Indian Institute of Technology Guwahati

Charged Lepton Flavor Violation at Belle & Belle II

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(On behalf of the Belle and Belle II Collaborations)

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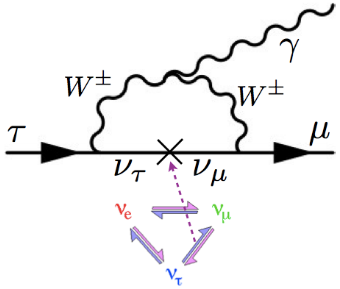
Outline of the Talk

- Introduction
- Review of the searches of LFV at Belle
- Status of Belle II and prospects of LFV at Belle II
- Conclusions

Introduction

- Observed neutrino oscillations signal violation of lepton flavor in the neutral leptonic sector.
  - What about LFV in the charged leptons?
- LFV violation in the charged leptons is highly suppressed in the SM even after the inclusion of neutrino masses:
  - Neutrino masses are expected to be much smaller compared to the electroweak scale, $M_W \approx 80.4$ GeV.
  - Searches of LFV in the SM is beyond experimental reach:



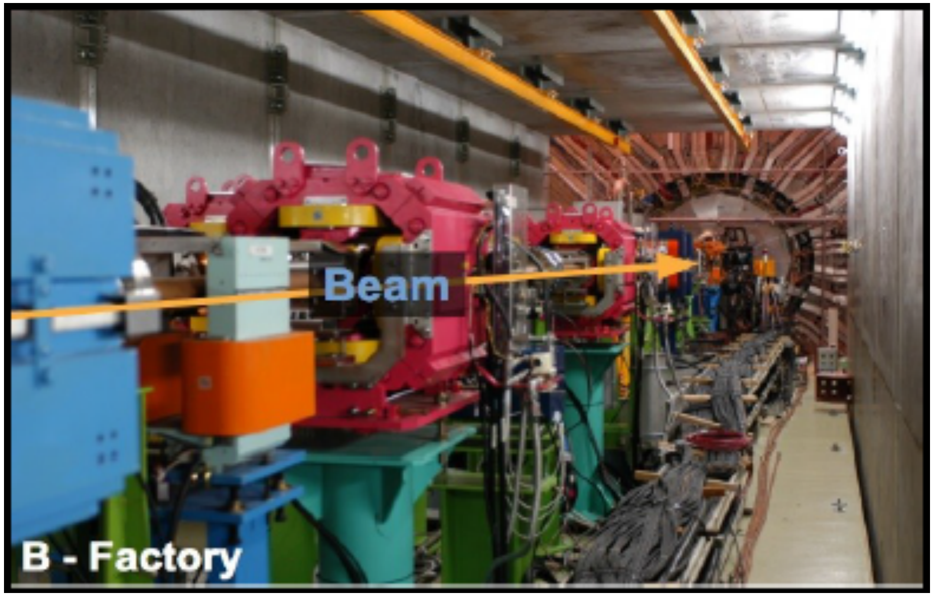
$$\mathcal{B}(\tau \to \ell\gamma) \propto \left(\frac{M_{\nu_\tau}^2 - M_{\nu_\ell}^2}{M_W^2}\right)^2 \approx 10^{-50} \sim 10^{-54}$$

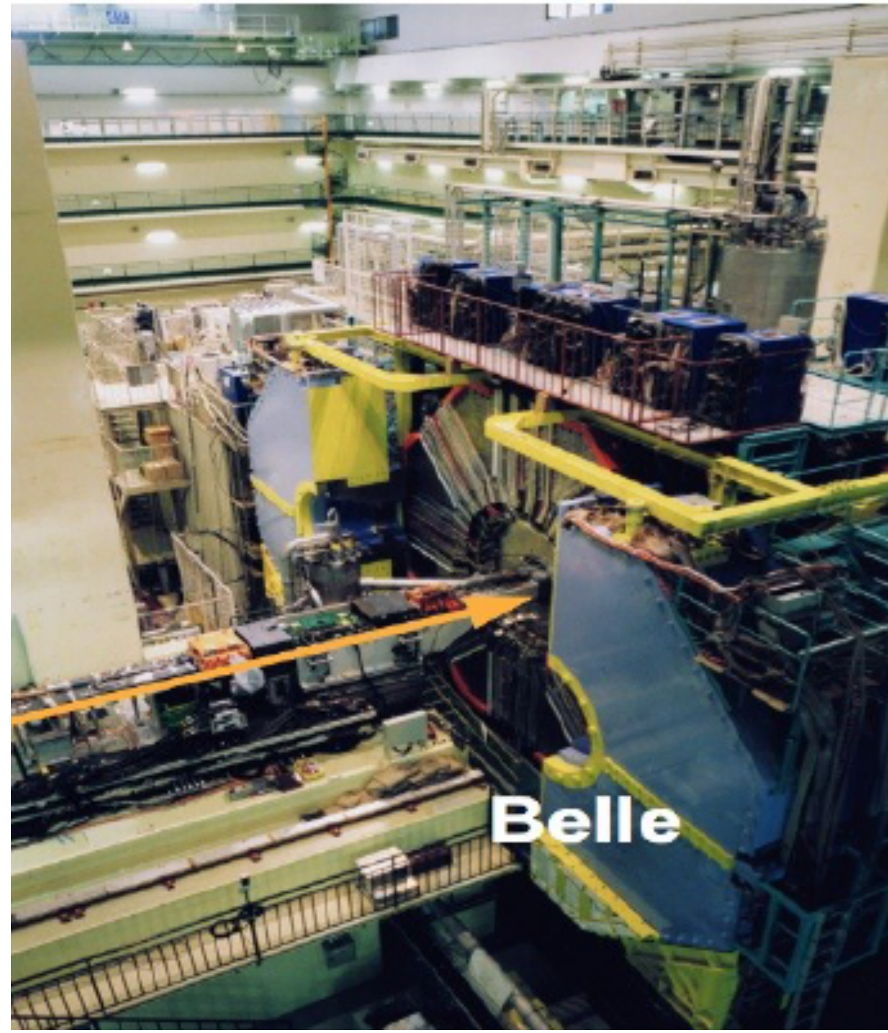
- Observation of LFV in the charged lepton is a clear signal for NP beyond SM:
  - Many extensions of the SM such as supersymmetry, little Higgs models, extra dimensions predict enhanced LFV.
  - LFV in τ decays can be as high as $O(10^{-8})$
    - Within the reach of current experiments such as Belle II

Introduction

- Searches for charged LFV is currently dominated by BaBar and Belle experiments.
  - Most of the results are in τ decays
    - Heaviest lepton: less GIM suppression compared to muon.
    - Strong coupling to NP contributions.
    - Many possible LFV decays
- τ LFV violation decays studied so far: 48 channels in total
  - $\tau \rightarrow 3l$
  - $\tau \rightarrow l V^0$ ($V^0 = \rho^0, K^{*0}, \overline{K}^{*0}, \omega, \phi$)
  - $\tau \rightarrow l h h'$ ($h = \pi, K$)
  - $\tau \rightarrow \Lambda h / \overline{\Lambda} h$
  - $\tau \rightarrow l \gamma$

