INVISIBLES 15
WORKSHOP

"THE FLAVOUR PORTAL TO DARK MATTER"

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JUNIO 22/2015

BASED ON:

LORENZO CALIBBI, ANDREAS CRIVELLIN, BZ

HEP-PH/1501.07268

MOTIVATION

* We know that DM exists,
  but... • Properties ?
  • Interactions ?

* We still have the Flavor puzzle
  • Why 3 families ?
  • Why these hierarchies ?

* "Simplicity" (use well motivated flavor symm. to explain DM)

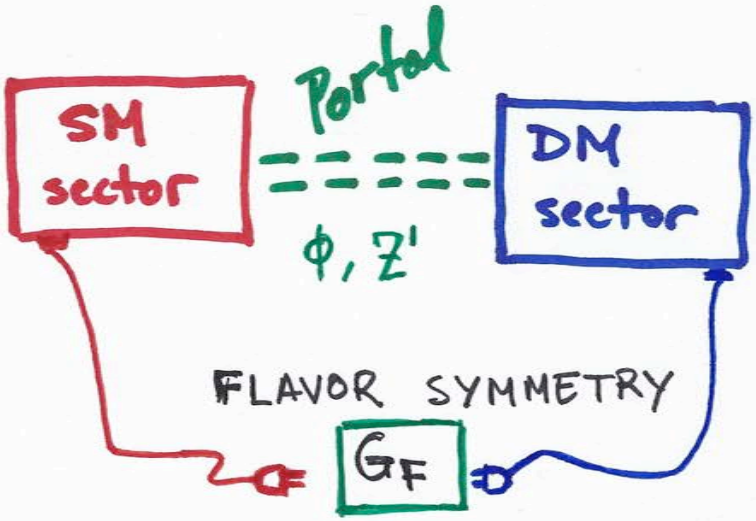
• Gain in knowledge of one from the other

• Hint on the scale of new physics ?

RELATED STUDIES

• Valle et al, 201
• Kile & Soni, 2011
• Kamenik & Zupan, 2011
• Spannowsky, 201
• Lopez-Honorez & Merlo, 2013
• Agrawal, 2014
• Kamenik et al, 2015

⊛ IDEA:



ϕ: Scalar field breaking G_F

Z': Gauge boson associated to G_F

⊛ IMPLEMENTATION: Froggatt-Nielsen

- $G_F = U(1)$ [but it doesn't have to]
- Provide charges to SM & DM
- Introduce flavons ϕ | $\langle\phi\rangle \Rightarrow \not{G_F}$

