Dark Side of the Universe 2015

Kyoto University

The Flavour Portal to Dark Matter

Lorenzo Calibbi

ITP CAS, Beijing

December 18th 2015

Why are we interested in Flavour Physics?

SM flavour puzzle

- Why three families?
- Why the hierarchies?

$m_t/m_e = 3.4 \times 10^5$

We need to find the scale of New Physics!

- LHC found a SM-like Higgs
- No sign 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?


基礎物理学研究所
YUKAWA INSTITUTE FOR THEORETICAL PHY
HIDEKI YUKAWA

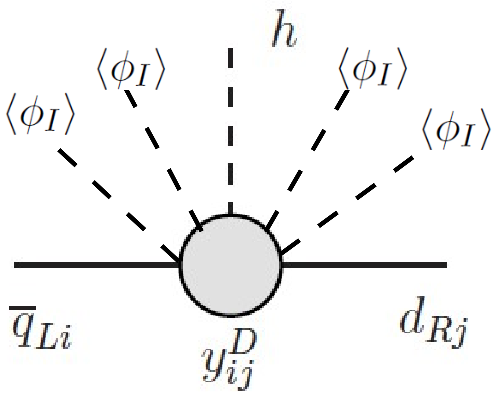
Froggatt-Nielsen flavour models

- 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

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

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

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



$\phi_I < M \Rightarrow \epsilon_I \equiv \langle \phi_I \rangle / M$ 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

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

$\Rightarrow$

$$y^u_{ij} = a^u_{ij}\,\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{u_j}}$$
$$y^d_{ij} = a^d_{ij}\,\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{d_j}}$$
$$\epsilon = \phi/M \approx 0.23$$

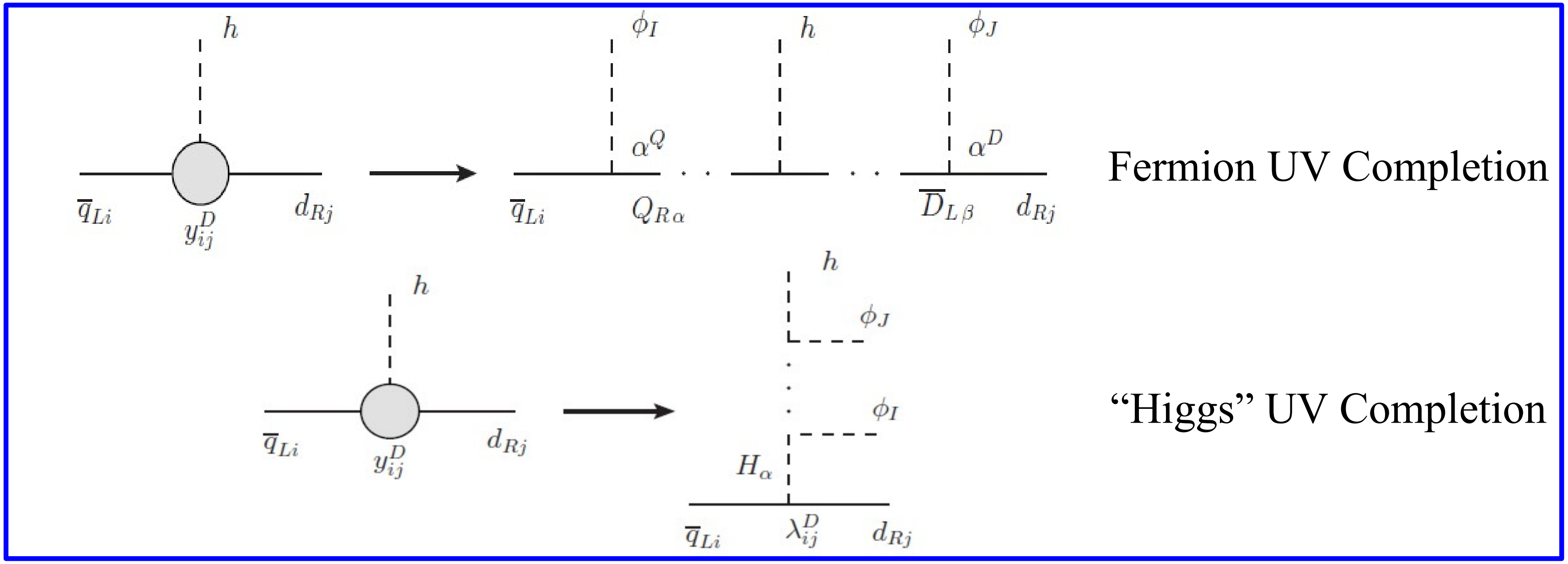
$$Y_u \sim \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \qquad Y_d \sim \begin{pmatrix} \epsilon^7 & \epsilon^5 & \epsilon^5 \\ \epsilon^6 & \epsilon^4 & \epsilon^4 \\ \epsilon^4 & \epsilon^2 & \epsilon^2 \end{pmatrix}$$

What is M ?