Belle at KEK

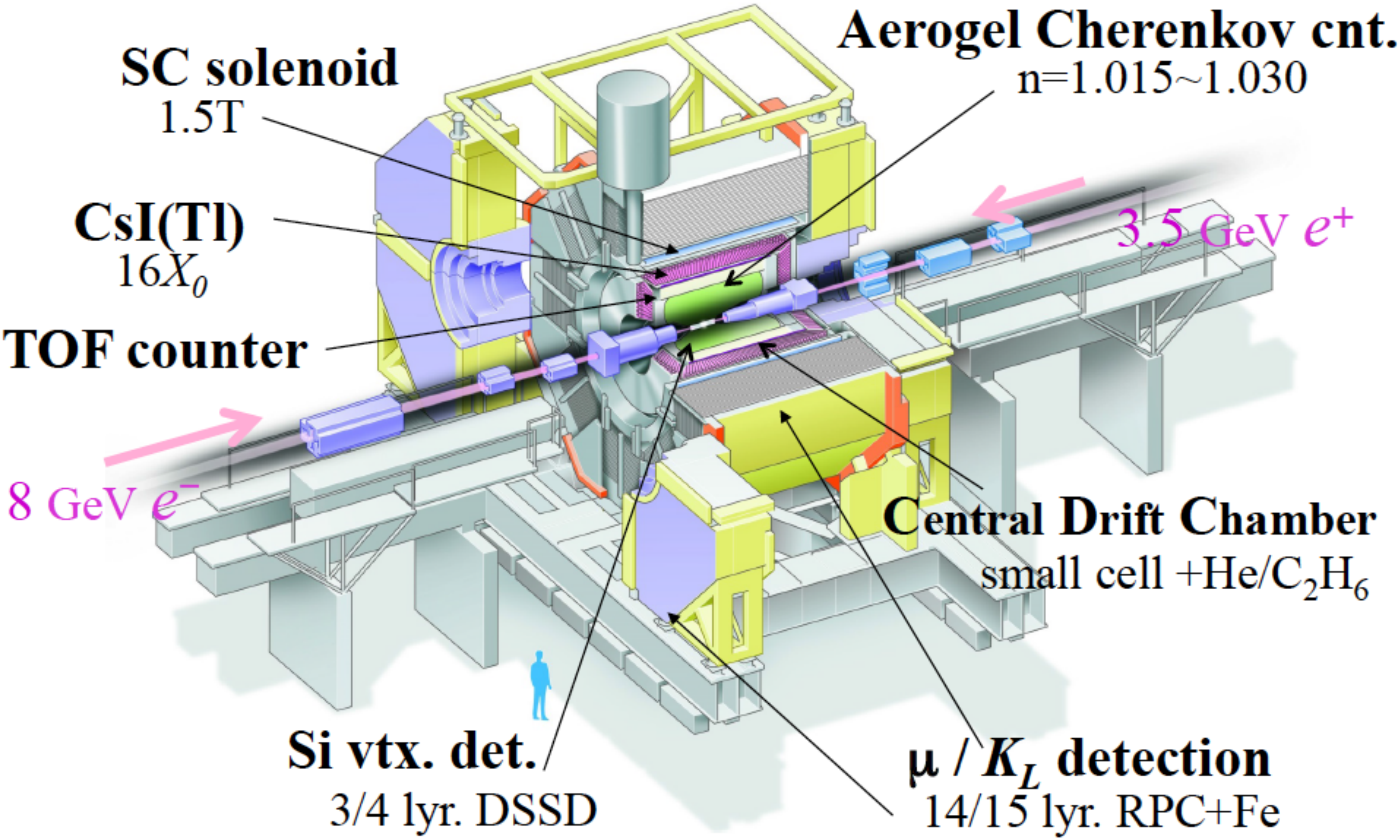




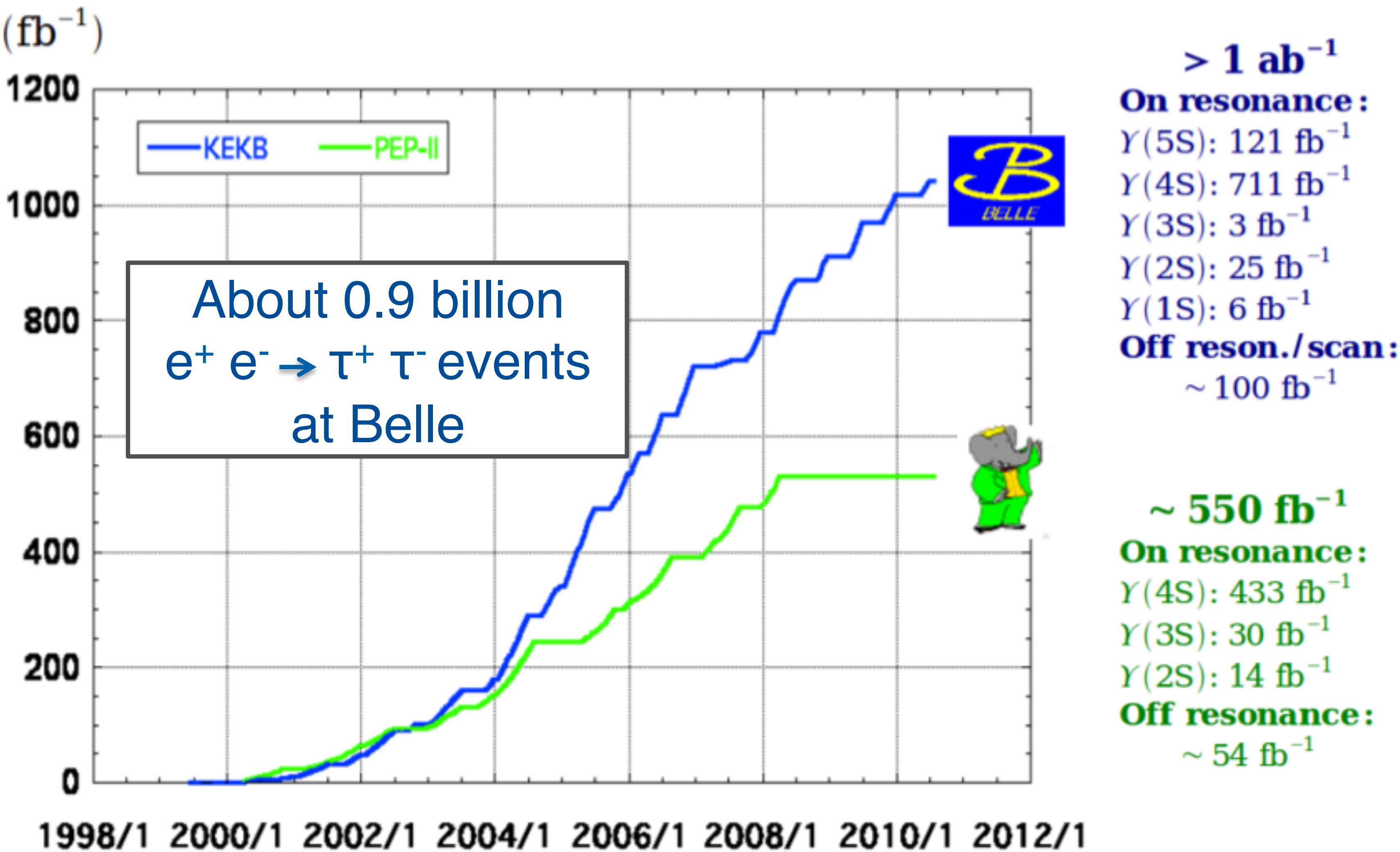
- Electron-positron collider (operated during 1999 – 2010)
- Asymmetric E: 8 GeV (e^-) and 3.5 GeV (e^+)
  - Mainly operated at the Υ(4S) resonance (10.58 GeV)
- Total accumulated luminosity: 1023 fb-1
  - τ cross section ~ 0.9 nb
  - About 9 x 10^8 ττ events at Belle

Belle Detector

Lepton ID efficiency ~ 90%
Fake rate ~0.1% (electrons), ~1% (muons)

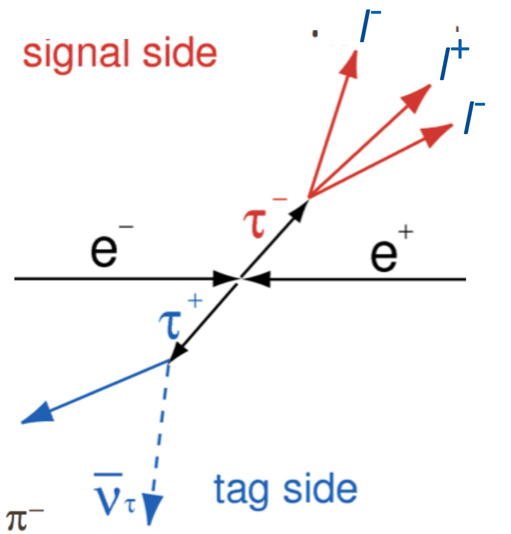


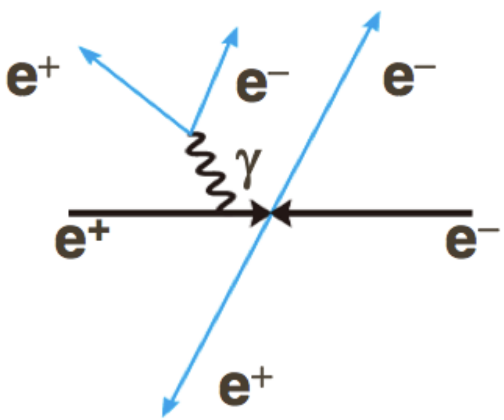
Luminosity at the *B* factories



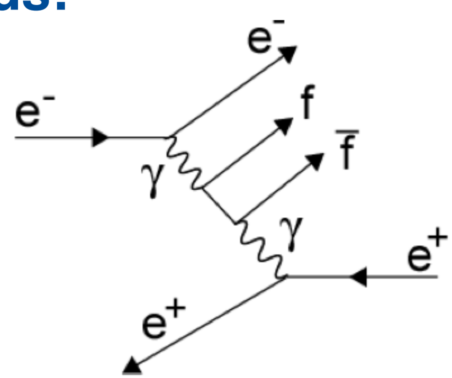
$\tau^- \rightarrow l^- l^+ l^-$: Analysis Strategy

- Blind analysis: optimization of event selection is based on MC samples
  - Signal and background MC events from $\tau^+ \tau^-$ decays are generated by KORALB/TAUOLA.
- $\tau^+ \tau^-$ events are divided into two hemispheres:
  - Signal τ: Look for τ decaying to 3 leptons
  - Tag τ: one charged track, any number of γ and ν
- Major backgrounds:

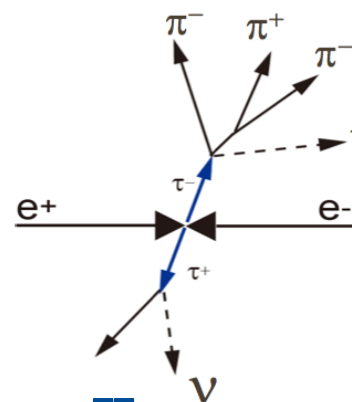




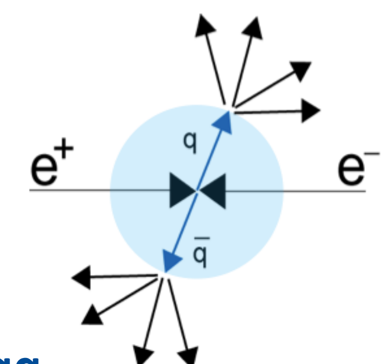
Radiative Bhabha



Two Photon



$\tau\tau$



qq

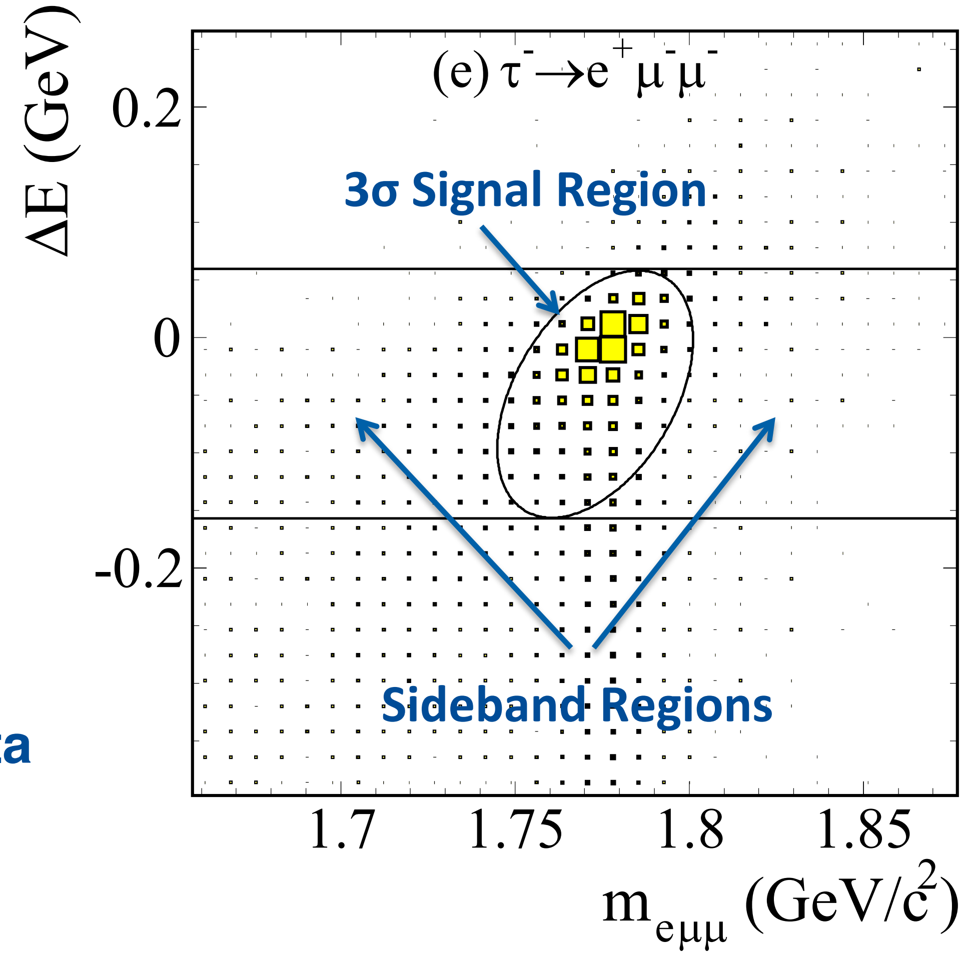
$\tau^- \to l^- l^+ l^-$: Analysis Strategy

On the signal side

Extract signal from the two dimensional plane of ΔE and 3 l invariant mass:

$$\Delta E = E_{3l}^{CM} - E_{beam}^{CM}$$

$$m_{3l} = \sqrt{E_{3l}^2 - p_{3l}^2}$$



Estimate background from the data sideband regions.

$\tau^- \rightarrow l^- l^+ l^-$ Results

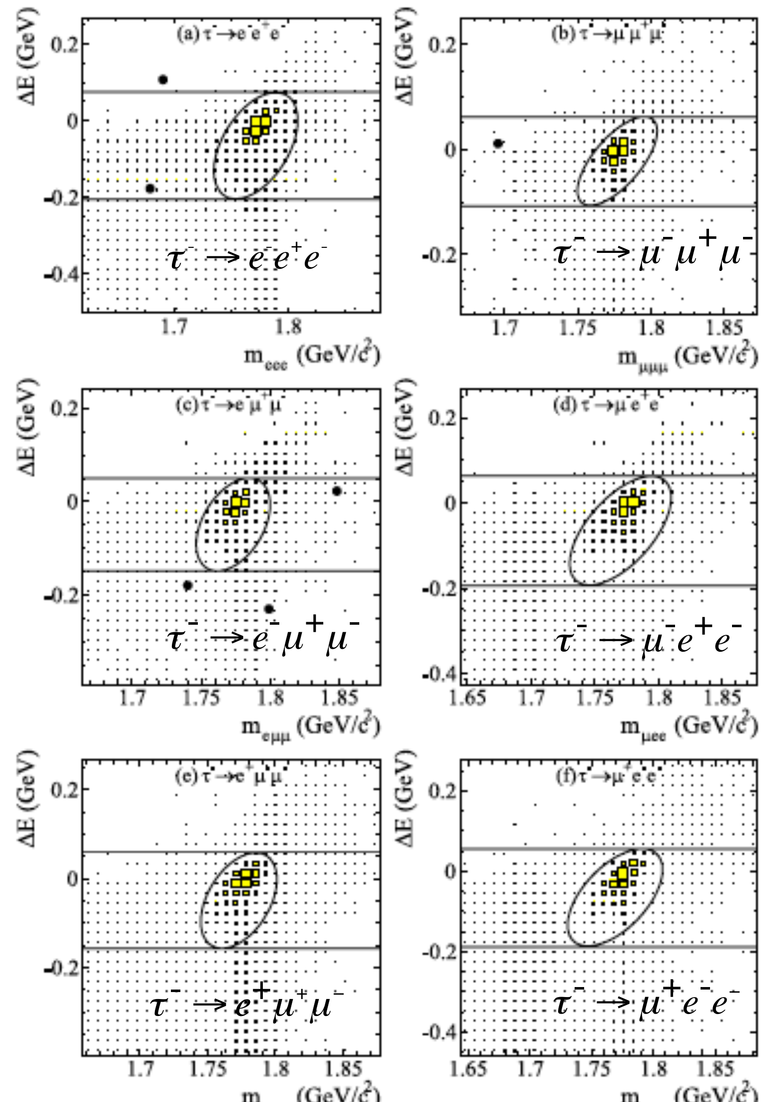
- Based on Belle data set: 782 fb^{-1}
- No events observed in the signal region for all the 6 modes studied
- Very good lepton ID
  - Almost no background
  - Expected background events:

    0.01 – 0.21

Br < (1.5 – 2.7) x 10^{-8} @ 90% C.L.
(Phys. Lett. B 687, 139 (2010))

Similar results from LHCb.

