Heavy Neutral Lepton Searches at Colliders

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27th Mini-workshop on the frontier of LHC

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Based on [毛英男、王泽人、张敬民、孙昊、王科臣、顾海勇、柏凌霄等，PRD 108 (2023) 095025, JHEP Physics 09 (2023) 152, PRD 107 (2023) 095008, PRD 106 (2022) 015006, JHEP 09 (2021) 026, PRD 101 (2020) 075046]

OUTLINE

- **Motivation**
- ***N* Productions & Limits**
- **Prompt *N* Studies**
- **Long-lived *N* Studies**
- **Discussion**

基础物理目前存在的大问题

实验上:

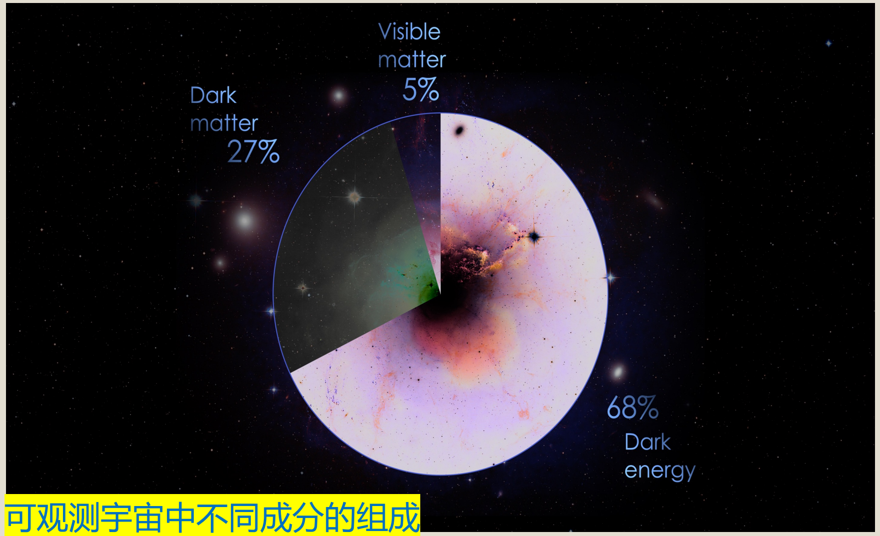
何为暗物质？

如何解释标准模型中微子质量？

为何宇宙中反物质很少？

何为暗能量？

……



可观测宇宙中不同成分的组成


暗物质存在的证据：子弹状星系团

基础物理目前存在的大问题

理论上:

希格斯粒子质量的自然性问题？
量子色动力学中的强CP问题？
强相互作用和电弱相互作用的统一？
引力相互作用的统一，量子引力如何实现？
粒子味存在的原因？

…………

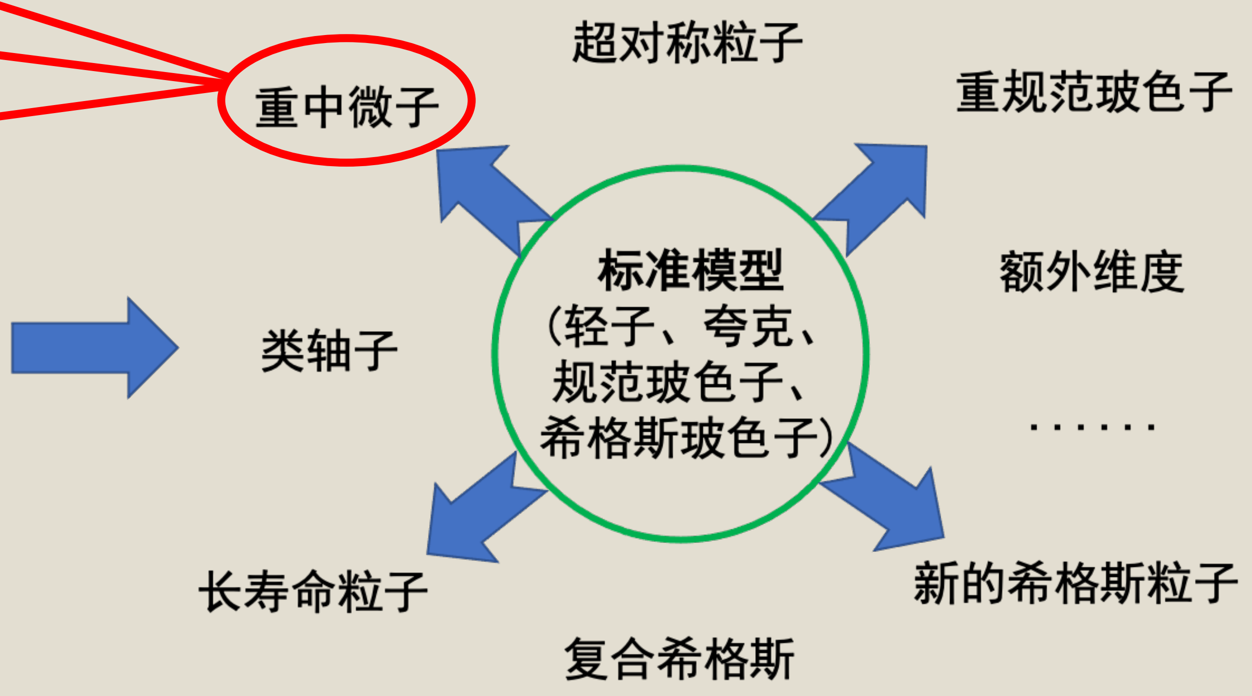

新物理

各种新物理理论模型

大的基本物理问题

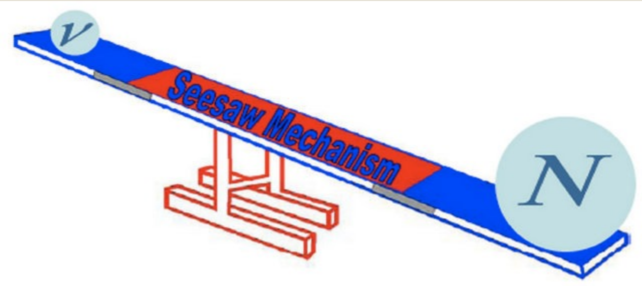
- 暗物质的存在
- 中微子的极小质量
- 正反物质的不对称
- 暗能量的存在
- 希格斯粒子质量的自然性
- 强相互作用中的强CP问题
- 强、电弱相互作用的统一
- 引力的统一: 量子引力
- 粒子“味”之谜
- ……

超越标准模型的新物理



Heavy Neutrino Models

Discovery of neutrino oscillations => neutrinos have mass
→ In SM, neutrinos are massless
→ A window to BSM physics



Type-I see-saw: Singlet (Sterile) Fermions

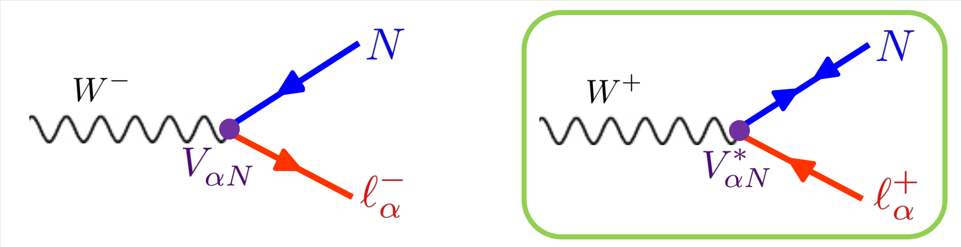
$$-\mathcal{L} = h_{\ell\alpha}\bar{L}_\ell\widetilde{\Phi}N_\alpha + \frac{1}{2}M_{N_{\alpha\beta}}\bar{N}^C_\alpha N_\beta + \text{H.c.}$$

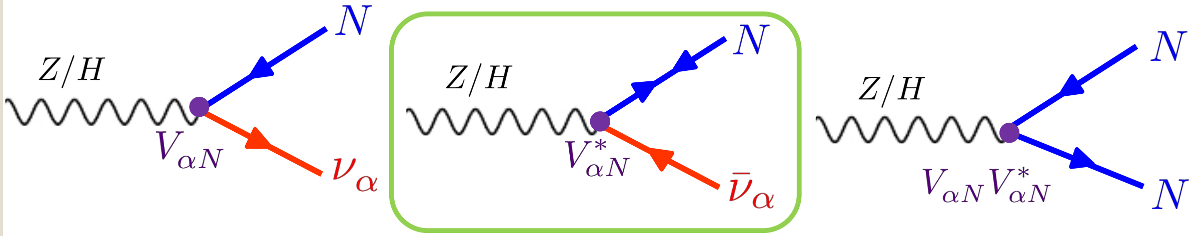
$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^\intercal & M_N \end{pmatrix}$$

$$M_\nu \simeq -M_D M_N^{-1} M_D^\intercal$$

$$V_{\ell N_\alpha} \sim M_D M_N^{-1}$$

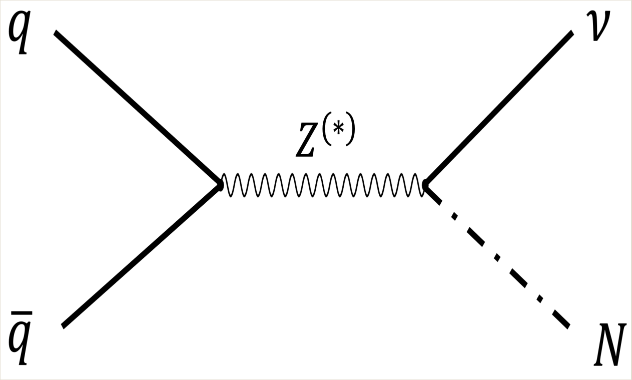
Interactions: [0901.3589]



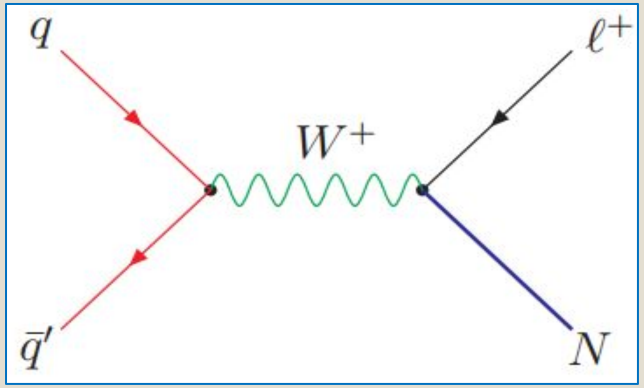


Simplified model with assumption for collider searches:
Assumption: Dirac/Majorana, # of Ns
Free parameters: m_N, $|V_{Ne}|^2$, $|V_{N\mu}|^2$, $|V_{N\tau}|^2$

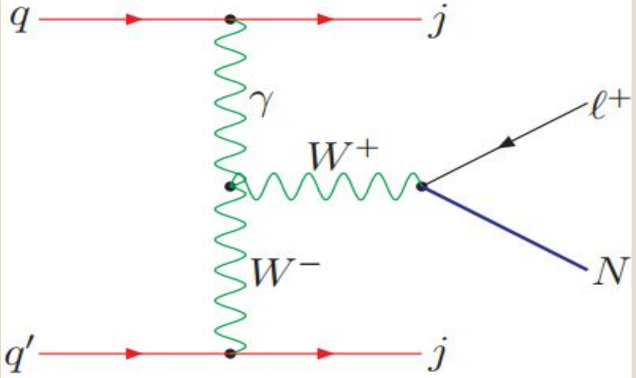
N Production @ *pp* Colliders



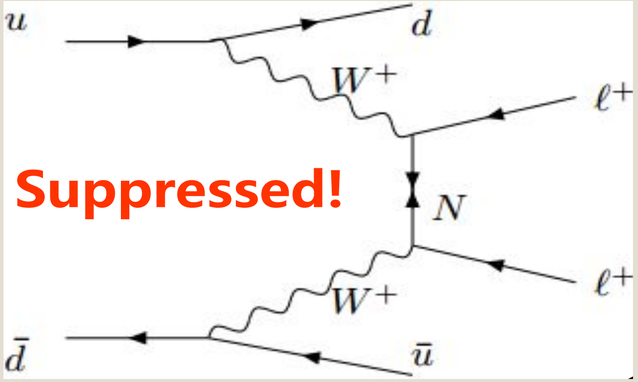
almost unobserved
(l^+l^- or $l^\pm$+MET suffer from huge BG)



mostly studied, can confirm LNV
(important for m_N < 1 TeV)
[L. Bai, Y. Mao and **K. Wang**, PRD 107 (2023) no. 9, 095008]

