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Research Article

Search for Excited u and d Quarks in Dijet Final States at Future pp Colliders

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Resonant production of excited u and d quarks at the Future Circular Collider and Super Proton-Proton Collider has been researched. Dominant jet-jet decay mode has been considered. It is shown that FCC and SppC have great potential for discovery of excited u (d) quark: up to 44.1 (36.3) and 58.4 (47.8) TeV masses, respectively. For degenerate case ($M_{u^\star} = M_{d^\star}$), these values are 45.9 and 60.9 TeV, respectively. This discovery will also afford an opportunity to determine the compositeness scale up to multi-PeV level.

1. Introduction

Standard model (SM) contains plenty of elementary particles and their parameters that are not completely explained. To overcome these unsolved problems that the SM does not give answers, new models have been developed beyond the standard model (BSM) such as composite models, supersymmetry, extra dimensions, string theory, and so on. These BSM theories require higher energy level than SM energy domain to bring solutions for unanswered problems. Therefore, the SM is considered as low energy configuration of the more fundamental theory.

Numbers of particles and parameters in the SM are reduced in the frame of the composite models [1–16]. According to composite models, while SM quarks and leptons are predicted as composite particles, preons are considered as the most fundamental particles. If excited states of the SM fermions are experimentally observed, this observation will be clear proof of quarks and leptons' compositeness.

Excited fermions are known to represent much heavier particles than the SM fermions and they could be split into two classes: excited quarks ($q^\star$) and excited leptons ($l^\star$). These heavy particles could also have spin-1/2 and spin-3/2 states. From the first publication on excited leptons in 1965 [17] until today, there have been plenty of phenomenological [18–38] and experimental [39–53] studies performed on excited fermions.

Excited states of SM quarks might be shown in four possible final states with light jets, $q^\star \longrightarrow jj$, $q^\star \longrightarrow \gamma j$, $q^\star \longrightarrow Wj$, and $q^\star \longrightarrow Zj$. Currently, the LHC puts experimental mass limits for all four final state cases [47, 51–54] that are $M_{q^\star}$ = 6.0 (6.0), 5.5 (5.5), 3.2 (5.0), and 2.9 (4.7) TeV for ATLAS (CMS), respectively. Like SM fermions, excited fermions also have three families and we focused on $u^\star$ and $d^\star$ productions which decay to dijet final states.

After the LHC physics mission is over, a new and more powerful collider will take place as an energy frontier discovery machine for the high energy physics. At CERN located in Geneva, Future Circular Collider (FCC) [55] is planned for the next step with $\sqrt{s}$ = 100 TeV. The other project, Super Proton-Proton Collider (SppC), is planned in China at multi-TeV center of mass (CM) energies [56]; we chose $\sqrt{s}$ = 136 TeV option in this study. Both projects

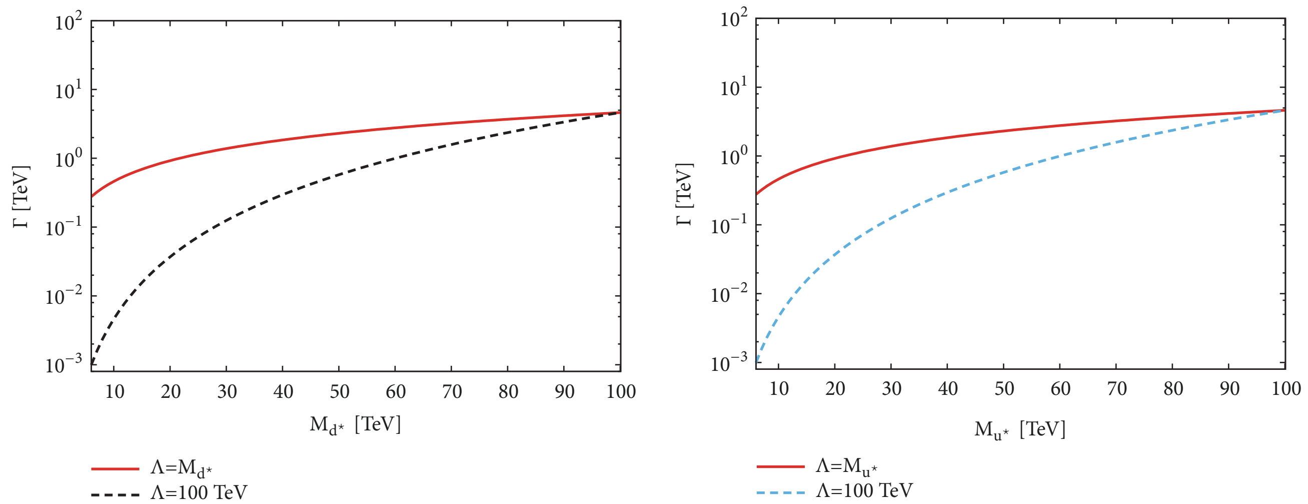

Figure 1: Decay widths versus first generation excited quark masses for both $\Lambda = M_{d^*}$, $\Lambda = M_{u^*}$, and $\Lambda = 100$ TeV.

Table 1: Planned operation time of FCC and SppC and their main parameters.

Collider Name	FCC Phase I	FCC Phase II	SppC
Operation Time	10 Years	15 Years	15 Years
$\sqrt{s}$ [TeV]	100		136
$\mathscr{L}_{int}$ [fb^{-1}]	2500	15000	22500
	17500		

promise very high luminosity. The FCC will be expected to reach 2500 fb^{-1} integrated luminosity in ten years (Phase I) and 15000 fb^{-1} integrated luminosity in 15 years (Phase II) [57–59]. Overall in 25 years, total integrated luminosity will be 17500 fb^{-1}. On the other hand, the SppC will deliver pp collisions with 22500 fb^{-1} integrated luminosity in 15 years (see Table 1).

