QUIRKS AT THE FORWARD PHYSICS FACILITY

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NEW FORCES AT THE FPF

- The SM contains many forces corresponding to gauge symmetries that are unbroken or broken in a variety of ways.

- There may also be new forces, motivated by hidden sectors, dark matter, experimental anomalies, etc., which may be unbroken or broken in a variety of ways, and it is important to investigate all of these at the FPF.

- SM
  - Abelian, unbroken: Electromagnetism $U(1)_{EM}$
  - Abelian, spontaneously broken: Hypercharge $U(1)_Y$
  - Non-Abelian, spontaneously broken: Weak SU(2)
  - Non-Abelian, dynamically broken: QCD SU(3)

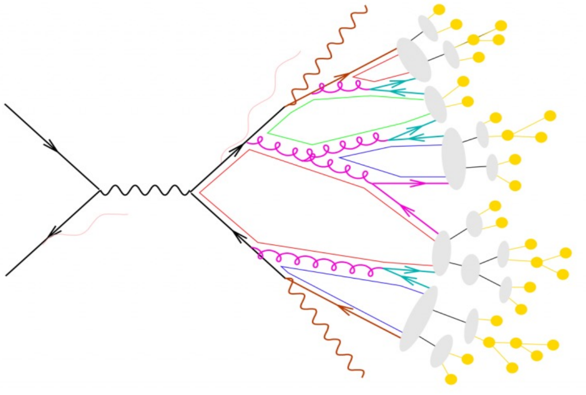
- BSM
  - Abelian, unbroken: millicharged particles (FORMOSA)
  - Abelian, spontaneously broken: dark photon, $B-L$, $L_\mu - L_\tau$ gauge bosons (FASER2, FASERν2, AdvSND, FLArE)
  - Non-Abelian, spontaneously broken: ?
  - Non-Abelian, dynamically broken: quirks (FASER2, FLArE, and others?)

QUIRKS

- Quirks are matter particles that are charged under a hidden strong force ("hidden QCD"), where $m_{\text{quirk}} \gg \Lambda_{\text{hidden}}$ for every quirk (we will typically assume there is just one). Kang, Luty (2008)

- In the most phenomenologically-interesting case, quirks have weak-scale masses and also SM charges. They are then pair produced at the LHC like 4th generation leptons/quarks (or sleptons/squarks) with high p_T.

- However, unlike 4th generation leptons or quarks, quirks are stable. In addition, they cannot hadronize wrt hidden QCD, because $m_{\text{quirk}} \gg \Lambda_{\text{hidden}}$: quirks are too heavy to be pair produced to break the color string.

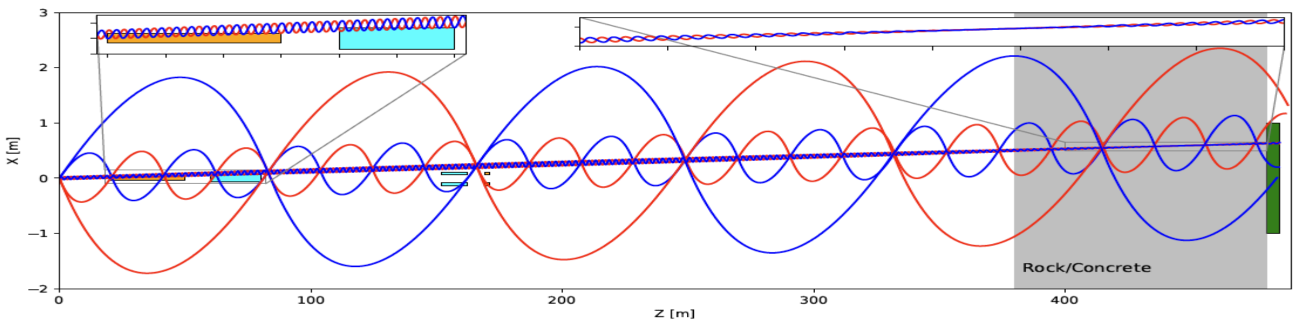


- Instead, quirk pairs are bound by the color string and oscillate around their COM with length scale $d_{\text{cm}} \sim m_{\text{quirk}}/\Lambda^2_{\text{hidden}}$. The quirk—anti-quirk bound state generically has low p_T, so can travel down the beamline and pass through far-forward detectors.

