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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

THE RESONANCE PRODUCTION OF THE SEXTET SCALAR DIQUARKS AT FUTURE CIRCULAR COLLIDER-BASED PROTON-PROTON, (FCC-PP)*

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ABSTRACT

In this study, the resonance production of the sextet scalar diquarks are studied for the FCC (Future Circular Collider) proton-proton collider with 100 TeV centre-of-mass planned to build at the European Organization for Nuclear Research, CERN. For the scalar diquarks, decay width and cross sections are calculated as a function of the diquark's mass. Also, to separate the diquark's signal from the background, the kinematic cuts are applied on diquarks mass and statistical significance calculations are obtained. As a result, at the FCC-pp, for the scalar diquark's mass, discovery (5σ), observation (3σ) and exclusion (2σ) limit values are given. These mass limit values are compared with mass limit values of the Large Hadron Collider (LHC) with 7 TeV centre-of-mass energy and the High Luminosity-Large Hadron Collider (HL-HLC) with 14 TeV centre-of-mass energy.

Keywords: *CERN, FCC-pp, Diquarks, Modelling, Resonance.*

FCC PROTON-PROTON ÇARPIŞTIRICISINDA RENK ALTILI SKALER DİKUARKLARIN REZONANS ÜRETİMİ

ÖZ

Bu çalışmada, Avrupa Nükleer Araştırma Merkezi'nde (CERN) kurulacak olan 100 TeV kütle merkezi enerjisine sahip geleceğin dairesel proton-proton tabanlı çarpıştırıcısında (FCC-pp), renk altılı skaler dikuarkların rezonans üretimi çalışılmıştır. Skaler dikuarklar için, dikuark kütlesine bağlı olarak bozunum genişliği ve tesir kesiti hesaplamaları yapılmıştır. Ayrıca dikuark sinyalini fondan ayırmak için kinematik kesmeleri uygulanıp istatistiksel önem hesaplamaları yapılmıştır. Sonuç olarak, 100 TeV kütle merkezi enerjili geleceğin dairesel proton-proton tabanlı çarpıştırıcısında (FCC-pp), skaler dikuarkların kütlesi için keşif (5σ), gözlem (3σ) ve dışarlama (2σ) limitleri verilmiştir. Bu kütle limit değerleri, 7 TeV kütle merkezi enerjisine sahip Büyük Hadron Çarpıştırıcısı (BHÇ) ve 14 TeV kütle merkezi enerjisine sahip Yüksek Işınlıklı Büyük Hadron Çarpıştırıcısından (YI-HLÇ) elde edilen değerler ile karşılaştırılmıştır.

Anahtar Kelimeler: *CERN, FCC-pp, Dikuarklar, Modelleme, Rezonans.*

1. INTRODUCTION

Standard Model (SM) plays an essential role in explaining fundamental particles and their interactions. Some of the very important discoveries such as top quark (CDF and D0 experiments at FERMILAB in 1995), the tau neutrino (DONUT experiment at FERMILAB in 2000) and Higgs boson (CMS and ATLAS collaborations at CERN in 2012) are predicted by the SM. Although SM works in harmony with experimental high energy physics, there are still unsolved mysteries in universe like neutrino mass, the quark-lepton symmetry, dark matter, dark energy, charge quantization and plenty numbers of elementary particles by SM theory. One of the unanswered questions is "why is there three generations in universe"? To solve this question, particle physics suggest composite models as called "preonic models". According to these models leptons and quarks, which are elementary particles, have composite structure. In these models, preons have been proposed as the new elementary particles. Due to their preonic interactions, a large number of new particles will be revealed such as diquarks, leptoquarks, excited quarks, excited leptons, etc (CERN Council, 2013; Abe et al., 1995; Kodama et al., 2001; Chatrchyan et al., 2012; Aad et al., 2012; D'Souza & Kalman, 1992).

Diquarks are predicted in composite models and superstring inspired E6 models. They are including many new physics. In addition, diquarks have been studied phenomenologically in different colliders. They have integer spin and carry baryon number with |B| = 2/3. They have two form, scalar and vector. Scalar forms have spin 0 while vector forms have spin 1. And also, they have electric charge with |Q|=1/3, 2/3 or 4/3 (Wudka, 1986; Hewwtt & Rizzo, 1989; Atağ, Cakir & Sultansoy, 1998; Cakır & Sahin, 2005; Sahin & Cakir, 2010).

