

# Probing quirk particle at the LHC forward detectors

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对撞机上新物理寻找

南京大学·苏州校区

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

# Outline

- 1 The quirk particle: theory and collider signature
- 2 The quirk production and evolution
  - Kinematic features at the LHC
  - Interactive propagation
  - Ionization energy loss in medium
  - Radiative energy loss and annihilation
- 3 The quirk search at the forward detectors
  - Signal characteristics and muon background estimation
  - Timing analyses at the FASER(2) detectors

# The quirk scenario

Particles with  $SM \otimes SU(N)_{IC}$  and  $m_Q \gg \Lambda_{IC}$

Theoretical foundation:

- ▶ **Neutral naturalness:**  $\Delta m_H^2 \sim -\frac{3y_t^2}{8\pi^2} \Lambda_{UV}^2 + \frac{N_{IC} \lambda_{partner}}{8\pi^2} \Lambda_{UV}^2$
- ▶ **Folded susy:** top squark with same electroweak charge but dark  $SU(3)$
- ▶ **Twin Higgs:** twin top quark with SM electroweak charges but a mirror/twin  $SU(3)$  color.

Gauge flux tube:

Nambu-Goto action and linear potential ( $\sigma = \Lambda^2$ )

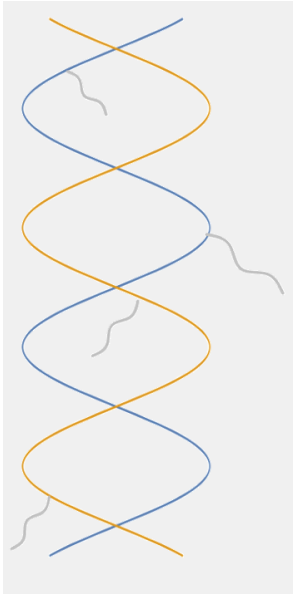
$$S = -m_Q \sum_{i=1}^2 \int d\tau_i - \sigma \int r dt + S_{\text{ext}}$$



The oscillation amplitude

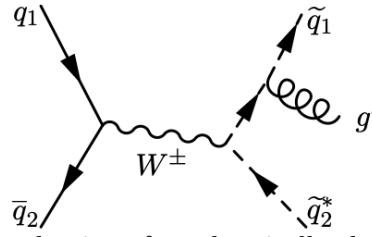
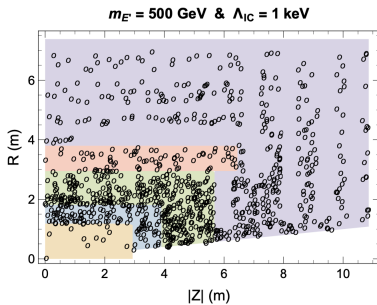
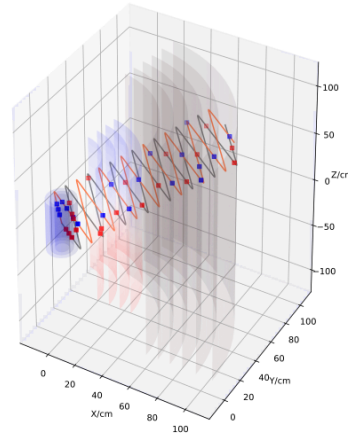
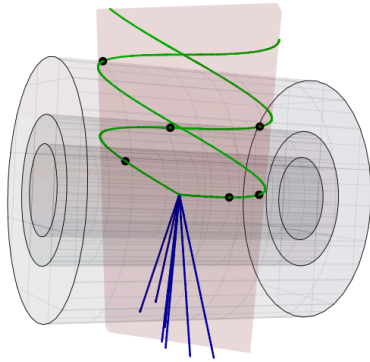
$$\ell \sim \mathcal{O}(1) \text{ cm} \times \left(\frac{1 \text{ keV}}{\Lambda}\right)^2 \times \left(\frac{m_Q}{100 \text{ GeV}}\right)$$

# The quirk particle signature – generic searches



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

# The quirk particle signature – specific searches



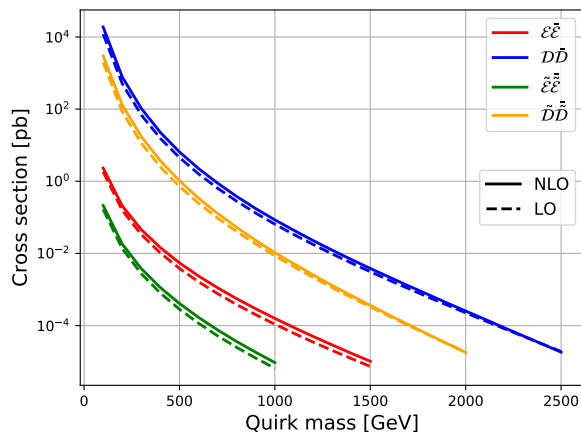
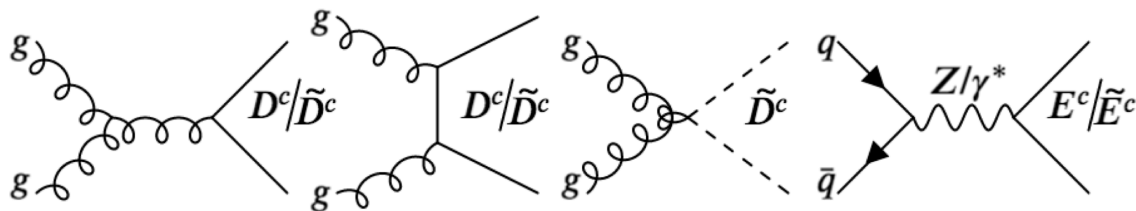
- ▶ Co-planar hits[1708.02243]
- ▶ Ionization energy loss in tracker[1911.02223]
- ▶ Out of time decay[1811.08903]
- ▶ Resonance + Displaced glueball[2504.02940]
- ▶ Soft-unclustered-energy patterns[2506.11192]
- ▶ **Far detectors:** (FASER, LHCb, CODEX, MATHUSLA,...) [2311.15486,2601.09023,...]

