中国科学院大学
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Hunting for sterile neutrino at colliders

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第九届中国LHC物理年会、上海

Hao Yang, Bingwei Long and QCF, arXiv:2309.16233

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Ⅰ. Sterile neutrinos and motivation

- Neutrinos are massless in the Standard Model (SM), the mass origin has become an important portal to physics beyond the standard model

- There are generally three types of theoretical explanations: see-saw mechanism, radiative generated mass and extra-dimensions

P. Minkowski, Phys. Lett. B 67, 421-428 (1977); R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980); R. Foot, H. Lew, X.-G. He, G.C. Joshi, Z. Phys. C 44, 441 (1989)

K. S. Babu and E. Ma, Mod. Phys. Lett. A 4, 1975 (1989)

N. Arkani-Hamed, S. Dimopoulos, G. R. Dvali and J. March-Russell, Phys. Rev. D 65, 024032 (2001)

Ⅰ. Sterile neutrinos and motivation

- While originally the see-saw mechanism resort the smallness to the presence of extra field with far beyond electroweak energy mass scale

- There are also models where extra fields are not so heavy, leaving the open possibility for eV to TeV scale extra sterile neutrinos, and hence feasible for collider searches

F. F. Deppisch, P. S. Bhupal Dev and A. Pilaftsis, New J. Phys. 17, 075019 (2015)

Ⅰ. Sterile neutrinos and motivation

- The reason for the smallness is yet not fully understood, but the verification of neutrino mass indicate the existence of a right-handed gauge singlet(sterile) neutrino N_R
- The Dirac or Majorana nature of N_R can be identified by neutrinoless double-beta decay 0νββ of nucleus or other $W^{*,\pm}W^{*,\pm} \to \ell^{\pm}\ell^{\pm}$ induced processes, which led to Standard Model forbidden lepton number violation ($\Delta L = 2$) processes

Ⅰ. Sterile neutrinos and motivation

- Various laboratory searches have put stringent constraints on sterile neutrino mixing with active ones in a broad mass range from eV to TeV

- For the sterile neutrino mass below MeV, it is proposed to search kinks in the Kurie plots in the nuclear beta decays of ^{187}Re, ^{3}H, ^{63}Ni, ^{35}S, ^{20}F, etc.

Ⅰ. Sterile neutrinos and motivation

- Analogously, search peaks in the energy spectra of two-body leptonic decays of charged pseudoscalar meson, e.g., π, K, for heavier sterile neutrino mass from MeV to GeV

- Sterile neutrino can be also tested via its effects on the lepton universality ratio $BR(M^+ \to \ell_1^+ \nu_{\ell_1})/BR(M^+ \to \ell_2^+ \nu_{\ell_2})$, where $M = \pi, K, D, D_s$

Ⅰ. Sterile neutrinos and motivation

- Testing the Majorana neutrino induced lepton number violation (LNV) through three/four body decay of heavy meson were performed, e.g., $D^+ \to \pi^-(K^-)e^+e^+$ at the CLEO, $B^+ \to D^-\ell^+\ell'^+$ at the Belle, $B^- \to \pi^+\mu^-\mu^-$ at the LHCb, $D \to K\pi e^+e^+$ at the BESIII

Ⅰ. Sterile neutrinos and motivation

- For heavy sterile neutrino mass above GeV, people used the possible production of sterile neutrino in the Z^0 boson decay $Z^0 \to \nu(\bar{\nu})N$, limits on the active-sterile mixing are obtained by L3 and DELPHI

- Similarly, the W boson decay $W \to \ell N$ was explored at the ATLAS

Ⅰ. Sterile neutrinos and motivation

- For mass above electroweak energy mass scale, direct searches were performed employing same-sign dileptons plus jets, or $N \to \ell jj$, $N \to \ell W$ at the LHC

- Yet, there have been hundreds of papers in the literature about the Sterile neutrino hunting

Ⅰ. Sterile neutrinos and motivation

- We recently make several complementary investigations to the previous work by studying the feasibility of collider test for sterile neutrino through: (1) direct production via e^+e^-, ep collision; (2) indirect production via heavy particles decays, the Higgs and heavy meson/baryon decays.

