Searches for heavy neutral leptons at the Future Circular Colliders

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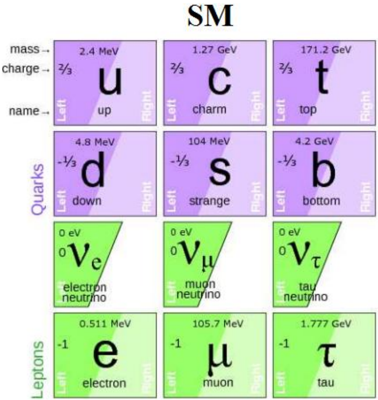
on behalf of the FCC collaboration,
CERN and
Institute of Nuclear Physics, Polish Academy of Science

15th Rencontres du Vietnam,
Quy Nhon, 4-10 August 2019

Particles of SM



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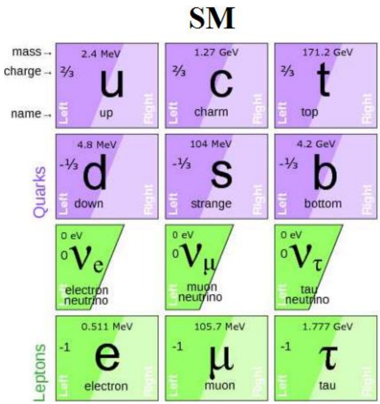
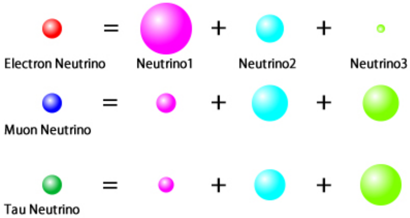


⇛ In the SM neutrinos do not appear in the right-handed state.

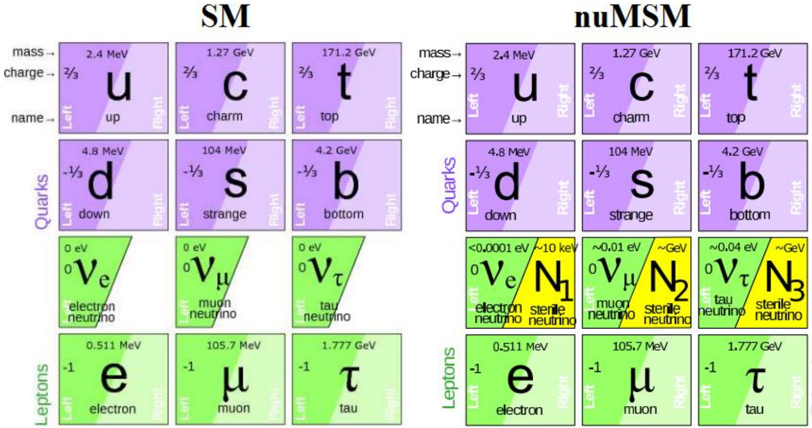
⇛ By construction neutrino are massless.

⇛ Neutrino oscillations are evidence for physics beyond the SM!



Extending the SM

⇛ A lazy person solution is to add the right-handed neutrinos in:



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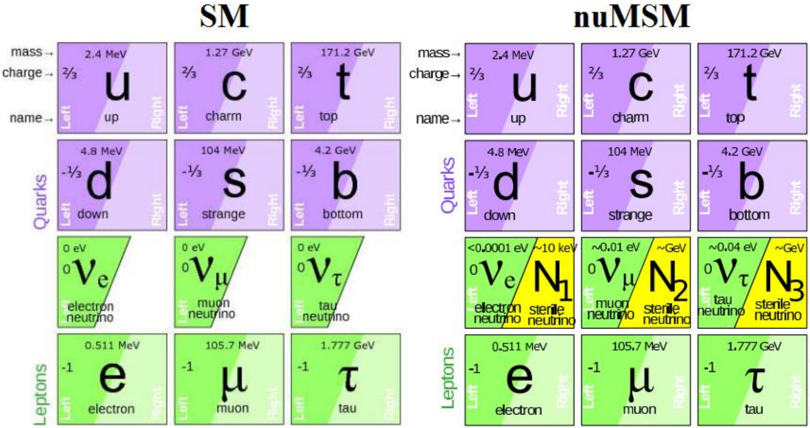
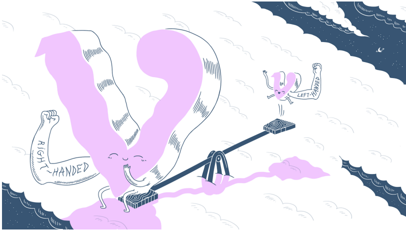


