北里大学
Kitasato University
理学部
School of Science

Tau LFV and LNV at Belle II

Outline

- B factory as tau factory
- Belle II status
- tau LFV/LNV search

Tomoyuki Konno
for the Belle II collaboration
Kitasato University
30/08/2019, Korea

B factory as tau factory

τ-factory at B-factory

B-factory is τ factory!

- KEKB: asymmetric e+(3.5 GeV) e-(8 GeV)
  - Peak luminosity: **2.1×10^{34} $cm^{-2}s^{-1}$**

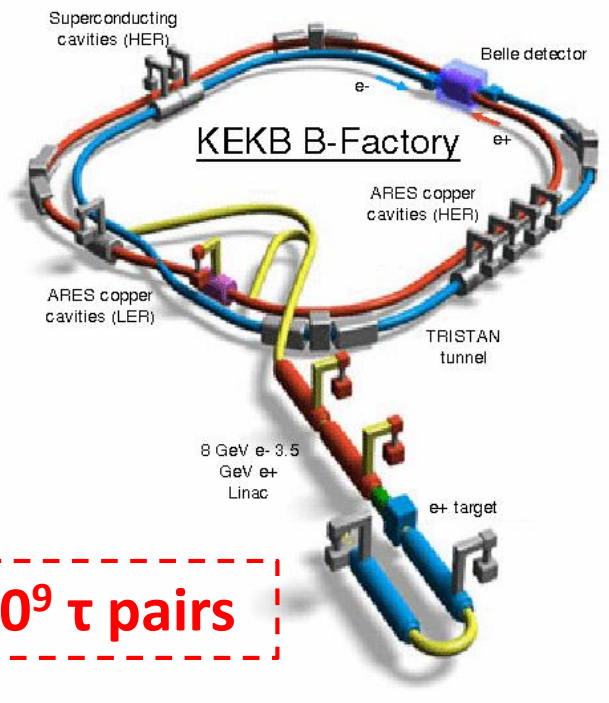
    => World highest peak luminosity
  - σ(ττ) ~ 0.9 nb
  - σ(bb) ~ 1.1 nb

    => Pure ττ can be collected
- Belle Detector:
  - Full event reconstruction

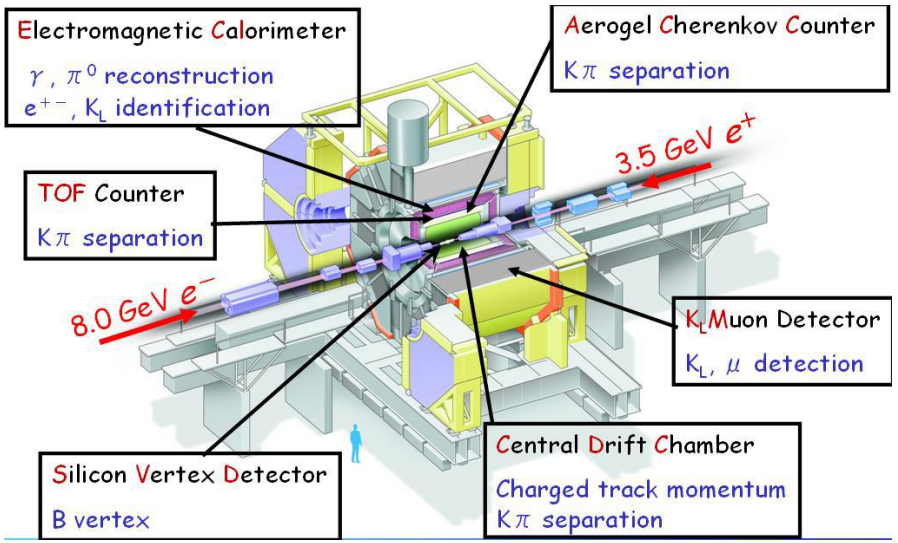
    => Lepton efficiency: 90 %

    Fake rate : O(0.1) % for e

    O(1) % for μ



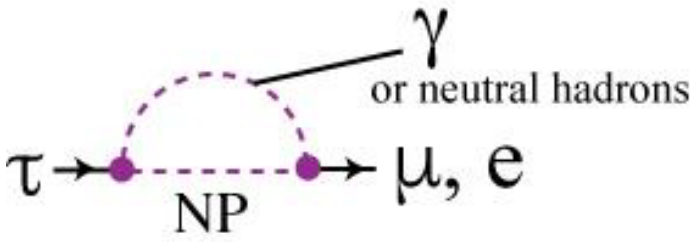
~10^9 τ pairs



Motivation to τ physics

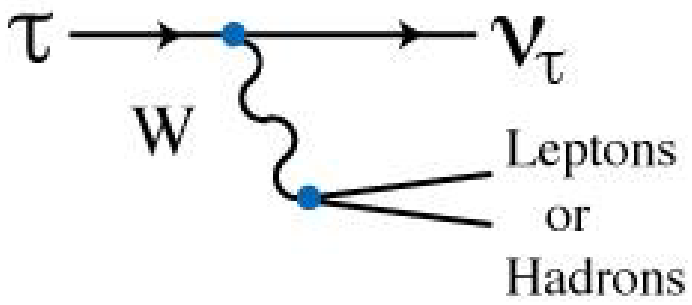
tau Physics has clear signature to New Physics!

- **Quest for New Physics**
  - Lepton flavor (number) violating decays is suppressed in SM
  - Clear hints to New Physics models



$$\mathcal{B}(\tau \to l\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\tau i} U_{\mu i} \frac{\triangle^2_{3i}}{m^2_W} \right|^2$$

- **Hadronic decays**
  - Unique tool for precise studies of low energy QCD and CP violation

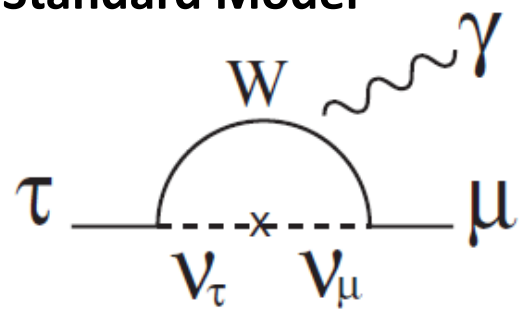


Search for tau LFV

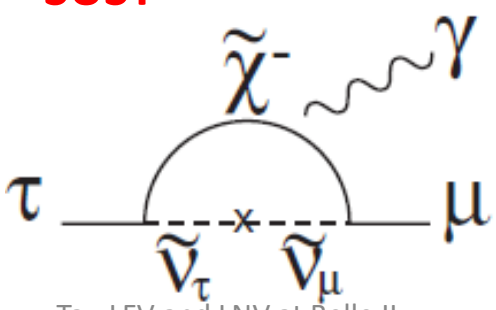
- **Lepton Flavor Violation (LFV)** is highly suppressed in the Standard Model (SM) even if neutrino oscillation is taken
  - Br < O($10^{-10\sim45}$) => Experimentally unreachable
- **Lepton Number Violation (LNV)** is also strongly suppress in SM
  - Observation of LNV will hint at light NP scale
- **Many extensions to SM** predict to enhance LFV to be Expected to be investigated by real experiments: Br ~ O(10^{-8})
- Tau lepton - the heaviest charged lepton coupling to the NP

=> Many possible LFV decay modes related to the NP models

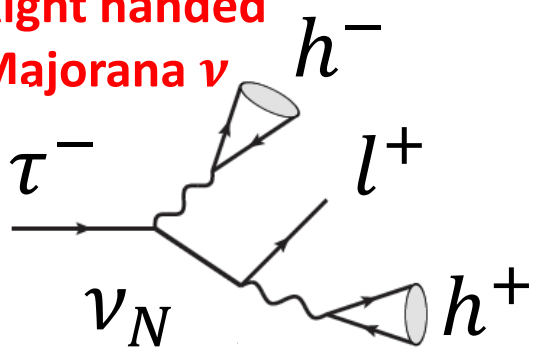
Standard Model



SUSY



Right handed Majorana ν

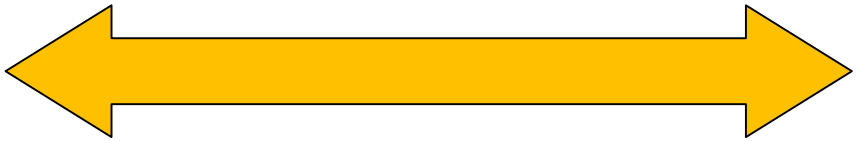


Predicted BF in various models

- Ratio of Tau LFV decay BF provides discrimination of NP models

(M.Blanke, et al., JHEP 0705, 013(2007), C.Yue, et al.,PLB547, 252 (2002))

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

Favorite modes $\tau \to \mu\gamma$  $\tau \to \mu\mu\mu$

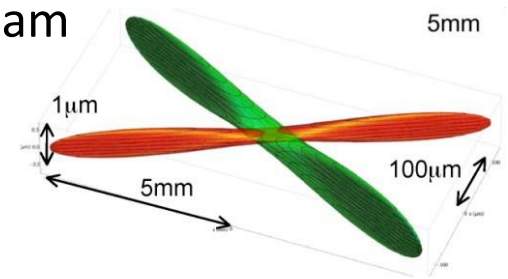
- It is important to search for various kinds of τ LFV

