6th ComHEP: Colombian Meeting on High Energy Physics

Long-lived charged particles and multi-lepton signatures from neutrino mass models

Carolina Arbeláez R.
co-author: Juan Carlos Helo
Universidad Técnica Federico Santa María
Valparaíso, Chile.

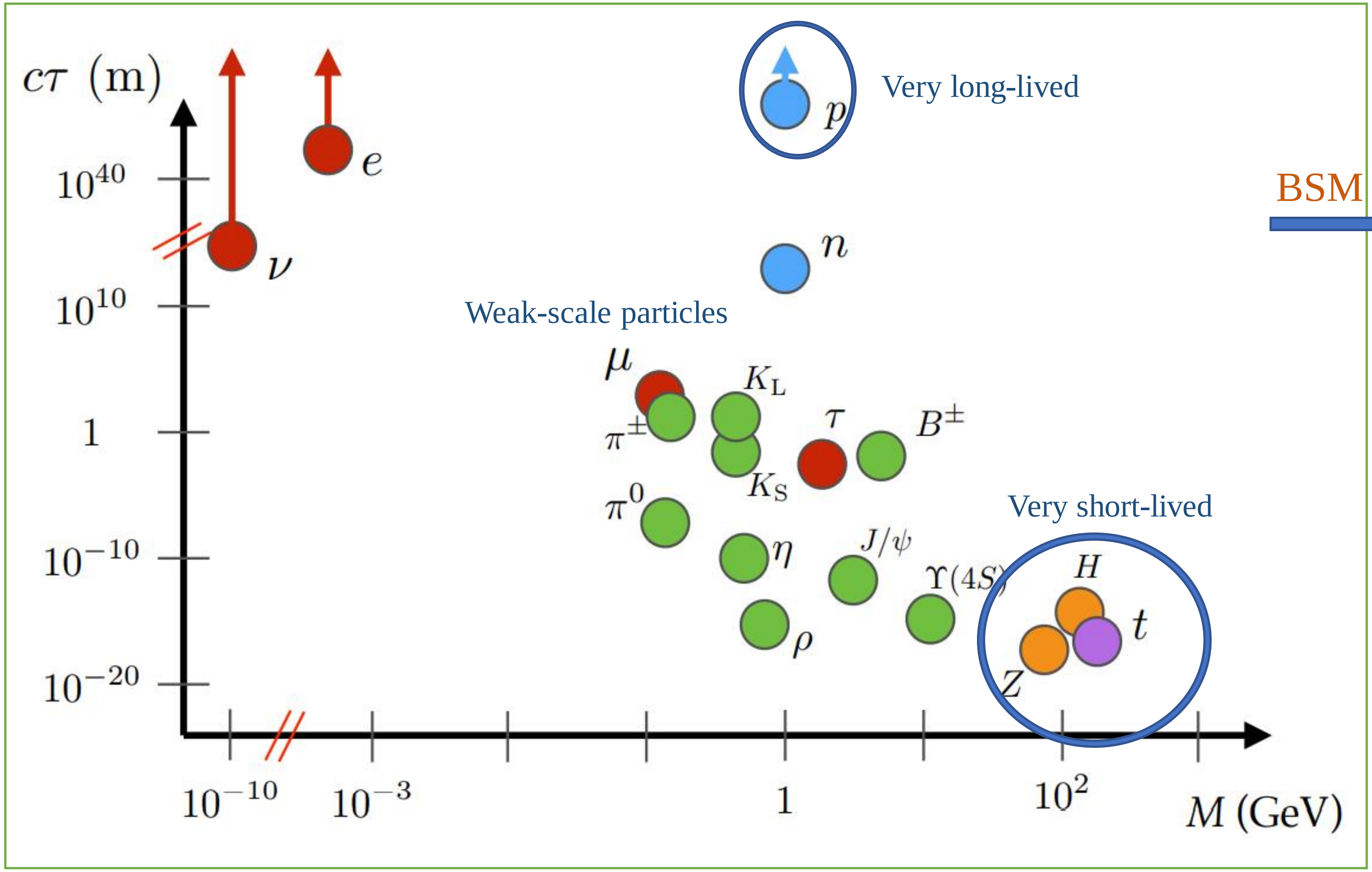
Long-lived charged particles and multilepton signatures from neutrino mass models
Arbeláez, Cottin, Helo, Hirsch. Phys.Rev.D 101 (2020) 9, 095033

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

What a long lived particle is?

SM particles have life times spanning a very wide range of magnitudes:



J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)

BSM

- Conserved symmetries.
- Small couplings between LLP and the lighter states.

Heavy LLP Mediators

Neutrino mass models

Some displaced N studies in:
G. Cottin, J.C. Helo and M. Hirsch, Phys. Rev. D98 (2018).
E. Izaguirre and B. Shuve, Phys. Rev. D91 (2015)
S. Dube, D. Gadkari, and A. M. Thalapillil, Phys. Rev. D96 (2017)
J. C. Helo, M. Hirsch, and S. Kovalenko, Phys. Rev. D89 (2014)
… and others

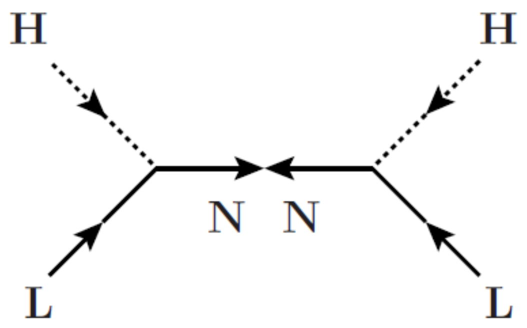
After produced, they could travel macroscopic distances:

$$c\tau \sim \frac{1}{\Gamma}$$

$$c\tau \gtrsim 1\, mm$$

Displaced vertex

Type-I seesaw



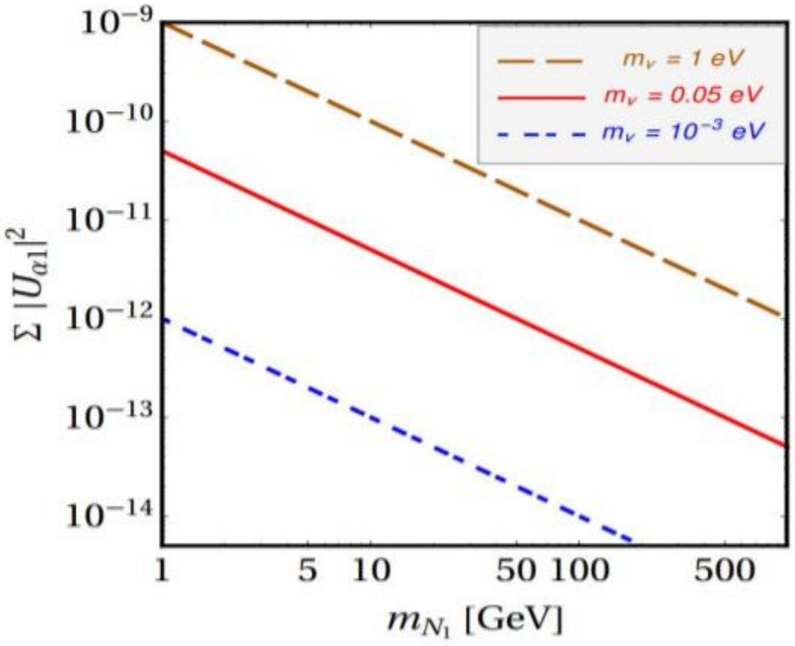
- In one-generation notation:

