Tau physics at Belle

Kiyoshi Hayasaka (KMI, Nagoya Univ.)

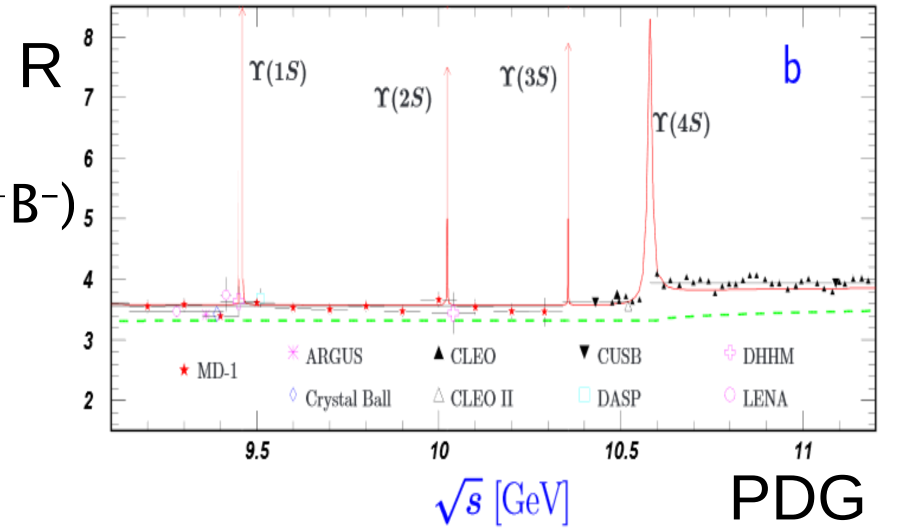
tau-production at B-factory

B-factory: E at CM = $\Upsilon(4S)$ ($\rightarrow B^0\overline{B^0}/B^+B^-$)

e^+(3.5 GeV) e^-(8 GeV)

$\rightarrow \sigma(\tau\tau):\sigma(b\overline{b})=0.9:1.1$ (nb)

- <u>A B-factory is also a tau-factory!</u>



In addition…

B-factory takes a data sample with $\sqrt{s}=$ $\Upsilon(4S)$ mass as well as data samples $\sqrt{s}=\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(5S)$ masses and off-resonance, i.e., 40~60MeV lower energy than $\Upsilon(nS)$ mass.

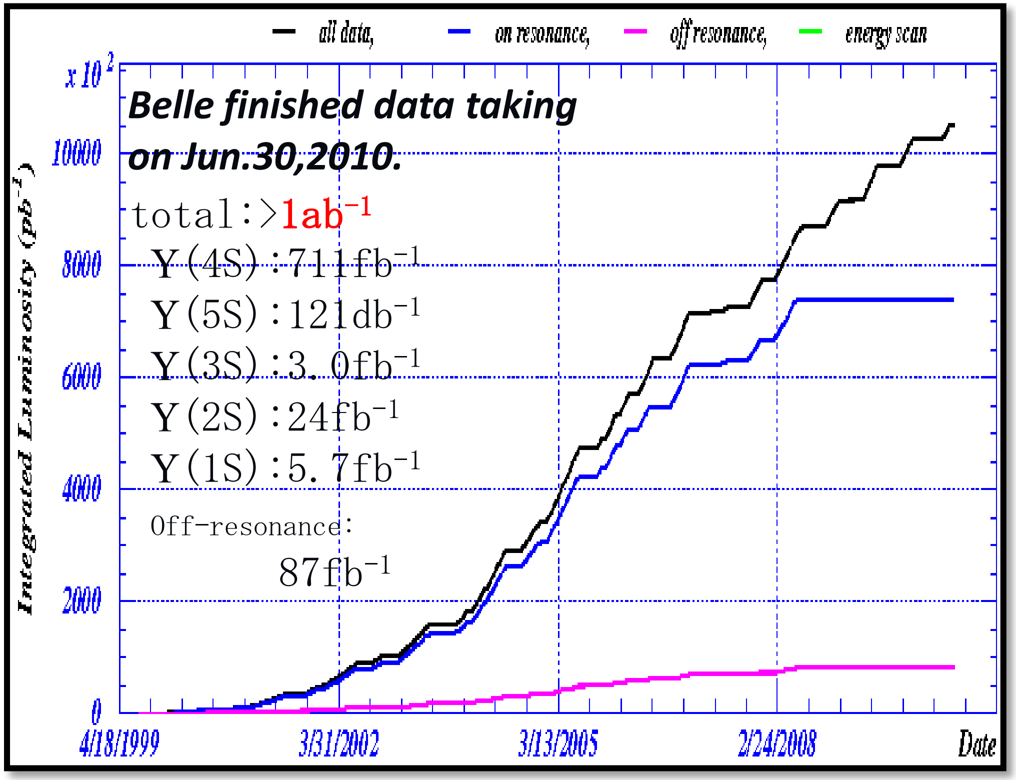
Usually, for B meson analysis, the only $\Upsilon(4S)$ mass sample is used.

(And, off-resonance sample is used to understand continuum BG.)

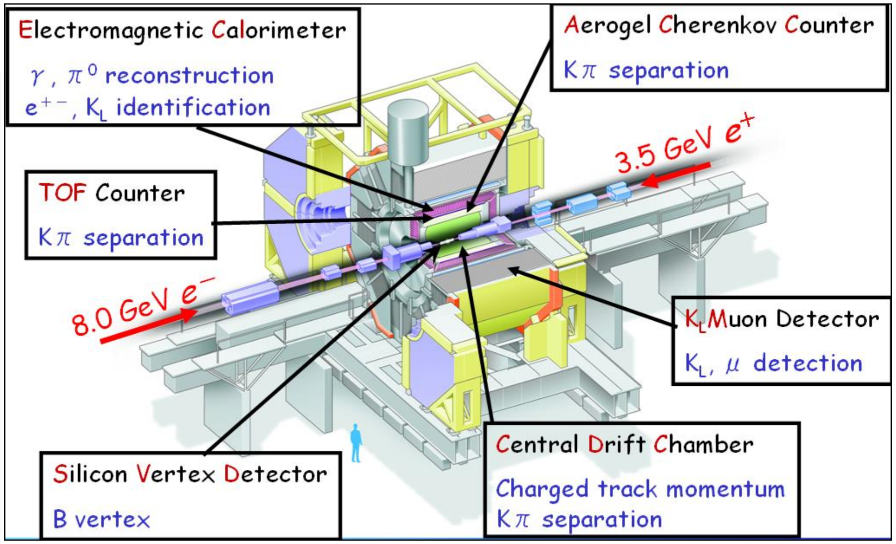
However, for tau analysis, all of them can be used!

KEKB collider and Belle detector

Asymmetric e+e- collider
(High luminosity: World Record of
2.11×10^{34} cm^{-2} s^{-1})



Asymmetric, multi-purpose detector



→ **τ -factory: world-largest τ data sample!**

- Good track reconstruction
- Good PID performance

Lepton ID ~ (80-90)%
Fake ID ~ (0.1-3)%

~9×10^{8} $\tau\tau$ at Belle

Tau physics at Belle

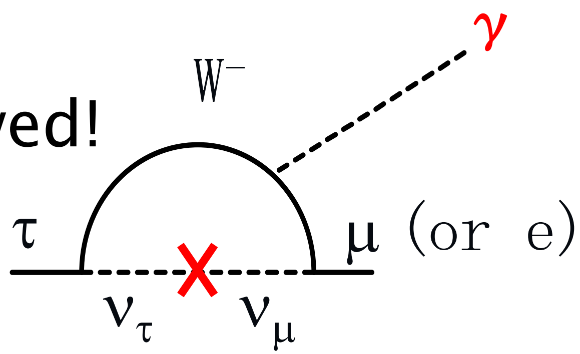
- New Physics search
  - Lepton Flavor Violation
  - CP Violation in Lepton sector
  - EDM/MDM
- SM precise measurement
  - Tau mass
  - Tau lifetime
  - Michael parameters
  - Hadron spectrum
  - 2^{nd} class current

Motivation for τ LFV

- Historically, as a radiative excitation mode, $\mu \rightarrow e\gamma$ has been searched for…
- Now, due to the neutrino oscillation,

we know that such possesses are allowed!

But, how frequent?



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

Experimentally possible to observe it…
This is almost forbidden decay in SM even if ν oscillation is taken in to account
→A clear signature of New Physics
if this kind of decays is observed.

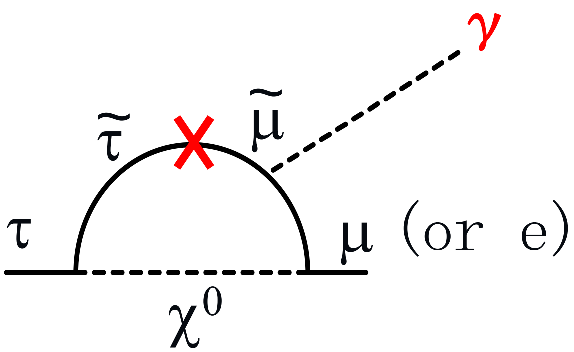
τ LFV with New Physics model

- τ LFV will be induced by New Physics. For example,

Most naïve consideration in SUSY case

$$(m^2_{\tilde{l}})_{ij} = (m_l m_l^\dagger)_{ij} + (\tilde{m}^2_l)_{ij} = \begin{pmatrix} \tilde{m}^2_{ee} & \tilde{m}^2_{e\mu} & \tilde{m}^2_{e\tau} \\ \tilde{m}^2_{\mu e} & \tilde{m}^2_{\mu\mu} & \tilde{m}^2_{\mu\tau} \\ \tilde{m}^2_{\tau e} & \tilde{m}^2_{\tau\mu} & \tilde{m}^2_{\tau\tau} \end{pmatrix}$$

slepton mass matrinx | lepton mass matrinx | SUSY breaking



Many prediction in various models

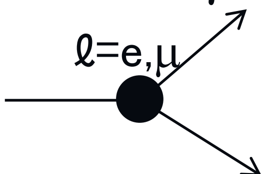
		τ→μγ	μμμ
SUSY Higgs	Dedes, Ellis, Raidal, PLB 549 (2002) 159 Brignole, Rossi, PLB 566 (2003) 517	10^{-10}	10^{-7}
SM + heavy Maj ν_R	Cvetic, Dib, Kim, Kim , PRD66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	Yue, Zhang, Liu, PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	Masiero, Vempati, Vives, NPB 649 (2003) 189 Fukuyama, Kikuchi, Okada, PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA + Seesaw	Ellis, Gomez, Leontaris, Lola, Nanopoulos, EPJ C14 (2002) 319 Ellis, Hisano, Raidal, Shimizu, PRD 66 (2002) 115013	10^{-7}	10^{-9}

Various τLFV modes (and μLFV modes)

Why I like τ? → Because it is the heaviest lepton

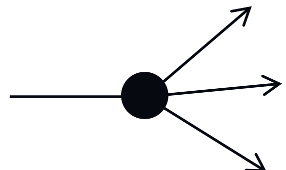
- Sensitive to NP
- possible to have various decay modes

$\tau^- \to \ell^- \gamma$



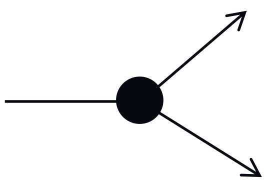
($\mu \to e\gamma$)

$\tau^- \to \ell^- \ell^+ \ell^-$



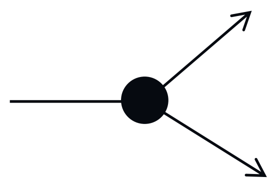
($\mu \to eee$)

$\tau^- \to \ell^- S^0/P^0$



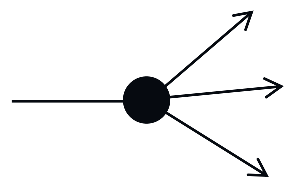
$S^0/P^0 = f^0, \pi^0, \eta, \eta', K_S^0$

$\tau^- \to \ell^- V^0$



$V^0 = \rho^0, K^{*0}, \overline{K^{*0}}, \phi, \omega$

$\tau^- \to \ell^- h^+ h^-$



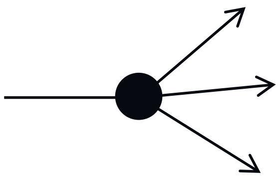
$h = \pi, K$

($\mu \to e$ conversion)

In additon …

possible to investigate modes
that can not appear in μLFV reaction.

