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A New Search for Heavy Neutral Leptons at *BABAR*

FIPs2022
(CERN)

BABAR

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on behalf of the *BABAR* Collaboration

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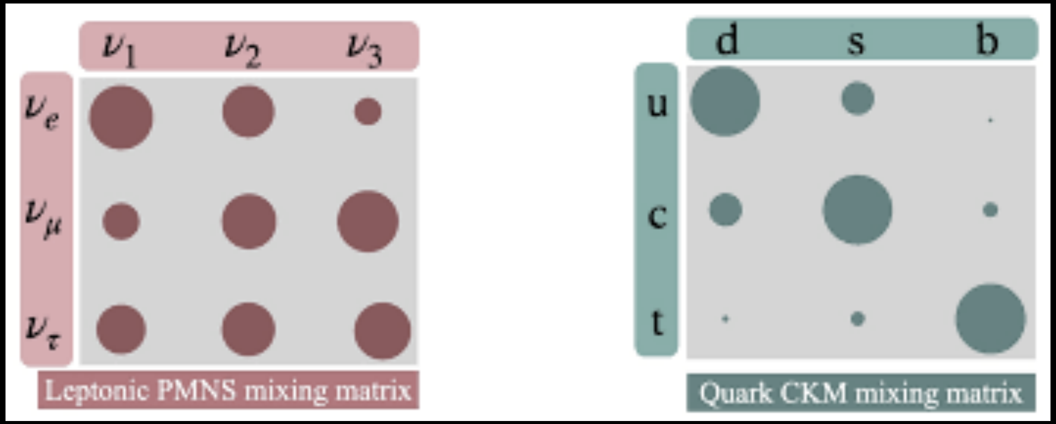
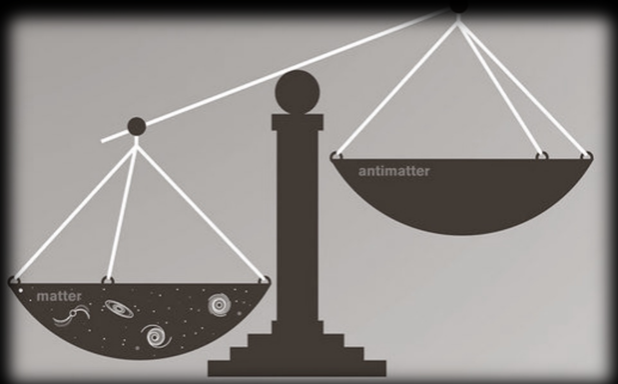
The Standard Model

- Although successful in explaining many things, sometimes with very high precision, there is need to extend the standard model