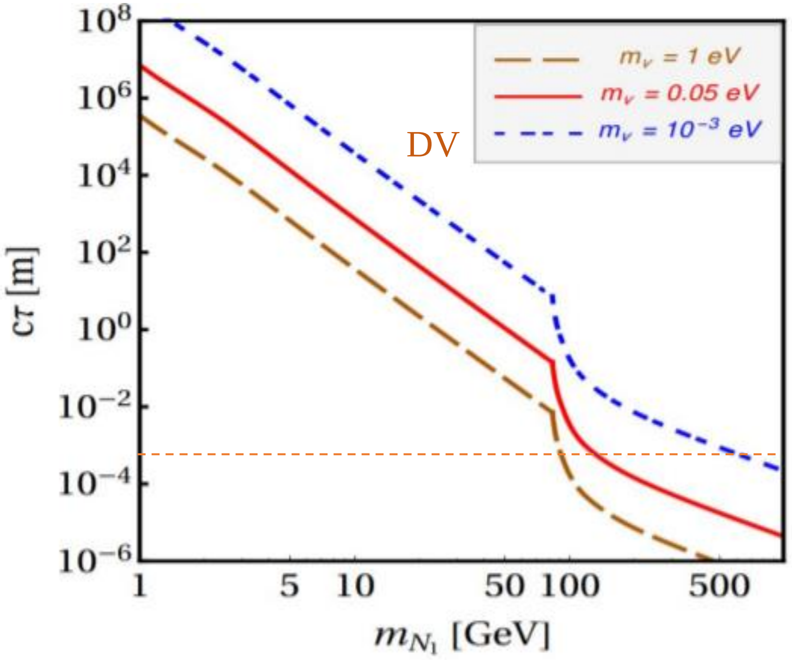
$$M = \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix}$$

For $m_D \ll M_M$, light neutrino eigenvalues and heavy-light neutrino mixing given by:

$$m_\nu \simeq -\frac{(m_D)^2}{M_N} = \frac{(Y_\nu v)^2}{M_N}$$

$$U_{HL} \propto \frac{(Y_\nu v)}{M_N} \propto \sqrt{m_\nu / M_N}$$

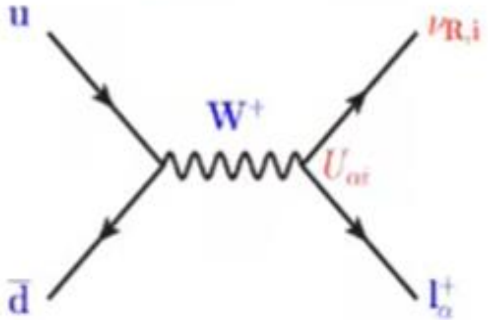




C.Arbelaez, J.C.Helo, M.Hirsch. Phys. Rev. D 100 (2019) 5, 055001

I. For electroweak or low m_N values, N could be long lived for a wide range of m_ν.

Very small mixings → small production X-section @ LHC!



The model will run out of events!

II. For mN above 100 GeV, $c\tau$ drops below 1 mm → No displaced vertex

…go to radiative or higher dimentional scenarios

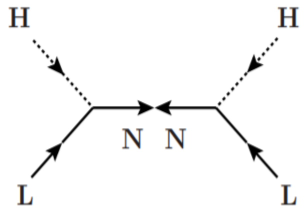
Majorana Neutrino mass generated at n-loop level and dimensión d-diagram:

$$\boxed{m_\nu \simeq \frac{(Yv)^2}{\Lambda}\cdot\epsilon\cdot\left(\frac{Y^2}{16\pi^2}\right)^n\cdot\left(\frac{Yv}{\Lambda}\right)^{d-5}}$$

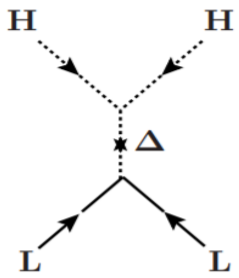
Tree level neutrino mass models

$n = 0, \quad d = 5,7,9\,\dots$

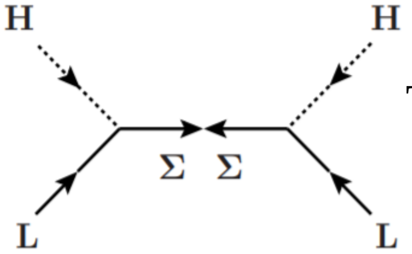
$d = 5$



Type-I — Only a singlet mediator.



Type-II
$\Delta = 3_1^S$

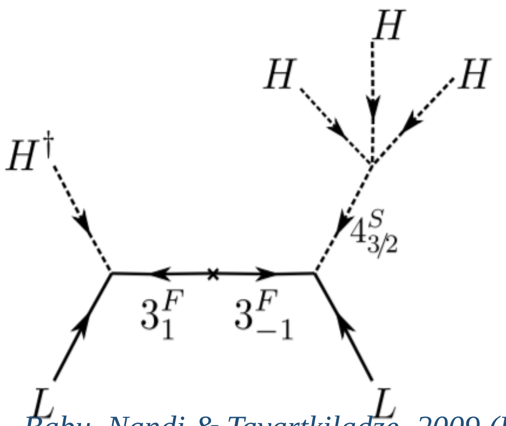


Type-III
$\Sigma = 3_0^F$

SU(2) triplets mediators with charged components.

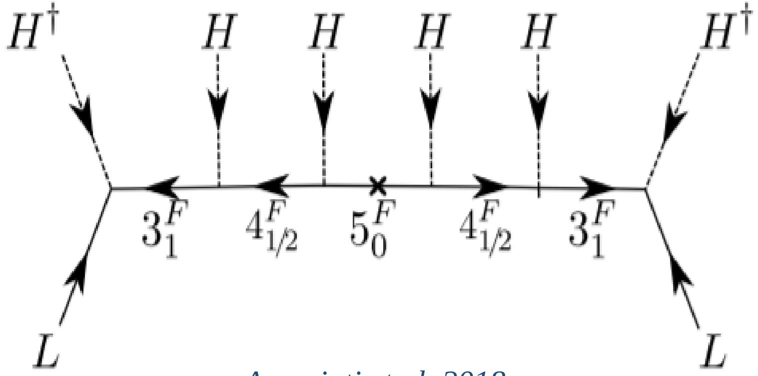
Models are easier to test that type-I seesaw!

