Status and Future Prospects for Charged Lepton Flavor Violation Searches at B Factories and Belle-II

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for the Belle II collaboration

KEK IPNS

25/08/2016, NuFact2016, Qyu Nhon, Vietnam

Introduction to tau LFV

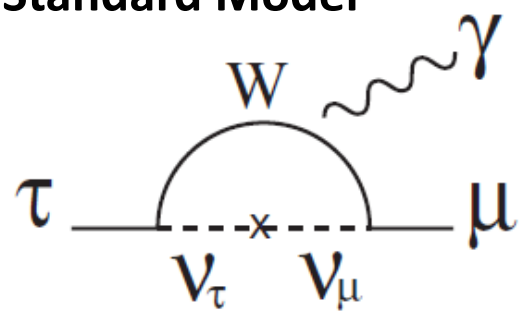
- **Lepton Flavor Violation (LFV)** is highly suppressed in the Standard Model (SM) even if neutrino oscillation is taken
  - Br < O(10^{-54}) => Experimentally unreachable
- **Many extensions to SM** predict to enhance LFV to be observable in current experiment facilities: Br ~O(10^{-8})

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

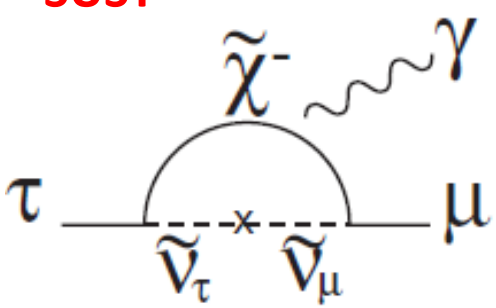
- Tau lepton - the heaviest charged lepton coupling to the NP

=> 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^{-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}

Numbers correspond to the most optimistic case

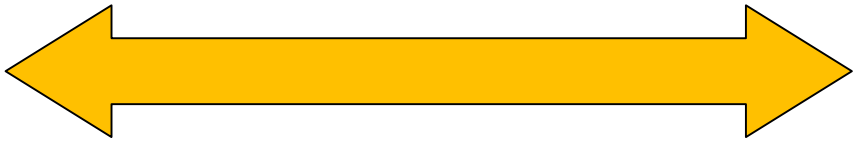
- B factory sensitivity (~10^{-8}) reaches a possible region to τ LFV!

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 ($\tau \to \mu\gamma$) @ Max	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

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

τ LFV search at Belle

B-factory at KEK

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

  => World highest peak luminosity
  - $\sigma(\tau\tau)\sim0.9$nb, $\sigma(bb)\sim1.1$nb

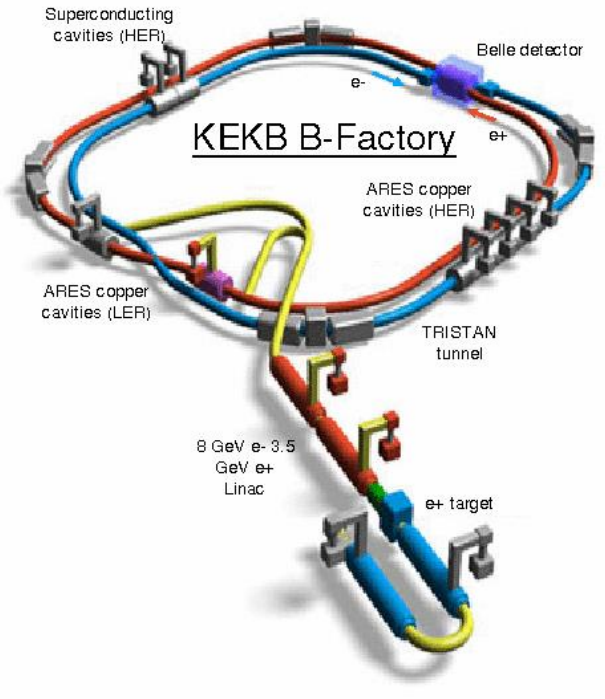
  => **B-factory is also τ factory!**
- Belle Detector:
  - Good track reconstruction
  - Good particle identification

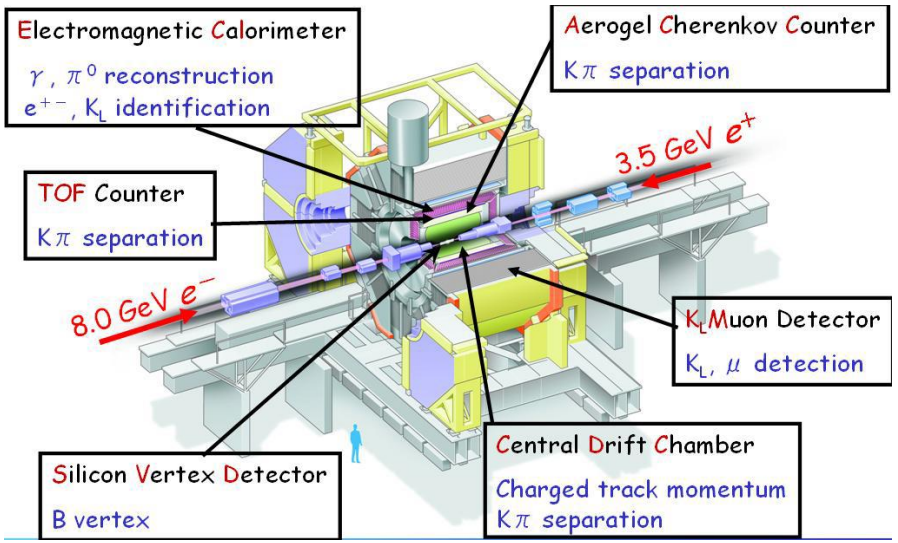
  => Lepton efficiency:90%

  Fake rate : O(0.1) % for e

  O(1)% for μ

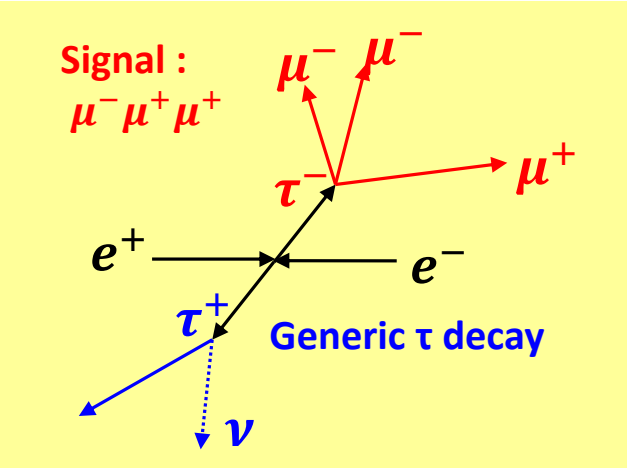
Collected ~10^9 τ pairs



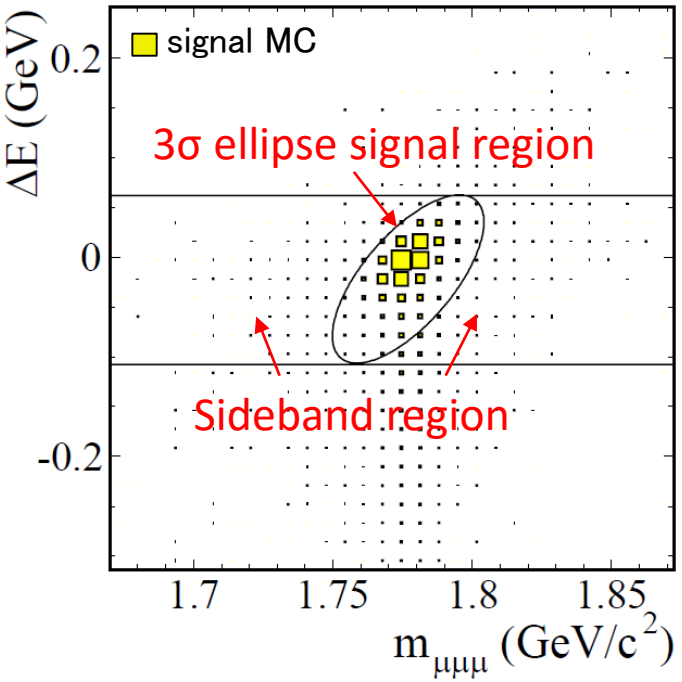


Analysis procedure

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

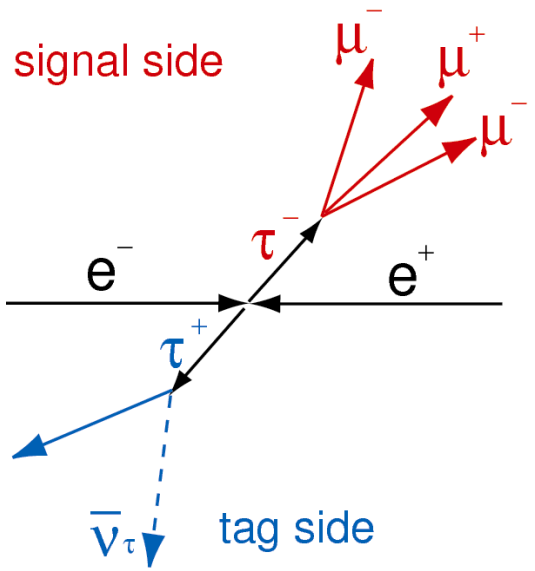


- Signal extraction: $m_{\mu\mu\mu} - \Delta E$ plane
  - $m_{\mu\mu\mu} = \sqrt{E^2_{\mu\mu\mu} - p^2_{\mu\mu\mu}} \sim m_\tau$
  - $\Delta E = E^{CM}_{\mu\mu\mu} - E^{CM}_{\text{beam}} \sim 0$
- Number of Background is estimated using sideband data and MC



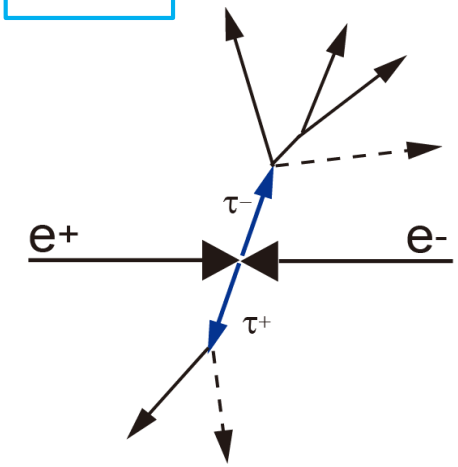
Signal and backgrounds

LFV Signal



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

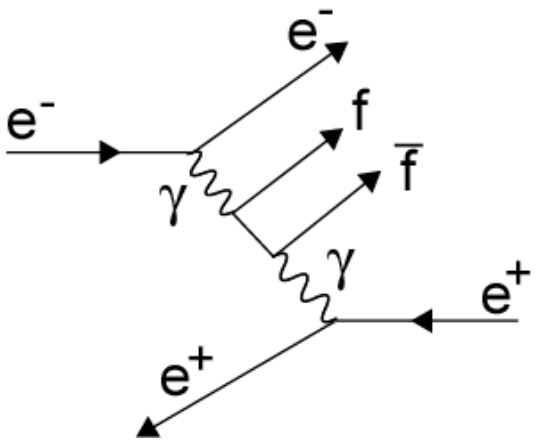
SM ττ



- Neutrinos in both sides
- Missing energy in signal side

2photon process

f = leptons, quarks



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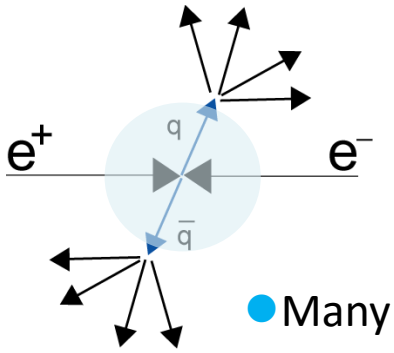
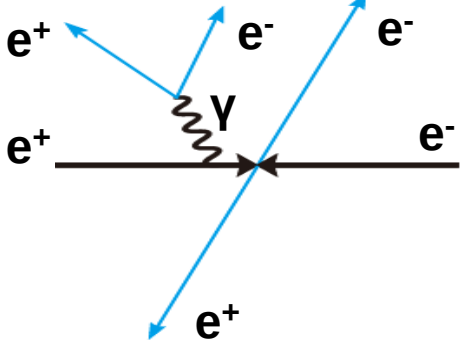