Neutrino masses

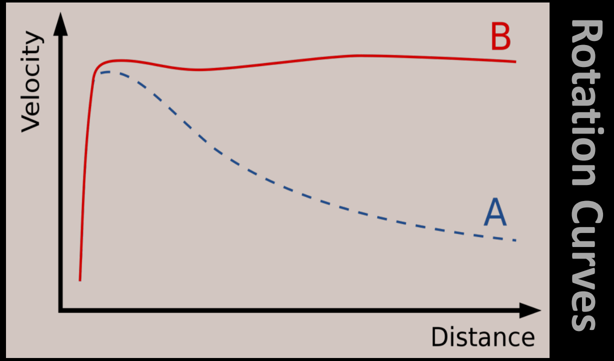


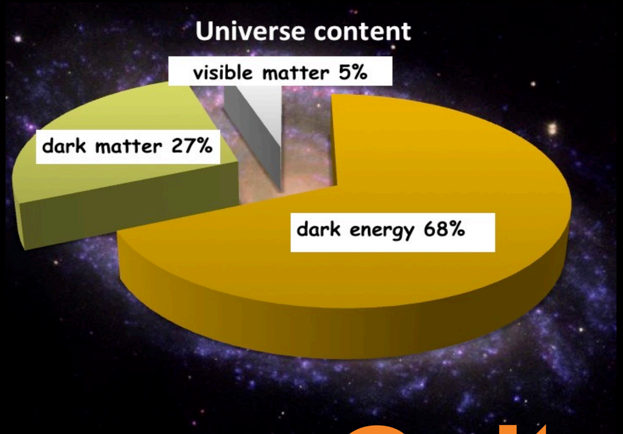
Baryonic Asymmetry in the universe



Astrophysical observations

→ existence of Dark Matter and Dark Energy





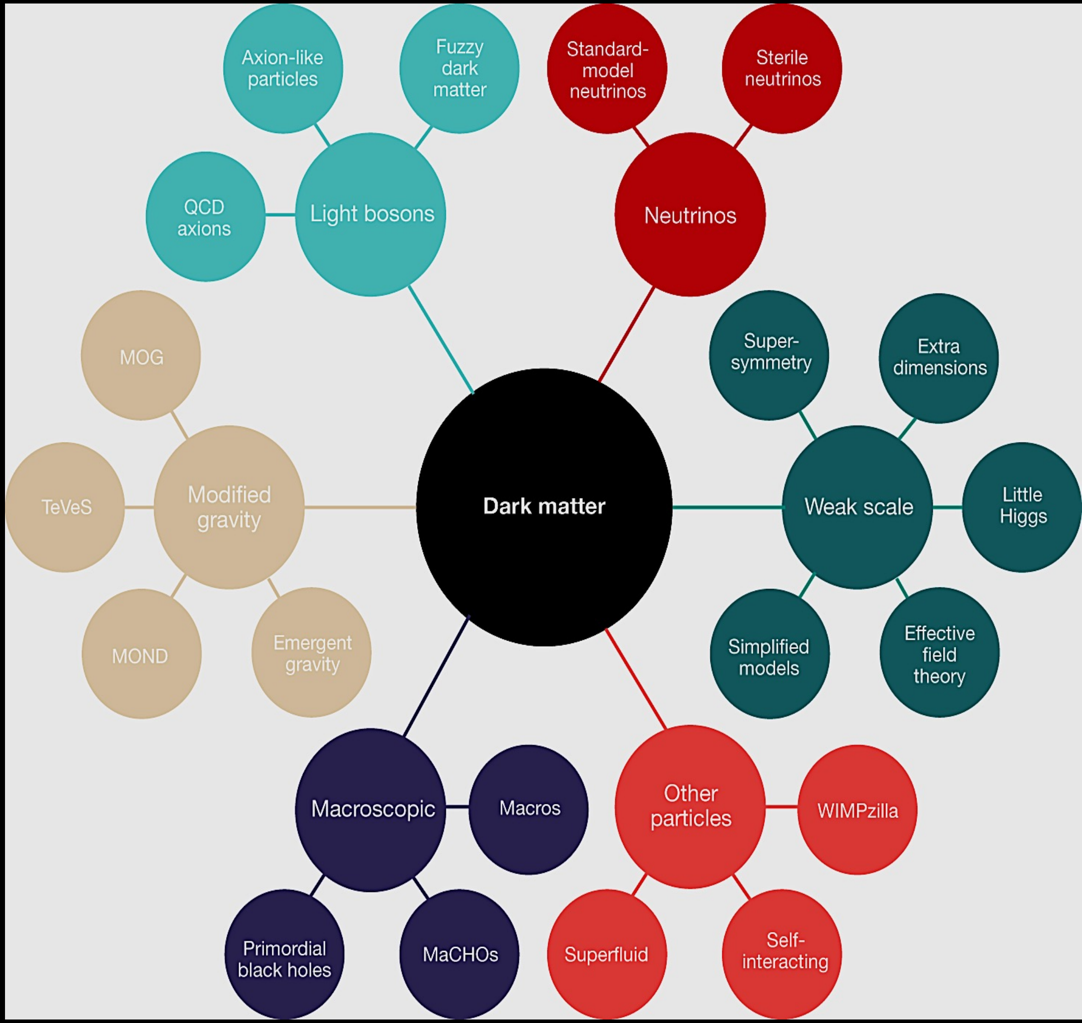
Dark Matter: The Neutrino Portal

Plethora of models to explain DM

- Search for new physics by incorporating new terms into Lagrangian

$\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	Vector Portal	**Dark photons**
$(A\,S + \lambda\,S^2)\,H^\dagger H$	Higgs Portal	**Dark Higgs**
$y N L H$	Neutrino portal	**Sterile neutrinos**

- This talk focused on the "Neutrino portal"



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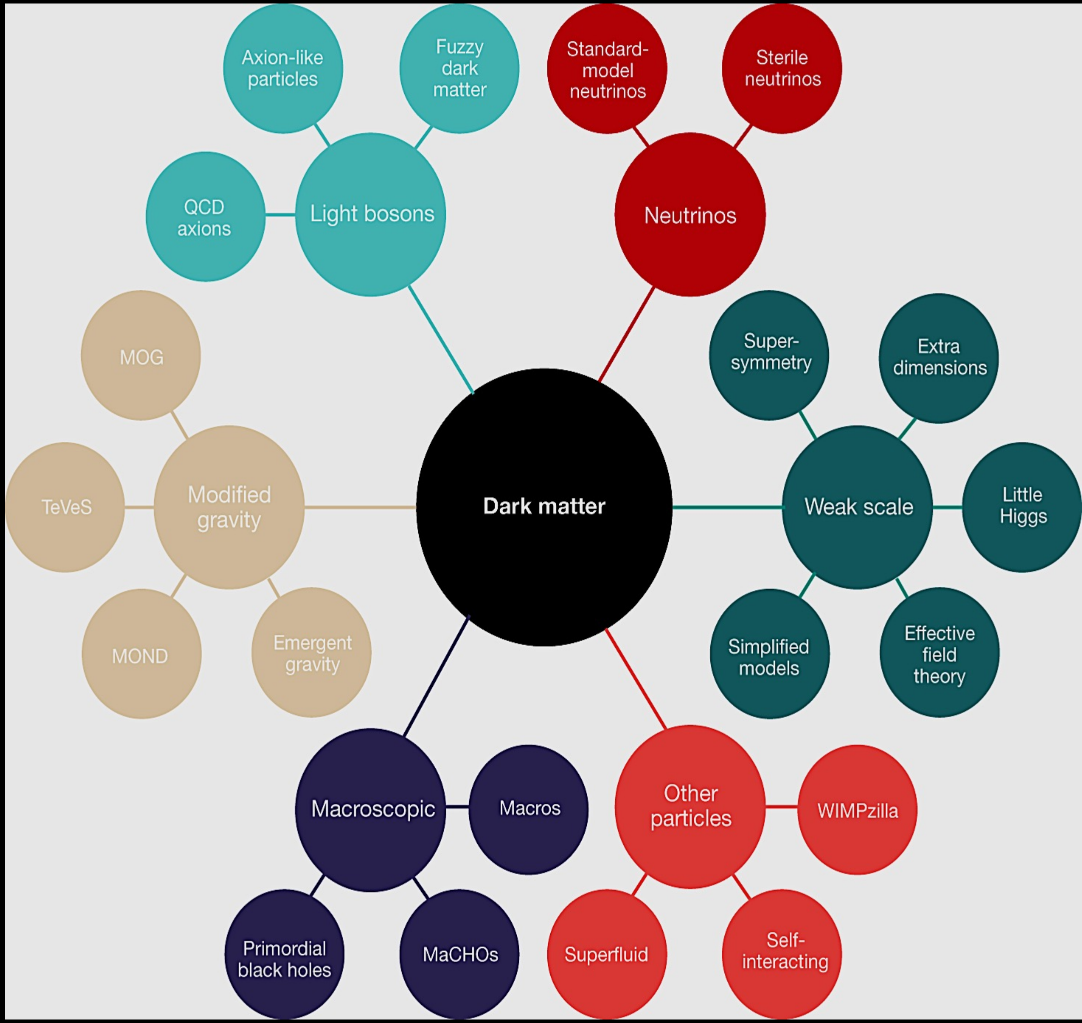


Neutrino Oscillations

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

- Neutrino oscillations are only experimentally verified physics beyond the SM → neutrinos have mass!
- 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 $\Delta m_{32}{}^2$

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

- But many unanswered questions in neutrino physics, including:
  - CP Violation?
  - Nature of neutrinos?
  - Why is mixing so different from CKM?
  - 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.

Heavy Neutral Leptons?

- Heavy Neutral Leptons (HNLs) are additional neutrino states. Have mass, but no weak hyper-charge, electric charge, weak isospin and color charge. Could be produced in experiments only via mixing with active neutrinos.
- HNLs are proposed by several beyond Standard Model (BSM) theories to explain three major observational phenomena:
  - Neutrino oscillations and origins of their mass via seesaw models etc. (Phys. Rev. D 23,165);
  - Baryonic asymmetry of Universe (Phys. Rev. Lett. 81, 1359);
  - Dark matter candidate (Phys. Lett.B 631, 151–156).
- If neutrinos get their mass from Higgs, Yukawa couplings must be exceedingly small. Not so in seesaw models with 5-dim operator and additional Majorana neutrinos.
- Lighter sterile (eV-scale) neutrinos can also help explain various experimental observations:
  - “Reactor Anti-neutrino anomaly:” (Phys. Rev. D 83, 07300).
  - “Gallium anomaly:” (Phys. Rev. C 80 015807).
  - “Accelerator anomaly:” LSND (Phys. Rev. D 64, 112007) MiniBooNE (Phys. Rev. Lett. 110, 161801)
- **This is why its important to explore additional neutrinos.**

