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BEIHANG UNIVERSITY

Belle II

Prospect of τ decays at Belle II

Based on the τ physics part of the Belle II Physics book (arXiv:1808.10567)

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LHCb and Belle II Opportunities for Model Builders

MITP, Mainz, Germany, from Jan 28 to Feb 1, 2019

Outline

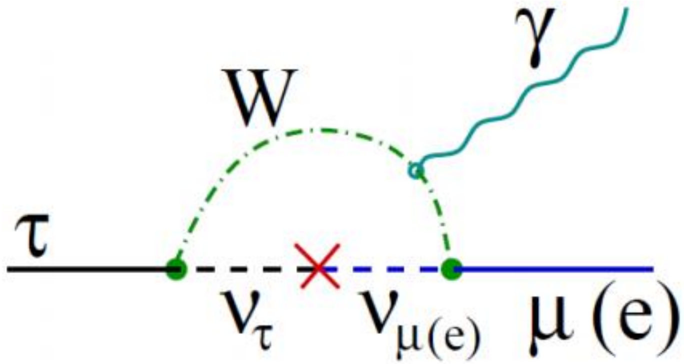
- Motivation for τ decays
- Belle II at SuperKEKB
- CLFV τ decays at Belle II
- CPV τ decays at Belle II
- Summary

Motivation for τ decays

- CLFV τ decays ➡ New physics
- CPV τ decays ➡ New physics

Motivation for CLFV τ decays (I)

- Charged Lepton flavor violating (CLFV) τ decays are suppressed in the Standard Model (SM), and their branching fractions (BFs) are tiny



$$\mathcal{B}(\tau \to l\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\tau i} U_{\mu i} \frac{\triangle^2_{3i}}{m^2_W}\right|^2 \leq 10^{-53} \sim 10^{-49}$$

- Even with neutrino oscillations taken into account

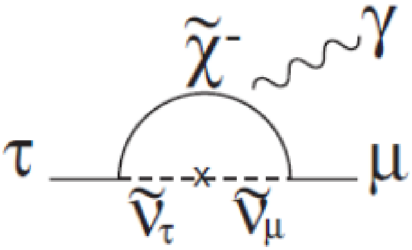
$$\mathcal{B}(\tau \to l\gamma) < O(10^{-45})$$

- The BFs are unreachable in current experiments
- Possible observation of CLFV τ decays will be an evidence for New Physics (NP)!

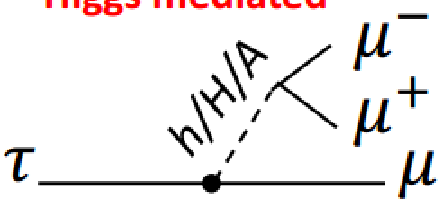
Motivation for CLFV τ decays (II)

- Many CLFV τ decays are related to NP models

SUSY



Higgs mediated



- Their Branch Fractions (BFs) are predicted by many NP models

Model	**Reference**	**τ→μγ**	**τ→μμμ**
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
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}

- Many of the BFs are large than $O(10^{-10})$, which is in the reach of Belle II experiment.

Motivation for CLFV τ decays (III)

- The ratios of the BFs of different CLFV τ decays given by different NP models varies

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z’
$\frac{\mathcal{B}(\tau \to \mu\mu\mu)}{\mathcal{B}(\tau \to \mu\gamma)}$	~2 x 10^{-3}	0.06 - 0.1	0.4 - 2.3	~16
$\frac{\mathcal{B}(\tau \to \mu ee)}{\mathcal{B}(\tau \to \mu\gamma)}$	~1 x 10^{-2}	~1 x 10^{-2}	0.3 - 1.6	~16
$\mathcal{B}(\tau \to \mu\gamma)_{\max}$	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

JHEP 0705, 013 (2007); PLB 547, 252 (2002)

- The more CLFV τ decays are investigated, the better these NP models are examined
- Almost all decay modes were studied using Belle data, no significant signals are observed, and more studies with big data samples from Belle II are urgently expected.

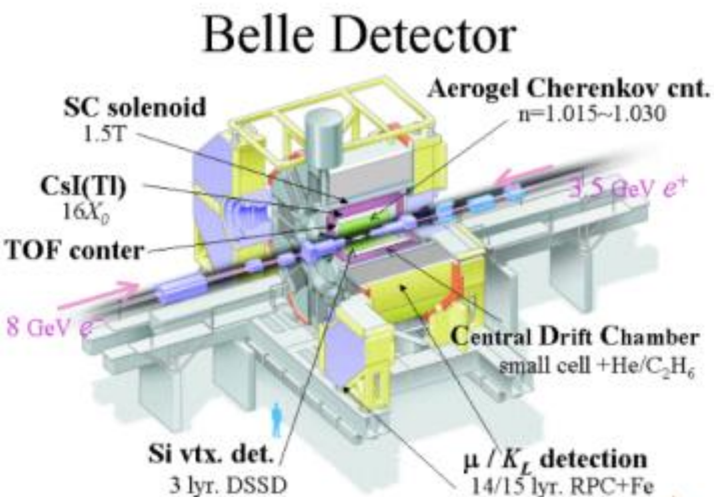
Motivation for CPV τ decays

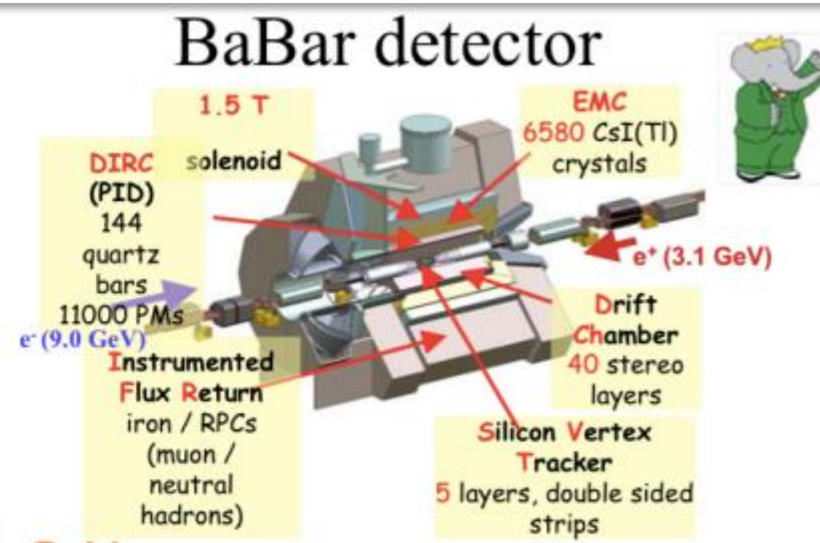
- CP violation (CPV) has never been observed in lepton decays
- It is strongly suppressed in the SM ($A^{CP} \leq 10^{-12}$), and possible observation of large CPV in lepton sector will be evidence of NP
- Many NP models predicts large CPV in lepton sector, for example:
  - minimum supersymmetric standard model [IHEP12,021;RMP80,577]
  - multi-Higgs-doublet-models [PRL37,657;NPB426,355]
- τ lepton provides a unique opportunity to search for CPV effects, as it is the only lepton decaying to hadrons, so that the associated strong phases allow us to visualize CPV in hadronic τ decays
- Decays have been suggested to measure CPV:
  - τ→2$\pi\nu$ [PRD50,4544]
  - $K\pi\nu$[PLB398,407]
  - 3$\pi\nu$[PRD52,1614]
  - K$\pi\pi\nu$, $KK\pi\nu$ [Z. Phys. G62,413; PRD78, 113008; PRD91, 073006]

