IRN Terascale @ Heidelberg

Hunting for Heavy Neutral Leptons at Future Lepton Colliders

Based on [2412.04331] & [2512.16734] with J. Kriewald, and A. M. Teixeira

Emanuelle Pinsard

DESY

HELMHOLTZ

Neutrinos beyond the SM

Standard Model lepton sector: neutrinos are strictly **massless**

⇒ **no source of charged Lepton Flavour Violation**

Neutrino oscillations: 1st laboratory **evidence of New Physics**

↝ neutrinos are **massive** & **leptons mix** $\mathcal{U}_{\alpha i}^{\mathrm{PMNS}}$

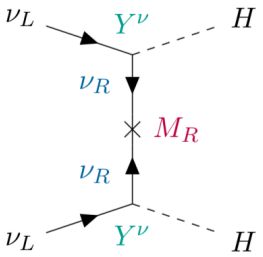
But many new open questions:

Absolute ν **mass scale**
Ordering of the light ν spectrum
Nature (**Dirac** vs. **Majorana**)
Lepton number violation
New sources of **CP violation**
New **states to generate neutrino masses**

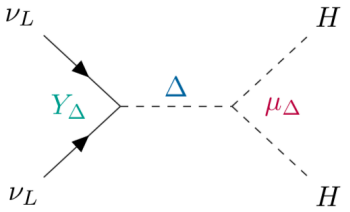
Generating neutrino masses

↪ **Seesaw** (and its variants):

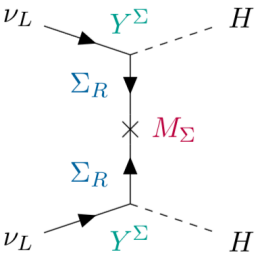
one of the most appealing mechanisms for m_ν **generation**



Type I



Type II

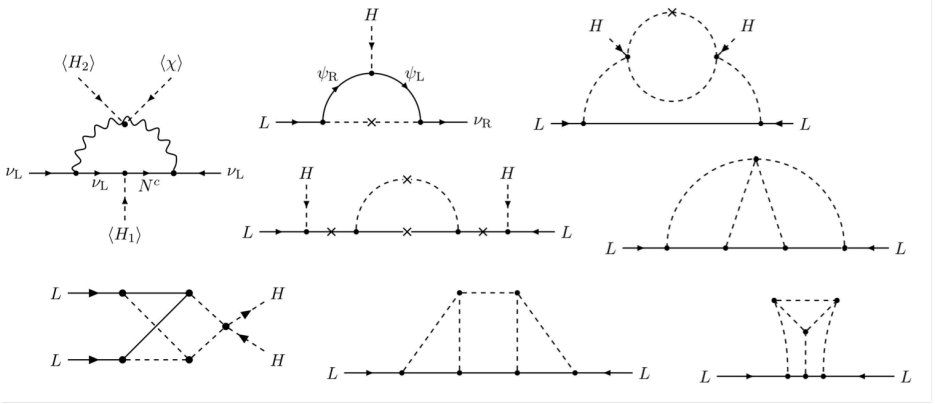


Type III

↪ **Low-scale** realisations:

Inverse seesaw, linear seesaw, νMSM, ...

↪ Several **other well-motivated** possibilities:



Cai et al. [1706.08524]

Tree or **loop**(s) generation,

Dirac or **Majorana**,

in SUSY, GUTs, with LQs, sterile ν, ...

Addressing (or not) other **tensions**

or **observational** caveats of the **SM**

Comprehensive review, Cepedello [2105.01896]

Introducing sterile fermions

Sterile fermions: ($\sim \nu_R$ RH neutrinos)

present in SM extensions accounting for **neutrino masses & mixings**

↝ Interactions with SM fields only through **mixings** with active neutrinos

↝ No bound on the **number** of the sterile states

↝ Common to numerous NP models, wide range of **scales**

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$\Longrightarrow$ **Phenomenological** implications strongly depend on their **masses**

Low-scale seesaw ↝ non-decoupled states, **modified lepton currents**!

Rich phenomenology at low-energies, high-intensity and colliders

EW precision tests, cLFV transitions and decays, $0\nu2\beta$ decays, rare meson decays, ...

Introducing sterile fermions

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Low-scale seesaw ↝ non-decoupled state[illegible] **dified lepton currents**!

Rich phenomenolo[illegible] tensity and colliders

Testability!

EW precision tests, cLFV [illegible]ons and decays, $0\nu2\beta$ decays, rare meson decays, ...

Impact of sterile neutrinos

How does the presence of **sterile neutrinos** affect the **SM** predictions?

Active-sterile mixing $\mathcal{U}_{\alpha i}$

Neutrino spectrum:

- **3 light** (mostly active) neutrinos
- 1 **heavy** **non-decoupled** state, sizeable **mixing** with active ν

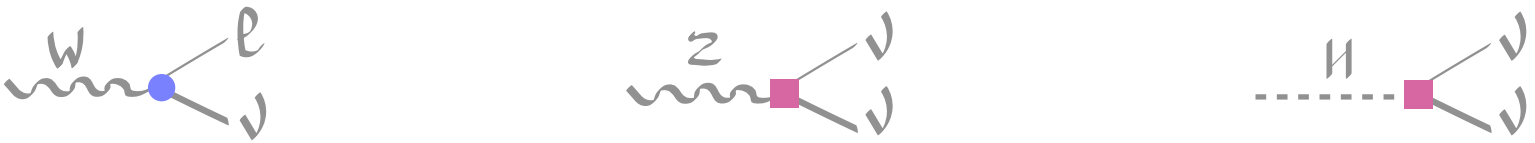
Left-handed lepton mixing $\tilde{\mathcal{U}}_{\text{PMNS}}$

3×3 sub-block **non-unitary**!

$$\mathcal{U}_{4\times4} = \begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} & \mathcal{U}_{e4} \\ \mathcal{U}_{\mu1} & \mathcal{U}_{\mu2} & \mathcal{U}_{\mu3} & \mathcal{U}_{\mu4} \\ \mathcal{U}_{\tau1} & \mathcal{U}_{\tau2} & \mathcal{U}_{\tau3} & \mathcal{U}_{\tau4} \\ \mathcal{U}_{s1} & \mathcal{U}_{s2} & \mathcal{U}_{s3} & \mathcal{U}_{s4} \end{pmatrix} \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{matrix}$$

n_1 n_2 n_3 n_4

$\Longrightarrow$ **Modified** **charged** & **neutral** lepton currents!



Impact of modified lepton currents

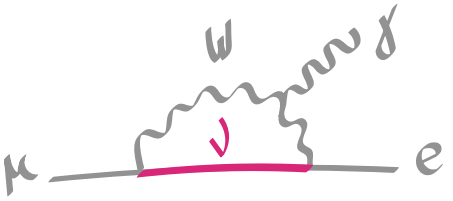
Sterile neutrinos & **non-unitary** **leptonic mixing**

Sizeable impact on **flavour observables** both at **tree** & **loop** **level**

↝ **Charged lepton flavour violation:** *Strictly forbidden in the SM*

Expect **significant contribution**

from **sterile neutrino** extensions



Negative cLFV searches

$\Longrightarrow$ **Strong bounds** on **HNL** extensions**:** often **most stringent** ones

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↝ **Electroweak precision observables** & **Lepton flavour universality**

Measurements in "good" agreement with **SM predictions**

$\Longrightarrow$ **Strong bounds** on **HNL** constructions

Searches for HNL

Where to search for **sterile neutrinos?**

↝ Via searches @ **high-intensities**

e.g. MEG, COMET, Mu2e, Mu3e, Belle II, neutrino dedicated, TRIUMF, NA62, ...

Meson decay & beam dump exp.: HNL **decay products** or **missing energy**

Neutrino **oscillation** experiments, Low-energy **cLFV** signatures,

Beta decay and **Neutrinoless double beta decay**

(Mainly) probe **low masses** (together with cosmological searches)

↝ And searches @ **colliders**

e.g. LHC, future CLIC, future FCC-ee, future muon colliders

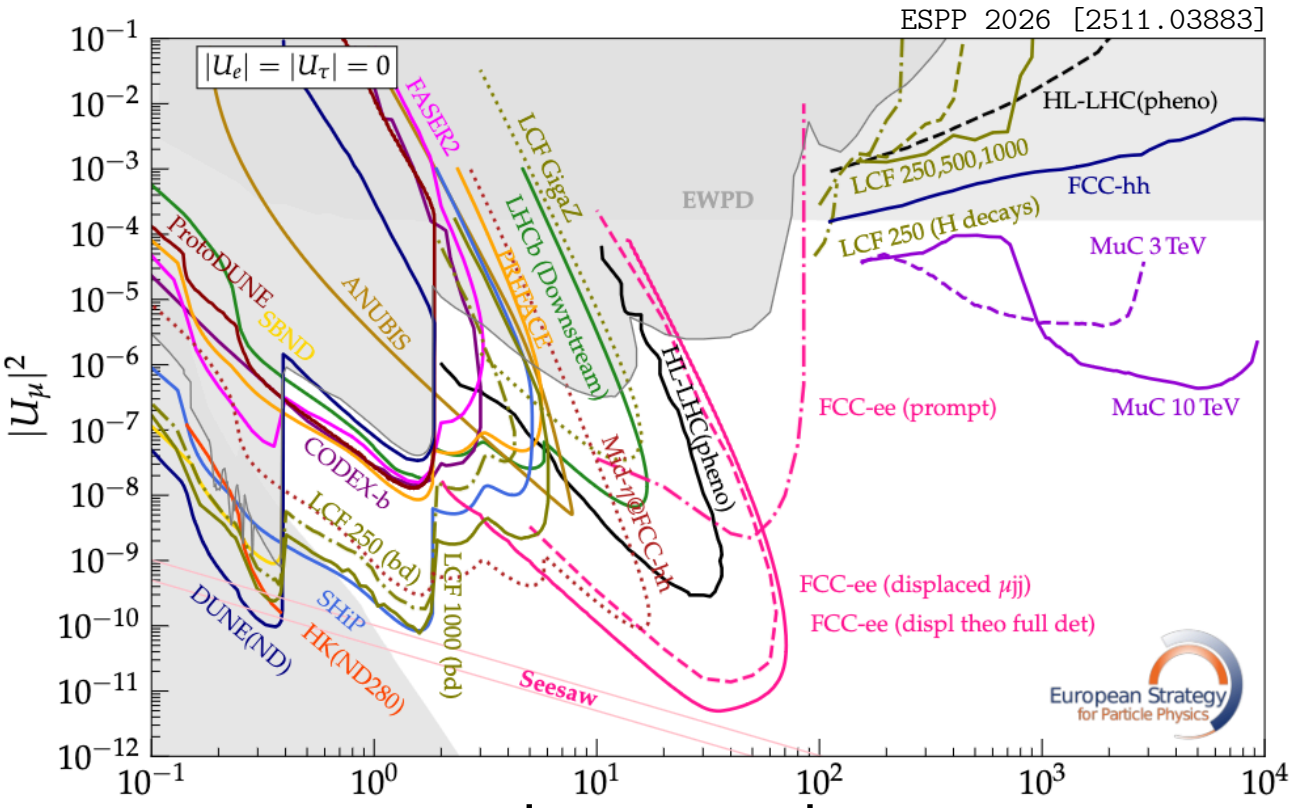
Direct production and **decay products**: $N \to W\ell, N \to Z\nu, N \to h\nu$

