці границі на обмеження зверху для аксіально-векторної константи взаємодії за різних значень маси Z'-бозона. Отримані обмеження сумісні з наведеними в літературі інтервалами значень, нещодавно отриманими з асиметрії розсіювання вперед-назад на LHC. Ми демонструємо, що кут змішування Z- Z' не може перевищувати $2{\sim}4\times10^{-4}$. Дані, отримані під час експерименту LHC на енергії 13 ТеВ, дають змогу дослідити області більш високих мас, тоді як найвищу точність на сьогодні дають дані 8 ТеВ. Дані прискорювача Теватрон також показують точність, співставну з LHC за енергій резонансу до 1 ТеВ.

Ключові слова: нові калібрувальні бозони, Tevatron, LHC, модельно-незалежний підхід.

В данной статье получено ограничение сверху на аксиально-векторные константы связи Z'-бозона с фермионами Стандартной модели. Для этого используются все доступные на данный момент данные по поискам Z'-бозона в приближении узкого резонанса в экспериментах на LHC при энергиях 7 ТэВ, 8 ТэВ и 13 ТэВ, а также на Теватроне Z'-бозон параметризуется с помощью эффективного низкоэнергетического лагранжиана в модельно-независимой параметризации. Сечение рассчитывается в приближении малой ширины. Это значение сравнивается с экспериментально установленными верхними границами отклонений от Стандартной модели с уровнем доверия 95%. Мы преобразуем эти границы в ограничения сверху для аксиально-векторной константы связи при различных значениях массы Z'-бозона. Полученные ограничения совместимы с приведенными в литературе интервалами значений, недавно полученными из асимметрии рассеяния вперед-назад на LHC. Мы показываем, что угол смешивания Z- Z' не может превышать $2{\sim}4\times10^{-4}$. Данные, полученные в эксперименте LHC на энергии 13 ТэВ, позволяют исследовать области более высоких масс, в то время как наибольшую точность на сегодня обеспечивают данные 8 ТэВ. Данные ускорителя Теватрон также дают точность, сравнимую с LHC при энергиях резонанса до 1 ТэВ.

Ключевые слова: калибровочные бозоны, Tevatron, LHC, модельно-независимый подход.

1. Introduction

Proton-(anti)proton scattering into a pair of leptons (known as the Drell-Yan process) is one of the most widely studied processes at modern hadron colliders – the Large Hadron Collider (LHC) and Tevatron – for two reasons. Firstly, final state particles in this case are easily detected in electromagnetic calorimeters and muon spectrometers, and the background noise in this case is relatively low. Secondly, a huge number of new physics effects beyond the Standard model (SM) of elementary particles is predicted to manifest themselves in this process. A new heavy neutral vector boson (Z' boson) [1,2] is one of those effects of numerous Grand Unification and Supersymmetry Theories. Both the Tevatron and LHC collaborations try to catch the particle as a resonance in the Drell-Yan process. Observing no peak they conclude that the Z' mass is no less than approximately 2.5-3.5 TeV [3-10]. However, in those searches the collaborations rely on a predefined set of Z' models with certain assumptions about Z' coupling strength.

The data presented by the collaborations in [3-10] are deviations of the Drell-Yan cross-section from the SM value within experimental uncertainties at 95% confidence level (CL) at certain energy scales. This uncertainty is considered to be the maximal deviation from the SM and the upper boundary for possible new physics effects, which are not detected because the hypothetical resonance is too weak. Hence, by comparing this boundary with theoretical predictions for a certain model (any kind of a Z' or, for example, a spin-2 Kaluza-Klein excitation) one can derive the model-dependent lower bound for mass of this hypothetical resonance.

In the present paper we use the data published in [3-10] in a slightly different way to derive an upper limit for axial-vector coupling of an Abelian Z' boson [2] to SM fermions. We calculate the Z' production cross section for several mass values in a simple narrow-width approximation (NWA) and compare it to the experimentally measured Drell-Yan uncertainties. From a simple inequality we compute upper limits for the Z' coupling at different resonance masses. We can compare our present results to the LHC [11] data fits. Finally, the presented estimations will indicate, which of the four hadron collider experiments have been the most accurate so far: Tevatron at $\sqrt{s}$=1.96 TeV, LHC at $\sqrt{s}$=7 TeV, LHC at $\sqrt{s}$=8 TeV, or LHC at $\sqrt{s}$=13 TeV.

2. Abelian Z' couplings to leptons and quarks

Being decoupled at energies of order of m_Z, the Abelian Z' boson interacts with the SM particles as an additional $\tilde{U}(1)$ gauge boson. Its couplings to the SM fermions are usually parameterized by the effective Lagrangian [2]:

$$L_{Z\bar{f}f} \quad = \quad Z'_\mu \bar{f}\gamma^\mu \left[(v_f + \gamma^5 a_f)\cos\theta_0 \right] f / 2. \tag{1}$$

Here f is an arbitrary SM fermion state; a_f and v_f are the Z' couplings to the axial-vector and vector fermion currents, respectively; θ_0 is the Z- Z' mixing angle. The a_f and v_f couplings are proportional to the Z' gauge coupling $\tilde{g}$. This parameterization is suggested by a number of natural conditions described in [2].

