Direct and indirect tests of low-scale seesaw models at colliders
(The seminar where you are the hero)

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Neutrino phenomena

- Neutrino oscillations (best fit from nu-fit.org):
  
  solar $\nu_e \rightarrow \nu_{\text{others}}$: $\theta_{12} \approx 34^\circ$, $\Delta m^2_{21} \approx 7.5 \times 10^{-5}\text{eV}^2$
  
  atmospheric $\nu_\mu \rightarrow \nu_\tau$: $\theta_{23} \approx 42^\circ$, $|\Delta m^2_{23}| \approx 2.5 \times 10^{-3}\text{eV}^2$
  
  reactor $\bar{\nu}_e \rightarrow \bar{\nu}_{\text{others}}$: $\theta_{13} \approx 8.5^\circ$
  
  accelerator $\nu_\mu \rightarrow \nu_{\text{others}}$

- Different mixing pattern from CKM, $\nu$ lightness $\leftrightarrow$ Majorana $\nu$

- Neutrino oscillations $=$ Neutral lepton flavour violation
  
  What about charged lepton flavour violation (LFV) ?

- Oscillations give no information on:
  
  Absolute mass scale $\rightarrow$ cosmology $\sum m_{\nu_i} < 0.23\text{ eV}$ [Planck, 2016]
  
  $\beta$ decays $m_{\nu_e} < 2.05\text{ eV}$ [Mainz, 2005; Troitsk, 2011]
  
  Dirac/Majorana nature of neutrinos $\rightarrow 0\nu 2\beta$ decays
  
  $m_{2\beta} < 0.061 - 0.165\text{ eV}$ [KamLAND-ZEN, 2016]
Massive neutrinos and New Physics

- Standard Model \( L = (\nu_L, \ell_L), \tilde{H} = (H^0, H^-) \)
  - No right-handed neutrino \( \nu_R \rightarrow \) No Dirac mass term
    \[ \mathcal{L}_{\text{mass}} = -Y_\nu \bar{L}\tilde{H}\nu_R + \text{h.c.} \]
  - No Higgs triplet \( T \rightarrow \) No Majorana mass term
    \[ \mathcal{L}_{\text{mass}} = -\frac{1}{2}mLTL^c + \text{h.c.} \]

- Necessary to go beyond the Standard Model for \( \nu \) mass
  - Radiative models
  - Extra-dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms \( \rightarrow \) \( \nu \) mass at tree-level
    - + BAU through leptogenesis
Dirac neutrinos?

- Add gauge singlet (sterile), right-handed neutrinos \( \nu_R \quad \Rightarrow \quad \nu = \nu_L + \nu_R \)

\[
\mathcal{L}^\text{mass}_{\text{leptons}} = -Y_\ell \bar{L}H\ell_R - Y_\nu \bar{L}\tilde{H}\nu_R + \text{h.c.}
\]

- After electroweak symmetry breaking \( \langle H \rangle = (0)_v \)

\[
\mathcal{L}^\text{mass}_{\text{leptons}} = -m_\ell \bar{\ell}_L\ell_R - m_D \bar{\nu}_L\nu_R + \text{h.c.}
\]

- 3 light active neutrinos: \( m_\nu \lesssim 1\text{eV} \Rightarrow Y^\nu \lesssim 10^{-11} \)
Majorana neutrinos?

- Add **gauge singlet** (sterile), right-handed neutrinos $\nu_R$

\[
\mathcal{L}_{\text{mass}}^{\text{leptons}} = - Y_\ell \bar{L} H \ell_R - Y_\nu \bar{L} \tilde{H} \nu_R - \frac{1}{2} M_R \bar{\nu}_R \nu^c_R + \text{h.c.}
\]

$\Rightarrow$ After electroweak symmetry breaking $\langle H \rangle = (0)^0$

\[
\mathcal{L}_{\text{mass}}^{\text{leptons}} = - m_\ell \bar{\ell} \ell_R - m_D \bar{\nu}_L \nu_R - \frac{1}{2} M_R \bar{\nu}_R \nu^c_R + \text{h.c.}
\]

$\Rightarrow$ 6 mass eigenstates: $\nu = \nu^c$

- $\nu_R$ gauge singlets
  $\Rightarrow$ $M_R$ not related to SM dynamics, not protected by symmetries
  $\Rightarrow$ $M_R \bar{\nu}_R \nu^c_R$ is gauge and Lorentz invariant, renormalizable

- $M_R \bar{\nu}_R \nu^c_R$ violates lepton number conservation $\Delta L = 2$
The seesaw mechanisms

- Seesaw mechanism: New fields with a mass $M >$ EW scale (in general) and Majorana mass terms
  ⇒ Generate $m_\nu$ in a renormalizable way and at tree-level
- 3 minimal tree-level seesaw models ⇒ 3 types of heavy fields
  - type I: right-handed neutrinos, SM gauge singlets
  - type II: scalar triplets
  - type III: fermionic triplets

\[
m_\nu = -\frac{1}{2} Y_\nu^T \frac{v^2}{M_R} Y_\nu
\]

\[
m_\nu = -2 Y_\Delta v^2 \frac{\mu \Delta}{M_\Delta^2}
\]

\[
m_\nu = -\frac{1}{2} Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma
\]
The inverse seesaw mechanism

- Inverse seesaw: Consider fermionic gauge singlets $\nu_R (L = +1)$ and $X (L = -1)$ [Mohapatra and Valle, 1986]

$$\mathcal{L}_{\text{inverse}} = -Y_\nu \bar{L} H \nu_R - M_R \nu_R^c X - \frac{1}{2} \mu_X \bar{X}^c X + \text{h.c.}$$

with $m_D = Y_\nu v$, $M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$

$$m_\nu \approx \frac{m_D^2}{M_R^2} \mu_X$$

$$m_{N_1,N_2} \approx \bar{M}_R + \frac{\mu_X}{2}$$

2 scales: $\mu_X$ and $M_R$

- Decouple neutrino mass generation from active-sterile mixing
- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1$ TeV
  $\Rightarrow$ within reach of the LHC and low energy experiments
Why supersymmetry?

