Flavor Symmetry and Its Collider Signatures

Alexander Natale
Korea Institute for Advanced Study
In collaboration with:
Ernest Ma

E. Ma, and A. Natale, *Phys. Lett.* **B740** (2015) 80-82,
arXiv:1410.2902

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Introduction

Dark Matters & ν mass: evidence for DM and $m_\nu \neq 0$ is strong, can't be minimal SM particles $\rightarrow$ new physics (NP)

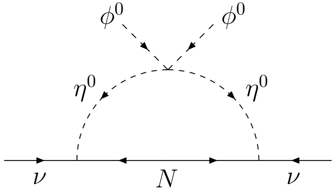
Radiative Connection: Long history of radiative m_ν mechanisms $\rightarrow$ maybe DM and m_ν are related radiatvely

Flavor/Horizontal Symmetries: Non-Abelian discrete symmetries still of continued interest to explain PMNS values

Compliments: Use direct detection, colliders, and precision to constrain models of DM/BSM physics, and the connection between DM-ν to probe nature of m_ν and the horizontal symmetry

Radiative Neutrino Mass and DM

- Paritlces in loop **odd under dark** Z_2
- Neutral fermion (N), $SU(2)$ scalar doublet η (no VEV)
- Majorana mass of N completes loop
- Mass splitting $(\lambda_5(\eta^\dagger\Phi)^2)$ makes loop finite
- Either η^0 or N are DM candidate



Flavor/Horizontal Symmetries

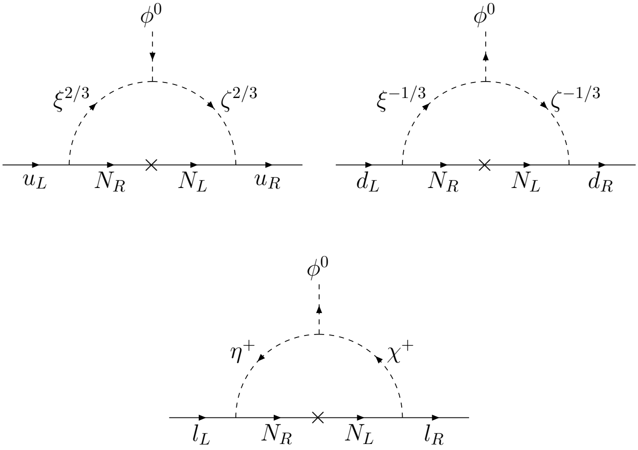
- Non-Abelian discrete groups (S_3,A_4, $\Delta(27)$, $\Delta(54)$, etc.) have been used to describe PMNS in models of m_ν
- Produce correlations between angles in PMNS, leads to specific patterns for $L-N$ coupling in Ma-like models

In the minimal Ma model:
N and $(e,\nu)_L$ are given non-trivial reps under the Horizontal symmetry (often add copies of N ie $N_{1,2,3}\sim 3_{A_4}$), N_i now carries flavor information.

In many A_4 models this yields $N_3\to\tau\eta$, $N_2\to\mu\eta$.

For example (Bhattacharya, Ma, AN, Rashed 2013): if $m_{N_1}\approx m_{N_2}$ then $\eta^{\pm}\eta^{\mp}\to e^{\pm}\mu^{\mp}N_1N_2$ with a BR $\sim 2/9$, where OSSF dilepton signals have a BR $\sim 1/9$.

Scotogenic Extensions to Ma Model



Expanded particle content yield scotogenic quark & lepton masses.

The 'Simplified' Scotogenic Model

Usual minimal scotogenic content: η, N_i (now a Dirac fermion)

Non-minimal particles:

χ^+ singlet, scalar

$(\xi^{2/3}, \xi^{-1/3})$ color-triplet, $SU(2)$ doublet, scalar

$\zeta^{-1/3}$ color-triplet, singlet, scalar

New Yukawa interactions:

$$\mathcal{L} = f(\bar{d}_R N_{1L} + \bar{s}_R N_{2L})\zeta^{-1/3} + f'(\bar{e}_R N_{1L} + \bar{\mu}_R N_{2L})\chi^- + \text{h.c.},$$

where $m_\zeta > m_{N_2} > m_\chi > m_{N_1}$

$\zeta \to dN_1,\ sN_2,$ and $N_2 \to e\mu N_1$ via χ^+

Relic Density

Relic density for DM with color-triplet, scalar, mediator previously calculated (for instance see Y.Bai & J.Berger arXiv:1308.0612):

