Prospect of the Electroweak Scale ν_R model in the Lifetime Frontier

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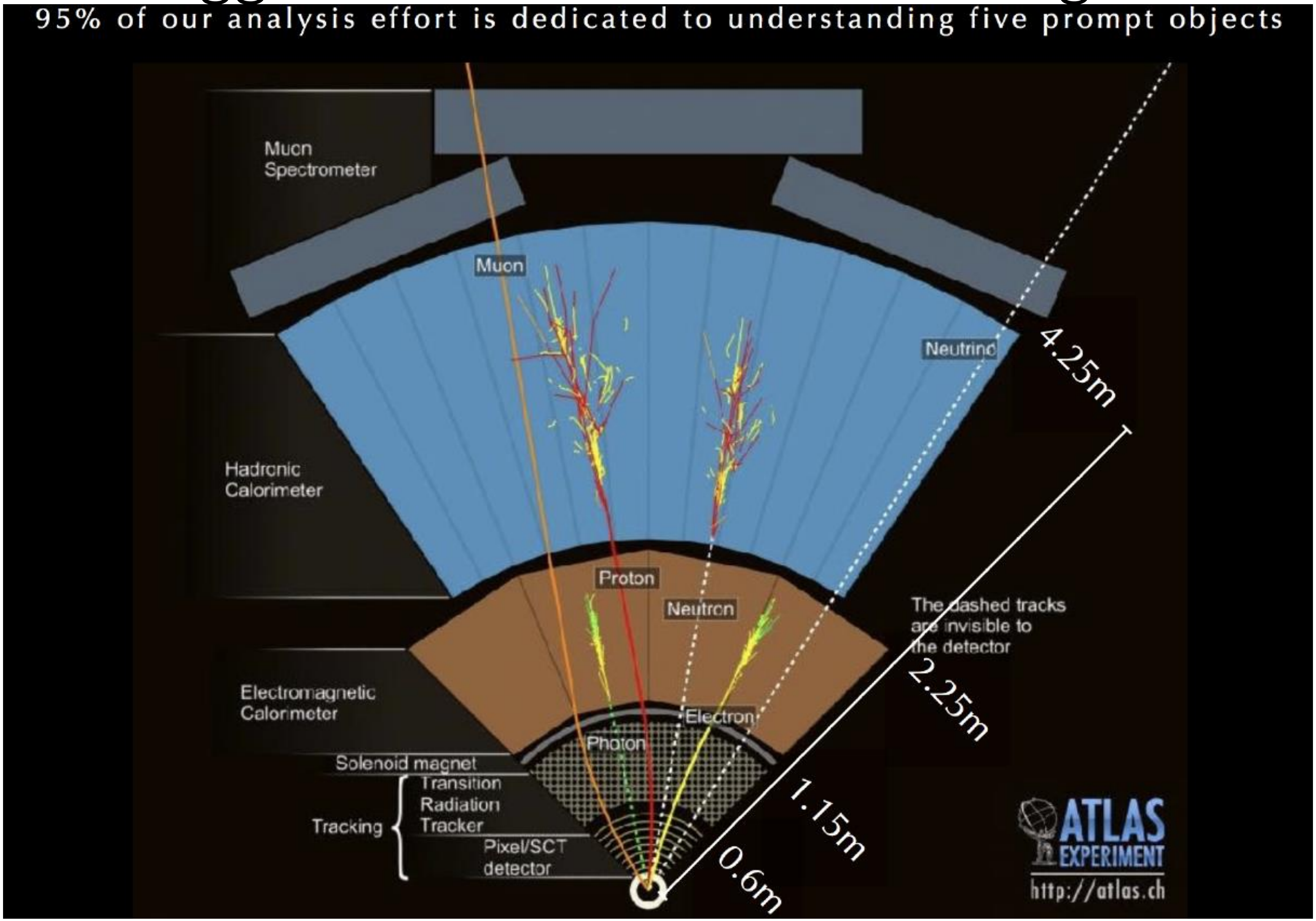
Chakdar, Ghosh, Hoang, Hung, Nandi, Phys.Rev. D95 (2017) no.1, 015014

Chakdar, Ghosh, Hoang, Hung, Nandi, Phys.Rev. D93 (2016) no.3, 035007

Chakdar, Ghosh, Hung, Khan (in preparation, arXiv: 2001.XXXXX)

