Resurrecting the Fraternal Twin WIMP Miracle

[2106.12578]

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Neutral Naturalness

- The Higgs mass is fine-tuned (which is considered unfortunate).
- The solutions to this fine-tuning (such as SUSY) started looking very uncomfortable/ruled out.
- In particular, this is due to:
    - Existence of colored light states (e.g. stops) that should be visible at colliders,
    - DM-like states (e.g. neutralinos) whose EW couplings to matter pushed them into tension with many direct detection experiments.
- As a result of this discomfort new ideas come into play. One of the solutions was 'Neutral Naturalness' [hep-ph/0506256]: the idea that the quadratic divergence is eliminated through existence of particles not charged under some of the SM groups (such as SU(3) color).
- The over-arching idea was that a U(4) would break down to $SU(2)_A \times SU(2)_B$, one of which would be identified with the $SU(2)_L$ of the SM. The $\mathbb{Z}_2$ symmetry $A \leftrightarrow B$ would switch these labels, and would change the SM color $SU(3)_{C,A}$ for a new gauge group $SU(3)_{C,B}$ as well as symmetry in couplings. This ensured that the cancellation from stop-like particles worked, but did not require states that were close to top-mass while strongly coupled to the SM protons.

Comments on Neutral Naturalness

- If the breaking is $\mathbb{Z}_2$ symmetric the SM Higgs vev v and the twin Higgs vev f will be identical and there will be a full mixing because of the operator $|H_A^2||H_B|^2$. This would lead to non-standard Higgs decay branching fractions and would be ruled out.
- However a hard breaking of $\mathbb{Z}_2$ can cause $f > v$, which reduces the mixing to $(v/f)^2$. As a result $f/v \sim 3$ is still palatable. This quantity is also a good indicator of how fine-tuned the Twin scenario is: how well we have to tune the hard breaking parameter.
- This model needs a UV completion. This can be achieved with SUSY e.g. [1312.1341], see our paper for more references.

Comments on Neutral Naturalness II

- The **Mirror Twin Higgs** models contain all generations in both sectors.
- **Fraternal Higgs Scenario** [1505.07109]: the fermionic content of the twin sector is reduced to the third generation: t', b', τ' and ν'_τ. The quarks are necessary to cancel the Higgs mass divergence, the leptons to cancel the anomaly. In the original FTH it is necessary to **modify the yukawas** for the b' and τ' in order to get the correct relic density. This is an explicity breaking of the $\mathbb{Z}_2$. Although less easthetic choice, it is a fair one.
- Instead we propose to resolve the issues of the FTH by spontaneously breaking hypercharge. The relic abundace/direct detection bounds are fixed this way. Yukawa symmetries are preserved and so we call our scenario $\mathbb{Z}_2$**FTH**.

Twin Higgs Problems

- The twin sector has all three generations of fermions: then the Cosmological bound on light degrees of freedom is violated due to twin neutrinos. (although that can be fixed by making neutrinos heavier, for example by modifying the twin sector see-saw mechanism)
- If the twin sector photon stays massless, then again we see a large contribution to the N_{eff}. This can be addressed by reducing the temperature of the twin sector or by not gauging the U(1)', or even breaking it at very high scale.
- The coupling of natural dark matter candidates in the Twin Higgs models (often the tau) is now ruled out by direct detection experiments.

Breaking the Hypercharge

We build on an excellent paper by Batell and Verhaaren [1904.10468] that shows it is possibly to break the twin sector hyppercharge in such as way that:

- Generates $f > v$.
- Generates a mass term for the twin photon
- Generates additional mass terms for the twin fermions.

This can be done in many ways, in particular we can break the hypercharge by $\Delta Y = 1$ or by $\Delta Y = 2$ units. As we will show it is the second choice that is interesting.

Breaking The Hypercharge II

Consider two scalar potential a Higgs charged under $U(4)$ and a Φ with charge $Y = 2$. The following potential that achieves a selective hypercharge breaking just in the twin sector:

$$\begin{aligned} V = & -M_H^2|H|^2 + \lambda_H|H|^4 - M_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \lambda_{H\Phi}|H|^2|\Phi|^2 \\ & + \delta_H(|H_A|^4 + |H_B|^4) + \delta_\Phi(|\Phi_A|^4 + |\Phi_B|^4) \\ & + \delta_{H\Phi}(|H_A|^2 - |H_B|^2)(|\Phi_A|^2 - |\Phi_B|^2) \end{aligned}$$

We need to ensure that $\delta_H > 0$ because this guarantees that both SM and twin sector develop a vev for their Higgses. On the other hand we chose $\delta_\Phi < 0$ because this will ensure only one of the two sectors spontaneously breaks hypercharge. Finally the $\delta_{H\Phi}$, after the hypercharge brekaing generates a $\mathbb{Z}_2$ breaking term that ensures that $f > v$ (explained above).

