Quirks

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Disclaimer

Only a small portion of this talk is based on my own work, in collaboration with Burdman, Goh, Harnik and Krenke.

In particular, I have borrowed liberally from the work of

- Luty, Kang and Nasri
- Cheu and Parnell-Lampen
- Harnik and Wizansky

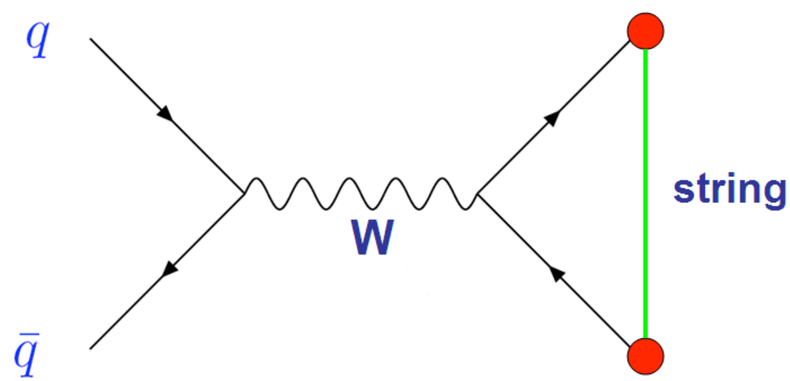
Much of this is work in progress.

Introduction

Consider the limit of QCD where all the quark masses are much larger than Λ_{QCD} , and there are no light quarks.

Gupta & Quinn

In this limit, what happens when quarks are pair-produced in a collider?



The absence of light quarks means that even when the quark separation exceeds Λ_{QCD}, the quarks remain joined by a QCD string! The string cannot snap because there are no light quarks, and there is not enough energy locally at any point along the string to pair-produce two heavy quarks. Very different from conventional QCD.

Could this be relevant to the real world? In particular, could something like this manifest itself at the LHC? Yes, if new physics at the weak scale includes `quirks'.

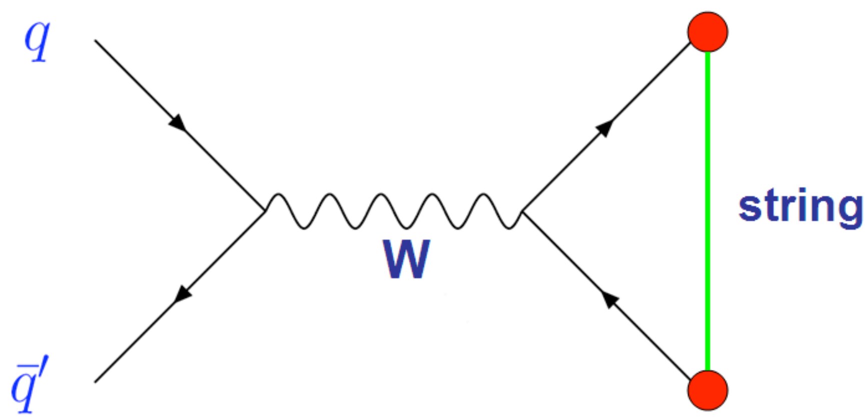
What are quirks?

Quirks are exotic vector-like fermions that transform as the fundamental (and anti-fundamental) under a hidden confining group, but also carry Standard Model charges.

By assumption, the quirk mass M is much larger than the confinement scale Λ. Furthermore, there are no additional fields charged under the confining group with mass less than M.

This system is then analogous to QCD with no light quarks, and behaves in much the same way.

Consider a quirk and anti-quirk that are pair-produced at a collider. Again, the crucial observation is that the two quirks cannot hadronize separately, because there are no light particles that transform as the fundamental of the confining group. Instead, at distances larger than Λ the two quirks remain connected by a string of hidden color.



Since the initial kinetic energy of the quirks is in general much larger than the confinement scale, the string can be very long, even macroscopic! Eventually the string pulls the quirks back together and they annihilate into Standard Model particles. Gives rise to striking collider signatures!

A brief (and possibly incomplete) history of quirks.

Khlopov (1981) briefly considered fermions charged under both the Standard Model and a hidden color (Y- color), in the context of fractionally charged particles.

Gupta and Quinn (1981) studied QCD with no light quarks, as a limit where non-perturbative effects are important.

Babu, Gogoladze and Kolda (2005) showed that in supersymmetric theories with quirks, the Higgs can be heavier than in the MSSM.

Strassler and Zurek (2006) considered theories with quirks as one interesting class of hidden valley models, with displaced vertices.

Luty, Kang and Nasri (2006) have been studying this class of theories, and their implications for the LHC. Were first to seriously consider the phenomenology of long strings. Came up with the name quirks.

Burdman, Z.C., Goh and Harnik (2006) found that scalar quirks arise naturally in the context of `folded supersymmetry', a new class of models for electroweak symmetry breaking.

Motivation for Studying Quirks

• An opportunity to study string theory in the lab! A very simple, concrete framework that leads to highly unusual collider signals. These signatures may be relevant to other models as well.

• Theories with multiple non-Abelian gauge groups, with matter charged under more than one gauge group, often arise in the low energy limit of string theory.

