Tau Physics at Belle II

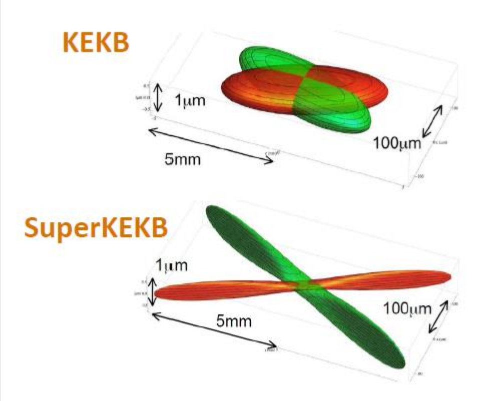
K.Hayasaka (Niigata U.)
for Belle II collaboration

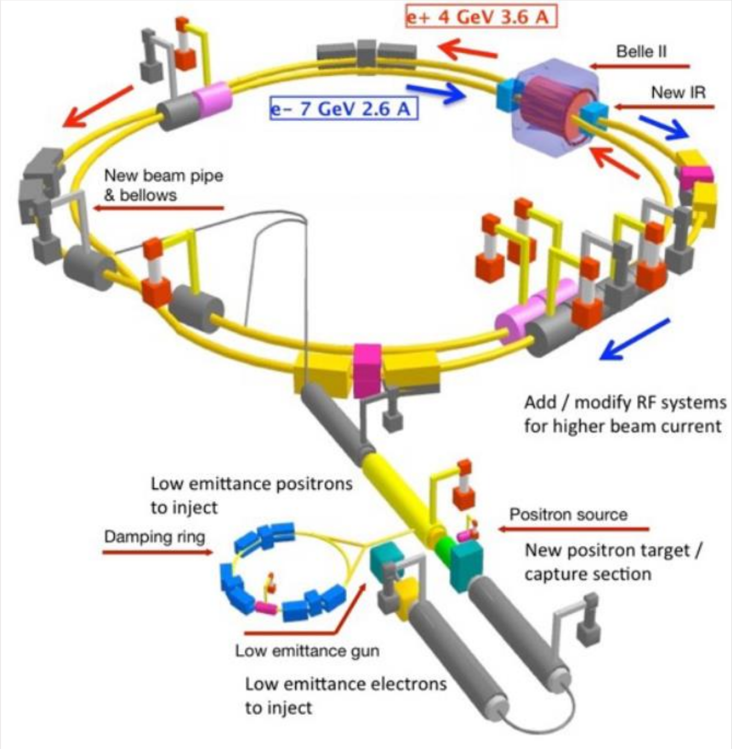
Contents

- SuperKEKB/Belle II
- τ lepton
- τ mass measurement with early Belle II data
- τ LFV search
- τ CPV search
- Summary

From KEKB to SuperKEKB

- To obtain 50x larger data sample than that at Belle, designed instant luminosity is 40x higher.
  - Beam current: 2x
  - Beam size: 1/20x

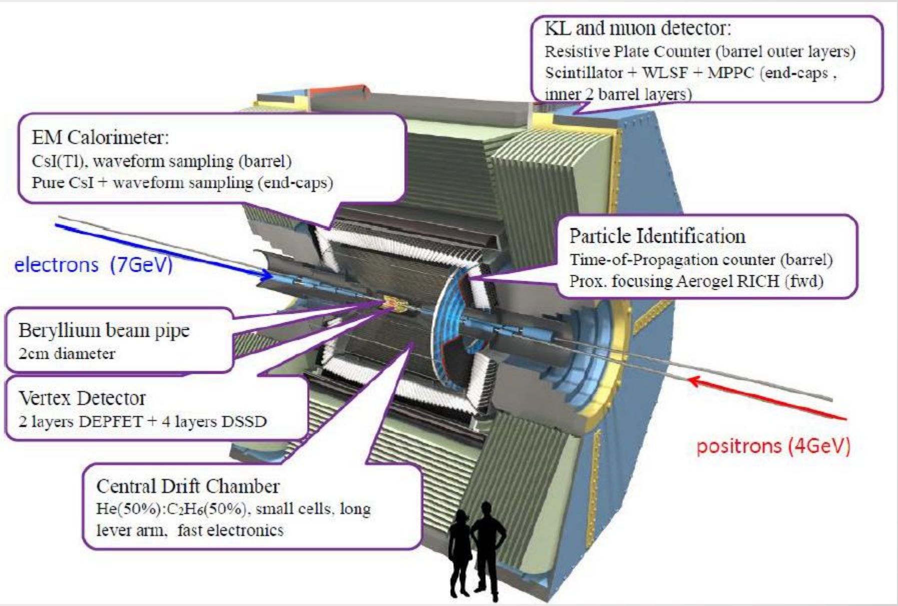


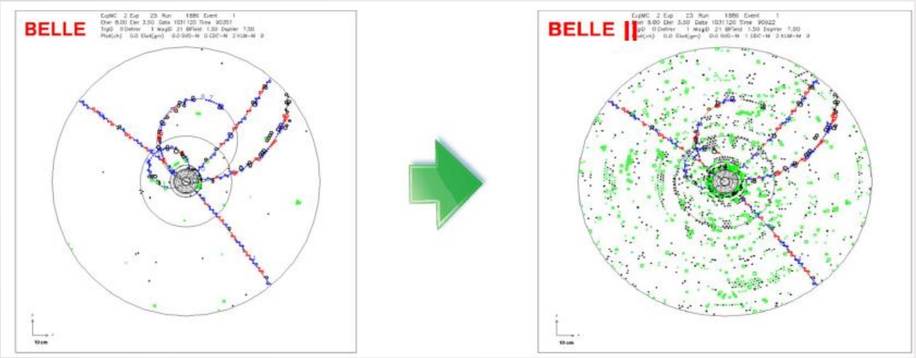


Beam asymmetry：8GeV/3.5GeV→7GeV/4GeV

Belle II detector upgrade

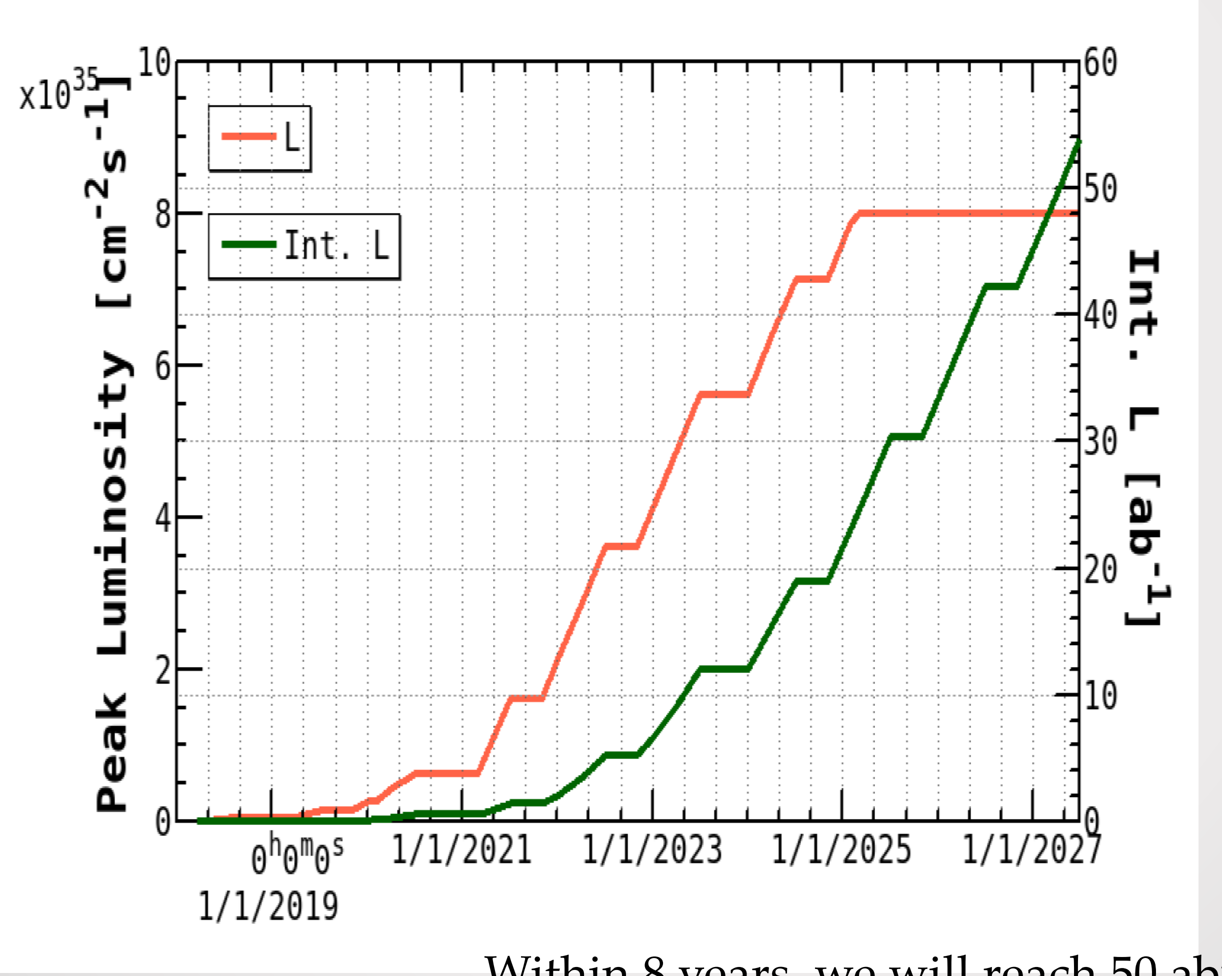
- To catch up the high rate event production
  - High rate read out
  - Short dead time
  - Reduce occupancy
  - High resolution against reduced asymmetry
- PID performance





Just an image for track finding in high background environment

Integrated luminosity prospect



1 div
= 4 months

Within 8 years, we will reach 50 ab^{-1}.

