北里大学
Kitasato University
理学部
School of Science

cLFV studies at Belle II

Outline
- Introduction
- Belle II status
- cLFV searches

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for the Belle II collaboration
Kitasato University
19/06/2019, Fukuoka, Japan

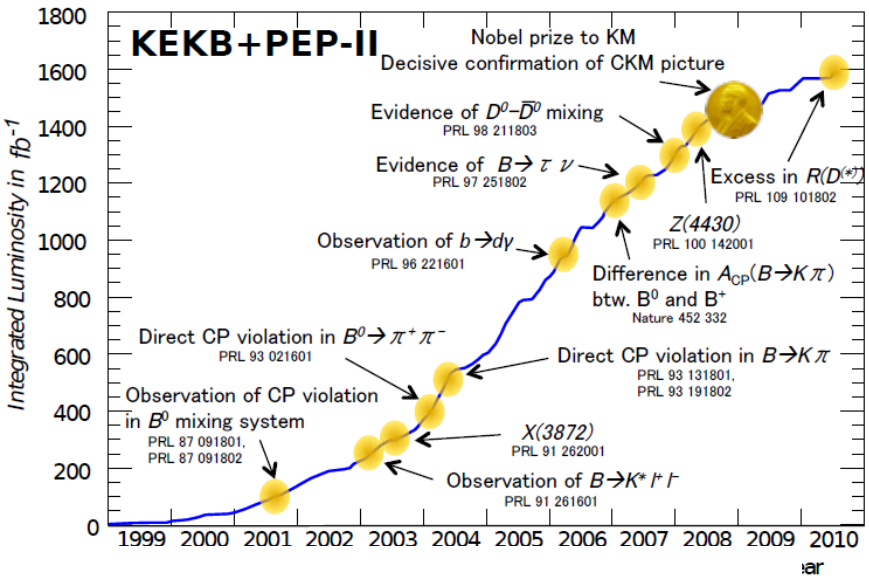
Introduction

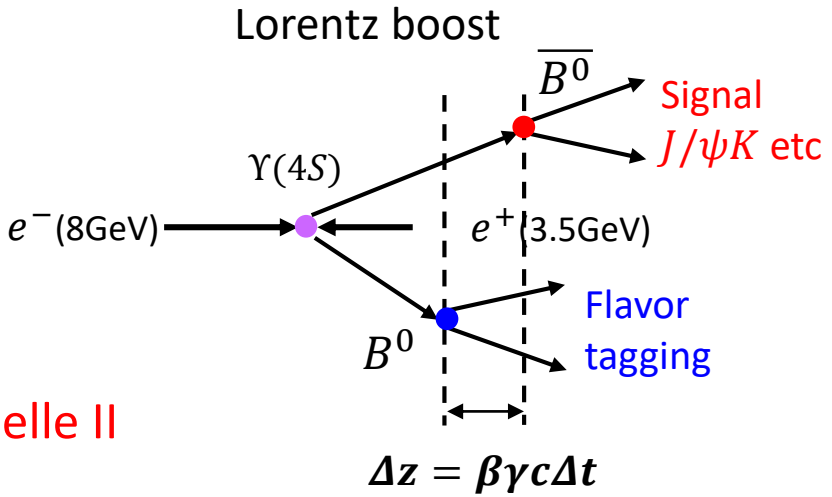
Motivation to Belle II

- **B factories (Belle / BaBar)** collected 1.5 ab^{-1}
  - Asymmetric energy : 3.5 / 8.0 GeV
- Many discoveries in the Standard Model
  - **CKM mechanism of CP violation**
- Next generation: Search for New Physics via precision measurements
- Advantages of a new B-Factory
  - Clean event topology
    - Full reconstruction/flavor tagging
    - Neutral particles in final state
  - Rich and clear Tau decays
  - Sensitive to NP mass ranges complemental with LHCb

  => Sensitive to Lepton Flavor Violation

Integrated Luminosity in Belle + BaBar

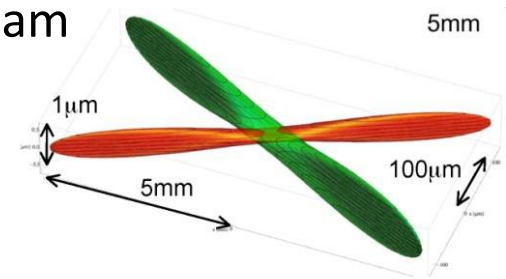


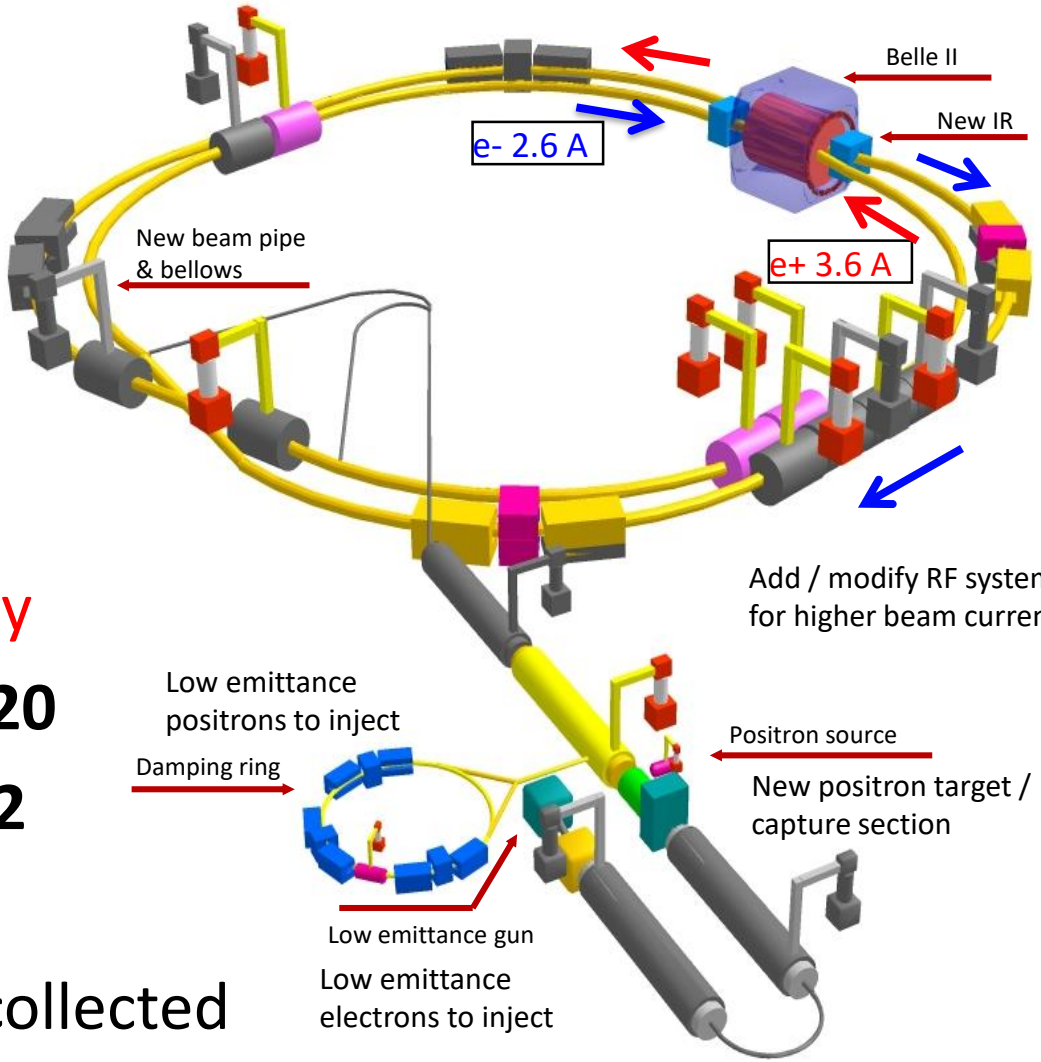


New Accelerator / Detector : SuperKEKB and Belle II

SuperKEKB / Belle II

Nano-beam scheme





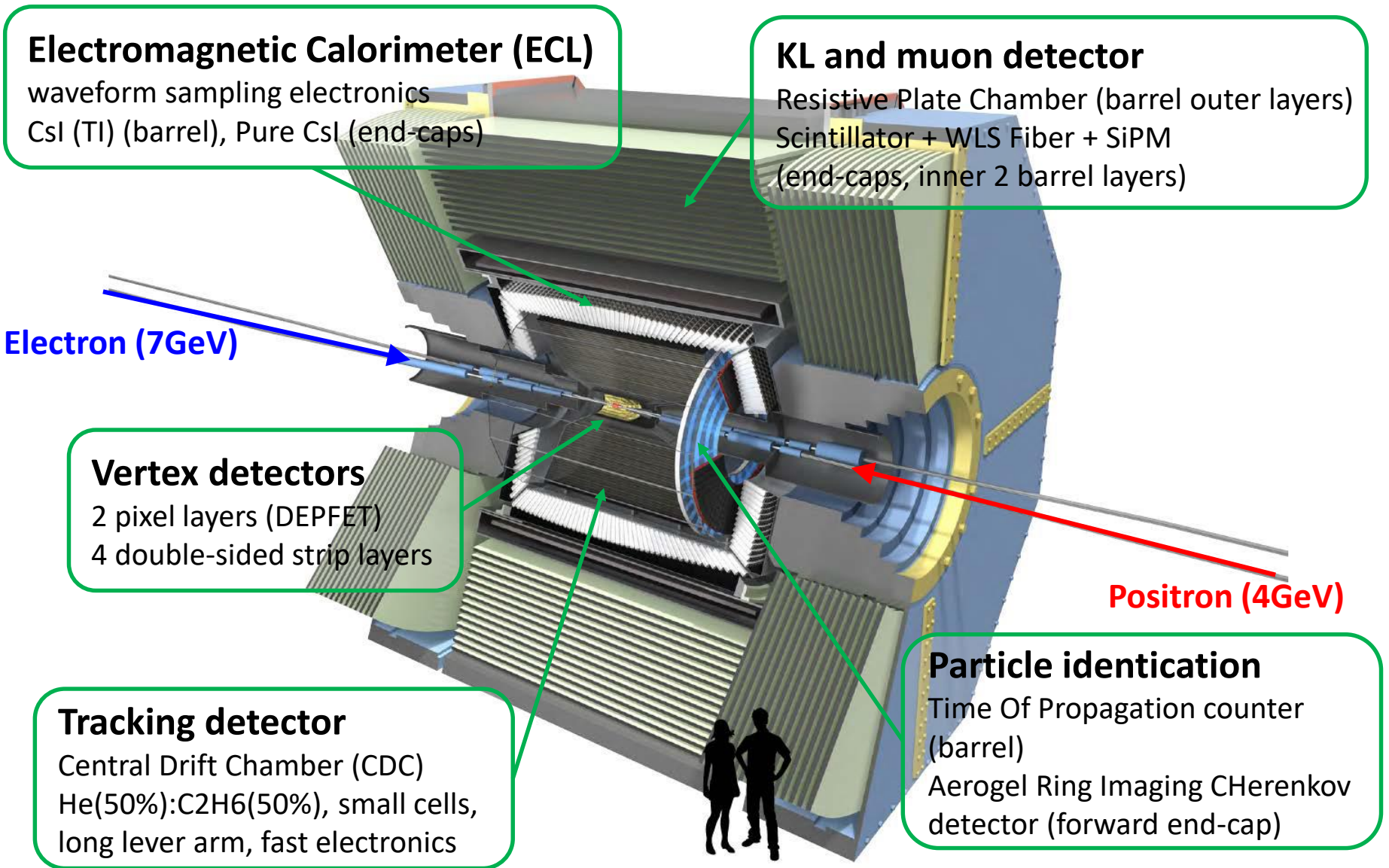
KEKB is upgraded to SuperKEKB !