=> Almost all decay modes are studied using the Belle data

Belle II Status

SuperKEKB / Belle II

Nano-beam scheme

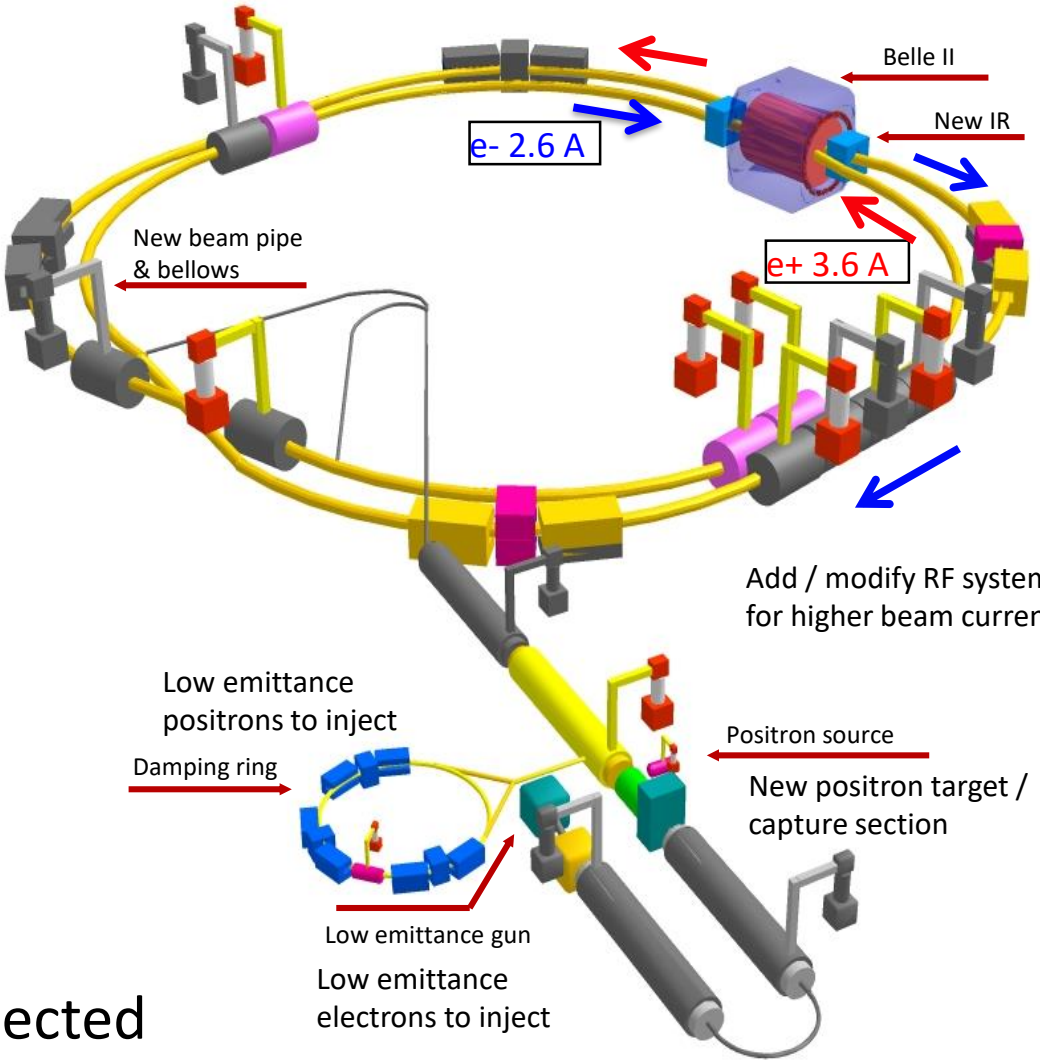


Super B factory is also Super τ factory!

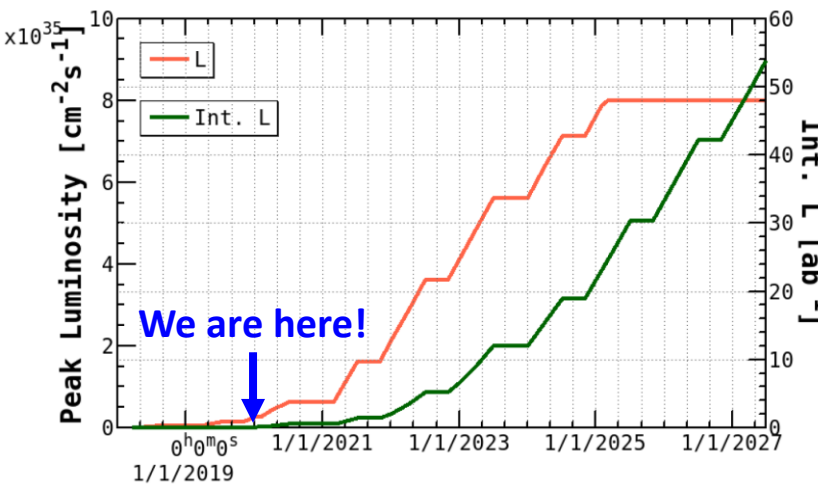
- 40 times higher luminosity
  - Focus on small β^*_y : **x 20**
  - Increase in current : **x 2**

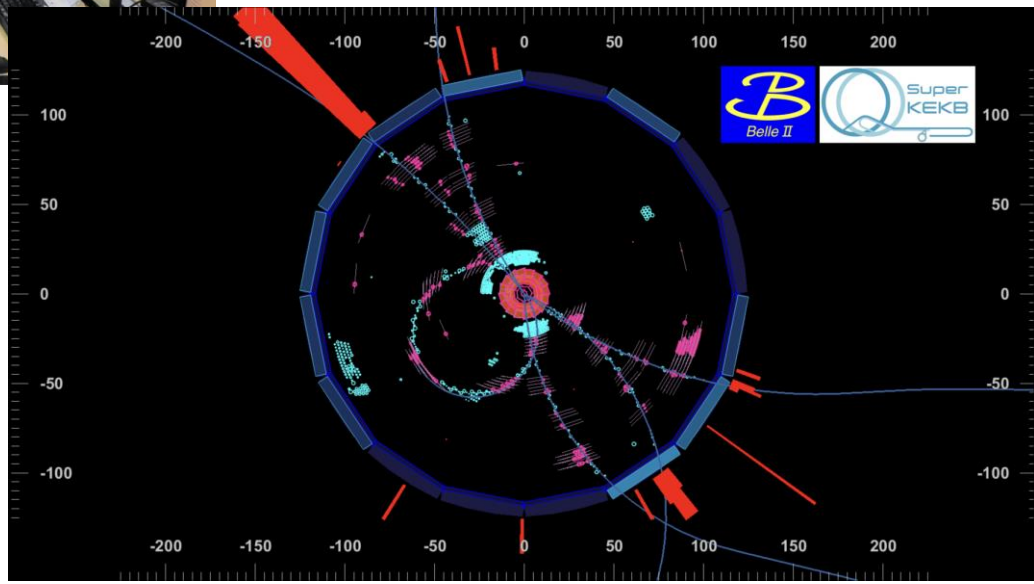
  => Integrated 50 ab^{-1}
- Full operation in 2019 with Belle II

=> **4.6 x 10^{10}** τ pairs will be collected



Phase III started for physics!





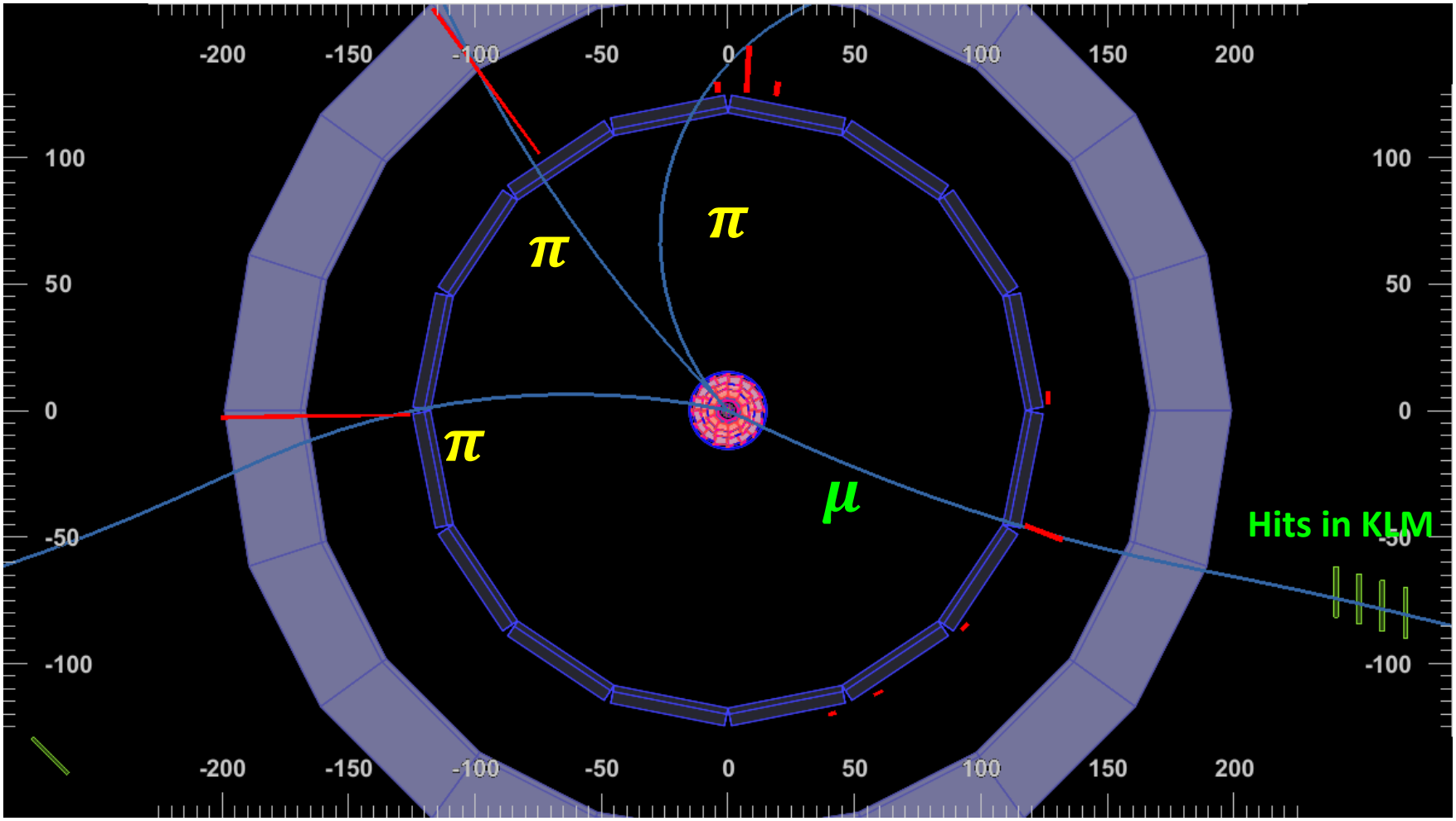
Restarted at 25th March 2019
with Full Belle II / SuperKEKB

