KEK, High Energy Accelerator
Research Organization

Flavor Physics Program at KEK

-SuperKEKB and J-PARC-

December 7, 2012

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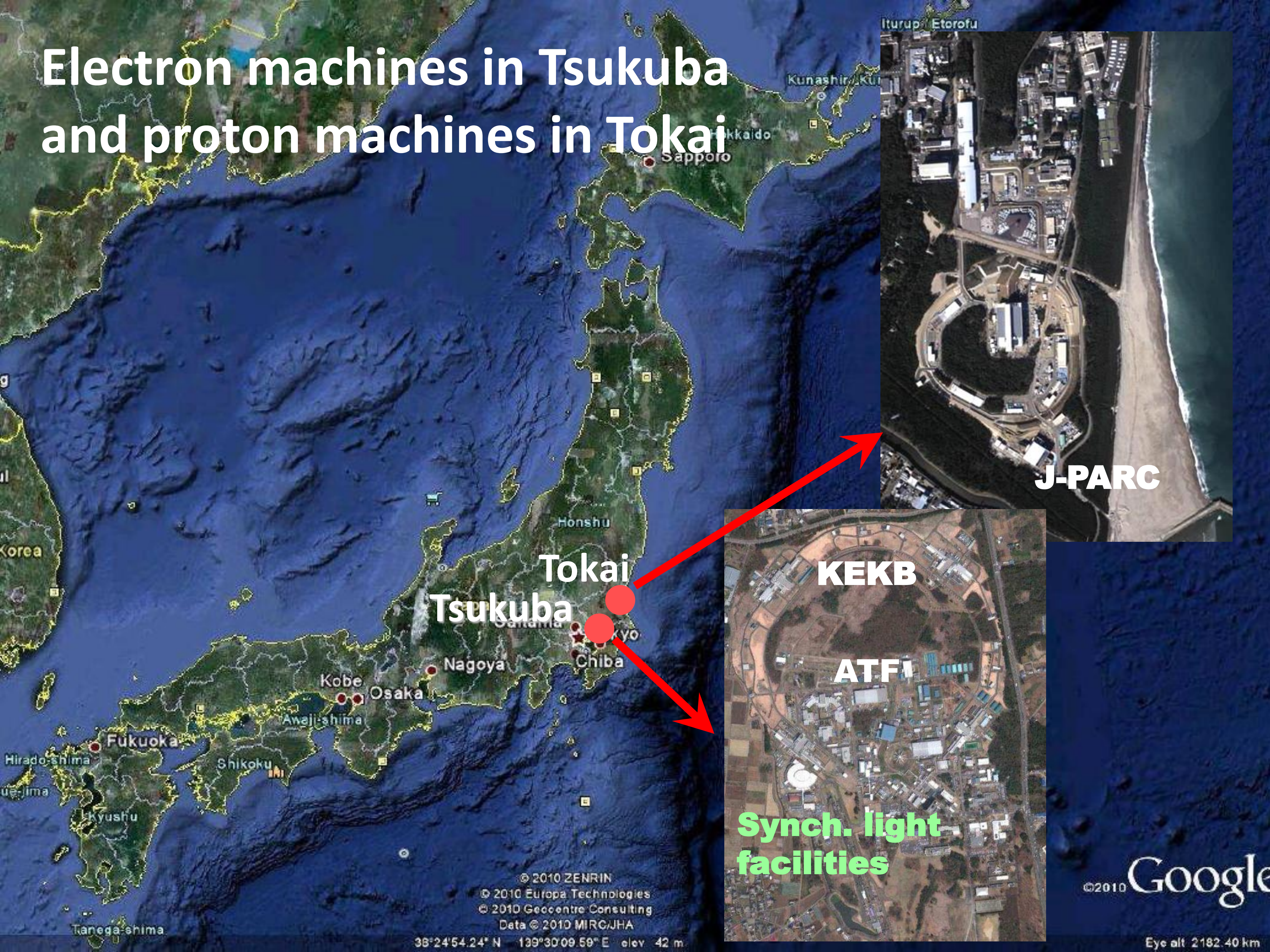
KEK

Outline

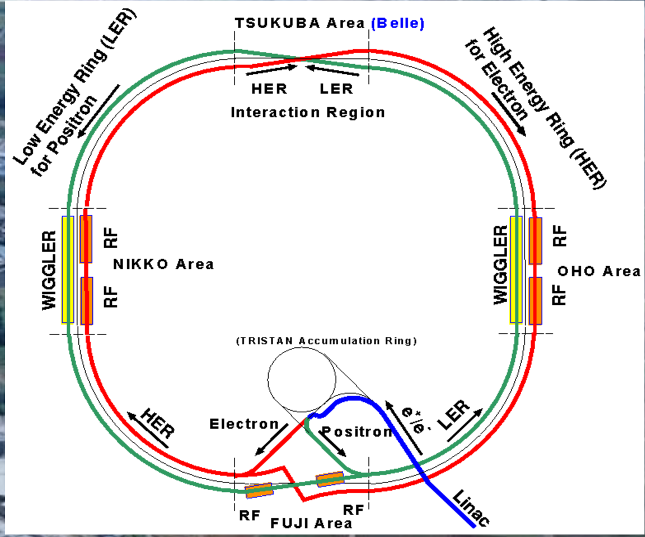
- Introduction – KEK's Roadmap
- SuperKEKB and Belle-II
- J-PARC Program
  - T2K – Long baseline neutrino experiment
  - KOTO – search for $K_L \rightarrow \pi^0 \nu\nu$
  - New endeavor – COMET
  - New g_μ-2 experiment
- Summary

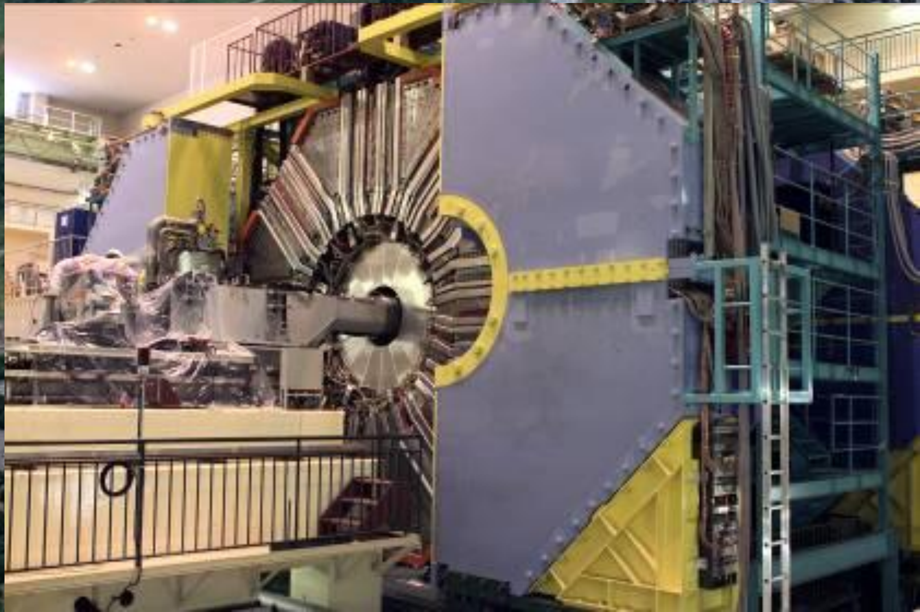
Electron machines in Tsukuba and proton machines in Tokai



KEKB and Belle

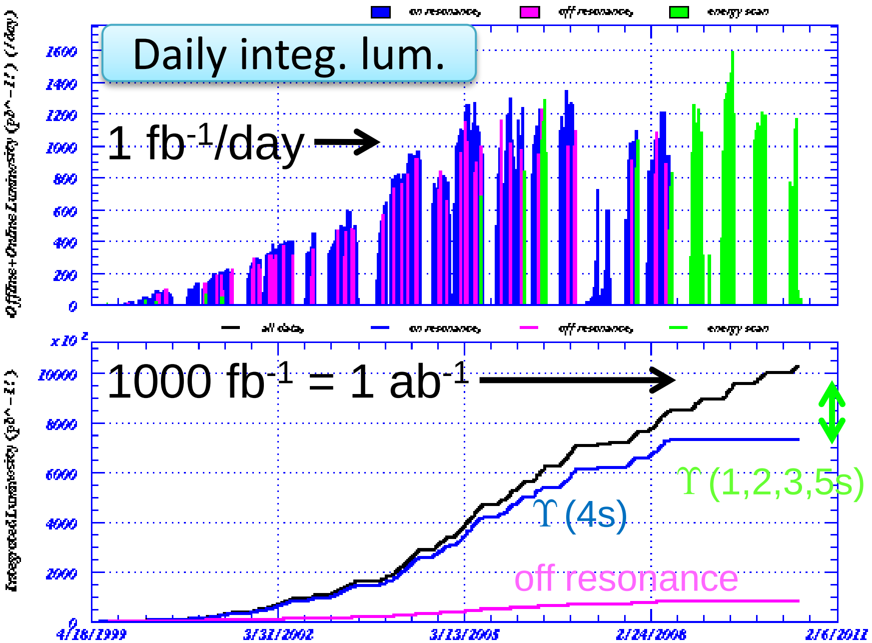
SuperKEKB and Belle II



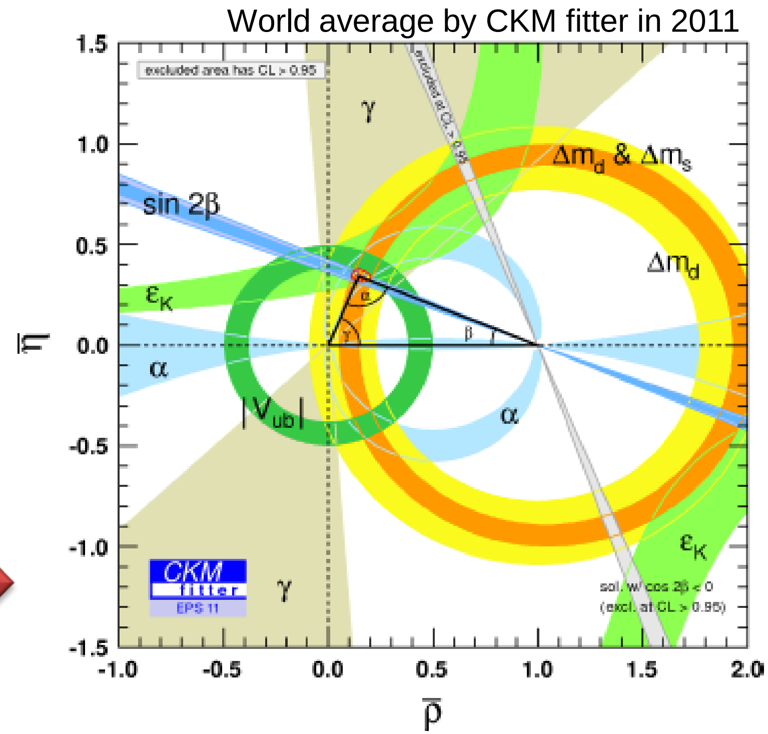


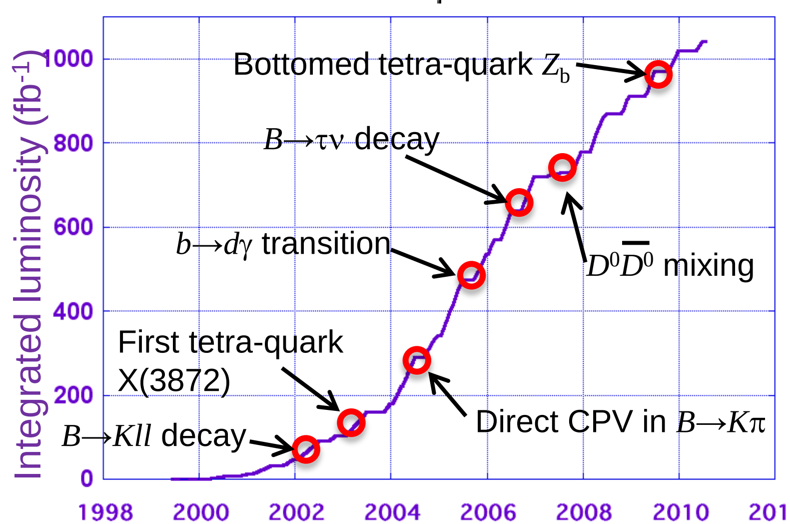
Achievements of KEKB and Belle

$\mathscr{L}_{peak} = 2 \times 10^{34}/cm^2/s$



11 years





What is next with flavour physics?

- LHC started to explore the TeV region, which is the scale of the electroweak symmetry breaking, and most probably related to the "New Physics" scale.
  - It is natural to assume that the NP effects are seen in $B/D/\tau$ decays.
  - Flavour structure of new physics?
  - CP violation in new physics?
  - These studies will be useful to identify mechanism of SUSY breaking, if NP=SUSY.

- Otherwise…
  - Search for deviations from SM in flavor physics will be one of the best ways to find new physics.

In order for the flavor physics to be useful in the coming LHC era, the precision of various flavor measurements must be significantly improved, both in terms of experimental reach and understanding of theoretical uncertainty.

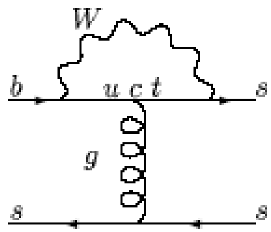
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

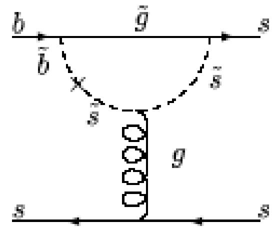
W. Altmannshofer, A. J. Buras, S. Gori, P. Paradisi, D. M. Straub, Nucl. Phys. B830, 17-94, 2010.

CPV in $b \to s$ penguin

In general, new physics contains new sources of flavor mixing and CP violation.