yukawas forbidden at renorm. level

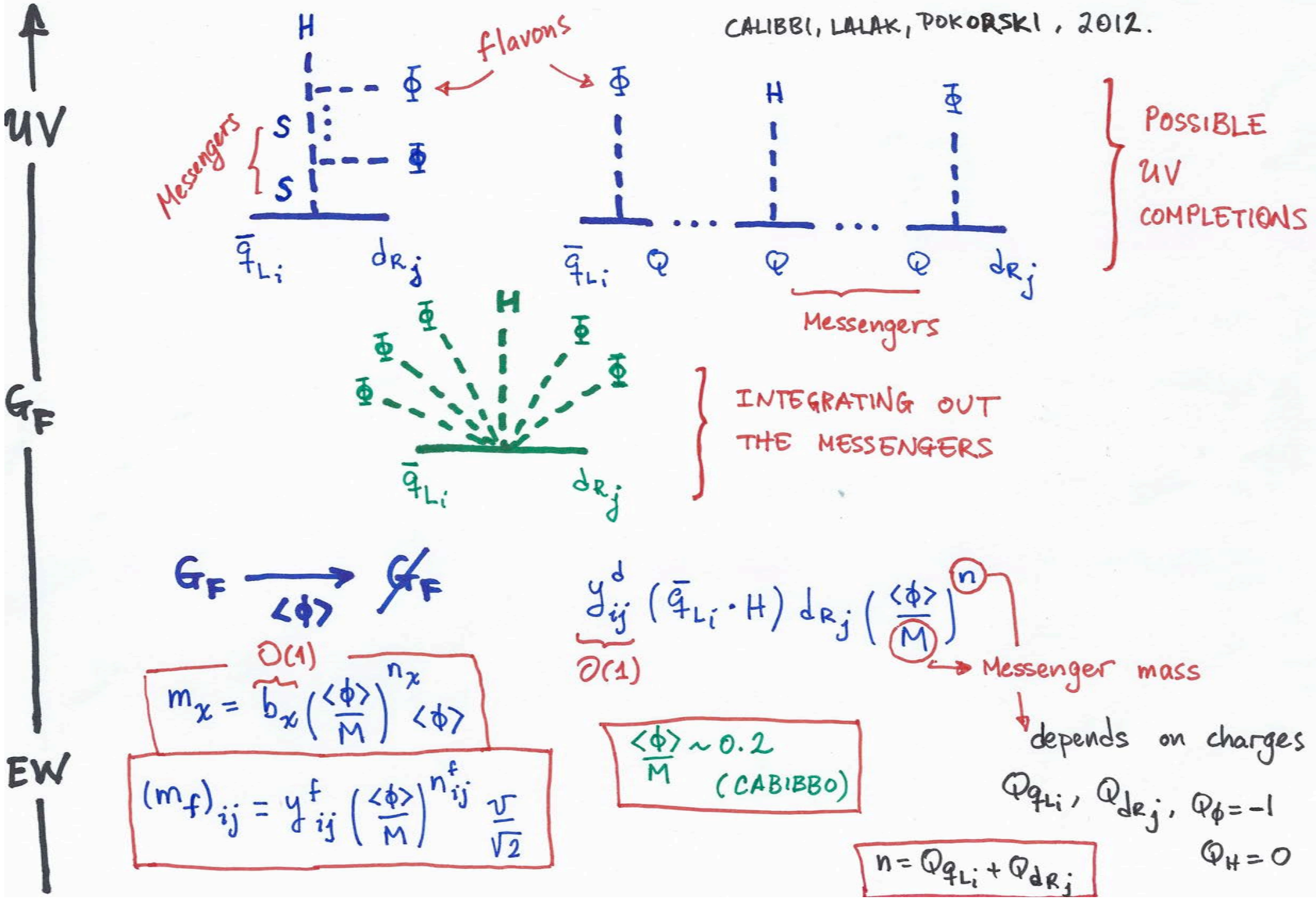
Fermion masses after EWSB

responsible for giving mass to DM

⊛ PARTICLE CONTENT

- Heavy (messenger) fields
- Flavons & extra gauge bosons
- Dark Matter
- Standard Model

CALIBBI, LALAK, POKORSKI, 2012.



$$G_F \xrightarrow[\langle\phi\rangle]{} \not{G}_F$$

$$y^d_{ij}\,(\bar{q}_{Li}\cdot H)\,d_{Rj}\left(\frac{\langle\phi\rangle}{M}\right)^n$$

$y^d_{ij} \sim \mathcal{O}(1)$

n → Messenger mass → depends on charges $Q_{q_{Li}}, Q_{d_{Rj}}, Q_\phi = -1, Q_H = 0$

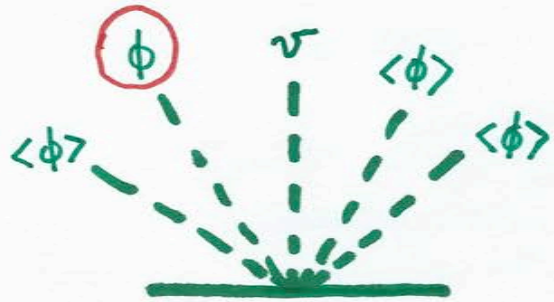
$$m_x = \underbrace{b_x}_{\mathcal{O}(1)}\left(\frac{\langle\phi\rangle}{M}\right)^{n_x}\langle\phi\rangle$$

$$(m_f)_{ij} = y^f_{ij}\left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}}\frac{v}{\sqrt{2}}$$

$$\frac{\langle\phi\rangle}{M} \sim 0.2 \quad \text{(CABIBBO)}$$

$$n = Q_{q_{Li}} + Q_{d_{Rj}}$$

FLAVON INTERACTIONS



⊛ with dark matter

$$\underbrace{\lambda_\chi}\ \chi_L \chi_R \phi$$

$$\hookrightarrow = \frac{d m_\chi}{d\langle\phi\rangle} = b_\chi (n_\chi + 1) \left(\frac{\langle\phi\rangle}{M}\right)^{n_\chi}$$

$$\Rightarrow \boxed{\lambda_\chi = \frac{(n_\chi + 1) m_\chi}{\langle\phi\rangle}}$$

