A WARPED SCALAR PORTAL TO FERMIONIC DARK MATTER

IFIC SEMINAR

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BASED ON

- ⋆ Adrian Carmona, Javier Castellano Ruiz, and Matthias Neubert. "A warped scalar portal to fermionic dark matter". In: *Eur. Phys. J. C* 81.1 (2021), p. 58. DOI: 10.1140/epjc/s10052-021-08851-0. arXiv: 2011.09492 [hep-ph]

- ⋆ Aqeel Ahmed, Adrian Carmona, Javier Castellano Ruiz, Yi Chung, and Matthias Neubert. "Dynamical origin of fermion bulk masses in a warped extra dimension". In: *JHEP* 08 (2019), p. 045. DOI: 10.1007/JHEP08(2019)045. arXiv: 1905.09833 [hep-ph]

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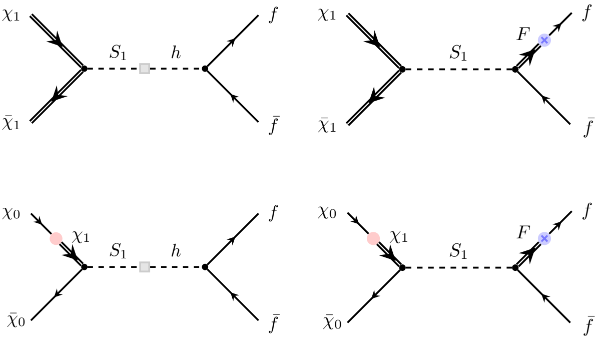
SPOILER!

At the end of the day, we are going to have a:

- ⋆ A fermionic DM candidate χ co-annihilating into the SM via the Higgs h and a heavy scalar mediator S_1



MOTIVATION

All this is going to come from a model accounting for

- ⋆ the hierarchy between M_{Planck} and the electroweak scale
- ⋆ the hierarchy between the different fermion masses
- ⋆ the observed relic abundance

which are issues that can not be addressed within the SM

In particular, I will take the path of adding a warped extra dimension (WED)

MOTIVATION

THE HEAVY SCALAR WILL BE A NATURAL MEDIATOR TO ANY FERMIONIC DARK SECTOR PROPAGATING INTO THE WARPED EXTRA DIMENSION

MOTIVATION

It is NATURAL because

- it was ordered to solve another problem
- it is *technically* natural, like any scalar in WEDs
- Once this guy is present, it has to couple to any fermion propagating into the WED

A BRIEF DETOUR

WHAT CAN AN XDIM DO AND NOT DO FOR YOU?

It can

- ✓ give you a technically natural light Higgs

- ✓ provide a rationale to understand the flavor puzzle

However,

- ✗ contrary to SUSY, it does not have a prime DM candidate

THE PRICE TO PAY

For every field propagating into the bulk of the warped extra dimension, there will be an infinite tower or Kaluza-Klein resonances

like there are infinite harmonics in a vibrating guitar string. We will identify the massless zero-mode with the corresponding SM field

THE PRICE TO PAY

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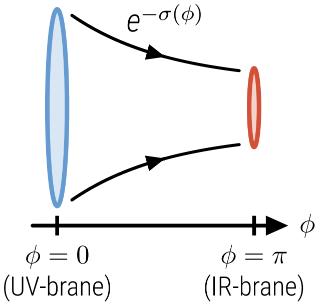
A NATURALLY LIGHT HIGGS

In WEDs, the fundamental scale of the theory $\mathcal{O}(M_{\rm Pl})$ is redshifted by the warp factor to a few TeV on the IR brane, where the Higgs is localized [Randall, Sundrum '99]



$$ds^2 = e^{-2\sigma(\phi)}\,\eta_{\mu\nu}dx^\mu dx^\nu - r^2\, d\phi^2$$

UV: $m \sim M_{\rm Pl} = 2 \cdot 10^{15}$ TeV

IR: $m \sim M_{\rm Pl} \cdot e^{-\sigma(\pi)} \sim$ TeV

The Higgs VEV (as any dimensionful parameter) gets redshifted

$$v_{\rm SM} \sim M_{\rm Pl} e^{-\sigma(\pi)} \qquad \sigma(\pi) = k\,r\,\pi, \qquad k\,r \sim 10$$

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A RATIONALE FOR THE FLAVOR PUZZLE

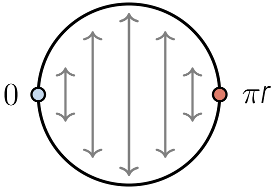
The smallest irrep of the 5D Clifford algebra $\{\Gamma^M, \Gamma^N\} = 2g^{MN}$ is 4D

$$\Gamma^5 = \pm\Gamma^0\Gamma^1\Gamma^2\Gamma^3 \;\Rightarrow\; \bar{\Gamma} \propto 1$$

1. $\psi(x, \phi)$ are vector-like and can have bulk masses $M = c/k$
2. We can still get a 4D chiral spectrum

$S^1/\mathbb{Z}_2$

$\phi \sim -\phi$



$$\psi_L(x, -\phi) = Z\psi_L(x, \phi) \qquad Z^2 = 1$$
$$\psi_L(x, y)|_{0,\pi} = 0 \qquad \partial_\phi \psi_L(x, y)|_{0,\pi} = 0$$

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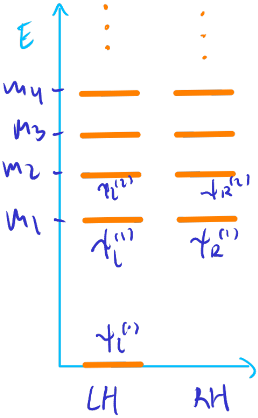
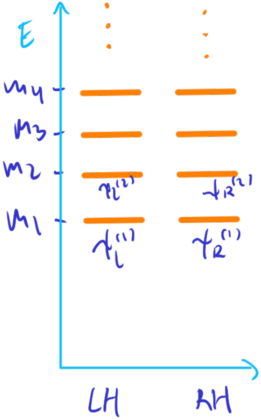
A RATIONALE FOR THE FLAVOR PUZZLE



$$f_R^{(n)}(0) = f_R^{(n)}(\pi r) = 0$$



$$f_R^{(n)}(0) = f_L^{(n)}(\pi r) = 0$$

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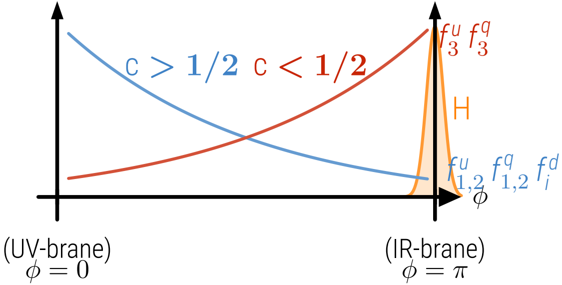
A RATIONALE FOR THE FLAVOR PUZZLE

