Symmetry violation in tau decays ~Tau Lepton Flavor violation and CP violation in Lepton sector~

Kiyoshi Hayasaka (KMI, Nagoya University)

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

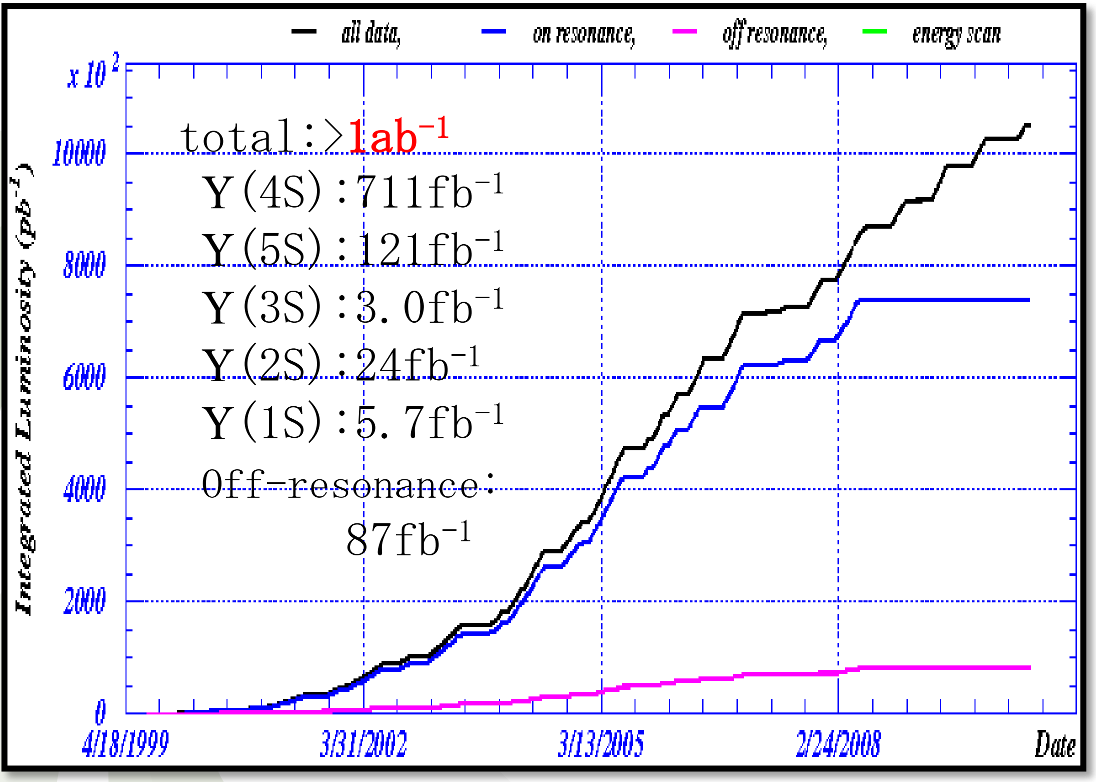
Tau lepton and B-factories

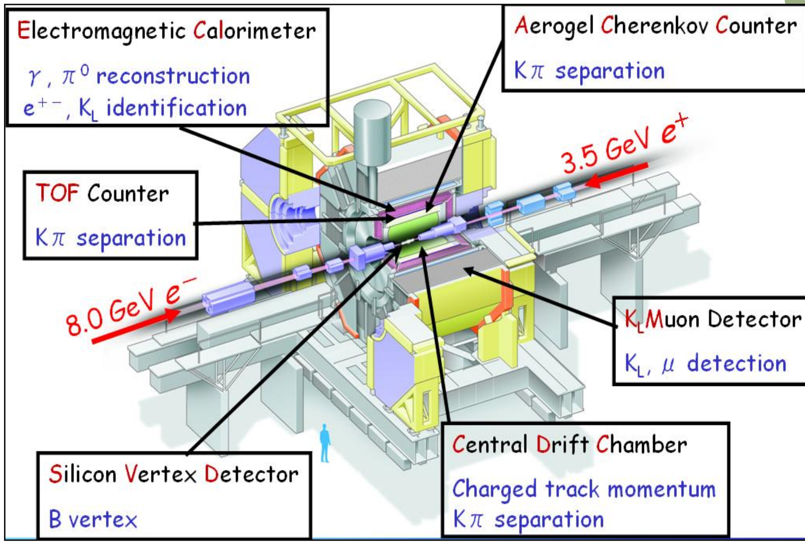
- Tau lepton
  - the heaviest lepton = 1.78GeV/c^2
  - the only lepton able to decay to meson(s) = various decays allowed
  - belonging to the third generation

- B-factory
  - $\sqrt{s}$ is set to 10.6GeV (=Υ(4S) mass)
  - There, $\sigma(b\bar{b})$=1.1nb while $\sigma(\tau\tau)$=0.9nb→similar number of tau-pairs are produced: A B-factory is also a tau-factory!
  - Since tau-pair is produced, clear tau-tag is possible. (cf. LHCb)
  - There are two B-factories in the world, i.e., Belle and BaBar experiments.

Belle Experiment @ KEK

Belle has finished data taking in 2010 with >1ab^{-1} of data: ~2x10^{9} taus

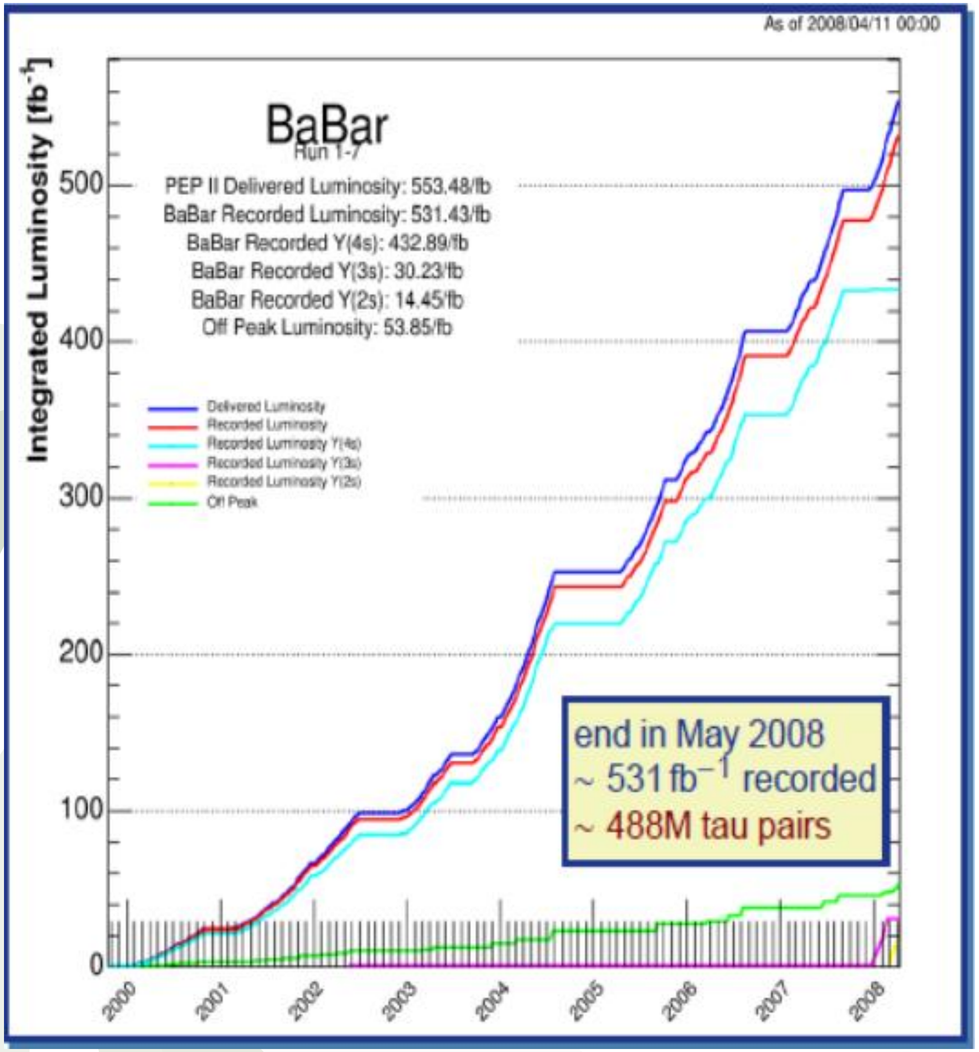


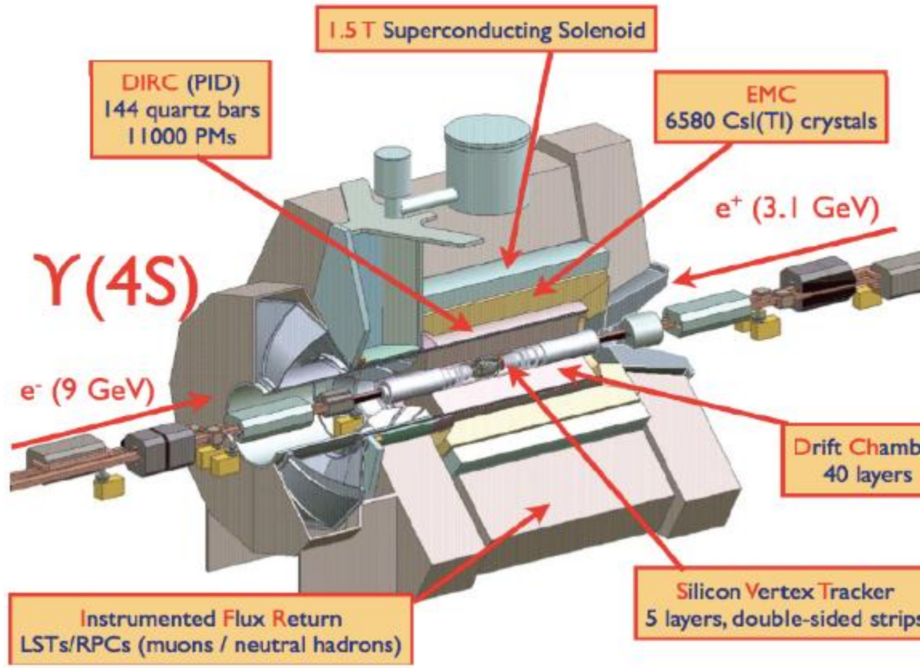


Belle detector is a multi-purpose and asymmetric detector and has good:

- K/pi separation
- lepton identification
- hermeticity

BaBar Experiment @ SLAC





Also BaBar has features similar to those for Belle, i.e., particle identification, etc.