In this study, we investigated three types the scalar diquarks. The scalar diquarks are described as scalar uu diquarks ($DQ_{(uu)}$), scalar ud diquarks ($DQ_{(ud)}$) and scalar dd diquarks ($DQ_{(dd)}$). Resonant production signal subprocesses of diquarks are given the following Eq. 1, 2 and 3;

$$pp \rightarrow DQ_{(uu)} + X \rightarrow u + u + X \qquad \textbf{(1)}$$

$$pp \rightarrow DQ_{(ud)} + X \rightarrow u + d + X \quad \textbf{(2)}$$
$$pp \rightarrow DQ_{(dd)} + X \rightarrow d + d + X \quad \textbf{(3)}$$

where, X denotes proton remnant.

In the high energy physics, proton-proton (pp) colliders reach high energy limits in the last decade and they provide good chance to discover new particles for the new physics study. One of them is the Large Hadron Collider-based on pp collision, (LHC-pp) with 7 TeV center of mass energy, (CM). The LHC started to collect data in 2010 and it stopped in June 2018 for an upgrade process (technical stop). Between these years it has recorded tremendous amount of data with an integrated luminosity of 192.29 fb^{-1}. The LHC is planning to restart at the end of 2021 with a high luminosity which is factor of ten higher than the current one. It is called High Luminosity-LHC (HL-LHC) with 14 TeV. The HL-LHC machine plans to reach integrated luminosity up to 3500 fb^{-1} in ten years. The resonant production of the scalar diquarks mass has been searched in both the LHC and the HL-LHC-based pp. The scalar diquarks mass limit is excluded up to 7.5 TeV in the LHC with 13TeV and up to 10 TeV in the HL-LHC with 14 TeV. It has been planning to build a new generation collider the FCC-pp at the CERN to operate for 25 years. The working plan of the FCC-pp divide into two segmentation, Phase I and Phase II according to its final integrated luminosity. It is expected to reach 2.5 ab^{-1} and 15 ab^{-1} final integrated luminosity after 10 years (Phase I) and 15 years (Phase II) of running period, respectively. End of two Phase sections, it is expected to reach 17.5 ab^{-1} in 25 years (CERN Council, 2013; Sirunyan et al., 2020; Kaya, 2020; Abada et al., 2019).

In this paper, the possibilities of existing of $DQ_{(uu)}$, $DQ_{(ud)}$ and $DQ_{(dd)}$ the scalar diquarks are investigated at Future Circular Collider-based proton-proton, (FCC-pp) with 100 TeV. In the Section 2, The FCC-pp and their parameters are presented and in the Section 3, interaction lagrangian, decay widths and total cross section calculations are shown. In the Section 4, in order to distinguish signal from background kinematic cuts are calculated. Finally, in the Section 5, discovery, observation and exclusion limits of the scalar diquarks mass are given.

2. FCC PROTON-PROTON COLLIDER

The FCC-pp is a hadron collider with 100 TeV CM, planned to build at the CERN between Switzerland and France borders. The circumference of the FCC-pp is 97.75 km and in order to keep proton beam at the circular orbit, it has magnetic field with 16T. It has planned to use injected beam with 3.3 TeV from the LHC machine at the CERN. In Figure 1, geological and schematic view of the FCC-pp machine is shown. On the left side in the Figure 1 give 3D view of the underground structure of the FCC-pp, while an illustration on the right side shows geological position and size of the FCC-pp project planned. The green line circle represents main the FCC-pp tunnel besides, blue line circle represents existing the LHC at the CERN (Abada et al., 2019).

