Heavy neutrino searches at future Z-factories and beyond

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J.-N. Ding, **QQ**, F.-S. Yu, 1903.02570
QQ, Q. Li, C.-D. Lu, F.-S. Yu, S.-H. Zhou, 1711.07243

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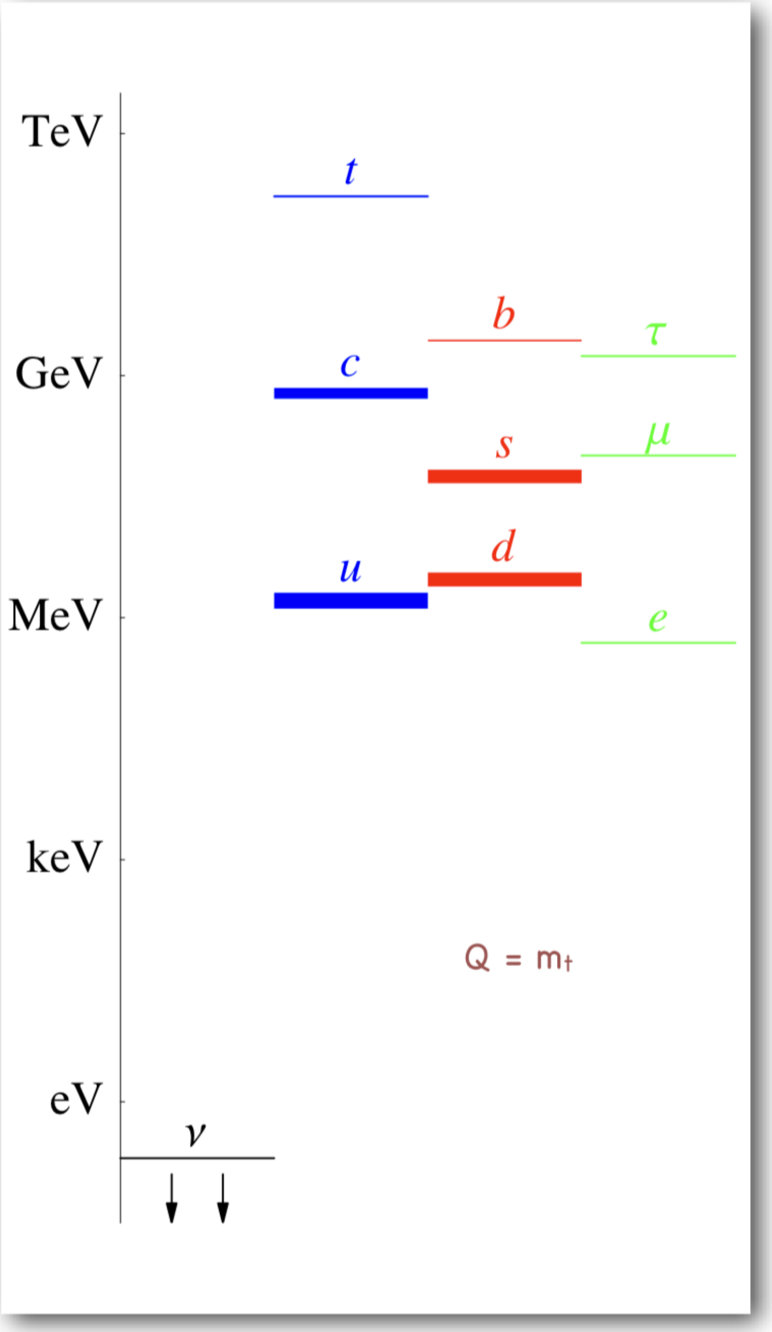
★ The **Standard Model** becomes the **Standard Theory**?

★ Unanswered questions (flavor sector):

- why three generations?
- why such representations?
- why so many parameters?
- **why mass hierarchy (flavor puzzle)?**
- **why tiny neutrino masses?**
- …

$$\sum m_\nu < 0.170\, eV$$ [PDG2019]



★ Type-I Seesaw mechanism: [Minkowski,'77;Mohapatra,Senjanovic,'80,...]

- introduce n right-handed neutrinos getting mass from higher scale
- naturally explain $m_\nu \simeq M_D M_N^{-1} M_D^T$
- with **n heavy neutrinos** with masses $\simeq M_D$

★ Low-scale seesaw models are of special interest

[Asaka,Shaposhnikov,05;Asaka,Blanchet,Shaposhnikov,'05...]

- may contain heavy neutrinos ~ O(10) GeV
- direct searches by LEP [Delphi,'97] and by LHC [CMS,'18]
- indirect constraints from 0v2β decays [Elliott,Engel,'04;Rodejohann,11';...]

Motivation

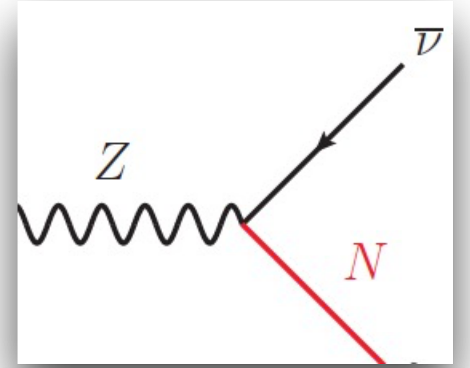
- ★ CEPC (FCC-ee) as a Higgs factory and a **Z-factory**
  - almost one million (?) times the Delphi data

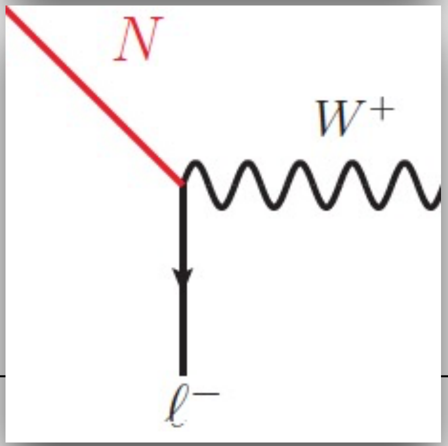
- ★ Also comparison with other direct and indirect searches

★ Introduce n right-handed neutrinos (singlets of the SM gauge group) with Majorana mass terms and neutrino Yukawa couplings

$$\mathcal{L} \ni \frac{1}{2}\sum_j \overline{R}_j i\partial\!\!\!/ R_j - \underbrace{\sum_{i,j} y_{ij}\overline{L}_i\widetilde{H}R_j}_{\text{Yukawa coupling}} - \frac{1}{2}\underbrace{\sum_j \overline{R}^c_j M_R R_j}_{\text{Majorana mass}} + h.c. \; ,$$

★ Diagonalising the mass matrix, we get 3 (light) + n (heavy) mass eigenstates, which get mixed in the weak interaction.



