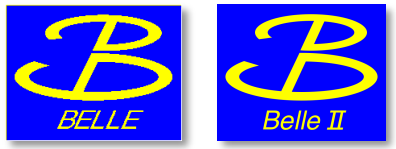


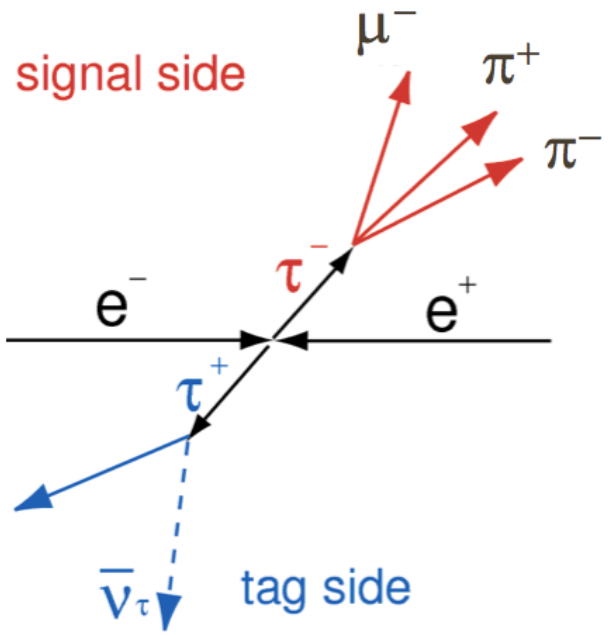
Charged lepton flavour violation at Belle and Belle II

Christoph Schwanda
Institute of High Energy Physics
Austrian Academy of Sciences

1st Conference on Charged Lepton Flavour Violation
May 6-8, 2013, Lecce, Italy

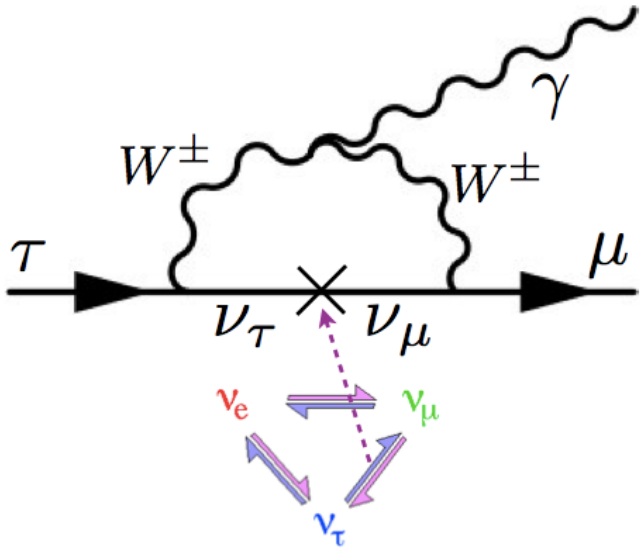
Outline of this talk

- A very brief introduction
- The Belle experiment
- τ LFV results from Belle
  - $\tau \to 3l$
  - $\tau \to lV^0$
  - $\tau \to lhh'$
  - $\tau \to \Lambda h/\bar{\Lambda} h$
  - $\tau \to l\gamma$
- The Belle II upgrade
- Prospects for τ LFV at Belle II



LFV in τ decays

- From an experimentalist's perspective
  - No SM background



$$\mathcal{B}(\tau^- \to l^- \gamma) \propto \left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2 < 10^{-50} \sim 10^{-54}$$

Beyond experimental sensitivity

→ Any signal is an unambiguous sign of New Physics

LFV in τ decays

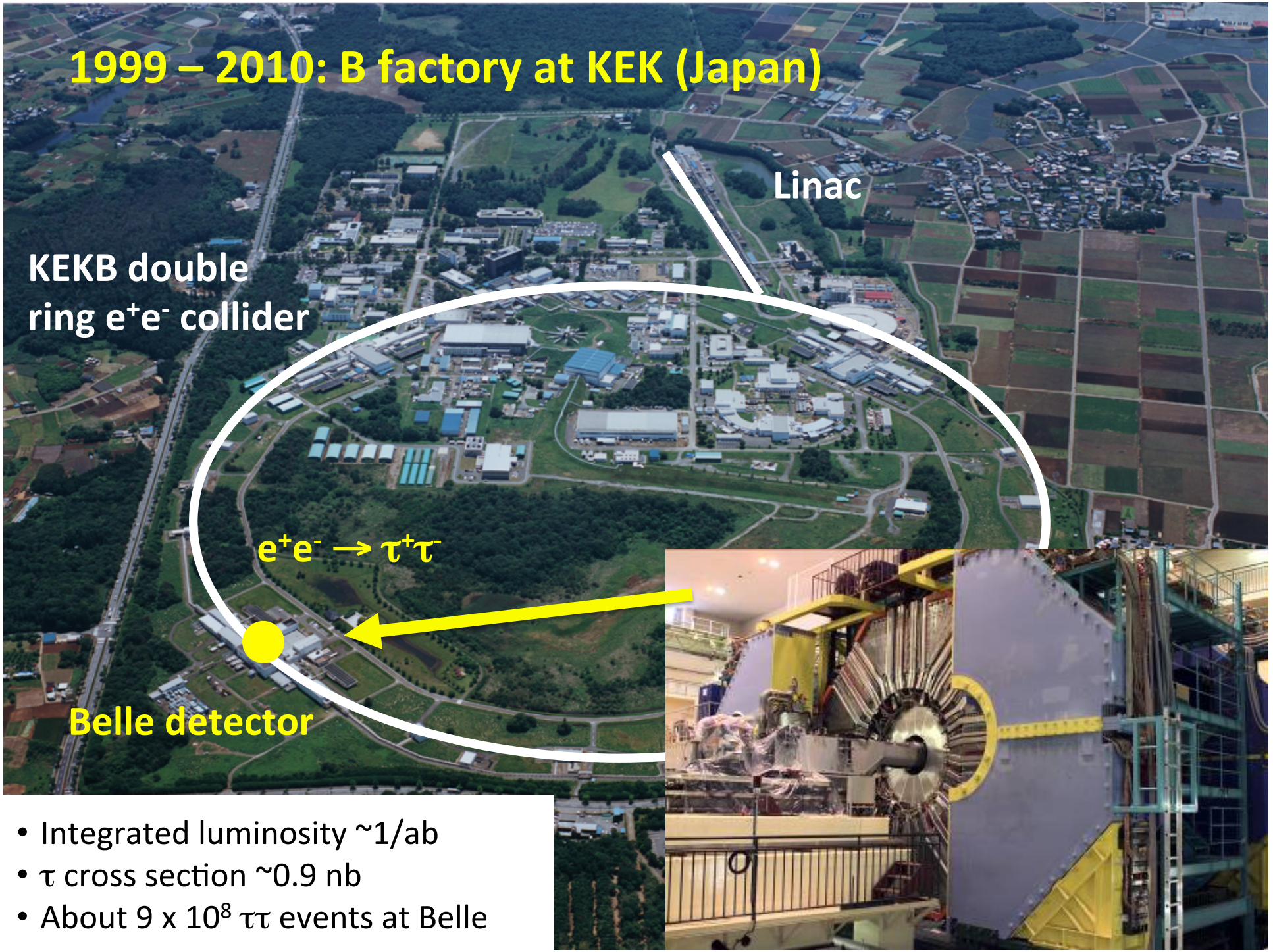
- From an experimentalist's perspective
  - Strong model dependence of the signals

Ratio	LHT	MSSM scenario 1	MSSM scenario 2
$BF(\tau \to 3e)/BF(\tau \to e\gamma)$	0.4 … 2.3	~1 x 10^{-2}	~1 x 10^{-2}
$BF(\tau \to 3\mu)/BF(\tau \to \mu\gamma)$	0.4 … 2.3	~2 x 10^{-3}	0.06 … 0.1
$BF(\tau \to e\mu\mu)/BF(\tau \to \mu\gamma)$	0.3 … 1.6	~2 x 10^{-3}	0.02 … 0.04
$BF(\tau \to \mu ee)/BF(\tau \to \mu\gamma)$	0.3 … 1.6	~1 x 10^{-2}	~1 x 10^{-2}
$BF(\tau \to 3e)/BF(\tau \to e\mu\mu)$	1.3 … 1.7	~5	0.3 … 0.5
$BF(\tau \to 3\mu)/BF(\tau \to \mu ee)$	1.2 … 1.6	~0.2	5 … 10

  - Belle has searched for 48 τ LFV modes

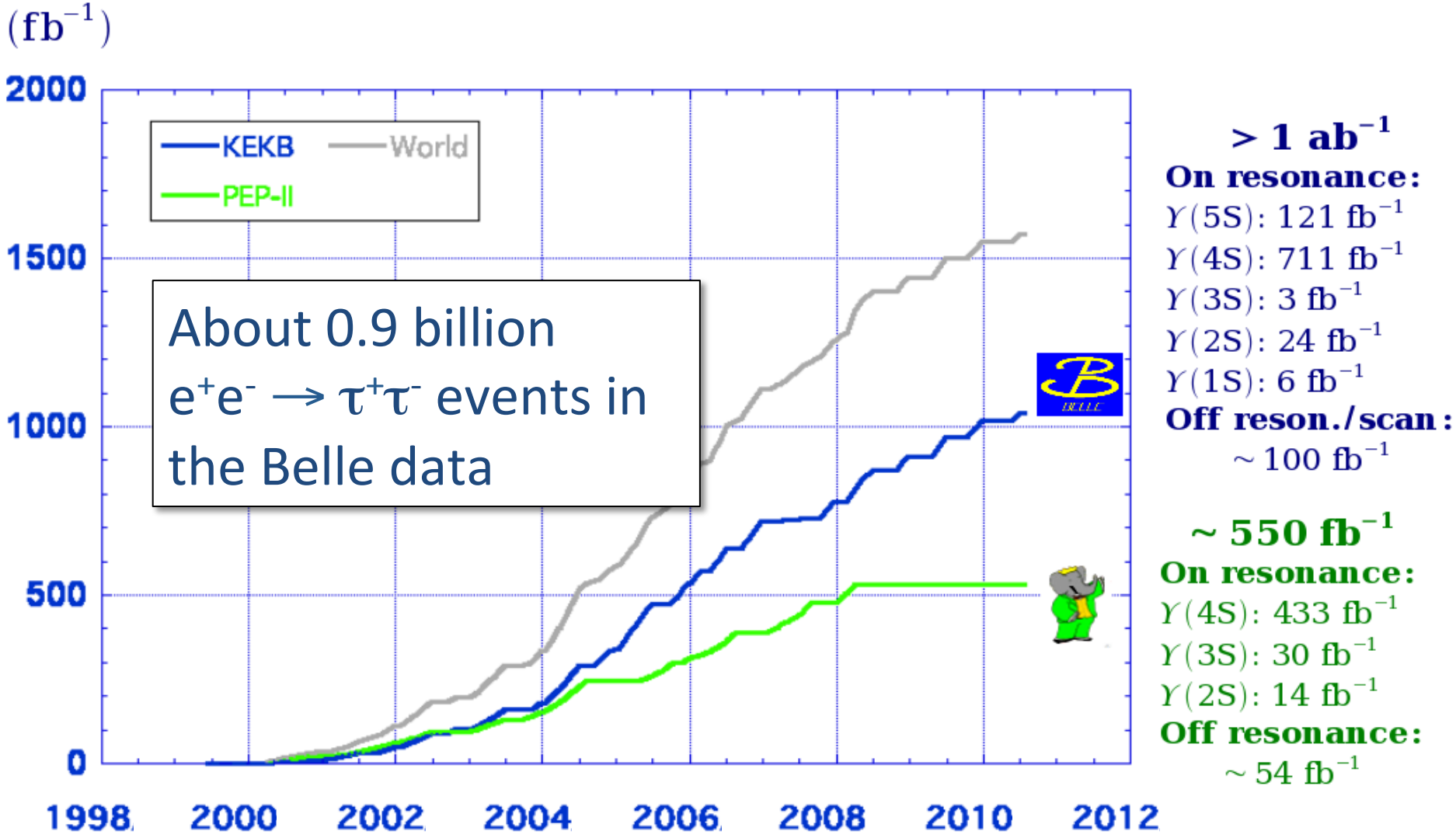
→ By observing the full pattern of τ LFV, we draw conclusions on the underlying NP scenario

