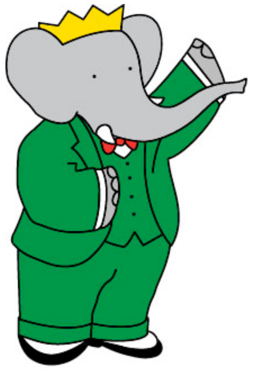
Search for Lepton Flavor Violation at BaBar



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DPF 2009

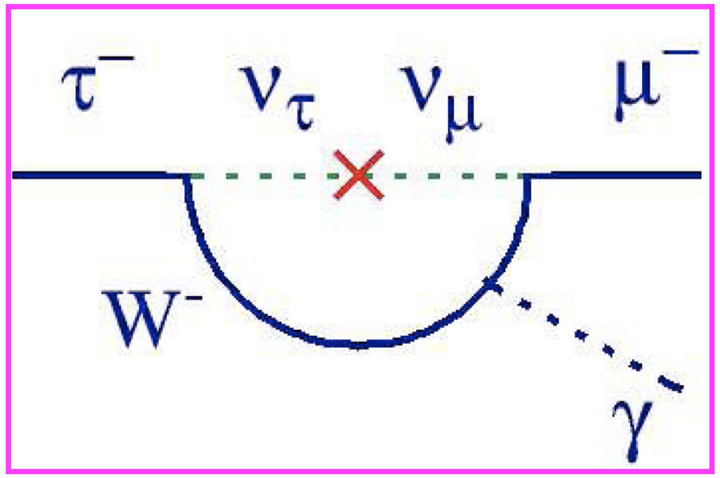
2009 Meeting of the Division of Particles and Fields of the American Physical Society (DPF 2009)

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



$\mathcal{B}(\tau^\pm \to \mu^\pm \gamma)$[Lee-Shrock, Phys. Rev. D **16**, 1444 (1977)]

$$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\mathrm{mix}} \mathcal{B}(\tau \to \mu \bar{\nu}_\mu \nu_\tau)$$

With $\Delta \sim 10^{-3}\,\mathrm{eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,\mathrm{eV}$

$\approx \mathcal{O}(10^{-54})$ (θ_{mix} : max)

... many orders below experimental sensitivity!

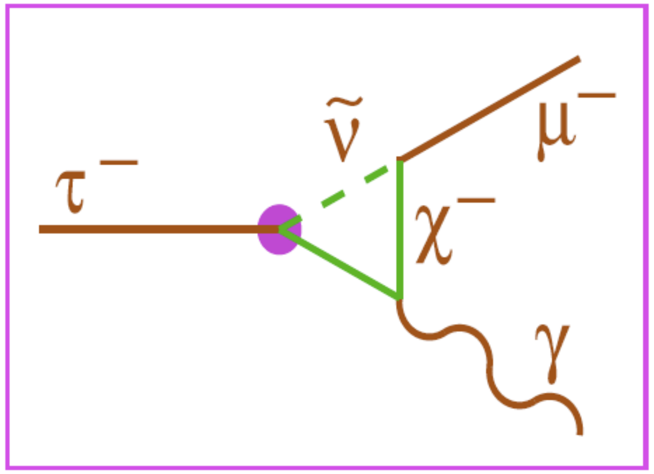
- Observation for LFV $\Rightarrow$ unambiguous signature of new physics

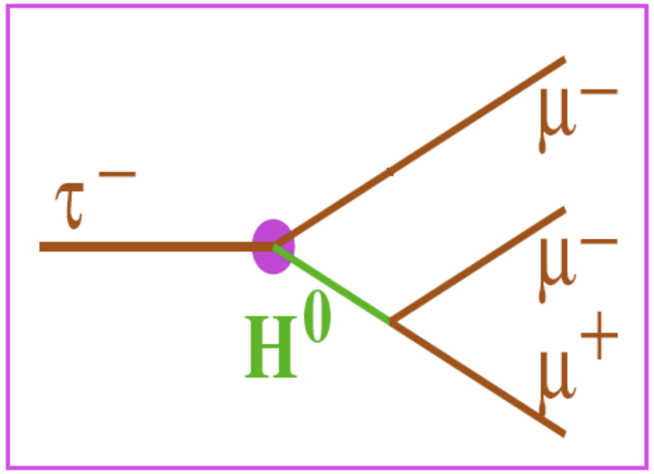
Lepton Flavor Violating Tau Decays

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

	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
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}

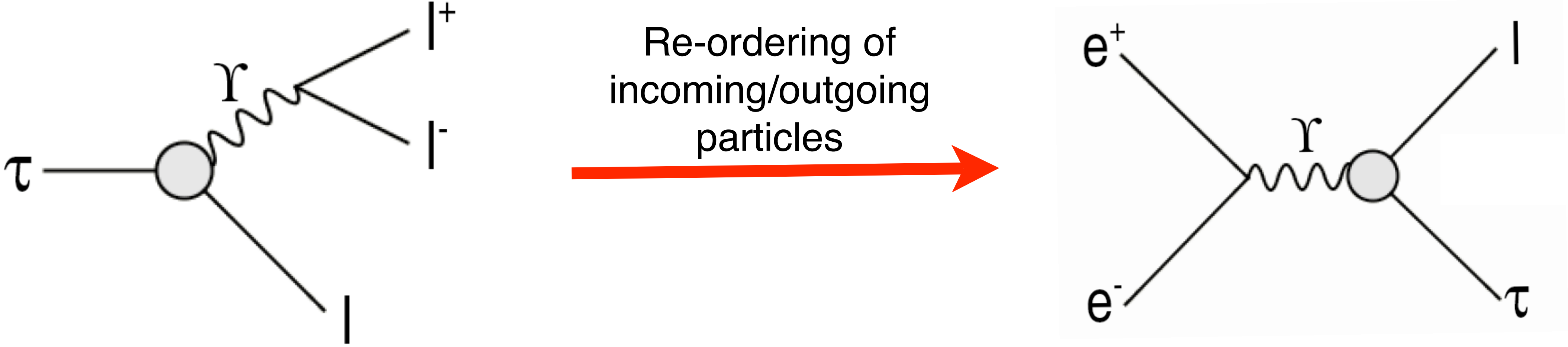
Illustrations:





Probing TeV scale via Upsilon Decays

- SUSY + Higgs (A.Brignole, A.Rossi, PLB566(2003)217)
  - $\mathcal{B}(\tau \to \ell\ell\ell) \simeq 10^{-7} \times (\frac{\tan\beta}{50})^6 \times (\frac{100GeV}{m_A})^4 \times (\frac{|50\Delta_L|^2+|50\Delta_R|^2}{10^{-3}})$
  - If Higgs light, s-particles $\sim \mathcal{O}(\text{ TeV})$, $\tan\beta \sim 50$
    - No direct observation, but $\tau \to \mu\mu\mu$ 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

$$\mathcal{B}(\Upsilon \to \ell\tau) \sim \frac{\mathcal{B}(\tau \to \ell\ell\ell)}{\mathcal{B}(\tau \to \ell\nu\overline{\nu})} \frac{\Gamma(W \to \ell\nu)^2}{\Gamma(\Upsilon)\Gamma(\Upsilon \to \ell\ell)} (M_\Upsilon/M_W)^6$$

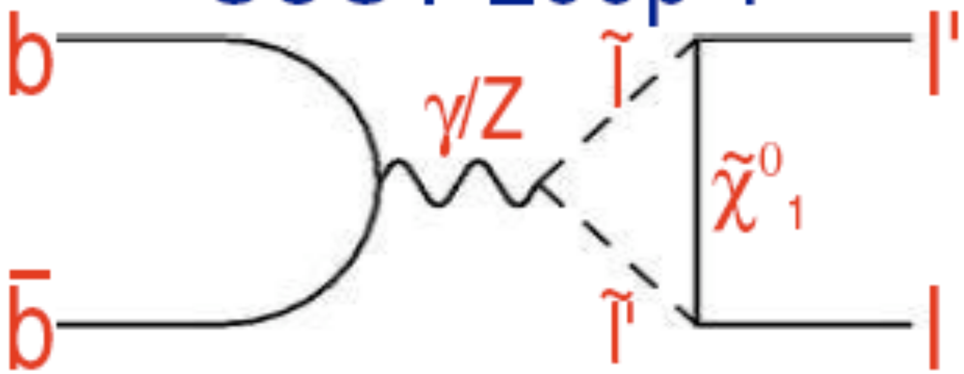
S.Nussinov, et. al.
PRD 63, 016003 (2001)

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

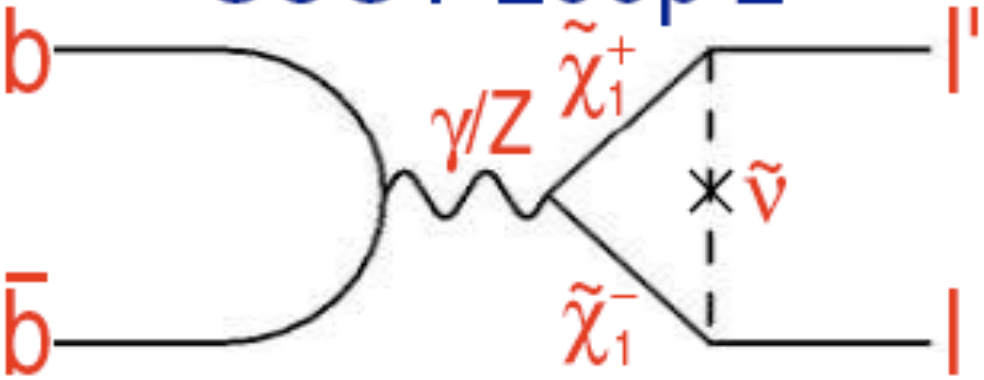
BaBar PRL 99, 251803 (2007), Belle PLB 660,154 (2008)

Lepton Flavor Violating Upsilon Decays

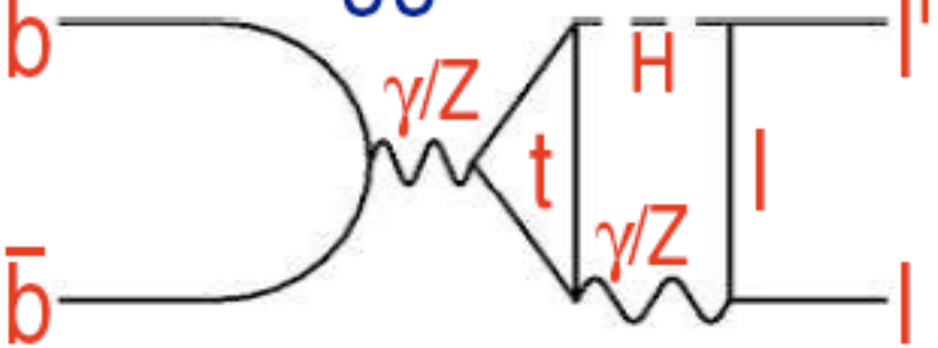
SUSY Loop 1



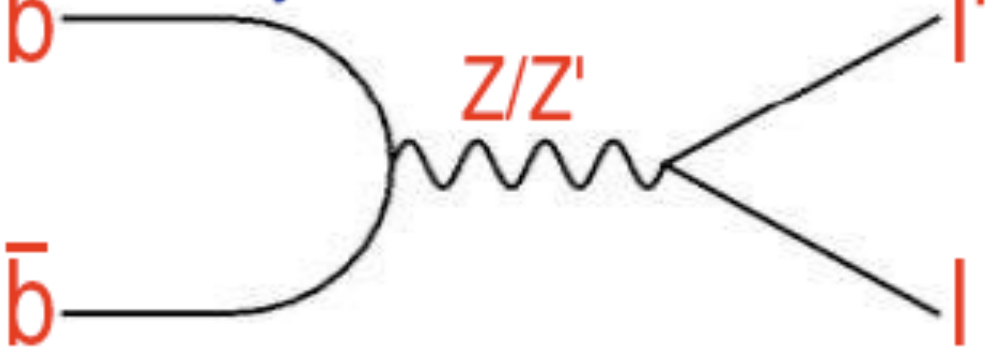
SUSY Loop 2



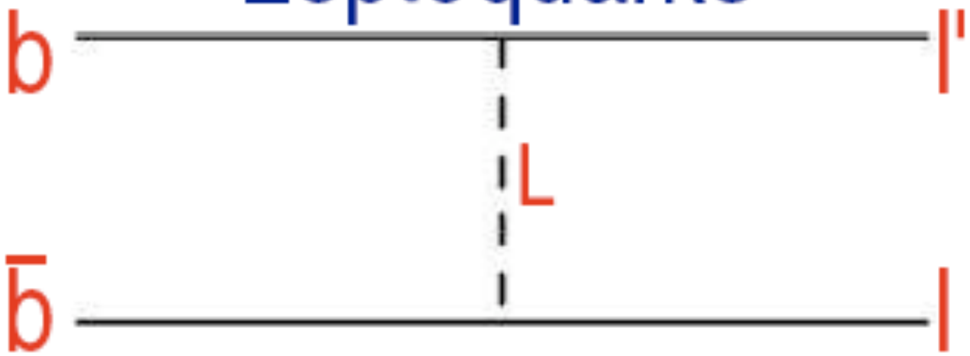
2nd Higgs Doublet



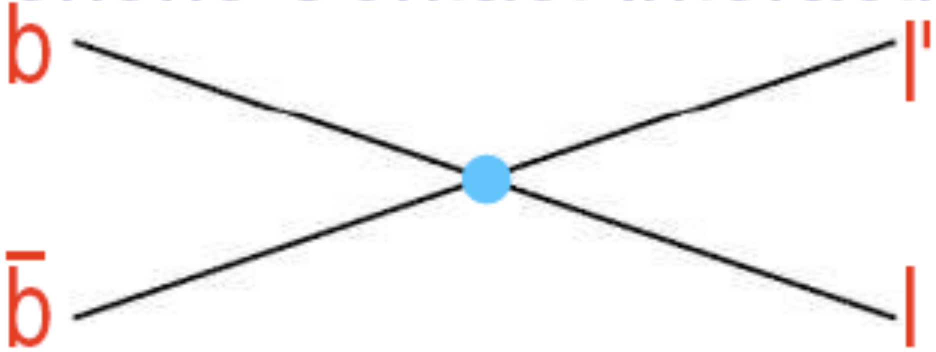
Heavy Z', Anomalous Z



Leptoquarks



Generic Contact Interaction



How small is the rate known to be?

- **BaBar/Belle searches for LFV in τ→ e/μγ decays at √s ≈ ϒ(4S)**
  - $\mathcal{L} = 232 fb^{-1} \Rightarrow N_\tau \approx 4 \times 10^8 : \mathcal{B}(\tau \to e\gamma) < 11 \times 10^{-8}$ @ 90% C.L.

    BaBar Collab., PRL 96, 041801 (2006)
  - $\mathcal{L} = 232 fb^{-1} \Rightarrow N_\tau \approx 4 \times 10^8 : \mathcal{B}(\tau \to \mu\gamma) < 6.8 \times 10^{-8}$ @ 90% C.L.

    BaBar Collab., PRL 95, 041802 (2005)
  - $\mathcal{L} = 535 fb^{-1} \Rightarrow N_\tau \approx 1 \times 10^9 : \mathcal{B}(\tau \to e\gamma) < 12 \times 10^{-8}$ @ 90% C.L.
  - $\mathcal{L} = 535 fb^{-1} \Rightarrow N_\tau \approx 1 \times 10^9 : \mathcal{B}(\tau \to \mu\gamma) < 4.5 \times 10^{-8}$ @ 90% C.L.

