Neutrino physics in high-energy proton-proton collisions

3rd FCC-France Meeting – LAPP Annecy

Richard E. Ruiz

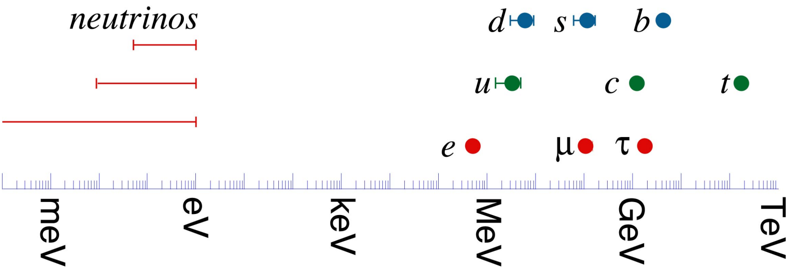
Institute of Nuclear Physics – Polish Academy of Science (IFJ PAN)

1 December 2021

thank you for the invitation!

the ν case for new physics

Problem: according to the SM, $m_\nu = 0$. (The data disagree, obviously.)

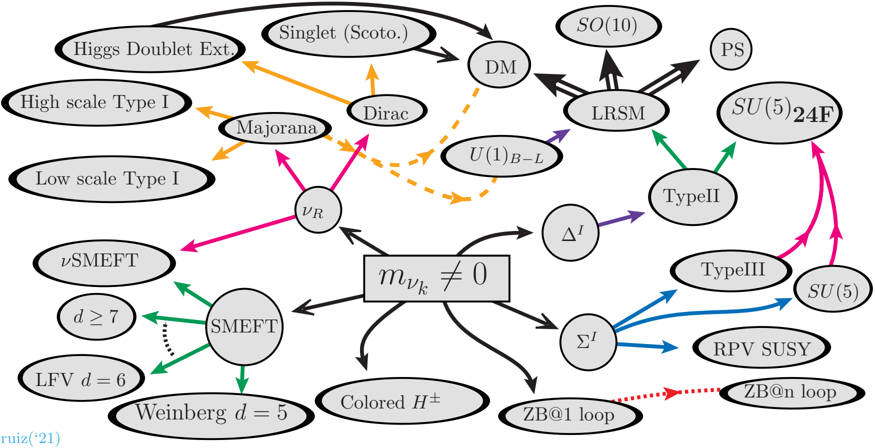


Neutrino masses ('15) $\Longrightarrow$ **many open questions:**

- ν have mass. What is generating m_ν?
- ν masses are *tiny*. What sets the scale of m_ν?
- m_ν are nearly degenerate. What sets the pattern of m_ν?
- ν carry no QCD/QED charge. Are $\nu, \overline{\nu}$ the same (Majorana)?

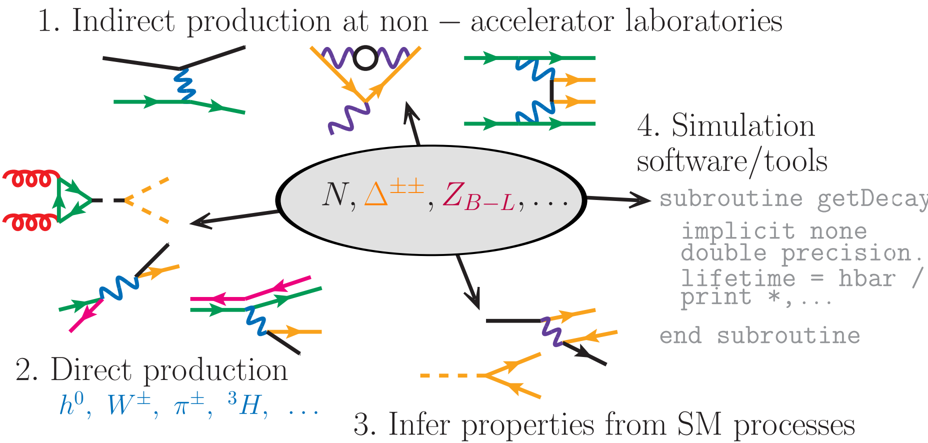
Neutrino mass (Seesaw) models give some answers to these questions

