Experimental Searches for Heavy Neutral Leptons

Flavor Physics and CP Violation Conference 2022
(University of Mississippi)

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on behalf of the BaBar Collaboration

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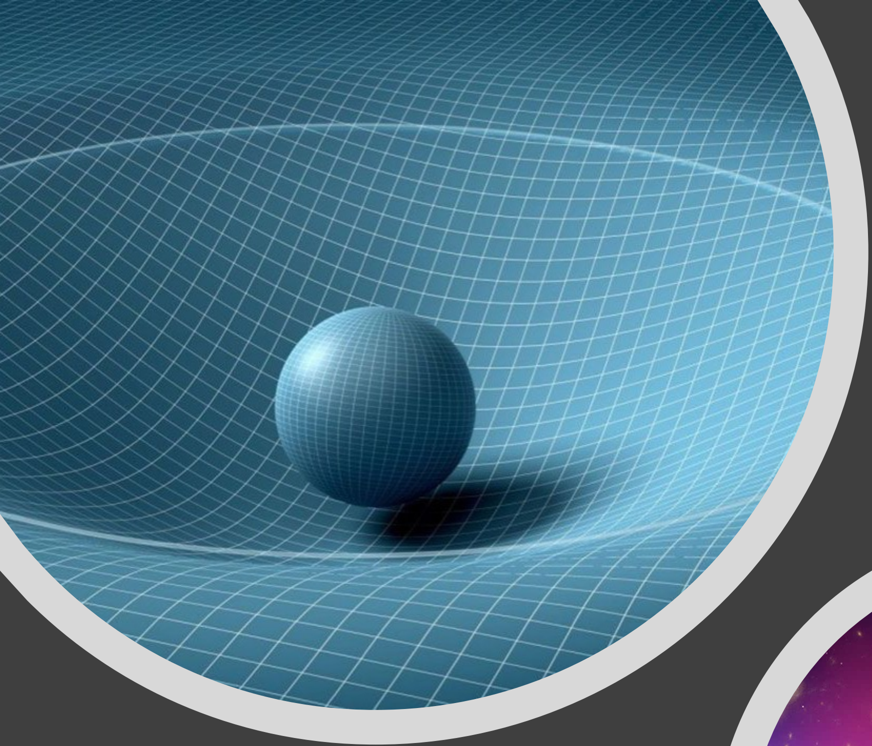
Outline

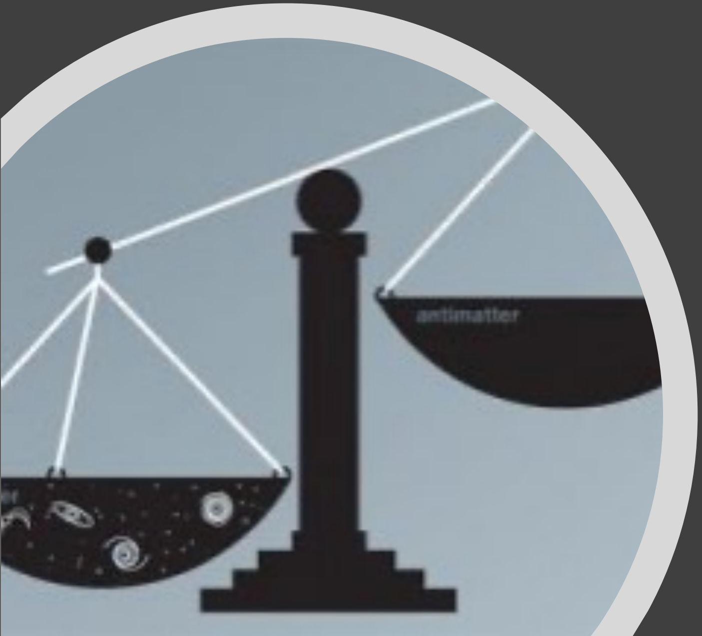
Motivations

Why are we searching for Heavy Neutral Leptons?



Beyond the Standard Model

The Standard Model (SM) is capable of successfully describing nature to good precision e.g. fine structure constant to one part per billion.



But unable to predict:

- The Baryon Asymmetry of the Universe;
- Observations of Dark Matter & Dark Energy;
- Non-vanishing mass of neutrinos;
- Fine tuning requirements (e.g. Higgs mass);
- Gravity at the quantum scale.

Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Neutrino oscillations are only experimentally verified physics beyond the SM. Proven valuable in elucidating the structure of the SM.
- Mixing parameterized using the PMNS matrix.
- Measurements of neutrino compositions at accelerators, reactors and underground facilities have provided measurements of the three Euler angles parametrizing the PMNS matrix and $\Delta m_{21}{}^2$ and $\Delta m_{32}{}^2$

But many unanswered questions in neutrino physics, including:

- Why is neutrino mass so small? What are the origins of this mass? An appealing possible explanation for this is a seesaw model - propose additional heavy neutral leptons. (PhysRevD.23.165, https://doi.org/10.3389/fphy.2018.00040)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P$$

Why Heavy Neutral Leptons?

See refs. on Slide #26 for theoretical motivations

- Heavy Neutral leptons are additional neutrino states which have some mass but no weak hyper-charge, electric charge, weak isospin and color charge.
- HNLs are proposed by many BSM models and could explain three major observational phenomena: Neutrino Oscillations; Baryonic Asymmetry; Dark Matter.
- HNLs can also help explain various experimental observations:
  1. "Reactor Anti-neutrino anomaly:" Analyses of the flux from reactors suggest deficit of $\bar{\upsilon}_e$ at the 98.6% C.L. (Phys. Rev. D 83, 07300).
  2. "Gallium anomaly:" Re-analysis of data from GALLEX and SAGE exposed unexplained 14 ± 5% deficit in number υ_e, could be sterile neutrinos of masses O(eV/c^2) (Phys. Rev. C 80 015807).
  3. "Accelerator anomaly:" LSND (Phys. Rev. D 64, 112007) evaluated oscillation $\upsilon_e \rightarrow \upsilon_\mu$ and saw an excess of neutrinos at 3.8 σ which could be sterile neutrino with $\Delta m^2{}_{41} \sim 1$(eV/c^2)^2. MiniBooNE (Phys. Rev. Lett. 110, 161801) experiment also saw this at 2.8 σ level.

Extended PMNS Matrix

- Extend the PMNS for additional neutrino states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \ddots & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix} .$$

- Experiments try to measure the matrix elements $|U_{ln}|^2$ where $l = e, \mu, \tau$ and $n = 4,5,6 \ldots$
- Introduce new mass states m_4, m_5…etc.
- What about the flavor states?

Possible Flavor of Additional Neutrinos

- Experimental data favors “3 lepton flavors”
- Additional neutrinos must be “sterile”

Number from e^+e^- Colliders

Number of Light ν Types

VALUE	*DOCUMENT ID*		*TECN*
2.9963±0.0074	[1] JANOT	20	

Number of Light ν Types from Direct Measurement of Invisible Z Width

In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+e^- \rightarrow \nu\overline{\nu}\gamma$. All are obtained from LEP runs in the E^{ee}_{cm} range 88–209 GeV.

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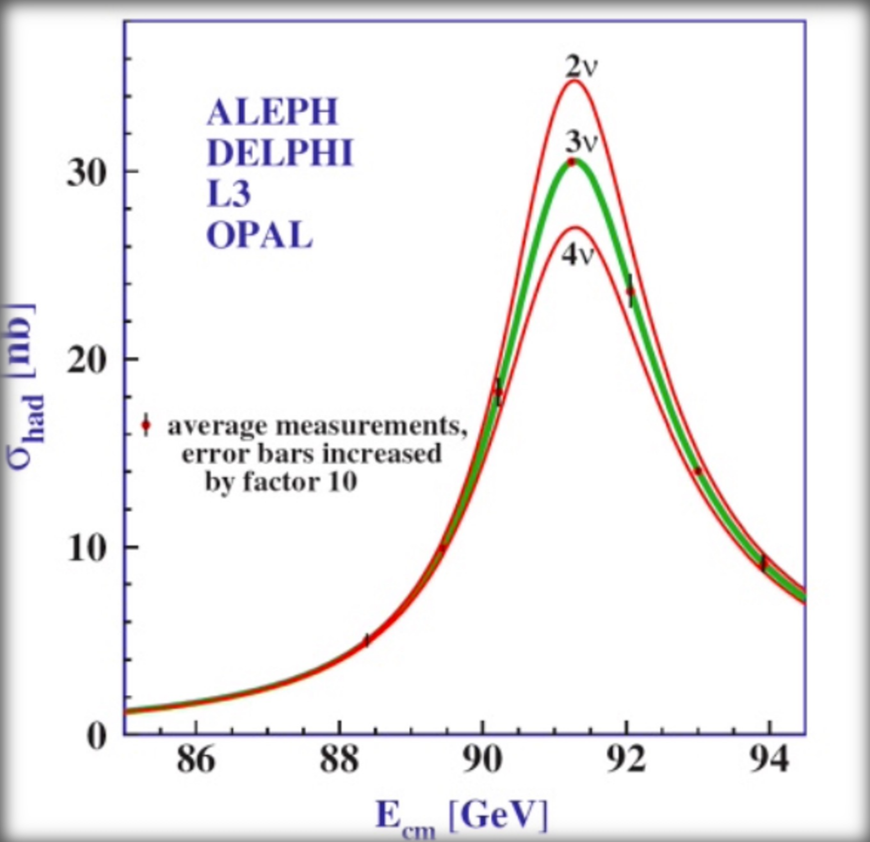
2.92±0.05 OUR AVERAGE	Error includes scale factor of 1.2.		



Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

Possible Mass of HNLs

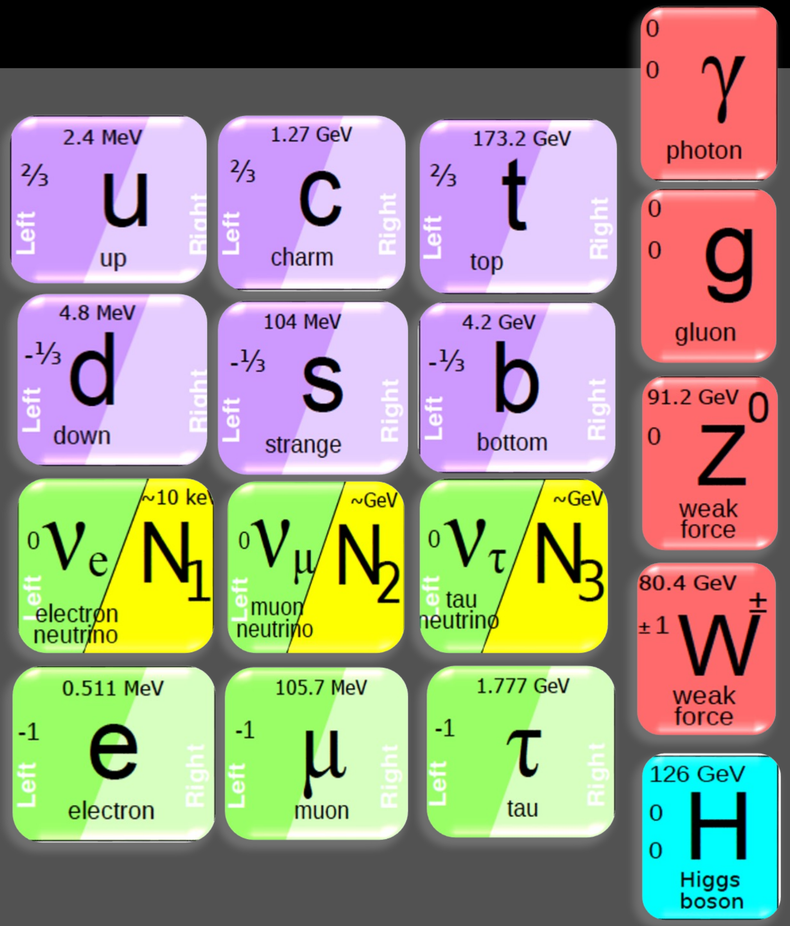
Depending on the model, wide range of models proposing HNLs across mass ranges :

1. $m_4 \sim O$ **(eV/c²):** solve so-called "oscillation anomalies".
2. $m_4 \sim O$ **(keV/c²):** warm dark matter candidate.
3. $m_4 \sim O$ **(MeV/c² - GeV/c²):** deviations in SM decays.
4. $m_4 \sim O$ **(GeV/c² - TeV/c²):** can explain Baryonic Asymmetry via low-scale scenarios of leptogenesis without conflict with other cosmological observations.