This can explain the huge hierarchy between the different fermion masses



$$\left(m_{u,d}\right)_{ij} \sim \frac{v}{\sqrt{2}} f_i^q Y_* f_j^{u,d}$$

We obtain naturally also a hierarchical mixing in the quark sector

$$\left|U_L^{u,d}\right|_{ij} \sim f_i^q / f_j^q \qquad \left|U_R^{u,d}\right|_{ij} \sim f_i^{u,d} / f_j^{u,d} \qquad i \leq j$$

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END DETOUR

OUR ORIGINAL MOTIVATION

To have a chiral spectrum, $\bar{\Psi}\Psi$ has to be $\mathbb{Z}_2$-odd. Normally, one just assumes

$$M\,\mathrm{sign}(\phi)\bar{\Psi}(x,\phi)\Psi(x,\phi)$$

However,

- ⋆ why $M\,\mathrm{sign}(\phi)$ and not any other $\mathbb{Z}_2$-odd function?
- ⋆ is it obvious that $M\,\mathrm{sign}(\phi)$ can be obtained dynamically?
- ⋆ what are the phenomenological consequences?

We explore the case where the fermion bulk masses comes trough a term

$$\Sigma(x,\phi)\bar{\Psi}(x,\phi)\Psi(x,\phi)$$

after the $\mathbb{Z}_2$-odd scalar field $\Sigma(x,\phi)$ takes a VEV [*Georgi et al '00*] for flat Xdim

$$\langle\Sigma(x,\phi)\rangle = \omega(\phi)$$

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A COUPLED GRAVITYSCALAR SYSTEM

The scalar action reads

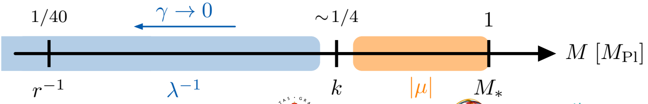
$$S_{5D} = 2\int d^4x \int_0^{\pi} d\phi \sqrt{g}\left\{\frac{1}{2}g^{MN}(\partial_M\Sigma)(\partial_N\Sigma) - V(\Sigma)\right\}, \qquad \text{with}$$

$$V(\Sigma) = \Lambda_B + \frac{\mu^2}{2}\Sigma^2 + \frac{\lambda}{4!}\Sigma^4$$

- ⋆ The potential induces a ϕ-dependant VEV: $v(\phi) = \sqrt{\frac{\lambda}{6|\mu|^2}}\,\omega(\phi)$
- ⋆ Coupled to gravity through $\gamma \equiv \frac{|\mu|^2}{\lambda M_*^3}$

$$0 = \sigma''(\phi) - \gamma v'^2(\phi) \qquad \sigma'|_{UV,IR} = \mp r\kappa^2 V_{UV,IR}$$

$$0 = v''(\phi) - 4\,\sigma'(\phi)\,v'(\phi) + |\mu r|^2\left[v(\phi) - v^3(\phi)\right] \qquad v|_{UV,IR} = 0$$



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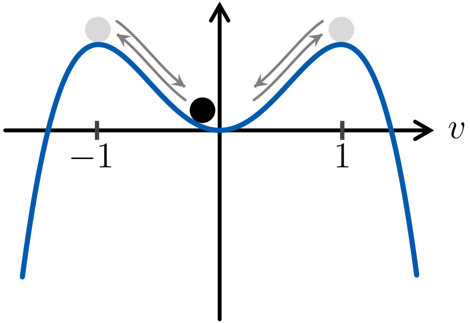
BACKGROUND SOLUTIONS

$$0 = \sigma''(\phi) - \gamma v'^2(\phi) \qquad \sigma'|_{\text{UV,IR}} = \mp r\kappa^2 V_{\text{UV,IR}}$$

$$0 = v''(\phi) - 4\,\sigma'(\phi)\,v'(\phi) + |\mu r|^2\left[v(\phi) - v^3(\phi)\right] \qquad v|_{\text{UV,IR}} = 0$$

$$\mathcal{V}(v) = |\mu r|^2\left[\frac{1}{2}v^2 - \frac{1}{4}v^4\right]$$



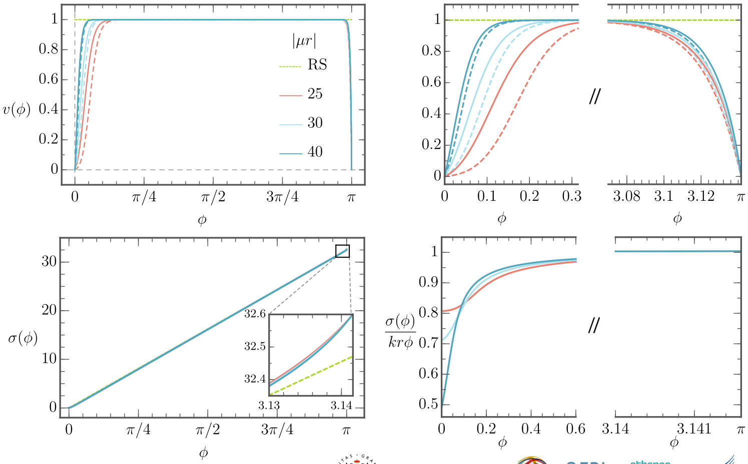
$$|\mu r|^2 - 4(kr)^2 \geq 1$$

BACKGROUND SOLUTIONS

$$0 = \sigma''(\phi) - \gamma v'^2(\phi) \qquad \sigma'|_{\mathrm{UV,IR}} = \mp r\kappa^2 V_{\mathrm{UV,IR}}$$

$$0 = v''(\phi) - 4\,\sigma'(\phi)\, v'(\phi) + |\mu r|^2 \left[v(\phi) - v^3(\phi)\right] \qquad v|_{\mathrm{UV,IR}} = 0$$

