



Energy dependence of dissociative J/ψ photoproduction as a signature of gluon saturation at the LHC



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ABSTRACT

We have developed a model in which the quantum fluctuations of the proton structure are characterised by hot spots, whose number grows with decreasing Bjorken- x . Our model reproduces the $F_2(x, Q^2)$ data from HERA at the relevant scale, as well as the exclusive and dissociative J/ψ photoproduction data from H1 and ALICE. Our model predicts that for $W_{\gamma p} \approx 500$ GeV, the dissociative J/ψ cross section reaches a maximum and then decreases steeply with energy, which is in qualitatively good agreement to a recent observation that the dissociative J/ψ background in the exclusive J/ψ sample measured in photoproduction by ALICE decreases as energy increases. Our prediction provides a clear signature for gluon saturation at LHC energies.

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1. Introduction

Perturbative QCD predicts that the gluon density in hadrons grows with energy, or equivalently with decreasing Bjorken- x , up to a point where non-linear effects set in to tame this growth, a phenomenon known as gluon saturation; see for example [1] and references therein.

Inclusive data on the proton structure function $F_2(x, Q^2)$ – where Q^2 is the virtuality of the photon – from deeply inelastic scattering at HERA [2] show that indeed the gluon density grows steeply at small x . At the same time the analysis of these data is inconclusive regarding the question of gluon saturation, because the data can be equally well described without, e.g. [2], or with, e.g. [3], the inclusion of saturation effects.

$F_2(x, Q^2)$ data are sensitive to longitudinal degrees of freedom. Exclusive vector meson photoproduction, see left panel of Fig. 1, is also sensitive to the distribution of gluons in the impact parameter plane, through the dependence of the cross section on t , the square of the momentum transfer at the target vertex. This process has been extensively studied at HERA [4]. For a recent review see [5]. For the case of J/ψ photoproduction, HERA measurements cover a range on $W_{\gamma p}$, the centre-of-mass energy of the photon–proton system, from 20 to 300 GeV, which corresponds to $10^{-4} \lesssim x \lesssim 0.02$, where $x = M_{J/\psi}^2/W_{\gamma p}^2$, with $M_{J/\psi}$ as the mass

of the J/ψ . ALICE has also published measurements of exclusive J/ψ photoproduction in p–Pb collisions at the LHC at low energies, $20 \text{ GeV} < W_{\gamma p} < 40 \text{ GeV}$, and at high energies $\langle W_{\gamma p} \rangle = 700 \text{ GeV}$ [6]. This last measurement corresponds to $x = 2 \cdot 10^{-5}$. As for the $F_2(x, Q^2)$ data, the exclusive J/ψ photoproduction data can be described with [7] or without [8] saturation effects.

In a Good–Walker formalism [9] exclusive diffractive processes are sensitive to the average over the different configurations of the target, while dissociative processes, where the target get excited and produces many particles, measure the variance over the configurations [10]. Dissociative vector meson photoproduction, see right panel of Fig. 1, has also been measured at HERA. Recently, H1 measured simultaneously the exclusive and dissociative photoproduction of J/ψ and reported both, the $W_{\gamma p}$ and the t dependence of these cross sections [11].

The t dependence of dissociative vector meson photoproduction at a fixed value of $W_{\gamma p}$ has been studied in a model where the transverse distribution of gluons in the proton is described as the sum of three independent gaussian distributions [12,13]. In that analysis it was shown that a good description of data is achieved when the geometrical position of these gaussian distributions fluctuate from event to event.

In this Letter we study the energy dependence of dissociative J/ψ photoproduction off protons, showing that it provides a clear signature of gluon saturation at the LHC. Our calculation reproduces correctly the rise with $W_{\gamma p}$ of this cross section as measured at HERA [11], and predicts that it reaches a maximum at $W_{\gamma p} \approx 500$ GeV, followed by a steep decrease at higher energies.

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In our model, as energy increases the different configurations of the proton resemble more and more each other, so the variance over configurations decreases. The LHC can explore a wide range of $W_{\gamma p}$, from a few tens of GeV to more than a TeV, making it an ideal place to look for this clear signature of gluon saturation.