⊛ with fermions

$$\underbrace{\lambda^f_{ij}}\ \bar{f}_{L_i} f_{R_j} \phi$$

$$\hookrightarrow = \frac{d(m^f_{ij})}{d\langle\phi\rangle} = \frac{v}{\sqrt{2}} y^f_{ij} n^f_{ij} \frac{\langle\phi\rangle^{n^f_{ij}-1}}{M^{n^f_{ij}}}$$

$$\Rightarrow \boxed{\lambda^f_{ij} = \frac{n^f_{ij}\, m^f_{ij}}{\langle\phi\rangle}}$$

- COUPLINGS SUPPRESSED BY $\langle\phi\rangle$
- FLAVONS PREFER HEAVIER FERMIONS
- COUPLINGS ARE FLAVOR VIOLATING

GAUGING FLAVOR SYMM.

$$\mathcal{L} \supset g_F \bar{\chi} \gamma^\mu (Q_{\chi_L} P_L + Q_{\chi_R} P_R) \chi Z'_\mu$$

$$+ g_F \bar{f} \gamma^\mu (Q_{f_L} P_L + Q_{f_R} P_R) f Z'_\mu$$

- COUPLINGS *NOT* SUPPRESSED BY $\langle\phi\rangle$
- Z' PREFERS LIGHTER QUARKS
- COUPLINGS ARE FLAVOR VIOLATING

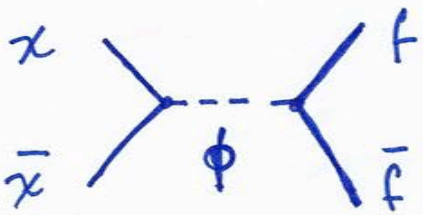
SUMMARY

	MASS	COUPLING TO FERMIONS	COUPLING TO DM
ϕ	$K\langle\phi\rangle$	$\frac{m_f n_f}{\langle\phi\rangle}$	$\frac{m_\chi}{\langle\phi\rangle}(n_\chi+1)$
Z'	$g_F\langle\phi\rangle$	$g_F n_f$	$g_F n_\chi$

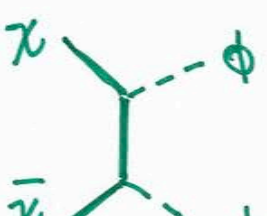
* ANOMALIES EXPECTED TO CANCEL IN THE HIDDEN SECTOR

DARK MATTER PHENOMENOLOGY

G_F GLOBAL



$m_\phi > m_\chi$



$m_\phi < m_\chi$

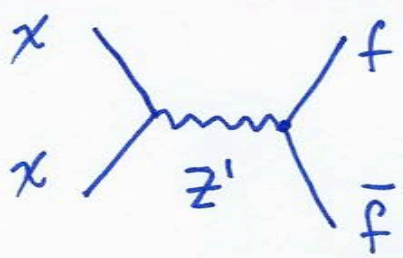
Relic Density

$$\langle \sigma_s^\phi v \rangle \sim \frac{\lambda_\chi^2 \lambda_f^2 m_\chi \, T}{(4m_\chi^2 - m_\phi^2)^2 + \Gamma_\phi^2 m_\phi^2}$$

(p-wave suppressed)

$$\langle \sigma_t^\phi v \rangle \sim \frac{\lambda_\chi^4 \, T}{m_\chi^3}$$

G_F LOCAL

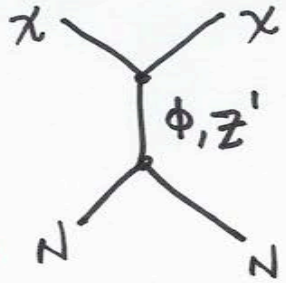


($M_{Z'} > m_\chi$ here from FLAVOR CONSTRAINTS)