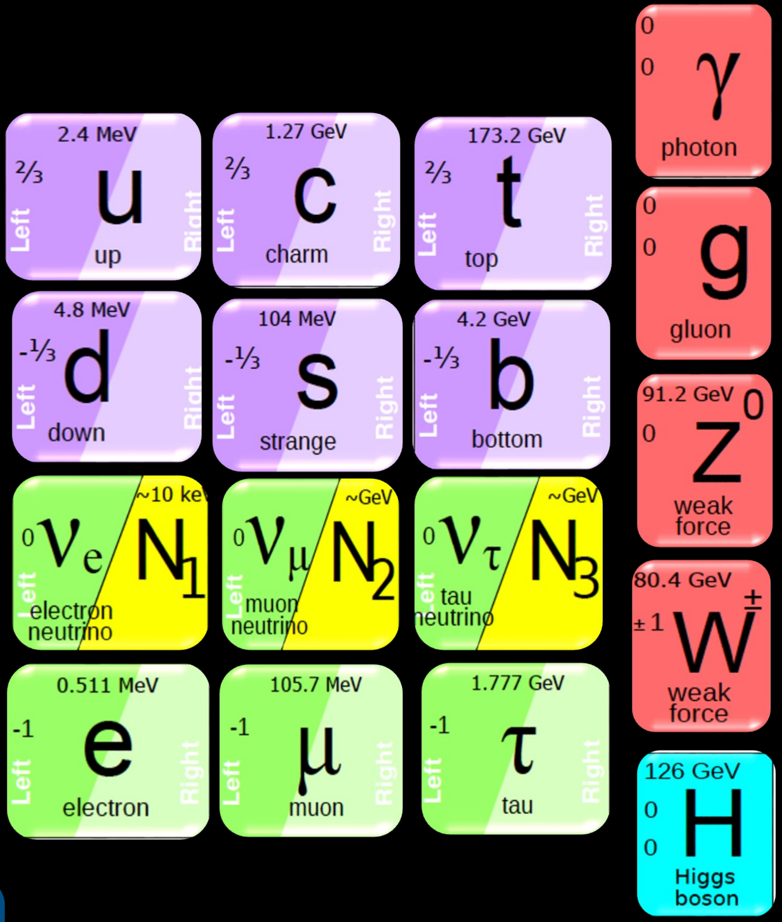
Possible Mass Scale

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:

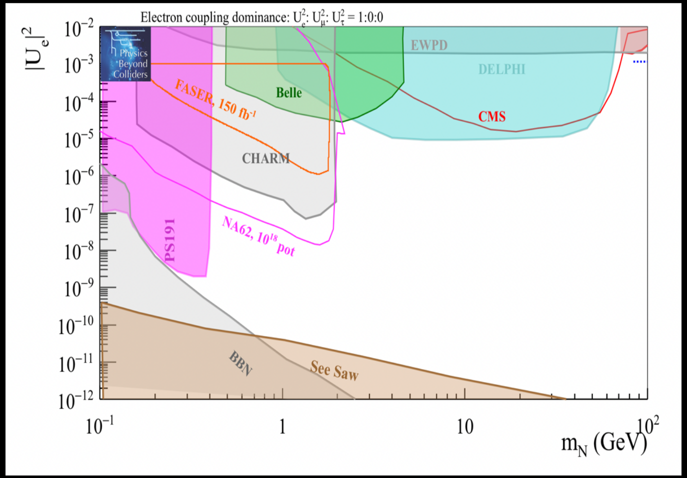
  - Two GeV/c² scale particles solve origin and smallness of SM neutrino mass with see saw mech.
  - Third HNL is dark matter candidate with mass ~keV/c². Also provides lepto-genesis due to Majorana mass term
  - (Phys. Rev. Lett. 81, 1359)
- *ν*-MSM fits with all current experimental constraints.

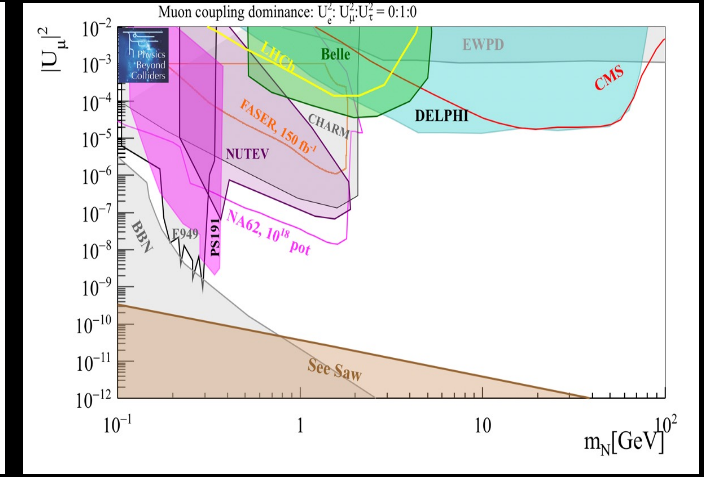


- Different methods/techniques needed to test such a variety of models
- HNLs in MeV-GeV scale can be searched for at existing accelerator-based experiments.

Extended PMNS and Current limits

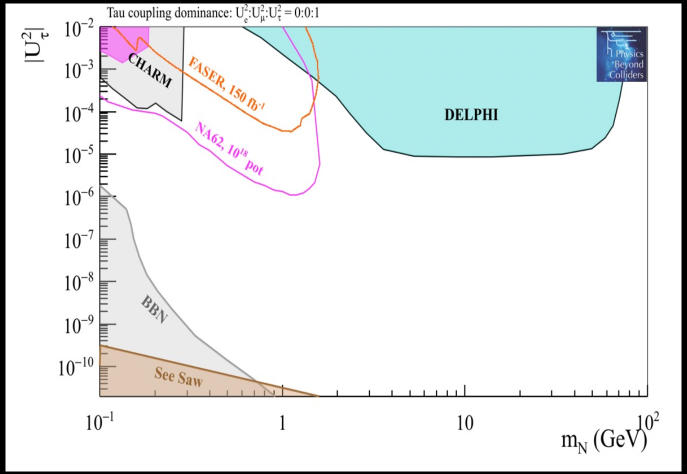
Bounded from below by the BBN constraint (JCAP 1210 (2012) 014, [1202.2841) and the see-saw limit (JCAP1009 (2010) 001, [1006.0133])





$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \vdots \end{pmatrix}
=
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\
U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\
\vdots & \vdots & \vdots & \ddots &
\end{pmatrix}
\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix} .
$$

