Theoretical Models for Dark Matter

Based on: 1612.03475

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Outline

1. DM models: from EFT to Simplified Models
   - Effective Field theories (EFT)
   - Simplified Models
   - Simplified Models: consistency
2. Gauge Invariance for spin 0 models
   - Minimal case: 1 higgs doublet
   - Next-to-Minimal case: 2 higgs doublets
   - Collider signatures
3. Summary
   - Conclusions

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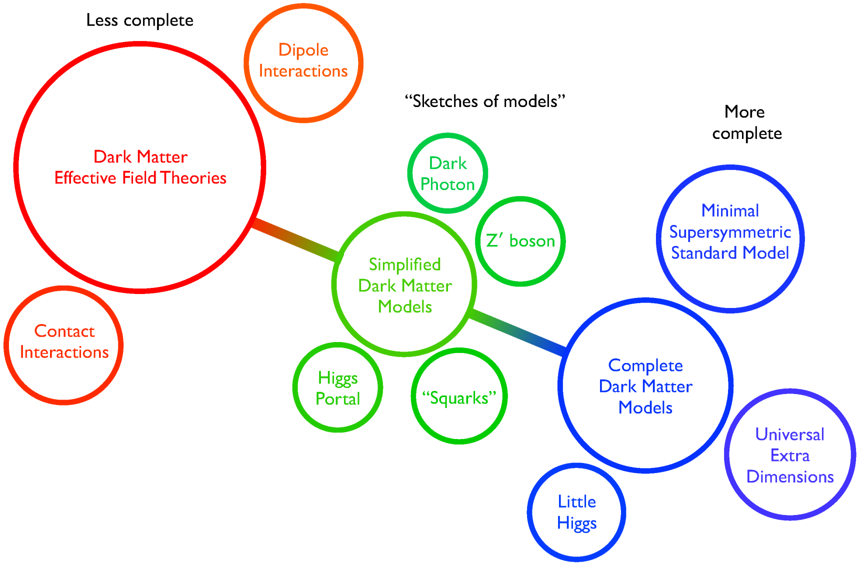

Less complete
Dipole Interactions
Dark Matter Effective Field Theories
Contact Interactions
"Sketches of models"
Dark Photon
Z′ boson
Simplified Dark Matter Models
Higgs Portal
"Squarks"
More complete
Minimal Supersymmetric Standard Model
Complete Dark Matter Models
Universal Extra Dimensions
Little Higgs

DM models: from EFT to Simplified Models

Effective Field theories (EFT)

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\ \bar{q}q$	m_q/Λ^3
D2	$\bar{\chi}\gamma^5\chi\ \bar{q}q$	im_q/Λ^3
D3	$\bar{\chi}\chi\ \bar{q}\gamma^5 q$	im_q/Λ^3
D4	$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	m_q/Λ^3
D5	$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu q$	$1/\Lambda^2$
D6	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu q$	$1/\Lambda^2$
D7	$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu\gamma^5 q$	$1/\Lambda^2$
D8	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu\gamma^5 q$	$1/\Lambda^2$
D9	$\bar{\chi}\sigma_{\mu\nu}\chi\ \bar{q}\sigma^{\mu\nu} q$	$1/\Lambda^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\ \bar{q}\sigma^{\mu\nu} q$	i/Λ^2
D11	$\bar{\chi}\chi\ G^{\mu\nu}G_{\mu\nu}$	$\alpha_s/4\Lambda^3$
D12	$\bar{\chi}\gamma^5\chi\ G^{\mu\nu}G_{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D13	$\bar{\chi}\chi\ G^{\mu\nu}\tilde{G}_{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D14	$\bar{\chi}\gamma^5\chi\ G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\alpha_s/4\Lambda^3$

- Only 2 parameters: Λ, m_χ
- Signal scales with Λ:

$$N_{events} = \mathcal{L}_{int}\frac{f(m_\chi)}{\Lambda^{2(d-4)}}$$

- Optimal choice for DD searches

Validity Condition

$$Q_{\rm tr}^2 < M^2 = g_\chi g_q \Lambda^2$$

To ensure EFT validity at LHC, we can throw away events with $Q_{\rm tr}^2 > M^2$ produced by your event generator (Truncation) [1307.2253, 1402.1275, 1405.3101]