$m_g^1 = 10$ TeV, $r = 40\, M_{\mathrm{Pl}}^{-1}$, with strong (no) backreaction - solid (dashed)



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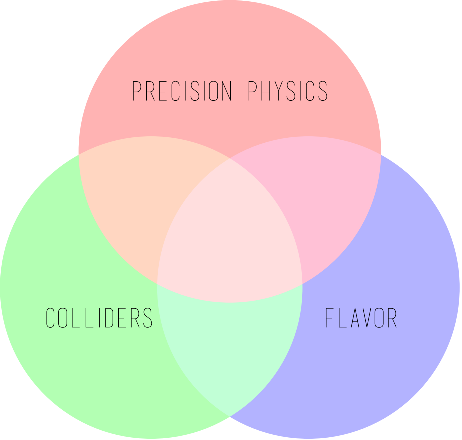
IMPLICATIONS

EWPT



KK SCALAR PRODUCTION

TOO HEAVY FOR THE LHC!

$K - \bar{K}$ MIXING

ϵ_K ...

IMPLICATIONS

All this and more in arXiv:1905.09833. We will concentrate on this talk on other effects, which we explored on arXiv:2011.09492

- ⋆ Mixing with a bulk-Higgs boson
- ⋆ Connection to dark sectors and DM

MIXING WITH A BULK HIGGS BOSON

- ⋆ In the previous discussion, we have neglected the mixing of Σ with the Higgs boson, but in general we will have

$$V(H,\Sigma) = \mu_H^2|H|^2 - \frac{\mu_S^2}{2}\Sigma^2 + \frac{\lambda_S}{4}\Sigma^4 + \lambda_{HS}|H|^2\Sigma^2$$

- ⋆ If the Higgs is also a bulk field, such mixing is unavoidable. We parametrize it by

$$\bar{\lambda} = \frac{\mu_S^2}{k^2}\frac{\lambda_{HS}}{\lambda_S}$$

- ⋆ The coupled system of equations become larger and nastier to solve. We do it perturbatively for a vanishing backreaction and smallish $\bar{\lambda}$

MIXING WITH A BULK HIGGS BOSON

We write the metric as

$$ds^2 = \frac{\epsilon^2}{t^2}\left(\eta_{\mu\nu}dx^\mu dx^\nu - \frac{dt^2}{M_{\rm KK}^2}\right), \quad t \in [0,1], \quad \epsilon = e^{-kr\pi} \sim \mathcal{O}(10^{-16})$$

Due to EWPT, we take $M_{\rm KK} = k\epsilon = 5$ TeV. In the unitary gauge,

$$H(x,t) = \left(0, \frac{t}{\epsilon\sqrt{2r}}\left[\varphi_H(t) + h(x,t)\right]\right)^T, \qquad \Sigma(x,t) = \varphi_S(t) + \frac{t}{\epsilon\sqrt{r}}S(x,t)$$

The equations of motion for the VEVs $\varphi_H(t)$ and $\varphi_S(t)$ are

$$\left[t^2\partial_t^2 - 3t\partial_t + \frac{\mu_S^2}{k^2}\left(1 - v_S^2 - \bar{\lambda}\frac{k^4}{\mu_S^4}\frac{\lambda_S}{r}t^2\frac{\varphi_H^2}{M_{\rm KK}^2}\right)\right]v_S(t) = 0,$$

$$\left[t^2\partial_t^2 + t\partial_t - \beta^2 - \bar{\lambda}v_S^2\right]\frac{\varphi_H(t)}{t} = 0.$$

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MIXING WITH A BULK HIGGS BOSON

The guys with no VEV will have the following KK-decomposition for $\bar{\lambda} = 0$

$$h(x,t) = \sum_{n=0}^{\infty} h_n(x)\chi_n^h(t), \qquad S(x,t) = \sum_{n=1}^{\infty} S_n(x)\chi_n^S(t)$$

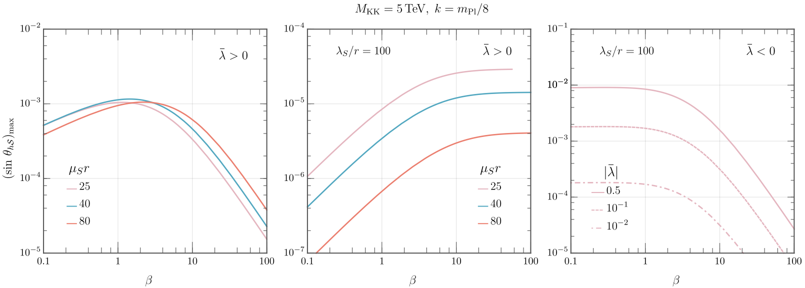
The lightest resonances $h_0(x), h_1(x), S_1(x)$ will mix whenever $\bar{\lambda} \neq 0$, leading to new mass eigenstates $h_{\text{phys}}(x), \mathcal{S}(x), \mathcal{H}(x)$,

$$h_0(x) = h_{\text{phys}}(x) + \sin\theta_{h\mathcal{S}}\, \mathcal{S}(x) + \sin\theta_{h\mathcal{H}}\, \mathcal{H}(x),$$

$$\mathcal{H}(x) = h_1(x) + \mathcal{O}(\bar{\lambda}), \quad \mathcal{S}(x) = S_1(x) + \mathcal{O}(\bar{\lambda})$$

$$\sin\theta_{h\mathcal{S}} = \bar{\lambda}\frac{\kappa_{h_0 S_1}^2}{x_{S_1}^2 - x_{h_0}^2} \approx \bar{\lambda}\frac{\kappa_{h_0 S_1}^2}{x_{S_1}^2} \qquad \sin\theta_{h\mathcal{H}} = \bar{\lambda}\frac{\kappa_{h_0 h_1}^2}{x_{h_1}^2 - x_{h_0}^2} \approx \bar{\lambda}\frac{\kappa_{h_0 h_1}^2}{x_{h_1}^2}$$

