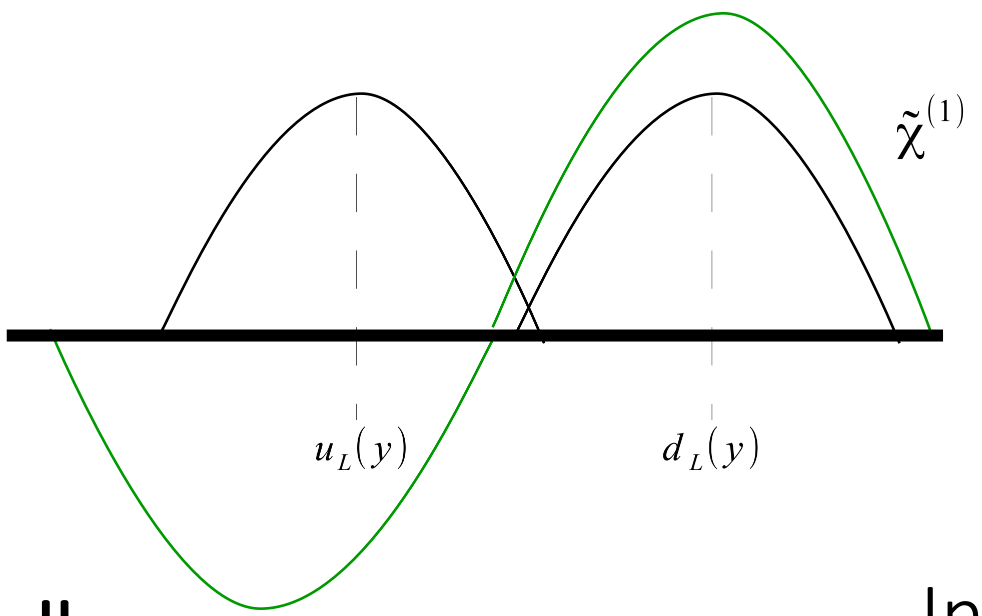
Domain Wall Standard Model

arXiv:1712.09323
arXiv:1801.03007



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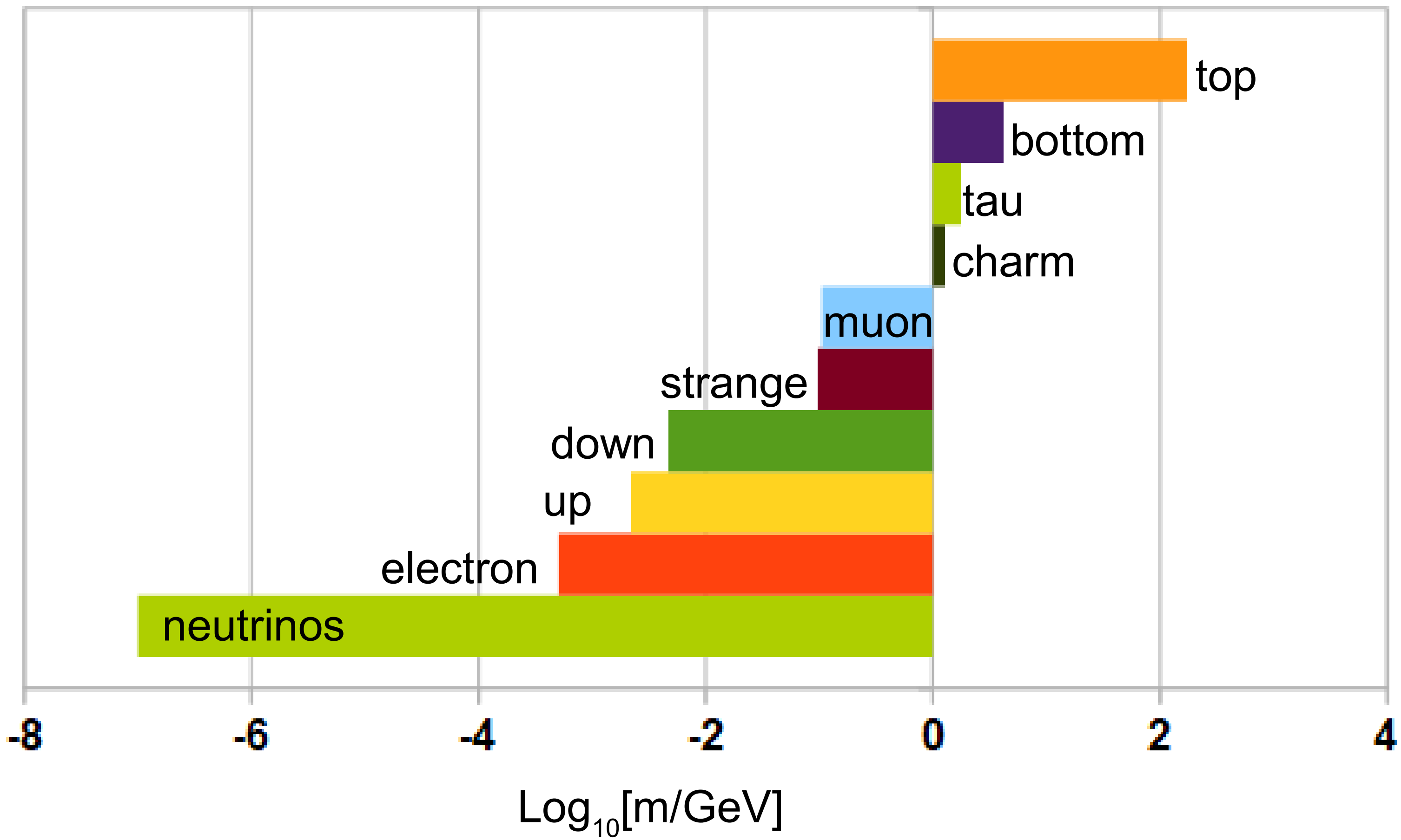
Outline