Twin photon

This has some obvious consequences for the twin photon mass. The

$$V = g_1^2 Y^2 f_\Phi^2 B_{B,\mu} B_B^\mu + g_2^2 f^2 W_{B,\mu} W_B^\mu$$

As a result not only are the twin Ws and Zs massive but so is the twin Photon. This also means that the masses of Z_B and A_B are dependent on both f and f_Φ and the mass eigenstates are admixtures of the B_B and $W_{3,B}$, however when

$$m_A \ll m_W \text{ or } m_A \gg m_W$$

the mixing is relatively small and the masses are closes to the diagonal mass terms. In this work we chose a reasonable convention: The twin photon is the state that has the higher contents of B_B and the twin Z is the state that has the higher contents of $W_{3,B}$.

Twin tau phenomenology

In the case of $Y = 2$ breking there are no new mass terms for the twin quarks because there is no twin quark bilinear with charge $Y = 2$. However, or leptons this is not the case. In particular these are the new possible mass terms stemming from these interactions (some coming from the UV completion):

$$V = \lambda_\tau \phi' \bar{E}_\tau \bar{E}_\tau + \frac{\xi_\tau}{\Lambda^2} \phi' (L'_\tau H'^\dagger)(L'_\tau H'^\dagger) + \frac{c_\tau}{\Lambda^2} |\phi'|^2 L'_\tau H'^\dagger \bar{E}'_\tau$$

These interactions, after spontaneous symmetry breaking, generate a mass matrix:

$$\begin{pmatrix} m_{LL} & m_{LR} \\ m_{LR} & m_{RR} \end{pmatrix}$$

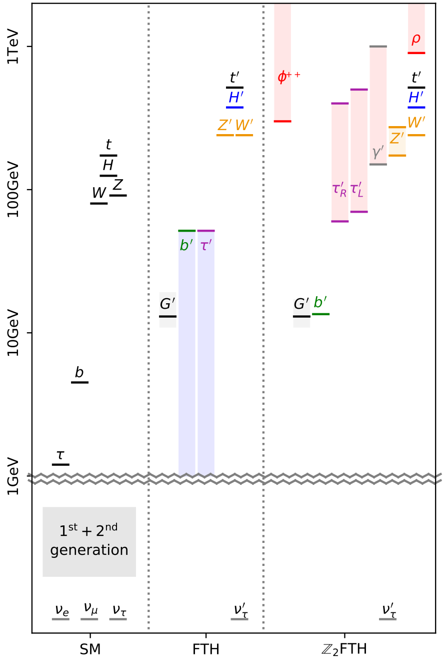
with

$$m_{LR} = \frac{y_\tau}{\sqrt{2}} f + \frac{\tilde{c}_\tau}{\sqrt{2}} \frac{f_\phi^2}{\Lambda^2} f,$$
$$m_{LL} = \xi_\tau \frac{f^2}{\Lambda^2} f_\phi,$$
$$m_{RR} = 2\lambda_\tau f_\phi,$$

Twin tau phenomenology II

- This mass matrix is a typical example of a see-saw (but in the charged lepton sector). We should not surprised by this: we broke hypercharge (charge) and the twin tau can now be its own anti-particle.
- Interestingly enough this actually stabilizes the twin τ total number. While it is true that charge is no longer conserved the tau is only allowed to decay by chaging the charge by two units and the only particle in the spectrum with negative charge is the anti-tau. As a result the only allowed decay is of form $\tau \to \bar{\tau} + X$ and the charge conserving $\tau \to \nu_\tau + \bar{t} + b$. The first is always kinematically forbidden and the second is easily enforced.
- We will distinguish some scenarios. Depending on which tau is lighter:
  - Mostly right tau: $m_{LL} > m_{RR} \gg m_{LR}$
  - Mostly left tau: $m_{RR} > m_{LL} \gg m_{LR}$
  - Pseudo dirac tau: $m_{LR} \gg m_{LL}, m_{RR}$
- However, the mostly left and pseudo-dirac cases have their mass dictated by their coupling to the twin Higgs and so suffer from the same problems the twin tau dark matter encounters in the original Fraternal Twin Higgs models – they are ruled out by direct detection experiments. As a result we focus on the scenarios in which the **mostly right twin tau is the lightest tau**.