In this research, we explore spin-1/2 excited u and d quark ($u^\star$ and $d^\star$) decaying into dijet final states at the FCC and the SppC. In the following sections, we state spin-1/2 excited quark interaction Lagrangian, decay widths, and cross section values in Section 2, signal-background analysis to determine cuts in Section 3, and attainable mass and compositeness scale (Λ) limits and conclusions in Section 4.

2. Interaction Lagrangian, Decay Widths, and Cross Sections

When left- and right-handed components of excited quarks are assigned to isodoublets, isospin structure of the first generation SM and excited quarks will be

$$\begin{bmatrix} u \\ d \end{bmatrix}_L, u_R, d_R \begin{bmatrix} u^\star \\ d^\star \end{bmatrix}_L, \begin{bmatrix} u^\star \\ d^\star \end{bmatrix}_R. \tag{1}$$

Since interaction Lagrangian is magnetic-moment type, it contains only left-handed quark doublet and consequently right-handed excited quark doublet. For that reason, as an effective interaction Lagrangian [20, 22, 25, 54], Equation (2) was utilized for the spin-1/2 excited quarks:

$$L_{eff} = \frac{1}{2\Lambda} \cdot \overline{q_R^\star}\sigma^{\mu\nu}\left[g_s f_s \frac{\lambda_a}{2} G^a_{\mu\nu} + g f \frac{\overrightarrow{\tau}}{2}\overrightarrow{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}\right] q_L + h.c. \tag{2}$$

where compositeness scale is represented as Λ, $q_R^\star$ denotes right-handed excited quark doublet, q_L depicts ground state left-handed quark doublet, and field strength tensors are $G^a_{\mu\nu}$ for gluon, $\overrightarrow{W}_{\mu\nu}$ for SU(2), and $B_{\mu\nu}$ for U(1). λ_a, $\overrightarrow{\tau}$, and Y are color parameters for gluon-quark interaction, Pauli spin matrices, and weak hyper-charge, respectively. Gauge coupling constants are g_s, g, and g'; and f_s, f, f' are free parameters that are taken as equal to 1 in numerical calculations. In addition, mentioned interactions with Higgs Boson as well as mass mixing among quarks and excited quarks can be neglected since $M_{u^\star} \gg \eta \gg M_u$ (η is vacuum expectation value of Higgs field). Indeed, $M_{u^\star} > 6$ TeV from the LHC data, $\eta \approx 245$ GeV, and M_u is in MeV region.

Interaction Lagrangian Equation (2) was implemented into CalcHEP [60] software by using LanHEP interface [61, 62]. In our calculations, CTEQ6L1 [63, 64] parton distribution function was used and factorizations and renormalization scale were taken equal to $M_{q^\star}$.

Partial decay widths of first generation excited quarks are listed in Table 2. Parameters in the last column of Table 2 are $f_Z = fT_3\cos^2\theta_W - f'(Y/2)\sin^2\theta_W$, $f_W = f/\sqrt{2}$, $f_\gamma = fT_3 + f'Y/2$, $g_W = \sqrt{4\pi\alpha}/\sin\theta_W$, and $g_Z = g_W/\cos\theta_W$; here T_3 is the third component of the weak isospin of $q^\star$. In Figure 1,

Table 2: Third component of isospins, charges, decay channels, and widths of up- and down-type excited quarks.

T_3	Q	Decay Modes	Partial Decay Widths
$\frac{1}{2}$	$\frac{2}{3}$	$u^\star \longrightarrow dW^+$	$\Gamma = \frac{1}{32\pi} g_W^2 f_W^2 \frac{M_{u^\star}^3}{\Lambda^2}\left(1-\frac{m_W^2}{M_{u^\star}^2}\right)^2\left(2+\frac{m_W^2}{M_{u^\star}^2}\right)$
		$u^\star \longrightarrow uZ$	$\Gamma = \frac{1}{32\pi} g_Z^2 f_Z^2 \frac{M_{u^\star}^3}{\Lambda^2}\left(1-\frac{m_Z^2}{M_{u^\star}^2}\right)^2\left(2+\frac{m_Z^2}{M_{u^\star}^2}\right)$
		$u^\star \longrightarrow ug$	$\Gamma = \frac{1}{3}\alpha_s f_s^2 \frac{M_{u^\star}^3}{\Lambda^2}$
		$u^\star \longrightarrow u\gamma$	$\Gamma = \frac{1}{4}\alpha f_\gamma^2 \frac{M_{u^\star}^3}{\Lambda^2}$
$-\frac{1}{2}$	$-\frac{1}{3}$	$d^\star \longrightarrow uW^-$	$\Gamma = \frac{1}{32\pi} g_W^2 f_W^2 \frac{M_{d^\star}^3}{\Lambda^2}\left(1-\frac{m_W^2}{M_{d^\star}^2}\right)^2\left(2+\frac{m_W^2}{M_{d^\star}^2}\right)$
		$d^\star \longrightarrow dZ$	$\Gamma = \frac{1}{32\pi} g_Z^2 f_Z^2 \frac{M_{d^\star}^3}{\Lambda^2}\left(1-\frac{m_Z^2}{M_{d^\star}^2}\right)^2\left(2+\frac{m_Z^2}{M_{d^\star}^2}\right)$
		$d^\star \longrightarrow dg$	$\Gamma = \frac{1}{3}\alpha_s f_s^2 \frac{M_{d^\star}^3}{\Lambda^2}$
		$d^\star \longrightarrow d\gamma$	$\Gamma = \frac{1}{4}\alpha f_\gamma^2 \frac{M_{d^\star}^3}{\Lambda^2}$

