IPMU

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Phenomenology of low-energy flavour models: rare processes and dark matter

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Why are we interested in Flavour Physics?

SM flavour puzzle	We need to find the scale of New Physics!
• Why three families?	• LHC found a SM-like Higgs
• Why the hierarchies? $m_t/m_e = 3.4 \times 10^5$	• No evidence of new phenomena
	• We know there is new physics somewhere (DM, neutrino masses, baryogenesis etc.)

Hierarchy of SM fermion masses and mixing

Up quarks

$$\frac{m_c}{m_t} \approx \epsilon^4, \quad \frac{m_u}{m_t} \approx \epsilon^8$$

Down quarks

$$\frac{m_s}{m_b} \approx \epsilon^3, \quad \frac{m_d}{m_b} \approx \epsilon^5$$

CKM matrix

$$V_{CKM} \approx \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

$$\epsilon \approx 0.23$$

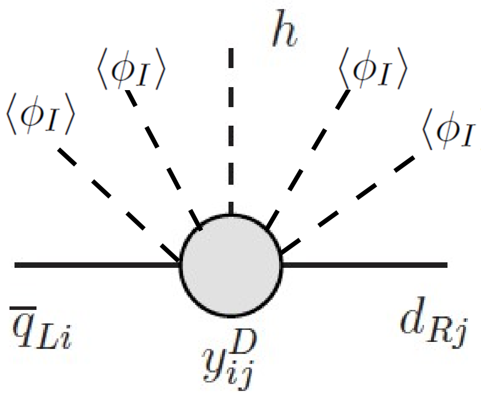
Hints for an organizing principle: is there a dynamical explanation?

Froggatt Nielsen '79
Leurer Seiberg Nir '92, '93

- SM fermions charged under a new horizontal symmetry G_F
- G_F forbids Yukawa couplings at the renormalisable level
- G_F spontaneously broken by "flavons" vevs $\langle \phi_I \rangle$
- Yukawas arise as higher dimensional operators

$$\mathcal{L}_{yuk} = y^U_{ij}\, \overline{q}_{Li} u_{Rj}\, \tilde{h} + y^D_{ij}\, \overline{q}_{Li} d_{Rj}\, h + \text{h.c.}$$

$$y^{U,D}_{ij} \sim \prod_I \left(\frac{\langle \phi_I \rangle}{M} \right)^{n^{U,D}_{I,ij}}$$



$\phi_I < M \Rightarrow \epsilon_I \equiv \langle \phi_I \rangle / M$ small exp. parameter

$n^{U,D}_{I,ij}$ dictated by the symmetry

What is G_F ?

G_F abelian or non-abelian, continuous or discrete

U(1), U(1)xU(1), SU(2), SU(3), SO(3), A_4...

Froggatt Nielsen ’79; Leurer Seiberg Nir ’92, ’93; Ibanez Ross ’94; Dudas Pokorski Savoy ’95; Binetruy Lavignac Ramond ’96; Barbieri Dvali Hall ’95; Pomarol Tommasini ’95; Berezhiani Rossi '98; King Ross ’01; Ma '02; Altarelli Feruglio ’05...

U(1) example

Chankowski et al. ‘05

$$(\mathcal{Q}_{q_1},\, \mathcal{Q}_{q_2},\, \mathcal{Q}_{q_3}) = (3,\, 2,\, 0)$$
$$(\mathcal{Q}_{u_1},\, \mathcal{Q}_{u_2},\, \mathcal{Q}_{u_3}) = (3,\, 2,\, 0) \quad \mathcal{Q}_\phi = -1$$
$$(\mathcal{Q}_{d_1},\, \mathcal{Q}_{d_2},\, \mathcal{Q}_{d_3}) = (4,\, 2,\, 2)$$

$\Rightarrow$

$$y^u_{ij} = a^u_{ij}\,\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{u_j}}$$
$$y^d_{ij} = a^d_{ij}\,\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{d_j}}$$

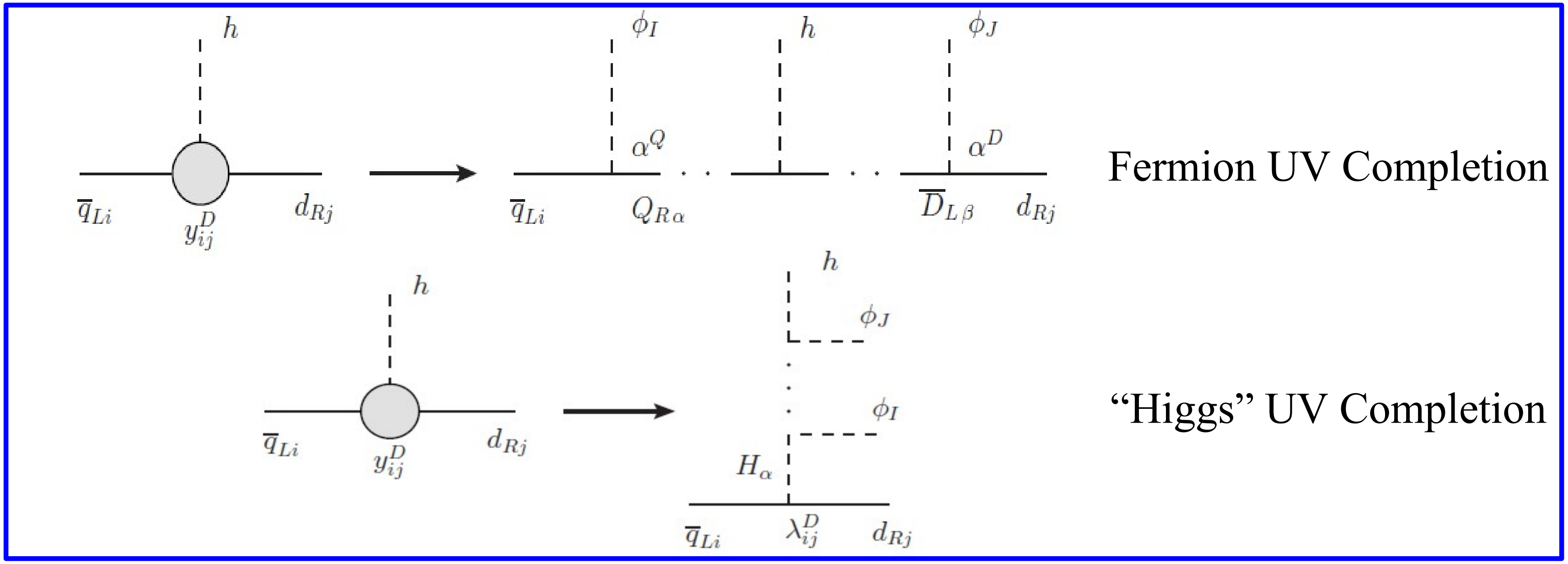
$$\epsilon = \phi/M \approx 0.23$$

$$Y_u \sim \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \qquad Y_d \sim \begin{pmatrix} \epsilon^7 & \epsilon^5 & \epsilon^5 \\ \epsilon^6 & \epsilon^4 & \epsilon^4 \\ \epsilon^4 & \epsilon^2 & \epsilon^2 \end{pmatrix}$$

What is M ?

