DARK MATTER AND CONTINUOUS FLAVOR SYMMETRIES

Jure Zupan
U. of Cincinnati

based on Kamenik, JZ, 1107.0623
Bishara, JZ, 1408.3852
Bishara, Greljo,Kamenik, Stamou, JZ, to appear

Naturalness 2014 -satellite worskhop, Nov 12, 2014

THE AIM/MOTIVATION

- SM has a very nontrivial flavor structure
  - hierarchical fermion masses
  - small flavor violation in quark sector, large in lepton sector
- can this have implications for dark matter searches?

OUTLINE

- three examples
- all based on continuous flavor symmetries in the quark sector
    - dark matter stability
        - metastable asymmetric DM
        - gauged flavor model+DM
    - flavor breaking and DM searches
        - mono-tops at the LHC

ASYMMETRIC DM & FLAVOR

ASYMMETRIC DM

- asymmetric DM addresses the coincidence problem
    - $\Omega_{DM} \sim 5\ \Omega_{baryon}$
    - is there a link between the two abundances?

Nussinov 1985; Barr 1991; Kaplan 1992;
Kaplan, Luty, Zurek, 0901.4117;
+many refs.

ASYMMETRIC DM

- cosmological history of the ADM

$T \gg T_{\mathrm{EWPT}}$	$B \longleftrightarrow \Delta\chi$	Asymmetric operators in equilibrium. Baryon asymmetry transferred to DM.
$T_f > T_{\mathrm{EWPT}}$	$B \; \cancel{\longleftrightarrow} \; \Delta\chi$	Asymmetric operators freezeout. DM number separately conserved.
$T \lesssim m_\chi$	$\chi\bar{\chi} \longrightarrow \mathrm{SM}, \gamma_d\gamma_d, \ldots$	Symmetric component of DM is efficiently annihilated away.

from a slide by F. Bishara, talk at Notre Dame

- note: more complicated cosmological histories possible

see e.g., Falkowski, Ruderman, Volansky, 1101.4936

OUR AIM

Bishara, JZ, 1408.3852

- for a subset of ADM models
  - the Z_2 that ensures the stability is *accidental* and *approximate*
- as a result
  - DM is metastable
  - decay times potentially close to its present observational bound $\tau \gtrsim 10^{26} s$
- the mediators can be below TeV
  - realistic flavor structure essential

DM MASS

- the relation Ω_{DM}~5.4 Ω_{baryon} fixes the DM mass

Bishara, JZ, 1408.3852

  - assuming SM visible sector

$$m_\chi = m_p \frac{\Omega_\chi}{\Omega_B} \frac{B}{B-L} \frac{B-L}{\Delta\chi} = (12.5 \pm 0.8)\text{GeV} \frac{1}{(B-L)_\chi^{\text{sum}}}$$

$$(B-L)_\chi^{\text{sum}} \equiv \sum_i \hat{g}_\chi^i (B-L)_\chi^i$$

- for instance, for a Dirac fermion g_χ=2

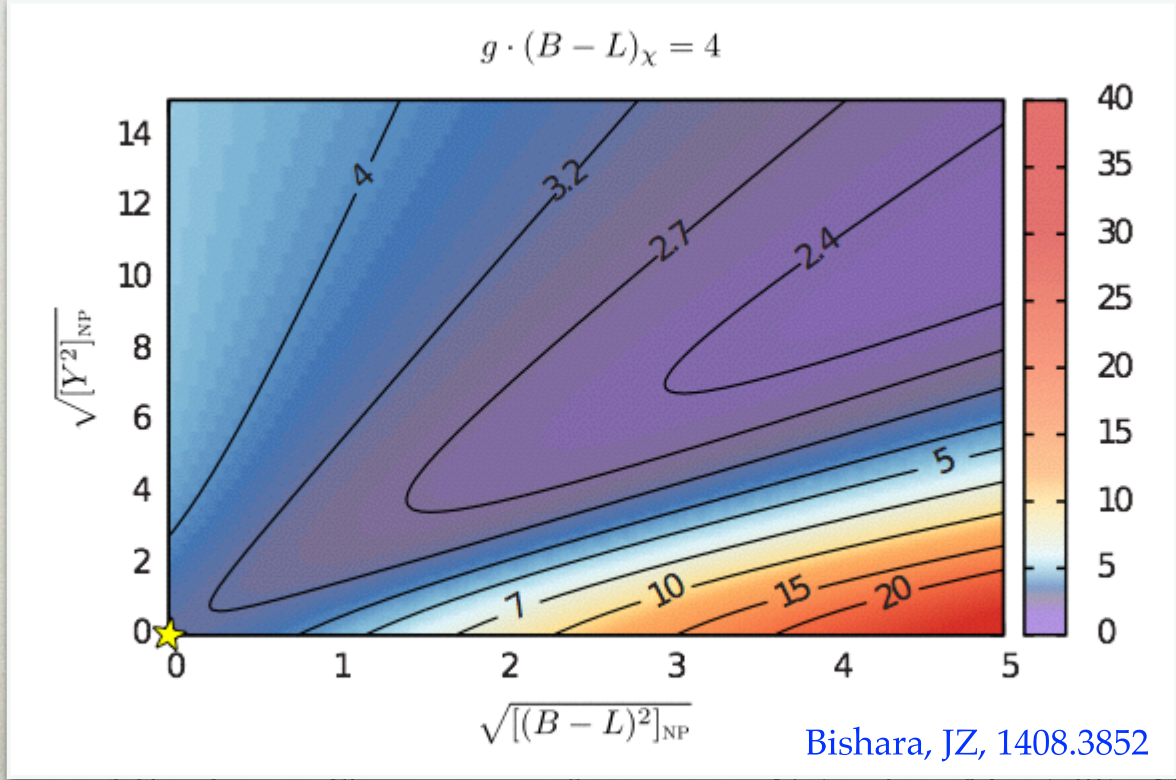
$$m_\chi = (6.2 \pm 0.4)\text{GeV} \frac{1}{(B-L)_\chi},$$

$$m_\chi = \{6.2, 3.1, 2.1\}\text{GeV}, \qquad \text{for} \quad (B-L)_\chi = \{1,2,3\},$$

- note: for B=3 DM cannot decay
  - accidental Z_2 (which is exact if B is exact)

ADM MASS

- if visible sector more complicated
  - the relation to DM mass more general
  - e.g. for *B*=2 complex scalar



Bishara, JZ, 1408.3852

ASYMMETRIC DM

- cosmological history of the ADM

$T \gg T_{\rm EWPT}$	$B \longleftrightarrow \Delta\chi$	Asymmetric operators in equilibrium. Baryon asymmetry transferred to DM.
$T_f > T_{\rm EWPT}$	$B \cancel{\longleftrightarrow} \Delta\chi$	Asymmetric operators freezeout. DM number separately conserved.
$T \lesssim m_\chi$	$\chi\bar{\chi} \longrightarrow \text{SM}, \gamma_d\gamma_d, \ldots$	Symmetric component of DM is efficiently annihilated away.

- symmetric annihilation needs to be efficient
  - have nothing new to say, a number of scenarios proposed

see e.g., Bhattacherjee, Matsumoto, Mukhopadhyay, Nojiri, 1306.5878; March-Russell, McCullough, 1106.4319; Lin, Yu, Zurek, 1111.0293

FREEZE-OUT OF ASYMMETRIC INTERACTIONS

- asymmetric operators, schematic form for B=2

$$\mathcal{O}_{\text{asymm.}} \sim \frac{C}{\Lambda^6}\chi(qq)^3,$$

- leads to asymmetric 2→5 interactions in the early universe
  - the freeze-out should be above EW phase transition
  - gives lower bounds:
    - Λ>730 GeV (Froggatt-Nielsen flavor model)
    - Λ>400 GeV (MFV breaking)
- naively expect that asymmetric mediators not much heavier
  - then self-consistent framework (need small m_χ for metastable DM)
    - at very high Λ the direct relation between m_χ and m_p is lost
  - however, easy to think of models with very massive mediators

DM DECAY TIME

- the asymmetric operators also lead to DM decays

$$\mathcal{O}_{\text{asymm.}} \sim \frac{C}{\Lambda^6}\chi(qq)^3,$$

- what is the corresponding decay time
  - MFV flavor model
  - Froggatt-Nielsen model

MINIMAL FLAVOR VIOLATION

- in the SM global flavor symmetry $U(3)^5$ broken by Yukawas
- also the minimal breaking that needs to be present in the presence of NP
- Minimal Flavor Assumption (MFV):
  - the SM Yukawas are also the only flavor breaking

MINIMAL FLAVOR VIOLATION

D'Ambrosio, Giudice, Isidori, Strumia, 2002

- quark sector formally inv. under $\mathrm{U(3)_Q}\otimes \mathrm{U(3)_u}\otimes\mathrm{U(3)_d}$, if the Yukawas promoted to spurions

$$\boxed{Y'_{u,d} = V_Q Y_{u,d} V_{u,d}^\dagger}$$

- use spurion analysis to construct NP opers./contribs.
- constrains possible FV structures, e.g. (V-A)⊗(V-A)
  - allowed: $\boxed{\bar{Q}(Y_u Y_u^\dagger)^n Q}$
  - not allowed: $\boxed{\bar{Q} Y_d^\dagger (Y_u Y_u^\dagger)^n Q}$
- it gives SM like suppression of FCNC's since

$$\boxed{(Y_u Y_u^\dagger)^n \sim (Y_u Y_u^\dagger) = V_{\rm CKM} \mathrm{diag}(0,0,1) V_{\rm CKM}^\dagger}$$