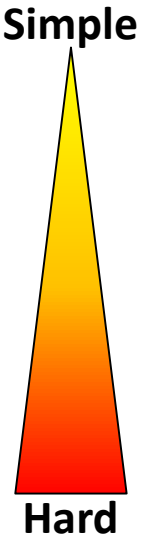
- Many tracks

radiative Bhabha



Analysis strategy

- Rare decay search :
  => Understand backgrounds and reduce as much as possible
- Search various decay modes:
  - $\tau \to \ell\ell\ell$
  - $\tau \to \ell K_s, \Lambda h$
  - $\tau \to \ell V_0 (\to hh')$
  - $\tau \to \ell P^0 (\to \gamma\gamma)$
  - $\tau \to \ell hh'$
  - $\tau \to \ell\gamma$

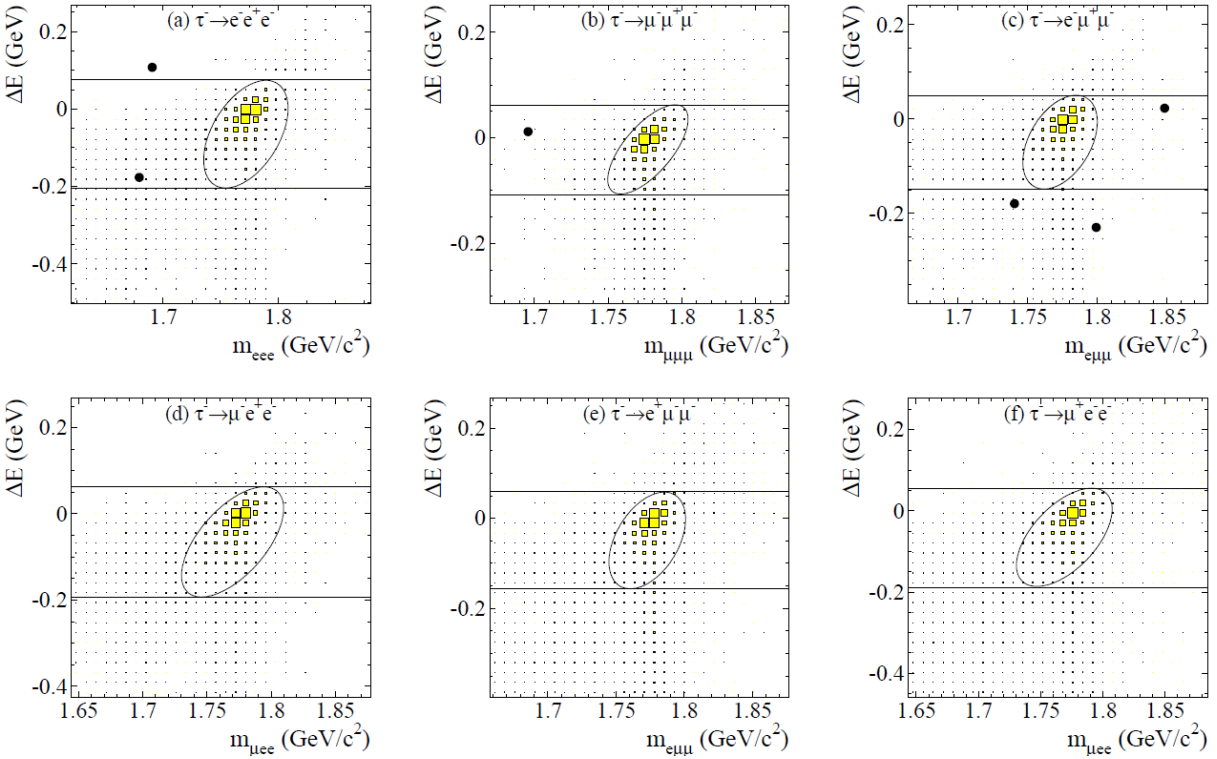


Difficulty of
background reduction

- Analyze the modes from simple selection to hard for background reduction
  - Provide feedback to next analysis of similar final state

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

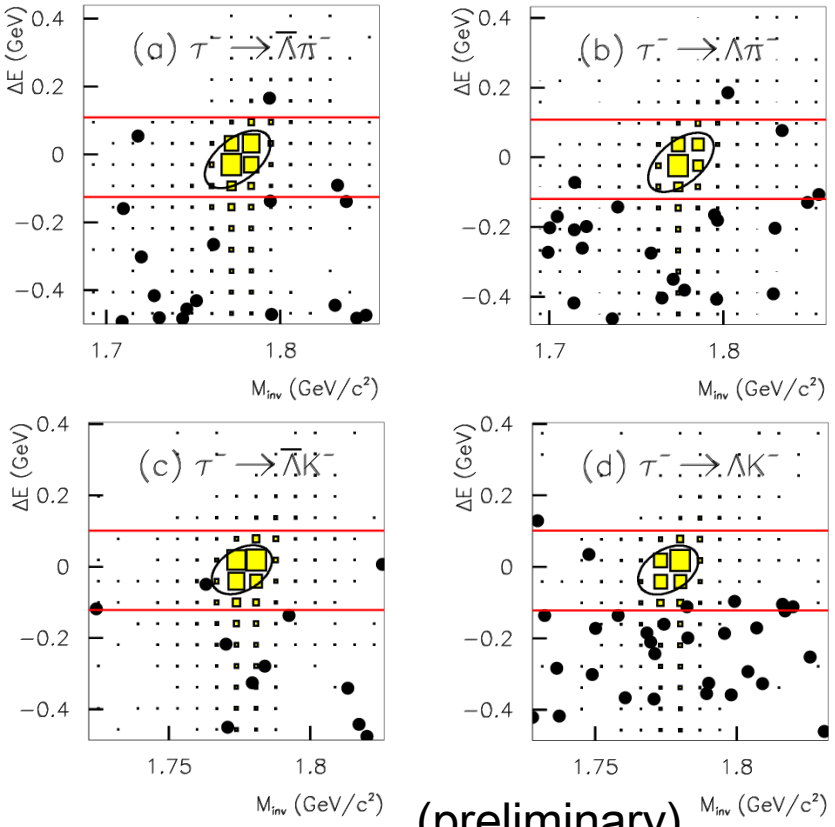
- Data: 782fb^{-1}
- No event s are found in the signal region.
- **Almost BG free**
  - Expected # of BG: 0.01-0.21
  - Good lepton ID
- Br < (1.5-2.7) x 10^{-8} at 90%CL



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

Phys.Lett.B687,139 (2010)

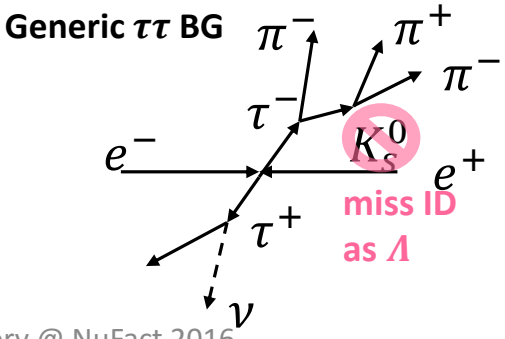
$\tau \to \Lambda h / \bar{\Lambda} h$

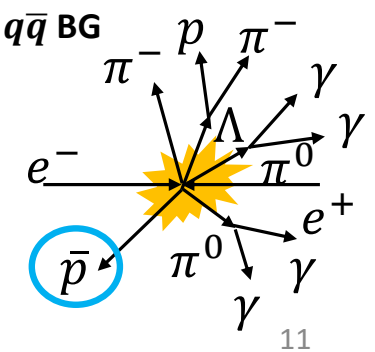


(preliminary)

Mode	ε (%)	N_{BG}^{EXP}	UL (x10^{-8})
$\tau^- \to \bar{\Lambda}\pi^-$	4.80	0.21±0.15	2.8
$\tau^- \to \bar{\Lambda}K^-$	4.11	0.31 ±0.14	3.1
$\tau^- \to \Lambda\pi^-$	4.39	0.31±0.18	3.0
$\tau^- \to \Lambda K^-$	3.16	0.42 ±0.19	4.2

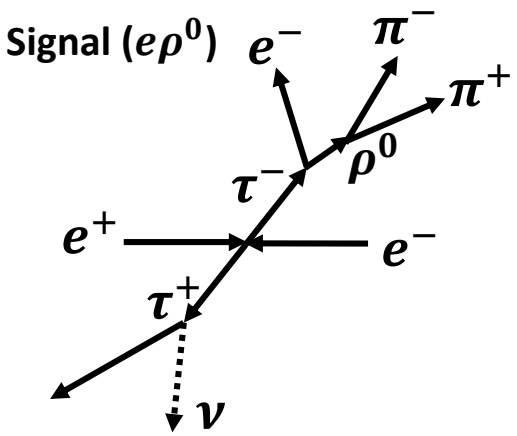
- No candidate events found
  => no significant excess
  - Expected # of BG: (0.21-0.42)
- $\tau\tau$ BG including K_S^0 miss ID as Λ
  - Reduce by K_S^0 mass
- $q\bar{q}$ BG including Λ : proton ID
- UL@90%CL (preliminary):
  - Br < (2.8-3.1) x10^{-8} : B-L cons.
  - Br < (3.0-4.2) x10^{-8} : B-L viol.

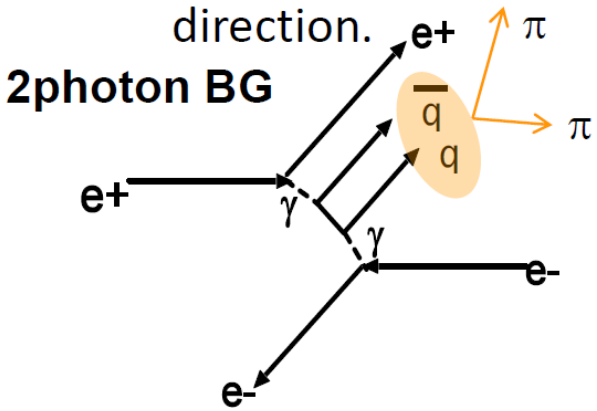


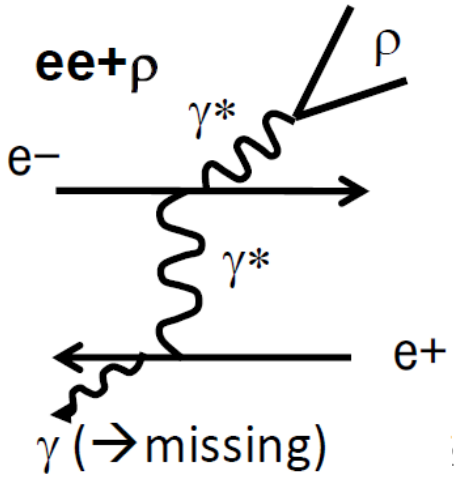


$\tau \to \ell V^0 (= \rho^0, K^{*0}, \omega, \phi)$

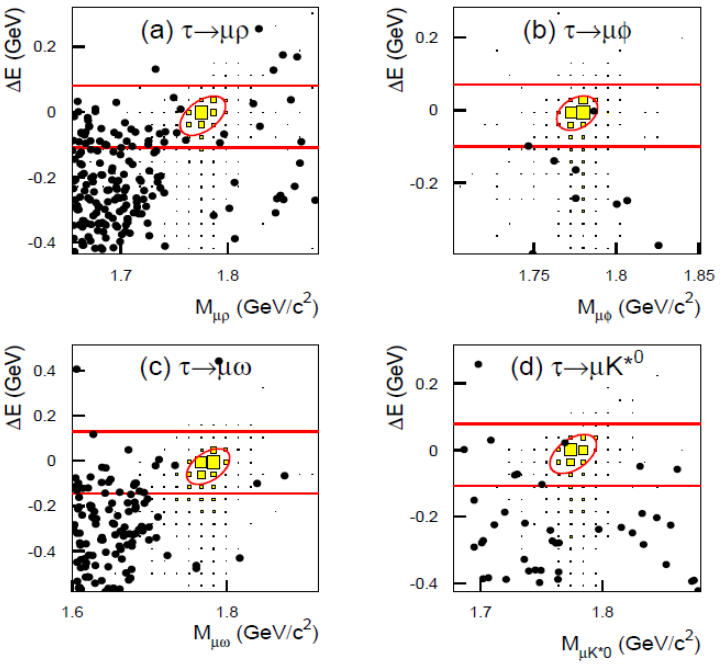
- Search with 854fb^{-1} data sample
  - Select one lepton and two hadrons
  - Require di-hadron mass to be consistent with a vector meson mass
- Possible backgrounds
  - For $\ell = \mu$, hadronic tau decay and $q\bar{q}$ with miss μ-ID
  - For $\ell = e$, 2photon processes could be large BG.
    - ee+X process also become large background.
      => Reduced using missing-momentum direction.







