Tau Lepton

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Standard model of particle physics

Material particle

Quark

Charge	+2/3	-1/3
Generation 1st	u Up	d Down
2nd	c Charm	s Strange
3rd	t Top	b Bottom

Lepton

0	-1
ν_e Electron neutrino	e Electron
ν_μ Mu neutrino	μ Muon
ν_τ Tau neutrino	τ Tau

Force propagation

Gauge boson

Electro-magnetic force
Photon
γ

Strong force
Gluons
g

Weak force
Weak bosons
$W^{\pm}$ Z^0

Origin of particle mass
Higgs boson
H

There is anti-particles.
Electron (e^-) ←→ Positron (e^+)

What is a Lepton?

- No strong interaction
- Weak interaction
- Electromagnetic interaction if charged lepton

- No internal structure/constituents
  - Hadron has internal constituents – quarks
- Spin 1/2

- Lepton number conservation
  - Charged leptons have associated neutrinos

Basic property of tau lepton

τ

$J = \frac{1}{2}$

Tau lepton property in PDG is listed here. Same spin with electron and muon. The mass is much heavy and the lifetime is short.

Mass $m = 1776.86 \pm 0.12$ MeV

$(m_{\tau^+} - m_{\tau^-})/m_{\text{average}} < 2.8 \times 10^{-4}$, CL = 90%

Mean life $\tau = (290.3 \pm 0.5) \times 10^{-15}$ s

$c\tau = 87.03\ \mu$m

Magnetic moment anomaly > -0.052 and < 0.013, CL = 95%

$\text{Re}(d_\tau) = -0.220$ to $0.45 \times 10^{-16}\ e$ cm, CL = 95%

$\text{Im}(d_\tau) = -0.250$ to $0.0080 \times 10^{-16}\ e$ cm, CL = 95%

Decay modes

$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e$

$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu$

$\tau^- \rightarrow \nu_\tau + \pi^-$

$\tau^- \rightarrow \nu_\tau + \rho^-$

$\tau^- \rightarrow \nu_\tau + \pi^- + \pi^+ + \pi^-$

$\tau^- \rightarrow \nu_\tau + \pi^- + \pi^+ + \pi^- + \pi^0$

- Spin 1/2
- Mass: 3600 x electron mass, 17 x muon mass
- Short lifetime
- Many decay modes

Tau decay

- Weak interaction

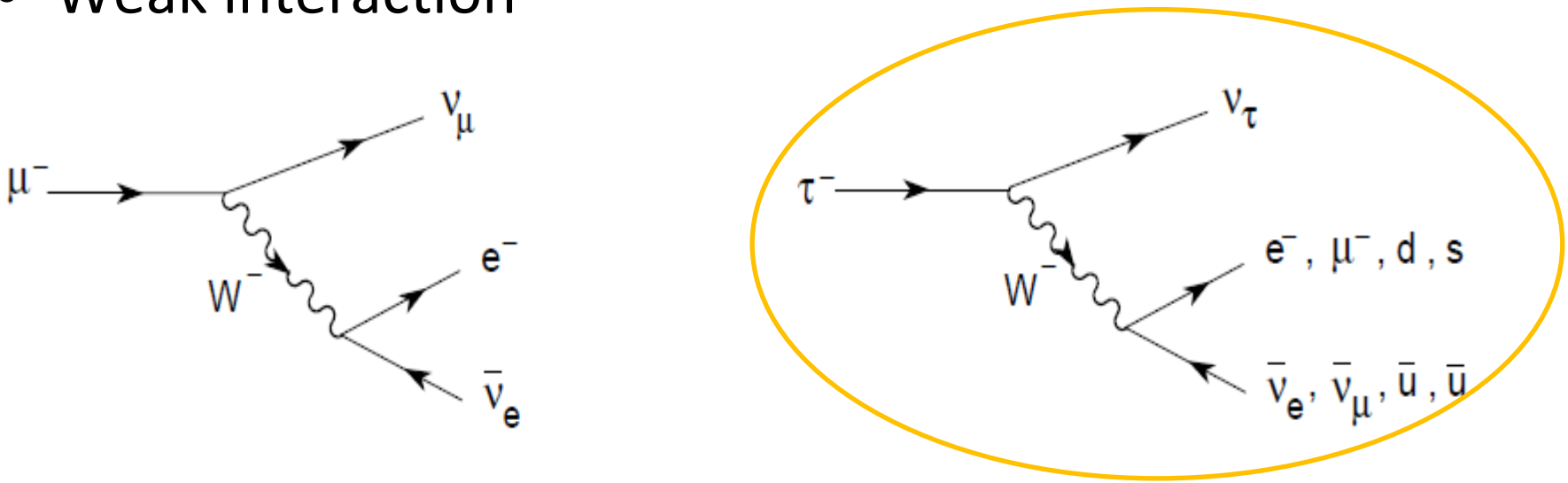


Figure 1: Feynman diagrams for $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ and $\tau^- \to \nu_\tau X^-$ $(X^- = e^- \bar{\nu}_e, \mu^- \bar{\nu}_\mu, d\bar{u}, s\bar{u})$.

  - Tau neutrino exists, because of the lepton number conservation
  - Tau produces hadrons since the tau mass is enough heavy.
    - → Many decay modes, short lifetime

Decay branching ratio

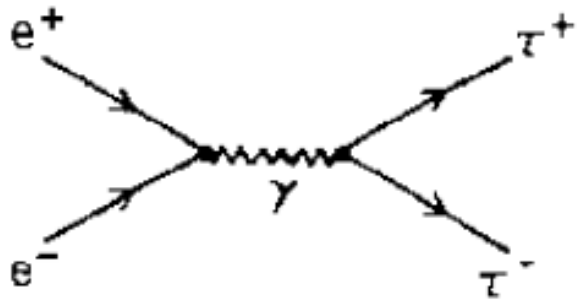
τ^- DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Modes with one charged particle				
particle$^-$ ≥ 0 neutrals $\geq 0 K^0 \nu_\tau$ ("1-prong")		(85.35 $\pm$0.07) %	S=1.3	–
particle$^-$ ≥ 0 neutrals $\geq 0 K^0_L \nu_\tau$		(84.72 $\pm$0.08) %	S=1.4	–
$\mu^- \overline{\nu}_\mu \nu_\tau$	[g]	(17.41 $\pm$0.04) %	S=1.1	885
$\mu^- \overline{\nu}_\mu \nu_\tau \gamma$	[e]	(3.6 $\pm$0.4) $\times 10^{-3}$		885
$e^- \overline{\nu}_e \nu_\tau$	[g]	(17.83 $\pm$0.04) %		888
$e^- \overline{\nu}_e \nu_\tau \gamma$	[e]	(1.75 $\pm$0.18) %		888
$h^- \geq 0 K^0_L \nu_\tau$		(12.05 $\pm$0.06) %	S=1.2	883
$h^- \nu_\tau$		(11.53 $\pm$0.06) %	S=1.2	883
$\pi^- \nu_\tau$	[g]	(10.83 $\pm$0.06) %	S=1.2	883
$K^- \nu_\tau$	[g]	(7.00 $\pm$0.10) $\times 10^{-3}$		820
$h^- \geq 1$ neutrals ν_τ		(37.11 $\pm$0.10) %	S=1.2	–
$h^- \geq 1 \pi^0 \nu_\tau$ (ex. K^0)		(36.59 $\pm$0.10) %	S=1.2	–
$h^- \pi^0 \nu_\tau$		(25.95 $\pm$0.09) %	S=1.1	878
$\pi^- \pi^0 \nu_\tau$	[g]	(25.52 $\pm$0.09) %	S=1.1	878
$\pi^- \pi^0$ non-$\rho(770) \nu_\tau$		(3.0 $\pm$3.2) $\times 10^{-3}$		878
$K^- \pi^0 \nu_\tau$	[g]	(4.30 $\pm$0.15) $\times 10^{-3}$		814
$h^- \geq 2 \pi^0 \nu_\tau$		(10.88 $\pm$0.11) %	S=1.2	–
$h^- 2 \pi^0 \nu_\tau$		(9.53 $\pm$0.11) %	S=1.1	862

Observation of tau

- Production process

$$e^+ + e^- \rightarrow \gamma_{virtual} \rightarrow \tau^+ + \tau^-$$

  - If the total energy is greater then twice the tau mass



- Production cross-section
  - Difference between spin 0 and 1/2 cases

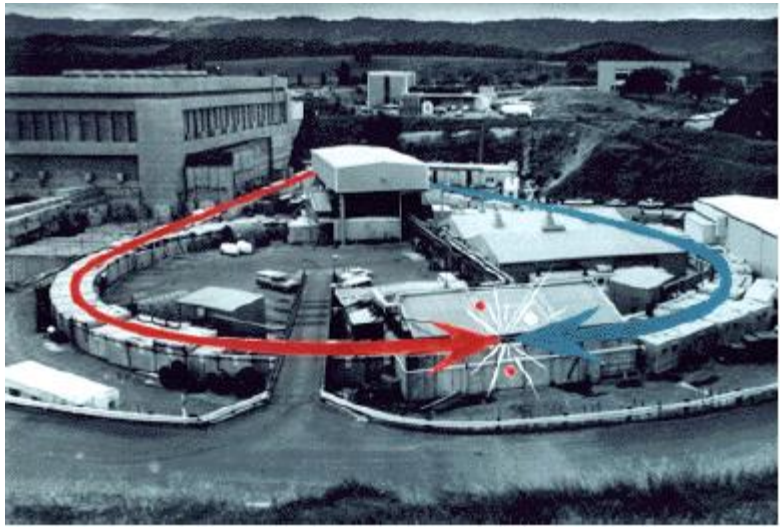
$$\text{spin } 0: \quad \sigma_{\tau\tau} = \frac{\pi\alpha^2\beta^3}{3s}$$

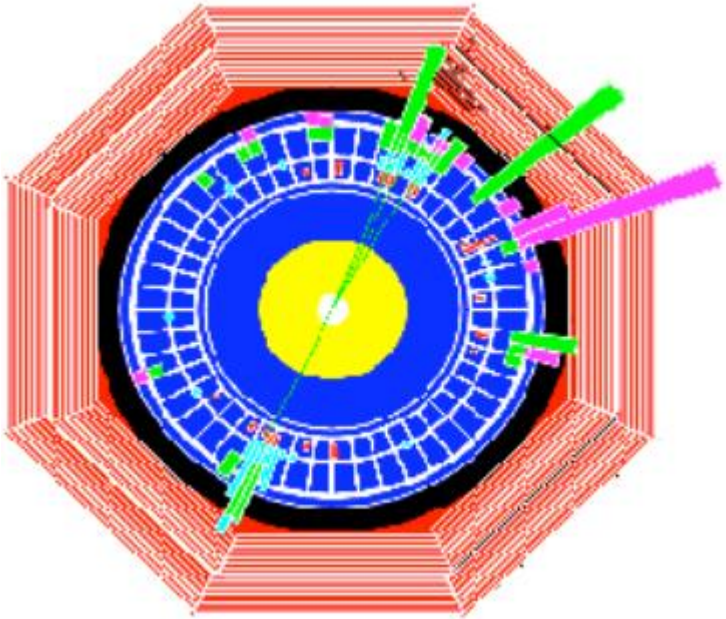
$$\text{spin } 1/2: \quad \sigma_{\tau\tau} = \frac{4\pi\alpha^2}{3s}\frac{\beta(3-\beta^2)}{2}$$

β: tau velocity in CM /c
α: fine structure constant
$s=E^2_{cm}$

SPEAR (one example of old experiment)

- e^+e^- collider experiment at SLAC
  - From 1972
  - Energy : 3GeV ~
  - Tau observation





Tau is observed in SPEAR experiment, which is electron-position collider experiment at SLAC.

Tau production signatures

- Experimental results
  - eμ events
    - Only two charged particles (electron/muon) detected
    - Total charge zero
  - SPEAR experiment

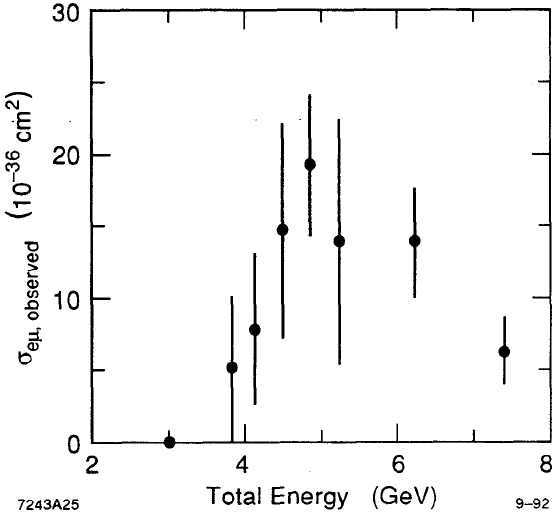


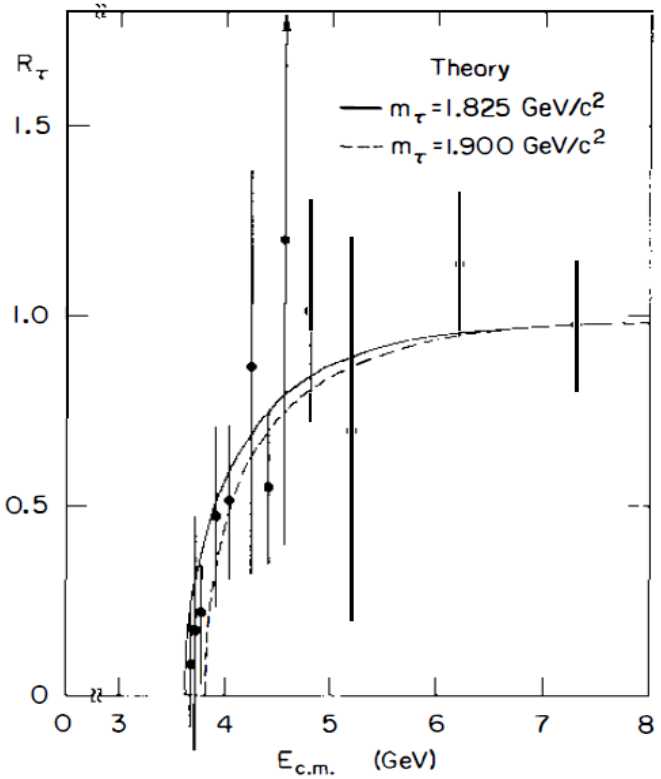
Fig. 4. From Perl *et al.* (1975): the observed cross section for the signature $e\mu$ events from the Mark I experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.

