The quirk signal at the FASER

arXiv:2108.06748

Junle Pei (ITP, CAS)

Co-authors: Jinmian Li (Sichuan University)
Longjie Ran (Sichuan University)
Wenxing Zhang (SJTU)

Tenth workshop of the LLP Community

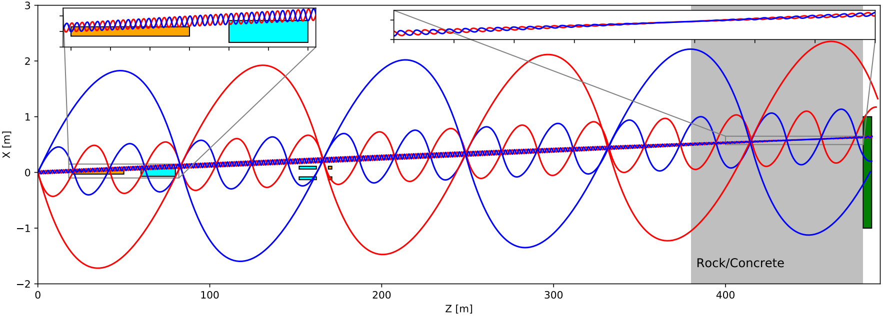
November 10, 2021

Quirk

quirk: an element particle beyond SM, which is long-lived and charged under both the SM gauge groups and a new confining SU(N) gauge group.

m_q: quirk mass. Λ: the confinement scale of the SU(N) gauge group.

$$m_q \gg \Lambda$$



Quirk motion inside materials

The quirk equation of motion (EoM) inside materials is given by

$$\frac{\partial(m\gamma\vec{v})}{\partial t} = \vec{F}_s + \vec{F}_{ext} \ , \tag{1}$$

$$\vec{F}_s = -\Lambda^2\sqrt{1-\vec{v}_\perp^2}\,\hat{s} - \Lambda^2\frac{v_\parallel \vec{v}_\perp}{\sqrt{1-\vec{v}_\perp^2}} \ , \tag{2}$$

$$\vec{F}_{\rm ext} = q\vec{v}\times\vec{B} + \frac{dE}{dx}\hat{v} \ , \tag{3}$$

where $\gamma = 1/\sqrt{1-\vec{v}^2}$, $v_\parallel = \vec{v}\cdot\hat{s}$ and $\vec{v}_\perp = \vec{v} - v_\parallel\hat{s}$ with $\hat{s}$ being a unit vector. In the centre of mass (CoM) frame, $\hat{s}$ is approximately parallel to the vector difference between positions of the two quirks (this is only true for $\Lambda^2 \gg |\vec{F}_{\rm ext}|$).

dE/dx

$$\vec{F}_{\text{ext}} = q\vec{v} \times \vec{B} + \frac{dE}{dx}\hat{v}$$

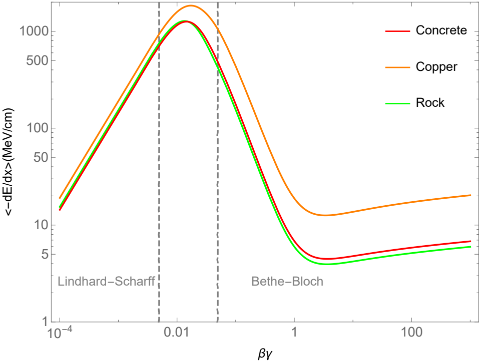


FIG. 2. The mean rates of energy loss for charged particle traveling through concrete, copper, and rock, supposing $z = 1$ and $m_e/M \ll 1$.

$\langle -dE/dx \rangle$ values between LS and BB regions are obtained by interpolation.

