B-meson FCNC decays as a probe of light Dark Matter

侯镖锋,李新强,沈 萌,杨亚东,袁兴博, JHEP06(2024)172 高孟超,李新强,杨亚东,袁兴博,张 欣, work in progress

第四届强子与重味物理理论与实验联合研讨会



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兰州大学,兰州,25.03.22



Dark Matter Detection





see also 武雷's talk

upper limits erved ected
ted dijet + ISR t. B 788 (2019) 316
ted di- <i>b</i> -jet + ISR
lved dijet + ISR ^{6.6 fb-1} t. B 795 (2019) 56
lved di-b-jet + ISF t. B 795 (2019) 56
TLA 3 fb ⁻¹ v. Lett. 121 (2018) 081801
jet 9 tb-1 v. D 98 (2018) 032016 (2020) 145
(2020) 145
angular v. D 96, 052004 (2017)
onance, 1L s. J. C 78 (2018) 565
onance, 0L
+ lenton









Dark Matter Detection



Hadron FCNC Decay

 $B^+ \rightarrow K^+ + \text{DM} + \text{DM}$ $\Lambda_b \to \Lambda + \mathrm{DM} + \mathrm{DM}$ $K^+
ightarrow \pi^+ + \mathrm{DM} + \mathrm{DM}$ $D^0 \rightarrow \pi^0 + \text{DM} + \text{DM}$



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+ lenton









Theoretically cleanest processes in heavy flavour physics

$$B_{s,d} - \bar{B}_{s,d}$$
 mixing

$$b \to u(c)\ell\bar{\nu}: B \to D\ell\bar{\nu}, B \to D^*\ell\bar{\nu}, \dots$$

$$b \rightarrow s(d)\gamma: B \rightarrow X_s\gamma, B \rightarrow K^*\gamma, \dots$$

$$b \to s(d)\ell^+\ell^-: B_s \to \ell^+\ell^-, B \to K^*\ell^+\ell^-$$

 $b \to s(d)\nu\bar{\nu}: B \to K\nu\bar{\nu}, K \to \pi\nu\bar{\nu}, \dots$









Light DM: a bottom-up view



Experimental Search

	Observable	SM	Exp	Unit
	$\mathcal{B}(B^+ \to K^+ \nu \bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
	$\mathcal{B}(B^0 \to K^0 \nu \bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
$b \rightarrow s$	$\mathcal{B}(B^+ \to K^{*+} \nu \bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
	$\mathcal{B}(B^0 \to K^{*0} \nu \bar{\nu})$	9.00 ± 0.87	< 18	10^{-6}
	$\mathcal{B}(B_s \to \phi \nu \bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
	$\mathcal{B}(B_s \to \nu \bar{\nu})$	≈ 0	< 5.9	10^{-4}
	$\mathcal{B}(B^+ \to \pi^+ \nu \bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
	$\mathcal{B}(B^0 o \pi^0 u ar{ u})$	6.52 ± 0.85	< 900	10^{-8}
$b \rightarrow d$	$\mathcal{B}(B^+ \to \rho^+ \nu \bar{\nu})$	4.06 ± 0.79	< 300	10^{-7}
	$\mathcal{B}(B^0 o ho^0 u ar{ u})$	1.89 ± 0.36	< 400	10^{-7}
	$\mathcal{B}(B^0 o \nu \bar{\nu})$	≈ 0	< 1.4	10^{-4}
$s \rightarrow d$	$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	8.42 ± 0.61	$10.6^{+4.0}_{-3.4}\pm0.9$	10^{-11}
	$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}

 $c \rightarrow u \quad D^+ \rightarrow \pi^+ + \text{inv}, D^0 \rightarrow \rho^0 + \text{inv}, \dots$





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Light DM: a bottom-up view





Light DM: a bottom-up view



It's natural to ask:

- other information ?



Effective Field Theory approach to combine the various experimental searches

In EFT, DM is a just singlet under the SM gauge group.



for light DM

Dark SMEFT $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, all the SM particles 2009 H.Zhang, Q.H.Cao, C.R.Chen, C.S.Li 2011 Kamenik, Smith 2014 Duch, Grzadkowski, Wudka 2017 Brod, Gootjes-Dreesbach, Tammaro, Zupan 2021 Criado, Djouadi, Perez-Victoria, Santiago 2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6) 2023 Song, Sun, Yu (basis@dim-8) Axion-like particle, see also H.Y.Cheng, Phys.Rept 1988 2020 Bauer, Neubert, Renner, Schnubel, Thamm 2023 Song, Sun, Yu (basis@dim-8)

 $SU(3)_C \otimes U(1)_{em}$, W, Z, h, t have been integrated out

 $\begin{array}{l} \mathcal{O}_{d\phi^2} = (\bar{d}_{Lp} d_{Rr}) \phi^2 \\ \mathcal{O}_{d\chi}^{V, LR} = (\bar{d}_{Lp} \gamma_{\mu} d_{Lr}) (\bar{\chi}_a \gamma^{\mu} \chi_b) \\ \mathcal{O}_{d\chi}^L = (\bar{d}_{Lp} \gamma_{\mu} d_{Lr}) X^{\mu\nu} X_{\nu} \end{array} \begin{array}{l} 2022 \quad \text{Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)} \\ 2022 \quad \text{He, Ma, Valencia (basis@dim-6)} \\ 2023 \quad \text{Liang, Liao, Ma, Wang (basis@dim-8)} \end{array}$

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$H_1 ightarrow H_2 ightarrow { m DM}$ theoretical calculation and experimental searches

$d_i \rightarrow d_j + \phi + \phi$

2011 Kamenik, Smith 2014 Bird, Jackson, Kowalewski, Pospelov 2019 G.Li, J.Y. Su, Tandean $\Lambda \rightarrow n + \phi \phi, \Sigma^+ \rightarrow p + \phi \phi, \Xi^0 \rightarrow \Lambda + \phi \phi,$ $\Xi^- \rightarrow \Sigma^- \phi \phi, \Omega^- \rightarrow \Sigma^- + \phi \phi$ 2020 X.G. He, X.D. Ma, Tandean, Valencia 2020 C.Q.Geng, Tandean, $K \rightarrow \pi \pi + \phi \phi$ 2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang 2022 Kling, S. Li, H. Song, S. Su, W. Su

$\blacktriangleright d_i \rightarrow d_j + \chi + \chi$

2011 Kamenik, Smith
2019 J.Y. Su, Tandean
2020 G. Li, T. Wang, Y. Jiang, J.B. Zhang, G.L. Wang
2021 Felkl, S. L. Li, Schmidt

$\blacktriangleright d_i \rightarrow d_j + X + X$

2011 Kamenik, Smith2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang2022 X.G. He, X.D. Ma, Valencia

$$> d_i \rightarrow d_j + a$$

2020 Camalich, Pospelov, Vuong, Ziegler, Zupan,
2021 Bauer, Neubert, Renner, Schnubel, Thamm
2022 Guerrera and S. Rigolin see also 刘佳's talk

- form factor • theoretically clean: $A \propto C \cdot \langle H_1 | O | H_2 \rangle \cdot DM$ current
- no GIM suppression
- possibly two-body decay _

enhancement



based on complete EFT basis (Dark LEFT)

HadronToNP: a package to calculate decay of hadron to new particles B.F. Hou, X.Q.Li, H.Yan, Y.D.Yang, **XBY** to be finished





$b \rightarrow s \nu \bar{\nu}$: DSMEFT

Can DSMEFT operators explain the Belle II excess, while satisfy other $b \rightarrow s$ bounds ?