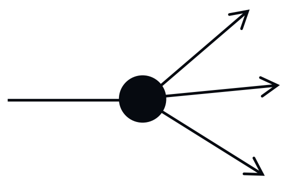
$\tau^- \to e^+\mu^-\mu^-$, $\mu^+e^-e^-$



doubly LFV decay

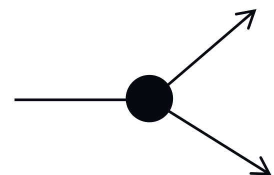
total LF variation: 4
(Δ(τ number):1, Δ(μ number):2, Δ(e number):1)

$\tau^- \to \ell^+ h^- h^-$ (h=π,K)



LNV decay
LNV:
lepton number violation

$\tau \to h\Lambda/\bar{\Lambda}$ (h=π,K)



LNV&BNV decay
BNV: Baryon number violation

Various τLFV decays and models

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.4\ldots 2.5$	$\sim 6\cdot 10^{-3}$	$\sim 6\cdot 10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.4\ldots 2.3$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.4\ldots 2.3$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.3\ldots 1.6$	$\sim 2\cdot 10^{-3}$	$0.02\ldots 0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.3\ldots 1.6$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$1.3\ldots 1.7$	~ 5	$0.3\ldots 0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$1.2\ldots 1.6$	~ 0.2	$5\ldots 10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-2}\ldots 10^{2}$	$\sim 5\cdot 10^{-3}$	$0.08\ldots 0.15$

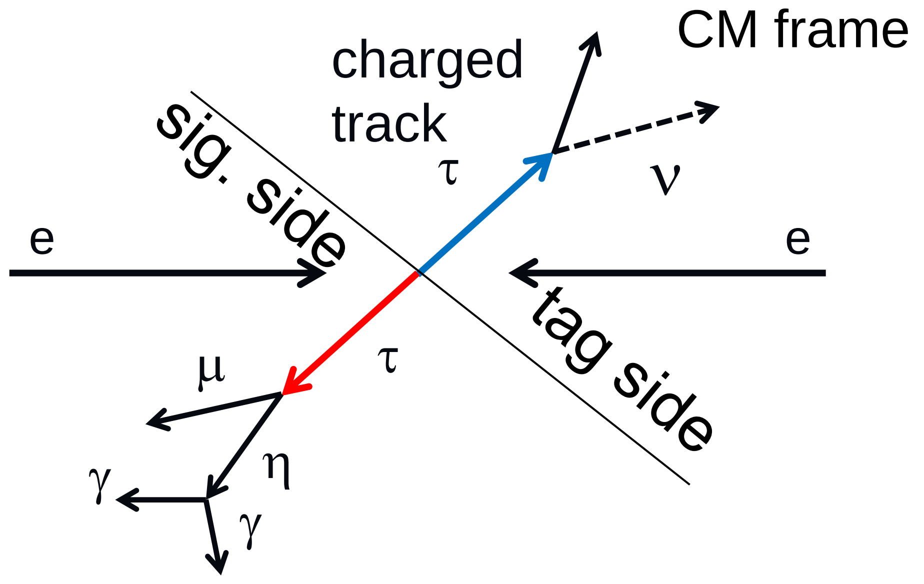
τLFV (rows 2–7)

Monika Blanke *et al* JHEP05(2007)013 doi:10.1088/1126-6708/2007/05/013

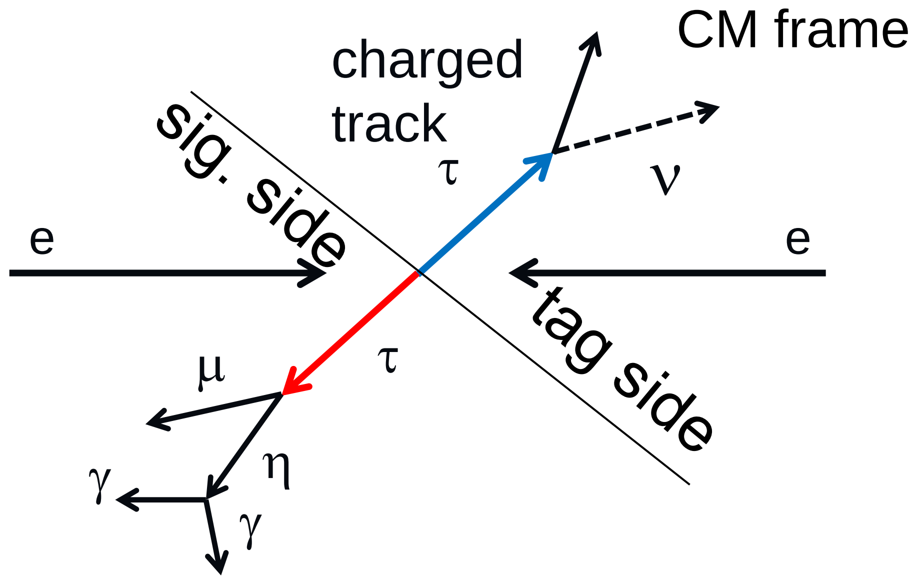
For observation of NP, anyway, finding of one LFV decay is important. However, to understand NP, measurement of the various LFV decays is also important.

Analysis method

1. Event having low no. of charged tracks and gammas.
(1-1: μγ, μη,… 3-1: μμμ,μππ,…)



Analysis method

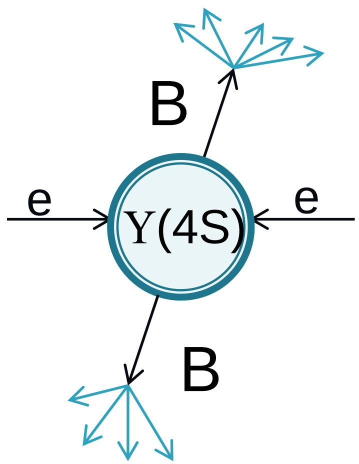


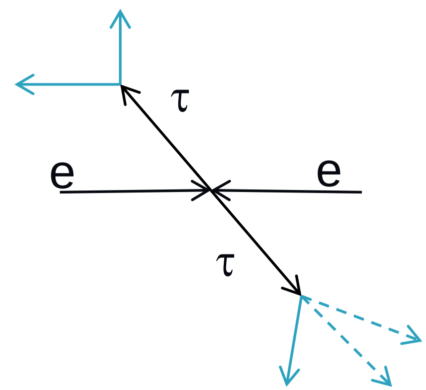
1. Event having low no. of charged tracks and gammas.
(1-1: μγ, μη,… 3-1: μμμ,μππ,…)
2.Large missing momentum

How to recognize ττ events?(1)

- Differently from BB events,

it is difficult to identify ττ events due to ν_τ!



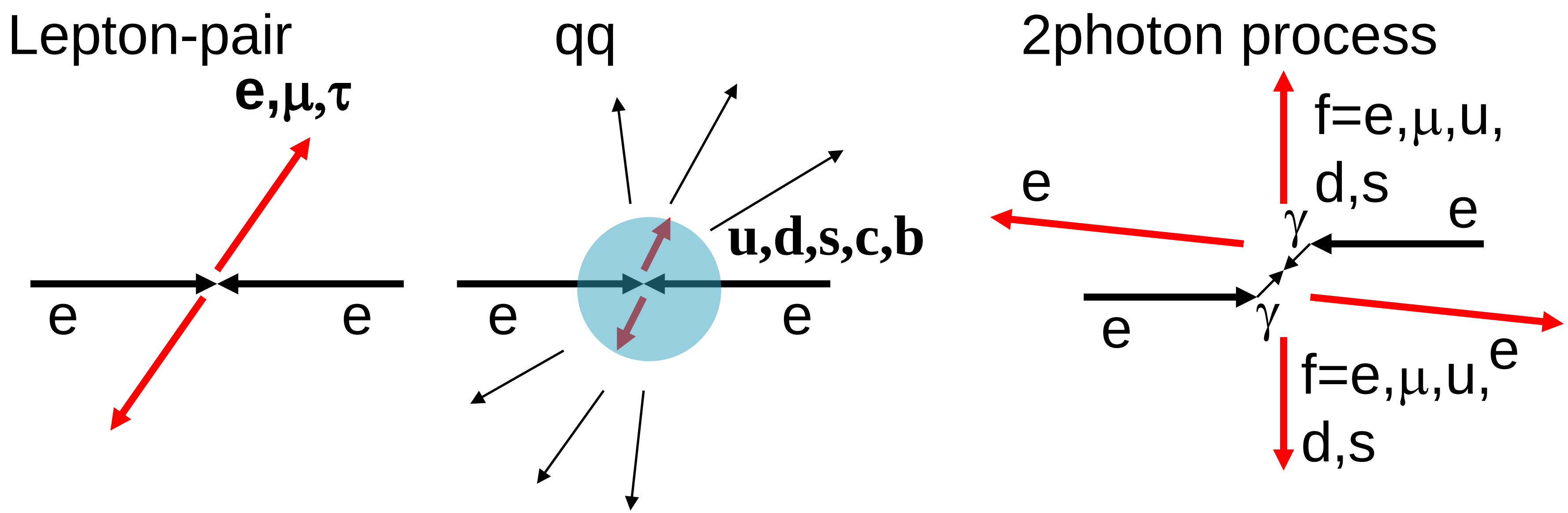


If you can reconstruct one B, remains must be daughters of another B and this is identifed as an Υ(4S) event

Due to ν in the τ decay, it is impossible to reconstruct τ completely…
→It is difficult to identify ττ events to reconstruct τ.

How to recognize ττ events?(2)

- What kind of events are produced in a B-factory?



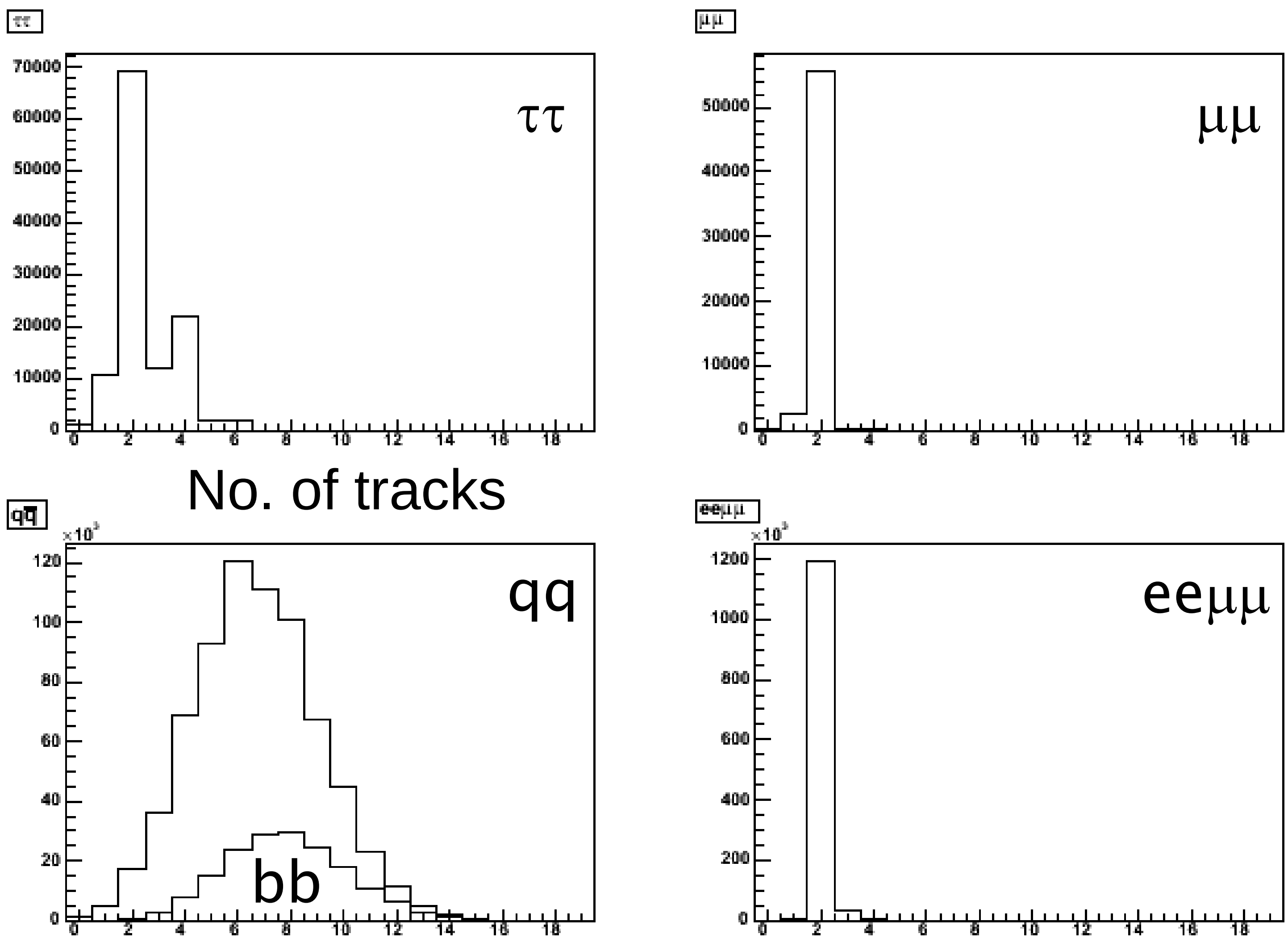
$\sigma(\mu\mu) \sim \sigma(dd) \sim \sigma(ss) \sim \sigma(bb) \sim \sigma(\tau\tau) \sim 1nb$

$\sigma(bhabha) \sim 120x\sigma(\tau\tau)$

$\sigma(eeee) \sim 40x\sigma(\tau\tau)$, $\sigma(ee\mu\mu) \sim 20x\sigma(\tau\tau)$, $\sigma(eeuu) \sim 10x\sigma(\tau\tau)$,

How to recognize ττ events?(3)

