Neutrino mass models at future colliders

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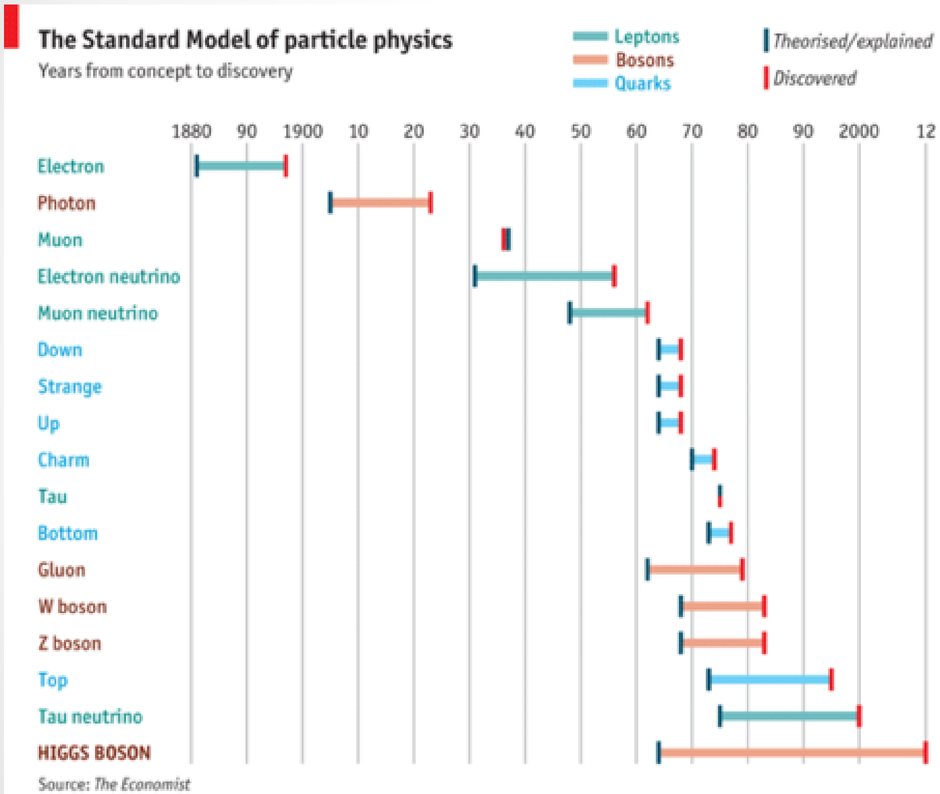
天津，2018.8.18-21

Outline

- Motivation
- Neutrino mass models at LHC upgrades
- CEPC and Dark Matter connection

a 115-year journey in atom



VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

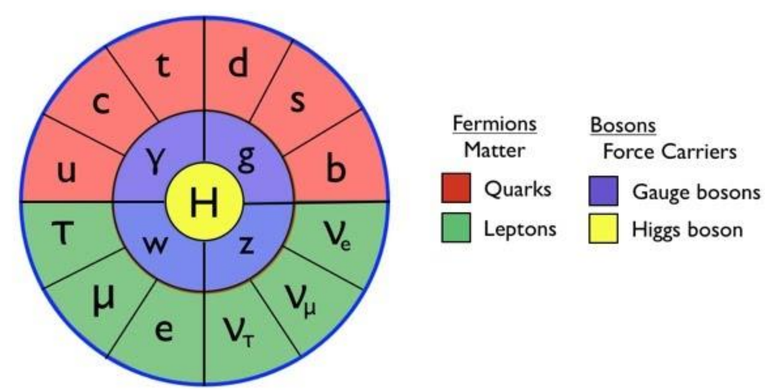
[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)



Particles of the Standard Model

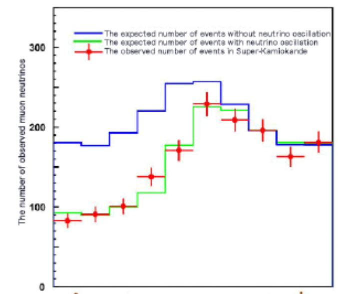
- The past particle colliders (LEP, $\mathrm{Sp}\bar{p}\mathrm{S}$, PETRA, SPEAR, SLC, Tevatron, and LHC) made important measurements for the SM particles.
- They have so far seen no conclusive evidence of Beyond the SM phenomena, although strong arguments based on naturalness imply TeV scale BSM physics.
- Not conclusive signs: e.g. deviations in flavor sector, indirect dark matter detection

Where is the BSM (TeV) scale? When? How?

BSM observation

- The only BSM physics observed so far in the lab is neutrino mass (from flavor change in oscillation, 1998)

$\nu_e \leftrightarrow \nu_\mu$ (SNO): $\begin{aligned} \nu_e + {}^2_1 D &\rightarrow p + p + e^- \\ \nu_\mu + {}^2_1 D &\rightarrow p + n + \nu_\mu \end{aligned}$ $\nu_\mu \leftrightarrow \nu_\tau$ (Super-K):



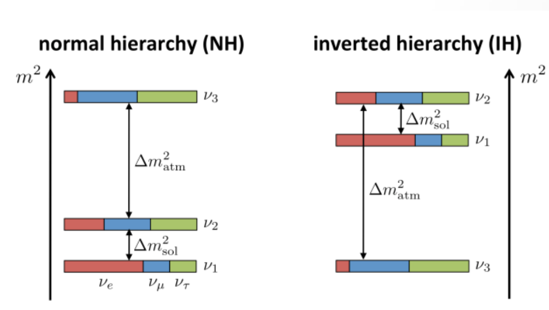
- What we know about neutrino:

$$\begin{aligned}
6.8 \times 10^{-5}\,\mathrm{eV}^2 &< \Delta m^2_{21} < 8.02 \times 10^{-5}\,\mathrm{eV}^2, \\
2.399 \times 10^{-3}\,\mathrm{eV}^2 &< \Delta m^2_{31} < 2.593 \times 10^{-3}\,\mathrm{eV}^2, \\
(-2.562 \times 10^{-3}\,\mathrm{eV}^2 &< \Delta m^2_{32} < -2.369 \times 10^{-3}\,\mathrm{eV}^2), \\
0.272 &< \sin^2\theta_{12} < 0.346, \\
0.418\ (0.435) &< \sin^2\theta_{23} < 0.613\ (0.616), \\
0.01981\ (0.02006) &< \sin^2\theta_{13} < 0.02436\ (0.02452), \\
144^\circ\ (192^\circ) &< \delta_{\mathrm{CP}} < 374^\circ (354^\circ),
\end{aligned}$$

$\theta_{13} \approx 8.4^\circ$ (Daya Bay)

$\delta_{CP} \approx 3\pi/2$ (T2K, NOvA)

$\sum m_\nu < 0.23$ eV (Planck)



- What we need to know:

normal or inverted mass hierarchy?

