Searches for New Physics at B-Factories

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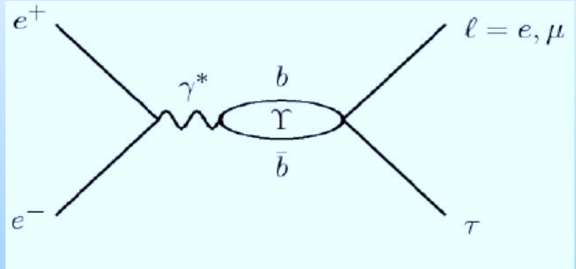
(On Behalf of the BaBar and Belle Collaborations)

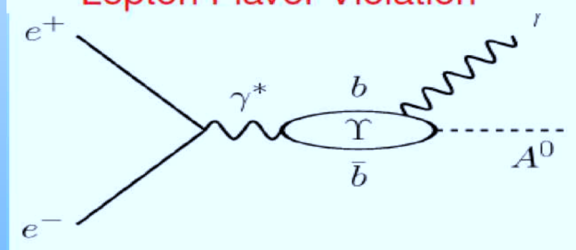
Signatures of New Physics

- Charged Lepton Flavor Violation:
  - $\tau \to l\gamma$ ($l=e,\mu$)
  - $\tau \to 3l$ ($l=e,\mu$)
  - $Y(2S,3S) \to l\tau$ ($l=e,\mu$)
- Light Higgs (A^0) decays:
  - $Y(2S,3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$
  - $Y(2S,3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$
  - $Y(2S,3S) \to \gamma A^0$, $A^0 \to$ invisible
  - $Y(2S) \to \pi^+\pi^- Y(1S)$, $Y(1S) \to \gamma A^0$, $A^0 \to$ invisible
- Lepton Non-Universality:
  - $Y(1S) \to \gamma A^0$, $A^0 \to l^+l^-$
- Invisible Bottomonium decays:
  - $Y(3S) \to \pi^+\pi^- Y(1S)$, $Y(1S) \to$ invisible
- Dark Sector Gauge Boson mediated decays:
  - $e^+e^- \to W_D^+ W_D^- \to l^+l^-l^+l^-$

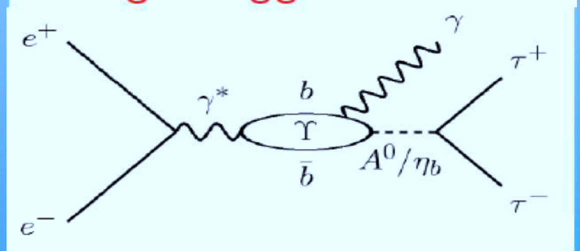
Some Illustrations:



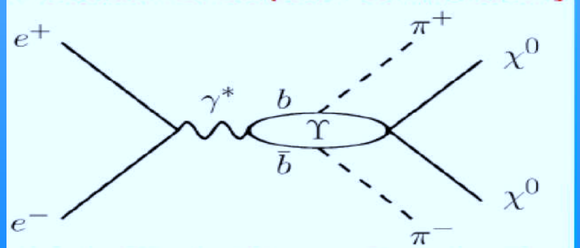
Lepton Flavor Violation



Light Higgs Production



Violation of Lepton Universality



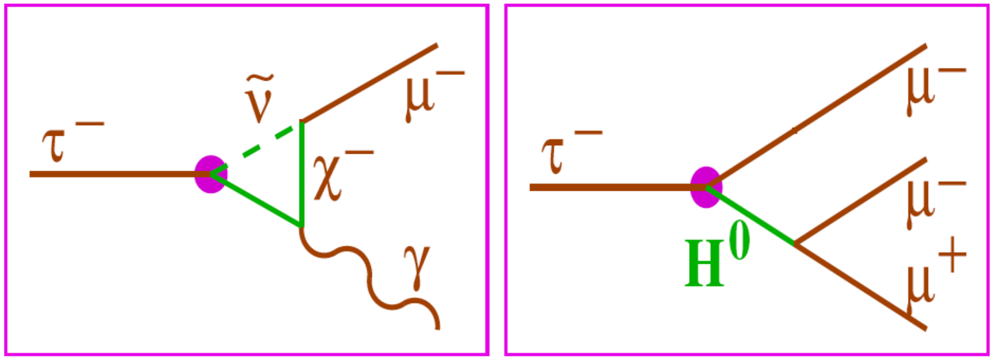
Light Dark Matter Production

Charged Lepton Flavor Violation

- Predicted by many beyond SM processes ... not forbidden by SM
  - SUSY models: non-diagonal slepton mass matrix $\Rightarrow$ 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

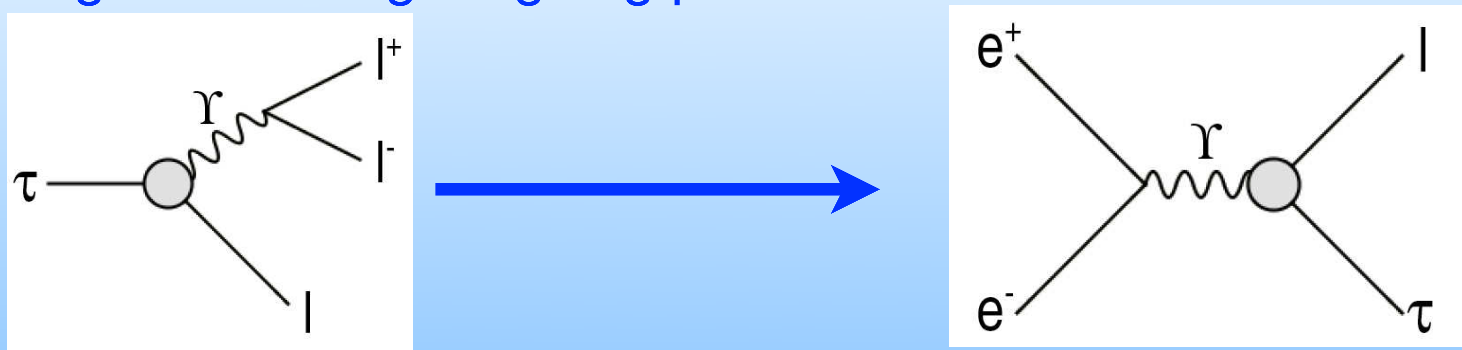
	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}
Non-Universal Z′ (PLB547(2002)252)	10^{-9}	10^{-8}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}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

Illustrations:



Probing TeV scale Physics

- Re-ordering of incoming/outgoing particles relates LFV in τ & ϒ decays



- $\mathcal{B}(\Upsilon \to \ell\tau) \sim \frac{\mathcal{B}(\tau \to \ell\ell\ell)}{\mathcal{B}(\tau \to \ell\nu\overline{\nu})} \frac{\Gamma(W \to \ell\nu)^2}{\Gamma(\Upsilon)\Gamma(\Upsilon \to \ell\ell)} (M_\Upsilon/M_W)^6$ S.Nussinov, et. al. PRD 63, 016003 (2001)
- $\mathcal{B}(\tau \to \ell\ell\ell) < 2 - 4 \times 10^{-8} \quad \Rightarrow \quad \mathcal{B}(\Upsilon \to \ell\tau) < 3 - 6 \times 10^{-3}$

- **CLEO search for ϒ→μτ, τ→eνν** PRL 101, 201601 (2008)

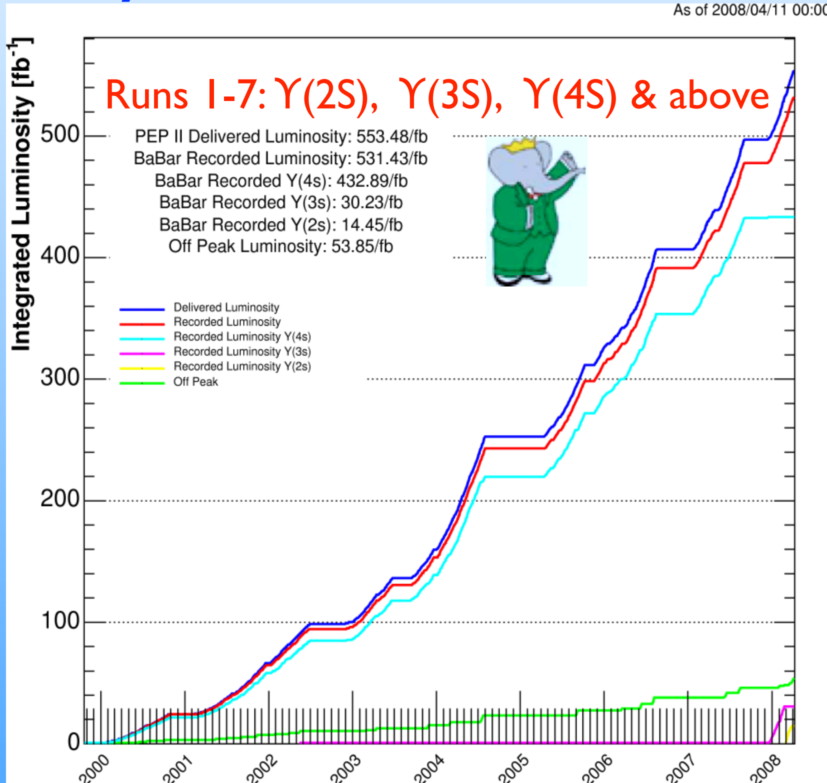
	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass (GeV/c^2)	9.46	10.02	10.36
N decays (millions)	20.8	9.3	5.9
$\Gamma(\Upsilon \to \mu\mu)$ (keV)	1.252	0.581	0.413
$\Gamma(\Upsilon)$ (keV)	53.0	43.0	26.3
$\mathcal{B}(\mu\mu)$ ($\times 10^{-3}$)	23.6	13.5	15.7
$\mathcal{B}(\mu\tau)$ (95% CL UL, $\times 10^{-6}$)	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