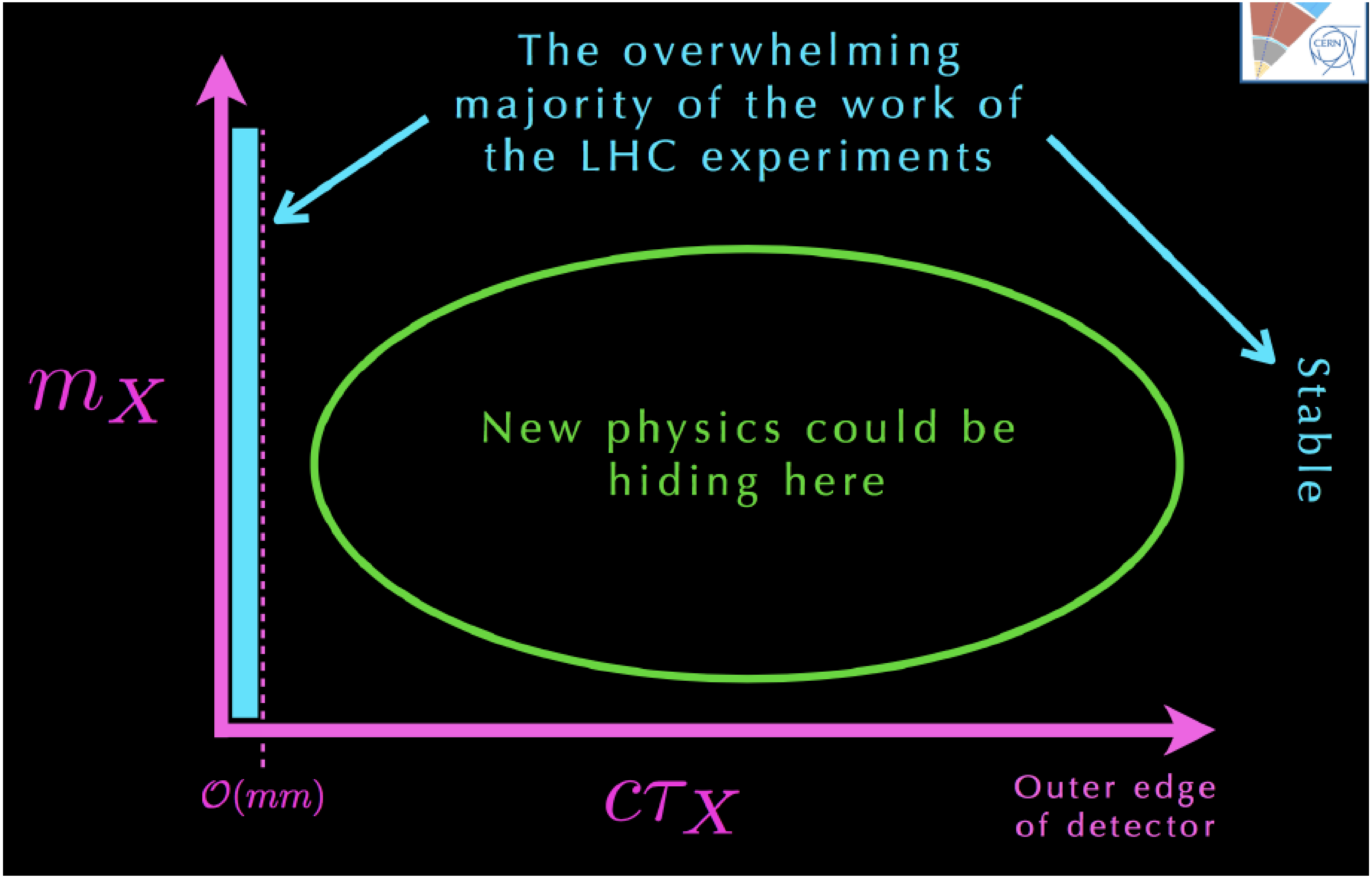
International Conference on Neutrinos and Dark Matter (NDM2020), Hurghada, 1/11-1/14

Post Higgs LHC: where are we looking at?



Slide: Beacham

New Physics at the LHC



Slide: Beacham

Long Lived particles (*LLPs*)

For our purposes, *LLP* = BSM particles with a non-negligible lifetime that gives up all its energy or decays to SM somewhere in the detector acceptance.

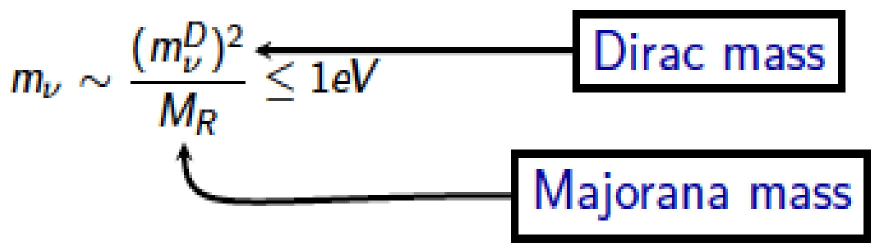
- *LLPs in SM:*
  - muons (2 μs), $\pi^+ \rightarrow \mu^+\nu_\mu$ (20 ns), b-quarks (ps)

- *LLPs in* BSM: variety of mechanisms can suppress decay width!
  - Small couplings, approximate symmetries, heavy mediators…
  - R-parity violating SUSY, Split SUSY, L-R Symmetric model….
  - Dedicated searches needed to look for *LLPs*…

LHCb, CMS, ATLAS, MilliQan, MoEDAL , FASER, MATHUSLA, SHiP

EWν_R Model and Framework

- Neutrino mass is the only evidence of NP so far!
- Neutrino (ν) masses → popular "Seesaw mechanism"
- In general Seesaw Mechanism:
  - $\nu_R \rightarrow SU(2)_L \times U(1)_Y$ singlet
  - RH neutrino mass at GUT scale ! NOT directly testable at LHC

