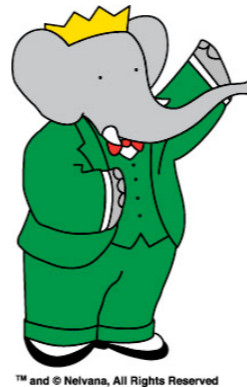


Search for Lepton Flavor Violation at BABAR



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Swagato Banerjee



University
of Victoria

British Columbia
Canada

DPF 2009



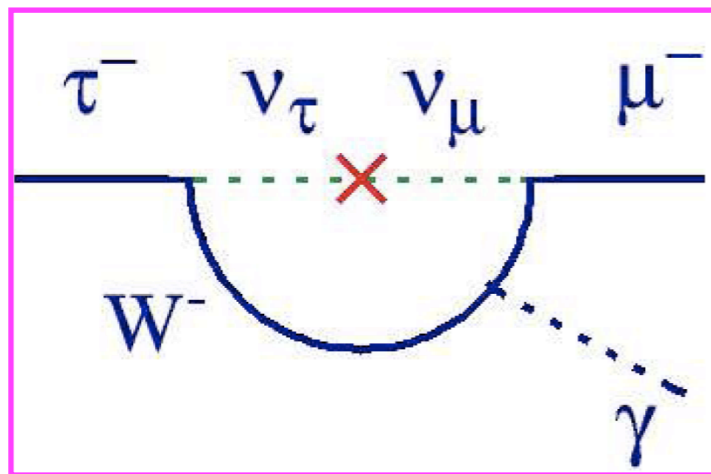
*2009 Meeting of the Division of Particles and
Fields of the American Physical Society (DPF 2009)*

26-31 JULY 2009

Wayne State University, Detroit, MI

Introduction

- Lepton flavor violation (LFV)
 - not forbidden by SM gauge symmetry
 - most new models naturally include LFV vertex
- In SM, LF is conserved for zero degenerate ν masses
- Now we have clear indication that ν 's have finite mass
 \Rightarrow Lepton Flavor is violated in Nature: but by how much?
- SM extended to include finite ν mass and mixing predicts LFV



$$\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \gamma) \text{ [Lee-Shrock, Phys. Rev. D 16, 1444 (1977)]}$$
$$= \frac{3\alpha}{128\pi} \left(\frac{\Delta m_{23}^2}{M_W^2} \right)^2 \sin^2 2\theta_{\text{mix}} \mathcal{B}(\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau)$$

With $\Delta \sim 10^{-3} \text{ eV}^2$, $M_W \sim \mathcal{O}(10^{11}) \text{ eV}$
 $\approx \mathcal{O}(10^{-54})$ ($\theta_{\text{mix}} : \text{max}$)

... many orders below experimental sensitivity!

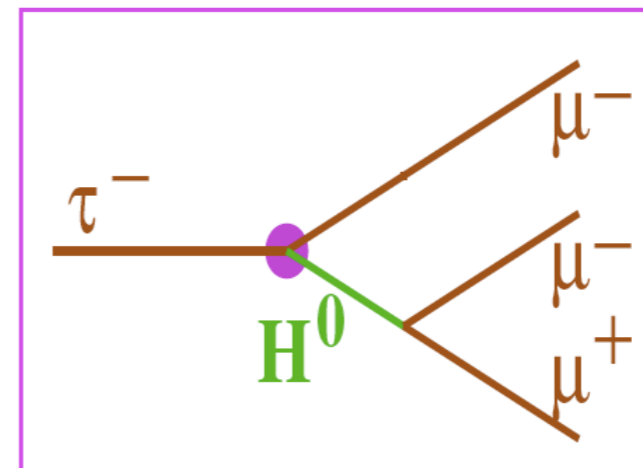
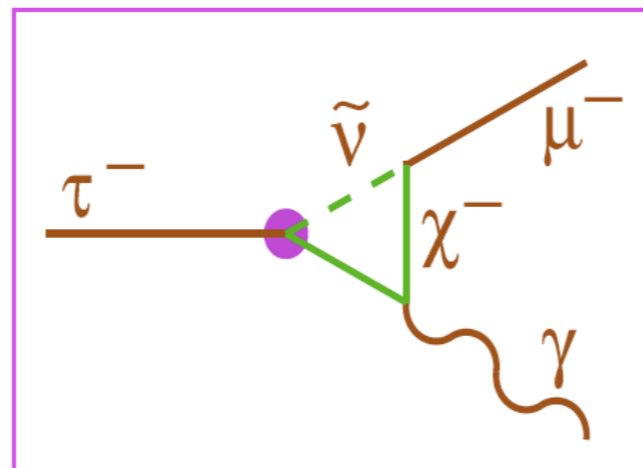
- Observation for LFV \Rightarrow unambiguous signature of new physics

Lepton Flavor Violating Tau Decays

- Predicted by many beyond SM processes ...
 - SUSY models: non-diagonal slepton mass matrix \Rightarrow LFV
 - Normal (Inverted) slepton hierarchy $\Rightarrow \tau^\pm \rightarrow \mu^\pm \gamma$ ($\tau^\pm \rightarrow e^\pm \gamma$)
- Some models: LFV upto existing experimental bounds

	$\mathcal{B}(\tau \rightarrow l\gamma)$	$\mathcal{B}(\tau \rightarrow lll)$
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}
Non-Universal Z' (PLB547(2002)252)	10^{-9}	10^{-8}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}

Illustrations:



Probing TeV scale via Upsilon Decays

SUSY + Higgs

(A.Brignole, A.Rossi, PLB566(2003)217)

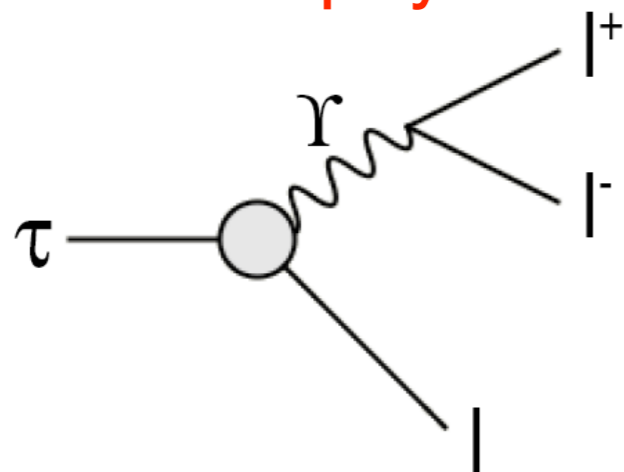
$$\mathcal{B}(\tau \rightarrow lll) \simeq 10^{-7} \times \left(\frac{\tan \beta}{50}\right)^6 \times \left(\frac{100 \text{ GeV}}{m_A}\right)^4 \times \left(\frac{|50\Delta_L|^2 + |50\Delta_R|^2}{10^{-3}}\right)$$

If Higgs light, s-particles $\sim \mathcal{O}(\text{TeV})$, $\tan \beta \sim 50$

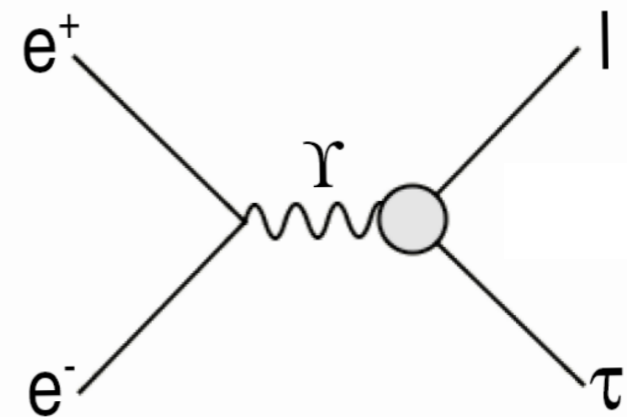
No direct observation, but $\tau \rightarrow \mu\mu\mu$ observable (?)

Sensitivity $\sim 10^{-8} - 10^{-10}$ at B-Factories, LHC

Same new physics at TeV scale also predicts LFV Upsilon Decays



Re-ordering of
incoming/outgoing
particles



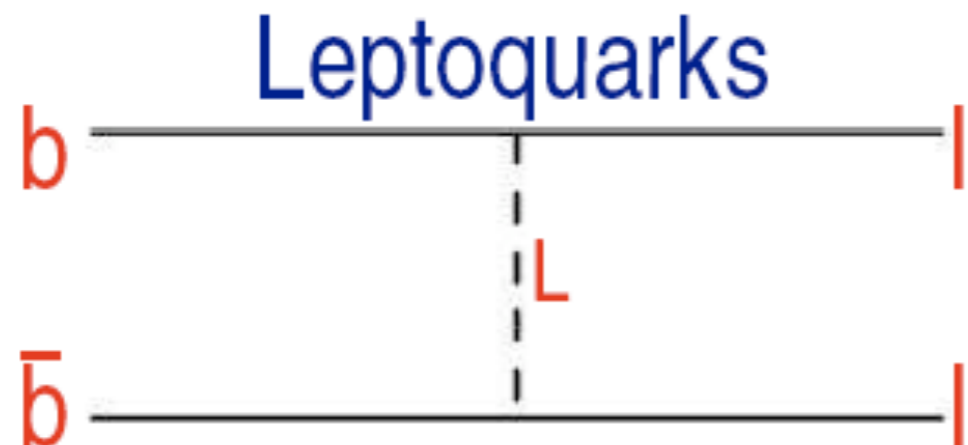
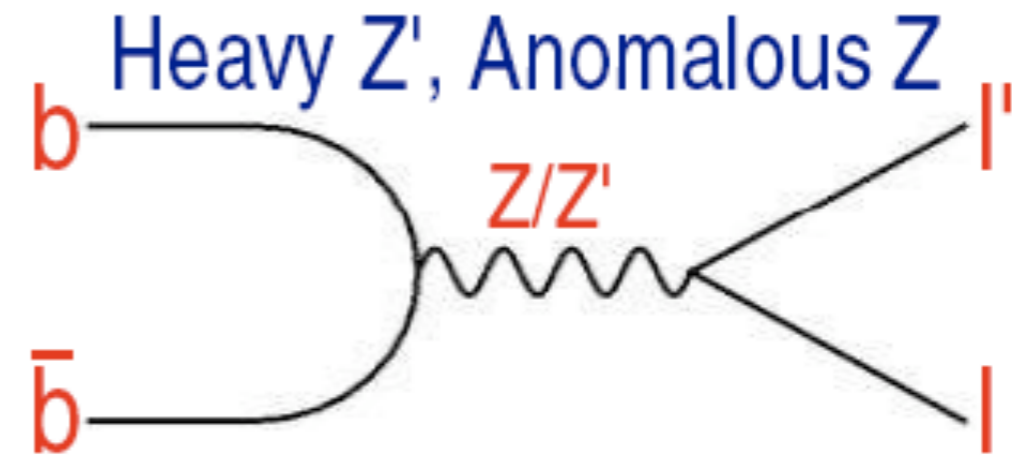
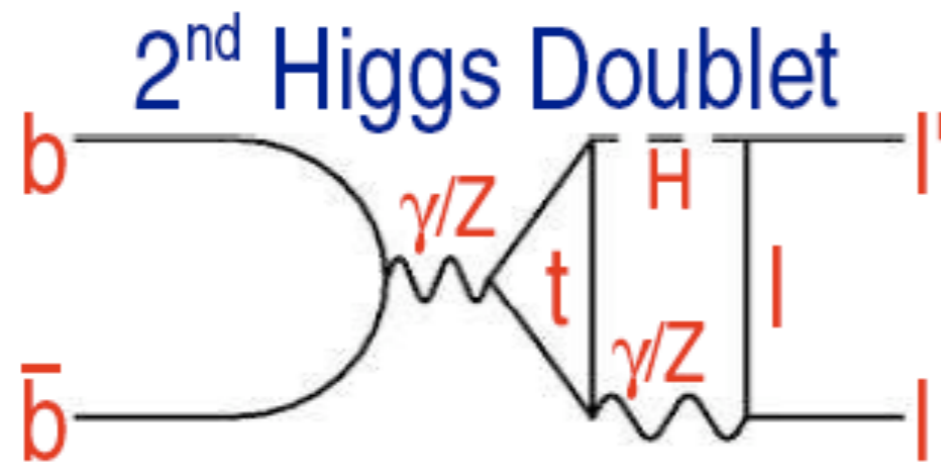
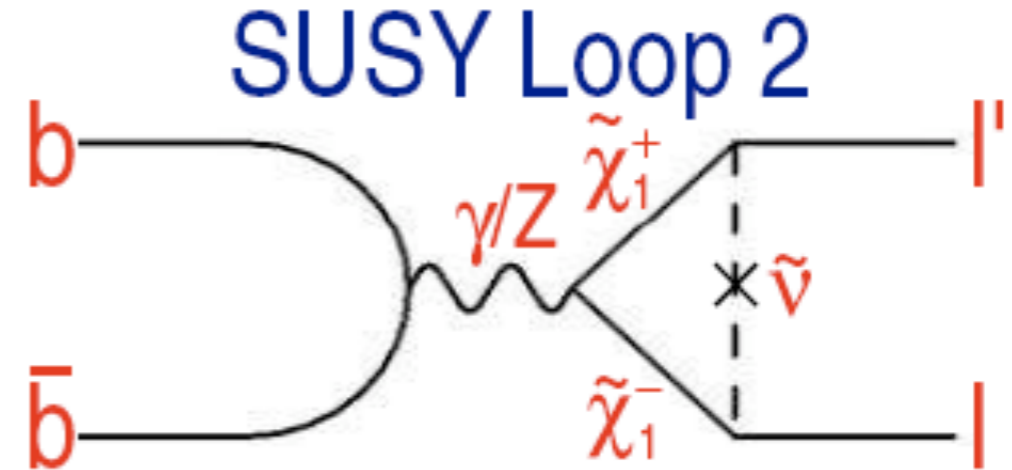
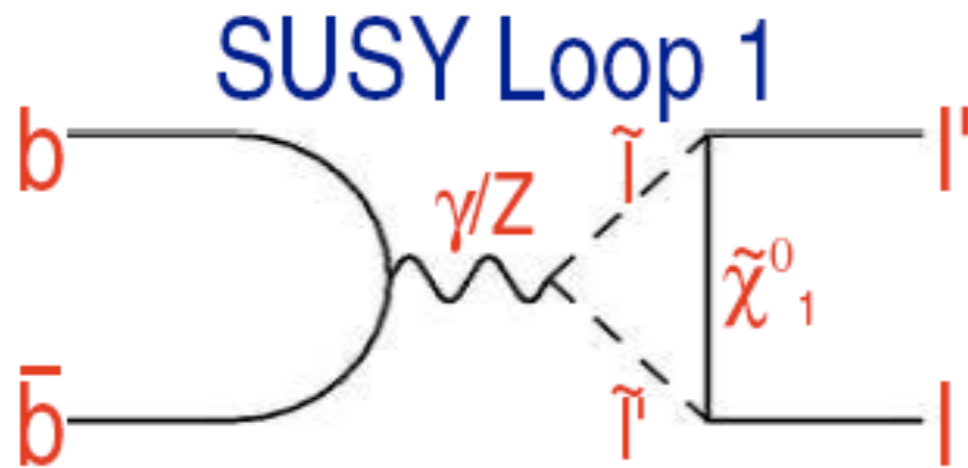
$$\mathcal{B}(\Upsilon \rightarrow l\tau) \sim \frac{\mathcal{B}(\tau \rightarrow lll)}{\mathcal{B}(\tau \rightarrow l\nu\bar{\nu})} \frac{\Gamma(W \rightarrow l\nu)^2}{\Gamma(\Upsilon)\Gamma(\Upsilon \rightarrow ll)} (M_\Upsilon/M_W)^6$$

S.Nussinov, et. al.
PRD 63, 016003 (2001)

$$\mathcal{B}(\tau \rightarrow lll) < 2 - 4 \times 10^{-8} \quad \Rightarrow \quad \mathcal{B}(\Upsilon \rightarrow l\tau) < 3 - 6 \times 10^{-3}$$

BaBar PRL 99, 251803 (2007), Belle PLB 660,154 (2008)

Lepton Flavor Violating Upsilon Decays



How small is the rate known to be?