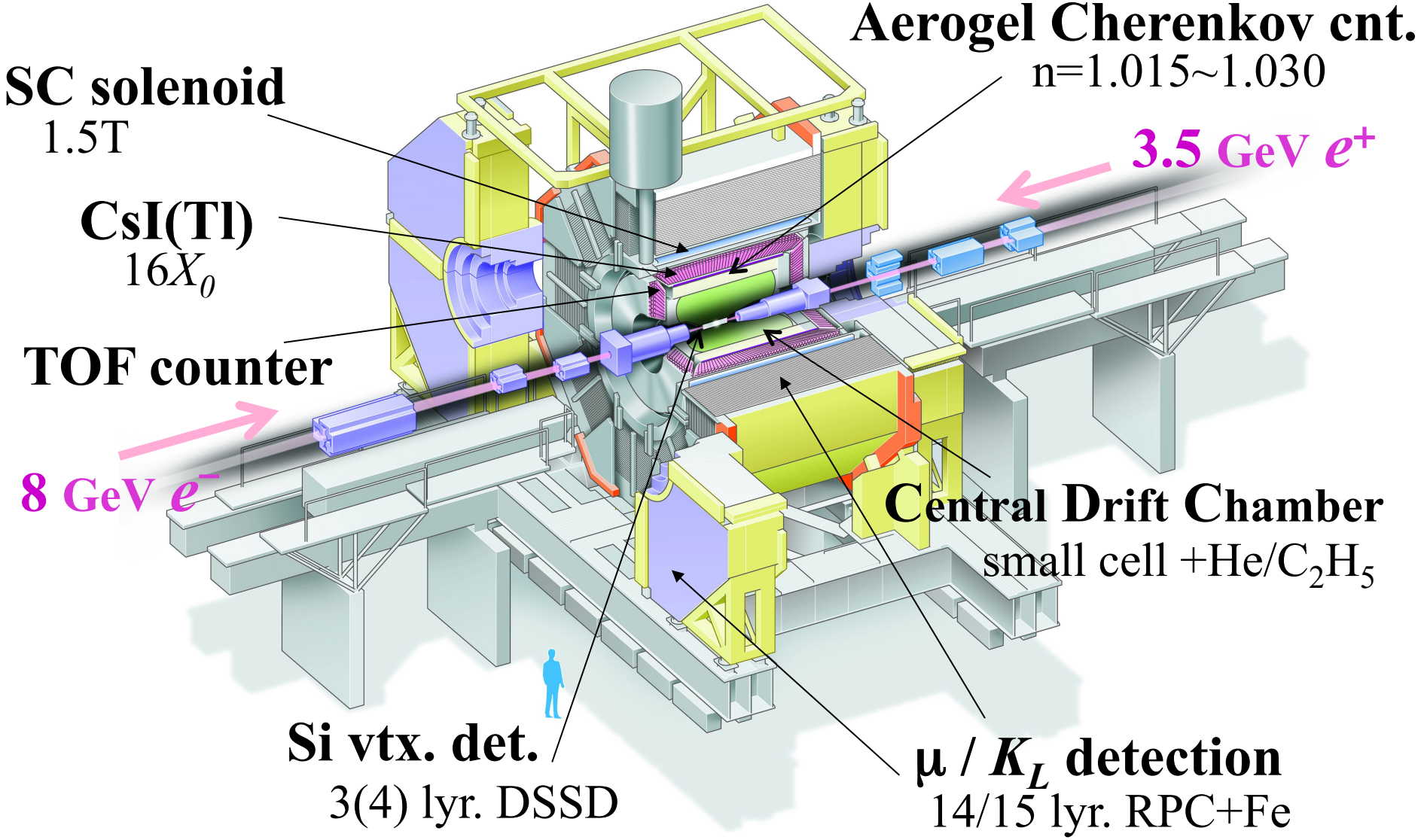
Belle



- Integrated luminosity ~1/ab
- τ cross section ~0.9 nb
- About 9 x 10^8 $\tau\tau$ events at Belle

Luminosity at B factories

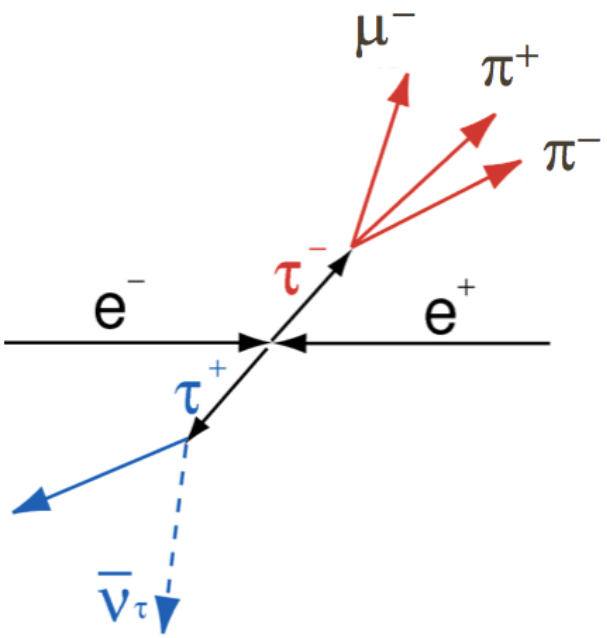




Lepton ID efficiency ~90%

Fake rate ~0.1% (electrons), ~1% (muons)

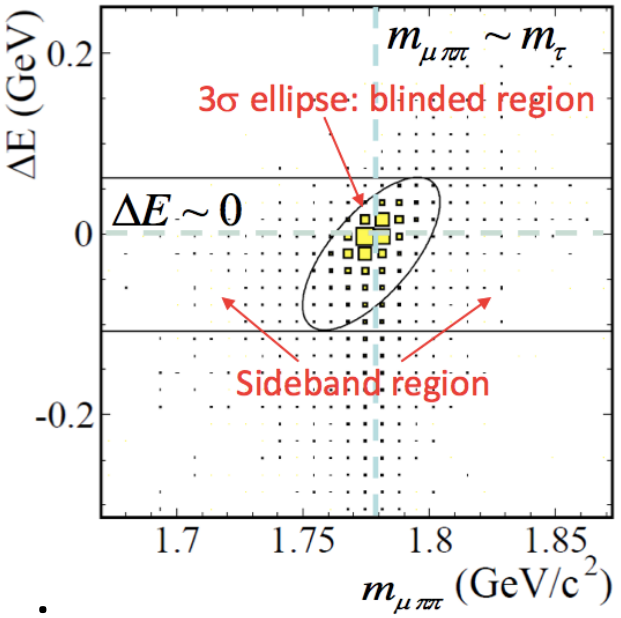
Analysis outline



Signal side: extract signal from M_τ vs. ΔE plane

$$m_{\mu\pi\pi} = \sqrt{(E^2_{\mu\pi\pi} - p^2_{\mu\pi\pi})}$$

$$\Delta E = E^{CM}_{\mu\pi\pi} - E^{CM}_{beam}$$

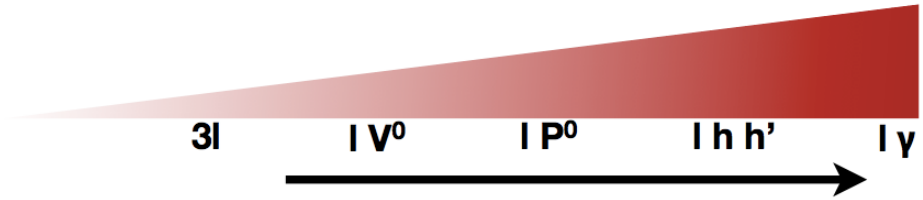


Tag side: select 1-prong decay ($\tau \to l\nu\nu$, $h\nu$, BR ~ 85%)

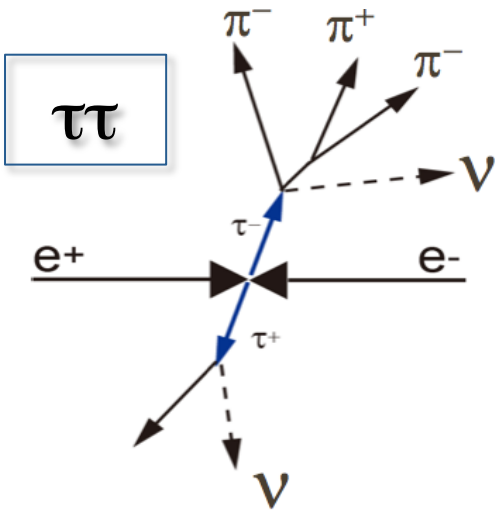
- Blind analysis (blinded signal region)
- Background estimated from sideband or MC simulation
- 90% C.L. upper limit set using Feldman-Cousin approach

Major backgrounds

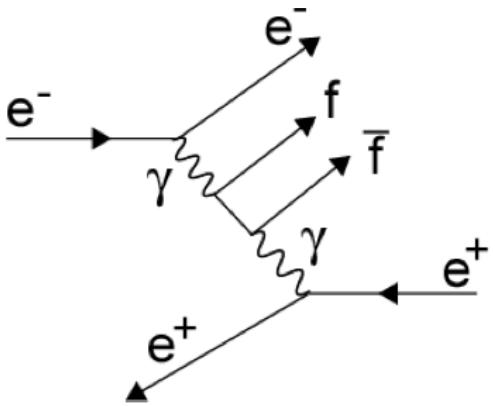
Difficulty of τ LFV analyses



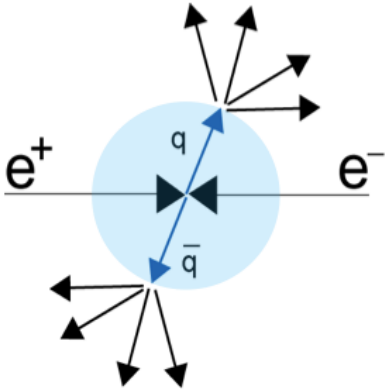
ττ



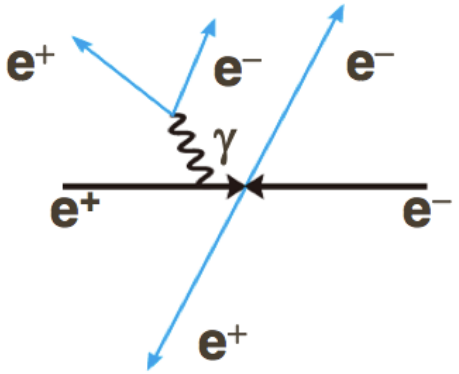
two photon



qq



Radiative Bhabha



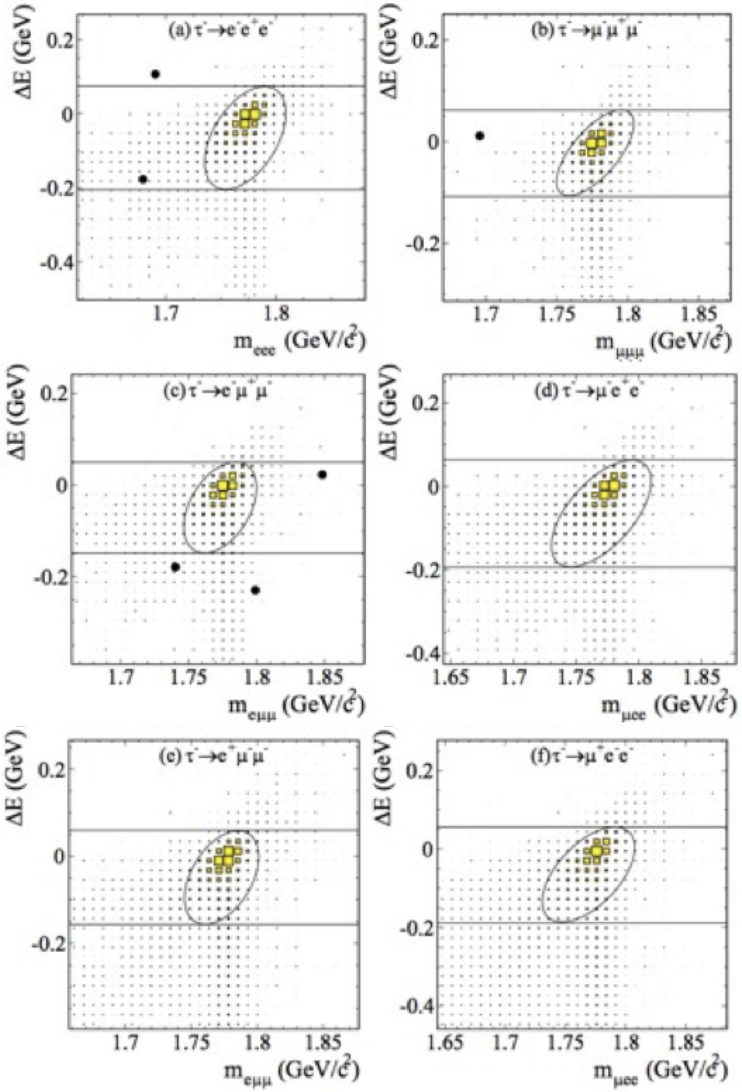
$\tau^+ \to l^+ l^- l^+$

Phys. Lett. B687, 139 (2010)

- Based on 782/fb of Belle data
- Virtually background free due to good lepton ID
- Zero events observed in all 6 modes

