

# Upper limits on branching ratios of $\tau \rightarrow \ell \gamma \gamma$ and $\tau \rightarrow \ell X$ decays

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# Introduction —Lepton Flavor Violation—

- Neutrino oscillations show lepton flavor is not strictly conserved (Super-K, Phys. Rev. Lett. 81, 1562 (1998)).
- Charged lepton flavor violation (CLFV) effects in the SM are too small to be observed (e.g.  $Br(\mu^+ \rightarrow e^+\gamma) \approx 10^{-54}$  ).  
→ **Searches for CLFV are a probe of new physics.**
- Many decay modes (e.g.  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow e\gamma\gamma$ ,  $\mu \rightarrow ee\bar{e}$ ,  $\tau \rightarrow \ell\gamma$ ) have been sought, but none observed.
- No experimental limit has been set on  $\tau \rightarrow e\gamma\gamma$  or  $\tau \rightarrow \mu\gamma\gamma$  decays.  
→ Here we used published BABAR data on  $\tau \rightarrow \ell\gamma$  to set limits on  $\tau \rightarrow \ell\gamma\gamma$

Summary of CLFV tau decay.

$Br(\text{decay})$ upper limit
$Br(\tau \rightarrow e\gamma) < 3.3 \times 10^{-8}$
$Br(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$
$Br(\tau \rightarrow ee\bar{e}) < 2.7 \times 10^{-8}$
$Br(\tau \rightarrow e\mu\bar{\mu}) < 1.7 \times 10^{-8}$
$Br(\tau \rightarrow \mu e\bar{e}) < 1.5 \times 10^{-8}$
$Br(\tau \rightarrow \mu\mu\bar{\mu}) < 2.1 \times 10^{-8}$
$Br(\tau \rightarrow e\pi^0) < 0.80 \times 10^{-7}$
$Br(\tau \rightarrow \mu\pi^0) < 1.1 \times 10^{-7}$

# Other CLFV Process Involving $X$

- Weakly interacting new bosons  $X$  (e.g. axions, familons) have been suggested to extend the SM.
- Searches for CLFV processes involving  $X$ .
  - $\mu^+ \rightarrow e^+ X$  :  $Br(\mu \rightarrow eX) < 10^{-5}$  in  $47.8 < m_X < 95.1 \text{ MeV}/c^2$  (PIENU)  
 $Br(\mu \rightarrow eX) < 10^{-5} \sim 10^{-6}$  in  $3.2 < m_X < 86.6 \text{ MeV}/c^2$  (TWIST)  
Phys. Rev. D 101, 052014 (2020) Phys. Rev. D 91,052020 (2015)
  - $\pi^+ \rightarrow \ell^+ \nu X$  :  $Br(\pi \rightarrow e\nu X) < 10^{-7} \sim 10^{-8}$  in  $0 < m_X < 120 \text{ MeV}/c^2$  and  
 $Br(\pi \rightarrow \mu\nu X) < 10^{-5} \sim 10^{-6}$  in  $0 < m_X < 34 \text{ MeV}/c^2$  (PIENU)  
Phys. Rev. D 103, 052006 (2021)
  - $\tau^+ \rightarrow \ell^+ X$  :  $Br(\tau \rightarrow \ell X) < 10^{-2}$  in  $m_X < 1.6 \text{ GeV}/c^2$  (ARGUS)  
Zeit. f. Phys. C 68, 25 (1995)
- Here we improved on the limits for  $\tau^+ \rightarrow \ell^+ X$  decays.

# $\tau \rightarrow \ell \gamma \gamma$ Decay

- The decay rate of  $\mu \rightarrow e \gamma \gamma$  was originally calculated by Dreitlein and Primakoff, Phys. Rev. 126, 375 (1962).
- Bowman et al. (Phys. Rev. Lett. 41, 442 (1978).) updated this decay rate and set the limit using two experimental data (Phys. Rev. Lett. 39, 1113 (1977), Phys. Lett B 72, 183 (1977).)  
 $\Rightarrow Br(\mu \rightarrow e \gamma \gamma) < 5 \times 10^{-8}$ .
- The most recent result by Crystal Box:  $Br(\mu \rightarrow e \gamma \gamma) < 7.2 \times 10^{-11}$   
 Phys. Rev. D 38, 2077 (1988).