Many possible origins of neutrino masses



rruiz('21)

Many ways to explore neutrino mass models



1. Indirect production at non − accelerator laboratories

4. Simulation software/tools

```
subroutine getDecay
  implicit none
  double precision.
  lifetime = hbar /
  print *,...
end subroutine
```

$N, \Delta^{\pm\pm}, Z_{B-L}, \ldots$

2. Direct production

$h^0,\ W^{\pm},\ \pi^{\pm},\ {}^3H,\ \ldots$

3. Infer properties from SM processes

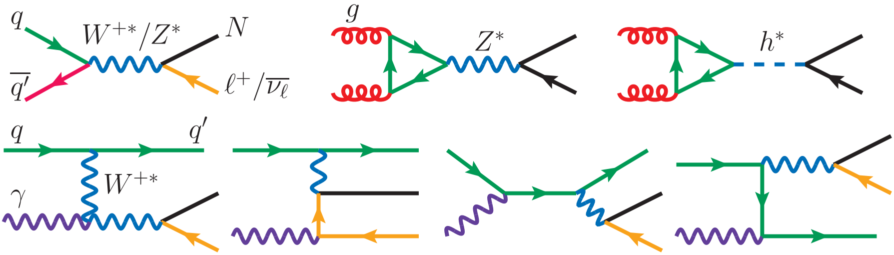
for reviews on LNV/LFV at colliders, see w/ Y. Cai, T. Li, T. Han [1711.02180], and w/ S. Pascoli, et. al. [1812.08750]

A snapshot

No time for exhaustive review, but enough time to flash numbers (and refs!):

- Low-scale Type I at 100 TeV ☺
- Type II at 100 TeV ☺
- Type III at 100 TeV ☺
- Gauge models at 100 TeV ☹ (see review!)
- Weinberg operator at 100 TeV ☺ (see backup!)

Sterile neutrinos at 100 TeV



Sterile neutrinos in practice (1 slide)

Generically paramerize active-sterile neutrino mixing via

Atre, Han, Pascoli, Zhang [0901.3589]

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell m'=4} N_{m'=4}}_{\text{mass basis}}$$

Sterile neutrinos in practice (1 slide)

Generically paramerize active-sterile neutrino mixing via

Atre, Han, Pascoli, Zhang [0901.3589]

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell m'=4} N_{m'=4}}_{\text{mass basis}}$$

The SM W chiral coupling to **leptons** in **flavor basis** is

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\overline{\ell}\gamma^\mu P_L \nu_\ell\right] + \text{H.c.}, \qquad \text{where } P_L = \frac{1}{2}(1-\gamma^5)$$

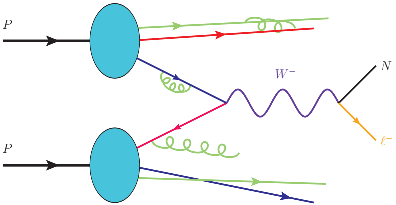
$\Longrightarrow$ SM W coupling to N and charged **leptons** in the **mass basis is**

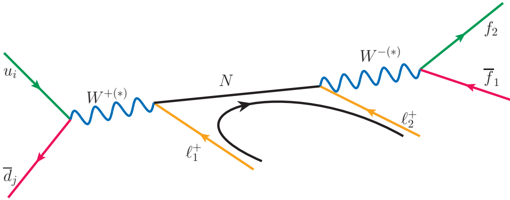
$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\overline{\ell}\gamma^\mu P_L \left(\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell N} N\right)\right] + \text{H.c.}$$