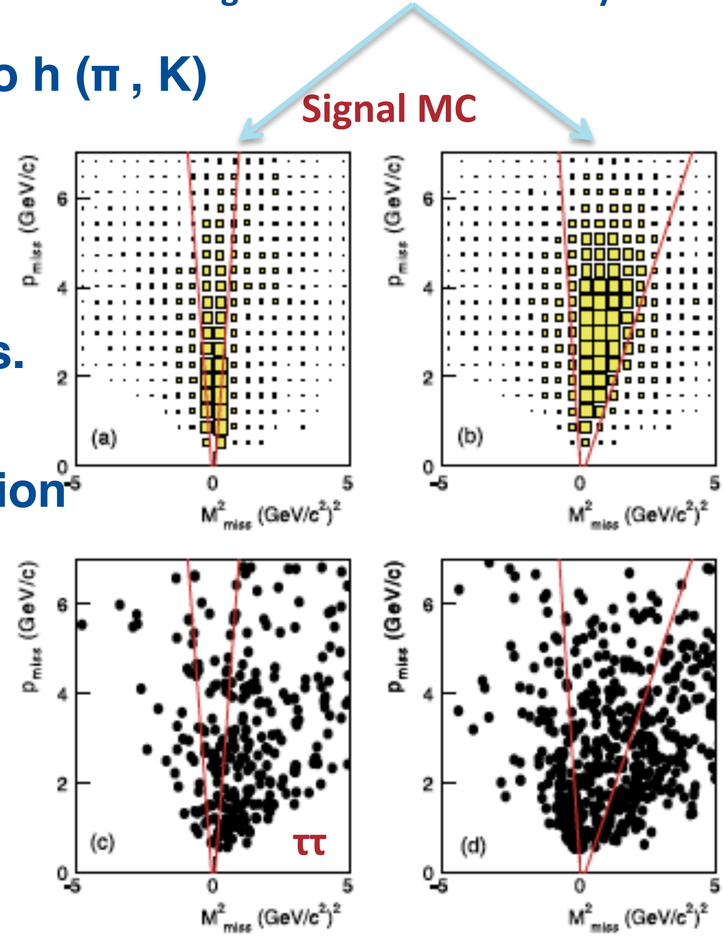
Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}$ ($\times 10^{-8}$)
$\tau^- \rightarrow e^- e^+ e^-$	6.0	0.21 ± 0.15	9.8	0	< 2.7
$\tau^- \rightarrow \mu^- \mu^+ \mu^-$	7.6	0.13 ± 0.06	7.4	0	< 2.1
$\tau^- \rightarrow e^- \mu^+ \mu^-$	6.1	0.10 ± 0.04	9.5	0	< 2.7
$\tau^- \rightarrow \mu^- e^+ e^-$	9.3	0.04 ± 0.04	7.8	0	< 1.8
$\tau^- \rightarrow e^+ \mu^- \mu^-$	10.1	0.02 ± 0.02	7.6	0	< 1.7
$\tau^- \rightarrow \mu^+ e^- e^-$	11.5	0.01 ± 0.01	7.7	0	< 1.5



$\tau \rightarrow l\, h\, h'$ at Belle

- Based on Belle data set: **854 fb^{-1}**
- Similar analysis strategy:
  - Signal side selection: a lepton (e or μ) and two h (π , K)
  - Tag side selection: a charged track (either a hadron or lepton), any number of γ and ν
- Major backgrounds: μ hh' : continuum and generic ττ decays, e hh': two photon processes.
- Suppress dominant backgrounds by either cutting on $M^2_{miss} = E^2_{miss} - p^2_{miss}$ or 2D distribution p_{miss} and M^2_{miss}
  - for ehh', μ π π, μ K K:
    - $-1.5\ \mathrm{GeV}^2 < M^2_{miss} < 1.5\ \mathrm{GeV}^2$ (hadronic tag)
    - $-1.0\ \mathrm{GeV}^2 < M^2_{miss} < 2.5\ \mathrm{GeV}^2$ (leptonic tag)
  - for μ π K: larger residual background
    - $p_{miss} > -8.0 \times M^2_{miss} - 0.5$ and $p_{miss} > 8.0 \times M^2_{miss} - 0.5$ (hadronic tag)
    - $p_{miss} > -9.0 \times M^2_{miss} + 0.4$ and $p_{miss} > 1.8 \times M^2_{miss} - 0.4$ (leptonic tag)

Removes 75% of the generic ττ background with an efficiency of ~ 75%

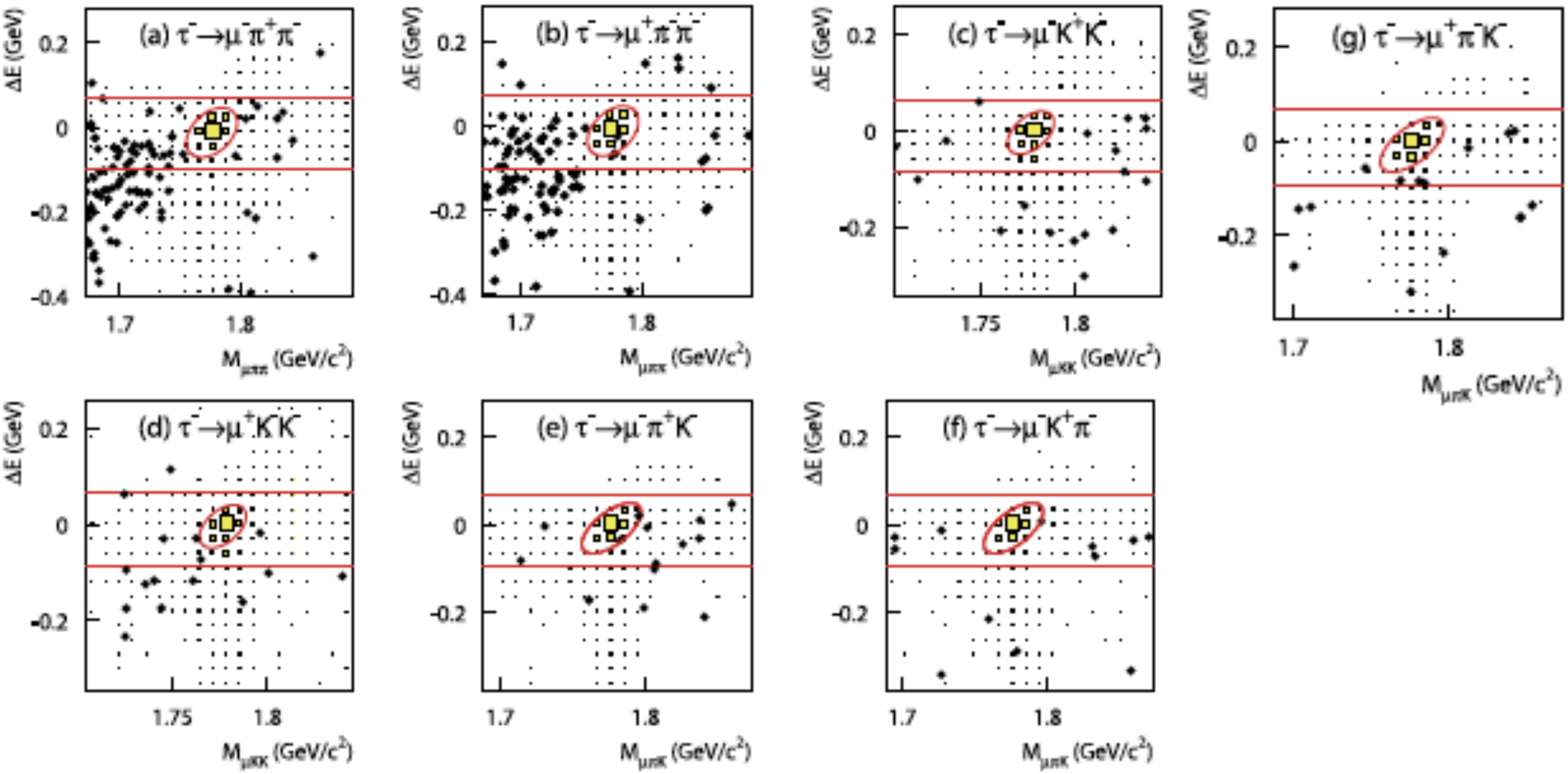


hadronic tag

leptonic tag

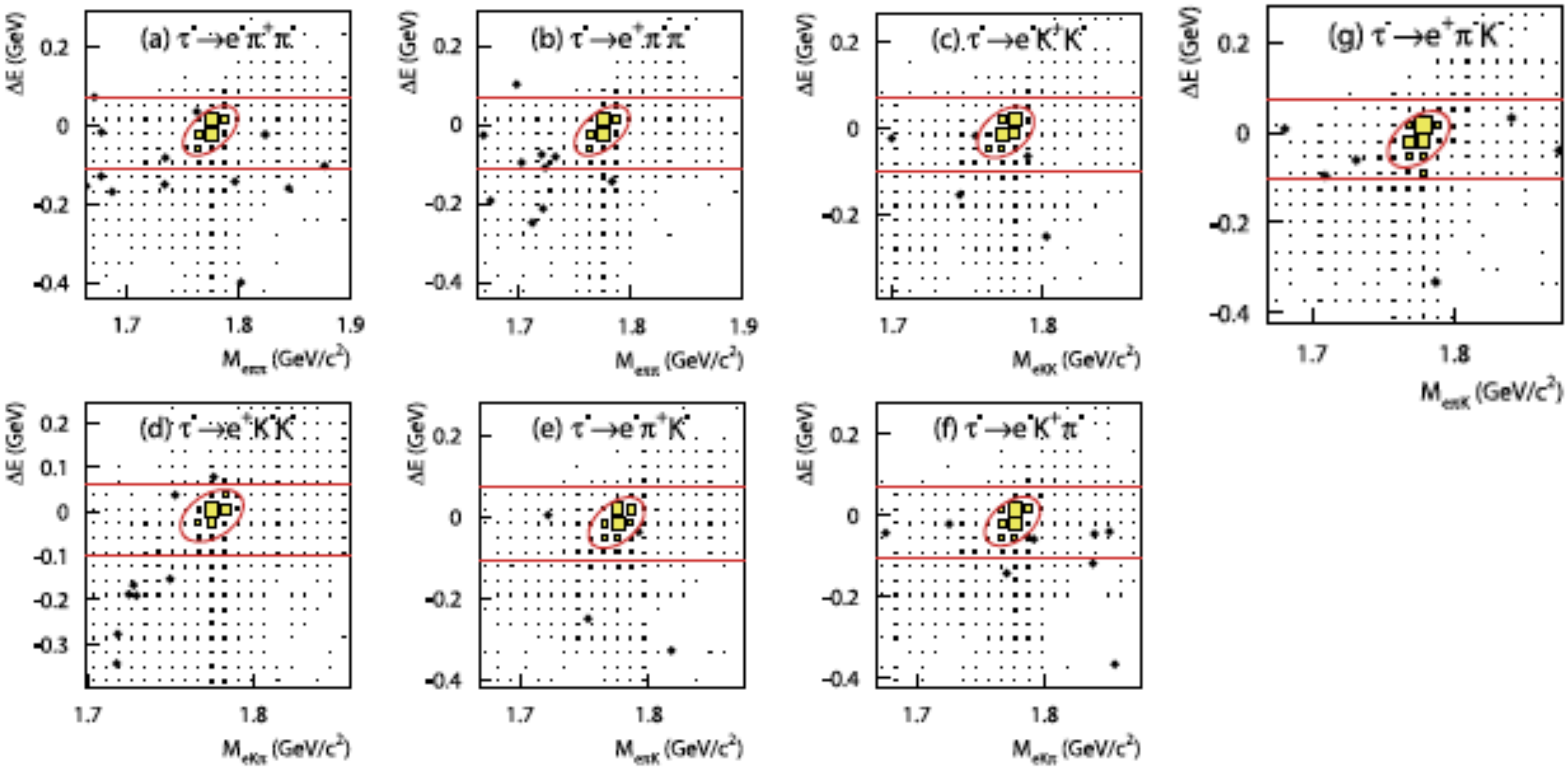
$\tau \rightarrow \mu\pi K$

$\tau \rightarrow \mu\ h\ h'$ Results



- In the signal region: 1 event in $\mu^+ \pi^- \pi^-$ and $\mu^- \pi^+ K^-$ (consistent with expected background). 0 events in other modes.

