Mar/29/2023

Status and prospect for tau physics at Belle II

K.Hayasaka (Niigata U., KEK)

Introduction for tau lepton

◦ Third lepton = τριτον

◦ The heaviest charged lepton:1.78 GeV/c² $(\gg m_\pi)$

→an unique lepton which can decay into meson(s).

→Various decay modes are allowed.

◦ In SM, it decays via weak interaction.

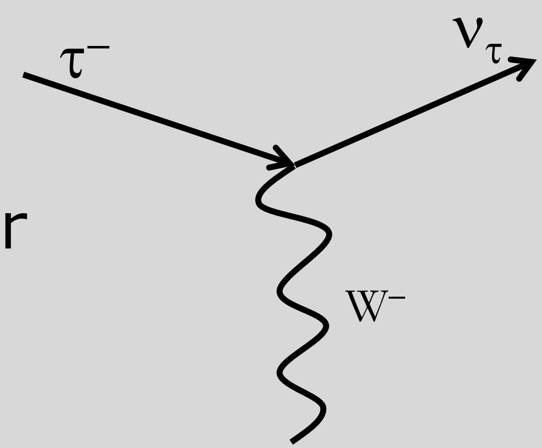
= neutrino(s) appears in the final state.

τ cannot be reconstructed

form the observed daughters.

(except neutrinoless lepton flavor

violation decays)

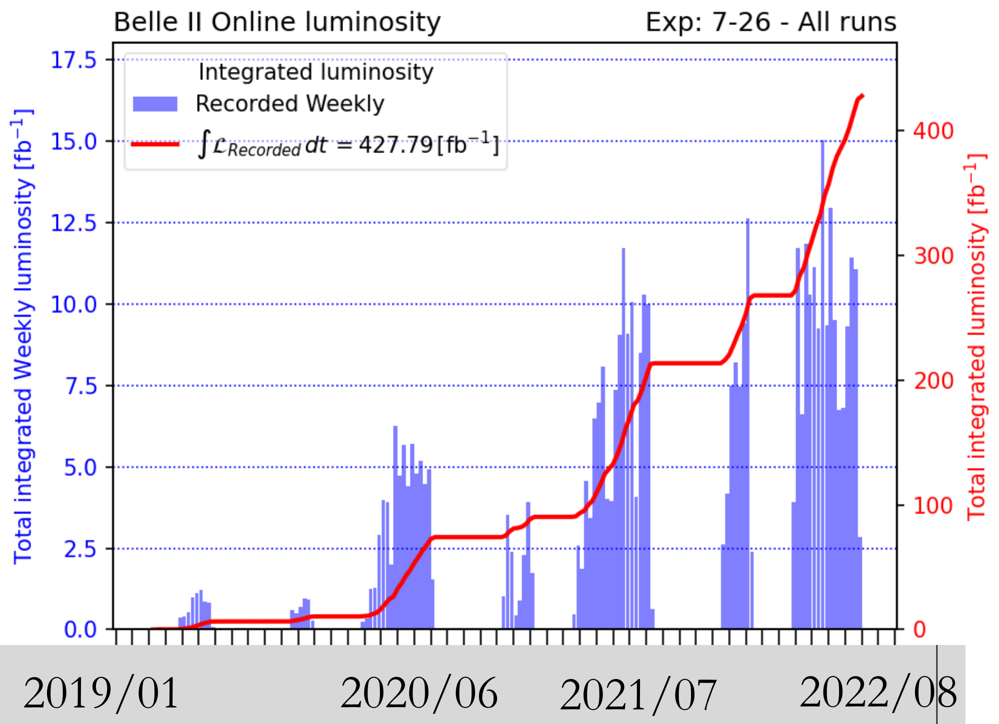


FERMIONS

Leptons spin = 1/2

Flavor		Mass GeV/c²	Electric charge
ν_e	electron neutrino	<1×10⁻⁸	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

Belle II/SuperKEKB



◦ Belle II@SuperKEKB is a good playground for tau physics:

– Electron positron collider: $\sqrt{s}$~10 GeV

– Highest luminosity in the world : 4.7×10^{34} /cm^2/s (Target 6×10^{35} /cm^2/s)

☆Collected : 428fb^{-1}, target : 50ab^{-1} around 2034

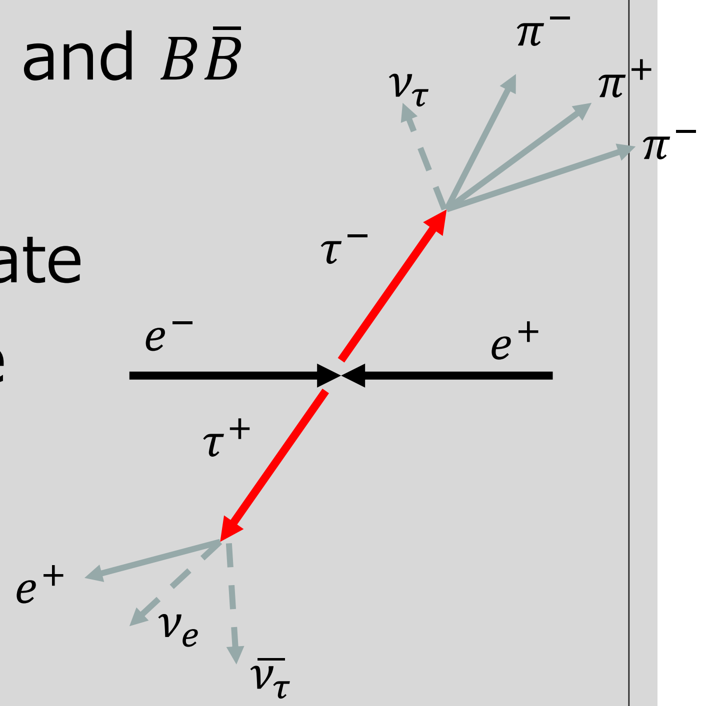
– 4π x 94% detector → 4-momentum conservation usable

– tau-pair creation: $e^+e^- \rightarrow \tau^+\tau^-$, cross section:0.9 nb ~$\sigma(b\bar{b})$

A B-factory is also a τ-factory!

How to identify τ-pair event at Belle II (1)

- No. of tracks and No. of phtons: lower than that of $q\bar{q}$ and $B\bar{B}$
- Large missing momentum and mass:
  due to the existence of the neutrino(s) in the final state
- Existence of lepton(s) and meson(s) at the same time



Since we cannot reconstruct τ lepton using invariant mass, we identify τ-pair event utilizing kinematics and PID.

4π coverage of the detector and good PID are so important.

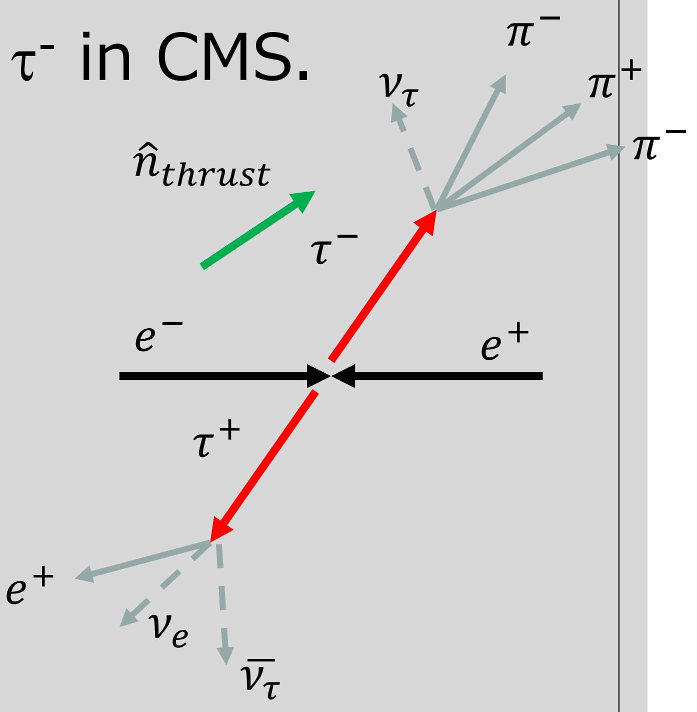
How to identify τ-pair event at Belle II (2)