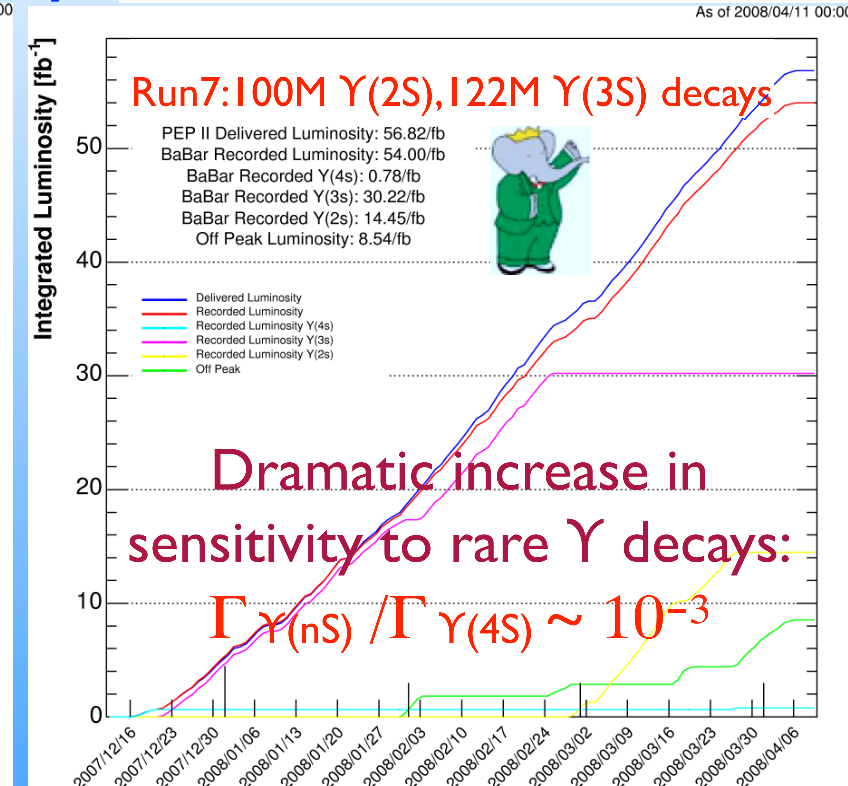
1000 times stronger than indirect limits

New Physics @ TeV Scale

Current Reach at B-Factories

A B-Factory is also a Flavor Factory: $\sigma(B\bar{B}) \approx 1.1nb \approx \sigma(c\bar{c}) \approx 1.3nb \approx \sigma(\tau^+\tau^-) \approx 0.9nb$





Improving Sensitivity for LFV discovery in τ Decays:

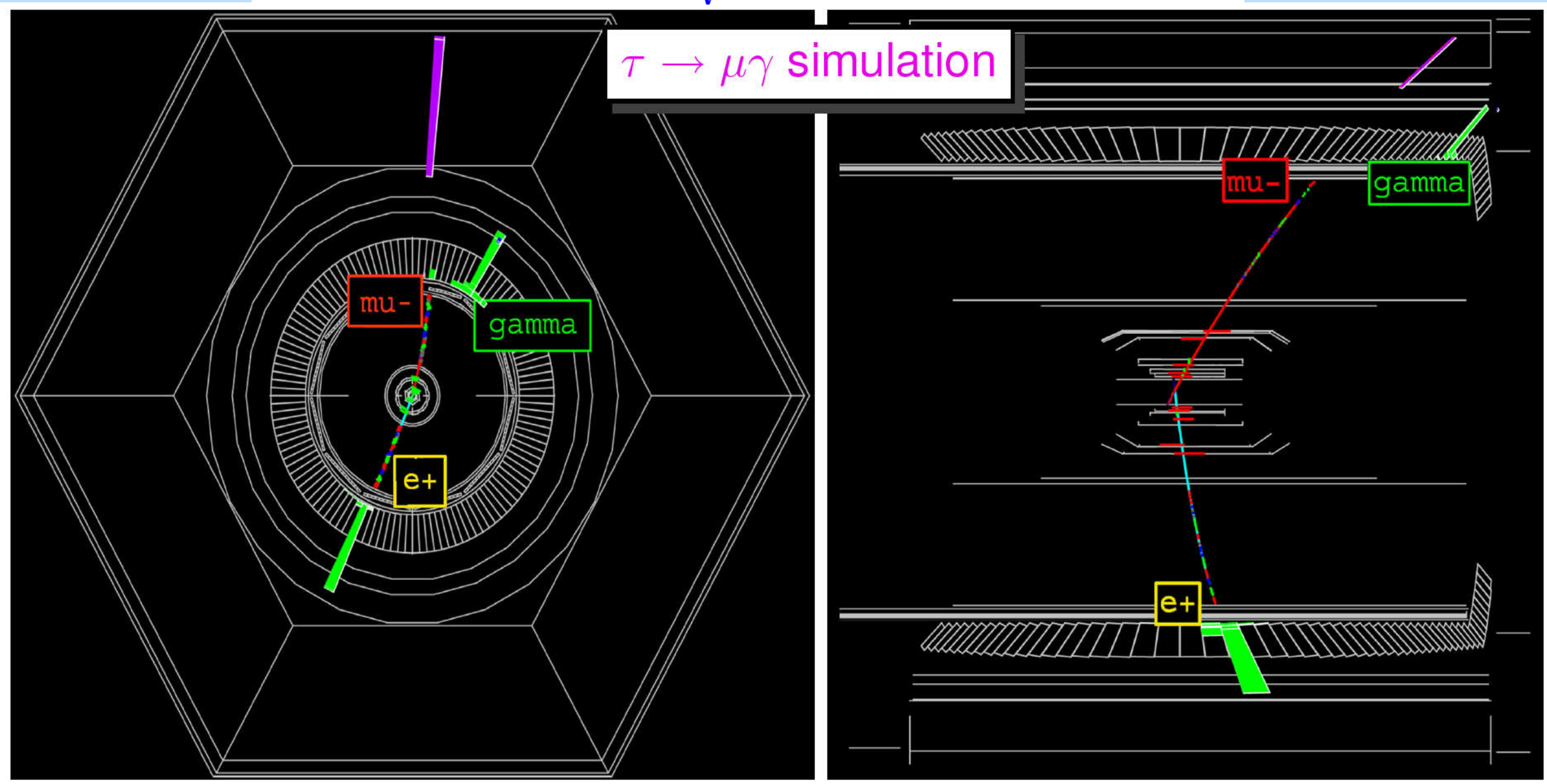
470 fb^{-1} @ ϒ(4S), 30 fb^{-1} @ ϒ(3S), 15 fb^{-1} @ ϒ(2S) ⇒ $N_\tau \sim 10^9$

Improving Sensitivity for LFV discovery in ϒ Decays:

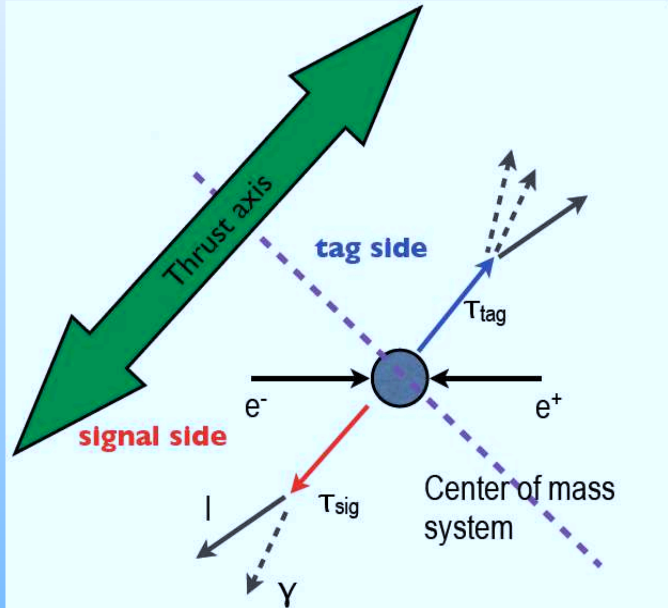
~20 times more ϒ(3S) decays than CLEO ⇨ lower limits by ~4

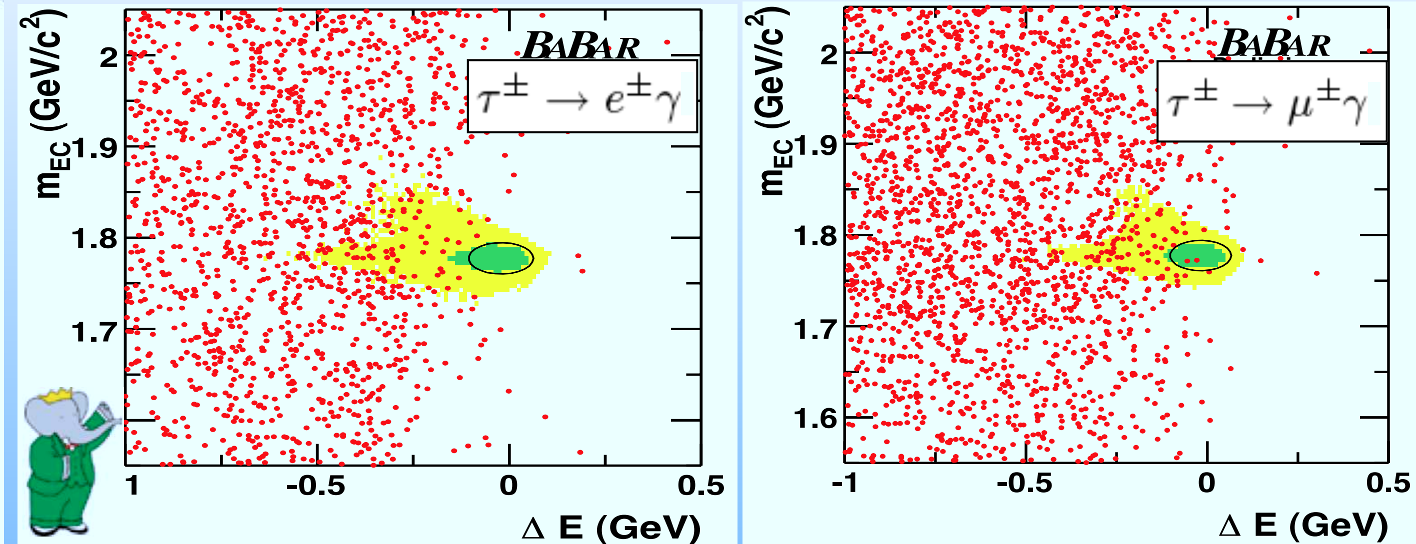
$\tau \rightarrow l\gamma$: Signal Characteristics

