LHC-signal and Dark matter in SO(5)×U(1) gauge-Higgs Unification

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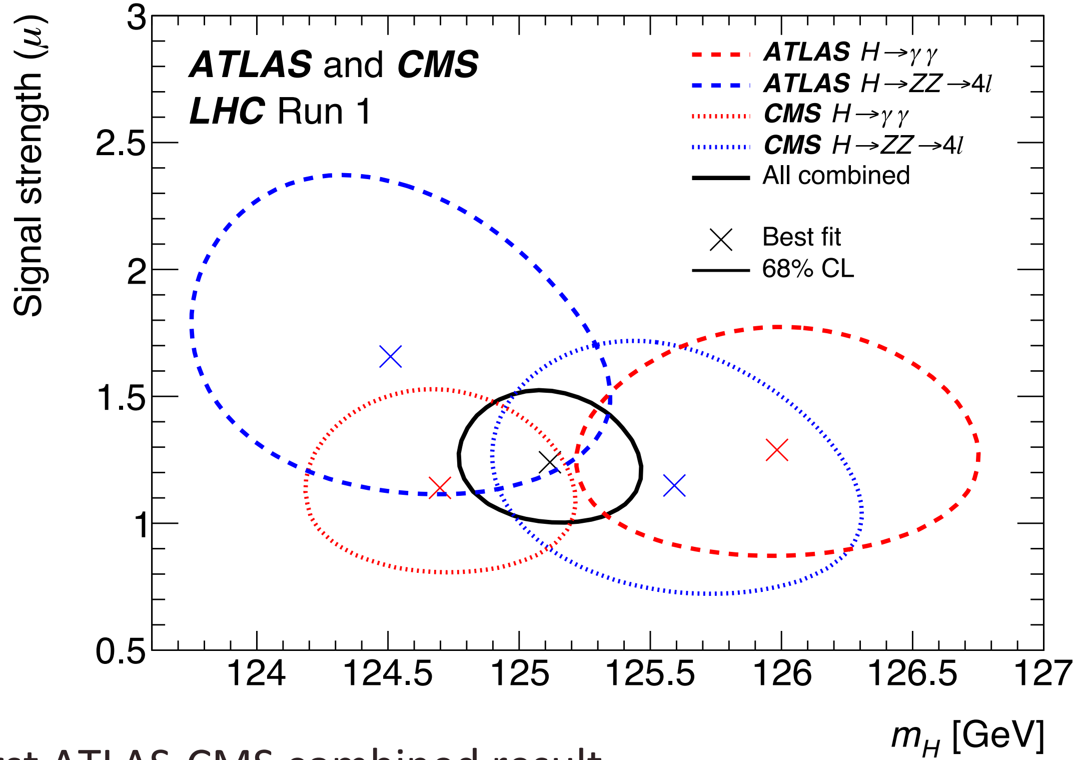
[“126GeV Higgs, H→γγ”: PLB722(13)94 (arxiv:1301.1744)]
[“LHC signals”: PRD89(14)095019 (arXiv:1404.2748)]
[“Dark Matter”: PTEP2014-11-113B01(arXiv:1407.3574)]
[“H→Zγ”, to appear soon] (Funatsu, HH, Hosotani)

Plan

- Intro
- SO(5)×U(1) GHU with 126GeV Higgs
  - $H \to \gamma\gamma$
  - universality, LHC signals
  - Dark Matter
- summary

Higgs mass (LHC combined)

1503.07589, PRL

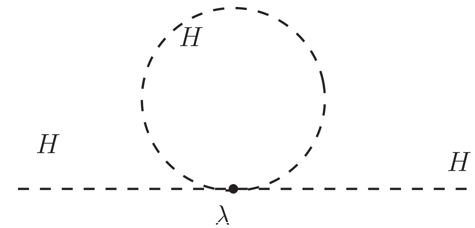


First ATLAS-CMS combined result

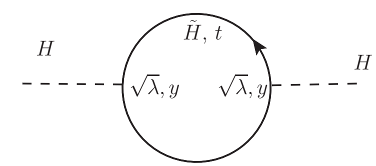
$$m_H=125.09\pm0.21(\mathrm{stat})\pm0.11(\mathrm{sys})\ \mathrm{GeV}$$

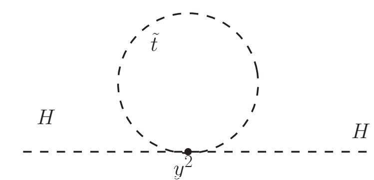
Gauge Hierarchy Problem

- Fine-tuning of Higgs mass
  - m_H=126GeV << M_{GUT}, M_{Planck}
  - triplet-doublet splitting in GUTs @tree level
  - quadratically divergent Higgs mass^2 @loop level
- solutions
  - Higgs compositeness
    - Technicolor, top-condensation
    - composite Higgs
  - scale invariance + dim. transmutation
    - Coleman-Weinberg
    - QCD-Landau-pole
  - "naturalness" (`t Hooft) ⇆new symmetry
    - supersymmetry
    - little Higgs (pseud Nambu-Goldstone Boson)
    - <u>Gauge-Higgs Unification[gauge symmetry]</u>



$$m_H^2 = m_{H0}^2 + \lambda\Lambda^2$$





Gauge-Higgs unification (GHU)

- Higgs as a extra-dimensional component of a gauge field (Fairlie '78, Manton '79)

$$A_M = (A_\mu, A_y = H)$$

- Gauge symmetry is broken by VEV of Wilson-loop : "Hosotani Mechanism" (Hosotani, '83)

$$W = \mathcal{P} \exp \oint igA_y dy$$

- Solution to the Gauge Hierarchy Problem (HH-Inami-Lim, '98)
  - Compact Extra Dimension : TeV scale
  - Higgs potential and masses:
    - no potential terms @ tree level (5D)

$$\because \quad -\frac{1}{4}F_{MN}F^{MN} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}F_{\mu 5}F^{\mu}{}_{5}$$

    - finite mass @ quantum level
    - finite Higgs mass is guaranteed by the higher-dimensional gauge symmetry

SO(5)×U(1) GHU with 126GeV Higgs

SO(5)xU(1) GHU model - overview

Hosotani-Oda-Ohnuma-Sakamura, PRD78 096002

Funatsu-HH-Hosotani-Orikasa-Shimotani, PLB722 94

- Space-time :
  Randall-Sundrum warped 5D spacetime
- Symmetry :
  SO(5)xU(1) gauge symmetry in the 5D bulk
- Fields:
  - SO(5)xU(1) gauge fields in the bulk ($\supset$gauge, Higgs)
  - SO(5)-vector fermions in the bulk ($\supset$quarks, leptons)
  - $SU(2)_R$ doublet right-handed brane fermions
  - $SU(2)_R$ doublet brane scalar
  - SO(5)-spinor fermions (dark fermions)

Space-time

Randall-Sundrum Spacetime

– slice of a 5D anti-de Sitter space (AdS_5)

– metric $$ds^2 = \frac{1}{z^2}\left(\eta_{\mu\nu}dx^\mu dx^\nu + \frac{dz^2}{k^2}\right) \quad 1 \le z \le e^{kL} \equiv z_L$$

$$z = 1 : \text{UV brane} \quad z = z_L : \text{IR brane}$$

or $$ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

$$\sigma(y+2L) = \sigma(y), \quad \sigma(y) = k|y| \text{ for } -L \le y \le +L$$

k : AdS_5 curvature, L : distance of branes

– orbifold S^1/Z_2 topology : break symmetries by b.c.s

– Hierarchy

- fundamental scales : k, L,
- KK scales : m_{KK}

$$\boxed{m_{KK} \equiv \frac{\pi k}{z_L - 1} \ll k, L^{-1}}$$

Fields

- SO(5)×U(1)$_X$ gauge fields in the *AdS*$_5$ bulk

$$A_M,\ B_M \quad (M=\mu,5),$$

- Bulk fermions in SO(5)-vector
  (4 bulk fermions/generation)

$$\Psi_1=\left(\begin{pmatrix} T & t \\ B & b\end{pmatrix}_L, t'_R\right)_{\frac{2}{3}},\ \Psi_2=\left(\begin{pmatrix} U & X \\ D & Y\end{pmatrix}_L, b'_R\right)_{-\frac{1}{3}}, \qquad \Psi_{\text{quark}}=\begin{pmatrix} i(T-b)/\sqrt{2} \\ -(T+b)/\sqrt{2} \\ -i(B+t)/\sqrt{2} \\ -(B-t)/\sqrt{2} \\ t' \end{pmatrix}$$

$$\Psi_3=\left(\begin{pmatrix} \nu_\tau & L_{1X} \\ \tau & L_{1Y}\end{pmatrix}_L, \tau'_R\right)_{-1},\ \Psi_4=\left(\begin{pmatrix} L_{2X} & L_{3X} \\ L_{2Y} & L_{3Y}\end{pmatrix}_L, \nu'_\tau\right)_{0}$$

- SU(2)$_R$-doublet scalar on the UV brane

$$\Phi_R$$

- three SU(2)$_R$-doublet right-handed fermions/generation (on the UV brane)

and 3 more for leptons...

$$\chi_{1R}=\begin{pmatrix} T_R \\ B_R\end{pmatrix}_{7/6},\ \chi_{2R}=\begin{pmatrix} U_R \\ D_R\end{pmatrix}_{1/6},\ \chi_{3R}=\begin{pmatrix} X_R \\ Y_R\end{pmatrix}_{-5/6},$$

- n$_F$ bulk fermions F in SO(5) spinor-representation

$$\Psi_{\text{spinor}}=\begin{pmatrix} \psi_{SU(2)_L} \\ \psi_{SU(2)_R}\end{pmatrix}$$

Action

- Action
$$S=\int_{-L}^{L}dy\int d^4x\sqrt{G}\{\mathcal{L}_5+\delta(y)\mathcal{L}_4\}$$
- 5D bulk :
$$\mathcal{L}_5=-\frac{1}{2}\mathrm{tr}F^{MN}F_{MN}-\frac{1}{2}B^{MN}B_{MN}$$
$$+\sum_f\bar{\Psi}_f\mathcal{D}(c_f)\Psi_f+\sum_F\bar{\Psi}_{\mathrm{sp},F}\mathcal{D}(c_F)\Psi_{\mathrm{sp},F}$$
$$\mathcal{D}(c)=i\Gamma^M(\partial_M-i\omega_M-ig_AA_M-ig_BQ_BB_M)-kc\epsilon(y),$$
$$\epsilon(y)=\sigma'(y)$$
- UV brane action :
$$\mathcal{L}_4=|D_M\Phi|^2-V(\Phi)+\sum_{a=1}^{3}[\bar{\hat{\chi}}^q_{aR}i\gamma^\mu D_\mu\hat{\chi}_{aR}+\bar{\hat{\chi}}^\ell_{aR}i\gamma^\mu D_\mu\hat{\chi}^\ell_{aR}]$$
$$-[\kappa^q_1\bar{\hat{\chi}}^q_{1R}\check{\Psi}_{1L}\tilde{\Phi}+\tilde{\kappa}^q\bar{\hat{\chi}}^q_{2R}\check{\Psi}_{1L}\tilde{\Phi}+\kappa^q_2\bar{\hat{\Psi}}^q_{2R}\check{\Psi}_{2L}\tilde{\Phi}+\kappa^q_3\bar{\hat{\Psi}}^q_{3R}\check{\Psi}_{3L}\Phi]+h.c.$$
$$-[\tilde{\kappa}^\ell\bar{\hat{\chi}}^\ell_{3R}\check{\Psi}_{3L}\tilde{\Phi}+\kappa^\ell_1\bar{\hat{\chi}}^\ell_{1R}\check{\Psi}_{3L}\tilde{\Phi}+\kappa^\ell_2\bar{\hat{\chi}}^\ell_{2R}\check{\Psi}_{4L}\tilde{\Phi}+\kappa^\ell_3\bar{\hat{\chi}}^\ell_{3R}\check{\Psi}_{4L}\Phi]+h.c.\quad \tilde{\Phi}\equiv i\sigma_2\Phi^*$$
$$D_\mu\Phi=(\partial_\mu-ig_AA_\mu+\tfrac{i}{2}g_BB_\mu)\Phi,\quad D_\mu\hat{\chi}=(\partial_\mu-ig_AA_\mu-iQ_Xg_BB_\mu)\hat{\chi}$$

Symmetry Breakings (1)

