The 13th International Workshop on Tau Lepton Physics
Aachen, Germany, 15-19 September, 2014

# *Measurement of*
# *$BF(\tau \rightarrow \ell \, \bar{\nu}_l \, \nu_\tau \, \gamma \; (\ell = e, \mu))$ at BaBar*

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*on behalf of the BaBar collaboration*

TAU2014, Aachen, Germany
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# Motivation

- *At present only measurement for* $\tau \to e\bar{\nu}\nu\gamma$ *and most precise for* $\tau \to \mu\bar{\nu}\nu\gamma$ *by CLEO with 4.68* $fb^{-1}$ *(for* $E^*_{\gamma,\,min}$ = 10 MeV)

$BF(\tau \to \mu\nu\nu\gamma)\ (E^*_{\gamma,\,min}$ 10 MeV) = $(3.61 \pm 0.16 \pm 0.35) \times 10^{-3}$
$BF(\tau \to e\nu\nu\gamma)\ (E^*_{\gamma,\,min}$ 10 MeV) = $(1.75 \pm 0.06 \pm 0.17) \times 10^{-2}$

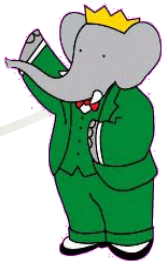
**CLEO 2000**
PRL84, 830, 2000

- *Radiative tau decays are especially sensitive to the Lorentz structure of* $\tau$ *the decay vertex*

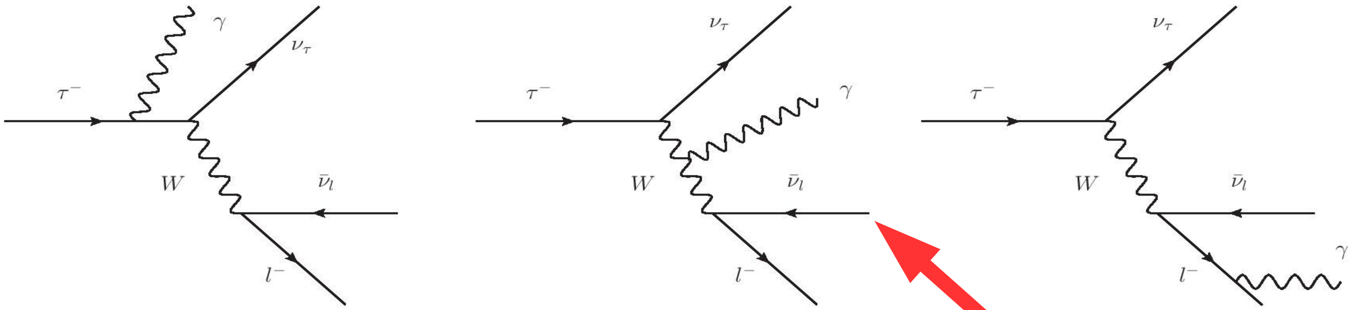
**M.L. Laursen,et al. Phys. Rev. D29 (1984)**
**Passera et al. : arXiv:1301.5302v1 (2013)**

- *Growing interest in the theoretical community to extract* $\tau$ *properties from* $\tau \to l\bar{\nu}\nu\gamma$ *at (future) B-factories (see M.Fael's talk later today)*

- *Opportunity for a test of EW interactions* <u>*at loop level*</u> *in* $\tau$ *decays*



# $\tau \to \ell\, \bar{\nu}_l\, \nu_\tau\, \gamma$ ($\ell$ = e, μ) in SM




**Suppressed by $(m_\tau/M_W)^2$**

- *SM prediction (eff. Lagrangian + W corr.):*

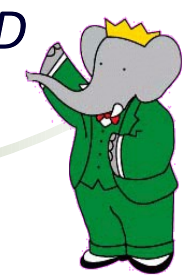
$BF(\tau \to \mu\bar{\nu}\nu\gamma)(E^*_{\gamma,\,min} = 10\ \text{MeV})$: $3.67 \times 10^{-3}$

$BF(\tau \to e\bar{\nu}\nu\gamma)(E^*_{\gamma,\,min} = 10\ \text{MeV})$: $1.84 \times 10^{-2}$

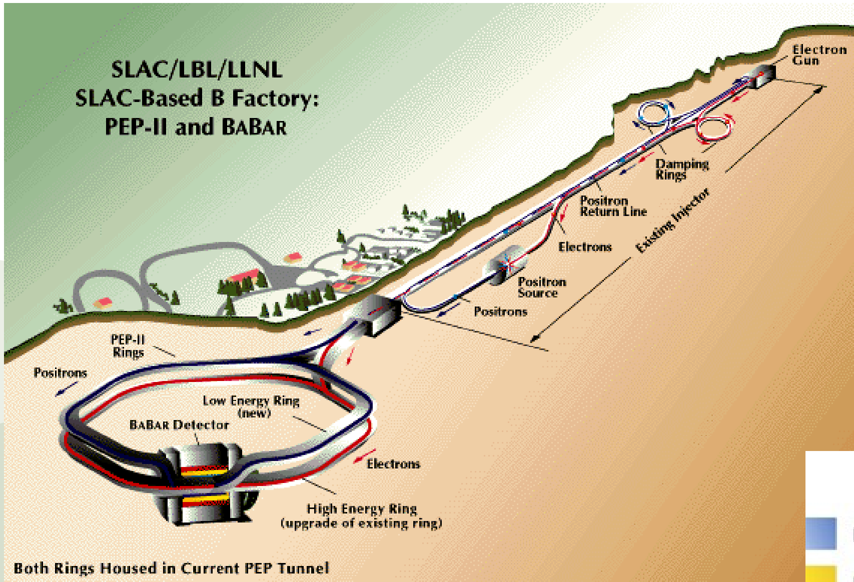
**Passera et al. : arXiv:1310.1081v2 (2013)**

$$\frac{d^3\Gamma^0}{dx\,dc\,dy} = \frac{\alpha G_F^2 M^5}{(4\pi)^6} \frac{8\pi^2\, x\beta}{1+\delta_W(m_\mu, m_e)}\, G_0(x,y,c).$$

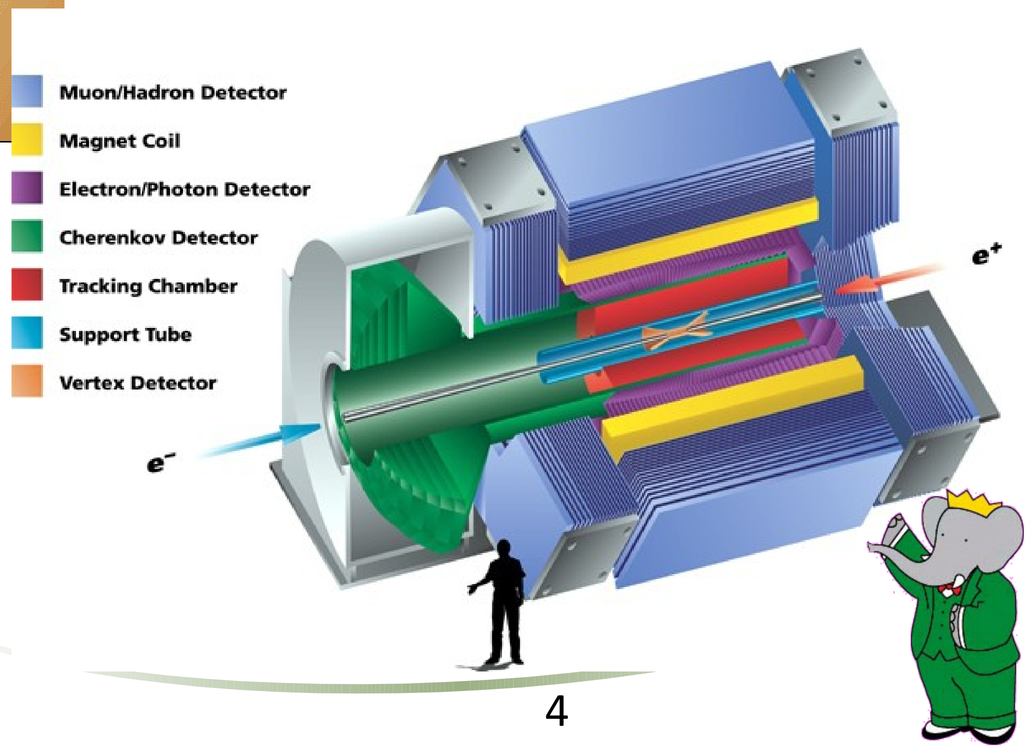
- *Weak correction contribution negligible up to NNLO ($BF(W)/BF < 10^{-4}$)*
- *At present no published value for $BF(\tau \to l\bar{\nu}\nu\gamma)$ at NLO: effect of QED radiative corrections (virtual + 2nd real soft photon) expected to be $O(10^{-2})$ → this precision is at the reach at BaBar*



# The BABAR experiment at SLAC




- *BaBar at PEP-II asymmetric $e^+$-$e^-$ collider at Stanford Linear Accelerator Center*
- *Operated (mainly) at Υ(4s) CM energy*
- *≈500 $fb^{-1}$ of $e^+$-$e^-$ collisions recorded from 1999 to 2008*



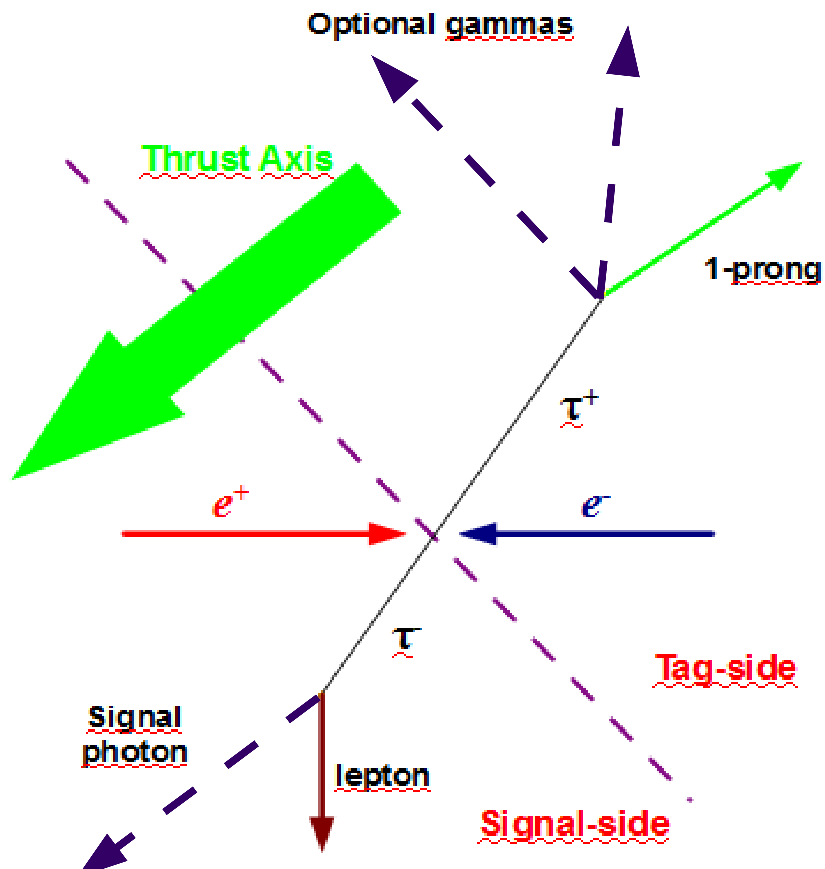

- *Tracking: 40 layer drift chamber + 5 layer silicon vertex detector*
- *PID: π/K separation using dE/dx + quartz Ring Imaging Cherenkov*
- *Cs(Tl) calorimeter for γ and e*
- *1.5 T superconducting solenoid*
- *Muon detectors in the field return*