- for (V-A) bilinear $\bar{b}_L s_L$ the suppression $\sim V_{tb} V_{ts}^*$

ADM AND MFV

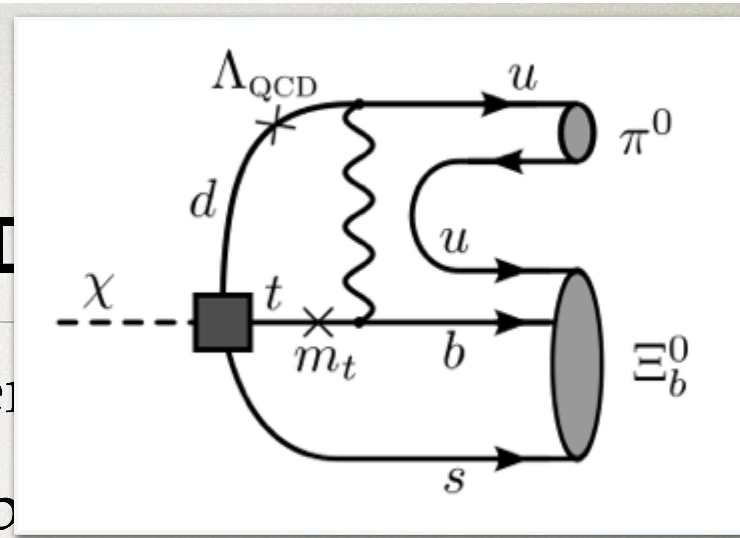
- take as an example *B=1* fermonic ADM
  - two types of asymm. operators

$$\mathcal{O}_1^{(B=1)} = (\chi\, u^c_\alpha Y_U^\dagger Y_D)_K (d^c_{N\beta} d^c_{M\gamma}) \epsilon^{KNM} \epsilon^{\alpha\beta\gamma}$$
$$\to (\chi\, u^c_{\rm MASS} Y_U^{\rm diag\dagger} V^\dagger_{\rm CKM} Y_D^{\rm diag})_{K\alpha} ([d^c_{\rm MASS}]_{N\beta} [d^c_{\rm MASS}]_{M\gamma}) \epsilon^{KNM} \epsilon^{\alpha\beta\gamma},$$
$$\mathcal{O}_2^{(B=1)} = (\chi\, q^*_{K\alpha i})([d^c_\beta Y_D^\dagger]_N q^*_{M\gamma j}) \epsilon^{ij} \epsilon^{KNM} \epsilon^{\alpha\beta\gamma}$$
$$\to (\chi\, u^*_{\rm MASS} V^\dagger_{\rm CKM})_{K\alpha} ([d^c_{\rm MASS} Y_D^{\rm diag\dagger}]_{N\beta} [d^*_{\rm MASS}]_{M\gamma}) \epsilon^{KNM} \epsilon^{\alpha\beta\gamma},$$

  - from here an NDA estimate for decay width

$$\Gamma_\chi^{(1)} \sim \frac{(y_t y_b)^2}{8\pi} \left(\frac{m_\chi}{\Lambda}\right)^4 \left(\frac{1}{16\pi^2} \frac{m_t \Lambda_{\rm QCD}}{m_W^2}\right)^2 \frac{m_\chi}{16\pi^2} = 6.6 \cdot 10^{-51} {\rm GeV} \left(\frac{y_b}{0.024}\right)^2 \left(\frac{4.0 \cdot 10^6 {\rm TeV}}{\Lambda}\right)^4,$$
$$\Gamma_\chi^{(2)} \sim \frac{|y_b V_{ub}|^2}{8\pi} \left(\frac{m_\chi}{\Lambda}\right)^4 \frac{m_\chi}{16\pi^2} = 6.6 \cdot 10^{-51} {\rm GeV} \left(\frac{y_b}{0.024}\right)^2 \left(\frac{4.3 \cdot 10^7 {\rm TeV}}{\Lambda}\right)^4,$$

ADM AND



- take as an example *B=1* fe
  - two types of asymm. op

$$
\begin{aligned}
\mathcal{O}_1^{(B=1)} =& (\chi\, u^c_\alpha Y_U^\dagger Y_D)_K (d^c_{N\beta} d^c_{M\gamma})\epsilon^{KNM}\epsilon^{\alpha\beta\gamma} \\
&\to (\chi\, u^c_{\rm MASS} Y_U^{\rm diag\dagger} V_{\rm CKM}^\dagger Y_D^{\rm diag})_{K\alpha} ([d^c_{\rm MASS}]_{N\beta}\, [d^c_{\rm MASS}]_{M\gamma})\epsilon^{KNM}\epsilon^{\alpha\beta\gamma}, \\
\mathcal{O}_2^{(B=1)} =& (\chi\, q^*_{K\alpha i})([d^c_\beta Y_D^\dagger]_N q^*_{M\gamma j})\epsilon^{ij}\epsilon^{KNM}\epsilon^{\alpha\beta\gamma} \\
&\to (\chi\, u^*_{\rm MASS} V_{\rm CKM}^\dagger)_{K\alpha}([d^c_{\rm MASS} Y_D^{\rm diag\dagger}]_{N\beta}[d^*_{\rm MASS}]_{M\gamma})\epsilon^{KNM}\epsilon^{\alpha\beta\gamma},
\end{aligned}
$$

  - from here an NDA estimate for decay width

$$
\begin{aligned}
\Gamma_\chi^{(1)} &\sim \frac{(y_t y_b)^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4 \left(\frac{1}{16\pi^2}\frac{m_t \Lambda_{\rm QCD}}{m_W^2}\right)^2 \frac{m_\chi}{16\pi^2} = 6.6\cdot 10^{-51}{\rm GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{4.0\cdot 10^6{\rm TeV}}{\Lambda}\right)^4, \\
\Gamma_\chi^{(2)} &\sim \frac{|y_b V_{ub}|^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4 \frac{m_\chi}{16\pi^2} = 6.6\cdot 10^{-51}{\rm GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{4.3\cdot 10^7{\rm TeV}}{\Lambda}\right)^4,
\end{aligned}
$$

FN MODELS

- U(1) Froggatt-Nielsen (FN) models of spontaneously broken horizontal symmetries
  - quarks carry horizontal charges *H(q*$_i$*), …*
- the two B=1 operators

$$\mathcal{O}_1^{(B=1)} = (\chi\, d^c_K)\,(u^c_N d^c_M) \to (\chi\, [d^c_{\text{MASS}}]_K)\,([u^c_{\text{MASS}}]_N [d^c_{\text{MASS}}]_M),$$
$$\mathcal{O}_2^{(B=1)} = (\chi\, q^*_{Ki})(d^c_N q^*_{Mj})\epsilon^{ij} \to (\chi\, [u^*_{\text{MASS}}]_K)\,([d^c_{\text{MASS}}]_N [d^*_{\text{MASS}}]_M)\,,$$

$$\mathcal{L} = \sum_i \frac{C_i}{\Lambda^{(D_i-4)}}\mathcal{O}_i.$$

  - have Wilson coefficients

$$C_1 \sim \lambda^{|H(d^c_K)+H(u^c_N)+H(d^c_M)|}, \qquad C_2 \sim \lambda^{|-H(q_K)+H(d^c_N)-H(q_M)|}.$$

  - expansion parameters $\lambda \sim 0.2$
  - we use the phenomenologically viable assignments:

$$H(q,d^c,u^c) \Rightarrow \begin{array}{cc} & \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{array}{c} q \\ d^c \\ u^c \end{array} & \begin{pmatrix} 3 & 2 & 0 \\ 3 & 2 & 2 \\ 3 & 1 & 0 \end{pmatrix} \end{array},$$

Leurer, Nir, Seiberg hep-ph/9212278; hep-ph/9310320

ADM DECAY TIMES

- the suppression scales that give τ=10^{26}s

ADM model			MFV			FN		
B	Dim.	m_χ [GeV]	decay	τ [s]	Λ [TeV]	decay	τ [s]	Λ [TeV]
1	6	6.2	$\chi \to bus$	10^{26}	4.0×10^6	$\chi \to bus$	10^{26}	8.1×10^8
2	10	3.1	$\chi \to udsuds$	10^{26}	0.63	$\chi \to udsuds$	10^{26}	2.5
3	15	2.1	forbidden	∞	–	forbidden	∞	–

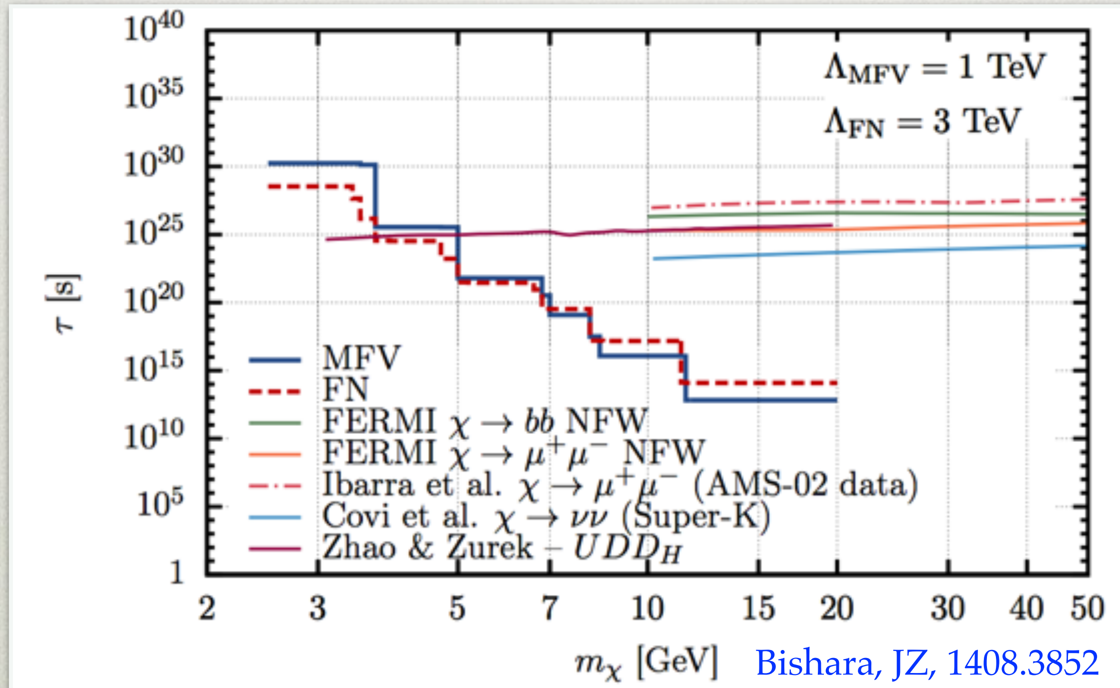
ADM DECAY TIMES

- the suppression scales that give $\tau = 10^{26}$s

ADM model			MFV			FN		
B	Dim.	m_χ [GeV]	decay	τ [s]	Λ [TeV]	decay	τ [s]	Λ [TeV]
1	6	6.2	$\chi \to bus$	10^{26}	4.0×10^6	$\chi \to bus$	10^{26}	8.1×10^8
2	10	3.1	$\chi \to udsuds$	10^{26}	0.63	$\chi \to udsuds$	10^{26}	2.5
3	15	2.1	forbidden	∞	–	forbidden	∞	–

