Probing quirk particle at the LHC far detectors

Jinmian Li (李金勉)



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$30\mathrm{th}$ Mini-workshop on the frontier of LHC

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with Jonathan Feng, Xufei Liao, Jian Ni, Junle Pei

- A TeV scale BSM: the quirk scenario Quirk production at hadron collider Quirk pair evolution
- ² The FASER detector and Future Far detectors
- ³ Timing analyses and sensitivity reach

Introduction to quirk particle

► Particles with $SM \otimes SU(N)_{IC}$ and $m_Q \gg \Lambda_{IC}$ Gauge flux tube:

$$\ell \sim \mathcal{O}(1) \text{ cm} \times (\frac{1 \text{ keV}}{\Lambda})^2 \times (\frac{m_Q}{100 \text{ GeV}})$$

. $\Lambda < 10$ eV: string tension is negligible compared to the magnetic force HSCP.

- . $\Lambda \in [100 \text{ eV}, 1 \text{ keV}]$: quirk track dropped in event reconstruction E_T^{miss} .
- . $\Lambda \in [10 \text{ keV}, 10 \text{ MeV}]$: oscillation amplitude of the quirk is microscopic Ultra-boosted, high ionization.
- . $\Lambda > 10$ MeV: the quirk pair system will oscillate intensively after production and annihilate into SM particles quickly resonance.

The quirk production at the LHC

Representation under $SU(N_{\rm IC}) \times SU_C(3) \times SU_L(2) \times U_Y(1)$

$$\begin{split} & \tilde{\mathcal{D}}: (N_{\mathrm{IC}}=2,3,1,-1/3), \quad \tilde{\mathcal{E}}: (N_{\mathrm{IC}}=2,1,1,-1) \\ & \mathcal{D}: (N_{\mathrm{IC}}=2,3,1,-1/3), \quad \mathcal{E}: (N_{\mathrm{IC}}=2,1,1,-1) \end{split}$$



13 TeV LHC



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Quirk-pair in the forward direction



Jinmian Li (李金勉) (SCU)

The quirk equation of motion



$$\frac{\partial(m\gamma\vec{v})}{\partial t} = \vec{F}_s + \vec{F}_{ext}$$
$$\vec{F}_s = -\Lambda^2 \sqrt{1 - \vec{v}_{\perp}^2} \hat{s} - \Lambda^2 \frac{v_{\parallel} \vec{v}_{\perp}}{\sqrt{1 - \vec{v}_{\perp}^2}}$$
$$\vec{F}_{ext} = q\vec{v} \times \vec{B} - \langle \frac{dE}{dx} \rangle \hat{v}$$
$$t_1 - t_2 = \vec{\beta} \cdot (\vec{r}_1 - \vec{r}_2), \ \beta = \frac{p_1 - p_2}{E_1 - E_2}$$

$$m_{\mathcal{Q}} = 800 \text{ GeV}$$

. $\vec{p}_1 = (-132.146, 121.085, 1167.35)$ GeV

.
$$\vec{p}_2 = (136.381, -123.865, 2061.56)$$

GeV

.
$$\Lambda = 50$$
 eV, 100 eV, 400 eV

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Radiation, decay and annihilation



$$(\tau^{\text{tot}})^{-1} = (\tau^{\text{IC}})^{-1} + (\tau^{\text{EM}})^{-1} + (\tau^{\text{QCD}})^{-1}$$

Each case modeled by assumption that every period of quirk oscillation the quirk-pair has a probability ϵ/ϵ' to emit infracolor glueballs / QCD hadron with the energy of $\Lambda / \Lambda_{\rm QCD}$.



Infracolor glueball radiation: dE/dt = - ϵΛ_{IC}/T
QCD hadron radiation: dE/dt = - ϵ'Λ_{QCD}/T
τ = ∫(dE)/(dE/dt)
ϵ = 0.1, ϵ' = 0.01
Electromagnetic radiation (Larmor formula) : dE/dt = - 16πQ²/2 α_{EM} a²

Quirk pair annihilation

Decay width of quirk-pair in the ground state

$$\Gamma(B \to X) = \sigma v(Q\bar{Q} \to X) \times |\psi(0)|^2$$



- . The ground state wave function $\psi(0)$ is calculated by solving the stationary Schrodinger equation with a Coulombic potential $V(r)=-\alpha_{\rm IC}/r$
- . $m_{\mathcal{Q}} \sim \mathcal{O}(100)$ GeV and $\Lambda \in [\text{keV}, \text{MeV}]$, the $|\psi(0)| \sim \mathcal{O}(10)$
- . Annihilation cross section in the CoM frame

$$\sigma v(\mathcal{Q}\bar{\mathcal{Q}} \to g'g') = \begin{cases} \frac{\pi \alpha_{\mathrm{IC}}^2(N_{\mathrm{IC}}^2 - 1)}{4m_{\mathcal{Q}}^2 N_C N_{\mathrm{IC}}} & \text{for fermion} \\ \frac{\pi \alpha_{\mathrm{IC}}^2(N_{\mathrm{IC}}^2 - 1)}{2m_{\mathcal{Q}}^2 N_C N_{\mathrm{IC}}} & \text{for scalar} \end{cases}$$

. Quirk-pair bounds state decays promptly once settles into the ground state

FASER detector



Newly proposed small ($\sim 0.05 \text{m}^3$) and inexpensive ($\sim 2\text{M}$ \$) experiment detector placed a few hundred meters downstream away from the ATLAS IP. Start taking LHC collision data in 2022.

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Future Forward Facility



MATHUSLA experiment



- The track resolution $\sigma(x) = 3$ cm.
- ▶ Dimension along y-axis: [-20,20] m.

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Quirk@LHC

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Two timing analyses

Time difference in the front and back scintilla-Arrival time at the timing scintillator (Delayedtor (Slow Track analysis) Track analysis)

- . A signal is detected that passes through the timing scintillator and the trackers.
- . The signal in the timing scintillator is outside the [-3 ns, 3 ns] muon timing window.
- . The signal in the trackers is two tracks that are separated by more than 16 $\mu \rm m$ in the vertical direction.
- . The momentum of each track is greater than 100 ${\rm GeV}$

- . A signal is detected that passes through the front and back scintillators and the trackers.
- . The time difference of the hits in the front and back scintillators is more than 2 ns greater than what it would be for particles traveling at the speed of light.
- . The signal in the trackers is two tracks that are separated by more than 16 μm in the vertical direction.
- . The momentum of each track is greater than 100 $\,{\rm GeV}$



Efficiencies of timing analyses (FASER2)

On event sample with $p_T(\mathcal{QQ})/|p(\mathcal{QQ})| < 0.005, \ \epsilon = 0.1, \ \epsilon' = 0.01$



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Limits -A comparison study



- ▶ Luminosity: FASER (300 fb⁻¹); FASER2 and MATHUSLA (3000 fb⁻¹)
- ▶ Mono-jet search, Heavy stable charged particle, Out of time decay

- We establish a comprehensive framework to discribe the quirk production and evoluation at the LHC
 - ▶ There are high fraction of quirk events in the foward direction
 - Ionization energy loss, radiation of soft particles, and annihibilition are important in the quirk evolution.
- ▶ FASER and other Forward derectors can supplement the LHC main detectors in quirk search
 - Forward detectors are particularly useful for colored neutral quirk (neutral natureness)



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