⇛ But where are they?

arXiv::hep-ph/0605047, M.Shaposhnikov

Seesaw mechanism

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\ell}_L F \nu_R \epsilon \Phi^* - \frac{1}{2}\bar{\nu_R^c} M_M \nu_R + \text{H.c.}$$



⇛ After the EWSB:

$$\frac{1}{2}\left(\bar{\nu_L}\bar{\nu_R^c}\right)\mathcal{M}\left(\nu_L^c \nu_R\right)^T$$

⇛ In the vanilla seesaw:

$$\mathcal{M} = \begin{pmatrix} 0 & M_D \\ M_D & M_M \end{pmatrix} \qquad \Rightarrow \lambda_+ \sim M_D, \quad \lambda_- \sim -\frac{M_M^2}{M_D}$$

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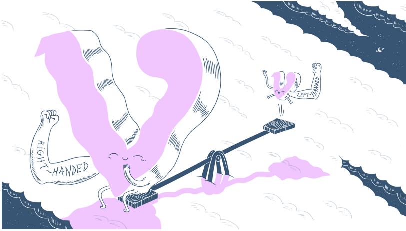

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$\Rrightarrow$ In reality:

$$\mathcal{M} = \begin{pmatrix} \delta m_\nu^{1loop} & M_D \\ M_D^T & M_M + \delta M_N^{1loop} \end{pmatrix}$$

Seesaw mechanism

⇛ Diagonalization matrix:

$$\mathcal{U} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta^\dagger) & \cos(\theta^\dagger) \end{pmatrix} \begin{pmatrix} U_\nu & \\ & U_N^* \end{pmatrix}$$

$$\mathcal{U}^\dagger \mathcal{M} \mathcal{U}^* = \begin{pmatrix} m_\nu^{\rm diag} & \\ & M_N^{\rm diag} \end{pmatrix}$$

with

$$M_N^{\rm diag} = U_N^T M_N U_N = \mathsf{diag}(M_1, M_2, M_3)$$
$$m_\nu^{\rm diag} = U_\nu^\dagger m_\nu U_\nu^* = \mathsf{diag}(m_1, m_2, m_3).$$

⇛ For small mixings:

$$\mathcal{U} = \left[\begin{pmatrix} \mathbb{I} - \frac{1}{2}\theta\theta^\dagger & \theta \\ -\theta^\dagger & \mathbb{I} - \frac{1}{2}\theta^\dagger\theta \end{pmatrix} + \mathcal{O}(\theta^3) \right] \begin{pmatrix} U_\nu & \\ & U_N^* \end{pmatrix},$$

Correction to SM processes

⇛ Charge currents:

$$j_{\mu}^{+} = \frac{g}{2}\theta_{\alpha}\bar{\ell}_{\alpha}\gamma_{\mu}N$$

⇛ Neutral currents:

$$j_{\mu}^{0} = \nu_{\alpha}\gamma_{\mu}\theta_{\alpha}N$$

⇛ The Yukawa couplings:

$$\mathcal{L}_{Yukawa} = \mathcal{L}_{Yukawa}^{SM}\theta_{\alpha}$$

Current status

⇛ Since the RHN are modifying fundamental properties of SM they are hugely constrained:

Indirect

- EW precision observables
- LFV, LNV
- Neutrinoless double beta decay
- Big Bang Nucleosynthesis

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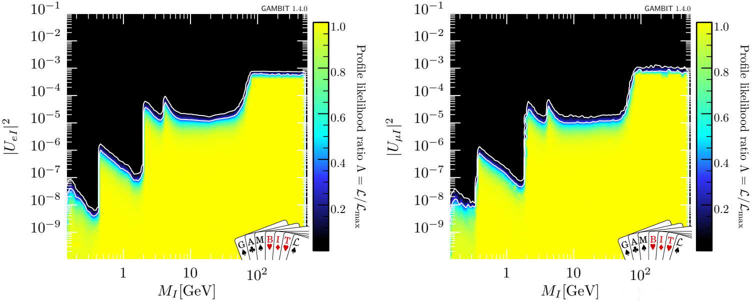
Direct