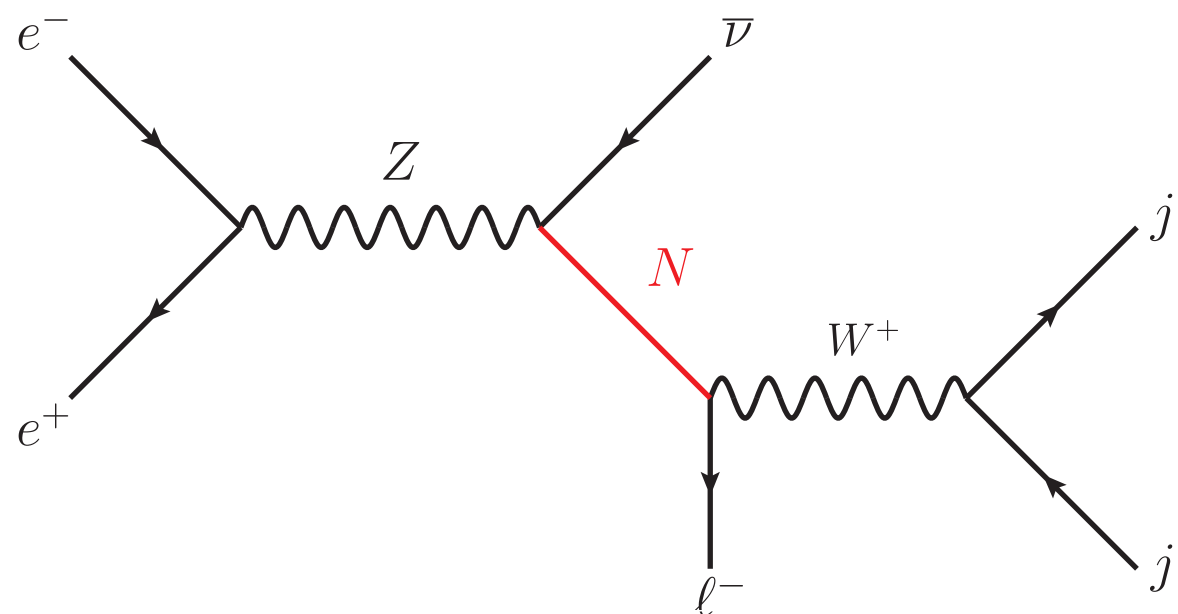


$$\mathcal{L} \ni -\frac{g}{2\cos\theta_W} Z_\mu \sum_\ell \left(\sum_{i=1}^{3} U^*_{\ell i}\overline{\nu}_i + \sum_{j=4}^{3+n} V^*_{\ell j}\overline{N}_j \right) \gamma^\mu P_L \left(\sum_{i'=1}^{3} U_{\ell i'}\nu_{i'} + \sum_{j'=4}^{3+n} V_{\ell j'} N_{j'} \right)$$

$$- \frac{g}{\sqrt{2}} W^+_\mu \sum_\ell \left(\sum_{i=1}^{3} U^*_{\ell i}\overline{\nu}_i \gamma^\mu P_L \ell + \sum_{j=4}^{3+n} V^*_{\ell j}\overline{N}_j \gamma^\mu P_L \ell \right) + h.c.$$

Signal Channel

★ We consider the channel:



- N decays into one charged lepton and two jets (all are visible)
- the new physics vertices are proportional to mixing parameters

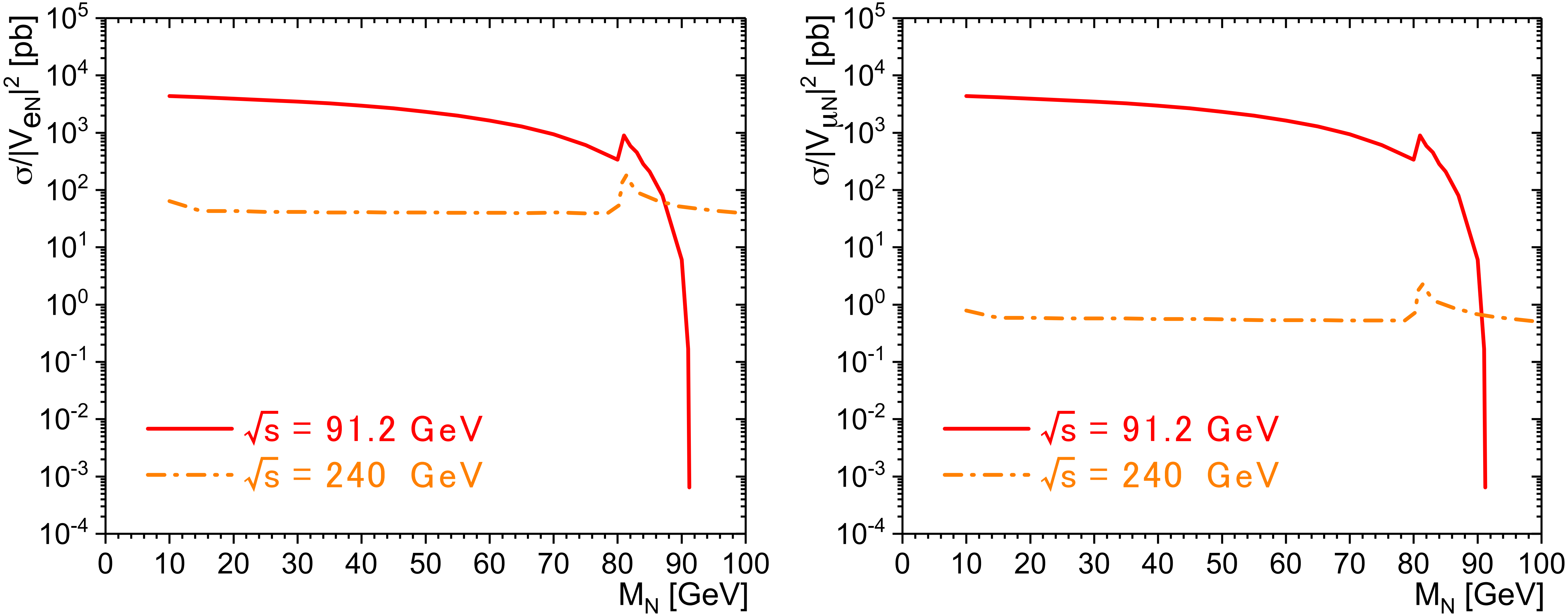
$$\sigma(e^+e^- \to \nu N \to \ell\nu jj) = \sigma(e^+e^- \to N\nu) \times Br(N \to \ell jj)$$

- $\sigma(e^+e^- \to N\nu) \propto \sum_{i=1}^{3} |(U^\dagger V)_{ij}|^2 \approx \sum_{\ell'} |V_{\ell' N}|^2$
- $Br(N \to \ell jj) \propto |V_{\ell N}|^2 / \sum_{\ell'} |V_{\ell' N}|^2$

$$\rightarrow \boxed{\sigma(e^+e^- \to \nu N \to \ell\nu jj) \propto |V_{\ell N}|^2}$$