$\Longrightarrow$ N is **accessible through** $W/Z/h$ bosons

Historically, searches for *N* relied on $(q\overline{q})$ annihilation

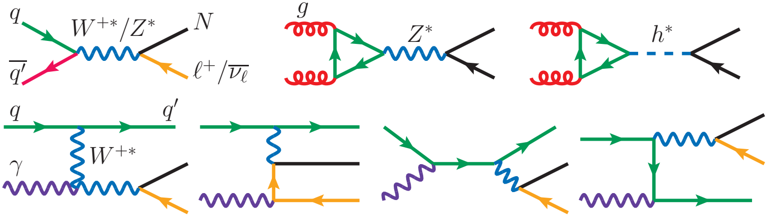
Keung & Senjanovic (PRL'83)





At the LHC, a **canonical** signature for *N*: $pp \to \ell_i^\pm \ell_j^\pm + nj +$ no MET

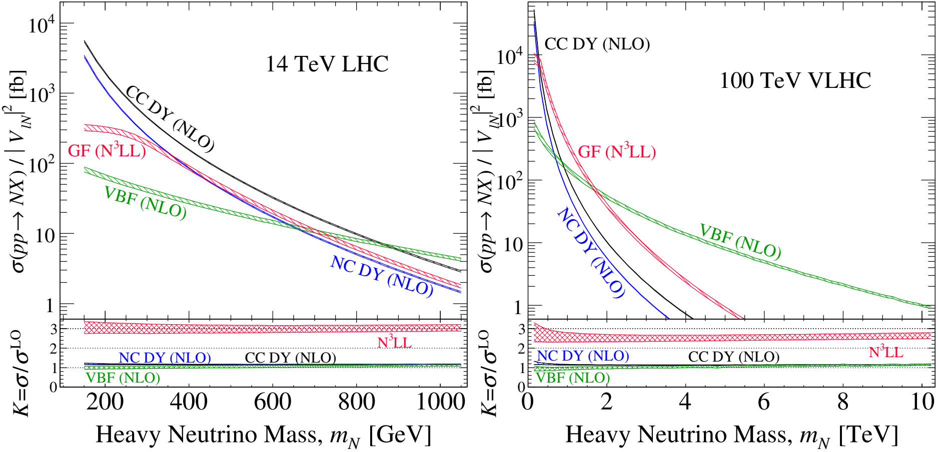
based on seminal works by K&S, del Aguila & Aguilar-Saavedra [0808.2468], and Atre, et al [0901.3589]



After lots of CPU hours (and coffee!)

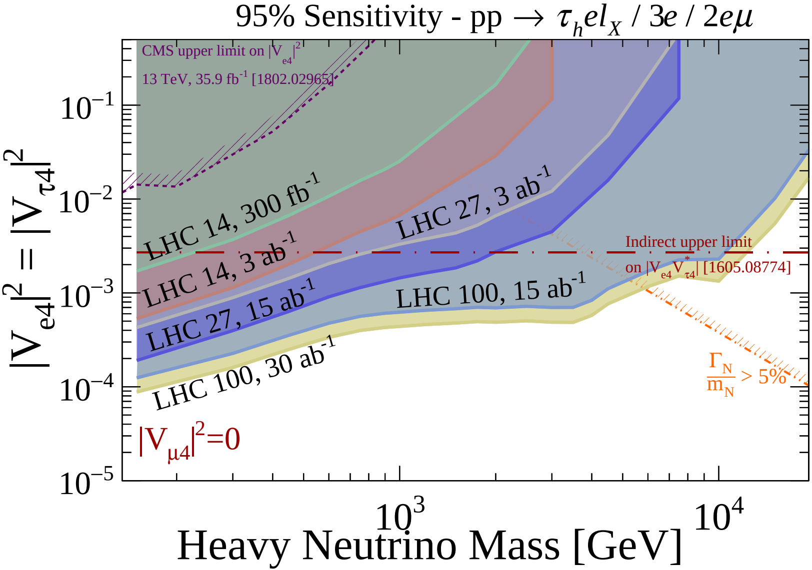
for details, see RR, et al, [1711.02180] and [1812.08750]

Plotted: Normalized production rate ($\sigma/|V|^2$) vs heavy N mass (m_N)



Wild interplay between proton structure and matrix elements!