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



$\tau \rightarrow l\gamma$

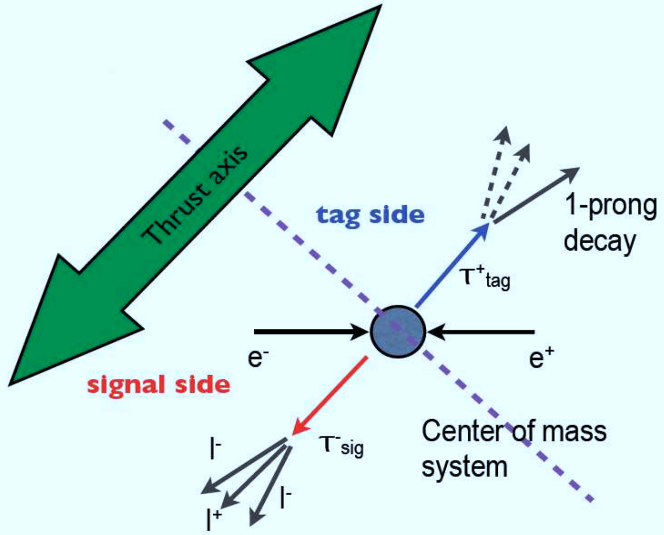


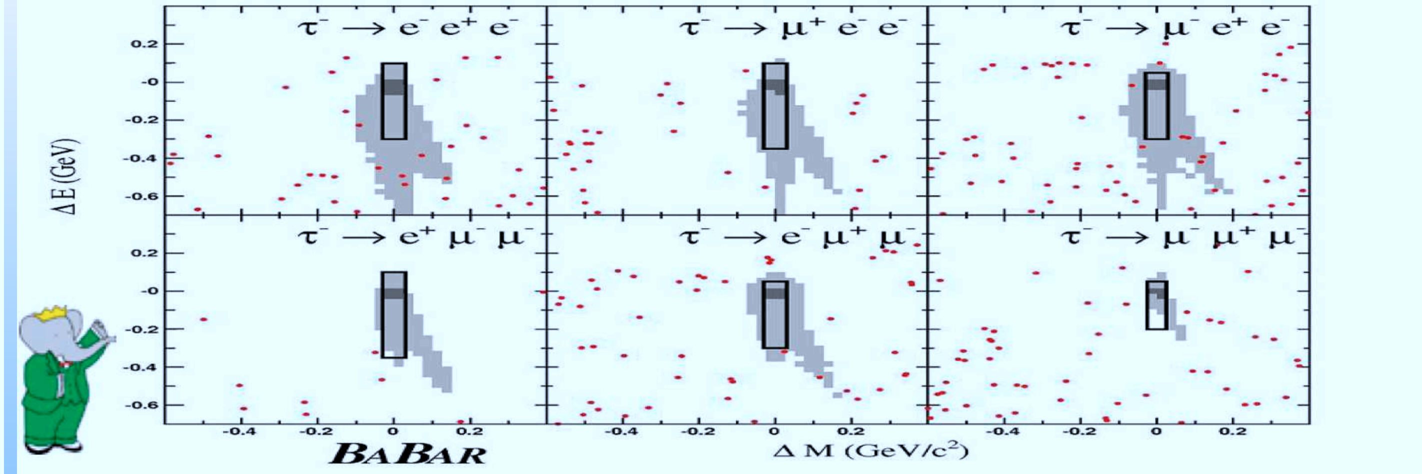


90% (50%) of signal MC events are shown as light- (dark-) shaded regions

Decay Mode	Experiment	Reference	Upper Limit @ 90% C.L.	Luminosity
			(10^{-8})	(fb^{-1} @ Υ(4S)) (unless otherwise mentioned)
$\tau^- \to e^- \gamma$	Belle	Phys.Lett.B666:16,2008	12	535
	BaBar	Phys.Rev.Lett.104:021802,2010	3.3	470 @ Υ(4S), 31 @ Υ(3S), 15 @ Υ(2S)
$\tau^- \to \mu^- \gamma$	Belle	Phys.Lett.B666:16,2008	4.5	535
	BaBar	Phys.Rev.Lett.104:021802,2010	4.4	470 @ Υ(4S), 31 @ Υ(3S), 15 @ Υ(2S)

τ→lll

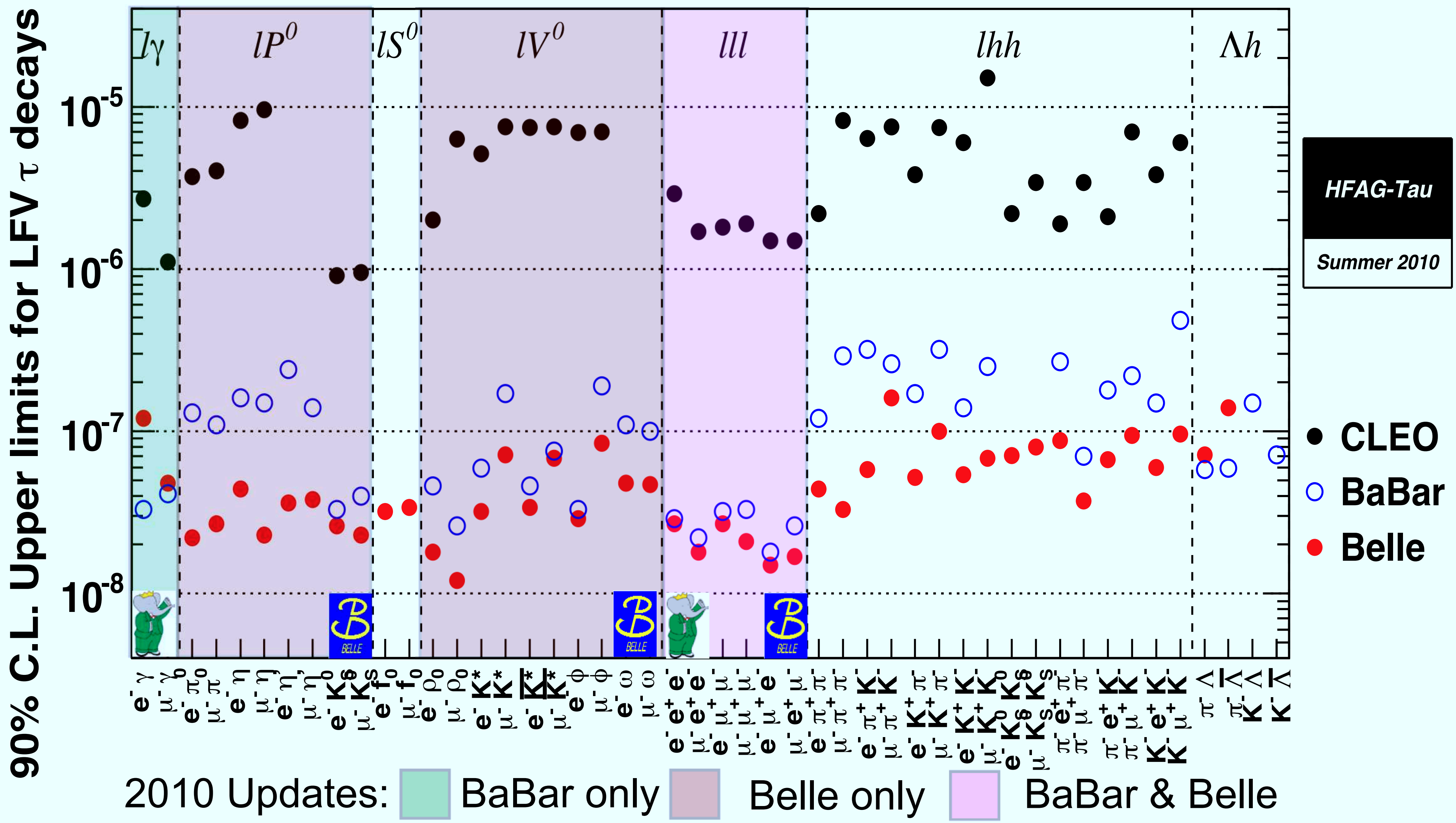




90% (50%) of signal MC events are shown as light- (dark-) shaded regions

Decay Mode	Experiment	Reference	Upper Limit @ 90% C.L.	Luminosity
			(10^{-8})	(fb^{-1} @ Υ(4S))
$\tau^- \to e^- e^+ e^-$	Belle	Phys.Lett.B687:139-143,2010	2.7	782
	BaBar	Phys.Rev.D81:111101(R),2010	2.9	468
$\tau^- \to \mu^- e^+ e^-$	Belle	Phys.Lett.B687:139-143,2010	1.8	782
	BaBar	Phys.Rev.D81:111101(R),2010	2.2	468
$\tau^- \to e^- \mu^+ \mu^-$	Belle	Phys.Lett.B687:139-143,2010	2.7	782
	BaBar	Phys.Rev.D81:111101(R),2010	3.2	468
$\tau^- \to \mu^- \mu^+ \mu^-$	Belle	Phys.Lett.B687:139-143,2010	2.1	782
	BaBar	Phys.Rev.D81:111101(R),2010	3.3	468
$\tau^- \to e^- \mu^+ e^-$	Belle	Phys.Lett.B687:139-143,2010	1.5	782
	BaBar	Phys.Rev.D81:111101(R),2010	1.8	468
$\tau^- \to \mu^- e^+ \mu^-$	Belle	Phys.Lett.B687:139-143,2010	1.7	782
	BaBar	Phys.Rev.D81:111101(R),2010	2.6	468

