Visible Quirk Signals at Colliders

Joshua Forsyth [1] Matthew Low [2] Chris Verhaaren [1]

[1]Department of Physics and Astronomy, Brigham Young University, Provo, UT, 84602, USA

[2]Pittsburgh Particle Physics Astrophysics and Cosmology Center, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA

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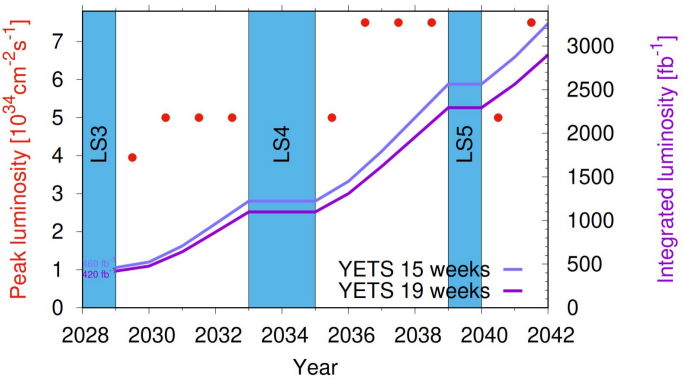
Collider Search Potential

LHC has made phenomenal achievements

- As a precision tool
  - Continues to push bounds, set limits.
  - Improved measurements of SM parameters.
  - HL-LHC will push further.[1]
- As a discovery tool
  - Last fundamental discovery was Higgs
  - Higher energies can probe further, but...
  - Could we be missing something at accessible energies?

Quirks could exist at reachable energies.



Figure

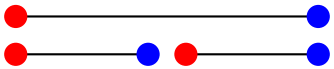
[1] https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

Parton Pair Production

Bound partons described by potential

$$V(r) \approx \sigma r \sim \Lambda^2 r \ . \qquad (\Lambda = \text{confining scale}) \tag{2.1}$$

Consider two states



with energies

$$E_1 \approx 2m_q + \Lambda^2 L \qquad \text{and} \qquad E_2 \approx 4m_q + \Lambda^2 \left(L - \frac{1}{2m_q} \right) \ . \tag{2.2}$$

The difference in energies is

$$\Delta E = E_1 - E_2 = 2m_q \left(\frac{\Lambda^2}{4m_q^2} - 1 \right) \ , \tag{2.3}$$

so

$$\Lambda > 2m_q \quad \Longrightarrow \quad \Delta E > 0 \quad \Longrightarrow \quad \text{fragmentation (hadronization)} \ .$$

SM Quarks vs. BSM Quirks

SM Quark Dynamics

Producing light quarks lowers the energy of a bound state. Consequences are:

- No free quarks.
- Jets etc

Figure: Pair production from bound SM quark-antiquark pair.

Quirk Dynamics

No light quirks $\implies$ suppressed pair production.
Consequences are:

- produced particles remain bound
- Radiation sheds energy and angular momentum (ℓ).
- Decays at $\ell = 0$ [2].

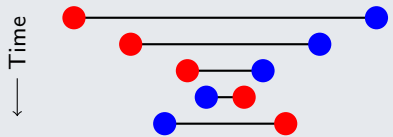


Figure: Bound quirks oscillate and decay at low angular momentum.

[2] Kang and Luty, 0805.464

Neutral Naturalness

Possible explanations for hierarchy problem:

- Fine-tuning
- Higgs mass naturally corrected

Most natural solutions compensate effects of top quark.

- Include top "partner" to approx. cancel loops from top.
- LHC bounds on SM color top partners: $m_{t'} \gtrsim 1.3$ TeV.

This project considers quirks motivated by Neutral Naturalness framework [3].

- Neutral: top quark's partner particle is not charged under SM QCD.

[3] Batell et al., 2203.05531

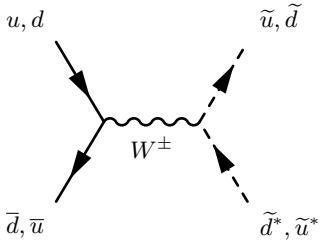
Simplified Scalar Quirk Model

One generation of scalar quirks ("squirks") with SM electroweak charge and hidden gauge color charge.

- Difference of electric charge $q_{\widetilde{u}} - q_{\widetilde{d}} = 1$.
- Agnostic to hidden gauge group. $SU(3)$ used to compare with Folded-SUSY[4].

Some other details:

- This project considers bound squirks ("squirkonium") states with net electric charge.
- Total bound state mass: $M \equiv m_u + m_d$, and
- Mass splitting between squirks: $\Delta \equiv m_u - m_d$.

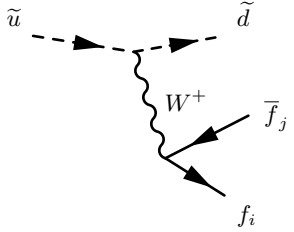


[4] Burdman et al., 0805.4667

β-decay into neutral squirkonium.

Neutral squirkonium has many more visible signals:

- $\gamma\gamma$, ZZ, W^+W^-, etc.



De-excitation and Annihilation

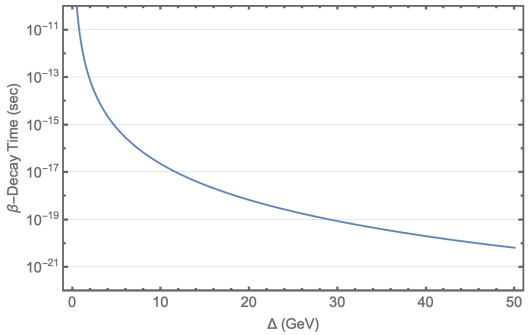
Radiates gauge bosons: photons, Z bosons (slower), hidden glue.

