Flavor and Dark Matter from the Electroweak Scale

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[Work in progress]

Flavour and Dark Matter 2018
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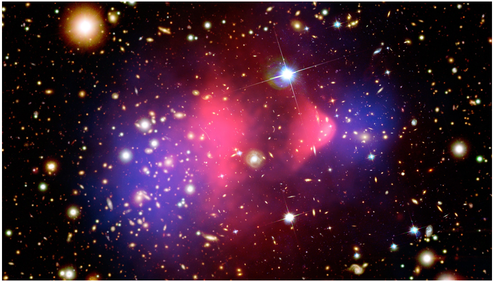
Max-Planck-Institut für Kernphysik Heidelberg

Universität Heidelberg
Zukunft seit 1386

International Max Planck Research School for Precision Tests of Fundamental Symmetries

Dark Matter Puzzle

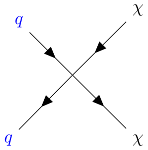


- Proposed solutions on many scales
- Axions to BHs
- EW scale: WIMPs
- Flavored Dark Sector
  1501.07268, 1405.6709, 1803.08080, ...
- Exact Scale not fixed

Collider Searches

WIMPs and Flavored Dark Matter testable @LHC

$$\mathcal{L}_{\mathsf{EFT}} = \frac{1}{\Lambda^2}\,\bar{q}\gamma_5 q\bar{\chi}\gamma_5\chi$$



$$p^2 \ll \Lambda^2$$

Break down @LHC
→ Restore Mediator

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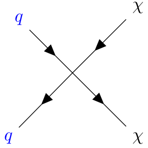
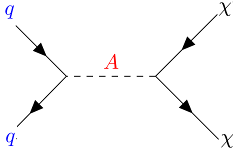


$$p^2 \ll \Lambda^2$$

Break down @LHC
→ Restore Mediator

$$\mathcal{L}_{\mathsf{simp}} = g_q A \bar{q}_L \gamma_5 q_R + g_\chi A \bar{\chi}_L \gamma_5 \chi_R$$



$$\propto \frac{g_q g_\chi}{p^2 - M^2}$$

Not gauge invariant
→ Unitarity Violation
→ Gauge invariant models

Flavor Hierarchy Problem

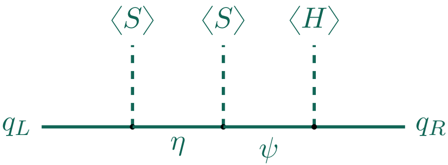
Explanation by Froggatt-Nielsen '79 :

→ Fermions charged under spontaneously broken $U_F(1)$

→ Effective Yukawa couplings

→ number of flavon insertions due to charges → Hierarchy

$$\mathcal{O} = y \left(\frac{S}{\Lambda}\right)^n \bar{Q} H q_R$$



Flavor Hierarchy Problem

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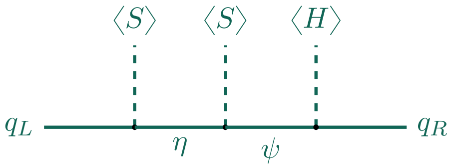
$$\mathcal{O} = y\left(\frac{S}{\Lambda}\right)^n \bar{Q}Hq_R \;\rightarrow\; y\left(\frac{\langle S\rangle}{\Lambda}\right)^n \bar{Q}Hq_R$$

Scale of $\langle S\rangle$ and Λ not determined!



