Tau Physics at the Super B-Factory

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- Introduction
- Lepton Flavor Violation
- CP Violation
- Summary

Introduction

- A fun of physics in τ lepton
  - The heviest lepton known to date
    $\Rightarrow$ Naively expected to be sensitive to the New Physics
  - The only lepton heavy enough to decay hadronically
    $\Rightarrow$ Include a rich physical contents
- Why τ in B-Factory?
  Production cross section @ $\sqrt{s}$ = 10.58 GeV:

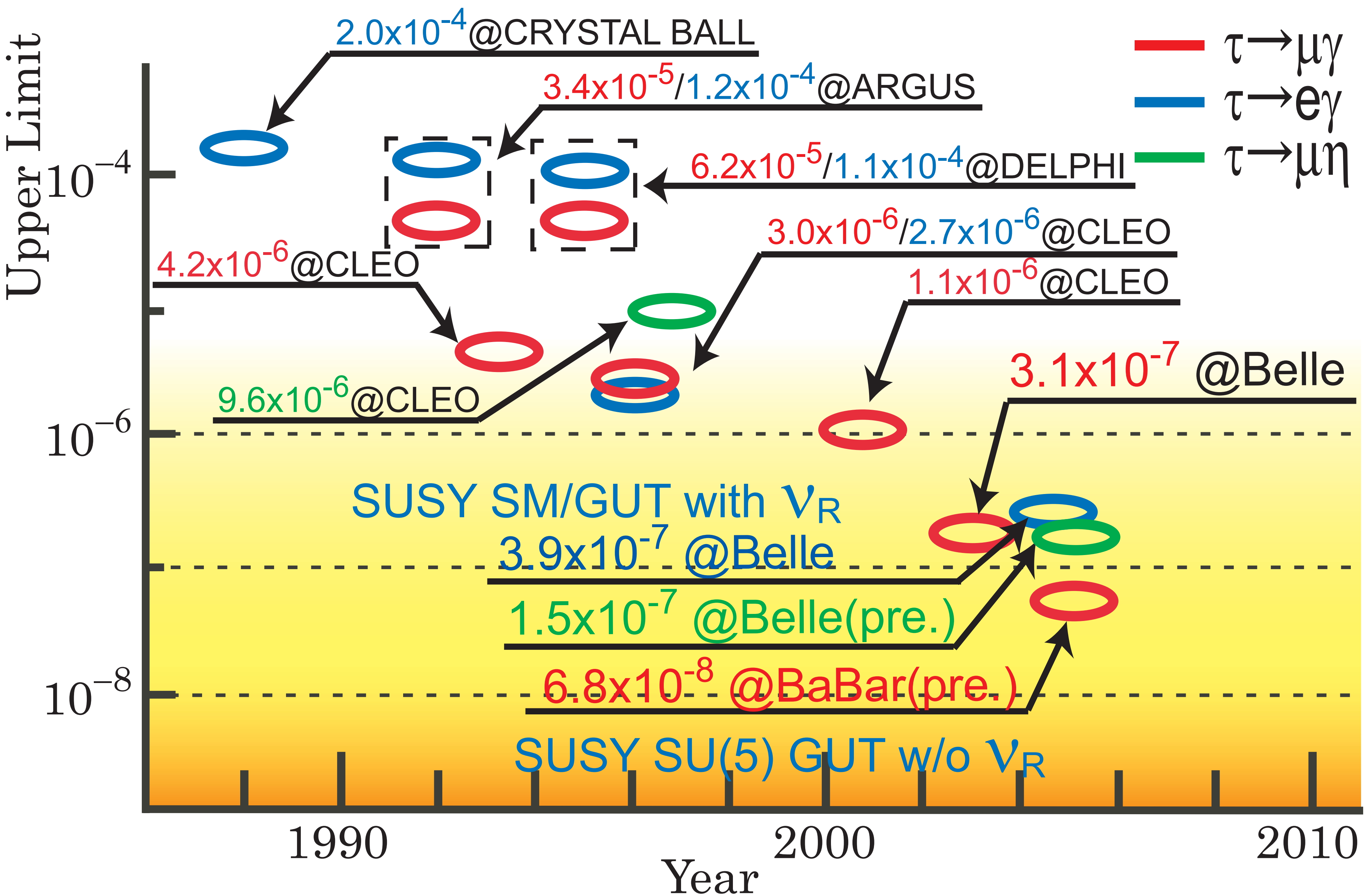
  $$\sigma(e^+e^- \to B\bar{B}) = 1.05\text{nb}, \quad \sigma(e^+e^- \to \tau^+\tau^-) = 0.89\text{nb}$$

  $\Rightarrow$ B-Factory = τ-Factory
- Plan of this talk
  Two major topics to search for the phyiscs beyond the SM at the current and Super B-Factory:
  - Search for the Lepton Flavor Violation in τ decays
  - Search for the CP Violation in τ lepton

