Non-sterile electroweak-scale right-handed neutrinos and a panorama of implications

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- Window into BSM at the LHC: EW-scale ν_R's and accompanying BSM Higgses.
- In any event, properties of the 126 GeV boson which are being revealed put severe constraints on any BSM.

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- Epilog

Why are neutrinos so light?

- Experimental summaries: $\Delta m^2_{atm} \sim 10^{-3} eV^2$; $\Delta m^2_{solar} \sim 10^{-5} eV^2$; Cosmology: $\sum_i m_i < (0.17 - 2.0) eV$; Cosmology + Oscillation: $0.04 eV < m_{heaviest} < (0.07 - 0.7) eV$.

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- Simplest realization: Add SM-singlet (sterile) ν_R's to the SM. Neutrino masses from $g_\nu \bar{l}_L \tilde{\phi} \nu_R$ where $l_L = (\nu_L, e_L)$ and $\tilde{\phi} = (\phi^{0*}, -\phi^-) \Rightarrow m_\nu \approx g_\nu (175\ GeV) \Rightarrow g_\nu < 10^{-11}$.

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- Lepton-number violating Majorana mass term: $M_R \nu_R^T \sigma_2 \nu_R$.
- "Standard" expectations: $m_D \propto \Lambda_{EW}$ and $M_R \propto M_{W_R}$ in Left-Right model and $M_R \propto \Lambda_{GUT}$ in GUT theories.

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- In fact, there is no reason (other than GUT prejudice) to think that ν_R's should be SM singlets.
- Important criterion: It has to be experimentally testable.

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- Other "less-practical motivations" for Mirror fermions?

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- Mirror fermions are incorporated and needed in a model of Luminogenesis where at the end of inflation dark matter was first created, followed by the conversion of $\sim 15\%$ of its mass density into luminous matter. P. Frampton and PQH.

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- Z width constraint (3 light neutrinos) $\Rightarrow M_R > M_Z/2 \sim 46\ GeV$.

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- $v_M \sim O(\Lambda_{EW}) \Rightarrow$ A "large" triplet VEV would spoil $\rho = 1$ at tree level! Recall $\rho = M_W^2/M_Z^2 \cos^2\theta_W$.

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- $\rho = (\sum_i [T(T+1) - T_3^2]_i v_i^2 c_{T,Y})/(2\sum_i T_{3i}^2 v_i^2)$. $\rho = 1/2$ for a complex triplet. $\rho = 1$ for a complex doublet.

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- Need to restore the Custodial Symmetry! Another triplet Higgs scalar $\xi = (3, Y/2 = 0)$ such that

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}$$

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- Vacuum alignment dictates $\langle\chi\rangle = \begin{pmatrix} v_M & 0 & 0 \\ 0 & v_M & 0 \\ 0 & 0 & v_M \end{pmatrix}$ and $\langle\Phi\rangle = \begin{pmatrix} v_2/\sqrt{2} & 0 \\ 0 & v_2/\sqrt{2} \end{pmatrix} \Rightarrow SU(2)_L \times SU(2)_R \rightarrow SU(2)_D$ (custodial).

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- What about the Dirac mass m_D? It will come from a product of 2 doublets i.e. $m_D(\nu_L^\dagger\,\nu_R + h.c.)$. What Higgs?

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- The very light ($\sim 100 keV$ or so) singlet scalar could have interesting cosmological implications. Mass-varying neutrino scenario: $v_S \sim O(\Lambda_{EW})$ but now $m_D = g_{Sl}\phi_S^{classical}$ with $\phi_S^{classical} \sim 10^5 eV \rightarrow$ $v_S \sim O(\Lambda_{EW})$ in the distant future. A scenario for Dark Energy.

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- The model has to satisfy the electroweak precision data because extra chiral doublets can do damage to the S parameter for example! This is where the Higgs sector of the model comes in.
- Note: The magnitude of the magnetic moment for the electron or muon is $\mu = (1+a)\frac{q}{2m}$ where $a = \frac{g-2}{2}$. $a^{(4)} \sim \frac{1}{45}(\frac{m}{m_{heavy}})^2(\frac{\alpha}{\pi})^2$. For $m_{heavy} \sim 200\, GeV$, $a_e^{(4)} \sim 10^{-18}$ and $a_\mu^{(4)} \sim 10^{-14}$.