Flavon at the Electroweak Scale

Babu-Nandi and Giudice-Lebedev 9907213, 0804.1753

$$\frac{S}{\Lambda} \rightarrow \frac{H^\dagger H}{\Lambda^2} \rightarrow \frac{v^2}{\Lambda^2}$$

Problems:

- Singlet under all gauge groups
  $\rightarrow$ Number of insertions n arbitrary
- Implies $g_{h\bar{b}b} = 3g^{\text{SM}}_{h\bar{b}b}$
  $\rightarrow$ Excluded by Higgs measurements

Flavor from the Electroweak Scale

Use 2nd Higgs Doublet 1506.01719, 1512.03458

$$\frac{S}{\Lambda} \rightarrow \frac{H_u H_d}{\Lambda^2} \rightarrow \frac{v_u v_d}{2\Lambda^2}$$

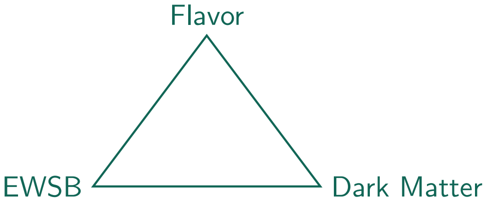
$$\tan\beta = \frac{v_u}{v_d}$$

$$\frac{v_u v_d}{2\Lambda^2} = \epsilon \approx \frac{m_b}{m_t} \quad \rightarrow \quad \Lambda \approx 1.5\ \text{TeV} \sqrt{\frac{\tan\beta}{1+\tan^2\beta}}$$

Advantages:

- Valid, predictable and testable model
- Connects flavor and the EW scale

This Work

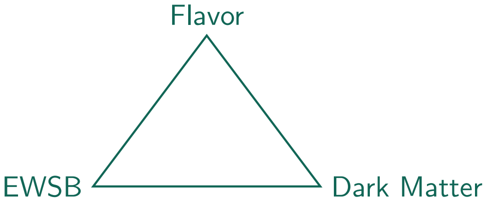


3 Phenomena: Dark Matter - Flavor - EWSB

→ 3 Possible Scales

What if all this happens at one scale?

This Work



3 Phenomena: Dark Matter - Flavor - EWSB

→ 3 Possible Scales

What if all this happens at one scale?

Very predictive model with interesting Pheno for Flavor, Collider and Dark Matter searches!

Model

Based on Two-Higgs-Doublet model (here Type II)

$$\mathcal{L} = y^u_{ij} \left(\frac{H_u H_d}{\Lambda^2}\right)^{a_i - a_{u_j} - a_{H_u}} \bar{Q}_i \, H_u \, u_{R_j}$$
$$+ \; y^d_{ij} \left(\frac{H_u H_d}{\Lambda^2}\right)^{a_i - a_{d_j} - a_{H_d}} \bar{Q}_i \, H_d \, d_{R_j}$$
$$+ \; c_\chi \frac{H_u^\dagger H_d}{\Lambda} \bar{\chi}\chi \; + \; c_5 \frac{H_u^\dagger H_d}{\Lambda} \bar{\chi}\gamma_5\chi \; + \; h.c.$$

Free (physical) Parameters:

$$M_A,\; M_H,\; M_{H^\pm},\; \tan\beta,\; \cos(\beta - \alpha),\; c_\chi,\; c_5,\; m_\chi$$

$$y^{u,d}_{ij} \in \mathcal{O}(1)$$

Higgs Couplings

$$g_{hff} = \kappa_f \, g_{hff}^{\text{SM}}$$
$$g_{hVV} = \kappa_V \, g_{hVV}^{\text{SM}}$$

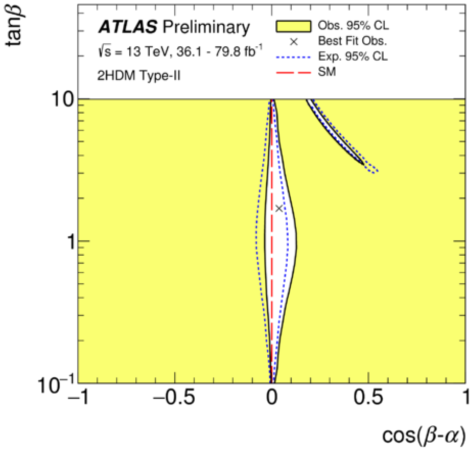
Here: Production as in 2HDMs

$$\kappa_t = \frac{\cos\alpha}{\sin\beta}$$
$$\kappa_V = \sin(\beta - \alpha)$$

But:

$$\kappa_b = \left(2\frac{\sin\alpha}{\cos\beta} - \frac{\cos\alpha}{\sin\beta}\right)$$

→ Decay widths change!