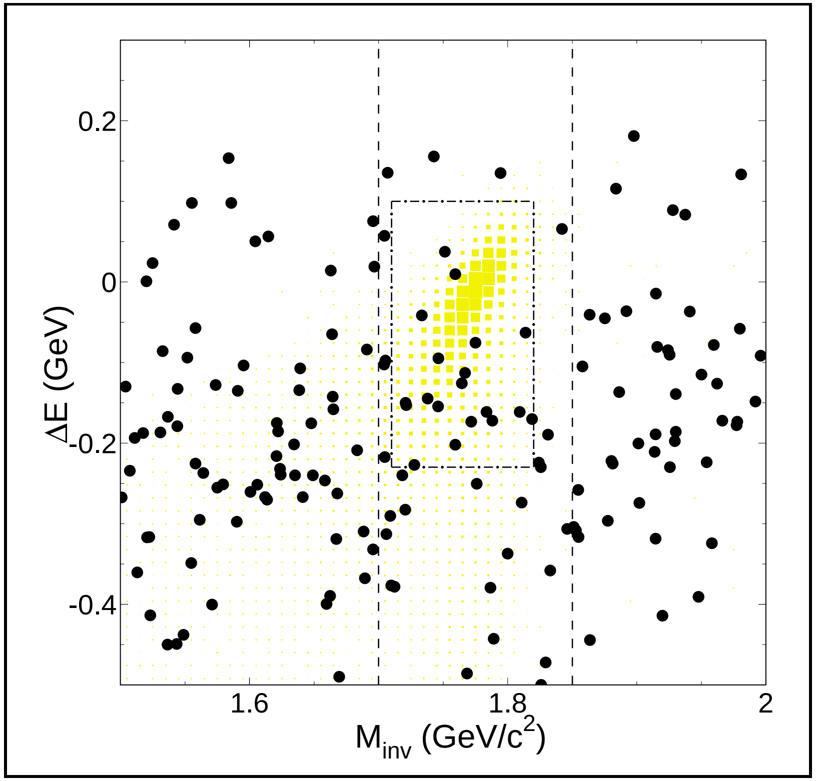
Lepton Flavor Violation in τ Lepton

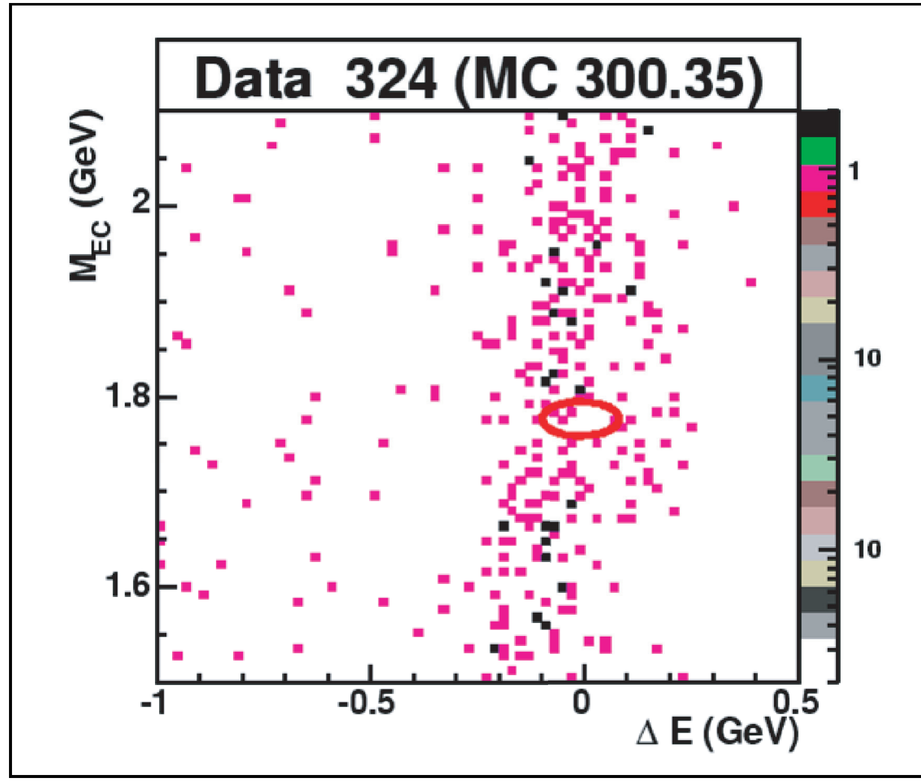
- Lepton Flavor Violation (LFV)
  Forbidden in the SM (w/ massless ν)
  - Charged lepton sector: Has not been observed
  - Neutrino sector: Observation of the neutrino oscillation
- LFV in the SM with ν-oscillation
  ν-oscillation induces the LFV in the charged lepton sector.
  However, it is suppressed drastically:
  $Br(\text{LFV } \tau \text{ decays}) \lesssim 10^{-40} (m_\nu / 1\text{eV})^4$
- LFV in Physics beyond the Standard Model: SUSY, GUT, $\cdots$
  $\Rightarrow$ Predictions can be observed in the (Super) B-Factory.
  Two promising modes expected in some SUSY models:
  - $\tau \to \mu\gamma$: cf) MSSM with Seesaw
    (J. Hisano et al., PR**D60**(1999)055008), $\cdots$
  - $\tau \to \mu\eta$: cf) Higgs mediated in MSSM
    (K. Babu and C. Kolda, PRL**89**(2002)241802), $\cdots$