# The quirk production at the LHC

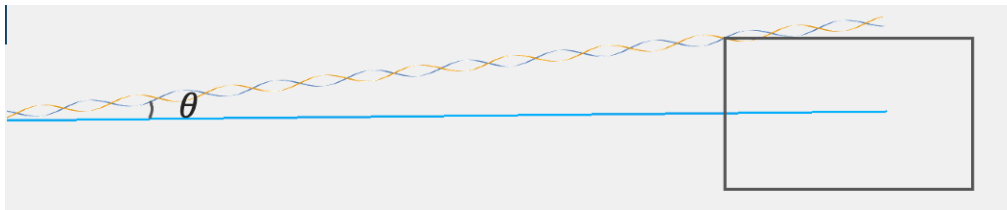
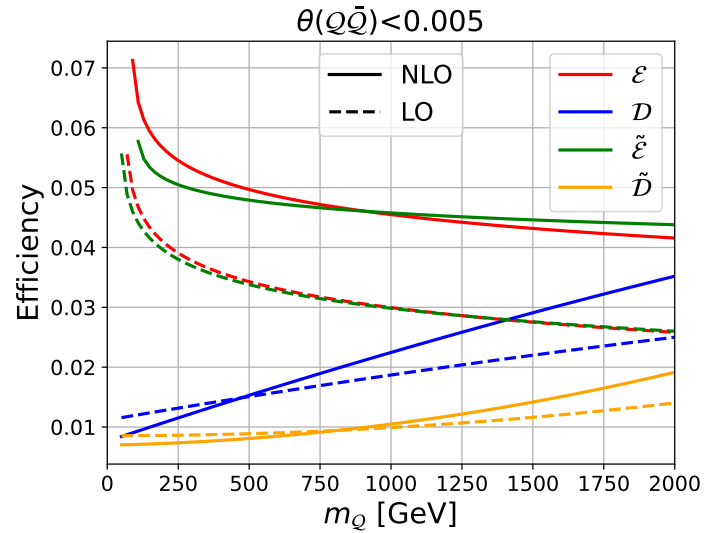
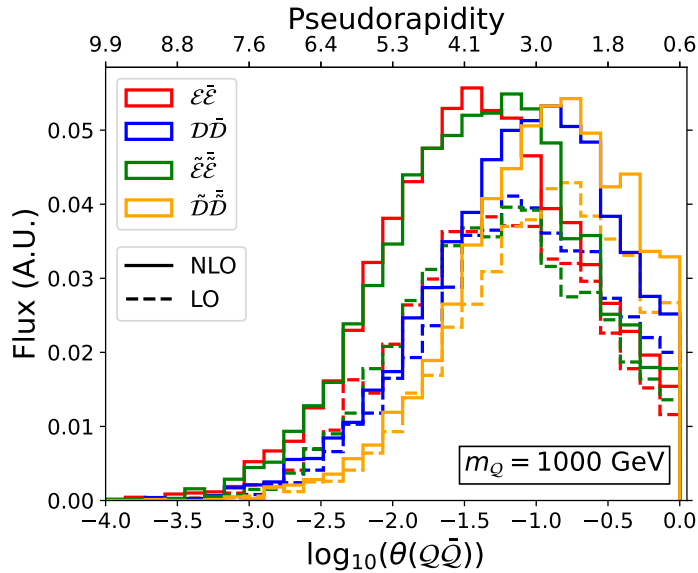
Representation under  $SU(N_{IC}) \times SU_C(3) \times SU_L(2) \times U_Y(1)$

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

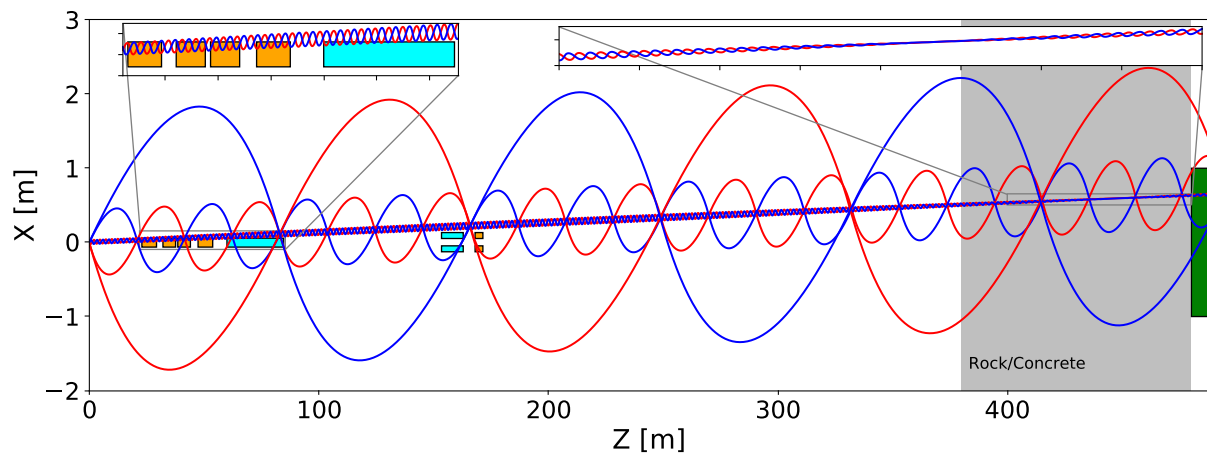
$$D : (N_{IC} = 2, 3, 1, -1/3), \quad \mathcal{E} : (N_{IC} = 2, 1, 1, -1)$$