QUIRKS

- Quirks are a generic possibility if there is a strong hidden force. They are an example of new ~TeV-scale physics that is preferentially produced along the beamline and completely inaccessible at fixed target experiments.

- The quirk trajectories are not easy to model (string force naturally modeled in quirk-quirk COM frame, quirk-matter interactions naturally modeled in lab frame), but this has been done in beautiful work by Li, Pei, Ran, Zhang (2021).



- Quirks lead to a variety of LHC signals, depending on $\Lambda_{\mathrm{hidden}}$. Detailed simulation is very difficult (e.g., impossible in Geant4), but there is work in progress using machine learning to search for anomalous, non-helical tracks.

Khlopov (1981); Gupta, Quinn (1981); Babu, Gogoladze Kolda (2005); Strassler Zurek (2006); Burdman, Chacko, Goh, Harnik (2005); Kang, Luty (2008); Harnik, Wizansky (2008); Harnik, Kribs, Martin (2011); Charcko, Curtin, Verhaaren (2015); Farina, Low (2017); Knapen, Lou, Papucci, Setford (2017), Evans, Luty (2018); …

QUIRK PRODUCTION

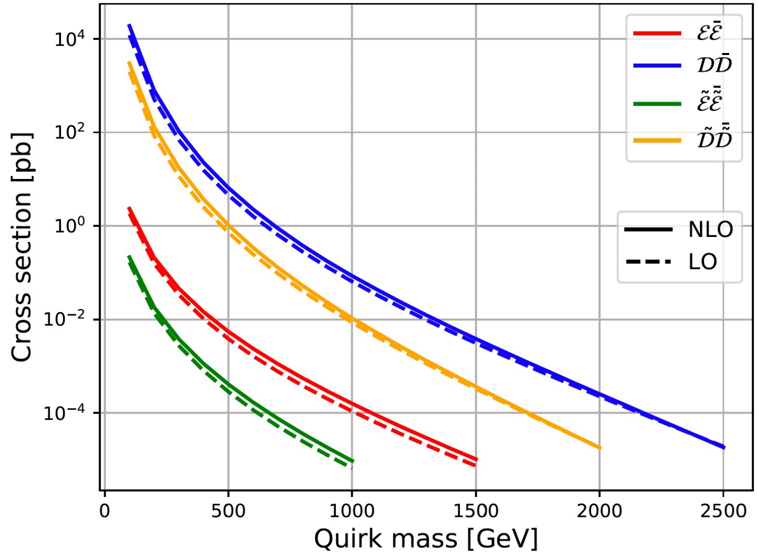
- Consider (vector-like) quirks and "squirks," e_R-type (uncolored) and d_R-type (colored). d_R-type quirks hadronize wrt to QCD, 30% of resulting hadrons have charge ± 1, rest are neutral. No fractionally charged particles.

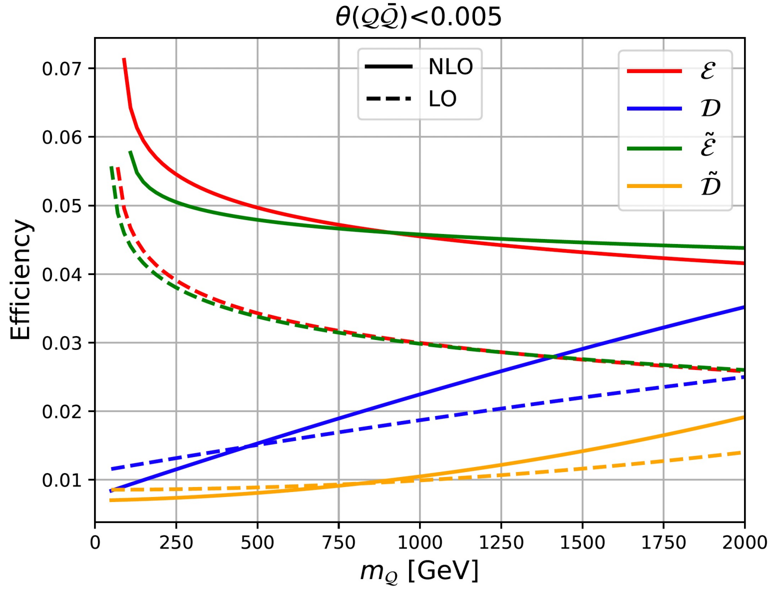
$$SU(N_{\mathrm{IC}}) \times SU_C(3) \times SU_L(2) \times U_Y(1)$$

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

- Consider hidden SU(2) ($\sigma_{\mathrm{quirk}} \propto N_{\mathrm{IC}}$).