τ →*e h h'* Results

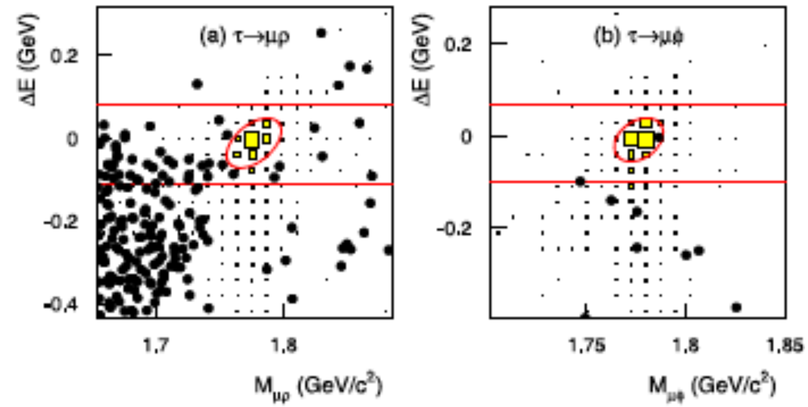


- **Br < (2.0 – 8.6) x 10^{-8} @ 90% C.L. (Phys. Lett. B 719, 346 (2013))**
- **Signal selection efficiency: 2.55% – 6.56%**

$\tau \rightarrow l\, V^0$ ($V^0 = \rho^0, K^{*0}, \bar{K}^{*0}, \omega, \phi$)

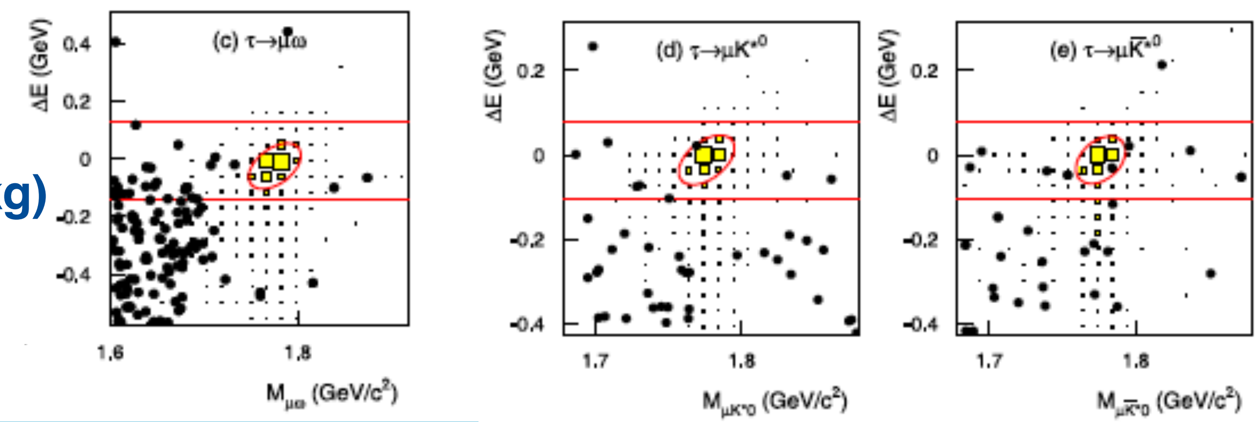
- Based on Belle data set: 854 fb^{-1}
- Similar analysis strategy as in 3 l and l h h' channels
  - Reconstruct ρ^0 from $\pi^+ \pi^-$ and ϕ from $K^+ K^-$, ω from $\pi^+ \pi^- \pi^0$, K^{*0} from $K^+ \pi^-$ and $\bar{K}^{*0}$ from $K^- \pi^+$
  - Charged K and π are identified based on PID. K (π) ID efficiency is 80% (88%) with mid-ID rate of ~ 10 – 12%.
- Major backgrounds:
  - μ V^0 : continuum and generic ττ decays,
  - e V^0: two photon processes and

  inelastic V^0 photoproduction ($e^+e^- \rightarrow e^+ e^- V^0$)
- Extract signal from the lV^0 invariant mass and ΔE distributions

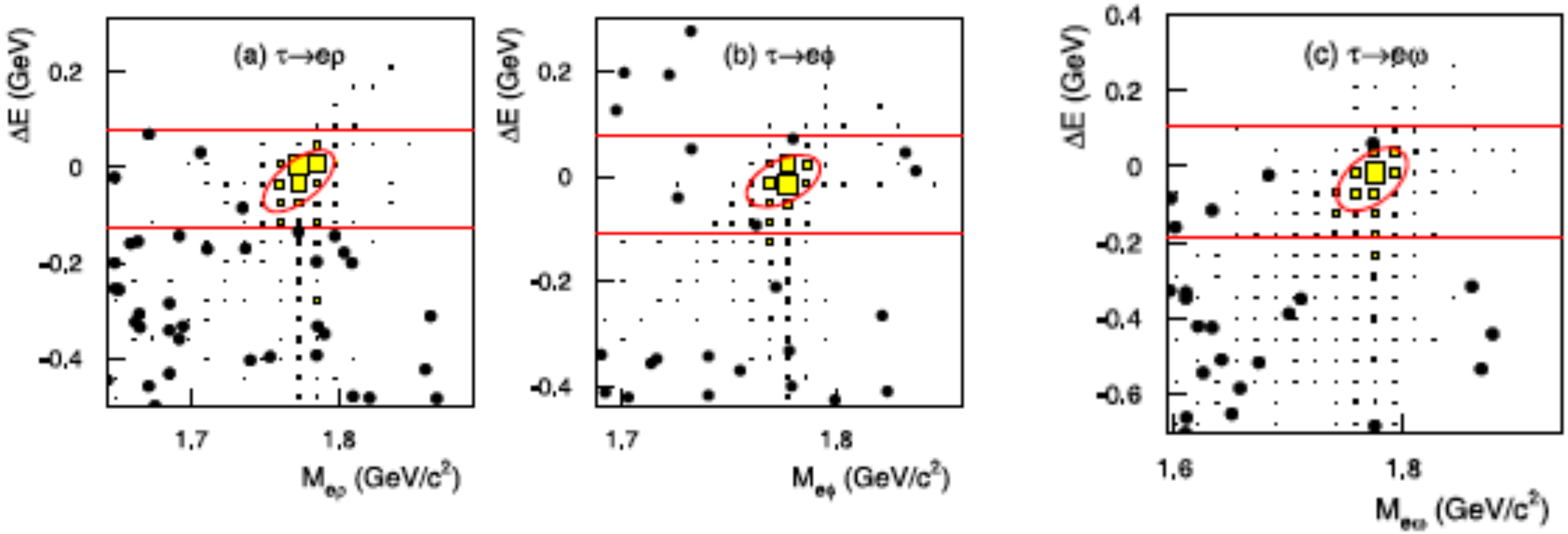


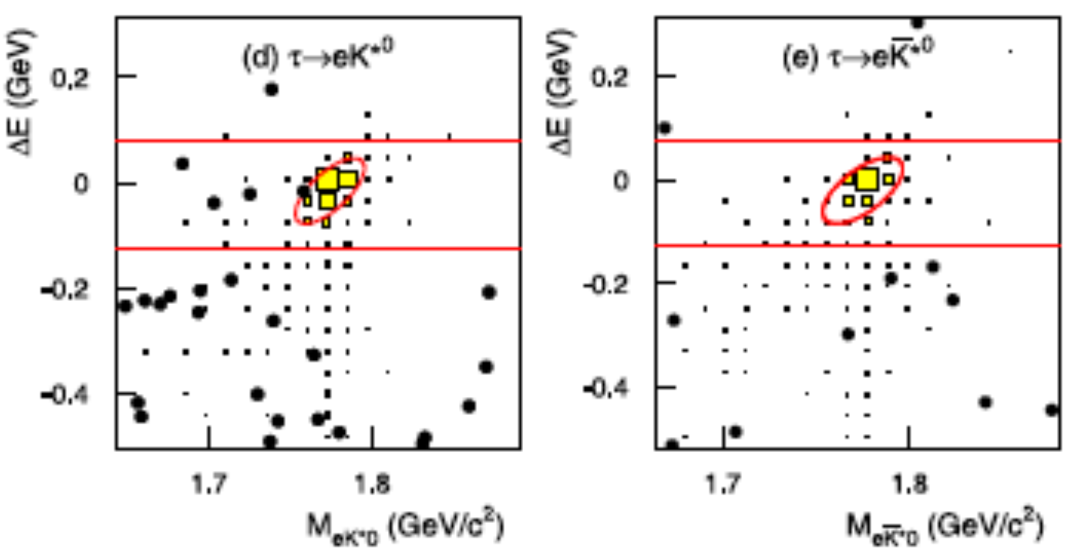
1 event in μφ, $\mu^- K^{*0}$ and $\mu^- \bar{K}^{*0}$(consistent with bkg)

0 event in other modes.



$\tau \rightarrow l\ V^0\ (V^0 = \rho^0, K^{*0}, \bar{K}^{*0}, \omega, \phi)$

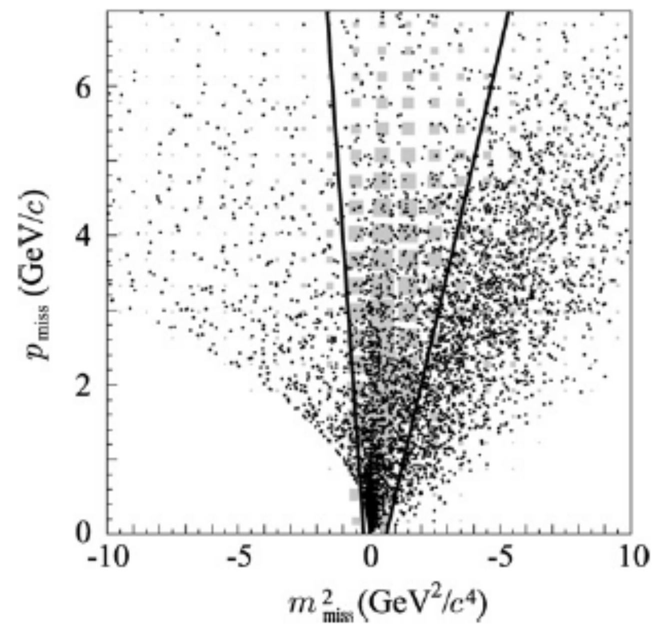




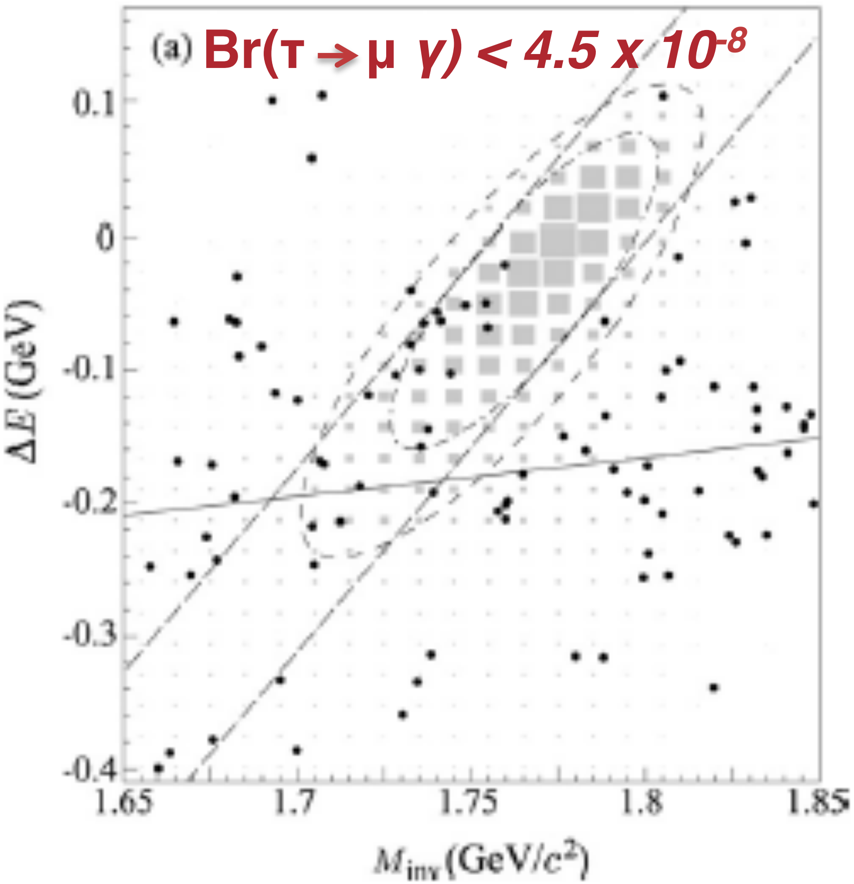
- Br < (1.2 – 8.4) x 10^{-8} @ 90% C.L. (Phys. Lett. B 699, 251 (2011))
- Signal selection efficiency: 2.38% – 7.58%