# Quirk-pair in the forward direction



# The quirk equation of motion



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

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

$$\vec{F}_{\text{ext}} = q\vec{v} \times \vec{B} - \left\langle \frac{dE}{dx} \right\rangle \hat{v}$$

- $m_Q = 800 \text{ GeV}$
- $\vec{p}_1 = (-132.146, 121.085, 1167.35) \text{ GeV}$
- $\vec{p}_2 = (136.381, -123.865, 2061.56) \text{ GeV}$
- $\Lambda = 50 \text{ eV}, 100 \text{ eV}, 400 \text{ eV}$

# The Time Simultaneity and Difficulty in GEANT4

## The Physics Challenge

- ▶ Sting is straight in c.m. frame.
- ▶ External forces continuously change the c.m. frame.
- ▶ **Loss of simultaneity and collineation** in the lab frame.

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

## The GEANT4 Challenge

- ▶ GEANT4 transports particles **independently**.
- ▶ But  $Q\bar{Q}$  is a highly **coupled two-body system**.
- ▶ EoMs rely on the spatial separation and shared force.

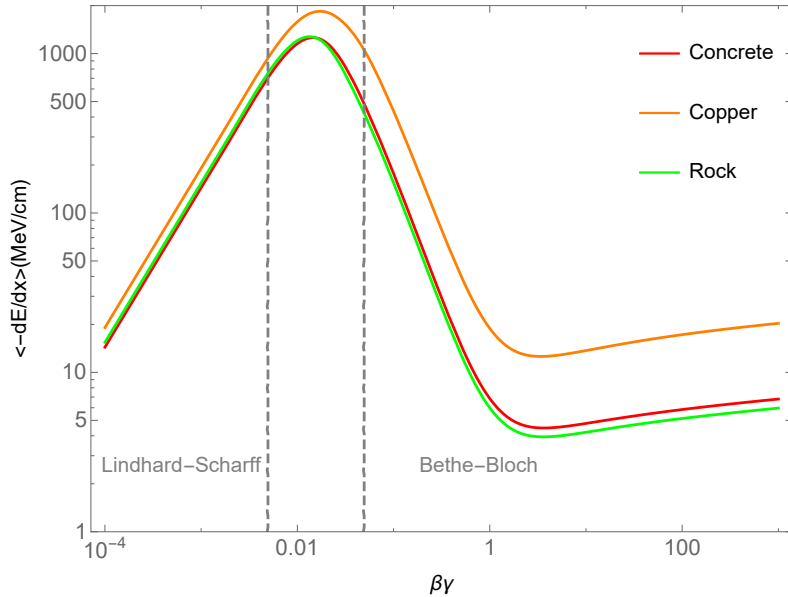
## Workaround & Limitations: “Ping-Pong” Stepping

**Method (G4UserStackingAction):** Quirk  $A$  takes a step  $\rightarrow$  updates string state  $\rightarrow$  put  $A$  to waiting stack  $\rightarrow$  Quirk  $B$  takes a step ... and repeats.

### The Heavy Price:

- ▶ **Low Efficiency:** Millions of stack push/pops per event.
- ▶ **Limited Precision:** Assumes string force is *constant* over a step.
- ▶ **Instability:** Needs complex interventions to keep tracks synchronized.

# Ionization energy loss for charged quirk



- Bethe-Bloch formula

$$\left\langle -\frac{dE}{dx} \right\rangle_{\text{BB}} = K\rho z^2 \frac{Z}{A} \frac{1}{\beta^2} \times \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

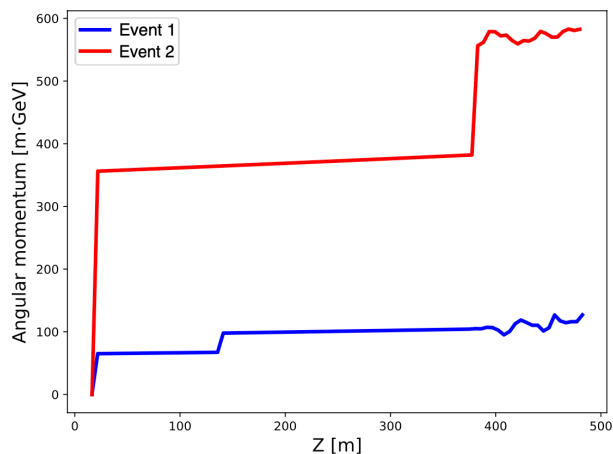
- Lindhard-Scharff (LS) formula

$$\left\langle -\frac{dE}{dx} \right\rangle_{\text{LS}} = 3.1 \times 10^{-11} \text{ GeV}^2 \times \frac{\rho}{\text{g/cm}^3} \frac{z^{7/6} Z/A}{(z^{2/3} + Z^{2/3})^{3/2}} \beta$$