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

  => Integrated 50 ab^{-1}

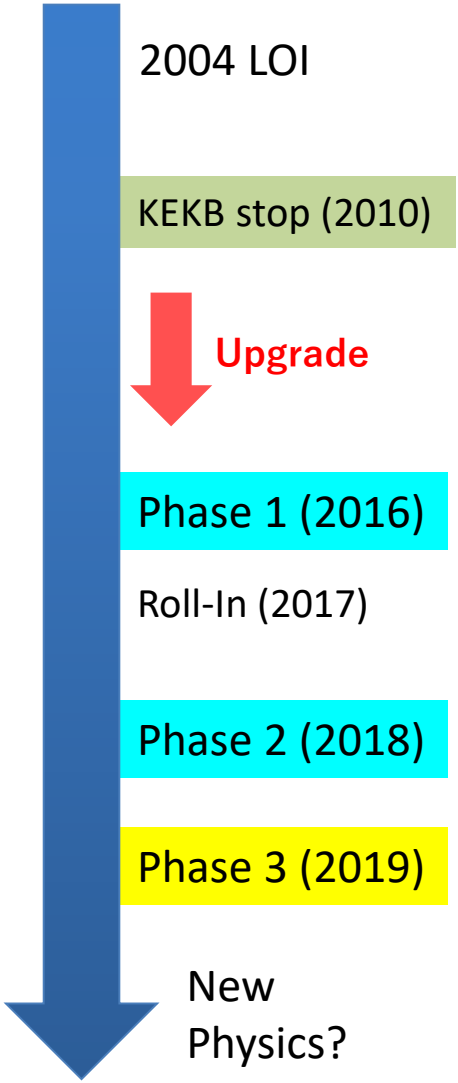
=> **4.6 x 10^{10}** τ pairs will be collected

Belle II detector

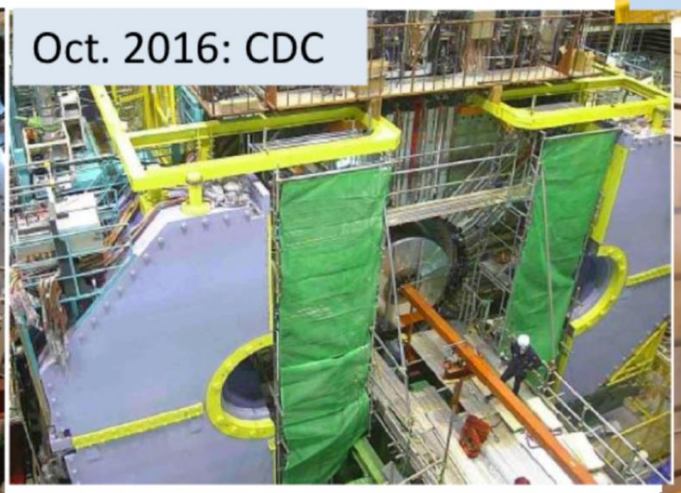


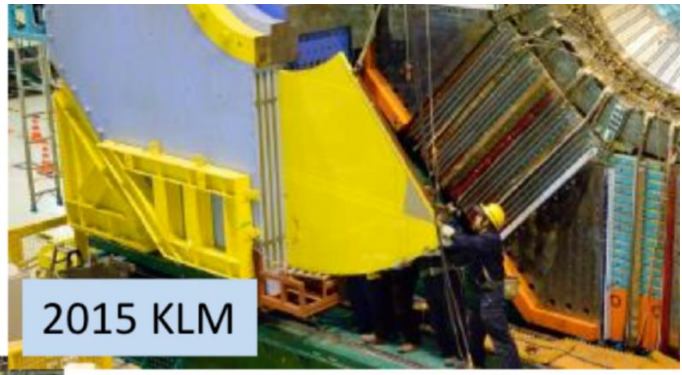
History of Belle II

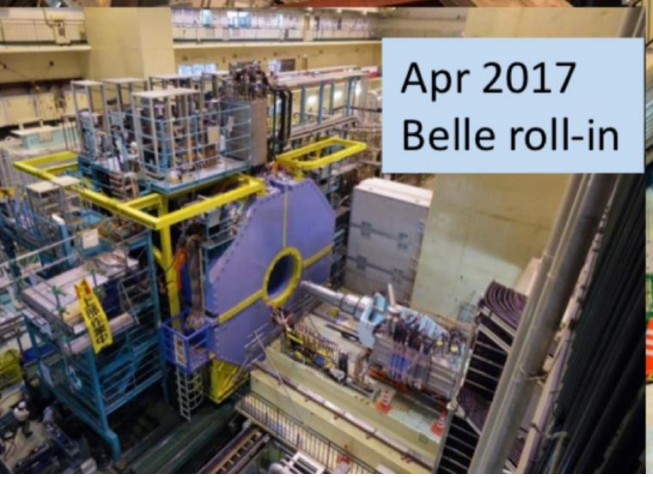
- KEKB stopped (2010)
- Phase 1 (2016)
  - SuperKEKB commissioning before collision
- Phase 2 (2018) : Beam collision
  - SuperKEKB +Belle II commissioning
  - Belle II (w/o VXD) + BEAST II (BG monitor)
- **Phase 3 (2019-) : Physics run**
  - Full Belle II (w/ VXD)
  - Search for new physics!

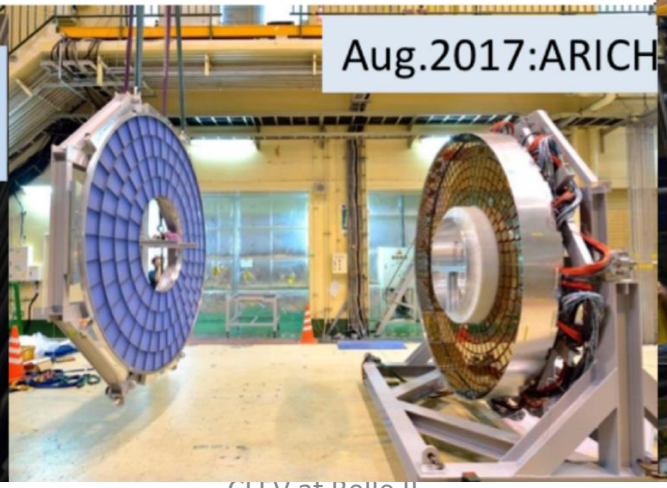


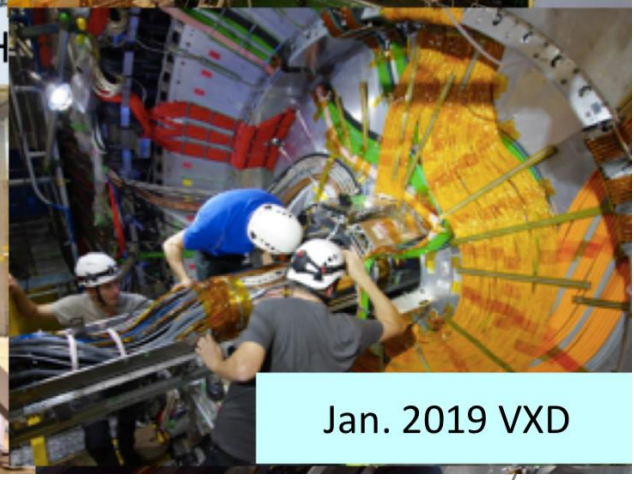
Belle II construction









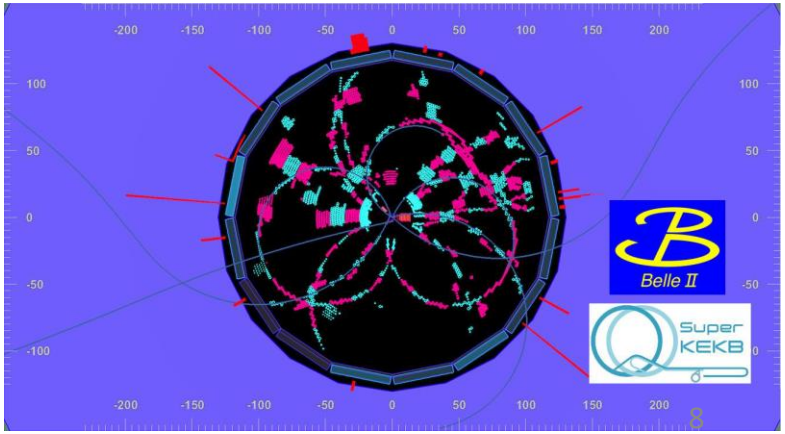


First Collision at Phase II run

First collision at 26/04/2018

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

Integrated Luminosity : ~500 pb^{-1}



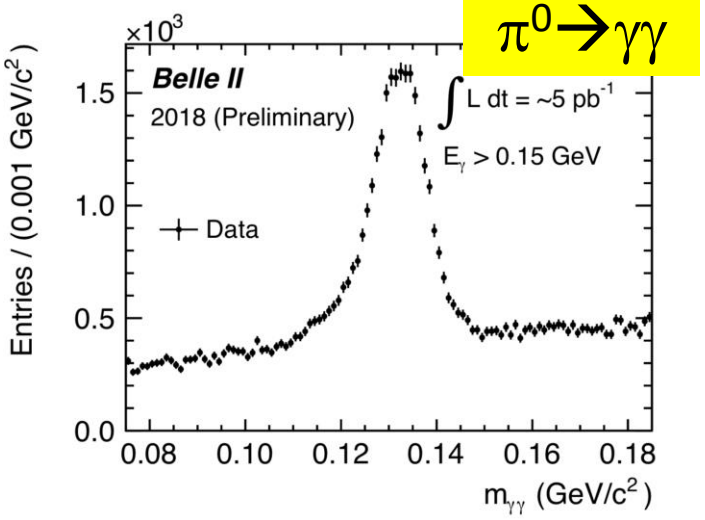
First plots

Rediscoveries in Phase II samples

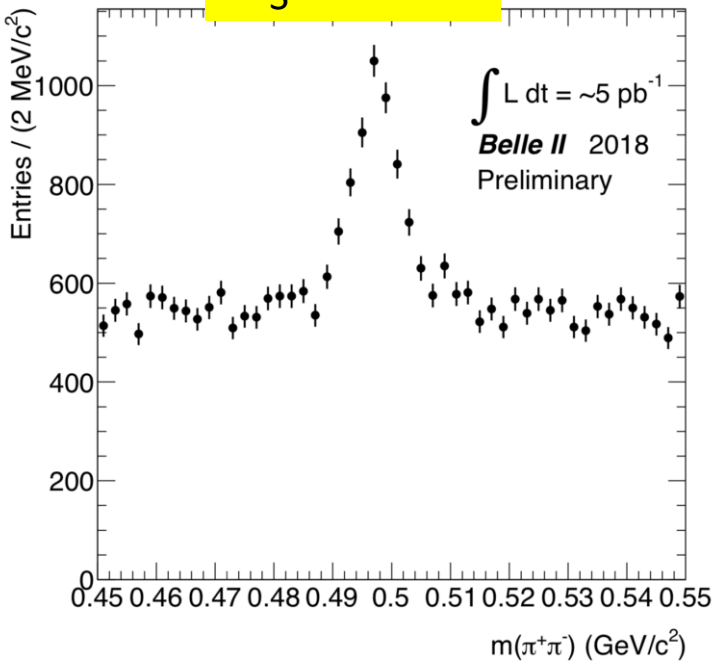
- Integrated Luminosity : ~5pb^{-1}
- Belle II is working nicely