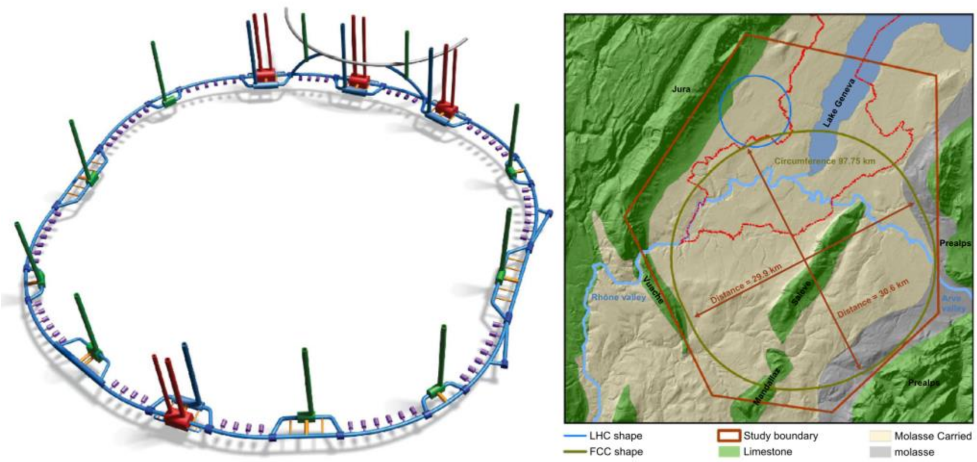


Figure 1. The geological and schematic structures of the FCC-pp machine. Left: 3D view of the underground structure. Right: geological position and size of the FCC-pp (green circle is the FCC-pp, blue circle is the LHC) (Abada et al., 2019).

When the FCC-pp begins to work, the maximum luminosity is planned to be $5x10^{34}$ $cm^{-2}s^{-1}$ as a starter parameter in the first years. In the next years, proposed luminosity will reach up to $3x10^{35}$ $cm^{-2}s^{-1}$ nominal value. At the beginning of the FCC-pp, the integrated luminosity will be provided as 2 fb^{-1} per year while for the nominal parameters is 8 fb^{-1} per year. The FCC-pp machine will be proved total energy by a factor of 20 more than the LHC. In addition, the level of the synchrotron radiation in arc is by a factor of 200 greater than the LHC. The radiation limit of the magnets of the FCC-pp is 30 MGy. Some of the compared systematic parameters of the FCC-pp, LHC and HL-LHC machine are given in Table 1.

Table 1. Some of the values of the FCC-pp machine compared to the LHC and HL-LHC (Abada et al., 2019).

	LHC	**HL-LHC**	**FCC-pp**	
			Initial	**Nominal**
Basic Parameters				
Maximum E_p (TeV)	7	14	100	
Peak luminosity 10^{34} $cm^{-2}s^{-1}$	1.0	5.0	5.0	<30.0
Average integrated luminosity/day (fb^{-1})	0.47	2.8	2.2	8
Total cross section σ (mbarn)	111/85		153/108	
Beam Parameters				
Number of bunches n	2808		10400	
Bunch spacing (ns)	25	25	25	
Beam current (A)	0.584	1.12	0.5	

3. DECAY WIDTH AND TOTAL CROSS SECTIONS

The decay widths of the diquarks were estimated from invariant effective Lagrangian Eq.4 for each quark pairs uu, ud and dd which scaler diquarks are decayed into. For this study, only the scalar diquarks with baryon number of 2/3 (|B|=2/3) are taken into account.

$$L_{|B|=\frac{2}{3}} = (g_{1L}\bar{q}_L^c i\tau_2 q_L + g_{1R}\bar{q}_R^c d_R) DQ_1^c + \tilde{g}_{1R}\bar{d}_R^c d_R \widetilde{DQ}_1^c + \tilde{g}'_{1R}\bar{u}_R^c u_R \widetilde{DQ}_1'^c \quad \textbf{(4)}$$

where, g_{1L} denotes coupling constant used as 0.1 for these calculations. $q_L = (u_L, d_L)$ represents left-handed quark doublet spinor and $q_R =$

(u_R, d_R) represents right-handed quark doublet spinor. DQ_1, $\widetilde{DQ}_1$ and $\widetilde{DQ}'_1$ are the scalar diquarks. Finally, quark conjugated field is given with q^c (Cakir & Sahin, 2005; Sahin & Cakir, 2010).

Figure 2 shows the results of decay width calculations for the scalar diquarks with coupling constant α_s=0.1. As it seen from the Figure 1, calculations of the decay width versus the invariant mass is linear as it expected. The distribution was obtained from 7,5 TeV to 100 TeV invariant mass range for the FCC-pp at 100 TeV. To discriminate signal from the background, decay width cuts are applied on an invariant mass of scalar $DQ_{(uu)}$, $DQ_{(ud)}$ and $DQ_{(dd)}$.