Summary of LFV in τ decays



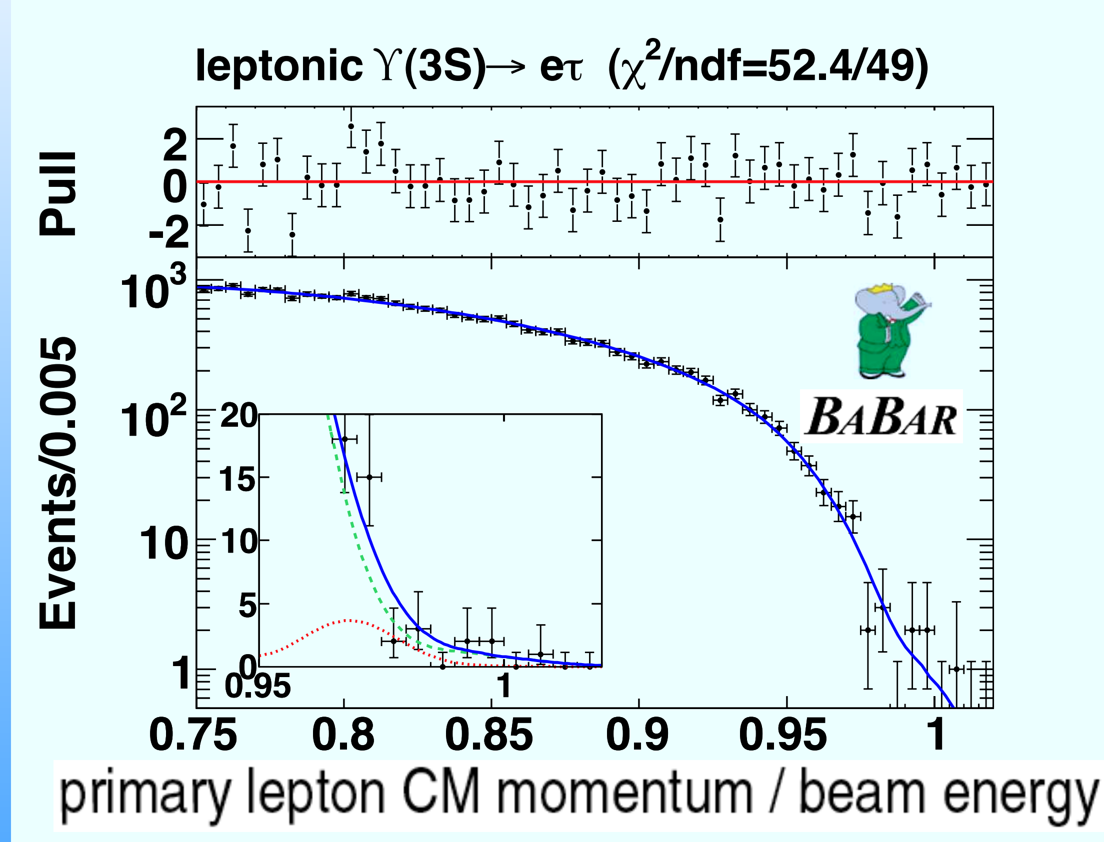
Belle Updates elaborated in K. Hayasaka's Talk (Session 6)

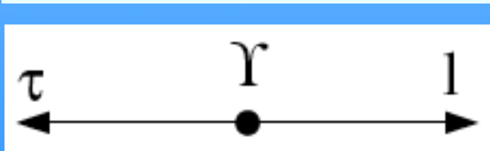
LFV in $\Upsilon(nS) \to l\tau$ ($l=e,\mu$) decays

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

BaBar, PRL 104, 151802 (2010)

	$\mathcal{B}\ (10^{-6})$	UL (10^{-6})
$\mathcal{B}(\Upsilon(2S)\to e^{\pm}\tau^{\mp})$	$0.6^{+1.5+0.5}_{-1.4-0.6}$	< 3.2
$\mathcal{B}(\Upsilon(2S)\to \mu^{\pm}\tau^{\mp})$	$0.2^{+1.5+1.0}_{-1.3-1.2}$	< 3.3
$\mathcal{B}(\Upsilon(3S)\to e^{\pm}\tau^{\mp})$	$1.8^{+1.7+0.8}_{-1.4-0.7}$	< 4.2
$\mathcal{B}(\Upsilon(3S)\to \mu^{\pm}\tau^{\mp})$	$-0.8^{+1.5+1.4}_{-1.5-1.3}$	< 3.1



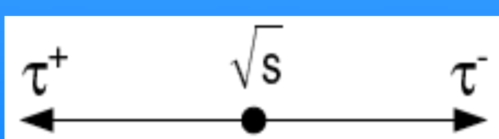


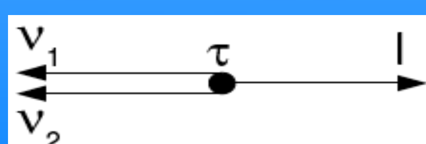
$E_l = (m_\Upsilon^2 - m_\tau^2 + m_l^2)/(2 m_\Upsilon)$

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

Signal: peak ~ 0.97

Bhabha/Mu-pair Background: peak ~ 1.0

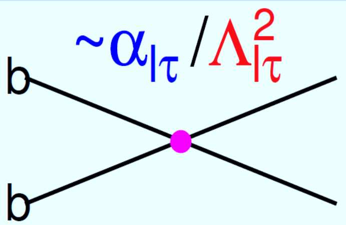




Tau-pair Background: Kinematic cut-off ~ 0.97

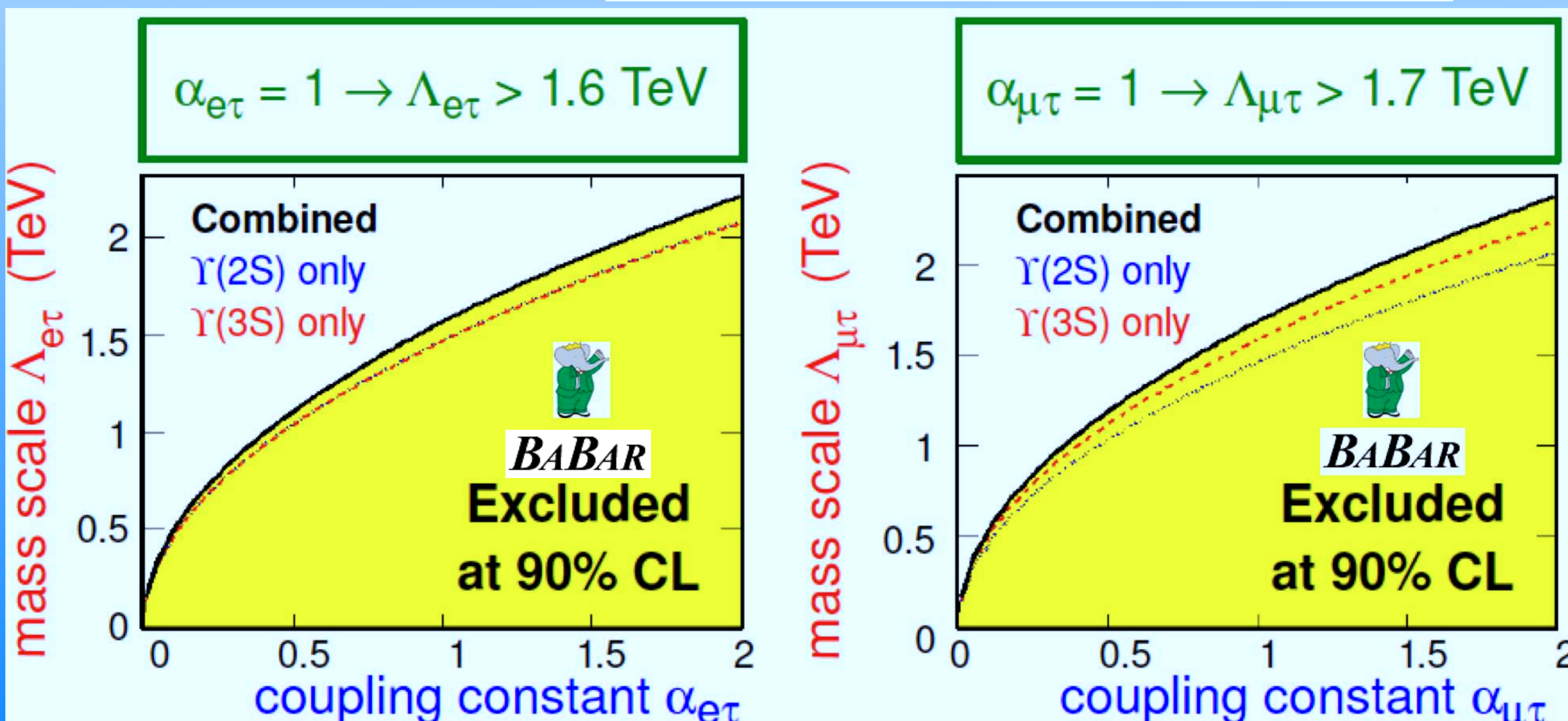
Limits on Contact Interaction

Constraints on *coupling constant* and *mass scale*:



$$\frac{\alpha_{l\tau}^2}{\Lambda_{l\tau}^4} = \frac{BF(\Upsilon(3S)\to l\tau)}{BF(\Upsilon(3S)\to ll)} \frac{2q_b\alpha^2}{(M_{\Upsilon(nS)})^4}$$

Silagadze Phys. Scripta 64.128 & Black et al. PRD 66.053002



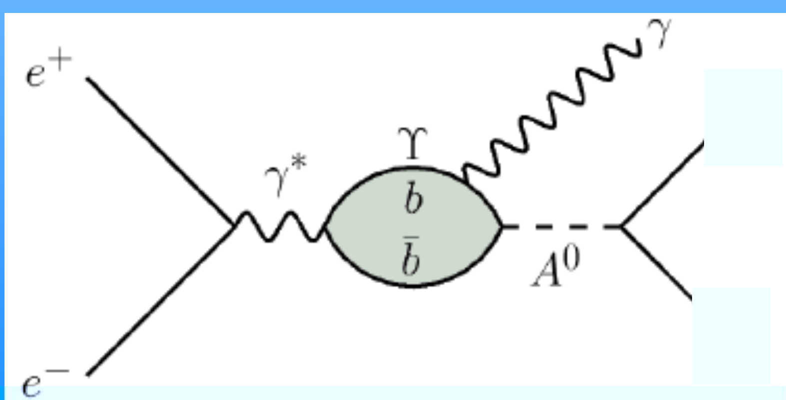
Light Higgs/Dark Matter in Υ decays ?