# $\tau \to \ell \bar{\nu}_l \nu_\tau \gamma$ ($\ell = e, \mu$) at BaBar

- *τ pair production rate comparable to B pair production*
- *→ total sample of 430 million τ pairs (σ=0.919 nb)*
- *Event is divided in 2 hemispheres by the Thrust axis: Tag Side & Signal Side*
- *Kinematics and event shape reject most Bhabha, di-muon and γγ events*

| Signal | Tag |
|---|---|
| $\tau \to e\nu\nu\gamma$ | $\mu\nu\nu$ |
| | $\pi\nu$ |
| | $\pi\pi^0\nu$ |
| | $\pi\pi^0\pi^0\nu$ |
| $\tau \to \mu\nu\nu\gamma$ | |
| | $e\nu\nu$ |
| | $\pi\nu$ |
| **1-1 Topology** | $\pi\pi^0\nu$ |
| | $\pi\pi^0\pi^0\nu$ |

**No e-e, μ-μ final states used in orde to reduce QED bkg**



# *Data & MC Samples*

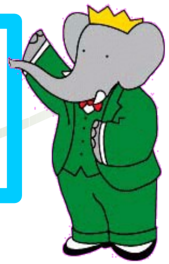
- *MC used for efficiency calculation and background evaluation*
- *Data: full BaBar Υ(4s) OnPeak sample (431 $fb^{-1}$)*
- *Signal MC is obtained from Kk2f+Tauola+PHOTOS package filtering leptonic decays with at least one photon emitted in decay*

| | KK2f (E*>10 MeV) | KORALB** (E*>10 MeV) |
|---|---|---|
| $BF(\tau \to e\nu\bar{\nu}\gamma)$ | (1.843±0.002)% | (1.86±0.01)% |
| $BF(\tau \to \mu\nu\bar{\nu}\gamma)$ | (0.3686±0.0009)% | (0.368±0.002)% |

** CLEO Coll. PRL84, 830, 2000

- $\tau \to e\nu\bar{\nu}\gamma$: *25M events*
- $\tau \to \mu\nu\bar{\nu}\gamma$: *5M events*
- *Background samples include: generic (non-signal) $\tau\bar{\tau}$, uds, $c\bar{c}$, $B\bar{B}$ ($B=B^+$, $B^0$), $\mu\bar{\mu}$ and Bhabha (from data)*

| | $\tau\bar{\tau}$ | $\mu\bar{\mu}$ | *uds* | $c\bar{c}$ | $B\bar{B}$ | *Bhabha** | DATA |
|---|---|---|---|---|---|---|---|
| $fb^{-1}$ | 742.63 | 441.83 | 777.69 | 868.11 | 1358.81 | 431.07 | 431.07 |

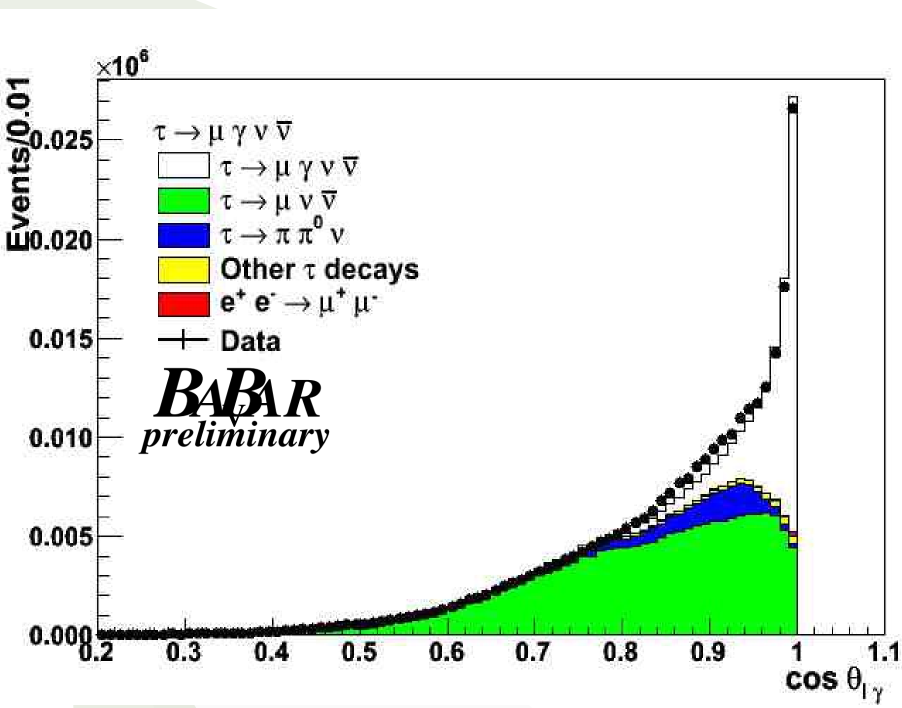


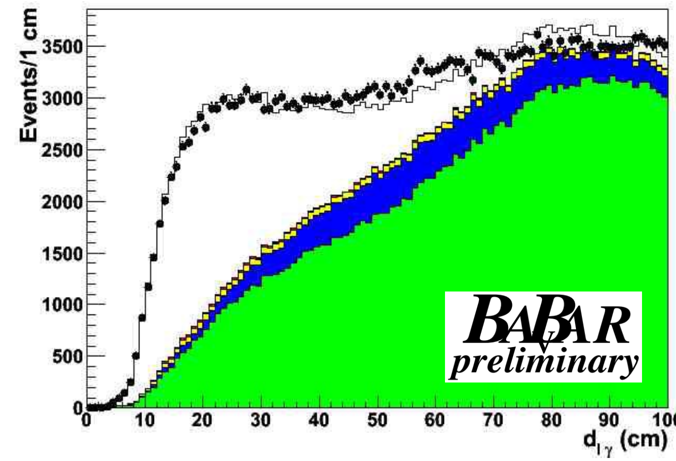


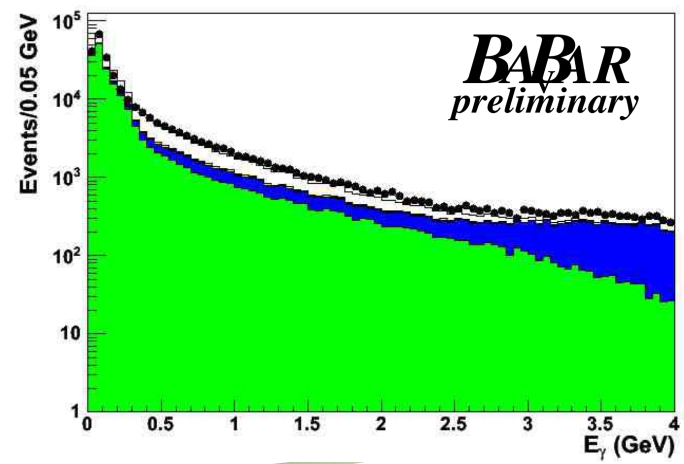
*pre-scaled

# Signal extraction $\tau \rightarrow \mu\bar{\nu}\nu\gamma$

- *Most important bkg: $\tau \rightarrow \mu\nu\bar{\nu}$ + photon from ISR, detector bkg*
- *Sizeable contribution from $\tau \rightarrow \pi\pi^0\nu$*
- *Small contribution by μμ and other τ decays*
- *Use $\cos\theta_{l\gamma,CM,MIN}$, $d_{l\gamma,EMC}$, $M_{l\gamma,MAX}$, $E_{\gamma,CM}$*

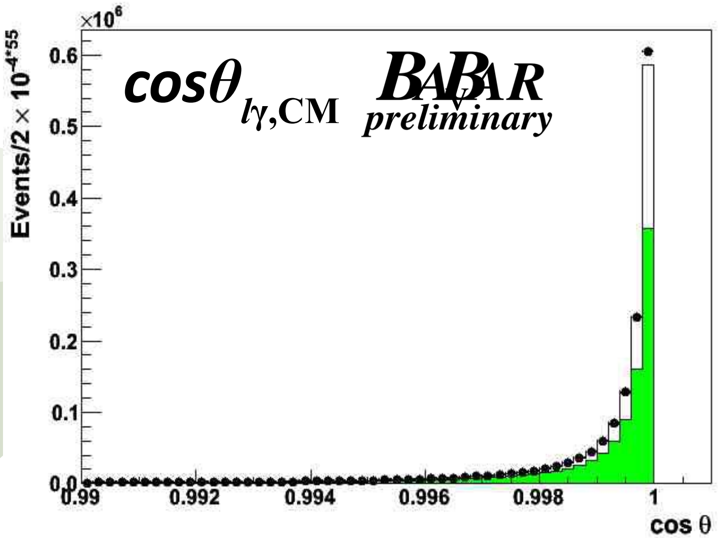


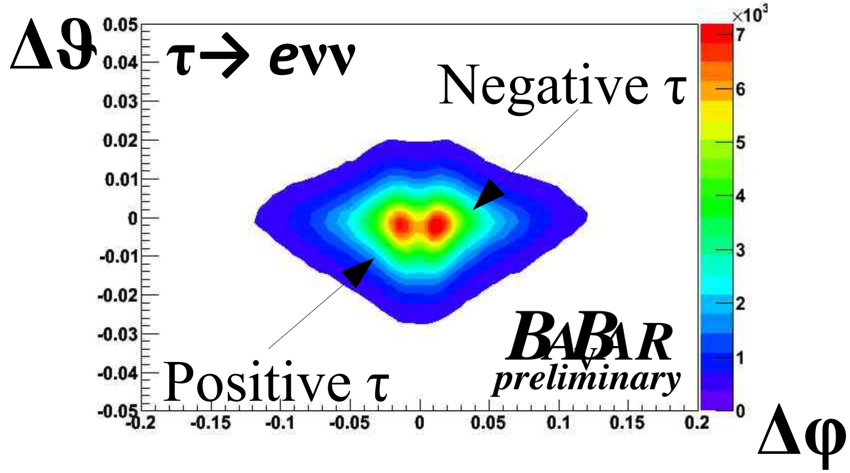



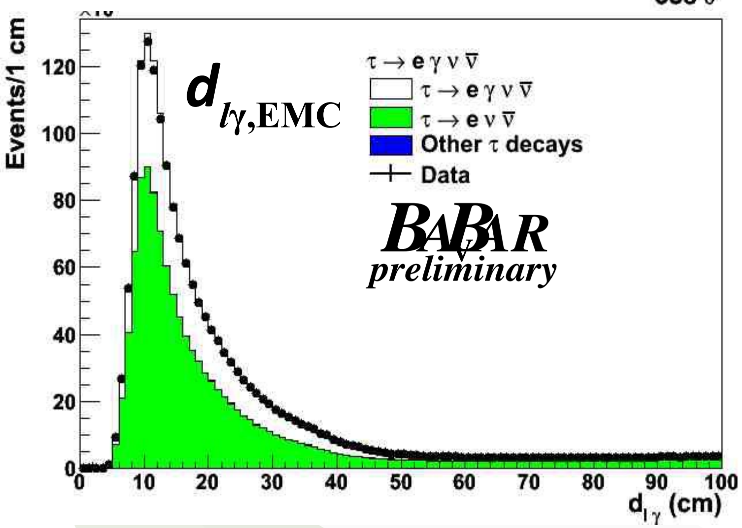



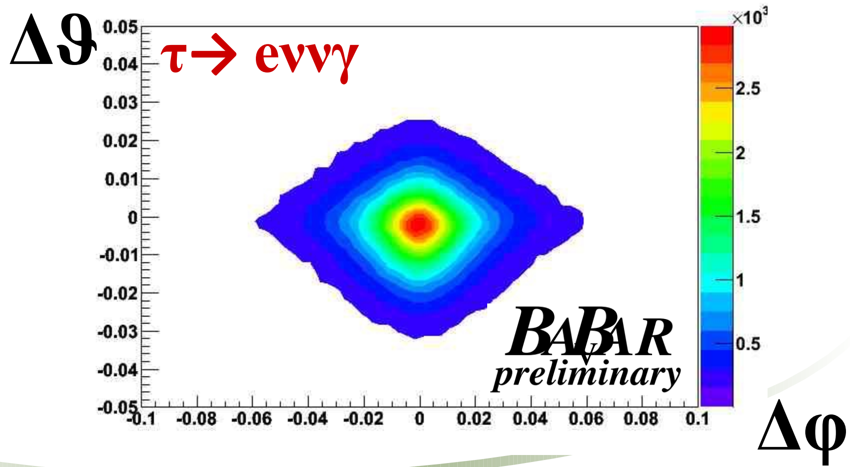
# Signal extraction $\tau \rightarrow e\bar{\nu}\nu\gamma$

