Heavy neutrinos and the search for their Dirac/Majorana nature

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Overview

Motivation for extra neutrinos

- Evidence of neutrino oscillations imply:
  Neutrinos are massive:

$$m_1,\ m_2,\ m_3: \quad \Delta m^2_{12} \sim 10^{-5}\ \mathrm{eV}^2, \quad \Delta \mathrm{m}^2_{23} \sim 10^{-3}\ \mathrm{eV}^2.$$

$$\sum_i m_i \lesssim 0.1\ \mathrm{eV} \quad \text{(Cosmology)}$$

  and mix: ν_1, ν_2, ν_3 combinations of ν_e, ν_μ, ν_τ:

$$\sin^2\theta_{12} \sim 0.3, \quad \sin^2\theta_{23} \sim 0.5, \quad \sin^2\theta_{13} \sim 0.02$$

- In the SM, neutrinos are massless (left handed Weyl fermions)

Open questions:

- Why neutrinos are so much lighter than all other fermions?
- How is the SM modified to include the massive neutrinos?

Motivation for extra neutrinos

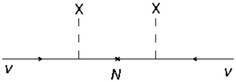
A top down approach:
A fundamental theory that explains m_ν as a consequence.

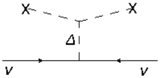
- How can the SM be modified to include massive neutrinos?
- SM + Higgs was already not a satisfactory theory.
- Extended gauge symmetries:
  - new interactions
  - larger fermion representations (extra ν_R fields?)
  - composite scalars?
  - other exotics?
- In terms of purely SM fields, the only (effective) term: [S. Weinberg (1979)]

$$\mathcal{L} \sim \frac{L\phi L\phi}{\Lambda} \quad \Rightarrow m_\nu \sim \frac{v^2}{\Lambda}.$$

- Add extra fields to get a renormalizable operator at tree level. Only 3 ways:
  - Type I seesaw: $(L\phi)$ forms a fermion singlet: extra N.
  - Type II seesaw: (LL) forms a scalar triplet: extra $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
  - Type III seesaw: $(L\phi)$ forms a fermion triplet: extra $\Sigma = (\Sigma^{+}, \Sigma^{0}, \Sigma^{-})$

Motivation for extra neutrinos





- More possibilities... masses from loops, RpV SUSY,...

Let us focus on Type 1 (extra singlet fermions, N).

- A Majorana mass of the singlet N violates Lepton number (and thus $B - L$):

$$-\mathcal{L} \sim M_\Lambda \, \overline{N^c} N + \ldots$$

  with $M_\Lambda \sim \Lambda$ (the scale of the extra gauge and L breaking)
- E.g.: a simple UV completion is the LR symmetric model, where $N \equiv \nu_R$ is part of a *right handed* doublet.
- ...other gauge groups such as $SO(10)$, E_6....

Motivation for extra neutrinos

- Consider a single $N \equiv \nu_R$ (per family) as in the LR symmetric model:

  $$-\mathcal{L} = y\overline{L}\phi^{\mathcal{C}}\nu_R + \frac{1}{2}M\overline{\nu}_R^c\nu_R + \dots$$

  $\Rightarrow$ After EWSB:

  $$-\mathcal{L} = \frac{1}{2}\left(\bar{\nu}_L,\ \bar{\nu}_R^c\right)\begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \dots$$

  with $m_D = yv/\sqrt{2}$.

- This is the original Type 1 *seesaw* model: [P. Minkowski (1977), T. Yanagida (1979)]

  Two Majorana neutrinos, ν_l and N, with masses $m_l \sim \dfrac{m_D^2}{M}, \quad m_N \sim M$,

  and mixing in the EW currents: $J_\mu^{(-)} = \bar{e}\gamma_\mu P_L\Big(V_{el}\ \nu_l + V_{eN}\ N\Big)$:

  $$V_{eN} \sim \frac{m_D}{M} \quad \sim \sqrt{\frac{m_l}{M}} \quad \sim 10^{-5}\sqrt{\frac{GeV}{M}}$$