$d = 7$



Babu, Nandi & Tavartkiladze, 2009 (BNT)

$d = 9$



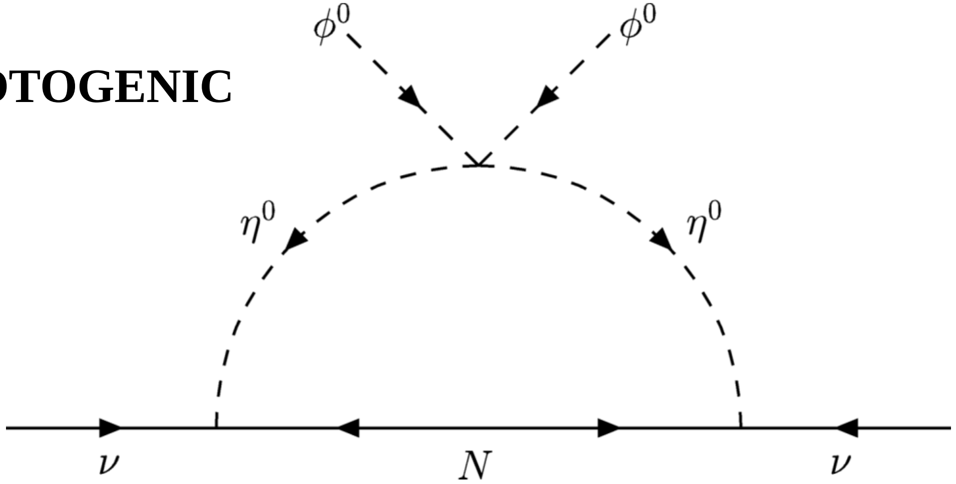
Anamiati et al. 2018

- Neutrino masses suppressed by $1/(\Lambda^{d-4})$.
- Predict multi-charged particles ➡ Large $c\tau$ values.
- More fields needed, but much richer phenomenology.

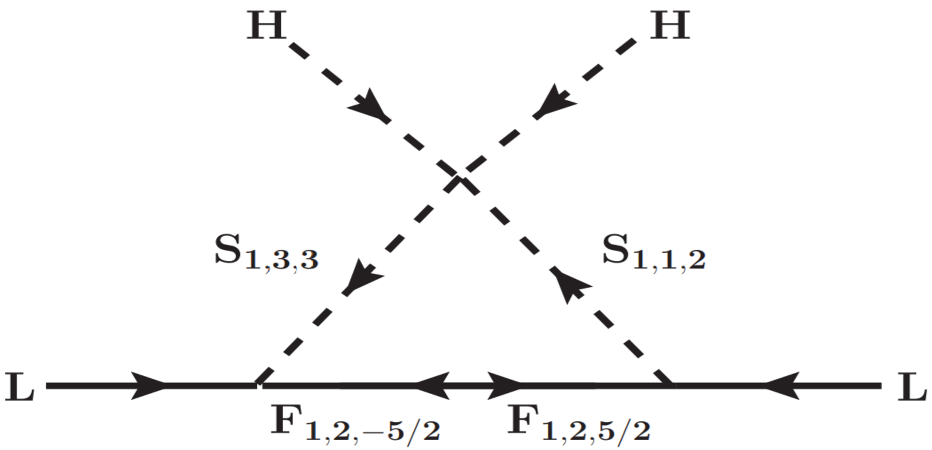
1-loop models

OUR MODEL

SCOTOGENIC



E. Ma, Phys. Rev. D73 (2006) 077301,



C. Arbelaez, G. Cottin, J.C. Helo, M.Hirsch
Phys.Rev.D 101 (2020) 9, 095033

Additional symmetry to the SM $SU(2)_L \times U_Y \times Z_2$

$$(\nu_i, l_i) \sim (2, -1/2; +), \quad l_i^c \sim (1, 1; +), \quad N_i \sim (1, 0; -),$$

$$(\phi^+, \phi^0) \sim (2, 1/2; +), \quad (\eta^+, \eta^0) \sim (2, 1/2; -).$$

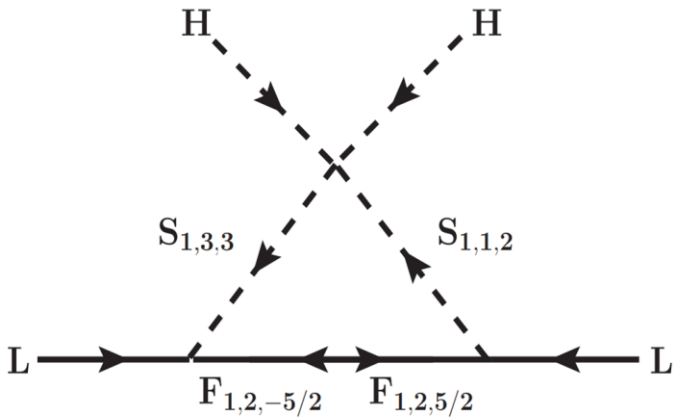
2 Dark Matter Candidates

No additional symmetries up to the SM

No Dark Matter Candidates

$$S_{1,1,2} = S_1^{2+}$$
$$S_{1,3,3} = (S_3^{4+}, S_3^{3+}, S_3^{2+})$$
$$F_{1,2,5/2} = (F^{3+}, F^{2+})$$

Neutrino mass scenario with multicharged components and then possible multilepton signals at the colliders.

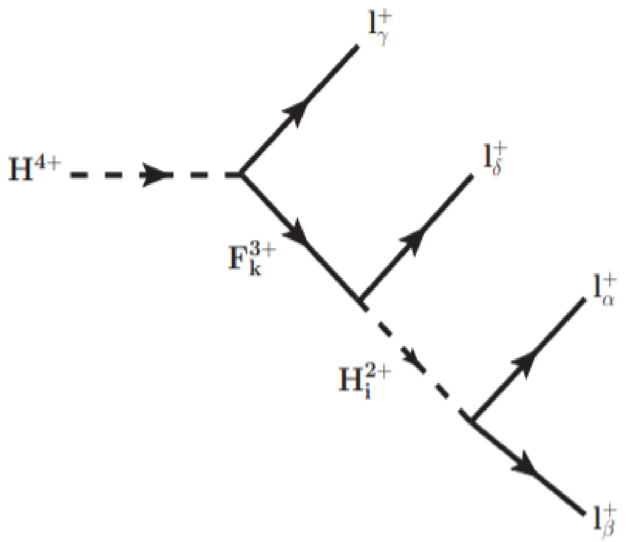


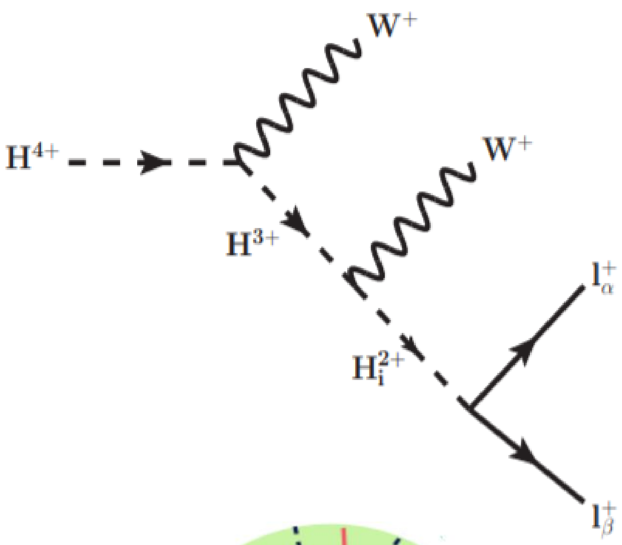
$$S_{1,1,2} = S_1^{2+} \longrightarrow S_1^{2+}$$

