# Exotic Signals

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# Motivation

No standard BSM model

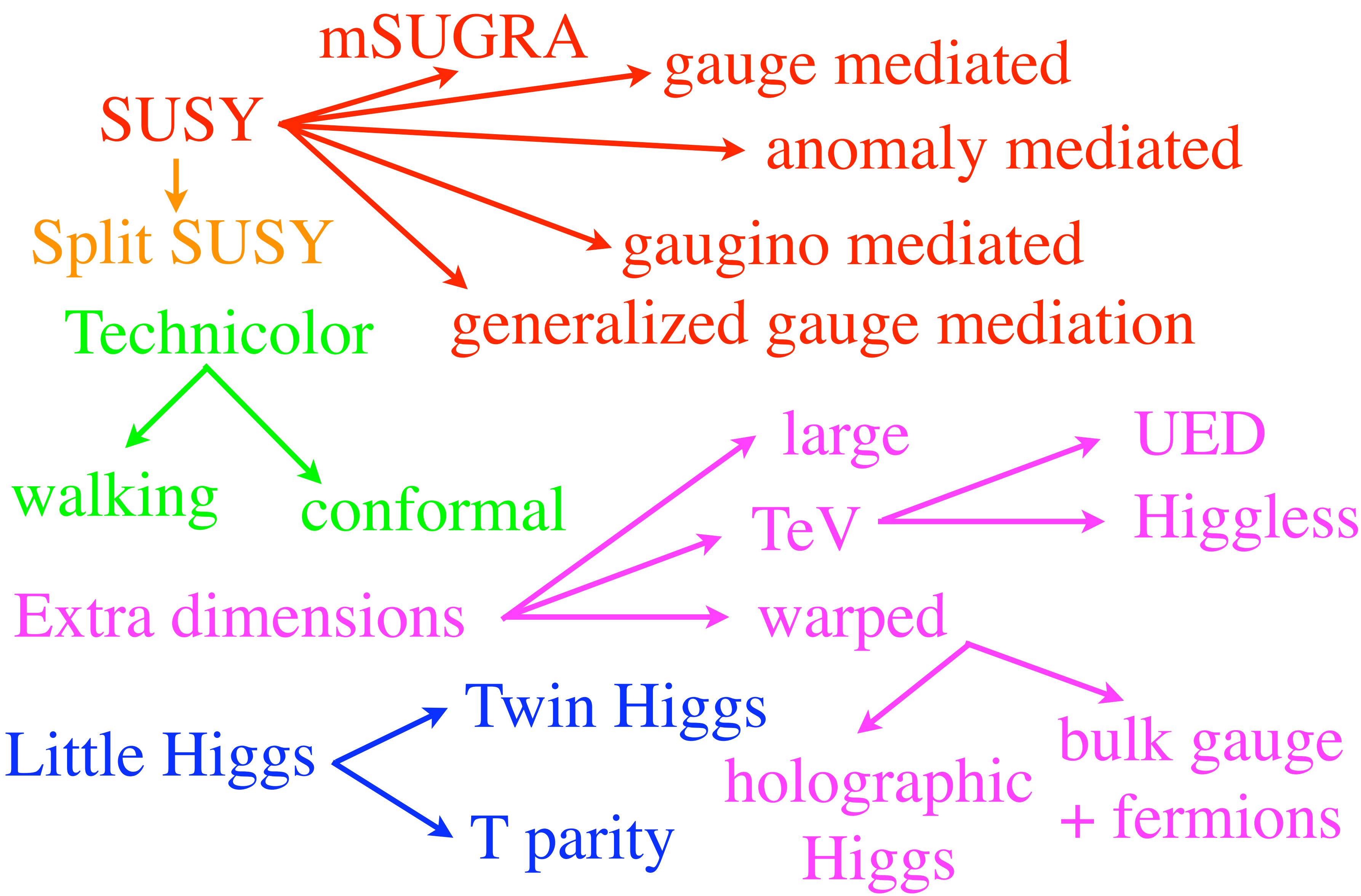
$\Rightarrow$ we don't know what we are looking for!

Lessons from 35 years of building models (check one):

☐ New physics is complicated

☐ We are missing something

# Too many theories?



# Or not enough signals?

High $p_T$ physics: $\ell,\ \gamma,\ \tau,\ j_b,\ j,\ \not{p}_T$

# This Talk

New physics in IR:

- Low mass hidden sectors

  “Unified dark matter”

  “Quirks”

  “Hidden valley”

  “Unparticles”

- Long-lived particles

  “Displaced dark matter”

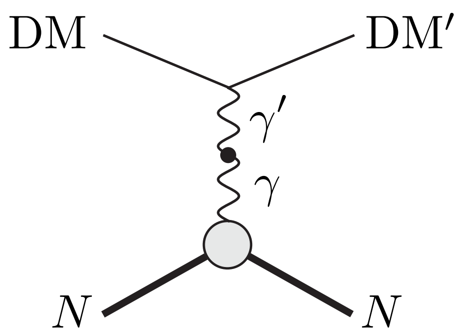
Explore “minimal non-minimal” models

# Unified Dark Matter

(Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008)

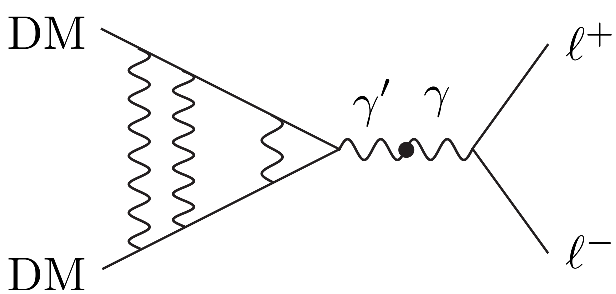
An ambitious attempt to explain *all* signals potentially related to dark matter