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

$$\tau^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\tau$$

$$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$$

$$R_{e\mu,observed} = 2R_\tau B(\tau \rightarrow e\nu's) B(\tau \rightarrow \mu\nu's) A_{e\mu}$$



Tau production signatures

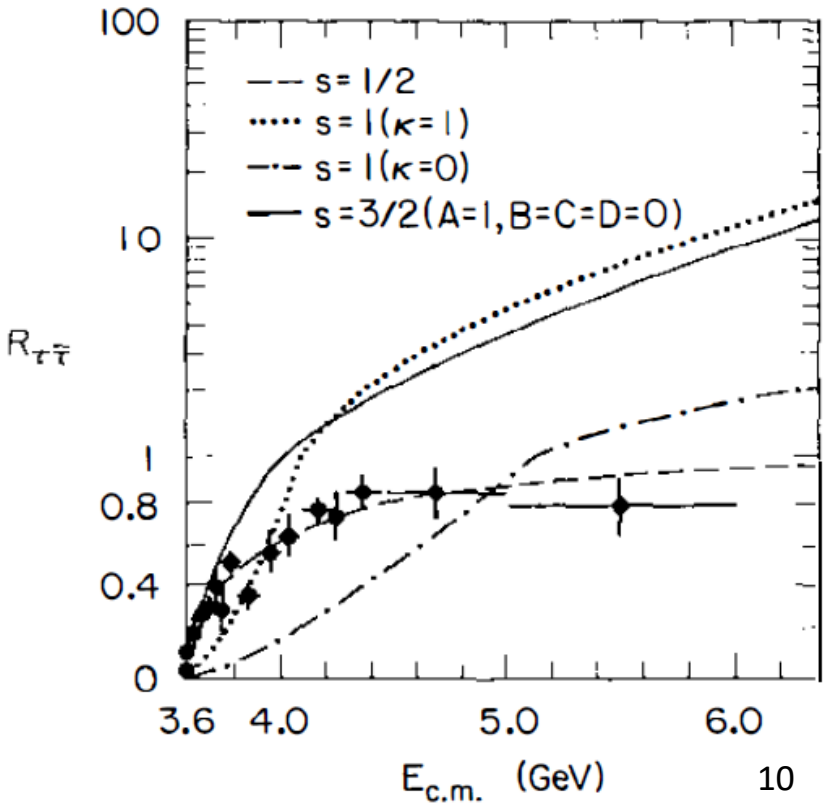
- Experimental results
  - Electron/muon + hadron events

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

$$\tau^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\tau$$

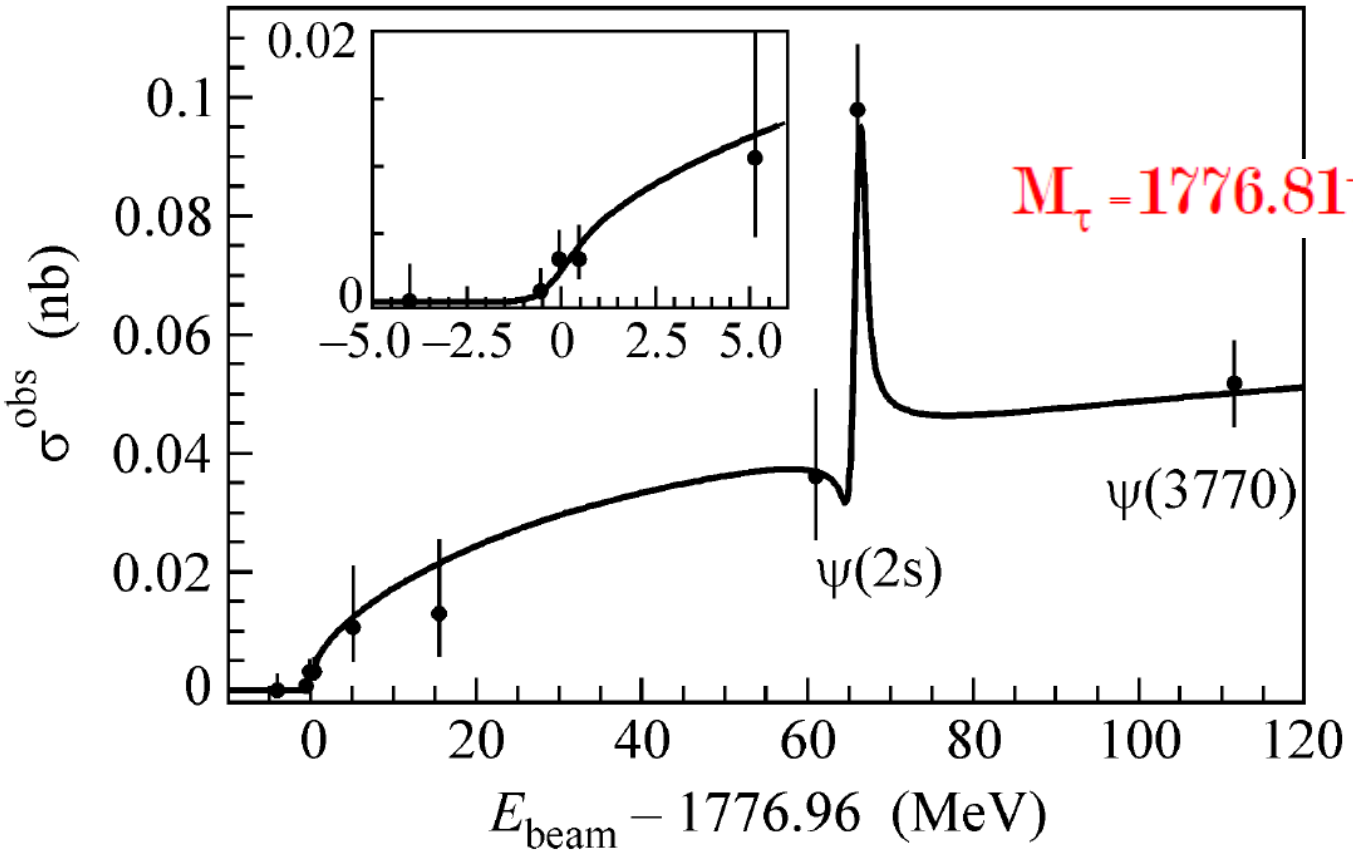
$$\tau^- \rightarrow \text{hadron}^- + \nu_\tau, \quad (\text{hadron} = \pi \text{ or } K)$$

  - DORIS, SPEAR experiments
  - Data indicates tau spin of 1/2.



Tau mass

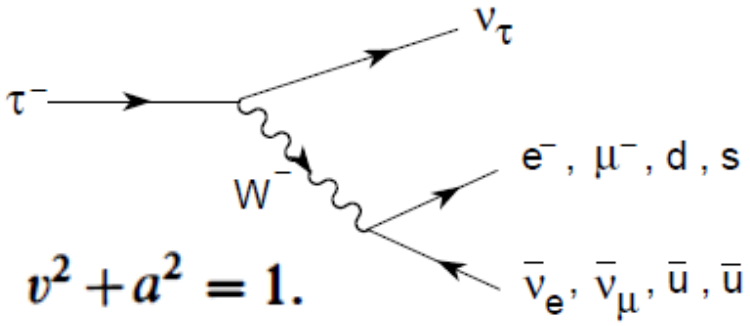
- Threshold scan
  - Measure cross-section of tau-like events depending on the beam energy in e^+e^- collider



$$M_\tau = 1776.81^{+0.25}_{-0.23} \pm 0.15 \text{ MeV}$$

Coupling

- Coupling in tau decay
  - Really weak coupling or not?



$$J^{\lambda}_{\tau\nu_\tau} = g_\tau \bar{u}_{\nu_\tau} \gamma^\lambda (v - a\gamma_5) u_\tau ;\ v, a \text{ real}, \quad v^2 + a^2 = 1.$$

  - → Measure momentum of decay products

$$dP/dy = y^2[6(v-a)^2(1-y) + (v+a)^2(3-2y)] \qquad 43.$$

where y = e or μ momentum/maximum e or μ momentum, and the e or μ mass and all neutrino masses are set to zero (Bjorken & Drell 1964). Of

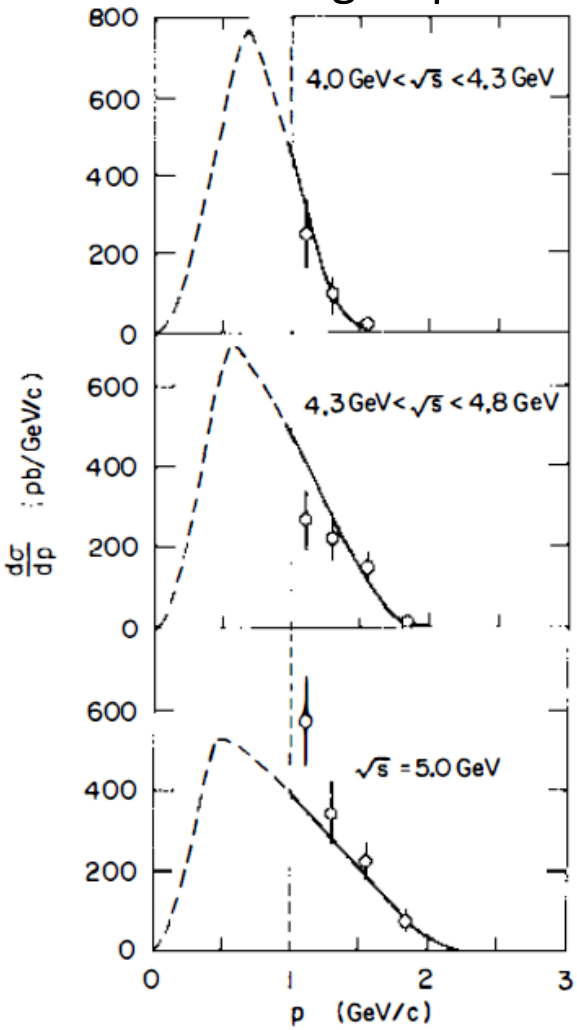
  - Pure weak coupling predicts V-A current.

Type	v	a
V − A	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
pure V	1	0
pure A	0	1
V + A	$\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$

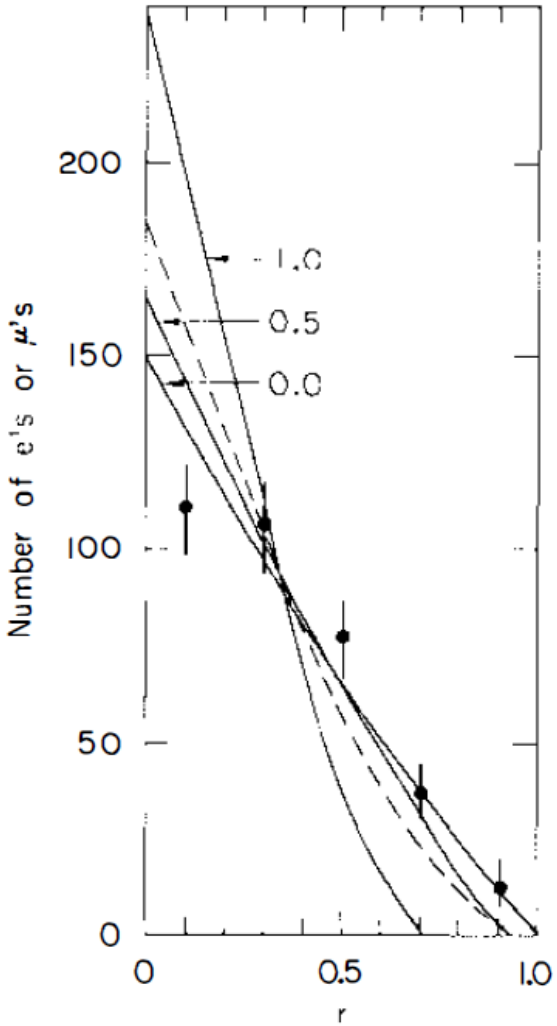
Coupling

- Results indicates: V-A coupling, spin 1/2

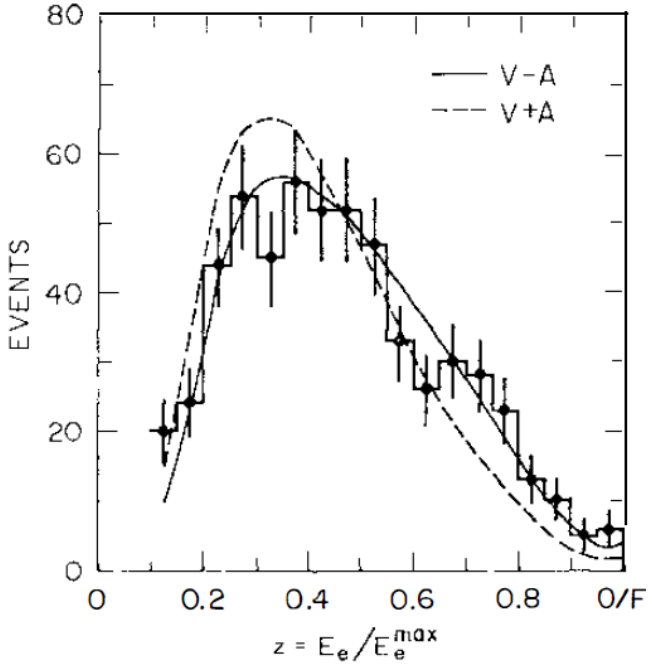
PLUTO group



SLAC-LBL

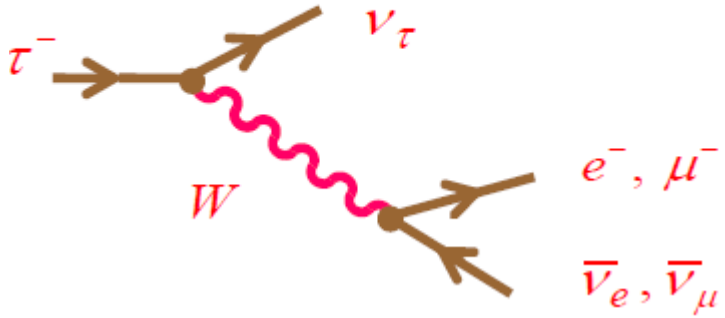


DELCO group

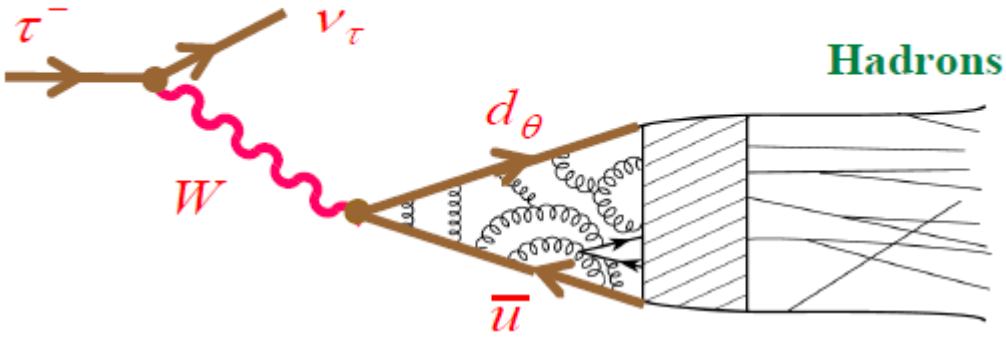


SM test / new physics searches by Tau

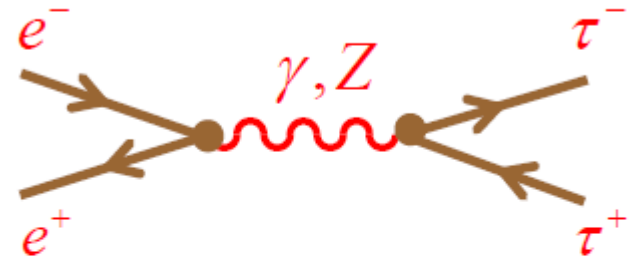
Decay

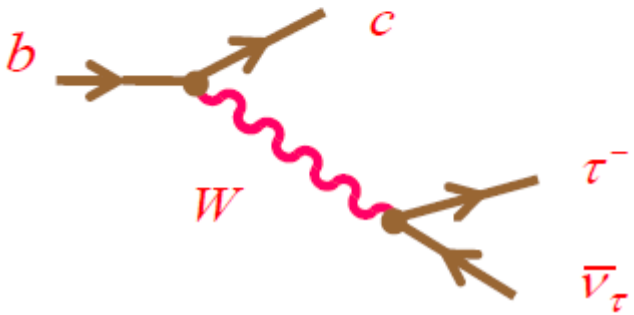


QCD

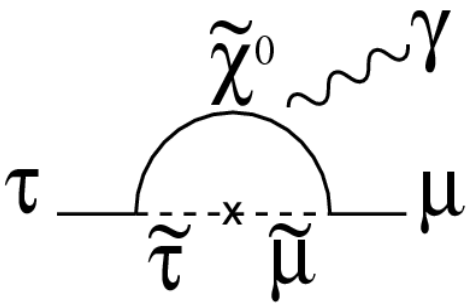


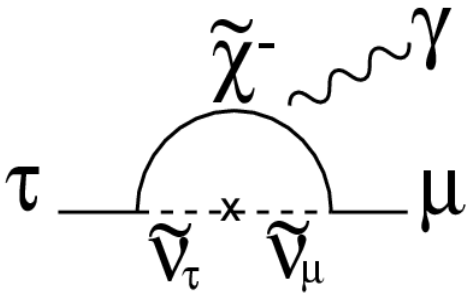
Production





New Physics





Data analysis by tau

- Tau mass, ν_τ mass, Lifetime
- Test of Universality
  - Br($\tau\to\mu\nu\nu$)/ Br($\tau\to e\nu\nu$), etc.
- Hadronic decays
  - Mass spectrum in $\tau\to\pi\pi^0\nu$
  - Search for $\tau\to\pi/K\phi\nu$, $\pi/K\eta\nu$, ...
  - $\tau\to K_s\pi\nu$, ... (α_s, strange quark mass)
  - CP violation in tau decay