- Peak Lumi. :4 x 10^{33} $cm^{-2}s^{-1}$
- Int. Lumi : 3 fb^{-1}

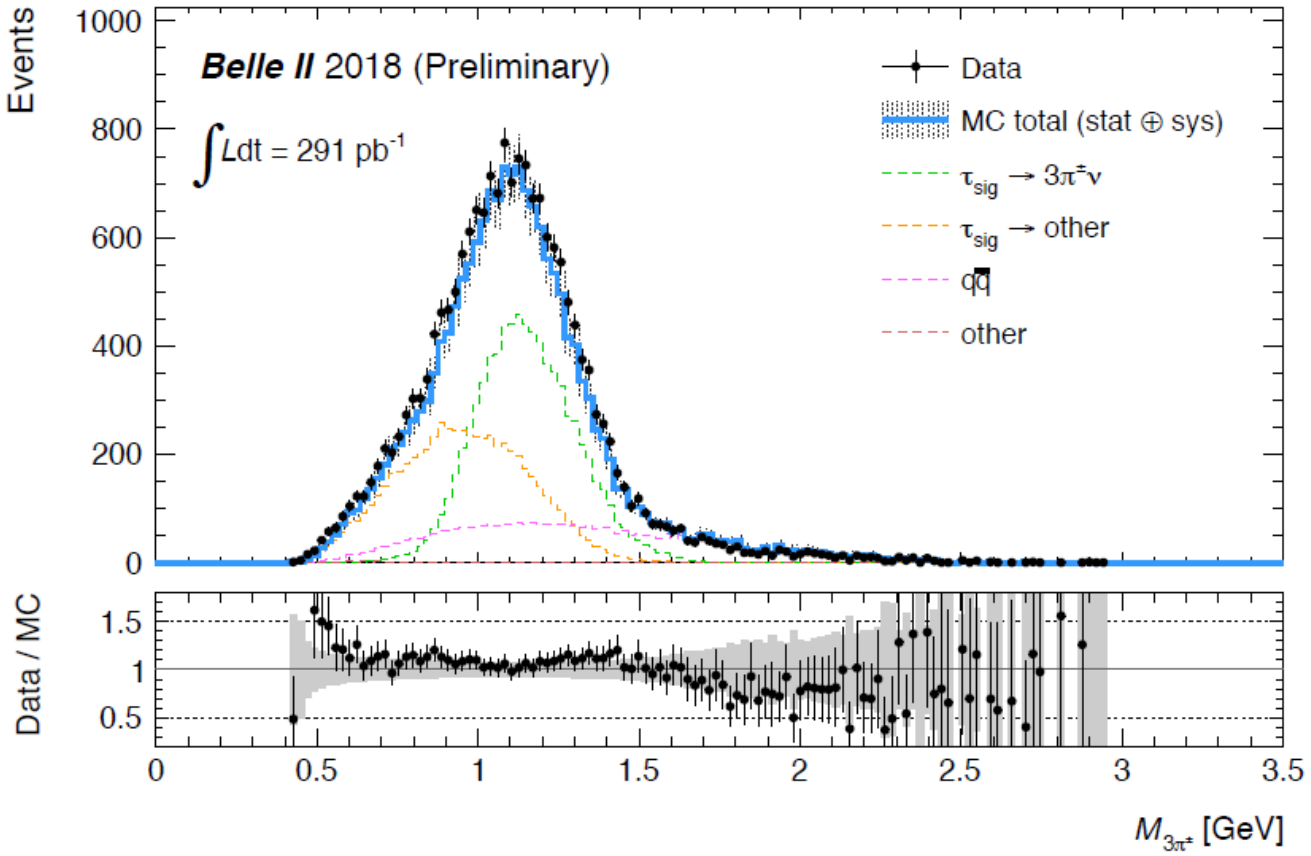
=> Increasing Luminosity !

τ pair candidates with τ->3πν

- τ pair are also extracted in the beam commissioning data



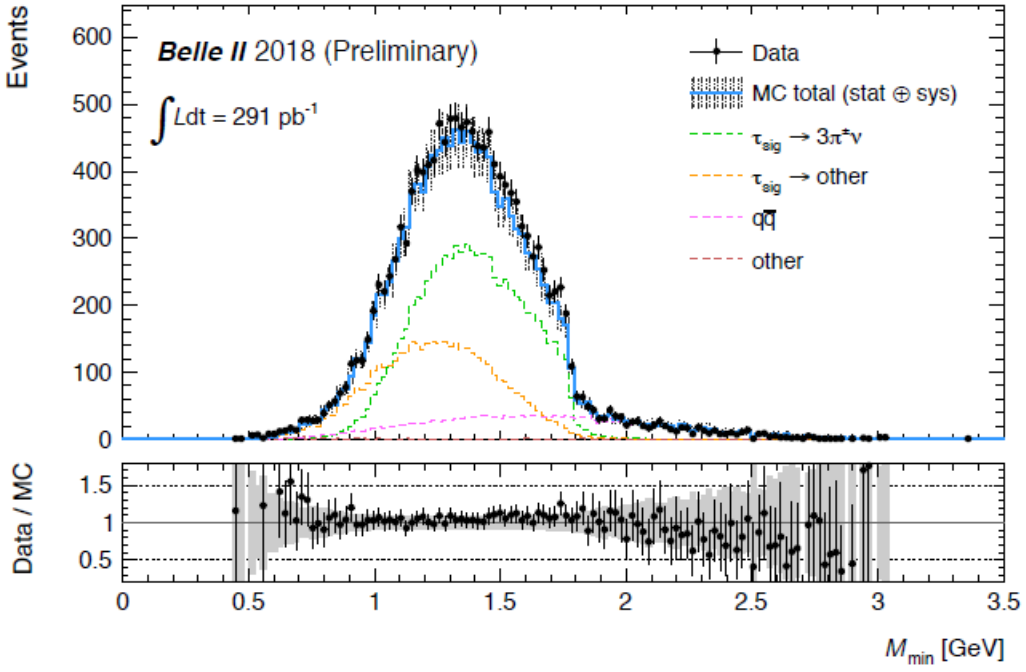
τ → 3πν in Belle II early data



- Data has good agreement with MC after selection cuts
- Performance of the subsystems is enough as expected

τ mass in Belle II early data

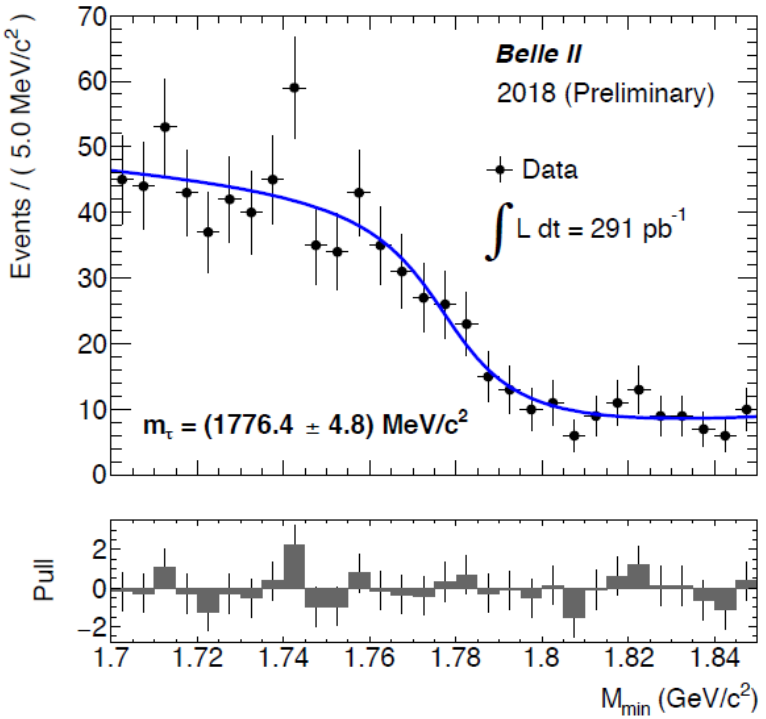
M_{min} distribution @ 291 pb^{-1}:



Measured in τ -> 3πν

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

Distribution of the pseudomass is fitted to a empirical edge curve



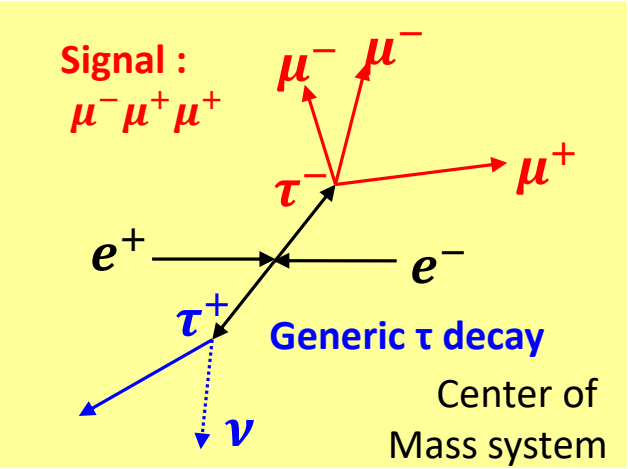
- Tau mass from Belle early data is consistent to previous results

m_τ = (1776.4 ± 4.8 (stat)) MeV/c2

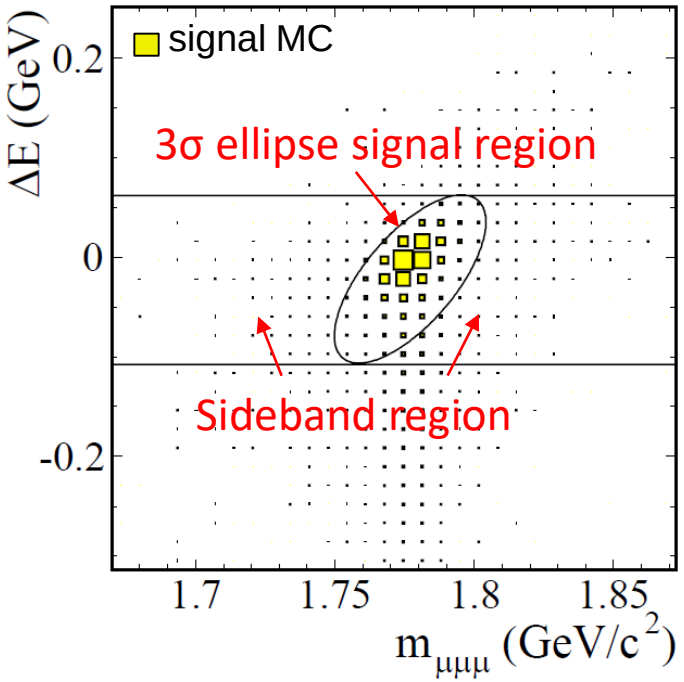
τ LFV / LNV search

Analysis procedure

- $e^+e^- \to \tau^+\tau^-$: No missing in signal side
  - **Signal side**: μμμ
    - Fully reconstructed
    - No missing energy
  - **Tag side**: 1 prong + missing
    - Br ~ 85 %