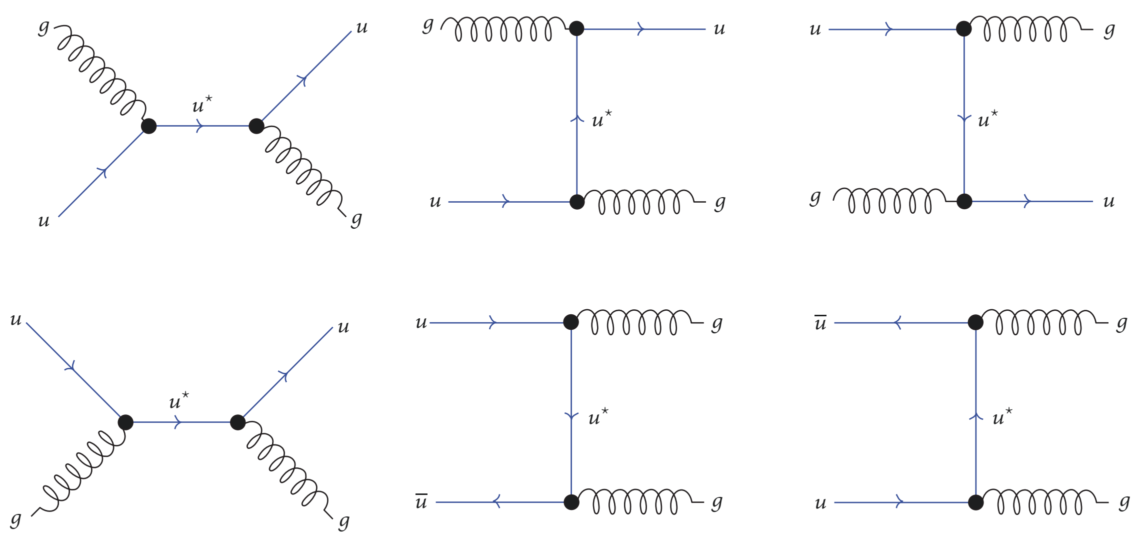

Figure 2: Feynman diagrams for direct (first column) and indirect production of $u^\star$ at pp colliders.

total decay widths are given for $\Lambda = M_{d^\star}$, $\Lambda = M_{u^\star}$, and $\Lambda = 100$ TeV by scanning excited quarks mass from 6 TeV to 100 TeV. Total decay widths of $u^\star$ and $d^\star$ are close to each other since dominant decay modes are $u^\star \longrightarrow gu$ and $d^\star \longrightarrow gd$. There are small differences caused by Z and γ channels. It is obviously seen that while $d^\star$ and $u^\star$ mass values are risen, decay widths are increased.

For the following parts of this study, we consider three cases to do analysis: (a) $M_{u^\star} < M_{d^\star}$, (b) $M_{d^\star} < M_{u^\star}$, and (c) $M_{u^\star} = M_{d^\star}$ (degenerate state) with $pp \longrightarrow u^\star + X \longrightarrow ug + X$, $pp \longrightarrow d^\star + X \longrightarrow dg + X$, and $pp \longrightarrow q^\star + X \longrightarrow qg + X$ signal processes, respectively (here, $q^\star$ denotes $u^\star + d^\star$). 6 Feynman diagrams emerge for cases (a) and (b), and 12 Feynman diagrams make contributions to signal cross section calculations for the case (c). Figure 2 presents the case (a) Feynman diagrams for illustration. Analytical expression for the cross sections at parton level corresponding to these diagrams is described by Equation (3):

$$\begin{aligned}\frac{d\hat{\sigma}}{d\hat{t}} &= \frac{f_s^4 g_s^4}{216\pi\Lambda^4\left(M_{u^\star}^2-\hat{s}\right)^2}\left[\frac{-48M_{u^\star}^8+68M_{u^\star}^6\hat{s}+11M_{u^\star}^4\hat{s}^2-34M_{u^\star}^2\hat{s}^3+6\hat{s}^4}{\left(M_{u^\star}^2-\hat{s}\right)^2}\right.\\ &+\frac{-8M_{u^\star}^8-11M_{u^\star}^6\hat{s}}{\left(M_{u^\star}^2-\hat{t}\right)^2}+\frac{32M_{u^\star}^6+33M_{u^\star}^4\hat{s}}{M_{u^\star}^2-\hat{t}}-16\hat{s}\hat{t}\\ &\left.-16\hat{t}^2+\frac{-8M_{u^\star}^8-11M_{u^\star}^6\hat{s}}{\left(M_{u^\star}^2+\hat{s}+\hat{t}\right)^2}+\frac{32M_{u^\star}^6+33M_{u^\star}^4\hat{s}}{M_{u^\star}^2+\hat{s}+\hat{t}}\right] \end{aligned} \tag{3}$$

