



Exotic Signatures (Theory)

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LHC LLP Community Workshop, CERN

Apr. 25th, 2017

Intro

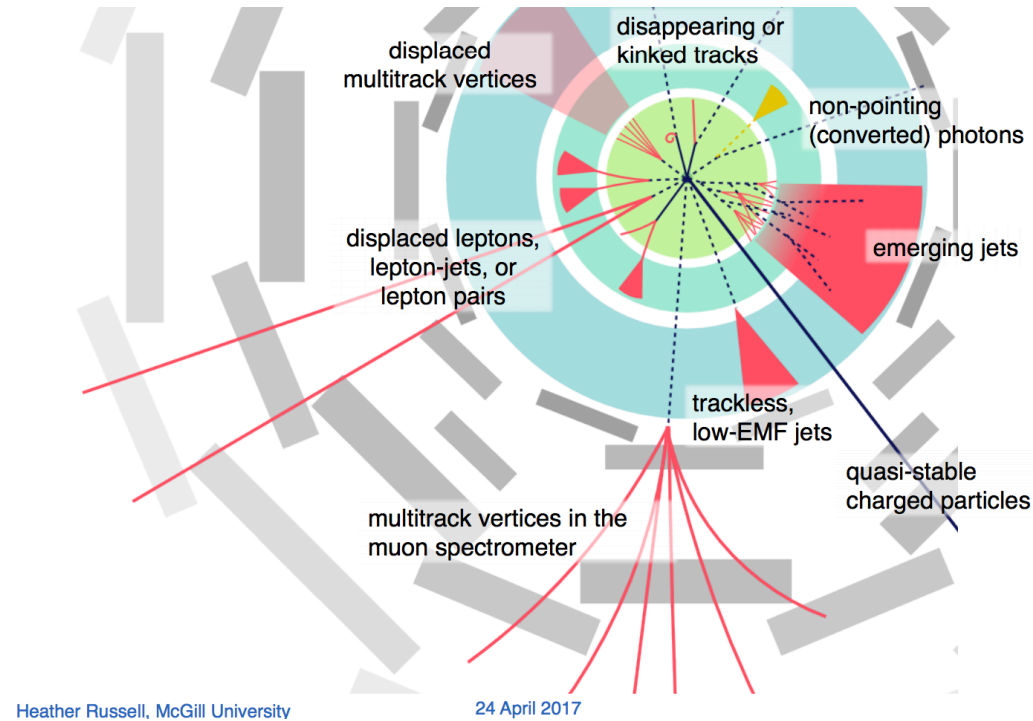
Exotic Signatures

any signatures that we did not discuss in the SUSY recast paper (with B. Tweedie, 15'), complementary to earlier talks in this workshop

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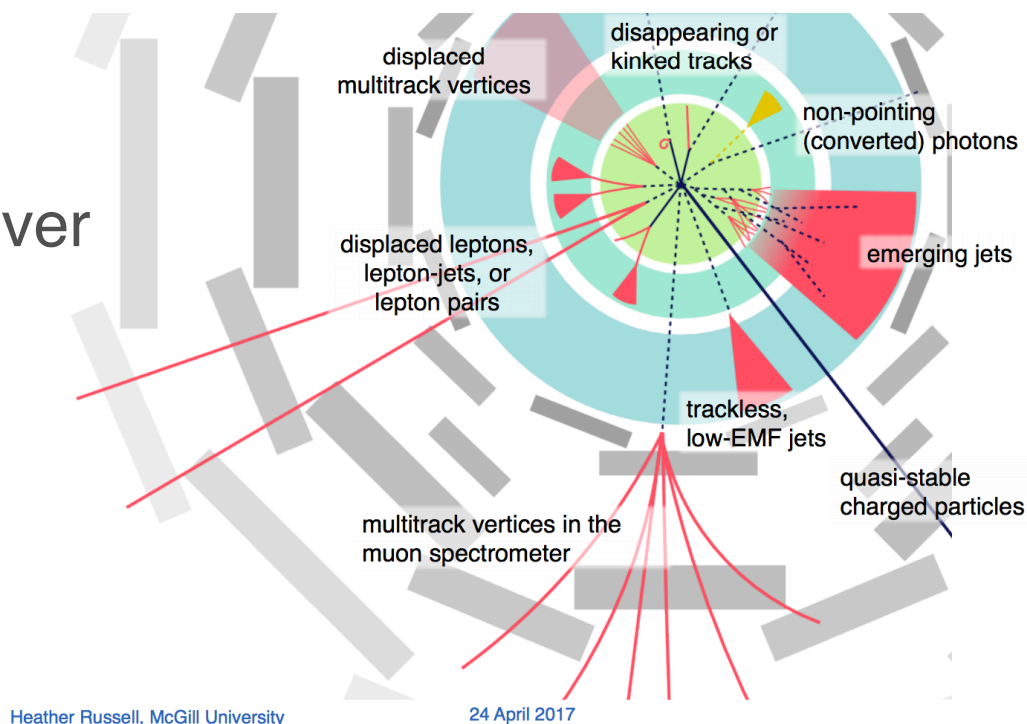
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Exotic Signatures

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Interesting task for me, will cover

- Quirk J. Kang, M. Luty, 08'
- Other exotics
- Disappearing track
- Displaced photon
- Stopped particle



