ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА. ЭКСПЕРИМЕНТ

# ON RESONANCE SEARCH
# IN DILEPTON EVENTS AT THE LHC

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The main distribution for a bump search is the dilepton-invariant-mass distribution with appropriate cut on an absolute value of pseudorapidity difference $\Delta\eta \equiv |\eta_1 - \eta_2|$ between the two leptons. The background from the Standard Model Drell–Yan process contributes mainly to the central pseudorapidity region $\Delta\eta \simeq 0$. By contrast, the excited bosons lead to a peak at $\Delta\eta \simeq 1.76$. We show that this property allows one to enhance the significance of their bump search by means of the new cut optimization. Nevertheless, in order to confirm an observation of the bump and reveal the resonance nature, other angular distributions should be used in addition.

Основным распределением для поиска резонансов является распределение по инвариантной дилептонной массе с подходящим условием отбора по абсолютной величине разности псевдобыстрот лептонов $\Delta\eta \equiv |\eta_1 - \eta_2|$. Фон от процесса Дрелла–Яна в стандартной модели дает вклад главным образом в центральной области псевдобыстрот $\Delta\eta \approx 0$. В противоположность этому максимум распределения для возбужденных бозонов достигается при $\Delta\eta \approx 1{,}76$. Показано, что это свойство позволяет значительно увеличить чувствительность поиска резонансов при оптимальном условии отбора. Тем не менее, чтобы подтвердить наличие пика и исследовать природу резонанса, необходимо дополнительно использовать угловые распределения.

PACS: 12.60.-i; 13.85.-t; 14.80.-j

## INTRODUCTION

The golden channel of resonances search at the hadron colliders is the lepton one with electrons or muons in a final state. Free from the huge QCD background, it clears the way for the resonance identification. Depending on the resonance electric charge, there are two possible signatures of the resonances search through their decay into a charged lepton and a neutrino with a missing transverse momentum or into a lepton pair (the Drell–Yan production process). The latter has a very clean signature and almost totally reconstructible kinematics[1], which allows for the investigation of the production and the decay of the new resonances.

In this letter, we will consider the case of the resonance production of new bosons up to spin 2 and their detection in the Drell–Yan process using the first CERN LHC data. We will concentrate mainly on the case of excited bosons, which have a unique angular

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[1]Up to small individual transverse momenta of the quarks.

distribution. The simple model of the excited bosons was proposed in [1]. Roughly speaking, it leads to a signal, $s$, of the two orders of magnitude higher than the Standard Model (SM) background, $b$. Therefore, as for the other benchmark models, the direct exclusion limits on a mass of 1.152 TeV and on a cross section times a branching ratio $\sigma B(Z^* \to \ell^+\ell^-) < 89$ fb have been obtained for the first time, based on 2010 ATLAS data [2].

In the general case, the coupling constants of the new bosons with quarks and leptons could be weaker, and their masses could be lighter than the obtained limit. In this case, the signal significance, $s/\sqrt{b}$, will decrease, which leads to a more complicated situation in the resonance search. The main background comes from the inclusive Drell–Yan process $pp \to \gamma/Z \to \ell^+\ell^-$ with $\gamma/Z$ exchanges and is practically unremovable. Therefore, instead of waiting for more data, one can include angular distributions in the analysis [3] as well.

We will use unique properties of angular distributions of the excited bosons in order to increase their signal sensitivity in the present data. In the next section, we will consider model-independent signal distributions of new physics from resonances up to spin 2. The present analysis is based on our study of dijet-mass angular distributions [4], which has been shown to play an important role in disentangling the resonance properties and revealing the unique signature of the excited bosons.

## 1. A UNIQUE SIGNAL OF EXCITED BOSONS

The distribution of a final-state lepton over a polar scattering angle $\theta$, being an angle between the axis of the lepton pair and the beam direction in the dilepton rest frame, is directly sensitive to the dynamics of the underlying process, where spins of the resonance and of the initial and final states uniquely define the angular distribution.