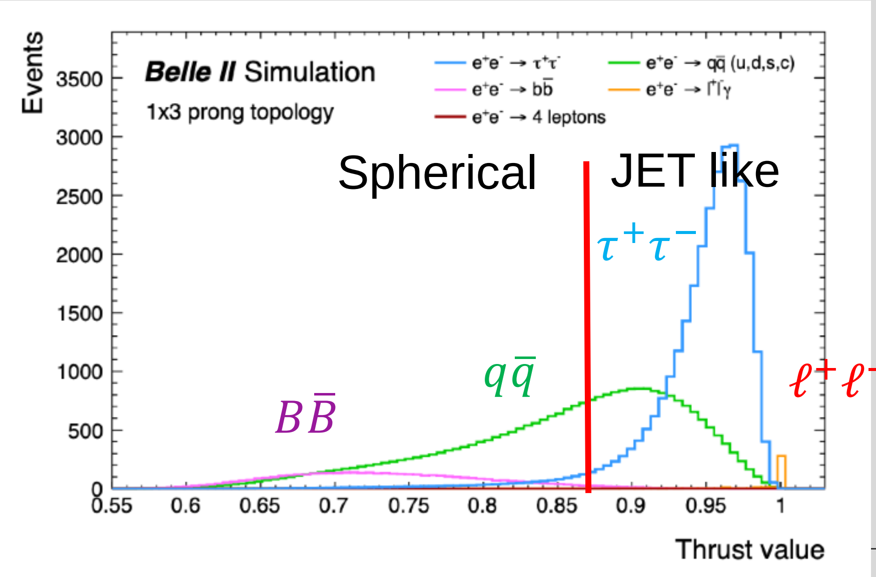
- τ-pair creation: well-separated daughters from τ^+ and τ^- in CMS.
- Trust value is a good parameter to distinguish from

other events like $q\bar{q}$ $(q = u, d, s, c)$, $\ell^+\ell^-$ $(\ell = e, \mu)$:

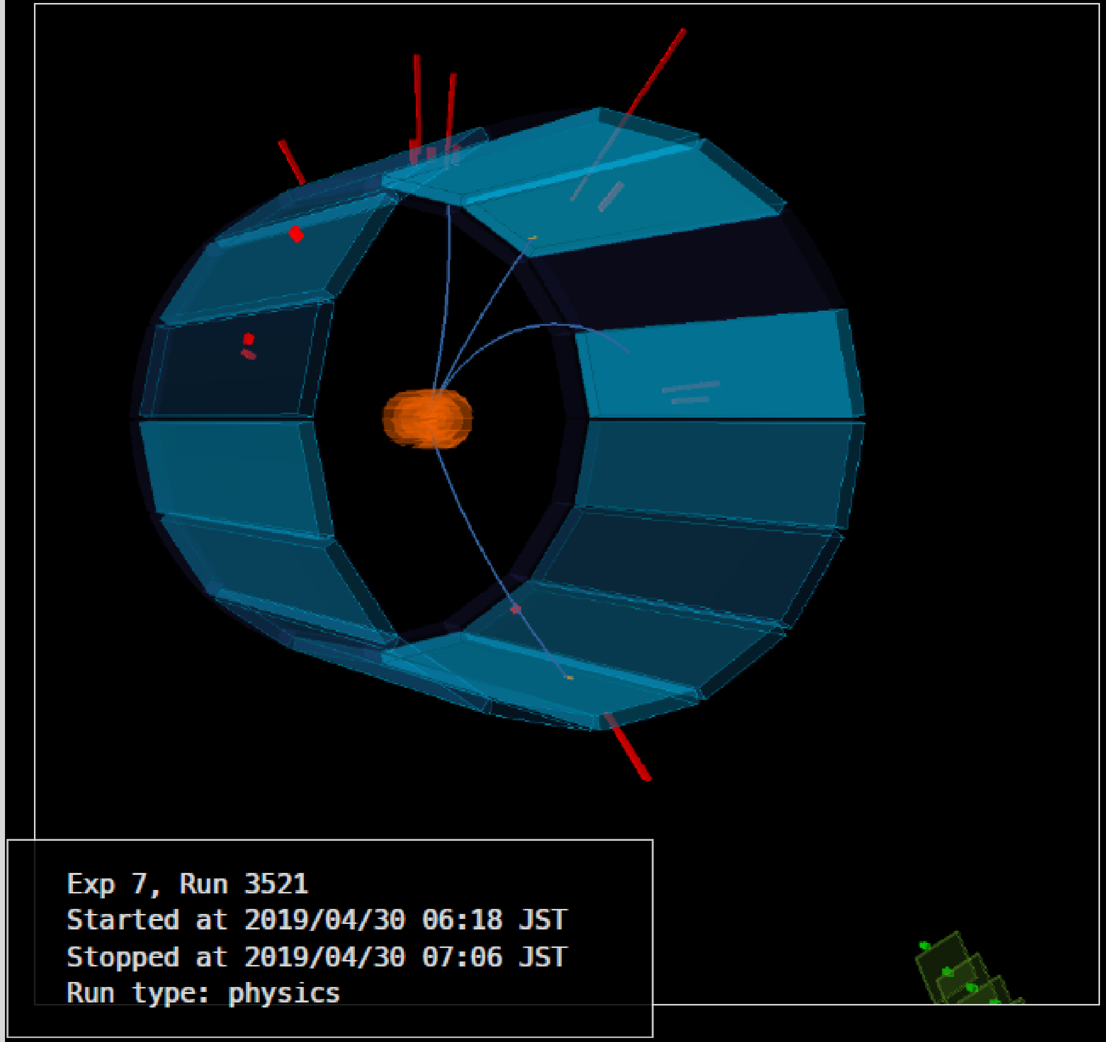
$$V_{thrust} = \frac{\sum_i |\vec{p}_i^{\,CM} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p}_i^{\,CM}|}$$

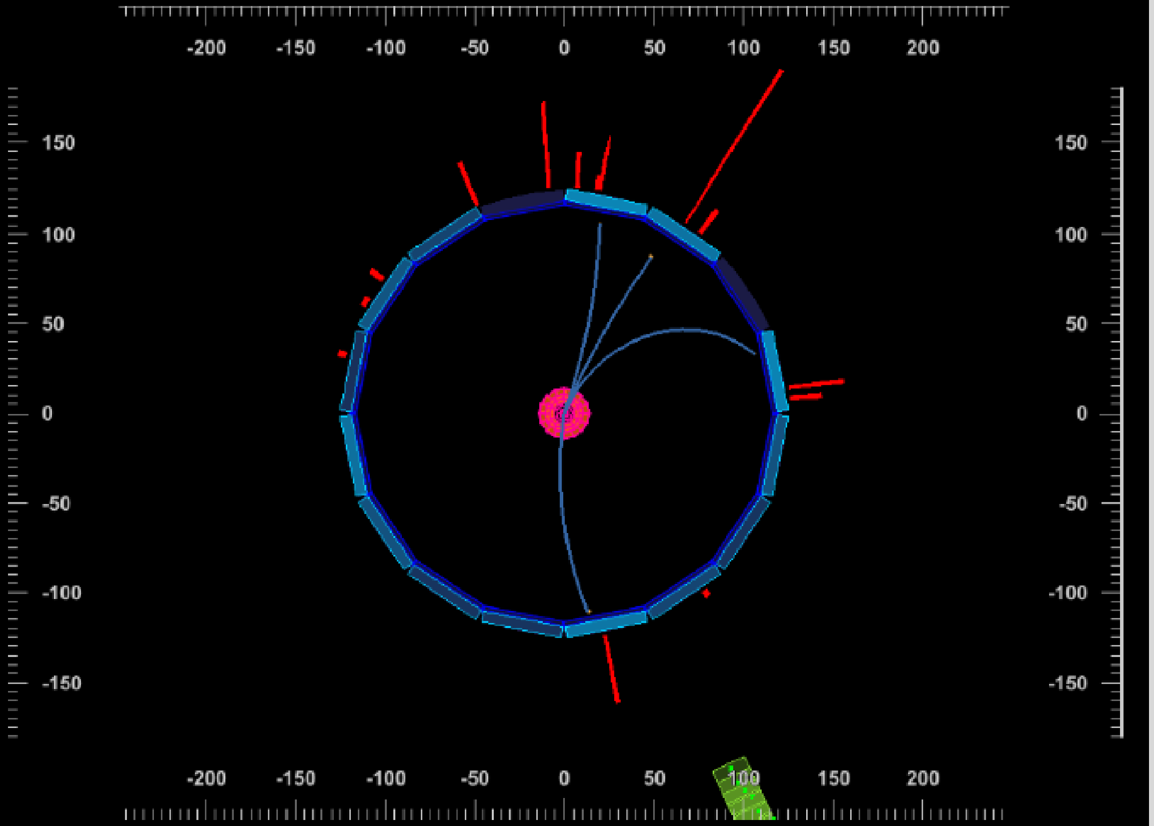
$\hat{n}_{thrust}$ is called `thrust vector' and determined to maximize V_{thrust}.