Renormalizable portal: $\Delta\mathcal{L} = \epsilon F^{\mu\nu} F'_{\mu\nu}$ $\quad m_{\gamma'} \sim \mathrm{GeV}$



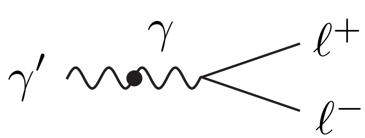

Inelastic dark matter ⇒ DAMA/LIBRA

(Tucker-Smith, Weiner, 2001)



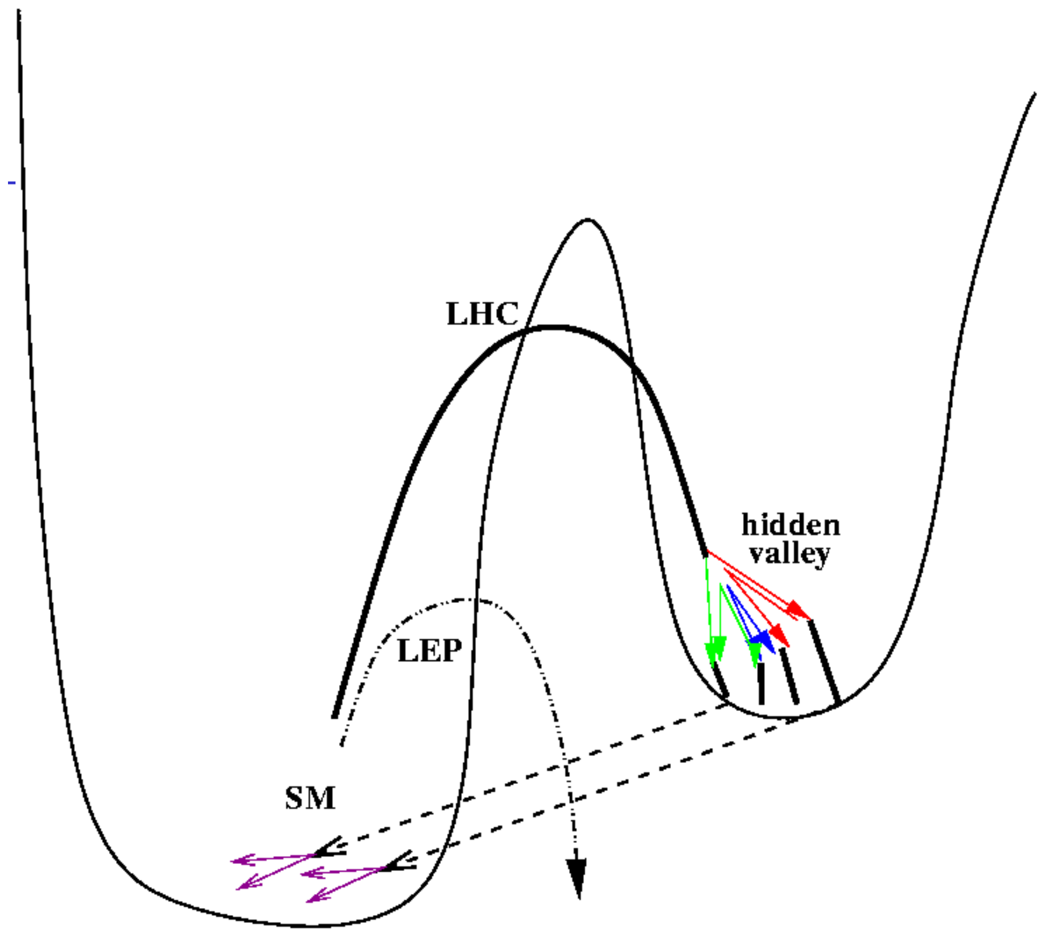

Somerfeld enhanced annihilation

⇒ PAMELA, FERMI, WMAP haze...