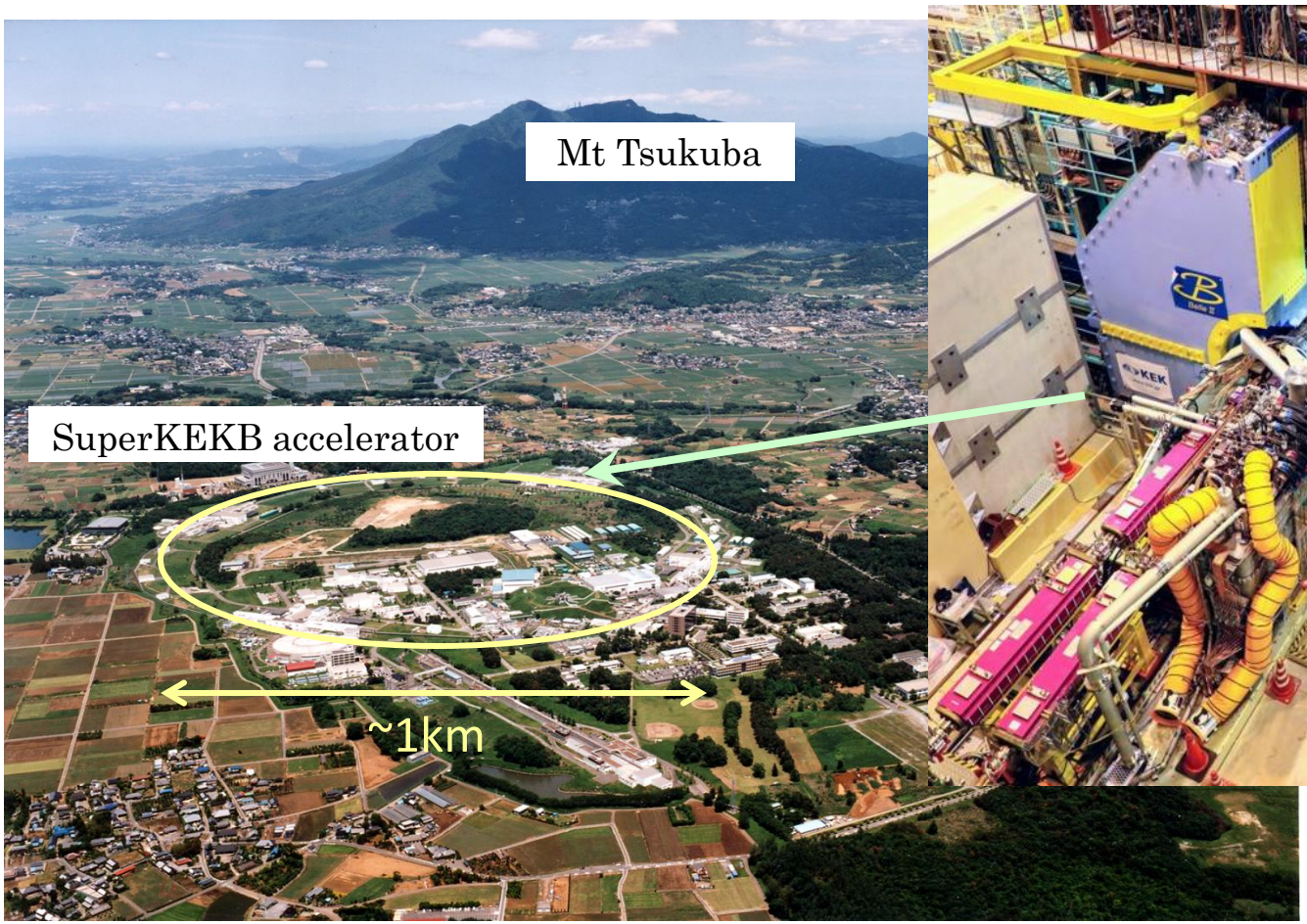
SM precise test

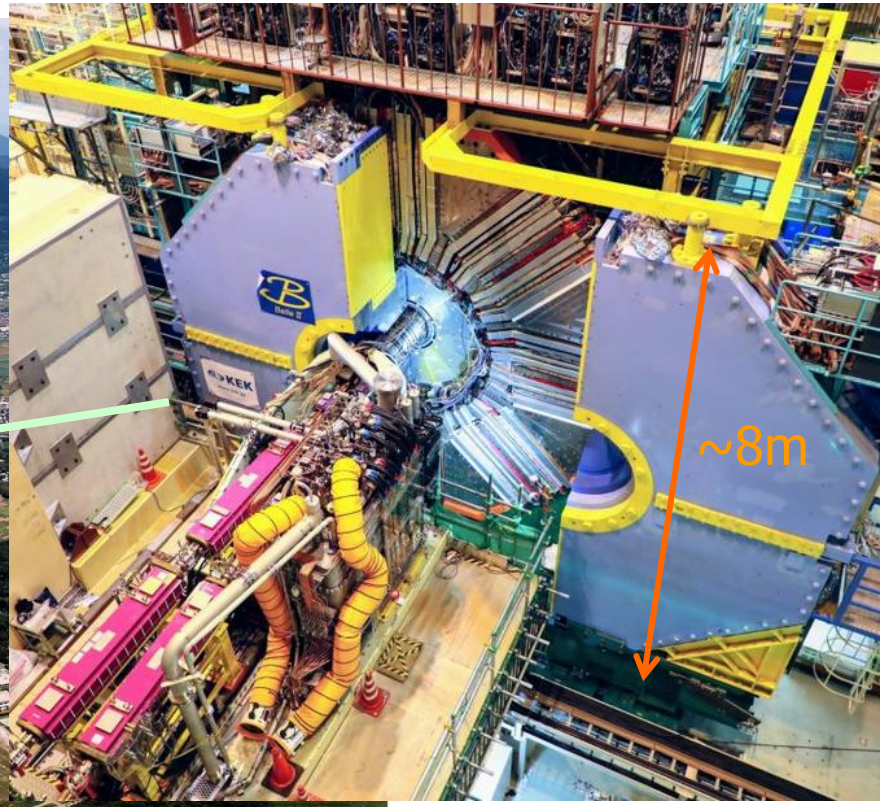
- Lepton flavor violating decays
  - $\tau\to\mu\gamma$, $e\gamma$, $\mu\eta$, $e\eta$, $p\gamma$, $\Lambda\pi$, lll, $ee\to\tau\mu$, ...
- Electric Dipole Moment (CP/T violation)

New physics searches

SuperKEKB/Belle II experiment

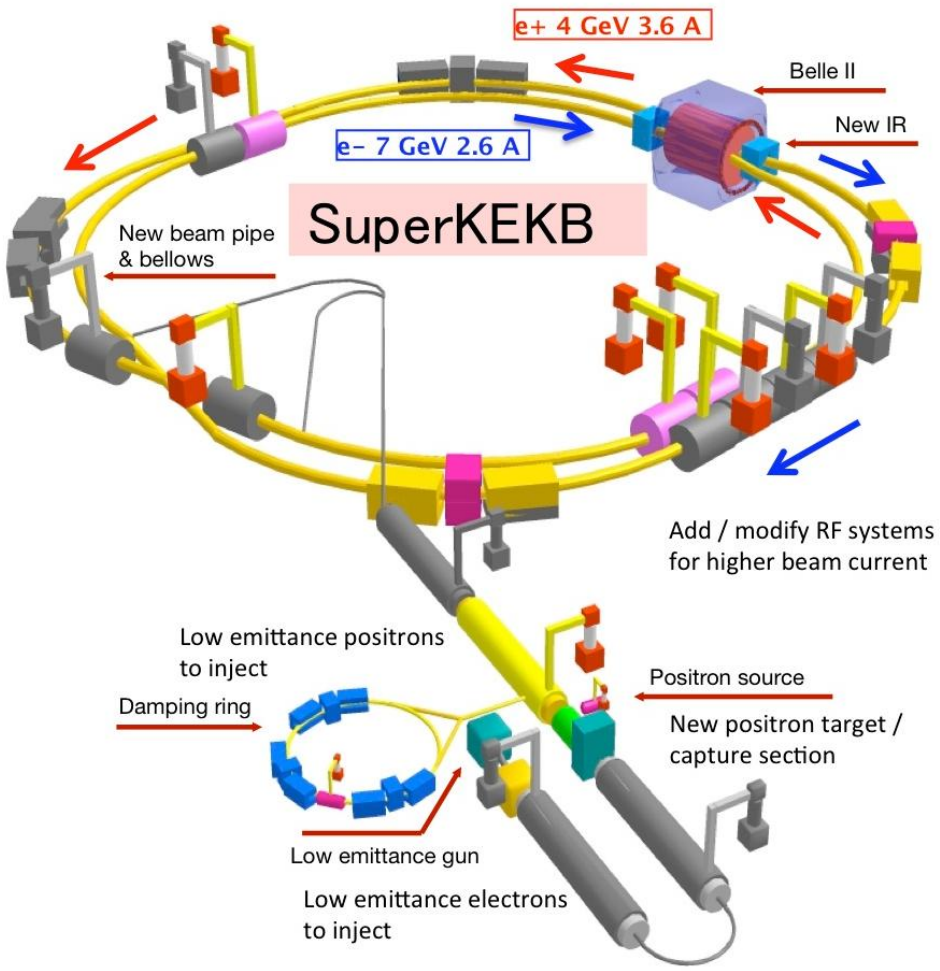
- Electron(7GeV)-positron(4GeV) collider experiment at KEK Tsukuba Japan
- Belle II detector; good tracking and particle identification, forward/backward asymmetric geometry.





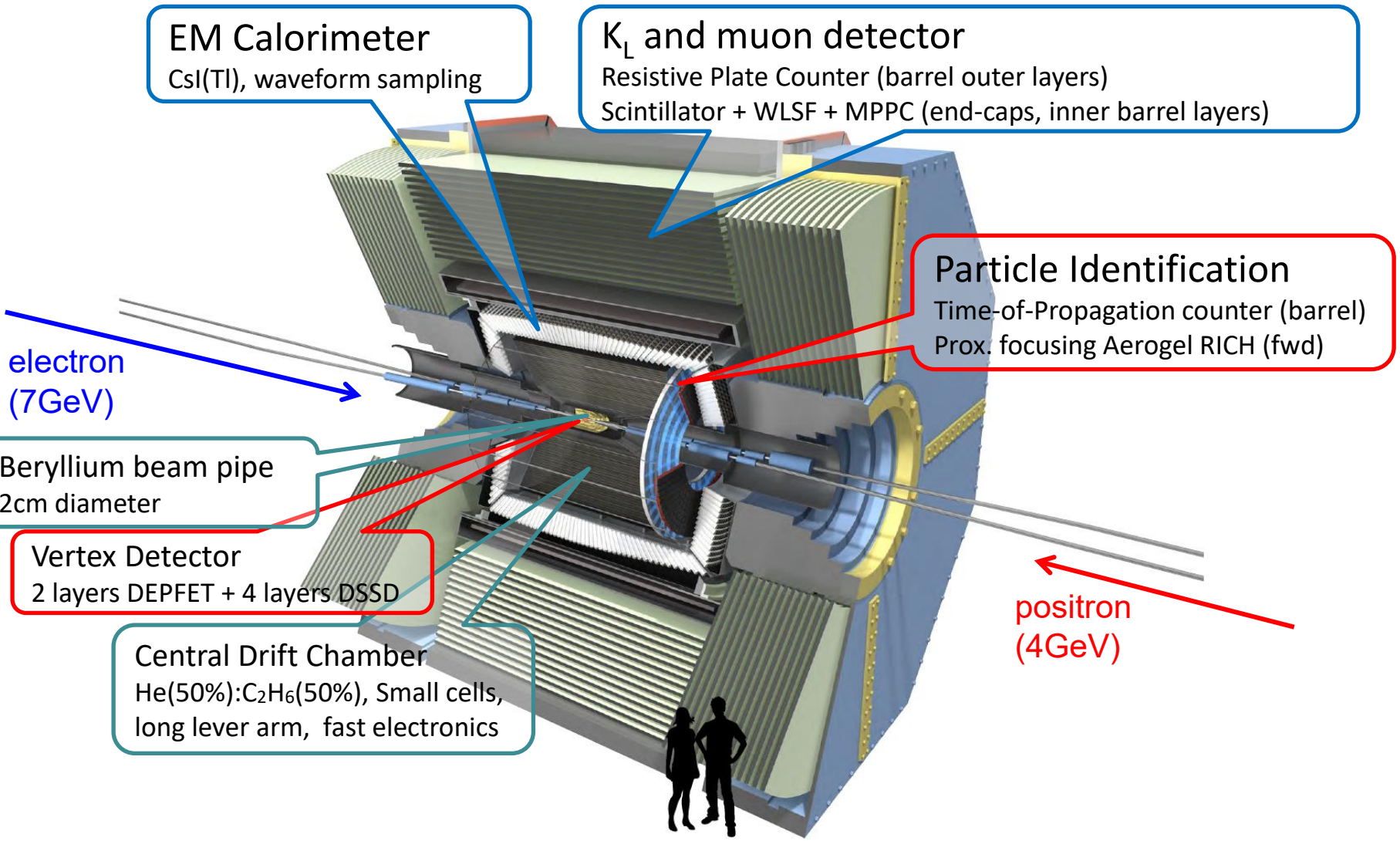
SuperKEKB accelerator

- Advanced B-factory
  - Upgraded from KEKB
- Challenges to higher luminosity
  - Narrower beam at IP
  - Higher beam current
  - Detector works with higher beam background and trigger rates
  - x50 higher than previous B factory