BaBar/Belle searches for LFV in $\tau \rightarrow e/\mu\gamma$ decays at $\sqrt{s} \approx \Upsilon(4S)$

● $\mathcal{L} = 232 fb^{-1} \Rightarrow N_\tau \approx 4 \times 10^8 : \mathcal{B}(\tau \rightarrow e\gamma) < 11 \times 10^{-8} @ 90\% \text{ C.L.}$

BaBar Collab., PRL 96, 041801 (2006)

● $\mathcal{L} = 232 fb^{-1} \Rightarrow N_\tau \approx 4 \times 10^8 : \mathcal{B}(\tau \rightarrow \mu\gamma) < 6.8 \times 10^{-8} @ 90\% \text{ C.L.}$

BaBar Collab., PRL 95, 041802 (2005)

● $\mathcal{L} = 535 fb^{-1} \Rightarrow N_\tau \approx 1 \times 10^9 : \mathcal{B}(\tau \rightarrow e\gamma) < 12 \times 10^{-8} @ 90\% \text{ C.L.}$

● $\mathcal{L} = 535 fb^{-1} \Rightarrow N_\tau \approx 1 \times 10^9 : \mathcal{B}(\tau \rightarrow \mu\gamma) < 4.5 \times 10^{-8} @ 90\% \text{ C.L.}$

Belle Collab., PLB 666, 16 (2008)

CLEO search for $\Upsilon \rightarrow \mu\tau, \tau \rightarrow e\nu\nu$

CLEO Collab., PRL 101, 201601 (2008)

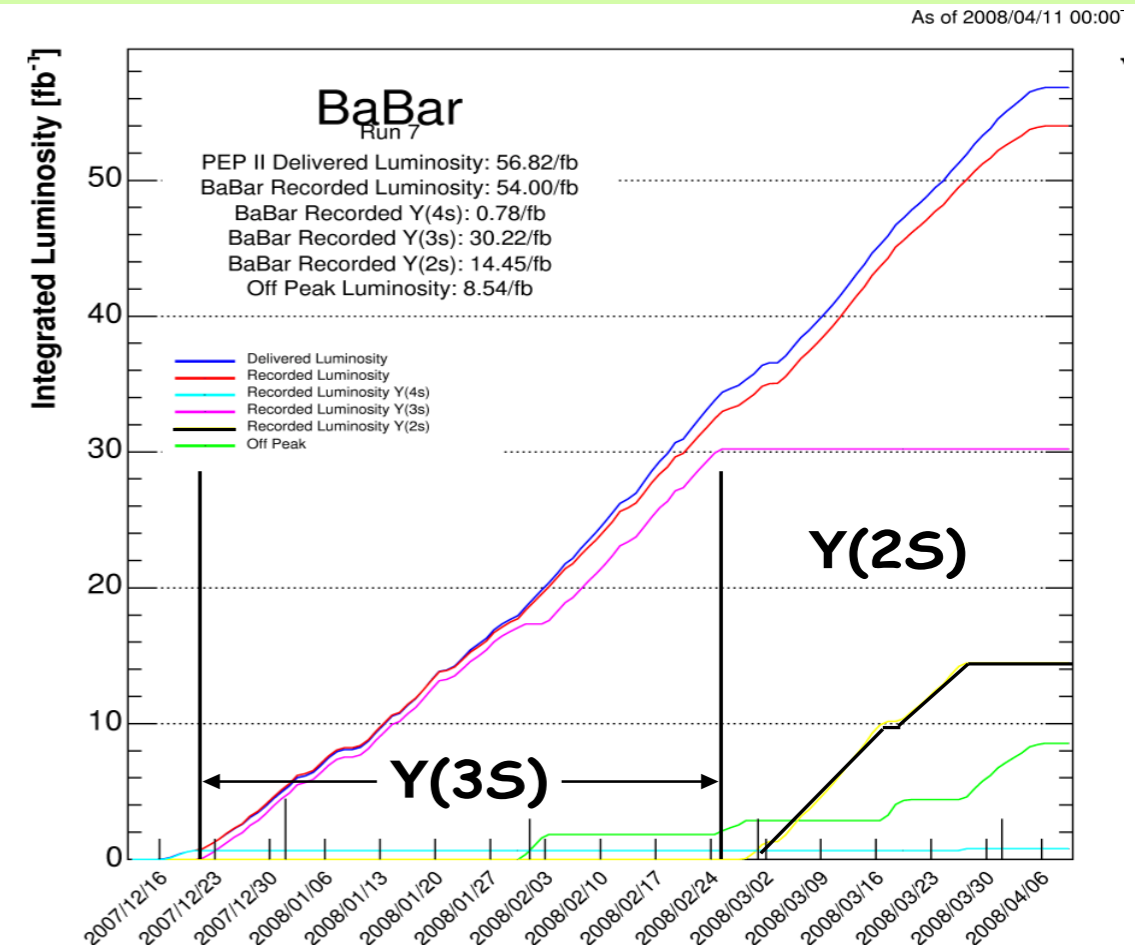
	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass (GeV/ c^2)	9.46	10.02	10.36
N decays (millions)	20.8	9.3	5.9
$\Gamma(\Upsilon \rightarrow \mu\mu)$ (keV)	1.252	0.581	0.413
$\Gamma(\Upsilon)$ (keV)	53.0	43.0	26.3
$\mathcal{B}(\mu\mu)$ ($\times 10^{-3}$)	23.6	13.5	15.7
$\mathcal{B}(\mu\tau)$ (95% CL UL, $\times 10^{-6}$)	6.0	14.4	20.3
$\mathcal{B}(\mu\tau)/\mathcal{B}(\mu\mu)$ (95% CL UL, $\times 10^{-3}$)	0.25	1.1	1.3
Λ (95% CL LL, TeV, $\alpha_N = 1.0$)	1.30	0.98	0.98

How small a rate can BABAR measure?

Between Dec 2007 - Apr 2008,
PEP II collected data below $\Upsilon(4S)$:
 $\sim 30 \text{ fb}^{-1}$ @ $\Upsilon(3S)$ (122 M decays)
 $\sim 15 \text{ fb}^{-1}$ @ $\Upsilon(2S)$ (100 M decays)

Dramatic increase in
sensitivity to rare decays:

$$\Gamma_{\Upsilon(4S)} / \Gamma_{\Upsilon(nS)} \sim 10^3$$



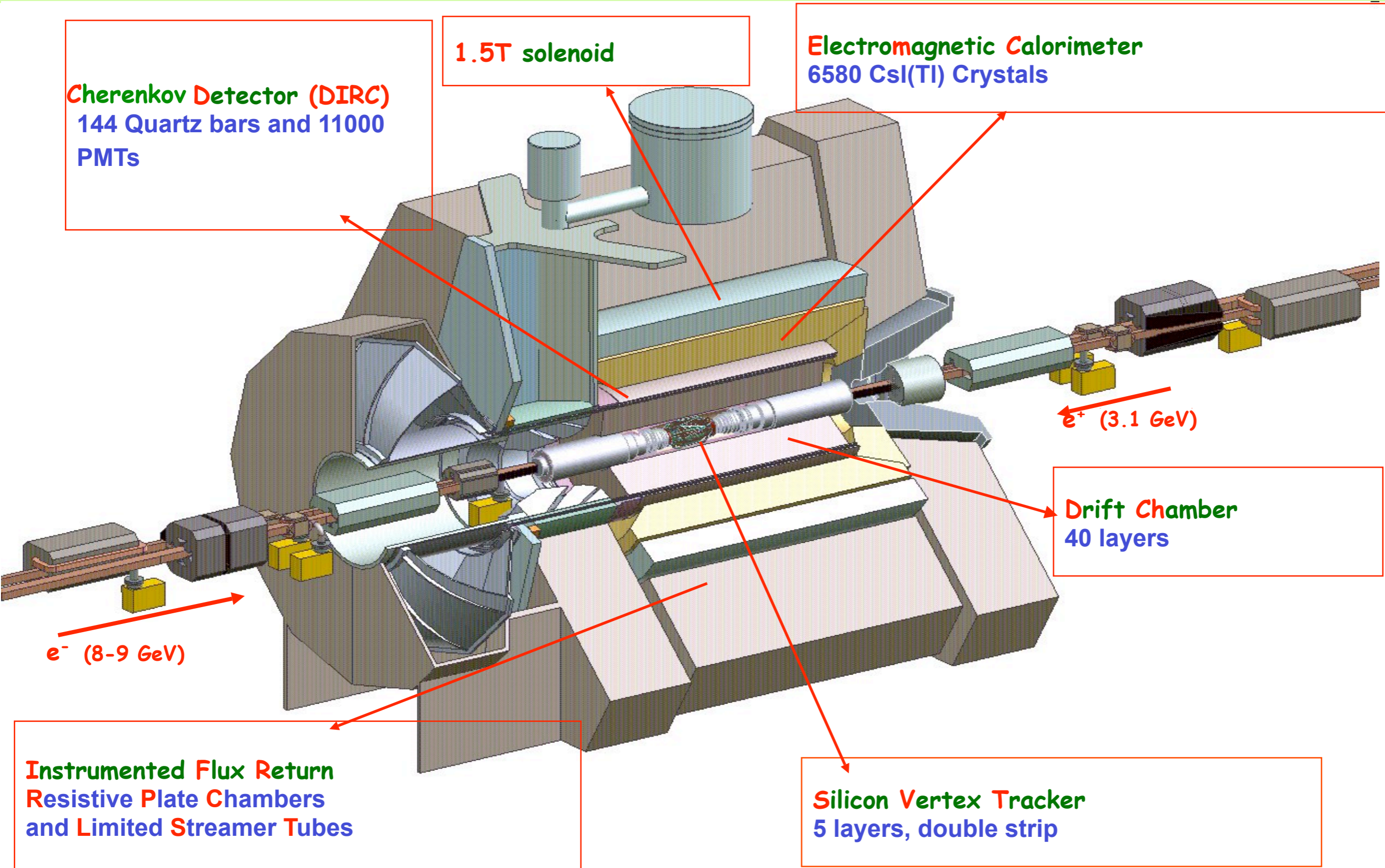
Improving Sensitivity for LFV discovery in Υ Decays:

~ 20 times more $\Upsilon(3S)$ decays than CLEO \Rightarrow lower limits by ~ 4

Improving Sensitivity for LFV discovery in τ Decays:

470 fb^{-1} @ $\Upsilon(4S)$, 30 fb^{-1} @ $\Upsilon(3S)$, 15 fb^{-1} @ $\Upsilon(2S)$ $\Rightarrow N_{\tau} \sim 10^9$

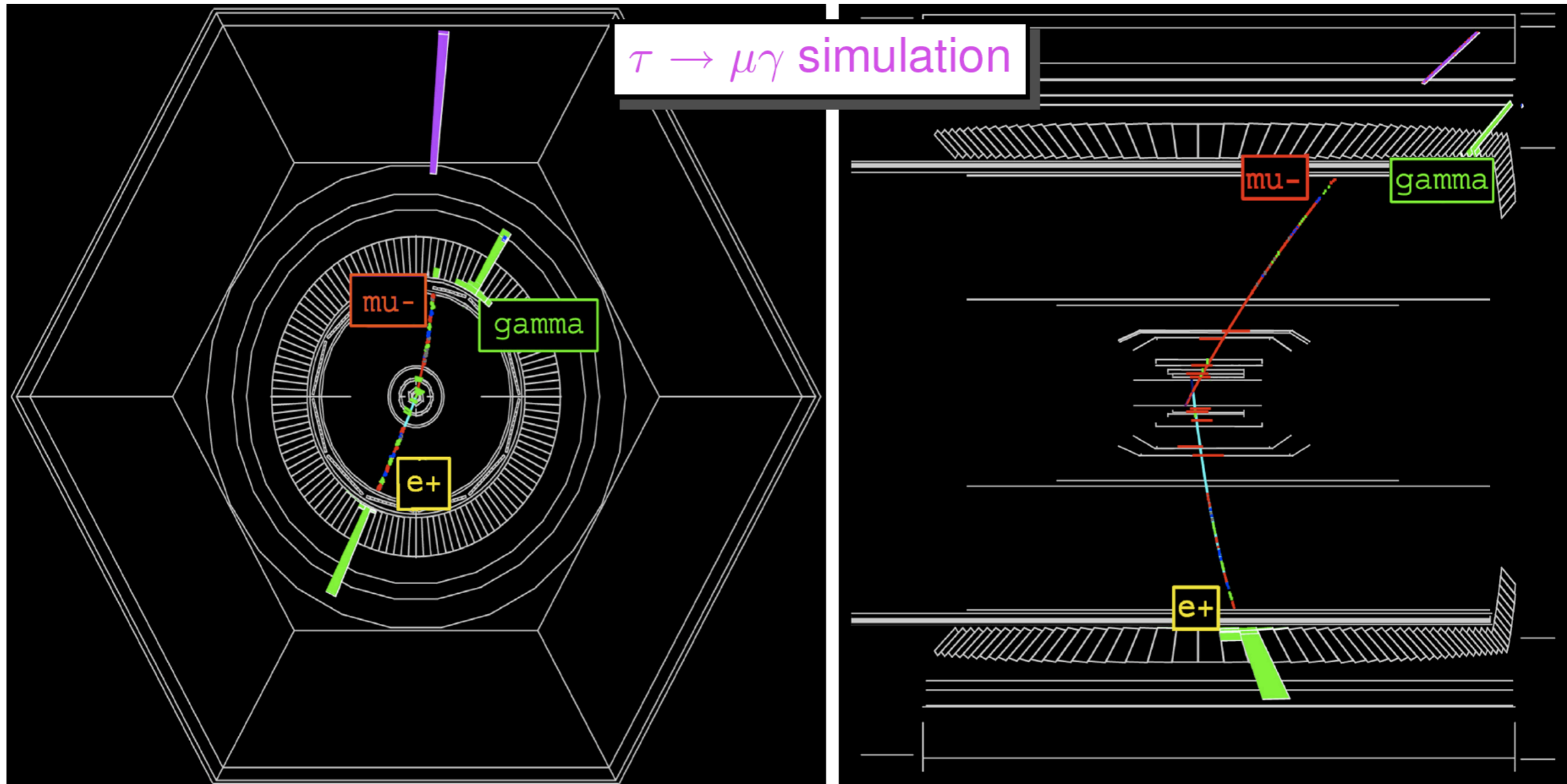
The BABAR Detector



$\tau \rightarrow \mu \gamma$: Signal Characteristics

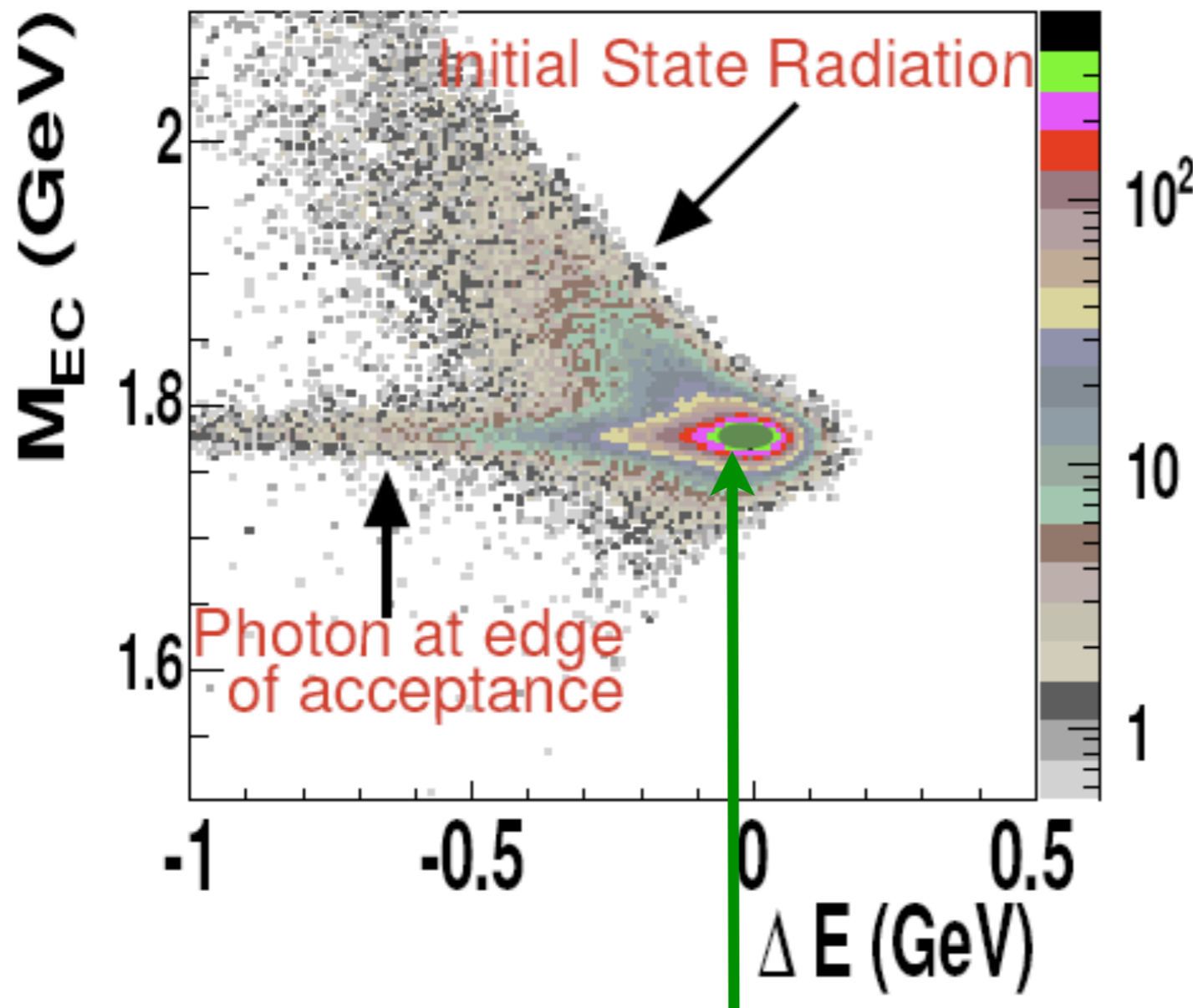
$m_{\mu\gamma} \sim m_\tau$

CM Frame: $\Delta E = \sqrt{P_\mu^2 + m_\mu^2} + E_\gamma - \sqrt{s}/2 \sim 0$



$\tau \rightarrow \mu \gamma$: Signal Characteristics

- (Energy, Mass)_{daughters} $\sim (\frac{\sqrt{s}}{2}, m_\tau)$ (upto resolution & radiation)