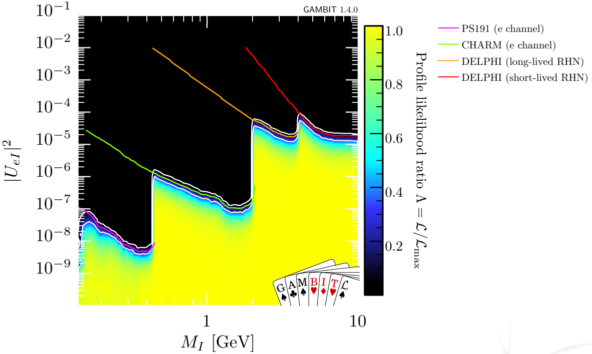
- Fix target experiments
- Collider searches (LEP, LHC, etc.)

Current status



$\Rightarrow$ M.C., M. Drewers, T. Gonzalo, J. Harz, S. Krishnamurthy, C. Weniger, arXiv::1908.02302

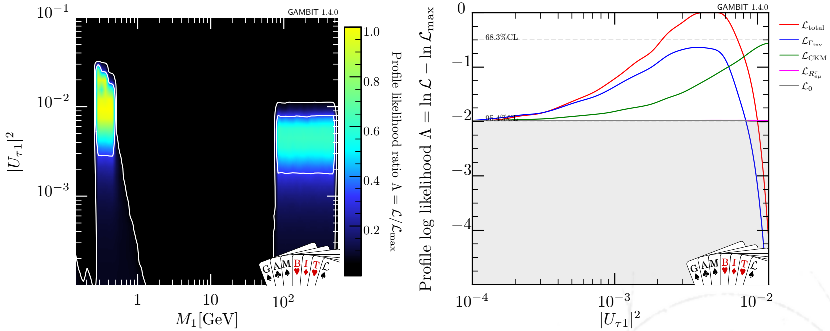
Where the constrains come from?



⇛ The direct searches are the strongest constraints where production cross sections are the largest.
⇛ arXiv::1908.02302

Indirect constraints

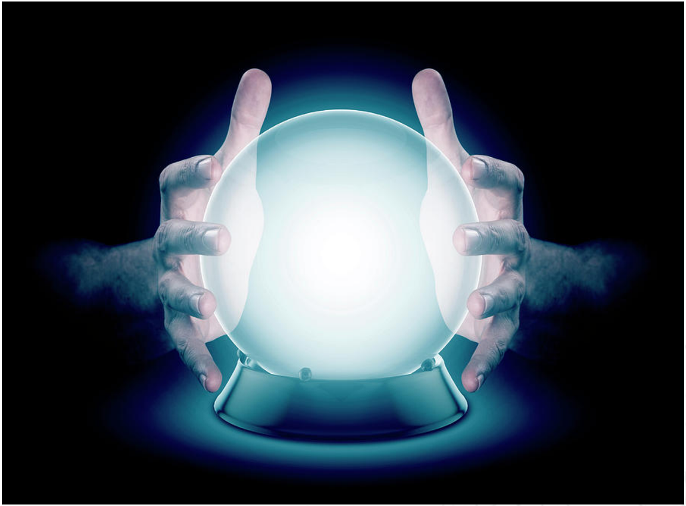
⇛ The indirect searches show power for high couplings:



⇛ Small excess is visible. Consistent with the fluctuation.

⇛ arXiv::1908.02302

What can happen in the future?