- The SM doesn’t only lack neutrino masses, e.g. no dark matter, hierarchy problem

- Extended frameworks to address SM issues:
  - Strongly coupled theories (e.g. Technicolor, Composite Higgs)
  - Extra-dimensions (e.g. Randall-Sundrum, Large extra dimension)
  - Extending the SM field content/gauge group (e.g. 2HDM, Little Higgs, GUT)
  - Supersymmetric extensions (e.g. MSSM)

- Advantages of supersymmetry (SUSY)
  - Most general extension of the Poincaré algebra
  - Gauge coupling unification
  - Dark matter candidate
The supersymmetric inverse seesaw model

- No $\nu_R$ in the MSSM $\Rightarrow$ Massless neutrinos
  $\rightarrow$ Implement a seesaw mechanism
- MSSM extended by singlet chiral superfields $\hat{N}$ and $\hat{X}$ with $L = -1$ and $L = +1$

$$\mathcal{W} = Y_d \hat{D} \hat{H}_d \hat{Q} + Y_u \hat{U} \hat{Q} \hat{H}_u + Y_e \hat{E} \hat{H}_d \hat{L} - \mu \hat{H}_d \hat{H}_u$$
$$+ Y_\nu \hat{N} \hat{L} \hat{H}_u + M_R \hat{N} \hat{X} + \frac{1}{2} \mu_X \hat{X} \hat{X}$$

- New couplings, e.g. $A_{Y_\nu} Y_\nu \hat{N} \hat{L} \hat{H}_u + \text{h.c.}$
- Work with a flavour-blind mechanism for SUSY breaking
  $\Rightarrow Y_\nu$ as the only source of LFV
- Right-handed sneutrino mass:

$$M_{\hat{N}}^2 = m_{\hat{N}}^2 + M_R^2 + Y_\nu Y_\nu^\dagger v_u^2 \sim (1\,\text{TeV})^2$$

$\Rightarrow$ Natural Yukawa couplings with a TeV new Physics scale
Probing the seesaw models

- Lepton number conservation is **accidental** in the SM (gauge group, field content and renormalizability)

- **Unique** dimension 5 operator for all seesaw mechanisms
  → Violates lepton number \( L \) ⇒ Majorana neutrinos

\[
\delta \mathcal{L}^{d=5} = c_5 \frac{LLHH}{\Lambda_{NP}}
\]

- To probe the several seesaw mechanisms, either
  - **Directly produce** the heavy states (LHC, LC, FCC)
  - Look for **dimension \( \geq 6 \)** operator effects → charged lepton flavour violation (cLFV), non-standard interactions, etc
(SUSY) Inverse seesaw experimental signatures

- **Collider signatures**
  - single lepton + dijet + missing energy [Das and Okada, 2013]
  - di-lepton + missing $p_T$ [Bhupal Dev et al., 2012, Bandyopadhyay et al., 2013]
  - LFV di-lepton + dijet [Arganda, Herrero, Marcano and CW, 2015]
  - tri-lepton + missing $E_T$ [Mondal et al., 2012, Das et al., 2014]...
  - invisible Higgs decays [Banerjee et al., 2013]

- **Low-energy / high-intensity:**
  - deviations from lepton universality [Abada, Das, Teixeira, Vicente and CW, 2013]
  - (semi)leptonic decays of mesons [Abada, Teixeira, Vicente and CW, 2014]
  - charged lepton flavour violation [Bernabéu et al., 1987]...
  - neutrinoless double beta decay [Awasthi et al., 2013]...
  - charged lepton anomalous magnetic moment [Abada et al., 2014a]
  - charged lepton electric dipole moment [Abada and Toma, 2016]

- **Dark matter candidate:** sterile neutrino [Abada et al., 2014] / sneutrino [De Romeri and Hirsch, 2012, Banerjee et al., 2013, Guo et al., 2014]...
Something changed in 2012

- \(\nu\) oscillations \(\Rightarrow\) Extension of the SM that generates \(\nu\) masses and mixing

- Numerous studies on TeV-scale neutrinos:
  - direct production at colliders
  - loop-induced effects
  - imprint on decays of hadrons, leptons and gauge bosons

Discovery of a scalar boson at the LHC in 2012, with properties compatible with the SM Higgs [ATLAS, 2012; CMS, 2012]

- New experimentally accessible observables and searches

- TeV-scale neutrinos + Large Yukawa couplings \(\Rightarrow\) Possibly large deviations from SM properties in the Higgs sector
Neutrinos impact on Higgs properties

- Effort to measure Higgs properties: mass, width, couplings
- We focused on two couplings: $HHH$ and $H \bar{\ell}_i \ell_j$ with $i \neq j$