- Signal extraction: $m_{\mu\mu\mu} - \Delta E$ plane
  - $m_{\mu\mu\mu} = \sqrt{E^2_{\mu\mu\mu} - p^2_{\mu\mu\mu}} \sim m_\tau$
  - $\Delta E = E^{CM}_{\mu\mu\mu} - E^{CM}_{\text{beam}} \sim 0$
- Number of Background is estimated using sideband data and MC

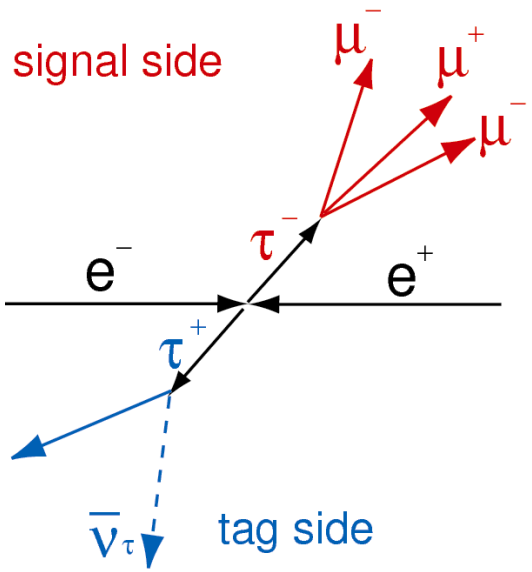


Search for tau LFV in B factory

- Various interesting channels can be studied in B factories
  - $\boldsymbol{\tau \to \ell\ell\ell}$ ➡ Possible to access in early Belle II
  - $\tau \to \ell K_S, \Lambda h$
  - $\tau \to \ell V_0 (\to hh')$
  - $\tau \to \ell P^0 (\to \gamma\gamma)$
  - $\boldsymbol{\tau \to \ell h h'}$ ➡ Both LFV and LNV decays
  - $\boldsymbol{\tau \to \ell \gamma}$ ➡ Sensitive to many NP models but More serious in BG in Belle II
- Rare decay search :
  => Understand backgrounds and reduce as much as possible
- **Review Belle results proceeding to Belle II**

Signal and backgrounds ($\tau \to lll$)

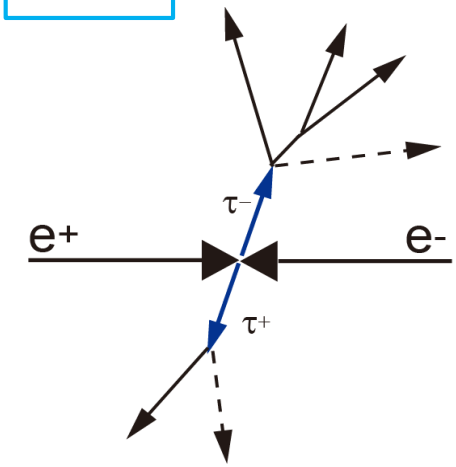
LFV Signal



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

Major BG differs among LFV decay channels

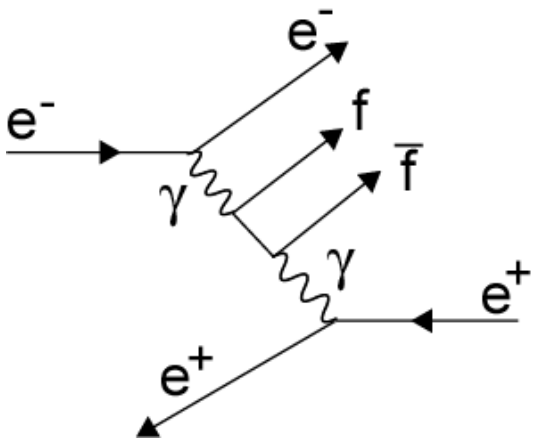
SM ττ



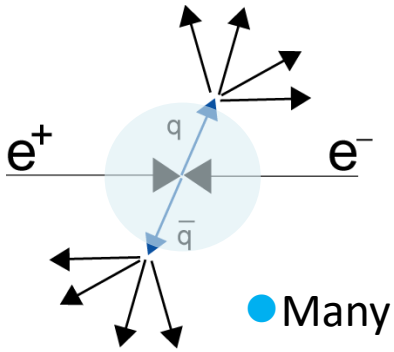
- Neutrinos in both sides
- Missing energy in signal side

2photon process

f = leptons, quarks

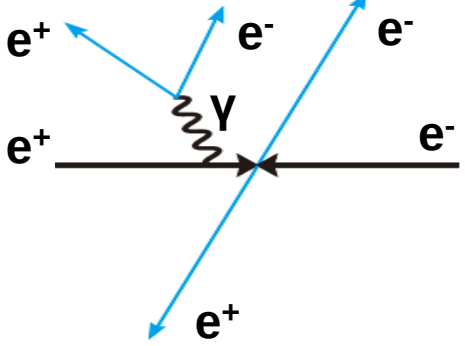


qq̄



- Many tracks

radiative Bhabha



Belle result :

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

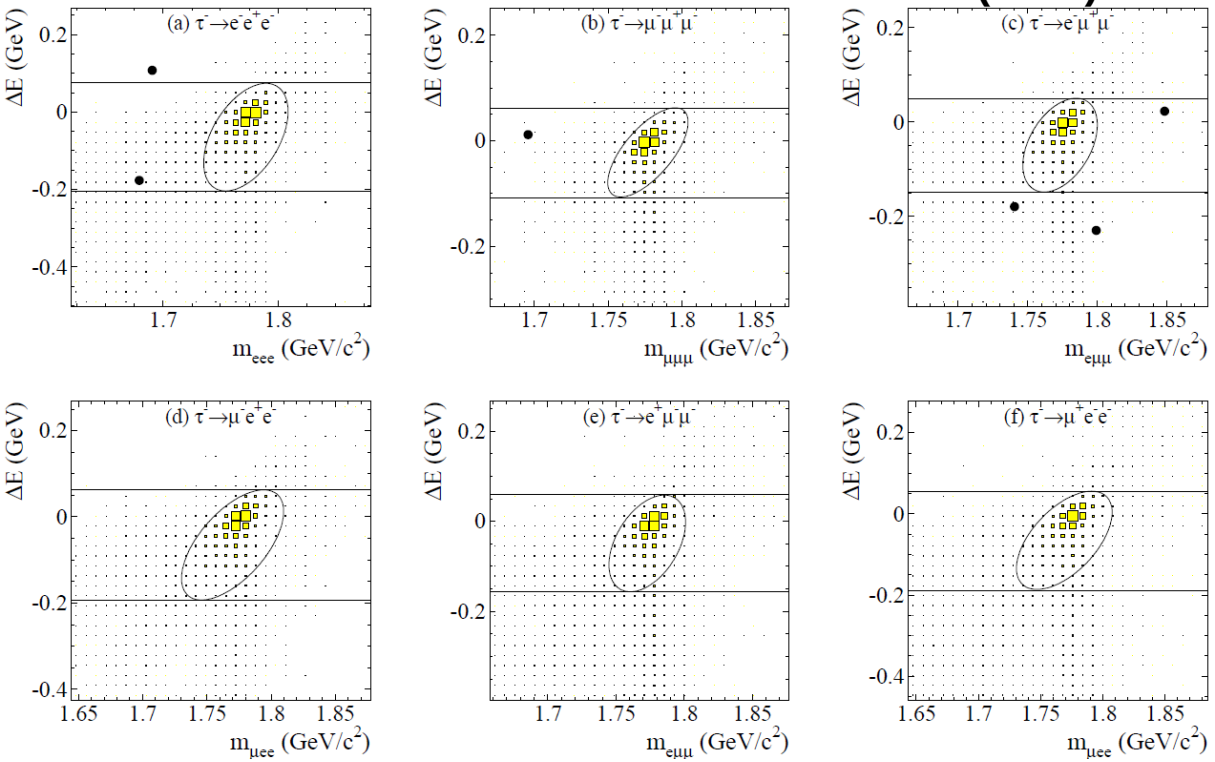
Phys.Lett.B687,139 (2010)

- Data: 782fb^{-1}
- No event s are found in the signal region.
- **Almost BG free !**
  - Expected # of BG: 0.01-0.21

  => Emphasize the low background compared to LHCb

Br < ~ 10^{-8} at 90%CL

Belle result (2010)