90% C.L. upper limits between 1.5×10^{-8} and 2.7×10^{-8}

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



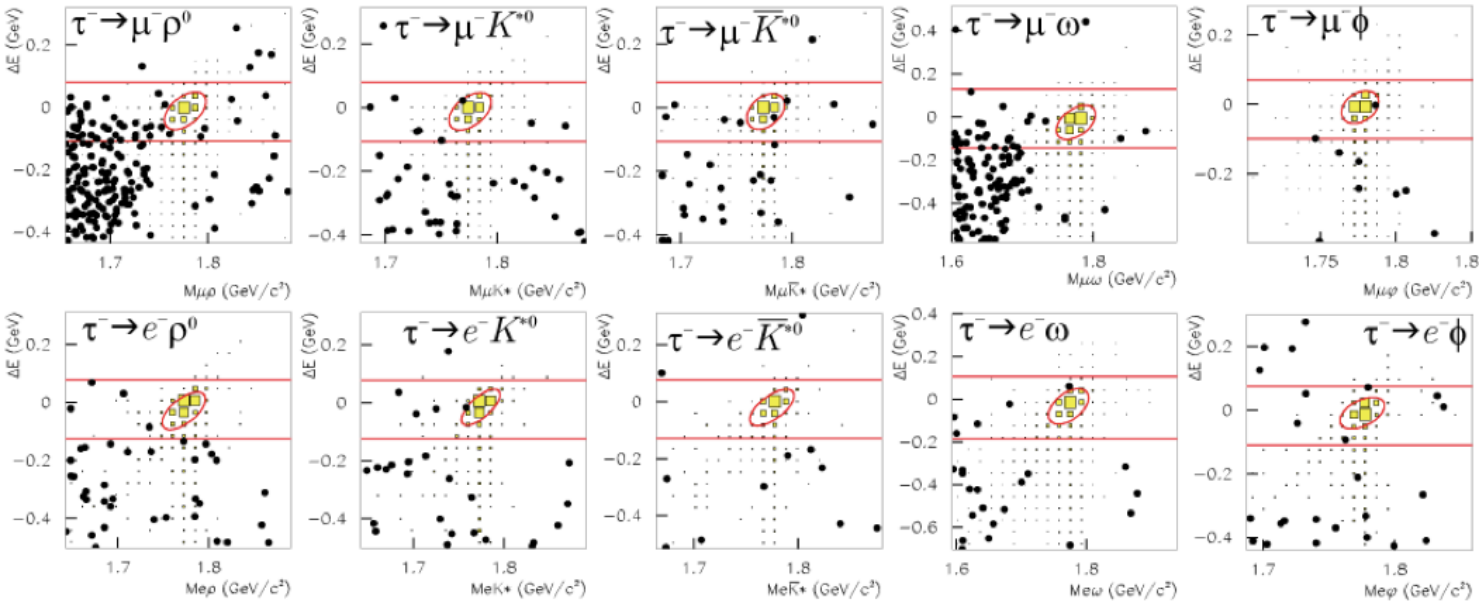
$\tau \to l V^0$ ($V^0 = \rho^0, K^{*0}, \bar{K}^{*0}, \omega, \phi$)

Phys. Lett. B699, 251 (2011)

- Based on 845/fb
- 2/3 particle masses required to be consistent with the vector meson mass
- Dominant backgrounds: hadronic τ decays and qq (μ modes), two photon (e modes)
- 1 event in $\mu\phi$ and μK^{*0}, zero events in other modes

Mode	ε (%)	N_{BG}	σ_{syst} (%)	$\mathcal{B}_{exp}$	N_{obs}	$\mathcal{B}_{obs}$
$\tau^- \to \mu^- \rho$	7.09	1.48 ± 0.35	5.3%	3.1	0	1.2
$\tau^- \to e^- \rho$	7.58	0.29 ± 0.15	5.4%	2.3	0	1.8
$\tau^- \to \mu^- \phi$	3.21	0.06 ± 0.06	5.8%	4.9	1	8.4
$\tau^- \to e^- \phi$	4.18	0.47 ± 0.19	5.9%	4.3	0	3.1
$\tau^- \to \mu^- \omega$	2.38	0.72 ± 0.18	6.1%	7.9	0	4.7
$\tau^- \to e^- \omega$	2.92	0.30 ± 0.14	6.2%	5.9	0	4.8
$\tau^- \to \mu^- K^{*0}$	3.39	0.53 ± 0.20	5.5%	5.4	1	7.2
$\tau^- \to e^- K^{*0}$	4.37	0.29 ± 0.14	5.6%	3.9	0	3.2
$\tau^- \to \mu^- \bar{K}^{*0}$	3.60	0.45 ± 0.17	5.5%	4.9	1	7.0
$\tau^- \to e^- \bar{K}^{*0}$	4.41	0.08 ± 0.08	5.6%	3.6	0	3.4

90% C.L. U.Ls. (1.2 - 8.4) x 10^{-8}

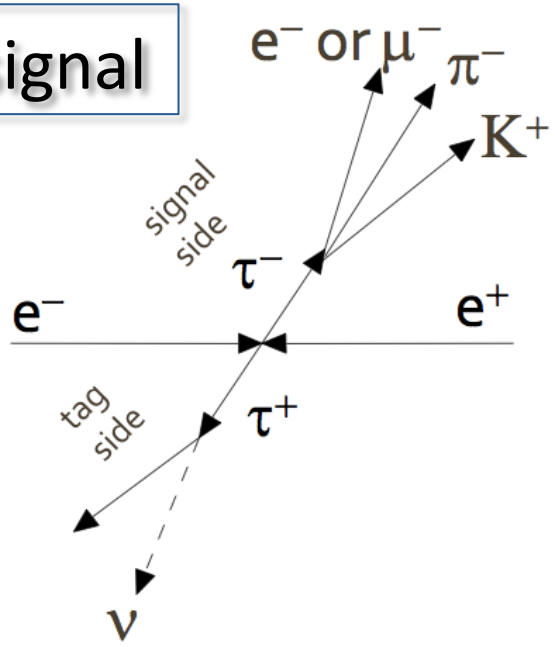


$\tau \to lhh'$

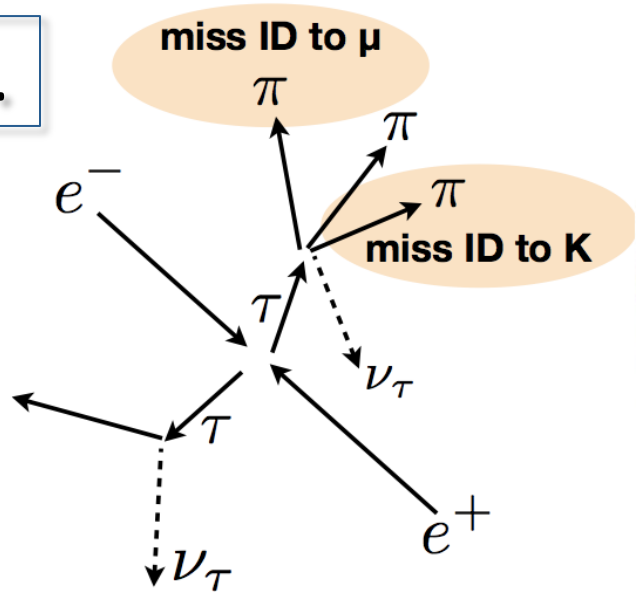
Phys. Lett. B719, 346 (2013)

- Based on 854/fb of Belle data
- 14 modes are searched for (h, h' = π,K)
  - $\tau^- \to l^- h^+ h'^-$ (8 lepton flavour violating modes)
  - $\tau^- \to l^+ h^- h'^-$ (6 lepton number violating modes)

signal



ττ bkgrd.



Background rejection

- μπK mode

  M^2_{miss} vs. p_{miss} 2d cut
  75% efficient while 75% of the BG is rejected

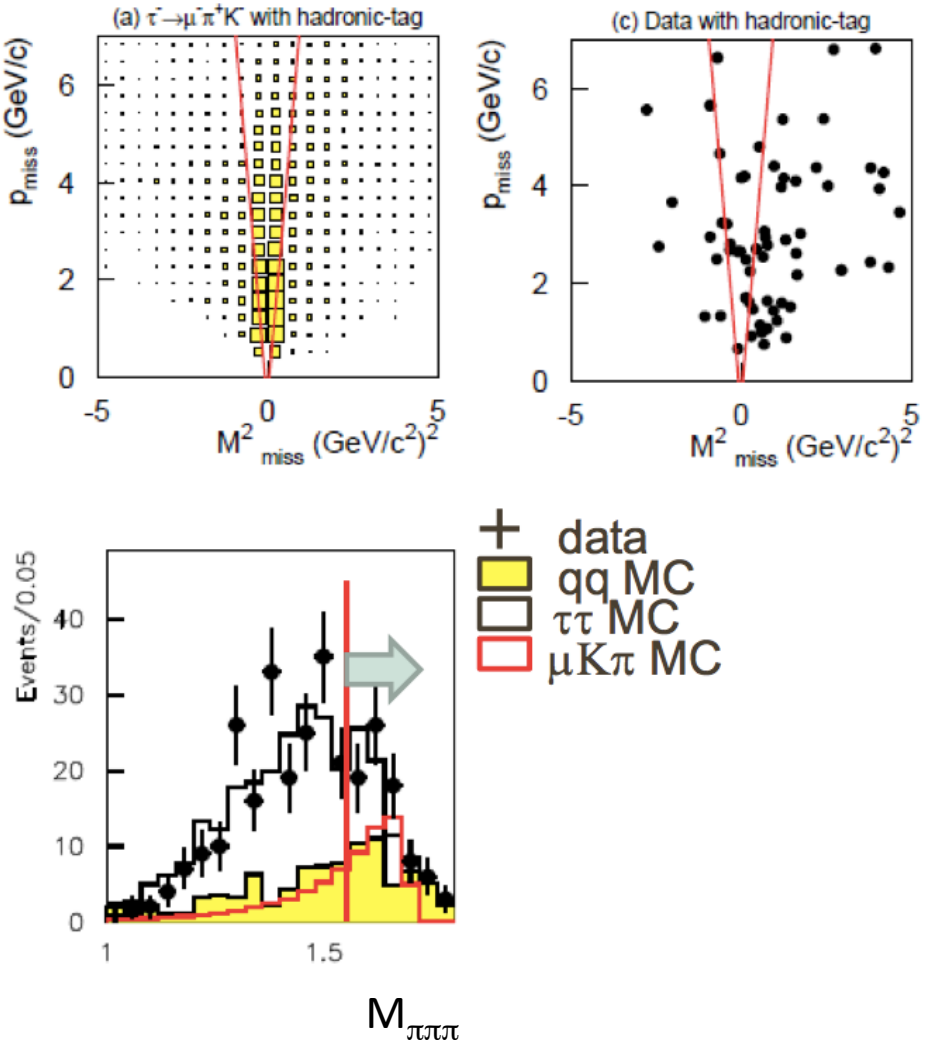
- ehh', μππ and μKK modes

  M^2_{miss} selection
  90% efficient while 50% of the BG is rejected

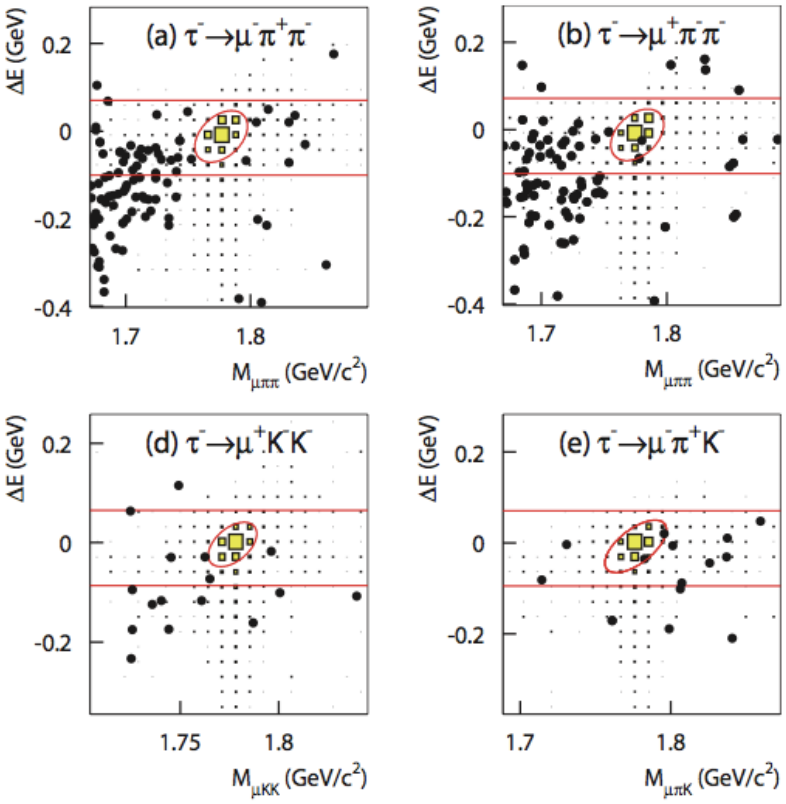
- πππν veto (for μπK mode)

  Assign ππ mass for selected events

  $M_{\pi\pi\pi} > 1.52$ GeV/c2
  65% efficient, 65% of the BG rejected



Results $\tau \to lhh'$



- In the signal window
  - 1 event in $\mu^+\pi^-\pi^-$ and $\mu^-\pi^+K^-$
  - Zero events in the other modes

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	5.7	0	1.87	2.1
$\tau^- \to \mu^+\pi^-\pi^-$	6.55	0.33 ± 0.16	5.6	1	4.01	3.9
$\tau^- \to e^-\pi^+\pi^-$	5.45	0.55 ± 0.23	5.7	0	1.94	2.3
$\tau^- \to e^+\pi^-\pi^-$	6.56	0.37 ± 0.19	5.5	0	2.10	2.0
$\tau^- \to \mu^-K^+K^-$	2.85	0.51 ± 0.19	6.1	0	1.97	4.4
$\tau^- \to \mu^+K^-K^-$	2.98	0.25 ± 0.13	6.2	0	2.21	4.7
$\tau^- \to e^-K^+K^-$	4.29	0.17 ± 0.10	6.7	0	2.29	3.4
$\tau^- \to e^+K^-K^-$	4.64	0.06 ± 0.06	6.5	0	2.39	3.3
$\tau^- \to \mu^-\pi^+K^-$	2.72	0.72 ± 0.28	6.2	1	3.65	8.6
$\tau^- \to e^-\pi^+K^-$	3.97	0.18 ± 0.13	6.4	0	2.27	3.7
$\tau^- \to \mu^-K^+\pi^-$	2.62	0.64 ± 0.23	5.7	0	1.86	4.5
$\tau^- \to e^-K^+\pi^-$	4.07	0.55 ± 0.31	6.2	0	1.97	3.1
$\tau^- \to \mu^+K^-\pi^-$	2.55	0.56 ± 0.21	6.1	0	1.93	4.8
$\tau^- \to e^+K^-\pi^-$	4.00	0.46 ± 0.21	6.2	0	2.03	3.2