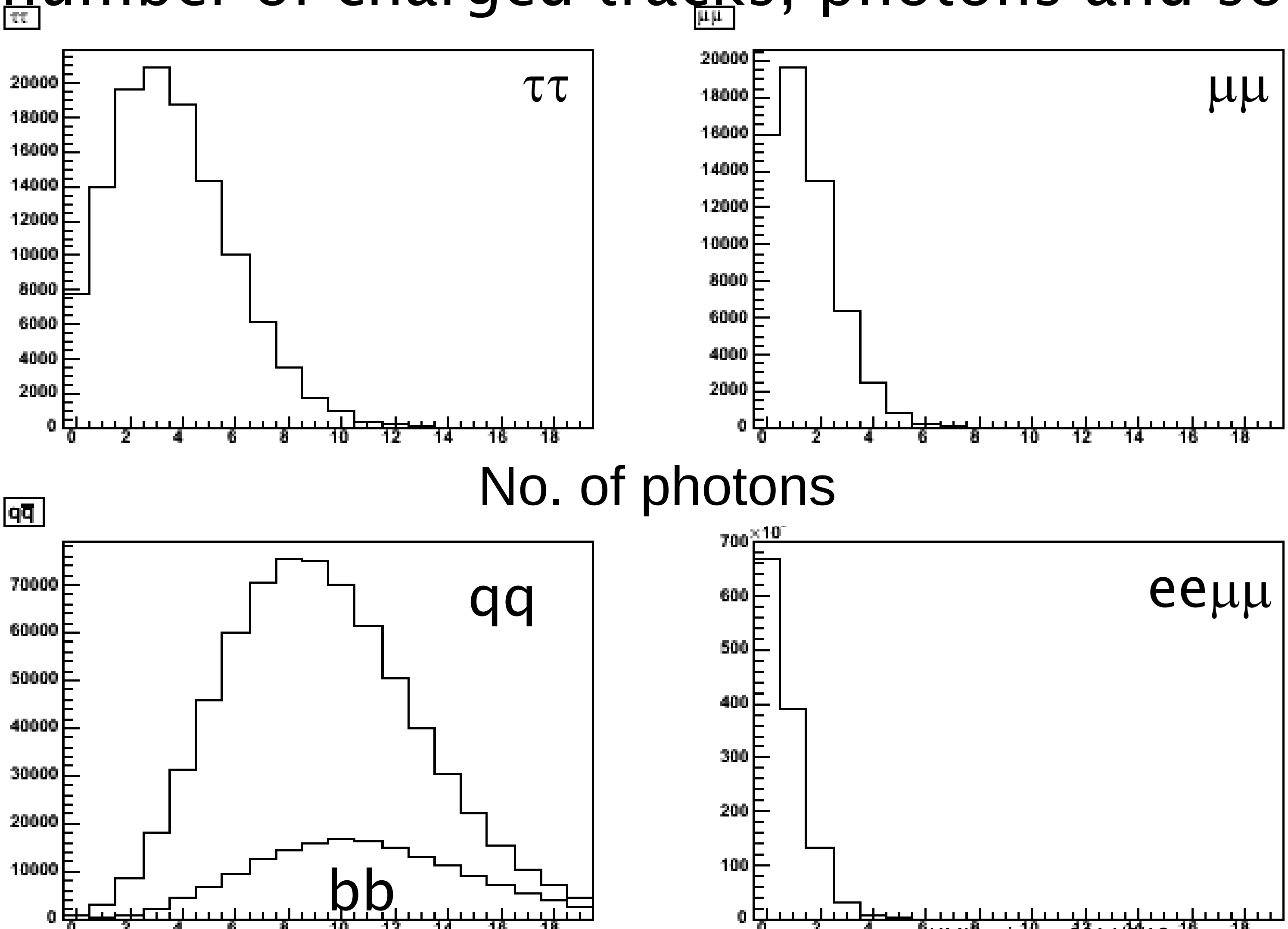
- Use total information in an event, such as the number of charged tracks, photons and so on.



In this case, actually measured no. of tracks. So, mis-recognized (fake) tracks are also Included.

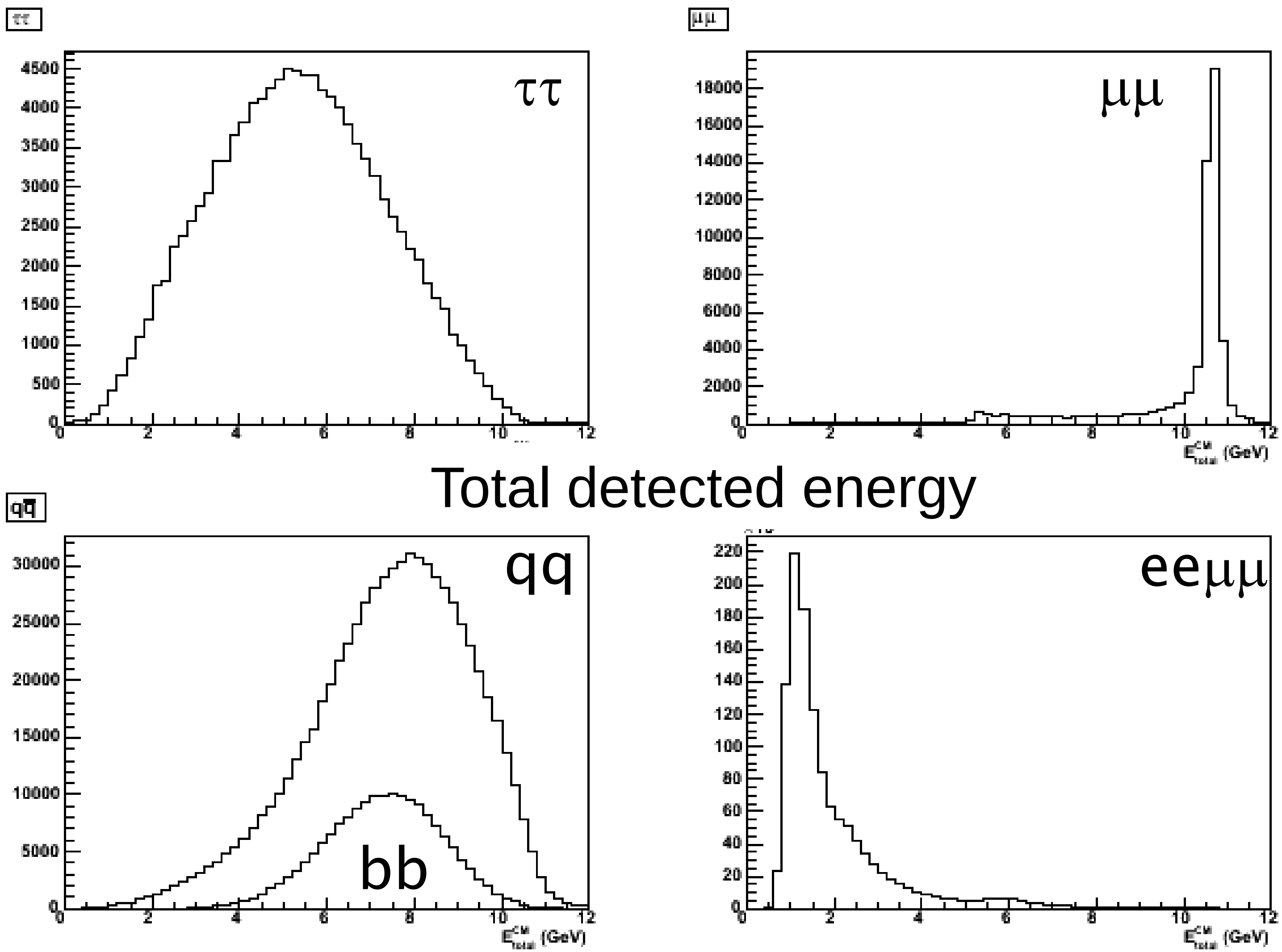
How to recognize ττ events?(4)

- Use total information in an event, such as the number of charged tracks, photons and so on.



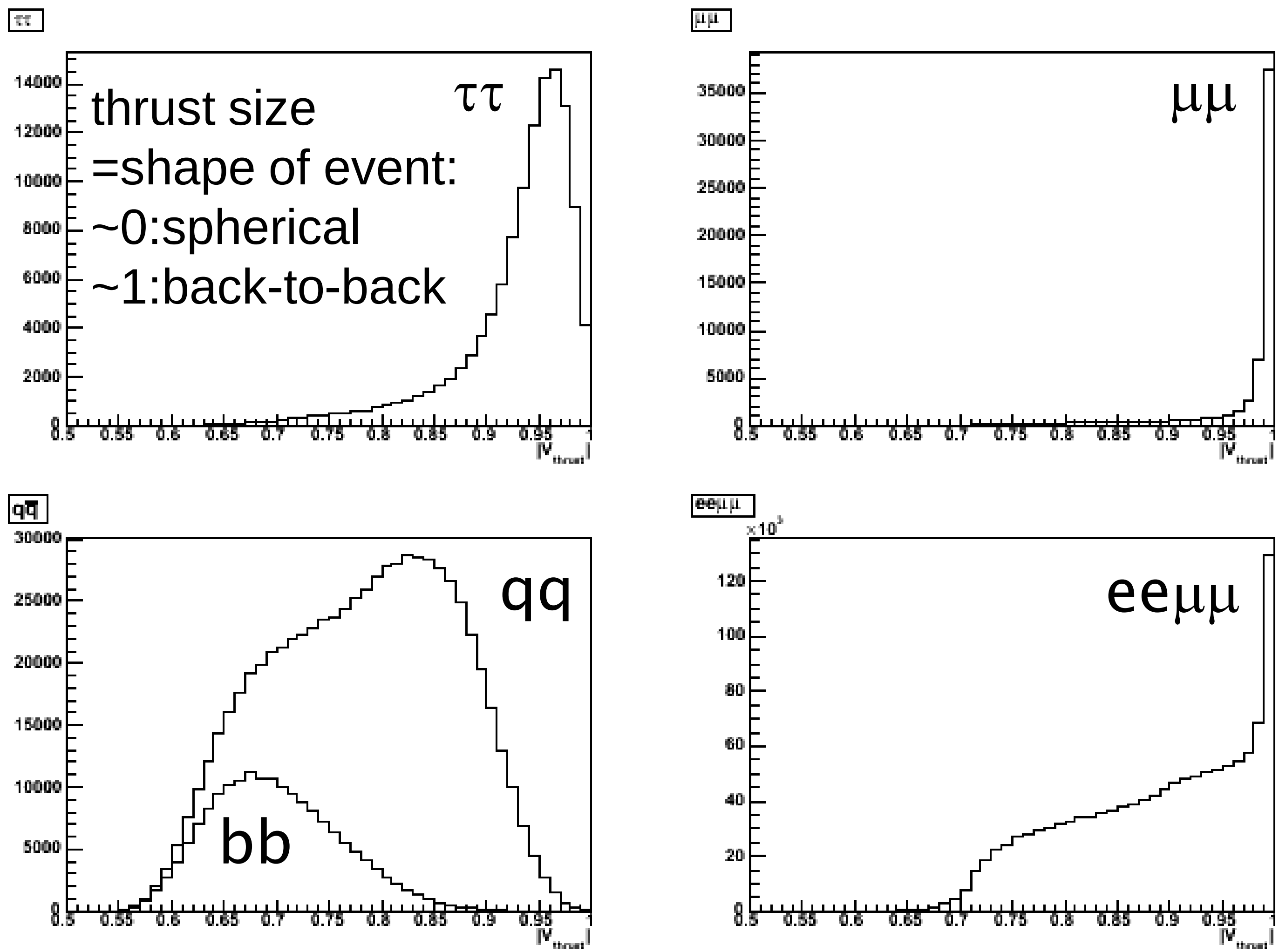
How to recognize ττ events?(5)

- Use total information in an event, such as the number of charged tracks, photons and so on.



How to recognize ττ events?(6)

- Use total information in an event, such as the number of charged tracks, photons and so on.