***e.g.* ν-MSM** model introduces three right-handed singlet HNLs:

- Two GeV/c² scale particles solve origin and smallness of SM neutrino mass with see saw mech.
- Third HNL is dark matter candidate with mass ~keV/c². Also provides leptogenesis due to Majorana mass term (Phys. Rev. Lett. 81, 1359)

- Hence to search/exclude these models we must search using many different styles of experiment.

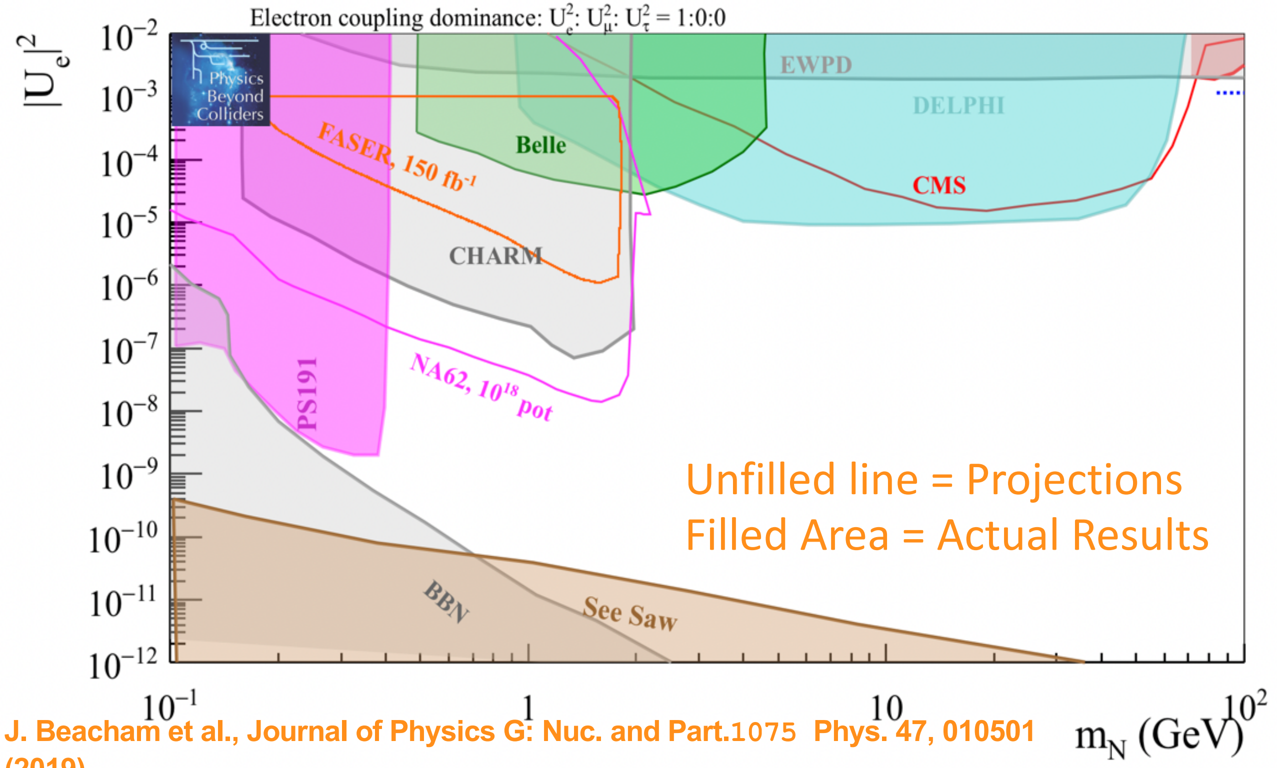


Established Limits

What do we know so far about the mixing probabilities?

Bounded from below by the BBN constraint (JCAP 1210 (2012) 014, [1202.2841) and the see-saw limit (JCAP1009 (2010) 001, [1006.0133])

Current Limits from Electrons: $|U_{e4}|^2$



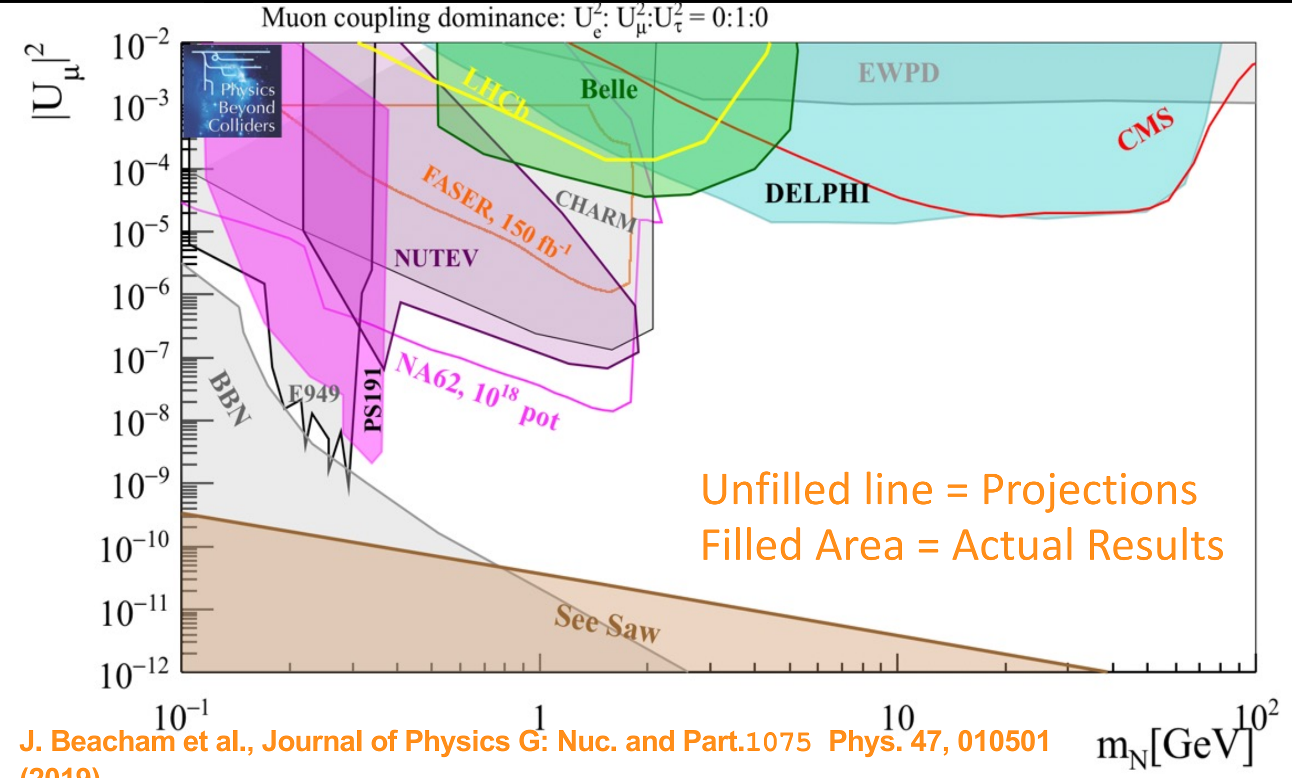
J. Beacham et al., Journal of Physics G: Nuc. and Part.1075 Phys. 47, 010501 (2019)

- CHARM @ CERN: beam dump of O(2 x 10^{18}) 400 GeV protons, looking for visible decays with electrons in the final state.
- PS 191 @ CERN: search for neutrino decays in a low-energy neutrino beam.
- Belle @ KEK: 772 M BB pairs. Using leptonic and semi-leptonic B mesons decays, $B \rightarrow Xl\nu_R$, where l = e, μ and X was a charmed meson $D^{(*)}$, a light meson (π, ρ, η etc.) or nothing (purely leptonic decays), in a range of masses between the kaon and the B mass.
- CMS @ LHC: searched in three prompt charged leptons sample in any combination of electrons and muons collected corresponding to an integrated luminosity of 35.9 fb^{-1}. The search is performed in the HNL mass range between 1 GeV and 1.2 TeV.

CHARM: Phys. Lett. 166B (1986) 473–478
PS191: Phys. Lett. B203 (1988) 332–334
Belle: Phys. Rev.D87 (2013) 071102, [1301.1105]
CMS: Phys. Rev. Lett. 120 (2018) 221801, [1802.02965]

Bounded from below by the BBN constraint (JCAP 1210 (2012) 014, [1202.2841) and the see-saw limit (JCAP1009 (2010) 001, [1006.0133])

Current Limits from Muons: $|U_{\mu 4}|^2$



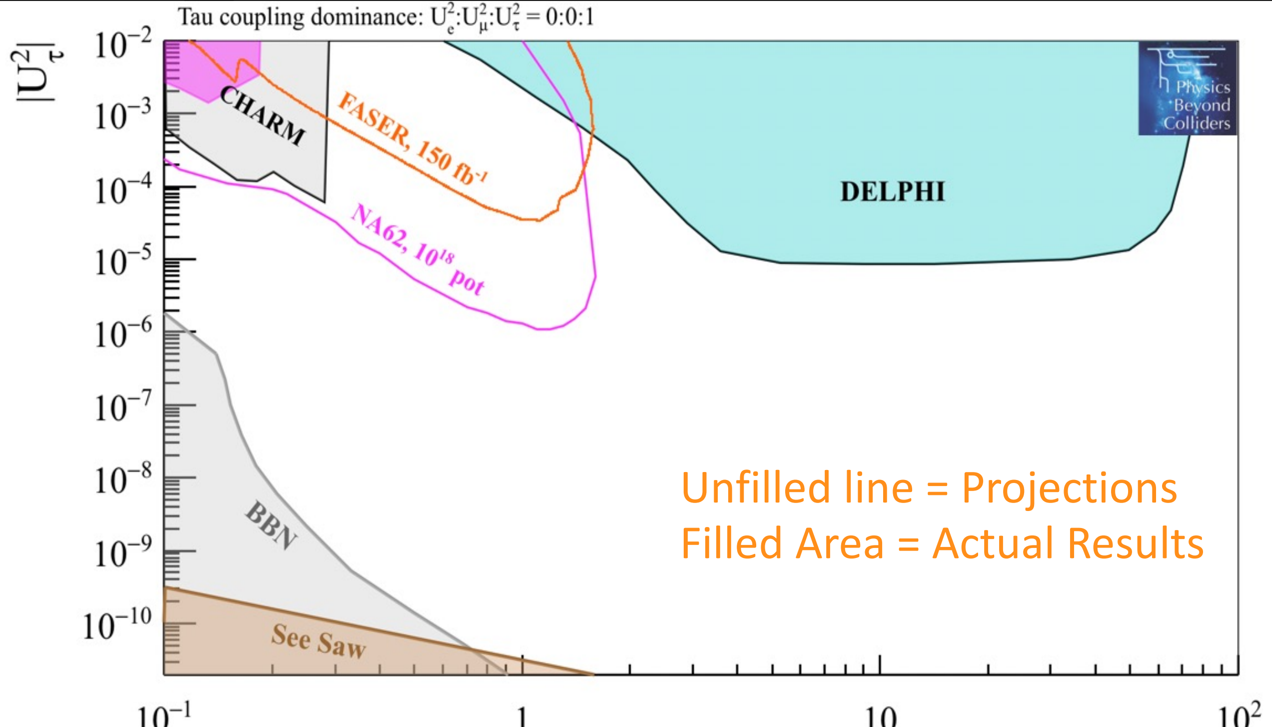
J. Beacham et al., Journal of Physics G: Nuc. and Part.1075 Phys. 47, 010501 (2019)

- **NuTeV @ Fermilab:** searched for HNLs decaying in muonic final states using 2 x 10^{18} 800 GeV protons interacting with a Beryllium-oxide target and a proton dump.
- **E949 @ BNL:** search for $K^+ \rightarrow \mu^+ \upsilon_R$ using 1.7 x 10^{12} stopped kaons.