LFV: Current Experimental Status



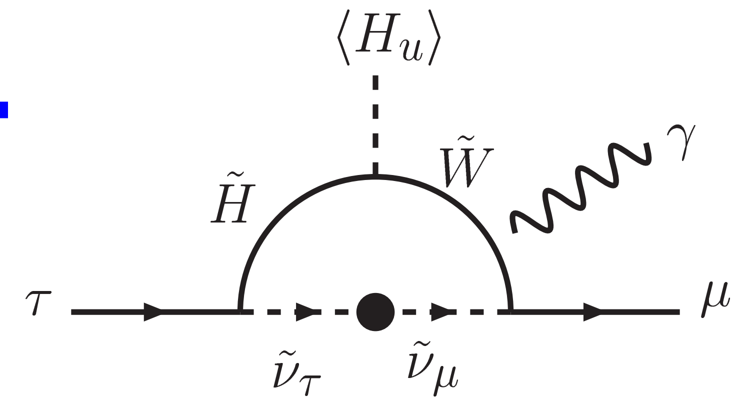
LFV: $\tau \rightarrow \mu\gamma$ of Belle/BaBar





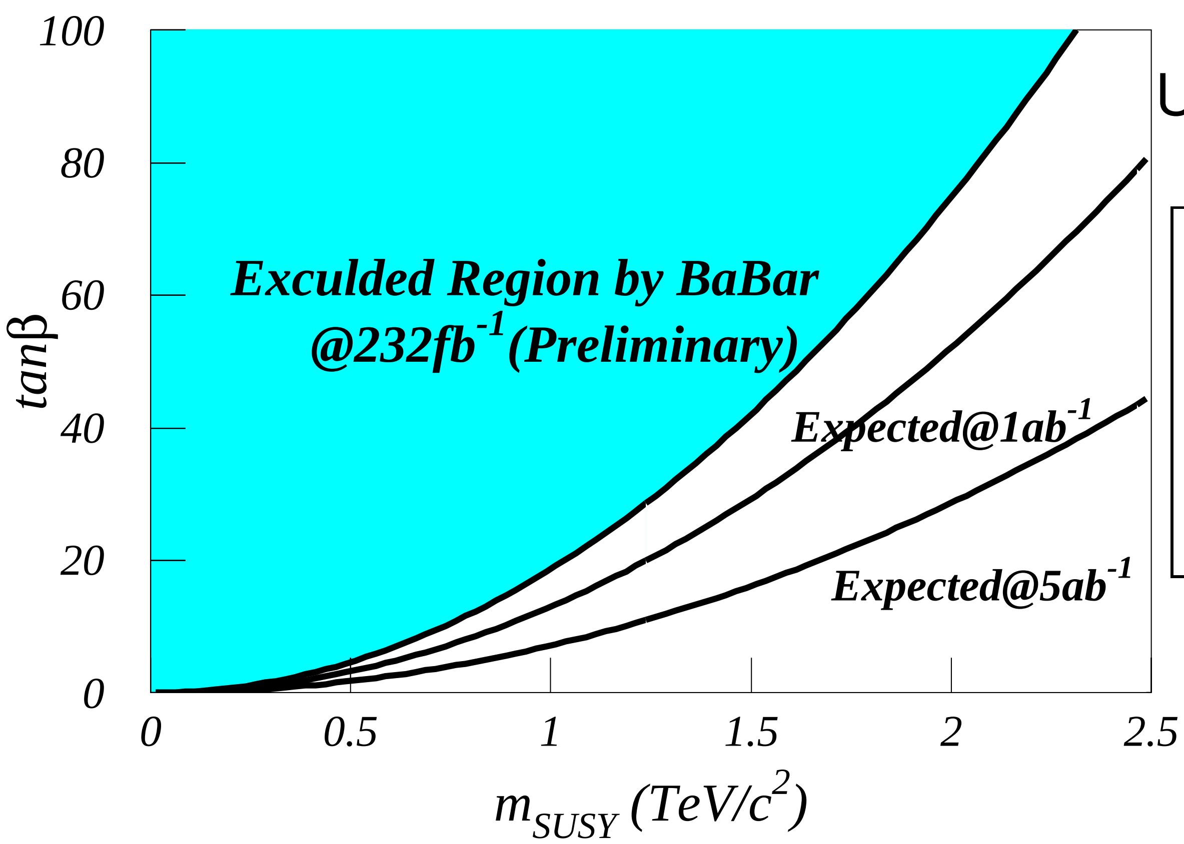
	Belle	Babar
Luminosity	86.7 fb^{-1}	232 fb^{-1}
Signal Region	$\pm 3\sigma$ box	$\pm\ 2\sigma$ ellipse
Efficiency	10.9%	7.42%
Expected BG	20.2 ± 2.1	6.2 ± 0.5
Observed ev	19	4
UL of Br $(\times 10^{-7})$	3.1	0.68