How to recognize ττ events?(7)

- Summary for rough selection of ττ event
  - No of charged tracks,photons

bhabha,μμ < 2photon < ττ << qq

  - Total energy (anti-correlating to missing)

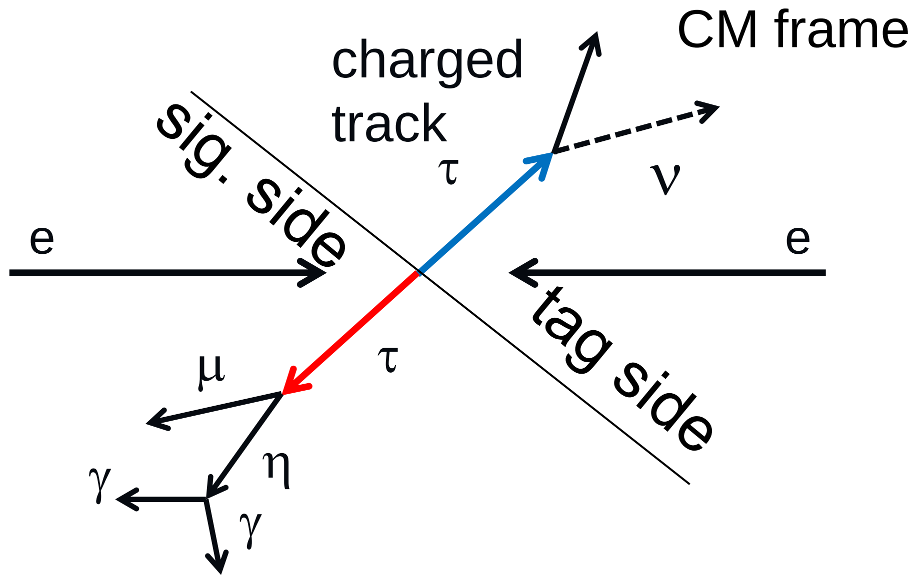
2photon << ττ < qq < bhabha, μμ

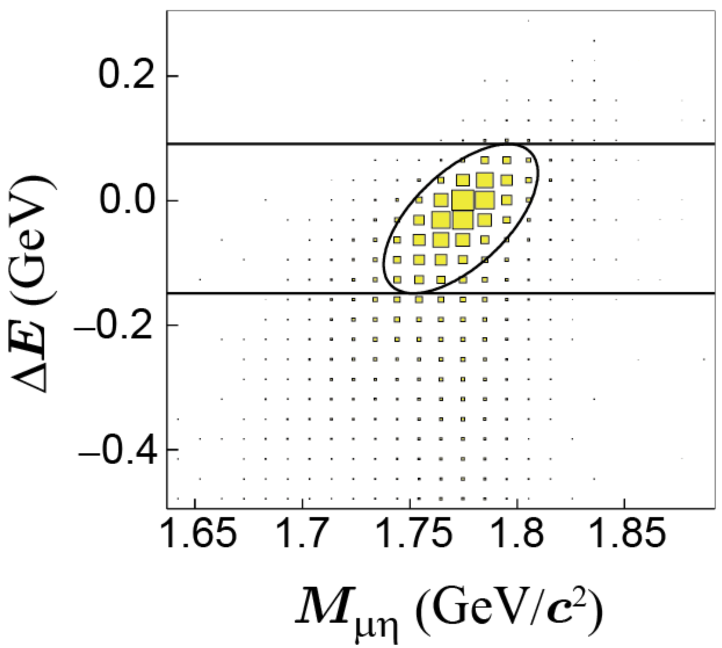
  - size of thrust vector

qq < ττ < bhabha, μμ

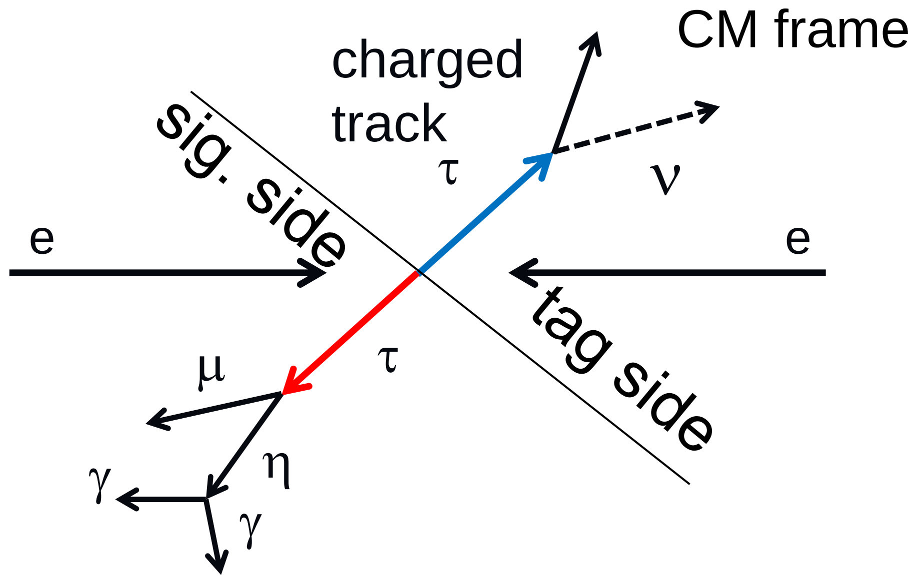
Analysis method

1. Event having low no. of charged tracks and gammas.
(1-1: μγ, μη,… 3-1: μμμ,μππ,…)
2. Large missing momentum
3. PID
4. Mode-specific selection
Ex.) select $m_{\gamma\gamma}$ in the η mass region





Analysis method



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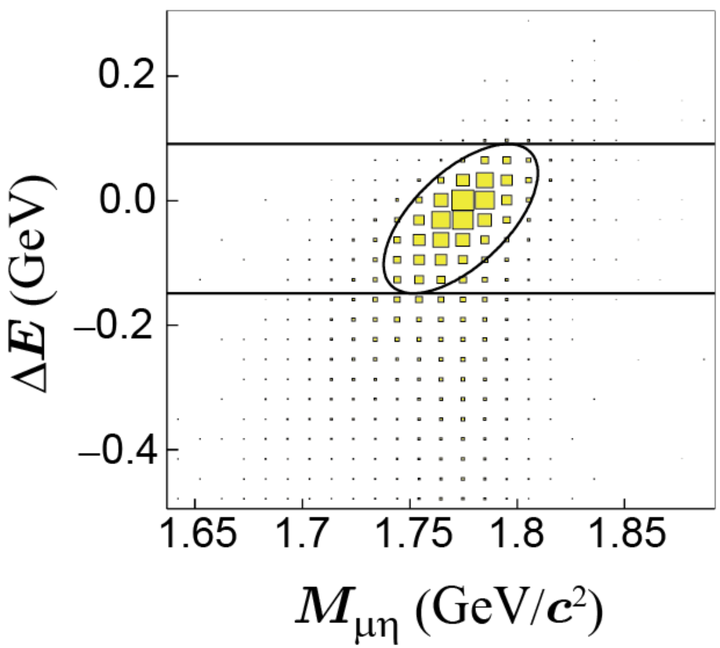
4.Mode-specific selection
5.

$$M_{\mu\eta} = \sqrt{(E_{\mu\eta}^2 - p_{\mu\eta}^2)}$$

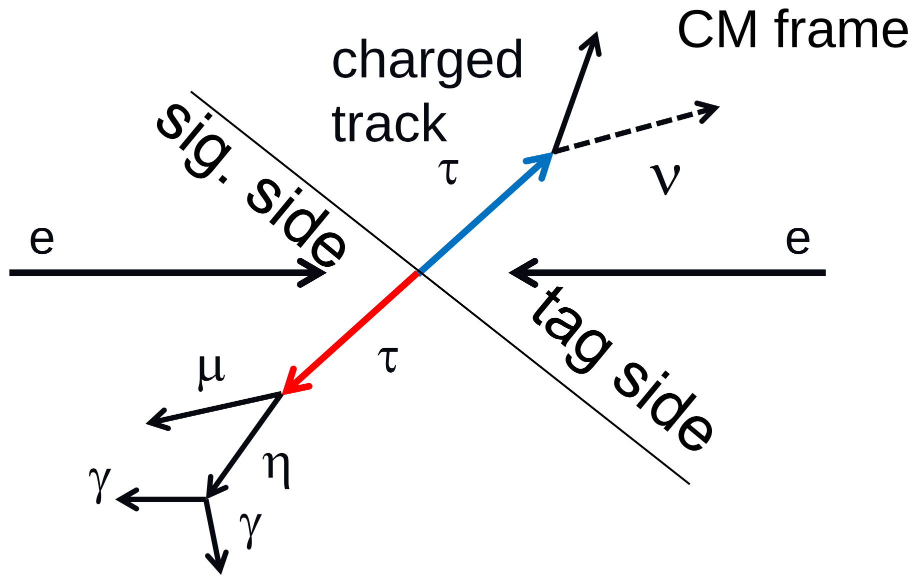
$$\Delta E = E_{\mu\eta}^{CM} - E_{beam}^{CM}$$

Discriminant on the plane



Taking the detector resolution into account, the region to extract the signal in decided.(=signal region)

Analysis method



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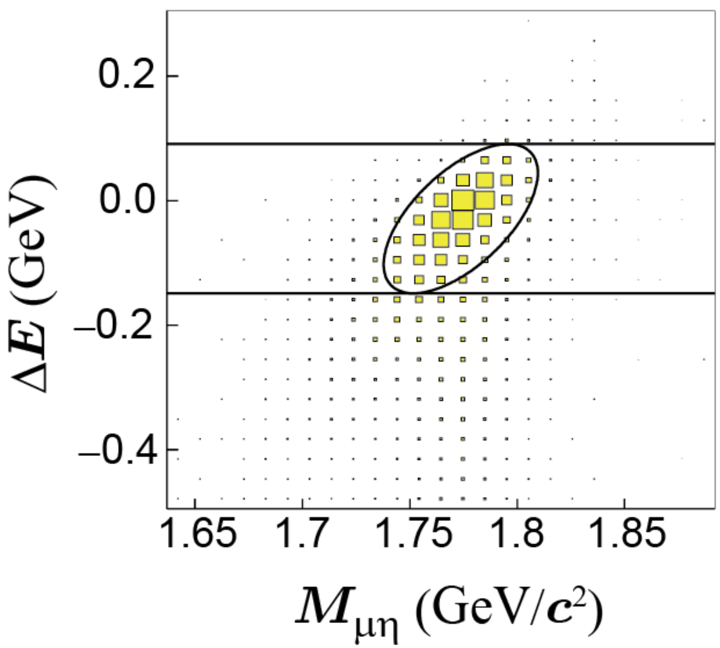
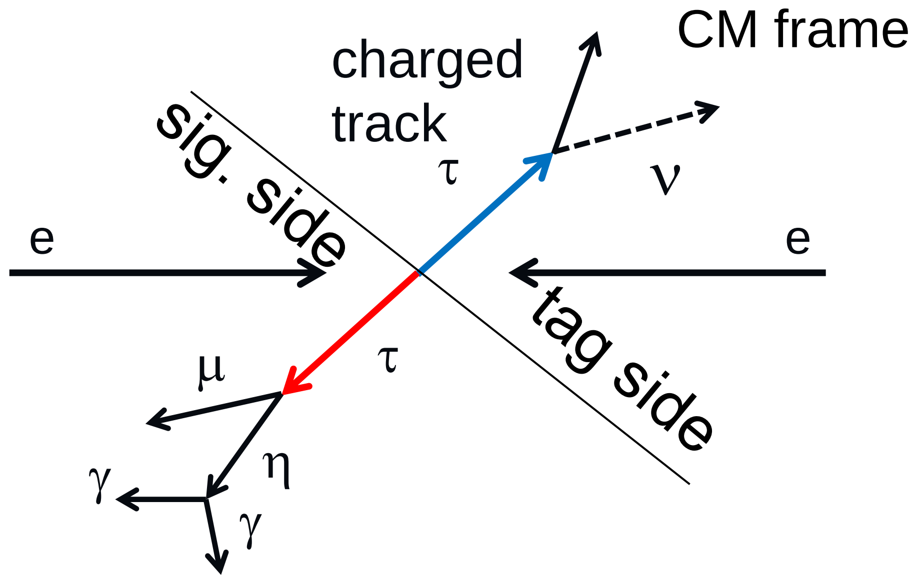


To avoid the any bias to estimate no. of BG in the signal region, we perform blind analysis. Thus, we do not see the events in the signal region until the estimation is fixed.

Analysis method



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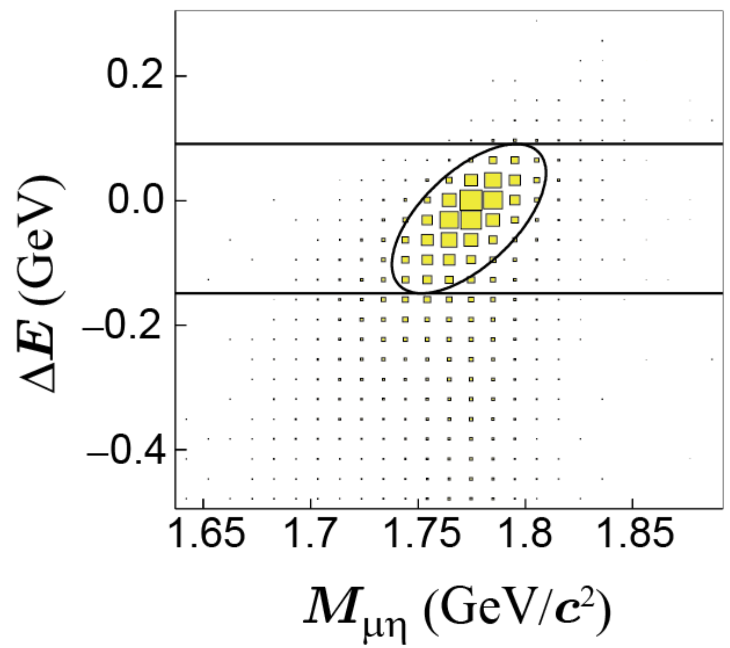
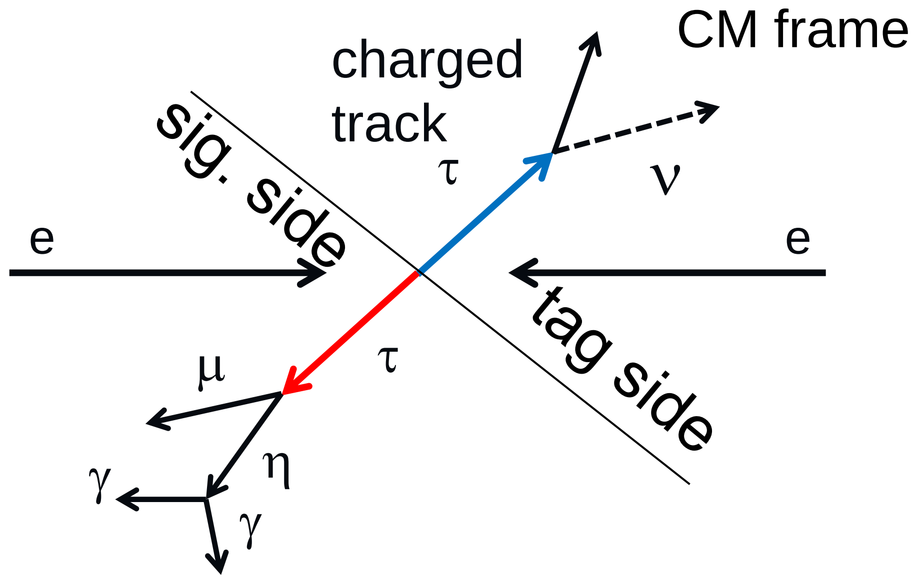
Discriminant on the plane

To avoid the any bias to estimate no. of BG in the signal region, we perform blind analysis. Thus, we do not see the events in the signal region until the estimation is fixed.