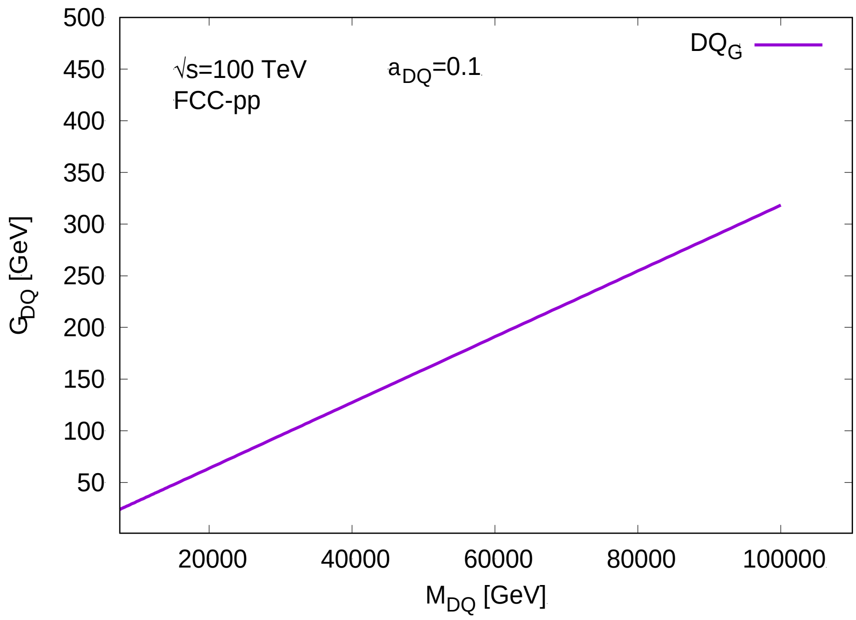


Figure 2. The decay widths calculations for the scalar diquarks.

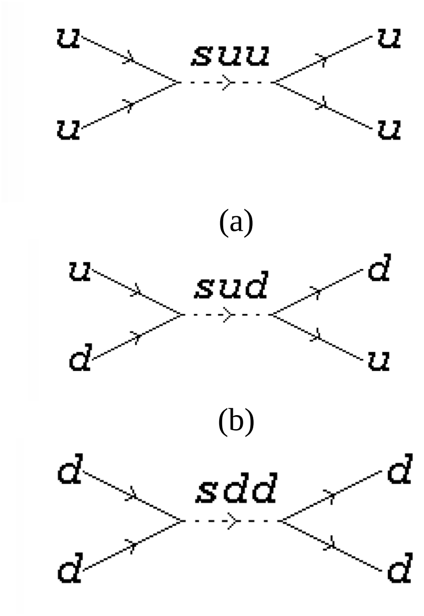
In this analysis all the calculations are obtained from the Eq. 4, which is implemented to simulation software CALCHEP in the version 3.8.5 via LANHEP programme. The Feynman diagrams of the resonant productions for scalar $DQ_{(uu)}$, $DQ_{(ud)}$ and $DQ_{(dd)}$ with CTEQL1 parton distribution function and coupling constant α_s=0.1 are presented in Figure 3 (Belyaev, Christensen & Pukhov, 2013; Semenov, 2002; Semenov, 2016; Pumplin, Stump, Huston, Lai, Nadolsky & Tung, 2002; Stump, Huston, Pumplin, Tung, Lai, Kuhlmann & Owens, 2003).

Process

$DQ_{(uu)}$

$DQ_{(ud)}$

$DQ_{(dd)}$



(a) (b) (c)

Figure 3. The Feynman diagrams of resonant production of the scalar diquarks for three type process. (a): uu type scalar diquark signal, (b): ud type scalar diquark signal and (c): dd type scalar diquark signal.

Total cross section distributions versus the scalar $DQ_{(uu)}$, $DQ_{(ud)}$ and $DQ_{(dd)}$ mass are given in the Figure 4. According to the SM, protons are composite particles made of two up (u) with charge 2/3 and one down (d) with charge -1/2 valance quarks. In this case, scalar uu diquark made of up quark pairs, scaler ud diquark made of up and down quark pairs and scalar dd diquark made of down quark pairs would have charge with 4/3, 1/3 and -2/3, respectively. As seen in Figure 4, the total cross section distributions of all three scalar diquarks are aligned. Since proton has two u valance quarks, the $DQ_{(uu)}$ type scalar diquark has the largest cross sections.

