Standalone Search for Quirk Pair Production with Timing Detector at HL-LHC

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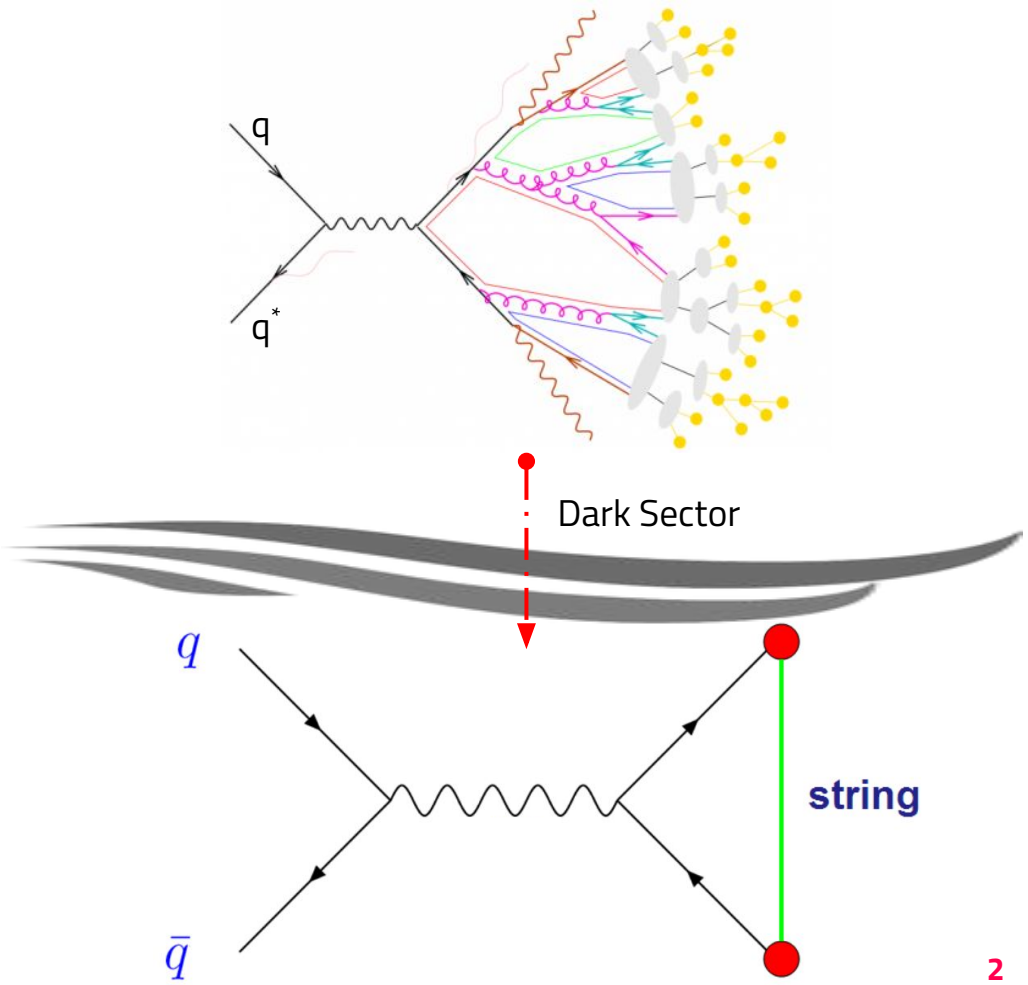
Lab-scale "String" Theory

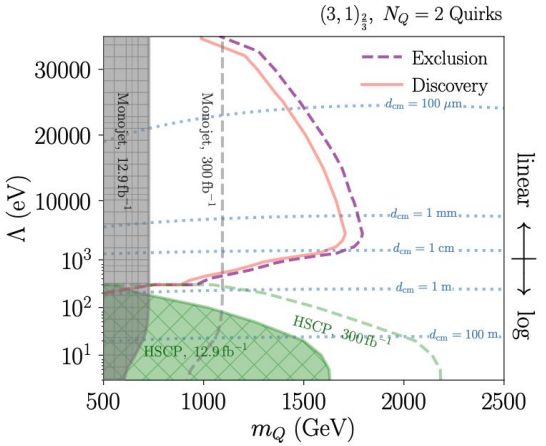
- Quirks: Heavy stable charged particles (vector-like fermions) connected by a flux tube of dark gluons (Luty, Kang)
- Thought Experiment
  - SM QCD: $m_{Quark} << \Lambda_{QCD}$
  - Dark/Quirk QCD:

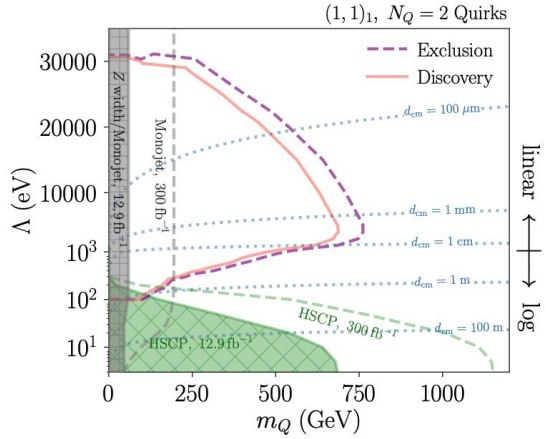
    $m_{Quirk} >> \Lambda_{Dark}$
- SM Case: Flux tube breaks, leading to radiation into lighter quarks
- Quirk Case: Flux tube does not break, causing macroscopic oscillatory motion and eventual annihilation