Issues

- Validity problems at LHC
- Validity conditions weakens exclusion regions and discovery potential

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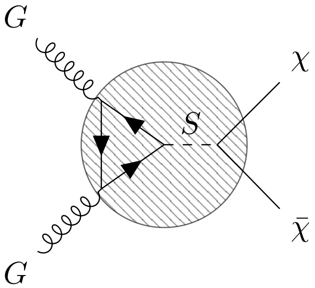
- Underlying idea: only one mediator of a given UV model plays an important role in DM phenomenology
- Approximate phenomenology given by model with 1 mediator + DM particle

$$\begin{aligned}
\mathcal{L}_{\mathrm{S(SS)}} &= \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}M_{\mathrm{med}}^2 S^2 - y_\chi S \bar{\chi}\chi - g_{u,d}\frac{m_i}{v} S \bar{q}_i q_i + \mathrm{h.c.} \\
\mathcal{L}_{\mathrm{P(PP)}} &= \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}M_{\mathrm{med}}^2 S^2 - y_\chi S \bar{\chi}\gamma_5\chi - g_{u,d}\frac{m_i}{v} S \bar{q}_i \gamma_5 q_i + \mathrm{h.c.} \\
\mathcal{L}_{\mathrm{V(VV)}} &= -\frac{1}{4}F_V^{\mu\nu} F_{V,\mu\nu} + \frac{1}{2}M_{\mathrm{med}}^2 V_\mu V^\mu - g_\chi V_\mu \bar{\chi}\gamma^\mu\chi - g_q V_\mu \bar{q}_i \gamma^\mu q_i \\
\mathcal{L}_{\mathrm{A(AA)}} &= -\frac{1}{4}F_V^{\mu\nu} F_{V,\mu\nu} + \frac{1}{2}M_{\mathrm{med}}^2 V_\mu V^\mu - g_\chi V_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q V_\mu \bar{q}_i \gamma^\mu \gamma_5 q_i
\end{aligned}$$

Name	Operator	Model
D1	$\bar{\chi}\chi\ \bar{q}q$	$S(SS)$
D4	$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	$P(PP)$
D5	$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu q$	$V(VV)$
D8	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu\gamma^5 q$	$A(AA)$
D11	$\bar{\chi}\chi\ G^{\mu\nu}G_{\mu\nu}$	$S(SS)$



- Simplest UV-safe models that yield EFT dim-6 operators
- Replace contact interactions with propagating degrees of freedom
- Scalar (and pseudoscalar) also introduce dim-7 operator with gluons through top loop
- D2,D3,D6,D7 can also be reproduced, by changing the coupling structure
- All other EFT dim-6 and 7 operators arise at loop level in such models

Outline

- A full UV consistent theory, features: only renormalizable interactions, gauge invariance $\longleftrightarrow$ renormalizable theory, anomaly-free
  - ✓ Only renormalizable interactions
  - ✓ Anomalies are neglected and the particles to fix them are supposed not to play an important role
  - ✗ Simplified models listed before are not (all) gauge invariant
- Models are invariant only under $SU(3)_c \times U(1)_{em}$, but not under $SU(2)_L \times U(1)_Y$, neither under $U(1)_{dark}$ in V, A models
  - Spin 1 models have a massive gauge boson whose mass term is not G.I.
  - Spin 0 models have $\bar{q}q$ terms that are not G.I.