- Naturalness problem: Higgs mass unstable under radiative corrections in Standard Model
- Possible solution: Minimal Supersymmetric Standard Model (2 Higgs doublets → $h, H, A, H^{\pm}$)

- Hierarchy Problem: Fine tune the scale of Electroweak symmetry breaking
- Possible solution: Next-to-Minimal Supersymmetric Standard Model (introduce Higgs singlet)

- Mixing of singlet with MSSM-like Higgs doublet can produce low mass CP-odd Higgs (A^0)
- If mixing is small, coupling of A^0 to Z is suppressed: this evades most LEP limits, including those from model independent Higgs search using recoil mass against $Z \to e^+ e^-$ or $\mu^+ \mu^-$
- If BR($H \to A^0 A^0$) > 0.7, $m_{A0} < 2m_b$, LEP limits on *Higgs* → *bb, bbbb* channels can be evaded

- Interesting possibility of Higgs discovery in $\Upsilon \to \gamma A^0$ decays via the Wilczek mechanism



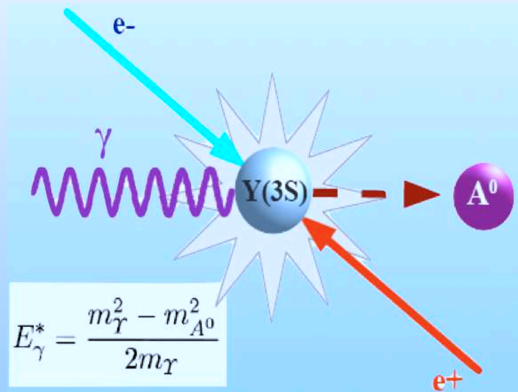
Depending on M(A^0), dominant decays are

- $A^0 \to$ *hadrons*
- $A^0 \to \tau^+ \tau^-$
- $A^0 \to \mu^+ \mu^-$
- $A^0 \to$ *invisible (Dark Matter?)*

References:
PRL 103, 181801 (2009)
PRL 103, 081803 (2009)
arXiv: 0808.0017

Can we solve the Dark Matter puzzle and discover Higgs at the same time?

Revisiting $A^0 \to$ invisible search

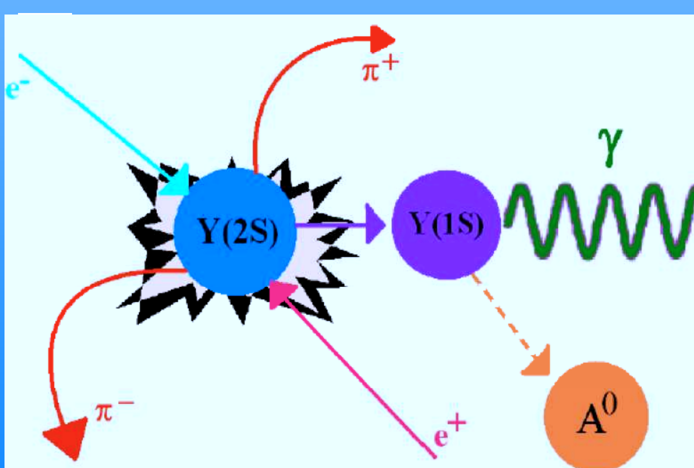


Search Strategy for Light Higgs (A^0)= $A_{MSSM}\ Cos\theta_A + A_{singlet}\ Sin\theta_A$

In Y(nS) rest frame, photon energy measures mass of A^0:

Search for monochromatic photon in the recoil mass spectrum

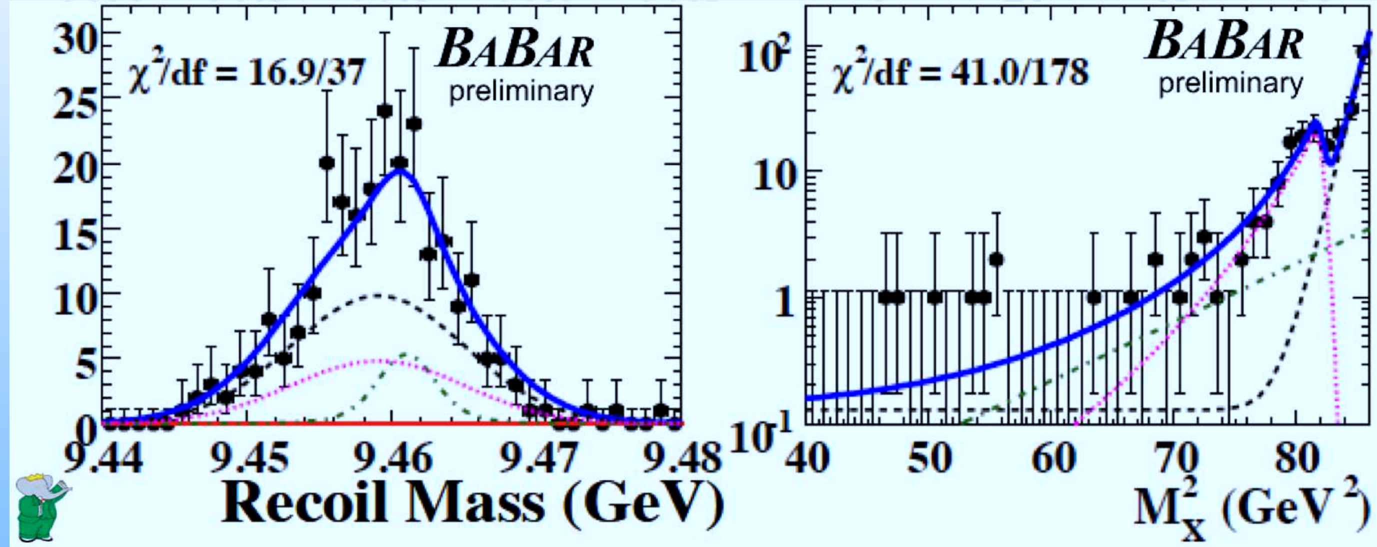
- $\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ invisible [arXiv: 0808.0017] search had large irreducible background contribution
- New search performed looking for $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to$ invisible decays
- Reduce backgrounds using Missing Mass & Di-pion recoil mass: $M^2_{\rm recoil} = M^2_{\Upsilon(2S)} + m^2_{\pi\pi} - 2M_{\Upsilon(2S)}E^*_{\pi\pi}$



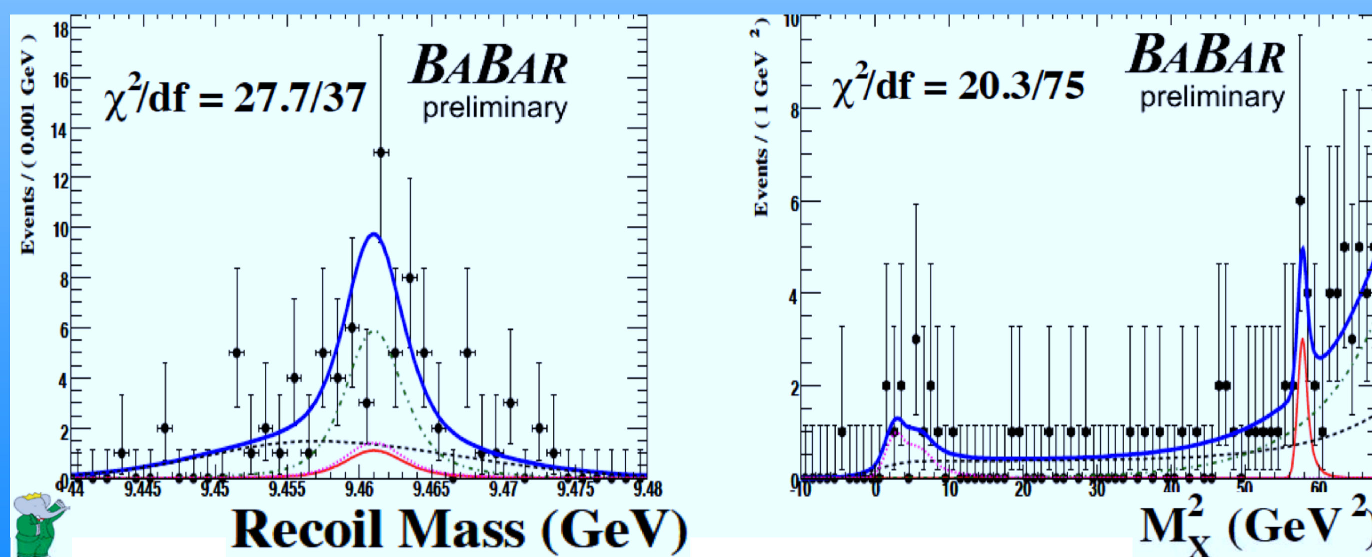
- Missing Mass: $M^2_X = (\mathcal{P}_{e^+e^-} - \mathcal{P}_{\pi\pi} - \mathcal{P}_\gamma)^2$
- Single Photon & di-pion trigger (for E_γ > 1.1 GeV)
- Only di-pion trigger (for E_γ < 1.1 GeV)
- Both single-photon & di-pion (these pions have low momentum) final states require modification of trigger

$A^0 \rightarrow$ invisible: Fit Results

Projections plots from the fit (solid blue line) with $N_{signal} = 0$, overlayed with contributions from continuum background (black dashed line), leptonic $\Upsilon(1S)$ decays (green dash-dotted line) and $e^+e^- \rightarrow \eta' \rightarrow \pi^+\pi^-\gamma$ (magenta dotted line) in the search for range: $7.5 \leq m_{A^0} \leq 9.2$ GeV