Spectrum


1TeV
100GeV
10GeV
1GeV
t
H
W
Z
b
τ
$1^{\mathrm{st}} + 2^{\mathrm{nd}}$ generation
ν_e
ν_μ
ν_τ
t'
H'
Z'
W'
b'
τ'
G'
ν'_τ
ϕ^{++}
ρ
t'
H'
W'
Z'
γ'
τ'_R
τ'_L
G'
b'
ν'_τ
SM
FTH
$\mathbb{Z}_2$FTH

Dark Matter

We know recover a working twin tau dark matter: it accidentally stable and it acquires the correct relic abundance for the right choice of f_Φ which is one-to-one also related to $m_{\gamma'}$. The freeze-out of τs into SM proceeds either through the twin Higgs, twin Z or twin photon into b' states that annihilate into the unstable twin Glueballs as was pointed out in the original Twin Higgs and FTH papers [1501.05310],[1505.07109].

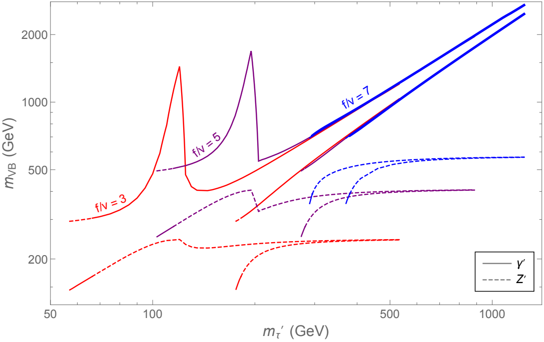


Figure: *Masses of twin gauge bosons that are necessary to ensure the correct relic abundance of the twin tau dark matter. The peaks are caused by the resonance with the twin Higgs.*

Dark Matter II

What does this mean for the direct detection? We have taken the allowed points from the previous plot and we vary the other parameters within their reasonable ranges (for example $\lambda_\tau < \mathcal{O}(1)$). We then calculate the possible range of nuclear cross-sections.

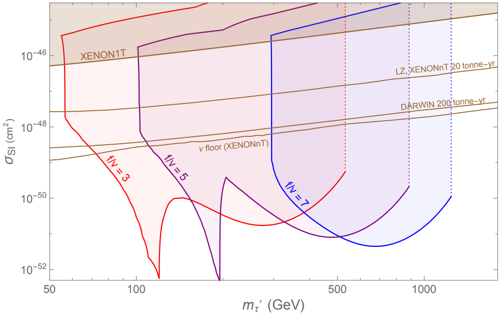


Figure: *Possible nuclear cross-sections for the* $\mathbb{Z}_2$*FTH model.*

Note that this scenario allows for dark matter that is just about to be discovered as well as dark matter that is well below the neutrino floor.

Signatures

Many of the signatures are inherited from FTH:

- Exotic Higgs decays into twin fermions.
- Longlived signatures of the twin Glueballs in colliders.
- Exotic decays of ϕ^{++} into same-sign leptons.
- $\Delta N_{eff} = 0.1$ (Stage 4 CMB will be sensitive to 0.02)
- The Glueball decays could be a source of the x-ray/gamma ray excesses in astrophysics.

Conclusions

- We can resurrect the FTH scenario, make it a little bit more symmetric by sponatenously breaking the hypercharge in the twin sector.
- As a result if the mass of the lighter twin tau is controlled by the coupling to the hypercharge breaking scalar, the resulting relic abundance and direct detection cross-section are consistent with the current bound and potentially discoverable with the next generation DD experiments.
- These models necessarily generate $\Delta N_{\mathrm{eff}} = 0.1$ and are discoverable in the future.
- They come with a host of collider signals that are attainable at the high luminosity LHC.
- **There are many more details** that did not fit into this presentation. I would urge to have a look at the paper [2106.12578].

Domain Walls?

One interesting aspect the Batell and Verhaaren construction is that the $\mathbb{Z}_2$ symmetry $A \leftrightarrow B$ implies that there are two possible vacua with identical energy densities. As a result, this leads to formation of domain walls which wreak cosmological havok. In order to get rid of this problem Batell and Verhaaren need to add an explicit $\mathbb{Z}_2$ breaking term

$$V = \delta m^2(|\Phi_A|^2 - |\Phi_B|^2). \tag{1}$$

Interestingly enough, in the $\mathbb{Z}_2$FTH this term is unnecessary. The two different scalars Φ_A and Φ_B get different loop contributions to their selfcoupling quartics because of the different number of fermions running in the loop. As a result as long as the λ_l the coupling of SM ϕ^{++} with any fermion is large enough, the radiative corrections resolve the vacuum degeneracy:

$$\lambda_l > 10^{-8} \tag{2}$$

Since this is smaller than the electron Yukawa, it is practically invisible.