LFV: $\tau \to \mu\gamma$



- MSSM with Seesaw
  (J. Hisano et al., PR**D60**(1999)055008):

$$Br(\tau \to \mu\gamma) \simeq 7 \times 10^{-7} \left(\frac{\tan\beta}{60}\right)^2 \left(\frac{1\text{TeV/c}^2}{m_{SUSY}}\right)^4$$



Upper Limit by BaBar's Preliminary result:

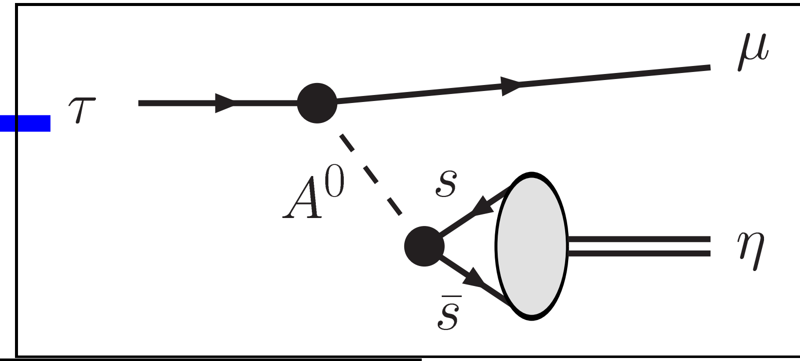
$$Br(\tau \to \mu\gamma) < 6.8 \times 10^{-8}$$

@BaBar (hep-ex/0502032)

$\Rightarrow$ Constraint on $\tan\beta$–m_{SUSY}

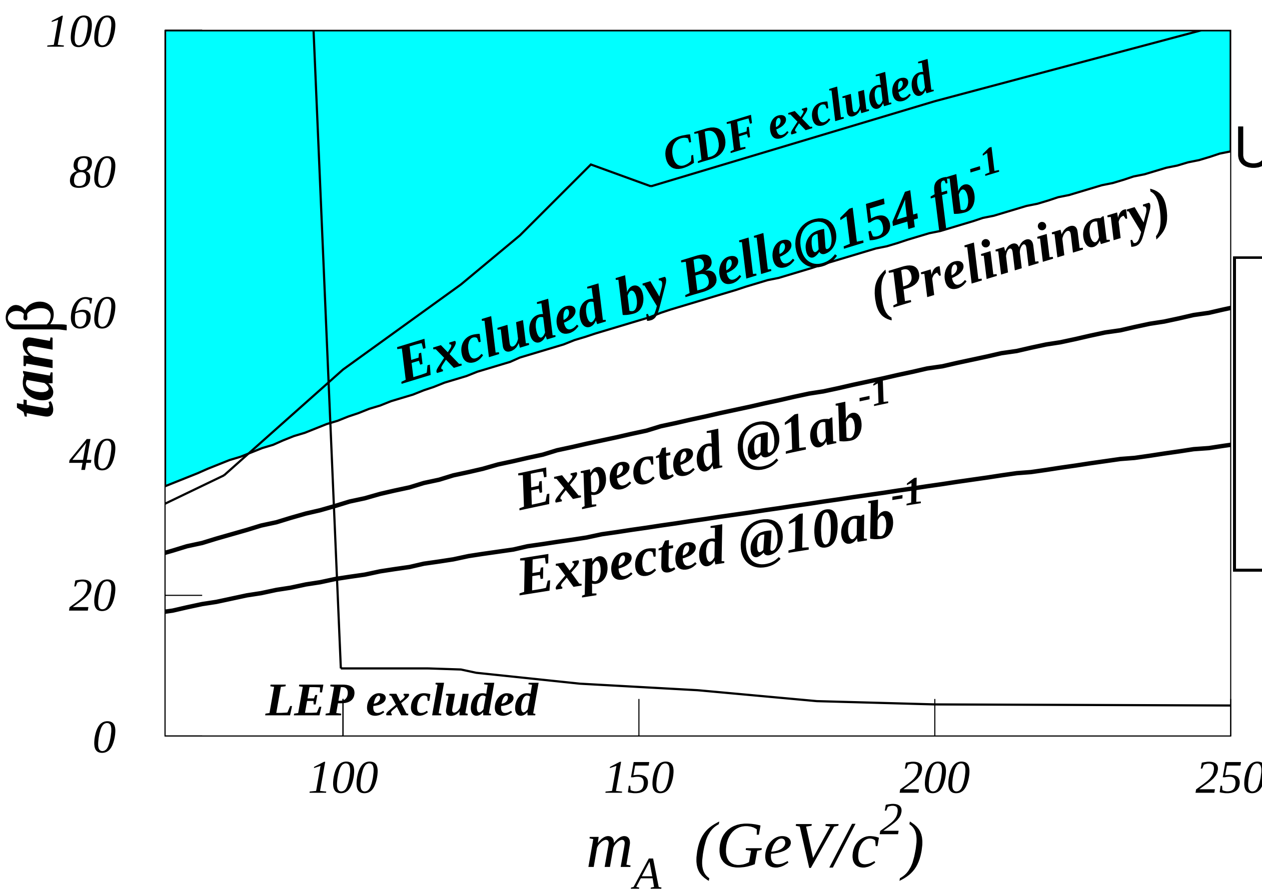
($\tan\beta \propto m^2_{SUSY}$)