90% C.L. upper limits

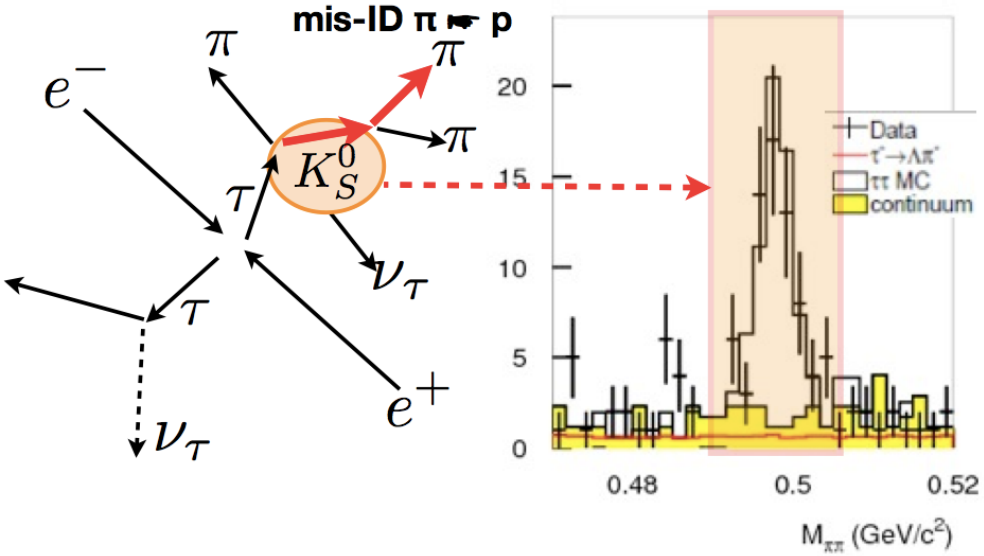
$Br(\tau \to lhh') < (2.0\text{-}8.6) \times 10^{-8}$

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

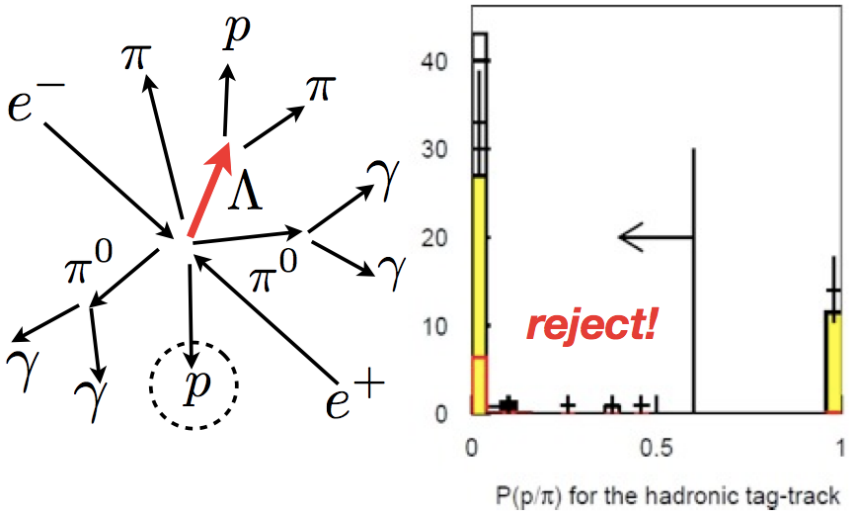
preliminary

- Based on 904/fb of Belle data
- 4 modes are searched for
  - $\tau^- \to \bar{\Lambda} h^-$ (B-L conserving)
  - $\tau^- \to \Lambda h^-$ (B-L violating)
- Select three hadrons on signal side, require Λ vertex

K_S veto

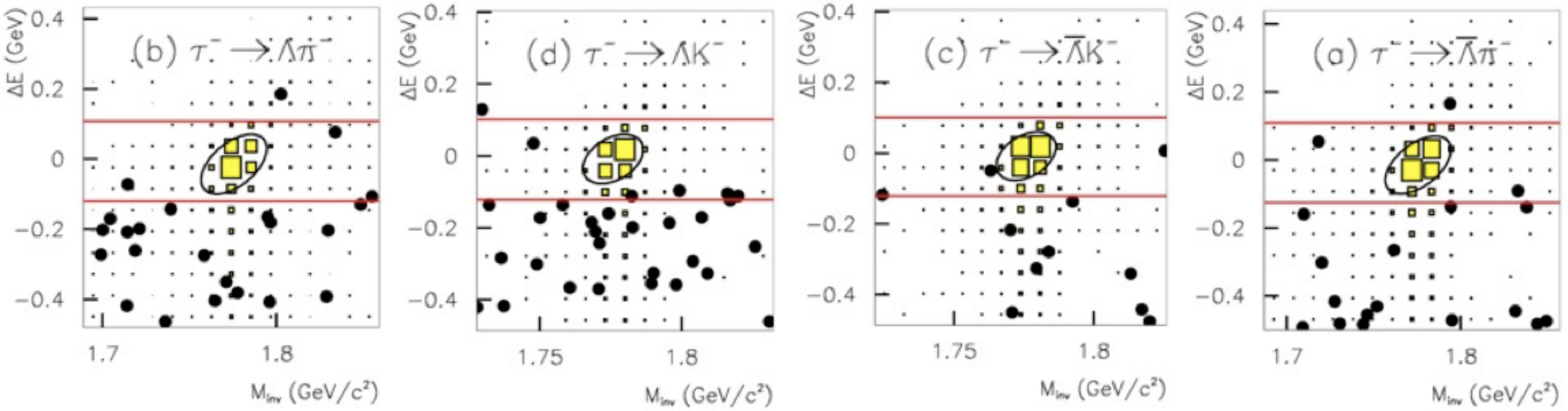


Proton veto tag side



Results $\tau \to \Lambda h, \bar{\Lambda} h$

preliminary

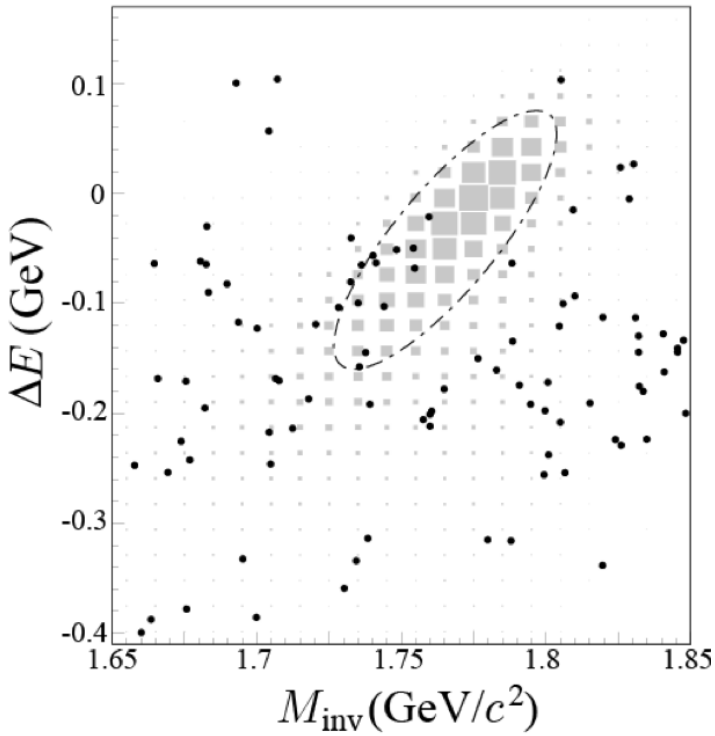


	Mode	$\epsilon(\%)$	$N_{\rm BG}$	$\sigma_{\rm syst.}$	$N_{\rm obs}$	s_{90}	$\mathcal{B}(10^{-8})$
B-L conv.	$\tau^- \to \bar{\Lambda}\pi^-$	4.80	0.21 ± 0.15	8.2	0	2.3	< 2.8
	$\tau^- \to \bar{\Lambda}K^-$	4.39	0.31 ± 0.18	8.2	0	2.3	< 3.1
B-L viol.	$\tau^- \to \Lambda\pi^-$	4.11	0.31 ± 0.14	8.6	0	2.2	< 3.0
	$\tau^- \to \Lambda K^-$	3.16	0.42 ± 0.19	8.6	0	2.1	< 4.2

Old result for $\tau \to \mu\gamma$

Phys. Lett. B666, 16 (2008)

- Based on 545/fb data
- Main backgrounds: $\tau \to \mu\nu\nu$ and dimuon events with ISR
- 94 events found in the 5σ signal region, while expecting (88 +/- 7)
- 90% C.L. upper limits
  - Expected: 7.8×10^{-8}
  - Observed: 4.5×10^{-8}

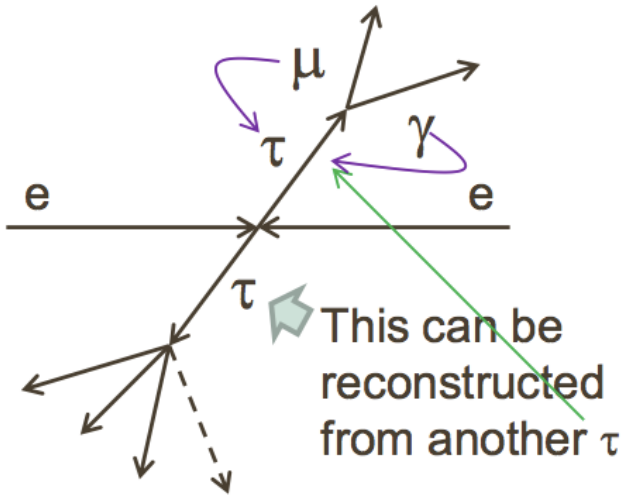


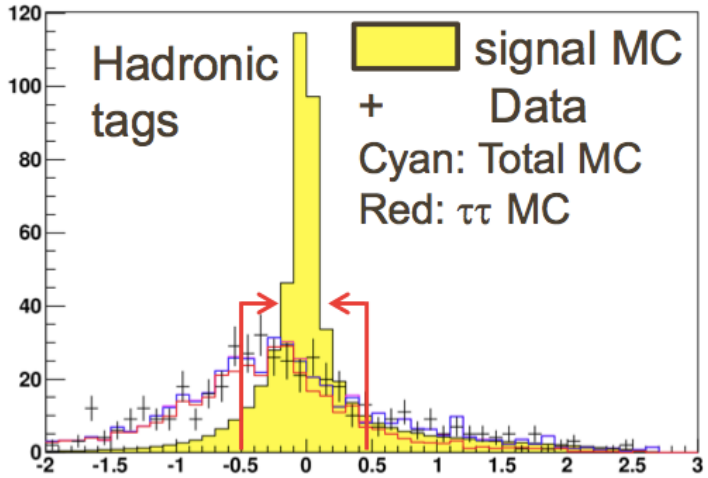
Now updating to the full Belle dataset (980/fb)…

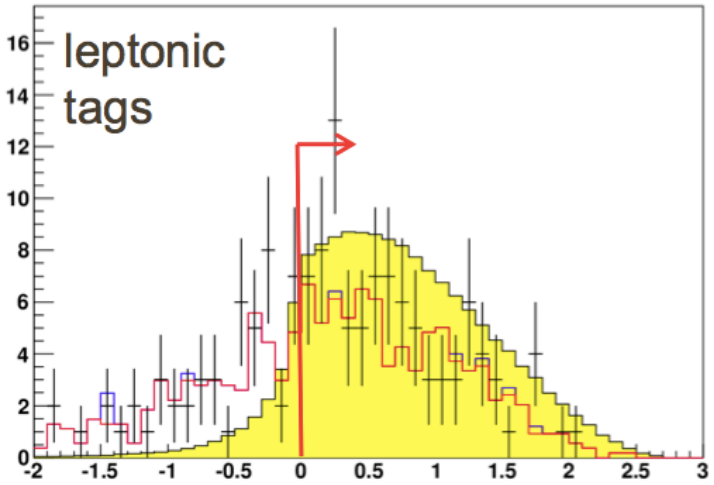
Tag-side missing mass

- Reconstructed τ momentum (from the signal side): p_τ
- Momentum sum of all particles associated to the tag side: p_{tag}
- Missing mass

$$M^2_{miss} = (p_\tau - p_{tag})^2$$

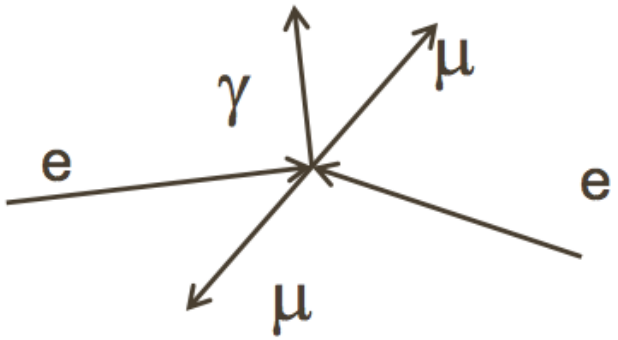


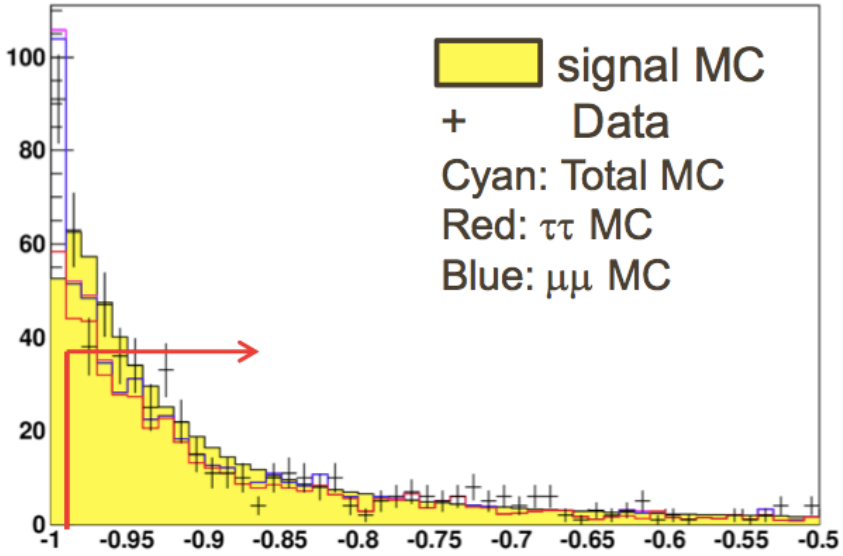




$e^+e^- \to \mu^+\mu^-\gamma$ rejection

- Some $e^+e^- \to \mu^+\mu^-\gamma$ events survive due to the muon ID inefficiency (μ veto on the tag-side)
- Additional requirement: In the eeγ rest frame, the muons from this process are back-to-back





