Probing quirk particle at the LHC forward detectors

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青岛

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

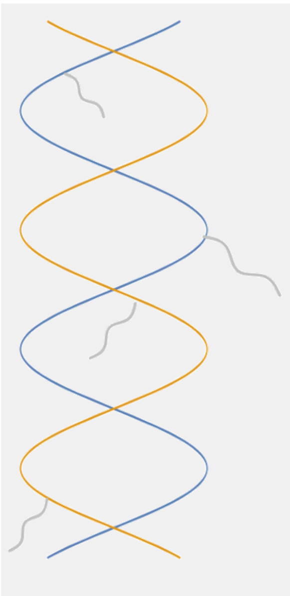
Outline

Introduction to quirk particle

- Particles with SM$\otimes SU(N)_{\rm IC}$ and $m_{\mathcal{Q}} \gg \Lambda_{\rm IC}$

Gauge flux tube:

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



- $\Lambda < 10$ 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 $E_T^{\rm miss}$.
- $\Lambda \in [10\ \text{keV}, 10\ \text{MeV}]$: 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 $SU(N_{\rm IC}) \times SU_C(3) \times SU_L(2) \times U_Y(1)$

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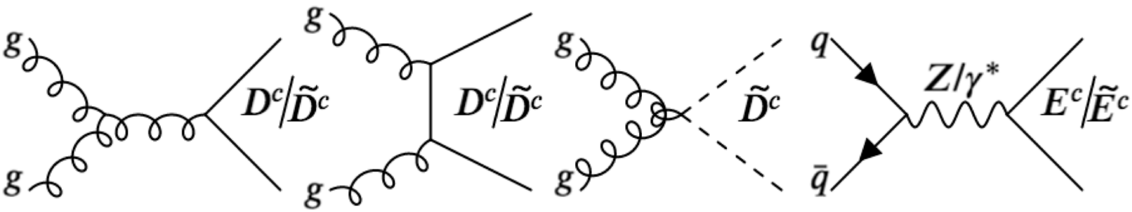
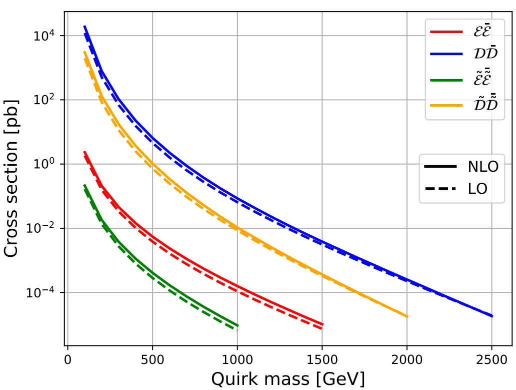
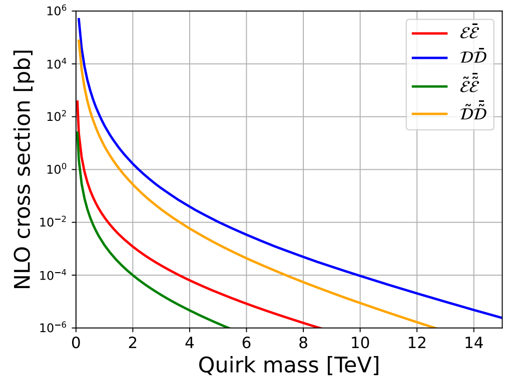