Delphi: Phys. Rev. D91 (2015) 052001,[1411.3963].
NuTev: Phys. Rev. Lett. 83 (1999) 4943–4946, [hepex/9908011]

Bounded from below by the BBN constraint (JCAP 1210 (2012) 014, [1202.2841) and the see-saw limit (JCAP1009 (2010) 001, [1006.0133])

Current Limits From Taus: $|U_{\tau 4}|^2$



J. Beacham et al., Journal of Physics G: Nuc. and Part.1075 Phys. 47, 010501 (2019)

- NOMAD @ CERN: used 4.1 x 10^{19} 450 GeV protons on target at the WANF facility. Searched for $D_s \rightarrow \tau \upsilon_R$ followed by the decay $\upsilon_R \rightarrow \nu_\tau e^+ e^-$.
- CHARM @ CERN: null result of a search for events produced by the decay of neutral particles into two electrons using 2 x 10^{18} 400 GeV protons on a solid copper target.
- Limits on $|U_{\tau N}|^2$ are weaker, motivating $|U_{\tau N}|^2 \gg |U_{eN}|^2, |U_{\mu N}|^2$

CHARM: Phys. Lett. B550 (2002) 8–15,[hep-ph/0208075].
NOMAD: Phys. Lett. B506 (2001) 27–38, [hep-ex/0101041].
DELPHI: Z. Phys. C74 (1997) 57–71.

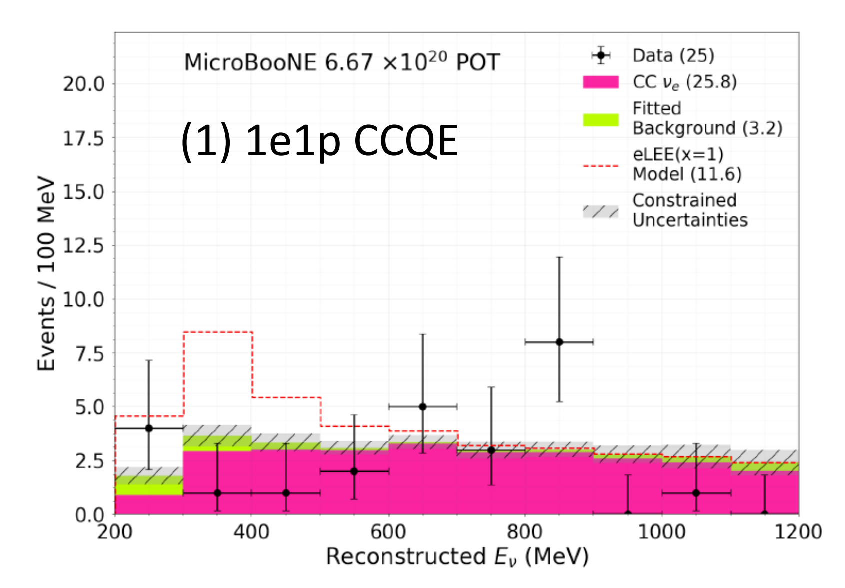
Recent Results in Muons & Electrons

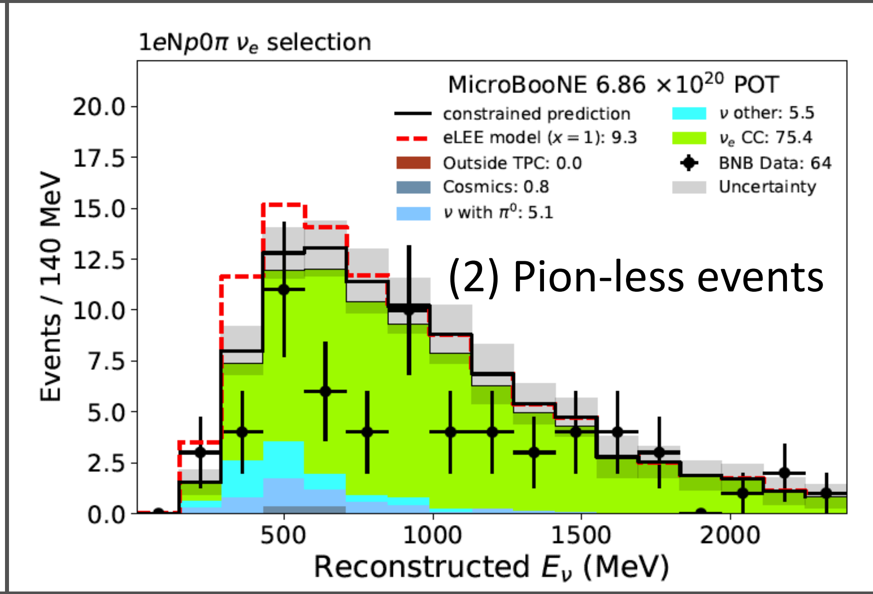
A summary of the latest results in experimental searches for HNLs

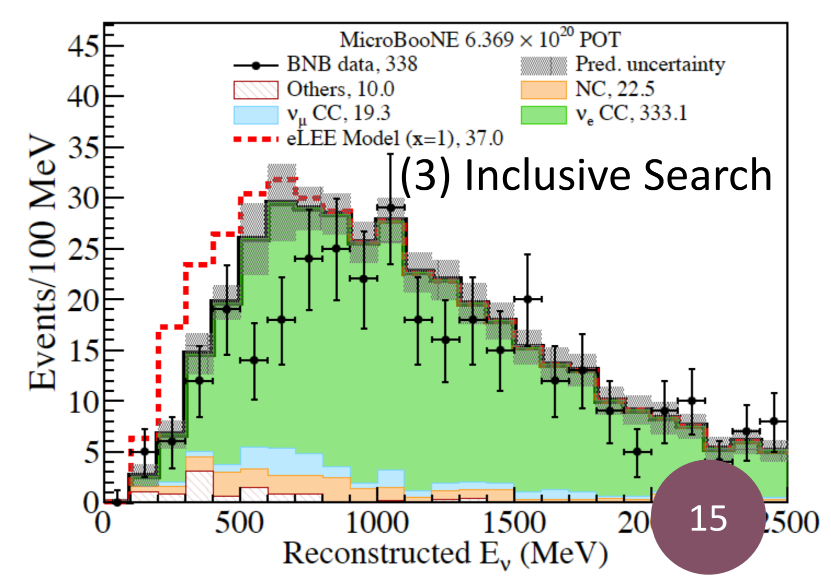
Electron Result: MicroBooNe

See talks later today on BSM @ MicroBooNe

- Recent results from MicroBooNe detailed in: https://arxiv.org/abs/2110.14054
- MicroBooNE has developed 3 distinct υ_e searches targeting the MiniBooNE signal:
  - an exclusive search for two-body υ_e charged current quasi-elastic(CCQE) scattering,
  - a semi-inclusive search for pion-less υ_e events,
  - an inclusive υ_e search containing any hadronic final state.
- Rules out electrons as the sole source of the MiniBooNe/LSND excess at a confidence greater than 99%.

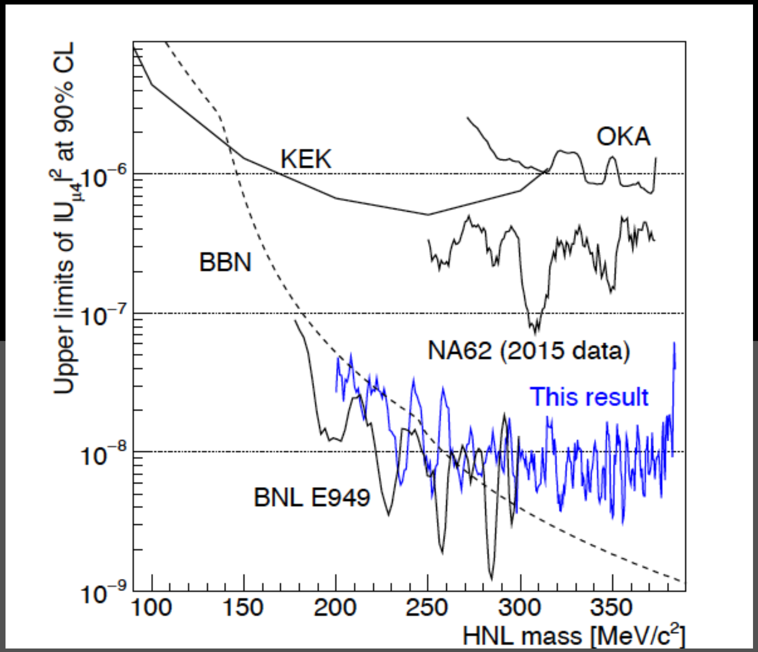




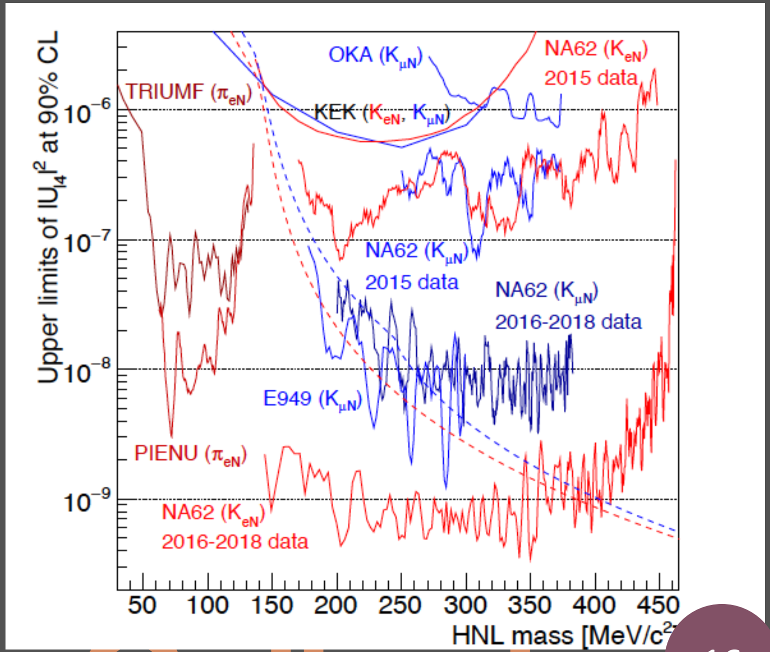


Muon & Electron Results: NA62

arXiv:2101.12304v2 [hep-ex]