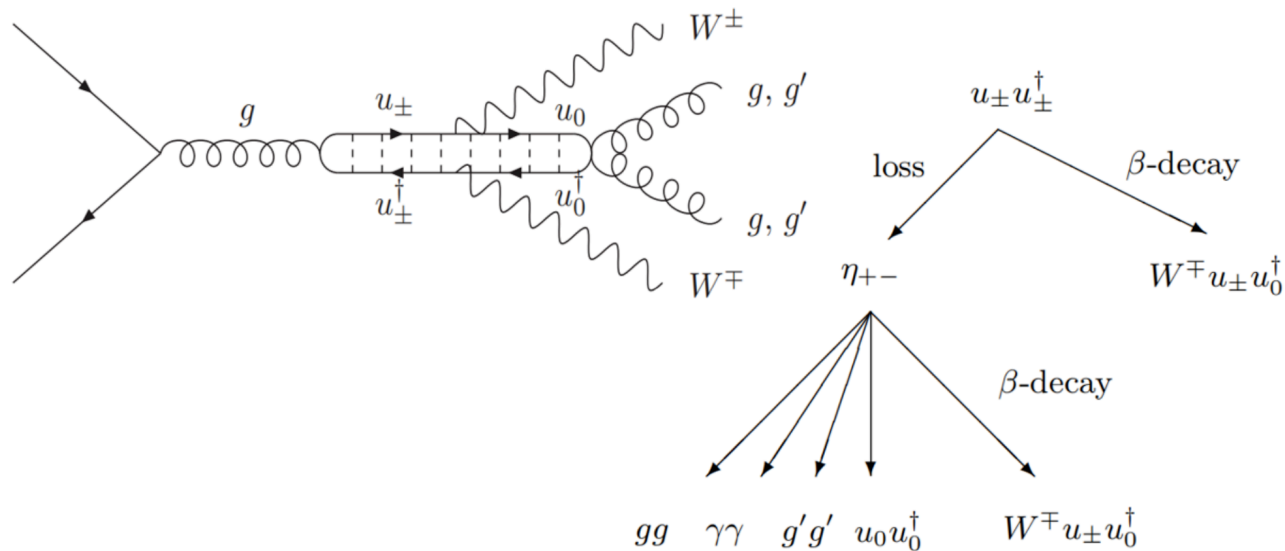
Material	$Z$ or $\langle Z \rangle$	$\langle Z/A \rangle$ [mol/g]	$\rho$ [g/cm <sup>3</sup> ]	$I$ [eV]	$a$	$k$	$x_0$	$x_1$	$\bar{C}$	$\delta_0$
Copper	29	29/63.546	8.960	322.0	0.14339	2.9044	-0.0254	3.2792	4.4190	0.08
Concrete	8.56	0.50274	2.300	135.2	0.07515	3.5467	0.1301	3.0466	3.9464	0.00
Rock	11	0.50000	2.650	136.4	0.08301	3.4120	0.0492	3.0549	3.7738	0.00

# Angular Momentum & ionization energy loss

- ▶ Ionization force  $\vec{F}_{\text{ion}}$  acts opposite to lab velocity  $\vec{v}$ ,  $\vec{F}' \nparallel \vec{v}'$  induces a non-zero torque in c.m. frame
- ▶ Integrating the CoM torque over one full oscillation yields  $\int_{1 \text{ period}} (T'_1 + T'_2) dg \approx 0$ .
- ▶ The angular momentum changes sharply **only at boundaries** or during asymmetric crossings (e.g., TAS, TAN, rocks).



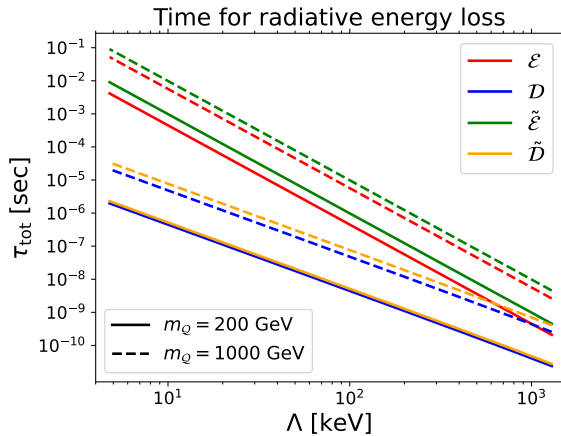
# Radiation, decay and annihilation



# Radiative energy loss - lifetime

IC and QCD radiation modeled by **assumption** that every period of quirk oscillation the quirk-pair has a probability  $\epsilon/\epsilon'$  to emit infracolor glueballs / QCD hadron with the energy of  $\Lambda_{\text{IC}} / \Lambda_{\text{QCD}}$ .

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



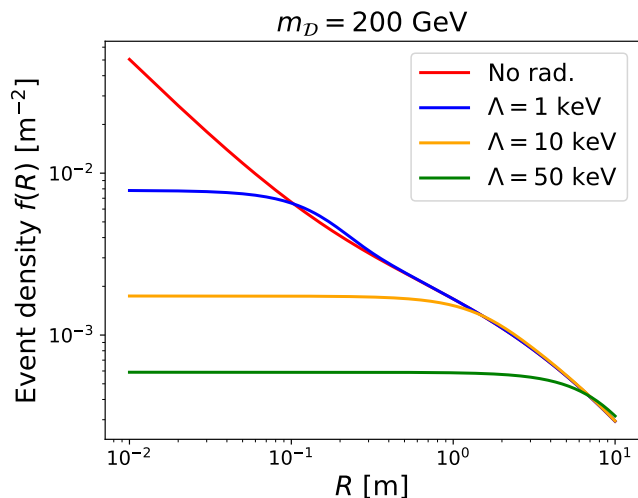
- ▶ Infracolor glueball radiation:  $\frac{dE}{dt} = -\frac{\epsilon\Lambda_{\text{IC}}}{T}$
- ▶ QCD hadron radiation:  $\frac{dE}{dt} = -\frac{\epsilon'\Lambda_{\text{QCD}}}{T}$
- ▶  $\tau = \int (dE)/(dE/dt)$
- ▶  $\epsilon = 0.1, \epsilon' = 0.01$
- ▶ Electromagnetic radiation (Larmor formula) :  $\frac{dE_\gamma}{dt} = -\frac{16\pi Q^2}{3}\alpha_{\text{EM}}a^2$