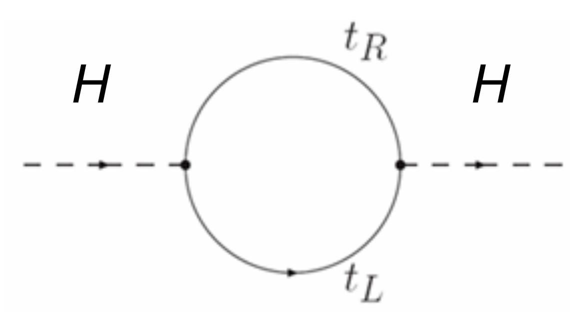
• Quirks are a characteristic feature of some new models of electroweak symmetry breaking.

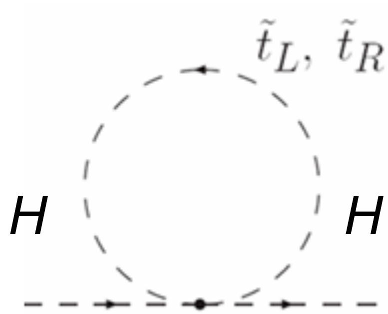
→ In theories with quirks it is possible to generate Higgs masses much larger than the MSSM upper bound, if Higgs has Yukawa couplings to the quirks. The hidden color group allows these couplings to be large.

Babu, Gogoladze & Kolda

The hierarchy problem of the Standard Model, which is related to the fine-tuning of the Higgs mass parameter, is the best motivation for new physics at the weak scale. The biggest source of this fine-tuning is the top loop, and the physics that cancels this loop is probably our best bet for new physics at the LHC.

The fine-tuning from all other sources is much smaller, and the corresponding new physics may not be accessible at the LHC. It is therefore very important to study all possible ways of cancelling the top loop. Not many ways are known. In folded supersymmetry, this loop is cancelled by scalar quirks.





scalar quirks

What parameters does quirk phenomenology depend on?

- The quirk mass M.
- The scale Λ at which the confining group gets strong.
- The Standard Model (SM) quantum numbers of the quirks. `Colorful' quirks carry SM color. `Colorless' quirks don't.

Quirks cannot couple directly at the renormalizable level to Standard Model fermions. Couplings to the Higgs require two or more quirks with different quantum numbers.

The phenomenology of scalar quirks, or `squirks', is similar to that of quirks. However squirks can couple directly at the renormalizable level to the Higgs.

$$|H|^2|\tilde{Q}|^2$$

This term has phenomenological consequences.

Anatomy of an Event

Any collider event involving quirks occurs in three stages.

- production
- energy loss
- annihilation

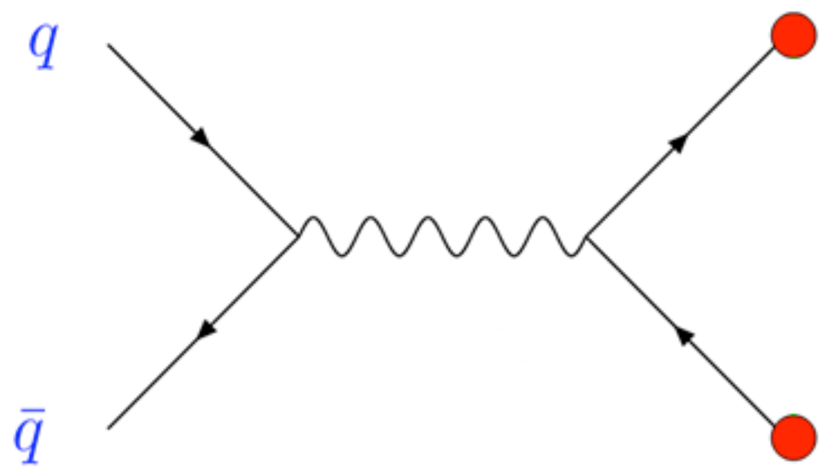
In the first stage the quirks are pair-produced through an off-shell gluon, W, Z or photon.

The quirks are initially produced with considerable kinetic energy. In the second stage, as the string pulls the quirks together, this energy is lost to hidden sector glueballs, photons, and Standard Model hadrons. For long strings, energy loss in the detector must also be accounted for.

In the final stage, the quirks pair-annihilate back into Standard Model particles, or into hidden sector states.