$\tau \rightarrow \mu \gamma$ simulation

$$\Delta E = E_{rec} - \frac{\sqrt{s}}{2} \sim 0$$

$$\sigma(\Delta E) \sim 42 \text{ MeV}$$

M_{EC} ($\sigma \sim 8.3 \text{ MeV}$)

Beam energy
constrained mass
after vertexing

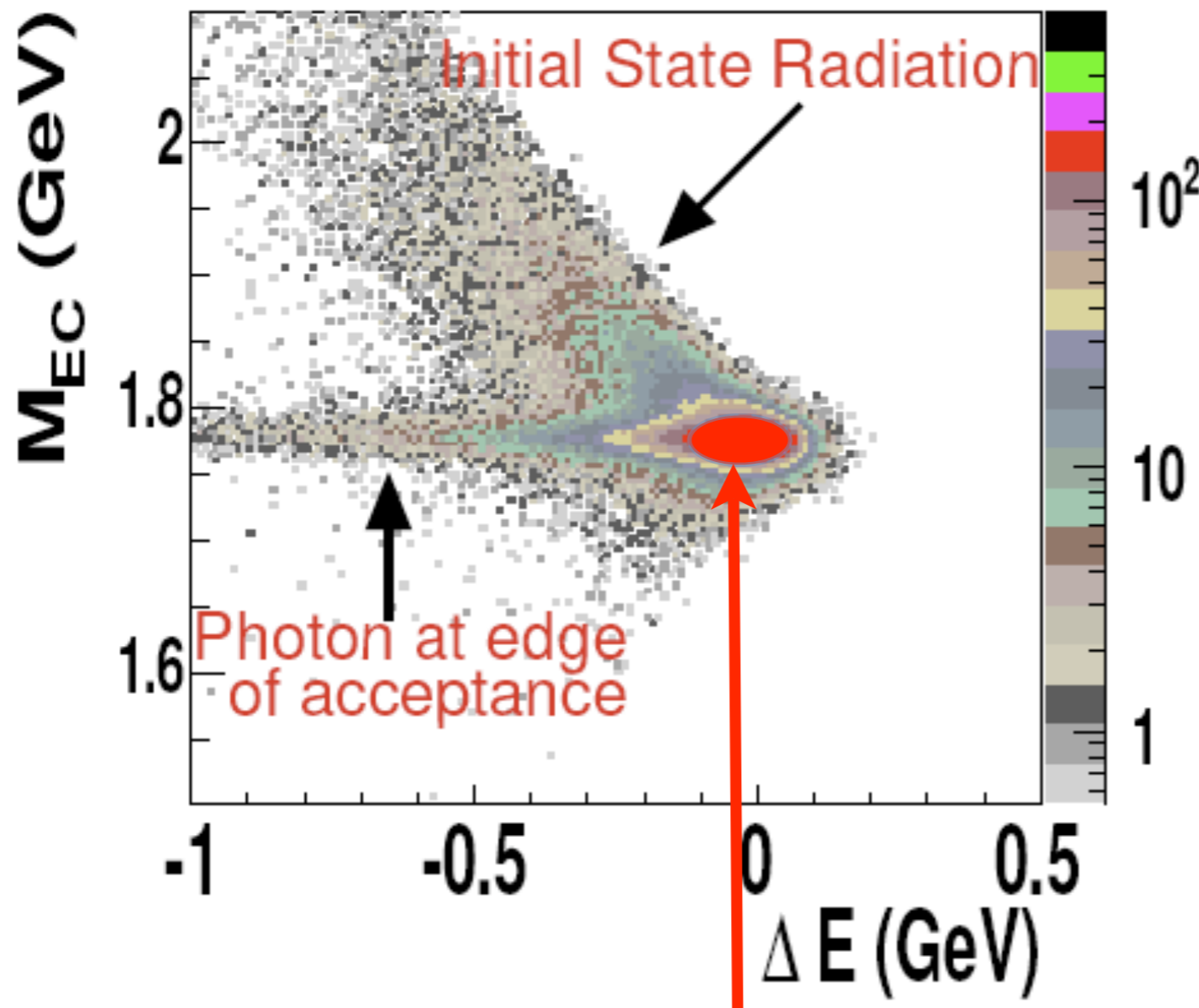
γ at μ POCA(XY)

[Inv. mass: $\sigma \sim 18 \text{ MeV}$]

Signal Region: $\pm 2 \sigma$ around $(\langle \Delta E \rangle, \langle M_{EC} \rangle)$

$\tau \rightarrow \mu \gamma$: Signal Characteristics

- (Energy, Mass)_{daughters} $\sim (\frac{\sqrt{s}}{2}, m_\tau)$ (upto resolution & radiation)



$\tau \rightarrow \mu \gamma$ simulation

$$\Delta E = E_{rec} - \frac{\sqrt{s}}{2} \sim 0$$

$$\sigma(\Delta E) \sim 42 \text{ MeV}$$

M_{EC} ($\sigma \sim 8.3 \text{ MeV}$)

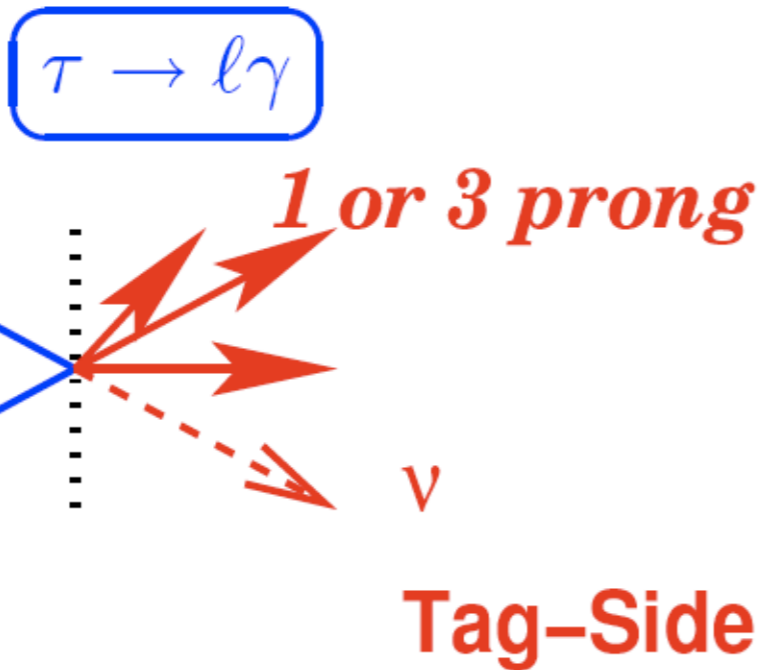
Beam energy
constrained mass
after vertexing

γ at μ POCA(XY)

[Inv. mass: $\sigma \sim 18 \text{ MeV}$]

Blinded Region: $\pm 3 \sigma$ around $(\langle \Delta E \rangle, \langle M_{EC} \rangle)$

Analysis Strategy in a clean $e^+e^- \rightarrow \tau^+\tau^-$ environment



Backgrounds:

- $\tau \rightarrow e\gamma$ ($\tau \rightarrow \mu\gamma$):
- Radiative Bhabha (di-muon)
- $\tau^+\tau^-\gamma$ ($\tau \rightarrow \ell\nu\bar{\nu}$)
- $q\bar{q}$ (γ)

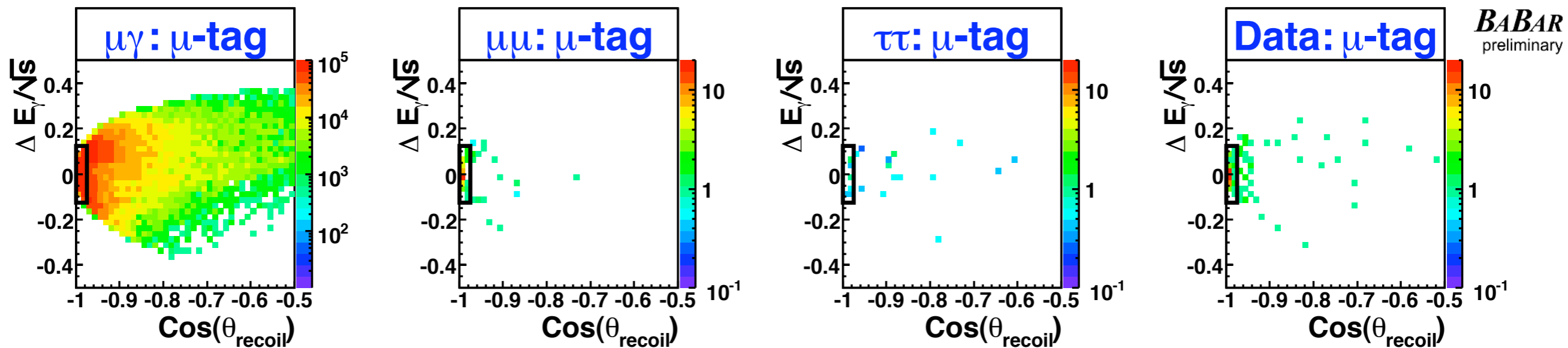
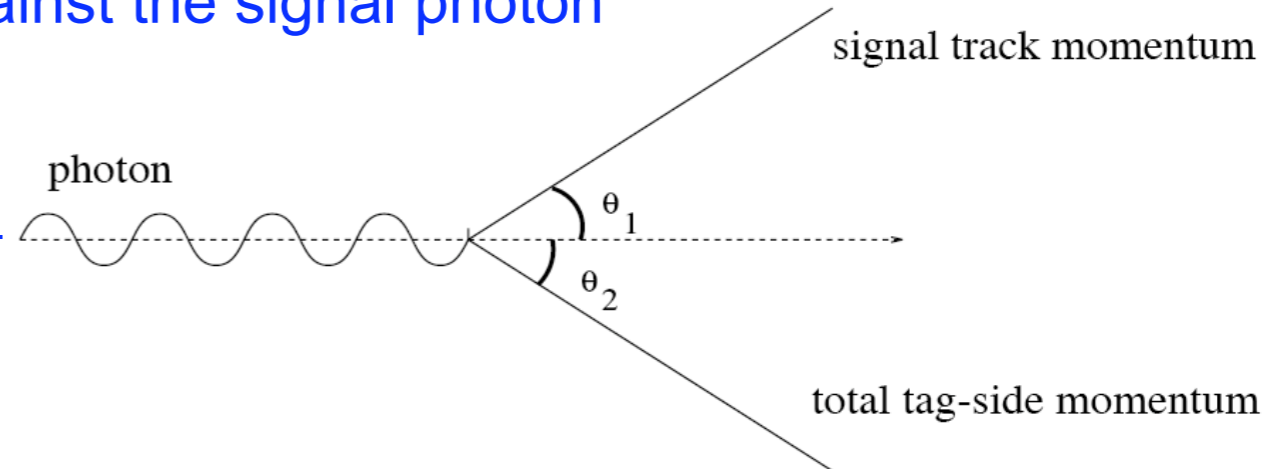
- Reconstruct final state from two or four charged tracks with zero total charge
- Divide event into signal-side and tag-side hemispheres perpendicular to Thrust axis
- Classify tag-side as e, μ , π , ρ , 3h tags
- For $\tau \rightarrow e\gamma$ search, veto e-tag because of very large radiative Bhabha cross-section
- For leptonic tags, reduce QED backgrounds characterized by zero missing momentum
- For hadronic tags, reduce backgrounds using cuts on tag-side missing mass
- Finally reduce remaining backgrounds using Neural Net based discriminators, tuned for each tag and at each center-of-mass energy
- Study backgrounds in Grand Signal Box (GSB)
 - $1.55 \text{ GeV}/c^2 < m_{\text{EC}} < 2.05 \text{ GeV}/c^2$
 - $-1.0 \text{ GeV} < \Delta E < 0.5 \text{ GeV}$.

QED Backgrounds in Leptonic Tags

Exploit correlation between 2 kinematic variables:

cosine of the opening angle $\cos(\theta_{recoil})$ between the signal-track and the total observed tag-side momentum in the reference frame recoiling against the signal photon

$$\frac{\Delta E_\gamma}{\sqrt{s}} \equiv \frac{E_\gamma^{CM}}{\sqrt{s}} - \frac{|\sin(\theta_1 + \theta_2)|}{\sin \theta_1 + \sin \theta_2 + |\sin(\theta_1 + \theta_2)|}$$



In both e and μ tags in $\tau \rightarrow \mu \gamma$ search, remove events passing