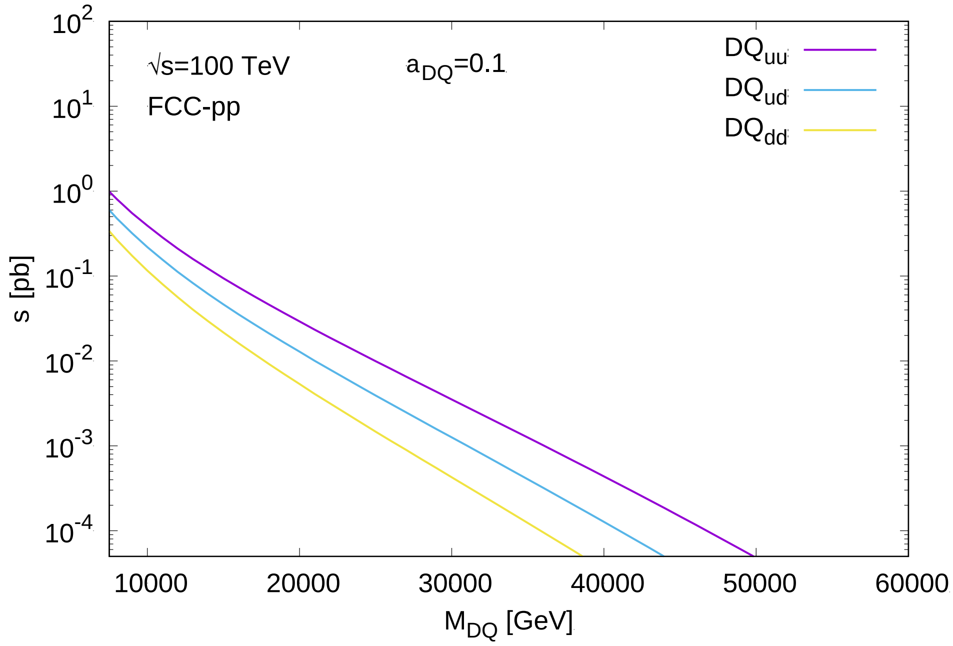


Figure 4. Total cross section distributions versus mass of the scalar diquarks types $DQ_{(uu)}$, $DQ_{(ud)}$ and $DQ_{(dd)}$ with coupling constant $\alpha_{DQ} = 0.1$ at the FCC-pp collisions.

4. SIGNAL AND BACKGROUND ANALYSIS

In order to distinguish signals from background, kinematics cuts are determined from transverse momentum, (p_T) and pseudorapidity, (η) distributions of the final state particles in the FCC-pp at 100TeV. Three type of scalar diquark signals, $DQ_{(uu)}$, $DQ_{(ud)}$ and $DQ_{(dd)}$, are defined in the Section 1. As a background processes, all SM defined quarks and anti-quarks are included except t and anti-t quark, $pp \rightarrow j$ and $j + X$ that is generated $(j \rightarrow u, \bar{u}, d, \bar{d}, c, \bar{c}, s, \bar{s}, b, \bar{b}\ and\ g)$. CTEQ6L1 Parton Distribution Function is used to generate all signal and background calculations and calculated by using CALCHEP_385 simulation software programme.

Figure 5 demonstrates p_T distributions of the final state scalar $DQ_{(uu)}$ jets and SM background for the FCC-pp with 100 TeV. The smooth purple line denotes SM background besides, each color denotes resonance peaks at mass values (7.5, 10, 20, 30, 40 and 50 TeV) of the scalar $DQ_{(uu)}$. As seen from distributions, if the p_T > 1000 GeV kinematic cut is applied at $\sqrt{s} =$ 100 TeV, enormous amount of the SM background clear away while final state scalar $DQ_{(uu)}$ jets at each mass does not show significant changes. Also final state scalar $DQ_{(ud)}$ and $DQ_{(dd)}$ jets show same characteristics with $DQ_{(uu)}$. Thus, as an illustration, the scalar $DQ_{(uu)}$ demonstrated for this paper.