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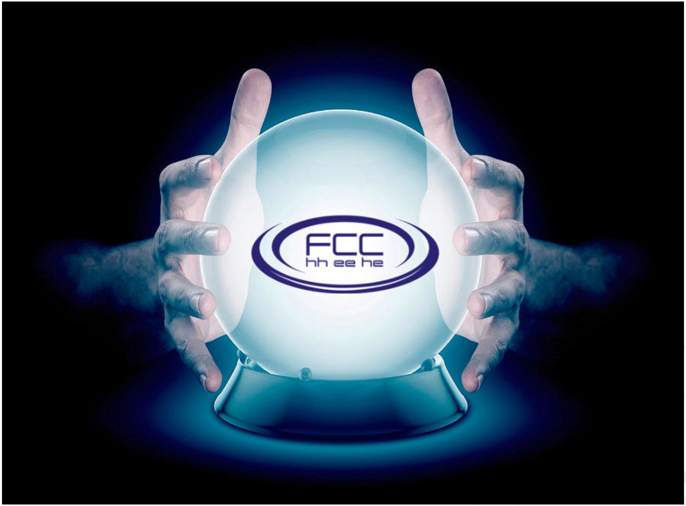
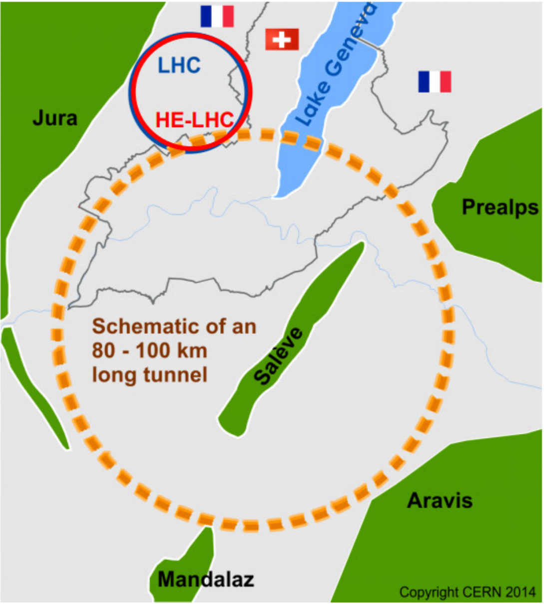


FCC



International FCC collaboration with CERN as host lab to study:

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- **e^+e^- collider (*FCC-ee*),** → potential first step
- ***pp*-collider (*FCC-hh*)** → long-term goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **HE-LHC** with *FCC-hh* technology
- **Ions** and **lepton-hadron** options with hadron colliders

FCC

FCC-ee:

- **~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)** (m_Z, m_W, m_{top}, $\sin^2 \theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$ $\alpha_s(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings)
- **Exploraing 10 - 100 TeV energy scale via couplings with precision measurements**
- ➢ **Machine design for highest luminosities at Z, WW, ZH and ttbar working points**

FCC-hh:

- **Highest center of mass energy for direct production up to 20 - 30 TeV**
- **Huge rates for single and multiple production of SM bosons (H,W,Z) and quarks**
- ➢ **Machine design for ~100 TeV c.m. energy & int. luminosity ~ 20ab^{-1} in 25 years**

HE-LHC:

- **Doubling LHC collision energy with FCC-hh 16 T magnet technology**
- **c.m. energy ~ 27 TeV = 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC**
- ➢ **Machine design within constraints from LHC CE and using HL-LHC and FCC techn.**

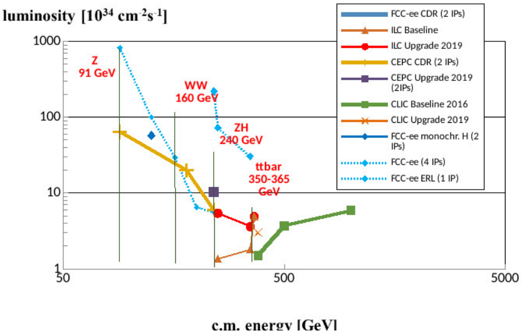
FCCee Physics

working point	assumed typical luminosity/IP [10^{34} $cm^{-2}s^{-1}$] = design value minus 15(10)%	total luminosity (2 IPs)/ yr; half of typical luminosity assumed in 1st two years (Z) and 1st year ($t\bar{t}$)	physics goal	run time [yr]
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	48 ab^{-1}/year		
W	25	6 ab^{-1}/year	10 ab^{-1}	1-2
H	7.0	1.7 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.4	0.34 ab^{-1}/year	1.5 ab^{-1}	4