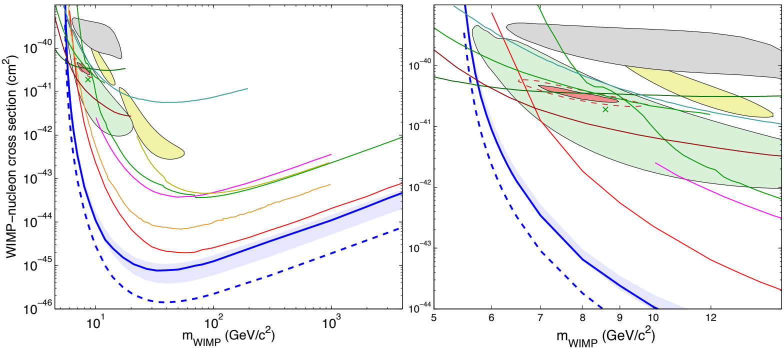
$$\langle \sigma v \rangle = \frac{1}{2}\left[\frac{3f^4 m_{N_1}^2}{32\pi(m_{N_1}^2 + m_\zeta^2)^2} + v^2 \frac{f^4 m_{N_1}^2 (11 m_\zeta^4 - 5 m_{N_1}^4 - 18 m_{N_1}^2 m_\zeta^2)}{256\pi(m_{N_1}^2 + m_\zeta^2)^4}\right]$$

$\rightarrow$ with mass choices cannot fit $\Omega_0 h^2$ for DM unless $f > 0.5$, however f also needed to radiatively generate m_u. To get correct m_u values $f \approx 0.01$.

Solution: $N_1 N_1 \rightarrow e^+ e^-$, using MicrOMEGAs with $f' \approx 0.5,\ f \approx 0.01,$ yields correct $\Omega_0 h^2$. f' is partially constrained by m_l $\rightarrow$ possible consequences for η Yukawa couplings to produce observed m_l, however possible direct detection/cosmological constraints on this channel.

Direct Detection

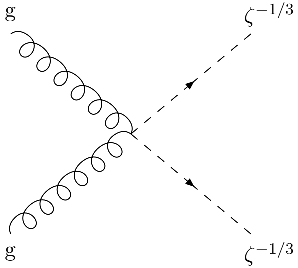
LUX results from: arXiv:1405.5906.



$$f \approx 0.01,\ m_\zeta = (600)\ 750\ \text{GeV},\ m_{N_1} = 120\ (160)\ \text{GeV}$$
$$\sigma_{\text{SI}} = 1.808\ (1.164) \times 10^{-11}\ \text{pb}\ = 1.808\ (1.164) \times 10^{-47}\ \text{cm}^2$$

→ lower than LUX 2016 bounds

Main collider production:



Other diagrams include quarks, t-channel, etc. but dominated by $gg \to \zeta\zeta$
In this model $m_{N_1} \neq m_{N_2}$ and $\zeta \to dN_1$ or $\zeta \to sN_2$ with approx. equal BR:
collider signature with dileptons is always OSOF This is important because off-Z OF events are used to estimate SUSY backgrounds.

$$\mathcal{L} = f(\bar{d}_R N_{1L} + \bar{s}_R N_{2L})\zeta^{-1/3} + f'(\bar{e}_R N_{1L} + \bar{\mu}_R N_{2L})\chi^- + \text{h.c.}$$

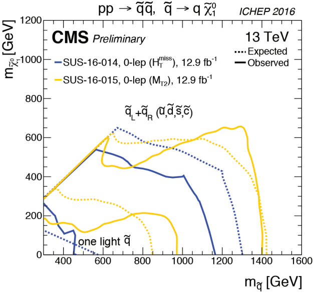
Generic Signatures:

- mono-X + $E_{\mathrm{T}}^{\mathrm{miss}}$ $\leftarrow$ same as simplified models (cf P.Ko, A.N., M.Park, & H.Yokoya arXiv:1605.07058)
- 2 jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ $\leftarrow$ **same as SUSY searches**
- 2 jets + 2 leptons (opposite-sign opposite-flavor) + $E_{\mathrm{T}}^{\mathrm{miss}}$
- 2 jets + four leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$

A common SUSY signature is opposite-sign same-flavor, positive signals (even $< 5\sigma$) yield constrains/rule out this scotogenic model (OSOF estimates flavor symmetric background so signal constrains excess OSOF)

Constraints from 13 TeV squark searches

From yesterday's CMS talk (SUS-16-014, SUS-16-015, SUS-16-016):



MT_2: $\rightarrow 400 < m_\zeta < 700$ GeV & $m_{N_1} > 100$ GeV H_T: $m_\zeta > 450$ GeV

And from ATLAS (ATLAS-CONF-2016-078):

Simplified model two degenerate squarks generations $m_{\tilde{q}} > 1.35$ TeV, but scotogenic model is closest to "one light squark"