- The differential decay rate for  $\tau \rightarrow \ell \gamma \gamma$  ( $\ell = e, \mu$ ) is

$$\frac{d\Gamma_{\tau \rightarrow \ell \gamma \gamma}}{dE_{\gamma_1} dE_{\gamma_2} d\cos\theta_{\gamma\gamma}} \propto \left( \frac{\sum_{\mathcal{O}} |\bar{c}_{\mathcal{O}}|^2}{\Lambda_{\tau \ell \gamma \gamma}^6} \right) E_{\ell} (E_{\gamma_1} E_{\gamma_2})^2 (1 - \cos\theta_{\gamma\gamma})^2$$

$E_{\ell}, E_{\gamma_{1,2}}$  : energy of lepton and photons

$\theta_{\gamma\gamma}$  : angle between two photons

# Search for $\tau \rightarrow \ell \gamma$ at BABAR

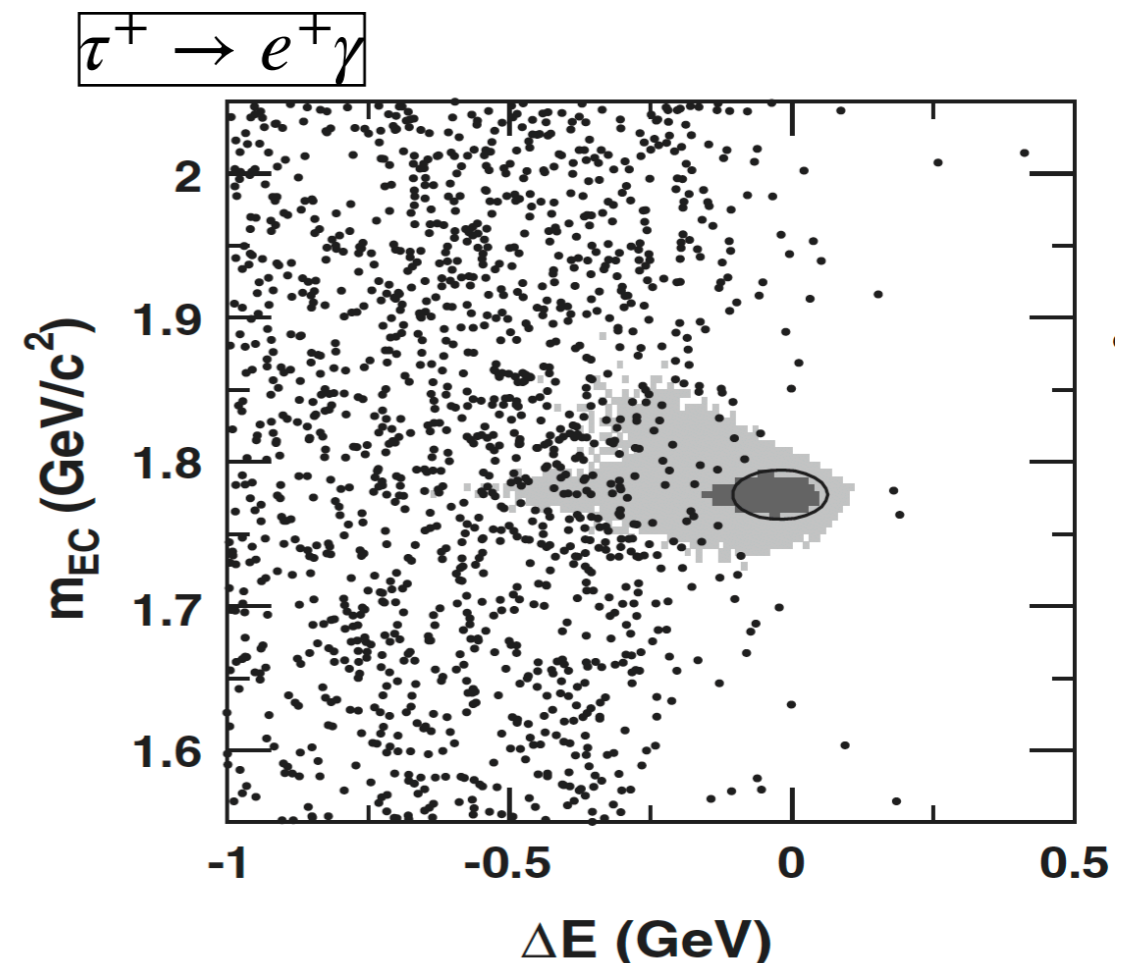
- The BABAR experiment searched for  $\tau \rightarrow \ell \gamma$  decays.

$$\Rightarrow Br(\tau^+ \rightarrow e^+ \gamma) < 3.3 \times 10^{-8}, Br(\tau^+ \rightarrow \mu^+ \gamma) < 4.4 \times 10^{-8}$$

Phys. Rev. Lett. 104, 021802 (2010)

- Signals were identified by two variables,  $\Delta E = E_{\ell\gamma}^{c.m.} - \sqrt{s}/2$  and beam energy constrained mass ( $m_{EC} = \sqrt{E_{\text{beam}}^2 - p_{\ell\gamma}^2} \approx m_\tau$ ).
- Single charged track and photon were required.

