# Constraining Quirky Tracks from Conventional Searches

(*or* things to do with 0T data)

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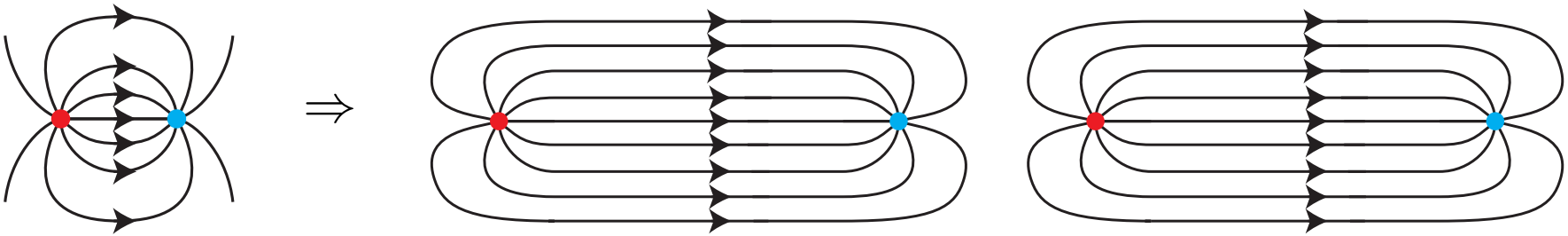
Institute for Advanced Study

based on **arXiv:1703.00912**

*with* Marco Farina

# Quirks in a Nutshell

- Consider quarks in QCD



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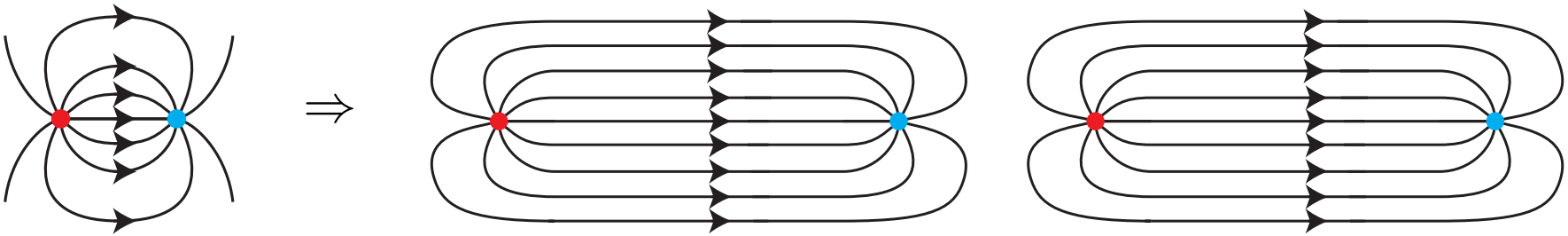
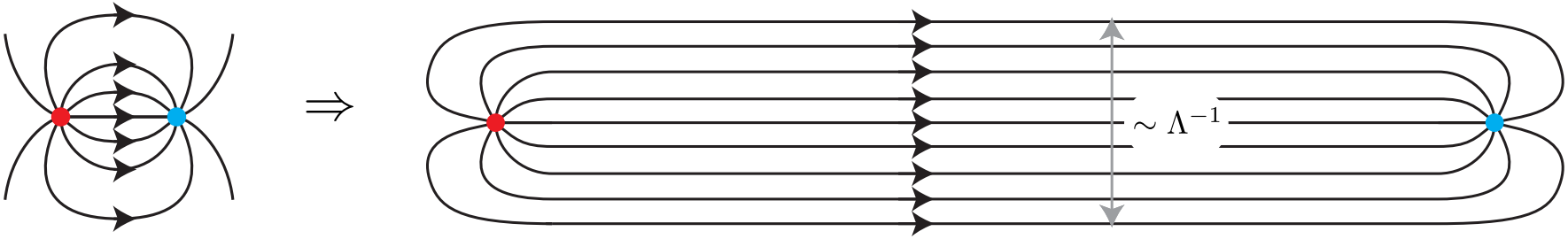


- Imagine there are no light quarks (where light means $m_q \lesssim \Lambda_{\rm QCD}$)



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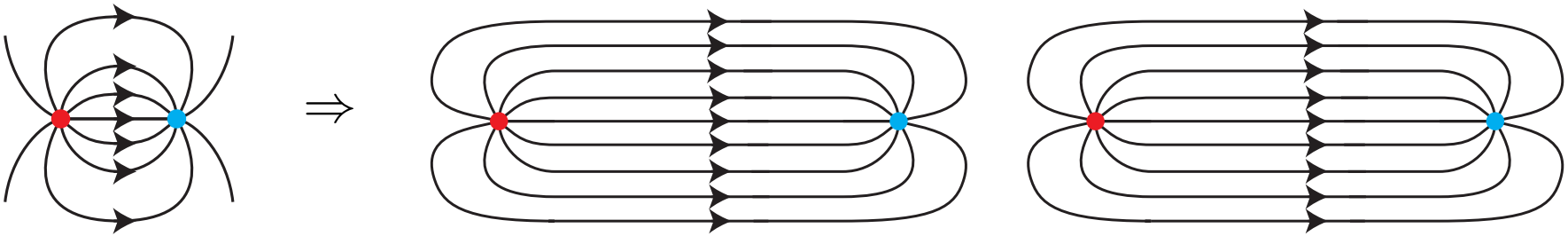

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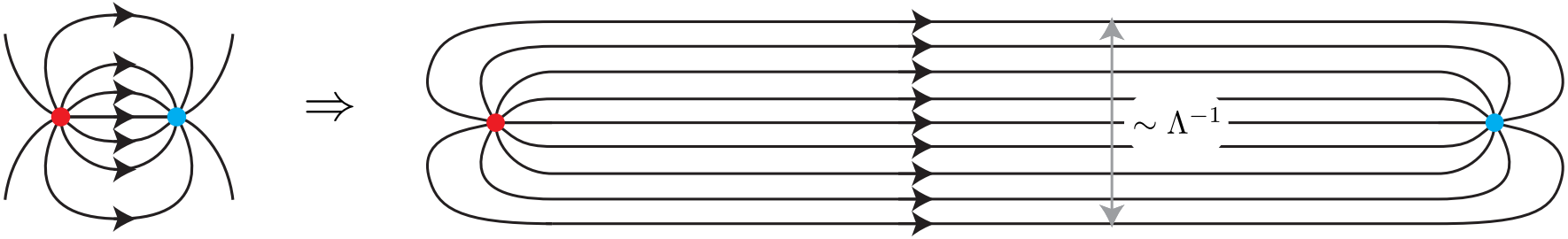


- New sector with confinement scale $\Lambda$
- Quirks correspond to $m_Q \gg \Lambda$ regime.