Displaced vertices, **LNV** signatures, **EWPO**

Allow probing **heavy masses**

Searches for HNL

Simplified scenario: **1 HNL** with **only 1 mixing** to 1 type of **active ν**



High-intensity facilities | FCC-ee @ Z pole | High-energy colliders & EWPO

5 GeV M_Z

HNL mediated cLFV scattering at μTRISTAN

μTRISTAN

μTRISTAN future **asymmetric μ^+e^-** collider (and possibly $\mu^+\mu^+$)

- **3 km ring** configuration
- Nominal **beam energies**
- **Polarisation** of beams
- $L^{\text{int}} \sim 100\,\text{fb}^{-1}$ per year
  $L^{\text{int}} \sim 1\,\text{ab}^{-1}$ in 10 years

E_{e^-} (GeV)	E_{μ^+} (GeV)	$\sqrt{s}$ (GeV)
20	200	126.5
30	1000	346.4
50	1000	447.2
100	3000	1095.4

[See e.g. Yamada et al, 2201.06664]

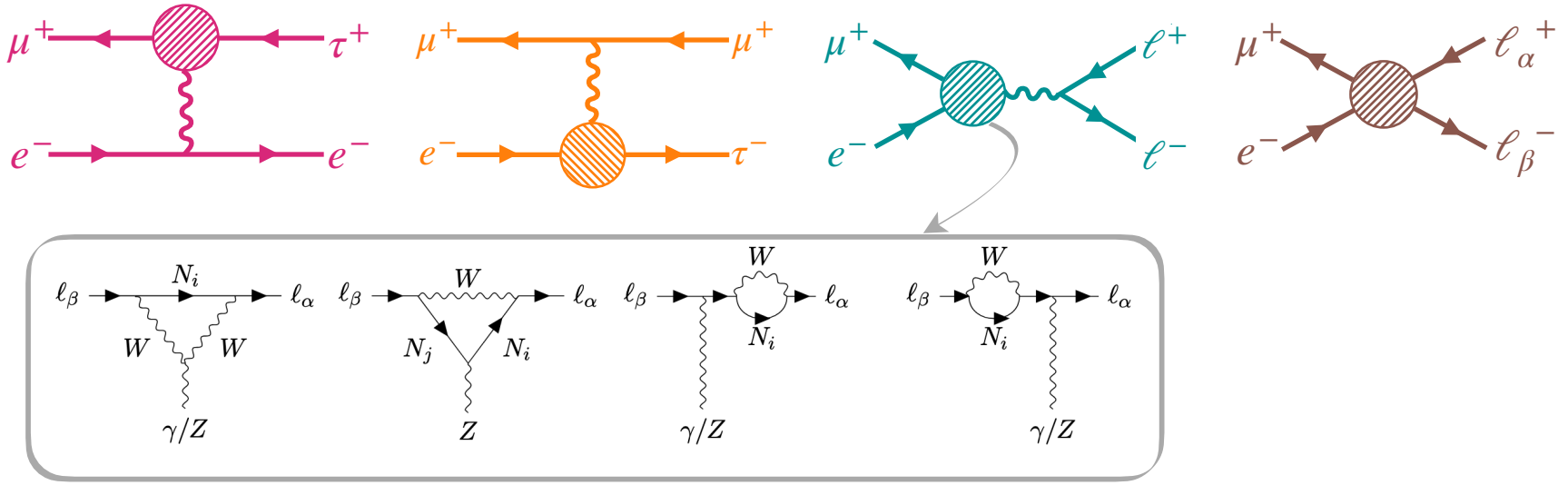
With μ^+e^- beams, **SM** processes are mainly from **higher-order**

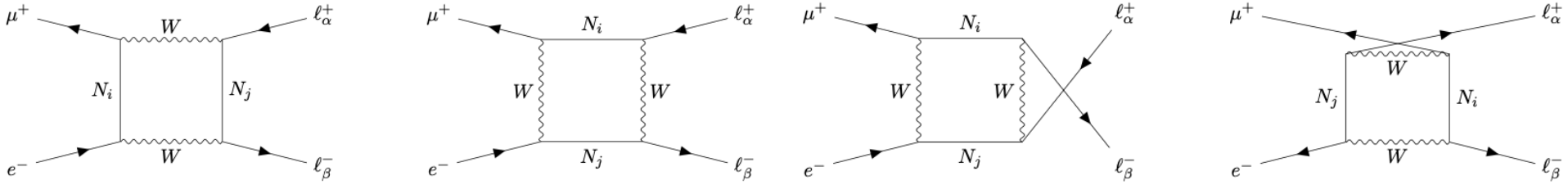
$\Rightarrow$ **Reduces physical background** (vs. $\ell^+\ell^-$ colliders)

cLFV scattering at μTRISTAN

μTRISTAN future **asymmetric μ^+e^-** collider ($\sqrt{s} \approx 126$ GeV - 1 TeV)

↪ Consider **HNL contributions** to $\mu^+e^- \to \ell_\alpha \ell_\beta$ ($\mu^+\tau^-$, τ^+e^-, $\tau^+\tau^-$, $e^+\mu^-$)





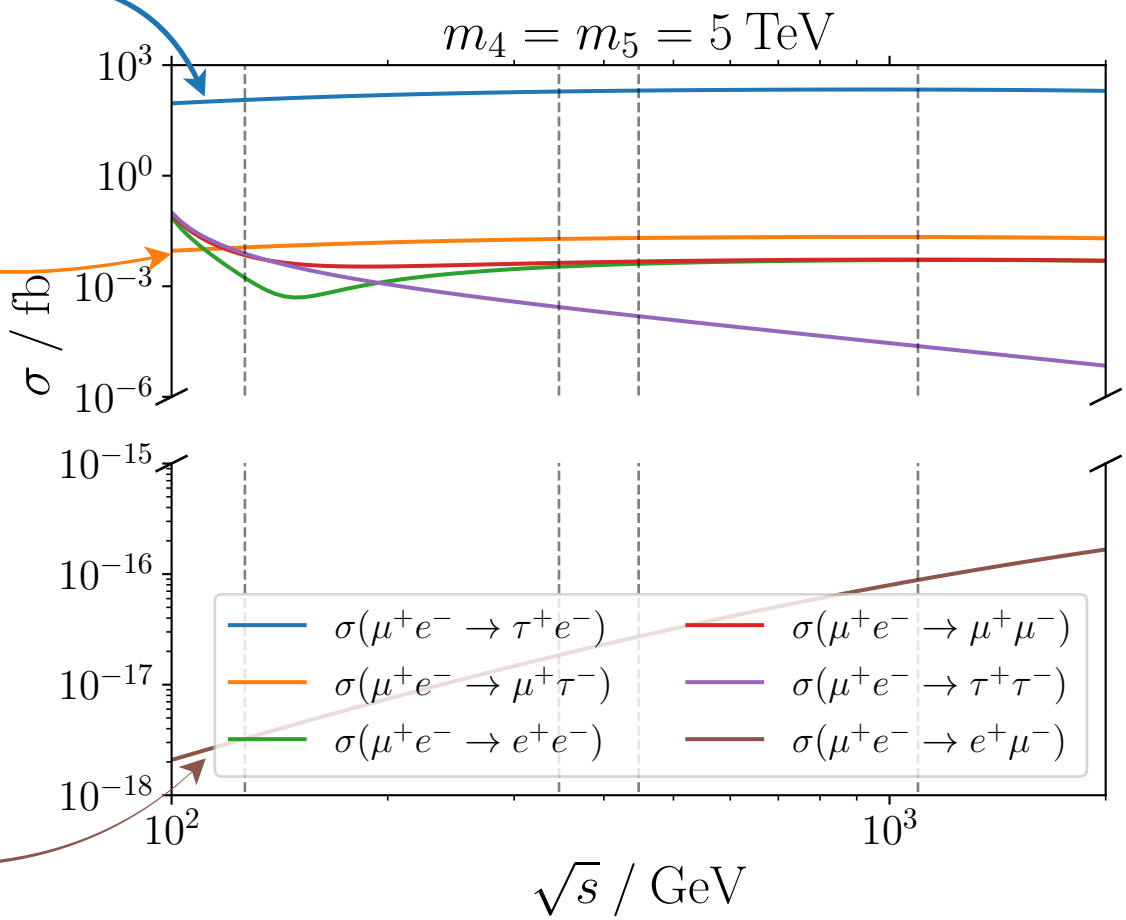
HNL mediated scattering

Illustration in **minimal 3+2** for a benchmark point **consistent with data**

t-channel mediated:
near **independence of** s

e^+e^- and $\mu^+\mu^-$ final states
competing s and t channels
(s at low c.o.m, interferences,
then t dominates)

Boxes subdominant



[Kriewald, EP, Teixeira, 2412.04331]

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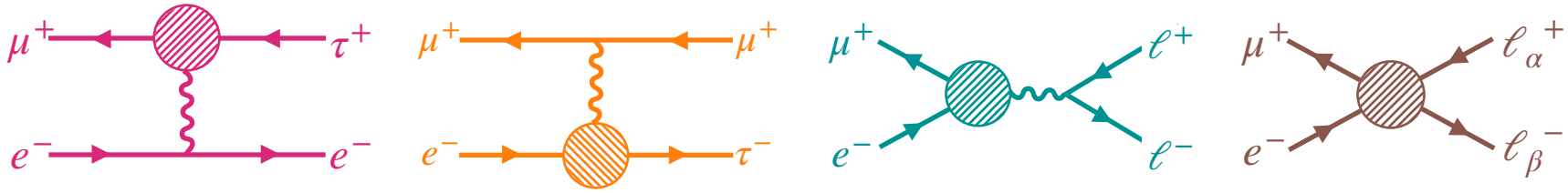
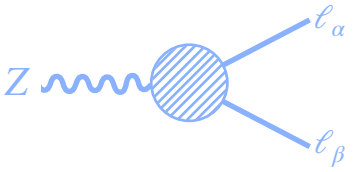
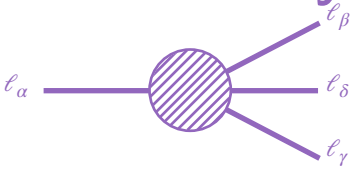


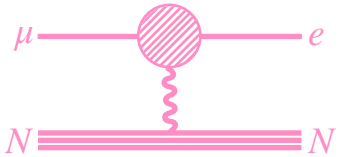
↝ **Clear connection** with **cLFV Z decays**

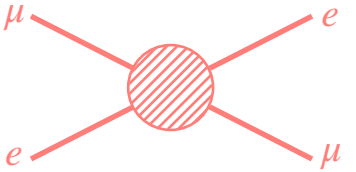


& **low-energy** cLFV: **cLFV radiative decays** & **cLFV three-body decays**



$\mu - e$ conversion in nuclei & **muonium oscillations**





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↝ Consider HNL contributions to $\mu^+e^- \to \ell_\alpha \ell_\beta$ ($\mu^+\tau^-$, τ^+e^-, $\tau^+\tau^-$, $e^+\mu^-$)

Can $\mu^+e^- \to \ell_\alpha \ell_\beta$ scattering at μTRISTAN be **competitive** with other **cLFV searches?** (low-energy and Z pole)

Illustrate results with **well-motivated m_ν mechanism: ISS(3,3)**

& I

cays

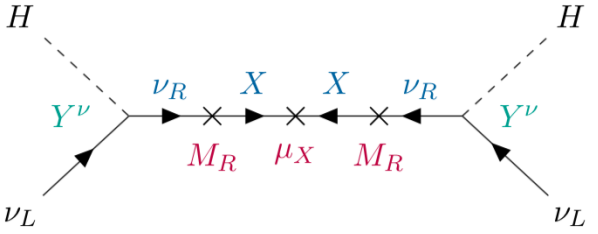
$\mu - e$ conversion in nuclei & muonium oscillations