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

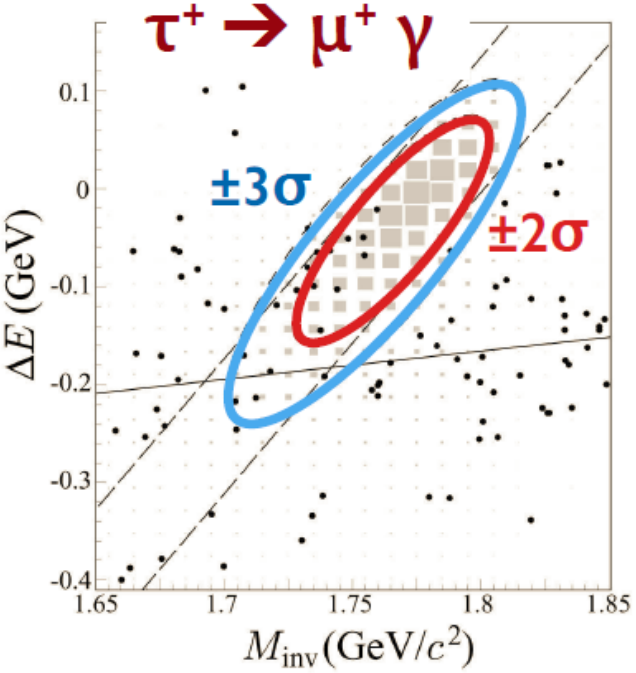
Belle result : $\tau \to \mu\gamma, e\gamma$

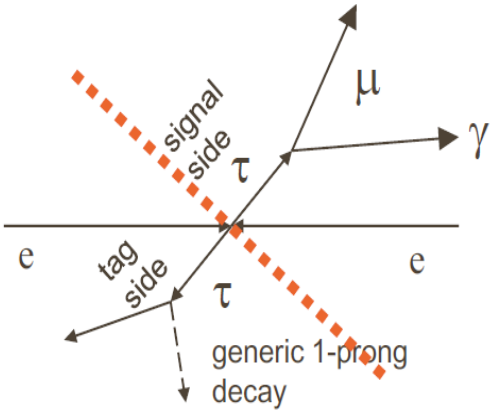
Phys. Lett. B 666, 16 (2008)

Blinding box approach evaluating BG out side the signal region

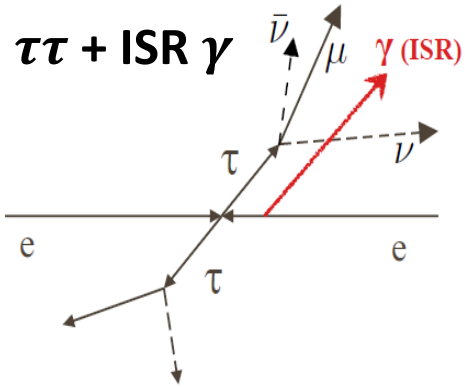
- Search with 545 fb^{-1}
  - Main BG : $\tau \to \mu\nu\nu$ + ISR γ
  - miss/missing tracks
- $\tau \to \mu\gamma$: Br < 4.5 x 10^{-8} (90%CL)
- $\tau \to e\gamma$: Br < 1.2 x 10^{-8} (90%CL)

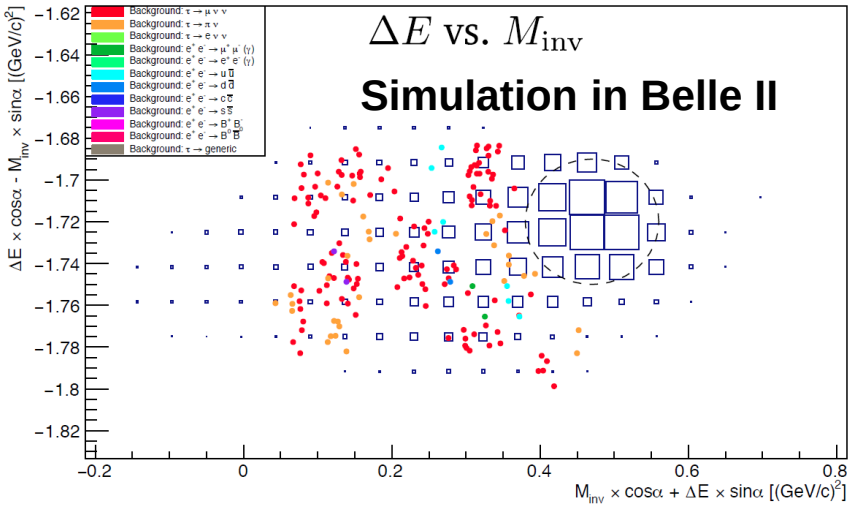
Belle result (2008)





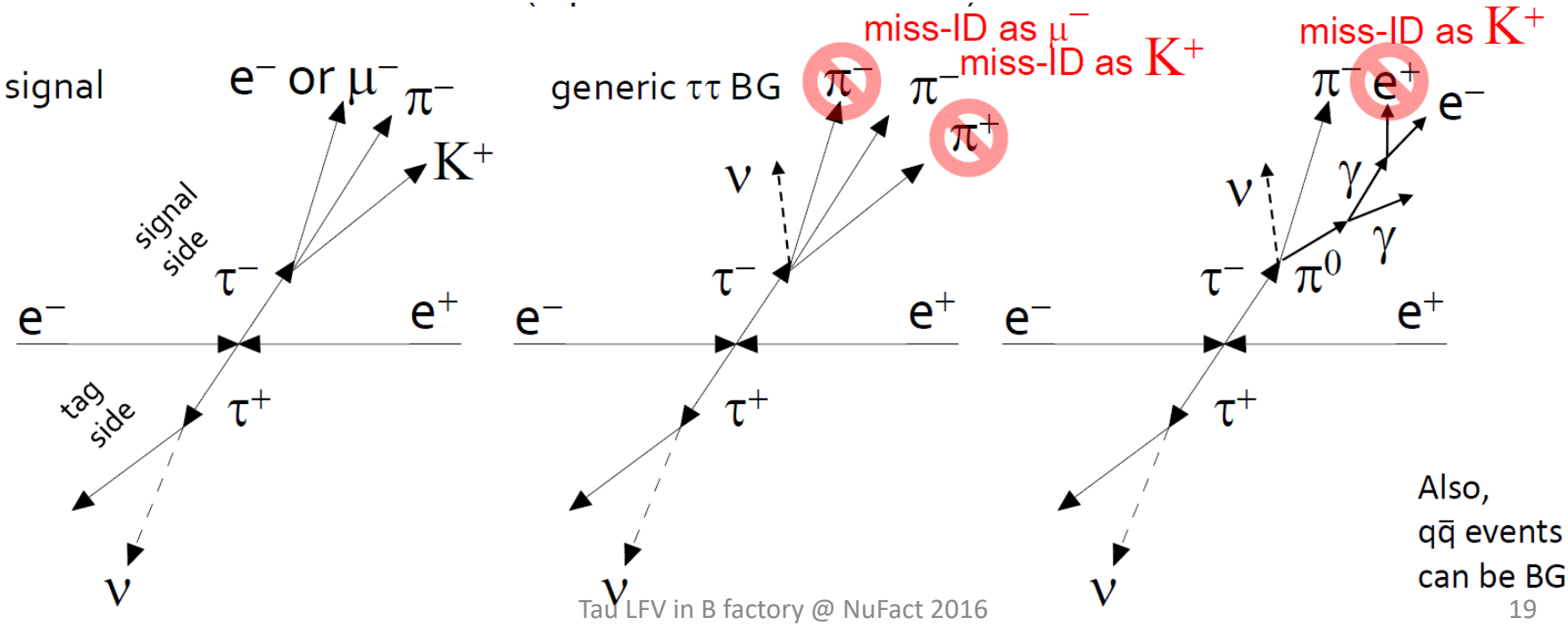
$\tau\tau$ + ISR γ





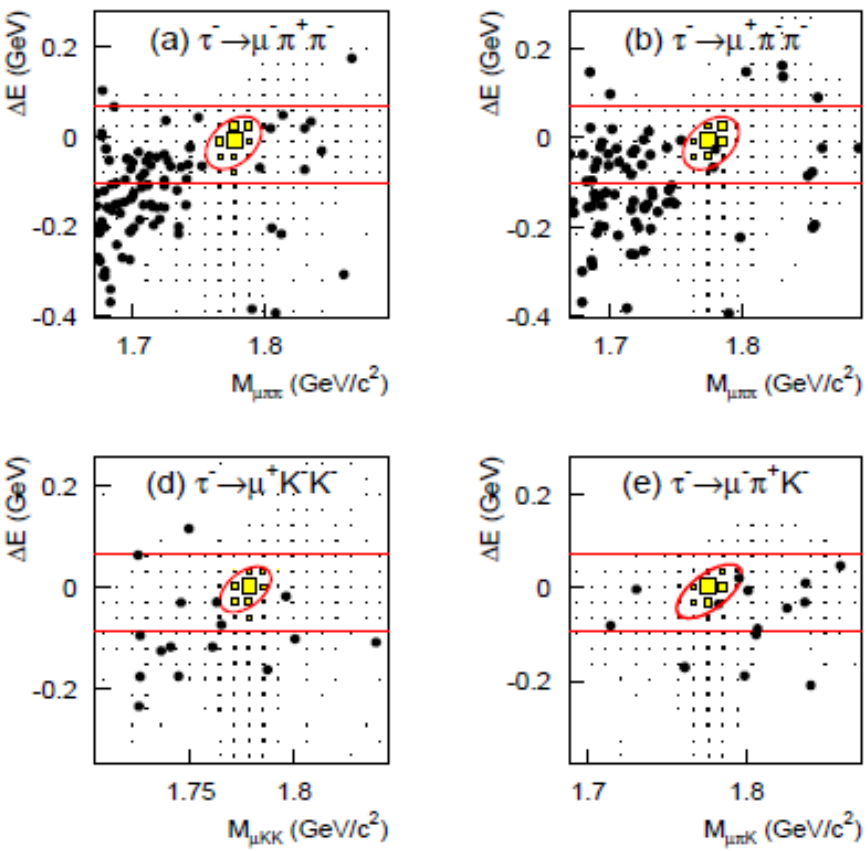
$\tau \to \ell hh'$

- Search with 854fb^{-1} data
  - BaBar: Br<(7-48)x10^{-8}at 221fb^{-1}
- 14 modes are investigated ($h, h' = \pi^{\pm}, K^{\pm}$)
  - $\tau^- \to \ell^- h^+ h'^-$: 8 modes (lepton flavor violation)
  - $\tau^- \to \ell^+ h^- h'^-$: 6 modes (lepton number violation)