- Consider m_{quirk} from 0.1 - 2 TeV. Despite ISR, FSR, many quirk pairs travel in the far-forward region: ~1-5% with θ < 0.005 (6 10^{-6} of solid angle).





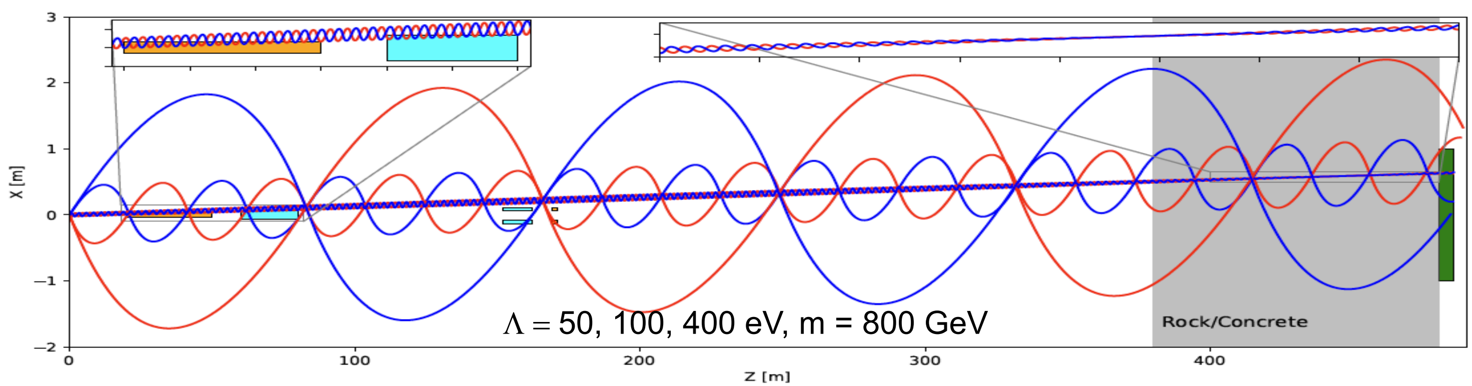
QUIRK PROPAGATION

- The quirk oscillation length is $d_{\text{cm}} \sim 2\ \text{cm}\ (\gamma - 1) \left(\frac{m_Q}{100\ \text{GeV}}\right) \left(\frac{\text{keV}}{\Lambda}\right)^2$

  where γ is the Lorentz boost factor of the quirks when produced.

- Consider Λ from 10 eV to MeV. For m_{quirk} ~ TeV,
  - Λ ~ 10 eV: d_{cm} ~ 50 m, quirks propagate almost independently, look like HSCPs
  - Λ ~ 100 eV – 10 keV: d_{cm} ~ 50 cm – 0.5 mm, quirks are bound together and can both go through FASER2
  - Λ ~ 100 keV – MeV: d_{cm}~ 500 nm - 5 nm, quirks oscillate rapidly, radiate hidden glueballs and photons and can annihilate before reaching the FPF

Evans, Luty (2018)



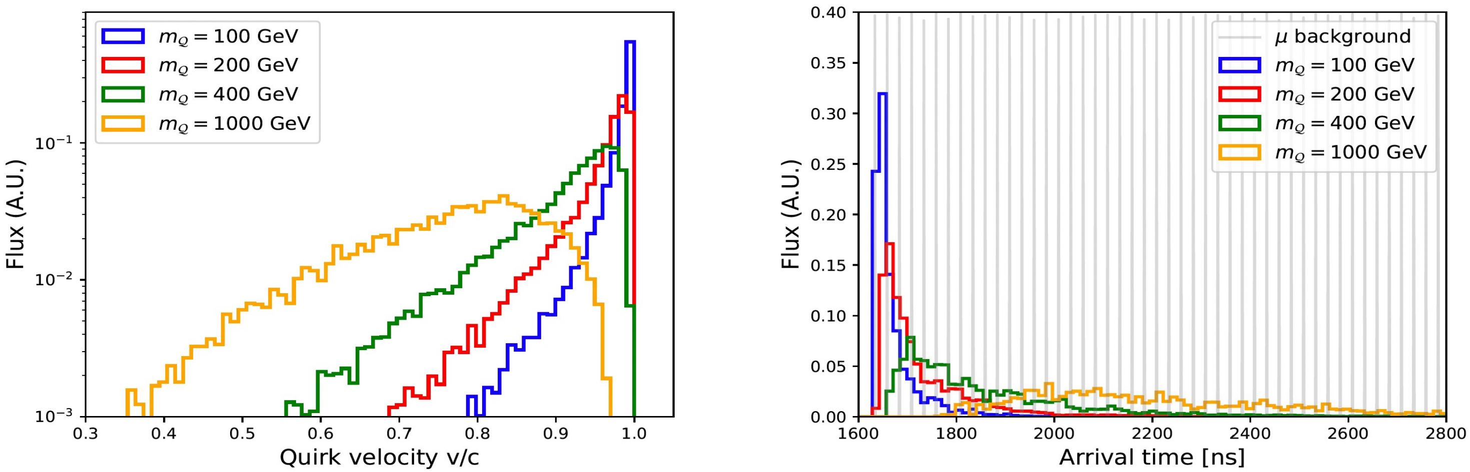
Li, Pei, Ran, Zhang (2021).