$H \bar{\ell}_i \ell_j$:
- 0 at tree-level → LFV from higher order processes
- 1-loop contribution negligible in the SM → evidence of new physics if observed
- probe the origin of lepton mixing

$HHH$:
- Measure needed to reconstruct the scalar potential and validate the Higgs mechanism as the origin of EWSB
- Sizeable SM 1-loop corrections ($\mathcal{O}(10\%)$) → Quantum corrections cannot be neglected
- One of the main motivations for future colliders

You decide to study:

- LFVHD
- HHH
- $\mu \tau jj$
Experimental searches of LFV

- Radiative decays, e.g. $\text{Br}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016]

- 3-body decays, e.g. $\text{Br}(\tau \rightarrow 3\mu) < 2.1 \times 10^{-8}$ [Belle, 2010]

- Neutrinoless muon conversion,  
e.g. $\mu^-, \text{Au} \rightarrow e^-, \text{Au} < 7 \times 10^{-13}$ [SINDRUM II, 2006]

- Meson decays, e.g. $\text{Br}(B^0 \rightarrow e\mu) < 2.8 \times 10^{-9}$ [LHCb, 2013]

- Z decays, e.g. $\text{Br}(Z^0 \rightarrow e\mu) < 1.7 \times 10^{-6}$ [OPAL, 1995]

- Higgs decays, e.g. $H \rightarrow \tau\mu$: $\text{Br} < 1.51\%$ [CMS, PLB749(2015)337]  
  $\text{Br} < 1.43\%$ [ATLAS, 1604.07730]
In the Feynman-'t Hooft gauge, same as [Arganda et al., 2005]:

Formulas adapted from [Arganda et al., 2005]

Diagrams 1, 8, 10 → dominate at large $M_R$

Enhancement from:
- $\mathcal{O}(1)$ $Y_\nu$ couplings
- TeV scale $n_i$
Most relevant constraints

- Neutrino data → Use specific parametrization

\[ \mu_X = M_R^T Y^{-1}_\nu U^*_{\text{PMNS}} m_\nu U^\dagger_{\text{PMNS}} Y^{T-1}_\nu M_R v^2 \]

- Charged lepton flavour violation
  → For example: \( \text{Br}(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13} \) \[\text{[MEG, 2013]}\]

- Lepton universality violation: less constraining than \( \mu \rightarrow e\gamma \)

- Electric dipole moment: 0 with real PMNS and mass matrices

- Invisible Higgs decays: \( M_R > m_H \), does not apply
Large LFV Higgs decay rates from textures I

What can we learn from a LHC discovery of LFV Higgs decays?
→ Look for the largest possible $\text{Br}(H \rightarrow \tau \mu)$

Strongest experimental constraint: $\mu \rightarrow e \gamma$

\[
\text{Br}^{\text{approx}}_{\mu \rightarrow e \gamma} = 8 \times 10^{-17} \text{GeV}^{-4} \frac{m_\mu^5}{\Gamma_\mu} \left| \frac{v^2}{2M_R^2} (Y_\nu Y_\nu^\dagger)_{12} \right|^2
\]

\[
\text{Br}^{\text{approx}}_{H \rightarrow \mu \bar{\tau}} = 10^{-7} \frac{V^4}{M_R^4} \left| (Y_\nu Y_\nu^\dagger)_{23} - 5.7 (Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{23} \right|^2
\]

\[
= 10^{-7} \frac{V^4}{M_R^4} \left| 1 - 5.7 [(Y_\nu Y_\nu^\dagger)_{22} + (Y_\nu Y_\nu^\dagger)_{33}] \right|^2 |(Y_\nu Y_\nu^\dagger)_{23}|^2
\]

Solution: Textures with $(Y_\nu Y_\nu^\dagger)_{12} = 0$ and $\left| \frac{Y_{ij}}{4\pi} \right|^2 < 1.5$
Large LFV Higgs decay rates from textures II

- Textures with \((Y_\nu Y_\nu^\dagger)_{12} = 0\) and \(\frac{|Y_{ij}|^2}{4\pi} < 1.5\)

\[
Y^{(1)}_{\tau\mu} = f \begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}, \quad Y^{(2)}_{\tau\mu} = f \begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & -1 \end{pmatrix}, \quad Y^{(3)}_{\tau\mu} = f \begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}
\]

- Flavour composition of the heavy neutrinos:
  \(Y_{\tau\mu}^{(1)}\):
  \(N_{1/2}\) - 1, \(N_{3/4}\) - 2, \(N_{5/6}\) - 3

- Flavour composition of the heavy neutrinos:
  \(Y_{\tau\mu}^{(2)}\):
  \(N_{1/2}\) - 1, \(N_{3/4}\) - 2, \(N_{5/6}\) - 3

- Flavour composition of the heavy neutrinos:
  \(Y_{\tau\mu}^{(3)}\):
  \(N_{1/2}\) - 1, \(N_{3/4}\) - 2, \(N_{5/6}\) - 3

- 3 very different flavour patterns

- Heavy neutrino mixing of \(\tau - \mu\) type is always present
Producing large $H \to \tau \mu$ rates

- Numerics done with the full one-loop formulas
- $f = \sqrt{6\pi}$
- Dotted: excluded by $\tau \to \mu\gamma$
  Solid: allowed by LFV, LUV, etc
- $\text{Br}^{\text{max}}(H \to \mu\bar{\tau}) \sim 10^{-5}$
- Same maximum branching ratio with hierarchical heavy $N$