- *Almost all bkg: $\tau \rightarrow e\nu\bar{\nu}$ + photon from "external bremsstrahlung"*
  *→ similar kinematics to $\tau \rightarrow e\bar{\nu}\nu\gamma$*



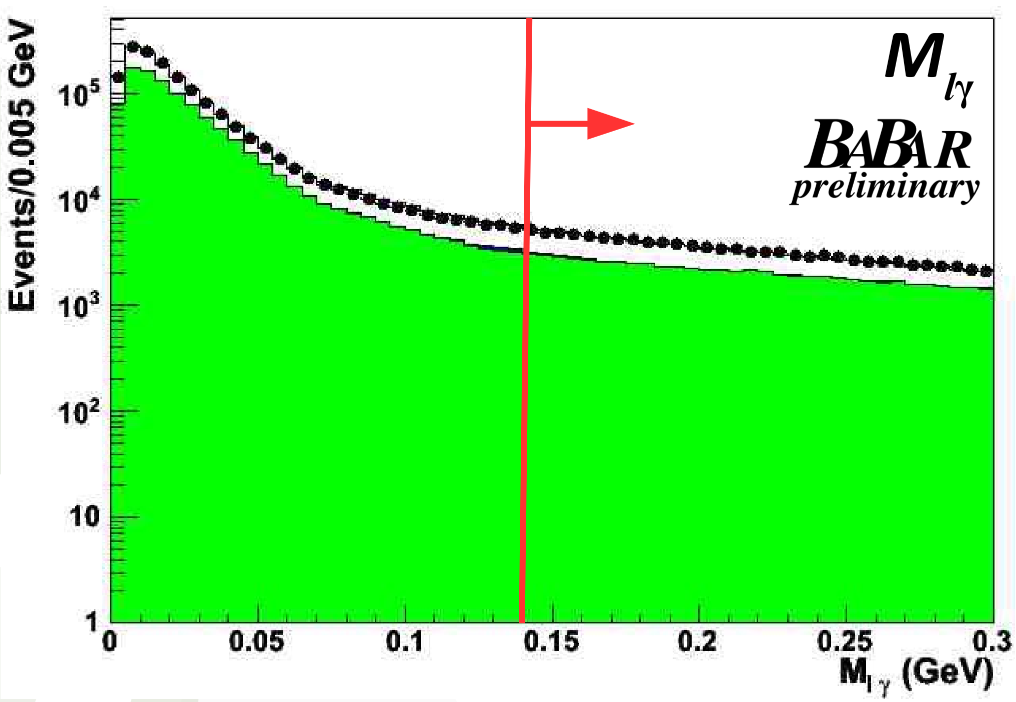



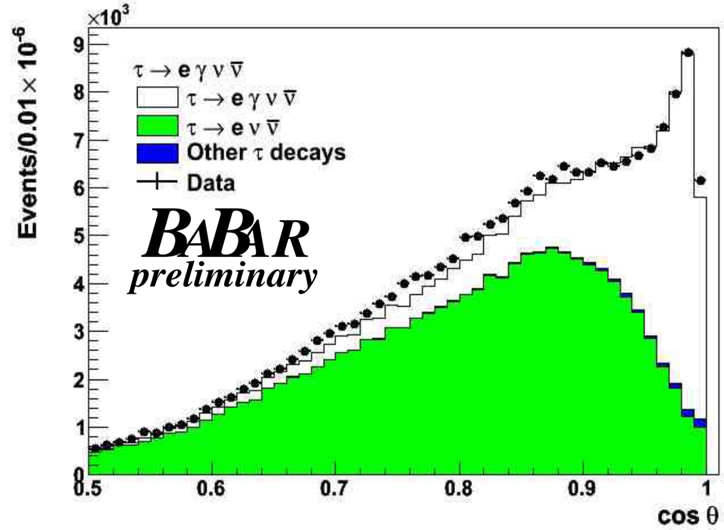



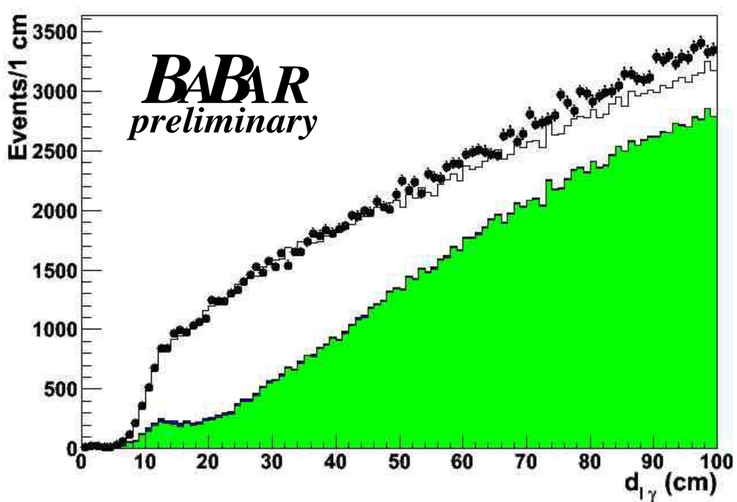



# Signal extraction $\tau \rightarrow e\bar{\nu}\nu\gamma$

- *Bremsstrahlung photons are peaked at $M_{l\gamma} \sim 0$*
- *We look at the high $M_{l\gamma}$ "tail"*




- *For signal selection we use:*
  $\cos\vartheta_{l\gamma,CM,MIN}$, $d_{l\gamma,EMC}$, $M_{l\gamma,\,MIN}$, $E_{\gamma,\,CM}$

# Selection Optimization

- *The main aim is to reduce systematic contributions*
- *Instead of using the standard FOM*

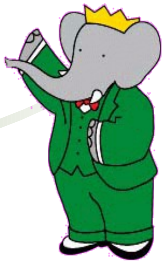
$$FOM = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg}}}$$

- *Assuming that the errors on the number of signal and background events are linear in $N_{bkg}$ and $N_{sig}$, in order to reduce the total error on BF, we use:*

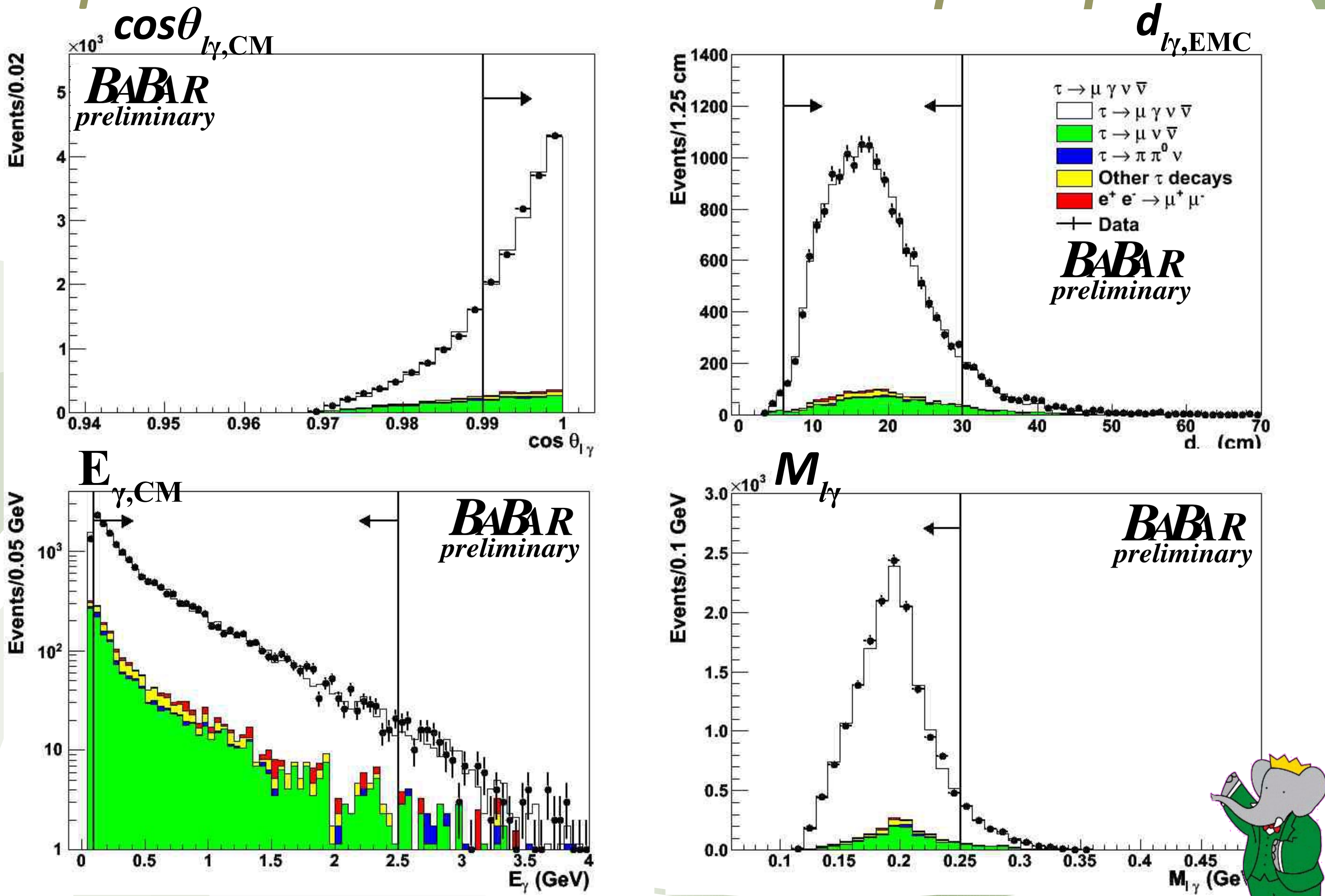
$$FOM = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg}(1 + \alpha^2 N_{bkg}) + \beta^2}}$$

- *$\alpha = \Delta N_{bkg}$ and $\beta = \Delta N_{sig}$ (systematic error on bkg and efficiency, see later)*
- *In order to maximize our FOM we impose a set of nominal cuts*
- *We vary each cut independently and set the one maximizing the FOM*
- *The procedure is repeated until all cuts are set*