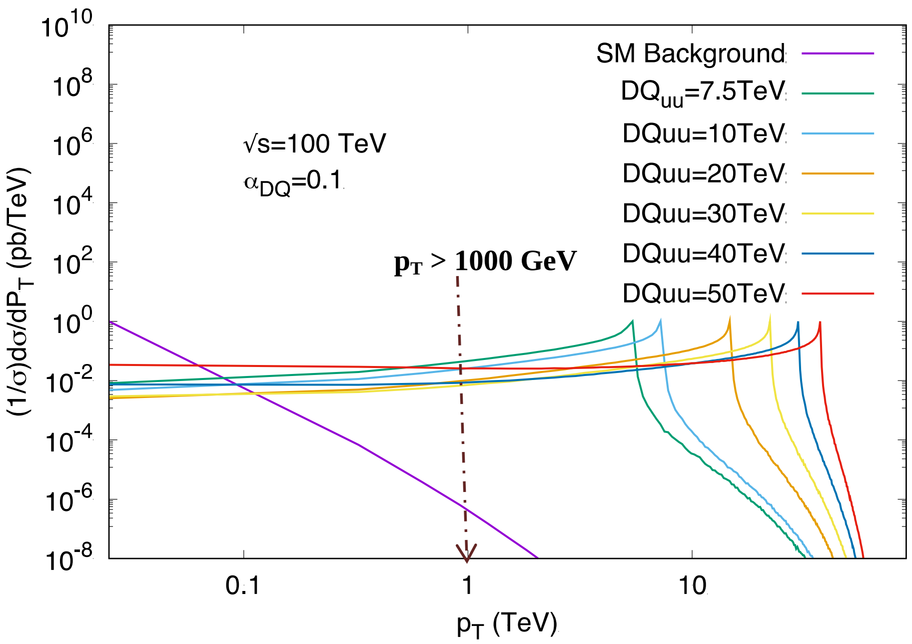


Figure 5. The pT distributions as a function of mass of the scalar diquarks $DQ_{(uu)}$, $DQ_{(ud)}$ and $DQ_{(dd)}$ with coupling constant $\alpha_{DQ} = 0.1$ at in the FCC-pp collisions at $\sqrt{s} = 100$ TeV.

Because of the detector's structure, pseudorapidty (η) distributions of the detector placed on the colliders like the CMS detector on the LHC shows symmetric distribution for both left and right side of the detector. In Figure 6, pseudorapidity distributions of final state background and scalar $DQ_{(uu)}$ jets are illustrated for the FCC-pp at $\sqrt{s} = 100$ TeV center of mass energy. η distributions are symmetric for both detector side for SM background and scalar $DQ_{(uu)}$ jets at seven mass values as expected. And also, both SM background and scalar $DQ_{(uu)}$ jets are mostly located at $-2.5 < \eta < 2.5$ region. Because of this reason, another kinematic cut $-2.5 < \eta < 2.5$ region is selected from distributions for the analysis.