- Similarly, $\text{Br}^{\text{max}}(H \to e\bar{\tau}) \sim 10^{-5}$ for $Y^{(i)}_{\tau e} (= Y^{(i)}_{\tau \mu}$ with rows 1 and 2 exchanged)

- Out of LHC reach, within the reach of future colliders
LFV in supersymmetric seesaw models

- Typically in SUSY, LFV appears through RGE-induced slepton mixing
  \[(\Delta m^2_L)_{ij}\; [\text{Borzumati and Masiero, 1986, Hisano et al., 1996, Hisano and Nomura, 1999}]\]
  \[\Rightarrow (\Delta m^2_L)_{ij} \propto (Y_{\nu}^\dagger Y_{\nu})_{ij} \ln \frac{M_{\text{GUT}}}{M_R}\]

- Contribute to all LFV observables
  \[\rightarrow \text{Dominant in most of the SUSY seesaw models}\]

- Type I seesaw \((Y_{\nu} \sim 1, M_R \sim 10^{14}\text{GeV}) \rightarrow (\Delta m^2_L)_{ij} \propto 5\)

- Inverse seesaw \((Y_{\nu} \sim 1, M_R \sim 1\text{TeV}) \rightarrow (\Delta m^2_L)_{ij} \propto 30\)
  \[\rightarrow \text{one-loop } \tilde{N}\text{-mediated processes are no longer suppressed}\]

- Similar enhancement in non-SUSY contributions [Ilakovac and Pilaftsis, 1995, Deppisch et al., 2006, Forero et al., 2011, Alonso et al., 2013, Dinh et al., 2012]
In the Feynman-'t Hooft gauge, same as [Arganda et al., 2005]:

- Formulas adapted from [Arganda et al., 2005]
- Enhancement from: $-\mathcal{O}(1) \, Y_\nu$ couplings
  - TeV scale $\tilde{\nu}$
**Dependence on** $M_R$

- $M_R$ degenerate and real, $m_A = 800$ GeV,
squark parameters safe from LHC (direct searches, Higgs mass)

- ▲: allowed by LFV radiative decays, ×: excluded

- At low $M_R$: dominated by chargino-sneutrino loops
  At large $M_R$ / small $f$: dominated by neutralino-slepton loops

- Can adjust other parameters ($A_\nu$, $m_{\tilde{\nu}_R}$) to reach $\text{Br}(h \rightarrow \tau \bar{\mu}) \sim 1\%$
 Dependence on $A_{\nu}$

- $M_R$ degenerate and real, $m_A = 800$ GeV, $M_R = m_{\tilde{L}} = m_{\tilde{\nu}_R} = m_{\tilde{X}} = 1$ TeV
- ▲: allowed by LFV radiative decays, ×: excluded
- $A_{\nu}$ in both $h^0 - \tilde{\nu}_L - \tilde{\nu}_R$ coupling and $\tilde{\nu}_L - \tilde{\nu}_R$ mixing
  → Dips when dominated by chargino loops
- Dips in BR($h \rightarrow \tau \bar{\mu}$) and BR($\tau \rightarrow \mu \gamma$) do not exactly coincide
Summary of cLFV Higgs decays

- **cLFV Higgs decays**: *complementary* to other cLFV searches

- Enhancement from the inverse seesaw but largest values excluded by \( \tau \rightarrow \mu \gamma / \tau \rightarrow e\gamma \)

- **non-SUSY ISS**: \( \text{Br}(H \rightarrow \bar{\tau}\mu) \leq 10^{-5} \)
  \( \text{Br}(H \rightarrow \bar{\tau}e) \leq 10^{-5} \)

- **SUSY loops**: \( \text{Br}(h \rightarrow \tau\bar{\mu}) \leq \mathcal{O}(1\%) \)

- SUSY contributions are within the LHC reach

- \( \tau\mu \) and \( \tau e \) will be probed at future LHC runs and future colliders

You decide to further study:

You are tired and want to end your travels:
Experimental prospects for the HHH coupling

- Extracted from HH production

- Future sensitivities to the SM HHH coupling:
  - HL-LHC: \( \sim 50\% \) for ATLAS or CMS [CMS-PAS-FTR-15-002]  
    \( \sim 35\% \) combined
  - ILC: 27\% at 500 GeV with 4 ab\(^{-1}\) [Fujii et al., 2015]  
    10\% at 1 TeV with 5 ab\(^{-1}\) [Fujii et al., 2015]
  - FCC-hh: 8\% per experiment with 3 ab\(^{-1}\) using only \( b\bar{b}\gamma\gamma \) [Yao, 2016]  
    \( \sim 5\% \) combining all channels
Modified HHH coupling

SM 1-loop corrections

taken from [Arhrib et al., 2015]

- tree-level: $\lambda_{HHH}^0 = -\frac{3M_H^2}{v}$

- Dominant contribution from top-quark loops
  [Kanemura et al., 2004]

$$\lambda_{HHH}(q^2, m_H^2, m^{*}_H) = -\frac{3m_H^2}{v} \left[ 1 - \frac{1}{16\pi^2} \frac{16m_t^4}{v^2m_H^2} \right]$$

$$\times \left\{ 1 + \mathcal{O}\left(\frac{m_H^2}{m_t^2}, \frac{q^2}{m_t^2}\right) \right\}$$