⇒ lepton jets at colliders

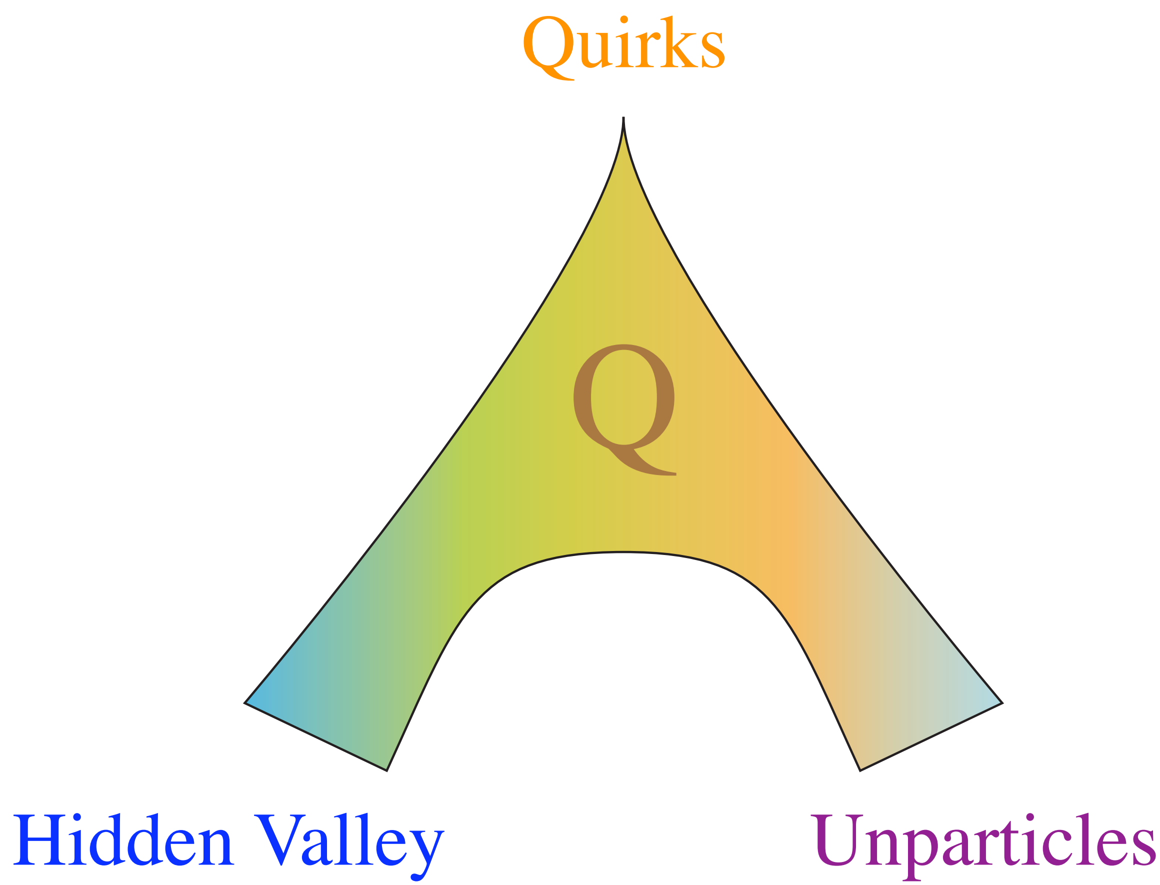
# Massive Portal



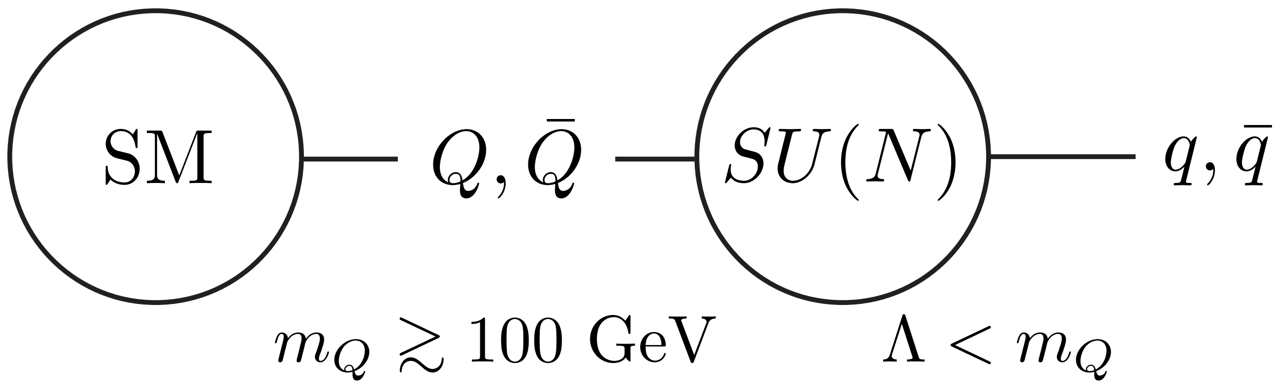

“Hidden Valley”

(Strassler, Zurek 2006)

# Unified Quirk/Hidden Valley/ Unparticle Model



# The Model

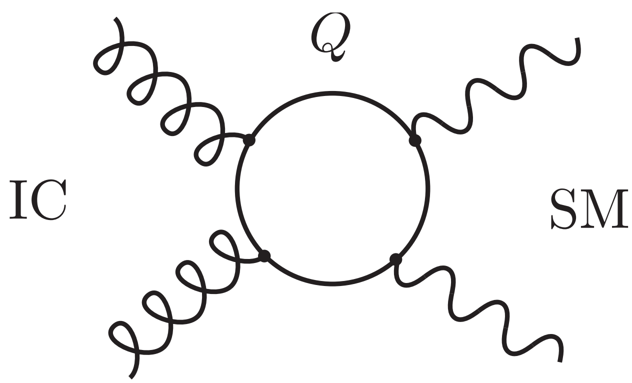



- $N_q = 0$ : stringy confinement $\Rightarrow$"quirks"
- $N_q \sim 1$ : QCD-like confinement $\Rightarrow$ "hidden valley"
- $N_q \sim N$ : conformal dynamics $\Rightarrow$ "unparticles"

# Quirks ($N_q = 0$)

(Kang, Luty 2008)