The messenger sector

- 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

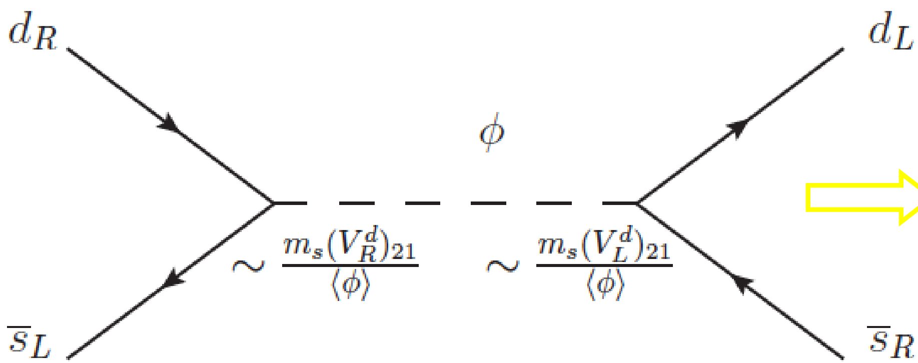
How light can the flavour dynamics be?

- 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?

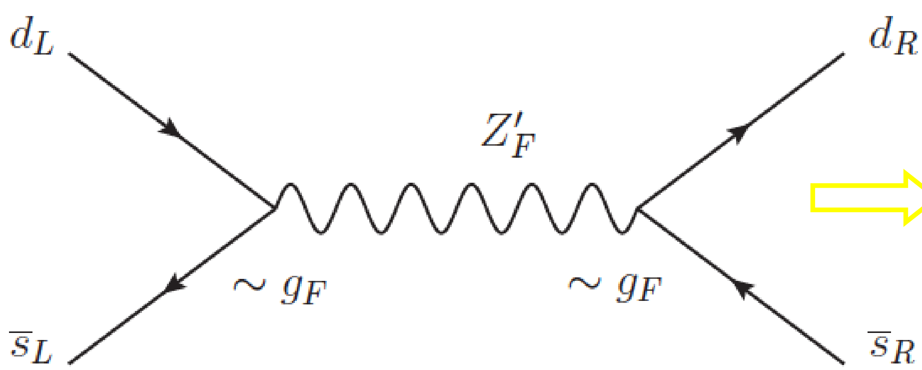
How light can the flavour dynamics be?

- 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?

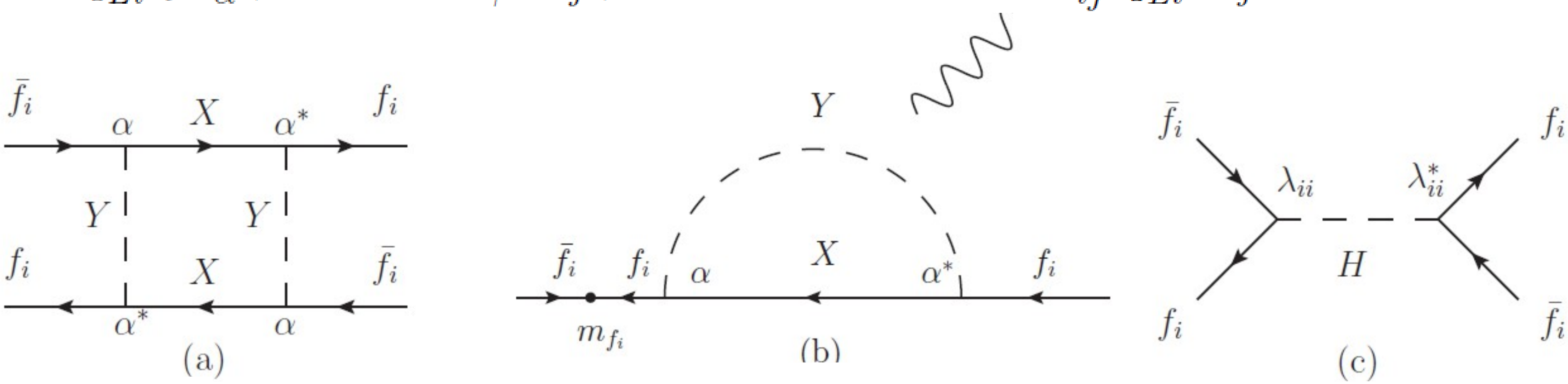
By construction always present couplings (with O(1) coeffs.) of the form:

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)]

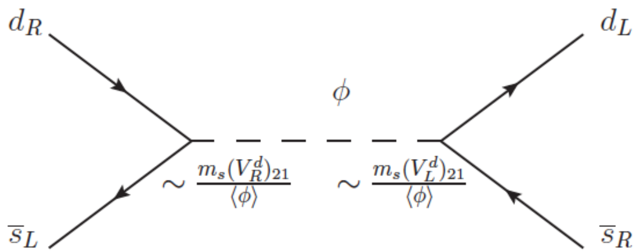
LC Lalak Pokorski Ziegler ‘12

FCNC bounds on FN models

U(1) example:

TeV-scale flavons are possible!