- SO(5)→SO(4)=SU(2)$_L$xSU(2)$_R$
  - by orbifold boundary conditions

$$A_\mu(y_i - y) = +P_i A_\mu(y_i + y) P_i^{-1}$$

$$A_y(y_i - y) = -P_i A_y(y_i + y) P_i^{-1}$$

$$\Psi_i(y_i - y) = \eta_\Psi \gamma_5 P_i \Psi_i(y_i + y), \quad \eta_\Psi = -1, \quad P_0 = P_1 = P$$

$$P^{\mathrm{vec}} = \begin{pmatrix} -1 & & & & \\ & -1 & & & \\ & & -1 & & \\ & & & -1 & \\ & & & & 1 \end{pmatrix}$$

$$P^{\mathrm{sp}} = \begin{pmatrix} I_{2\times 2} & \\ & -I_{2\times 2} \end{pmatrix}$$

  - gauge zero modes $A_M^{(0)} = \left(\begin{array}{c|c} A_\mu^{SO(4),(0)} & A_y^{SO(5)/SO(4),(0)} \\ \hline A_y^{SO(5)/SO(4),(0)} & 0 \end{array}\right)$

    $A_y^{(0)}$: SO(4)-vector → "Higgs"

$$A_y^{(0)} = \begin{pmatrix} & & & & A_y^{\hat{1}} \\ & & & & A_y^{\hat{2}} \\ & & & & A_y^{\hat{3}} \\ & & & & A_y^{\hat{4}} \\ -A_y^{\hat{1}} & -A_y^{\hat{2}} & -A_y^{\hat{3}} & -A_y^{\hat{4}} & 0 \end{pmatrix}$$

  - fermion zero modes

$$\Psi_{vec}^{(0)} = \begin{pmatrix} \psi_{1L} \\ \psi_{2L} \\ \psi_{3L} \\ \psi_{4L} \\ \psi_{5R} \end{pmatrix}$$

Symmetry Breakings (2)

- $SO(4) \times U(1)_X \to SU(2)_L \times U(1)_Y$ by VEV of UV brane scalar
- EWSB: by Hosotani mechanism
  - θ_H: Wilson-line (Aharonov-Bohm phase)parameter

$$W = \exp[ig_A \oint \langle A_y \rangle dy] = \exp\left[i\theta_H \begin{pmatrix} & & & & 0 \\ & & & & 0 \\ & & & & 0 \\ & & & & -i \\ 0 & 0 & 0 & i & \end{pmatrix} \right]$$

$$[W, T^a] = 0, \quad T^a \in U(1)_{\mathrm{em}},$$
$$[W, X^a] \neq 0, \quad X^a : \text{broken generators}$$

  - fermions obtain mass terms by $\bar{\Psi} g \Gamma^y \langle A_y \rangle \Psi \subset i \bar{\Psi} \Gamma^y D_y \Psi$

Wilson line (Aharonov-Bohm phase)

- b.c. of a charged field

$$\phi(x^\mu, y + 2\pi R) = e^{i\alpha}\psi(x^\mu, y), \quad D_{M=\mu,y}\phi \equiv (\partial_M - ieA_M)\phi$$

  - KK expansion

$$\phi(x^\mu, y) = \sum_{n=-\infty}^{\infty} \phi_n(x^\mu) e^{i(n+\frac{\alpha}{2\pi})y}$$

  - VEV of Ay and Wilson-loop

$$g\langle A_y\rangle = v \neq 0, \quad W = \exp[ig\int_0^{2\pi R} dy\,\langle A_y\rangle] = \exp[i2\pi gvR] \equiv \exp[i\theta]$$

- twisted gauge

$$\langle \tilde{A}_y\rangle = \Omega\langle A_y\rangle\Omega^{-1} - \frac{i}{g}\partial_y\Omega\Omega^{-1} = 0, \quad \tilde{\phi} = \Omega\phi, \quad \Omega = e^{-i\theta y/2\pi R}$$

  - twisted b.c.

$$\tilde{\phi}(y + 2\pi R) = e^{i(\alpha-\theta)}\tilde{\phi}(y), \quad \tilde{\phi} = \sum_{n=-\infty}^{\infty} \tilde{\phi}_n(x^\mu) e^{i(n+\frac{\alpha-\theta}{2\pi})}$$

Non-Abelian Wilson-line phase

- symmetry breaking

$$[\langle W \rangle, T^a] = 0 : \text{unbroken generators}$$

$$[\langle W \rangle, X^a] \neq 0 : \text{broken generators}$$

- example : SU(3)

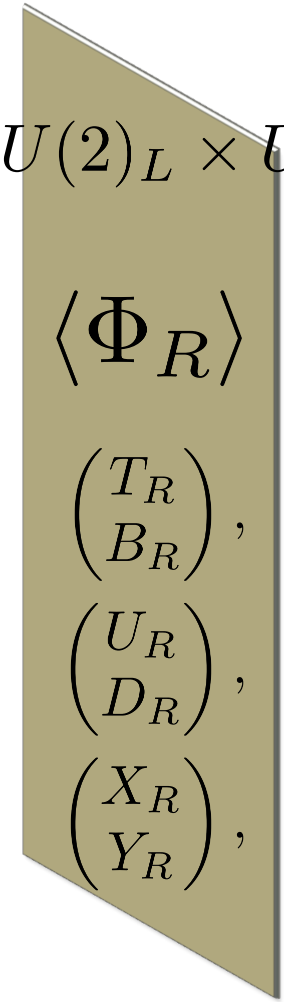
$$\langle W \rangle = \text{diag}[e^{i\theta_1}, e^{i\theta_2}, e^{i\theta_3}],$$

$$\{\theta_1, \theta_2, \theta_3\} = \{0,0,0\},\ \{\frac{2\pi}{3}, \frac{2\pi}{3}, -\frac{4\pi}{3}\} \qquad : SU(3) \text{ symmetrc}$$

$$\{\theta_1, \theta_2, \theta_3\} = \{0,\pi,-\pi\},\ \{0, \frac{\pi}{3}, -\frac{\pi}{3}\} \qquad : SU(2) \times U(1) \text{ symmetric}$$

$$\{\theta_1, \theta_2, \theta_3\} = \{0, \frac{2\pi}{3}, -\frac{2\pi}{3}\} \qquad : U(1)^2 \text{ symmetric}$$

$z = 1$ $\qquad\qquad$ $z = z_L$



$$SO(5) \times U(1)_X$$

$SU(2)_L \times U(1)_Y$

$SO(4) \times U(1)_X$
$\simeq SU(2)_L \times SU(2)_R \times U(1$

$$A_\mu^{SO(4)}, \quad B_\mu$$

$\langle \Phi_R \rangle$

$$A_y^{SO(5)/SO(4)} = H$$

$\begin{pmatrix} T_R \\ B_R \end{pmatrix}, \quad \begin{pmatrix} U_R \\ D_R \end{pmatrix}, \quad \begin{pmatrix} X_R \\ Y_R \end{pmatrix},$

$$\Psi_1 = \left(\begin{pmatrix} T & t \\ B & b \end{pmatrix}_L, t'_R \right)_{\frac{2}{3}}, \ \Psi_2 = \left(\begin{pmatrix} U & X \\ D & Y \end{pmatrix}_L, b'_R \right)_{-\frac{1}{3}},$$

$$\Psi_3 = \left(\begin{pmatrix} \nu_\tau & L_{1X} \\ \tau & L_{1Y} \end{pmatrix}_L, \tau'_R \right)_{-1}, \ \Psi_4 = \left(\begin{pmatrix} L_{2X} & L_{3X} \\ L_{2Y} & L_{3Y} \end{pmatrix}_L, \nu'_\tau \right)_0$$

$$F = \begin{pmatrix} \psi_L^{SU(2)_L} \\ \psi_R^{SU(2)_R} \end{pmatrix}$$

$$F(y_0 - y) = \eta_F \gamma_5 P_0 F(y_0 + y),$$
$$F(y_1 - y) = \eta_F \gamma_5 P_1 F(y_1 + y),$$
$$P_0 = -P_1 = \begin{pmatrix} I & \\ & -I \end{pmatrix},$$
$$\eta_F = \pm 1$$

Gauge Transformation

- gauge VEV

$$\langle A_z \rangle = T^{\hat{4}} v \sqrt{\frac{2}{k(z_L^2 - 1)}} z,$$

$$\exp[\tfrac{i}{2}\theta_H 2\sqrt{2} T^{\hat{4}}] = \exp[i g_A \int_1^{z_+} dz \langle A_z \rangle], \quad \theta_H = \frac{1}{2} g_A v \sqrt{\frac{z_L^2 - 1}{k}}$$

- twisted gauge

$$\Omega(z) = \exp[i\theta(z)\sqrt{2} T^{\hat{4}}], \quad \theta(z) = \frac{z_L^2 - z^2}{z_L^2 - 1}\theta_H,$$

$$\tilde{\Psi} = \Omega \Psi \qquad \langle \tilde{A}_z \rangle = \Omega \langle A_z \rangle - \frac{i}{g_A}\partial_z \Omega \Omega^{-1} = 0,$$

  – boundary conditions

$$\tilde{P}_1 = P_1,$$

$$\tilde{P}_0 = \Omega(z=1) P_0 \Omega^\dagger(z=1),$$

4D effective theory

- almost SM-like for @ low energy ($<<m_{KK}$)
- $W^{\pm}$, Z, photon(γ) and their KK excitations
- heavy $W_R^{\pm}$, Z_R $A_{4\wedge}$vector bosons (no zero modes)

$$A_\mu \oplus B_\mu = \gamma_\mu + W_\mu^{\pm} + Z_\mu + W_{R\mu}^{\pm} + Z_{R\mu} + A_\mu^{\hat{4}}$$

- one physical Higgs (other $A_y^{(0)}$ are goldstones)
- SM quarks and leptons (and their KK excitations)
- exotic fermions $t^{5/3}$, T, B, $b^{-3/4}$ (no zero modes)

bulk wave functions

- bosons: C, S

$$\left(\frac{d^2}{dz^2} - \frac{1}{z}\frac{d}{dz} + \lambda^2\right)\begin{pmatrix} C(z,\lambda) \\ S(z,\lambda) \end{pmatrix} = 0,$$

$$C(z_L;\lambda) = z_L, \quad C'(z_L;\lambda) = 0, \quad S(z_L;\lambda) = 0, \quad S'(z_L;\lambda) = \lambda$$

$$C_L S' - SC' = \lambda z,$$

- fermions: $C_{L,R}$, $S_{L,R}$

$$(D_+ D_- - \lambda^2)\begin{pmatrix} C_R(z,\lambda,c) \\ S_R(z,\lambda,c) \end{pmatrix}, \quad (D_- D_+ - \lambda^2)\begin{pmatrix} C_L(z,\lambda,c) \\ S_L(z,\lambda,c) \end{pmatrix}, \qquad D_\pm(c) \equiv \pm\frac{d}{dz} + \frac{c}{z},$$

$$C_R = C_L = 1, \quad D_- C_R = D_+ C_L = 0,$$
$$S_R = S_L = 0, \quad D_- S_R = D_+ S_L = \lambda \quad \text{at } z = z_L$$

$$D_+\begin{pmatrix} C_L \\ S_L \end{pmatrix} = \lambda\begin{pmatrix} S_R \\ C_R \end{pmatrix}, \quad D_-\begin{pmatrix} C_R \\ S_R \end{pmatrix} = \lambda\begin{pmatrix} S_L \\ C_L \end{pmatrix}, \quad C_L S_R - S_L S_R = 1,$$

Explicit form of bulk functions

$$F_{\alpha,\beta}(u,v) = J_\alpha(u)Y_\beta - Y_\alpha(u)J_\beta(v),$$

$$C = +\frac{\pi}{2}\lambda\sqrt{zz_L}F_{1,0}(\lambda z, \lambda z_L), \quad C' = +\frac{\pi}{2}\lambda\sqrt{zz_L}F_{0,0}(\lambda z, \lambda z_L),$$
$$S = -\frac{\pi}{2}\lambda\sqrt{zz_L}F_{1,1}(\lambda z, \lambda z_L), \quad S' = +\frac{\pi}{2}\lambda\sqrt{zz_L}F_{0,1}(\lambda z, \lambda z_L),$$

$$C_L = +\frac{\pi}{2}\lambda\sqrt{zz_L}F_{c+\frac{1}{2},c-\frac{1}{2}}(\lambda z, \lambda z_L), \quad S_L = -\frac{\pi}{2}\lambda\sqrt{zz_L}F_{c+\frac{1}{2},c+\frac{1}{2}}(\lambda z, \lambda z_L),$$
$$C_R = -\frac{\pi}{2}\lambda\sqrt{zz_L}F_{c-\frac{1}{2},c+\frac{1}{2}}(\lambda z, \lambda z_L), \quad S_R = +\frac{\pi}{2}\lambda\sqrt{zz_L}F_{c-\frac{1}{2},c-\frac{1}{2}}(\lambda z, \lambda z_L),$$

boundary conditions at z=1 are affected by

1. Wilson-line phase (Aharonov-Bohm effect)
2. UB-boundary interactions

Kaluza-Klein Mass Spectra

- W tower

$$2S(1;\lambda_n)C'(1;\lambda_n) + \lambda_n \sin^2\theta_H = 0,$$

$$m_{W^{(n)}} = k\lambda_n, \quad m_{W^{(0)}} = m_W = 80.4\text{GeV}$$

or, using asymptotic form of Bessel function, one has

$$\boxed{m_W \sim \sqrt{k/L}e^{-kL}|\sin\theta_H| \sim \frac{m_{KK}}{\pi\sqrt{kL}}|\sin\theta_H|}$$