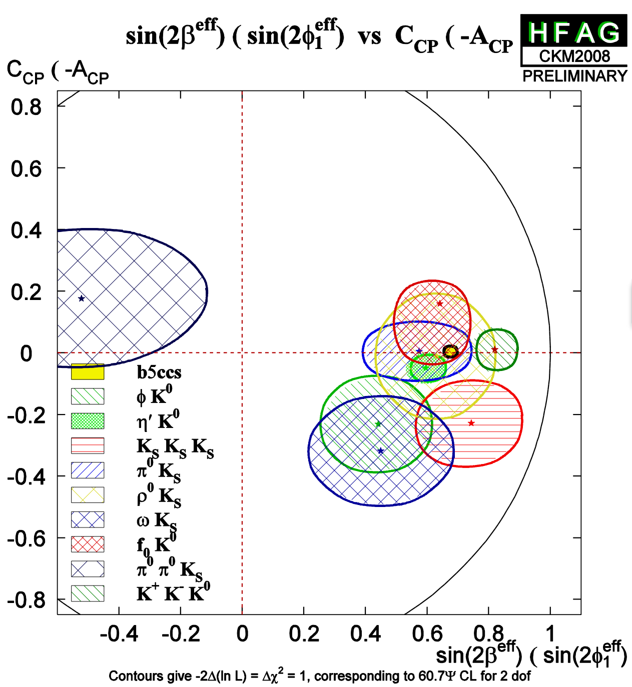


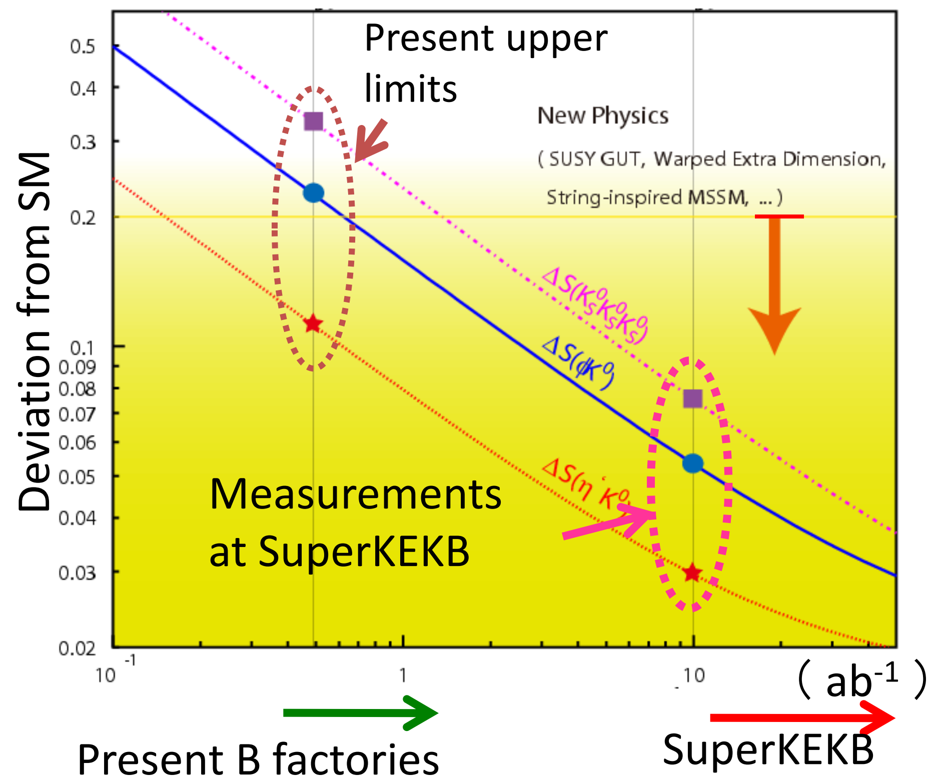
SM



SUSY contribution

- In SUSY models, for example, SUSY particles contribute to the $b \to s$ transition, and their CP phases change CPV observed in $B \to \phi K$, $\eta' K$ etc.





T-dependent CPV to search for L-R symmetry

$B \to K^* (\to K_S \pi^0)\gamma$
t-dependent CPV

SM:
$S_{CP}^{K^*\gamma} \sim -(2m_s/m_b)\sin 2\phi_1 \sim -0.04$

Left-Right Symmetric Models:
$S_{CP}^{K^*\gamma} \sim 0.67 \cos 2\phi_1 \sim 0.5$

D. Atwood et al., PRL79, 185 (1997)
B. Grinstein et al., PRD71, 011504 (2005)

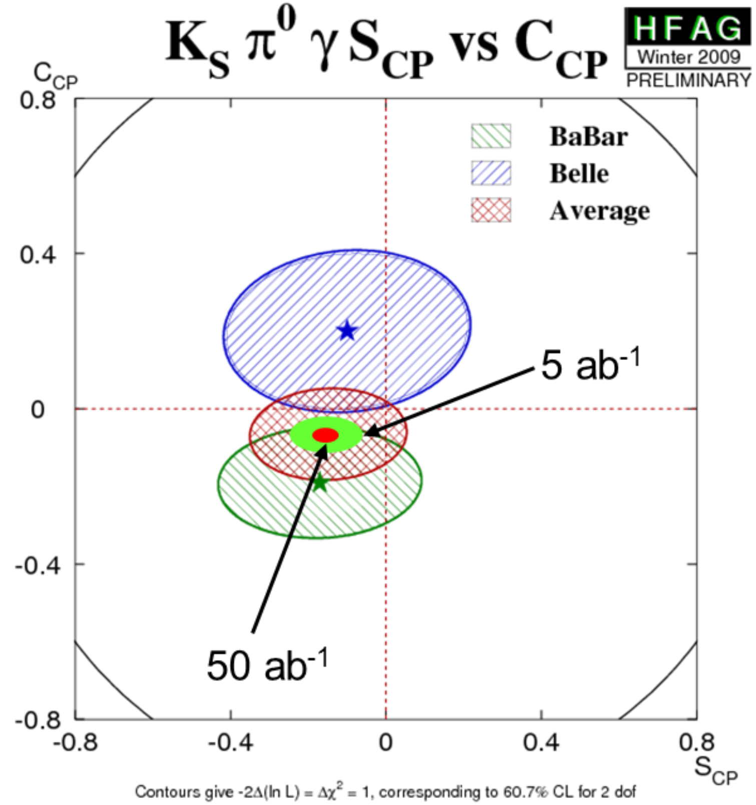
$S_{CP}^{K_S\pi^0\gamma} = -0.15 \pm 0.20$
$A_{CP}^{K_S\pi^0\gamma} = -0.07 \pm 0.12$

HFAG, Summer'11

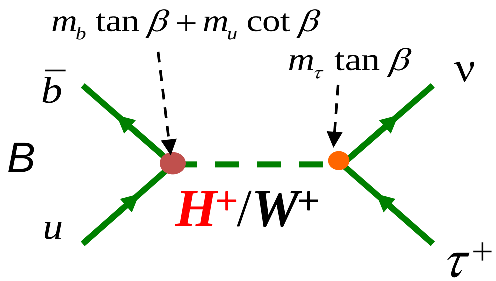
$\sigma(S_{CP}^{K_S\pi^0\gamma}) =$ 0.09 @ 5 ab^{-1}
0.03 @ 50 ab^{-1}
(~SM prediction)

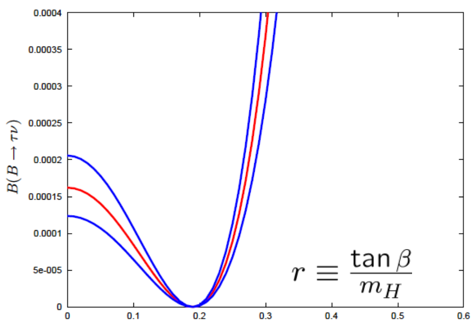
t-dependent decays rate of $B \to f_{CP}$;
S and A: CP violating parameters

$$P(B^0 \to f;\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 + S_{CP}^f \sin(\Delta m \Delta t) + A_{CP}^f \cos(\Delta m \Delta t)\right]$$

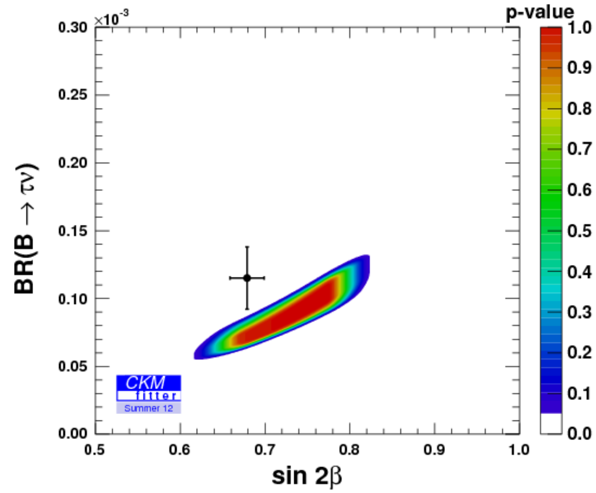


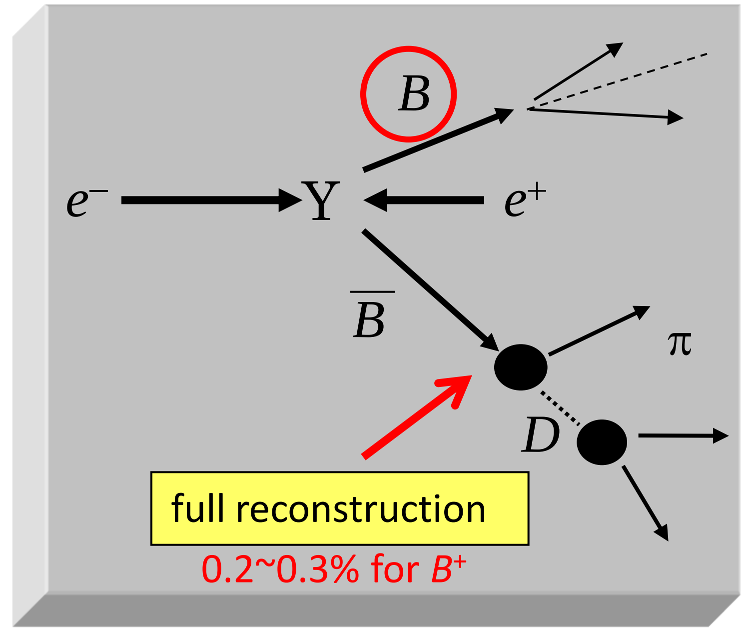
$H^{\pm}$ search in B to τ decays

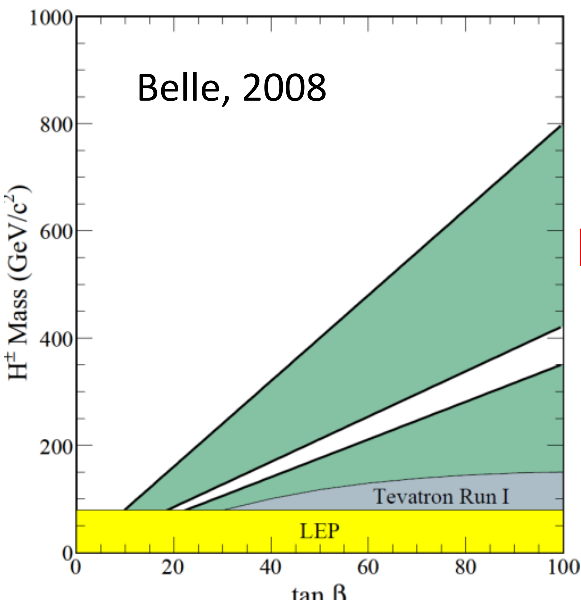


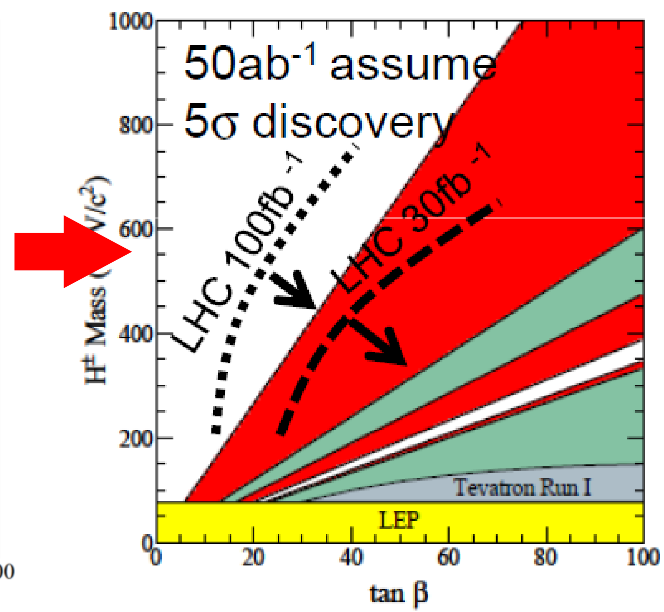


$$\mathcal{B}(B\to\tau\nu) = (1.15 \pm 0.23)\times10^{-4}$$

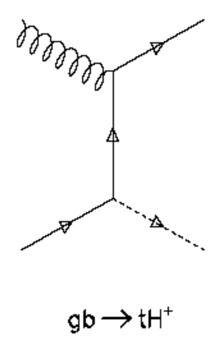


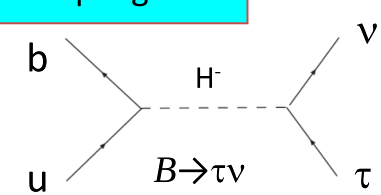


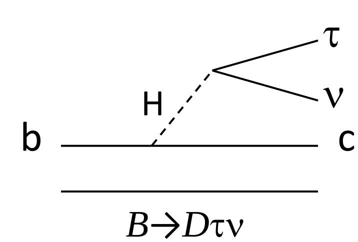




B->τν: H-b-u coupling
B->Dτν : H-b-c coupling
gb->tH: H-b-t coupling

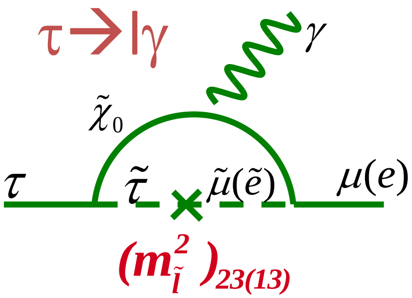


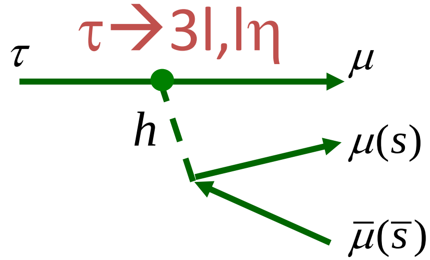




LFV in τ Decays

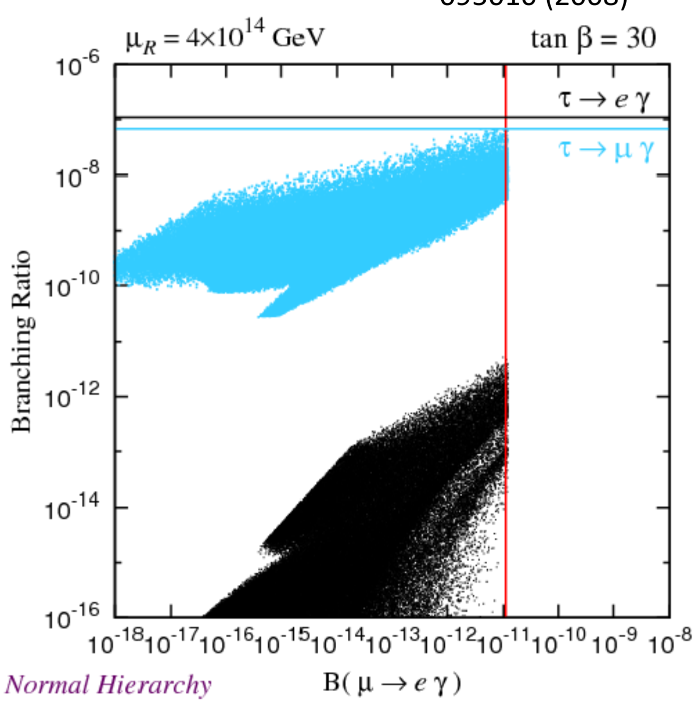
SU(5)+ν_R, non-degenerate ν_R(I),
Normal hierarchy