CPV IN LEPTON SECTOR

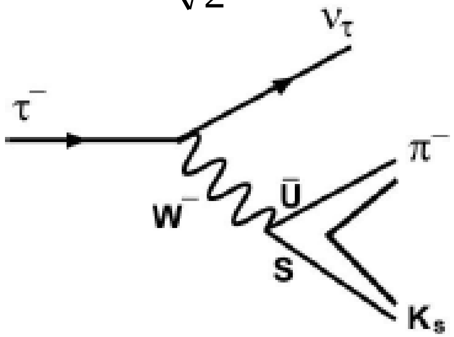
CPV in lepton sector

- CPV in lepton sector has not been observed yet.
- CPV in lepton sector is strongly suppressed in SM.
  - An observation means a clear signal of the new physics!
- Tau is a good probe for it. One possible decay including CPV is $\tau \to K_S^0 \pi \nu$:

-Effective Hamiltonian

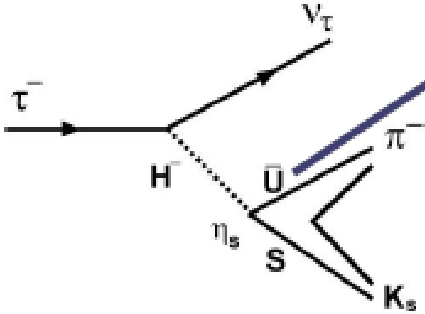
SM

$$H_{SM} = \sin\theta_C \frac{G}{\sqrt{2}} \left(\bar{\nu}\gamma^{\mu}(1-\gamma_5)\tau\right)\left(\bar{s}\gamma_{\mu}(1-\gamma_5)u\right)$$



Scalar Boson

$$H_{NP} = \sin\theta_C \frac{G}{\sqrt{2}} \left(\bar{\nu}(1+\gamma_5)\tau\right)\eta_s \bar{s}u$$



NP

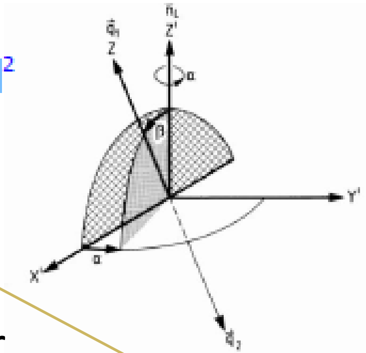
When NP is considered, this scalar interaction is possible and induces CP violation.

Differential decay width and CPV

- The effect from CPV appears via the interference between SM term and NP term.

$$\frac{d\Gamma(\tau^-)}{dQ^2 d\cos\theta d\cos\beta} = \left[A(Q^2) - B(Q^2)(3\cos^2\Psi - 1)(3\cos^2\beta - 1)\right]\cdot |F|^2 + m_\tau^2 |F_s|^2$$
$$- C(Q^2)\cos\beta\cos\psi \cdot \mathrm{Re}(F F_s^*(\eta_s))$$

Contain CPV terms



$Q^2 = M_{K\pi}^2$, $A(Q^2), B(Q^2), C(Q^2)$: known function.

β: direction of Ks in $K_s\pi$ rest frame

Ψ: direction of τ in the $K_s\pi$ rest frame.

(θ: direction of $K_s\pi$ system in the τ rest frame. Correlated with Ψ)

F: Vector form factor

Fs: Scalar form factor

This term will vanish when it is Integrated over Q^2.

$$A_i^{\mathrm{cp}} = \frac{\iiint_{Q_{1,i}^2}^{Q_{2,i}^2} \cos\beta\cos\psi \left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}{\frac{1}{2}\iiint_{Q_{1,i}^2}^{Q_{2,i}^2} \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}$$
$$\simeq \langle\cos\beta\cos\psi\rangle_{\tau^-}^i - \langle\cos\beta\cos\psi\rangle_{\tau^+}^i$$

This is an experimental observable extracting CPV term from the differential decay width.

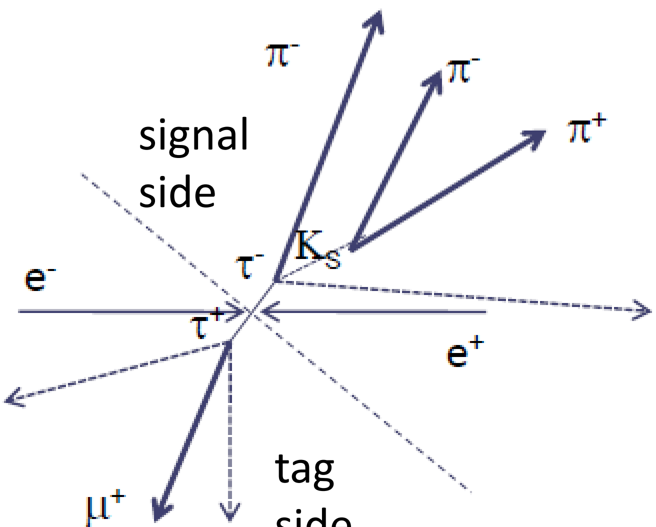
with $d\omega = dQ^2 d\cos\theta d\cos\beta$.

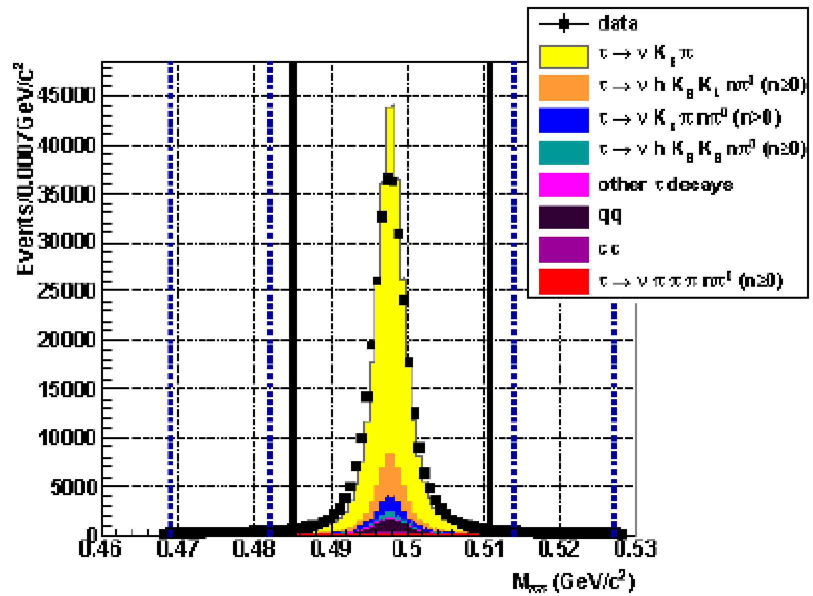
By normalizing numbers of tau+ and tau- to be same, K^0-$\overline{K^0}$ mixing does not affect this analysis.

CPV search in lepton sector@Belle (1)

Phys. Rev. Lett. 107 (2011) 131801

- 700fb^{-1} data sample used





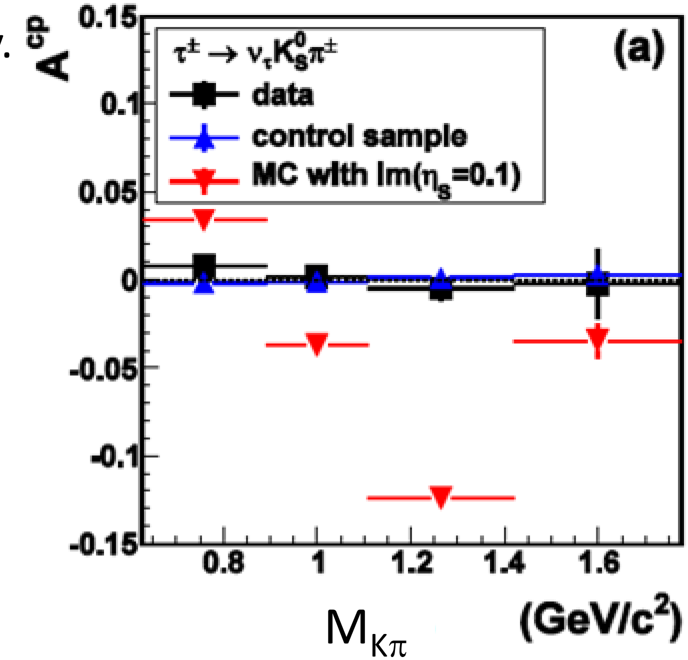
Basic requirement:
3-1 charged tracks,
one K_S^0 (mass, flight length, etc.),
πID,
leptonic decay in tag side

$\pi\pi$ invariant mass for K_S^0 candidate
→free from BGs not including K_S^0

CPV search in lepton sector@Belle (2)

Totally, 162K $\tau^{\pm}\rightarrow K_s^0\pi^{\pm}\nu$ candidates are selected, respectively.
Almost 20% comes from BG, mainly $\tau^{-}\rightarrow K_s^0 K_L^0\pi^{-}\nu$, $K_s^0\pi^{-}\pi^0\nu$
Corrections are:

- to the detector; $O(10^{-3})$
- to the F-B asymmetry; $O(10^{-4})$
- $\tau\rightarrow\pi\pi\pi\nu$ is used for the calibration.