Dirac ($m_D \overline{\nu_L} \nu_R$) or Majorana ($M_R \overline{\nu_R{}^c} \nu_R$, L number violation)?

why $m_\nu \ll m_{l,q}$? mass theory?

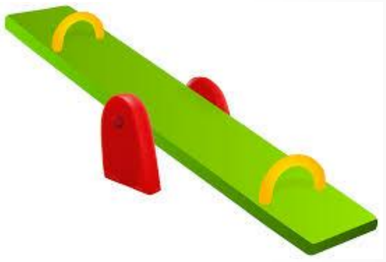
Neutrino mass theories

- "Weinberg operator" $\frac{\alpha}{\Lambda}(LH)(LH)$ minimally permits three tree-level seesaw mechanisms:

  Type I (singlet fermion)

  Type II (triplet scalar)

  Type III (triplet fermion)



- hybrid seesaws (e.g. Type I+II, I+III)
- gauge extension (e.g. $U(1)_{B-L}$, LRSM)
- higher dimension operators
- radiative mass models (e.g. Zee-Babu)

Y. Cai, T. Han, T. Li, R. Ruiz, arXiv: 1711.02180

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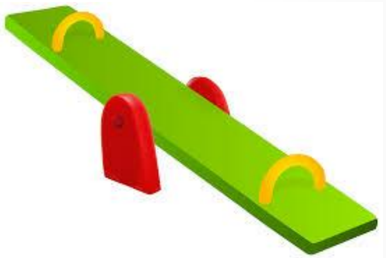

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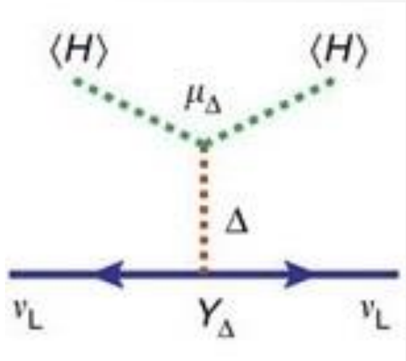
Y. Cai, T. Han, T. Li, R. Ruiz, arXiv: 1711.02180

Type II Seesaw

- Break B-L symmetry by adding a triplet Higgs to SM
  $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0}) \sim (1,3,1)$
- Δ acquires a vev via its SM Higgs coupling:
  $$\mu H^T \, i\sigma_2 \, \Delta^\dagger \, H \; \rightarrow \; v_\Delta = \mu v^2 / {M_\Delta}^2$$
- neutrino masses generated via its Yukawa coupling:
  $$Y_\nu \, L^T \, C \, i\sigma_2 \Delta \, L \; \rightarrow \; m_\nu = Y_\nu \, v_\Delta$$
- M_Δ can be of TeV scale if Y_ν or μ is small



Konetschny, Kummer, 1977; Schechter, Valle, 1980; Cheng, Li, 1980; Lazarides, Shafi, Wetterich, 1981; Mohapatra, Senjanovic, 1981

Neutrino Masses and the CERN LHC: Testing Type II Seesaw

Pavel Fileviez Perez (Wisconsin U., Madison), Tao Han (Wisconsin U., Madison & Santa Barbara, KITP), Gui-yu Huang (Wisconsin U., Madison), Tong Li (Wisconsin U., Madison & Nankai U.), Kai Wang (Wisconsin U., Madison)

May 2008 - 50 pages

Phys.Rev. D78 (2008) 015018
DOI: 10.1103/PhysRevD.78.015018
MADPH-08-1510, NSF-KITP-08-65
e-Print: arXiv:0805.3536 [hep-ph] | PDF

Abstract (arXiv)
We demonstrate how to systematically test a well-motivated mechanism for neutrino mass generation (Type-II seesaw) at the LHC, in which a Higgs triplet is introduced. In the optimistic scenarios with a small Higgs triplet vacuum expectation value vd < 10^{-4} GeV, one can look for clean signals of lepton number violation in the decays of doubly charged and singly charged Higgs bosons to distinguish the Normal Hierarchy (NH), the Inverted Hierarchy (IH) and the Quasi-Degenerate (QD) spectrum for the light neutrino masses. The observation of either H+ --> tau+ nubar or H+ --> e+ nubar will be particularly robust for the spectrum test since they are independent of the unknown Majorana phases. The H++ decays moderately depend on a Majorana phase Phi2 in the NH, but sensitively depend on Phi1 in the IH. In a less favorable scenario vd > 2 10^{-4} GeV, when the leptonic channels are suppressed, one needs to observe the decays H+ --> W+ H_1 and H+ --> t bbar to confirm the triplet-doublet mixing which in turn implies the existence of the same gauge-invariant interaction between the lepton doublet and the Higgs triplet responsible for the neutrino mass generation. In the most optimistic situation, vd approx 10^{-4} GeV, both channels of the lepton pairs and gauge boson pairs may be available simultaneously. The determination of their relative branching fractions would give a measurement for the value of vd.

- Low energy neutrino oscillation data lead to correlations with the flavor structure of the lepton number violating decays of the charged Higgs bosons $H^{\pm\pm},\ H^{\pm}$.
- the division of $H^{++} \to \ell^+\ell^+$ ($\Gamma \propto Y_\nu{}^2 M_\Delta$) and W^+W^+ ($\Gamma \propto v_\Delta{}^2 M_\Delta{}^3/v^4$): $v_\Delta \approx 10^{-4}$ GeV
- leptonic channels in $H^{++}H^{--}, H^{\pm\pm}H^{\mp}$ production at hadron collider

ATLAS CONF Note

ATLAS-CONF-2017-053

5th July 2017

Search for doubly-charged Higgs boson production in multi-lepton final states with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV

The ATLAS Collaboration

A search for doubly-charged Higgs bosons with pairs of prompt, isolated, highly energetic leptons with the same electric charge is presented. The search uses the pp data sample corresponding to 36.1 fb^{-1} of integrated luminosity collected in 2015 and 2016 by the ATLAS detector at the LHC at the centre-of-mass energy of 13 TeV. The search scans through various doubly-charged Higgs branching ratio (Br) hypotheses, where $Br(H^{\pm\pm} \to e^{\pm}e^{\pm}) + Br(H^{\pm\pm} \to e^{\pm}\mu^{\pm}) + Br(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}) \leq 100\%$, in several exclusive signal regions. No significant evidence of signal was observed and corresponding limits on the production cross-section and consequently the lower limit on $m(H^{\pm\pm})$ were derived at 95% CL. Defining $\ell = e, \mu$, the observed lower limit on $H_L^{\pm\pm}$ mass varies from 770 GeV to 870 GeV (850 GeV expected) for $Br(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) = 100\%$ and is still above 450 GeV, for both observed and expected, for $Br(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) = 10\%$ for any combination of partial branching ratios.