LFV: $\tau \to \mu\eta$



- Higgs mediated in MSSM
  (Babu & Kolda PRL**89**(2002)241802):

$$Br(\tau \to \mu\eta) = 8.4 \times 10^{-7} \left(\frac{\tan\beta}{60}\right)^6 \left(\frac{100\text{GeV/c}^2}{m_A}\right)^4$$



Upper Limit by Belle's Preliminary result:

$Br(\tau \to \mu\eta) < 1.5 \times 10^{-7}$
@Belle (hep-ex/0503041)
$\Rightarrow$ Constraint on $\tan\beta$–m_A
($\tan\beta \propto m_A^{2/3}$)

We've obtained more stringent limit than CDF.

CP Violation in τ Lepton

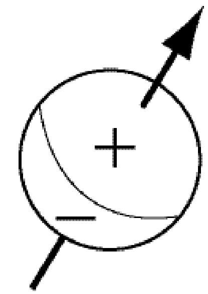
Thanks to Prof. I. Bigi, here is a summary of the CPV in τ Physics.

- CPV is necessary for baryogenesis.
  However, CKM dynamics is irrelvant for it.
- One attracitve alternative: Leptogenesis driving baryogenesis
  cf) Previous talk by H. Paes
  $\Rightarrow$ Search for CPV in lepton sector
- CPV in the lepton sector
  Has not been observed yet, in contrast with the quark sector.
  - Search for CPV in the neutrino sector
    A very tough challenge.
  - Search for EDM of charged leptons
    In some model, τ is most sensitive due to its heviest mass.
  - Search for CPV in tau decays
    One of the most promising mode: $\tau \to K\pi\nu$
    (J. Kühn and E. Mirkes, PL **B398**(1997)407)
    Bigi pointed out: $\mathcal{O}(10^{-3})$ is expected in $\tau \to K_S\pi\nu$

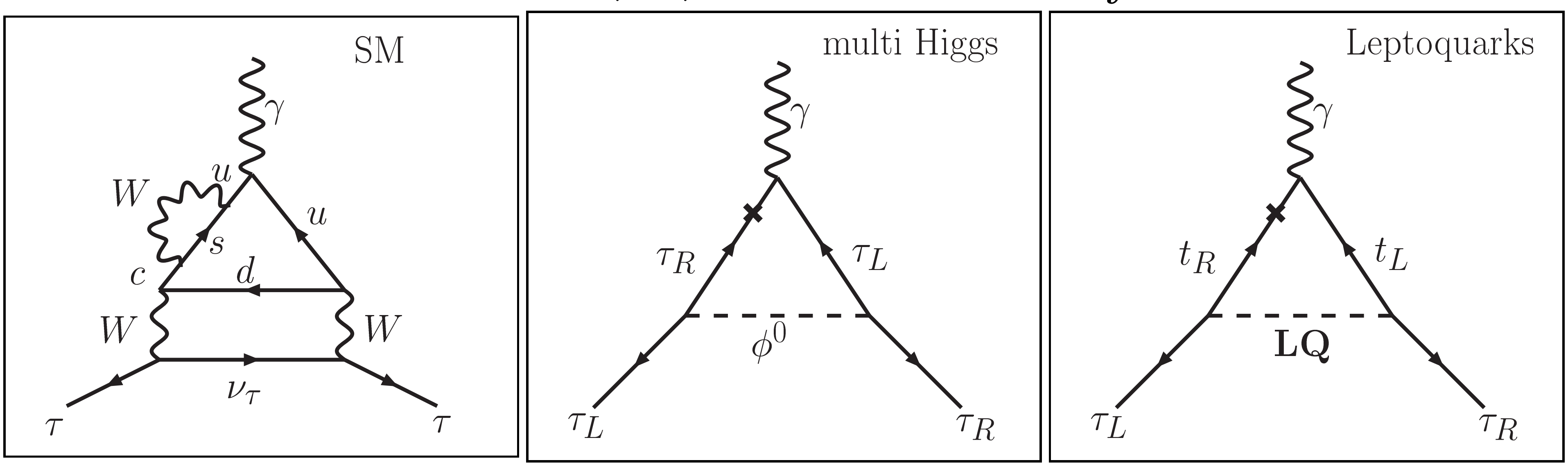
τ's EDM

- Non-vainshing τ's EDM, $d_\tau \quad \Rightarrow \quad \mathbf{T}$ Violation ($\Leftrightarrow$ CPV under CPT)
  - d_τ should be proportional to the spin S: $d_\tau \propto S$
  - Under $\mathbf{T}$ transformation: $d_\tau \to d_\tau, \quad S \to -S$