- Z tower

$$2S(1;\lambda_n)C'(1;\lambda_n) + \lambda_n \frac{1}{\cos^2\theta_W}\sin^2\theta_H = 0, \quad \sin^2\theta_W \simeq 0.23,$$

$$m_{Z^{(n)}} = k\lambda_n, \quad m_{Z^{(0)}} = m_Z = 91.2\text{GeV}$$

- top tower

$$2(1+\frac{\tilde{\mu}^2}{\mu_2^2})S_L(1;\lambda_n,c_1)S_R(1;\lambda_n,c_1) + \sin^2\theta_H = 0, \quad \frac{\tilde{\mu}}{\mu_2} \simeq \frac{m_b}{m_t}$$

$$m_{t^{(n)}} = k\lambda_n, \quad m_{t^{(0)}} = m_t = 173\text{GeV}$$

Effective Potential (1)

When a Kaluza-Klein tower is given by

$$1 + \tilde{Q}(\lambda_n) f(\theta_H) = 0, \qquad\qquad m_n = k\lambda_n$$

then the ffective Potential is given by

$$\begin{aligned} V(\theta_H) &= \frac{1}{2} \int \frac{d^4p}{(2\pi)^4} \sum_n \ln[p^2 + m_n(\theta_H)^2] \\ &= \frac{(k/z_L)^4}{(4\pi)^2} \int_0^\infty dq\, q^3 \ln[1 + Q(q) f(\theta_H)], \end{aligned}$$

$$Q(q) = \tilde{Q}(iq/z_L)$$

Effective Potential (2)

$$
\begin{aligned}
V_{\rm eff} &= 4I[Q_W] + 2I[Q_Z] + 3I[Q_D] \\
&\quad - 12\{I[Q_{\rm top}] + I[Q_{\rm bottom}]\} - 8n_F I[Q_F], \\
Q_W &= \cos^2\theta_W Q_Z = \frac{1}{2}Q_D = \frac{1}{2}Q_0[q;\frac{1}{2}]\sin^2\theta_H, \\
Q_{\rm top} &= \frac{Q_{\rm bottom}}{r_t} = \frac{Q_0[q,c_t]}{2(1+r_t)}\sin^2\theta_H, \quad r_t \simeq (m_b/m_t)^2, \\
Q_F &= Q_0[q;c_F]\cos^2\frac{\theta_H}{2}, \\
Q_0[q;c] &\equiv \frac{z_L}{q^2}\frac{1}{\hat{F}_{c-\frac{1}{2},c-\frac{1}{2}}(q/z_L,q)\hat{F}_{c+\frac{1}{2},c+\frac{1}{2}}(q/z_L,q)}, \\
\hat{F}_{\alpha,\beta}(u,v) &\equiv I_\alpha(u)K_\beta(v) - e^{-i(\alpha-\beta)\pi}K_\alpha(u)I_\beta(v),
\end{aligned}
$$

Effective Potential and Higgs mass

- Higgs (AB phase) potential is induced @ loop level a la Coleman-Weinberg

$$V_\Phi \equiv \tfrac{1}{2}\sum_n \int \frac{d^4p}{(2\pi)^4}\ln[p^2+m_{\Phi_n}^2]$$

$$V_{\rm eff}^{\rm total}(\theta_H) = V_W + V_Z + V_{\rm top} + n_F V_F[c_F]$$

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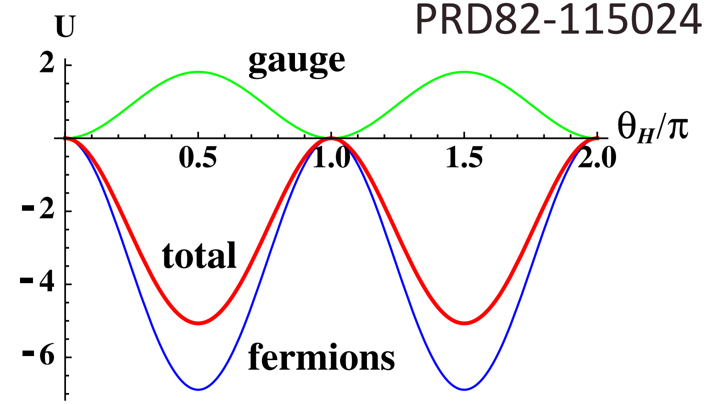
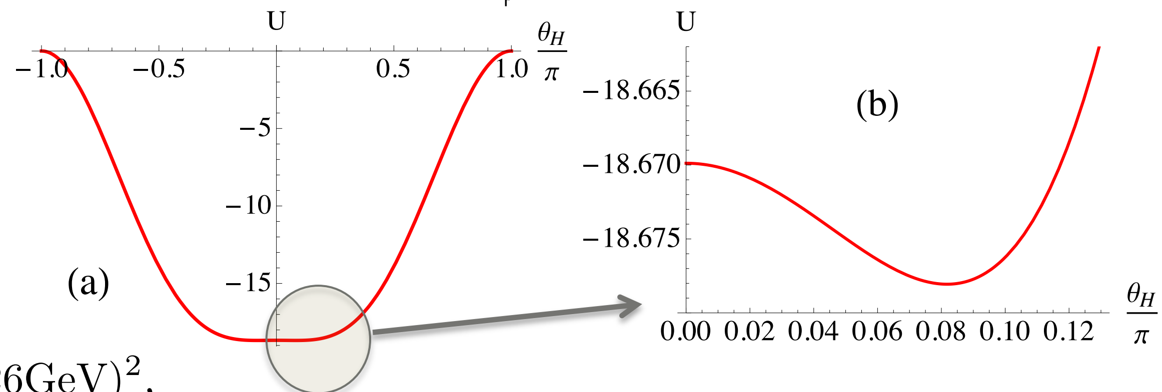


- Old model (n_F=0)
  - $\theta_H=\pi/2$ is selected (H-parity)
    - HVV and Yukawa coupling vanish
    - Higgs is stable (H-parity odd) →Higgs as DM [Hosotani-Ko-Tanaka]

- New model(n_F>0)
  - $\theta_H<\pi/2$
  - Higgs can decay
  - Higgs mass

$$m_H^2 = \frac{1}{f_H^2}\frac{d^2V_{\rm eff}}{d\theta_H^2}\bigg|_{\rm min} = (126{\rm GeV})^2,$$

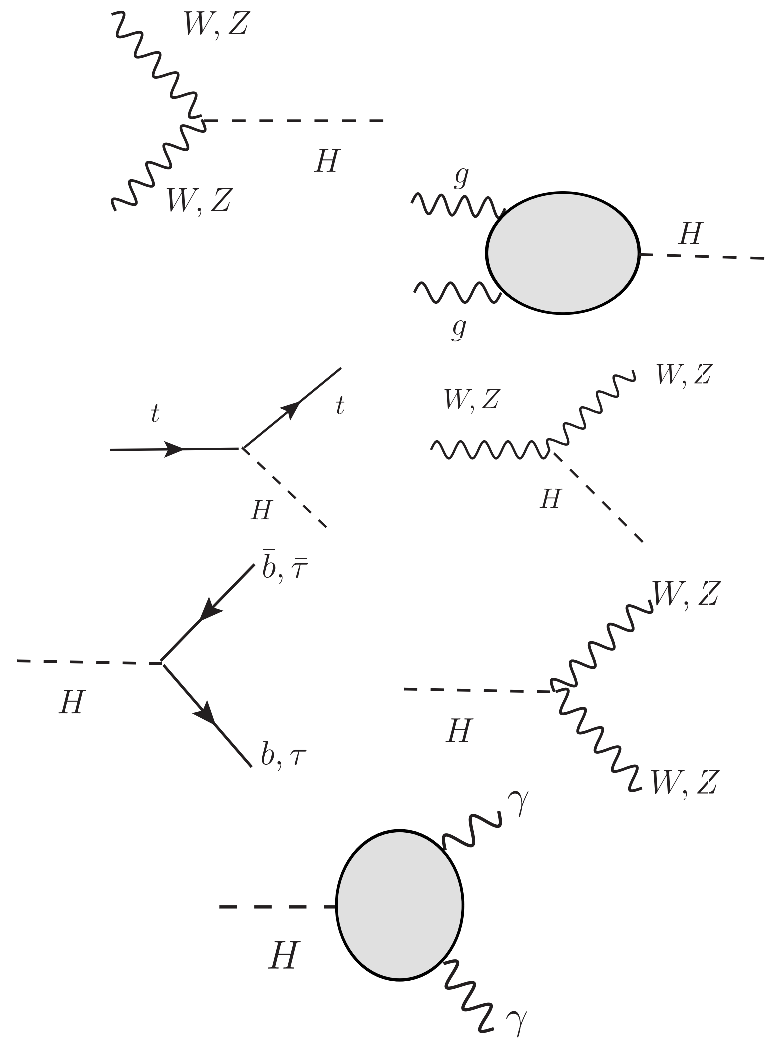
$$f_H = \frac{2}{g_w}\sqrt{\frac{k}{L(z_L^2-1)}}$$



Higgs decays to $\gamma\gamma$, $Z\gamma$

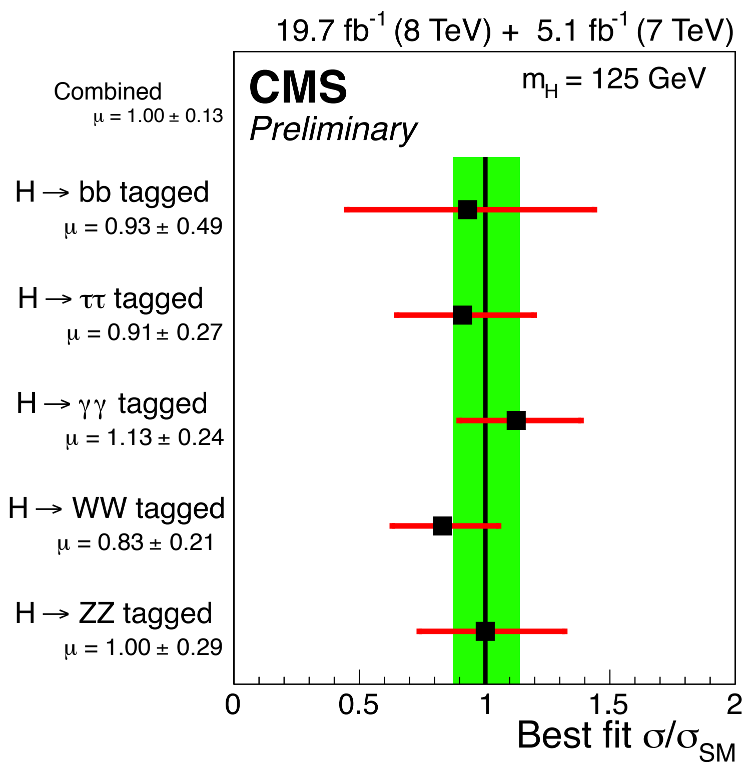
Higgs production & decay

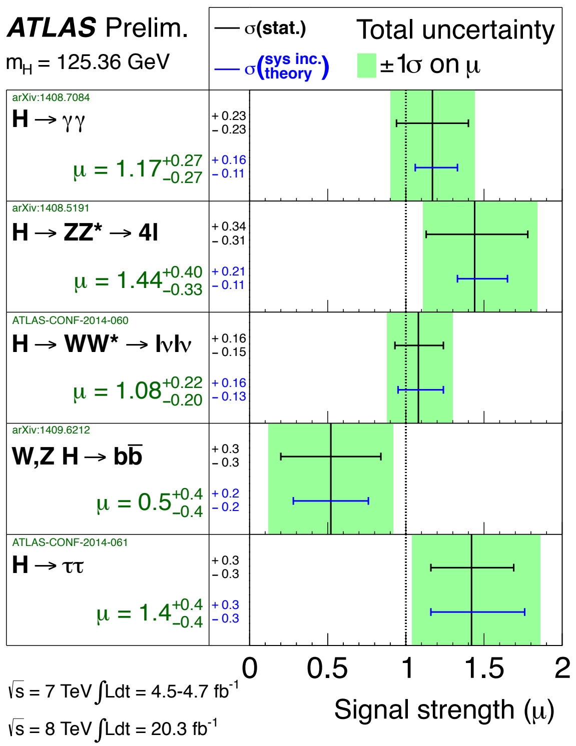
- production
  - Vector-boson-fusion
  - gluon fusion
  - associate production
- decay
  - b-bbar, tau-taubar
  - WW, ZZ (off-shell decays)
  - two photons (2γ)