Search Regimes

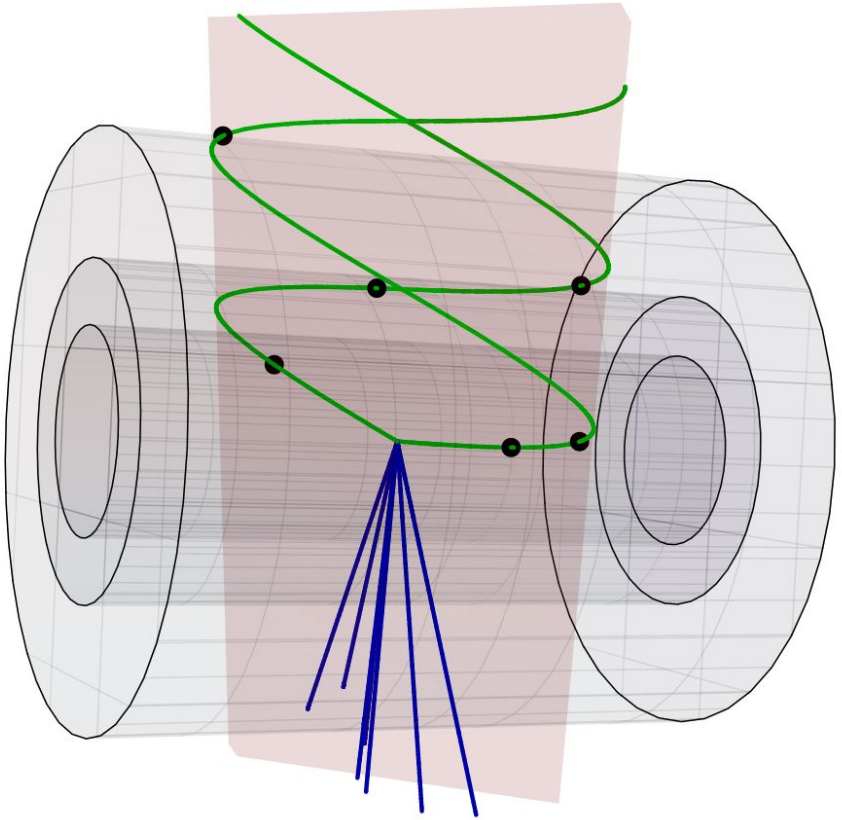
- *Λ ≤ 100 eV*
  - *String length is equal to or greater than detector size*
  - *Constrained by existing HSCP searches*
- **100 eV ≤ Λ ≤ 10 keV**
  - **Oscillation amplitude d ~ 0.1-10 cm**
  - **Constrained by jets + MET search**
- *Λ ≥ 30 keV*
  - *Oscillation amplitude is smaller than detector resolution (~100 μm)*
  - *Resolved as single high p_T, dE/dx track*
- **Current searches limited by standard trigger acceptances**
  - **Any additional kinematic data may improve reach**





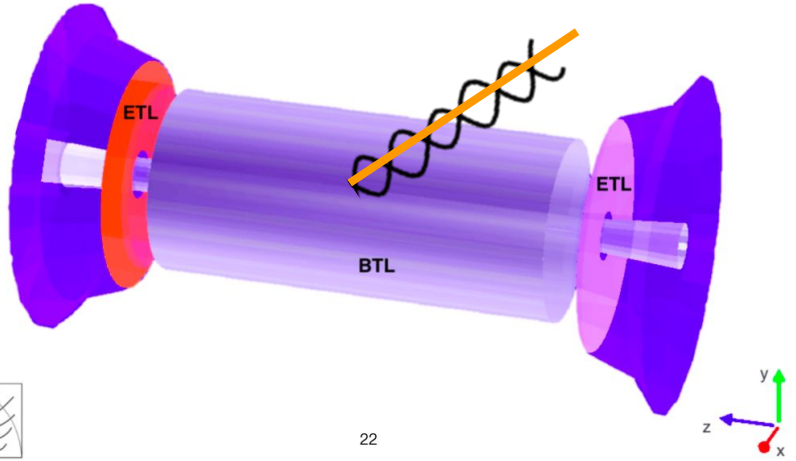
Quirk Dynamics

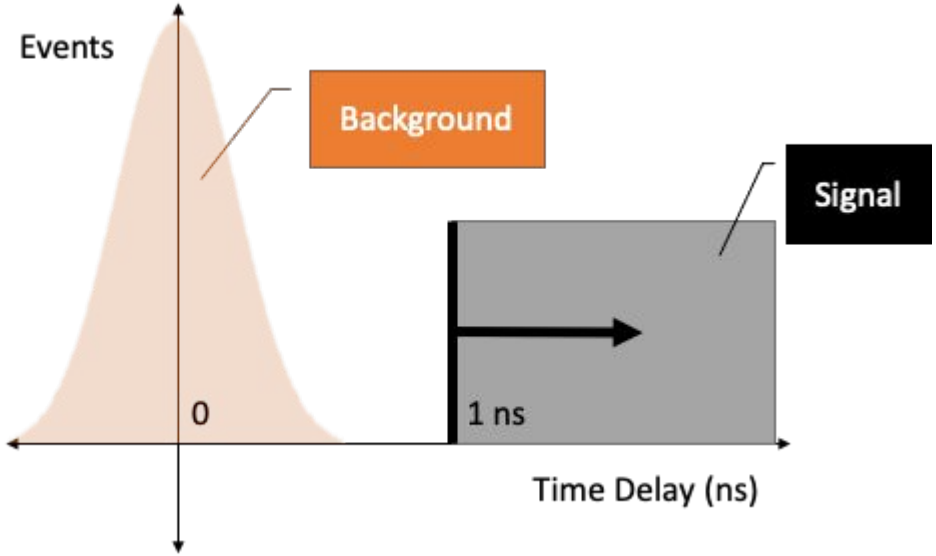
- Linked quirk/anti-quirk pair oscillates while moving outward from the initial collision
- Interaction with inner detector does not change angular momentum of quirk system → planar oscillation
- Current reconstruction algorithms are not designed to handle this signature