Production

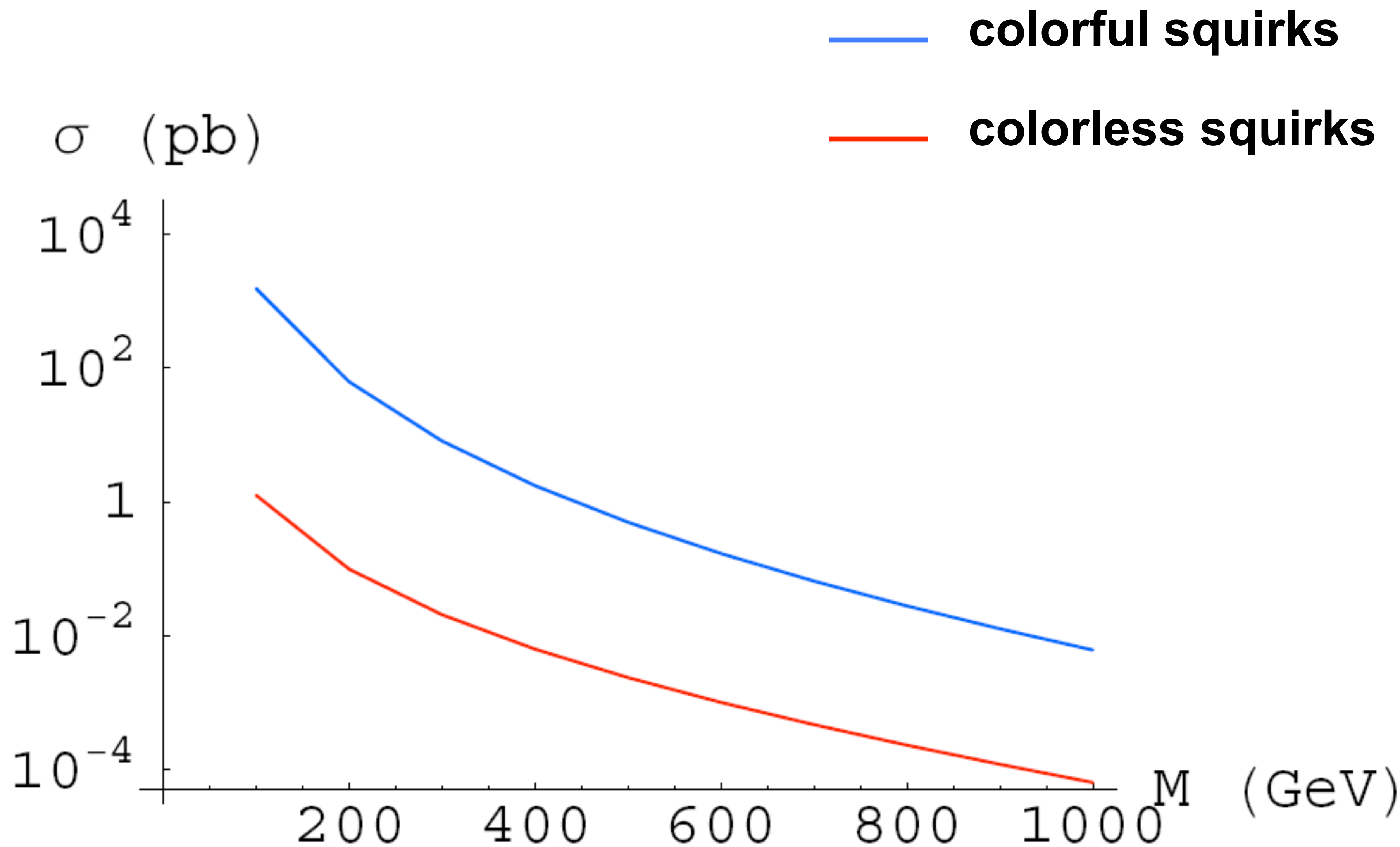
The quirks are pair-produced in the s-channel through an off-shell gluon, W, Z or photon. The rate depends on the Standard Model quantum numbers of the quirks and is straightforward to calculate. The confining group only determines a trivial multiplicity factor.



If the quirks are charged under Standard Model color, at the LHC production through the gluon dominates. However, for quirks produced through this channel, the dominant visible annihillation channel is to hadrons, and so the background is also large.

For quirks without Standard Model color charge, but with weak charge, production through the W dominates. This has the advantage that the quirks cannot annihilate purely to invisible states because electric charge must be conserved.

Production through the Z and photon is also significant in this case. However, for most values of Λ annihilation to invisible states is not negligible, and must be taken into account. Therefore the signal is somewhat reduced.



colorful squirks
colorless squirks
σ (pb)
10^4
10^2
1
10^-2
10^-4
M (GeV)
200
400
600
800
1000

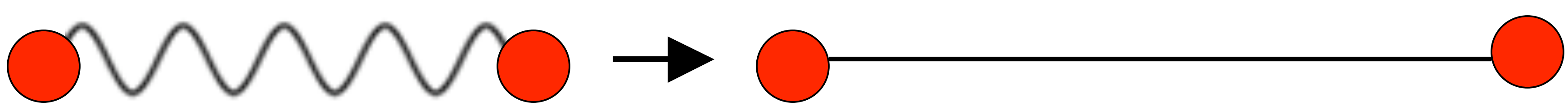
Energy Loss

What can quirks lose energy to?

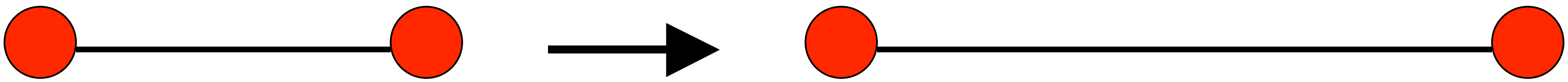
- photons
- glueballs of the confining group
- Standard Model hadrons (if the quirks are colored)
- the detector (if the string is long enough)

Let us understand how this happens.

Once the quirks are separated by a distance much more than $1/\Lambda$, a string forms between them. The lowest energy configuration of the string corresponds to when it is straight. As the quirks separate, the string gets straightened out.



As the quirks move further apart, the length of the string grows, and it remains approximately straight. During this period, because of the glueball mass gap, we don't expect significant energy loss to glueballs. Also, locally there is no lower energy configuration for the string to de-excite to.



The string has a tension $T \sim \Lambda^2$, which causes the two quirks to decelerate, and eventually come to rest. The string length L is then of order E/Λ^2 , where E is the initial kinetic energy of the quirks.

For E ~ 100 GeV, and

- $\Lambda \sim 1$ KeV, L ~ 10 mm → displaced vertex
- $\Lambda \sim 100$ eV, L ~ 1m → quirks enter detector → energy loss

The acceleration of the quirks caused by the string tension causes them to radiate photons. The photon frequency is of order Λ^2/M. This is the origin of the photon energy loss.