Higgs signal strength

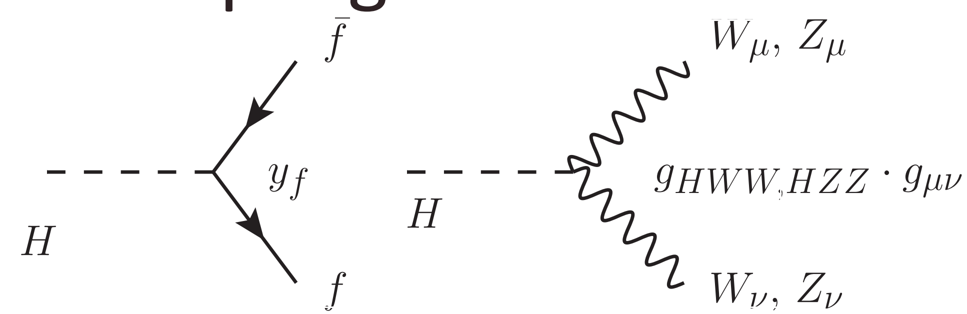
$$\mu(xx \to h \to XX) = \sigma(xx \to h) \cdot \mathcal{B}(h \to XX)$$





Higgs Decay in GHU @ tree level

- HWW, HZZ, and Yukawa couplings are suppressed by $\cos\theta_H$



$$y_f^{\rm GHU} = y_f^{\rm SM} \cdot \cos\theta_H\,, \quad g_{HWW,HZZ}^{\rm GHU} = g_{HWW,HZZ}^{\rm SM} \cdot \cos\theta_H$$

- →Production cross-sections and decay rates are suppressed by $(\cos\theta_H)^2$

$$\sigma(WW, ZZ, \bar{q}q \to H)_{\rm GHU} = \sigma(WW, ZZ, \bar{q}q \to H)_{\rm SM} \cdot \cos^2\theta_H\,,$$
$$\Gamma(H \to WW, ZZ, \bar{f}f)_{\rm GHU} = \Gamma(H \to WW, ZZ, \bar{f}f)_{\rm SM} \cdot \cos^2\theta_H$$

Higgs couplings in GHU

- mass structure

$$\mathcal{L}_{\rm eff}(\theta_H) \supset -m_W^2(\theta_H) W^{+\mu} W_\mu^- - \frac{1}{2} m_Z^2(\theta_H) Z^\mu Z_\mu - m_f(\theta_H) \bar{f} f$$

$$\begin{pmatrix} m_{W,Z}^2(\theta_H) \\ m_f(\theta_H) \end{pmatrix} \simeq \begin{pmatrix} m_{W,Z} \\ m_F \end{pmatrix} \sin\theta_H = \begin{pmatrix} m_{W,Z}^{\rm SM} \\ m_f^{\rm SM} \end{pmatrix}$$

- → effective couplings

$$\theta_H \to \hat{\theta}_H = \theta_H + \frac{h}{f_H}$$

$$\mathcal{L}_{\rm eff}(\hat{\theta}_H) \supset -g_{HWW} H W_\mu^+ W_\mu^- - \frac{1}{2} g_{HZZ} Z^\mu Z_\mu - y_f H \bar{f} f$$

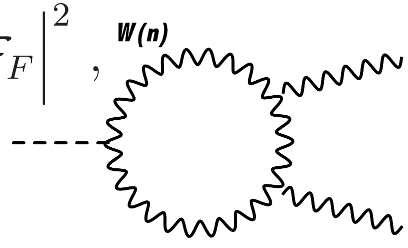
$$\begin{pmatrix} g_{HWW,HZZ}^{\rm GHU} \\ y_f^{\rm GHU} \end{pmatrix} \simeq \begin{pmatrix} g_{HWW,HZZ}^{\rm SM} \\ y_f^{\rm SM} \end{pmatrix} \cot\theta_H$$

$\theta_H \to \pi/2$: anomalous coupling

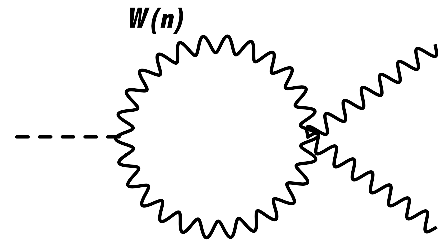
Higgs to 2γ decay

- Decay rate

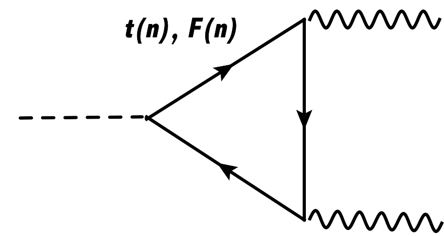
$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2 g_w^2}{1024\pi^3} \frac{m_H^3}{m_W^2} \left| \mathcal{F}_W + \frac{4}{3}\mathcal{F}_{\rm top} + \left(2(Q_X^{(F)})^2 + \tfrac{1}{2} \right) n_F \mathcal{F}_F \right|^2 ,$$



$$\mathcal{F}_W = \sum_{n=0}^{\infty} \frac{g_{HW^{(n)}W^{(n)}}}{g_w\, m_W} \frac{m_W^2}{m_{W^{(n)}}^2} F_1(\tau_{W^{(n)}}) ,$$ W-loop



$$\mathcal{F}_{\rm top} = \sum_{n=0}^{\infty} \frac{y_{t^{(n)}}}{y_t^{\rm SM}} \frac{m_t}{m_{t^{(n)}}} F_{1/2}(\tau_{t^{(n)}}) ,$$ top loop



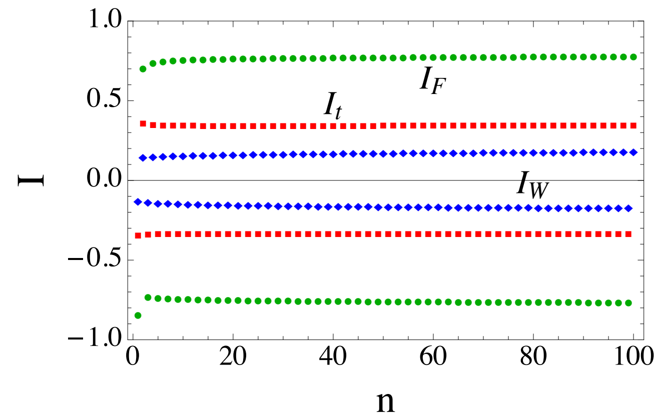
$$\mathcal{F}_F = \sum_{n=1}^{\infty} \frac{y_{F^{(n)}}}{y_t^{\rm SM}} \frac{m_t}{m_{F^{(n)}}} F_{1/2}(\tau_{F^{(n)}}) ,$$ New fermions' loop

Higgs to 2γ (2)

$$\mathcal{F}_W = \sum_n I_{W(n)} \frac{m_W}{m_{W(n)}} \cos\theta_H F_1(\tau_{W(n)}),$$

$$\mathcal{F}_t = \sum_n I_{t(n)} \frac{m_t}{m_{t(n)}} \cos\theta_H F_{1/2}(\tau_{t(n)}),$$

$$\mathcal{F}_F = \sum_n I_{F(n)} \frac{m_t}{m_F} \sin\frac{\theta_H}{2} F_{1/2}(\tau_{F(n)}),$$



log-type convergence: (Falkowski 2008, Maru-Okada 2008)

$$\log(1+x) = \sum_{n=1} \frac{-(-1)^n x^n}{n}$$

Higgs to 2γ (3)

Hosotani@Tohoku 2013

$H \to \gamma\gamma$

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2 g_w^2}{1024\pi^3} \frac{m_H^3}{m_W^2} \left| \mathcal{F}_{\rm total} \right|^2$$

$$\mathcal{F}_{\rm total} = \mathcal{F}_W + \frac{4}{3}\mathcal{F}_t + \frac{1}{2} n_F \mathcal{F}_F$$

θ_H	0.117	0.360
$\mathcal{F}_{W^{(0)}}$	8.330	7.873
$\mathcal{F}_W / \mathcal{F}_{W^{(0)}}$	0.9996	0.998
$\mathcal{F}_{t^{(0)}}$	-1.372	-1.305
$\mathcal{F}_t / \mathcal{F}_{t^{(0)}}$	0.998	0.990
$\mathcal{F}_F / \mathcal{F}_{t^{(0)}}$	-0.0034	-0.033
$\mathcal{F}_{\rm total}$	6.508	6.199
$\mathcal{F}_{\rm total} / (\mathcal{F}_{W^{(0)}} + \mathcal{F}_{t^{(0)}})$	1.001	1.011

Physics
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H to 2γ(4) : signal strength

- Signal strength : $\sigma^{\mathrm{H-prod}} \cdot Br(H \to \gamma\gamma)$

$$\frac{\sigma^{\mathrm{H-prod}}_{\mathrm{GHU}}}{\sigma^{\mathrm{H-prod}}_{\mathrm{SM}}} \simeq \cos^2\theta_H$$

$$\frac{Br(H \to \gamma\gamma)_{GHU}}{Br(H \to \gamma\gamma)_{SM}} \simeq 1 \qquad \because\ Br_{\mathrm{GHU}} = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma_{\mathrm{total}}} \simeq \frac{\Gamma(H \to \gamma\gamma)_{\mathrm{SM}}\cos^2\theta_H}{\Gamma_{\mathrm{SM,total}}\cos^2\theta_H}$$

$$\Rightarrow \frac{[\sigma \cdot Br(H \to \gamma\gamma)]_{\mathrm{GHU}}}{[\sigma \cdot Br(H \to \gamma\gamma)]_{\mathrm{SM}}} \simeq \cos^2\theta_H$$

$$1 - \cos^2(0.360) \approx 0.124$$

$$1 - \cos^2(0.117) \approx 0.014$$

$H \to Z\gamma$ decay

In a naïve model [Maru-Okada, 2012], decay rate of this mode vanishes.

In our model, Unlike the $\gamma\gamma$ decay,

- KK non-converving $ZW(n)W(m)$, $Zt(m)t(n)$, $(m \neq n)$ couplings
- ZWW_R, ZW_RW_R couplings,
- ZtB couplings

are allowed

Summing up all KK modes, the amplitude is found to be finite.
(HH, Hosotani, Funatsu, to appear soon)

Universality and Collider Signature

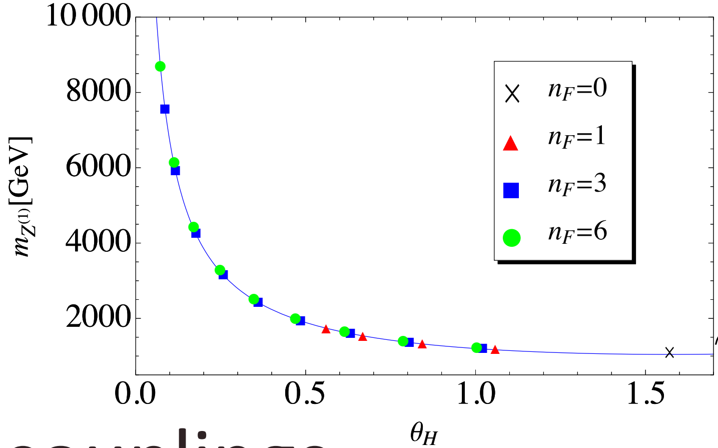
PRD89,095019 [arXiv:1402.2748]

Universality

- # free parameters $(z_L, n_F, c_F) \xrightarrow{m_h = 126\mathrm{GeV}}$ 2 parameters