Search Strategy: Time Delay

Quirks as oscillating, heavy masses travel slowly

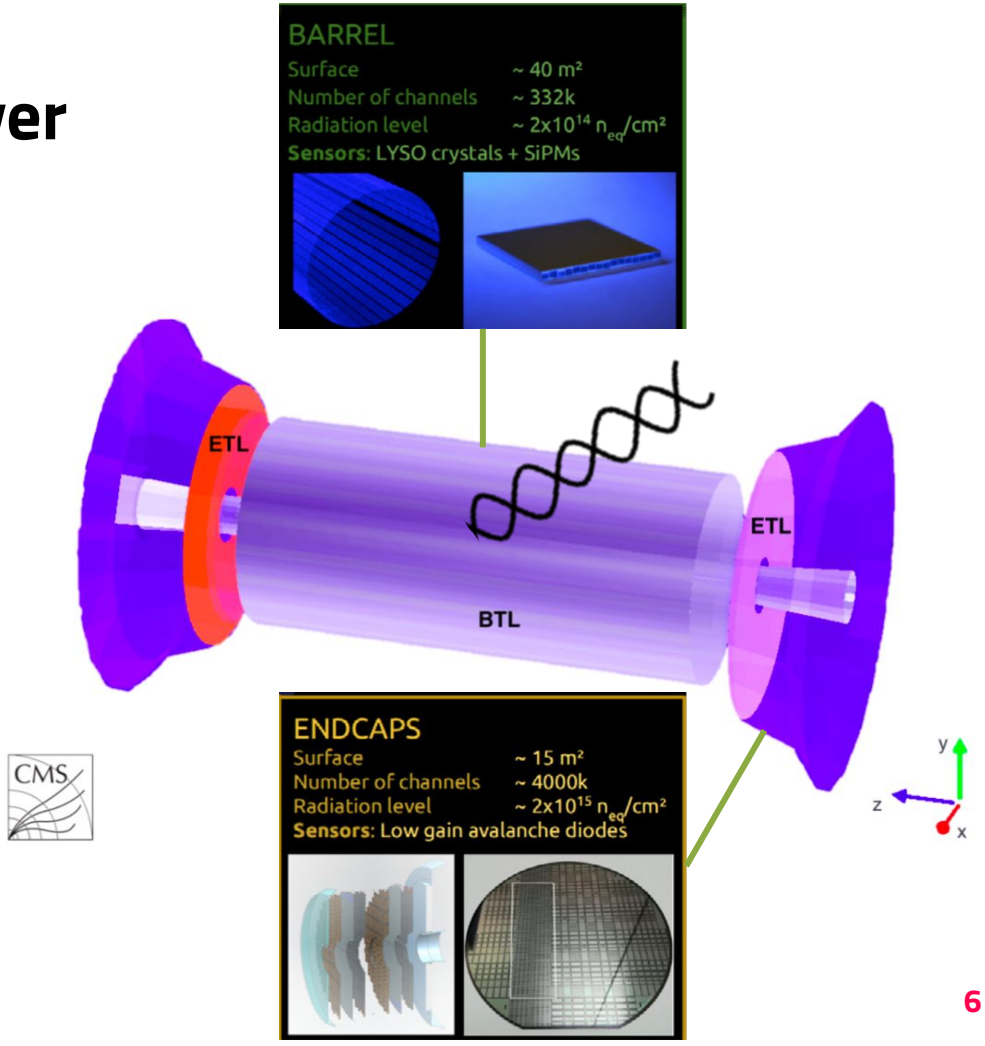




Time Delay = $t_{Quirk} - t_{Light}$

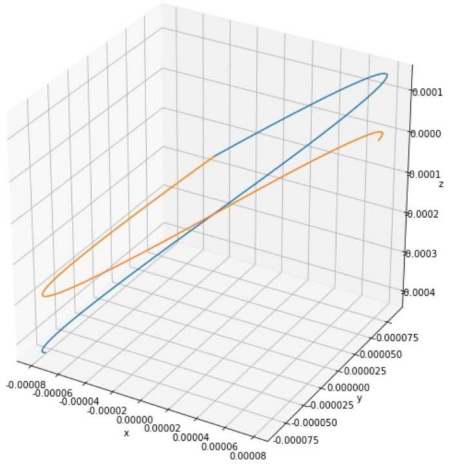
CMS Proposed MTD Layer

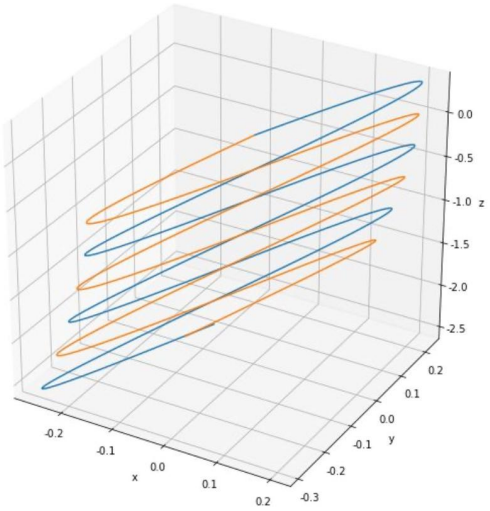
- 4 mm timing detector layer between tracker and ECAL for charged particles
- Timing resolution: 30 ps
- BTL
  - LYSO:Ce read out with SiPMs
- ETL
  - Radiation-tolerant LGADs