Cédric Weiland (IPPP Durham)
Beyond SM: simplified 3+1 model (PRD94(2016)013002)

- A first approach to clearly illustrate the impact of a new, TeV-scale fermion

- Simplified model with 3 light active and 1 heavy sterile Dirac neutrinos, parametrized by masses $m_1, \ldots, m_4$ and active-sterile mixing in $B$

- Modified couplings to $W^\pm$, $Z^0$, $H$

\[
\mathcal{L} \equiv - \frac{g_2}{\sqrt{2}} \bar{\ell}_i \gamma^\mu W^-_\mu B_{ij} P_L n_j - \frac{g_2}{2 \cos \theta_W} \bar{n}_i \gamma^\mu Z_\mu (B^\dagger B)_{ij} P_L n_j - \frac{g_2}{2 M_W} \bar{n}_i (B^\dagger B)_{ij} H (m_n P_L + m_{n_j} P_R) n_j
\]

\[
B_{3\times 4} = \begin{pmatrix} \bar{B}_{e1} & \bar{B}_{e2} & \bar{B}_{e3} & \bar{B}_{e4} \\ \bar{B}_{\mu 1} & \bar{B}_{\mu 2} & \bar{B}_{\mu 3} & \bar{B}_{\mu 4} \\ \bar{B}_{\tau 1} & \bar{B}_{\tau 2} & \bar{B}_{\tau 3} & \bar{B}_{\tau 4} \end{pmatrix}
\]
New contributions and constraints

- **Sterile $\nu$** gives rise to new 1-loop diagrams and new counterterms → Evaluated with *FeynArts* and *LoopTools*

- Strongest experimental constraints on active-sterile mixing: EWPO

  $|B_{e4}| \leq 0.041$
  $|B_{\mu4}| \leq 0.030$
  $|B_{\tau4}| \leq 0.087$

- Loose (tight) perturbativity of $\lambda_{HHH}$:

  $\left( \frac{\max \left| (B^\dagger B)_{i4} \right| g_2 m_{n4}}{2M_W} \right)^3 < 16\pi \left( 2\pi \right)$

- Width limit: $\Gamma_{n4} \leq 0.6 m_{n4}$
Modified HHH coupling

Momentum dependence

- $\Delta^{(1)} \lambda_{HHH} = \frac{1}{\lambda^0} \left( \lambda^{1r}_{HHH} - \lambda^0 \right)$
- Assume $B_{\tau 4} = 0.087$, $B_{e 4} = B_{\mu 4} = 0$
- Deviation of the BSM correction with respect to the SM correction in the insert
- $(B^\dagger B)_{44} m_{n_4} = m_t \rightarrow m_{n_4} = 2.7 \text{ TeV}$
  - tight perturbativity of $\lambda_{HHH}$ bound: $m_{n_4} = 7 \text{ TeV}$
  - width bound: $m_{n_4} = 9 \text{ TeV}$

- Largest positive correction at $q_{H}^* \simeq 500 \text{ GeV}$, heavy $\nu$ decreases it
- Large negative correction at large $q_{H}^*$, heavy $\nu$ increases it
Results in 3+1 simplified model

\[ \Delta_{BSM} = \frac{1}{\lambda_{r,SM}^H} \left( \lambda_{r,full}^{HHH} - \lambda_{r,SM}^{HHH} \right) \]

- Red line: tight perturbativity of \( \lambda_{HHH} \) bound
- Heavy \( \nu \) effects at the limit of HL-LHC sensitivity (35%)
- Heavy \( \nu \) effects clearly visible at the ILC (10%) and FCC-hh (5%)
- Similar behaviour for active-sterile mixing \( B_{e4} \) and \( B_{\mu4} \)
From the 3+1 Dirac model to the ISS

- TeV-scale neutrino induces **sizeable corrections to** $\lambda_{HHH}$
  - Decrease at $q_H^* \approx 500 \text{ GeV}$
  - Increase at large $q_H^*$

- Effects could be used to **constrain the active-sterile mixing** at the ILC and FCC-hh

- What are the effects in a realistic, appealing low-scale seesaw model?  
  - Additional constraints need to be included
Most relevant constraints for the ISS

- Accomodate low-energy neutrino data using parametrization

\[ \mu_X = M_R^T Y^{-1}_\nu U^*_{\text{PMNS}} m_\nu U^\dagger_{\text{PMNS}} Y_T^{-1} M_R v^2 \text{ and beyond} \]

- Charged lepton flavour violation

- Global fit to EWPO and lepton universality tests [Fernandez-Martinez et al., 2016]

- Yukawa coupling perturbativity \( \rightarrow |\frac{y^2}{4\pi}| < 1.5 \)
Results in the ISS

- Similar diagrams to the 3+1 Dirac scenario but with Majorana neutrinos
- $\mu_X$-parametrization extended beyond the standard seesaw limit
- Assume $Y_\nu$ diagonal, hierarchical heavy neutrinos, $m_1 = 0.01$ eV
- $\Delta_{BSM}^{max} \simeq +30\%$, at the limit of the HL-LHC sensitivity (35\%)
- Effects clearly visible at the ILC (10\%) and FCC-hh (5\%)
- Effects generically larger than 3+1 but stronger constraints

Preliminary

\[
\begin{array}{c}
\Delta_{BSM} \text{ map with } q_{H^*} = 2500 \text{ GeV} \\
\end{array}
\]
Summary of HHH coupling