Tau decay event in early Belle II data





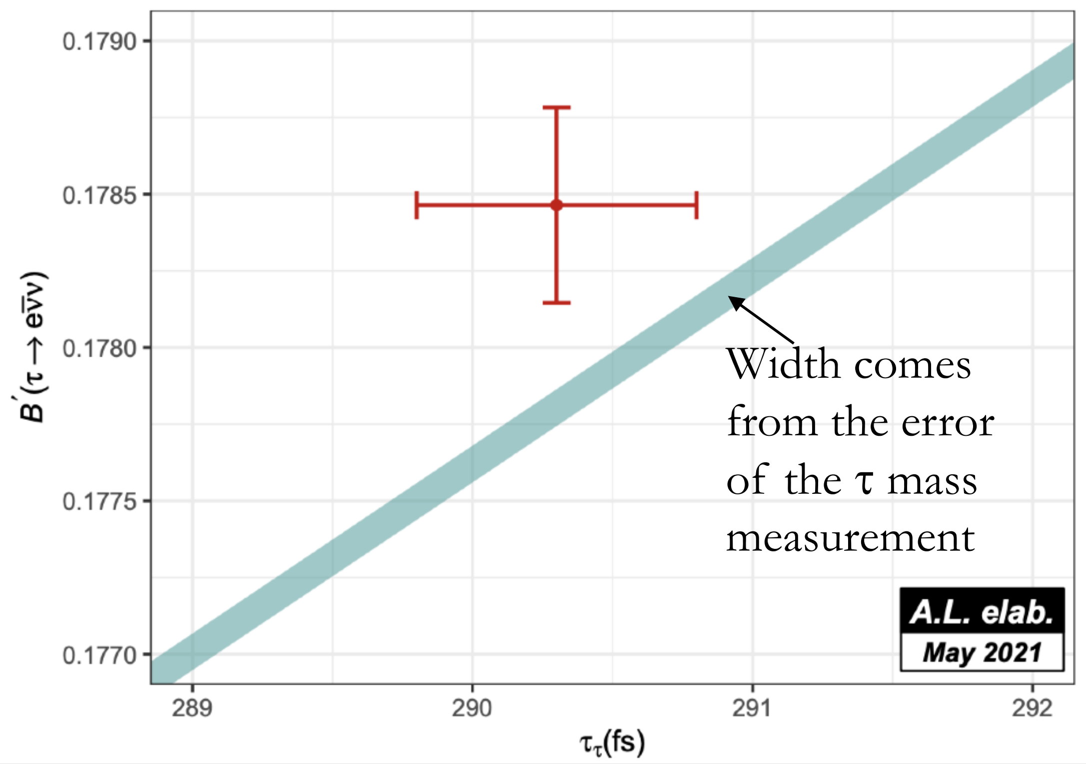
Recent results from Belle II

- τ mass measurement
- Search for τ lepton flavor violating decays:
  - $\tau \to \ell$ +missing
  - $\tau \to \ell + \phi$

Fundamental parameters

- Measurement of Fundamental parameters of τ like mass and lifetime also affects test of SM.

$$Br(\tau \to e\nu\nu) \sim Br(\mu \to e\nu\nu)\frac{\tau_\tau}{\tau_\mu}\frac{m_\tau^5}{m_\mu^5}$$



arXiv:1804.08436

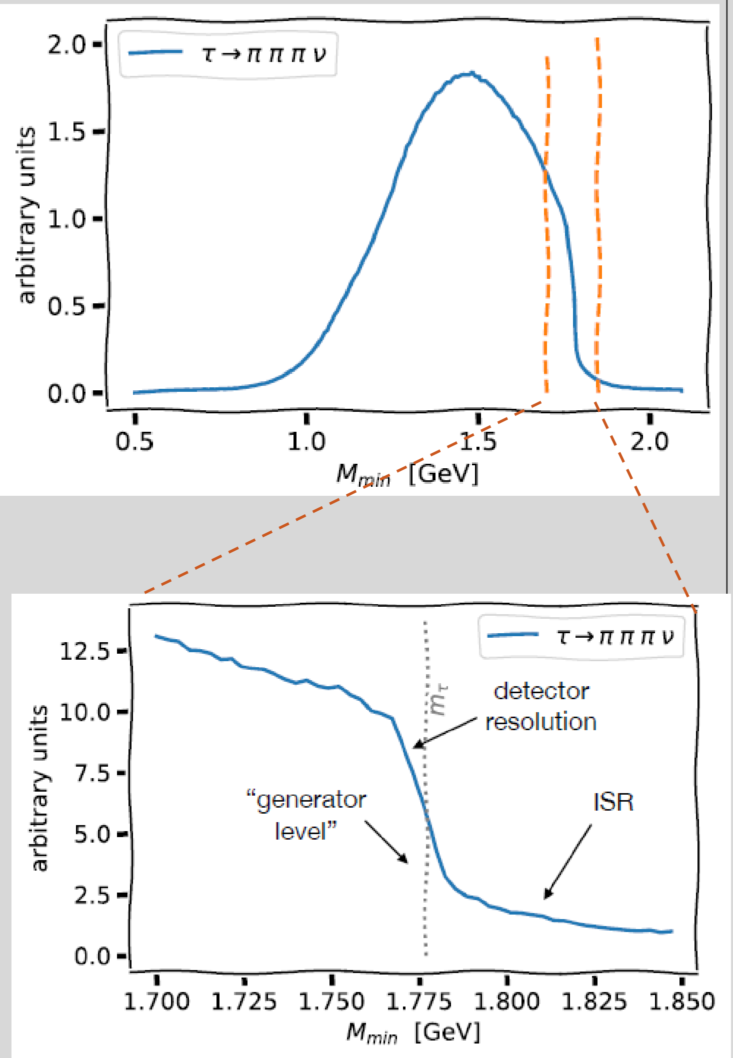
τ mass measurement

- Basic strategy

Signal signature:

$\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu,\ \tau^{\mp} \rightarrow \pi^{\mp}(\pi^{0})\nu, \ell^{\mp}\nu\nu$

$$M_{min} = \sqrt{M_{3\pi}^{2} + 2\left(\frac{\sqrt{s}}{2} - E_{3\pi}^{CM}\right)\left(E_{3\pi}^{CM} - p_{3\pi}^{CM}\right)} < m_{\tau}$$