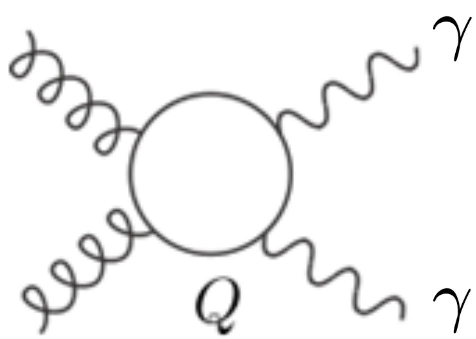
Once maximum separation has been reached, the string tension causes the quirks to move back towards each other. Since the net angular momentum of the system is small, of order a few, the impact parameter is of order $1/M$. Since this is smaller than $1/\Lambda$, we expect some energy loss to hidden sector glueballs when the quirks cross. If the quirks carry Standard Model color, there will also be energy loss to hadrons.

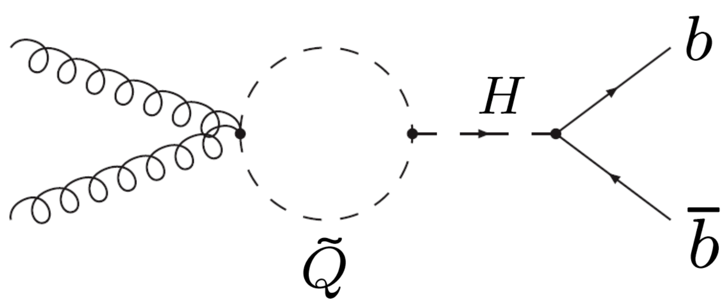
The number of oscillations the quirks perform before annihilating depends on the efficiency of these energy-loss mechanisms. If inefficient, we expect displaced vertices and tracks in the detector even for larger values of Λ. The quirks may also annihilate before losing all their energy.

Can we detect hidden glueballs?

It is possible to detect hidden glueballs if they decay inside the detector. In the case of colorless quirks, the dominant decay channel is to photons, through a loop of virtual quirks. For colorful quirks, for values of Λ greater than a few GeV, decays to hadrons are preferred. These decays will happen in the detector for Λ > 20 GeV.

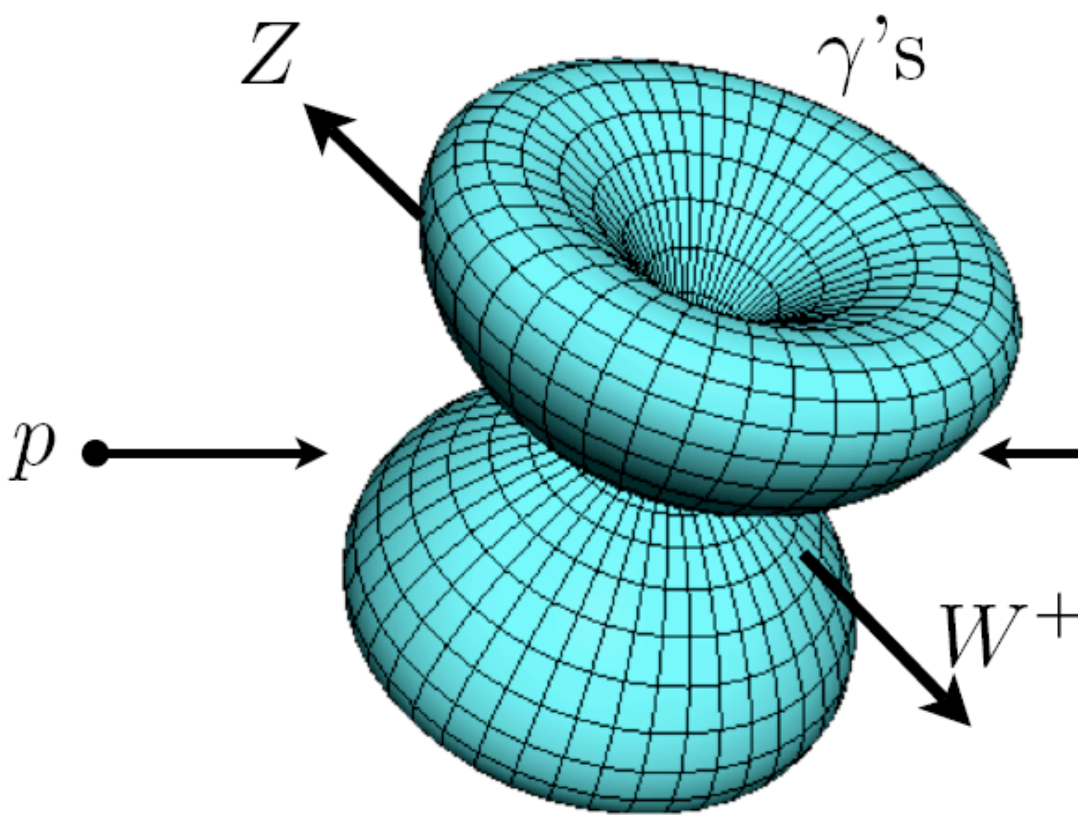
In the case of scalar quirks, because of the renormalizable couplings to the Higgs, decays to Standard Model fermions may be preferred. For Λ > 20 GeV, these are to b's.