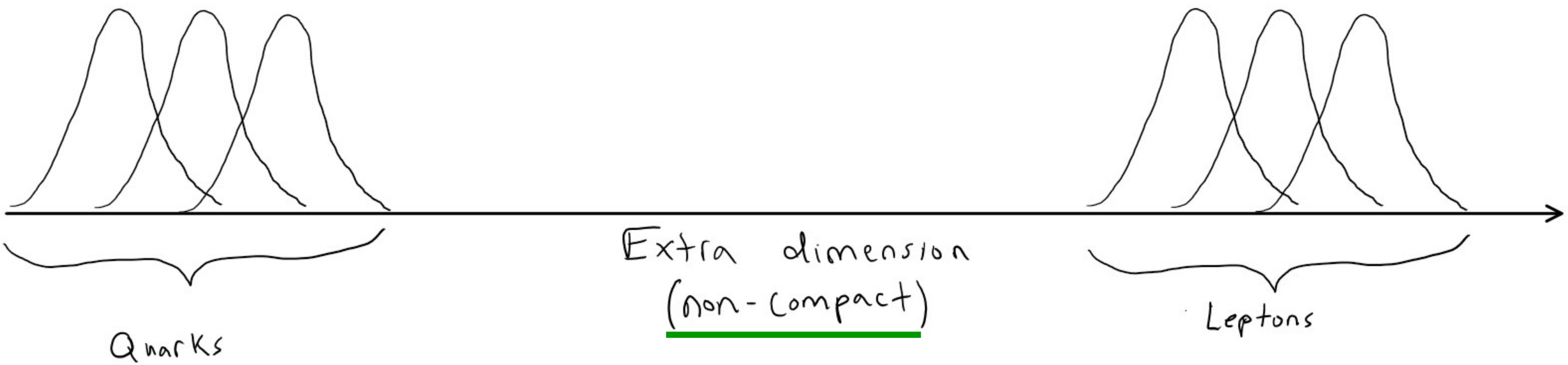
- Motivation
- DW Fermion
- DW Gauge
- DW Implications
- Phenomenology
- Future directions

Why DW?