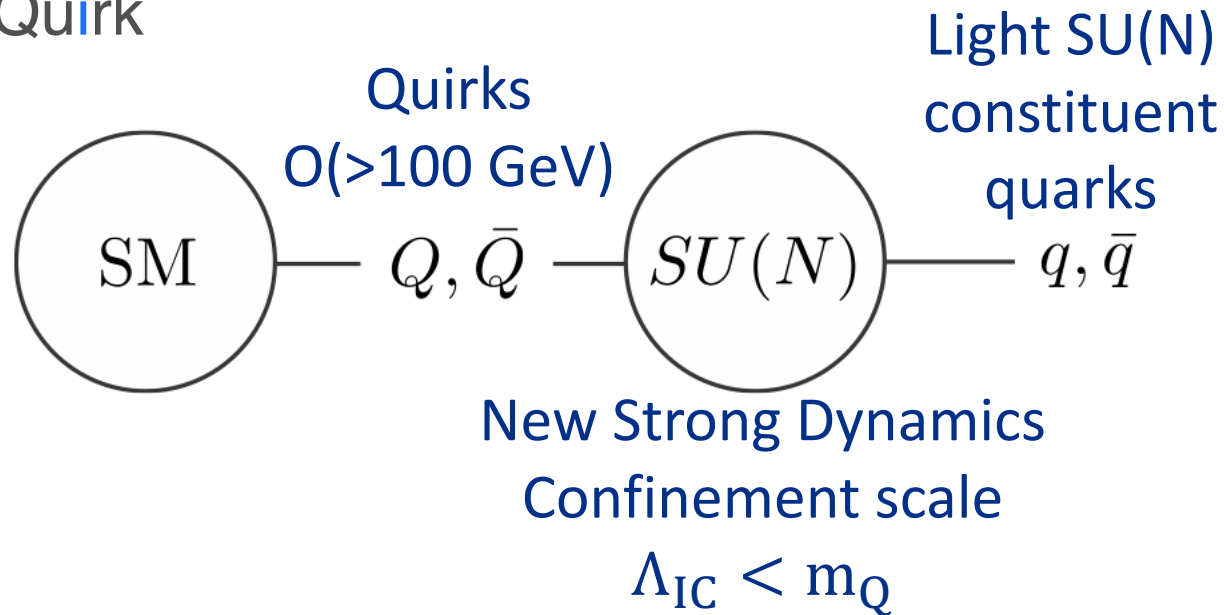
Quirk

- Strong dynamics \rightarrow String dynamics
- Quark \rightarrow Quirk

J. Kang, M. Luty, 08'

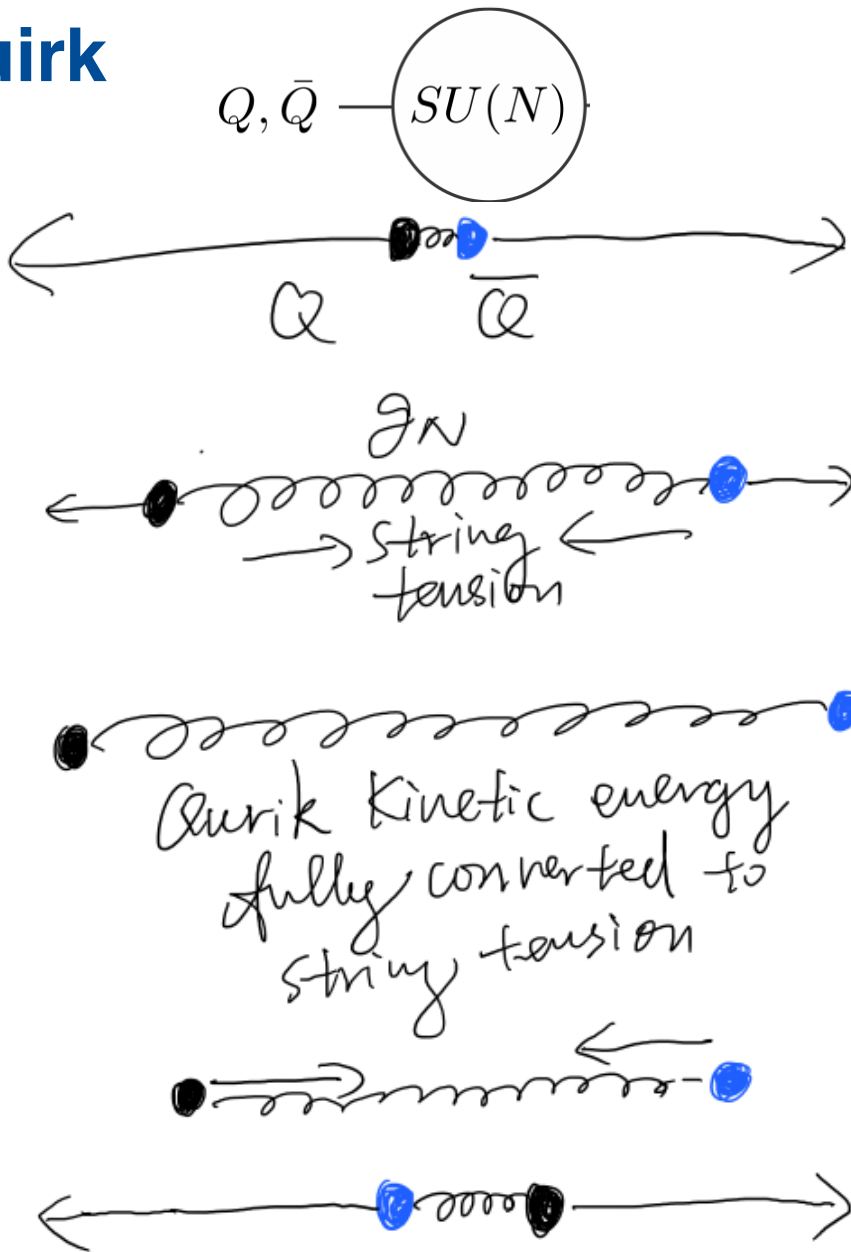
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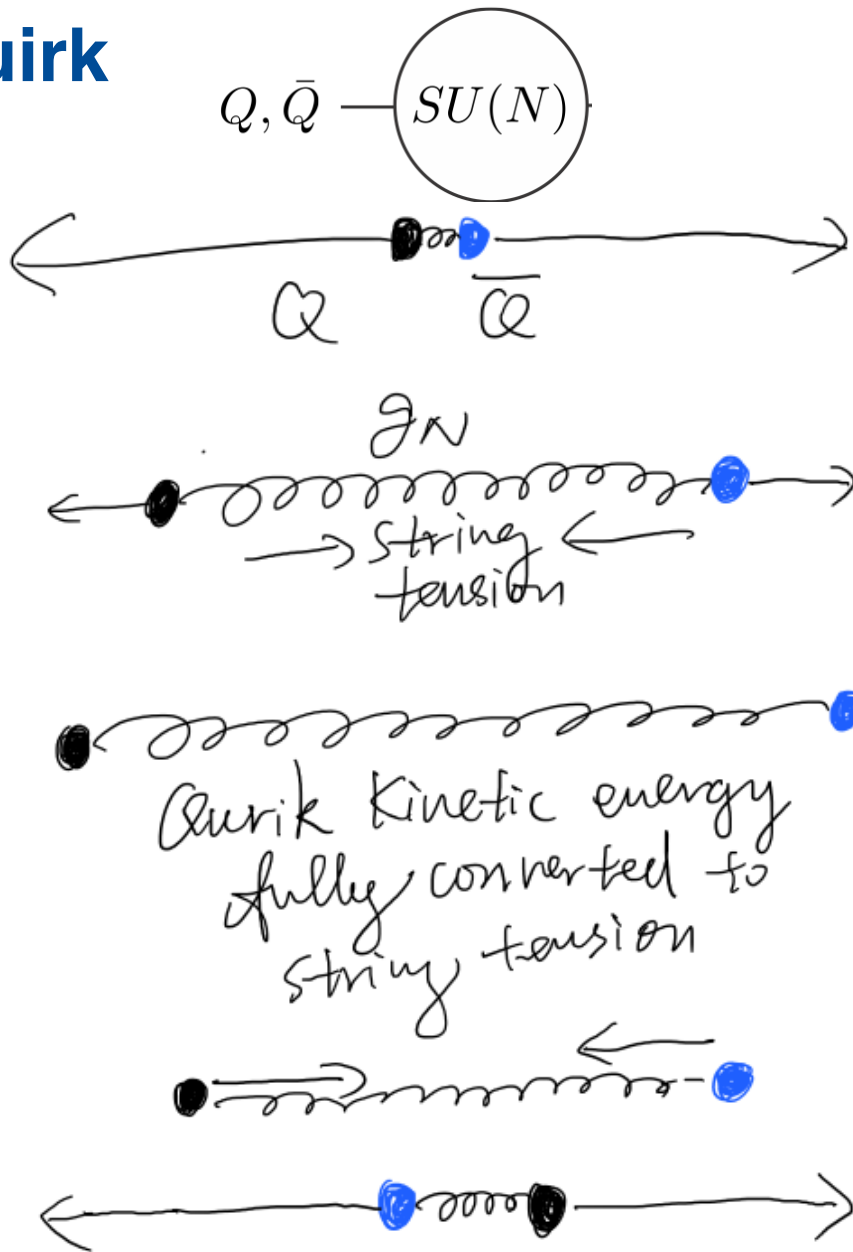


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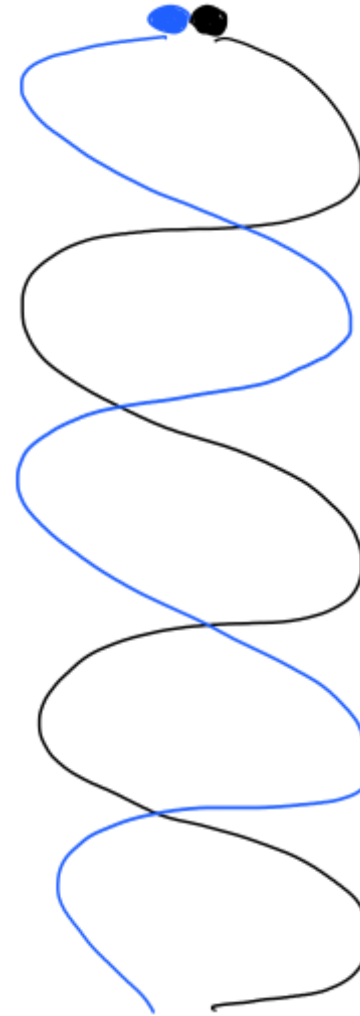
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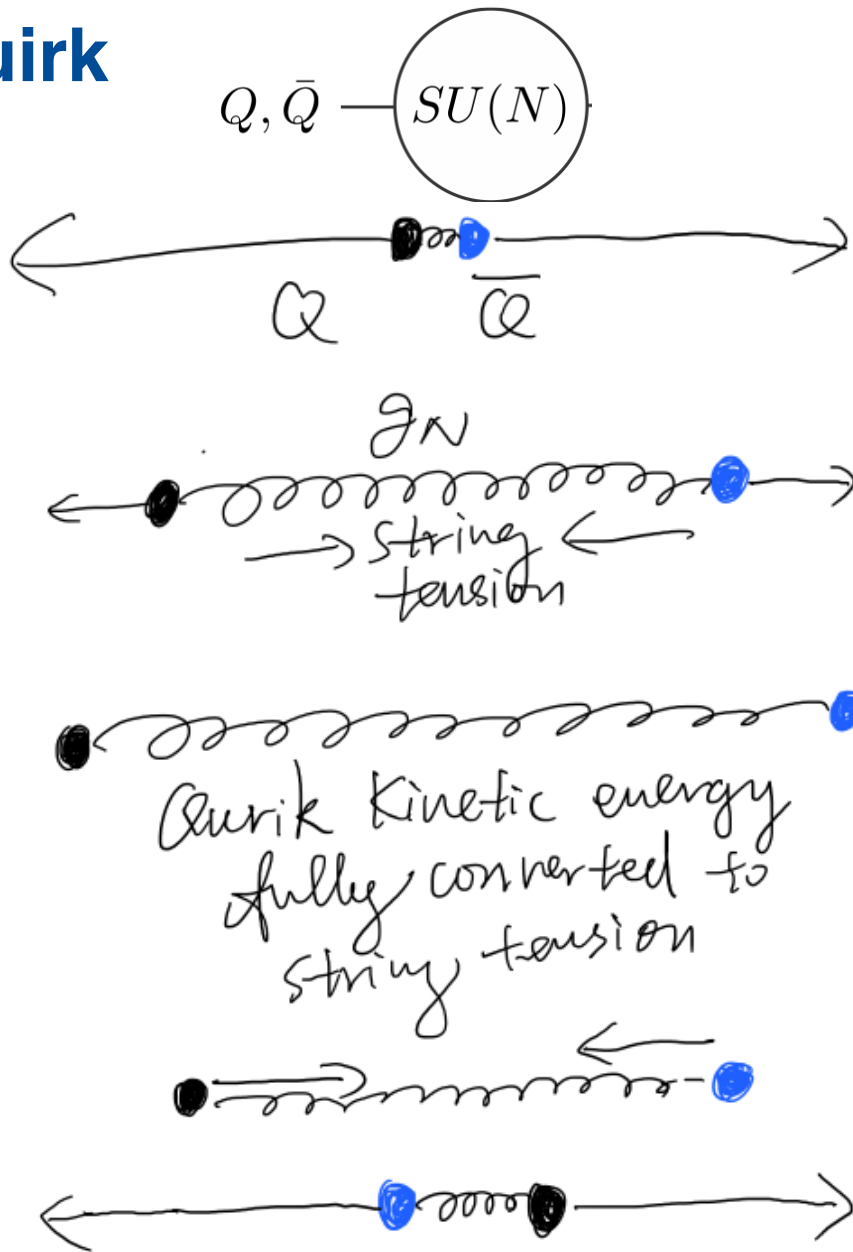
Quirk