*(Okun; Kang, Luty)*

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$$\ell_{\text{eff}} \sim \frac{m_Q}{\Lambda^2} v^2$$

- Wide range of string lengths

$$\ell_{\text{eff}} \approx 10 \text{ m} \left(\frac{m_Q}{1 \text{ TeV}}\right) \left(\frac{100 \text{ eV}}{\Lambda}\right)^2 \left(\frac{v}{0.7}\right)^2$$

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| | | |
|---|---|---|
| $10 \text{ keV} \lesssim \Lambda \lesssim 1 \text{ MeV}$ | $0.1 \ \mu\text{m} \lesssim \ell_{\text{eff}} \lesssim 1 \text{ mm}$ | *Microscopic* |
| $1 \text{ eV} \lesssim \Lambda \lesssim 10 \text{ keV}$ | $1 \text{ mm} \lesssim \ell_{\text{eff}} \lesssim 100 \text{ km}$ | *Macroscopic* |
| $\Lambda \gtrsim 1 \text{ eV}$ | $\ell_{\text{eff}} \gtrsim 100 \text{ km}$ | *Megascopic* |

# Quirks in a Nutshell

- Dynamics from Nambu-Goto action

$$S = \sum_Q \left( -m_Q \int d\tau + q_Q \int A_\mu dX^\mu \right) - \Lambda^2 \int d\tau d\sigma \sqrt{-\det \gamma}$$

- Can lead to frenetic-looking trajectories

$$\frac{\partial}{\partial t} \left( \gamma m_Q \vec{v} \right) = q\vec{v} \times \vec{B} - \Lambda^2 \sqrt{1 - \vec{v}_\perp^2}\, \hat{s} - \Lambda^2 \frac{v_\parallel \vec{v}_\perp}{\sqrt{1 - \vec{v}_\perp^2}}$$

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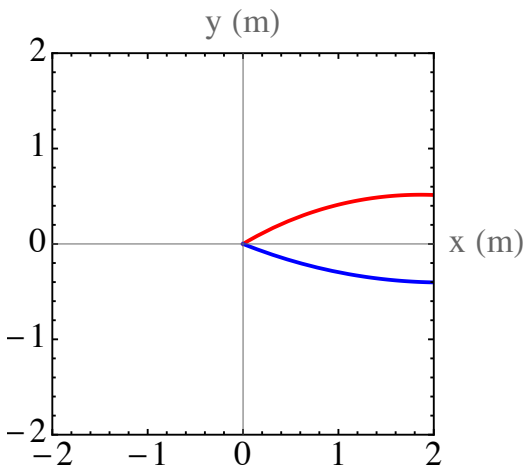
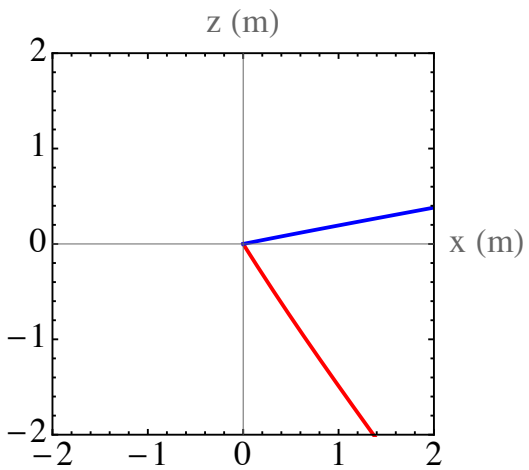
- Example trajectory (tiny $\Lambda$)



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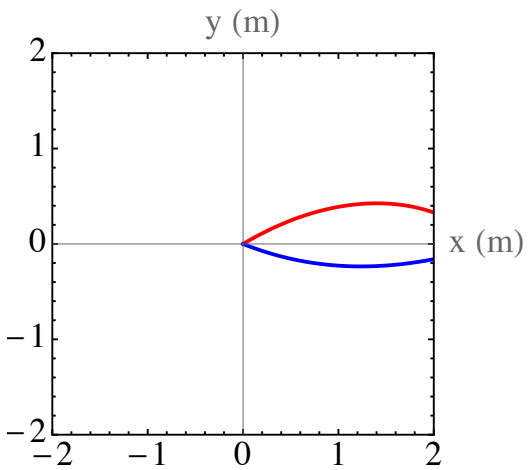
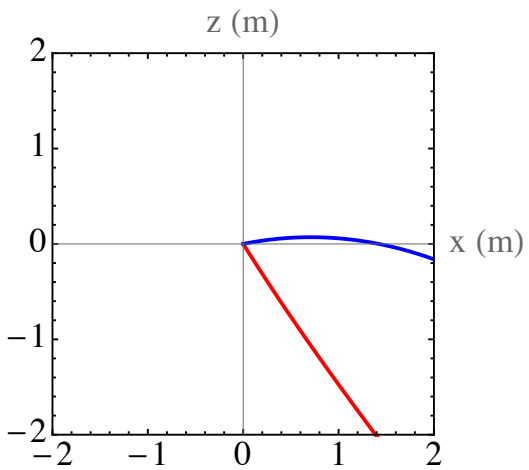
- Example trajectory (small $\Lambda$)



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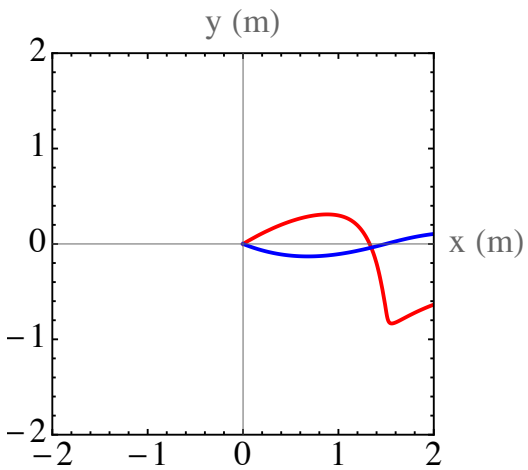
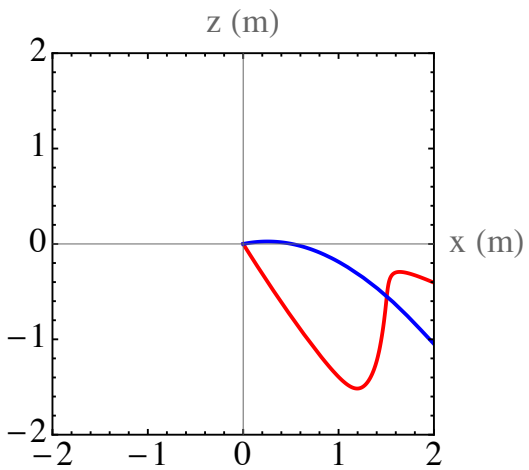
- Example trajectory (medium $\Lambda$)



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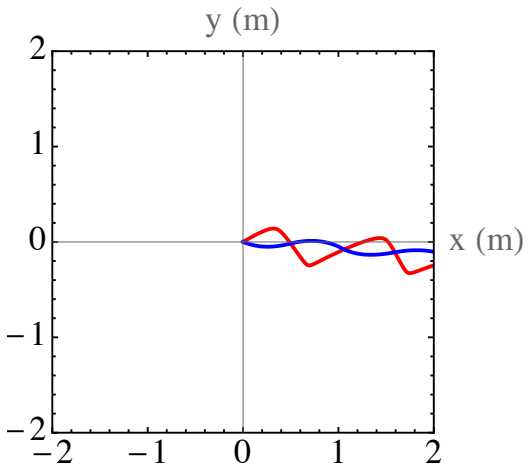
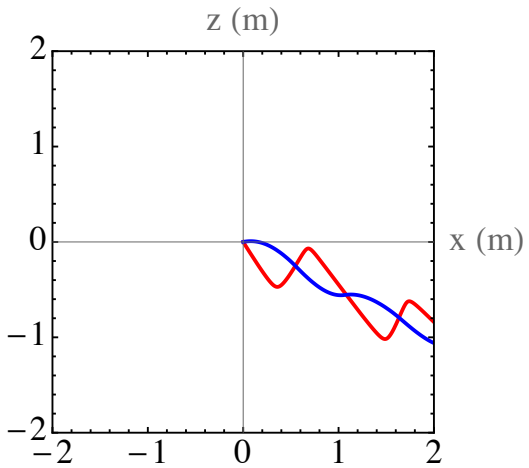
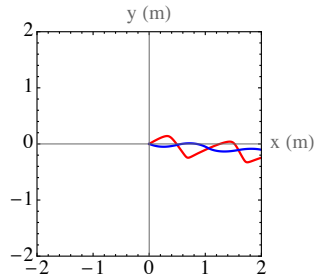