# Radiation - random walk in transverse plane

The transverse displacement of the quirk-pair in the laboratory frame due to  $N_{\text{rad}}$  radiation

$$\text{PDF}(\Delta \vec{R}) = \frac{1}{2\pi\sigma_R^2} e^{-\frac{\Delta x^2 + \Delta y^2}{2\sigma_R^2}}$$

$$\frac{\sigma_R}{d_{\text{IP-FASER}}} \sim \begin{cases} \frac{\Lambda \times 0.34 N_{\text{rad}}^{1/2}}{p(QQ)} \sim 1.7 \sqrt{\epsilon} \left[ \frac{\Lambda}{10^7 \text{ eV}} \right]^2 & \text{for } \mathcal{E} \\ \frac{\Lambda_{\text{QCD}} \times 0.34 N_{\text{rad}}^{1/2}}{p(QQ)} \sim 1.7 \sqrt{\epsilon'} \left[ \frac{\Lambda}{10^6 \text{ eV}} \right] & \text{for } \mathcal{D} \end{cases}$$

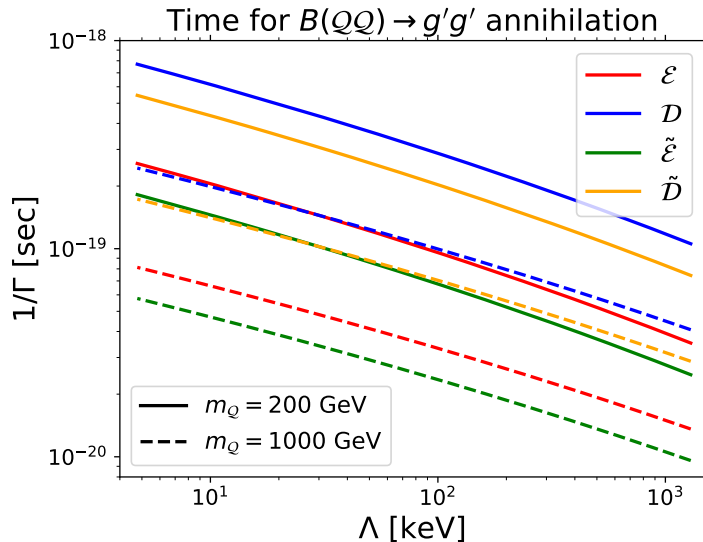


- ▶ For  $\mathcal{E}$ , the deflection angle  $\frac{\sigma_R}{d_{\text{IP-FASER}}} \lesssim 10^{-4}$  for  $\Lambda \lesssim 10^5 \text{ eV}$ . Since the detector opening angle with respect to the ATLAS IP is at least  $0.1/480$ , the deflection due to radiation is negligible.
- ▶ For  $\mathcal{D}$ , the deflection  $\sim$  the opening angle for  $\Lambda \lesssim 10^4 \text{ eV}$ , large  $\Lambda$  can significantly reduce the central density.

# Quirk pair annihilation

Decay width of quirk-pair in the ground state

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

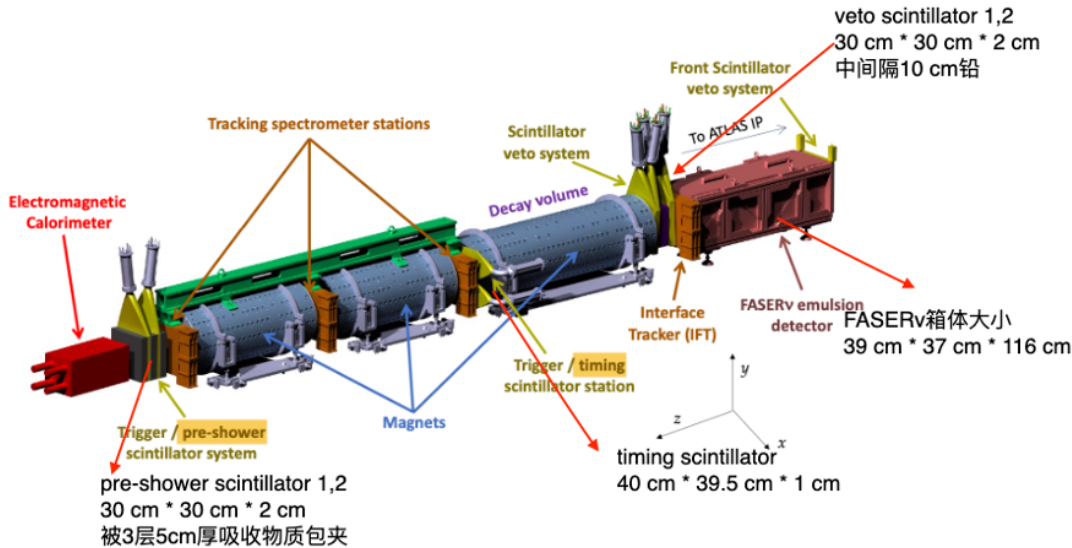
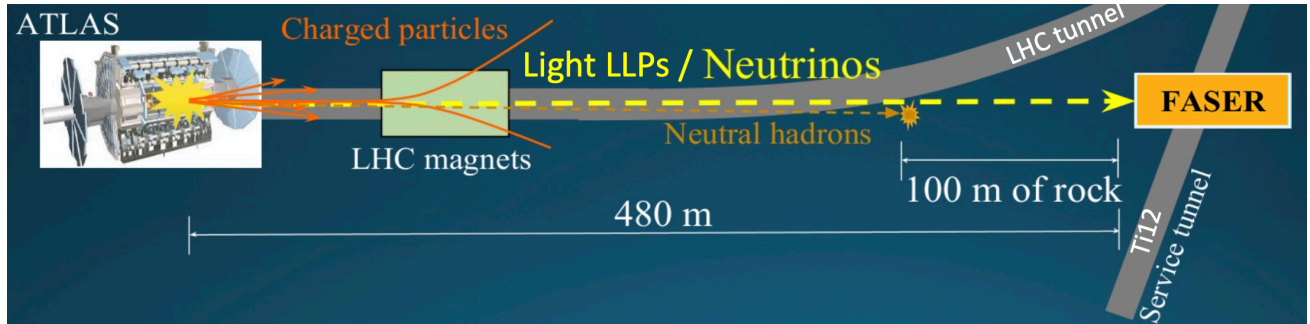