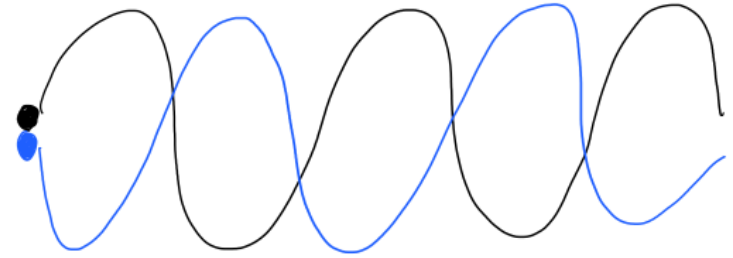
Spatially



Quirk



Spatially



Why so?

Stable strings

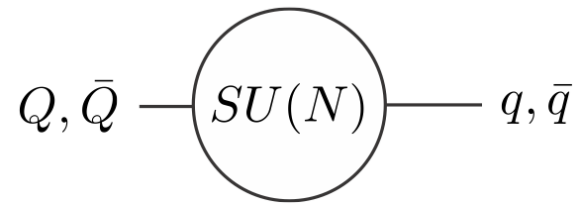
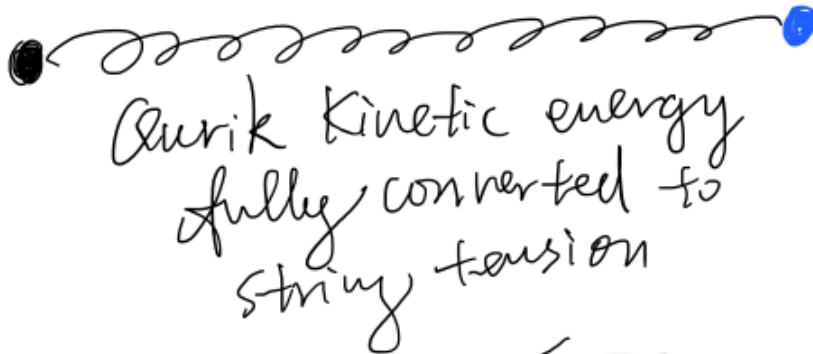
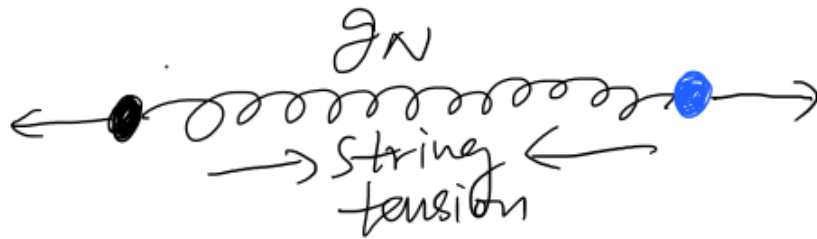
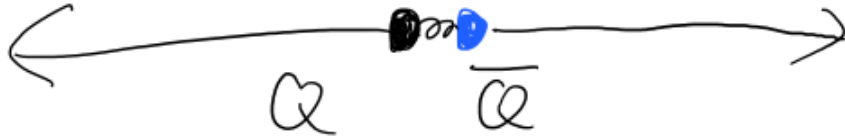
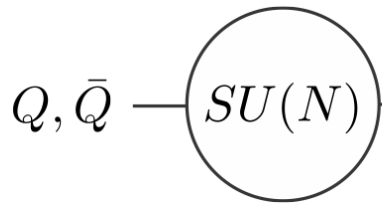
$$\Delta E \sim 2m_Q - \Lambda^2 \Delta L$$

$$\Rightarrow \Gamma_{\text{break}} \sim e^{-m_Q^2/\Lambda^2}$$

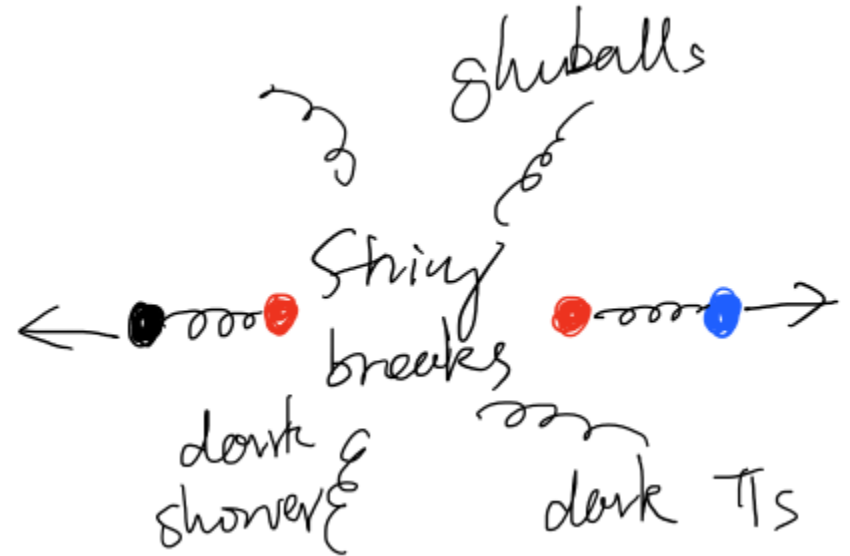
Modeled by a constant force between two particles.

String break exponentially suppressed

Quirk



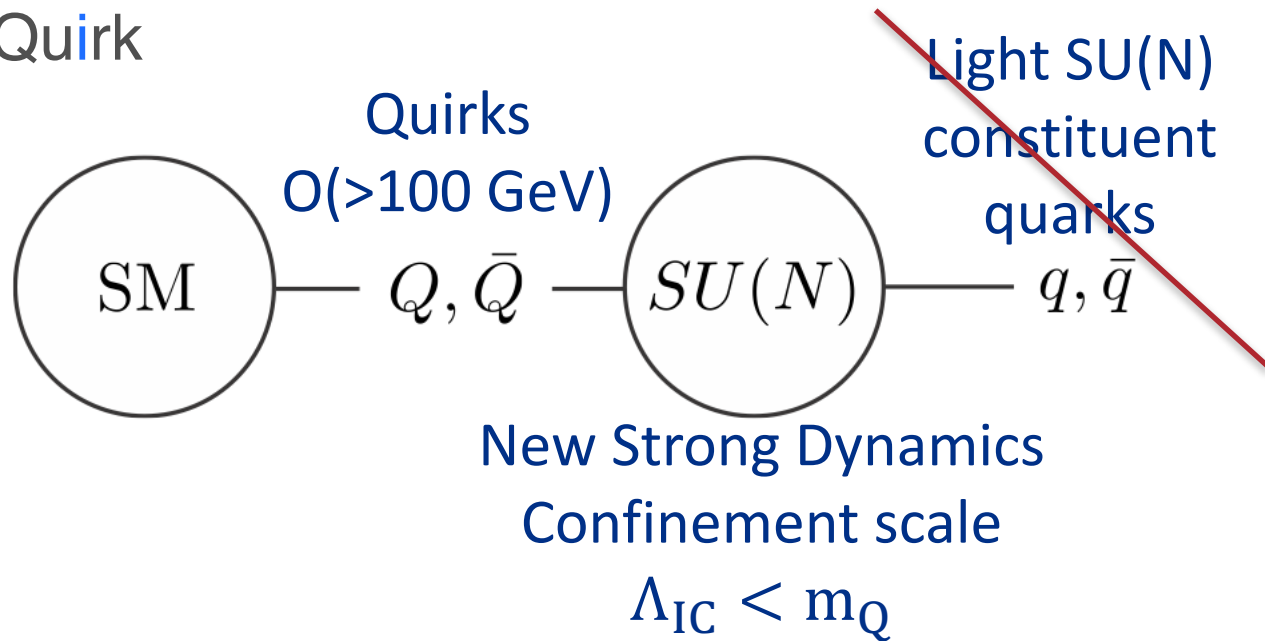
Alternatively,



Covered in talks by
P. Schwaller and
Ted Kolberg

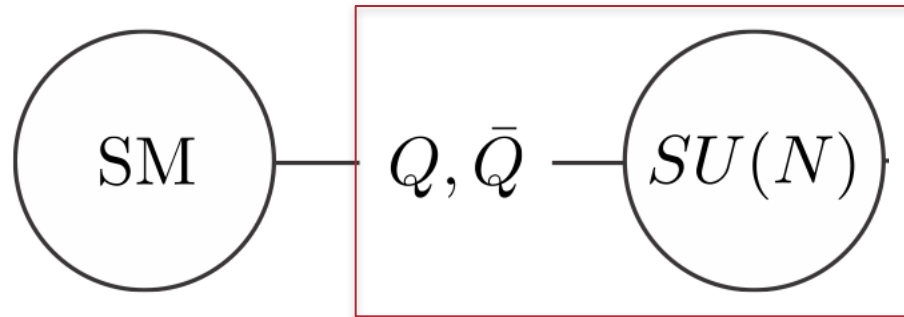
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Quirk