- Note: for low Λ, the tracks are essentially straight within the detector.

SLOW QUIRKS

- What is the best way to search for quirks? Quirks with electric charge appear in far-forward detectors as heavy muons, but they come in pairs and can have velocities well below c.

- Velocity distributions depend strongly on m, insensitive to Λ and quirk type.



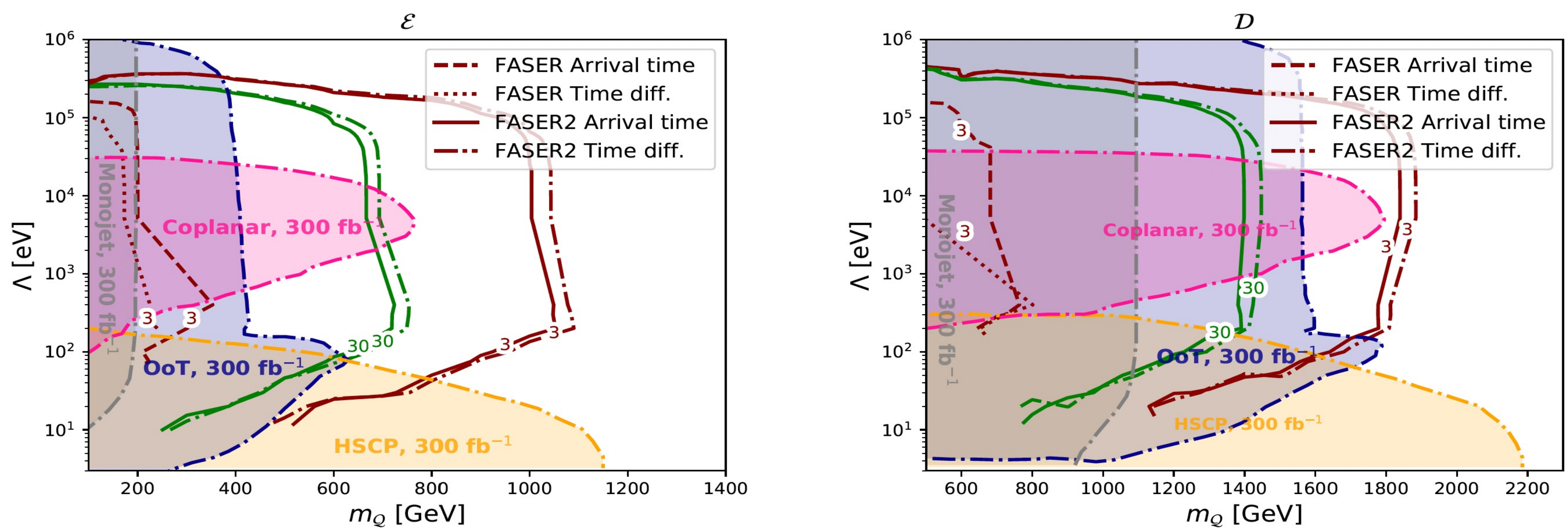
- Possible signals:
  - Ionization: high dE/dx ($v < 0.7$).
  - Arrival time: quirks arrive out of time with bunch crossings. FPF is so far from ATLAS that even a particle with $v < 0.998$ arrives 3 ns late. Requires bunch crossing information.
  - Time difference: measure the time difference between when a particle passes through the front and back scintillators. Self-contained: independent of bunch crossing time.