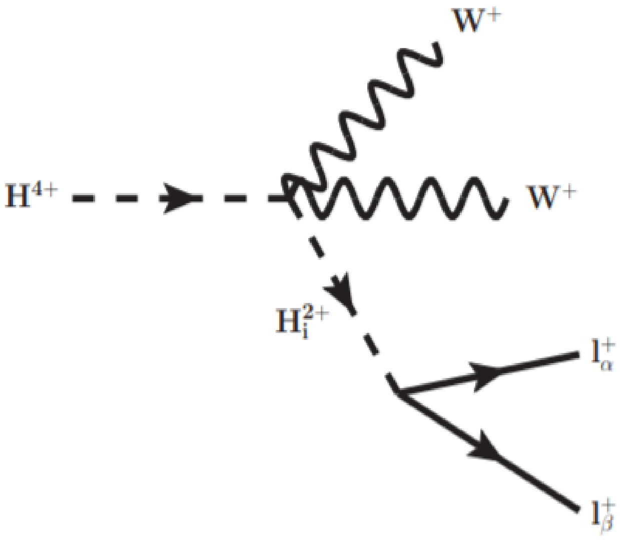
$$S_{1,3,3} = (S_3^{4+}, S_3^{3+}, S_3^{2+}) \longrightarrow (H^{4+}, H^{3+}, S_3^{2+})$$

All these particles will decay to SM ones with at least two same-sign leptons!

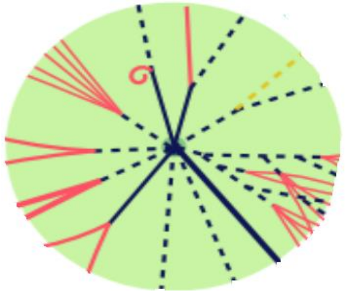
The two final states : ***4l*** and ***2l2W*** represent: exotic LNV signatures



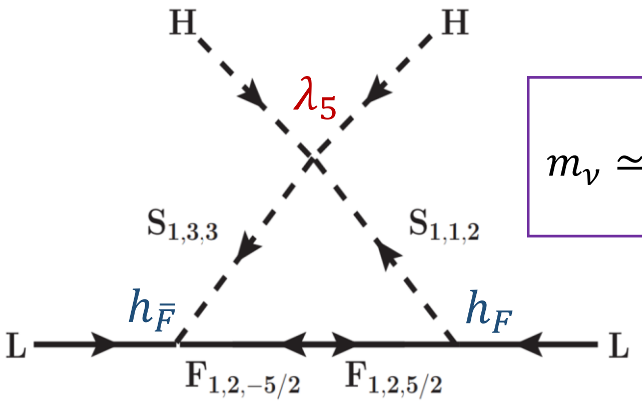




Desplace vertex where several charged leptonic tracks are originated at macroscopic distance of the production points.



$$c\tau \gtrsim 1\,mm \qquad \Gamma = \frac{1}{c\tau} \lesssim 10^{-13}\,m^{-1}$$



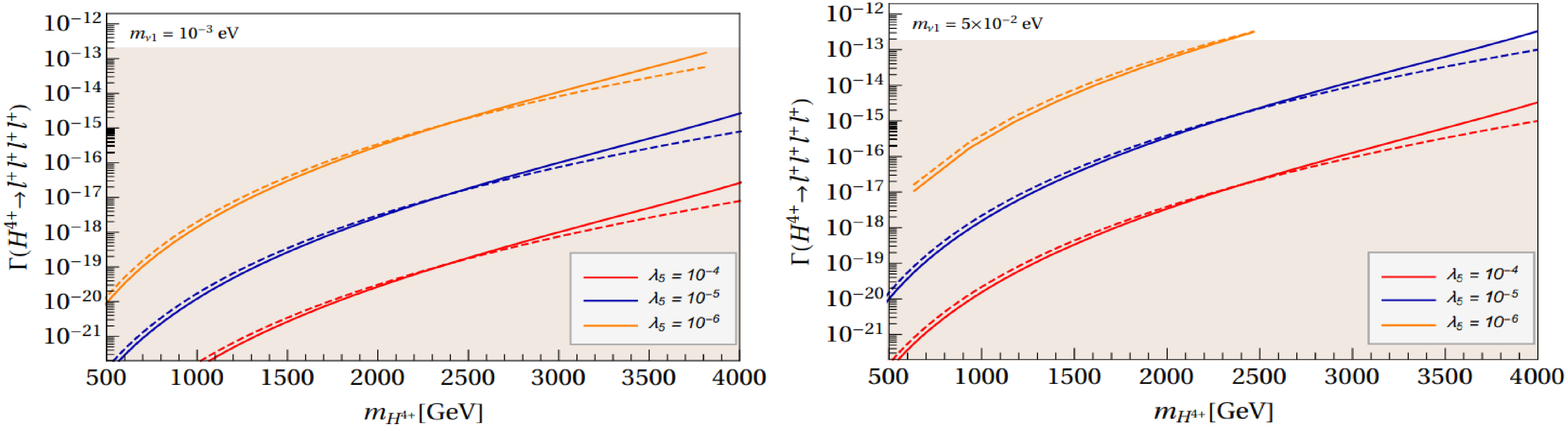
$$\boxed{m_\nu \simeq 0.05\left(\frac{\lambda_5}{10^{-6}}\right)\left(\frac{h_F}{10^{-2}}\right)\left(\frac{h_{\bar{F}}}{10^{-2}}\right)\left(\frac{1\,TeV}{\Lambda}\right)\text{ eV.}}$$

$$\Gamma(H^{4+} \to l_\alpha^+ l_\beta^+ l_\gamma^+ l_\delta^+) \to \frac{c_4}{f(4)}\left|\left\langle\frac{h_{F\bar{F}}^{\gamma\delta}}{m_F}\right\rangle\right|^2 \frac{|(h_{ee})_{\alpha\beta}|^2}{m_{H_2^{2+}}^4} m_{H^{4+}}^7$$