=> Good Tracking, Clustering, PID

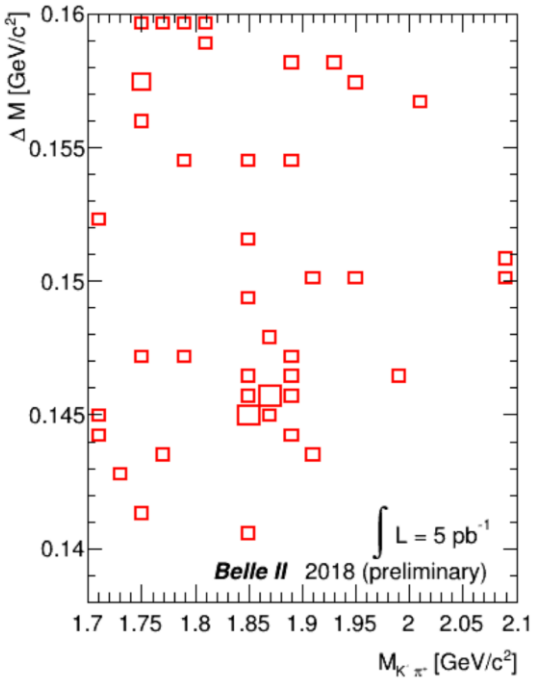
$\pi^0 \rightarrow \gamma\gamma$

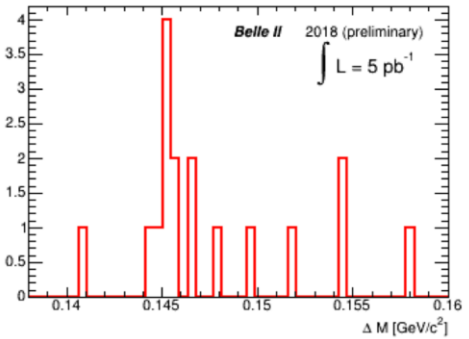


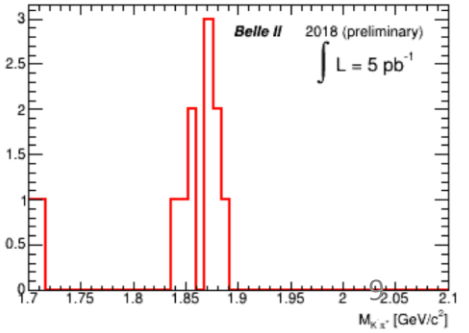
$K_S \rightarrow \pi^+\pi^-$



$D^* \rightarrow D^0(\rightarrow K^-\pi^+)\pi$







First plots

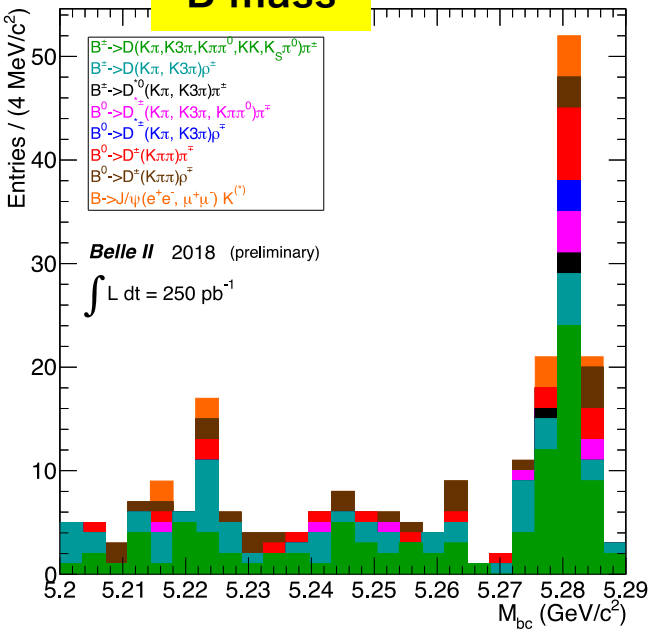
Rediscoveries in Phase II samples

- Integrated Luminosity：~5pb^{-1}
- Belle II is working nicely

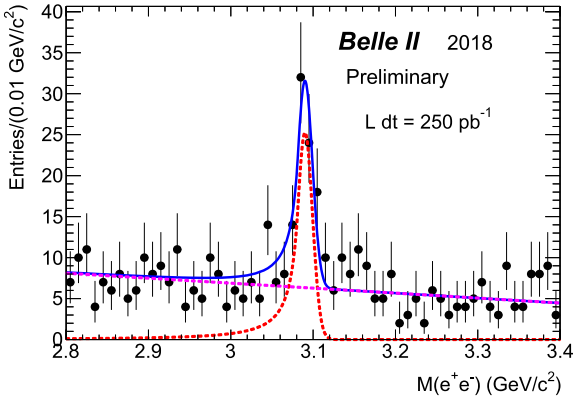
=> Good Tracking, Clustering, PID

$$M_{bc} = \sqrt{(E_{CM})^2 - (\sum p_i)^2}$$

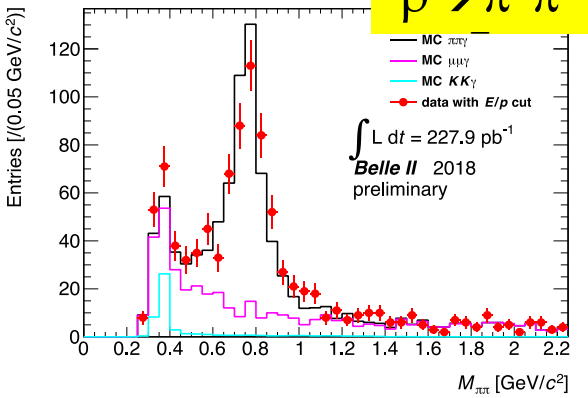
B mass



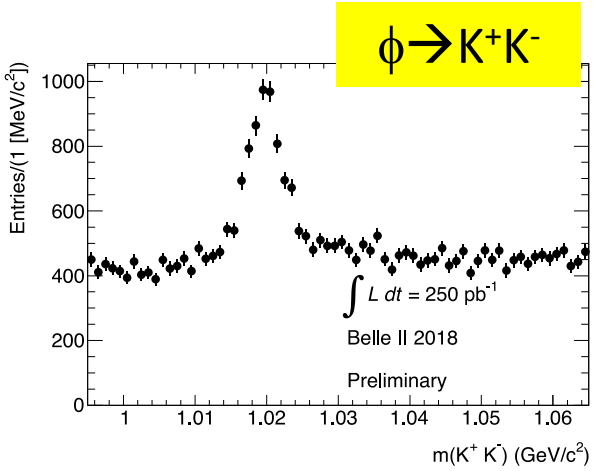
$J/\psi \rightarrow e^+e^-$



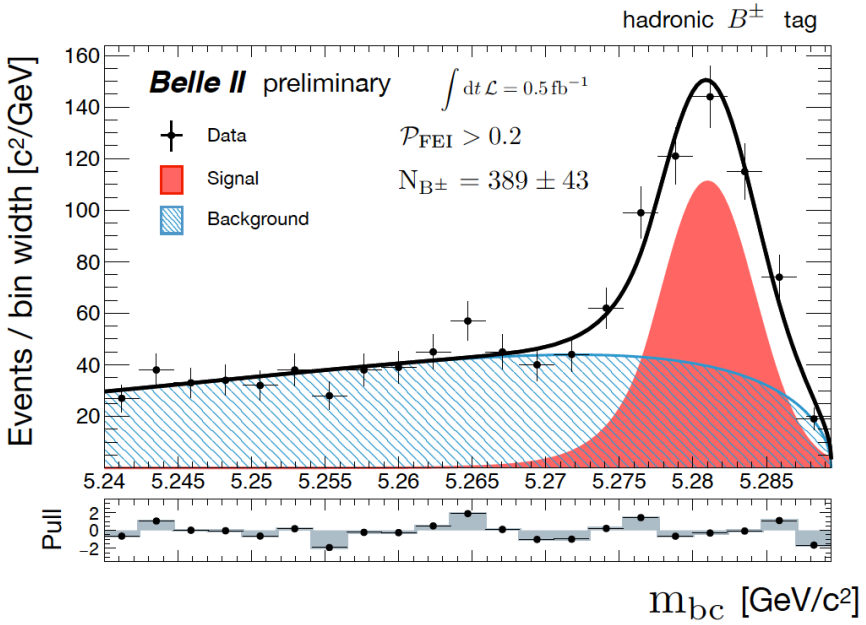
$\rho \rightarrow \pi^+\pi^-$

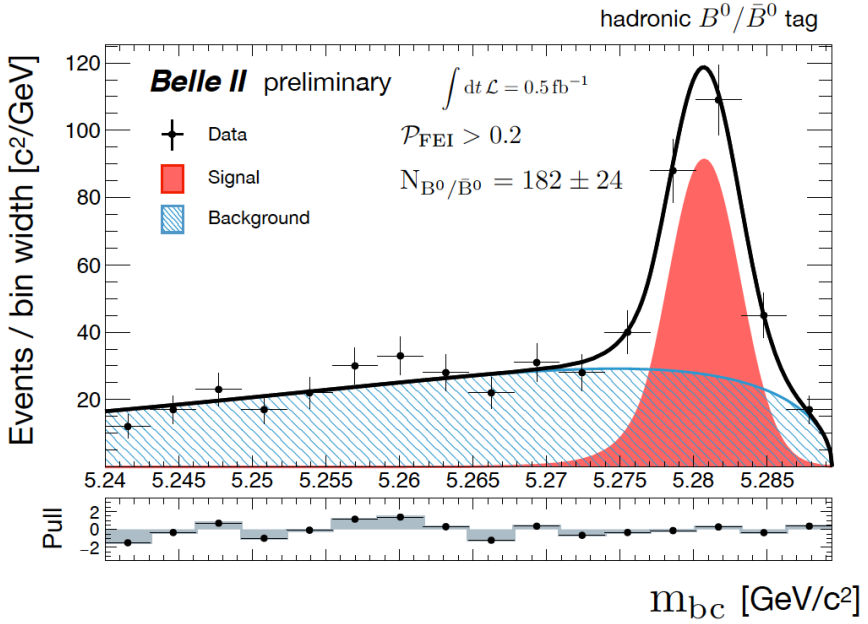


$\phi \rightarrow K^+K^-$



Full event reconstruction for B tag

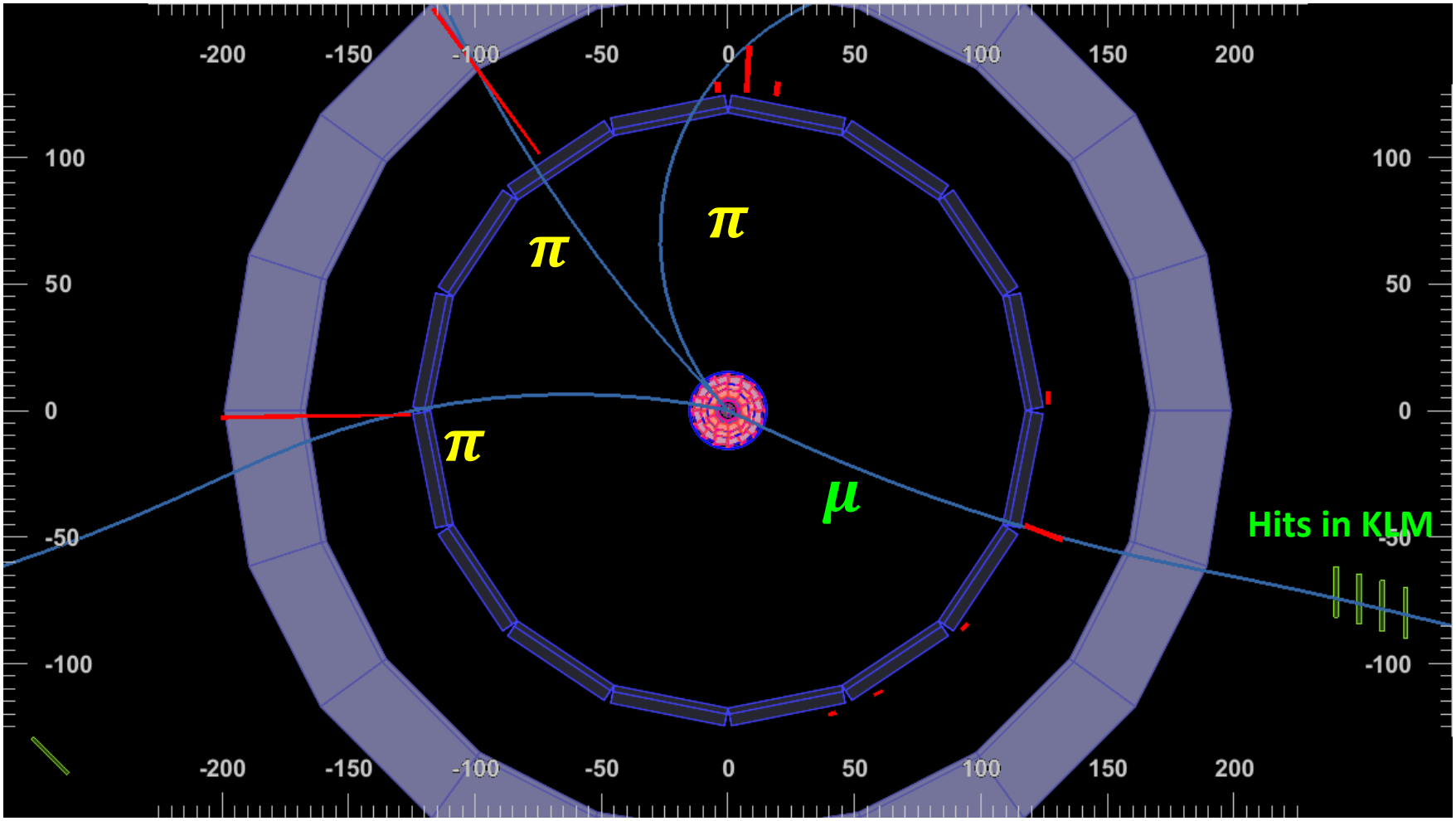




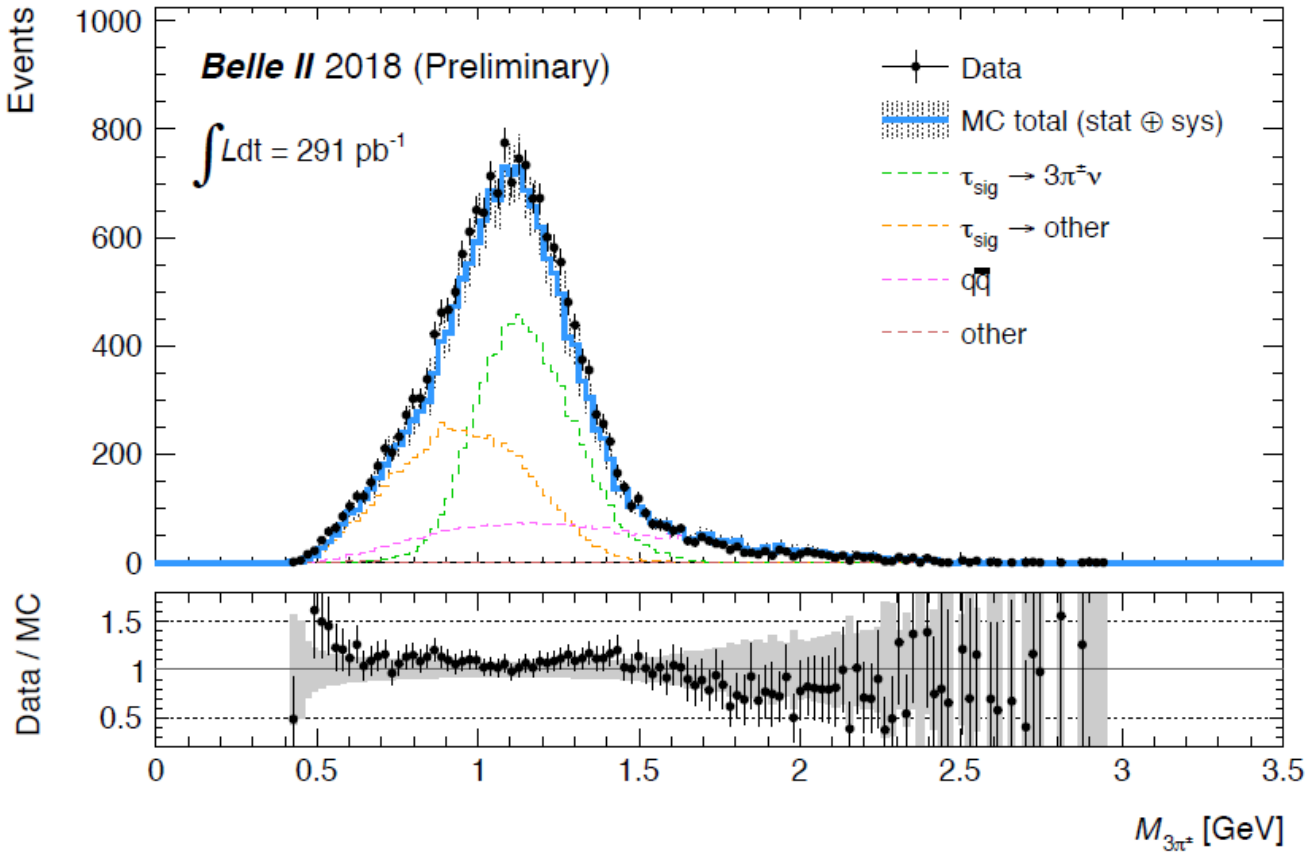
- ~571 (389+182) fully reconstructed B mesons
- Improvement of a factor of ~O(3.6) in overall efficiency
  => Advanced analysis method covering more decay channels
  - The Full Event Interpretation arXiv:1807.08680

τ pair candidates with τ->3πν

- τ pair are also extracted in the beam commissioning data



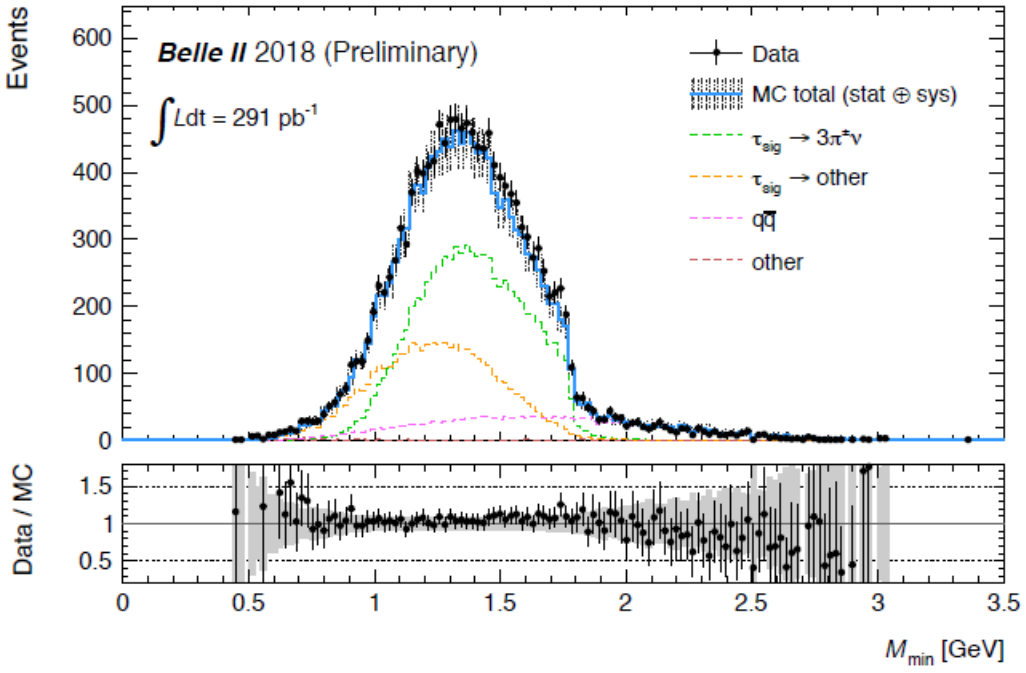
τ → 3πν in Belle II early data



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

τ mass in Belle II early data

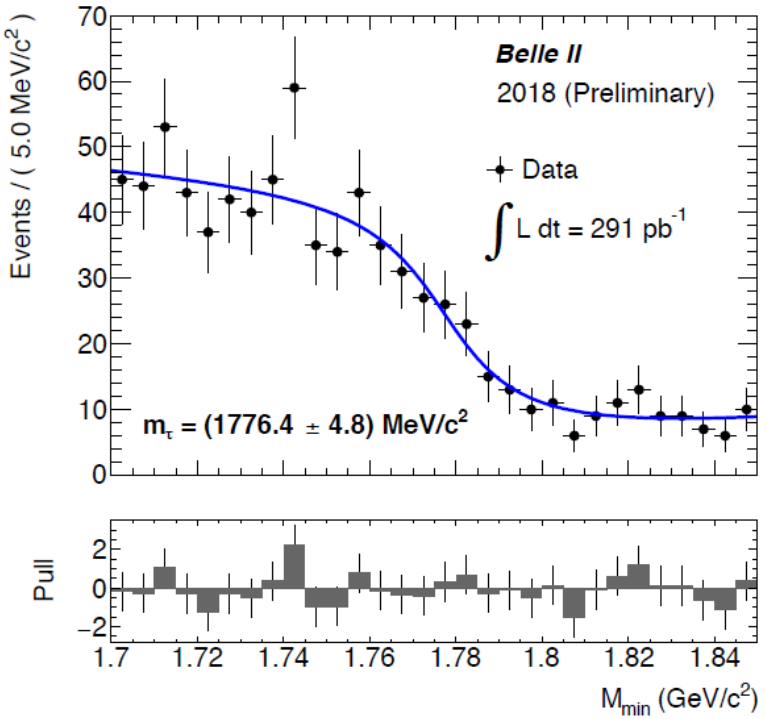