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

(s-wave)

- **Direct Detection**



SPIN INDEPENDENT

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

$$\sigma_{SI}^{Z'} \sim \frac{g_F^2 \lambda_{Z'N}^2}{M_{Z'}^4} \mu_{\chi N}^2$$

EXPLICIT MODEL EXAMPLE

- $G_F = U(1)$
- One flavon field

- CHARGE ASSIGNMENT

$$(Q_{q_1}, Q_{q_2}, Q_{q_3}) = (3,2,0)$$
$$(Q_{u_1}, Q_{u_2}, Q_{u_3}) = (3,2,0)$$
$$(Q_{d_1}, Q_{d_2}, Q_{d_3}) = (4,2,2)$$

} Reproduces the V_{CKM} structure

Note:

$Q_{t_L} + Q_{t_R} = 0 \not\Rightarrow \boxed{\lambda_t = 0}$

- $\lambda_t \, \bar{t} t \phi$: not present
- $\lambda_{tc} \, \bar{t}_L c_R \phi$: LARGEST FLAVON COUPLING

⊛ FLAVOR CONSTRAINTS

- Assume $\not{CP}$ phases are suppressed (ignore ϵ_K)
- K-$\bar{K}$ mixing (tree-level)

$$\begin{cases} (\bar{s}_L d_R)(\bar{s}_R d_L) \rightsquigarrow \phi \\ (\bar{s}_L \gamma^\mu d_L)(\bar{s}_R \gamma_\mu d_R) \rightsquigarrow Z' \end{cases} \quad \begin{cases} m_\phi \gtrsim \sqrt{k} \cdot 580 \text{ GeV} \\ M_{Z'} \gtrsim \left(\frac{g_F}{10^{-3}}\right) 210 \text{ GeV} \end{cases}$$

- D-$\bar{D}$ mixing (boxes)

$$\{ m_\phi \gtrsim k \cdot 2,3 \text{ TeV}$$

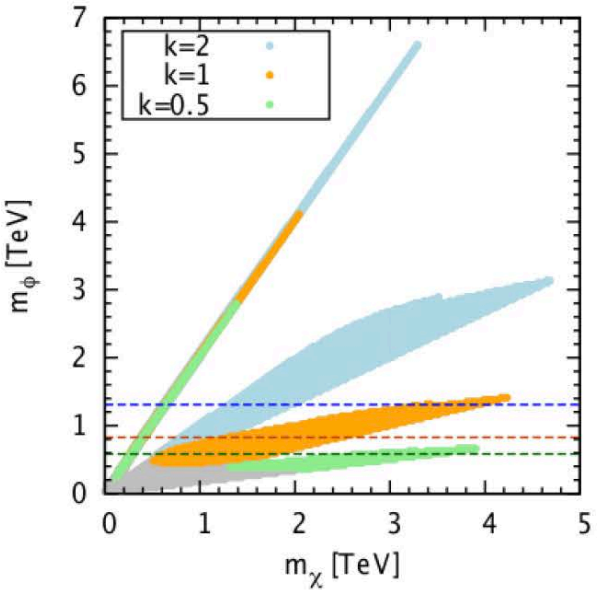
RESULTS FROM DM.

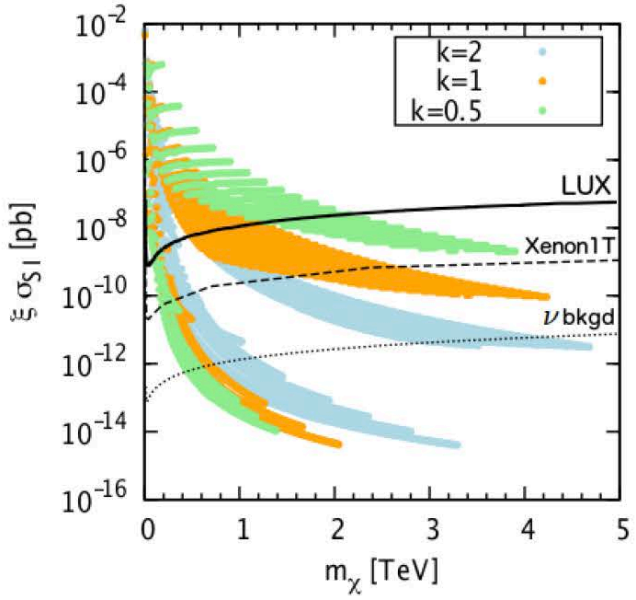
- FOR A GIVEN CHARGE ASSIGNMENT, THE MODEL IS COMPLETELY DETERMINED BY: → modulo $\mathcal{O}(1)$ coeff.