Motivation for extra neutrinos

- Other Type 1, with more extra neutrinos per family:
  e.g. *low scale seesaw models* [R.N. Mohapatra & J.W.F. Valle (1986)]

$$-\mathcal{L} = y\bar{L}\phi^{\mathcal{C}}\nu_R + M\ \bar{S}_L\nu_R + \frac{1}{2}\mu_R\bar{\nu}_R^c\nu_R + \frac{1}{2}\mu_S\bar{S}_L S_L^c + \dots$$

$$\Rightarrow -\mathcal{L} = \frac{1}{2}\left(\bar{\nu}_L,\ \bar{\nu}_R^c,\ \bar{S}_L\right)\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & \mu_R & M \\ 0 & M^T & \mu_S \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \\ S_L^c \end{pmatrix} + \dots$$

- Now the masses: $m_l \sim \mu_S\frac{m_D^2}{M^2}, \quad m_{N_{1,2}} \sim M, \quad \Delta m_N \sim \mu_S$
- L is conserved and one massless mode if $\mu_S = \mu_R = 0$.
- ν_l: one light Majorana; the smallness is dictated by a small μ_S
- $N_{1,2}$: two heavy Majorana (quasi-Dirac if $\Delta m_N \lesssim \Gamma_N$).
- Mixing is less constrained: $V_{eN} \sim \frac{m_D}{M} \quad \sim \sqrt{\frac{m_l}{\mu_S}}$
- More seesaw scenarios (linear, double, lobsided, ...) [E. Ma (2009)]

Motivation for extra neutrinos

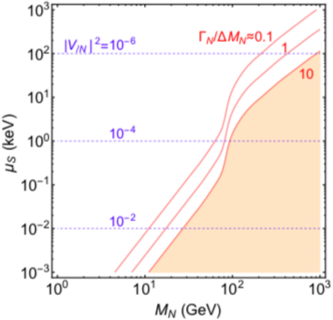
- The decay width also depends on m_N and $V_{\ell N}$:

$$\Gamma_N \sim \frac{G_F^2}{10\pi^3} m_N^5 \sum_\ell |V_{\ell N}|^2$$

$$\frac{\Gamma_N}{\Delta m_N} \sim \left(\frac{1 keV}{\mu_S}\right)^2 \left(\frac{m_N}{100 GeV}\right)$$

See figure:

- white zone: N is Majorana.
- red zone: N is Dirac.



from F. Deppisch, P.S.B. Dev & A. Pilaftsis (2015)

Motivation for extra neutrinos

Therefore:

- Extra neutrinos can be in a wide range of masses (keV → GUT scale).
- Heavy-to-light mixings also cover a wide theoretical range (there are experimental constraints).
- It is important to determine the Dirac or Majorana character of $N's$ to distinguish between different scenarios.

Searches for heavy Dirac/Majorana neutrinos

Current bounds on V_{eN}:

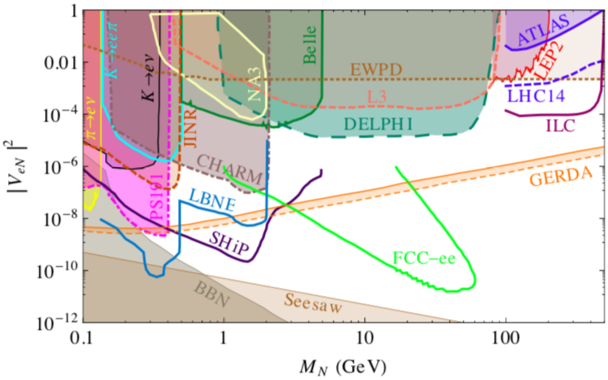


Figure from F. Deppisch, P.S.B. Dev & A. Pilaftsis, New J.Phys. 17, 075019 (2015).

Searches for heavy Dirac/Majorana neutrinos

Current bounds on $V_{\mu N}$:

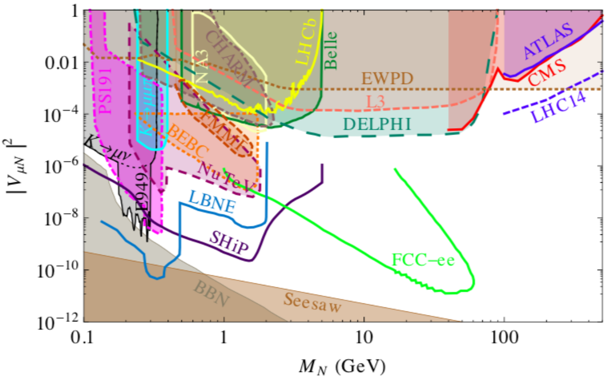


Figure from F. Deppisch, P.S.B. Dev & A. Pilaftsis, New J.Phys. 17, 075019 (2015).