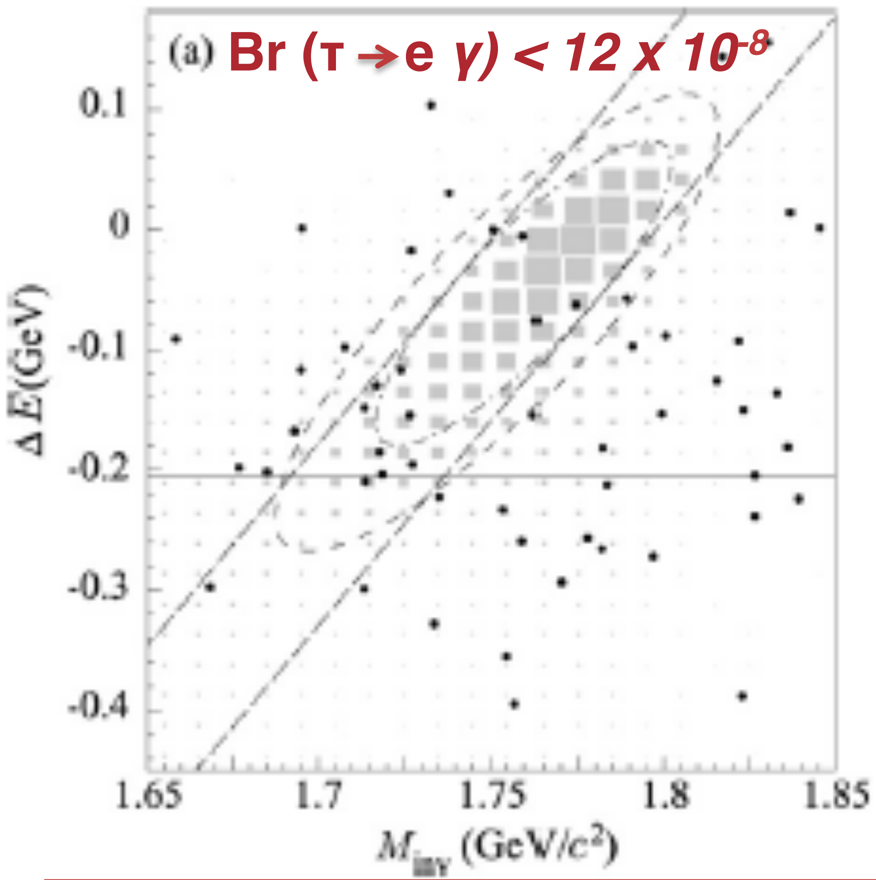
$\tau \to l\, \gamma$

- Existing published result is based on Belle data set: 535 fb^{-1} (Phys. Lett. B 666 (2008)
- Similar analysis strategy as in 3 l and l h h' channels
  - Identify signal side lepton based on PID, tracking detector and ECL.
    - μ ID efficiency is 90% with pion fake rate probability of 0.8%
    - e ID efficiency: 95% with pion fake rate: 0.07%
  - Charged track in the tag side is required to be not a μ (e) for the μ (e) channel.
- Dominant backgrounds:
  - μ γ: ττ events with $\tau \to \mu \nu\nu$ or $\tau \to \pi\nu$ (with π misID) + ISR photon or beam BG.
  - e γ: radiative Bhabha and $\tau^+ \tau^- \gamma$
- Apply selection cuts on p_{miss} and m^2_{miss} distribution to remove ττ background



$\tau \rightarrow l\ \gamma$



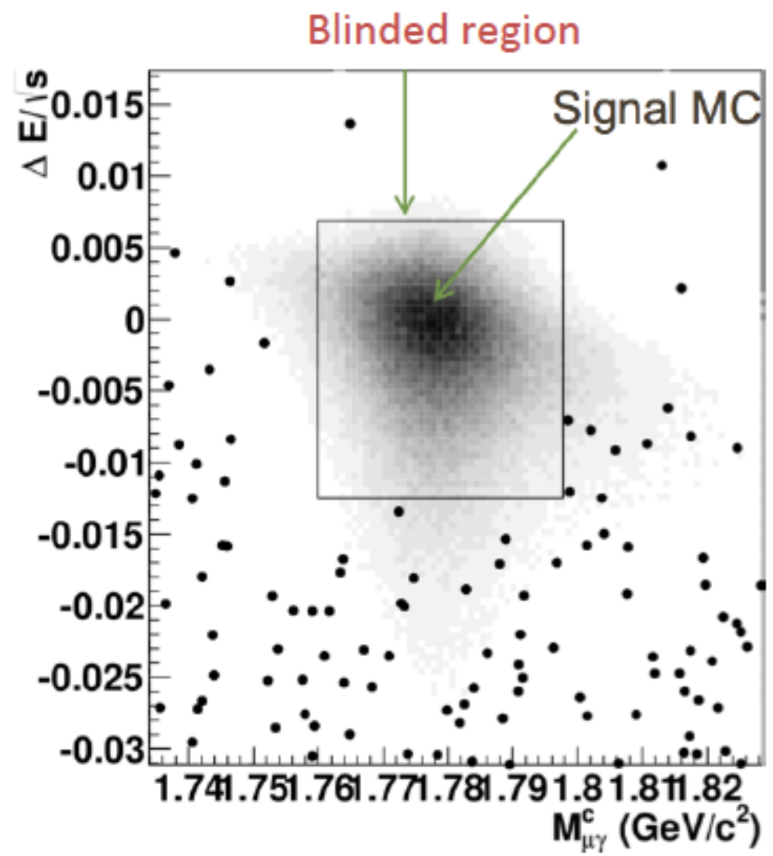


Observed 94 (23) events in the 5 σ (3σ) regions.
Expected: 88.4 ± 7.4 (15 ± 3.1)

Observed 55 (13) events in the 5 σ (3σ) regions.
Expected: 42.8 ± 3.7 (8.1 ± 1.6)

$\tau \rightarrow \mu\ \gamma$: *Updated Analysis*

- Full data sample from Belle: 980 fb^{-1} .
- ~6.5% signal selection efficiency
- Expected background: 115 ± 11
- About a factor of 1.5 increase in sensitivity.



Preliminary results

$\tau \rightarrow \Lambda h, \bar{\Lambda} h$ ($h = \pi, K$)

Allowed within GUT framework

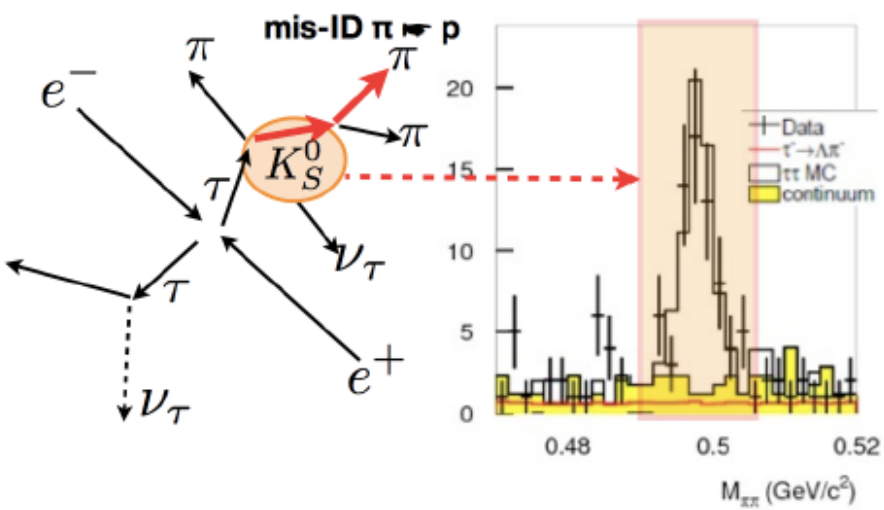
- Based on 906 fb^{-1} of data from Belle
- 4 decay modes studied
  - $\tau^- \rightarrow \bar{\Lambda} h^-$ (*B-L* Conserving)
  - $\tau^- \rightarrow \Lambda h^-$ (*B-L* Violating)
- Select three hadrons on the signal side, require Λ vertex, reconstruct Λ from a proton and a π
- Dominant backgrounds:
  - $\tau \rightarrow \pi K_s \nu$ with K_s mis-ID as Λ : Rejected by K_s veto using $M_{\pi\pi}$
  - qq background having Λ and π. Reject by vetoing proton on the tag side.

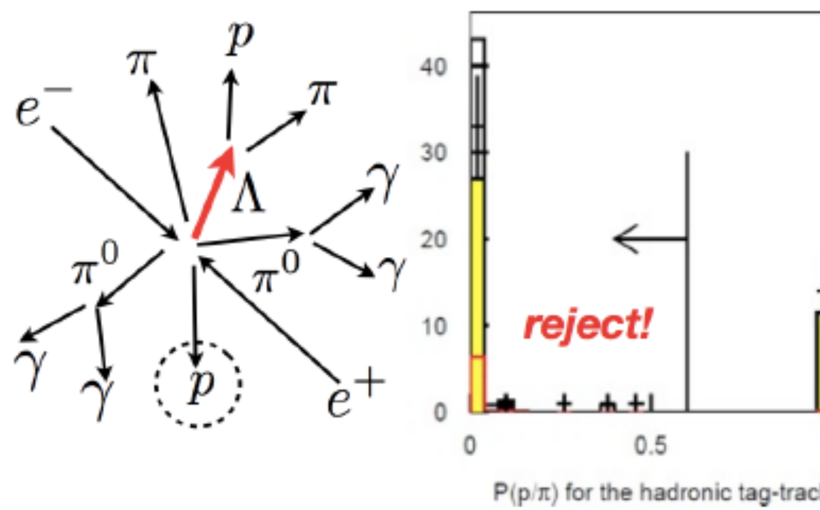
	τ^-	$\bar{\Lambda}$	$\pi^- K^-$
B	0	-1	0
L	1	0	0
B-L	-1	-1	0