MIXING WITH A BULK HIGGS BOSON



$$m_h^2 \approx \left(x_{h_0}^2 + \bar{\lambda}\,\kappa_{h_0}^2\right) M_{\rm KK}^2$$

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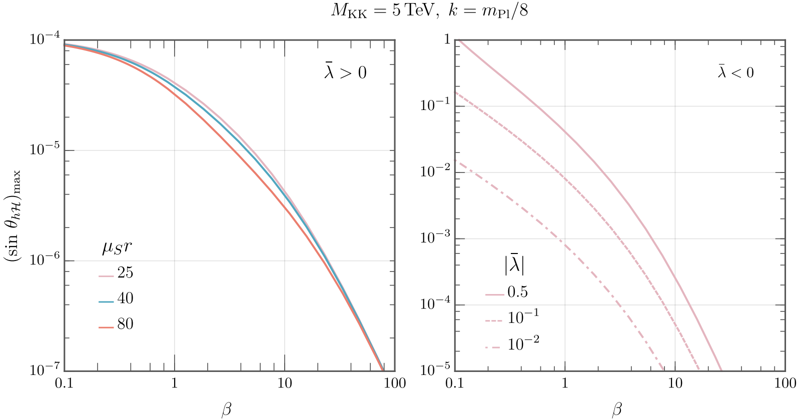
MIXING WITH A BULK HIGGS BOSON



$$m_h^2 \approx \left(x_{h_0}^2 + \bar\lambda\,\kappa_{h_0}^2\right) M_{\rm KK}^2$$

A WINDOW TO DARK FERMIONS

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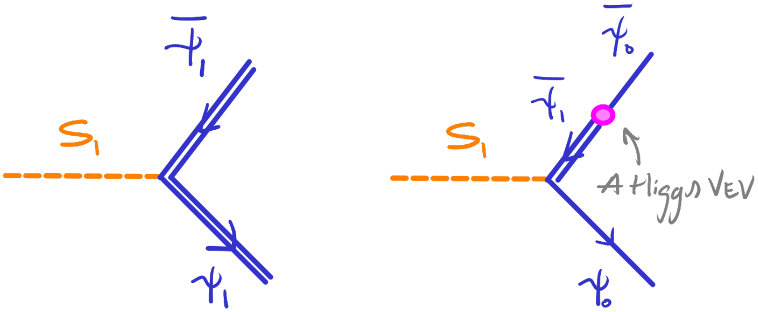
A WINDOW TO DARK FERMIONS

ANY fermion $\psi(x) \subset \Psi(x,t)$ propagating into the bulk of the extra dimension has to interact with $S_1(x) \subset \Sigma(x,t)$,

$$S_{5D} \supset -\int d^5x\sqrt{g}\,\mathcal{Y}\bar{\Psi}(x,t)\Psi(x,t)\Sigma(x,t) \to y_{aA\mathcal{S}}S_1(x)\bar{\psi}(x)\psi^{(\prime)}(x)$$



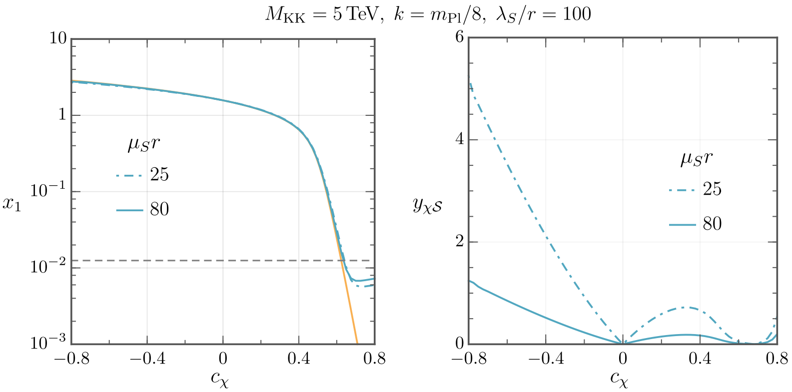
A WINDOW TO DARK FERMIONS

Consider a dark sector composed of N_χ 5D fermions, singlets of the SM

- ⋆ The lightest KK resonance will be stable, even if dark fermions are charged under a dark gauge group
- ⋆ The lightest fermion can be a chiral zero-mode or a massive KK fermion, depending on the boundary conditions
  - A chiral zero-mode will require a dark Higgs
  - A massive KK fermion can be made much lighter than $M_{\rm KK}$
- ⋆ For the sake of concreteness, we chose the second option

A WINDOW TO DARK FERMIONS

The first KK fermion resonance can be very light too Agashe, Servant, '04



Where we have defined $x_1 = m_\chi/M_{\rm KK}$ and $c_\chi = \mathcal{Y}_\chi \sqrt{\frac{6}{\lambda_S}}\mu_S/k$

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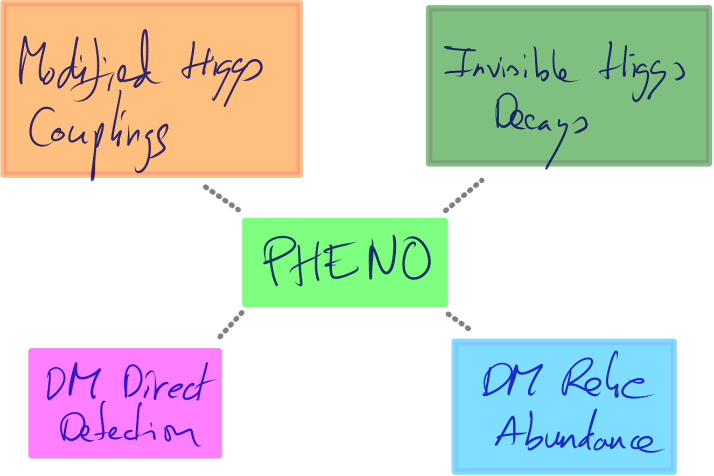
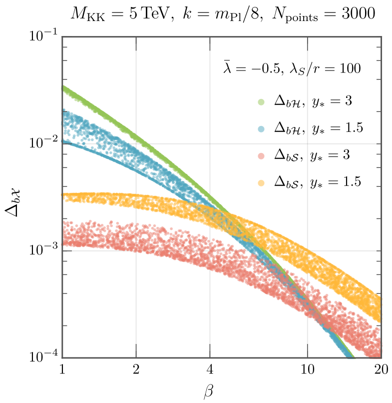
A WINDOW TO DARK FERMIONS