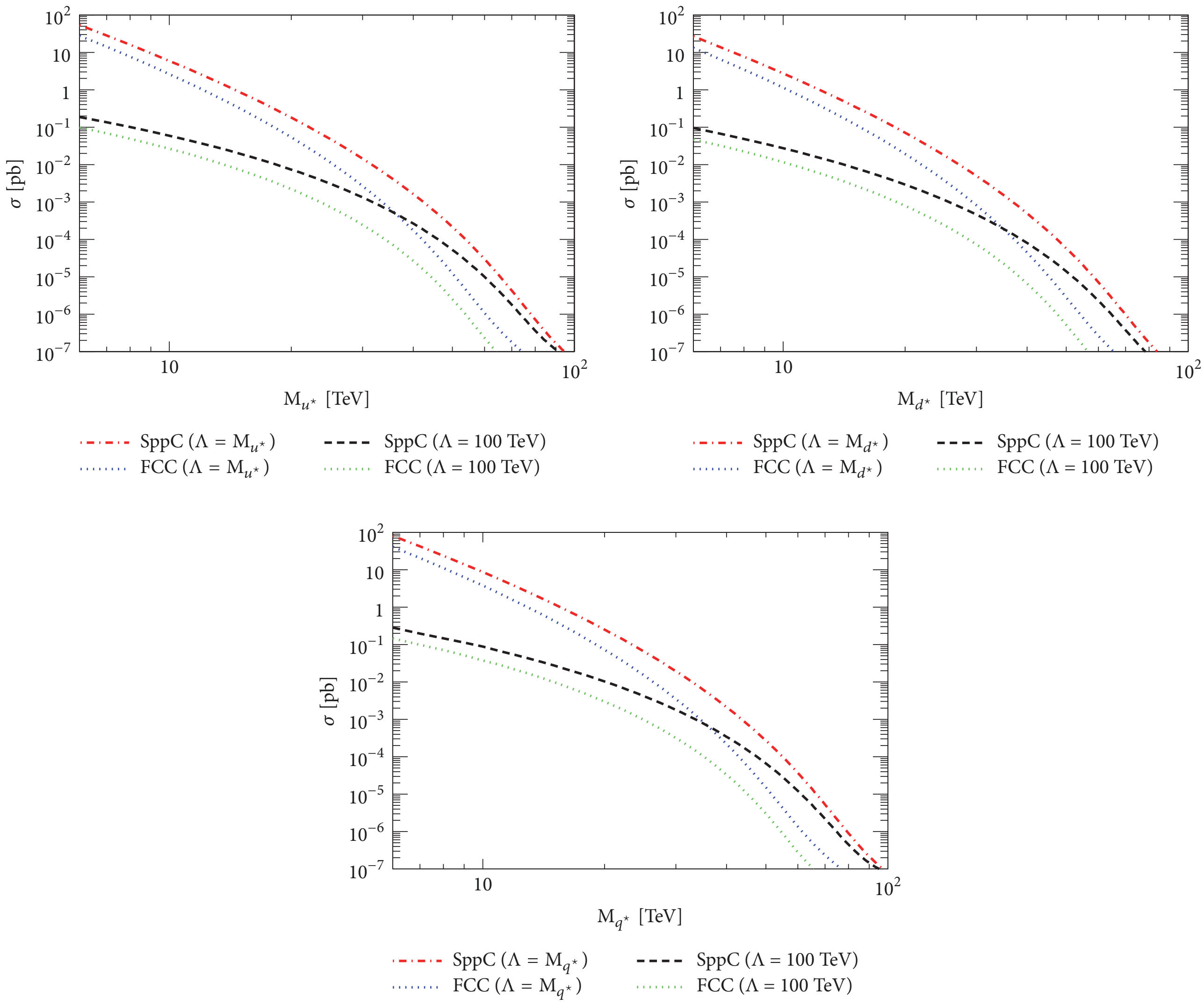

Figure 3: Cross section values of the first generation $u^\star$, $d^\star$, and $q^\star$ (degenerate state) excited quarks at the FCC and SppC.

In Figure 3, first generation excited quarks cross section values for three cases mentioned above are plotted for the FCC ($\sqrt{s}$ = 100 TeV) and the SppC ($\sqrt{s}$ = 136 TeV) with $\Lambda = M_{u^\star}$, $\Lambda = M_{d^\star}$, $\Lambda = M_{q^\star}$ (degenerate state), and $\Lambda = 100$ TeV. When the compositeness scale value is taken as equal to excited quark masses, cross section values are about 300 times higher at 6 TeV mass value for both collider options. Indeed, it seems that excited quark could be produced at very high mass values for both collider options. It should be noted that as the LHC experimental studies on excited quarks with dijet final states do not consider SM interference contribution to cross section [47, 51], we did not simulate interference with SM for the FCC and SppC at this stage. For the same reason, QCD corrections were disregarded in this analysis [47, 52, 65–67].

3. Signal and Background Analysis

Signal processes were defined in previous section. Background process which is used in calculation is $pp \longrightarrow jj + X$; here j denotes $u, \overline{u}, d, \overline{d}, c, \overline{c}, s, \overline{s}, b, \overline{b}$ and g for three signal cases. It is important to determine transverse momentum (P_T), pseudo rapidity (η), and invariant mass (M_{jj}) cut values for selecting clear signal. To illustrate cut selection, only final state particles distribution originated by excited u quark plots are included in Figure 4. According to these figures, P_T cuts are applied as 2 TeV, and η cuts are determined as $|\eta| < 2.5$ in signal and background cross section calculations for three cases. Also, the cone angle radius is chosen as $\Delta R > 0.5$ for both colliders. Additionally, invariant mass cuts are applied as $M^\star - 2\Gamma^\star < M_{jj} < M^\star + 2\Gamma^\star$ mass window for again both collider options; here $M^\star$ denotes excited quarks ($u^\star, d^\star$, and $q^\star$) mass and $\Gamma^\star$ is total decay widths of the excited quarks.