6. eval. expeted BG and systematics



Analysis method



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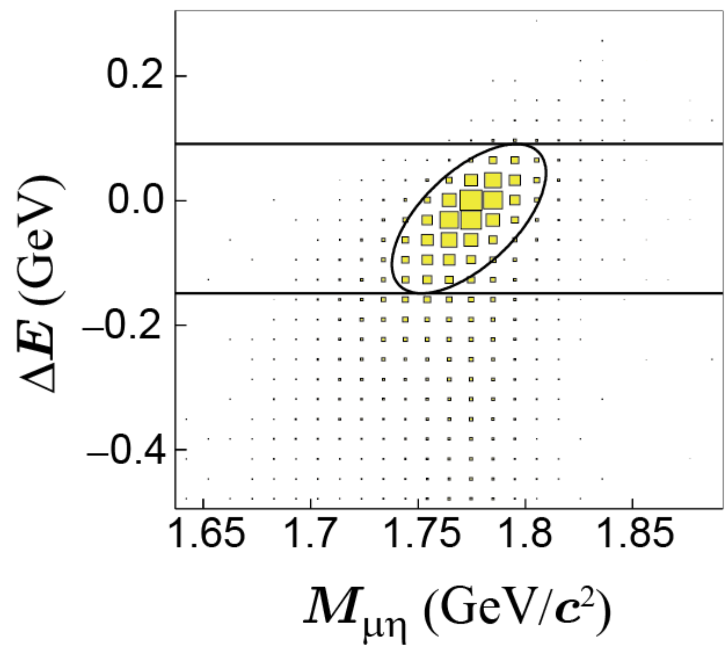
Discriminant on the plane



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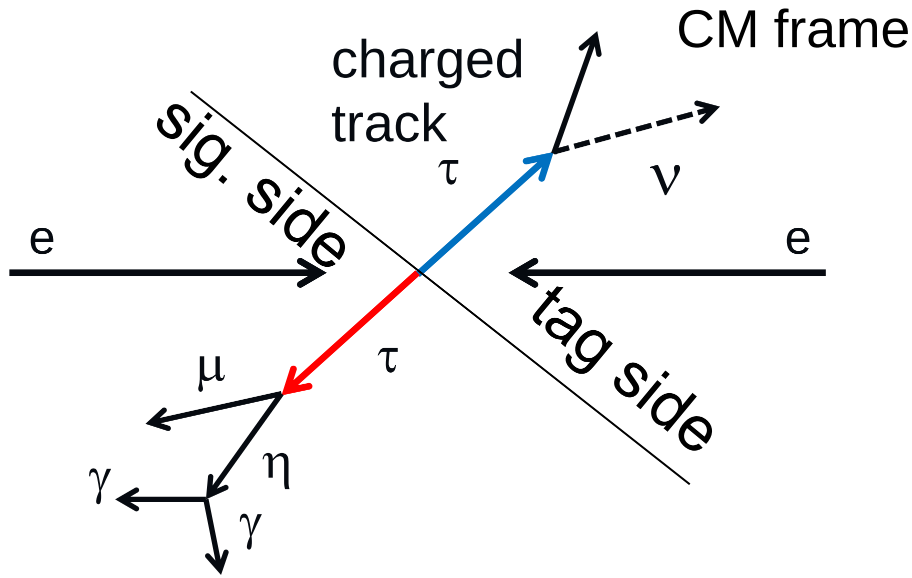
6. eval. expeted BG and systematics
7.Open the blind

Analysis method



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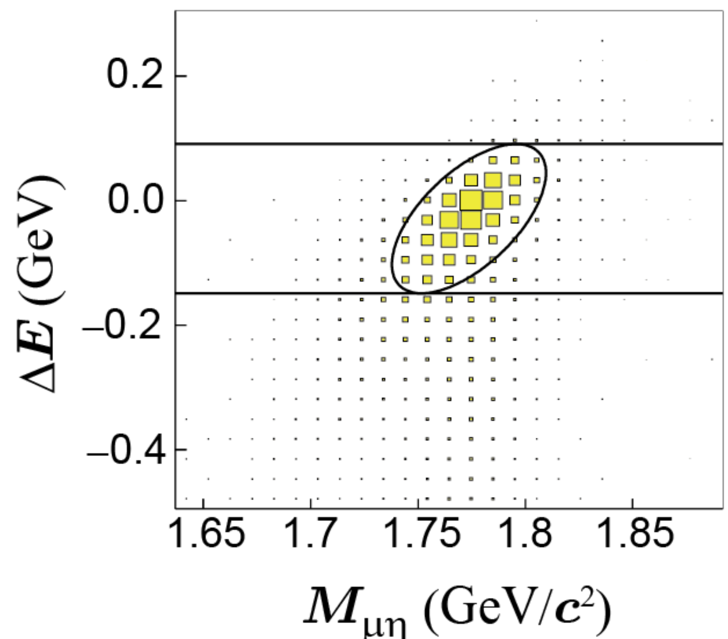
Discriminant on the plane

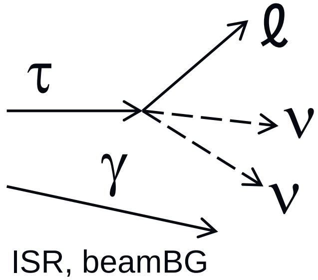


To avoid the any bias to estimate no. of BG in the signal region, we perform blind analysis. Thus, we do not see the events in the signal region until the estimation is fixed.

6. eval. expeted BG and systematics
7.Open the blind
8.Evaluate the no. of signal or UL on the no. of signal
（Freaquentist: counting or fit using sig/BG dist.）

Main Background

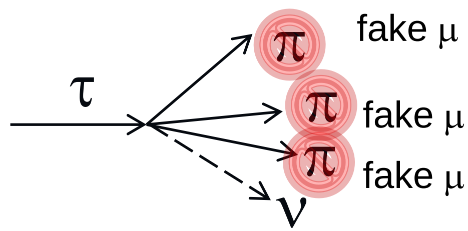
$\tau^- \to \ell^- \gamma,\ \ell^- \eta$



Since actual μ and γ are captured, only kinematics can reject these BGs.

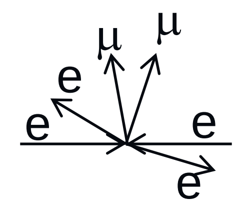
Use missing momentum

$\tau^- \to \mu^- \mu^+ \mu^-$



Probability of 3 time mis-PID is very low: ~O(10^{-4}). In addition, $M_{\mu\mu\mu}$ can hardly reach m_τ.

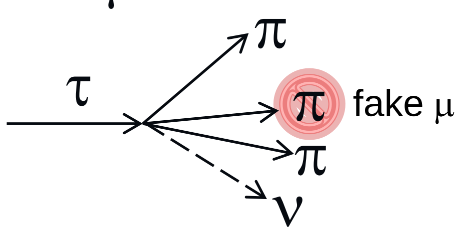
$\tau^- \to e^- \mu^+ \mu^-$



2 photon process

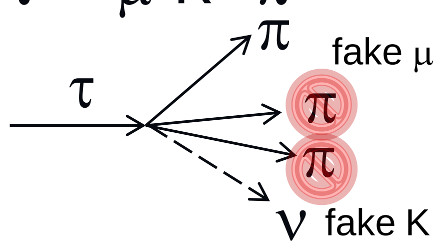
Since actual 2μ and e are captured, no more electron is required.

$\tau^- \to \mu^\mp \pi^\pm \pi^-$



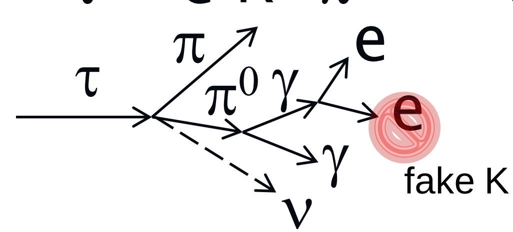
Due to the existance of ν, $M_{\mu\pi\pi}$ can hardly reach m_τ.

$\tau^- \to \mu^\mp K^\pm \pi^-$



Since Kaon is assigne to π, $M_{\mu K\pi}$ can reach m_τ due to the heaviear mass assignment.

$\tau^- \to e^+ K^\pm \pi^-$



$\pi 0$ daughter γ induces γ-conversion and then e is misidentifed as K.
The K-mis-mass assignment makes $M_{eK\pi}$ able to reach $m\tau$.
Check MeK with electron mass assignment.

Result for ℓγ

PLB666,16(2008)

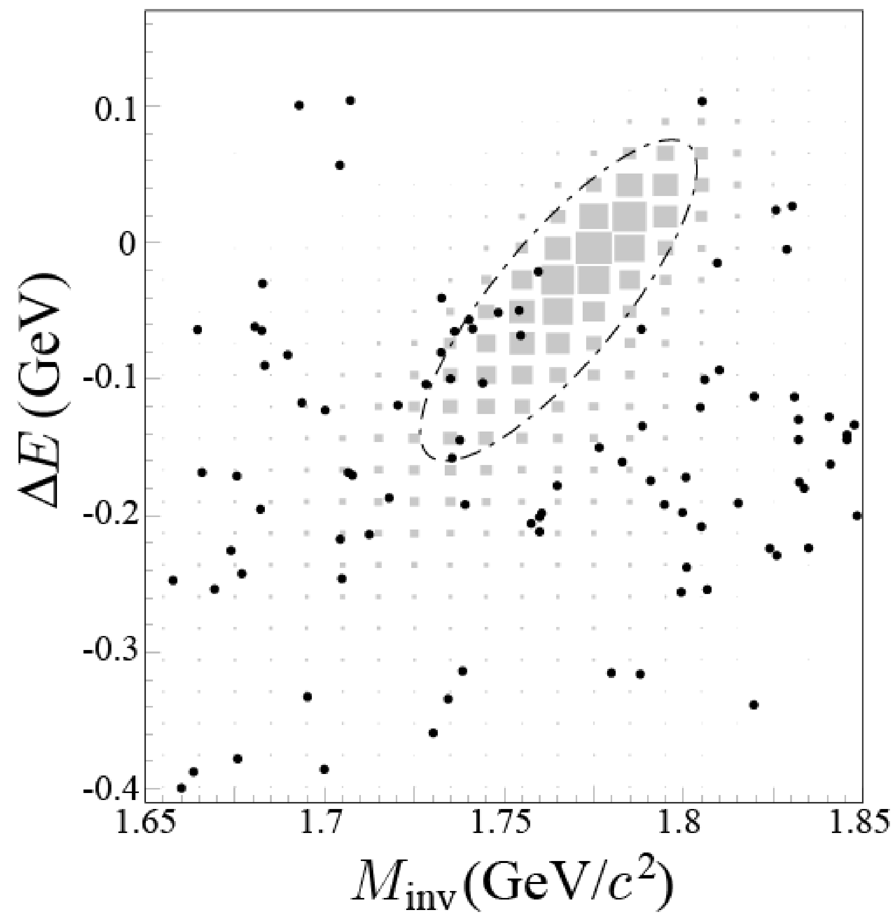
- Data:545fb^{-1}
- τ→μγ

Detection eff.:6．1%

Observed events:10

Unbinned maximum likelihood

- Expected UL: 7.8x10^{-8} @90%CL
- Obtained UL:4.5x10^{-8} @90%CL

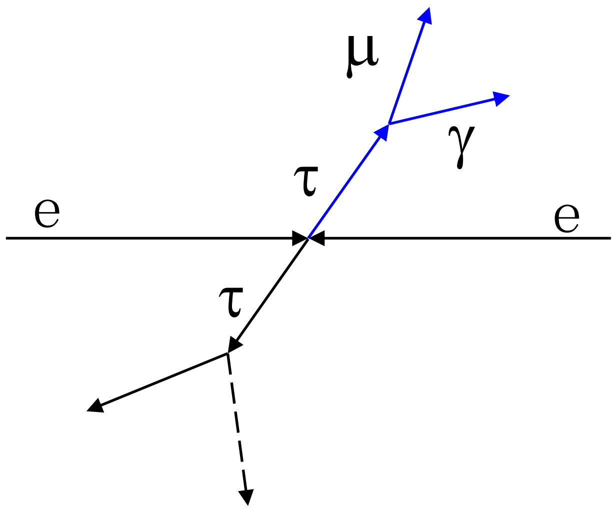


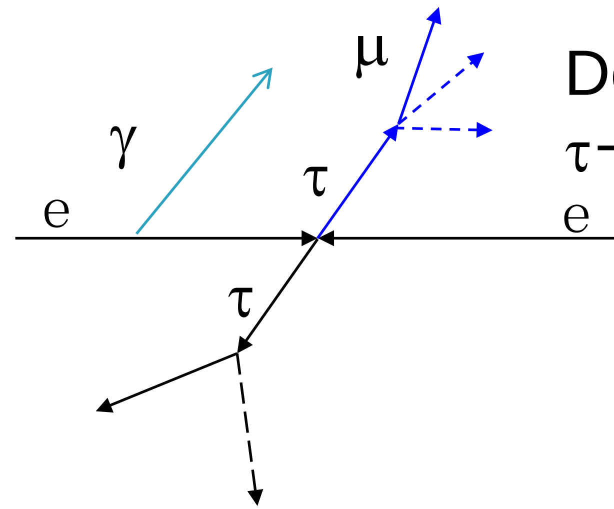
- τ→eγ

B<1.2x10^{-7}@90%CL

(Expected: 9x10^{-8})