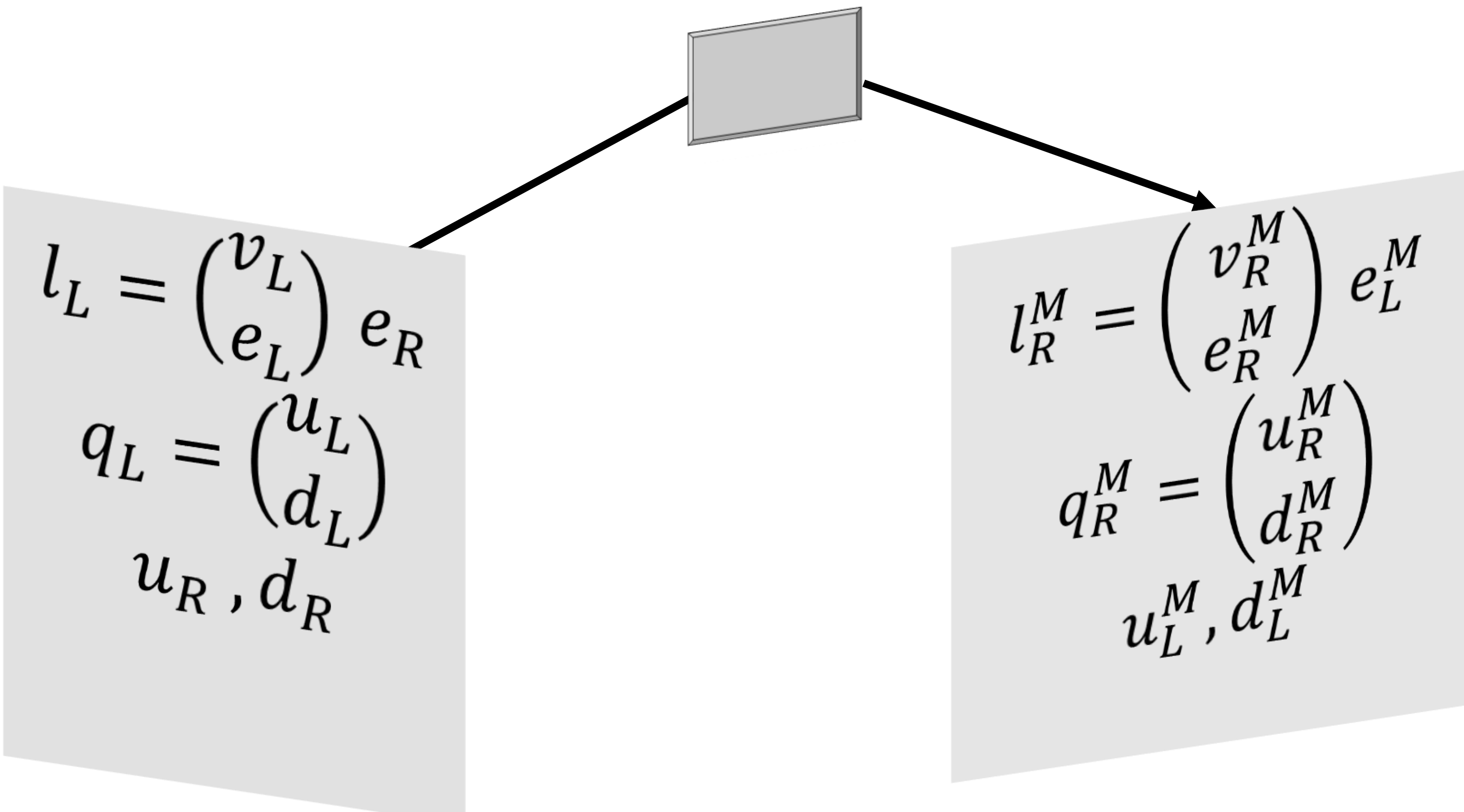


- Stand scenes: L-R : $m_D \sim \Lambda_{EW}$, $M_R \sim M_{WR}$, GUT: $M_R \sim \Lambda_{GUT}$
- ν_R's are Sterile in standard scenarios
- What if $M_R \sim \Lambda_{EW}$? Can ν_R 's be non-sterile?

EWν_R Model and mirror fermions

SM + Mirror Fermions + extended scalar sector

Gauge Group : $SU(3)_c \times SU(2)_W \times U(1)_Y$



$$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \; e_R$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

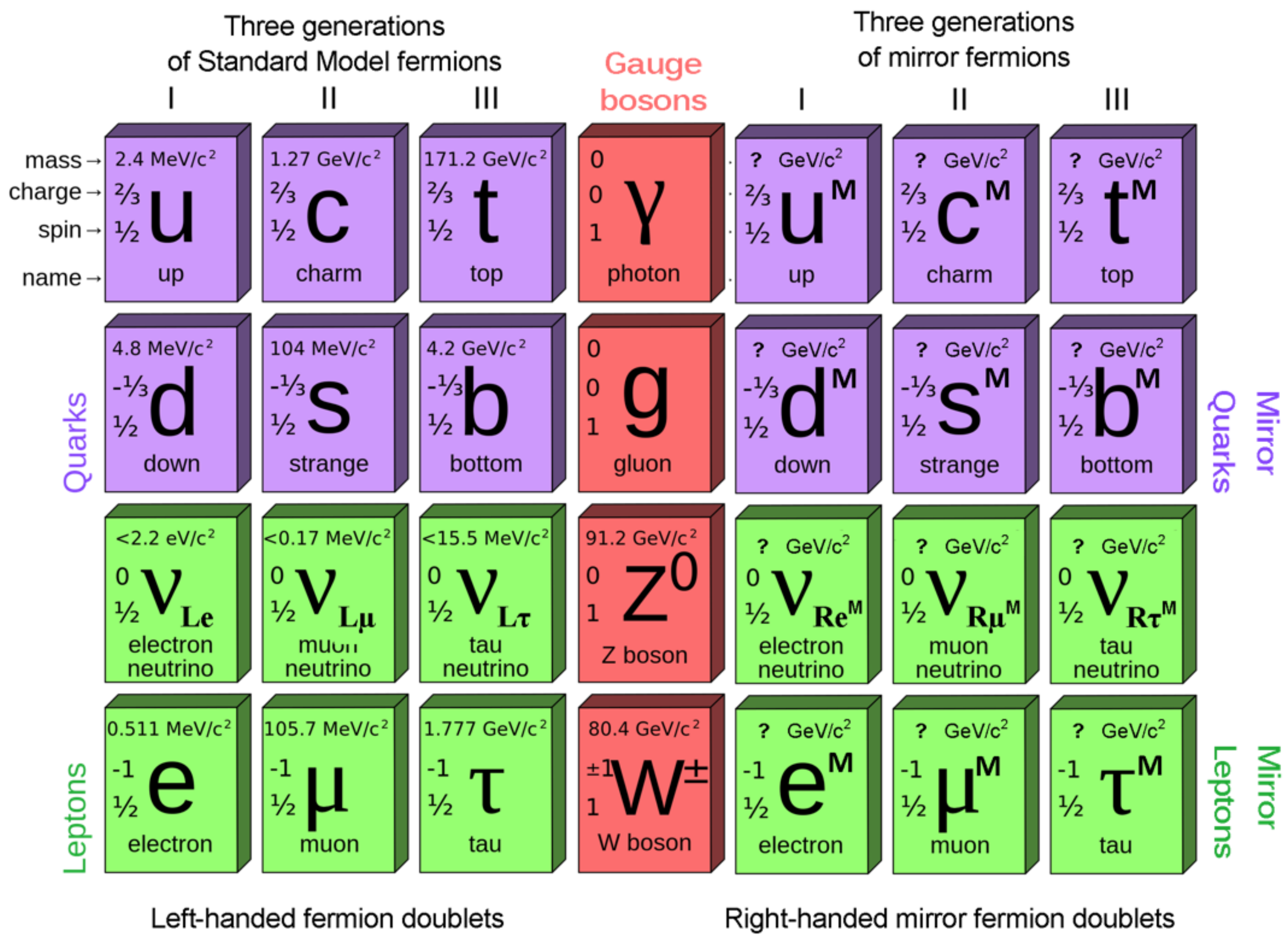
$$u_R \, , d_R$$

$$l_R^M = \begin{pmatrix} \nu_R^M \\ e_R^M \end{pmatrix} \; e_L^M$$

$$q_R^M = \begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}$$

$$u_L^M , d_L^M$$

Particle content of EWν_R model



Majorana and Dirac masses

- $\nu_R' s$ are non-sterile, RH doublets couples to the same W

Majorana

$$\mathcal{L}_M = g_M \left(l_R^{M,T} \sigma_2 \right) \left(i\, \tau_2\, \tilde{\chi} \right) l_R^M + h.c.$$