Signal Channel

★ For M_N < 80 GeV, a Z-factory is much better than a Higgs factory



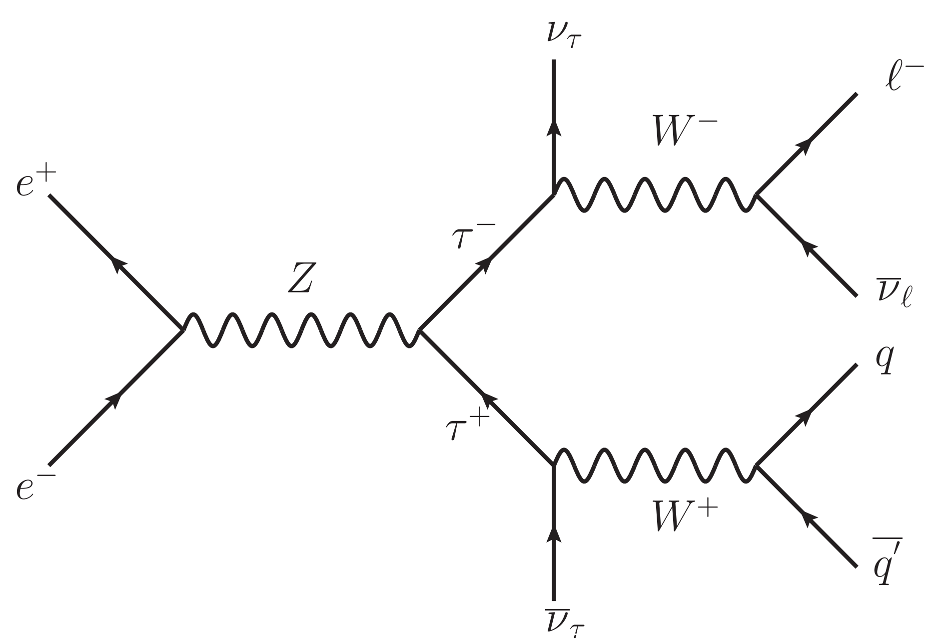
Production cross section of **eN** and **μN** final states

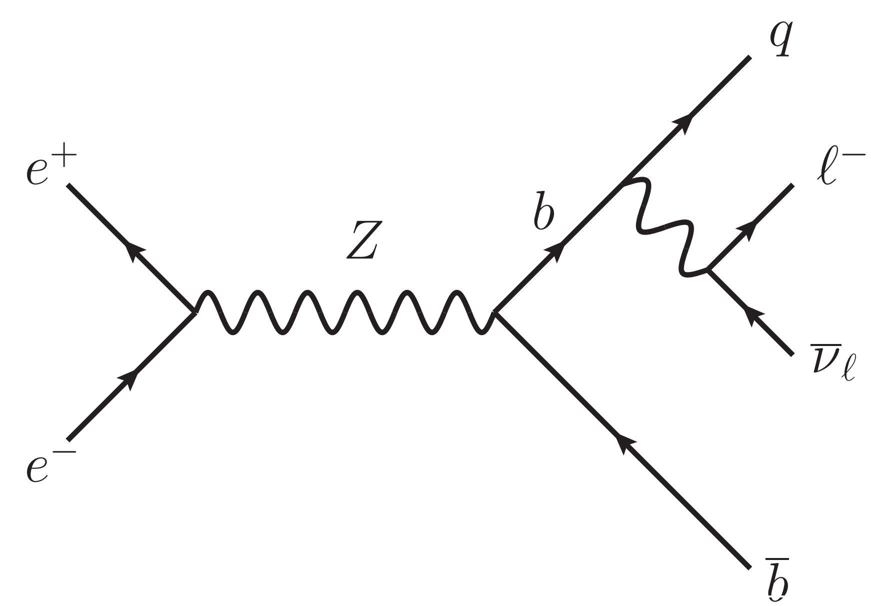
Background Analysis

1/10000 assumed

★ We consider the SM background, which can mimic the $\not{E}\ell jj$ signal

- **4 jets**, with one misidentified as a lepton and one undetected
- 2 jets 2 leptons, with one lepton undetected
- 4 leptons (negligible)
- ττ and bb shown by the diagrams below





★ Simulation is done via FeynRules, MadGraph, Pythia8 and Delphes

Background Analysis

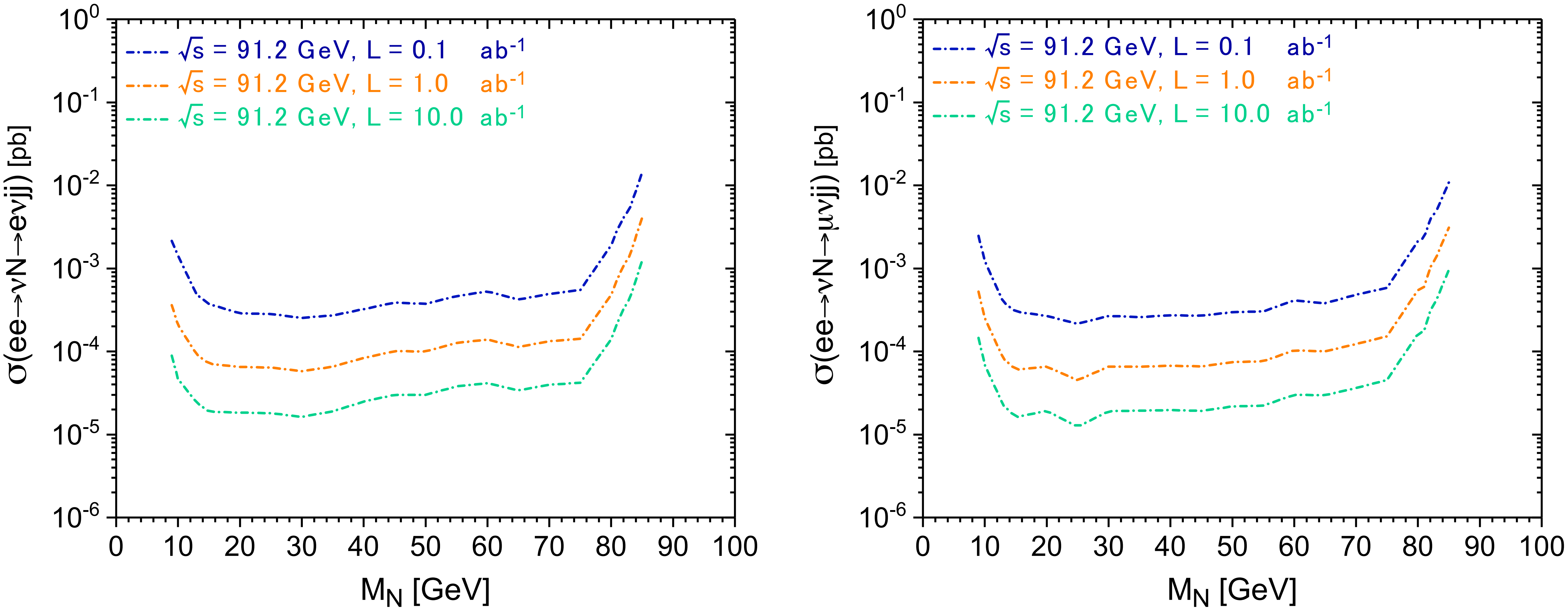
★ To increase the significance, we set different cuts according to different heavy neutrino masses M_N