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II. Searching for sterile neutrino signatures at colliders

- Direct production

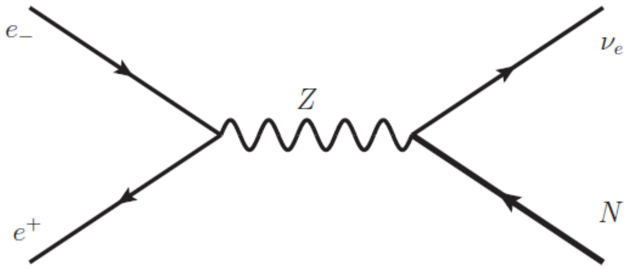
In the presence of one or several sterile neutrinos, active neutrinos in the flavor base are a mixture of the light and heavy sterile neutrinos in mass eigenstates

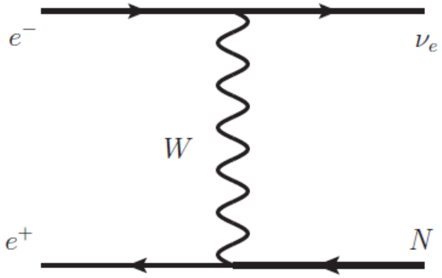
We have the interaction Lagrangian

$$
\begin{aligned}
-\mathcal{L} = & \frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \bar{\nu}_m \gamma_\mu P_L \ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \bar{N}_{m'}^c \gamma_\mu P_L \ell \right) + h.c. \\
& + \frac{g}{2\cos\theta_W} Z_\mu \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \bar{\nu}_m \gamma_\mu P_L \nu_\ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \bar{N}_{m'}^c \gamma_\mu P_L \nu_\ell \right) + h.c., \\
& + \frac{g m_N}{2 m_W} H \sum_{\ell=e}^{\tau} V_{\ell N}^* \bar{N}^c P_L \nu_\ell + h.c.,
\end{aligned}
$$

II. Searching for sterile neutrino signatures at colliders

- For sterile neutrino production in e^+e^- collision, there are two dominant production channels, one is an annihilation channel through Z boson (s-channel), another is given by the exchange of a W boson (t-channel)





II. Searching for sterile neutrino signatures at colliders

- In fact this mechanism has already been greatly investigate

  S. Antusch, E. Cazzato and O. Fischer, Int. J. Mod. Phys. A 32, 1750078 (2017)

- Our concern is what the future linear colliders, STFC, SuperKEKB, CEPC, and ILC, may tell us about the sterile neutrino

- Here, the sterile neutrinos are thought to be reconstructed by $\mu\pi$-channel for light mass region and by ℓjj-channel for heavy mass region

II. Searching for sterile neutrino signatures at colliders

- Given the luminosities of various future colliders:

TABLE I: The center-mass energy and integrated luminosity of current and future e^+e^- colliders. The integrated luminosity is estimated by 10^{34} cm^{-2}s^{-1} $\sim$ 1 ab^{-1}/10 years.

Collider	STCF	SuperKEKB	CEPC	ILC
$\sqrt{s}$(GeV)	7	10.6	250	500
$\int d\mathcal{L}$(ab^{-1})	5	80	3	1.8

- For the same strength of mixing parameter $U_{\ell N}$, the t-channel is enhanced approximately by 1~2 magnitudes compared with the s-channel and hence get a better sensitivity for $|U_{\ell N}|^2$.

II. Searching for sterile neutrino signatures at colliders

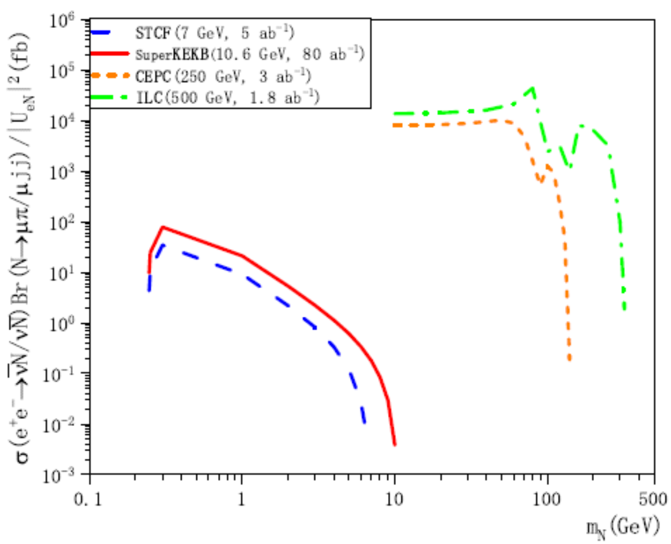
- However, the s-channel can be largely enhanced at the Z-pole for CEPC and ILC, somehow like in Z decay
- The decay width for Dirac sterile neutrino is estimated to be