INDIRECT DETECTION CONSTRAINTS

- the most relevant indirect constraints from antiproton flux and gamma ray spectra



- for *3.1GeV B=2* DM the bounds are

$$\Lambda_{\rm MFV} \gtrsim 0.49 \text{ TeV} \qquad \Lambda_{\rm FN} \gtrsim 1.9 \text{ TeV},$$

MEDIATOR MASS

- these bounds imply for the mass of asymmetric mediators
  - MFV: $m_{mediator}$ >*490 (210, 90)*GeV
  - FN: $m_{mediator}$ >*1900 (830, 360)*GeV
  - if asymmetric operators are generated at tree(1-loop,2-loop)-level
- these mediators can be searched for at the LHC
- note: without flavor structure the bound would be Λ>7.3 TeV
  - out of LHC reach

MEDIATOR MODELS

- for LHC pheno. consider two toy-model completions
- MFV model with scalar mediators

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	G_F	$U(1)_{B-L}$
ϕ_L	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$2/3$
φ_L	$\mathbf{6}$	$\mathbf{1}$	$1/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$
ϕ_R	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$

- FN model with fermionic and scalar mediators

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
ϕ	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$2/3$
ψ	$\mathbf{1}$	$\mathbf{1}$	0	1

$T \gg T_{\text{EWPT}}$	$B \longleftrightarrow \Delta\chi$		Asymmetric operators in equilibrium. Baryon asymmetry transferred to DM.
$T_f > T_{\text{EWPT}}$	$B \not\longleftrightarrow \Delta\chi$		Asymmetric operators freezeout. DM number separately conserved.
$T \lesssim m_\chi$	$\chi\bar{\chi} \longrightarrow \text{SM}, \gamma_d\gamma_d, \ldots$		Symmetric component of DM is efficiently annihilated away.

- for … ons
- MF…

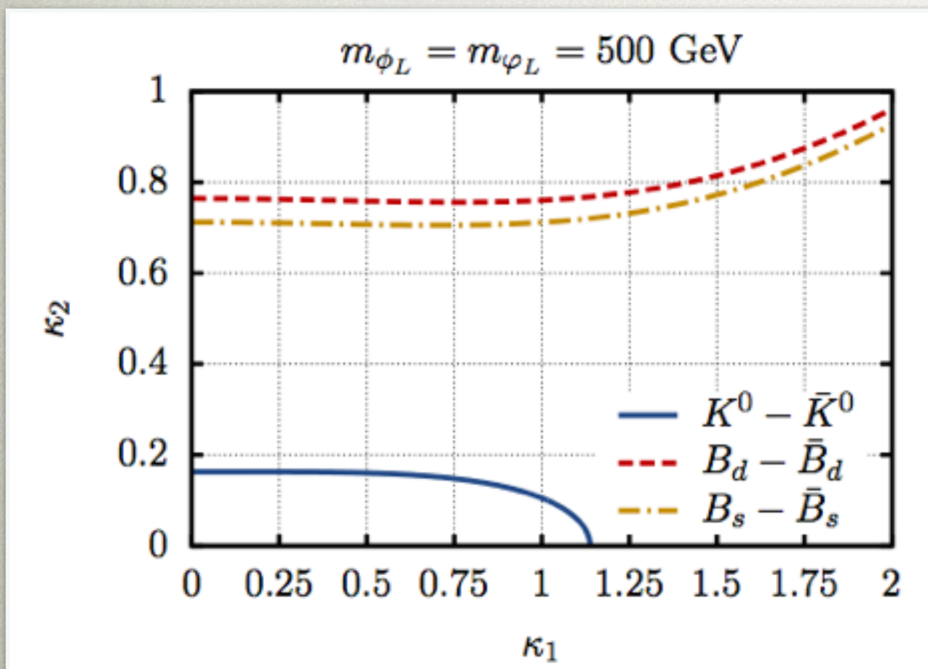
Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	G_F	$U(1)_{B-L}$
ϕ_L	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$2/3$
φ_L	$\mathbf{6}$	$\mathbf{1}$	$1/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$
ϕ_R	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$

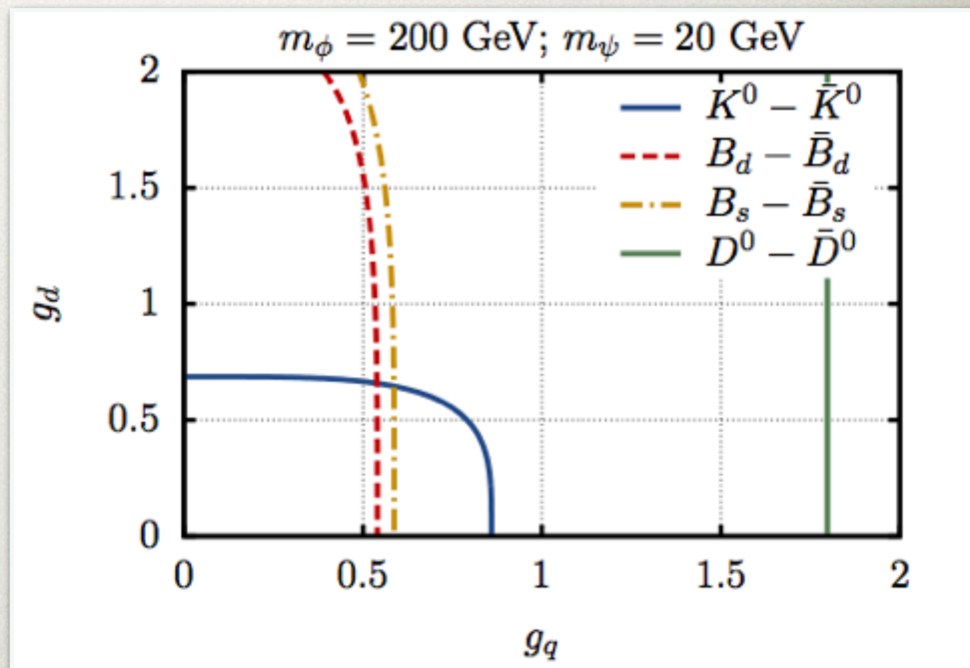
- FN model with fermionic and scalar mediators

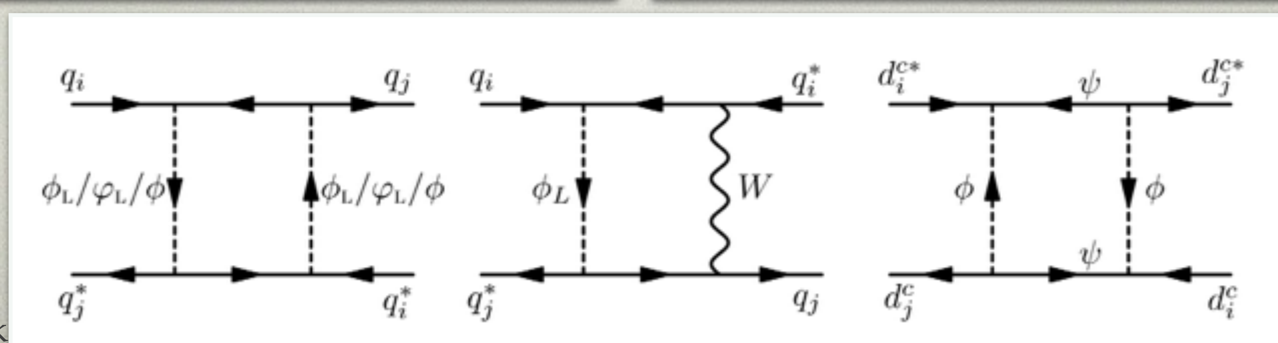
Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
ϕ	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$2/3$
ψ	$\mathbf{1}$	$\mathbf{1}$	0	1