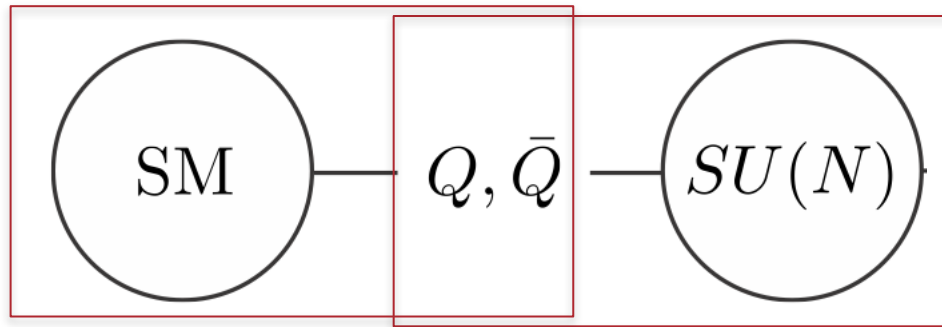
- Strong dynamics \rightarrow String dynamics
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Drives the quirky
oscillation

Quirk

- Strong dynamics \rightarrow String dynamics
- Quark \rightarrow Quirk



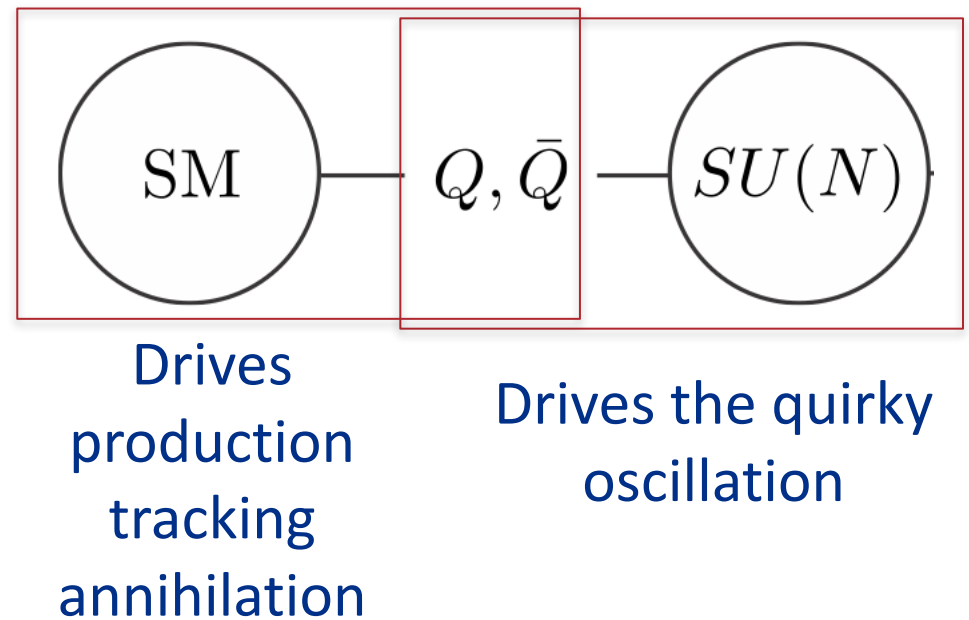
Drives
production
tracking
annihilation

Drives the quirky
oscillation

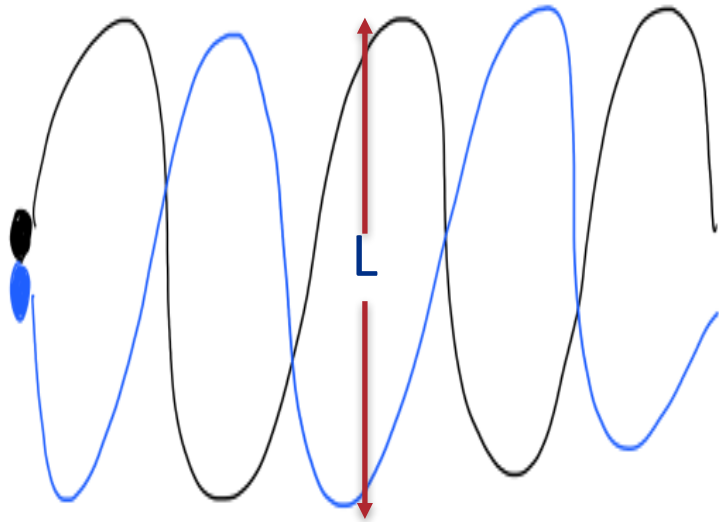
Quirk Motivation

Recently catch more and more attention

- Neutral Naturalness
- Alternative solution of hierarchy problem
- Exotic phenomenology



Quirky signatures



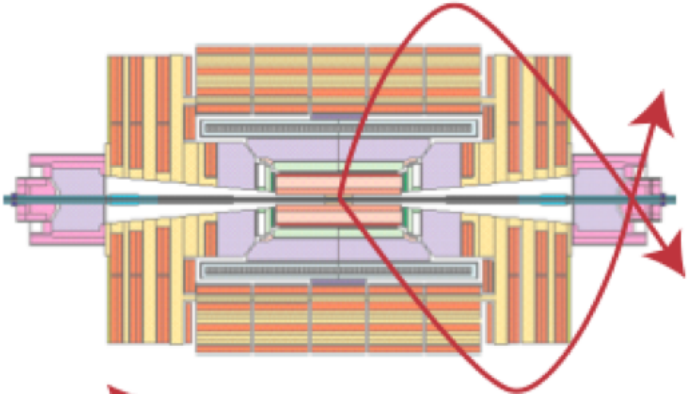
The amplitude of the oscillation is determined by

$$L \sim \frac{K}{\Lambda_{IC}^2} \sim 10 \text{ cm} \left(\frac{\text{keV}}{\Lambda_{IC}} \right)^2 \left(\frac{K}{\text{TeV}} \right)$$

where K is relative kinetic energy of the di-quirk system $O(m_Q)$

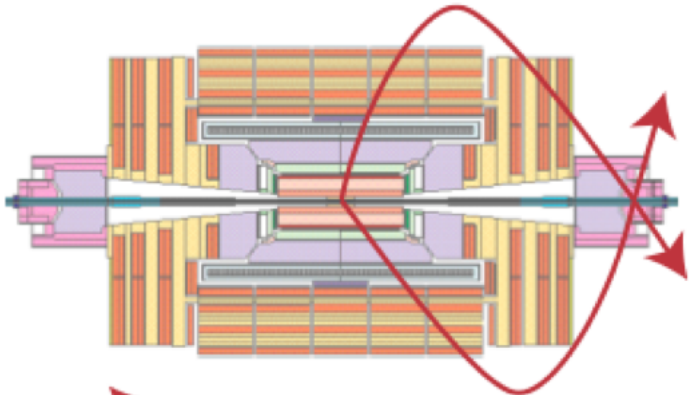
Depending on the value of L , the phenomenology differs drastically
I will present a few striking ones

Quirky signature ($L > 10 m$; $\Lambda_{IC} < 100 eV$)