- Corrections to the HHH coupling from heavy $\nu$ as large as 30%: measurable at future colliders
  - Larger effects when additional heavy neutrinos are present
  - Can probe a new part of the parameter space, unconstrained otherwise
  - Would deliver new constraints on active-sterile mixing: impact on astroparticle physics, cosmology, neutrino physics

- **Generic effect**, expected to be present in all models including multi-TeV fermions with large Higgs couplings

- **New observable** to probe $\nu$ mass models in a regime difficult to access

- Could similar diagrams lead to a modified Higgs production cross-section at colliders? 😊

You decide to further study:
You are tired and want to end your travels:
Heavy neutrinos production and decays at the LHC

Main production channel: Drell-Yan

$\tau - \mu$ mixing in $N$ 

$\Rightarrow \mu^{\pm} \tau^{\mp} jj$ signal with no $E_T$

$W\gamma$ fusion relevant at large $M_R$ [Dev et al., 2014, Alva et al., 2015]

Contribute to $\mu^{\pm} \tau^{\mp} jj$ signal if extra-jets are soft or collinear 

$\rightarrow p_T < p_T^{\max}$

Numerics done with MadGraph5 and NNPDFQED, $M_R$ real and degenerate
Most relevant constraints

- Neutrino data → Use specific parametrization

\[ \mu_X = M_R^T Y_{\nu}^{-1} U_{\text{PMNS}}^* m_{\nu} U_{\text{PMNS}}^\dagger Y_{\nu}^{T-1} M_R v^2 \]

- Charged lepton flavour violation
  → For example: \( \text{Br}(\mu \rightarrow e \gamma) < 5.7 \times 10^{-13} \) [MEG, 2013]

- EWPO:
  \[ |B_{e4}|^2 < 3.0 \times 10^{-3} \]
  \[ |B_{\mu4}|^2 < 3.2 \times 10^{-3} \]
  \[ |B_{\tau4}|^2 < 6.2 \times 10^{-3} \]

- Yukawa perturbativity: → \( |\frac{Y_{\nu}^2}{4\pi}| < 1.5 \)
Enhanced cross-sections from textures I

- What can we learn from a LHC discovery of LFV Higgs decays?
  → Look for the largest possible \( \text{Br}(H \to \tau \mu) \)

- Strongest experimental constraint a priori: \( \mu \to e\gamma \)

\[
\text{Br}^{\text{approx}}_{\mu \to e\gamma} = 8 \times 10^{-17} \text{GeV}^{-4} \frac{m_{\mu}^5}{\Gamma_{\mu}} \left| \frac{v^2}{2M_R^2} (Y_{\nu} Y_{\nu}^\dagger)_{12} \right|^2
\]

- What is the largest possible \( \sigma(pp \to \mu\tau jj) \)?
  → Suppress \( \text{Br}(\mu \to e\gamma) \)

- Solution: Textures with \( (Y_{\nu} Y_{\nu}^\dagger)_{12} = 0 \) and \( \frac{|Y^i_j|^2}{4\pi} < 1.5 \)
Enhanced cross-sections from textures II

- Textures with $(Y_\nu Y_\nu^\dagger)_{12} = 0$ and $|Y_{ij}|^2 < 1.5$

$$Y^{(1)}_{\tau\mu} = f \begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}, \ Y^{(2)}_{\tau\mu} = f \begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & -1 \end{pmatrix}, \ Y^{(3)}_{\tau\mu} = f \begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}$$

- Flavour composition of the heavy neutrinos:

- 3 very different flavour patterns
- Heavy neutrino mixing of $\tau - \mu$ type is always present
Large production at LHC14:
\[ \sigma \sim 0.1 - 100 \text{fb} \]

Associated lepton depends on \( N_i \)

Decays behave similarly
\[ pp \rightarrow \mu \tau jj \text{ events at LHC14 for } Y_{\tau \mu}^{(3)} \]

Lower line: production only from Drell-Yan

Shaded regions: \( W \gamma \) fusion added with \( p_T^{\text{max}} = 10, 20, 40 \text{ GeV} \)

(darker to lighter)

Up to \( \mathcal{O}(100) \) events, naively background free
**N production and decays**

**pp → μτjj events at LHC14 for Y_{τμ}^{(1)}**

- Lower line: production only from Drell-Yan
- Shaded regions: $Wγ$ fusion added with $p_T^{max} = 10, 20, 40$ GeV (darker to lighter)

**Excluded by τ → μγ**

- $\sqrt{s} = 14$ TeV
- $\mathcal{L} = 300$ fb$^{-1}$
- $Y_{τμ}^{(1)}$

**DY + γW**

**DY**

- $f = 1$
- $f = 1/3$
- $f = 1/10$

**M_R (GeV)**

- Lower line: Up to $\mathcal{O}(10)$ events, naively background free
$pp \rightarrow \mu\tau jj$ events at LHC14 for $Y_{\tau\mu}^{(2)}$

Excluded by $\tau \rightarrow \mu \gamma$

$\sqrt{s} = 14 \text{ TeV}$

$\mathcal{L} = 300 \text{ fb}^{-1}$

$Y_{\tau\mu}^{(2)}$

- Lower line: production only from Drell-Yan
- Shaded regions: $W\gamma$ fusion added with $p_T^{\text{max}} = 10, 20, 40 \text{ GeV}$ (darker to lighter)
- Up to $\mathcal{O}(200)$ events, naively background free
Production at a 100 TeV collider