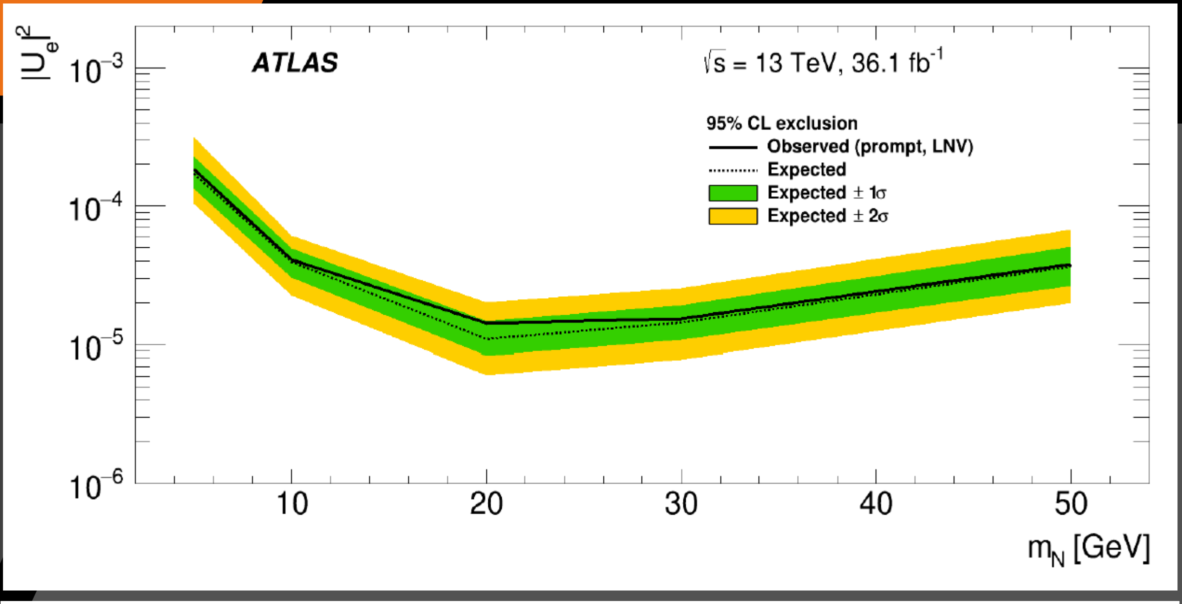


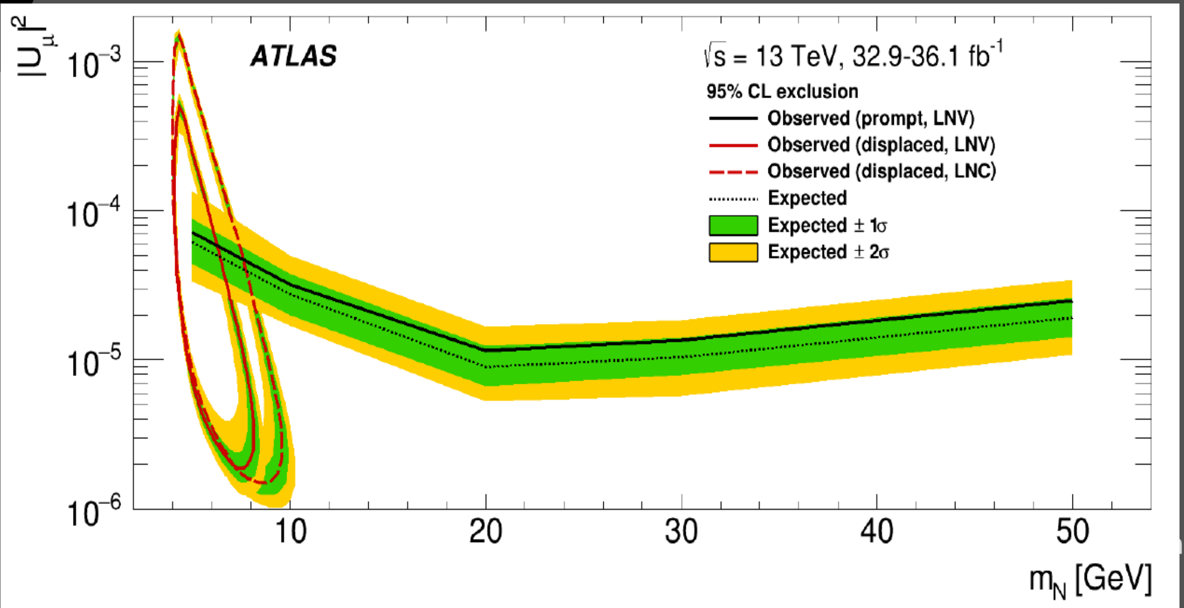
- The NA62 experiment at CERN reports searches for $K^+ \to \mu^+ +$ HNL, using the 2016-2018 data set.
- Upper limits of O(10^{-8}) of the neutrino mixing parameter $|U_{\mu4}|^2$ for N masses in the range 200-384 MeV/c^2 and lifetime exceeding 50 ns.

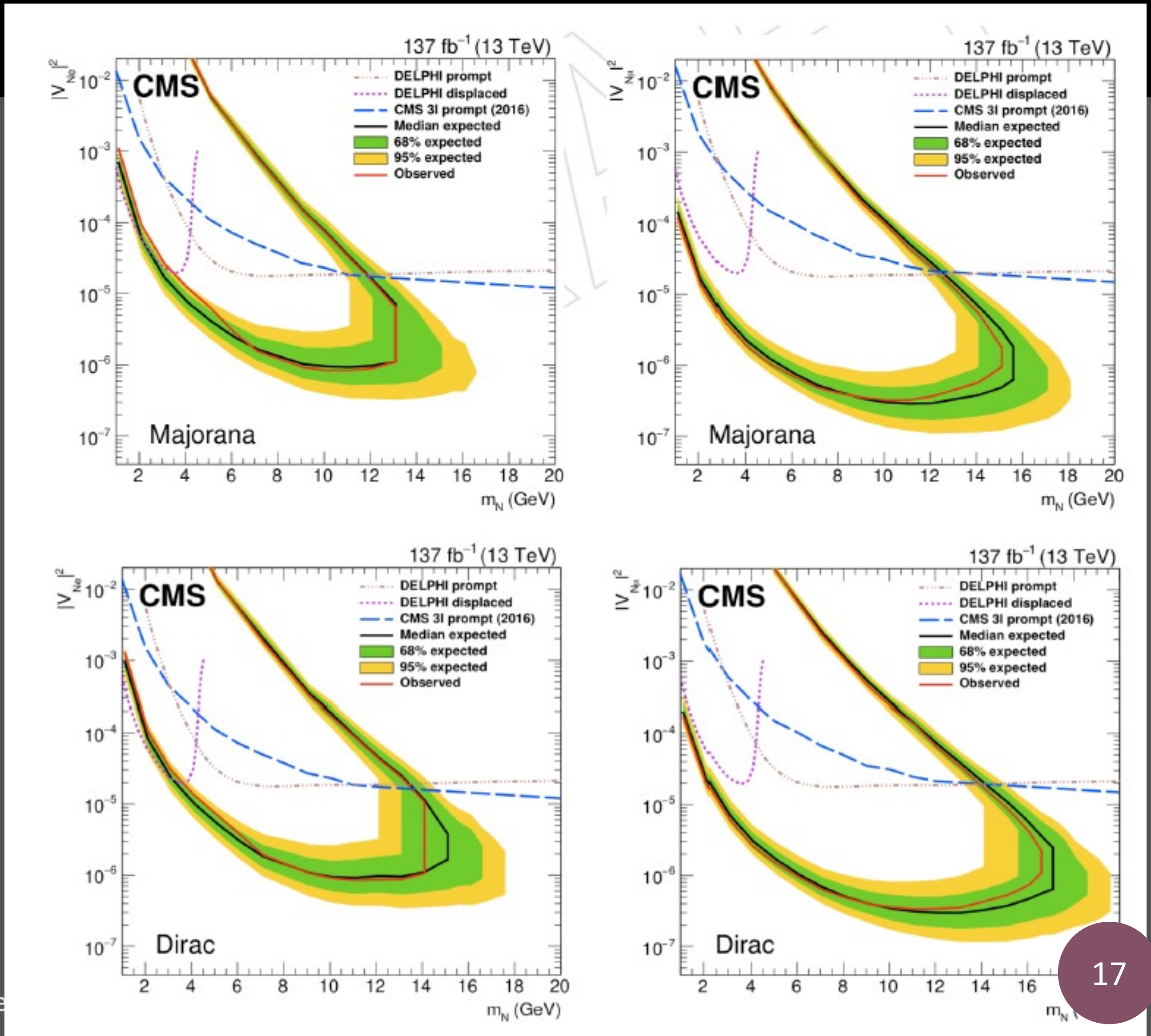


Muon & Electron Results: LHC

G. Aad et al. (ATLAS), JHEP 10, 265 (2019), 1905.09787.
A. Tumasyan et al. (CMS) (2022), 2201.05578.
R. Aaij et al. (LHCb), Eur. Phys. J. C 81, 248 (2021), 2011.05263.



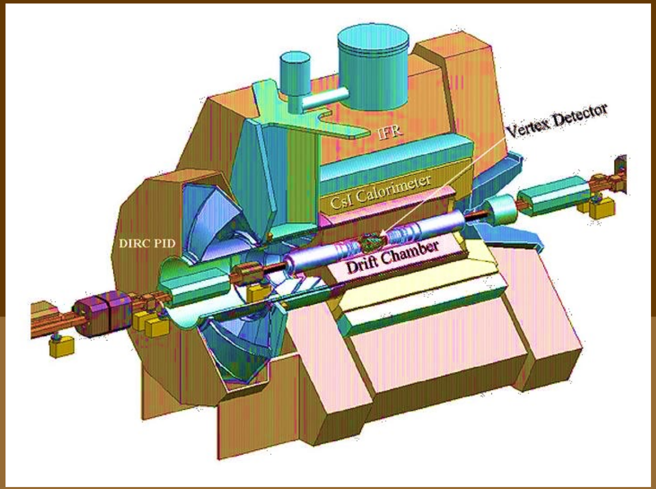




Recent Results in Taus

A summary of the latest results in experimental searches for HNLs

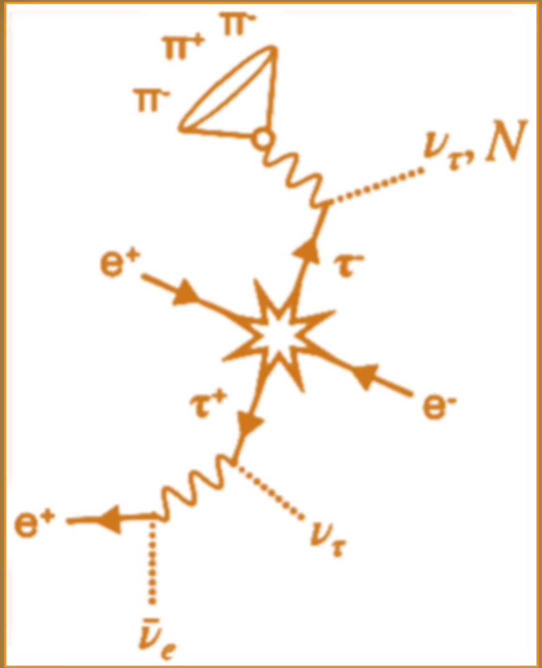
Searching for HNLs at BaBar



- For overview of experiment: Nucl. Instrum. Meth. A 729, 615 (2013).
- New analysis from BaBar – using the kinematics of hadronic tau decays:
  - $\sigma(ee \rightarrow \tau\tau) = 0.919 \pm 0.003$ nb
  - Integrated luminosity in runs used = 424 fb^{-1}