The EW-scale ν_R model: The Higgs sector

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- Under the custodial symmetry group $SU(2)_D$, these 10 physical degrees of freedom decompose as

$$
\begin{aligned}
\text{five-plet (quintet)} \quad &\rightarrow \quad H_5^{\pm\pm},\ H_5^{\pm},\ H_5^0; \\
\text{triplet} \quad &\rightarrow \quad H_3^{\pm},\ H_3^0; \\
\text{two singlets} \quad &\rightarrow \quad H_1^0,\ H_1^{0\prime}
\end{aligned}
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The EW-scale ν_R model: The Higgs sector

- These scalars are expressed in terms of the original fields as

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H_5^{++} &= \chi^{++},\ H_5^{+} = \zeta^{+},\ H_3^{+} = c_H \psi^{+} - s_H \phi^{+}, \\
H_5^{0} &= \frac{1}{\sqrt{6}}\left(2\xi^{0} - \sqrt{2}\chi^{0r}\right),\ H_3^{0} = \imath\left(c_H \chi^{0\imath} + s_H \phi^{0\imath}\right), \\
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The EW-scale ν_R model: The Higgs sector

- The phenomenology of this sector has been studied by Aranda, Hernandez-Sanchez, PQH and will be updated.
- These scalars make important contributions to the electroweak precision parameters which offset those of the mirror fermions!

Electroweak precision constraints on the EW-scale ν_R model

Vinh Hoang, PQH, Ajinkya Kamat

- Why should we care? Because we now have extra chiral fermion doublets. For 3 families, we have extra 9 RH quark doublets (for 3 colors) and 3 RH lepton doublets.

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- The new Physics contributions to the S and T parameters are constrained to be $\tilde{S} = -0.02 \pm 0.14$; $\tilde{T} = 0.06 \pm 0.14$
- Big problems for any model with a lot of chiral fermions. That was one of the reasons why Running Technicolor $\Rightarrow$ Walking Technicolor $\Rightarrow$ Stopping Technicolor?.

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- Fortunately, in the EW-scale ν_R model, the positive contributions to S from mirror fermions cancel against the negative contributions from the scalar sector, in particular the Higgs triplets.

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- The total sum generates points in the parameter space of the model which fall inside the 1σ and 2σ ellipses as shown

Electroweak precision constraints on the EW-scale ν_R model

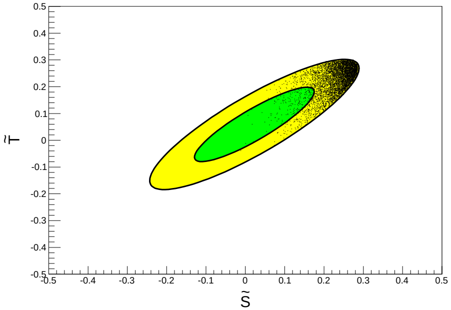

Figure: Total $\tilde{T}$ versus $\tilde{S}$ with the 1 and 2 σ experimental contours

Electroweak precision constraints on the EW-scale ν_R model

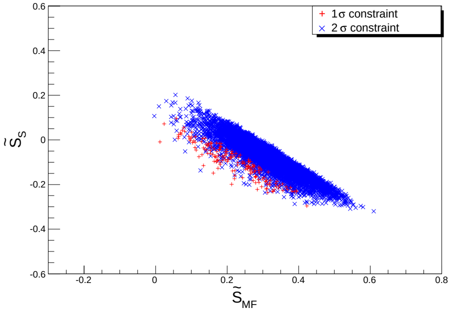

Figure: Constrained $\tilde{S}_S$ versus $\tilde{S}_{MF}$

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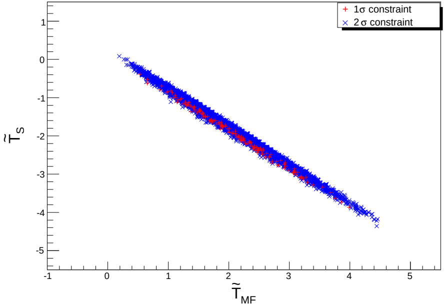