(Inverse seesaw mechanism)

Low-scale mechanism for **neutrino mass generation**

↪ **ISS(3,3):** SM + 3 **RH neutrinos** ν_R and 3 **sterile states** X

$$\mathcal{L}_{\rm ISS} = -\frac{1}{2}(\overline{\nu_L^c}, \overline{\nu_R}, \overline{X^c}) \begin{pmatrix} \mathbb{0} & m_D^T & \mathbb{0} \\ m_D & \mu_R & M_R \\ \mathbb{0} & M_R^T & \mu_X \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \\ X \end{pmatrix}$$



3 **light** (mostly active) neutrinos: $m_\nu \simeq m_D^2 \dfrac{\mu_X}{M_R^2}$

3 **heavy pseudo-Dirac** pairs: $M_{\rm heavy} \approx M_R \pm \mu_X$

Smallness of m_ν from **interplay** of **2 scales:** M_R and μ_X

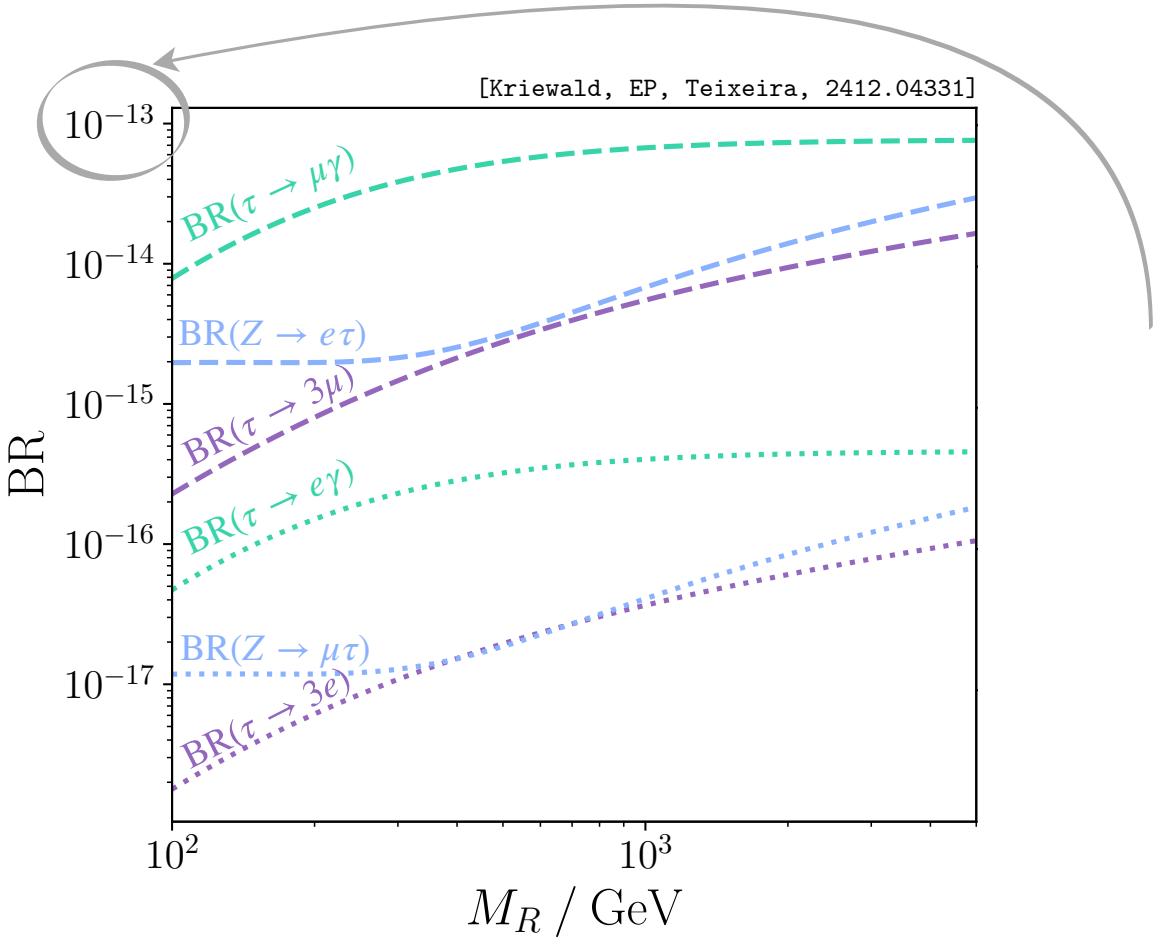
$\mu_X \to 0$ **lepton number** is restored ⇒ Small values of μ_X technically natural

↪ **Low NP scale** $\sim M_R$ and **sizeable mixings** ($\theta \propto m_D M_R^{-1}$)

Very rich phenomenology

μTRISTAN and τ-cLFV

Low-energy τ-cLFV and $Z \to \tau\ell$ vs. $\sigma(\mu^+e^- \to \ell_\alpha^+\ell_\beta^-)$ at **μTRISTAN**



In the **Inverse Seesaw (3,3)**
$\Rightarrow$ **Low-energy τ-cLFV**
and **cLFV $Z \to \tau\ell$**
far below future sensitivities

$$\mathrm{BR}(\tau \to \ell\gamma) \lesssim 10^{-9}$$
$$\mathrm{BR}(Z \to \tau\ell) \lesssim 10^{-10}$$
$$\mathrm{BR}(\tau \to 3\ell) \lesssim 10^{-10}$$

μTRISTAN and τ-cLFV

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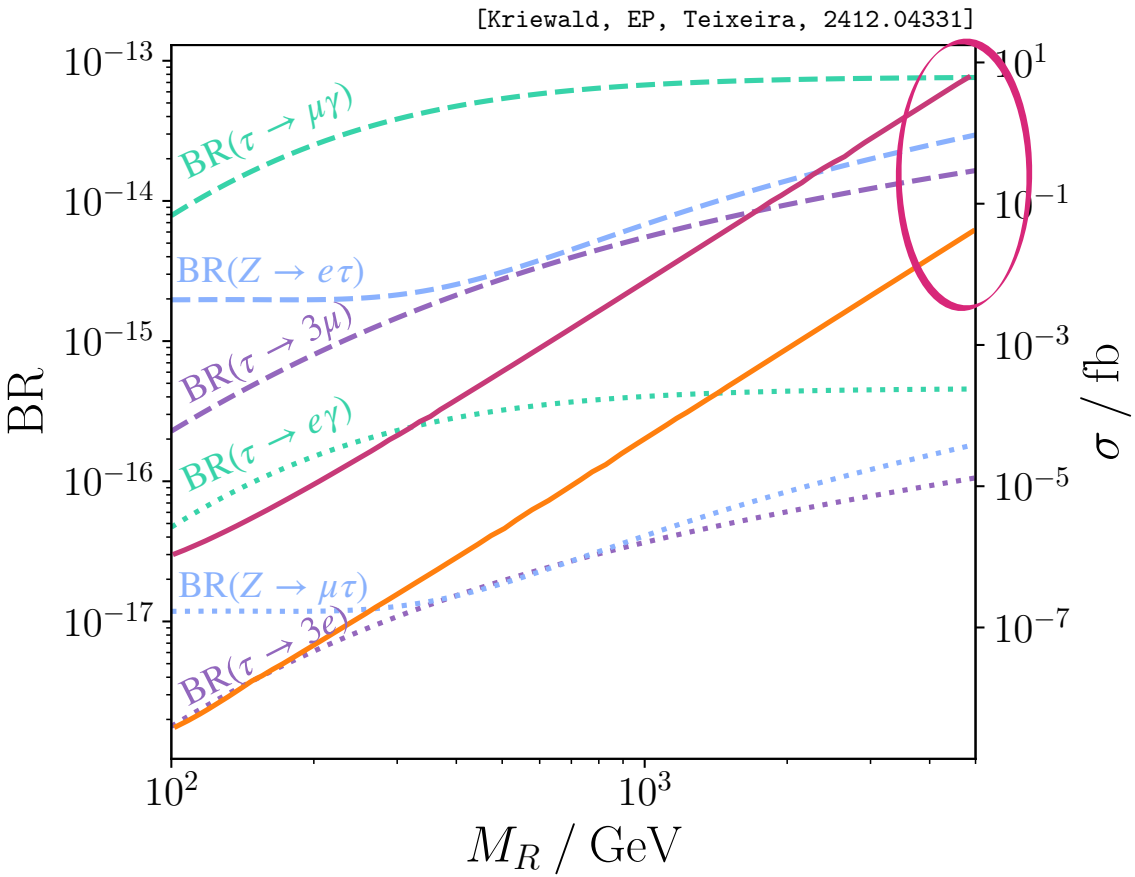

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far below future sensitivities

BUT sizeable $\mu^+e^- \to \tau^+e^-$
& **$\mu^+e^- \to \mu^+\tau^-$**
Leading up to **100(0) events**

Competitive prospects for
τ-cLFV searches at **μTRISTAN**

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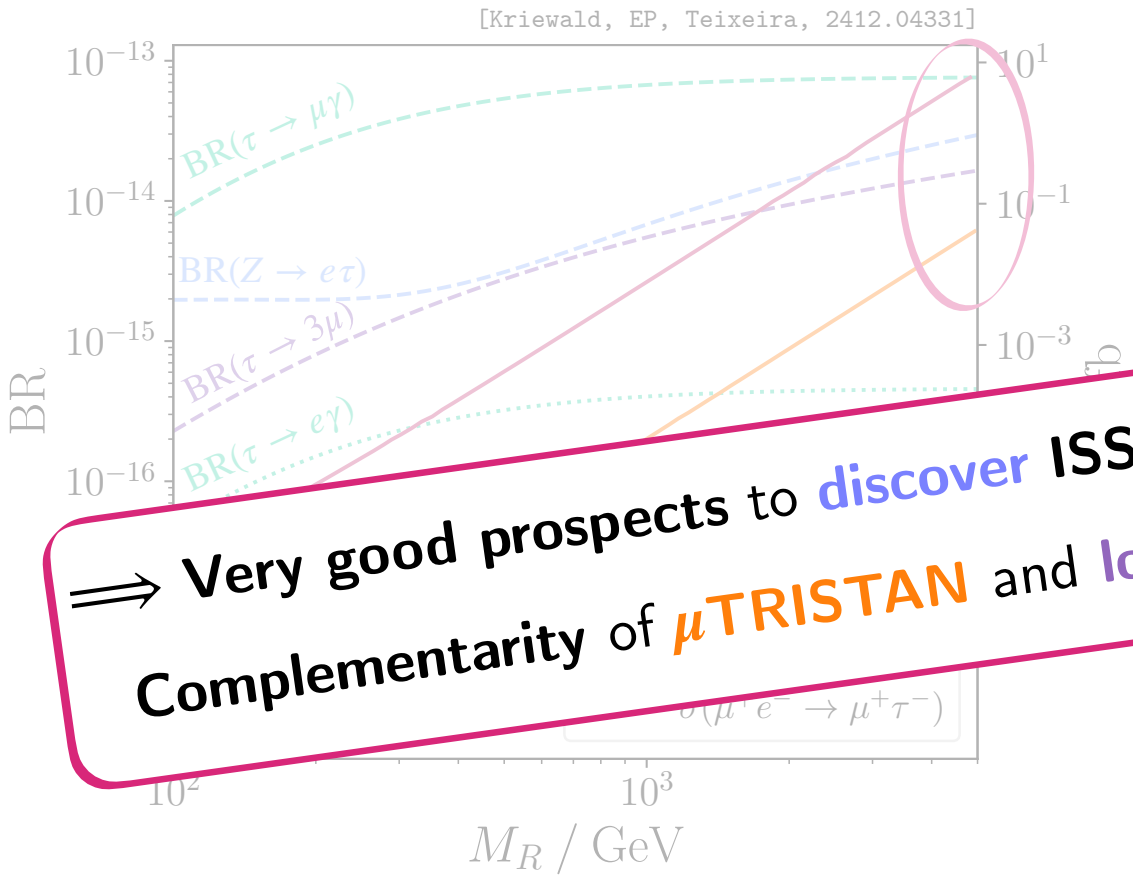
Low-energy τ-cLFV and $Z \to \tau\ell$ vs. $\sigma(\mu^+e^- \to \ell_\alpha^+\ell_\beta^-)$ at **μTRISTAN**