FLAVOR BOUNDS

- typical FCNC bounds

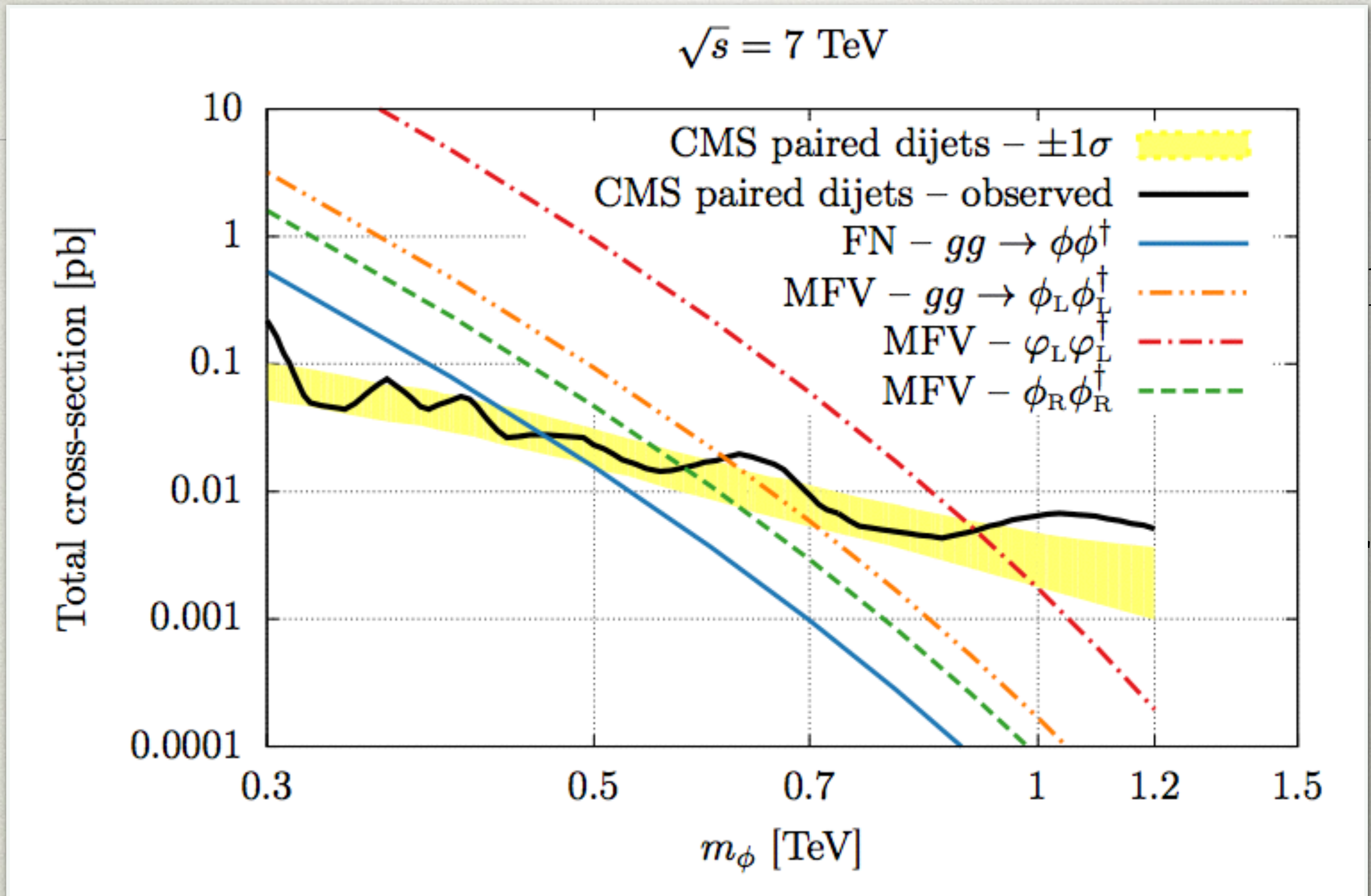






LHC SIGNATURES

- colored mediators inevitable: present in both toy models
  - can be searched for at the LHC through pair production or single production
- the decay channels depend on flavor quantum numbers of scalars
  - $\phi \to tb$, $\phi' \to bj$, $\phi'' \to jj$
  - a combined analysis of all three modes would be desirable
- as a simplified rule of thumb compare with CMS paired dijet-resonance search



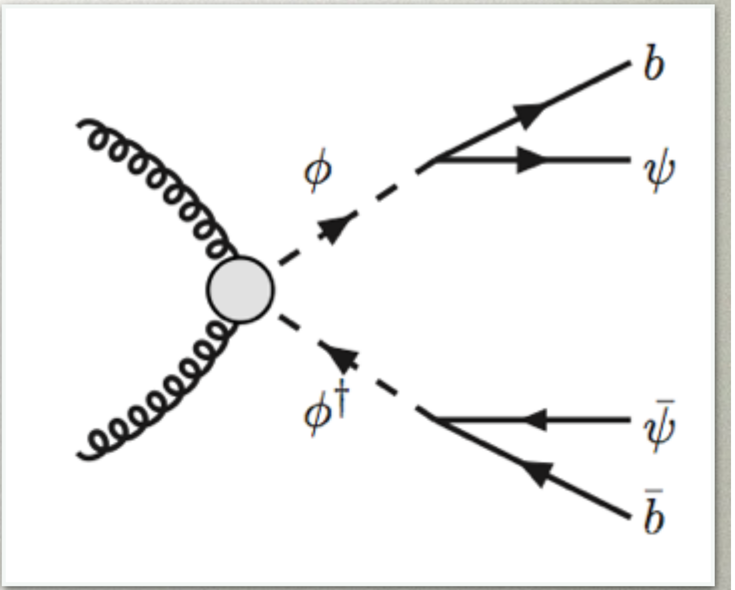
ls

rs

- as a simplified rule of thumb compare with CMS paired dijet-resonance search

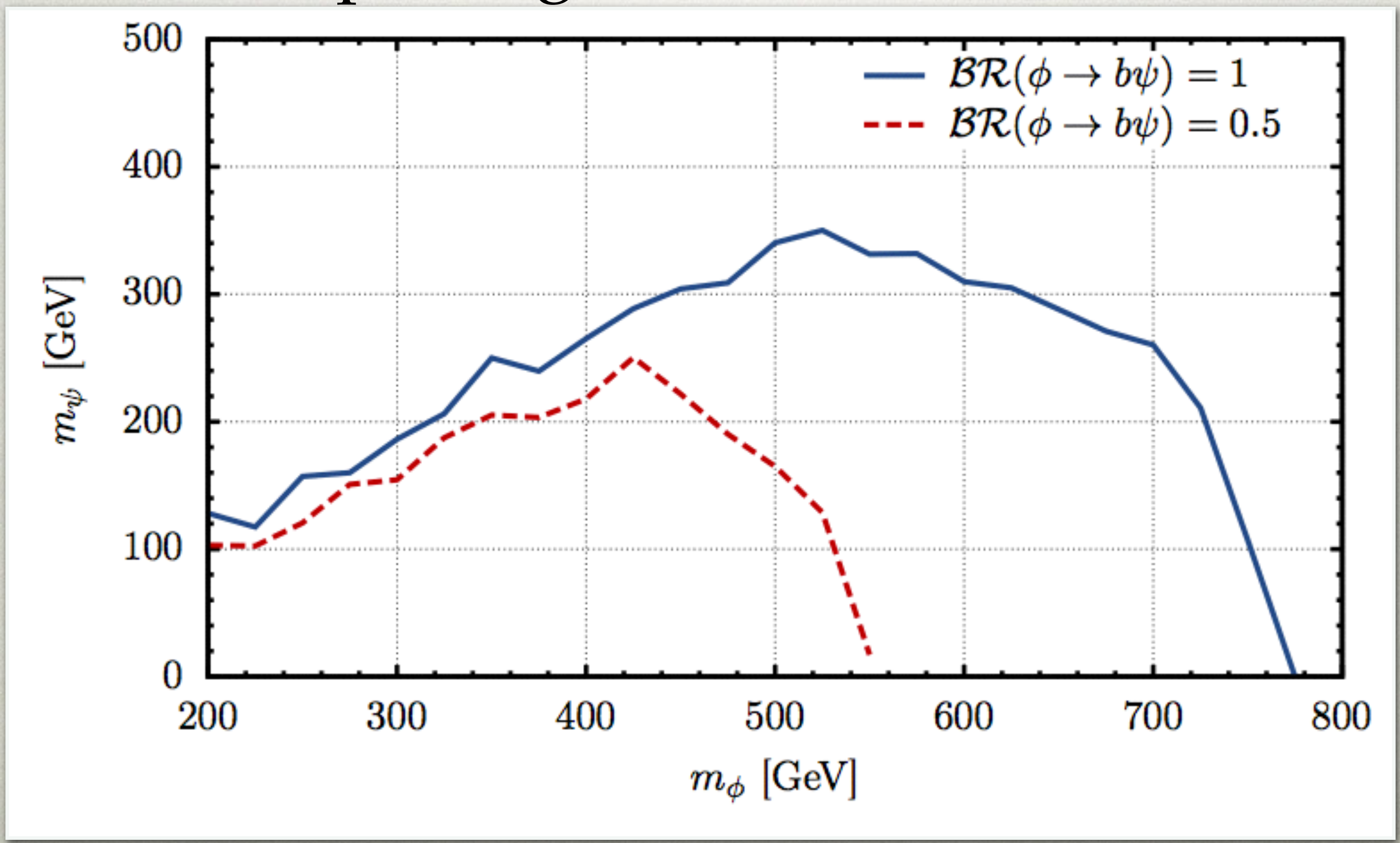
LHC SIGNATURES

- in corners of parameter space other signatures possible
- for instance, allowing for a hierarchy of couplings
  - $\phi \to \bar{b}\psi$ may dominate, and ψ escapes detection
  - the signal is $b\bar{b}$+*MET, s*bottom searches apply



LHC SIGNATURES

- reinterpreting CMS sbottom search



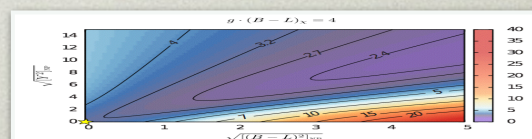
DM STABILITY & CONTINUOUS SYMMETRIES

SM flavor group

- the breaking of flavor group may leave an exact discrete group exact
  - this is true in the SM
- if zero Yukawas large flavor group: $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$
- we consider quark subgroup, SU(3) factors $G_F = SU(3)_Q \times SU(3)_U \times SU(3)_D$

$$Q_L \sim (3,1,1)$$

$$U_R^c \sim (1,\bar{3},1)$$

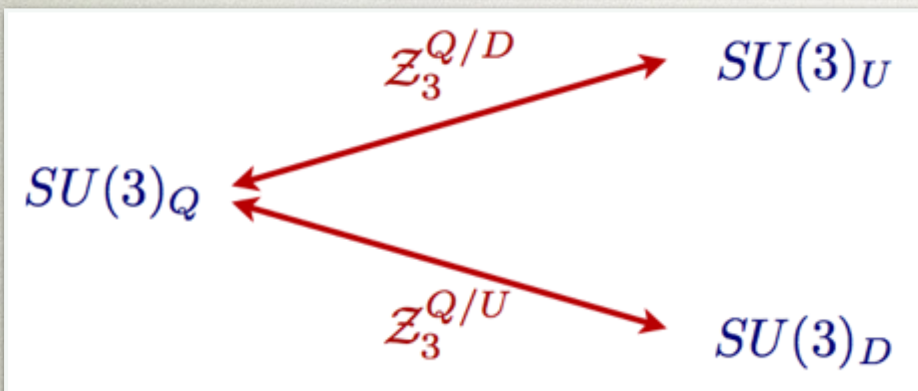


Batell, Pradler, Spannowsky, 1105.1781
Batell, Lin, Wang,1309.4462
Bishara, Greljo,Kamenik, Stamou, JZ, to appear