The rest of this Letter is organised as follows. In the next section we present all the formulae used in this work. Section 3 explains how the parameters have been fixed and compares the predictions of our model to experimental data. In Section 4 we comment on the model, present our main conclusion and remark on other potentially interesting measurements that can be carried out to test our model. Section 5 gives a brief summary.

2. The amplitude for diffractive photoproduction of vector mesons

Diagrams for the exclusive and dissociative production of vector mesons are shown in Fig. 1 where the photon source is a lead ion, which corresponds to the ideal case to study vector meson photoproduction off the proton at the LHC [14]. At HERA the source was either a positron or an electron. In the dipole colour model [15,16], the interaction of the photon with the target proceeds in steps: first the photon fluctuates into a quark–antiquark pair, then this pair interacts with the target with the colour dipole cross section σ_{dip} and finally the dipole forms a vector meson. In this approach the amplitude can be written as follows (see for example [17]),

$$A(x, Q^2, \vec{\Delta})_{T,L} = i \int d\vec{r} \int_0^1 \frac{dz}{4\pi} (\Psi^* \Psi_V)_{T,L} \times \int d\vec{b} e^{-i(\vec{b} - (1-z)\vec{r}) \cdot \vec{\Delta}} \frac{d\sigma_{\text{dip}}}{d\vec{b}}, \quad (1)$$

where $-t = \vec{\Delta}^2$, Ψ_V is the wave function of the vector meson, Ψ is the wave function of a virtual photon fluctuating into a quark–antiquark colour dipole, \vec{r} is the transverse distance between the quark and the antiquark, z is the fraction of the longitudinal momentum of the dipole carried by the quark and \vec{b} is the impact parameter. The subindices T and L refer to the contribution of the transversal and longitudinal degrees of freedom of the virtual photon, respectively.

The physics of the interaction is encoded in the dipole–target cross section, which is related, via the optical theorem, to the imaginary part of the forward dipole–target amplitude $N(x, \vec{r}, \vec{b})$:

$$\frac{d\sigma_{\text{dip}}}{d\vec{b}} = 2N(x, \vec{r}, \vec{b}). \quad (2)$$

The main goal of our analysis is to study the effect of fluctuations in the configuration of the proton using the energy dependence of the dissociative cross section. In order to isolate these two contributions we use a factorised form for the dipole amplitude:

$$N(x, r, \vec{b}) = \sigma_0 N(x, r) T(\vec{b}). \quad (3)$$

Here, r is the magnitude of \vec{r} , σ_0 is a constant that provides the normalisation and $T(\vec{b})$ describes the proton profile in the impact parameter plane. Such a factorised model has been successfully used in the past; e.g. in [18]. There are several possibilities to chose a model for $N(x, r)$; e.g., [19,3]. For simplicity, we chose the form of $N(x, r)$ given by the model of Golec-Biernat and Wusthoff [20]:

$$N(x, r) = \left(1 - e^{-r^2 Q_s^2(x)/4}\right), \quad (4)$$

with the saturation scale given by

$$Q_s^2(x) = Q_0^2(x_0/x)^\lambda, \quad (5)$$

where λ , x_0 and Q_0^2 are parameters. The latter is normally set to 1 GeV^2 as done in this study.

The proton is a quantum object, so its structure fluctuates from interaction to interaction. In our model all fluctuations are included in the proton profile $T(\vec{b})$. Following [12,13] we define the proton profile as the sum of N_{hs} regions of high gluon density, so called hot spots, each of them having a gaussian distribution:

$$T(\vec{b}) = \frac{1}{N_{hs}} \sum_{i=1}^{N_{hs}} T_{hs}(\vec{b} - \vec{b}_i), \quad (6)$$

with

$$T_{hs}(\vec{b} - \vec{b}_i) = \frac{1}{2\pi B_{hs}} e^{-\frac{(\vec{b} - \vec{b}_i)^2}{2B_{hs}}}, \quad (7)$$

where each \vec{b}_i is obtained from a 2-dimensional gaussian distribution centred at $(0, 0)$ and having a width B_p . The parameters $2B_p$ and $2B_{hs}$ can be interpreted as the average of the squared transverse radius of the proton or the hot spots, respectively. Such a profile has already been used before in a study of nuclear targets [21].