$$|\Delta E_\gamma| < 0.125\sqrt{s} \text{ and } \cos \theta_{recoil} < -0.975$$

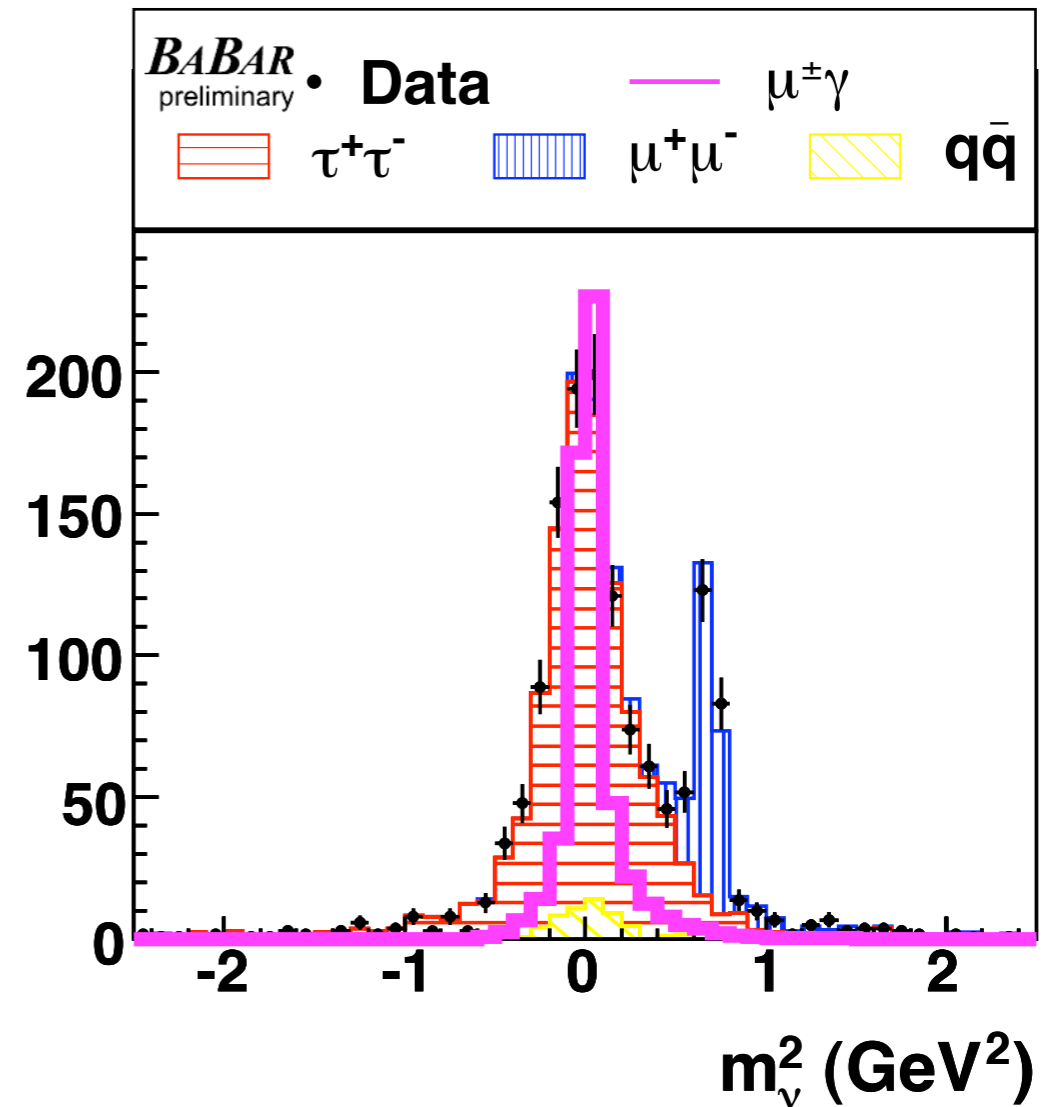
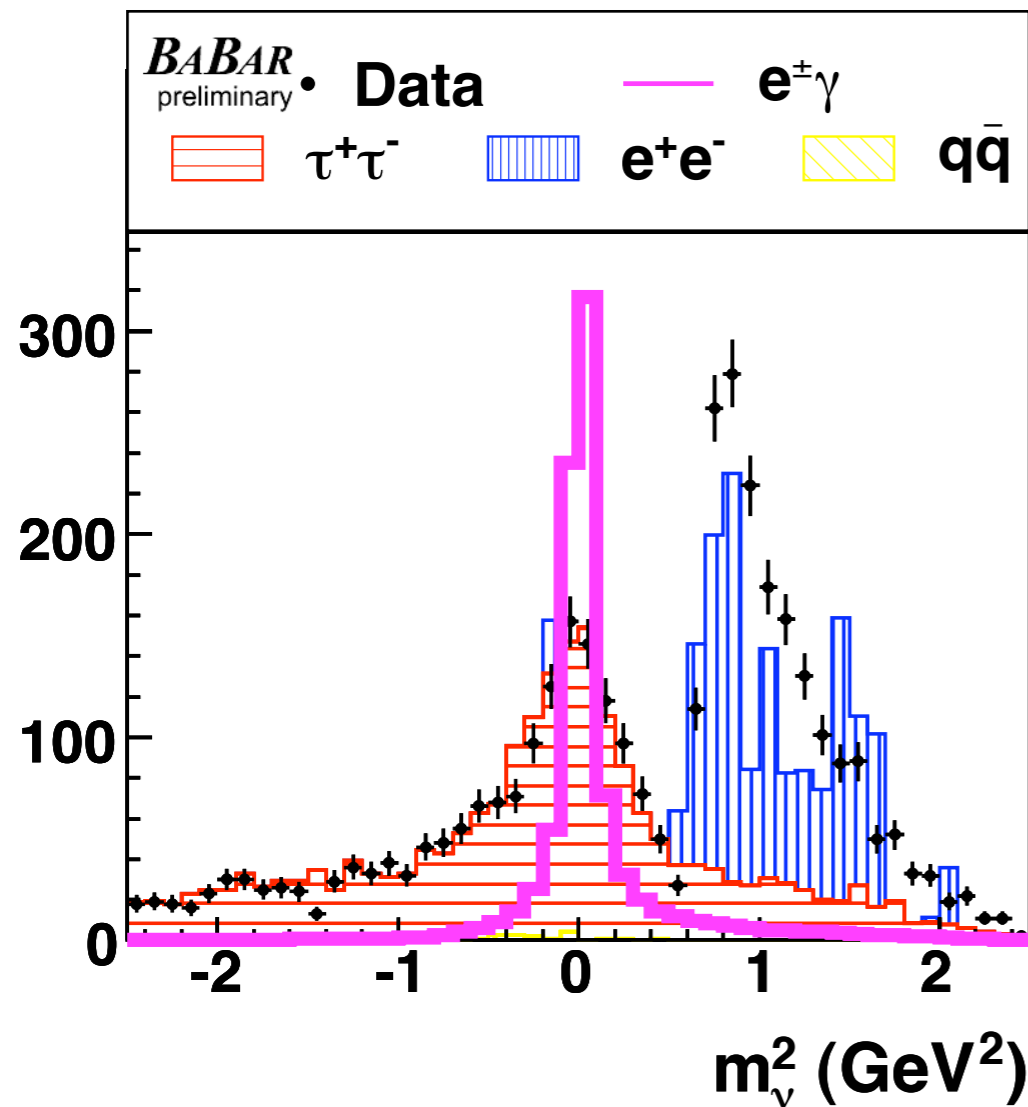
In $\tau \rightarrow e \gamma$ search, not enough background events in μ tag \Rightarrow so no additional cut needed

Tag-side Missing Mass for Hadronic Tags

- Exploit the unique feature that signal-side τ decay is neutrino-less
 \Rightarrow fully reconstruct the direction of tag-side τ assumed to be $\sqrt{s}/2$ in CM frame

$$\tau^\pm \rightarrow e^\pm \gamma$$

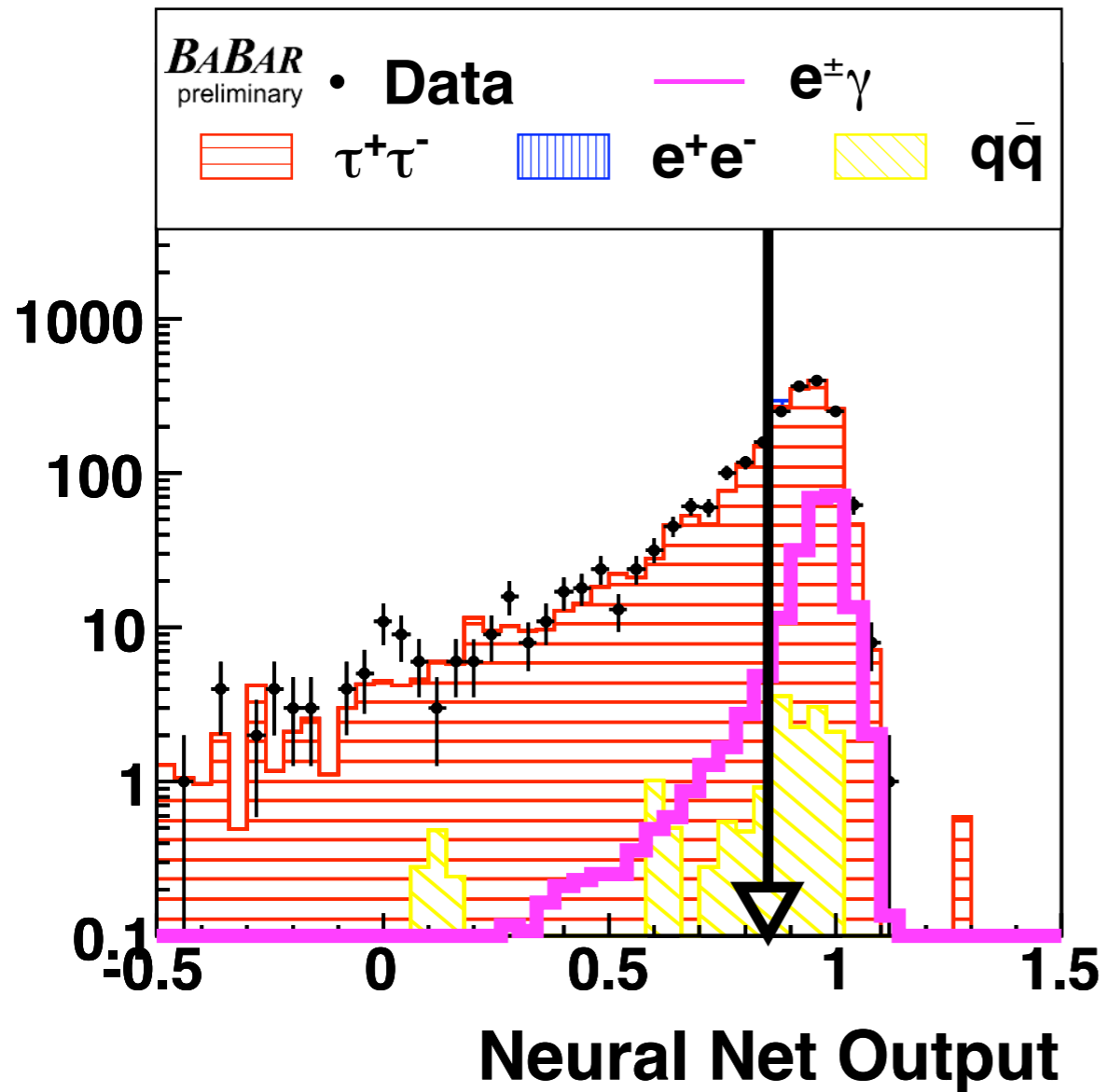
$$\tau^\pm \rightarrow \mu^\pm \gamma$$



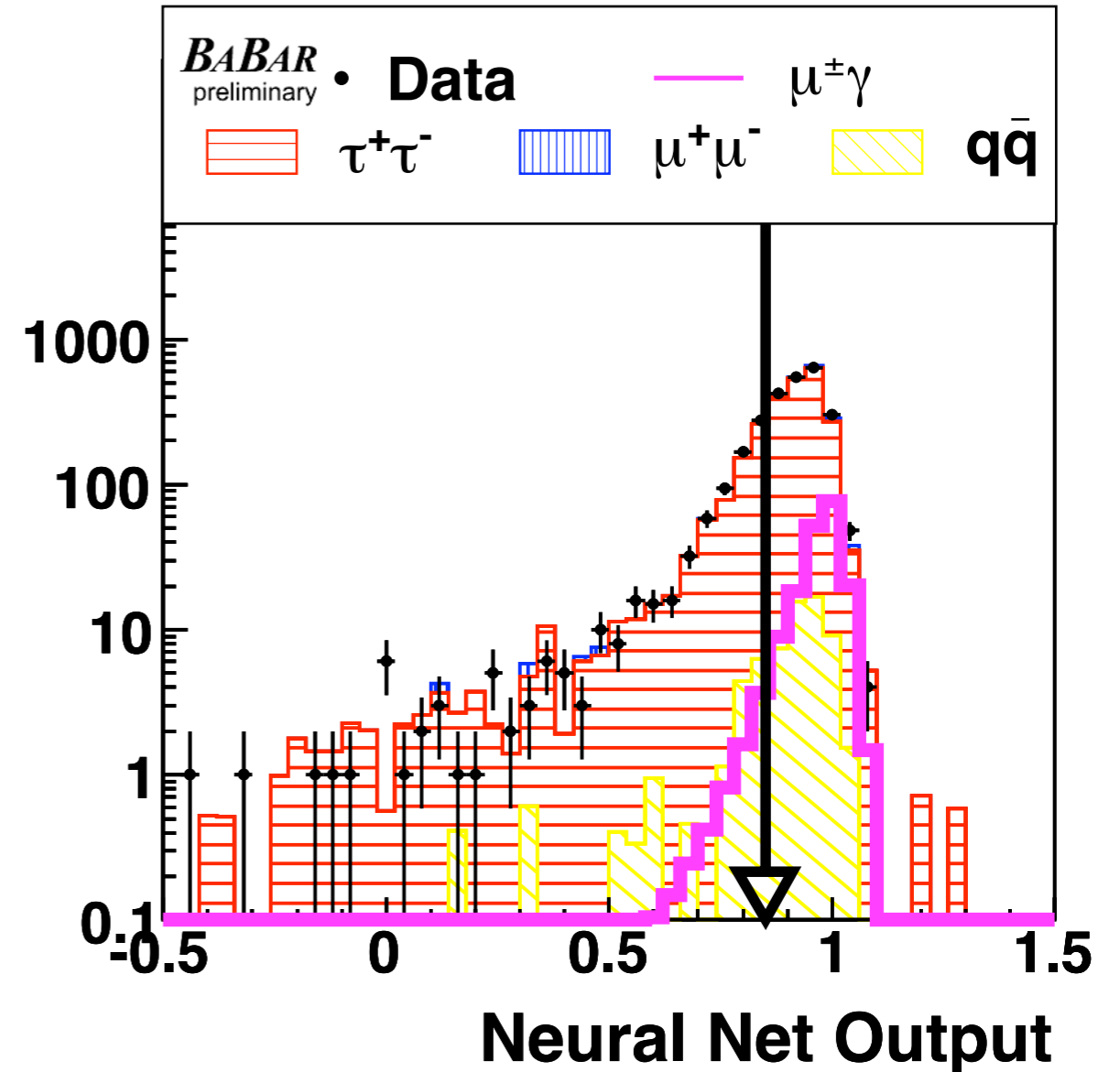
Require: $|m_\nu^2| < 0.25 \text{ GeV}^2$ for π^- - and $3h$ -tags, and $|m_\nu^2| < 0.50 \text{ GeV}^2$ for ρ -tag.

Neural Net Based discriminator

$$\tau^\pm \rightarrow e^\pm \gamma:$$



$$\tau^\pm \rightarrow \mu^\pm \gamma:$$



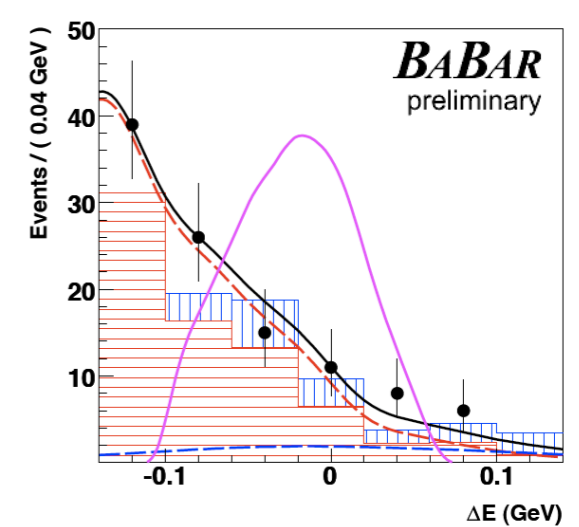
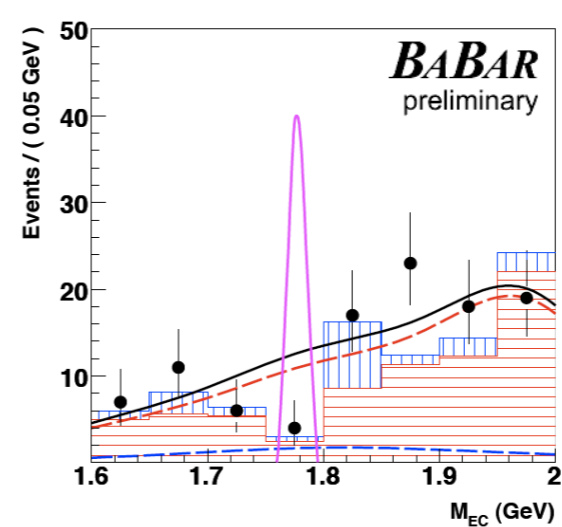
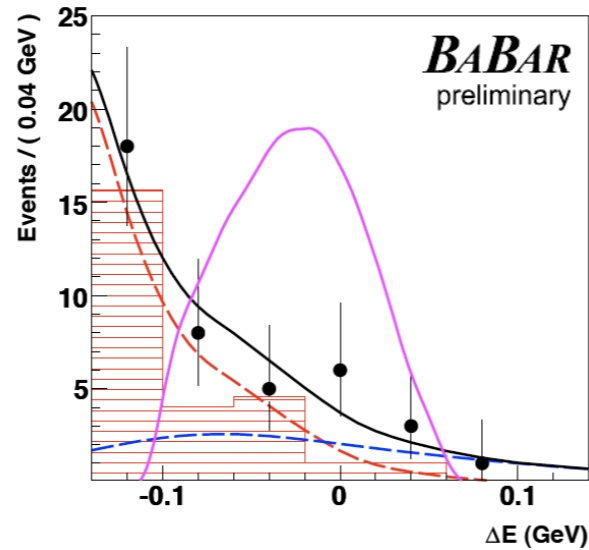
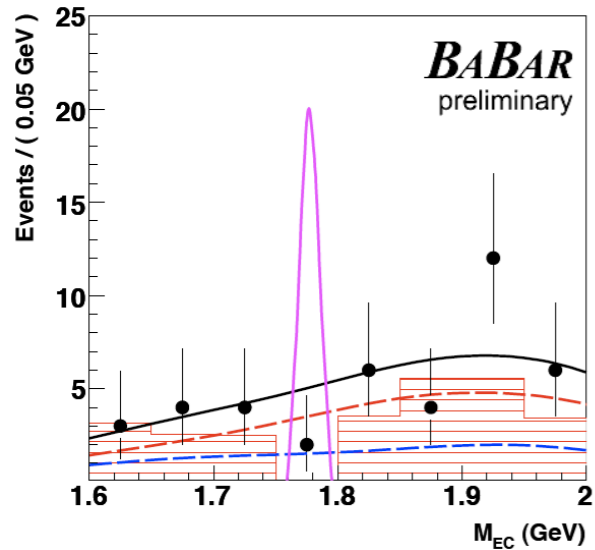
A cut of NN output $> .85$ improves Signal/Background by 40% for $\tau \rightarrow e \gamma$ search and by 30% for $\tau \rightarrow \mu \gamma$ search