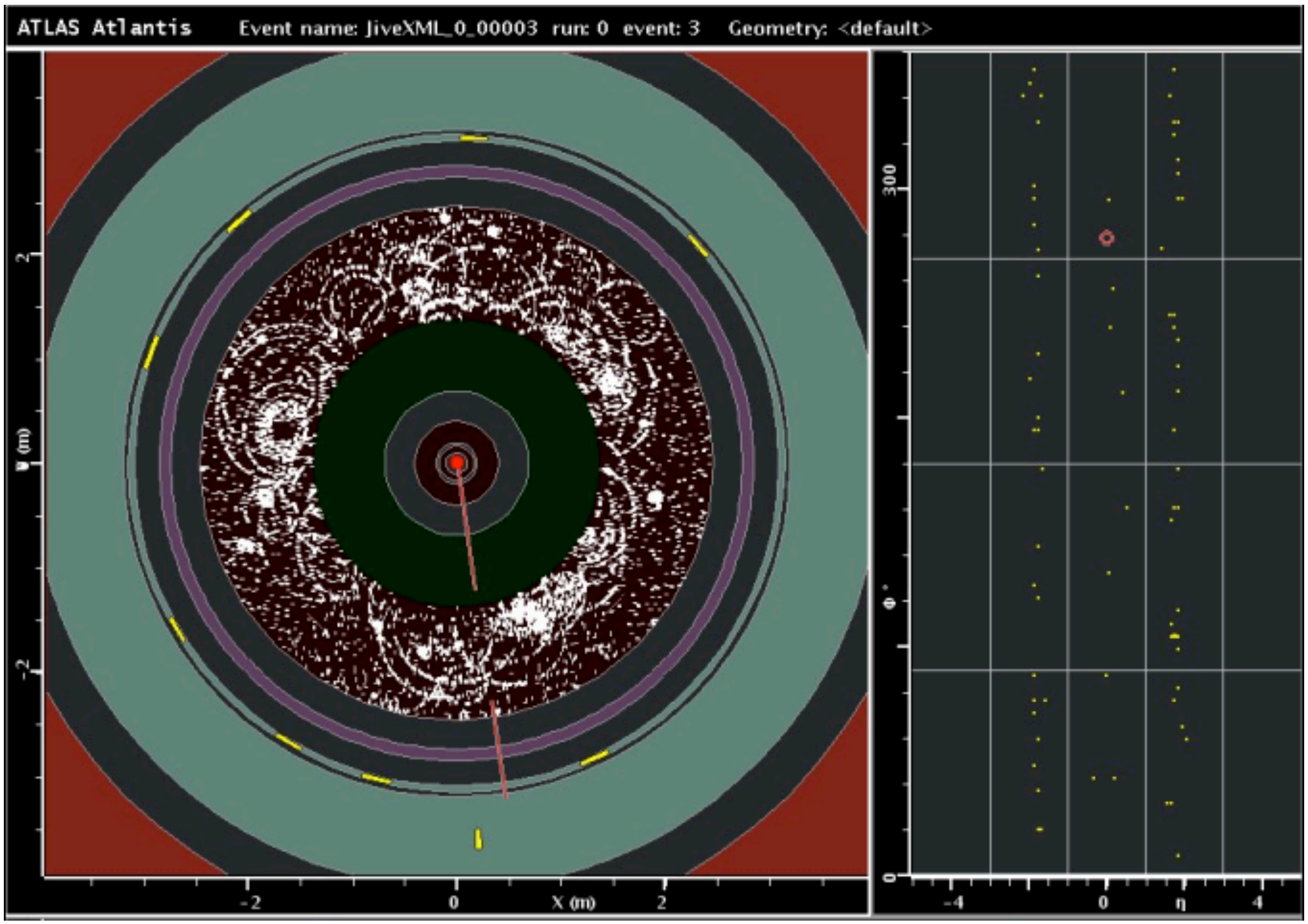


Can the Soft Photons be Detected?