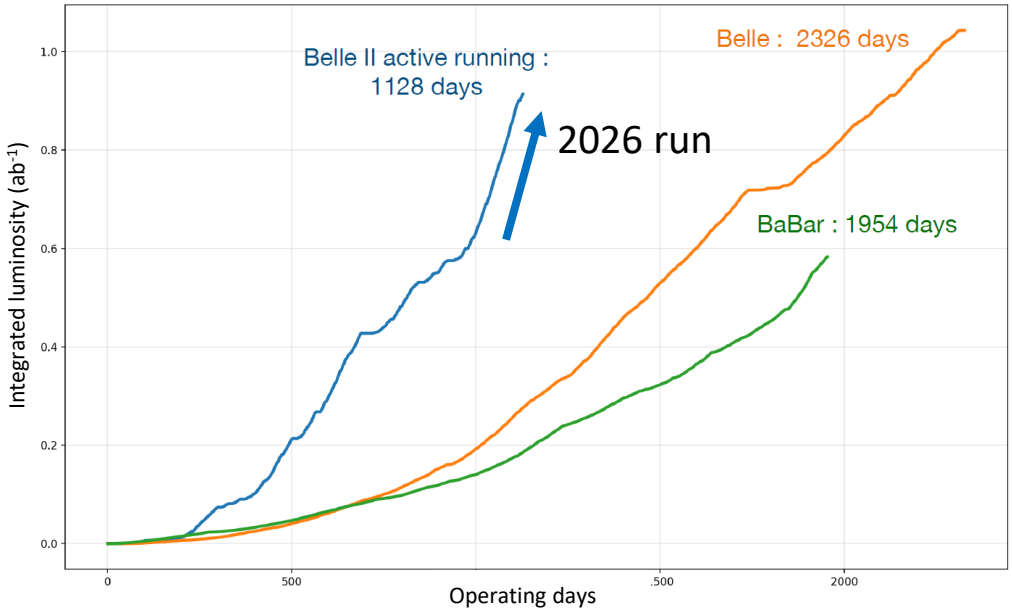
Belle II detector

General purpose, forward/backward asymmetric acceptance



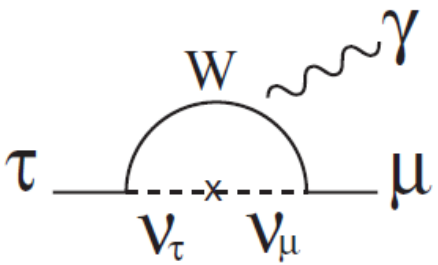
Belle/Belle II data

- Belle
  - Peak luminosity: $2.1 \times 10^{34} cm^{-2} s^{-1}$
  - Record $>1000 fb^{-1}$ at Y(4S)
- Belle II
  - Peak luminosity: $5.3 \times 10^{34} cm^{-2} s^{-1}$
  - Integrated luminosity:~$914 fb^{-1}$
- Collected same amount of data as at twice Belle's speed
  - 2026 run is 5 to 6 times faster than Belle's



Lepton Flavor Violation in tau decay

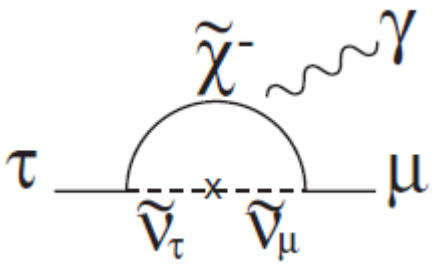
In the Standard Model, LFV is highly suppressed.
Impossible to access; Br<O(10^{-54})



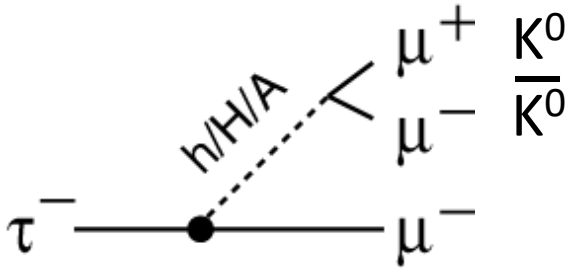
Many extensions of the SM predict LFV decays.
Their branching fractions are enhanced as high as current experimental sensitivity
⇒Observation of LFV is a clear signature of New Physics (NP)

Tau lepton : the heaviest charged lepton

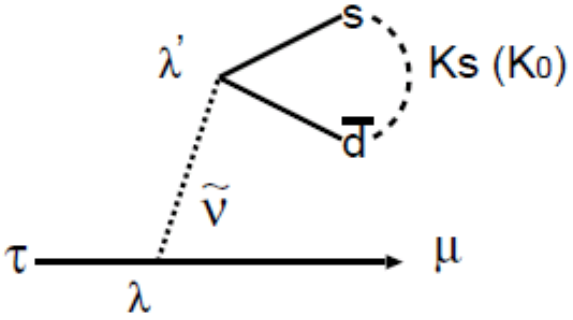
- Opens many possible LFV decay modes which depend on NP models



SUSY

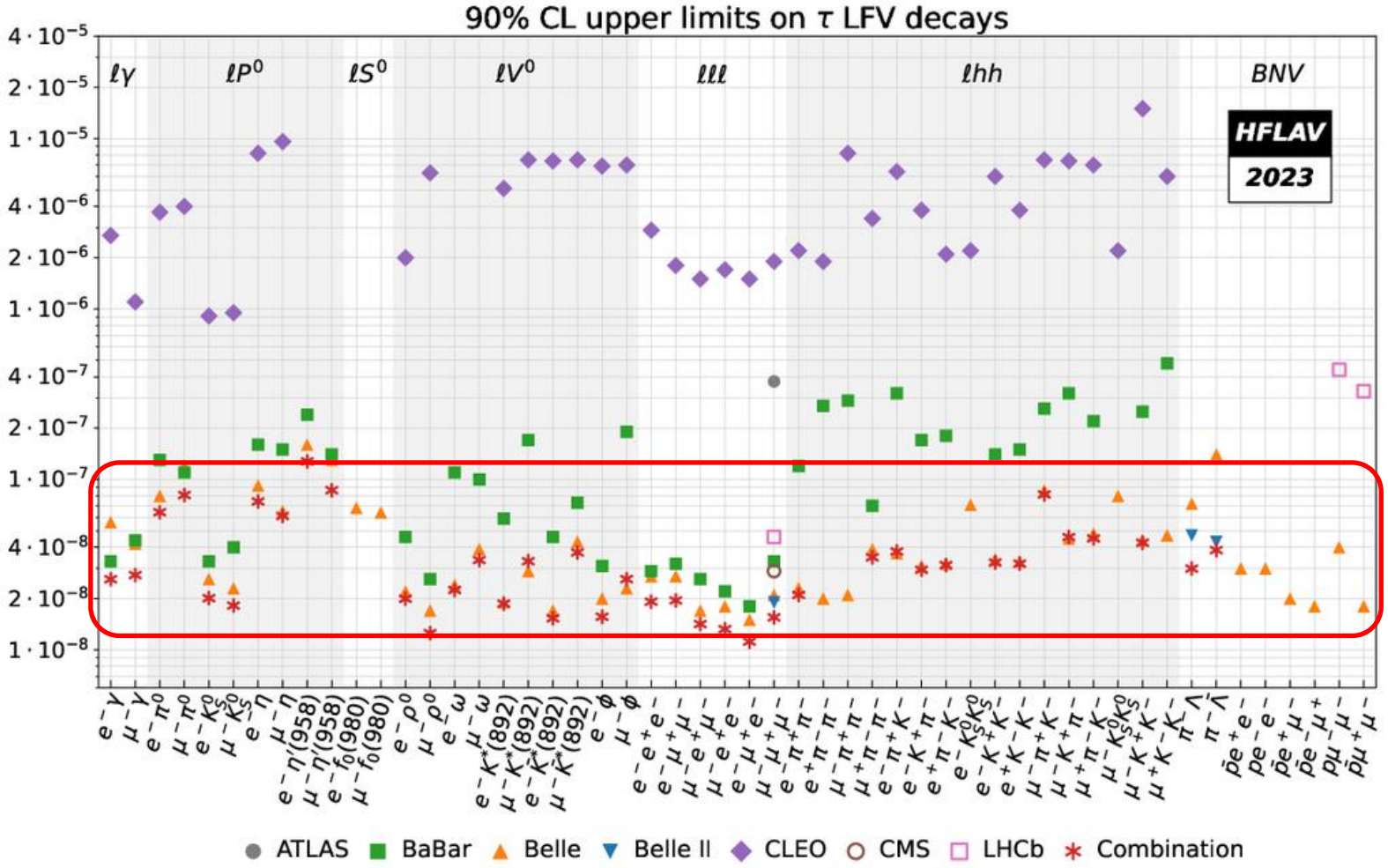


Higgs-mediation LFV



R-parity violation

Upper limits on LFV τ decays

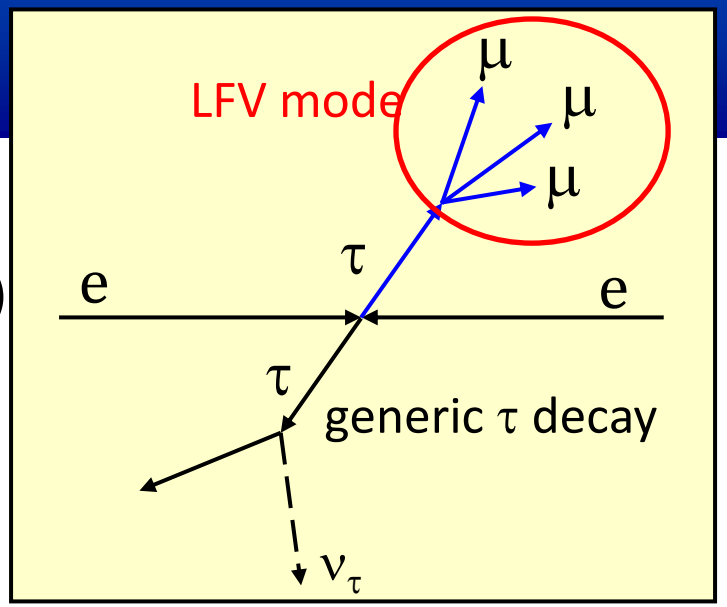


- Belle, Babar reached O(10^{-8}) branching ratio, LHCb improving the result
- $\tau \rightarrow \ell\ell\ell$, ℓ+mesons (to charged particles) show better sensitivity because of less background.

Tau LFV analysis

- $e^+e^- \to \tau^+\tau^-$ Br~85%
  - 1 prong + missing (tag side)
  - $\mu\mu\mu$ (LFV mode, signal side)

Fully reconstructed

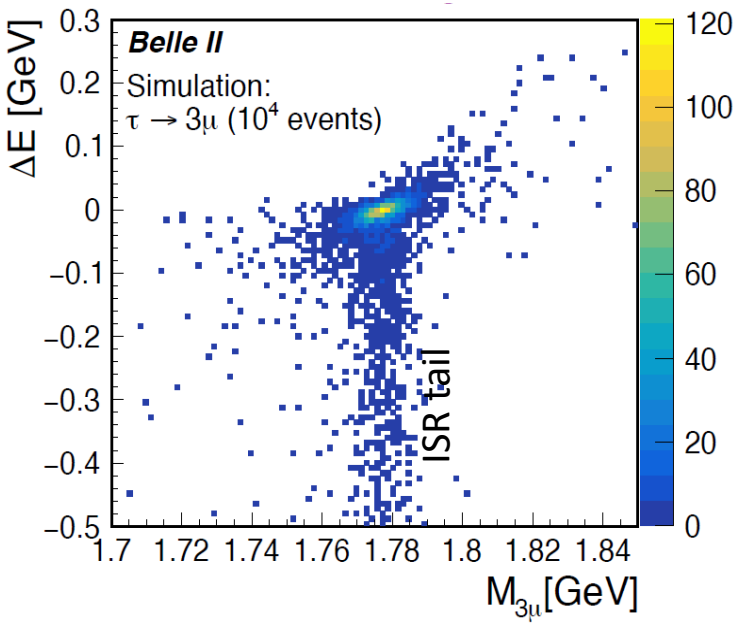


Signal extraction: $M_{3\mu}$–ΔE plane

$$\Delta E = E_{3\mu} - E_{beam}$$

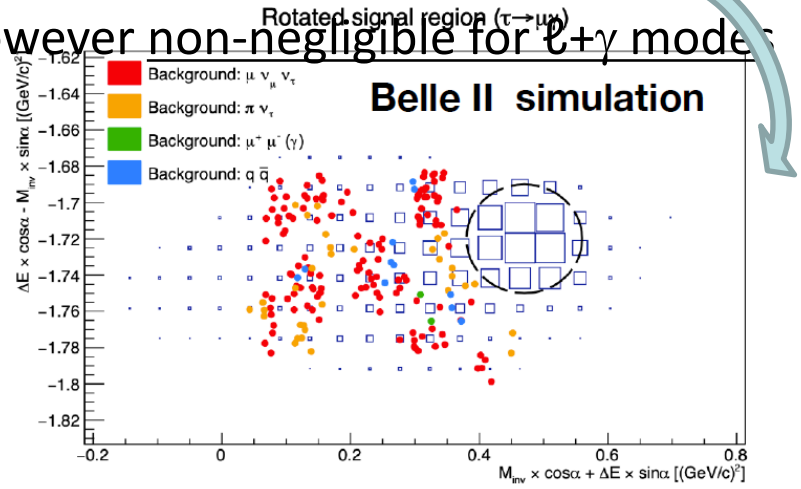
(or rotated signal plane to reduce correlation)

Evaluate background from side band



BG contribution is small for 3lepton modes because of good PID performance,

however non-negligible for $\ell+\gamma$ modes



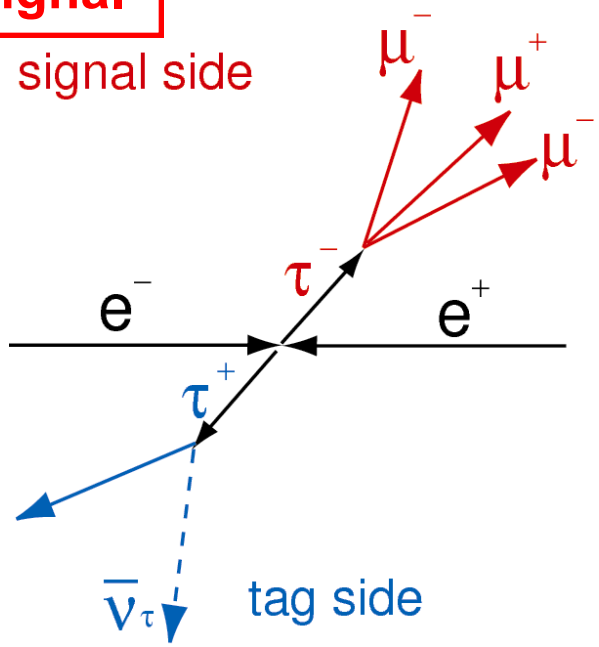
The Belle II Physics Book arXiv:1808.10567v2

