A Search for Heavy Neutral Leptons in tau decays at *BABAR*

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(Louisville, KY)

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on behalf of the *BABAR* Collaboration

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Motivations

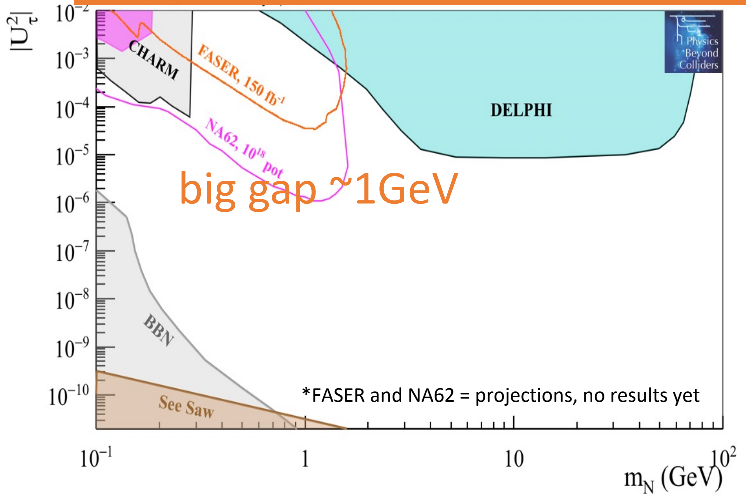
Heavy Neutral Leptons (HNLs) are additional neutrino states. They have mass but are neutral in all respects.

- 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).**
- *ν*-MSM proposes three keV-GeV scale HNLs.

- Experiments generally quote results in parameter space of elements $|U_{ln}|^2$ .v. HNL mass hypothesis.
- **Tau sector historically less explored…**

Journal of Physics G: Nuc. & Part.1075 Phys. 47, 010501 (2019)

Tau Mixing Parameter .v. HNL mass



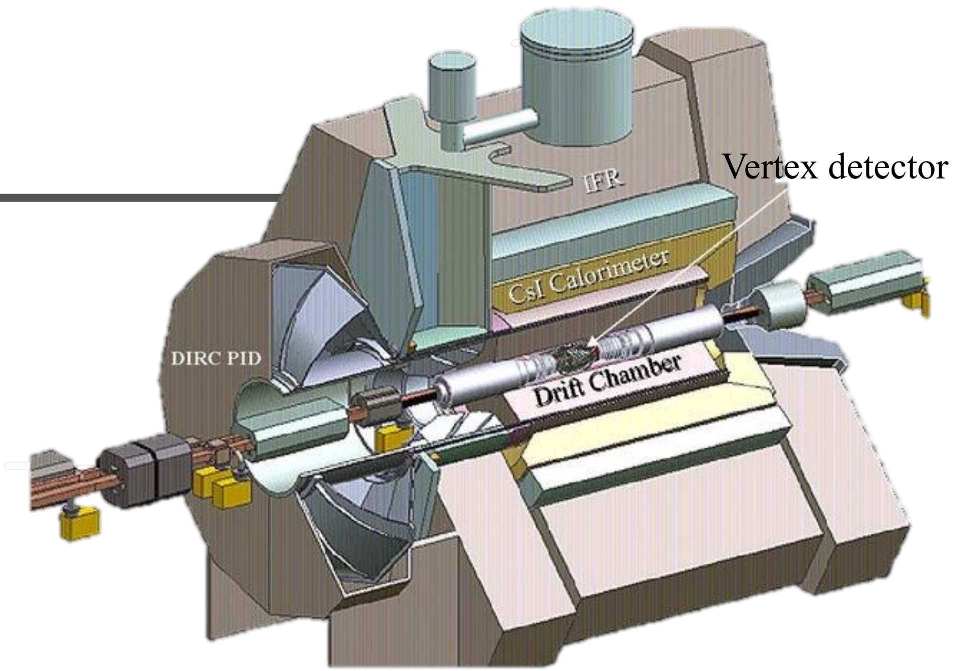
$\sigma(e^+e^- \rightarrow \tau^+\tau^-) = \mathbf{0.919 \pm 0.003}$ **nb**