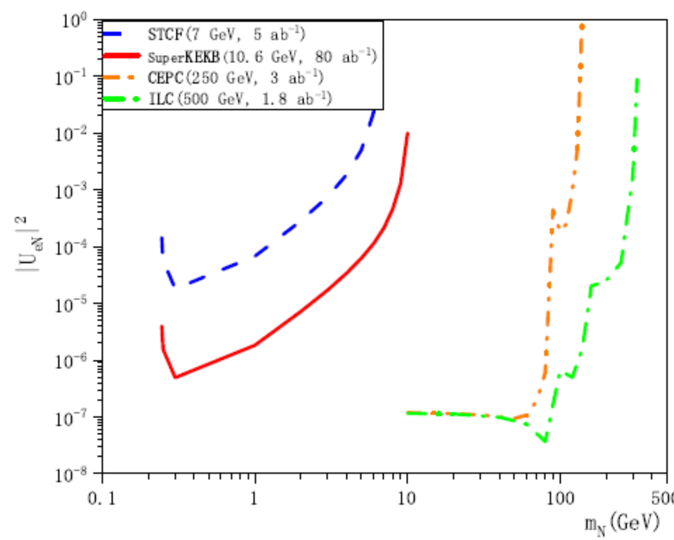
$$\Gamma_N^{Dirac} = \begin{cases} 5 \sum_{\ell=e,\mu\tau} |U_{\ell N}|^2 \frac{G_F^2 m_N^5}{96\pi^3} & m_N < m_W \\ \sum_{\ell=e,\mu\tau} |U_{\ell N}|^2 \frac{3 G_F m_N^3}{16\pi\sqrt{2}} & m_N > m_W , \end{cases}$$

G. Zhang and B. Q. Ma, Phys. Rev. D 103, 033004 (2021); A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP 05, 030 (2009)

II. Searching for sterile neutrino signatures at colliders

- where the mixing parameters $U_{\ell N}$ for three leptons are taken to be universal. And for Majorana sterile neutrino, $\Gamma_N^{Majorana} \approx 2\Gamma_N^{Dirac}$ is adopted





To suppress the dominant background $e^+e^- \rightarrow W^*W^* \rightarrow \mu\, \bar{\nu}_\mu\, j\, j$, open angle cuts are employed

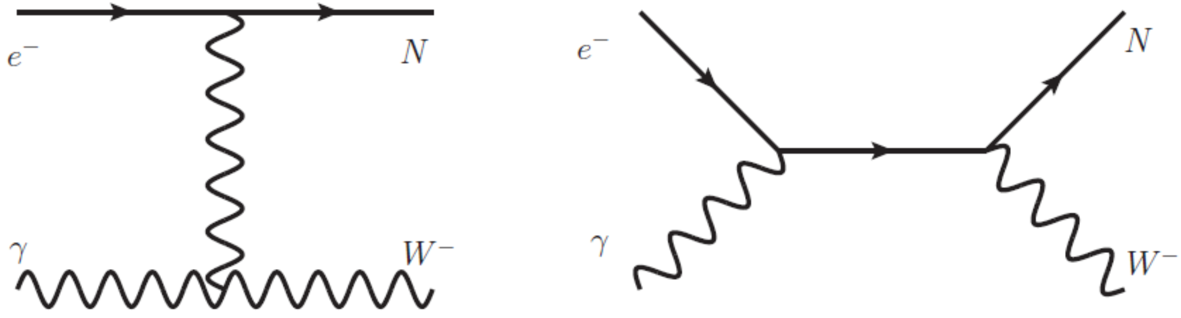
II. Searching for sterile neutrino signatures at colliders

- Results indicate that the signatures for GeV sterile neutrino can be well explored and hence sets up a constraint for active-sterile mixing $|U_{\ell N}|^2$.

- At STCF, the center-of-mass energy can reach 7 GeV, the lower-limit of $|U_{eN}|^2$ can reach $10^{-3} - 10^{-4}$ at 0.3-2 GeV with 5 ab^{-1} integrated luminosity.

II. Searching for sterile neutrino signatures at colliders

- For sterile neutrino production in e-p collision, we explore the production mechanism of sterile neutrino in the context of γ-W* interaction, where the photon is produced via proton bremsstrahlung



II. Searching for sterile neutrino signatures at colliders

- We consider the production of sterile neutrino through $e^{-}\gamma \rightarrow NW^{-}$ channel at the future electron-proton collider, i.e., the LHeC. For the events reconstruction, $N \rightarrow \mu jj$ channel is adopted

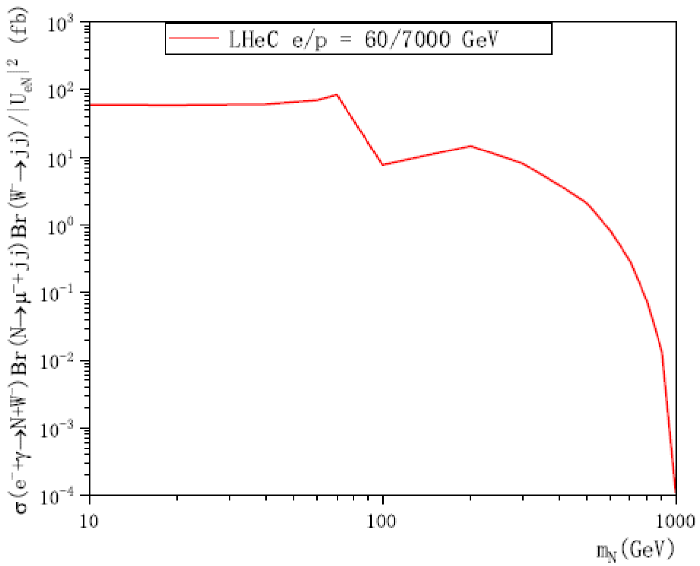
- The LHeC is presumably designed to reach a luminosity of 1.05×10^{34}, led to approximately the 1 ab^{-1} integrated luminosity for 10 years operation.