# Sketch of Parameter Space

$\Lambda$

$\Lambda \sim 10$ keV

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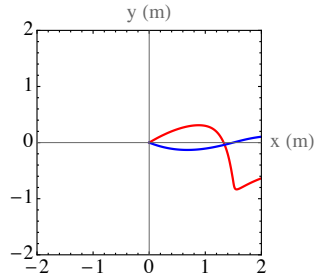
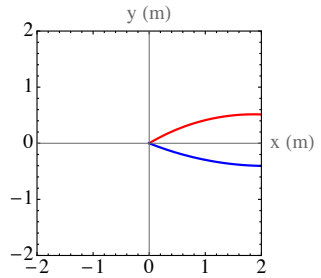



$\Lambda \sim 1$ eV



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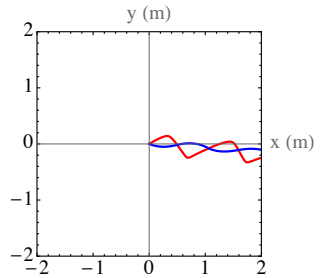
$m_Q \gtrsim 120$ GeV

*(DZero, 1008.3547)*

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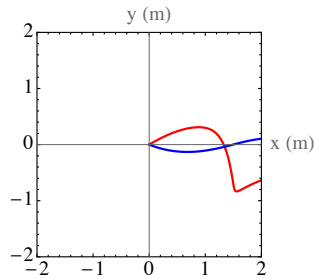


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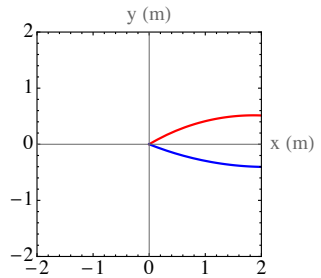

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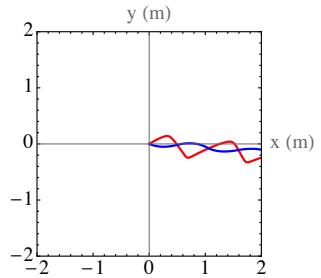


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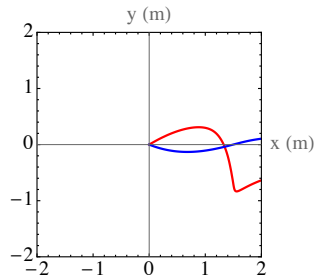


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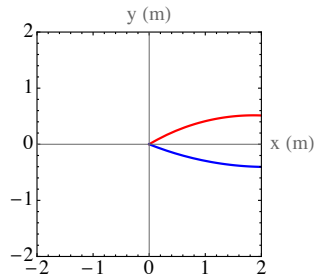

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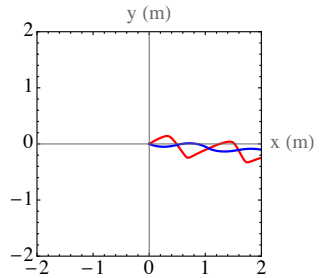


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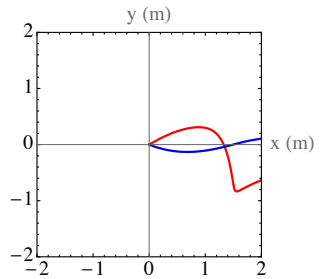
- Can already make progress with:
  - HSCP
  - Monojet

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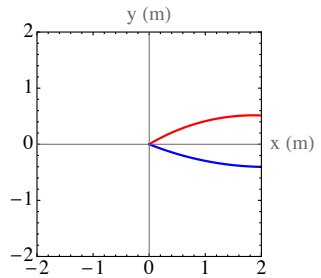
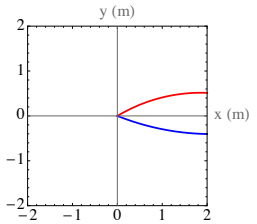
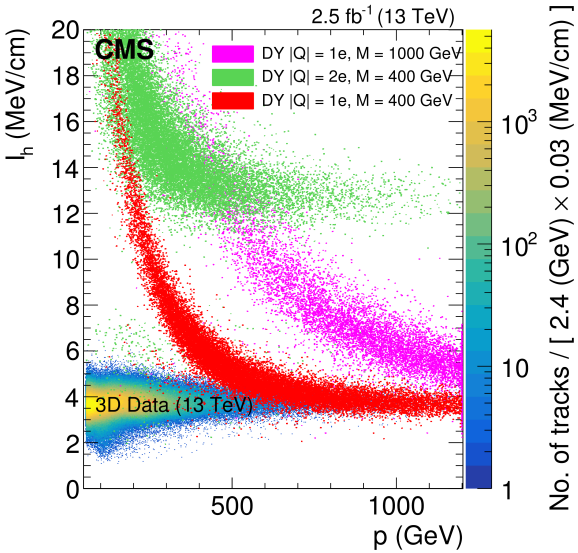


# Reintepreting: HSCP

- Heavy Stable Charged Particles (HSCP)
  - Pair-produced heavy particles
  - Leave slow and highly-ionizing tracks
  - Limits set on long-lived stops, staus, etc.
  - Can be reinterpreted when $\Lambda \neq 0$ is a minor effect




- ATLAS, 3.2 fb$^{-1}$ (SUSY-2016-02, SUSY-2016-03)

  $m_{\tilde{t}} > 890$ GeV

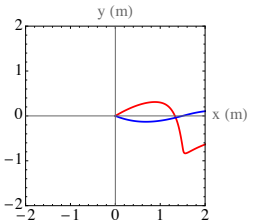
- CMS, 12.9 fb$^{-1}$ (EXO-16-036)

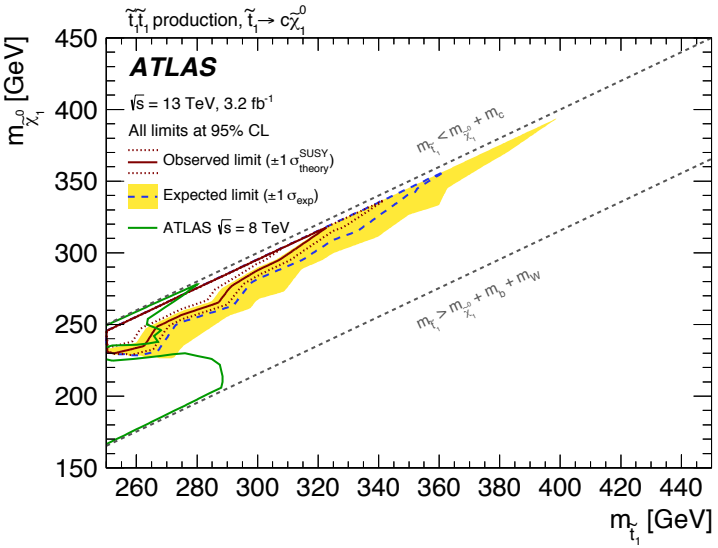
  $m_{\tilde{t}} > 1200$ GeV

See talks by Andy Haas and Jamie Antonelli

# Reintepreting: Monojet

- Monojet
  - Pair-produced heavy particles *and* initial jet
  - $\geq 1$ hard jets and large missing energy
  - Limits set on various new physics scenarios
  - Can be reinterpreted when track is missed