Introduction to τ lepton

- Third lepton = τριτον

FERMIONS

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

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  1.78 GeV/c^2 (>> m_π)

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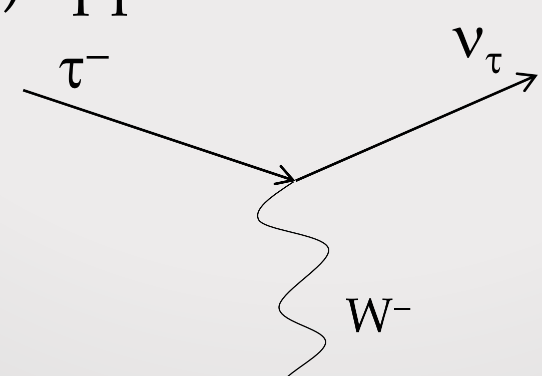
- In SM, it decays via weak interaction = neutrino(s) appears in the final state.



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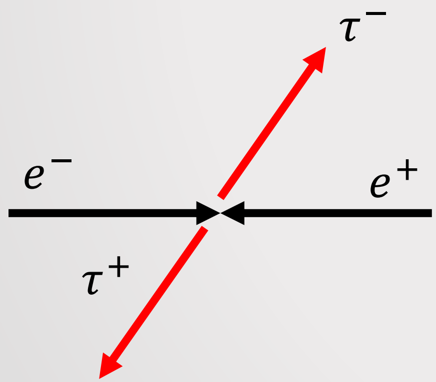
τ production at SuperKEKB

- At Υ(4S), $\sigma(\tau^+\tau^-) = 0.9$ nb while $\sigma(b\bar{b}) = 1.1$ nb.

→B factory is also τ factory: With 50 ab^{-1}, ~5x10^{10} τ-pairs are expected.

Always, τ appears in τ-pair production.



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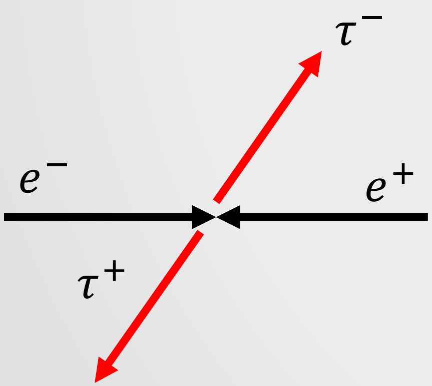

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$M_{\Upsilon(4S)} >> 2 \times M_\tau$
τ has high momentum.

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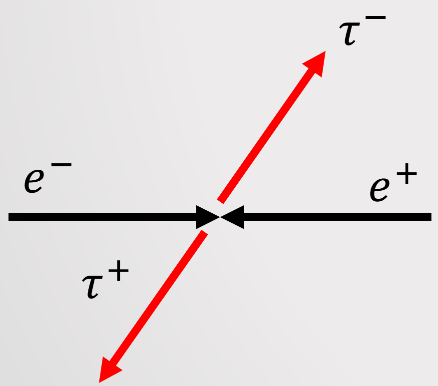

Well separated:
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Low multiplicity event
2-prong: 73%
4-prong: 26%
>6-prong:1%

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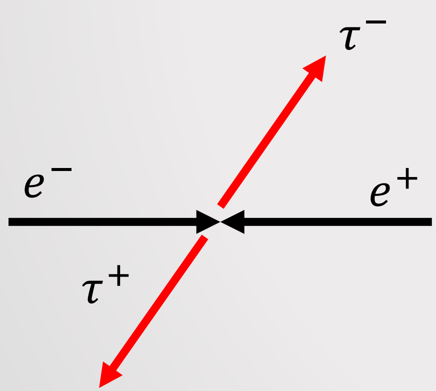

τ analysis in τ-pair events is expected to be clean because of low multiplicity and topologically distinct backgrounds.

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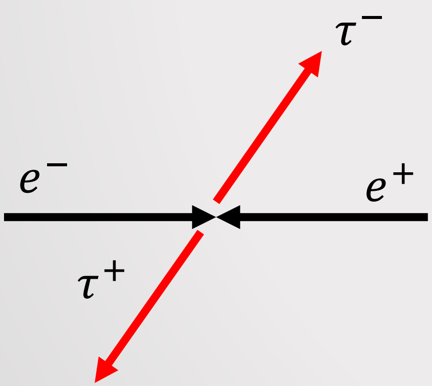

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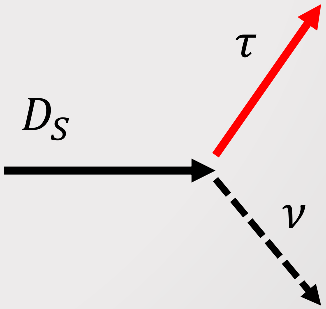
At LHCb, τ appears as a decay-product in D_S decays, mainly. (BF($D_S \to \tau\nu$)=5.5%)

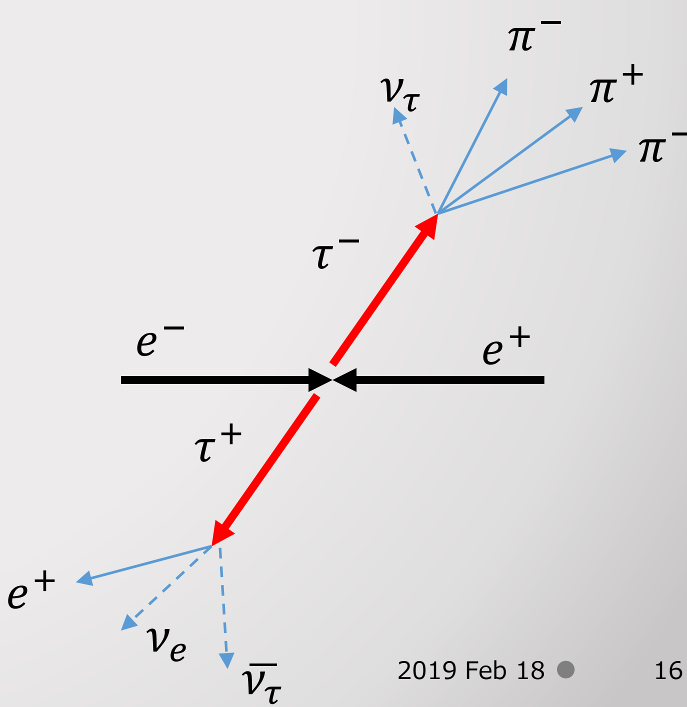


3fb^{-1}:~10^{11} τ's

τ analysis with the early Belle II data

τ→3πν in Belle II early data

- $(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau)(\tau^+ \to one\ track + \overline{\nu_\tau})$(and its charge conjugate): one of typical τ-pair events.



$\tau \rightarrow 3\pi\nu$ in Belle II early data

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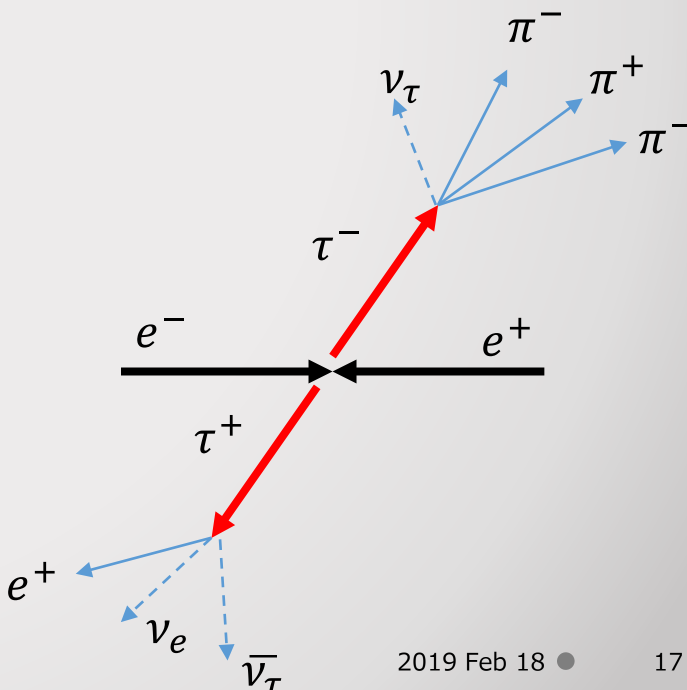
$q\bar{q}$ BG: event shape is spherical.



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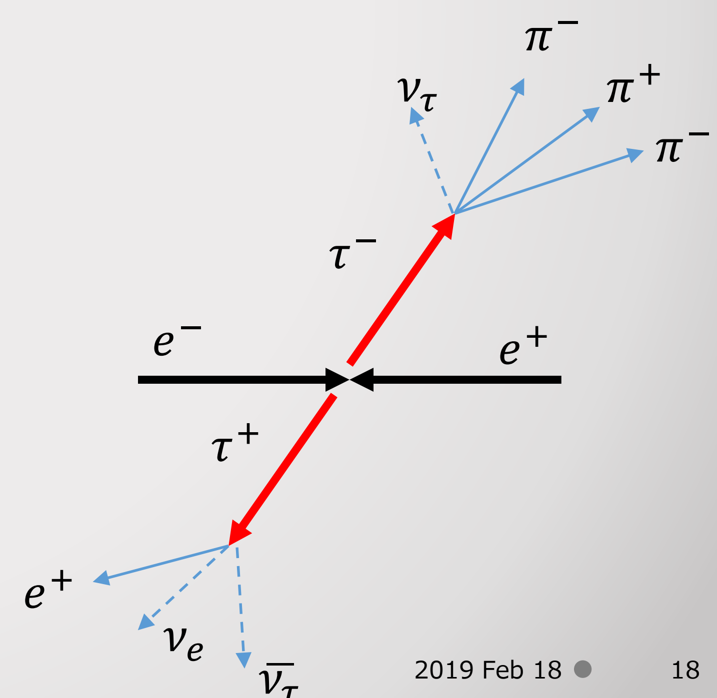
High purity is expected.