- *The whole procedure is done on MC without looking at data*

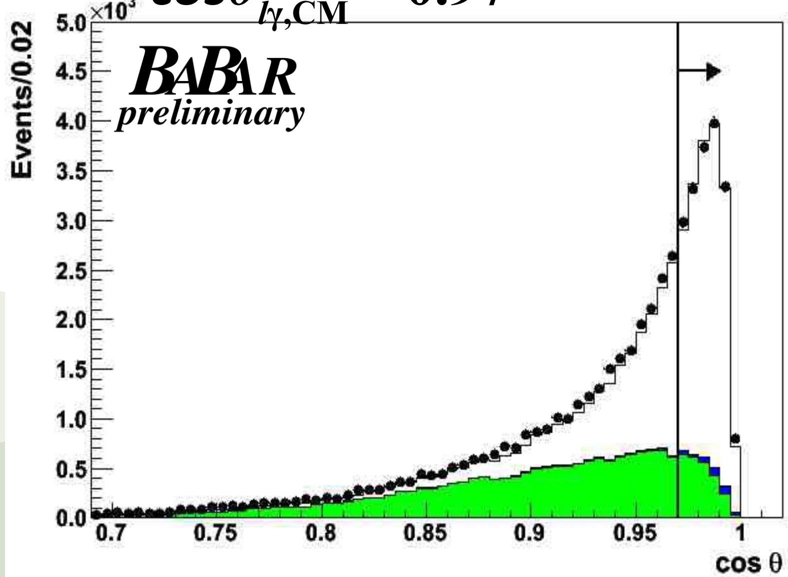


# Optimized selection $\tau \to \mu\bar{\nu}\nu\gamma$

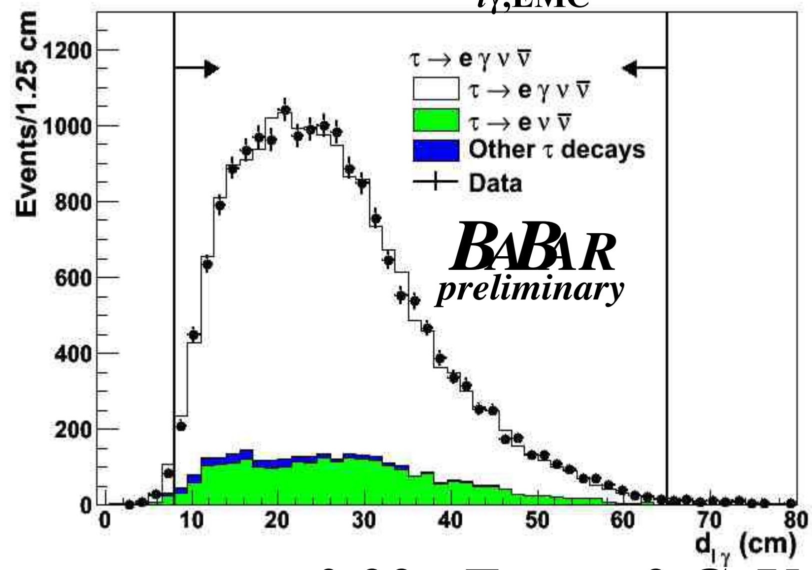


# *Optimized selection* $\tau \rightarrow e\bar{\nu}\nu\gamma$

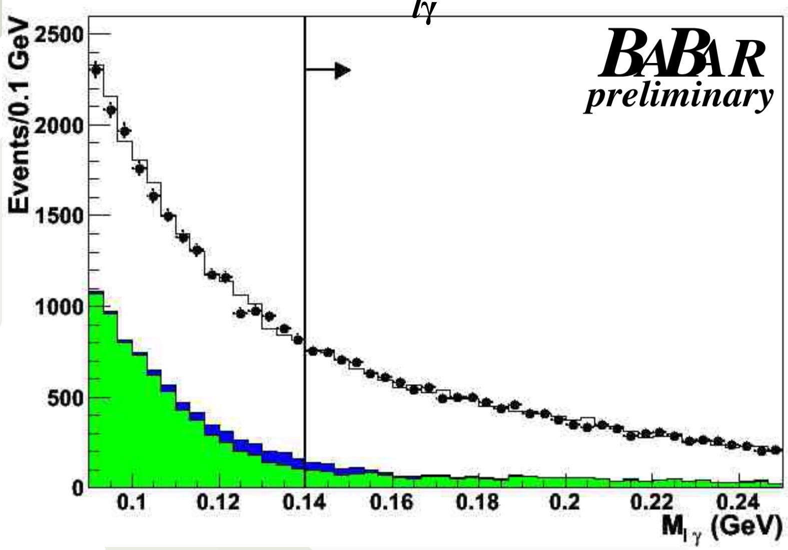
$cos\theta_{l\gamma,CM} > 0.97$



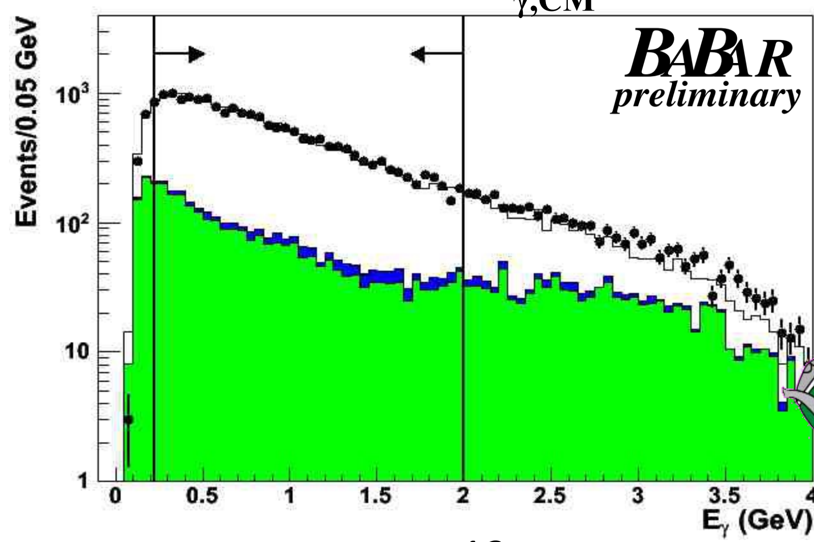

$8 < d_{l\gamma,EMC} < 65$ cm




$M_{l\gamma} > 0.25$ GeV




$0.22 < E_{\gamma,CM} < 2$ GeV




# Optimized Selection

## $\tau \to \mu \bar{\nu} \nu \gamma$

*$\alpha$ = 8%, $\beta$ = 2.5% (see later)*

| | $\tau \to \mu \bar{\nu} \nu \gamma$ |
|---|---|
| $N_{exp}$ | 15649 |
| S/S+B | 0.90 |
| $\cos\theta_{l\gamma}$ | 0.99 |
| $m_{inv}$ | 0.25 GeV |
| $E_{min}$ | 0.10 GeV |
| $E_{max}$ | 2.5 GeV |
| $d_{min}$ | 6 cm |
| $d_{max}$ | 30 cm |

## $\tau \to e \bar{\nu} \nu \gamma$

*$\alpha$ = 4%, $\beta$ = 3.2% (see later)*

| | $\tau \to e \bar{\nu} \nu \gamma$ |
|---|---|
| $N_{exp}$ | 18115 |
| S/S+B | 0.84 |
| $\cos\theta_{l\gamma}$ | 0.97 |
| $m_{inv}$ | 0.14 GeV |
| $E_{min}$ | 0.22 GeV |
| $E_{max}$ | 2.0 GeV |
| $d_{min}$ | 8 cm |
| $d_{max}$ | 65 cm |

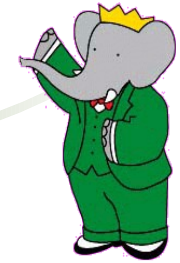
$$FOM = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg}(1 + \alpha^2 N_{bkg}) + \beta^2}}$$

# Systematics Overview

- *Signal efficiency:*
  - *Limited MC statistics*
  - *Trigger & Background Filters*
  - *Tracking and resolution*
  - *Particle ID*
  - *Photon efficiency*
  - *Dependence on selection cuts*
  - *PDG branching fractions*
- *Background evaluation:*
  - *MC/data matching*
- *Other Systematics:*
  - *Luminosity and cross section*

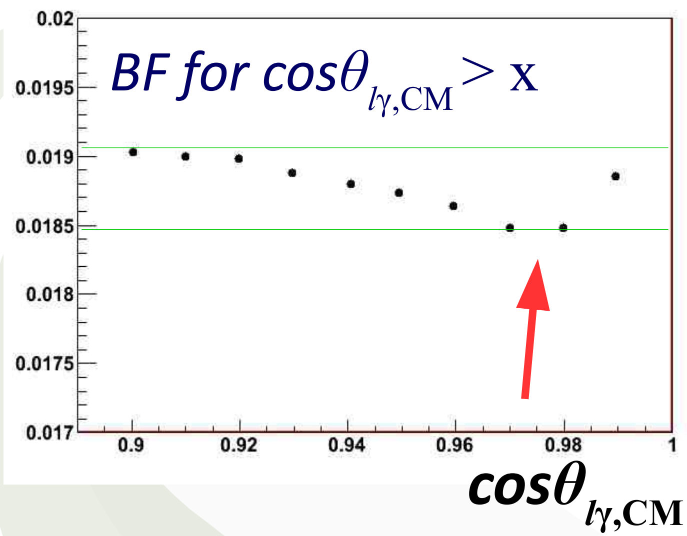
**BABAR** *preliminary*

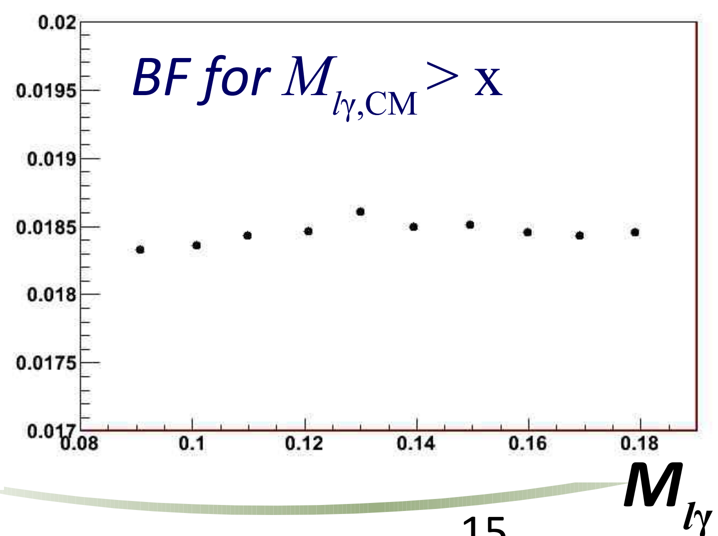
| | $\tau \to \mu\gamma\nu\bar{\nu}$ | $\tau \to e\gamma\nu\bar{\nu}$ |
|---|---|---|
| Selection Criteria | – | 2.0% |
| Photon efficiency | 1.8% | 1.8% |
| Particle Identification | 1.5% | 1.5% |
| Background Evaluation | 0.9% | 0.7% |
| PDG BF | 0.7% | 0.7% |
| Luminosity and Cross Section | 0.6% | 0.6% |
| MC Statistics | 0.5% | 0.6% |
| Trigger Selection | 0.5% | 0.6% |
| Track Reconstruction | 0.3% | 0.3% |
| Total: | 2.8% | 3.4% |