SM FLAVOR BREAKING

- the SM Yukawas break $G_F \to Z_3^{QUD}$

$$\mathcal{L}_Y = \bar{Q}_L \tilde{H} y_u U_R + \bar{Q}_L H y_d D_R + \text{h.c.}\,.$$



$$Z_3^{QUD}$$

$$\{U_R, D_R, Q_L\} \to e^{i2\pi/3}\{U_R, D_R, Q_L\}$$

- Z_3^{QUD} is an accidental symmetry of the SM
  - preserved in presence of any MFV NP
  - in the SM is a subgroup of $U(1)_B$ (not in general NP)

DARK MATTER STABILITY

- all SM fields: neutral under diag. subgroup $Z_3^{\chi} \subset Z_3^{QUD} \times Z_3^{c}$
- color neutral dark matter charged under Z_3^{χ} is automatically stable
  - suitable G_F representations have nonzero flavor triality

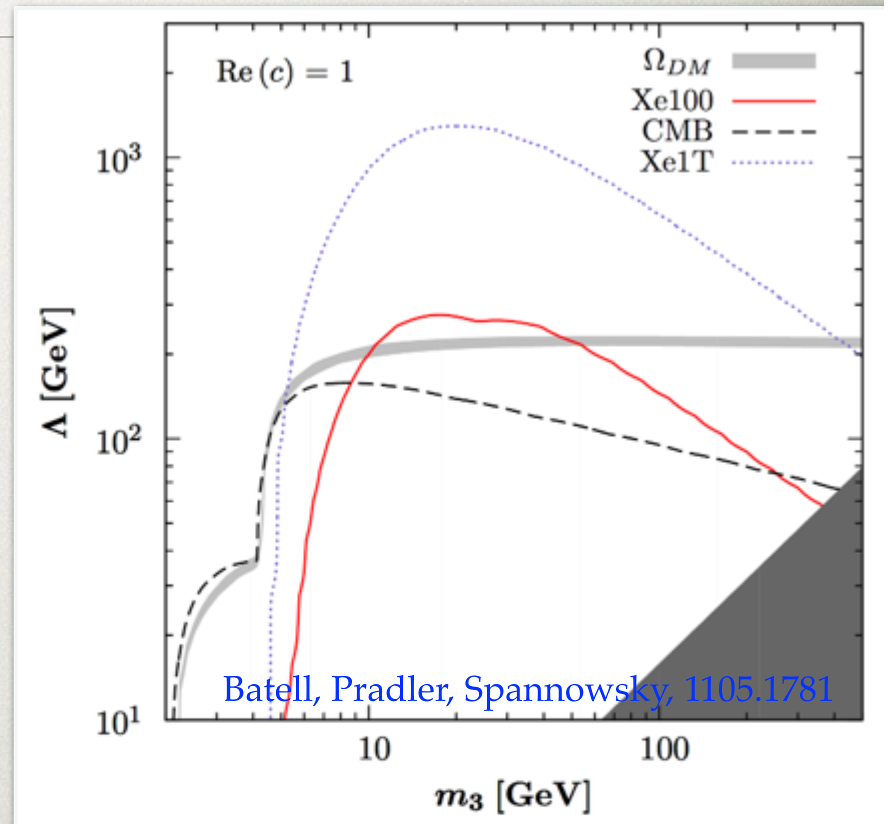
$$\chi \sim (n_Q, m_Q)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R}$$

$$(n-m) \bmod 3 \neq 0. \qquad \begin{aligned} m &\equiv m_Q + m_u + m_d. \\ n &\equiv n_Q + n_u + n_d \end{aligned}$$

- in contrast the flavor breaking vevs should have zero flavor triality: $(n_{vev} - m_{vev}) mod\ 3 = 0$ so that Z_3^{χ} unbroken
  - an example: SM Yukawas which are in bi-fundamental

MFV DM

- an example is DM with MFV interactions
  - EFT analysis
  - structure of DM-SM interactions in MFV DM dictated by MFV power counting
  - example: SM singlet $S \sim (3, 1, 1)_{GF}$
  - for inverted spectrum annihilation dominated by $\chi_3\chi_3 \rightarrow b\bar{b}$
- does it have to be MFV?
- dynamical origin of interactions?
- will show a non-MFV example
  - not being in EFT limit will be numerically beneficial



see also
Lopez Honorez, Merlo, 1303.1087
Batell, Lin, Wang,1309.4462
Agrawal, Blanke & Gemmler, 1405.6709
Bishara, Greljo,Kamenik, Stamou, JZ, to appear

GENERAL FLAVORED DM

Bishara, Greljo,Kamenik, Stamou, JZ, to appear

- basic requirement for flavored DM stable due to Z_3^{QUD}
  - G_F is a good symmetry in UV
  - broken by spurions ϕ_{vev} in representations with zero flavor triality
    - $(n_{vev} - m_{vev}) mod\ 3 = 0$
      - e.g., any vev in adjoint or bi-fundamental ok
  - stable color singlet(s) in representations with nonzero flavor triality
    - $(n_\chi - m_\chi) mod\ 3 \neq 0$

GAUGED FLAVOR SYMMETRY

Grinstein, Redi, Villadoro, 1009.2049
Bishara, Greljo,Kamenik, Stamou, JZ, to appear

- fully gauged G_F
  - spontaneously broken by vevs

$$Y_u \sim (\bar{3},3,1) \qquad Y_d \sim (\bar{3},1,3)$$

  - to ensure anomaly cancellation a set of chiral fermions

$$\Psi_{dL} \sim (1,1,3) \qquad \Psi_{uL} \sim (1,3,1) \qquad \Psi^c_{dR} \sim (\bar{3},1,1) \qquad \Psi^c_{uR} \sim (\bar{3},1,1)$$

  - mass term (after EWSB and flavor breaking)

$$\begin{aligned}\mathcal{L}_{\text{mass}} \supset\ & \lambda_u \bar{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \bar{\Psi}_{uL} Y_u \Psi_{uR} + M_u \bar{\Psi}_{uL} U_R \\ & + \lambda_d \bar{Q}_L H \Psi_{dR} + \lambda'_d \bar{\Psi}_{dL} Y_d \Psi_{dR} + M_d \bar{\Psi}_{dL} D_R + \text{h.c.},\end{aligned}$$

flavor symmetric mixing

breaks flavor after SSB

flavor symmetric mixing

SM YUKAWAS

- the SM Yukawas are generated after $Y_{u,d}$ obtain vevs and Ψ_i integrated out

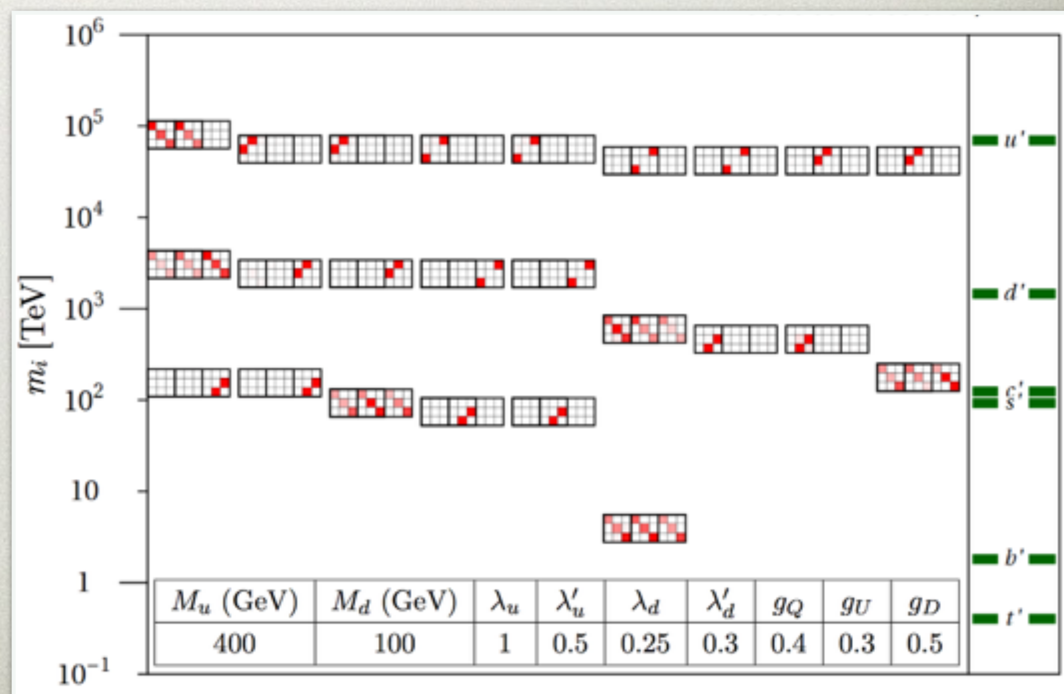
$$y_u = \frac{\lambda_u M_u}{\lambda'_u \langle Y_u \rangle} \qquad y_d = \frac{\lambda_d M_d}{\lambda'_d \langle Y_d \rangle}$$