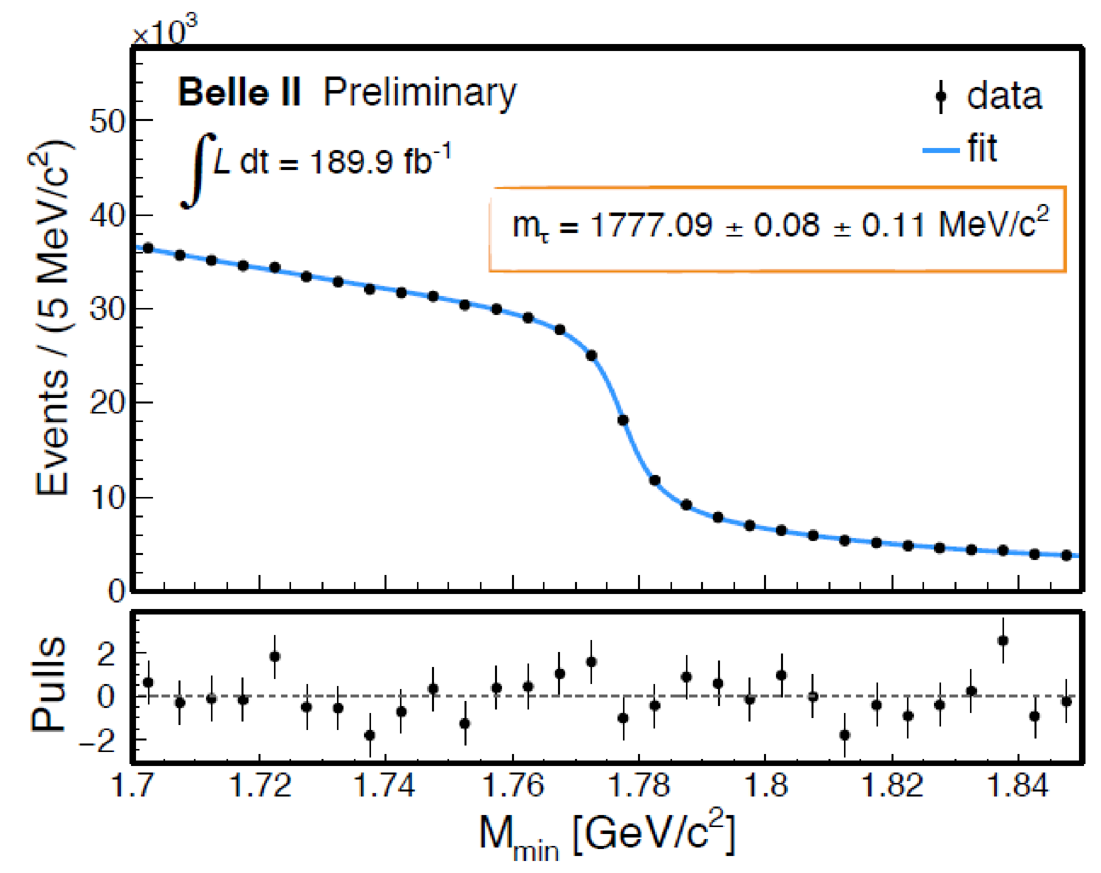


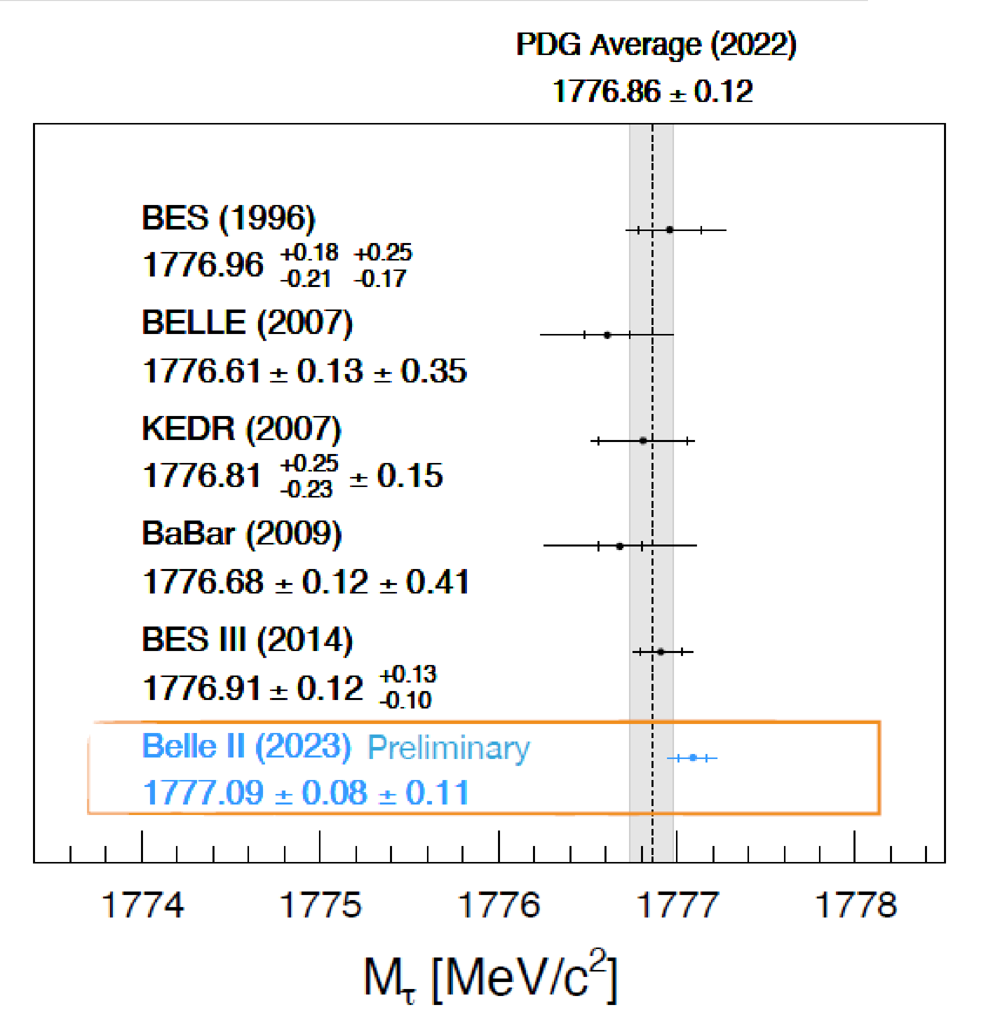
Fitting function:

$-P_3 \tan^{-1}\left(\frac{x-P_1}{P_2}\right)$ with 2nd polynomial

P_1 indicates τ mass.