Belle II at SuperKEKB

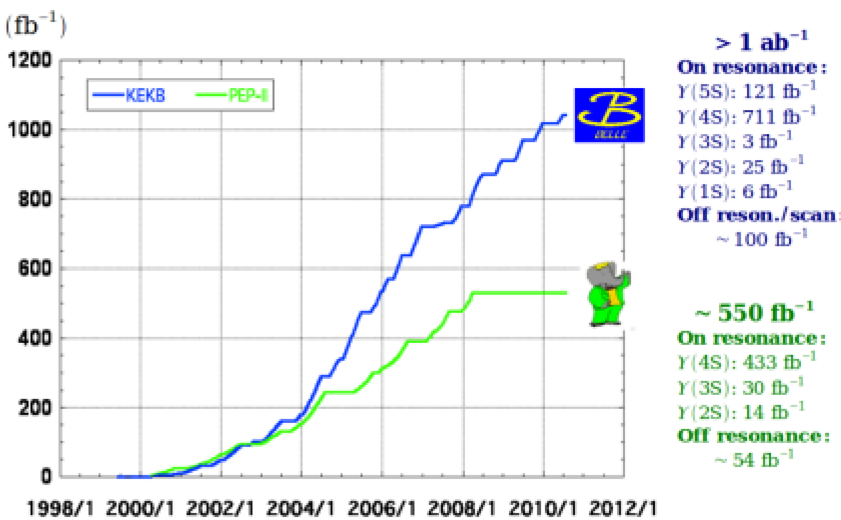
- B factories are also τ factories
- SuperKEKB and Belle II
- Belle II early data

B factories are also τ factories!





$\sqrt{s}=10.58$ GeV



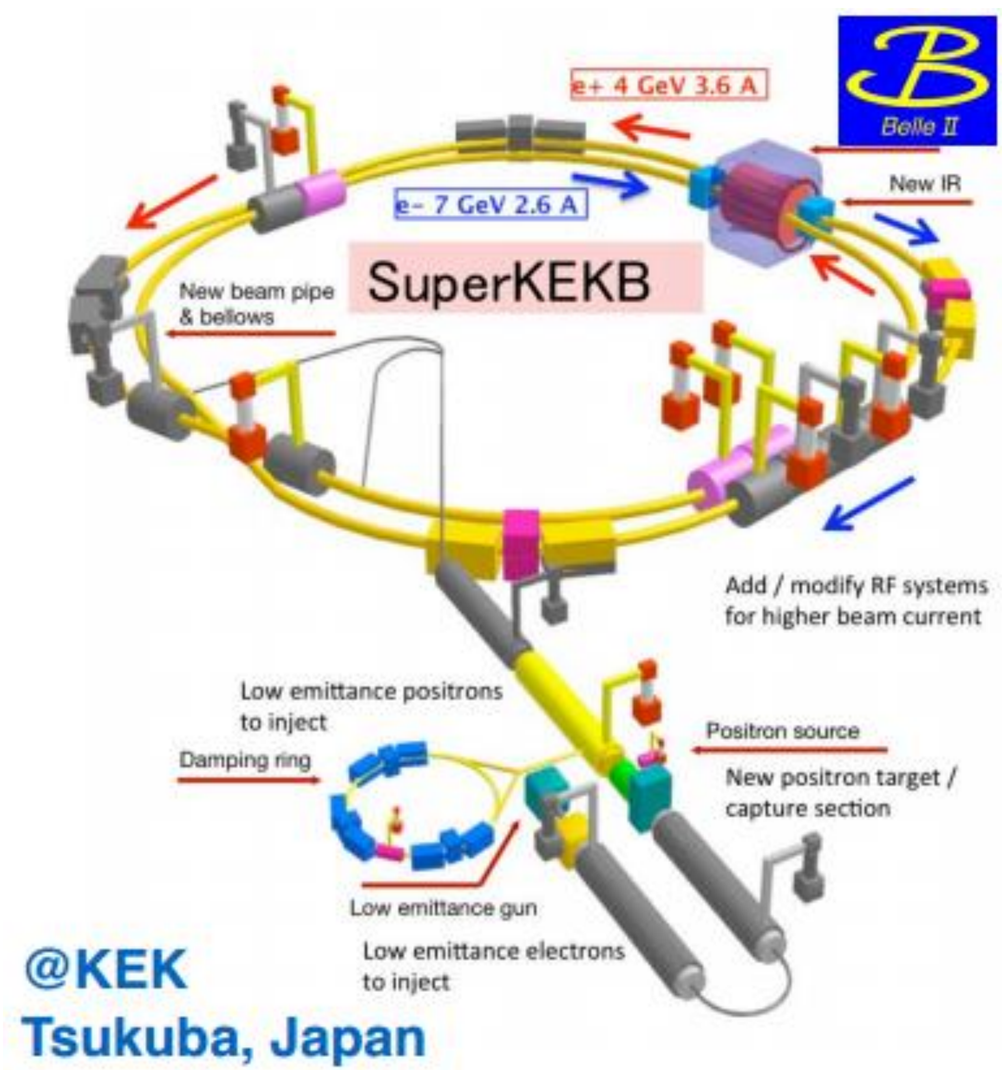
$\sigma(e^+e^- \rightarrow \Upsilon(4s)) = 1.05$ nb

$\sigma(e^+e^- \rightarrow \tau\,\tau) = 0.92$ nb

τ pairs and B pairs are produced in the same order of magnitude!

~10^9 τ pairs at Belle

SuperKEKB (I)



- Super B factory

  (Super τ factory too!)

  $\sigma(e^+e^- \rightarrow \Upsilon(4s)) = 1.05$ nb
  $\sigma(e^+e^- \rightarrow \tau\,\tau) = 0.92$ nb

- Integrated luminosity expected: 50 ab-1 (x50 of that of previous B factories)

4.6×10^{10} τ pairs

SuperKEKB (II)

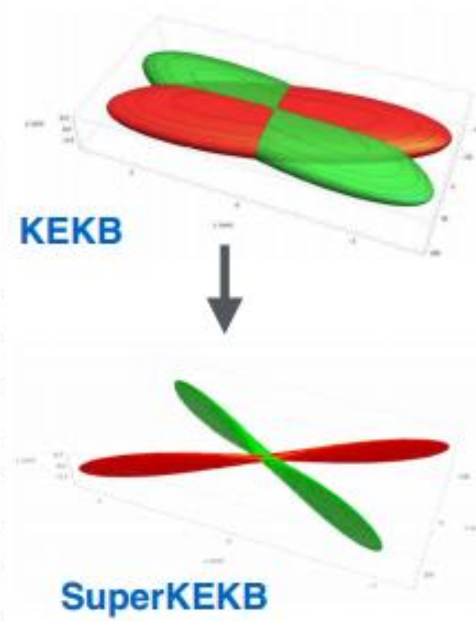
- Target luminosity is $\mathscr{L} = 8\times10^{35}\ cm^{-2}s^{-1}$ (x40 w.r.t. BELLE)
- Achievable in the *nano-beam scheme* (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @ IP by 1/20