ATLAS-CONF-2017-053
10 July 2017

current LHC bound: $M_{H^{++}} \gtrsim 800$ GeV for BR($\boldsymbol{\ell}^+\boldsymbol{\ell}^+$)=100%, $\boldsymbol{\ell} = e, \mu$

Correlation

- The Yukawa interactions of the doubly charged Higgs:

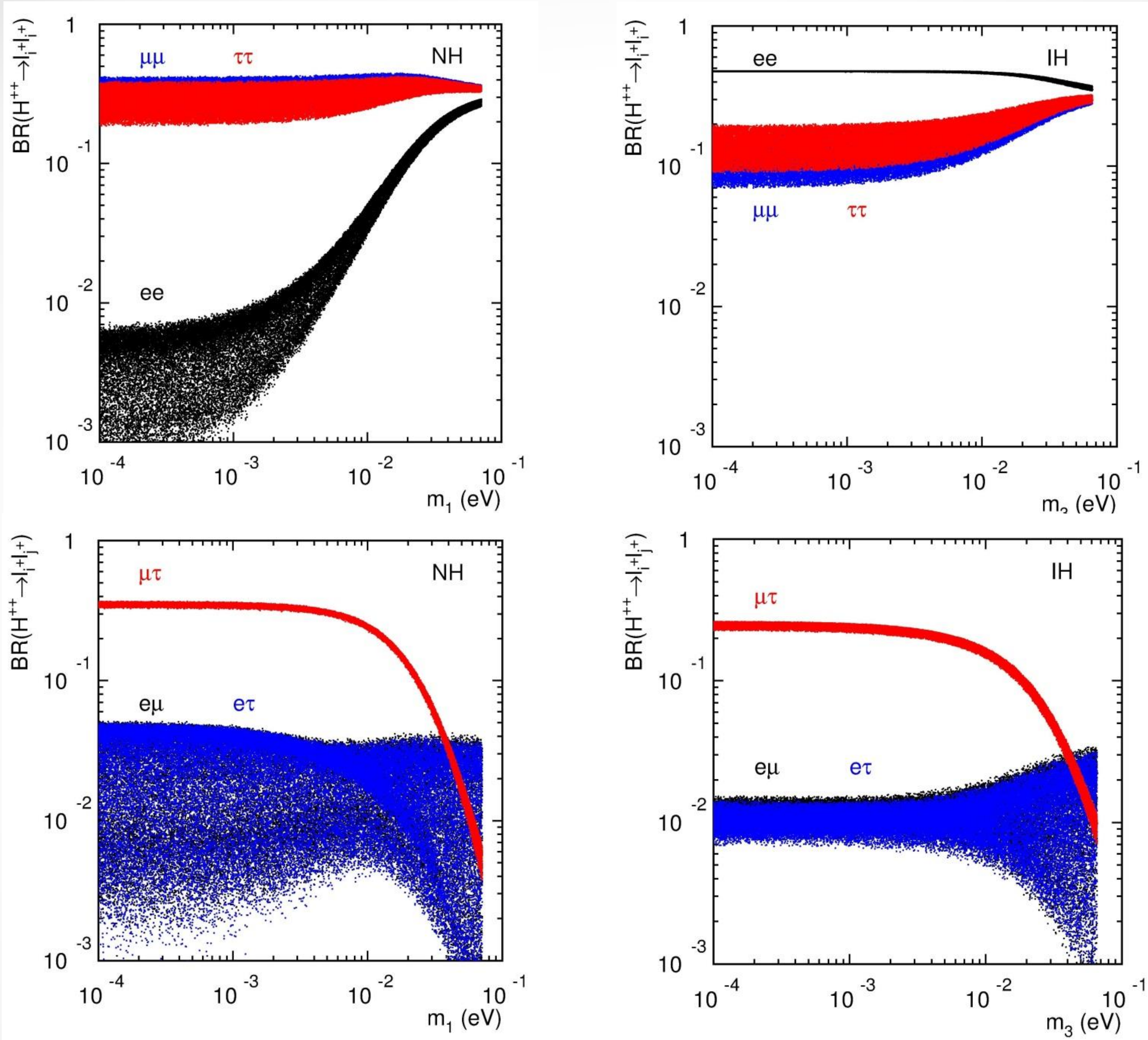
$$Y_\nu\, L^T\, C\, i\sigma_2 \Delta\, L \;\rightarrow Y_\nu{}^{++}\, \boldsymbol{\ell}_L{}^T\, C\, H^{++}\, \boldsymbol{\ell}_L$$

$$Y_\nu{}^{++} = U_{PMNS}{}^* \frac{m_\nu{}^{diag}}{v_\Delta} U_{PMNS}{}^\dagger$$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{12}s_{13}s_{23}e^{i\delta} - c_{23}s_{12} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -c_{23}s_{12}s_{13}e^{i\delta} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \times \mathrm{diag}(e^{i\Phi_1/2}, 1, e^{i\Phi_2/2})$$

- For $v_\Delta < 10^{-4}$ GeV, the decay branching ratios of H^{++} are only governed by $Y_\nu{}^{++}$

P.F. Perez, T. Han, G.-Y. Huang, T. Li, K. Wang, arXiv: 0805.3536



BR(ττ)~BR(μμ)>>BR(ee) in NH, BR(ττ)~BR(μμ)<BR(ee) in IH

BR(μτ)>>BR(eμ),BR(eτ) in NH and IH

Remark I:

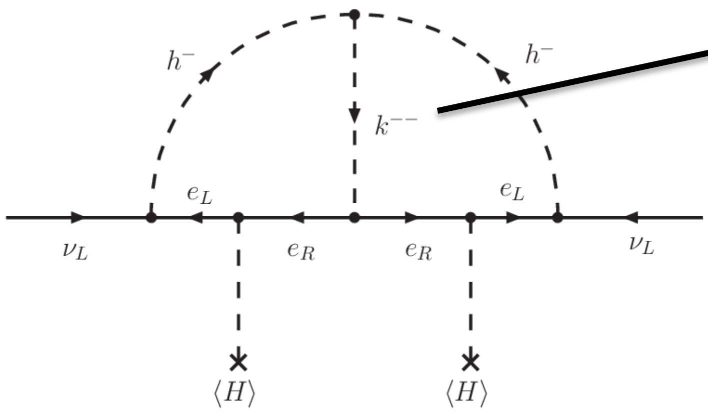
The channels with tau lepton in doubly charged Higgs decays play an important role in the correlation between neutrino oscillation data and Yukawa structure.

Models with doubly charged Higgs

- DCH can arise from different heavy scalar mediated neutrino mass mechanisms.