- If smaller than M_{Pl}, M can be interpreted as the mass scale of new degrees of freedom: the "flavour messengers"
- New fields in vector-like representations of the SM group and G_F-charged
- Effective Yukawa couplings generated by integrating out the messengers.
- Two possibilities: heavy fermions or heavy scalars:

LC Lalak Pokorski Ziegler '12



⇨ messengers mix with SM fermions or scalar fields and induce FCNC

Bounds on effective FCNC operators

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_{ij}^{(d)}}{\Lambda_{NP}^{d-4}} O_{ij}^{(d)}$$

Hadronic FCNC and CPV:

Isidori Nir Perez '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

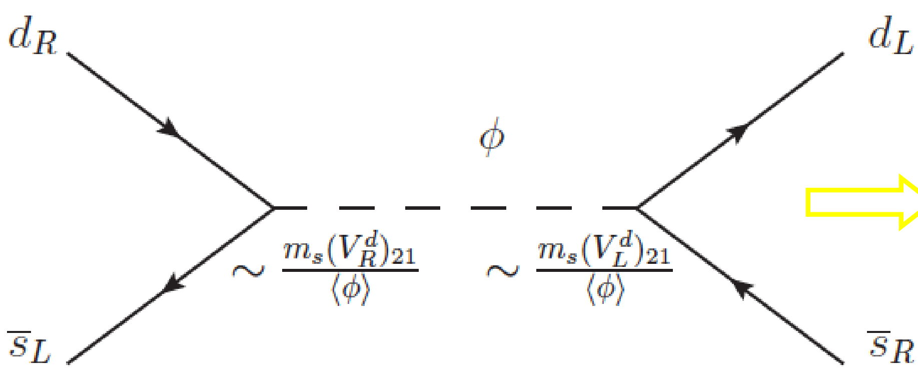
How light can the flavour dynamics be?

- Effective Yukawas imply fermion-flavon couplings

$$(m_f)_{ij} = a^f_{ij} \left(\frac{\langle \phi \rangle}{M} \right)^{n^f_{ij}} \frac{v}{\sqrt{2}} \quad \Rightarrow \quad \mathcal{L} \supset n^f \frac{m_f}{\langle \phi \rangle} f_L f_R \phi$$

- Generically flavour violating
- FCNC induced at tree-level, but suppressed by small quark masses, e.g.:

Leurer Seiberg Nir '92, '93



$$\Rightarrow \quad (\overline{s}_L d_R)(\overline{s}_R d_L)$$

- What if the flavour symmetry is local?

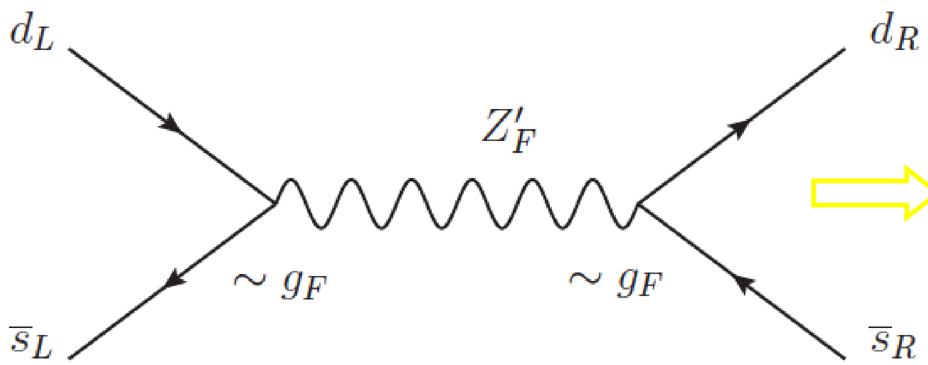
How light can the flavour dynamics be?

- Local flavour symmetry ⇒ flavour gauge bosons, e.g. abelian Z' :

$$\mathcal{L} \supset \; g_F \, \overline{f} \gamma^\mu (\mathcal{Q}_{f_L} P_L + \mathcal{Q}_{f_R} P_R) f \;\, Z'_\mu$$

- FV couplings to fermions (different generations have different charges)

- FCNC also arise at tree-level, e.g.:



⇒ $(\overline{s}_L \gamma^\mu d_L)(\overline{s}_R \gamma_\mu d_R)$

- Additional contributions arise from the messenger sector

How light can the messenger sector be?

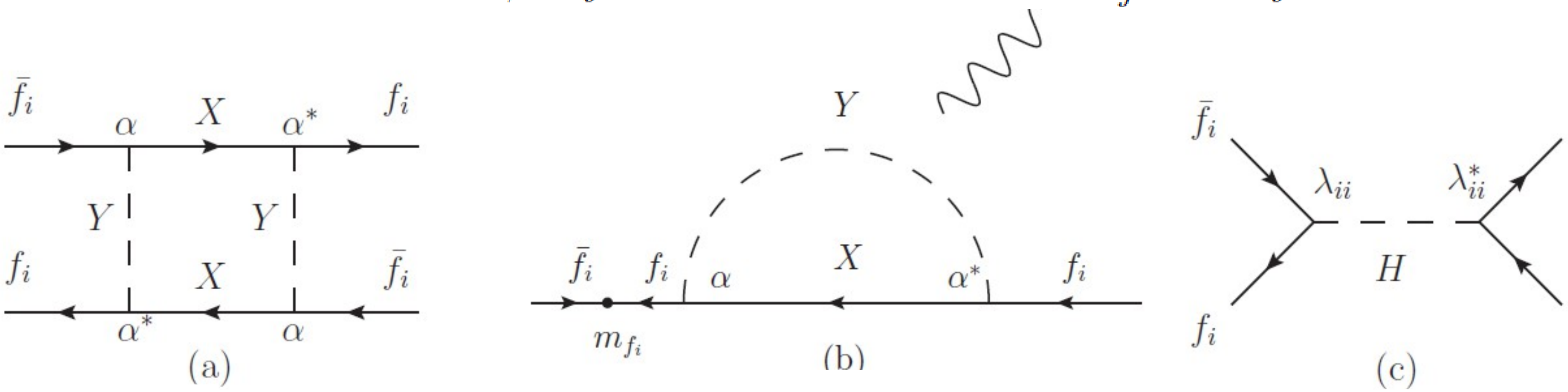
By construction always present couplings (with O(1) coeffs.) of the form:

FUVC

$$\mathcal{L} \supset \alpha^Q \, \overline{q}_{Li} Q_{R\alpha} \, \phi_I + \alpha^D \, \overline{D}_{L\beta} d_{Rj} \, \phi_J + \text{h.c.}$$

HUVC

$$\mathcal{L} \supset \lambda^D_{ij} \, \overline{q}_{Li} d_{Rj} \, H_\alpha + \text{h.c.}$$



$$\mathcal{L}_{eff} \supset \frac{|\alpha|^4}{16\pi^2 M^2} (\overline{f}_{Li} \gamma^\mu f_{Li})^2 \qquad \mathcal{L}_{eff} \supset \frac{|\alpha|^2}{16\pi^2 M^2} m_i \, \overline{f}_{Li} \sigma^{\mu\nu} f_{Ri} F_{\mu\nu} \qquad \mathcal{L}_{eff} \supset \frac{|\lambda_{ij}|^2}{M^2} (\overline{d}_{Li} d_{Rj})(\overline{d}_{Rj} d_{Li})$$

Flavour conserving ⇨ Flavour violating in the mass basis: $d_{Li} \to d_{Li} + \sum_{j \neq i} \theta^{DL}_{ij} d_{Lj}$

[Abelian models: no cancellations (different O(1) coefficients)]

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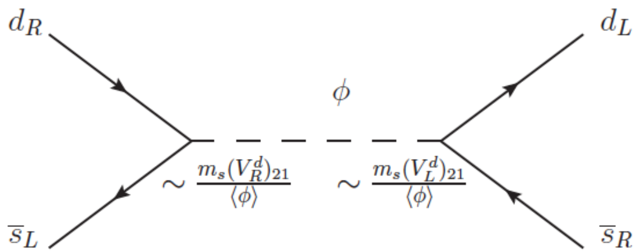
FCNC bounds on FN models

U(1) example:

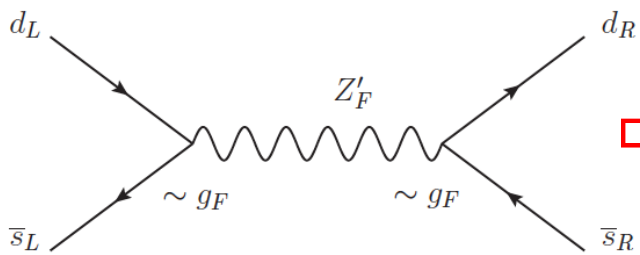
TeV-scale flavons are possible!



$$\Delta M_K : \ m_\phi \gtrsim 580 \text{ GeV}$$

$$\epsilon_K : \ m_\phi \gtrsim 2.3 \text{ TeV}$$

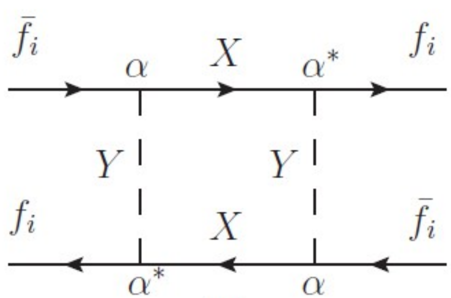
[with $\mathcal{O}(1)$ phases]



$$\Delta M_K : \ m_\phi \gtrsim \left(\frac{g_F}{10^{-3}}\right) \times 210 \text{ GeV}$$

$$\epsilon_K : \ m_\phi \gtrsim \left(\frac{g_F}{10^{-3}}\right) \times 3.3 \text{ TeV}$$

[with $\mathcal{O}(1)$ phases]



(a)

$$\Delta M_K : \ m_\phi \gtrsim 1.7 \text{ TeV}$$

$$\epsilon_K : \ m_\phi \gtrsim 27 \text{ TeV} \quad \text{[with } \mathcal{O}(1) \text{ phases]}$$

(indirect bounds from messenger sector)

LC Crivellin Zaldivar '15

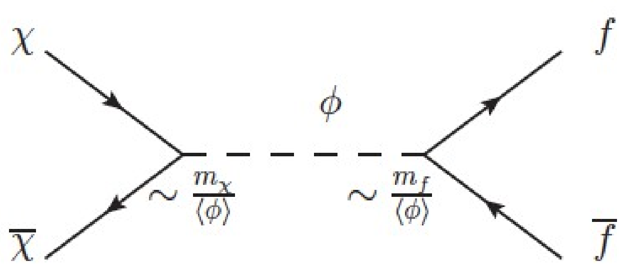
- DM must interact weakly with the SM, likely to be a SM singlet
- We introduce DM: fermionic SM singlets charged under the flavour symmetry G_F
- Flavour interactions are the only connection between dark and visible sector
- Global G_F : DM and SM communicate only through flavon exchange
- Local G_F : interactions can be also mediated by flavour gauge bosons

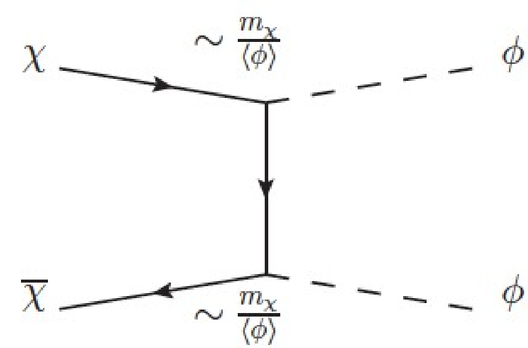
Global G_F

$$(m_f)_{ij} = a^f_{ij} \left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}} \frac{v}{\sqrt{2}} \qquad m_\chi = b_\chi \left(\frac{\langle\phi\rangle}{M}\right)^{n^\chi} \langle\phi\rangle \qquad m_\phi = k\langle\phi\rangle$$

$$\mathcal{L} \supset n^f \frac{m_f}{\langle\phi\rangle} f_L f_R \phi + (n^\chi + 1)\frac{m_\chi}{\langle\phi\rangle} \chi_L \chi_R \phi \;\equiv\; \lambda_f f_L f_R \phi + \lambda_\chi \chi_L \chi_R \phi$$