LFV τ decays; Signal and Background

- $e^+e^- \rightarrow \tau^+ \tau^-$
  - 1 prong tau decay (BR~85%)

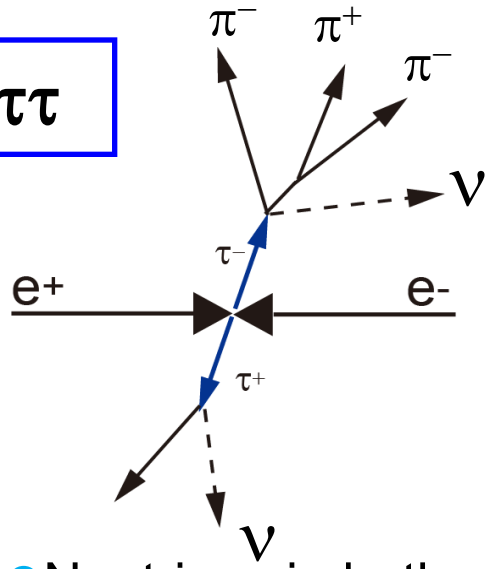
signal

signal side



- Neutrino(s) in tag side
- Particle ID
- (Mass of mesons)

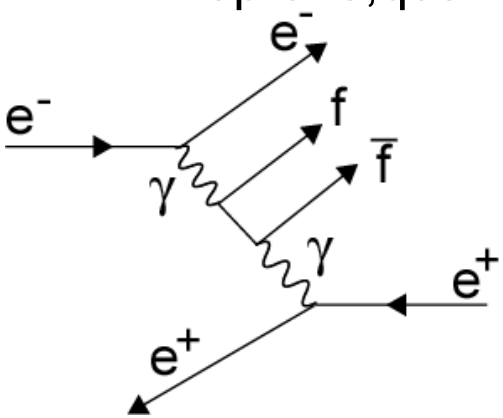
ττ



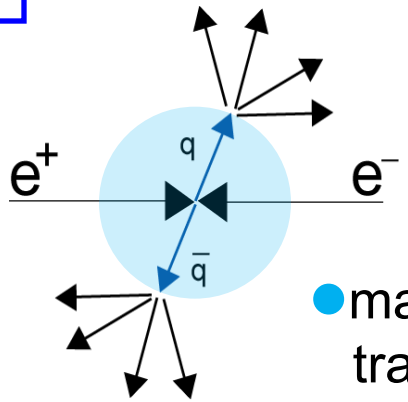
- Neutrinos in both side
- Missing energy in signal side

2photon process

f=leptons,quarks

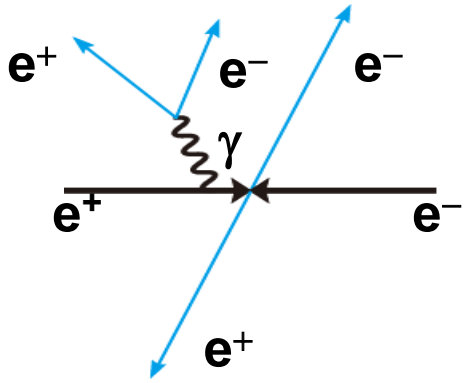


qq̄

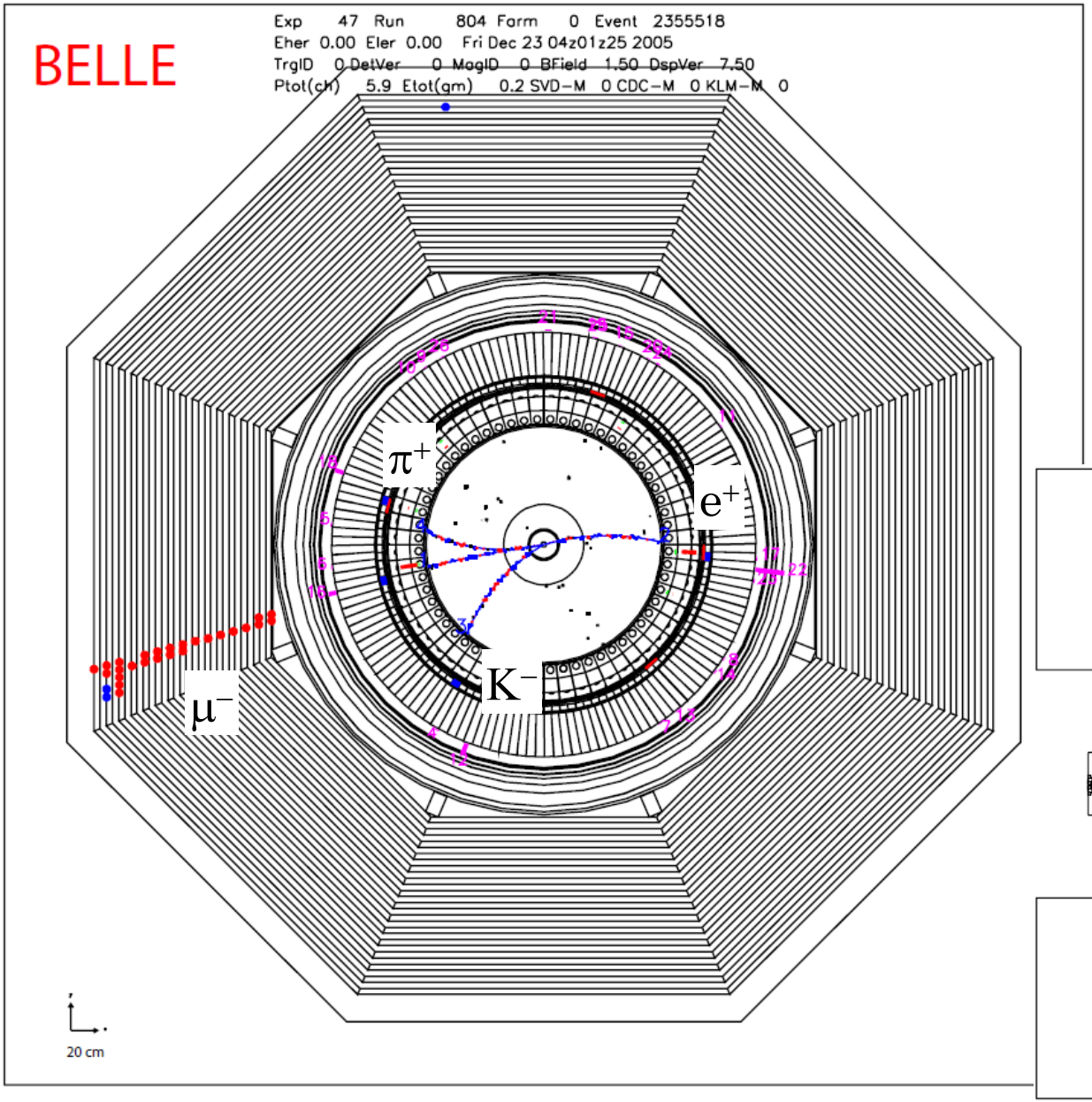


- many tracks

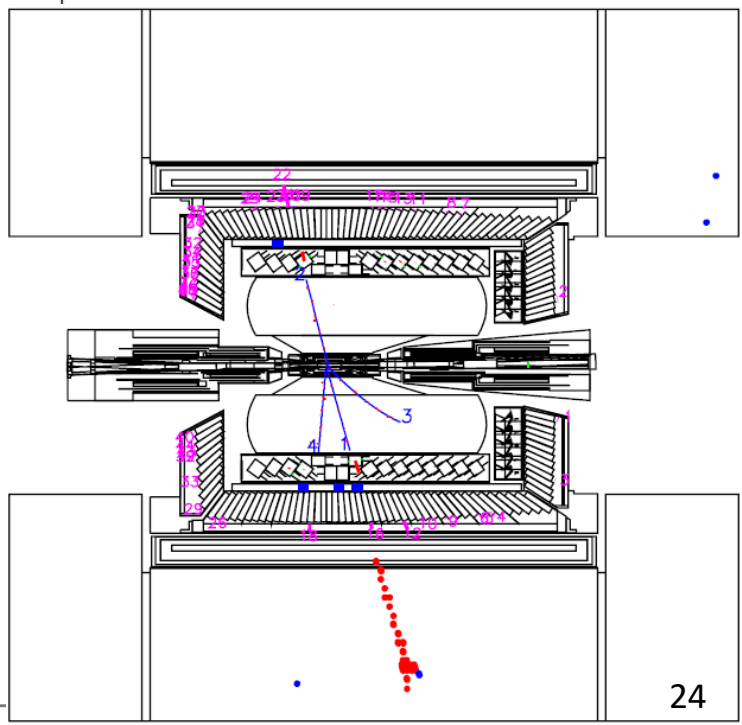
radiative Bhabha process



Event display



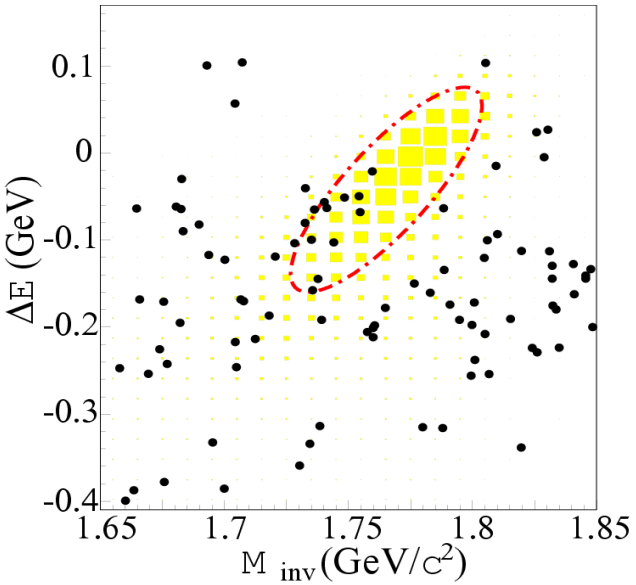
$\tau \rightarrow \mu \bar{K}^*$ candidate



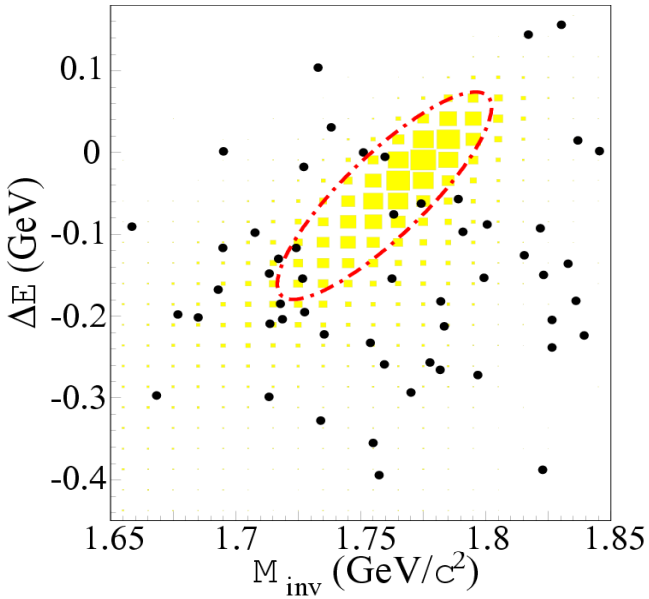
$\tau \to \mu\gamma$, $e\gamma$

Phys. Lett. B 666, 16 (2008)

- Data; 535fb^{-1}
  - $\tau \to \mu\gamma$



    - Br<4.5x10^{-8} at 90%C.L.
  - $\tau \to e\gamma$



    - Br<1.2x10^{-7} at 90%C.L.

- Dominant background

  $e^+e^- \to \tau^+\tau^-\gamma$, $\tau \to \mu\nu\nu$ (~70%)

$\tau \to \mu\gamma$, $e\gamma$

Phys.Rev.Lett.104:021802,2010

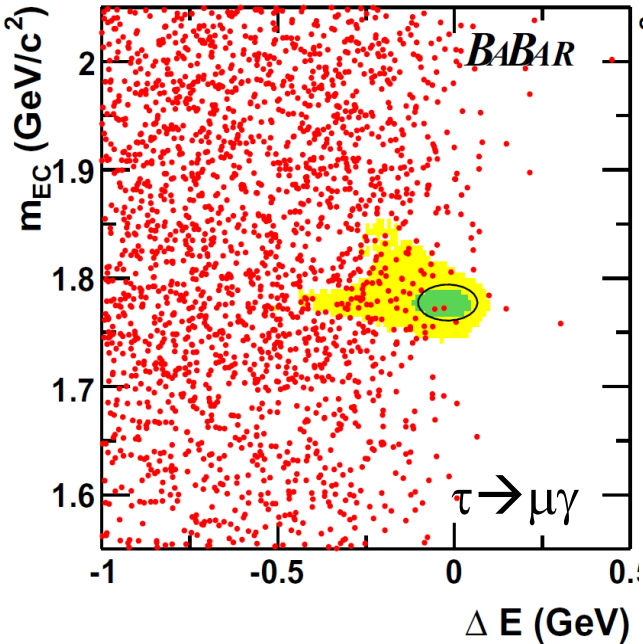
- Data: 470fb^{-1}+31fb^{-1}@Υ(3S)+15fb^{-1}@Υ(2S)
  - (963$\pm$7)x10^6 τ decays
- Dominant BG:

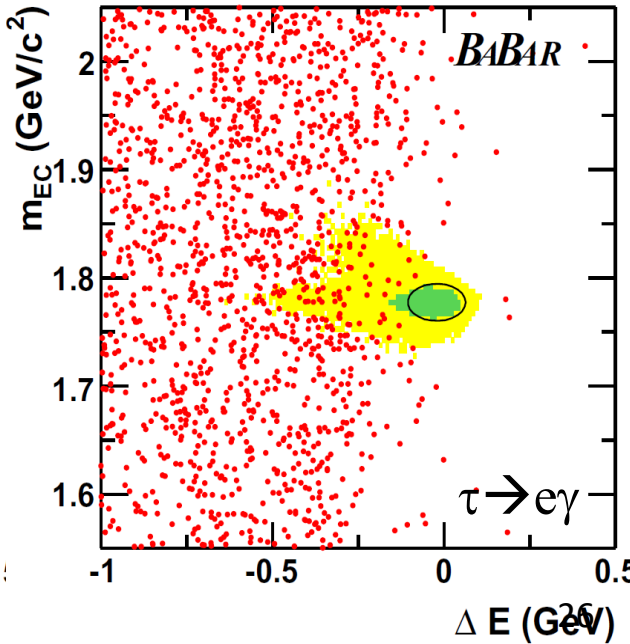
  $\tau \to l\nu\nu$ + radiation

  (<u>irreducible BG</u>)

Decay modes	2σ signal ellipse		ε	UL ($\times 10^{-8}$)	
	obs	exp	(%)	obs	exp
$\tau^{\pm} \to e^{\pm}\gamma$	0	1.6$\pm$0.4	3.9$\pm$0.3	3.3	9.8
$\tau^{\pm} \to \mu^{\pm}\gamma$	2	3.6$\pm$0.7	6.1$\pm$0.5	4.4	8.2