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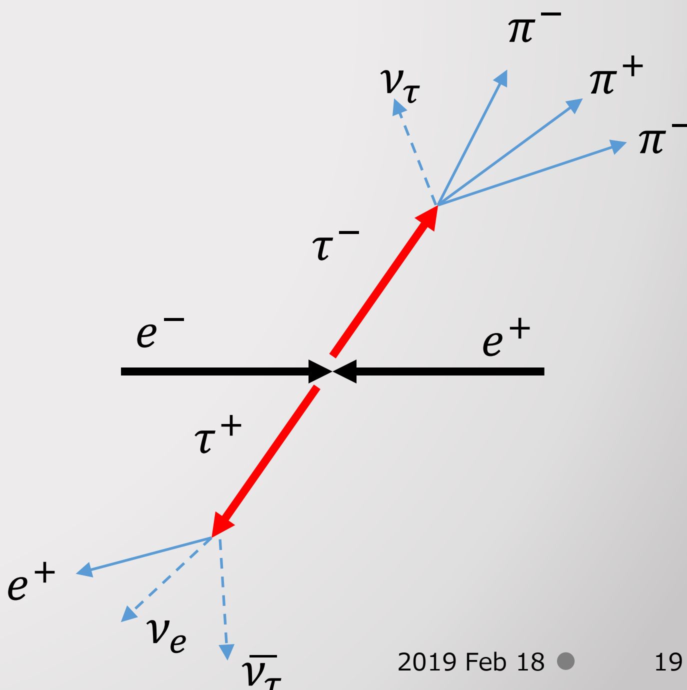
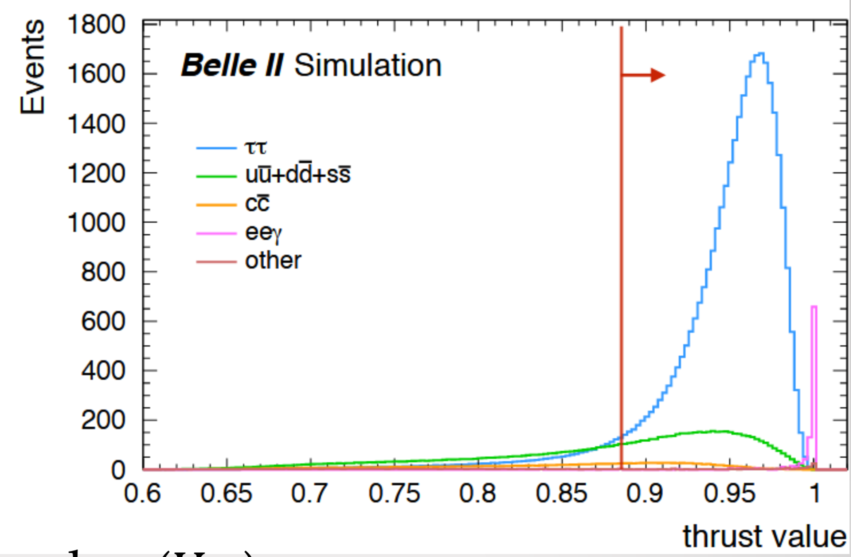
As a demonstration, we analyze these events in Belle II early data and measured tau mass.



Event selection



- 1-3 prong topology
  - Definition of thrust vector:

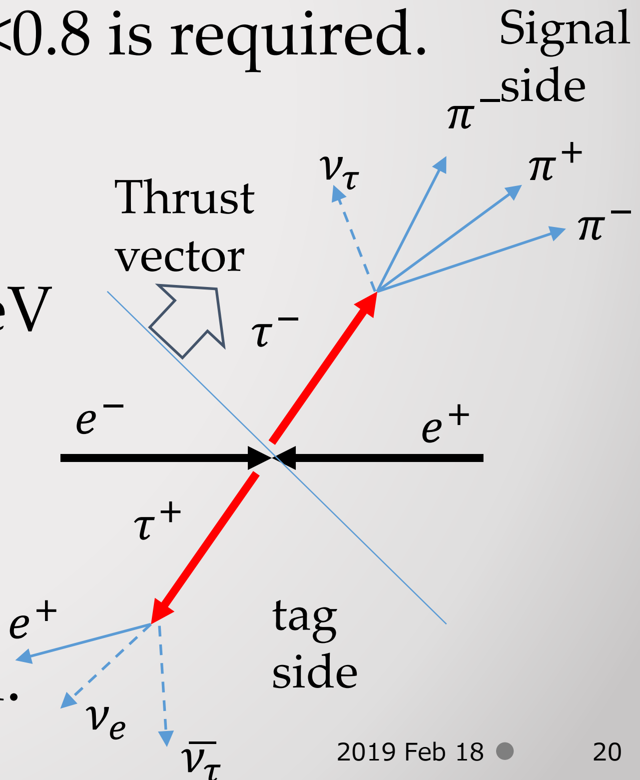
$$V_{th} = \sum_{i}^{all\ particle} \frac{|\overrightarrow{n_{th}} \cdot \overrightarrow{p_i}|}{|\overrightarrow{p_i}|}$$

Thrust vector ($\overrightarrow{n_{th}}$) maximizes thrust value (V_{th}).

- To reject electron, for signal side, E/P_{lab}<0.8 is required.
- $Vth > 0.87$
- Visible Energy in CMS < 9.7 GeV
- Energy for signal side in CMS < 5.29 GeV
- Energy for tag side in CMS < 5.22 GeV

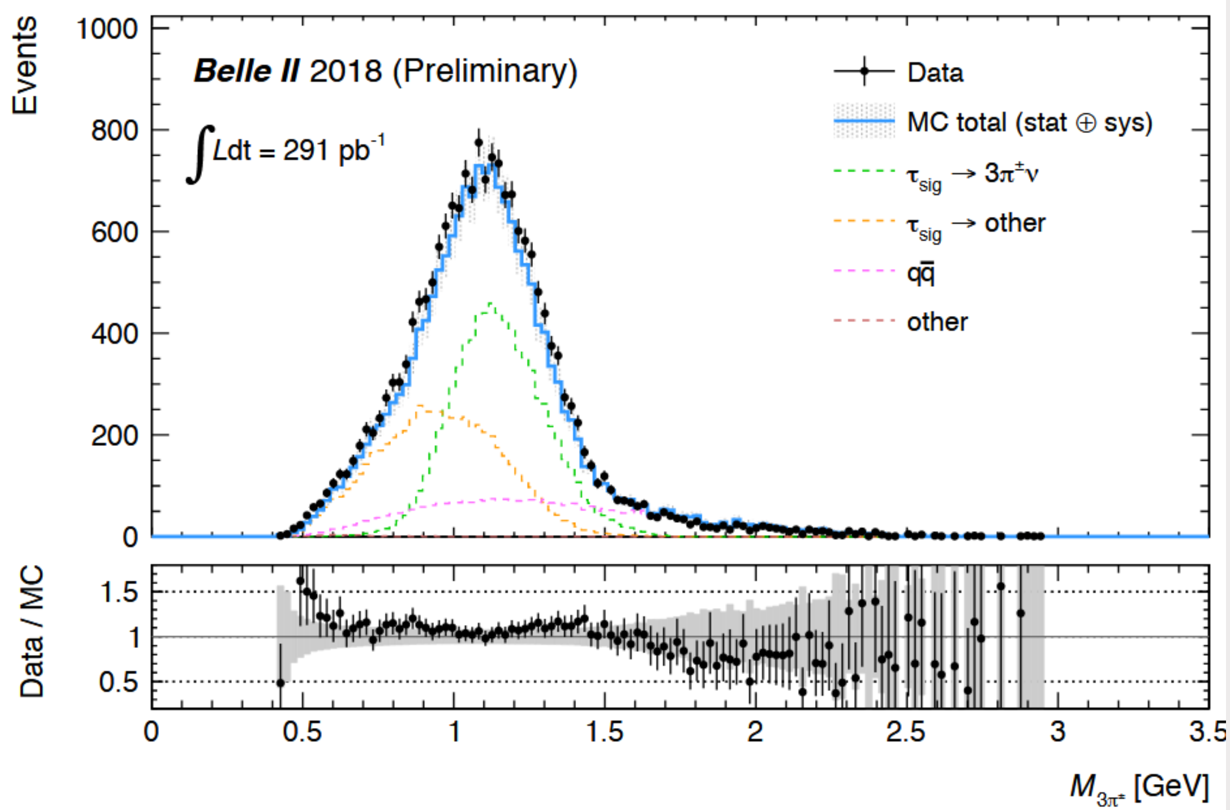
For signal side, at most 1 γ is allowed to accept ISR or FSR photon.

For tag side, any number of γ are allowed.