The new ingredient in our model is that we introduce an indirect energy dependence of the proton profile $T(\vec{b})$ by making the number of hot spots grow with decreasing x . That is, $N_{hs} = N_{hs}(x)$, where the exact definition used in our model is given below in Eq. (19). This implements the hypothesis that, at a given fixed scale, as energy increases, the number of gluons available for the interaction increases.

Putting together all ingredients, and taking advantage that some of the integrals can be performed analytically, the amplitude can be written as

$$A(x, Q^2, \vec{\Delta})_{T,L} = i A_b(\vec{\Delta}) A_r(x, Q^2, \vec{\Delta})_{T,L}, \quad (8)$$

where,

$$A_b \equiv \int d\vec{b} e^{-i\vec{b} \cdot \vec{\Delta}} T(\vec{b}) \quad (9)$$

$$= e^{-B_{hs} \Delta^2/2} \frac{1}{N_{hs}} \sum_{i=1}^{N_{hs}} e^{-i\vec{b}_i \cdot \vec{\Delta}}. \quad (10)$$

and, after integration over the angular variable,

$$A_r(x, Q^2, \Delta)_{T,L} \equiv \int dr r N(x, r) A_z(r, \Delta)_{T,L}, \quad (11)$$

with

$$A_z(r, \Delta)_{T,L} \equiv \int dz (\Psi^* \Psi_V)_{T,L} J_0(r(1-z)\Delta). \quad (12)$$

Using this amplitude, the cross sections are

$$\left. \frac{d\sigma(\gamma p \rightarrow J/\psi p)}{dt} \right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi} \left| \left\langle A(x, Q^2, \vec{\Delta})_{T,L} \right\rangle \right|^2, \quad (13)$$

for the exclusive process, and

$$\left. \frac{d\sigma(\gamma p \rightarrow J/\psi X)}{dt} \right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi} \left(\left| \left\langle A(x, Q^2, \vec{\Delta})_{T,L} \right\rangle \right|^2 - \left| \left\langle A(x, Q^2, \vec{\Delta})_{T,L} \right\rangle \right|^2 \right), \quad (14)$$

for dissociative production, where $R_g^{T,L}$ is the so-called skewedness correction [22] given by

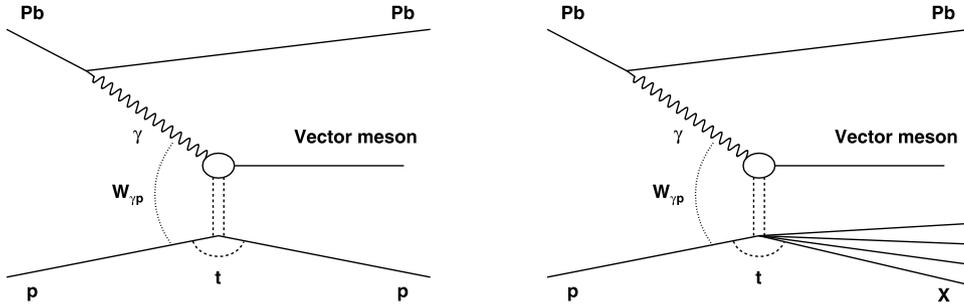


Fig. 1. Diagrams for exclusive (left) and dissociative (right) vector meson photo-production. The source of photons is a lead nucleus as in p–Pb collisions at the LHC. For the case of HERA, the source of photons was either an electron or a positron.