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



- After event selection
  - 1 event in $\mu\phi$, μK^{*0}, $\mu \bar{K}^{*0}$
  - 0 events others in the signal region
    =>No significant excess

  => expected # of BG: 0.06-1.48
- Br($\tau \to \ell V^0$) < (1.2-8.4)x10^{-8}@90%CL

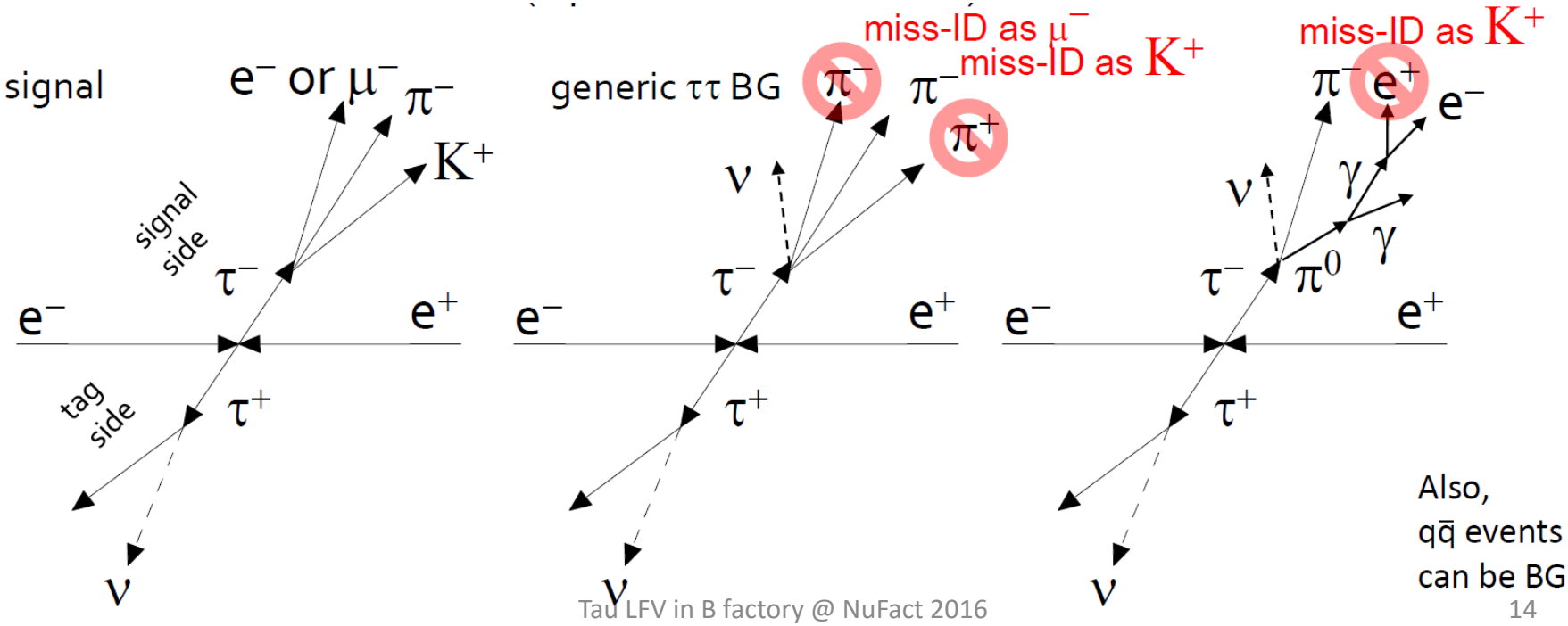
Phys.Lett.B699,251 (2011)

Mode	ε (%)	N_{BG}^{EXP}	$N_{obs.}$	UL (x10^{-8})
$e^-\rho^0$	7.6	0.29±0.15	0	1.8
$\mu^-\rho^0$	7.1	1.48±0.35	0	1.2
$e^-\phi$	4.2	0.47±0.19	0	3.1
$\mu^-\phi$	3.2	0.06±0.06	1	8.4
$e^-\omega$	2.9	0.30±0.14	0	4.8

Mode	ε (%)	N_{BG}^{EXP}	$N_{obs.}$	UL (x10^{-8})
e^-K^{*0}	4.4	0.39±0.14	0	3.2
μ^-K^{*0}	3.4	0.53±0.20	1	7.2
$e^-\bar{K}^{*0}$	4.4	0.08±0.08	0	3.4
$\mu^-\bar{K}^{*0}$	3.6	0.45±0.17	1	7.0
$\mu^-\omega$	2.4	0.72±0.18	0	4.7

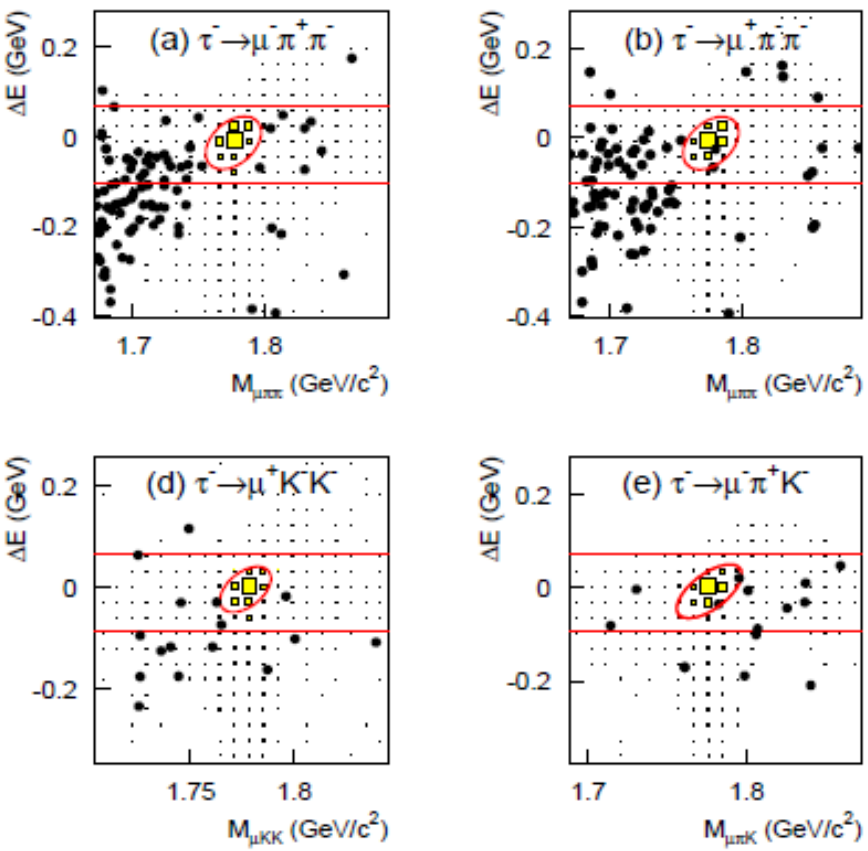
$\tau \to \ell hh'$

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



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

$\tau \to \ell hh'$



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

=> Expected # of BG: 0.06-0.72

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

Upper limits at 90%CL:

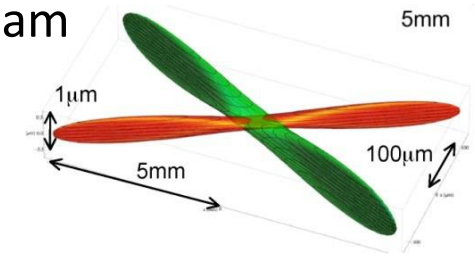
Br($\tau \to \ell hh'$) < (2.0-8.4)x10^{-8}

Phys.Lett.B719,346 (2013)