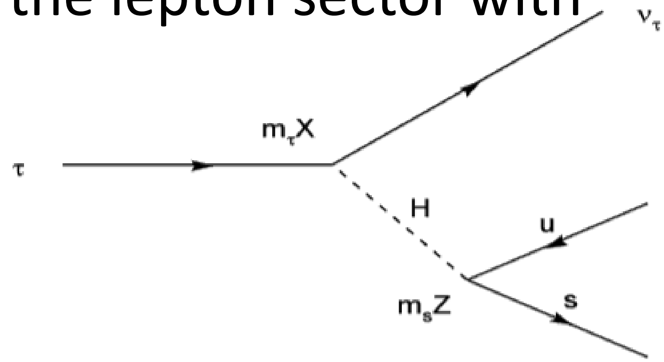
Result:

$M_{K\pi}$ (GeV/c²)	A_{CP}(x10^{-3})
0.625-0.890	$7.9\pm3.0(stat)\pm2.8(sys)$
0.890-1.110	$1.8\pm2.1(stat)\pm1.4(sys)$
1.110-1.420	$-4.6\pm7.2(stat)\pm1.7(sys)$
1.420-1.775	$-2.3\pm19.1(stat)\pm5.5(sys)$

Interpretation: $|Im(\eta_s)|<$ (0.012-0.026) at 90 %C.L. (due to the unknown strong phase)

CPV search in lepton sector@Belle (3)

The 3 Higgs Doublet Model predicts CPV in the lepton sector with complex higgs coupling constant X,Z:



Relation between η_s and 3HDM model parameters:

$$\eta_s \cong \frac{m_\tau m_s}{M_{H^\pm}^2} X^* Z$$

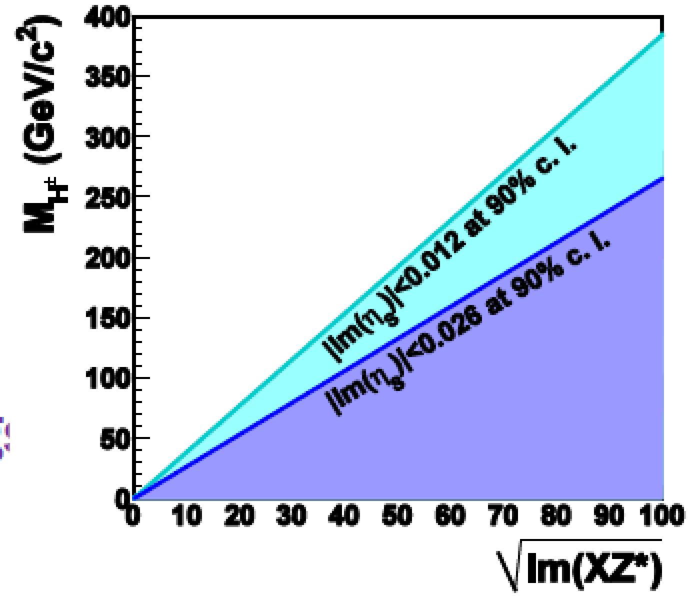
$M_{H^\pm}$: mass of lightest charged Higgs in MHDM

Z : complex coupling constant btw Higgs and lepton.

X : complex coupling constant btw Higgs and down-type quark

- **The result ($Im(\eta_s)<0.026$) limits the coupling**

$$|\,\mathrm{Im}(XZ^*)\,| \leq 0.15\,\frac{M_H^2}{(1GeV)^2}$$



CPV search in lepton sector@BaBar

Phys. Rev. D85 (2012) 031102

- Using 500fb^{-1} of data, BaBar evaluate much simpler asymmetry:

$$A_Q = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

$A_Q = (0.33 \pm 0.01)\%$ in SM due to CPV in $K^0 - \overline{K}^0$ mixing.

In this analysis, any number of π^0 is allowed in the signal decay.

- 170k $\tau^\pm \to K_s^0 \pi^\pm (\geqq 0\pi^0)\nu$ events are picked up, respectively, by similar selection to the Belle case. Remaining BG contents are also similar, i.e., mainly come from $\tau^- \to K_s^0 K_L^0 \pi^- \nu$.
- Finally, after the correction asymmetry is evaluated:

$$A_Q = (-0.36 \pm 0.23 \pm 0.11)\%$$

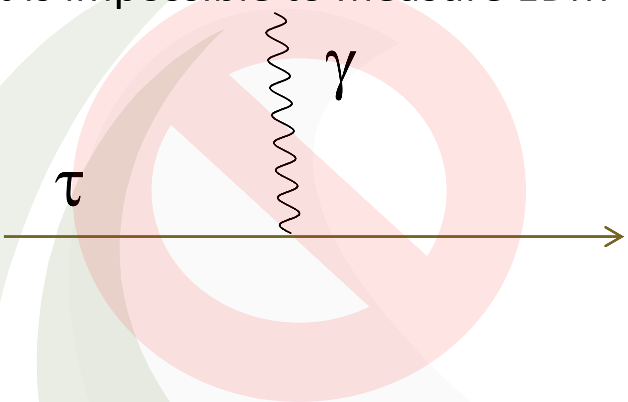
2.8 σ from SM prediction

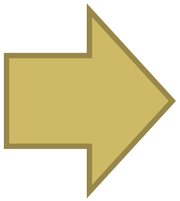
Similarly to Belle analysis, using $\tau \to \pi\pi\pi\nu$, correction is evaluated and applied.

tau EDM search

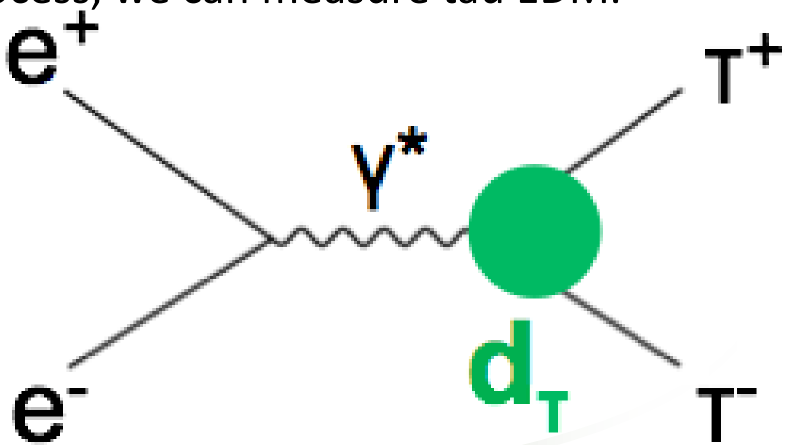
- Tau electric dipole moment search is also a kind of CPV search.
- Tau electric dipole moment should be suppressed since tau is an elementary particle.
- But, a new physics effect can enhance tau electric dipole moment. Several SUSY models predict it, for example.

Due to the short tau life time,
it is impossible to measure EDM with flying tau.





Instead, by evaluating tau-pair producing process, we can measure tau EDM.



tau EDM search @ Belle (1)

- By using “Optimal Observable”

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  - Amplitude to produce ττ with tau EDM term can be written down:

$$\mathcal{M}^2_{prod} = \mathcal{M}^2_{SM} + Re(d_\tau)\mathcal{M}^2_{Re} + Im(d_\tau)\mathcal{M}^2_{Im}$$

$$\begin{aligned}\mathcal{M}^2_{SM} = \frac{e^4}{k_0^2}[&k_0^2 + m_\tau^2 + |\mathrm{k}^2|(\hat{\mathrm{k}}\hat{\mathrm{p}})^2 - S_+S_-|\mathrm{k}|^2(1-((\hat{\mathrm{k}}\hat{\mathrm{p}})^2)] \\ &+2(\hat{\mathrm{k}}S_+)(\hat{\mathrm{k}}S_-)(|\mathrm{k}|^2 + (k_0 - m_\tau)^2(\hat{\mathrm{k}}\hat{\mathrm{p}})^2) \\ &-2k_0(k_0 - m_\tau)(\hat{\mathrm{k}}\hat{\mathrm{p}})((\hat{\mathrm{k}}S_+)(\hat{p}S_-) + (\hat{\mathrm{k}}S_+)(\hat{p}S_-)) \\ &+2k_0^2(\hat{p}S_+)(\hat{p}S_-)\end{aligned}$$

$p : e^+$ momentum

$k : \tau^+$ momentum

$S_\pm : \tau^\pm$ spin vector

@CM frame

$$\mathcal{M}^2_{\mathrm{Re}} = 4\frac{e^3}{k_0}|\boldsymbol{k}|\left[-\left(m_\tau + (k_0 - m_\tau)(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2\right)(\boldsymbol{S}_+ \times \boldsymbol{S}_-)\cdot\hat{\boldsymbol{k}} + k_0(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})(\boldsymbol{S}_+ \times \boldsymbol{S}_-)\cdot\hat{\boldsymbol{p}}\right],$$

$$\mathcal{M}^2_{\mathrm{Im}} = 4\frac{e^3}{k_0}|\boldsymbol{k}|\left[-\left(m_\tau + (k_0 - m_\tau)(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2\right)(\boldsymbol{S}_+ - \boldsymbol{S}_-)\cdot\hat{\boldsymbol{k}} + k_0(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})(\boldsymbol{S}_+ - \boldsymbol{S}_-)\cdot\hat{\boldsymbol{p}}\right],$$

By defining

$$\boxed{\mathcal{O}_{Re} = \frac{\mathcal{M}^2_{Re}}{\mathcal{M}^2_{SM}}}$$

$$\langle\mathcal{O}_{Re}\rangle \propto \int \mathcal{O}_{Re} d\sigma \propto \int \mathcal{O}_{Re}\mathcal{M}^2_{prod} d\phi$$