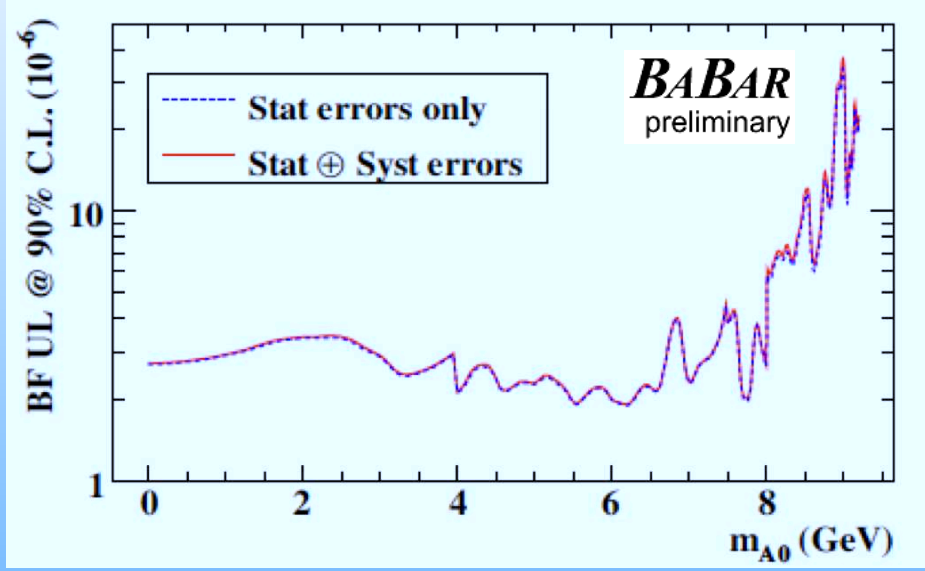
Projections plots from the fit (solid blue line) with $N_{signal} = 5.6\,^{+3.9}_{-3.1} \pm 0.5$ (significance of 2.0 σ), overlayed with contributions from continuum background (black dashed line), leptonic $\Upsilon(1S)$ decays (green dash-dotted line), hadronic $\Upsilon(1S)$ decays (magenta dotted line) & signal (red solid line) with $m_{A^0} = 7.58$ GeV. Probability for such fluctuation to appear *anywhere* in our data >30%.



New limits on $A^0 \to$ invisible

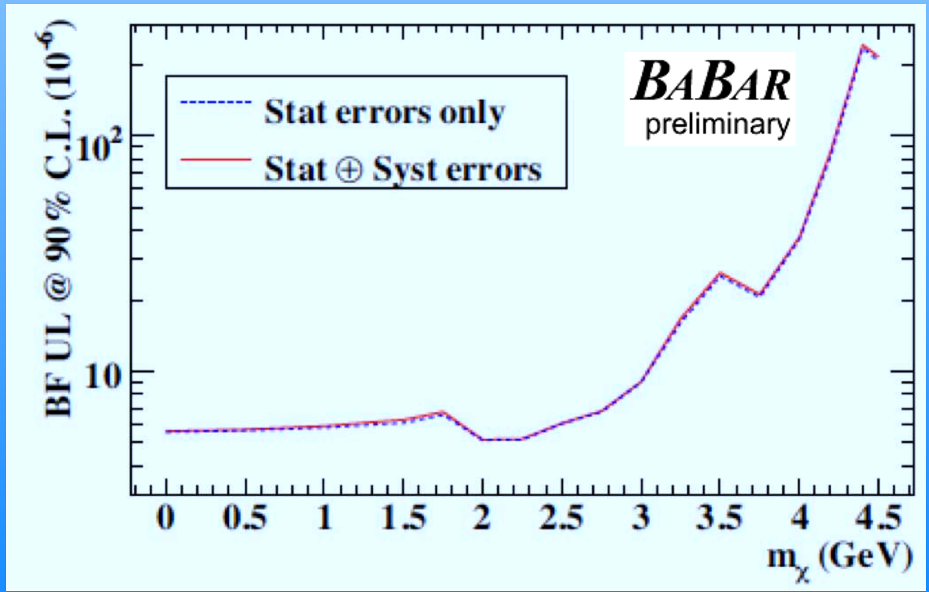
BaBar/PUB-10/023

$$\mathcal{B}(\Upsilon(1S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \text{invisible}) < (1.9 - 37) \times 10^{-6}$$
$$\text{for } 0 \leq m_{A^0} \leq 9.2 \text{ GeV}$$
$$\text{at } 90\% \text{ C.L.}$$

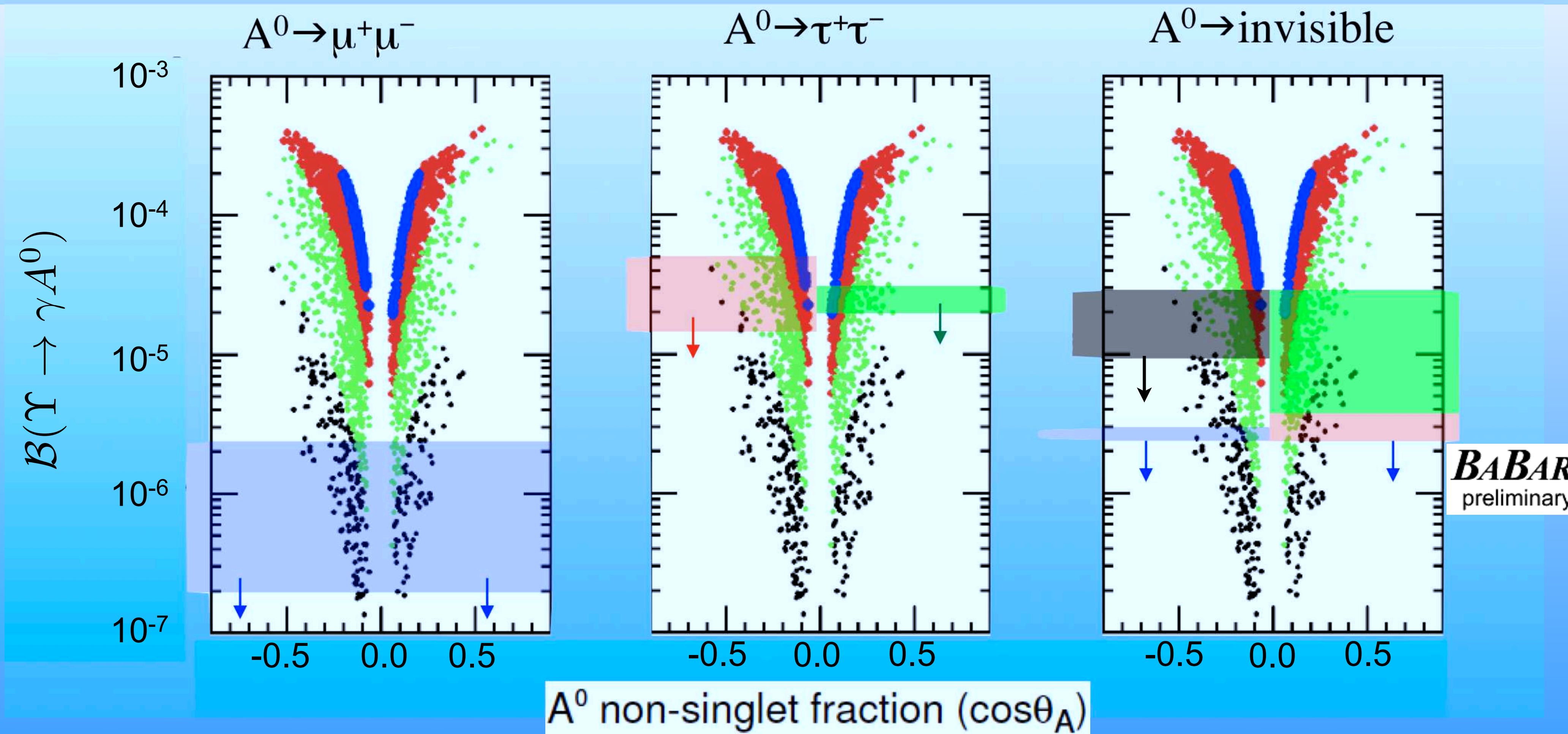


BaBar/PUB-10/023

$$\mathcal{B}(\Upsilon(1S) \to \gamma \chi \bar{\chi}) < (0.5 - 24) \times 10^{-5}$$
$$\text{for } 0 \leq m_\chi \leq 4.5 \text{ GeV}$$
$$\text{at } 90\% \text{ C.L.}$$



NMSSM Predictions vs. BaBar



$m_{A0}<2m_\tau$
$2m_\tau<m_{A0}<7.5$ GeV
7.5 GeV$<m_{A0}<8.8$ GeV
8.8 GeV$<m_{A0}<9.2$ GeV

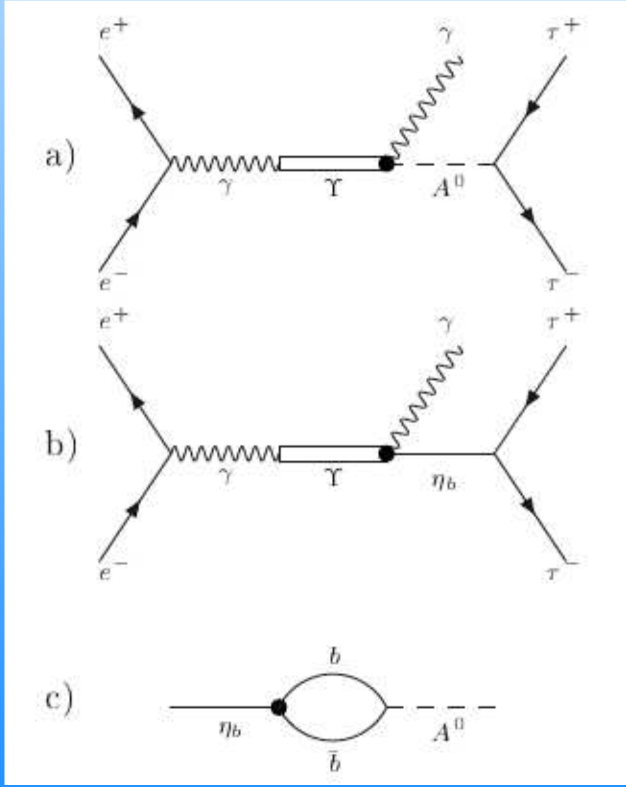
References:
PRL 103, 181801 (2009)
PRL 103, 081803 (2009)
BaBar/PUB-10/023 NEW