- Ellipse: signal region.
- Light (dark) shaded region: 90% (50%) of signal by MC.
- Black dots: data
- BG:  $e^+e^- \rightarrow \ell^+\ell^-\gamma$



# $\tau \rightarrow \ell \gamma \gamma$ Limits Using BABAR Data

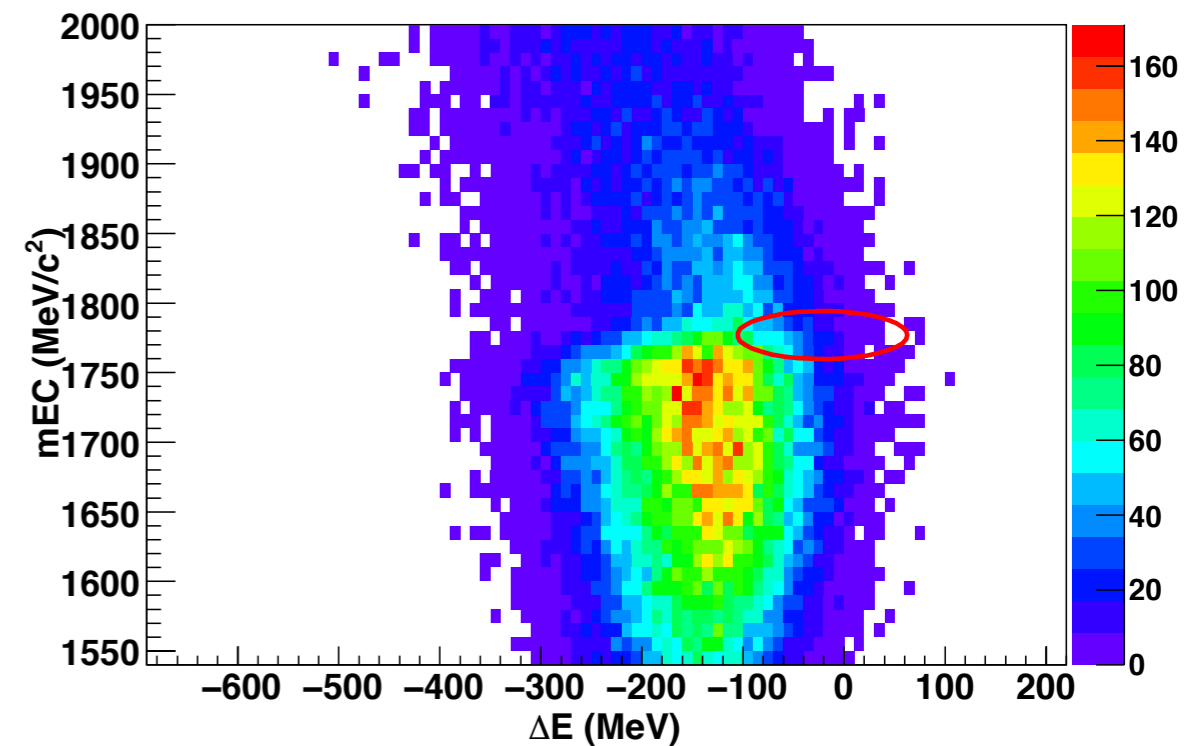
- MC simulation of  $\tau \rightarrow \ell \gamma \gamma$  decays with the calculated angular distribution was performed.
- The same cuts as for  $\tau \rightarrow \ell \gamma$  in BABAR were applied.
  - The resolutions were included.
  - Detector acceptance was considered (NIMA 479 (2002) 1-116)
    - One  $\gamma$  inside and other  $\gamma$  outside the acceptance

$$Br(\tau \rightarrow e \gamma \gamma) < \frac{Br^{\text{BABAR}}(\tau \rightarrow e \gamma) \times \epsilon_{e\gamma}}{\epsilon_{e\gamma\gamma}} = 2.5 \times 10^{-4}$$

$$Br(\tau \rightarrow \mu \gamma \gamma) < \frac{Br^{\text{BABAR}}(\tau \rightarrow \mu \gamma) \times \epsilon_{\mu\gamma}}{\epsilon_{\mu\gamma\gamma}} = 5.8 \times 10^{-4} \quad (90\% \text{ C.L.})$$