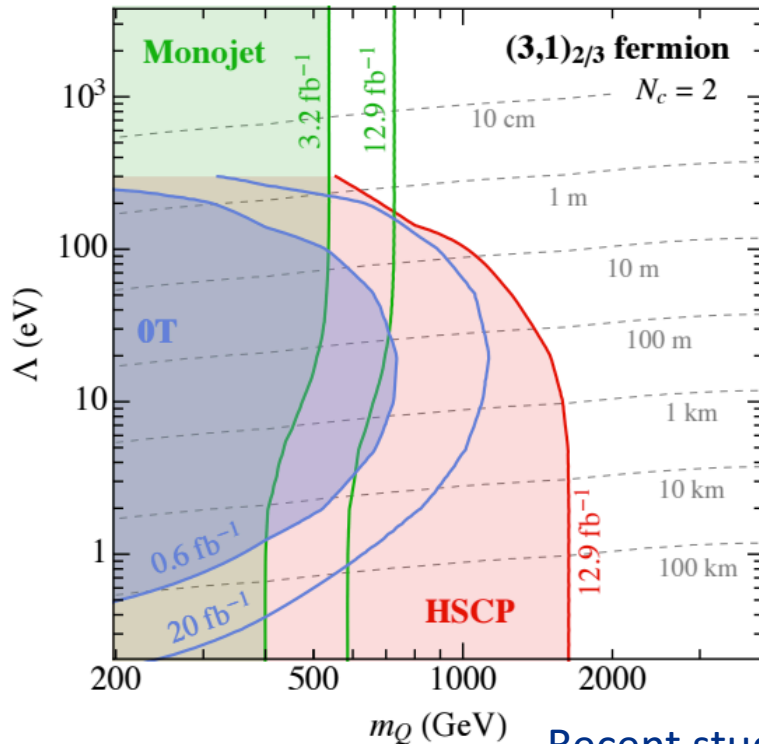


Weak SU(N) force, perturbation to nominal HSCP search

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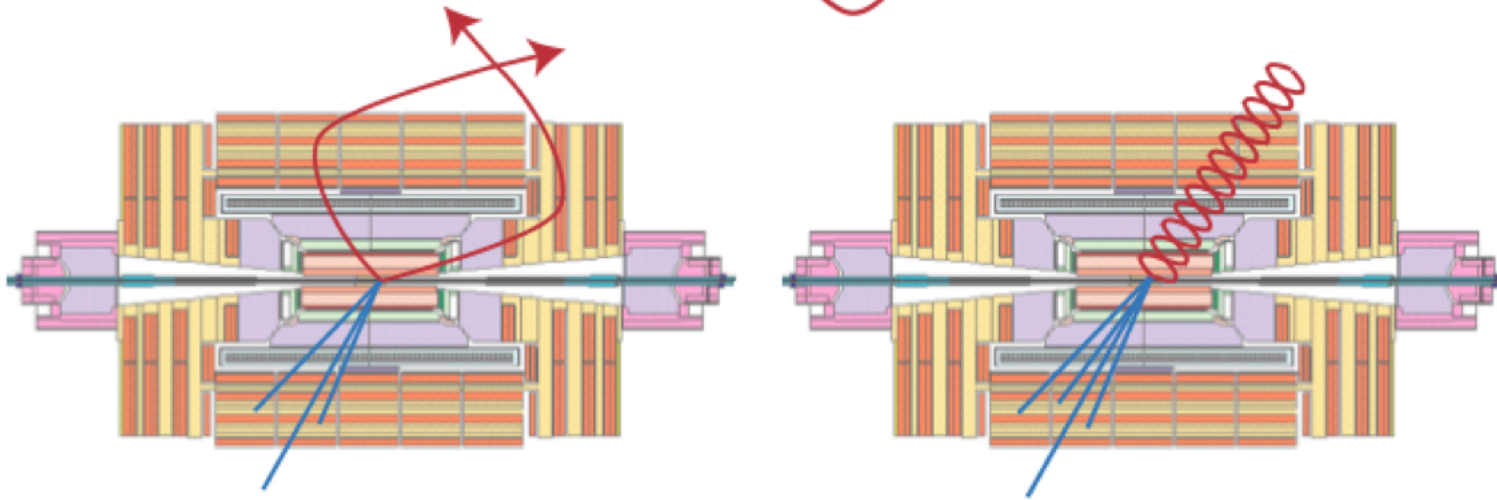


Weak SU(N) force, perturbation to nominal HSCP search



Recent study by M. Farina and M. Low, 17'

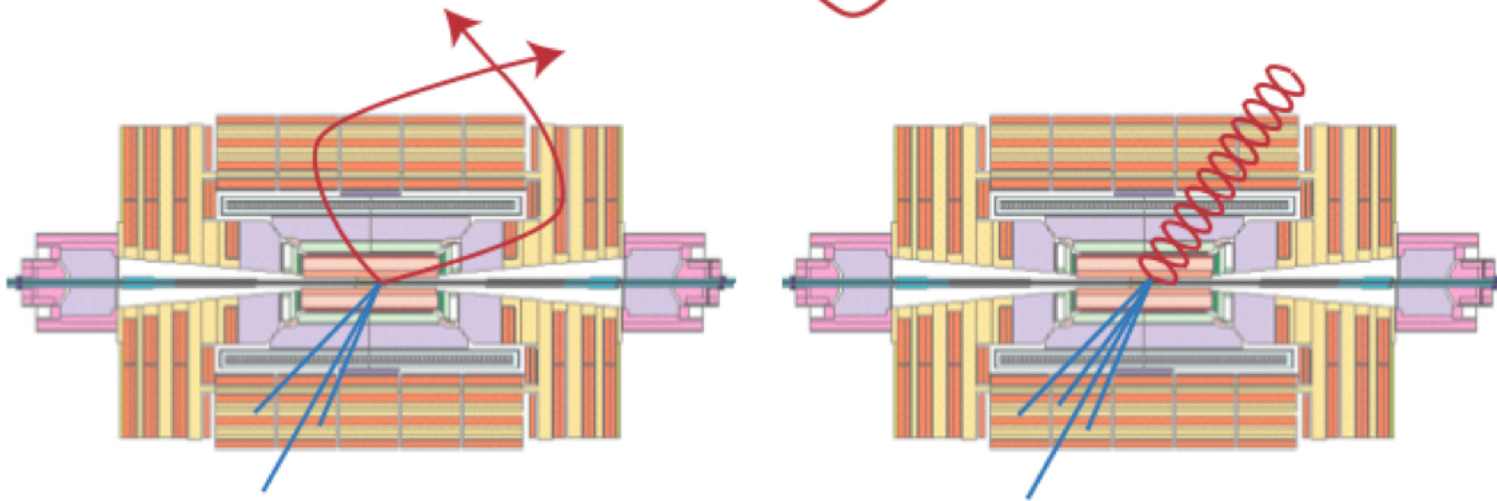
Quirky signature ($L \sim cm \sim m; 100 \text{ eV} < \Lambda_{IC} < 1 \text{ keV}$)



Exotic Curves

- Not follow HSCP for a given EM charge because of the string pulling
- Pair of coplanar tracks

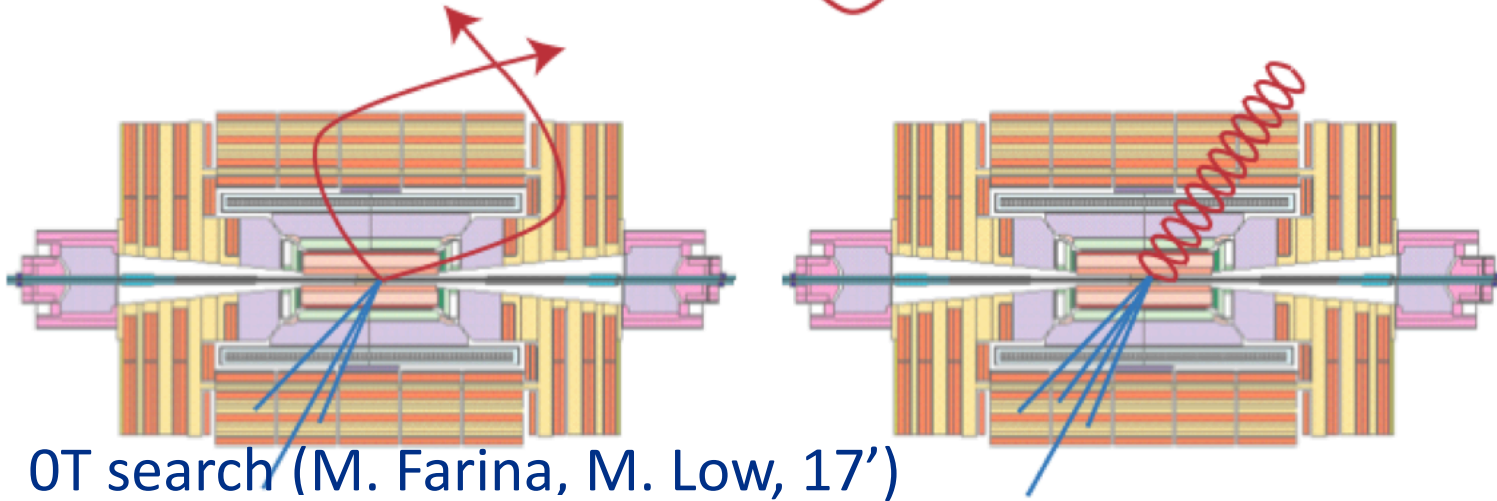
Quirky signature ($L \sim mm \sim m; 100 \text{ eV} < \Lambda_{IC} < 1 \text{ keV}$)