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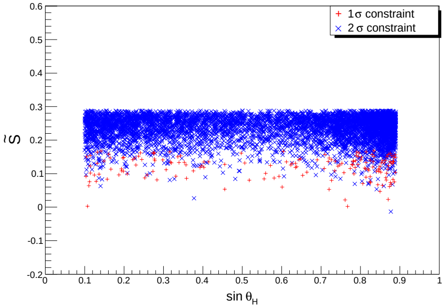

Figure: Constrained $\tilde{S}$ versus $\sin\theta_H$

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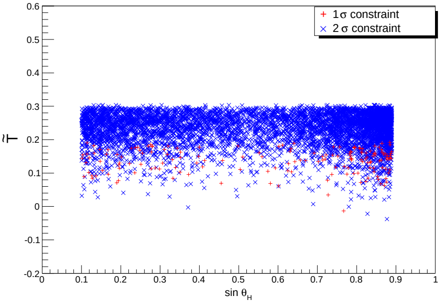

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The EW-scale ν_R model and the 126 GeV boson

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- Beside the existence of charged scalars (including doubly-charged Higgses), there are 4 neutral scalars:

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- Since the 126 GeV object "looks" very much like the SM Higgs, the main production is through gluon fusion.

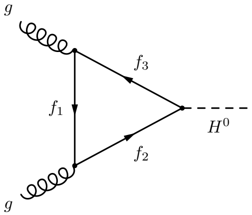

Figure: Generic gluon fusion

The EW-scale ν_R model and the 126 GeV boson

- Since the Higgs fields χ and ξ do not couple to SM and mirror quarks, H_5^0 and $H_1^{0\prime}$ could not be candidates. This leaves H_3^0, a CP-odd boson, and H_1^0 a CP-even boson.

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- Way too large! H_1^0 is Out! (BR are taken into account) (similar to the factor of 9 too large for SM4 with one Higgs)

The EW-scale ν_R model and the 126 GeV boson

- Could H_3^0 be the 126 GeV?

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- Unfortunately, recent spin-parity analysis of the 126 GeV object seemed to favor the CP-even 0^+ and disfavor by 3 σs or so (although not completely rule out) the CP-odd 0^-. What does one do next?

Extension of the minimal EW-scale ν_R model

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- Extension of minimal EW-scale ν_R model: One Higgs doublet couples to SM left-handed fermion doublets and another one to Mirror right-handed fermion doublets. To do that, invent a global symmetry $U(1)_{SM} \times U(1)_{MF}$ such that...

Extension of the minimal EW-scale ν_R model

- $$\begin{aligned} U(1)_{SM} \quad : \quad & \Phi_1 \rightarrow e^{\imath\alpha_{SM}}\, \Phi_1 \\ & (q_L^{SM}, l_L^{SM}) \rightarrow e^{\imath\alpha_{SM}}\, (q_L^{SM}, l_L^{SM}), \end{aligned}$$

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- All other fields are singlets under $U(1)_{SM} \times U(1)_{MF}$.

Extension of the minimal EW-scale ν_R model

- One extra Higgs doublet $\Rightarrow$ 4 more degrees of freedom $\Rightarrow$ physical states of custodial $SU(2)_D$: a five-plet $H_5^{\pm\pm,\pm,0}$, *two* triplets $H_{3,1}^{\pm,0}$, $H_{3,2}^{\pm,0}$ and *three* singlets H_1^0, H_{1M}^0, $H_1^{0\prime}$

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- Three CP-even states: $H_1^0 = \phi_2^{0r}$, $H_{1M}^0 = \phi_{2M}^{0r}$, $H_1^{0\prime} = \frac{1}{\sqrt{3}}\left(\sqrt{2}\chi^{0r} + \xi^0\right)$

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- Mass eigenstates from mixings of *three* singlets H_1^0, H_{1M}^0, $H_1^{0\prime}$:

$$\begin{pmatrix} \tilde{H}_1^0 \\ \tilde{H}_{1M}^0 \\ \tilde{H}_1^{0\prime} \end{pmatrix} = \begin{pmatrix} a_{1,1} & a_{1,1M} & a_{1,1'} \\ a_{1M,1} & a_{1M,1M} & a_{1M,1'} \\ a_{1',1} & a_{1',1M} & a_{1',1'} \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_{1M}^0 \\ H_1^{0\prime} \end{pmatrix}$$

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- Let us assume that $\tilde{H}_1^0$ is the lightest CP-even scalar, namely the 126-GeV boson. First look at the case where the dominant component of $\tilde{H}_1^0$ is H_1^0.