MODIFIED HIGGS COUPLINGS

$$\delta y_{fh}^{\text{phys}} \equiv 1 - \frac{y_{fh}^{\text{phys}}}{y_{fh}^{\text{SM}}} \simeq (1 - \varkappa_f) + \Delta_{f\mathcal{H}} + \Delta_{f\mathcal{S}} \qquad y_* = \frac{\sqrt{k(1+\beta)}}{2+\beta} Y_{5D},$$



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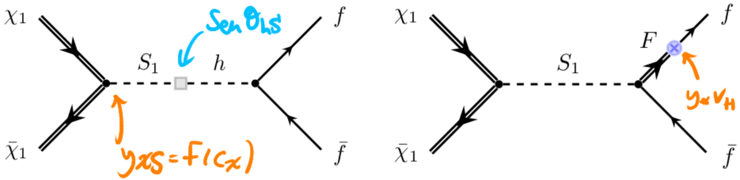
DM COANNIHILATION



- ⋆ The mixing of the Higgs with S_1 is controlled by $\sin\theta_{hS} \lesssim 10^{-3}$
- ⋆ m_χ and $y_{\chi S}$ are both controlled by c_χ, as we have seen before
- ⋆ $y_* = \mathcal{O}(1)$ is related to the 5D Yukawa coupling and controls the localization of the different SM fermions and therefore the mixing between

$$Q_L t_R, \quad q_L T_R, \ \ldots$$

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DM COANNIHILATION

We consider two cases,

- ⋆ the usual freeze-out mechanism

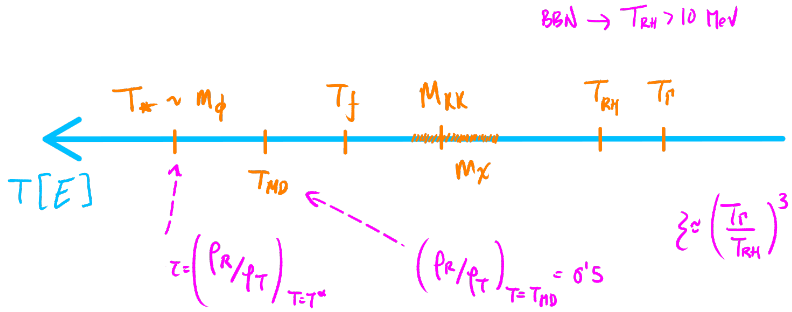
$$\Omega_\chi h^2 \simeq \frac{x_f}{2\sqrt{g_{\star S}(m_\chi/x_f)}} \frac{10^{-9}\text{GeV}^{-2}}{\langle \sigma v \rangle}$$

- ⋆ that DM freeze-out happens during an early period of matter-domination Hamdan, Unwin, '18, which makes

$$H \propto T^{3/2} \quad \text{instead of} \quad H \propto T^2$$

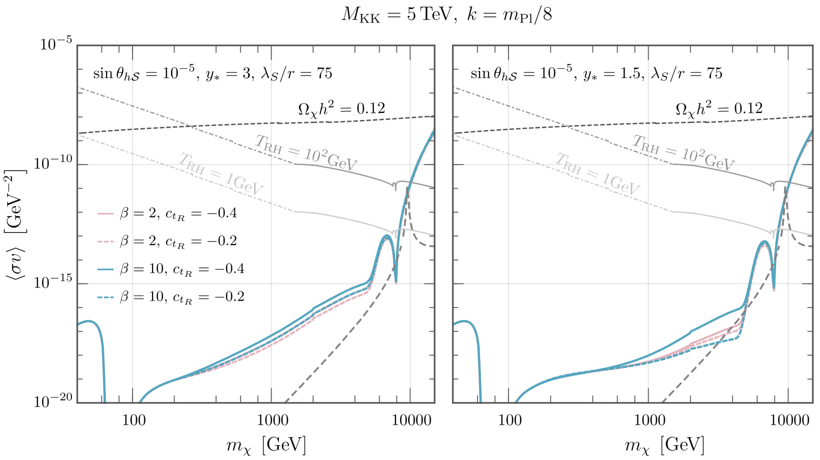
A COSMOLOGICAL SOAP OPERA

We can think of a scalar field ϕ living on the UV brane and relatively long-lived



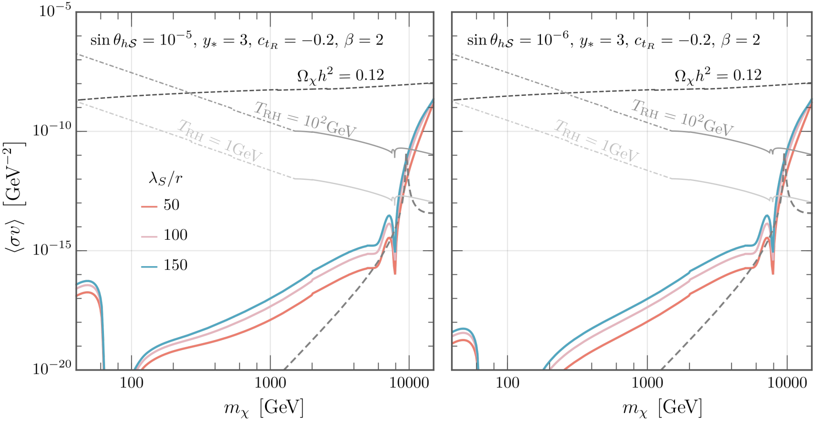
Eventually, in the scenario of matter domination (MD), we are going to have three parameters: T_*, τ and $T_{\rm RH}$