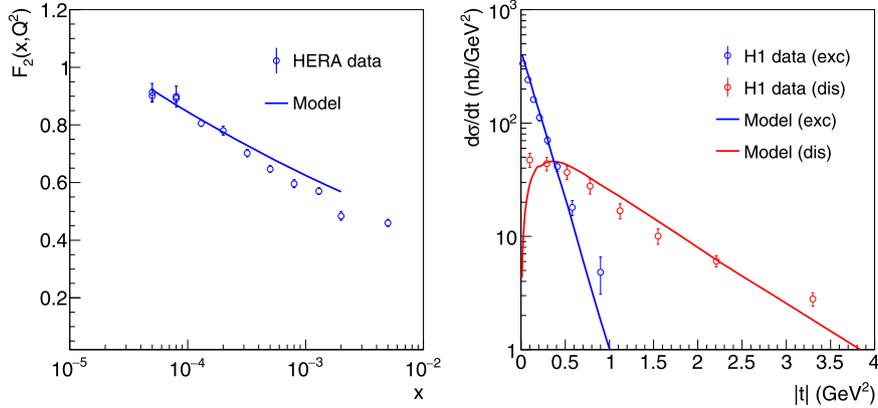


Fig. 2. Comparison of the model (solid lines) to data (open bullets) on (left) the structure function of the proton $F_2(x, Q^2)$ at $Q^2 = 2.7 \text{ GeV}^2$ as measured by H1 and Zeus [26] and (right) the $|t|$ distribution of exclusive (blue) and dissociative (red) photoproduction of J/ψ as measured by H1 [11] at $(W_{\gamma p}) = 78 \text{ GeV}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$R_g^{T,L}(\lambda_g^{T,L}) = \frac{2^{2\lambda_g^{T,L}+3} \Gamma(\lambda_g^{T,L} + 5/2)}{\sqrt{\pi} \Gamma(\lambda_g^{T,L} + 4)}, \quad (15)$$

with $\lambda_g^{T,L}$ given by

$$\lambda_g^{T,L} \equiv \frac{\partial \ln(A_{T,L})}{\partial \ln(1/x)}. \quad (16)$$

The total cross section is the sum of the T and L contributions.

We also compute $F_2(x, Q^2)$, for which we use

$$F_2(x, Q^2) = \frac{Q^2}{4\pi^2 \alpha_{em}} \left(\sigma_T^{\gamma^* p}(x, Q^2) + \sigma_L^{\gamma^* p}(x, Q^2) \right), \quad (17)$$

where α_{em} is the electromagnetic coupling constant and

$$\sigma_{T,L}^{\gamma^* p}(x, Q^2) = \sigma_0 \int d\vec{r} \int_0^1 dz |\Psi_{T,L}(z, r, Q^2)|^2 N(r, \tilde{x}), \quad (18)$$

where, using the approach of [20], we use $\tilde{x} = x(1 + (4m_f^2)/Q^2)$ with m_f an effective mass for light quarks set to 140 MeV.

3. Results: comparison to data and predictions

For $\Psi_{T,L}$ we use the definitions and parameter values of [20] and for the wave function of the vector meson, Ψ_V , we use the boosted gaussian model [23,24], with the numerical values of the parameters as in [17].

The parameters of the model were fixed as follows. The value of λ is constrained by the energy dependence of exclusive J/ψ photoproduction to $\lambda = 0.21$. The parameter B_p is constrained by the

t distribution of the same data and set to $B_p = 4.7 \text{ GeV}^{-2}$. We define $\sigma_0 \equiv 4\pi B_p$. The x_0 parameter is strongly correlated to σ_0 , so once B_p is fixed, the normalisation of the data yields $x_0 = 0.0002$. The parameter B_{hs} is constrained by the t dependence of the dissociative process and it is set to $B_{hs} = 0.8 \text{ GeV}^{-2}$. Finally, as we relate the number of hot spots with the number of gluons available for the interaction, we follow standard functional forms for the gluon distribution as used in PDF fits; e.g. [25], and parametrise

$$N_{hs}(x) = p_0 x^{p_1} (1 + p_2 \sqrt{x}), \quad (19)$$

where we set $p_0 = 0.011$, $p_1 = -0.58$ and $p_2 = 250$ in order to reproduce the energy dependence of H1 measurements of dissociative J/ψ photoproduction. The parameters p_0 and p_1 are strongly correlated. For the quoted value of p_0 , a similar description of data is found when varying the value of p_1 by $\pm 5\%$ and of p_2 by $\pm 15\%$. Note that there is a trade off between the normalisation of the data in the right panel of Fig. 3 and that of the dissociative data in the right panel of Fig. 2. Improving the normalisation of the data in the right panel of Fig. 3 would worsen unacceptably the description of the $|t|$ distribution of the dissociative cross section. The chosen parameters are those that yield a correct simultaneous description of the data in both figures. With these parameters a $\chi^2/d.o.f \approx 1$ is obtained for the comparison of the model predictions and the data from H1 on the energy dependence of the exclusive and dissociative cross sections.