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



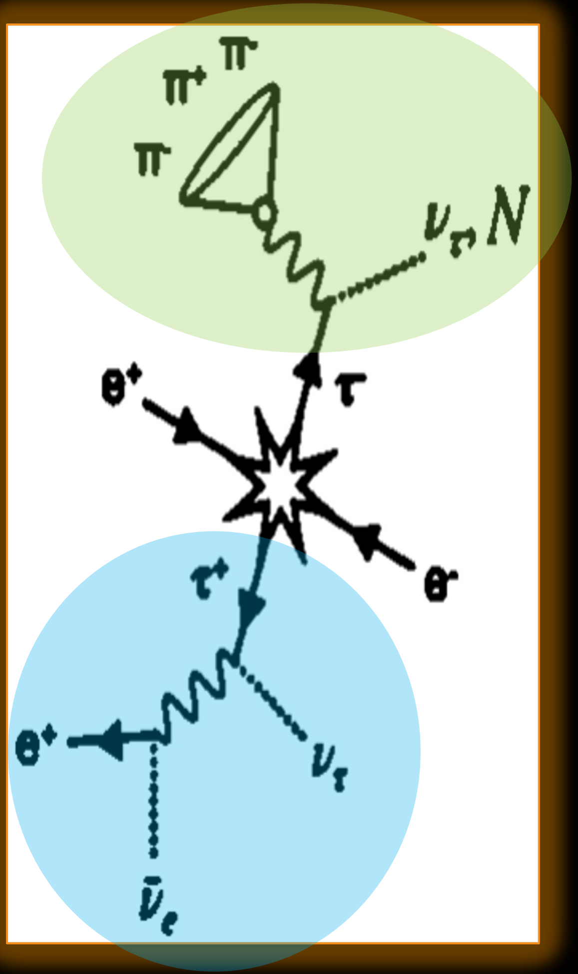
- Experiments try to measure the matrix elements $|U_{ln}|^2$ where $l = e, \mu, \tau$ and $n = 4,5,6 \ldots$
- Experiments generally quote results in parameter space of elements $|U_{ln}|^2$ .v. HNL mass hypothesis.
- Tau sector historically less explored…

The BABAR Search

$\sigma(e^+e^- \to \tau^+\tau^-) = \mathbf{0.919 \pm 0.003}$ **nb**
Integrated luminosity in runs used = **424 fb $^{-1}$**
→ **$N_{\tau\tau}$ = 4.6 × 10^8 events**

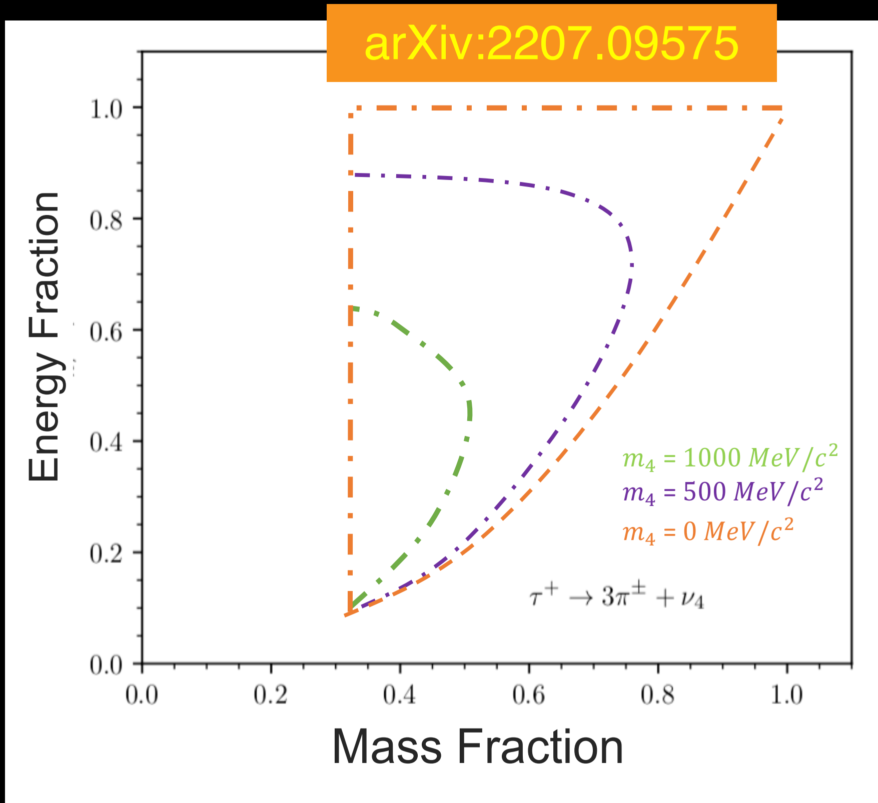
arXiv:2207.09575

- For overview of experiment: Nucl. Instrum. Meth. A 729, 615 (2013).
- New analysis from ***BaBar*** – using the kinematics of hadronic tau decays based on ALEPH technique (Eur. Phys. J.1137C 2, 395).
- Looks only at kinematics, no assumptions on underlying model, except that there must be some small mixing with tau sector.:
  - “signal side” : three pronged pionic tau decay $(\tau^- \to \pi^-\pi^-\pi^+\upsilon_\tau)$ as it allows access to region $100 < m_4 < 1360$ MeV/c^2 where current limits are loose.
  - “tag side” : 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.


arXiv:2207.09575

- Model 3-pronged decay as 2-body with outgoing HNL and hadronic system
- 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:

$$3m_{\pi^\pm} < m_h < m_\tau - m_4$$

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

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

SM Tau Decay **BSM Tau Decay**

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

arXiv:2207.09575

Background and Signal Simulations

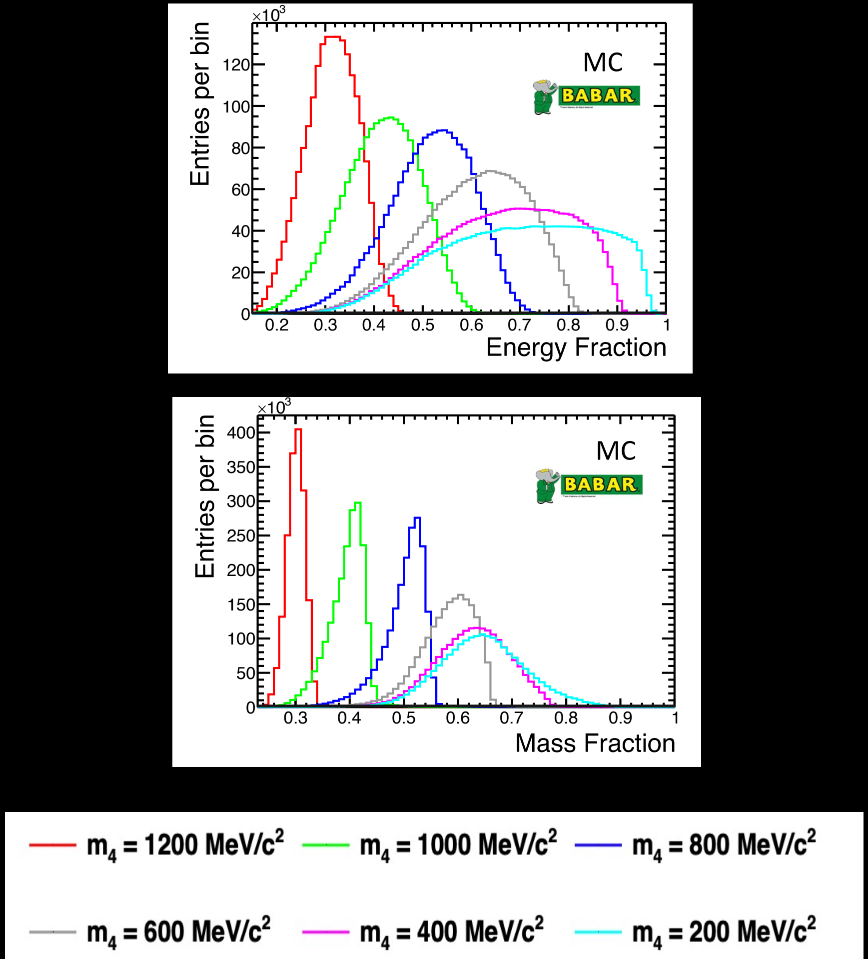
TAUOLA: Comp. Phys. Co. 130, 260–325 (2000)
KK2F: Comp. Phys. Co. 64, 275 (1991)
EvetGen: Nucl. Instrum. Meth. A 462, 152 (2001)
JetSet: Comp. Phys. Co. 39, 347 (1986)