2-dim Fit with Background PDFs only

$$PDF_{tot} = (f_{e^+e^-/\mu^+\mu^-} \times PDF_{e^+e^-/\mu^+\mu^-}) + ([1 - f_{e^+e^-/\mu^+\mu^-}] \times PDF_{\tau})$$

$$\tau^{\pm} \rightarrow e^{\pm}\gamma:$$

$$\tau^{\pm} \rightarrow \mu^{\pm}\gamma:$$



The number of background events ($N_{2\sigma}^{data}$) inside the $\pm 2\sigma$ ellipse is estimated as:

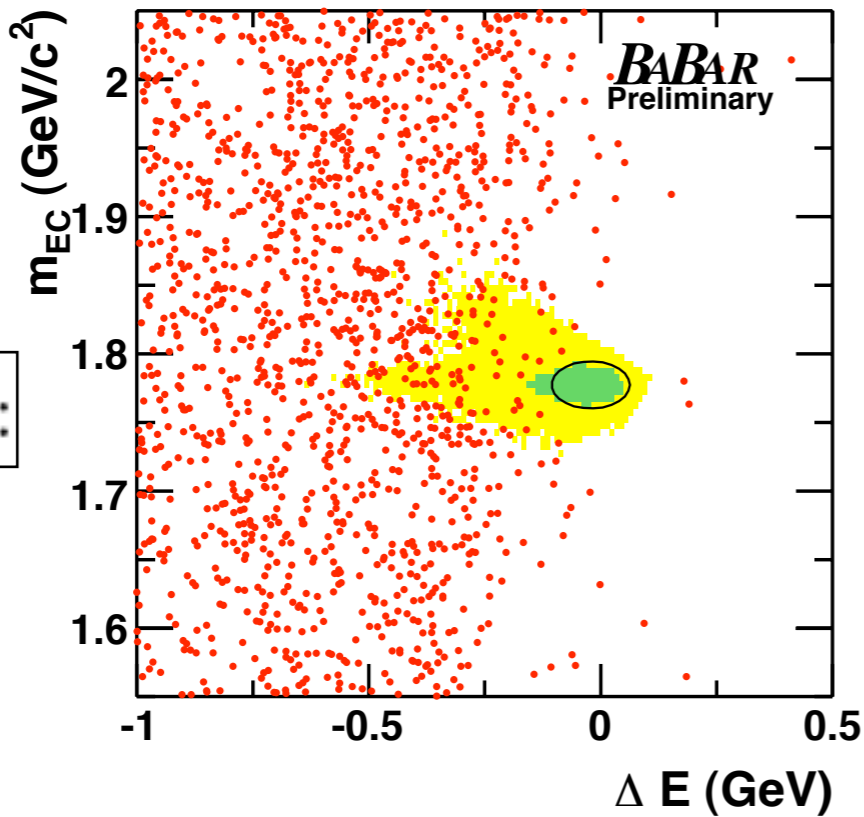
$$N_{2\sigma}^{data} = \frac{\int_{2\sigma} PDF_{tot}}{\int_{FitBox-3\sigma} PDF_{tot}} \times N_{FitBox-3\sigma}^{data}$$

Cross-check neighbouring ellipses shifted in the mass variable:

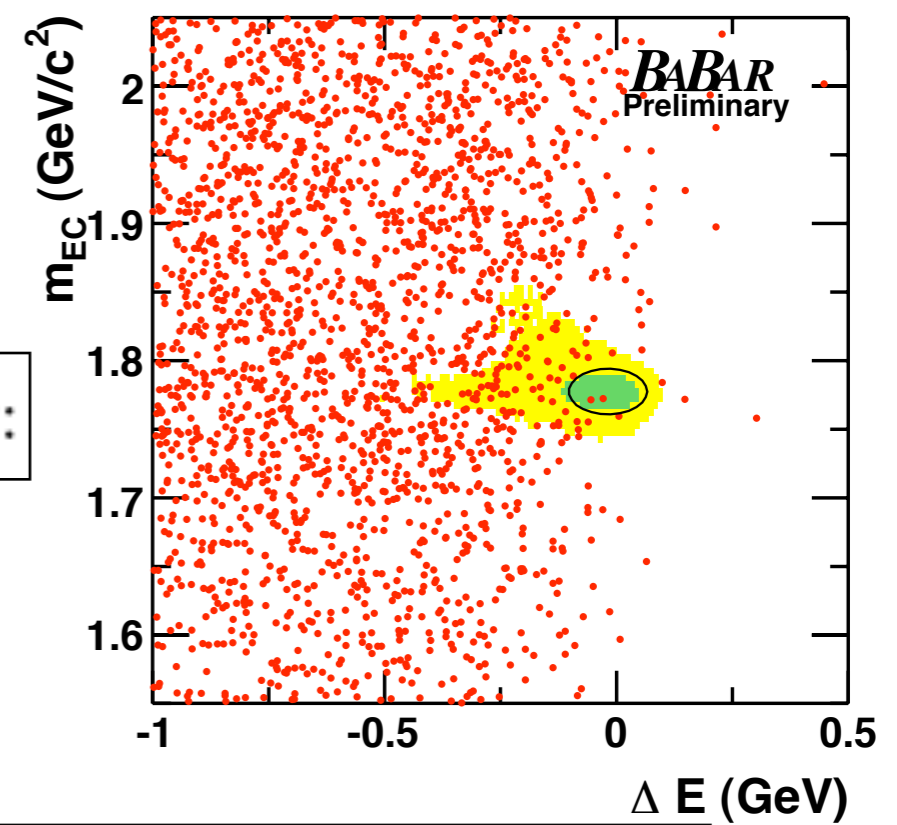
Decay modes	# of events	-9 σ	-5 σ	0	+5 σ	+9 σ
$\tau^{\pm} \rightarrow e^{\pm}\gamma$	Observed	2	1	?	2	2
	Expected	1.2 \pm 0.2	1.4 \pm 0.2	1.6 \pm 0.3	1.9 \pm 0.3	2.1 \pm 0.3
$\tau^{\pm} \rightarrow \mu^{\pm}\gamma$	Observed	3	1	?	4	6
	Expected	2.8 \pm 0.3	3.1 \pm 0.3	3.6 \pm 0.4	4.2 \pm 0.4	4.8 \pm 0.5

Results

$$\tau^\pm \rightarrow e^\pm \gamma$$



$$\tau^\pm \rightarrow \mu^\pm \gamma$$



N_τ

$(963 \pm 7) \times 10^6$

$\tau^\pm \rightarrow e^\pm \gamma$ search

Number of background events expected in 2σ signal ellipse

(1.6 ± 0.4)

Efficiency in 2σ signal ellipse

$(3.9 \pm 0.3)\%$

Expected Feldman & Cousins Upper Limit (w/o systmatics)

$\mathcal{B}(\tau^\pm \rightarrow e^\pm \gamma) < 9.8 \times 10^{-8}$ at 90% CL

Expected Feldman & Cousins Upper Limit (with systmatics)

$\mathcal{B}(\tau^\pm \rightarrow e^\pm \gamma) < 9.8 \times 10^{-8}$ at 90% CL

Numbers of events observed in 2σ signal ellipse

0

Observed Feldman & Cousins Upper Limit

$\mathcal{B}(\tau^\pm \rightarrow e^\pm \gamma) < 3.3 \times 10^{-8}$ at 90% CL

NEW

$\tau^\pm \rightarrow \mu^\pm \gamma$ search

Number of background events expected in 2σ signal ellipse

(3.6 ± 0.7)

Efficiency in 2σ signal ellipse

$(6.1 \pm 0.5)\%$

Expected Feldman & Cousins Upper Limit (w/o systmatics)

$\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \gamma) < 7.9 \times 10^{-8}$ at 90% CL

Expected Feldman & Cousins Upper Limit (with systmatics)

$\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \gamma) < 8.2 \times 10^{-8}$ at 90% CL

Numbers of events observed in 2σ signal ellipse

2

Observed Feldman & Cousins Upper Limit

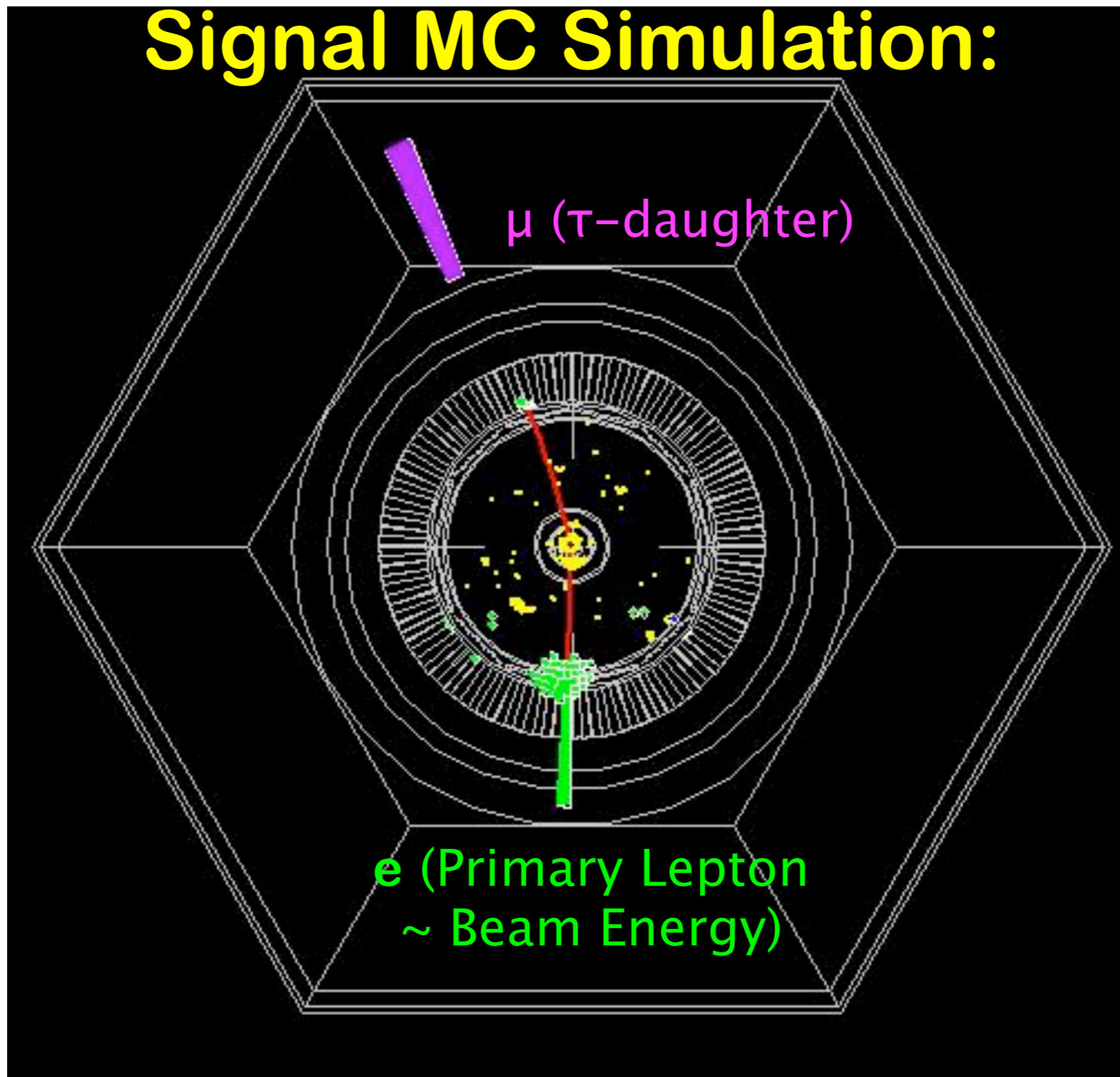
$\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \gamma) < 4.4 \times 10^{-8}$ at 90% CL

NEW

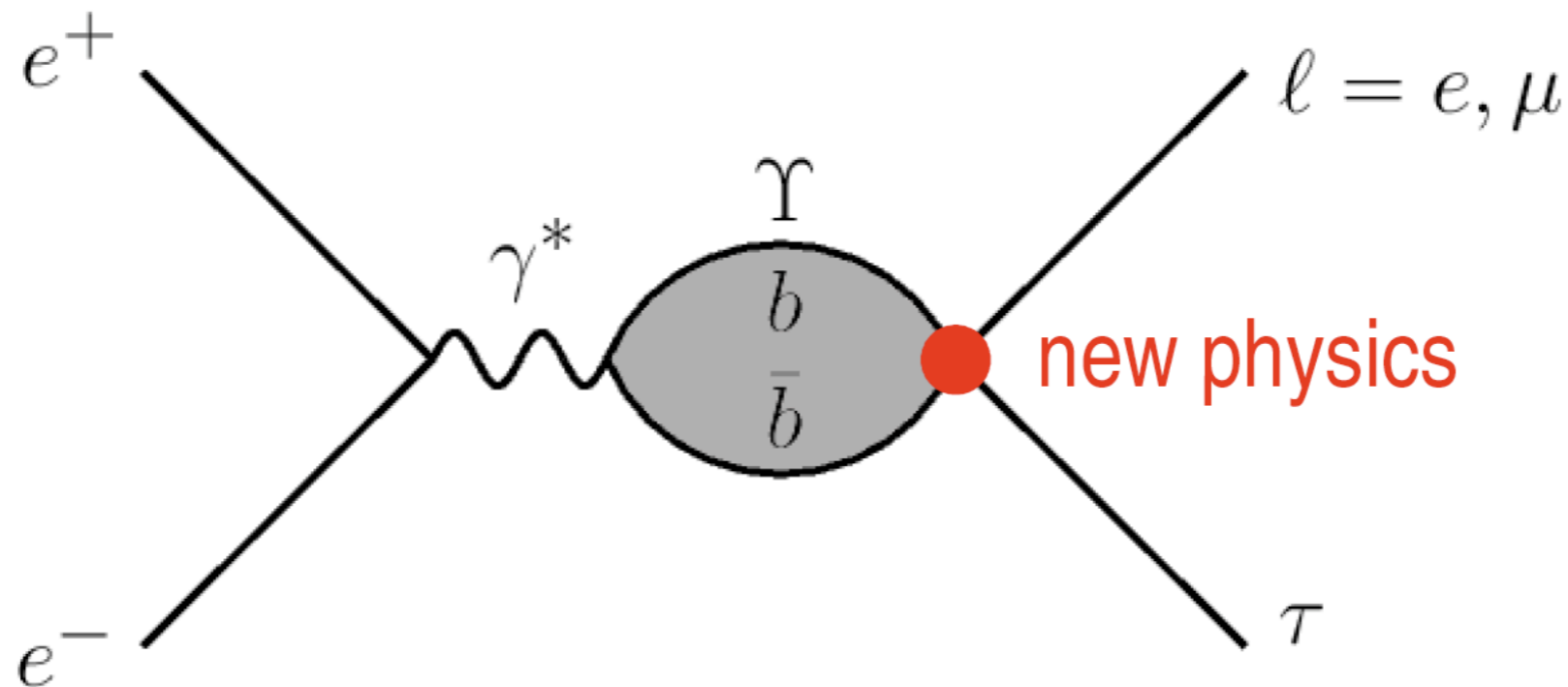


$\Upsilon \rightarrow e\tau, \tau \rightarrow \mu\nu\nu$: Signal Characteristics

Signal MC Simulation:



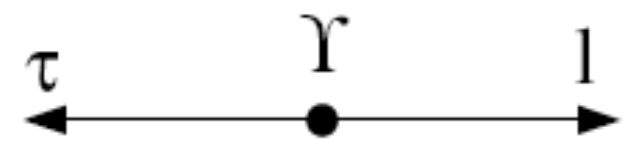
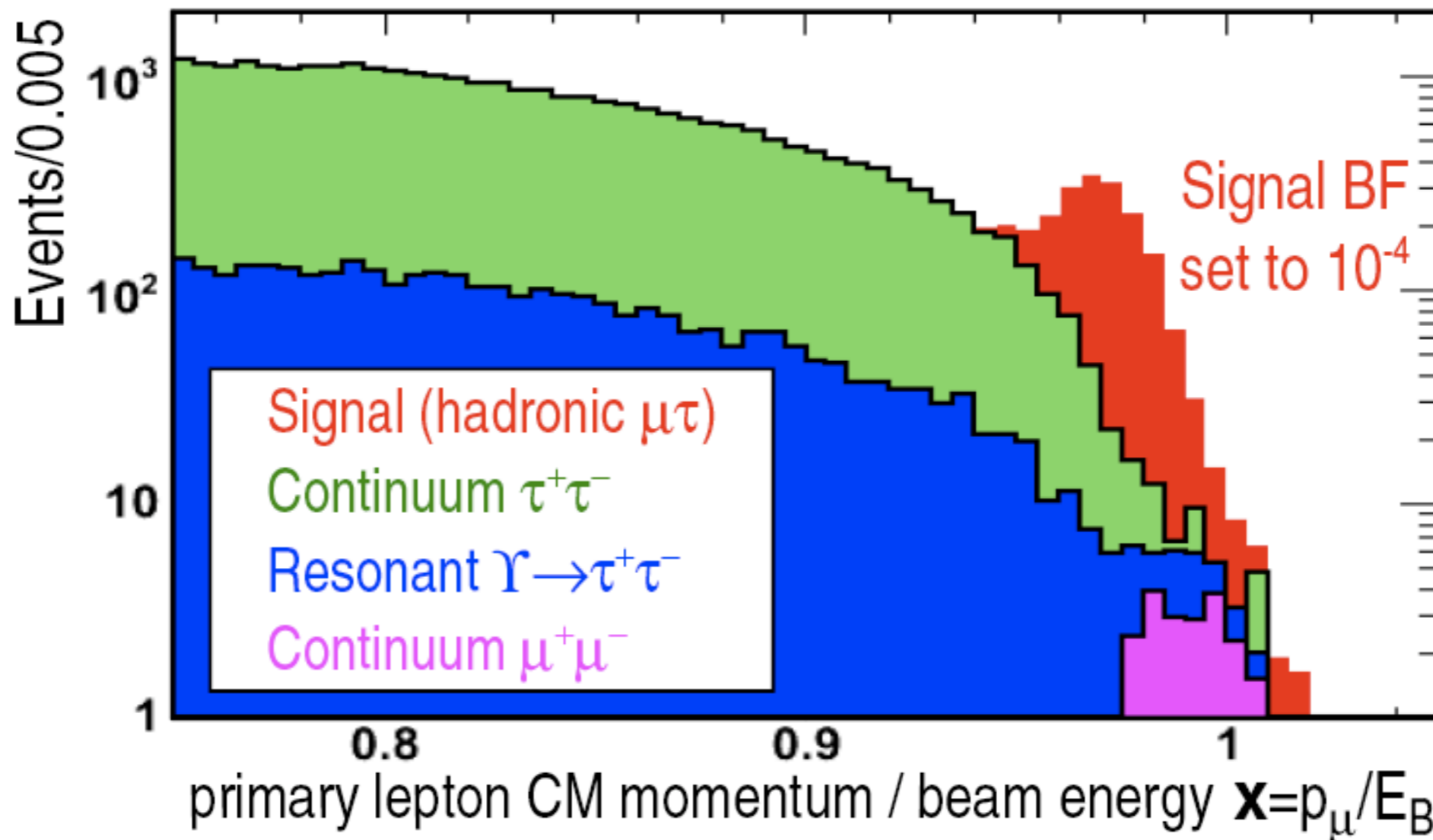
Event Selection



- Reconstruct final state from
 - two oppositely charged tracks
 - one or two additional neutral pions
- Primary lepton (e/μ) near beam energy
- τ decay with missing energy in other hemisphere decaying into a lepton with opposite flavor or ρ/a₁
- τ decay with same flavor lepton or a single π vetoed to reduce QED bkgd.

Process	τ Decay	Channel
$\Upsilon(3S) \rightarrow e\tau$	$\tau \rightarrow \mu\nu\nu$	leptonic eτ
$\Upsilon(3S) \rightarrow e\tau$	$\tau \rightarrow \pi^{\pm}\pi^0\nu / \pi^{\pm}\pi^0\pi^0\nu$	hadronic eτ
$\Upsilon(3S) \rightarrow \mu\tau$	$\tau \rightarrow e\nu\nu$	leptonic μτ
$\Upsilon(3S) \rightarrow \mu\tau$	$\tau \rightarrow \pi^{\pm}\pi^0\nu / \pi^{\pm}\pi^0\pi^0\nu$	hadronic μτ

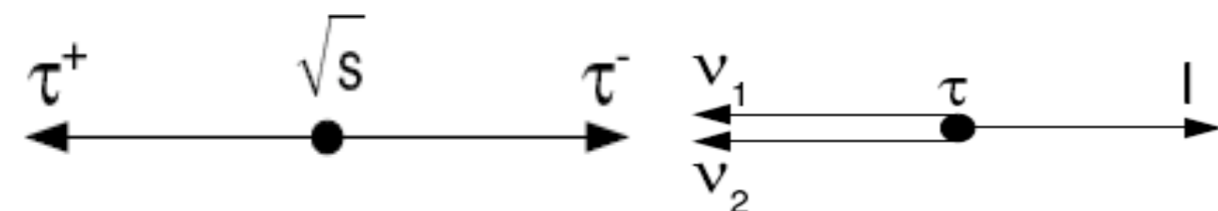
The discriminating variable



$$E_l = (m_\Upsilon^2 - m_\tau^2 + m_l^2) / (2m_\Upsilon) \quad p_l / E_B = \sqrt{4(E_l^2 - m_l^2) / m_\Upsilon^2}$$

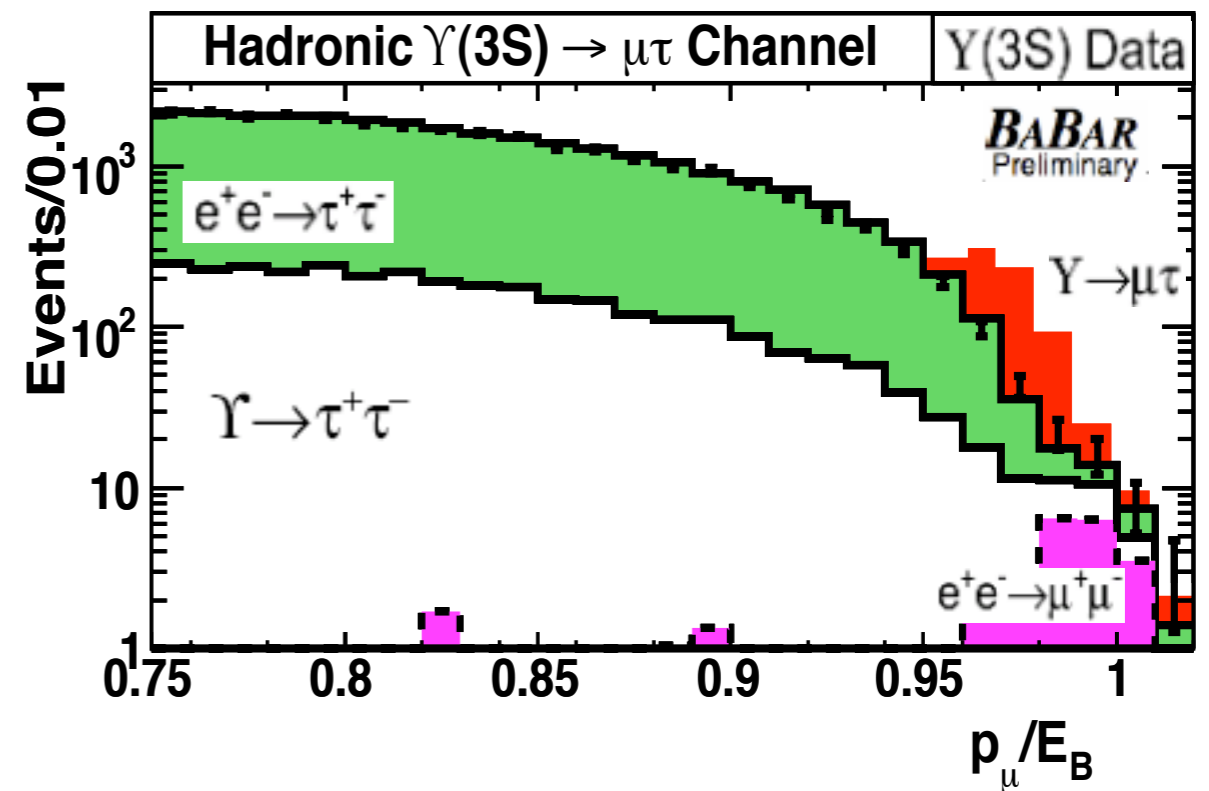
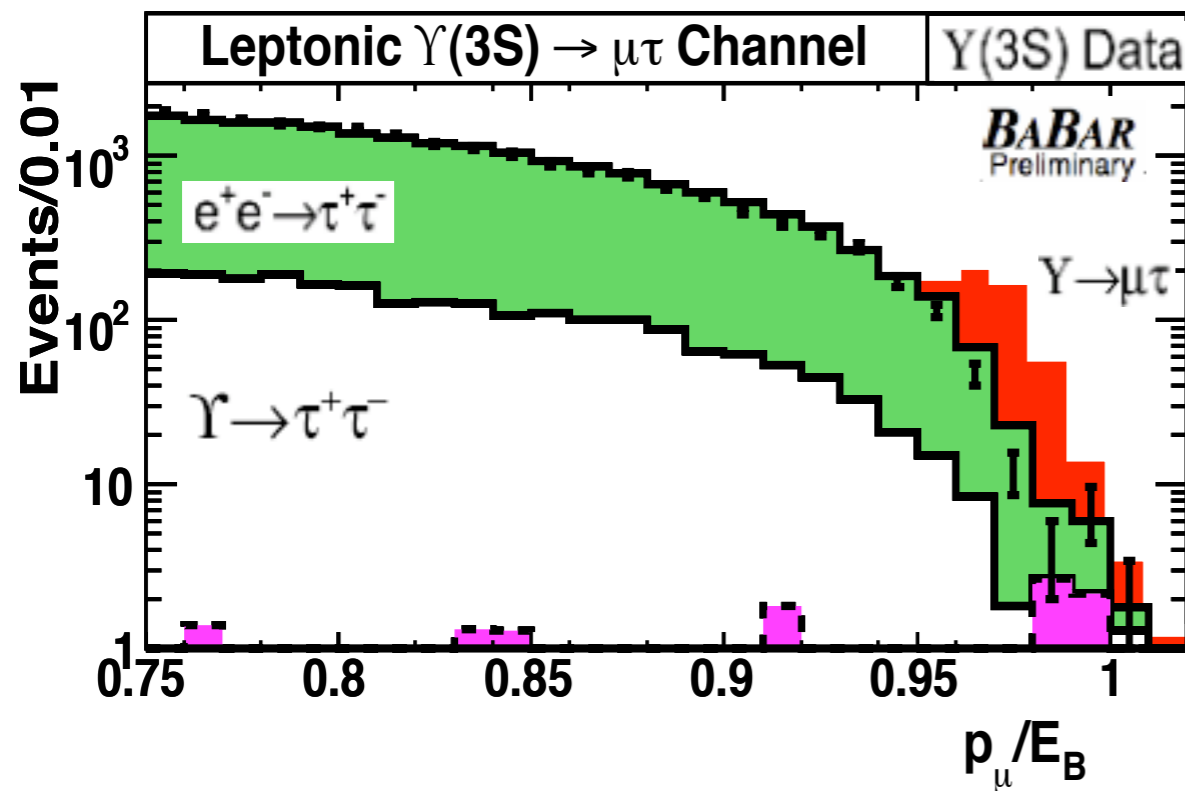
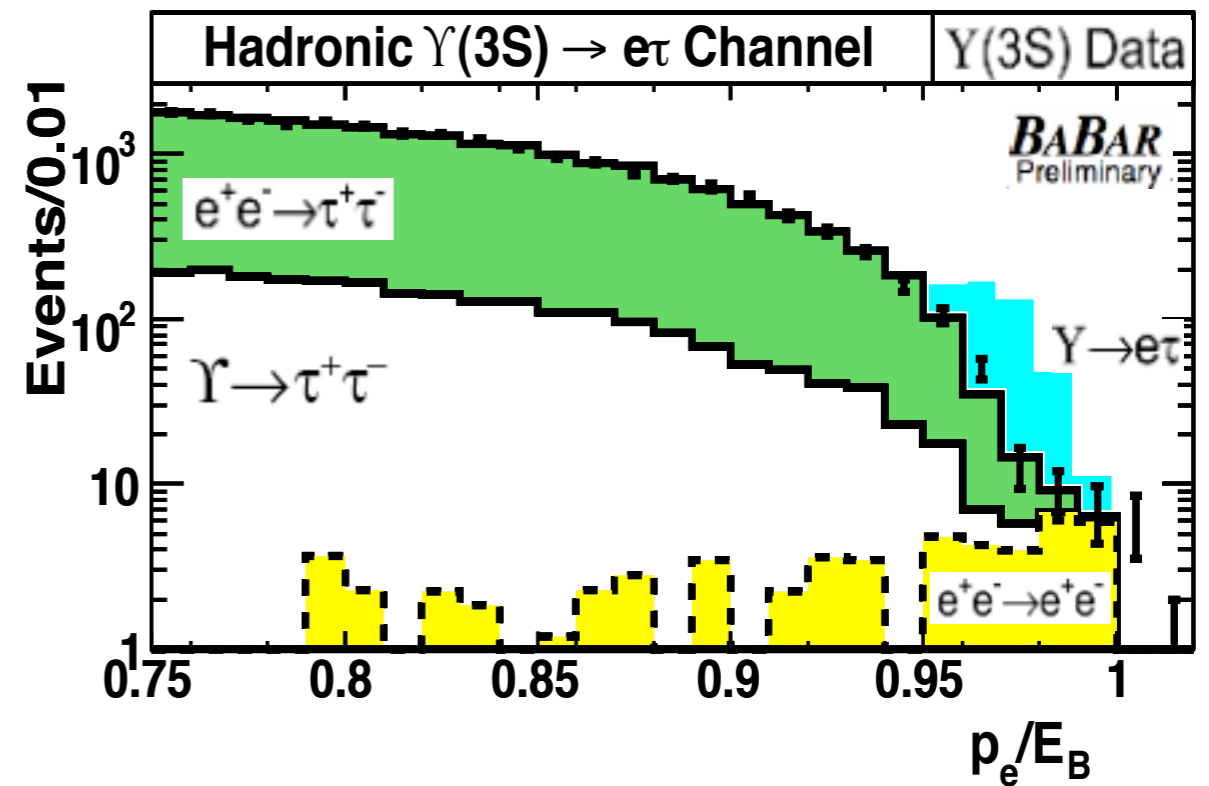
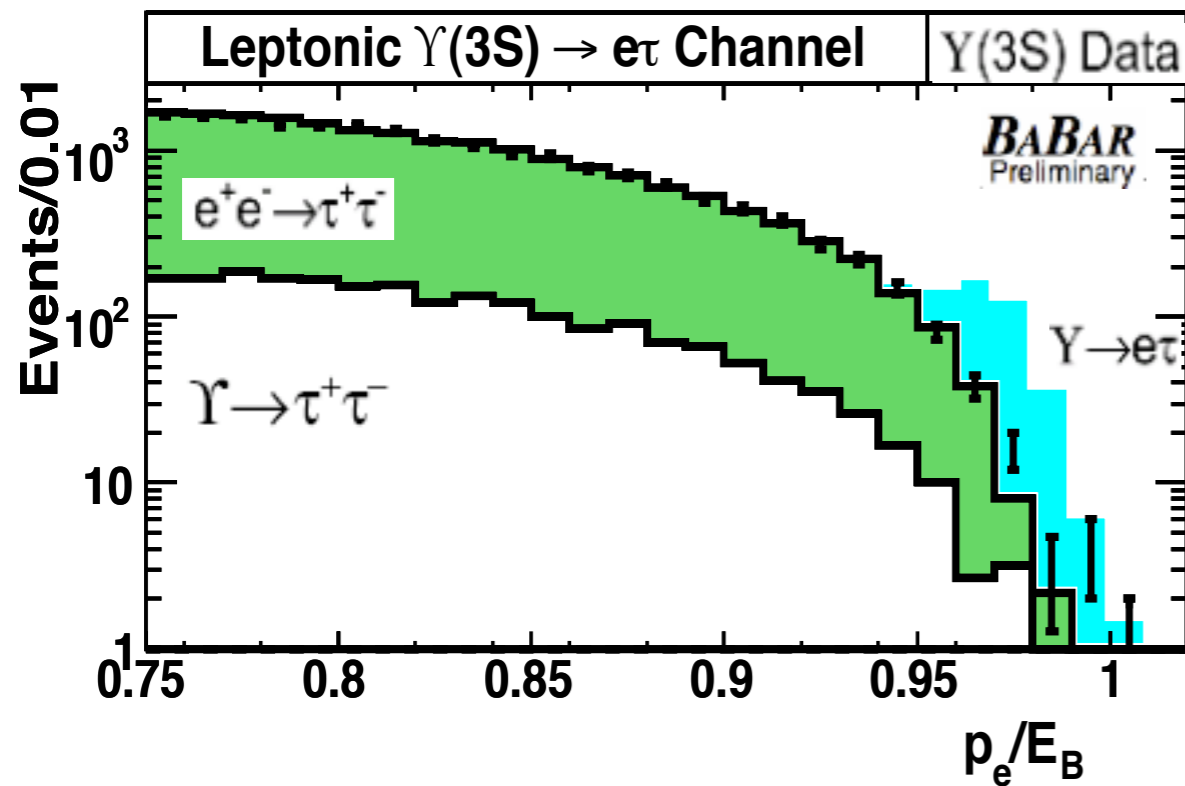
Signal: peak ~ 0.97