...and more recent bound from LHCb [S. Antusch, E. Cazzato & O. Fisher (2017)].

Searches for heavy Dirac/Majorana neutrinos

Current bounds on $V_{\tau N}$:

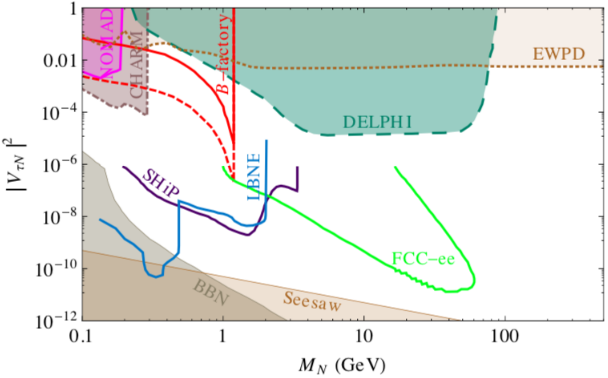


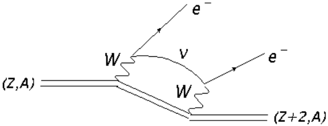
Figure from F. Deppisch, P.S.B. Dev & A. Pilaftsis, New J.Phys. 17, 075019 (2015).

Searches for heavy Dirac/Majorana neutrinos

◇ Search for heavy sterile neutrinos in processes:

- Majorana:
  - violation of Lepton Flavor (LFV),
  - violation of Lepton Number (LNV).
- Dirac:
  - violation of LFV only (L# is conserved).

◇ Search for Majorana *N*: best processes are nuclear $0\nu\beta\beta$ decays
...but there can be cancellations even if *N* are Majorana (e.g. CP phases).



Searches for heavy Dirac/Majorana neutrinos

◇ Search for heavy sterile neutrinos at colliders:

- For $m_N > M_W$, preferred channel is $pp \to \ell^\pm \ell^\pm jj$ (Majorana N only). (see also talk by O. Fischer on LFV $e^\pm \mu^\mp jj$ at future colliders).

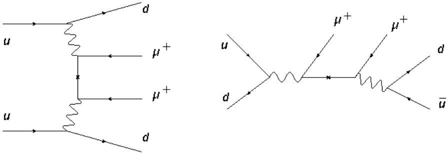


Figure : Left: N in the t-channel; right: dominant for resonant N.

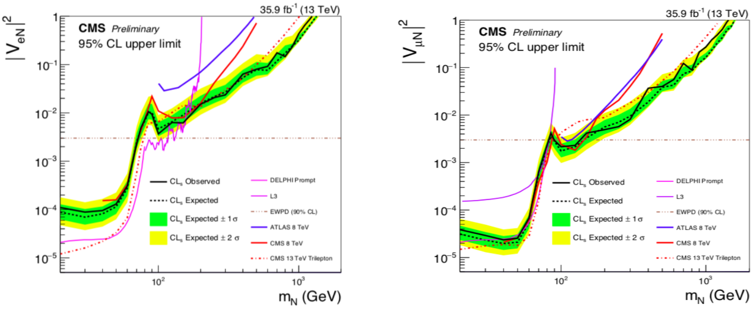
- $\sigma(pp \to W)$ decreases with m_N: LHC sensitive up to ~ 1 TeV
- Larger $\sigma(pp \to W_R)$ for larger m_N: stronger bounds for LR sym. model.

Searches for heavy Dirac/Majorana neutrinos

Search by CMS at $\sqrt{s} = 13$ TeV with 35.9 fb^{-1} pp collisions
into same-sign dilepton + jets.