Integrated luminosity in runs used **= 424 fb $^{-1}$**

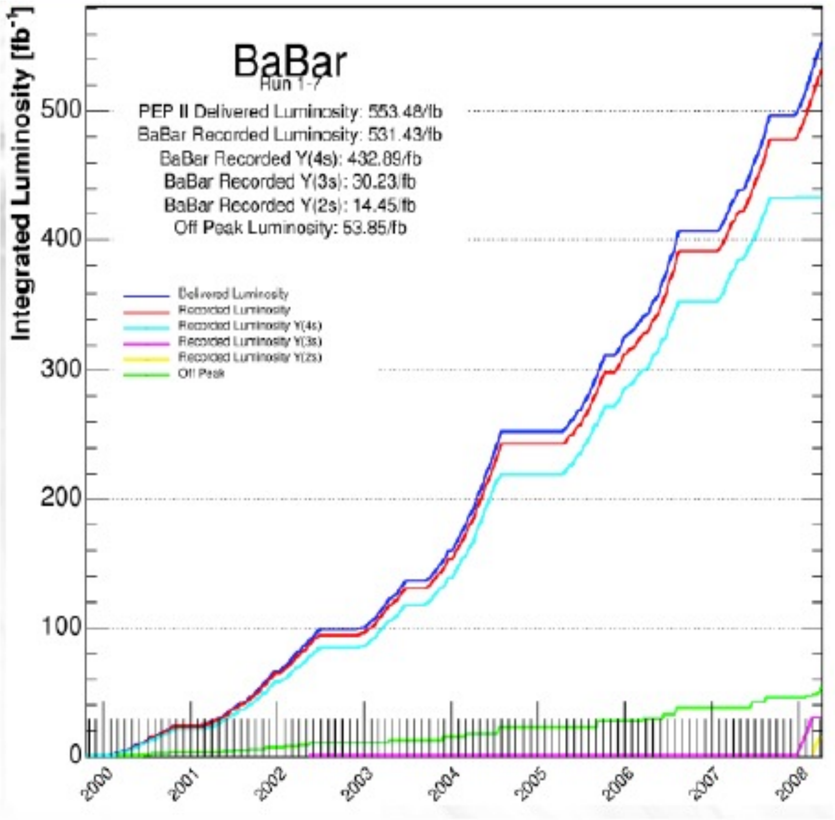
→ **$N_{\tau\tau}$ ~ 4 × 10^8 events**

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

The BABAR Experiment



- For overview of experiment: **Nucl. Instrum. Meth. A 729, 615 (2013)**.
- Asymmetric e^+e^- collider with $\sqrt{s}$ = 10.58 GeV/c^2 i.e. Υ(4S) resonance: 9 GeV electrons collide with 3 GeV positrons.
- **Total luminosity: 432 fb^{-1} (4.7 x 10^8 $\overline{B}B$) on peak.**



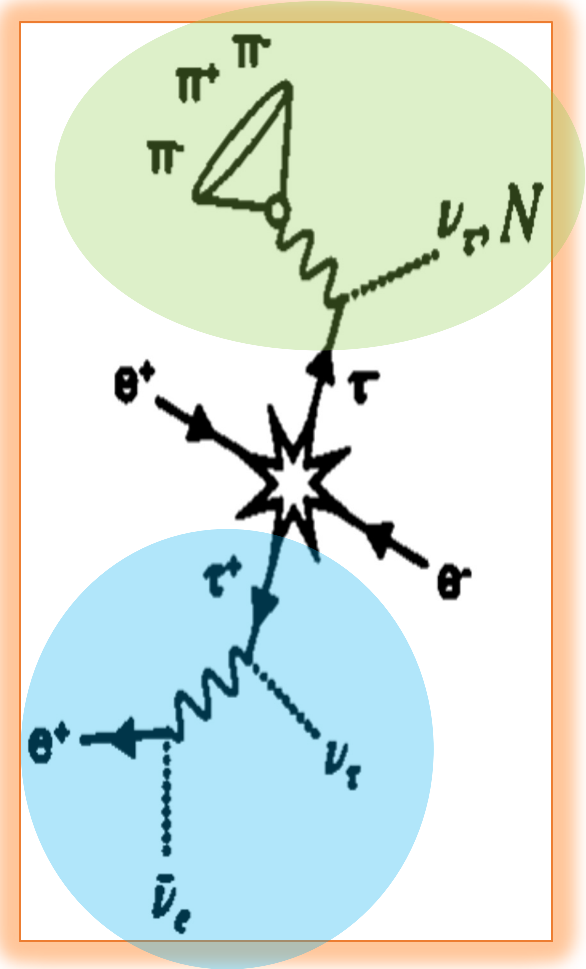
Detectors:

- **Reconstruct tracks:** Silicon Vertex Tracker (SVT) + 40-layer Drift Chamber (DCH), in 1.5-T solenoid.
  - Momentum resolution = 0.47% at 1 GeV/c
- **Measure energy:** Electromagnetic Calorimeter (EMC)
  - Energy resolution = 3% at 1 GeV.
- **PID:**
  - Identify charged pions, kaons and electrons using Ring Imaging Cherenkov detector (DIRC) + ionization loss measurements in the SVT and DCH.
  - Instrumented flux return of solenoid used to identify muons.