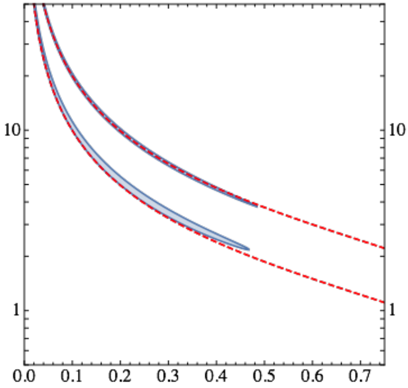


ATLAS-CONF-2018-31

Higgs Signal Strength Fit

$$\mu_X = \frac{\sigma_{\text{prod}}}{\sigma^{\text{SM}}_{\text{prod}}} \frac{\Gamma_{h\to X}}{\Gamma^{\text{SM}}_{h\to X}} \frac{\Gamma^{\text{SM}}_{h,\text{tot}}}{\Gamma_{h,\text{tot}}}$$

ATLAS-CONF-2018-31



Preliminary Plots

- 2HDM of Type II
- Restricted to $\kappa_b \approx \pm 1$
- Far from decoupling limit

Electroweak Precision, Perturbativity, Unitarity

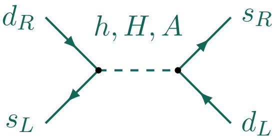
Deviation from decoupling limit + Perturbativity of potential of quartic couplings
$\rightarrow$ New Scalars not arbitrary heavy
$\rightarrow$ Mediator to Dark Matter can not decouple

Stability + Unitarity + Electroweak Precision tests
$\rightarrow$ Limits on mass splittings between the new states

$$M_A \approx M_H \approx M_{H^\pm} \lesssim 700 \text{ GeV}$$

Flavor Bounds

Potentially dangerous FCNCs at tree-level

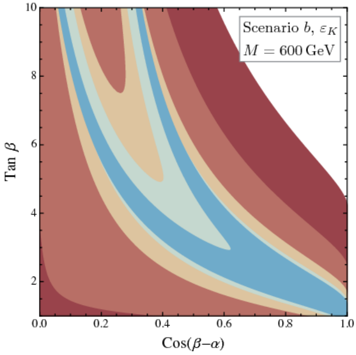


Under Control because of various suppressions

$$\propto \frac{f^2(\alpha,\beta)}{m_h^2}\, g^2(y) \left(\frac{m_s}{v}\epsilon\right)^2$$

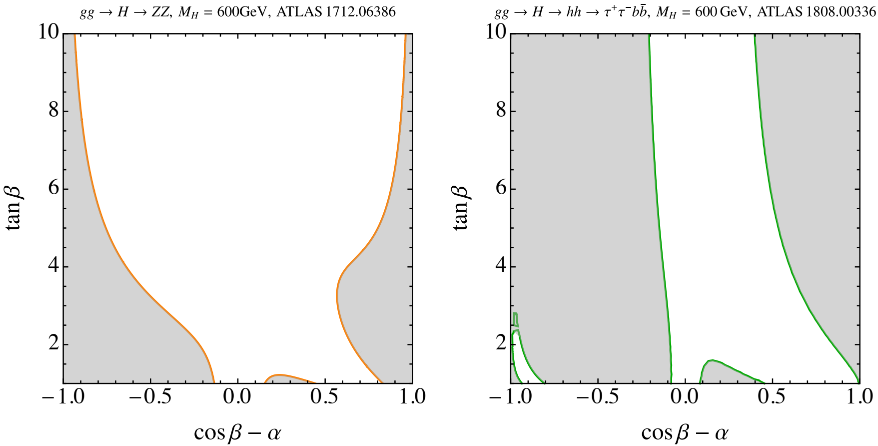
$$\approx \frac{10^{-15}}{\text{GeV}^2}$$

$$< \frac{10^{-17}}{\text{GeV}^2} \text{ exp. bound}$$



1512.03458

Heavy Resonance Searches



Preliminary Plots

Previously relevant: $A \to hZ$

Consistent Model for Pseudoscalar Mediator

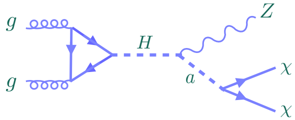
$$\mathcal{L}_\chi \supset c_5 \, \frac{H_u^\dagger H_d}{\Lambda} \, \bar{\chi}\gamma_5\chi + h.c.$$