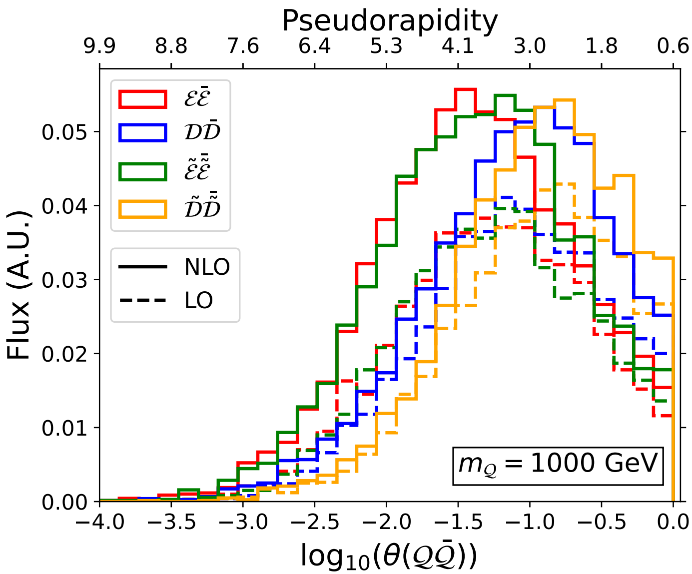
13 TeV

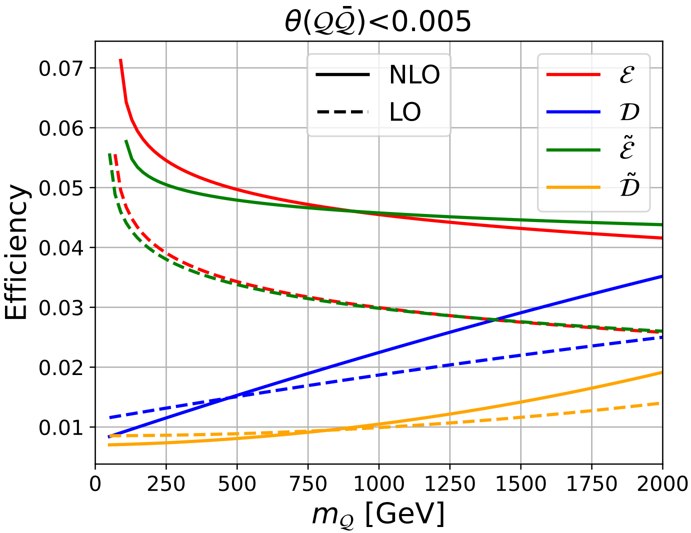


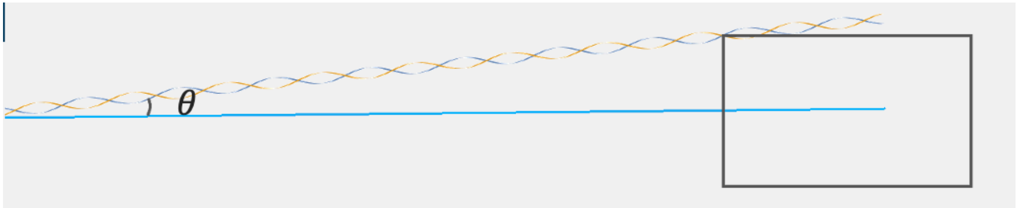
100 TeV



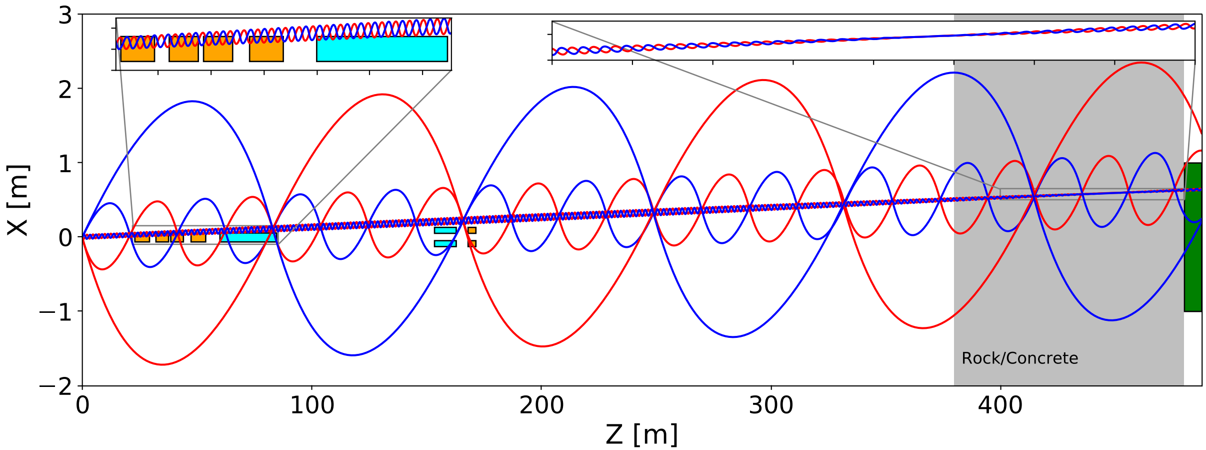
Quirk-pair in the forward direction







The quirk equation of motion



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

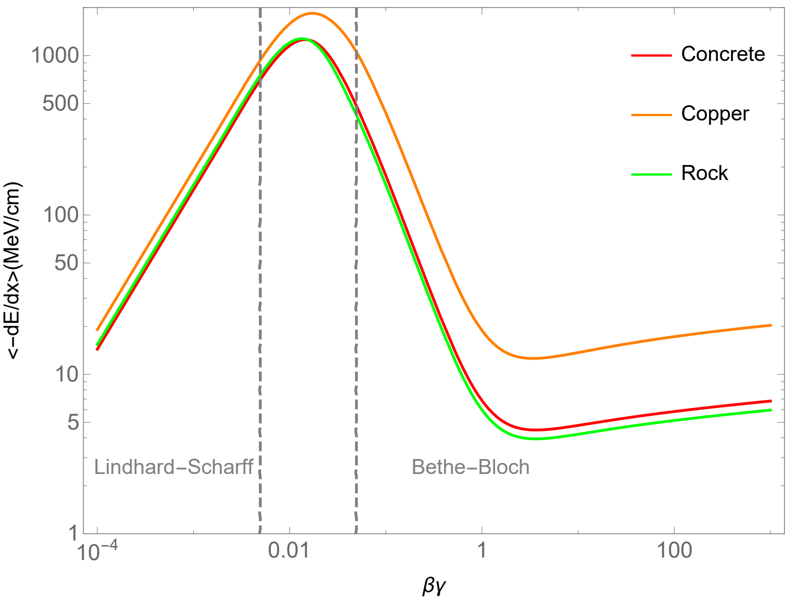
$$\vec{F}_s = -\Lambda^2\sqrt{1-\vec{v}_\perp^2}\,\hat{s} - \Lambda^2\frac{v_\parallel \vec{v}_\perp}{\sqrt{1-\vec{v}_\perp^2}}$$

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

$$t_1 - t_2 = \vec{\beta}\cdot(\vec{r}_1 - \vec{r}_2),\ \ \beta = \frac{p_1 - p_2}{E_1 - E_2}$$