$$\tilde{\chi}\ (3, \frac{Y}{2} = 1)$$

$$M_R = g_M v_M;\ < \chi^0 > = v_M \sim \Lambda_{EW}$$

$$\tilde{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}}\chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}}\chi^+ \end{pmatrix}$$

Dirac

$$\mathcal{L}_S = g_{Sl} \bar{l}_L \phi_S l_R^M + h.c.$$

$$\phi_S\ (1, \frac{Y}{2} = 0)$$

$$m_\nu^D = g_{Sl} v_S \quad \text{where} \quad < \phi_S > = v_S$$

$$m_\nu \leq 1eV \quad \Rightarrow \quad v_S \sim 10^{5-6} eV \text{ with } g_{Sl} \sim \mathcal{O}(1)$$

$$\text{or} \quad v_S \sim \Lambda_{EW} \text{ with } g_{Sl} \sim \mathcal{O}(10^{-6})$$

- Testable see-saw signals in the reach of the LHC!

Mirror fermion decay

Yukawa interactions in terms of quark mass eigenstates

$$L_S = \bar{q}_L^d \, U_L^{d\dagger} M_\phi^d U_R^{d^M} \, q_R^{M,d} + h.c.$$

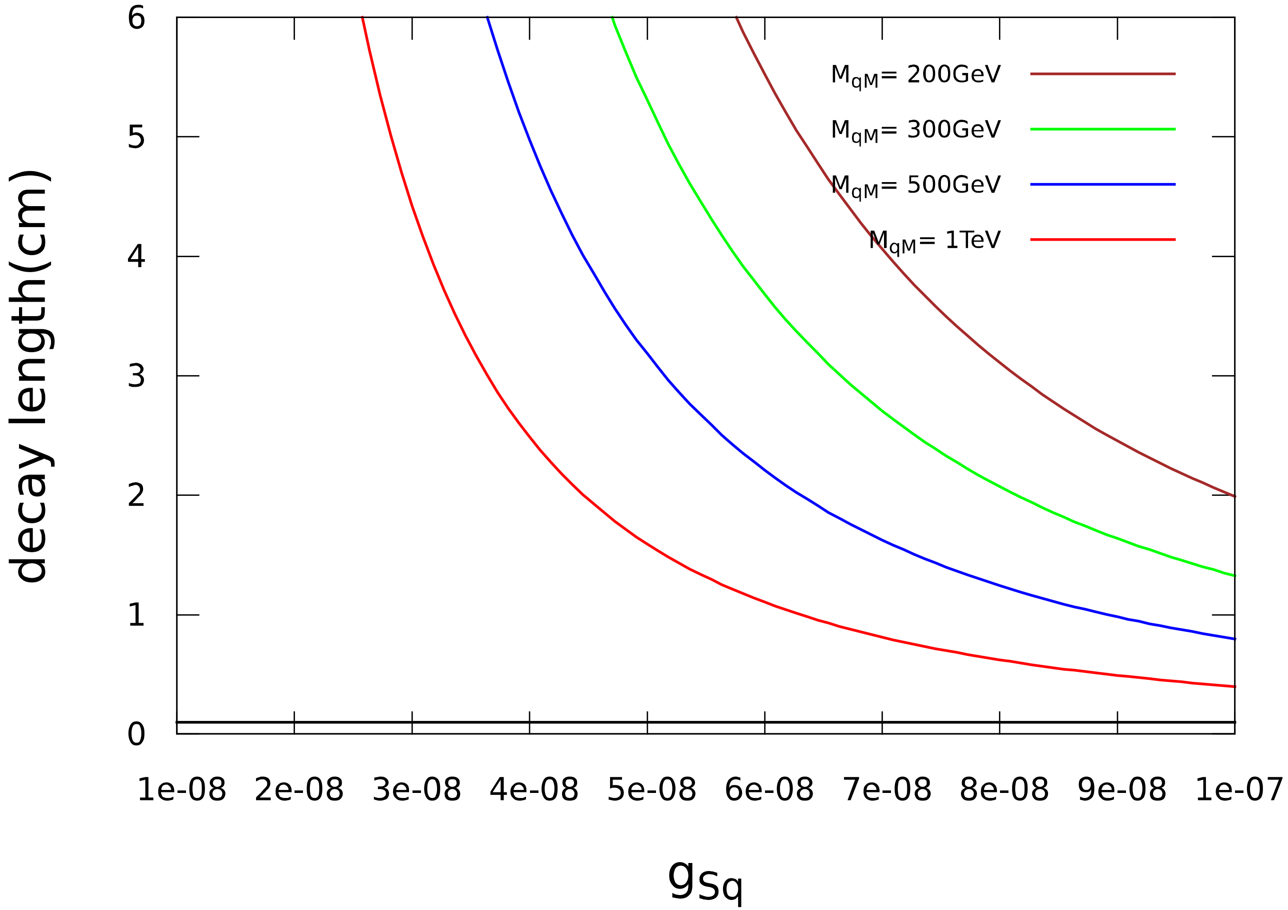
$$= \bar{q}_L^d \, \bar{M}_\phi^d \, q_R^{M,d} + h.c. \quad \text{where } M_\phi^d \text{ is mixing matrix}$$

$$M_\phi^{d,u} = \begin{pmatrix} g_{0S}^{d,u}\phi_{0S} & g_{1S}^{d,u}\phi_{3S} & g_{2S}^{d,u}\phi_{2S} \\ g_{2S}^{d,u}\phi_{3S} & g_{0S}^{d,u}\phi_{0S} & g_{1S}^{d,u}\phi_{1S} \\ g_{1S}^{d,u}\phi_{2S} & g_{2S}^{d,u}\phi_{1S} & g_{0S}^{d,u}\phi_{0S} \end{pmatrix}$$