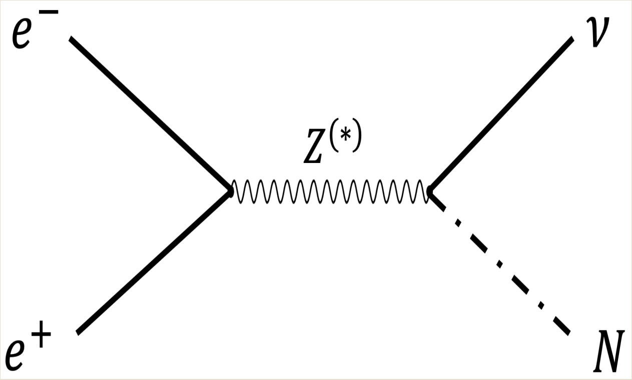


can confirm LNV
(More important for m_N > 1 TeV)

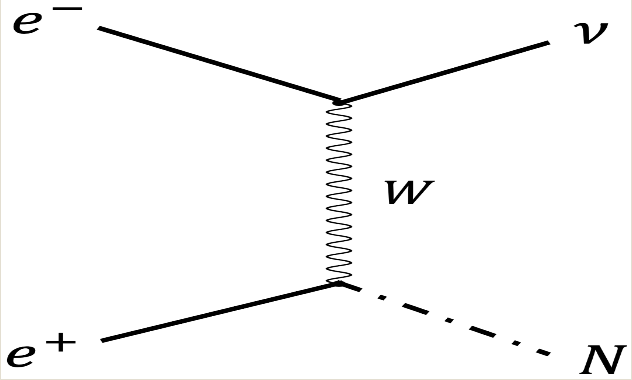


can confirm LNV
(no resonance enhancement)

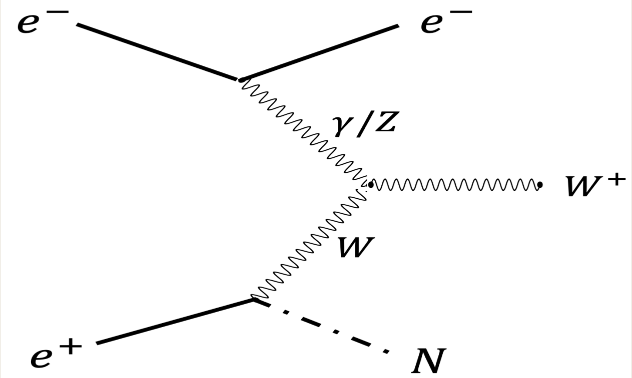
N Production @ ee Colliders



mostly studied @ Z-pole
(important for $m_N < m_Z$)

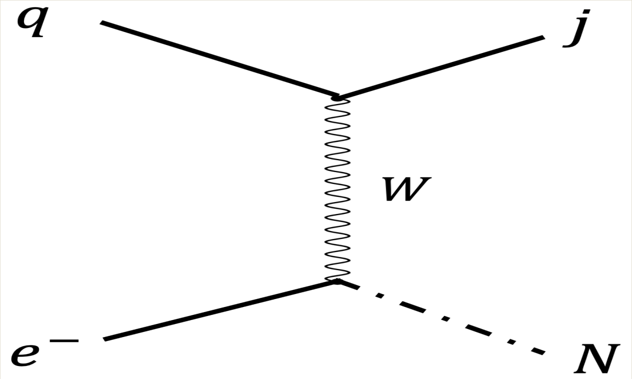


contribute to signal
(important for large m_N)



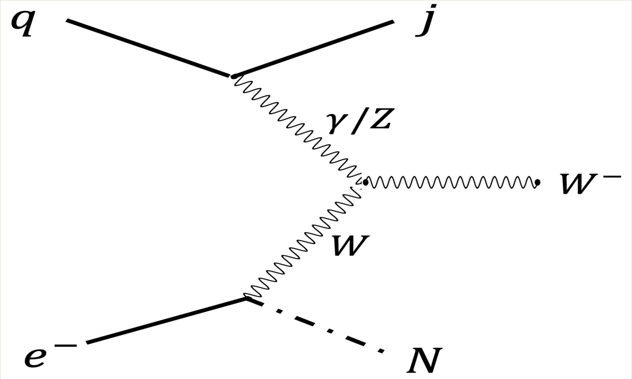
can confirm LNV
(important for large m_N , need large $\sqrt{s}$)

N Production @ *pe* Colliders



mostly studied, can confirm LNV
(sensitive to wide range, esp. $m_N > m_Z$)

[H. Gu, Y. Mao, H. Sun and **K. Wang**, JHEP 09 (2023) 152]
[H. Gu and **K. Wang**, PRD 106 (2022) no. 1, 015006]

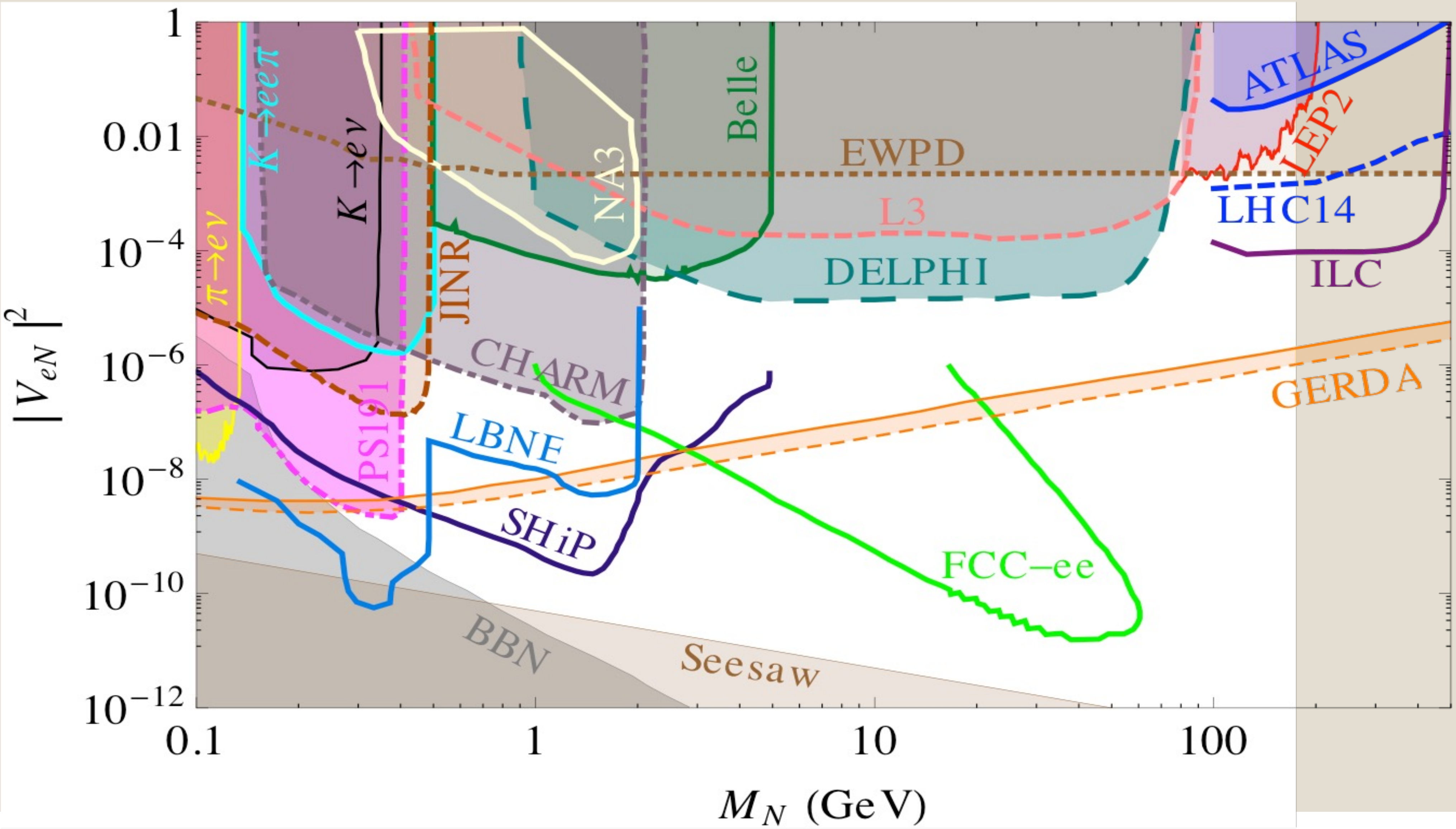


can confirm LNV
(need large $\sqrt{s}$)

Global Constraints

[Deppisch, Dev and Pilaftsis, New J. Phys. 17 (2015) 085019]

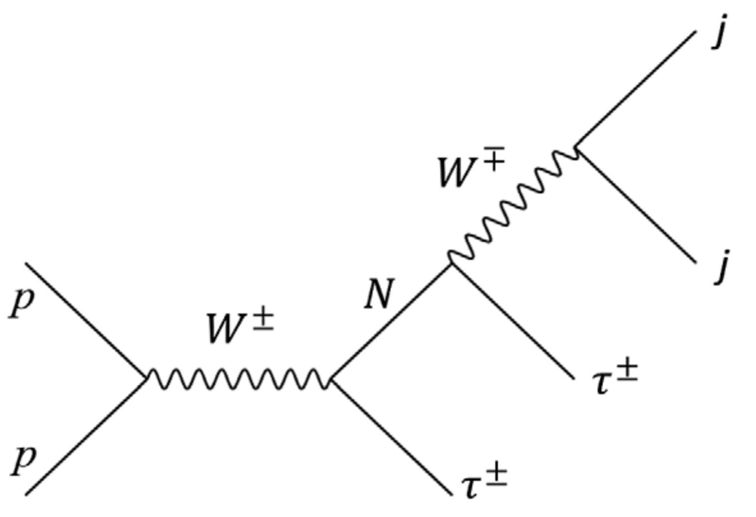
m_N: 0.1 ~ 500 GeV



Probe $|V_{\tau N}|^2$

Signal @ *pp* colliders

$|V_{\tau N}|^2 \neq 0$ $\quad |V_{eN}|^2 = |V_{\mu N}|^2 = 0$



both taus are required to decay leptonically into muons

MVA-BDT method to reject the bkg

[L. Bai, Y. Mao and **K. Wang**, PRD 107 (2023) 095008]

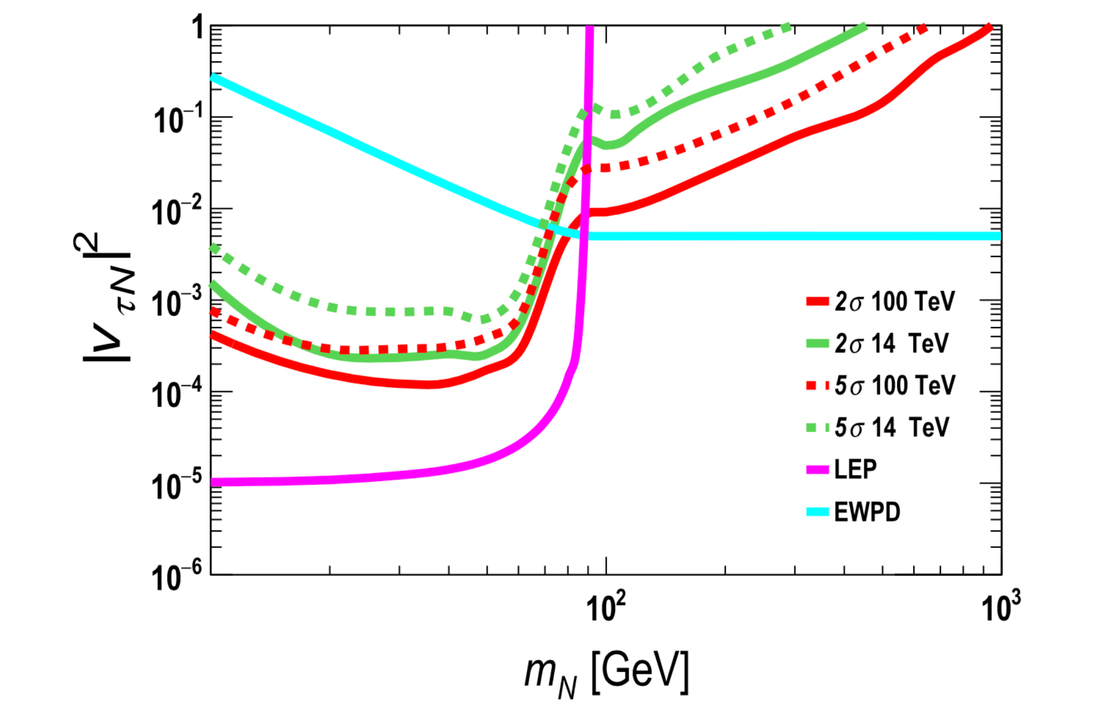
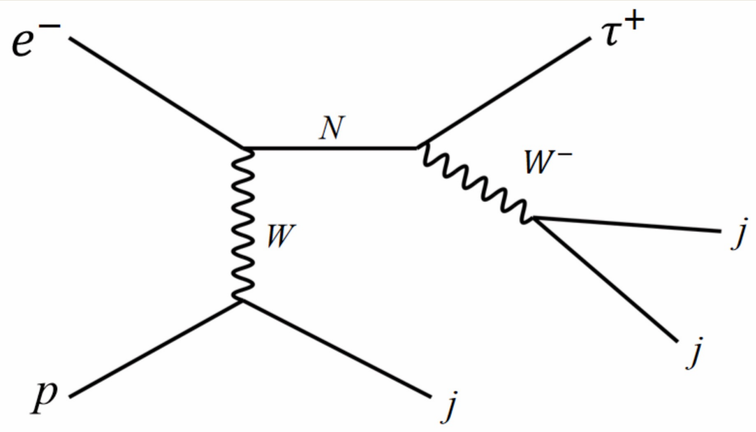


FIG. 4. Upper limits on mixing parameter $|V_{\tau N}|^2$ for the heavy neutrino mass in the range of 10 to 1000 GeV, based on our derivation from measurements of rare Z-boson decay at the LEP [66] and the electroweak precision data (EWPD) [63,67–71], and analyses of the $pp \to \tau^\pm\tau^\pm jj$ signal at the HL-LHC and SppC/FCC-hh.