LET US COANNIHILATE



For the MD case, we take $T_\star = 10^5$ GeV and $\tau = 0.99$

LET US COANNIHILATE



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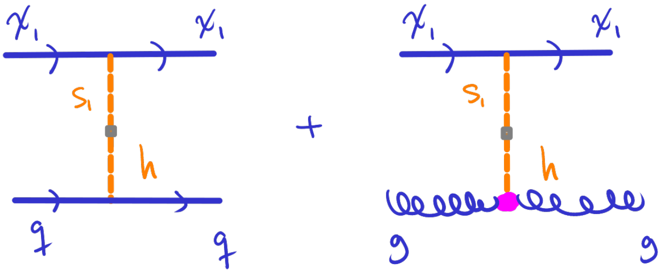
DM DIRECT DETECTION

Since S_1 is very heavy, constraints from DM direct detection come mostly through Higgs exchange



which is controlled by $\sin\theta_{h\mathcal{S}}$. Indeed, the WC for the effective vertex $\bar{q}q\bar{\chi}\chi$ reads

$$\alpha_q = y_{\chi\mathcal{S}} \left\{ \frac{y_{q\mathcal{S}}}{m_{\mathcal{S}}^2} + \frac{y_{qh}\sin\theta_{h\mathcal{S}}}{m_h^2} \right\}$$

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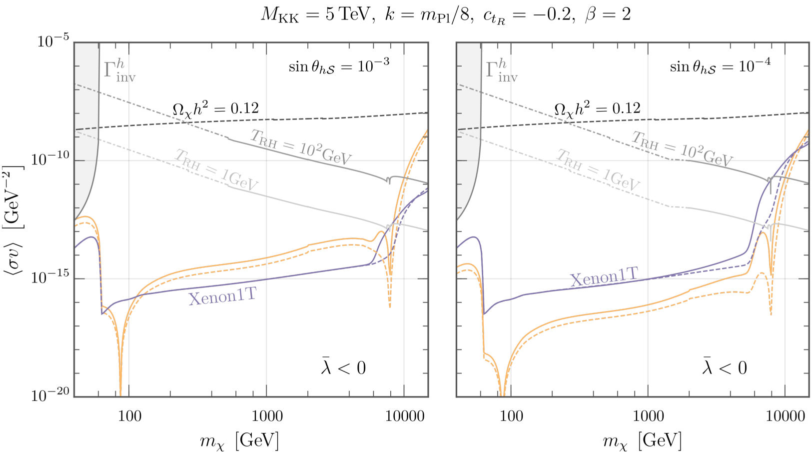
WE NEED TO CHECK ALL THE CONSTRAINTS

We do not have infinite freedom, e.g. ✗ Chorizo, ✗ Huevo, ✗ Piña, . . .

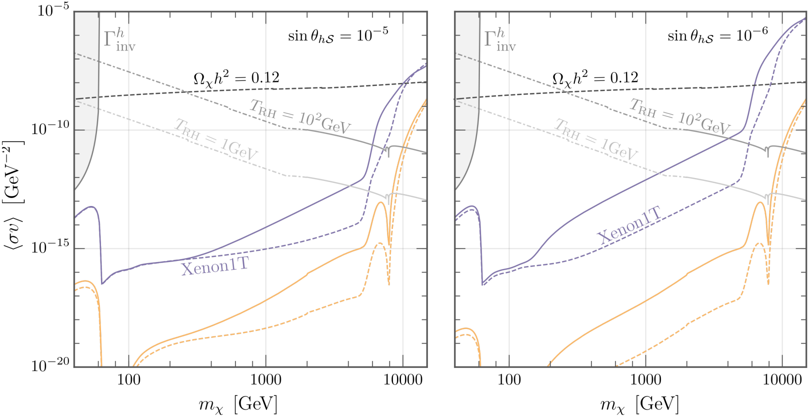
ALL THE STUFF TOGETHER



For the MD case, we take $T_\star = 10^5$ GeV and $\tau = 0.99$

ALL THE STUFF TOGETHER

$M_{\rm KK} = 5\,{\rm TeV},\ k = m_{\rm Pl}/8,\ c_{t_R} = -0.2,\ \beta = 2$



For the MD case, we take $T_\star = 10^5$ GeV and $\tau = 0.99$

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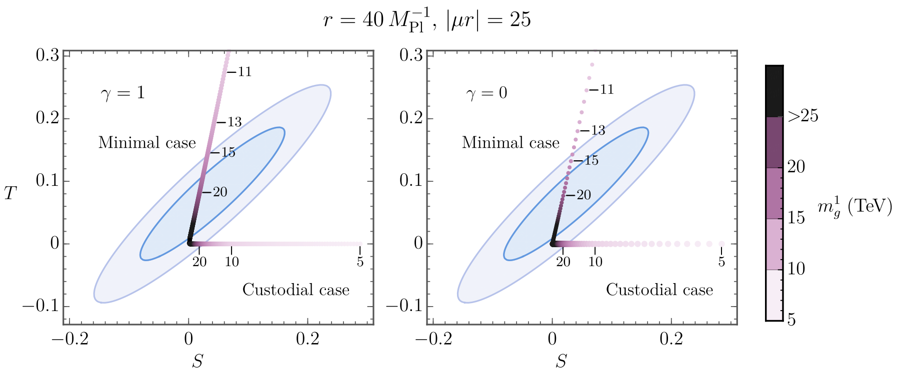
CONCLUSIONS

- ⋆ 5D fermion masses can be obtained dynamically
- ⋆ This require adding a $\mathbb{Z}_2$-odd field $\Sigma(x, \phi)$
- ⋆ Every 5D fermion has to couple to Σ
- ⋆ We have therefore a natural window to any 5D fermion sector
- ⋆ S_1-mediated DM can provide a fraction of the observed relic abundance or all of it, in the case of a MD freeze-out

THANKS!