MadGraph Signal Generation

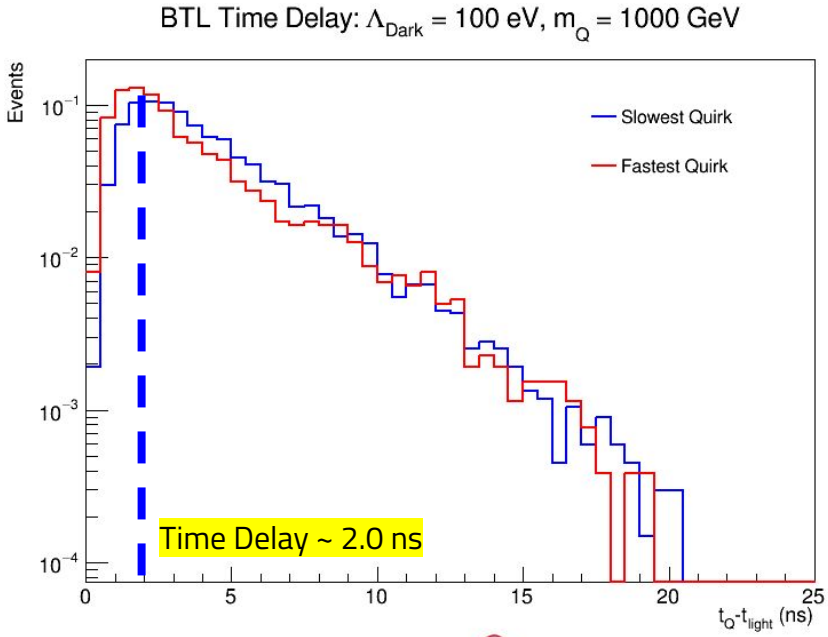
- m_{quirk} x Λ_{dark} Parameter Space Scan
  - m_{quirk}: [500 GeV, 2500 GeV]
  - Λ_{dark}: [100 eV, 3 keV]
- Model: VLQ_UFO
  - Extension of SM with vector-like top partners
  - Focusing on T-type quark as category for quirk
- Samples generated with {0,1} extra jets
  - Quirk evolution done through self-made codebase

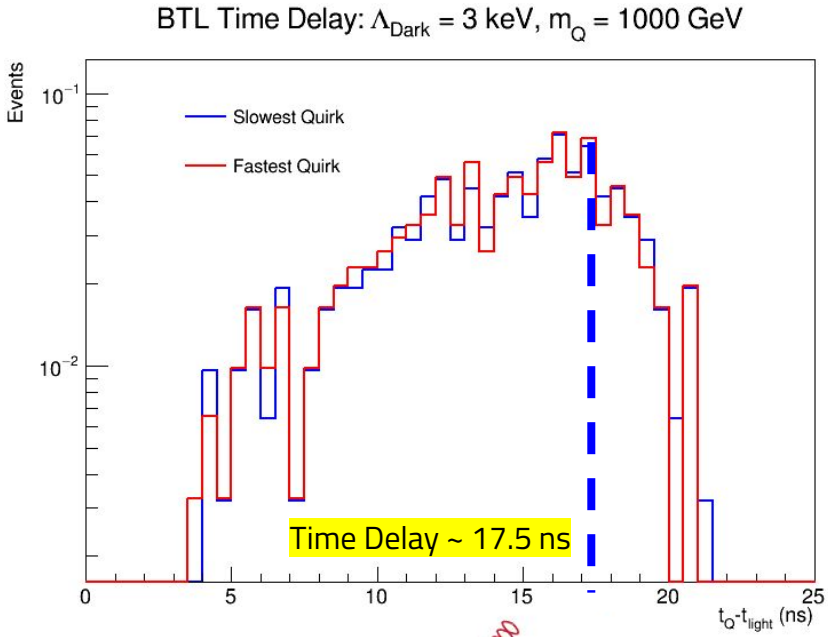


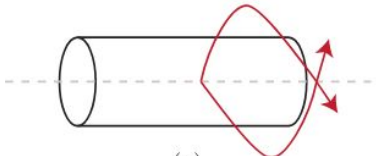


BTL Time Delay Distributions

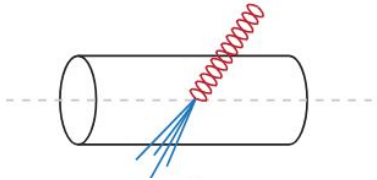
BTL yields greater time delay stats in the **low** Λ_{Dark} region