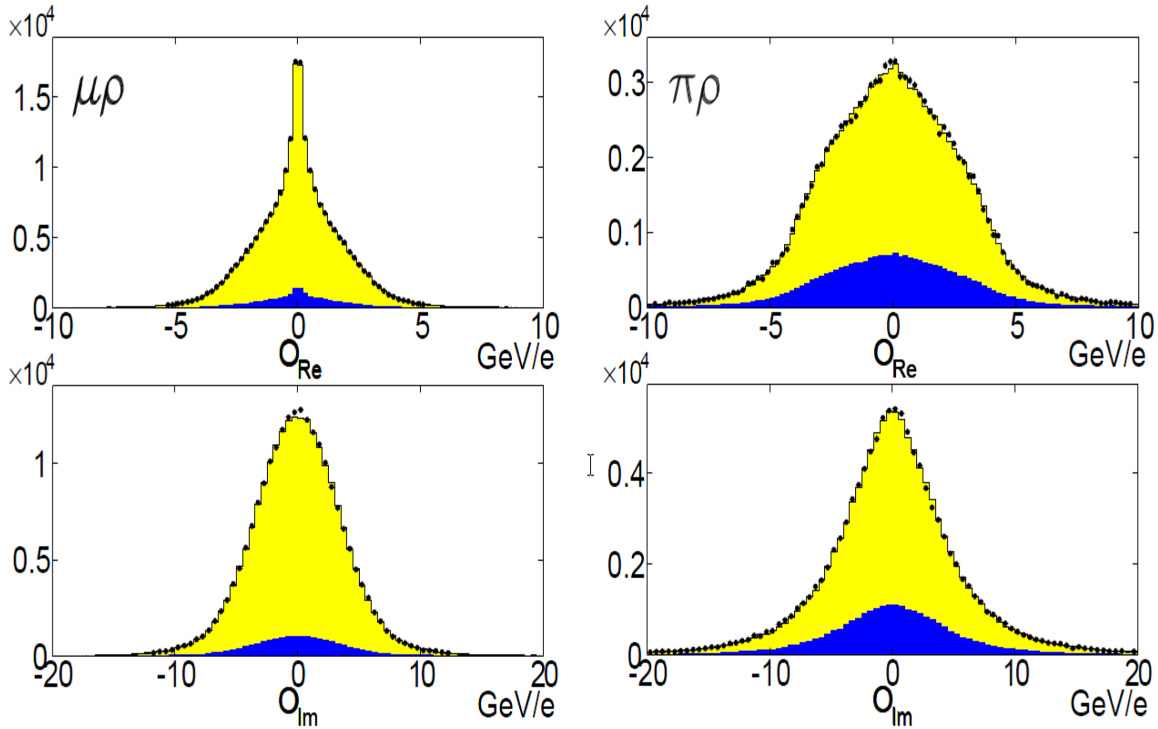
$$= \underbrace{\int \mathcal{M}^2_{Re} d\phi}_{b} + \underbrace{Re(d_\tau)}_{\text{EDM}} \underbrace{\int \frac{(\mathcal{M}^2_{Re})^2}{\mathcal{M}^2_{SM}} d\phi}_{a}$$

Measuring <O$_{Re}$>, EDM can be extracted. (a,b will be obtained from MC sample.)

tau EDM search @ Belle (2)

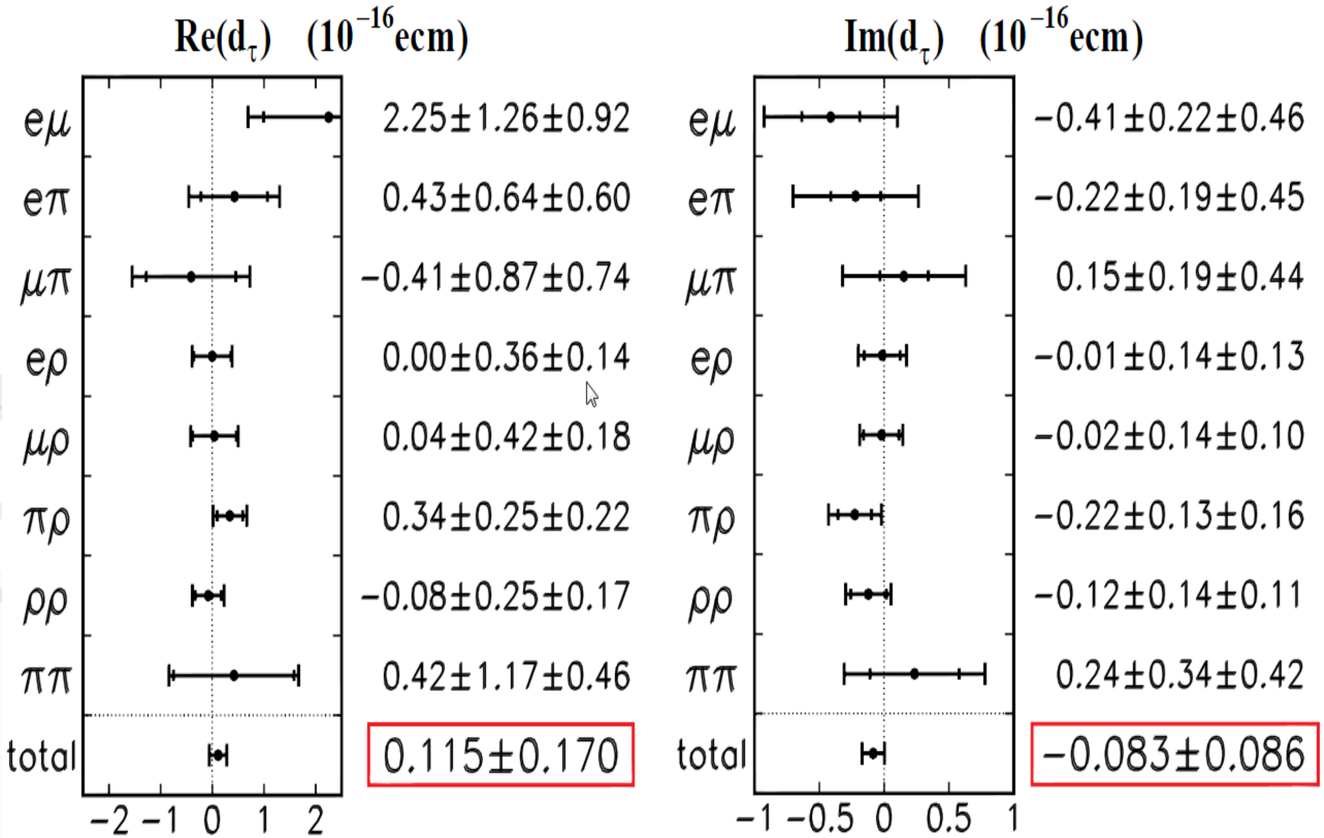
- 30fb^{-1}, ee→ττ / τ→eνν,μνν,πν,ρν

where, to avoid bhabha and di−muon, τ→eνν/τ→eνν, τ→μνν/τ→μνν have not been taken into account.



Yello: Signal
Blue: BG
Dot: data

tau EDM search @ Belle (3)



$|Re(d_\tau)| < 4.0 \times 10^{-17} e\,\mathrm{cm}$, $|Im(d_\tau)| < 2.2 \times 10^{-17} e\,\mathrm{cm}$, @95%CL

full data analysis is on-going and will finish soon.

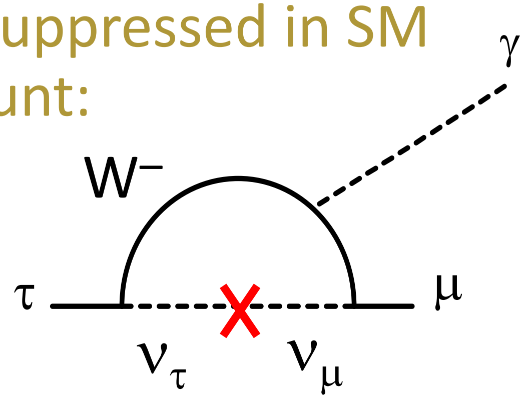
TAU LEPTON FLAVOR VIOLATION

Tau Lepton Flavor Violation

- A charged lepton flavor violation (LFV) has not yet been observed in any leptons and is also strongly suppressed in SM even if neutrino oscillation is taken into account:

$$Br(\tau \to \mu\gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2} \right)^2 < 10^{-54}$$

(Phys. Rev. D16 (1977) 1444)



  - This is impossible to observe it experimentally. Therefore, tau LFV can be a clear signature of a new physics. (Similarly, muon LFV)
  - Various models beyond SM predict it as largely as the current experimental sensitivity can reach there.
- Tau provides various kinds of lepton-flavor-violating decays since hadronic decays are allowed. (cf. muon)
  - Various decay modes tell us what model is favored.

Comparison between NP models

Ratios of tau LFV decay BF allow to discriminate between new physics models.

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z' boson
$\left(\frac{\tau \to \mu\mu\mu}{\tau \to \mu\gamma}\right)$	$\sim 2 \times 10^{-3}$	0.06~0.1	0.4~2.3	~16
$\left(\frac{\tau \to \mu ee}{\tau \to \mu\gamma}\right)$	$\sim 1 \times 10^{-2}$	$\sim 1 \times 10^{-2}$	0.3~1.6	~16
$Br(\tau \to \mu\gamma)$ @Max	$<10^{-7}$	$<10^{-10}$	$<10^{-10}$	$<10^{-9}$

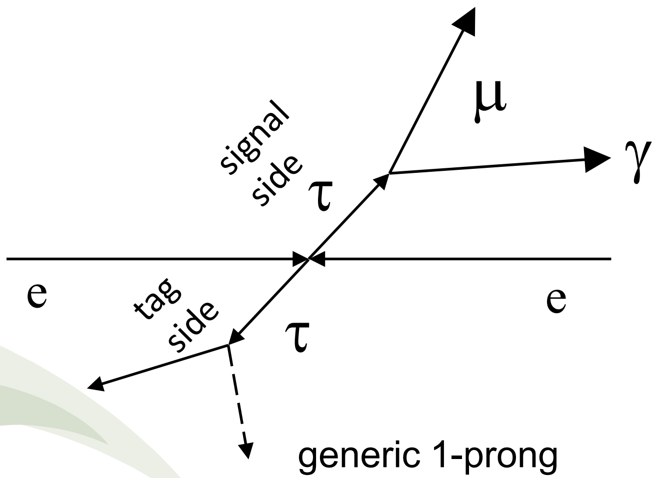
(JHEP 0705, 013(2007), PLB54 252 (2002))