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP

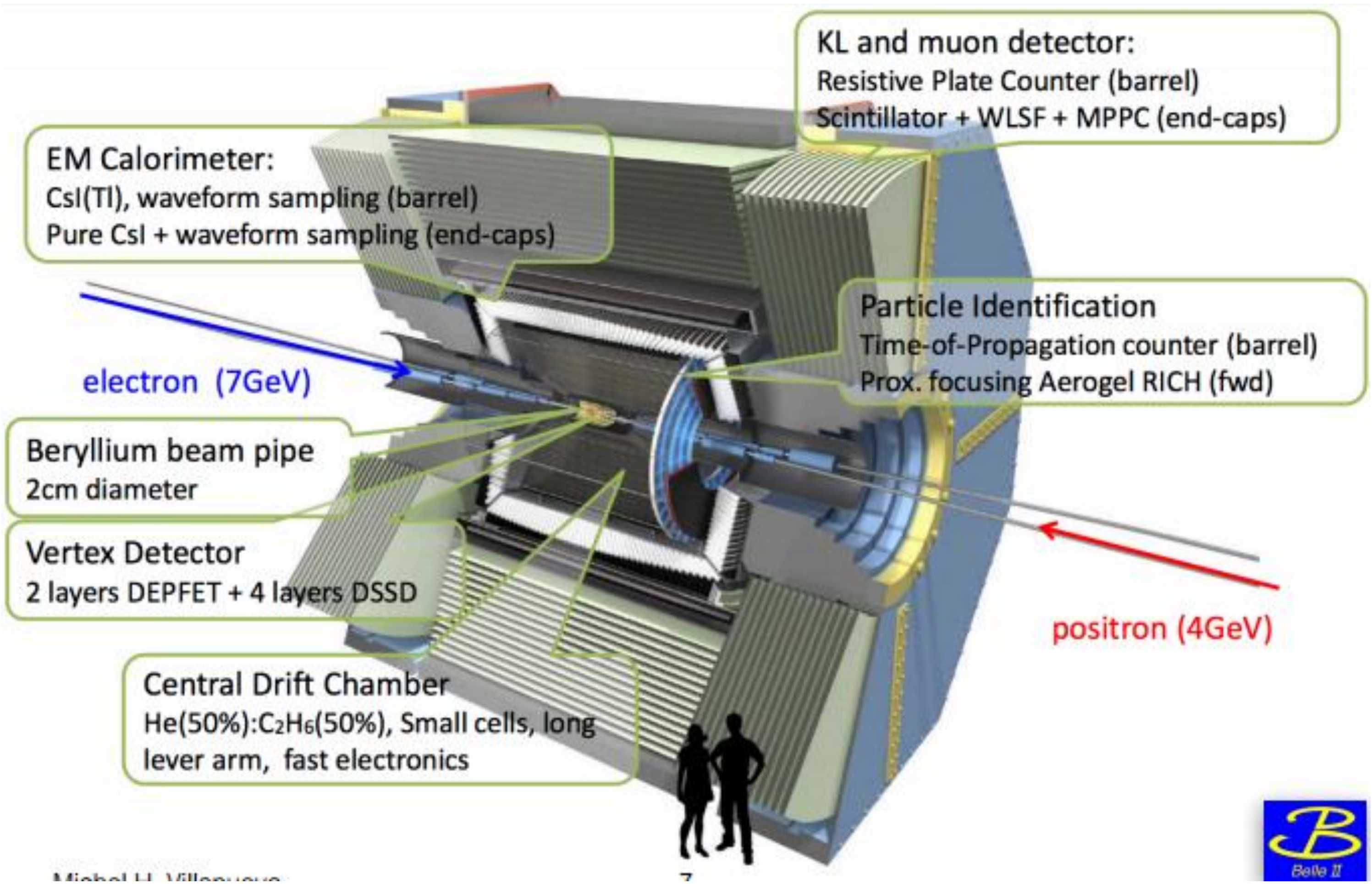
"Nano-beams": vertical beam size is 50nm at the IP.

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	φ	11		41.5		mrad
horizontal emittance	ε_x	18	24	3.2	4.6	nm
emittance ratio	κ	0.88	0.66	0.37	0.40	%
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam parameter	ξ_y	129	90	0.0881	0.0807	
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	$\mathscr{L}$	2.1x10		8×10^{35}		$cm^{-2}s^{-1}$



- Higher background (Radiative Bhabha, Touschek, beamgas scattering, etc.)
- Higher trigger rates (High performance DAQ, computing)

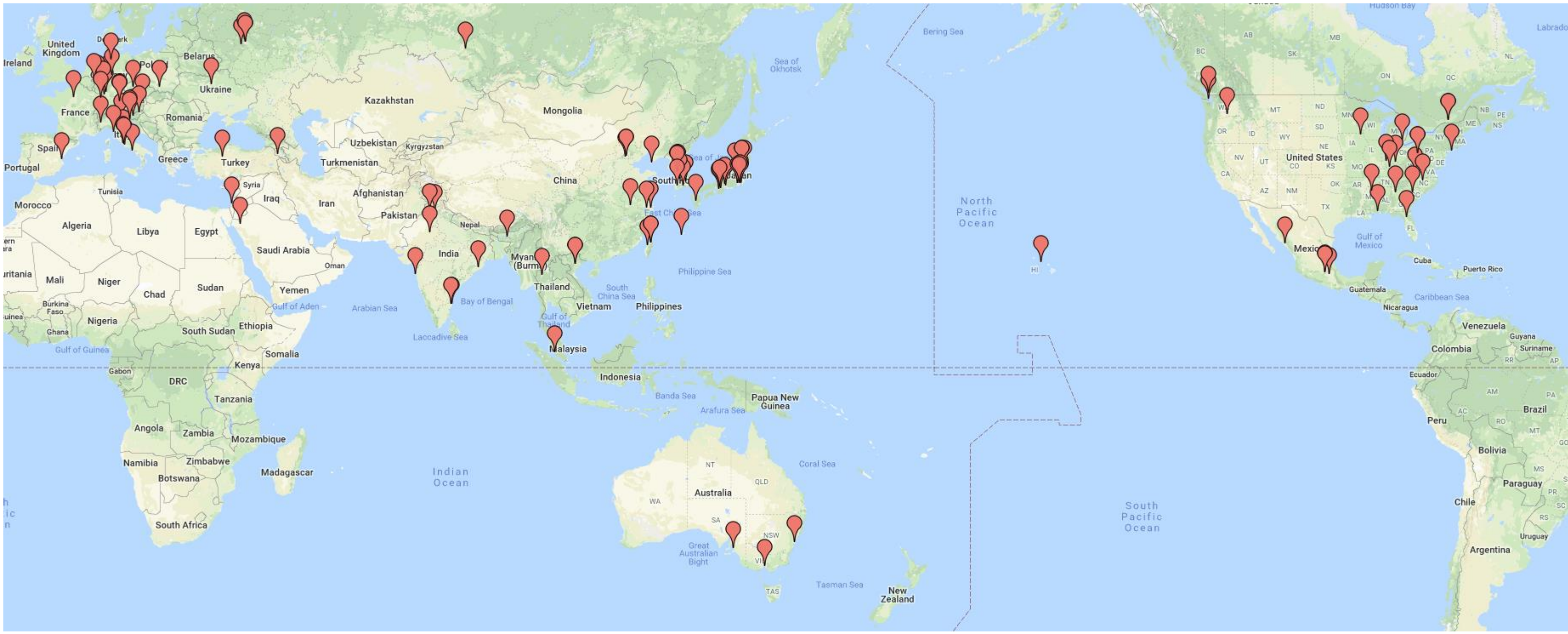
Belle II detector



All sub-detectors are upgraded from Belle, expect for ECL crystals and a part of Barrel KLM