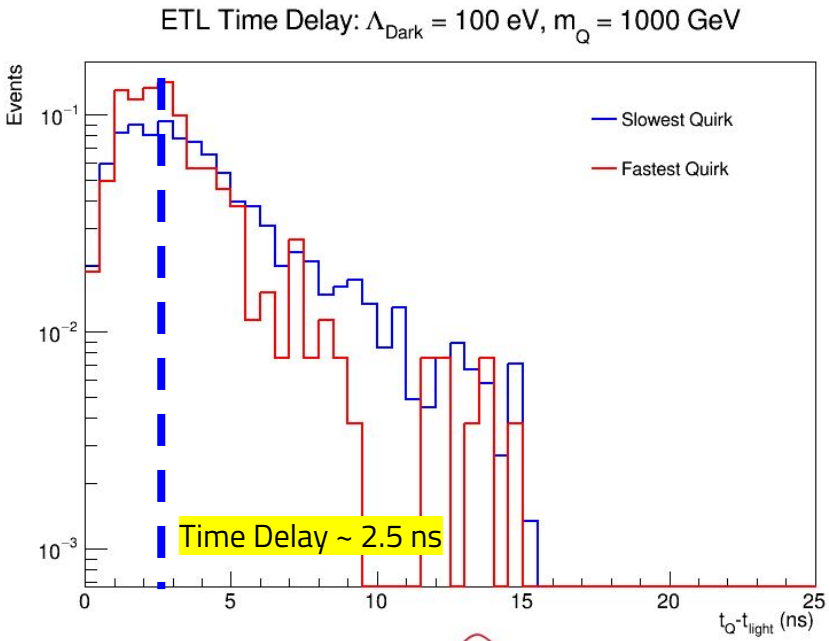


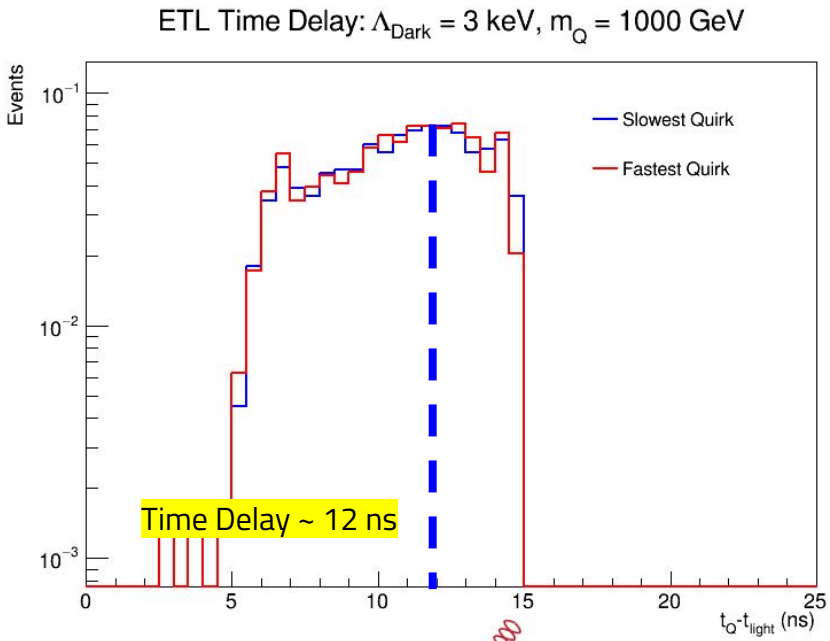
$$t_{light} = d_{origin}/c$$

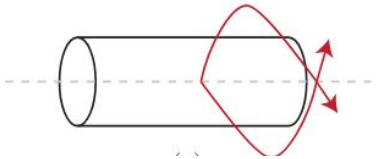


ETL Time Delay Distributions

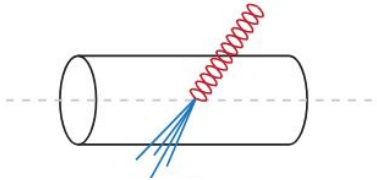
ETL yields greater time delay stats in the **high** Λ_{Dark} region







$$t_{light} = d_{origin}/c$$



Geometric Cut

Higher quirk masses yield lower signal efficiencies*	BTL is better for low Λ_{Dark}, ETL is better for high Λ_{Dark}

BTL	Λ_{Dark}= 100 eV	825 eV	1.55 keV	2.275 keV	3 keV
m_Q = 500 GeV	0.591	0.073	0.070	0.066	0.062
1000 GeV	0.696	0.035	0.032	0.032	0.032
1500 GeV	0.743	0.016	0.013	0.012	0.012
2000 GeV	0.763	0.007	0.005	0.005	0.005
2500 GeV	0.783	0.003	0.002	0.001	0.001
ETL	Λ_{Dark}= 100 eV	825 eV	1.55 keV	2.275 keV	3 keV
m_Q = 500 GeV	0.288	0.166	0.148	0.137	0.127
1000 GeV	0.243	0.102	0.081	0.073	0.068
1500 GeV	0.223	0.061	0.040	0.036	0.034
2000 GeV	0.215	0.032	0.017	0.015	0.014
2500 GeV	0.197	0.015	0.006	0.005	0.005

Geometric cut refers to at least one quirk reaching specified layer after center of mass time > 12.5 ns

Timing | Geometric Cut

BTL region maintains more signal efficiency after timing cut overall

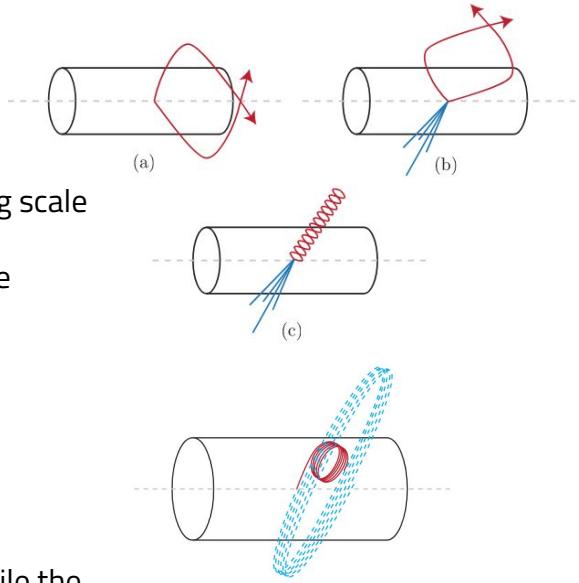
High efficiency (>95%) for both BTL+ETL for $\Lambda_{Dark} \geq 825$ eV