Observable	\mathbf{SM}	Exp	Unit	
$\mathcal{B}(B^+ \to K^+ \nu \bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}	
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${\cal B}(B^0 o ho^0 u ar u)$	1.89 ± 0.36	< 400	10^{-7}	$\mu_{\mathbf{FW}}$
$\mathcal{B}(B^0 o \nu \bar{\nu})$	pprox 0	< 1.4	10^{-4}	
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$\mathcal{B}(K_L o \pi^0 \nu \bar{\nu})$	3.41 ± 0.45	< 300	10 ⁻¹¹	
			K	
			- * ****	ин- И h

DM DM **Dark SMEFT** $\mathcal{Q}_{d\phi} = \left(ar{q}_p
ight)$ $\mathcal{Q}_{\phi q} = ig(ar{q}_p$ $\mathcal{Q}_{q\chi} = \left(\bar{q}_p \right)$ $\mathcal{Q}_{dHX} = ig(ar{q}_{p}$ $\mathcal{Q}_{qa}=ig(ar{q}_{p}$

Dark LEF $\mathcal{O}_{d\phi} = (\bar{d}$

 $egin{aligned} \mathcal{O}^{V,\,LR}_{d\chi} &= (ar{d})^{V,\,LR}_{d\chi} &= (ar{d})^{T}_{d\chi} &= (ar{d})^{T}_{d\chi} &= (ar{d})^{L}_{d\chi} &= (ar{d})^{L}_{d\chi} &= (ar{d})^{L}_{d\chi} &= (ar{d})^{L}_{\chi} &$



$_{p}d_{r}H)\phi + \mathrm{h.c.},$ $_{p}\gamma_{\mu}q_{r})\left(i\phi_{1}\overleftrightarrow{\partial^{\mu}}\phi_{2}\right),$	$\mathcal{Q}_{d\phi^2} = \left(\bar{q}_p d_r H\right) \phi^2 + \text{h.c.},$ $\mathcal{Q}_{\phi d} = \left(\bar{d}_p \gamma_\mu d_r\right) \left(i\phi_1 \overleftrightarrow{\partial^\mu} \phi_2\right),$	scalar: 4
$_{p}\gamma_{\mu}q_{r}ig)(ar{\chi}\gamma^{\mu}\chiig),$	$\mathcal{Q}_{d\chi} = \left(\bar{d}_p \gamma_\mu d_r \right) (\bar{\chi} \gamma^\mu \chi),$	fermion: 2
$(p\sigma_{\mu\nu}d_r)HX^{\mu\nu}$	$\mathcal{Q}_{dX^2} = \left(\bar{q}_p d_r H\right) X_\mu X^\mu$	vector: 1+13
$\partial_p \gamma_\mu q_r \big) \partial^\mu a$	$\mathcal{Q}_{da} = \left(ar{d}_p \gamma_\mu d_r ight) \partial^\mu a$	ALP: 2
T		
$(\bar{d}_{Lp}d_{Rr})\phi + ext{h.c.},$	$\mathcal{O}_{\phi d}^{L} = (\bar{d}_{Lp} \gamma_{\mu} d_{Lr}) (i \phi_1 \overleftrightarrow{\partial^{\mu}} \phi_2),$	scalar: 4
$ar{d}_{Lp}\gamma_\mu d_{Lr})(ar{\chi}_a\gamma^\mu\chi_b)$	$,\mathcal{O}_{d\chi}^{V,RR}=(ar{d}_{Rp}\gamma_{\mu}d_{Rr})(ar{\chi}_{a}\gamma^{\mu}\chi_{b}),$	fermion: 5
$\bar{l}_{Lp}\sigma_{\mu u}d_{Rr})X^{\mu u}_{a}$	$\mathcal{O}_{dXX}^{L} = \left(\bar{d}_{Lp}\gamma_{\mu}d_{Lr}\right)X^{\mu\nu}X_{\nu}$	vector: 1+10
$ar{l}_{Lp}\gamma_\mu d_{Lr}ig)\partial^\mu a,$	$\mathcal{O}^R_{da} = ig(ar{d}_{Rp} \gamma_\mu d_{Rr} ig) \partial^\mu a$	ALP: 2





Dark SMEFT: Scalar





Dark SMEFT: Vector











Dark SMEFT: Fermion, ALP



All the operators survive from the constraints of the various FCNC decays. (e.g., $B^0 \to K^0 + inv$) and CEPC (e.g., $B_s \to \phi + inv$ and $B_s \to inv$) measurements.



In the future, all the parameter space to explain the Belle II anomaly can be covered by combing the Belle II





Dark SMEFT: dB/dq^2



Difficult to distinguish the DSMEFT operators by considering only the $B^+ \to K^+ \nu \bar{\nu}$ decay. However,

Dark SMEFT: dB/dq^2 , F_I



All the operators are distinguishable from each other by combing these observables

$m_{\rm DM} = 1500 \, {\rm MeV}$



Effective Field Theory approach to combine the various experimental searches

In EFT, DM is a just singlet under the SM gauge group.



for light DM

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Top-flavored DM

\triangleright Dark SMEFT with 3rd generation@ $\mu_{\rm EW}$

$$\mathcal{Q}_{u\chi} = (\bar{u}_p \gamma_\mu u_r)(\bar{\chi} \gamma^\mu \chi), \Longrightarrow (\bar{t}_R \gamma_\mu t_R)(\bar{\chi} \gamma^\mu \chi)$$
$$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r)(\bar{\chi} \gamma^\mu \chi),$$
$$\mathcal{Q}_{u\chi^2} = (\bar{q}_p u_r \widetilde{H})(\bar{\chi} \chi), \qquad \mathcal{C} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathcal{C}_{33}$$







- 2013 Tongyan Lin, Kolb, Lian-Tao Wang
- 2015 Kilic, Klimek, Jiang-Hao Yu
- 2015 Haisch, Re
- 2015 Boucheneb, Cacciapaglia, Deandrea, Fuks
- 2017 Blanke, Kast
- 2021 Blanke, Pani, Polesello, Rovelli
- 2021 Haisch, Polesello, Schulte
- 2021 Hermanna, Worek
- 2022 Yandong Liu, Bin Yan, Rui Zhang

2019 ATLAS [JHEP05(2019)142]

Dark SMEFT one-loop matching

 $\mu_{
m EW}$

... ...

direct detection

Dark LEFT



 $\mathcal{O}_{g\phi} = G^a_{\mu\nu} G^{\mu\nu,a} \phi^2,$ $\mathcal{O}_{gX} = G^a_{\mu\nu} G^{\mu\nu,a} X_\rho X^\rho,$ $\mathcal{O}_{g\chi} = G^a_{\mu\nu} G^{\mu\nu,a} \bar{\chi} \chi$ + operators with u, d, s