DM annihilation to SM:





$$\langle\sigma^{\rm S}_\phi v\rangle \sim \frac{\lambda_\chi^2 \lambda_f^2 m_\chi}{(4m_\chi^2 - m_\phi^2)^2 + \Gamma_\phi^2 m_\phi^2} T \qquad \langle\sigma^{\rm t}_\phi v\rangle \sim \frac{\lambda_\chi^4}{m_\chi^3} T$$

Global G_F

$$(m_f)_{ij} = a^f_{ij}\left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}}\frac{v}{\sqrt{2}} \qquad m_\chi = b_\chi\left(\frac{\langle\phi\rangle}{M}\right)^{n^\chi}\langle\phi\rangle \qquad m_\phi = k\langle\phi\rangle$$

$$\mathcal{L} \supset n^f\frac{m_f}{\langle\phi\rangle}f_L f_R \phi + (n^\chi + 1)\frac{m_\chi}{\langle\phi\rangle}\chi_L\chi_R\phi \;\equiv\; \lambda_f f_L f_R\phi + \lambda_\chi \chi_L\chi_R\phi$$

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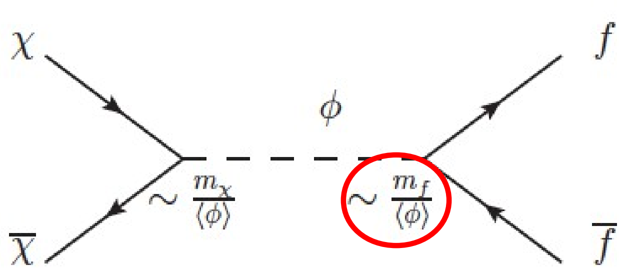
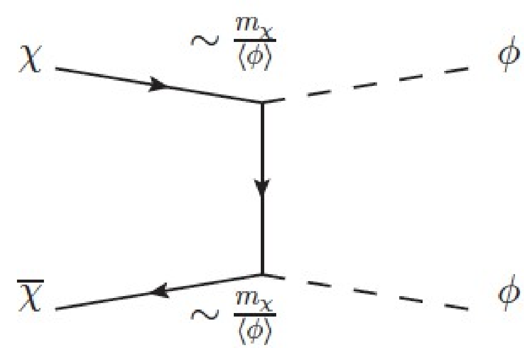




$$\langle\sigma^S_\phi v\rangle \sim \frac{\lambda^2_\chi\lambda^2_f m_\chi}{(4m^2_\chi - m^2_\phi)^2 + \Gamma^2_\phi m^2_\phi}T \qquad \langle\sigma^t_\phi v\rangle \sim \frac{\lambda^4_\chi}{m^3_\chi}T$$

annihilation to heavy flavours preferred

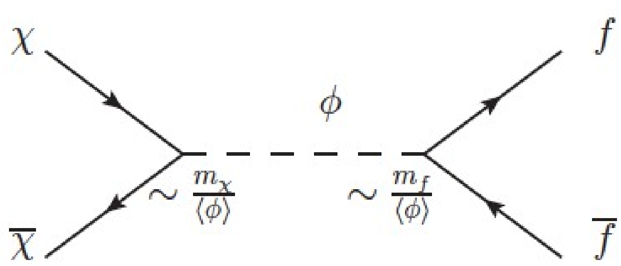
Generic setup: flavon mediation

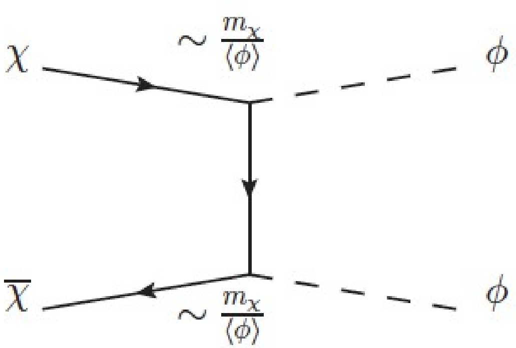
Global G_F

$$(m_f)_{ij} = a^f_{ij} \left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}} \frac{v}{\sqrt{2}} \qquad m_\chi = b_\chi \left(\frac{\langle\phi\rangle}{M}\right)^{n^\chi} \langle\phi\rangle \qquad m_\phi = k\langle\phi\rangle$$

$$\mathcal{L} \supset n^f \frac{m_f}{\langle\phi\rangle} f_L f_R \phi + (n^\chi + 1)\frac{m_\chi}{\langle\phi\rangle}\chi_L\chi_R\phi \equiv \lambda_f f_L f_R\phi + \lambda_\chi \chi_L\chi_R\phi$$

DM annihilation to SM:





$$\langle\sigma^S_\phi v\rangle \sim \frac{\lambda^2_\chi \lambda^2_f m_\chi}{(4m^2_\chi - m^2_\phi)^2 + \Gamma^2_\phi m^2_\phi} T \qquad \langle\sigma^t_\phi v\rangle \sim \frac{\lambda^4_\chi}{m^3_\chi} T$$

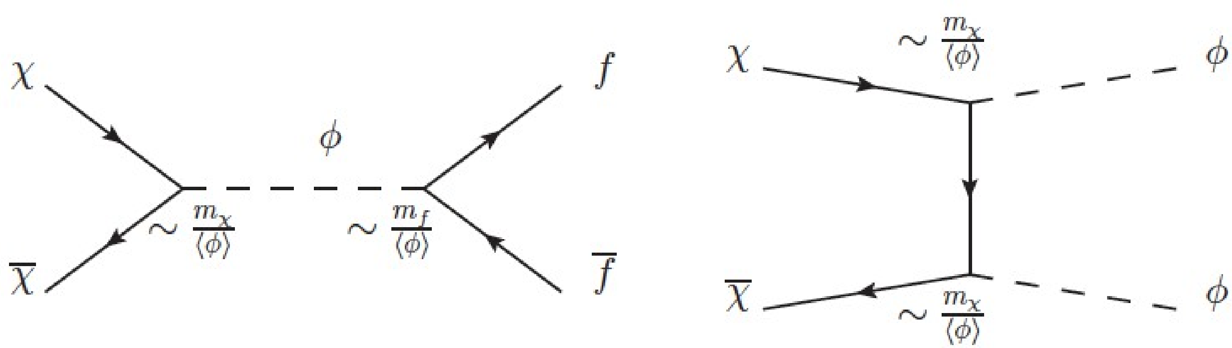
no coupling suppression

Global G_F

$$(m_f)_{ij} = a^f_{ij} \left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}} \frac{v}{\sqrt{2}} \qquad m_\chi = b_\chi \left(\frac{\langle\phi\rangle}{M}\right)^{n^\chi} \langle\phi\rangle \qquad m_\phi = k\langle\phi\rangle$$