3π mass distribution in τ→3πν

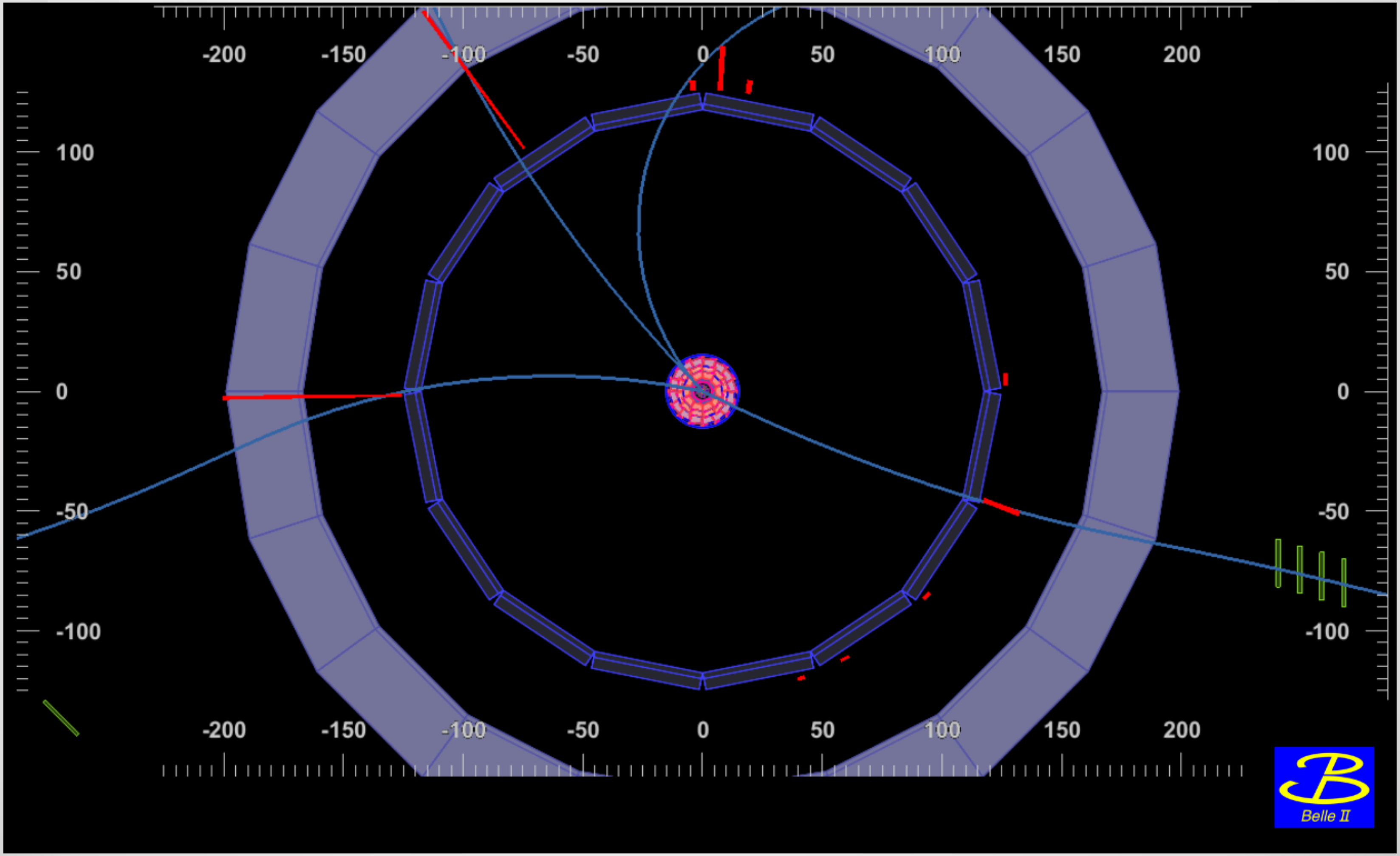
- After the selection, we can obtain:



$M_{3\pi}$ distribution @ 291 pb^{-1}

Good agreement between data and MC is found.
Simulation works well.
Data is well-understood.

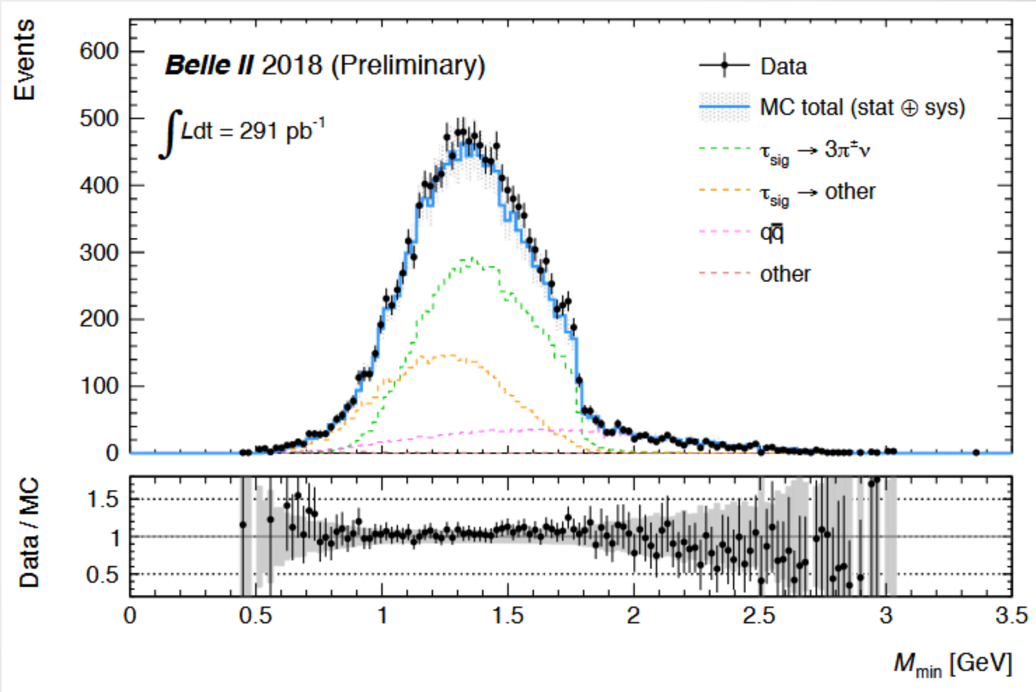
Event display of typical event candidate



τ mass measurement (1)

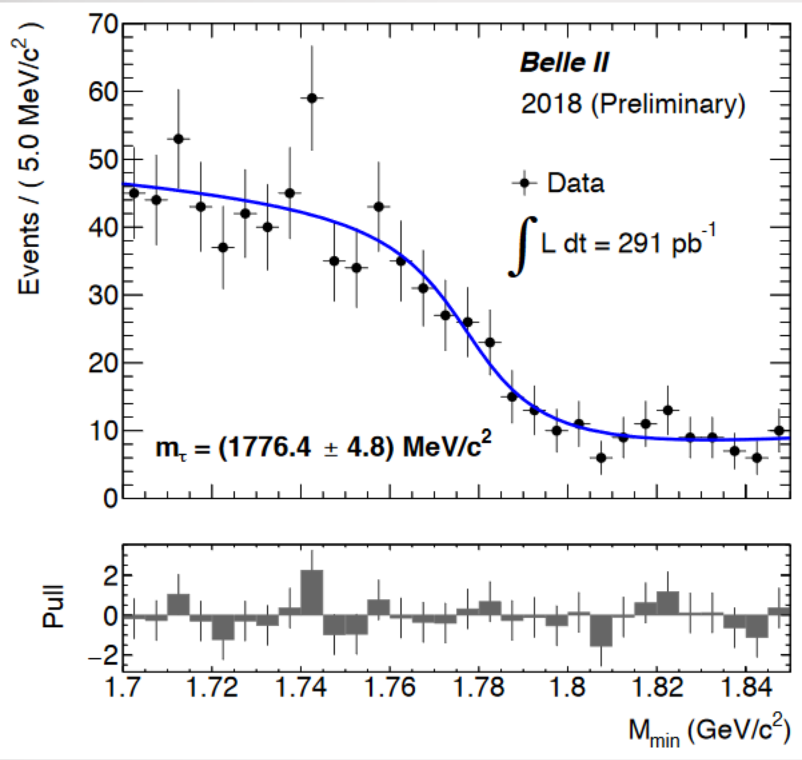
- Since it is difficult to reconstruct τ fully in SM decay, it cannot be seen as a peak at the τ mass, i.e., apparent existence of τ.
- On the other hand, in the special distribution, called pseudo mass, the distribution has some drop, that indicates τ mass.

$$\text{Pseudo mass} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$



τ mass measurement (2)

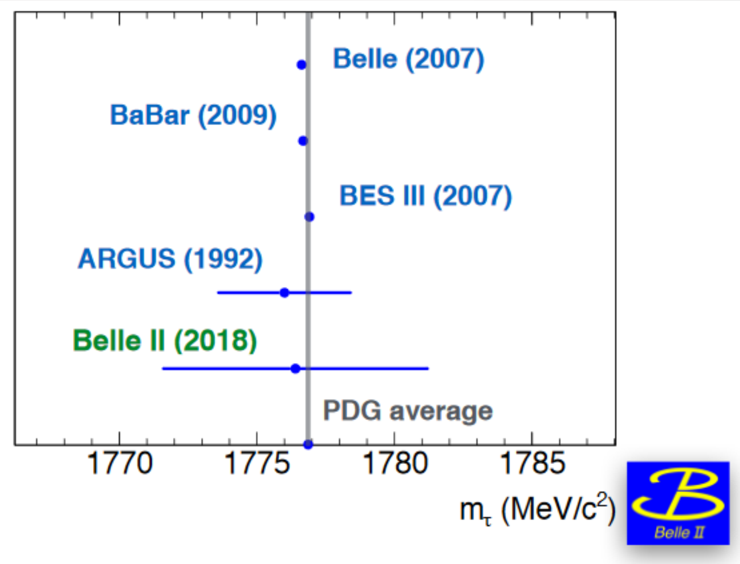
- Zoom of the previous plot



Fit by empirical PDF:

$$(p_3 + p_4 M)\tan^{-1}\left[\frac{(M - p_1)}{p_2}\right]$$
$$+p_5 M + 1$$

$p_1, p_2, \ldots, p_5$ are fit parameters and p_1 shows the evaluated τ mass.
The result is: $(1.776.4 \pm 4.8)$ GeV/c²
(only statistical error is given.)