- B($\tau \to \mu\gamma$)<4.4x10^{-8}
- B($\tau \to e\gamma$)<3.3x10^{-8}





Search for τ→μγ

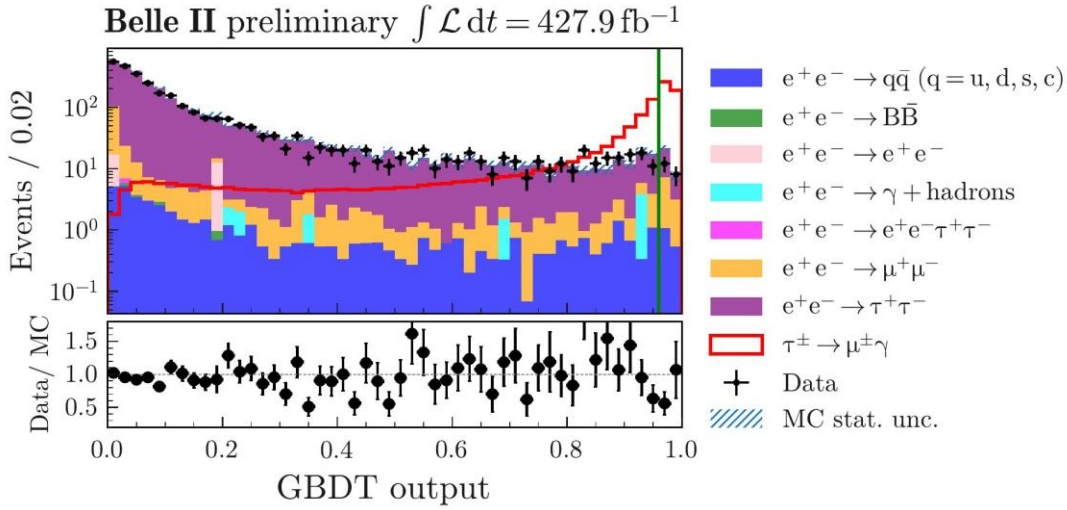
[Tau2025 talk]

- Belle II: 427 fb^{-1}
- Event selection by GBDT
- Preliminary result:

$$\mathcal{B}(\tau^- \to \mu^-\gamma)^{\rm exp} < 5.8 \times 10^{-8}$$
$$\mathcal{B}(\tau^- \to \mu^-\gamma)^{\rm obs} < 9.5 \times 10^{-8}$$

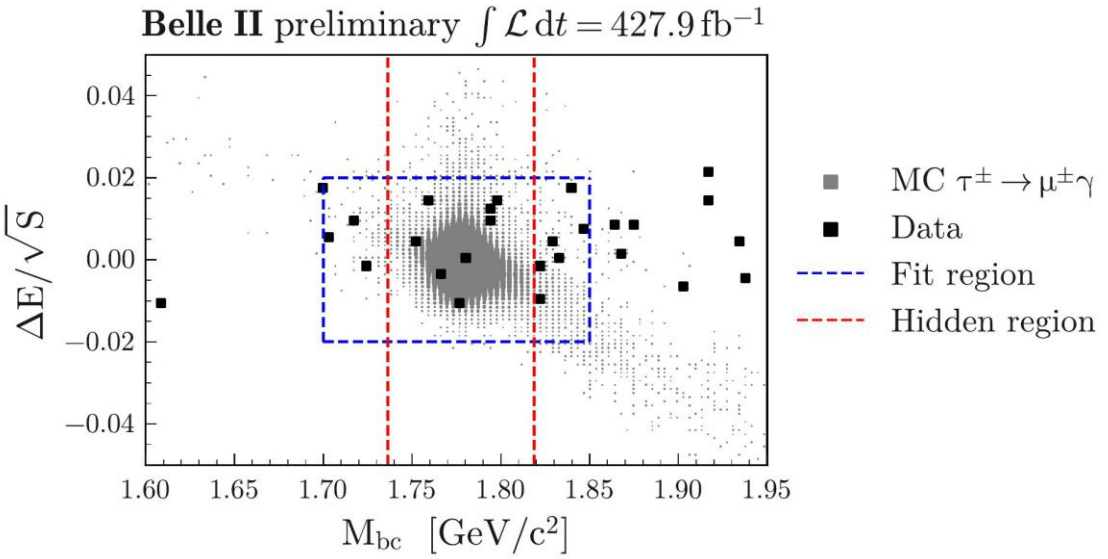
at 90%CL

- Remaining BG: ττ, μμ, qq



$\epsilon_{sig} = 3.4\ \%$
$b^{exp} = 5.8 \pm 0.04$

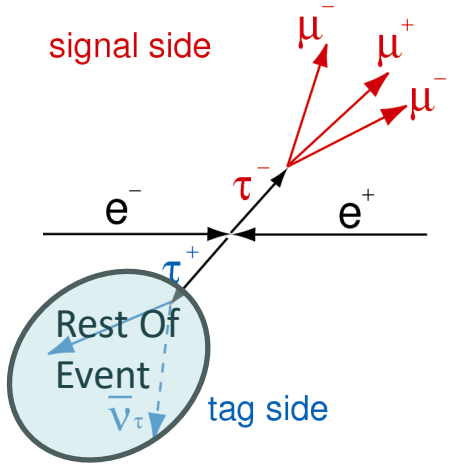
$\epsilon_{sig} = 5.21 \pm 0.01\%$
$b^{exp} = 1.1 \pm 0.02$

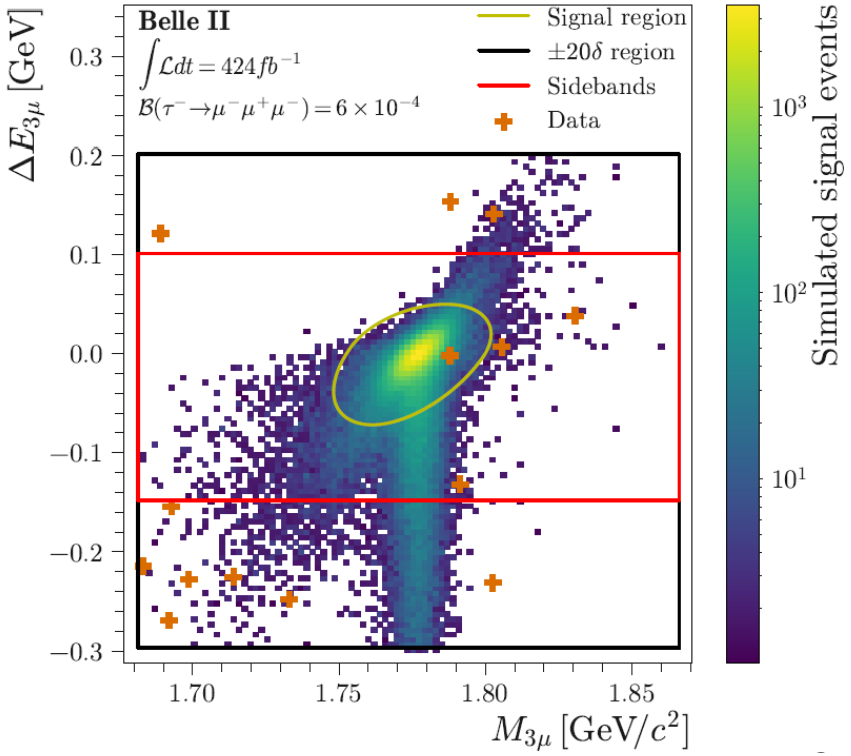


Search for τ→μμμ

Belle II: [JHEP 09 (2024) 062]

- Updated by Belle II using 424 fb^{-1} data
- Reconstruct signals with inclusive untagged approach to improve signal eff.
- Reject backgrounds with data-driven selections + Boosted Decision Tree classifier
  - Using Rest-Of-Event properties
- Signal efficiency improved
  - 20% (~3 x Belle)
- One events in the signal region
  - 0.7 events expected
- Br<1.9x10^{-8} at 90% CL
  - World's best sensitivity
  - Previous: 2.1x10^{-8} by Belle (782 fb^{-1})

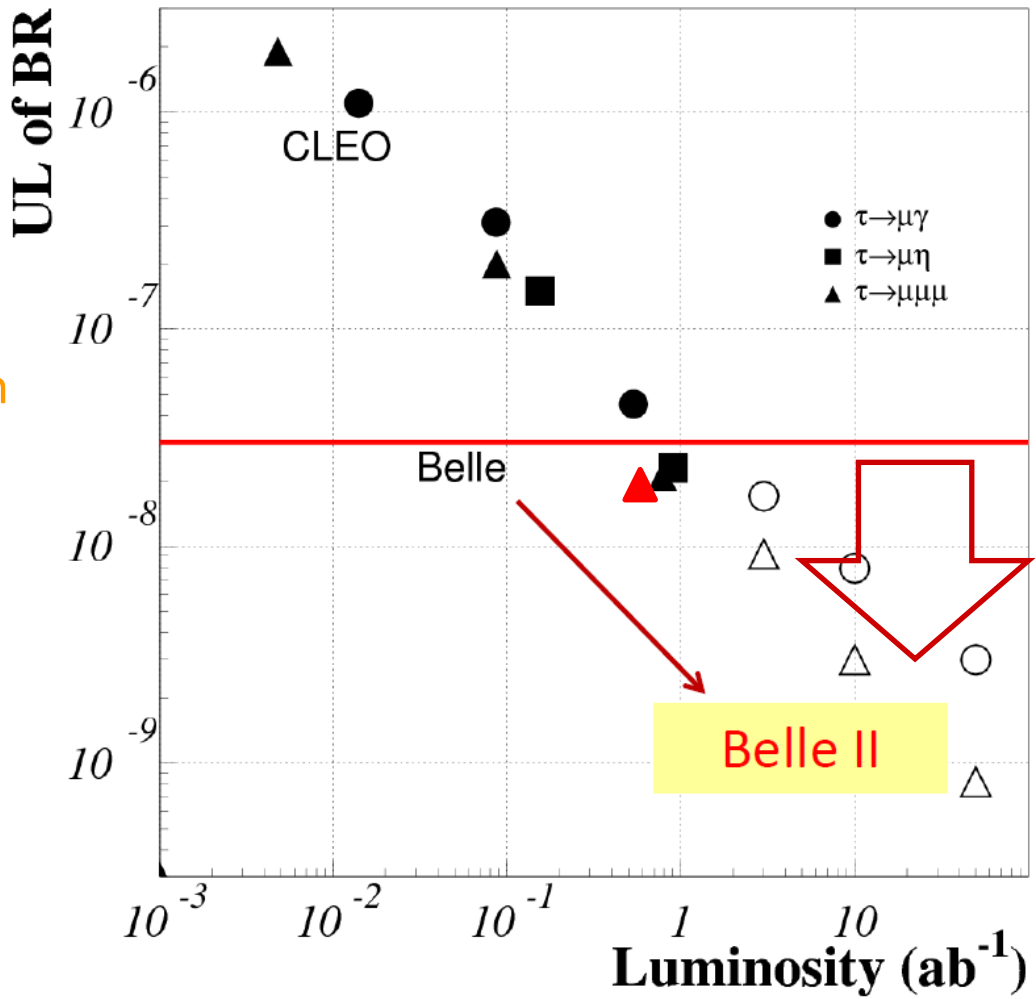




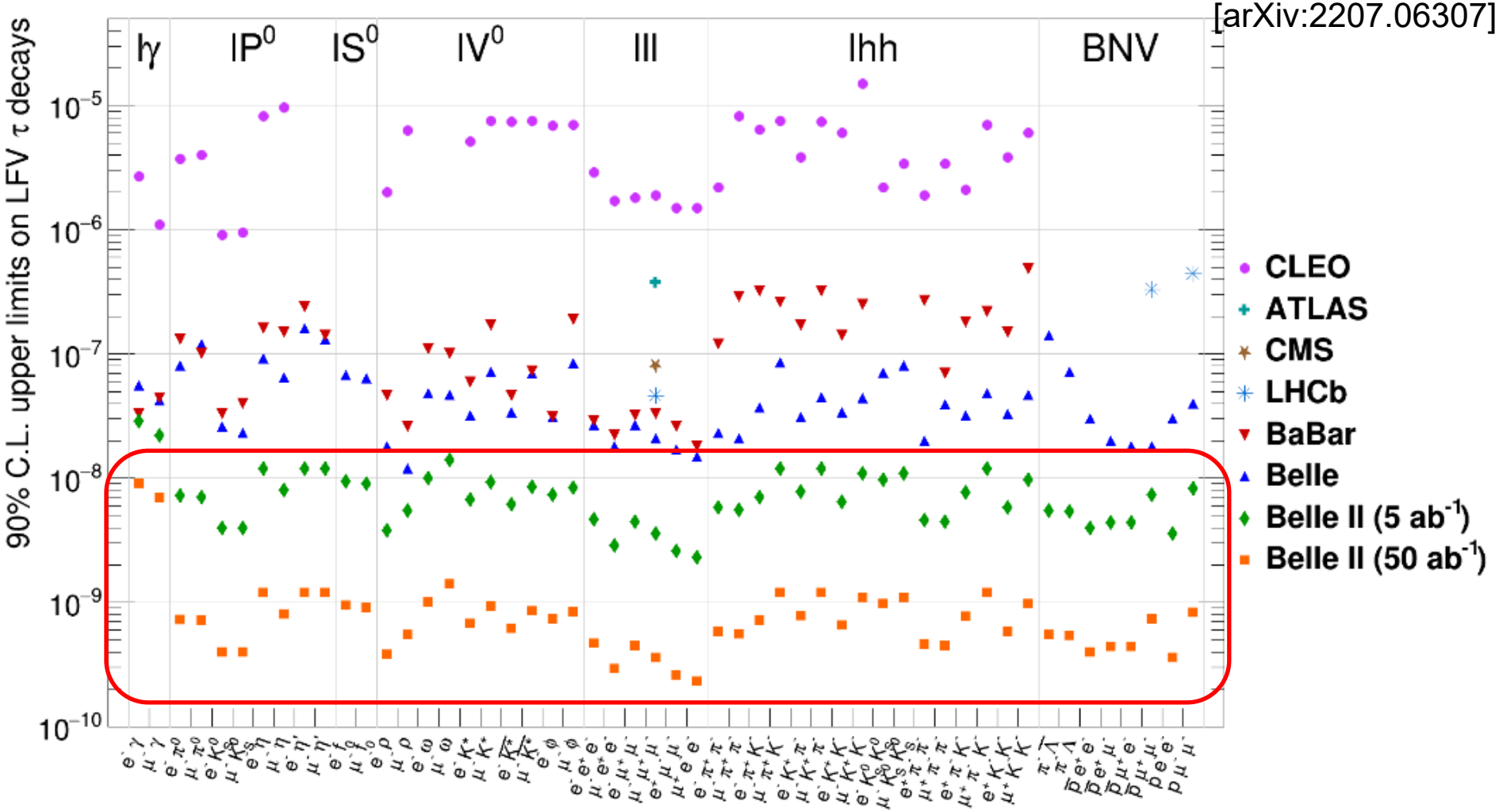
LFV prospects at Belle II

- Will collect 50ab^{-1} data, with upgrading detector and accelerator
- B($\tau \rightarrow \mu\mu\mu$)~O($10^{-10}$) at ~50ab^{-1}

- Background suppression with high signal efficiency is key issue.
  - Understanding of background (beam BG, fake PID etc.)
    → Improvement of reconstruction algorisms
  - Intelligent event selection by machine learning technique