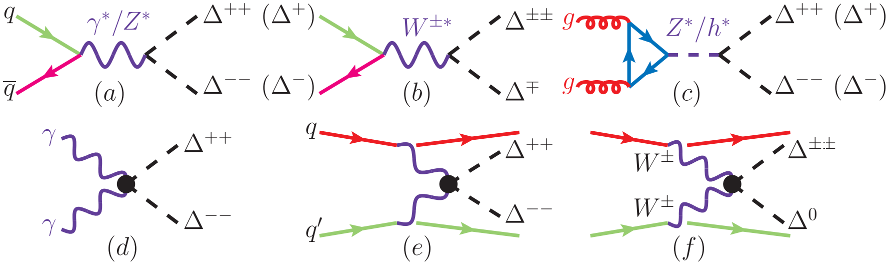
- **Take away:** GF and VBF dominate at 100 TeV for $m_N \gtrsim 1$ TeV



New analysis for had. environment ⟹ new sensitivity to LNV + cLFV

Only a few results. See the big paper for various flavor, Dirac vs Majorana, and $\sqrt{s}$ permutations [1812.08750]

Type II Seesaw at 100 TeV[1]



---

[1] Konetschny and Kummer ('77); Schechter and Valle ('80); Cheng and Li ('80); Lazarides, et al ('81); Mohapatra and Senjanovic ('81)

The Type II Seesaw Mechanism is special: generates neutrino masses ***without*** hypothesizing right-handed neutrinos

- Important example that $m_\nu \neq 0 \not\Rightarrow$ that ν_R exist

The Type II Seesaw Mechanism is special: generates neutrino masses ***without*** hypothesizing right-handed neutrinos

- Important example that $m_\nu \neq 0 \not\Rightarrow$ that ν_R exist

Hypothesize a **scalar** $\mathrm{SU}(2)_L$ triplet with **lepton number** $L = -2$

$$\hat{\Delta} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^0 & -\Delta^+ \end{pmatrix}, \quad \text{with} \quad \mathcal{L}_{\Delta\Phi} \ni \mu_{h\Delta}\left(\Phi^\dagger \hat{\Delta} \cdot \Phi^\dagger + \text{H.c.}\right)$$

The mass scale $\mu_{h\Delta}$ breaks lepton number, and induces $\langle \Delta \rangle \neq 0$:

$$\sqrt{s}\langle \hat{\Delta} \rangle = v_\Delta \approx \frac{\mu_{h\Delta} v_{\mathrm{EW}}^2}{\sqrt{2} m_\Delta^2}$$

which leads to **left-handed Majorana masses** for neutrinos

$$\Delta\mathcal{L} \quad = \quad -\frac{y_\Delta^{ij}}{\sqrt{2}} \overline{L^c} \hat{\Delta} L \quad = \quad -\frac{y_\Delta^{ij}}{\sqrt{2}} \begin{pmatrix} \overline{\nu^{jc}} & \overline{\ell^{jc}} \end{pmatrix} \begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix} \begin{pmatrix} \nu^i \\ \ell^i \end{pmatrix}$$

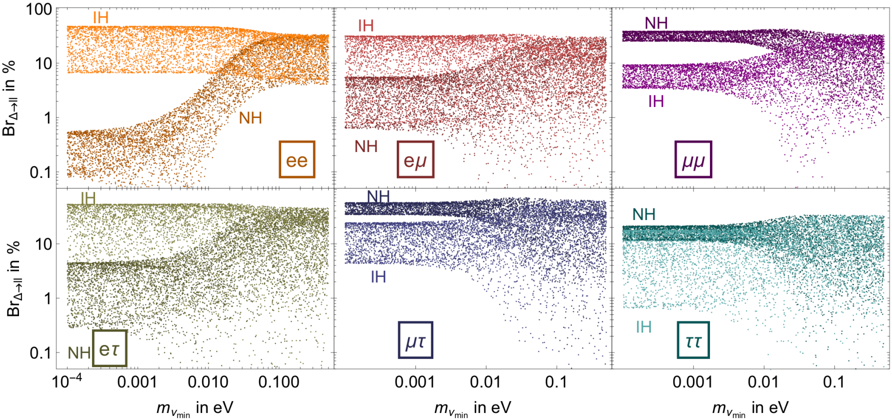
$$\ni -\frac{1}{2} \underbrace{\left(\sqrt{2} y_\Delta^{ij} v_\Delta\right)}_{= m_\nu^{ij}} \overline{\nu^{jc}} \nu^i$$