Decay mode of the lightest mirror quark is $q^M \to q\phi_S$ or $b\phi_S$, with $\phi_S \approx miss E_T$

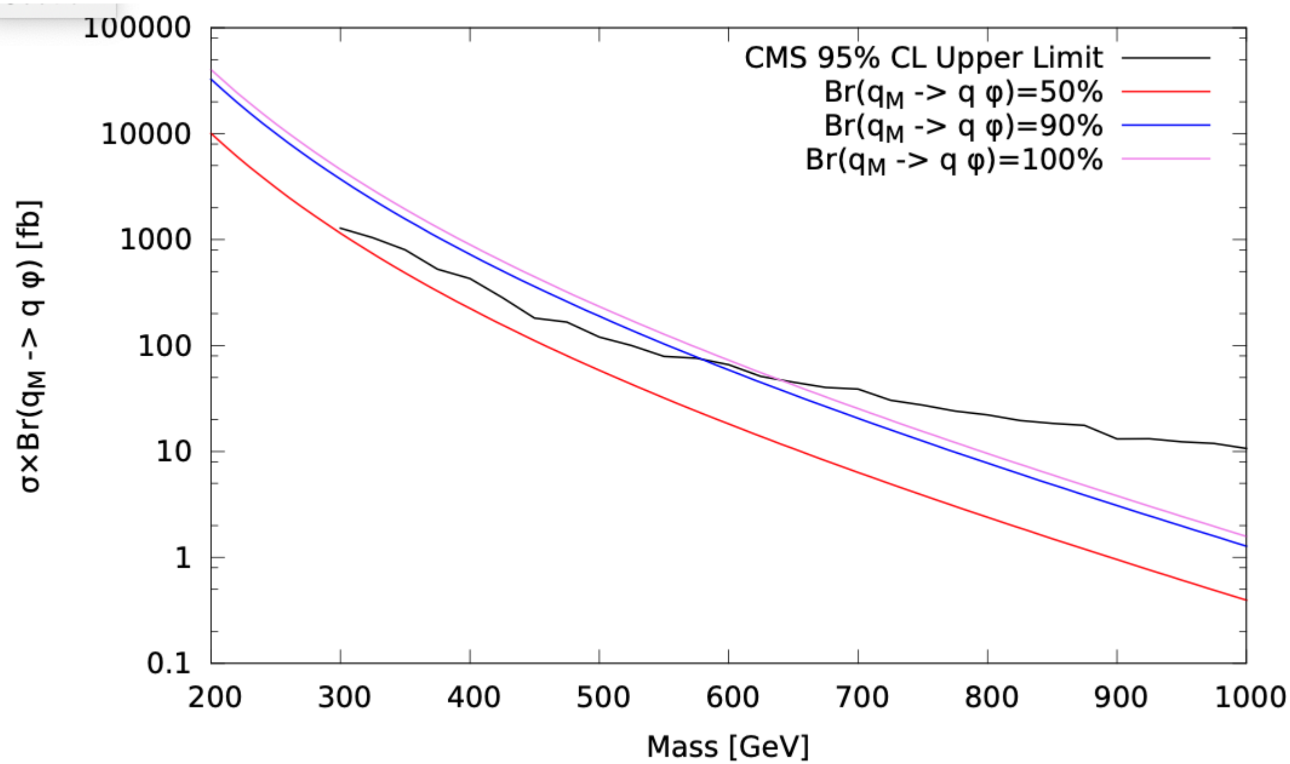
$$\Gamma(q^M \to q + \phi_S) \;=\; \frac{g_{Sq}^2}{64\pi} m_{q^M} \left(1 - \frac{m_q^2}{m_{q^M}^2}\right) \left(1 + \frac{m_q}{m_{q^M}} - \frac{m_q^2}{2m_{q^M}^2}\right),$$

Mirror quarks Decay width



- Decay length can be substantially LARGE in this case
- Easily distinguishable from b-displaced vertices(~0.5mm)

LHC exclusion plot



For large BR mirror quark mass below about 600 GeV is excluded

If mirror quark to light quark BR < 50 %, NO bound on mirror quark mass

Bounds applicable only on mirror quarks decay at hard scattering point

Decay width could be small enough for hadronization → bounds don't apply!

Constraints from the lepton sector

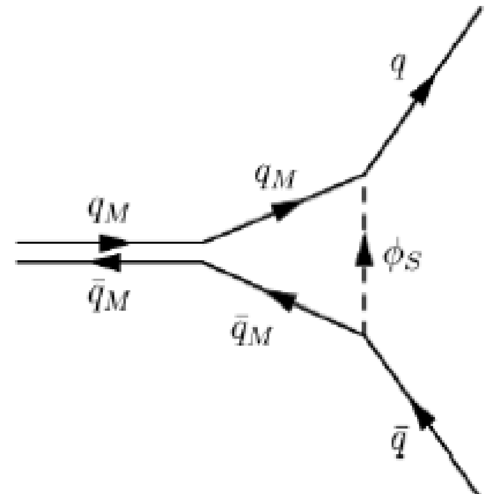
- Constraints from $\mu \rightarrow e\gamma$, μ to e conversion: $g_{sl} < 10^{-4}$
- Mirror fermions ↔ Axion-less solution to strong CP problem (Ref: arXiv:1712.09701)
- Constraints from the so-far absence of the neutron dipole moment: $\bar{\theta} < 10^{-10}$
- This framework has global Symmetry $U(1)_{SM}$ X $U(1)_{MF}$
- Corresponds to $\bar{\theta} \propto m_\nu$ in this framework
- Constraint on $\bar{\theta}$ → Constraint on couplings $g_{sq} < g_{sl}$