Also,
$q\bar{q}$ events
can be BG

$\tau \to \ell hh'$



- No significant excess
  - 1 event: $\mu^-\pi^+\pi^-$, $\mu^-\pi^+K^-$
  - no events: other modes

=> Expected # of BG: 0.06-0.72

Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^-\pi^+\pi^-$	5.83	0.63 ± 0.23	5.3	0	1.87	2.1
$\tau^- \to \mu^+\pi^-\pi^-$	6.55	0.33 ± 0.16	5.3	1	4.02	3.9
$\tau^- \to e^-\pi^+\pi^-$	5.45	0.55 ± 0.23	5.4	0	1.94	2.3
$\tau^- \to e^+\pi^-\pi^-$	6.56	0.37 ± 0.18	5.4	0	2.10	2.0
$\tau^- \to \mu^-K^+K^-$	2.85	0.51 ± 0.18	5.9	0	1.97	4.4
$\tau^- \to \mu^+K^-K^-$	2.98	0.25 ± 0.13	5.9	0	2.21	4.7
$\tau^- \to e^-K^+K^-$	4.29	0.17 ± 0.10	6.0	0	2.28	3.4
$\tau^- \to e^+K^-K^-$	4.64	0.06 ± 0.06	6.0	0	2.38	3.3
$\tau^- \to \mu^-\pi^+K^-$	2.72	0.72 ± 0.27	5.6	1	3.65	8.6
$\tau^- \to e^-\pi^+K^-$	3.97	0.18 ± 0.13	5.7	0	2.27	3.7
$\tau^- \to \mu^-K^+\pi^-$	2.62	0.64 ± 0.23	5.6	0	1.86	4.5
$\tau^- \to e^-K^+\pi^-$	4.07	0.55 ± 0.31	5.7	0	1.97	3.1
$\tau^- \to \mu^+K^-\pi^-$	2.55	0.56 ± 0.21	5.6	0	1.93	4.8
$\tau^- \to e^+K^-\pi^-$	4.00	0.46 ± 0.21	5.7	0	2.02	3.2

Upper limits at 90%CL:

Br($\tau \to \ell hh'$) < (2.0-8.4)x10^{-8}

Phys.Lett.B719,346 (2013)

Expectation of LFV search at Belle II

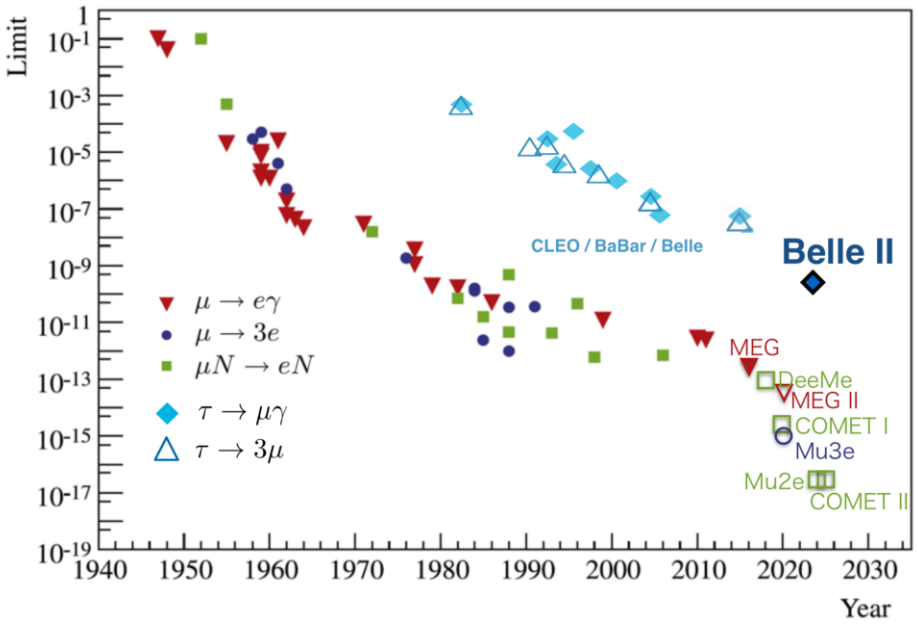
Belle II will reach the New Physics Models in first several years

- Sensitivity depends on BG level

  => Improve achievable sensitivity

With final statistics at 50ab^{-1}

- $B(\tau \to \mu\gamma)$~O(10^{-9}) and $B(\tau \to \mu\mu\mu)$~O(10^{-9})
- Slopes depend on background

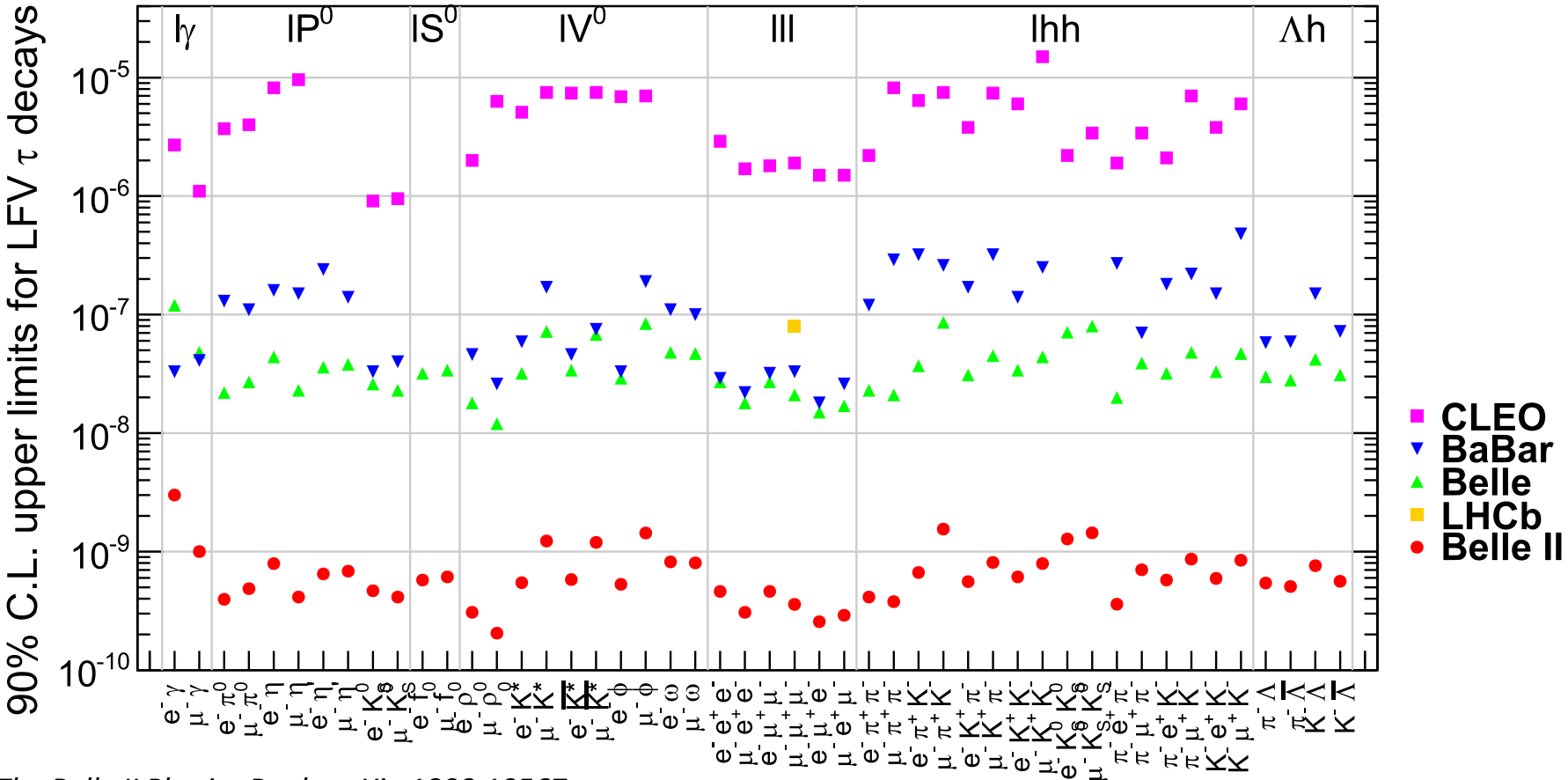


old plots, conservative

Upper limits at (Super) B factories

- Current estimation with Belle II final statistics : ~10^{-2} lower

=> Several models are expected to be investigated in in Belle II !



The Belle II Physics Book arXiv:1808.10567

Summary

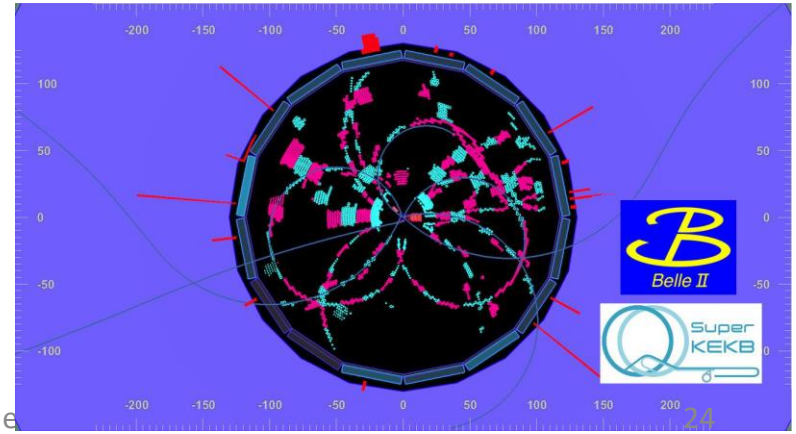
- B factory is also open for τ physics in new physics search
  - Studies with τ pairs are carried out in Belle and BaBar
  - No significant result for LFV/LNV has been found yet
- Belle II experiment started full operation in early 2019!
- Many of τ LFV channels are possible to study in early Belle II
  - Improved Upper limit of Branching fraction by $O(10^{-2})$
- Hadronic decays of τ lepton is also interesting for New Physics
  - Limited by statistics and possible to be improved in Belle II
- More details are in "The Belle II Physics Book" arXiv:1808.10567

Belle II started Collision!