 $\langle N | \mathcal{O}_j | N \rangle$





One-Loop Matching between Dark SMEFT and Dark LEFT Dark SMEFT

$$\mathcal{L}_{\text{DSMEFT}} \supset \sum_{i} \mathcal{C}_{i} \mathcal{Q}_{i}^{(4)} + \left(\frac{1}{\Lambda} \sum_{j} \mathcal{C}_{j} \mathcal{Q}_{j}^{(5)}\right) + \left(\frac{1}{\Lambda^{2}} \sum_{k} \mathcal{C}_{k} \mathcal{Q}_{k}^{(6)}\right) + \left(\frac{1}{\Lambda^{3}} \sum_{l} \mathcal{C}_{l} \mathcal{Q}_{l}^{(7)}\right)$$

$$\mathcal{Q}_{u\phi^{2}} = (\bar{q}_{p}u_{r}\tilde{H})\phi^{2} + \text{h.c.} \quad \mathcal{Q}_{\phi u} = (\bar{u}_{p}\gamma_{\mu}u_{r})(i\phi_{1}\overleftrightarrow{\partial}^{\mu}\phi_{2}) \quad \mathcal{Q}_{\phi q} = (\bar{q}_{p}\gamma_{\mu}q_{r})(i\phi_{1}\overleftrightarrow{\partial}^{\mu}\phi_{2}) \quad \cdots \cdots \quad \text{scalar}$$

$$\mathcal{Q}_{u\chi^{2}} = (\bar{q}_{p}u_{r}\tilde{H})(\chi^{T}C\chi) \quad \mathcal{Q}_{u\chi} = (\bar{u}_{p}\gamma_{\mu}u_{r})(\bar{\chi}\gamma^{\mu}\chi) \quad \mathcal{Q}_{q\chi} = (\bar{q}_{p}\gamma_{\mu}q_{r})(\bar{\chi}\gamma^{\mu}\chi) \quad \cdots \cdots \quad \text{fermion}$$

$$\mathcal{Q}_{qXX} = (\bar{q}_{p}\gamma_{\mu}q_{r})X^{\mu\nu}X_{\nu} \quad \mathcal{Q}_{u\tilde{X}X} = (\bar{u}_{p}\gamma_{\mu}u_{r})\tilde{X}^{\mu\nu}X_{\nu} \quad \mathcal{Q}_{uX^{2}} = (\bar{q}_{p}u_{r}\tilde{H})X_{\mu}X^{\mu} + \text{h.c.} \quad \cdots \cdots \quad \text{vector}$$

Matching



$$\mathcal{L}_{\text{DLEFT}} \supset \sum_{k} L_{k} \mathcal{O}_{i}^{(4)} + \left[\frac{1}{v} \sum_{i} L_{i} \mathcal{O}_{i}^{(5)}\right] + \left[\frac{1}{v^{2}} \sum_{j} L_{j} \mathcal{O}_{j}^{(6)}\right] + \left[\frac{1}{v^{3}} \sum_{l} L_{l} \mathcal{O}_{k}^{(6)}\right] + \left[\frac{1}{v^{3}} \sum_{l} L$$

Dark LEFT: hadron detection



One-Loop Matching between Dark SMEFT and Dark LEFT Dark SMEFT

$$\mathcal{L}_{\text{DSMEFT}} \supset \sum_{i} \mathcal{C}_{i} \mathcal{Q}_{i}^{(4)} + \frac{1}{\Lambda} \sum_{j} \mathcal{C}_{j} \mathcal{Q}_{j}^{(5)} + \frac{1}{\Lambda^{2}} \sum_{k} \mathcal{C}_{k} \mathcal{Q}_{k}^{(6)} + \frac{1}{\Lambda^{3}} \sum_{l} \mathcal{C}_{l} \mathcal{Q}_{l}^{(7)}$$

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$$\mathcal{Q}_{u\chi^{2}} = (\bar{q}_{p}u_{r}\tilde{H})(\chi^{T}C\chi) \quad \mathcal{Q}_{u\chi} = (\bar{u}_{p}\gamma_{\mu}u_{r})(\bar{\chi}\gamma^{\mu}\chi) \quad \mathcal{Q}_{q\chi} = (\bar{q}_{p}\gamma_{\mu}q_{r})(\bar{\chi}\gamma^{\mu}\chi) \quad \cdots \cdots \qquad \text{fermion}$$

$$\mathcal{Q}_{qXX} = (\bar{q}_{p}\gamma_{\mu}q_{r})X^{\mu\nu}X_{\nu} \quad \mathcal{Q}_{u\tilde{X}X} = (\bar{u}_{p}\gamma_{\mu}u_{r})\tilde{X}^{\mu\nu}X_{\nu} \qquad \mathcal{Q}_{uX^{2}} = (\bar{q}_{p}u_{r}\tilde{H})X_{\mu}X^{\mu} + \text{h.c.} \quad \cdots \cdots \qquad \text{vector}$$

Matching





$$\mathcal{L}_{\text{DLEFT}} \supset \sum_{k} L_{k} \mathcal{O}_{i}^{(4)} + \left[\frac{1}{v} \sum_{i} L_{i} \mathcal{O}_{i}^{(5)}\right] + \left[\frac{1}{v^{2}} \sum_{j} L_{j} \mathcal{O}_{j}^{(6)}\right] + \left[\frac{1}{v^{3}} \sum_{l} L_{k} \mathcal{O}_{k}^{(6)}\right] + \left[\frac{1}{v^{3}} \sum_{l}$$

Dark LEFT: direct detection



Hadron decay vs Direct detection







Hadron decay vs Direct detection







Hadron decay vs Direct detection



 $m_{\rm dm}$

upper bound from **direct detection** upper bound from **B FCNC decay** . .



Conclusion

It's natural to ask:

1. Compared to DM direct detection, what's the advantage of hadron decays? which DM scenario is more sensitive to ? Can provide other information ?

Angular distribution (F_L); top-flavored DM

- 2. Can we build NP model, in which hadron decays into DM reach the future Belle II/STCF sensitivities, while providing enough DM relic density and satisfying the bounds from DM direct detection ?
- 3. Is it possible to obtain the flavour structure of light DM?

HadronToNP: a package to calculate decay of hadron to new particles $B \rightarrow K + DM$, $B \rightarrow \rho + DM$, $\Lambda_b \rightarrow \Lambda + DM$, $\Upsilon \rightarrow DM$, ... to be find $D \rightarrow \pi + DM$, $D \rightarrow \rho + DM$, $\Xi_c \rightarrow \Xi + DM$, $J/\psi \rightarrow DM$, ...

Thank You !