DM models: from EFT to Simplified Models

Simplified Models: consistency spin 1

- Pure Vector can acquire mass with Stuckelberg mechanism, no higgs required
- Presence of any new axial coupling implies requirement for new higgs
- New higgs ϕ will in general mix with SM higgs Φ via $\Phi^\dagger\Phi\phi^\dagger\phi$
- Axial couplings for SM particles require SM higgs charge under new $U(1)$, resulting in $Z - Z'$ mixing

Model	Gauge Invariant	Dark Higgs	$h - h'$	$Z - Z'$	Mediators
VV	Yes	No	No	No	1
VA	No	Yes	Yes	No	1-3
AV	No	Yes	Yes	Yes	2-4
AA	No	Yes	Yes	Yes	2-4

1510.02110

DM models: from EFT to Simplified Models

Simplified Models: consistency spin 0

- Dark matter (singlet) can only couple to a singlet scalar S
- SM fermions can only couple to scalars that have the same quantum numbers of an higgs doublet
- A new singlet scalar S can acquire a coupling only by mixing with the scalar inside the doublet
- Minimal choice: only one higgs doublet $\rightarrow S - h$ mixing
- Next to minimal choice: 2HDM $\rightarrow S - H$ mixing

Model	G. Inv.	Dark Singlet	Doublets	$S - h$	$S - H$	Mediators
SS	No	Yes	1	Yes	-	2
SP	No	Yes	1	Yes	-	2
SS	No	Yes	2	No*	Yes	2*
SP	No	Yes	2	No*	Yes	2*
PS	No	Yes	2	No*	Yes	2*
PP	No	Yes	2	No*	Yes	2*

Outline

Gauge Invariance for scalar models

Minimal case: 1 higgs doublet

$$\mathcal{L}_{new} = \frac{1}{2}\partial^\mu S \partial_\mu S + \frac{1}{2}M_{SS}^2 S^2 - \frac{1}{2}\lambda_{HS}\phi^\dagger\phi S^2 - \frac{1}{4!}\lambda_S S^4 - y_{DM} S\bar{\chi}\chi$$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\epsilon & -\sin\epsilon \\ \sin\epsilon & \cos\epsilon \end{pmatrix} \begin{pmatrix} \phi^0 - \langle\phi^0\rangle \\ S - \langle S\rangle \end{pmatrix}$$

$$\mathcal{L}_{int} = -y_i \bar{Q}_L^i u_R^i \widetilde{\phi} = -m_i \bar{u}_L^i u_R^i (1 + \cos\epsilon\frac{h}{v} - \sin\epsilon\frac{s}{v})$$

Also the higgs now couples to DM:

$$-y_{DM} S\bar{\chi}\chi \to -y_{DM}\left(\sin\epsilon h + \cos\epsilon s\right)\bar{\chi}\chi$$

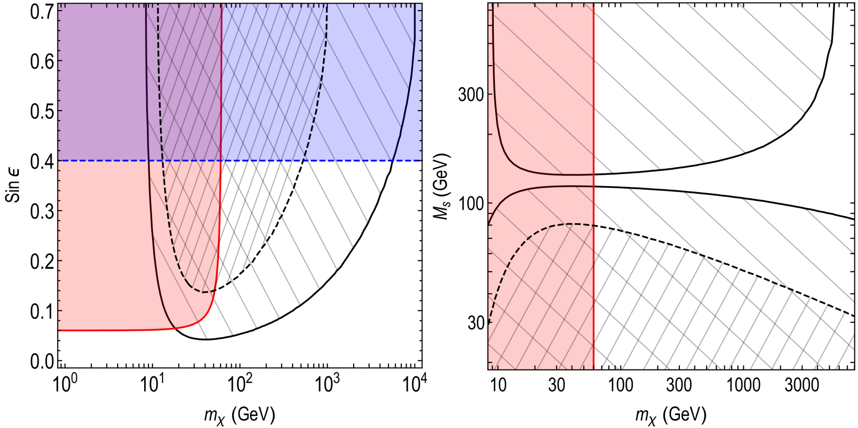
Both mediators therefore contribute to all cross sections:

$$\sigma_{\bar{q}q\to\bar{\chi}\chi+X} \propto (y_\chi y_q \sin\epsilon\cos\epsilon)^2 \left(\frac{1}{Q^2 - M_h^2} - \frac{1}{Q^2 - M_s^2}\right)^2$$

The mixing requires also the Higgs to couple to DM, and the product of the couplings for h and s is equal and opposite