- The ground state wave function  $\psi(0)$  is calculated by solving the stationary Schrodinger equation with a Coulombic potential  $V(r) = -\alpha_{\text{IC}}/r$
- $m_Q \sim \mathcal{O}(100)$  GeV and  $\Lambda \in [\text{keV}, \text{MeV}]$ , the  $|\psi(0)| \sim \mathcal{O}(10)$
- Annihilation cross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

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

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

# FASER detector



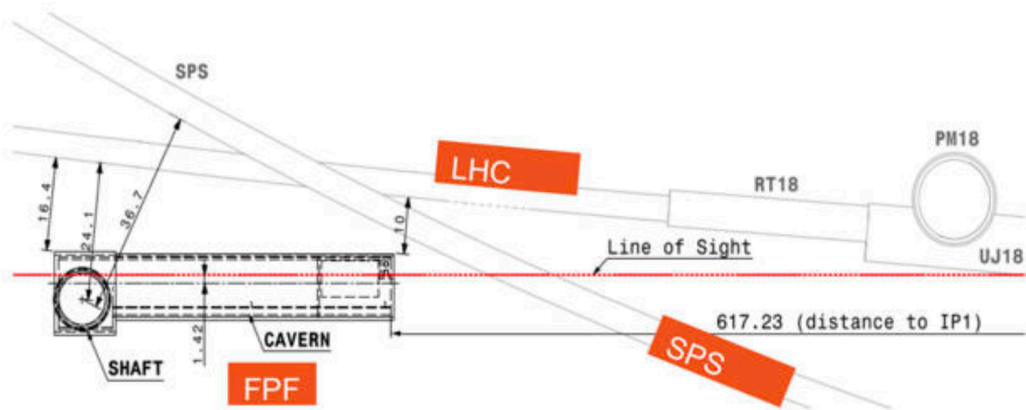
Time precision of scintillator:  
 $\sigma_t \sim \mathcal{O}(100)$  ps

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.

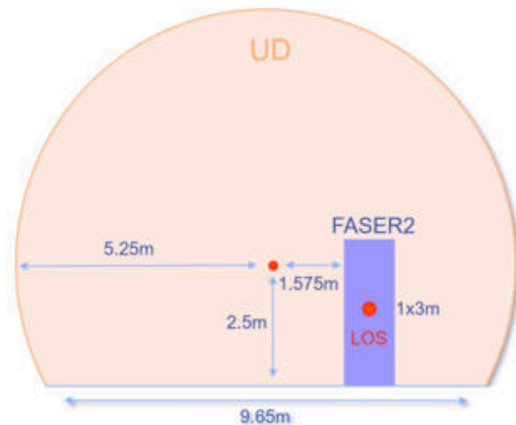
# The Timing and Spatial Resolution of FASER Detector

- ▶ The FASER detector utilizes multiple scintillator stations (front, timing, and back) to provide critical timing information.
- ▶ The timing scintillator achieves a resolution of  $\approx 500$  ps (dominated by the time-walk effect).
- ▶ The standard deviation of the time difference between the front and back scintillators is superior at 350 ps.
- ▶ The tracking layers provide excellent spatial resolutions of  $16 \mu m$  in the vertical coordinate and  $816 \mu m$  in the horizontal coordinate.

# Future Forward Experiments



Scintillator	Longitudinal position [m]		
	FASER	FASER2	UD
Front	480	650	617
Timing	481.55	660	637
Back	484.17	670	682



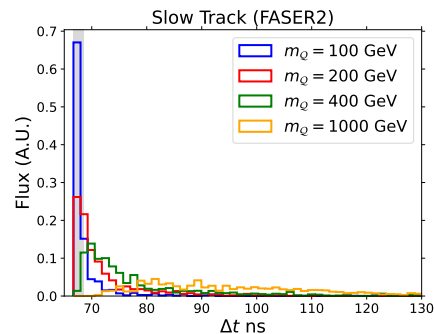
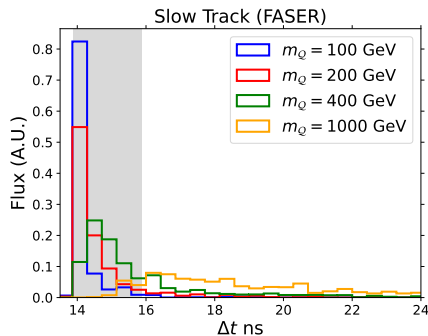
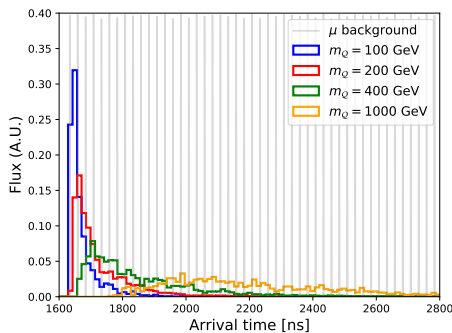
# Two timing analyses