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 × 10^8 events

- ***BaBar*** 2022 analysis used the kinematics of hadronic tau decays based on previous technique (*Phys.Rev.D* 91 (2015) 5, 053006 Kobach and Dobbs).
- 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 $(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$ as it allows access to region $100 < m_4 < 1360$ MeV/c^2 where limits were loose.
  - "tag side" : Second tau decay must be leptonic, due to cleaner environment.



CPT assumed to hold, combining + and – signal sides.

Branching Fractions:
1-prong (electron or muon) ~ **34 %**
3-prong (3 pion) ~ **9%**

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Method

Templates for each mass in the form of 2D plots of E_h.v. m_h. Boundary of curved region in this plot characteristic of a massive neutrino.

SM Tau Decay | **BSM Tau Decay**

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

- Model 3-pronged decay as 2-body with outgoing HNL and hadronic system (h).
- Define E_h as reconstructed energy and m_h as the invariant mass of the visible, hadronic products.
- $E_\tau = \frac{E_{cms}}{2}$ in the limit of no ISR. The value of E_h and m_h can exist, in principle, in the ranges:

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

and

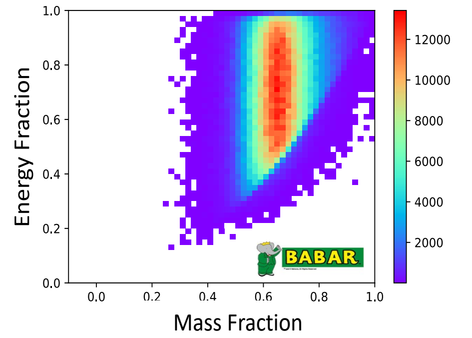
$$E_\tau - \sqrt{m_4^2 + q_+^2} < E_h < E_\tau - \sqrt{m_4^2 + q_-^2},$$

where

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

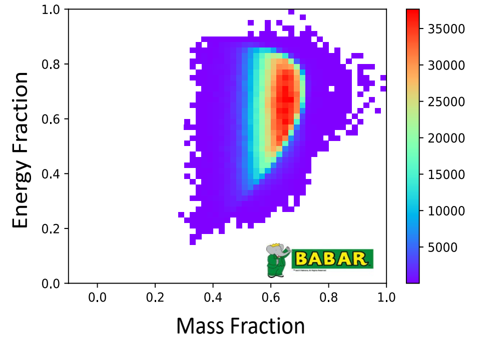
$m_4 = 100\ MeV/c^2$

BABAR-MC



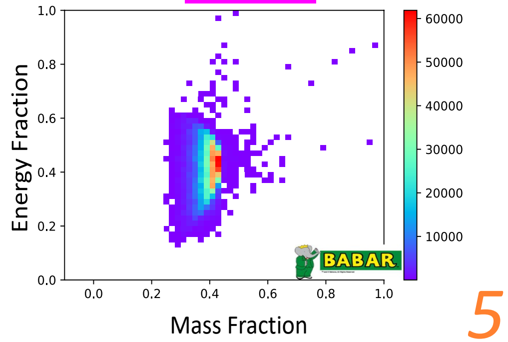
$m_4 = 500\ MeV/c^2$

BABAR-MC



$m_4 = 1000\ MeV/c^2$

BABAR-MC



Signal samples made in modified TAUOLA, and passed through G4 + BABAR reco. alg.

Background and Signal Simulations

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)

- 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 prong decay to 3 charged pions ($\tau^- \to \pi^-\pi^-\pi^+\upsilon_\tau$)
  2. Other SM tau decays accidentally tagged as (1)
  3. SM non-tau backgrounds:
     - $e^+e^- \to \Upsilon(4S) \to B^+B^-$ and $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$
     - $e^+e^- \to \bar{u}u, \bar{d}d, \bar{s}s$ and $e^+e^- \to \bar{c}c$
     - $e^+e^- \to \mu^+\mu^-(\gamma)$

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

Fit Model

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

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

Nuisance parameters

where:

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

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

Expected non-tau SM background events: $\hat{\nu}_{\text{BKG},ij} = n^{\text{reco}}_{BKG,ij} = n^{\text{reco}}_{\tau-\text{other},ij} + n^{\text{reco}}_{\text{non}-\tau,ij},$