Infracolor glueball and electromagnetic radiations

The total energy losses due to infracolor glueball and electromagnetic radiations can be estimated:

$$E_{IC} \sim 2 \times \frac{\Lambda^2}{[100\ \text{eV}]^2} \times \Lambda \ , \tag{4}$$

$$E_{EM} \sim 1.7 \times 10^{-7} \times \alpha_{EM} \times \frac{\Lambda^4}{[100\ \text{eV}]^4}\ [\text{eV}] \ . \tag{5}$$

Both values are much smaller than the typical kinetic energy of quirk at the LHC. So it is safe to simply ignore the effects of infracolor glueball and electromagnetic radiations in our simulation.

Quirk production

In our work, we take simplified model frameworks as benchmark. The quantum number assignments for the quirks of interest under $SU(N_{\rm IC}) \times SU_C(3) \times SU_L(2) \times U_Y(1)$ are given as

$$\begin{aligned}
\tilde{\mathcal{D}} &= (N_{\rm IC}, 3, 1, -1/3) \ , \\
\tilde{\mathcal{E}} &= (N_{\rm IC}, 1, 1, -1) \ , \\
\mathcal{D} &= (N_{\rm IC}, 3, 1, -1/3) \ , \\
\mathcal{E} &= (N_{\rm IC}, 1, 1, -1) \ ,
\end{aligned}$$

where we take $N_{\rm IC} = 2$ for the infracolor gauge group. $\tilde{\mathcal{D}}$ and $\tilde{\mathcal{E}}$ have spin zero, $\mathcal{D}^c$ and $\mathcal{E}^c$ are fermions.

Quirk production

- The effects of initial state radiation (ISR), final state radiation (FSR), and the hadronization of colored final state are simulated with Pythia8.
- $R_{\text{FASER2}}/d_{\text{IP-FASER}} \sim 1\ \text{m}/480\ \text{m} \sim 0.002$.

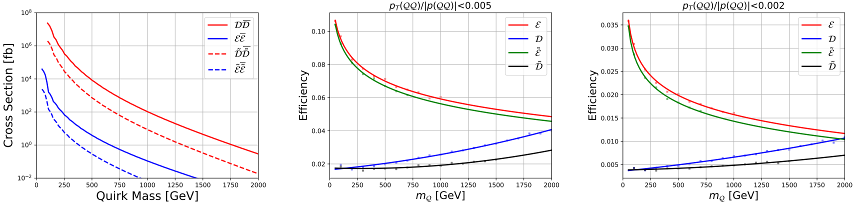


FIG. 3. The leading order production cross sections for the quirk pair production at the 13 TeV LHC (left panel). The fraction of events that have $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.005$ (middle panel) and 0.002 (right panel) for different quirks and their masses.

Configurations between the ATLAS IP and FASER

Component	x, y, R[m]	z[m]
TAS (Copper)	$R > 0.017$	19−20.8
D1 (3.5 T)	$R < 0.06$	59.92−84.65
TAN (Copper)	$\lvert x\rvert < 0.047,\ -0.538 < y < 0.067$	140−141
D2 (3.5 T)	$(x \pm 0.093)^2 + y^2 < 0.08$	153.48−162.93
Concrete	$R > 0$	380−390
Rock	$R > 0$	390−480
Tracker of FASER	$\lvert x\rvert < 0.16,\ \lvert y\rvert < 0.16$	$\lvert z - 481.6/482.8/484.0\rvert < 0.041$
Tracker of FASER 2	$\lvert x\rvert < 1,\ \lvert y\rvert < 1$	$\lvert z - 485.1/486.3/487.5\rvert < 0.041$

TABLE I. The configurations of infrastructures between the ATLAS IP and the FASER (FASER 2) detector. The ATLAS IP is the ordinate origin and the transverse distance is $R = \sqrt{x^2 + y^2}$.