Fewer free parameters $\Longrightarrow$ richer experimental predictions

Fileviez Perez, Han, Li, et al, [0805.3536], Crivellin, et al [1807.10224], Fuks, Nemevšek, RR [1912.08975] + others

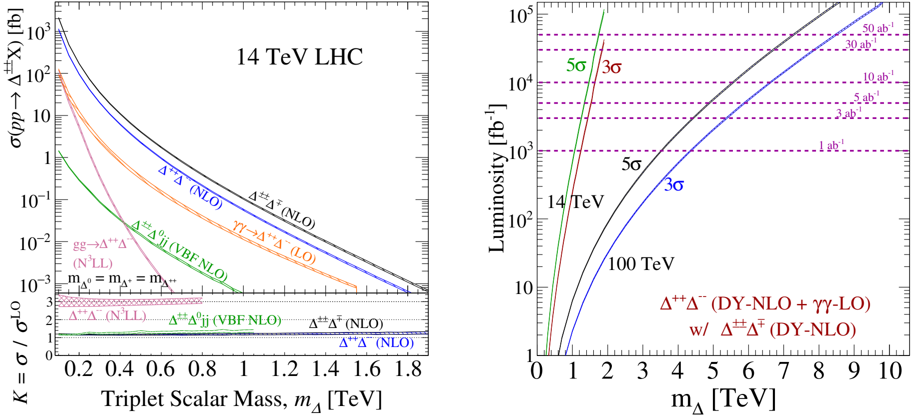
- E.g., Δ branching rates encode inverse (IH) vs normal (NH) ordering of light neutrino masses

$$\mathrm{BR}(\Delta^{\pm\pm} \to \ell_i^{\pm} \ell_j^{\pm}) \sim y_\Delta^{ij} \sim (U^*_{\rm PMNS} \tilde{m}_\nu^{\rm diag} U^\dagger_{\rm PMNS})_{ij}$$



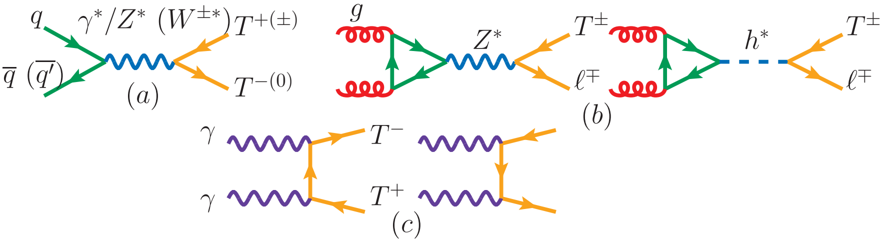
A new outlook for both $\sqrt{s} = 14$ TeV and 100 TeV!

w / Fuks and Nemevšek [1912.08975]



- At LHC with $\mathcal{L} = 5$ ab^{-1}, 3σ sensitivity up to $m_\Delta \sim 1.5$ TeV
- At $\sqrt{s} = 100$ TeV with $\mathcal{L} = 30 - 50$ ab^{-1} $\Longrightarrow$ $m_\Delta \approx 8 - 9$ TeV
- **Warning**: can be improve for specialized final state / parameter space

Type III Seesaw at 100 TeV



Type III Seesaw combines main features of Types I and II Seesaws:

- **Idea:** add $\mathrm{SU}(2)_L$ fermion triplet ($Y = 0$) with mass m_Σ
- Key to reconciling GUTs with proton decay E.g., Bajc, Senjanovic [hep-ph/0612029], ...