## Arrival time at the timing scintillator (Delayed Track analysis)

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

## Time difference in the front and back scintillator (Slow Track analysis)

- A signal is detected that passes through the front and back scintillators.
- 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  $16\ \mu\text{m}$  in the vertical direction.
- The momentum of each track is greater than  $100\ \text{GeV}$

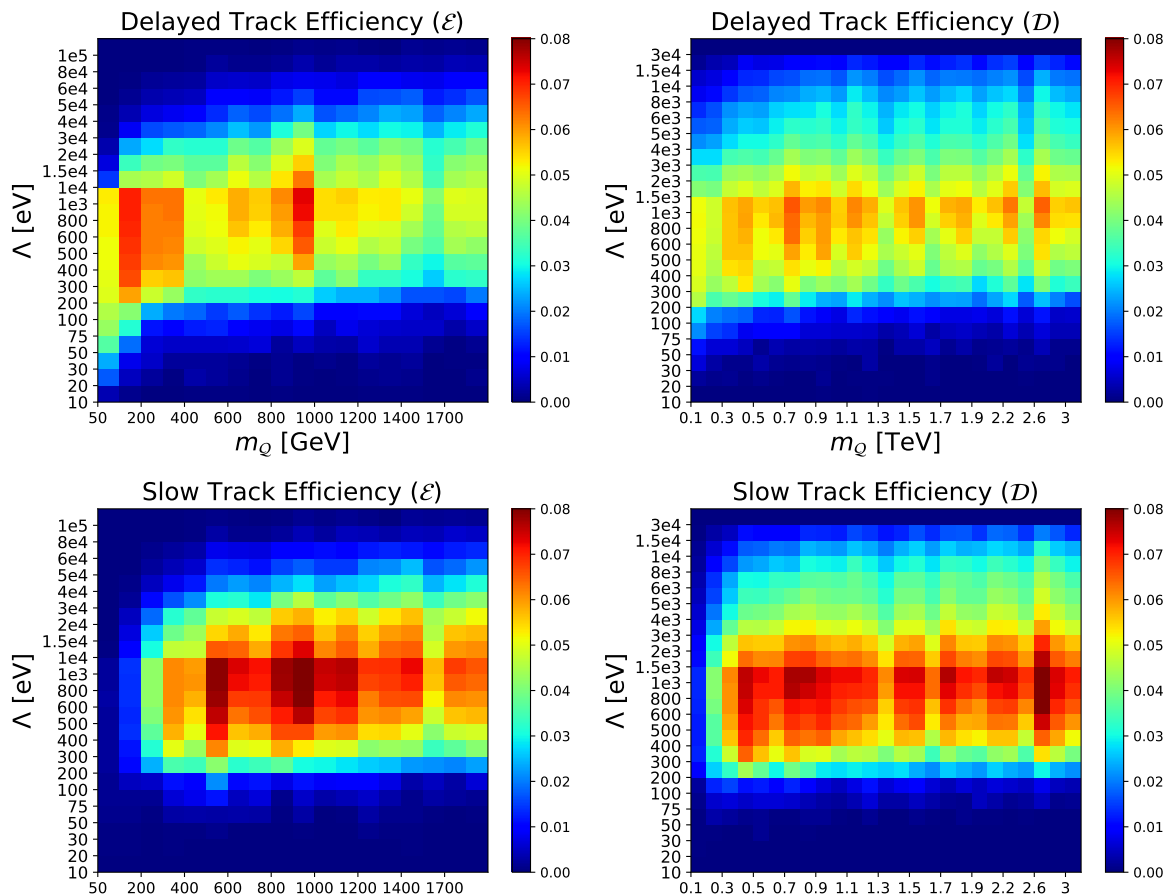


# The Muon Background Estimation

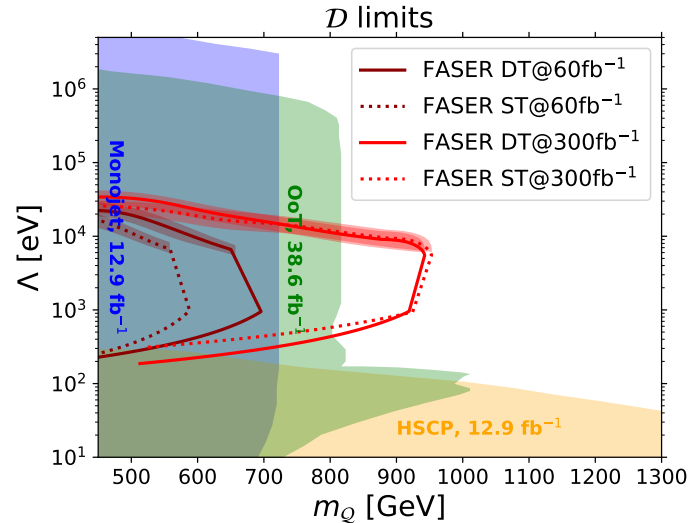
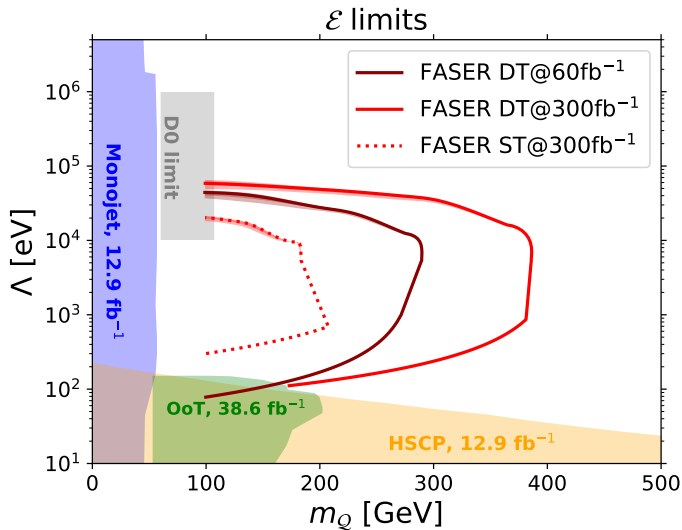
- ▶ The dominant background comes from high-energy **muons** ( $> 100$  GeV) from the ATLAS IP:  $\sim 1 \times 10^9$  at FASER (Run 3,  $300 \text{ fb}^{-1}$ ).
- ▶ The probability of a muon undergoing a timing fluctuation of  $> 1.75$  ns ( $5\sigma$  deviation) is only  $\sim 3 \times 10^{-7}$ : Applying this timing cut reduces the background to only  $\sim 300$  **single fake delayed muons** in FASER.
- ▶ The probability of *two* independent delayed muons arriving at the exact same time is completely negligible.
- ▶ **Fake two-tracks** (e.g., a delayed muon radiating  $\gamma \rightarrow e^+ e^-$ ) are eliminated by requiring *each* track to have  $p > 100$  GeV.
- ▶ The background for a high-energy, delayed/slow, 2-track signal is essentially **zero**.