Exotic tracks

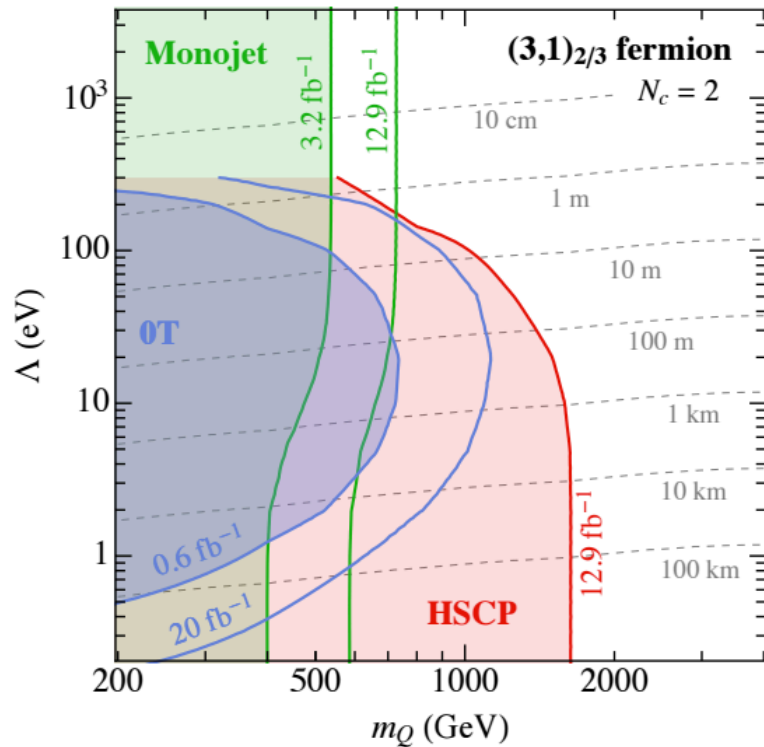
- Not follow HSCP for a given EM charge because of the string pulling
- Pair of **coplanar** tracks
- Would be constrained by mono-jet search
- a large room to improve from directly searching for these exotic tracks

Quirky signature ($L \sim mm \sim m; 100 \text{ eV} < \Lambda_{IC} < 1 \text{ keV}$)



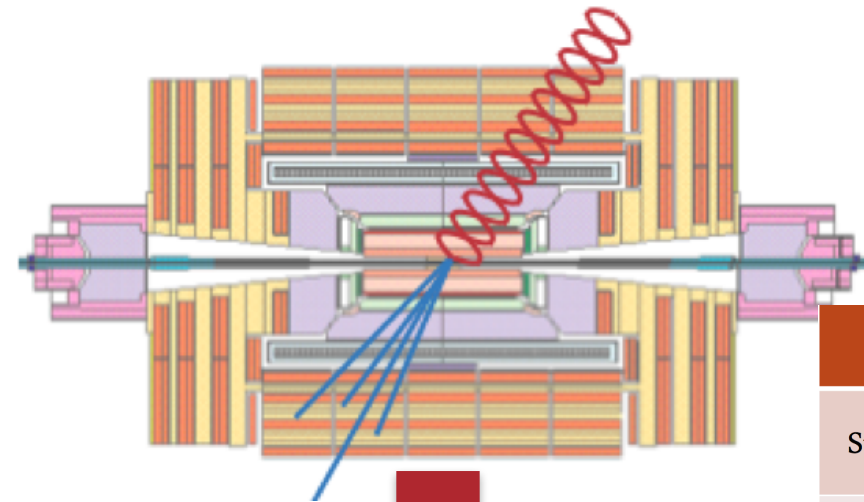
OT search (M. Farina, M. Low, 17')

OT—SM particle no curvature;
Quirk stands out.



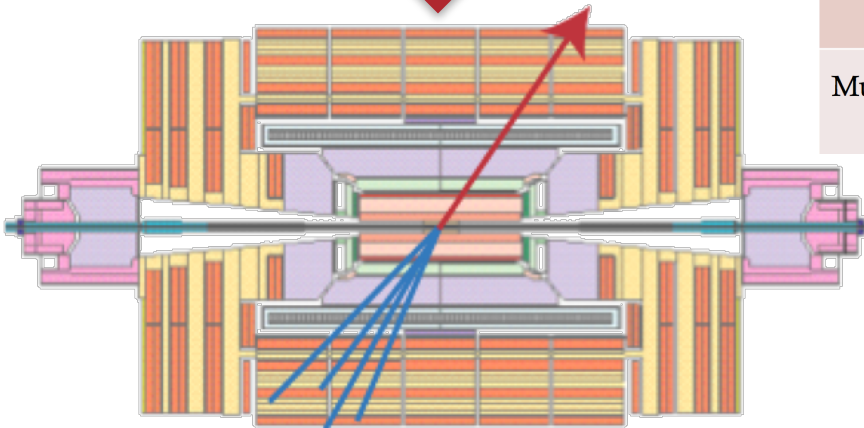
See also, Coplanar track seeking (LBNL group, T. Low et al, in progress)

Quirky signature ($L < mm; \Lambda_{IC} > 1 keV$)



Highly ionizing tracks

Interactions	Effects
String dynamics	Glueball radiations, small energy loss when Λ/m is small
Magnetic field	Introduces small torque. Effects cancel out over many oscillations
Energy loss from detector	Small changes to energy/momentum, negligible in the pixel layers
Multiple scattering in detector	Leads to angular momentum changes, suppresses annihilation



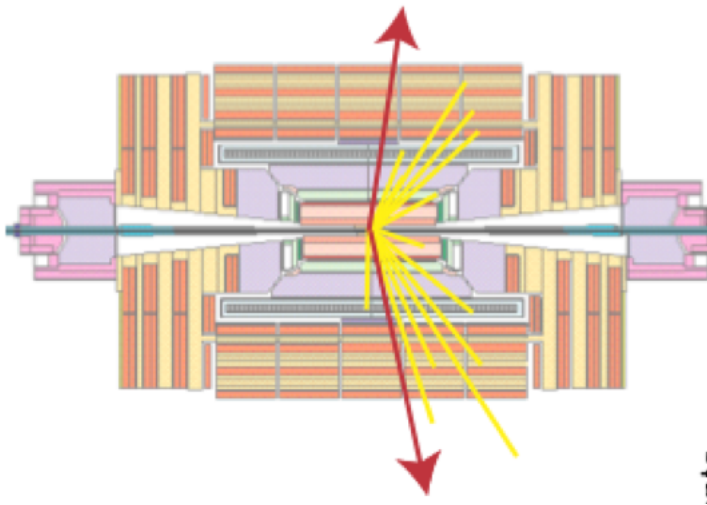
Simple oscillation pattern not perturbed much

Table from T. Low's LBNL LLP trigger workshop



Quirky signature ($\Lambda_{IC} > MeV$)

Quickly form bound state
annihilates



Semiclassical picture: probability of annihilation
per classical crossing time $T \sim L \sim m_Q/\Lambda_{IC}^2$

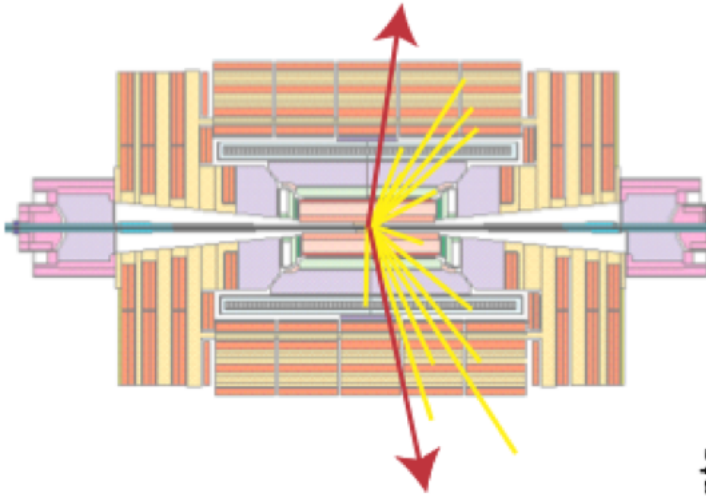
$$\frac{\text{Prob}}{\text{crossing}} = T\sigma v_{\text{rel}} |\psi(0)|^2 = \frac{m^2 \beta}{\pi} \sigma v_{\text{rel}} \quad \beta \ll 1$$

$$\sim \frac{1}{20} \quad \text{QCD}$$

$$\sim \frac{1}{400} \quad \text{QED}$$

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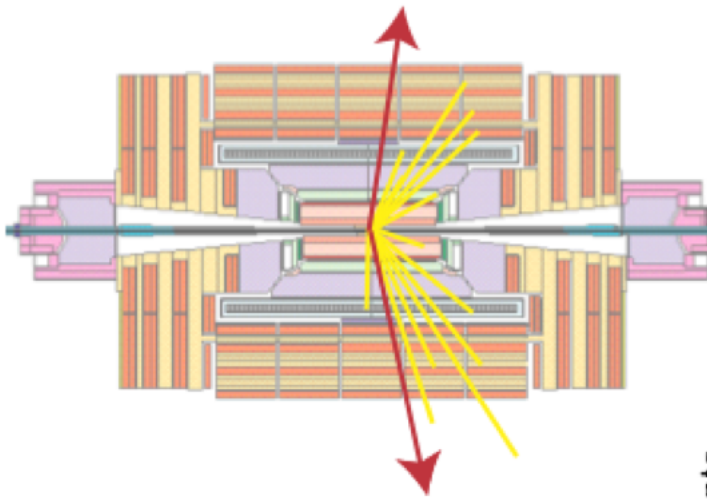
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Decays into di-jet, di-boson, di-gluonball,
etc (see e.g., R. Fok, G. Gribs 11', Z Chacko, D. Curtin, C.
Verhaaren 15'; Cheng, Salvoni, Tsai 16')