Favorite modes $\tau \to \mu\gamma$ ⟷ $\tau \to \mu\mu\mu, \mu ee$

Analysis method of tau LFV at B-factory

$e^+e^- \rightarrow \tau^+\tau^-$

⇒ clean environment

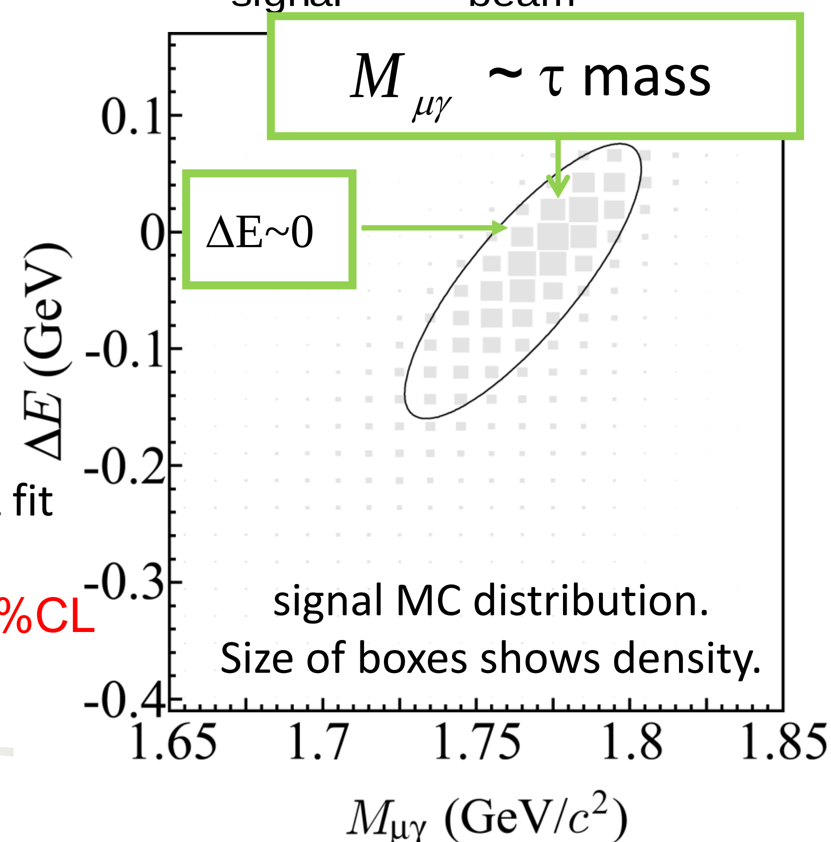


Since signal decay is neutrinoless, signal tau can be reconstructed, differently from SM decay.

Signal Extraction

$$M_{\mu\gamma} = \sqrt{\left(E^{\mathrm{CM}}_{\mathrm{signal}}\right)^2 - \left(p^{\mathrm{CM}}_{\mathrm{signal}}\right)^2}$$

$$\Delta E = E^{\mathrm{CM}}_{\mathrm{signal}} - E^{\mathrm{CM}}_{\mathrm{beam}}$$



Blind analysis
⇒Blind signal region

Estimate BG level using sideband data and MC

The signal extraction is performed by the UEML fit or counting on the $M_{\mu\gamma}$-ΔE plane.

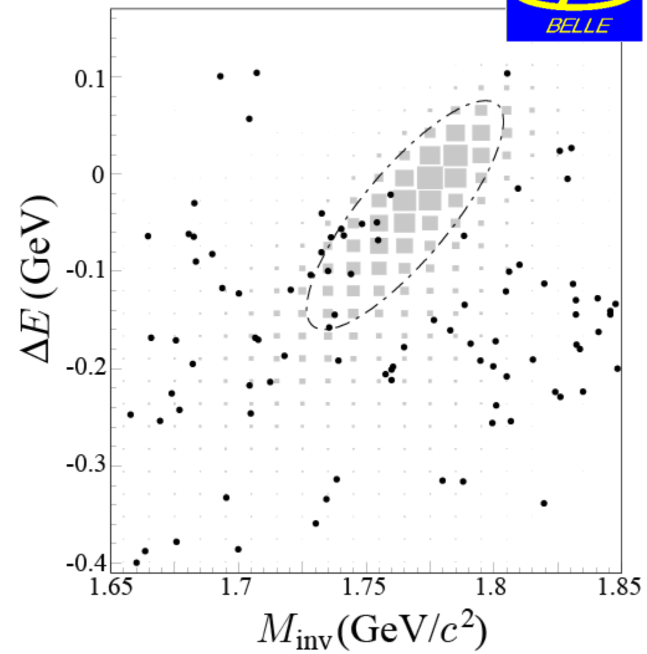
If no excess is found, set upper limits @ 90%CL using the UEML fit and toy MC or counting method. (Depending on mode)

Result for τ→μγ search @ Belle/BaBar

Belle: data: 545 fb^{-1} (PLB 666, 16 (2008))

- 94 events are found while (88.4±7.4) BG events are expected in 5σ region and the detection eff. is 6.1%.
- Upper Limits are evaluated by 2d UEML fit on M-ΔE plane.
  - Expected UL: 7.8×10^{-8} @90%CL
  - Obtained UL: 4.5×10^{-8} @90%CL

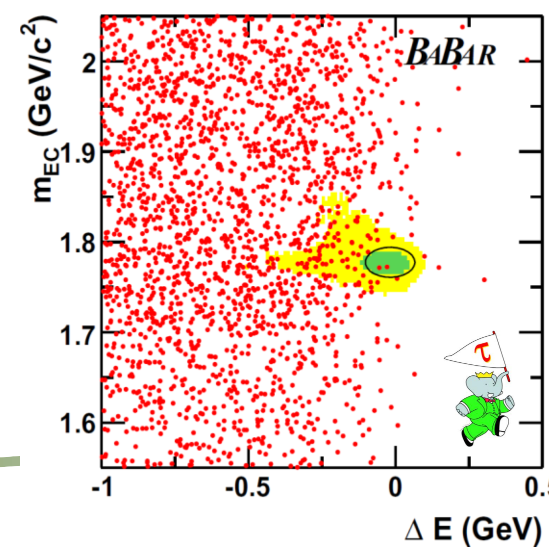
Remaining dominant BG is ee→ττ(→μνν)γ and this limits the sensitivity…



(PRL104,021802(2010))

BaBar: Data: 482M τ pairs (including Υ(2,3S) data)

Decay modes	2σ signal ellipse		ε	UL ($\times 10^{-8}$)	
	obs	exp	(%)	obs	exp
$\tau^\pm \to \mu^\pm \gamma$	2	3.6±0.7	6.1±0.5	4.4	8.2



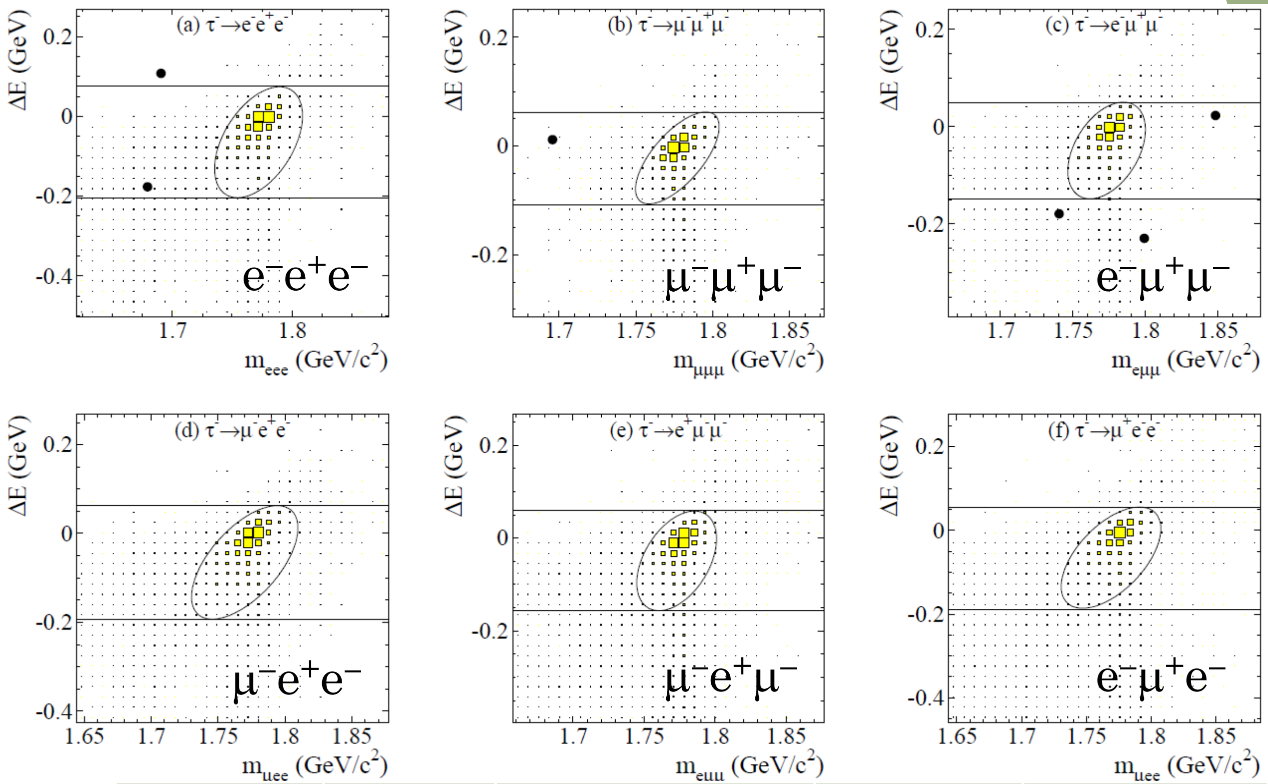
At Belle, with the full data sample, updated analysis is on-going.

Result for $\tau \rightarrow$ 3leptons search @ Belle

Data: 782fb^{-1}

- No event is found in the signal region.
- **Almost BG free**
  - Expected # of BG: 0.01-0.21
  - good lepton ID
- Br<(1.5-2.7)x10^{-8} at 90%CL.

$\rightarrow$most sensitive results



Mode	ε (%)	N_{BG}^{EXP}	σ_{syst} (%)	UL (x10^{-8})
$e^-e^+e^-$	6.0	0.21±0.15	9.8	2.7
$\mu^-\mu^+\mu^-$	7.6	0.13±0.06	7.4	2.1
$e^-\mu^+\mu^-$	6.1	0.10±0.04	9.5	2.7
$\mu^-e^+e^-$	9.3	0.04±0.04	7.8	1.8
$\mu^-e^+\mu^-$	10.1	0.02±0.02	7.6	1.7
$e^-\mu^+e^-$	11.5	0.01±0.01	7.7	1.5

Phys.Lett.B 687,139 (2010)

Result for τ→3leptons search @ BaBar

Data:477fb^{-1}

Improve lepton ID eff.