Probe $|V_{\tau N}|^2$

Signal @ *pe* colliders

$$|V_{\tau N}|^2 = |V_{eN}|^2 = |V_{\ell N}|^2$$



both hadronic τ_h and leptonic τ_μ final states

MVA-BDT method to reject the bkg

[H. Gu, Y. Mao, H. Sun and **K. Wang**, JHEP 09 (2023) 152]

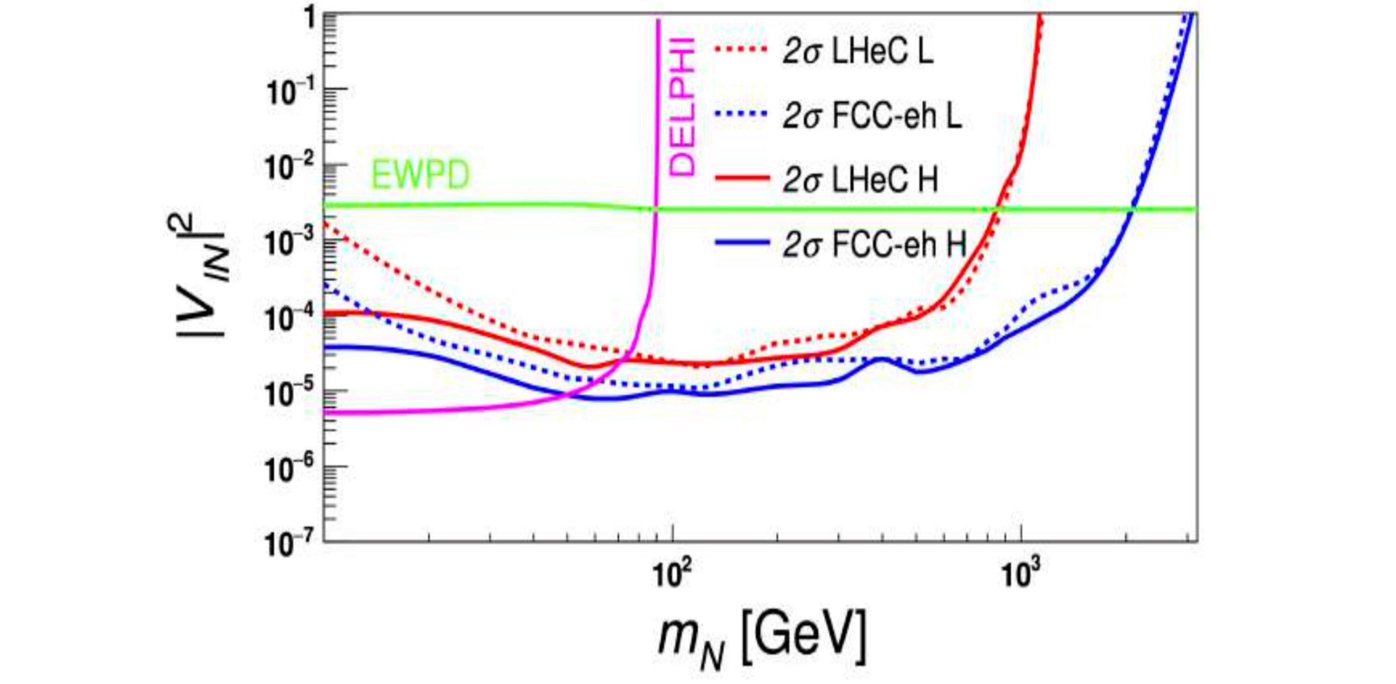


Figure 8. Assuming the mixing parameter $|V_{\ell N}|^2 = |V_{\tau N}|^2 = |V_{eN}|^2$, the discovery sensitivities on $|V_{\ell N}|^2$ at 2-σ significance as the heavy neutrino mass changes from 10 to 3000 GeV for Hadronic τ_h (H) and Leptonic τ_μ (L) final states at the LHeC and FCC-eh. The constraints from EWPD [47–51, 53] (green solid line) and DELPHI experiments [46] (purple solid line) are derived and displayed in the same plot for the comparison, see more details in appendix A.

Probe $|V_{lN}|^2$ & Discover a Majorana N

Signal @ *pe* colliders

$$|V_{\ell N}|^2 = |V_{eN}|^2 = |V_{\mu N}|^2$$

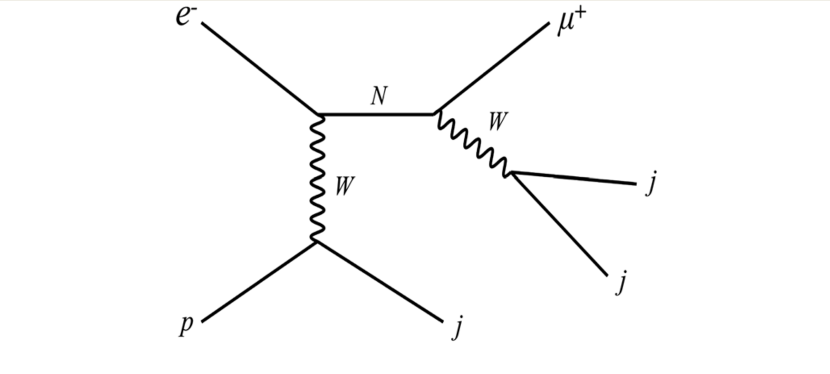


FIG. 1. The production process of the LNV signal via a Majorana heavy neutrino N at ep colliders.

TABLE I. The production cross sections of dominant background processes at the LHeC and FCC-eh.

	σ (pb)	LHeC	FCC-eh
B1	$\mu^+\mu^-e^-jjj$	0.58	2.1
B2	$\mu^+\mu^-\nu_e jjj$	8.6×10^{-2}	0.39
B3	$\mu^+\nu_\mu e^- jjj$	0.28	1.6
B4	$\mu^+\nu_\mu\nu_e jjj$	8.1×10^{-6}	9.3×10^{-5}

MVA-BDT method to reject the bkg

[H. Gu and **K. Wang**, PRD 106 (2022) no. 1, 015006]

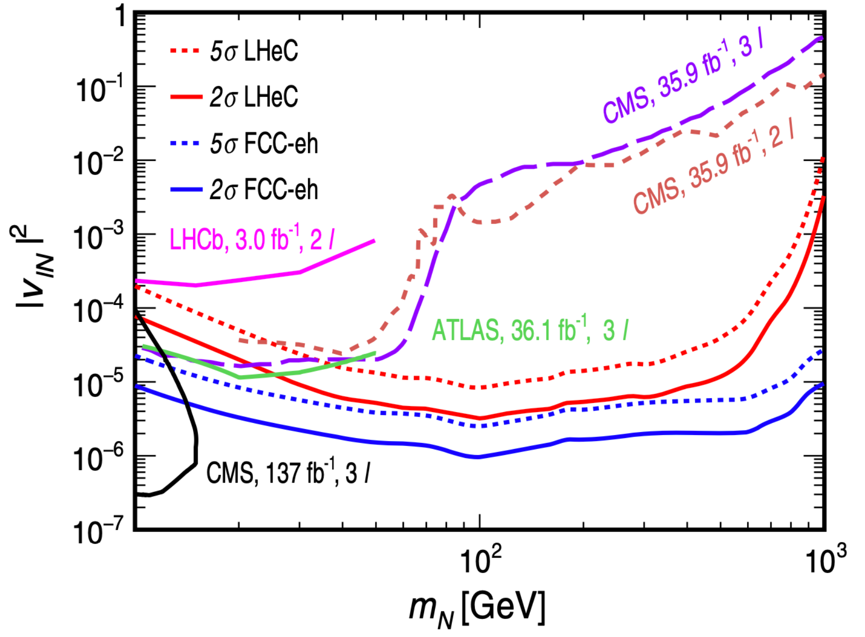


FIG. 5. 2σ and 5σ limits on mixing parameter $|V_{\ell N}|^2$ for the heavy neutrino mass in the range of 10–1000 GeV at the LHeC and FCC-eh. Also shown are the current experimental limits at 95% confidence level from the trilepton searches (CMS, 35.9 fb^{-1}, 3ℓ [24], CMS, 137 fb^{-1}, 3ℓ [26], and ATLAS, 36.1 fb^{-1}, 3ℓ [27]) and dilepton searches (CMS, 35.9 fb^{-1}, 2ℓ [25] and LHCb, 3.0 fb^{-1}, 2ℓ [28]) at the LHC.

Idea of LLP searches @ colliders

When a LLP produced at 0 (usually the IP),

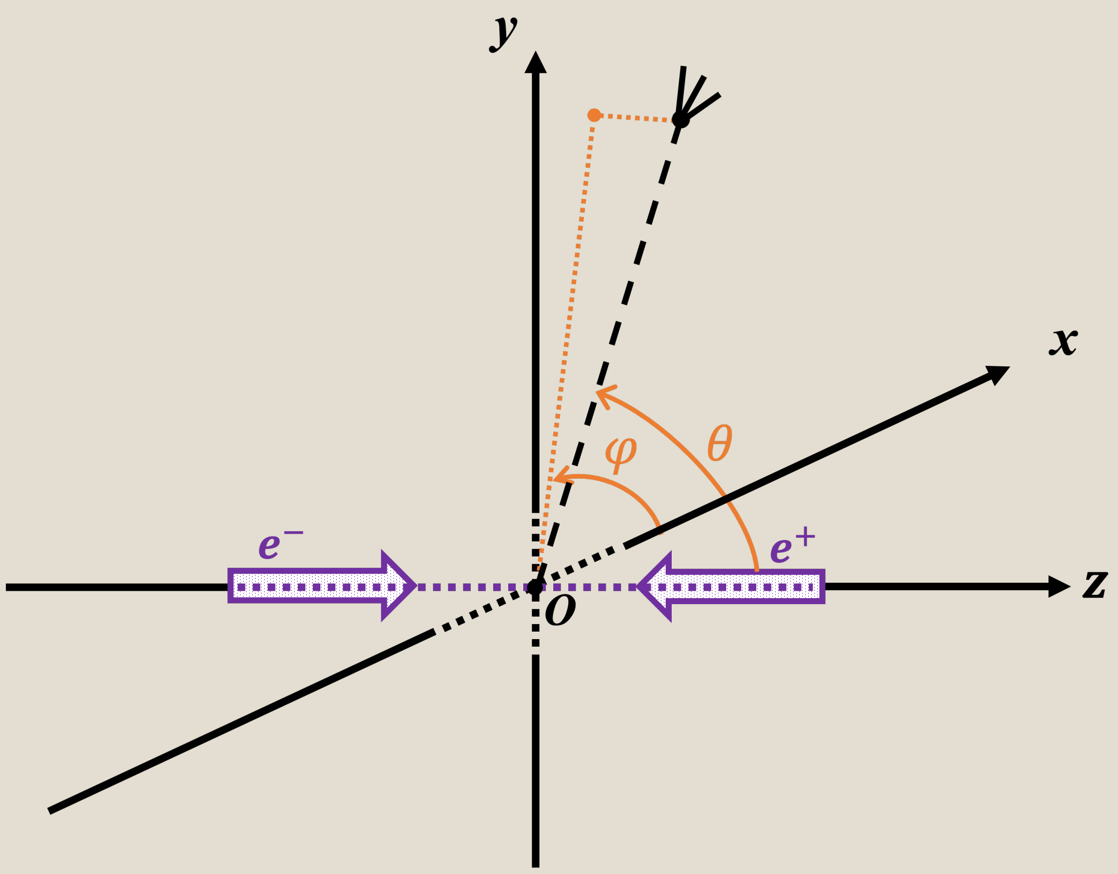
Probability of still existing (does not decay) at L

$$P(L) = e^{-L/\lambda}$$

where decay length in the lab. frame

$$\lambda = \beta\gamma\, c\tau = \left(\frac{p}{m}\right)\ (c\tau)$$

Kinematics   lifetime in the rest frame



Near Detector @ LHC

[K. Cheung, **K. Wang**, and Z. S. Wang, JHEP 09 (2021) 026]