BACKUP SLIDES

EWPT



γ	m_g^1 (TeV) – minimal	m_g^1 (TeV) – custodial	M_{KK} (TeV) – minimal
1	15.3	17.0	22.8
10^{-1}	14.7	17.0	7.4
10^{-2}	14.6	17.0	6.1
0	14.6	17.0	5.9

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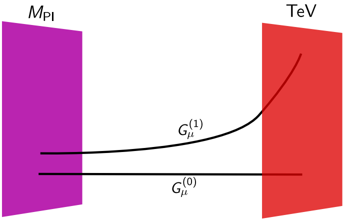
FLAVOR

Different fermion localizations lead to family dependent couplings to massive KK gauge bosons, which are IR localized



$$g_\alpha^{(1)} \approx g_s \left(-\frac{1}{\sqrt{L}} + f_\alpha^2 \gamma(c_\alpha) \right)$$

$$\sqrt{L} = \sqrt{kr\pi} \approx 5 \quad \gamma(c_\alpha) \sim \mathcal{O}(1)$$

For UV localized fermions $\Rightarrow f_\alpha \ll 1 \Rightarrow g_\alpha^{(1)} \approx -0.2 g_s$

RS-GIM Mechanism

Off-diagonal couplings are suppressed by CKM entries and by ratios of mixing and masses. Still, Δm_K and ϵ_K impose some tunning.

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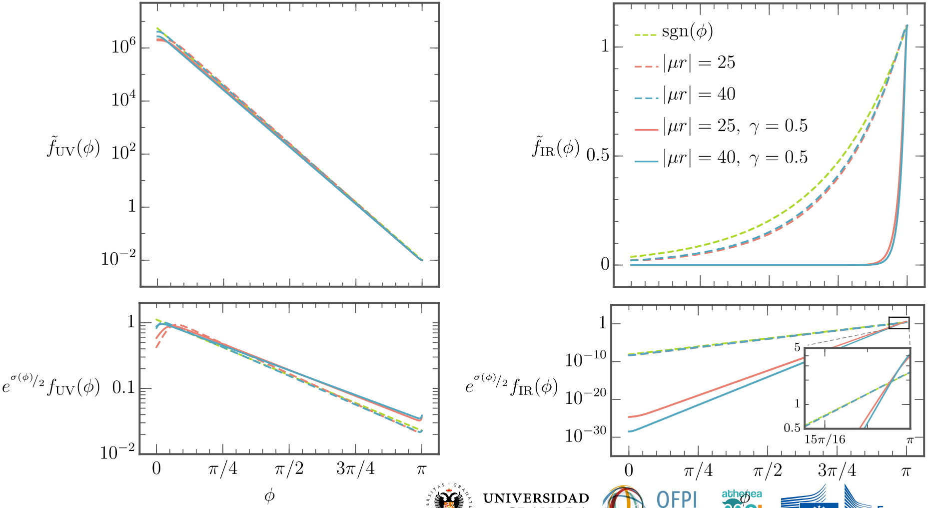
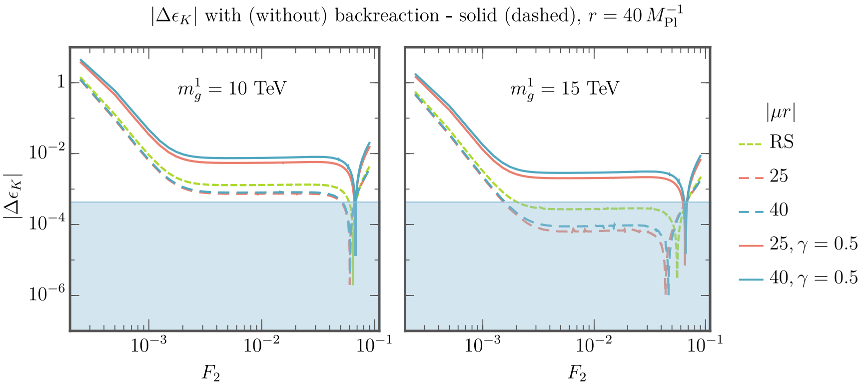
SM masses: $(Y_q^{\text{eff}})_{ij} = F(c_{Q,i})\,(Y_q)_{ij}\,F(c_{q,i})$

$m_g^1 = 10$ TeV, $r = 40\,M_{\text{Pl}}^{-1}$, with (without) backreaction - solid (dashed)



FLAVOR CONSTRAINTS A CASE STUDY

A BENCHMARK POINT



$Q_1^{sd} \propto (\bar{d}_L \gamma^\mu s_L)(\bar{d}_L \gamma_\mu s_L)$

$\widetilde{Q}_1^{sd} \propto (\bar{d}_R \gamma^\mu s_R)(\bar{d}_R \gamma_\mu s_R)$

$Q_4^{sd} \propto (\bar{d}_R s_L)(\bar{d}_L s_R)$

$Q_5^{sd} \propto (\bar{d}_L \gamma^\mu s_L)(\bar{d}_R \gamma_\mu s_R)$

$$\Delta \equiv |\epsilon_K - \epsilon_K^{\rm SM}| \propto \Im \left[C_1 + \tilde{C}_1 + 213 \left(C_4 + \frac{C_5}{N_c} \right) \right]$$

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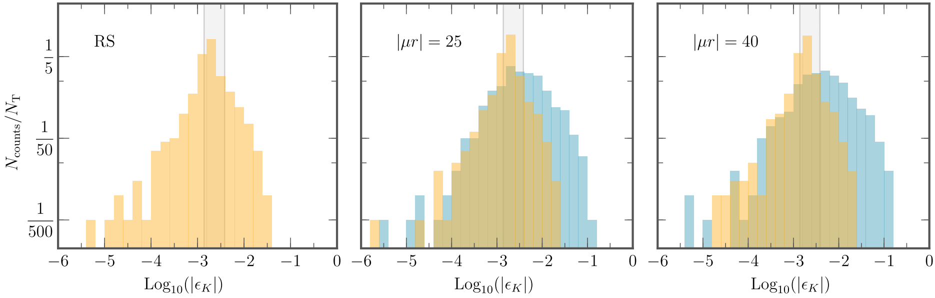
SCANNING OVER YUKAWA MATRICES

$r = 40\,M_{\rm Pl}^{-1}\,, m_g^1 = 15\ \text{TeV}\,, F_2 = 10^{-2}\,,$ with (without) backreaction - blue (yellow)