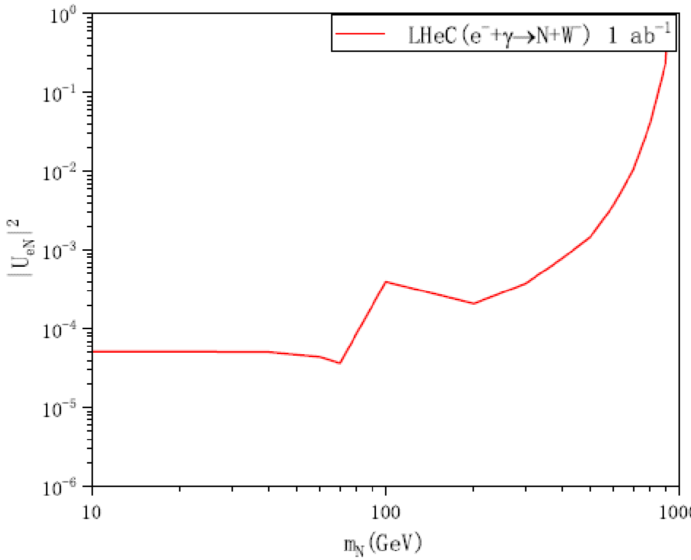
II. Searching for sterile neutrino signatures at colliders

- The signal for $e^{-}\gamma \rightarrow NW^{-}$ channel is μ^{-}+di-jet + W-jet without missing energy.

- The main background signals come from $e^{-} + \gamma \rightarrow \nu_e + Z + W^{-}$ where Z decays into $\ell\ \bar{\nu}_{\ell}$ + jj, and $e^{-} + \gamma \rightarrow \nu_e + W^{-} + W^{-} + W^{+}$ with W decays into leptons or jets, the two cross sections are below experiments tag limit $1/\int \mathcal{L} \approx 1$ ab.

II. Searching for sterile neutrino signatures at colliders





- The cross section for $e^- \gamma \to N\, W^-$ process will reach hundreds of fb for the electroweak energy mass scale sterile neutrino

II. Searching for sterile neutrino signatures at colliders

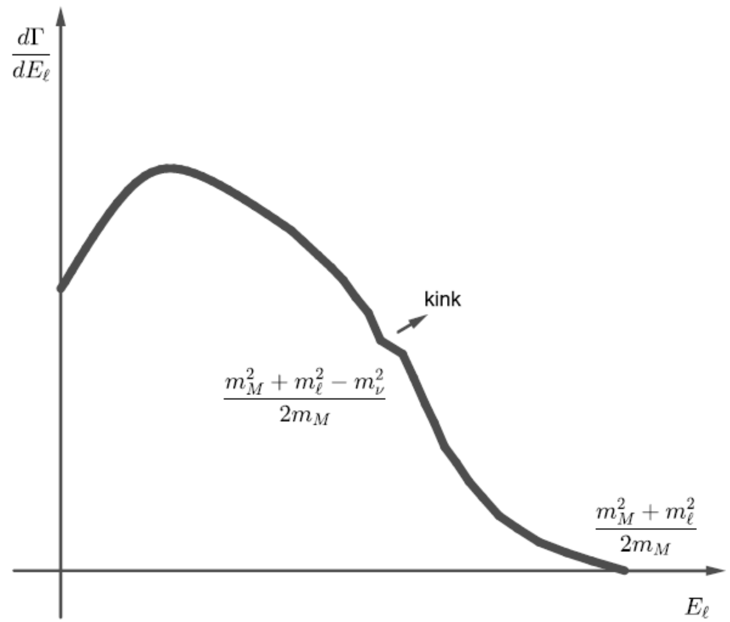
- However, the cross section decreases to tens of fb when for $m_N \sim 500$ GeV, and hence provides tests for heavy sterile neutrino in this region which is poorly constrained

- The sensitivity of active-sterile neutrino mixing $|U_{eN}|^2$ with $100 < m_N < 500$ GeV is estimated to be $10^{-3} \sim 10^{-4}$ level, therefore may provide helpful information to search the heavy sterile neutrino in this region.