# Systematics on signal efficiency

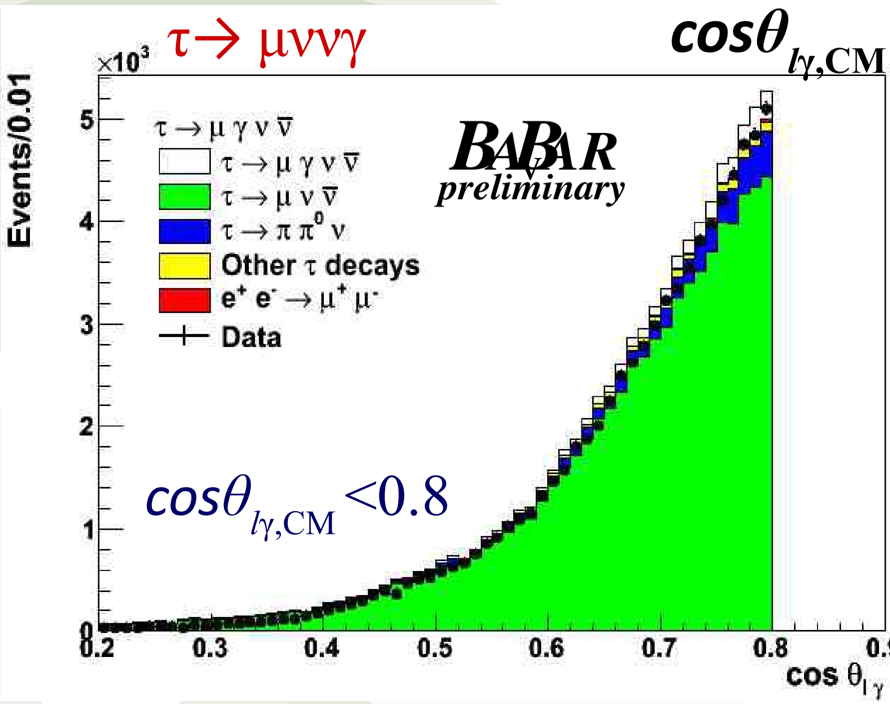
- *Particle-ID: we correct for* $\varepsilon_{MC}/\varepsilon_{Data}$*, the uncertainty on* $\varepsilon_{MC}/\varepsilon_{Data}$ *is 1% for muons with p>300 MeV and for electrons with p>500 MeV.*
  *We assign 1.5% uncertainty per event for both channels.*
- *Photon efficiency: from BR(* $\tau \to \rho\nu$*)/BR(*$\tau \to \pi\nu$*) single photon efficiency modelling has been measured to be good to less than 1.8%.*
  *For E>1 GeV photons from* $ee \to \mu\mu\gamma$ *the uncertainty is below 1%.*
- *In the* $\tau \to e\bar{\nu}\nu\gamma$ *channel the result depends significantly on the choice of the selection cuts. The maximum observed variation* $(BF_{max} - BF_{min})$ *is 3% → we introduce an additional 2% systematic on efficiency*

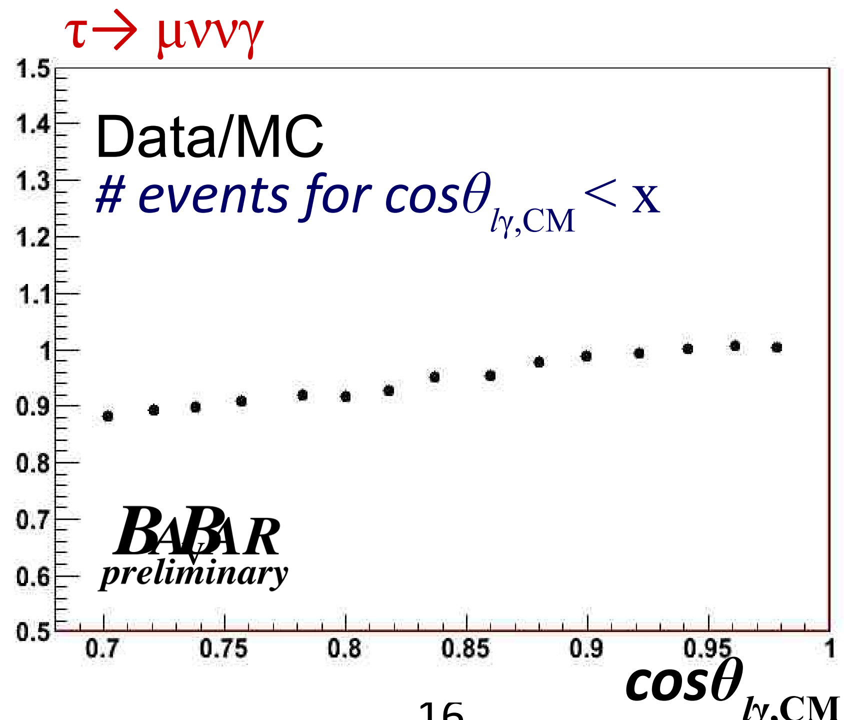


# Background evaluation $\tau \rightarrow \mu\bar{\nu}\nu\gamma$

- *To account for MC/data mismatching and non-simulated or unknown backgrounds we studied bkg in sidebands*
- *For* $\tau \rightarrow \mu\bar{\nu}\nu\gamma$ *we invert the cut on* $\cos\theta_{l\gamma,CM}$
  *For* $\cos\theta_{l\gamma,CM} < 0.8 \rightarrow S/(S+B)_{max} < 3\%$ *and* $[(N_{MC} - N_{Data})/N_{Data}]_{max} = 8\%$
  *which we take as estimate on* $\Delta N_{BKG}$

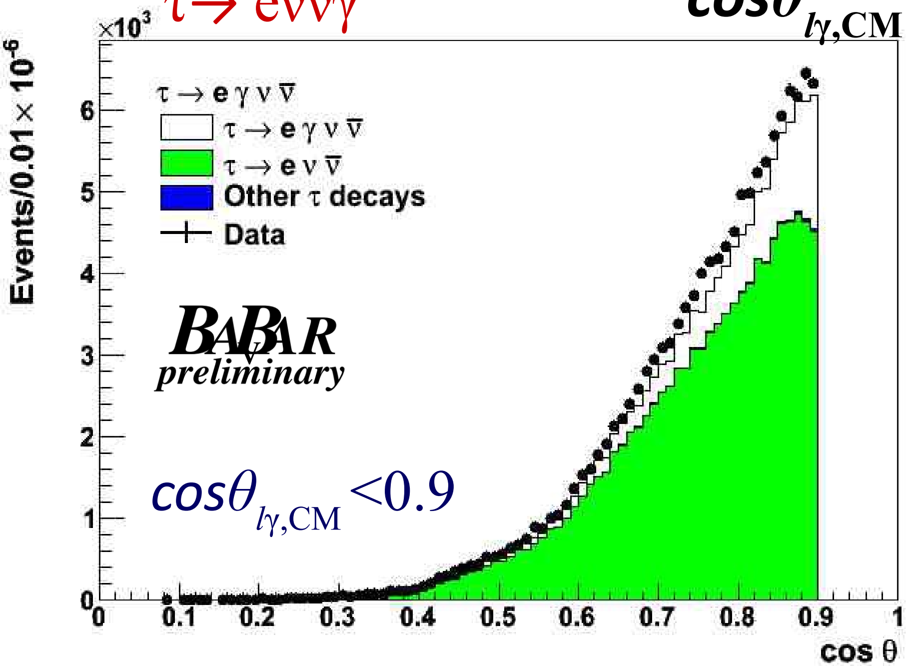


# Background evaluation $\tau \to e\bar{\nu}\nu\gamma$

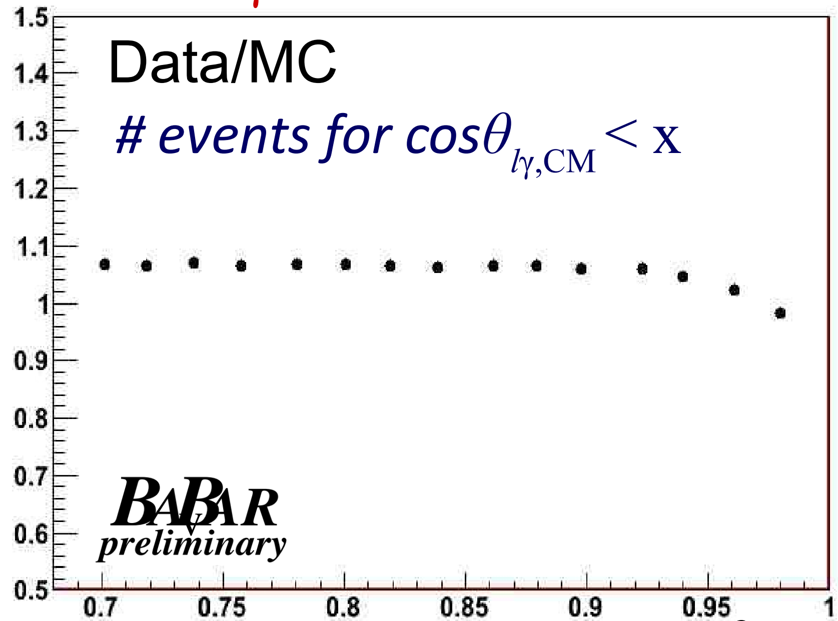
- *For* $\tau \to e\bar{\nu}\nu\gamma$ *the main background is peaking in* $\cos\theta_{l\gamma,CM}$
- *We first impose* $M_{l\gamma,MIN} > 0.14$ *and the invert the cut on* $\cos\theta_{l\gamma,CM}$
- *For* $\cos\theta_{l\gamma,CM} < 0.9 \to S/(S+B)_{max} < 10\%$ *and* $[(N_{MC} - N_{Data})/N_{Data}]_{max} = 4\%$ *which we take as estimate on* $\Delta N_{BKG}$