Hidden sector = light glueballs



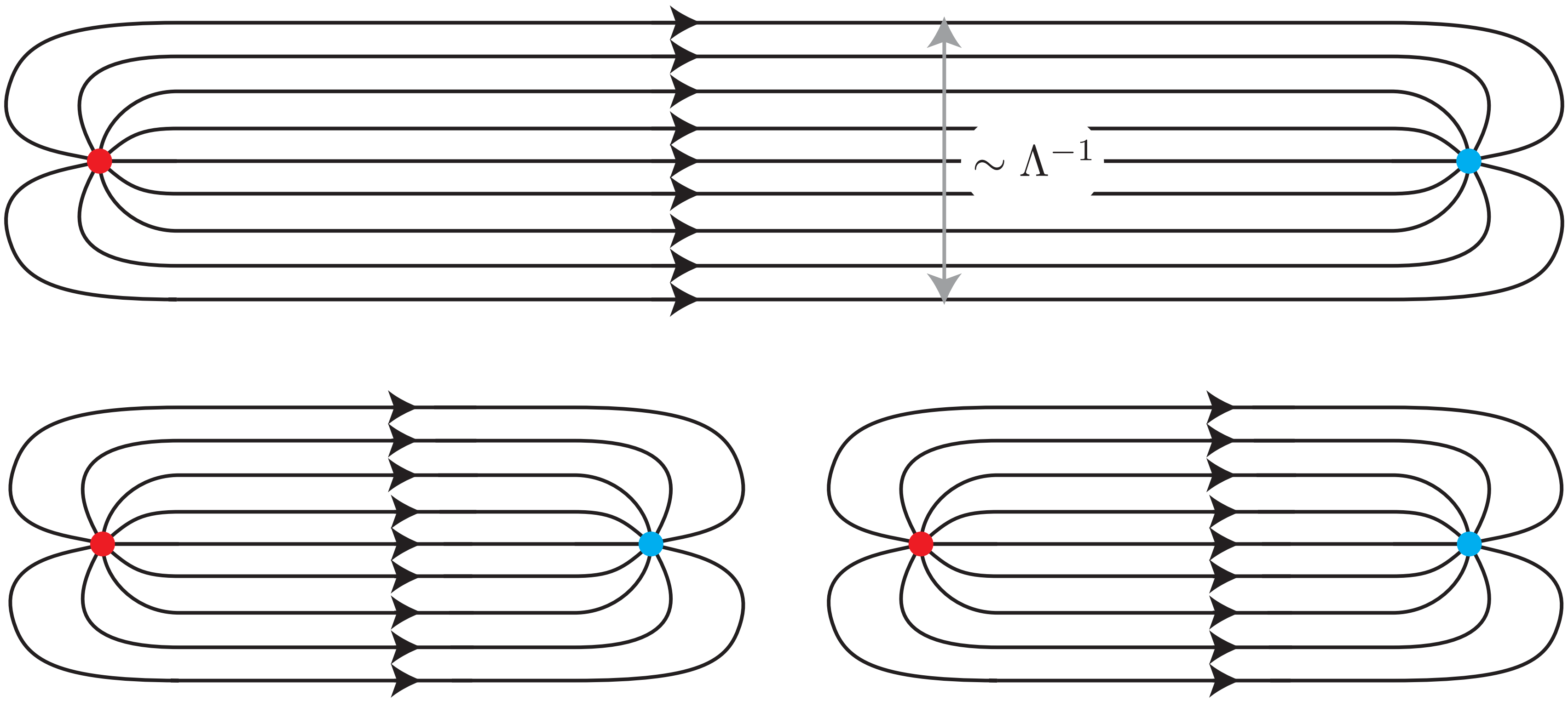

$$\Rightarrow \quad \mathcal{L}_{\text{eff}} \sim \frac{g^2 g'^2}{16\pi^2 m_Q^4} F_{\mu\nu}^2 F_{\rho\sigma}'^2$$

Very decoupled from SM

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

# What's so quirky?

Stable strings!




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

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

# String Length

Convert quirk kinetic energy to string energy

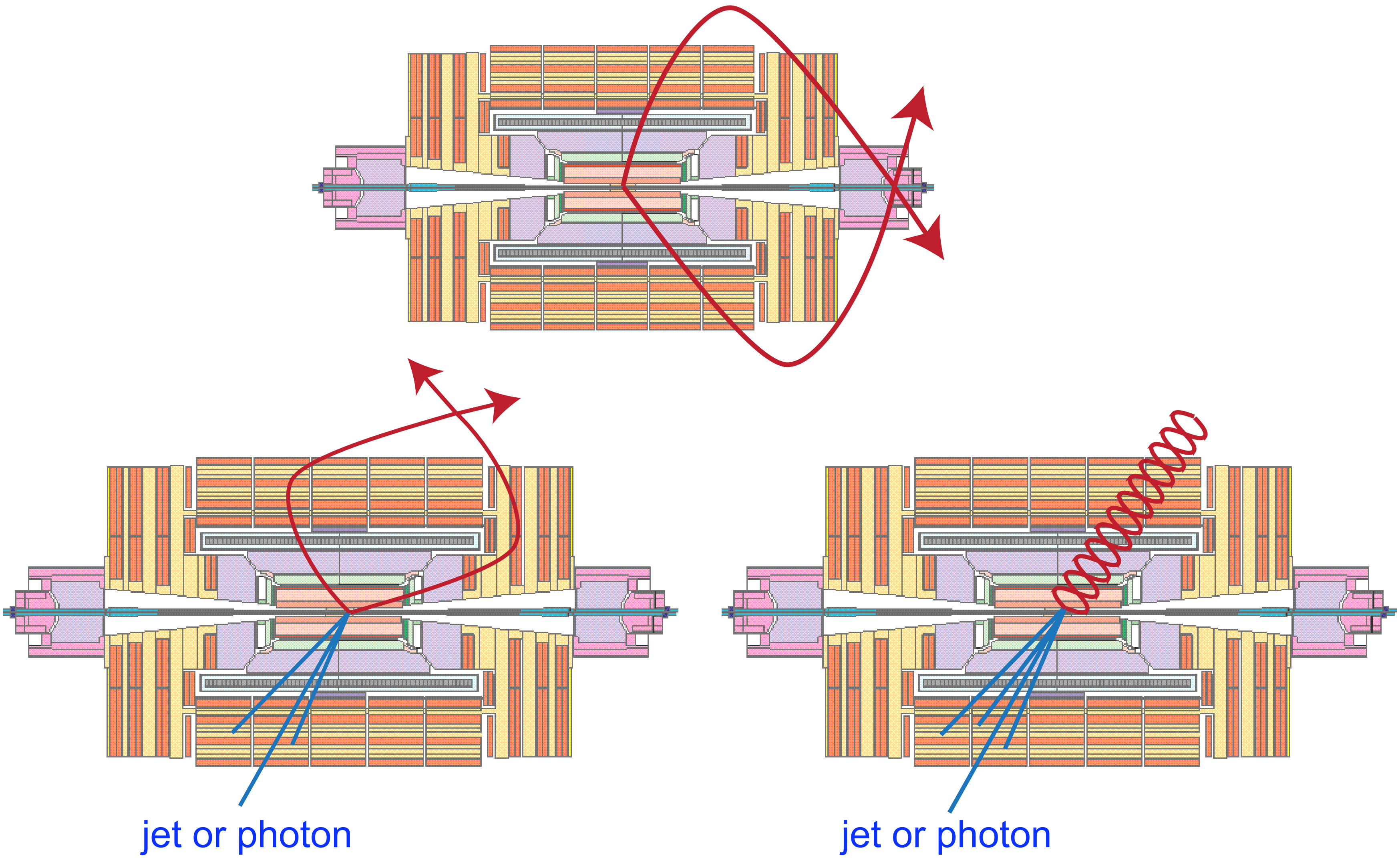
$$K \sim m_Q \sim \Lambda_{\rm IC}^2 L \Rightarrow L \sim \frac{m_Q}{\Lambda_{\rm IC}^2} \gg \underbrace{\Lambda^{-1}}_{\text{effective string}}$$