Backup

$$\mathcal{C} = \begin{cases} \mathcal{C}_t & \text{for } \bar{u}_L \gamma^{\mu} \mathcal{C} u_L, \, u_R \gamma^{\mu} \mathcal{C} u_R, \, \bar{u}_L \\ V^{\dagger} \mathcal{C}_t V & \text{for } \bar{d}_L \gamma^{\mu} \mathcal{C} d_L, \\ V^{\dagger} \mathcal{C}_t & \text{for } \bar{d}_L \mathcal{C} u_R, \, \bar{d}_L \sigma^{\mu\nu} \mathcal{C} u_R, \end{cases}$$

$$V^{\dagger} C_{t} V = C_{33} \begin{pmatrix} V_{td}^{*} V_{td} \ V_{td}^{*} V_{ts} \ V_{ts}^{*} V_{tb} \\ V_{ts}^{*} V_{td} \ V_{ts}^{*} V_{ts} \ V_{ts}^{*} V_{tb} \end{pmatrix} \qquad \qquad C_{t} \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & C_{33} \end{pmatrix} \\ = C_{33} \begin{pmatrix} 0.71 & -3.09 - 1.45i & 76.81 + 34.29i \\ -3.09 + 1.45i & 16.43 & -404.93 + 7.87i \\ 76.81 - 34.29i & -404.93 - 7.87i & 9982.86 \end{pmatrix} \times 10^{-4}$$

$$V^{\dagger} C_{t} = C_{33} \begin{pmatrix} 0 & 0 & V_{td}^{*} \\ 0 & 0 & V_{ts}^{*} \\ 0 & 0 & V_{tb}^{*} \end{pmatrix} = C_{33} \begin{pmatrix} 0 & 0 & 0.77 + 0.34i \\ 0 & 0 & -4.05 + 0.08i \\ 0 & 0 & 99.91 \end{pmatrix} \times 10^{-2}$$

$$C_{i} = \begin{cases} C_{t}^{i} & \text{for } Q_{i} = \\ (C_{t}^{i}, V^{\dagger}C_{t}^{i}) & \text{for } Q_{i} = \\ (C_{t}^{i}, V^{\dagger}C_{t}^{i}V) & \text{for } Q_{i} = \end{cases}$$

$\mathcal{L}\mathcal{C}u_R, \, \bar{u}_L \sigma^{\mu\nu} \mathcal{C}u_R,$

 $\begin{array}{l} \mathcal{Q}_{\phi u}, \ \mathcal{Q}_{u\chi}, \ \mathcal{Q}_{uX}, \ \mathcal{Q}_{HuX}, \ \mathcal{Q}_{uXX}, \ \mathcal{Q}_{u\widetilde{X}X}, \ \mathcal{Q}_{DuX^2}, \ \mathcal{Q}_{ua}, \\ \mathcal{Q}_{u\phi}, \ \mathcal{Q}_{u\phi^2}, \ \mathcal{Q}_{u\chi^2}, \ \mathcal{Q}_{qu\chi l}, \ \mathcal{Q}_{uHX}, \ \mathcal{Q}_{uX^2}, \ \mathcal{Q}_{uHX^2}, \\ \mathcal{Q}_{\phi q}, \ \mathcal{Q}_{q\chi}, \ \mathcal{Q}_{q\chi}, \ \mathcal{Q}_{qX}, \ \mathcal{Q}_{HqX}^{(1,3)}, \ \mathcal{Q}_{qXX}, \ \mathcal{Q}_{q\widetilde{X}X}, \ \mathcal{Q}_{DqX^2}, \ \mathcal{Q}_{qa}, \end{array}$

Hadron decay vs Relic density and Indirect detection

 $m_{\rm dm}$

 ${\cal Q}_{u\phi^2}$ ${\cal Q}_{u\chi}$ ${\cal Q}_{q\chi}$ ${\cal Q}_{u\chi^2}$ ${\cal Q}_{uX^2}$ \mathcal{Q}_{uXX} \mathcal{Q}_{qXX}

Hadron decay vs Relic density and Indirect detection

Conclusion

SMEFT

Belle II excess (if confirmed in the future) implies:

- impossible to explain in SMEFT with MFV
- NP flavour structure is highly non-trivial
- NP structure in quark sector is beyond MFV
- flavour violation is beyond Yukawa coupling

HadronToNP: a package to calculate decay of hadron to new particles $B \to K + DM, B \to \rho + DM, \Lambda_b \to \Lambda + DM, \Upsilon \to DM, \dots$ to be finished $D \rightarrow \pi + DM, D \rightarrow \rho + DM, \Xi_c \rightarrow \Xi + DM, J/\psi \rightarrow DM, \dots$

$b \rightarrow s \nu \bar{\nu}$: exp & theory

2021 Apr

2023 Aug

$b \rightarrow s \nu \bar{\nu}$: exp & theory

	Observable	\mathbf{SM}	Exp	Unit
	$\mathcal{B}(B^+ \to K^+ \nu \bar{\nu})$	4.16 ± 0.57	$23\pm5^{+5}_{-4}$	10^{-6}
	$\mathcal{B}(B^0 \to K^0 \nu \bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
b a	$\mathcal{B}(B^+ \to K^{*+} \nu \bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
$D \rightarrow S$	$\mathcal{B}(B^0 \to K^{*0} \nu \bar{\nu})$	9.00 ± 0.87	< 18	10^{-6}
	$\mathcal{B}(B_s \to \phi \nu \bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
	$\mathcal{B}(B_s \to \nu \bar{\nu})$	≈ 0	< 5.9	10^{-4}
	$\mathcal{B}(B^+ \to \pi^+ \nu \bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
	$\mathcal{B}(B^0 o \pi^0 \nu \bar{\nu})$	6.52 ± 0.85	< 900	10^{-8}
$b \rightarrow d$	$\mathcal{B}(B^+ \to \rho^+ \nu \bar{\nu})$	4.06 ± 0.79	< 300	10^{-7}
	${\cal B}(B^0 o ho^0 u ar u)$	1.89 ± 0.36	< 400	10^{-7}
	$\mathcal{B}(B^0 o u ar{ u})$	pprox 0	< 1.4	10^{-4}
$c \rightarrow d$	$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	8.42 ± 0.61	$10.6^{+4.0}_{-3.4}\pm0.9$	10^{-11}
5 -7 U	$\mathcal{B}(K_L o \pi^0 u ar{ u})$	3.41 ± 0.45	< 300	10^{-11}

Why such a large NP effect has not shown up in other $b \rightarrow s$ decays ? in $b \rightarrow d, s \rightarrow d$ decays ?