BTL	Λ_{Dark}= 100 eV	825 eV	1.55 keV	2.275 keV	3 keV
m_Q = 500 GeV	0.413	0.999	1.0	1.0	1.0
1000 GeV	0.584	1.0	1.0	1.0	1.0
1500 GeV	0.731	1.0	1.0	1.0	1.0
2000 GeV	0.830	1.0	1.0	1.0	1.0
2500 GeV	0.890	1.0	1.0	1.0	1.0
ETL	Λ_{Dark}= 100 eV	825 eV	1.55 keV	2.275 keV	3 keV
m_Q = 500 GeV	0.335	0.967	0.958	0.956	0.954
1000 GeV	0.550	0.998	0.997	0.999	0.998
1500 GeV	0.727	1.0	1.0	1.0	1.0
2000 GeV	0.853	1.0	1.0	1.0	1.0
2500 GeV	0.927	1.0	1.0	1.0	1.0

Timing | geometric cut refers to a 3 ns time delay cut applied on all events passing the geometric cut

Discussion

- Conclusions
  - Search represents a departure from probing the electroweak breaking scale
  - Quirk trajectories were successfully simulated and signal events were generated using MadGraph
  - Time delay proved to be valuable discriminants for the quirk signal
    - Use of the MTD (BTL and ETL) is motivated
    - BTL proves more effective in probing the low Λ_{Dark} regime, while the ETL proves more effective in probing the high Λ_{Dark} regime



Discussion

- In Progress
  - Explore plane-fitting seeded by timing hits as an additional discriminant
  - Determine and generate possible backgrounds to quirk signal
    - Timing: SoftQCD with finite MTD timing resolution
  - Expand analysis to investigate other quirk signatures
    - Currently only looking at quirks produced through DY
    - Colored cases from QCD + one charged, one neutral (Luty, Kang 2009 at right)

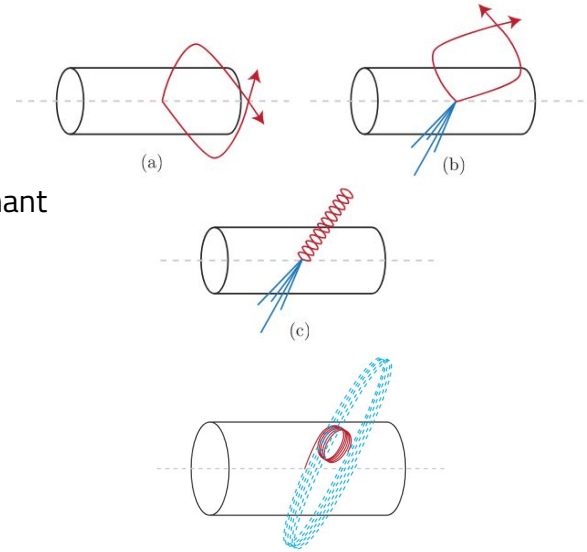


Figure References

2	A. May Journal Club: Statistical hadronization and thermalization
2	A. Z. Chacko: Quirks
3, 17, 18	A. Simon Knapen, Hou Keong Lou, Michele Papucci, and Jack Setford: Tracking down Quirks at the Large Hadron Collider
11, 12	A. Junhai Kang and Markus A. Luty: Macroscopic Strings and "Quirks" at Colliders

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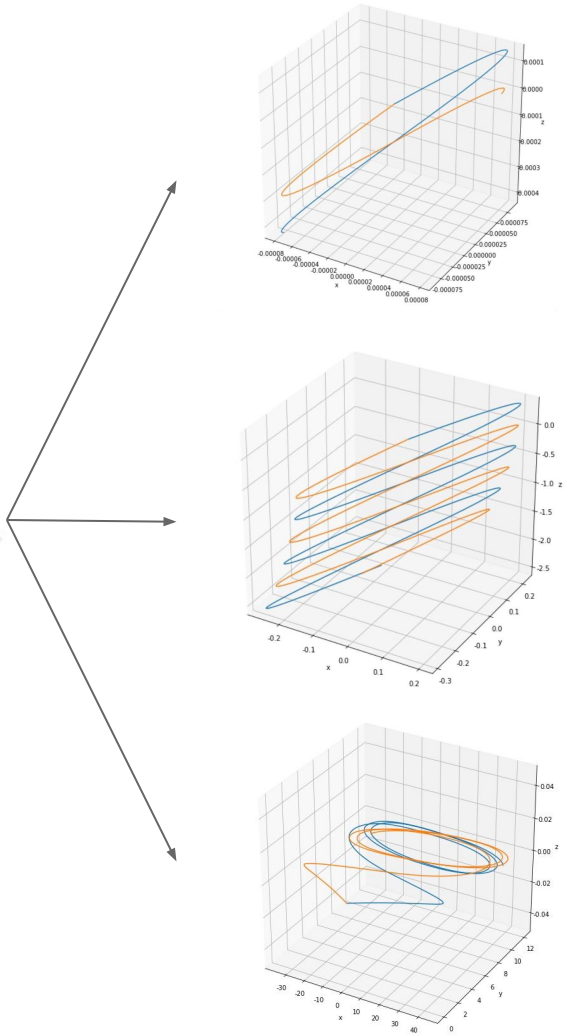
Backup Slides

Quirk Trajectories

$$\frac{\partial}{\partial t}(m\gamma \boldsymbol{v}) = -\Lambda^2 \left(\frac{\sqrt{1-v_\perp^2}}{v_\parallel} \boldsymbol{v}_\parallel + \frac{v_\parallel}{\sqrt{1-v_\perp^2}} \boldsymbol{v}_\perp \right) + \boldsymbol{F}_{\text{ext}},$$

- Single Quirk Equation of Motion (arXiv: 1708.02243)



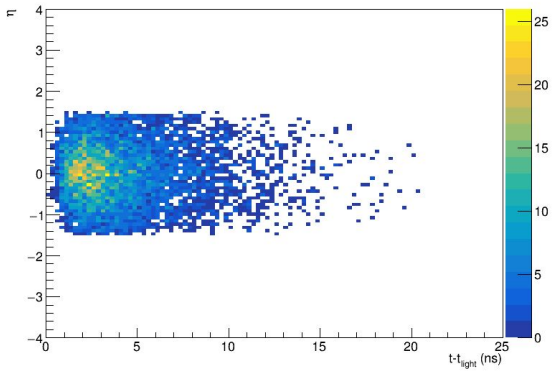
Bunch Timing Cut (t_{COM} < 12.5 ns)