Type II Seesaw: $L \supset y\,\overline{\boldsymbol{\ell}_L{}^c}\boldsymbol{\ell}_L\Delta^{++} + h.c.$

Zee-Babu model: $L \supset y\,\overline{\boldsymbol{\ell}_R{}^c}\boldsymbol{\ell}_R\kappa^{++} + h.c.$ $\kappa^{++} \sim (1,1,2)$

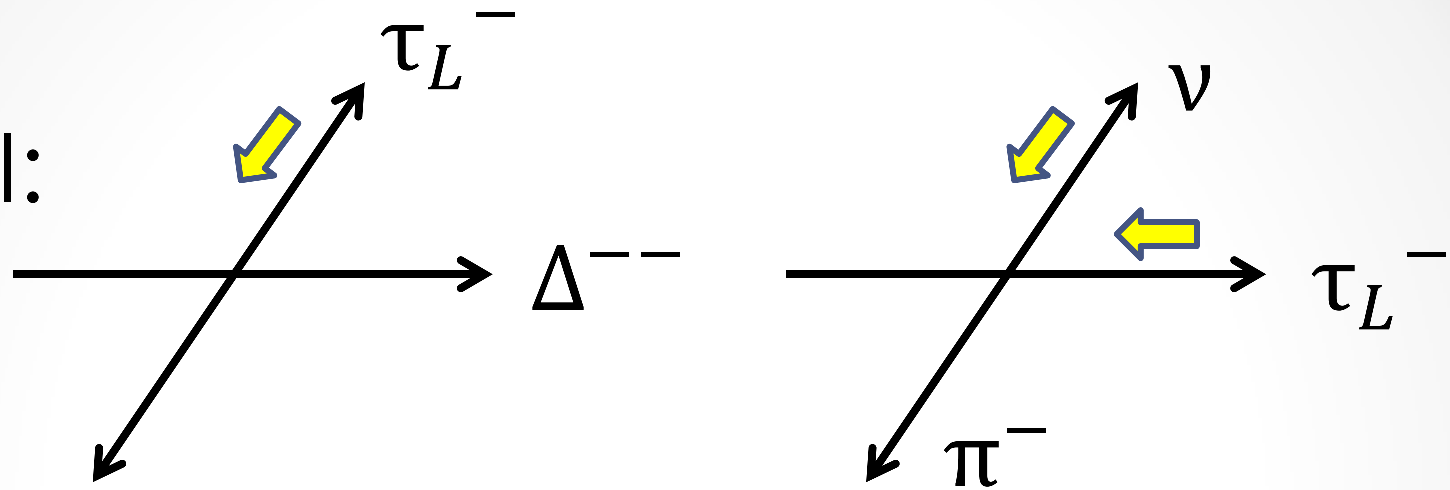


Zee, 1986; Babu, 1988

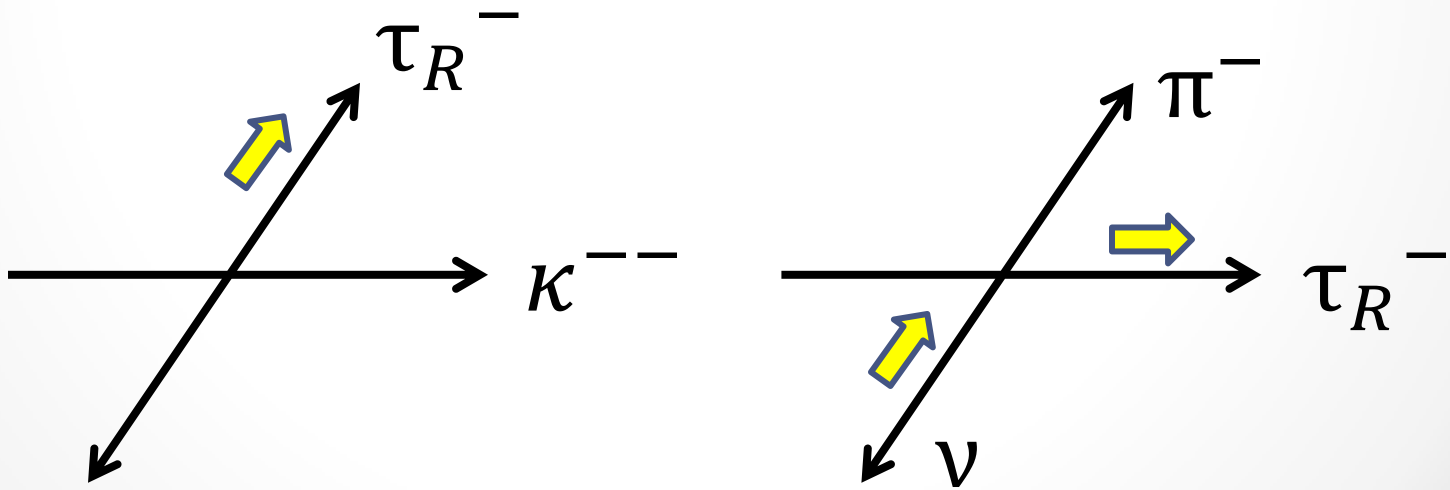
- how to discriminate them? (except total xsec)

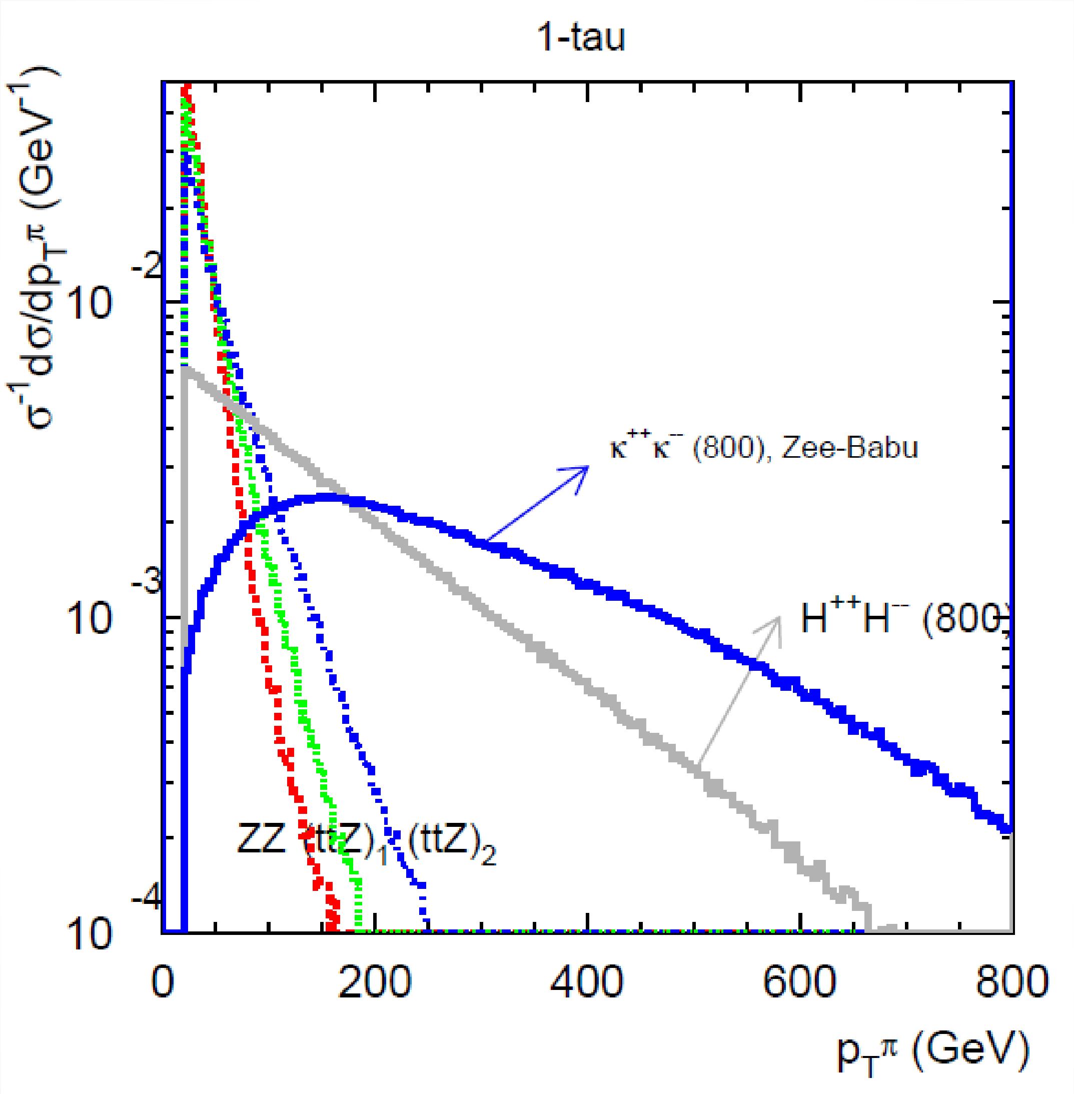
Consider tau decay mode $\tau^- \to \pi^- \nu_\tau$