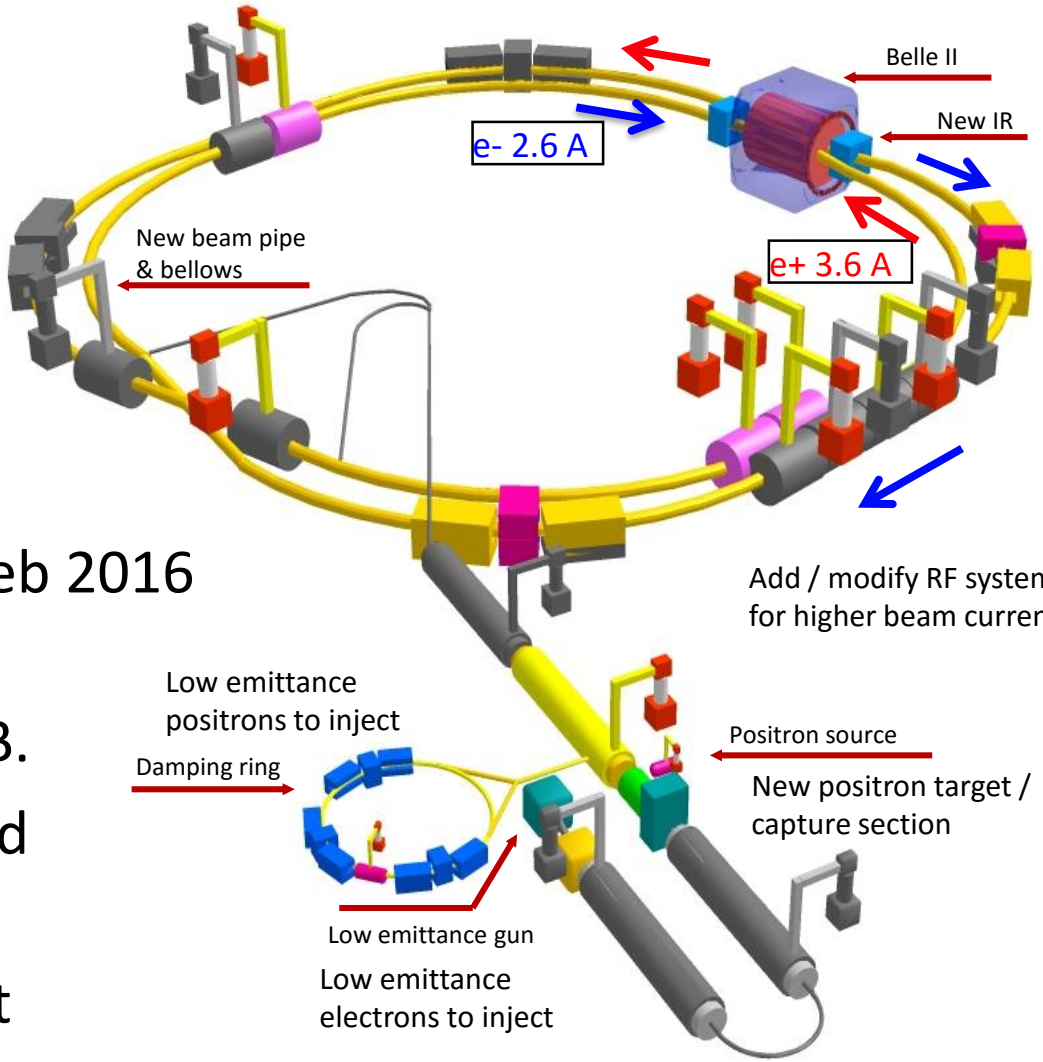
Future prospects at Belle II

SuperKEKB accelerator

Nano-beam scheme

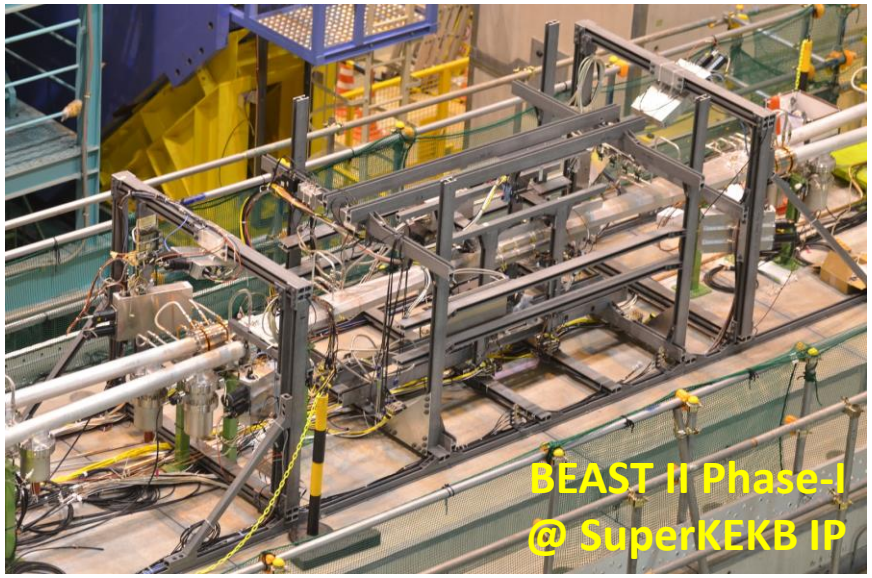


- 40 times higher luminosity
  - Focus on small β^*_y : **x 20**
  - Increase in current : **x 2**
- First tunings was achieved Feb 2016
- Beam background is also 40 times higher than at KEKB.
  - Reduce by collimators and shielding
  - Background measuement



Beam background studies

- **Beam Exorcism for a Stable ExperimenT II (BEAST II)**:
  - Measure beam background for safe roll-in of Belle II.
  - Feedback to SuperKEKB : injector tuning, vacuum scrubbing...
  - Detailed tuning and verification of simulation essential for Belle II operation

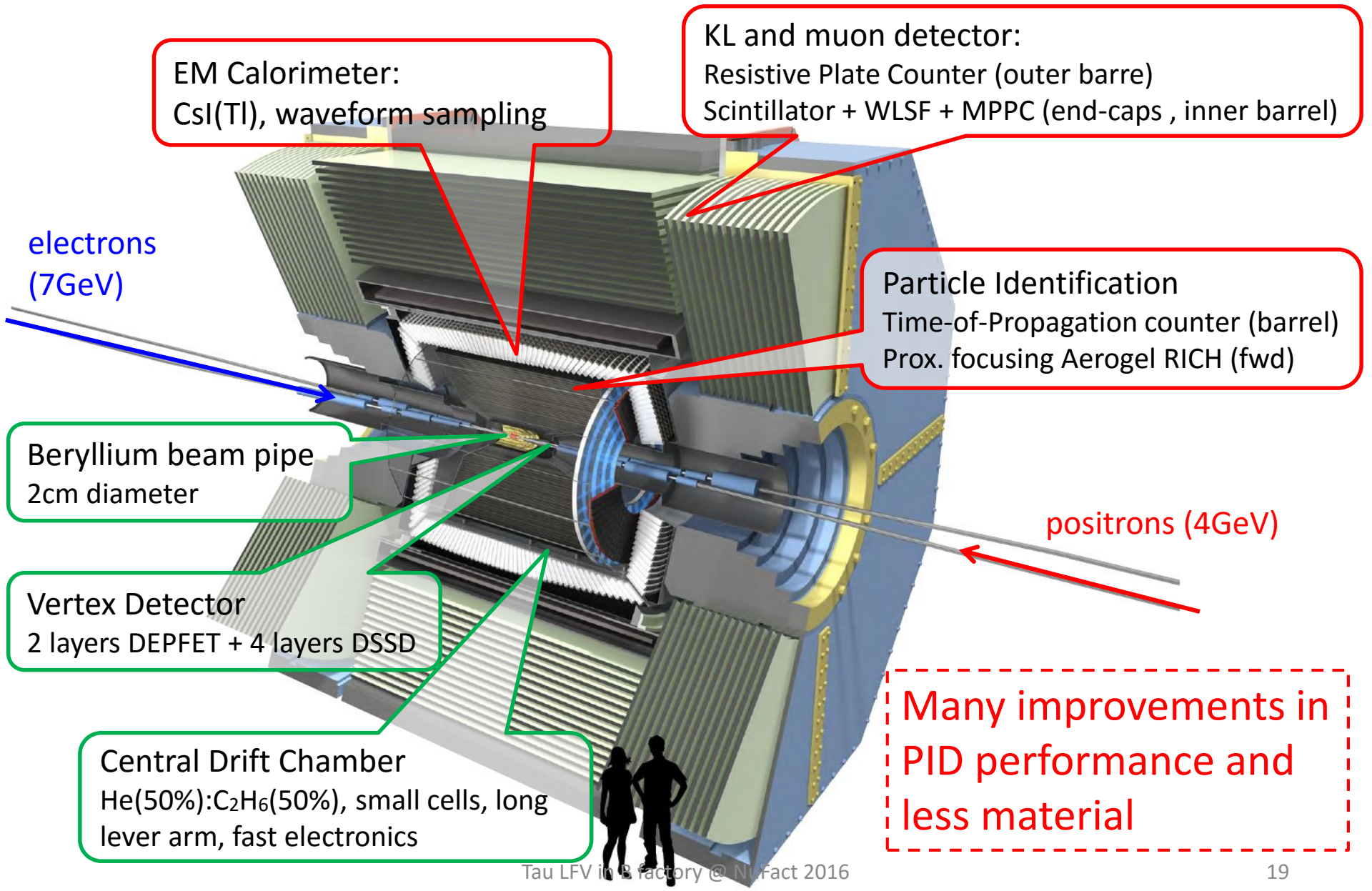


Phase-I (Feb-June 2016): finished
- Single beam background studies
- Analysis is now ongoing

Phase-II (Dec 2017-)
- First beam collisions
- BEAST II VXD for background commissioning
- Full Belle II outer detector

Belle II Detector

arXiv:1011.0352 (2011)

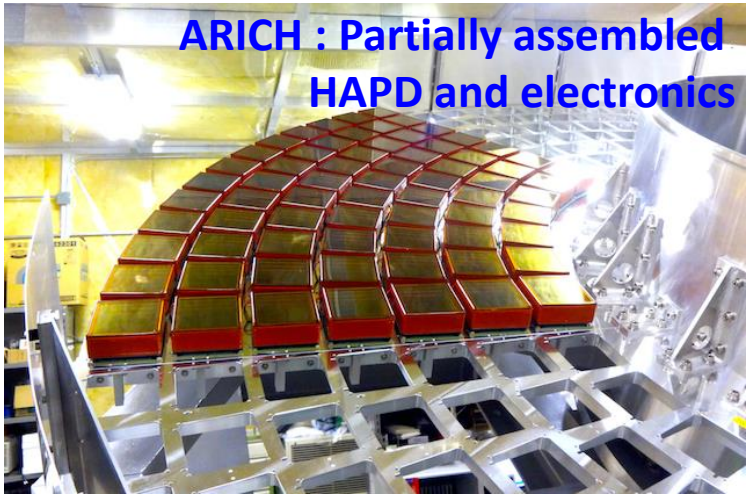


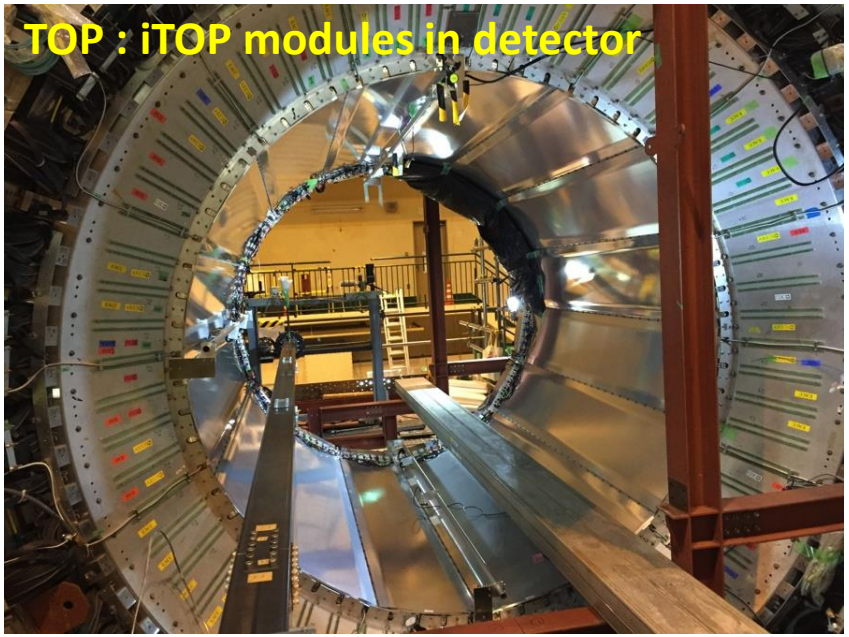
Many improvements in PID performance and less material

Belle II detector status

Outer detector installation in progress

- KLM and ECL are installed
- All 16 TOP modules are installed now
- CDC installation is in progress
- ARICH is in construction

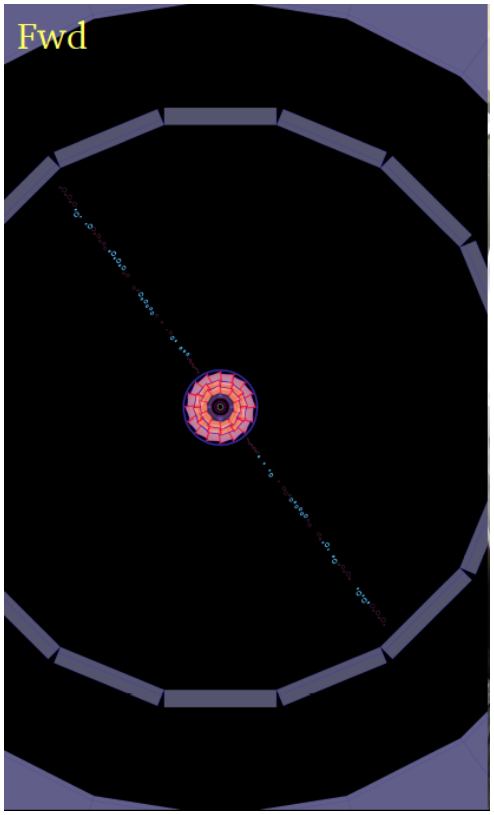




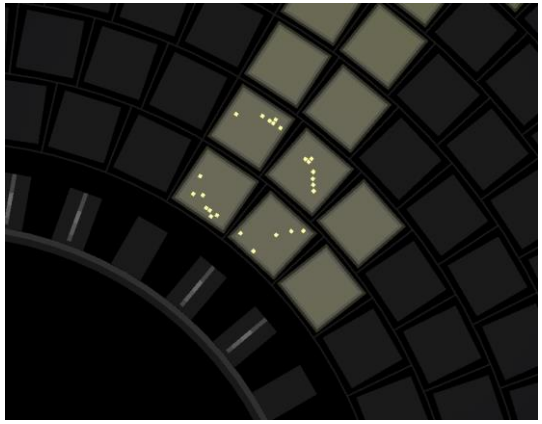
Cosmic ray & beam test

- Cosmic ray tests are in progress
  - KLM/TOP:
    Electronics studies
  - ECL/CDC:
    More than 10 months
    with cosmic data taking
  - ARICH: First cosmic ring
    image was observed