- small-mass range: $10 < M_N < 65$ GeV
- middle-mass range: $65 < M_N < 80$ GeV
- large-mass range: $80 < M_N < 85$ GeV

– $P_T^j > 10$ GeV, $|\eta_j| < 2$, $\Delta R_{jj} > 0.4$, $M_{jj} > 55$ GeV, btag < 0.8, TauTag $= 0$, BTag $= 0$;
– $P_T^\ell > 3$ GeV, $|\eta_\ell| < 1$;
– $\not{E}_T > 5$ GeV, $|E_{\rm rec} - M_Z| < 10$ GeV, $|\not{E} - \not{E}_0| < \Gamma_{1/2}^{\not{E}}$, $|M_{\ell jj} - M_N| < \Gamma_{1/2}^{M}$;
– $1.5 < \Delta R_{\not{E}j} < 5.5$, $1.5 < \Delta R_{\not{E}\ell} < 5.0$.

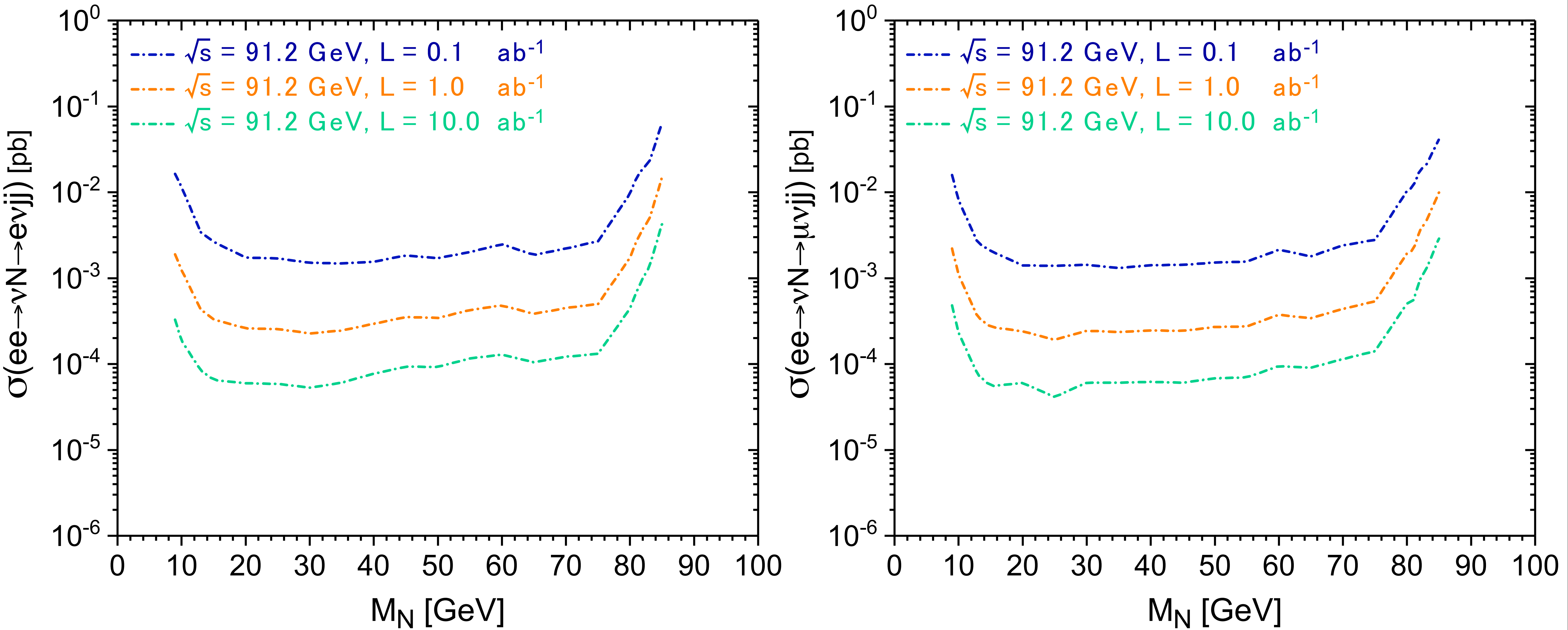
[J.-N. Ding, **QQ**, F.-S. Yu, EPJC79(2019)766]

★ The upper bounds at 95% CL on the signal production cross section at Z-factories (no signal observed)



[J.-N. Ding, **QQ**, F.-S. Yu, EPJC79(2019)766]

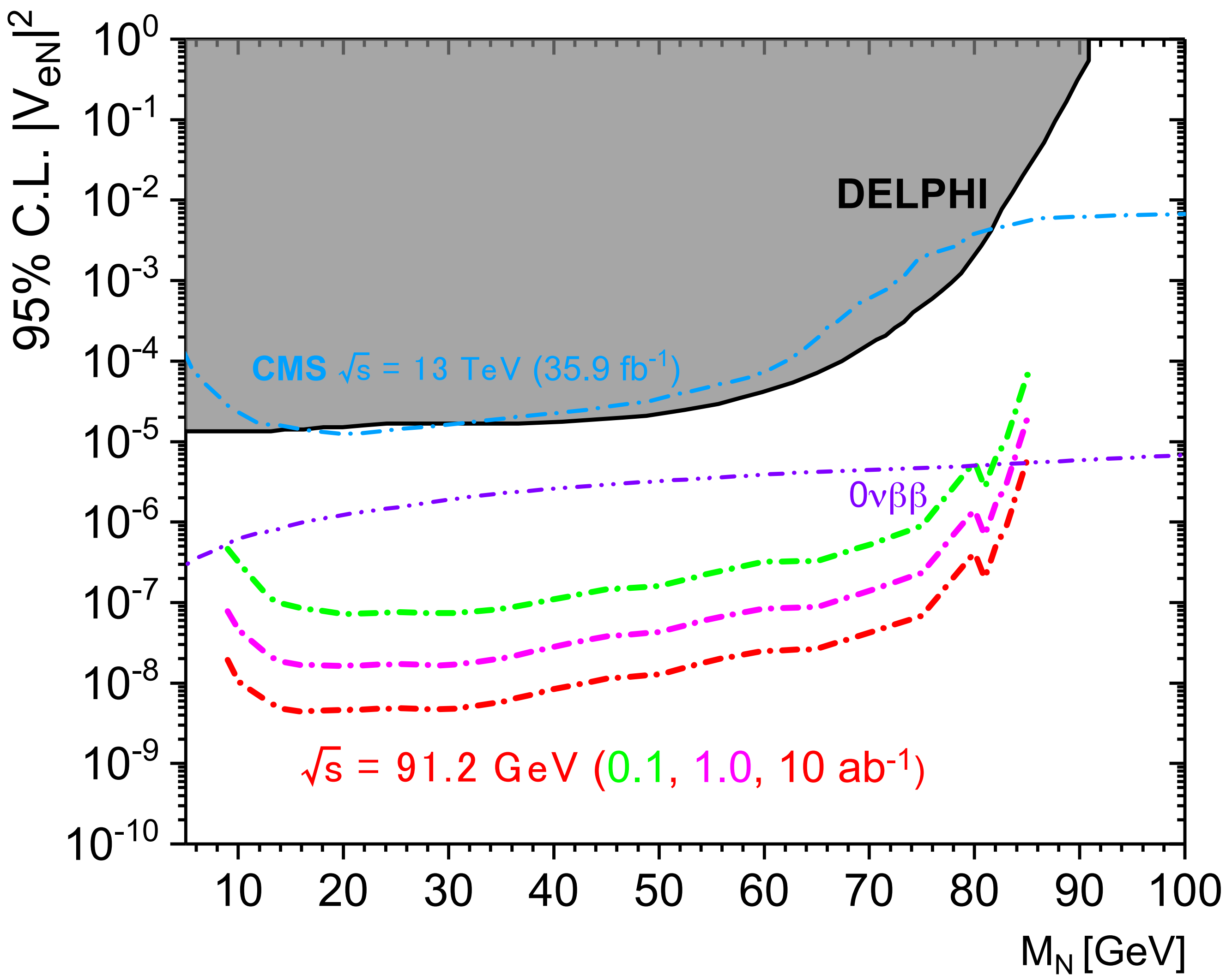
★ The discovery sensitivity (5σ) of the signal events

