Searching for Quirk Signal at the LHC

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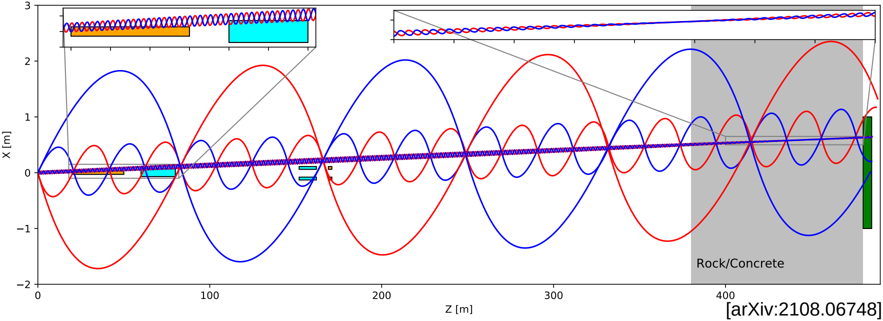
Quirk

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.

$$m_q \gg \Lambda$$



[arXiv:2108.06748]

Quirk

Λ plays an important role in the phenomenology of quirk signal inside tracker.

$\Lambda \gtrsim \mathcal{O}(10)$ MeV: intensive oscillations; photon and hidden glueball radiation; annihilating promptly.
$\Lambda \in [10$ keV, 10 MeV$]$: The electric neutral quirk-pair system will leave a straight line inside the tracker.
$\Lambda \in [100$ eV, 10 keV$]$: macroscopic oscillation amplitude; Each quirk trajectory can not be simply reconstructed as a helix.
$\Lambda \lesssim \mathcal{O}(10)$ eV: two helical trajectories.

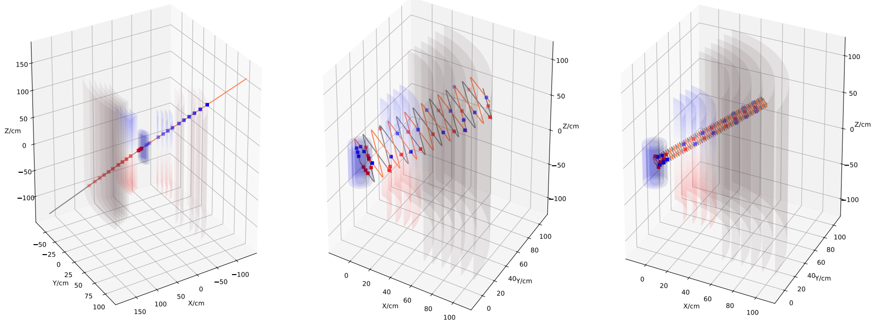


FIG. 1. Trajectories of two quirks inside the CMS tracker, with the confinement scale chosen as 1 eV, 1 keV and 2 keV (from left to right). The quirk system in different panels have common initial momentum and the quirk mass is 100 GeV. The cylinder segments indicate the barrel layers. [arXiv:1911.02223]

Motivations for quirk signal

- New SU(N) gauge symmetries are introduced in many BSM models such as folded supersymmetry, minimal neutral naturalness model, quirky little Higgs, twin Higgs and so on.
- Traditional analyses failed to find any new physics signals beyond the standard model (BSM) from data collected by LHC at its Run-1 and Run-2.
- In quirk scenario with $\Lambda \in$ [100 eV, 10 keV], the quirk pair oscillation amplitude can be macroscopic ($\sim$ cm) and hits caused by the non-helical trajectories through tracking layers will be completely ignored in conventional event reconstruction at the LHC.

Quirk motion inside materials

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

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

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

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

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 $\Lambda^2 \gg |\vec{F}_{\text{ext}}|$).

Numerical solutions of the EoM

time steps: ϵ_i

In the lab frame, four momenta of the two quirks are denoted by $(E_i, \vec{P}_i)$ and space time position by $(t_i, \vec{r}_i)$ with $i = 1, 2$. In the CoM frame, $\hat{s}$ is approximately parallel to the vector difference between positions of the two quirks. In order to ensure the simultaneity in the CoM frame, the following condition needs to be fulfilled

$$t_1 - t_2 = \vec{\beta} \cdot (\vec{r}_1 - \vec{r}_2) \tag{4}$$

with $\vec{\beta} = (\vec{P}_1 + \vec{P}_2)/(E_1 + E_2)$. As a result, the time moving step $\epsilon_i (\ll 1)$ in solving each quirk EoM should satisfy

$$\begin{aligned}\epsilon_1[1 - \vec{v}_1 \cdot \vec{\beta} - \frac{\vec{r}_1 - \vec{r}_2}{E_1 + E_2} \cdot (\vec{F}_1 - \vec{v}_1 \cdot \vec{F}_1 \vec{\beta})] = \\ \epsilon_2[1 - \vec{v}_2 \cdot \vec{\beta} - \frac{\vec{r}_2 - \vec{r}_1}{E_1 + E_2} \cdot (\vec{F}_2 - \vec{v}_2 \cdot \vec{F}_2 \vec{\beta})].\end{aligned} \tag{5}$$