Bhabha/Mu-pair Background: peak ~ 1.0

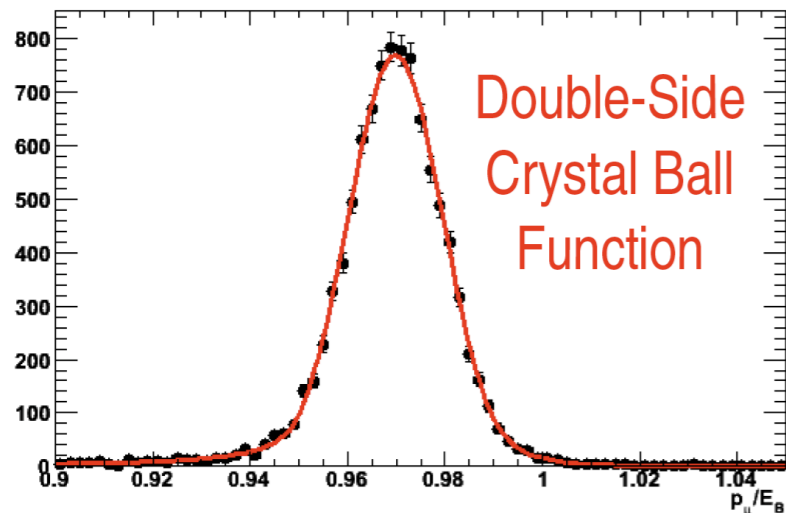


Tau-pair Background: Kinematic cut-off ~ 0.97

The primary lepton momentum spectrum

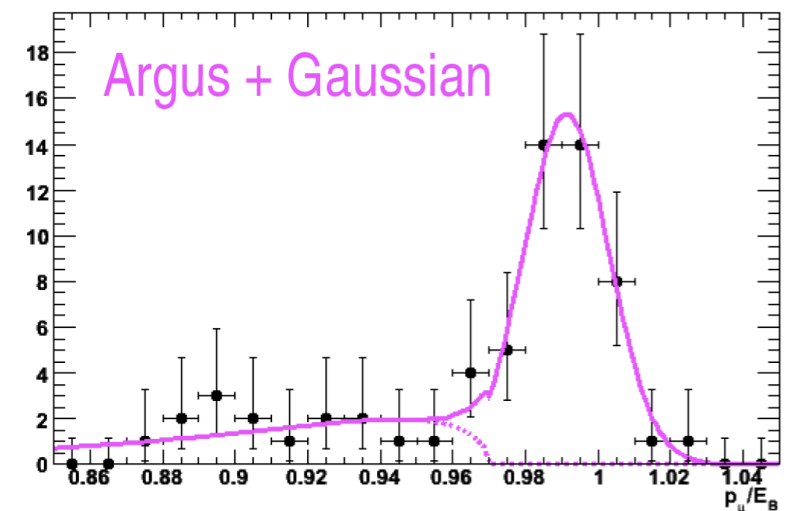


Signal and background shapes



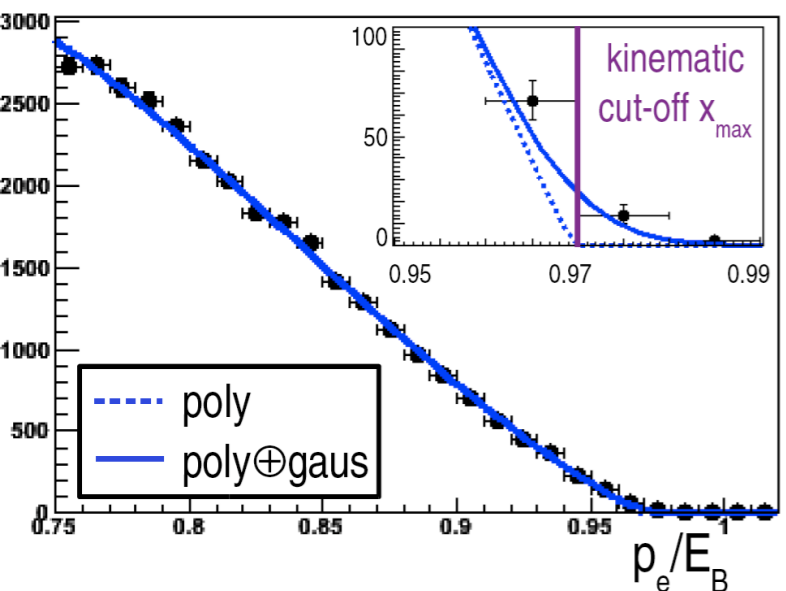
← • Signal PDF: double-sided CB function peaked at $x=p_1/E_B = 0.97$

– Extract shape from fits to signal MC



← • Bhabha/m-pair Background PDF: Argus threshold function + Gaussian peaked at $x \approx 1$

– Extract shape from fits to signal MC



← • τ -Pair Background PDF: 3rd-order poly \oplus detector resolution function

– $\text{poly}(x) = (1-x/x_{\text{MAX}}) + c_2(1-x/x_{\text{MAX}})^2 + c_3(1-x/x_{\text{MAX}})^3$

• x_{MAX} = kinematic cutoff parameter: extracted from fit to $\Upsilon(4S)$ data control sample

• c_2, c_3 = polynomial shape parameters: floated in fit to $\Upsilon(3S)$ data

– detector resolution function extracted from MC

• Global PDF = signal + bhabha (μ -pair) + τ -Pair components for $e\tau$ ($\mu\tau$) channels

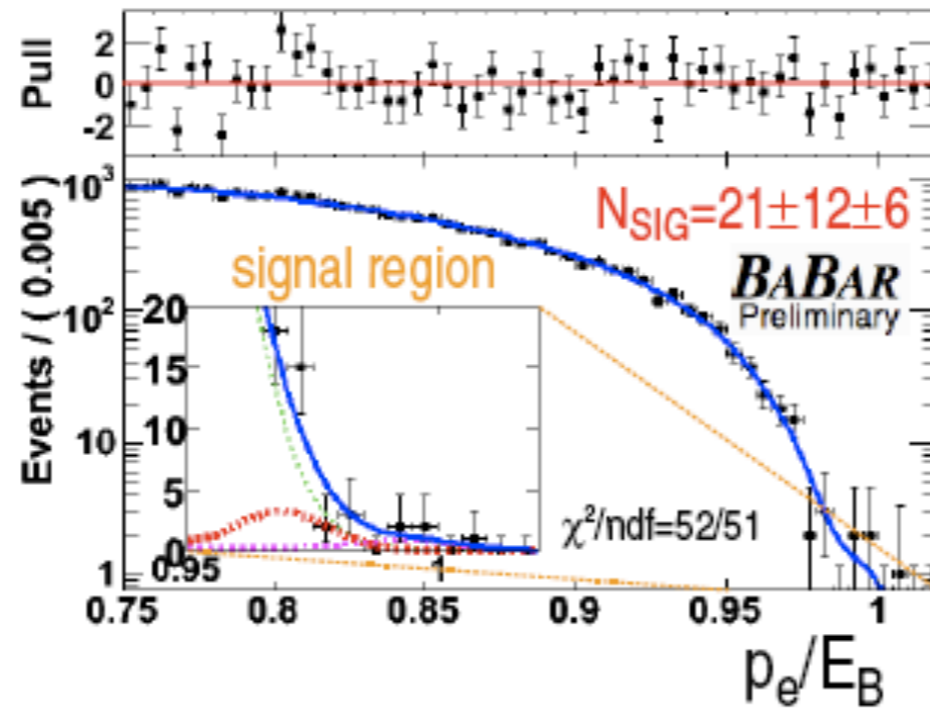
– Float component yields and polynomial shape parameters in fit to $\Upsilon(3S)$ data

Fit Results

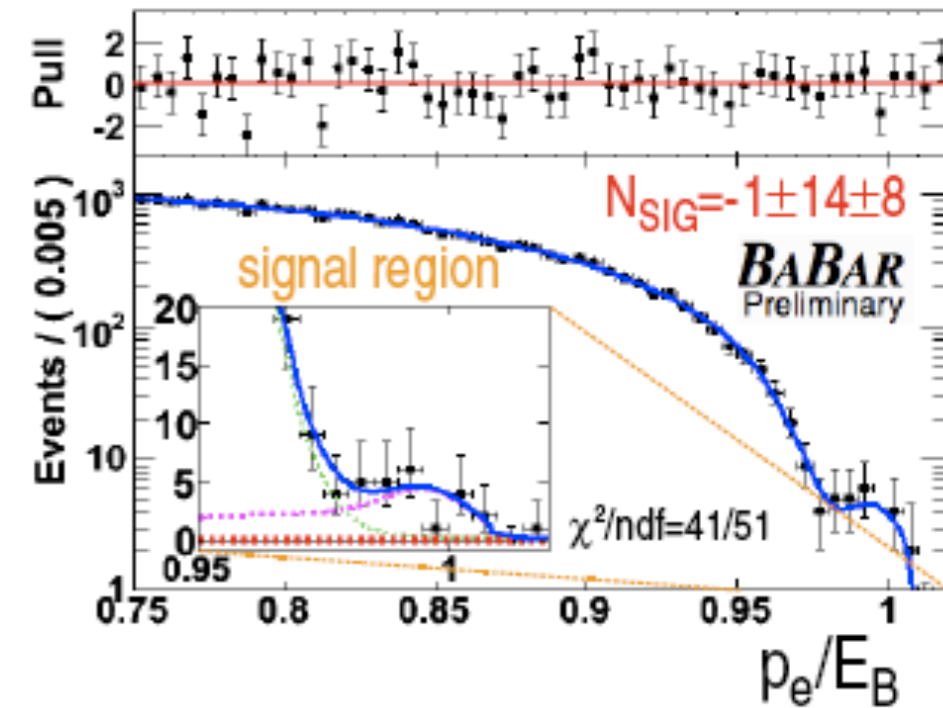
Global PDF
 Signal
 τ -pair Bkg
 Bhabha/
 μ -pair Bkg