[CMS PAS-EXO 17-028 (2018)]

- Found no signal above background: bounds on $|U_{eN}|$ and $|U_{\mu N}|$ for $m_N < 1$ TeV.

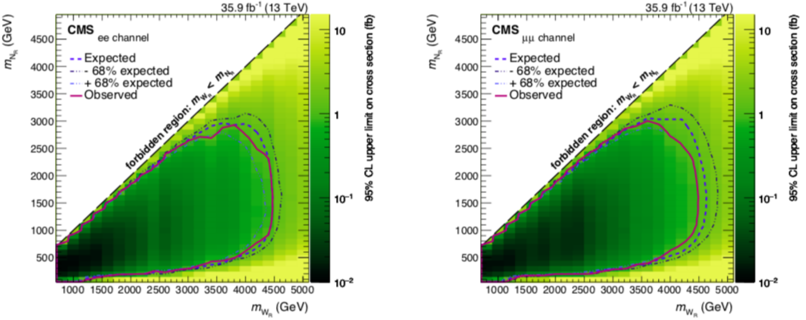


Searches for heavy Dirac/Majorana neutrinos

Search for W_R and N by CMS at $\sqrt{s} = 13$ TeV with 35.9 fb^{-1}
$pp \to W_R \to \ell N \to \ell\ell W_R^* \to \ell\ell jj$

[CMS coll., JHEP 1805, 148 (2018)]

- Larger expected rates imply bounds $M_{W_R} > 4.5$ TeV and m_N up to 3 TeV.



Searches for heavy Dirac/Majorana neutrinos

◇ Search for heavy sterile neutrinos at colliders:

- For $m_N > M_W$, preferred channel is $pp \to \ell^\pm \ell^\pm jj$ (Majorana N only)...
- ...but for $m_N < M_W$, jets are softer ⇒ trilepton modes are preferred.

$$pp \to e^\pm e^\pm \mu^\mp \nu, \quad pp \to \mu^\pm \mu^\pm e^\mp \nu$$

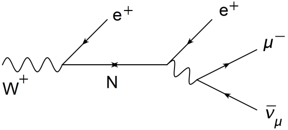
[E. Izaguirre & B. Shuve (2015)]

- Missing final ν: cannot test L conservation directly.
- Majorana N:
  sum of two rates (LNV + LNC):
  e.g. $W^+ \to e^+ e^+ \mu^- \bar{\nu}_\mu + W^+ \to e^+ e^+ \mu^- \nu_e$
- Dirac N:
  LNC rate only: $W^+ \to e^+ e^+ \mu^- \nu_e$.

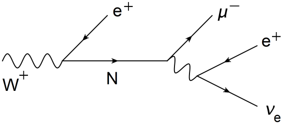
Searches for heavy Dirac/Majorana neutrinos

$W^+ \to e^+ e^+ \mu^- \nu$:

- Lepton Number Violating (LNV) mode:
  caused by Majorana N only: $W^+ \to e^+ e^+ \mu^- \bar{\nu}_\mu$:



- Lepton Number Conserving (LNC) mode:
  caused by both Majorana and Dirac N: $W^+ \to e^+ e^+ \mu^- \nu_e$:



- How can we tell whether N is Dirac or Majorana?
- Exploit the fact that μ^- (the odd lepton) in the N decay is attached to a different current.

Searches for heavy Dirac/Majorana neutrinos

$W^+ \to e^+ e^+ \mu^- \nu$:

- How to tell a Majorana from a Dirac N:
- Exploit the fact that μ^- (the odd lepton) in the N decay is attached to a different current.

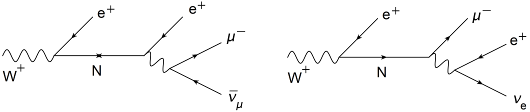
- Three possible differences:
  1. Different heavy-to-light mixing elements (different rates).
  2. Different μ energy spectrum.
  3. Different μ angular distributions.