- Motivating factors:
  - Mass hierarchy → Akani-Hamed, Schmaltz [hep-ph/9903417]
  - Several interesting phenomenology aspects and possibility of detecting signatures at LHC

5D Setup



- Consider a 5D system:

$$diag(\eta_{MN}) = \{1, -1, -1, -1, -1\}$$
$$M, N = 0,1,2,3, y$$

  - "Slice" of extra dimension "3 brane"
  - Localization of fermions due to coupling to domain wall
  - Localization of gauge/Higgs field is due to geometry

DW Fermions

5D real scalar:

$$L_5 \supset \frac{1}{2}(\partial_M \phi)(\partial^M \phi) - V(\phi),$$

$$V(\phi) = \frac{m_\phi^4}{2\lambda} - m_\phi^2 \phi^2 + \frac{\lambda}{2}\phi^4$$

Kink solution (Domain Wall)

$$\phi_0 = \frac{m_\phi}{\sqrt{2}} \tanh(m_\phi y)$$

$$\phi_0(+\infty) \to \frac{m_\phi}{\sqrt{2}}, \; \phi_0(-\infty) \to -\frac{m_\phi}{\sqrt{2}}$$

translation invariance in y broken!

5D fermion $(\psi = \psi_L + \psi_R)$

$$L_5 \supset i\bar{\psi}(\gamma^\mu \partial_\mu + i\gamma^5 \partial_5)\psi + Y\phi_0 \bar{\psi}\psi$$
$$= i\bar{\psi}_L \gamma^\mu \partial_\mu \psi_L + i\bar{\psi}_R \gamma^\mu \partial_\mu \psi_R$$
$$-\bar{\psi}_L \partial_y \psi_R + \bar{\psi}_R \partial_y \psi_L + Y\phi_0(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

Using the Kaluza-Klien(KK) decomposition

$$\psi_i(x, y) = \sum_n \psi_i^{(n)}(x) \chi_i^{(n)}(y)$$

$$\textit{where} \;\; i = L, R$$

DW Fermions

EOM for χ_L, χ_R

$$\chi_L^{(n)}{}'' + (m_n^2 + Y\phi_0' - Y^2\phi_0^2)\chi_L^{(n)} = 0$$
$$\chi_R^{(n)}{}'' + (m_n^2 - Y\phi_0' - Y^2\phi_0^2)\chi_R^{(n)} = 0$$

$\Rightarrow$

$$\left[-\partial_y^2 - \frac{V_L}{\cosh^2(m_\phi(y-y_0))}\right]\chi_L^{(n)} = E\chi_L^{(n)}$$
$$\left[-\partial_y^2 - \frac{V_R}{\cosh^2(m_\phi(y-y_0))}\right]\chi_R^{(n)} = E\chi_R^{(n)}$$

1+1-D Schrödinger Eq

Define

$$E = m_n^2 - \frac{m_\phi^2 Y^2}{\lambda}$$ **(for bound E<0)**

$$V_L = \frac{m_\phi^2 Y}{\sqrt{\lambda}}\left(\frac{Y}{\sqrt{\lambda}} + 1\right),\quad V_R = \frac{m_\phi^2 Y}{\sqrt{\lambda}}\left(\frac{Y}{\sqrt{\lambda}} - 1\right)$$

In general the solutions are F[a,b;c;z], for our discussion $Y/\sqrt{\lambda} = 2$

$$\psi_L(x,y) = \frac{\sqrt{3\mathrm{m}_\phi}}{2}\left[\frac{1}{\cosh^2(m_\phi(y-y_0))}\right]\psi_L^{(0)}(x) + \frac{\sqrt{3\mathrm{m}_\phi}}{2}\left[\frac{\sinh(m_\phi(y-y_0))}{\cosh^2(m_\phi(y-y_0))}\right]\psi_L^{(1)}(x)$$

$$\psi_R(x,y) = 0 + \frac{\sqrt{m_\phi}}{2}\left[\frac{1}{\cosh(m_\phi(y-y_0))}\right]\psi_R^{(1)}(x)$$

zero mode projected out!

$\Rightarrow$ Only **left handed chiral fermion** persists in effective 4D theory

$$m_n^2 = m_\phi^2 n_L\left(\frac{2\mathrm{Y}}{\sqrt{\lambda}} - n_L\right);\ n_L = 0,1,.. < Y/\sqrt{\lambda}$$