Cosmic track though CDC →

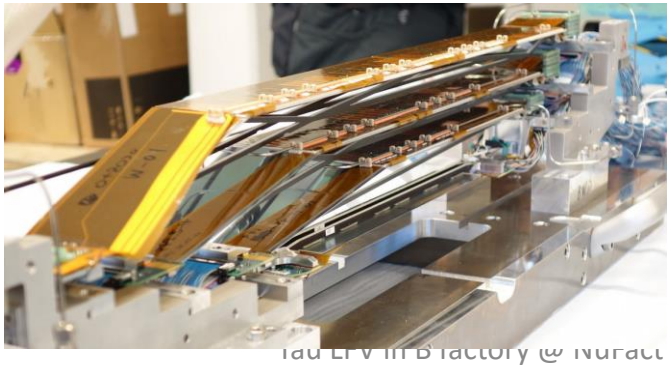


↓Cherenkov ring in ARICH

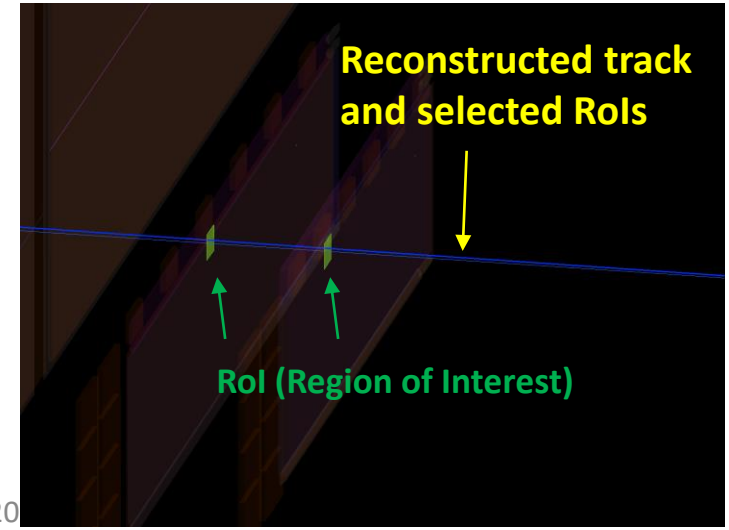


- VXD Beam test at DESY April, 2016

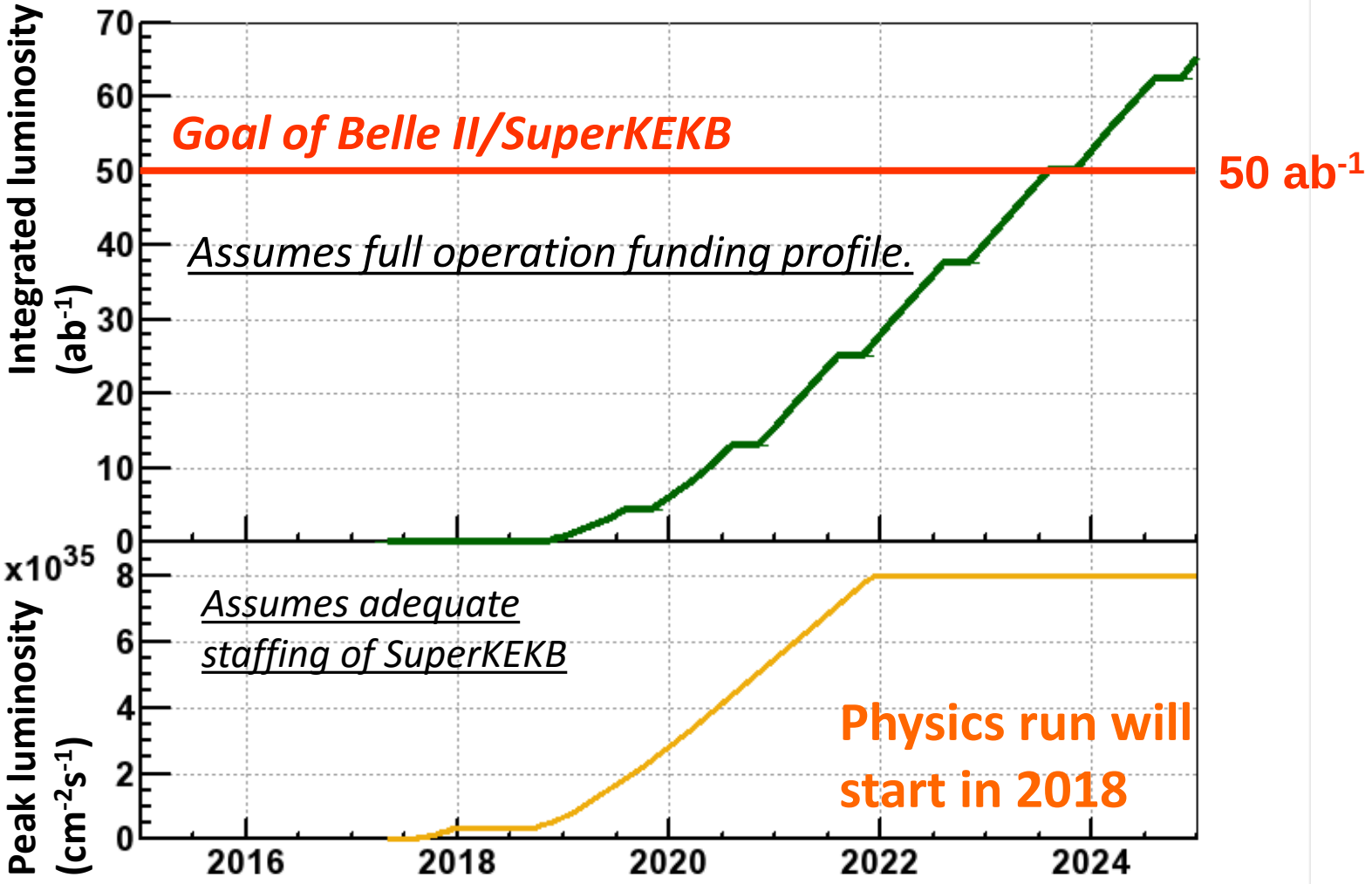
=> Data reduction and slow control schemes



VXD Prototype detector @ DESY beam test



SuperKEKB Luminosity profile

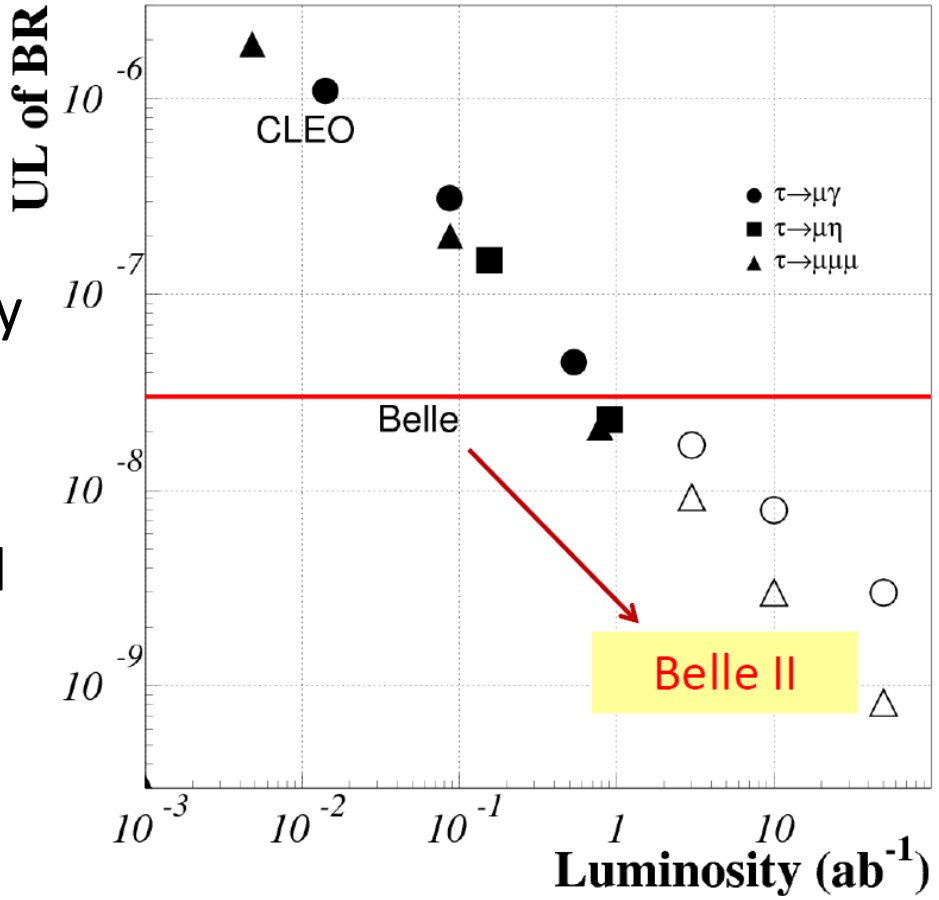


Target integrated luminosity = 50ab^{-1} => ~5x10^{10} τ pairs

Prospects at Belle II

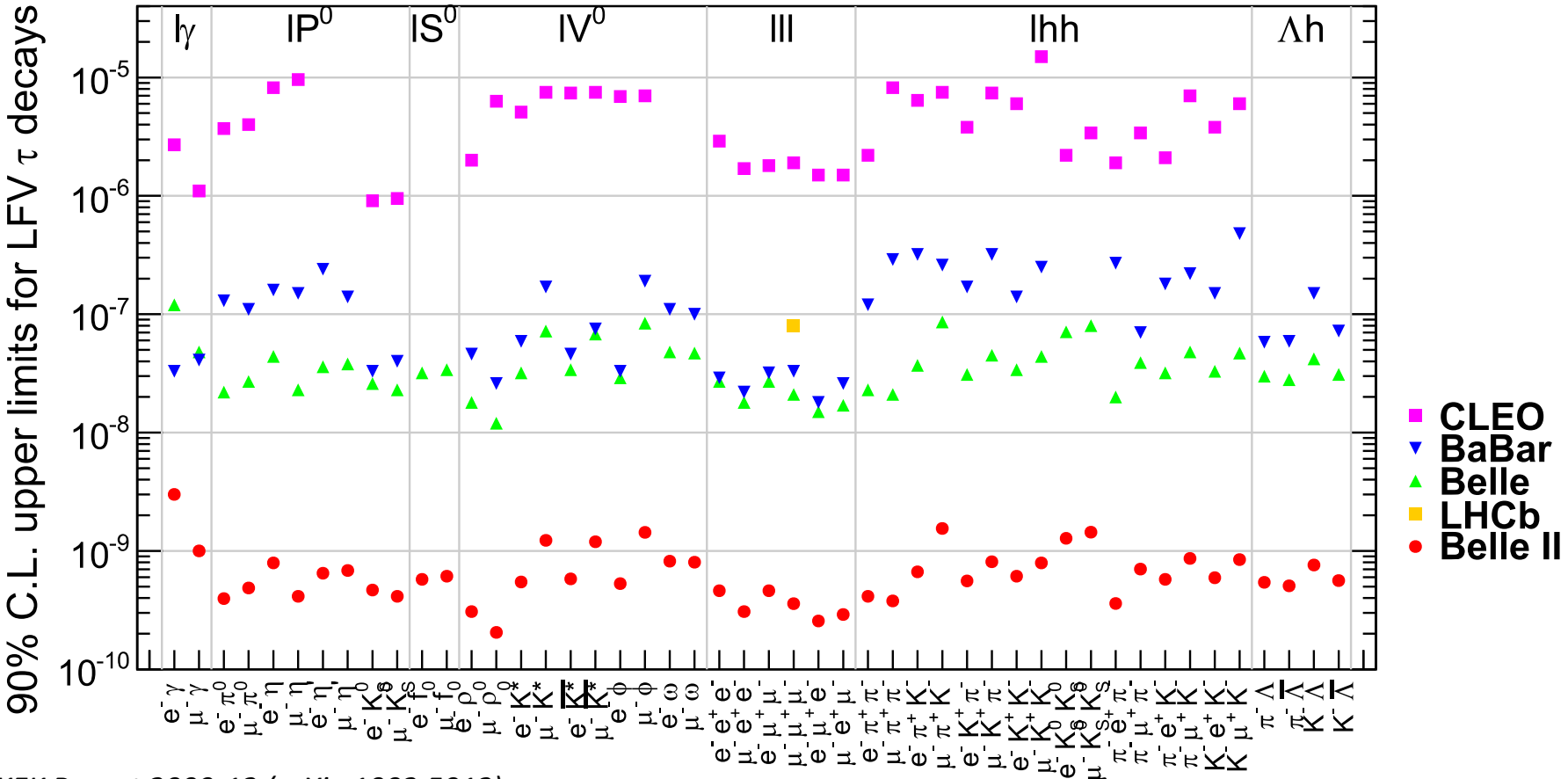
- Sensitivity depends on BG level
  - Recent improvement of the analysis (BG understaning , optimized selection)