- ATLAS, 3.2 fb$^{-1}$ (EXOT-2015-03)

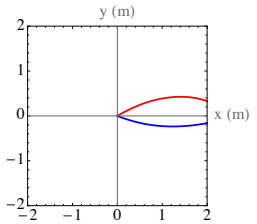
  $m_{\tilde{t}} > 322$ GeV

- CMS, 12.9 fb$^{-1}$ (EXO-16-037)

  Simplified DM, $\mathcal{BR}(H \to \text{inv}) < 0.44$, etc.

See talks by Marco Vanadia and Kristian Hahn

# New: 0T (at CMS)




- CMS collected data with 0T magnetic field
  - $\sqrt{s} = 13$ TeV
  - $\int dt\mathcal{L} = 0.6$ fb$^{-1}$
  - Charged particles leave straight tracks ...

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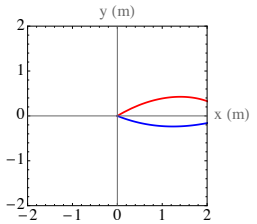


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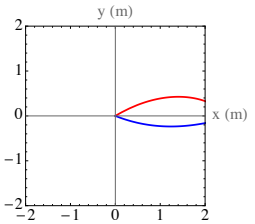


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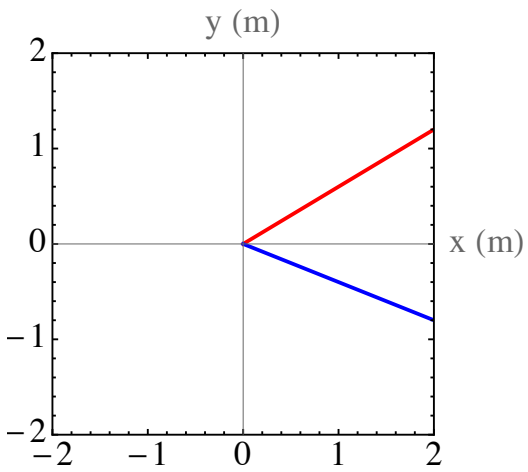
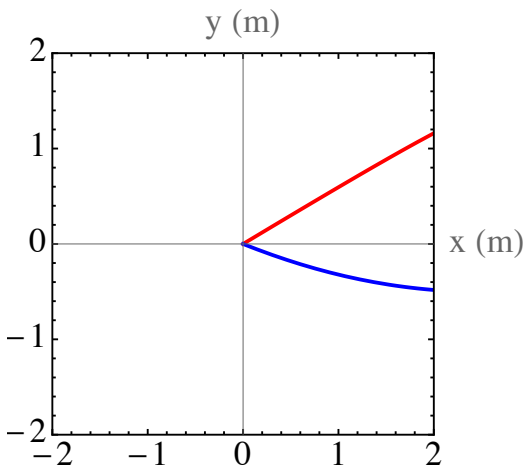
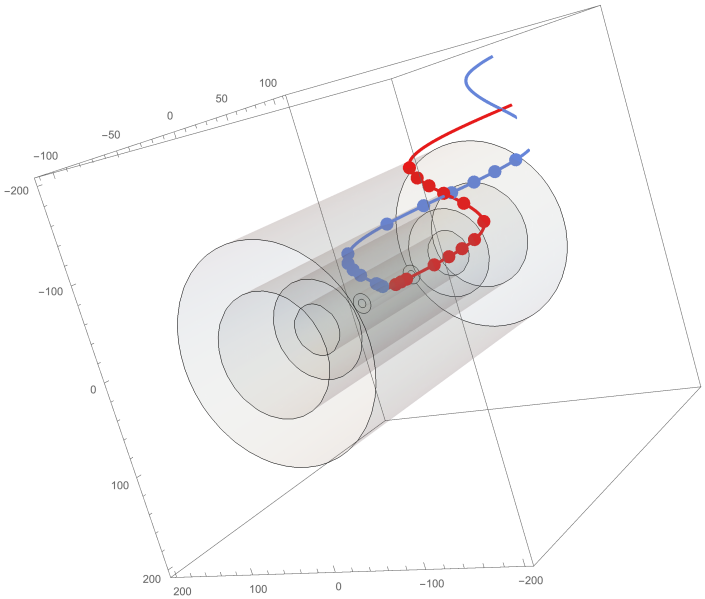


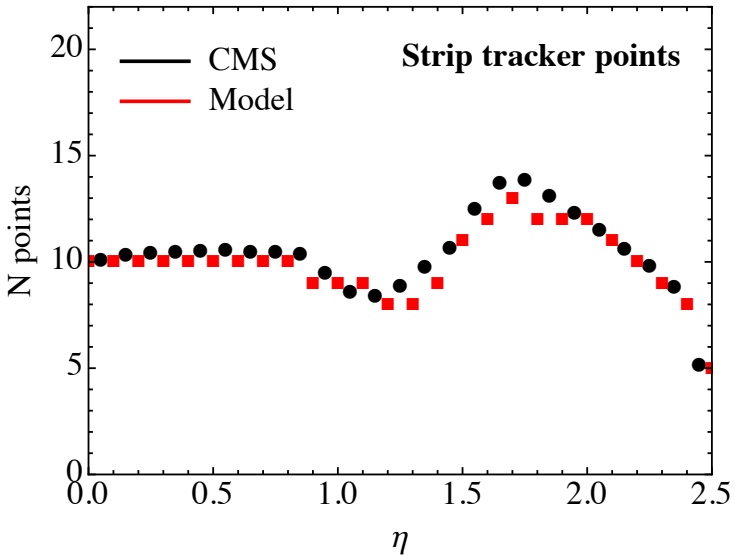

$$\Lambda \neq 0$$
$$\Rightarrow$$



# Track Efficiencies

- Model the CMS tracker
  - Pixel layers: 3 barrel, 2 end cap
  - Inner strip layers: 4 barrel, 3 end cap
  - Outer strip layers: 6 barrel, 9 end cap