In order to calculate statistical significance, Equation (4) is used:

$$SS = \frac{\sigma_S}{\sqrt{\sigma_S + \sigma_B}} \sqrt{\mathscr{L}_{int}} \quad (4)$$

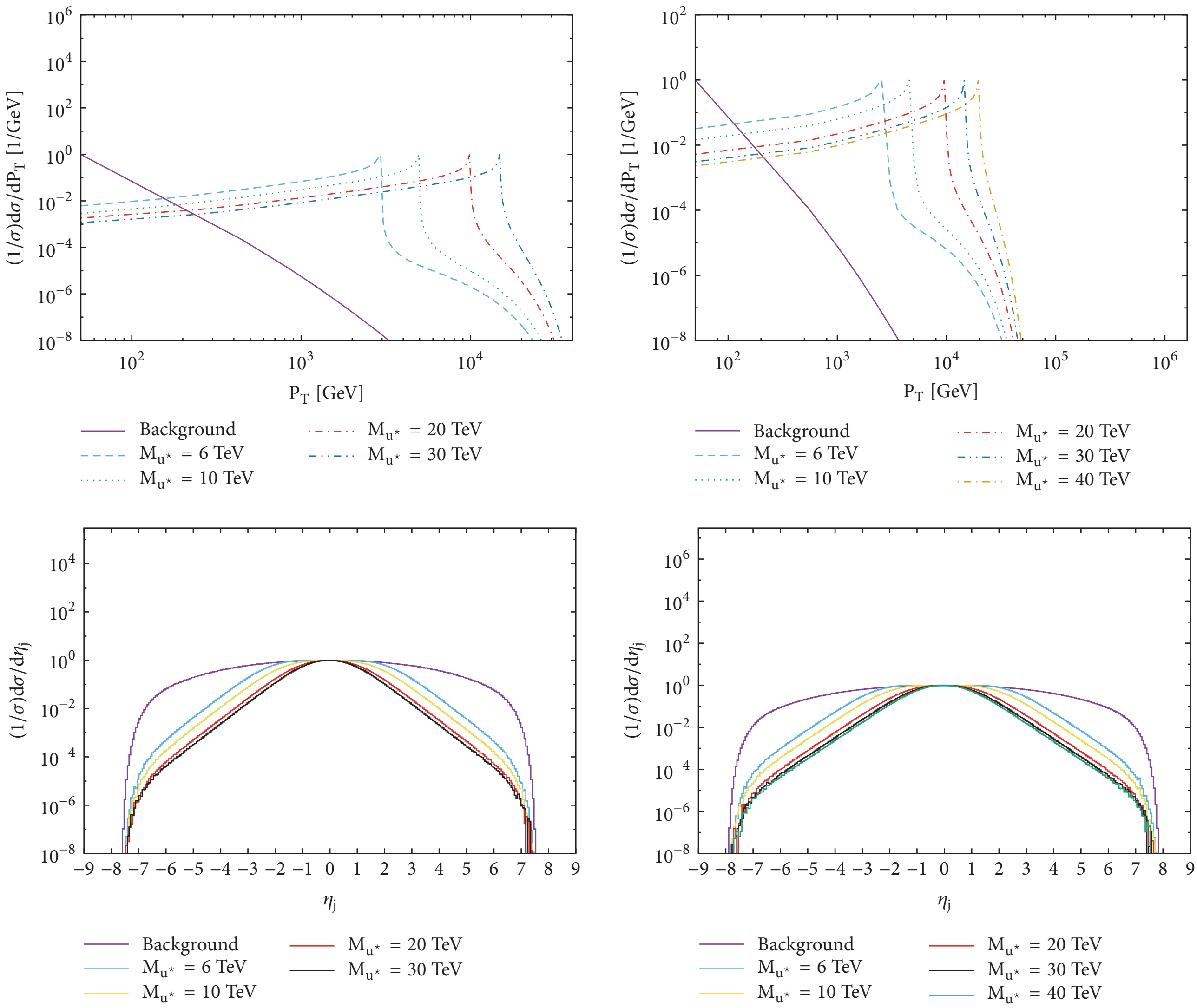

Figure 4: Transverse momentum and η distribution plots for FCC (left column) and SppC (right column).

where σ_S and σ_B denote signal and background cross section values, respectively, and $\mathscr{L}_{int}$ represents integrated luminosity. Using Equation (4), we have calculated excited quarks mass' discovery (5σ), observation (3σ), and exclusion (2σ) limits on prospective frontier machines, namely, FCC and SppC.

4. Results and Conclusions

Discovery, observation, and exclusion limits on the mass of excited quarks for three cases depending on integrated luminosity of the FCC and SppC with $\Lambda = M^{\star}$ cases are plotted in Figure 5. Attainable mass limits for all three cases for FCC-Phases I and II and SppC with their final integrated luminosity values at the end of operating times are listed in Table 3. It is seen that FCC-Phase I will afford an opportunity to discover, observe, or exclude degenerate case of excited quarks up to 40.1, 43.2, and 45.6 TeV, respectively. At the end of the FCC-Phase II, these values become $M_{q^{\star}} = 45.9$ TeV (5σ), $M_{q^{\star}} = 48.9$ TeV (3σ), and $M_{q^{\star}} = 51.3$ TeV (2σ). On the other hand, corresponding values for SppC are $M_{q^{\star}} = 60.9$ TeV (5σ), $M_{q^{\star}} = 65.0$ TeV (3σ), and $M_{q^{\star}} = 68.1$ TeV (2σ) that essentially exceed the FCC limits.