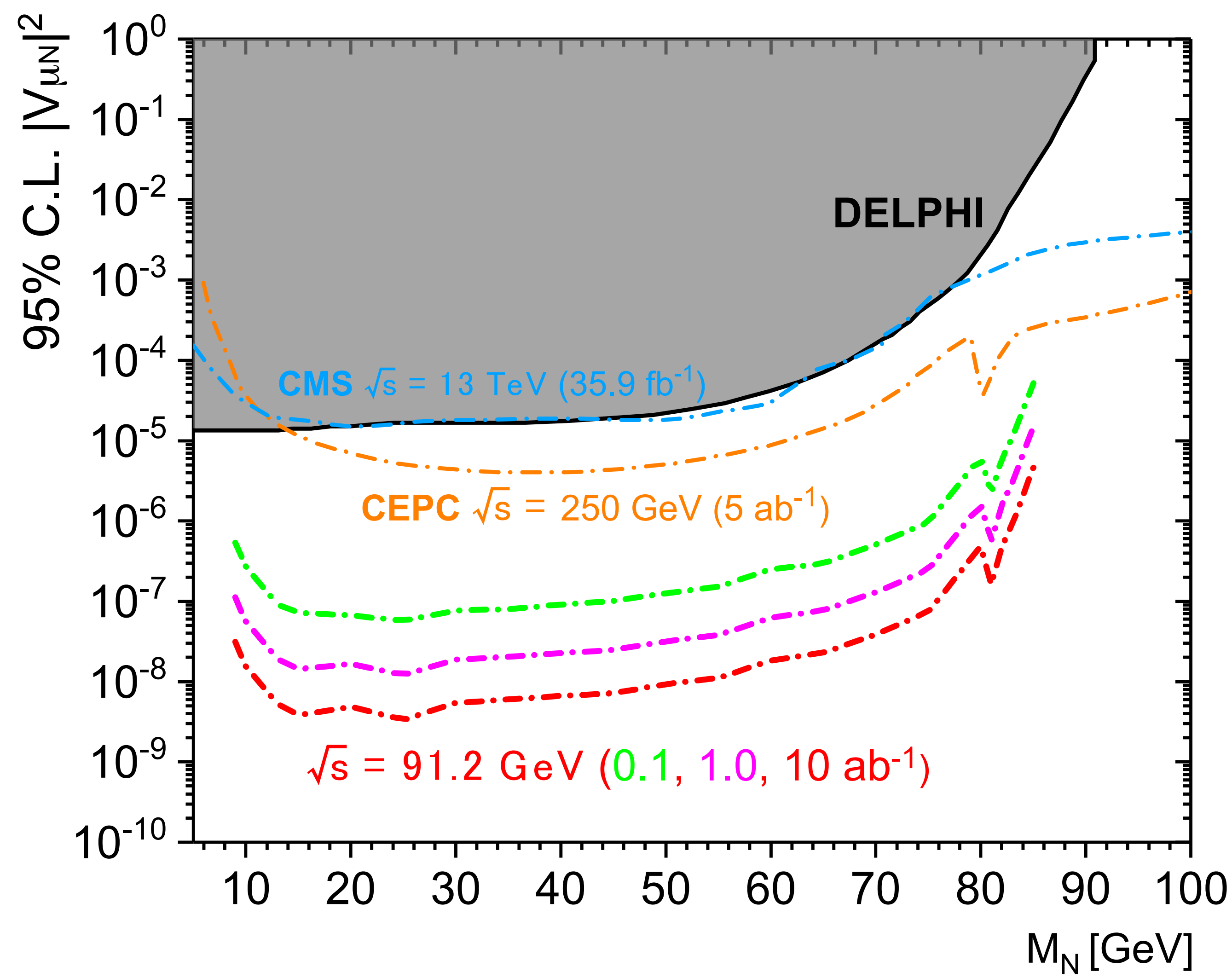


Results

[J.-N. Ding, **QQ**, F.-S. Yu, EPJC79(2019)766]

★ Assuming the lepton mixing is the only new physics (*N* decays are fixed), we obtain also the upper bounds for the mixing parameters