Pseudoscalar embedded in the 2nd Higgs Doublet 1712.06597

→ Minimalistic way to restore Gauge Invariance

→ Safe from Direct Detection 1711.02110

Coupling to DM via effective operators → Universal signals

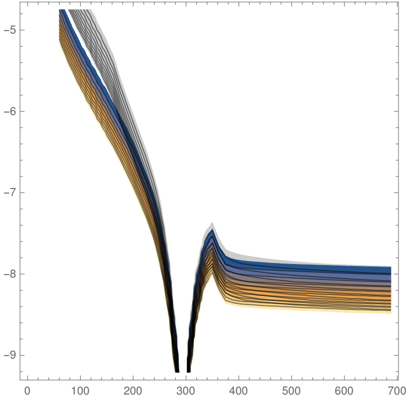


Mono-Z

Resonantly enhanced if

$M_H \geqslant M_A + M_Z$

Relic Density

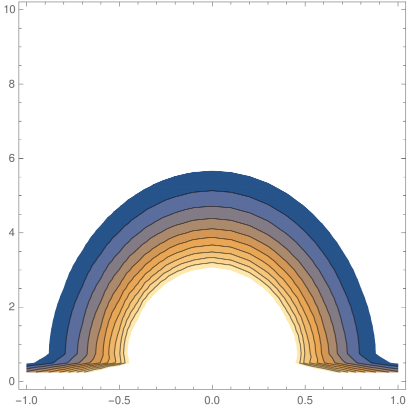


- $M_A = M_H = M_{H^\pm} = 600$ GeV
- $c_\chi = 0$
- $\tan\beta = 4$
- $\cos(\beta - \alpha) = 0.22$

Preliminary Plots

1609.04026 (CMB)

Relic Density



- $M_A = M_H = M_{H^\pm} = 600$ GeV
- $c_\chi = 0$
- $m_\chi = 140$ GeV
- $c_5 = 0.005$

Preliminary Plots

1609.04026 (CMB)

Summary and Outlook I

- Consistent model for Flavor and Dark Matter at the Electroweak Scale
- Flavor and Higgs constraints point to same parameter region
- Predicts new particles around 1 TeV
- Left over region testable by future LHC runs!

- More detailed analyses, projections for LHC27

Collider Searches – Reminder

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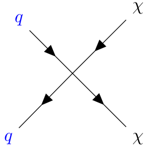

$$p^2 \ll \Lambda^2$$

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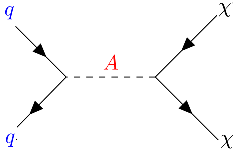