# Track Efficiencies

- Track selection
  - Acceptance: $|\eta|$
  - Trigger: $v$, $p_T^{\text{eff}}$
  - Quality: $n_{\text{hits}}$, $\chi^2/\text{NDF}$
  - Curved?: $R$
- $\chi^2$ from fit to helix $\{h_x, h_y, h_z\}$ with parameters $\{R, \lambda, \phi\}$

$$h_x(t; R, \phi, \lambda) = R\cos(\phi \pm (t/R)\cos\lambda) - \cos\phi$$

$$h_y(t; R, \phi, \lambda) = R\sin(\phi \pm (t/R)\cos\lambda) - \sin\phi$$

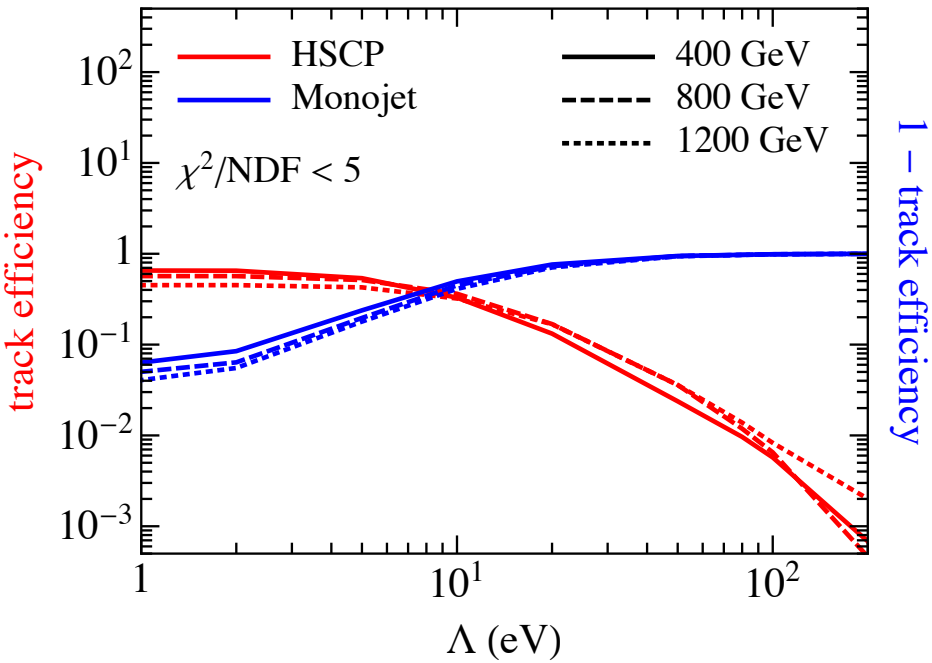
$$h_z(t; R, \phi, \lambda) = t\sin\lambda$$

- Use spatial resolution of 30 $\mu$m

# Track Efficiencies

- HSCP efficiencies
  - Selection follows EXO-16-036
  - Uses muon trigger (cut on $p_T^{\text{eff}}$)

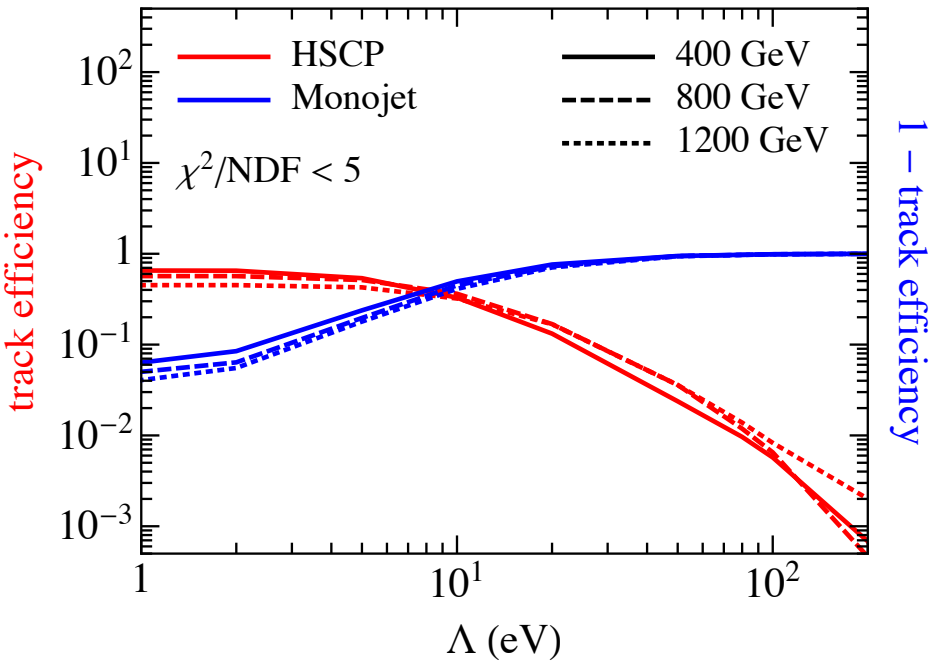
| cut | HSCP |
|---|---|
| $\lvert\eta\rvert$ | $< 2.1$ |
| $n_{\text{hits}}$ | $\geq 9$ |
| $v$ | $> 0.6$ |
| $p_T^{\text{eff}}$ | $> 65$ GeV |
| $\chi^2/\text{NDF}$ | $< 5$ |
| $R$ | – |



# Track Efficiencies

- Monojet efficiencies
  - Selection follows EXO-16-037
  - Uses $H_T/\not{E}_T$ trigger
  - Discards identified tracks

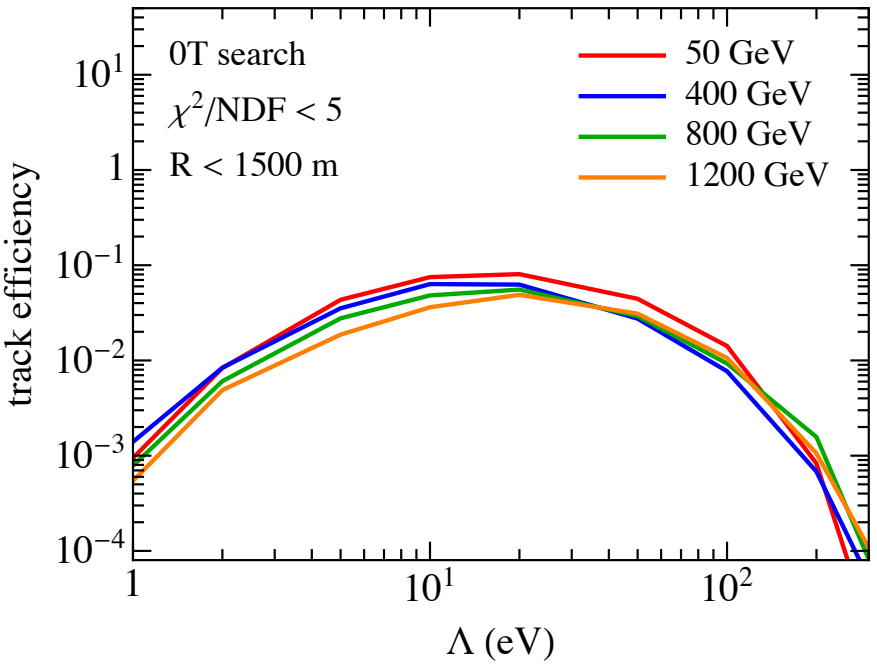
| cut | monojet |
|---|---|
| $\lvert\eta\rvert$ | $< 2.5$ |
| $n_{\text{hits}}$ | $\geq 9$ |
| $v$ | – |
| $p_T^{\text{eff}}$ | $> 10$ GeV |
| $\chi^2/\text{NDF}$ | $< 5$ |
| $R$ | – |