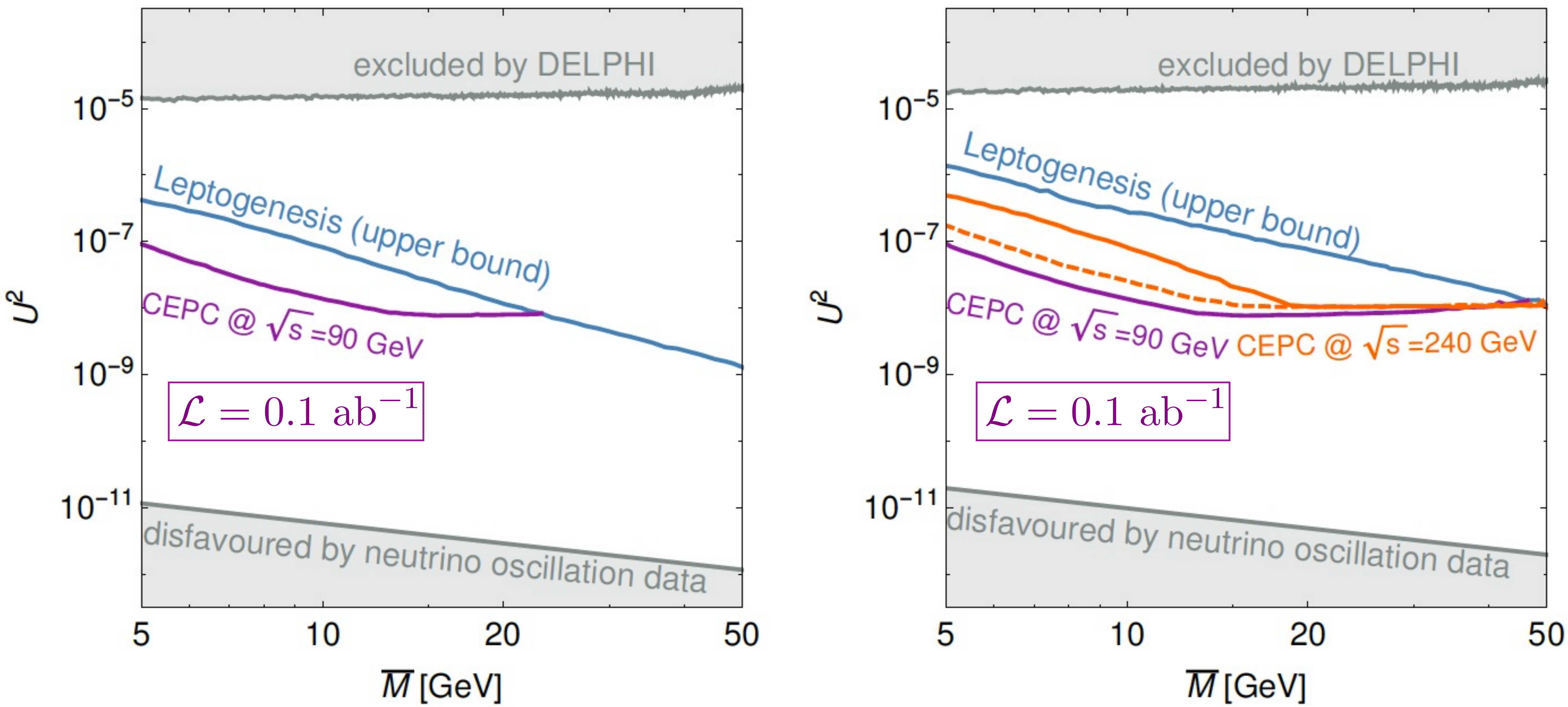




Other relevant studies

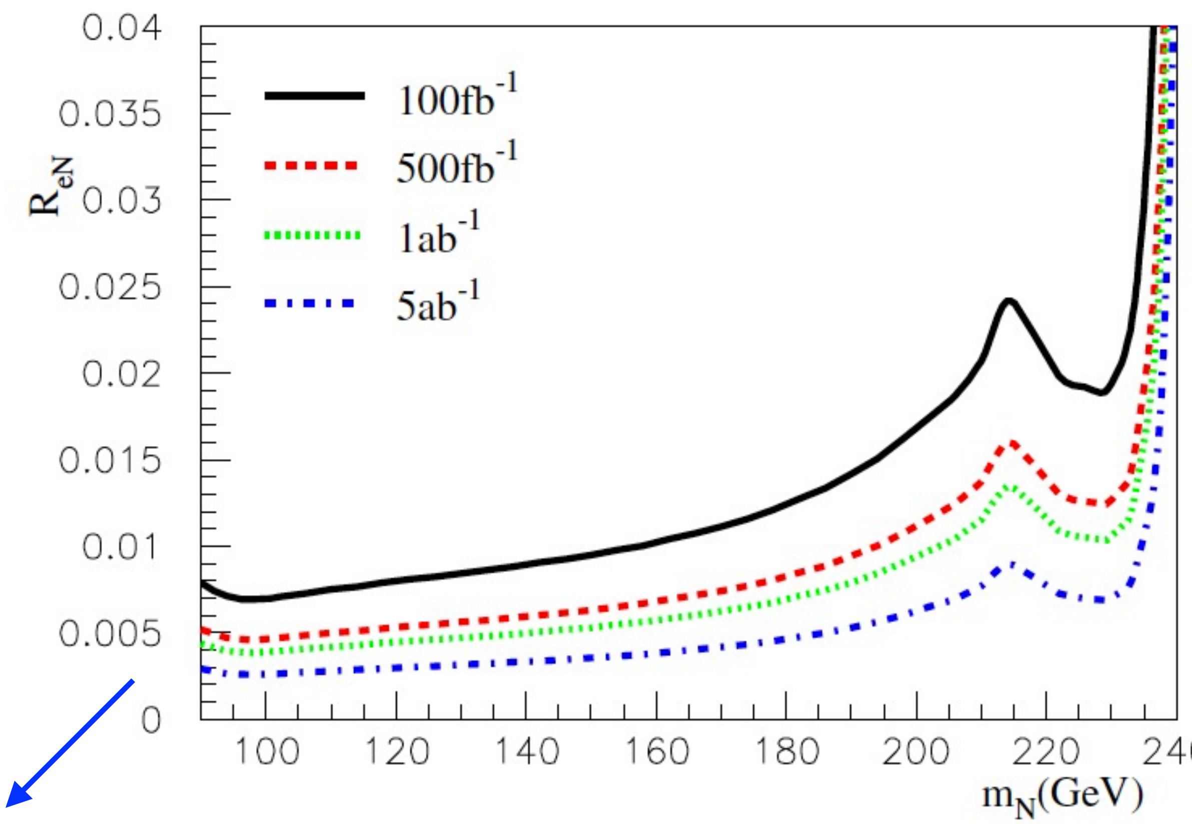
★ More stringent upper bounds can be obtained by making use of information from displaced vertices **(model dependent)**