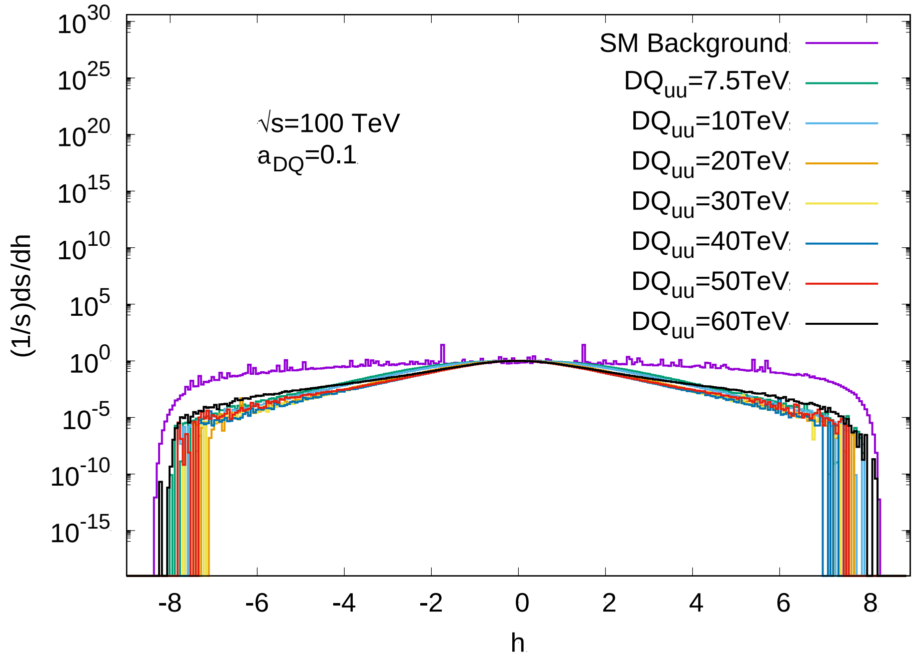


Figure 6. Pseudorapidity distributions of final background and scalar $DQ_{(uu)}$ jets for the FCC-pp with $\sqrt{s} = 100$ TeV center of mass energy.

5. CONCLUSION

In this study, resonance production of the scalar diquarks for the FCC-pp with 100 TeV are studied. As a kinematic cuts which were specified for this work to discriminate background from signal, transverse momentum $p_T >$ 1000 GeV, pseudorapidity $-2.5 < \eta < 2.5$ are applied on mass of the final state the scalar diquarks. Furthermore, in order to select particle jets cone angle radius, cut $\Delta R > 0.4$ is applied for the FCC-pp, in addition, invariant mass cut $M-2\Gamma < Mjj < M+2\Gamma$ is applied, where M denotes the final state scalar diquark mass and Γ is total decay width given in the Section 3. In this analysis, statistical significance (SS) calculations are performed using the following formula (Eq.5),

$$SS = \frac{\sigma_S}{\sqrt{\sigma_S + \sigma_B}} \sqrt{\mathcal{L}_{int}} \quad \textbf{(5)}$$

where, σ_S and σ_B represent the signal and background cross sections, respectively. The L_{int} denotes integrated luminosity of the FCC-pp during the phase I (Sahin, Aydin & Gunaydin, 2019).

As a result, after all these calculations, the limit values of the discovery (5σ), observation (3σ) and exclusions (2σ) of the final state resonance the scalar diquarks are presented for the FCC-pp at first round (Phase I) that total integrated luminosity will reach 2.5 ab^{-1} in 10 years.

In Figure 7, distributions of the discovery (5σ), observation (3σ) and exclusions (2σ) mass limits depending on integrated luminosity for the scalar $DQ_{(uu)}$ are shown. The red dots denote discovery of the mass limit values of skalar $DQ_{(uu)}$ changing from 44 TeV up to 53 TeV between 200 and 2500 fb^{-1} integrated luminosity for the FCC-pp at 100 TeV. The observation of the mass limit values depending on increasing integrated luminosity are pointed out with green dots. The observation (3σ) range is from 48 to 57 TeV for scalar $DQ_{(uu)}$ mass. Also, the exclusion limit values of the scalar $DQ_{(uu)}$ for the FCC-pp are figured out with blue dots. At the FCC-pp with 100 TeV center of mass, the exclusion limit values change between 52 and 60 TeV.

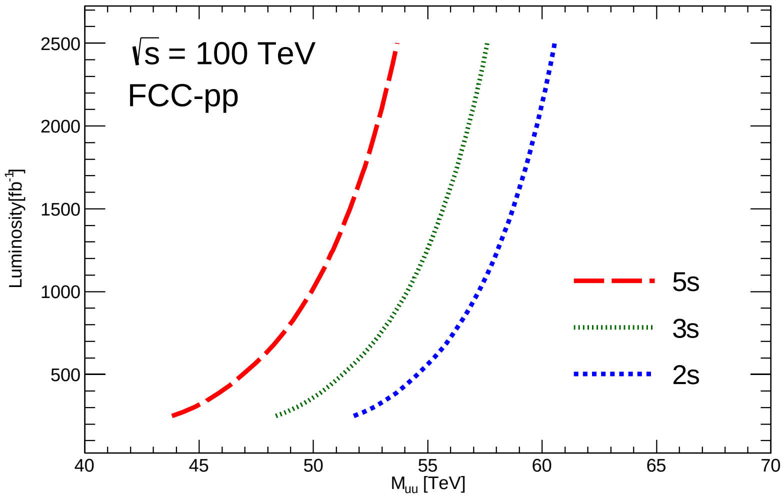


Figure 7. Discovery (5 σ), observation (3 σ) and exclusions (2 σ) mass limits values depending on integrated luminosity for the scalar $DQ_{(uu)}$ in the FCC-pp with $\sqrt{s} = 100$ TeV.