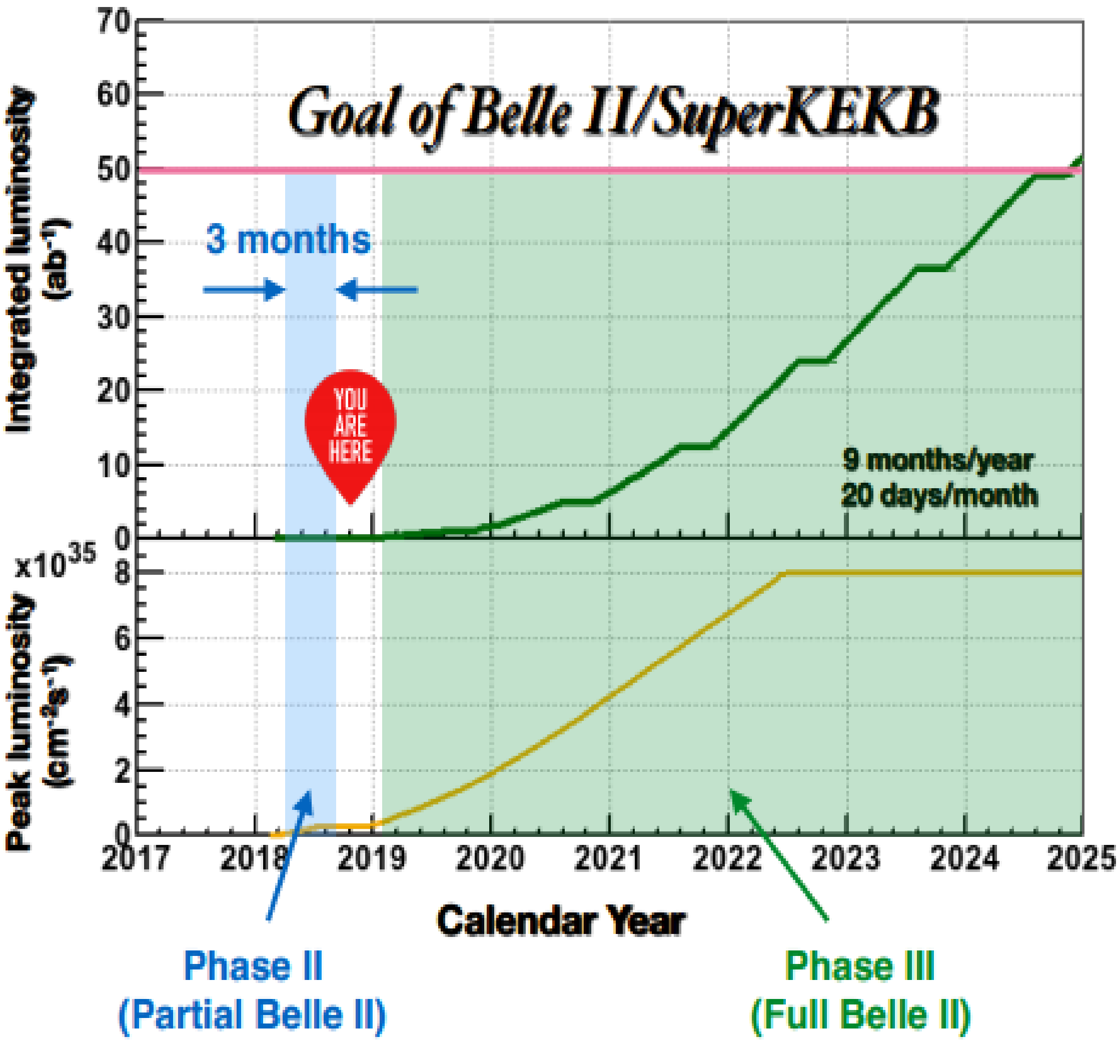
- Improved IP and secondary vertex resolution
- Better K/π separation and flavor tagging
- Higher Ks, π^0 and slow pion reconstruction efficiency

Belle II Collaboration



~900 colleagues, 108 institutions, 25 countries/regions

Belle II Schedule

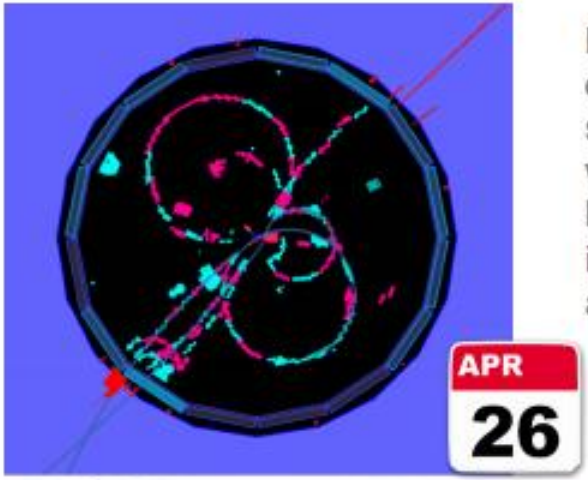


Phase I: commissioning of the main ring; installation of outer detectors; vacuum scrubbing and beam background Studies

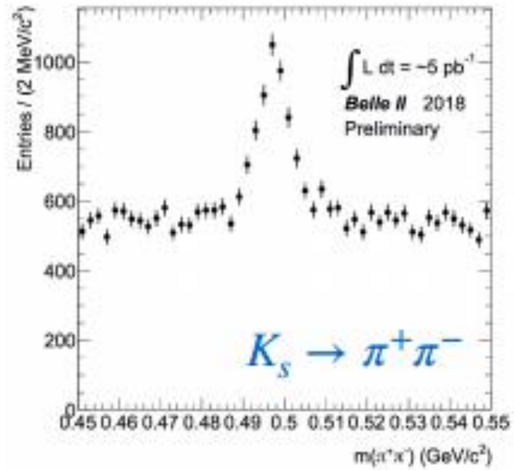
Phase II: start of the collisions, detector commissioning without vertex detector; physics runs on Y(4S) [April 2018 - July 2018]

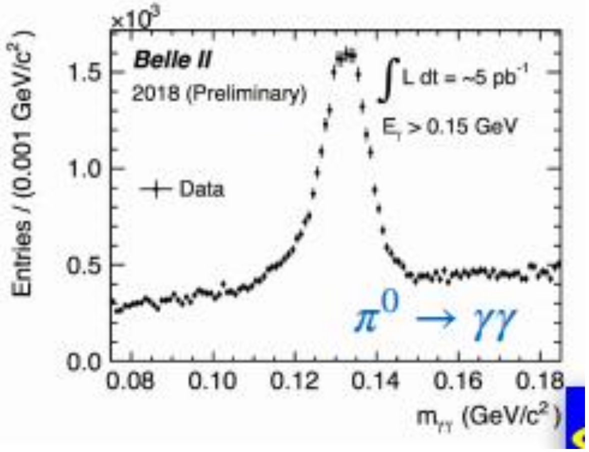
Phase III: full detector operation at the beginning of 2019