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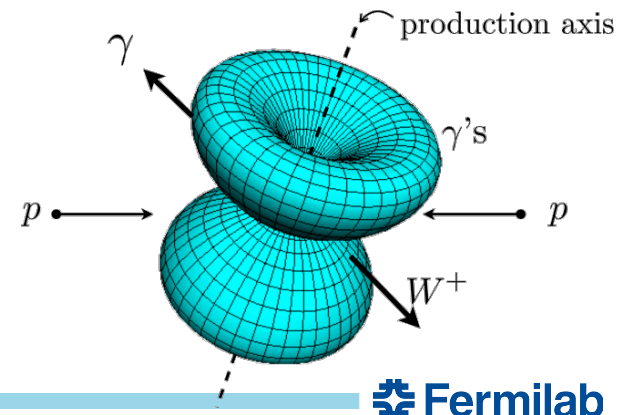
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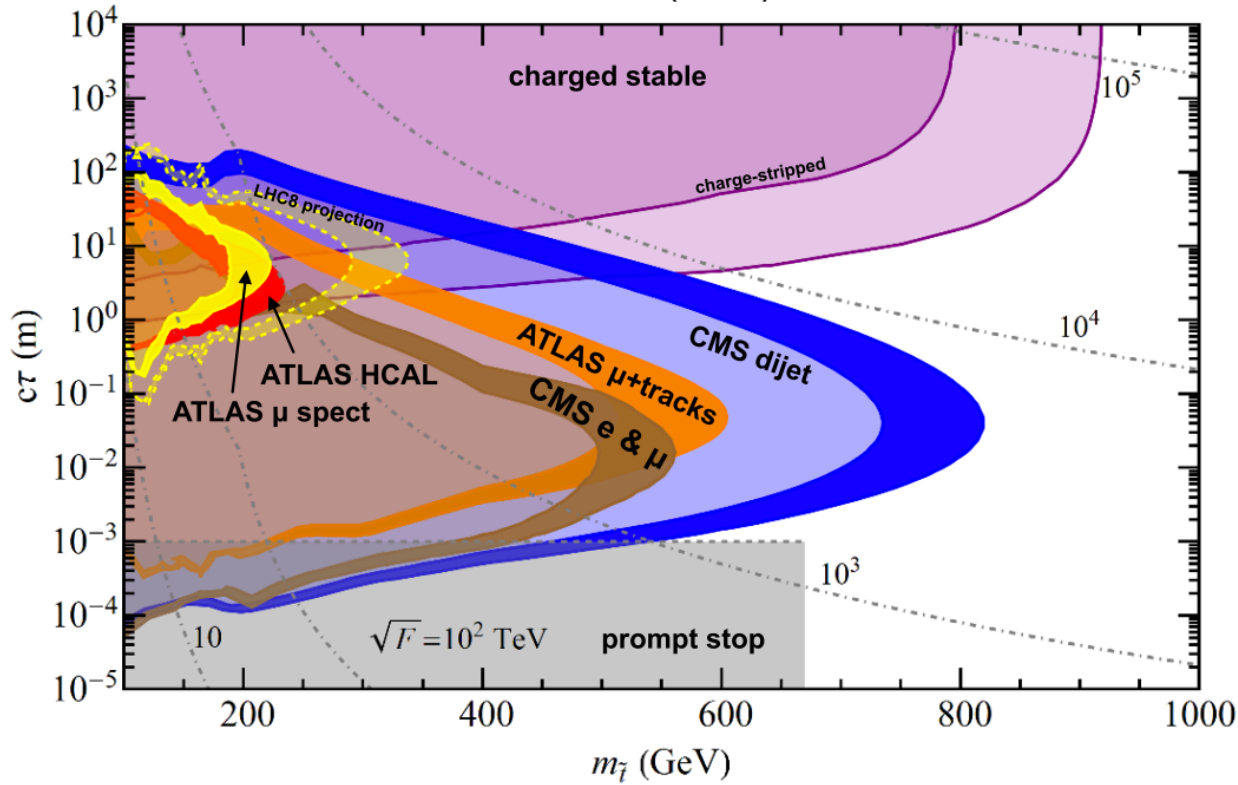
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If Quirks are QCD colored, additional jet halo;
If Quirky are only QED charged, additional photon halo (R. Hanik, T. Wizansky 08')



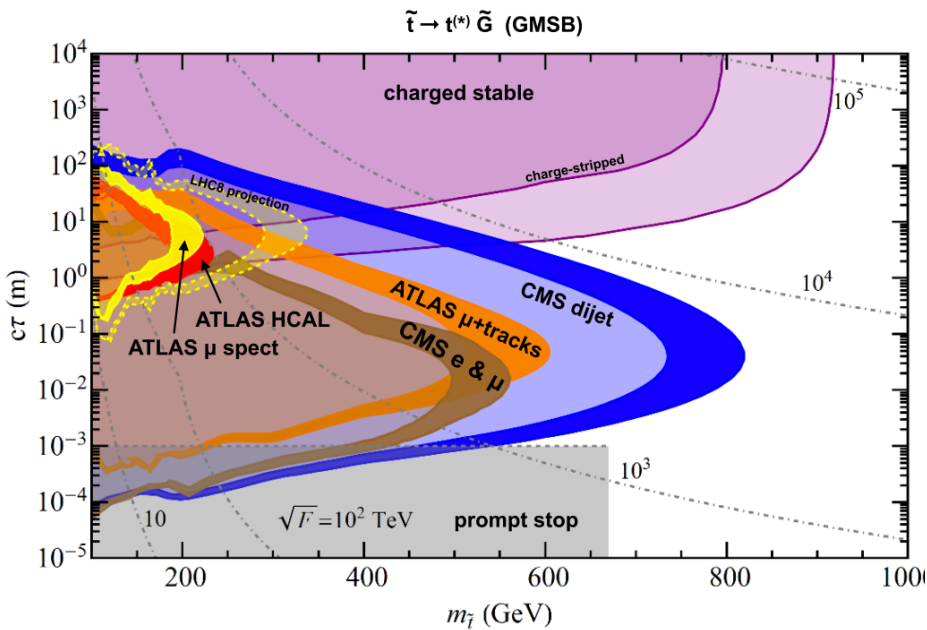
More (or less) exotics

$\tilde{t} \rightarrow t^{(*)} \tilde{G}$ (GMSB)



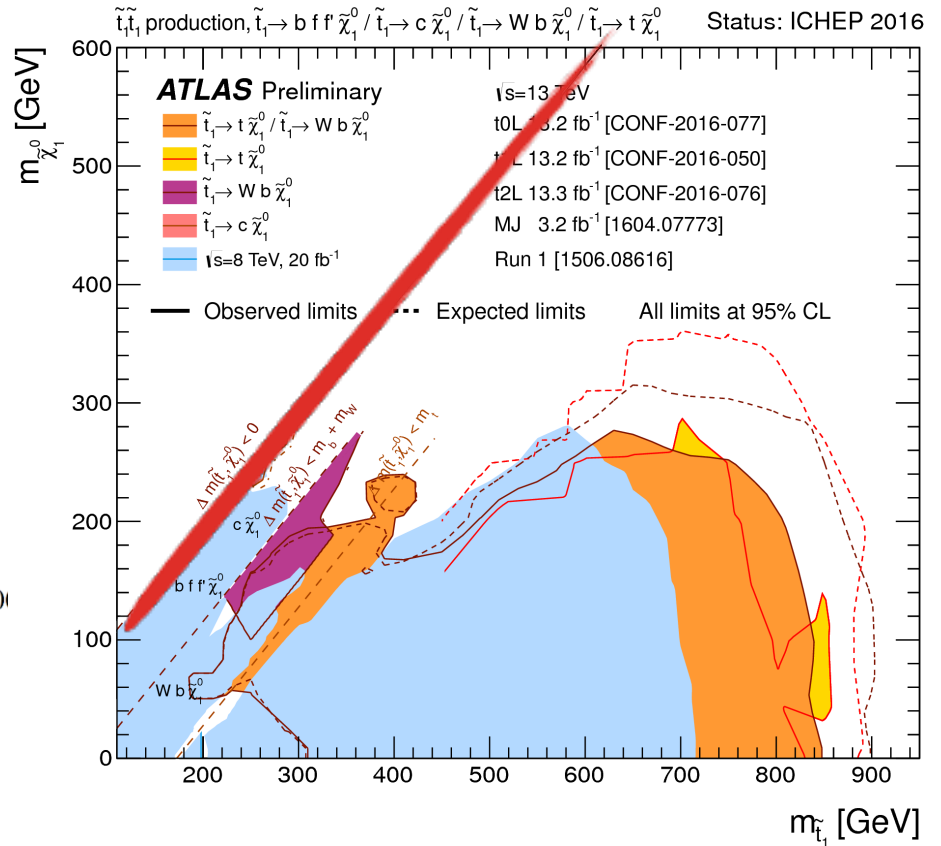
SUSY fully covered, any lifetime?