$\hat{s}$ in the lab frame

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

$v_\parallel = \vec{v}\cdot\hat{s}$, $\vec{v}_\perp = \vec{v} - v_\parallel \hat{s}$.

By boosting the infracolor force in the CoM frame to the lab frame, we find $\hat{s}$ in the lab frame are given by the unit vectors of

$$\vec{r}_{s1} = (\vec{r}_1 - \vec{r}_2) - (t_1 - t_2)\vec{v}_1 \ , \tag{6}$$

$$\vec{r}_{s2} = (\vec{r}_2 - \vec{r}_1) - (t_2 - t_1)\vec{v}_2 \ , \tag{7}$$

for each quirk respectively.

dE/dx

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

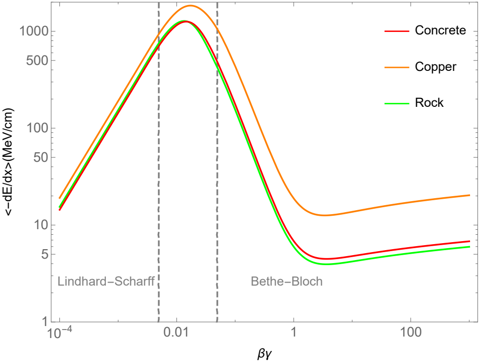


FIG. 2. The mean rates of energy loss for charged particle traveling through concrete, copper, and rock, supposing $z = 1$ and $m_e/M \ll 1$. [arXiv:2108.06748]

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

Infracolor glueball and electromagnetic radiations

The energy loss due to infracolor glueball and electromanetic radiations in a crossing time t_p are estimated as $\Delta E_{IC} = \epsilon \Lambda_{IC}$ ($\epsilon \sim \mathcal{O}(0.1)$) and $\Delta E_{EM} = \alpha_{EM}/t_p$.

The crossing time of the quirk pair is

$$t_p = 0.132\sqrt{\left(\frac{E_1 + E_2}{2m}\right)^2 - \frac{1}{1-\beta^2}}\,\frac{m}{[100\ \mathrm{GeV}]}\,\frac{[\mathrm{keV}]^2}{\Lambda^2}[\mathrm{ns}]\ , \qquad (8)$$

corresponding to the typical number of crossing (from IP to FASER)

$$N_{\text{crossing}} = \frac{120}{\beta\sqrt{(\frac{E_1+E_2}{2m})^2 - \frac{1}{1-\beta^2}}}\,\frac{[100\ \text{GeV}]}{m}\,\frac{\Lambda^2}{[\text{keV}]^2} \sim 20 \times \frac{\Lambda^2}{[100\ \text{eV}]^2}\ . \qquad (9)$$

Infracolor glueball and electromagnetic radiations

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

$$E_{IC} \sim 2 \times \frac{\Lambda^2}{[100\ \text{eV}]^2} \times \Lambda\ , \tag{10}$$

$$E_{EM} \sim 1.7 \times 10^{-7} \times \alpha_{EM} \times \frac{\Lambda^4}{[100\ \text{eV}]^4}\ [\text{eV}]\ . \tag{11}$$

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 signal inside the tracker

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- The trajectories of two quirks are located near a plane within a distance of $d \propto \frac{mq|\vec{B}|}{\Lambda^4}$.
- The velocities of two quirks can be small when they are the farthest from each other, which will lead to large ionization energy loss (dE/dx) when travelling through the tracker layers.
- The large missing transverse energy (E_T^{miss}) of the quirk pair will lead to dozens of hits when two quirks travel out of the tracker transversely.

By using the information of dE/dx, a dedicated algorithm to separate the quirk hits from SM particles hits inside tracker has been designed.

The quirk signal at the FASER

Quirk production

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

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

where we take $N_{\text{IC}} = 2$ 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.
- $R_{\text{FASER2}}/d_{\text{IP-FASER}} \sim 1\text{ m}/480\text{ m} \sim 0.002$.