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$\Rightarrow$ **Low-energy τ-cLFV**
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far below future sensitivities

leading up to **100(0) events**

$\Longrightarrow$ **Very good prospects** to **discover ISS(3,3)** via **τ-cLFV scattering**

Complementarity of **μTRISTAN** and **low-energy τ-cLFV** searches

Competitive prospects for
τ-cLFV searches at **μTRISTAN**

ISS(3,3) at μTRISTAN

Constraining the **ISS(3,3)** parameter space (μ_X, M_R) with **μTRISTAN?**

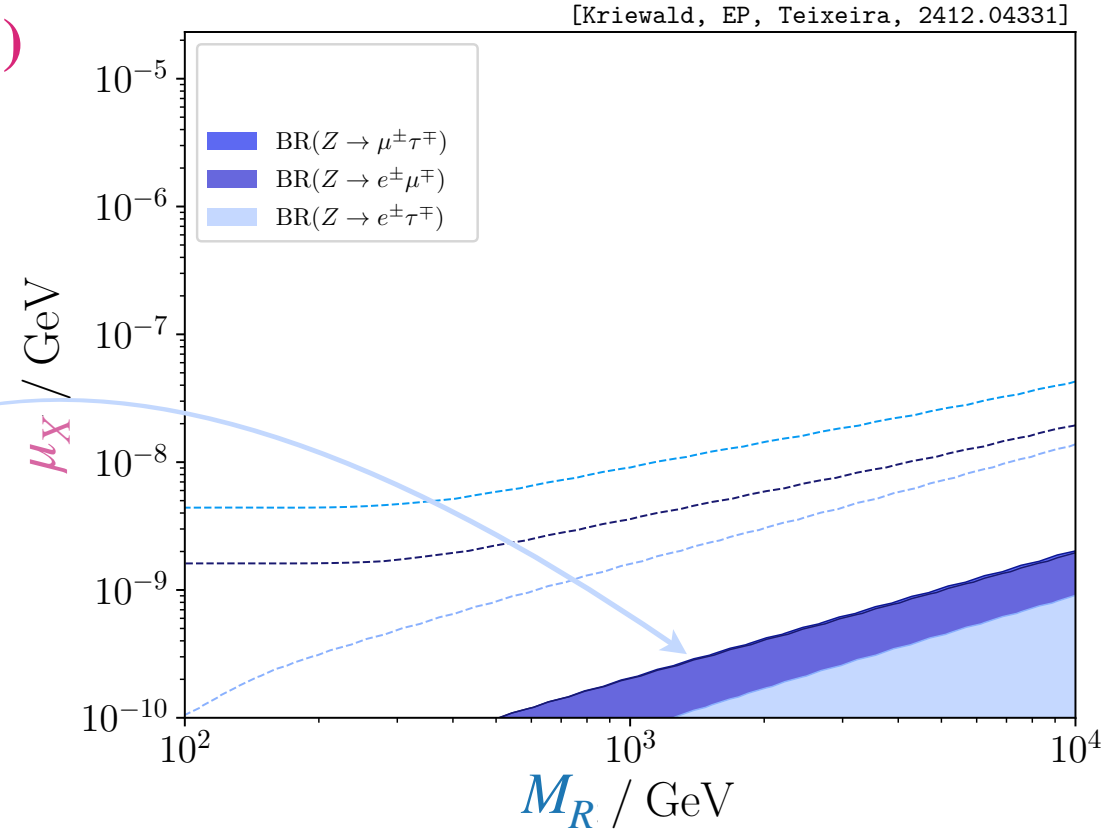
$Z \to \ell_\alpha \ell_\beta$ vs. $\sigma(\mu^+ e^- \to \ell_\alpha^+ \ell_\beta^-)$

$Z \to \ell_\alpha \ell_\beta$ constrains **small part** of the **ISS(3,3) parameter space:**

very **small** μ_X & **large** M_R

Future sensitivity:

expect some improvement



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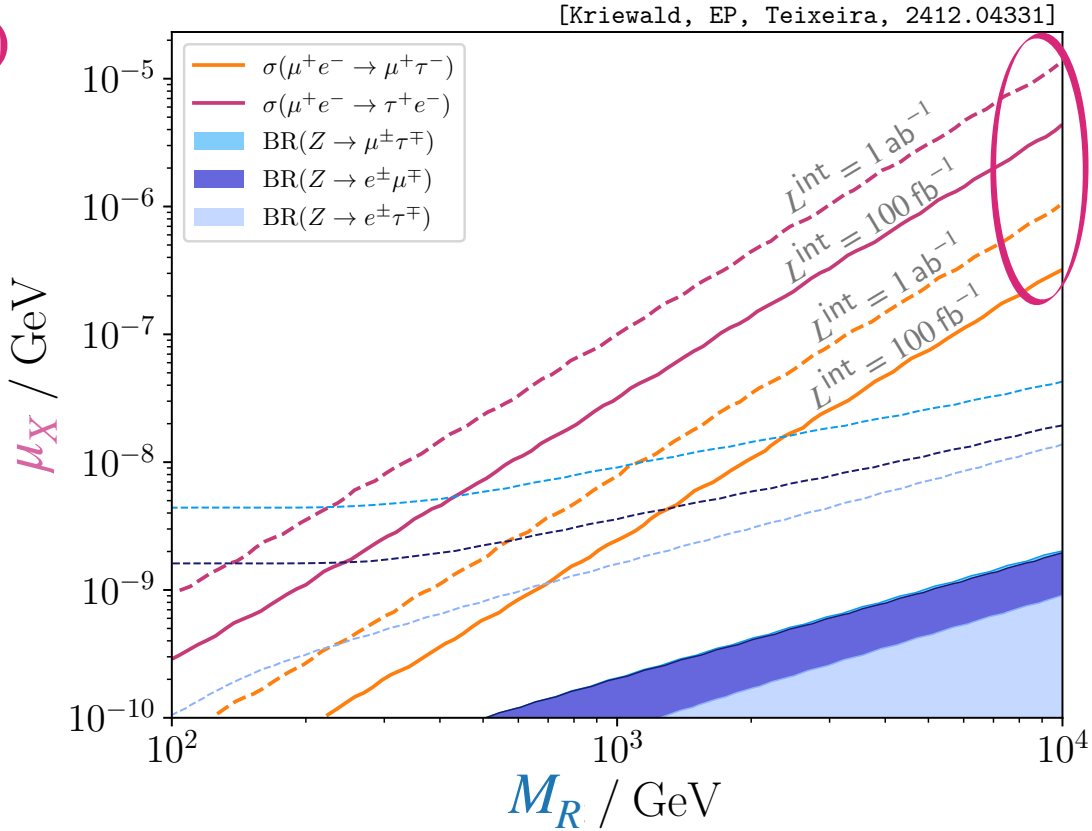
$Z \to \ell_\alpha \ell_\beta$ vs. $\sigma(\mu^+ e^- \to \ell_\alpha^+ \ell_\beta^-)$

Assume **1% signal** efficiency

Require **10 events** detection

$\Longrightarrow$ **Probe important region** the **ISS(3,3) parameter space** with **large** μ_X



μTRISTAN can **vastly outperform** future **FCC-ee** sensitivities

cLFV scattering at μTRISTAN

Complementarity with **low-energy cLFV** and Z **pole** searches

Stronger probes for cLFV involving τ **leptons**

Rich prospects for the **observation** of $\tau - \ell$ flavour violation (even in the absence of other cLFV signals)

Very good prospects to discover
ISS heavy sterile states through cLFV scattering at μTRISTAN

Di-Higgs production at future high-energy lepton colliders

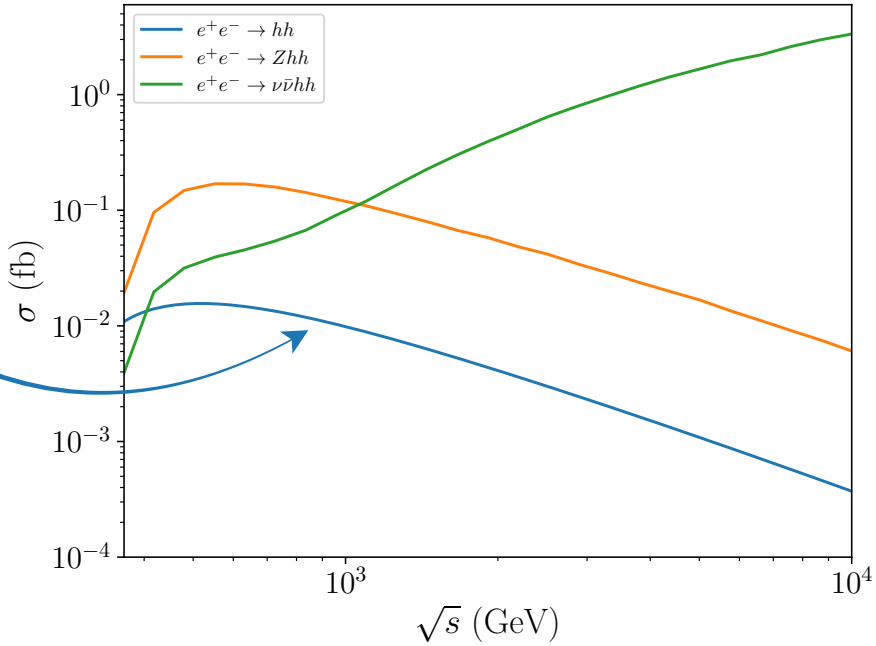
Di-Higgs production in the SM

In the **SM**, the **di-Higgs production** at e^+e^- colliders occurs via

- Double VBF $e^+e^- \to W^+W^- \to hh\nu\nu$
- Double Higgs-strahlung $e^+e^- \to Zhh$
- (Mostly) loop-induced $e^+e^- \to hh$

  $\Rightarrow$ **Subdominant process**

Kriewald, **EP**, Teixeira [2512.16734]