M_{min} distribution @ 291 pb^{-1}:



Measured in τ -> 3πν

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

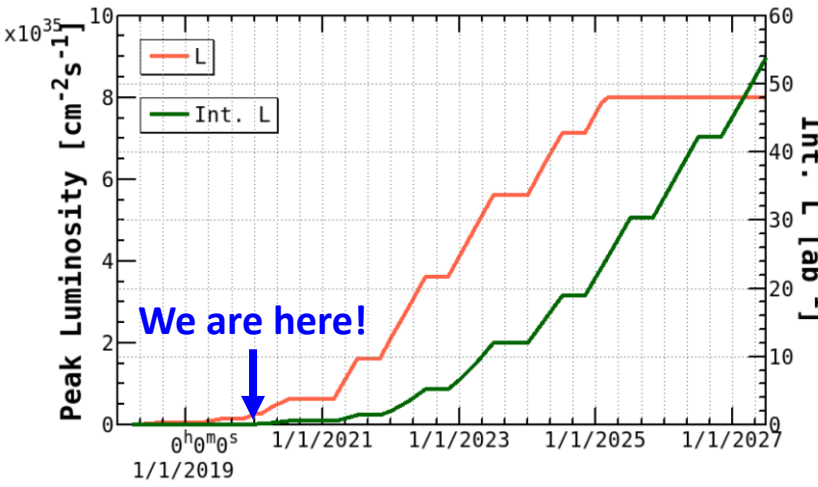
Distribution of the pseudomass is fitted to a empirical edge curve

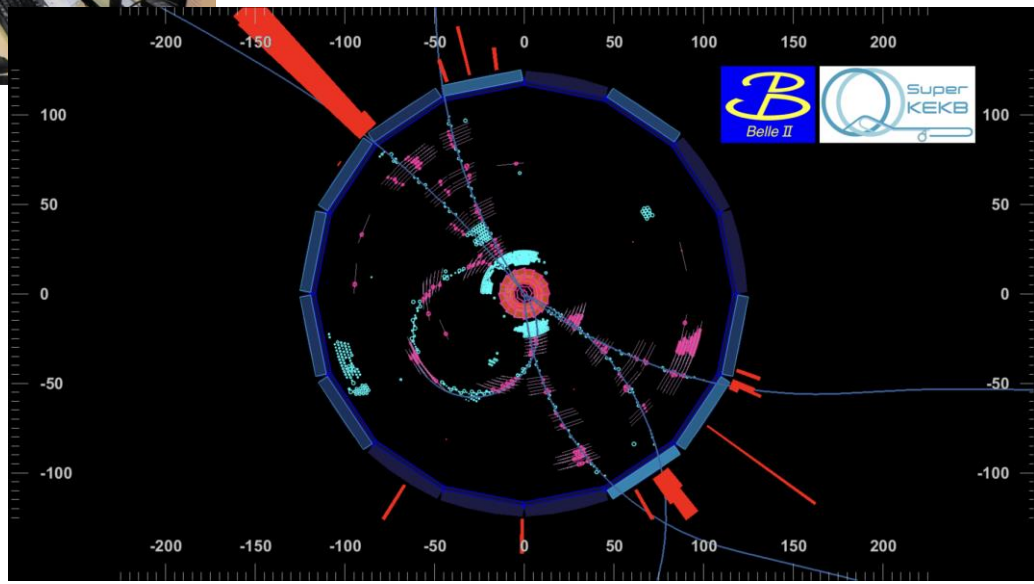


- Tau mass from Belle early data is consistent to previous results

m_τ = (1776.4 ± 4.8 (stat)) MeV/c2

Phase III started for physics!





Restarted at 25th March

with Full Belle II / SuperKEKB

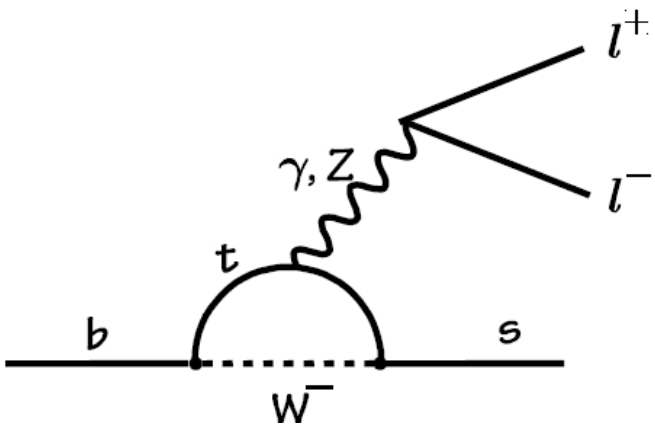
- Peak Lumi. :4 x 10^{33} $cm^{-2}s^{-1}$
- Int. Lumi : 3 fb^{-1}

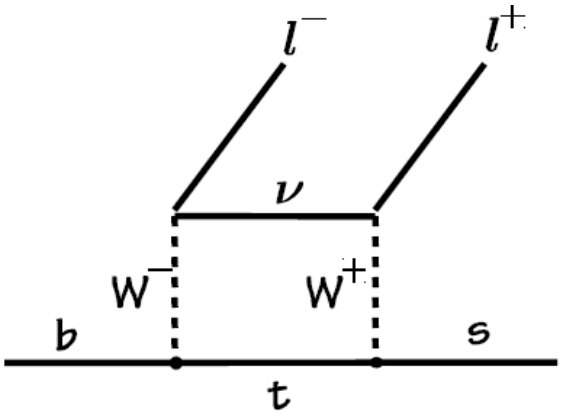
=> Increasing Luminosity !

Channels to cLFV in Belle II

- A number of studies for charged Lepton Flavor Violation is carried out using (almost) full Belle data samples of $1ab^{-1}$
  - $\boldsymbol{b \to lls}$: LFV in B decays
  - $\boldsymbol{\tau}$ **physics** : tau decays from tau pair productions
- Both are very rare decay search and possible to investigate in B factory experiment thanks to clean signature
  - More statistics in Belle II will bring us to prediction in NP
- Review based on Belle results to prospect to Belle II

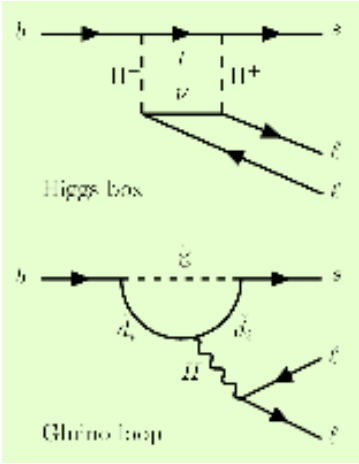
Flavor anomaly in $b \to sll$

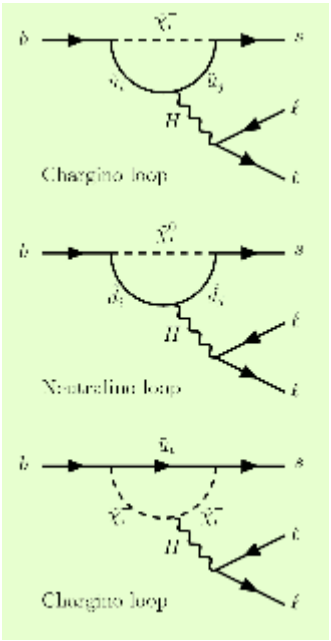




- $b \to s\gamma$ followed by $\gamma \to ll$
  - Added a box diagram
  - Rare decay in the SM
  - Sensitive to Supersymmetry 2HDM, Fourth generation, ...