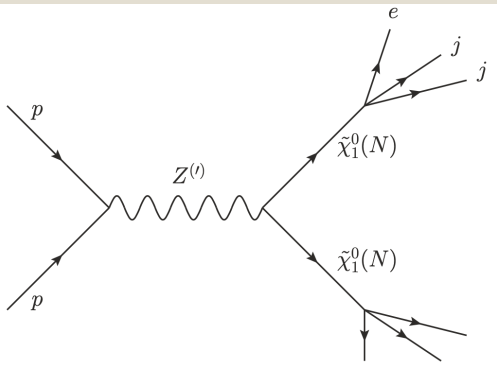
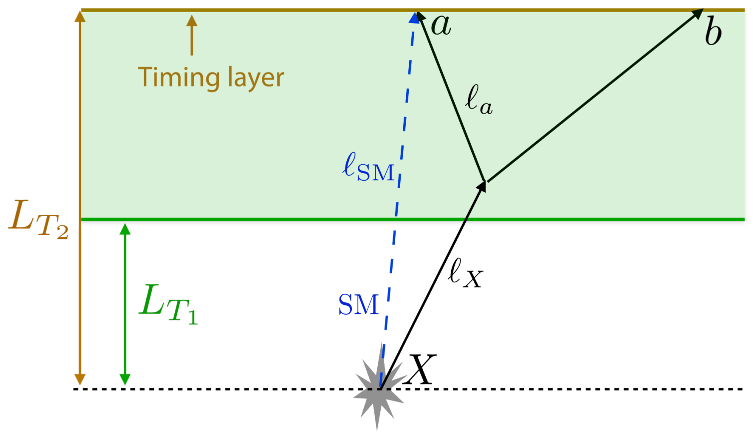


Figure 4. Feynman diagram of the signatures. We require at least one neutralino or HNL to decay into the ejj final state, as well as one hard prompt ISR jet in the event analysis.



[Jia Liu, Zhen Liu and Lian-Tao Wang, PRL 122 (2019) 131801]

Signal rate

$$N_s^N = \sigma^N \cdot \mathcal{L} \cdot \mathrm{Br}(N \to ejj) \cdot 2 \cdot \epsilon^N, \quad (4.2)$$

where $N^Z \simeq 1.9 \times 10^{11}$ is the total number of Z-bosons resonantly produced with 3 ab^{-1} integrated luminosity [78], σ^N is the *inclusive* scattering cross section of $pp \to Z' \to NN$ calculated by MadGraph5 at the leading order (see the right plot of figure 2), and $\epsilon^{\tilde{\chi}_1^0}$ and ϵ^N are the event acceptance rates including the requirement of one hard ISR prompt jet. $\mathrm{Br}(\tilde{\chi}_1^0 \to e^- u\bar{s}$ or $e^+\bar{u}s) = 0.5$,[3] and $\mathcal{L} = 3$ ab^{-1} labels the integrated luminosity at the HL-LHC. Finally, the factor 2 that appears in both eq. (4.1) and eq. (4.2) accounts for the fact that in each signal event a pair of LLPs are produced and we require only one of them to decay into the specified final states.

Key observable: timing information

The time delay, Δt, is computed as follows,

$$\Delta t = t^e_{\mathrm{arrival}} - t^e_{\mathrm{prompt}}, \quad (3.1)$$

where $t^e_{\mathrm{arrival}} = \frac{l_{\mathrm{LLP}}}{\beta_{\mathrm{LLP}}} + l_e$ is the arrival time of the electron at the MTD, with l_{LLP} (l_e) being the distance traveled by the LLP (displaced electron) before the LLP decays (the electron hits the MTD), and β_{LLP} being the speed of the LLP, while t^e_{prompt} is the time when the electron would arrive at the same position, *had it been promptly produced at the IP and traveling with the speed of light.*

Near Detector @ LHC

[K. Cheung, **K. Wang**, and Z. S. Wang, JHEP 09 (2021) 026]

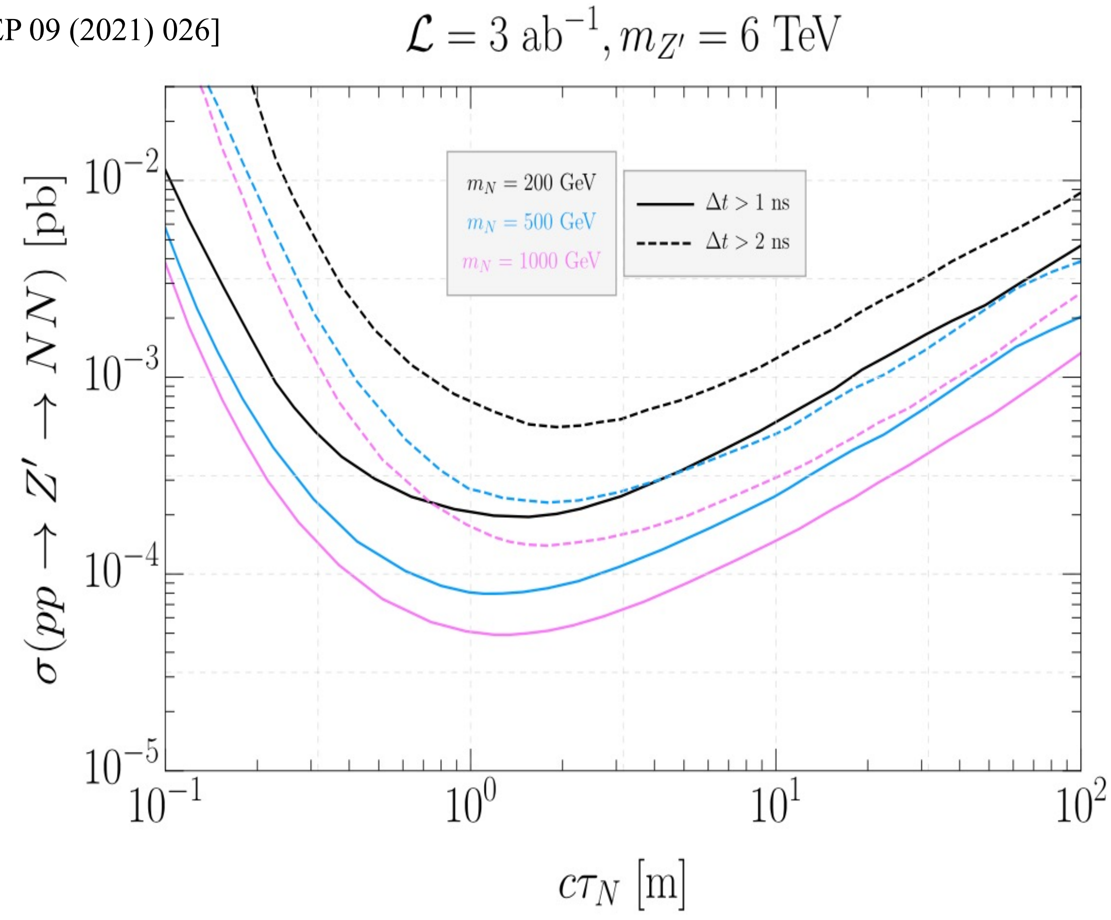
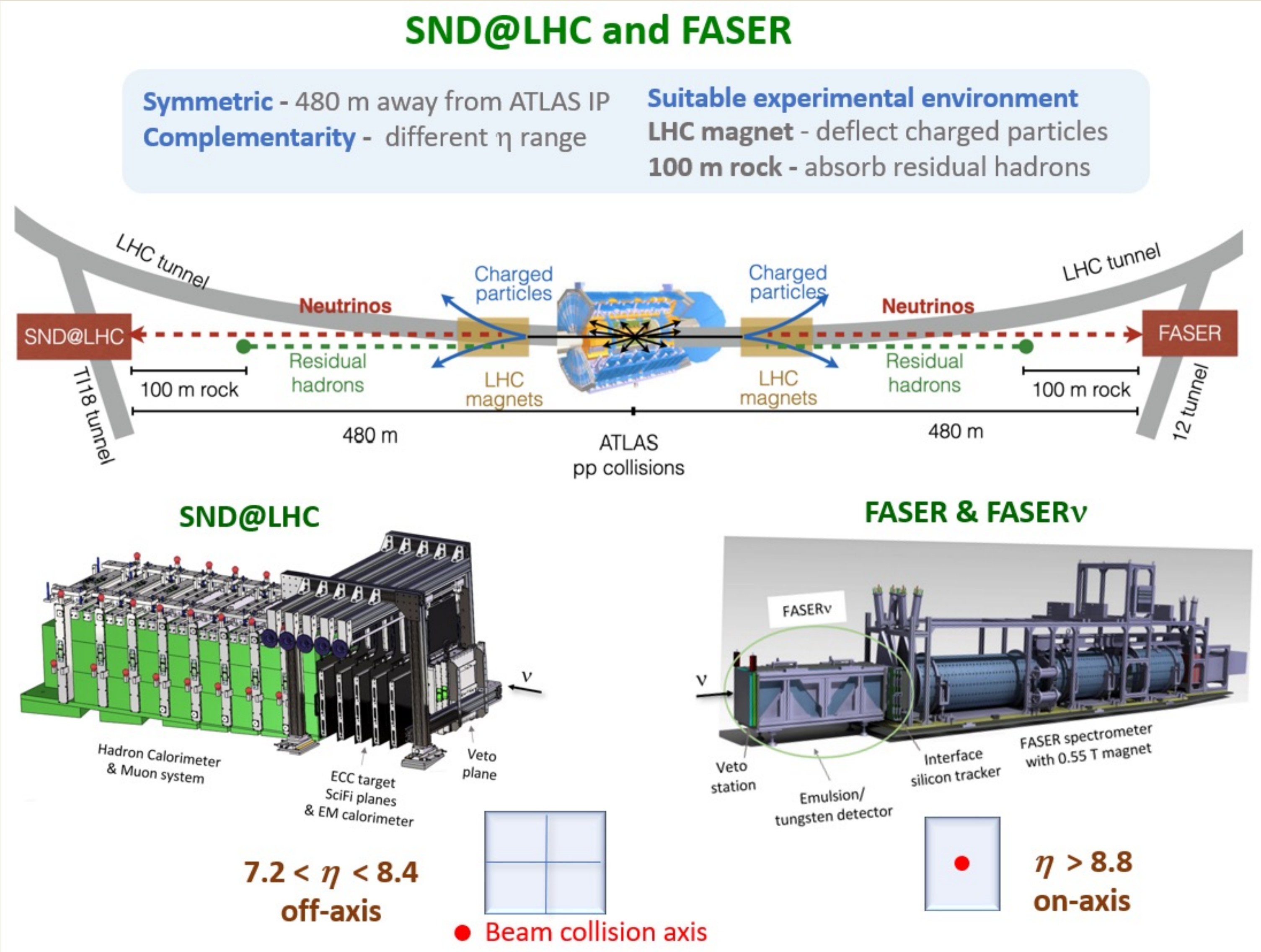


Figure 12. 95% C.L. exclusion limits on σ^N when varying $c\tau_N$, for $m_N = 200, 500$, and 1000 GeV.