- Use MC to estimate expected background contributions
- Detector response modelled using GEANT4, event generator specific to each source
- Three potential sources of non-signal events in data:
  1. SM 3 pronged decay to 3 charged 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)

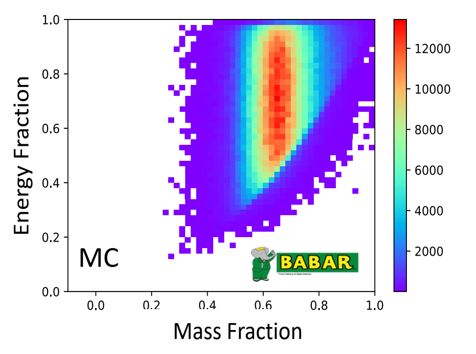
- HNL : characterized by large missing mass (TAUOLA+KK2F – custom function, mass modified to attribute masses in range 100 – 1300 MeV/c^2)

Example Signal Simulations

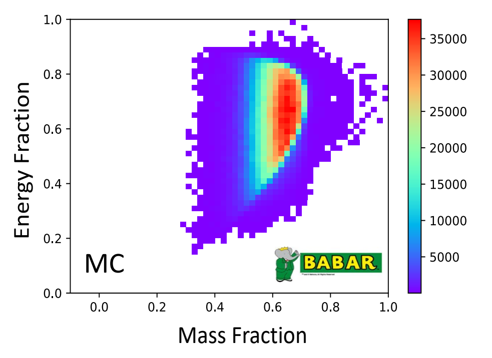
- Plots illustrate in 1D projections and final 2D templates for $\tau^- \rightarrow \pi^-\pi^-\pi^+\upsilon_X$
- Show parameter space changes with HNL mass



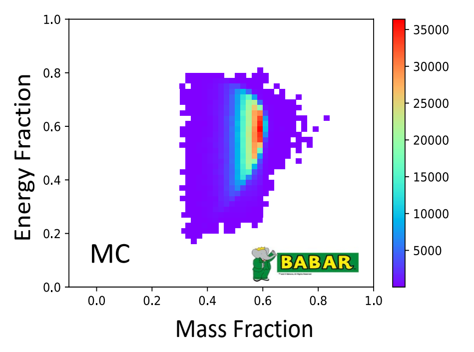
$m_4 = 100\ MeV/c^2$



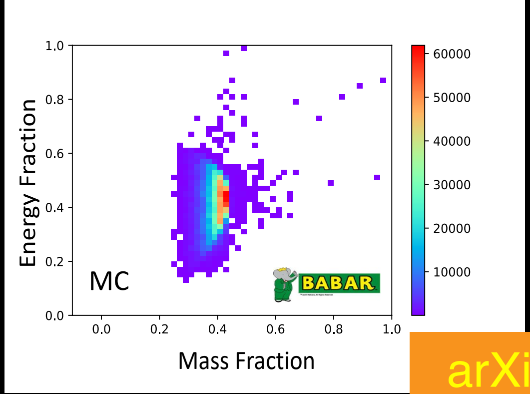
$m_4 = 500\ MeV/c^2$



$m_4 = 700\ MeV/c^2$



$m_4 = 1000\ MeV/c^2$



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largest sensitivity for large masses

Fit Model

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

$$\mathcal{L} = \prod_{ij} f(n_{ij}; n_{\mathrm{obs}}, \vec{\theta}) = \prod_{ij} \frac{(\boxed{\nu_{\mathrm{HNL}}} + \boxed{\nu_{\tau-\mathrm{SM}}} + \boxed{\nu_{\mathrm{BKG}}})_{ij}^{(n_{\mathrm{obs}})_{ij}} e^{-(\nu_{\mathrm{HNL}}+\nu_{\mathrm{BKG}}+\nu_{\tau-\mathrm{SM}})_{ij}}}{(n_{\mathrm{obs}})_{ij}!} \times \boxed{\prod_{k} f(\theta_k, \tilde{\theta}_k),}$$

Where:

Nuisance parameters

Potential signal events:

$$\hat{\nu}_{\mathrm{HNL},ij} = n^{\mathrm{reco}}_{\mathrm{HNL},ij} = N_{\tau,\mathrm{gen}} \cdot (|U_{\tau 4}|^2) \cdot p_{\mathrm{HNL},ij},$$

Expected tau SM background events:

$$\hat{\nu}_{\tau-\mathrm{SM},ij} = n^{\mathrm{reco}}_{\tau-SM,ij} = N_{\tau,\mathrm{gen}} \cdot (1-|U_{\tau 4}|^2) \cdot p_{\tau-SM,ij},$$

Expected non-tau SM background events:

$$\hat{\nu}_{\mathrm{BKG},ij} = n^{\mathrm{reco}}_{BKG,ij} = n^{\mathrm{reco}}_{\tau-\mathrm{other},ij} + n^{\mathrm{reco}}_{\mathrm{non}-\tau,ij},$$

Use Wilk's theorem to find limits:

$$q = -2\ln\left(\frac{\mathcal{L}_{H_0}(|U_{\tau 4}|^2_0; \hat{\hat{\theta}}_0, \mathrm{data})}{\mathcal{L}_{H_1}(|\hat{U}_{\tau 4}|^2; \hat{\theta}, \mathrm{data})}\right) = -2\ln(\Delta\mathcal{L}).$$