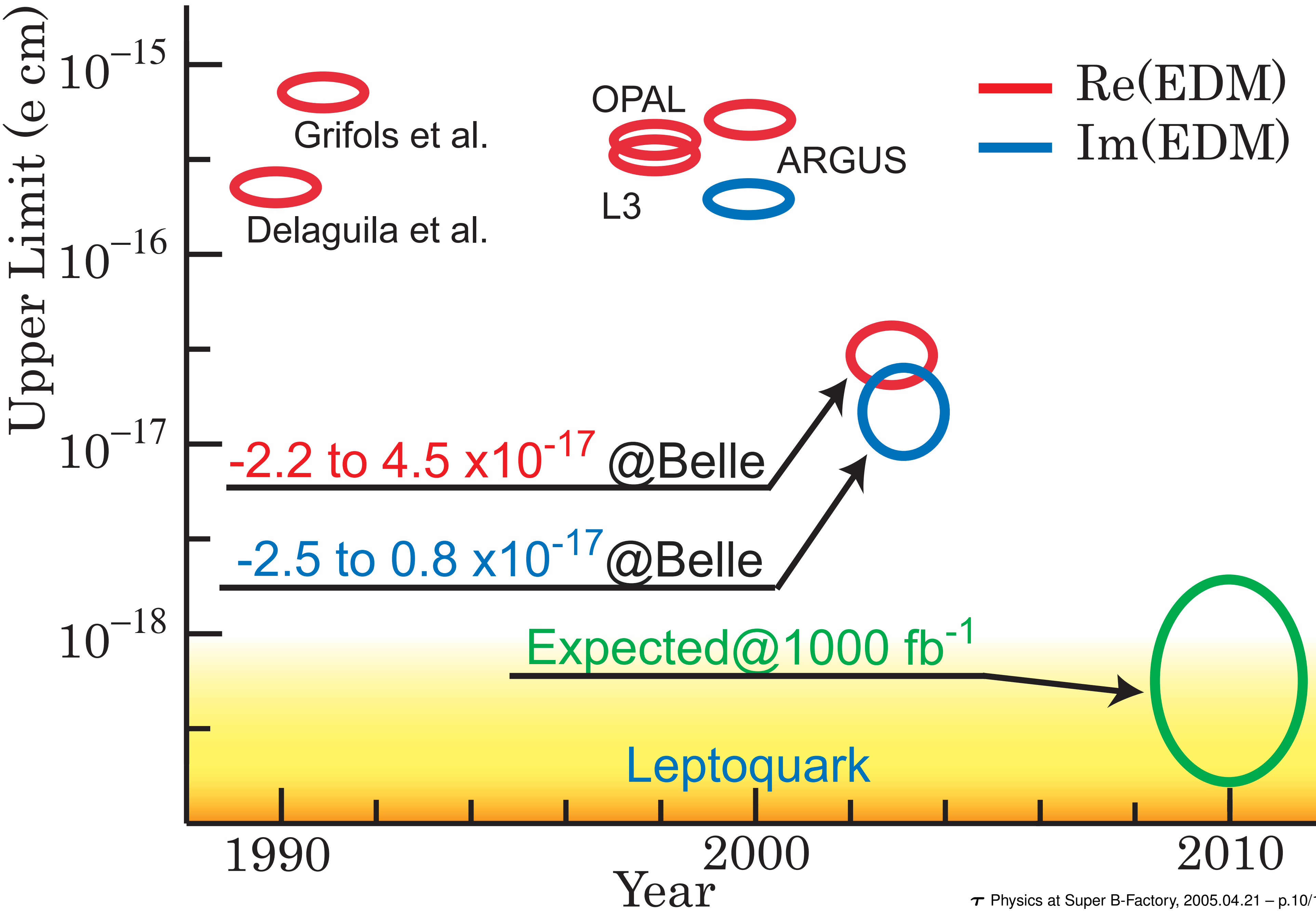
  $\Rightarrow$ If $\mathbf{T}$ is retained, $d_\tau = 0$.



- Theoretical predictions
  - SM (w/ massless ν): $|d_\tau| \lesssim 10^{-34} e$ cm
  - Mult-Higgs: $|d_\tau| \lesssim 10^{-23} e$ cm ($\propto m_\ell^3 / m_\phi^2$)
  - Leptoquarks: $|d_\tau| \lesssim 10^{-19} e$ cm ($\propto m_t^2 m_\tau$)



τ's EDM: Experimental Status



DCPV in $\tau \to K_S \pi \nu$

According to the similar argument as the DCPV of $D^+ \to K_S \pi^+ \nu$ in the Bigi and Sanda's famous text book, DCPV in $\tau^- \to K_S \pi^- \nu$