total program duration: 15 years – *incl. machine modifications*

phase 1 (*Z*, *W*, *H*): 9 years, phase 2 (top): 6 years

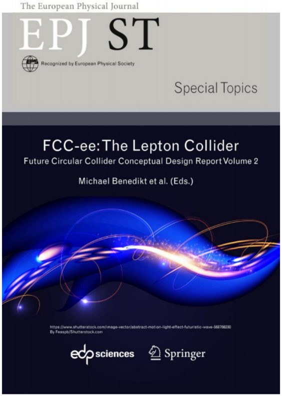
FCCee in context



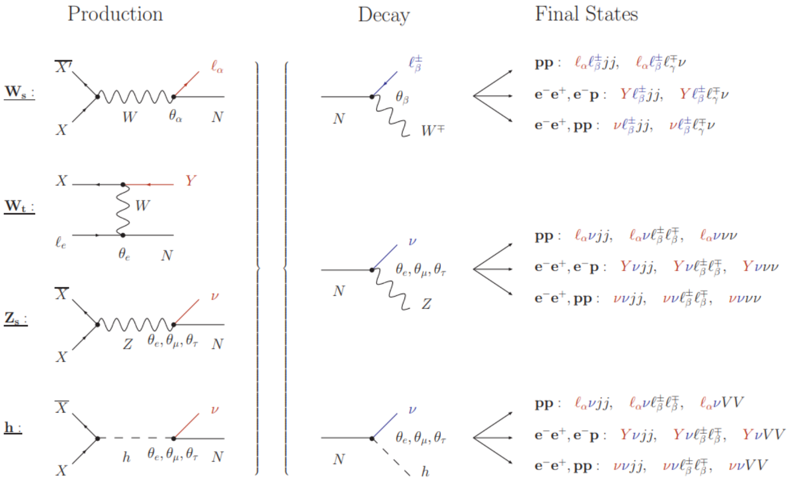
⇛ Check out the CDR : CERN-ACC-2018-0057

⇛ Also the theory report: arXiv:1905.05078

⇛ The FCCee is the most efficient machine up to the $t\bar{t}$ threshold.

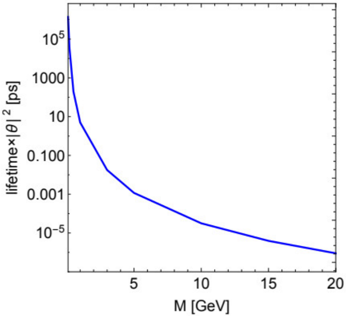


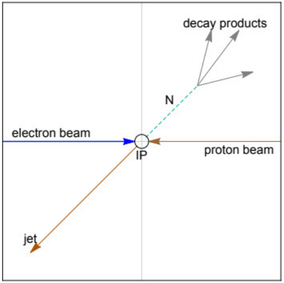
Schematizing sterile neutrino searches at FCC



Credit to S.Antusch, E.Cazzato, O.Fischer, arXiv::1612.02728

Displaced vertexes





Example: FCC-he

- ⇛ In the interesting region: $m < m_W$ and $\theta < 10^{-5}$
- ⇛ Displacement: measurement of primary (production) vertex.
- ⇛ Secondary vertex with „large" displacement
- ⇛ ee he: A few times tracking resolution: $\mathcal{O}(10)\mu\mathrm{m}$,
- ⇛ hh: Beyond background, detector noise, pileup: $\mathcal{O}(10)\mathrm{cm}$.

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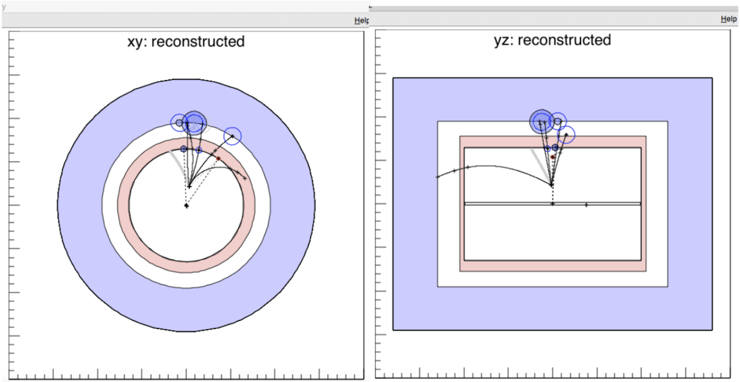