Far Detector @ LHC



Current running FD experiments @ LHC

[http://www.ship-korea.com/SND.html]

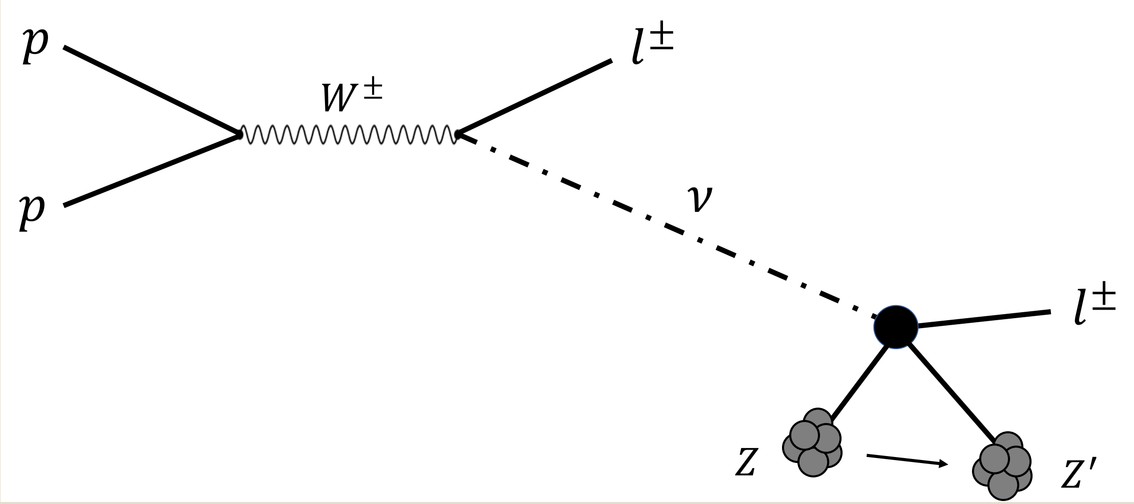
[https://faser.web.cern.ch/index.php/]

[https://snd-lhc.web.cern.ch/]

[2210.02784, SND@LHC: The Scattering and Neutrino Detector at the LHC]

Far Detector @ LHC

Signal & Sensitivities for SM ν with EFT Operator



$$N_S^\nu = \sigma_\nu \cdot \mathcal{L} \cdot \epsilon_{\text{trigger}} \cdot \epsilon_{\text{window}} \cdot \langle \epsilon_{\text{h. f.}} \cdot P_{\text{scatt.}} \rangle$$

larger than four. A general framework with such operators including the neutrinos is known as the Standard Model Effective Field Theory (SMEFT) (see Ref. [91] for a review). In particular, SMEFT higher-dimensional operators which are LNV and include two quarks, one charged lepton, and a neutrino, arise at mass dimension 7 [92, 93].[4] Here, we focus on the operator $\epsilon_{ij}(L^i C\gamma_\mu e)(\bar{d}\gamma^\mu u)H^j$ with Wilson coefficient labeled as $1/\Lambda^3$, where H is the Higgs doublet, ϵ_{ij} is the $SU(2)$ index tensor, C is the Dirac charge conjugation matrix, Λ denotes the new-physics scale, leading to the neutrino-nucleus scattering into an electron

[Y. Mao, **K. Wang** and Z. S. Wang, arXiv: 2305.03908]

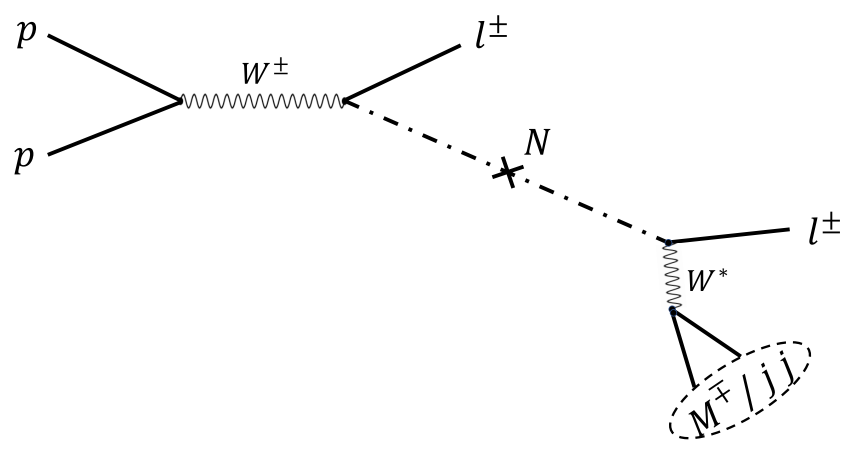
N_S^ν	e^+	e^-	μ^+	μ^-
FASERν	1.5×10^{-14}	8.5×10^{-15}	7.7×10^{-15}	2.0×10^{-15}
SND@LHC	2.2×10^{-14}	1.5×10^{-14}	3.7×10^{-14}	9.3×10^{-15}
FASERν2	2.0×10^{-12}	1.3×10^{-12}	1.0×10^{-12}	2.4×10^{-13}
AdvSND(far)	7.7×10^{-13}	5.0×10^{-13}	1.2×10^{-12}	2.1×10^{-13}
FLArE-10	6.6×10^{-13}	3.6×10^{-13}	1.0×10^{-12}	4.6×10^{-14}
FLArE-100	6.2×10^{-12}	2.9×10^{-12}	8.5×10^{-12}	1.3×10^{-12}

Table 4. Table of numerical results of N_S^ν for light neutrino produced via an s-channel W-boson decay and scattering via the dim-7 LNV operator $\epsilon_{ij}(L^i C\gamma_\mu e)(\bar{d}\gamma^\mu u)H^j$ with a coefficient $1/\Lambda^3 \sim 1/(5\text{ TeV})^3$, where the neutrino helicity flip is not included.

Only method to confirm LNV / Majorana nature of ν at colliders !

Far Detector @ LHC

Signal & Sensitivities for *N*



$$N_S^N = \frac{\sigma_\nu}{\mathrm{BR}(W \to e\,\nu)} \cdot \mathrm{BR}(W^\pm \to e^\pm N) \cdot \mathcal{L} \cdot \epsilon_{\mathrm{trigger}} \cdot \langle P_{\mathrm{decay}} \rangle \cdot \mathrm{BR}(N \to e^\pm jj/M^\mp)$$

[Y. Mao, **K. Wang** and Z. S. Wang, arXiv: 2305.03908]

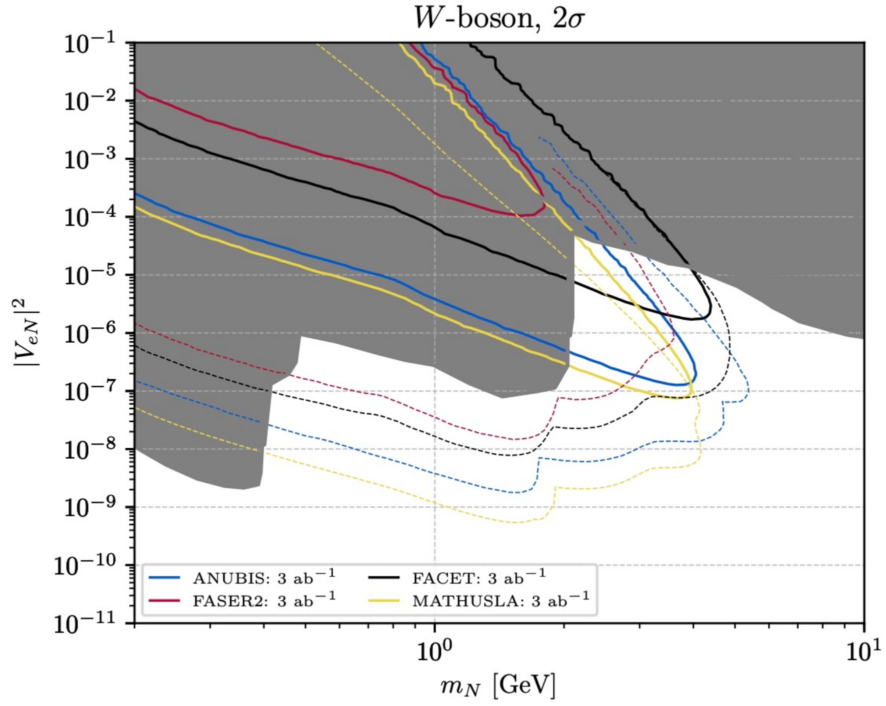


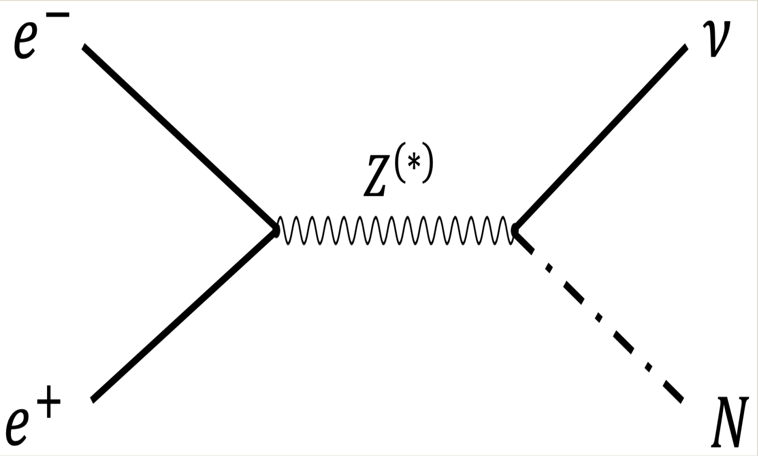
Figure 3. 2σ exclusion-bound plot for the displaced-vertex search associated with same-sign prompt and displaced leptons, produced from a W-boson decay at the IP and from the N decay in the far detectors, respectively. The gray area is the currently excluded parameter region, extracted from Refs. [102–106]. The solid lines are the sensitivity reach of the considered experiments with the LNV searches from this study, while the dashed lines correspond to inclusive displaced-vertex searches for HNLs produced from D and B-mesons' decays, as well as W-boson decays (important for ANUBIS and MATHUSLA only), extracted from Refs. [56, 58, 107]. We emphasize that the latter results cannot confirm LNV of the signal events and hence determine the Majorana nature of the HNLs.

N Production @ CEPC

[Zeren Simon Wang, **K. Wang**, PRD 101 (2020) no.7, 075046]

scenario		$Z \to N\nu$	
LLP		N	
production $e^- e^+ \to$		Z	
$\sqrt{s}$ [GeV]		91.2	
N_h	CEPC	-	
	FCC-ee		
N_Z	CEPC	7.0×10^{11} [16]	**16 ab^{-1}, 2 years, 2 IPs**
	FCC-ee	5.0×10^{12} [20]	**150 ab^{-1}, 4 years, 2 IPs**