# Efficiencies of timing analyses (FASER2)

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

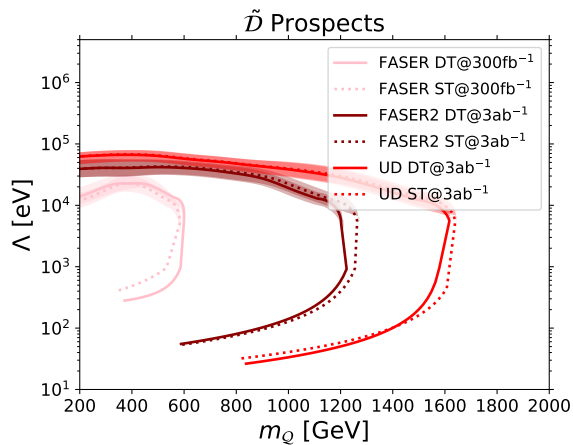
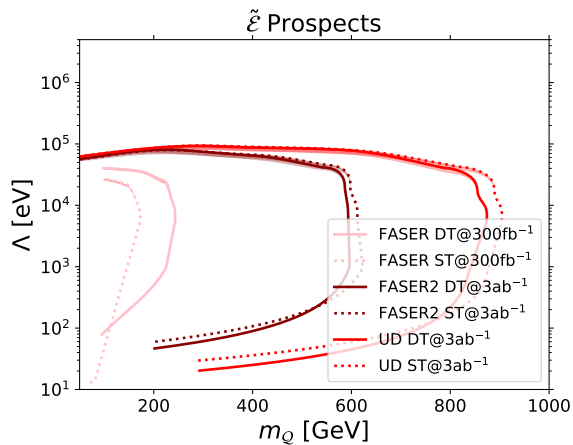
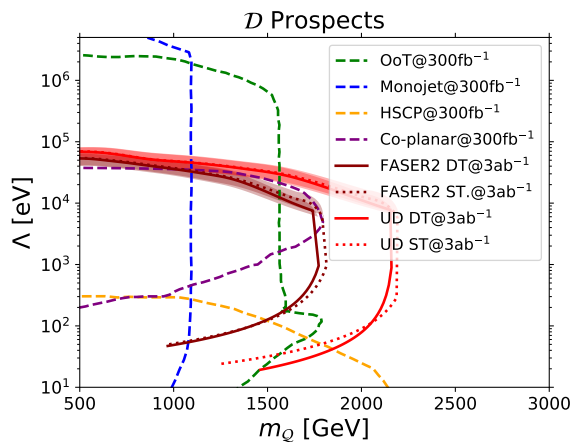
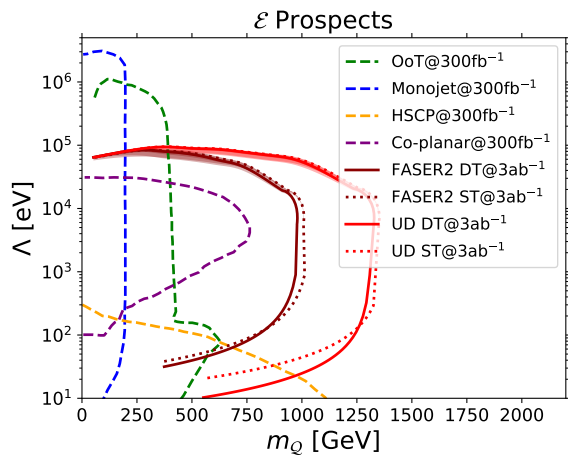


# Existing limits - A comparison study



- ▶ Mono-jet search, Heavy stable charged particle, Out of time decay
- ▶ FASER with the current dataset (60 fb<sup>-1</sup>) and the full Run 3 dataset (300 fb<sup>-1</sup>)

# Prospects at the LHC FPF



# Conclusion

- ▶ We establish a comprehensive framework to describe the quirk production and evolution at the LHC
  - ▶ There is a high fraction of quirk events in the forward direction
  - ▶ Ionization energy loss, radiation of soft particles are important in the quirk evolution.
- ▶ FASER and other Forward detectors can supplement the LHC main detectors in quirk search
  - ▶ Forward detectors are particularly useful for colored neutral quirk (neutral natureness)
  - ▶ Decayed time, a pair of tracks with large ionization energy loss are the smoking gun



*Thank you!*

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