$\tau \to e\nu\nu\gamma$ $\cos\theta_{l\gamma,CM}$




$\cos\theta_{l\gamma,CM} < 0.9$

$\tau \to e\nu\nu\gamma$



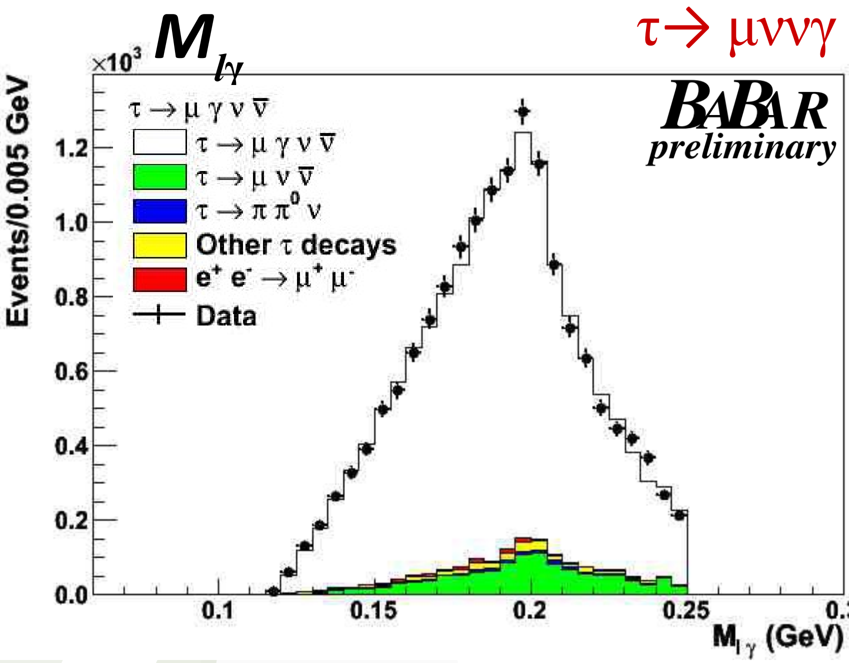

*# events for* $\cos\theta_{l\gamma,CM} < x$

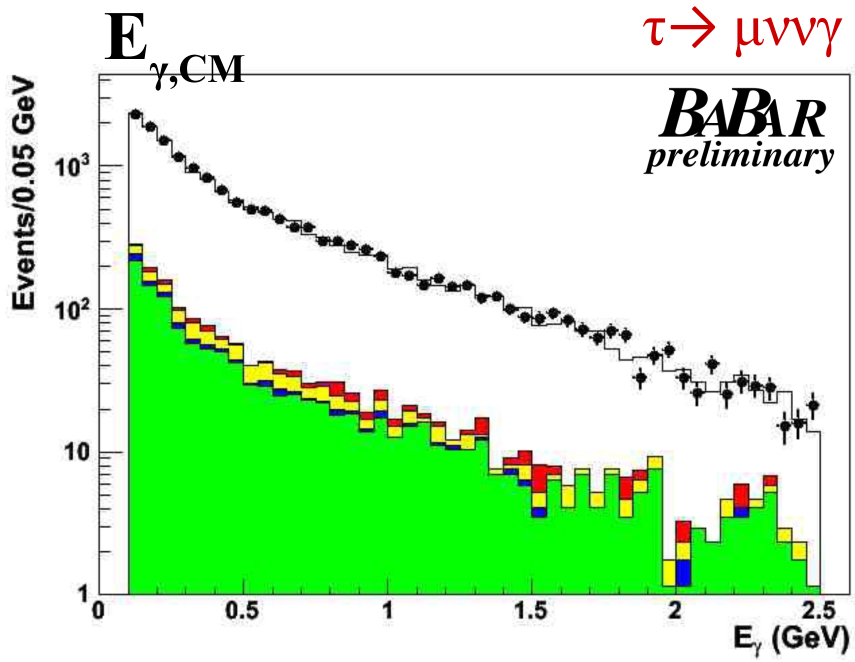
$\cos\theta_{l\gamma,CM}$

# Results: $\tau \to \mu\bar{\nu}\nu\gamma$

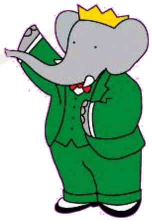
- *Expected events: 15649*
- *Observed events: 15688*
- *Expected bkg: 1594*

BABAR preliminary



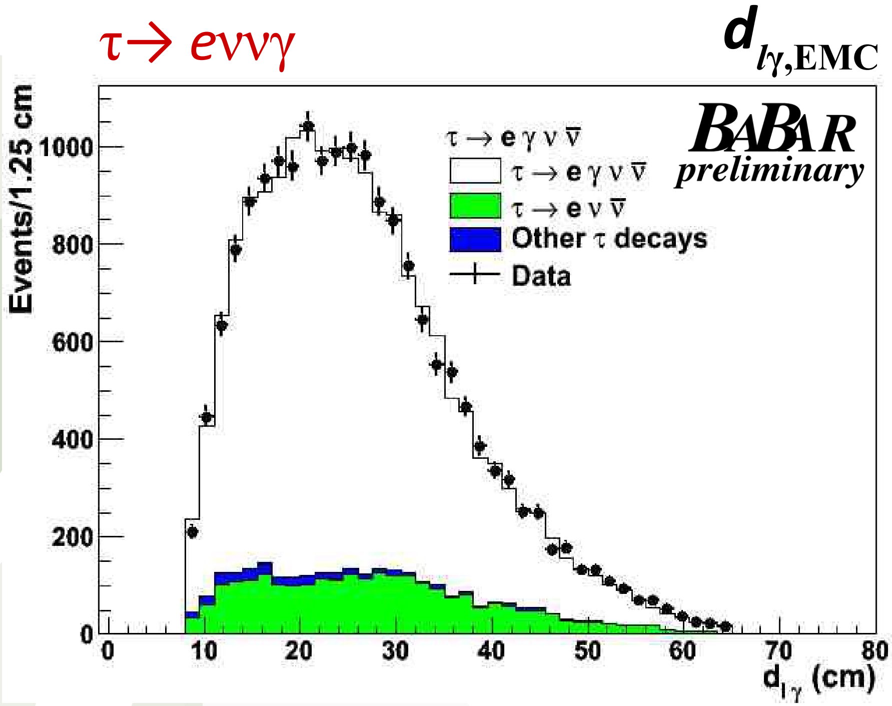



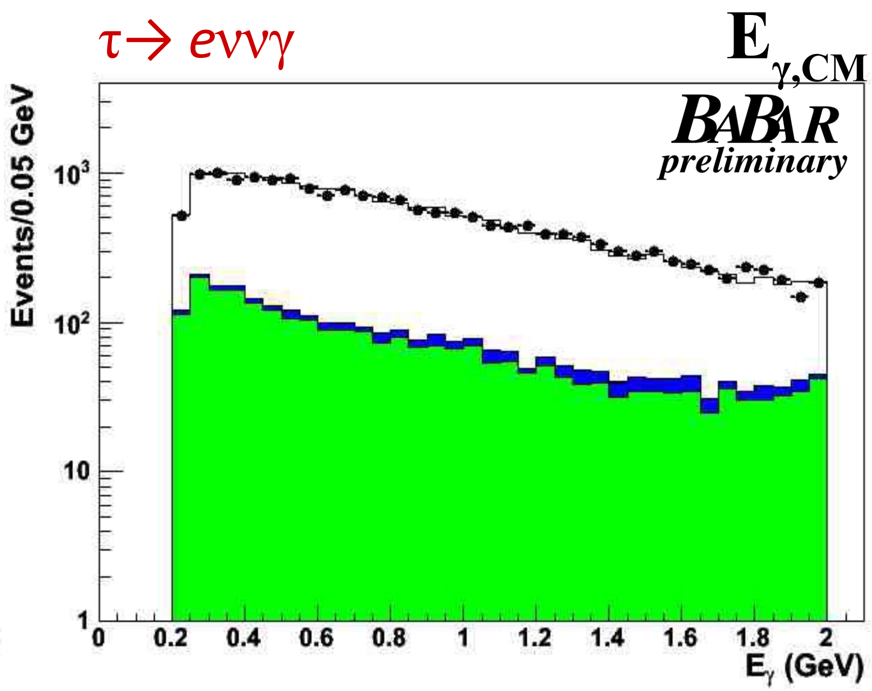

**BF($\tau \to \mu\bar{\nu}\nu\gamma$) (E*>10 MeV) = (3.69 ± 0.03 (stat) ± 0.10 (syst)) x $10^{-3}$**



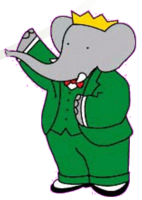
# Results: $\tau \to e\bar{\nu}\nu\gamma$


- *Expected events: 18115*
- *Observed events: 18149*
- *Expected bkg: 2823*

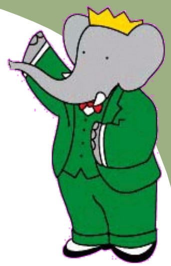



**BF($\tau \to e\bar{\nu}\nu\gamma$) (E*>10 MeV) = (1.847 ± 0.015 (stat) ± 0.052 (syst)) x $10^{-2}$**



# Summary



- *We performed the measurement of* $BF(\tau \to l\bar{\nu}\nu\gamma)$ *with* $E^*_{\gamma,\, min} > 10$ *MeV*
- *Our selection allows much lower bkg contamination and higher statistics with respect to existing measurement*
- *Main contribution to total error from uncertainty on efficiency*
- *Our results improve existing results by a factor 3 to 4*
- *Results agree with SM predictions (at LO) and existing measurements*

publication in preparation

BABAR preliminary

- *The* $\tau$ *sector with BaBar statistics offers a clean environment for precise measurements of rare SM processes and to search for new physics effects*
- *Other recent results include: charged LFV, CPV, high multiplicity* $\tau$ *decays.. ..and various analyses are still ongoing (EDM,* $\tau \to K\,(n)\pi^0\,\nu_\tau$*, etc..)*

*..more to come soon!*

# *Backups*

# *Result Comparison*

BABAR preliminary

- *THEORY (at LO):*

$BF(\tau \to \mu\nu\nu\gamma) = 0.37 \times 10^{-2}$

$BF(\tau \to e\nu\nu\gamma) = 1.84 \times 10^{-2}$

Passera et al. : arXiv:1310.1081v2 (2013)

- *MC (TAUOLA + PHOTOS):*

$BF(\tau \to \mu\nu\nu\gamma) = (0.3686 \pm 0.0009\ (stat)) \times 10^{-2}$

$BF(\tau \to e\nu\nu\gamma) = (1.843 \pm 0.002\ (stat)) \times 10^{-2}$

- *CLEO:*

$BF(\tau \to \mu\nu\nu\gamma) = (0.361 \pm 0.016\ (stat) \pm 0.035\ (syst)) \times 10^{-2}$

$BF(\tau \to e\nu\nu\gamma) = (1.75 \pm 0.06\ (stat) \pm 0.17\ (syst)) \times 10^{-2}$

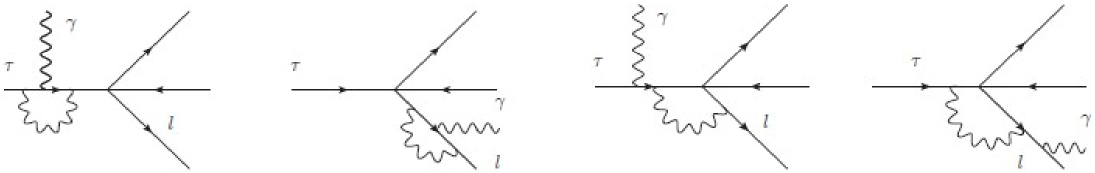
- ***BaBar:***

$\mathbf{BF(\tau \to \mu\nu\nu\gamma) = (0.369 \pm 0.003\ (stat) \pm 0.010\ (syst)) \times 10^{-2}}$

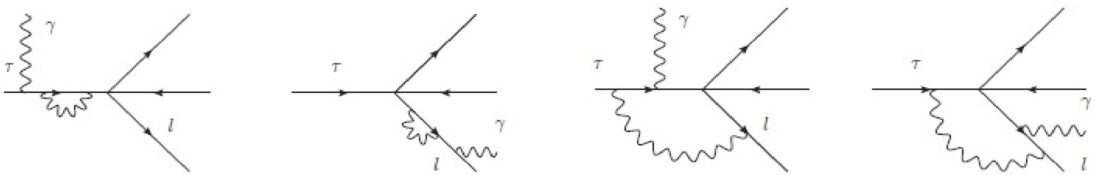
$\mathbf{BF(\tau \to e\nu\nu\gamma) = (1.847 \pm 0.015\ (stat) \pm 0.052\ (syst)) \times 10^{-2}}$