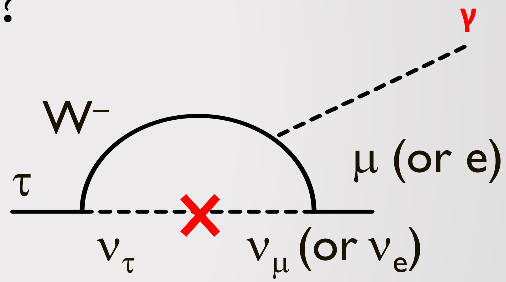


τ LFV search

Charged Lepton Flavor Violation

- In the neutrino sector, lepton flavor has not been conserved.
  - →LF is not exact symmetry.
    - →How about the charged lepton sector?
- SM + ν oscillation

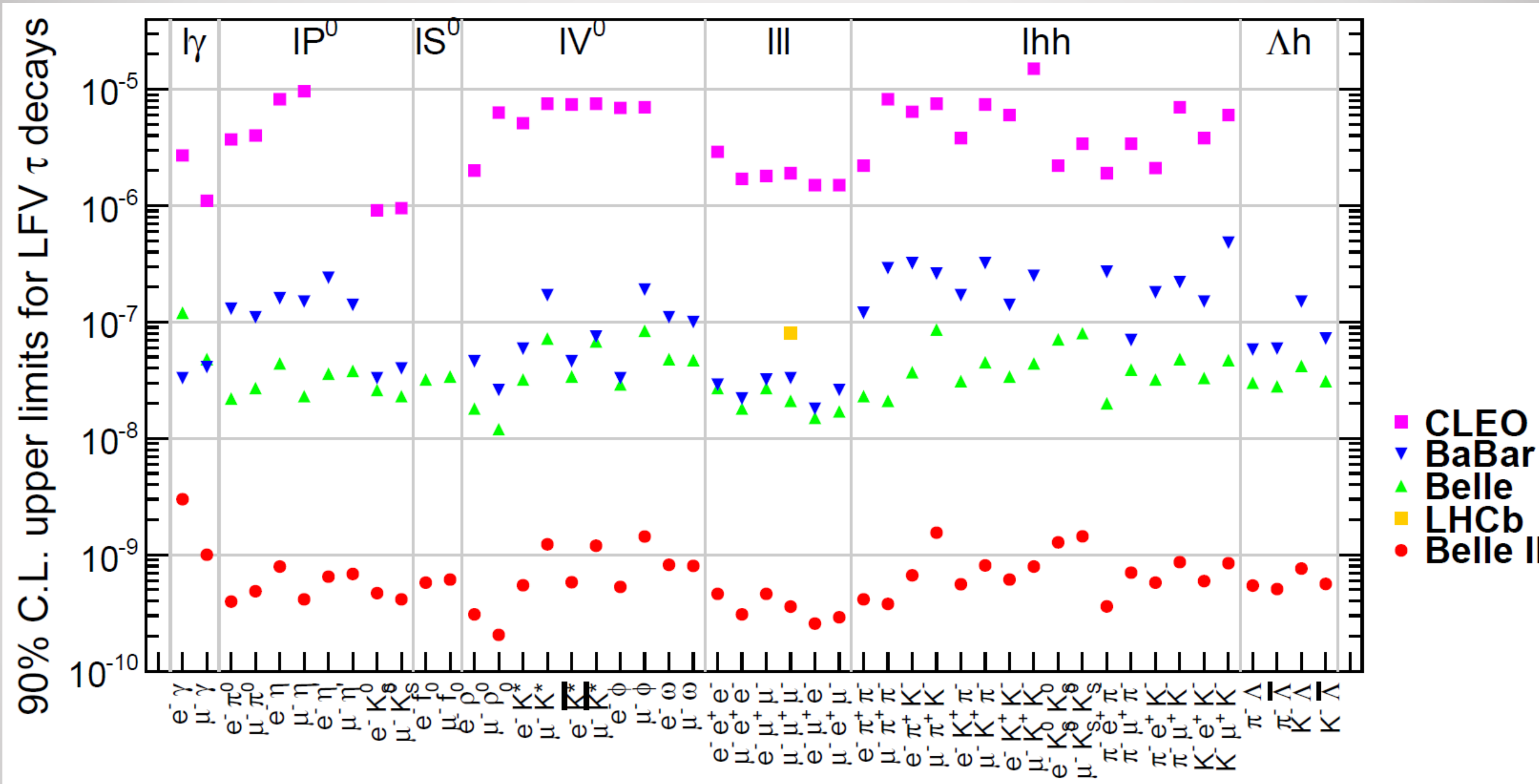
$$Br(\tau \to \ell\gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$$



Not reachable in the current experiments

Observation of the LFV decay indicates the existence of New physics.

Tau LFV at Belle → Belle II

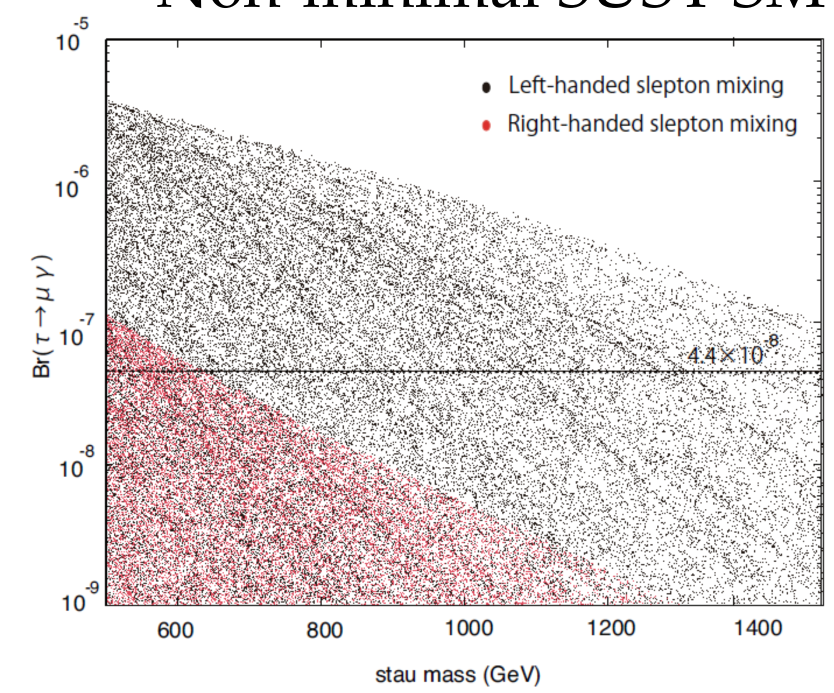


At Belle, almost 50 tau LFV decays have been searched for and set the $O(10^{-8})$ UL.
Here, Belle II expectation is evaluated by simple extrapolation of the data amount.
It may be too optimistic because of the backgrounds.

Theoretical prediction for $\tau \rightarrow \mu\gamma$

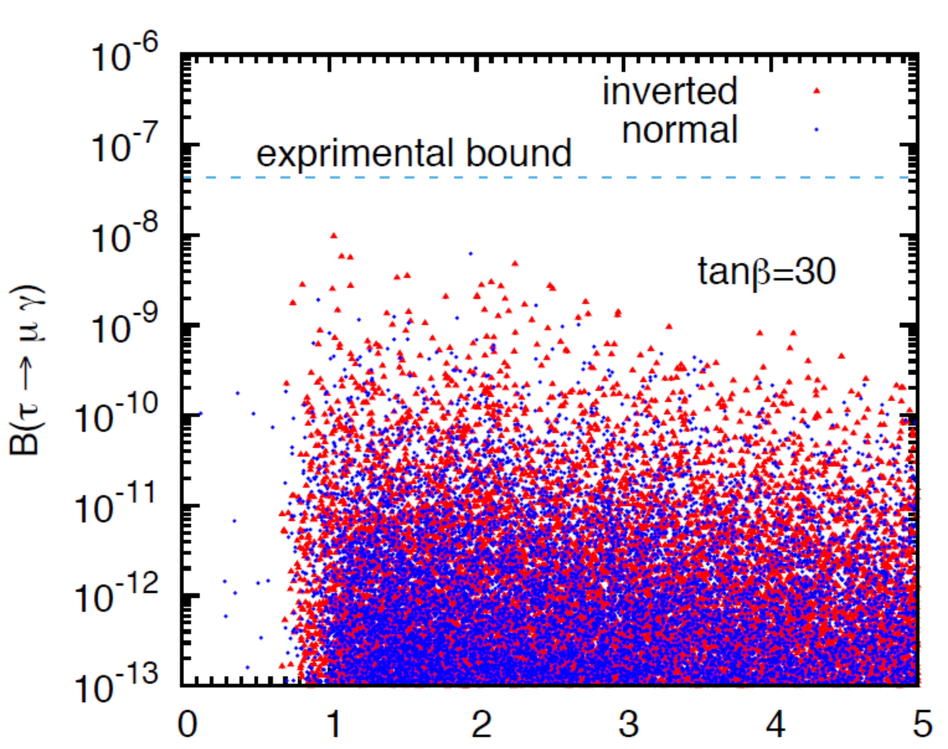
When the recent experimental results are considered, MSSM cannot make $\tau \rightarrow \mu\gamma$.

Non-minimal SUSY SM



M_{bino}=250 GeV tanβ=30
M_{wino}=500 GeV LH slepton mix=0.5~2 TeV
$M_{higgsino}$=1 TeV RH slepton mix=5 TeV

CMSSM



M_o>0.5 TeV μ>0
$M_{1/2}$<10 TeV |A_0|<3

The Belle II Physics Book
arXiv:1808.10567

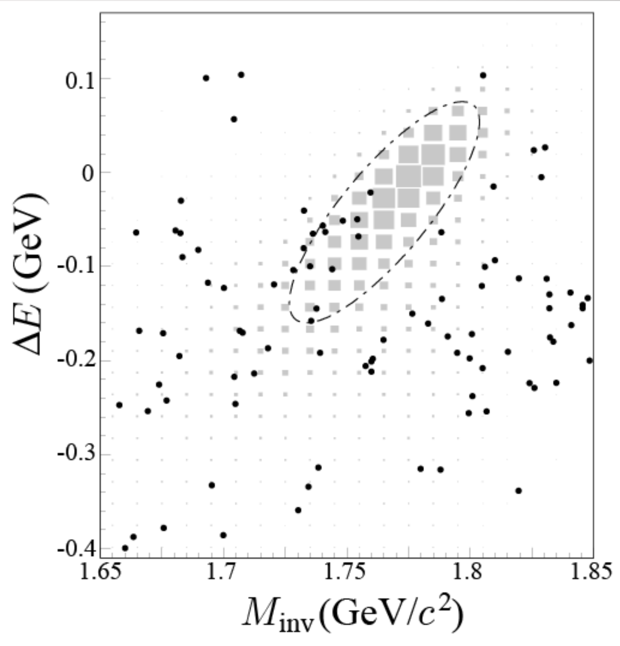
These models predict $\tau \rightarrow \mu\gamma$ with reachable BF by Belle II!