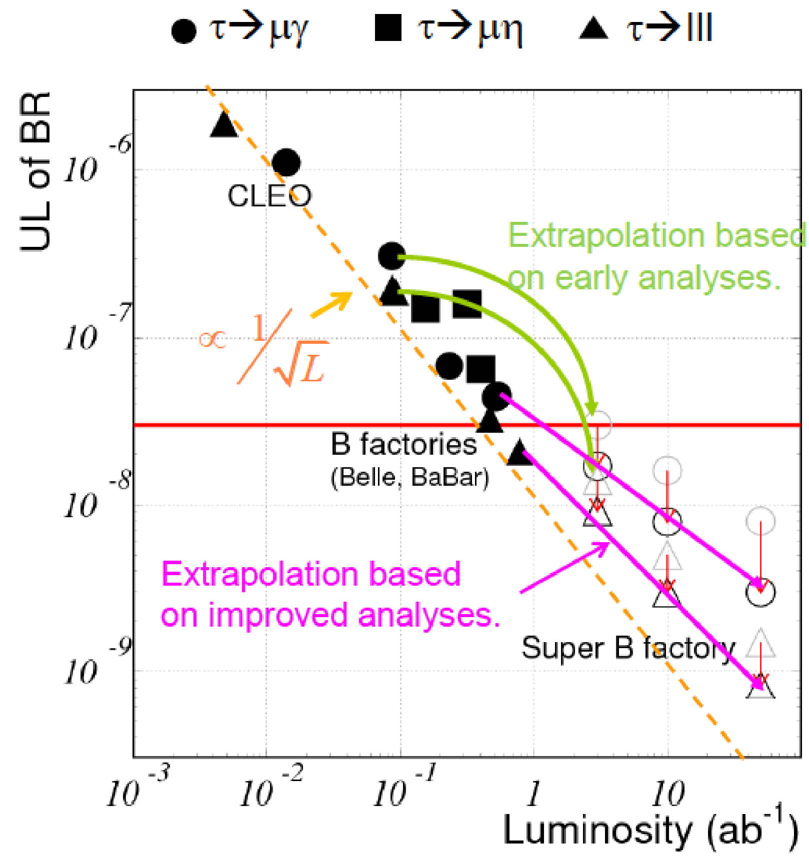




model	Br(τ→μγ)	Br(τ→lll)
mSUGRA+seesaw	10^{-7}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-Universal Z'	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-7}

Goto et al.,PRD77, 095010 (2008)





Physics Sensitivity of Belle-II (1)

Observable	Belle 2006	SuperKEKB		†LHCb	
	(~0.5 ab^{-1})	(5 ab^{-1})	(50 ab^{-1})	(2 fb^{-1})	(10 fb^{-1})
Leptonic/semileptonic B decays					
$\mathcal{B}(B^+ \to \tau^+\nu)$	3.5σ	10%	3%	-	-
$\mathcal{B}(B^+ \to \mu^+\nu)$	†† $< 2.4\mathcal{B}_{SM}$	4.3 ab^{-1} for 5σ discovery		-	-
$\mathcal{B}(B^+ \to D\tau\nu)$	-	8%	3%	-	-
$\mathcal{B}(B^0 \to D\tau\nu)$	-	30%	10%	-	-
LFV in τ decays (U.L. at 90% C.L.)					
$\mathcal{B}(\tau \to \mu\gamma)$ $[10^{-9}]$	45	10	5	-	-
$\mathcal{B}(\tau \to \mu\eta)$ $[10^{-9}]$	65	5	2	-	-
$\mathcal{B}(\tau \to \mu\mu\mu)$ $[10^{-9}]$	21	3	1	-	-
Unitarity triangle parameters					
$\sin 2\phi_1$	0.026	0.016	0.012	~0.02	~0.01
ϕ_2 $(\pi\pi)$	11°	10°	3°	-	-
ϕ_2 $(\rho\pi)$	$68° < \phi_2 < 95°$	3°	1.5°	10°	4.5°
ϕ_2 $(\rho\rho)$	$62° < \phi_2 < 107°$	3°	1.5°	-	-
ϕ_2 (combined)		2°	$\lesssim 1°$	10°	4.5°
ϕ_3 $(D^{(*)}K^{(*)})$ (Dalitz mod. ind.)	20°	7°	2°	8°	
ϕ_3 $(DK^{(*)})$ (ADS+GLW)	-	16°	5°	5-15°	
ϕ_3 $(D^{(*)}\pi)$	-	18°	6°		
ϕ_3 (combined)		6°	1.5°	4.2°	2.4°
$\|V_{ub}\|$ (inclusive)	6%	5%	3%	-	-
$\|V_{ub}\|$ (exclusive)	15%	12% (LQCD)	5% (LQCD)	-	-
$\bar{\rho}$	20.0%		3.4%		
$\bar{\eta}$	15.7%		1.7%		

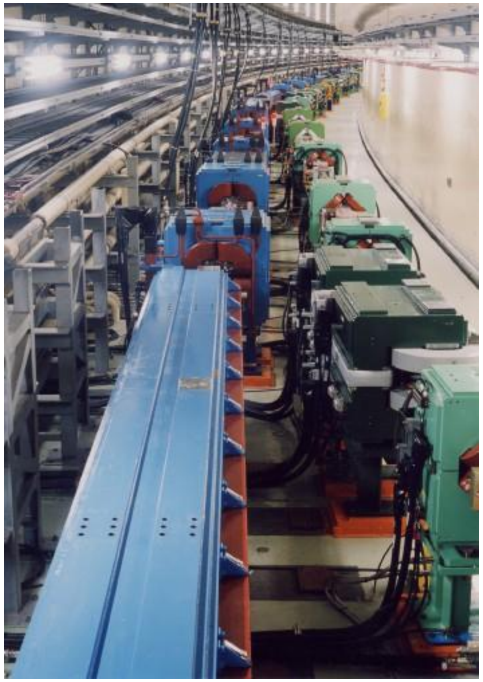
Physics Sensitivity of Belle-II (2)

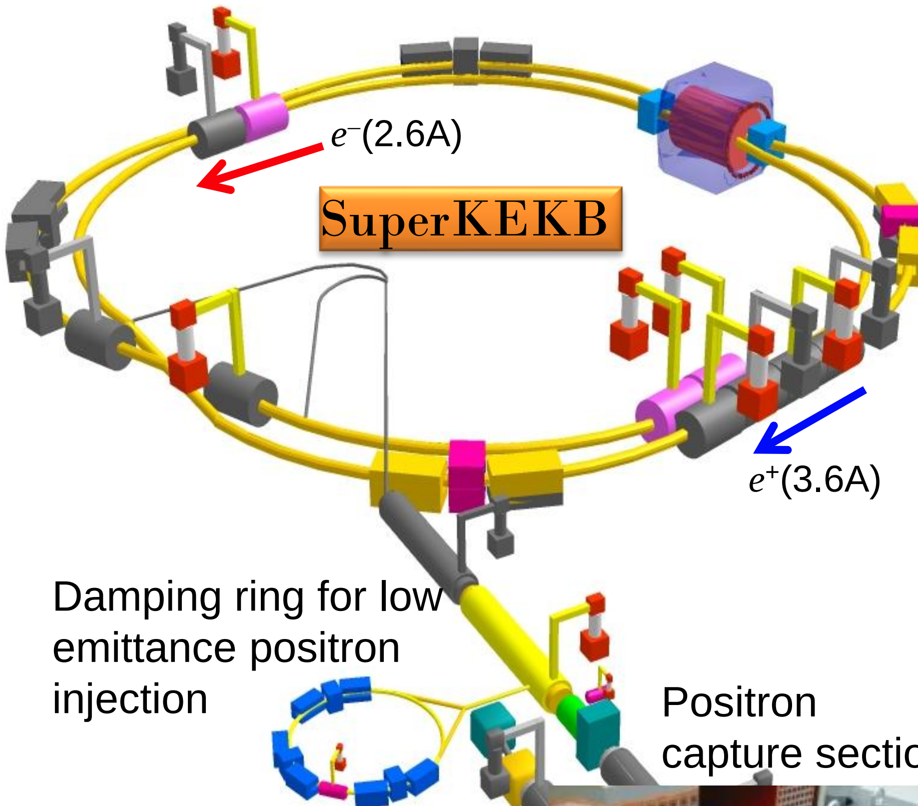
Observable	Belle 2006	SuperKEKB		†LHCb	
	(~0.5 ab^{-1})	(5 ab^{-1})	(50 ab^{-1})	(2 fb^{-1})	(10 fb^{-1})
Hadronic $b \to s$ transitions					
$\Delta\mathcal{S}_{\phi K^0}$	0.22	0.073	0.029		0.14
$\Delta\mathcal{S}_{\eta' K^0}$	0.11	0.038	0.020		
$\Delta\mathcal{S}_{K^0_S K^0_S K^0_S}$	0.33	0.105	0.037	-	-
$\Delta\mathcal{A}_{\pi^0 K^0_S}$	0.15	0.072	0.042	-	-
$\mathcal{A}_{\phi\phi K^+}$	0.17	0.05	0.014		
$\phi_1^{eff}(\phi K_S)$ Dalitz		3.3°	1.5°		
Radiative/electroweak $b \to s$ transitions					
$\mathcal{S}_{K^0_S \pi^0 \gamma}$	0.32	0.10	0.03	-	-
$\mathcal{B}(B \to X_s\gamma)$	13%	7%	6%	-	-
$A_{CP}(B \to X_s\gamma)$	0.058	0.01	0.005	-	-
C_9 from $A_{FB}(B \to K^*\ell^+\ell^-)$	-	11%	4%		
C_{10} from $A_{FB}(B \to K^*\ell^+\ell^-)$	-	13%	4%		
C_7/C_9 from $A_{FB}(B \to K^*\ell^+\ell^-)$	-		5%		7%
R_K		0.07	0.02		0.043
$\mathcal{B}(B^+ \to K^+\nu\nu)$	†† $< 3\ \mathcal{B}_{\rm SM}$		30%	-	-
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	†† $< 40\ \mathcal{B}_{\rm SM}$		35%	-	-
Radiative/electroweak $b \to d$ transitions					
$\mathcal{S}_{\rho\gamma}$	-	0.3	0.15		
$\mathcal{B}(B \to X_d\gamma)$	-	24% (syst.)		-	-

Physics reach with 50 ab^{-1}: Physics at Super B Factory (Belle II authors + guests) hep-ex arXiv:1002.5012

Accelerator upgrade

Low emittance lattice



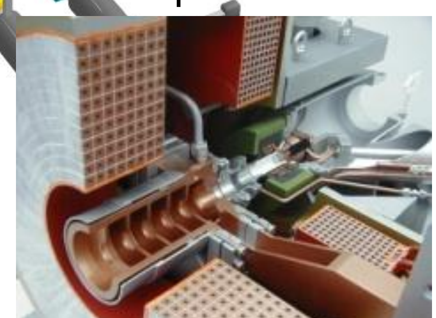


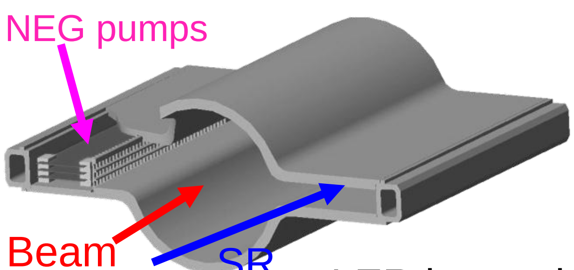
IR with β_y*=0.3mm
SC final focus system

Add RF systems for
higher beam current

Damping ring for low
emittance positron
injection

Positron
capture section





LER beampipe to suppress
photoelectron instability

SuperKEKB – Machine parameters

Parameter	Units	KEKB		SuperKEKB	
		HER (e^-)	LER (e^+)	HER (e^-)	LER (e^+)
Circumference	m	3016.3		3016.3	
Energy	GeV	8	3.5	7	4
Crossing angle	mrad	22		83	
β_x at IP	cm			2.5	3.2
β_y at IP	mm	5.9	5.9	0.30	0.27
ε_x (emittance)	10^{-9} m	24	18	5.3	3.2
Emittance ratio	%			0.35	0.40
σ_z	mm	6	6	5	6
Beam current	mA	1190	1640	2620	3600
σ_x at IP	10^{-6} m			7.75	10.2
σ_y at IP	10^{-9} m	940	940	59	59
ξ_x (tune shift)				0.0028	0.0028
ξ_y		0.090	0.129	0.0875	0.09
Luminosity	cm^{-2} s^{-1}	2×10^{34}		8×10^{35}	