Use Wilk's theorem to find limits: $q = -2\ln\left(\frac{\mathcal{L}_{H_0}(|U_{\tau 4}|^2_0; \hat{\hat{\theta}}_0, \text{data})}{\mathcal{L}_{H_1}(|\hat{U}_{\tau 4}|^2; \hat{\theta}, \text{data})}\right) = -2\ln(\Delta\mathcal{L}).$

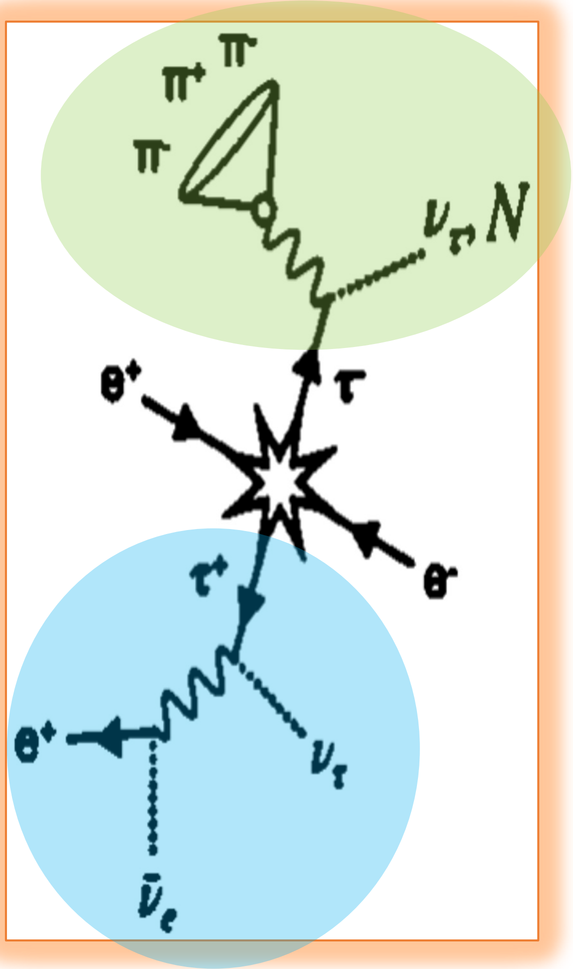
→ nuisance parameters maximized for a given value of $|U_{\tau 4}|^2$ i.e. it is the conditional maximum-likelihood. Includes background only case

→ maximized (unconditional) likelihood giving the MLE of $|U_{\tau 4}|^2$ a vector of nuisance parameters which maximize the likelihood.

Event Selection

- Selection optimized $\tau^{\pm} \rightarrow l^{\pm}v_{l}$ (tag) and $\tau^{\mp} \rightarrow \pi^{\mp}\pi^{\mp}\pi^{\pm}v_{4?}$ (3h)