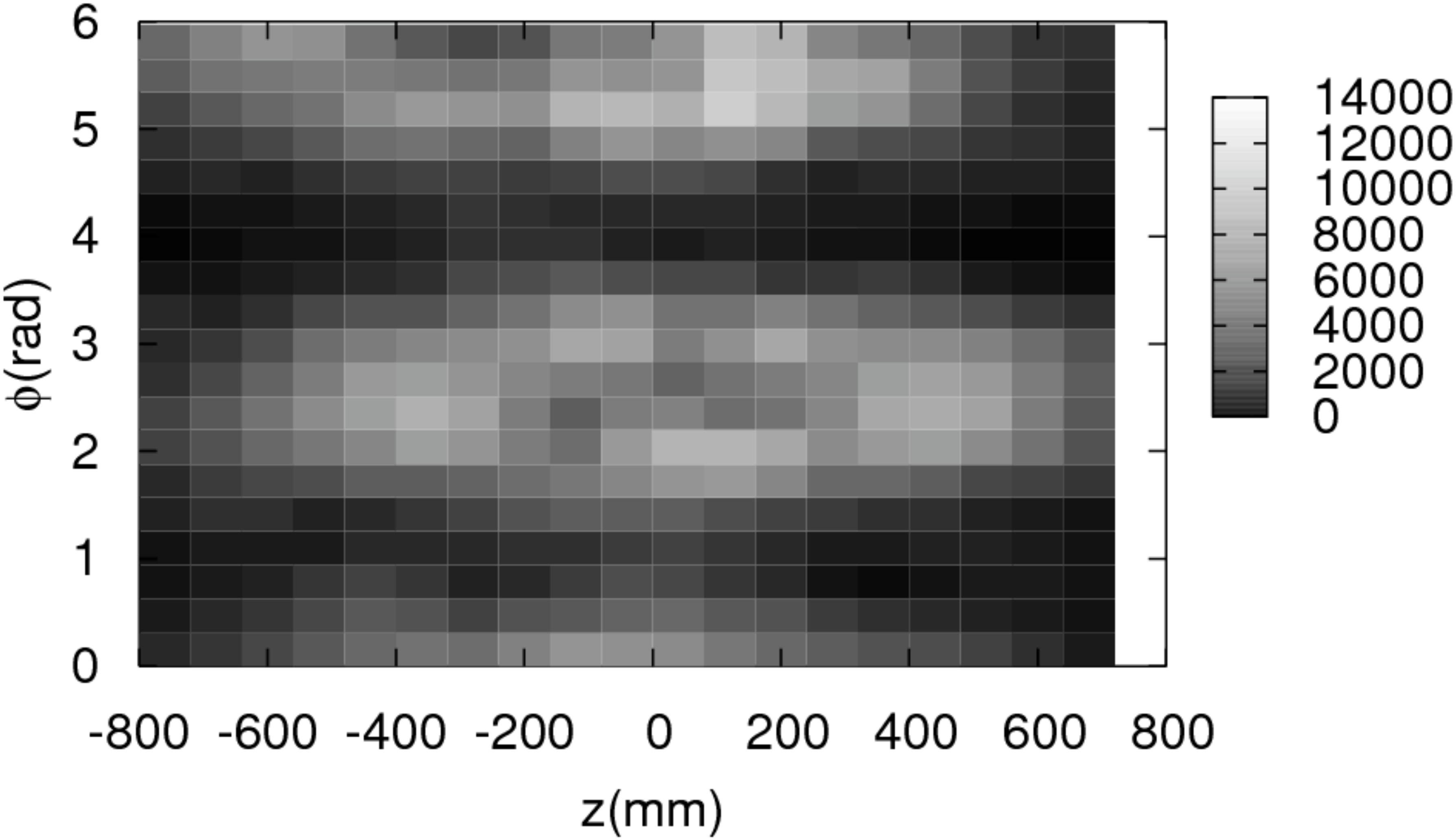
For Λ ~ 10 GeV the soft photons have frequencies of order 100 MeV to 1 GeV, and have a characteristic angular distribution.



Soft photons of this energy can be picked up by the tracking system, as seen in this picture from the ATLAS event display. (Cheu and Parnell-Lampen)

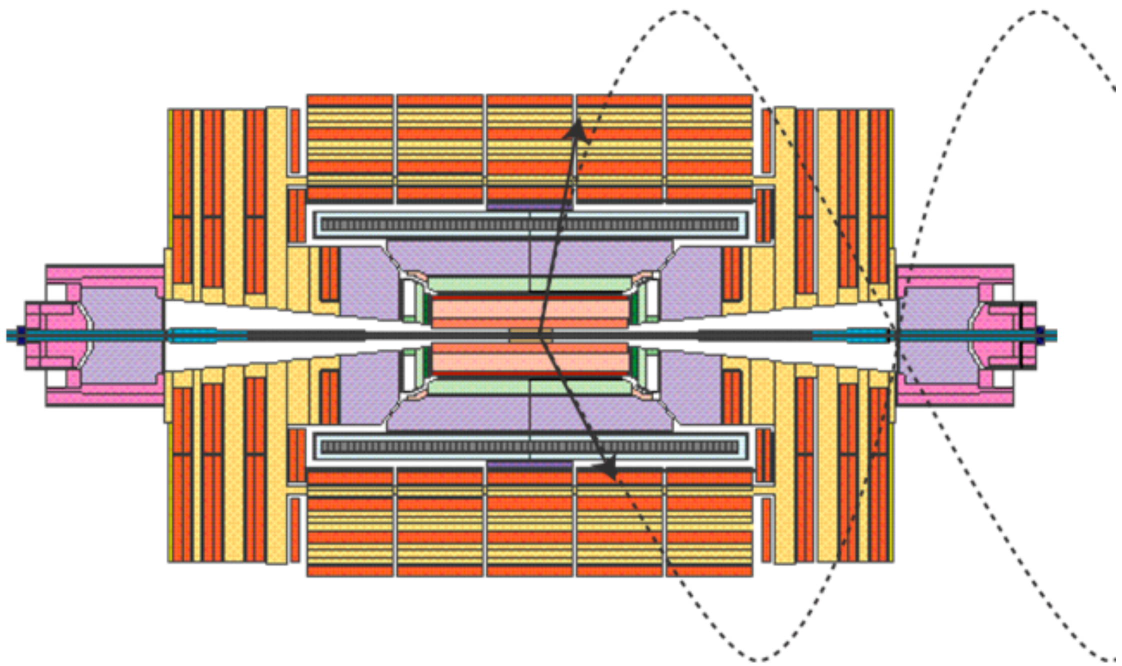


This picture shows the angular distribution of the energy that reaches the electromagnetic calorimeter. It represents about half the total energy in photons. (Harnik & Wizansky)