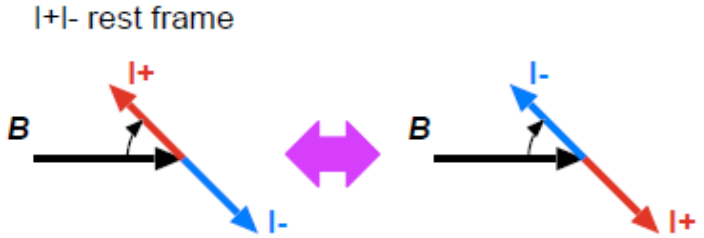
=> Nice place to look for new physics



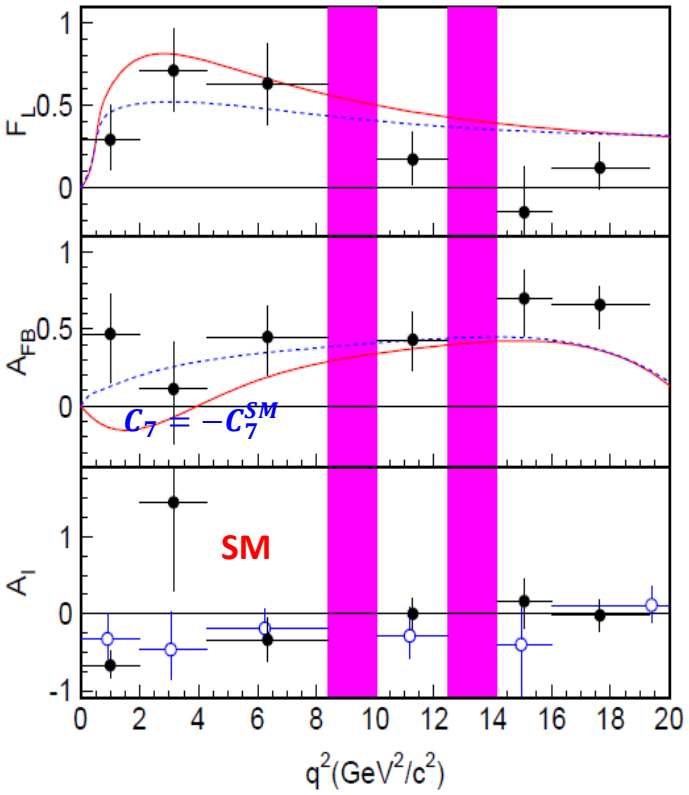


$B \to K^* l^+ l^-$

proceeding to LHCb



PRL 103:171801,2009



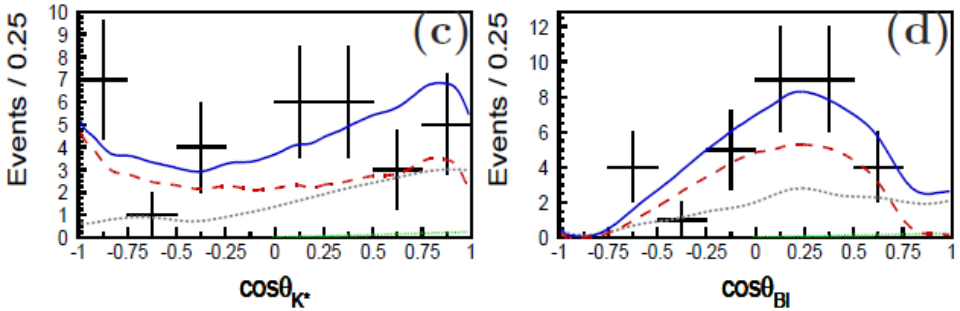
- Forward-backward Asymmetry to parent B

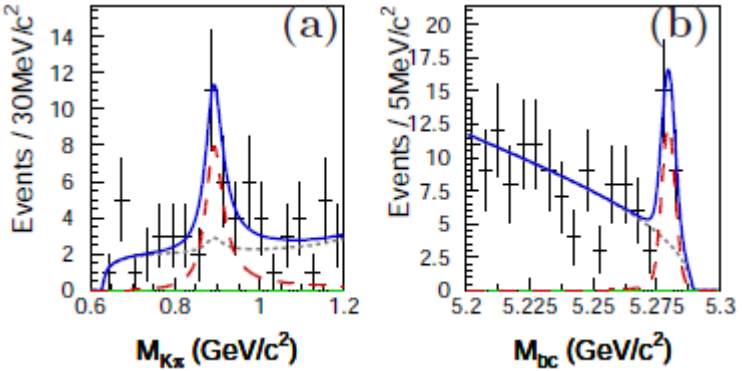
$$\frac{d\overline{A}_{\rm FB}(q^2)}{dq^2} = \frac{N(q^2;\,\theta_{B\ell+} > \theta_{B\ell-}) - N(q^2;\,\theta_{B\ell+} < \theta_{B\ell-})}{N(q^2;\,\theta_{B\ell+} > \theta_{B\ell-}) + N(q^2;\,\theta_{B\ell+} < \theta_{B\ell-})}$$

- Measured Wilson coefficients

$$\frac{d\overline{A}_{\rm FB}(q^2)}{dq^2} = -C_{10}\xi(q^2) \times \left[{\rm Re}(C_9)F_1 + \frac{1}{q^2}C_7 F_2\right]$$

- A deviation => Hints to New Physics?





$B \to K^* l^+ l^-$ sensitivity in Belle II

- Rich channels to probe not only LFV but LUV

=> Still difficult to measure the branching ratio preciously

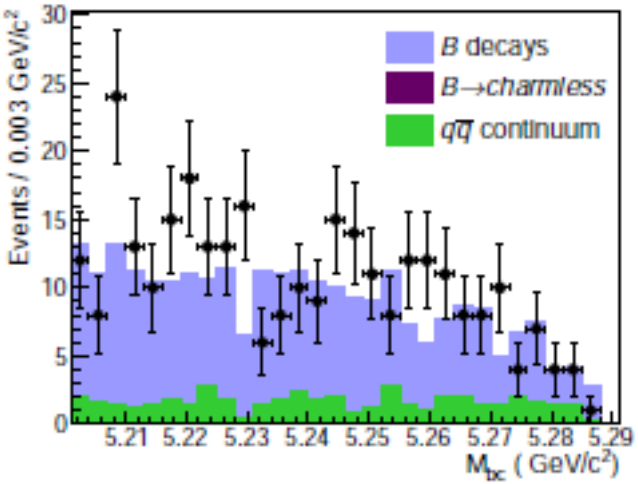
- Belle II provides more precision measurements

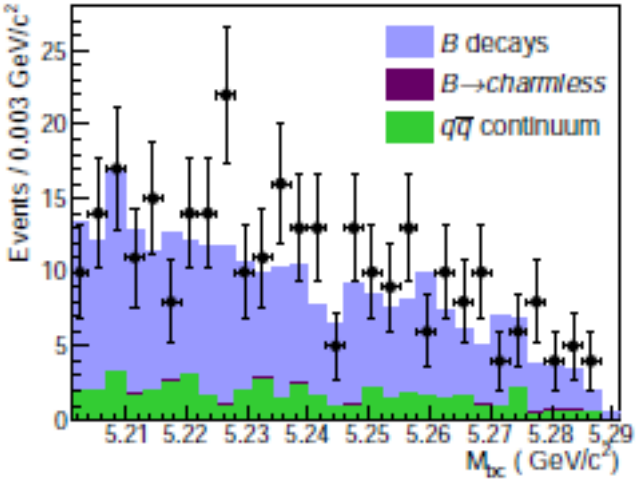
PRL 103:171801,2009

R(K*) = 0.83 ± 0.17 ± 0.08
R(K) = 1.03 ± 0.19 ±0.06

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ($[1.0, 6.0]\,\mathrm{GeV}^2$)	28%	11%	3.6%
R_K ($> 14.4\,\mathrm{GeV}^2$)	30%	12%	3.6%
R_{K^*} ($[1.0, 6.0]\,\mathrm{GeV}^2$)	26%	10%	3.2%
R_{K^*} ($> 14.4\,\mathrm{GeV}^2$)	24%	9.2%	2.8%
R_{X_s} ($[1.0, 6.0]\,\mathrm{GeV}^2$)	32%	12%	4.0%
R_{X_s} ($> 14.4\,\mathrm{GeV}^2$)	28%	11%	3.4%

LFV $K^* l^+ l^-$ decays





[Belle , arXiv :1807.03267]

Mode	ε (%)	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}^{\rm UL}$ (10^{-7})
$B^0 \to K^{*0}\mu^+ e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	5.2	1.2
$B^0 \to K^{*0}\mu^- e^+$	9.3	$0.40^{+4.8}_{-4.5}$	7.4	1.6
$B^0 \to K^{*0}\mu^\pm e^\mp$ (combined)	9.0	$-1.18^{+6.8}_{-6.2}$	8.0	1.8

Belle opened world best constraints of the LFV $K^* l^+ l^-$ modes

$$\mathcal{B}(B^0 \to K^{*0}\mu^+ e^-) < 1.2 \times 10^{-7}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^- e^+) < 1.6 \times 10^{-7}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 1.8 \times 10^{-7}$$

Belle II can reach 90% of UL at O(10^{-8}) with 50 ab^{-1}

Search for tau LFV

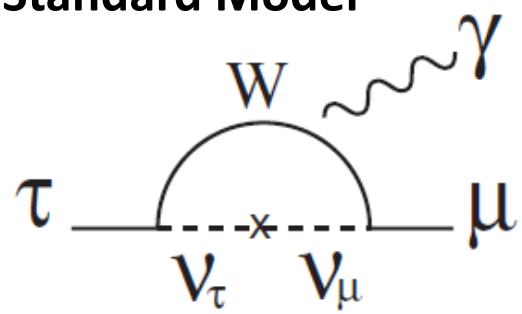
- **Lepton Flavor Violation (LFV)** is highly suppressed in the Standard Model (SM) even if neutrino oscillation is taken
  - Br < O(10^{-54}) => Experimentally unreachable
- **Many extensions to SM** predict to enhance LFV to be observable in current experiment facilities: Br ~ O(10^{-8})

=> Observation of LFV is an clear signature of the New Physics (NP)!

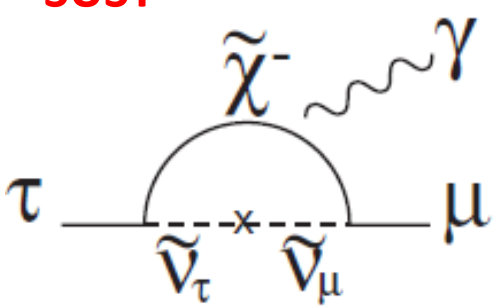
- Tau lepton - the heaviest charged lepton coupling to the NP

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

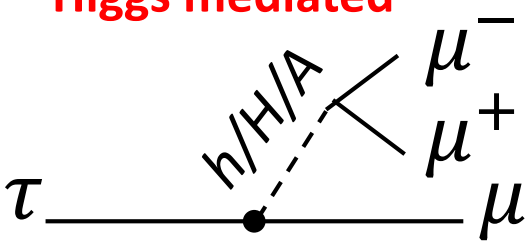
Standard Model



SUSY



Higgs mediated



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	$< 10^{-54}$	---
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

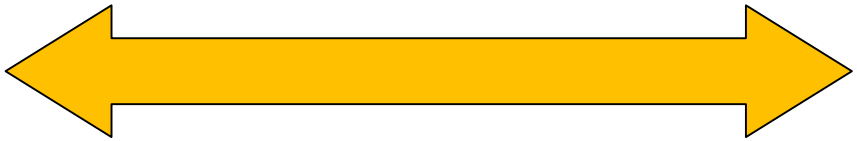
Super B factory will reach a possible region to τ LFV!