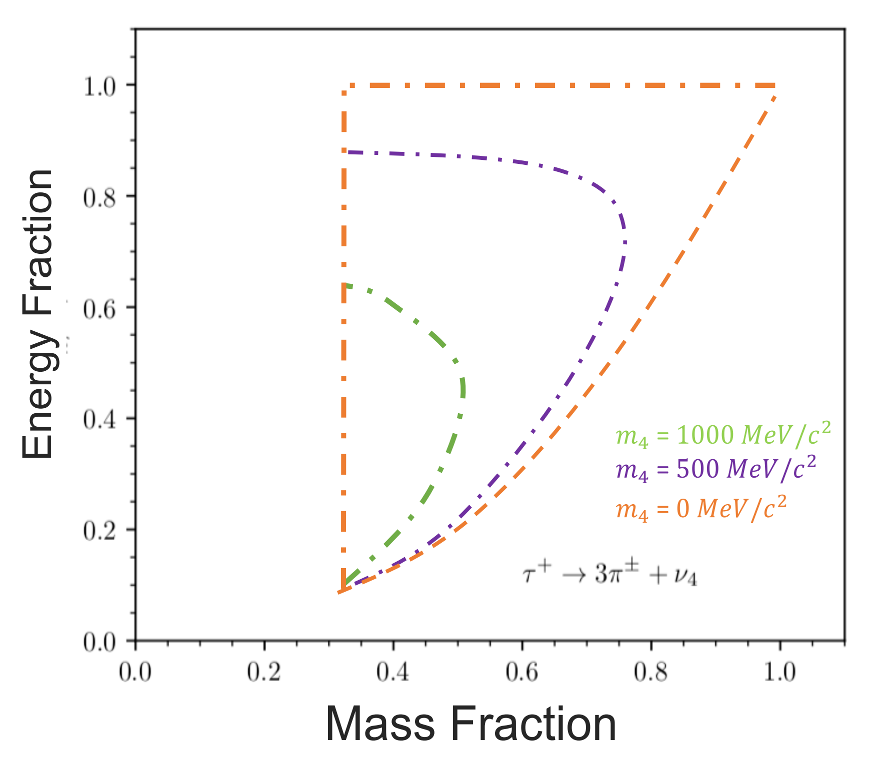
=> $N_{\tau\tau} = 4.6 \times 10^8$ events in Runs 1 - 6

- Follows from proposal in **Phys. Rev. D 91, 0530061135 (2015)** based on ALEPH technique (**Eur. Phys. J.1137C 2, 395 (1998)**).
- Looks only at kinematics, no assumptions on underlying model, measures mixing with tau sector.
- Looking at three pronged pionic tau decay $(\tau^- \rightarrow \pi^-\pi^-\pi^+\upsilon_\tau)$ allows access to region $100 < m_4 < 1360$ MeV/c^2 where current limits are loose.
- Second tau decay must be leptonic, due to cleaner environment.



Method

Templates for each mass in the form of 2D plots of E_h v. m_h. Boundary of curved region in this plot due to massive neutrino if present.



- Model 3-pronged decay as if it were 2-body with HNL and hadronic system as outgoing particles.
- Define E_h as energy and m_h as the invariant mass of the hadronic products.
- $E_\tau = \frac{E_{cms}}{2}$ in the limit of no ISR. The value of m_h can exist, in principle, in the range: $3m_{\pi^\pm} < m_h < m_\tau - m_{HNL}$. The range of E_h is

$$E_\tau - \sqrt{m_4^2 + q_+^2} < E_h < E_\tau - \sqrt{m_4^2 + q_-^2},$$

$$q_\pm = \frac{m_\tau}{2}\left(\frac{m_h^2 - m_\tau^2 - m_4^2}{m_\tau^2}\right)\sqrt{\frac{E_\tau^2}{m_\tau^2} - 1} \pm \frac{E_\tau}{2}\sqrt{\left(1 - \frac{(m_h + m_4)^2}{m_\tau^2}\right)\left(1 - \frac{(m_h - m_4)^2}{m_\tau^2}\right)};$$

$$\frac{d\Gamma_{\text{tot}}(\tau^- \to \nu h^-)}{dm_h dE_h} = (1 - |U_{\tau 4}|^2)\left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{m_\nu = 0} + |U_{\tau 4}|^2 \left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{m_\nu = m_4}.$$

SM Tau Decay

BSM Tau Decay

Backgrounds and Signal Simulations

- All SM neutrinos are assumed to have no mass, upper limit on heaviest mass neutrino is currently < 18.2 MeV/c^2 .i.e. << our search HNL masses.
- All backgrounds are subtracted using reconstructed Monte Carlo (MC).
- MCs passed through GEANT4 simulation of experiment plus digitization and reconstruction modelling. Beam background and data filters are included.
- Four potential sources of events in data:

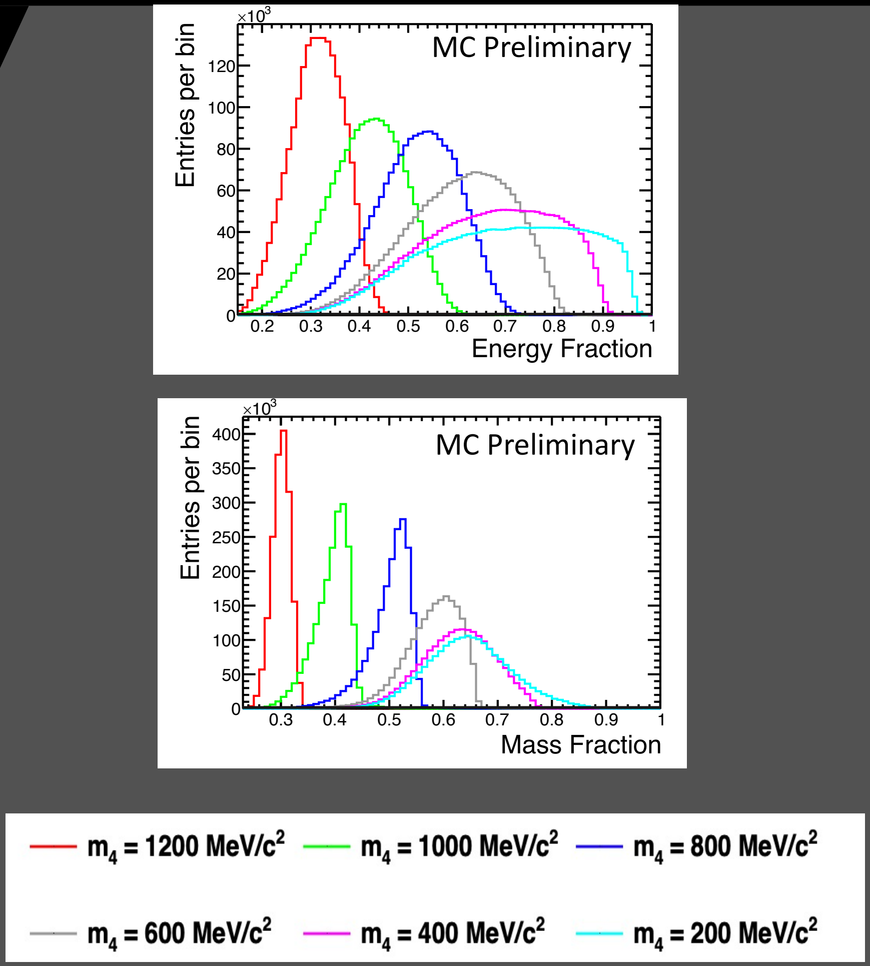
Backgrounds

1. SM 3 pronged decay to 3 charge pions ($\tau^- \rightarrow \pi^-\pi^-\pi^+\upsilon_\tau$) - (TAUOLA, KK2F)
2. Other SM tau decays accidentally tagged as (1) - (TAUOLA, KK2F)
3. SM non-tau backgrounds:
   - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-$ and $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$ - (EvtGen)
   - $e^+e^- \rightarrow \bar{u}u, \bar{d}d, \bar{s}s$ and $e^+e^- \rightarrow \bar{c}c$ - (JETSET)
   - $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ - (KK2F)
4. Signal, characterized by large missing mass, (TAUOLA+KK2F – parameters modified)

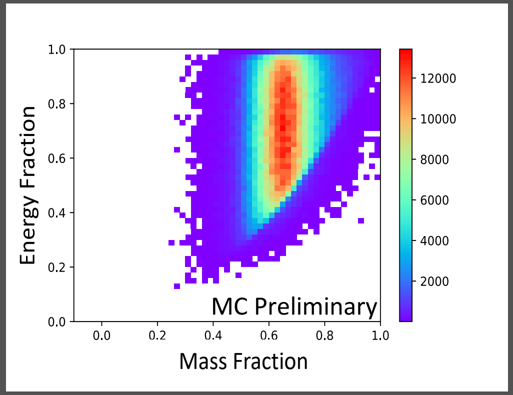
TAUOLA: Comp. Phys. Co. 130, 260–325 (2000)
KK2F: Comp. Phys. Co. 64, 275 (1991)
EvtGen: Nucl. Instrum. Meth. A 462, 152 (2001)
JetSet: Comp. Phys. Co. 39, 347 (1986)

Signal Samples

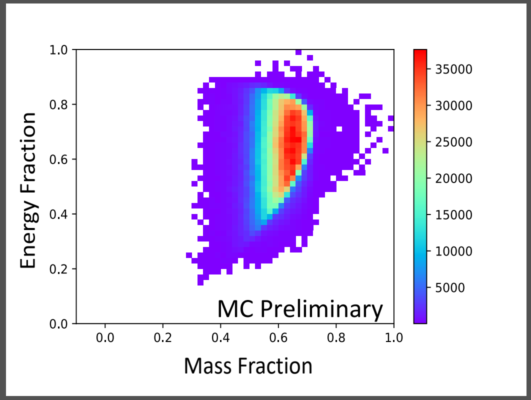
- Plots illustrate in 1D projections and final 2D templates
- Show phase space changes with HNL mass
- Plots for leptonic (electron 1 prong + BSM 3-prong process).