Gauge Invariance for scalar models

Minimal case: 1 higgs doublet



Interference between the two mediators

Gauge Invariance for scalar models

Minimal case: 1 higgs doublet

- Higgs couples to DM
- Stringent DD constraints on ϵ, even $M_s \to \infty$ (but not for $M_s \sim M_h$)
- DD blind window at $M_s \sim M_h$ [1509.05771]
- Bounds on h invisible give stringent constraints for $m_\chi \lesssim M_h/2$
- Coupling to leptons arises as well
- Small couplings to fermions, $\sim y_f \sin\epsilon \lesssim 0.4 y_f$

Outline

Gauge Invariance for scalar models

Next-to-Minimal case: 2 higgs doublets

Alignment limit: $M_{i,j} = \begin{pmatrix} M^{\rho}_{hh} & 0 & 0 \\ 0 & M^{\rho}_{HH} & M^{\rho}_{HS} \\ 0 & M^{\rho}_{HS} & M^{\rho}_{SS} \end{pmatrix}$

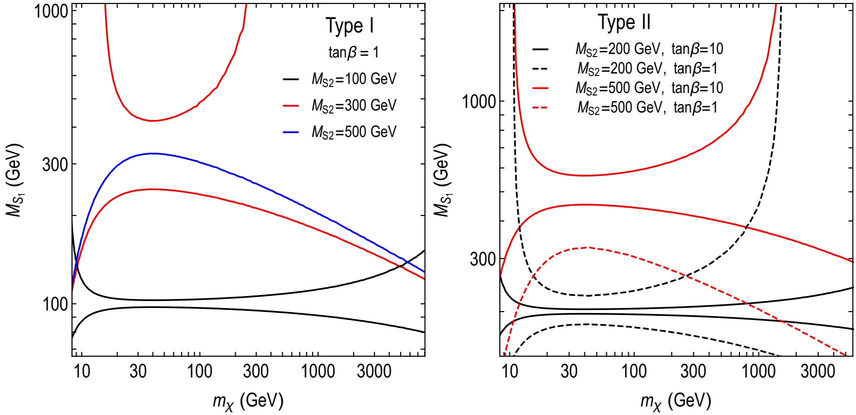
$$\mathcal{L}_{new} = -y_{DM}(\cos\theta S_2 + \sin\theta S_1)\bar{\chi}\chi - \frac{y_f \xi^f}{\sqrt{2}}(\cos\theta S_1 - \sin\theta S_2)\bar{f} f$$

	Type I	Type II
ξ^u	$\cot\beta$	$\cot\beta$
ξ^d	$\cot\beta$	$-\tan\beta$
ξ^ℓ	$\cot\beta$	$-\tan\beta$

- Type II can allow an enhanced coupling to down quarks, for large values of $\tan\beta$
- u, d quarks have same-sign couplings in Type I and opposite sign couplings in Type II

Gauge Invariance for scalar models

Next-to-Minimal case: 2 higgs doublets



Not only interference between the two mediators, but also interference between different flavours (Type II)

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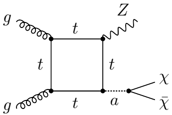
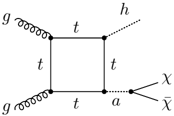
Gauge Invariance for scalar models

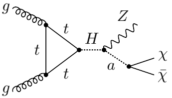
Collider signatures

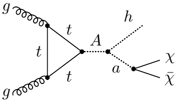
- Gen I models were all very similar and had similar signatures, i.e. mono-X from ISR (spin-1) and loop (spin-0)
- This difference was arising because of the structure of the couplings for spin 0/1

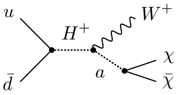




- G. inv. models with multiple mediators have additional differentiation. For scalar models, tighter connection with higgs sector and EW interactions mean additional sources of Mono-$Z/W/h$







Outline

- Construction of simple models valid at LHC and describing the relevant phenomenology
- EFT to simplified models is a first step in this direction
- First generation of SM not gauge invariant
- Gauge invariance implies multiple portals
- DD: presence of blind spots and negative interference effects
- LHC: more differentiation between spin 0 and spin 1
    - Enhanced mono-$W/Z/h$ signals for spin-0