DW Gauge Boson

Consider a U(1) gauge field

$$L_5 = \frac{-1}{4} s(y) F^{NM} F_{NM},$$

$$\text{where } A^M = \{A^\mu, A^y\}$$

$$s(y) = \frac{1}{g_5^{\,2}(y)}, \text{ and } \underline{s(\pm\infty) \to 0}$$

$\longrightarrow$

$$L_5 = \tfrac{1}{2} s A^\mu (\eta_{\mu\nu} \partial^2 - \partial_\mu \partial_\nu) A^\nu - \tfrac{1}{2} s A_y \partial^2 A_y$$
$$\tfrac{-1}{2} A_\mu (s \partial_y A^\mu) - \underline{(\partial_\mu A^\mu) \partial_y (s A_y)}$$

mixing term

Applying the R$_\xi$ gauge fixing procedure to 5D theory: $L = L_5 + L_{GF} = L_{scalar} + L_{gauge}$

$$L_{scalar} = \frac{-1}{2} s A_y \partial^2 A_y + \frac{1}{2} s \xi A_y \partial_y \left(\frac{1}{s} \partial_y (s A_y)\right)$$

$$L_{gauge} = \frac{1}{2} s A^\mu \left(\eta_{\mu\nu} \partial^2 - \left(1 - \frac{1}{\xi}\right) \partial_\mu \partial_\nu\right) A^\nu - \frac{1}{2} A_\mu \partial_y (s \partial_y A^\mu)$$

EOM for KK modes

$$A_\mu:\ \partial_y \left(s \partial_y \chi^{(n)}\right) + s\, m_n^2 \chi^{(n)} = 0$$

$$A_y:\ \partial_y \left(\frac{1}{s} \partial_y (s \psi^{(n)})\right) + m_n^2 \psi^{(n)} = 0$$

DW Gauge Boson

The zero modes are found

$$\partial_y\left(s\,\partial_y \chi^{(n)}\right)=0$$
$$\partial_y\left(\frac{1}{s}\partial_y\left(s\,\psi^{(n)}\right)\right)=0$$

$\longrightarrow$

$$\chi^{(0)}(y)=c_\chi+\tilde{c}_\chi\int dy'(s(y'))^{-1}$$
$$\psi^{(0)}(y)=\frac{1}{s(y)}\left[c_\psi+\tilde{c}_\psi\int dy'\,s(y')\right]$$

Recall that $s(\pm\infty)\rightarrow 0$

and a normalization condition

$$\int dy\,s(y)\chi^{(n)}(y)\chi^{(n)}(y)<\infty$$

$\longrightarrow$

$$A_\mu(x,y)=\underline{c_\chi A_\mu^{(0)}(x)}+\sum_{n=1} A_\mu^{(n)}(x)\chi^{(n)}(y)$$
$$A_y(x,y)=\underline{\quad 0 \quad}+\sum_{n=1} A_y^{(n)}(x)\psi^{(n)}(y)$$

zero mode projected out!
(axial gauge A_y=0)

The higher modes can be found after s(y) is specified

$$s(y)=\frac{M}{(\cosh(m_V y))^{2\gamma}},$$
where $M,\ \gamma>0$

DW Gauge Boson

EOM can be recast as

$$\left[-\partial_y^2 - \frac{\gamma(\gamma+1)m_V^2}{\cosh^2(m_V y)}\right]\tilde{\chi}^n = (m_n{}^2 - \gamma^2 m_V{}^2)\tilde{\chi}^n$$

$$\left[-\partial_y^2 - \frac{\gamma(\gamma-1)m_V^2}{\cosh^2(m_V y)}\right]\tilde{\psi}^{(n)} = (m_n{}^2 - \gamma^2 m_V{}^2)\tilde{\psi}^n$$

1+1-D Schrödinger Eq

Where the fields are redefined as

$$\tilde{\chi}^{(n)} = \left(\frac{\sqrt{M}}{(\cosh(m_V y))^\gamma}\right)\chi^{(n)}$$

$$\tilde{\psi}^{(n)} = \left(\frac{\sqrt{M}}{(\cosh(m_V y))^\gamma}\right)\psi^{(n)}$$

essentially same solution as for fermions!