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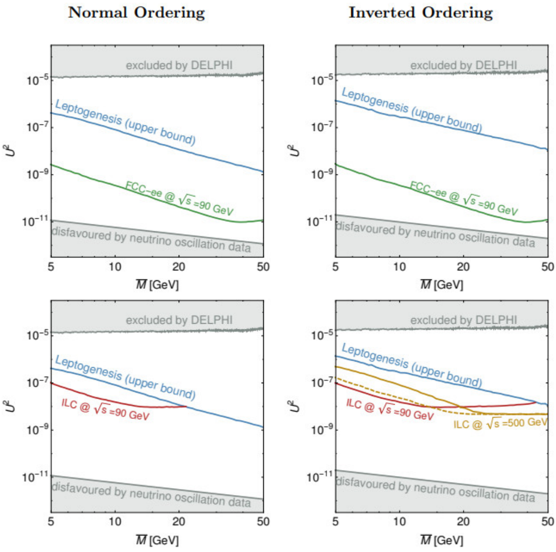
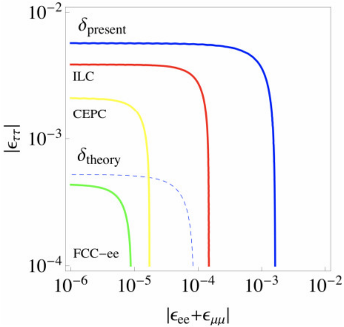
Credit to S.Antusch, E.Cazzato, O.Fischer, arXiv::1612.0272

FCCee direct

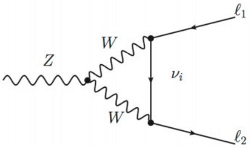


arXiv::1710.03744, S.Antusch, E.Cazzato, M.Drewes, O.Fischer, B.Garbrecht, D.Gueter, I.Klaric

FCCee indirect



Antusch, OF; JHEP 1410 (2014) 094

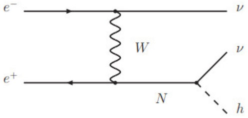


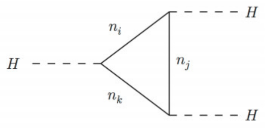
Exotic lepton flavor violating Z boson decays

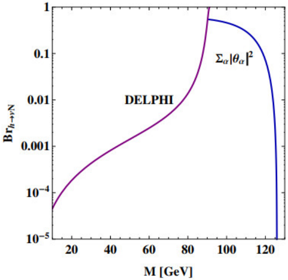
A. Abada *et al.*; JHEP04 (2015) 051

- ⇛ Modification of the theory prediction of precision observables.
- ⇛ Also CKM unitarity, cLFV, LUV.
- ⇛ Currently still dominated by LEP!

FCCee Higgs portal







S. Antusch, OF; JHEP **1604** (2016) 189

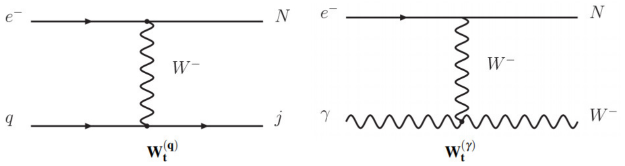
⇛ Mono-Higgs production mechanism!

⇛ New Higgs decays:

- Modification of Higgs Branching fractions.
- New decays: $H \to N\nu$.
- Invisible width modification.

⇛ Modification of triple Higgs coupling.