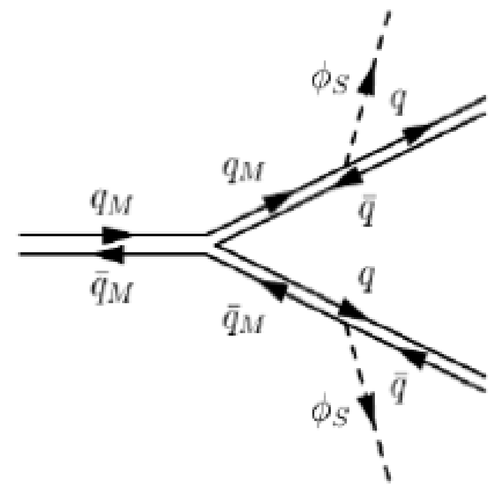
$$g_{sq} < g_{sl} < 10^{-4}$$

- Lightest mirror fermions are *LLPs*
- Connection between Neutrino physics and QCD!

Mirror Meson formation

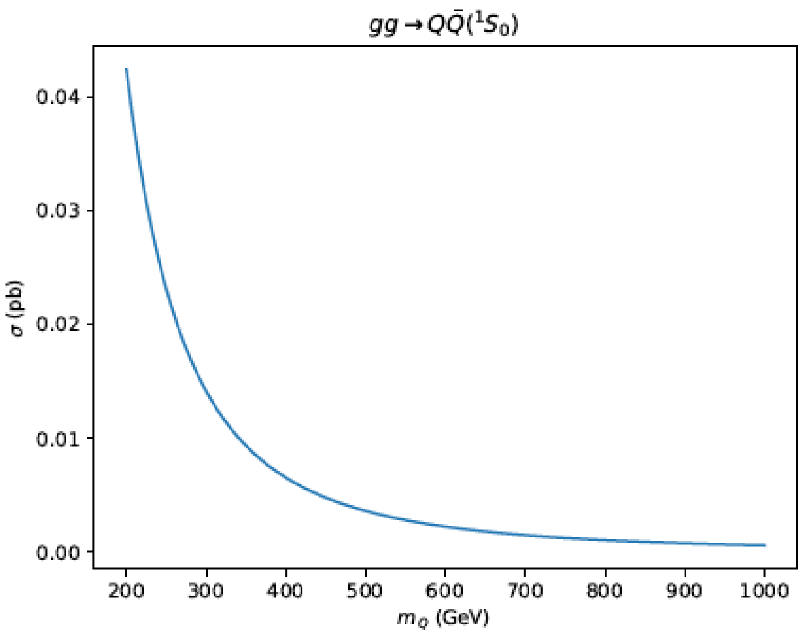
- Typical decay lengths >> Hadronization length $\sim O(fermi)$
- Formation of QCD bound states
- Mirror mesons $\bar{q}^M q^M$ and hybrid mesons $\bar{q}^M q$ get formed first before decay





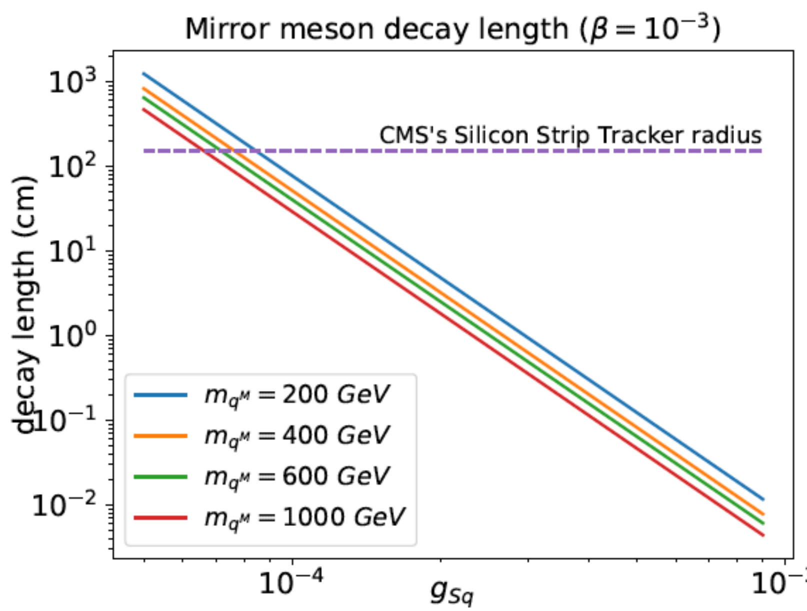
Mirror meson production & decays

Mirror meson production at 13 TeV LHC



Mirror-meson decay lengths:

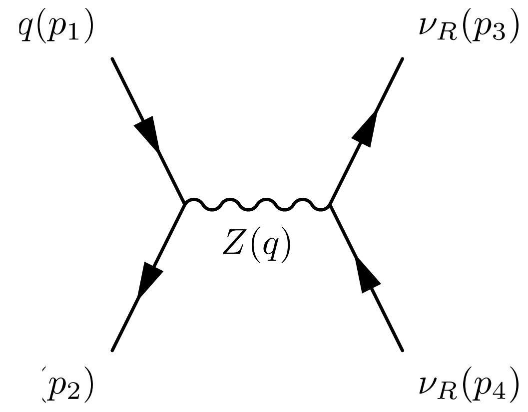
Displaced Vertices $> O(cm)$ for $g_{Sq} < 10^{-4}$.