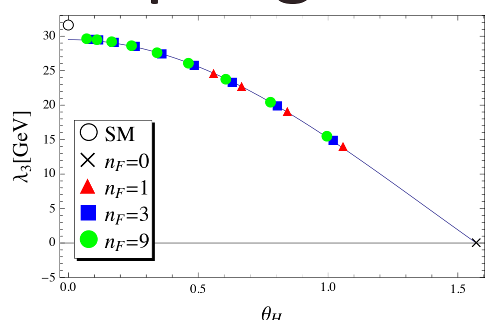
  $\xrightarrow{?}$ 1 parameter

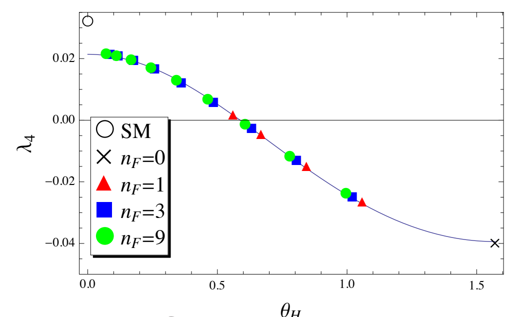
- KK scale, $Z^{(1)}$ mass



$$m_{KK} \sim \frac{1350\mathrm{GeV}}{(\sin\theta_H)^{0.787}}$$

- Higgs self couplings

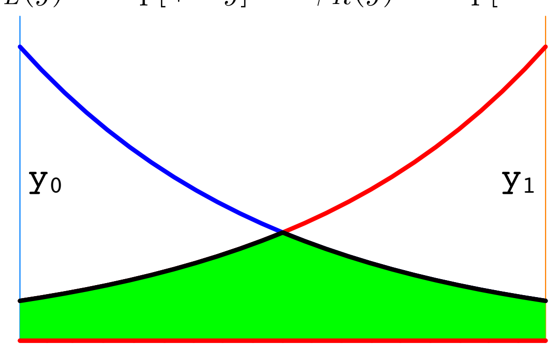




- masses and couplings of SM fields are governed by one parameter : θ_H

Vector boson-fermion coupling

Large right-handed couplings to 1st KK bosons in the RS space



fermion wave-functions (in the flat orbifold)

localization:
←IR brane, UV brane→

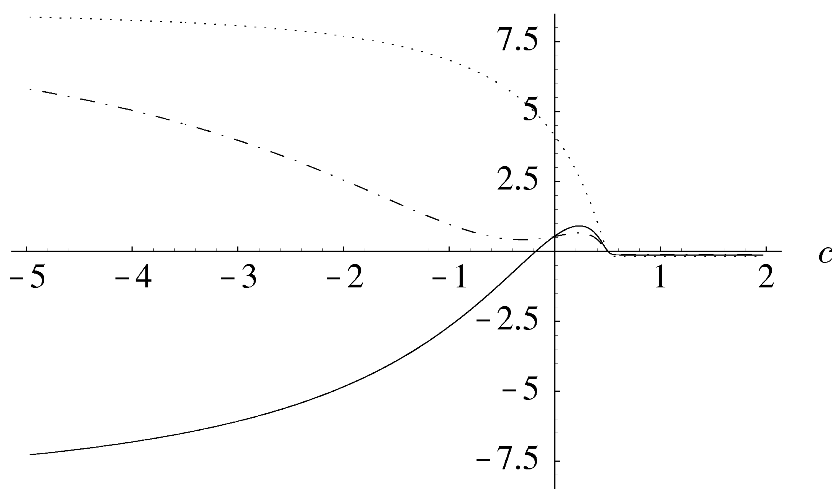
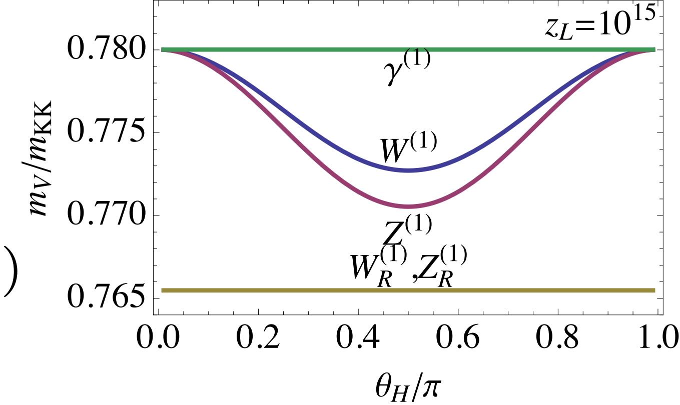


Fig. 1. The ratio of the gauge couplings, $g^{(n)}/g$, for $n=1$ (dotted line), $n=2$ (solid line) and $n=3$ (dashed-dotted line), as a function of the dimensionless fermion mass parameter c.

Gherghetta-Pomarol (2000):
dotted : $g^{(1)}/g$

Z' search

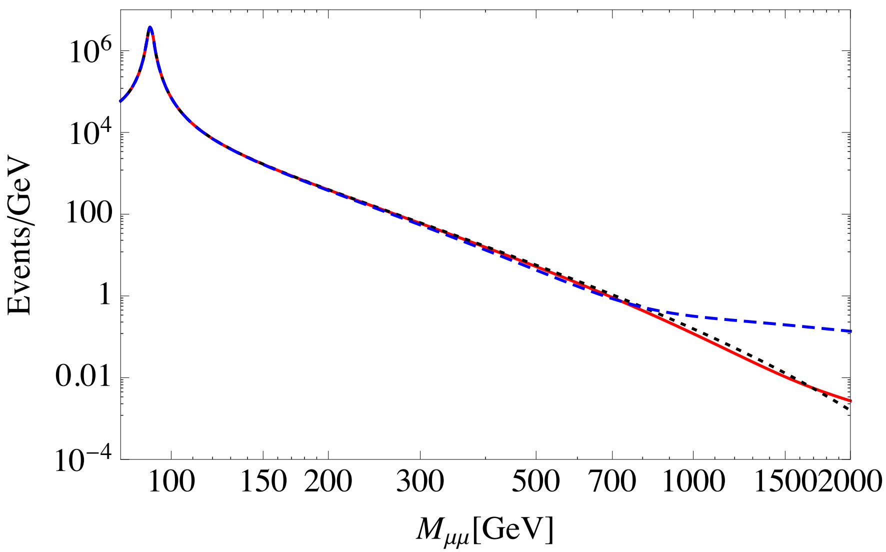
$$Z' = \gamma^{(1)}, Z^{(1)}, Z_R^{(1)}$$



- 1st KK SM particles and $W_R^{(1)}$, $Z_R^{(1)}$ bosons: nearly degenerated
- In GHU in warped space, 1st KK gauge bosons have large right-handed couplings to the SM fermions
- Z' states with broad resonances in $pp \to l^+ l^-$ processes
- SM couplings are "universal" – depend only on θ_H(or z_L), irrespective to the number of spinor. rep. fermions.

Table 1: Parameters and masses in the case of degenerate dark fermions with $n_F = 5$. All masses and k are given in units of TeV.

z_L	θ_H	m_{KK}	k	c_t	c_F	$m_{F^{(1)}}$	$m_{Z_R^{(1)}}$	$m_{Z^{(1)}}$	$m_{\gamma^{(1)}}$
10^9	0.473	2.50	7.97×10^8	0.376	0.459	0.353	1.92	1.97	1.98
10^8	0.351	3.13	9.97×10^7	0.357	0.445	0.502	2.40	2.48	2.48
10^7	0.251	4.06	1.29×10^7	0.330	0.430	0.735	3.11	3.24	3.24
10^6	0.172	5.45	1.74×10^6	0.292	0.410	1.11	4.17	4.37	4.38
10^5	0.114	7.49	2.38×10^5	0.227	0.382	1.75	5.73	6.07	6.08
10^4	0.0730	10.5	3.33×10^4	0.0366	0.333	2.91	8.00	8.61	8.61



LHC(8TeV) $\theta_H = 0.251, 0.114$

$[z_L = 10^7, 10^5]$

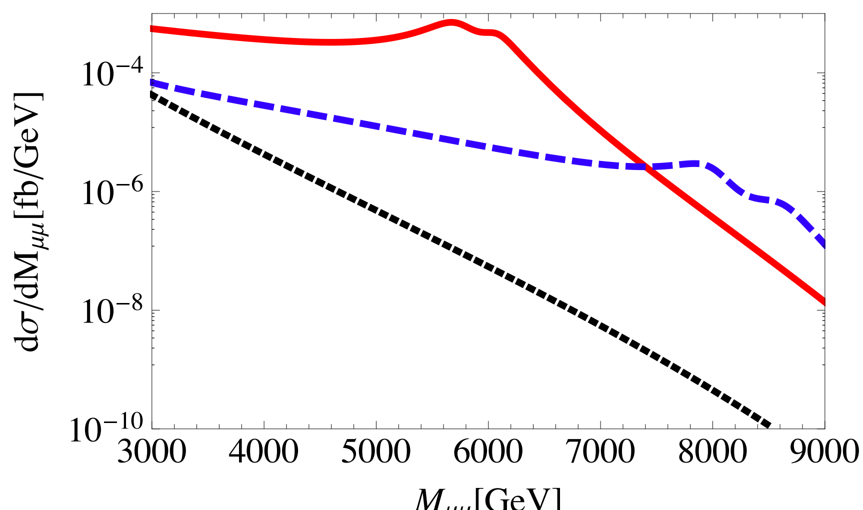
$$\Rightarrow \theta_H \lesssim 0.2$$

$$(z_L \lesssim 10^6)$$

LHC(14TeV)

$\theta_H = 0.114, 0.073$

$[z_L = 10^5, 10^4]$

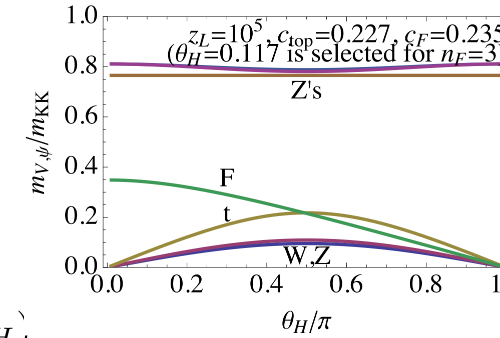


Dark Matter

[arXiv:1407.3574, PTEP]

SO(5)-spinor fermion as Dark Fermion

- SO(5)-spinor fermions : no mixing with SO(5) vector fermion
  - conserving fermion number
  - lightest and neutral one : DM candidate "Dark Fermion"



- DF does not have zero mode

$$m_{F(1)} \propto m_{KK} \cos(\theta_H/2)$$

c.f. $m_{SM} \propto m_{KK} \sin(\theta_H)$

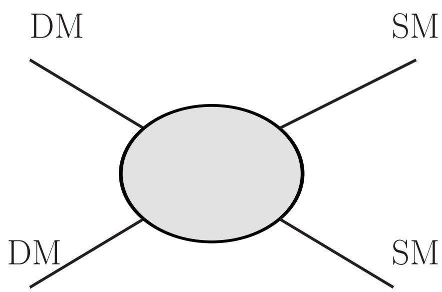
  - F(1) can be around a half of 1st KK boson masses
  - small Yukawa coupling [Y_F is suppressed by $\sin(\theta_H/2)$]
- F is the mixture of $SU(2)_L$ and $SU(2)_R$ doublets

$$\Psi^{\rm spinor} = \begin{pmatrix} \psi_{SU(2)_L} \\ \psi_{SU(2)_R} \end{pmatrix} \sim \begin{pmatrix} \sin(\theta_H/2) \\ \cos(\theta_H/2) \end{pmatrix} \otimes \begin{pmatrix} F^+ \\ F^0 \end{pmatrix}$$

  - WFF,ZFF couplings : suppressed by $\sin^2(\theta_H/2)$

WIMP DM relic abundance

$$\Omega h^2 \approx \frac{1.04\times 10^9}{M_{Pl}}\frac{x_F}{\sqrt{g_*}}\frac{1}{a+3b/x_F}, \quad \langle\sigma v\rangle = a + b\langle v^2\rangle + \cdots , \quad x_F = m/T_F,$$



$$\frac{dn}{dx} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{eq}^2)$$

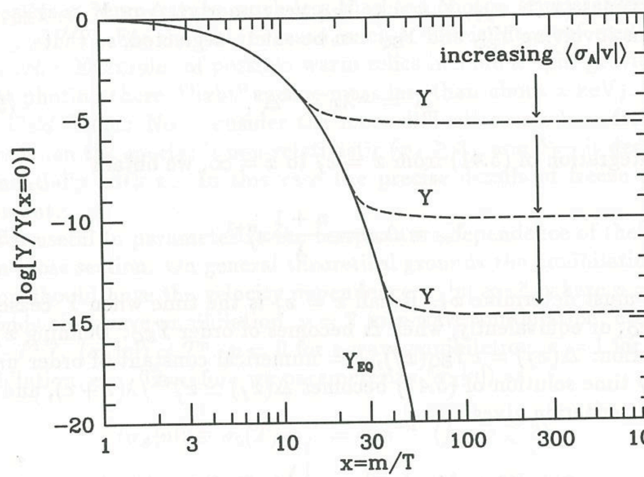


Fig. 5.1: The freeze out of a massive particle species. The dashed line is the actual abundance, and the solid line is the equilibrium abundance.