- $m_{\mathcal{Q}} = 800$ 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

Ionization energy loss for **charged quirk**



- Bethe-Bloch formula

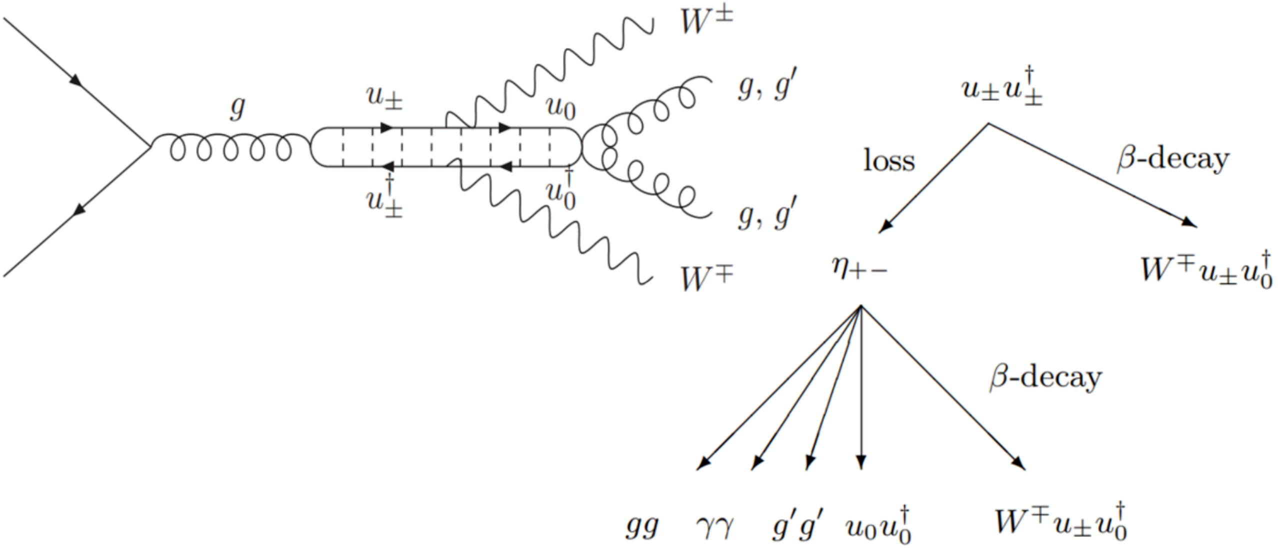
$$\left\langle -\frac{dE}{dx} \right\rangle_{\rm BB} = K\rho z^2 \frac{Z}{A}\frac{1}{\beta^2} \times \left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

- Lindhard-Scharff (LS) formula

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

Material	Z or $\langle Z\rangle$	$\langle Z/A\rangle$[mol/g]	ρ[g/cm^3]	I[eV]	a	k	x_0	x_1	$\bar{C}$	δ_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

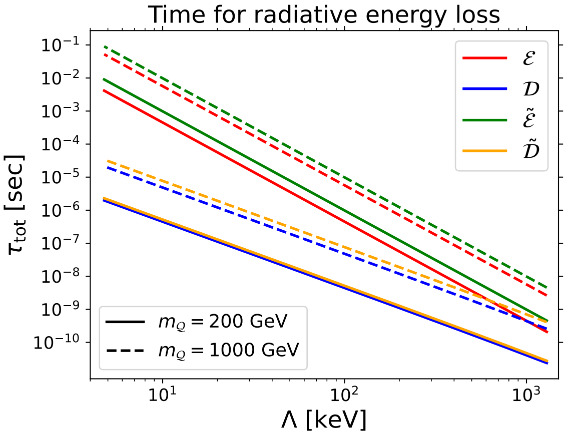
Radiation, decay and annihilation



Radiative energy loss - lifetime

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

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 Λ / $\Lambda_{\rm QCD}$.

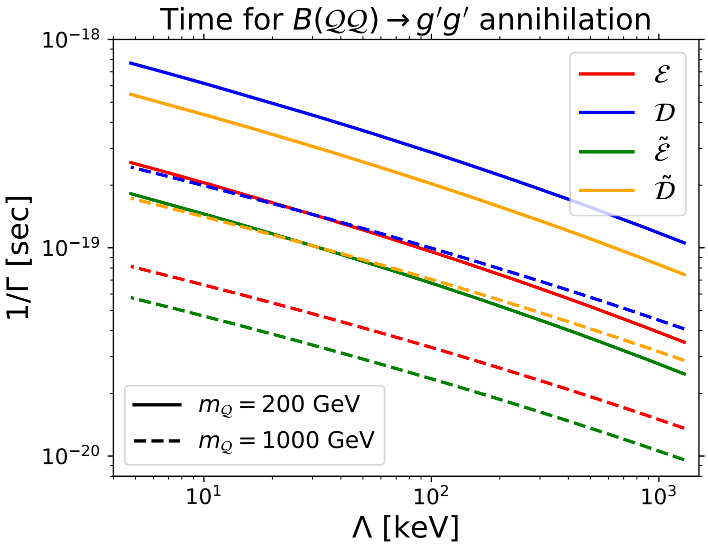


- Infracolor glueball radiation: $\frac{dE}{dt} = -\frac{\epsilon \Lambda_{\rm IC}}{T}$
- QCD hadron radiation: $\frac{dE}{dt} = -\frac{\epsilon' \Lambda_{\rm QCD}}{T}$
- $\tau = \int (dE)/(dE/dt)$
- $\epsilon = 0.1$, $\epsilon' = 0.01$
- Electromagnetic radiation (Larmor formula) : $\frac{dE_\gamma}{dt}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