$$\Gamma(H^{4+} \to W^+W^+ l_\alpha^+ l_\beta^+) \to \frac{1}{f(4)} \frac{\left(g_2^2 \sin\theta\, |(h_{ee})_{\alpha\beta}|\right)^2}{m_W^4} m_{H^{4+}}^5$$

$$\sin 2\theta \propto \lambda_5$$

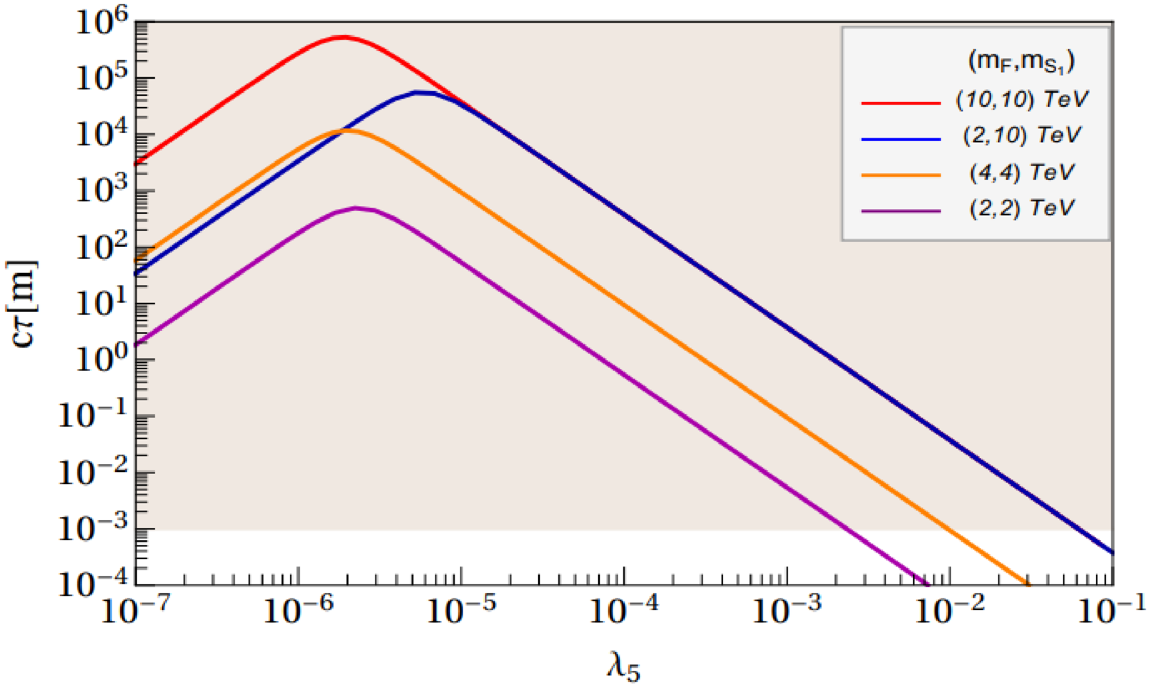
Decay widths very suppressed



Partial widths for H^{4+} for the final state $H^{4+} \to l\,l\,l\,l$ as a fuction of $m_{H^{4+}}$.

- Measurable small widths, i.e $\Gamma \lesssim 10^{-13}\, m^{-1}$ can occur even for large scalar masses.
- Since the lightest neutrino mass is currently unknown, even smaller widths (or larger decay lengths) are also posible.

Long-Lived Multi-Charged Particles



Decay lenght $c\tau$ of H^{4+} as a fuction of λ_5

$$m_\nu \simeq 0.05\left(\frac{\lambda_5}{10^{-6}}\right)\left(\frac{h_F}{10^{-2}}\right)\left(\frac{h_{\bar{F}}}{10^{-2}}\right)\left(\frac{1\,TeV}{\Lambda}\right)\text{ eV.}$$

$$\Gamma\left(H^{4+}\to l_\alpha^+ l_\beta^+ l_\gamma^+ l_\delta^+\right)\to\frac{c_4}{f(4)}\left|\left\langle\frac{h_{F\bar{F}}^{\gamma\delta}}{m_F}\right\rangle\right|^2\frac{\left|(h_{ee})_{\alpha\beta}\right|^2}{m_{H_2^{2+}}^4}m_{H^{4+}}^7$$

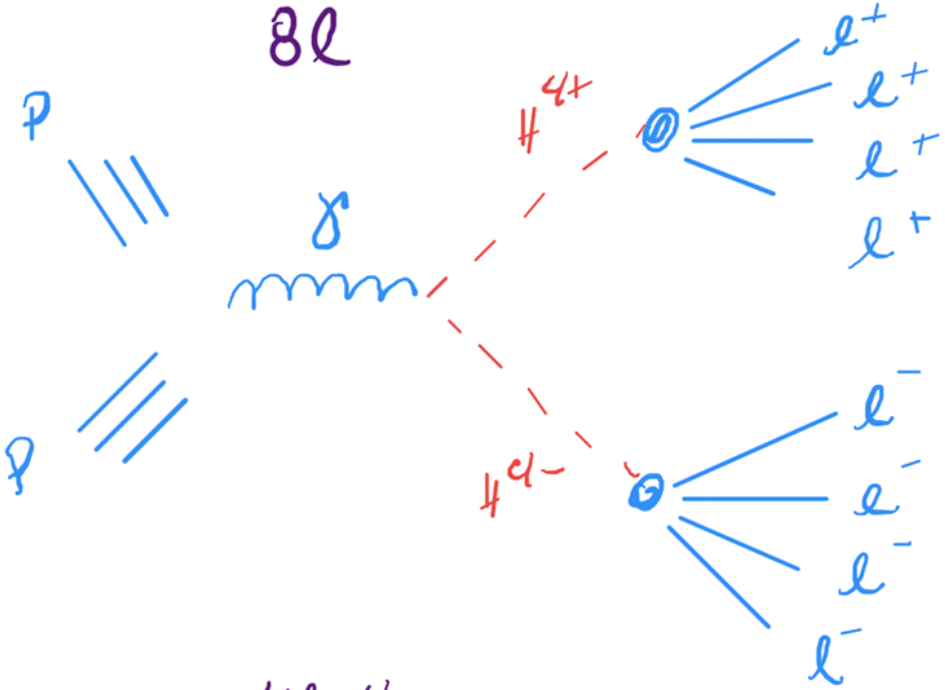
$$\Gamma\left(H^{4+}\to W^+W^+l_\alpha^+ l_\beta^+\right)\to\frac{1}{f(4)}\frac{\left(g_2^2\sin\theta\left|(h_{ee})_{\alpha\beta}\right|\right)^2}{m_W^4}m_{H^{4+}}^5$$