    Belle Collab., PLB 666, 16 (2008)

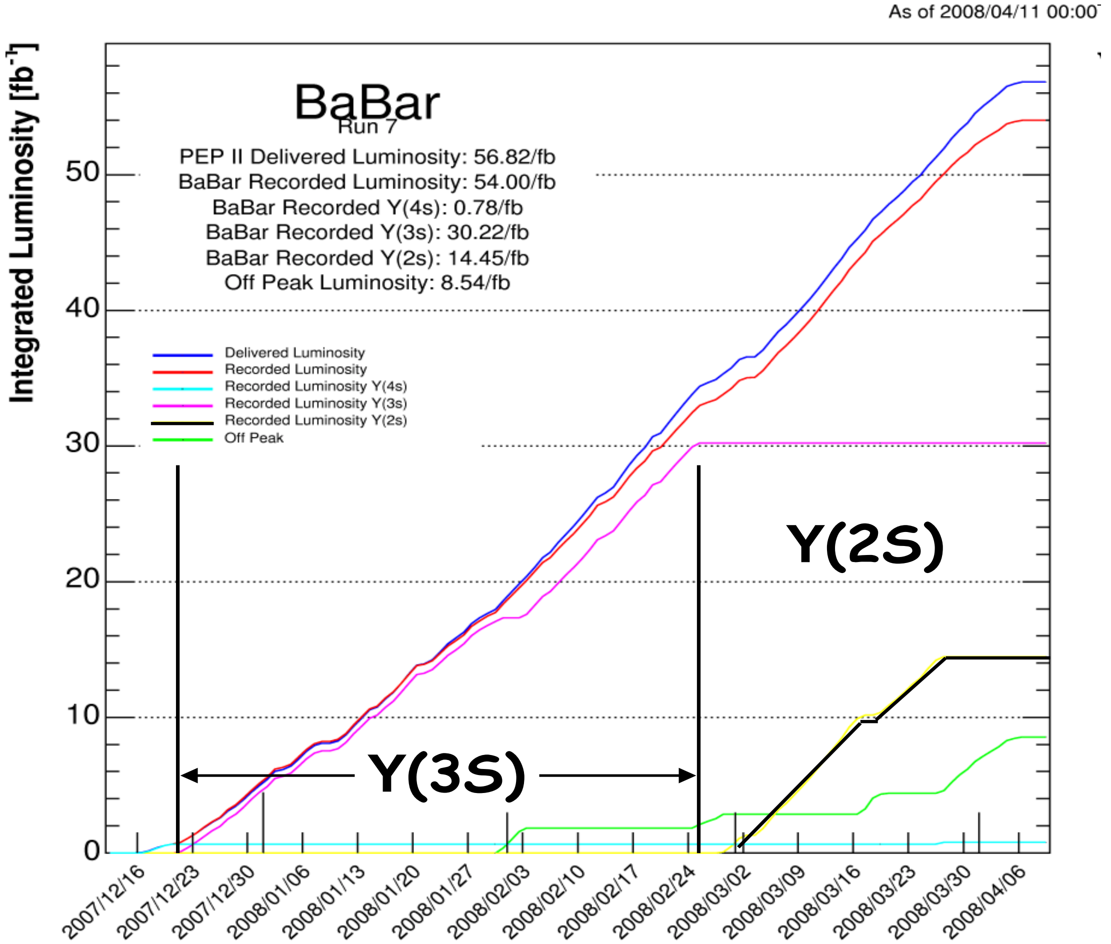
- **CLEO search for ϒ→μτ, τ→eνν**

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
$\Gamma(\Upsilon \to \mu\mu)$ (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 $\Upsilon(4S)$:
~ 30 fb^{-1} @ $\Upsilon(3S)$ (122 M decays)
~ 15 fb^{-1} @ $\Upsilon(2S)$ (100 M decays)



Dramatic increase in
sensitivity to rare decays:
$\Gamma_{\Upsilon(4S)} / \Gamma_{\Upsilon(nS)} \sim 10^3$

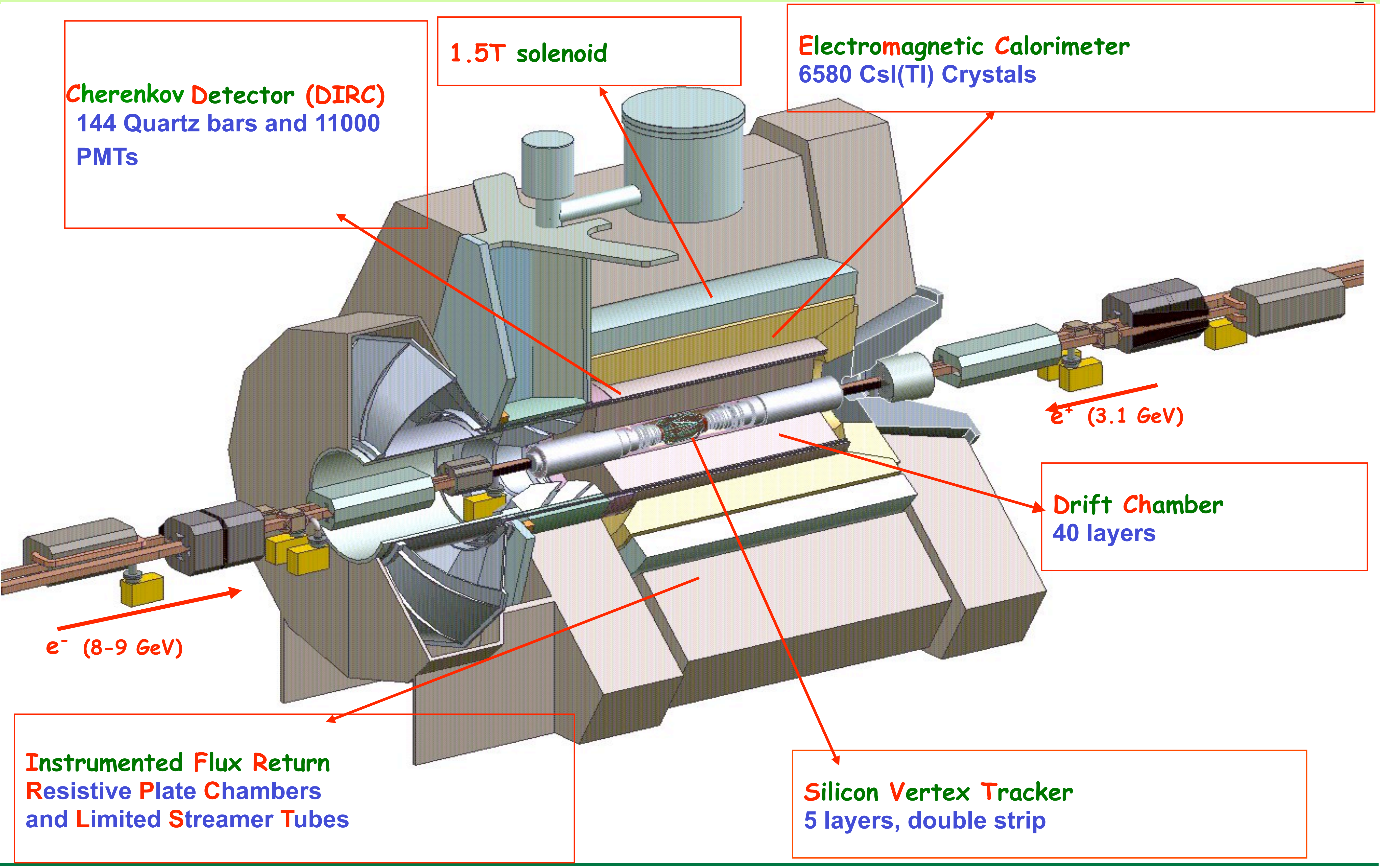
Improving Sensitivity for LFV discovery in Υ Decays:

~20 times more $\Upsilon(3S)$ decays than CLEO ➪ 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} @ $\Upsilon(2S)$ ⇒ $N_\tau \sim 10^9$

The BABAR Detector



Cherenkov Detector (DIRC)
144 Quartz bars and 11000 PMTs

1.5T solenoid

Electromagnetic Calorimeter
6580 CsI(Tl) Crystals

e^+ (3.1 GeV)

Drift Chamber
40 layers

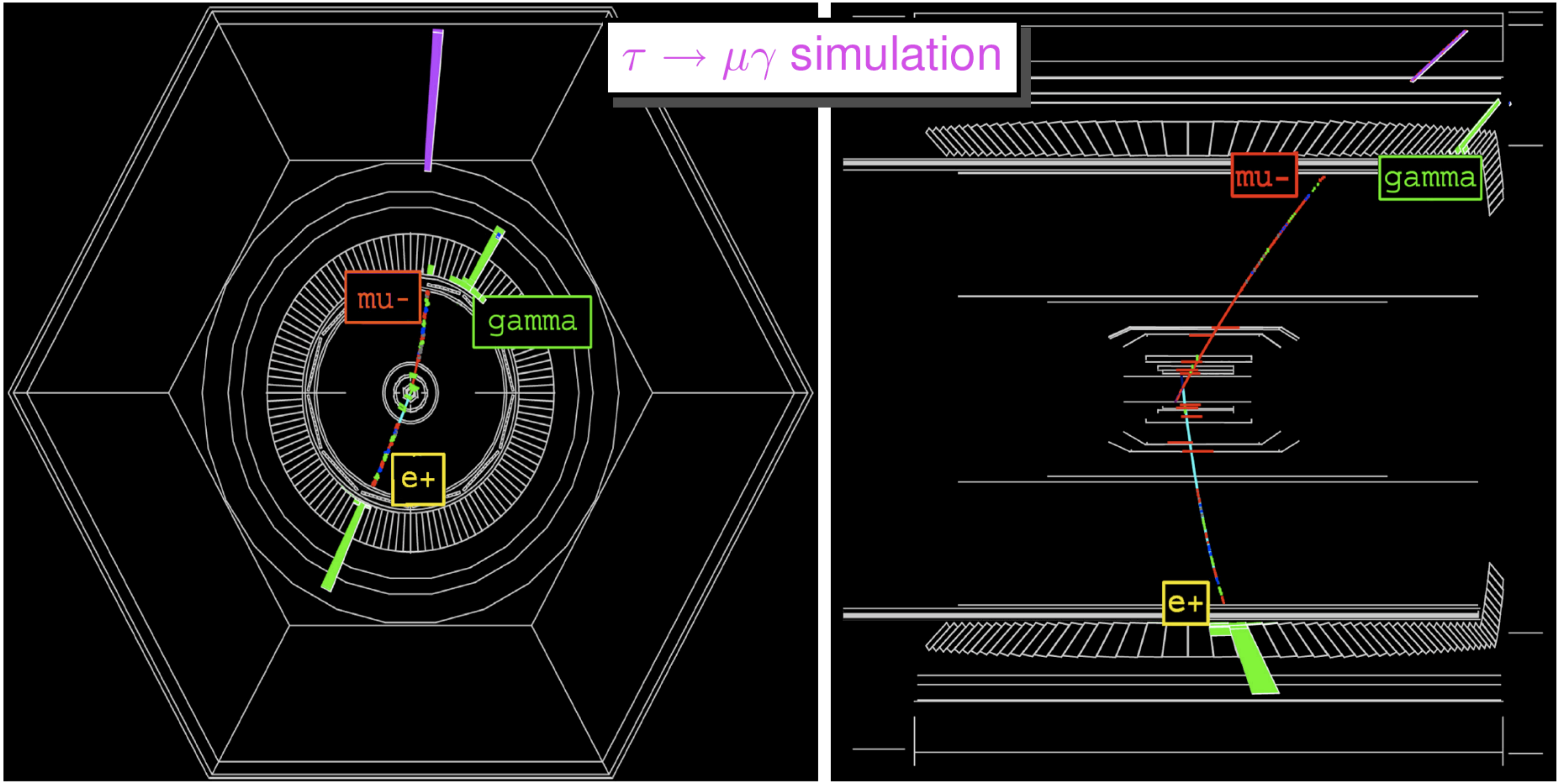
e^- (8-9 GeV)

Instrumented Flux Return
Resistive Plate Chambers
and Limited Streamer Tubes

Silicon Vertex Tracker
5 layers, double strip

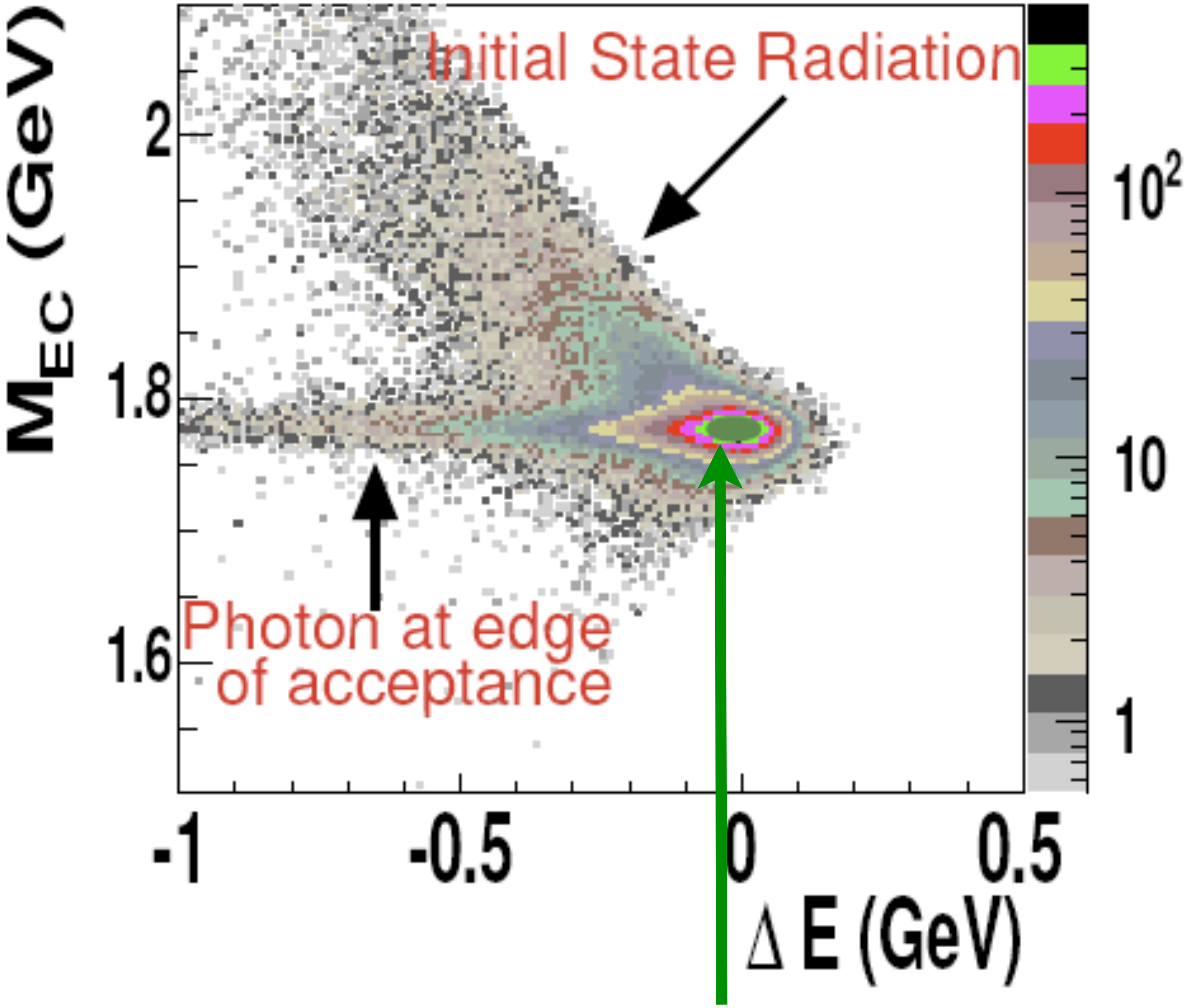
$\tau \rightarrow \mu \gamma$: Signal Characteristics