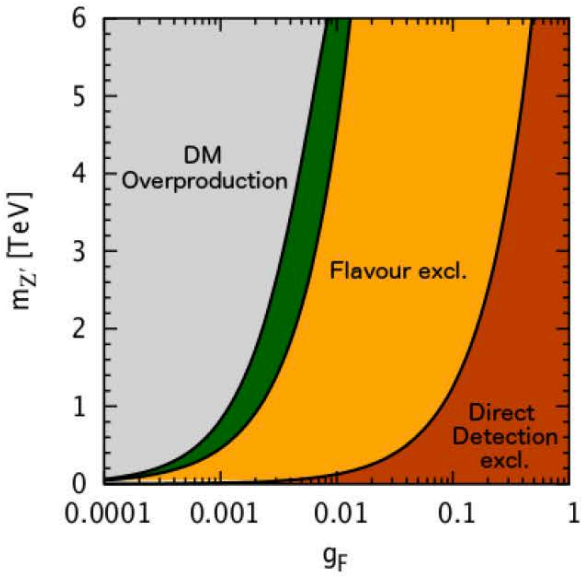
  m_ϕ, m_χ, $k \equiv m_\phi / \langle\phi\rangle$ (GLOBAL)

  $M_{Z'}$, m_χ, g_F, k (LOCAL)

* DM charges appropriately chosen to deliver m_χ





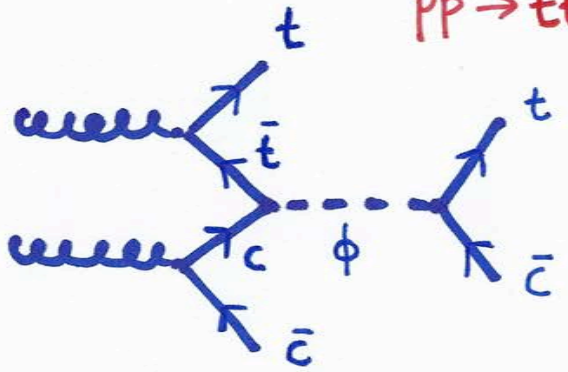


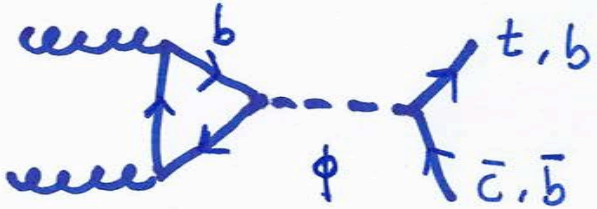
COLLIDER SIGNATURES ?

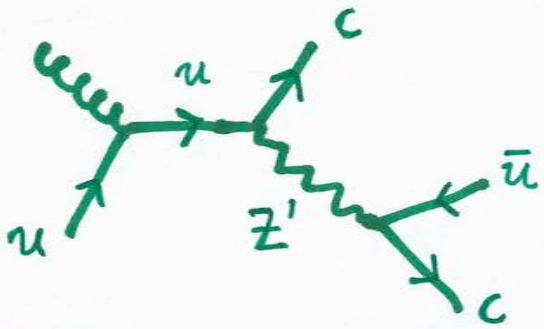
ONGOING WORK

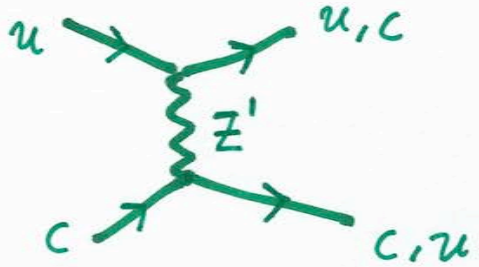
$pp \to t\bar{t}c\bar{c}$, $b\bar{b}b\bar{b}$

GLUON FUSION









PROMISING

⊛ TOO LOW CROSS SECTION AT LHC @14 TeV

FLAVONS OF $M_\phi =$ 500 GeV, 1 TeV

0.1 fb, 10^{-3} fb

⊛ GOOD CHANCES FOR 100TeV COLLIDER !!!