Type II:



ZB:

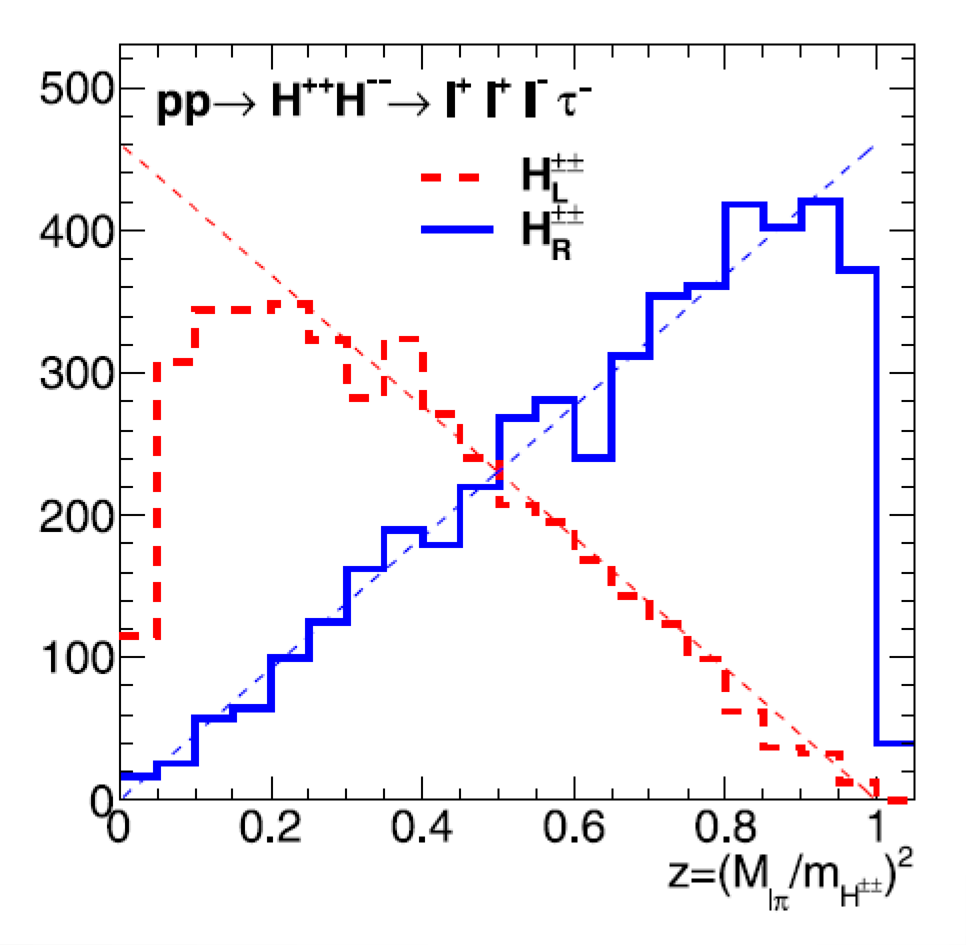




T. Li, arXiv: 1802.00945

- This feature can also be understood by the distribution of the pion energy fraction (fragmentation function)

$$z \equiv E_\pi / E_\tau = {M_{\ell\pi}}^2 / {M_{H^{++}}}^2 \text{ (collinear limit)}$$



Sugiyama, Tsumura, Yokoya, 2012

Remark II:

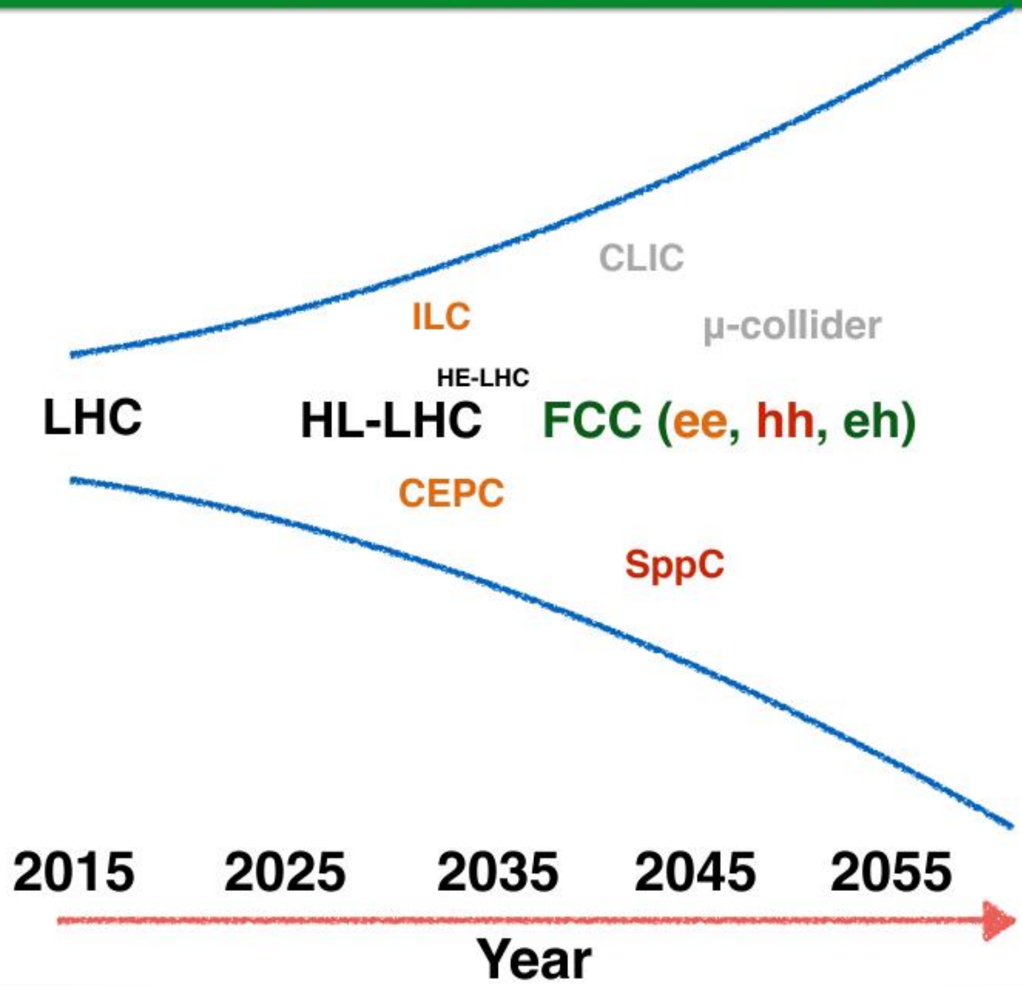
Tau polarization can help to determine the chiral property of its parent particle and thus discriminate different heavy scalar mediated neutrino mass mechanisms, such as Type II Seesaw and Zee-Babu model.