Factorization

 $\mathscr{A} \propto C_L \cdot \langle K | \bar{s} \gamma^{\mu} b | \bar{B} \rangle \cdot \bar{\nu} \gamma_{\mu} \nu$ quark current neutrino current Wilson coef

theoretically, simple and clean one of the cleanest channels in flavour physics

 $\mathcal{O}_L = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu P_L \nu)$ in the SM

$$\mathcal{O}_R = (\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L \nu)$$
 possible in BSM

operator structure highly constrained by LH neutrino

 $\mathcal{O}_L = (\bar{s}P_L b)(\bar{\nu}P_L \nu) \mathbf{X}$ $\mathcal{O}_R = (\bar{s}P_R b)(\bar{\nu}P_R \nu) \mathbf{X}$ $\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu}b)(\bar{\nu}\sigma^{\mu\nu}\nu) \mathbf{X}$

$$\mathcal{O}_{T5} = (\bar{s}\sigma_{\mu\nu}\gamma_5 b)(\bar{\nu}\sigma^{\mu\nu})$$

$b \rightarrow s \nu \bar{\nu}$: exp & theory

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Why such a large NP effect has not shown up in other $b \rightarrow s$ decays ? in $b \rightarrow d, s \rightarrow d$ decays ? NP flavour structure

Minimal Flavour Violation

Flavour symmetry without Yukawa

 $G_{\rm QF} = SU(3)_q \otimes SU(3)_u \otimes SU(3)_d$

Flavour symmetry breaking only from SM Yukawa

 $-\mathcal{L}_{V} = \bar{q} Y_{d} H d + \bar{q} Y_{u} \tilde{H} u + \text{h.c.}$

 \triangleright Flavour symmetry recovering: Yukawa coupling \Longrightarrow spurion field

$$Y_u \sim ig(\mathbf{3}, \mathbf{ar{3}}, \mathbf{1} ig) \qquad \qquad Y_d \sim ig(\mathbf{3}, \mathbf{1}, \mathbf{A} ig)$$

EFT with MFV: operators, constructed from SM and Yukawa spurion fields, are invariant under CP and G_{OF}

$$\mathcal{C}^{\mathrm{MFV}} = \begin{cases} f(\mathsf{A},\mathsf{B}) & \text{for } \bar{q}\gamma^{\mu}\mathcal{C}q, & f(\mathsf{A},\mathsf{B}) = \epsilon_0 1 + \epsilon_1 \mathsf{A} + \epsilon_2 \mathsf{B} + \epsilon_3 \mathsf{A}^2 + \epsilon_4 \mathsf{B}^2 + \epsilon_5 \mathsf{A}\mathsf{B} + \dots \\ f(\mathsf{A},\mathsf{B})Y_d & \text{for } \bar{q}\mathcal{C}d, \ \bar{q}\sigma^{\mu\nu}\mathcal{C}d, & \mathsf{A} = Y_u Y_u^{\dagger} \\ \epsilon_0 \mathbbm{1} + Y_d^{\dagger}g(\mathsf{A},\mathsf{B})Y_d & \text{for } \bar{d}\gamma^{\mu}\mathcal{C}d, & \mathsf{B} = Y_d Y_d^{\dagger} \end{cases}$$

 $\overline{\mathbf{3}}$

D'Ambrosio, Giudice, Isidori, Strumia, 2009

Minimal Flavour Violation

Spurion function

 $f(\mathsf{A},\mathsf{B}) = \epsilon_0 1 + \epsilon_1 \mathsf{A} + \epsilon_2 \mathsf{B} + \epsilon_3 \mathsf{A}^2 + \epsilon_4 \mathsf{B}^2 + \epsilon_5 \mathsf{A}\mathsf{B} + \dots$

 \triangleright Cayley-Hamilton identity for 3×3 invertible matrix X

$$X^{3} = \operatorname{Det} X \cdot \mathbb{1} + \frac{1}{2} [\operatorname{Tr} X^{2} - (\operatorname{Tr} X)^{2}] \cdot X + \operatorname{Tr} X$$

Spurion function after resummation

$$f(\mathsf{A},\mathsf{B}) = \epsilon_0 \mathbb{1} + \epsilon_1 \mathsf{A} + \epsilon_3 \mathsf{A}^2 + \epsilon_5 \mathsf{A}\mathsf{B} + \epsilon_7 \mathsf{A}\mathsf{B}\mathsf{A} + \epsilon_{10} \mathsf{A}$$

 $+ \epsilon_2 \mathsf{B} + \epsilon_4 \mathsf{B}^2 + \epsilon_6 \mathsf{B}\mathsf{A} + \epsilon_9 \mathsf{B}\mathsf{A}\mathsf{B} + \epsilon_8 \mathsf{B}$

> assumption #1: neglect tiny imaginary parts of ϵ_i > assumption #2: neglect spurion B (suppressed by $\mathcal{O}(\lambda_d^2)$)

$$f(\mathsf{A},\mathsf{B}) \approx \epsilon_0 \mathbb{1} + \epsilon_1 \mathsf{A} + \epsilon_2 \mathsf{A}^2$$

 $X \cdot X^2$

Colangelo, Nikolidakis, Smith, 2009 Mercolli, Smith, 2009

 $_{0}\mathsf{A}\mathsf{B}^{2}+\epsilon_{12}\mathsf{A}^{2}\mathsf{B}^{2}+\epsilon_{14}\mathsf{B}^{2}\mathsf{A}\mathsf{B}+\epsilon_{15}\mathsf{A}\mathsf{B}^{2}\mathsf{A}^{2}$ $\mathbf{A}\mathbf{A}^2 + \epsilon_{13}\mathbf{B}^2\mathbf{A}^2 + \epsilon_{11}\mathbf{A}\mathbf{B}\mathbf{A}^2 + \epsilon_{16}\mathbf{B}^2\mathbf{A}^2\mathbf{B}.$

Minimal Flavour Violation

MFV coupling FCNC controlled by CKM

$$C^{\rm MFV} = \begin{cases} \epsilon_0 1 + \epsilon_1 \Delta_q & \text{for } \bar{d}_L \gamma^{\mu} C d_L \\ \epsilon_0 \hat{\lambda}_d + \epsilon_1 \Delta_q \hat{\lambda}_d & \text{for } \bar{d}_L C d_R, \ \bar{d}_L \sigma^{\mu\nu} C d_R & \Delta_q = V^{\dagger} \hat{\lambda}_u^2 V \\ \epsilon_0 1 & \text{for } \bar{d}_R \gamma^{\mu} C d_R & \text{No Right-handed down-t} \end{cases}$$

Numerics

$$\Delta_q = \begin{pmatrix} 0.8 & -3.3 - 1.5i & 79.3 + 35.4i \\ -3.3 + 1.5i & 16.6 & -397.5 + 8.1i \\ 79.3 - 35.4i & -397.5 - 8.1i & 9839.0 \end{pmatrix} \times 10^{-4}$$
$$a_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18 - 0.08i & 191.3 + 85.4i \\ -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \end{pmatrix} \times 10^{-6}.$$

 $\begin{pmatrix} -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \\ 0.21 - 0.10i & -21.1 - 0.4i & 23728.1 \end{pmatrix} \times$ $\Delta_q \lambda_d =$

type FCNC !