The comparison of the model with HERA data for $F_2(x, Q^2)$ at $Q^2 = 2.7 \text{ GeV}^2$ as measured by H1 and Zeus [26] is shown in the left panel of Fig. 2. This scale is chosen since it is similar to that of J/ψ photoproduction, which is often set to $(M_{J/\psi}/2)^2 = 2.4 \text{ GeV}^2$ [27]. Although the model is relatively simple and has been developed to describe vector meson photoproduction, it describes well the $F_2(x, Q^2)$ data. The comparison with H1 data [11]

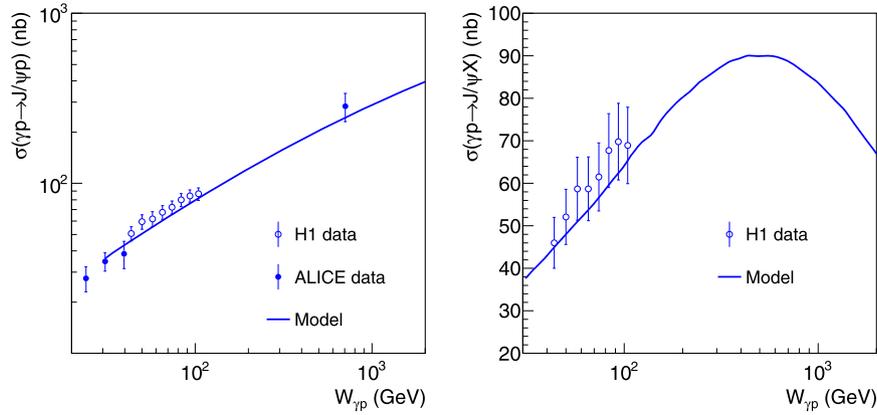


Fig. 3. Comparison of the model (solid lines) to data on the $W_{\gamma p}$ dependence of the cross section for exclusive (left) and dissociative (right) photoproduction of J/ψ as measured by H1 [11] and ALICE [6] (open and solid bullets, respectively).

on the t dependence of J/ψ photoproduction is shown in the right panel of the same figure for the data at $\langle W_{\gamma p} \rangle = 78$ GeV. Both the exclusive and the dissociative processes are reasonably well described. The left panel of Fig. 3 shows the energy dependence of the model and compares it to data from H1 [11] and from ALICE p–Pb collisions at a 5.02 TeV centre-of-mass energy [6]. Again, the model describes quite well the data.

Our main result is shown in the right panel of Fig. 3. We show that the model describes correctly the energy evolution of the dissociative cross section for the available data. We also show that the model predicts that the cross section will reach a maximum at $W_{\gamma p} \approx 500$ GeV and it will then turn around and decrease for higher energies. This decrease of the dissociative J/ψ photoproduction cross section is significantly large and can be observed in the $W_{\gamma p}$ energy range accessible at the LHC.

4. Discussion

Several comments are in order. The chosen numerical values of the parameters are quite reasonable: B_p is similar to that measured at HERA [11] and λ is similar to the value found at HERA for a scale $Q^2 \approx 2\text{--}3$ GeV² [28]. Regarding the value of B_{hs} , it corresponds to a hot spot radius of 0.35 fm, quite close to the values around 0.3 fm discussed in [29–31].

In our model the energy dependence shown in the right panel of Fig. 3 has a geometrical origin reminiscent of percolation. At some point the number of hot spots is so large that they overlap. When the overlap is large enough, different configurations look the same and the variance (see Eq. (14)) decreases. A percolation approach has been explored for the fusion of strings yielding a quark gluon plasma [32], where interestingly the radius of the strings is also found to be around 0.3 fm. For the parameters that we have employed in this study, the maximum at $W_{\gamma p} \approx 500$ GeV is reached when some 10 hot spots are present, indicating a sizeable overlap of hot spots.