All channels
give signal
yield within
 $\pm 2.1\sigma$ of zero

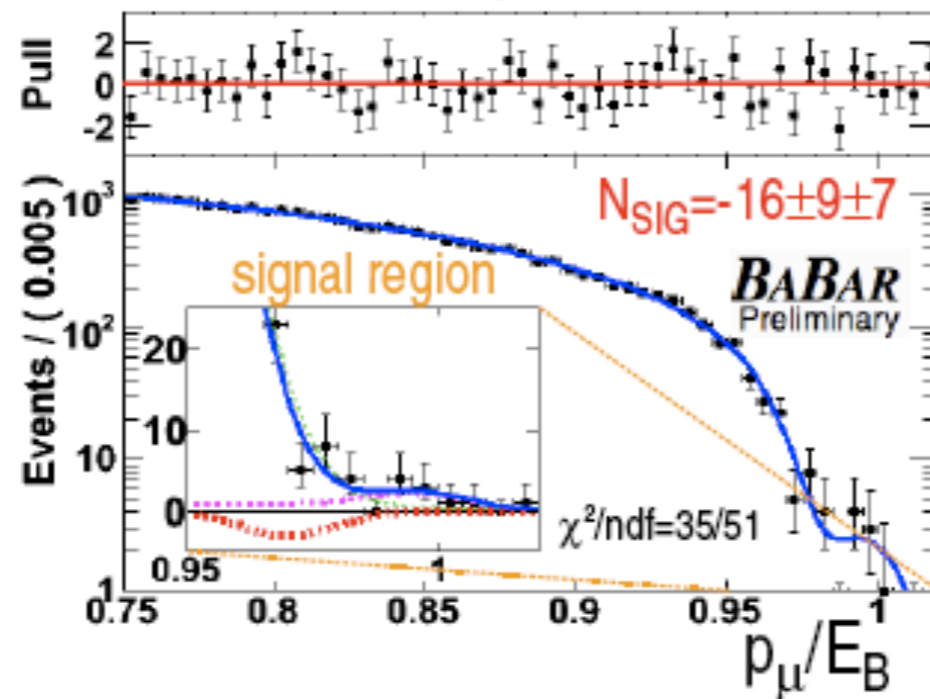
leptonic $e\tau$ channel



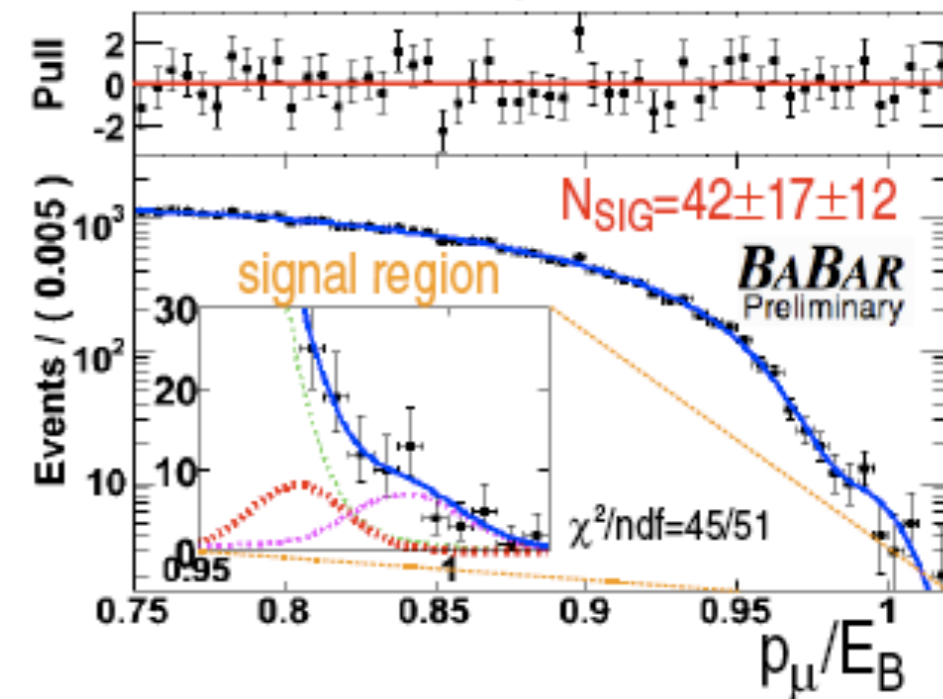
hadronic $e\tau$ channel



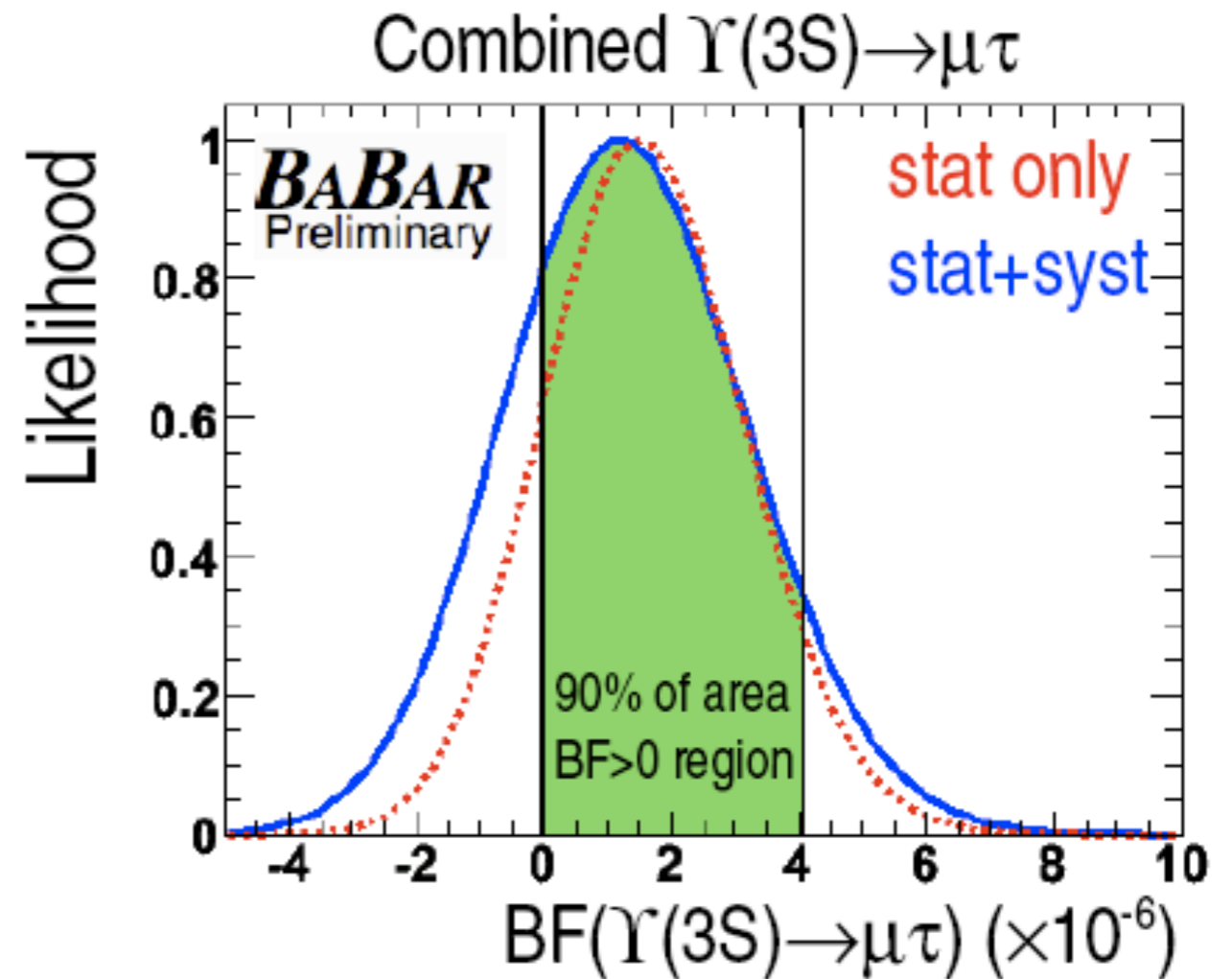
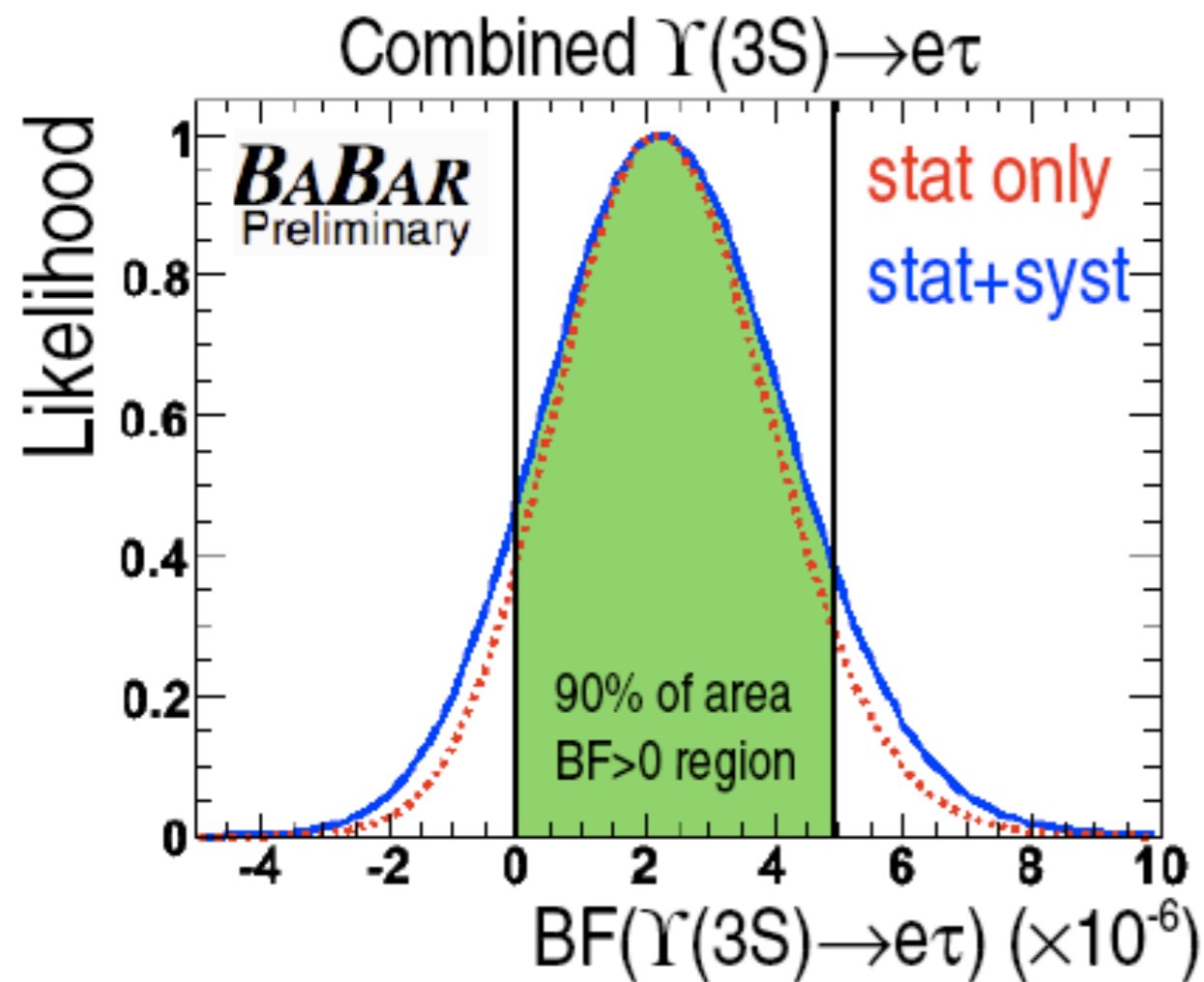
leptonic $\mu\tau$ channel



hadronic $\mu\tau$ channel



BF($\Upsilon(3S) \rightarrow e\tau, \mu\tau$) Upper Limits @ 90% CL



$$\text{BF}(\Upsilon(3S) \rightarrow e\tau) < 5.0 \times 10^{-6}$$

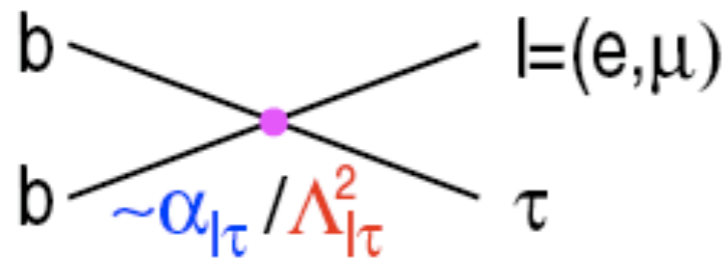
(first upper limit)

$$\text{BF}(\Upsilon(3S) \rightarrow \mu\tau) < 4.1 \times 10^{-6}$$

(>4x better than previous UL)

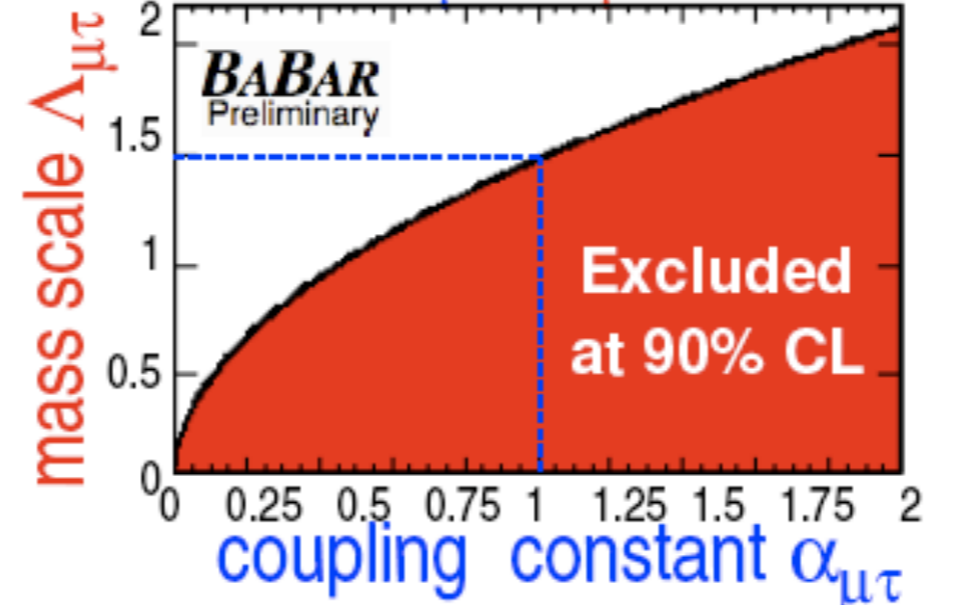
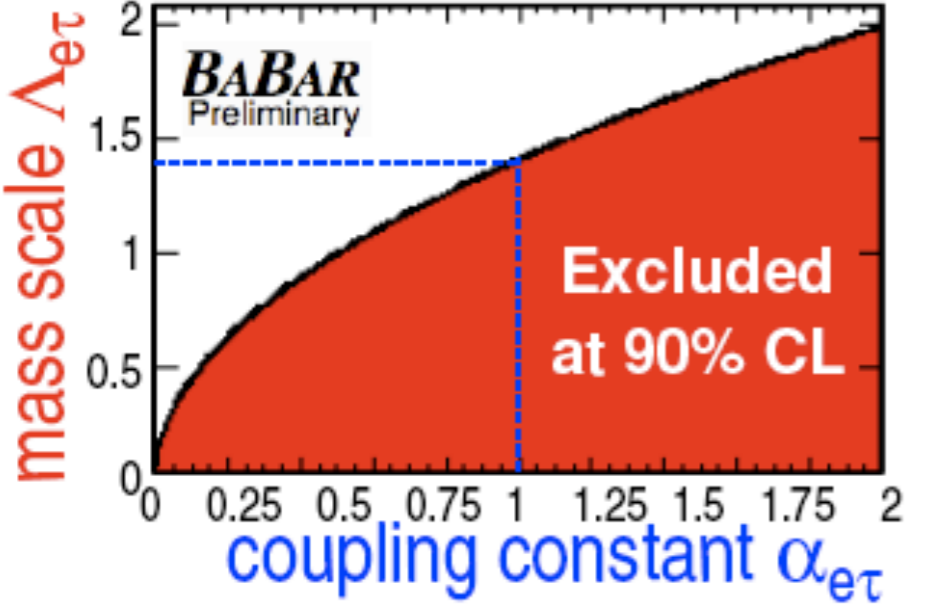
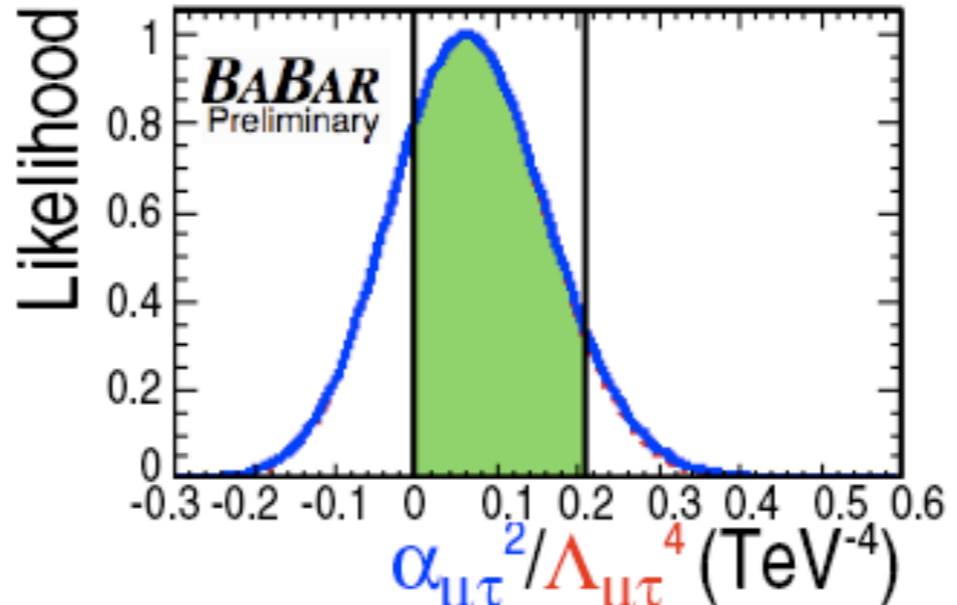
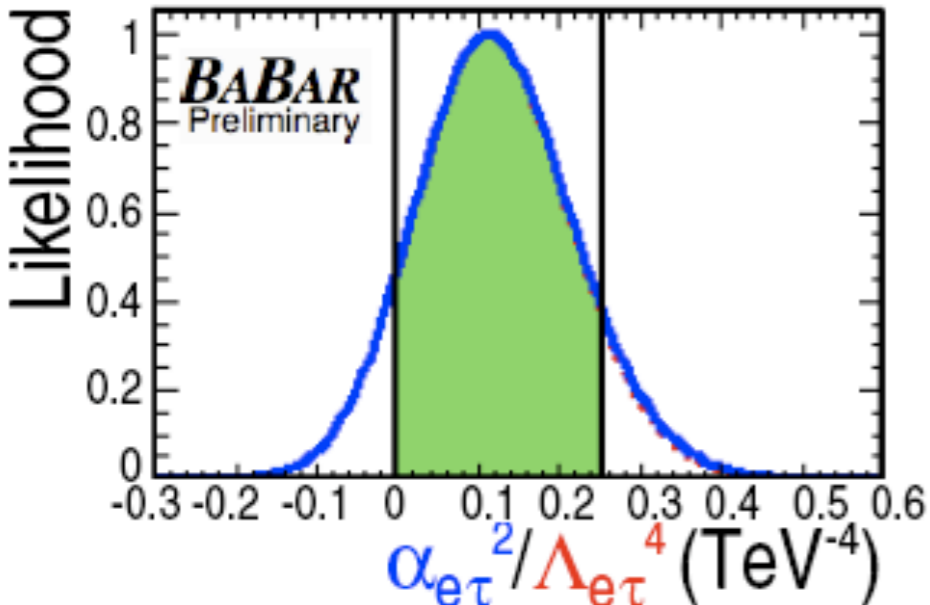
BaBar Collab., arXiv: 0812.1021 [hep-ex]

Limits on Generic Contact Interaction



$$\frac{\Gamma(\Upsilon(3S) \rightarrow l^\pm \tau^\mp)}{\Gamma(\Upsilon(3S) \rightarrow l^+ l^-)} = \frac{1}{2q_b^2} \left(\frac{\alpha_N^{(l\tau)}}{\alpha} \right)^2 \left(\frac{M_{\Upsilon(3S)}}{\Lambda^{(l\tau)}} \right)^4 \quad (l = e, \mu)$$

$q_b = b$ quark charge
 $\alpha =$ fine structure constant
 assumes vector coupling
 Silagadze Phys. Scripta 64.128
 Black et al. PRD 66.053002



Assume strong coupling
 $\alpha_{e\tau} = \alpha_{\mu\tau} = 1:$

$$\Lambda_{e\tau} > 1.4 \text{ TeV}$$

$$\Lambda_{\mu\tau} > 1.5 \text{ TeV}$$

Conclusions

- No evidence of LFV τ decays with $N_\tau \approx 1 \times 10^9$ decays
 - $\mathcal{B}(\tau \rightarrow e\gamma) < 3.3 \times 10^{-8}$ @ 90% C.L. *BABAR*
preliminary
 - $\mathcal{B}(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$ @ 90% C.L. *BABAR*
preliminary
- No evidence of LFV Υ decays with $N_{\Upsilon(3S)} \approx 1 \times 10^8$ decays
 - $\mathcal{B}(\Upsilon(3S) \rightarrow e\tau) < 5.0 \times 10^{-6}$ @ 90% C.L. *BABAR*
preliminary
 - $\mathcal{B}(\Upsilon(3S) \rightarrow \mu\tau) < 4.1 \times 10^{-6}$ @ 90% C.L. *BABAR*
preliminary
- More results to be available soon with $\Upsilon(2S)$ decays