Dirac/Majorana distinction in trilepton events ($\ell^{\pm}\ell \pm \ell'^{\mp}\nu$)

1. Different heavy-to-light mixing elements (different rates).

[C.D., C.S. Kim, K. Wang, J. Zhang (2016)]

- Consider e.g. $W^+ \to e^+ e^+ \mu^- \nu$:



$$\Gamma_{LNV} \sim |V_{eN}|^4 \qquad \Gamma_{LNC} \sim |V_{eN}|^2 |V_{\mu N}|^2$$

- If N is Dirac:

$$\begin{array}{l} \Gamma(e^+e^+\mu^-) \sim |U_{eN}|^2 |U_{\mu N}|^2 \\ \Gamma(\mu^+\mu^+e^-) \sim |U_{eN}|^2 |U_{\mu N}|^2 \end{array} \quad \Rightarrow \Gamma(e^+e^+\mu^-) = \Gamma(\mu^+\mu^+e^-)$$

- If N is Majorana:

$$\begin{array}{l} \Gamma(e^+e^+\mu^-) \sim |V_{eN}|^4 + |V_{eN}|^2 |V_{\mu N}|^2 \\ \Gamma(\mu^+\mu^+e^-) \sim |V_{\mu N}|^4 + |V_{eN}|^2 |V_{\mu N}|^2 \end{array} \quad \begin{array}{c} \Rightarrow \Gamma(e^+e^+\mu^-) \neq \Gamma(\mu^+\mu^+e^-) \\ \text{if } |V_{eN}| \neq |V_{\mu N}| \end{array}$$

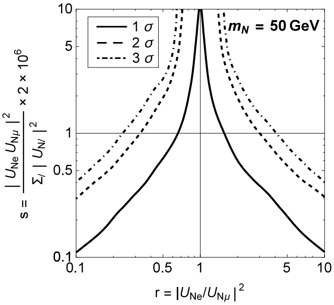
Dirac/Majorana distinction in trilepton events ($\ell^{\pm}\ell \pm \ell'^{\mp}\nu$)

1. Different heavy-to-light mixing elements (different rates).
   [C.D., C.S. Kim, K. Wang, J. Zhang (2016)]

- $|V_{eN}| \neq |V_{\mu N}$ ... but how different must they be?
- Simulations for 14 TeV pp collisions with 3000 fb^{-1}:

Figure: confidence levels for excluding the Dirac case given a Majorana scenario, for $m_N = 50$ GeV.

- For larger s (more events), $r \equiv \dfrac{|V_{eN}|^2}{|V_{\mu N}|^2}$ can be closer to 1.

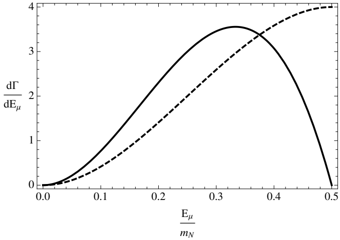


Dirac/Majorana distinction in trilepton events ($\ell^\pm \ell \pm \ell'^\mp \nu$)

2. Different μ energy spectrum in $W^+ \to e^+ e^+ \mu^- \nu$.
   [C.D. & C.S. Kim, PRD 92, 093009 (2015)]
   - Muon energy in the N rest frame: $\epsilon_\mu = E_\mu / m_N$
   - The spectra:

$$\begin{aligned}\Gamma(W^+ \to e^+ e^+ \mu^- \bar{\nu}_\mu)_{(LNV)} &\sim r \cdot s \times \int_0^{1/2} d\epsilon_\mu \left(\epsilon_\mu^2 - 2\epsilon_\mu^3\right), \\ \Gamma(W^+ \to e^+ e^+ \mu^- \nu_e)_{(LNC)} &\sim s \times \int_0^{1/2} d\epsilon_\mu \left(\frac{1}{2}\epsilon_\mu^2 - \frac{2}{3}\epsilon_\mu^3\right).\end{aligned}$$

Muon spectrum:
- LNV (solid);
- LNC (dashed);



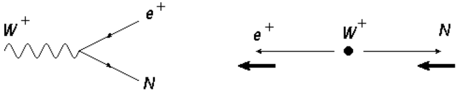
Dirac/Majorana distinction in trilepton events ($\ell^{\pm}\ell \pm \ell'^{\mp}\nu$)

3. Different μ angular distributions.

[C. Arbelaez, C.D., I. Schmidt & J.C. Vasquez (2018)]

$W^+ \to e^+ N$, followed by $N \to e^+\mu^-\bar{\nu}_\mu$ or $N \to \mu^- e^+ \nu_e$:

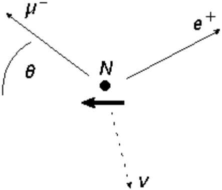
- N produced mainly with left handed helicity in $W^+ \to e^+ N$:



$$\mathcal{P}_{left} = \frac{2M_W^2}{2M_W^2 + m_N^2} \qquad \mathcal{P}_{right} = \frac{m_N^2}{2M_W^2 + m_N^2}$$

- Polarized N decays have different angular distributions:

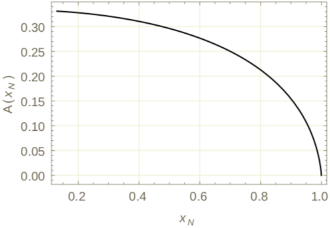
$$\frac{d\Gamma(N_{pol} \to e^+\mu^-\bar{\nu}_\mu)}{d\cos\theta} \sim (1 - \cos\theta),$$
$$\frac{d\Gamma(N_{pol} \to \mu^- e^+ \nu_e)}{d\cos\theta} \sim (1 + A(m_N)\cos\theta)$$



Dirac/Majorana distinction in trilepton events ($\ell^{\pm}\ell \pm \ell'^{\mp}\nu$)

3. Different μ angular distributions.

...where $A(m_N)$ is the *analyzing power :*



Different forward-backward asymmetries of the muon in the N frame, depending on whether N is Dirac or Majorana:

$$A_{FB} = \frac{\mathcal{N}(\cos\theta > 0) - \mathcal{N}(\cos\theta < 0)}{\mathcal{N}(\cos\theta > 0) - \mathcal{N}(\cos\theta < 0)}.$$

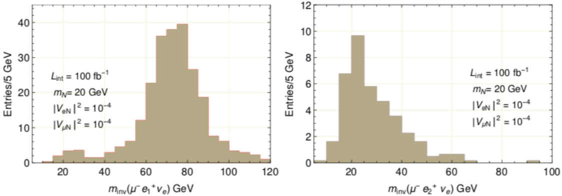
- Dirac: $A_{FB} = -1/6$ independent of mixings $|V_{\ell N}|$.
- Majorana: depends on $|V_{\ell N}|$.
  If $|V_{eN}| > |V_{\mu N}|$, $A_{FB} = -1/2$ ($\to -1/6$ as $m_N \to M_W$).
  If $|V_{eN}| < |V_{\mu N}|$, use the mode $\mu^{\pm}\mu^{\pm}e^{\mp}$ instead.

Dirac/Majorana distinction in trilepton events $(\ell^{\pm}\ell \pm \ell'^{\mp}\nu)$

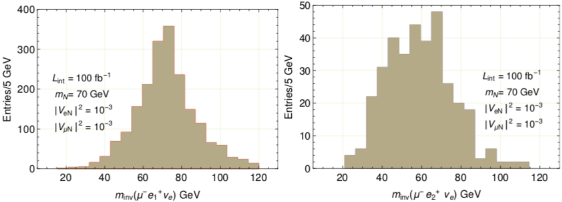
Some difficulties:

- need to determine the N rest frame: need to identify the primary positron.

For $m_N = 20$ GeV
(define $E_{e_1} > E_{e_2}$):



For $m_N = 70$ GeV
(define $E_{e_1} > E_{e_2}$):



- Primary lepton is the least energetic for large m_N and the most energetic for smaller m_N.

Dirac/Majorana distinction in trilepton events ($\ell^{\pm}\ell \pm \ell'^{\mp}\nu$)

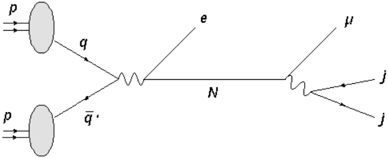
4. (there is always a forth way) put everything together:
   MVA (multivariate analysis)
   [C.D., C.S. Kim, Kechen Wang (2017)]

- Simulations for 14 TeV *pp* collisions with integrated luminosity of 3000 fb^{-1}.
- Majorana-Dirac distinction can be reached at 5σ significance for m_N between 20 GeV and 75 GeV, provided:
  - $|V_{eN}|^2 \sim |V_{\mu N}|^2 \gtrsim 10^{-5}$
  - $|V_{eN}|^2$ or $|V_{\mu N}|^2 \gtrsim 10^{-6}$ and the other is considerably smaller.
- For $m_N \lesssim 15$ GeV the N production and decay vertices are spatially separated in the detector.
  This vertex displacement drastically helps on the kinematics and on BKG reduction.