II. Searching for sterile neutrino signatures at colliders

- Indirect production
  - The sterile neutrino can be also investigated by searching kinks in lepton energy spectrum of the B meson semileptonic decay, due to the kinematic effect

R. E. Shrock, Phys. Lett. B 96, 159-164 (1980)



II. Searching for sterile neutrino signatures at colliders

- The kink method may provide another insight in sterile neutrino searching in B decay at the SuperKEKB, with design luminosity of 8×10^{35} $cm^{-2}s^{-1}$, the low sensitivity limit for $|U_{\ell N}|^2$ can be extended to 10^{-7}-level at 1–4 GeV mass region.

- The same technique is also applicable to BES-III and STCF in $\psi(3770) \to D\,\bar{D}$ decays.

II. Searching for sterile neutrino signatures at colliders

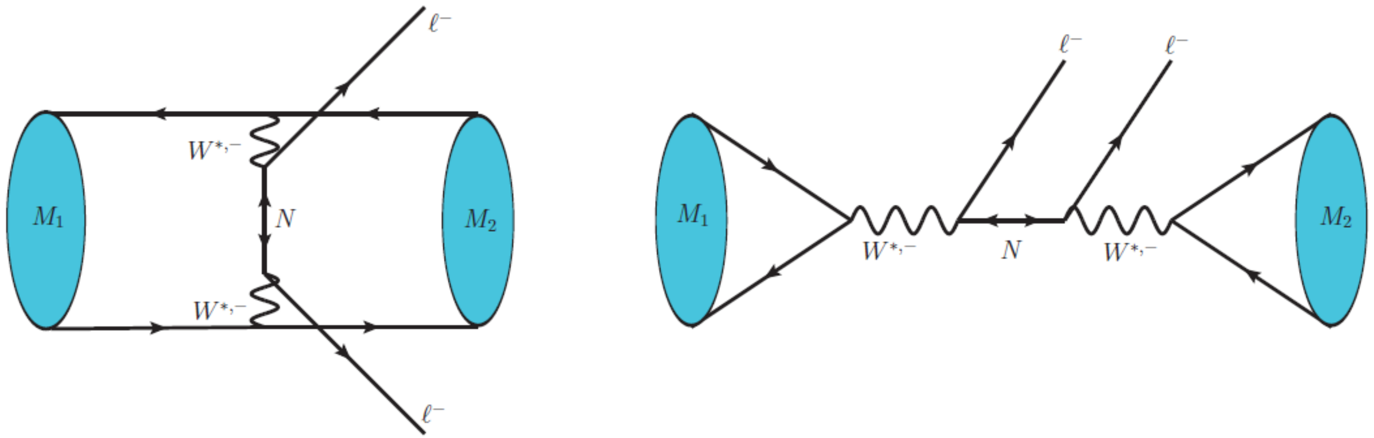
- In meson decays
  - The $0\nu\beta\beta$ decay branching ratios of charged meson (π,K,$D_{(s)}$,$B_{(s,c)}$) induced by W^*W^* is normally too small

$$Br(K^+ \to \pi^- + \mu^+\mu^+) \sim 1.6 \times 10^{-12}(\frac{1\ GeV}{m_N})^2|U_{\mu N}|^4$$

  - However, if the neutrino mass lie between $m_\pi + m_\mu \leq m_N \leq m_K - m_\mu$, the branching ratio can be greatly enhanced by the resonant effect

C. Dib, V. Gribanov, S. Kovalenko and I. Schmidt, Phys. Lett. B 493, 82-87 (2000)

II. Searching for sterile neutrino signatures at colliders

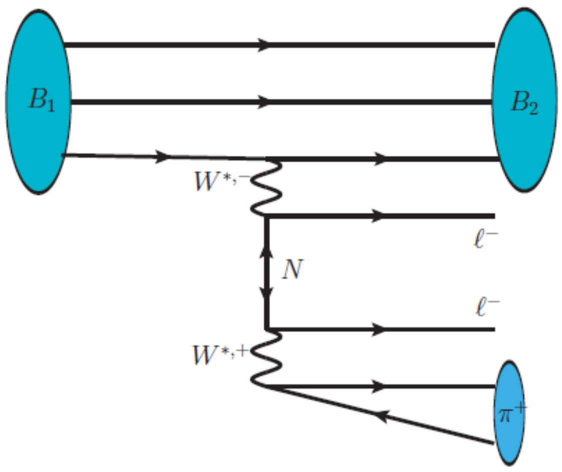


- The numbers of D/B meson produced at LHC is estimated to be about $10^{13}/10^{12}$, there are extensive investigation upon this topic, thus provide experimental limits on sterile neutrino mixing elements ($|U_{\ell N}|$) in mass region of $m_N = 1 \sim 4$ GeV.