$$\mathcal{L}_{\nu\ \mathrm{Yuk.}} = -y_\Sigma \overline{L}\Sigma\Phi_{\mathrm{SM}} = -y_\Sigma \begin{pmatrix}\overline{\nu_L} & \overline{\ell_L}\end{pmatrix} \begin{pmatrix}\Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0\end{pmatrix} \begin{pmatrix}\langle\Phi_{\mathrm{SM}}\rangle + h \\ 0\end{pmatrix}$$

$$= \underbrace{-y_\Sigma\langle\Phi_{\mathrm{SM}}\rangle}_{=m_D}\overline{\nu_L\Sigma^0} + \ \ldots$$

Type III Seesaw combines main features of Types I and II Seesaws:

- **Idea:** add $SU(2)_L$ fermion triplet ($Y=0$) with mass m_Σ
- Key to reconciling GUTs with proton decay E.g., Bajc, Senjanovic [hep-ph/0612029], . . .

$$\mathcal{L}_{\nu\ \mathrm{Yuk.}} = -y_\Sigma \overline{L}\Sigma\Phi_{\mathrm{SM}} = -y_\Sigma \begin{pmatrix}\overline{\nu_L} & \overline{\ell_L}\end{pmatrix}\begin{pmatrix}\Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0\end{pmatrix}\begin{pmatrix}\langle\Phi_{\mathrm{SM}}\rangle + h \\ 0\end{pmatrix}$$

$$= \underbrace{-y_\Sigma\langle\Phi_{\mathrm{SM}}\rangle}_{=m_D}\overline{\nu_L\Sigma^0} + \ \dots$$

Assuming that m_Σ (Majorana mass) $\gg y_\Sigma\langle\Phi\rangle$ (Dirac mass)

$$m_{\mathrm{light}} \approx y_\Sigma^2 v^2/2m_\Sigma, \quad m_{\mathrm{heavy}} \approx -m_\Sigma$$

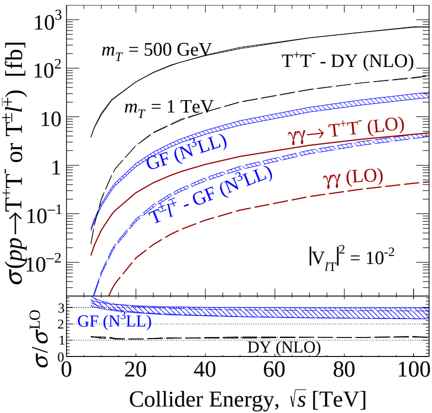
For $m_{\mathrm{light}} = 0.1$ eV, if $y_\Sigma \sim \mathcal{O}(y_e) \sim 1\cdot 10^{-6}$, $m_{\mathrm{heavy}} \approx 300$ GeV!

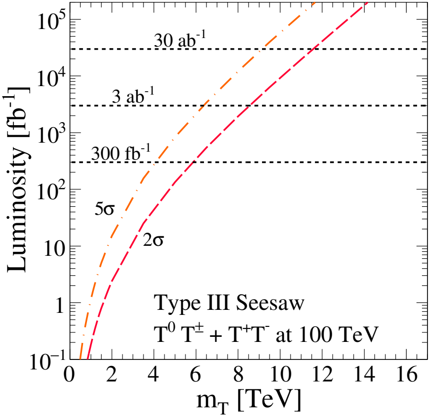
After rotating into the mass basis, mixing-induced cLFV:

$$|T^0\rangle = \cos\theta\ |\Sigma^0\rangle + \sin\theta\ |\nu_\ell\rangle \approx (1-\varepsilon^2/2)\ |\Sigma^0\rangle + \epsilon\ |\nu_\ell\rangle$$
$$|T^\pm\rangle = \cos\phi\ |\Sigma^\pm\rangle + \sin\phi\ |\ell^\pm\rangle \approx (1-\varepsilon^2/2)\ |\Sigma^\pm\rangle + \epsilon\ |\ell^\pm\rangle$$

Collider prediction: heavy charged ($T^{\pm}$) and neutral (T^{0}) leptons:

- Production through gauge couplings to W, Z, γ
- Decays to SM leptons through mixing, e.g., $T^{\pm} \to \ell^{\pm}\nu$

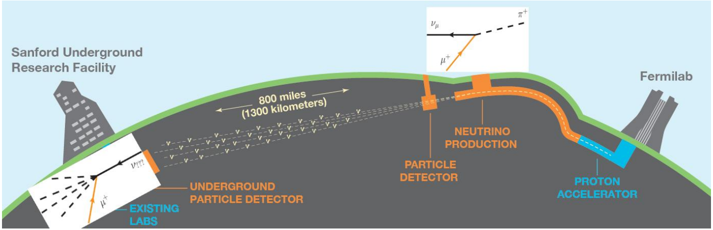




RR [1509.05416]

$\mathcal{O}(10)$ TeV charged and neutral leptons discoverable at 100 TeV

Summary



Big picture: ν unambiguously point the existence of new physics!!

Active research community using accelerators to investigate how and why some matter (ν) is *much* lighter than others

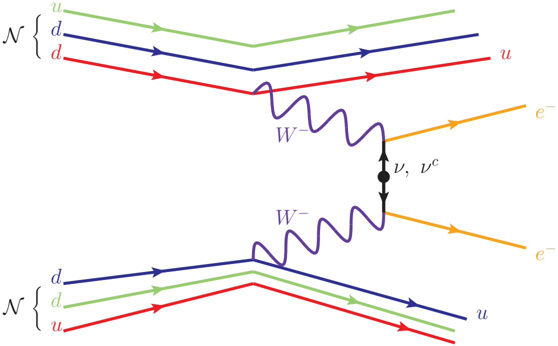
Outlook: is incredibly encouraging!

- The LHC has collected only $< 5\%$ of full dataset ($20\times$ still to come!)
- The FCC can open the door to $\mathcal{O}(10-40)$ TeV mass scales!
- New ideas are creating new windows into the nature of ν


mechanism
review
impact
veto
channel
system
leading
searche
epton
hadron
decay
heavy
discovery
LRSM
test
data
range
boson
neutrino
Monte
GeV
current
order
sses
cross
Type
seesaw
high
rate
process
ture
jet
ransverse
one
collider
top
context
VBS
iii
pair
NLO
mass
tool
Higgs
Carlo
quark
NNLO
via
100
large
model
tate
LHC
TeV
due
well
find
ale
rocesses
QCD
production
tandard
result
probe
available
case
using
correcti

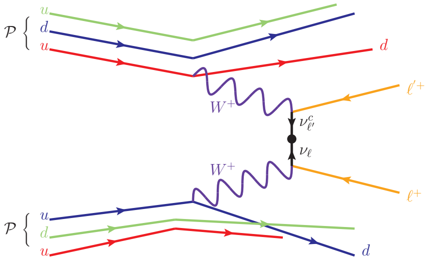
Thank you.

Weinberg Operator[2]



---

[2] Fuks, Neundorf, Peters, RR, Saimpert [2011.02547, 2012.09882]

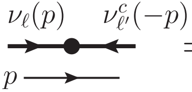


The helicity amplitude for the $0\nu\beta\beta$ process $q\overline{q'} \to \ell_1^+ \ell_2^+ \overline{f} f'$ is

$$\mathcal{M}_{LNV} = J^{\mu}_{f_1 f_1'} J^{\nu}_{f_2 f_2'} \Delta^W_{\mu\alpha} \Delta^W_{\nu\beta} \underbrace{T^{\alpha\beta}_{LNV} \mathcal{D}(p_\nu)}_{\text{lepton current}}$$

Difficult to simulate since Weinberg op. modifies propagator of ν_ℓ

modern Monte Carlo tools work in mass basis and do not like the idea of modifying $\langle 0 | \overline{\nu_{\ell'}} \nu_\ell | 0 \rangle$



$$= \frac{i\not{p}}{p^2} \; \frac{-iC_5^{\ell\ell'} v^2}{\Lambda} \; \frac{i\not{p}}{p^2} = \frac{i m_{\ell\ell'}}{p^2}$$