QUIRK SIGNALS FROM TIMING

- Arrival time: require 2 charged particles with p>100 GeV that pass through FASER2 at the same time, and both arrive outside [-3 ns, 3 ns] window.

- Time difference: require 2 charged particles with p>100 GeV that pass through FASER2 at the same time, and both have time difference between front and back scintillators that is > 2 ns delayed (20 m for FASER2) (background free based on measured muon flux, current FASER scintillator performance). Boyd, Petersen (2023)

- No sensitivity at $\Lambda\sim$ 10 eV (2 tracks too separated to both pass through FASER2), and no sensitivity at $\Lambda \sim \mathrm{MeV}$ (quirk pair annihilates before getting to FASER2). But significant sensitivity beyond ATLAS/CMS searches for intermediate Λ.



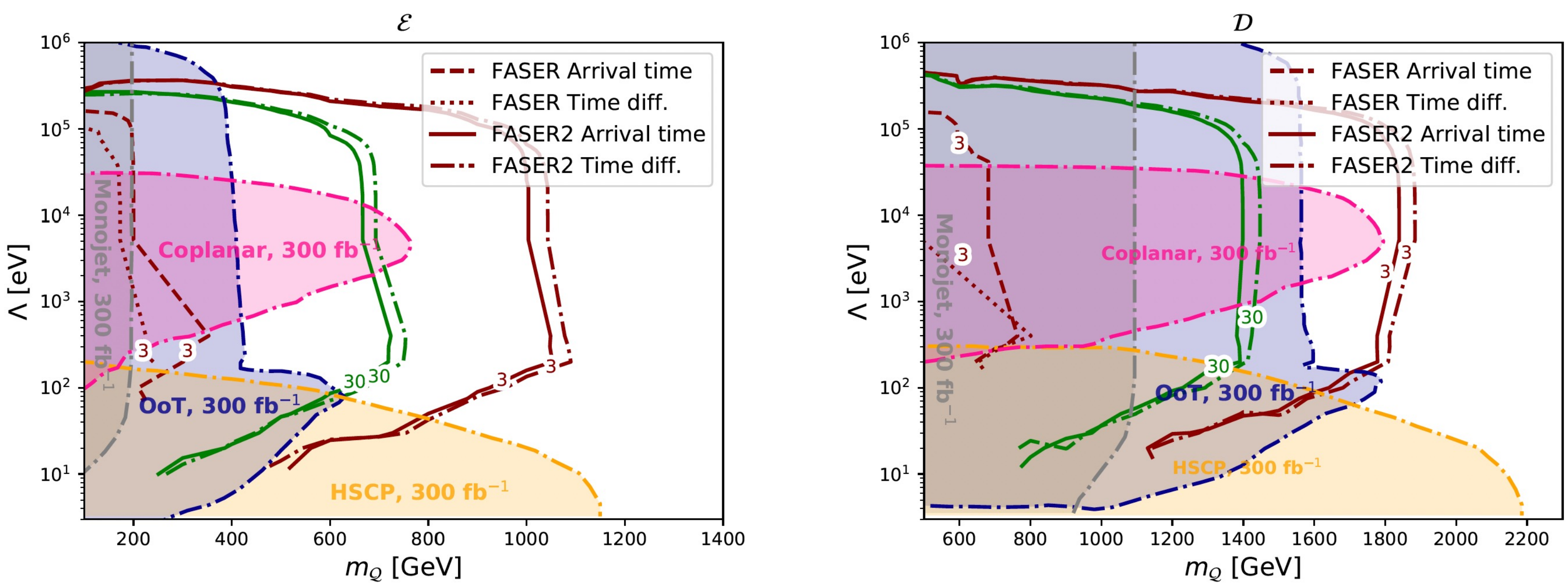
Feng, Li, Liao, Ni, Pei (in progress)

SUMMARY AND OUTLOOK

- Quirks are a generic possibility if there is a strong hidden force. They are an example of new ~TeV-scale physics that is preferentially produced along the beamline and completely inaccessible at fixed target experiments.

- The FPF appears to have sensitivity to quirk parameter space beyond competing constraints for both uncolored and colored quirks at the TeV scale.

- Analyzed for FASER2, but would also be interesting to consider FLArE and other FPF detectors, either proposed or new.



Feng, Li, Liao, Ni, Pei (in progress)