Result

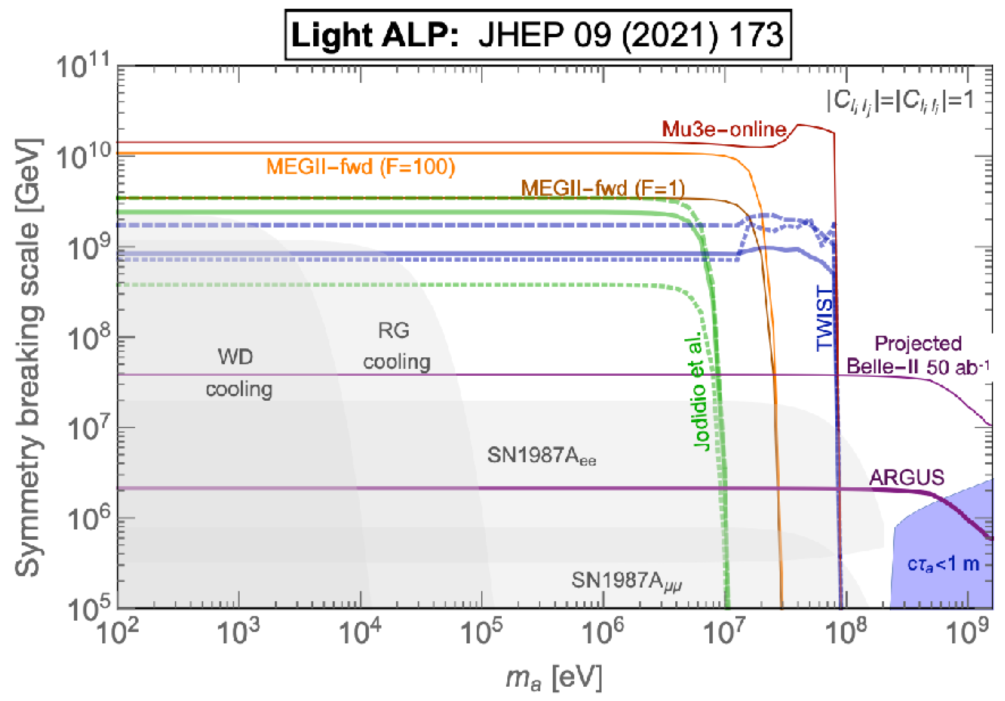


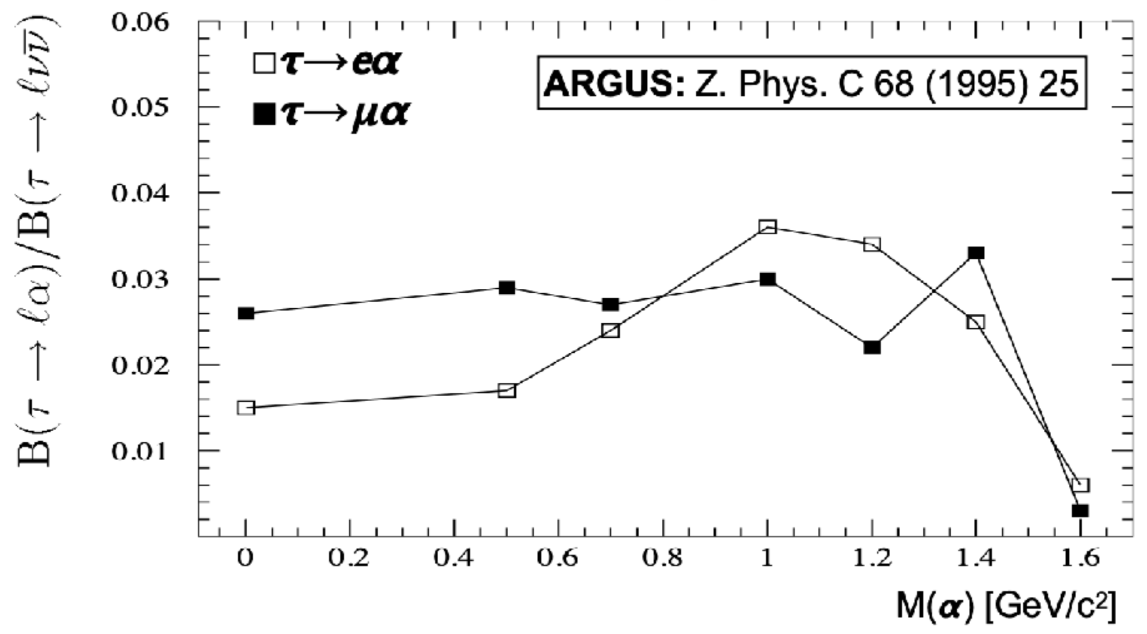


Most precise measurement!

Search for $\tau \to \ell$+missing

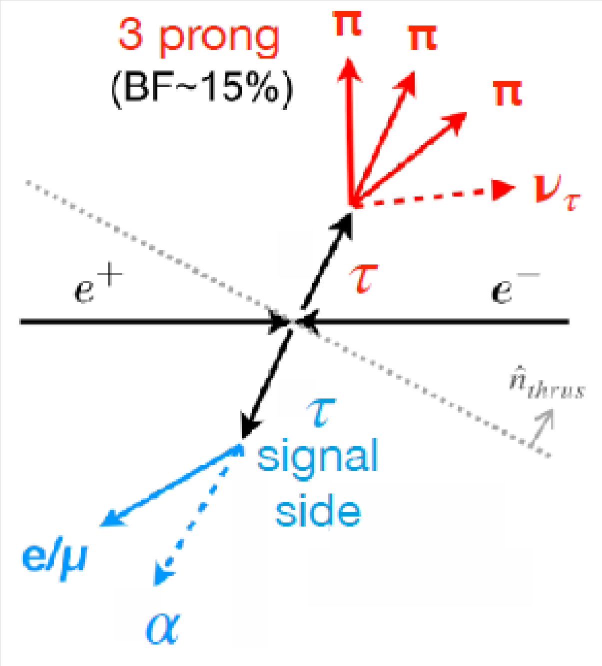
- After ARGUS search (1995), no one updates this search.
- Missing corresponds to neutral boson predicted as LFV Z', light ALP and so on.



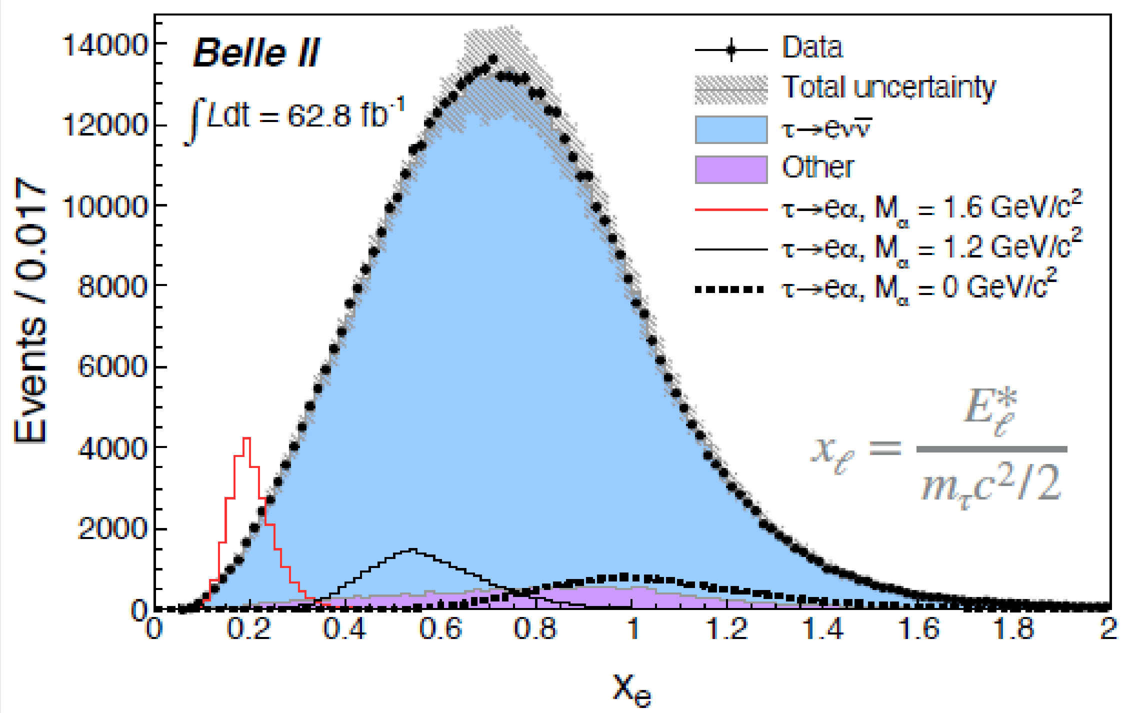


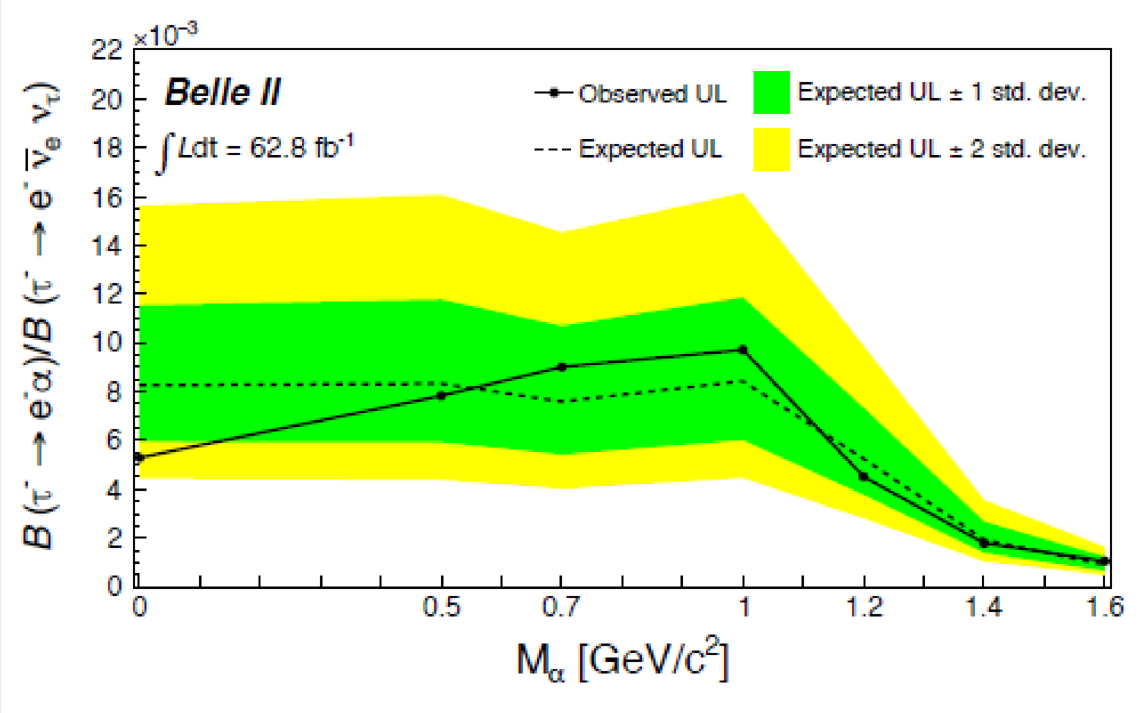
Analysis method

- Utilize monochromatic momentum (energy) in τ-rest frame as a signal signature.
- But, τ cannot be reconstructed and it is impossible to take t-rest frame.
- Using $\tau \to \pi\pi\pi\nu$ decay on the opposite τ, and hadron 3π direction is considered as pseudo τ since almost 3π comes from a_1, whose mass is close to τ mass, we can define pseudo-τ rest frame.