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

Macroscopic, mesoscopic, and microscopic string all possible

# Macroscopic Strings

$$\text{mm} \lesssim L \lesssim 10\ \text{m} \quad \Longleftrightarrow \quad 100\ \text{eV} \lesssim \Lambda_{\text{IC}} \lesssim 10\ \text{keV}$$



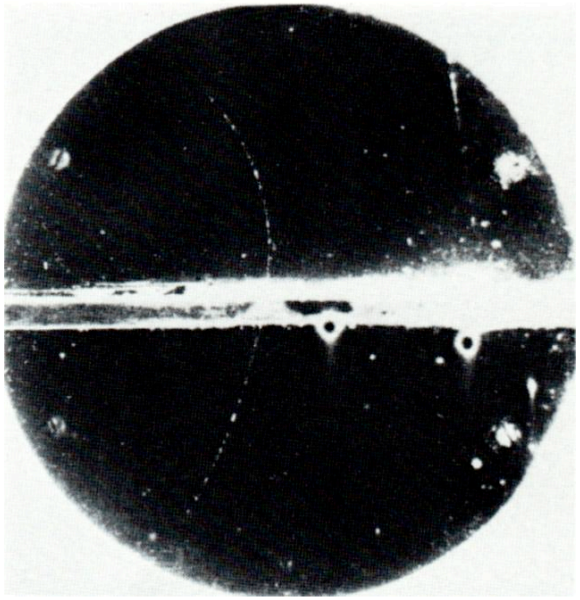
# Is it observable?

- Triggering?
- Track finding/reconstruction?
- Request to include in GEANT4 in progress...

Potential for discovery with single event:

$$\vec{p},\ dE/dx,\ \text{timing} \Rightarrow m_Q$$

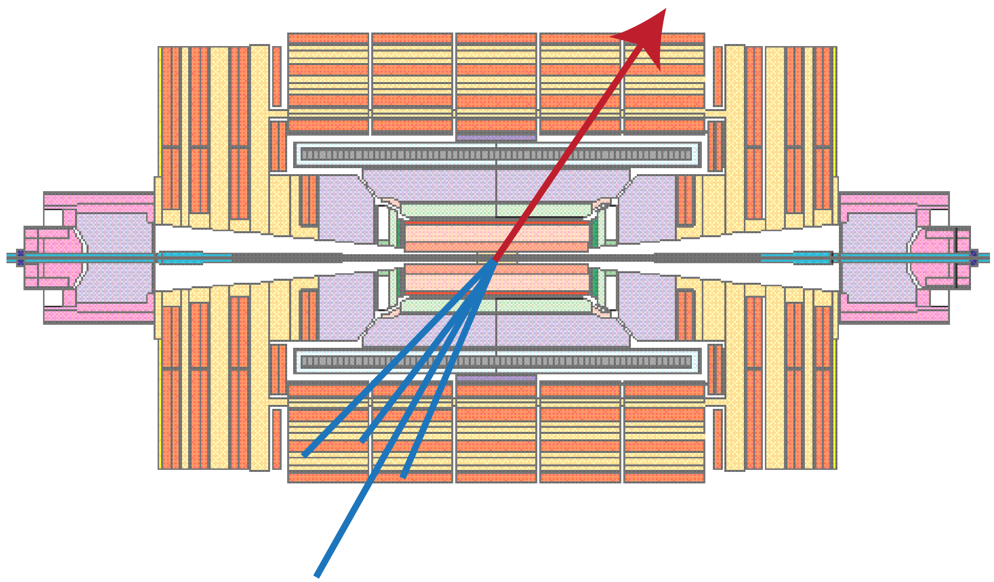
$$\vec{F} = m\vec{a} \Rightarrow \Lambda$$



Positron discovery
(Anderson 1932)

# Mesoscopic Strings

$$\text{Å} \lesssim L \lesssim \text{mm} \qquad \Longleftrightarrow \qquad 10\ \text{keV} \lesssim \Lambda \lesssim \text{MeV}$$