Why $\tau \to \mu\gamma$ is so difficult…(1)



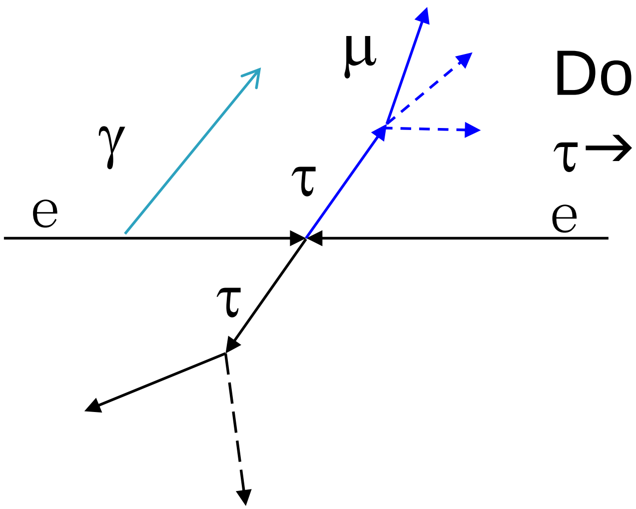


Dominant BG
$\tau \to \mu\nu\nu$+ISR γ

Available information:
Captured μ, γ, tag as well as beam 4-momenta
$M_{\mu\gamma}$, $E_{\mu\gamma}$ should be used
For the final signal extraction

In the case where the combination of μ and γ happens to be τ-like for reconstructed mass and energy, we have no way to reject such events!!

Why $\tau \rightarrow \mu\gamma$ is so difficult…(2)

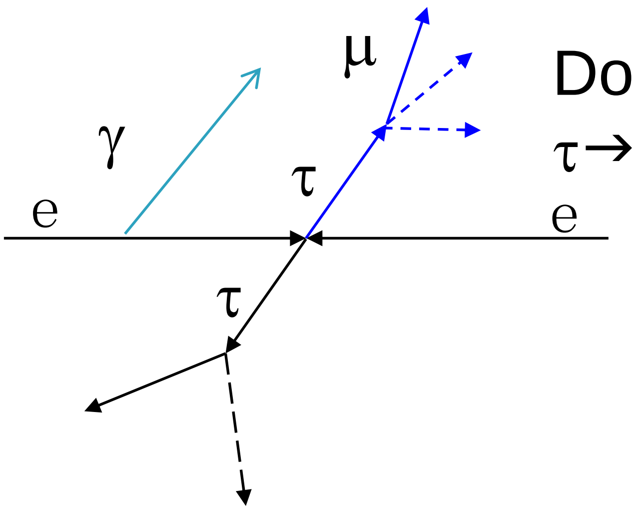


Dominant BG
$\tau \rightarrow \mu\nu\nu$+ISR γ

In the case where the combination of μ and γ happens to be τ-like for reconstructed mass and energy, we have no way to reject such events!!

- Since we can capture the final state particles, we have no way to know when γ appears.
- Since a photon does not make any track, we have no way to know where γ comes from.
- Almost rejected: This is also a cause of this difficulty;

Why $\tau \rightarrow \mu\gamma$ is so difficult…(3)



Dominant BG
$\tau \rightarrow \mu\nu\nu$+ISR γ

In the case where the combination of μ and γ happens to be τ-like for reconstructed mass and energy, we have no way to reject such events!!

- Almost rejected: This is also a cause of this difficulty;
O(10^9) tau events→
O(10^8) $\tau \rightarrow \mu\nu\nu$ events→
a half of them have ISR→
10 events observed…
We have already had $10^{6\sim7}$ rejection power!
But, we need one order more rejection power!!
The only way is kinematical understanding for the ISR event? → no answer now…

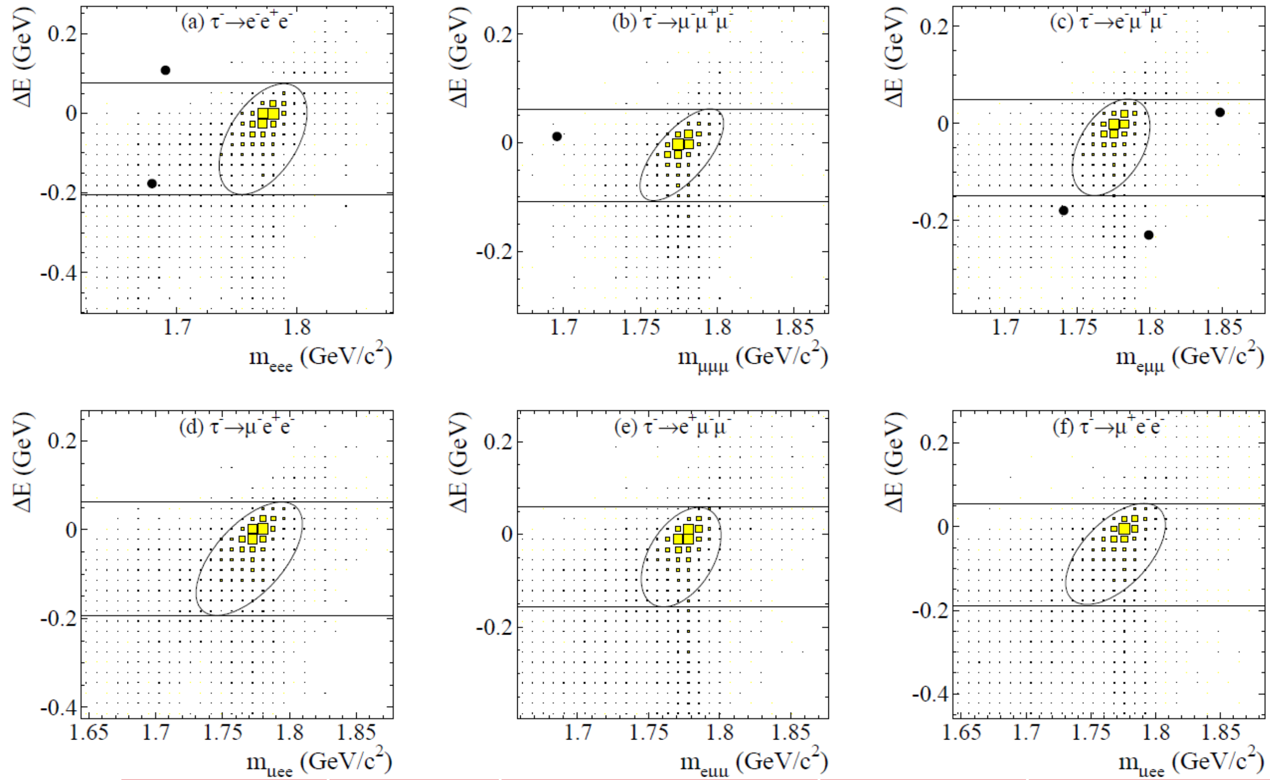
Result for $\ell\ell\ell$

Phys.Lett.B 687,139 (2010)

- Data: 782fb^{-1}
- No events are found.

UL is evaluated by counting method

- Br<(1.5–2.7)x10^{-8} at 90% CL.



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

In the case of low BG, counting method is taken.

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

- used 8×10^{10} τs, in $1fb^{-1}$ 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.

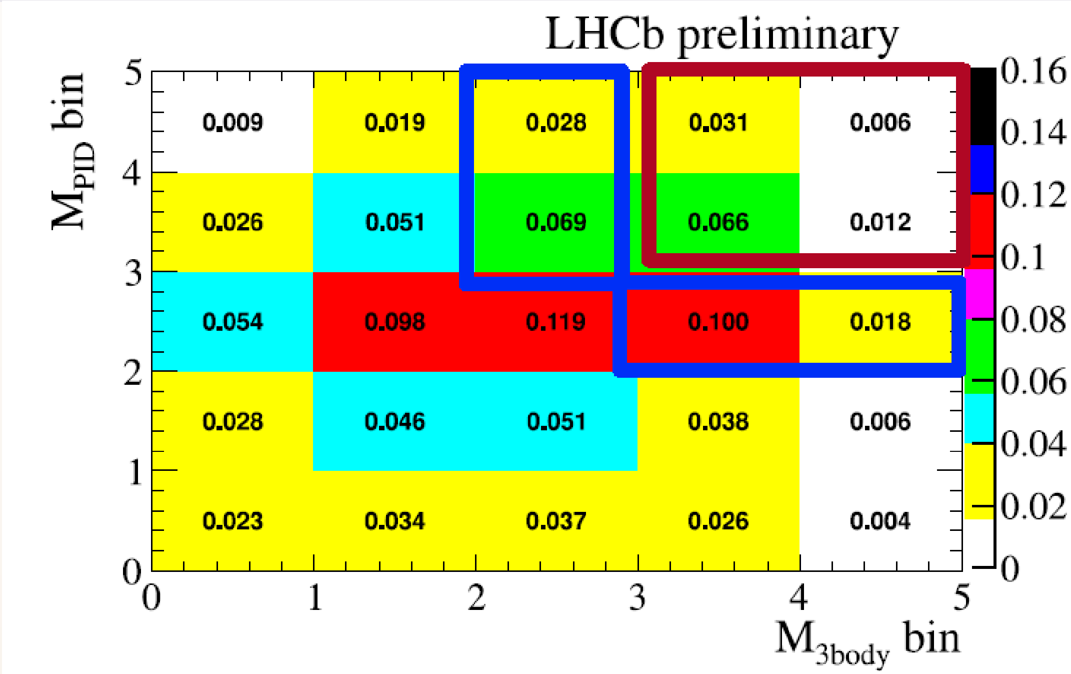
signal likelihoods

1 fb^{-1}

LHCb-CONF-2012-015

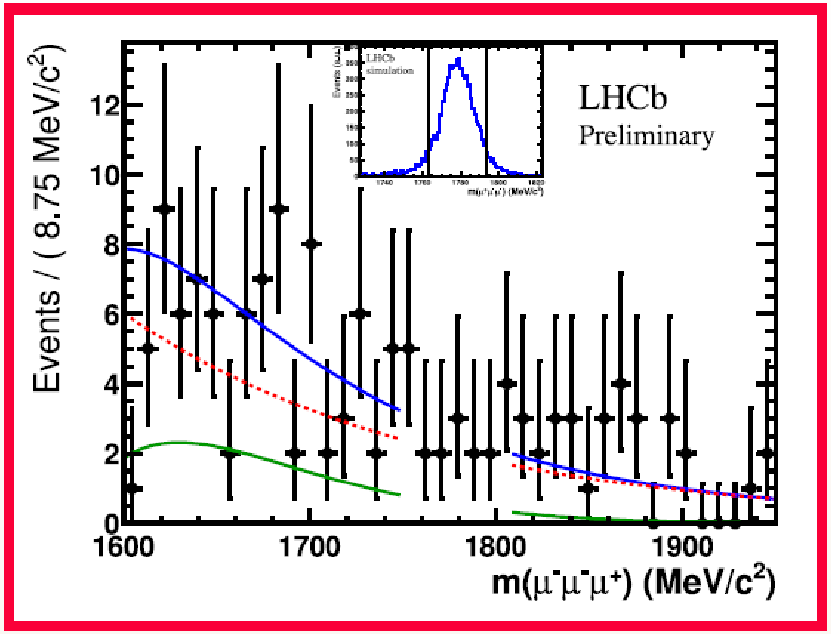
combined signal distribution

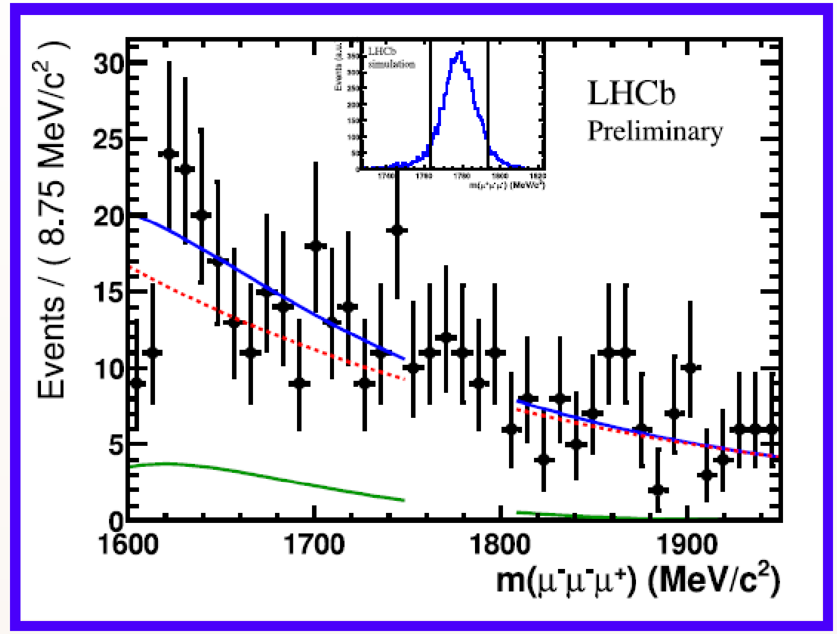
- events distributed over 25 likelihood bins
- background estimate from mass sidebands