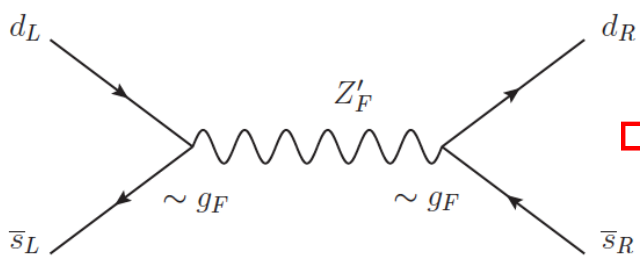
$$m_\phi = k\langle\phi\rangle$$



$$\Delta M_K : \; m_\phi \gtrsim \sqrt{k} \times 580 \text{ GeV}$$

$$\epsilon_K : \; m_\phi \gtrsim \sqrt{k} \times 2.3 \text{ TeV}$$

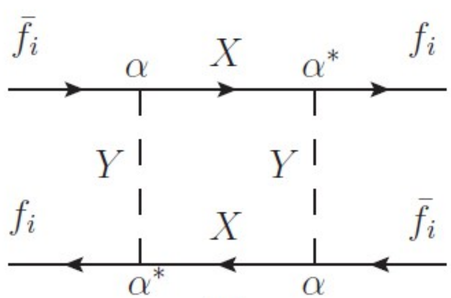
[with $\mathcal{O}(1)$ phases]



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

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

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



(a)

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

$$\epsilon_K : \; m_\phi \gtrsim k \times 27 \text{ TeV}$$

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

(indirect bounds from messenger sector)

LC Crivellin Zaldivar '15

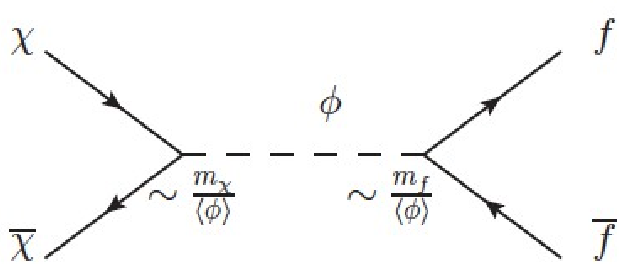
- DM must interact weakly with the SM, likely to be a SM singlet
- We introduce DM: fermionic SM singlets charged under the flavour symmetry G_F
- Flavour interactions are the only connection between dark and visible sector
- Global G_F : DM and SM communicate only through flavon exchange
- Local G_F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

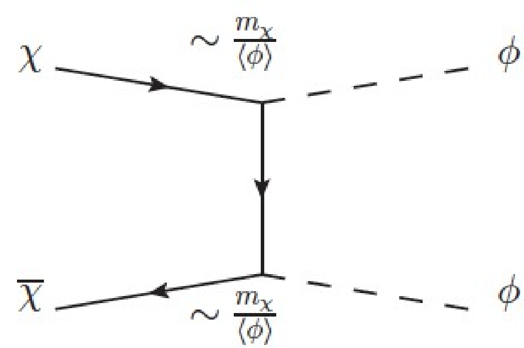
Global G_F

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

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

DM annihilation to SM:





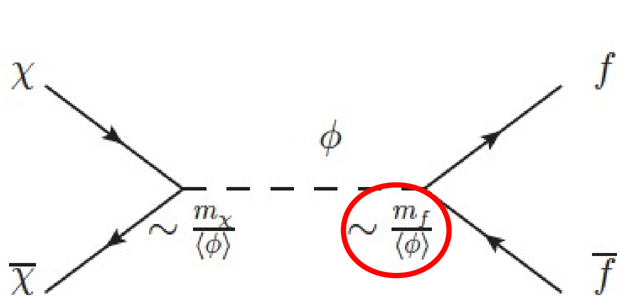
$$\langle\sigma^{\rm S}_\phi v\rangle \sim \frac{\lambda^2_\chi \lambda^2_f m_\chi}{(4m^2_\chi - m^2_\phi)^2 + \Gamma^2_\phi m^2_\phi} T \qquad \langle\sigma^{\rm t}_\phi v\rangle \sim \frac{\lambda^4_\chi}{m^3_\chi} T$$