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

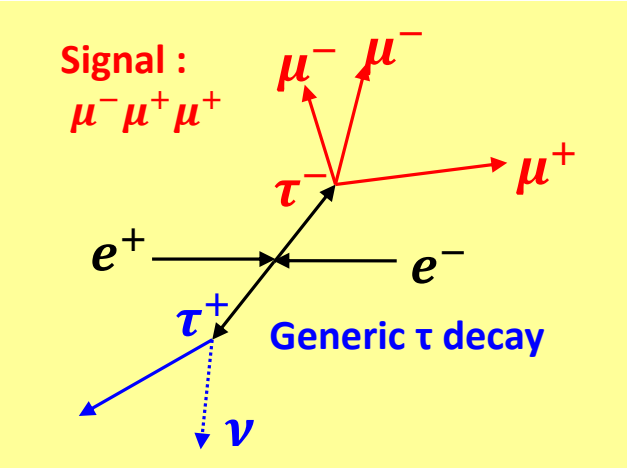
=> Almost all decay modes were studied using the Belle data

Search for tau LFV in B factory

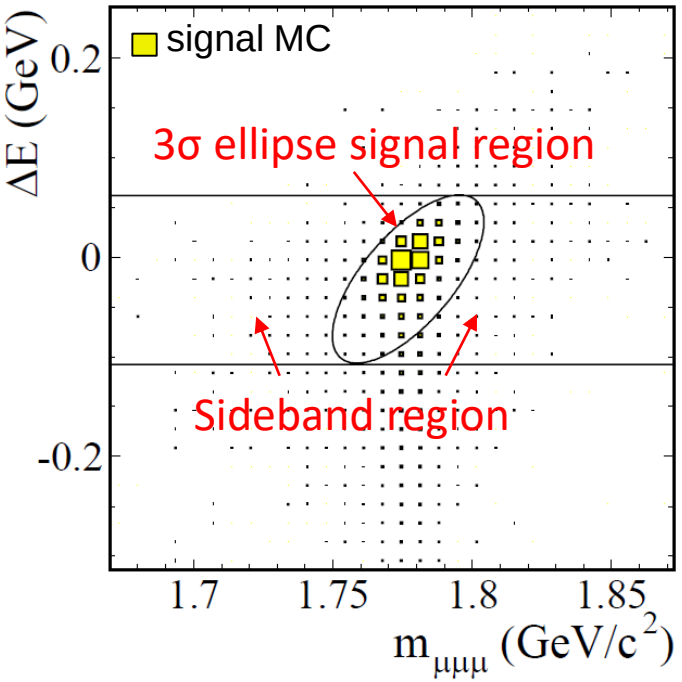
- Various interesting channels studied in B factories
  => Pick up **two modes** in this talk
  - $\boldsymbol{\tau \to \ell\ell\ell}$ ➡ Possible to access in early Belle II
  - $\tau \to \ell K_S, \Lambda h$
  - $\tau \to \ell V_0 (\to hh')$
  - $\tau \to \ell P^0 (\to \gamma\gamma)$
  - $\tau \to \ell hh'$
  - $\boldsymbol{\tau \to \ell\gamma}$ ➡ 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**

Analysis procedure

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

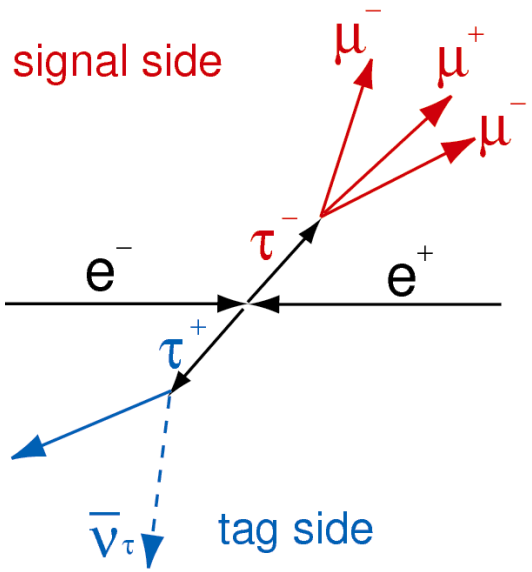


- Signal extraction: $m_{\mu\mu\mu} - \Delta E$ plane
  - $m_{\mu\mu\mu} = \sqrt{E^2_{\mu\mu\mu} - p^2_{\mu\mu\mu}} \sim m_\tau$
  - $\Delta E = E^{CM}_{\mu\mu\mu} - E^{CM}_{\text{beam}} \sim 0$
- Number of Background is estimated using sideband data and MC



Signal and backgrounds

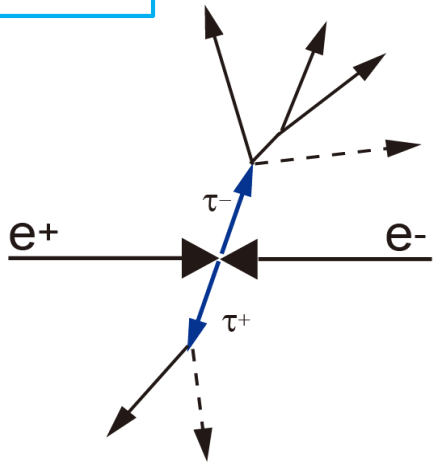
LFV Signal



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

Major BG differs between LFV decay channels

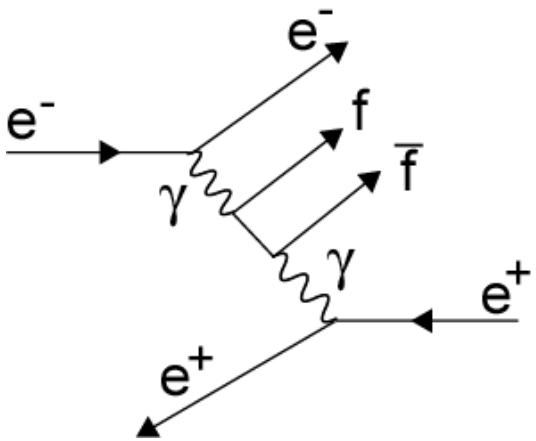
SM ττ



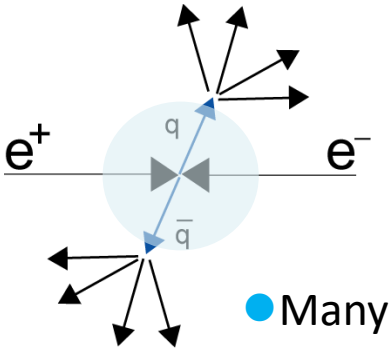
- Neutrinos in both sides
- Missing energy in signal side

2photon process

f = leptons, quarks

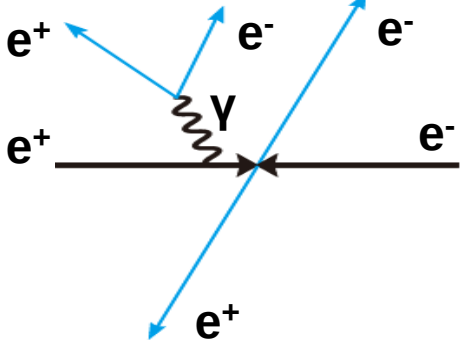


qq̄



- Many tracks

radiative Bhabha



Belle result :

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

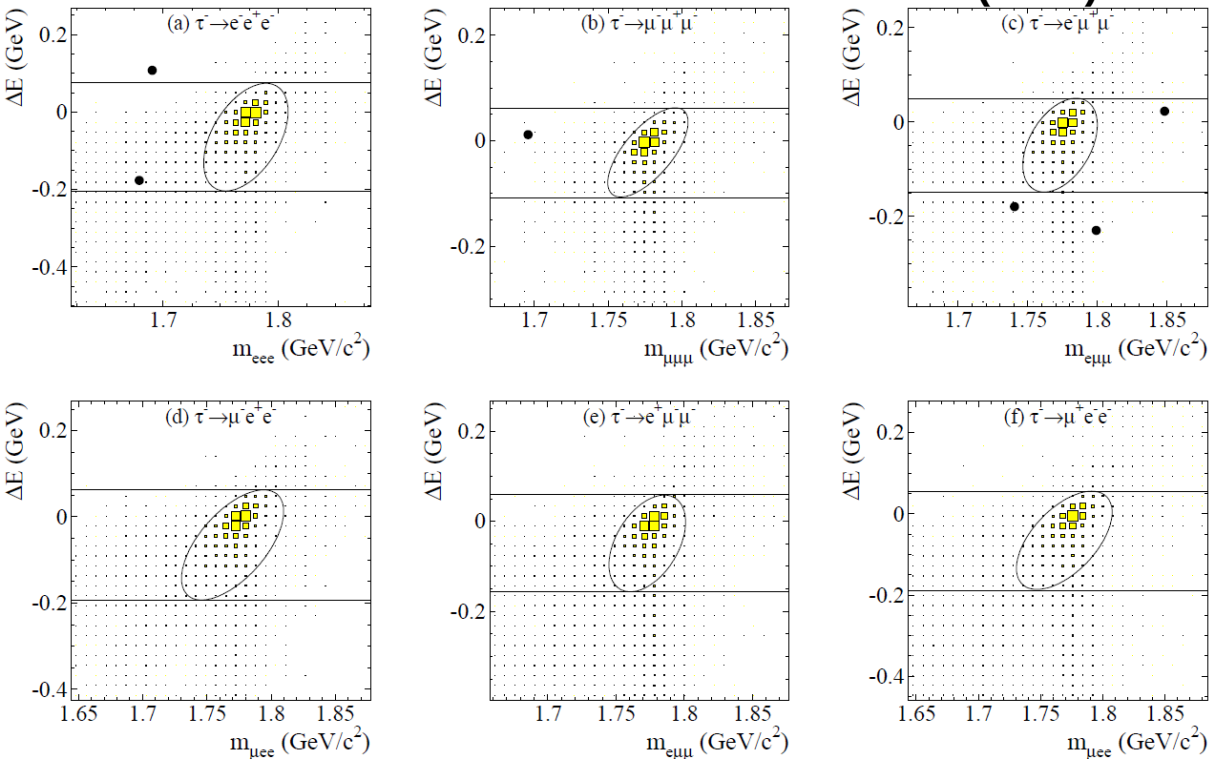
Phys.Lett.B687,139 (2010)

- 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)



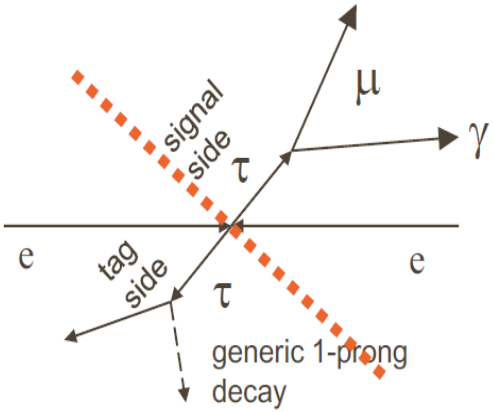
Mode	ε (%)	N_{BG}^{EXP}	σ_{syst} (%)	UL (x10^{-8})
$e^-e^+e^-$	6.0	0.21±0.15	9.8	2.7
$\mu^-\mu^+\mu^-$	7.6	0.13±0.06	7.4	2.1
$e^-\mu^+\mu^-$	6.1	0.10±0.04	9.5	2.7
$\mu^-e^+e^-$	9.3	0.04±0.04	7.8	1.8
$\mu^-e^+\mu^-$	10.1	0.02±0.02	7.6	1.7
$e^-\mu^+e^-$	11.5	0.01±0.01	7.7	1.5

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

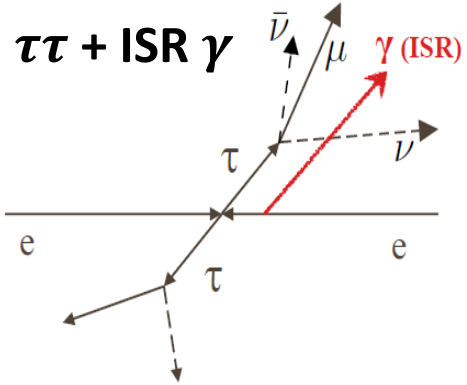
Phys. Lett. B 666, 16 (2008)

Blinding box approach evaluating BG out side the signal region

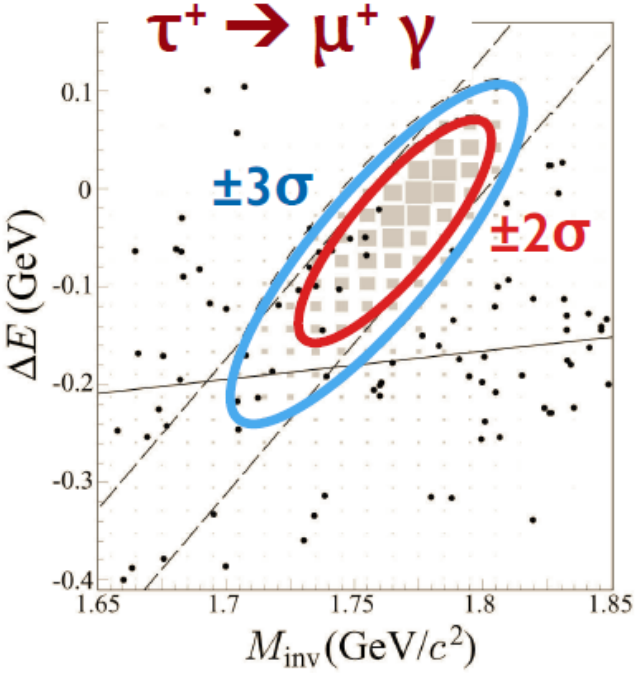
- Search with 545 fb^{-1}
  - Main BG : $\tau \to \mu\nu\nu$ + ISR γ
  - miss/missing tracks
- $\tau \to \mu\gamma$: Br < 4.5 x 10^{-8} (90%CL)
- $\tau \to e\gamma$: Br < 1.2 x 10^{-8} (90%CL)