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

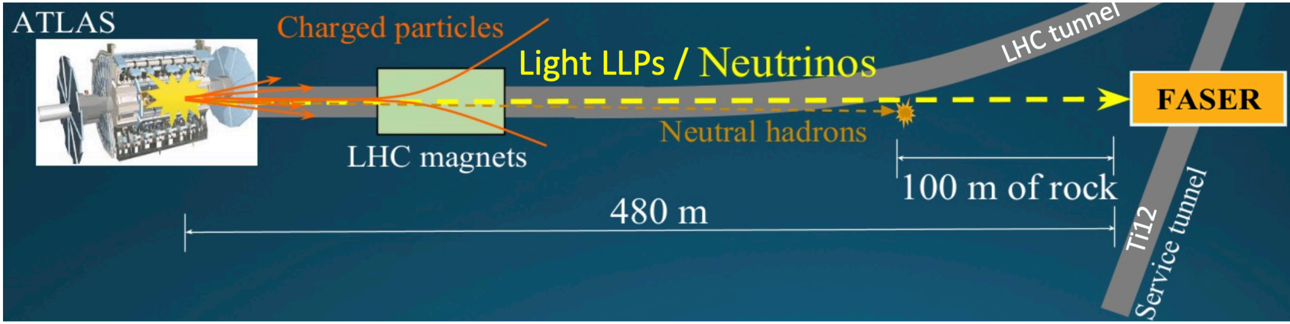
$$\sigma v(\mathcal{Q}\bar{\mathcal{Q}} \to g'g') = \begin{cases} \frac{\pi\alpha_{\rm IC}^2(N_{\rm IC}^2-1)}{4m_{\mathcal{Q}}^2 N_C N_{\rm IC}} & \text{for fermion} \\ \frac{\pi\alpha_{\rm IC}^2(N_{\rm IC}^2-1)}{2m_{\mathcal{Q}}^2 N_C N_{\rm IC}} & \text{for scalar} \end{cases}$$

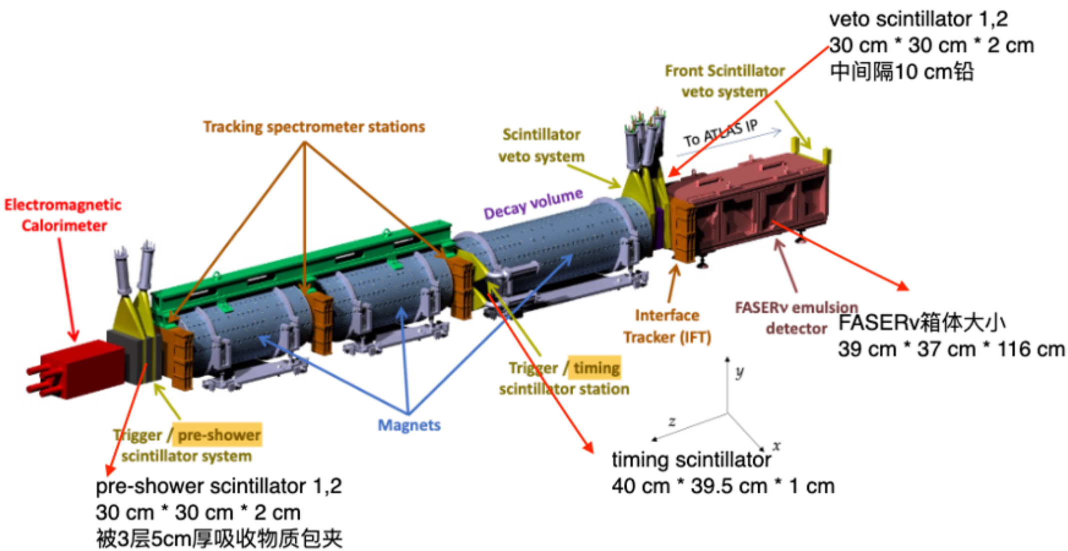
- Quirk-pair bounds state decays promptly once settles into the ground state

All annihilation channels

Annihilation Process	Fermion quirk	Scalar quirk
$\mathcal{Q}\bar{\mathcal{Q}} \to g'g'$	$\frac{\pi\alpha_{\rm IC}^2(N_{\rm IC}^2-1)}{4m^2 N_C N_{\rm IC}}$	$\frac{\pi\alpha_{\rm IC}^2(N_{\rm IC}^2-1)}{2m^2 N_C N_{\rm IC}}$
$\mathcal{Q}\bar{\mathcal{Q}} \to \gamma\gamma$	$\frac{N_{\rm IC}\pi\alpha_{\rm EM}^2 Q^4}{N_C m^2}$	$\frac{2N_{\rm IC}\pi\alpha_{\rm EM}^2 Q^4}{N_C m^2}$
$\mathcal{Q}\bar{\mathcal{Q}} \to \gamma \to ee$	$\frac{N_{\rm IC}\pi\alpha_{\rm EM}^2 Q^2}{N_C m^2}$	$-$
$\mathcal{Q}\bar{\mathcal{Q}} \to uu$	$\frac{\pi\alpha_s^2(N_C^2-1)N_{\rm IC}}{4m^2 N_C}$	$-$
$\mathcal{Q}\bar{\mathcal{Q}} \to gg$	$\frac{N_{\rm IC}\pi\alpha_S^2(N_C^4-3N^2+2)}{8m^2 N_C^3}$	$\frac{N_{\rm IC}\pi\alpha_S^2(N_C^4-3N^2+2)}{4m^2 N_C^3}$
$\mathcal{Q}\bar{\mathcal{Q}} \to g\gamma$	$\frac{N_{\rm IC}\pi\alpha_{\rm EM}\alpha_S(N_C^2-1)Q^2}{m^2 N_C^2}$	$\frac{2N_{\rm IC}\pi\alpha_{\rm EM}\alpha_S(N_C^2-1)Q^2}{m^2 N_C^2}$