Signal extraction and result.





Instead of the momentum at tau rest frame, normalized energy is used.
Both should be monochromatic in 2-body decay.
Due to the incompleteness of τ direction reconstruction, singnal distribution has “width”.

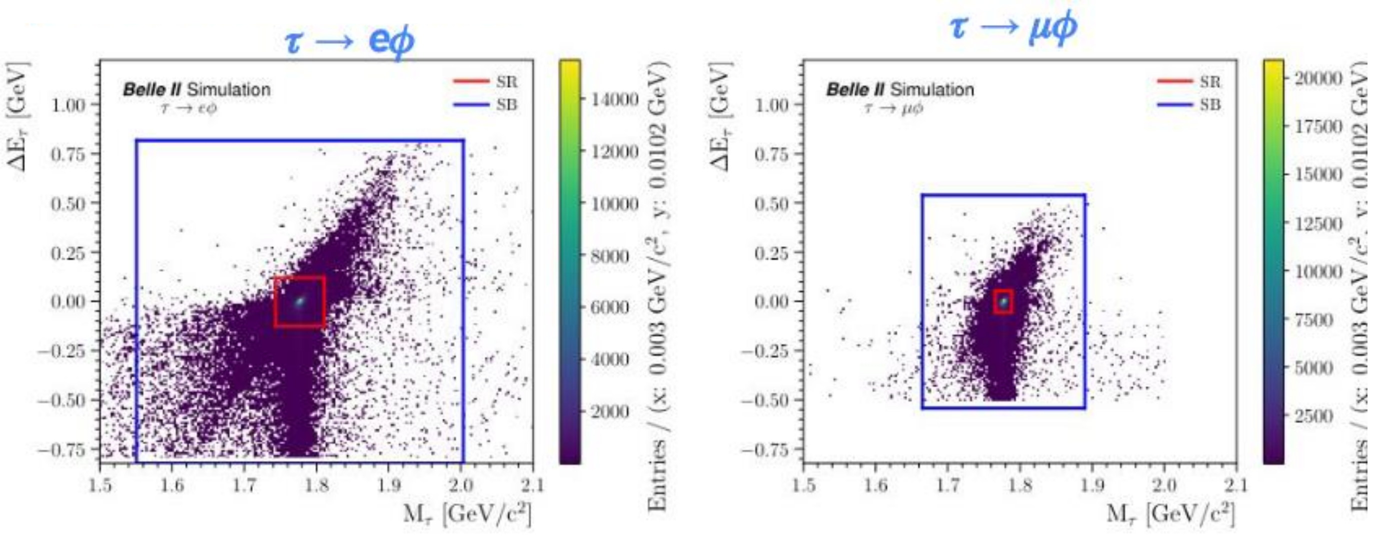
2.2 to 14 times more stringent upper limit has been obtained than that of the previous limit.
accepted by PRL (arXiv:2212.03634)

Search for $\tau \to \ell + \phi$

- Nuetrinoless τ lepton flavor violating decays can reconstruct τ mass. It is a food parameter to distinguish the signal from BG.
- At e⁺e⁻ collider, one more parameter good to indicate the signal exists: $\Delta E = E_{\tau}^{CM} - \frac{\sqrt{s}}{2}$

We reconstruct ϕ from $K^{+}K^{-}$.

For tag side τ, inclusively included. (Completely different from BaBar, Belle)

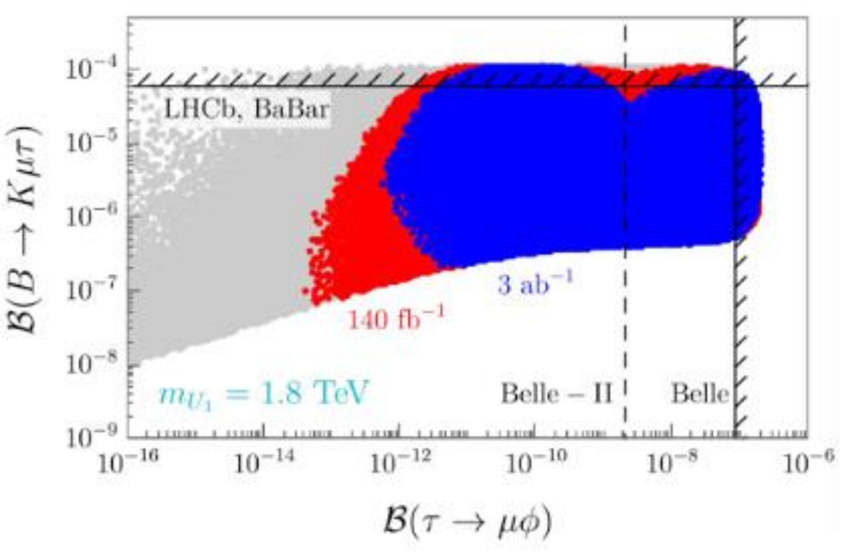


Signal MC distribution on $M_{\tau} - \Delta E$ plane

Motivation for $\tau \to \ell + \phi$ search

◦ Some Lepto-quark model predicts $\tau \to \ell + \phi$

These days, some attention has been paid to Lepto-quark model since it might explain R(D*) anomaly⋯
So, also in $\tau \to \ell + \phi$, such an effect is expected to appear.



Phys. Rev. D 104, 055017 (2021)

Result…

- This night (18:10 JST), at Moriond QCD, the result will be shown.

Inclusive method for tag side τ and BDT selection lead to a good result.

https://moriond.in2p3.fr/QCD/2023/MorQCD23Prog.html

(Near) future

- On-going/discussing analyses

Tau lifetime measurement

Lepton Flavor Universality

Vus measurement

LFV search

CPV search

SCC search

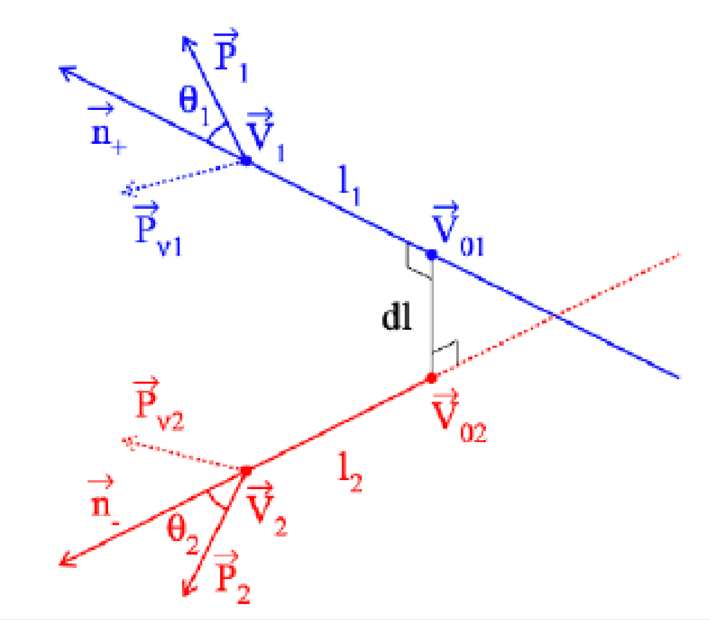
Tau lifetime measurement

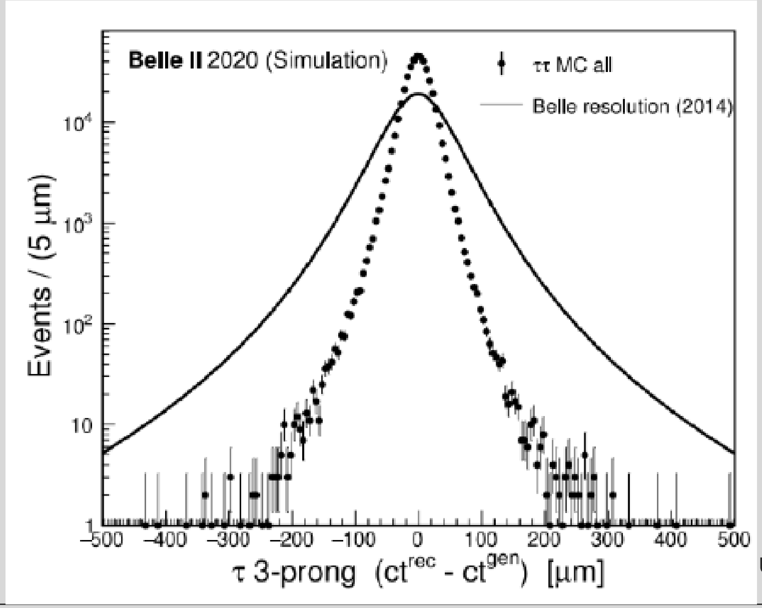
- Tau lifetime is also an important parameter.