Further, we will consider a distribution on the absolute value of the dilepton pseudorapidity difference, which is related to the angle $\theta$ by $\Delta\eta \equiv |\eta_1 - \eta_2| = \ln\left[(1 + |\cos\theta|)/(1 - |\cos\theta|)\right] \geqslant 0$. It has been shown [5] that the excited boson distribution on $\Delta\eta$ drastically differs from the SM and other exotic models. So, while the SM processes are dominated by $\gamma/Z$ exchanges, which lead to the well-known $1 + \cos^2\theta$ distribution[1], exotic physics processes can deviate from this distribution.

Let us consider different possibilities for a spin of a resonance and its possible interactions with quarks and leptons. The simplest case of the resonance production of a (pseudo)scalar particle $h$ with spin 0 in $s$-channel leads to a uniform decay distribution on the scattering angle

$$\frac{d\Gamma_0(h \to \ell^+\ell^-)}{d\cos\theta} \propto |d_{00}^0|^2 \sim 1. \tag{1}$$

The variable transformation

$$\frac{d\Gamma}{d\Delta\eta} = \frac{d\cos\theta}{d\Delta\eta}\frac{d\Gamma}{d\cos\theta} \tag{2}$$

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[1] The choice of the variables, which depend on the absolute value of $\cos\theta$, cancels out the apparent dependence on $\cos\theta$.

in the uniform distribution (1) from $\cos\theta$ to $\Delta\eta$

$$\frac{1}{\Gamma_0}\frac{d\Gamma_0}{d\Delta\eta} = \frac{2\mathrm{e}^{\Delta\eta}}{(\mathrm{e}^{\Delta\eta}+1)^2} \tag{3}$$

leads to a kinematical peak at $\Delta\eta = 0$ (the dotted curve in Fig. 1), which corresponds to the polar angle $\theta = 90°$. The result coincides with the common belief that an expected signal of new physics should be in perpendicular direction to the beam.
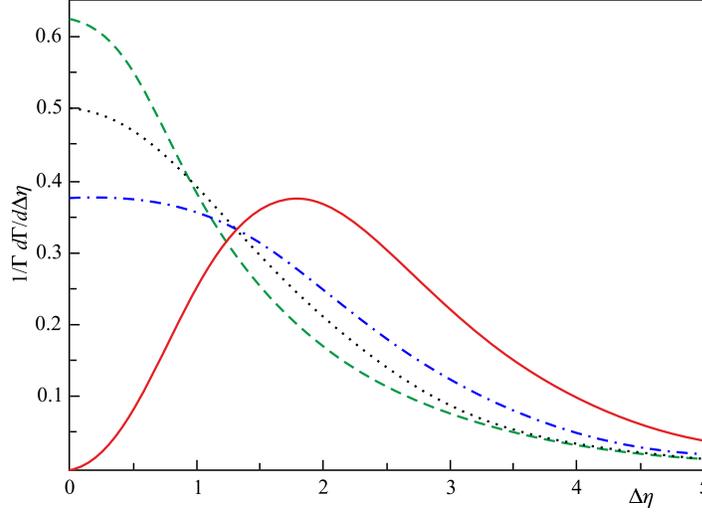


Fig. 1. The normalized angular lepton distributions as functions of $\Delta\eta$ for the scalar, spin-1 bosons with the minimal couplings, the excited bosons and spin-2 resonances are shown with the dotted, dash-dotted, solid and dashed curves, respectively