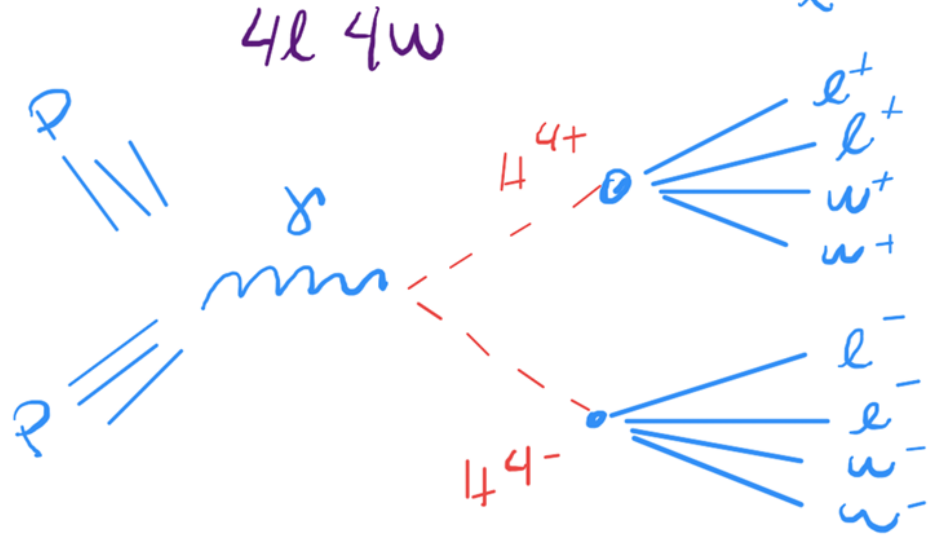
- The H^{4+} decays are very slow $\longrightarrow$ long charged tracks are expected in large part of the parameter space.
- $c\tau$ is maximized for intermediate values of λ_5 $\longleftarrow$ $\Gamma\left(H^{4+}\to \underbrace{l_\alpha^+ l_\beta^+ l_\gamma^+ l_\delta^+\right)=\Gamma\left(H^{4+}\to W^+W^+l_\alpha^+ l_\beta^+}\right)$

Exotic $6l\,2W$ **LNV signature** after *pp* collision at LHC

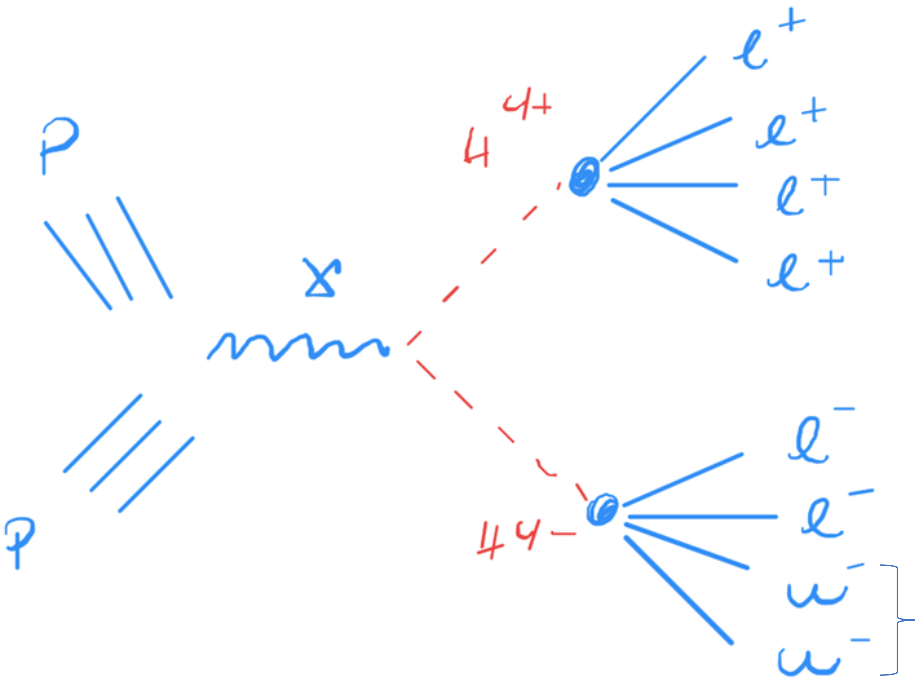
- The possibility to experimentally observe LNV is larger for the points with the largest $c\tau$

Pair production of H^{4+} $\longrightarrow$ multi-lepton events final states with at least **four charged leptons!**