As mentioned above, we did not anticipate interference of the signal model with the SM contribution. In order to estimate this contribution, we compared discovery limits for $u^{\star}$ at the FCC-Phase II. As seen from Table 3, this limit was 44.1 TeV in our case. If one takes interference terms into account, discovery limit becomes 45.0 TeV. The latter value was obtained using same discovery cuts together with corresponding statistical signification equation, namely,

$$SS = \frac{\left|\sigma_{tot} - \sigma_B\right|}{\sqrt{\sigma_{tot}}} \sqrt{\mathscr{L}_{int}} \qquad (5)$$

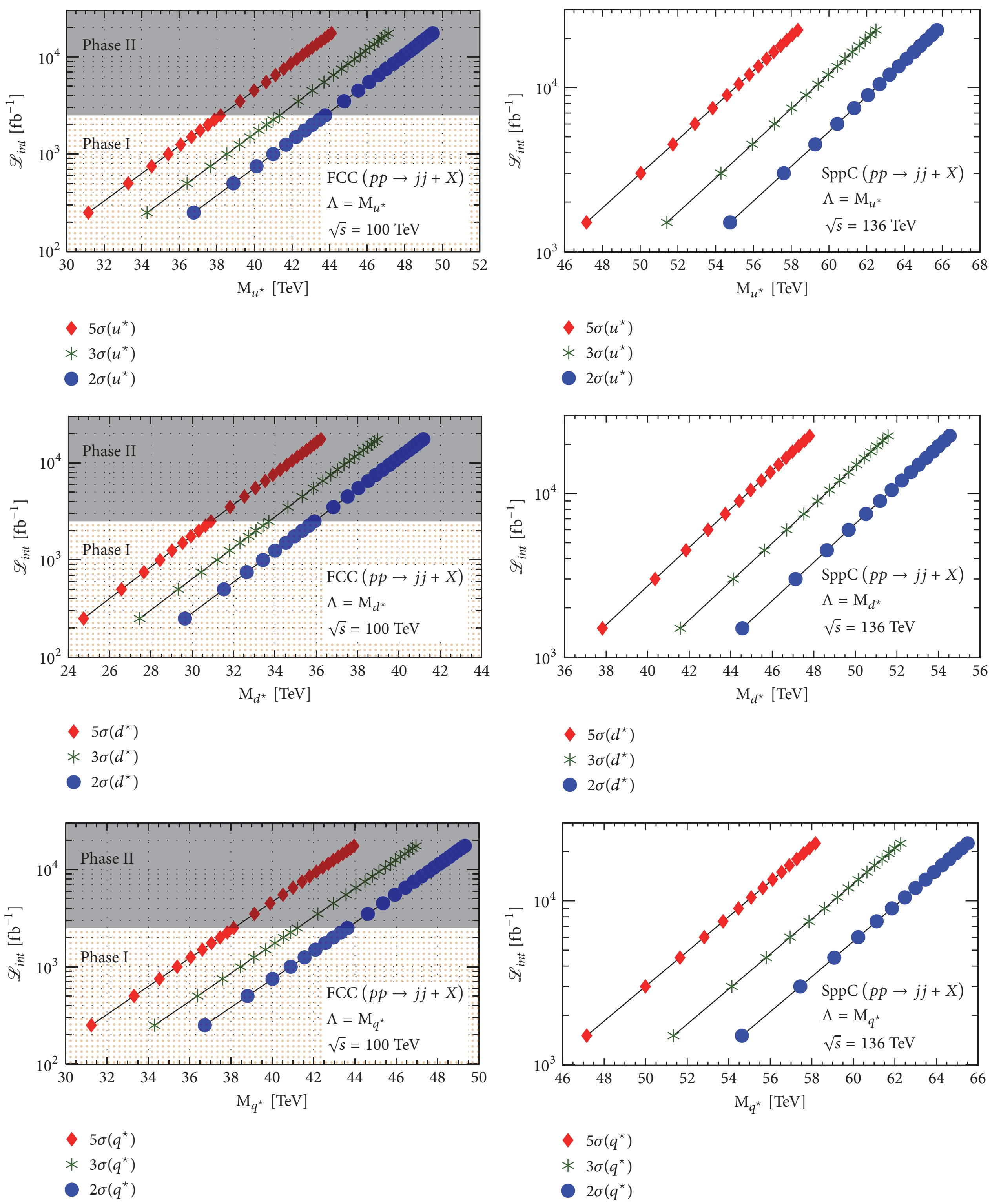

FIGURE 5: Mass dependence on luminosity at all confidence levels for the FCC (left column) and SppC (right column).

Table 3: Attainable mass limits for all three cases at FCC and SppC with corresponding final integrated luminosity values. Compositeness scale is chosen equal to excited quarks mass values.

Colliders		FCC-Phase I			FCC-Phase II			SppC		
Integrated Luminosity [fb^{-1}]		2500			17500			22500		
Significance		5σ	3σ	2σ	5σ	3σ	2σ	5σ	3σ	2σ
Excited Quark Mass [TeV]	$M_{u^\star}$	38.2	41.3	43.8	44.1	47.1	49.5	58.4	62.5	65.7
	$M_{d^\star}$	30.9	33.7	35.9	36.3	39.0	41.2	47.8	51.6	54.5
	$M_{q^\star}$	40.1	43.2	45.6	45.9	48.9	51.3	60.9	65.0	68.1

Table 4: Compositeness scale values corresponding to some selected mass quantities for all three cases at FCC with final integrated luminosity values.

	FCC ($\mathscr{L}_{int}$=17500 fb^{-1}) Compositeness Scale Λ [PeV]								
Mass [TeV]		$u^\star$			$d^\star$			$q^\star$	
	5σ	3σ	2σ	5σ	3σ	2σ	5σ	3σ	2σ
6	13.5	22.4	33.6	7.61	12.7	19.0	19.4	32.3	48.5
10	6.21	10.4	15.5	3.15	5.25	7.88	9.22	15.4	23.1
20	1.20	1.99	2.99	.489	.815	1.22	1.78	2.97	4.46
30	.311	.518	.776	.102	.171	.256	.448	.747	1.12

Table 5: Compositeness scale values corresponding to some selected mass quantities for all three cases at SppC with final integrated luminosity values.