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



$\tau \to \mu\,\gamma$: Signal Characteristics

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



$\tau \to \mu\gamma$ simulation

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

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

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

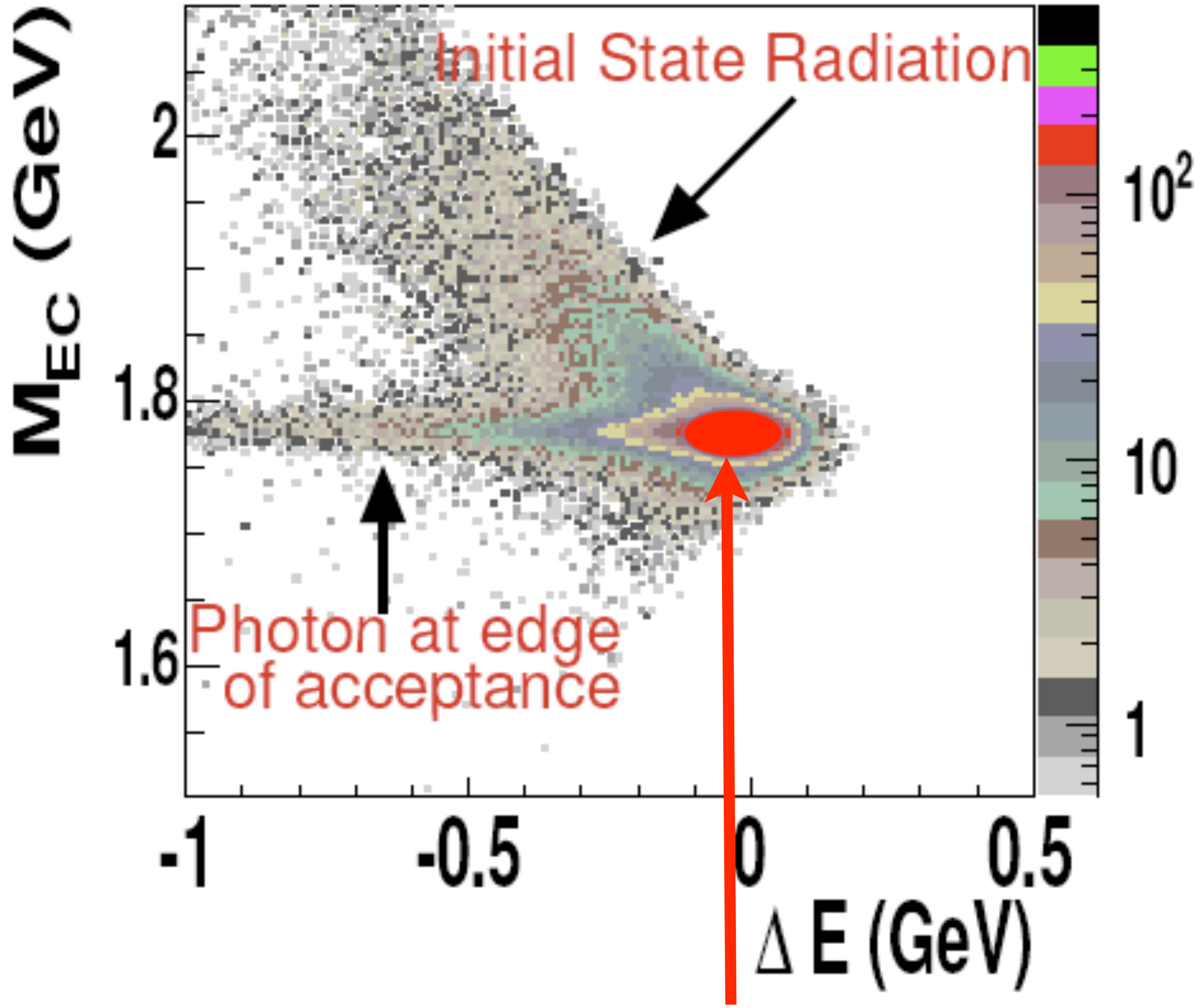
Beam energy constrained mass after vertexing γ at μ $_{\text{POCA(XY)}}$

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

☞ Signal Region: ± 2 σ around ($\langle\Delta E\rangle$, $\langle M_{EC}\rangle$)

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

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



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M$_{\mathrm{EC}}$ ($\sigma \sim 8.3\mathrm{MeV}$)

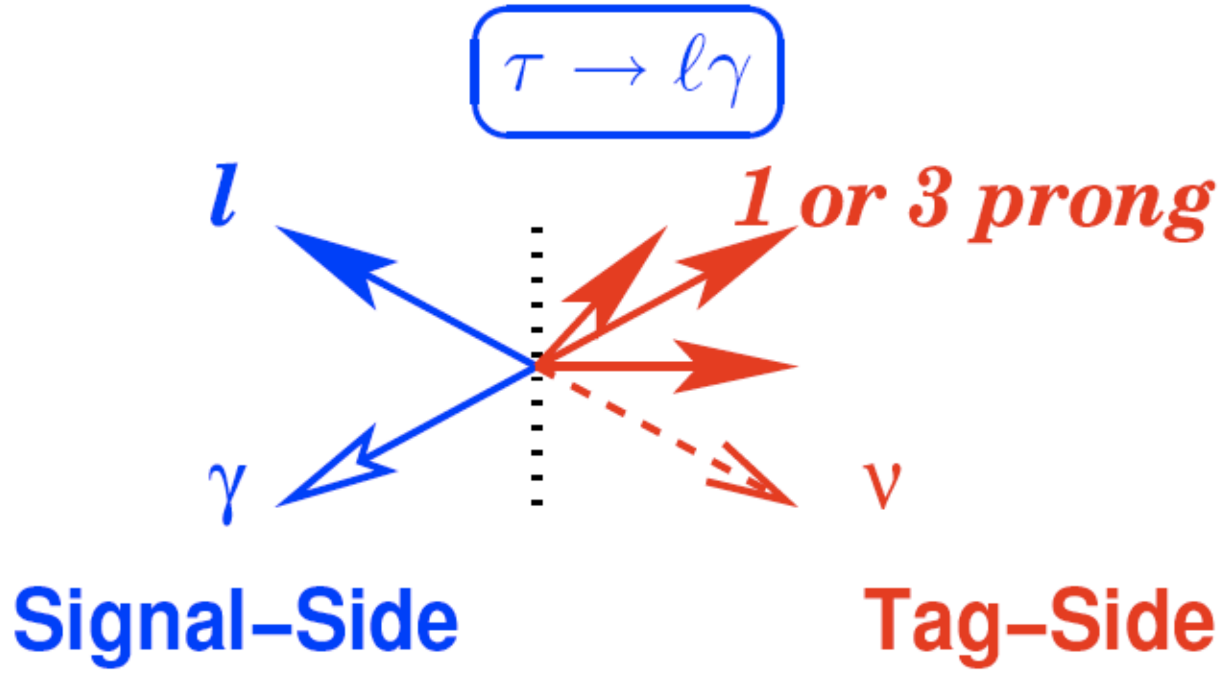
Beam energy constrained mass after vertexing

γ at μ $_{\mathrm{POCA(XY)}}$

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

☛ Blinded Region: $\pm$ 3 σ around ($\langle\Delta\mathrm{E}\rangle$, $\langle\mathrm{M}_{\mathrm{EC}}\rangle$)

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



Backgrounds:

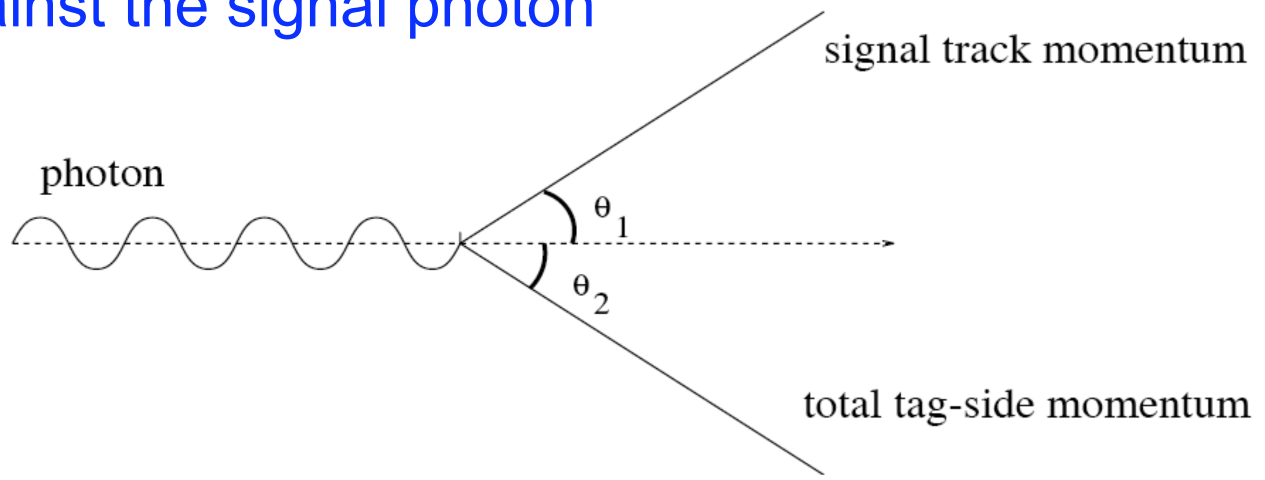
- $\tau \to e\gamma$ ($\tau \to \mu\gamma$):
  - Radiative Bhabha (di-muon)
  - $\tau^+\tau^-\gamma(\tau \to \ell\nu\overline{\nu})$
  - $q\overline{q}$ (γ)

- 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 $\tau \to e\gamma$ 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)
  - $1.55\,\mathrm{GeV}/c^2 < m_{\mathrm{EC}} < 2.05\,\mathrm{GeV}/c^2$
  - $-1.0\,\mathrm{GeV} < \Delta E < 0.5\,\mathrm{GeV}.$

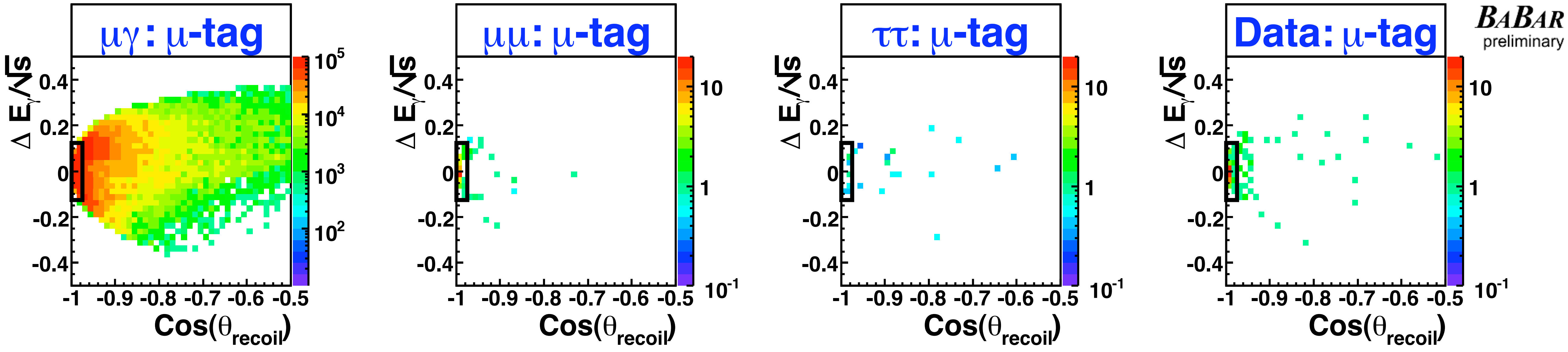
QED Backgrounds in Leptonic Tags

Exploit correlation between 2 kinematic variables:

- cosine of the opening angle $\cos(\theta_{\text{recoil}})$ 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 τ → μ γ search, remove events passing

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

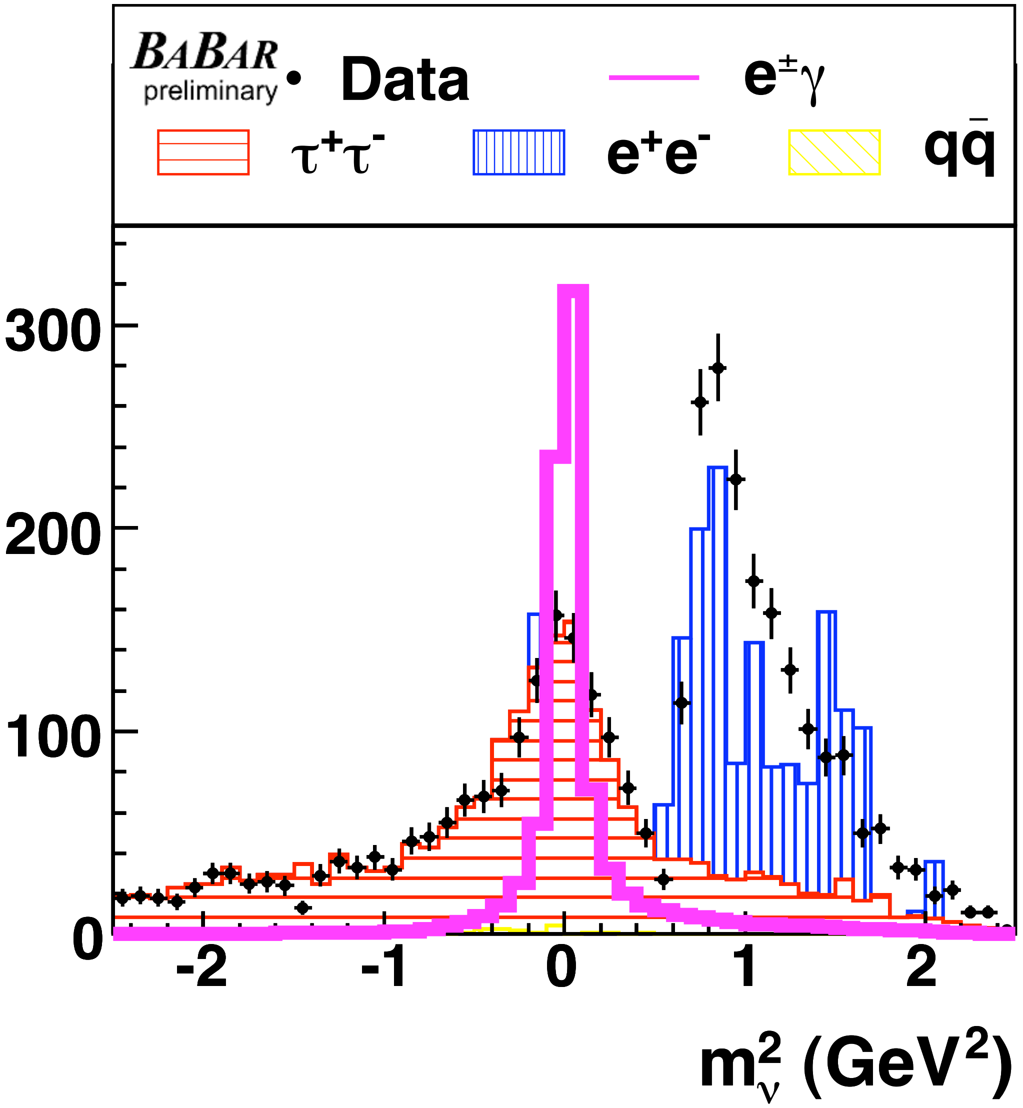
- In τ → e γ search, not enough background events in μ tag ⇒ so no additional cut needed