Di-lepton Signals in Lepton Sector

Lepton-number violating signals at LHC

$$q\bar{q} \to Z \to \nu_R \, \nu_R$$



$$\nu_{Ri} \to e^M_{Rj} + W^+ \text{ followed by } e^M_{Rj} \to e_{Lk} + \phi_s$$

1. OSD Signals from production of ${e^M}_R{}^{\pm}$

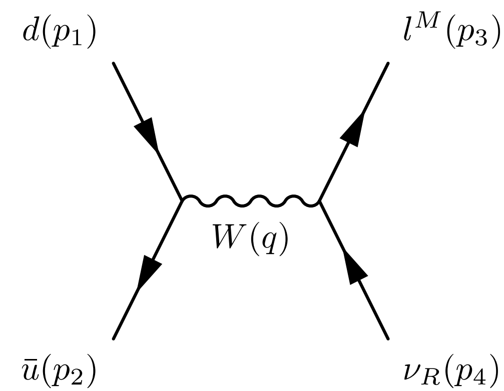
$$pp \to e^{M+}e^{M-} \to (e^+\phi_S)(e^-\phi_S) \to e^+e^- + \not{p}_T.$$

2. SSD and OSD Signals from production and decays of ${e^M}_R{}^{\pm}{\nu_R}^M$

$$pp \to e_R^{M\pm}\nu_R^M \to (e^\pm\phi_S)(e_R^{M\pm}W^\mp) \to e^\pm e^\pm qq'\phi_S\phi_S \text{ (SSD+2-jets + } \not{p}_T)$$

$$(e^\pm\phi_S)(e_R^{M\pm}W^\mp),\ (e^\pm\phi_S)(e_R^{M\mp}W^\pm) \to e^\pm e^\pm e^\mp \nu_L\phi_S\phi_S \text{ (3-leptons + } \not{p}_T)$$

$$pp \to e_R^{M\pm}\nu_R^M \to (e^\pm\phi_S)(e_R^{M\mp}W^\pm) \to e^\pm e^\mp qq'\phi_S\phi_S \text{ (OSD+2-jets + } \not{p}_T)$$



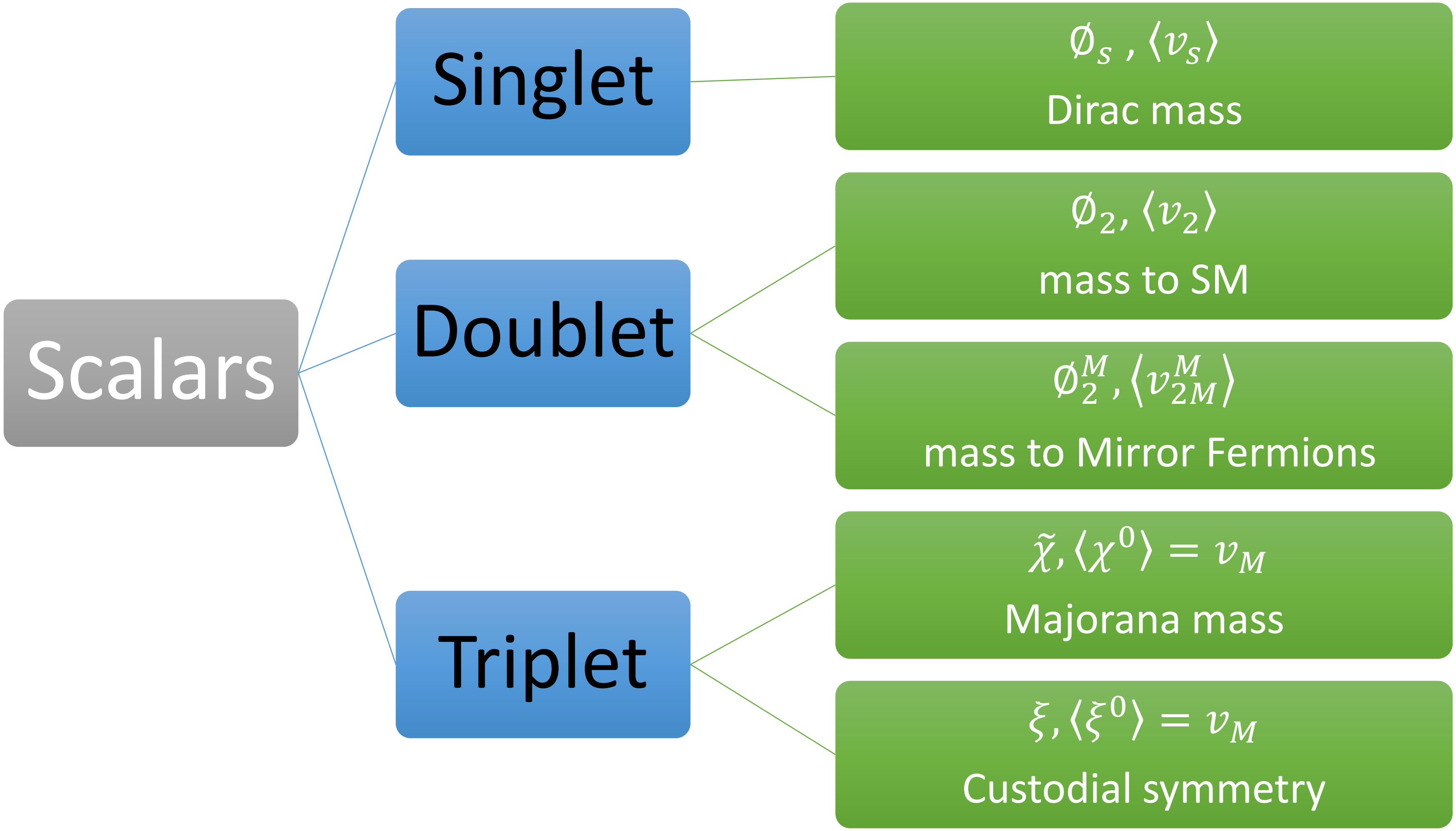
LLP Signals in Lepton Sector

- Pair production ν_R of gives rise to more di-lepton signals

$$
pp \to \nu_R^M \nu_R^M \begin{cases} (e_R^{M\pm} W^{\mp})(e_R^{M\pm} W^{\mp}) \begin{cases} e^{\pm}e^{\pm}qq'qq'\phi_S\phi_S & \text{(SSD+4-jets} + \not{p}_T) \\ e^{\pm}e^{\pm}e^{\mp}\nu_L qq'\phi_S\phi_S & \text{(3l+2-jets} + \not{p}_T) \\ e^{\pm}e^{\pm}e^{\mp}e^{\mp}\nu_L\nu_L\phi_S\phi_S & \text{(4-leptons} + \not{p}_T) \end{cases} \\ (e_R^{M\pm} W^{\mp})(e_R^{M\mp} W^{\pm}) \begin{cases} e^{\pm}e^{\pm}e^{\mp}\nu_L qq'\phi_S\phi_S & \text{(3l+2-jets} + \not{p}_T) \\ e^{\pm}e^{\mp}qq'qq'\phi_S\phi_S & \text{(OSD+4-jets} + \not{p}_T) \end{cases} \end{cases}
$$