# Track Efficiencies

- 0T efficiencies
  - Selection similar to HSCP
  - Uses $H_T/\not{E}_T$ trigger*
  - Adds $R$ cut to distinguish from straight tracks

| cut | 0T |
|---|---|
| $\lvert\eta\rvert$ | $< 2.1$ |
| $n_{\text{hits}}$ | $\geq 9$ |
| $v$ | – |
| $p_T^{\text{eff}}$ | $> 65$ GeV |
| $\chi^2/\text{NDF}$ | $< 5$ |
| $R$ | $< 1500$ m |

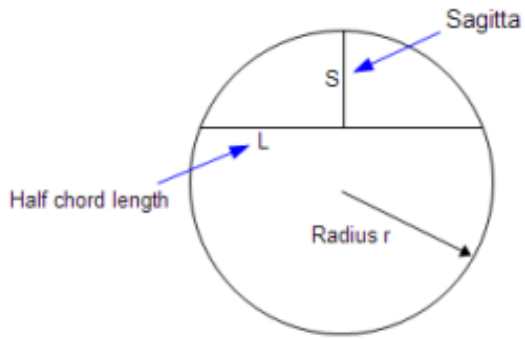



* need a recoiling jet for $xy$ curvature

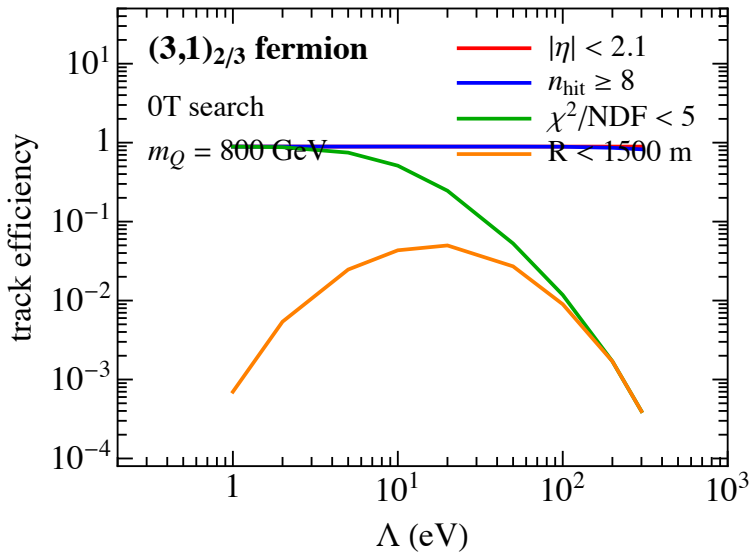
# Track Efficiencies

- Curved vs. straight
  - Require sagitta $> 3\sigma$ (w.r.t. resolution)

$$s \approx \frac{d_{\max}^2}{8R}$$

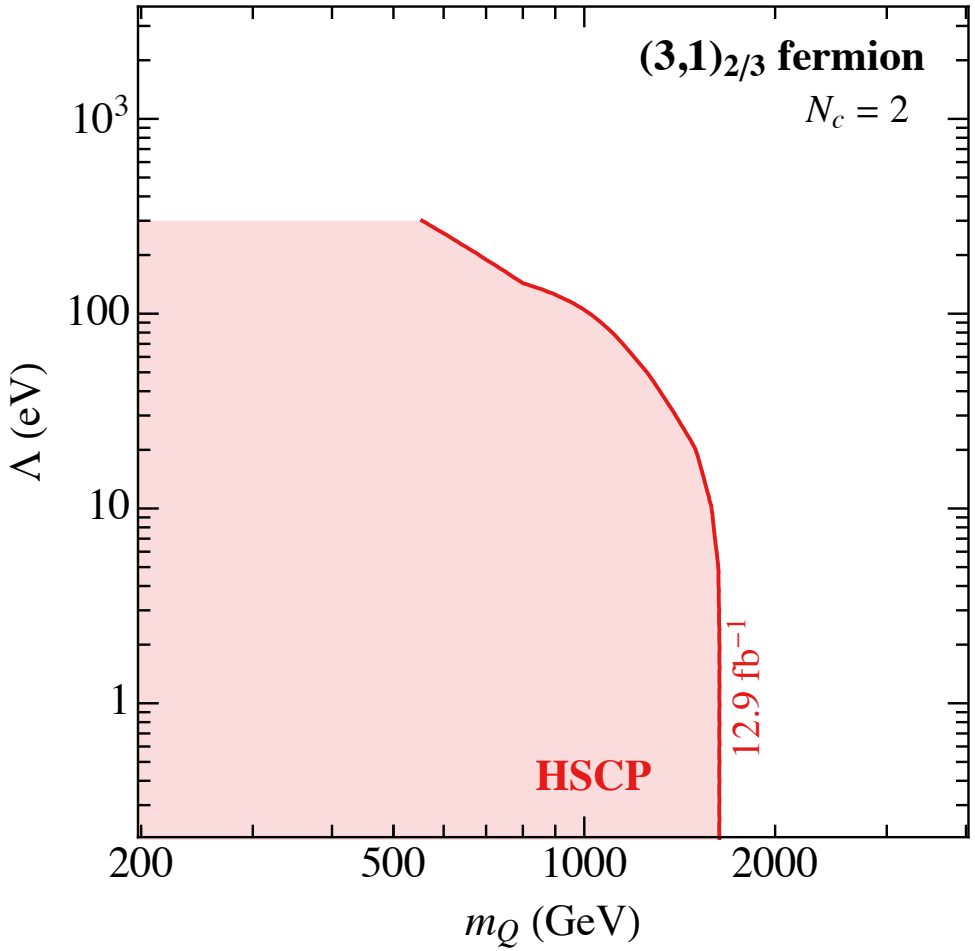



  - Find $R < 1500$ m (using $d_{\max} = 1$ m)