- note that the SM Yukawas are non-analytic in spurions $\langle Y_{u,d} \rangle$
  - the model is not of the usual MFV-type
  - gauge fields inverse mass hierarchy $m_A^2 \sim (y_{ui} y_{uj})^{-1}$
  - low energy observables have MFV structure

NEW STATES

Grinstein, Redi, Villadoro, 1009.2049

- inverted mass hierarchy for the extra fermions
- flavored gauge bosons (FGBs) that couple to light quarks are heavy
  - despite non-MFV structure FCNCs under control
  - a benchmark: $m_{t'}$~ 520 GeV, m_{FGB}^{min} ~3.2TeV (potentially in conflict with LHC)



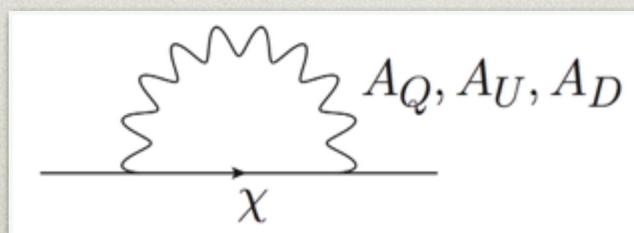
DARK MATTER

- take DM to be a fermion
  - vector-like, so that no anomalies
  - take it to be in fundamental of $SU(3)_U$

$$\chi_L \sim (1,3,1), \qquad \chi_R^c \sim (1,\bar{3},1).$$

$$\mathcal{L}_{\rm mass}^{\rm DM} = m_\chi \bar{\chi}_L \chi_R + {\rm h.c.}\,.$$

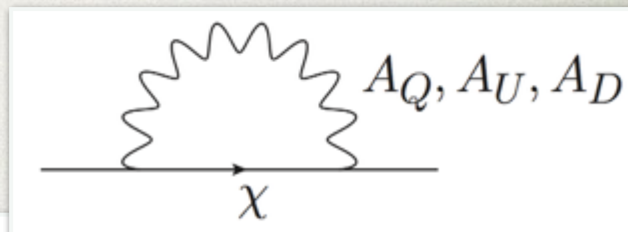
- the DM mass splitting could be due to
  - radiative corrections alone



  - additional source of flavor breaking

RADIATIVE SPLITTING

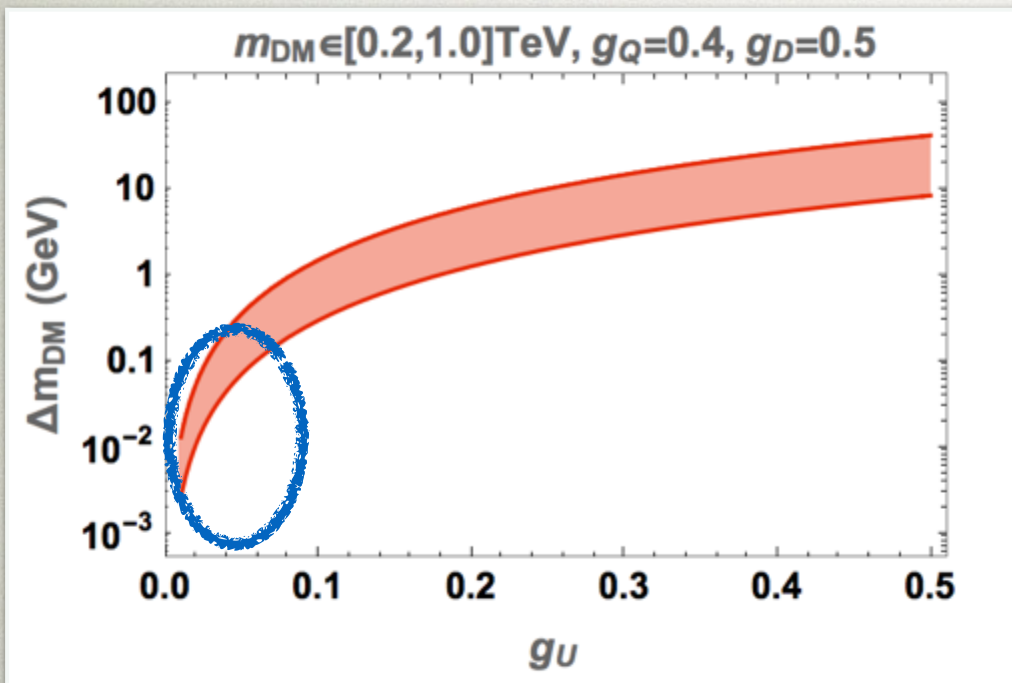
- if mass degeneracy broken only by radiative corrections
  - in the limit of $m_\chi \ll m_A$



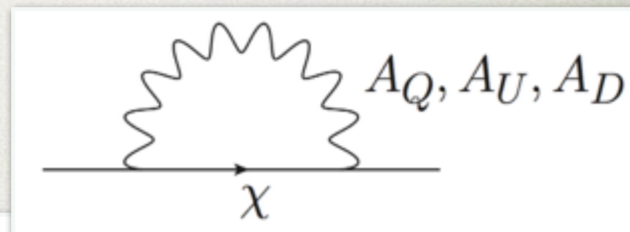
$$\mathcal{L}^{\rm DM}_{\rm break} = -\frac{m_\chi g_U^2}{16\pi^2}\bar{\chi}\lambda^a(\log \mathcal{M}_A^2/\mu^2)^{ab}\lambda^b\chi,$$

- typical splitting *~few GeV* to ~few 10GeV
  - long enough lifetimes that problems with BBN, CMB, …
- if splitting below m_π cosmologically metastable
  - DM composed of three states
  - χ_1 the lightest state

PLITTING



- nly by radiative



$$\ldots M_A^2/\mu^2)^{ab}\lambda^b\chi,$$

- typical splitting ~*few* GeV to ~ few 10GeV
  - long enough lifetimes that problems with BBN, CMB, …
- if splitting below m_π cosmologically metastable
  - DM composed of three states
  - χ_1 the lightest state

ADDITIONAL SPLITTING

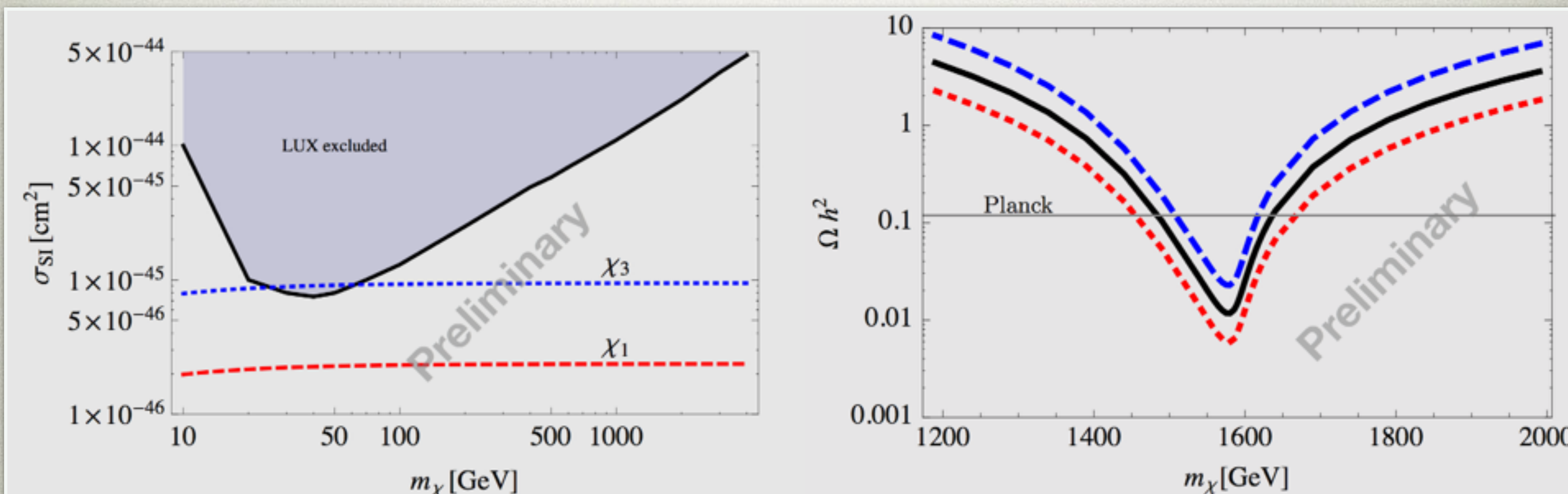
- if extra splitting due to direct flavor breaking from additional spurion
  - e.g. due to a scalar in the adjoint of $SU(3)_U$
  - the DM states χ_1, χ_2, χ_3 can have masses split by O(1)
  - heavier states decay before BBN
  - DM is the lightest χ state
    - can be either χ_1, χ_2, or χ_3

RELIC ABUNDANCE

- the two cases of mass splitting qualitatively different
  - radiative splitting: co-annihilation of χ_2, χ_3, while χ_1 chemically decoupled
  - additional splitting: simple thermal relic
- only the lightest gauge boson relevant for the DM interactions
  - approximately T_8 diagonal in $SU(3)_i$
  - DM annihilates to $t'\bar{t}'$, $t\bar{t}$, jj
- viable set of benchmarks seem to require $m_\chi \sim m_A/2$
- there is a lower bound on m_χ due to flavor and collider constraints on flavored gauge bosons

RELIC ABUNDANCE

- the two cases of mass splitting qualitatively different
  - radiative splitting: co-annihilation of χ_2, χ_3, while χ_1



- viable set of benchmarks seem to require $m_\chi \sim m_A/2$
- there is a lower bound on m_χ due to flavor and collider constraints on flavored gauge bosons

DM & FLAVOR VIOLATION

THE AIM

Kamenik, JZ, 1107.0623

- most of the time flavor breaking irrelevant in DM searches
  - is there an instant where it is important?