First collision at 26/04/2018

- 3 months operation until 18th July
- Almost full detector worked well

Integrated Luminosity : ~500 pb^{-1}



Predicted BF in various models

- Various models predict BF for $\tau \to \mu\gamma$ and $\tau \to \mu\mu\mu$

	Reference	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SM+ ν mixing	EPJ C8 (1999) 513	$10^{-10\sim45}$	---
SM + heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

Numbers correspond to the most optimistic case

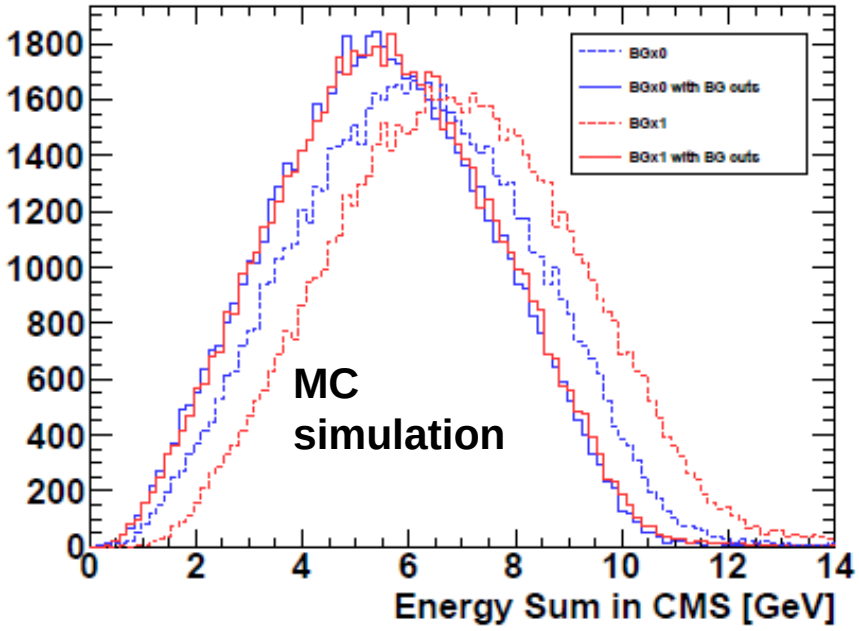
Super B factory will reach a possible region to τ LFV!

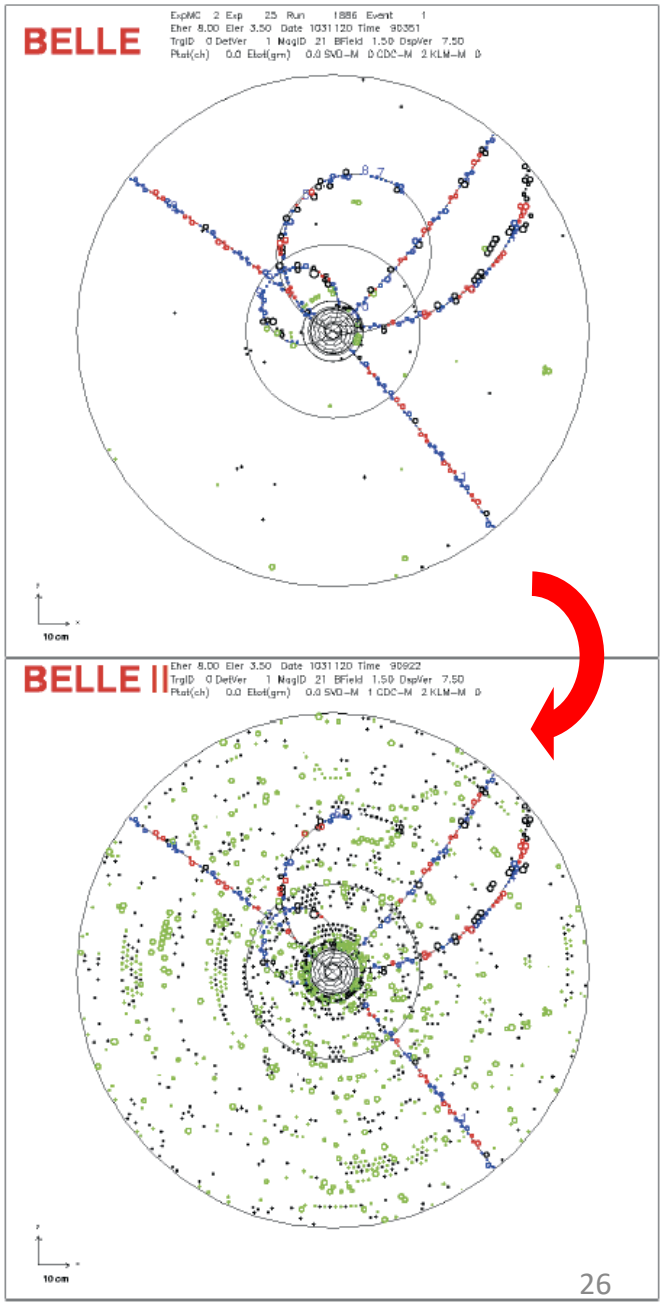
Beam background

Understanding beam background is essential for τ physics in Belle II

- Beam related background is expected to be 20 times higher than Belle
- Several hardware improvements applied

=> Beam related background is controllable by track reductions in an event

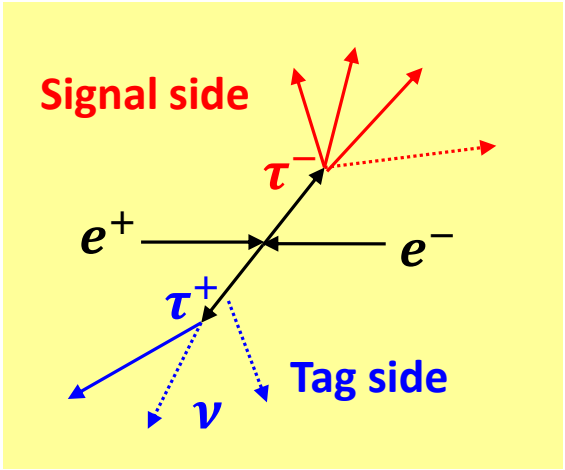


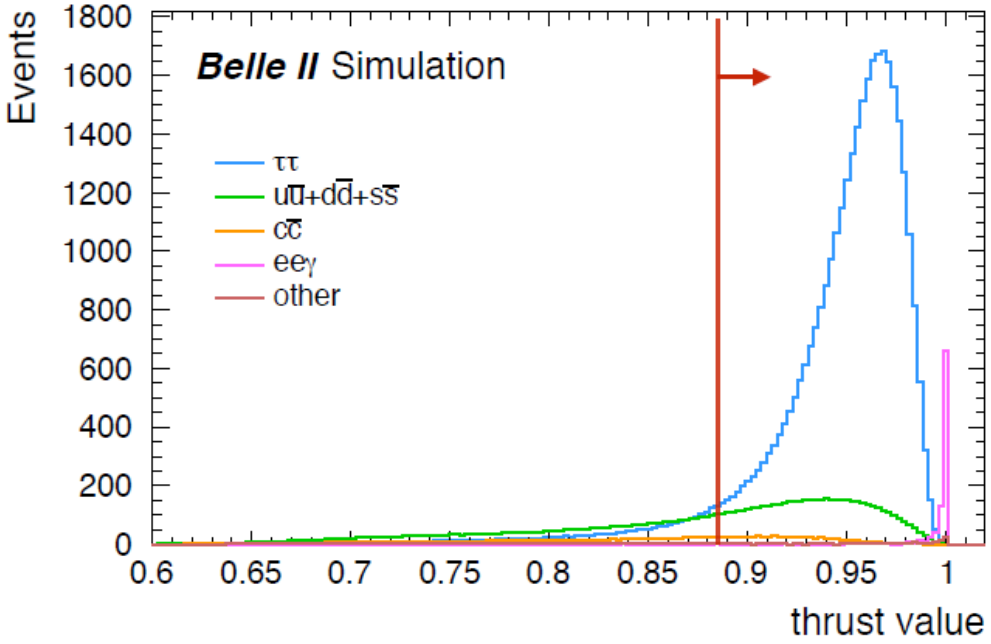


Extraction of τ pairs

Huge τ pairs samples are collected by tagging method

- $e^+e^- \to \tau^+\tau^-$
  - **Signal side**: 3 tracks
  - **Tag side**: 1 prong + missing





spherical ⟵ ⟶ 2 body-like

Event shapes helps to reduce backgrounds significantly

$$T = \frac{\sum_{i=1}^{N} |\mathbf{T} \cdot \mathbf{p_i}|}{\sum_{i=1}^{N} |\mathbf{p_i}|}$$

Thrust vector, minimizing T, shows sphericity of an event

Violations in τ hadronic decay

CP violation in $\tau \to K_s \pi \nu$

- CPV from a charged scalar boson exchange causes a difference in decay angular distributions

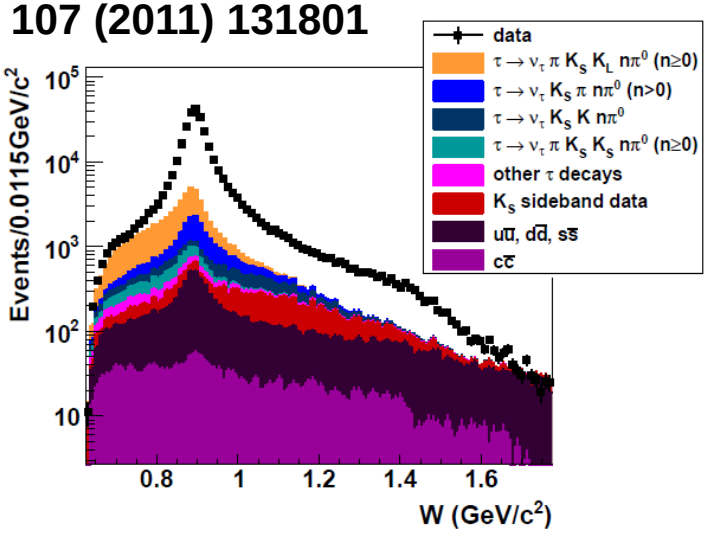
$$A_i^{CP} = \frac{\iint_{Q_{1,i}^2}^{Q_{2,i}^2} \cos\beta \cos\psi \left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}{\frac{1}{2} \iint_{Q_{1,i}^2}^{Q_{2,i}^2} \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}$$