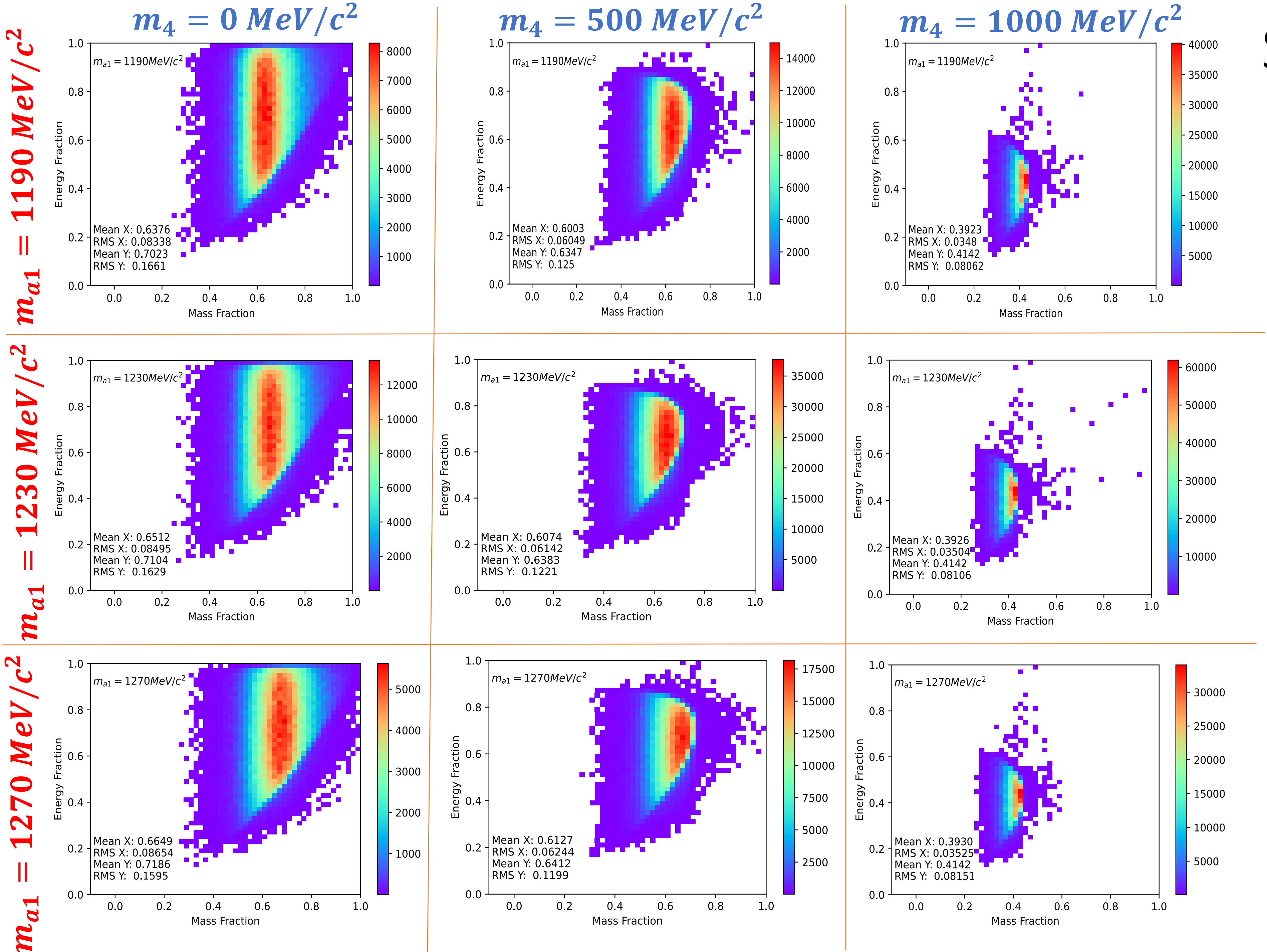
Cut	Purpose
Number of tracks	Ensure 1+3 prong topology
Total charge on all 4 charged tracks is 0	Charge conservation
$p_{CM}^{miss} > 0.9\% \sqrt{s}$	Suppresses non-tau backgrounds
All tracks: $p_{trans} > 250\text{MeV/c}$	To reach DIRC
All tracks: $-0.76 < \cos(\theta) < 0.9$	Acceptance of DIRC
1 prong: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



Normalization Uncertainties

- Normalization uncertainties affect 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

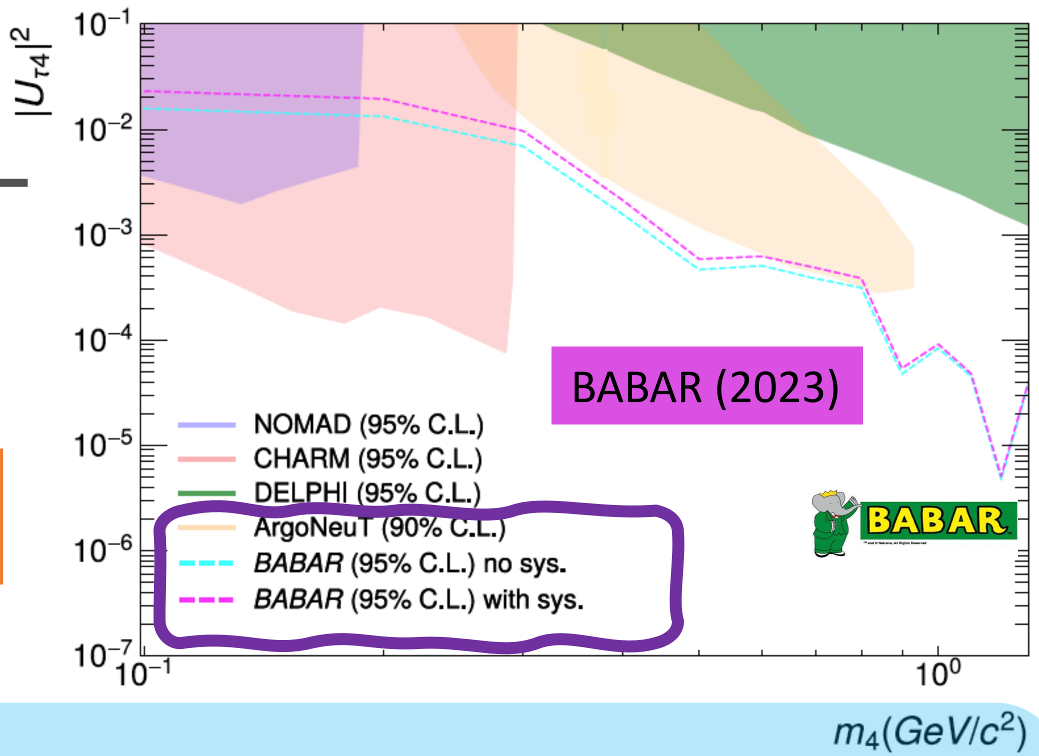
- $\tau^- \to \pi^-\pi^-\pi^+\upsilon_\tau$ is mediated by the a_1 resonance 97% of the time.
- **Dominant shape systematic in signal and tau backgrounds are from modelling of the hadronic tau decays in TAUOLA.**
- Experimental (PDG) uncertainties large:
  - $m_{a_1} = 1230 \pm 40$ MeV/c^2
  - $\Gamma_{a_1} = 420 \pm 35$ MeV/c^2 (we use PDG estimates 250 – 600 MeV/c^2)
- To account for this looked at templates with mass and width varied to these extremes and re-calculated the likelihood
- Γ_{a_1} error has largest effect:
  - Shift in RMS of $\sim 6-7\%$ in m_h and $\sim 1-3\%$ in E_h .
  - Shift in mean values for E_h and m_h shift by only $\sim 1-2\%$.