For $\gamma = 2$ and after normalization (bound modes)

$$A_y(x,y) = \sqrt{\frac{2}{3}}\, g \cosh(m_V y)\,\psi^{(1)}(x)$$

$$A_\mu(x,y) = \underline{g\, A_\mu(x)} + \sqrt{2}\, g \sinh(m_V y)\, A_\mu^{(1)}(x)$$

zero mode has universal coupling

$$m_n^2 = n(2\gamma - n)\, m_V^2\, ;\, n = 0,1,.. < \gamma$$

Definition of coupling

$$g = \sqrt{\frac{3 m_V}{4M}}$$

Same procedure can be applied to Higgs, assuming same s(y) and $\gamma = 2$

$$h(x,y) = \underline{h^{(0)}(x)} + \sqrt{2}\, g \sinh(m_\phi y)\, h^{(1)}(x)$$

SM Higgs

DW Fermion Mass

Yukawa Lagrangian

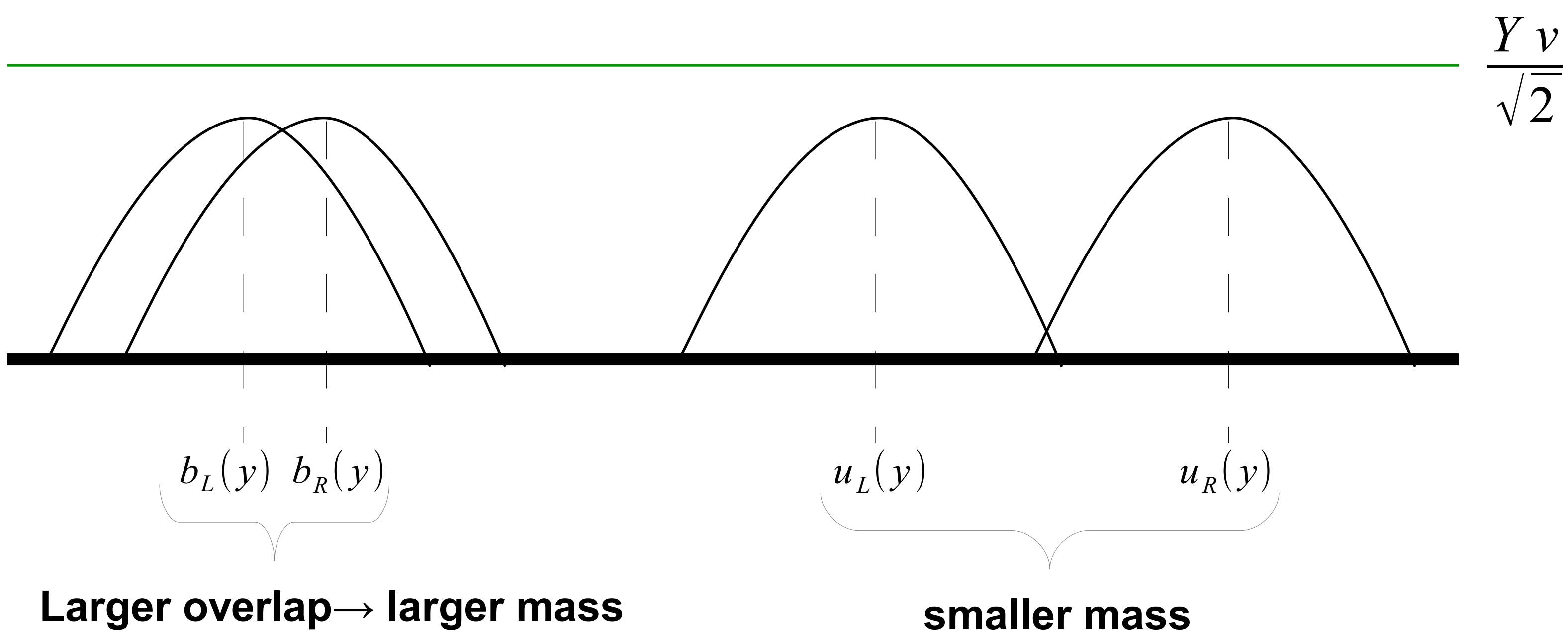
$$L_Y = -Y\,\bar{\psi}_L\, h\, \tilde{\psi}_R + H.C.$$

with $\langle h^{(0)}(x)\rangle = \frac{v}{\sqrt{2}}$

Generate mass hierarchy through different localization points!