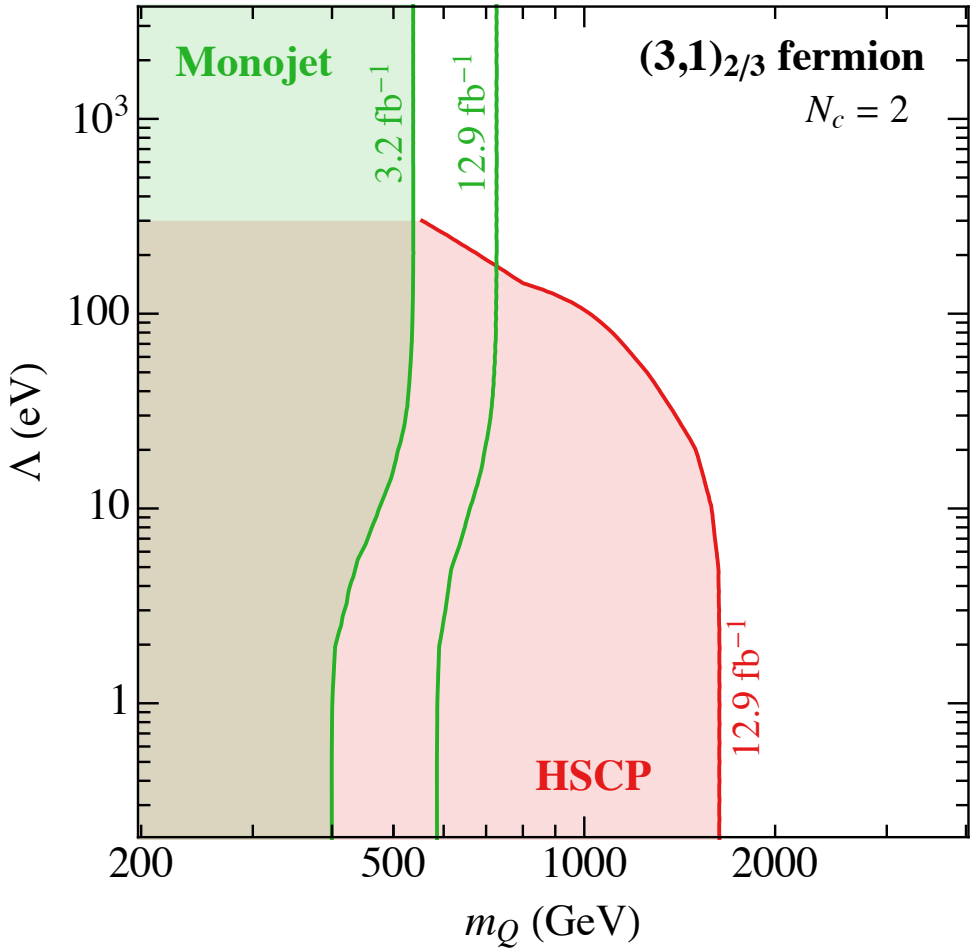
# Results

- Benchmark case:
  - Colored fermion $q = 2/3$
  - Multiplicity $N_c = 2$
  - At small $\Lambda$, $m_Q > 1.6$ TeV



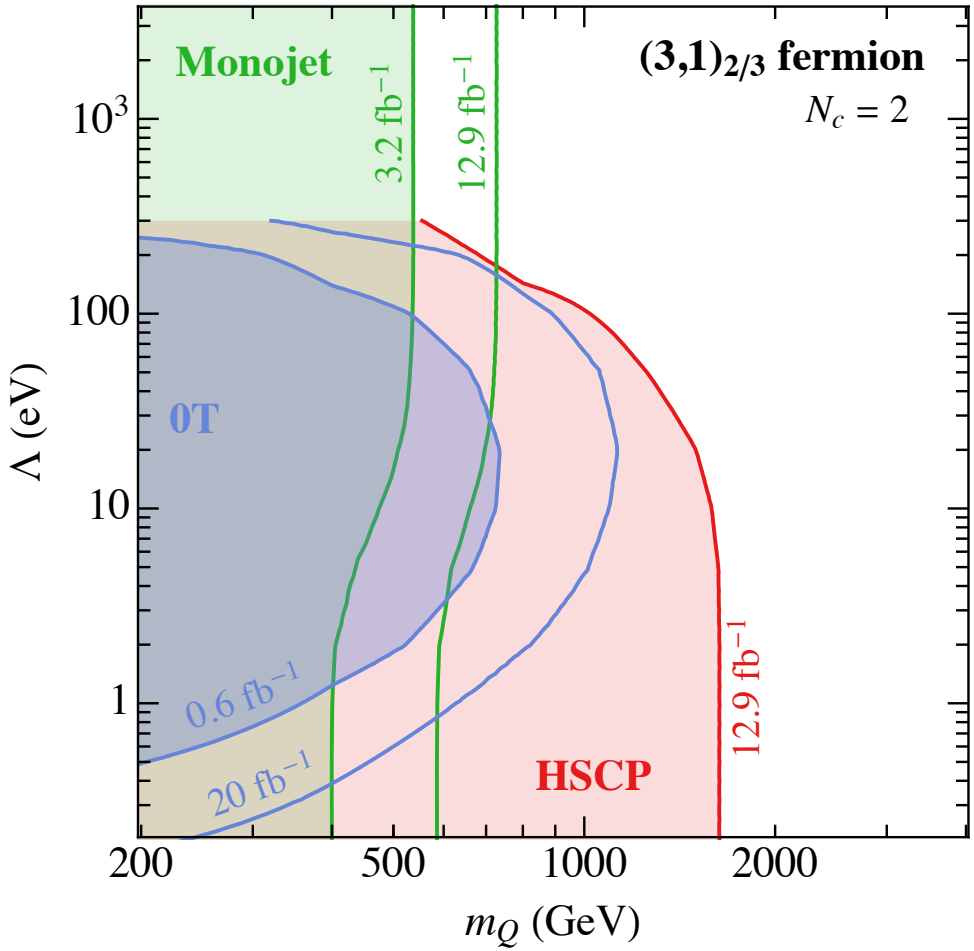
# Results

- Benchmark case:
  - Colored fermion $q = 2/3$
  - Multiplicity $N_c = 2$
  - At small $\Lambda$, $m_Q > 1.6$ TeV
  - At large $\Lambda$, $m_Q > 0.5$ TeV



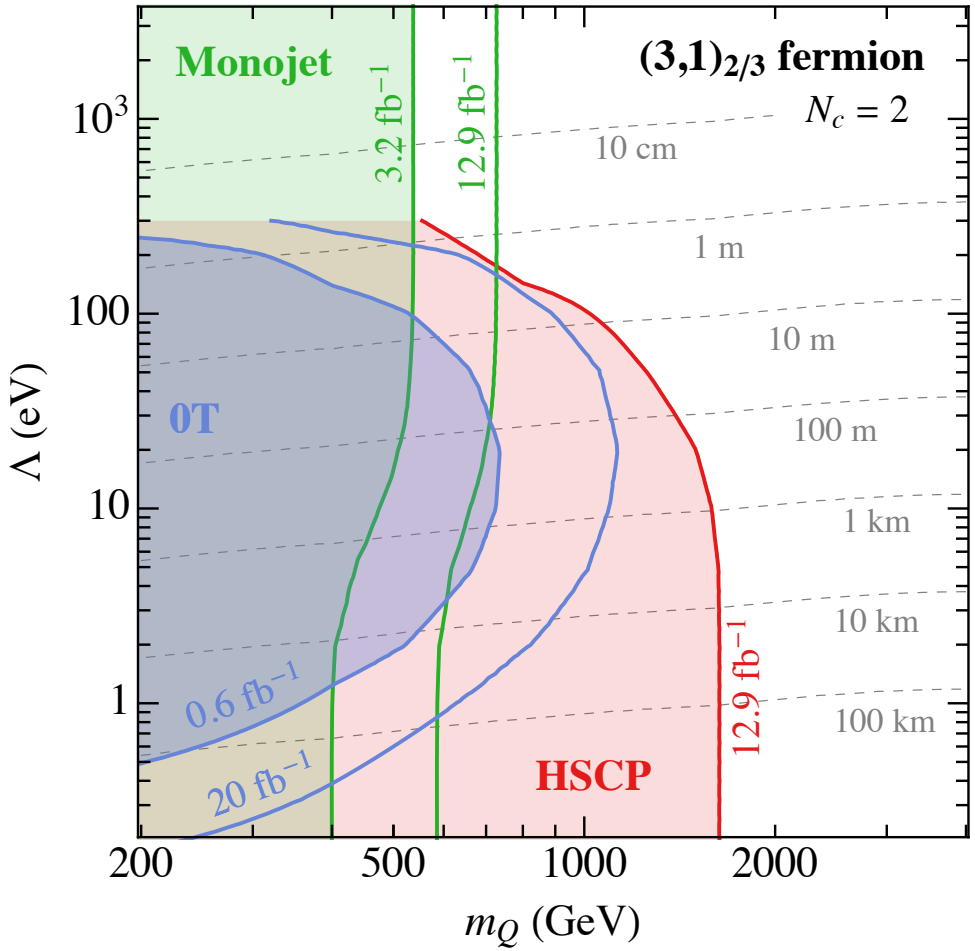
# Results

- Benchmark case:
  - Colored fermion $q = 2/3$
  - Multiplicity $N_c = 2$
  - At small $\Lambda$, $m_Q > 1.6$ TeV
  - At large $\Lambda$, $m_Q > 0.5$ TeV
  - Need $\sim 20$ fb$^{-1}$ of 0T to compete
  - Assuming zero background