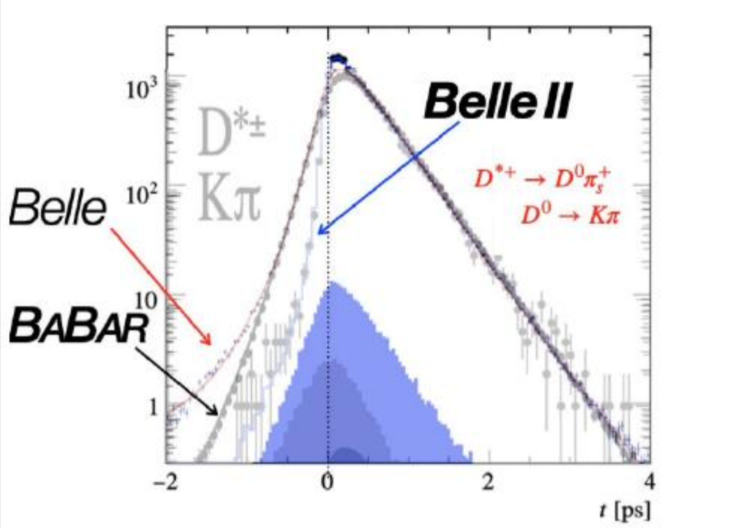
Using 3π decay vertices and nearest point of τ tracks, we can evaluate τ lifetime.

Thanks to better resolution of Belle II,

We can expect the better result.







$\tau(D^0) = 410.5 \pm 1.1(\text{stat}) \pm 0.8(\text{syst})$ fs

$\tau(D^+) = 1030.4 \pm 4.7(\text{stat}) \pm 3.1(\text{syst})$ fs

Actually, we have obtained the better result for D lifetime than that for Belle and BaBar.
(Phys. Rev. Lett. 127, 211801)

Test of the Lepton Flavor Universality

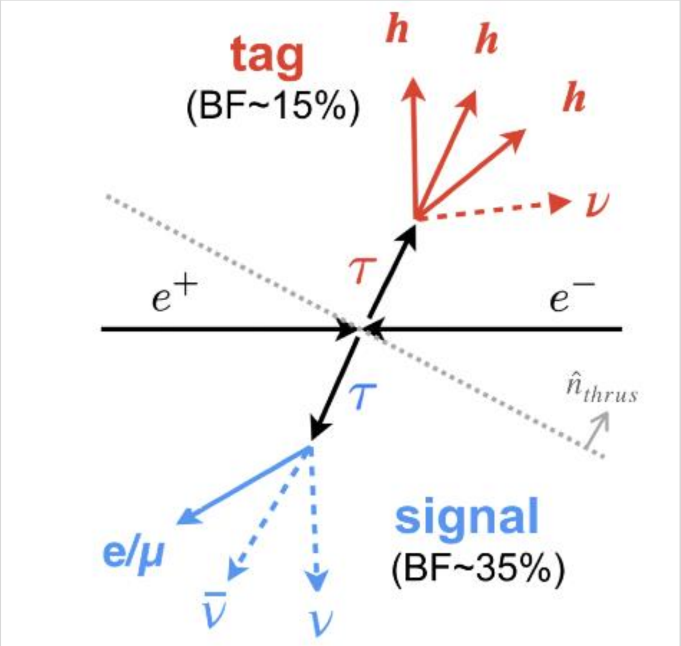
- For the leptonic (Michel) decay of τ, we can test of LFU for the coupling of the weak decay.

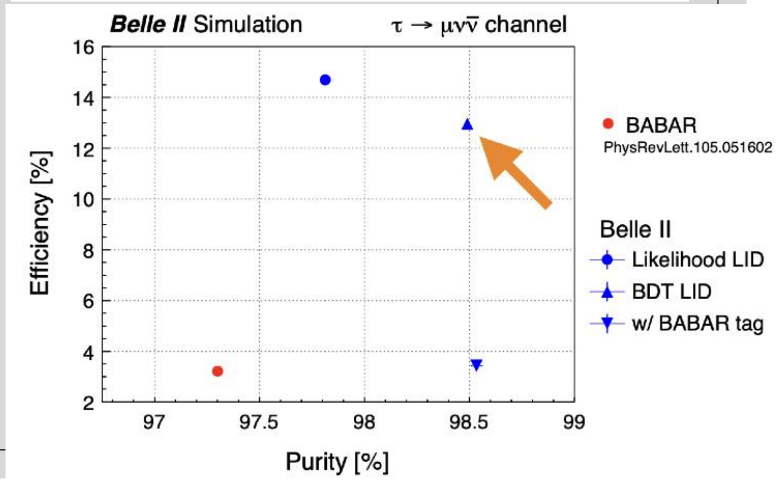
$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{Br(\tau\to\mu\nu\nu)}{Br(\tau\to e\nu\nu)}\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

Current world average is

$$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020\ .$$

Key of the analysis is systematic study.
PID, tracking and so on.





Other tests of SM

- As another kind of LFU test:

$$\left(\frac{g_\tau}{g_\mu}\right)_h \sim \sqrt{\frac{Br(\tau\to h\nu)}{Br(h\to\mu\nu)}\frac{2m_h m_\mu^2 \tau_h}{m_\tau^3 \tau_\tau}\frac{1-m_\mu^2/m_h^2}{1-m_h^2/m_\tau^2}},$$

$h = \pi, K$

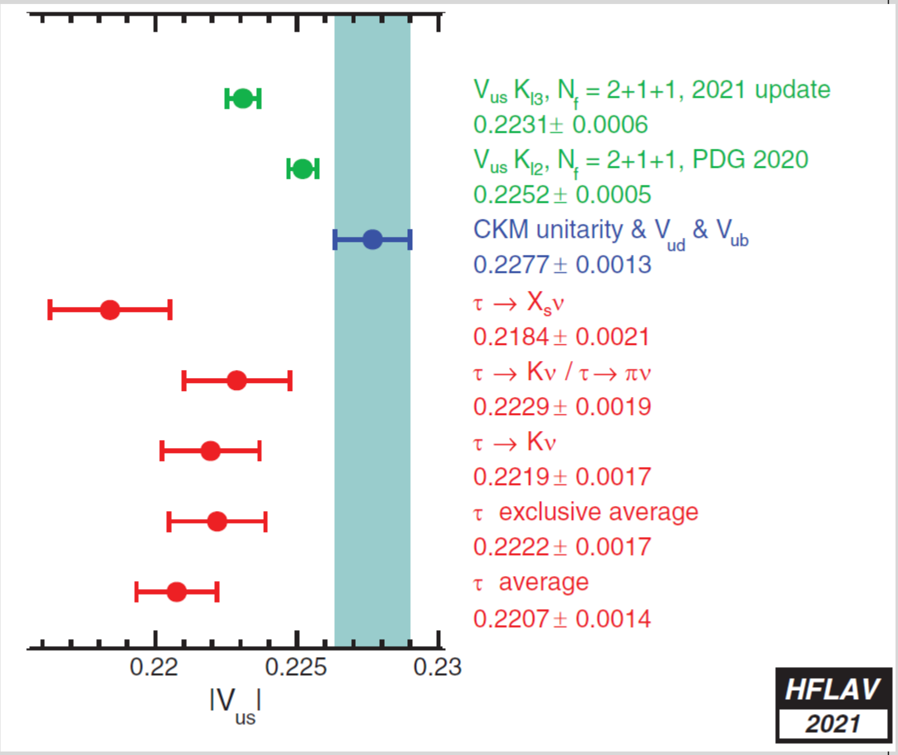
Current average:

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9959 \pm 0.0038,$$

$$\left(\frac{g_\tau}{g_\mu}\right)_K = 0.9855 \pm 0.0075.$$

$\tau \to K\nu, \pi\nu$ measurement is also important.