Test of Lepton Universality

$$\mathcal{R}_{\tau/\ell} = \frac{\mathcal{B}_{\tau\tau} - \mathcal{B}_{\ell\ell}}{\mathcal{B}_{\ell\ell}} = \frac{\mathcal{B}_{\tau\tau}}{\mathcal{B}_{\ell\ell}} - 1$$

Standard Model: $\mathcal{R}_{\tau/\ell} \simeq 0$

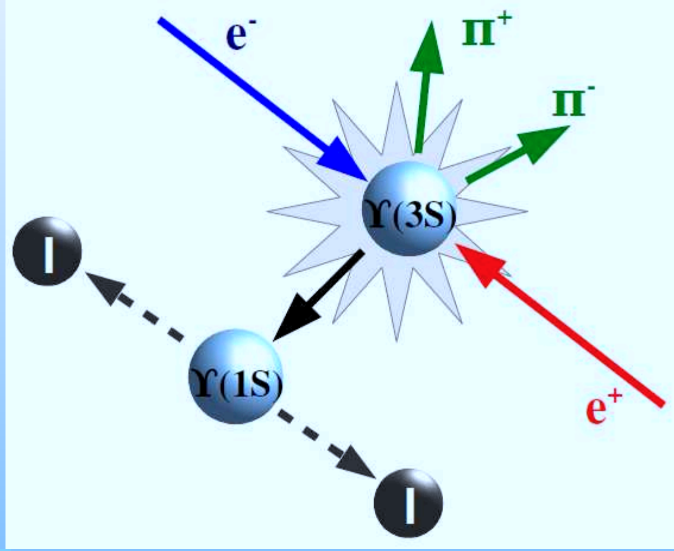
New Physics: as large as 4% (with $\Upsilon(nS)\rightarrow\tau\tau$ decays)



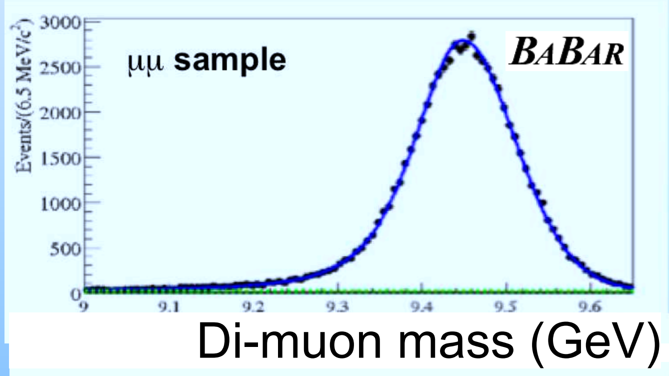
Int.J.Mod.Phys. A19, 2183 (2004);
PL B653, 67 (2007);
JHEP 0901, 061 (2009)

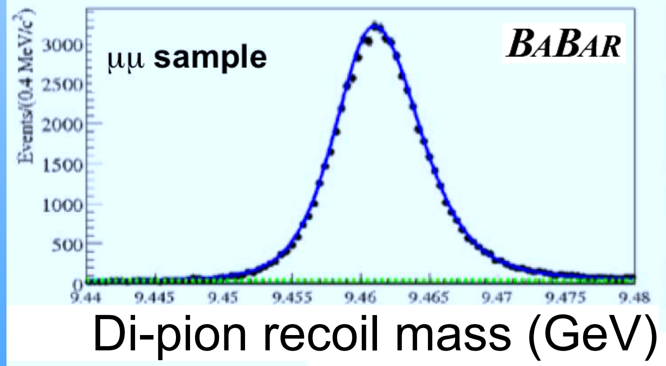
Previous result: $R_{\tau\mu}(\Upsilon(1S)) = 1.02 \pm 0.02(stat) \pm 0.05(syst)$ CLEO PRL 98,052002 2007

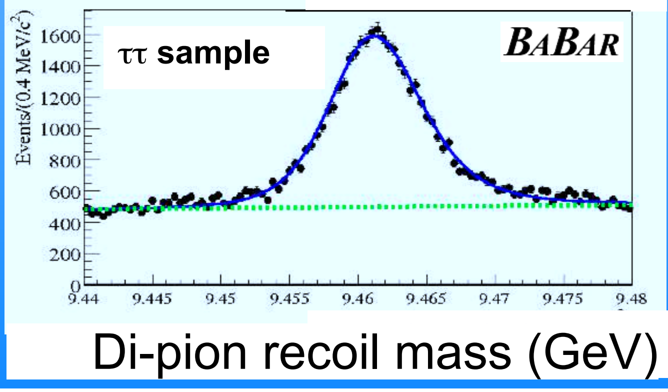
Υ(1S)→ll: Event Topology



BaBar, PRL104, 191801 (2010)







- Υ(1S)→μμ : Efficiency = 45%
  - fit to di-muon mass & di-pion recoil mass
- Υ(1S)→ττ (1-prong decays): Efficiency = 17%
  - fit to di-pion recoil mass
- Simultaneous fit to extract:

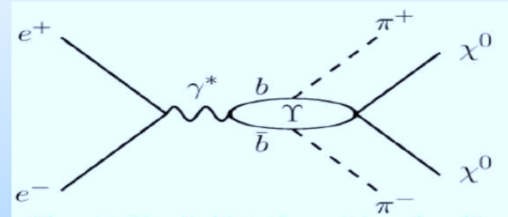
  $R_{\tau\mu}$(Υ(1S)) = 1.005 ± 0.013(stat) ± 0.022(syst)

  No deviation from SM ($R_{\tau\mu}$ = 0.992) observed

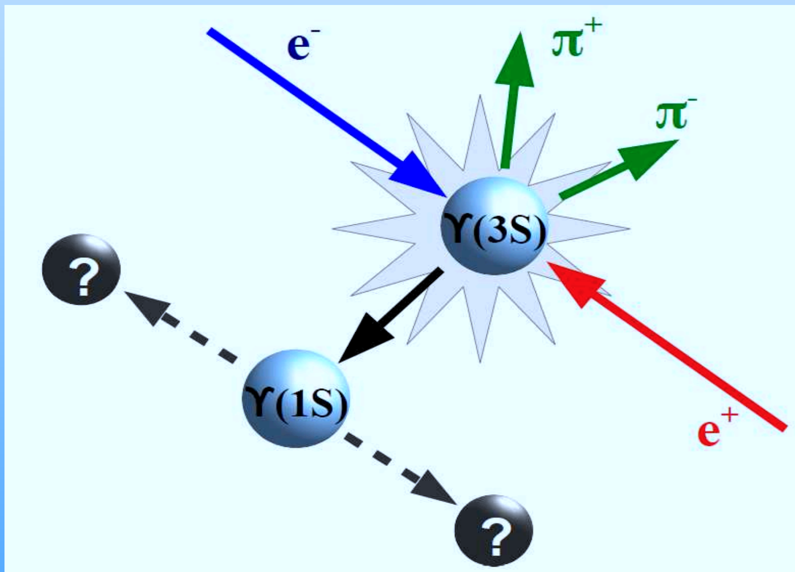
Υ(1S)→Invisible

- B(Υ(1S) →νν)~1 x 10^{-5} in SM
  - can be enhanced to ~10^{-4}–10^{-3} by decays into pairs of low mass Dark Matter candidates

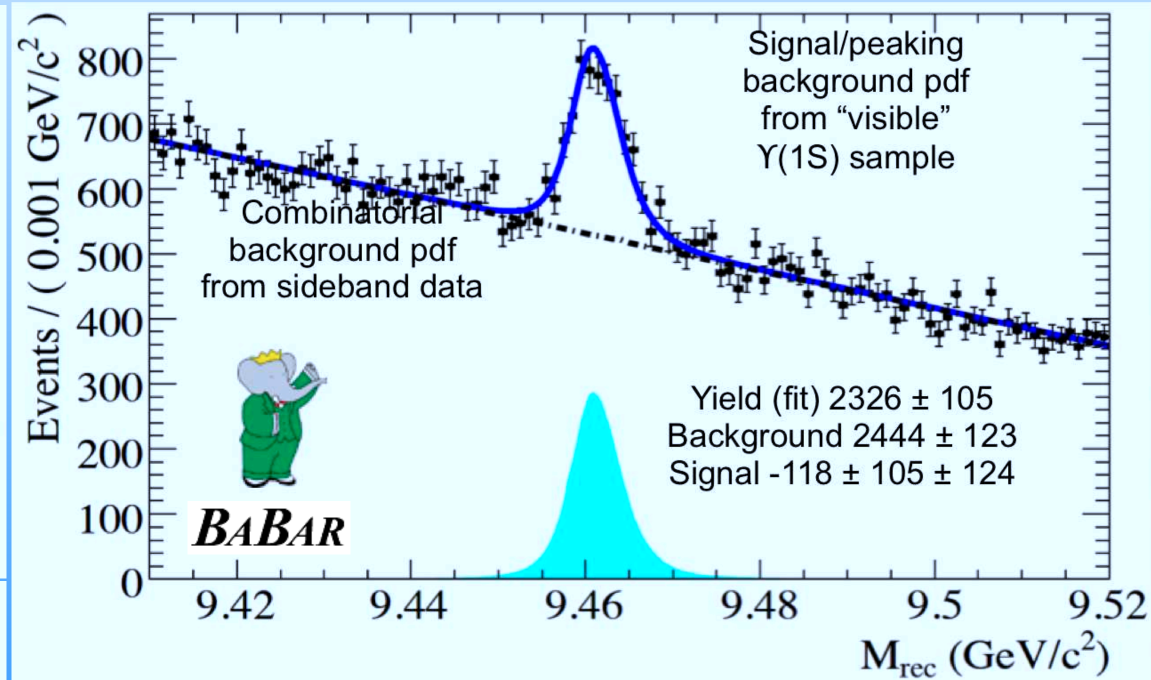
R. McElarth, PRD72, 103508 (2005)



Light Dark Matter Production



$$M^2_{\rm rec} = s + M^2_{\pi\pi} - 2\sqrt{s}E^*_{\pi\pi}$$



B(Υ(1S)→invisible) = (-1.6 ± 1.4(stat) ± 1.6(syst)) x 10^{-4}
< 3.0 x 10^{-4} at 90% C.L.