First collisions on Phase II



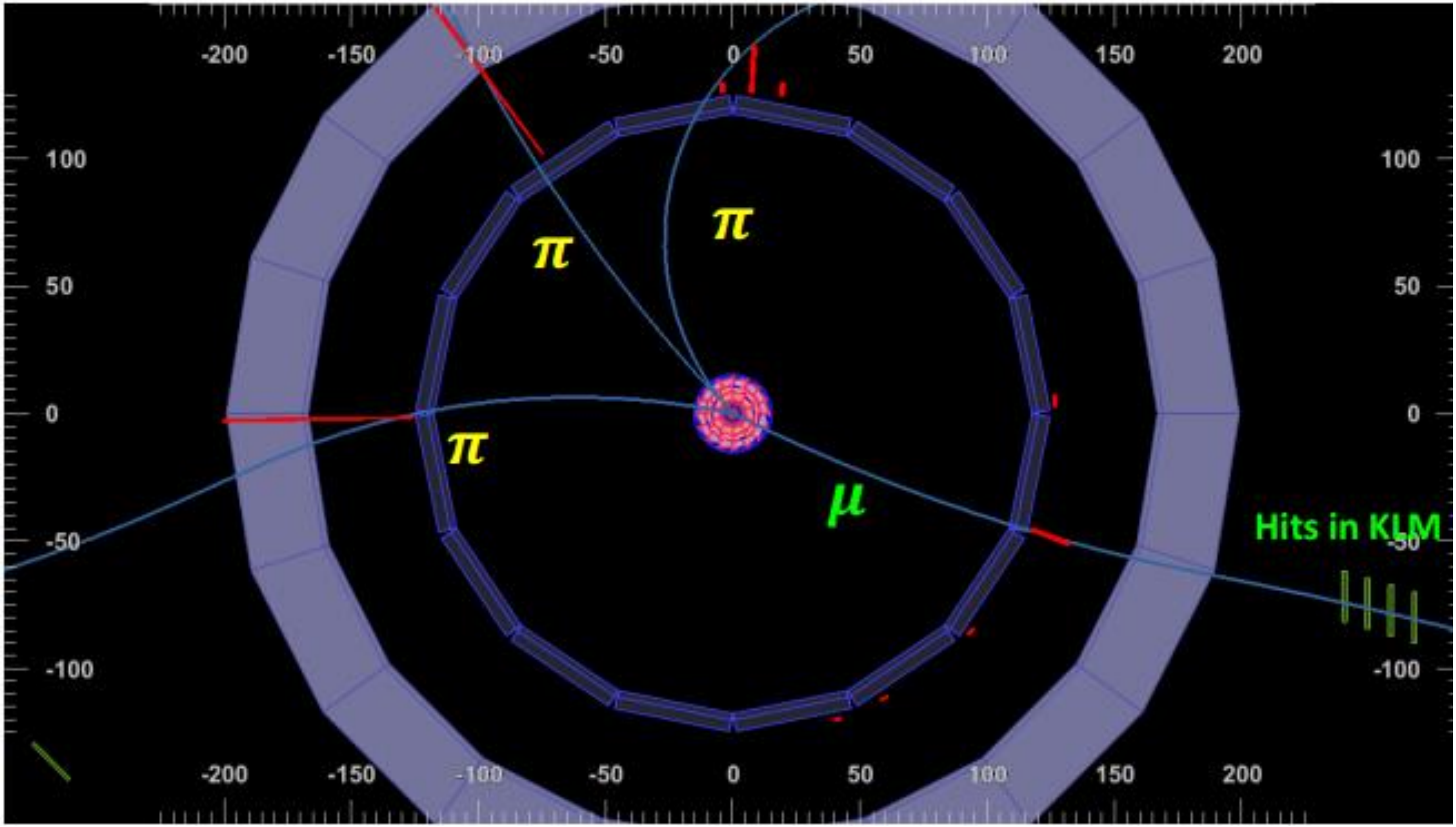
Most of the Belle II detector subsystems are working well. We have signals involving photons and charged tracks.



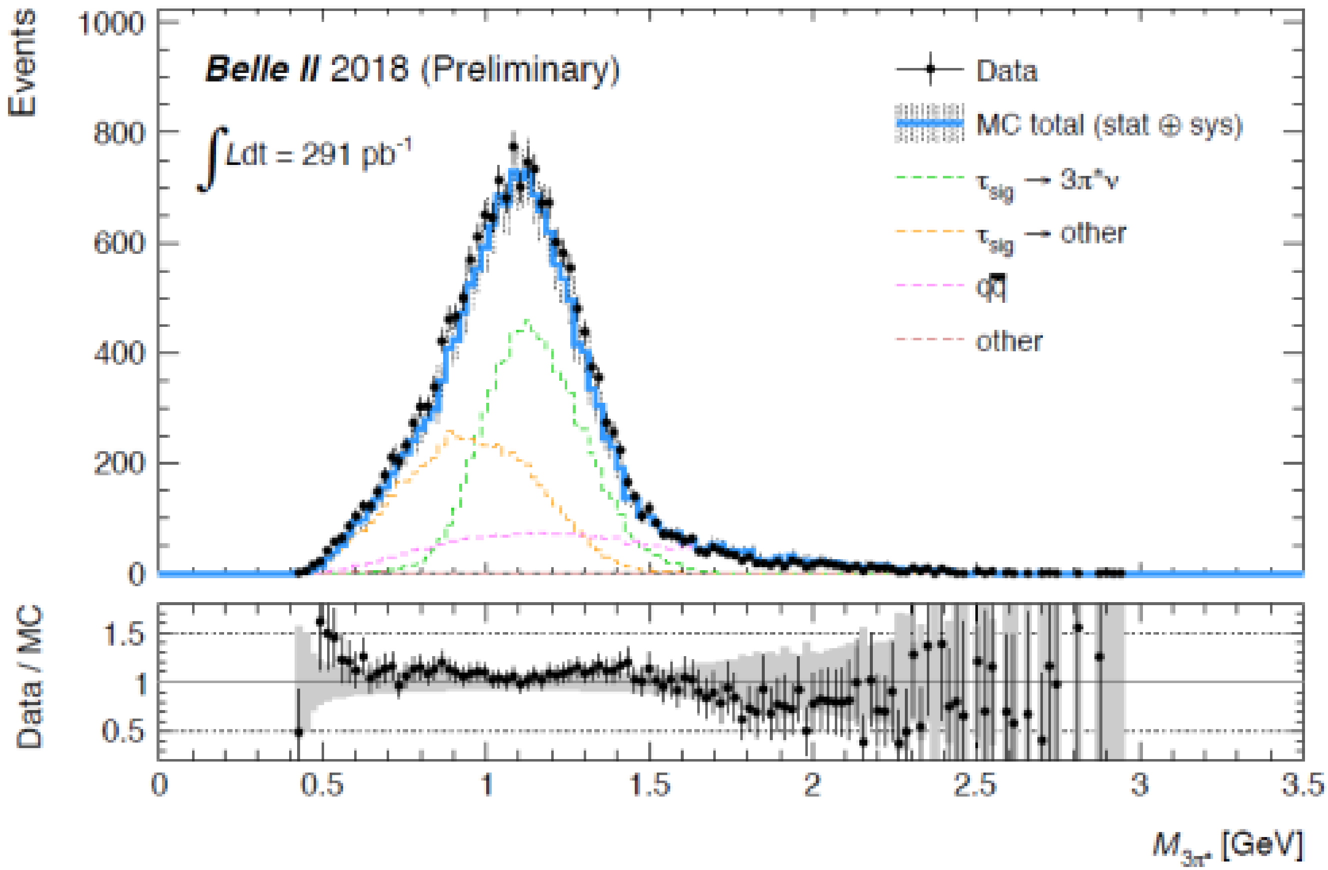


- **Phase II: from 26/04/2018 to 18/07/2018**
- **Total integrated luminosity: 500 $\mathbf{pb^{-1}}$**

A tipical τ pair candidate ($\tau \rightarrow 3\pi\nu$&&$\tau \rightarrow \mu\nu\nu$)



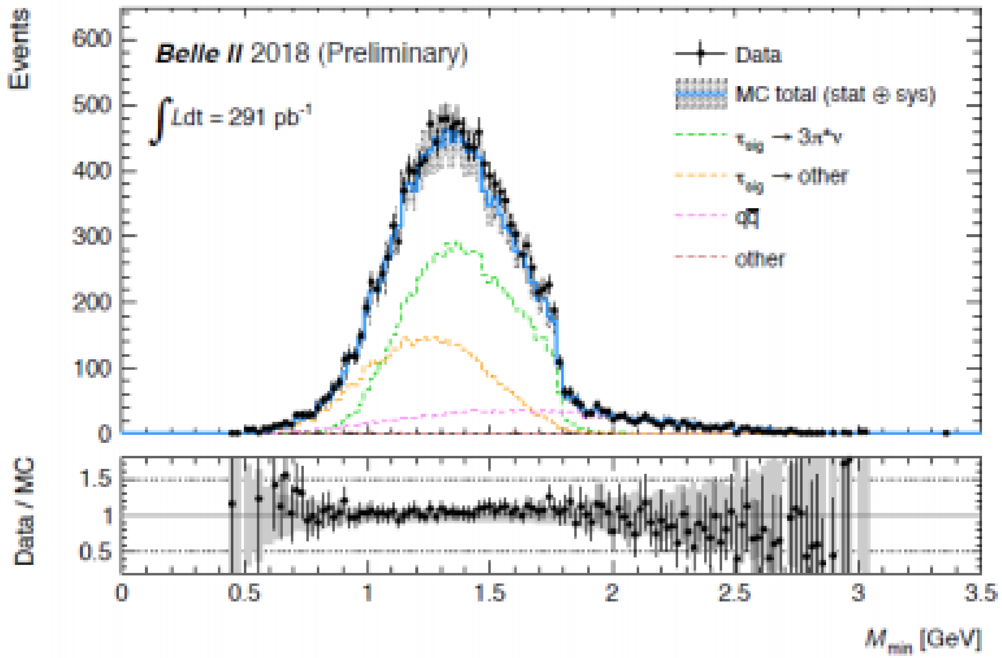
$\tau \rightarrow 3\pi\nu$ in Belle II early data