The BaBar Result

Mass [MeV]	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}	3.58×10^{-4}
900	4.70×10^{-5}	5.28×10^{-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}

At 95 % C.L

BABAR (2023):
Phys.Rev.D 107 5, 052009



- Binned likelihood fit incorporating nuisance parameters.
- Dominant systematic from modelling uncertainties in hadronic tau decays.
- Presents new upper limits on $|U_{\tau 4}|^2$ at 95 % *C.L.* between 100 MeV/c^2 – 1300 MeV/c^2 :
  - **World-leading constraints at time of acceptance for publication.**
- In 2021-2023 there have also been new results in this region from:
  - ArgoNEUT: Phys. Rev. Lett., 127, 121801 (shown)
  - Boiarska et al.: Phys. Rev. D 104, 095019 (indirect use of CHARM electron and muon result)
  - Barouki et al. : SciPost Phys., 13:118, 2022. (BEBC reanalysis)

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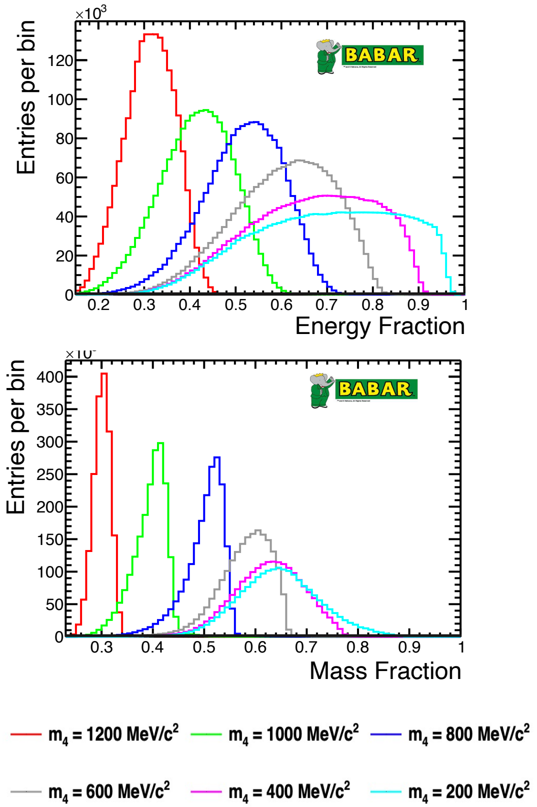
Summary

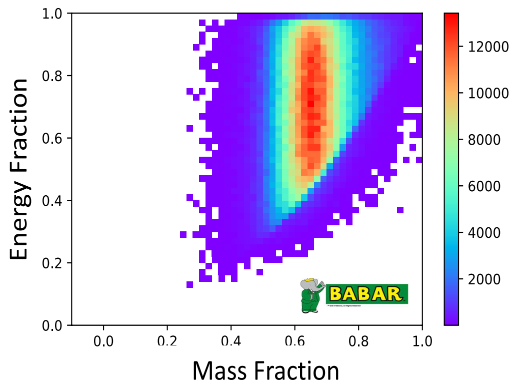
- Heavy Neutral Leptons offer ways of explaining several observational phenomena.
- The possible masses of the additional neutrino state is model dependent and can range from eV/c^2 up to very heavy masses.
- In the last few years, several new results have been published including results from collider-based experiments and neutrino experiments.
- Constraints in tau sector now comparable to those in the electron and muon sector.
- Many of these results are not from new experiments, they are in fact new studies using old data.
- This talk has given details on the latest 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 in the range $10^{-6} < |U_{\tau 4}|^2 < 10^{-2}$.