$b \rightarrow s \nu \bar{\nu}$: SMEFT with MFV

Prediction

$$\frac{\mathcal{B}(B^{+} \to K^{+}\nu\bar{\nu})}{\mathcal{B}(B^{0} \to K^{*0}\nu\bar{\nu})} = \frac{\mathcal{B}(B^{+} \to K^{+}\nu\bar{\nu})_{SM}}{\mathcal{B}(B^{0} \to K^{*0}\nu\bar{\nu})_{SM}} = 0.46 \pm 0.07 \qquad \text{SMEFT}$$

$$\frac{\mathcal{B}(B^{+} \to K^{+}\nu\bar{\nu})}{\mathcal{B}(B^{+} \to \pi^{+}\nu\bar{\nu})} = \frac{\mathcal{B}(B^{+} \to K^{+}\nu\bar{\nu})_{SM}}{\mathcal{B}(B^{+} \to \pi^{+}\nu\bar{\nu})_{SM}} = 29.7 \pm 5.6 \qquad \text{SMEFT}$$

$$\frac{\mathcal{Q}_{Hq}^{(1)} = (H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r}),}{\mathcal{Q}_{Hq} = (H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{q}_{p}\tau^{I}q^{\mu}q_{r}),} \qquad \text{induce }\bar{s}bZ \text{ interaction} \\
\mathcal{Q}_{Hq}^{(1)} = (H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{q}_{p}\tau^{I}q^{\mu}q_{r}), \qquad \text{induce }\bar{s}bZ \text{ interaction} \\
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\mathcal{Q}_{Hd} = (H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{q}_{p}\tau^{I}q^{\mu}q_{r}), \qquad \text{otherwises ally affect} \\
\mathcal{Q}_{lq} = (\bar{l}_{p}\gamma^{\mu}l_{r})(\bar{d}_{s}\gamma_{\mu}q_{l}), \qquad \mathcal{Q}_{lq} = (\bar{l}_{p}\gamma^{\mu}l_{r})(\bar{d}_{s}\gamma_{\mu}q_{l}), \qquad \mathcal{Q}_{lq} = (\bar{l}_{p}\gamma^{\mu}\tau_{l})(\bar{q}_{s}\gamma_{\mu}q_{l}), \qquad \mathcal{Q}_{lq}^{(1)} = (\bar{l}_{p}\gamma^{\mu}\tau_{l})(\bar{q}_{s}\tau^{I}\gamma_{\mu}q_{l}), \qquad \mathcal{Q}_{lq}^{(1)} = (\bar{l}_{p}\gamma^{\mu}\tau_{l})(\bar{l}_{p}\gamma^{\mu}\tau_{\mu}), \qquad \mathcal{Q}_{lq}^{(1)} = (\bar{l}_{p}\gamma^{\mu}\tau_{l})(\bar{l}_{p}\gamma^{\mu}\tau_{\mu}), \qquad \mathcal{Q}_{lq}^{(1$$

$$\mathscr{B}(B^{0} \to K^{*0} \nu \bar{\nu})_{\text{SM}} = (9.00 \pm 0.87) \times 10^{-6}$$
$$\mathscr{B}(B^{0} \to K^{*0} \nu \bar{\nu})_{\text{MFV}} = (50^{+17}_{-16}) \times 10^{-6}$$
$$\mathscr{B}(B^{0} \to K^{*0} \nu \bar{\nu})_{\text{exp}} < 18 \times 10^{-6}$$

$$\mathscr{B}(B^+ \to \pi^+ \nu \bar{\nu})_{\text{SM}} = (1.40 \pm 0.18) \times 10^{-7}$$
$$\mathscr{B}(B^+ \to \pi^+ \nu \bar{\nu})_{\text{MFV}} = (7.8^{+2.8}_{-2.6}) \times 10^{-7}$$
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$b \rightarrow s \nu \bar{\nu}$: SMEFT with MFV

Prediction

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Belle II excess (if confirmed in the future) implies:

- impossible to explain in SMEFT with MFV
- NP flavour structure is highly non-trivial
- NP structure in quark sector is beyond MFV
- flavour violation is beyond Yukawa coupling

This conclusion only assumes the quark MFV. No lepton flavour structure is assumed.

$b \rightarrow s \nu \bar{\nu}$: SMEFT

SMEFT

 μ_b

$$\begin{split} \mathcal{Q}_{Hq}^{(1)} &= \left(H^{\dagger}i\overleftrightarrow{D}_{\mu}H\right)\left(\bar{q}_{p}\gamma^{\mu}q_{r}\right), \\ \mathcal{Q}_{Hq}^{(3)} &= \left(H^{\dagger}i\overleftrightarrow{D}_{\mu}^{I}H\right)\left(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r}\right), \\ \mathcal{Q}_{Hd} &= \left(H^{\dagger}i\overleftrightarrow{D}_{\mu}H\right)\left(\bar{d}_{p}\gamma^{\mu}d_{r}\right), \\ \mathcal{Q}_{Id} &= \left(\bar{l}_{p}\gamma^{\mu}l_{r}\right)\left(\bar{d}_{s}\gamma_{\mu}d_{t}\right), \\ \mathcal{Q}_{lq}^{(1)} &= \left(\bar{l}_{p}\gamma^{\mu}l_{r}\right)\left(\bar{q}_{s}\gamma_{\mu}q_{t}\right), \\ \mathcal{Q}_{lq}^{(3)} &= \left(\bar{l}_{p}\gamma^{\mu}\tau^{I}l_{r}\right)\left(\bar{q}_{s}\tau^{I}\gamma_{\mu}q_{t}\right), \end{split}$$

$$\mu_{\rm EW}$$

$$\mathsf{LEFT} \qquad \mathcal{O}_L^{\nu_i\nu_j} = (\bar{s}\gamma_\mu P_L b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$$

$$\mathcal{O}_R^{\nu_i\nu_j} = (\bar{s}\gamma_\mu P_R b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$$

 operator structure highly constrained by Left-handed neutrino

$$\begin{array}{c} 20 \underbrace{} & 10 \\ & & & \\ 0 & & \\$$

Bause, Gisbert, Hiller, 2309.00075 Allwicher, Becirevic, Piazza, Rosauro-Alcaraz, Sumensari, 2309.02246 Chen, Wen, Xu, 2401.11552

$b \rightarrow s \nu \bar{\nu}$: SMEFT

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 $\mu_{\rm EW}$

 μ_b

LEFT
$$\mathcal{O}_{L}^{\nu_{i}\nu_{j}} = \left(\bar{s}\gamma_{\mu}P_{L}b\right)\left(\bar{\nu}_{i}\gamma^{\mu}P_{L}\nu_{j}\right)$$
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$b \to s \nu \bar{\nu} and b \to s \ell \ell$

B.F.Hou, X.Q.Li, M.Shen, Y.D.Yang, **XBY**, 2402.19208

Prediction

$$\frac{\mathcal{B}(B^+ \to K^+ \nu \bar{\nu})}{\mathcal{B}(B^0 \to K^{*0} \nu \bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+ \nu \bar{\nu})_{SM}}{\mathcal{B}(B^0 \to K^{*0} \nu \bar{\nu})_{SM}} = 0.46 \pm 0.07$$

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Only $\mathcal{O}_{lq}^{(3)}$ is relevant with $R_{D^{(*)}}$

Only $\mathcal{O}_{lq}^{(3)}$ is relevant with $R_{D^{(*)}}$
 \mathcal{O}_{ld} can explain the $B^+ \to K^+ \nu \bar{\nu}$ data
 \mathcal{O}_{ld} also induce $O'_{9,ij}$ and $O'_{10,ij}$

They can't improve the $b \to s \mathscr{C} \mathscr{C}$ fit
 O'_{9e} and $O'_{10\mu}$ worsen the fit. weird (LFV, $\tau\tau \gg ee, \mu\mu$)
 $O'_{9,ij}$ and $O'_{10,ij}$ with $i = j = \tau$ has no effect.
 $O'_{9,ij}$ and $O'_{10,ij}$ with $i \neq j$ (i.e. LFV) has no effect.