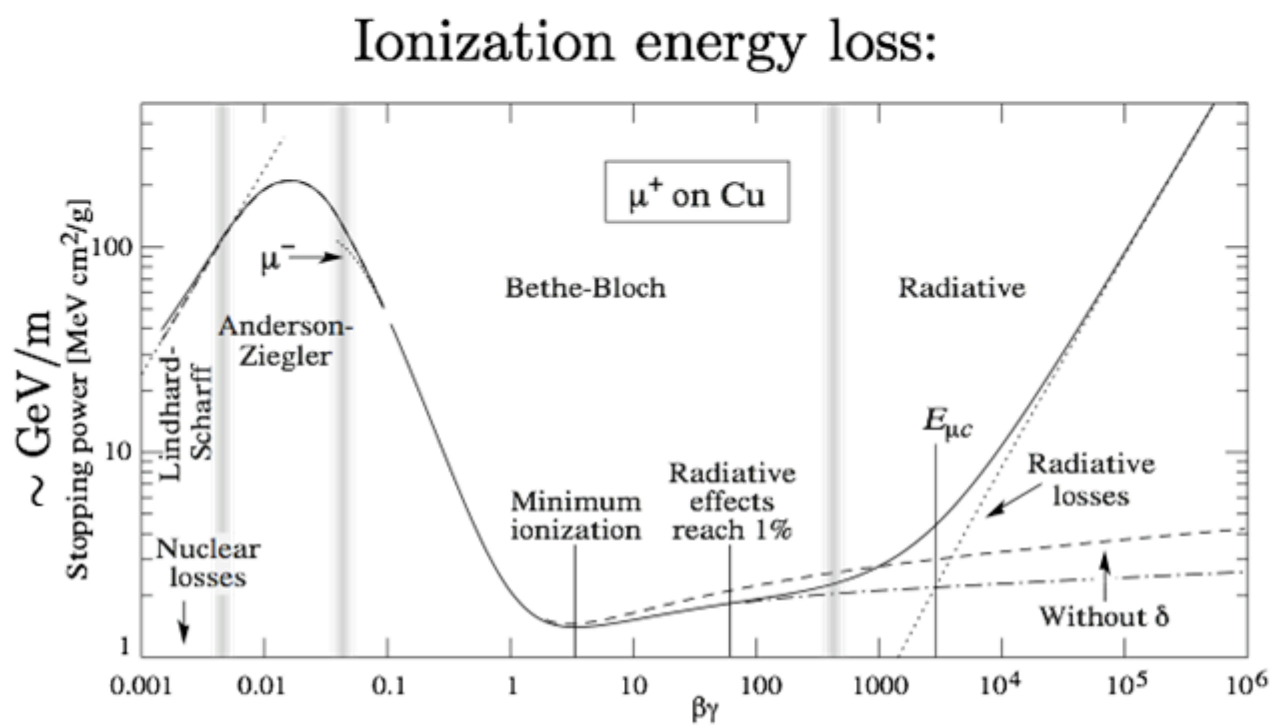


Quirks in the detector (Luty, Kang and Nasri)

For values of Λ of order 100 eV or less there is a significant probability for quirks to enter the detector. The string tension causes their tracks to bend differently than those of muons and other charged particles. In such a scenario a single event might suffice for discovery!

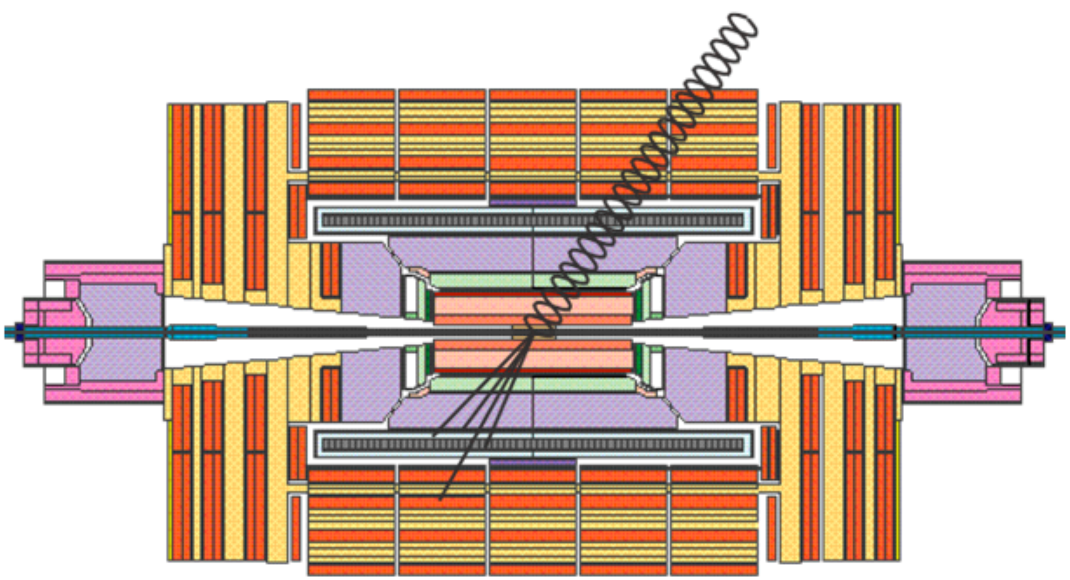


Energy losses in the detector can be large enough to catalyze annihilation. Electromagnetic energy loss dominates over hadronic energy loss. In this scenario, annihilation generally occurs away from the beam axis, and is not prompt.