- **Data agrees well with MC after event selection**
- **Performance of subsystems is good enough as expected**

τ mass in Belle II early data

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



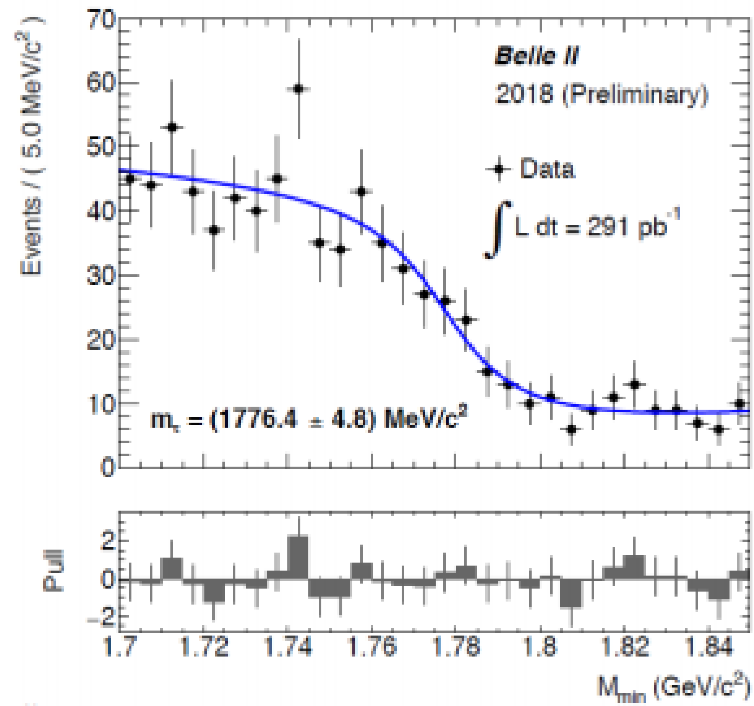
- Tau mass from Belle early data is consistent to previous results

m_τ = (1776.4 ± 4.8 (stat)) MeV/c2

Measured in τ -> 3πν

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

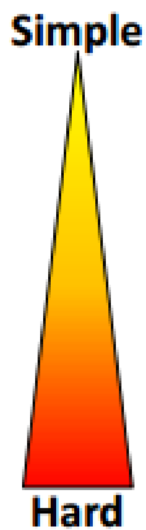
Distribution of the pseudomass is fitted to a empirical edge curve



CLFV τ decays at Belle II

Analysis strategy

- Key to searching for rare decays:
  Understand backgrounds and reduce them as much as possible
- Search for various decay modes:
  - $\tau \to \ell\ell\ell$
  - $\tau \to \ell K_s, \Lambda h$
  - $\tau \to \ell V_0(\to hh')$
  - $\tau \to \ell P^0\ (\to \gamma\gamma)$
  - $\tau \to \ell hh'$
  - $\tau \to \ell\gamma$

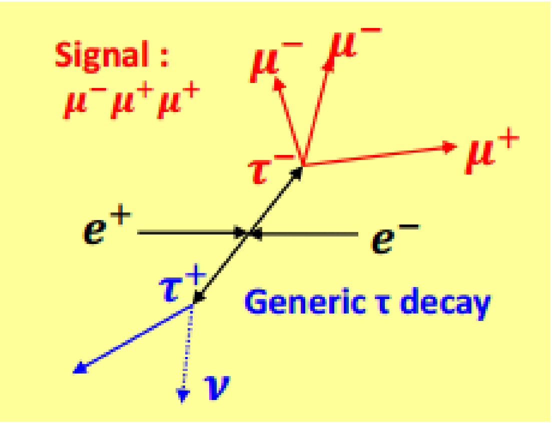


Difficulty of background reduction

- Analyze the modes from simple ones to hard ones
- Provide feedback to next analyses of similar final states

Analysis procedure

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

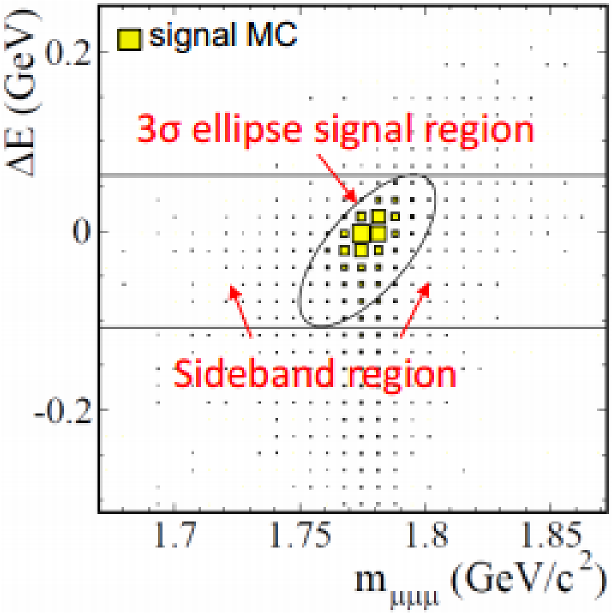


- Signal extraction: $m_{\mu\mu\mu} - \Delta E$ plane

  $$- m_{\mu\mu\mu} = \sqrt{E_{\mu\mu\mu}^2 - p_{\mu\mu\mu}^2} \sim m_\tau$$

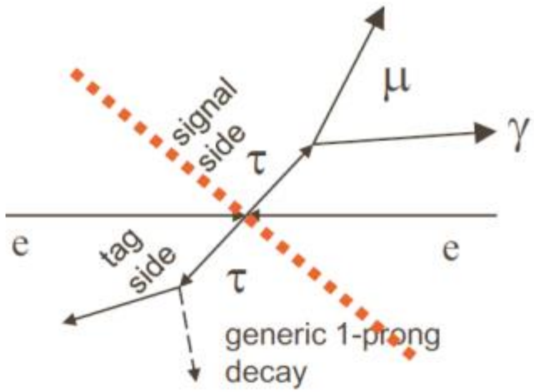
  $$- \Delta E = E_{\mu\mu\mu}^{CM} - E_{\text{beam}}^{CM} \sim 0$$