High beam current

Nanobeam

x40

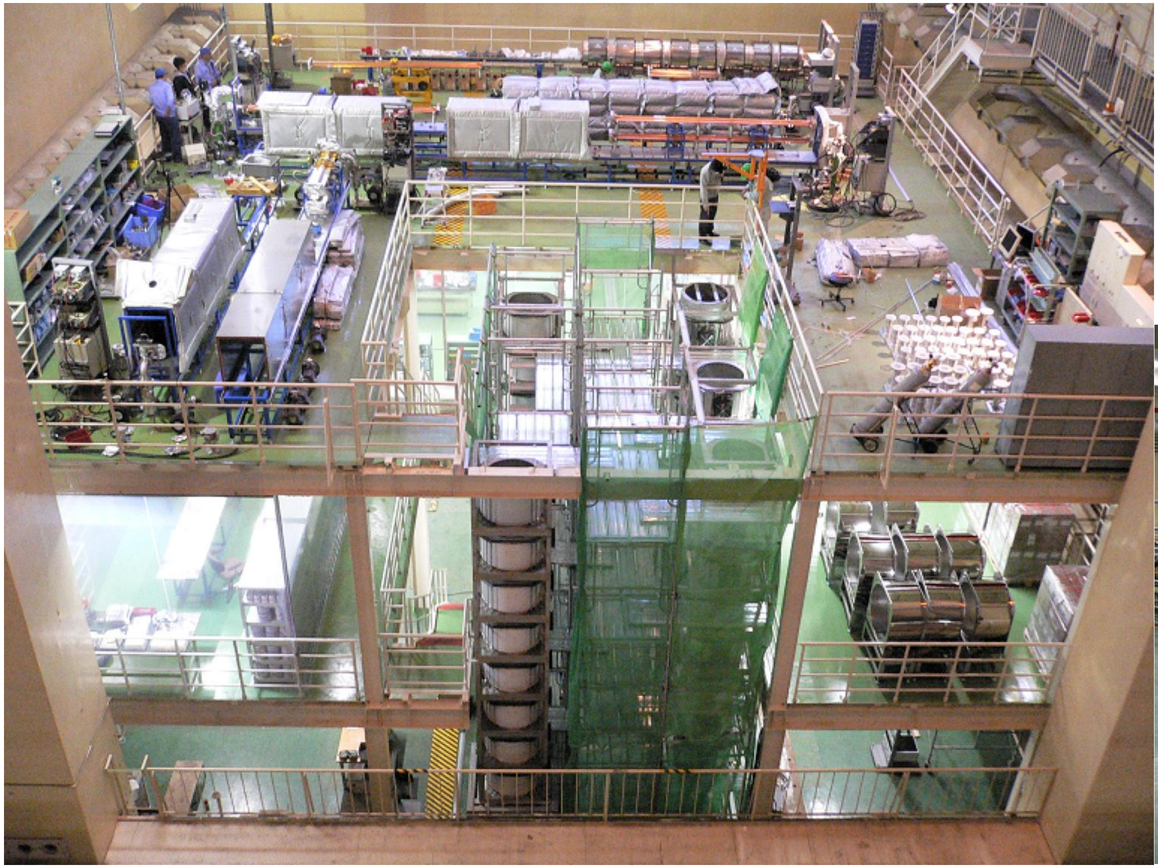
Beam pipe production at BINP

Basic design of the vacuum system is near completion, and mass production of main components is going on:

- Al beam pipes with an antechamber for LER arc sections of 2 km length
- Cu beam pipes for the wiggler sections and the straight sections

Beam pipe fabrication and surface coating

- All the aluminum beam pipes have been delivered.
- Surface treatment facility has been built in KEK. Baking and TiN coating is now being started.
- 1100 beam pipes will be treated in 2 years.