Constructed **TauDecay** to simulate polarized tau decays
(K. Hagiwara, T. Li, K. Mawatari, J. Nakamura, arXiv: 1212.6247)

Remark III:

Due to the low tau identification efficiencies, future colliders with high energy and luminosity enables one to investigate and search for doubly charged Higgs decaying to tau(s).

The Road Ahead

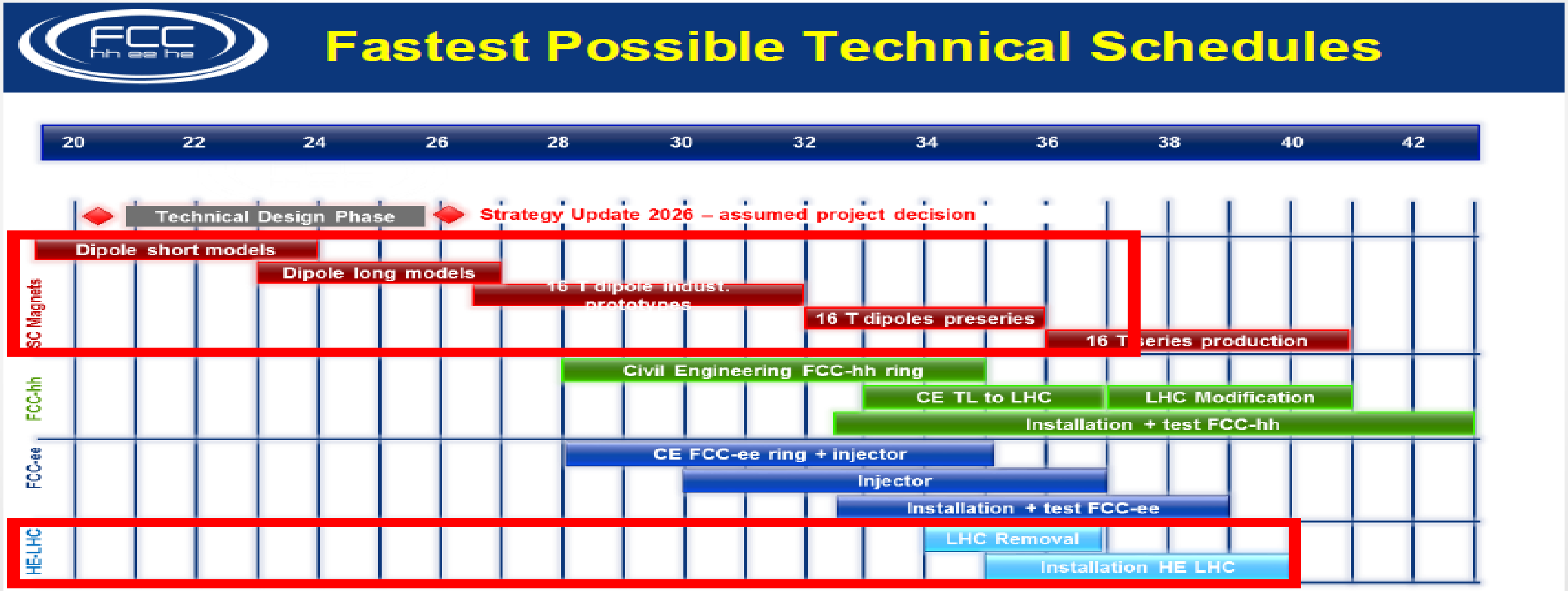


Klute, 2016

High-Energy LHC Machine

- HE-LHC physics goals: M. Benedikt, F. Zimmermann, 2017

1. 2x LHC collision energy with FCC-hh magnet technology
2. c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33 T
3. target luminosity >= 4 x HL-LHC



technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

HE-LHC design & construction

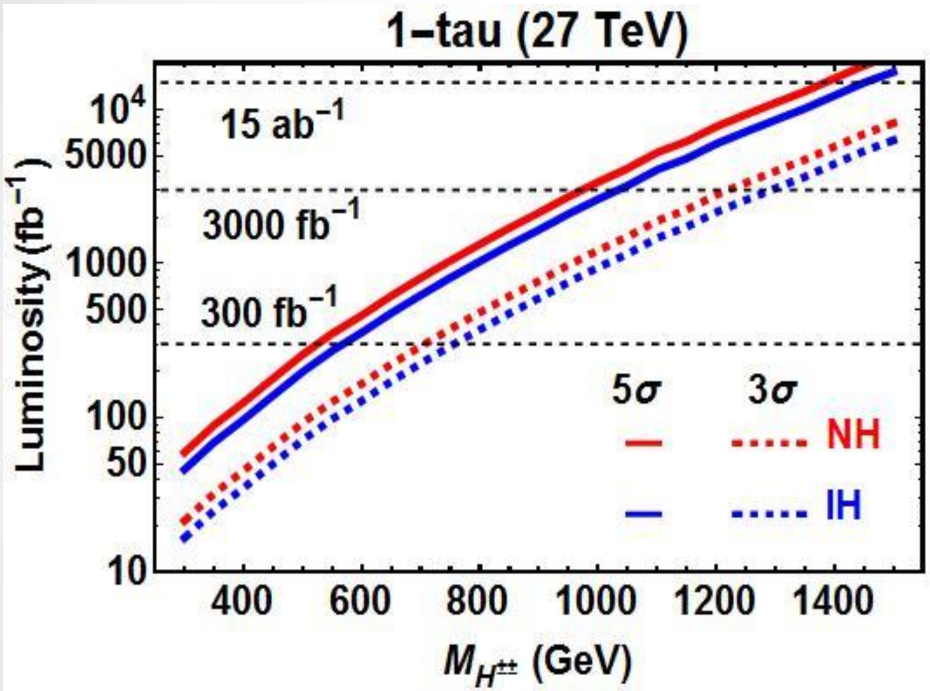
M. Benedikt

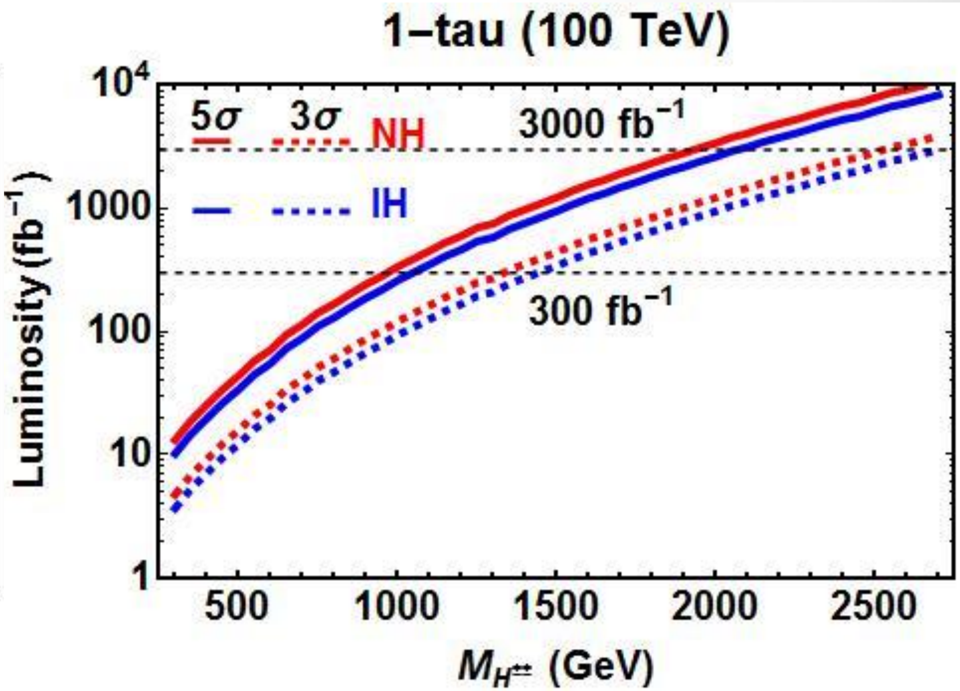
Type II Seesaw at LHC upgrades

- $pp \to H^{++}H^{--} \to \tau^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$ with $\tau^{-} \to \pi^{-}\nu_{\tau}$ $(BR{\sim}11\%)$
- realistic H^{++} decay BR in NH and IH

BR	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
NH	0	2.5%	2.5%	30%	35%	30%
IH	50%	1%	1%	12%	24%	12%

- strengthened pT of ℓ and π;
  $Z \to \ell^{+}\ell^{-}$ veto;
  $\ell^{\pm}\ell^{\pm}$ resonance

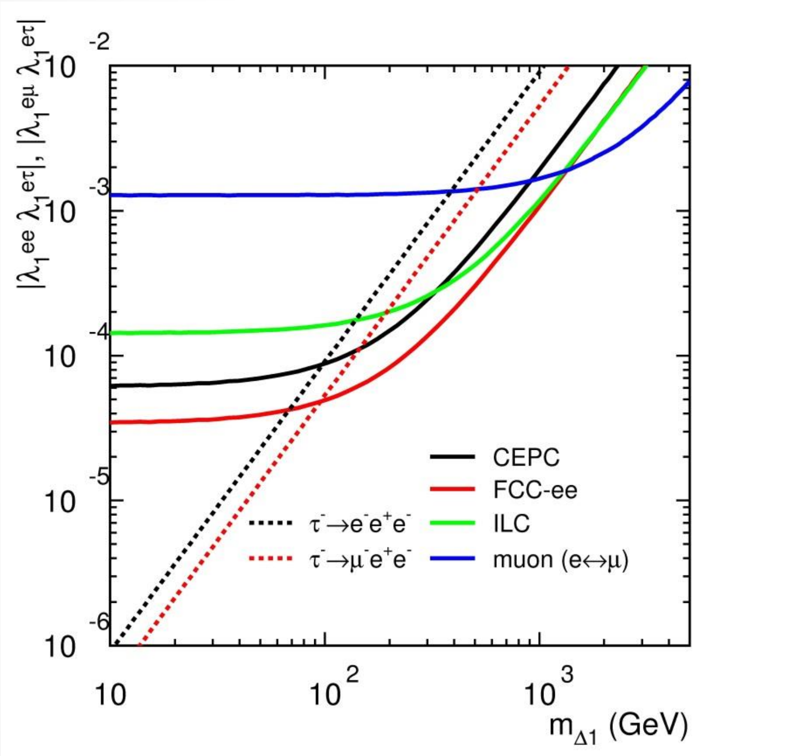


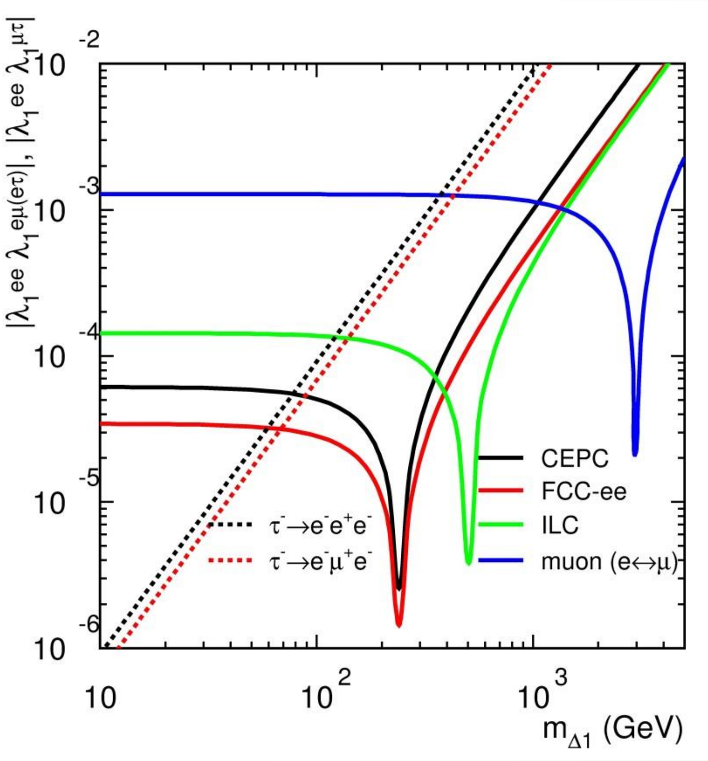


T. Li, arXiv: 1802.00945

LFV at CEPC

- DCH mediates LFV processes at lepton colliders
- left: $e^+e^- \to e^\pm\tau^\mp$ ($\mu^\pm\tau^\mp$) through t channel
- right: $e^-e^- \to e^-\tau^-$ ($\mu^-\tau^-$) through s channel