Searches for heavy Dirac/Majorana neutrinos

◇ Search for $m_N < 15$ GeV at colliders: displaced vertices.

- For $m_N \lesssim 15$ GeV , N lives long. i.e. decay vertex visibly displaced from production vertex:



- New bounds on $|V_{\mu N}|^2$ in the range $m_N = 4.5 - 10$ GeV from LHCB
  [S. Antusch, E. Cazzato & O. Fischer, Phys.Lett. B774, 114 (2017)].

Searches for heavy Dirac/Majorana neutrinos

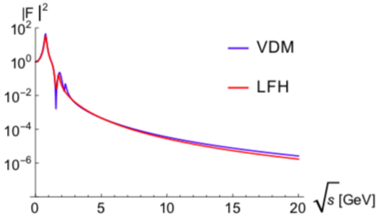
◇ Search for $m_N < 15$ GeV at colliders: exclusive semileptonic modes.

- Semileptonic modes may be difficult to detect for low m_N (low p_t jets lost in bkgnd).
- Exclusive semileptonic with displaced vertices may help: try

$$N \to \ell^{\pm}\pi^{\mp}, \quad N \to \ell^{\pm}\pi^{\mp}\pi^{0}, \quad N \to \ell^{\pm}\pi^{\pm}\pi^{\mp}\pi^{\mp}.$$

[C.D., C.S. Kim, N. Neill & X-B. Yuan (2017)]

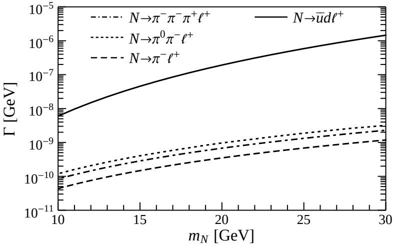
For 2-pion and 3-pion modes, need for factors.
VDM for 2-pion and 3-pion. [BaBar coll., PRD 86, 032013 (2012)] and
Light Front Holography (LFH) for 2-pion
[S. Brodsky et al, P. Rept. 584, 1 (2015)] .



Searches for heavy Dirac/Majorana neutrinos

◇ Search for $m_N < 15$ GeV at colliders: exclusive semileptonic modes.

- Single pion mode is suppressed by f_π / m_N.
-Two-pion and three-pion modes are comparable.



- Can 2-pion and 3-pion modes be seen at the LHC?
- 2-pion mode has one neutral pion (two-photon signal???)
- 3-pion signal has no neutrals, but it is a bit smaller.
- Must study the observability of modes: $pp \to W \to \ell\ell(n\pi)$.
- For a sample of $\sim 10^9$ W's by the end of LHC Run 2, ATLAS / CMS should be able to put new limits $|V_{\ell N}|^2 \sim 2 \times 10^{-6}$ in the mass range 5 GeV $< m_N <$ 15 GeV.
- Study of particle id. and background rejection (in progress).

Summary

- Neutrino masses lead us to physics beyond the Standard Model.
- Most explanations for the very small neutrino masses imply the existence of extra neutrinos, either Majorana or Dirac ...or in between.
- It is important to know the Dirac / Majorana character of neutrinos to distinguish between theoretical scenarios.
- Here we focus on searches for heavy neutrinos in high energy collisions:
- Semileptonic modes: $\ell^\pm \ell^\pm jj$, $e^\pm \mu^\mp jj$.
- Trilepton modes $e^\pm e^\pm \mu^\mp \nu$, $\mu^\pm \mu^\pm e^\mp \nu$.
- Dirac/Majorana character difficult to detect in trileptons ...
  ... but it can be done.
- For $m_N < 15$ GeV, displaced vertices due to long living N helps in background reduction (can use semileptonic modes again).

Thank you