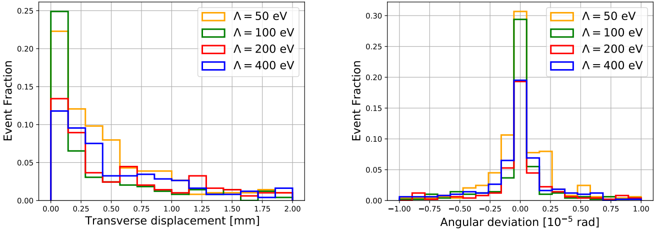


FIG. 4. The distributions of the transverse displacement and the angular deviation of the total momentum of the quirk-pair system at the first crossing point after the quirk pair travels across D2 between the cases when the influence of D1 and D2 are considered or not. $m_Q = 300$ GeV.

Signal efficiency

The odd tracks induced by the quirk pair can be identified easily in the tracker of FASER (FASER 2) because the background rate is negligible.

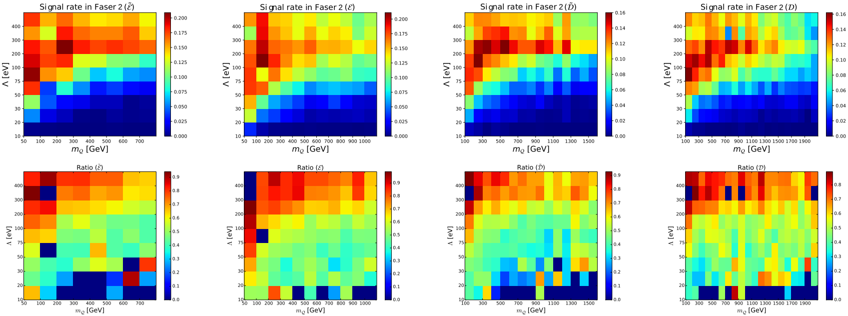


FIG. 5. Upper panels: the fractions of quirk events (in event sample with $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.005$) that have at least one quirk entering the tracker of FASER 2. Lower panels: among the events which can enter the tracker of FASER 2, the ratio between the number of events with $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.002$ and $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.005$ in initial state. Quirks with four different quantum numbers as given in Eq. II.1-Eq. II.4 are considered.

Dependence of the signal efficiency on quirk mass

- For quirk production at the LHC, heavier quirk has lower velocity, thus suffers from stronger ionization force.
- For a heavy quirk-pair system with initial momentum pointing to the tracker of FASER 2, the ionization force will continually change the moving direction and make the quirk pair system fall outside the FASER 2 tracker eventually.
- The signal efficiency becomes lower for heavier quirk.

Dependence of the signal efficiency on Λ

In cases with $|\vec{F}_s| \gg |\vec{F}_{\rm ion}|$, the characteristic oscillation amplitude of the quirk pair in the lab frame can be expressed as

$$L = \frac{\mathcal{R}}{\rho}\ell_c \ , \tag{6}$$

where

$$\ell_c = 2\ \text{cm}(\sqrt{1+\rho^2}-1)\frac{m}{[100\ \text{GeV}]}\frac{[\text{keV}]^2}{\Lambda^2}\ , \tag{7}$$

$$\rho = \sqrt{\frac{(E_1+E_2)^2-(\vec{P}_1+\vec{P}_2)^2}{4m^2}-1}\ , \tag{8}$$

$$\mathcal{R} = \frac{|\vec{P}_1 \times \vec{P}_2|}{m|\vec{P}_1+\vec{P}_2|}\ . \tag{9}$$

$\vec{P}_1$ (E_1) and $\vec{P}_2$ (E_2) are initial momenta (energies) of two quirks in the lab frame. The ℓ_c is half of the largest distance between the two quirks during the oscillation in the CoM frame. The L stands for half the width of the belt that can cover the trajectories of the two quirks in the lab frame.