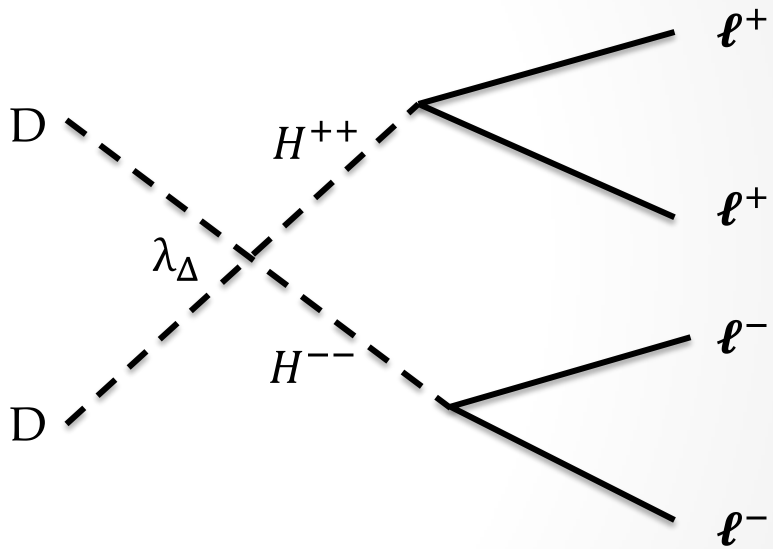


Sui, Zhang, 2017
T. Li, M. Schmidt, to appear

Connection with dark matter

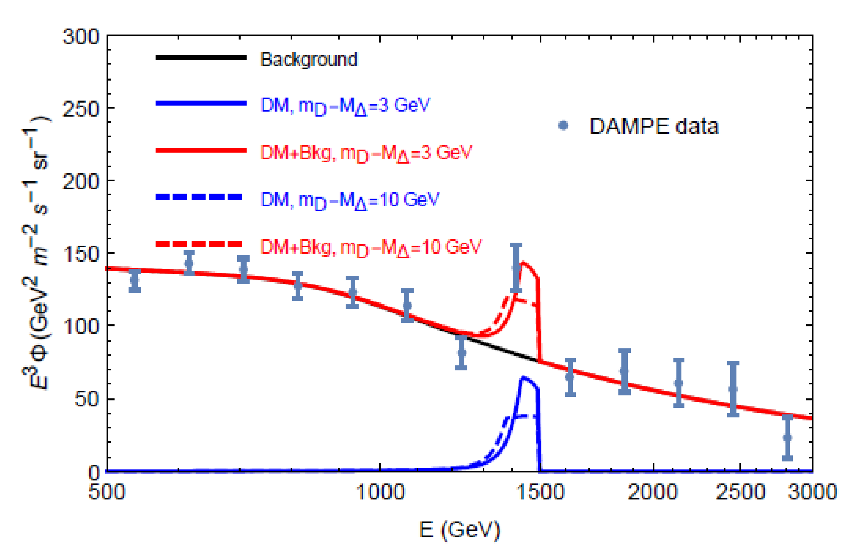
- A simple way to allow for DM (singlet scalar D, Z2 symmetry) in Type II Seesaw

$$V \supset \lambda_\Delta \, D^2 \, tr(\Delta^\dagger \Delta)$$

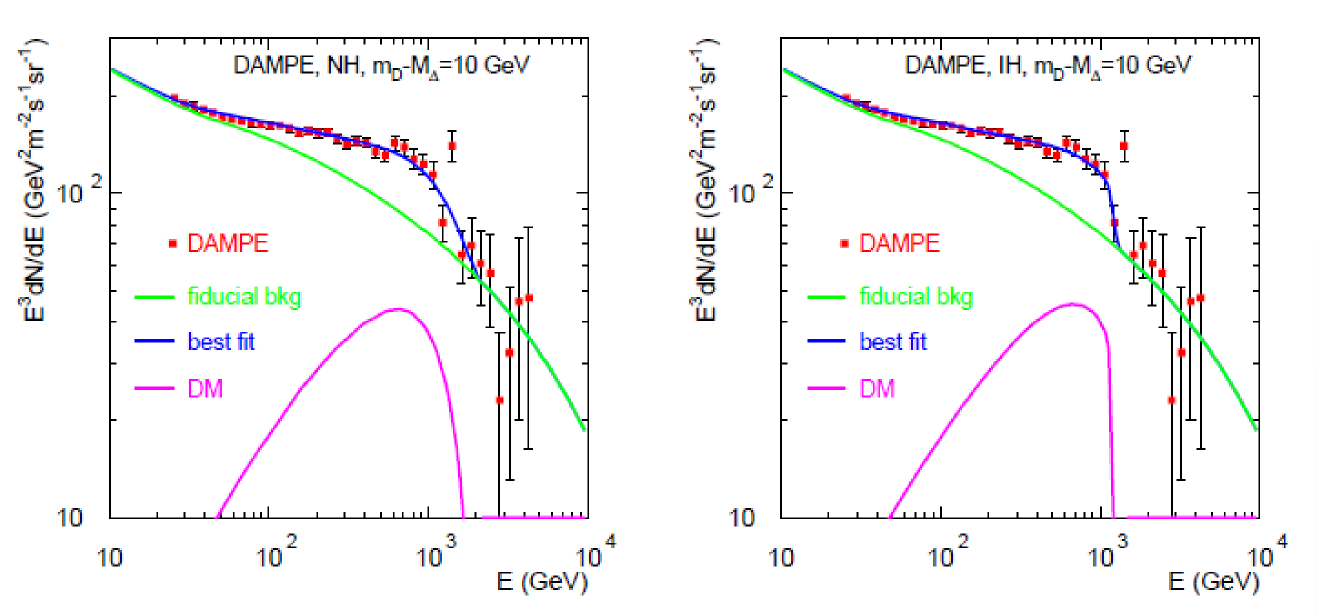


T. Li, N. Okada, Q. Shafi, arXiv: 1712.00869, arXiv: 1804.09835

- Fit $e^{\pm}$ spectrum (AMS-02, DAMPE, Fermi-LAT)



IH more preferred



- T. Li, N. Okada, Q. Shafi, arXiv: 1712.00869, arXiv: 1804.09835

Summary

- The tau lepton plays important role in correlating neutrino oscillation data and Yukawa structure, and determining the chirality nature in heavy scalar mediated neutrino mass models, in light of the neutrino oscillation experiments and its polarization measurement.
- The leptonic processes (LNV & LFV) with tau lepton from doubly charged Higgs can be probed at future colliders.

Thank you!