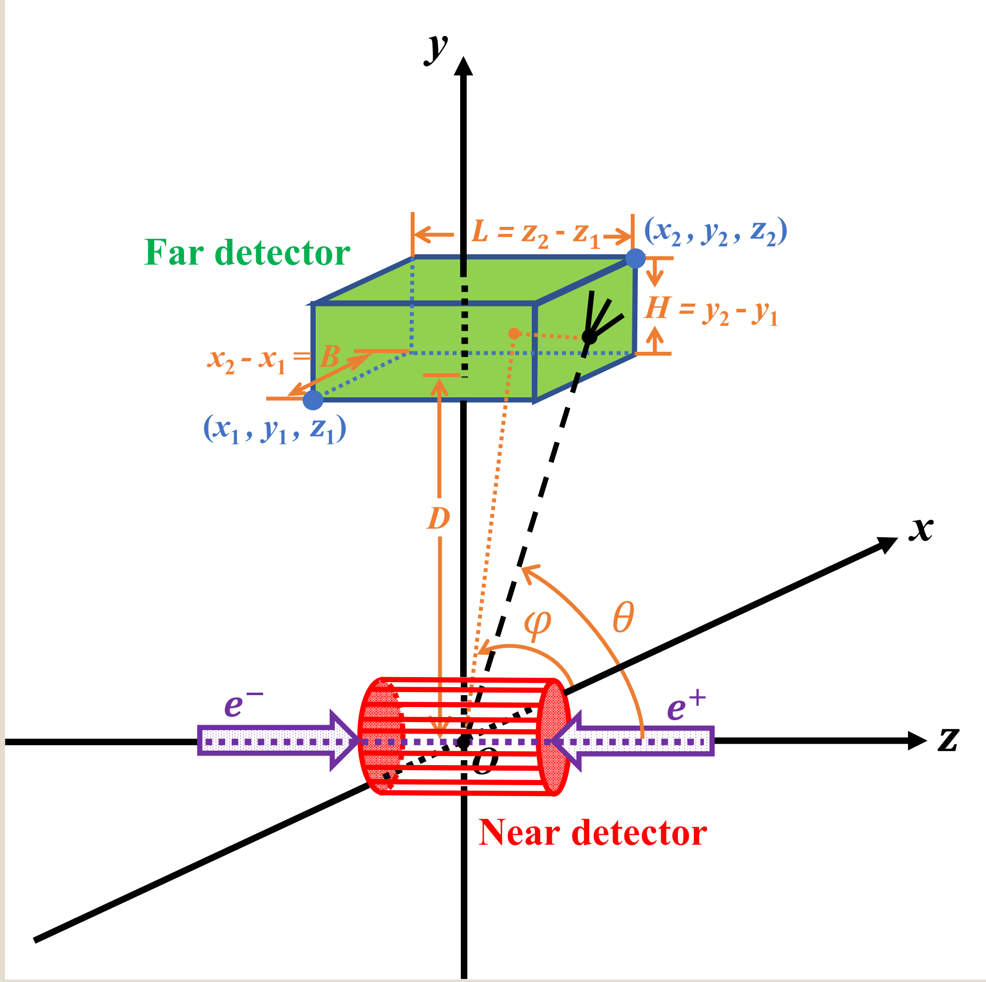
Signal Production



Near and Far Detectors @ CEPC

Far Detector Designs

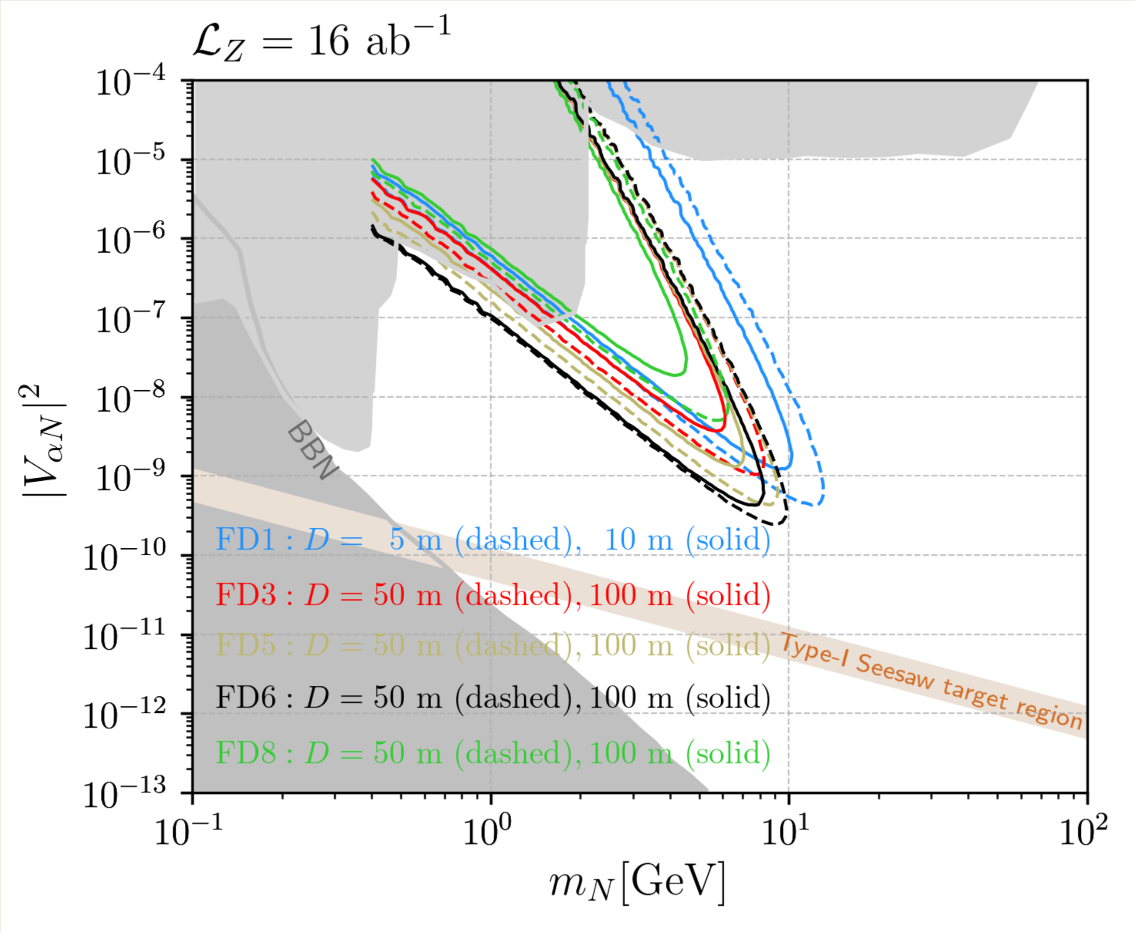
	V [m^3]	B [m]	H [m]	L [m]	(x_1, y_1, z_1) [m]	(x_2, y_2, z_2) [m]	D [m]
FD1	5.0×10^3	10	10	50	(5, -5, -25)	(15, 5, 25)	5
					(10, -5, -25)	(20, 5, 25)	10
FD2	8.0×10^5	200	20	200	(-100, 50, 50)	(100, 70, 250)	50
					(-100, 100, 100)	(100, 120, 300)	100
FD3	8.0×10^5	200	20	200	(-100, 50, -100)	(100, 70, 100)	50
					(-100, 100, -100)	(100, 120, 100)	100
FD4	8.0×10^5	100	80	100	(-50, 50, -50)	(50, 130, 50)	50
					(-50, 100, -50)	(50, 180, 50)	100
FD5	3.2×10^6	200	80	200	(-100, 50, -100)	(100, 130, 100)	50
					(-100, 100, -100)	(100, 180, 100)	100
FD6	8.0×10^7	1000	80	1000	(-500, 50, -500)	(500, 130, 500)	50
					(-500, 100, -500)	(500, 180, 500)	100
FD7	8.0×10^5	2000	20	20	(-1000, 50, -10)	(1000, 70, 10)	50
					(-1000, 100, -10)	(1000, 120, 10)	100
FD8	8.0×10^5	20	20	2000	(-10, 50, -1000)	(10, 70, 1000)	50
					(-10, 100, -1000)	(10, 120, 1000)	100

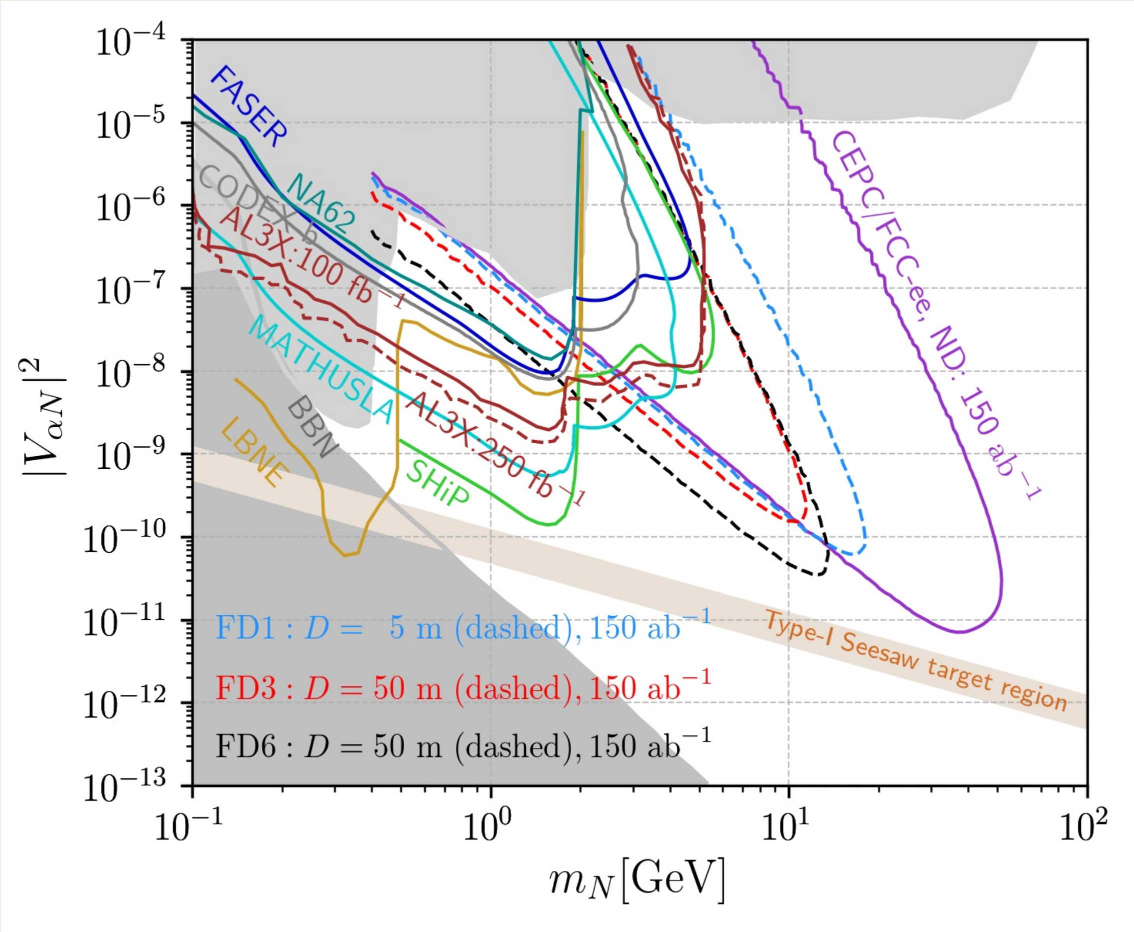


Simple shape: cuboid, similar to MUTHUSLA
Varying: position & geometry size

Near and Far Detectors @ CEPC

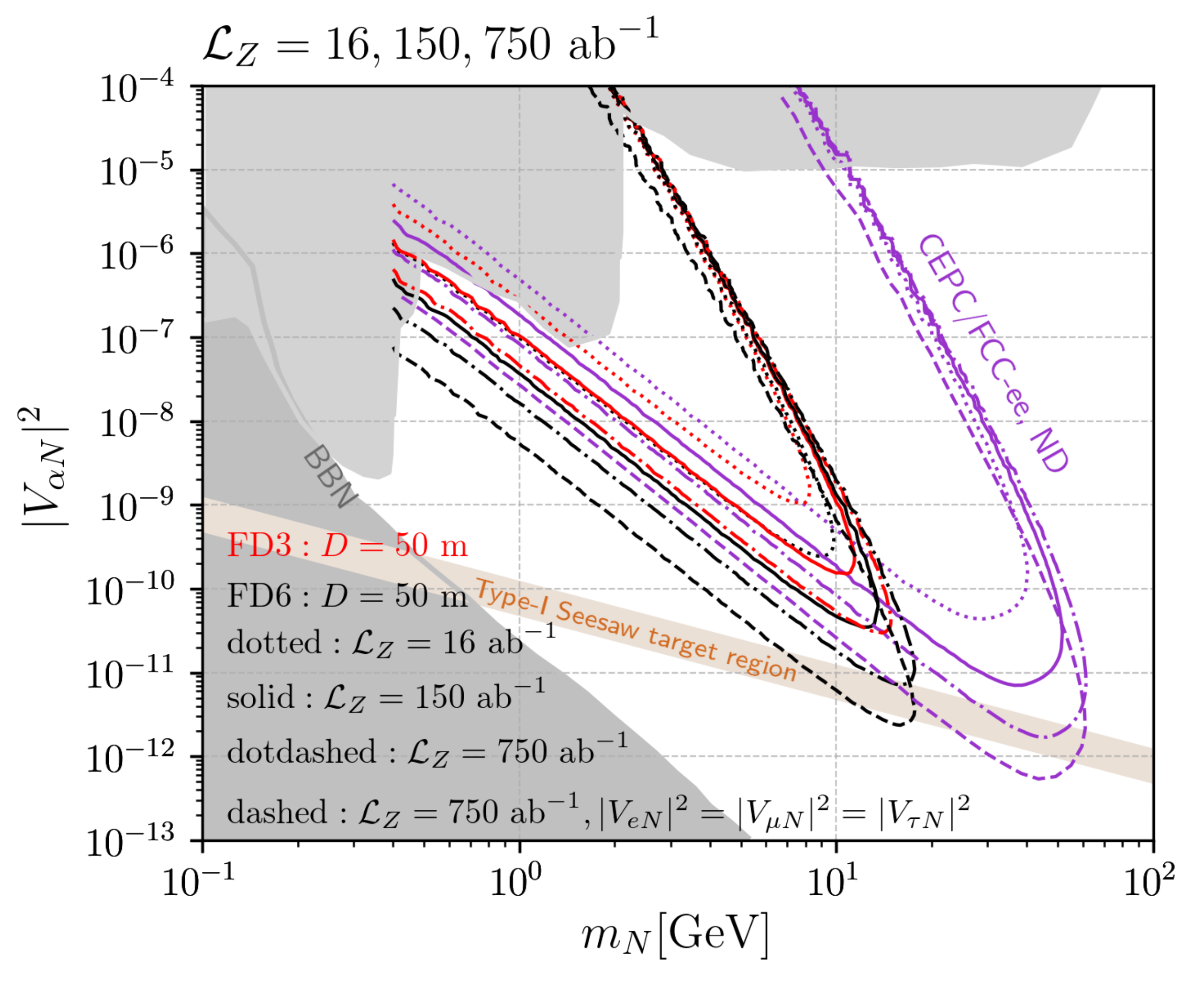
$Z \to N\nu$ @ $\sqrt{s} = 91.2$ GeV





Near and Far Detectors @ CEPC

$Z \to N\nu$ @ $\sqrt{s} = 91.2$ GeV



750 ab^{-1}, 10 years, 4 IPs;
or to increase the instantaneous luminosity;
or to relax the theoretical assumptions

Can test the Type-I seesaw directly!