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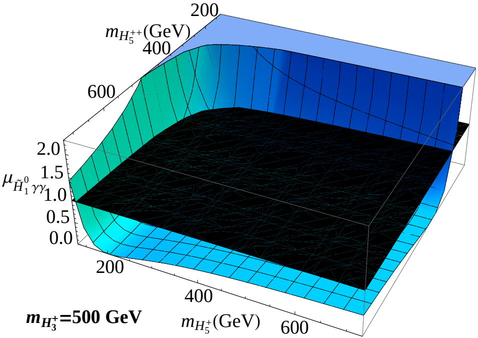
- In the next slides, plots showing the predicted signal strengths with the corresponding experimental values.

Extension of the minimal EW-scale ν_R model



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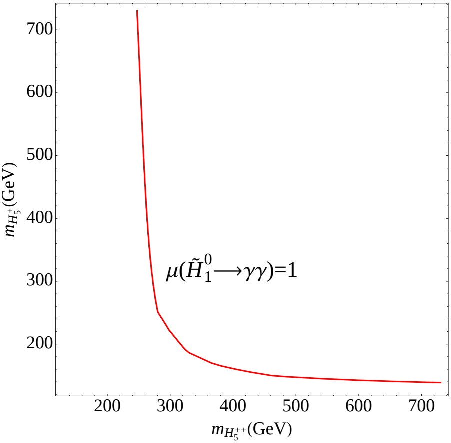

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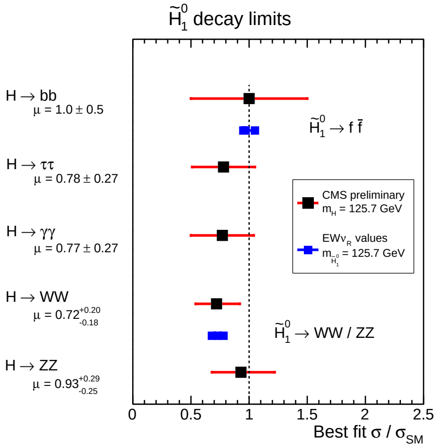

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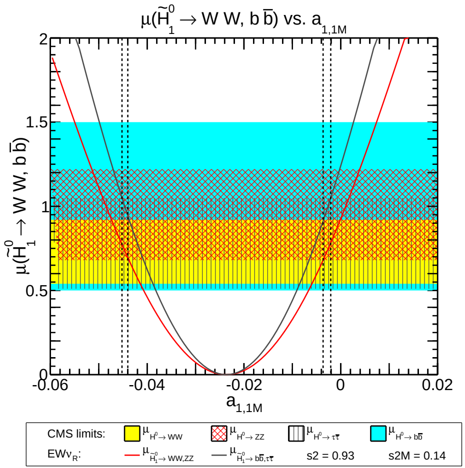

Extension of the minimal EW-scale ν_R model

Some examples.

- $\tilde{H} \sim H_1^0$: Almost SM-like.
  $\sigma_{SM} \sim \sigma_{EW\nu_R}$ and $BR_{SM} \sim BR_{EW\nu_R} \Rightarrow \mu \sim 1$ for $\tilde{H} \rightarrow WW, ZZ, b\bar{b}, \tau\bar{\tau}, \gamma\gamma$

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- $\tilde{H} \sim H_1^{0\prime}$: 126 is an impostor.
  $\sigma_{SM} \sim 0.66\,\sigma_{EW\nu_R}$ and $BR_{SM} \sim 1.6\,BR_{EW\nu_R} \Rightarrow \mu \sim 0.94$ for $\tilde{H} \to \gamma\gamma$ for example.