According to [4,6], there are only two different possibilities for the spin-1 resonances to interact with the light fermions. All known gauge bosons have minimal interactions with the light fermions

$$\mathcal{L}_{Z'} = \sum_f \left( g_{LL}^f \overline{\psi_L^f}\gamma^\mu\psi_L^f + g_{RR}^f \overline{\psi_R^f}\gamma^\mu\psi_R^f \right) Z'_\mu , \tag{4}$$

which preserve the fermion chiralities and possess maximal helicities $\lambda = \pm 1$. It is assumed that the hypothetical $Z'$ bosons also have similar couplings. At a symmetric $pp$ collider, like the LHC, such interactions lead to a specific symmetric angular distribution of the resonance decay products

$$\frac{d\Gamma_1(Z' \to \ell^+\ell^-)}{d\cos\theta} \propto |d_{11}^1|^2 + |d_{-11}^1|^2 \sim 1 + \cos^2\theta. \tag{5}$$

Similar to the uniform distribution, Eq. (5) also leads to the kinematical peaks at $\Delta\eta = 0$ (the dash-dotted curve in Fig. 1):

$$\frac{1}{\Gamma_1'}\frac{d\Gamma_1'}{d\Delta\eta} = \frac{3\mathrm{e}^{\Delta\eta}(\mathrm{e}^{2\Delta\eta}+1)}{(\mathrm{e}^{\Delta\eta}+1)^4}. \tag{6}$$

Another possibility is the resonance production and the decay of the new longitudinal spin-1 $Z^*$ bosons with the helicity $\lambda = 0$. The new gauge bosons with such properties arise in many extensions [6] of the SM, which solve the Hierarchy Problem.

While the $Z'$ bosons with the helicities $\lambda = \pm 1$ are produced in the left(right)-handed quark and the right(left)-handed antiquark fusion, the longitudinal $Z^*$ bosons are produced through the anomalous chiral couplings with the ordinary light fermions

$$\mathcal{L}_{Z^*} = \sum_f \frac{g_{RL}^f}{M} \overline{\psi_R^f} \sigma^{\mu\nu} \psi_L^f \partial_{[\mu} Z_{\nu]}^* + \text{h.c.} \tag{7}$$

in the left-handed or the right-handed quark–antiquark fusion [1]. The anomalous interactions (7) are generated on the level of the quantum loop corrections and can be considered as effective interactions. The $Z^*$ resonances are some types of «excited» states as far as the only orbital angular momentum with $L = 1$ contributes to the total angular moment, while the total spin of the system is zero. This property manifests itself in its derivative couplings to fermions and a different chiral structure of the interactions in contrast to the minimal gauge interactions (4).

The anomalous couplings lead to an angular distribution

$$\frac{d\Gamma_1(Z^* \to \ell^+\ell^-)}{d\cos\theta} \propto |d_{00}^1|^2 \sim \cos^2\theta, \tag{8}$$

which differs from the ones previously considered. A striking feature of the distribution is the forbidden decay direction perpendicular to the beam. It leads to a profound dip at $\cos\theta = 0$ [1]. The same dip also occurs at $\Delta\eta = 0$ [5] (the solid curve in Fig. 1):

$$\frac{1}{\Gamma_1^*} \frac{d\Gamma_1^*}{d\Delta\eta} = \frac{6e^{\Delta\eta}(e^{\Delta\eta} - 1)^2}{(e^{\Delta\eta} + 1)^4}. \tag{9}$$

It can be seen from Fig. 1 that the excited bosons have a unique signature in the angular distribution. They manifest themselves through the absolute minimum at $\Delta\eta = 0$ and the absolute maximum at $\Delta\eta = \ln(3 + \sqrt{8}) \approx 1.76$. The latter corresponds to the polar angle $\theta = 45°$ and slightly contradicts the commonly held opinion about an expected signal from new physics.