	SppC ($\mathscr{L}_{int}$=22500 fb^{-1}) Compositeness Scale Λ [PeV]								
Mass [TeV]		$u^\star$			$d^\star$			$q^\star$	
	5σ	3σ	2σ	5σ	3σ	2σ	5σ	3σ	2σ
6	19.2	32.0	48.0	11.5	19.2	28.8	28.6	47.6	71.4
10	10.1	16.8	25.2	5.59	9.31	14.0	15.4	25.7	38.5
20	2.68	4.47	6.71	1.29	2.15	3.23	4.16	6.94	10.4
30	.993	1.66	2.48	.418	.696	1.04	1.51	2.52	3.78
40	.383	.638	.957	.139	.231	.347	.562	.936	1.41

where σ_{tot} includes signal, SM, and interference contributions. Interference terms lead to slightly higher discovery limit. Therefore, presented results in this study can be considered as a bit conservative.

Concerning the role of systematic uncertainties caused by choice of PDF, factorization and renormalization scales, analysis performed at the ATLAS and CMS experiments show that their impact is less than 1% for $q^\star \longrightarrow jj$ channel [47]. As for the efficiency of jet registration, it is nearly 100% for jets with P_T above 20 GeV [47].

In principle, compositeness scale might be quite higher than excited quark mass. If excited u and d quarks are not discovered at FCC or SppC, one can evaluate lower limits on compositeness scale. For illustration, we plot achievable compositeness scale depending on $u^\star$, $d^\star$, and $q^\star$ mass for ultimate luminosity values at both colliders in Figure 6. If it is assumed that $u^\star$ mass equals 20 TeV and it is not seen at FCC in resonant channel, according to Figure 6, this means that compositeness scale is larger than 1.2 PeV (5σ), 2.0 PeV (3σ), and 3.0 PeV (2σ). Achievable scales for other values of $u^\star$ as well as $d^\star$ and $q^\star$ (degenerate state) are presented in Table 4. Similar results for the SppC are given in Table 5.

In Figure 7, necessary luminosities for observation and discovery of 20 TeV mass excited u quark depending on compositeness scale are plotted for both energy-frontier colliders. It is seen that if $\Lambda = 1000$ TeV, FCC will observe $u^\star$ with 4500 fb^{-1} integrated luminosity and $\mathscr{L}_{int} = 12000\ fb^{-1}$ is needed for discovery, which correspond to 12 and 19.5 operation years, respectively. Concerning the SppC, it will observe $u^\star$ with 20 TeV mass within first year and discover it in 2 years if compositeness scale is equal to 1000 TeV.