Tag-side Missing Mass for Hadronic Tags

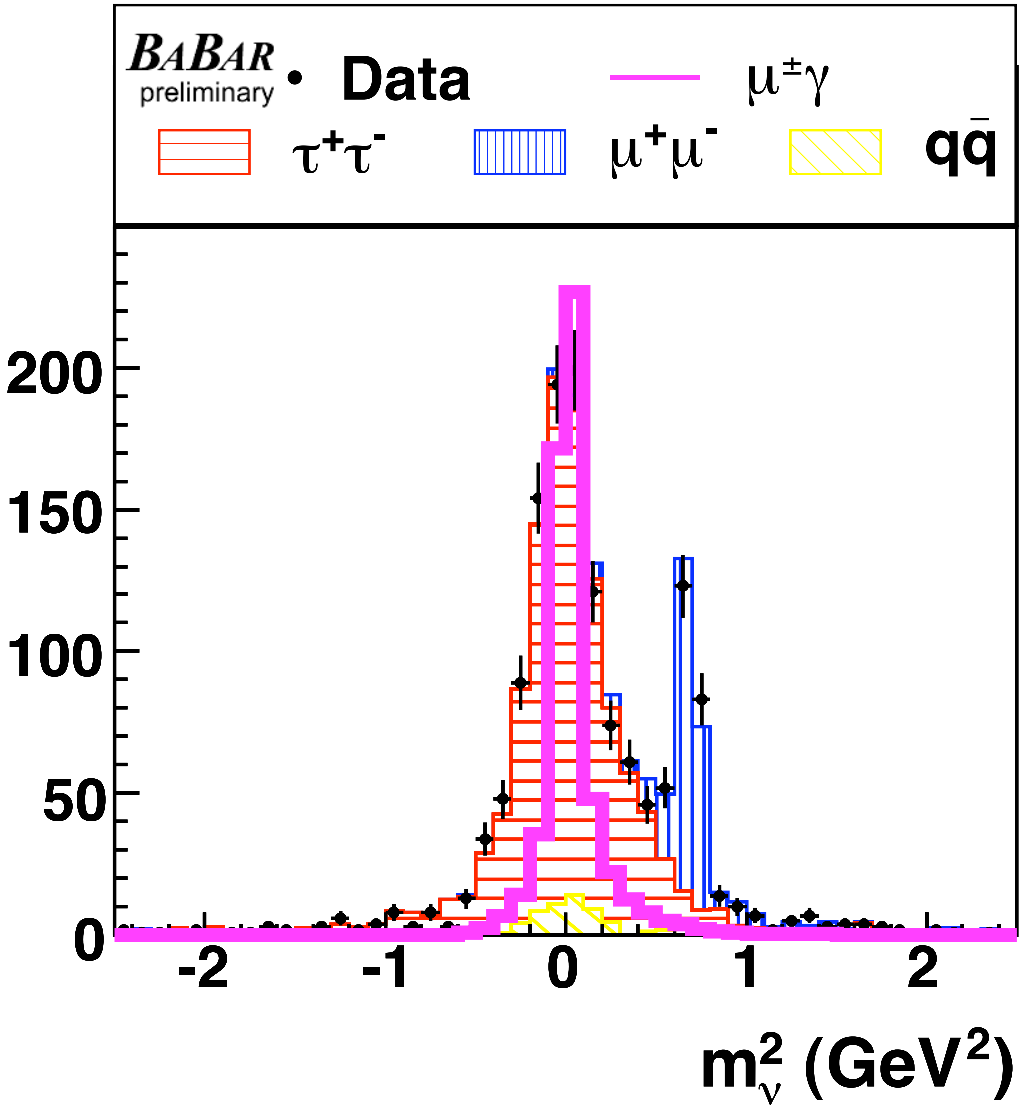
- Exploit the unique feature that signal-side τ decay is neutrino-less

⇒ fully reconstruct the direction of tag-side τ assumed to be $\sqrt{s}/2$ in CM frame

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



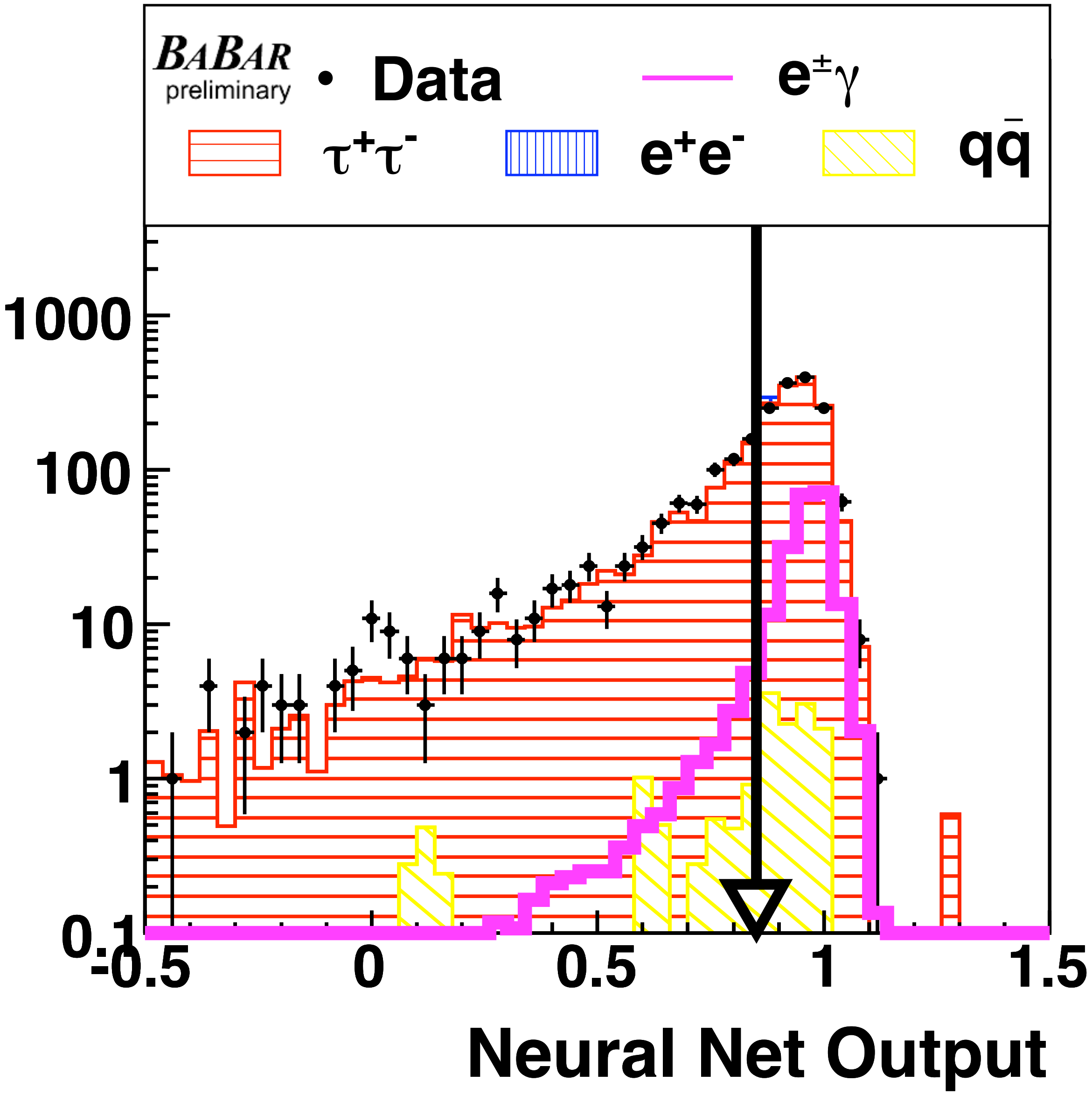
$\tau^\pm \to \mu^\pm\gamma$:



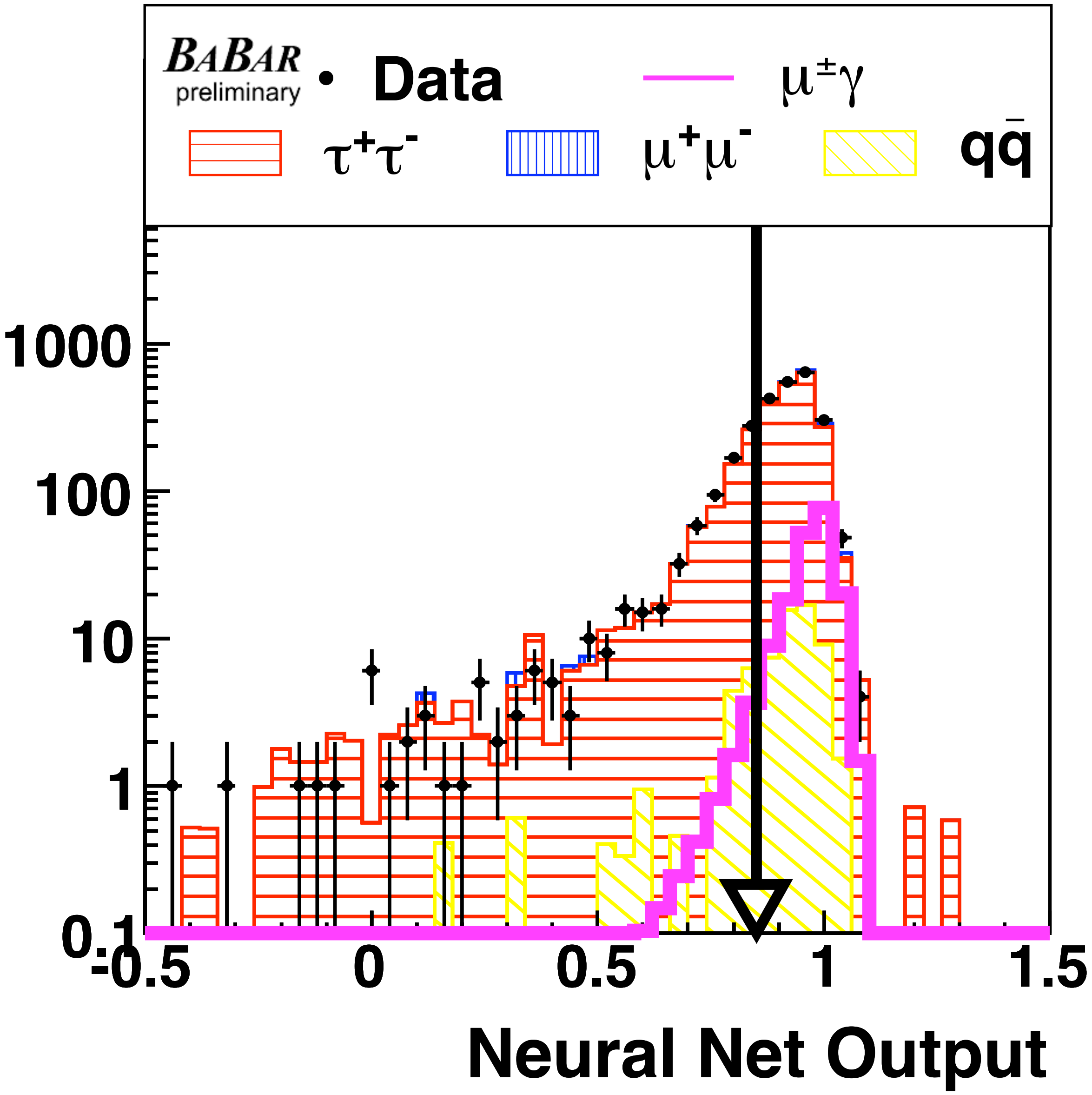
Require: $|m_\nu^2| < 0.25\ GeV^2$ for π- and $3h$-tags, and $|m_\nu^2| < 0.50\ GeV^2$ for ρ-tag.

Neural Net Based discriminator

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



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

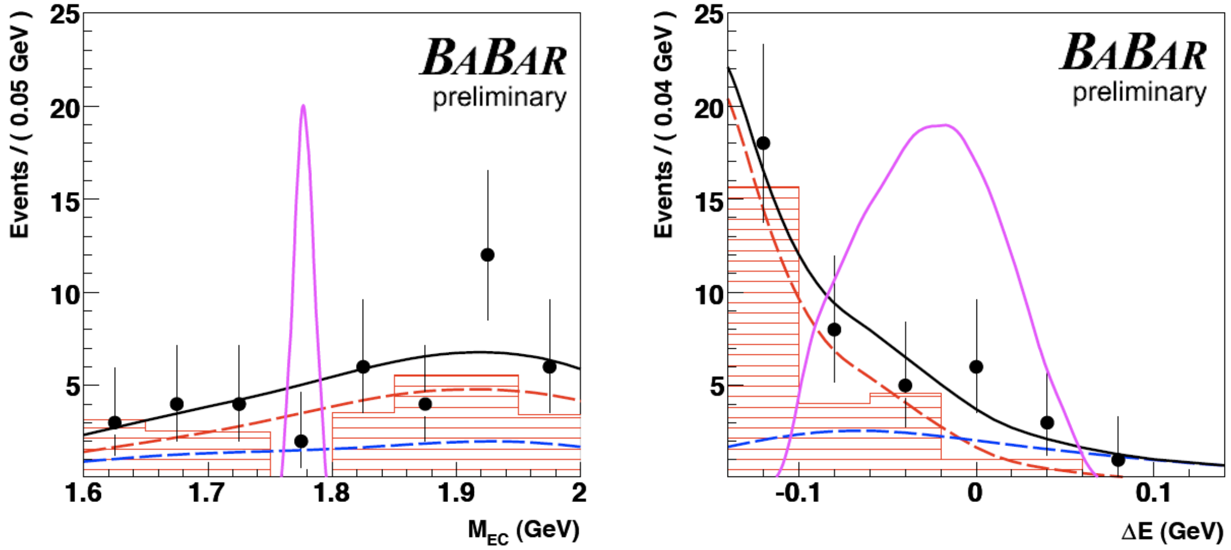


A cut of NN output > .85 improves Signal/Background by 40% for $\tau \rightarrow e\gamma$ search and by 30% for $\tau \rightarrow \mu\gamma$ search