Backup Slides

Just one additional scalar coupled with generic couplings $g_q y_i$, y_χ

$$\mathcal{L}_{new} = \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}M^2 S^2 - \frac{g_q}{\sqrt{2}} S \sum_q y_i \bar{q}_i q_i - y_{DM} S \bar{\chi}\chi$$

The interaction term of S with quarks is not gauge invariant, as

$$\bar{q}_i q_i = \bar{q}^i_L q^i_R + \bar{q}^i_R q^i_L$$

is not SM singlet

Assumptions

- S is a scalar, and is a portal to DM
- χ is a SM singlet
- S is exchanged in the s-channel
- Structure of SM yukawa lagrangian is not modified
- There is only one Higgs doublet

Implications

- S is a SM singlet
- S has to mix with SM higgs, as a quark scalar bilinear can only couple to a particle that has the same quantum numbers as an Higgs doublet

Backup Slides

A possible Gauge invariant version

A Gauge invariant version of this model could be obtained by the following lagrangian (Z_2 on S)

$$\mathcal{L}_{new} = \frac{1}{2}\partial^\mu S \partial_\mu S + \frac{1}{2}M_{SS}^2 S^2 - \frac{1}{2}\lambda_{HS}\phi^\dagger\phi S^2 - \frac{1}{4!}\lambda_S S^4 - y_{DM} S \bar{\chi}\chi$$

EW symmetry breaking mixes the SM higgs with the new scalar

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\epsilon & -\sin\epsilon \\ \sin\epsilon & \cos\epsilon \end{pmatrix} \begin{pmatrix} \phi^0 - \langle\phi^0\rangle \\ S - \langle S \rangle \end{pmatrix}$$

The mixing angle ϵ has to be small, so that higgs and EW phenomenology does not get affected much (all SM signal strengths involving the higgs get a $\cos^2\epsilon$ factor)

Consequently, $\cos\epsilon \sim 1$, $\sin\epsilon < 0.4$

Backup Slides

A possible Gauge invariant version

The $h - s$ mixing gives s a coupling to Standard Model fermions:

$$\mathcal{L}_{int} = -y_i \bar{Q}^i_L u^i_R \widetilde{\phi} = -m_i \bar{u}^i_L u^i_R (1 + \cos\epsilon \frac{h}{v} - \sin\epsilon \frac{s}{v})$$

The coupling of s to quarks is indeed proportional to yukawas

$$g_q \equiv -\sin\epsilon$$

Also the higgs now couples to DM:

$$-y_{DM} S \bar{\chi}\chi \to -y_{DM} \left(\sin\epsilon h + \cos\epsilon s\right) \bar{\chi}\chi$$

Both mediators therefore contribute to all cross sections:

$$\sigma_{\bar{q}q \to \bar{\chi}\chi + X} \propto (y_\chi y_q \sin\epsilon \cos\epsilon)^2 \left(\frac{1}{s - M_h^2} - \frac{1}{s - M_s^2}\right)^2$$

The mixing requires also the Higgs to couple to DM, and the product of the couplings for h and s is equal and opposite

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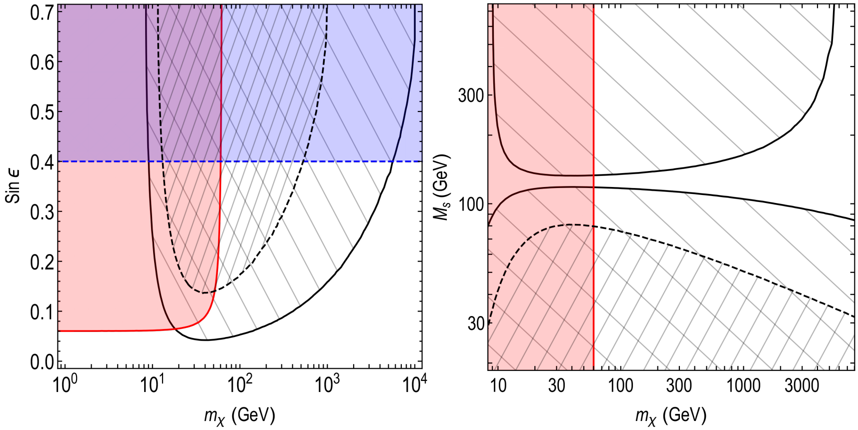
Direct Detection Constraints