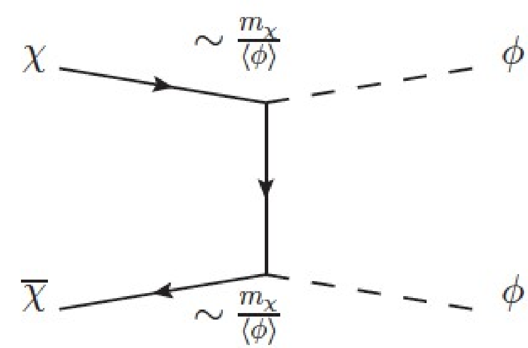
Global G_F

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

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

DM annihilation to SM:





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

annihilation to heavy flavours preferred

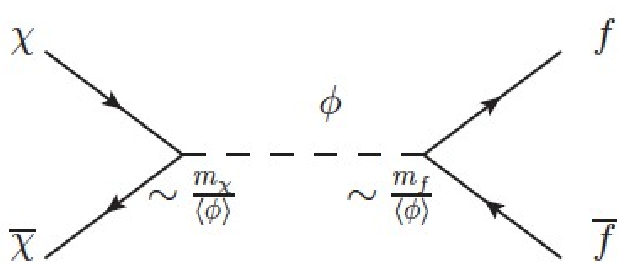
Generic setup: flavon mediation

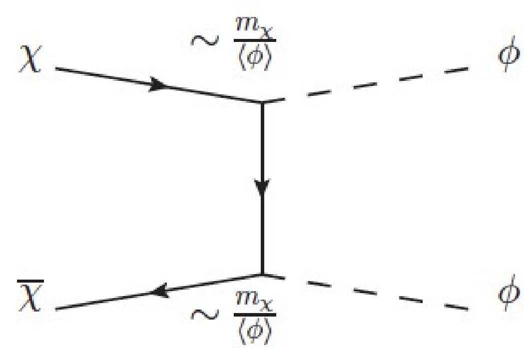
Global G_F

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

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

DM annihilation to SM:





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

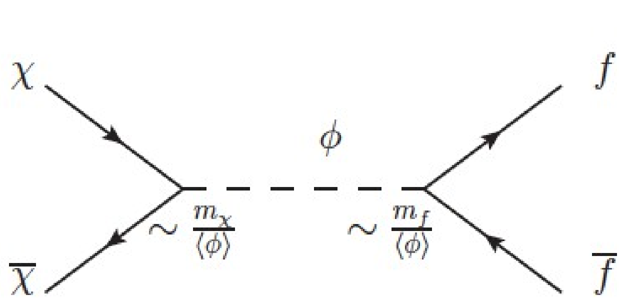
no coupling suppression

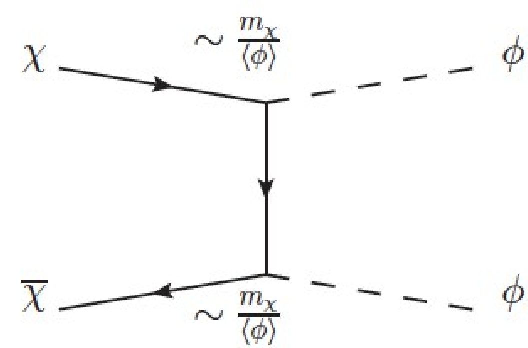
Global G_F

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

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

DM annihilation to SM:





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

p-wave (velocity suppressed)

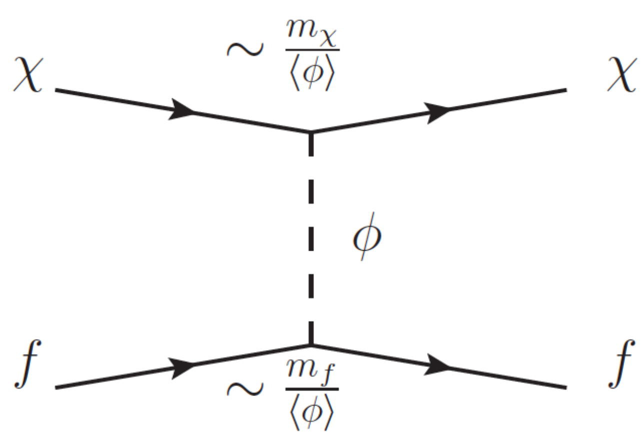
Generic setup: flavon mediation

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 scattering with nuclei:



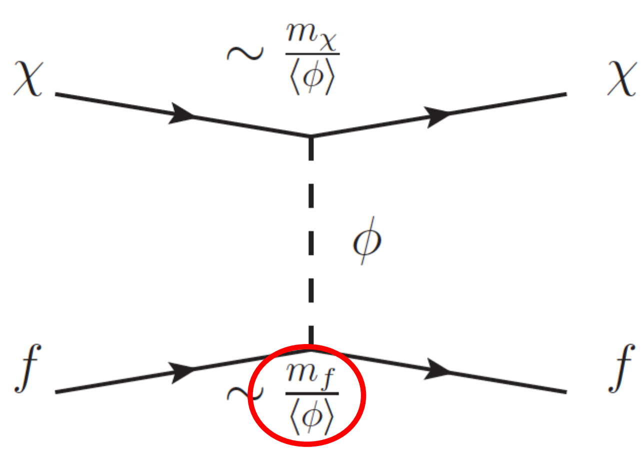
$$\sigma^{\rm SI}_\phi \sim \frac{\lambda^2_\chi \lambda^2_{\phi N}}{m^4_\phi}\mu^2_{\chi N}$$

Global G_F

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

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

DM scattering with nuclei:



$$\sigma^{\rm SI}_\phi \sim \frac{\lambda_\chi^2 \lambda_{\phi N}^2}{m_\phi^4} \mu_{\chi N}^2$$

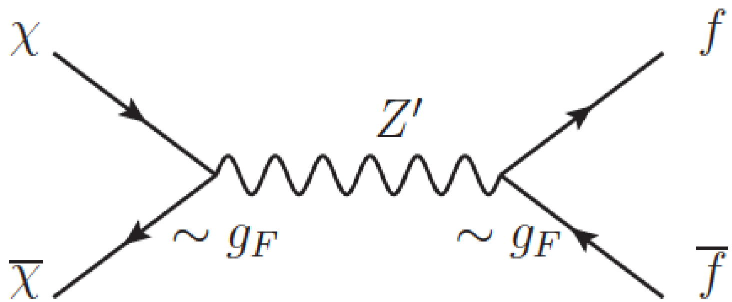
suppressed by light quark masses/matrix elements

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:

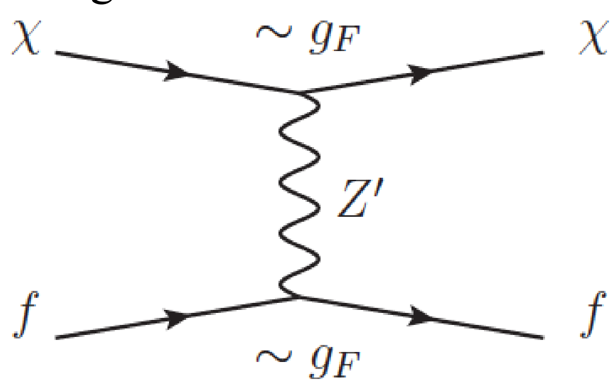
$$m_{Z'} = \sqrt{2} g_F \langle \phi \rangle$$



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

no velocity suppression
no quark mass dependence

DM scattering with nuclei:

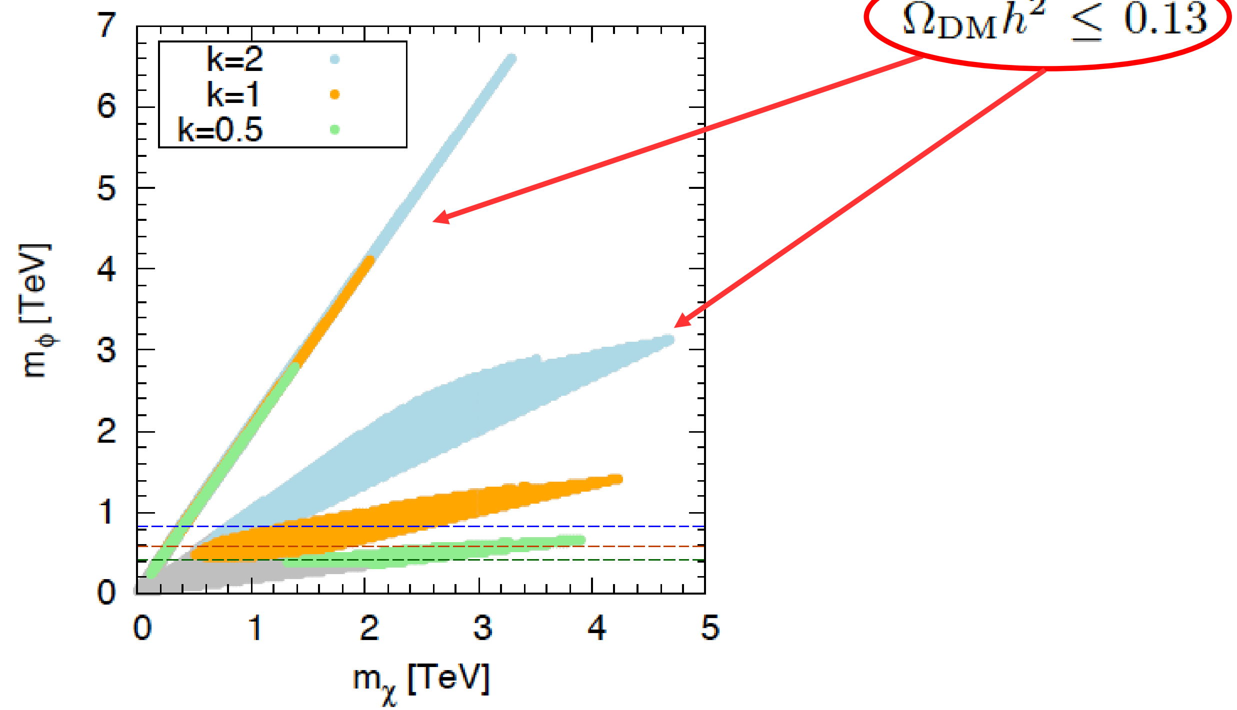


$$\sigma_{Z'}^{\rm SI} \sim \frac{g_F^2 \lambda_{Z'N}^2}{m_{Z'}^4} \mu_{\chi N}^2 \qquad \lambda_{Z'N} \propto g_F$$

Explicit example

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

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

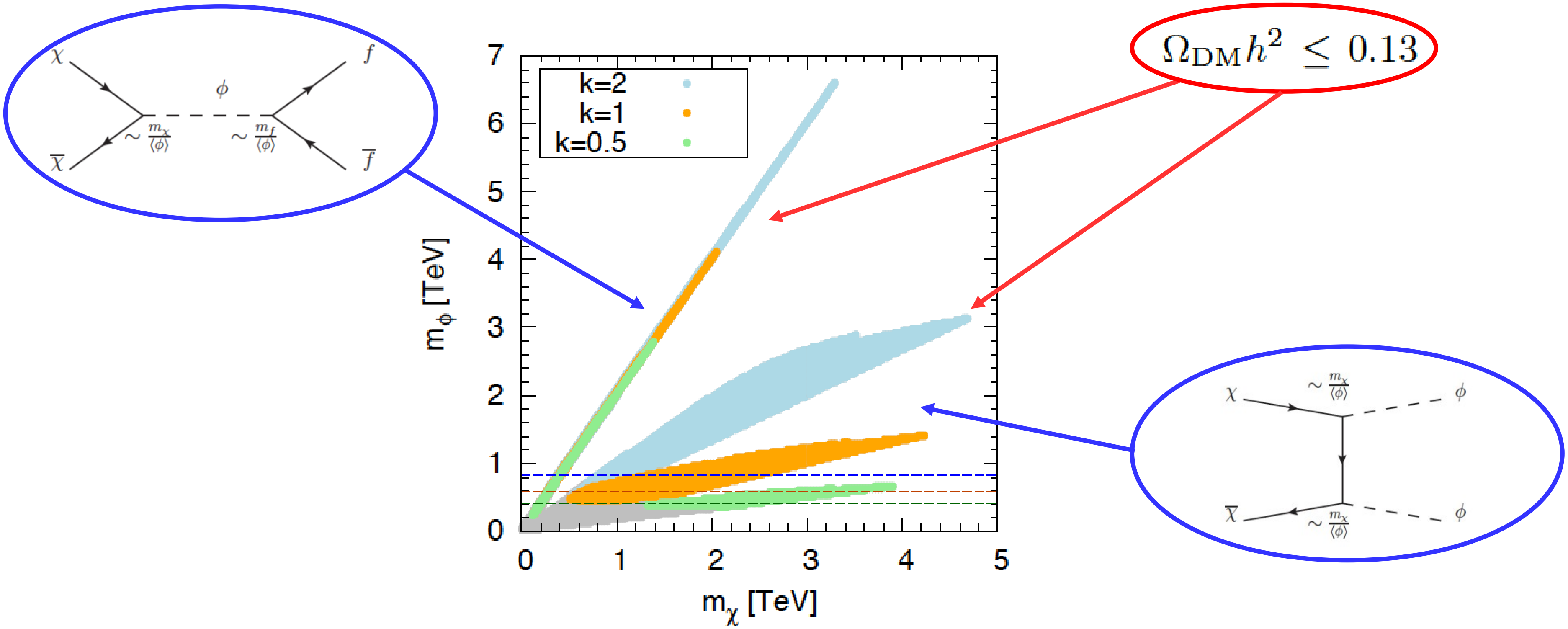


Thermal freeze-out via flavour portal motivation for TeV-scale flavour dynamics!