FASER detector

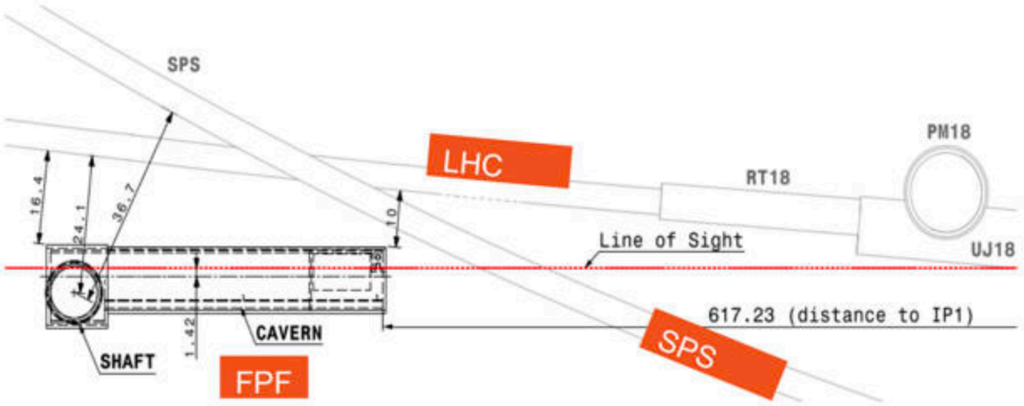




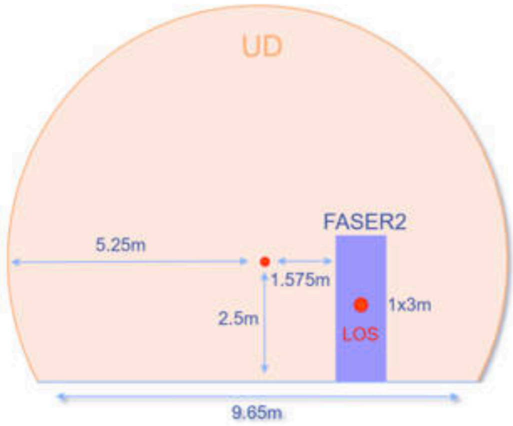
Time precision of scintillator:
$\sigma_t \sim \mathcal{O}(100)$ ps

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

Future Forward Experiments



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



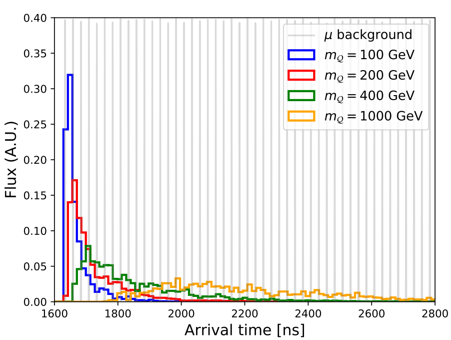
Two timing analyses

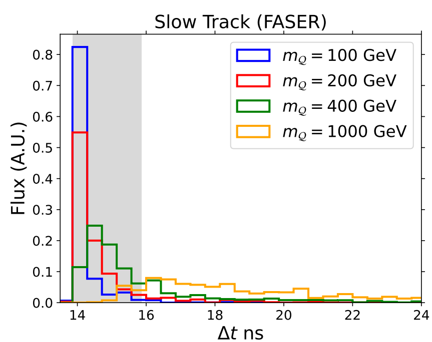
Arrival time at the timing scintillator (Delayed Track analysis)

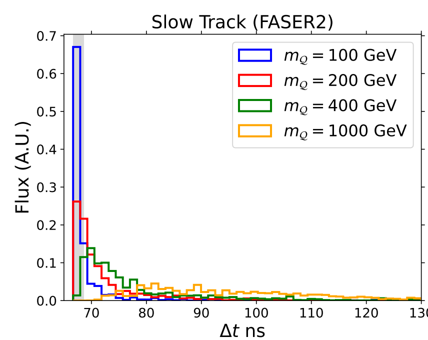
- A signal is detected that passes through the timing scintillator and the trackers.
- The signal in the timing scintillator is outside the $[-3\,\text{ns}, 3\,\text{ns}]$ muon timing window.
- The signal in the trackers is two tracks that are separated by more than 16 μm in the vertical direction.
-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