Dependence of the signal efficiency on Λ

- When the Λ is sizable such that the oscillation amplitude $L \ll \mathcal{O}(1)$ m, only the quirk pairs satisfying $p_T(\mathcal{Q}\mathcal{Q})/|p(\mathcal{Q}\mathcal{Q})| < 0.002$ can enter the FASER 2 tracker.
- In the small Λ region where $L \gtrsim \mathcal{O}(10)$ m, many quirk events will bypass the FASER 2 detector even though the $p_T(\mathcal{Q}\mathcal{Q})/|p(\mathcal{Q}\mathcal{Q})| < 0.002$ condition is fulfilled, leading to very low signal efficiency.
- The signal efficiency is highest in the moderate Λ region where $L \sim \mathcal{O}(1)$ m. In this region, beside the events with $p_T(\mathcal{Q}\mathcal{Q})/|p(\mathcal{Q}\mathcal{Q})| < 0.002$, others with $p_T(\mathcal{Q}\mathcal{Q})/|p(\mathcal{Q}\mathcal{Q})| \gtrsim 0.002$ will also enter the FASER 2 tracker due to the sizable oscillation amplitudes.

Sensitivity

The total number of quirk events in the FASER (FASER 2) can be calculated by

$$N_{\mathsf{sig}} = \sigma \times \epsilon_{\mathrm{fid}} \times \epsilon_{0.005} \times \mathcal{L}. \tag{10}$$

- σ is the quirk production cross section at the 13 TeV LHC.
- ϵ_{fid} corresponds to the efficiency of selecting events with $p_T(\mathcal{Q}\mathcal{Q})/|p(\mathcal{Q}\mathcal{Q})| < 0.005$ in quirk pair production.
- $\epsilon_{0.005}$ is signal efficiency of events with $p_T(\mathcal{Q}\mathcal{Q})/|p(\mathcal{Q}\mathcal{Q})| < 0.005$.
- The integrated luminosity $\mathcal{L}$ is taken as 150 (3000) fb^{-1} for FASER (FASER 2).

Sensitivity

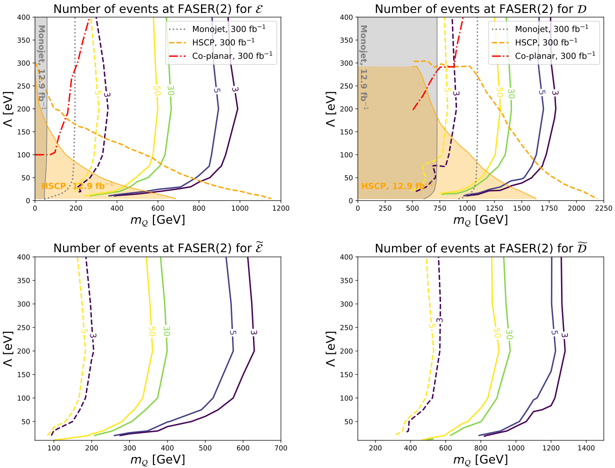


FIG. 6. Contours of the number of quirk events that can reach the tracker of FASER (FASER 2) in the $m_{\mathcal{Q}}$ versus Λ plane for integrated luminosity of 150 (3000) fb^{-1}, which are dashed (solid). For two fermionic quirks ($\mathcal{E}$ and $\mathcal{D}$), the projected bounds from Heavy Stable Charged Particle (HSCP) search [10], mono-jet search [10], and coplanar search [22] (the exclusion limits are taken) are shown by dotted line, dashed line, and dash-dotted line, respectively. Those bounds are provided in Ref. [22].

Conclusion

- The ionization effects in different materials are treated carefully when solving the quirk EoM. The Gaussian distribution of the ionization energy loss for a charged quirk in the BB region is also taken into account.
- For an integrated luminosity of 3000 (150) fb^{-1}, given negligible background, the FASER 2 (FASER) will be able to exclude the $\mathcal{E}$, $\mathcal{D}$, $\tilde{\mathcal{E}}$ and $\tilde{\mathcal{D}}$ quirks with mass below 990 (360) GeV, 1800 (900) GeV, 630 (200) GeV and 1270 (580) GeV, respectively, when $\Lambda \gtrsim \mathcal{O}(150)$ eV. The FASER 2 is much more sensitive than other searches when $\Lambda \gtrsim \mathcal{O}(100)$ eV, especially for the color neutral $\mathcal{E}$.