B-L Conserving

	τ^-	Λ	$\pi^- K^-$
B	0	1	0
L	1	0	0
B-L	-1	1	0

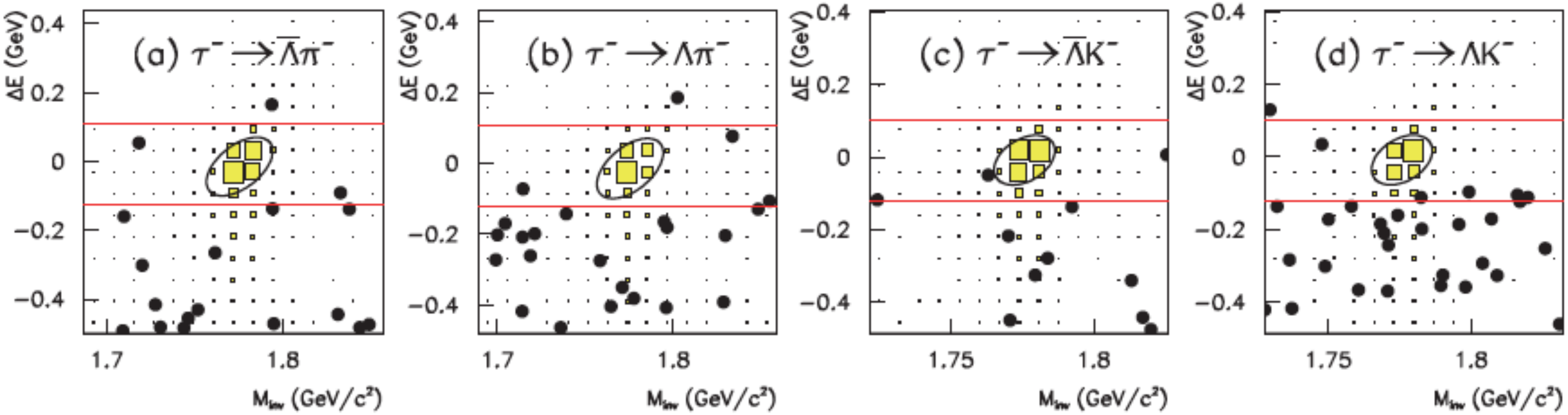
B-L Violating





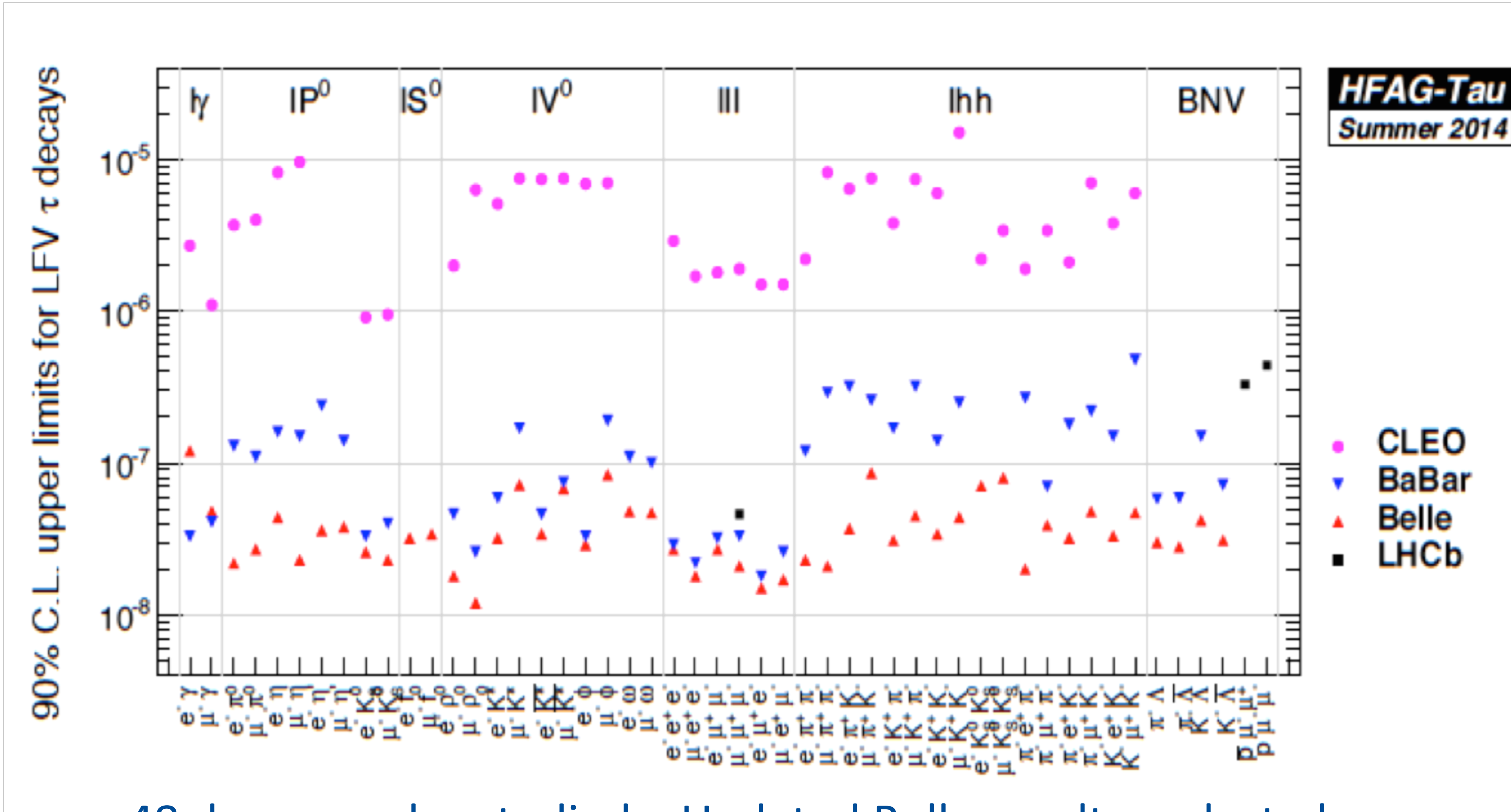
τ → Λ h, $\bar{\Lambda}$ h (h = π, K)

No events seen in the signal region.



Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \Lambda\pi^-$	4.80	0.21 ± 0.15	8.2	0	2.26	2.8
$\tau^- \to \Lambda\pi^-$	4.39	0.31 ± 0.18	8.2	0	2.17	3.0
$\tau^- \to \bar{\Lambda}K^-$	4.11	0.31 ± 0.14	8.6	0	2.17	3.1
$\tau^- \to \Lambda K^-$	3.16	0.42 ± 0.19	8.6	0	2.08	4.2

Summary of tau LFV searches at *B*-factories.



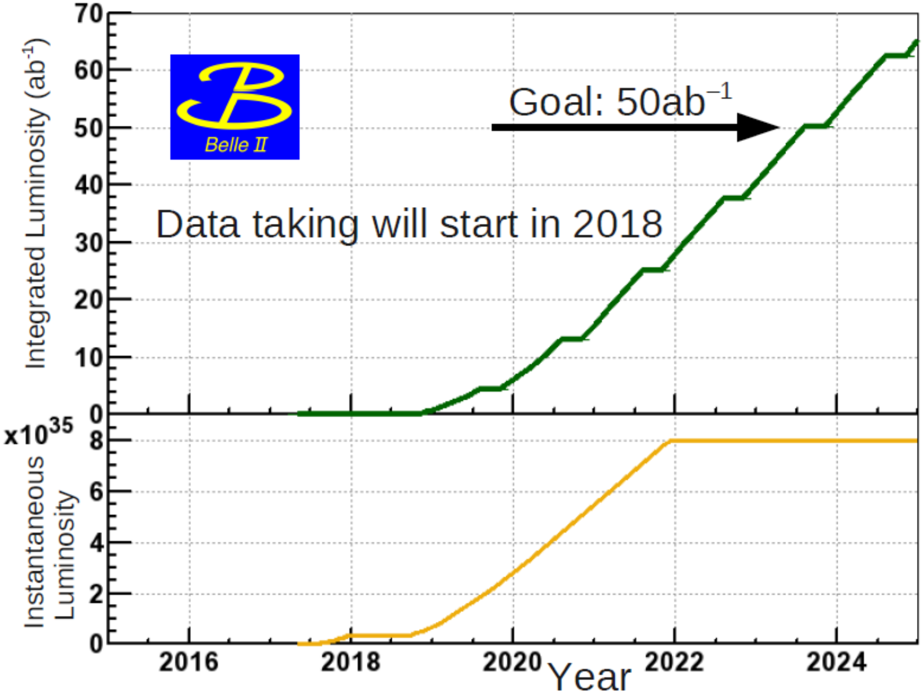
48 decay modes studied – Updated Belle results on l γ to be released soon.

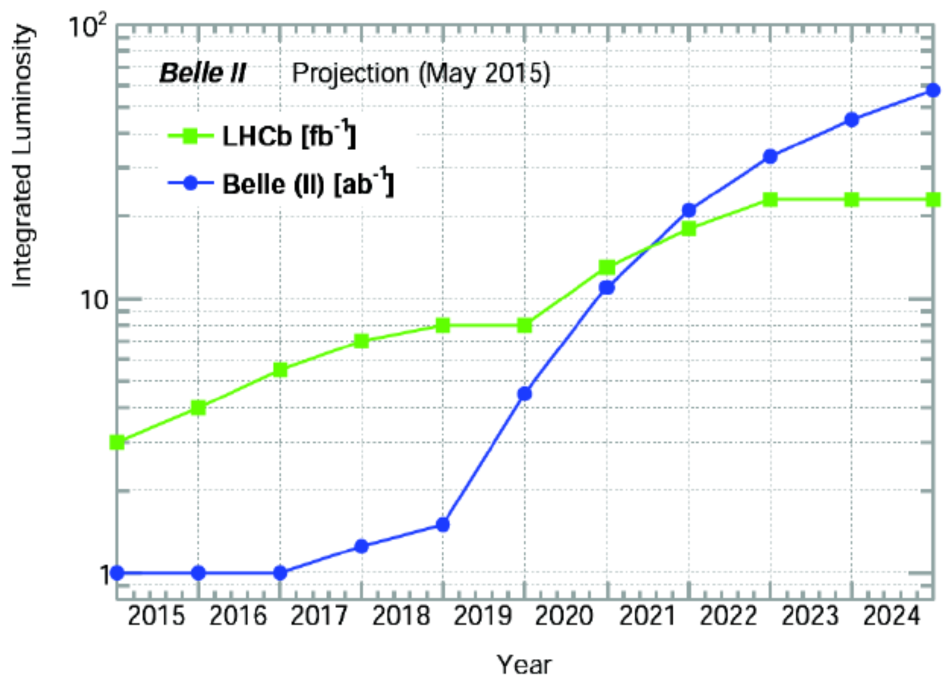
Belle II at SuperKEKB

- **KEKB is being upgraded to the SuperKEKB Collider**
  - **Target: achieve 40 times more luminosity than KEKB**
  - **Higher luminosity -> higher background -> the Belle detector needs to be upgraded.**

Belle becomes Belle II

- **Belle II will collect about 10^{11} τ leptons compared to 10^{9} presently available.**





SuperKEKB nanobeams

At SuperKEKB, we increase the luminosity based on "Nano-Beam" scheme (originally proposed for SuperB by P. Raimondi)

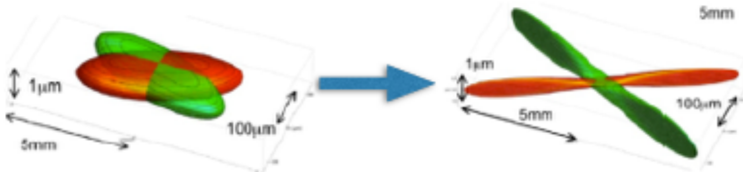
$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{\pm}\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

Luminosity Gain

- Vertical β function at IP: 5.9 → 0.27/0.30 mm (x20)
- Beam current: 1.7/1.4 → 3.6/2.6 A (x2)

→ $L = 2\times10^{34} \rightarrow 8\times10^{35}\ cm^{-2}s^{-1}$ (x40)