$Br^{\text{BABAR}}$  : BABAR's results

$\epsilon_{\ell\gamma}, \epsilon_{\ell\gamma\gamma}$  : Signal efficiency in MC



D. Bryman, S. Ito, R. Shrock, [arXiv:2106.02451](https://arxiv.org/abs/2106.02451)

# Improved Limits on $\tau^+ \rightarrow \ell^+ X$ Decays

- The limits on  $\tau^+ \rightarrow \ell^+ X$  decays were examined using the experimental and the SM branching ratios  $\tau \rightarrow \nu_\tau \ell \bar{\nu}_\ell$
- The averaged values in PDG are

$$Br(\tau \rightarrow \nu_\tau e \bar{\nu}_e) = 0.1782 \pm 0.0004$$

$$Br(\tau \rightarrow \nu_\tau \mu \bar{\nu}_\mu) = 0.1739 \pm 0.0004$$

- The ratios of the experiment to the SM calculation are

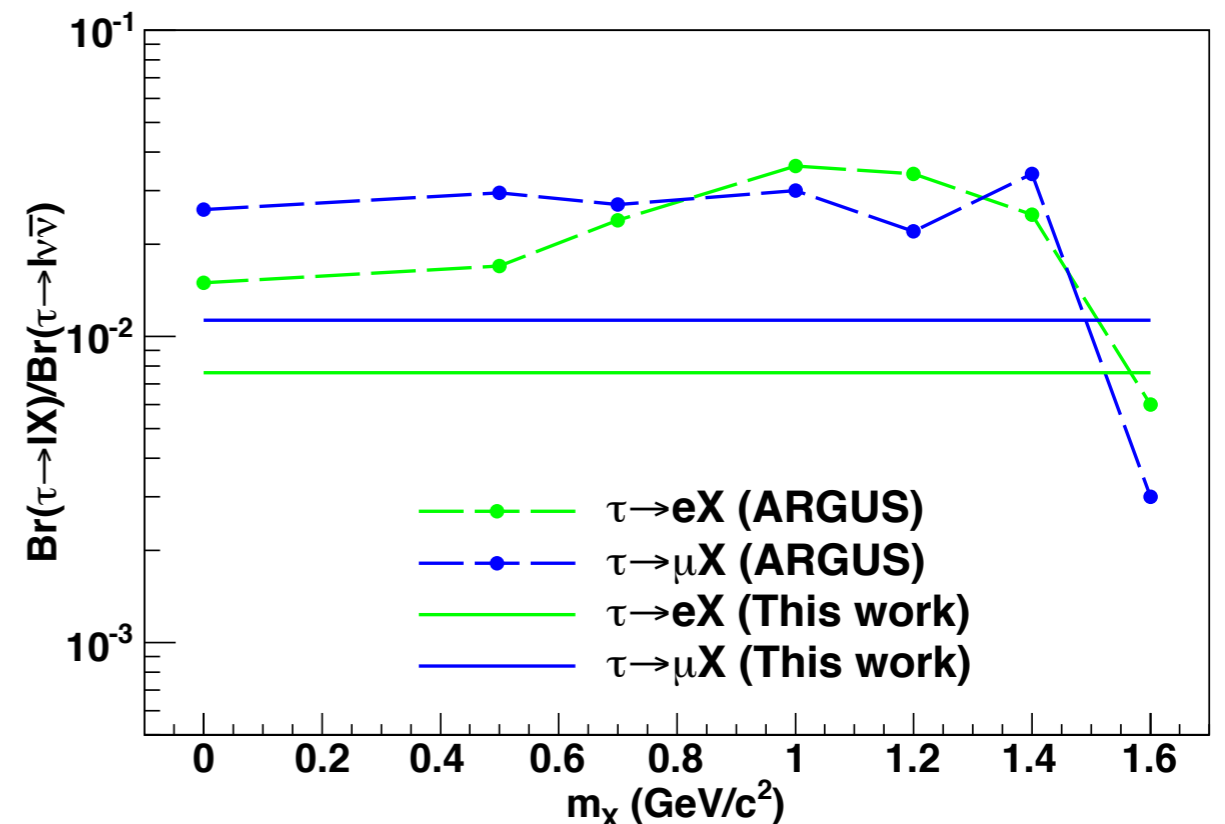
$$R_{\tau \rightarrow e} = 1.0022 \pm 0.0028 < 1.008$$

$$\Rightarrow \frac{Br(\tau \rightarrow eX)}{Br(\tau \rightarrow \nu_\tau e \bar{\nu}_e)} < 0.008 \text{ (95 \% C.L.)}$$

$$R_{\tau \rightarrow \mu} = 1.0056 \pm 0.0029 < 1.011$$

$$\Rightarrow \frac{Br(\tau \rightarrow \mu X)}{Br(\tau \rightarrow \nu_\tau \mu \bar{\nu}_\mu)} < 0.011 \text{ (95 \% C.L.)}$$