$$Y = n/s$$

DM complementarity

1. Relic Density → DM annihilation

2. Direct Detection → DM-nucleon scattering

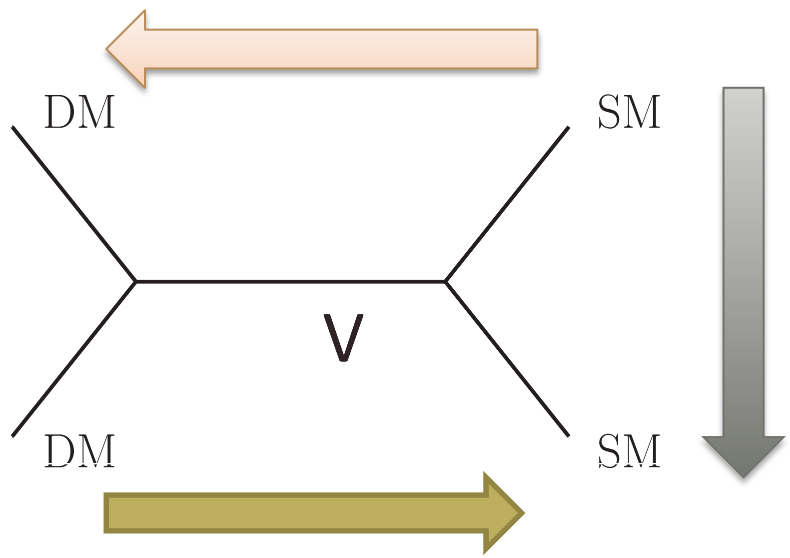
3. LHC signal → DM pair creation

$$\sigma_{\mathrm{ann,prod}} \propto \left(\frac{1}{s - m_V^2 + i m_V \Gamma_V}\right)^2$$

$$s \simeq 4m_{DM}^2$$

$$\sigma_{\mathrm{scat}} \propto \left(\frac{1}{t - m_V^2 + i m_V \Gamma_V}\right)^2$$

$$t \sim m_{DM}^2 v^2, \quad v \ll c$$



Not only structure of interaction operator

$$\bar{\chi}_{\mathrm{DM}} \mathcal{O} \chi_{\mathrm{DM}} \cdot \bar{q} \mathcal{O}' q, \quad \mathcal{O}, \mathcal{O}' = 1, \gamma_5, \gamma_\mu, \gamma_\mu \gamma_5, \sigma_{\mu\nu},$$

kinematical suppressions/enhancements are also important

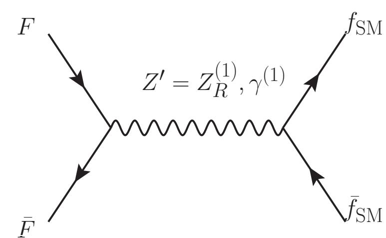
- Suitable annihilation cross section of multi TeV dark matter

$$\Omega h^2 \sim 0.1 \times \left(\frac{\langle \sigma v \rangle}{\mathcal{O}(1\mathrm{pb} \cdot c)} \right)^{-1}$$

  can be obtained :

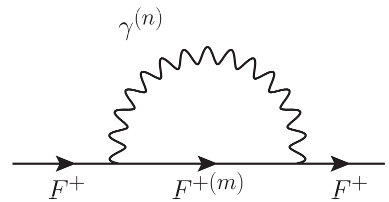
  1. Enhancement due to Breit-Wigner resonances when $m_F \approx m_V/2$
  2. Large right-handed couplings to 1st KK bosons in the RS space-time also enhance the annulation cross section

- Annihilation of DFs are dominated by following processes:

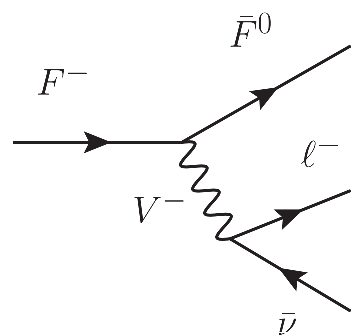


- small ZFF, HFF coupling save from constraints by DM direct detection

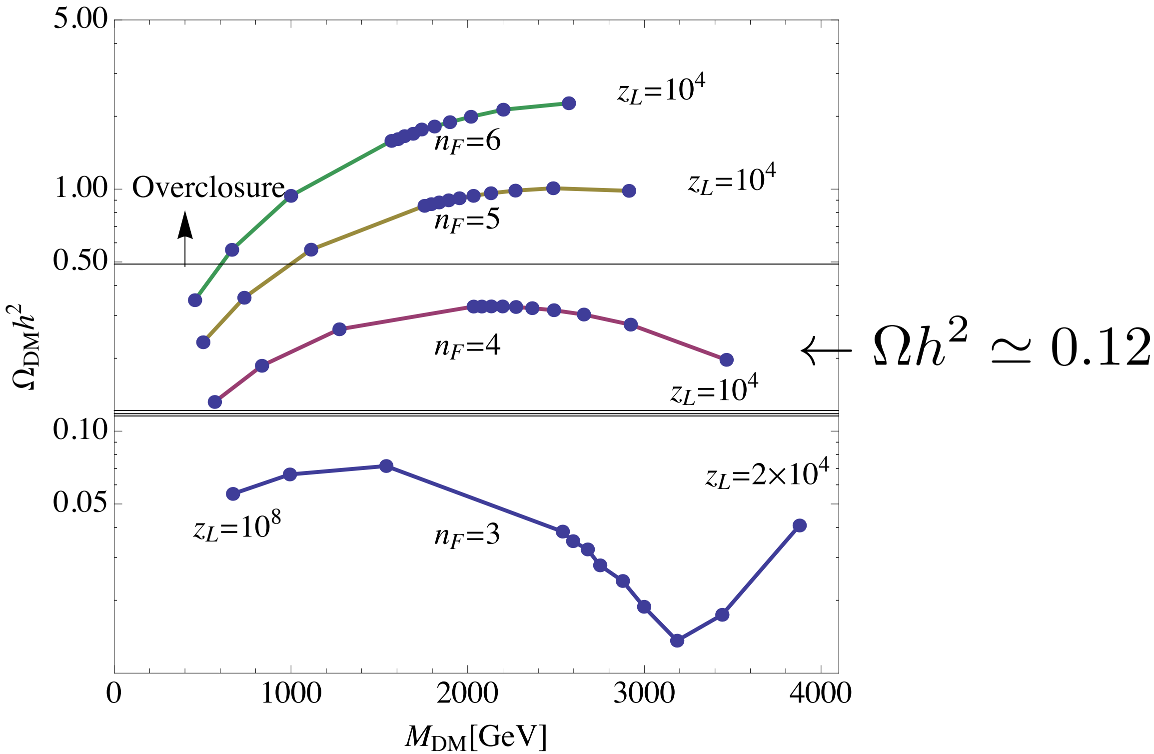
- F^+, F^0 : degenerate @ tree level
- degeneracy is lifted @ 1-loop level



- F^+ becomes heavier than F^0 by a few GeV
- after the freeze-out, F^+ decays to F^0 (beta-decay like)



V=W



- In n_F=3 case, $2m_F$ is very close to $\mathrm{m}_{Z(1)}$, BW enhancement occures
- n_F>=4, relic densities are bigger than the experimental bounds for z_L<10^5

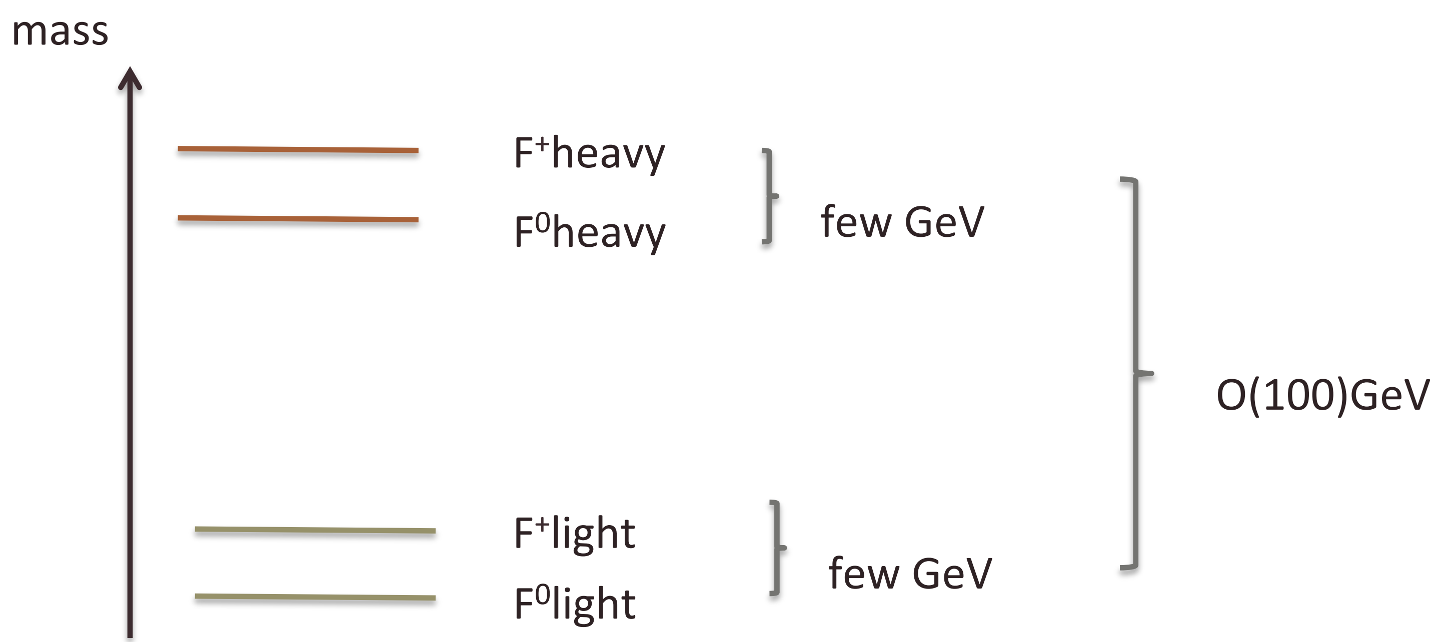
non-degenerate DF

- Degenerate cases
  - n_F = 3, too few DM
  - n_F>=4, too much DM
- For n_F >=4, to reduc DM density, we consider non-degenerate cases
  - n_F DFs → light DFs light and heavy DFs

$$n_F F_i \to n_F^{\text{light}} F_l,\ (c_F^{\text{light}}) + n_F^{\text{heavy}} F_h,\ (c_F^{\text{heavy}}), \quad \Delta c_F \equiv c_F^{\text{light}} - c_F^{\text{heavy}}$$

  - Relic densities are reduced to n_F^{light}/n_F of degenerate one
    - bulk mass parameters ($c_F^{\text{light,heavy}}$) are tuned so that m_H=126GeV and θ_H unchanged
      →new tunable parameter : Δc_F
    - mixings between F_h and F_l comes from mixing mass terms in bulk or on branes
      →F_h obey opposite b.c. (η_F= -1)
    - in heavy dark fermions, SU(2)L components dominate

$$\Psi_F^{\text{heavy}} = \begin{pmatrix} \psi_{SU(2)_L}^{\text{heavy}} \\ \psi_{SU(2)_R}^{\text{heavy}} \end{pmatrix} \sim \begin{pmatrix} \cos(\theta_H/2) \\ \sin(\theta_H/2) \end{pmatrix} \otimes \begin{pmatrix} F_{\text{heavy}}^{+} \\ F_{\text{heavy}}^{0} \end{pmatrix}$$