SMEFT notation:
$$l = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$
, $q = \begin{pmatrix} u \\ d \end{pmatrix}_L$, d

SMEFT

$$\begin{aligned}
\mathcal{Q}_{Hq}^{(1)} &= (H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{q}_{p}\gamma^{\mu}q_{r}), \\
\mathcal{Q}_{Hq}^{(3)} &= (H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r}), \\
\mathcal{Q}_{Hd} &= (H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{d}_{p}\gamma^{\mu}d_{r}), \\
\mathcal{Q}_{Id} &= (\bar{l}_{p}\gamma^{\mu}l_{r})(\bar{d}_{s}\gamma_{\mu}d_{t}), \\
\mathcal{Q}_{lq}^{(1)} &= (\bar{l}_{p}\gamma^{\mu}l_{r})(\bar{q}_{s}\gamma_{\mu}q_{t}), \\
\mathcal{Q}_{lq}^{(3)} &= (\bar{l}_{p}\gamma^{\mu}\tau^{I}l_{r})(\bar{q}_{s}\tau^{I}\gamma_{\mu}q_{t}), \\
\mathcal{Q}_{L}^{(3)} &= (\bar{s}\gamma_{\mu}P_{L}b)(\bar{\nu}_{i}\gamma^{\mu}P_{L}\nu_{j}) \\
\mathcal{Q}_{R}^{\nu_{i}\nu_{j}} &= (\bar{s}\gamma_{\mu}P_{R}b)(\bar{\nu}_{i}\gamma^{\mu}P_{L}\nu_{j})
\end{aligned}$$
one LEFT operato just the SM operat

$$O_{9,ij}' = (\bar{b}\gamma^{\mu}P_R s)(\bar{\ell}_i\gamma_{\mu}\ell_j)$$
$$O_{10,ij}' = (\bar{b}\gamma^{\mu}P_R s)(\bar{\ell}_i\gamma_{\mu}\gamma_5\ell_j)$$

$b \rightarrow s \nu \bar{\nu}$: exp picture

2011 Kamenik, Smith

- 2014 Duch, Grzadkowski, Wudka
- 2017 Brod, Gootjes-Dreesbach, Tammaro, Zupan
- 2021 Criado, Djouadi, Perez-Victoria, Santiago
- 2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)
- 2023 Song, Sun, Yu (basis@dim-8)

see also H.Y.Cheng, Phys.Rept 1988 2020 Bauer, Neubert, Renner, Schnubel, Thamm 2023 Song, Sun, Yu (basis@dim-8)

example

2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6) $\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_{Lp}\gamma_{\mu}d_{Lr})(\bar{\chi}_{a}\gamma^{\mu}\chi_{b}) 2022 \text{ He, Ma, Valencia (basis@dim-6)}$ 2023 Liang, Liao, Ma, Wang (basis@dim-8) $\mathcal{O}_{da}^{L} = \left(\bar{d}_{Lp}\gamma_{\mu}d_{Lr}\right)\partial^{\mu}a$

Dark SMEFT with MFV

▶ MFV coupling $b \rightarrow s, b \rightarrow d, s \rightarrow d$ are connected with each other.

$$\mathcal{C}_{i}^{\mathrm{MFV}} = \begin{cases} \epsilon_{0}^{i} \hat{\lambda}_{d} + \epsilon_{1}^{i} \Delta_{q} \hat{\lambda}_{d} & \text{for } \mathcal{Q}_{i} = \mathcal{Q}_{d\phi}, \mathcal{Q}_{d\phi^{2}}, \mathcal{Q}_{dHX}, \mathcal{Q}_{dHX^{2}}, \mathcal{Q}_{dX^{2}}, \\ \epsilon_{0}^{i} \mathbb{1} + \epsilon_{1}^{i} \Delta_{q} & \text{for } \mathcal{Q}_{i} = \mathcal{Q}_{\phi q}, \mathcal{Q}_{q\chi}, \mathcal{Q}_{qXX}, \mathcal{Q}_{q\tilde{X}X}, \mathcal{Q}_{DqX^{2}}, \mathcal{Q}_{qX}, \mathcal{Q}_{HqX}^{(1,3)}, \mathcal{Q}_{qa}, \\ \epsilon_{0}^{i} \mathbb{1} & \text{for } \mathcal{Q}_{i} = \mathcal{Q}_{\phi d}, \mathcal{Q}_{d\chi}, \mathcal{Q}_{dXX}, \mathcal{Q}_{d\tilde{X}X}, \mathcal{Q}_{DdX^{2}}, \mathcal{Q}_{dX}, \mathcal{Q}_{HdX}, \mathcal{Q}_{da}, \end{cases}$$

Numerics

$$\Delta_q = \begin{pmatrix} 0.8 & -3.3 - 1.5i & 79.3 + 35.4i \\ -3.3 + 1.5i & 16.6 & -397.5 + 8.1i \\ 79.3 - 35.4i & -397.5 - 8.1i & 9839.0 \end{pmatrix} \times 10^{-4}$$

 $\Delta_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18 - 0.08i & 191.3 + 85.4i \\ -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \\ 0.21 - 0.10i & -21.1 - 0.4i & 23728.1 \end{pmatrix} \times 10^{-6}$

8 operators are eliminated

Dark SMEFT with MFV: Scalar

all the operators survive some ones highly constrained

Dark SMEFT with MFV: Fermion, ALP

all the operators survive

Dark SMEFT with MFV: Vector

all the operators survive, some ones highly constrained

Backup

$$\begin{aligned}
\mathcal{Q}_{d\phi} &= \left(\bar{q}_p d_r H\right) \phi + \text{h.c.}, & \mathcal{Q}_{d\phi^2} &= \left(\bar{q}_p d_r H\right) \phi^2 + \text{h.c.}, \\
\mathcal{Q}_{\phi q} &= \left(\bar{q}_p \gamma_\mu q_r\right) \left(i\phi_1 \overleftrightarrow{\partial^{\mu}} \phi_2\right), & \mathcal{Q}_{\phi d} &= \left(\bar{d}_p \gamma_\mu d_r\right) \left(i\phi_1 \overleftrightarrow{\partial^{\mu}} \phi_2\right), & (4.2) \\
\mathcal{Q}_{q\chi} &= \left(\bar{q}_p \gamma_\mu q_r\right) (\bar{\chi} \gamma^{\mu} \chi), & \mathcal{Q}_{d\chi} &= \left(\bar{d}_p \gamma_\mu d_r\right) (\bar{\chi} \gamma^{\mu} \chi), & (4.3)
\end{aligned}$$

$$\mathcal{Q}_{dHX} = \left(\bar{q}_p \sigma_{\mu\nu} d_r\right) H X^{\mu\nu} + \text{h.c.}, \qquad (4.4)$$