Explicit example

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

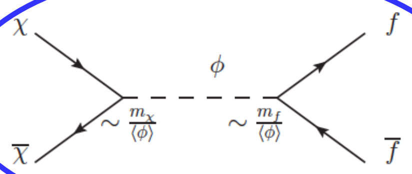
$$\lambda_{ij}^{(u,d)} = a_{ij}^{(u,d)}\left(\mathcal{Q}_{q_i} + \mathcal{Q}_{(u_j,d_j)}\right)\epsilon^{\mathcal{Q}_{q_i}+\mathcal{Q}_{(u_j,d_j)}}\frac{v}{\langle\phi\rangle}$$

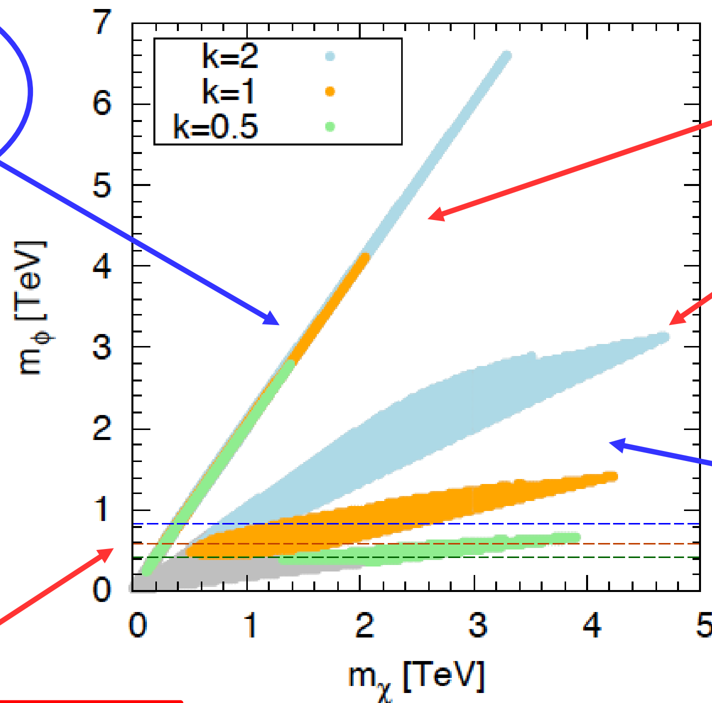


Explicit example

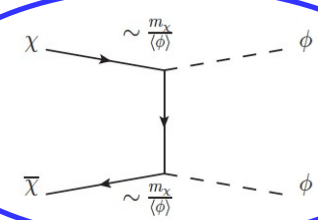
Simple U(1)$_F$, only few parameters (besides O(1) coeffs.): $m_\phi,\ m_\chi,\ k \equiv m_\phi/\langle\phi\rangle$