FV AND DM

- FV couplings can be important
  - when DM couplings to quarks are chirality flipping
  - since then couplings to two different EW representations
    - typically in two different flavor representations as well
- numerically, the FV couplings can dominate in mono tops

DIRECT PRODUCTION

- use EFT for DM interactions with quarks

$$\mathcal{L}_{\rm int} = \sum_a \frac{C_a}{\Lambda^{n_a}} \mathcal{O}_a$$

- only interested in interactions with quarks

$$\mathcal{J}^\mu_{V,A} = \bar\chi \gamma^\mu \{1, \gamma_5\} \chi$$

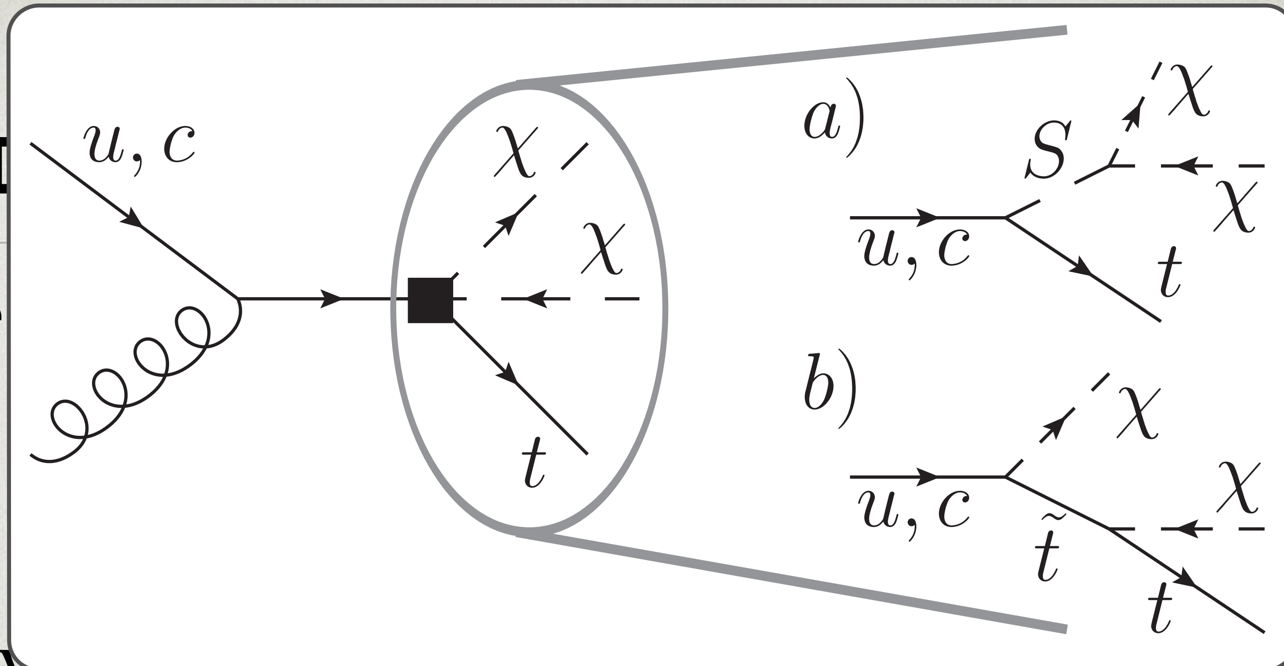
$$\begin{aligned}
\mathcal{O}^{ij}_{1a} &= \big(\bar Q^i_L \gamma_\mu Q^j_L\big) \mathcal{J}^\mu_a\,, & & \\
\mathcal{O}^{ij}_{2a} &= \big(\bar u^i_R \gamma_\mu u^j_R\big) \mathcal{J}^\mu_a\,, & \mathcal{O}^{ij}_{3a} &= \big(\bar d^i_R \gamma_\mu d^j_R\big) \mathcal{J}^\mu_a\,, \\
\mathcal{O}^{ij}_{4a} &= \big(\bar Q^i_L H u^j_R\big) \mathcal{J}_a\,, & \mathcal{O}^{ij}_{5a} &= \big(\bar Q^i_L \tilde H d^j_R\big) \mathcal{J}_a\,,
\end{aligned}$$

$$\mathcal{J}_{S,P} = \bar\chi \{1, \gamma_5\} \chi$$

- full set includes other ops.

D

- use



- only interested in interactions with quarks

$$\mathcal{J}^{\mu}_{V,A} = \bar{\chi}\gamma^{\mu}\{1,\gamma_5\}\chi$$

$$\mathcal{O}^{ij}_{1a} = (\bar{Q}^i_L \gamma_\mu Q^j_L)\mathcal{J}^\mu_a\,,$$

$$\mathcal{O}^{ij}_{2a} = (\bar{u}^i_R \gamma_\mu u^j_R)\mathcal{J}^\mu_a, \qquad \mathcal{O}^{ij}_{3a} = (\bar{d}^i_R \gamma_\mu d^j_R)\mathcal{J}^\mu_a\,,$$

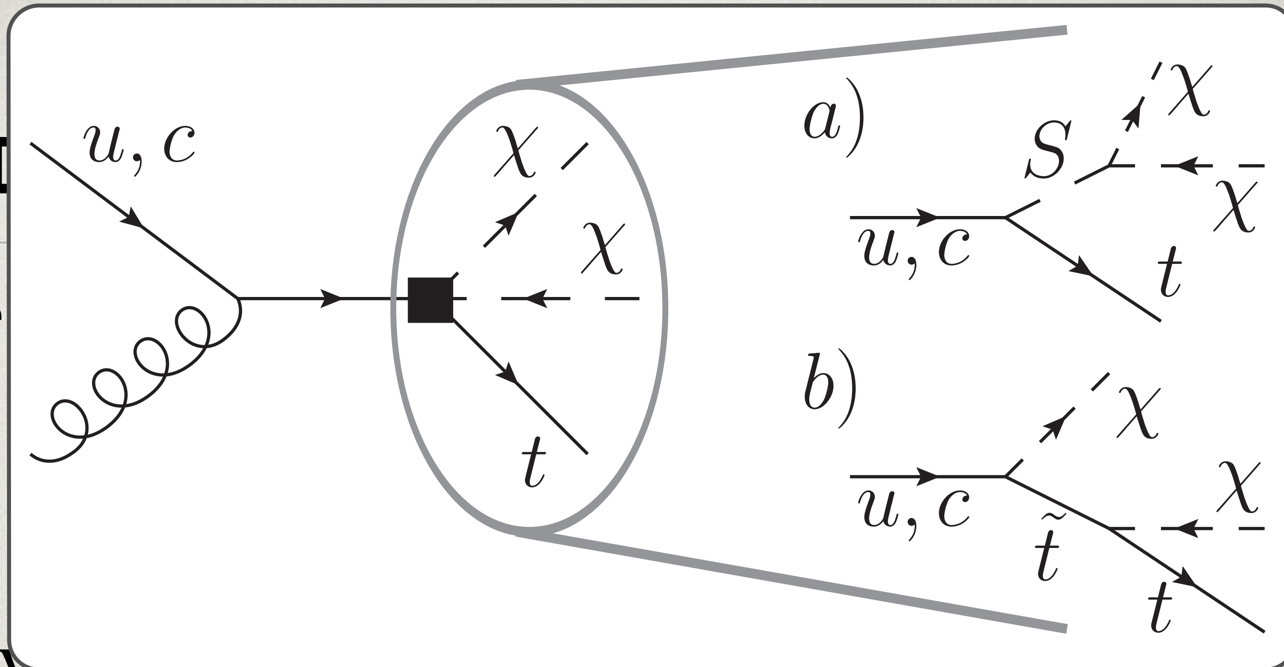
$$\mathcal{O}^{ij}_{4a} = (\bar{Q}^i_L H u^j_R)\mathcal{J}_a\,, \qquad \mathcal{O}^{ij}_{5a} = (\bar{Q}^i_L \tilde{H} d^j_R)\mathcal{J}_a\,,$$

$$\mathcal{J}_{S,P} = \bar{\chi}\{1,\gamma_5\}\chi$$

- full set includes other ops.

D

- use … s



- only interested in interactions with quarks

$$\mathcal{J}^{\mu}_{V,A} = \bar{\chi}\gamma^{\mu}\{1,\gamma_5\}\chi$$

$$\mathcal{O}^{ij}_{1a} = (\bar{Q}^i_L\gamma_\mu Q^j_L)\,\mathcal{J}^\mu_a\,,$$

$$\boxed{\begin{aligned}\mathcal{O}^{ij}_{2a} &= (\bar{u}^i_R\gamma_\mu u^j_R)\,\mathcal{J}^\mu_a\,,\\ \mathcal{O}^{ij}_{4a} &= (\bar{Q}^i_L H u^j_R)\,\mathcal{J}_a\,,\end{aligned}}$$

$$\mathcal{O}^{ij}_{3a} = (\bar{d}^i_R\gamma_\mu d^j_R)\,\mathcal{J}^\mu_a\,,$$

$$\mathcal{O}^{ij}_{5a} = (\bar{Q}^i_L \tilde{H} d^j_R)\,\mathcal{J}_a\,,$$

$$\mathcal{J}_{S,P} = \bar{\chi}\{1,\gamma_5\}\chi$$

- full set includes other ops.

HORIZONTAL SYMMETRIES EXAMPLE

- an example: abelian horizontal symm.