Also, in $|V_{us}|$ evaluation using τ decay, some discrepancy is seen.



LFV searches

- $\tau \to \ell\ell\ell$

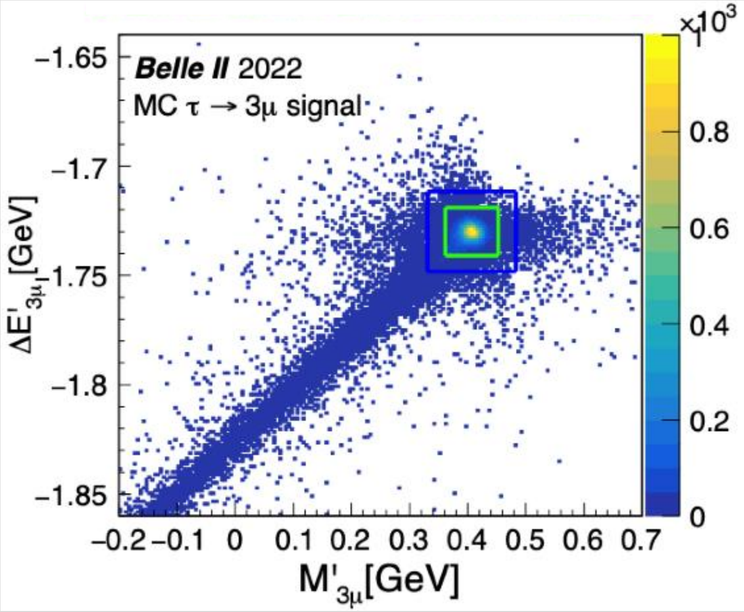
For 3μ, higher signal detection efficiency is achieved: 16% (Belle 8%) by including lower momentum track, introducing BDT, keeping 0 BG.

- $\tau \to \ell\gamma$ is also on-going,

introducing BDT.

- Other LFV modes are also

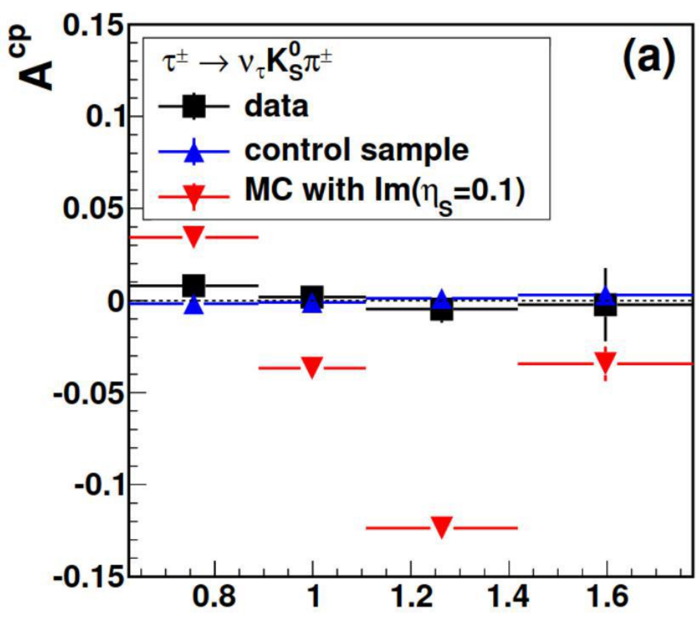
discussed / on-going.



CP Violation in lepton sector

- $A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \nu) - \Gamma(\tau^- \to \pi^- K_S^0 \nu)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \nu) + \Gamma(\tau^- \to \pi^- K_S^0 \nu)}$ is expected to be $(0.36 \pm 0.01)\%$ due to the K_S^0's CP Violation within SM.
- On the other hand, BaBar reports $A_\tau^{BaBar} = (-0.36 \pm 0.23 \pm 0.11)\%$.

→2.8σ discrepancy has been observed.



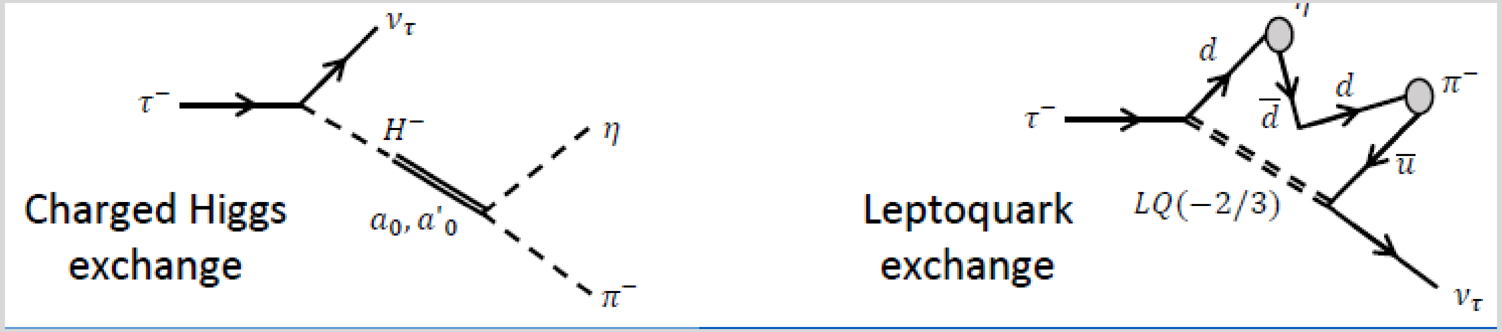
On the other hand, Belle focused on the angular distribution of the hadronic system and evaluate the CP asymmetry of that depending on the invariant mass of the hadronic system.

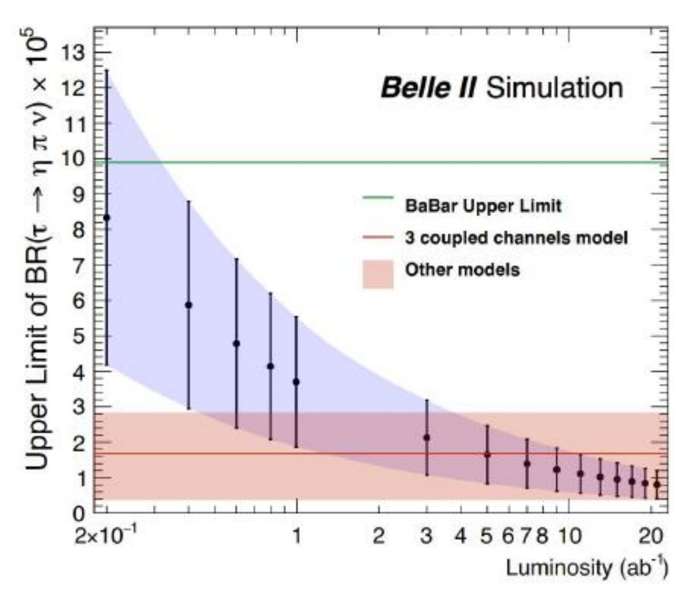
As a first priority, analysis to corss-check the BaBar result is on-going.

Second class current search

- Second class currents (SCC) violate G-parity, still present in the SM because of the charge and mass differences between up and down quarks, but heavily suppressed.
- $\tau \to \pi\eta\nu$ decay is induced by SCC and not yet observed. Its Br is estimated around 10^{-5}.

It might be enhanced by New Physics:





Summary

- Belle II is a good/unique playground for tau physics.
  - These days, we have several results:

    τ mass: the most precise measurement

    Search for $\tau \to \ell$+ missing: most stringent UL

    Search for $\tau \to \ell + \phi$
  - Various analyses are on-going:

With a good new detector, Belle II and a good accelerator, SuperKEKB, we perform many interesting analyses.

Just started!

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- Belle II is a good/unique playground for tau physics.
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    τ mass: the most precise measurement
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  - Various analyses are on-going:

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In full bloom!