In conclusion, the main result is that our model predicts that the dissociative photoproduction cross section decreases at high energies, which are reachable at the LHC. Furthermore, experimental data from (i) ALICE [6] and (ii) H1[11] suggests that this is indeed so, which we take as a further support of the chosen parameters of our model:

(i) ALICE has measured the cross section for exclusive J/ψ photoproduction in p–Pb collisions [6]. The main background to this process is dissociative J/ψ photoproduction. For the conditions existing in ALICE, $|t|$ is related to the square of the transverse momentum of the J/ψ (p_T). The dissociative contribution populates the large $|t|$ region (see right panel of Fig. 2) so in ALICE it pop-

ulates the large p_T region. This contribution is clearly present in the upper panel of Fig. 2 in Ref. [6] which correspond to $W_{\gamma p}$ ranging from 20 to 40 GeV, but it is almost absent in the lower panel of Fig. 2 in Ref. [6] depicting the high energy data sample at $\langle W_{\gamma p} \rangle = 700$ GeV. Qualitatively, the behaviour of these ALICE data is similar to that of our predictions shown in the left panel of Fig. 3. We take this observation as an indication that the prediction of our model is qualitatively correct. Indeed, the behaviour of the background from dissociative J/ψ photoproduction observed by ALICE seems to indicate that the turn around may be even at smaller energies.

(ii) Inspecting H1 data, specifically Table 2 of [11], one can observe that the reported cross sections at the highest values of $W_{\gamma p}$ are the same for the last three measurements, albeit with somewhat large errors. This seems to suggest that the growth of the dissociative cross section with decreasing x may already be slowing down at HERA energies.

In our model the shape of the t dependence of the cross sections for the dissociative and exclusive processes does not vary with x . However, if the dissociative J/ψ cross section disappears at relatively high energies as predicted in our model, it will simplify subtracting the dissociative background in the measurement of the t distribution of exclusive vector meson photoproduction, particularly at large t values. This is important since the appearance of diffractive dips in the t -distribution at large t has been proposed as a good observable for gluon saturation effects [33,7].

In addition, it will be interesting to study, experimentally and phenomenologically, the corresponding process with nuclear targets at the LHC. Both the t and the $W_{\gamma Pb}$ dependence may offer interesting insights since nuclear effects are expected to be significantly stronger than in γ -proton interactions [34]: At a given rapidity, coherent J/ψ photoproduction in Pb–Pb reaches values of x almost a factor three larger than in p–Pb, because the energy of the incoming proton beam is larger than that of the incoming Pb beam. This implies, see Eq. (19), that $N_{hs}(x)$ is smaller for the nucleons in Pb targets, but as there are so many nucleons, the total number of hot-spots is greatly increased. Existing results from ALICE [35,36] and CMS [37] on coherent J/ψ photonuclear production are very promising.

In principle, such a process can also be studied in proton–proton collisions at the LHC. The advantages would be a higher centre-of-mass energy and a larger available luminosity. The disadvantages would be a much smaller photon flux from a proton with respect to that from a lead ion and the fact that it is not known which proton act as a source. It could be argued that the dissociative system can be used to tag the target proton, but in proton–proton collisions the probability of extra exchange of soft

gluons is important (see e.g. [38]) and these gluons could produce the dissociation of the proton. As these are soft processes they cannot be completely computed in pQCD and have to be modelled, adding extra uncertainties to the extraction of photoproduction cross sections. Nonetheless, first measurements of the exclusive contribution have already been performed by LHCb and a model dependent extraction of the exclusive cross section has been attempted [39].

As a final remark, we note that in Fall 2016, the LHC Collaborations are collecting proton-lead data at 8 TeV for the first time. These data are expected to test the predictions presented in this Letter. The unambiguous discovering of gluon saturation effects at the LHC, would boost the proposal for future electron–proton and electron–ion colliders [40–42], where this phenomenon could be studied with much more precision and with many more observables than at the LHC.

5. Summary and outlook

We have presented a model for the dissociative J/ψ photoproduction cross section. The model incorporates a fluctuating hot spot structure of the proton in the impact parameter plane. The new ingredient of the model is that the number of hot spots grows with decreasing x . The model describes correctly the behaviour of $F_2(x, Q^2)$ at the relevant scale, as well as the $W_{\gamma p}$ and t dependence of the exclusive and dissociative J/ψ photoproduction cross section as measured by H1 and ALICE. The model predicts that the energy dependence of the dissociative process increases from low energies up to $W_{\gamma p} \approx 500$ GeV and then decreases steeply. This behaviour happens within the energy range accessible at the LHC.

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