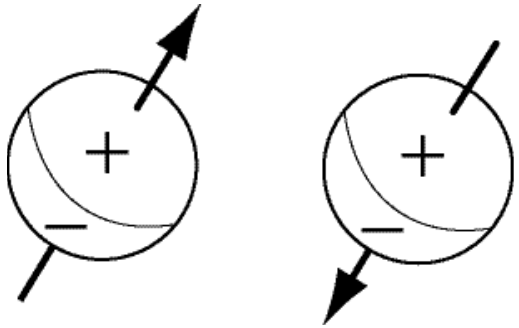
Prospects at Belle II



- Estimates assuming the background level scaled by luminosity
  - Recent analyses have already improved the S/N.
- Belle II will push the sensitivity down to $O(10^{-9 \to 10})$ at 5 → 50 ab^{-1}

Electric Dipole Moment of tau lepton

- Electric dipole moment
  - Charge distribution in particle
    - Charge unbalance along spin direction



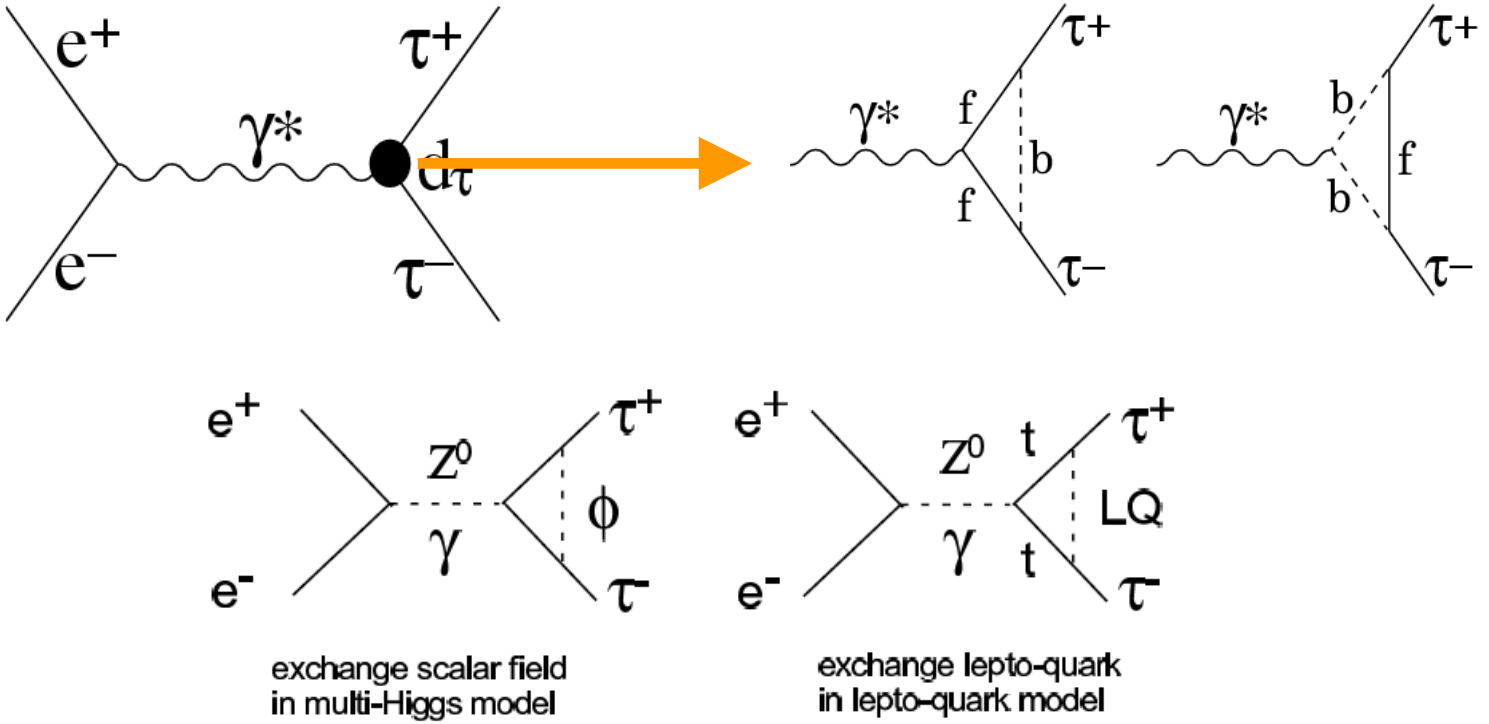
  - Electromagnetic interaction $\mathcal{H}_{\rm int} = \rho_{\rm m}\boldsymbol{\sigma}\cdot\boldsymbol{H} + \rho_{\rm e}\boldsymbol{\sigma}\cdot\boldsymbol{E}$
    - T transformation ; $\sigma \rightarrow -\sigma,\ H \rightarrow -H,\ E \rightarrow E$
    - If EDM exists ($\rho_e \neq 0$) ➔ T violates
  - If EDM exists, the decay distribution is distorted.

Electric dipole moment means the charge distribution in the particle. The electromagnetic interaction changes the sign by T/CP transformation.

EDM with new physics

- EDM is CPV parameter in tau-pair production
- Because of new physics reactions, EDM value may be non-zero

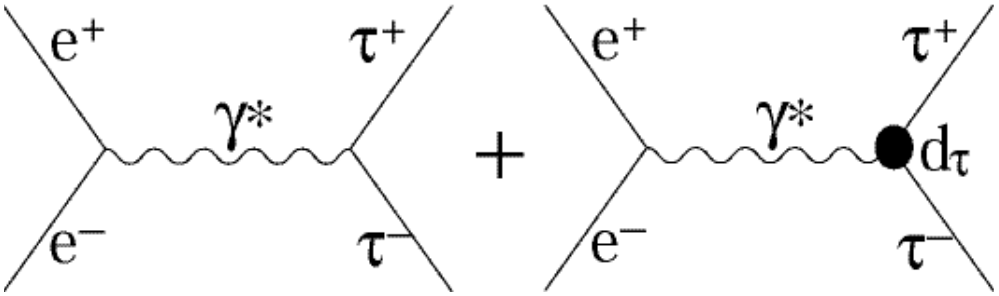
$$\mathcal{L}_{CP} = -\frac{i}{2}\bar{\tau}\sigma^{\mu\nu}\gamma_5\tau d_\tau(s)F_{\mu\nu}$$



EDM effect on event shape

- Effective Lagrangian with EDM interaction

$$\mathcal{L}_{\text{eff}} = \bar{\psi}(i\,\partial\!\!\!/ - eQ\,A\!\!\!/)\psi \qquad -id_\tau\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi\partial_\mu A_\nu$$



- Squared spin density matrix （~cross-section）

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

  - Interference term

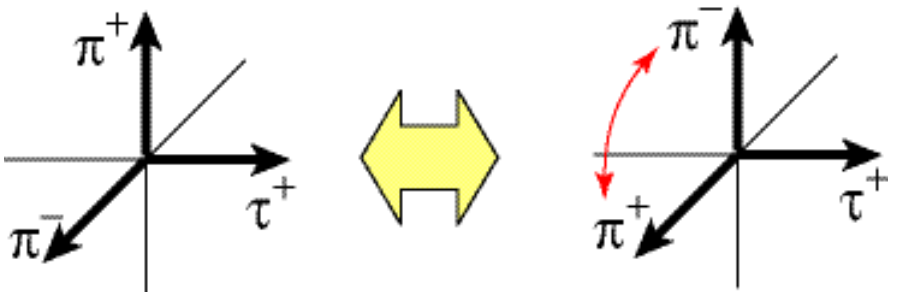
    → CP violating spin-momentum correlation

$$\mathcal{M}^2_{Re} \sim (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{k}} \;,\; (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{p}} \quad : \text{CP-odd, T-odd}$$
$$\mathcal{M}^2_{Im} \sim (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{k}} \;,\; (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{p}} \quad : \text{CP-odd, T-even}$$

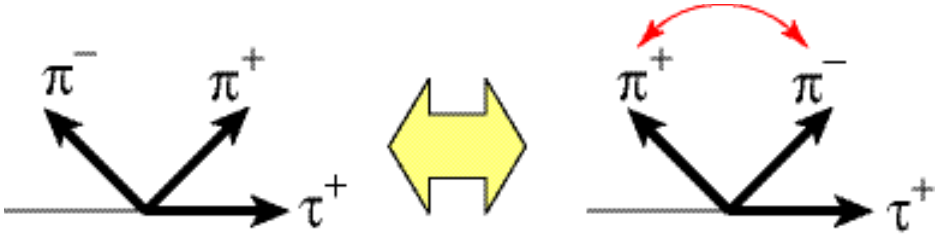
$\boldsymbol{S}_\pm$: Spin vectors of $\tau^\pm$
$\hat{\boldsymbol{k}}, \hat{\boldsymbol{p}}$: Momenta of τ^+ and e^+ beam

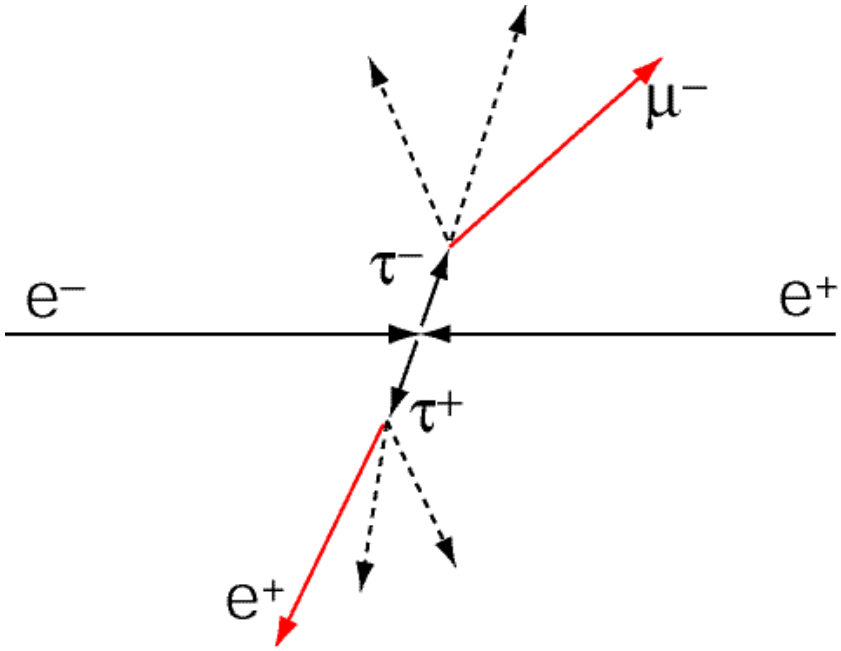
How to measure EDM?

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



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





- → Momentum correlation

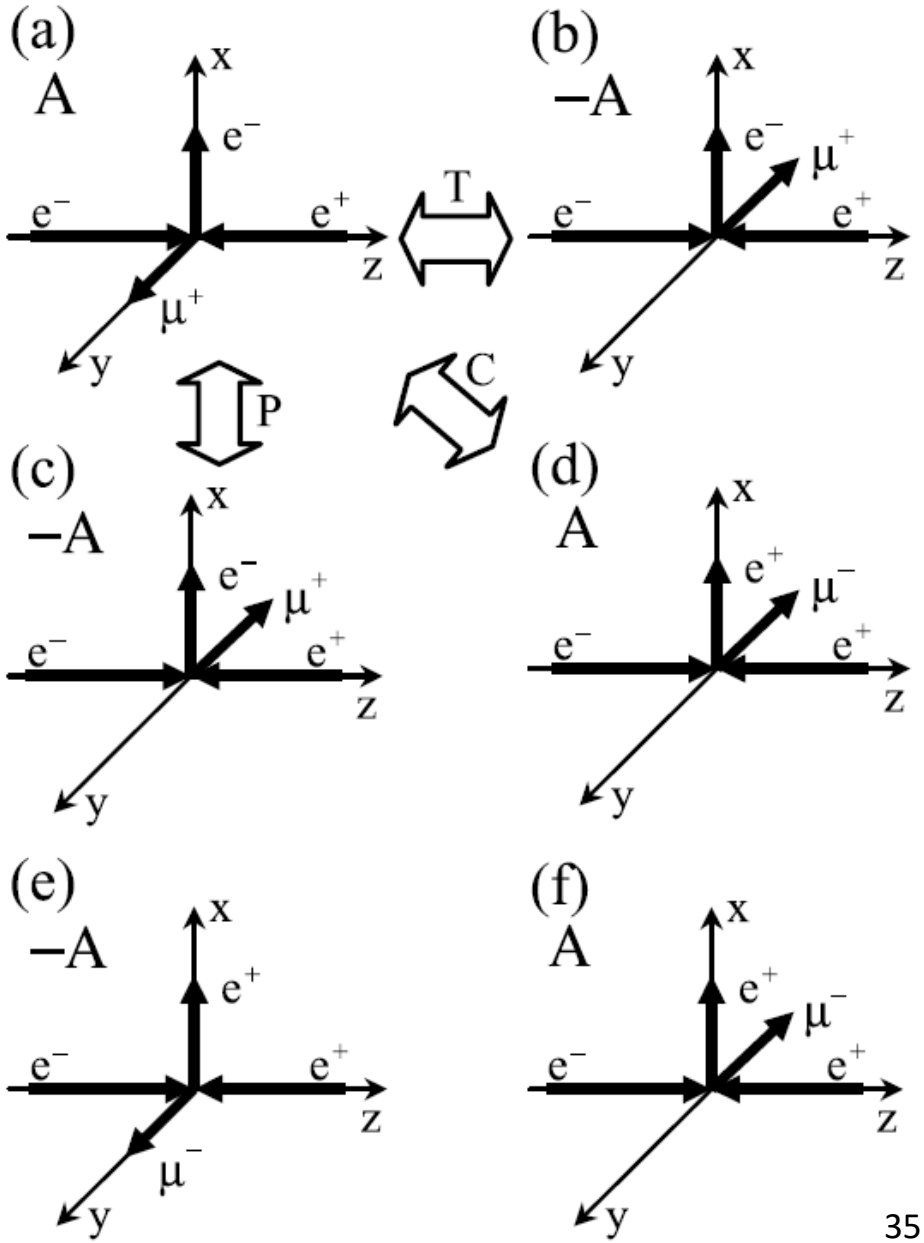
The real part of EDM indicates the asymmetry in the polar angle direction. The imaginary part of EDM is from forward-backward asymmetry.