[arXiv:2106.02451](https://arxiv.org/abs/2106.02451)



# Summary

- First limits were obtained on  $\tau \rightarrow e\gamma\gamma$  and  $\tau \rightarrow \mu\gamma\gamma$  using the published BABAR data.
- Improved limits on  $\tau \rightarrow eX$  and  $\tau \rightarrow \mu X$  were obtained.
- ➔ Details of these studies can be seen in [arXiv:2106.02451](https://arxiv.org/abs/2106.02451)
- Belle-II will accumulate data  $50 \text{ ab}^{-1}$ , which corresponds to about 50 times larger statistics than Belle/BABAR.
- ➔ These decays can be sought with much higher sensitivity.

Thank you for your attention!!!

# Back Up

# The Differential Decay Rate

$$\frac{d\Gamma_{\tau \rightarrow \ell \gamma \gamma}}{dE_{\gamma_1} dE_{\gamma_2} d\cos\theta_{\gamma\gamma}} \propto \left( \frac{\sum_{\mathcal{O}} |\bar{c}_{\mathcal{O}}|^2}{\Lambda_{\tau\ell\gamma\gamma}^6} \right) E_{\ell} (E_{\gamma_1} E_{\gamma_2})^2 (1 - \cos\theta_{\gamma\gamma})^2 ,$$

where

$$\sum_{\mathcal{O}} |\bar{c}_{\mathcal{O}}|^2 = |\bar{c}_{\tau\ell\gamma\gamma,LR;FF}|^2 + |\bar{c}_{\tau\ell\gamma\gamma,RL;FF}|^2 + |\bar{c}_{\tau\ell\gamma\gamma,LR;F\tilde{F}}|^2 + |\bar{c}_{\tau\ell\gamma\gamma,RL;F\tilde{F}}|^2$$