To get 40x luminosity of Belle

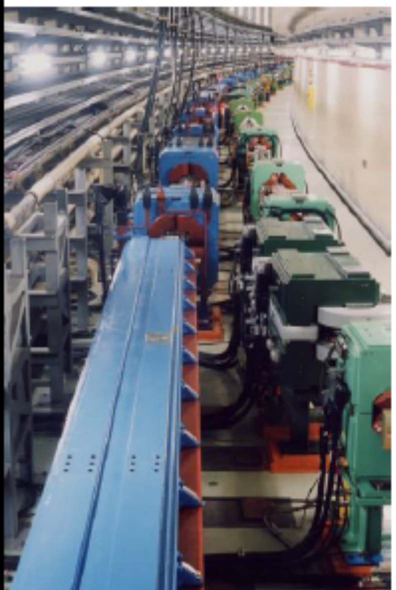


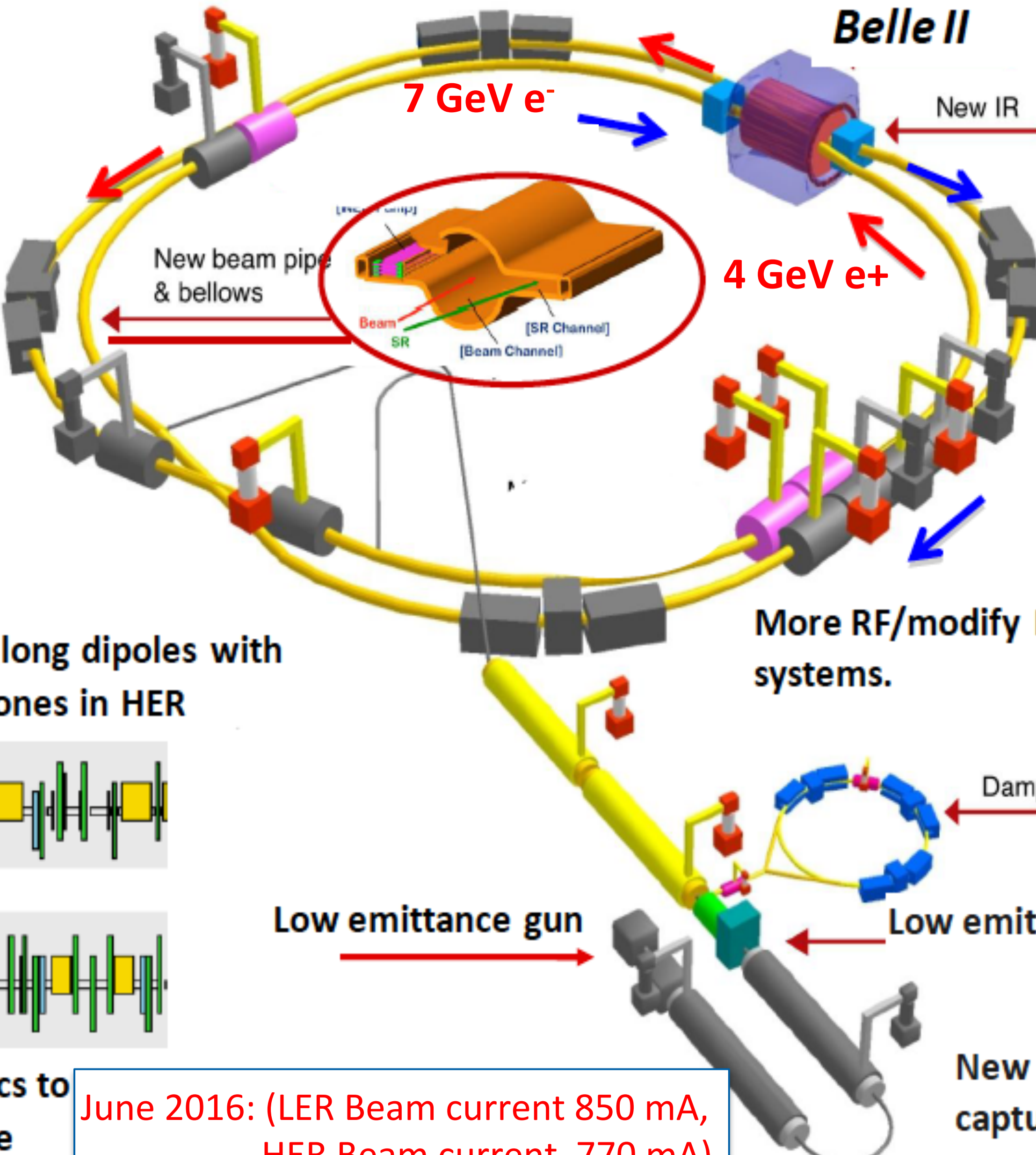
Reduce beam size to a few 100 atomic layers!

Parameter		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	0.881	0.0807	
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	$\mathcal{L}$	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

KEKB upgrade → SuperKEKB(nano-beam)

Feb 2016: First turns at SuperKEKB

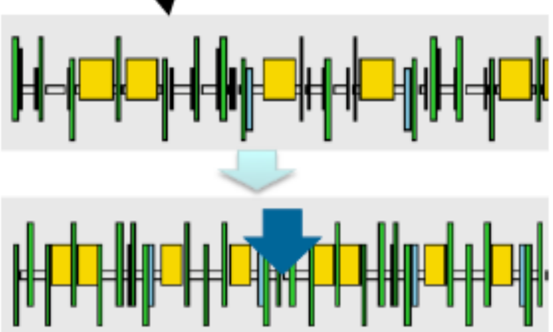




Two separate focusing quads/each 2 beams closer to IP; Superconducting / permanent magnets

More RF/modify RF systems.

Replace long dipoles with shorter ones in HER



Redesign the HER arcs to reduce the emittance

Low emittance gun

Low emittance positrons

New positron target / capture section

June 2016: (LER Beam current 850 mA, HER Beam current 770 mA)

Detector upgrade

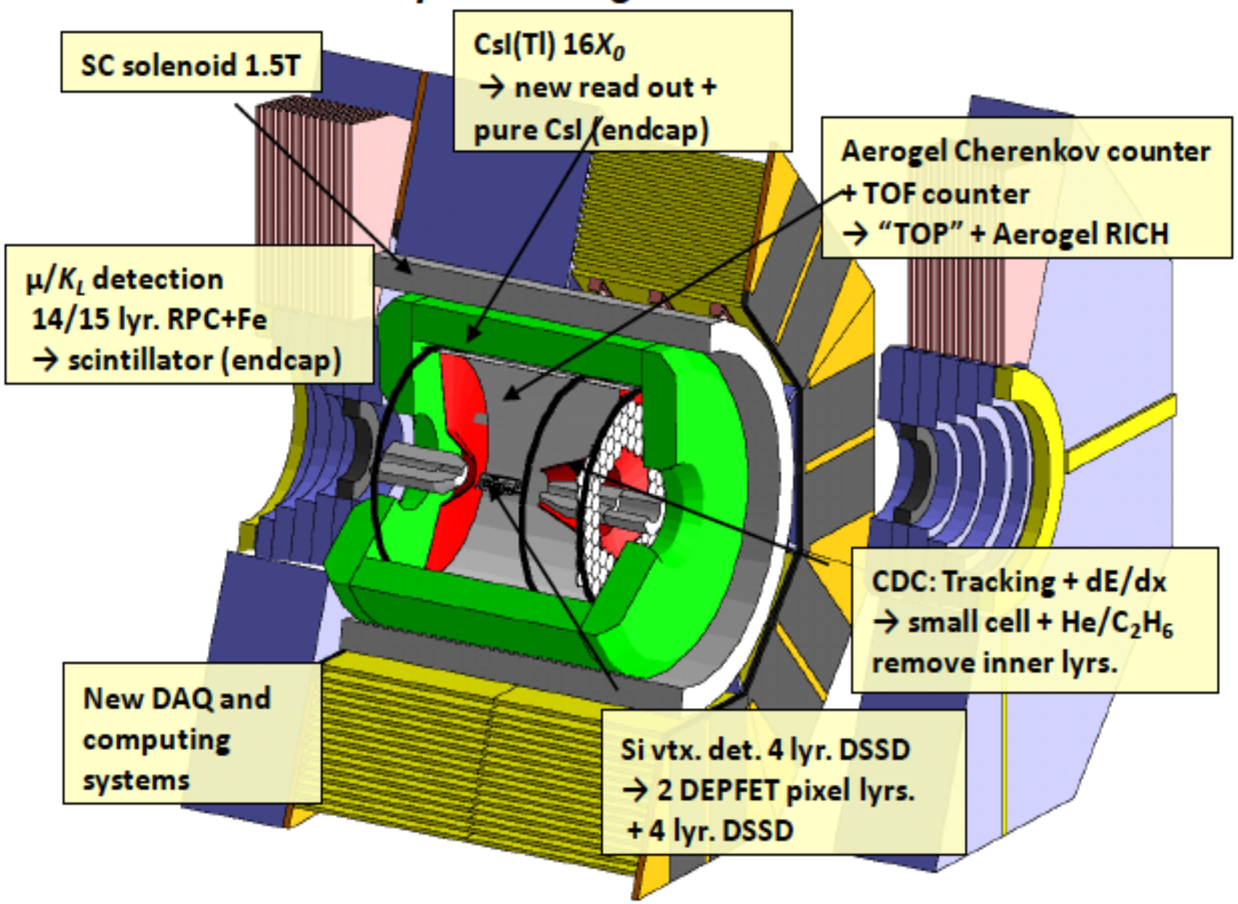
Critical issues at $L = 8 \times 10^{35}/cm^2/sec$

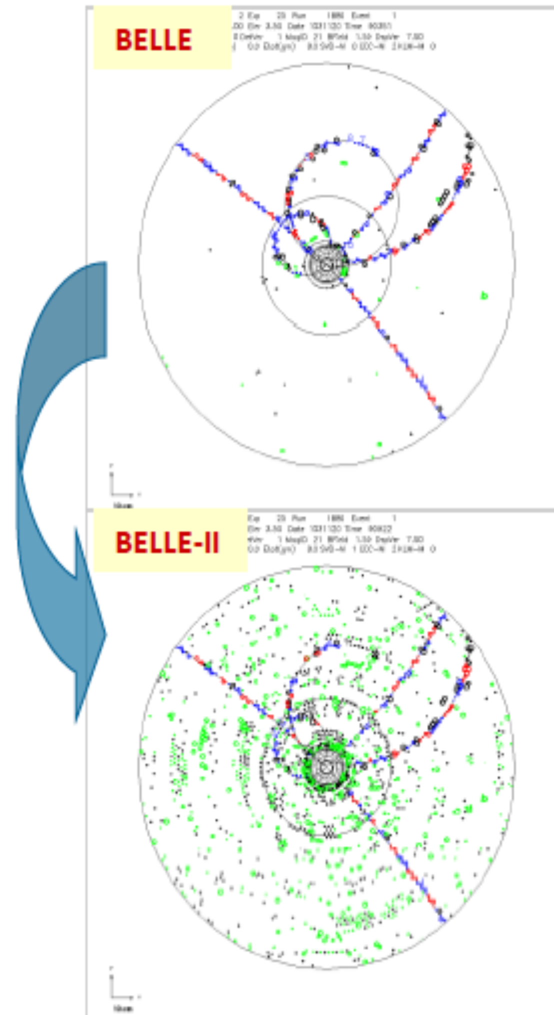
- Higher event rate
  - higher rate trigger, DAQ and computing

  \+

  - Improve performance
    - try better PID options
    - low p μ identification for $b \rightarrow s\mu\mu$ efficiency
    - hermeticity → missing E "reconstruction"

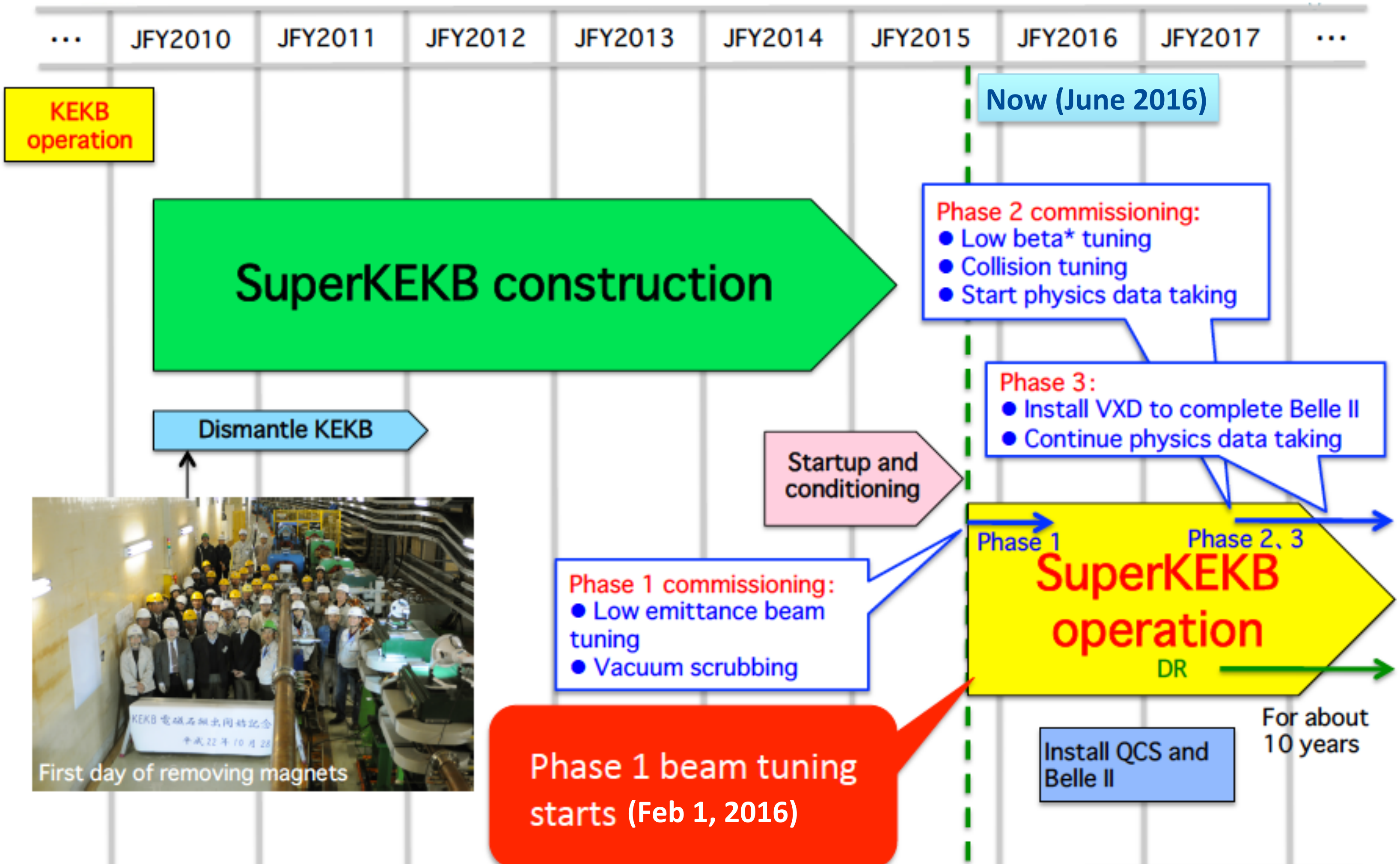
- Higher background
  - radiation damage and occupancies
  - fake hits and pile-up noise in the ECL