  => Improve achievable sensitivity
- $B(\tau \to \mu\gamma) \sim O(10^{-9})$ and $B(\tau \to \mu\mu\mu) \sim O(10^{-10})$ at $50 ab^{-1}$
  - Slopes depend on background
- Improvement of BG reduction is important.
  - Beam BG
  - Signal resolution



LFV Upper limits @ B factories

- Current estimation with Belle II final statistics : ~10^{-2} lower
  - Many decay modes are accessible



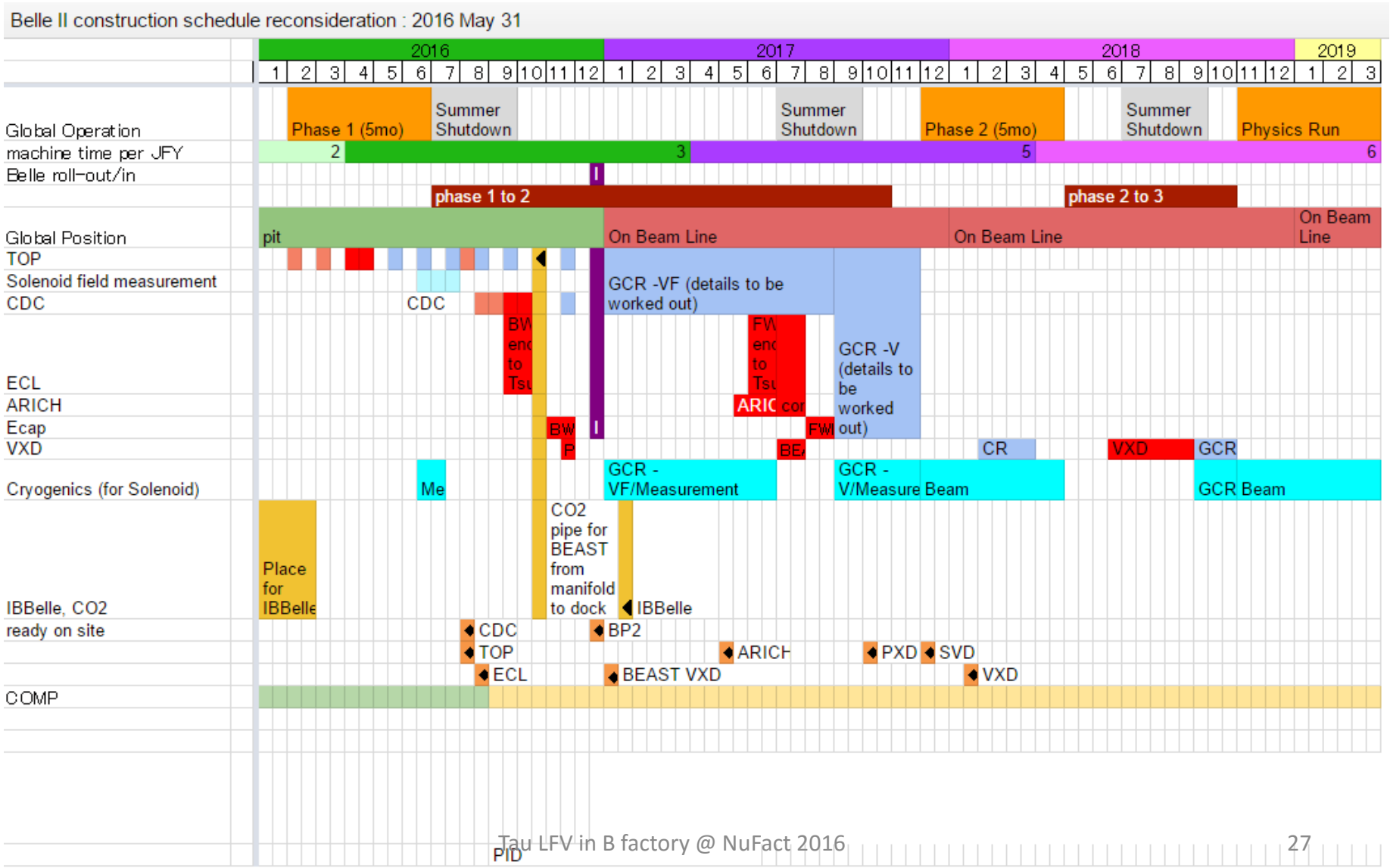
KEK Report 2009-12 (arXiv:1002.5012)
belle II internal node #21

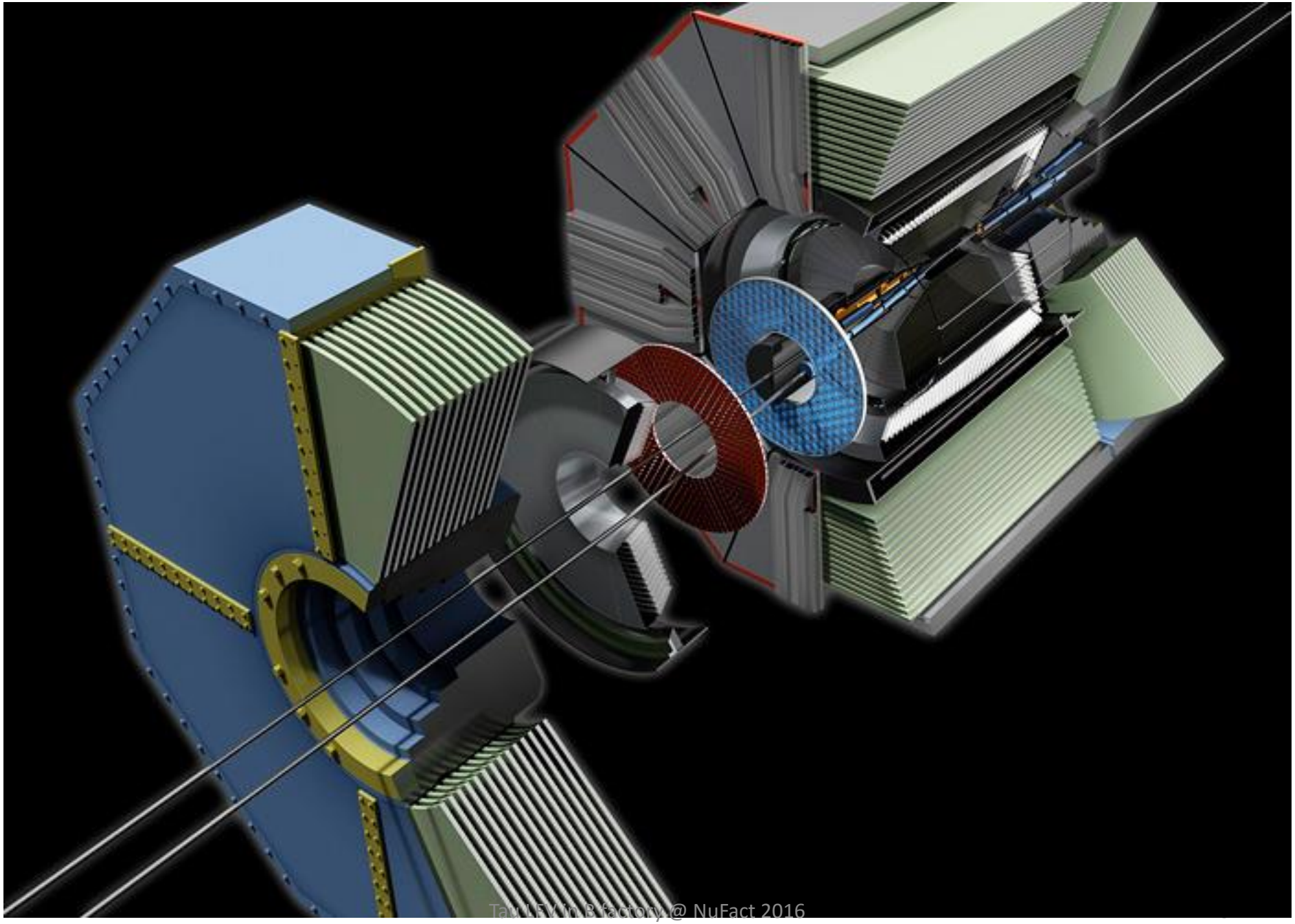
Summary

- Belle collected a 1ab^{-1} data sample containing ~10^9 τ pairs
  - Almost all upper limits on BF for τLFV are analyzed with Belle's full data sample and reach O(10^{-8})
- Belle II experiment is scheduled to start at 2018 and collect ~5 x 10^{10} τ pairs in 50ab^{-1} data sample
  - LFV Sensitivity depends on statistics
  - Background free modes, such as $\tau \to \ell\ell\ell$ can be reached to O(10^{-10}) branching ratio sensitivity while $\tau \to \ell\gamma$ modes will be O(10^{-9}), highly depends on the background situation
- First tuning of SuperKEKB was succeeded
  - BEAST II will provide more knowledge of beam background
- Detector construction is ongoing with cosmic ray/beam tests
  - Belle II rolls in at the end of the year

backup

Belle II schedule

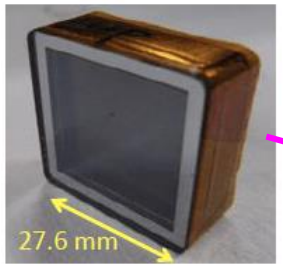




Barrel PID : iTOP

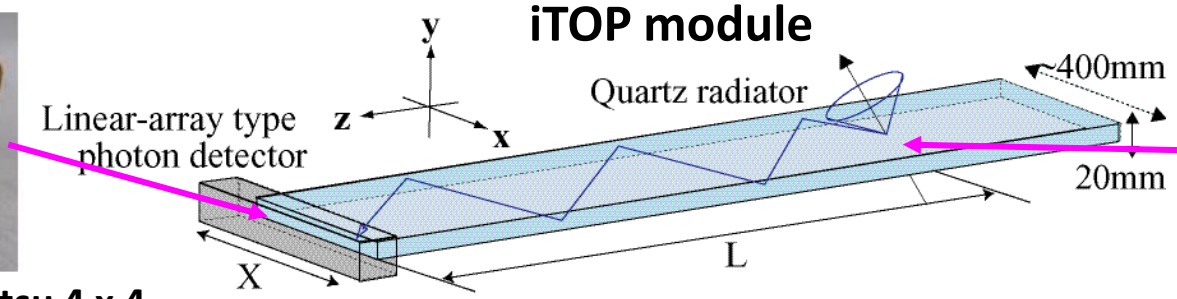
Detection of internally reflected Cherenkov (DIRC):

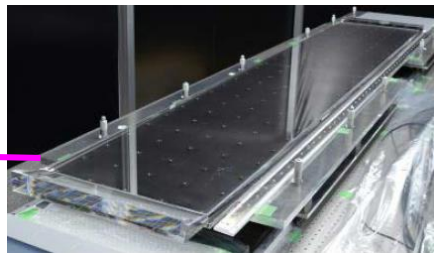
- Cherenkov pattern in two hit coordinates and time of propagation.