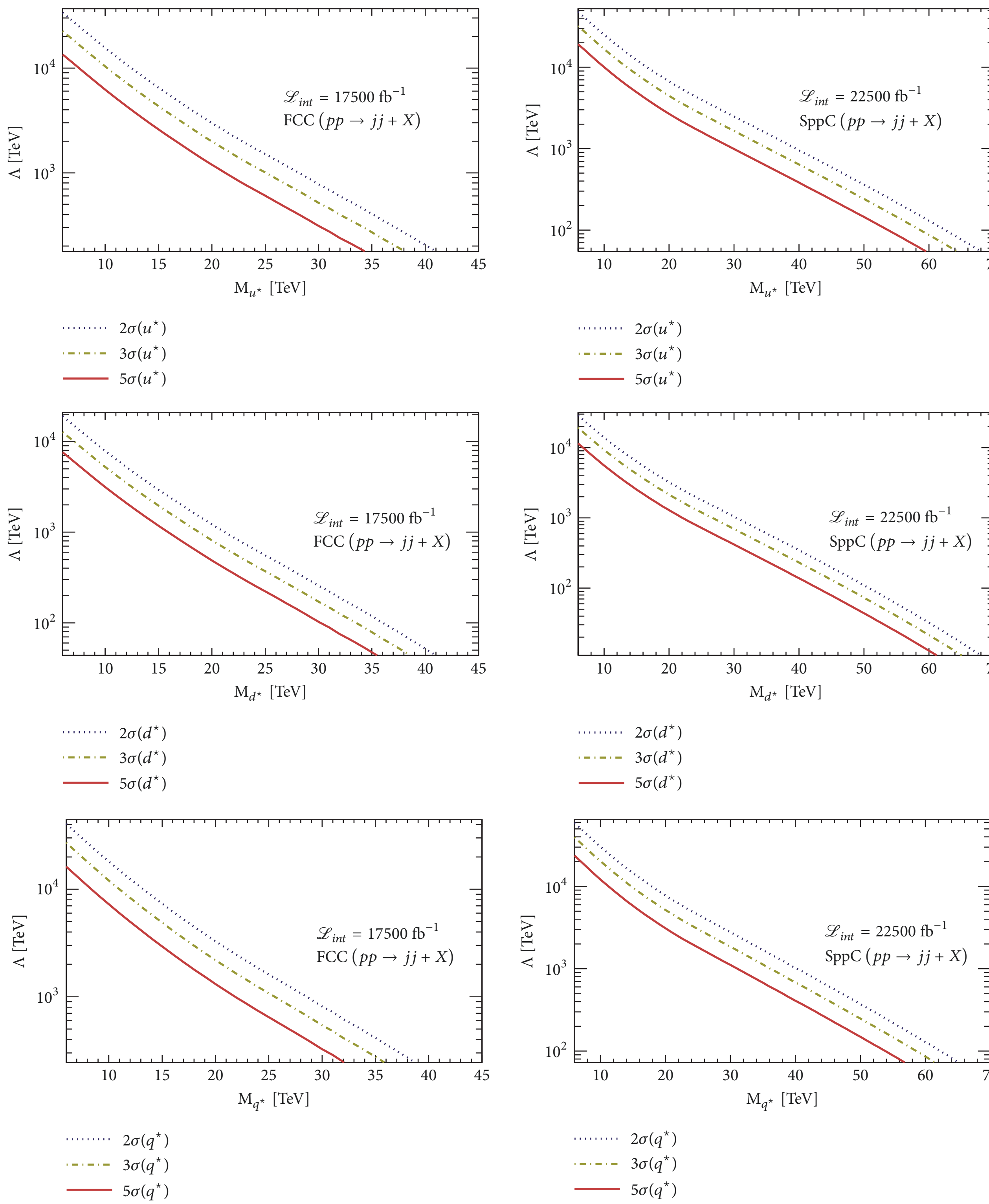

FIGURE 6: Compositeness scale dependence on $u^\star$ mass for the FCC (left column) and SppC (right column).

In conclusion, FCC and SppC have excellent potential for discovery of excited u and d quarks. If compositeness scale coincides with excited quark masses, FCC reaches $M_{u^\star}$ = 44 TeV, $M_{d^\star}$ = 36 TeV, and $M_{q^\star}$ = 46 TeV (degenerate state). Corresponding values for SppC are 58 TeV, 48 TeV, and 61 TeV, respectively. If compositeness scale is higher than excited quark masses, discovery of excited quarks will afford an opportunity to determine Λ at the same time.

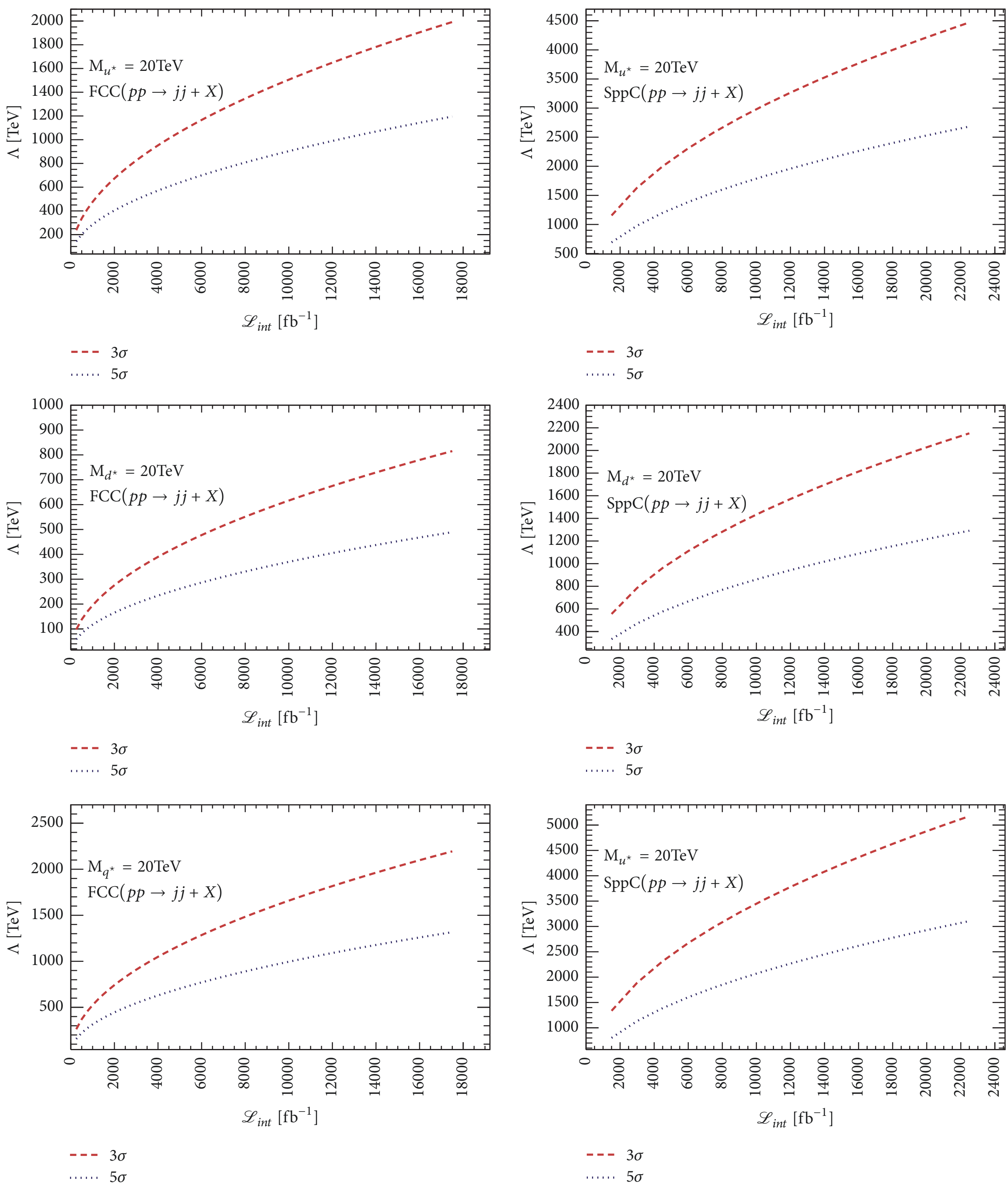

FIGURE 7: Compositeness scale-luminosity correlation plots for the FCC (left column) and SppC (right column).

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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