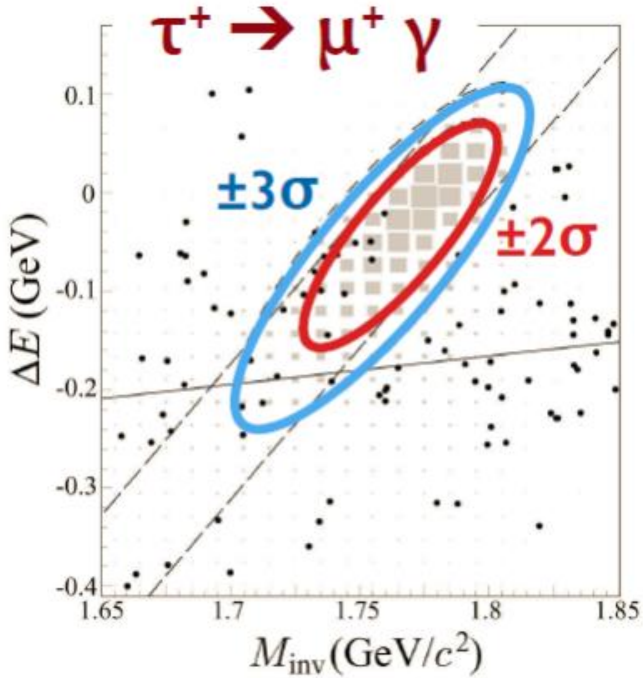
- Number of Background is estimated using sideband data and MC



Past searches for τ→lν at B factories

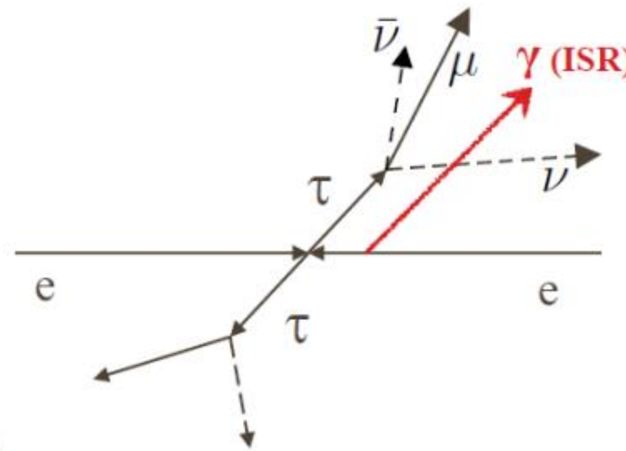
- Signal regions after BG rejection cuts — data (points) and signal MC (shaded):





Irreducible background

- $\tau \rightarrow \ell \nu\nu$ with ISR



- $B(\tau^- \rightarrow \mu^- \gamma) < 4.5 \times 10^{-8}$
- $B(\tau^- \rightarrow e^- \gamma) < 12.0 \times 10^{-8}$ @ 90%CL

Belle: PLB 666,16(2008)

- $B(\tau^- \rightarrow \mu^- \gamma) < 4.4 \times 10^{-8}$
- $B(\tau^- \rightarrow e^- \gamma) < 3.3 \times 10^{-8}$

best limits, BaBar: PRL 104,021802(2010)

$\tau \to \gamma\mu$ sensitivity at Belle II

- Sensitivity using Belle II MC samples with background simulation
- Main backgrounds

— $\tau \to \mu\nu\nu$ + γ
— $\tau \to e\nu\nu$ + γ
— $\tau \to \pi\nu$ + γ

— $ee \to ee/\mu\mu\ (\gamma)$
— $ee \to$ hadronic

- Backgound rejected by event shape variables, such asThurst, Fox Wolfram moments and so on.

	Belle (535 fb^{-1})	Belle II (1 ab^{-1})
$\mathcal{L}$ (cm^2/s)	2.11×10^{34}	80×10^{34}
ε_{signal}	5.09%	4.59%
n_{BG}	10	-
$B_{90}(\tau \to \mu\gamma)$	**4.5×10^{-8}**	**2.7×10^{-8}**

→

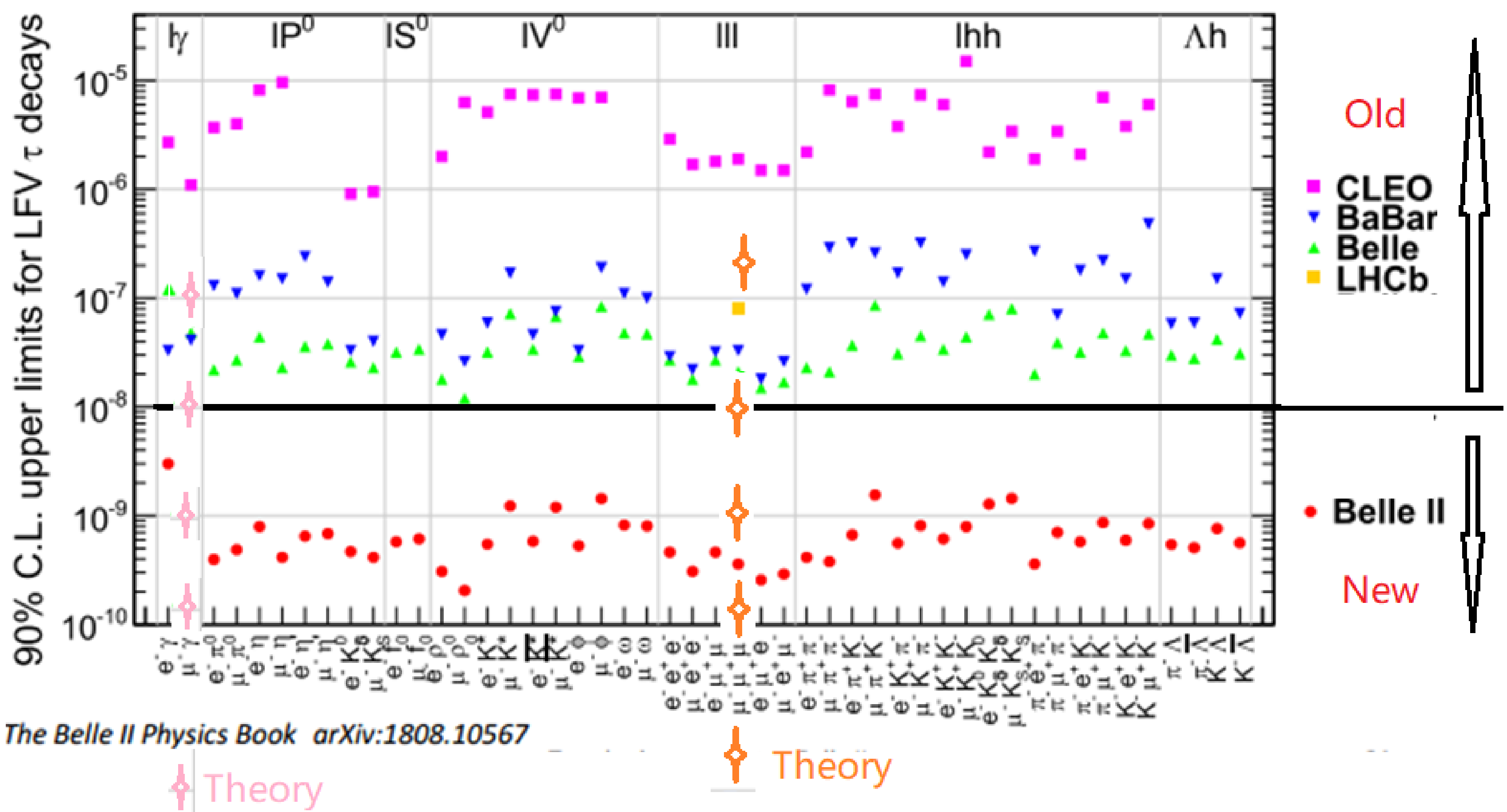
Belle II (50 ab^{-1})
5.5×10^{-10}

a naive extrapolation by luminosity

- Even with much higher backgrounds, the sensitivity is compared with Belle (Scaled by luminosity)
- Signal region is almost background free

Upper limits of CLFV τ decays at Belle II

- 48 different decays were studied at B factories, no significant signals are observed.
- Belle achieves the Best results, the upper limits are between $O(10^{-7})$ and $O(10^{-8})$



The Belle II Physics Book arXiv:1808.10567

- Current estimation with Belle II final statistics : ~10^{-2} lower
- Many decay modes predicted by NP models are reachable at Belle II

CPV τ decays at Belle II

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).