T/CP/CPT transformation

- Tau pair reaction
  - $e^+e^- \rightarrow \tau^+\tau^- \rightarrow e\ \mu\ 4\nu$
- Measured value

$$\mathcal{A} \equiv \hat{q} \cdot (\hat{p}_1 \times \hat{p}_2)$$

  - q; beam e- direction
  - p_1, p_2; $\tau^{\pm}$decay direction
  - → Change the sign after C, P, T transformation



Electric dipole moment of τ lepton

- Optimal observable

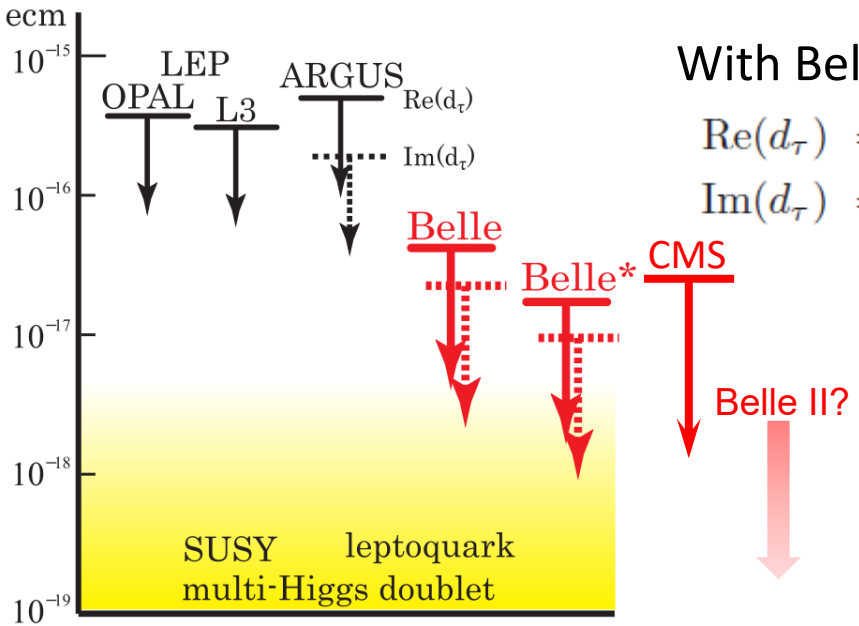
$$\mathcal{O}_{\mathrm{Re}} = \frac{\chi_{\mathrm{Re}}}{\chi_{\mathrm{SM}}}, \quad \mathcal{O}_{\mathrm{Im}} = \frac{\chi_{\mathrm{Im}}}{\chi_{\mathrm{SM}}}$$

$$\chi_{\mathrm{prod}} = \chi_{\mathrm{SM}} + \mathrm{Re}(d_\tau)\chi_{\mathrm{Re}} + \mathrm{Im}(d_\tau)\chi_{\mathrm{Im}} + |d_\tau|^2\chi_{d^2}$$

  - Maximize sensitivity (S/N)
  - Calculate event-by-event; Using tau flight direction and spin direction (from decay products)
  - Average value is proportional to EDM

$$\langle \mathcal{O}_{\mathrm{Re}} \rangle \propto \int \mathcal{O}_{\mathrm{Re}} \chi_{\mathrm{prod}} d\phi = \int \chi_{\mathrm{Re}} d\phi + \mathrm{Re}(d_\tau) \int \frac{(\chi_{\mathrm{Re}})^2}{\chi_{\mathrm{SM}}} d\phi$$

- Result



With Belle's 833 fb^{-1} data (~7.6x10^8 τ pairs)

$$\mathrm{Re}(d_\tau) = (-0.62 \pm 0.63) \times 10^{-17}\ e\mathrm{cm},$$
$$\mathrm{Im}(d_\tau) = (-0.40 \pm 0.32) \times 10^{-17}\ e\mathrm{cm}.$$

at 95% C.L.

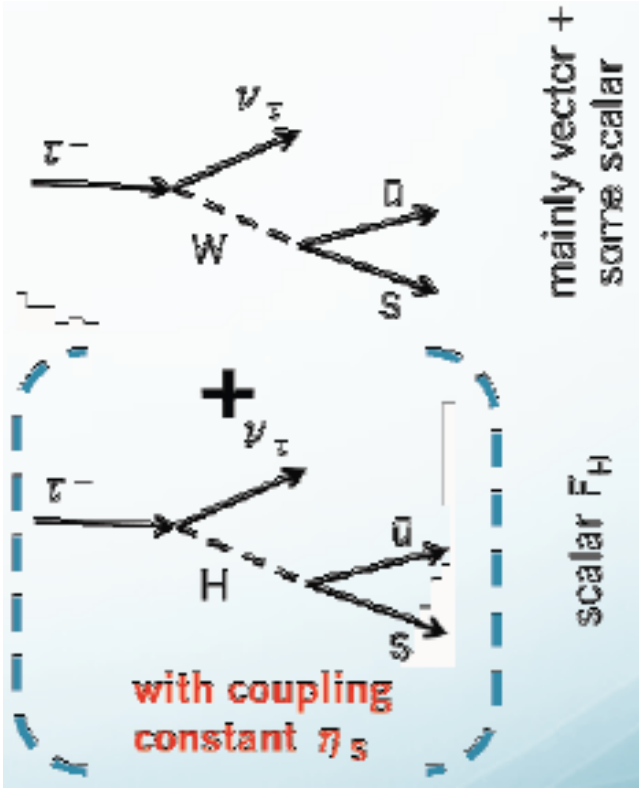
[JHEP 2204, 110 (2022)]

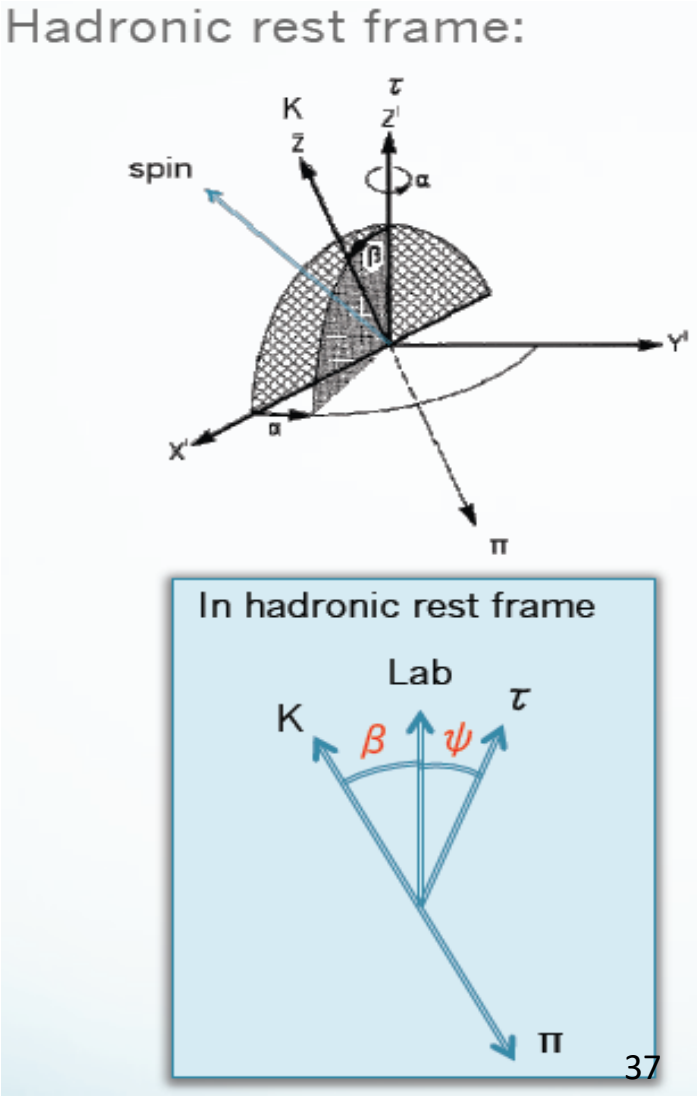
Sensitivity of O(10^{-19}) *e*cm can be achievable in near future, by improving analysis method.

CP violation in tau decay

- New physics affects to decay distribution
  - May cause CP violating effect

  → Angular distribution of decay products



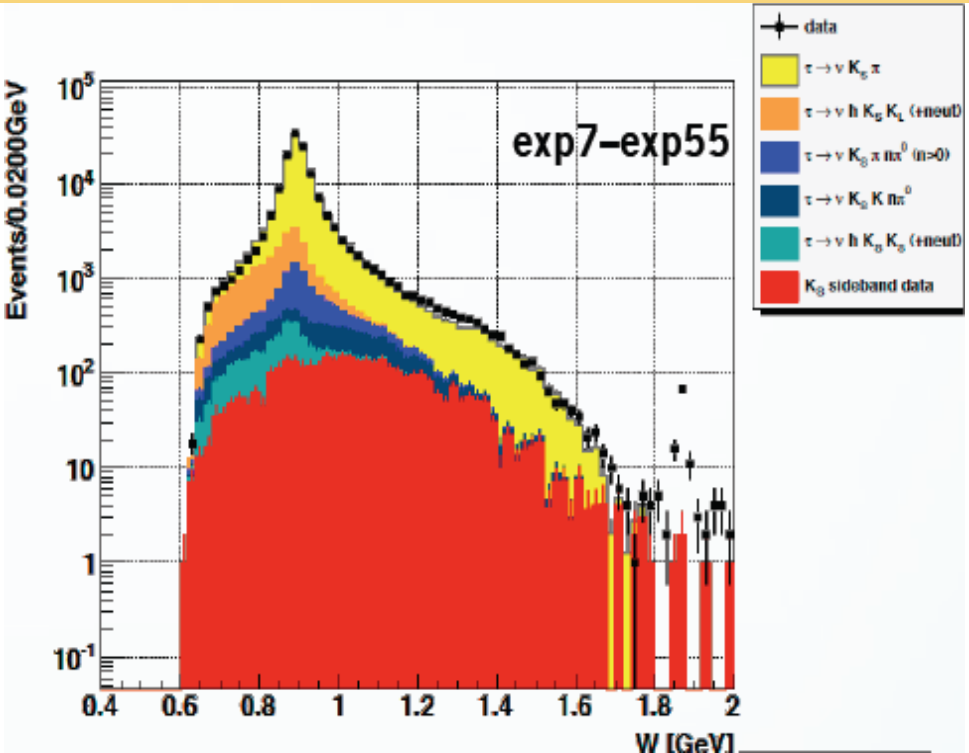


CPV analysis at Belle

- $\tau^- \rightarrow \pi^- K_S \nu$
  - ~150,000 events
  - Main BG from $\tau \rightarrow \pi K_S K_L \nu$
    - Escaping K_L
  - CPV by angular distribution of τ^+/τ^-

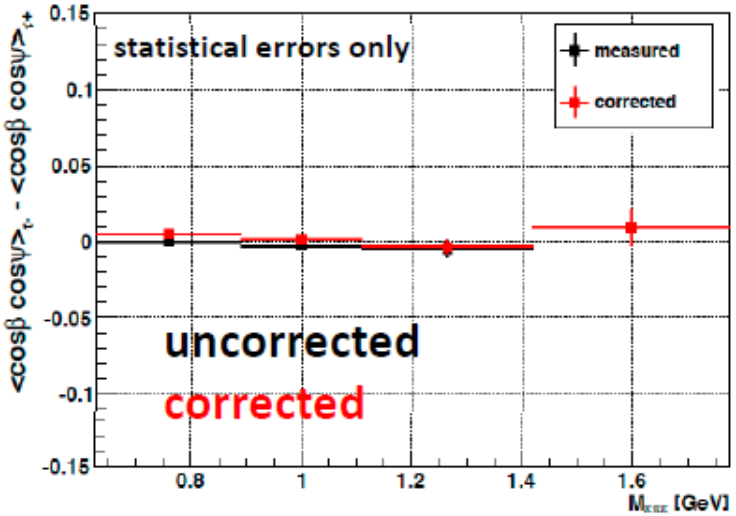
CP violation search by the angular correlation is performed by the Belle experiment, with ~150k events.

$$\frac{1}{2}(d\Gamma_{\tau^-} - d\Gamma_{\tau^+}) \propto \frac{4}{m_\tau}\sqrt{Q^2}|\vec{q}_1|\Im(FF_H^*)\Im(\eta_S) \times [C\cos\psi\cos\beta]$$



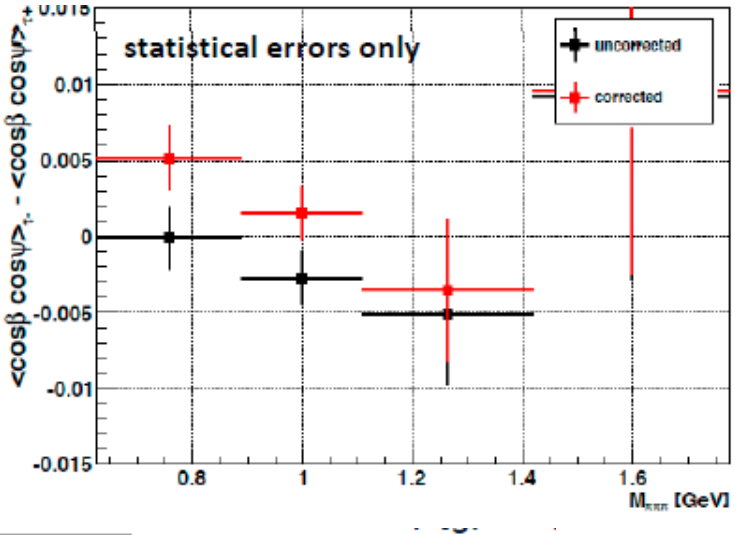
CPV analysis

Angle asymmetry depending on hadron mass

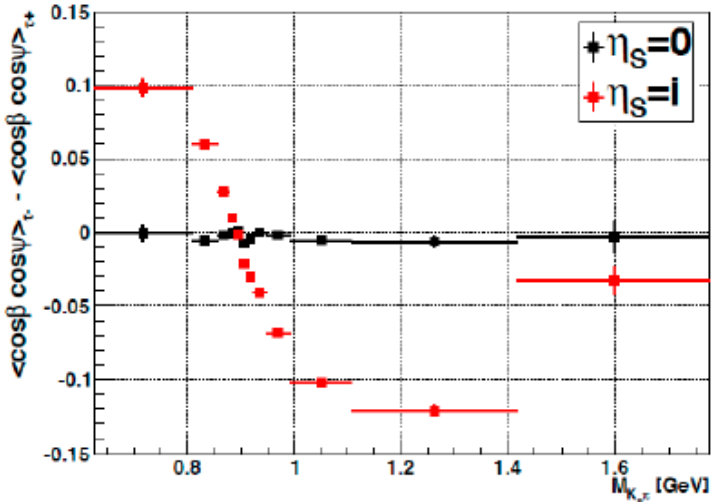


Zoom in:

before background subtraction



MC results



Zero CPV results

Angle asymmetry is measured depending on the hadron mass, since the new physics effect may be different by the intermediate states; scaler, vector, etc.
Measured results indicates zero CPV.

Summary

- Tau lepton is a good probe for precise measurement of SM and the new physics beyond the standard model.

- Belle II will collect $O(10^{10})$ τ pairs
  - Good field for precise measurement (huge data + τ-pair)
  - Tau LFV searches will reach the higher sensitivity compared to the previous experiments
    - The background free modes, such as $\tau \rightarrow$ 3 leptons, can be reached to $O(10^{-10})$ branching ratio sensitivity.
  - We can expect more precise analysis on tau CPV/EDM using improved detector performance.

Future view

- Plan to upgrade for higher luminosity in 2032-2033 (Long Shutdown 2)
- Accelerator: Improve beam lifetime and accelerator stability
  - IP Beam pipe replacement
    - New beam pipe design to reduce the synchrotron radiation from the accelerator near IP
  - Beam abort & monitoring
    - Additional diamonds to protect from beam loss
  - RF cavity, Collimator head, etc.
- Detector: Background Tolerance
  - New Vertex detector
    - Higher max hit rate:
    - 120 MHz/cm^2 → 600 MHz/cm^2
  - Tracking system
    - Low gas gain operation
    - Silicone inner tracker