II. Searching for sterile neutrino signatures at colliders

- In baryon decays
  - The resonant mechanism can be extended to baryon decays

$$Br(B_1 \to B_2 + \ell\ell + \pi) = \frac{\Gamma(B_1 \to B_2 + \ell N)}{\Gamma(B_1)} \frac{\Gamma(N \to \ell\pi)}{\Gamma(N)}$$



II. Searching for sterile neutrino signatures at colliders

- In previous research, $\Lambda_{b/c}$ baryons has been considered, here we explore the four-body $|\Delta L| = 2$ decays of the $\Xi_{cc}^{++}, \Xi_c^+, \Xi_c^0$ baryons

$$\Xi_{cc}^{++} \to \Xi_c^+ + \mu^+\mu^+\pi^-,$$

$$\Xi_{cc}^{++} \to \Lambda_c^+ + \mu^+\mu^+\pi^-,$$

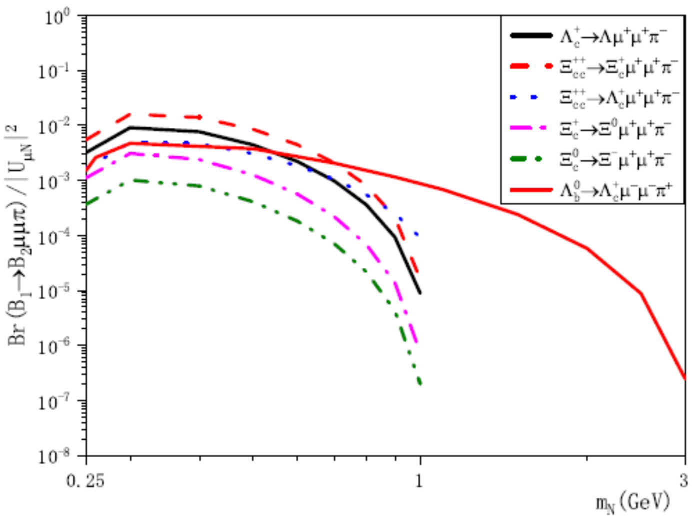
$$\Xi_c^+ \to \Xi^0 + \mu^+\mu^+\pi^-,$$

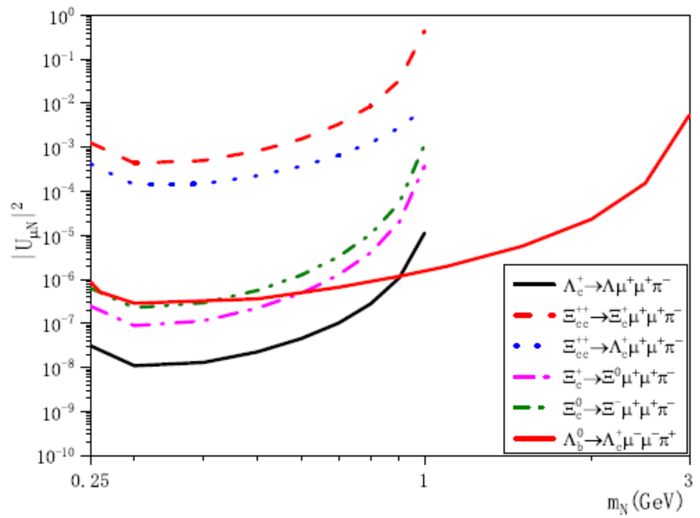
$$\Xi_c^0 \to \Xi^- + \mu^+\mu^+\pi^-,$$

which may exhibit in the exchange of Majorana neutrino with kinematically allowed mass, $m_\mu + m_\pi < m_N < m_{B1} - m_{B2} - m_\mu$.

II. Searching for sterile neutrino signatures at colliders

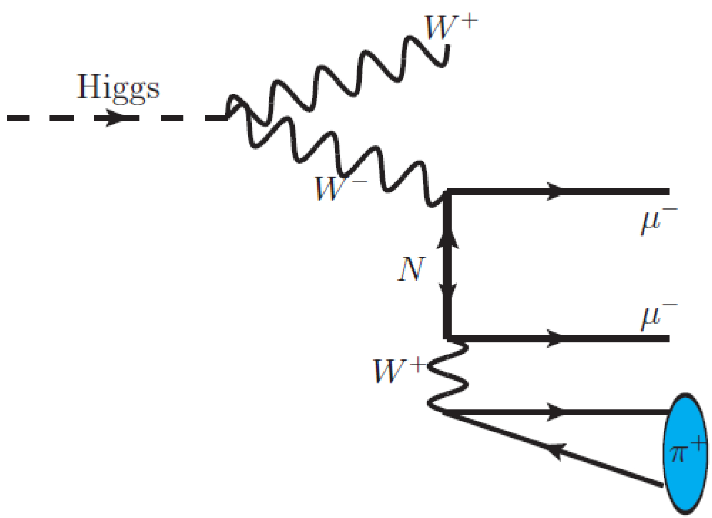
- There are about 10^{12} various concerned baryons accumulated at the LHCb in next run, and hence enforce some constraint on $|U_{\mu N}|^2$