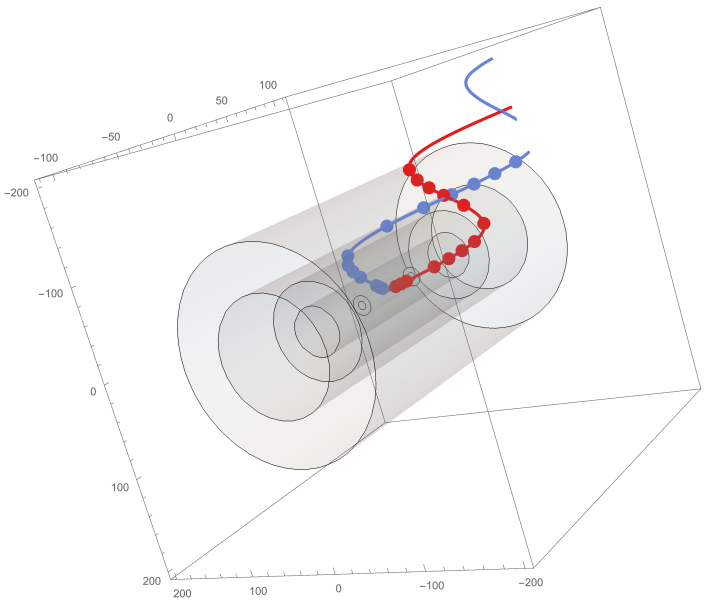
# Results

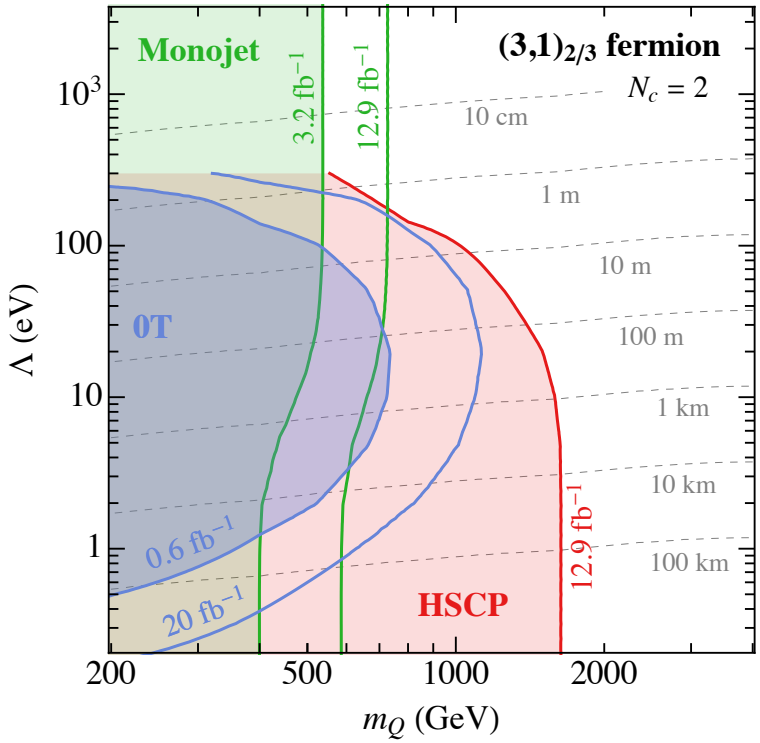
- Benchmark case:
  - Colored fermion $q = 2/3$
  - Multiplicity $N_c = 2$
  - At small $\Lambda$, $m_Q > 1.6$ TeV
  - At large $\Lambda$, $m_Q > 0.5$ TeV
  - Need $\sim 20$ fb$^{-1}$ of 0T to compete
  - Assuming zero background
  - Contours show constant $\ell_{\text{eff}}$



# Conclusions

- Quirks offer an interesting set of collider signals
- Ideal use case for new tracking algorithms
- Can already make substantial progress with HSCP and monojet searches
- New use for the 0T data





# Backup: Tracker model

- **Pixel barrel** (3 layers)
  $r = 4.4$ cm, $7.3$ cm, $10.2$ cm
  $|z| = 0$ cm $-$ $26.5$ cm
- **Pixel end cap** (2 layers)
  $|z| = 34.5$ cm, $46.5$ cm
  $r = 6$ cm $-$ $15$ cm
- **Tracker inner barrel** (4 layers)
  $r = 25.5$ cm, $33.9$ cm, $41.85$ cm, $49.8$ cm
  $|z| = 0$ cm $-$ $70.0$ cm
- **Tracker outer barrel** (6 layers)
  $r = 60.8$ cm, $69.2$ cm, $78.0$ cm, $86.8$ cm, $96.5$ cm, $108.0$ cm
  $|z| = 0$ cm $-$ $109.0$ cm
- **Tracker inner disk** (3 layers)
  $|z| = 80.0$ cm, $85.0$ cm, $90.0$ cm
  $r = 20.0$ cm $-$ $50.0$ cm
- **Tracker end caps** (9 layers)
  $|z| =$
  $124.0$ cm, $141.0$ cm, $155.0$ cm, $169.5$ cm, $188.0$ cm, $207.5$ cm, $228.0$ cm, $253.5$ cm, $280.0$ cm
  $r = 22.0$ cm, $22.0$ cm, $22.0$ cm, $30.0$ cm, $30.0$ cm, $30.0$ cm, $42.0$ cm, $42.0$ cm, $52.0$ cm

# Backup: Additional Limits

| spin | charge | $N_c$ | $m_Q$ ($\Lambda = 1$ eV) | $m_Q$ ($\Lambda = 100$ eV) | $m_Q$ ($\Lambda = 10^3$ eV) |
|---|---|---|---|---|---|
| fermion | $(\mathbf{3},\mathbf{1})_{2/3}$ | 2 | 1.6 TeV | 1.0 TeV | 500 GeV |
| scalar | $(\mathbf{3},\mathbf{1})_{2/3}$ | 2 | 1.3 TeV | 700 GeV | 350 GeV |
| fermion | $(\mathbf{1},\mathbf{1})_{-1}$ | 2 | 650 GeV | 150 GeV | – |
| scalar | $(\mathbf{1},\mathbf{1})_{-1}$ | 2 | 350 GeV | 60 GeV | – |
| fermion | $(\mathbf{3},\mathbf{1})_{2/3}$ | 5 | 1.8 TeV | 1.1 TeV | 600 GeV |
| scalar | $(\mathbf{3},\mathbf{1})_{2/3}$ | 5 | 1.4 TeV | 850 GeV | 450 GeV |
| fermion | $(\mathbf{1},\mathbf{1})_{-1}$ | 5 | 800 GeV | 200 GeV | 30 GeV |
| scalar | $(\mathbf{1},\mathbf{1})_{-1}$ | 5 | 450 GeV | 80 GeV | – |