Quirk Pairs in the Detector (Luty, Kang and Nasri)

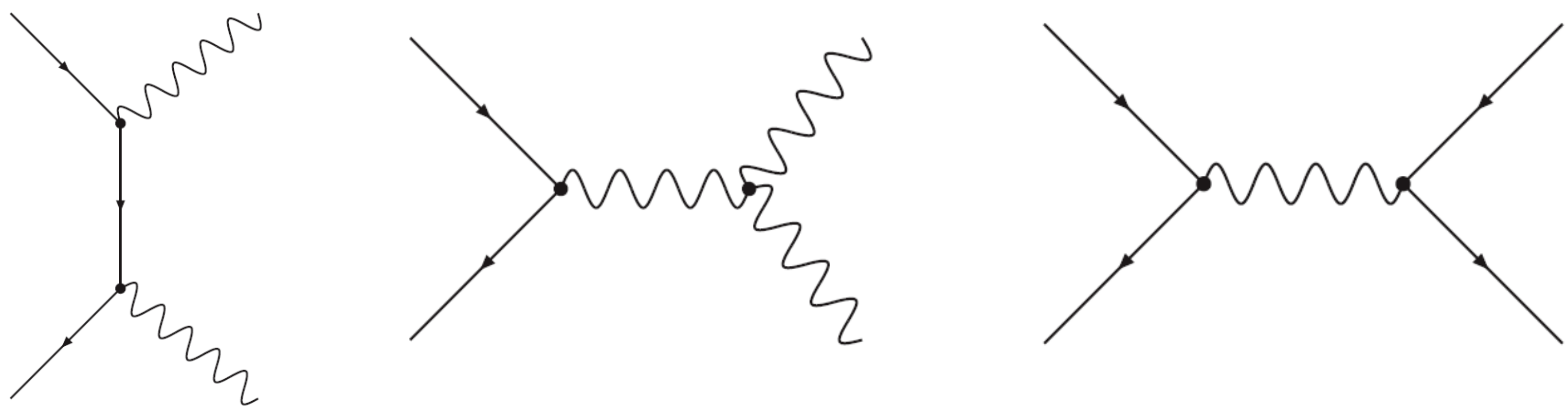
For Λ in the 10 KeV to MeV range, the string length is of order a mm or less. If energy loss is somewhat inefficient, the quirk lifetime could be long enough that a quirk pair could enter the detector as a single unit. These would ionize very differently from the familiar SM particles, since the oscillations of the quirks mean that their true trajectories are much longer than would be apparent from the (single) track. Also, the bound state has a different invariant mass event by event because of the energy in the string.



Annihilation

Annihilation of Colorful Quirks

In the case of colorful quirks, the dominant visible annihilation channel is to two jets. This process can occur either in the t-channel to two gluons, or in the s-channel to quark and anti-quark, or to two gluons. The s-channel annihilation is simply the reverse of the production process. We expect that the jets will be accompanied by a shower of soft hadrons arising from the energy loss.



Since the LHC backgrounds are large, it may be useful to focus on top jets, or on sub-leading channels like 2 Z's.

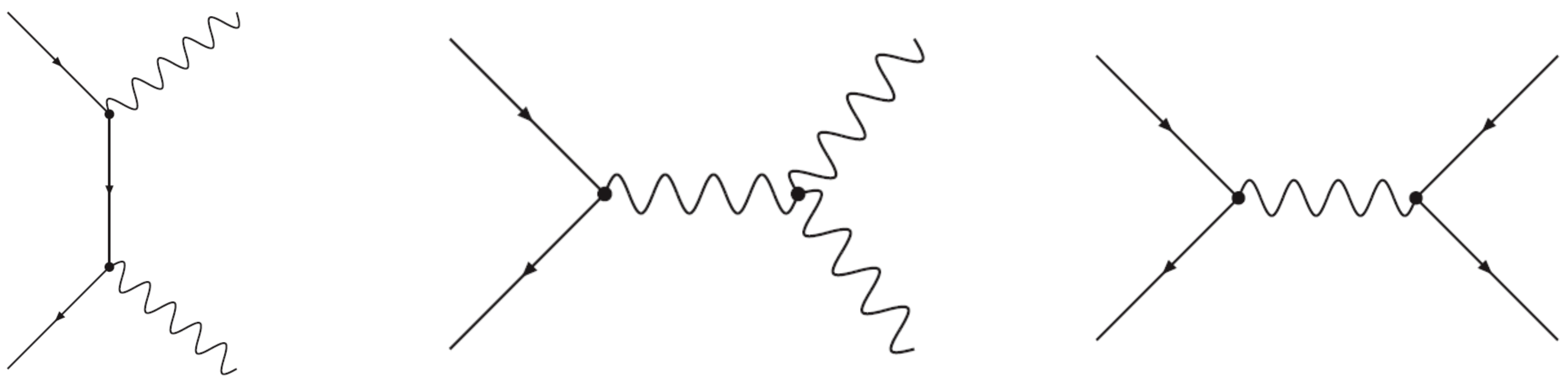
Annihilation of Colorless Quirks

For quirks pair-produced through a W, the leading annihilation channels are to

- W + Z, either through the exchange of a t-channel quirk or an s-channel W

- W + photon, through exactly the same channels

- two Standard Model fermions, through an s-channel W



For values of Λ greater than about a GeV, the process to two hidden sector glueballs and a W, though phase space suppressed, may also play a role.

For quirks pair-produced through a Z, the leading visible annihilation channels are to

- Z + Z, through the exchange of a t-channel quirk
- 2 photons, through exactly the same channel
- Z + photon, through exactly the same channel
- 2 fermions, through s-channel Z or photon
- 2 W's through s-channel Z or photon, or t-channel quirk

Unfortunately, the channel to hidden sector glueballs is important, and dominates for larger values of Λ.

In both cases, quirk production through a W as well as quirk production through a Z, there are non-negligible Standard Model backgrounds in all the channels. It would help if the energy loss is efficient, so the distribution is sharply peaked, or if there are displaced vertices.

Conclusions

Summary of Weird Signatures