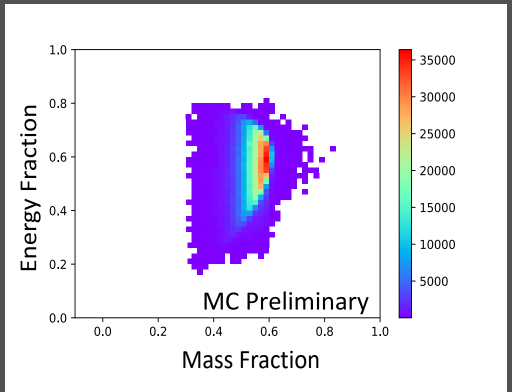
$m_4 = 100\ MeV/c^2$



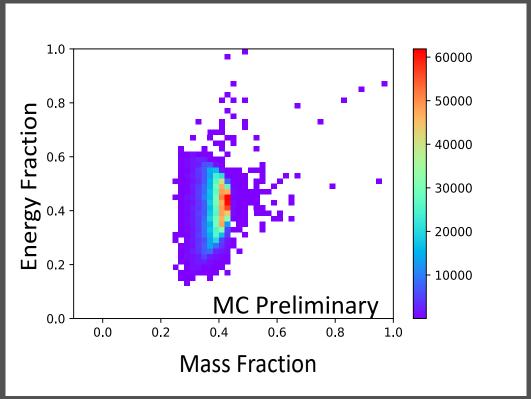
$m_4 = 500\ MeV/c^2$



$m_4 = 700\ MeV/c^2$



$m_4 = 1000\ MeV/c^2$



Assume each bin (i, j) in 2D plots can be represented by a Poisson sampling function:

Events observed

Parameter of Interest

Extracted From MC

$$\mathcal{L} = \prod_{charge}^{+-}\left(\prod_{channel}^{e\mu}\left(\prod_{bin}^{ij}\left(\frac{1}{n_{obs,ij}!}\left[N_{\tau,gen}\cdot|U_{\tau4}|^2\cdot p_{HNL,ij} + N_{\tau,gen}\cdot(1-|U_{\tau4}|^2)\cdot p_{\tau-SM,ij} + n^{reco}_{BKG,ij}\right]^{(n_{obs})_{ij}} \times exp\left[-\left(N_{\tau,gen}\cdot|U_{\tau4}|^2\cdot p_{HNL,ij} + N_{\tau,gen}\cdot(1-|U_{\tau4}|^2)\cdot p_{\tau-SM,ij} + n^{reco}_{BKG,ij}\right)\right]\right)_{bin} \times \prod_k f(\theta_k,\tilde{\theta}_k)\right)_{channel}\right)_{charge}$$

Nuisance parameters

Number of generated taus:

$$N_{\tau,gen} = \mathcal{L} * \sigma * BR(3\pi) * BR(lepton)$$

Contains information from the reconstructed 2D templates:

$$p_{s\,(or\ \tau-SM),ij} = \varepsilon_{reco}\varepsilon_{sel}\frac{n_{ij}}{\sum_i^N\sum_j^M n_{ij}}$$

Find parameter of interest through minimizing ratio:

$$q = -2\ln\left(\frac{\mathcal{L}_{H_0}(|U_{\tau4}|^2_0;\hat{\hat{\theta}}_0,\text{data})}{\mathcal{L}_{H_1}(|\hat{U}_{\tau4}|^2;\hat{\theta},\text{data})}\right) = -2\ln(\Delta\mathcal{L}).$$

Where n_{ij} is content of a given bin in 2D template, N and M are number of bins on each direction (=50)

Selection Criteria

Signature:

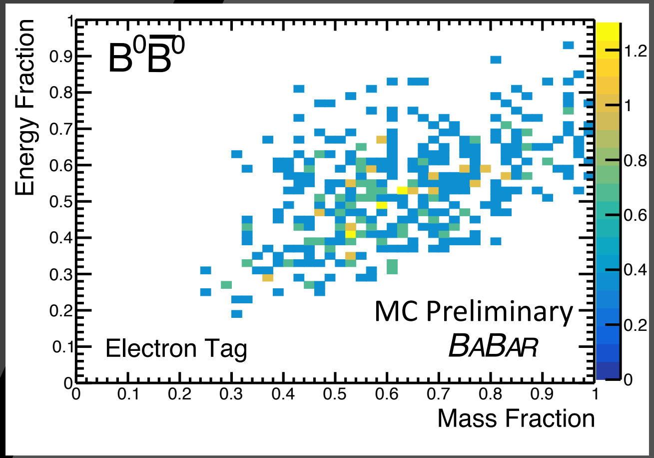
$e^+e^- \to \tau^+\tau^-$ followed by $\tau^\pm \to l^\pm \upsilon_l$ & $\tau^\mp \to \pi^\mp\pi^\mp\pi^\pm\upsilon_{HNL?}$

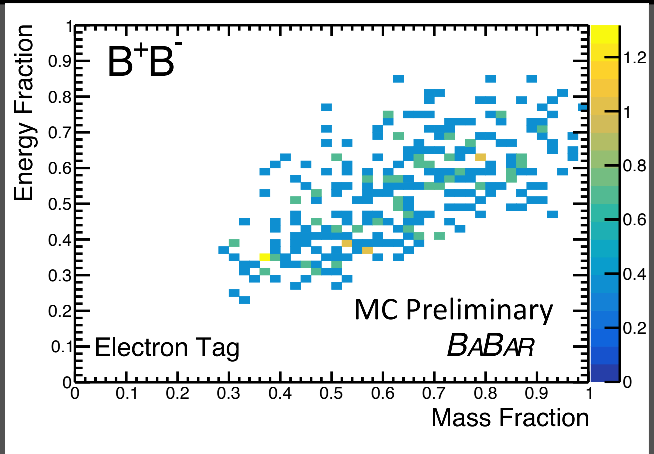
- Set of criteria enforced to improve signal selection and remove problematic backgrounds:

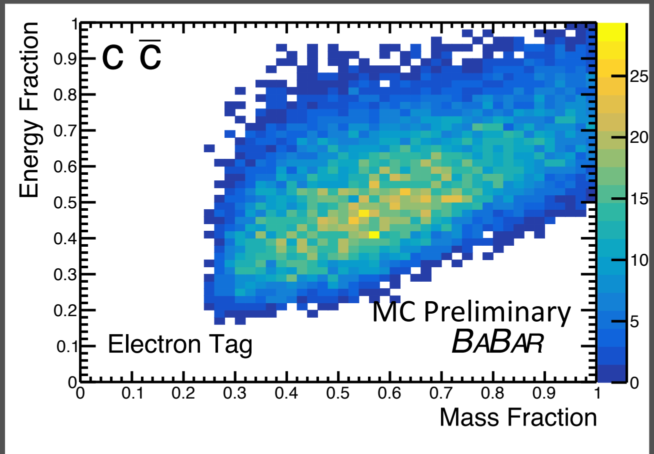
Cut	Purpose
Number of tracks	Ensure 1+3 prong topolgy
Total charge on all 4 charged tracks is 0	Charge conservation
$p_{CM}^{miss} > 0.9\% \sqrt{s}$	Suppresses non-tau backgrounds
All tracks: $p_{trans} > 250\text{MeV/c}$	To reach DIRC[1]
All tracks: $-0.76 < \cos(\theta) < 0.9$	Acceptance of DIRC[1]
1 prong: $\frac{2p}{E} < 0.9\%$	Consistent with tau decay
PID Requirements	Uses Electron and Muon ID algorithms

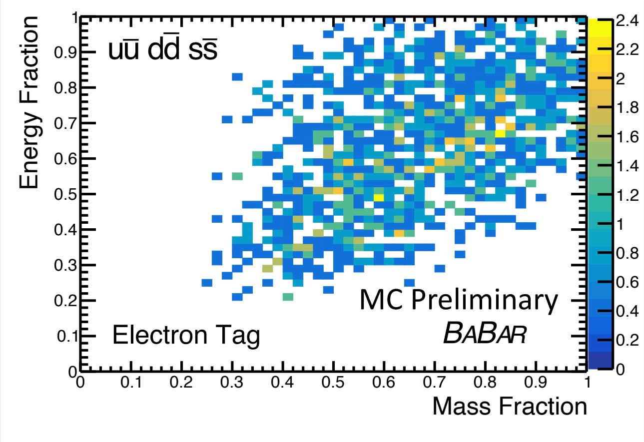
[1] Detection of Internally Reflected Cherenkov light = BaBar PID Detector System