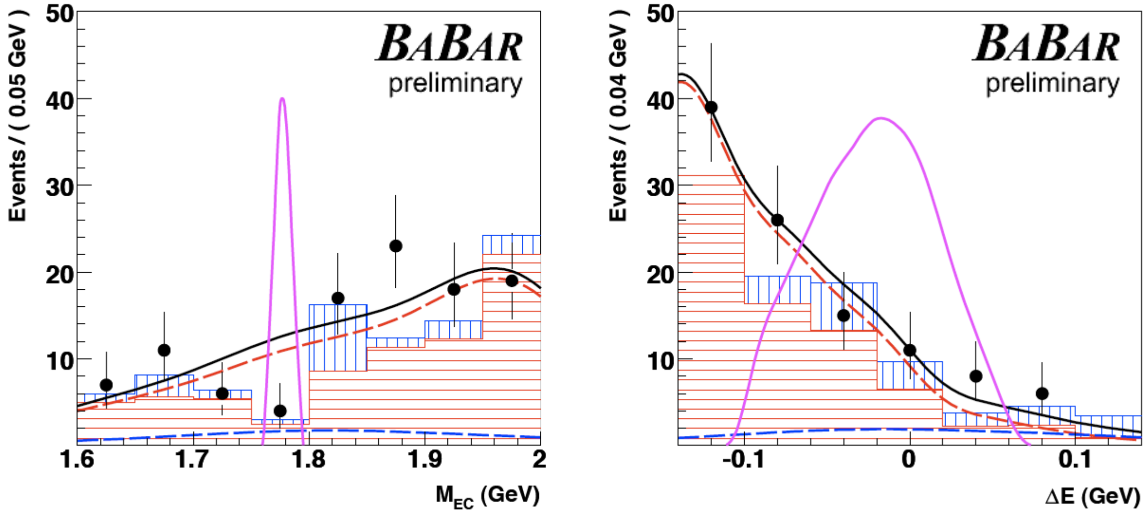
2-dim Fit with Background PDFs only

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

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



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



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

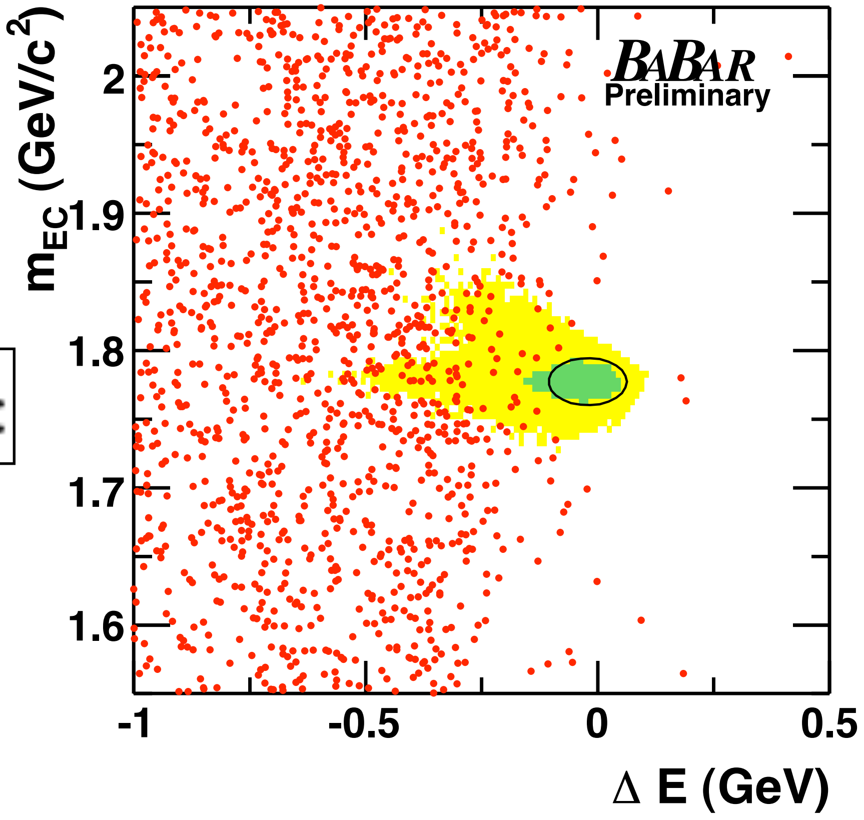
$$N^{data}_{2\sigma} = \frac{\int_{2\sigma} PDF_{tot}}{\int_{FitBox-3\sigma} PDF_{tot}} \times N^{data}_{FitBox-3\sigma}$$

Cross-check neighbouring ellipses shifted in the mass variable:

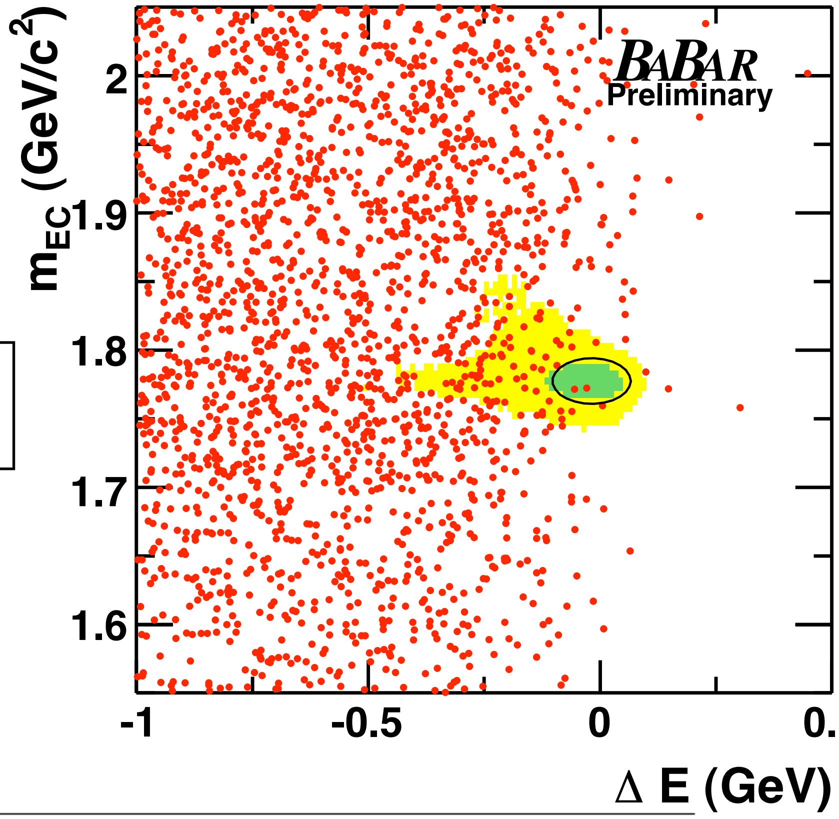
Decay modes	# of events	-9σ	$-5\ \sigma$	0	$+5\ \sigma$	$+9\ \sigma$
$\tau^{\pm} \rightarrow e^{\pm}\gamma$	Observed	2	1	?	2	2
	Expected	1.2±0.2	1.4±0.2	1.6±0.3	1.9 ±0.3	2.1±0.3
$\tau^{\pm} \rightarrow \mu^{\pm}\gamma$	Observed	3	1	?	4	6
	Expected	2.8±0.3	3.1±0.3	3.6±0.4	4.2±0.4	4.8±0.5

Results

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



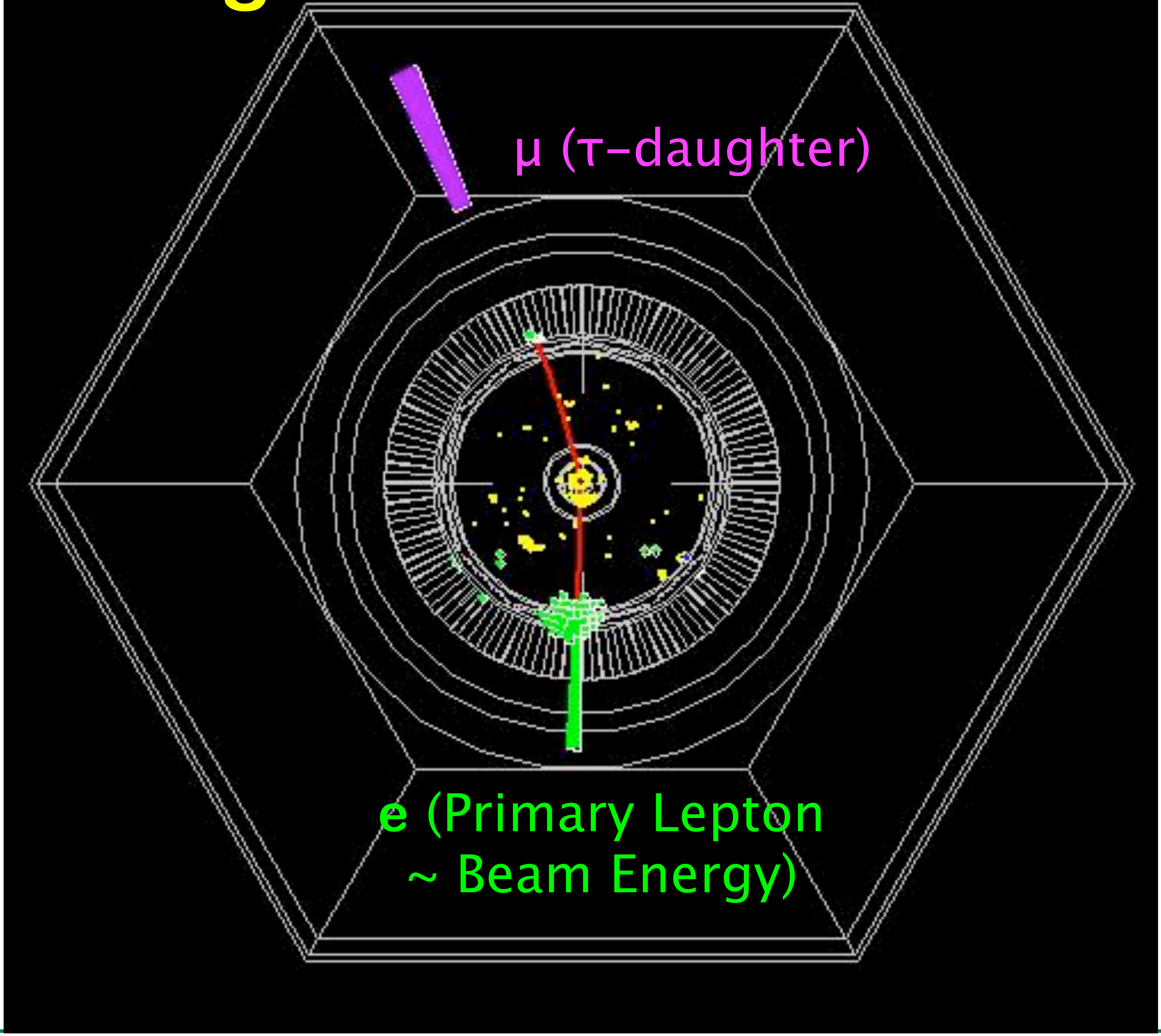
$\tau^{\pm} \to \mu^{\pm}\gamma$:



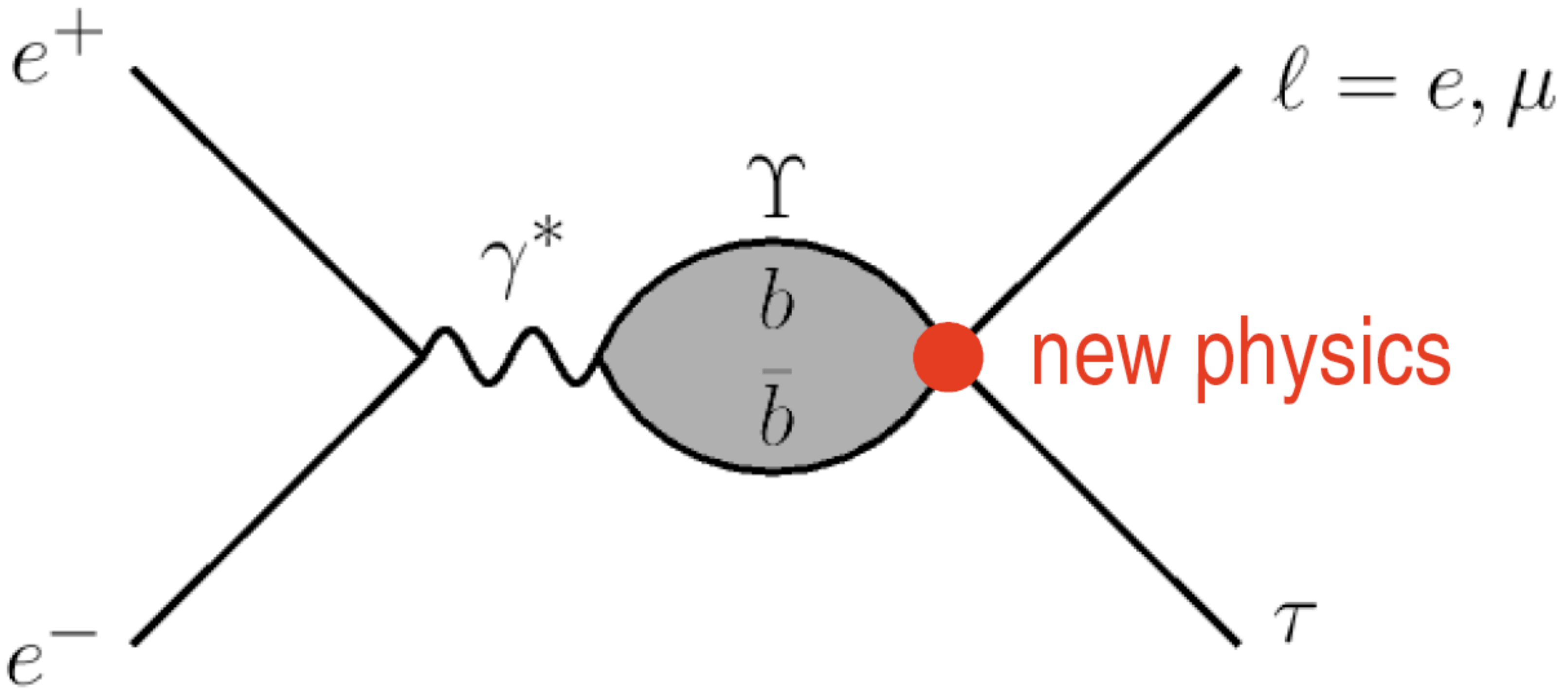
N_τ	$(963 \pm 7) \times 10^6$	
	$\tau^{\pm} \to e^{\pm}\gamma$ search	
Number of background events expected in 2σ signal ellipse	(1.6 ± 0.4)	
Efficiency in 2σ signal ellipse	$(3.9 \pm 0.3)\%$	
Expected Feldman & Cousins Upper Limit (w/o systmatics)	$\mathcal{B}(\tau^{\pm} \to e^{\pm}\gamma) < 9.8 \times 10^{-8}$ at 90% CL	
Expected Feldman & Cousins Upper Limit (with systmatics)	$\mathcal{B}(\tau^{\pm} \to e^{\pm}\gamma) < 9.8 \times 10^{-8}$ at 90% CL	NEW
Numbers of events observed in 2σ signal ellipse	0	
Observed Feldman & Cousins Upper Limit	$\mathcal{B}(\tau^{\pm} \to e^{\pm}\gamma) < 3.3 \times 10^{-8}$ at 90% CL	
	$\tau^{\pm} \to \mu^{\pm}\gamma$ 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)	$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\gamma) < 7.9 \times 10^{-8}$ at 90% CL	
Expected Feldman & Cousins Upper Limit (with systmatics)	$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\gamma) < 8.2 \times 10^{-8}$ at 90% CL	NEW
Numbers of events observed in 2σ signal ellipse	2	
Observed Feldman & Cousins Upper Limit	$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\gamma) < 4.4 \times 10^{-8}$ at 90% CL	

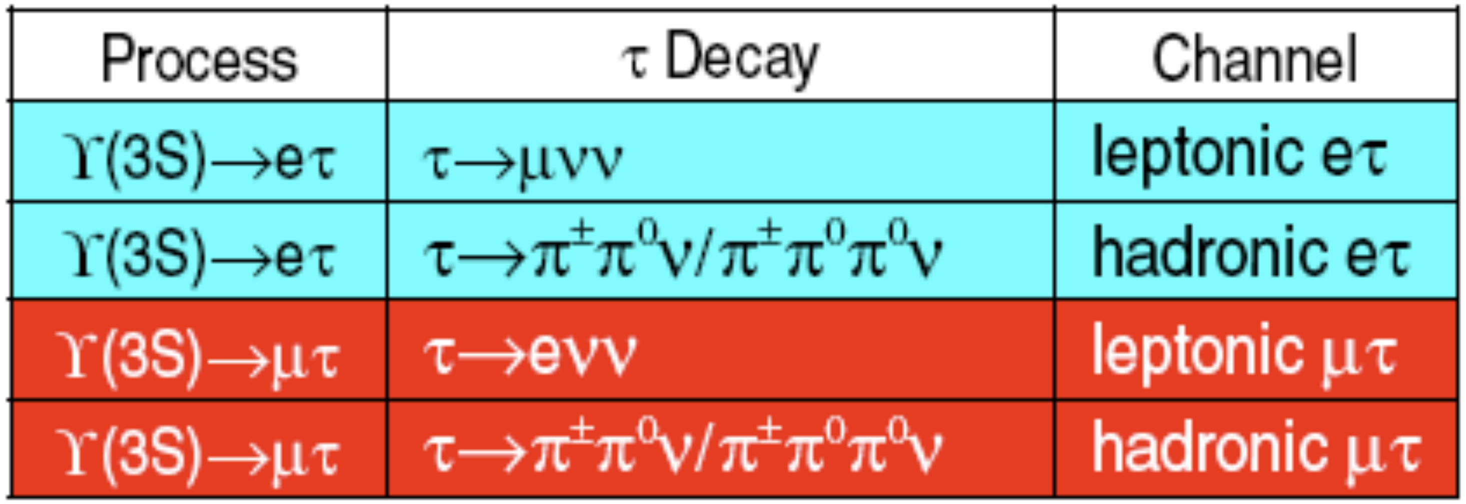
$\Upsilon \to e\tau, \tau \to \mu\nu\nu$: Signal Characteristics