Example Signal Simulations

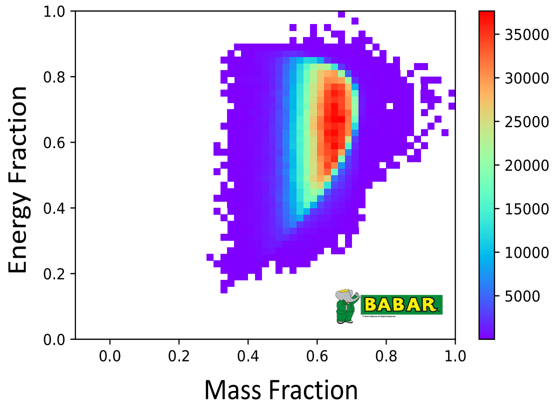
largest sensitivity for large masses



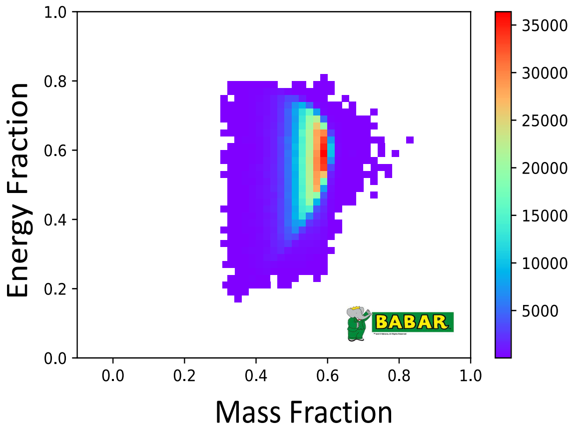
$m_4 = 100\ MeV/c^2$



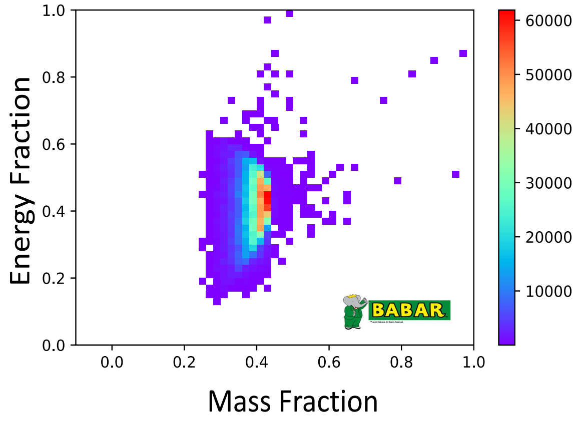
$m_4 = 500\ MeV/c^2$



$m_4 = 700\ MeV/c^2$



$m_4 = 1000\ MeV/c^2$



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

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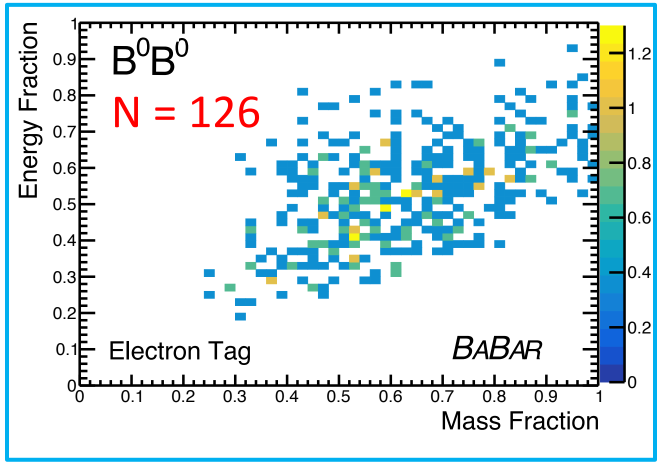
Example 2D Plots