Belle result for $\tau \to \mu\gamma$

- Belle result with 550 fb^{-1}
  - Signal detaction efficiency: 6.1%
  - 10 events are found in signal ellipse.
  - BF < 4.5×10^{-8} @90%CL
  - Main BG

    $\tau \to \mu\nu\nu$+extra γ

It is impossible to be distinguished from the signal by PID.



■: Signal MC dense
▪ : data

Belle result for τ→μγ

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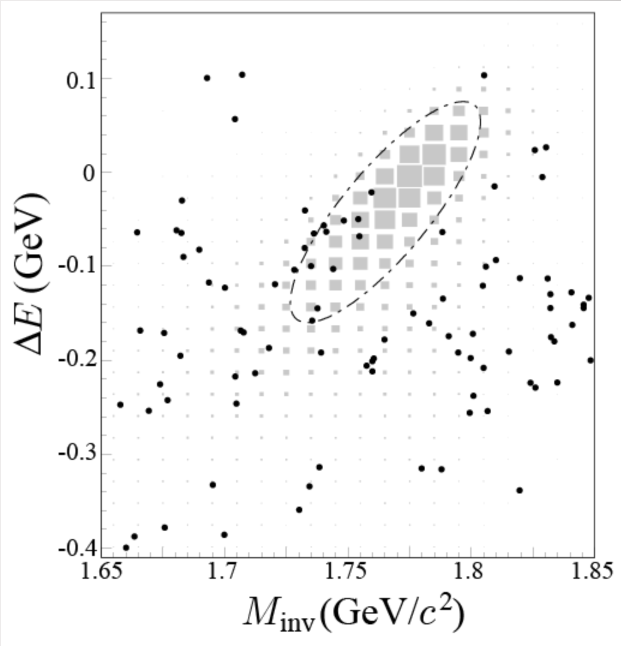

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Source of extra γ

ISR γ: 90%

Beam BG: 10%

(Beam BG means the fake γ induced by the beam particle which did not join the collision.)

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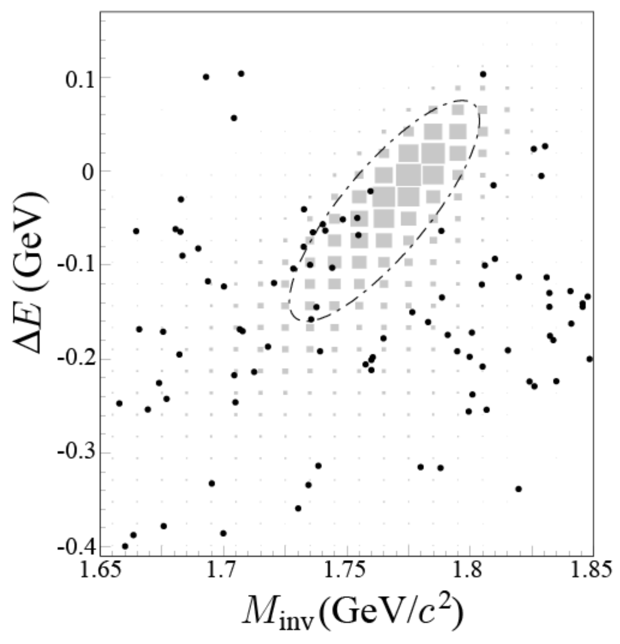

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(Beam BG means the fake γ induced by the beam particle which did not join the collision.)

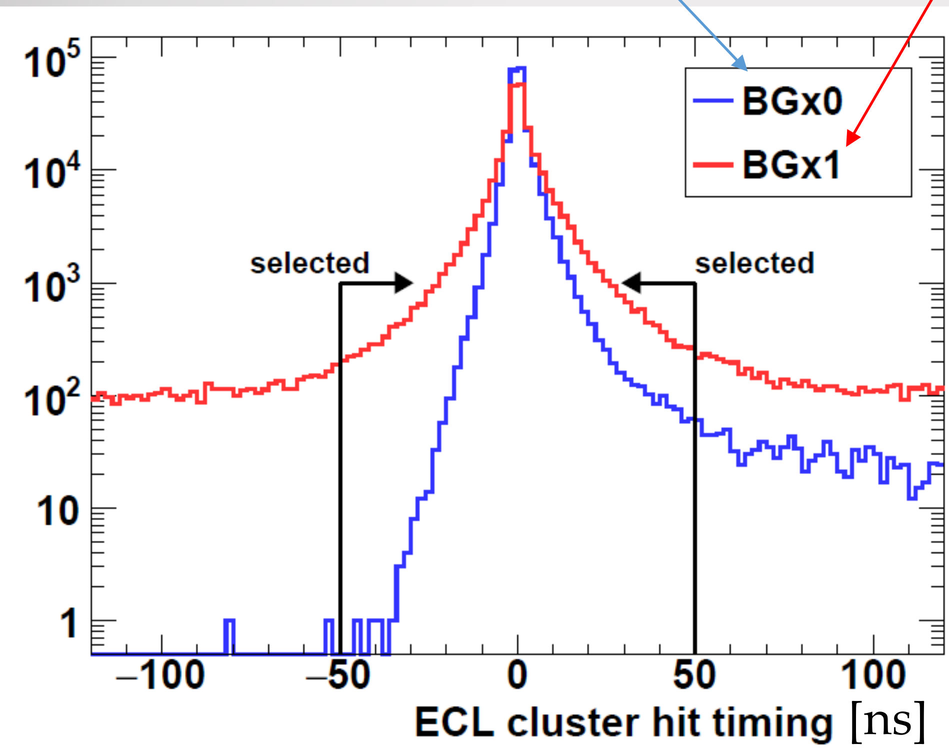
On Belle II, beam BG will be large due to the instant luminosity increase.

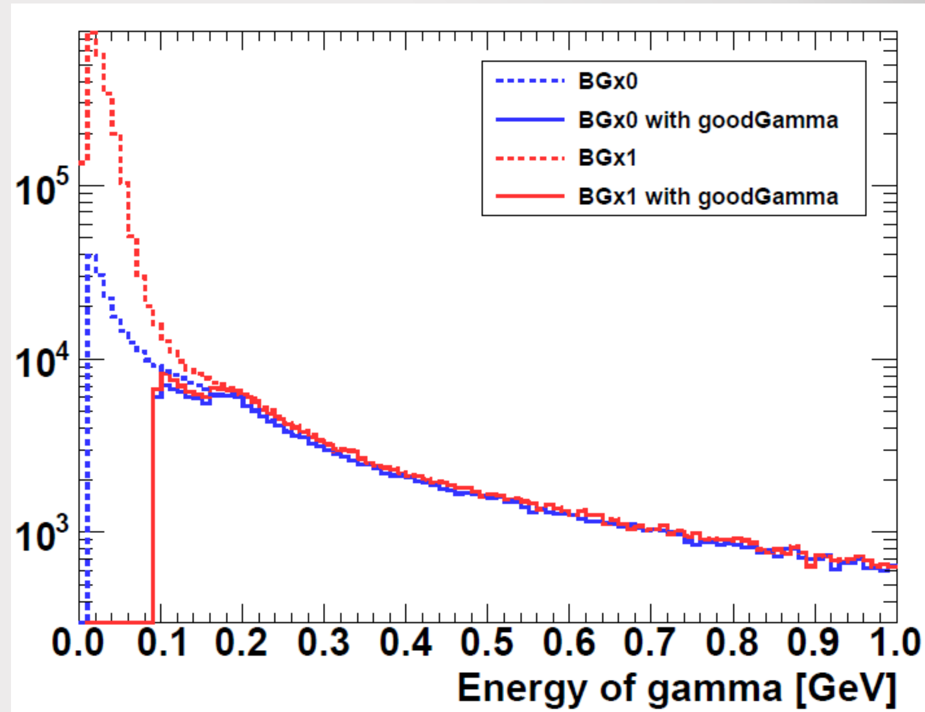
→Need to develop the way to reduce fake γ in the analysis.

Beam BG reduction

MC not included beam BG

MC included beam BG

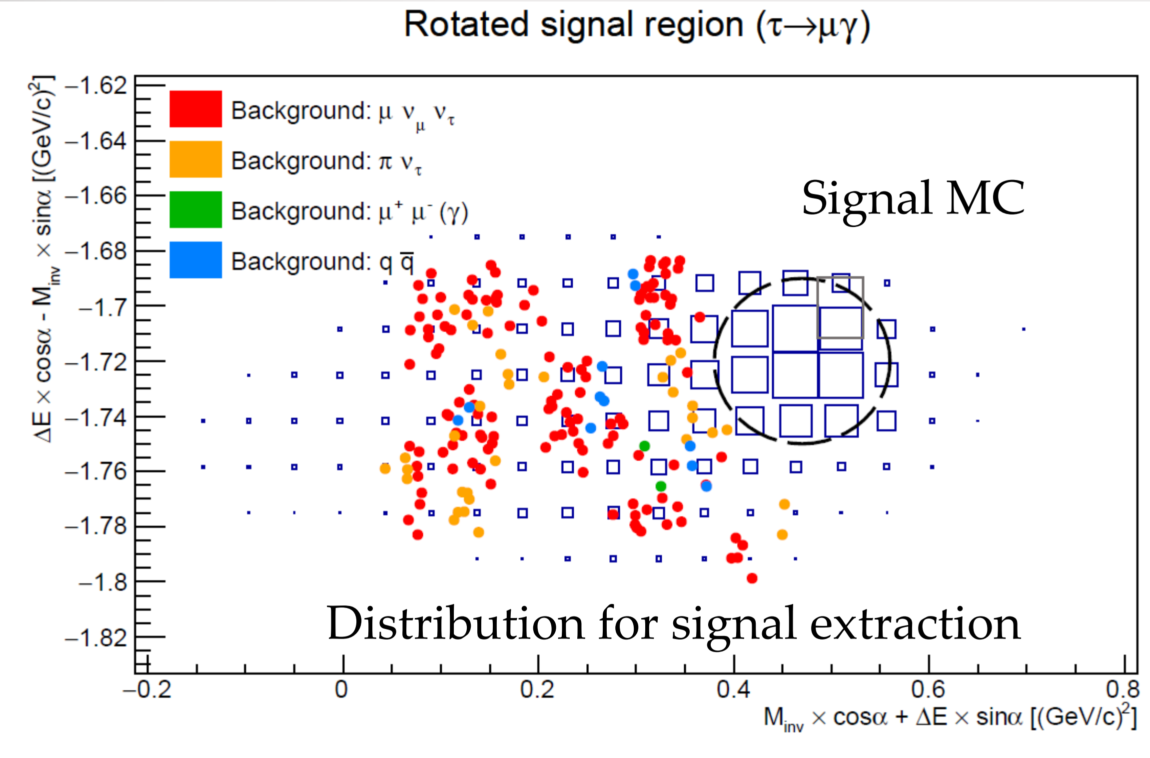




MC study tells us timing information and rejection of the low energy γ candidate reduce beam BG mostly while the signal detection efficiency is lost around 16% relatively in $\tau \to \mu\gamma$ analysis.