FCCeh



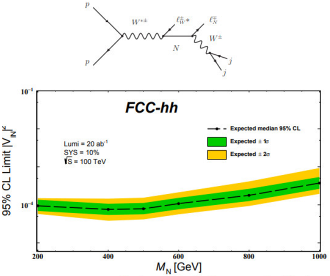
⇛ Large Lorentz boost makes the displaced vertexes clearly visible.
⇛ Many final states to look at:

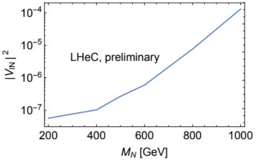
Name	Final State	$\lvert\theta_\alpha\rvert$ Dependency	LFV
lepton-trijet	$jjj\ell_\alpha^-$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓
jet-dilepton	$j\ell_\alpha^-\ell_\beta^+\nu$	$\frac{\lvert\theta_e\theta_\alpha\rvert^{2\,(*)}}{\theta^2}$	✓
trijet	$jjj\nu$	$\lvert\theta_e\rvert^2$	×
monojet	$j\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×

Name	Final State	$\lvert\theta_\alpha\rvert$ Dependency	LFV
lepton-quadrijet	$jjjj\ell_\alpha^-$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓
dilepton-dijet	$\ell_\alpha^-\ell_\beta^+\nu jj$	$\frac{\lvert\theta_e\theta_\alpha\rvert^{2\,(*)}}{\theta^2}$	✓
trilepton	$\ell_\alpha^-\ell_\beta^-\ell_\gamma^+\nu\nu$	$\frac{\lvert\theta_e\theta_\alpha\rvert^{2\,(*)}}{\theta^2}$	✓
quadrijet	$jjjj\nu$	$\lvert\theta_e\rvert^2$	×
electron-di-b-jet	$e^-b\bar{b}\nu\nu$	$\lvert\theta_e\rvert^2$	×
dijet	$jj\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×
monolepton	$\ell_\alpha^-\nu\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×

Credit to S.Antusch, E.Cazzato, O.Fischer, arXiv::1612.02728

FCChh

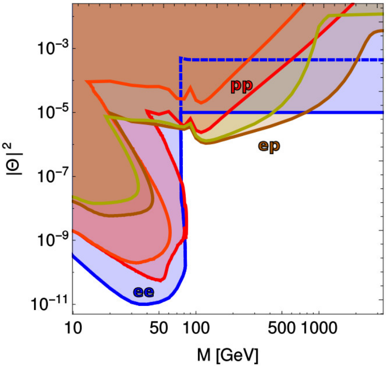




S. Antusch, E. Cazzato, O. Fischer, A. Hammad and K. Wang, JHEP **1810** (2018) 067

- ⇛ LFV is the thing to look for!!!
- ⇛ The best final states: $\ell^{\pm}_{\alpha}\ell^{\mp}_{\beta}jj$, $\ell^{\pm}\ell^{\mp}\ell^{\pm}_{\gamma}$
- ⇛ For ep machine the more sensitive ones are: μjjj and τjjj.
- ⇛ Also LNU are there: $\mu^{\pm}\mu^{\pm}j$ (pp) and $e^{+}j$ (ep).

FCC in total



⇛ FCCee:

- Dominates the exclusion below the m_W mass.
- Precision indirect constraints: EWPO, CKM, etc.

⇛ FCCeh, FCChh:

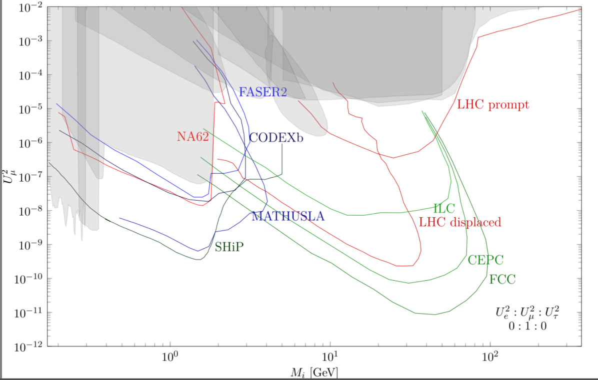
- Sensitivity in high mass region.
- Higgs potential.
- LFV, LNV.

Credit to S.Antusch, E.Cazzato, O.Fischer, arXiv::1612.02728

Summary

- ⇛ Hunting for RHN is very well motivated.
- ⇛ Neutrino program has to be considered a core of future colliders.
- ⇛ FCC has unique sensitivity for RHN!
- ⇛ Huge amount of measurements and constraints to be performed.
- ⇛ Complementarity between different colliders.

Credit to M. Drewers, [Slides]



Backup