512 Hamamatsu 4 x 4 MCP-PMT

iTOP module

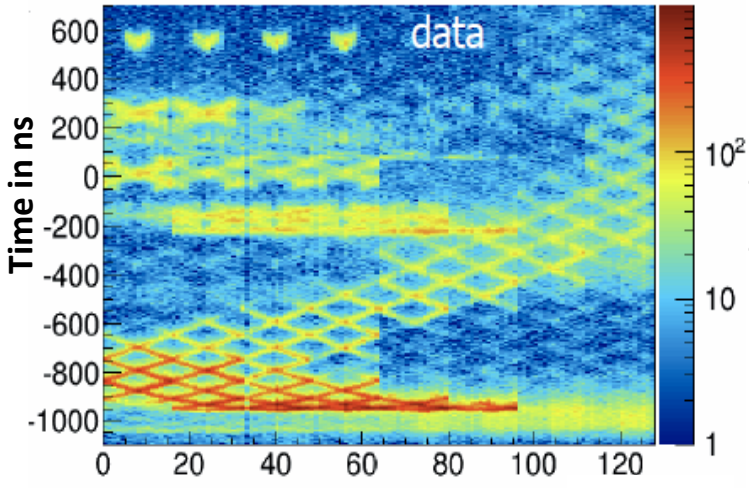


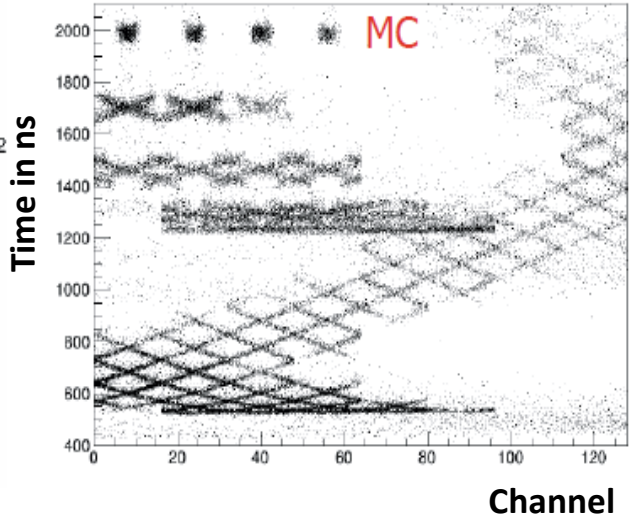


Quartz radiator

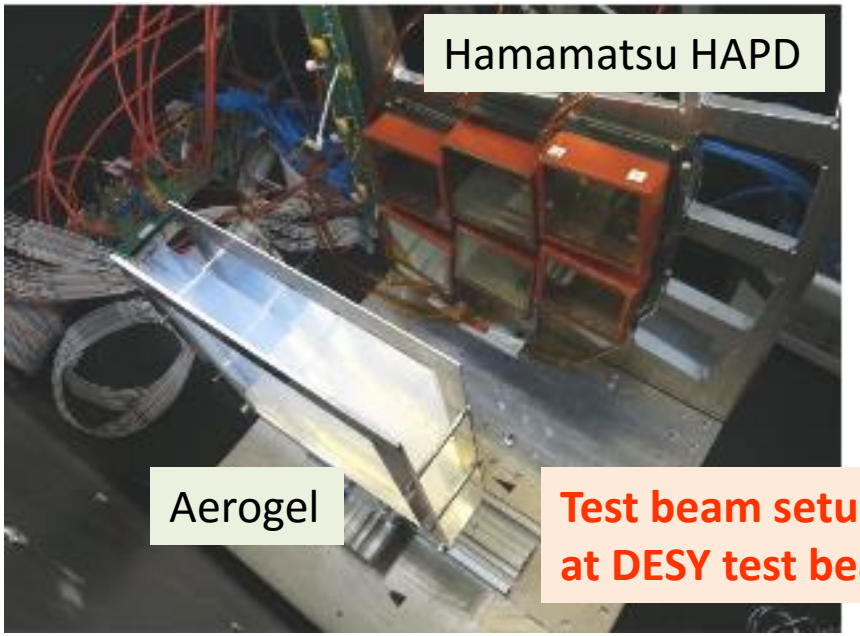
TOP test beam data

- Good conformity in data and MC
- **Assembly of iTOP modules is ongoing**

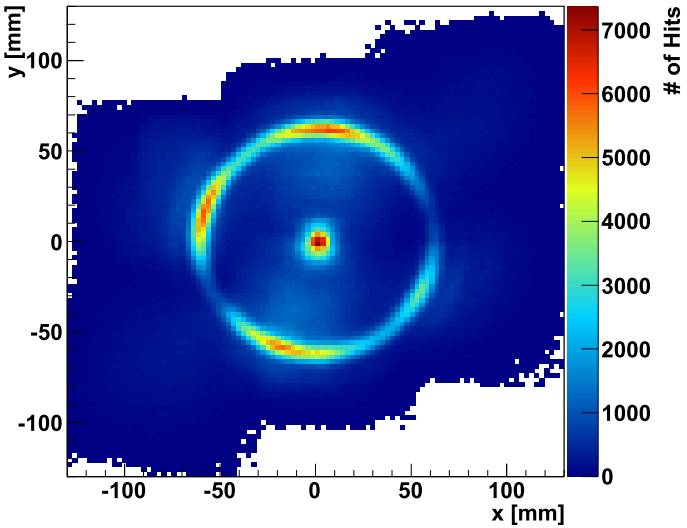




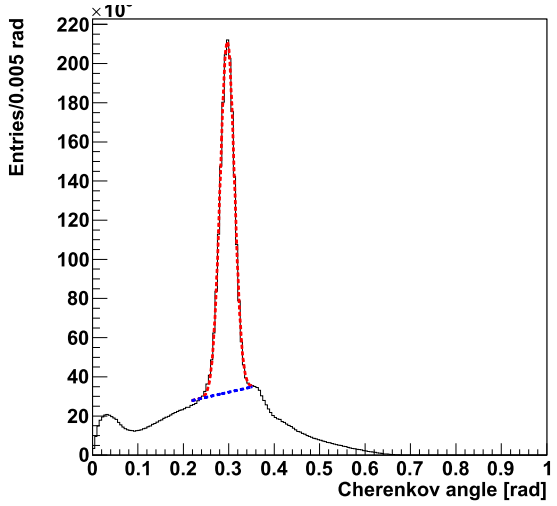
End-cap PID: Aerogel RICH



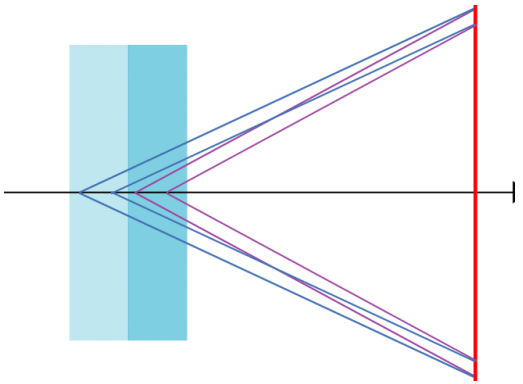
Clear Cherenkov image observed



Cherenkov angle distribution

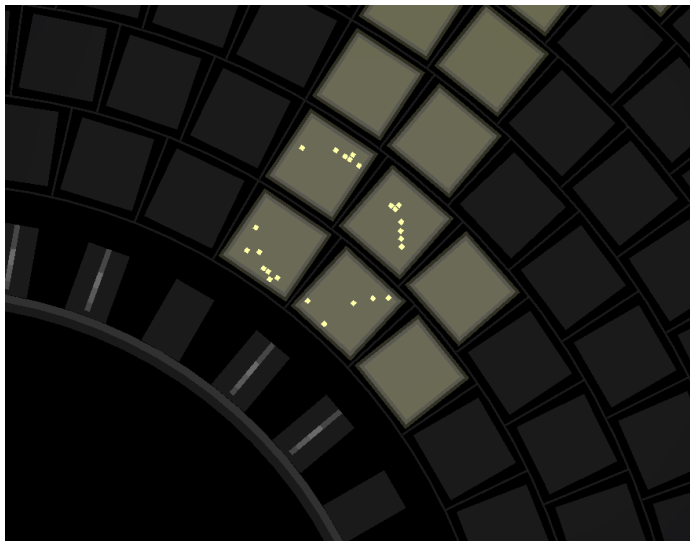


- Employ multiple layers with different refractive indices
- Cherenkov images from individual layers overlap on the photon detector
- **Mass test of HAPD is on going**

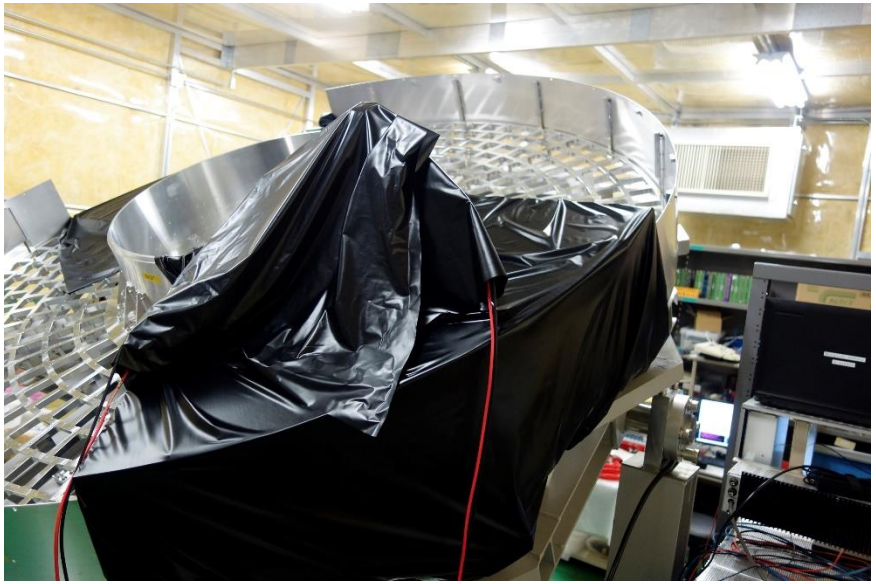


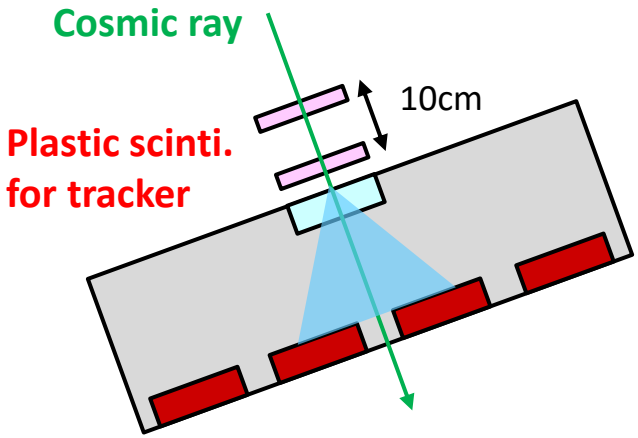
Cosmic ray test at Tsukuba BF4

- Coincidence of 2 plastic scintillators
  - Less than 0.1Hz but clean signal
- One Aerogel tile is inside black box
  - 6 HAPDs are applied HVs and GBs.
- Parameter tuning was done last week
- **First ring images was observed!**
  - Long run will start this week