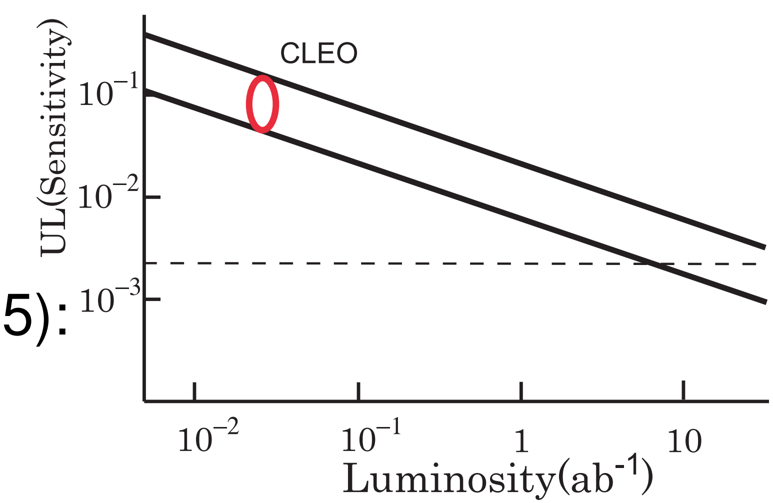
$$\mathcal{A}_{\mathcal{CP}} = \frac{\Gamma(\tau^+ \to K_S \pi^+ \nu) - \Gamma(\tau^- \to K_S \pi^- \nu)}{\Gamma(\tau^+ \to K_S \pi^+ \nu) + \Gamma(\tau^- \to K_S \pi^- \nu)} \simeq 3 \times 10^{-3}$$

is expected due to the well-known CP impurity in K_S:

$$K_S = \frac{(1-\epsilon)K^0 - (1+\epsilon)\overline{K^0}}{\sqrt{2}}$$

⇒ This should be observed!

Only CLEO searched for CPV in this mode (PRL **88** (2002) 111803, PR **D64** (2001) 092005):



$$-0.172 < Im(\Lambda) < 0.067$$

for the coupling constant Λ defined as

$$A(\tau^- \to K\pi^-\nu) \sim \bar{\nu}\gamma_\mu(1-\gamma_5)\tau f_V Q^\mu + \Lambda\bar{\nu}(1+\gamma_5)\tau f_S M$$

We can reach the sensitivity of 10^{-3} order at a few ab^{-1}

⇒ CPV in lepton sector can be found at the Super B-Factory!

Summary

- Current status of two major topics to search for the physics beyond the Standard Model in τ Lepton are reviewed:
  - Lepton Flavor Viloation: $\tau \to \mu\gamma, \quad \tau \to \mu\eta$
  - CP Violation: τ's EDM, $\quad \tau \to K_S \pi \nu$
- We discussed the expected sensitivities in these physics at the Super B-Factory.
  - LFV
    We have already obtained the constraints on parameter spaces of the models of New Physics. More stringent limits can be obtained, or we can observe the New Physics at the Super B-Factory.
  - CPV
    We've not observed any CPV in the lepton sector including τ. We can reach the sensitivity to the prediction of the New Physics at the Super B-Factory. Especially, DCPV in $\tau \to K_S \pi \nu$ should be observed.
    One of the important advantage of the B-Factory (e^+e^- collider) to the hadron collider: We can look for τ polarization depencent CP asymmetry w/o needing polarized beam!

Backup

τ's EDM: How to measure?

- Effective Lagrangian with non-zero EDM term:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm EDM} = \bar{\psi}(i\partial\!\!\!/ - eQA\!\!\!/)\psi - \frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi d_\tau F_{\mu\nu}$$

$\Rightarrow$ Deviation of the cross section, i.e. amplitude $\mathcal{M}$, from the SM:

$$\mathcal{M}^2_{e^+e^-\to\tau^+\tau^-} = \mathcal{M}^2_{\rm SM} + Re(d_\tau)\mathcal{M}^2_{\rm Re} + Im(d_\tau)\mathcal{M}^2_{\rm Im} + O(d_\tau^2)$$

where

$\mathcal{M}^2_{Re} \sim (S_+ \times S_-)\cdot\hat{k}, \quad (S_+ \times S_-)\cdot\hat{p},$

$\mathcal{M}^2_{Im} \sim (S_+ - S_-)\cdot\hat{k}, \quad (S_+ - S_-)\cdot\hat{p}$

$S_\pm$: $\tau^\pm$ spin vector, $\hat{p}$: e^+ direction, $\hat{k}$: τ^+ direction.

- Optimal Observable for the τ's EDM:

$$\mathcal{O}_{Re} = \mathcal{M}^2_{Re}/\mathcal{M}^2_{SM}, \quad \mathcal{O}_{Im} = \mathcal{M}^2_{Im}/\mathcal{M}^2_{SM} \quad \Rightarrow \text{Maximize S/N}$$

We can extract the τ's EDM from $\mathcal{O}$ by using the following Eq.:

$$\langle\mathcal{O}_{Re}\rangle = a_{Re}\cdot Re(d_\tau) + b_{Re}$$
$$\langle\mathcal{O}_{Im}\rangle = a_{Im}\cdot Im(d_\tau) + b_{Im}$$

Evaluation of $\mathcal{A}_{\mathcal{CP}}(\tau^+ \to K_S \pi^+ \nu)$

In the SM one has

$\Gamma(\tau^+ \to K^0 \pi^+) = \Gamma(\tau^- \to \overline{K^0} \pi^-)$.