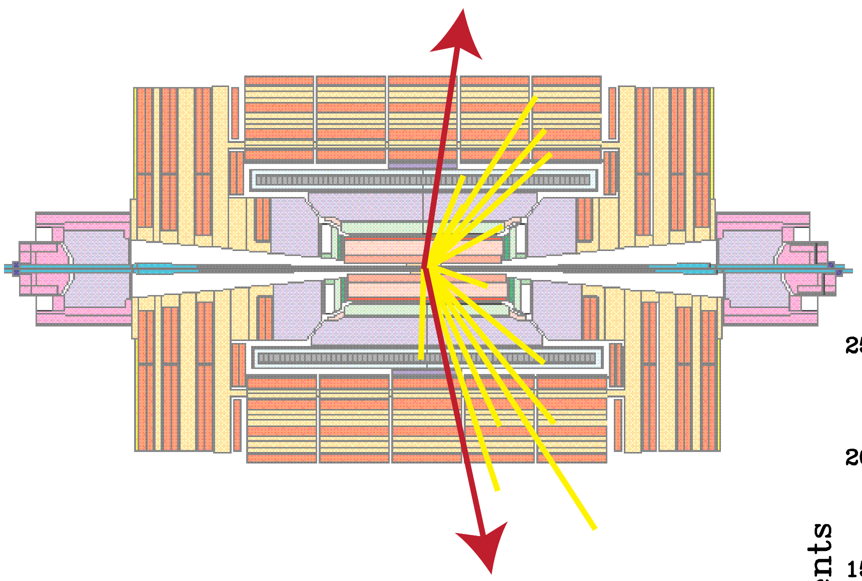


CHAMP-like with invariant mass distribution

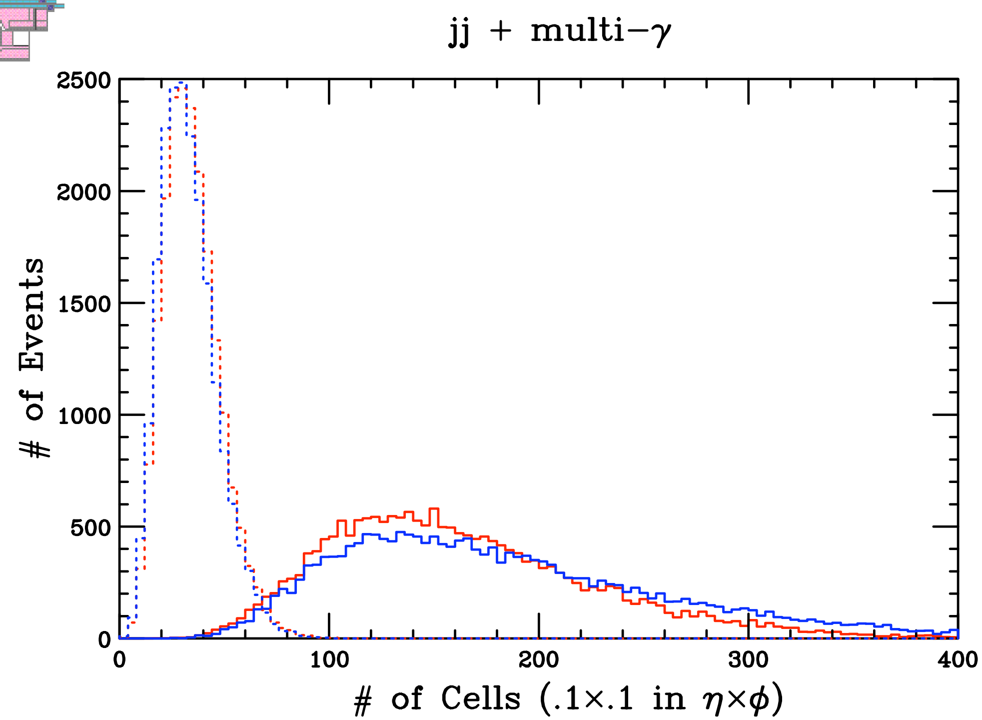
First quirk search (D0): jet + highly ionizing track

# Microscopic Strings

- Annihilation to di-jet, -lepton, or -photon
- Colored quirks lose energy to soft hadrons

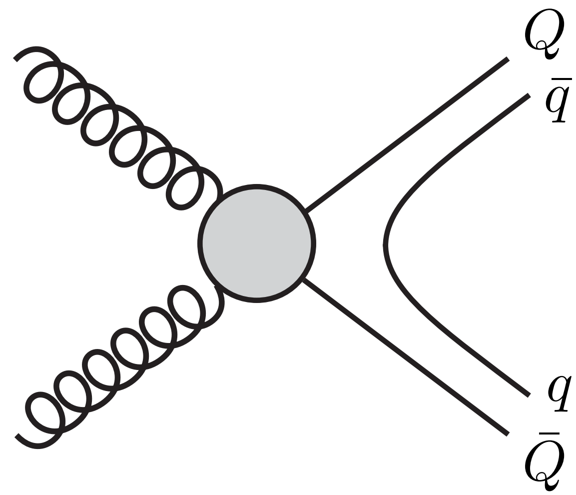


(Harnik, Huang, ML, Medina, Mrenna, in preparation)