Solution: Treat vertex as a particle! Invent unphysical Majorana fermion with (small) mass $m_{\ell\ell}$ that couples to all lepton flavors

recovers right behavior!

$$T^{\alpha\beta}_{LNV} \mathcal{D}(p_\nu) \propto \gamma^\alpha P_L \frac{i(\not{p} + m_{\ell\ell'})}{p^2 - m^2_{\ell\ell'}} \gamma^\beta P_R = \gamma^\alpha P_L \frac{i m_{\ell\ell'}}{p^2} P_L \gamma^\beta \times \left[1 + \mathcal{O}\left(\left| \frac{m^2_{\ell\ell'}}{p^2} \right| \right) \right]$$

Plotted: Normalized production rate ($C_5 = 1$) vs scale (Λ)

w/ Fuks, Neundorf, Peters, Saimpert [2012.09882]

Full $2 \to 4$ calculation at NLO(+PS) in QCD is more involved

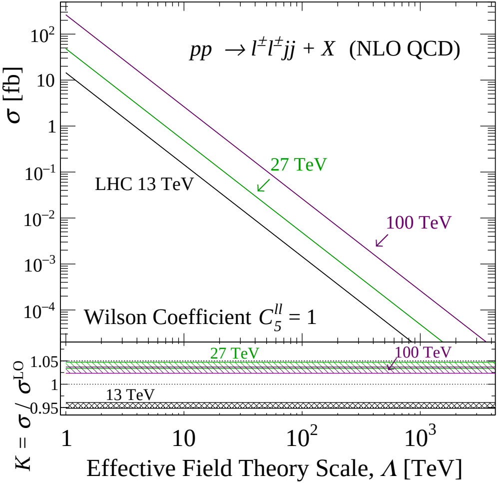
Used `mg5amc` + NEW `SMWeinberg` UFO libraries

Driven by $W_0^+ W_0^+$ scattering

$$\hat{\sigma}(W^+W^+ \to \ell^+\ell^+) \sim \frac{|C_5^{\ell\ell}|^2}{18\pi\Lambda^2}$$

Once σ is obtained for a "high" scale, i.e., $C_5^{\ell\ell'} = 1, \Lambda = 200$ TeV, rescale for other Λ / C_5.

C_5^{ee}/Λ is heavily constrained. **What can the LHC say about $C_5^{\ell\ell'}$?**

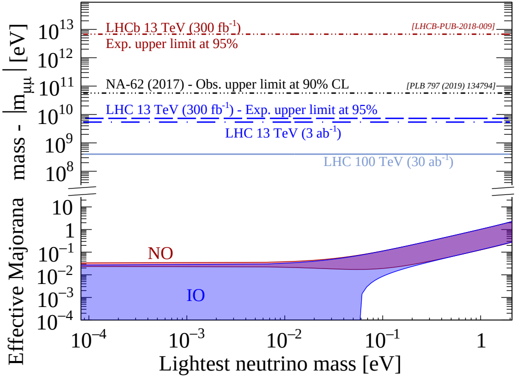


With a VBS-style analysis $\mathcal{L} = 300\ (3000)\ \text{fb}^{-1}$

$$\Lambda/|C_5^{\mu\mu}| \lesssim 8.3\ (11)\ \text{TeV} \implies |m_{\mu\mu}| \gtrsim 7.3\ (5.4)\ \text{GeV}$$

Plotted: Allowed and projected reach of $|m_{\mu\mu}|$ vs lights ν mass

$$|m_{\ell\ell'}| = |C_5^{\ell\ell'}|\langle\Phi\rangle^2/2\Lambda = |\sum_{k=1}^{3} U_{\ell k} m_{\nu_k} U_{\ell' k}|$$



Competitive race between accelerator-based experiments; all analyses can be improved!

Grand Unified Theories and
Theories with Gauged Lepton Number[3]

Arise when UV completing simplified Seesaw Models. No time!

---

[3] Many, many omissions: e.g., SO(10), U(1)$_{B-L}$, etc. See [1711.02180] for details!