- The appearance of Like-sign dileptons!
- All Like-sign and opposite sign di-leptons signals @ displaced vertex or near the beam pipe (g_sl)

Scalar Sector



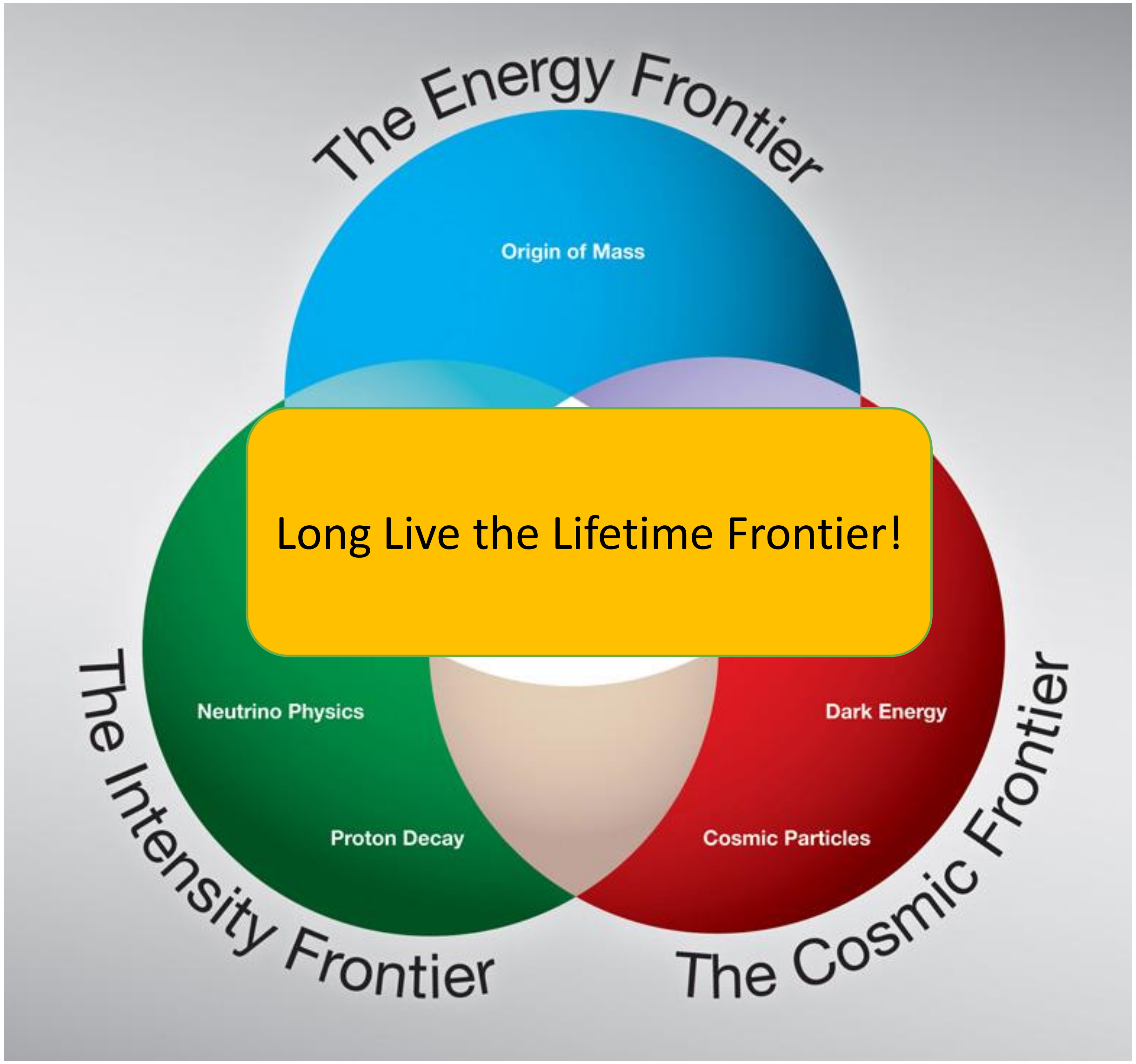
Singlet DM Prospect

- Imaginary part of Complex Singlet Scalar field φ is investigated to be a feasible DM candidate
- This Nambu goldstone boson (0^- state) comes into play due to the explicit breaking term of the U(1) symmetry present in the Higgs potential
- φ gives the Dirac neutrino masses: $m_\nu^D = g_{sl}\, v_s$ in the see-saw formula: m = $m_D^2/M_R \sim O$ (< eV)
- M_R are in EW Scale (~ 250 GeV) and from $\mu \to e\gamma$, μ to e conversion bound on the coupling $g_{sl} < 10^{-4} \leftrightarrow v_s \sim O$(1 GeV)
- The singlet connecting SM to Mirror world can be KeV scale DM candidate!
- Collider searches of DM promising through the *Lifetime* frontier due to the possibility of large displaced vertex ($e_R^M \to e + \varphi$)

Remarks

- Looking for NP shifting from theory driven ↔ signature driven search strategies
- *LLP*s predicted in many Theory models receiving resurgence in interest
- EWν_R scenario links see-saw mechanism, strong CP and DM
- EWν_R framework contains *LLP* signals with large displaced vertices (mm-cm) in quark and lepton sectors
- Promising signatures at LHC environment and *LLP* detectors due to characteristic signals and low bkds (<u>Dedicated searches needed</u>!)

THANK YOU!



The Energy Frontier
Origin of Mass
Long Live the Lifetime Frontier!
The Intensity Frontier
Neutrino Physics
Proton Decay
The Cosmic Frontier
Dark Energy
Cosmic Particles