# Hidden Valley $(N_q = 1)$

Hidden sector = 1-flavor QCD



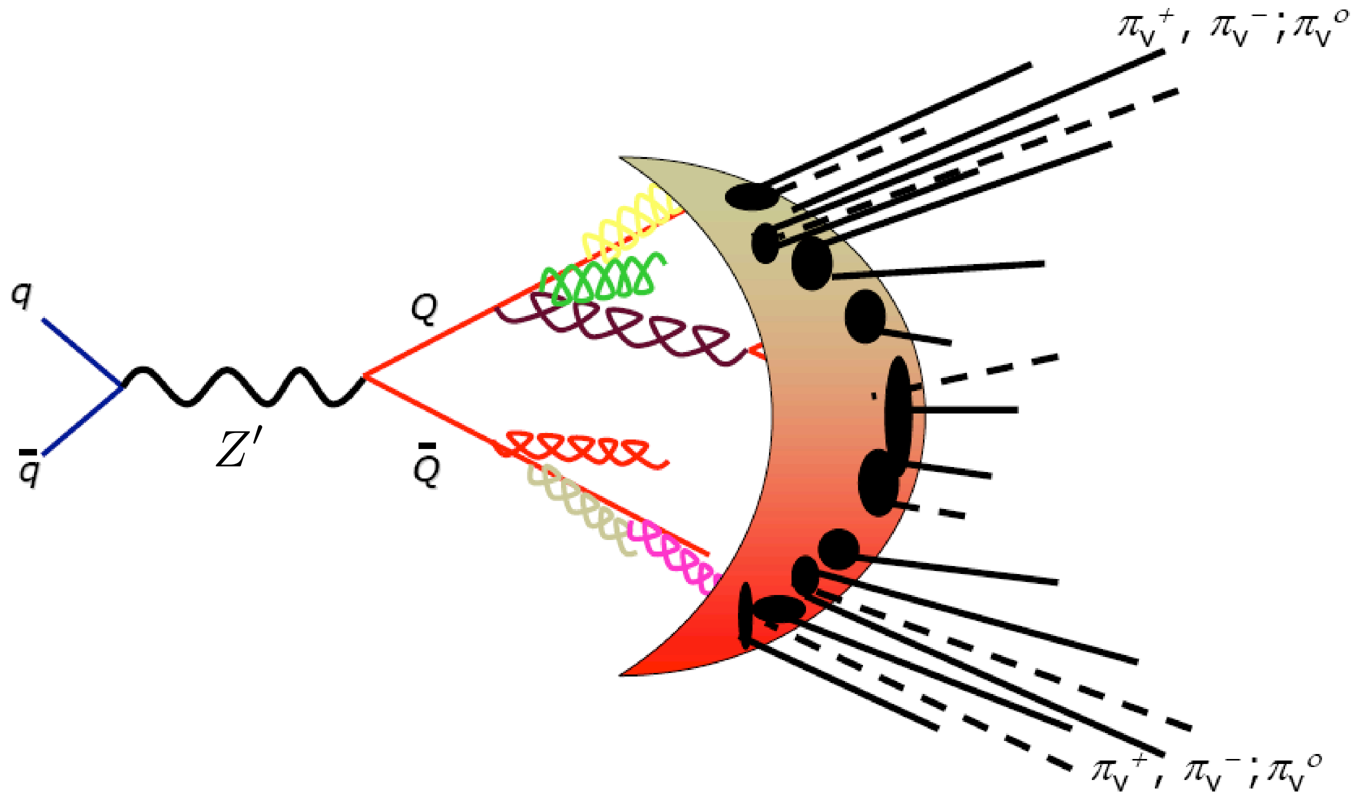

$$\Delta\mathcal{L} = y\bar{Q}Hq \;\Rightarrow\; Q \to qh^0 \quad (q \text{ sterile})$$

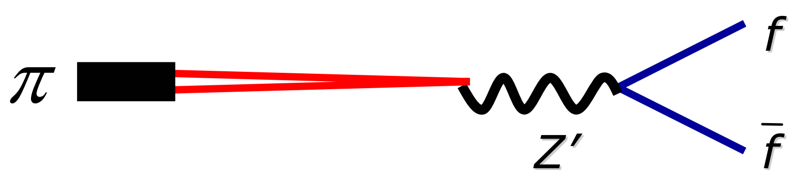
mesons: $(\bar{q}q) \to (h^0)^* \to \bar{b}b, \bar{\tau}\tau, \ldots$

baryons: $(qqq) = \text{stable} \Rightarrow \not{E}_T$

# “Classic” Hidden Valley

(Strassler, Zurek 2006)




Familiar, straightforward to simulate

# Hidden Valley Signals

- High multiplicity (from hadronization in hidden sector)
- MET (from stable hadrons)
- Heavy flavors (from meson decays)
- Displaced leptons/jets
- Studies underway at ATLAS/CMS

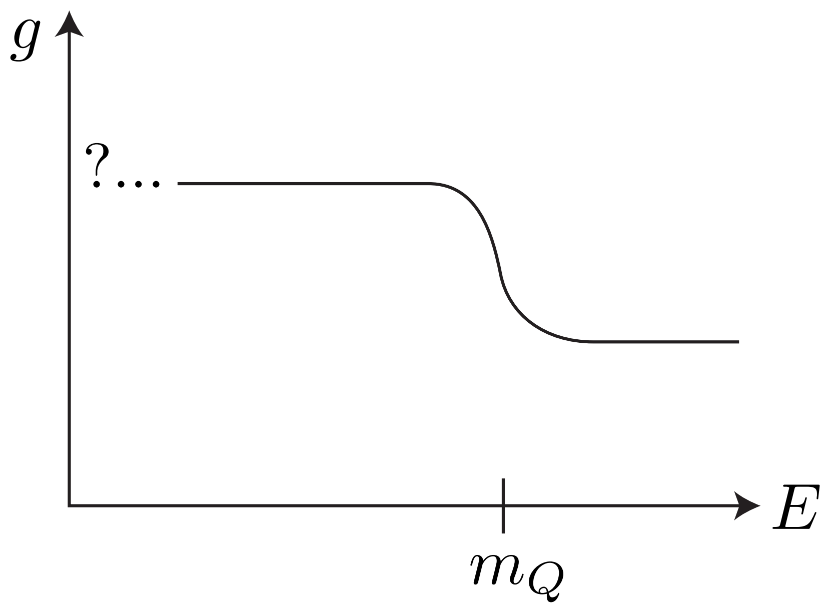
# Unparticles ($N_q \sim N$)