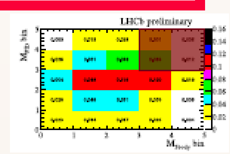
- 11 % signal efficiency
- 21 % signal efficiency
- for illustration: high likelihood range shown

observed events

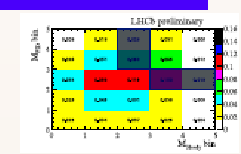




11 % of the signal
0.03 % of the background



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

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

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extracted limit

result (preliminary)

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

1 fb^{-1}

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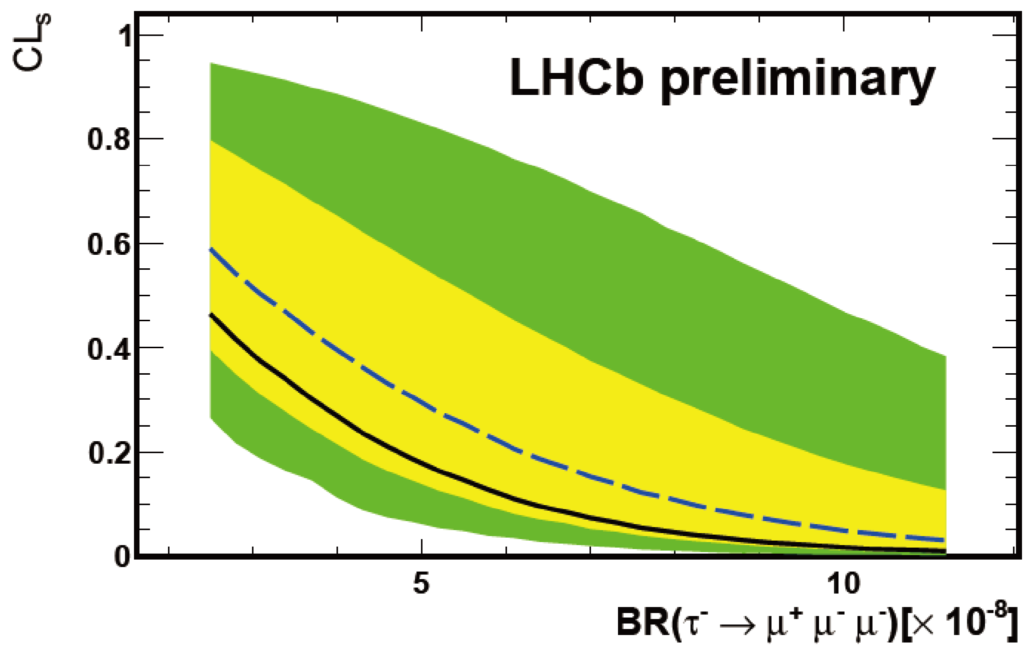


After publication (PLB 724,36(2913)), UL is corrected to 8.0×10^{-8} at 90%CL

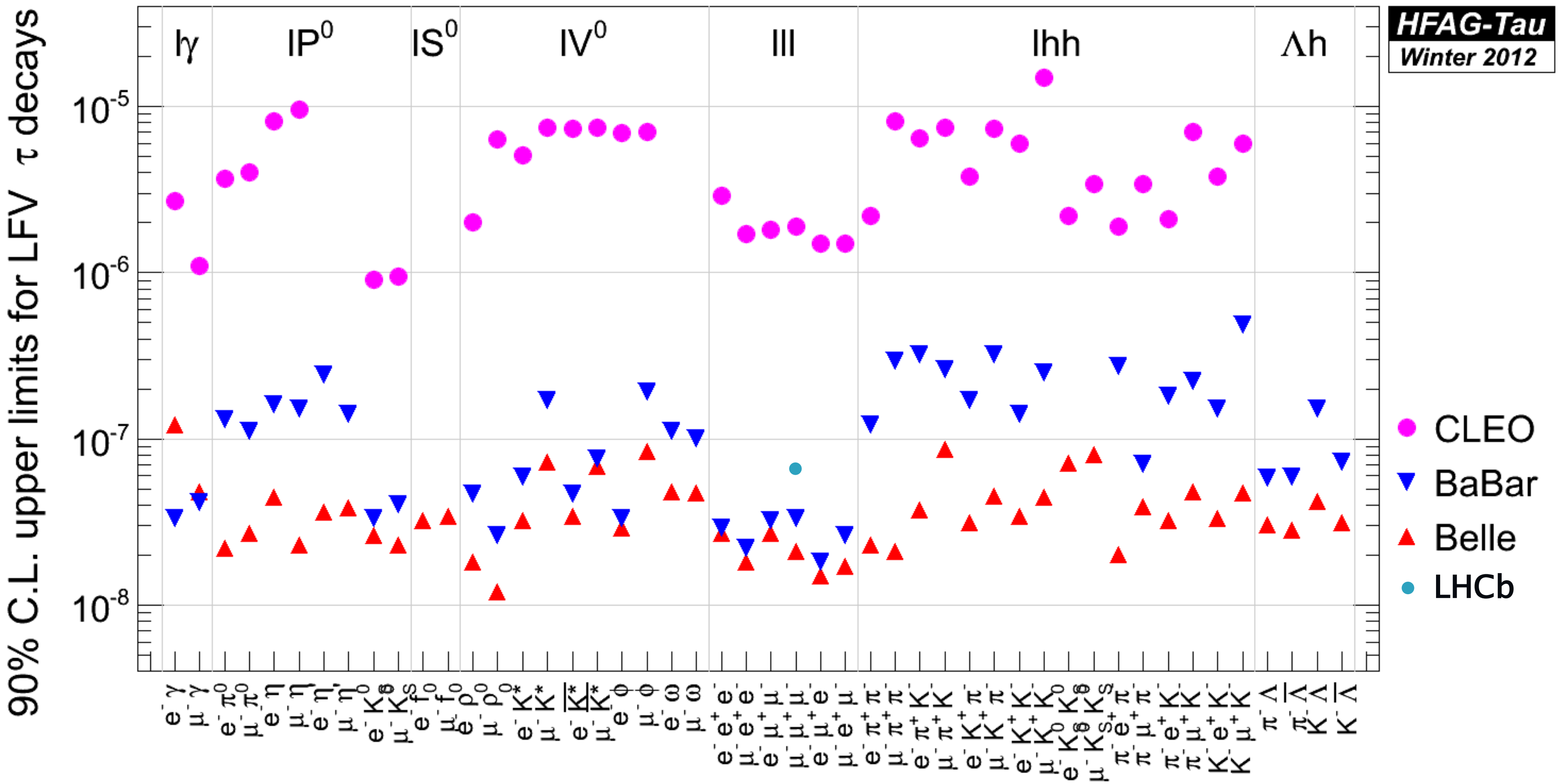
Belle $2.1x10^{-8}$ @ 90 % CL
Phys. Lett. B **687**, 139 (2010)

BaBar $3.3x10^{-8}$ @ 90 % CL
Phys. Rev. D **81**, 111101(R) (2010)

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

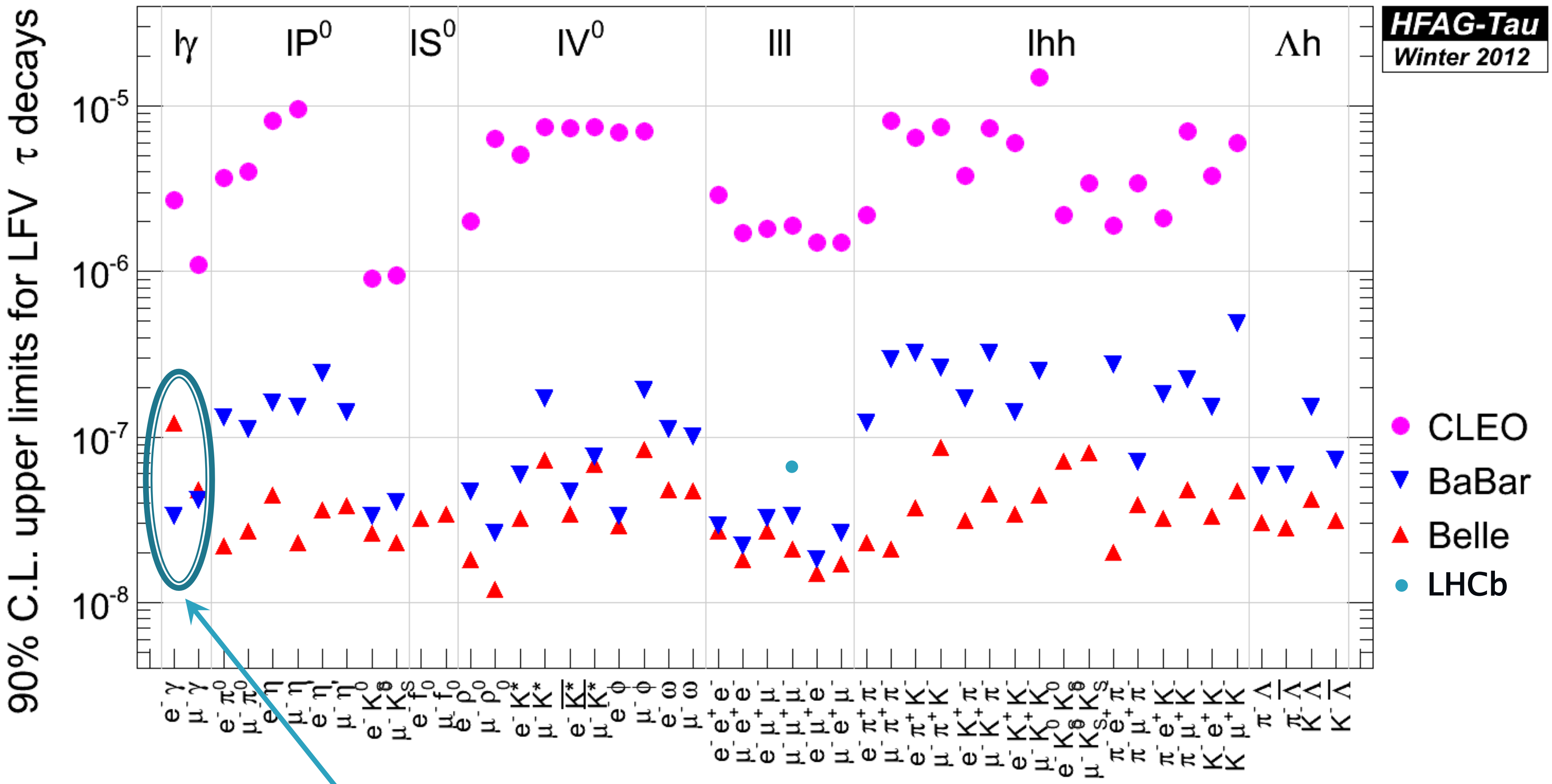
- Very near future: $1fb^{-1} \to 3fb^{-1}$
  - 8TeV $2fb^{-1}$ data sample will be added since that has already obtained.
  - Since $\sigma(cc)$ at LHC is almost proportional to $\sqrt{s}$, no. of τ approximately become 3.3 times larger.
  - Since BG is large, around $\sqrt{3.3}$ times more sensitivity will be obtained, i.e. $B<4\times10^{-8}$ @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
  - Totally, 15 times more sensitive $\to B<6\times10^{-9}$
- $\tau\to\mu\phi(\to KK)$, $\tau\to\mu K^*(\to K\pi)$ searches are also possible. ($\tau\to\mu\mu p$ has been done in the current one)

Summary of UL for BF on τLFV decays



Almost all modes reach O(10^{-8}) sensitivity for BF
100x more sensitive than CLEO）

Summary of UL for BF on τLFV decays



My final homework is to obtain the result for **τ→eγ/μγ** with Belle's full data sample…

Why your result is worse than BaBar's?