$\tau\tau$ + ISR γ

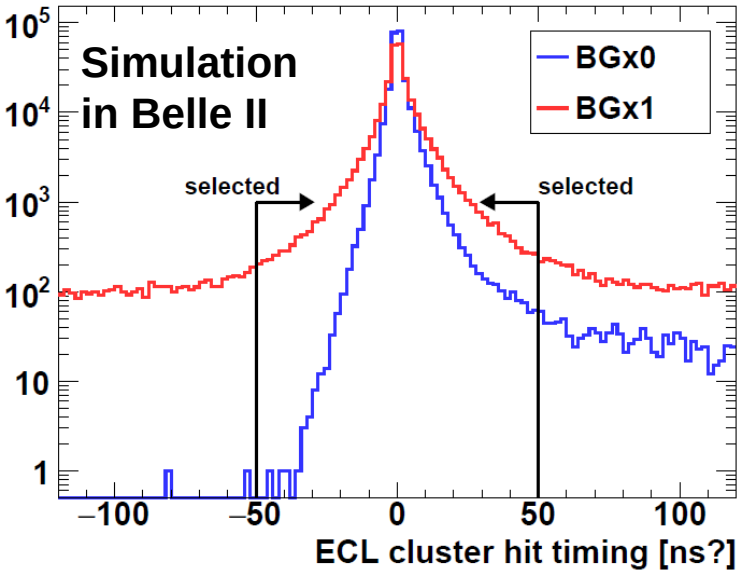


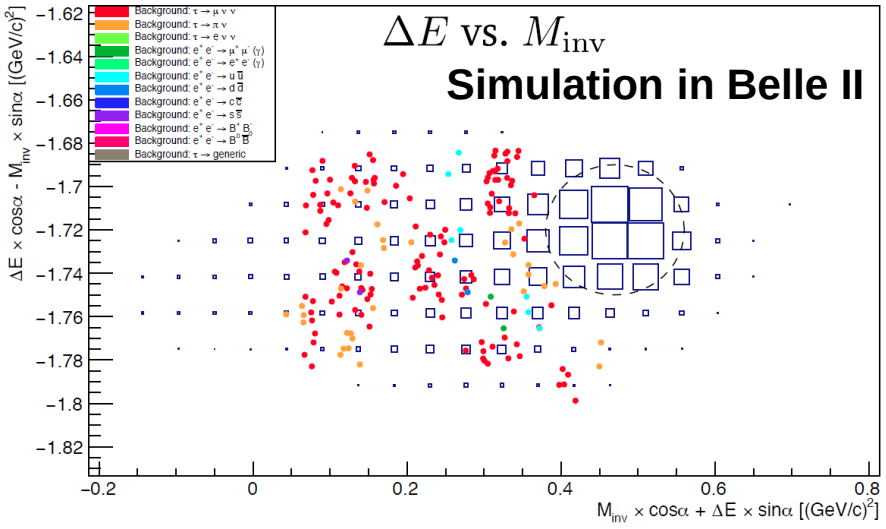
Belle result (2008)

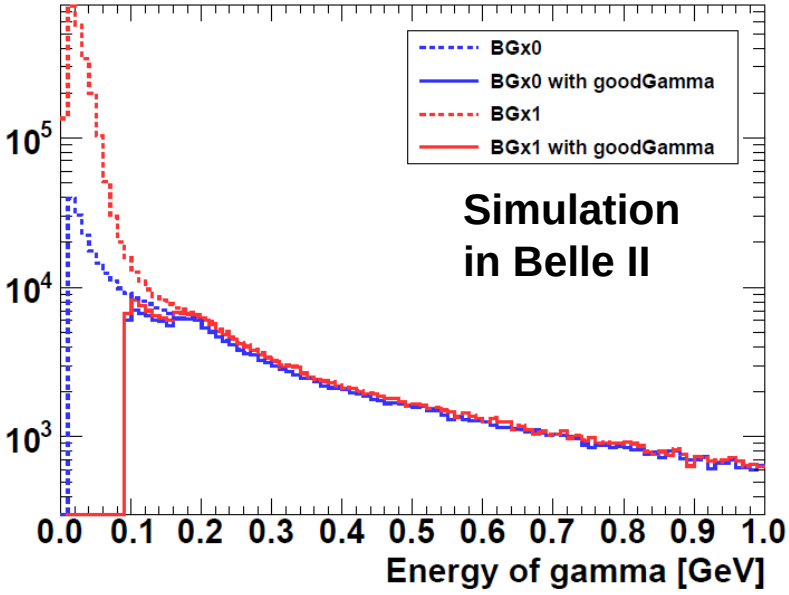


Background reduction at Belle II

- Timing information helps to reduce γ from beam BG
  - 16 % inefficiency in $\tau \to \mu\gamma$
- Event shape information provides good separation of ISR- from signal







Expectation of LFV search at Belle II

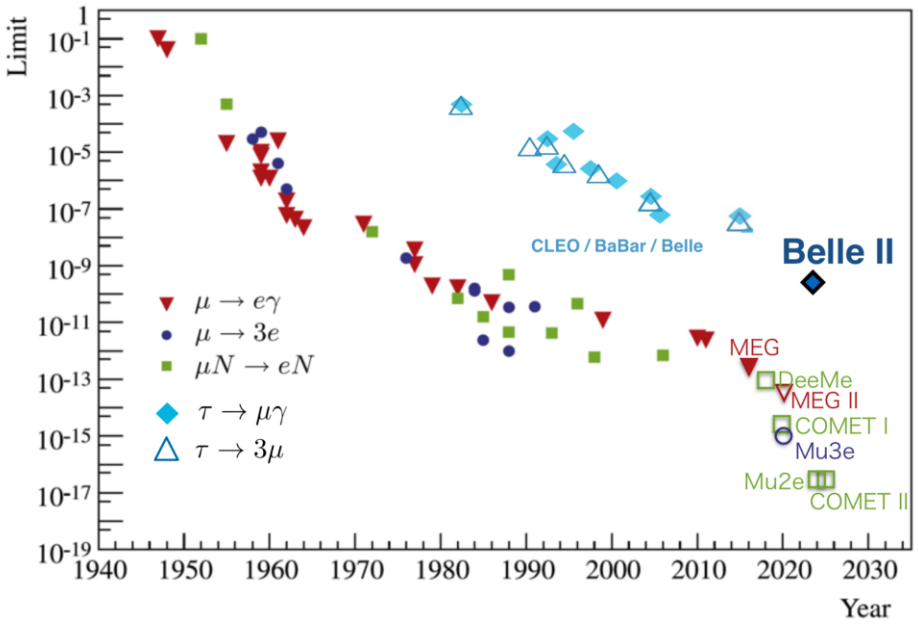
Belle II will reach the New Physics Models in first several years

- 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

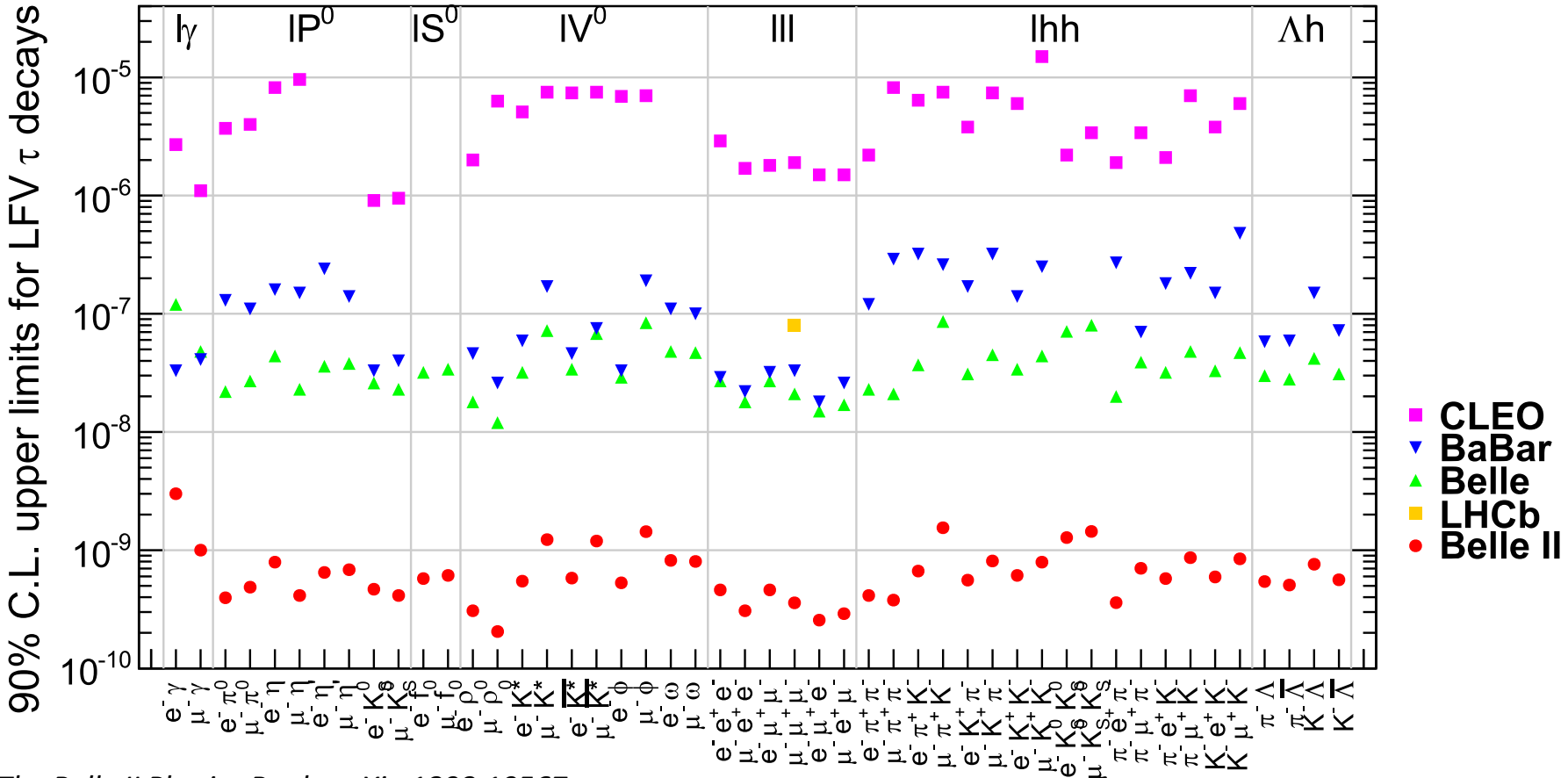


old plots, conservative

Upper limits at (Super) B factories

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

=> Many decay modes are reachable in Belle II !