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





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

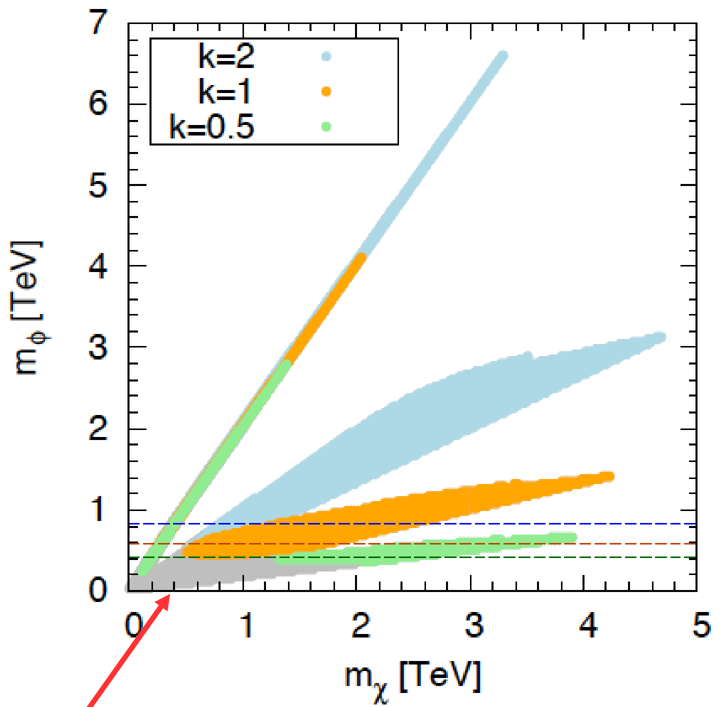


$m_\phi \gtrsim \sqrt{k} \times 580\ \text{GeV}$

Explicit example

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

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

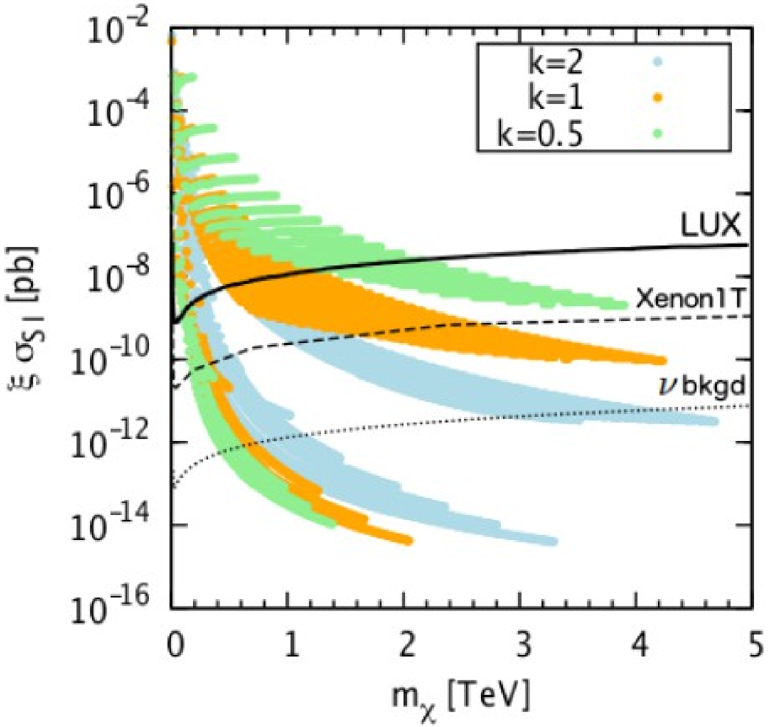


Excluded by direct searches

Explicit example

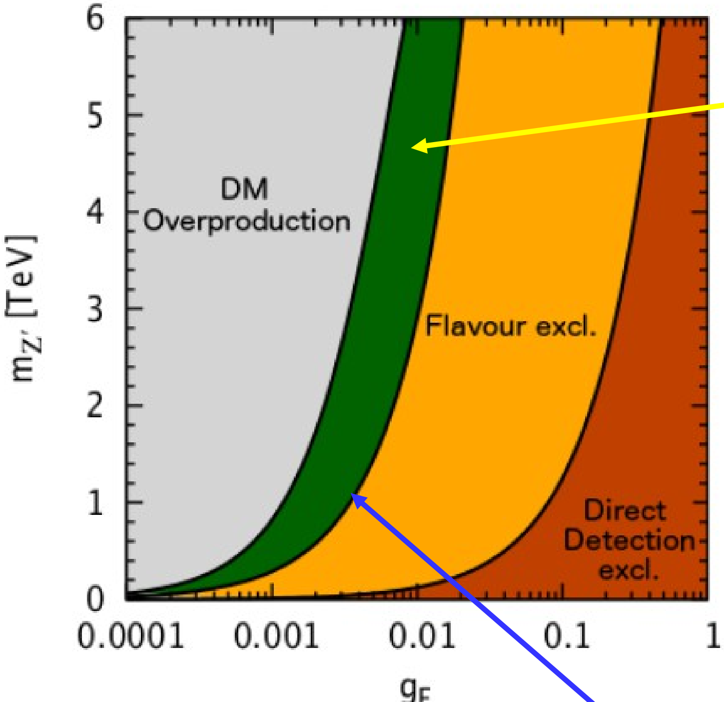
Simple $U(1)_F$, only few parameters (besides O(1) coeffs.): $m_\phi,\ m_\chi,\ k \equiv m_\phi/\langle\phi\rangle$

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



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

$m_\chi \approx m_{Z'}/2$



Viable region

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

Conclusions

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。

Additional Slides

Bounds on effective FCNC operators

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

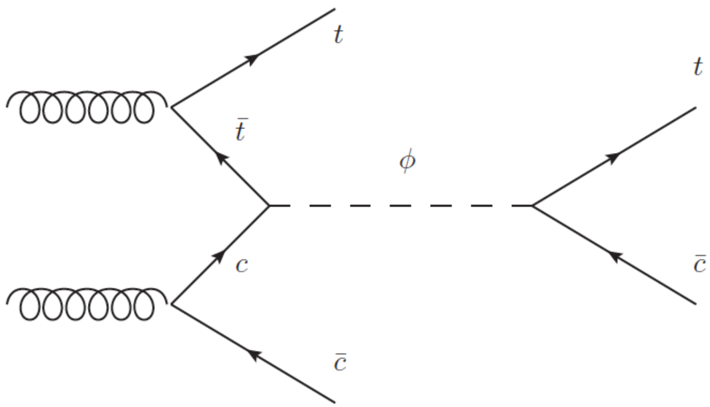
Hadronic FCNC and CPV:

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}

Collider signatures?

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

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