4D effective Lagrangian with $h^{(0)}$ mode

$$L_Y^4 \supset Y\frac{v}{\sqrt{2}}\int dy\, \chi_L^{(0)}(y-y_L)\,\tilde{\chi}_R^{(0)}(y-y_R)$$



DW Gauge Interaction

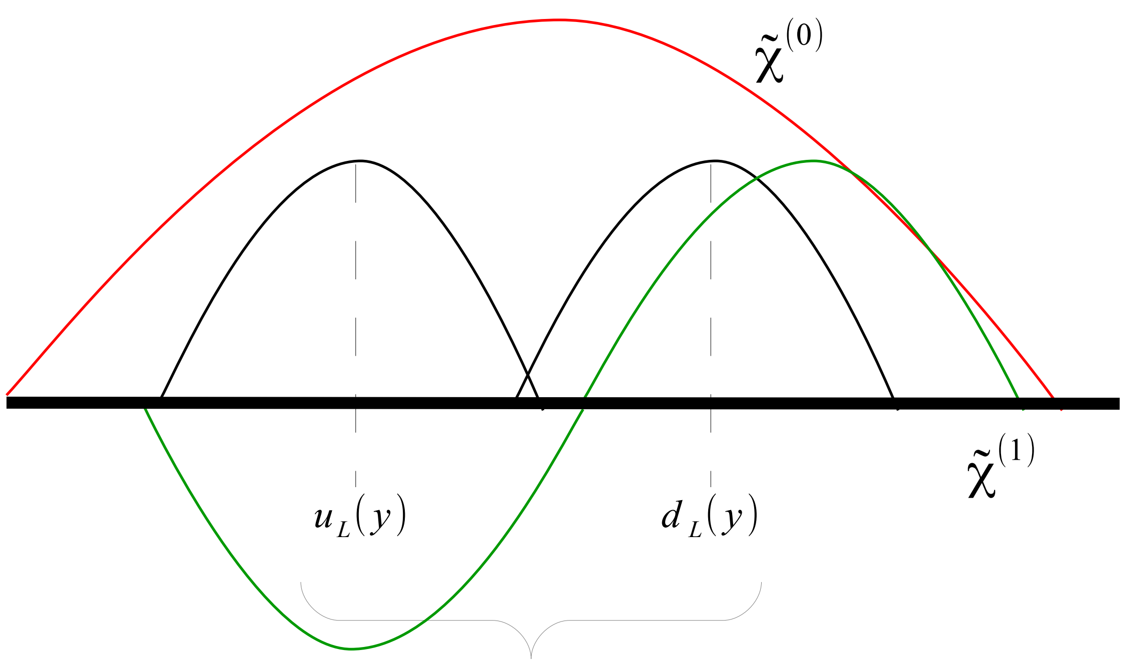
Consider a chiral fermion in effective 4D

$$L_4 = i\,\bar{\psi}_L \gamma^\mu (\partial_\mu - i\,Q\,g\,A_\mu^{(0)})\psi_L + \sum_{n=1}^{\infty} Q\,g_{eff}^{(n)} A_\mu^{(n)} \bar{\psi}_L^{(0)} \gamma^\mu \psi_L^{(0)}$$

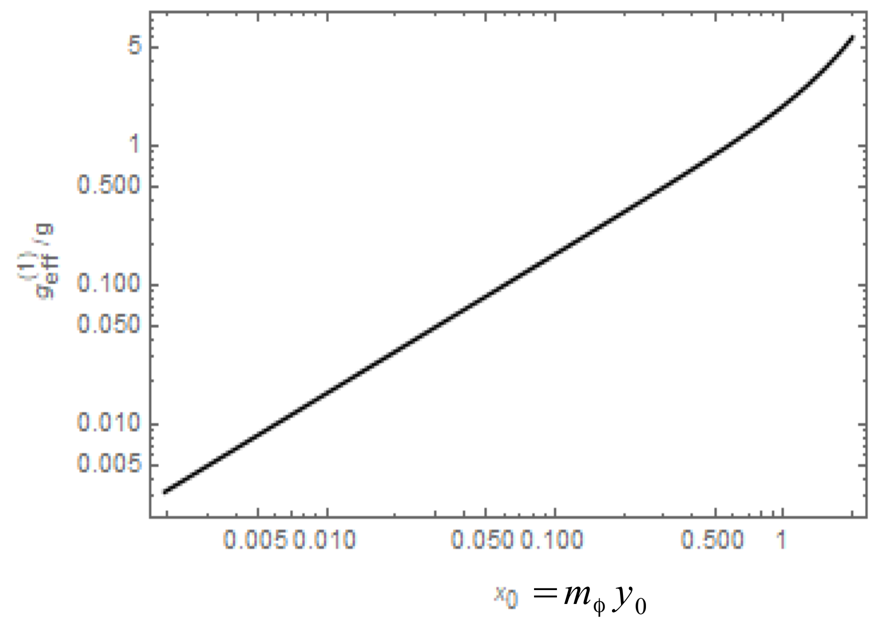
where $g_{eff}^{(n)} = g \int dy (\chi_L^{(0)}(y))^2 \chi^{(n)}(y)$