# NLO corrections

- *Virtual corrections:*

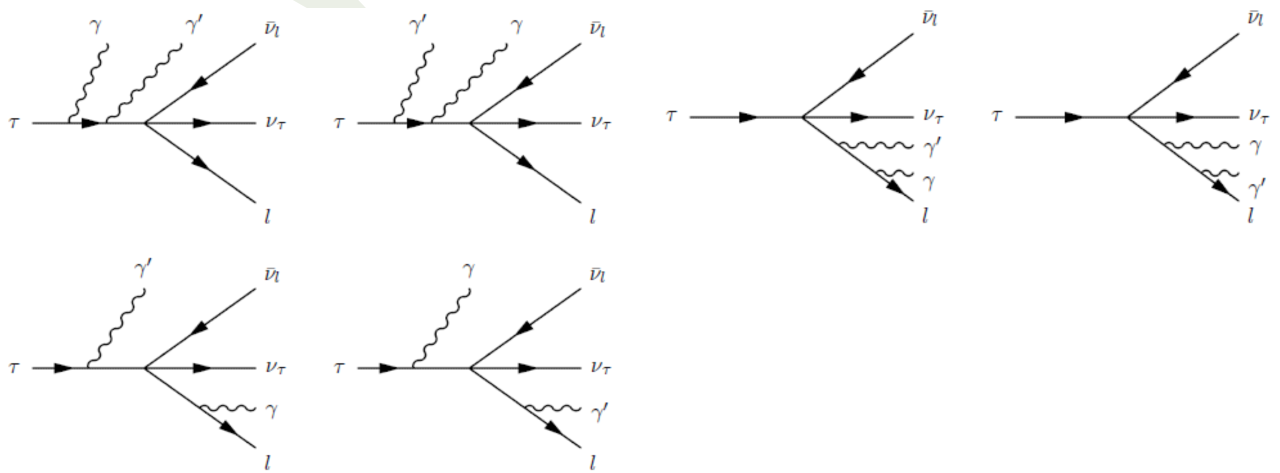



(A) QED triangles (B) Weak triangles




(C) Selfenergies (D) Boxes

- *Real corrections (E' < Emin):*




- *Weak corrections are negligible up to 2-loop QED*

# Selection Optimization

$$\Delta(BR_{\tau\to X\gamma\nu\nu,X=e,\mu}) = \Delta(\frac{N_{obs}-N_{bkg}}{N_{sig}})BR_{\tau\to X\gamma\nu\nu,X=e,\mu} \quad (31)$$

and, since we want to minimize the relative error on the branching fraction, our figure of merit is given by

$$\frac{\Delta(BR_{\tau\to X\gamma\nu\nu,X=e,\mu})}{BR_{\tau\to X\gamma\nu\nu,X=e,\mu})} = \Delta(\frac{N_{obs}-N_{bkg}}{N_{sig}}). \quad (32)$$

At this point if one neglects systematic contributions, the only error contributing to 32 is the poissonian error on $N_{obs}$, which rewriting $N_{obs} = N_{sig} + N_{bkg}$ leads to the maximization of the well known quantity

$$FOM = \frac{N_{sig}}{N_{sig+N_{bkg}}}. \quad (33)$$

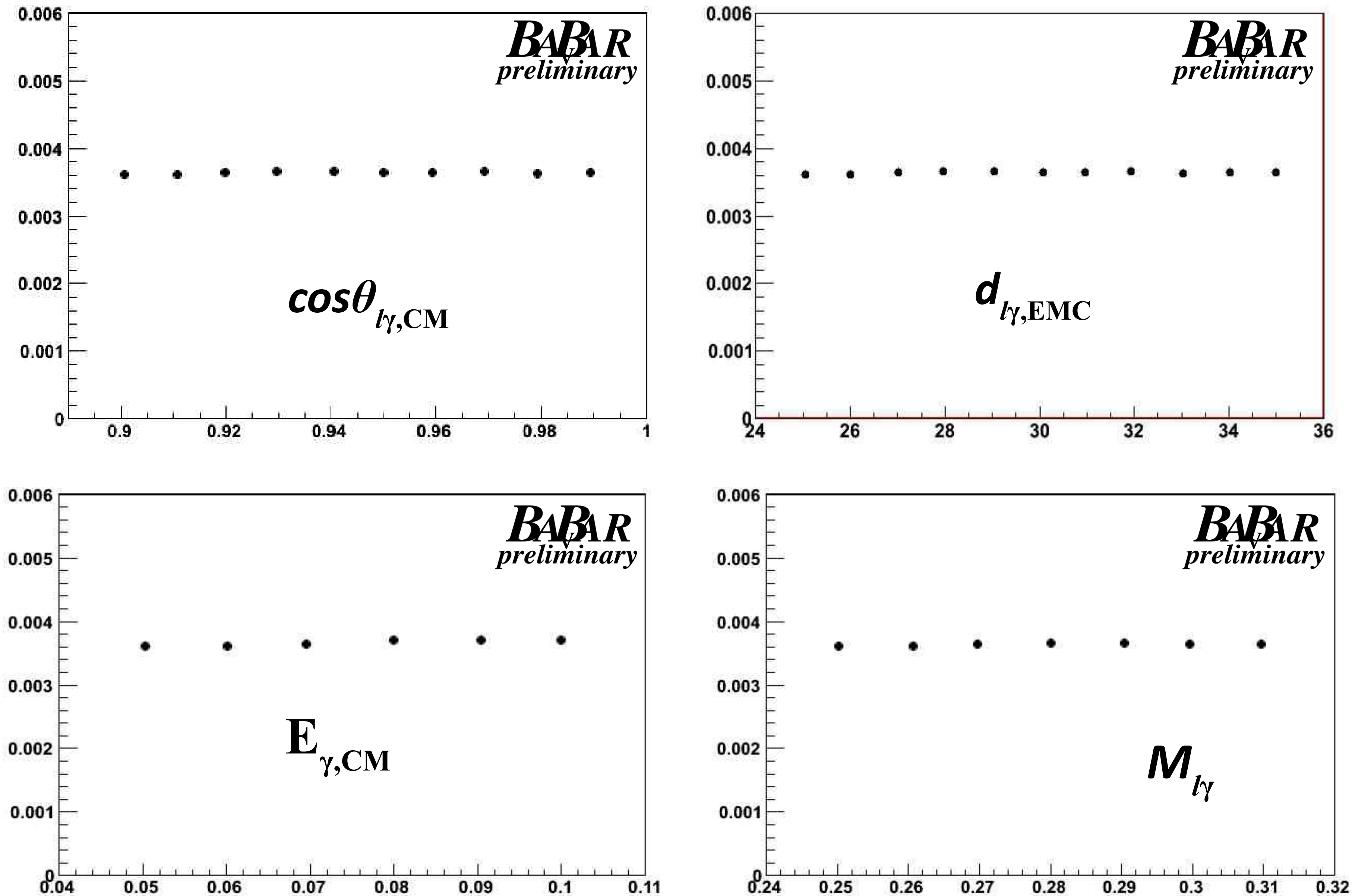
In our case however the aim is to define the optimization procedure in such a way as to minimize the total error and consequently we return back to 32 and write the right hand side as

$$\frac{\Delta(BR_{\tau\to X\gamma\nu\nu,X=e,\mu})}{BR_{\tau\to X\gamma\nu\nu,X=e,\mu}} = \sqrt{\frac{\Delta(N_{obs})^2}{N_{sig}^2} + \frac{\Delta(N_{bkg})^2}{N_{sig}^2} + \frac{\Delta(N_{sig})^2}{N_{sig}^4}}. \quad (34)$$

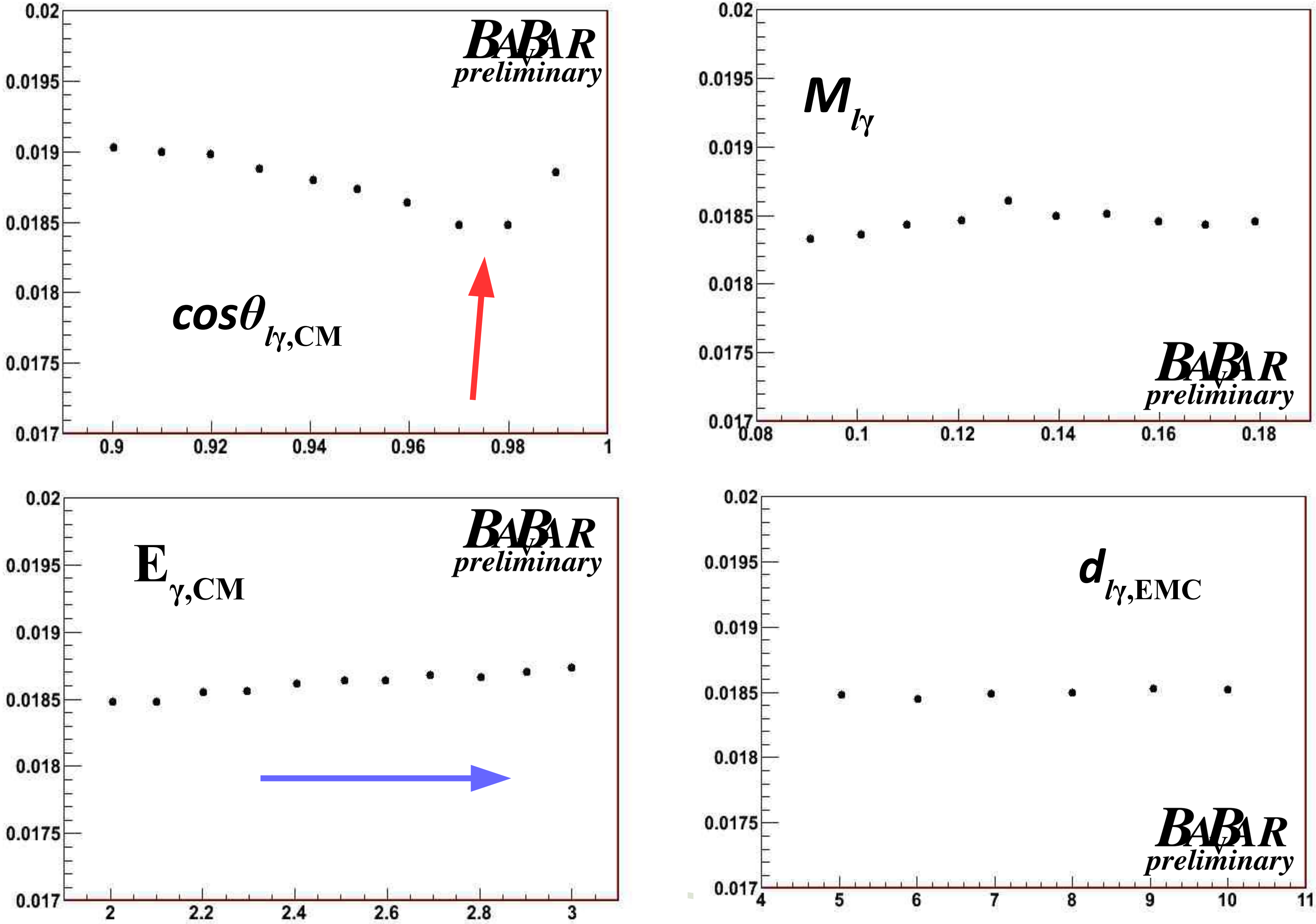
Now we assume systematic the error on MC signal and background events to be linear in the same quantities, i.e. $\Delta N_{bkg} = \alpha N_{bkg}$ and $\Delta N_{sig} = \beta N_{sig}$ while $N_{obs}$ has the usual statistic error, so

$$\frac{\Delta(BR_{\tau\to X\gamma\nu\nu,X=e,\mu})}{BR_{\tau\to X\gamma\nu\nu,X=e,\mu}} = \sqrt{\frac{N_{obs}}{N_{sig}^2} + \frac{\alpha^2 N_{bkg}^2}{N_{sig}^2} + \frac{\beta^2}{N_{sig}^2}} \quad (35)$$