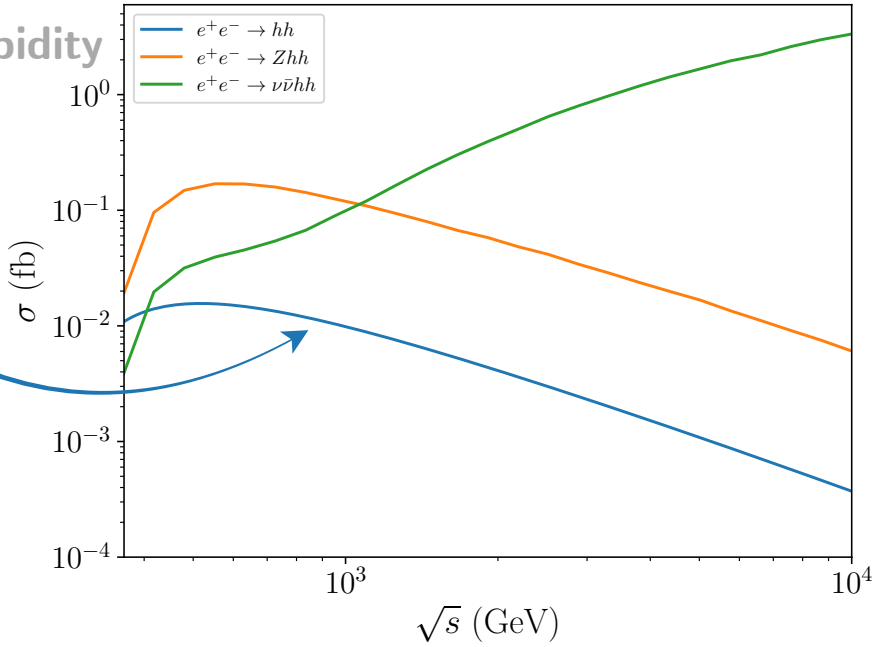


Di-Higgs production in the SM

In the **SM**, the **di-Higgs production** at e^+e^- colliders occurs via

Can be distinguished due to the **distinct pseudo-rapidity** & **transverse-momentum distributions**

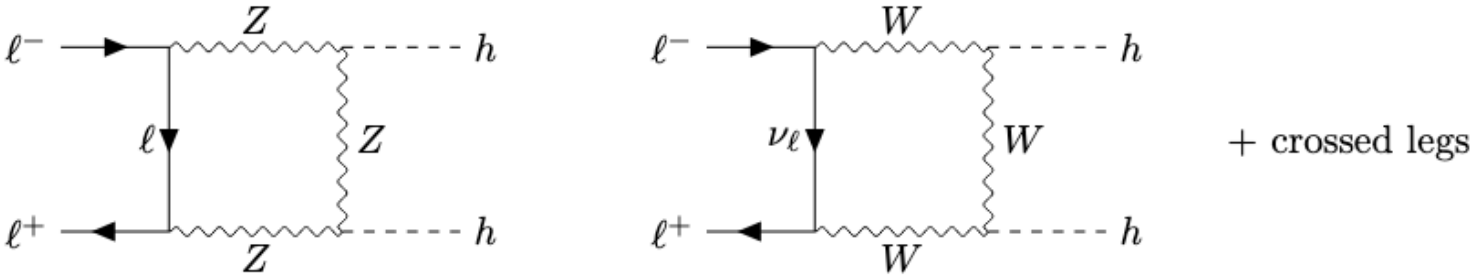
Kriewald, **EP**, Teixeira [2512.16734]



- (Mostly) loop-induced $e^+e^- \to hh$
  ⇒ **Subdominant process**

  Loop-suppressed
  Vanishing Z^*, γ^* triangles (no CPV)
  Tree & triangles $\propto m_e$

Only **SM** contributions:



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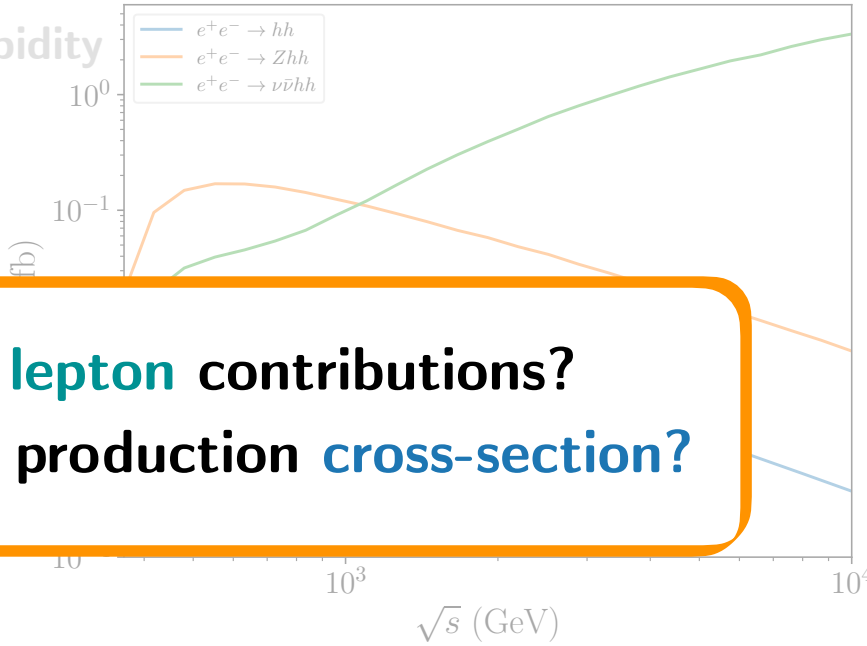


Can be distinguished due to the **distinct pseudo-rapidity & transverse-momentum distributions**

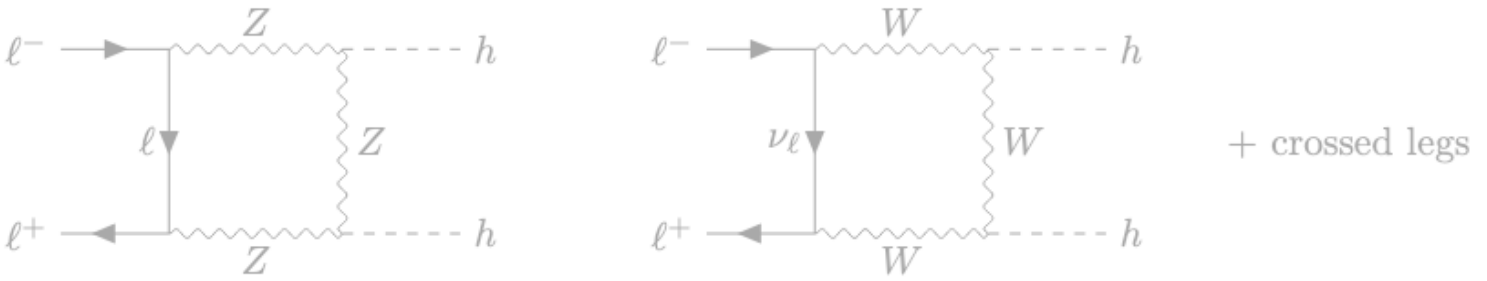
- (M

Vanishing Z^*, γ^* triangles (no CPV)

Tree & triangles $\propto m_e$

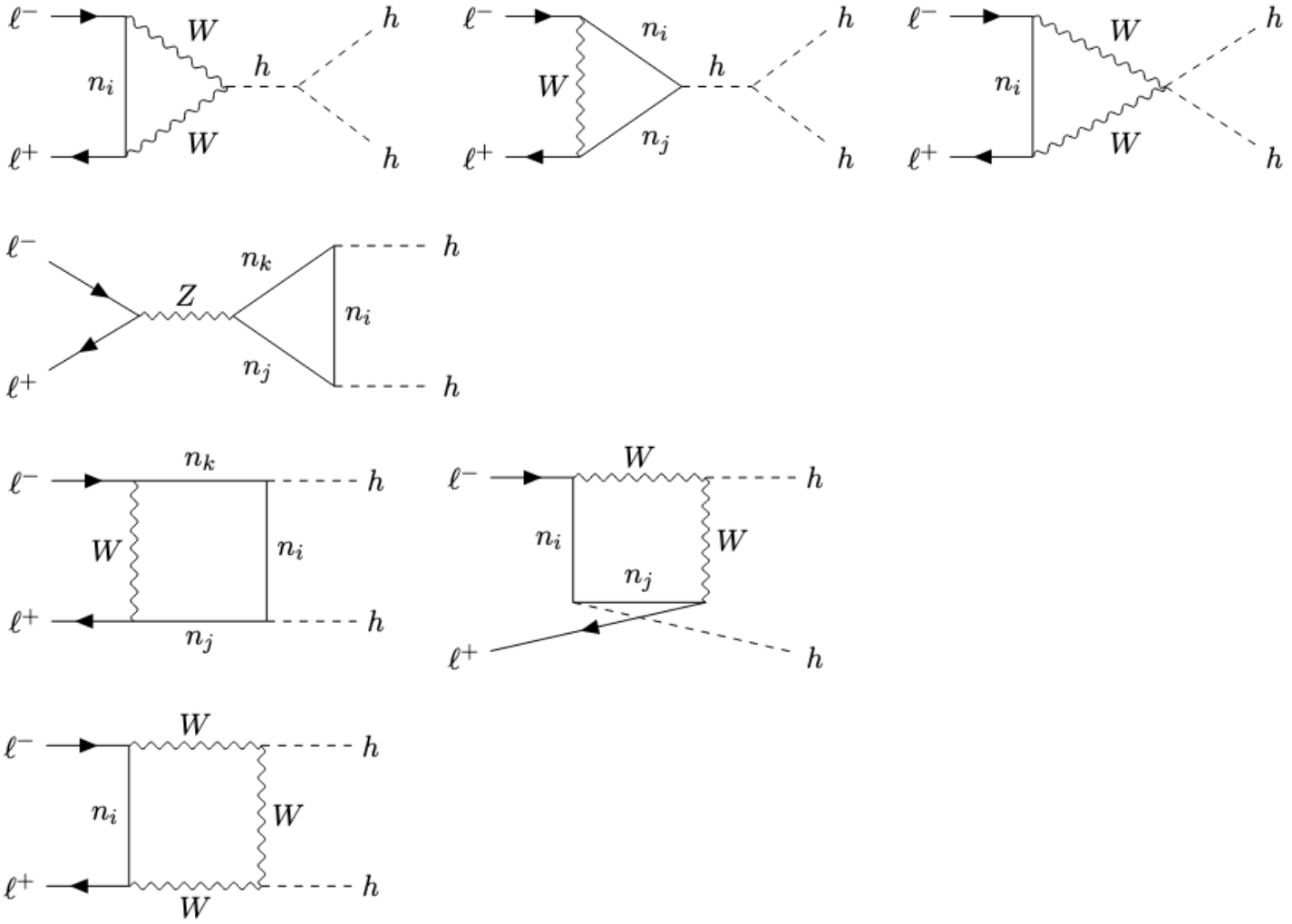
What about **heavy neutral lepton contributions?**
Can they **enhance** the **di-Higgs production cross-section?**

Only SM contributions:



HNL contributions

Relevant **one-loop HNL contributions to** $\ell^+\ell^- \to hh$ $(\ell = e, \mu)$