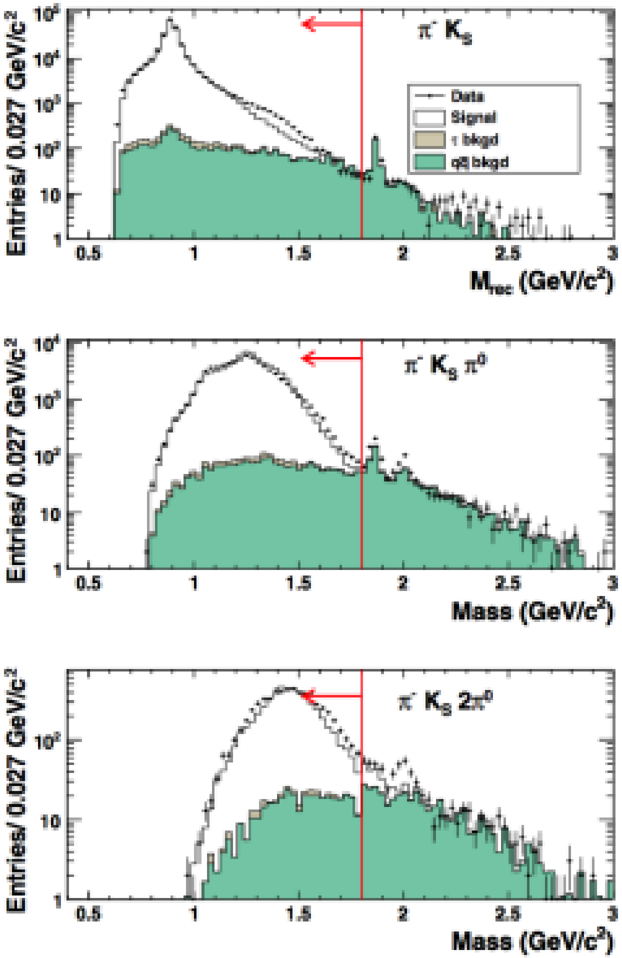
Y. Grossman and Y. Nir, JHEP 2012.4 (2012).

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

➡ 2.8σ discrepancy from SM

- Belle II will provide an improvement

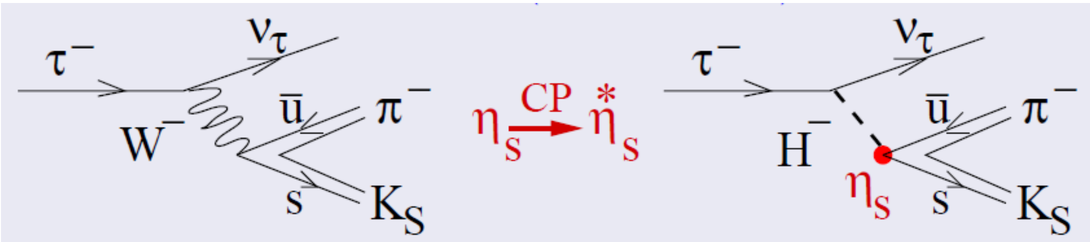
J.P. Lees et.al (BaBar)
Phys.Rev D85 (2012) 031102

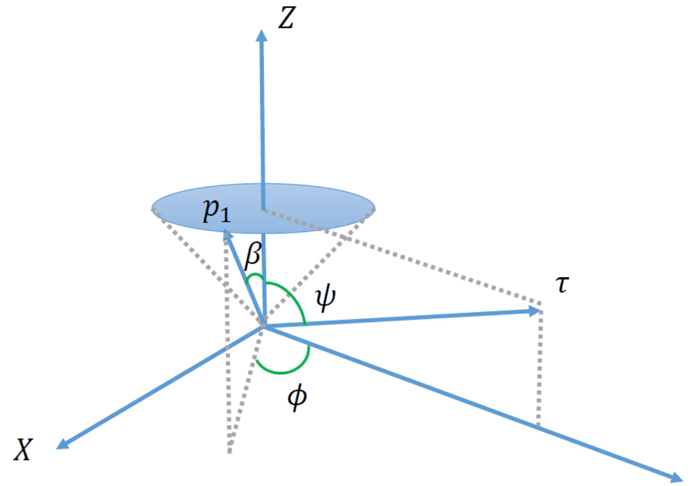


CP violation in $\tau \to K_s \pi \nu$

II: CPV in $\tau^- \to \pi^- K_s \nu_\tau$ at Belle (PRL107, 131801(2011); 699 fb^{-1})

Angular distributions were analyzed, $A_{CP}(W = M_{Ks\pi})$ was measured

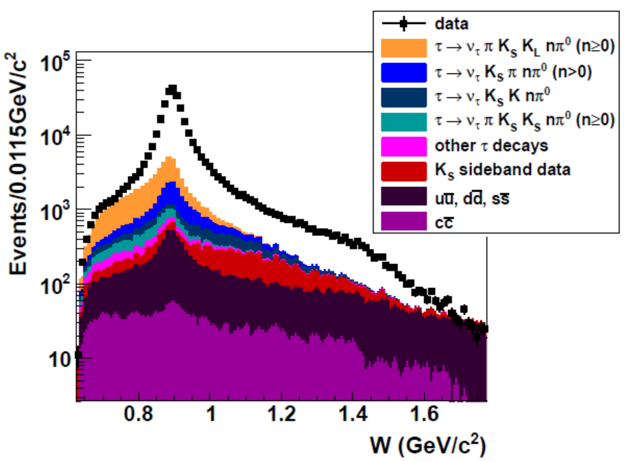


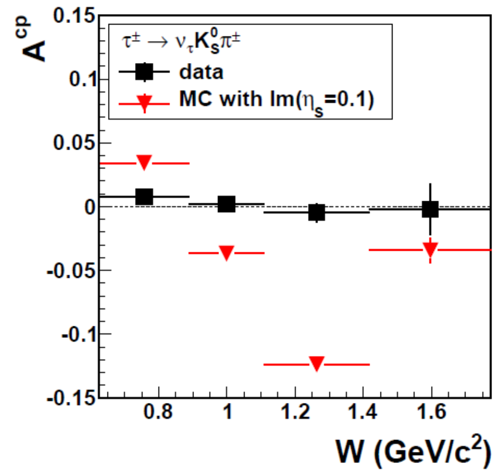


η_s is the dimensionless complex coupling constant

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

$$\simeq \langle \cos\beta \cos\psi \rangle_{\tau^-}^i - \langle \cos\beta \cos\psi \rangle_{\tau^+}^i, \quad d\omega = dQ^2 d\cos\theta d\cos\beta$$





With 50 ab-1 data at Belle II, we expect 70 times improvement, i.e., $|A^{CP}| < (0.5 - 3.8) \times 10^{-4}$, at 90% C.L. *assuming the central value* $A^{CP} = 0$

Summary

- CLFV τ decays are extremely good laboratory to search for NP, and hadronic τ decays are important to test CPV
- Studies with τ pairs to search for NP are carried out at B factories. No significant result has been obtained yet
- Belle II experiment at SuperKEKB factory starts data taking in 2018 and will start full operation in early 2019
- Many of LFV τ decays are reachable at Belle II, Improve upper limits of their branching fractions by O(10^{-2})
- Hadronic decays of τ lepton is also interesting for NP, to be improved in Belle II
- For more details (including other aspects of τ physics), please refere to "The Belle II Physics Book" arXiv:1808.10567

Need O(100x) more data → Next generation B-factories