ISR γ reduction

- MC BG study for τ→μγ using 1 ab^{-1}



By introducing event shape variable called a Fox-Wolfram moment into the selection criteria, it turns out that a high-purity signal region can be defined.

→Need to confirm this with larger MC sample.

τ CPV search

τ CPV Search

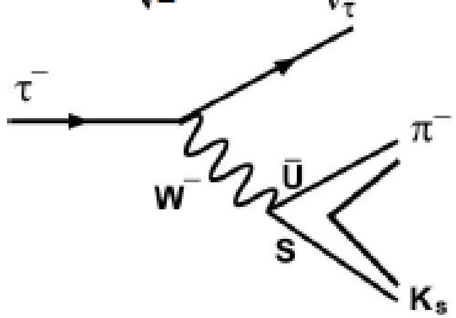
- CPV in lepton sector has not been seen yet.
  - Some model predicts that CPV appears in the decay angle difference between τ^+ and τ^-.
  - This will be induced by charged Higgs-like particle. So, CPV is expected to appear $|\Delta s|=1$ process rather than $|\Delta s|=0$.
    - $\tau \rightarrow K\pi\nu$, $\tau \rightarrow K\pi\pi\nu$

CPV search in $\tau \to \pi K_S^0 \nu$

-Effective Hamiltonian

SM

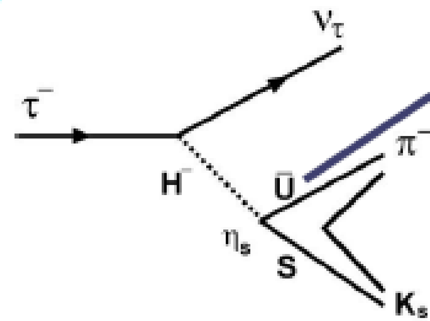
$$H_{SM} = \sin\theta_c \frac{G}{\sqrt{2}} \left(\bar{\nu}\gamma^{\mu}(1-\gamma_5)\tau\right)\left(\bar{s}\gamma_{\mu}(1-\gamma_5)u\right)$$



Scalar Boson

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

Complex coupling constant



NP

$$J_\mu^{K\pi} = \langle K(p_1)\pi(p_2) | \bar{s}\gamma_\mu u | 0 \rangle$$

$$= (p_1 - p_2)^{\nu} T_{\nu\mu} F(Q^2) + Q_\mu F_s(Q^2)$$

$$T_{\mu\nu} = g_{\mu\nu} - \frac{Q_\mu Q_\nu}{Q^2}$$

Form factor : F (Vector)

F_s (Scalar)

$$F_s(Q^2) \to F_s(Q^2) = F_s(Q^2) + \frac{\eta_s}{m_\tau} F_H(Q^2)$$

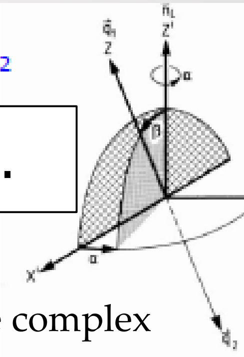
$$F_H(Q^2) \equiv \langle K(p_1)\pi(p_2) | \bar{s}u | 0 \rangle$$

Differential decay width and CPV

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

$$- C(Q^2)\cos\beta\cos\psi \cdot \mathrm{Re}(F F_s^*(\eta_s))$$

CPV appears here.



η should be complex

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

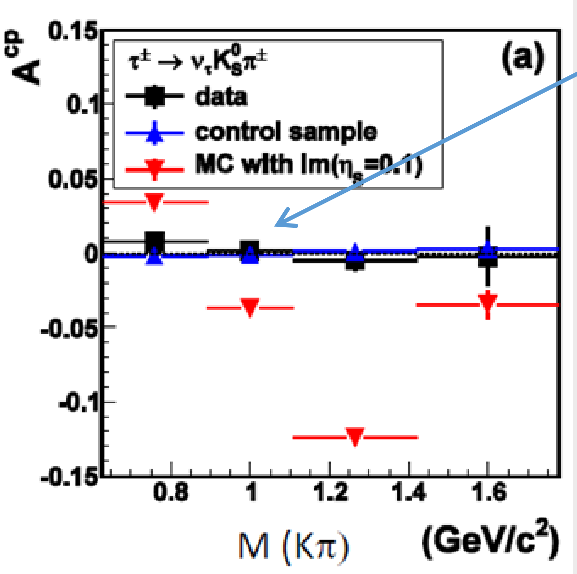
$$A_i^{\mathrm{cp}} = \frac{\iiint_{Q_{1,i}^2}^{Q_{2,i}^2} \cos\beta\cos\psi \left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}{\frac{1}{2}\iiint_{Q_{1,i}^2}^{Q_{2,i}^2} \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}$$

$$\simeq \langle\cos\beta\cos\psi\rangle_{\tau^-}^i - \langle\cos\beta\cos\psi\rangle_{\tau^+}^i$$

experimental observable

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

Belle result and prospect for Belle II



Black : data

Blue : data in sideband region (CS)

Red : MC having CPV
with the 10x larger CPV
than that of UL evaluated by CLEO

data : 700 fb^{-1}

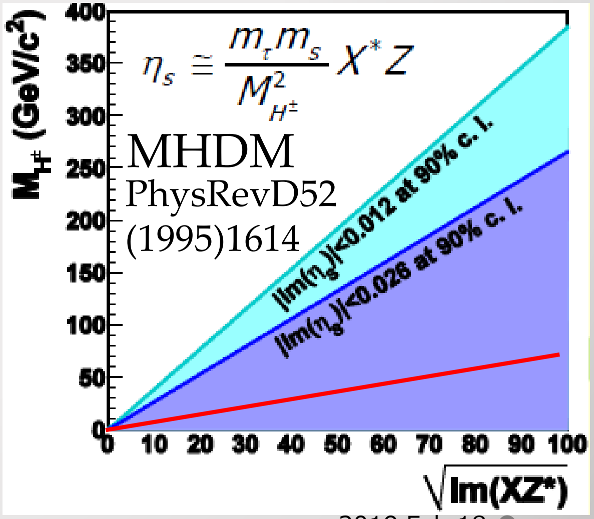
$$A_{cp} = (1.8 \pm 2.1(stat) \pm 1.4(sys))x10^{-3}$$

$|Im(\eta_s)| < (0.012\text{-}0.026)$ at 90 %C.L.

To correct detector and selection-biased asymmetry control sample of $\tau \to \pi\pi\pi\nu$ is used since the final state is similar to $K_S{}^0\pi\nu$.

Statistics of control sample dominates the systematics of this analysis.

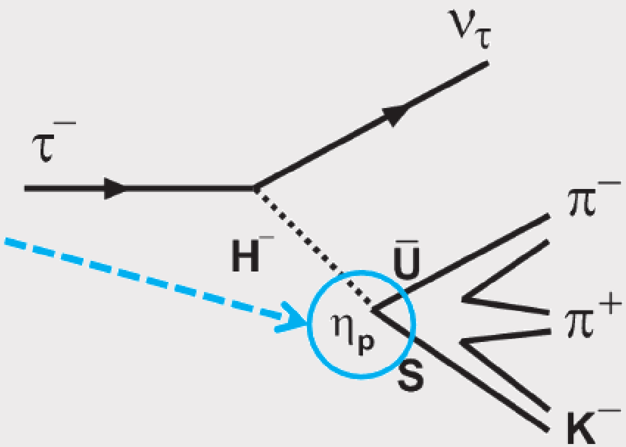
So, with 50 ab^{-1}, 10 x more sensitive result can be expected.



CPV in τ→Kππν (1)

Very similar to $\tau \to K_S^0 \pi \nu$ analysis, not scalar but pseudo-scalar will induce to CPV.

$$F_4 \longrightarrow \tilde{F}_4 = F_4 + \frac{f_H}{m_\tau} \eta_p$$



$$\begin{aligned} J^\mu &\equiv \langle K^-(p_1)\pi^-(p_2)\pi^+(p_3) \mid \bar{s}\gamma^\mu(1-\gamma^5)u \mid 0 \rangle \\ &= [F_1(s_1, s_2, Q^2)(p_1 - p_3)\nu + F_2(s_1, s_2, Q^2)(p_2 - p_3)\nu] T^{\mu\nu} \\ &\quad + iF_3(s_1, s_2, Q^2)\epsilon^{\mu\nu\rho\sigma} p_{1\nu} p_{2\rho} p_{3\sigma} + F_4(s_1, s_2, Q^2) Q^\mu \end{aligned}$$