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

- 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 GeV

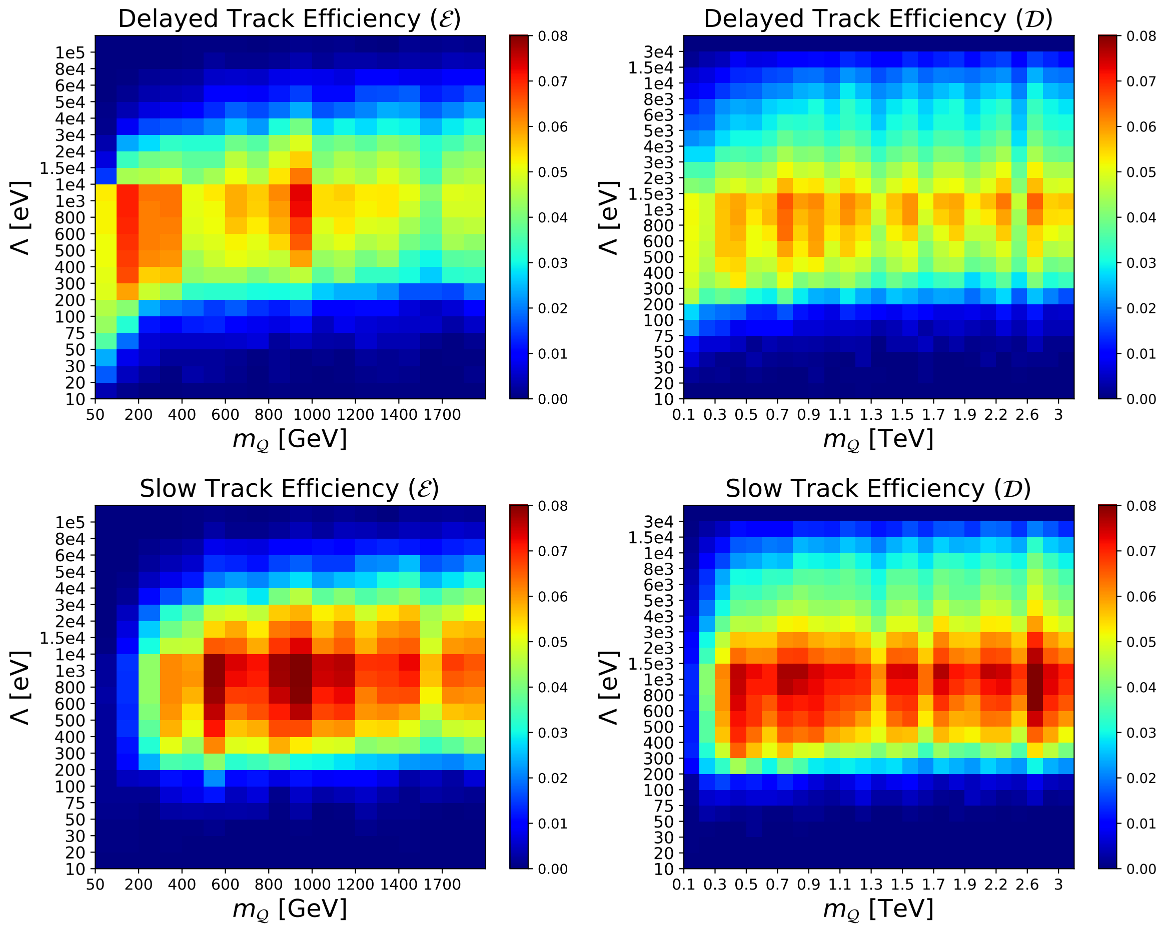




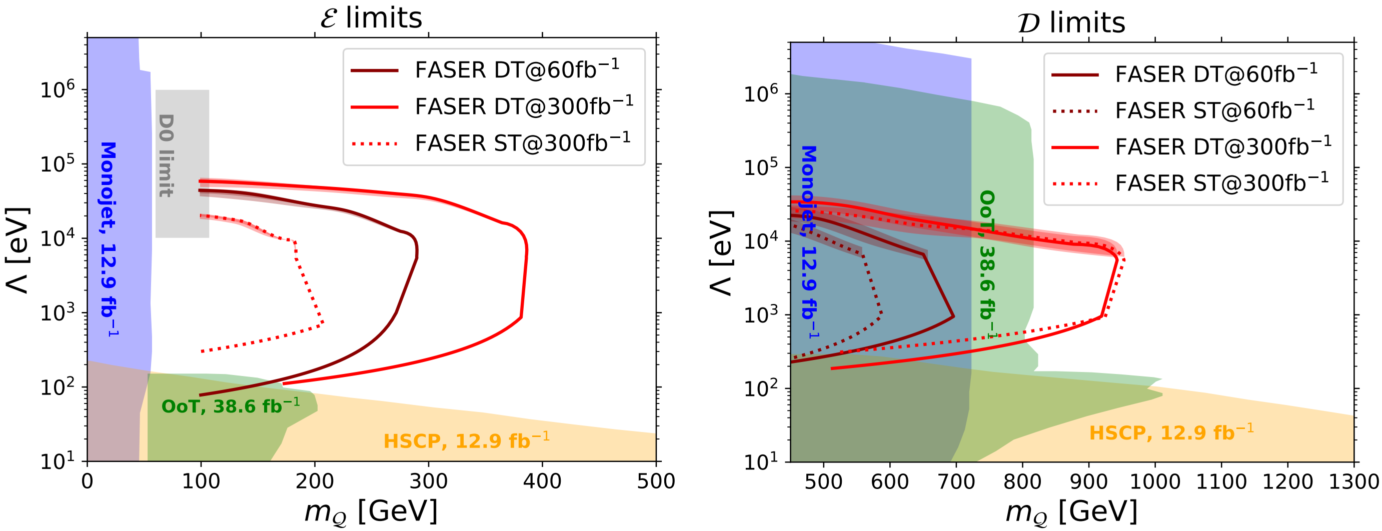


Efficiencies of timing analyses (FASER2)