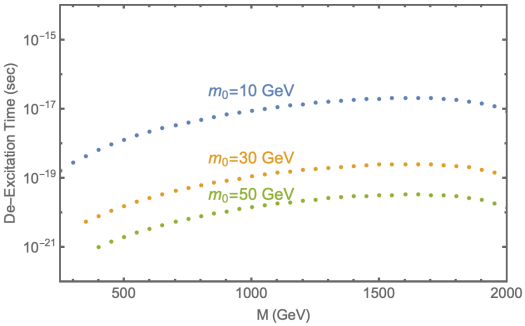
- Could be produced along with hidden glue.
- Could lead to additional, displaced decays through hidden glue.

Two decay signals:

- $W\gamma$ and WZ

Decay Times





β-decay time depends on mass splitting Δ.

- E.g. For $\Delta = 10$ GeV, $t_\beta \sim 10^{-17}$ $\implies$ de-excitation and decay more probable for $m_0 = 30, 50$ GeV and for $M \lesssim 500$ GeV with $m_0 = 10$ GeV.

Branching Ratios

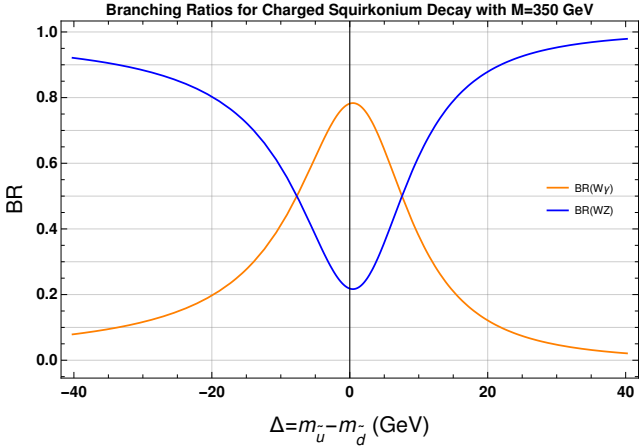
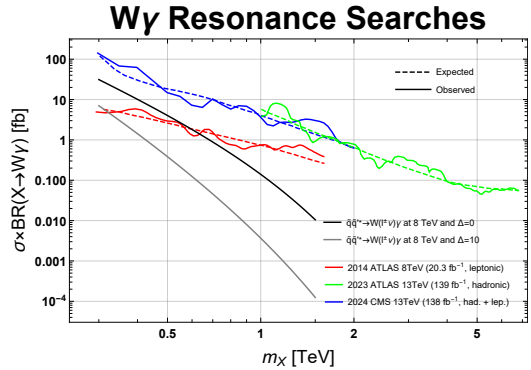
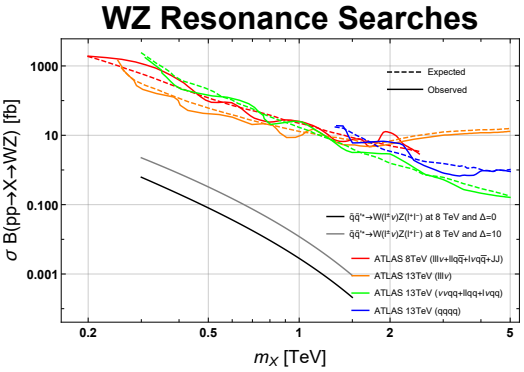


Figure: Analytical BR for charged squirkonium decay signals. Parameters: $M \equiv m_H + m_L$ and $\Delta \equiv m_H - m_L$.

Experimental $W\gamma$[5] and WZ[6] resonance searches could lead to detection.

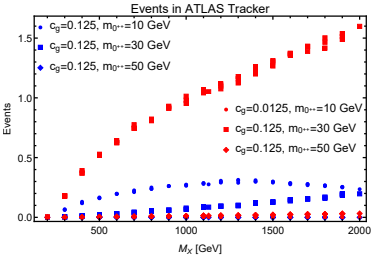
- Increased sensitivities or new strategies[7] will help.

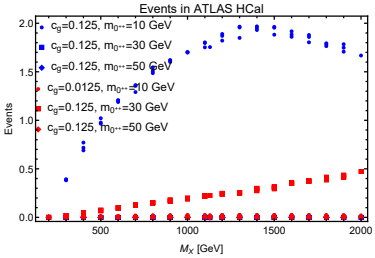


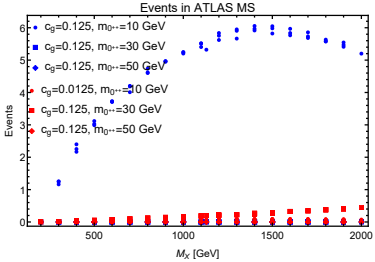


[5] See 1407.8150, 2304.11962, 2024 CMS Analysis Summary
[6] See 1406.4456, ATLAS PUB Note
[7] Capdevilla et al., 1912.08234

Decays with Hard Glueball (Preliminary Results)







Conclusions

Summary:

- Quirks have masses significantly larger than their confinement scale, preventing jet signals.
- Quirks produced in bound state de-excite and decay quickly.
  - Hidden glueball mass impacts likelihood of β-decay vs. de-excitation.
  - $\Delta < 10$ GeV robustly de-excite and decay before β-decay.
  - Can have greater mass splitting for larger confinement scale
- Mass splitting has noticeable implications for possible detection.
  - Branching Ratios vary significantly with mass splitting.

Future work:

- Neutral squirkonium has more decay products available (and more searches to compare against)
- Displaced decays: quirkonium decays into hidden glueballs that later decay into visible signals
  - GlueShower [8] or an updated version [9] could help in modeling hidden glue showers.
- Follow same procedure for fermionic quirks

[8] Curtin et al., 2202.12899
[9] Batz et al., 2310.13731