$$\mathcal{L} \supset n^f \frac{m_f}{\langle\phi\rangle} f_L f_R \phi + (n^\chi + 1)\frac{m_\chi}{\langle\phi\rangle}\chi_L\chi_R\phi \;\equiv\; \lambda_f f_L f_R \phi + \lambda_\chi \chi_L \chi_R \phi$$

DM annihilation to SM:



$$\langle\sigma^{\rm S}_\phi v\rangle \sim \frac{\lambda_\chi^2 \lambda_f^2 m_\chi}{(4m_\chi^2 - m_\phi^2)^2 + \Gamma_\phi^2 m_\phi^2} T \qquad \langle\sigma^{\rm t}_\phi v\rangle \sim \frac{\lambda_\chi^4}{m_\chi^3} T$$

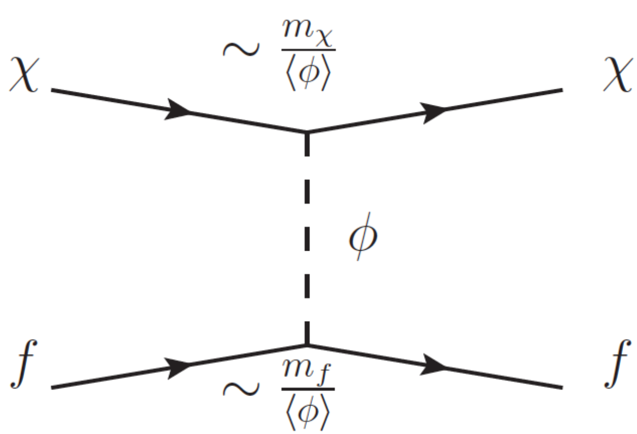
p-wave (velocity suppressed)

Global G_F

$$(m_f)_{ij} = a^f_{ij} \left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}} \frac{v}{\sqrt{2}} \qquad m_\chi = b_\chi \left(\frac{\langle\phi\rangle}{M}\right)^{n^\chi} \langle\phi\rangle \qquad m_\phi = k\langle\phi\rangle$$

$$\mathcal{L} \supset n^f \frac{m_f}{\langle\phi\rangle} f_L f_R \phi + (n^\chi + 1)\frac{m_\chi}{\langle\phi\rangle}\chi_L \chi_R \phi \equiv \lambda_f f_L f_R \phi + \lambda_\chi \chi_L \chi_R \phi$$

DM scattering with nuclei:



$$\sigma^{\rm SI}_\phi \sim \frac{\lambda^2_\chi \lambda^2_{\phi N}}{m^4_\phi} \mu^2_{\chi N}$$

Global G_F

$$(m_f)_{ij} = a^f_{ij} \left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}} \frac{v}{\sqrt{2}} \qquad m_\chi = b_\chi \left(\frac{\langle\phi\rangle}{M}\right)^{n^\chi} \langle\phi\rangle \qquad m_\phi = k\langle\phi\rangle$$

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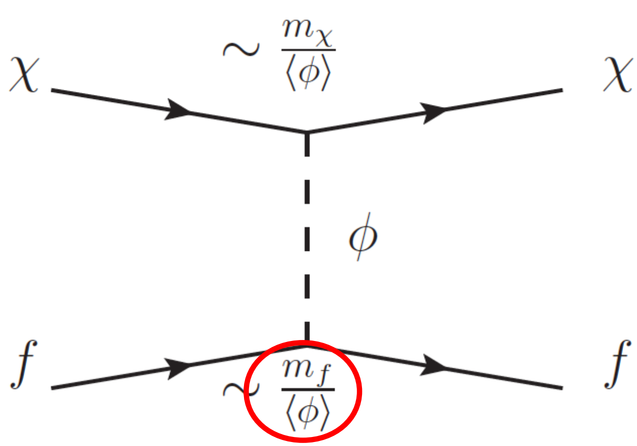


$$\sigma^{\rm SI}_\phi \sim \frac{\lambda^2_\chi \lambda^2_{\phi N}}{m^4_\phi} \mu^2_{\chi N}$$

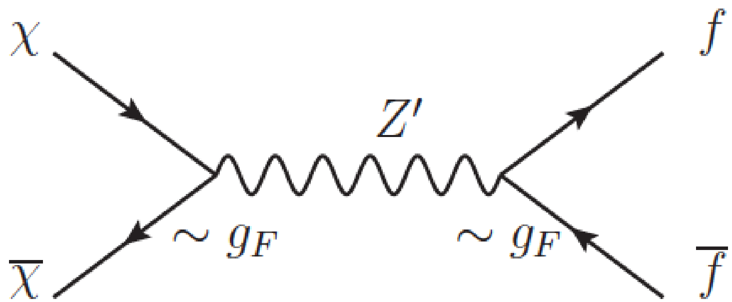
suppressed by light quark masses/matrix elements

Local G_F

$$\mathcal{L} \supset g_F\,\overline{\chi}\gamma^\mu(\mathcal{Q}_{\chi_L}P_L + \mathcal{Q}_{\chi_R}P_R)\chi\; Z'_\mu + g_F\,\overline{f}\gamma^\mu(\mathcal{Q}_{f_L}P_L + \mathcal{Q}_{f_R}P_R)f\; Z'_\mu$$

DM annihilation to SM:

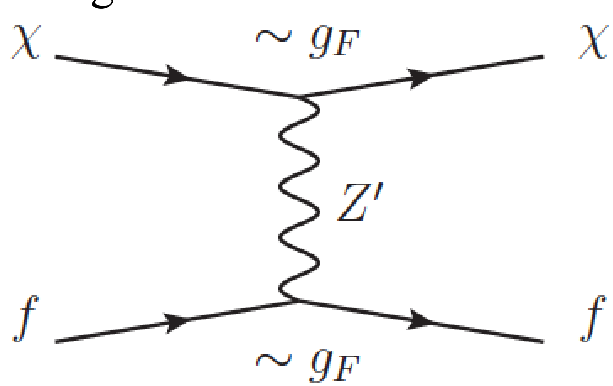
$$m_{Z'} = \sqrt{2}g_F\langle\phi\rangle$$



$$\langle\sigma_{Z'}v\rangle \sim \frac{g_F^4}{(m_{Z'}^2-4m_\chi^2)^2+\Gamma_{Z'}^2 m_{Z'}^2}m_\chi^2$$

no velocity suppression
no quark mass dependence

DM scattering with nuclei:

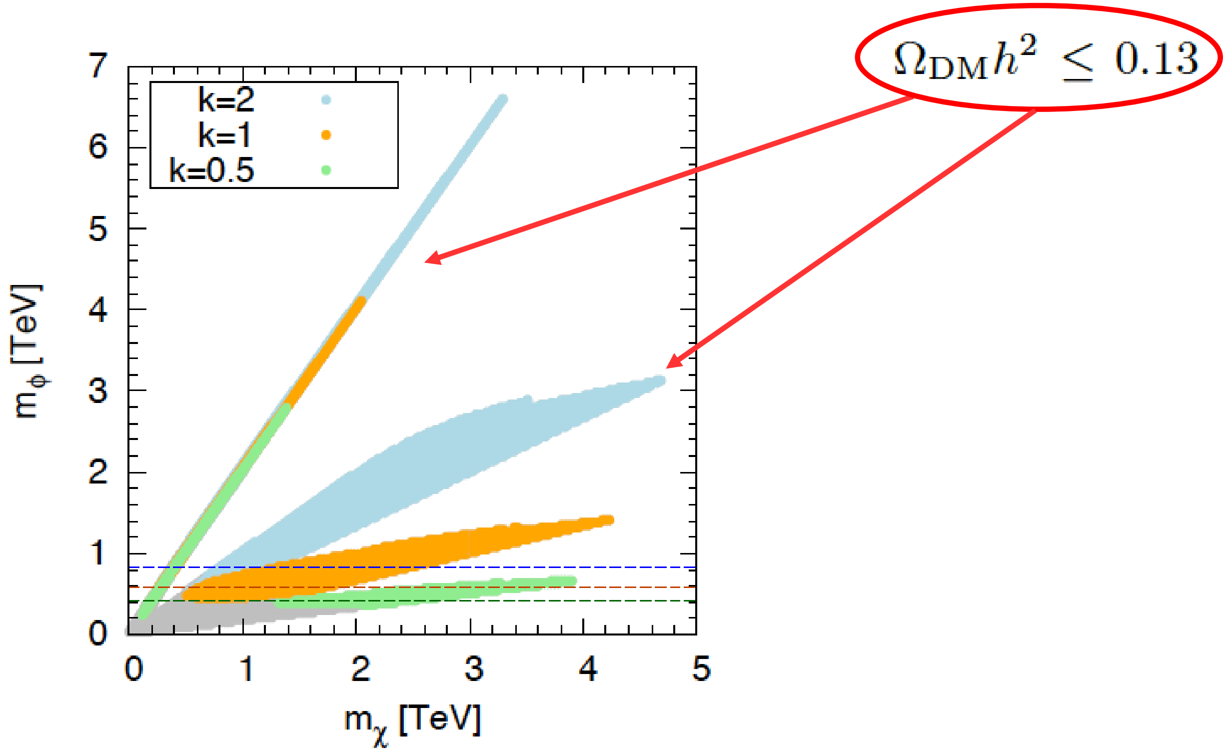


$$\sigma_{Z'}^{\mathrm{SI}} \sim \frac{g_F^2\lambda_{Z'N}^2}{m_{Z'}^4}\mu_{\chi N}^2 \qquad \lambda_{Z'N} \propto g_F$$

Explicit example

Simple U(1)$_F$, only few parameters (besides O(1) coeffs.): $m_\phi,\, m_\chi,\, k \equiv m_\phi/\langle\phi\rangle$

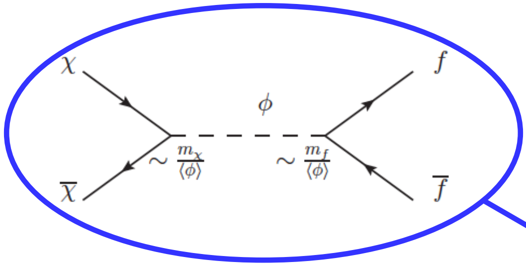
$$\lambda_{ij}^{(u,d)} = a_{ij}^{(u,d)}(\mathcal{Q}_{q_i} + \mathcal{Q}_{(u_j,d_j)})\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{(u_j,d_j)}}\frac{v}{\langle\phi\rangle}$$

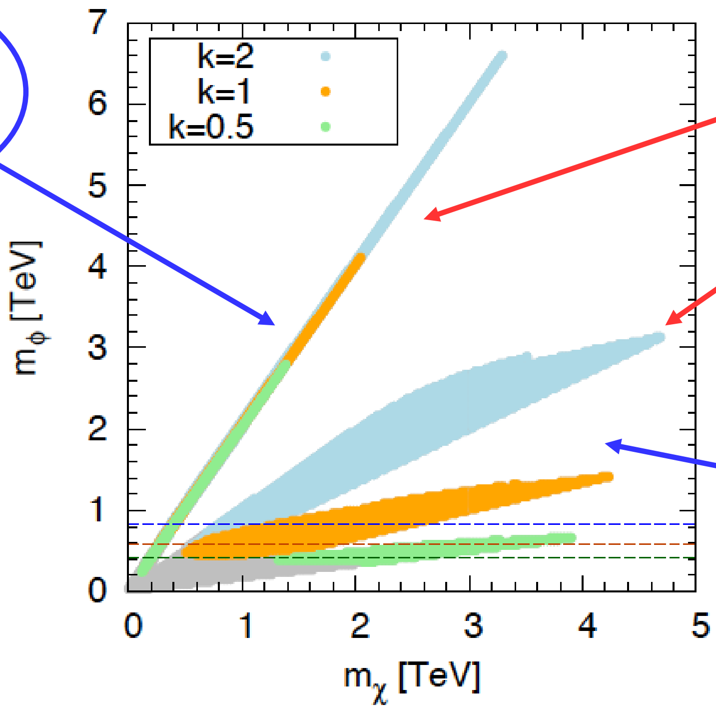


Thermal freeze-out via flavour portal motivation for TeV-scale flavour dynamics!