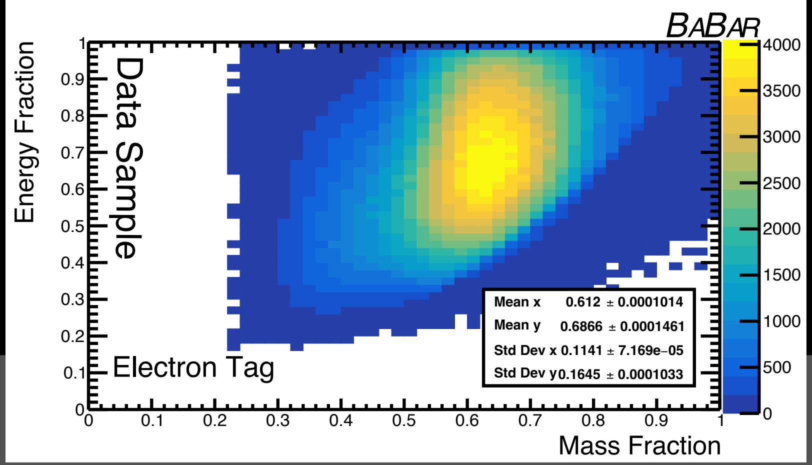
Example 2D Plots

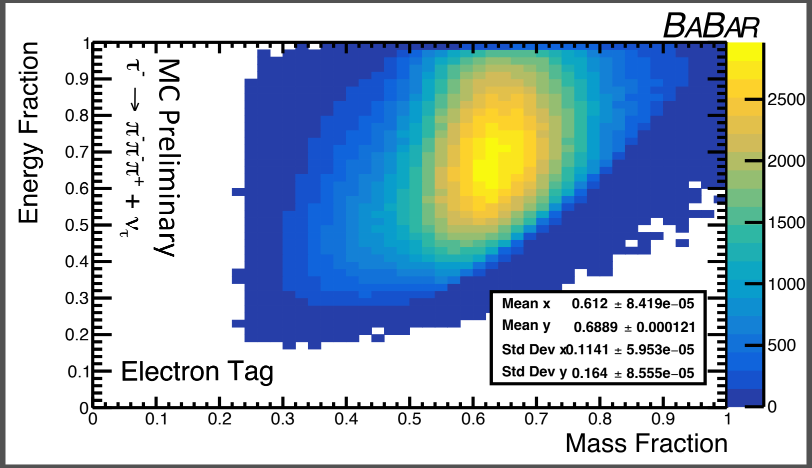


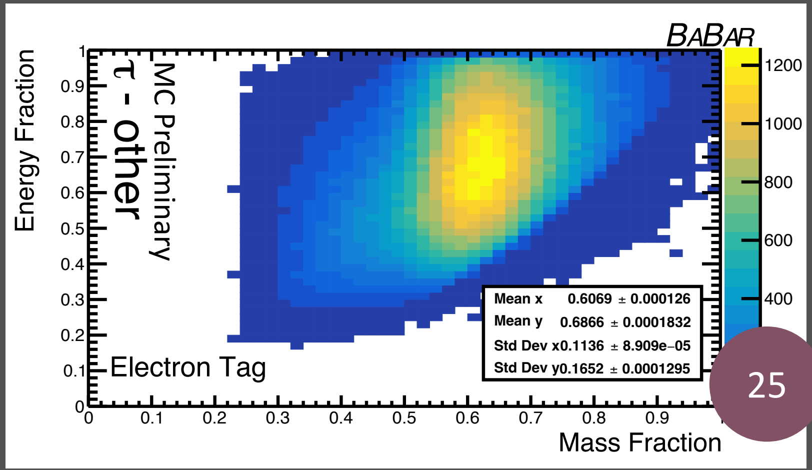








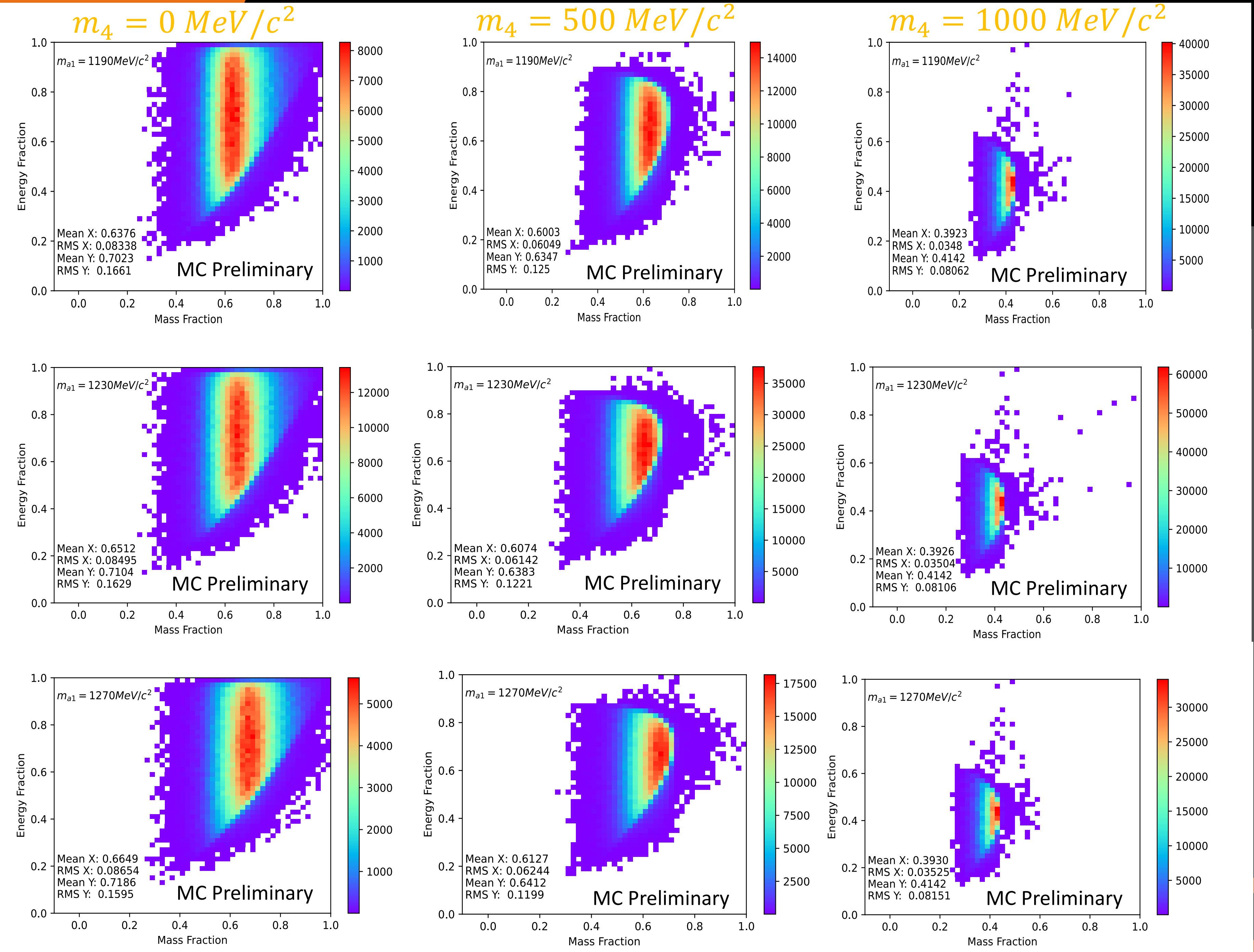




Normalization Uncertainties

- Normalization uncertainties effect all bins uniformly.
- Have small effect on overall yield.
- They will be characterized as Gaussian nuisance parameters in the likelihood.

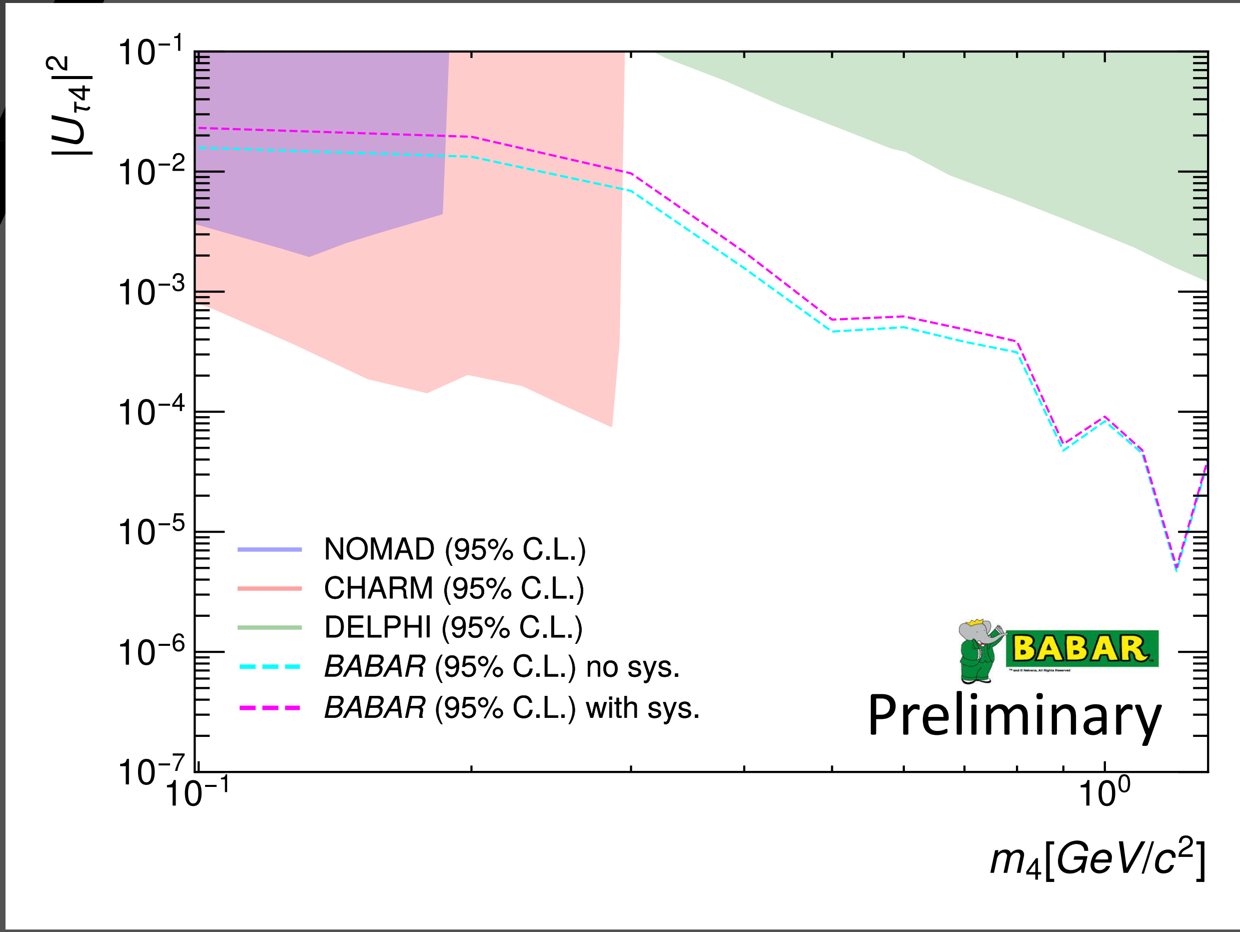
Uncertainty	Contribution
Luminosity	0.44 % [BaBar]
Cross-section	0.31% [Data]
Branching fraction of 1-prong tau decays	Electron : 0.23 % [PDG] Muon: 0.23% [PDG]
Branching fraction of 3–prong tau decays	3 pions : 0.57 % [PDG]
PID Efficiency	Electron : 2 % [BaBar] Muons : 1 % Pions : 3 %
$q\bar{q}$ and Bhabha Contamination	0.3 % [Control region analysis]
Bin Size	< 1% [Alter bins, check results]
Tracking Efficiency	N/A
Detector Modelling	N/A
Tau Mass uncertainty	N/A
Tau Energy	N/A



Systematic Shape Uncertainties

- Dominant shape systematic from modelling of the hadronic tau decays in TAUOLA
- $\tau^- \rightarrow \pi^-\pi^-\pi^+\upsilon_\tau$ is mediated by the a_1 resonance 97% of the time.
- $m_{a_1} = 1230 \pm 40$ MeV/c^2 and $\Gamma_{a_1} = 420 \pm 35$ MeV/c^2 (PDG estimates 250 – 600 MeV/c^2)

Searching for HNLs at BaBar



- Binned profile likelihood approach used to find 95% C.L. on $|U_{\tau 4}|^2$.
- Considers both lepton tags and + and – signal tau channels.
- Provides new upper limits for HNLs mixing with taus in range 400 < $|U_{\tau 4}|^2$ < 1300 MeV/c^2

Future Projections

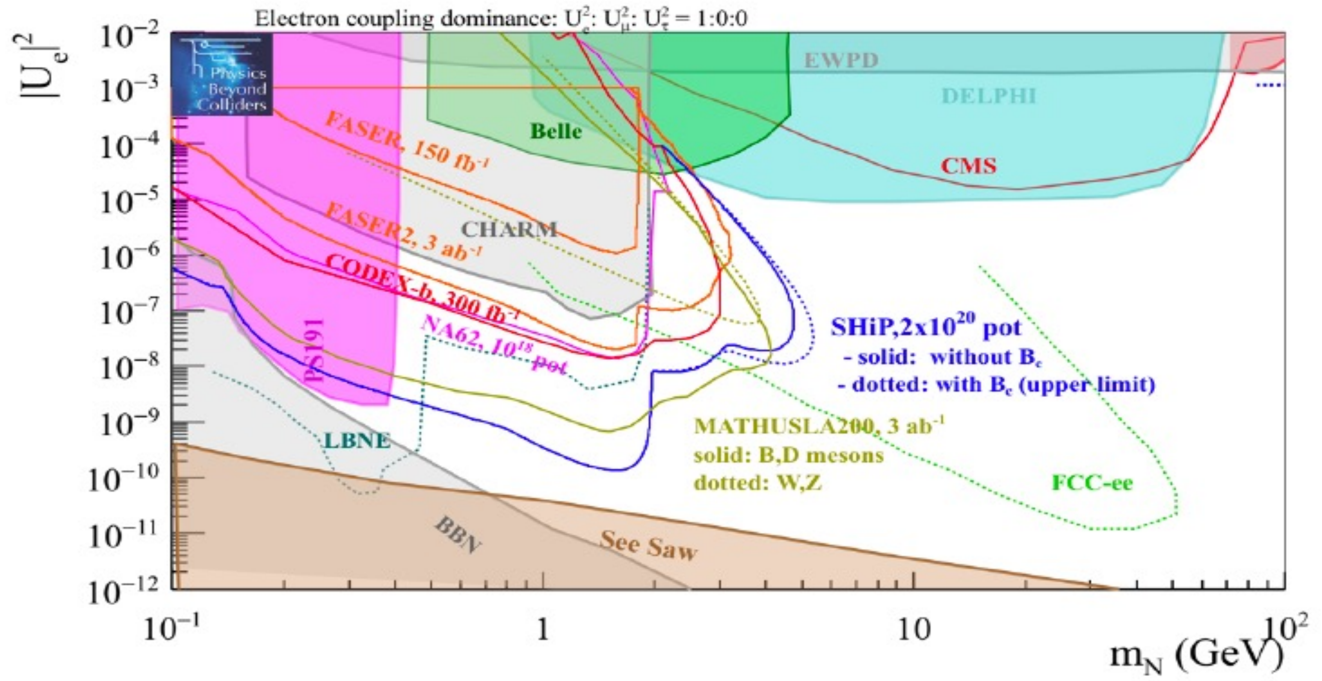
How do these limits compare to what we might see in other near-future experiments?