METRIC SCALAR SYSTEM

Scalar-gravity action ($\kappa^{-2} \equiv 2M_*^3$)

$$S = 2\int d^4x \int_0^\pi d\phi \sqrt{g}\left\{-\frac{\mathcal{R}}{2\kappa^2} + T(\Sigma) - V(\Sigma) - \sum_i \frac{\sqrt{|\hat{g}_i|}}{\sqrt{g}} V_i(\Sigma)\delta(\phi-\phi_i)\right\}$$

Einstein's equation and EOM for ω

$$\mathcal{R}_{MN} - \frac{1}{2} g_{MN}\mathcal{R} = \kappa^2\, T_{MN},$$

$$-\frac{1}{\sqrt{g}}\partial_M\left(\sqrt{g} g^{MN}\partial_N\omega\right) = \frac{\partial V(\omega)}{\partial\omega} + \sum_i \frac{\sqrt{|\hat{g}_i|}}{\sqrt{g}}\frac{\partial V_i(\omega)}{\partial\omega}\delta(\phi-\phi_i),$$

Energy-momentum tensor T_{MN} for ω

$$T_{MN} = \partial_M\omega\partial_N\omega - g_{MN}\left[\frac{1}{2} g^{PQ}\partial_P\omega\partial_Q\omega - V(\omega)\right]$$

$$+\sum_i \frac{\sqrt{|\hat{g}_i|}}{\sqrt{g}} V_i(\omega)\hat{g}^i_{\mu\nu}\delta^\mu_M\delta^\nu_N\delta(\phi-\phi_i)$$

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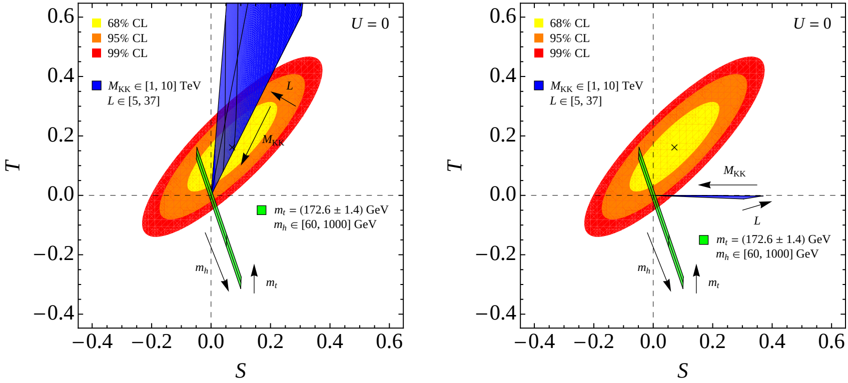
EWPT

$$T = \frac{\pi^2 v_h^2 r^2}{c_W^2} \int_0^\pi d\phi_1 e^{2\sigma(\phi_1)}, \qquad S = 8\pi^2 v_h^2 r^2 \int_0^\pi d\phi_1 e^{2\sigma(\phi_1)} \int_{\phi_1}^\pi d\phi_2$$



Minimal case

Custodial case

M. Neubert et al - [0807.4937]

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KAON MIXING

$$\epsilon_K = \frac{\kappa_\epsilon \, e^{i\phi_\epsilon}}{\sqrt{2}\,(\Delta m_K)_{\text{exp}}} \, \text{Im} \, \langle K^0 | \mathcal{H}_{\text{eff}}^{\Delta S=2} | \bar{K}^0 \rangle$$

- Effective $\Delta S = 2$ Hamiltonian

$$\mathcal{H}_{\text{eff}}^{\Delta S=2} = \sum_{i=1}^{5} C_i Q_i^{sd} + \sum_{i=1}^{3} \widetilde{C}_i \widetilde{Q}_i^{sd}$$

- Relevant operators (at TL in RS)

$$Q_1^{sd} \propto (\bar{d}_L \gamma^\mu s_L)\,(\bar{d}_L \gamma_\mu s_L) \qquad \widetilde{Q}_1^{sd} \propto (\bar{d}_R \gamma^\mu s_R)\,(\bar{d}_R \gamma_\mu s_R)$$

$$Q_4^{sd} \propto (\bar{d}_R s_L)\,(\bar{d}_L s_R)$$

$$Q_5^{sd} \propto (\bar{d}_L \gamma^\mu s_L)\,(\bar{d}_R \gamma_\mu s_R)$$

KAON MIXING

- Effective $\Delta S = 2$ Hamiltonian

$$\mathcal{H}_{\text{eff}}^{\Delta S=2} = \sum_{i=1}^{5} C_i Q_i^{sd} + \sum_{i=1}^{3} \widetilde{C}_i \widetilde{Q}_i^{sd}$$

- Wilson coefficients:

$$C_1^{\text{RS}} \propto \left(\widetilde{\Delta}_D\right)_{12} \otimes \left(\widetilde{\Delta}_D\right)_{12} \qquad \tilde{C}_1^{\text{RS}} \propto \left(\widetilde{\Delta}_d\right)_{12} \otimes \left(\widetilde{\Delta}_d\right)_{12}$$

$$C_4^{\text{RS}} \propto \left(\widetilde{\Delta}_D\right)_{12} \otimes \left(\widetilde{\Delta}_d\right)_{12}$$

$$C_5^{\text{RS}} \propto \left(\widetilde{\Delta}_D\right)_{12} \otimes \left(\widetilde{\Delta}_d\right)_{12}$$

$$\left(\widetilde{\Delta}_F\right)_{mn} \otimes \left(\widetilde{\Delta}_{f'}\right)_{m'n'} \propto \int_0^{\pi} d\phi \int_0^{\pi} d\phi' \, e^{\sigma(\phi)} \, e^{\sigma(\phi')} D(\phi, \phi') \times \left[\mathrm{C}_m^{(F)}(\phi) \, \mathrm{C}_n^{(F)}(\phi)\right] \times \left[\mathrm{C}_{m'}^{(f')}(\phi') \, \mathrm{C}_{n'}^{(f')}(\phi')\right],$$