Using previous definitions for $\gamma = 2$ and $m_V = m_\phi$

$$\frac{g_{eff}^{(1)}}{g} = \frac{3\sqrt{2}}{4} m_\phi \int dy \left(\frac{\sinh(m_\phi y)}{\cosh^4(m_\phi(y - y_0))} \right)$$

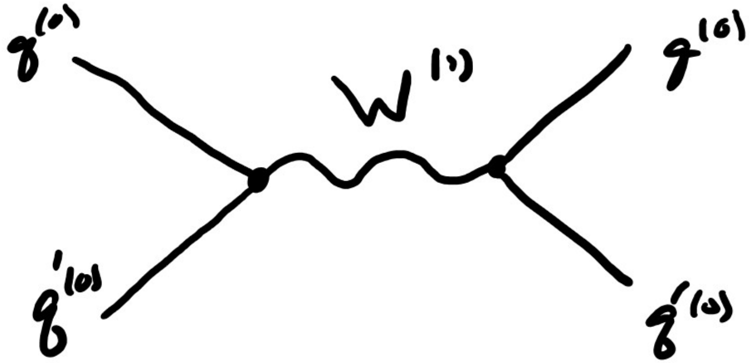


different KK mode gauge couplings

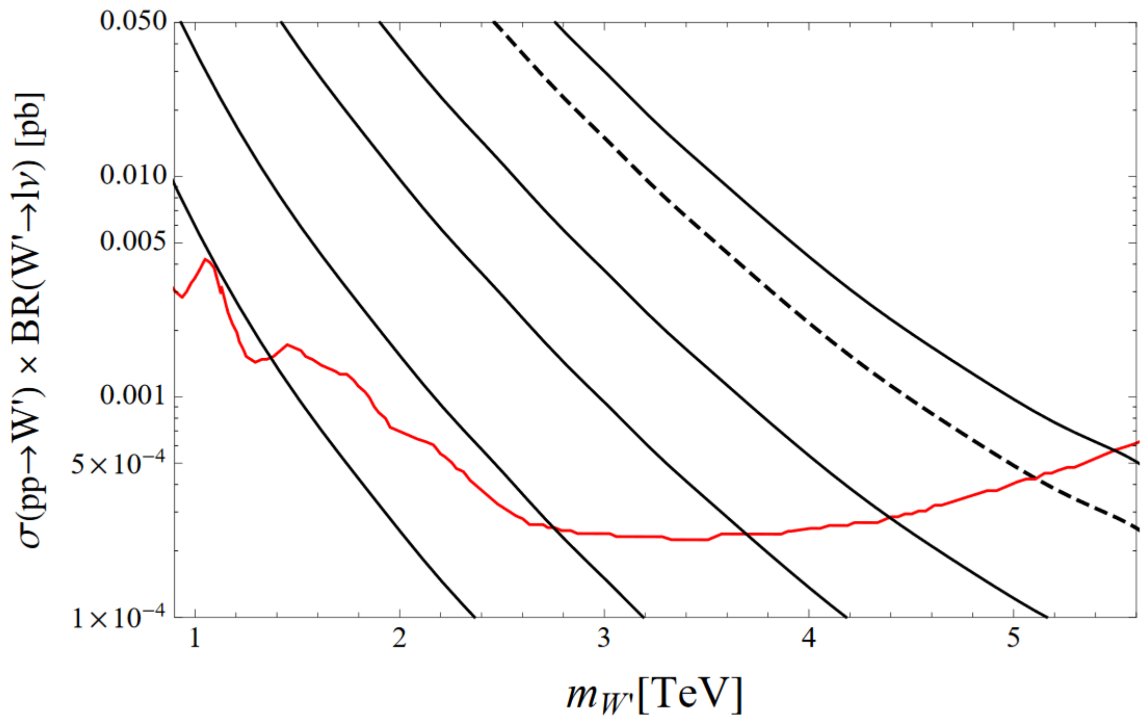


Higher KK mode coupling depends on fermion location

Phenomenology of KK $W^{(1)}$ boson



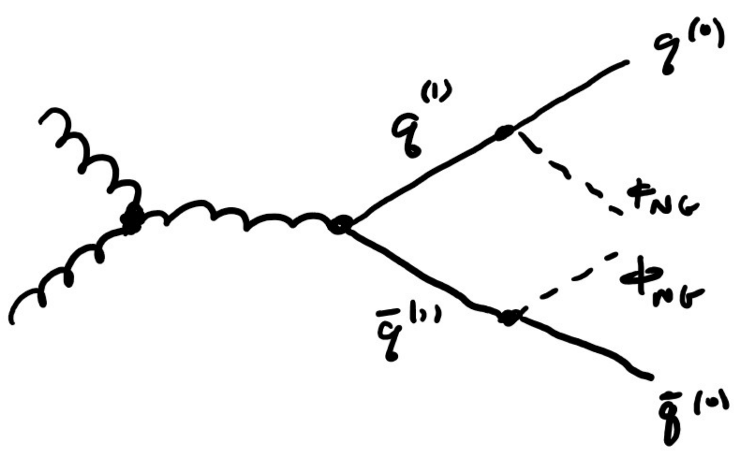
$W^{(1)}$ KK mode propagating



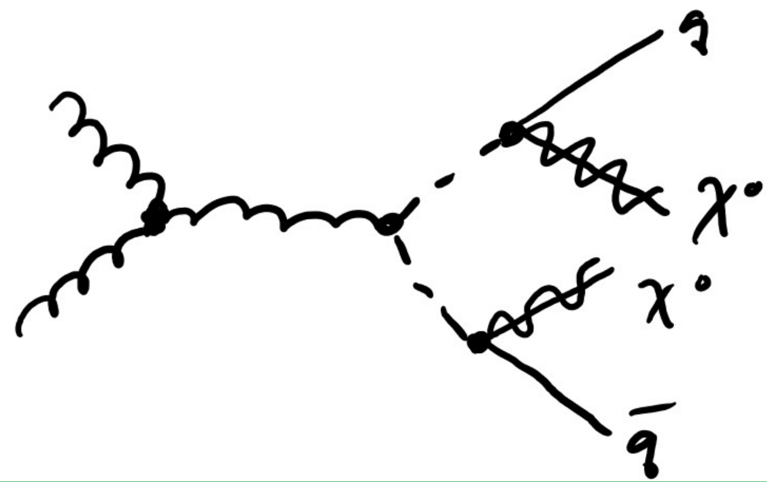
- Comparing our model of a KK gauge boson $W^{(1)}$ to ATLAS & CMS constraint on W'_{SSM}
- ATLAS 2017 Data(red line) at 13 TeV and 36 fb^{-1} puts a constraint at $m_{W'}$=5.1 TeV for SSM theory prediction(dotted line)
- SSM process in the narrow width approximation is $\sigma(q\bar{q}'\rightarrow W')\propto g^2$, interpretation to ours for various effective couplings (solid lines) is found from

$$\sigma(q\bar{q}'\rightarrow W^{(1)})=\sigma(q\bar{q}'\rightarrow W')\left(\frac{g_{eff}^{(1)}}{g}\right)^2$$

Phenomenology of KK fermions



KK mode fermion decay



SUSY superpartner decay(simplified SUSY)

Considering the effective 4D interaction between the kink NG mode and fermions

$$L_4 \supset Y_{eff}\,\phi_{NG}(x)\,\bar{\psi}_L^{(0)}(x)\,\psi_R^{(1)}(x) + H.C.$$

where $Y_{eff} = Y\,\dfrac{9\pi}{16}\sqrt{\dfrac{m_\phi}{2}}$

- LHC signature would be SM jets and missing energy
- Very similar final state from SUSY decay
- We can interpret the ATLAS/CMS constraints on SUSY process to set a lower bound for the KK mode quarks of about $m_{KK} > 1.5\,TeV$

Work to do

- Higgs KK phenomenology
- Reproducing SM mass hierarchy
- FCNC KK modes
- DW gravity sector