And we know that K_S is CP impurity as the experimental result:

$$K_S = \frac{1}{\sqrt{2}} \left(\frac{1-\epsilon}{\sqrt{1+\epsilon^2}} K^0 - \frac{1+\epsilon}{\sqrt{1+\epsilon^2}} \overline{K^0} \right) \equiv q_K K^0 + p_K \overline{K^0}.$$

We here consider the amplitude of this decay mode:

$$A(\tau^+ \to K^S \pi^+) = A(\tau^+ \to \overline{K^0} \pi^+) \langle K_S | \overline{K}^0 \rangle + A(\tau^+ \to K^0 \pi^+) \langle K_S | K^0 \rangle$$

We can neglect $A(\tau^+ \to K^0 \pi^+)/A(\tau^+ \to \overline{K^0} \pi^+)$ and obtain

$\Gamma(\tau^+ \to K^S \pi^+) \simeq \Gamma(\tau^+ \to \overline{K^0} \pi^+) |q_K|^2$

and similarly,

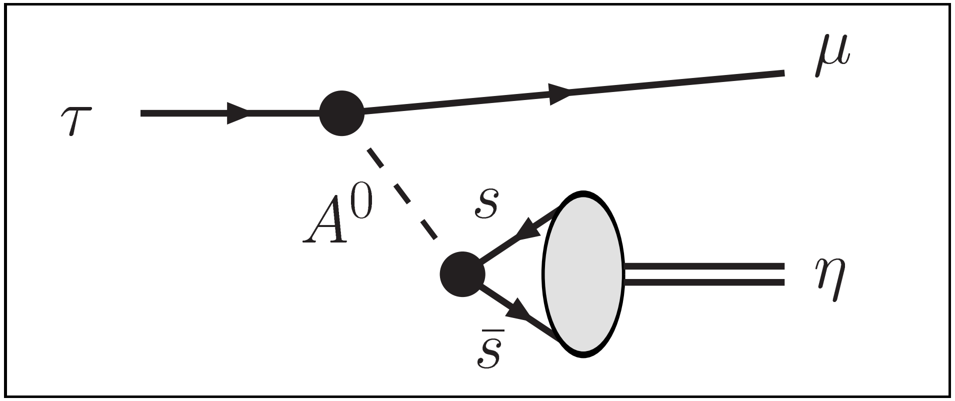
$\Gamma(\tau^- \to K^S \pi^-) \simeq \Gamma(\tau^+ \to \overline{K^0} \pi^+) |p_K|^2$.

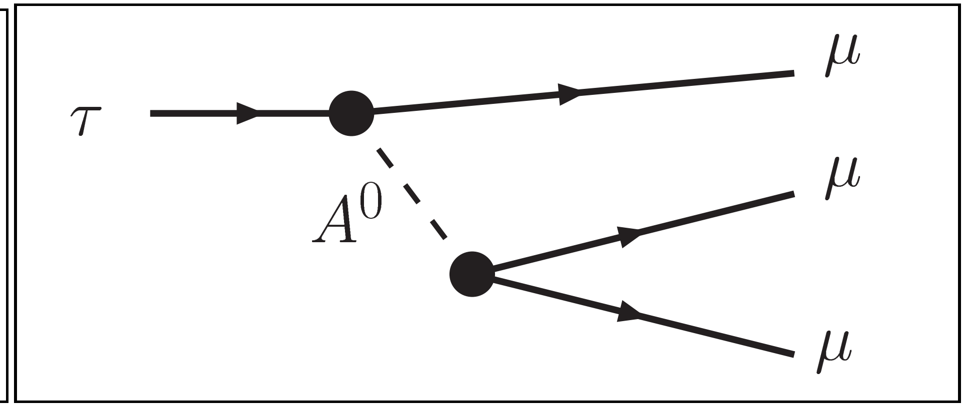
Finally,

$$\mathcal{A}_{\mathcal{CP}} \simeq \frac{|q_K|^2 - |p_K|^2}{|q_K|^2 + |p_K|^2} \simeq 2Re(\epsilon) \simeq 10^{-3},$$

we here used measured value of ϵ in $K_L \to \pi\pi$.

LFV: $\tau \to \mu\eta$ vs $\tau \to 3\mu$





Babu and Kolda pointed out (PRL**89**(2002)241802)):

$$Br(\tau \to \mu\eta) : Br(\tau \to 3\mu) : Br(\tau \to 3\mu) = 8 : 1.5 : 1$$

for Higgs mediated process.

Comparing $\tau \to \mu\eta$ with $\tau \to 3\mu\eta$:

- Color factor: 3
- Phase space: 2-body and 3-body decay
- Mass: $m_s > m_\mu$

τ LFV: Other Modes

Red: Preliminary   Blue: Published

□: CLEO Result   △: BaBar Result   ●: Belle Result