Summary & Discussion

- ❖ Big experimental & theoretical problems in fundamental physics imply new physics.
- ❖ Test various theory models & find one key to new physics.
- ❖ HNL is one important direction.
- ❖ HNL searches at *pp*, *pe* & ee colliders.
  - → Prompt & long-lived studies
  - → Probe $|V_{\tau N}|^2$, discover a Majorana *N*
  - → Near & far detectors
- ❖ Complementarity & synergy.

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[L. Bai, Y. Mao and **K. Wang**, PRD 107 (2023) 095008]

TABLE I. Production cross sections of signal process with $m_N = 50$ GeV and $|V_{\tau N}|^2 = 10^{-4}$, and dominant background processes at the HL-LHC and SppC/FCC-hh.

	σ (pb)	HL-LHC	SppC/FCC-hh
S	$\tau^\pm\tau^\pm jj$	0.180	1.12
B1	$W^\pm jj$	1.21×10^5	1.31×10^6
B2	Zjj	1.10×10^4	1.25×10^5
B3	$W^\pm Zjj$	3.44×10^2	5.67×10^3
B4	W^+W^-jj	1.68×10^2	2.32×10^3
B5	$ZZjj$	1.03×10^2	1.56×10^3
B6	$t\bar{t}$	5.97×10^2	2.47×10^4

$\mathrm{Br}(Z \to N\nu_\tau, N\bar{\nu}_\tau) < 1.3\times10^{-6}$

the modifications in Γ_Z and σ_H

$$\sigma_H = \frac{12\pi\Gamma_{Z\to e^+e^-}\Gamma_{Z\to \mathrm{had}}}{m_Z^2\Gamma_Z^2}$$

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[H. Gu, Y. Mao, H. Sun and **K. Wang**, JHEP 09 (2023) 152]

	σ [pb]	LHeC	FCC-eh
B1	$\tau^+\tau^-e^-jjj$	0.22	0.86
B2	$\tau^+\tau^-\nu_e jjj$	0.052	0.29
B3	$\tau^+\nu_\tau e^-jjj$	0.28	1.6
B4	$\tau^+\nu_\tau\nu_e jjj$	8.2×10^{-6}	9.3×10^{-5}
B5a	$\nu_e jjjj$	309	1159

Table 1. The production cross sections of background processes at the LHeC and FCC-eh for the hadronic τ_h final state.

	σ [pb]	LHeC	FCC-eh
B1	$\tau^+\tau^-e^-jjj$	0.22	0.86
B2	$\tau^+\tau^-\nu_e jjj$	0.052	0.29
B3	$\tau^+\nu_\tau e^-jjj$	0.28	1.6
B4	$\tau^+\nu_\tau\nu_e jjj$	8.2×10^{-6}	9.3×10^{-5}
B5	$\mu^+\mu^-e^-jjj$	0.58	2.1
B6	$\mu^+\mu^-\nu_e jjj$	8.6×10^{-2}	0.39
B7	$\mu^+\nu_\mu e^-jjj$	0.28	1.6
B8	$\mu^+\nu_\mu\nu_e jjj$	8.1×10^{-6}	9.3×10^{-5}

Table 3. The production cross sections of background processes at the LHeC and FCC-eh for the leptonic τ_μ final state.

$\mathrm{Br}(Z \to N\nu_\tau, N\bar{\nu}_\tau) < 1.3\times10^{-6}$

obtain the modification of the Z-boson total decay width as

$$\frac{\Gamma_Z}{\Gamma_{Z,\mathrm{SM}}} = \frac{G_W}{G_F}\left[1 + 0.175\,|V_{eN}|^2 - 0.133\left(|V_{eN}|^2 + |V_{\tau N}|^2\right)\left(1 - f\left(\frac{m_N}{m_Z}\right)\right)\right]. \quad (A.16)$$

If $m_N > m_Z$, eq. (A.16) becomes

$$\frac{\Gamma_Z}{\Gamma_{Z,\mathrm{SM}}} = 1 + 0.541\,|V_{eN}|^2 - 0.133\,|V_{\tau N}|^2. \quad (A.17)$$

Some useful observables in EWPD study are defined as [103, 104]

$$R_\ell \equiv \frac{\Gamma_{Z\to\mathrm{had}}}{\Gamma_{Z\to\ell^+\ell^-}}, \qquad R_q \equiv \frac{\Gamma_{Z\to q\bar{q}}}{\Gamma_{Z\to\mathrm{had}}}, \quad \text{and}$$

$$\sigma_H \equiv \sigma_{e^+e^-\to Z\to\mathrm{had}} = \frac{12\pi\,\Gamma_{Z\to e^+e^-}\,\Gamma_{Z\to\mathrm{had}}}{m_Z^2\,\Gamma_Z^2}. \quad (A.18)$$

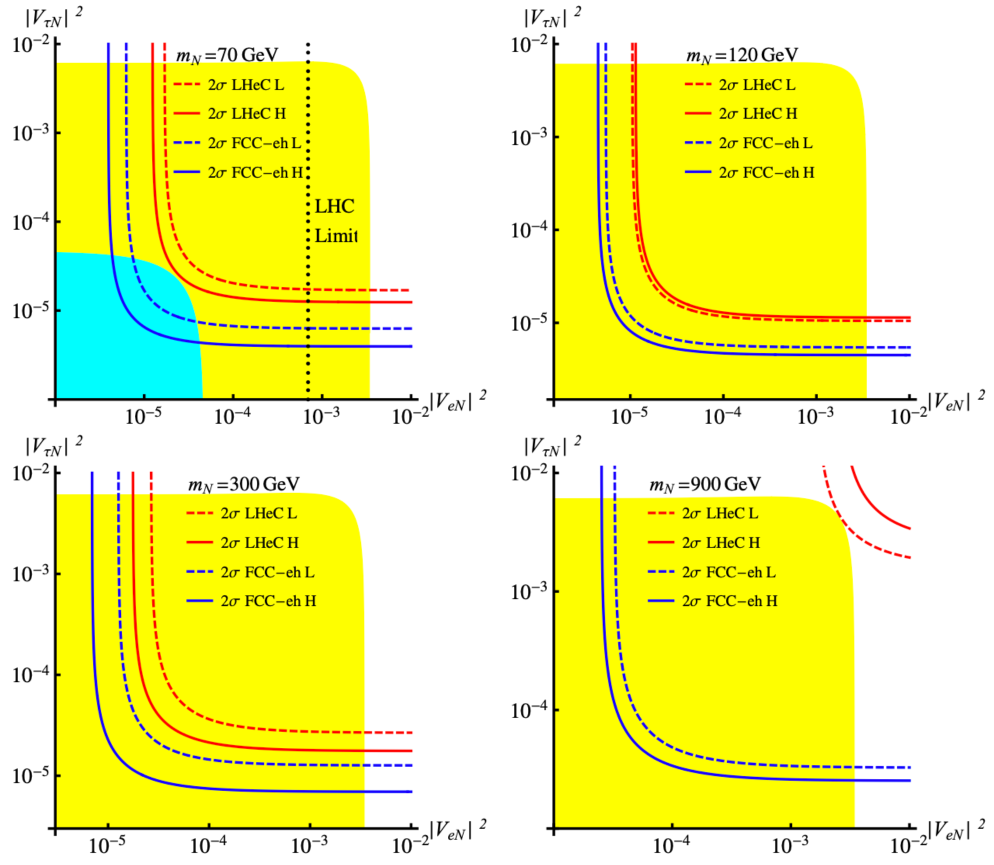

Figure 9. Assuming m_N = 70, 120, 300, 900 GeV, the 2-σ sensitivity curves for the Hadronic τ_h (H, solid) and Leptonic τ_μ (L, dashed) final states at the LHeC (red) and FCC-eh (blue) in the $|V_{\tau N}|^2$ vs. $|V_{eN}|^2$ plane, where the top right parameter space of the curves are excluded. From appendix A, yellow regions in all plots are allowed by the EWPD [47–51, 53], while the cyan region in the top left plot is allowed by the DELPHI measurement [46]. Constraints on $|V_{eN}|^2$ from the LHC experiments [36, 37, 39] are shown as black dotted line, which appears only in the top left plot, because 播客 onstraints are too weak for large m_N.

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Signatures of LLPs in ND

When $\lambda \sim \mathcal{O}(1)$ m,

Mainly decay inside the near detector

Appear as displaced vertex

Various final states depending on different decay products

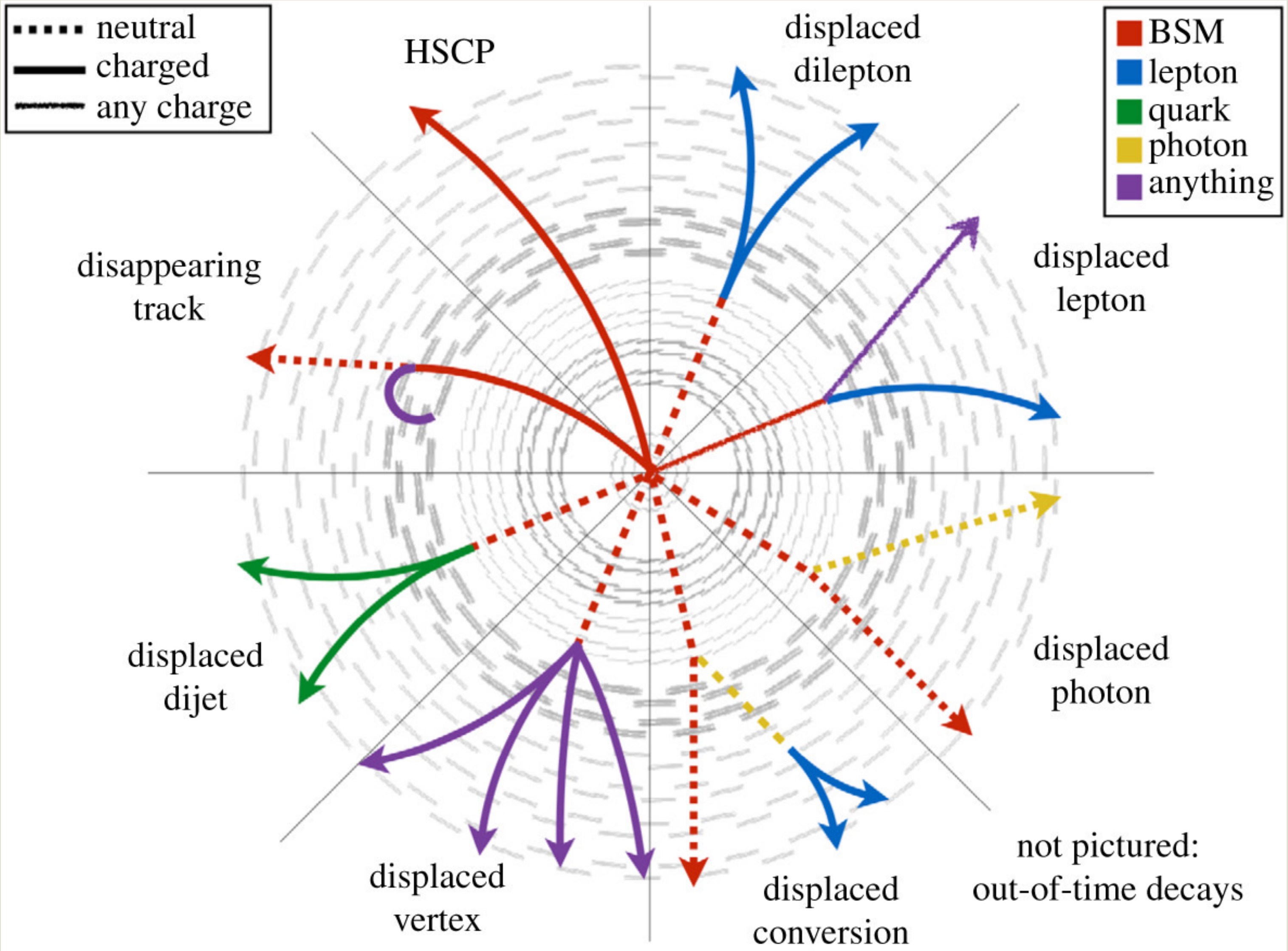

Figure from [A. De Roeck, Phil. Trans. Roy. Soc. Lond. A 377, 20190047 (2019)]