# Optimization checks: $\tau \to \mu\nu\nu\gamma$



# Optimization checks: $\tau \rightarrow e\nu\nu\gamma$



# $\tau \to \mu\nu\nu\gamma$ Optimization Results

- *Optimization results for $\alpha = 8\%$, $\beta = 2.5\%$*

**This analysis**

$$FOM = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg}(1 + \alpha^2 N_{bkg}) + \beta^2}}$$

| | $\tau \to \mu\nu\nu\gamma$ |
|---|---|
| $N_{exp}$ | 15649 |
| S/S+B | 0.90 |
| $\cos\theta_{l\gamma}$ | 0.99 |
| $m_{inv}$ | 0.25 GeV |
| $E_{min}$ | 0.10 GeV |
| $E_{max}$ | 2.5 GeV |
| $d_{min}$ | -- |
| $d_{max}$ | 30 cm |

**Standard FOM**

$$FOM = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg}}}$$

| | $\tau \to \mu\nu\nu\gamma$ |
|---|---|
| $N_{exp}$ | 75781.2 |
| S/S+B | 0.66 |
| $\cos\theta_{l\gamma}$ | 0.94 |
| $m_{inv}$ | 0.54 GeV |
| $E_{min}$ | 0.05 GeV |
| $E_{max}$ | 3.1 GeV |
| $d_{min}$ | 5 cm |
| $d_{max}$ | 65 cm |

BABAR preliminary

# $\tau \rightarrow e\nu\nu\gamma$ Optimization Results

- *Optimization results for $\alpha = 4\%$, $\beta = 3.2\%$*

$$FOM = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg}(1+\alpha^2 N_{bkg}) + \beta^2}}$$

| | $\tau \rightarrow e\nu\nu\gamma$ |
|---|---|
| $N_{exp}$ | 19139 |
| S/S+B | 0.84 |
| $\cos\theta_{l\gamma}$ | 0.97 |
| $m_{inv}$ | 0.14 GeV |
| $E_{min}$ | 0.22 GeV |
| $E_{max}$ | 2.0 GeV |
| $d_{min}$ | 8 cm |
| $d_{max}$ | 65 cm |

This analysis

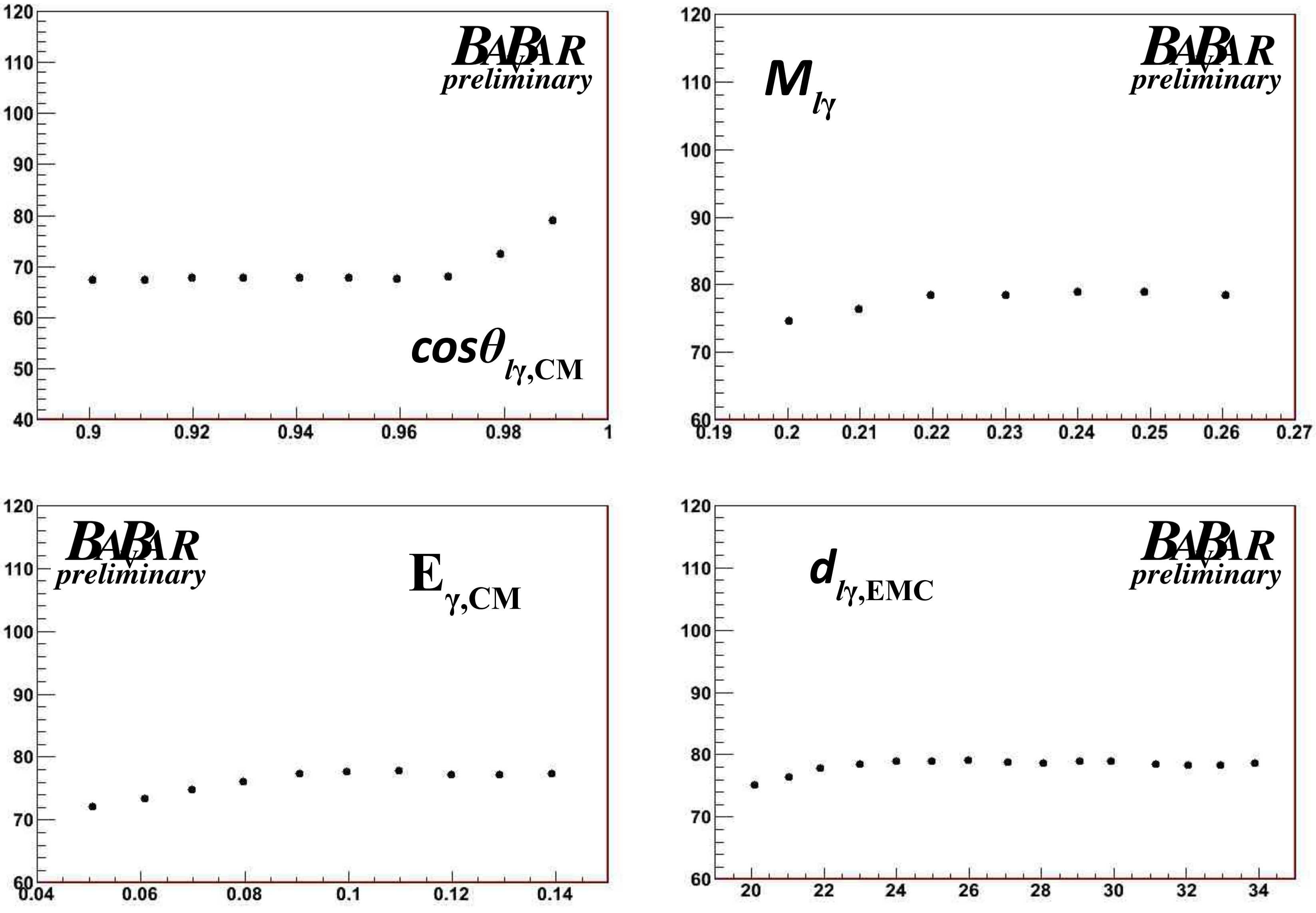
$$FOM = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg}}}$$

| | $\tau \rightarrow e\nu\nu\gamma$ |
|---|---|
| $N_{exp}$ | 1525182 |
| S/S+B | 0.35 |
| $\cos\theta_{l\gamma}$ | 0.90 |
| $m_{inv}$ | 0.0 GeV |
| $E_{min}$ | 0.05 GeV |
| $E_{max}$ | 4.7 GeV |
| $d_{min}$ | 6 cm |
| $d_{max}$ | 100 cm |

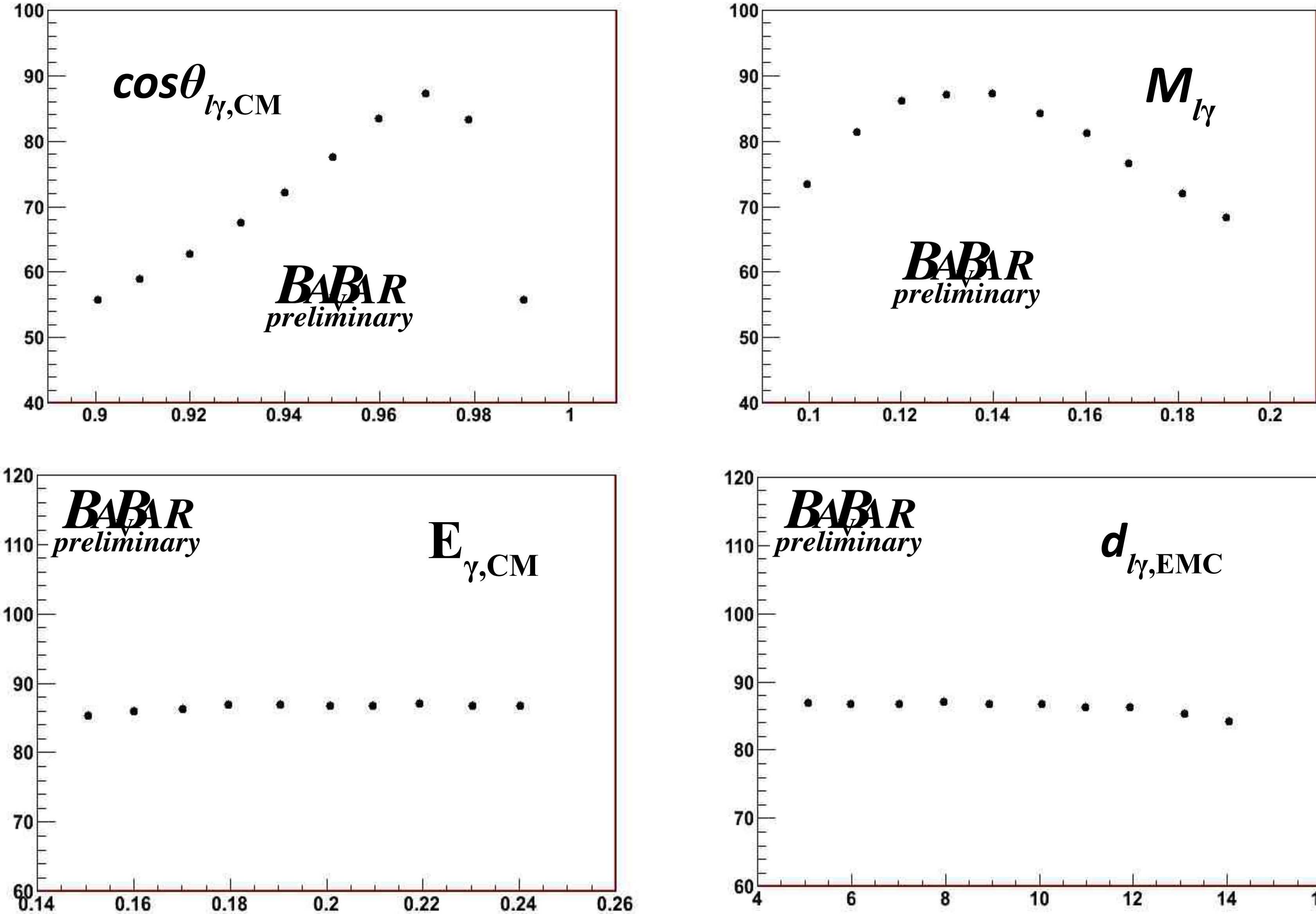
Standard FOM

BABAR preliminary

# Optimization plots: $\tau \rightarrow \mu\nu\nu\gamma$



# Optimization plots: $\tau \rightarrow e\nu\nu\gamma$



# Common Preselection

- *For both signal channels we further require:*
  - *Exactly 2 tracks in EMC acceptance, 0 net charge*
  - *Minimum $p_{T,LAB}$>300 MeV*
  - *Minimum missing $p_{T,tot,LAB}$>500 MeV*
  - *Cosine of -0.75 < $p_{miss,LAB}$ < 0.99*
  - *0.85 < Thrust Magnitude < 0.995*
  - *Max 5 neutrals in EMC, minimum E>50 MeV*
  - *No conversions in SVT and no $K_S$*
  - *$0.5<p_{CM}<4$ GeV for both tracks*

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- *Signal side: one track and exactly one neutral deposit in EMC*
- *Distance between neutral bump in EMC and track < 100 cm*
- *Tag side: one charged track, 1, 2 or 4 neutrals*
  *for every 2 neutrals we require a reconstructed $\pi^0$*