Leurer, Nir, Seiberg hep-ph/9212278; hep-ph/9310320

- the yukawas are given by

$$(Y_u)_{ij} \sim \lambda^{|H(\bar{u}_R^j)+H(Q^i)|}, \quad (Y_d)_{ij} \sim \lambda^{|H(\bar{d}_R^j)+H(Q^i)|}$$

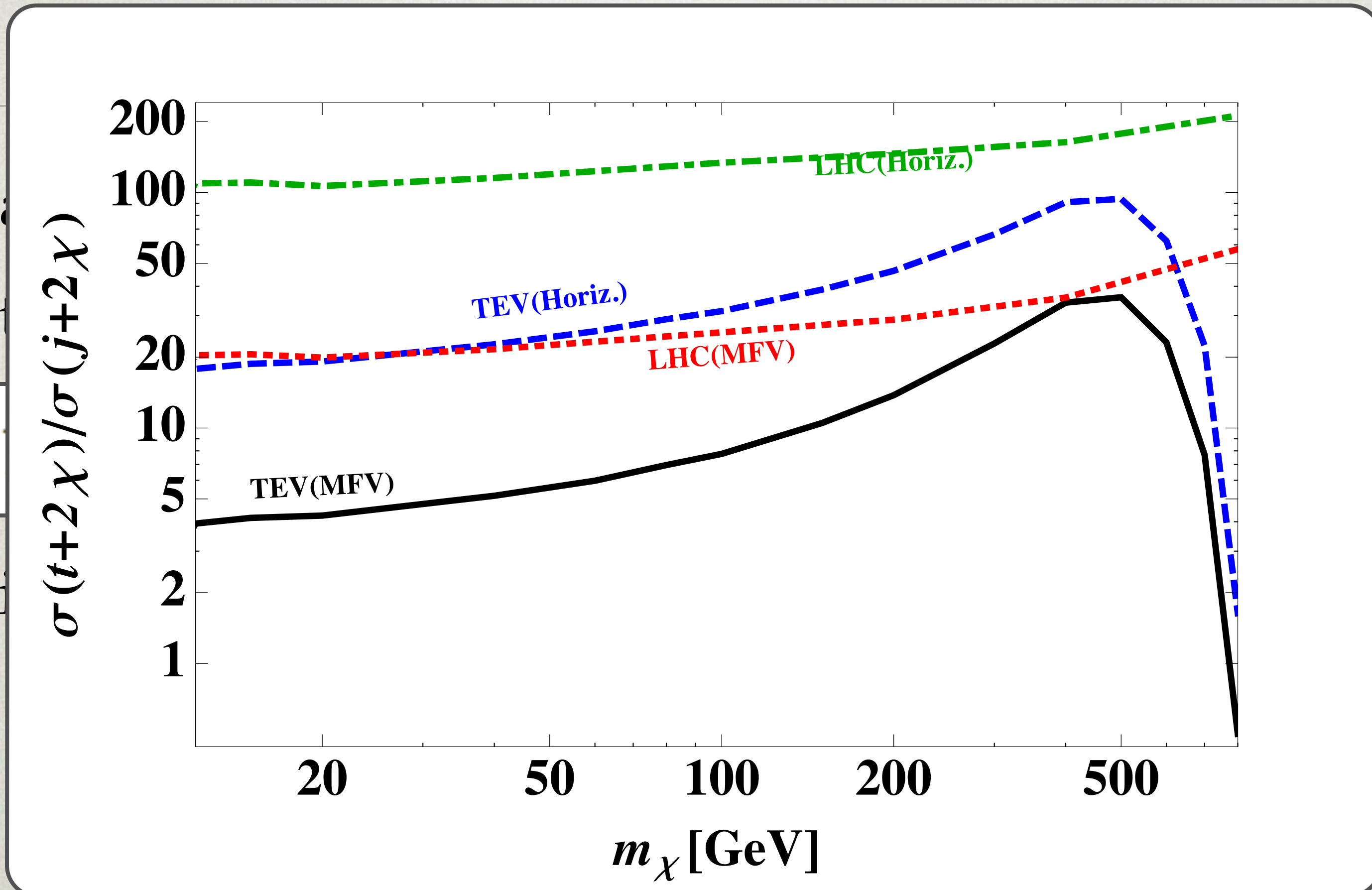
- in the same way the couplings to DM

$$C_2 \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^3 \\ \lambda^2 & 1 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}, \quad C_4 \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix}$$

- note: *c*-*t*-DM coupling parametrically larger
- even larger effects if DM charged under flavor

HORIZONTAL SYMMETRIES

278; hep-ph/9310320



- note: *c*-*t*-DM coupling parametrically larger
- even larger effects if DM charged under flavor

HORIZONTAL SYMMETRIES EXAMPLE

- an example: abelian horizontal symm.

Leurer, Nir, Seiberg hep-ph/9212278; hep-ph/9310320

- the yukawas are given by

$$(Y_u)_{ij} \sim \lambda^{|H(\bar{u}_R^j)+H(Q^i)|}, \quad (Y_d)_{ij} \sim \lambda^{|H(\bar{d}_R^j)+H(Q^i)|}$$

- in the same way the couplings to DM

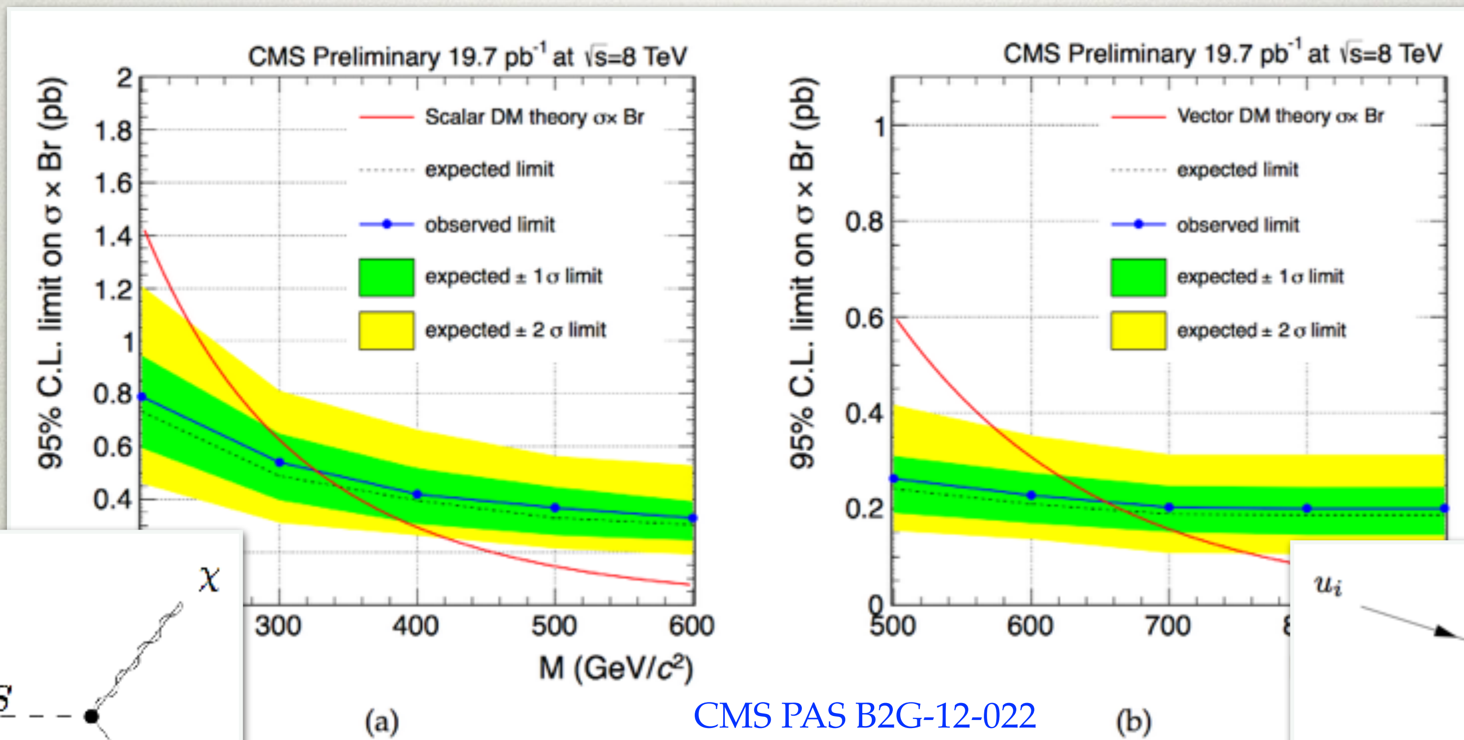
$$C_2 \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^3 \\ \lambda^2 & 1 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}, \quad C_4 \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix}$$

- note: *c*-*t*-DM coupling parametrically larger
- even larger effects if DM charged under flavor

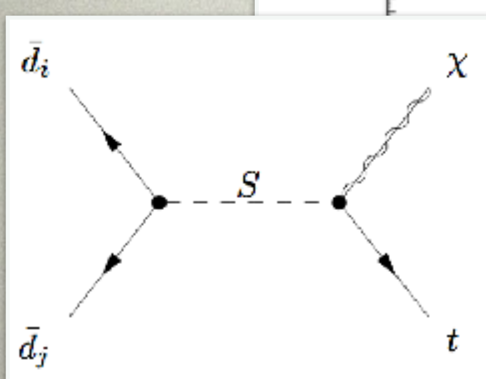
MONOTOP EXPERIMENTAL RESULTS

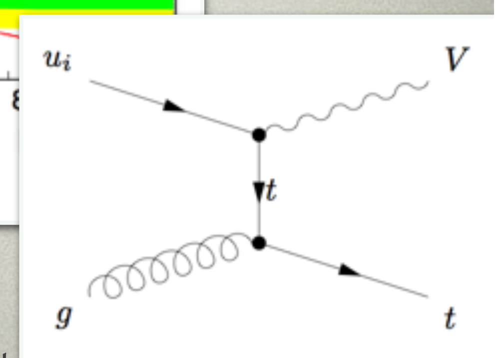
- CMS results on monotop searches
  - couplings set to 0.1
  - uses hadronic tops: 3j+MET channel

CMS PAS B2G-12-022;
improves CDF 1202.5653;



(a) CMS PAS B2G-12-022 (b)





Andrea, Fuks, Maltoni, 1106.6199

CONCLUSIONS

- have shown three examples where flavor important for understanding DM
  - (meta-)stability of DM
  - monotop signals

BACKUP SLIDES