At low energies the Z' couplings enter the cross section together with the inverse Z' mass, so it is convenient to introduce the dimensionless couplings

$$\bar{a}_f = a_f m_Z / (\sqrt{4\pi} m_{Z'}), \quad \bar{v}_f = v_f m_Z / (\sqrt{4\pi} m_{Z'}), \tag{2}$$

which are constrained by experiments. Below the Z' decoupling threshold the effective $\tilde{U}(1)$ symmetry is a trace of the renormalizability of an unknown complete model with the Z' boson, and it leads to additional relations between the Z' couplings [2]:

$$\bar{a}_{q_d} = \bar{a}_l = -\bar{a}_{q_u} = -\bar{a}_{\nu_l} = \bar{a}, \qquad \bar{v}_{q_d} = \bar{v}_{q_u} + 2\bar{a}, \qquad \bar{v}_l = \bar{v}_{\nu_l} + 2\bar{a}, \tag{3}$$

where q_u, q_d, l, and ν_l are the up-type and the down-type quark, the lepton, and the neutrino inside any fermion generation, correspondingly, and $\bar{a}$ is a universal coupling constant, which defines also the Z- Z' mixing angle in (1):

$$\theta_0 \approx -2\bar{a}\sin\theta_W \cos\theta_W m_Z / (m_{Z'}\sqrt{\alpha_{em}}). \tag{4}$$

Z' peak searches are not sensitive to the Z- Z' mixing angle, and a region of energies near Z boson peak should be used to obtain θ_0 value. However, in case of Abelian Z', Eq. (4) allows to estimate the mixing angle by using axial-vector coupling value obtained from high-energy data.

In the narrow width approximation the cross section of the $pp(p\bar{p}) \to l^+l^-$ is obtained in the following simple form:

$$\sigma_{NWA} = (\bar{a}^2\sigma_1 + \bar{v}_u^{\,2}\sigma_2 + \bar{a}\bar{v}_u\sigma_3)(\bar{a}^2\Gamma_1 + \bar{v}_l^{\,2}\Gamma_2 + \bar{a}\bar{v}_l\Gamma_3). \tag{5}$$

Here $\sigma_{1,2,3}$ and $\Gamma_{1,2,3}$ are numerical factors. To obtain widest-possible estimations for $\bar{a}^2$, we set $\bar{v}_u$ and $\bar{v}_l$ in Eq. (5) to zero and compare Eq. (5) at several Z' mass values with the experimentally measured bounds for 95% CL uncertainties presented in [3-10].

3. Conclusions

The results of our estimations for $\bar{a}^2$ are presented in Table 1. We consider ATLAS results for dileptons at 7 TeV [3], 8 TeV [4], and 13 TeV [5], CMS results for dileptons at 7 TeV [6], and 8 TeV [7], D0 results for dielectrons at 1.96 TeV [8], and CDF results for dielectrons [9] and dimuons [10] at 1.96 TeV. The CMS collaboration also published their results for the 13 TeV Run, but that paper uses a cross section normalization factor and does not provide specific numerical value for this factor, so we have to refrain from using that data at the moment. The table contains upper limits for $\bar{a}^2$ from separate data sets. For the Z' masses up to 3 TeV the most strict upper limits come from the 8 TeV ATLAS data (40 fb^{-1} combined). The Z-Z' mixing angle θ_0 corresponding to the most strict values are calculated using Eq. (4) and also presented in Table 1. We can see that for $m_{Z'} > 1.2$ TeV values of $\theta_0 > 4\times10^{-4}$ can be excluded at 95% CL by ATLAS data.

Each of the Tevatron experiments gathered about 3~4 fb^{-1} of integrated luminosity, and the values obtained from this data are close to the estimations from the LHC data.

Recently the 92% CL interval for $\bar{a}^2$ ($0.1\times10^{-5} < \bar{a}^2 < 22.1\times10^{-5}$ at $m_{Z'}$=1.2~4.5 TeV) [11] was obtained from CMS Drell-Yan forward-backward asymmetry at 7 and 8 TeV. For Z' masses over 3 TeV this interval overlaps with our most strict upper limits, while for lighter Z' bosons the interval from [11] is one order of magnitude apart from our estimates.

The LHC currently operates at 13 TeV collision energy and has already broken its own integrated luminosity record set during 8 TeV run. This novel data has not been processed and published yet, so while the current run provides higher energy reach, the previous run gives more strict limits for Z' couplings.

Table 1

The upper limits for axial-vector coupling $\overline{a}^2$ obtained from data from different.

mZ',TeV	ATLAS 13	ATLAS 8	ATLAS 7	CMS 8	CMS 7	D0, ee	CDF, ee	CDF, μμ	θ0
0.5	3.49×10^{-6}	1.54×10^{-6}	4.24×10^{-6}	2.77×10^{-6}	5.70×10^{-6}	1.24×10^{-5}	9.92×10^{-5}	1.56×10^{-5}	0.002
1	1.26×10^{-6}	4.90×10^{-7}	1.92×10^{-6}	1.02×10^{-6}	2.09×10^{-6}	1.99×10^{-5}	2.17×10^{-5}	2.65×10^{-5}	6×10^{-4}
1.5	8.18×10^{-7}	3.13×10^{-7}	1.72×10^{-6}	1.11×10^{-6}	2.96×10^{-6}				3×10^{-4}
2.0	6.90×10^{-7}	3.00×10^{-7}	2.34×10^{-6}	1.21×10^{-6}	3.73×10^{-6}				2×10^{-4}
2.5	6.74×10^{-7}	3.65×10^{-7}	4.23×10^{-6}	1.70×10^{-6}					2×10^{-4}
3.0	7.47×10^{-7}	5.39×10^{-7}	1.15×10^{-5}	2.48×10^{-6}					2×10^{-4}
3.5	9.04×10^{-7}	9.23×10^{-7}							2×10^{-4}
4.0	1.21×10^{-6}								2×10^{-4}
4.5	1.75×10^{-6}								2×10^{-4}

The highlighted cells are the most strict limits. The last column contains the mixing angle corresponding to the most strict limits

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