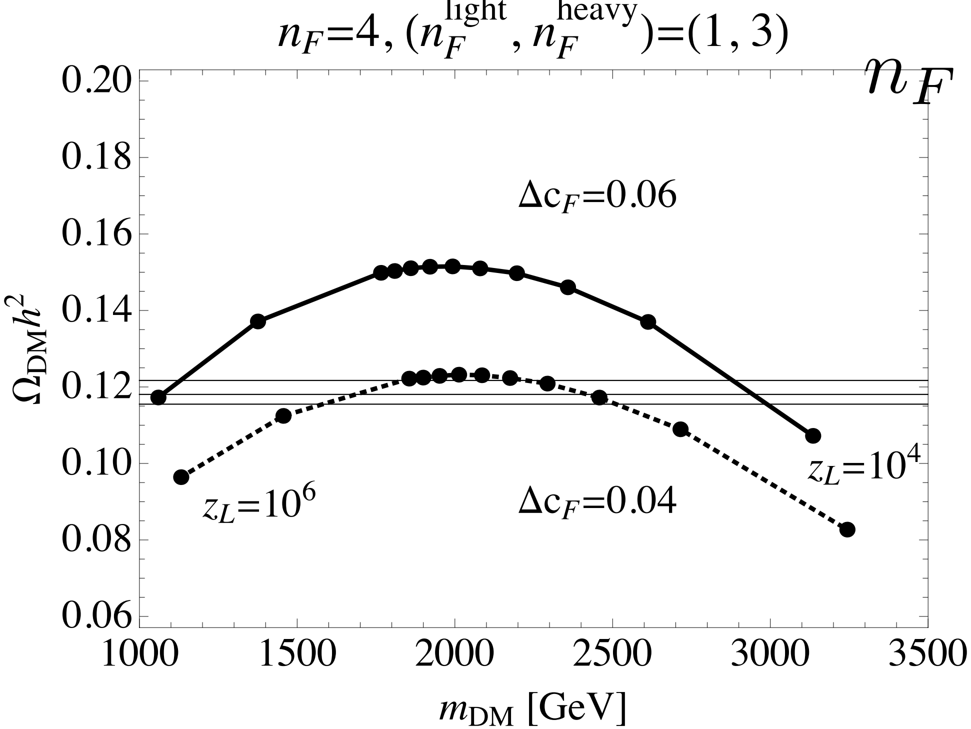
- heavy fermions' number density is suppressed by Boltzman factor:

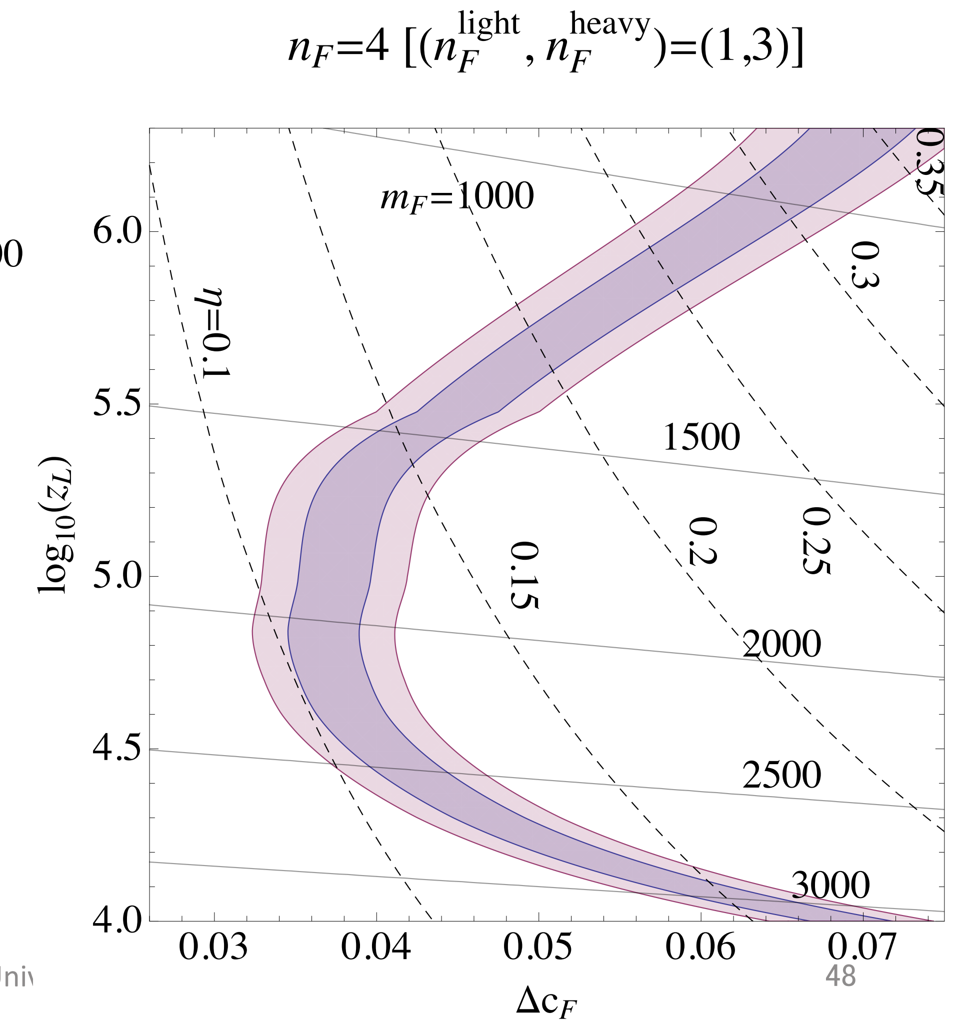
$$\exp(-\eta \frac{m_F}{T_F}), \quad \eta \equiv \frac{m_F^{\mathrm{heavy}} - m_F^{\mathrm{light}}}{m_F}$$

- If eta is sufficiently large, at the freeze-out, number density of heavy fermions becomes negligible.
→ relic density is reduced

$$\rho_{\mathrm{rel}}^{\mathrm{non-deg}} \sim \rho_{F_{\mathrm{light}}} \sim \frac{n_F^{\mathrm{light}}}{n_F} \rho_{rel}^{\mathrm{degenerate}}$$

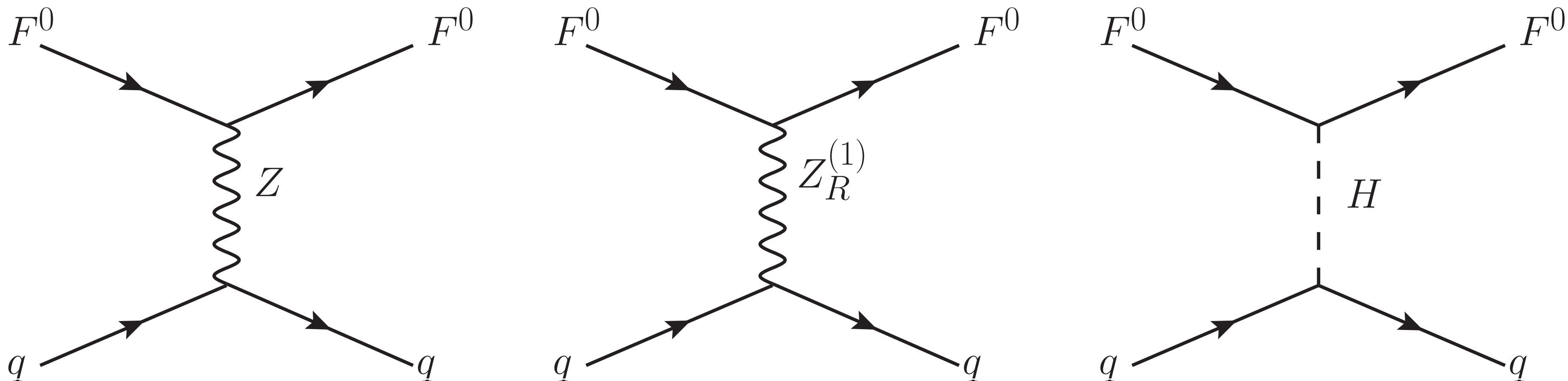
$$n_F = 4\,[(n_F^{\text{light}}, n_F^{\text{heavy}}) = (1,3)]$$





DM direct detection

- dominant scattering processes:

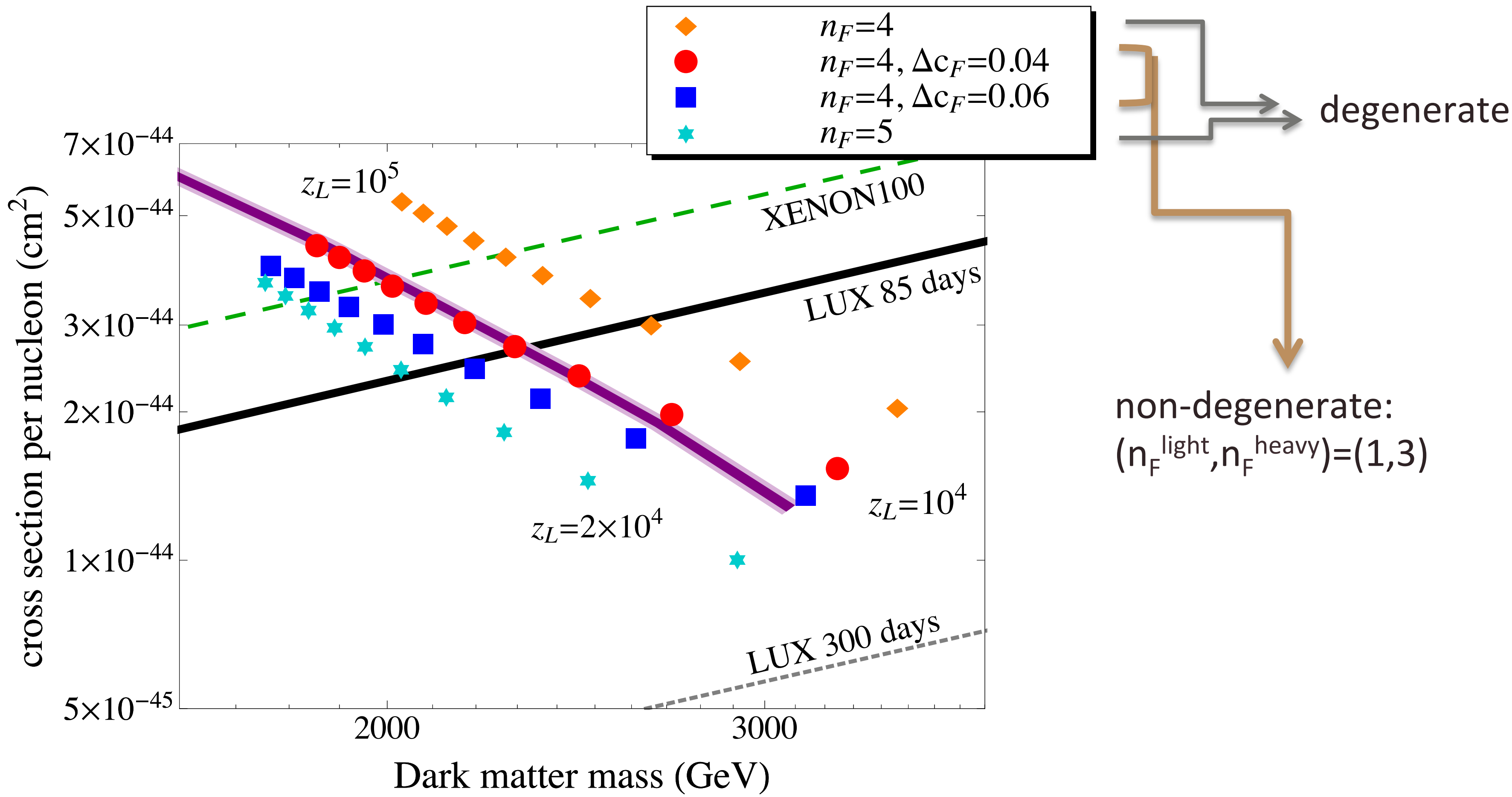


$\sin^2(\frac{\theta_H}{2})$ $\quad$ $(m_Z)^2/(m_{Z_R}^2)$ $\quad$ $\sin(\theta_H)$

suppression factors

DM-nucleon cross section

predicutions and experimental upper bounds



purple band: allowed region for relic density

Summary

- Gauge-Higgs Unification model which yields 126GeV Higgs mass is constructed
- $H \to \gamma\gamma$ is finite, and small deviation from SM value for small θ_H
- SM part of this model is approximately described by one free parameter (universality)
  - Higgs triple and quartic couplings depend on θ_H. In particular quartic coupling deviates significantly from the SM.
- Z' signals in LHC8, LHC14 are studied.
  - LHC8 has constrained $z_L < 10^5$
- Neutral Spinorial Fermions are possible DM candidate.
  - Degenerate cases: too little DM for nF=3 and too much for nF>=4
  - Non-degenrate cases: 1-light and 3-heavy DF with zL <=4*10^4 is possible solution
    $\to$ to be checked future direct detection experiments

BACK UP SLIDES

Plan

- SO(5)×U(1) GHU with 126GeV Higgs
- Higgs production/decay (H→γγ,gg)
- LHC signals
- Dark Matter

toward a realistic GHU model

- $S^1 \to S^1/Z_2$
  - chiral structure of fermions
  - SU(2) fund. repl. Higgs
- Warped geometry (Randall-Sundrum, etc.)
  - small Kaluza-Klein scale
  - top quark heavier than W boson
- Extending unified group G_{EWU} ($\supset SU(2)_L x U(1)_Y$)
  - to accommodate custodial SO(4) symmetry
  - tune Weinberg angle : extra U(1)
- $\to$ SO(5)xU(1) GHU model : a minimal model of realistic GHU