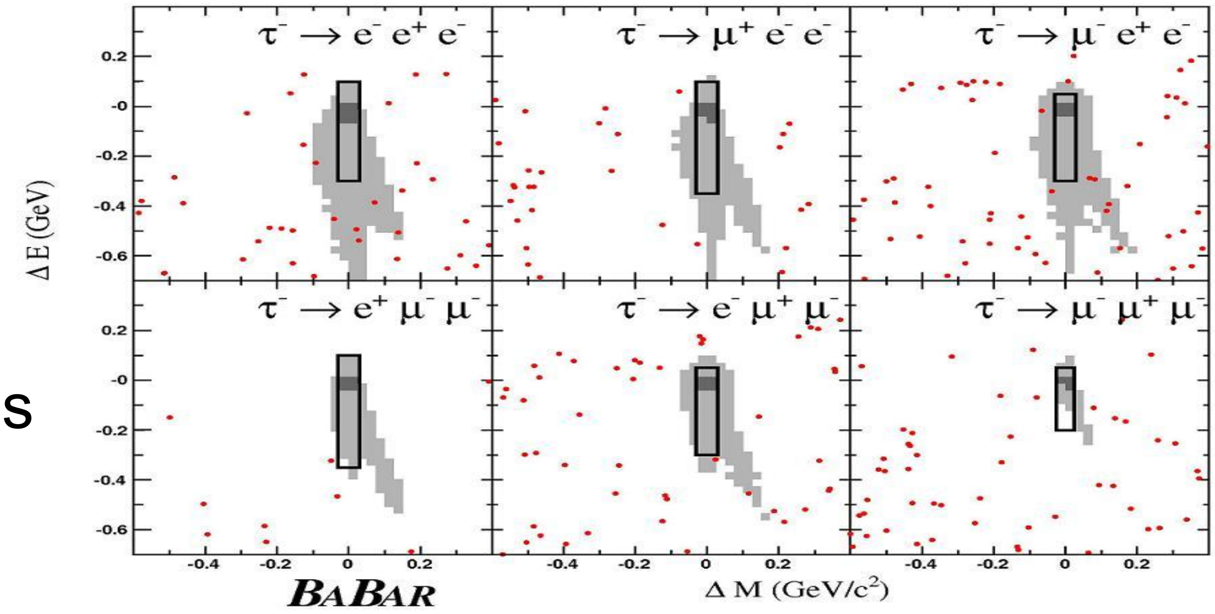
- μ: 66%→77%
- e: 89%→91%

→Better BG rejection

no events in signal region for all modes

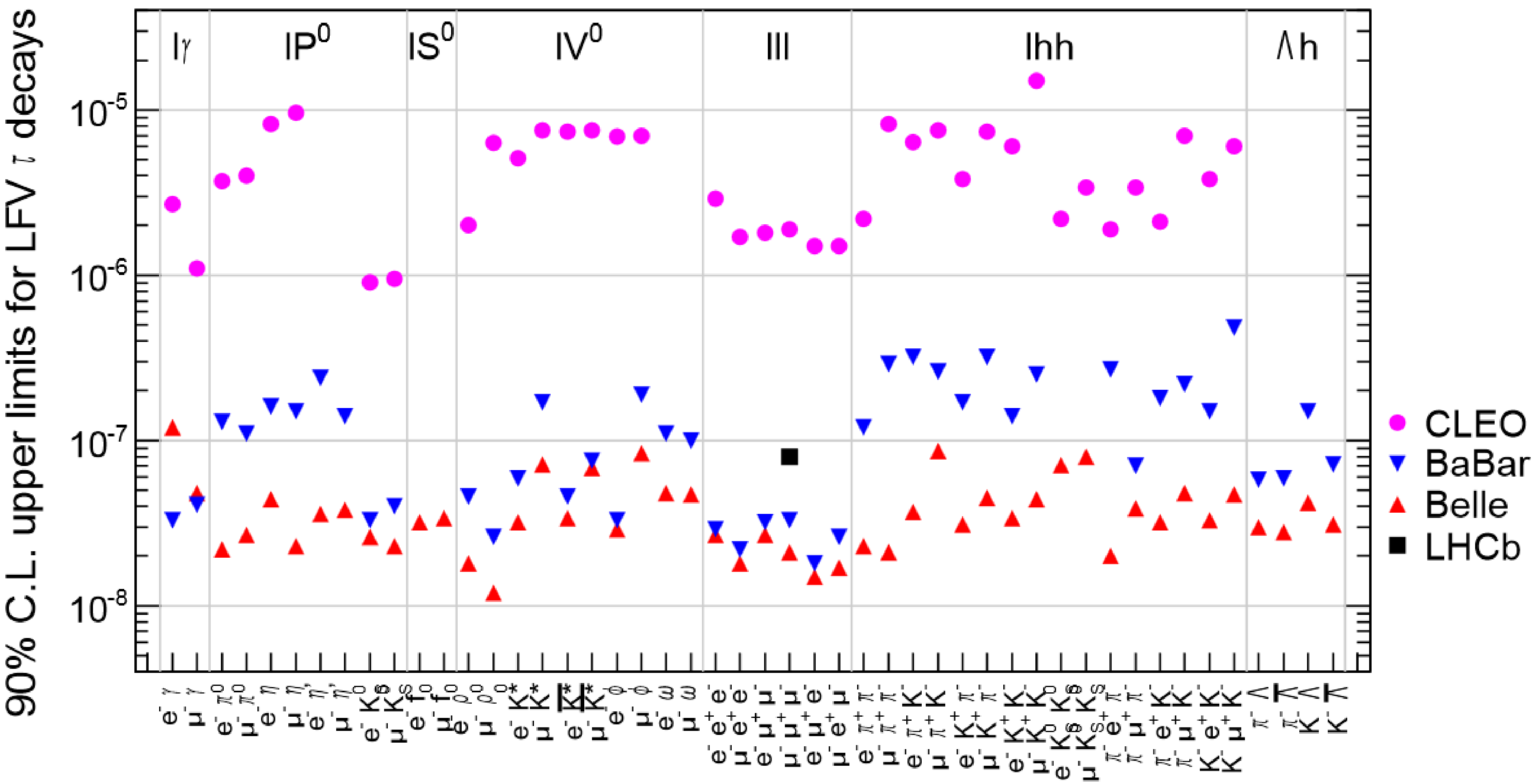
Br<(1.8-3.3)x10^{-8} @90%CL

Phys. Rev. D 81 (2010) 111101(R)



Channel	Efficiency (%)	N_{bgd}	Exp. UL	N_{obs}	UL
$e^+e^-e^+$	8.6 ± 0.2	0.12 ± 0.02	3.4×10^{-8}	0	2.9×10^{-8}
$e^+e^-\mu^+$	8.8 ± 0.5	0.64 ± 0.19	3.7×10^{-8}	0	2.2×10^{-8}
$e^+e^+\mu^-$	12.6 ± 0.7	0.34 ± 0.12	2.2×10^{-8}	0	1.8×10^{-8}
$e^+\mu^-\mu^+$	6.4 ± 0.4	0.54 ± 0.14	4.6×10^{-8}	0	3.2×10^{-8}
$e^-\mu^+\mu^+$	10.2 ± 0.6	0.03 ± 0.02	2.8×10^{-8}	0	2.6×10^{-8}
$\mu^+\mu^-\mu^+$	6.6 ± 0.6	0.44 ± 0.17	4.0×10^{-8}	0	3.3×10^{-8}

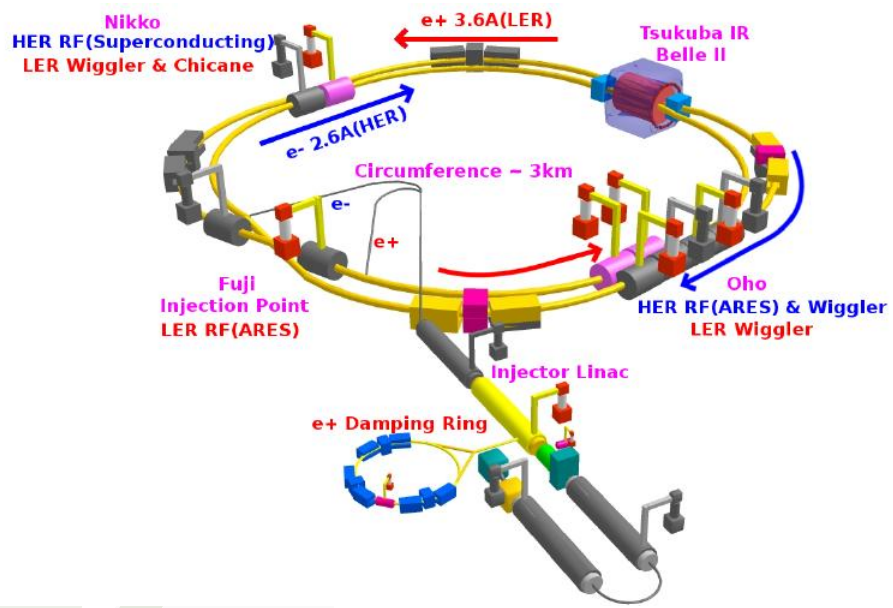
Summary of recent tau LFV searches

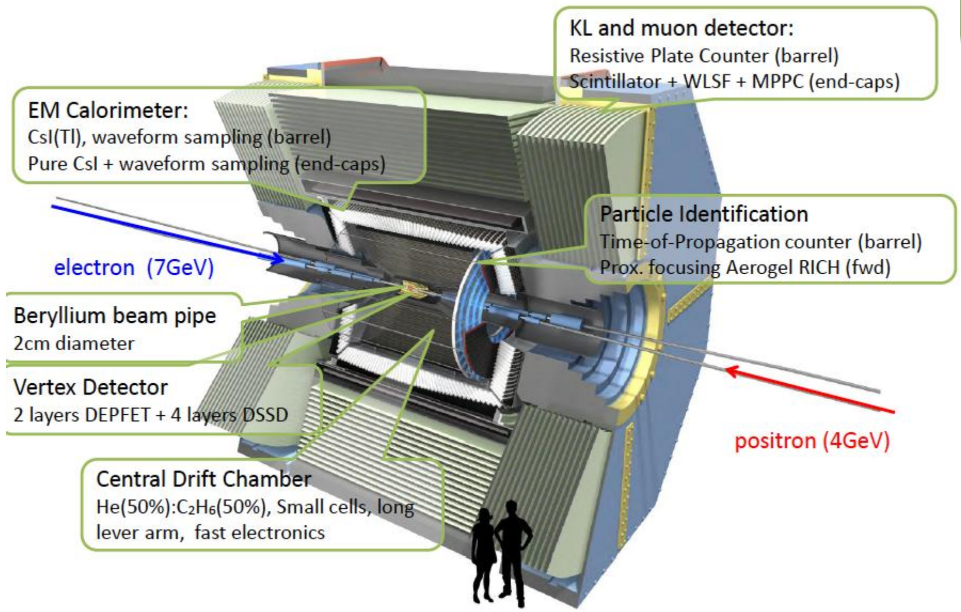


48 tau LFV modes have been searched for at B-factories and obtained 100x more sensitive results than CLEO's. Recently LHCb also made the search for μμμ, etc. The results are comparable to the B-factories'.