$$\propto \frac{g_q g_\chi}{p^2 - M^2}$$

Not gauge invariant
→ Unitarity Violation
→ Gauge invariant models

Extended Dark Matter EFT

Combine advantages of both approaches 1712.07626

SM + Scalar Mediator $\mathcal{S}$ + fermionic Dark Matter χ up to dimension 5

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$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\text{int}} \supset & - \lambda'_{H\mathcal{S}} v |H|^2 \mathcal{S} - \lambda_{H\mathcal{S}} |H|^2 \mathcal{S}^2 \\
& - y_{\mathcal{S}} \mathcal{S} \bar{\chi}\chi - \frac{y_{\mathcal{S}}^{(2)} \mathcal{S}^2 + y_H |H|^2}{\Lambda} \bar{\chi}\chi \\
& - \frac{\mathcal{S}}{\Lambda} \sum_{f=u,d,l} y_f^{\mathcal{S}} \bar{F}_{\mathrm{L}} H f_{\mathrm{R}} + \text{h.c.} \\
& - \frac{\mathcal{S}}{\Lambda} \left[C_{BB}^{\mathcal{S}} B_{\mu\nu} B^{\mu\nu} + C_{WW}^{\mathcal{S}} W^{i\mu\nu} W_{\mu\nu}^{i} + C_{GG}^{\mathcal{S}} G^{a\mu\nu} G_{\mu\nu}^{a} \right]
\end{aligned}
$$

Extended Dark Matter EFT

Combine advantages of both approaches 1712.07626

SM + Scalar Mediator $\mathcal{S}$ + fermionic Dark Matter χ up to dimension 5

$$\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\text{int}} \supset & - \lambda'_{H\mathcal{S}} v |H|^2 \mathcal{S} - \lambda_{H\mathcal{S}} |H|^2 \mathcal{S}^2 \\
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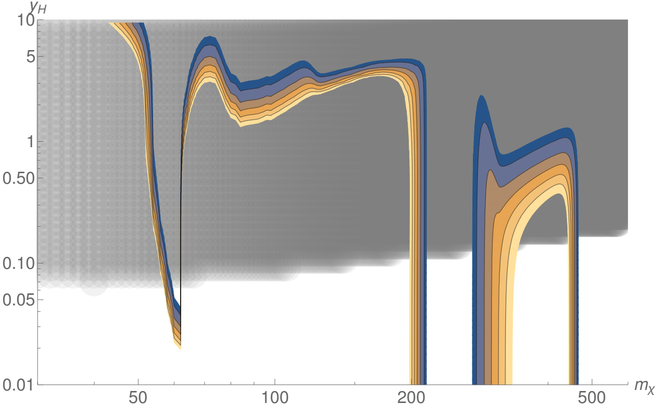
\end{aligned}$$

Example: Higgs + Gauge-boson portal



Preliminary Plots

- $y_{\mathcal{S}} = 1$
- $C_{BB}^{\mathcal{S}} = C_{WW}^{\mathcal{S}} = 0.2$
- $m_{\mathcal{S}} = 500$ GeV

Example: Matching 2HDM + $\mathcal{S}$

$$\mathcal{L}_{\mathrm{2HDM}+\mathcal{S}} \supset \mathcal{L}_{\mathrm{2HDM}} + \lambda_{12}^{\mathcal{S}} v\, H_1^\dagger H_2\, \mathcal{S} + \lambda_{12}^{2\mathcal{S}}\, H_1^\dagger H_2\, \mathcal{S}^2 + y_{\mathcal{S}} \mathcal{S} \bar{\chi}\chi$$

↓ H_2 heavy - motivated by Higgs measurements

$$\mathcal{L}_{\mathrm{eff}}^{\mathcal{S}\mathrm{int}} \supset \frac{-\lambda_{12}^{\mathcal{S}} v}{\Lambda^2}\, \mathcal{S} \left(Z_6 |H|^4 + \sum_{f=u,d,l} \frac{\eta_f\, y_f}{\tan\beta}\, \bar{F}_{\mathrm{L}}\, H\, f_{\mathrm{R}} + 2\mathcal{S}^2 |H|^2 \lambda_{12}^{2\mathcal{S}} \right)$$

$$- \;\ldots\; \mathcal{S}\, \left[c_{BB}^{\mathcal{S}} B_{\mu\nu} B^{\mu\nu} + c_{WW}^{\mathcal{S}} W^{i\mu\nu} W^i_{\mu\nu} \right]$$ 1-loop level

Summary and Outlook II

- Increase applicability of Dark Matter EFT
- Rich phenomenology
- Matches to wide classes of UV theories

- Include LHC analyses + Indirect Detection
- Constrain Wilson coefficients
- Match complex theories: Composite Models, NMSSM ...