Signal MC Simulation:



Event Selection

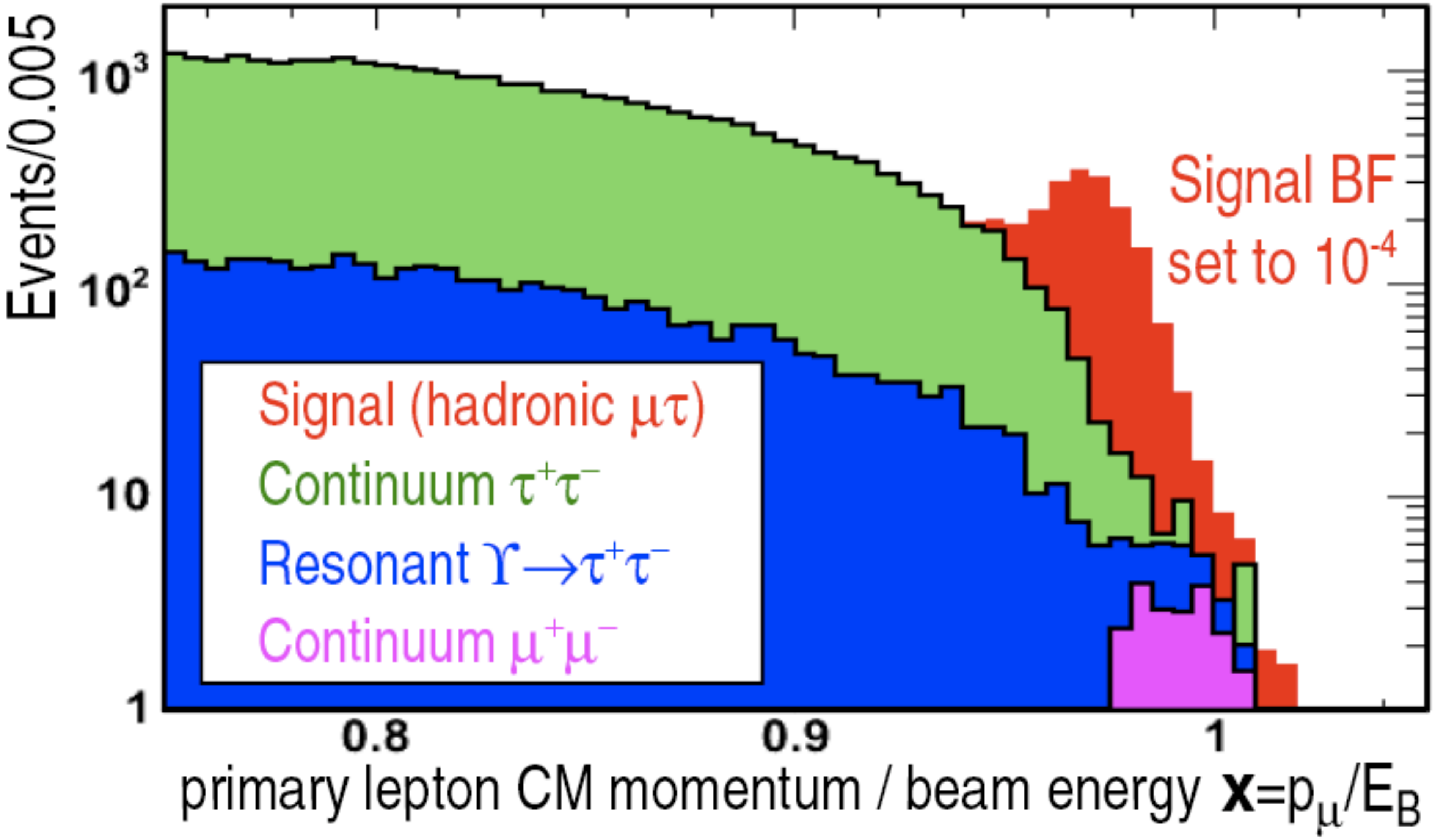


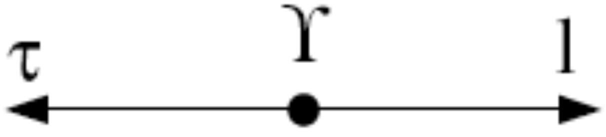


Process	τ Decay	Channel
$\Upsilon(3S)\to e\tau$	$\tau\to\mu\nu\nu$	leptonic $e\tau$
$\Upsilon(3S)\to e\tau$	$\tau\to\pi^{\pm}\pi^{0}\nu/\pi^{\pm}\pi^{0}\pi^{0}\nu$	hadronic $e\tau$
$\Upsilon(3S)\to \mu\tau$	$\tau\to e\nu\nu$	leptonic $\mu\tau$
$\Upsilon(3S)\to \mu\tau$	$\tau\to\pi^{\pm}\pi^{0}\nu/\pi^{\pm}\pi^{0}\pi^{0}\nu$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

- 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/a_1
- τ decay with same flavor lepton or a single π vetoed to reduce QED bkgd.

The discriminating variable

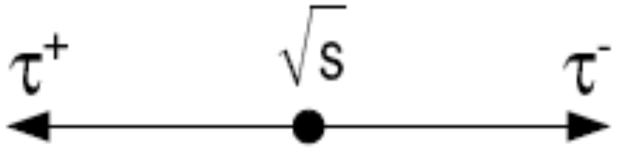


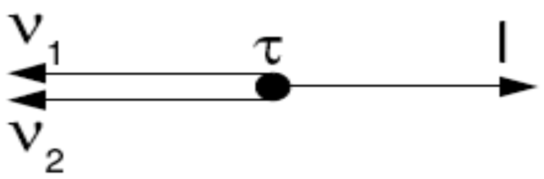


$E_l = (m_\Upsilon^2 - m_\tau^2 + m_l^2)/(2\,m_\Upsilon)$ $\quad p_l/E_B = \sqrt{4\,(E_l^2 - m_l^2)/m_\Upsilon^2}$