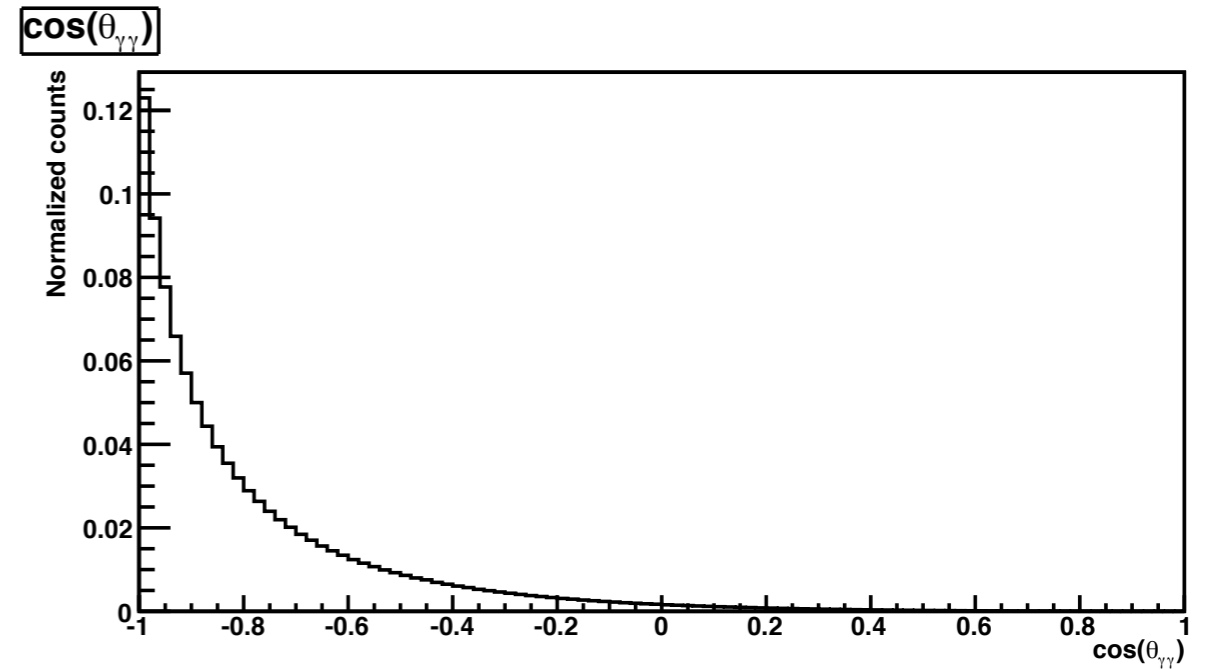
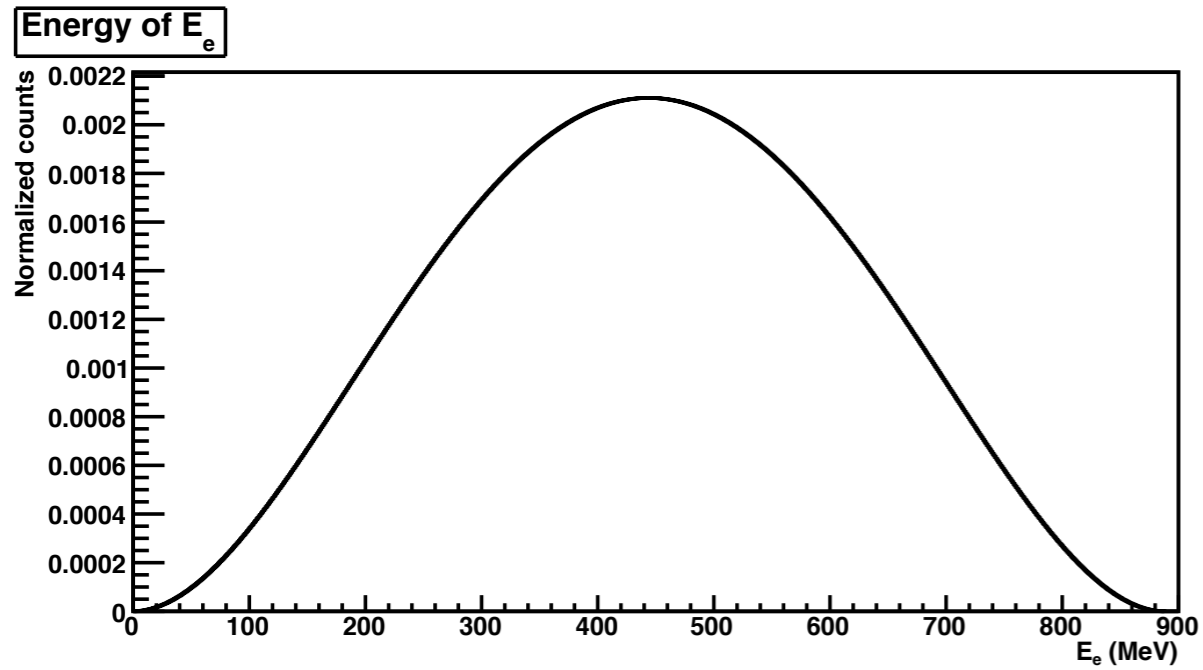
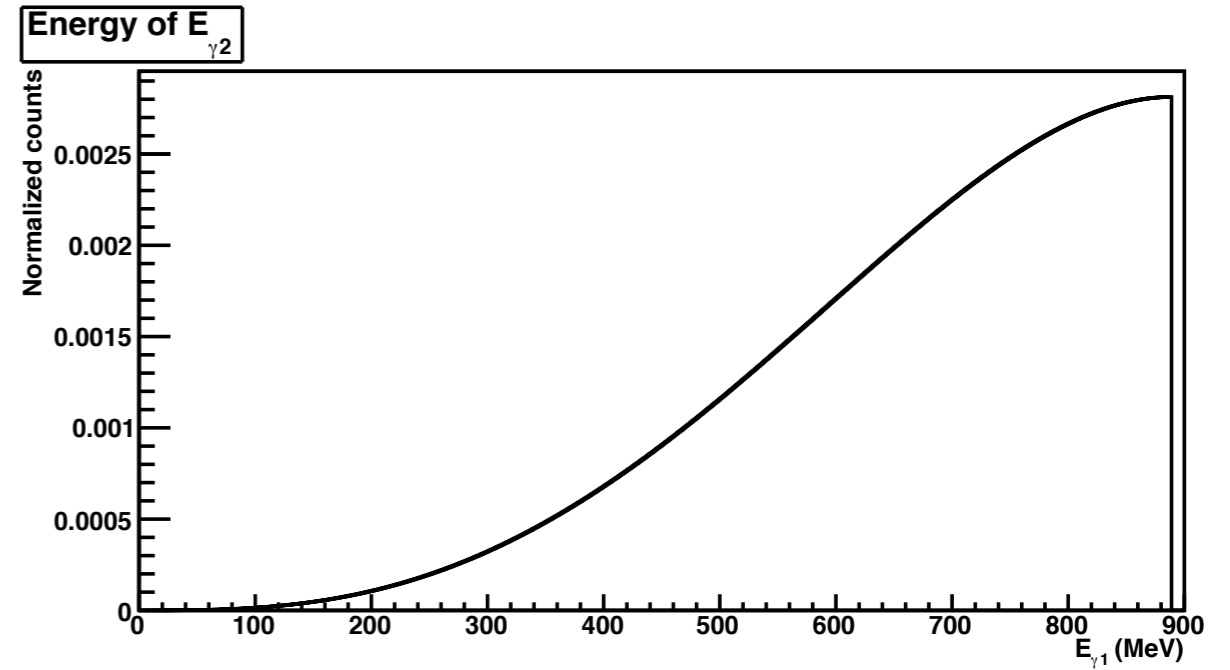
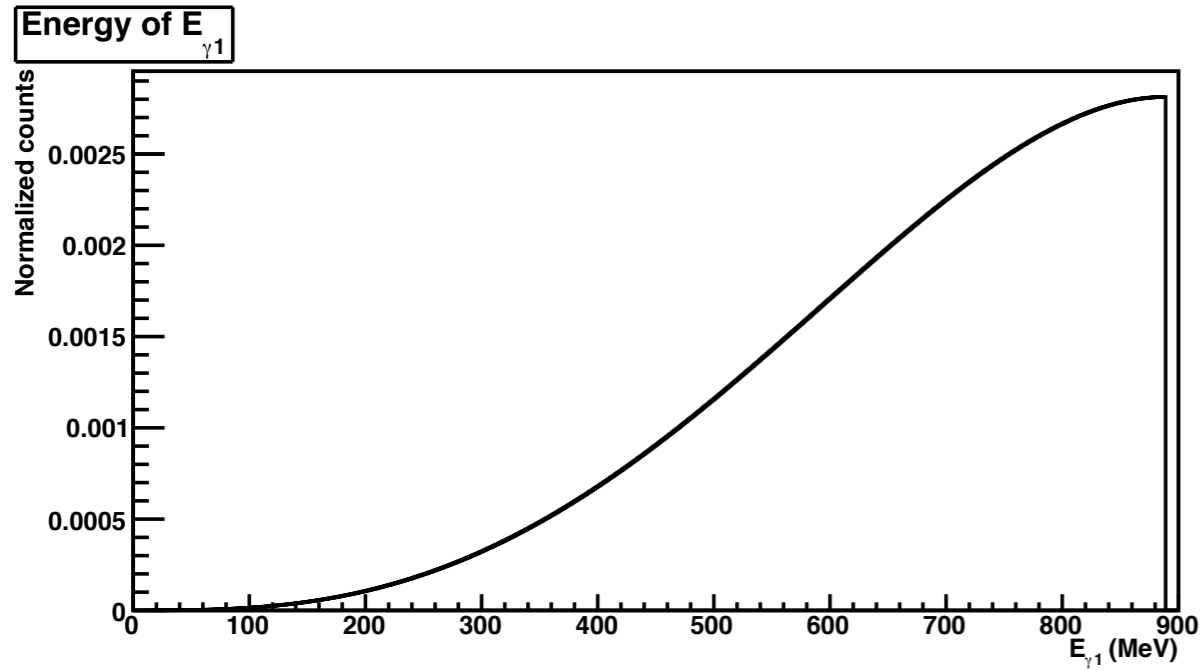
$$\begin{aligned} \mathcal{L}_{eff,\tau\ell\gamma\gamma} = & c_{\tau\ell\gamma\gamma,LR;FF} [\bar{\ell}_L \tau_R] F_{\alpha\beta} F^{\alpha\beta} + c_{\tau\ell\gamma\gamma,RL;FF} [\bar{\ell}_R \tau_L] F_{\alpha\beta} F^{\alpha\beta} + c_{\tau\ell\gamma\gamma,LR;F\tilde{F}} [\bar{\ell}_L \tau_R] F_{\alpha\beta} \tilde{F}^{\alpha\beta} \\ & + c_{\tau\ell\gamma\gamma,RL;F\tilde{F}} [\bar{\ell}_R \tau_L] F_{\alpha\beta} \tilde{F}^{\alpha\beta} + h.c. , \end{aligned}$$