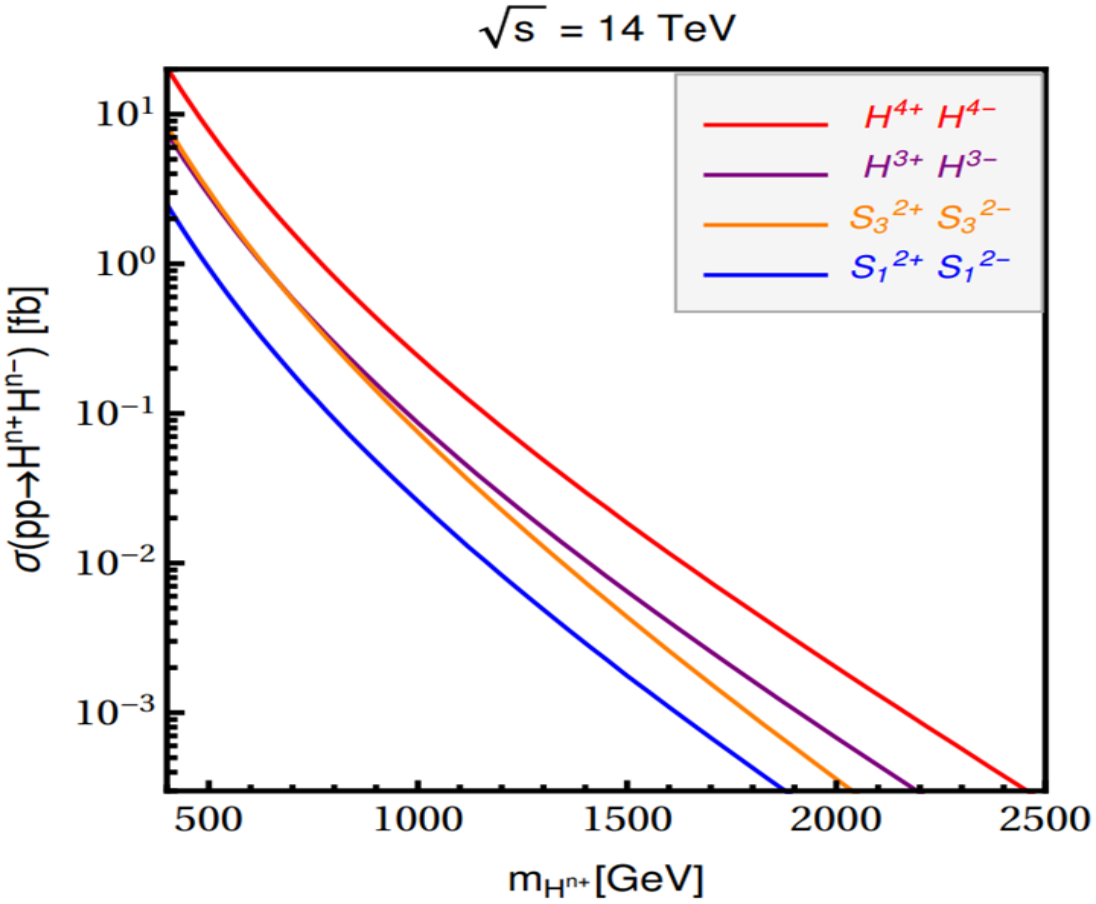


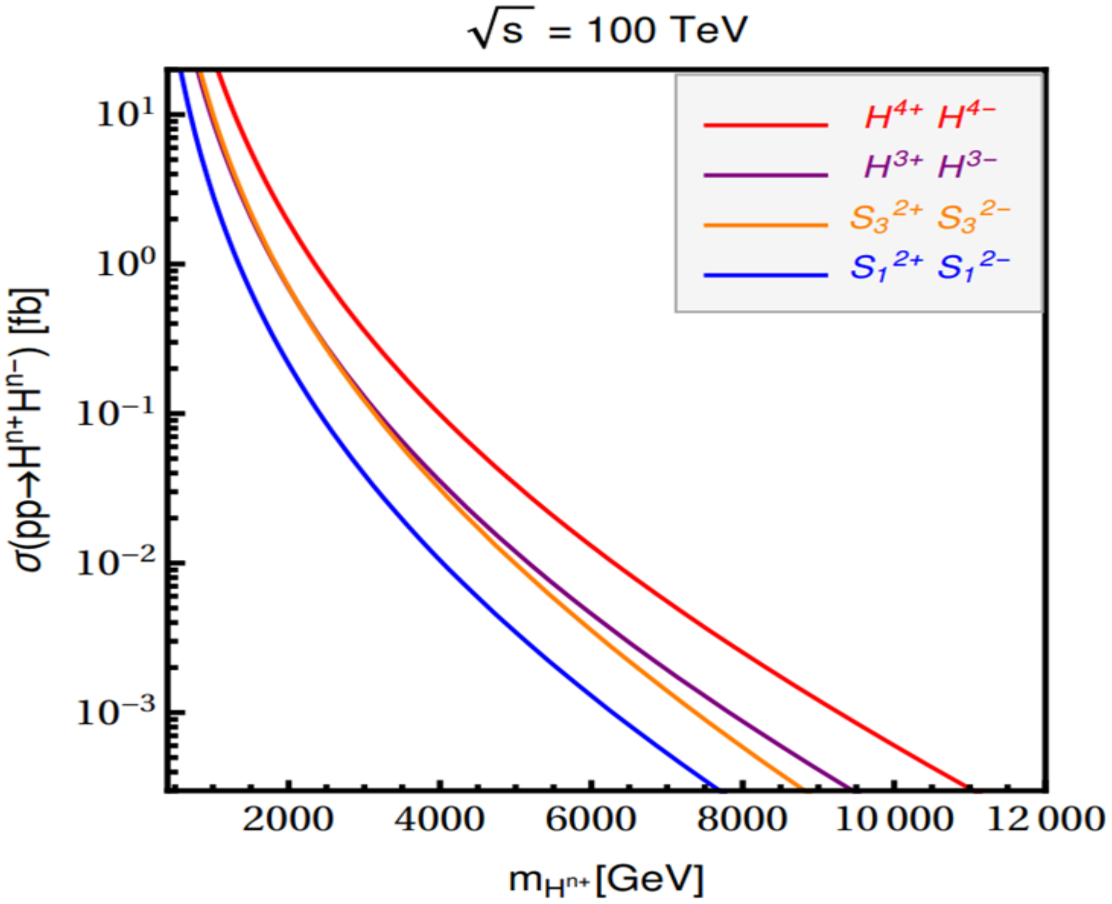
6ℓ 2W LNV!!



Decay hadronically.

Pair production of MCP is dominated by photon-photon fusion diagrams for large scalar masses.





We have used LUXqed17_plus_PDF4LHC15_nnlo_100 PDFs. See Manohar, Nason, Salam, Zanderigui. Phys. Rev. Lett. 117 (2016) 242002

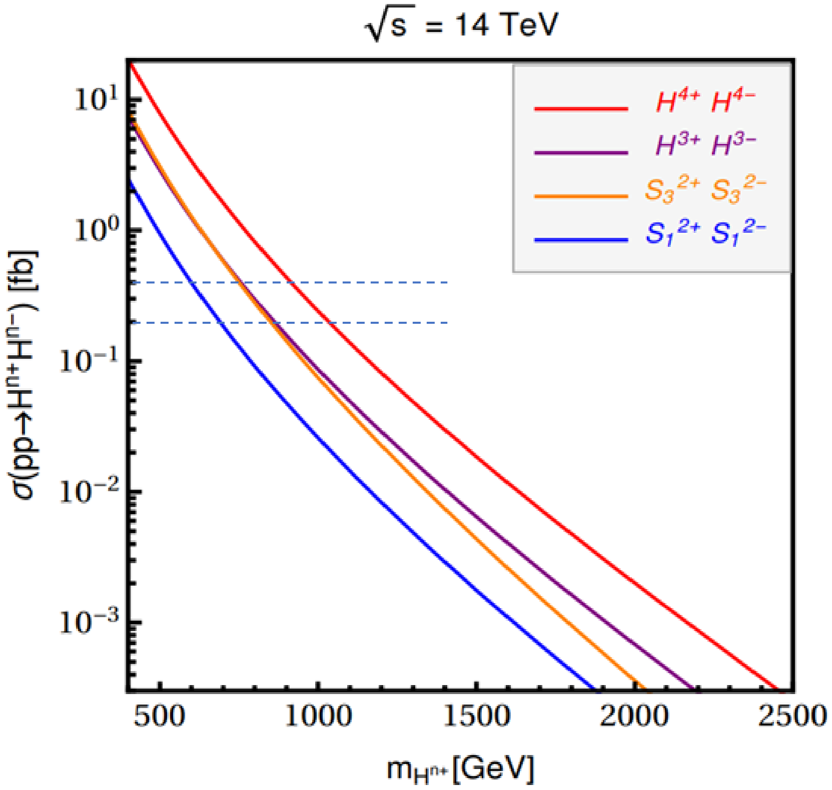
LHC searches put limits on the model parameter space.

Current limits:

$c\tau$ > detector size.

ATLAS collaboration, M. Aaboud et al.,Phys. Rev. D99 (2019) 052003,

-Based on the anomalously large ionization of MCP that are long-lived enough to reach the muon spectrometer.
-Upper limits on the cross section (0.2-0.4) fb set limits on the scalar mases:
$M_{H4+} \gtrsim 980$ GeV, $M_{H3+} \gtrsim 820$ GeV, $M_{H2+} \gtrsim 800$ GeV, $M_{H3+} \gtrsim 660$ GeV,
- Limits only applies for $c\tau$ larger than 10m!