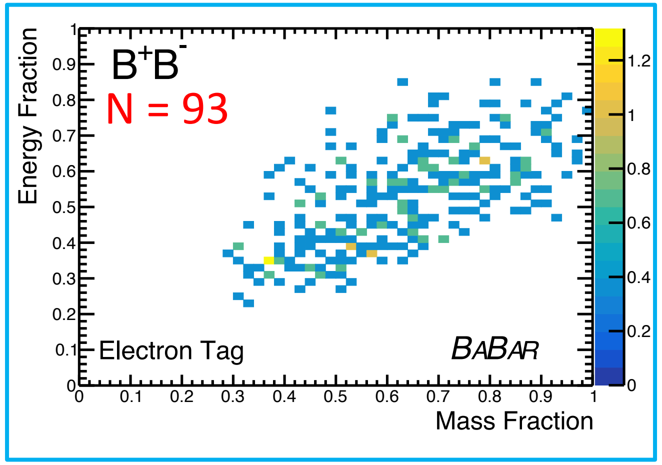
Data Total = 1273291
MC Total = 1283654

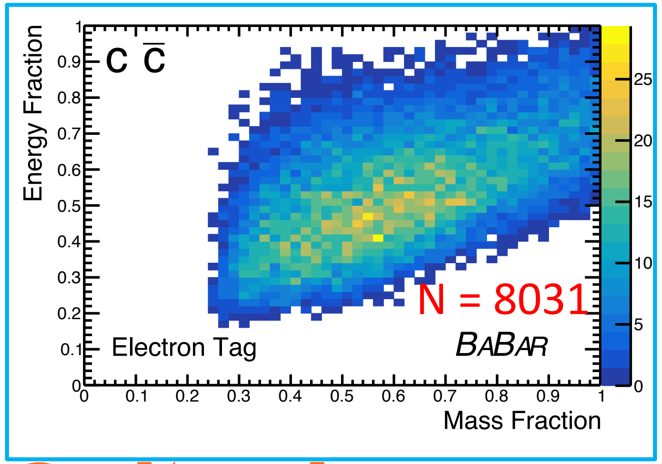
$\tau^+ \rightarrow e\bar{\nu}_e$ **(tag)**

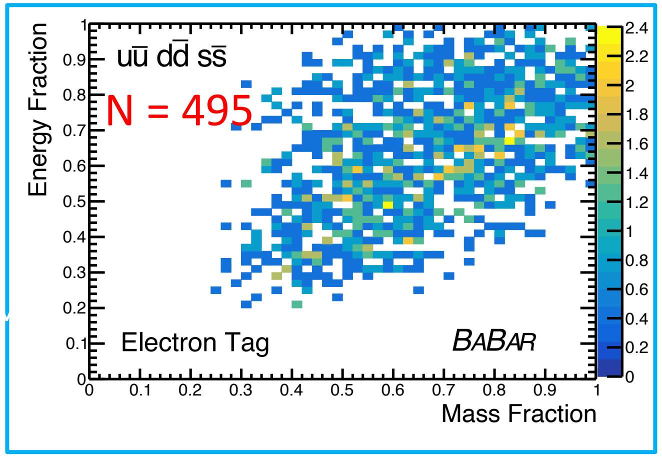
$\tau^- \rightarrow \pi^-\pi^-\pi^+ + HNL$ **(sig)**

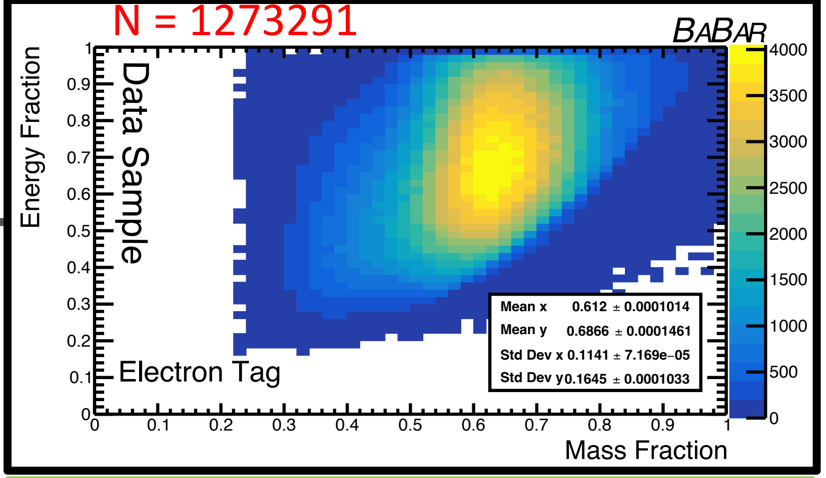
Non-tau Backgrounds











SM-tau Backgrounds