- Because the evaluation of UL is some kind of gamble!
  - Expected UL is estimated by the sensitivity of the analysis, in other words, goodness of the analysis, including the amount of the data sample, detector performance and the choice of the selection criteria.
    - This should be, perhaps, in the similar experiment, with similar size of the data sample, similar.
  - However, observed UL is decided not only by the sensitivity but also by the observed events!
    - This is the experimental result!

Expected BG and evaluated upper limt

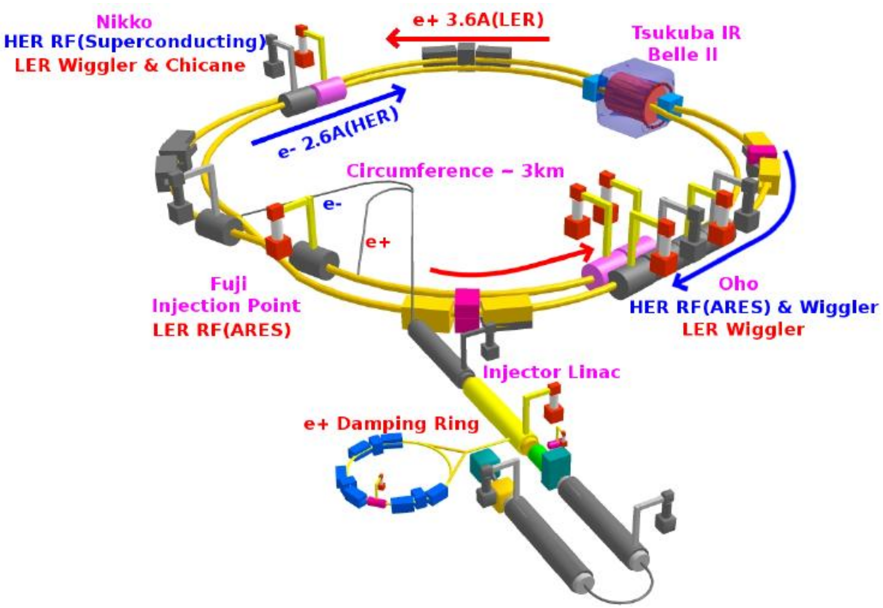
- Poisson probability:
  - When expected number of BG is 5.0,
    - The possibility of the 4-event observation is 18%.
    - The possibility of the 5-event observation is 18%.
    - The possibility of the 6-event observation is 15%.
- Feldman & Cousin method:
  - When expected number of BG is 5.0,
  - 90% CL UL for no.of signal events is..
    - 5.4 with 4-event observation
    - 6.7 with 5-event observation
    - 8.1 with 6-event observation

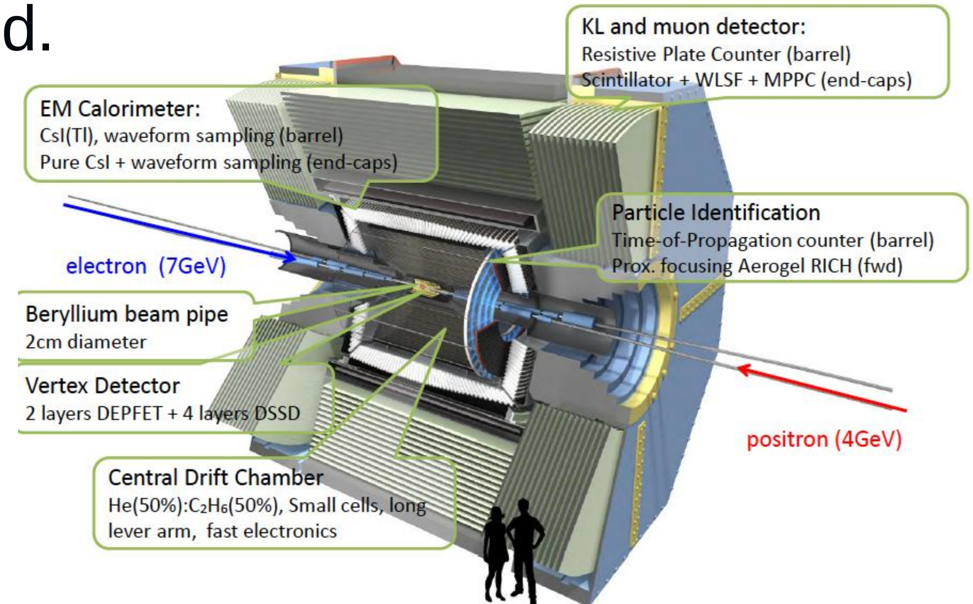
1.5x worse

When expected no. is around 1, the tendency become extreme:
1.8 with 0-ev obs., 3.4 with 1-ev obs., 4.9 with 2-ev obs.

SuperKEKB and BelleII

Finally, $50ab^{-1}$ will be collected.





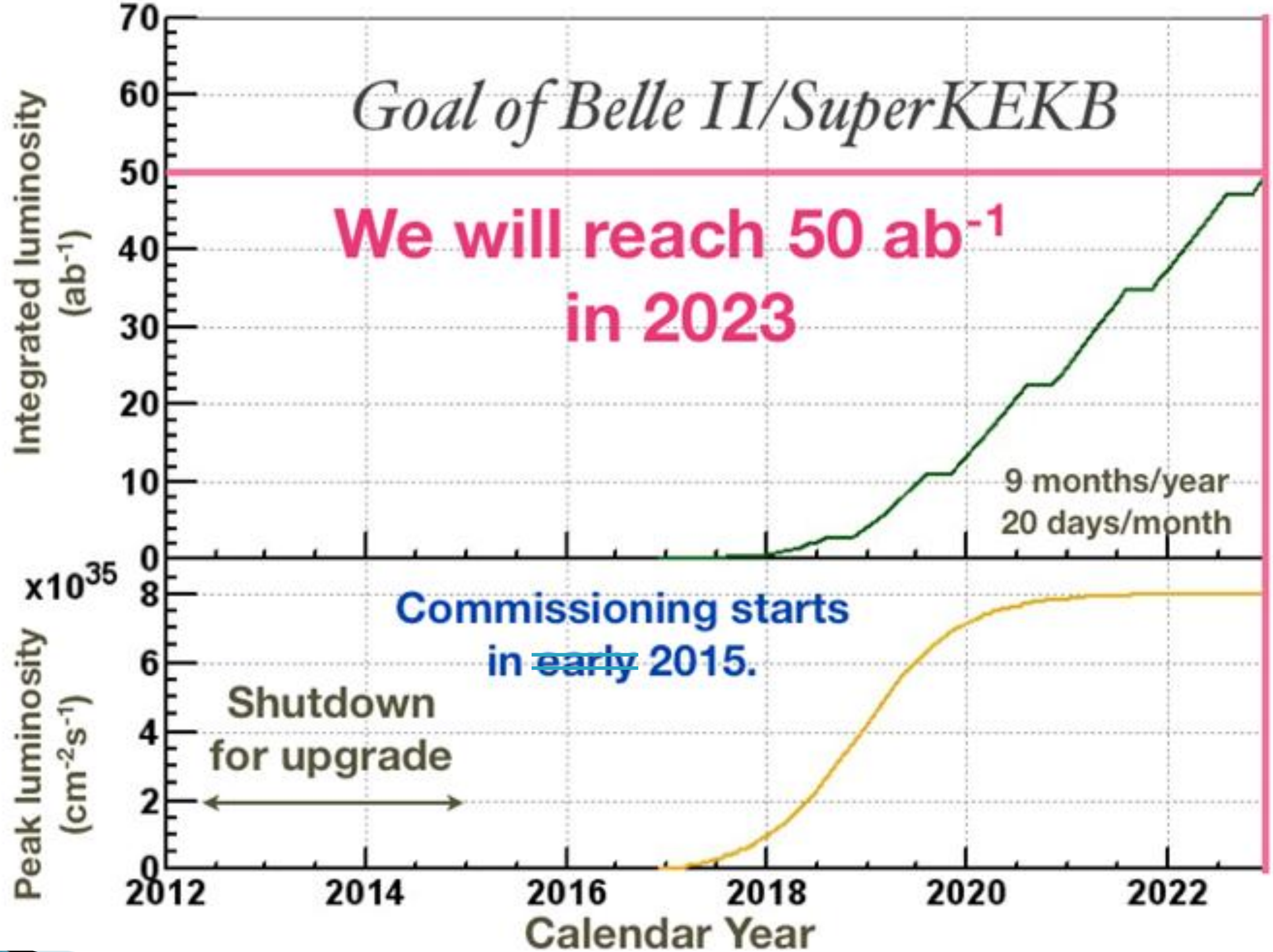
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

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)

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

Detector modification is not so effective for τ LFV searches. (of course, under the high rate/background, stable data-taking is important.)

Plan for data-taking



τLFV @ Belle II

- Sensitivity will be…

BG free: $\propto 1/(\text{no.of } \tau)$

BG non-free: $\propto 1/\sqrt{(\text{no.of } \tau)}$

- BG amount for each mode

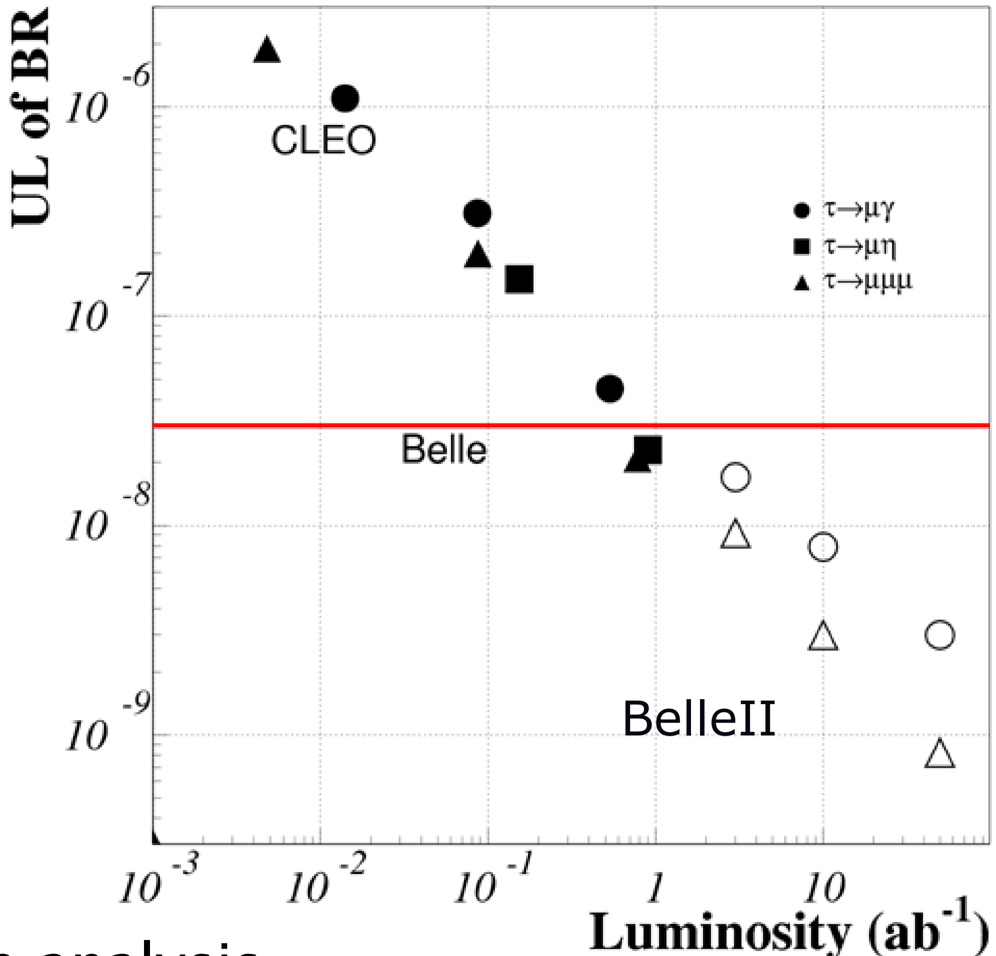
$\tau\to\mu\gamma$: BG non-free (rich)

$\tau\to\mu\eta$: not-so-many BG

$\tau\to\mu\mu\mu$: 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

- A B-factory is also a τ-factory!
  - Same order number of τ as that of B is accumulated.

  →Belle has O(10^9) τ sample: the world-largest one
  - Belle leads various τ studies: New physics searches and SM precise measurements
- LFV is a signature for the New Physics
- 48 τLFV modes have been searched for
  - 100 more sensitive results than those at CLEO

  →O(10^{-8}) sensitivity
- At SuperKEKB/Belle II experiment, one or two order more sensitivity is expected.

→O($10^{-9\sim-10}$) sensitivity