- $g_q = \sin\epsilon \leq 1$ means low to moderate sensitivity
- Higgs couples to DM
- Stringent DD constraints on ϵ, even $M_s \to \infty$ (but not for $M_s \sim M_h$)
- DD blind window at $M_s \sim M_h$ [1509.05771]
- Too weak signal at LHC unless at least one of the 2 mediators can go on shell
- Bounds on h invisible give stringent constraints for $m_\chi \lesssim M_h/2$
- Coupling to leptons arises as well!
- VBF operator arises

$$L_{int,VBF} = -\sin\epsilon\left(2\frac{M_W^2}{v}W_\mu^+W^{-\mu} + \frac{M_z^2}{v}Z_\mu Z^\mu\right)s$$

- Conclusions of the previous slides are quite general
  - A more complex scalar sector would still lead to similar conclusions
- To get more freedom with couplings to quarks, the only way is to add an additional Higgs doublet
- New Lagrangian will contain the singlet S as well, for a total of 3 scalars

$$
\begin{aligned}
V(\Phi_1, \Phi_2, S) &= M_{11}^2 \Phi_1^\dagger \Phi_1 + M_{22}^2 \Phi_2^\dagger \Phi_2 + (M_{12}^2 \Phi_2^\dagger \Phi_1 + h.c.) \\
&+ \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\
&+ \lambda_4 (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \frac{1}{2}\left(\lambda_5 (\Phi_2^\dagger \Phi_1)^2 + h.c.\right), \\
&+ \frac{1}{2} M_{SS}^2 S^2 + \frac{1}{3}\mu_S S^3 + \frac{1}{4}\lambda_S S^4 \\
&+ \frac{\lambda_{11S}}{2}(\Phi_1^\dagger \Phi_1) S^2 + \frac{\lambda_{22S}}{2}(\Phi_2^\dagger \Phi_2) S^2 + \frac{1}{2}(\lambda_{12S} \Phi_2^\dagger \Phi_1 S^2 + h.c.)
\end{aligned}
$$

- The 3 scalars will in general mix with arbitrary mixing angles
  - There is always a region of the parameter space where one can decouple the first doublet and make it SM-like $\cos(\beta-\alpha)=0$
  - This region may rise up naturally in presence of some symmetries of the full UV model
  - In that case S mixes only with the scalar of the second doublet, and there is no constraints on the mixing angle
  - SM phenomenology doesn't get affected in this limit, and no VBF operator arises

- In 2HDM, natural alignment arises in presence of the symmetry
$$\lambda_1 = \lambda_2 = \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_5\right)$$
- Under such symmetry, rotating the doublets of an angle β leave the couplings $\lambda_{1,\ldots,5}$ invariant
- Rotating in the higgs basis, where $\langle\Phi_1\rangle = \left(\begin{array}{c} 0 \\ \frac{v}{\sqrt{2}} \end{array}\right)$ and $\langle\Phi_2\rangle = \left(\begin{array}{c} 0 \\ 0 \end{array}\right)$ one gets the mass matrix

$$M^\rho = \left(\begin{array}{ccc} M^\rho_{hh} & 0 & M^\rho_{hS} \\ 0 & M^\rho_{HH} & M^\rho_{HS} \\ M^\rho_{hS} & M^\rho_{HS} & M^\rho_{SS} \end{array}\right) \quad (1)$$

- To avoid the SM higgs to mix with the singlet state, one needs to require that in the new basis $\lambda_{11S} = 0$

In the alignment limit ($\beta - \alpha = \pi/2$), ones gets (neglecting scalar interactions))

$$\begin{aligned} L &= L_{SM} + \frac{1}{2}\partial^\mu S_i \partial_\mu S_i - \frac{1}{2}M_i^2 S_i^2 (i = 1, 2) + \bar{\chi}(i\not{\partial} - m_\chi)\chi \\ &- y_{DM}(\cos\theta S_2 + \sin\theta S_1)\bar{\chi}\chi - \frac{y_f \xi^f}{\sqrt{2}}(\cos\theta S_1 - \sin\theta S_2)\bar{f} f \end{aligned}$$