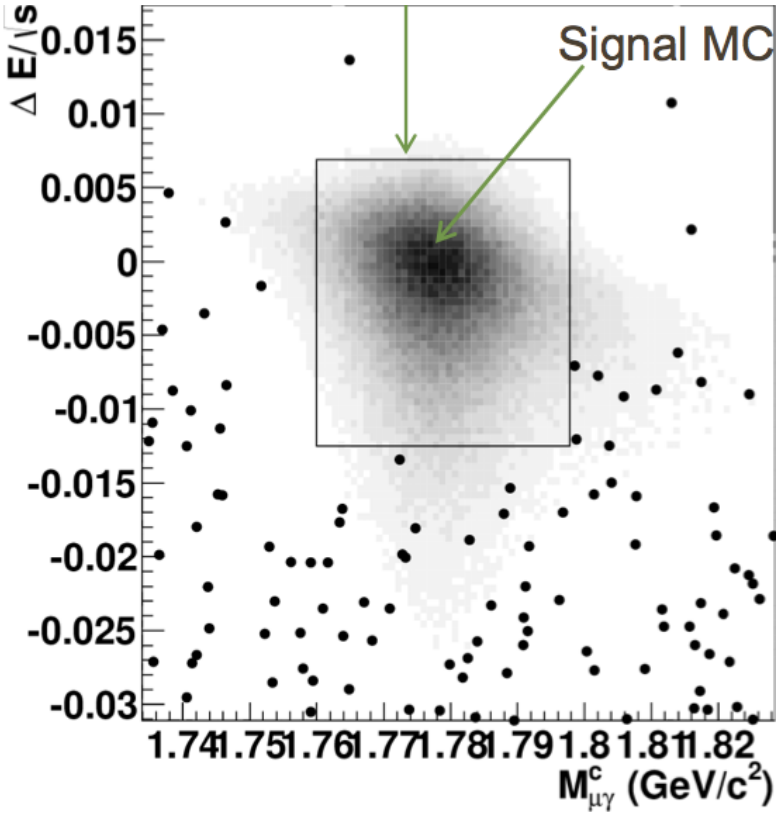
cosα = opening angle between signal- and tag-side tracks in e-e-γ rest frame.

Expected results for $\tau \to \mu\gamma$

preliminary

- New analysis
  - 6.5% efficiency
  - 115 +/- 11 background events expected
  - About a factor of 1.5 increase in sensitivity

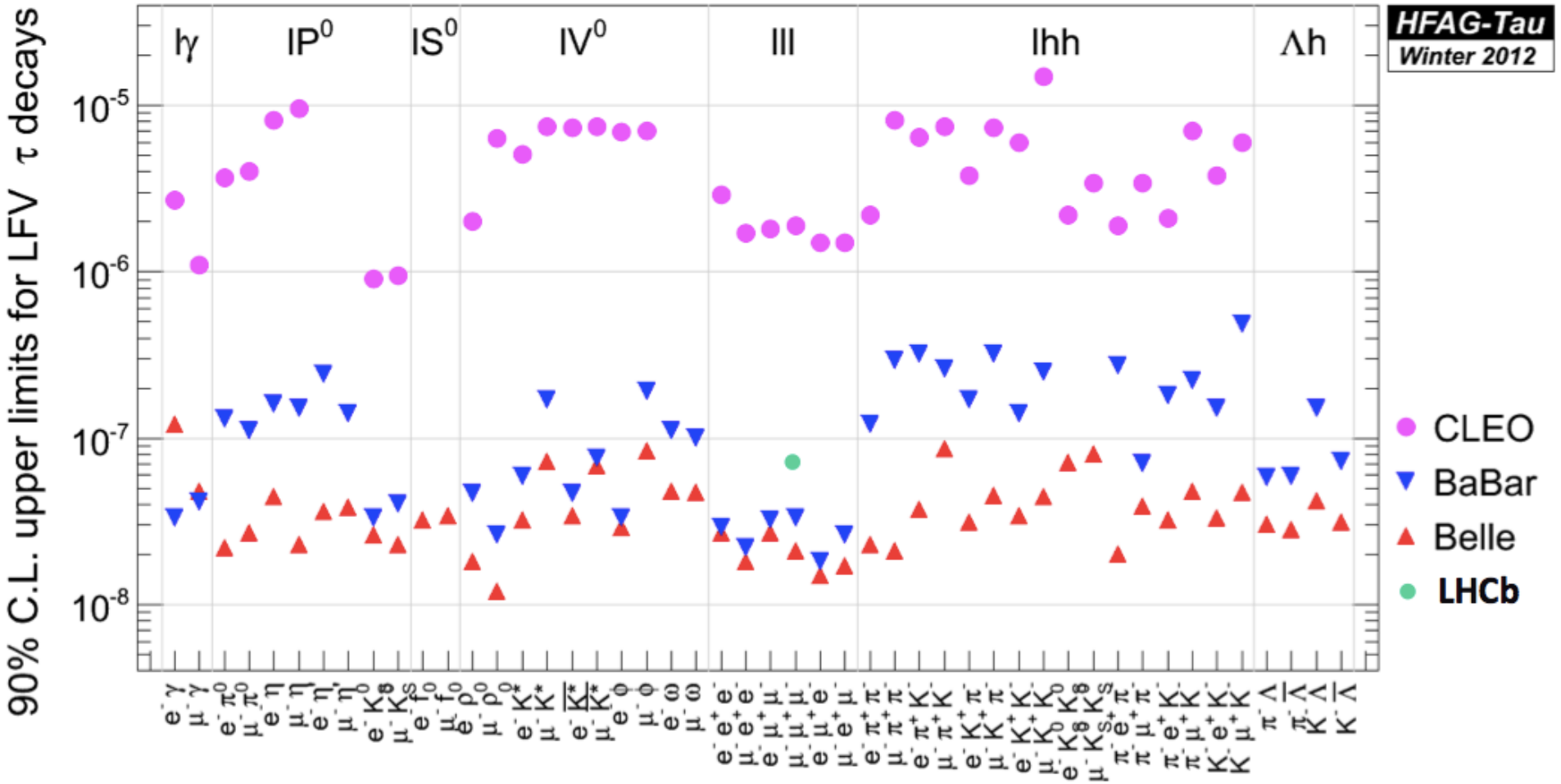
Blinded region



	Previous	New analysis
Lum.	545fb^{-1}	980fb^{-1}
Eff.	6.1%	6.5%
#BG	94	115
Expected UL	7.8×10^{-8}	5.3×10^{-8}

preliminary

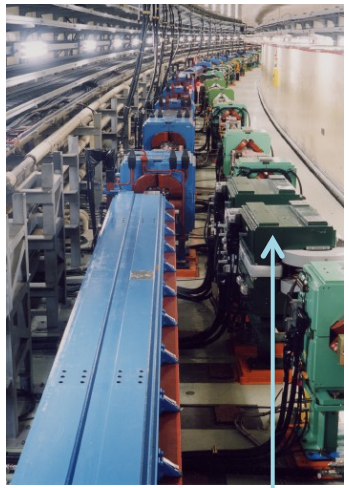
Summary Belle τ LFV results



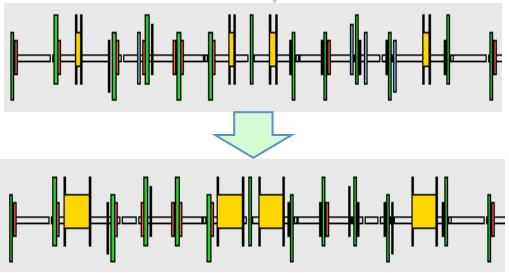
48 modes searched for, U.L.s around ~10^{-8}

Belle II

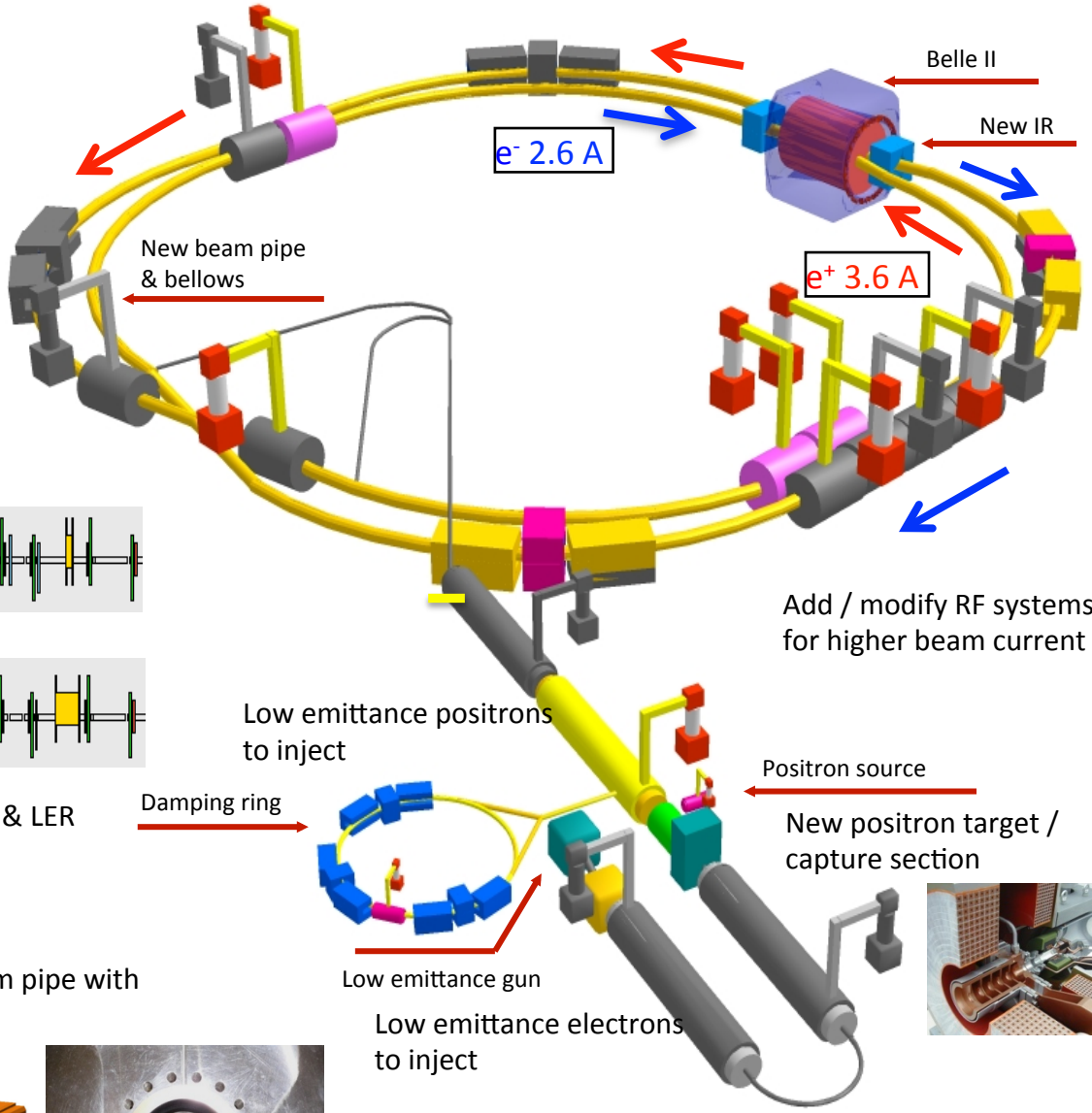
From KEKB to SuperKEKB

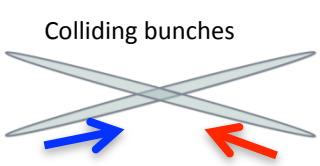


Replace short dipoles with longer ones (LER)