The spin-2 resonances, like Kaluza–Klein excitations, lead to the following decay distributions depending on the initial parton configurations:

$$\frac{d\Gamma_{gg}(G^* \to \ell^+\ell^-)}{d\cos\theta} \propto |d_{2,1}^2|^2 + |d_{2,-1}^2|^2 \sim 1 - \cos^4\theta \tag{10}$$

and

$$\frac{d\Gamma_{q\bar{q}}(G^* \to \ell^+\ell^-)}{d\cos\theta} \propto |d_{1,1}^2|^2 + |d_{1,-1}^2|^2 \sim 1 - 3\cos^2\theta + 4\cos^4\theta. \tag{11}$$

Taking into account their corresponding weights ($3/5$ and $2/5$) and using Eq. (2), one can obtain the distribution on $\Delta\eta$ (the dashed curve in Fig. 1) for the inclusive process $pp \to G^* \to \ell^+\ell^-$ [7]

$$\frac{1}{\Gamma_2} \frac{d\Gamma_2}{d\Delta\eta} = \frac{2e^{\Delta\eta}(e^{4\Delta\eta} + 18e^{2\Delta\eta} + 1)}{(e^{\Delta\eta} + 1)^6}. \tag{12}$$

It also peaks at $\Delta\eta = 0$ as in the most exotic models.

## 2. CUT OPTIMIZATION FOR EXCITED BOSONS

From Fig. 1, one can see that all the distributions, except for the excited bosons, peak at $\Delta\eta = 0$. Since the main background comes from the $\gamma/Z$ bosons, which have the minimal gauge couplings with quarks and a lepton, they also populate the central pseudorapidity region. Therefore, it is difficult to disentangle a new physics signal using this distribution, except in the case of the excited bosons. Applying the proper cut $\Delta\eta > a$, one can suppress the unwanted background contribution and enhance the signal significance, $\mathcal{S} = s/\sqrt{b}$, choosing its maximum.

So we can define the relative significance of a $Z^*$ signal to a $Z'$-like background as a ratio of the definite integral from $a$ to infinity of the normalized signal distributions (9) to the square root of the SM background dominated by the distribution (6)

$$\mathcal{S}(a) = \frac{\int\limits_{a}^{\infty} \frac{1}{\Gamma_1^*} \frac{d\Gamma_1^*}{d\Delta\eta} d\Delta\eta}{\sqrt{\int\limits_{a}^{\infty} \frac{1}{\Gamma_1'} \frac{d\Gamma_1'}{d\Delta\eta} d\Delta\eta}} = \frac{1 - \left(\frac{e^a - 1}{e^a + 1}\right)^3}{\sqrt{1 - \frac{e^{3a} - 1}{(e^a + 1)^3}}}. \tag{13}$$

The distribution reaches the maximum value around 1.14 at $a \approx 1.02$ (Fig. 2).
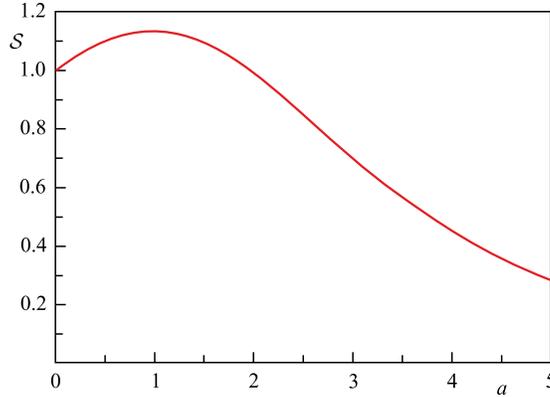


Fig. 2. The relative signal significance distribution of the excited bosons as the functions of the cut parameter $a$ on $\Delta\eta$

The corresponding cut at the maximum signal significance suppresses around 38% of the background and only 10% of the signal. This leads to a relative enhancement in sensitivity, which is tantamount to adding approximately 29% of data in comparison with the usual sensitivity without any cuts.

## CONCLUSIONS

In this paper, we have presented $\Delta\eta$-distributions for all the possible resonances with a spin up to 2. On this basis, we have proposed a novel optimization of the angular distribution cut aimed at the most effective search for the new resonances with different angular distributions

in dilepton events. In particular, this allows one to enhance the significance of bump search for the excited bosons.

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