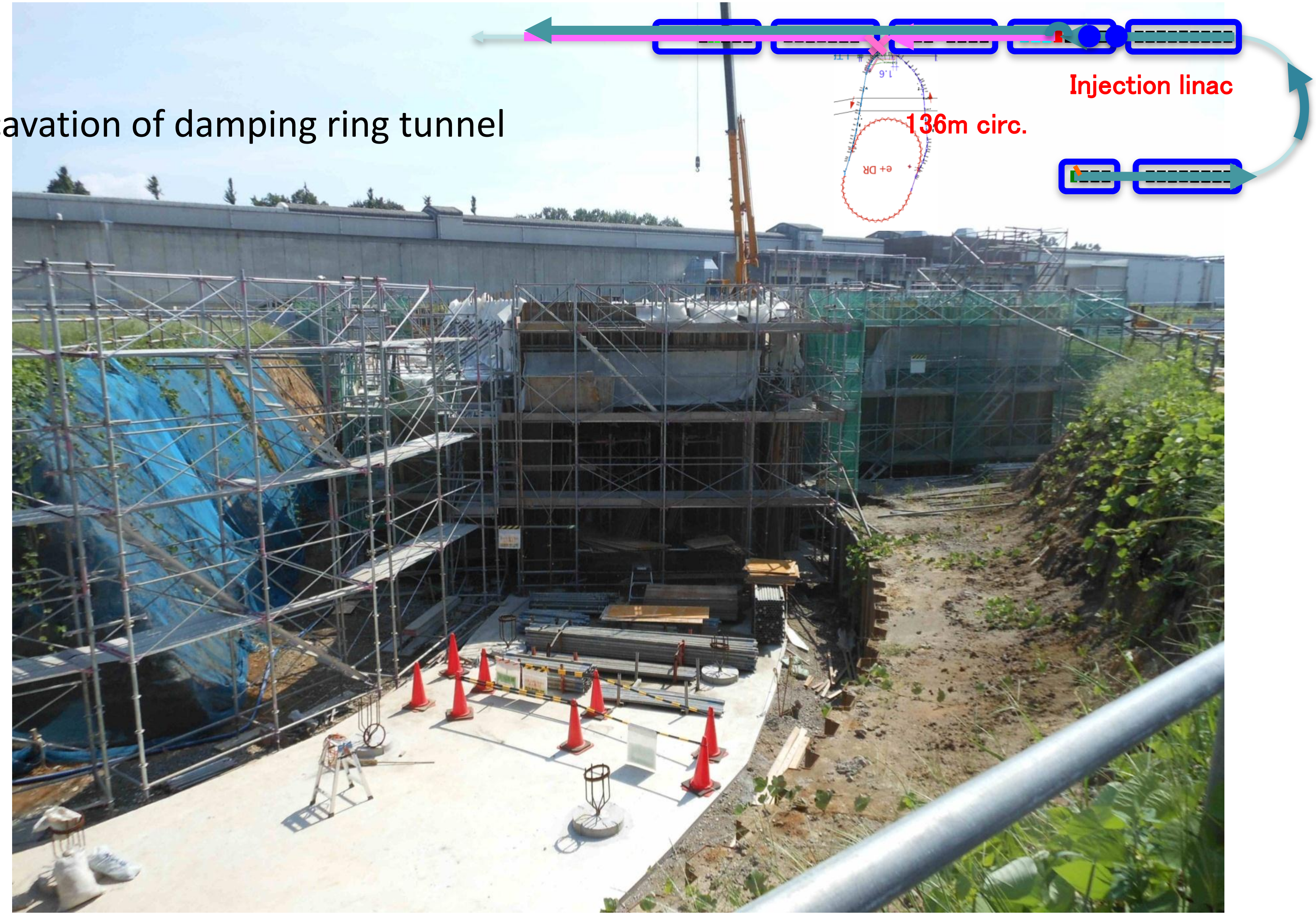


Installation of the new bending magnet at the KEKB tunnel

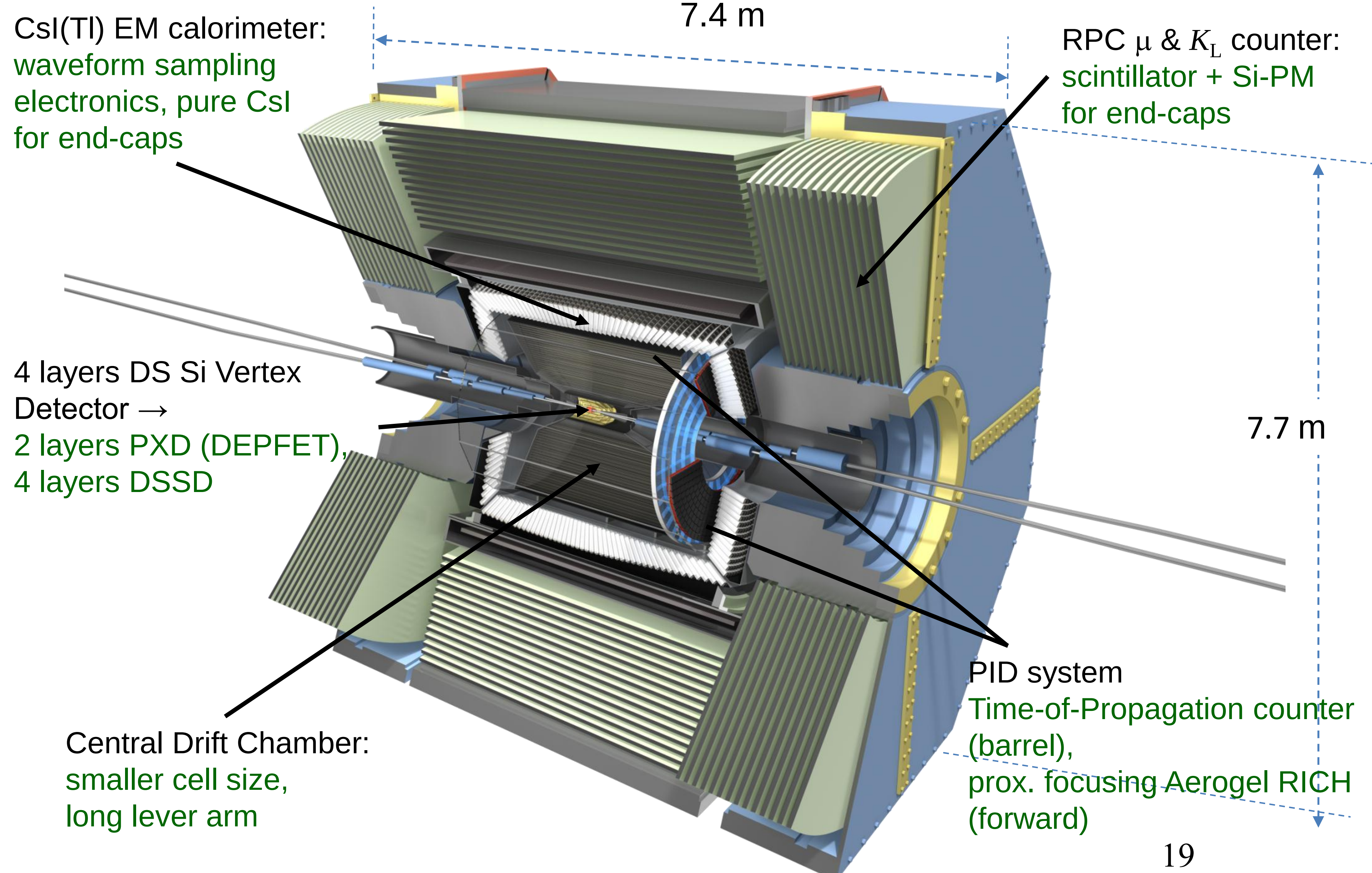
Field mapping

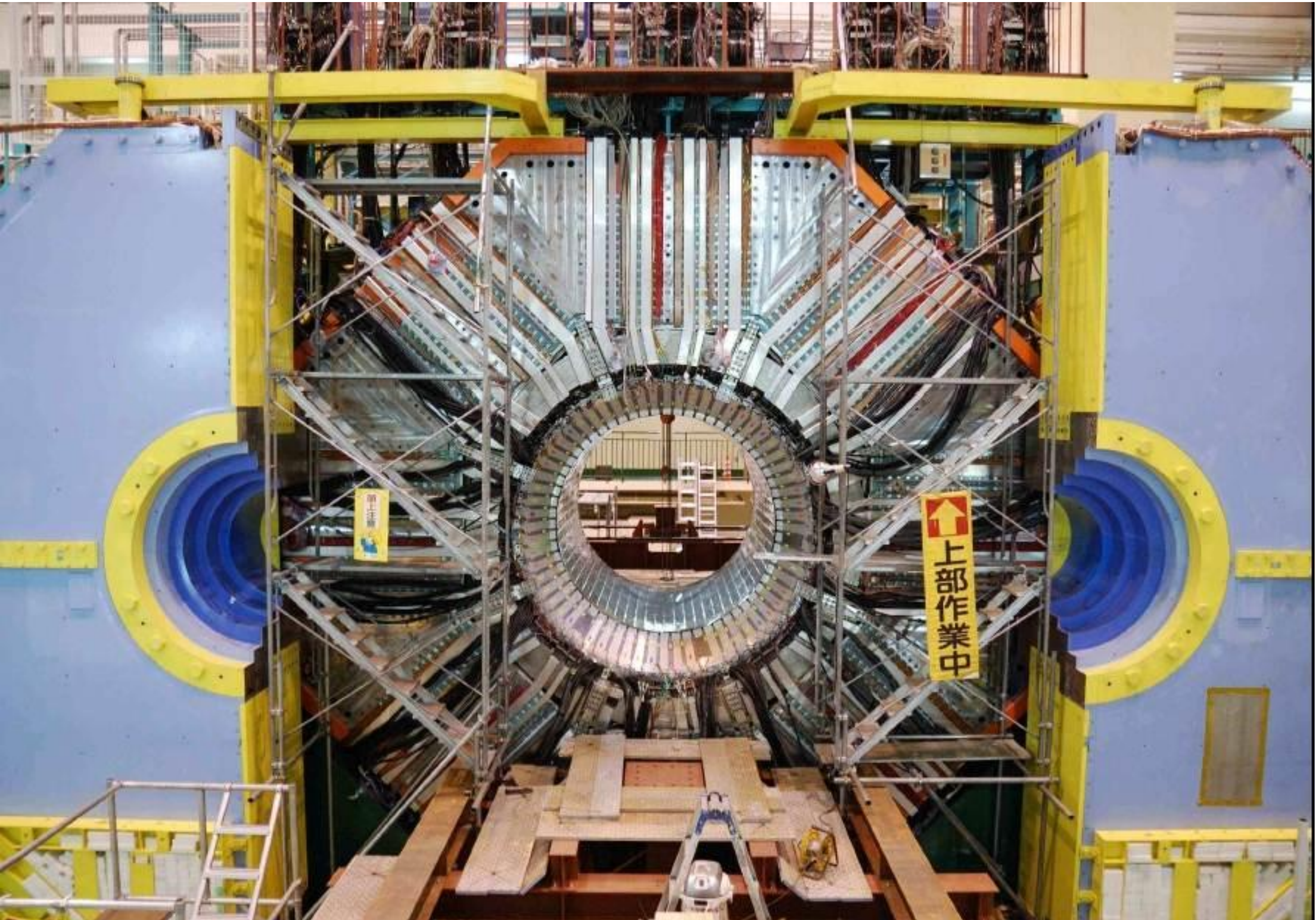
Positron Damping Ring

Excavation of damping ring tunnel



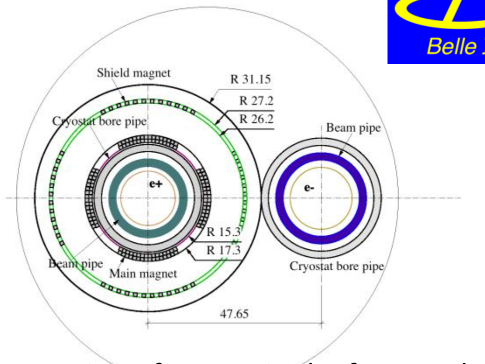
Belle II Detector Upgrade




上部作業中

IR Design

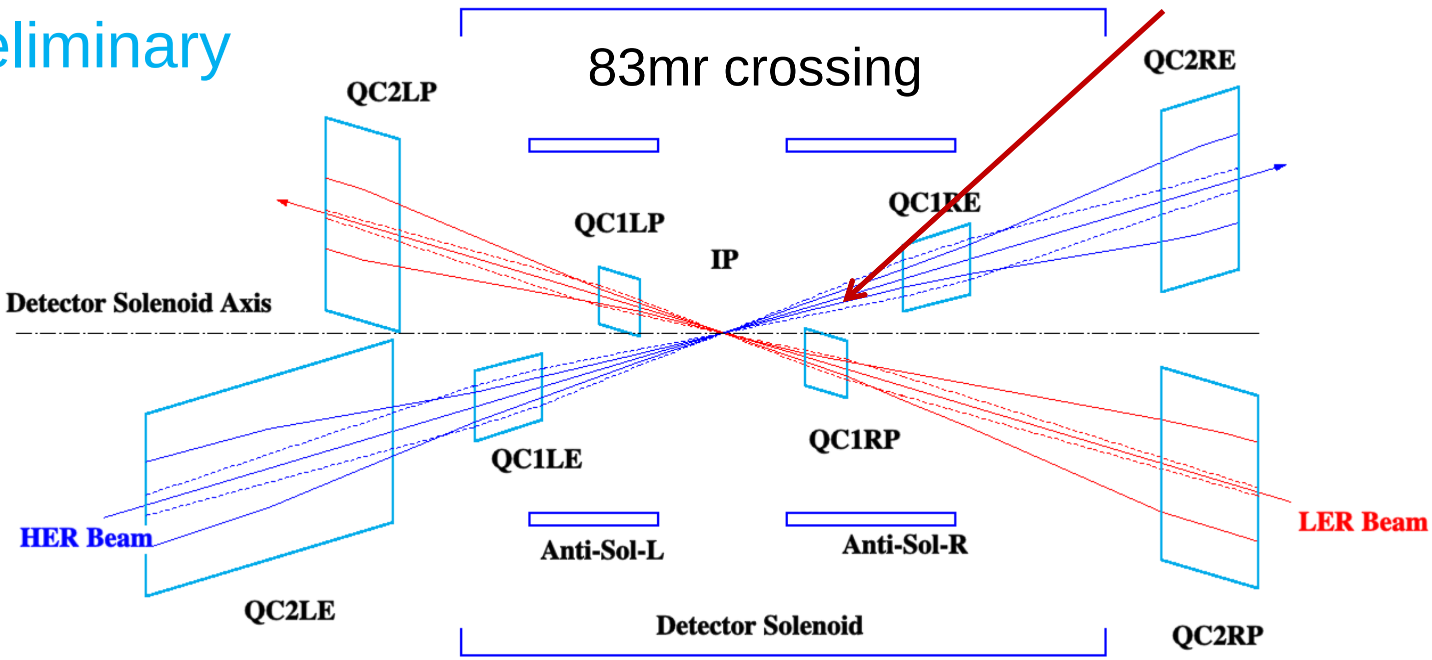
- Large crossing angle = 83mrad.
- Separated quads. for the final focus.



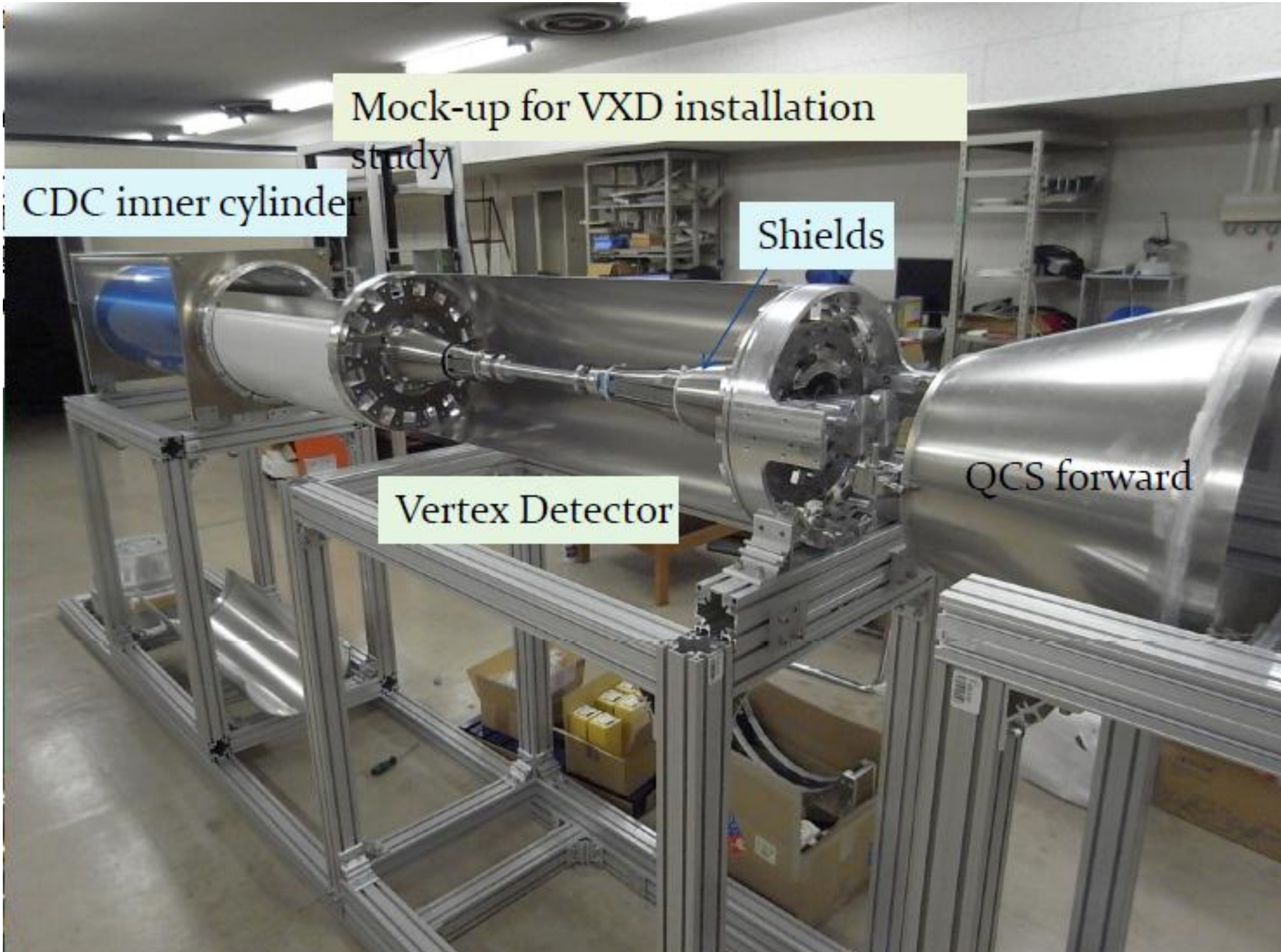
Cross section of QC1RP in the front end
Active shield quadrupole (corn type)

New IR design

preliminary

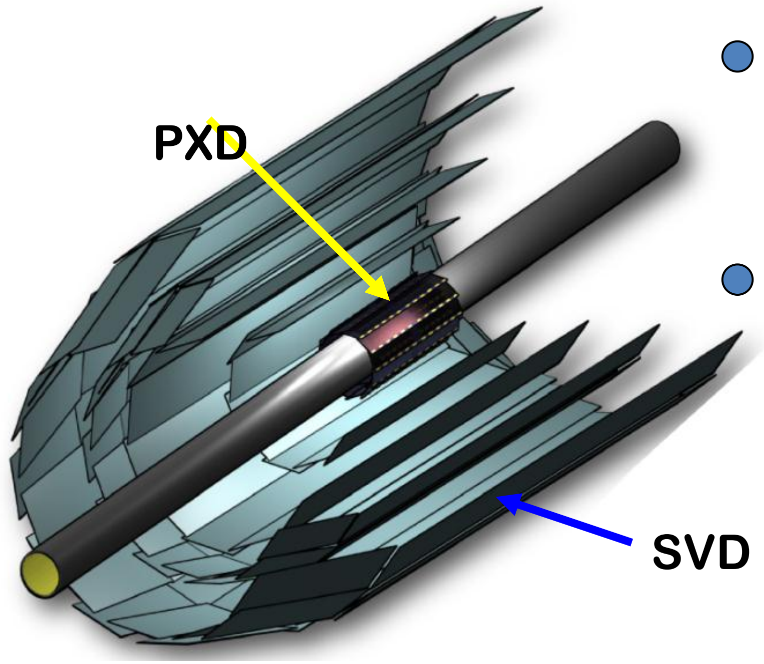


Basic design has been done. Detailed design optimization is in progress.


Mock-up for VXD installation study
CDC inner cylinder
Shields
QCS forward
Vertex Detector

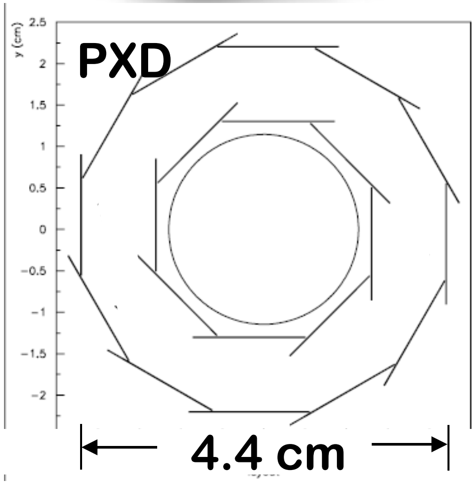
Vertex Detector

Nano beam option: 1 cm radius of beam pipe



- 2 layer Si pixel detector (DEPFET technology) ← „PXD“
  (R = 1.4, 2.2 cm) monolithic sensor
  thickness 75 μm (!), pixel size ~50 x 50 μm²
- 4 layer Si strip detector (DSSD) ← „SVD“
  (R = 3.8, 8.0, 10.5, 13.5 cm)

Significant improvement in z-vertex resolution

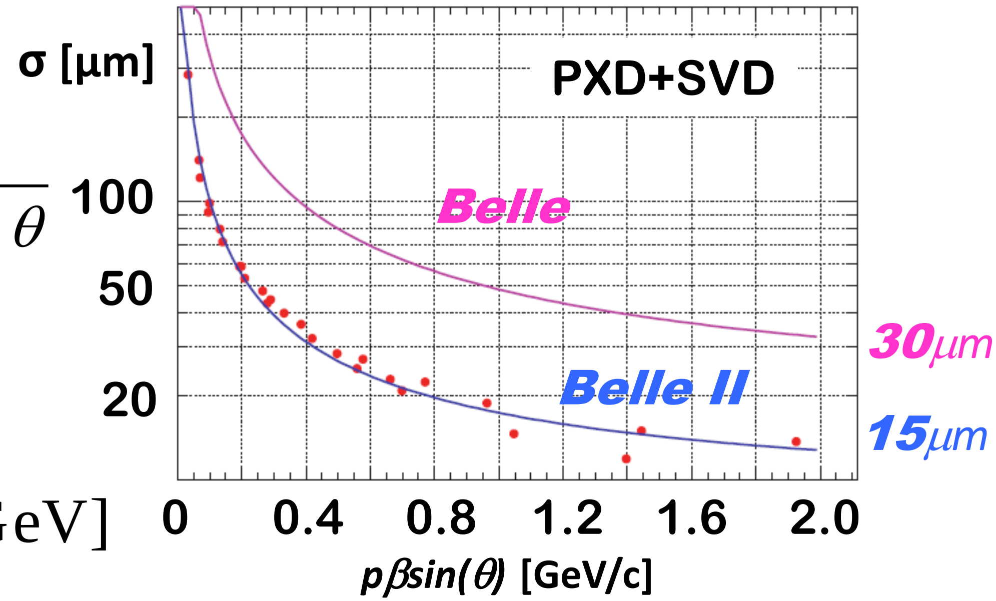


$$\sigma = a + \frac{b}{p\beta \sin^{5/2}\theta}$$

Belle II:

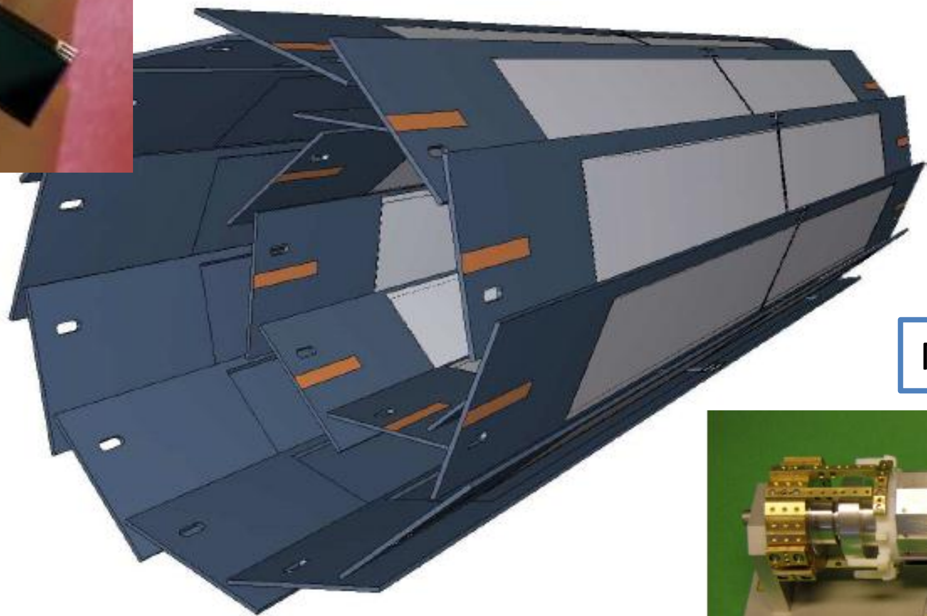
$$a = 8.5[\mu m]$$

$$b = 9.6[\mu m\ \mathrm{GeV}]$$

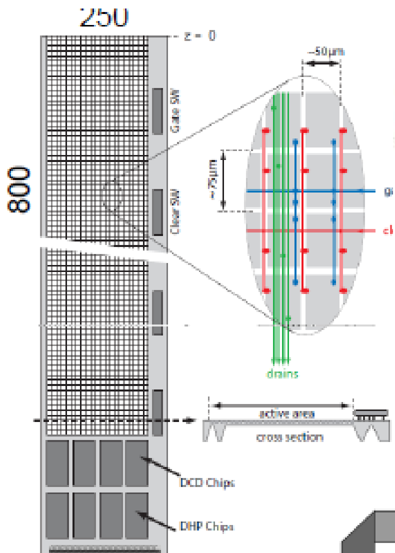


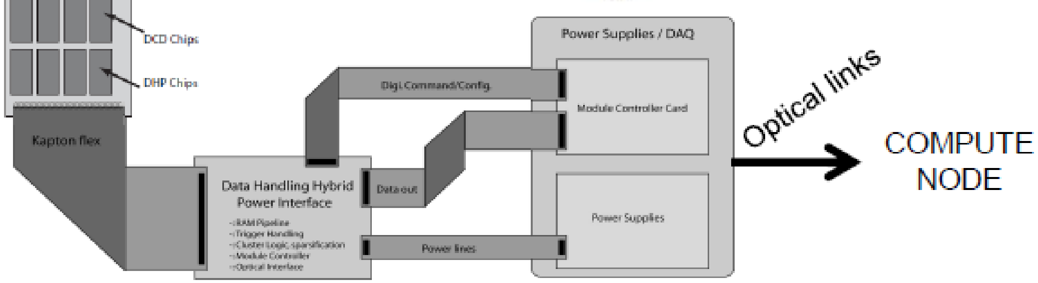
DEPFET pixels for Belle II

	radius	pixel	thickness
Layer 1	r = 14mm	50x50µm^2	75µm(0.21%X0)
Layer 2	r = 22mm	50x75µm^2	75µm



total of 8 M pixels

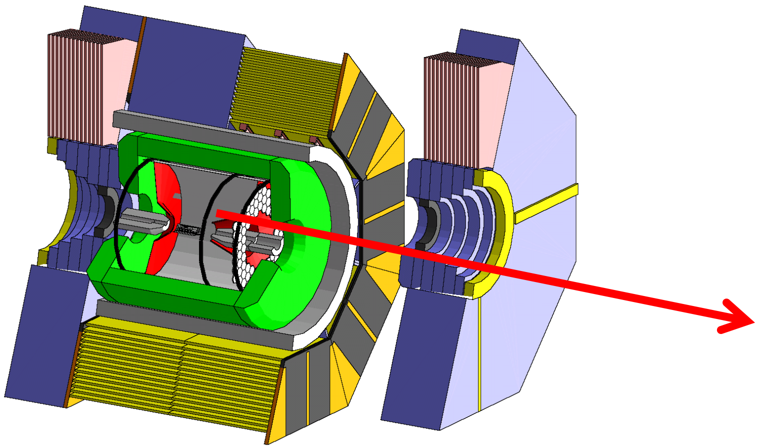




Mechanical mockup

Power consumption in sensitive area: 0.1W/cm^2 => air-cooling sufficient

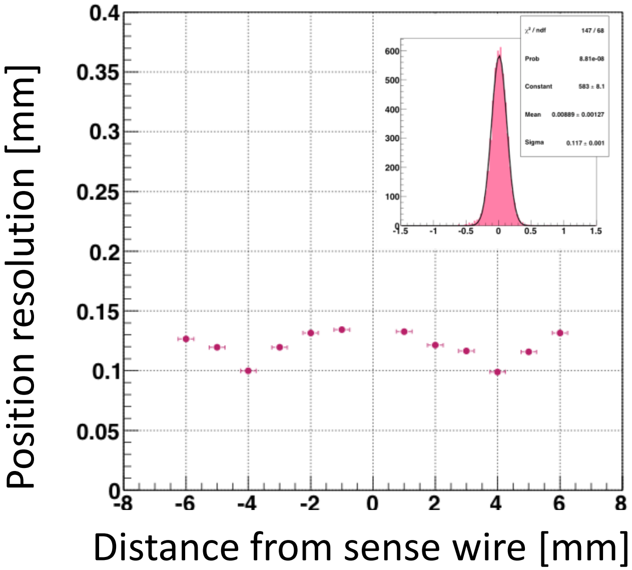
Central Drift Chamber



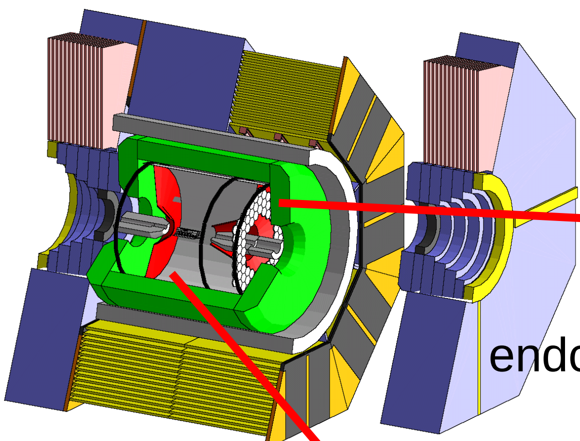
- Small cell (15mm × 18mm) configuration
- $He(50\%)+C_2H_6(50\%)$ + Al field wires → $0.3\%X_0$
- $\sigma_p/p \sim 0.3\%+0.1\% \times p(\mathrm{GeV})$ in B=1.5T
- $\sigma(dE/dx) \sim 6\%$

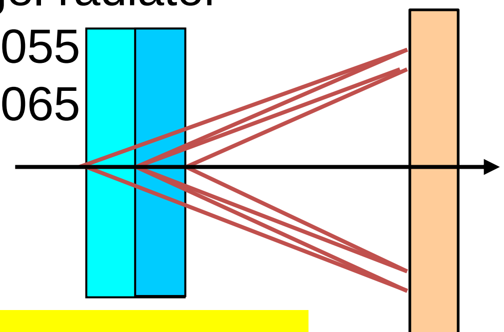
Prototype of compact readout board : ready
- ASIC (Preamp + Shaper + Discriminator)
- 1nsec TDC for drift time measurement
- 30MHz 10bit FADC for dE/dx measurement
- Ring buffer (5μsec) + Event buffer (16 events)

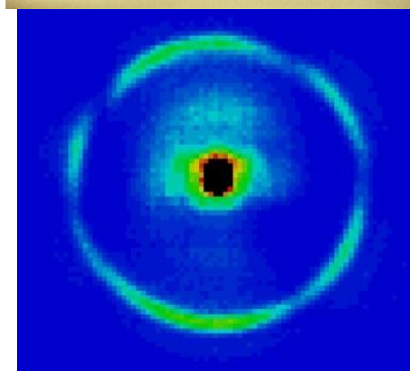
Beam test: done successfully



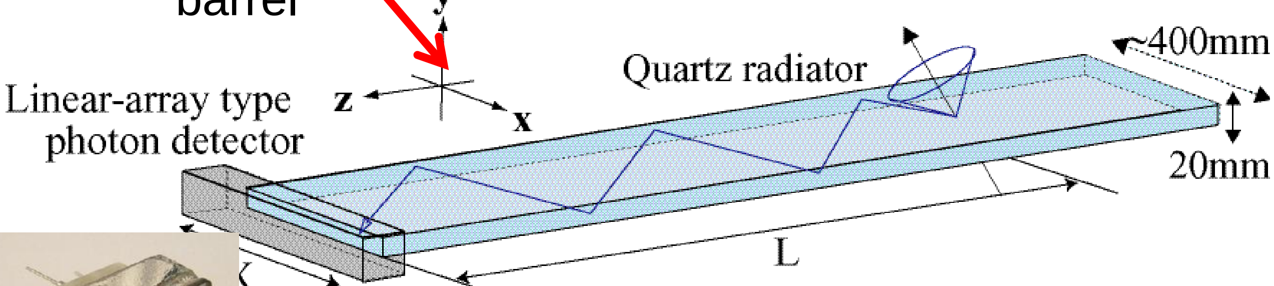
- Ring imaging Cherenkov detectors to separa
  4GeV/c with >4σ