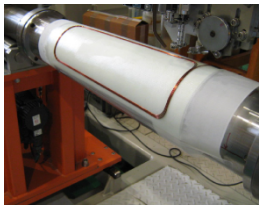


Redesign the lattices of HER & LER to squeeze the emittance



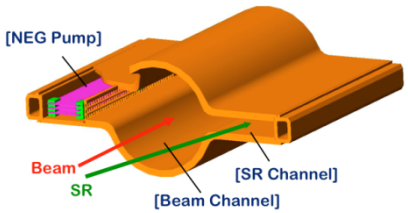


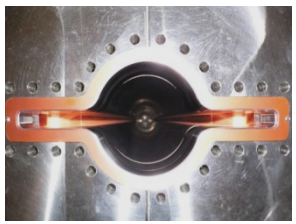
New superconducting / permanent final focusing quads near the IP



Add / modify RF systems for higher beam current

TiN-coated beam pipe with antechambers

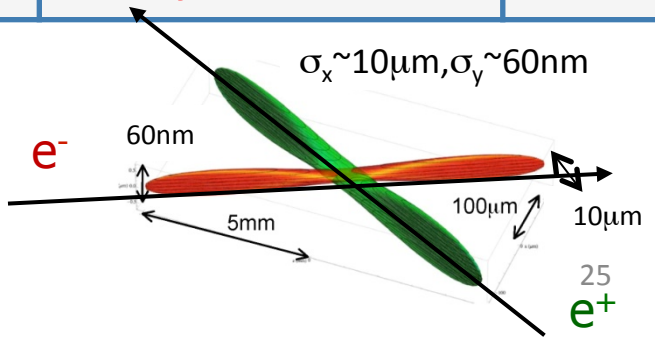




SuperKEKB machine parameters

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	ϕ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	5.0	nm
Emittance ratio	κ	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^*/ β_y^*	1200/5.9		32/0.27	25/0.31	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0886	0.0830	
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

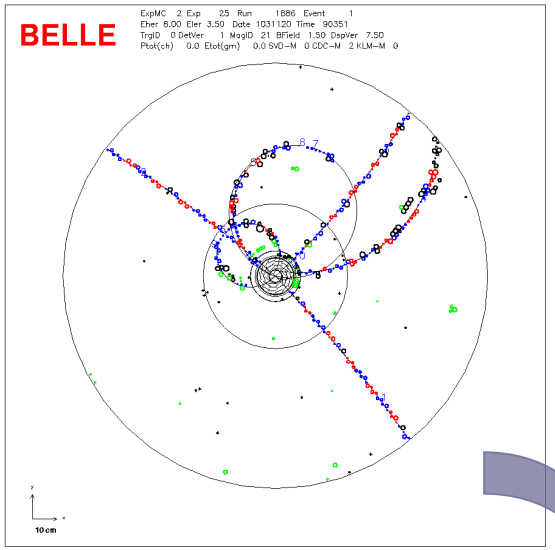
- Small beam size ("nano-beam") and higher currents to increase luminosity
- Smaller boost to improve LER lifetime

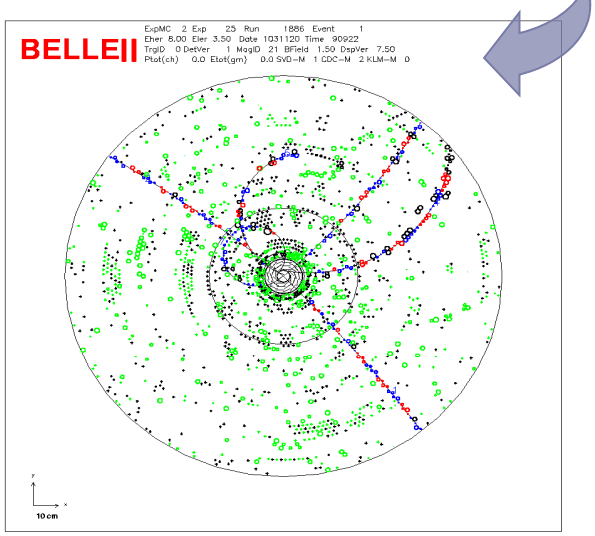


Detector upgrade

Critical issues at L= $8\times10^{35}/cm^2/s$:

- Higher background (×10-20)
  - radiation damage and higher occupancy
  - fake hits and pile-up noise in EM calorimeter
- Higher event rates (×10)
  - higher rate trigger (L1 trigg. 0.5→30 kHz)
  - DAQ, computing
- Target:
  - Maintain or improve over Belle I data quality in the high background/ high rate environment

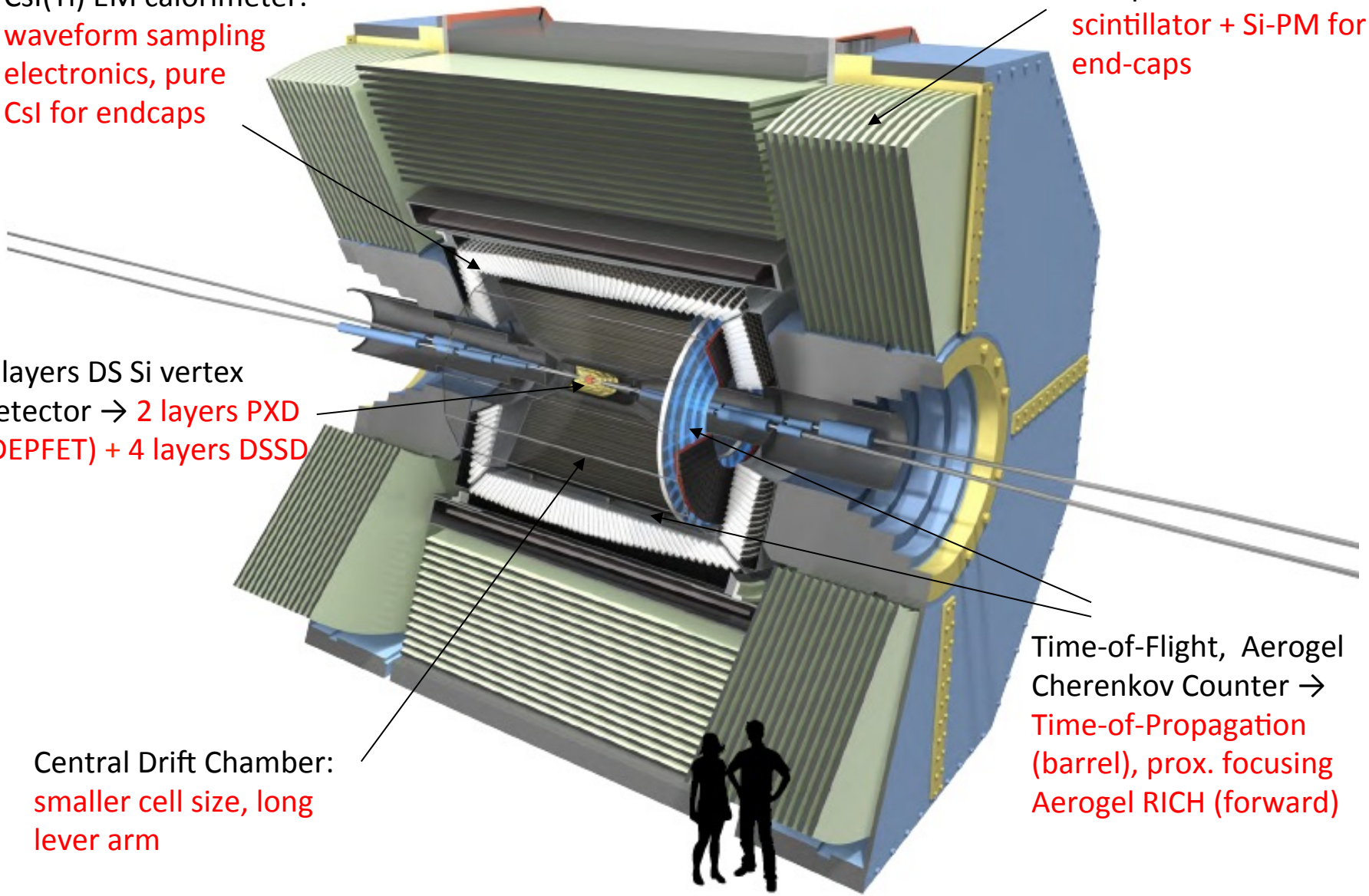




The Belle II detector

CsI(Tl) EM calorimeter: waveform sampling electronics, pure CsI for endcaps

RPC μ & K_L counter: scintillator + Si-PM for end-caps



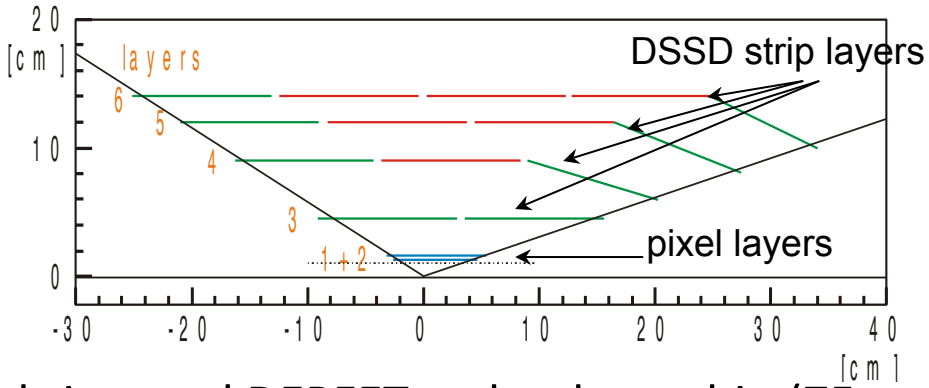
4 layers DS Si vertex detector → 2 layers PXD (DEPFET) + 4 layers DSSD

Time-of-Flight, Aerogel Cherenkov Counter → Time-of-Propagation (barrel), prox. focusing Aerogel RICH (forward)

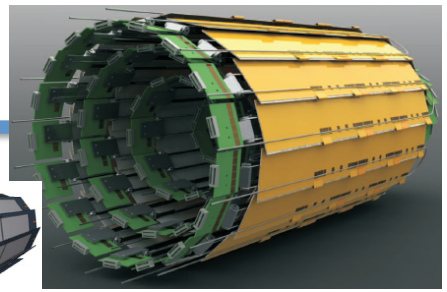
Central Drift Chamber: smaller cell size, long lever arm

Inner tracking (PXD, SVD)

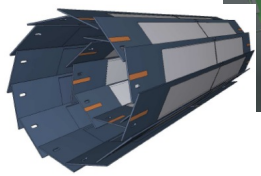
- PXD + SVD in Belle II (in Belle only strip layers)

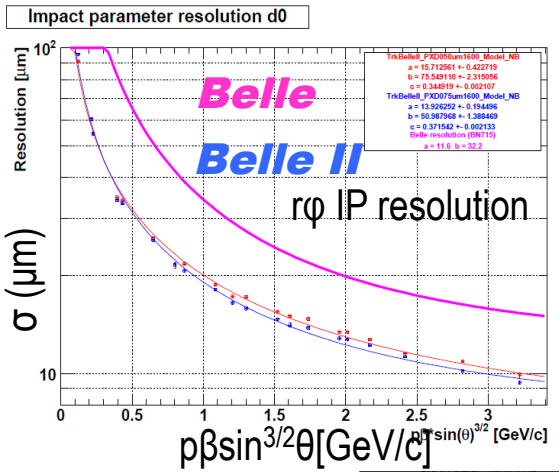


SVD

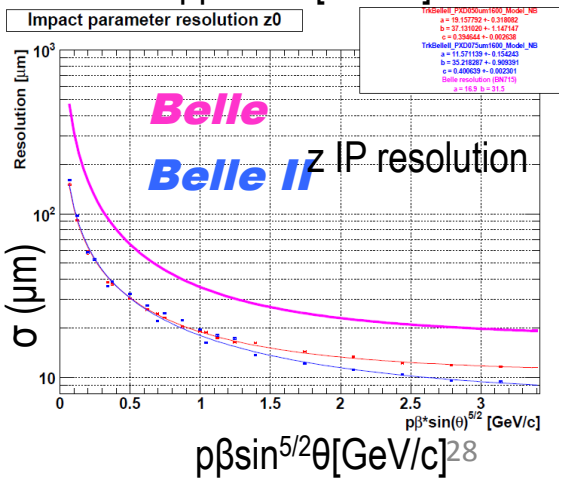


PXD





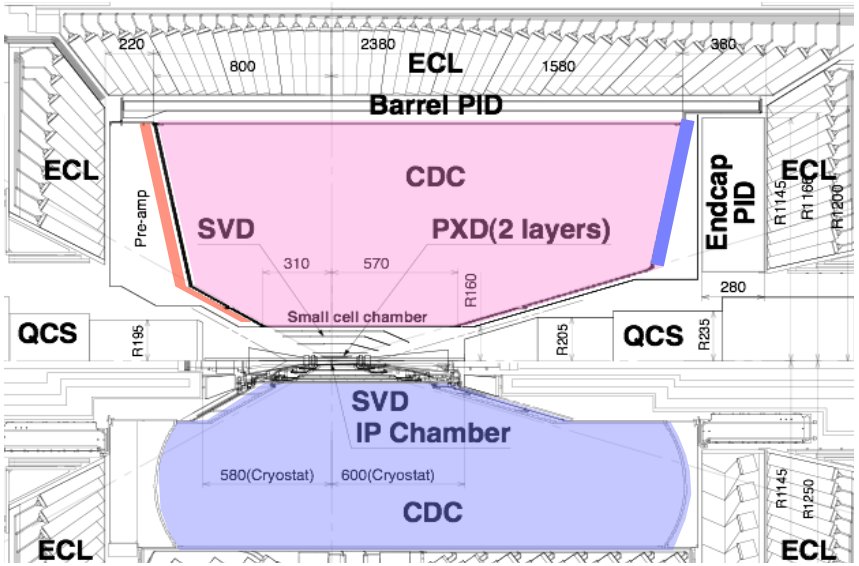
- Pixels in novel DEPFET technology: thin (75μm) sensors give little multiple scattering, close to the IR
- Fast strip readout with APV25 chip (50 ns), low occupancy
- Improved IP resolution and low momentum tracking (p_T < 100MeV), 30% larger eff. of $K_S \rightarrow \pi^+\pi^-$ with vertex info