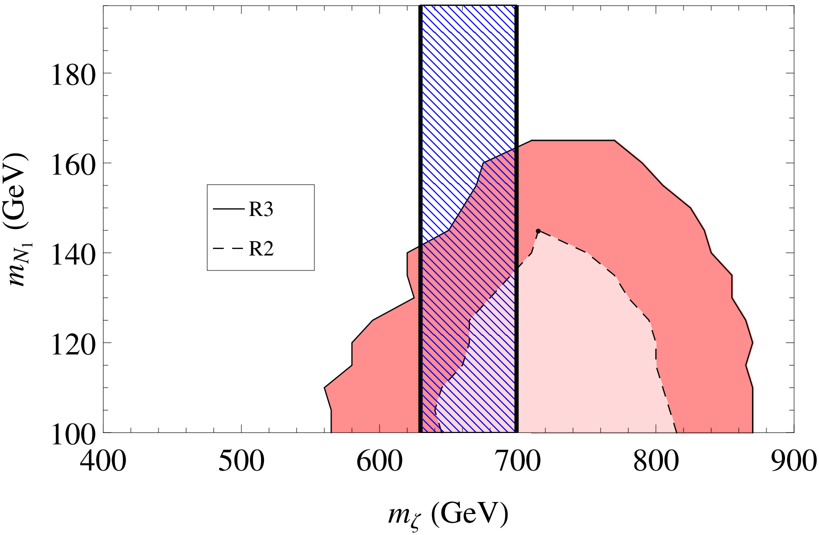
$m_\zeta \gtrsim 675$ GeV ($\sim 1/2$ reported limit?)

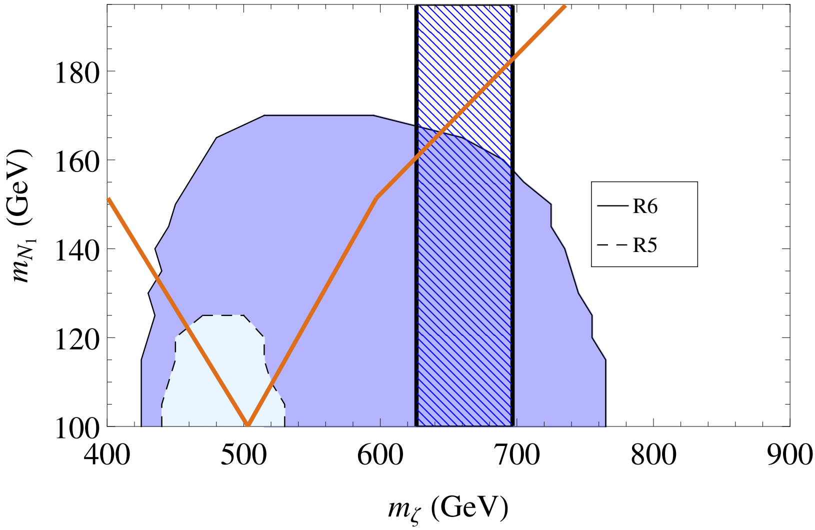
Methods

- SUSY Simplified topology production compared to LO calculation in CalcHEP to scale to NLO values.
- Main background from $\bar{t}t$ decays, calculated & scaled to NLO.
- Various cuts and masses tried, final analysis uses $m_{N_2} = 400$ GeV, $m_\chi = 200$ GeV, $m_\zeta > 400$ GeV, 180 GeV $\geq m_{N_1} \geq 100$ GeV
- 6 cut regions used, only 4 cuts produce large enough signal-to-background
- Cuts on scalar sum of hadronic transverse momentum (H_T) utilized
- For simulation: $E_{CM} = 13$ TeV, CTEQ6M, CalcHEP → PYTHIA 8

Cuts used:

- R2: MET: 200 GeV, H_T: 600, $p_T^{j(l)}$: 30 (20) GeV
- R3: MET: 275 GeV, H_T: 600, $p_T^{j(l)}$: 30 (20) GeV
- R5: MET: 200 GeV, H_T: 350, $p_T^{j(l)}$: 30 (20) GeV
- R6: MET: 200 GeV, H_T: 350, $p_T^{j(l)}$: 150 (25) GeV


180
160
140
120
100
400
500
600
700
800
900
m_{N_1} (GeV)
m_ζ (GeV)
R3
R2


180
160
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600
700
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900
m_{N_1} (GeV)
m_ζ (GeV)
R6
R5

Summary & Conclusions

- DM and m_ν could be connected through radiative quark & lepton mass
- Interesting collider searches with some overlap with SUSY but major differences
- Detailed look at recent CMS and ATLAS results required to determine constraints on scotogenic models with colored scalars

Some questions worth studying:

- EW SUSY searches and the Ma model?
- How would a horizontal/flavor symmetry signal affect SUSY SF estimates?

Thank you!

감사합니다