	Type I	Type II
ξ^u	$\cot\beta$	$\cot\beta$
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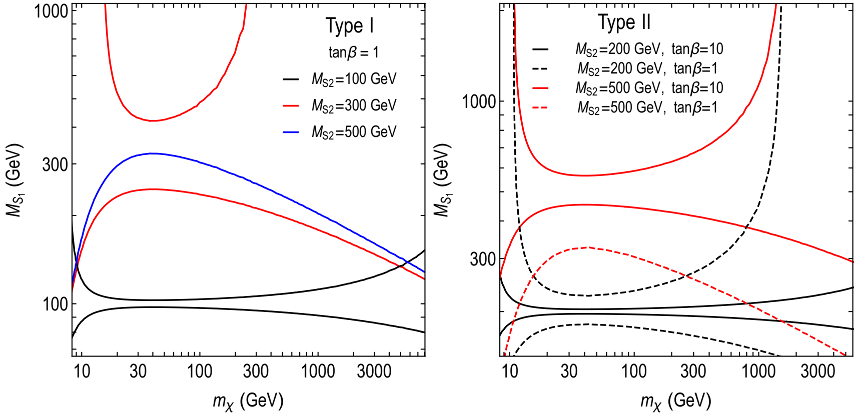
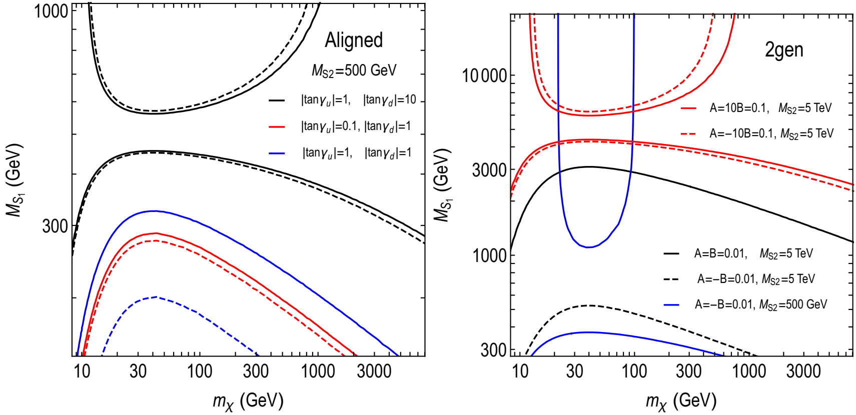


Not only interference between the 2 mediators, but also interference between different flavours (Type II)

- The most general case is Type III
  - In this case, FCNC generally appear at tree level
- To get rid of them at tree level, one needs flavour-diagonal couplings (in mass eigenstates basis)
- In absence of symmetry, loop level FCNC will appear
- Examples of Yukawa patterns that are ”protected” against loop level FNCN:
  - Aligned yukawas: $y_H^U = \tan\gamma_u y_h^U, y_H^D = \tan\gamma_d y_h^D, y_H^l = \tan\gamma_l y_h^l$
  - Coupling only to first 2 generations: $y_H^{u,c} = A, y_H^{d,s} = B, y_H^{b,t,l} = 0$



Interference between flavours only happens for a certain ratio between the yukawa couplings

Model	Singlet	Type I	Type II	Type III
2 Mediators	Yes	Yes	Yes	Yes
MAX g_q	$\lesssim 0.4$	$\mathcal{O}(1)$	$q_u \sim \mathcal{O}(1)$ $g_d \sim \mathcal{O}(\frac{m_t}{m_b})$	$\mathcal{O}(\frac{m_t}{m_q})$
VBF	Yes	No	No	No
SM constr.	Yes	No	No	No
Num. Par.	$4(+1\Gamma)$	$6(+2\Gamma)$	$6(+2\Gamma)$	$14(+2\Gamma)$
NFC	N/D	Yes	Yes	No
MFV	Yes	Yes	Yes	Yes
Flavour constr.	No	Moderate	Moderate	Depends