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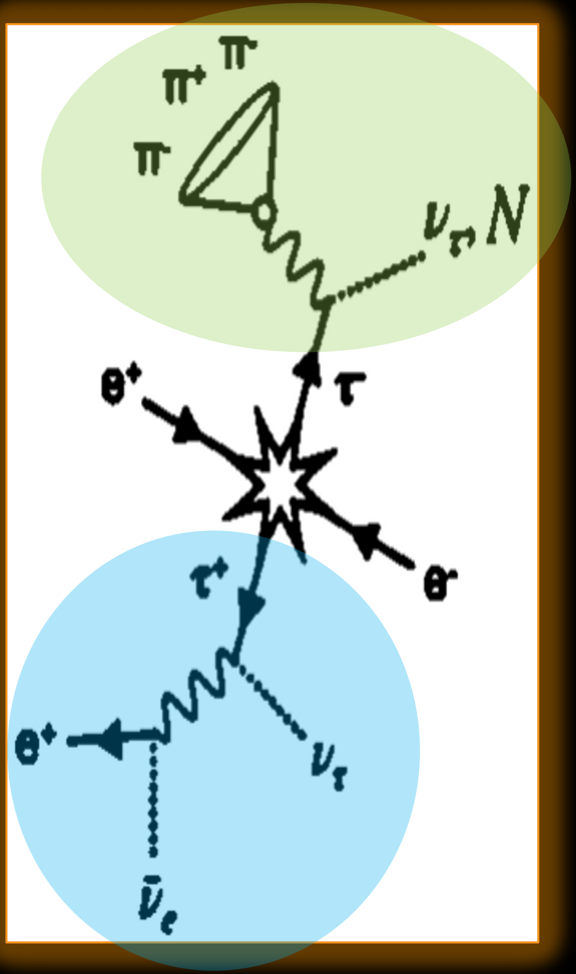
Event Selection

- Selection optimized $\tau^{\pm} \rightarrow l^{\pm}\upsilon_{l}$ (tag) and $\tau^{\mp} \rightarrow \pi^{\mp}\pi^{\mp}\pi^{\pm}\upsilon_{HNL?}$ (3h)

Cut	Purpose
Number of tracks	Ensure 1+3 prong topology
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

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Example 2D Plots

Plots for
Sig = Neg. 3 prong
Tag = Pos. electron

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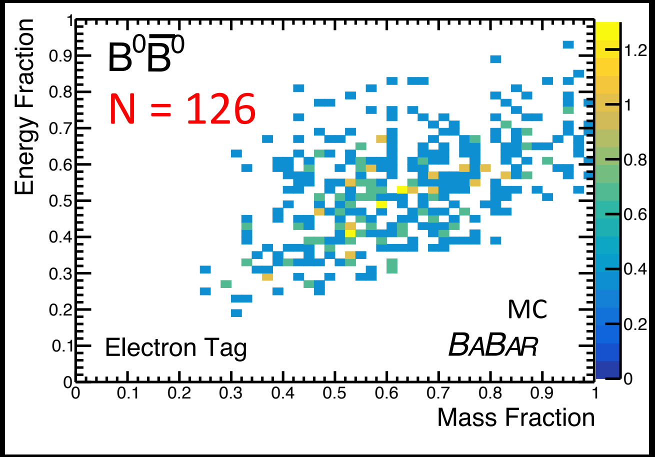
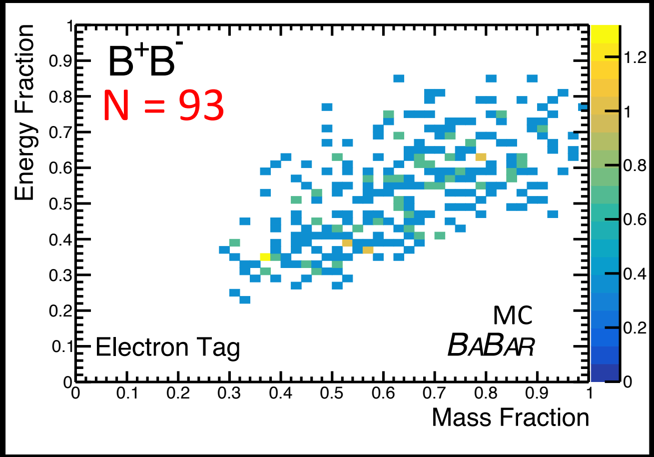
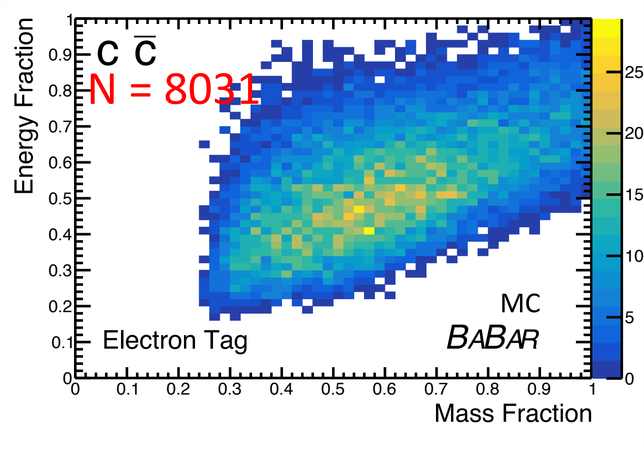
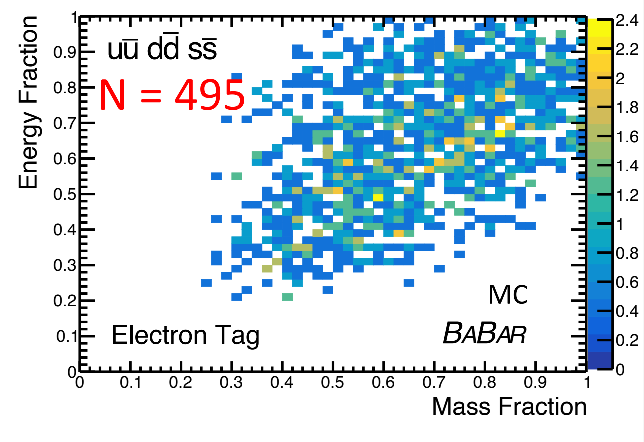
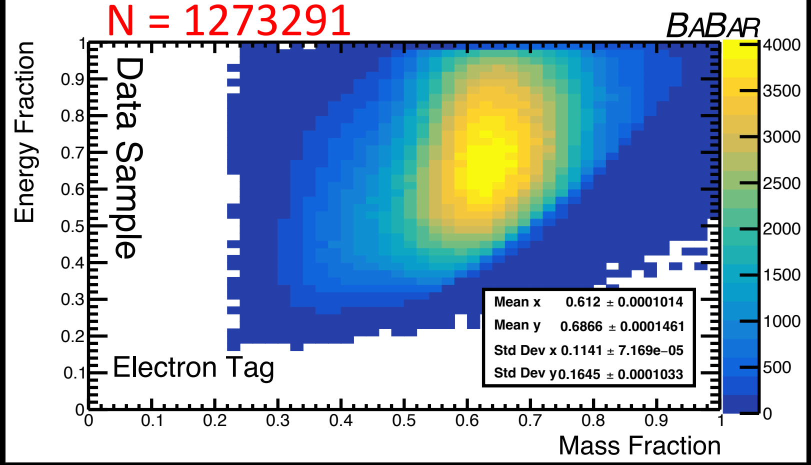
Data Total = 1273291, MC Total = 1283654