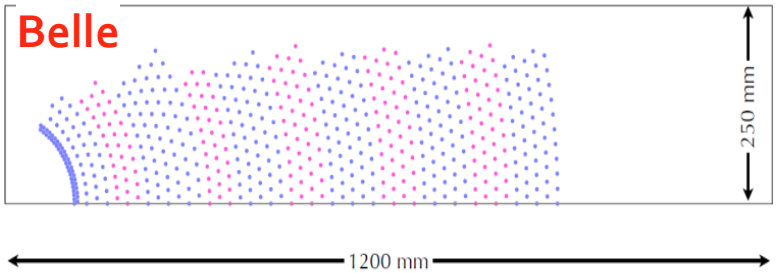


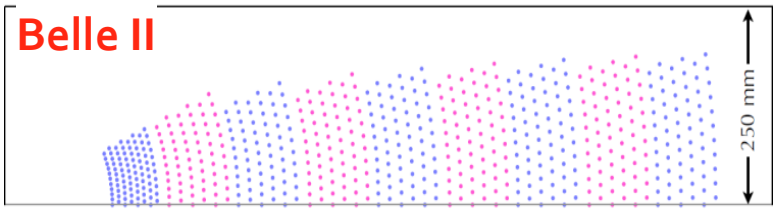
Mechanical mockup of pixel detector

DEPFET sensor

Central drift chamber (CDC)

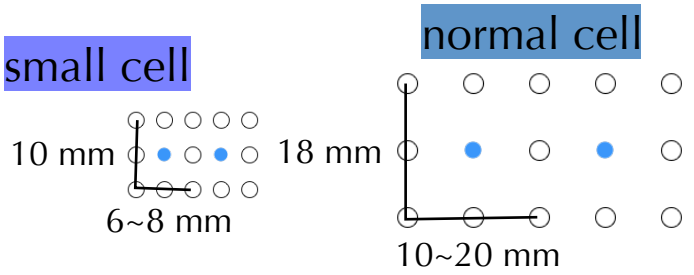






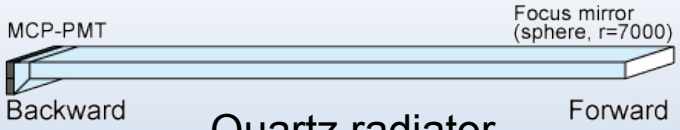
- Extended outer radius, longer lever arm → improved momentum and dE/dx resolutions
- Larger inner radius, smaller cells near beampipe → more background-hard

	Belle	Belle II
inner most sense wire	r=88mm	r=168mm
outer most 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)



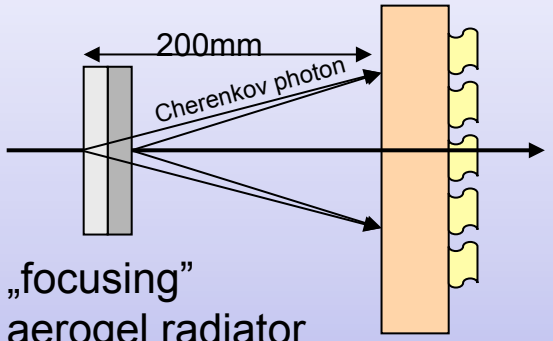
Particle Identification (TOP, ARICH)

Barrel PID: Time of Propagation Counter

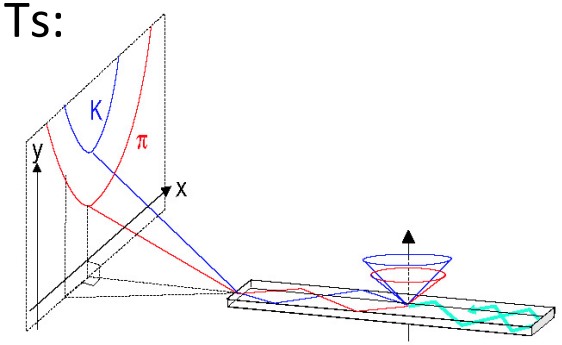


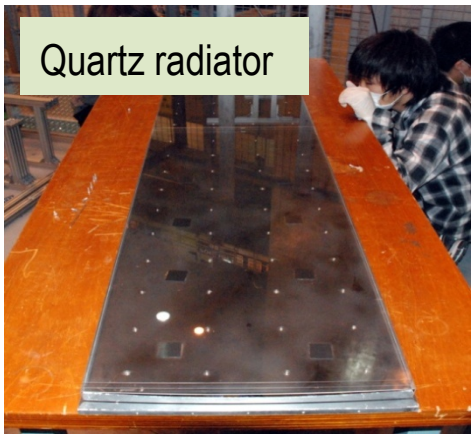
Small expansion block
Hamamatsu MCP-PMT (measure t, x and y)

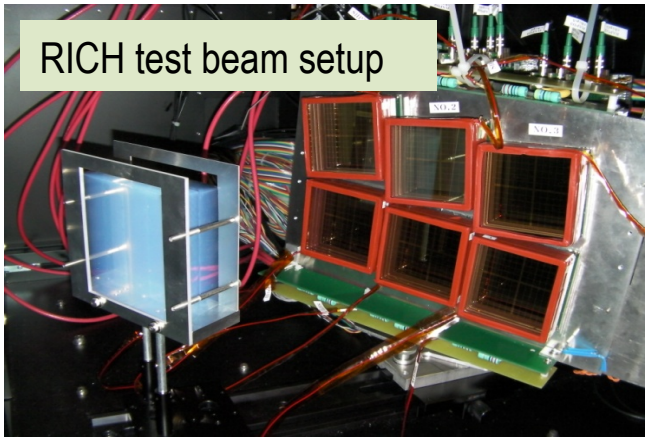
Endcap PID: Aerogel RICH

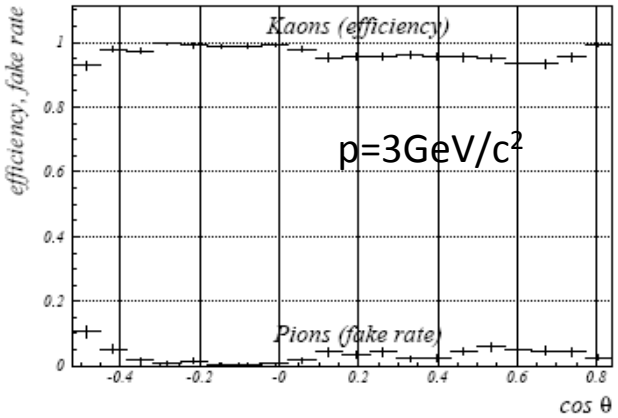


- TOP: reconstructs Cherenkov rings using 3D info from PMTs: x,y and time of photon propagation (40 ps resolution)
- ARICH: measures Cherenkov angle. Inhomogeneous aerogel radiator to improve photon resolution
- Improved K/π separation in wide momentum range



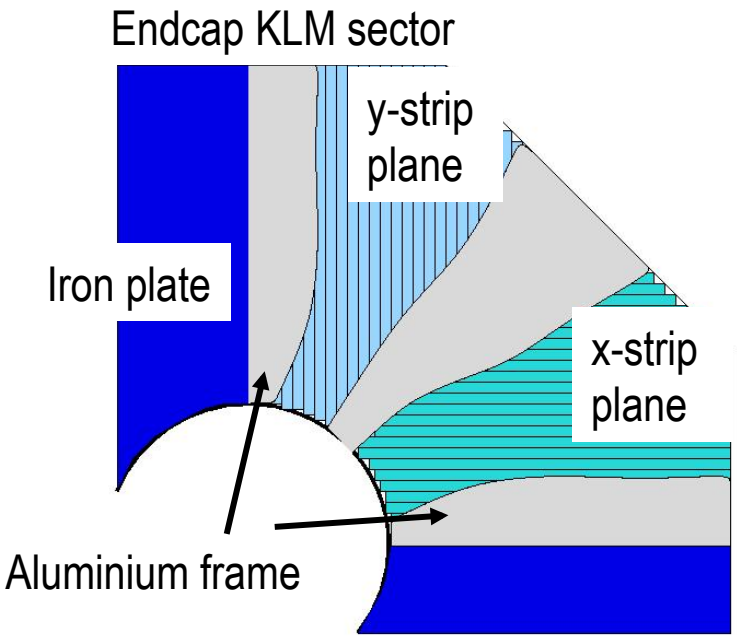


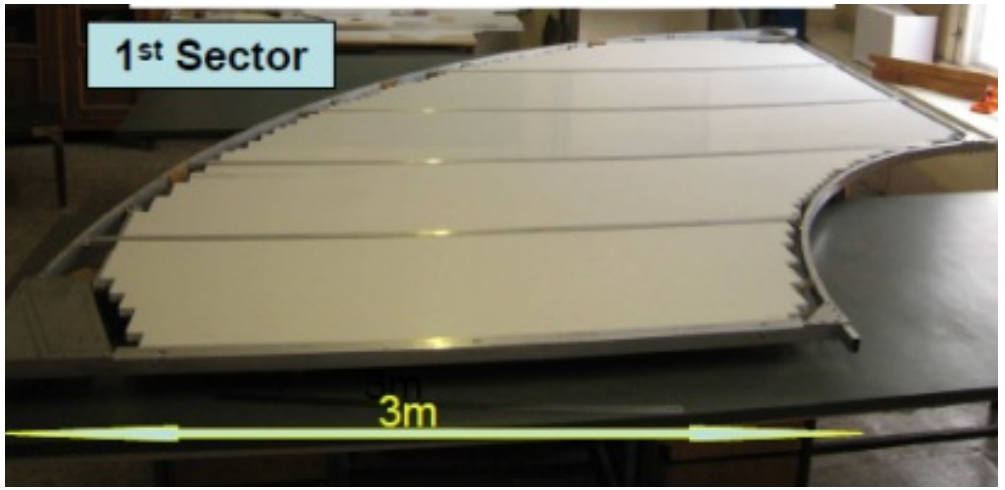


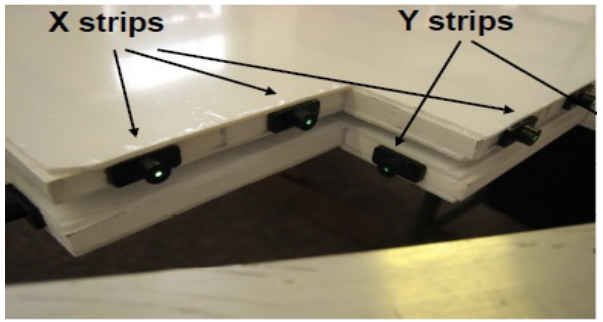


K_L and muon detection

- End-caps upgrade: Resistive Plate Chambers → scintillator- based detector
- 20x background increase in RPCs (worse shielding of neutrons along beams)
- Scintillators + SiPM: better beam-background tolerance
- Barrel KLM: some RPC layers may be replaced as background increases with luminosity