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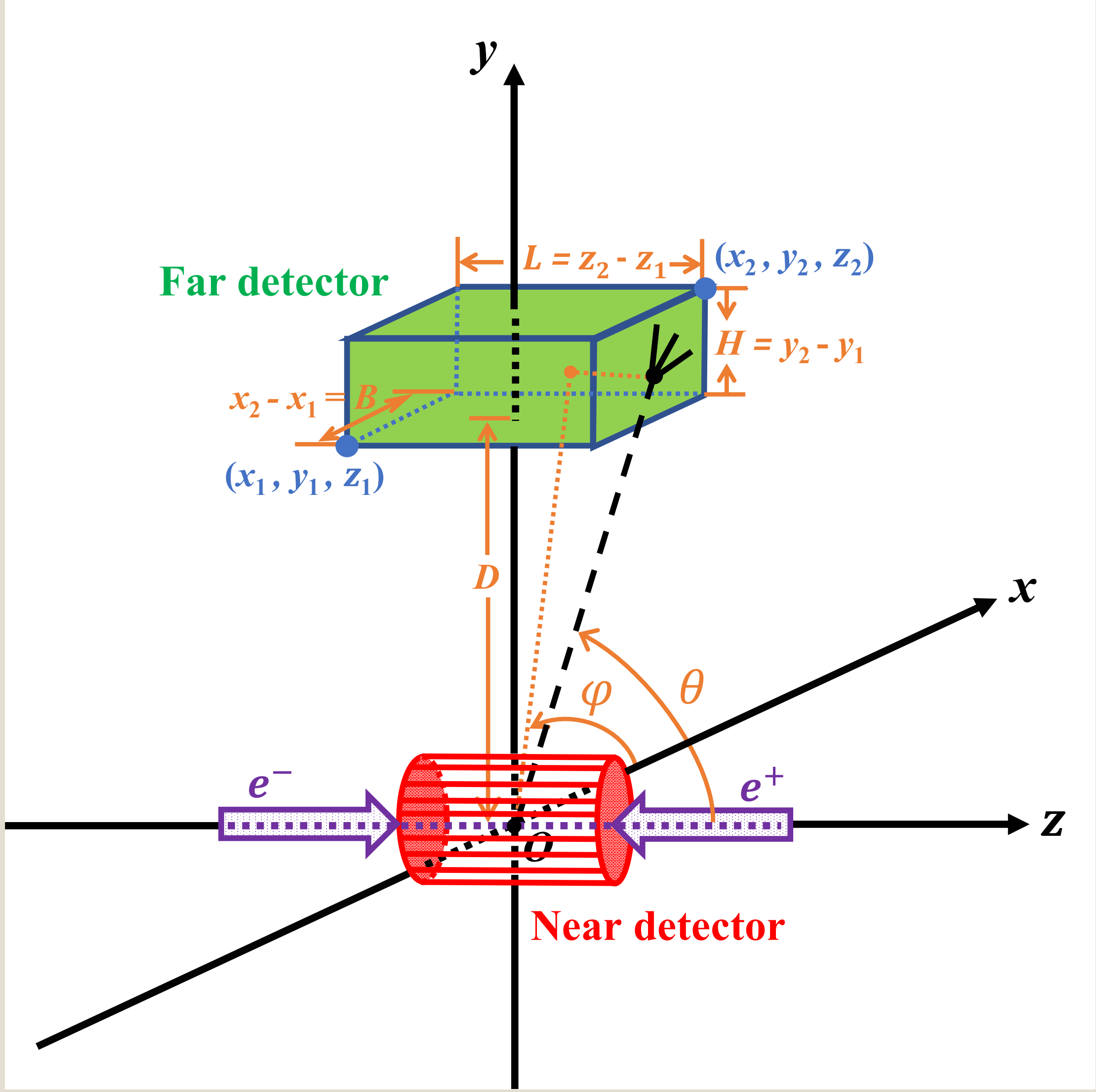
Signatures of LLPs in FD

When $\lambda \sim \mathcal{O}(100)$ m,

Mainly travel through and acts as missing energy in the near detector.

Far detector is more likely to observe the decay process, and reconstruct the time, position, direction, momentum, mass, etc.

Far detector can enhance the discovery potential for LLPs with very long decay length.



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Proposed Far Detectors @ LHC

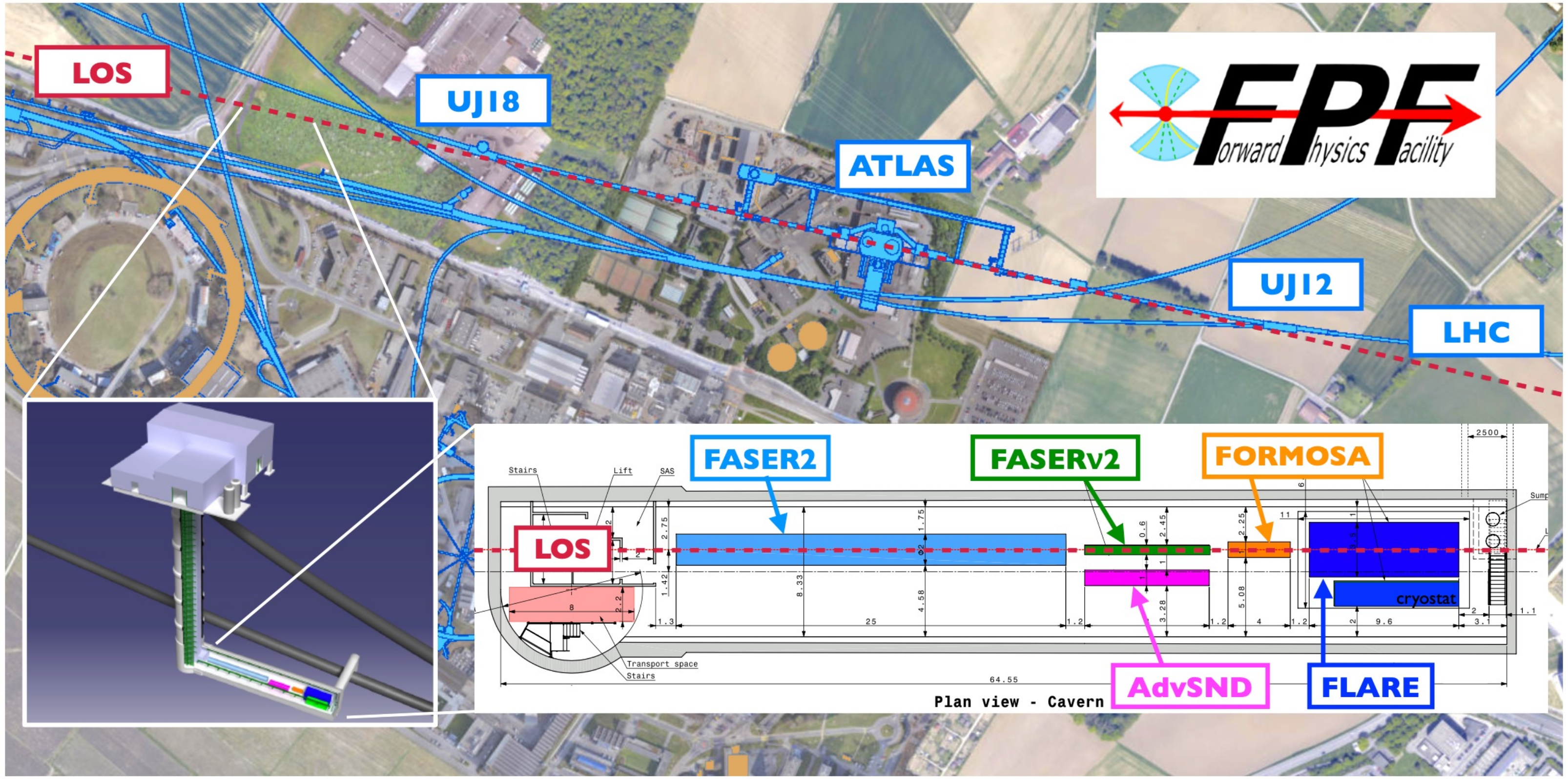

Figure 1: The preferred location for the Forward Physics Facility, a proposed new cavern for the High-Luminosity era. The FPF will be 65 m-long and 8.5 m-wide and will house a diverse set of experiments to explore the many physics opportunities in the far-forward region.

MATHUSLA; FASER2, FASERv2, AdvSND, FLArE, FORMOSA; CODEX-b; AL3X; ...

[2203.05090, The Forward Physics Facility at the High-Luminosity LHC]

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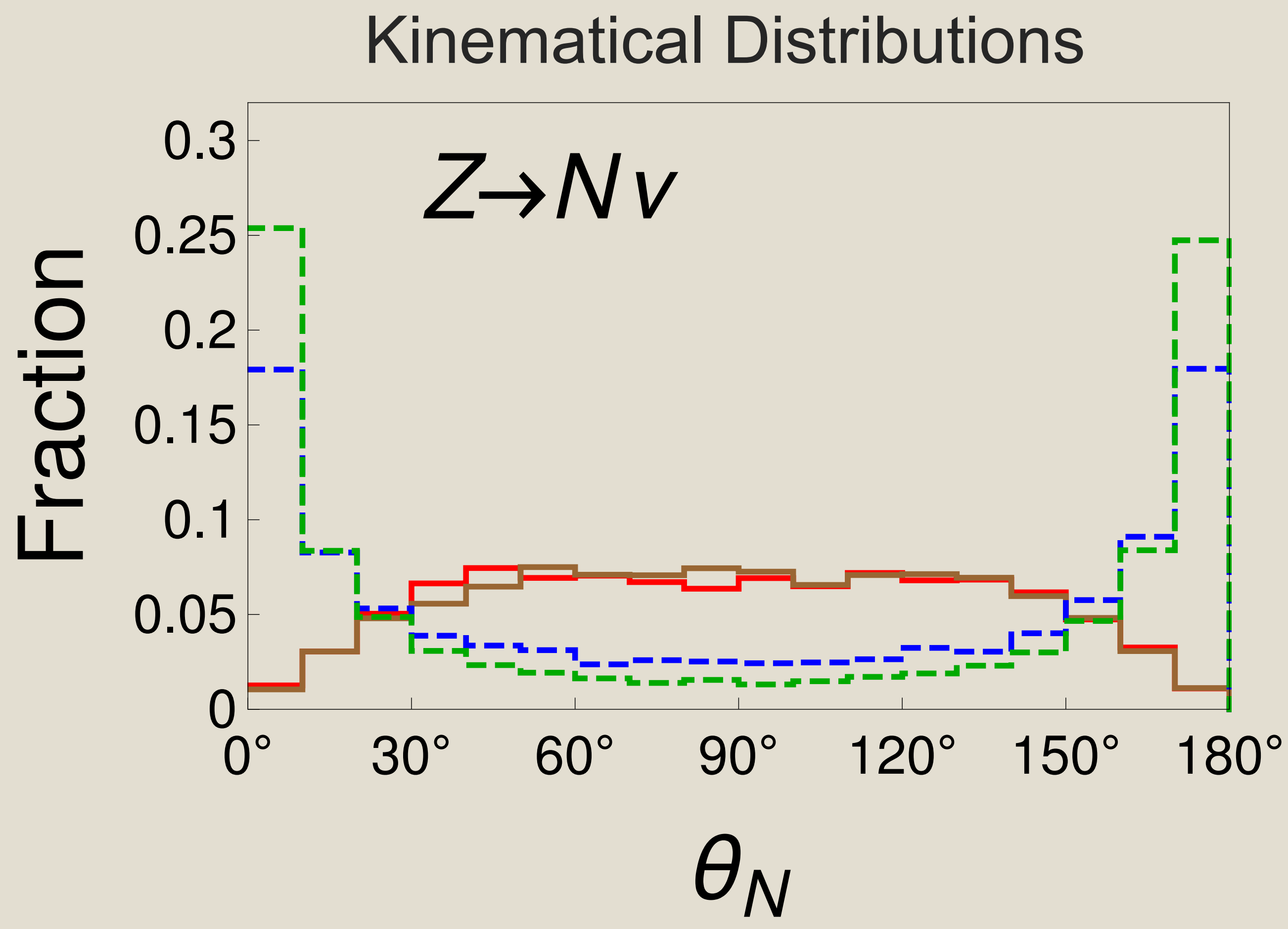
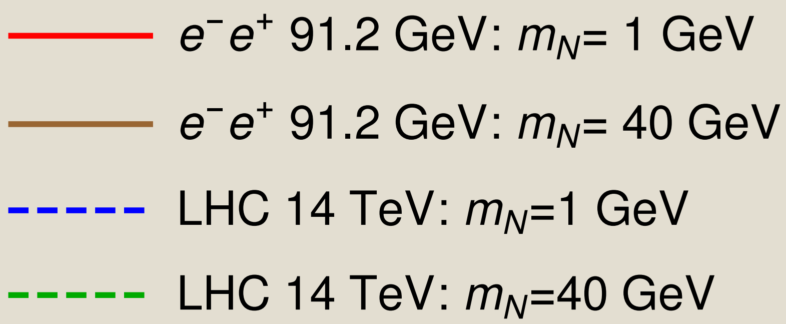


N **Production @ CEPC**

@ pp: very forward direction
@ ee: more in the transverse direction



FDs in the very forward direction like FASER may not work at ee colliders.
Better to be installed in the central region.