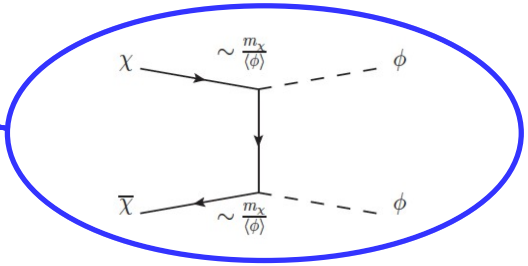
Simple U(1)$_F$, only few parameters (besides O(1) coeffs.): $m_\phi,\ m_\chi,\ k \equiv m_\phi/\langle\phi\rangle$

$$\lambda_{ij}^{(u,d)} = a_{ij}^{(u,d)}(\mathcal{Q}_{q_i} + \mathcal{Q}_{(u_j,d_j)})\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{(u_j,d_j)}} \frac{v}{\langle\phi\rangle}$$





$\Omega_{\rm DM}h^2 \leq 0.13$



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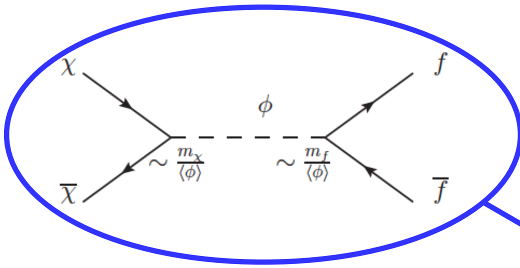

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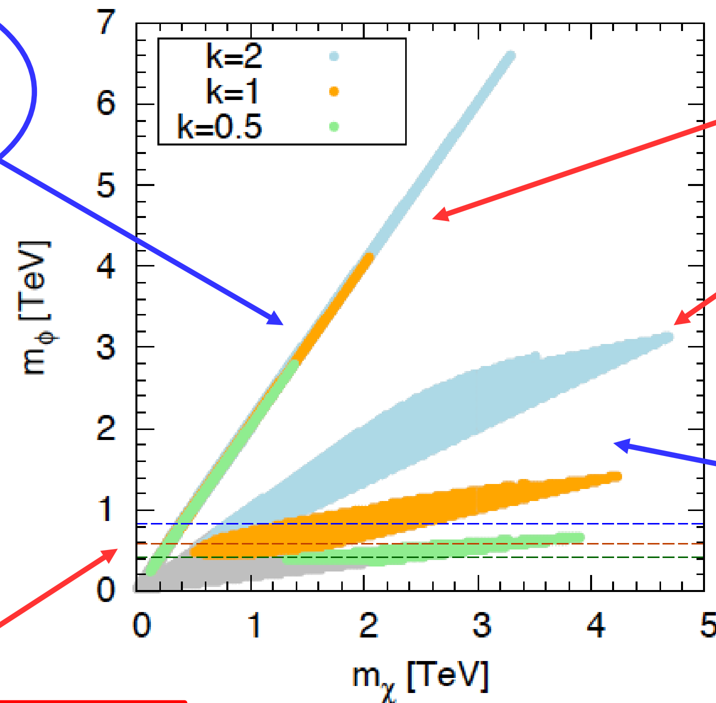
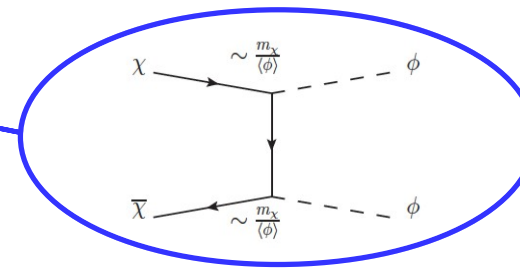
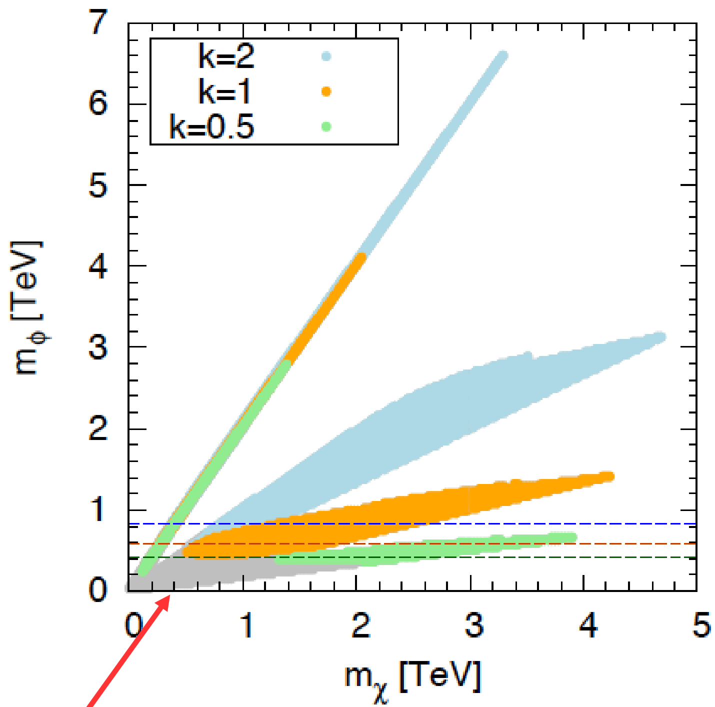




$m_\phi \gtrsim \sqrt{k} \times 580\ \text{GeV}$

Simple U(1)$_F$, only few parameters (besides O(1) coeffs.): $m_\phi,\ m_\chi,\ k \equiv m_\phi/\langle\phi\rangle$

$$\lambda_{ij}^{(u,d)} = a_{ij}^{(u,d)}(\mathcal{Q}_{q_i} + \mathcal{Q}_{(u_j,d_j)})\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{(u_j,d_j)}}\frac{v}{\langle\phi\rangle}$$