Summary and Outlook II

- Increase applicability of Dark Matter EFT
- Rich phenomenology
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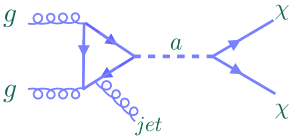
Thanks for your attention!

The speaker acknowledges support by the IMPRS-PTFS.

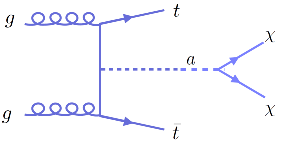
Collider Channels

Intital State Radiation:

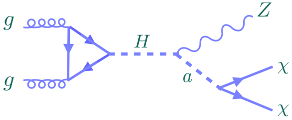
mono-jet $>$ mono-γ $>$ mono-Z $>$ mono-h



Mono-jet



$t\bar{t}A$ Production



Mono-Z

Resonantly enhanced if

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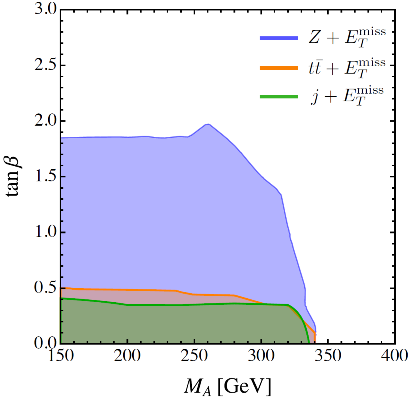
Mono-X Bounds



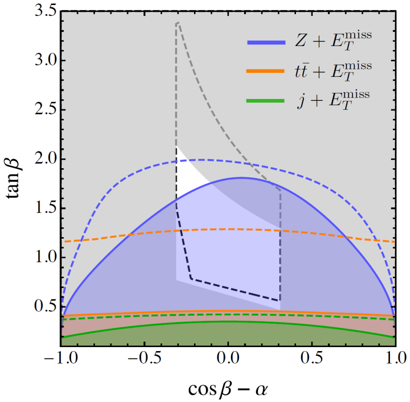
- $m_\chi = 70$ GeV
- $C_5 = 0.37$
- $c_\chi = 0$
- $\cos(\beta - \alpha) = 0$
- $M_H = M_{H^\pm} = 500$ GeV

1712.06597

Resonantly enhanced Mono-Z provides the strongest bounds!

CMS PAS EXO-16-038 ($Z + E_T^{\text{miss}}$), CMS PAS EXO-16-005 ($t\bar{t} + E_T^{\text{miss}}$), ATLAS-CONF-2017-060 ($j + E_T^{\text{miss}}$)

Final Result 1712.06597



Mono-Z searches have the potential to exclude almost all of the parameter space!

Examples of possible UV completions

Additional SM singlet pseudoscalar [1]

$$\mathcal{L} = \sum_{i,j=1}^{3} y_{ij}^{u} \bar{Q}_i H_u u_j + \sum_{i,j=1}^{3} y_{ij}^{d} \bar{Q}_i H_d d_j + \sum_{i,j=1}^{3} y_{ij}^{l} \bar{L}_i H_d l_j$$

$$+ \kappa a H_u^{\dagger} H_d + c_a a \bar{\chi} \gamma_5 \chi + h.c.$$

Additional electroweak fermion doublet $\psi = \left(\chi^{+} \chi^{0}\right)$ [2]

$$\mathcal{L} = \sum_{i,j=1}^{3} y_{ij}^{u} \bar{Q}_i H_u u_j + \sum_{i,j=1}^{3} y_{ij}^{d} \bar{Q}_i H_d d_j + \sum_{i,j=1}^{3} y_{ij}^{l} \bar{L}_i H_d l_j$$

$$+ c_1 \bar{\psi} H_u^{\dagger} \chi + c_2 \bar{\psi} \tilde{H}_d \chi + h.c.$$

[1] M. Bauer, U. Haisch, F. Kahlhoefer, 1701.07427

[2] A. Freitas, S. Westhoff, J. Zupan, 1506.04149