- Production dominated by gluon fusion → specific to 100 TeV collider
- NLO adds 15 – 40% to $\sigma(pp \rightarrow N\ell^\pm)$
- Model file and details available in [Degrande et al., 2016]
pp → µτjj events at 100 TeV

(\text{arXiv:1606.00947})

\[ \sqrt{s} = 100 \text{ TeV, } L = 10 \text{ ab}^{-1} \]

- ▲: allowed by experimental constraints
- ×: excluded
- Contributions from \( N_{5/6} \) only, inclusive production
- Up to \( \mathcal{O}(10^5) \) events

\[ Y^{(1)}_{\tau \mu} \]

\( N_{1/2} \)

\( N_{3/4} \)

\( N_{5/6} \)

\( e \)

\( \mu \)

\( \tau \)
Summary of $pp \rightarrow \mu \tau jj$

- Signal that can probe all low-scale seesaw models
- Exotic LFV $\mu \tau jj$ signal with $M_{jj} = M_W$, naively background free
- 10-200 events would be expected at LHC14
- $O(10^5)$ events would be expected at a 100 TeV collider

You decide to further study: LFVHD
You are tired and want to end your travels: end
Conclusions

* It’s the end.
Conclusions

* ASRIEL blocks the way!
Conclusions

- $\nu$ oscillations $\rightarrow$ **New physics is needed** to generate masses and mixing

- Inverse seesaw: appealing example of low-scale seesaw mechanisms
  - $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 100 \text{ GeV} - 10 \text{ TeV}$

- **Complementarity** of LFV lepton decays and Higgs decays because of their different dependence on the seesaw parameters

- non-SUSY ISS: $\text{Br}(h \rightarrow \bar{\tau}\mu) \leq 10^{-5}$
  - $\text{Br}(h \rightarrow \bar{\tau}e) \leq 10^{-5}$

- SUSY ISS: already within CMS and ATLAS reach
Conclusions

- Corrections to the HHH coupling from heavy $\nu$ as large as 30%: measurable at future colliders
  - Larger effects when additional heavy neutrinos are present
  - Can probe a new part of the parameter space, unconstrained otherwise
  - Would deliver new constraints on active-sterile mixing: impact on astroparticle physics, cosmology, neutrino physics

- Generic effect, expected to be present in all models including multi-TeV fermions with large Higgs couplings

- Exotic LFV $\mu\tau jj$ signal with $M_{jj} = M_W$, naively background free

- 10-200 events at LHC14, $O(10^5)$ at a 100 TeV collider

- Can we find other collider processes to search for heavy neutrinos? 😊
Conclusions

* you won... congratulations.
Backup slides
Renormalization procedure for the HHH coupling I

- No tadpole: \( t_H^{(1)} + \delta t_H = 0 \implies \delta t_H = -t_H^{(1)} \)
- Counterterms:

\[
M_H^2 \rightarrow M_H^2 + \delta M_H^2 \\
M_W^2 \rightarrow M_W^2 + \delta M_W^2 \\
M_Z^2 \rightarrow M_Z^2 + \delta M_Z^2 \\
e \rightarrow (1 + \delta Z_e)e \\
H \rightarrow \sqrt{Z_H} = (1 + \frac{1}{2} \delta Z_H)H
\]  

(1)

- Full renormalized 1–loop triple Higgs coupling: \( \lambda_{HHH}^{1r} = \lambda^0 + \lambda_{HHH}^{(1)} + \delta \lambda_{HHH} \)

\[
\frac{\delta \lambda_{HHH}}{\lambda^0} = \frac{3}{2} \delta Z_H + \delta t_H \frac{e}{2 M_W \sin \theta_W M_H^2} + \delta Z_e + \frac{\delta M_H^2}{M_H^2} \\
- \frac{\delta M_W^2}{2 M_W^2} + \frac{1}{2} \cos^2 \theta_W \left( \frac{\delta M_W^2}{M_W^2} - \frac{\delta M_Z^2}{M_Z^2} \right)
\]
Renormalization procedure for the HHH coupling II

- OS scheme

\[ \delta M_W^2 = Re \Sigma_{WW}^T (M_W^2) \]
\[ \delta M_Z^2 = Re \Sigma_{ZZ}^T (M_Z^2) \]
\[ \delta M_H^2 = Re \Sigma_{HH}^T (M_H^2) \]

(2)

- Electric charge:

\[ \delta Z_e = \frac{\sin \theta_W}{\cos \theta_W} \frac{Re \Sigma_{\gamma Z}^T (0)}{M_Z^2} - \frac{Re \Sigma_{\gamma \gamma}^T (M_Z^2)}{M_Z^2} \]

- Higgs field renormalization

\[ \delta Z_H = -Re \left. \frac{\partial \Sigma_{HH}^T (k^2)}{\partial k^2} \right|_{k^2=M_H^2} \]
NLO terms in the $\mu_X$-parametrisation

- Weaker constraints on diagonal couplings $\rightarrow$ Large active-sterile mixing $m_D M_R^{-1}$ for diagonal terms

- Previous parametrizations built on the 1st term (LO) in the $m_D M_R^{-1}$ expansion $\rightarrow$ Parametrizations breaks down