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

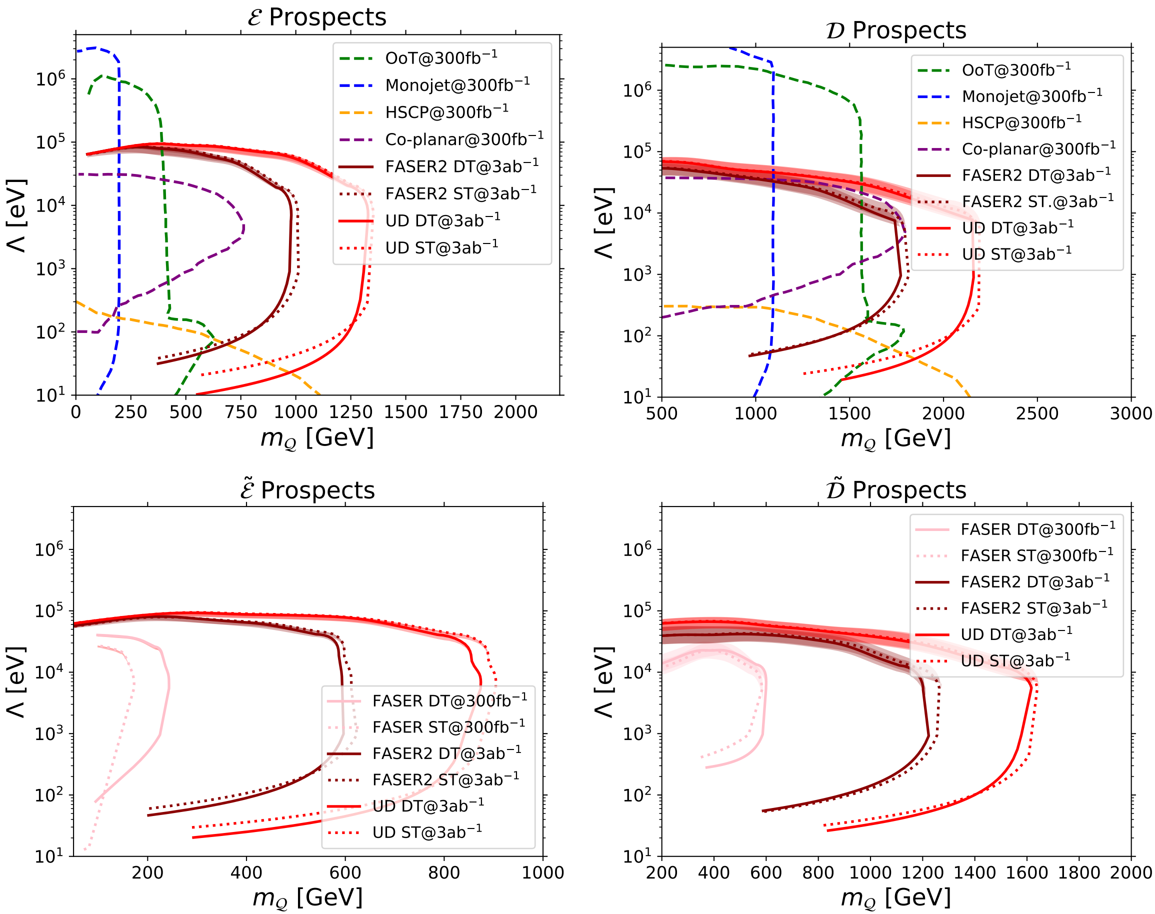


Existing limits -A comparison study

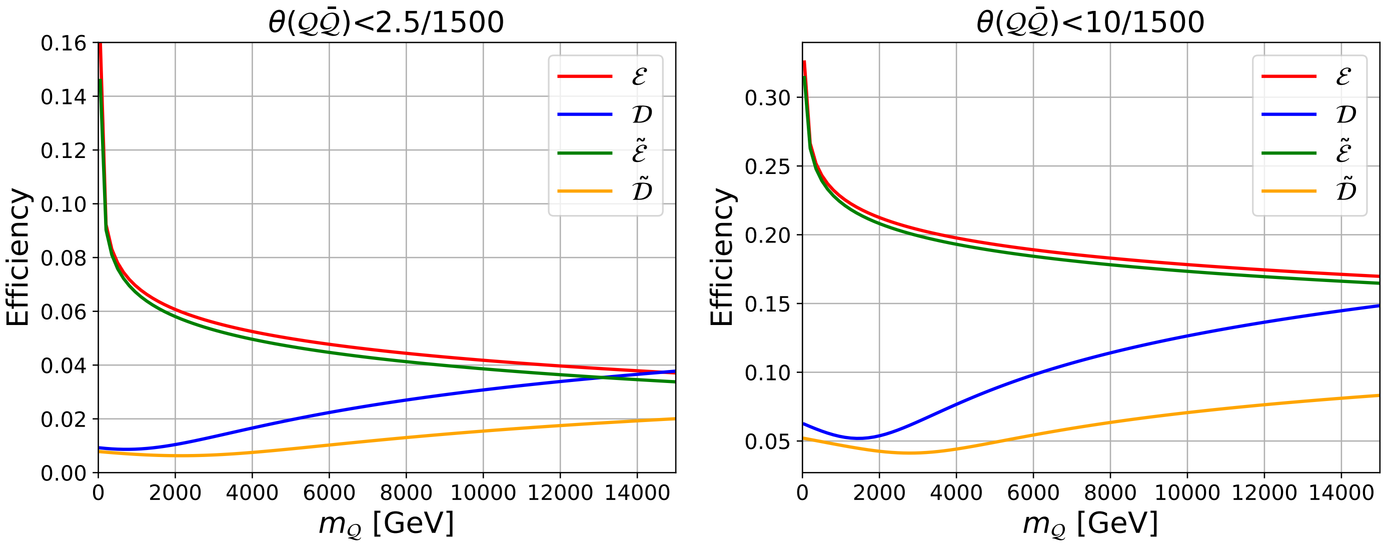


- Mono-jet search, Heavy stable charged particle, Out of time decay
- FASER with the current dataset (60 fb^{-1}) and the full Run 3 dataset (300 fb^{-1})

Prospects at the LHC FPF

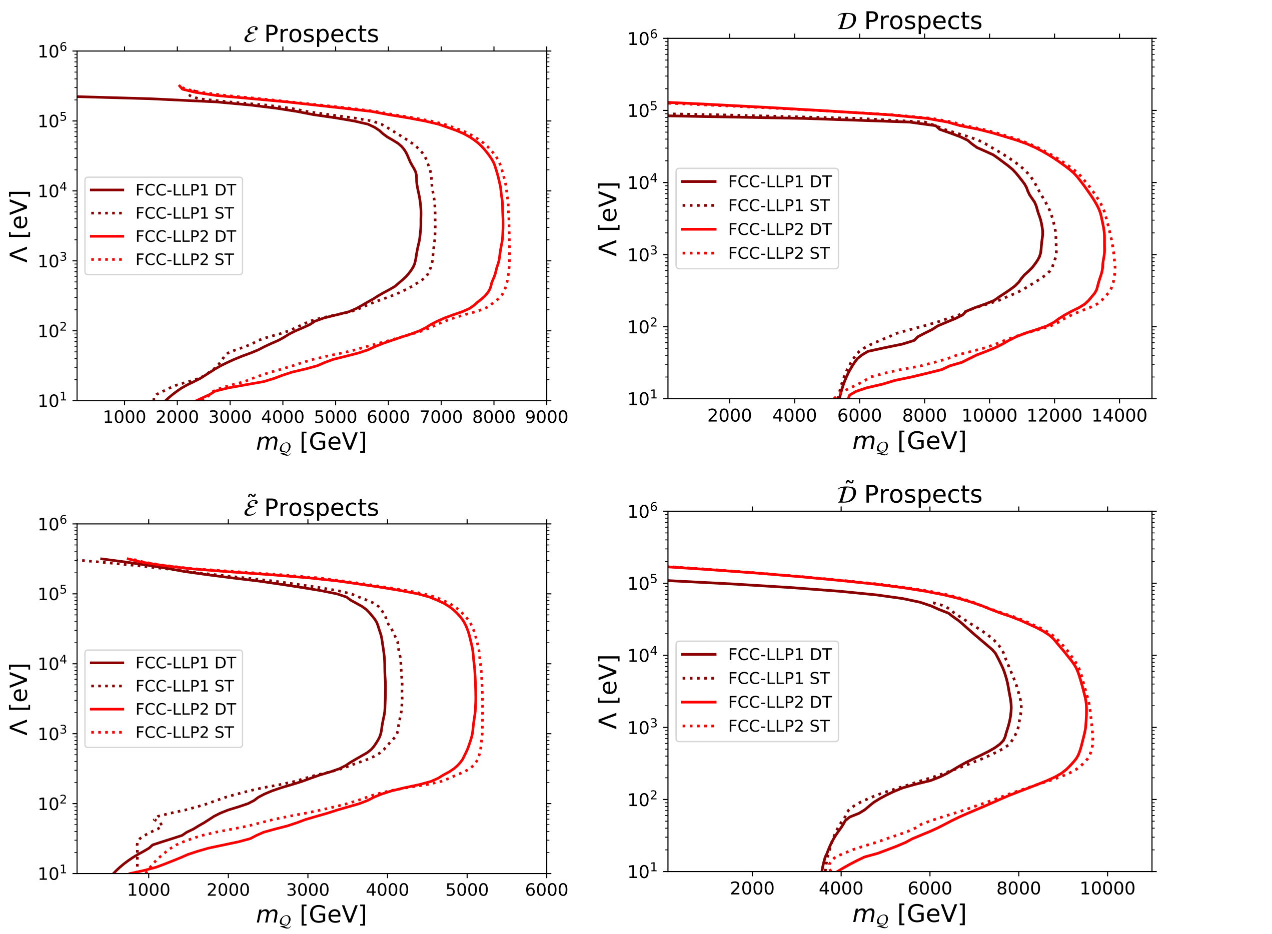


Quirk at FCC 100 TeV



Scintillator	Transverse size [m × m]		Longitudinal position [m]	
	FCC-LLP1	FCC-LLP2	FCC-LLP1	FCC-LLP2
Front	5 × 5	20 × 20	1500	1500
Back	5 × 5	20 × 20	1550	1900

Prospects at the 100 TeV p-p collider (30 ab^{-1})



Conclusion

- 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 annihialtion 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)


Thank you!
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