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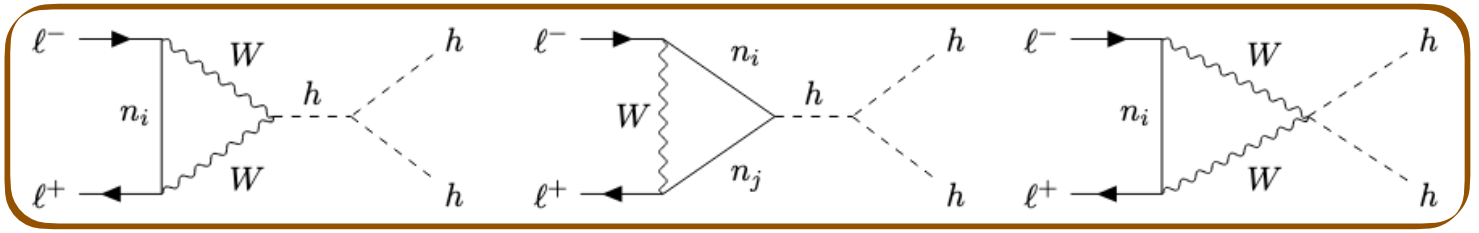
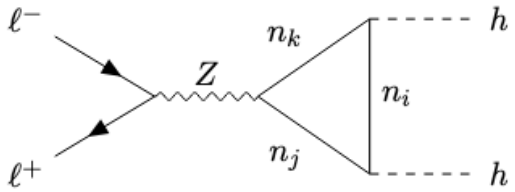
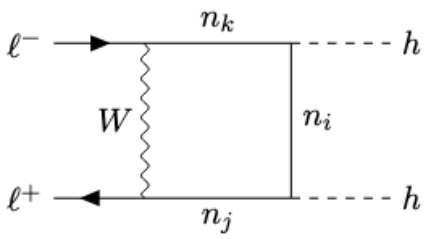
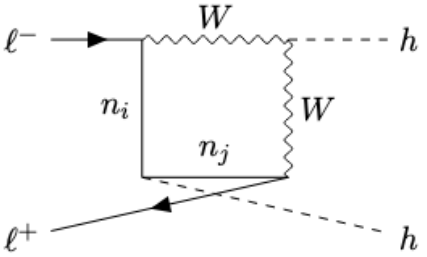
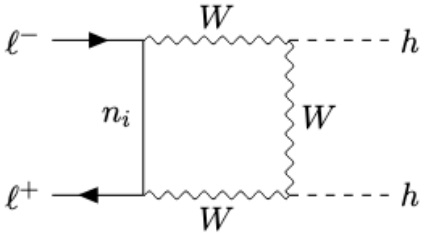


$\propto m_\ell \to 0$



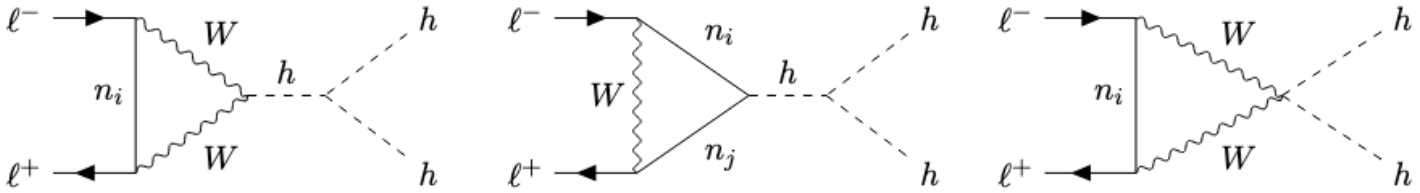


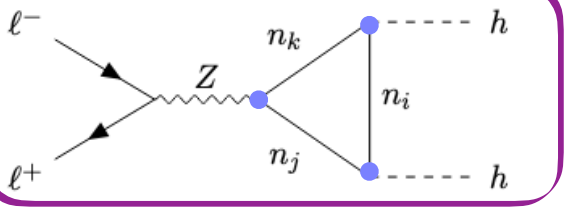




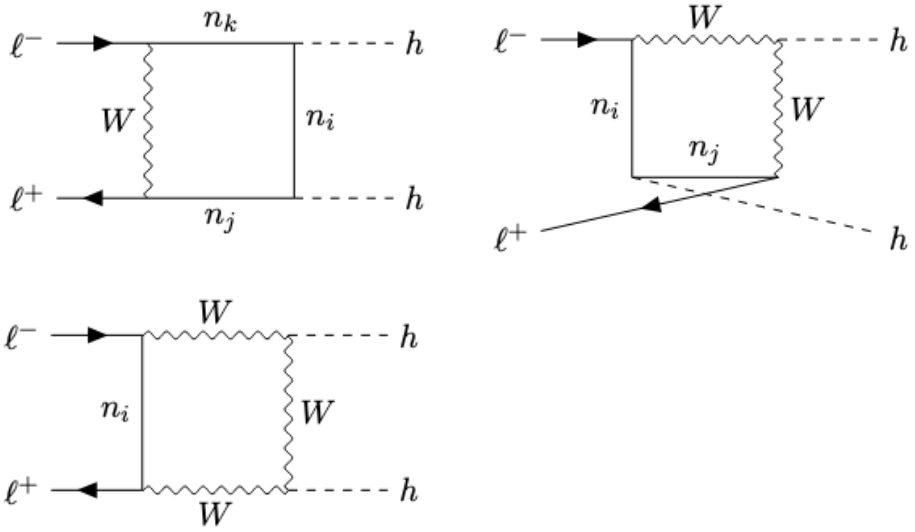
HNL contributions

Relevant **one-loop HNL contributions to** $\ell^+\ell^- \to hh$ $(\ell = e, \mu)$



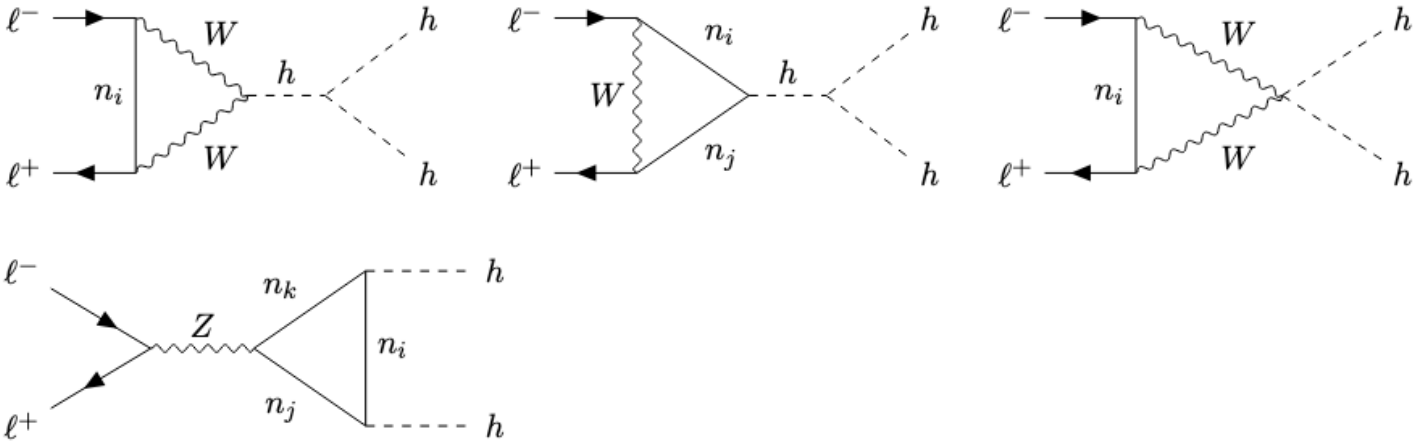


$$\propto \frac{M_N}{s} C_{ij} C_{jk} C_{ki} \to \textbf{Negligible} \qquad C_{ij} = \sum_{\rho=1}^{3} \mathcal{U}^{\dagger}_{i\rho} \mathcal{U}_{i\rho}$$



HNL contributions

Relevant **one-loop HNL contributions to** $\ell^+\ell^- \to hh$ $(\ell = e, \mu)$

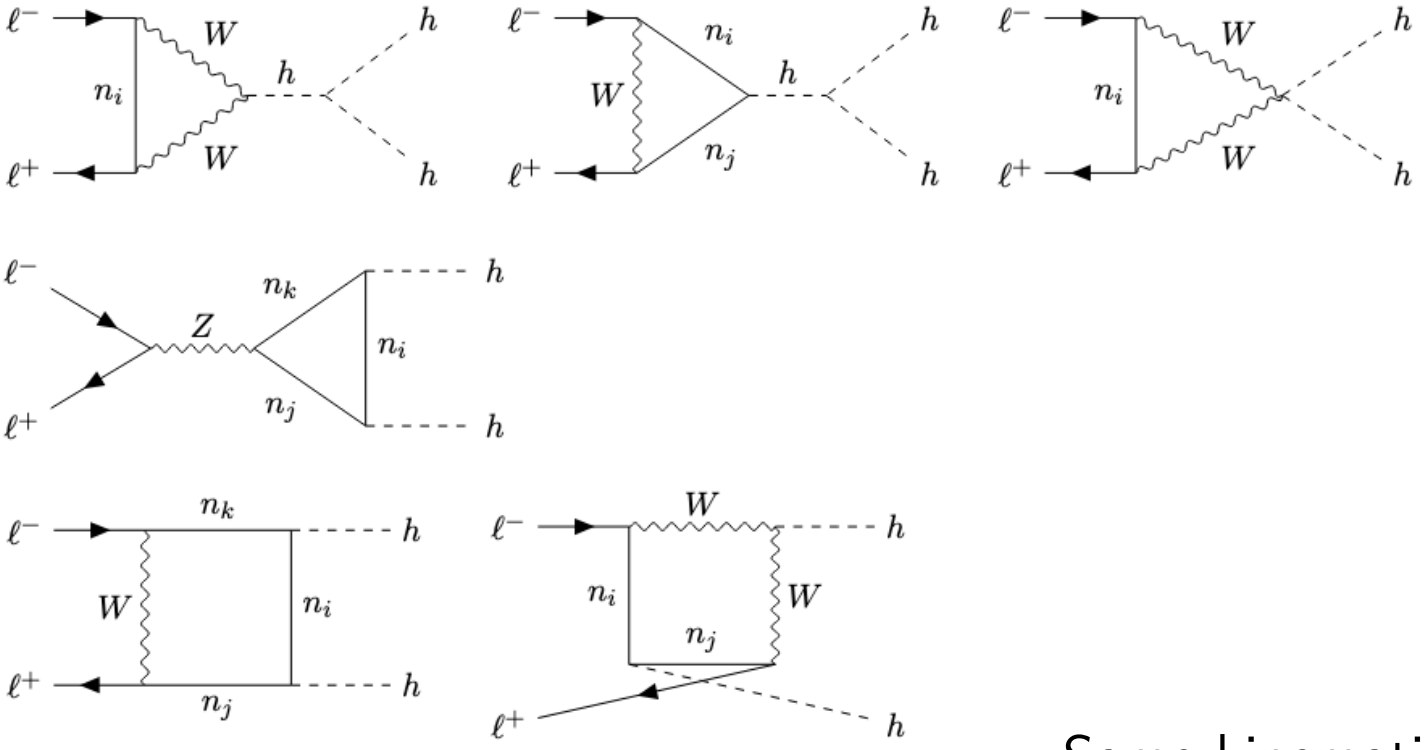


$\propto \mathcal{U}^*_{\ell k}\mathcal{U}_{\ell j}C_{ki}C_{ij}$ and $\propto \mathcal{U}^*_{\ell i}\mathcal{U}_{\ell j}C_{ij}$

$\Rightarrow$ **Mixing suppressions**

HNL contributions

Relevant **one-loop HNL contributions to** $\ell^+\ell^- \to hh$ $(\ell = e, \mu)$



$\propto \mathcal{U}^*_{\ell i}\mathcal{U}_{\ell i}$

$\Rightarrow$ **Dominates**

Same kinematical dependence, p_T and η distributions as **SM**

Possible **enhancement** of the **cross-section?**

HNL contributions

Relevant **one-loop HNL contributions to** $\ell^+\ell^- \to hh$ $(\ell = e, \mu)$

Illustrate our results with an **Inverse Seesaw (3,3) realisation**
leading to charged lepton flavour **conservation** *(up to oscillation data)*

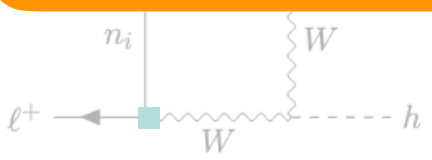
Parametrisation encoding low-energy data & cLFV into Yukawa couplings