- Solution: Build a parametrization including the next order terms

- The NLO $\mu_X$-parametrisation is then

\[
\mu_X \simeq \left( 1 - \frac{1}{2} M_R^{*-1} m_D^\dagger m_D M_R^{T-1} \right)^{-1} M_R^T m_D^{-1} U_{PMNS}^\dagger m_\nu U_{PMNS}^\dagger m_D^T M_R^{-1} M_R \\
\times \left( 1 - \frac{1}{2} M_R^{-1} m_D^T m_D^* M_R^{*-1} \right)^{-1}
\]
Finding the dominant contribution (JHEP1411(2014)048)

- Non-degenerate $\mu_X$ and $R \neq 1$: large $\tau - \mu$ rates and ok with $\mu - e$ within the reach of Belle II
- At low $M_R$ / high $M_{SUSY}$: dominant contributions from non-SUSY boxes and $Z$-penguins
- At low $M_{SUSY}$ / high $M_R$: dominant contributions from SUSY $\gamma$-penguins
- Ratios: sensitive to the dominant contribution (SUSY or non-SUSY)
Modified Casas-Ibarra parametrization [Casas and Ibarra, 2001]

\[ \nu Y_{\nu}^T = V^\dagger \text{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}) \ R \ \text{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) \ U_{PMNS}^\dagger \]

\[ M = M_R \mu_X^{-1} M_R^T \]
**Constraints: focus on $\mu \rightarrow e\gamma$**

- $M_R$ and $\mu_X$ real and degenerate, Casas-Ibarra (C-I) parametrization
- Constrains $\mu_X$
- Perturbativity $\rightarrow |\frac{Y_{\nu}^2}{4\pi}| < 1.5$ (Dotted line = non-perturbative couplings)

\[
\frac{v^2(Y_{\nu}Y_{\nu}^\dagger)_{km}}{M_R^2} \approx \frac{1}{\mu_X} \left( U_{PMNS} \Delta m^2 \frac{U_{PMNS}^T}{2m_{\nu_1}} \right)_{km}
\]
Dependence on ISS parameters: $\mu_X$ and $M_R$

$BR_{H\rightarrow\mu\tau}^{\text{approx}} = 10^{-7} \left( \frac{v^4}{M_R^4} \right) \left| (Y_{\nu} Y_{\nu}^\dagger)_23 - 5.7 (Y_{\nu} Y_{\nu}^\dagger Y_{\nu} Y_{\nu}^\dagger)_23 \right|^2$

- $R = 1$, $M_R$ and $\mu_X$ degenerate and real, C-I parametrization
- Dips come from interferences between diagrams
- Can be understood using the mass insertion approximation

$$\frac{v^2 (Y_{\nu} Y_{\nu}^\dagger)_km}{M_R^2} \approx \frac{1}{\mu_X} \left( \frac{U_{\text{PMNS}} \Delta m^2 U_{\text{PMNS}}^T}{2m_{\nu_1}} \right)_{km}$$

and

$$\frac{v^2 (Y_{\nu} Y_{\nu}^\dagger Y_{\nu} Y_{\nu}^\dagger)_km}{M_R^2} = \frac{M_R^2 (U_{\text{PMNS}} \Delta m^2 U_{\text{PMNS}}^T)_km}{v^2 \mu_X^2}$$
Conclusion

Dependence on Casas-Ibarra parameters: $R$ matrix

- $M_R$ and $\mu_X$ degenerate and real
- Independent of $R$ for real mixing angles
- Increase with complex angles, but increase limited by $\mu \rightarrow e\gamma$
  $\Rightarrow$ Complex $R$ matrix doesn’t change our results
Searching for maximal $\text{Br}(H \to \bar{\tau} \mu)$

- $M_X$ and $\mu_X$ degenerate and real
- Excluded by $\mu \to e\gamma$
- Non-perturbative $Y_\nu$
- $\text{Br}(H \to \bar{\tau} \mu) \leq 10^{-10}$
- End of the story?

$R = 1$

$m_{\nu_1} = 0.1 \text{ eV}$
Hierarchical heavy $N$

- Similar growth with $M_{R_3}$ and $\mu_X$ as in the degenerate case with $M_R$ and $\mu_X$

- Excluded by $\mu \rightarrow e\gamma$

- Non-perturbative $Y_\nu$

- $\text{Br}(H \rightarrow \bar{\tau}\mu) \leq 10^{-9}$
Impact of the $R$ matrix for hierarchical $N$

- Contrary to degenerate case, $R$ dependence
- Varying $\theta_1$: Same conclusions as before
- Dotted = non-perturbative couplings
  Cross = Excluded by $\mu \rightarrow e\gamma$
- $\theta_2 \sim \pi/4$:
  $\text{Br}(H \rightarrow e\tau) > \text{Br}(H \rightarrow \mu\tau)$
- Results quite insensitive to $\theta_3$
Conclusion

Dependence on $m_{\tilde{\nu}_R}$ and $m_{\tilde{X}}$

- $M_R$ degenerate and real, $m_A = 800$ GeV
- ▲: allowed by LFV radiative decays, ×: excluded

- At low $m_{\tilde{\nu}_R}$: dominated by chargino-sneutrino loops
  - At large $m_{\tilde{\nu}_R}$: dominated by neutralino-slepton loops

- Can reach allowed values up to $\text{BR}(h \rightarrow \tau \bar{\mu}) = 1.1\%$