$$\begin{aligned} \mathcal{Q}_{dX} &= \left(\bar{d}_{p}\gamma_{\mu}d_{r}\right)X^{\mu}, & \mathcal{Q}_{HdX} &= \left(H^{\dagger}H\right)\left(\bar{d}_{p}\gamma^{\mu}d_{r}\right)X_{\mu}, \\ \mathcal{Q}_{qX} &= \left(\bar{q}_{p}\gamma_{\mu}q_{r}\right)X^{\mu}, & \mathcal{Q}_{HqX}^{(1)} &= \left(H^{\dagger}H\right)\left(\bar{q}_{p}\gamma^{\mu}q_{r}\right)X_{\mu}, \\ \mathcal{Q}_{dX^{2}} &= \left(\bar{q}_{p}d_{r}H\right)X_{\mu}X^{\mu} + \text{h.c.}, & \mathcal{Q}_{HqX}^{(3)} &= \left(H^{\dagger}\tau^{I}H\right)\left(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r}\right)X_{\mu}, \\ \mathcal{Q}_{qXX} &= \left(\bar{q}_{p}\gamma_{\mu}q_{r}\right)X^{\mu\nu}X_{\nu}, & \mathcal{Q}_{dXX} &= \left(\bar{d}_{p}\gamma_{\mu}d_{r}\right)X^{\mu\nu}X_{\nu}, \\ \mathcal{Q}_{qXX} &= \left(\bar{q}_{p}\gamma_{\mu}q_{r}\right)\tilde{X}^{\mu\nu}X_{\nu}, & \mathcal{Q}_{dXX} &= \left(\bar{d}_{p}\gamma_{\mu}d_{r}\right)\tilde{X}^{\mu\nu}X_{\nu}, \\ \mathcal{Q}_{DqX^{2}} &= i\left(\bar{q}_{p}\gamma^{\mu}D^{\nu}q_{r}\right)X_{\mu}X_{\nu} + \text{h.c.}, & \mathcal{Q}_{DdX^{2}} &= i\left(\bar{d}_{p}\gamma^{\mu}D^{\nu}d_{r}\right)X_{\mu}X_{\nu} + \\ \mathcal{Q}_{dHX^{2}} &= \left(\bar{q}_{p}\sigma_{\mu\nu}d_{r}H\right)X_{1}^{\mu}X_{2}^{\nu} + \text{h.c.}, & \mathcal{Q}_{DdX^{2}} &= i\left(\bar{d}_{p}\gamma^{\mu}D^{\nu}d_{r}\right)X_{\mu}X_{\nu} + \\ \end{aligned}$$

$$Q_{qa} = \left(\bar{q}_p \gamma_\mu q_r\right) \partial^\mu a, \qquad \qquad Q_{da} = \left(\bar{d}_p \gamma_\mu d_r\right) \partial^\mu a, \qquad (4.7)$$

$$\mathcal{C}_{i} = \tilde{\mathcal{C}}_{i} \cdot \begin{cases} (m_{X}/\Lambda)^{2} & \text{for } \mathcal{Q}_{i} = \mathcal{Q}_{dX^{2}}, \mathcal{Q}_{DdX^{2}}, \mathcal{Q}_{DqX^{2}}, \mathcal{Q}_{dHX^{2}}, \\ (m_{X}/\Lambda) & \text{for } \mathcal{Q}_{i} = \text{others.} \end{cases}$$

 $_{r})X_{\mu},$

+ h.c.,

(4.5)

Backup

One can also apply the MFV hypothesis to the lepton sector. However, since the mechanism of neutrino mass generation is still unknown, there are different approaches to formulate the leptonic MFV [73–79]. Here, we consider the realization of leptonic MFV within the so-called minimal field content [73, 74], in which the neutrino masses are generated by the Weinberg operator. In this case, the Yukawa interactions in the lepton sector can be written as

$$-\Delta \mathcal{L} = \bar{e} Y_e H^{\dagger} l + \frac{1}{2\Lambda_{\rm LN}} \left(\bar{l}^c \tau_2 H \right) Y_{\nu} \left(H^T \tau_2 l \right) + \text{h.c.}, \qquad (2.18)$$

where *l* denotes the left-handed lepton doublet with the charge conjugated field given by $l^c = -i\gamma_2 l^*$, and e is the right-handed charged lepton singlet. $\Lambda_{\rm LN}$ denotes the breaking scale of the lepton number symmetry $U(1)_{\rm LN}$. Y_e and Y_{ν} stand for the 3×3 Yukawa coupling matrices in flavour space. In the absence of these Yukawa couplings, the lepton sector respects the flavour symmetry

$$G_{\rm LF} = SU(3)_l \otimes SU(3)_e. \tag{2.19}$$

finite polynomial of A_{ℓ} and B_{ℓ} . After neglecting all the terms involving B_{ℓ} , which are suppressed by the small lepton Yukawa couplings Y_e , we obtain

$$\mathcal{C}_{\rm MFV} \approx \kappa_0 + \kappa_1 \mathsf{A}_{\ell} + \kappa_2 \mathsf{A}_{\ell}^2, \qquad (2.21)$$

where the coefficients $\kappa_{0,1,2}$ are free real parameters. In the numerical analysis, we keep only the leading lepton flavour violation term A_{ℓ} for simplicity, i.e., $\kappa_2 = 0$. Turning to the lepton mass eigenbasis, the current $\bar{l}\gamma^{\mu}Cl$ gives in the MFV hypothesis the following interactions:

$$\bar{e}_L \gamma^\mu (\kappa_0 \mathbb{1} + \kappa_0 \Delta_\ell) e_L + \bar{\nu}_L \gamma^\mu (\kappa_0 \mathbb{1} + \kappa_0 \hat{\lambda}_\nu^2) \nu_L, \qquad (2.22)$$

where the basic LFV coupling Δ_{ℓ} can be obtained from A_{ℓ} and takes the form

$$\Delta_{\ell} = U \hat{\lambda}_{\nu}^2 U^{\dagger}, \qquad (2.23)$$

 $\Delta_{\ell}^{\text{NO}} = \begin{pmatrix} -0.19 - 0.01i & -0.25 - 0.02i & 0.31 - 0.04i \\ 0.12 + 0.01i & 0.28 - 0.00i & 0.29 + 0.04i \\ -0.37 - 0.01i & 0.21 - 0.05i & -0.03 + 0.01i \end{pmatrix}, \quad \Delta_{\ell}^{\text{IO}} = \begin{pmatrix} 0.21 + 0.09i & -0.34 + 0.05i & 0.03 + 0.11i \\ 0.31 + 0.12i & 0.19 + 0.00i & -0.15 - 0.14i \\ 0.12 - 0.02i & 0.04 - 0.19i & 0.34 - 0.10i \end{pmatrix}$

RECONSTRUCTION AND SELECTION

- Charged particles: $p_T > 100$ MeV/c, close to collision point, in the central part of the detector
- Neutral particles: E > 100 MeV, in the central part of the detector
- Signal kaon candidates reconstructed applying kaon-enriching selection