The mass limit values of discovery (5σ), observation (3σ) and exclusion (2σ) depending on integrated luminosity for the scalar $DQ_{(ud)}$ are given in Figure 8. As seen from the Figure 8, discovery (5σ), of the mass limit values of scaler $DQ_{(ud)}$ changes from 35 TeV up to 44 TeV between 200 and 2500 fb^{-1} integrated luminosity for the FCC-pp at 100 TeV. The observation (3σ) range is from 39 to 48 TeV, while exclusion limit values change between 52 and 60 TeV of the scalar $DQ_{(ud)}$ for the FCC-pp with $\sqrt{s} = 100$ TeV.
As seen from Figure 9, discovery (5σ), of the mass limit values of scalar $DQ_{(dd)}$ are illustrated from 31 TeV up to 38 TeV while observation (3σ) limits are from 35 to 42 TeV. And, exclusion limit values change between 34.5 and TeV of the scalar $DQ_{(ud)}$ for the FCC-pp with $\sqrt{s} = 100$ TeV.

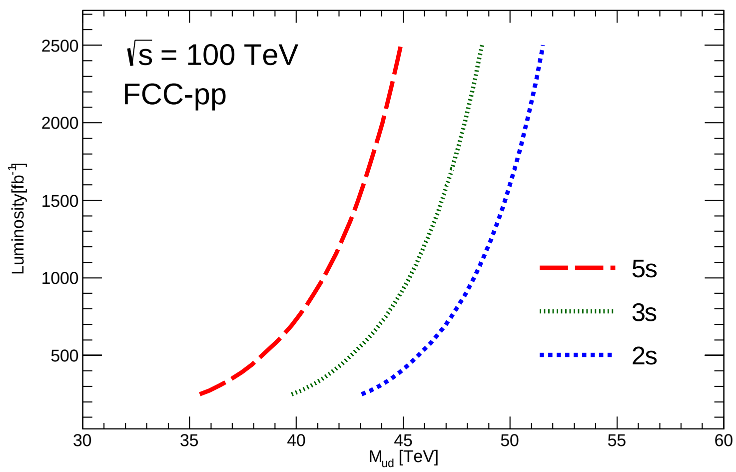


Figure 8. Discovery (5 σ), observation (3 σ) and exclusions (2 σ) mass limit values depending on integrated luminosity for the scalar $DQ_{(ud)}$ in the FCC-pp with $\sqrt{s} = 100$ TeV.

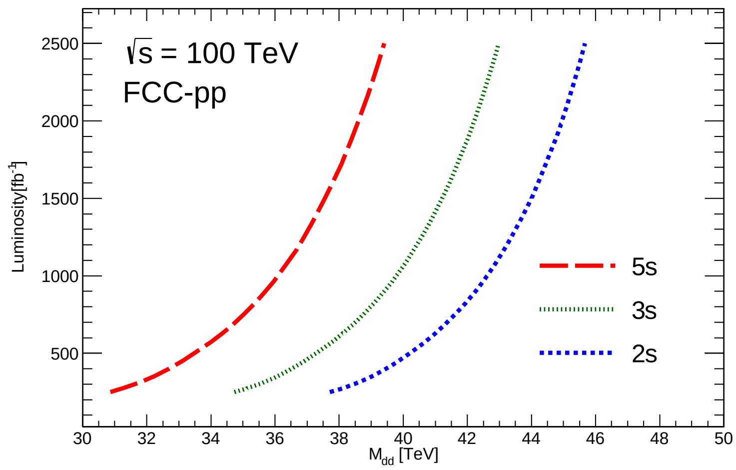


Figure 9. Discovery (5 σ), observation (3 σ) and exclusions (2 σ) mass limit values depending on integrated luminosity for the scalar $DQ_{(dd)}$ in the FCC-pp with $\sqrt{s} = 100$ TeV.

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