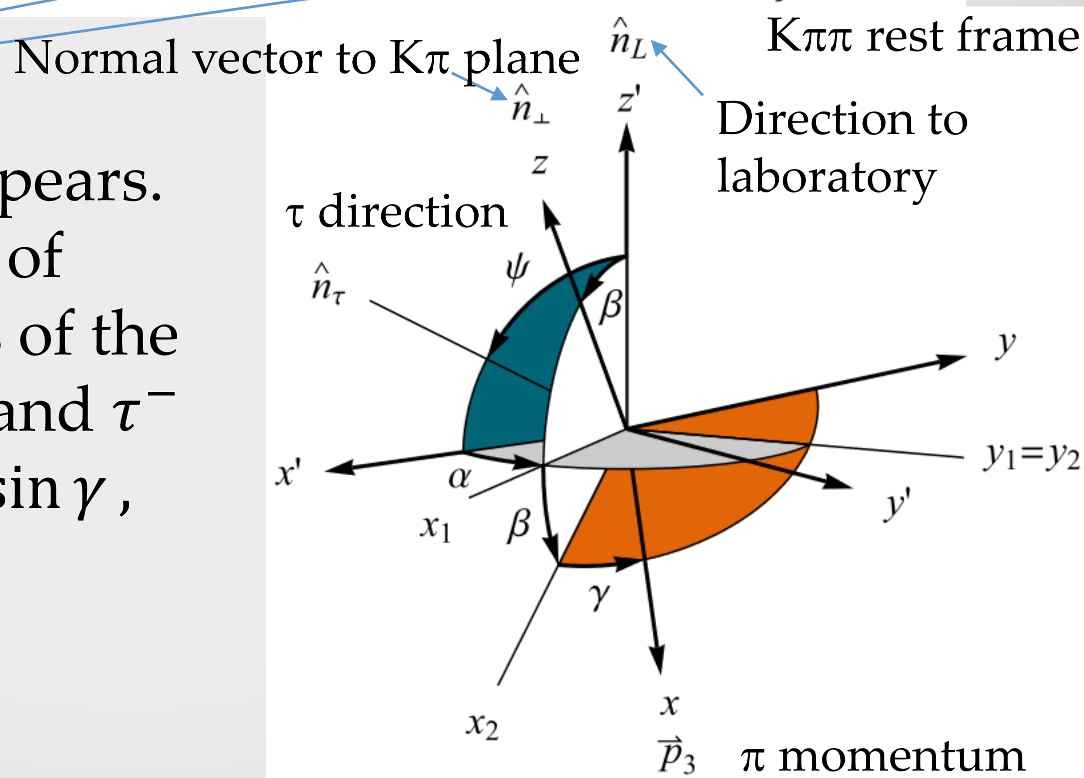
Belle, BaBar have not searched for it.

CPV in τ→Kππν (2)

Differential decay width is written down:

$$\frac{d\Gamma}{dQ^2 ds_1 ds_2 d\gamma\, d\cos\beta\, d\cos\theta} = \frac{G_F^2 \sin^2\theta_c}{512(2\pi)^6} \frac{(m_\tau^2 - Q^2)^2}{m_\tau^3 Q^2} \Big\{ \Big[\frac{2}{3}K_1 + K_2 + \frac{1}{3}\bar{K}_1(3\cos^2\beta - 1)/2\Big](|B_1|^2 + |B_2|^2)$$
$$+ \Big[\frac{2}{3}K_1 + K_2 - \frac{2}{3}\bar{K}_1(3\cos^2\beta - 1)/2\Big]|B_3|^2 + K_2|B_4|^2 - \frac{1}{2}\bar{K}_1\sin^2\beta\cos2\gamma(|B_1|^2 - |B_2|^2)$$
$$+ \bar{K}_1\sin^2\beta\sin2\gamma\,\mathrm{Re}(B_1B_2^*) + 2\bar{K}_3\boxed{\sin\beta\sin\gamma\,\mathrm{Re}(B_1B_3^*)} + 2\bar{K}_2\boxed{\sin\beta\cos\gamma\,\mathrm{Re}(B_1B_4^*)}$$
$$+ 2\bar{K}_3\boxed{\sin\beta\cos\gamma\,\mathrm{Re}(B_2B_3^*)} - 2\bar{K}_2\boxed{\sin\beta\sin\gamma\,\mathrm{Re}(B_2B_4^*)} + 2\bar{K}_3\boxed{\cos\beta\,\mathrm{Im}(B_1B_2^*)}$$
$$+ \bar{K}_1\sin2\beta\cos\gamma\,\mathrm{Im}(B_1B_3^*) - \bar{K}_1\sin2\beta\sin\gamma\,\mathrm{Im}(B_2B_3^*) + 2\bar{K}_2\boxed{\cos\beta\,\mathrm{Im}(B_3B_4^*)}\Big\}, \quad (25)$$

Via these terms, CPV appears. Similarly to the analysis of $\tau\to\pi K_S^0\nu$, the differences of the decay angle between τ^+ and τ^- are evaluated, i.e., $\sin\beta\sin\gamma$, $\sin\beta\cos\gamma$ and $\cos\beta$.



CPV in τ→Kππν (3)

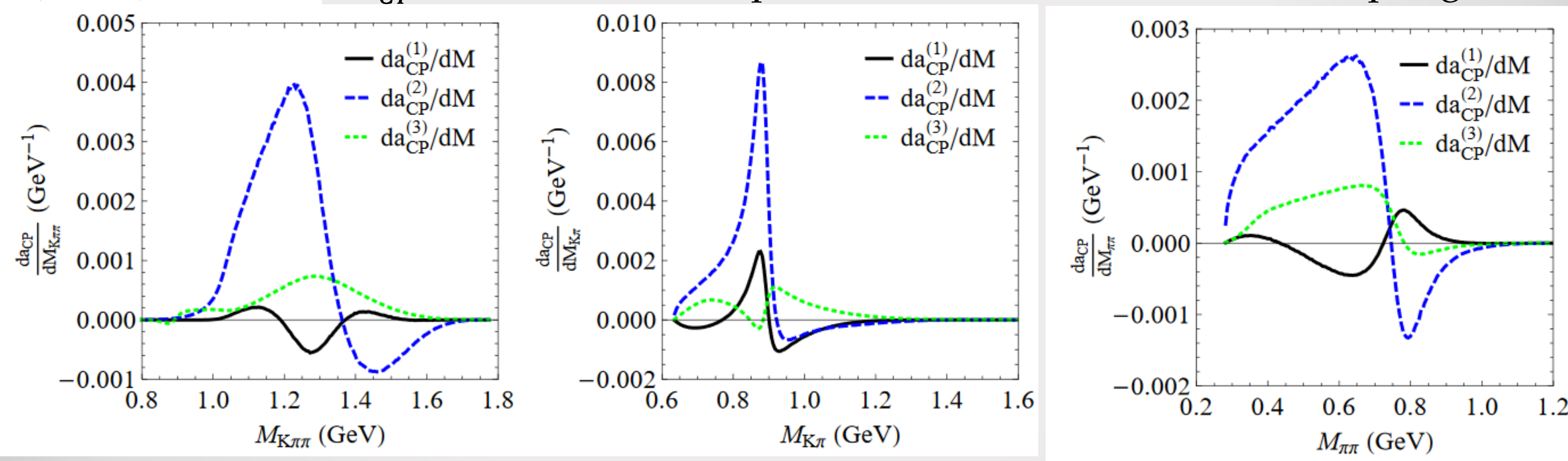
- In $\tau \to K_S \pi \nu$, A_{CP} is evaluated bin by bin of $M(K_S\pi)$.

→ 3 body-decay, evaluated of $M(K\pi\pi)$, $M(K\pi)$, $M(\pi\pi)$

Since dA_{CP}/dM takes both negative and positive values,

dA_{CP}/dM is more sensitive to CP asymmetry.

$A_{CP}^{(i)} = a_{CP}^{(i)} f_H \,\mathrm{Im}(\eta_P)$, $a_{CP}^{(i)}$ distributions independent from form factor and coupling



i: 1=sinβsinγ, 2=sinβcosγ, 3=cosβ

Phys. Rev. D78, 113008 (2008)

Difficulty of $\tau \to K\pi\pi\nu$ analysis

- In $\tau \to K\pi\pi\nu$ analysis, large BGs appear.

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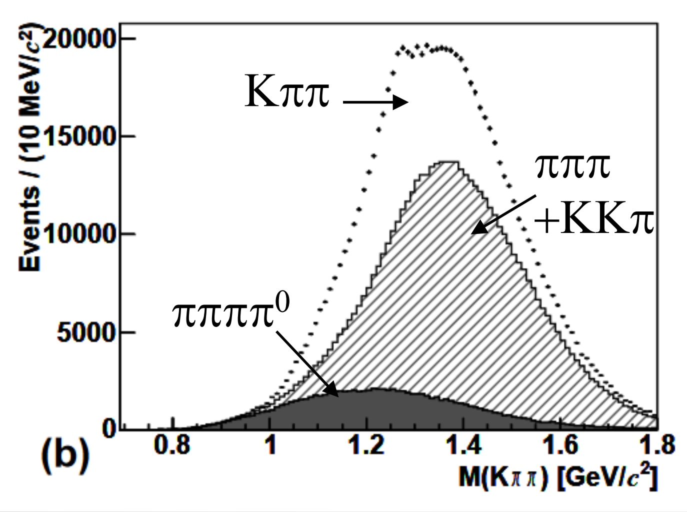
  - Br($\tau \to \pi\pi\pi\nu$)~10%, Br($\tau \to \pi\pi\pi\pi^0\nu$)~4.5% while Br($\tau \to K\pi\pi\nu$)~0.3%

  → misID rate seriously affects the analysis.

Difficulty of $\tau \to K\pi\pi\nu$ analysis

- In $\tau \to K\pi\pi\nu$ analysis, large BGs appear.
  - $Br(\tau \to \pi\pi\pi\nu) \sim 10\%$, $Br(\tau \to \pi\pi\pi\pi^0\nu) \sim 4.5\%$ while $Br(\tau \to K\pi\pi\nu) \sim 0.3\%$

  $\to$ misID rate seriously affects the analysis.



Phys.Rev.D81,113007(2010)

In Belle analysis, πππ BG is 2x-3x more than signals.
In Belle II, since PID devices are improved, less BGs are expected.
(But, almost same amount of BGs is estimated.)

Summary

- Belle II is a great place to study tau physics.
- Recently, with early data, tau mass is evaluated.
- Near future,

Tau LFV will be searched for with 10-50x more sensitivity.

Tau CPV will be searched for with 10x more sensitivity.