$c\tau$ = 1 mm -1 m detector size.

CMS collaboration, Phys. Rev. Lett. 114 (2015) 061801, [1409.4789].
CMS collaboration, Search for displaced leptons in the e-mu channel, CMS-PAS-EXO-16-022.
ATLAS collaboration, G. Aad et al.Phys. Rev. D92 (2015) 072004, [1504.05162].
CMS collaboration, A. M. Sirunyan et al., JHEP 08 (2018) 016, [1804.07321].
ATLAS collaboration, M. Aaboud et al.,, JHEP 06 (2018) 022, [1712.02118].
J. A. Evans and J. Shelton,, JHEP 04 (2016) 056, [1601.01326].
R. Mahbubani, P. Schwaller and J. Zurita, JHEP 06 (2017) 119, [
ATLAS collaboration, M. Aaboud et al., Phys. Rev. D97 (2018) 052012, [1710.04901].
ATLAS collaboration, M. Aaboud et al.,Phys. Rev. D99 (2019) 052003,

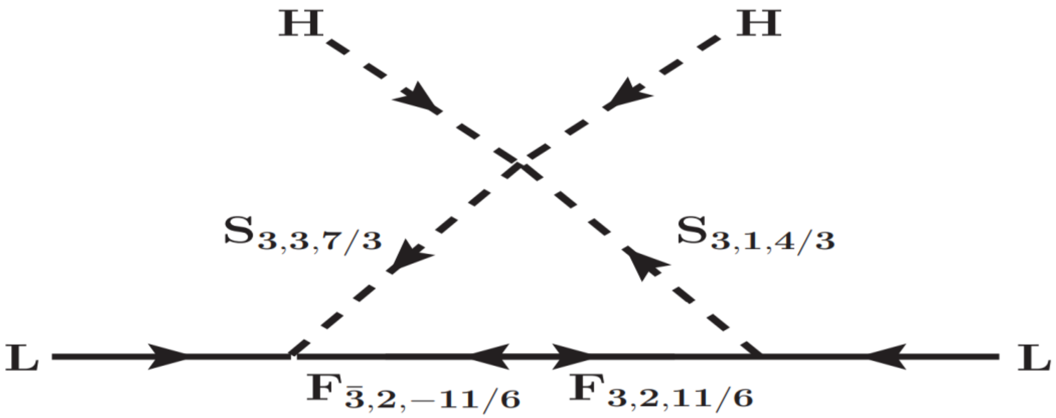
Displaced vertex and disappearing tracks searches can give limits to our model.

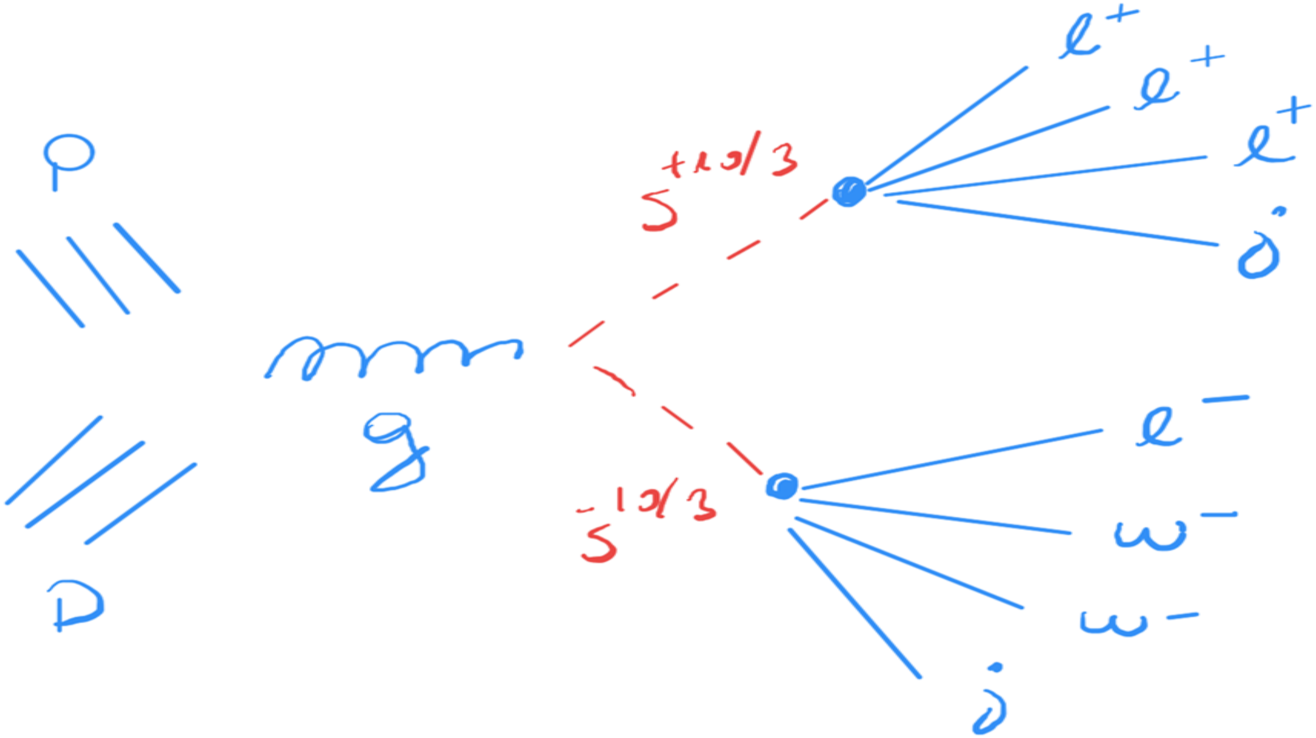
$c\tau$ < 1mm. Promt decays

CMS collaboration, A. M. Sirunyan et al., Search for physics beyond the standard model in multilepton final states in proton-proton collisions at √ s = 13 TeV JHEP 03 (2020) 051

For the parameter region of our model where the scalars decay promptly, various "seesaw searches" can give limits to our model.

Other models can be constructed that lead to exotic multi-lepton signals!





LNV!

$4\ell\ 2W\ 2j$

$$S_{3\,3\,\frac{7}{3}} = \left(S^{4/3}, S^{7/3}, S^{10/3}\right)$$

all with color!!

Conclusions

We discussed a 1-loop neutrino mass model where the smallness of the observed neutrino masses, together with the high multiplicity of the final states, lead to Long-Lived Multi-Charged particles.

The final signals open the possibility of having multi-lepton LNV final states at the LHC.

Different searches can be sensitive to our model: from searches of stable MCP, to displaced vertex signals, depending on the half-life of the new particles.

Other interesting models that lead to multi-lepton signatures can be built such as the ones with long-lived colored multi-charge particles.

Thank you!