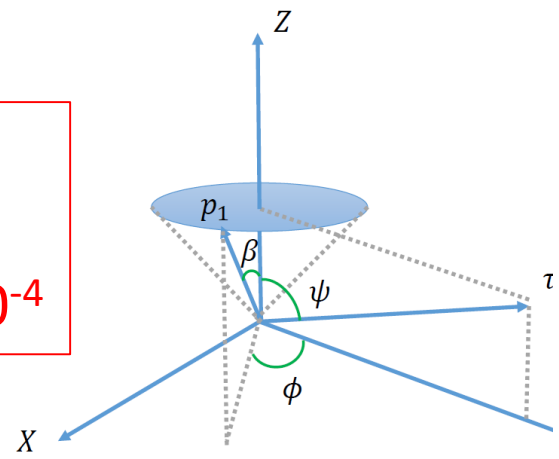
$$\simeq \langle \cos\beta \cos\psi \rangle_{\tau^-}^i - \langle \cos\beta \cos\psi \rangle_{\tau^+}^i,$$

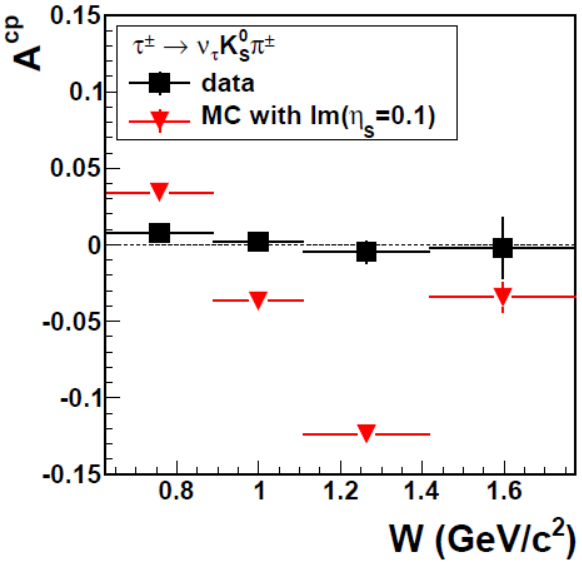
$$d\omega = dQ^2 d\cos\theta d\cos\beta$$

70 times improvement is expected in Belle II
=> $|A^{CP}| < (0.5 - 3.8) \times 10^{-4}$

M. Bischofberger et. al (Belle)
PRL 107 (2011) 131801







CP violation in $\tau \to K_s \pi(\geq 0\pi^0)\nu$

- τ decays with K_s meson in final states
  - Nonzero decay rate asymmetry due CP violation to Kaon sector

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

- SM prediction : $(3.6 \pm 0.1) \times 10^{-3}$

I. Bigi and A. I. Sanda, Phys. Lett. B 625, 47 (2005).

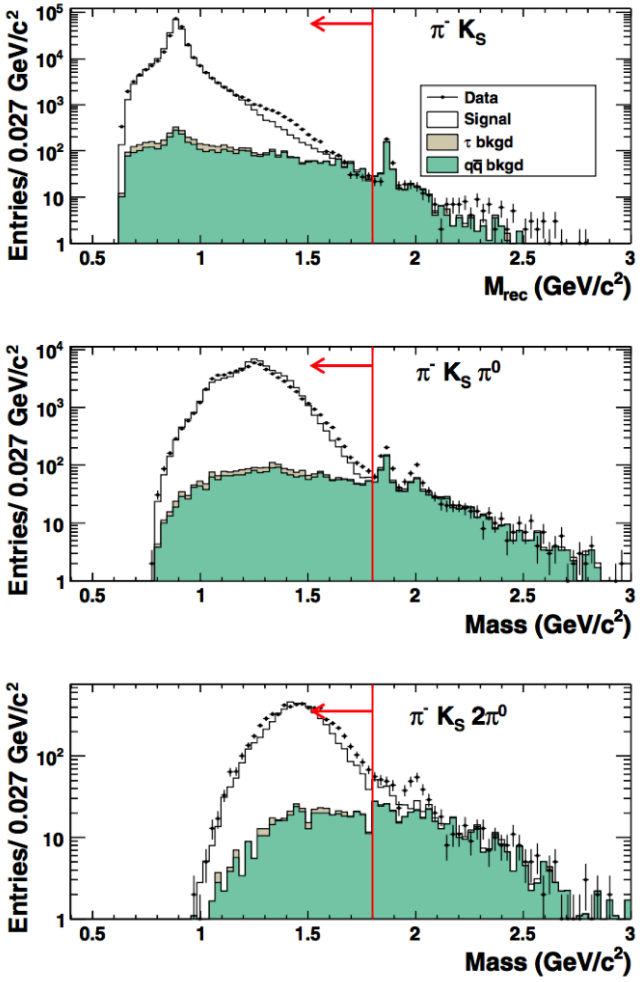
Y. Grossman and Y. Nir, JHEP 2012.4 (2012).

- BaBar results : $(-3.6 \pm 2.3 \pm 1.1) \times 10^{-3}$

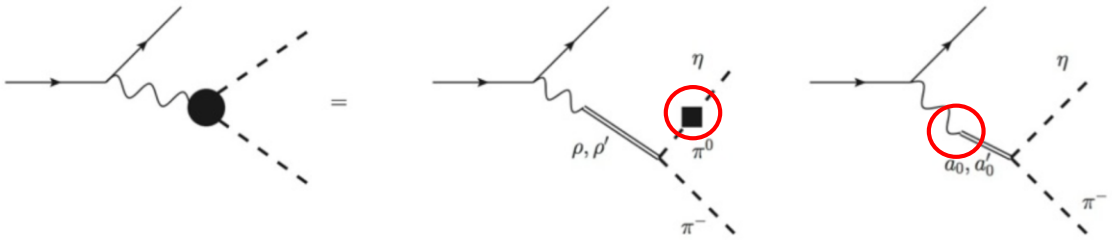
➡ 2.8σ discrepancy from SM

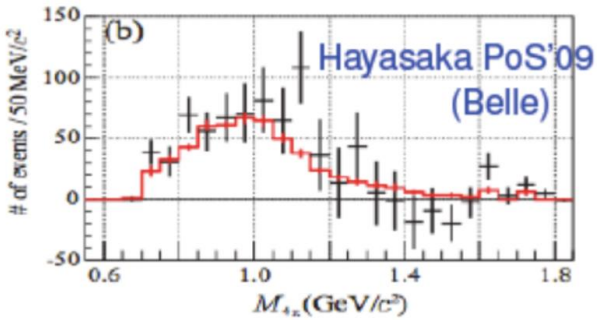
- Belle II will provide an improvement

J.P. Lees et.al (BaBar)
Phys.Rev D85 (2012) 031102

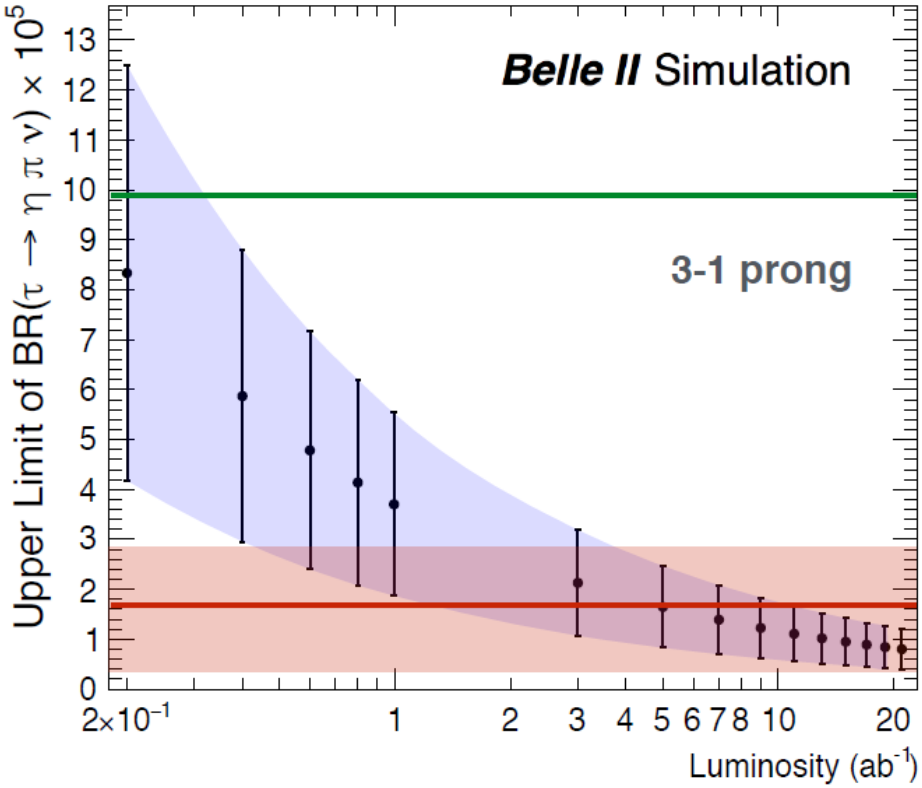


Second class currents : $\tau \to \eta\pi\nu$ decay





Br (Belle) < 7.3x10^{-5}, 90%CL



- **SM : Isospin violation**

$$\epsilon_{\eta\pi} = \frac{\langle \pi^0 | H | \eta \rangle}{m_\eta^2 - m_{\pi^0}^2} = \frac{\sqrt{3}}{4} \frac{m_d - m_u}{m_s - \bar{m}} \sim 1.5 \times 10^{-2}$$

- SM contribution is suppressed
  - BR in SM ~ 10^{-5}

=> Clear signal will suggest new Physics

- Belle II will investigate in the first years of data taking