The Belle II Physics Book arXiv:1808.10567

Summary

- B factory is open for both B and τ physics in new physics search
  - Studies with B/τ pairs are carried out in Belle and BaBar
  - No significant result has been found yet
- **Belle II started full operation at March 2019!**
  - Belle II detector is confirmed in Phase II run of 2018
- LFV in B decays into dileptons is nice to look for new physics
  - Search for $B \to K^* l^+ l^-$ in Belle opened best constraints
- Many of τ LFV channels are reachable in early years of Belle II
  - Improved Upper limit of Branching fraction by O(10^{-2})
- More details are in "The Belle II Physics Book" arXiv:1808.10567

Backup

τ-factory at Belle

τLFV search using full Belle data

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

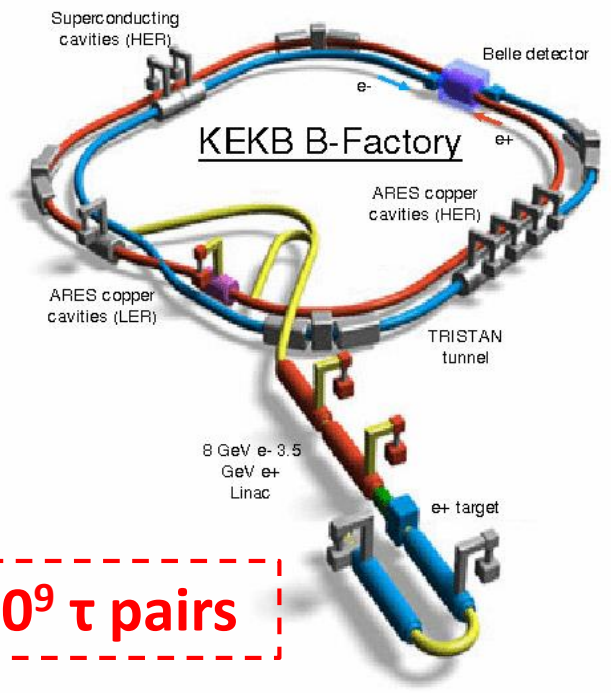
  => World highest peak luminosity
  - σ(ττ) ~ 0.9 nb
  - σ(bb) ~ 1.1 nb

  => pure ττ can be collected
- Belle Detector:
  - Good tracking and PID

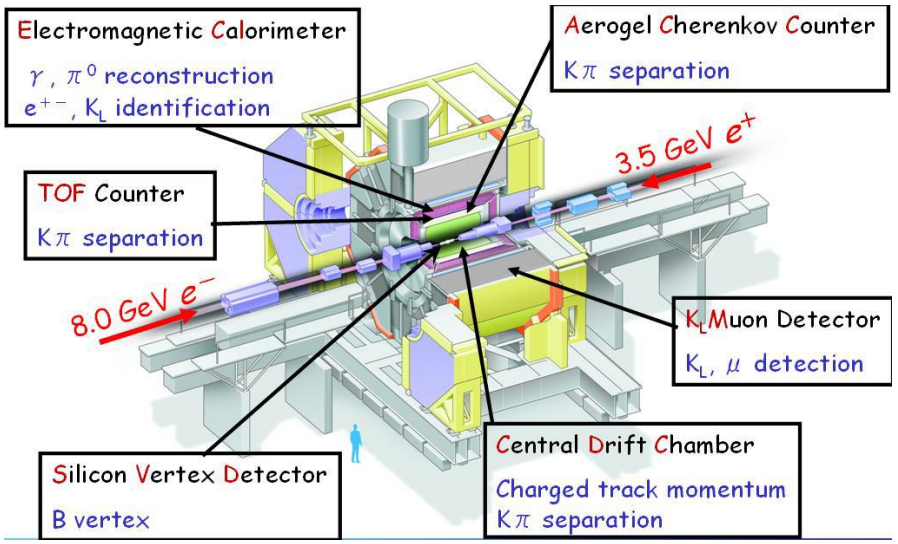
  => Lepton efficiency: 90 %

  Fake rate : O(0.1) % for e

  O(1) % for μ



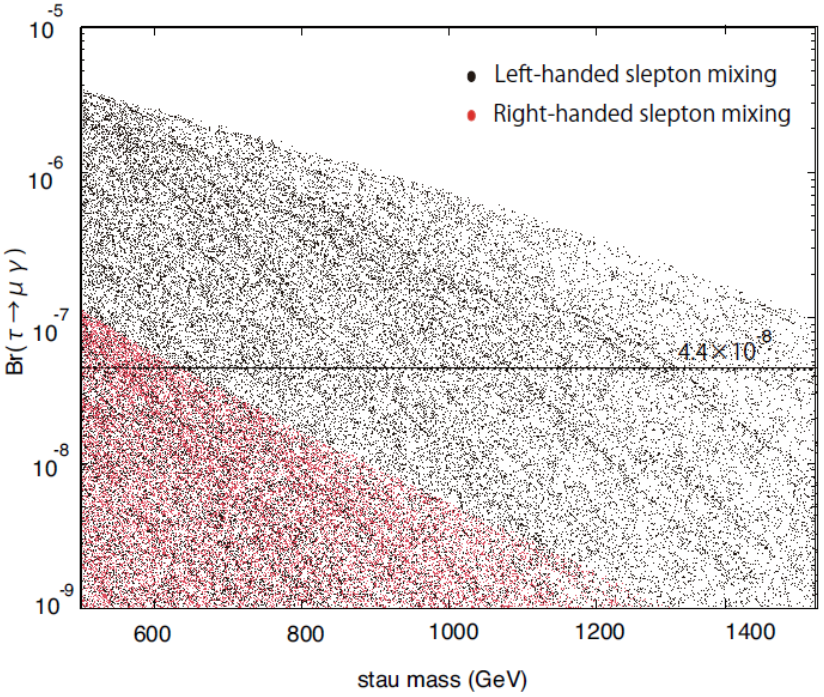
~10^9 τ pairs



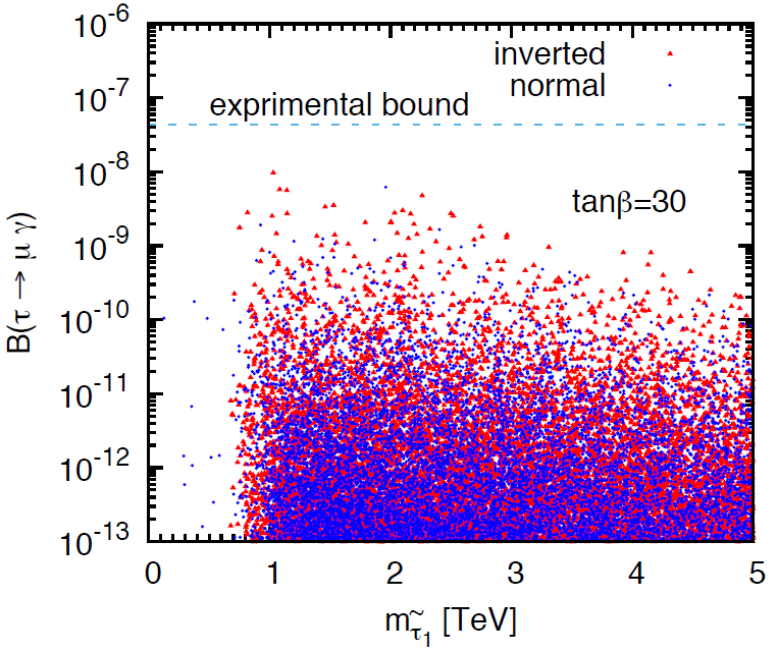
Theoretical predictions

- MSSM cannot make $\tau \to \mu\gamma$ according to recent results

Non-minimal SUSY SM



CMSSM

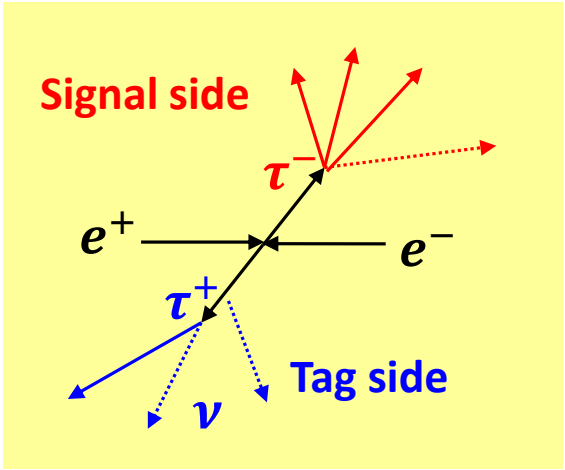


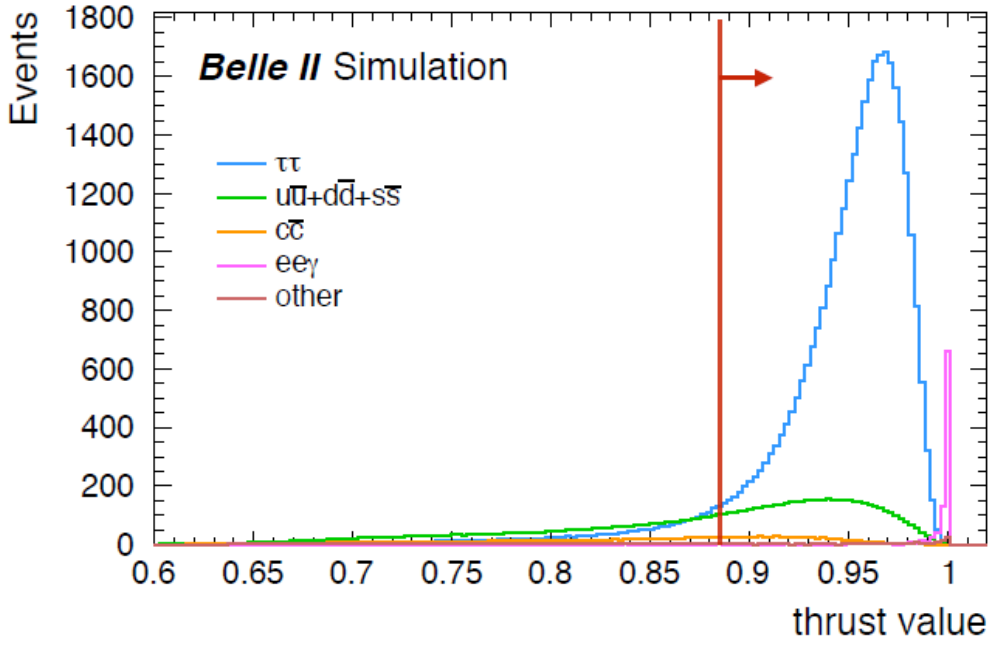
=> These models are possible to search by $\tau \to \mu\gamma$ in Belle II

τ pairs selection in Belle II data

τ pairs are collected by tagging method

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





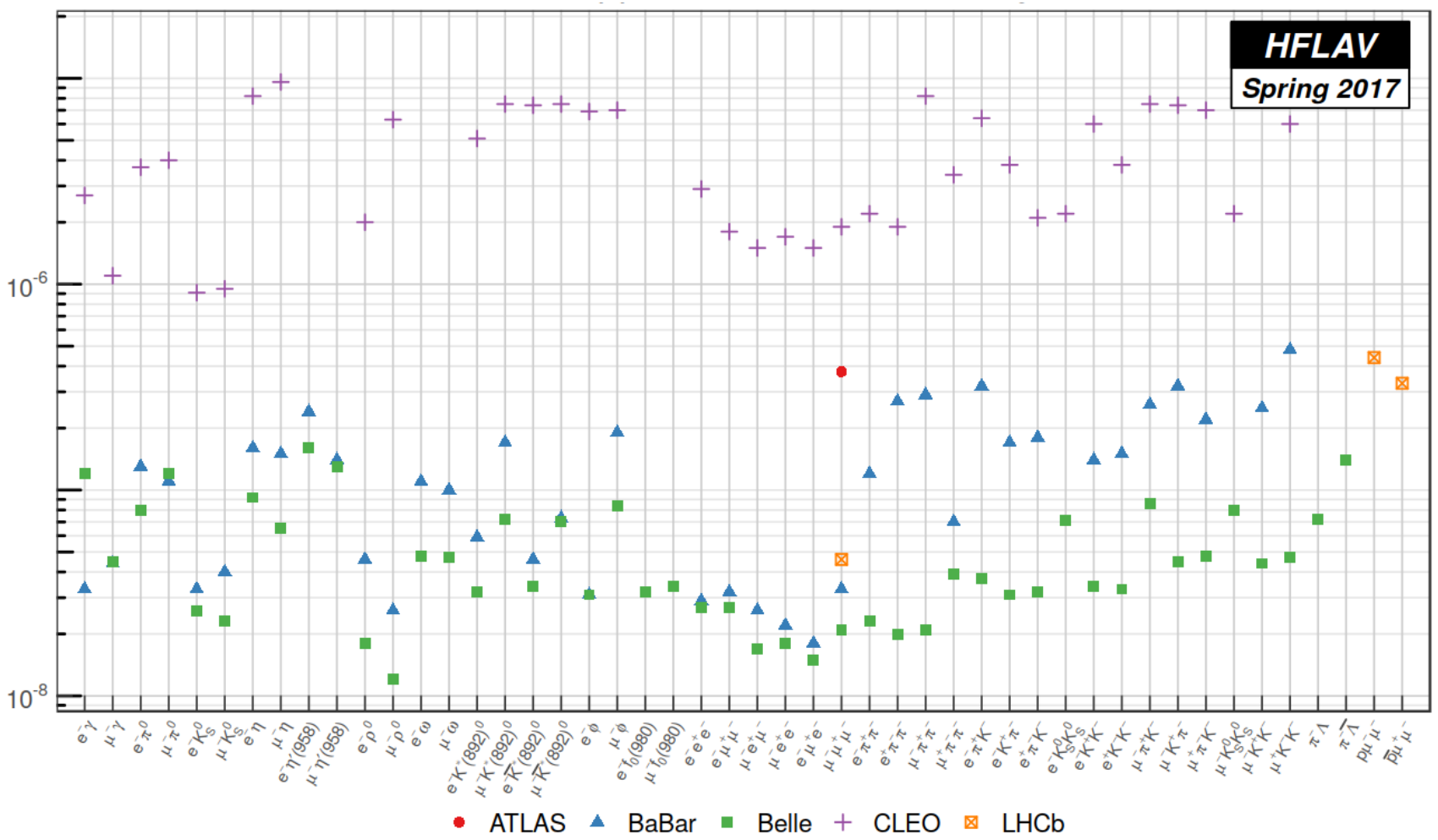
spherical ⬅ ➡ 2 body-like

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

Upper Limits of Tau LFV



- Belle best upper limits in most of the channels