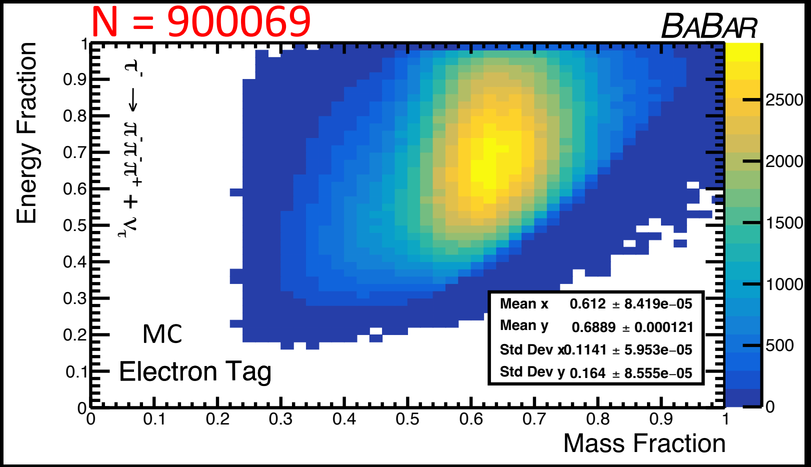


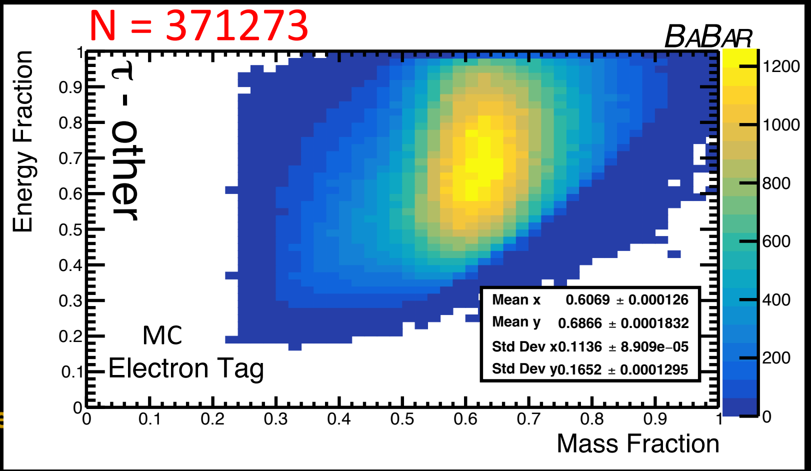












Normalization Uncertainties

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

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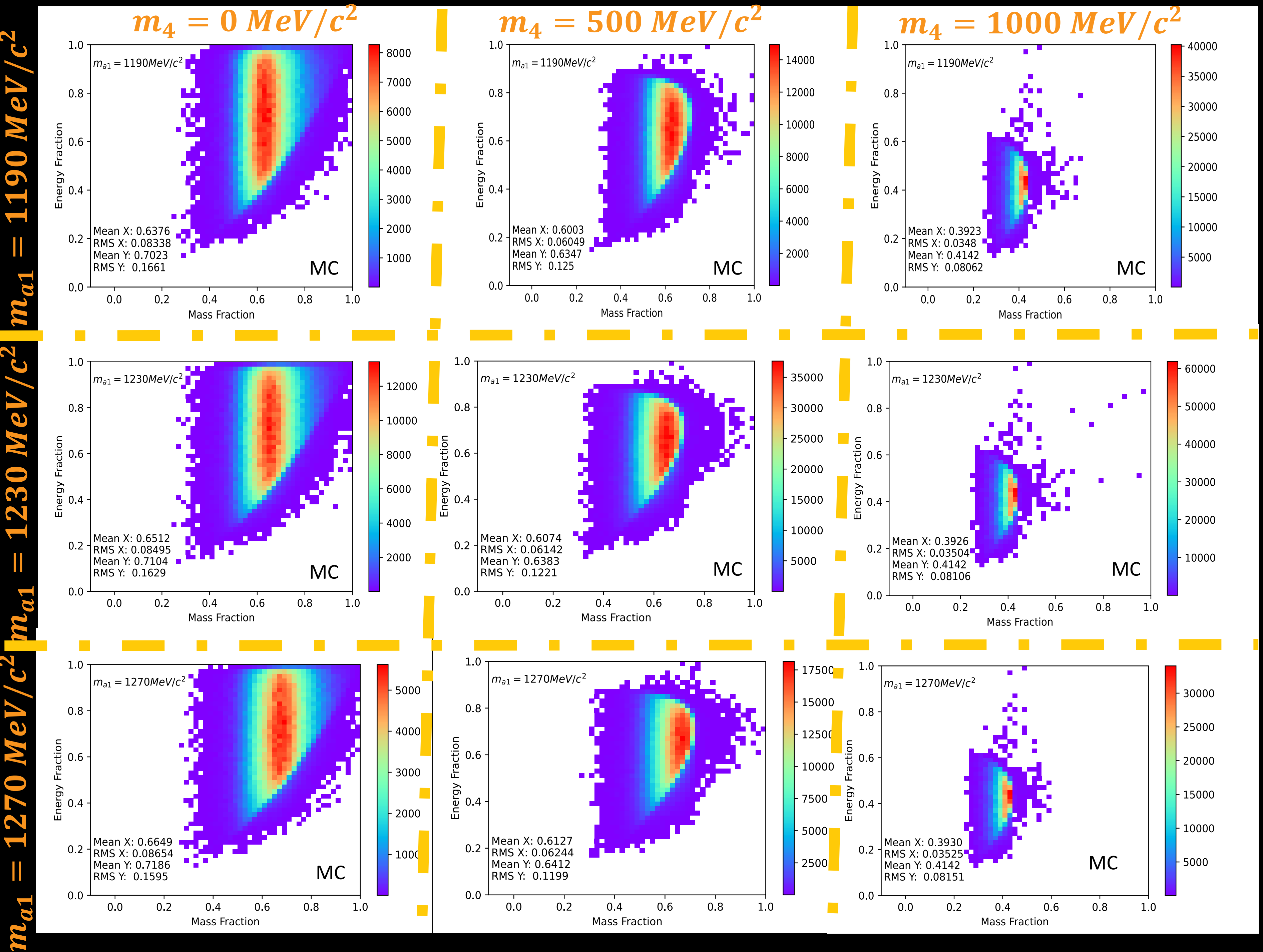
- Normalization uncertainties affect all bins uniformly.
- Have small effect on overall yield.
- They will be characterized as Gaussian nuisance parameters in the likelihood.