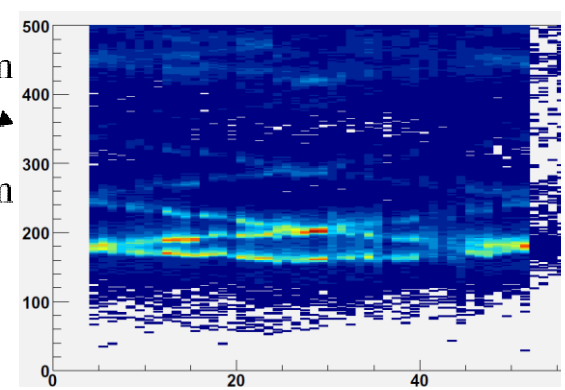


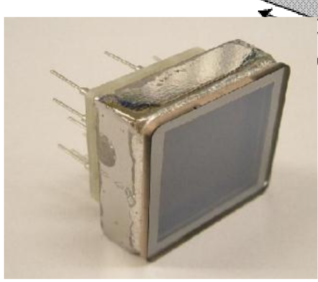




Aerogel RICH



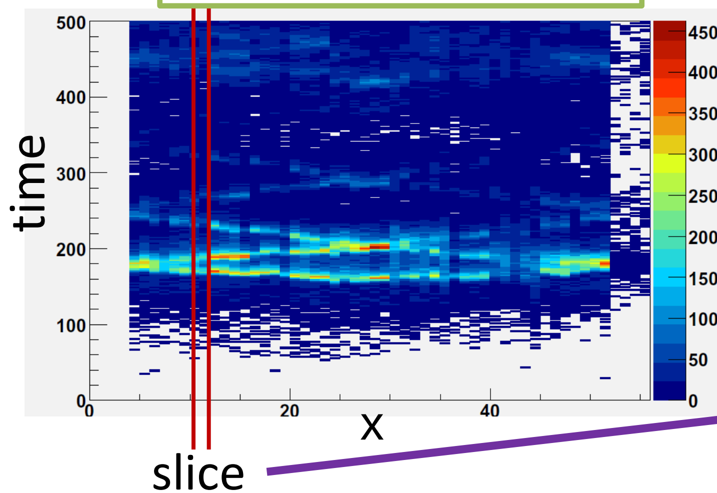


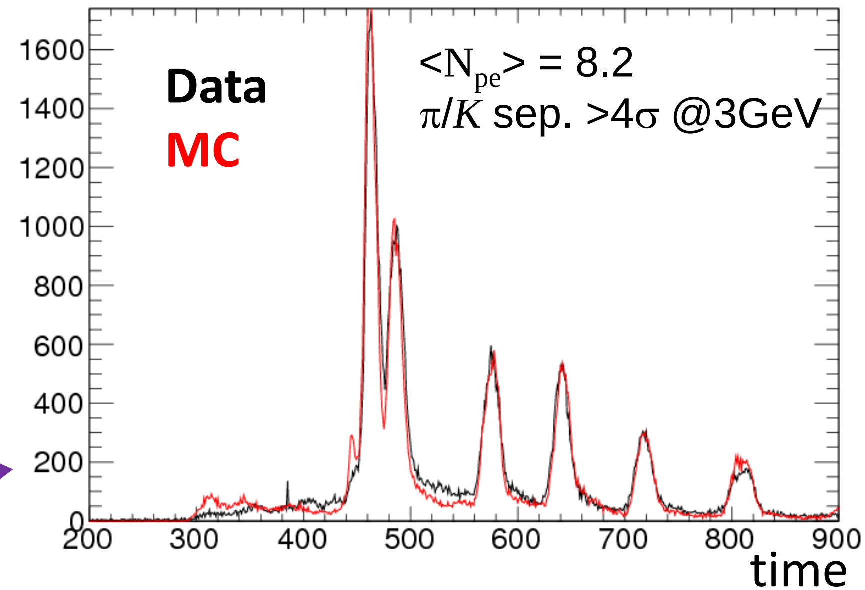


TOP (Time-Of-Propagation) Counter

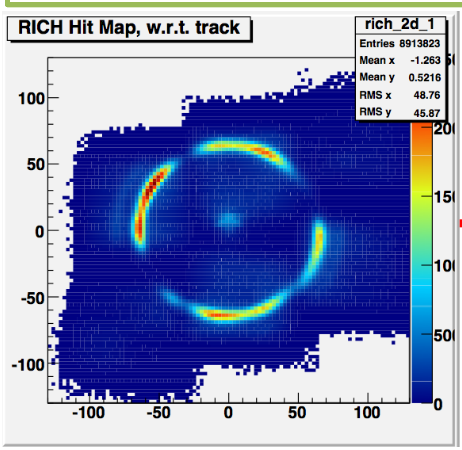
PID Detectors – Beam tests

Cherenkov “ring” by TOP

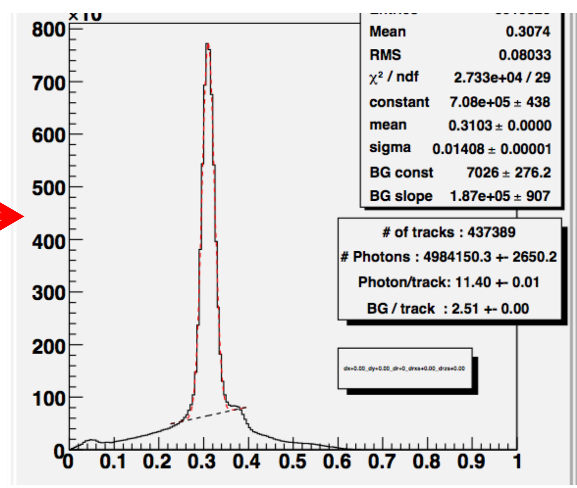




Cherenkov ring by ARICH



Radial distribution



Q.E.~21% achieved with Hamamatsu HAPD

<Npe> = 11.4

σ = 14.1 mrad

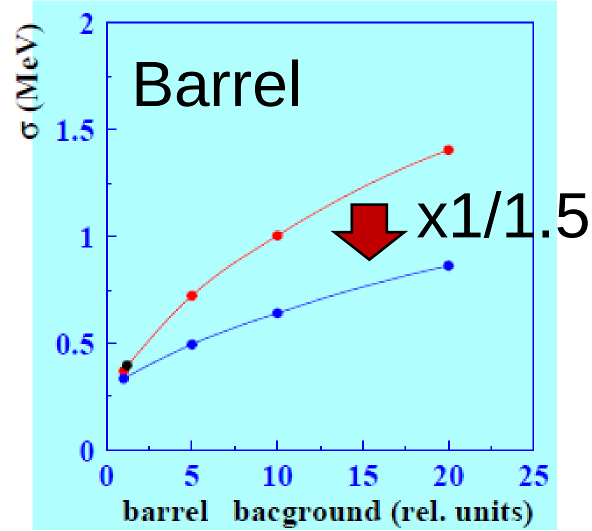
π/K sep. >5.5σ @4GeV

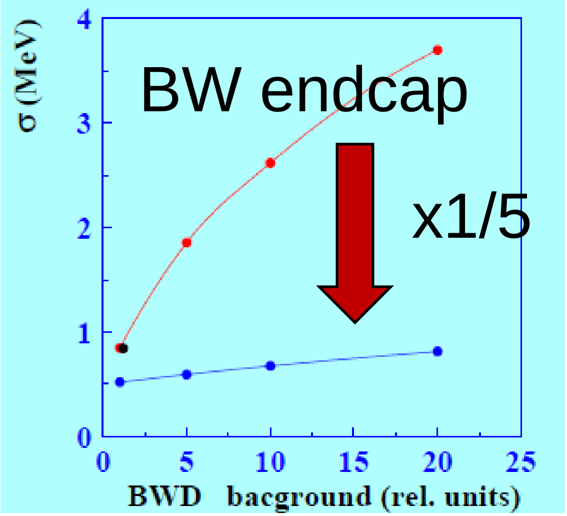
EM Calorimeter Upgrade

- Increase of dark currents due to neutron flux
- Fake clusters & pile-up noise

- Barrel:
  0.5μs shaping + 2MHz w.f. sampling.
- Endcap:
  pure CsI + photopentods
  30ns shaping + 43MHz w.f. sampling

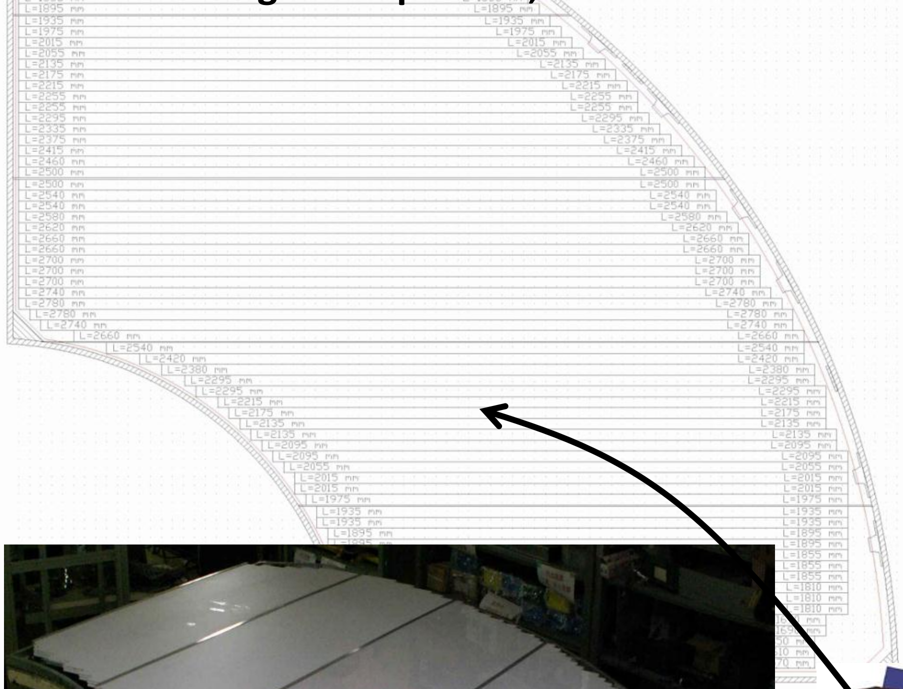
Pure CsI & photopentods



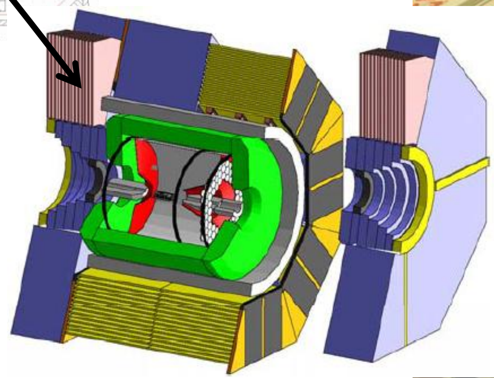


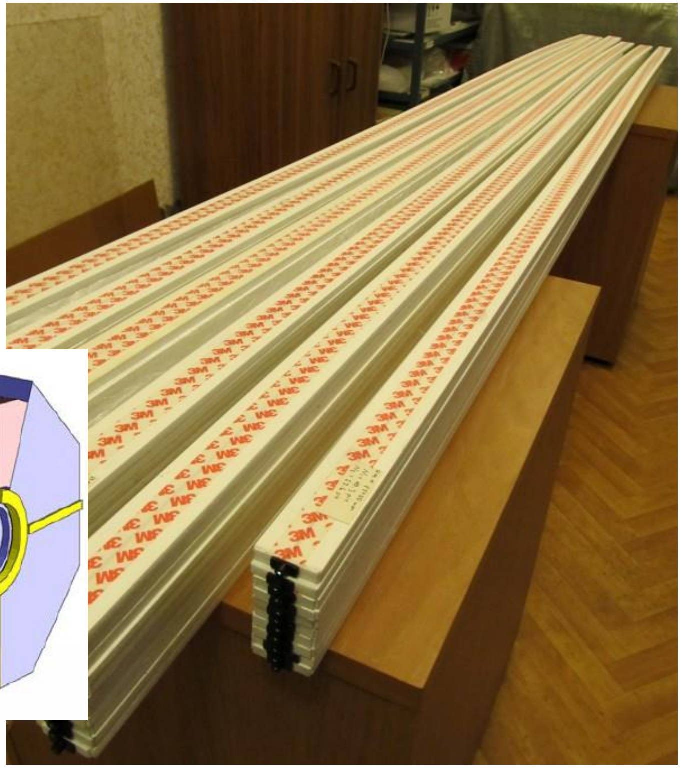
Endcap $K_L\mu$ Detector

- 75 strips (4 cm width)/1 layer/sector = 150 strips/superlayer
- 16800 strips for F&B endcap KLM
- the longest strip 2.8 m; the shortest 0.6 m

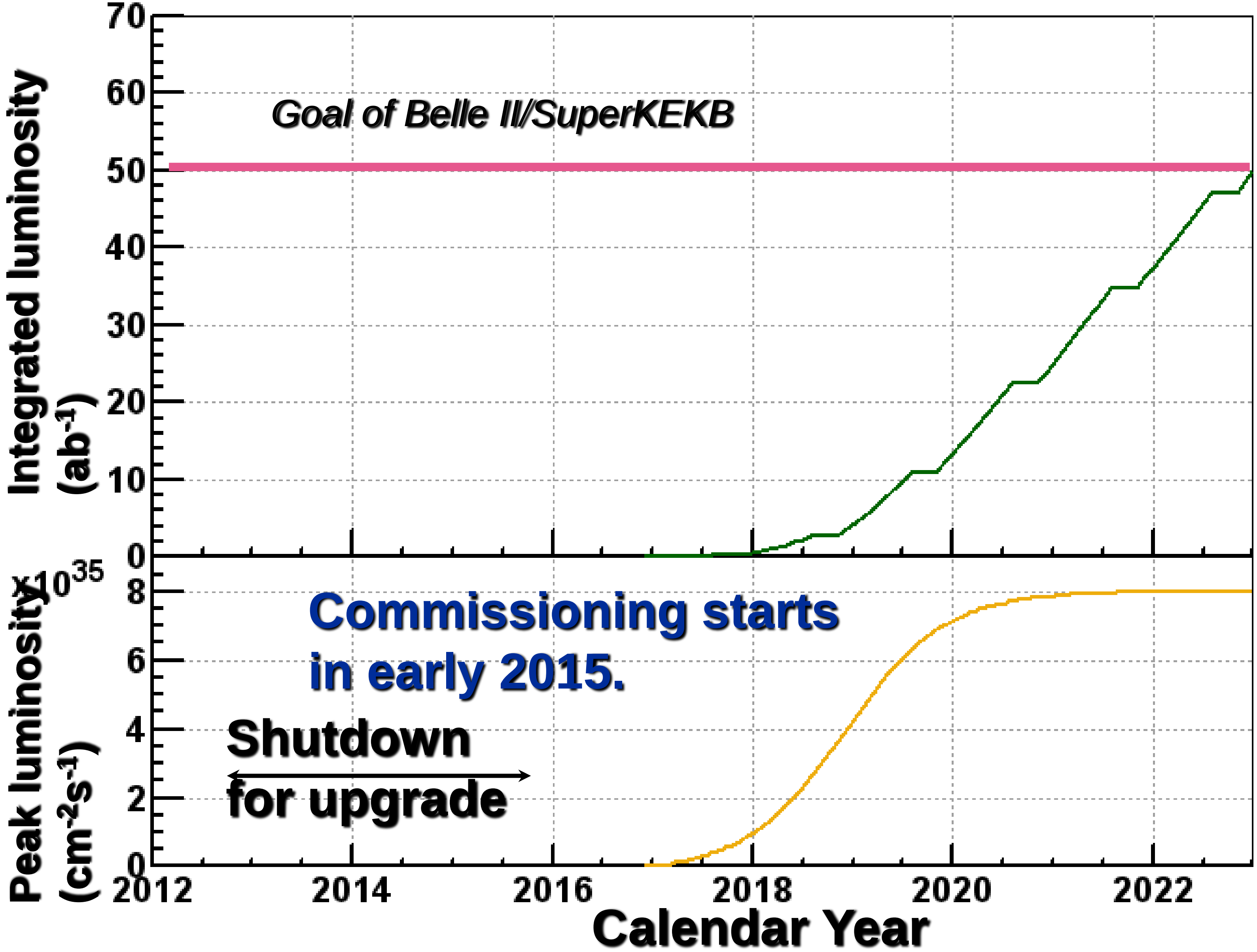


- WLS (blue → green) fiber in each strip (Y11 MC D=1.2mm)
- SiPM at one fiber end (at outer sector radius)
- mirrored far fiber end