SO(5)-spinorial fermions as DM

- spinorial-representation fermions do not decay quarks/leptons
  → the lightest states are stable
  "dark fermions"
- Choosing $U(1)_X$ charge Q_X=1/2
  → one of the fermion in SU(2) doublet is neutral
  → possible dark-matter candidate
- Features
  - DM scattering cross section is small due to suppressed Higgs-Yukawa and Z-boson couplings
  - rich structure of annihilation cross section

Vector bosons A_M,B_M decomposes

$$A_\mu, B_\mu \to \gamma_\mu^{(n)}, W_\mu^{\pm(n=\text{even,odd})}, Z_\mu^{(n=\text{even,odd})}, W_{R\mu}^{\pm(n)}, Z_{R\mu}^{(n)}, A_\mu^{\hat{4}(n)}$$

Two SO(5)-vector bulk fermions decomposes

$$\Psi_1 = \left(\begin{pmatrix} T & t \\ B & b \end{pmatrix}_L, t'_R \right), \Psi_2 = \left(\begin{pmatrix} U & X \\ D & Y \end{pmatrix}_L, t'_R \right)$$

$$\to t_{+2/3}^{(n=\text{even,odd})}, t'^{(n)}_{+2/3}, \psi_{+5/3}^{(n)}, \quad b_{-1/3}^{(n=\text{even,odd})}, b'^{(n)}_{-1/3}, \psi_{-4/3}^{(n)}$$

and Ψ_3 , Ψ_4 for leptons…

SO(5)-spinor fermion

$$\Psi_F = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}, \quad \psi_{L/R}\text{: SU(2) doublets}$$

$$\to F = \begin{pmatrix} F^1 \\ F^2 \end{pmatrix}, \quad Q_{EM}^{1,2} = Q_X \pm \frac{1}{2}$$

$$\Psi_F(y_i - y) = \eta_{F_i} \gamma_5 P_{\text{sp}} \Psi_F(y_i + y), \quad i = 0, 1,$$

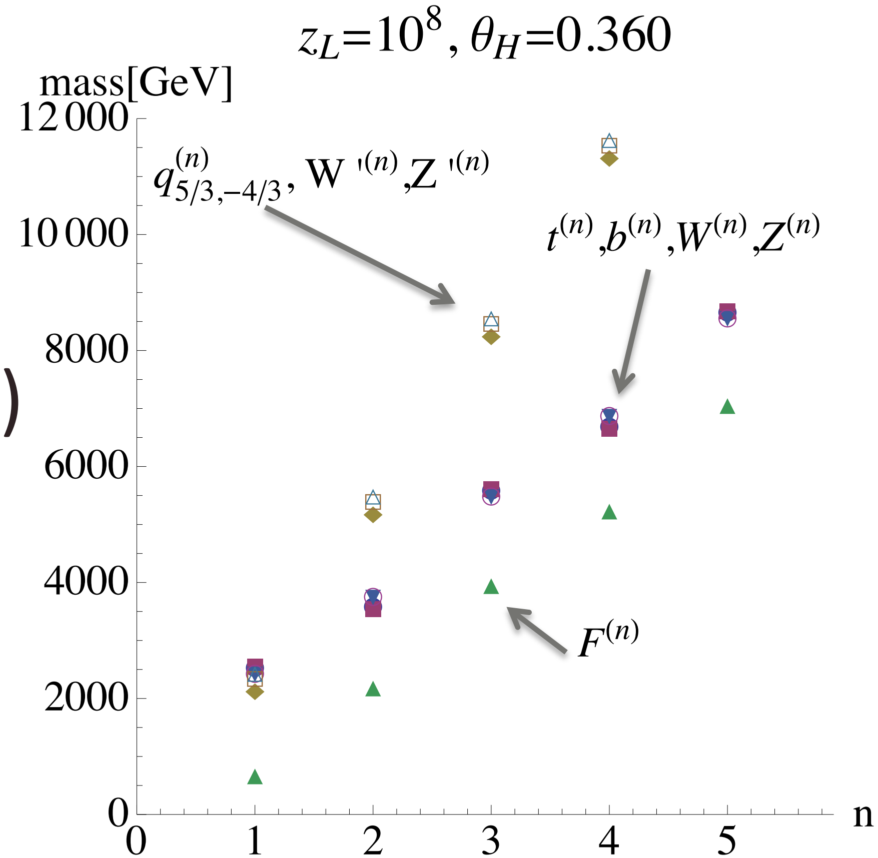
$$\eta_{F_0} = -\eta_{F_1} = \eta_F = +1, \quad P_{\text{sp}} = \begin{pmatrix} 1_2 & \\ & -1_2 \end{pmatrix}$$

- F has no mixing with SM fermions
  →lightest mode $F^{(1)}$ is stable
- Q_X=±1/2
  → one of F is neutral

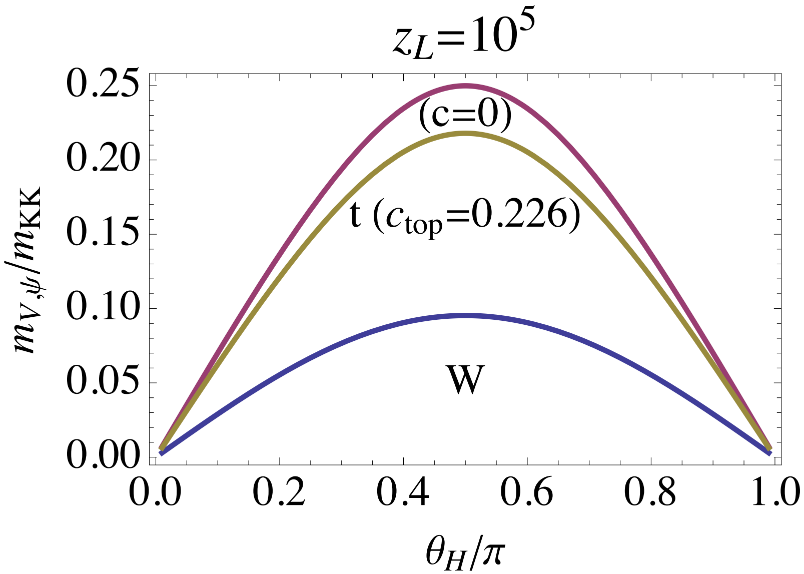
F can be WIMP DM
"Dark Fermion"

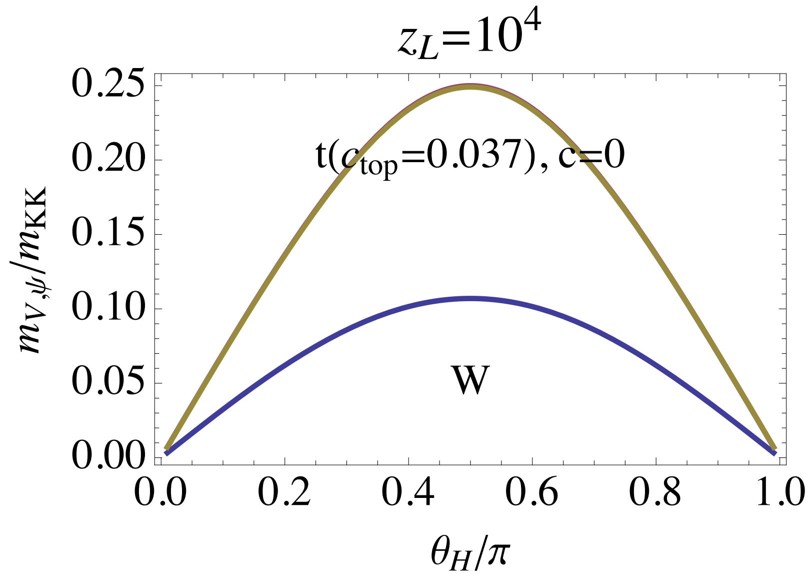
mass spectra

- SM particles and their KK excited states
  (zero and KK modes)
- exotic particles (KK modes)
  $Z_{R\mu},\ W_{R\mu},\ \hat{A}^4_\mu,$
  $q^{(+5/3)},\ q^{(-4/3)},\ \ell^{(+1)},\ \ell^{(-2)}$
- extra fermion doublets F $Q_{\rm EM} = Q_X \pm \frac{1}{2}$
  - electric charge
  - lightest non-SM particles



lower bound of z_L





For z_L < 10^4, no solution of c_{top} with which m_t=173GeV is satisfied

couplings

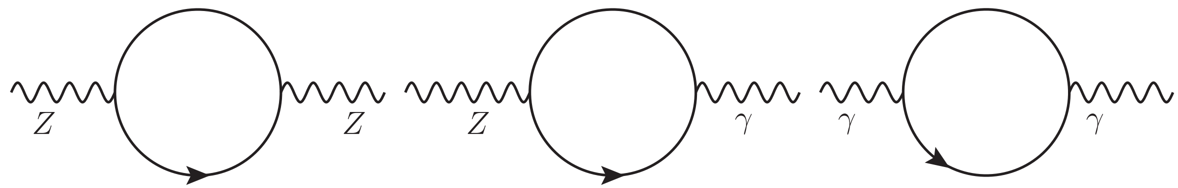
- once KK spectra of the fields, one can obtain the couplings between fields, in terms of the overlap of the wave-functions in the extra dimension
- We have summarized the couplings between SM fermion [spinorial fermions] and vector bosons/Higgs boson in Appendices of our recent papers
  (1404.2748 and 1407.3574)

Dark Fermion - couplings

F is a mixture of SU(2)L and SU(2)R doublets
→ couplings can be suppressed by the mixing: $\sin^n(\theta_H/2)$

	$\eta_F = +1$	$\eta_F = -1$
WFF, ZFF	suppressed	unsuppressed
$W^{(1)}FF$, $Z^{(1)}FF$	suppressed	unsuppressed
Z_RFF	unsuppressed, large RH-couplings	
W_RFF	unsuppressed, large RH-couplings (no couplings with quarks/leptons)	
HFF (Yukawa)	suppressed	
γFF	unsuppressed	
$\gamma^{(1)}FF$	unsuppressed, large RH-couplings	
HFF (Yukawa)	suppressed	

S-parameter



- Both F_l and F_h couples to the Z-boson in almost vector-like way.

couplings to Higgs

- Effective Lagrangian

$$\mathcal{L} = m_W(\hat{\theta})^2 W_\mu^2 + m_Z(\hat{\theta})^2 Z_\mu^2 + m_t(\hat{\theta})\bar{t}t + \cdots ,$$

- SM particles

$$m_W,\, m_Z,\, m_t \propto m_{KK} \sin\theta_H$$

$$\to g_{HWW},\, g_{HZZ},\, g_{H\bar{t}t} \propto \cos\theta_H$$

- New fermions

$$m_F \propto m_{KK} \cos(\theta_H/2)$$

$$\to g_{HFF} \propto \sin(\theta_H/2)$$

- other exotic KK states

$$m_X \propto m_{KK} \times \text{const.}$$

$$\to g_{HXX} = 0$$

Higgs Production & Decay

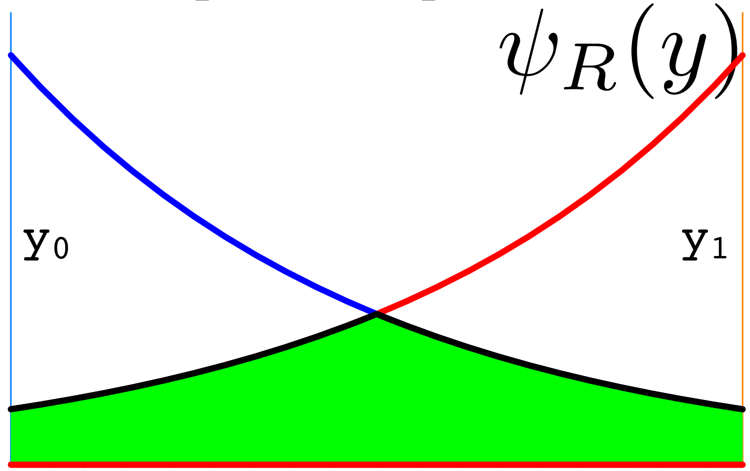
Introduction

Fermion mass hierarchy in GHU

- Example : flat extra dimension

$$\psi_L(y) \propto \exp[-my]$$

$$\psi_R(y) \propto \exp[+my]$$



$$\propto \frac{m}{\sinh[\pi m R]}$$