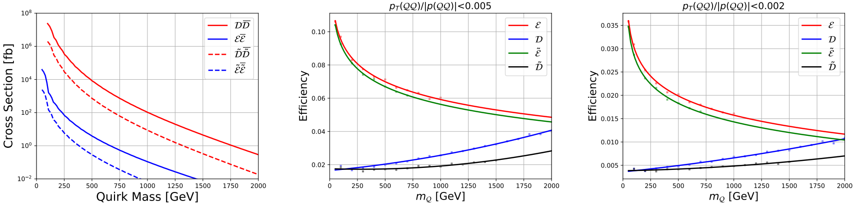

FIG. 3. The leading order production cross sections for the quirk pair production at the 13 TeV LHC (left panel). The fraction of events that have $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.005$ (middle panel) and 0.002 (right panel) for different quirks and their masses. [arXiv:2108.06748]

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 $R = \sqrt{x^2 + y^2}$.

Signal efficiency

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

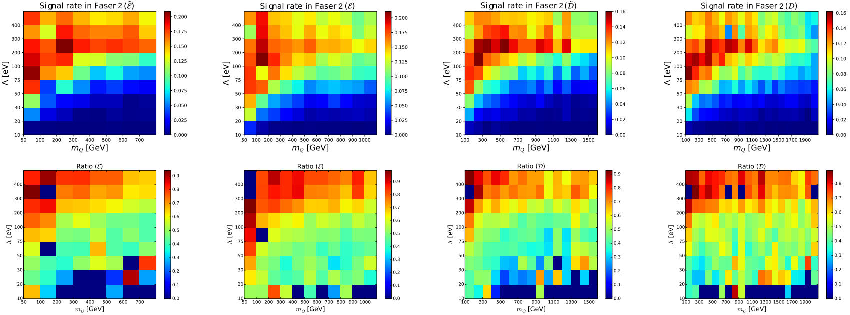

FIG. 5. Upper panels: the fractions of quirk events (in event sample with $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.005$) that have at least one quirk entering the tracker of FASER 2. Lower panels: among the events which can enter the tracker of FASER 2, the ratio between the number of events with $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.002$ 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. [arXiv:2108.06748]

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

$$L = \frac{\mathcal{R}}{\rho} \ell_c \ , \tag{12}$$

where

$$\ell_c = 2\ \text{cm}(\sqrt{1+\rho^2} - 1)\frac{m}{[100\ \text{GeV}]}\frac{[\text{keV}]^2}{\Lambda^2}\ , \tag{13}$$

$$\rho = \sqrt{\frac{(E_1+E_2)^2 - (\vec{P}_1+\vec{P}_2)^2}{4m^2} - 1}\ , \tag{14}$$

$$\mathcal{R} = \frac{|\vec{P}_1 \times \vec{P}_2|}{m|\vec{P}_1 + \vec{P}_2|}\ . \tag{15}$$

$\vec{P}_1$ (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

$$N_{\text{sig}} = \sigma \times \epsilon_{\text{fid}} \times \epsilon_{0.005} \times \mathcal{L}. \tag{16}$$

- 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

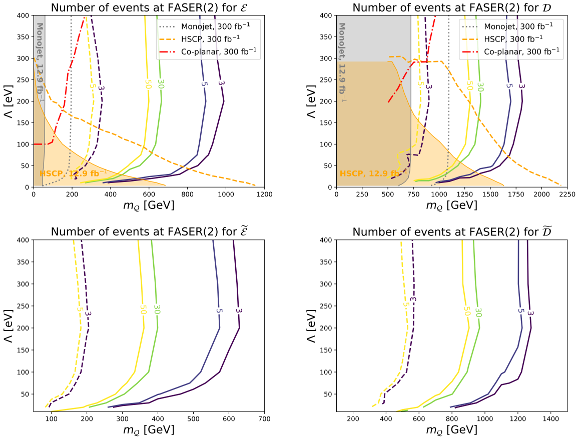

FIG. 6. Contours of the number of quirk events that can reach the tracker of FASER (FASER 2) in the $m_{\mathcal{Q}}$ versus Λ plane for integrated luminosity of 150 (3000) fb^{-1}, which are dashed (solid). For two fermionic quirks ($\mathcal{E}$ and $\mathcal{D}$), the projected bounds from Heavy Stable 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]. [arXiv:2108.06748]

Conclusion

- We provide the procedures of numerically solving the equations of quirk motion. The ionization effects in different materials are treated carefully when solving the quirk EoM.
- 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 $\mathcal{E}$.