$E_{\ell}, E_{\gamma_{1,2}}$  : energy of lepton and photons

$\theta_{\gamma\gamma}$  : angle between two photons

$\Lambda_{\tau\ell\gamma\gamma}$  : effective mass scale

# Calculated Energy and Cosine Distributions



# BABAR

- C.M. energy:  $\sqrt{s} = 10.58 \text{ GeV}$
- Silicon vertex tracker (SVT) and drift chamber (DC).
- Electromagnetic calorimeter (EMC): CsI(Tl)
- Cherenkov detector: charged kaons and pions
- Instrumented flux return barrel: muon

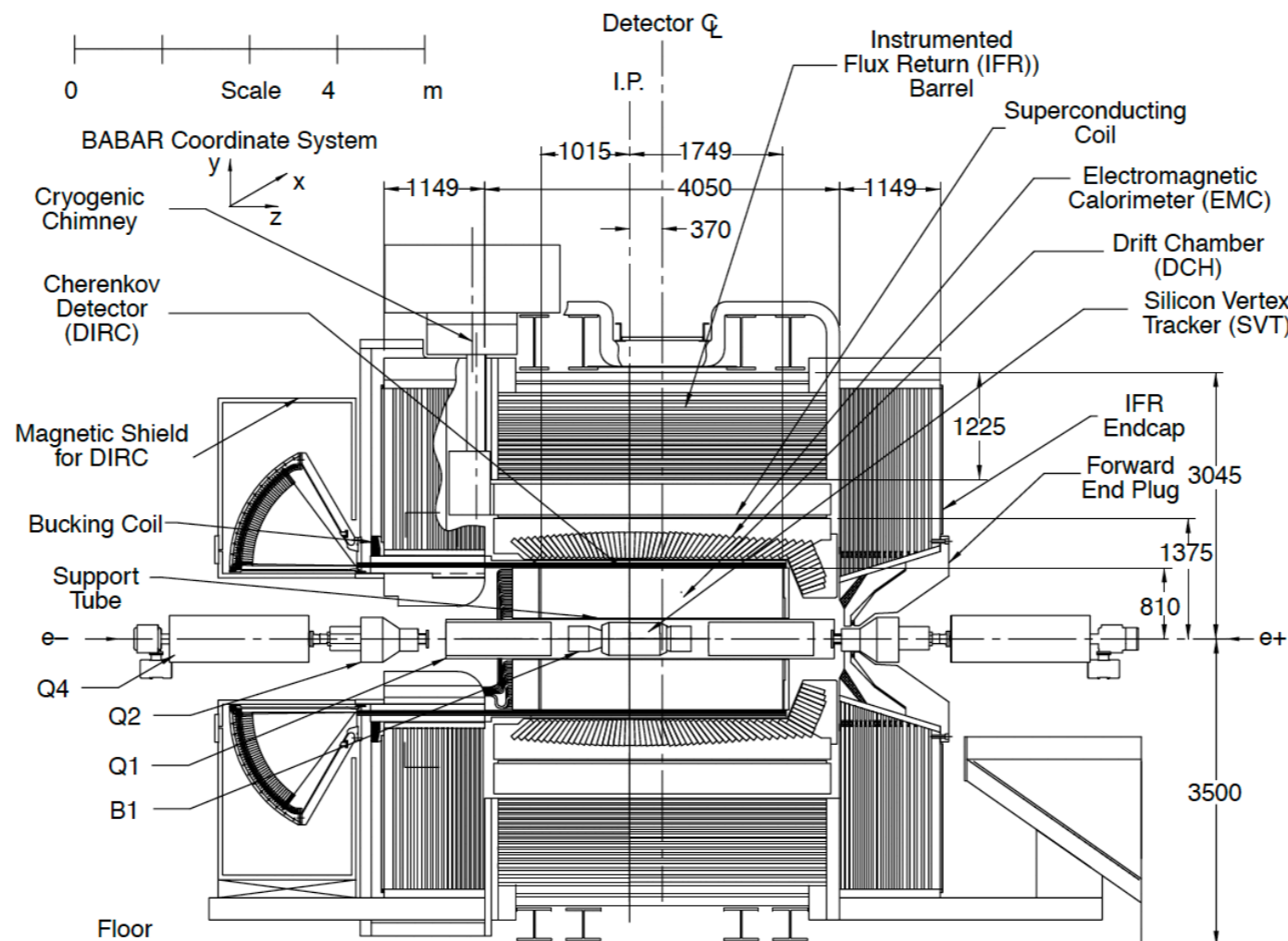


Fig. 1. BABAR detector longitudinal section.

(NIMA 479 (2002) 1-116)