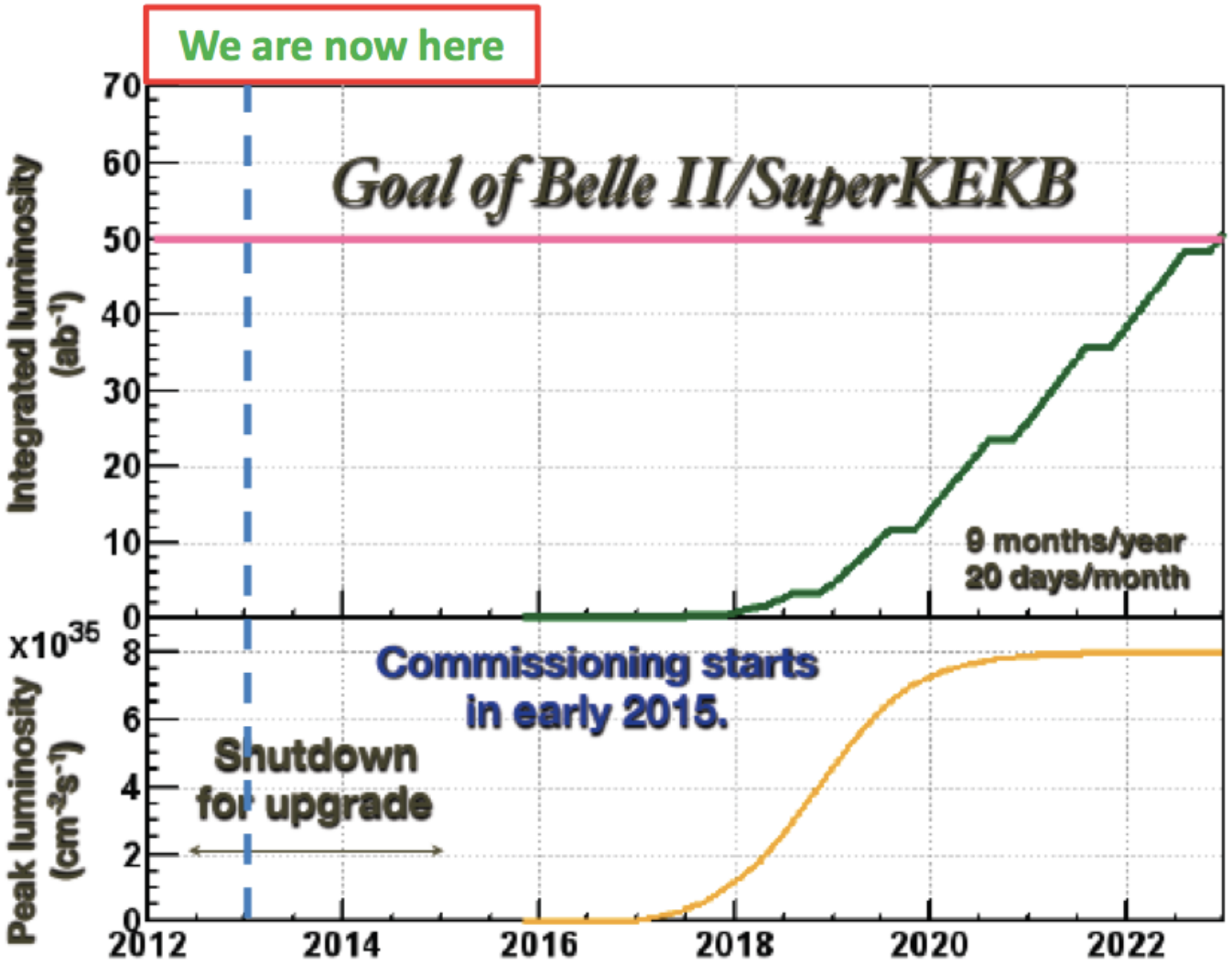


The Belle II collaboration*)

*) This slide is slightly outdated. Now we have members from 21 countries.

~400 members with ~150 participants from Europe

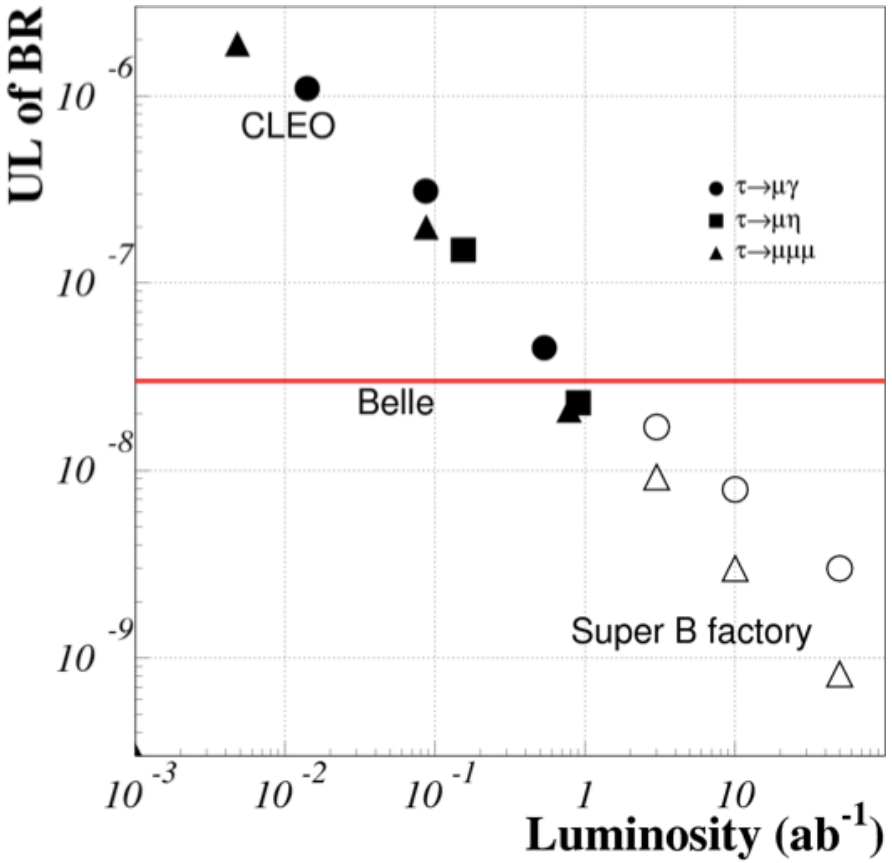
Expected luminosity



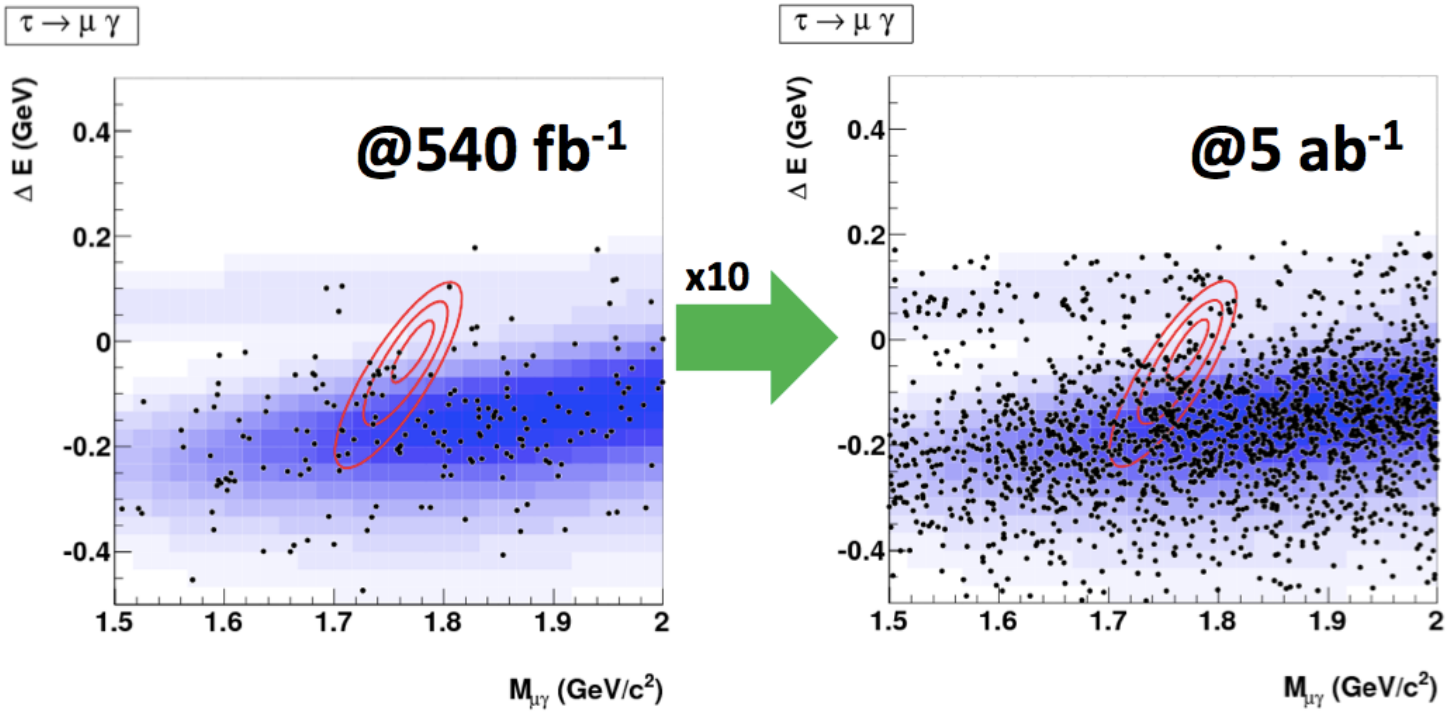
50/ab by the end of 2022

Prospects for τ LFV at Belle II

- Belle II will collect ~10^{11} τ-leptons (50/ab)
- Sensitivity depends on the background level
  - $\tau \rightarrow 3l$ still clean even at Belle II
  - For $\tau \rightarrow \mu\gamma$ better understanding of backgrounds, signal resolution and intelligent selections are needed



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



180 BG events in total

1800 BG events in total

The upper half ellipse will be the main signal search field at Belle II

Summary

Summary

- Belle
  - The Belle data sampe contains ~10^9 τ-pairs, the world's largest sample
  - 48 τ LFV modes have been studied and 90% C.L. upper limits in the O(10^{-8}) have been set
  - The final analysis of $\tau \rightarrow e\gamma/\mu\gamma$ is ongoing and final results will come soon
  - There are also results on CLFV in B and D decays (see backup slides)
- Belle II
  - Now the KEK B factory (KEKB and Belle) undergoes a major upgrade to become a Super B factory (SuperKEKB and Belle II)
  - The start of the physics run is foreseen for 2016, the luminosity goal is 50/ab by 2022, or ~5 x 10^{10} τ-pairs
  - This will allow to probe τ LFV at the level of O(10^{-9})

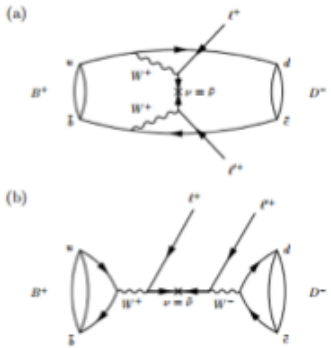
Backup

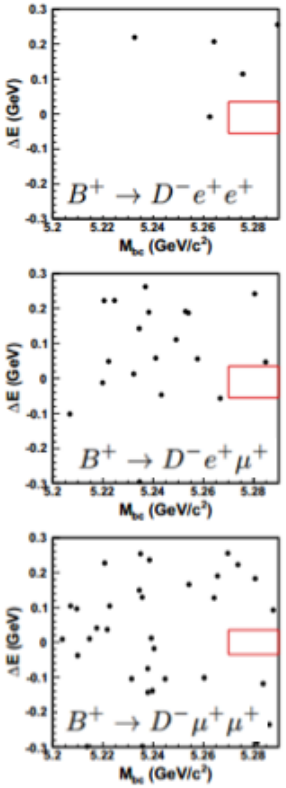
CLFV in B and D decays

$B^+ \to D^- l^+ l'^+$ (first measurement)

Phys. Rev. D84 (2011) 071106

Theory: $\mathcal{B}(B^+ \to D^- l^+ l'^+) > 10^{-7}$





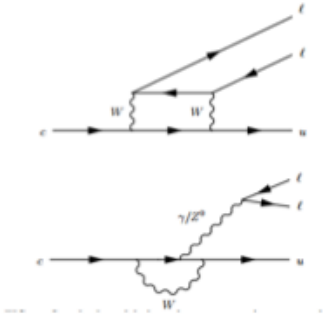
$$\Delta E = E_B - E_{beam}$$

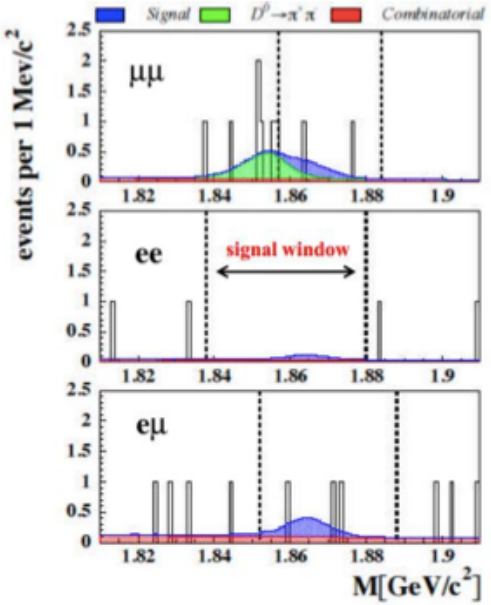
$$M_{bc} = \sqrt{E_B^2 - p_B^2}$$

Mode	ϵ [%]	N_{obs}	N_{exp}^{bkg}	U.L. [10^{-6}]
$B^+ \to D^- e^+ e^+$	1.2	0	0.18±0.13	< 2.6
$B^+ \to D^- e^+ \mu^+$	1.3	0	0.83±0.29	< 1.8
$B^+ \to D^- \mu^+ \mu^+$	1.9	0	1.44±0.43	< 1.0

$D^0 \to l^+ l'^-$

PR D81 (2010) 091102R





No evidence for signal observed!

	$D^0 \to \mu^+\mu^-$	$D^0 \to e^+e^-$	$D^0 \to e^\pm\mu^\mp$
N_{bkg}	3.1 ± 0.1	1.7 ± 0.2	2.6 ± 0.2
N	2	0	3
$\epsilon_{\ell\ell}$[%]	7.02 ± 0.34	5.27 ± 0.32	6.24 ± 0.27
$\epsilon_{\pi\pi}$[%]	12.42 ± 0.10	10.74 ± 0.09	11.22 ± 0.09
$f[10^{-8}]$	$4.84(1 \pm 5.3\%)$	$6.47(1 \pm 6.4\%)$	$5.48(1 \pm 4.8\%)$
UL [10^{-7}]	1.4	0.79	2.6