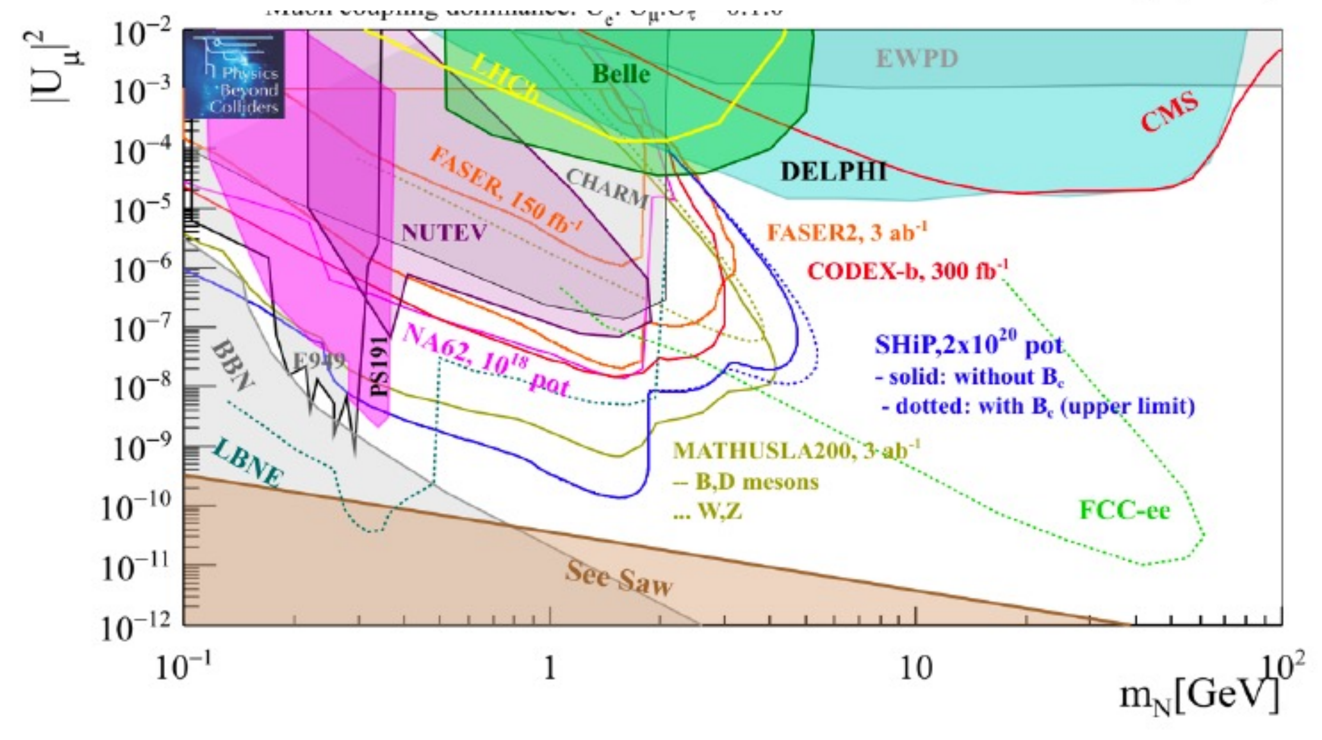
Future Projections

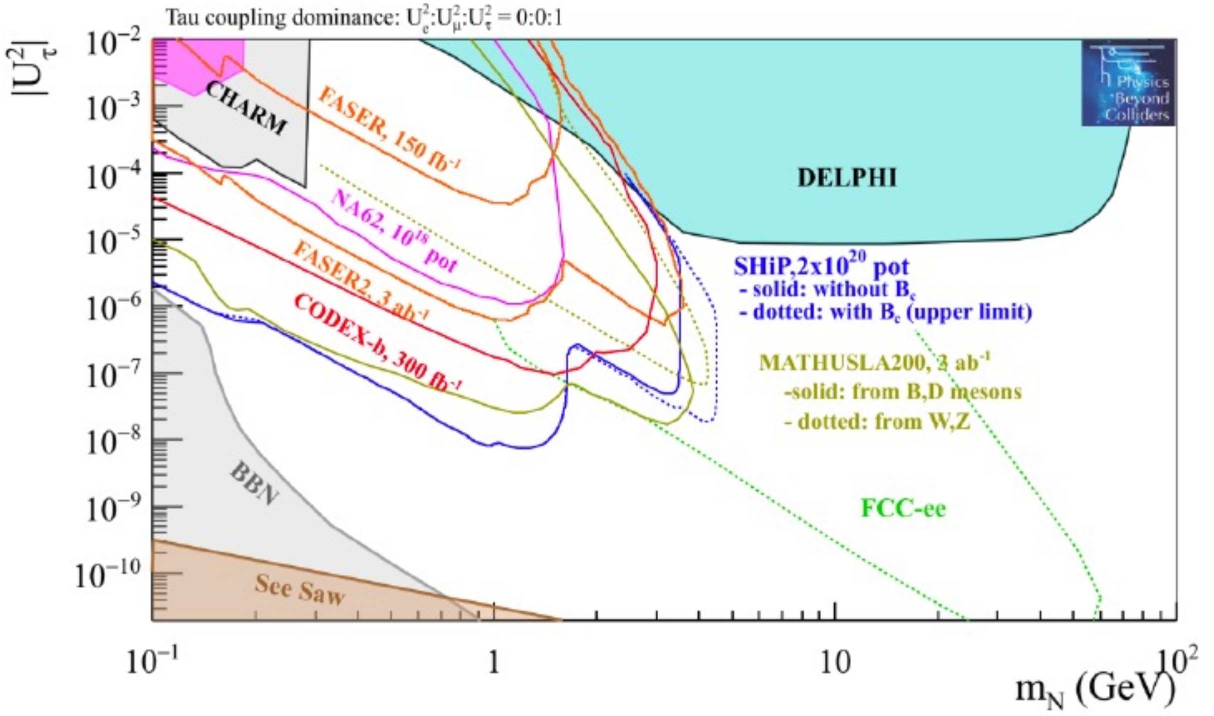
- In the coming decades several collider-based and neutrino sector experiments will further constrain HNLs:
  - Electrons: NA62-dump, NA62 K+ decays, FASER, PIONEER, SHADOWS, DarkQuest, SHiP, DUNE, T2K, Hyper-K
  - Muons: NA62-dump, NA62 K+ decays, FASER, DarkQuest, SHADOWS, PIONEER, SHiP, DUNE, Hyper-K, T2K low mass
  - Taus: NA62-dump, FASER, SHADOWS, DUNE, DarkQuest, and SHiP.

For Review of Near-term Projections: J. Beacham et al., Journal of Physics G: Nuc. and Part. Phys. 47, 010501 (2019).

Future Projections







For Review of Near-term Projections: J. Beacham et al., Journal of Physics G: Nuc. and Part. Phys. 47, 010501 (2019).

Conclusions

Summary & Outlook

- HNLs offer ways of explaining several observational phenomena.
- The possible masses of the HNLs is model dependent and can range from eV/c^2 up to very heavy masses.
- In the last few years several new results have been published including results from collider-based experiments and neutrino experiments.
- This talk has given details on the newest analysis from BaBar which presents new upper limits on $|U_{\tau 4}|^2$ at 95 % C.L. between 100 MeV/c^2 – 1300 MeV/c^2 :
  - Competitive with projections for experiment results expected in coming decade.
  - New technique can be applied to data from other experiments e.g. Belle-II.
  - Expect publication in next few months.

Useful Resources for Additional Reading

- J. Beacham et al., Journal of Physics G: Nuc. and Part. Phys. 47, 010501 (2019).
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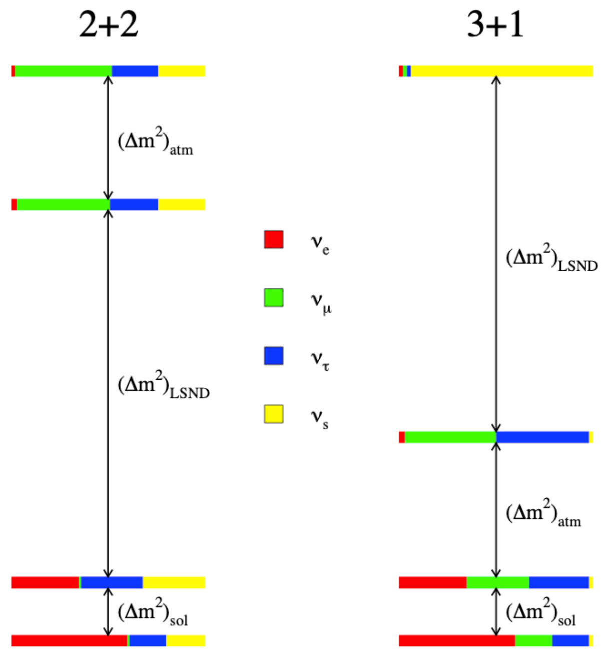
Event Yields

Bkg. Type	Electron Tag MC Yield	[%]	Muon Tag MC Yield	[%]
$\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau$	894864	70	810586	71
$\tau^+ \to \pi^+\pi^+\pi^-\pi^0\bar{\nu}_\tau$	332008	26	278830	24
$\tau^+ \to \pi^+\pi^+\pi^-2\pi^0\bar{\nu}_\tau$	34050	2.7	28841	2.5
$\tau^+ \to 2\pi^\pm K^\pm\bar{\nu}_\tau$	3391	0.27	3101	0.27
$\tau^+ \to \pi^+\pi^+\pi^-3\pi^0\bar{\nu}_\tau$	1541	0.12	821	0.07
$\tau^+ \to \pi^\pm\pi^0\bar{\nu}_\tau$	498	0.039	207	0.017
$\tau^+ \to \pi^\pm 2\pi^0\bar{\nu}_\tau$	252	0.02	92	0.27
$\tau^+ \to 2K^\pm\pi^\pm\bar{\nu}_\tau$	207	0.016	146	0.013
$e^+e^- \to \Upsilon(4S) \to c\bar{c}$	8031	0.63	6512	0.55
$e^+e^- \to \Upsilon(4S) \to u\bar{u}, s\bar{s}, d\bar{d}$	542	0.043	13898	1.19
$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$	108	0.009	99	0.0084
$e^+e^- \to \Upsilon(4S) \to B^+B^-$	100	0.008	89	0.0076
$e^+e^- \to \mu^+\mu^-$	0	0	15	0.0013
Total MC	1278339	-	1143237	-
Data	1265698	-	1137521	-

Bkg. Type	Electron Tag MC Yield	[%]	Muon Tag MC Yield	[%]
$\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$	900069	70	817342	70
$\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$	334565	26	281613	25
$\tau^- \to \pi^-\pi^-\pi^+2\pi^0\nu_\tau$	34255	2.7	29287	2.5
$\tau^- \to 2\pi^\pm K^\pm\nu_\tau$	3567	0.27	3228	0.27
$\tau^- \to \pi^-\pi^-\pi^+3\pi^0\nu_\tau$	1535	0.12	795	0.07
$\tau^- \to \pi^\pm\pi^0\nu_\tau$	476	0.039	217	0.019
$\tau^- \to \pi^\pm 2\pi^0\nu_\tau$	240	0.02	92	0.08
$\tau^- \to 2K^\pm\pi^\pm\nu_\tau$	202	0.016	152	0.013
$e^+e^- \to \Upsilon(4S) \to c\bar{c}$	8031	0.63	6837	0.58
$e^+e^- \to \Upsilon(4S) \to u\bar{u}, s\bar{s}, d\bar{d}$	495	0.043	16602	1.42
$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$	126	0.009	98	0.0083
$e^+e^- \to \Upsilon(4S) \to B^+B^-$	93	0.008	103	0.0088
$e^+e^- \to \mu^+\mu^-$	0	0	10	0.0009
Total MC	1283654	-	1155920	-
Data	1273291	-	1150350	-

Additional Neutrinos



$\Rightarrow$ 2+2 requires large sterile effects in either solar or atmospheric oscillations, not observed