J. Kriewald & A. M. Teixeira [2412.13696]

Look at **di-Higgs production** $\ell^+\ell^- \to hh$ $(\ell = e, \mu)$ at future **colliders**

FCC-ee $(\sqrt{s} = 365$ GeV**)**, **LCF** $(\sqrt{s} = 1{,}3$ TeV**)**, **PWA** $(\sqrt{s} = 10$ TeV**)**

Muon Collider $(\sqrt{s} = 3,\ 10$ TeV**)**



$\Rightarrow$ **Dominates**

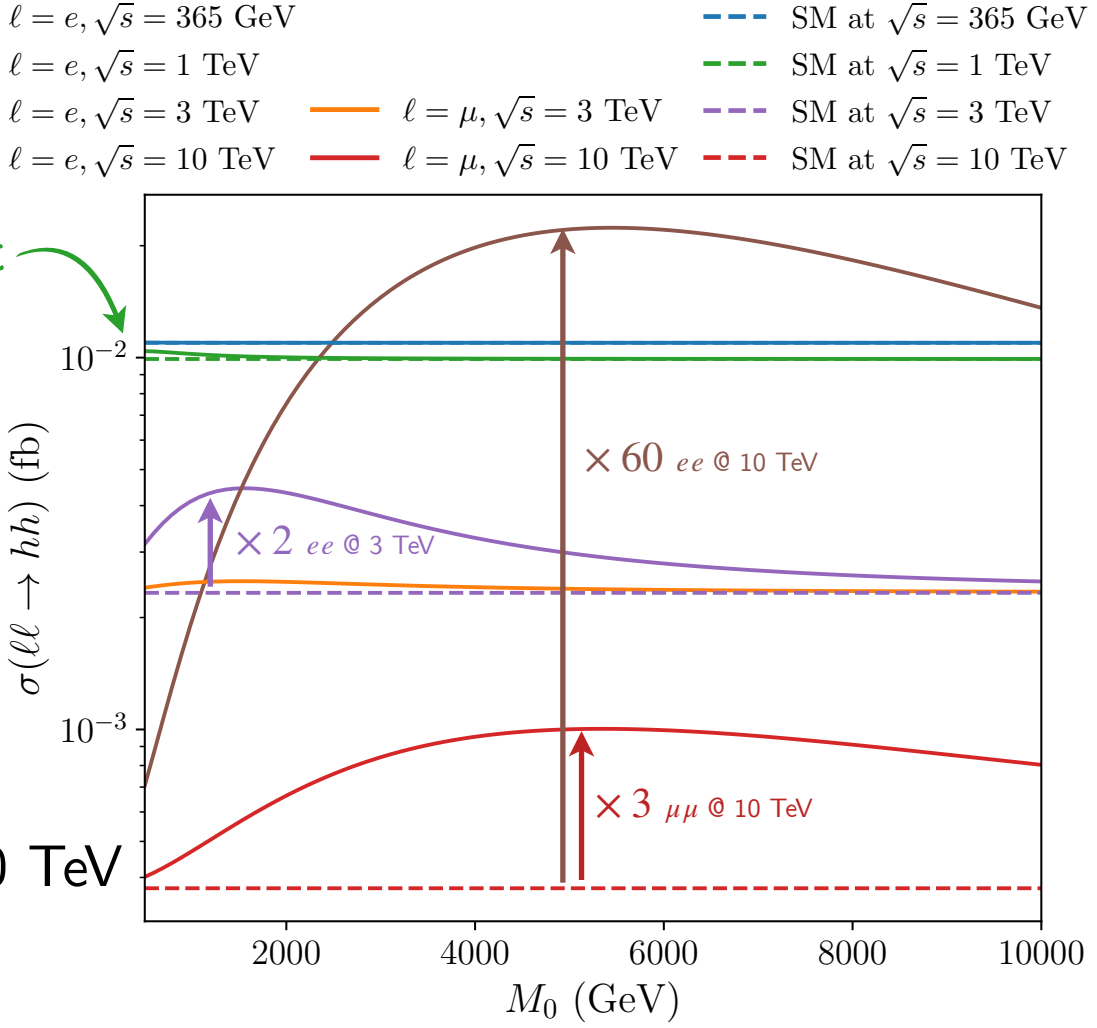
Possible **enhancement** of the **cross-section?**

$\sigma(\ell^+\ell^- \to hh)$ with HNL

For $\sqrt{s} \leq 1\text{TeV}$
Small (%-level) enhancement

Difference electron vs. **muon**
due to the ν mixing bounds
(10 times **stronger** for muons)

$\sigma(\mu\mu \to hh)$ up to $3 \times \sigma_{\text{SM}}$ at 10 TeV



@ **PWA** can have an **enhancement** of $\sigma(e^+e^- \to hh)$ up to a **factor 60!**

Kriewald, **EP**, Teixeira [2512.16734]

$\sigma(\ell^+\ell^- \to hh)$ with HNL

For $\sqrt{s} \leq 1\text{TeV}$
Small (%-level) enhancement

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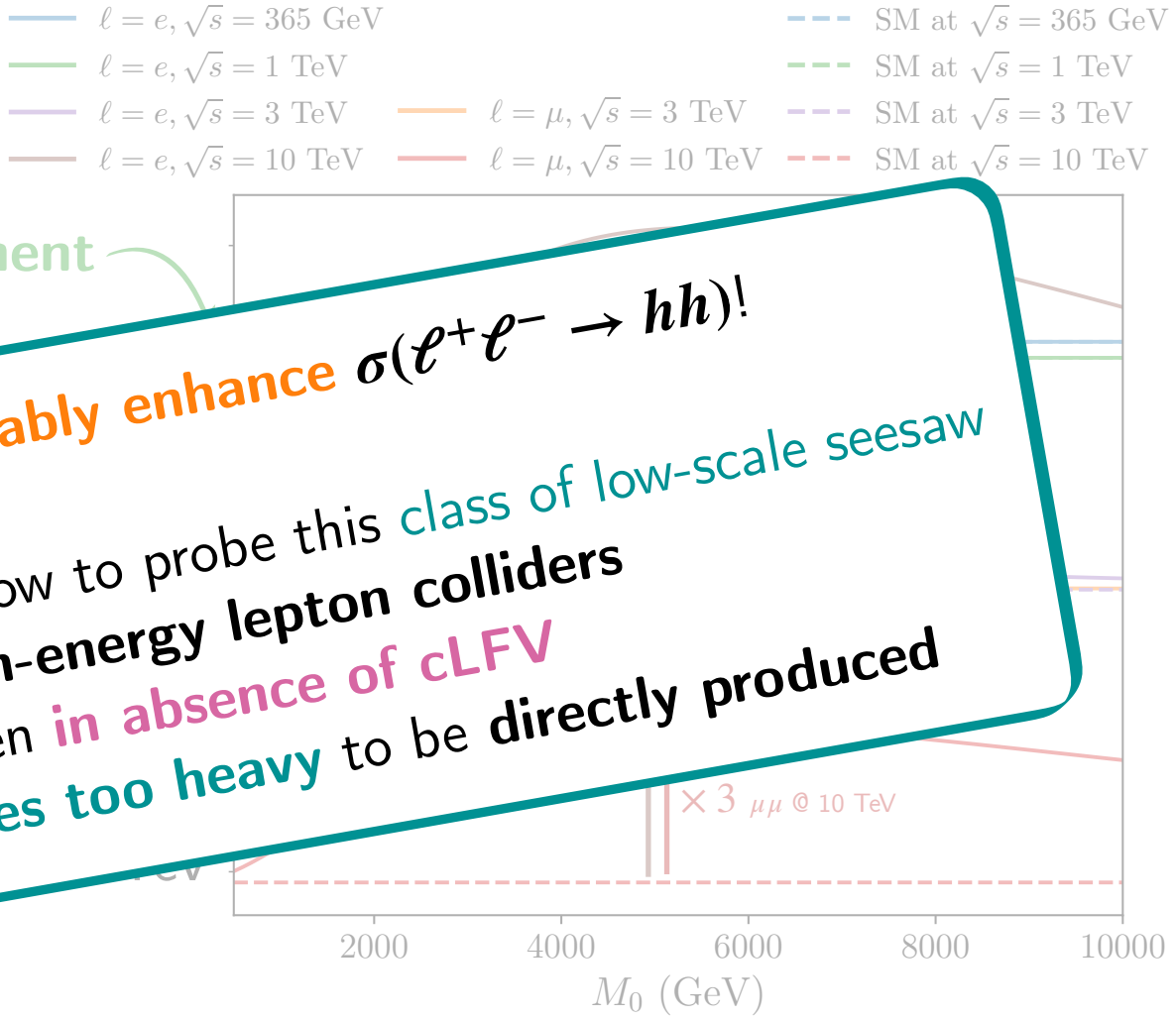
$\sigma(\mu\mu$



HNLs can **sizeably enhance** $\sigma(\ell^+\ell^- \to hh)$!

Complementary window to probe this class of low-scale seesaw
at **high-energy lepton colliders**
even **in absence of cLFV**
& for **HNL masses too heavy** to be **directly produced**

@ **PWA** can have an **enhancement** of $\sigma(e^+e^- \to hh)$ up to a **factor 60!**

Kriewald, **EP**, Teixeira [2512.16734]

Complementarity di-Higgs and LFC

Large mixings can lead to important **contributions** to **LFC observables**

What is the **impact on** $Z \to \ell_\alpha \ell_\alpha$**?**

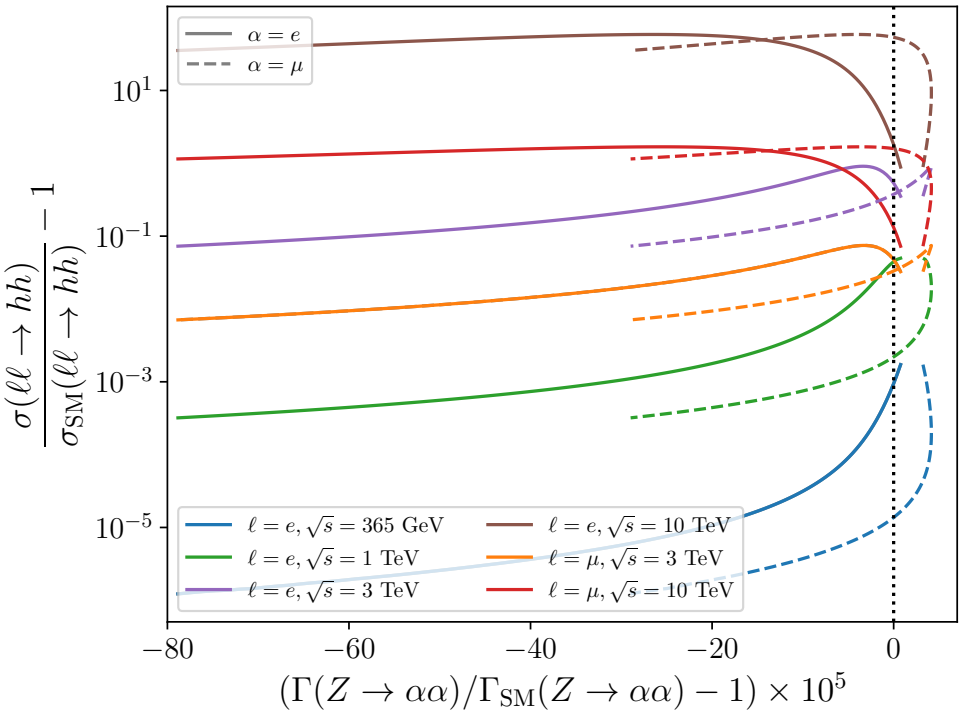
HNL induce **destructive interferences** in $Z \to \ell_\alpha \ell_\alpha$

↪ $\mathcal{O}(10^{-4})$ **suppression**

Can be **probed** at **FCC-ee**

$\mathcal{O}(10^{-4(5)})$ precision at Z-pole

Kriewald, **EP**, Teixeira [2512.16734]



Even **without** any large **deviations of LFC**, **di-Higgs can be enhanced**!