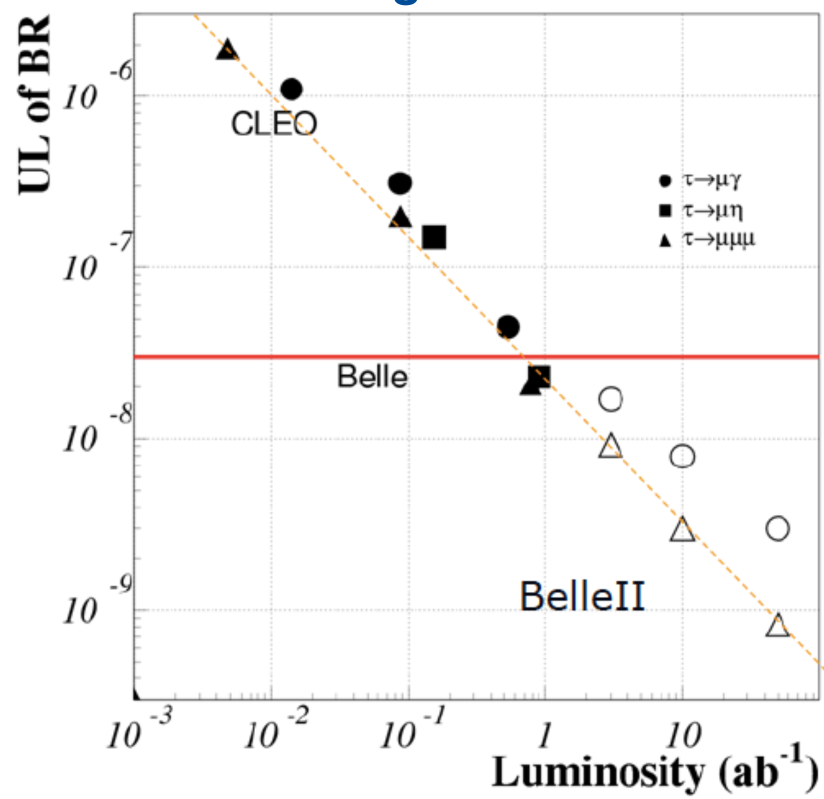
Schedule

- **3 phases in commissioning ⟶ operation :**
  - **Phase I: without Belle II detector, Phase II: Belle II rolled in, no SVD, Phase III: Full detector on**



Prospects of LFV at Belle II

- **Belle II will collect about 10^{11} τ leptons compared to 10^{9} presently available.**
- **Sensitivity depends on the background**
  - **τ→3 leptons mode is still very clean at Belle II**
  - **For τ→μ γ better understanding and control of the background will be necessary.**



- Sensitivity improves as $1/\int L dt$ for decays without bkg
- Sensitivity improves as $1/\sqrt{\int L dt}$ for decays with bkg

Belle II Collaboration

- 23 countries,
- **98 institutions,**
- **615 collaborators as of June 2016.**

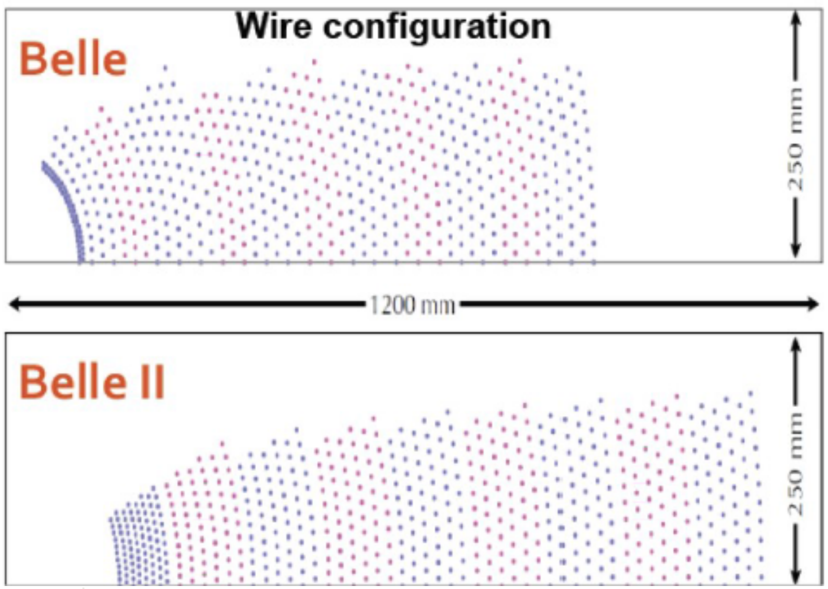
Summary

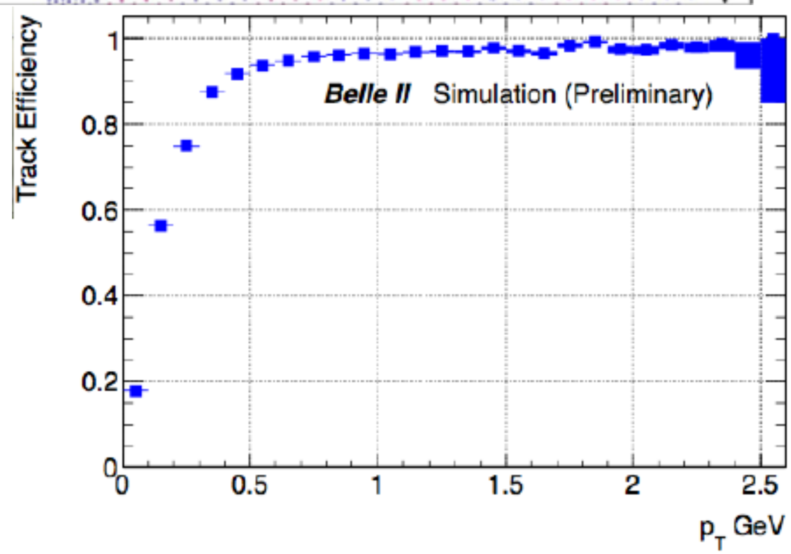
- *B*-factories are also τ factories. Produced *O*(10^9) *tau pairs so far.*
  - Studied 48 LFV decay modes at Belle, x100 increase in sensitivity compared to CLEO.
  - No signal event is seen in any of the modes. Set 90% CL upper limits in *O*(10^{-8}).

- The prospect to search for CLFV at Belle II looks brighter
  - The full range of τ LFV is only accessible at Belle II.
  - Accelerator upgrade is finished, beam was turned on in Feb 2016. Detector up gradation is continuing.
    - With higher luminosity, expect higher background for modes like $l\gamma$: efficient background reduction will be key.
    - Sensitivity for modes like 3 leptons will pretty much scale with the luminosity.
  - Start of full Physics run: 2018, reach 50 ab^{-1} by 2023 – 2024.
    - Sensitivity reach for CLFV up to *O*($10^{-9} - 10^{-10}$)

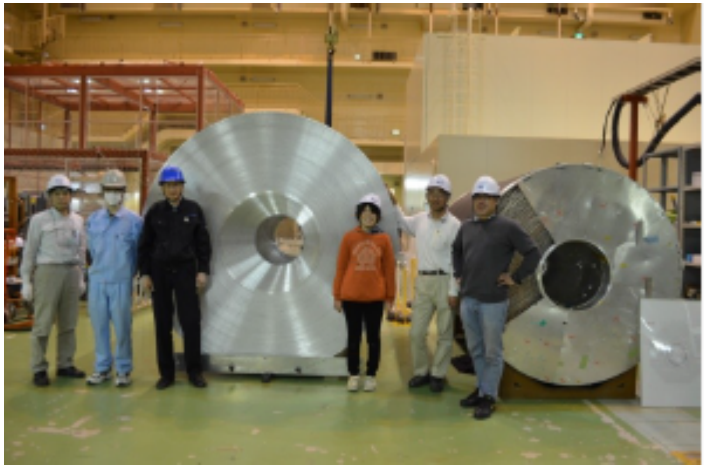
Backup Slides

Central Drift Chamber (CDC)



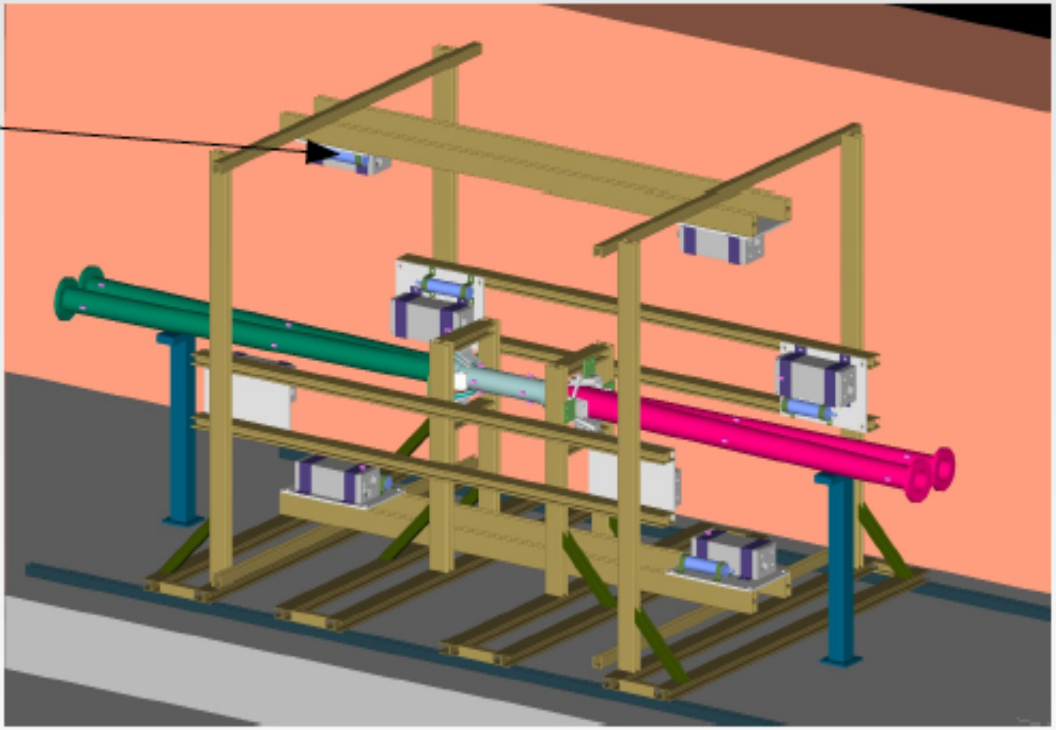


	Belle	Belle II
Innermost sense wire	r=88mm	r=168mm
Outermost sense wire	r=863mm	r=1111.4mm
Number of layers	50	56
Total sense wires	8400	14336
Gas	He:C_2H_6	He:C_2H_6
Sense wire	W(Φ30μm)	W(Φ30μm)
Field wire	Al(Φ120μm)	Al(Φ120μm)



Commissioning the Machine

- During phases 1 and 2 a commissioning detector will be used – BEAST II (Beam Exorcisms for A Stable ExperimenT).
- Will be used to measure beam backgrounds, before Belle II is rolled in and fully installed.
- Phase 1: 2 MicroTPCs in 8 positions used to measure neutron backgrounds, and PIN diodes used to measure ionising particle backgrounds.
- Every other PIN diode coated in gold paint, to allow for separation of charged particle and x-ray contributions.



Slide from M. Barrett