More (or less) exotics



SUSY fully covered, any lifetime?

Compressed SUSY
Easily long-lived

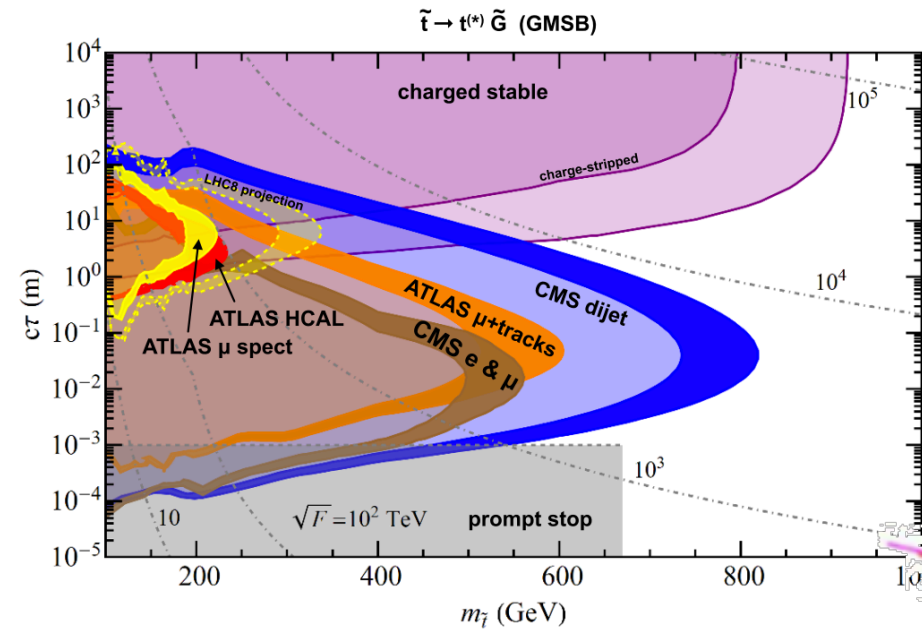


Mono-jet + displaced tracks

Work in progress with H. An and A. Rigway
And case for electroweakino, w J. Evans

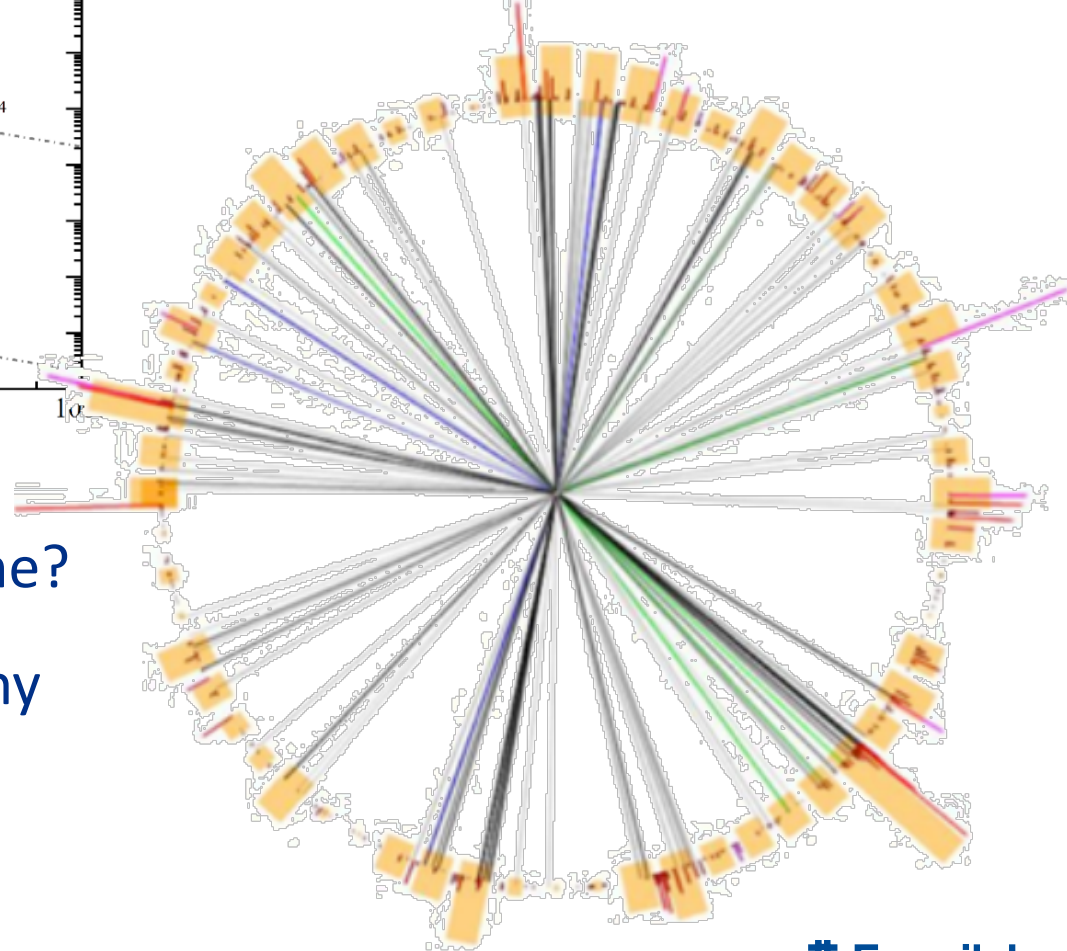


More (or less) exotics



“Soft Bombs”

SK, S. Pagan Griso, M. Papucci, D. Robinson : 1612.00850



SUSY fully covered, any lifetime?

Extremely stealthy
SUSY

Conclusion

Impressive progress in the LLP field

Yesterday I was still learning SUSY LLP signatures

Today, they are considered “standard”

More interesting and well-motivated exotic signatures

Quirk with dark confinement

- Exotic tracks
- Oscillating tracks
- Coplanar tracks
- Highly ionizing tracks
- Di-SM particle resonances with halos
- Soft bomb/Fireballs

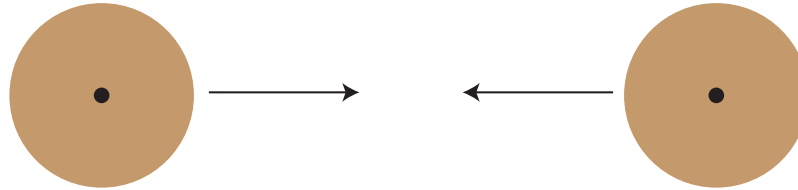
There is also a lot of room in SUSY signatures

compressed LLP SUSY

Backup

Brown Muck Energy Loss

QCD or infracolor strong interactions



$\sigma \sim \text{geometrical} \Rightarrow 1 \text{ interaction}/T$

$$\Delta E \sim \Delta p \sim \Lambda \quad \Delta J \sim 1$$

$N \text{ interactions} \Rightarrow \Delta J \sim \sqrt{N}$

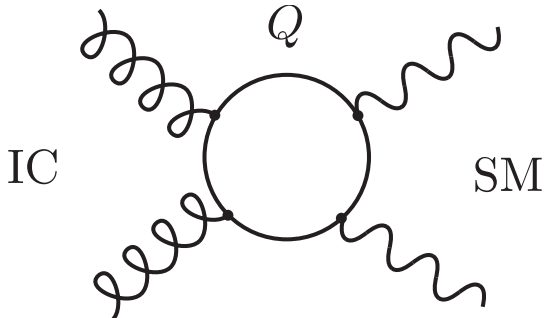
$$\text{Survival probability} \sim (1 - P) \left(1 - \frac{P}{\sqrt{2}}\right) \cdots \left(1 - \frac{P}{\sqrt{N}}\right)$$

$$\sim 5\% \text{ for } P \sim 1/20 \quad N \sim 10^3$$

Quirks ($N_q = 0$)

(Kang, Luty 2008)

Hidden sector = light glueballs



The diagram shows a central circle representing a quirk loop. Four wavy lines, representing Standard Model (SM) particles, are attached to the circle at the top, bottom, left, and right. The top wavy line is labeled 'Q'. To the left of the diagram is the label 'IC' and to the right is 'SM'. An arrow points from the diagram to the right, leading to the effective Lagrangian equation.

$$\Rightarrow \mathcal{L}_{\text{eff}} \sim \frac{g^2 g'^2}{16\pi^2 m_Q^4} F_{\mu\nu}^2 F_{\rho\sigma}'^2$$

Very decoupled from SM

- No constraints from star cooling, *etc.*
- Cosmology OK if $T_{\text{RH}} \lesssim \text{GeV}$