EL KHATROOUN

CONCLUSIONS

- DARK MATTER CAN BE EXPLAINED BY RELATING IT TO THE FLAVOR SECTOR
- FLAVONS RESPONSIBLE FOR CKM ACT AS PORTAL TO DARK MATTER
- DM PHENOMENOLOGY COMPATIBLE WITH $\mathcal{O}$(TeV) FLAVOR SECTOR (NOT YET EXCLUDED BY FLAVOR CONSTR.)
- DM ANNIHILATION MAY BE RESONANT, HOWEVER, GOOD PROSPECTS FOR NEAR FUTURE DIRECT DETECTION
- COLLIDER SIGNATURES UNDER STUDY, ALTHOUGH CHALLENGING FOR LHC-14 TeV. $\Rightarrow$ 100 TeV

GRACIAS !!

BCKP

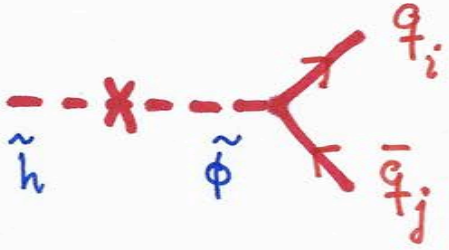
HIGGS-FLAVON MIXING

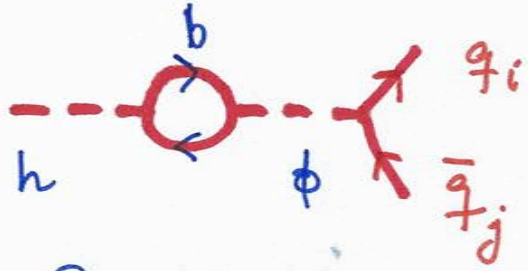
$$V = \mu^2 |H|^2 + \lambda |H|^4 + \mu_\phi^2 |\Phi|^2 + \lambda_\phi |\Phi|^4 + \lambda_{h\phi} |H|^2 |\Phi|^2$$

$$h = \tilde{h}\cos\alpha + \tilde{\phi}\sin\alpha$$
$$\phi = -\tilde{h}\sin\alpha + \tilde{\phi}\cos\alpha$$

$\Longrightarrow$ SMALL $\lambda_{\phi h}$

$$m_h^2 \approx \mu^2 + \frac{\lambda_{h\phi}}{2} v_\phi^2$$
$$m_\phi^2 \approx \mu_\phi^2 + \frac{\lambda_{h\phi}}{2} v^2$$





$$y_{ij}^q\Big|_{tree} \sim \sin\alpha \left[(Q_{q_i} + Q_{u,d_j}) \left(\frac{\langle\phi\rangle}{M}\right)^{Q_{q_i} + Q_{u,d_j}} \frac{v}{v_\phi} \right]$$

$$10^{-6}\,\lambda_{h\phi} \lesssim y_{ij} \lesssim 10^{-3}\,\lambda_{h\phi} \quad \text{for} \quad \begin{matrix} K = 2 \\ m_\phi = 1.3\,\text{TeV} \end{matrix}$$

FV bounds of Higgs decays

$K^\bullet$ oscillations on $y_{\bar{s}d}$ $\Rightarrow$ $\lambda_{h\phi} \lesssim 0.01$

DM stability

- IF ONLY IN THE QUARK SECTOR

  $\chi(ddu) \rightarrow$ Baryon # violation

- IF MODEL EXTENDED TO LEPTON SECTOR

  WATCH OUT DM-ν_R MIXING (INVOKE L #?)

  OR SUITABLE UV COMPLETION