II. Searching for sterile neutrino signatures at colliders

- In Higgs decays
  - The collider search for massive sterile neutrino in Higgs boson decays provide an interesting arena as well, especially for heavy ones



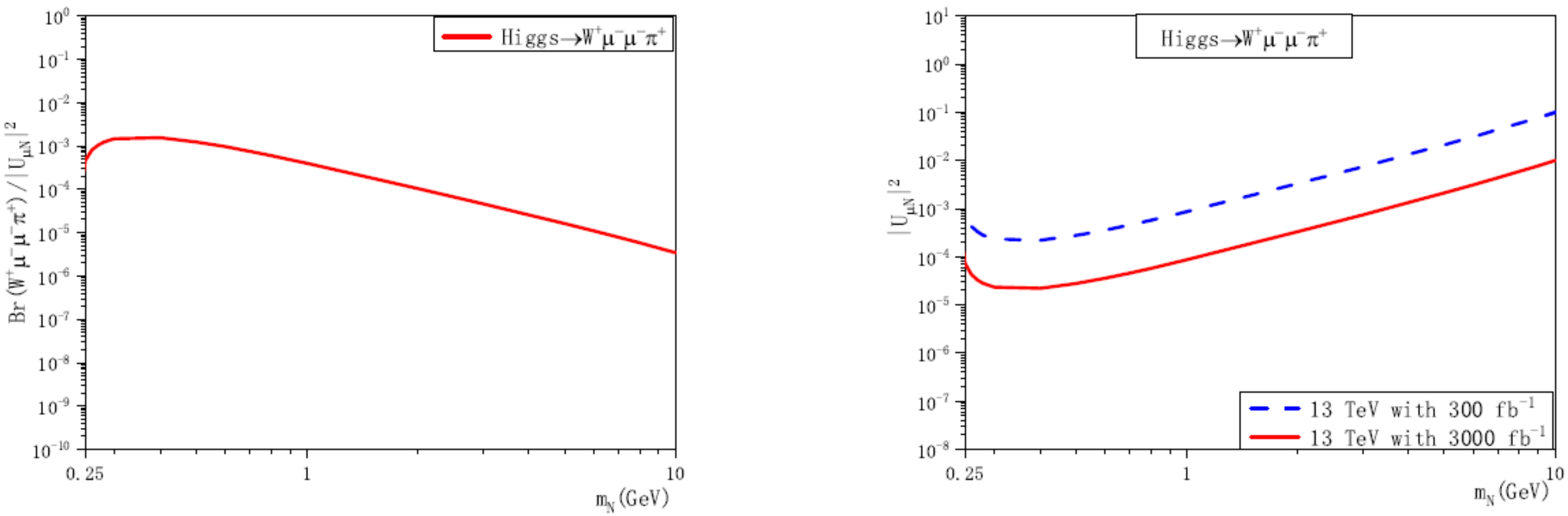
II. Searching for sterile neutrino signatures at colliders

- We calculate the branching fraction for Higgs →WW(→μμπ), the decay width can be formulated as

$$\Gamma(\mathrm{H} \to W^+\mu^-\mu^-\pi^+) = \Gamma(\mathrm{H} \to W^+\mu^- N)\frac{\Gamma(N \to \mu^-\pi^+)}{\Gamma(N)}$$