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/c² and $\Gamma_{a_1} = 420 \pm 35$ MeV/c² (PDG estimates 250 – 600 MeV/c²)

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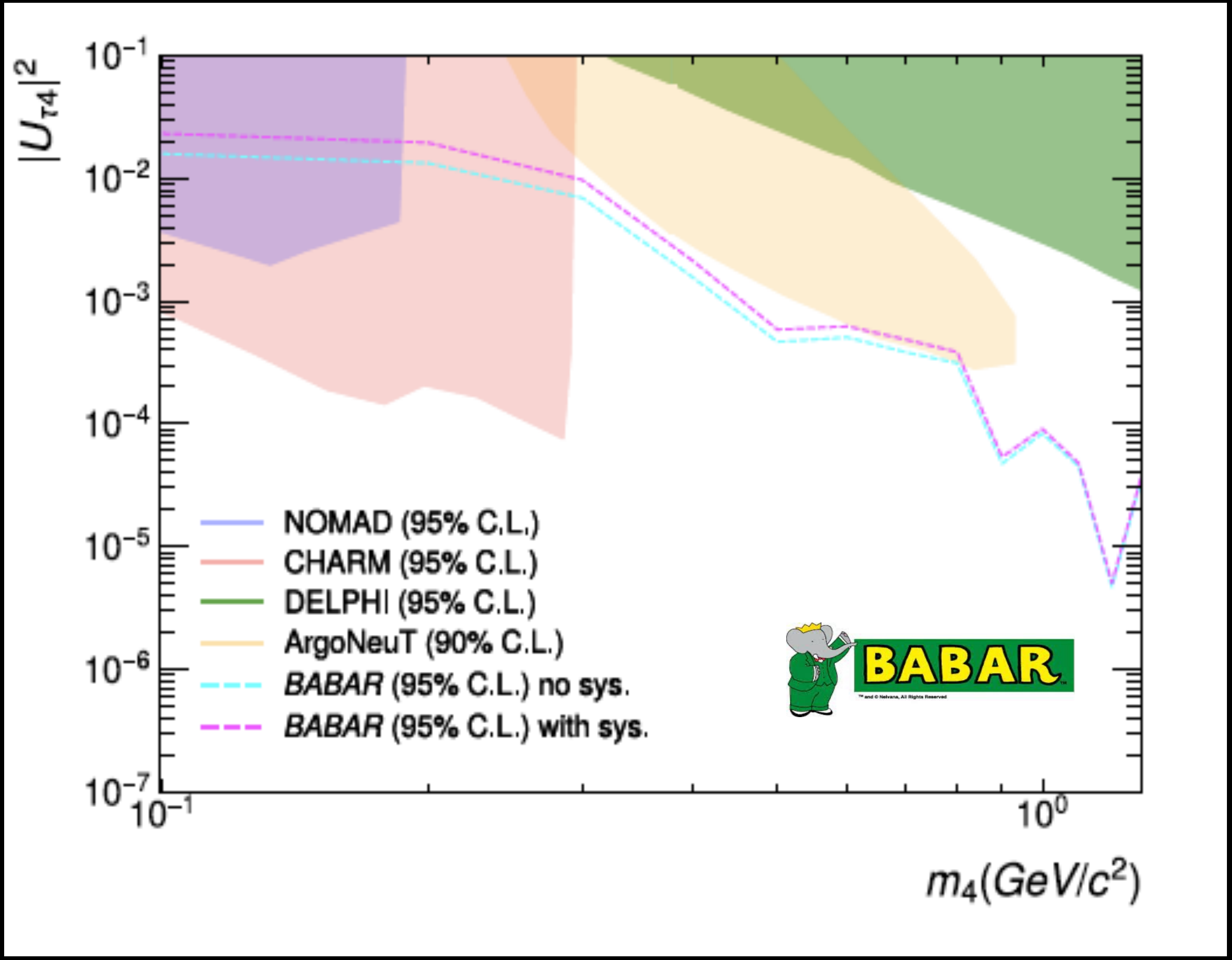
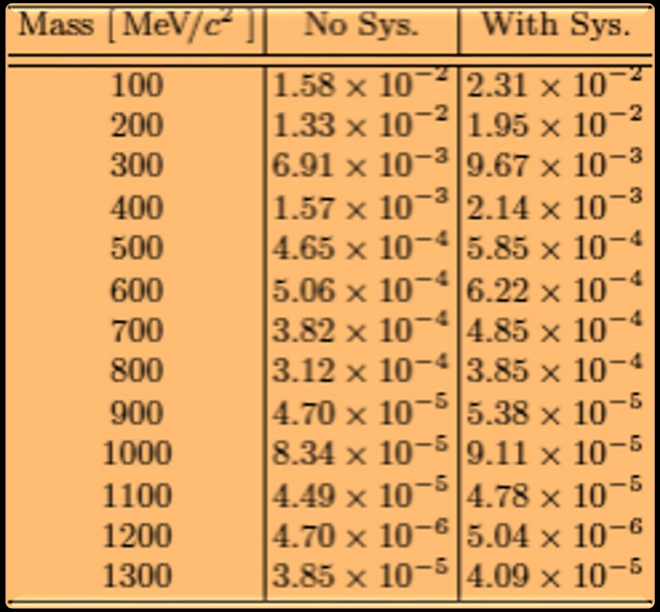
Caltech

Result



- Binned profile likelihood approach used to find 95% C.L. on $|U_{\tau4}|^2$.
- Considers both lepton tags and + and – signal tau channels.
- Provides upper limits for HNLs mixing with taus in range 100 < $|U_{\tau4}|^2$ < 1300 MeV/c^2



Mass [MeV/c^2]	No Sys.	With Sys.
100	1.58×10^{-2}	2.31×10^{-2}
200	1.33×10^{-2}	1.95×10^{-2}
300	6.91×10^{-3}	9.67×10^{-3}
400	1.57×10^{-3}	2.14×10^{-3}
500	4.65×10^{-4}	5.85×10^{-4}
600	5.06×10^{-4}	6.22×10^{-4}
700	3.82×10^{-4}	4.85×10^{-4}
800	3.12×10^{-4}	3.85×10^{-4}
900	4.70×10^{-5}	5.38×10^{-5}
1000	8.34×10^{-5}	9.11×10^{-5}
1100	4.49×10^{-5}	4.78×10^{-5}
1200	4.70×10^{-6}	5.04×10^{-6}
1300	3.85×10^{-5}	4.09×10^{-5}

arXiv:2207.09575

Summary and 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.
  - Accepted in to PhysRevD.

arXiv:2207.09575

Useful Resources for Additional Reading

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