BaBar, PRL 103, 251801 (2009)

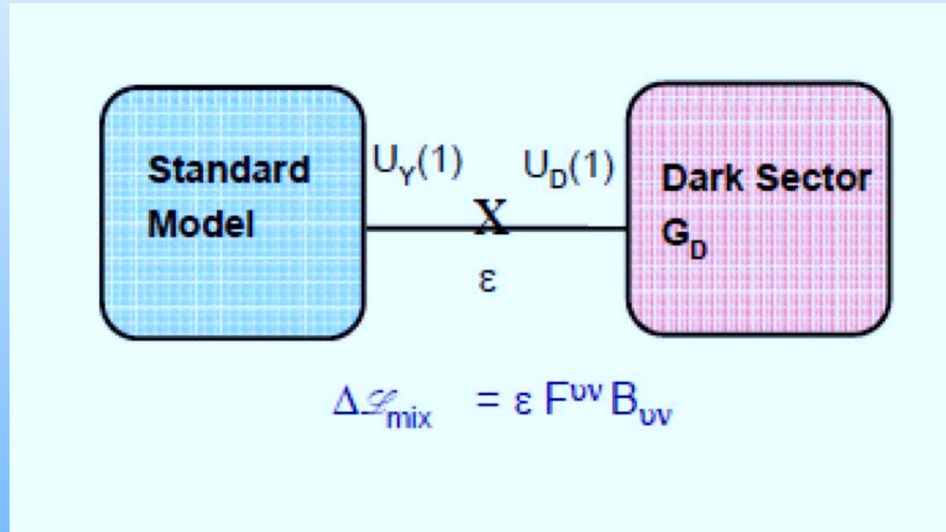
Previous measurements B(Υ(1S) → invisible)

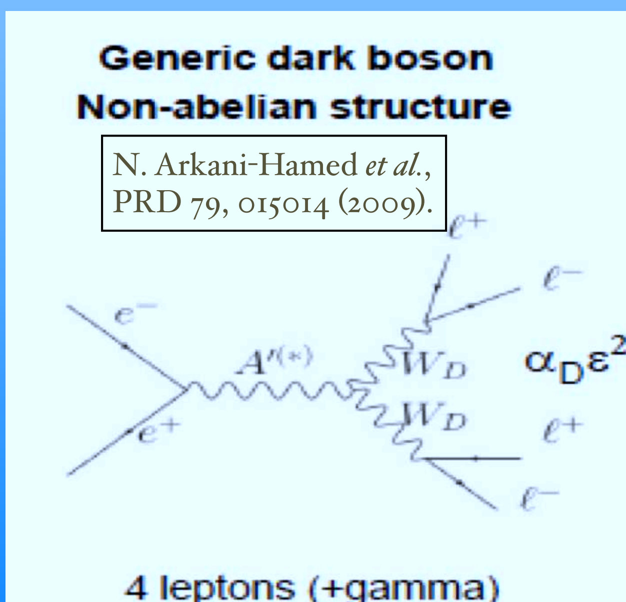
CLEO: B < 3.9 x 10^{-3} @ 90% CL PRD 75 (2007) 031104

Belle: B < 2.5 x 10^{-3} @ 90% CL PRL 98 (2007) 132001

Gauge Bosons from Dark Sector

Motivated by the galactic positron excess seen by PAMELA and ATIC/PPB-BETS





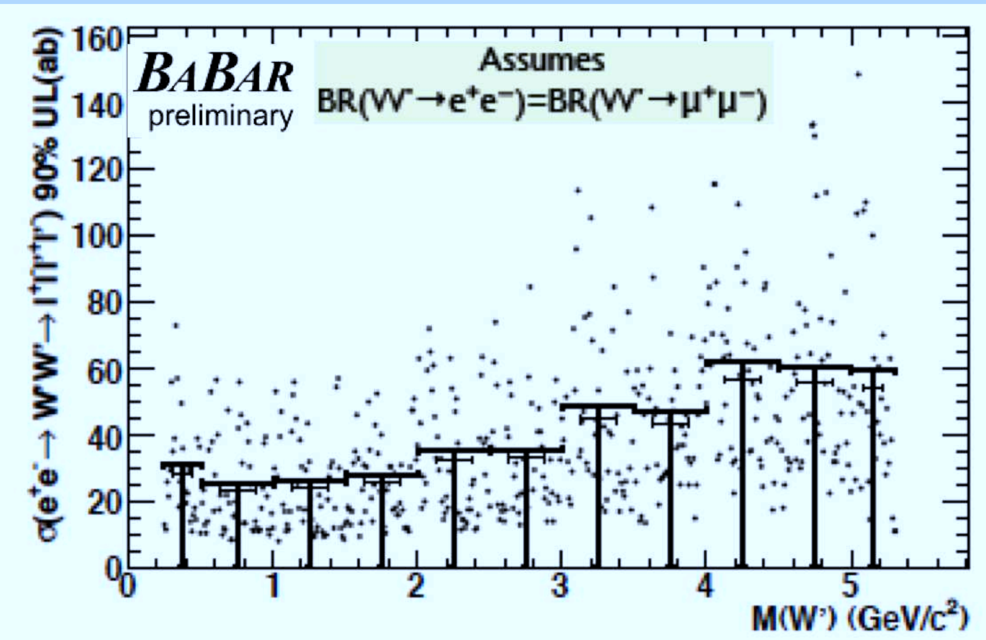
Gauge bosons from the dark sector could be ~ GeV, even though the dark matter particles are ~ TeV

"Dark" Gauge bosons could decay into lepton pairs, but not into proton pairs if its mass is < 2 GeV

Would explain the high energy positron excess, but no anti-protons

Direct Search for Dark Matter

Combined Limits from
(4e, 4mu, 2e2mu) channels



For a dark W' with mass $m_{W'}$ the cross section can be parameterized by

$$\sigma(e^+e^- \to W'W') = \frac{\pi\varepsilon^2\alpha_{D,eff}\alpha}{E_{cm}^2}\left(1 - \frac{4m_{W'}^2}{E_{cm}^2}\right)^{3/2}$$

Essig, Schuster, Toro

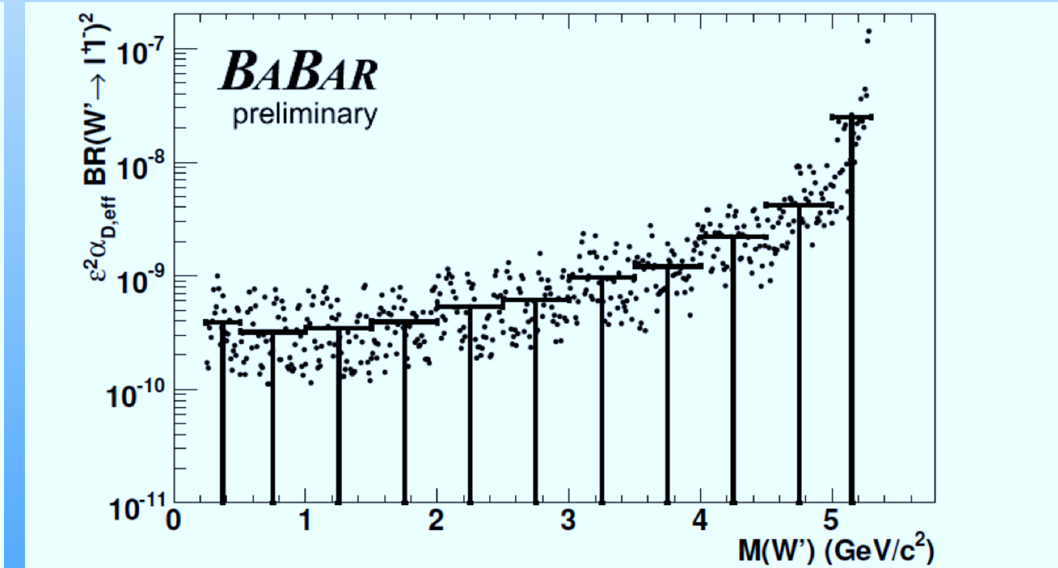


Figure 16: The 90% upper limit on $\varepsilon^2\alpha_{D,eff}$ versus $m(W')$. The points are the upper limit for each $m(W')$ bin while the lines are the average of the limits over many bins.

$$\sigma(e^+e^- \to W'W' \to l^+l^-l'^+l'^- < (25 - 60)\,\mathrm{ab}$$

BaBar, arXiv: 0908.2821

Summary

Searches for New Physics continues ...

- UL obtained on LFV in τ and Υ decays ~ 10^{-8} and 10^{-6}, respectively
- UL on $B(\Upsilon \to \gamma A^0)$ ~ 10^{-6} - 10^{-4}, $B(\Upsilon \to \gamma$ invisible) ~ 10^{-5}, $B(\Upsilon \to$ invisible) ~ 10^{-4}
- Some of the smallest ever UL in B-Factories obtained on Dark Gauge Bosons

Future prospects...

  - Background free (dominated) searches scale as 1/Luminosity ($1/\sqrt{\text{Luminosity}}$)
  - Searches in the Dark Sector scale as $1/\sqrt[4]{\text{Luminosity}}$

- Searches for LFV and rare Υ decays can be improved with Super B-Factory
- Muon decays of Light Higgs can be improved with LHC
- New generation of fixed target experiments can improve searches in the Dark Sector