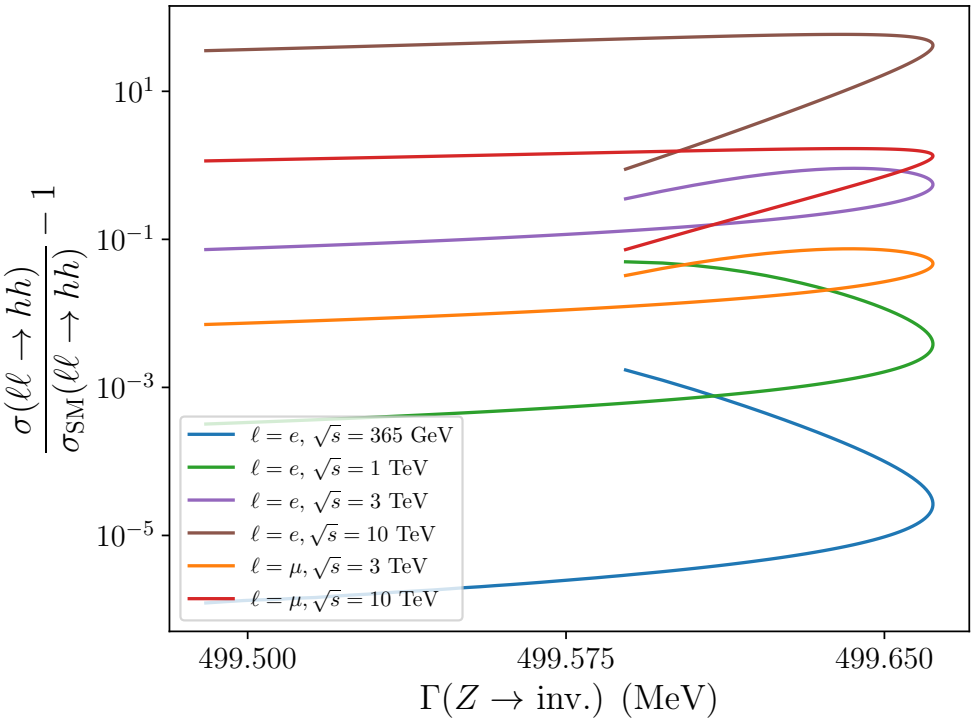
Complementarity **di-Higgs production** and $Z \to \ell_\alpha \ell_\alpha$ **at FCC-ee**

Di-Higgs vs. EWPO

HNL with **large mixings** can lead to important **contributions** to **EWPO**

What is the **impact on** $Z \to \text{inv}.$ **?**

Kriewald, **EP**, Teixeira [2512.16734]



Strong effect in $\Gamma(Z \to \text{inv.})$

↪ Predictions **significantly smaller** than **SM** for **all** $\sigma(\ell\ell \to hh)$

Testable at FCC-ee

Waiting for very high-energy PWA or muon collider,
FCC-ee could **test such extensions** with improved sensitivity on **EWPO**

HNL mediated di-Higgs production

Sizeable enhancements - up to a **factor 60!** - of the cross-section
even for **HNL** extensions **without cLFV**

Offers a complementary window to probe this **class of models**
even **in absence of cLFV** and **without deviation** in **LFC boson decays**

Complementarity with future **FCC-ee** ($Z, h \to \ell\ell$ and $Z \to \text{inv.}$)

Concluding remarks

Neutrino oscillations: 1^{st} laboratory evidence of **New Physics**

HNL: very appealing hypothesis to explain **neutrino masses & mixings**
strong impact on flavoured observables & **very constrained** by **cLFV**

Hunting for sterile neutrinos at future lepton colliders:
Complementary windows

↝ **Flavour imprints: cLFV can reveal the presence of HNL**

↝ **Higgs sector: HNL-enhancement of Higgs-related processes**

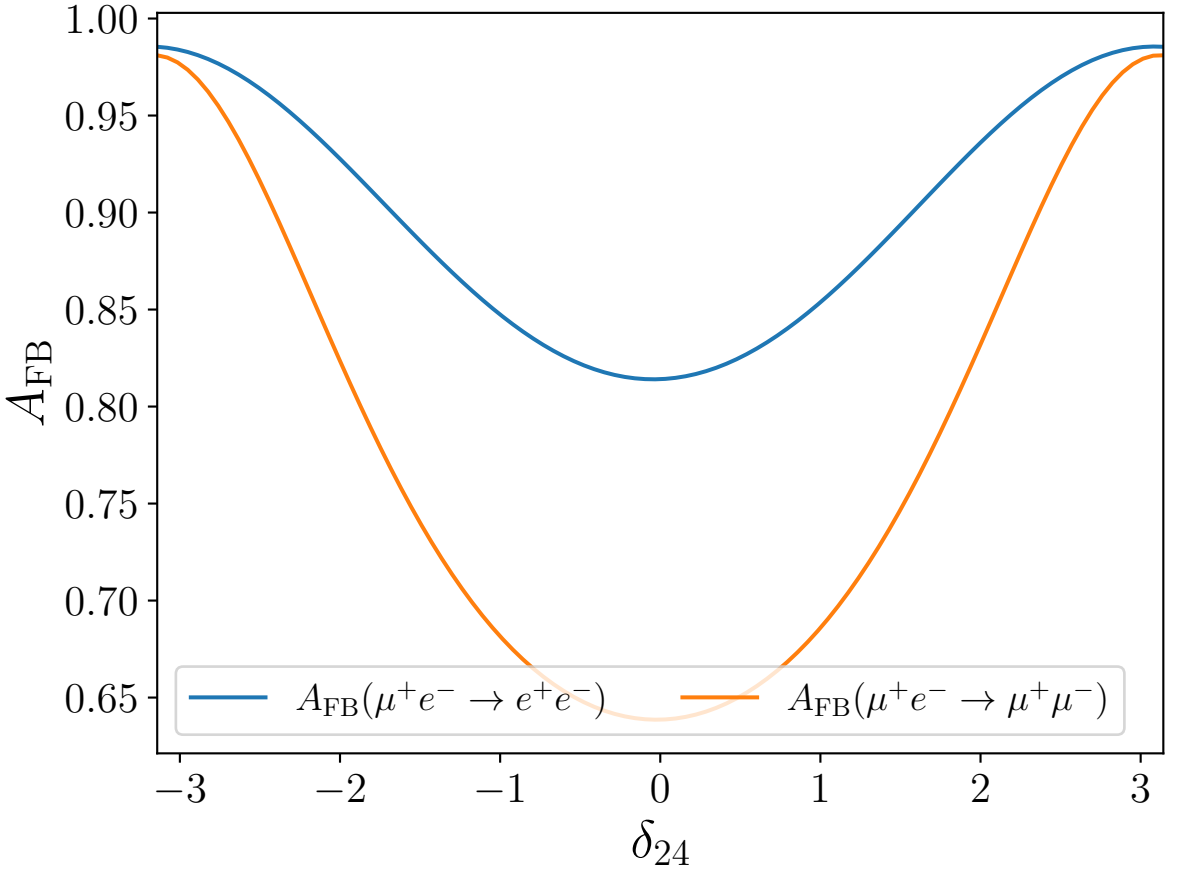
Among many other signatures: cLFV decays, LFU(V), EWPO, ...

Very good prospects to probe HNL at future colliders

Thank you for your attention

CPV phases and A_{FB}

Considering $\sqrt{s} = 126.5$ GeV and $m_4 = m_5 = 1$ TeV (fixed mixing angles)



Clear **impact** of the **Dirac CPV phase** on A_{FB} (suppression of the Z-penguins, altering the interferences between s- and t-channel penguins)

Estimation for μTRISTAN

Total cross-section: No 4π-coverage ⇒ **Cut on the pseudo-rapidity** $\eta \leq 4$ envisaged for ATLAS HL-LHC upgrade

Background from $\mu^+e^- \to \ell^+_\alpha \ell^-_\beta \nu\nu$ ($\sigma \simeq 21$ fb)
⇒ Select events with $E_T \leq 10$ GeV + in the forward region
⇒ Require $2.0 \leq \eta_\ell \leq 4.0$

Leading to $\sigma_{\text{bkg,cut}} \simeq 6 \times 10^{-4}$ fb $=$ **1 background event** for $L_{\text{int}} = 1\text{ab}^{-1}$

Signal efficiency 25% + τ-tagging of 40%: Estimate signal efficiency 10%
Consider signal loss (misid., contamination decaying μ) ⇒ **Assume 1%**

Require **10 signal events** ⇒ **total significance** of $\mathcal{S} = \dfrac{S}{\sqrt{S+B}} \sim 3\sigma$

SVD parametrisation

Deviation from PMNS unitarity:

$U_{\rm PMNS} \to \tilde{U}_{\rm PMNS} = (1-\eta)\, U_{\rm PMNS}$

$$\mathcal{L}_{\rm ISS} = -\frac{1}{2}\,(\overline{\nu_L^c},\, \overline{\nu_R},\, \overline{X^c}) \begin{pmatrix} \mathbb{0} & m_D^T & \mathbb{0} \\ m_D & \mu_R & M_R \\ \mathbb{0} & M_R^T & \mu_X \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \\ X \end{pmatrix}$$

Singular value decomposition of the matrix $Y_D = m_D/v$ $\quad \eta \sim \frac{1}{2} m_D^* (M_R^{-1})^\dagger (M_R^{-1}) m_D^T$

Parametrisation of the the Yukawa coupling

$$Y_D = \frac{1}{v}\mathscr{V}_1\, \mathrm{diag}(y_1, y_2, y_3)\, \mathscr{V}_2^\dagger M_R^T \quad \text{with } \mathscr{V} \text{ unitary matrices}$$

parametrised via 3 Euler angles θ, 3 Dirac phases δ and 3 Majorana phases φ:

$$\mathscr{V} = O_{23} O_{13} O_{12} \mathrm{diag}(e^{i\varphi_1}, e^{i\varphi_2}, e^{i\varphi_3}) \quad \text{and} \quad O_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} e^{i\delta_{23}} \\ 0 & -\sin\theta_{23} e^{-i\delta_{23}} & \cos\theta_{23} \end{pmatrix}$$

$$\text{with } \eta = \frac{1}{2}\mathscr{V}_1^*\, \mathrm{diag}(y_1^2, y_2^2, y_3^2)\, \mathscr{V}_1^T = \begin{pmatrix} \eta_{ee} & \sqrt{\eta_{ee}\eta_{\mu\mu}}\, a e^{i\delta_{12}} & \sqrt{\eta_{ee}\eta_{\tau\tau}}\, b e^{i\delta_{13}} \\ \sqrt{\eta_{ee}\eta_{\mu\mu}}\, a e^{-i\delta_{12}} & \eta_{\mu\mu} & \sqrt{\eta_{\mu\mu}\eta_{\tau\tau}}\, c e^{i\delta_{23}} \\ \sqrt{\eta_{ee}\eta_{\tau\tau}}\, b e^{-i\delta_{13}} & \sqrt{\eta_{\mu\mu}\eta_{\tau\tau}}\, c e^{-i\delta_{23}} & \eta_{\tau\tau} \end{pmatrix}$$

that **encodes low-energy data** ⇒ **Control cLFV!**