Signal: peak ~ 0.97

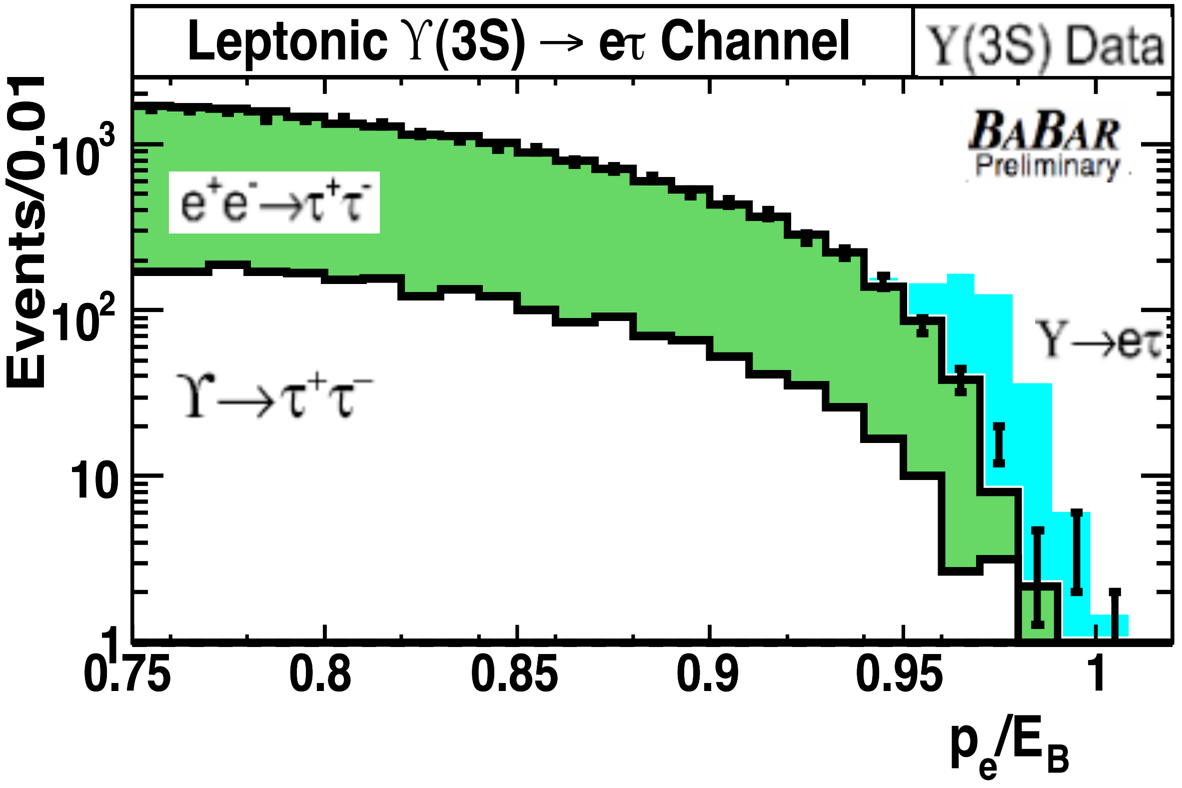
Bhabha/Mu-pair Background: peak ~ 1.0

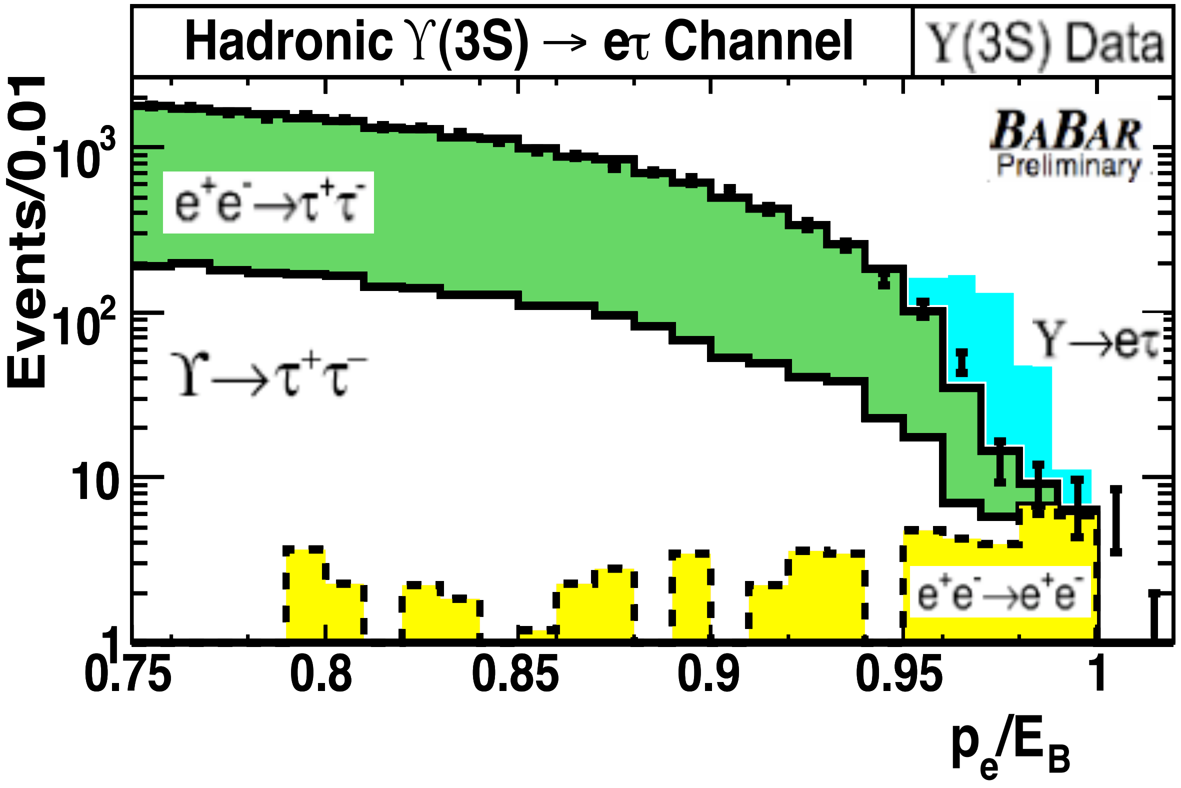


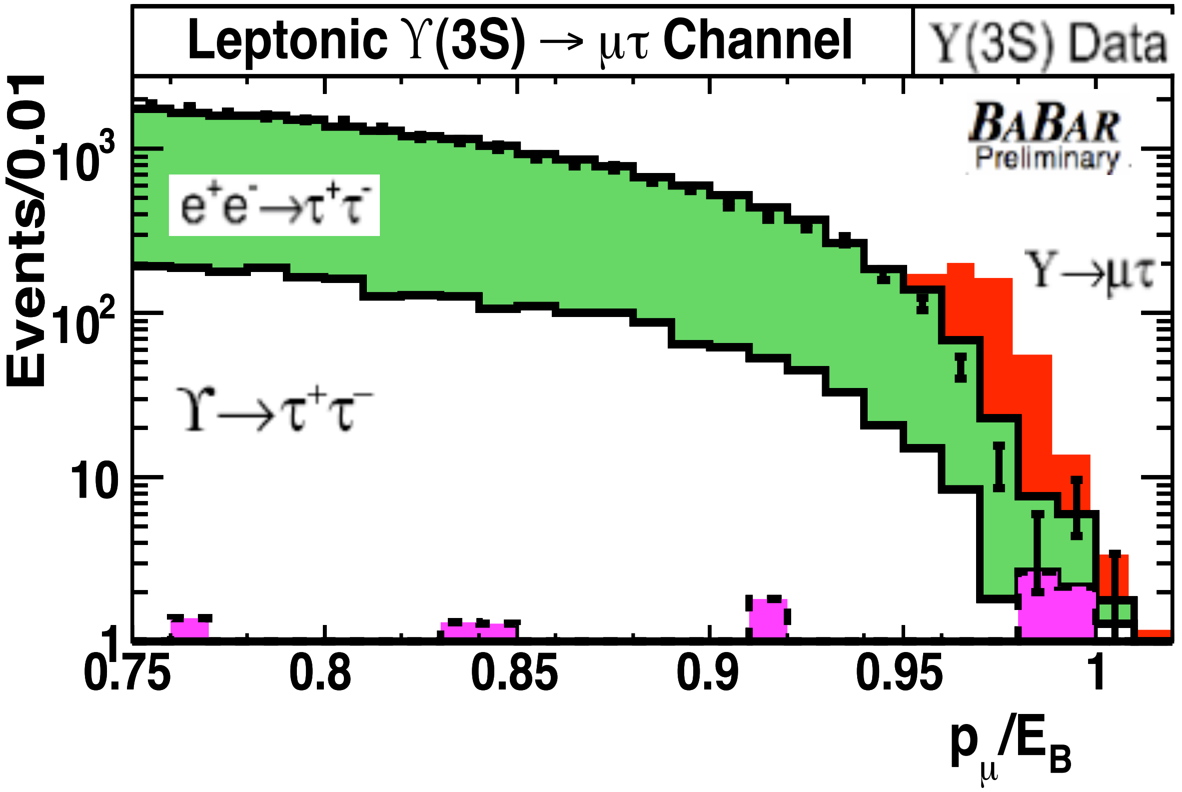


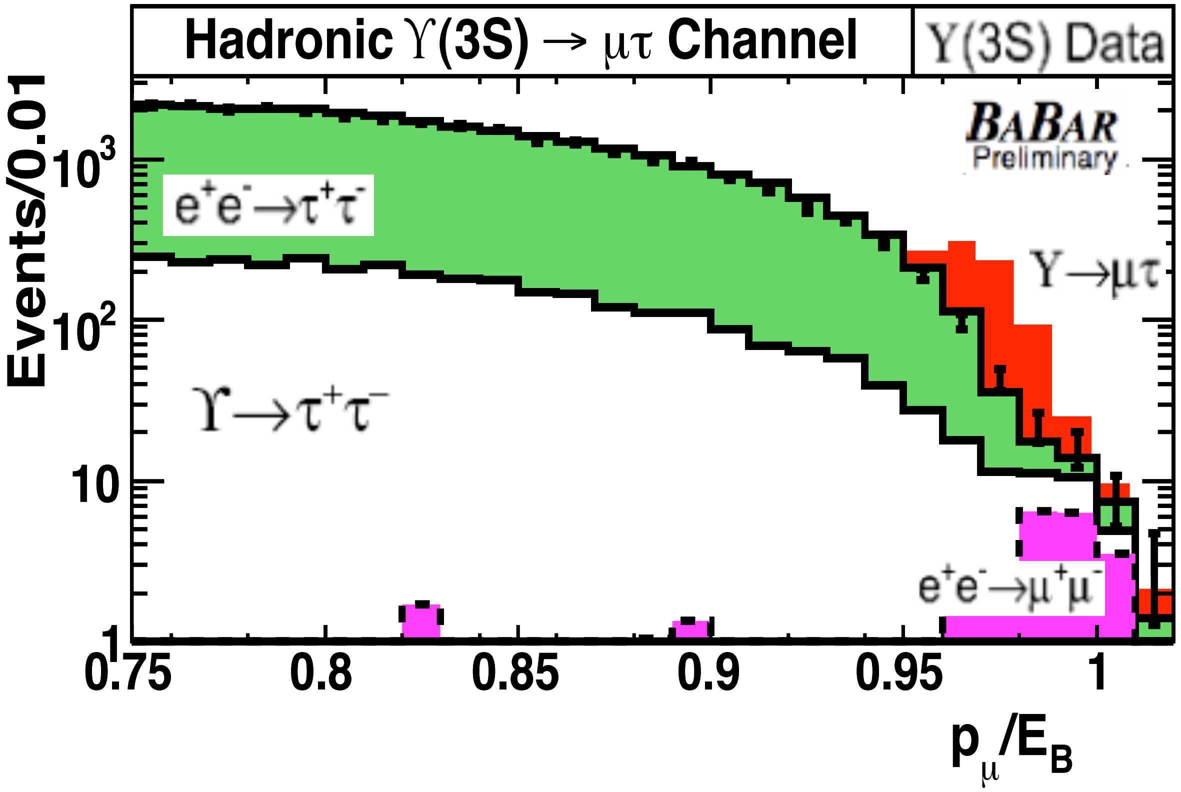
Tau-pair Background: Kinematic cut-off ~ 0.97

The primary lepton momentum spectrum

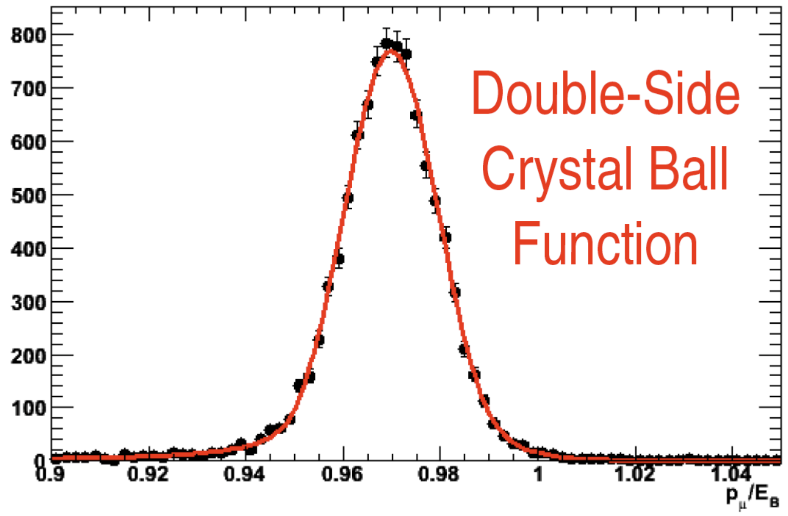


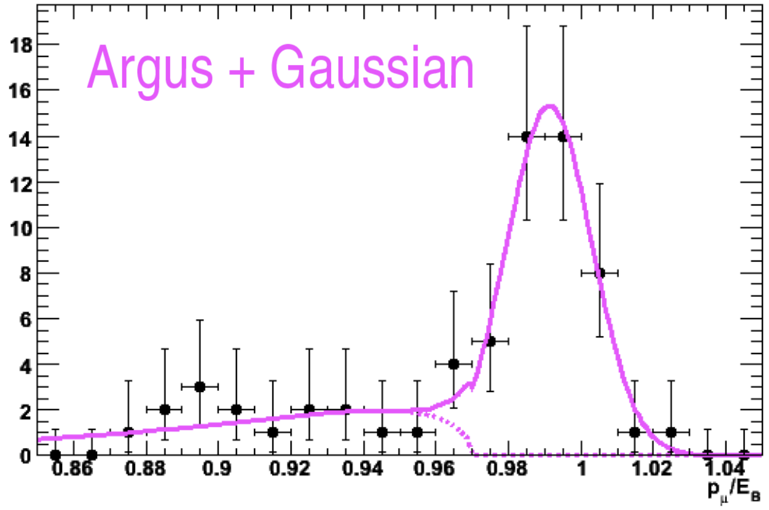


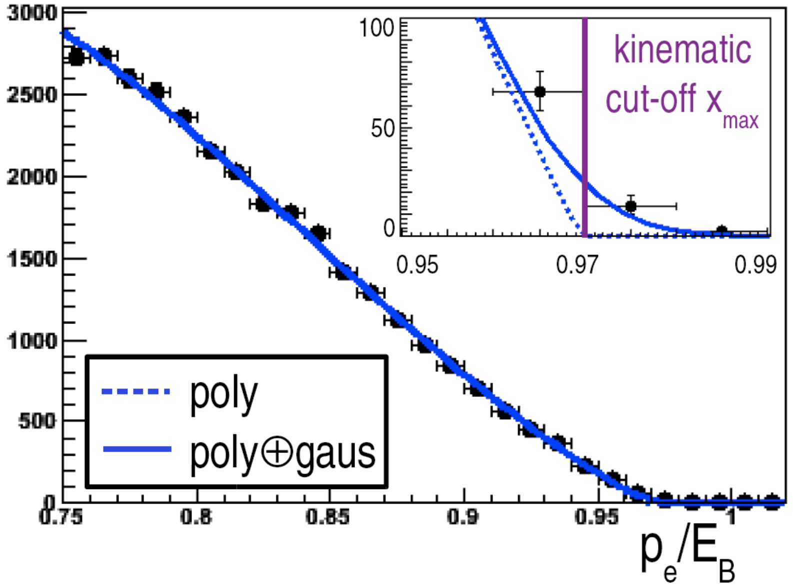




Signal and background shapes



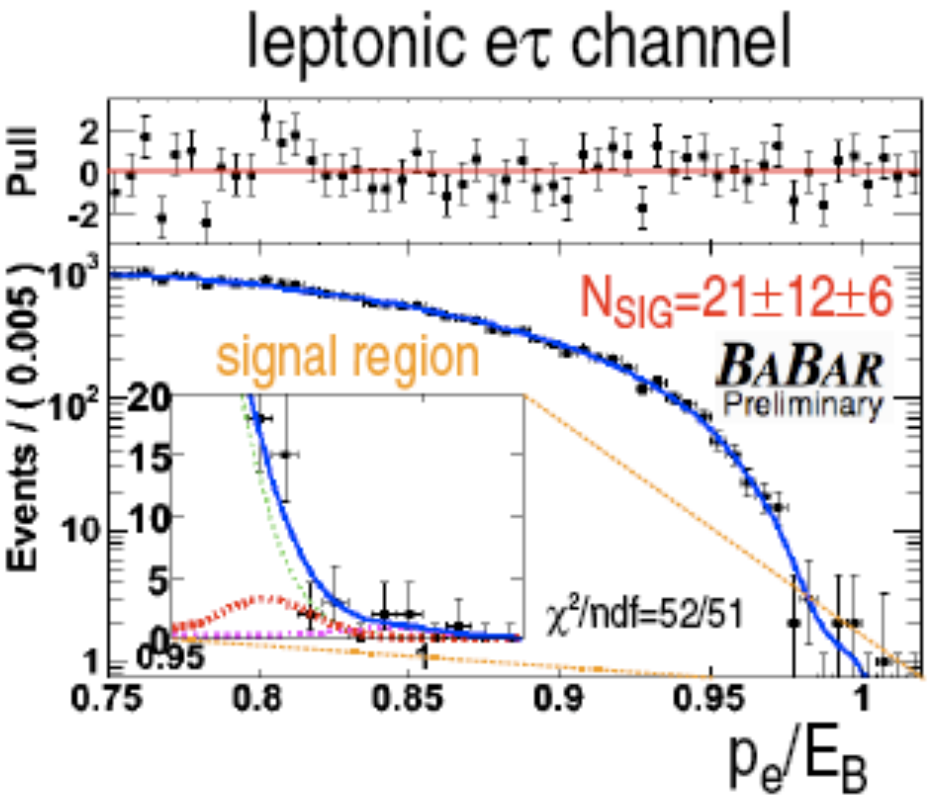


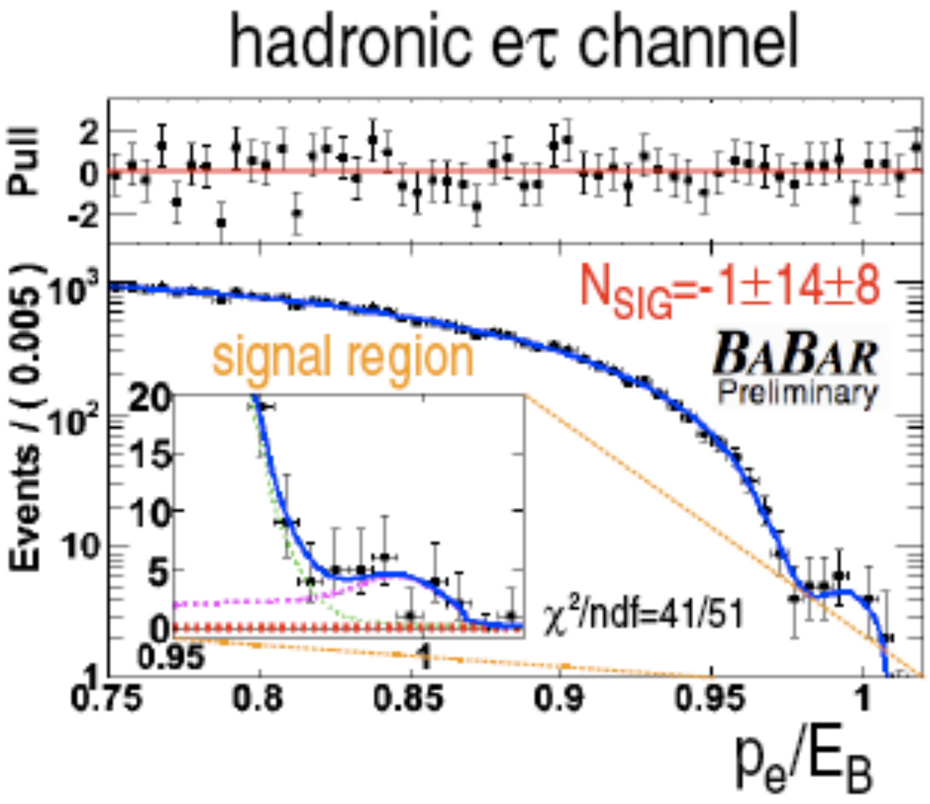


- Signal PDF: double-sided CB function peaked at $x=p_1/E_B = 0.97$
  - Extract shape from fits to signal MC
- Bhabha/m-pair Background PDF: Argus threshold function + Gaussian peaked at $x \approx 1$
  - Extract shape from fits to signal MC
- τ-Pair Background PDF: 3rd-order poly ⊕ detector resolution function
  - $poly(x)=(1-x/x_{MAX})+c_2(1-x/x_{MAX})^2+c_3(1-x/x_{MAX})^3$
    - x_{MAX} = kinematic cutoff parameter: extracted from fit to Υ(4S) data control sample
    - c_2, c_3 = polynomial shape parameters: floated in fit to Υ(3S) data
  - detector resolution function extracted from MC
- Global PDF = signal + bhabha (μ-pair) + τ-Pair components for eτ (μτ) channels
  - Float component yields and polynomial shape parameters in fit to Υ(3S) data