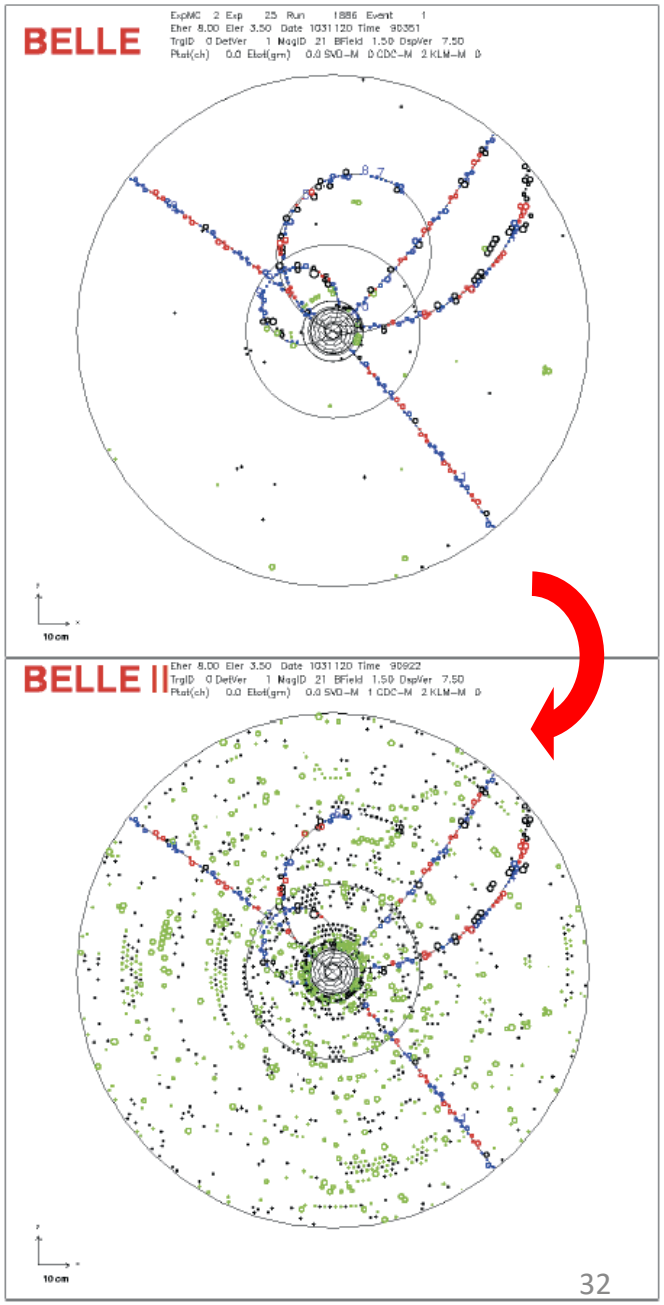
Cosmic tracker on the ARICH structure





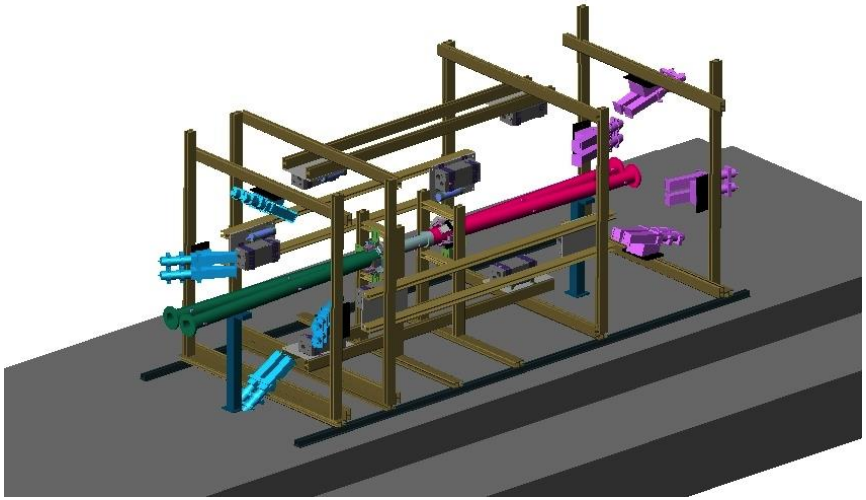
Experimental challenge at higher luminosity

- For a higher luminosity
  - More beam background (**20 x**)
  - Higher trigger rate (**0.5 -> 30kHz**)
  - More radiation hardness
- Important improvements
  - Hermeticity for full reconstruction
    => Finer granularity (more channels)
  - Impact parameter resolution
    => Smaller beam pipe (**1.5cm -> 1.0cm**)
    => Pixel detector (DEPFET)
  - K_s vertex reconstruction efficiency
    => Lager SVD coverage
  - Better K / π separation
    => New Particle ID devices

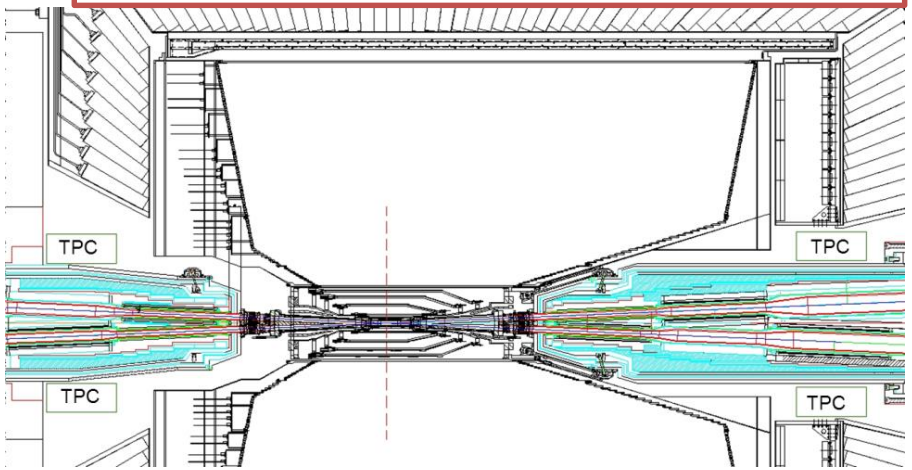


Two Phases of the BEAST (Beam Background Commissioning Experiment)

Phase I installation on-going



Now finalizing the suite of BEAST detectors and converging on design.

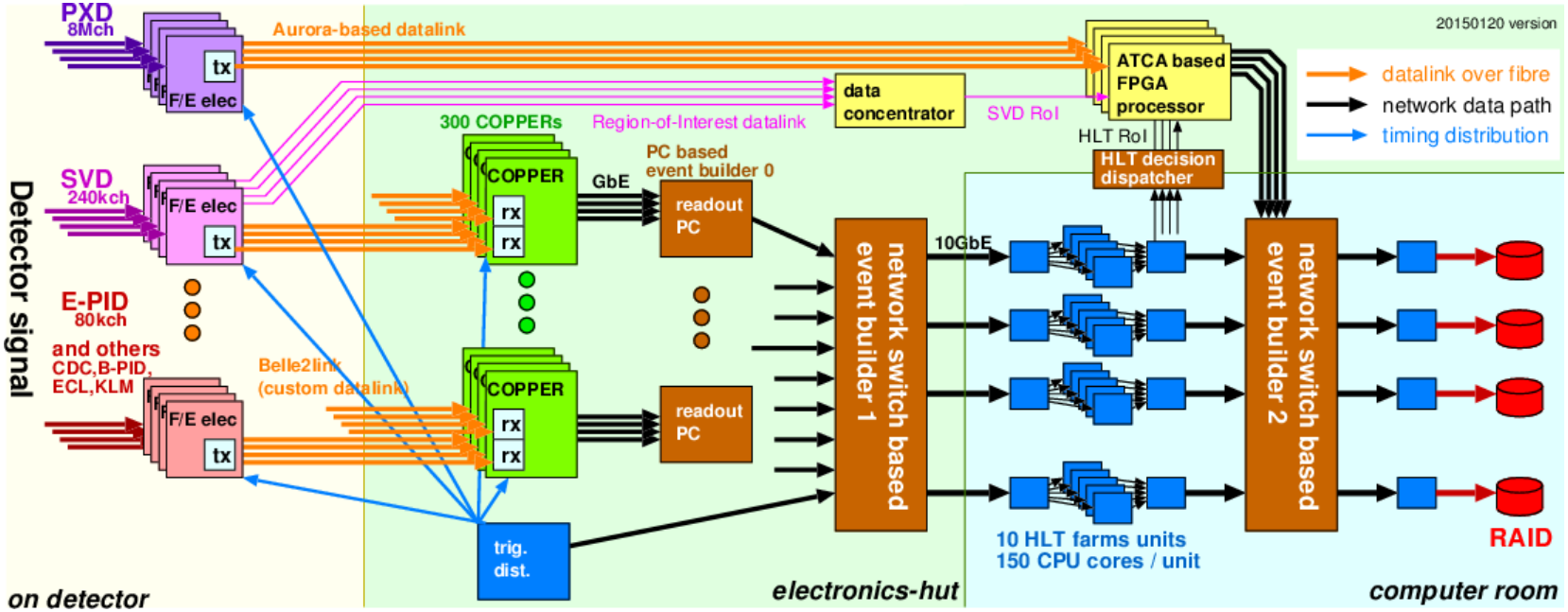


BEAST Phase 2: ~May 2017

- BelleII outer detector rolled in.
- VXD BEAST Assembly
- BEAST detectors in dock space and around QCS
- **BEAST DAQ & Belle DAQ**

BEAST Phase I beampipe now installed (3.1 km of ring is complete)

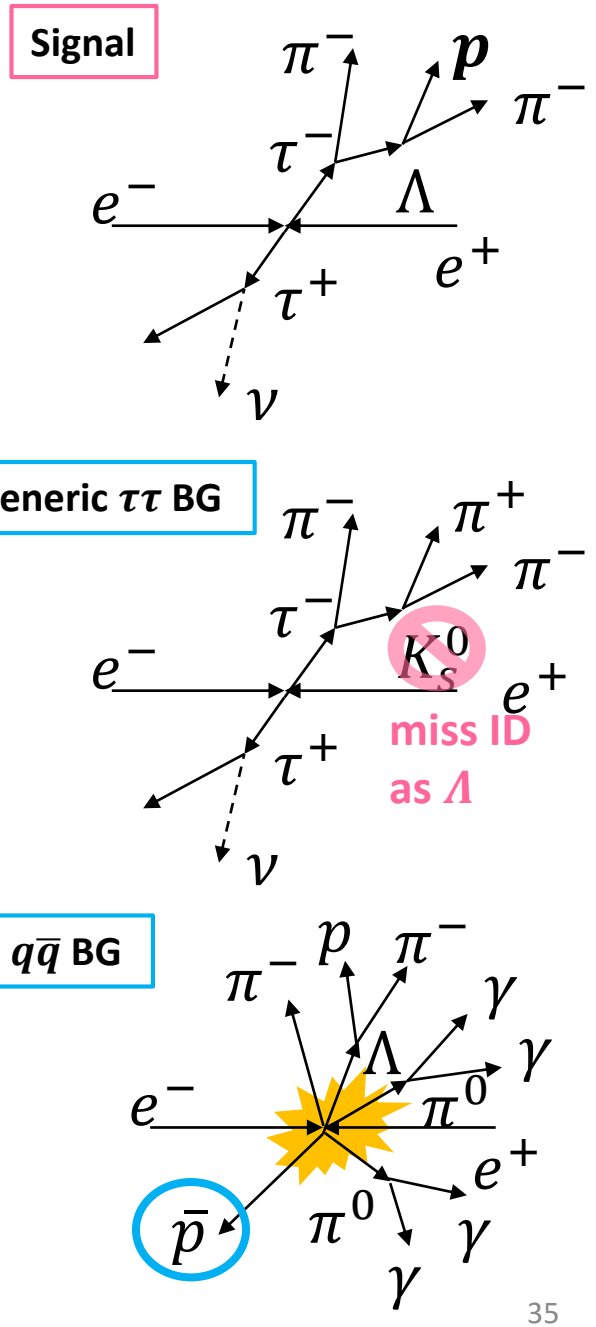
Belle II DAQ system



- Belle2Link : High speed serial link for unified readout scheme except PXD
  - COPPER : Platform for receiver part of Belle2Link
- Special readouts for PXD reduce data size according to Region of Interests
- Unified trigger timing distribution for FEEs and COPPERs
- Two layers of event building in network data flow
- High Level Trigger (HLT) farm analyzing online data using offline software

$\tau \to \Lambda h / \bar{\Lambda} h$

- Search with 904fb^{-1} data sample
  - Select three hadrons
  - Require Λ vertex
- 4 modes are searched for. ($h = p, K$)
  - $\tau \to \Lambda h^-$: (B-L) conserving decay
  - $\tau \to \bar{\Lambda} h^-$: (B-L) violating decay
- $\tau\tau$ BG including K_S^0 miss ID as Λ
  - Reconstruct K_S^0 and reduce reject events that are likely to be K_S^0
- $q\bar{q}$ BG including Λ
  - Reject events with proton in tag side



$\tau \to \mu\gamma, e\gamma$

Phys. Lett. B 666, 16 (2008)

- Previous results:
- Search with 545 fb^{-1}
  - Main BG : $\tau \to \mu\nu\nu$ + ISR γ

  ISR: Initial State Radiation
- $\tau \to \mu\gamma$: Br < 4.5x10^{-8} at 90%C.L.
- $\tau \to e\gamma$: Br < 1.2x10^{-8} at 90%C.L.