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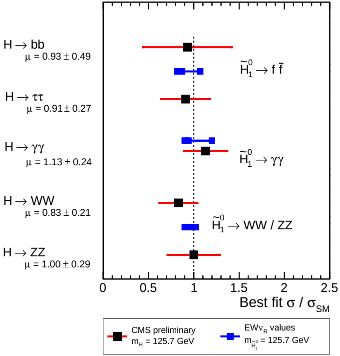
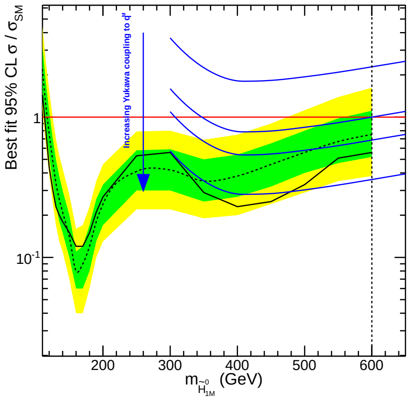


The figure shows predictions of $\mu(\tilde{H} \to W^+W^-,\ ZZ, b\bar{b}, \tau\bar{\tau})$ by EWν_R model in $\tilde{H} \sim H^0_{1M}/H^{0\prime}_1$ scenario.

Extension of the minimal EW-scale ν_R model

$\tilde{H}^0_{1M}$? Look at the LHC constraint for $\mu(\tilde{H}^0_{1M} \to W^+ W^-)$



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- What break(s) the electroweak symmetry?

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Signals

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- Also: $e^-_L + e^-_L \rightarrow e^{-,M}_R + e^{-,M}_R \rightarrow e^-_L + e^-_L + \phi_S + \phi_S$. The final polarized electrons are not back-to-back!

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- Phenomenology of mirror quarks and leptons under study with Vinh Hoang, PQH, Ajinkya Kamat, Alfredo Aranda.

A new view on U_{PMNS} and the charged-lepton mass matrix

- Experimentally

$$|U_{PMNS}| = \begin{pmatrix} 0.779\ldots0.848 & 0.510\ldots0.604 & 0.122\ldots0.190 \\ 0.183\ldots0.568 & 0.385\ldots0.728 & 0.613\ldots0.794 \\ 0.200\ldots0.576 & 0.408\ldots0.742 & 0.589\ldots0.775 \end{pmatrix}$$

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- Why are the mixing matrices of the quark and lepton sectors so different from one another?

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- The Higgs structure of the EW-scale ν_R model allows us to use the discrete symmetry group A_4 on the Dirac mass matrix part of the neutrinos involving the Higgs singlets ϕ_S to reproduce U_{PMNS} without running into trouble with what we know about the properties of the 126-GeV Higgs boson.

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- Paper under preparation with Trinh Le.

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- Furthermore, the PMNS mixing matrix is obtained in this model using the discrete A4 symmetry in a very different way than the previous scenarios where a "large" number of Higgs doublets was required. (With Trinh Le)

Conclusions

- Can we construct a model in which, at the end of inflation, only Dark Matter was created followed by the "appearance" of an asymmetry which gets converted into a lepton asymmetry which, in turn, gets converted into a baryon asymmetry through the EW sphaleron? Yes and the construction of the model requires the incorporation of mirror fermions of the EW-scale ν_R model. P. F. Frampton and P. Q. Hung. Self-interacting dark matter $\Rightarrow$ Resolution to the problems of dwarf-galaxy structures and dark-matter cusps at the centers of galaxies associated with WIMPS.

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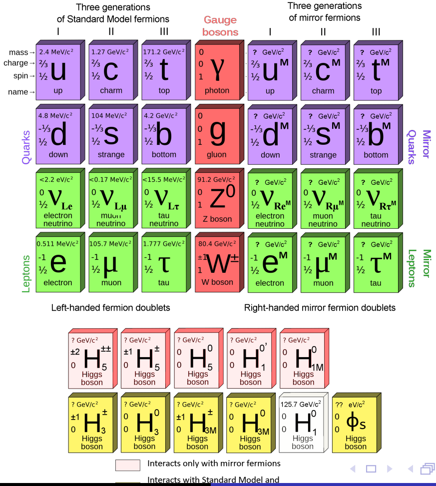
- Dark matter gets confined when the coupling of its gauge group $SU(4)$ becomes of order unity at a scale Λ_{DM} $\Rightarrow$ DM dynamical mass. Λ_{DM} depends on the inflation scale. Tight constraints. PQH, Kevin Ludwick.

Conclusions



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Mucho gracias, Mauro, fefo, Qaisar, Bashkar and the organizers!

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Mucho gracias, Mauro, fefo, Qaisar, Bashkar and the organizers!

Last but not least...

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Conclusions

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