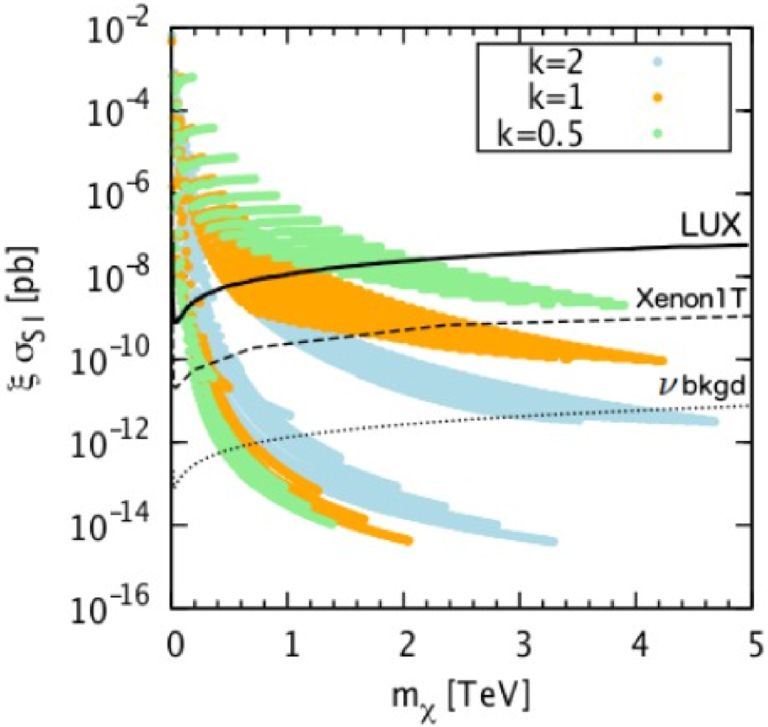


Excluded by direct searches

Explicit example

Simple U(1)$_F$, only few parameters (besides O(1) coeffs.): $m_\phi,\ m_\chi,\ k \equiv m_\phi/\langle\phi\rangle$

$$\lambda_{ij}^{(u,d)} = a_{ij}^{(u,d)}(\mathcal{Q}_{q_i} + \mathcal{Q}_{(u_j,d_j)})\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{(u_j,d_j)}}\frac{v}{\langle\phi\rangle}$$



Local $U(1)_F$, relic density bound only fulfilled on the resonance: $m_\chi \approx m_{Z'}/2$

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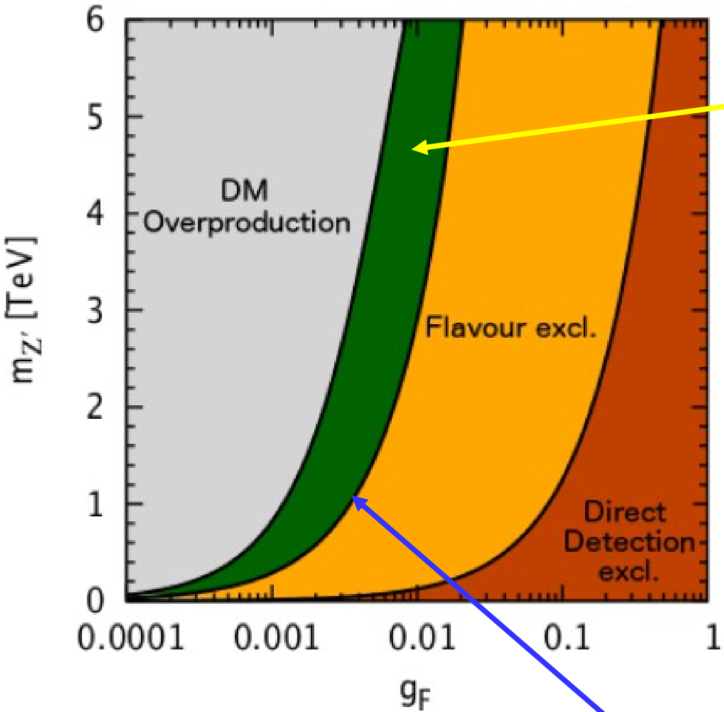
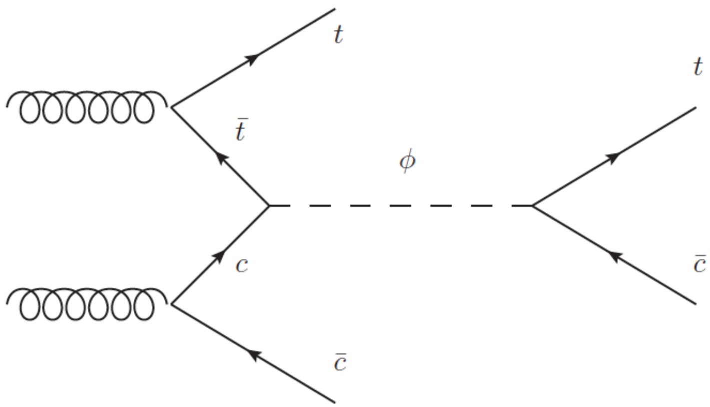


Viable region

$$m_{Z'} \gtrsim \left(\frac{g_F}{10^{-3}}\right) \times 210 \text{ GeV}$$

Flavon production and decay → distinctive signatures, e.g. same-sign tops

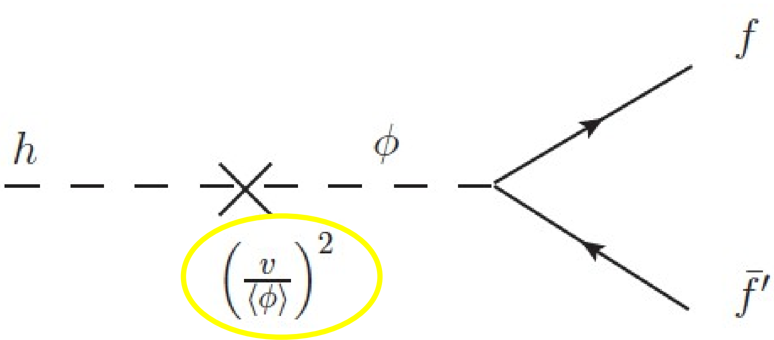


Low production at the LHC:

0.1 (10^{-3}) fb for 500 (1000) GeV flavon

Flavon-Higgs mixing → flavour-violating Higgs decays

$$\mathcal{L} \supset \; H^\dagger H \phi^\dagger \phi$$



Froggatt-Nielsen flavour models are possible explanation of hierarchies in fermion masses and mixing

FCNC constraints still allows TeV-scale flavour dynamics

Dark Matter can be a thermal relic charged under the flavour symmetry only

No ad hoc quantum numbers are needed: SM-DM interactions dictated by the flavour dynamics (“Flavour Portal”)

Direct DM searches and flavour experiments can test this class of models

ありがとうございます。