NEAR FUTURE EXPERIMENT

SuperKEKB/Belle II





KEKB → superKEKB

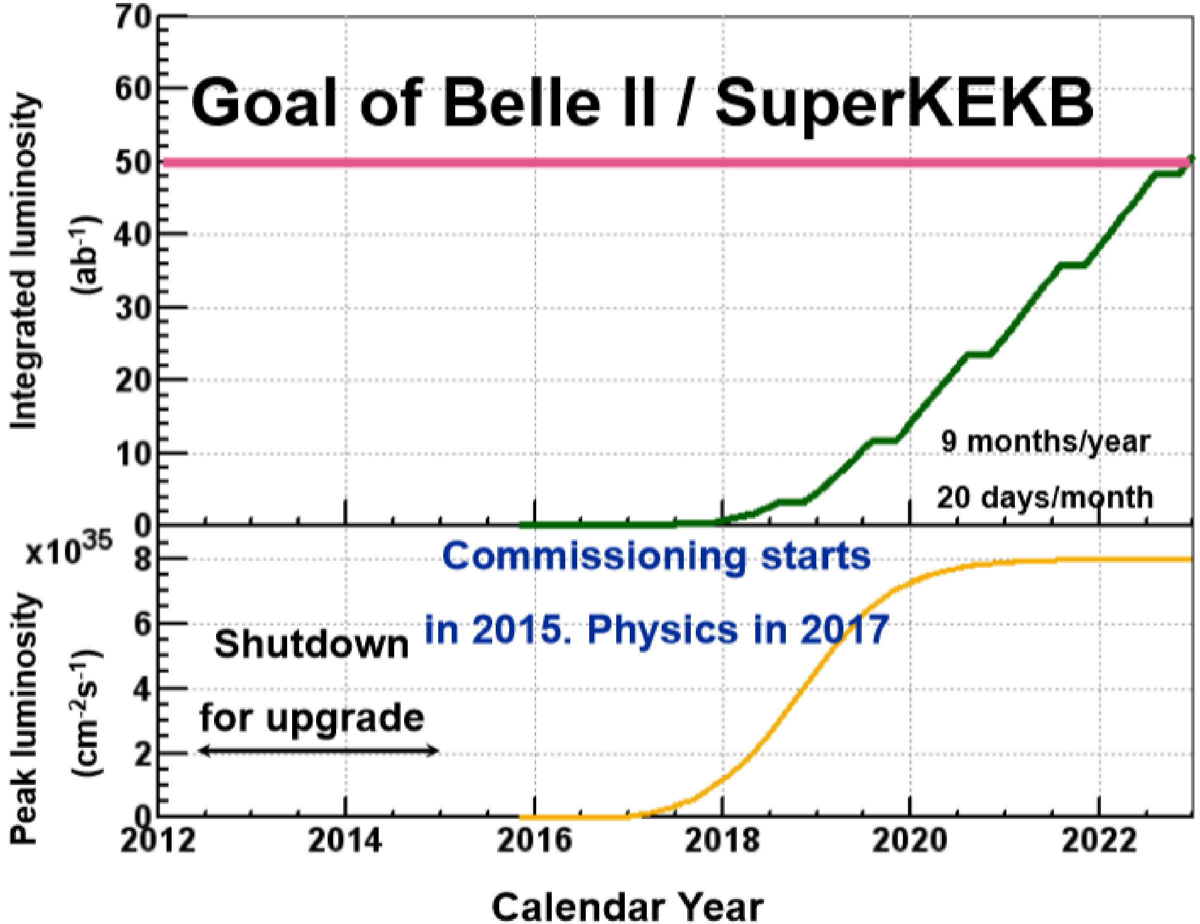
Vertical β function: 5.9 mm → 0.27/0.30 mm (x20)

Beam current: 1.7/1.4 A → 3.6/2.6 A (x2)

→ L = 2×10^{34} $cm^{-2}s^{-1}$ → 8×10^{35} $cm^{-2}s^{-1}$ (x40)

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

Expected integrated luminosity on SuperKEB/Belle II



We will reach 50 ab^{-1} in 2022-2023

~O(10^{11}) tau sample

Future prospect on τLFV @ Belle II

- Sensitivity will be…

BG free: ∝ 1/(no.of τ)

BG non-free: ∝ 1/√(no.of τ)

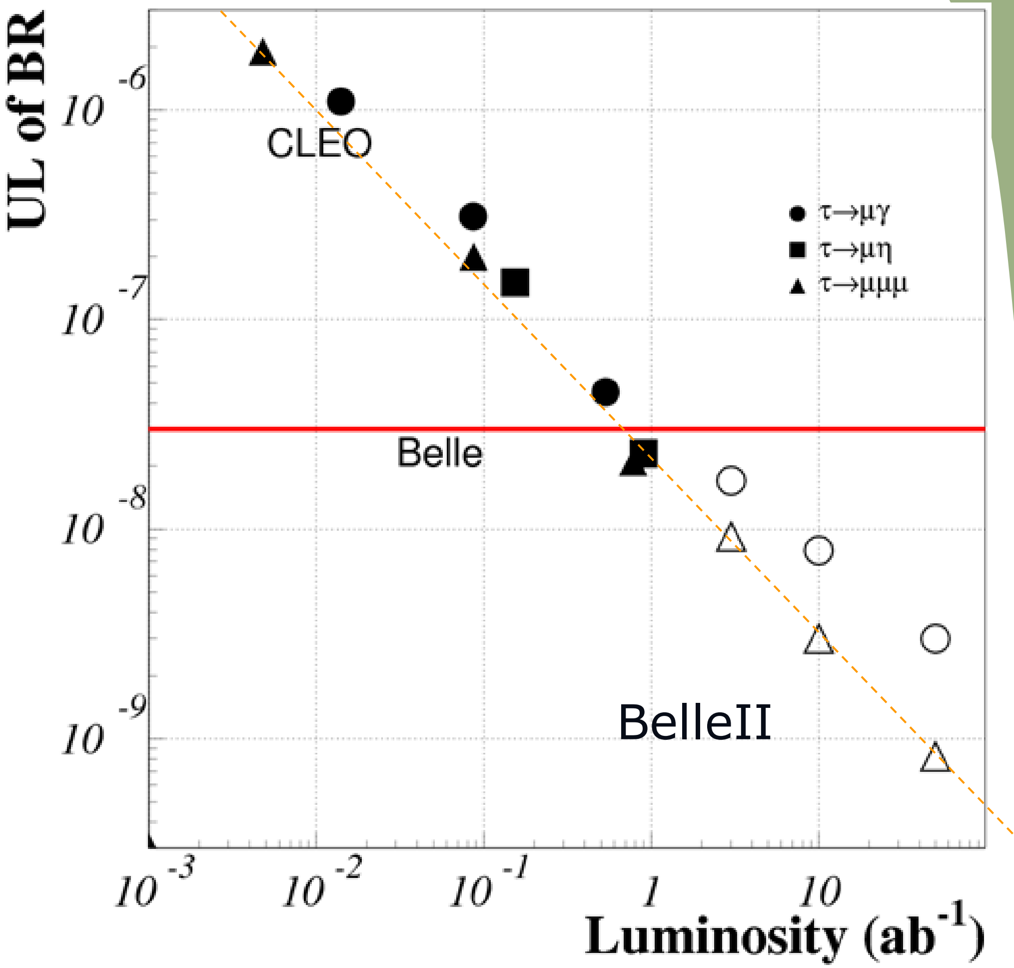
- BG amount for each mode

  $\tau \rightarrow \mu\gamma$: BG non-free (rich)

  $\tau \rightarrow \mu\mu\mu$: BG free

→expected: B(μμμ)~O(10^{-10})

B(μγ)~O(10^{-9})



Since we WILL NOT apply same analysis,

(Because, with larger sample, we can understand BG much better.)

Sensitivity will be better than expected.

Summary

- Tau lepton is a good probe to NP phenomena such as tau LFV and CPV in lepton sector.
- B-factories provide us the huge data sample of tau ($O(10^9)$) and various analyses to search for NP have been performed.
- CPV search in tau decay having K_s^0 has been performed:
  - Belle's result is 10x more sensitive than CLEO's.
  - BaBar's result is 2.8σ away from SM prediction.
- tau EDM has also been measured. Still zero-consistent result:
  - $|Re(d_\tau)|<4.0\times10^{-17}$, $|Im(d_\tau)|< 2.2\times10^{-17}$ @95%CL
  - New analysis is on-going and will finish soon.
- 48 tau LFV modes have been searched at B-factories and 100x sensitive results have been obtained than CLEO's.
  - The sensitivity is $O(10^{-9})$. LHCb can search for some modes and the current sensitivity is comparable to B-factories'.
  - With Belle's full data sample, $\tau\rightarrow\mu\gamma/e\gamma$ analyses is on-going and will finish soon.
- Next generation B-factory, that is superKEKB/Belle II, will have 50x larger data sample. NP searches using tau will continue and more sensitive result will be obtained in the future.