$N_q \sim N \Rightarrow$ conformal dynamics in hidden sector

(Georgi, 2007)

$Q = \text{stable} \Rightarrow$ "massive unparticle"

= massive particle + radiation




CHAMP + $\not{E}_T$

$Q \to qh^0 \Rightarrow \bar{b}b, \bar{\tau}\tau, \ldots + \not{E}_T$

# Displaced Dark Matter

(Chang, ML, in preparation)

- SuperWIMP (Feng, Rajaraman, Takayama 2003)

  $Y$ = would-be LSP

  $Y \to X + \mathrm{SM}$, $X$ never in equilibrium

  $$\Rightarrow \Omega_X = \frac{m_X}{m_Y}\Omega_Y \qquad m_X \sim m_Y \sim 100 \text{ GeV}$$

- Asymmetric dark matter (Kaplan, Luty, Zurek 2009)

  $\bar{X} \neq X$

  Transfer standard model particle-antiparticle asymmetry to dark matter by interactions in equilibrium at high $T$

  $$\Rightarrow \Omega_X \sim \frac{m_X}{m_B}\Omega_B \qquad m_X \sim 10 \text{ GeV}$$

# Cosmic Coincidence?

Both models *require* long-lived $Y$ decays

- SuperWIMP

$$\Gamma(Y \to X + \mathrm{SM}) \lesssim H \quad \text{at} \quad T \sim m_Y/25$$

$$\Rightarrow c\tau \gtrsim 10 \text{ m} \quad \text{for} \quad m_Y \sim 100 \text{ GeV}$$

- Asymmetric dark matter

Interactions that transfer asymmetry $\Rightarrow R(X) \neq 0$

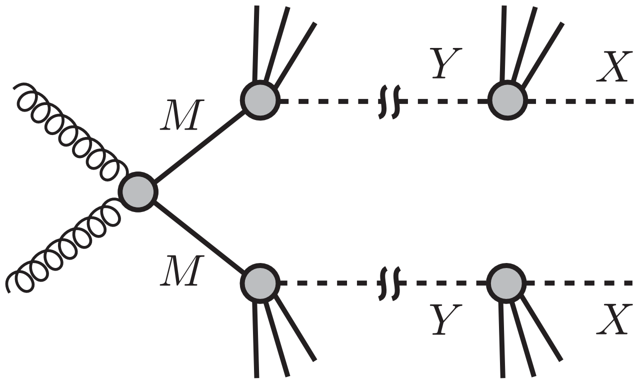
$$\Gamma(Y \to X + \mathrm{SM}) \lesssim H \quad \text{for} \quad T \lesssim m_X$$

$$\Rightarrow c\tau \gtrsim 10 \text{ m} \quad \text{for} \quad m_X \sim 10 \text{ GeV}$$

# Classify Models

| Coupling | NLSP Decay | NLSP Signal |
|---|---|---|
| $XH_uH_d$ | $\chi^0 \to X + (h, Z)$<br>$\chi^\pm \to X + (H^\pm, W^\pm)$ | vertex $\to (h, Z) + \not{E}_T$<br>track $\to (H^\pm, W^\pm) + \not{E}_T$ |
| $XLH_u$ | $\chi^\pm \to X + \ell^\pm$<br>$\tilde{\nu} \to X + (h, Z)$<br>$\tilde{\ell}^\pm \to X + (H^\pm, W^\pm)$ | track $\to \ell^\pm + \not{E}_T$<br>vertex $\to (h, Z) + \not{E}_T$<br>track $\to (H^\pm, W^\pm) + \not{E}_T$ |
| $XLLe^c$ | $\tilde{\ell}^\pm \to X + \ell'^\pm$<br>$\tilde{\nu} \to X + \ell' + \bar{\ell}$ | track $\to \ell'^\pm + \not{E}_T$<br>vertex $\to \ell' + \bar{\ell} + \not{E}_T$ |
| $XQLd^c$ | $\tilde{\ell}^\pm \to X + u + \bar{d}$<br>$\tilde{\nu} \to X + d + \bar{d}$<br>$\tilde{u} \to X + \ell^+ + d$<br>$\tilde{d} \to X + \nu + d$ | track $\to$ 2 jets $+ \not{E}_T$<br>vertex $\to$ 2 jets $+ \not{E}_T$<br>$R$-hadron $\to \ell^\pm +$ jet $+ \not{E}_T$<br>$R$-hadron $\to$ jet $+ \not{E}_T$ |
| $Xu^cd^cd^c$ | $\tilde{u} \to X + \bar{d} + \bar{d}'$ | $R$-hadron $\to$ 2 jets $+ \not{E}_T$ |

# Reconstruction




Look at events with *one* displaced vertex in detector

$\Delta\vec{x}, \Delta t$ from displaced visible particles $\Rightarrow \vec{v}_Y$

unknown $-$ constraints for $k$ events:

$$\underbrace{8k}_{2\times p^\mu_Y} - \underbrace{2k}_{\not{p}_T} - \underbrace{2(2k-1)}_{M,Y\text{ mass}} - \underbrace{3k}_{\vec{v}_Y} = -k+2$$

Complete reconstruction of prompt event with 2 events!

$$m_X = \sqrt{(m_Y - E_{\rm vis})^2 - p^2_{\rm vis}}$$

# Conclusions

- It is important to think about all signals that will be missed if we don’t look for them.

- “Minimal non-minimal” extensions of the standard model can give qualitatively new phenomenology.

- Expect the unexpected!