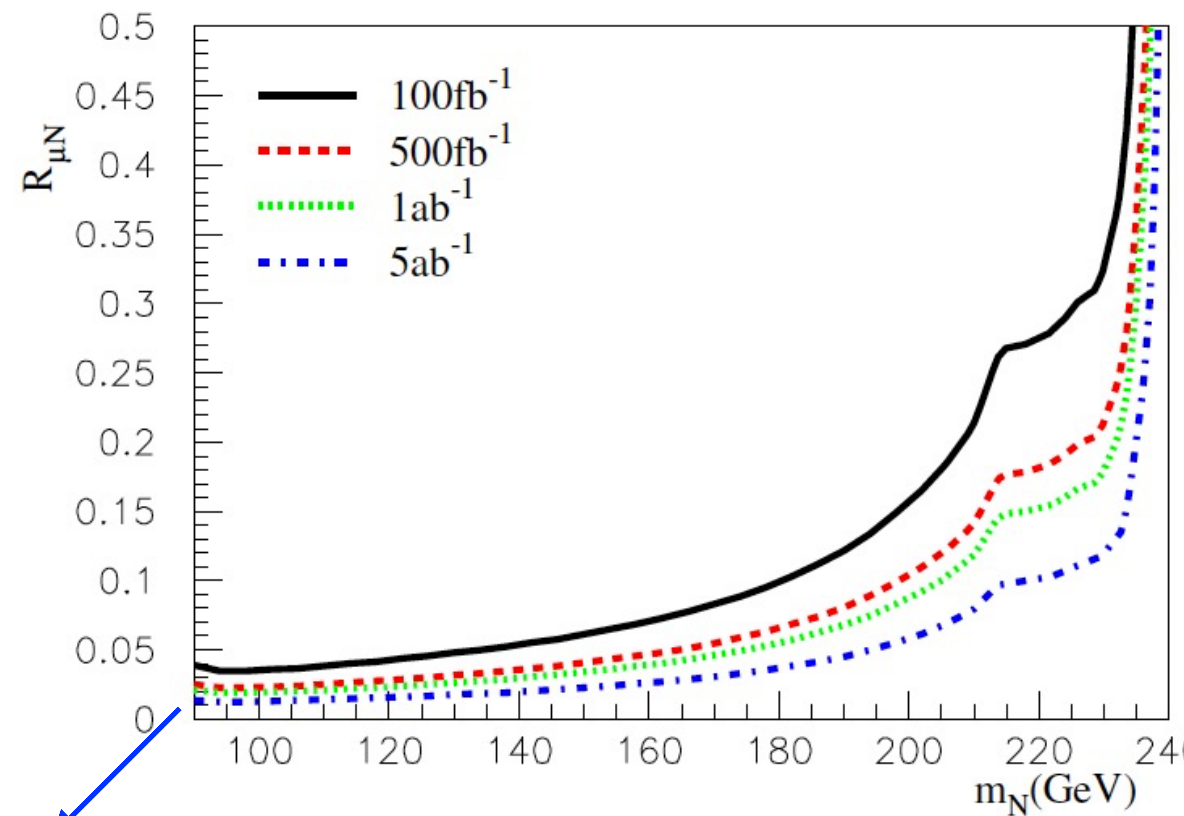
[S. Antusch, E. Cazzato, M. Drewes, O. Fischer, B. Garbrecht, D. Gueter, J. Klari, ‘17]



Other relevant studies

[W. Liao, X.-H. Wu, ‘17]



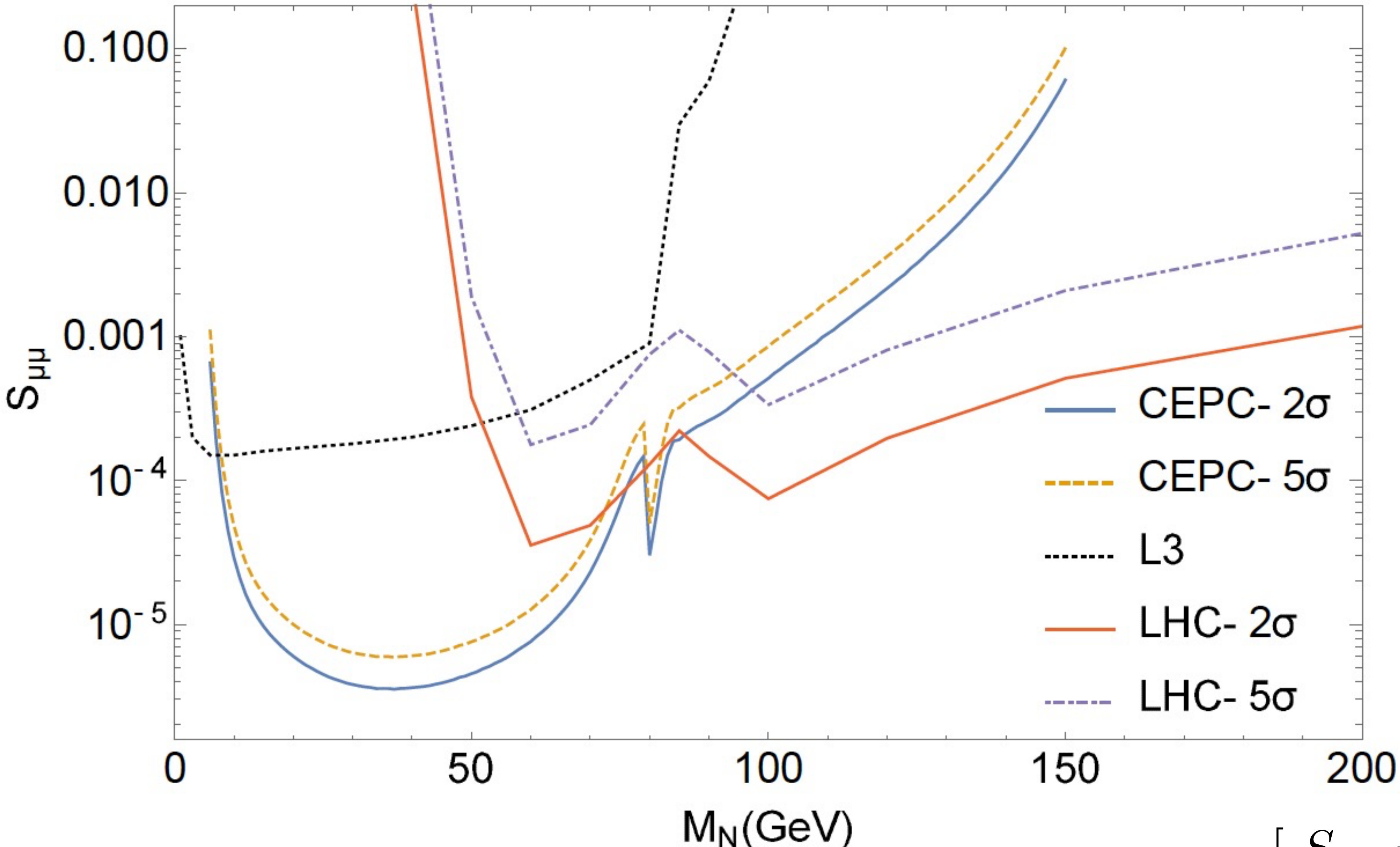


$|V_{eN}|^2 \sim 10^{-5}$ $|V_{\mu N}|^2 \sim 10^{-6}$ $[\ R_{\ell N} = V_{\ell N}\ ]$

for **90 < M*N* < 240 GeV** at a Higgs factory using the signal channel $e^+e^- \to \nu N \to \nu \ell^\pm W^\mp$