Mass (GeV)↧	*Efficiency*
500	0.9878
1000	0.9695
1500	0.9377
2000	0.8983
2500	0.8466

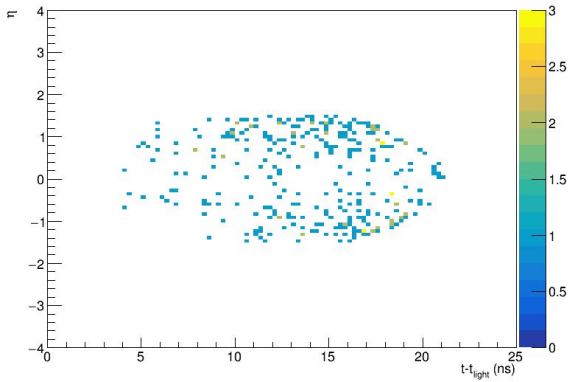
η-space x Time Delay Distribution

- Low Λ_{Dark} region
  - Majority of events in the low eta, low time delay region
- High Λ_{Dark} region
  - Majority of events in the high eta, high time delay region

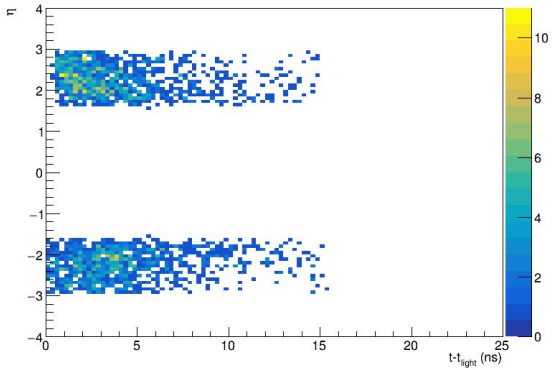
BTL, Λ_{Dark} = 100 eV, m_Q = 1000 GeV



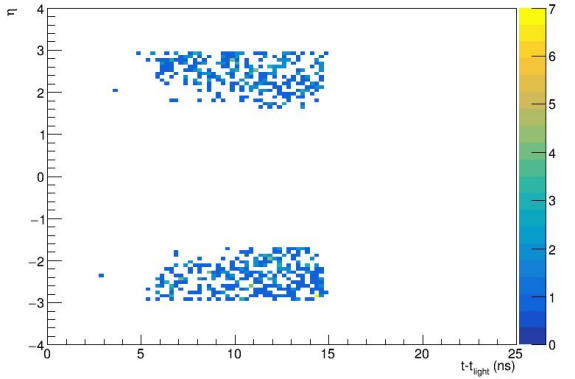
BTL, Λ_{Dark} = 3 keV, m_Q = 1000 GeV



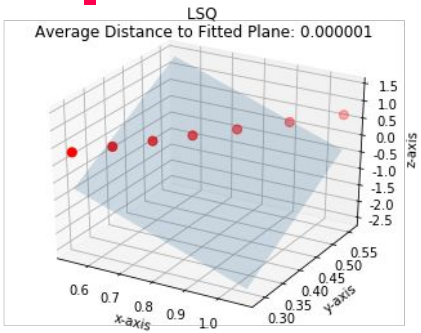
ETL, Λ_{Dark} = 100 eV, m_Q = 1000 GeV

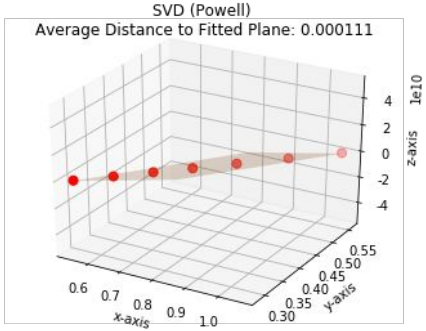


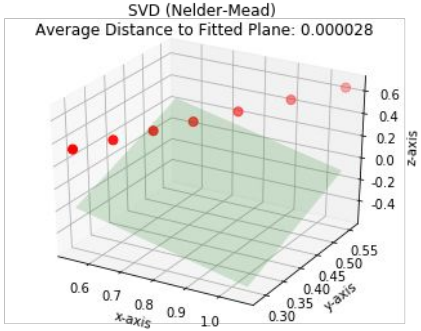
ETL, Λ_{Dark} = 3 keV, m_Q = 1000 GeV

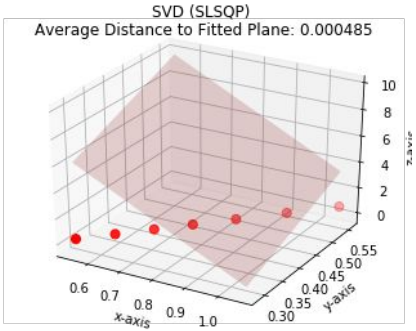


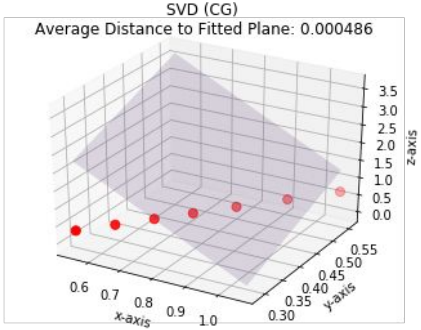
Plane-Fitting Algorithms Comparison (m)