$\tau \to \mu\mu\mu$ at LHCb

- used 8×10^{10} τs, in $1 fb^{-1}$ data sample at $\sqrt{s}$=7 TeV collected in 2011
  - 80% of τs comes from $D_S \to \tau\nu$
  - There is no way for B-factory-like τ–tag since τ does not come from τ-pair production.
    - More BG is expected than that at B-factory
- $D_S \to \phi(\mu\mu)\pi$ is also analyzed as a "reference".
  - Mass is very close to τ's and this process is also 3-prong decay.
  - By counting no.of D_S, no.of τ is evaluated.
- Used 3-prong likelihood,3μ-PID likelihood and M($\mu\mu\mu$)to evaluate $\tau \to \mu\mu\mu$ likelihood.

signal likelihoods

combined signal distribution

- events distributed over 25 likelihood bins
- background estimate from mass sidebands

LHCb 1 fb^{-1}

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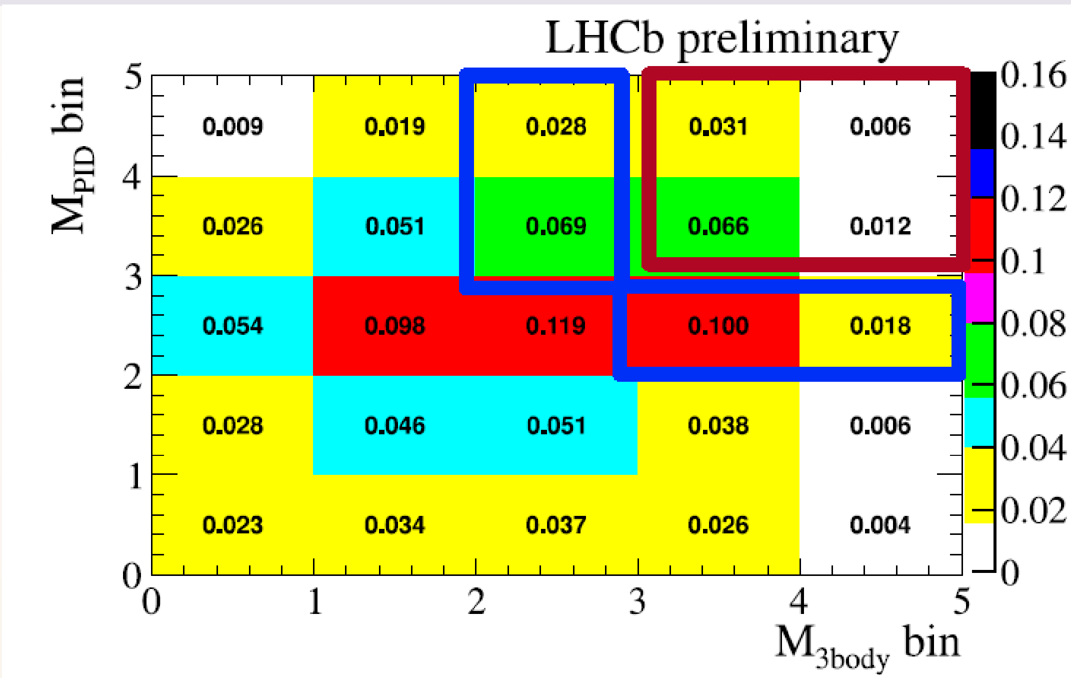
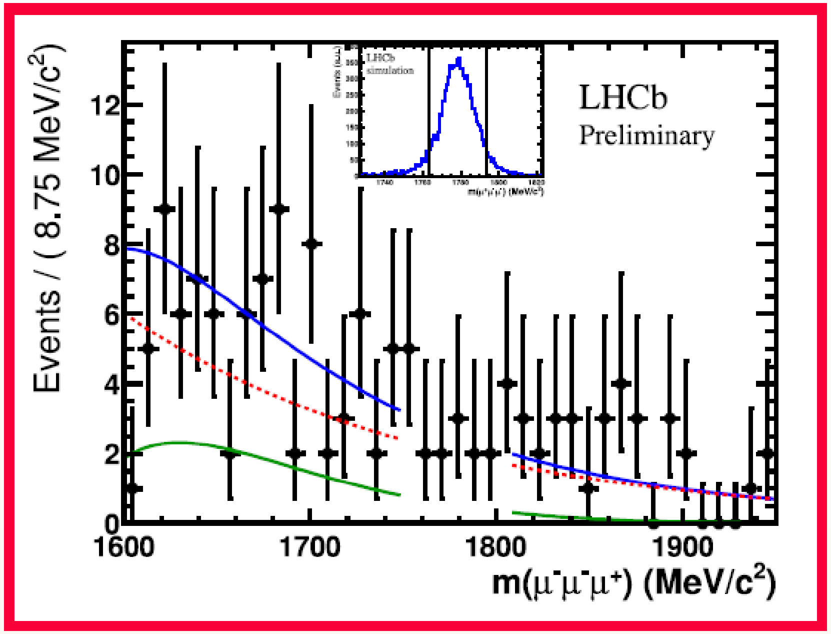
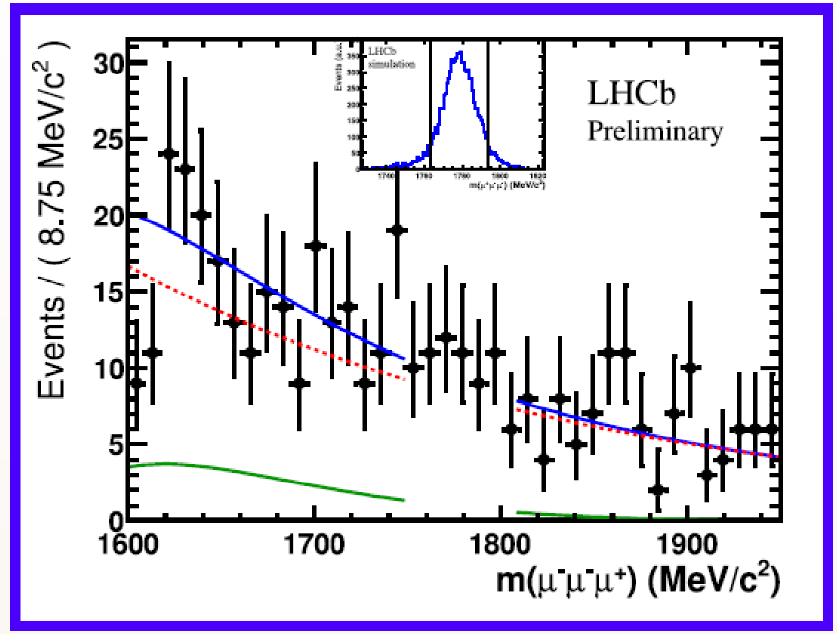


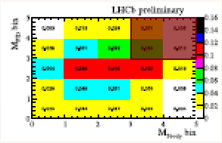
- 11 % signal efficiency
- 21 % signal efficiency
- for illustration: high likelihood range shown

observed events

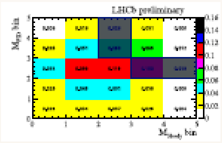




11 % of the signal
0.03 % of the background



21 % of the signal
0.14 % of the background



red dashed combinatorial background

green $D_s^+ \to \eta(\mu^-\mu^+\gamma)\mu^+\nu_\mu$

blue combined background

LHCb 1 fb^{-1}

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extracted limit

result (preliminary)

	observed	expected	
$\mathcal{B}(\tau \rightarrow \mu\mu\mu)$	$< 6.3 \times 10^{-8}$	8.2×10^{-8}	@ 90 % CL
	$< 7.8 \times 10^{-8}$	9.9×10^{-8}	@ 95 % CL

LHCb $1\ \mathrm{fb}^{-1}$

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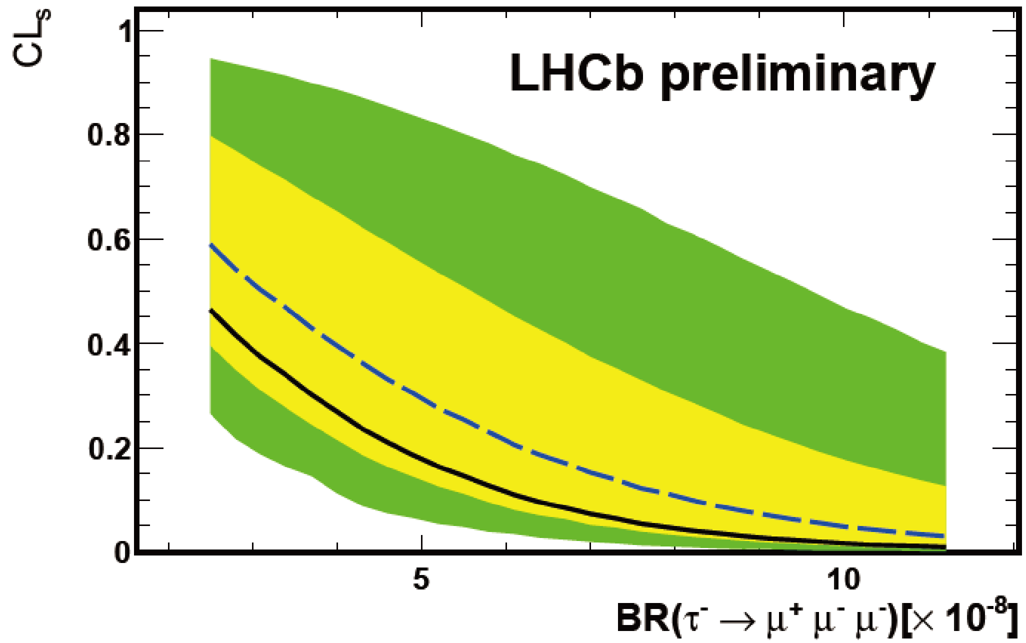

After publication (PLB 724,36(2913)), UL is corrected to 8.0×10^{-8} at 90%CL

Belle 2.1×10^{-8} @ 90 % CL
Phys. Lett. B **687**, 139 (2010)

BaBar 3.3×10^{-8} @ 90 % CL
Phys. Rev. D **81**, 111101(R) (2010)

Private estimation for the future prospect of $\tau \to \mu\mu\mu$ at LHCb

- Very near future: $1fb^{-1} \to 3fb^{-1}$
  - 8TeV $2fb^{-1}$ data sample will be added since that has already obtained.
  - Since $\sigma(cc)$ at LHC is almost proportional to $\sqrt{s}$, no. of τ approximately become 3.3 times larger.
  - Since BG is large, around $\sqrt{3.3}$ times more sensitivity will be obtained, i.e. $B<4x10^{-8}$ @90%
- Finally: $50fb^{-1}$ (2030? Anyway after 2020 LS2)
  - At 14TeV,100 times more τ will be obtained.
  - They try to improve the trigger eff.: twice better
  - Tottaly, 15 times more sensitive $\to B<6x10^{-9}$
- $\tau \to \mu\phi(\to KK)$, $\tau \to \mu K^*(\to K\pi)$ searches are also possible. ($\tau \to \mu\mu p$ has been done in the current one)