Other relevant studies

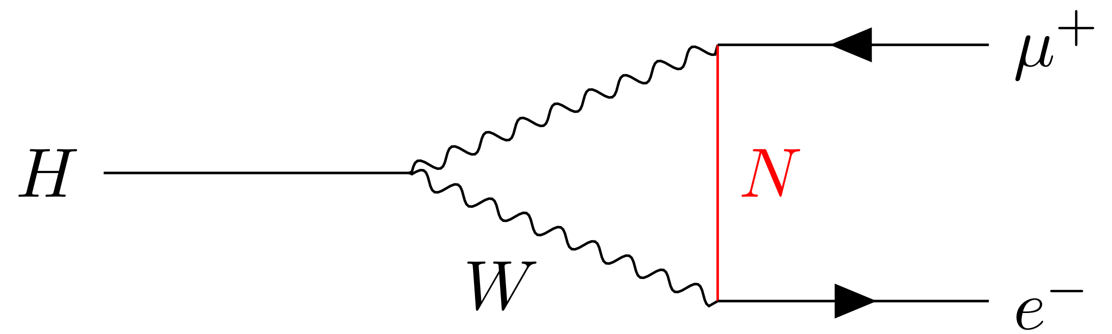
[Y. Zhang, B. Zhang, '18]

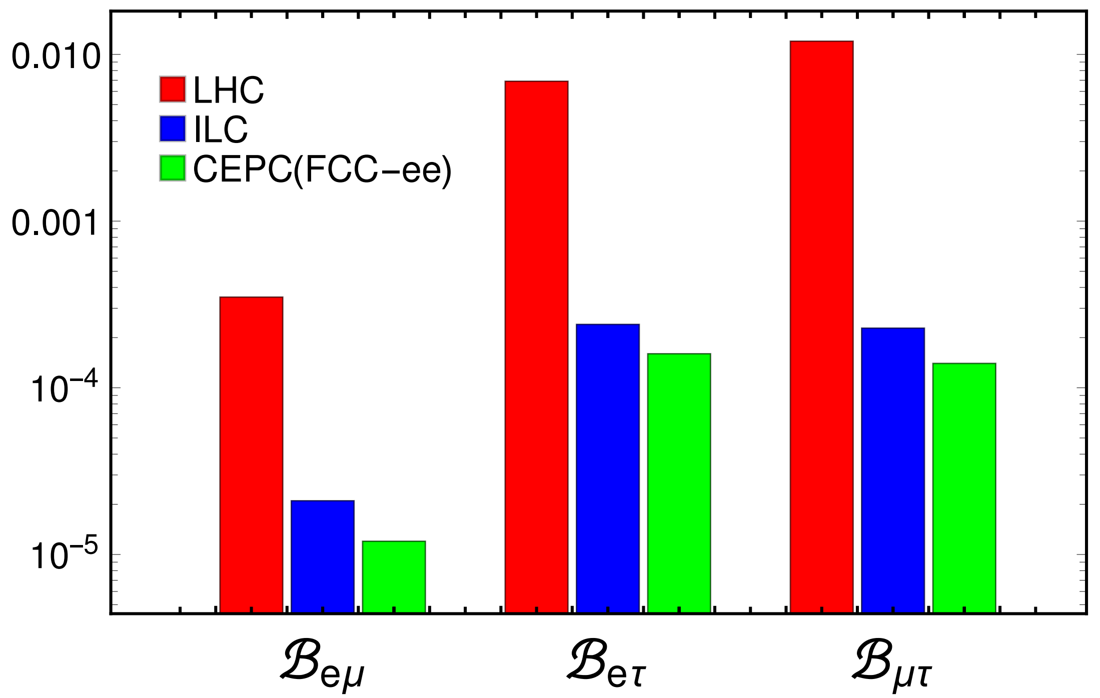


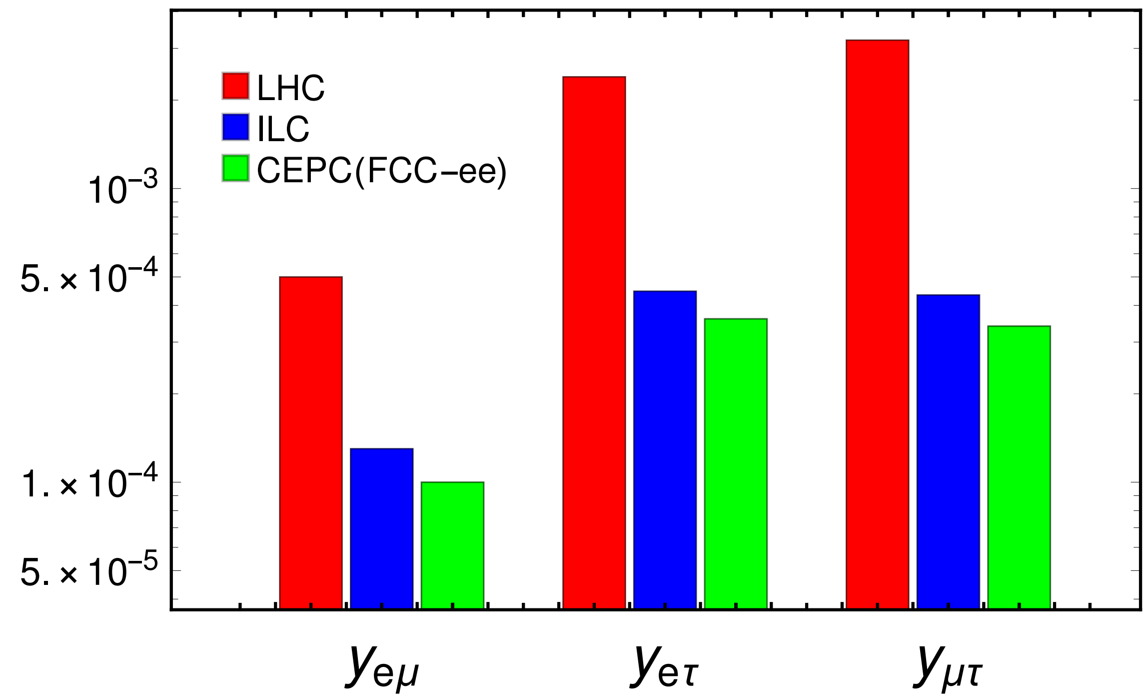
[$S_{\mu\mu} = |V_{\mu N}|^2$]

for **10 < M_N < 200 GeV** at CEPC using the signal channel $e^+e^- \to N\mu^\pm W^\mp \to \mu^\pm\mu^\pm + 4j$

★ For M_N beyond the energy of CEPC (and other lepton colliders), indirect searches can also provide constraints, e.g.,







[**QQ**, Q. Li, C.-D. Lu, F.-S. Yu, S.-H. Zhou,EPJC78(2018)835]

Summary

★ Direct searches for heavy neutrinos with $10 < M_N < 85$ GeV at future Z-factories are studied. The constraints on the mixing parameters are found to be improved by at least 2 orders of magnitude.

★ Other studies on heavy neutrinos in different mass ranges, searches at different machines (or stages) and with different strategies are briefly reviewed.

★ For heavier neutrinos, CEPC might also be able to give constraints via indirect searches.

Thank you!