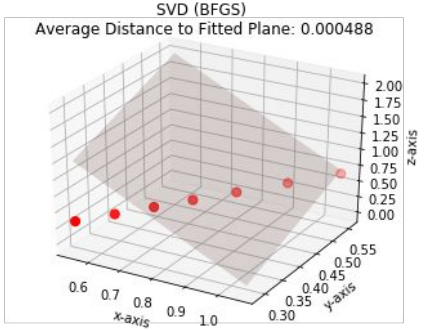


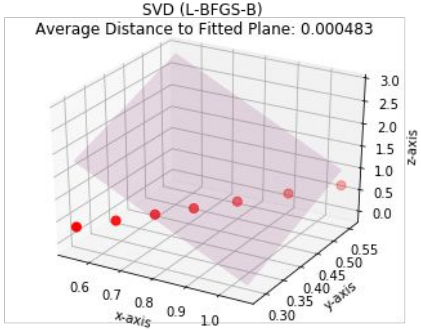


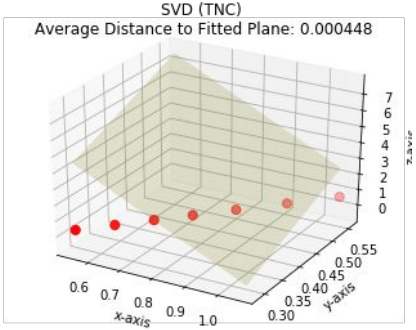






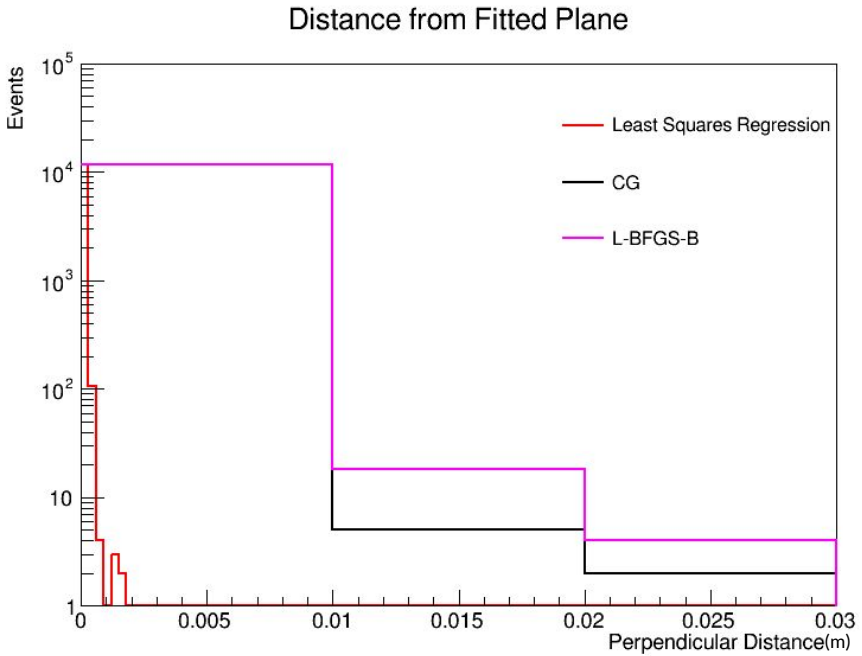


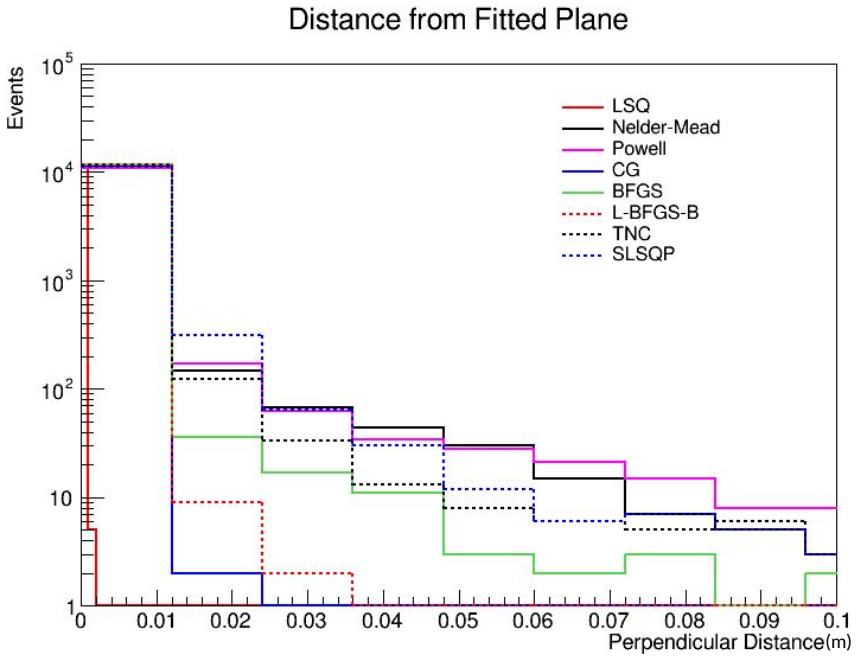




Note: Single quirk event, plane constructed from intersections with multiple tracker layers

Average Perpendicular Distance to Fit





For small hit counts, simple LSQ performs the best, generating the most planes in the 0 bin
(Left plot only features the top performing methods)

BTL Plane Fitting Tolerance Cut

	Λ_{Dark} = 100 eV
m_Q= 500 GeV	0.87
1000 GeV	0.83
1500 GeV	0.78
2000 GeV	0.72
2500 GeV	0.67

Low quirk mass yields highest signal efficiencies after 40 microns cutoff to plane thickness