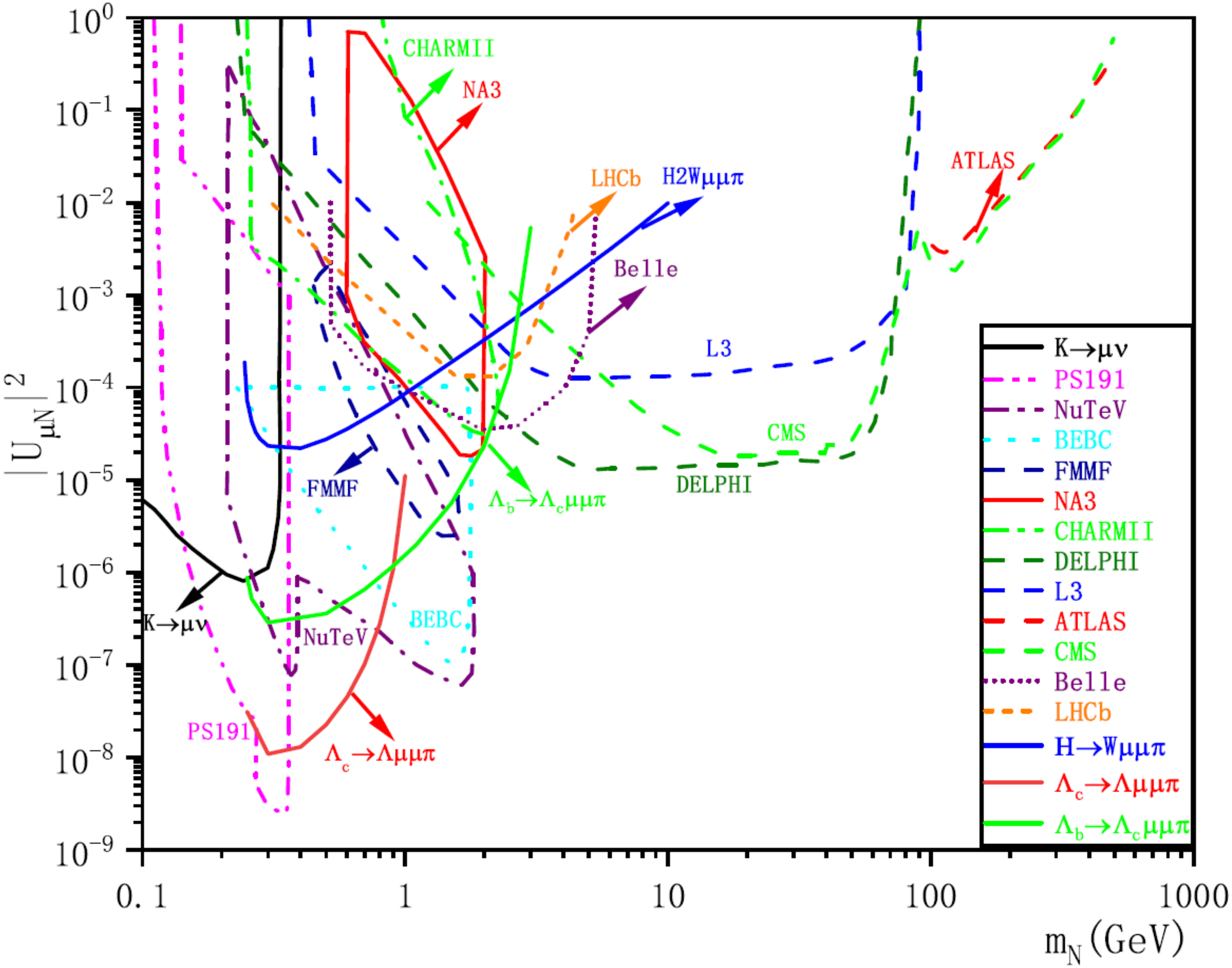
- At the LHC, in short run we may have $\sim 10^6$ Higgs, and in future the number may increase to $\sim 10^8$

II. Searching for sterile neutrino signatures at colliders



- Branching fraction for Higgs → WW(→ μμ) and the $|U_{\mu N}|^2$ sensitivity at the 95% confidence level in 13 TeV LHC with integrate luminosity of 300/3000 fb^{-1} respectively

II. Searching for sterile neutrino signatures at colliders



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- We have studied the production mechanisms for sterile neutrino with collider signatures, the direct production channels at the e^+e^-, ep colliders and indirect production through heavy particles decay are considered.

- For direct production channel at e^+e^- collider, we investigate the W-exchange mechanism at the STCF, the SuperKEKB, the CEPC and the ILC

Ⅲ. Conclusions

- According to our estimation, the lower limit of $|U_{eN}|^2$ can reach 10^{-4} in 0.3 − 2 GeV region for lower energy e^+e^- collider, e.g., the STCF and the SuperKEKB; extended to 10^{-7} in electroweak energy mass region for high energy collider, e.g., the CEPC and the ILC.

Ⅲ. Conclusions

- We also studied the indirect production channels via hadron (meson and baryon) and Higgs decay. For heavy meson, we proposed a new search method for sterile neutrino via kink structure in lepton energy spectrum of B-meson semileptonic decay

Ⅲ. Conclusions

- For heavy baryon decays, we explore the four-body decay of Λ_c, Ξ_c, Ξ_{cc} and Λ_b. Numerical results show that the $|U_{\ell N}|2$ are sensitive slightly above the $\mu\pi$ threshold. The constraint on it from the LHCb experiment is given.

- For Higgs decay, we investigate $H \to W\mu\mu\pi$ process, which having a relatively clean signal. Constraint of the mixing parameter is obtained.

One more concluding remark

About neutrino, there are still so many puzzles, and hence theories, how to proceed and break through the dilemma is a big issue

THANKS

III. 衍生——从量变到质变