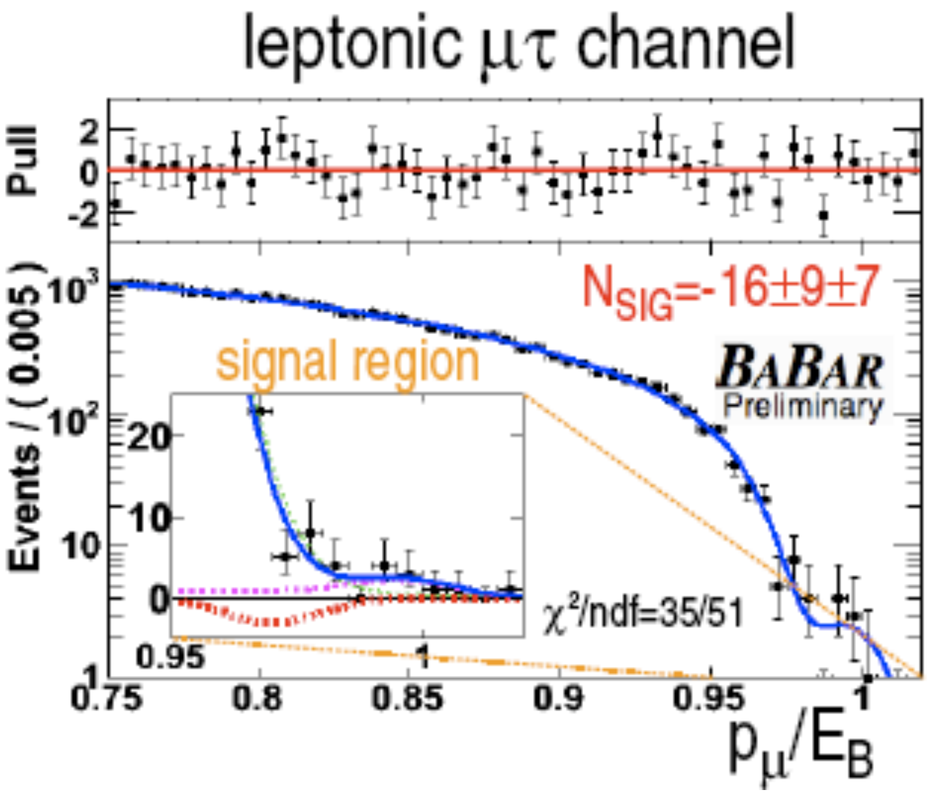
Fit Results

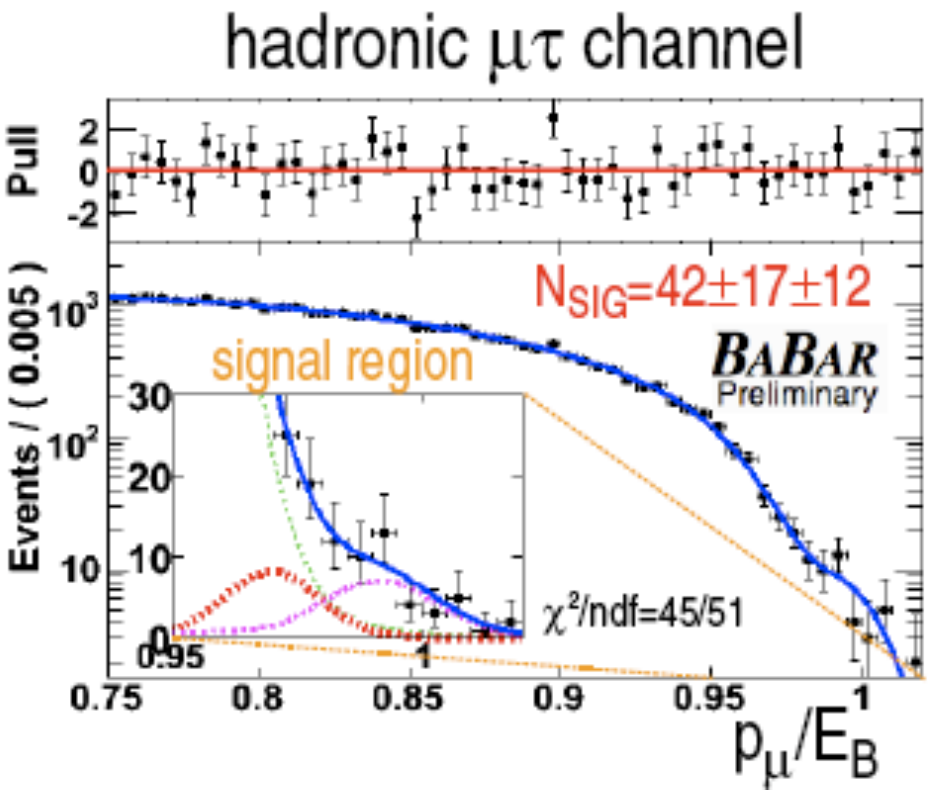
Global PDF
Signal
τ-pair Bkg
Bhabha/
μ-pair Bkg


leptonic eτ channel

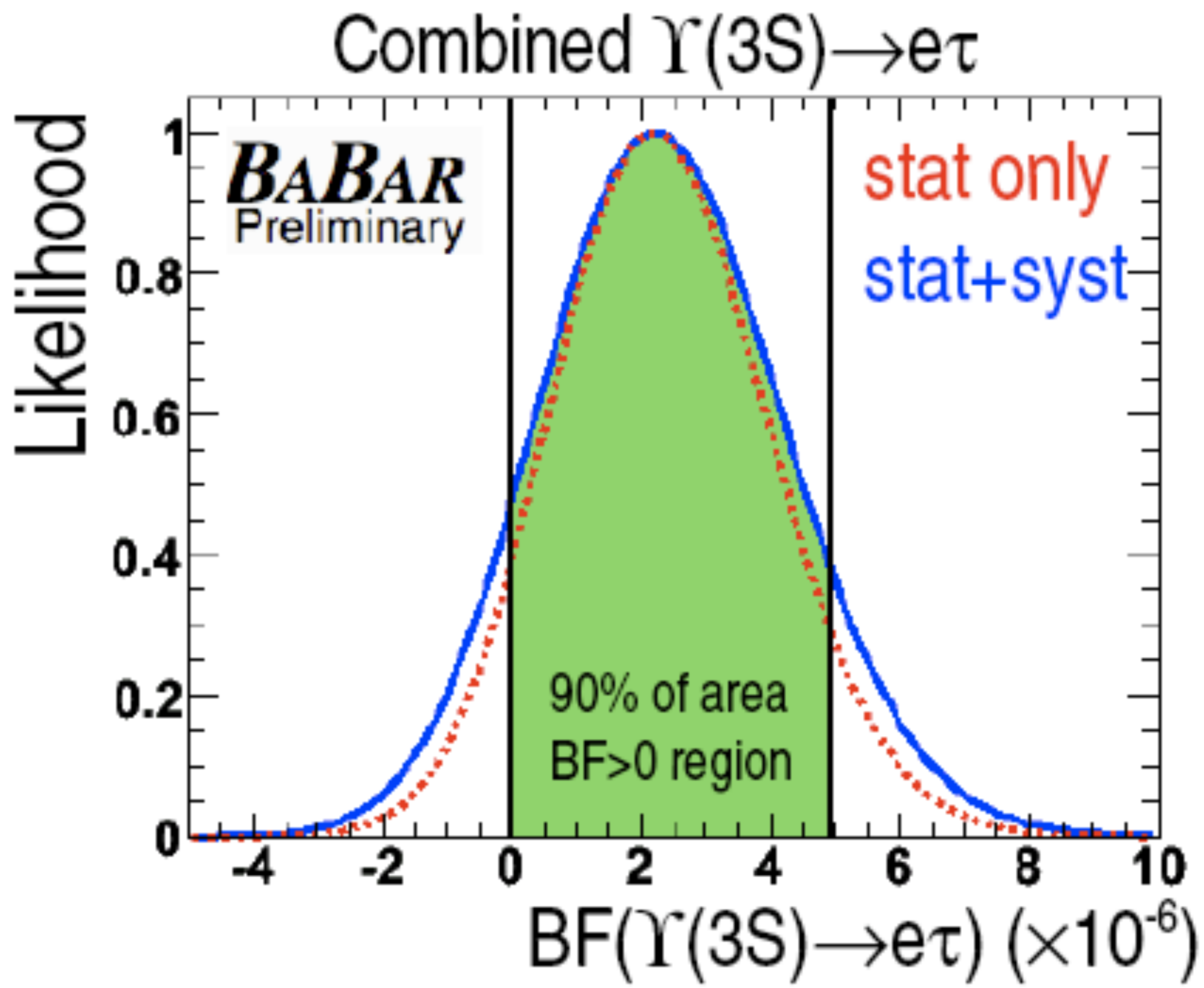

hadronic eτ channel

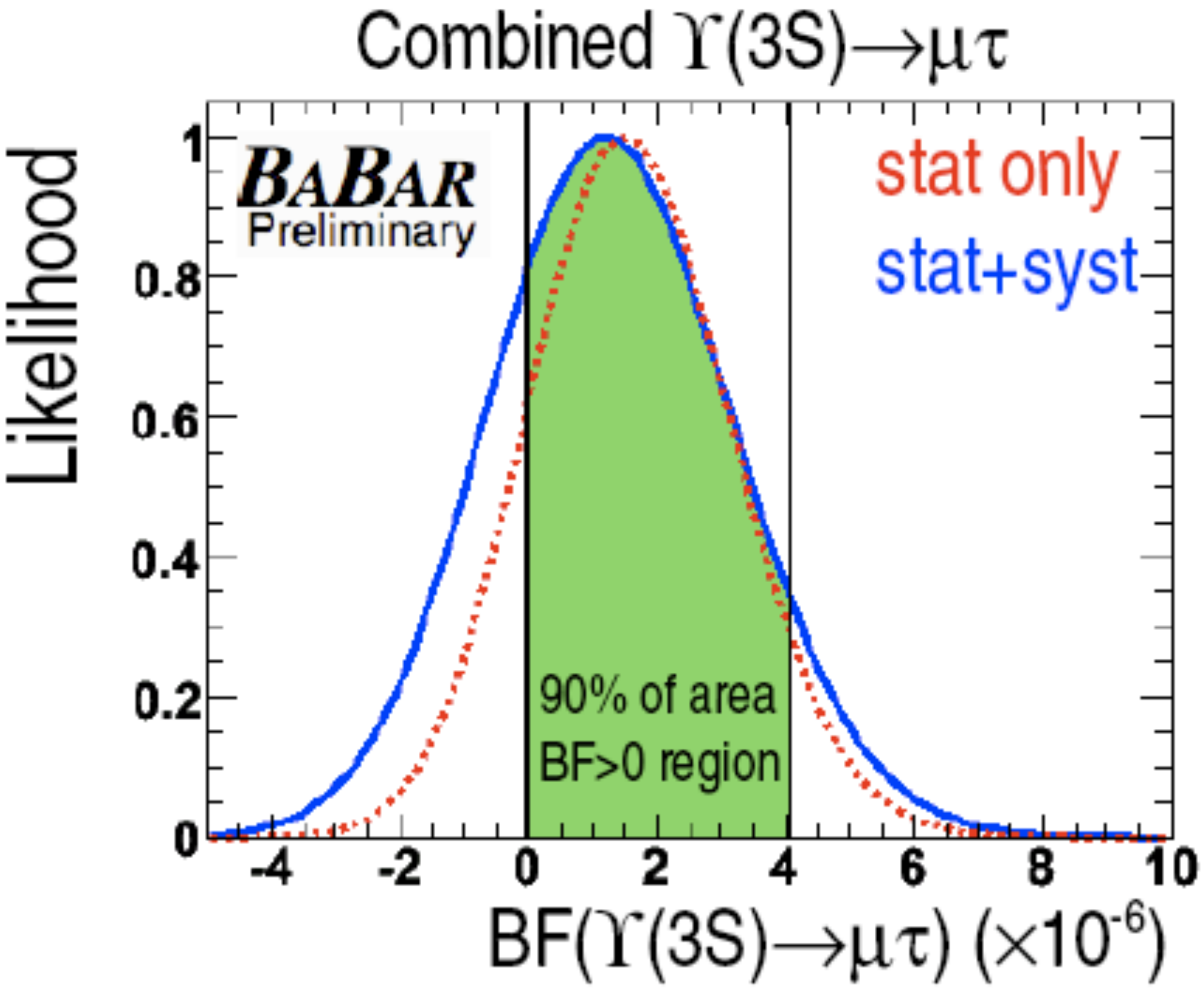
All channels give signal yield within ±2.1σ of zero


leptonic μτ channel


hadronic μτ channel

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





BF($\Upsilon(3S)\to e\tau$) < 5.0×10^{-6}

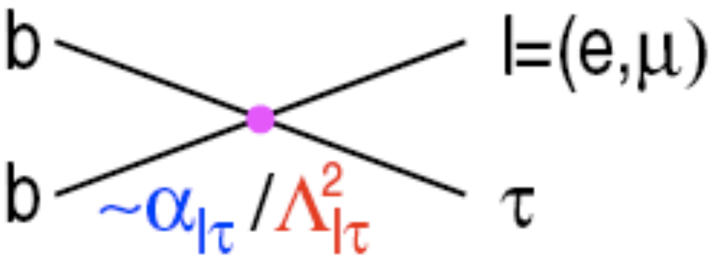
(first upper limit)

BF($\Upsilon(3S)\to \mu\tau$) < 4.1×10^{-6}

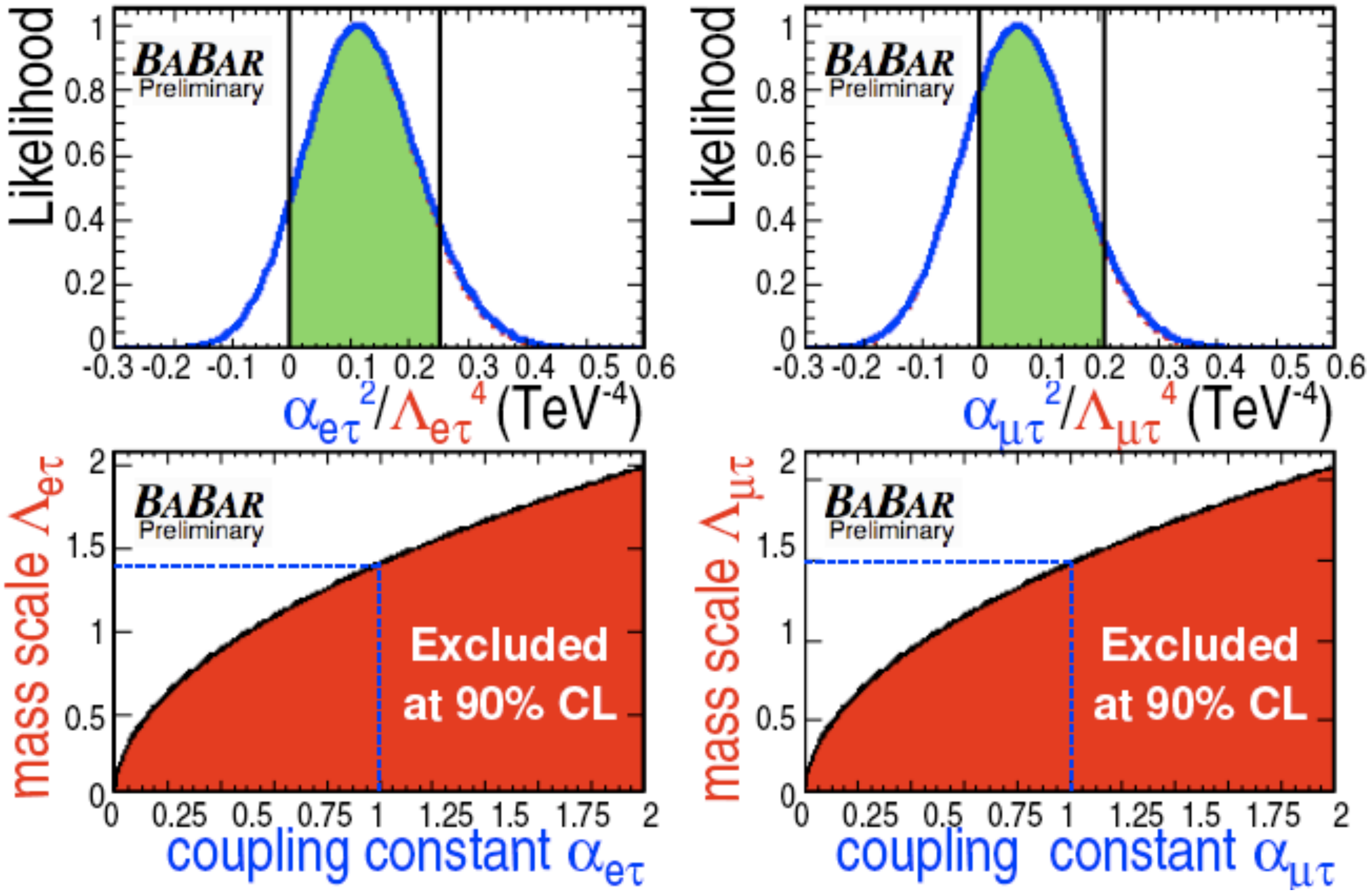
(>4x better than previous UL)

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

Limits on Generic Contact Interaction



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



q_b = b quark charge

α = fine structure constant

assumes vector coupling

Silagadze Phys. Scripta 64.128

Black et al. PRD 66.053002

Assume strong coupling

$\alpha_{e\tau} = \alpha_{\mu\tau} = 1$:

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

$\Lambda_{\mu\tau} > 1.5$ 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.
  - $\mathcal{B}(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$ @ 90% C.L.

- 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.
  - $\mathcal{B}(\Upsilon(3S) \rightarrow \mu\tau) < 4.1 \times 10^{-6}$ @ 90% C.L.

- More results to be available soon with $\Upsilon(2S)$ decays