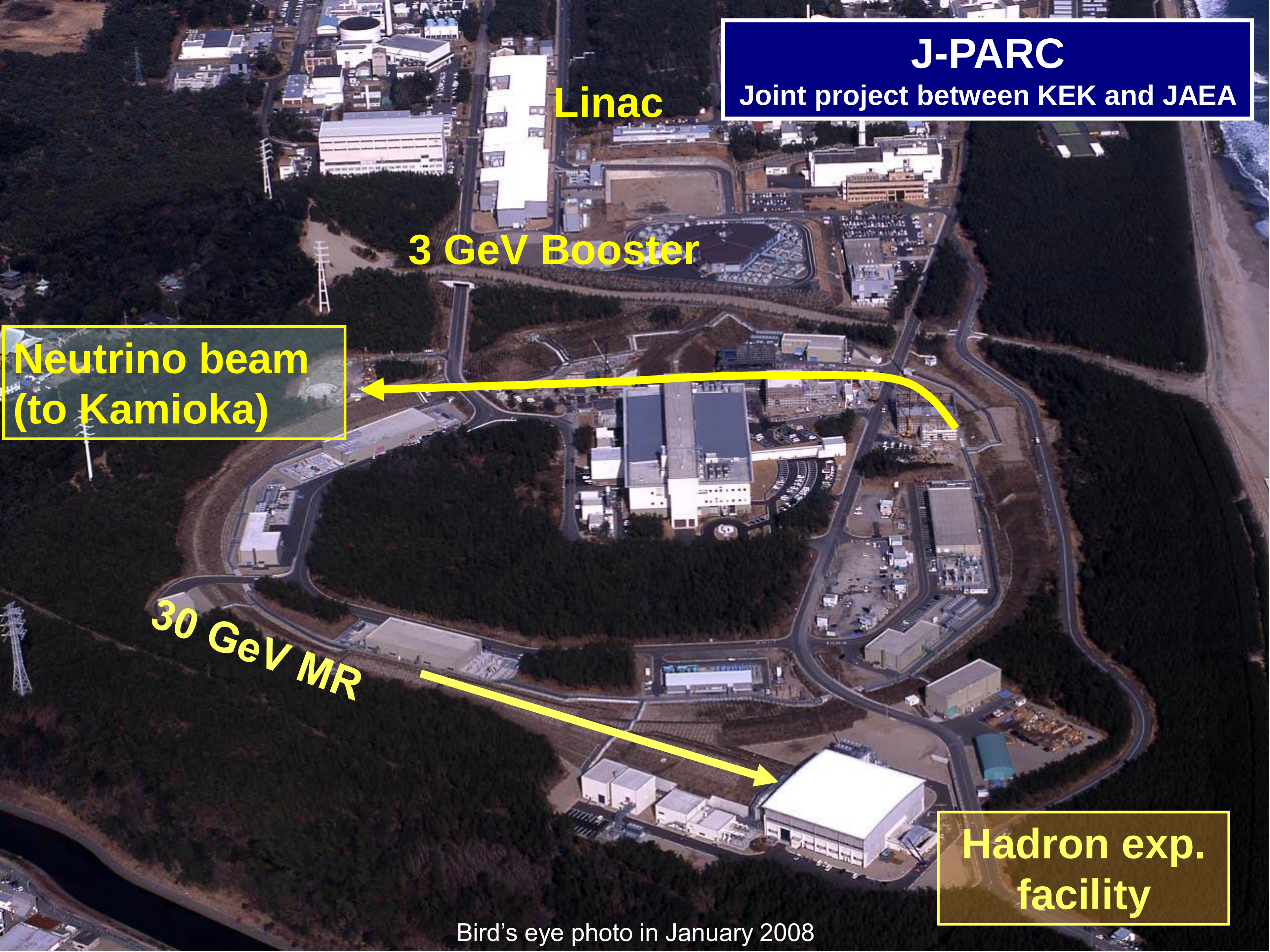


SuperKEKB luminosity projection



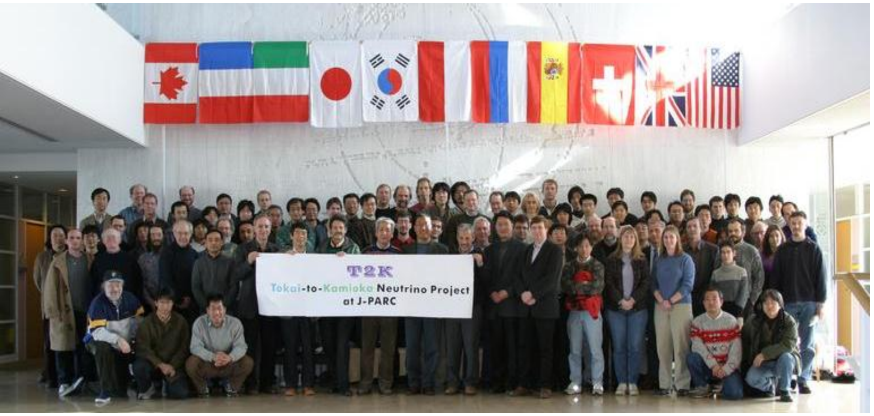
Belle-II Collaboration

- ~420 collaborators from 70 institutions in 20 countries
- Spokesperson:
  Peter Krizan (Ljubljana)
- Series of open collaboration meetings in 2008.03 ~2012.11



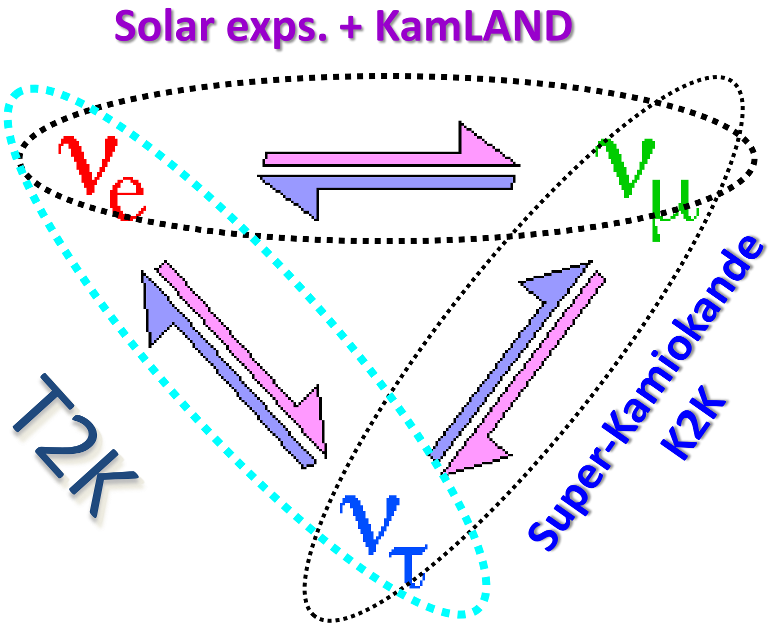
Bird’s eye photo in January 2008

T2K : Long Baseline Neutrino Experiment

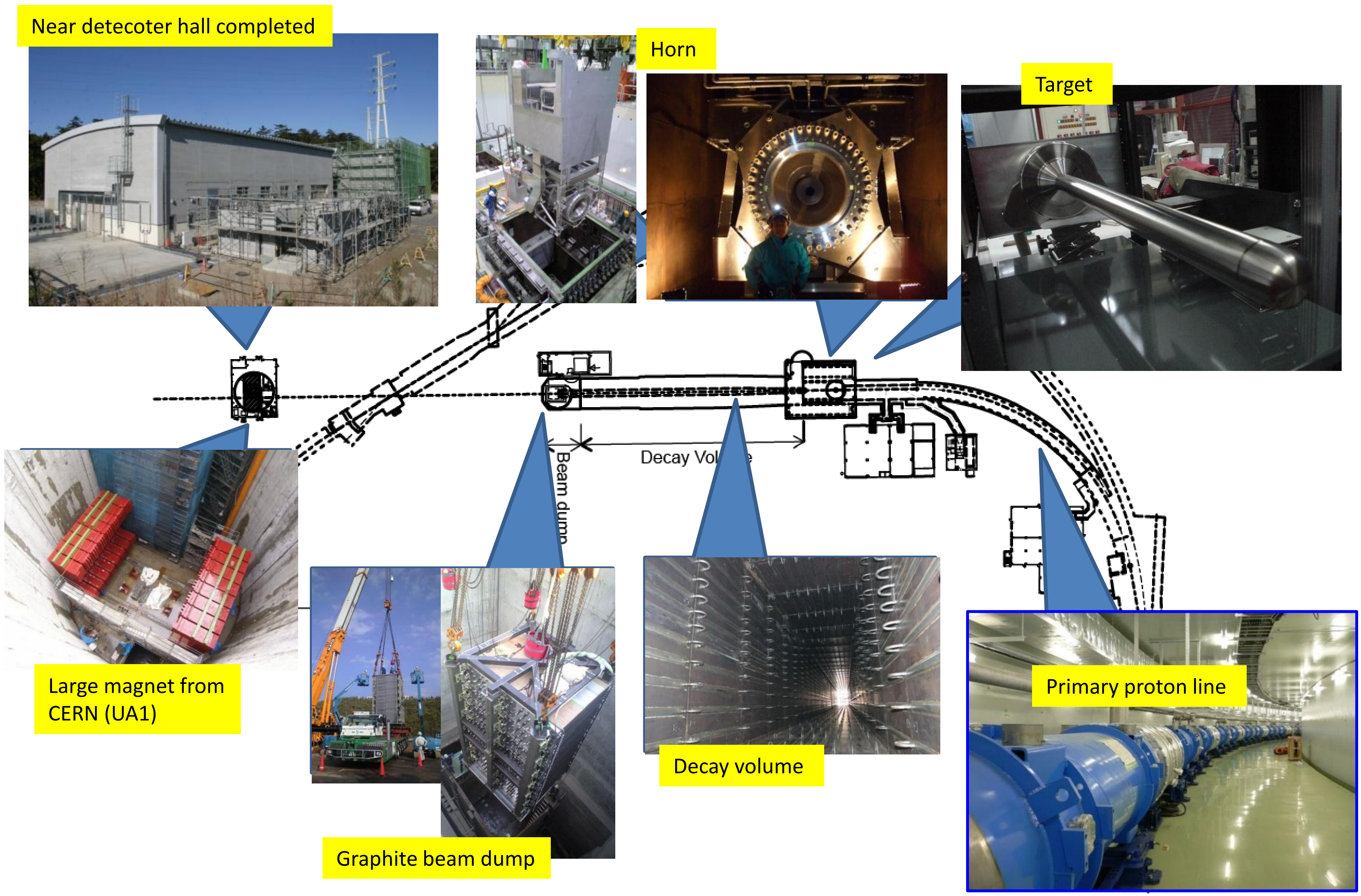


~400 members from 12 Countries:

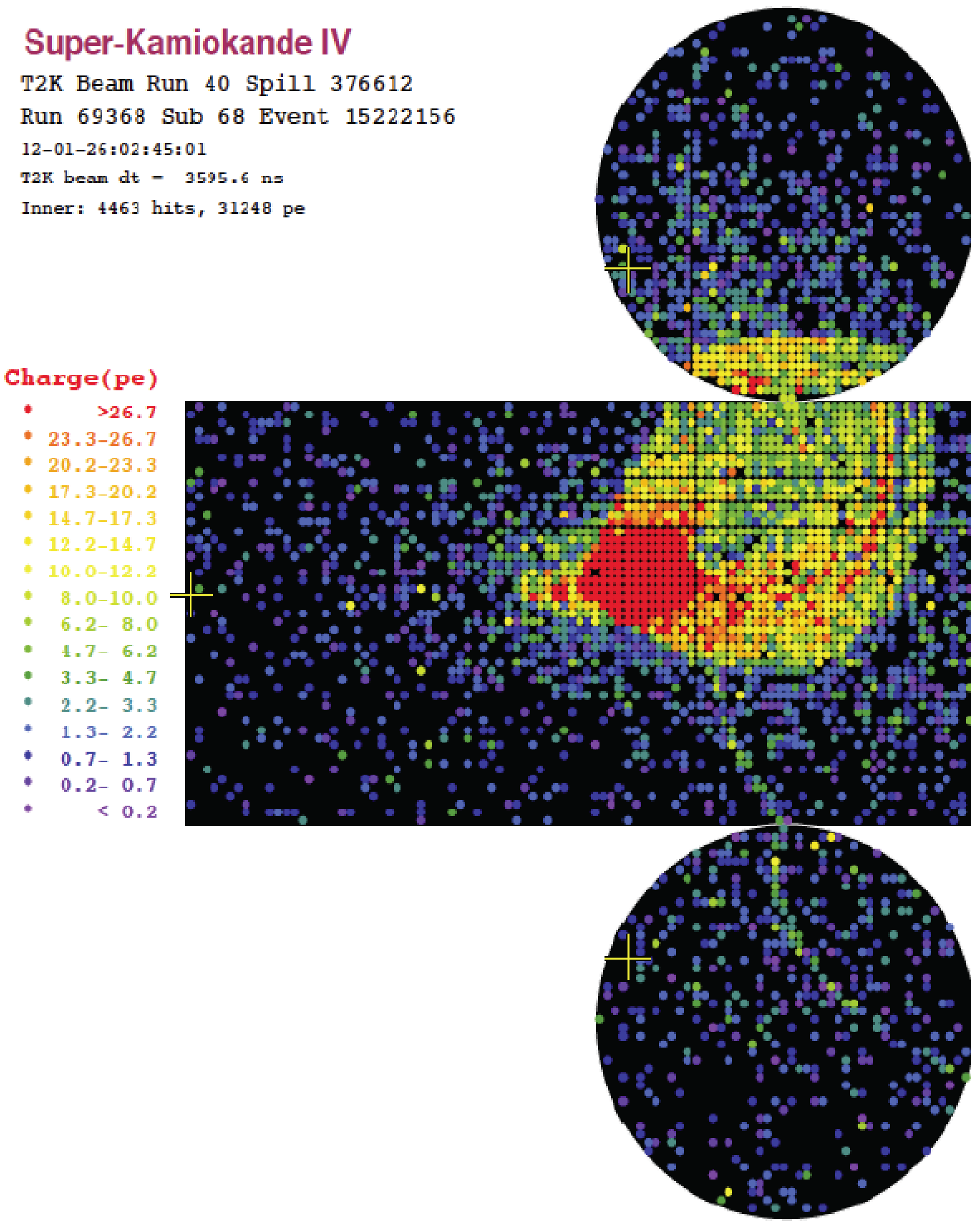
Japan(66), US(58), Canada(50),France(38), UK(37)
Switzerland(31),
Poland(22), Korea(13), Russia(12),
Spain(11), Italy(9), Germany(2)

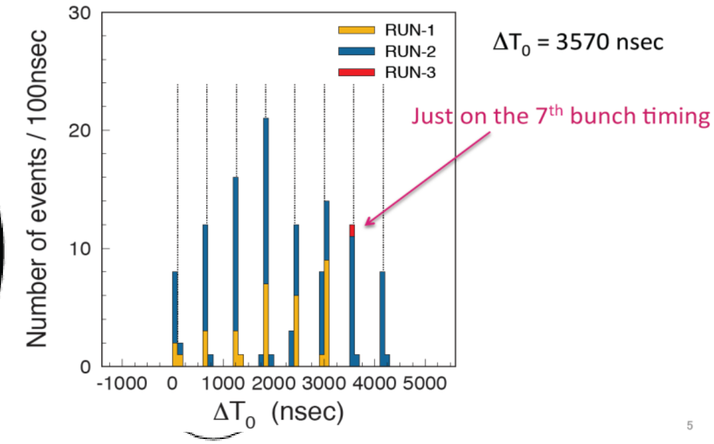


T2K beamline



First event in SK aft. the earthquake

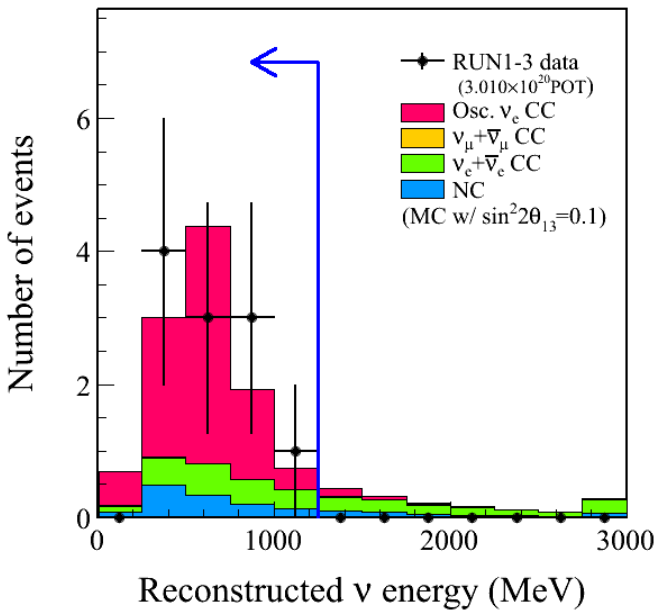


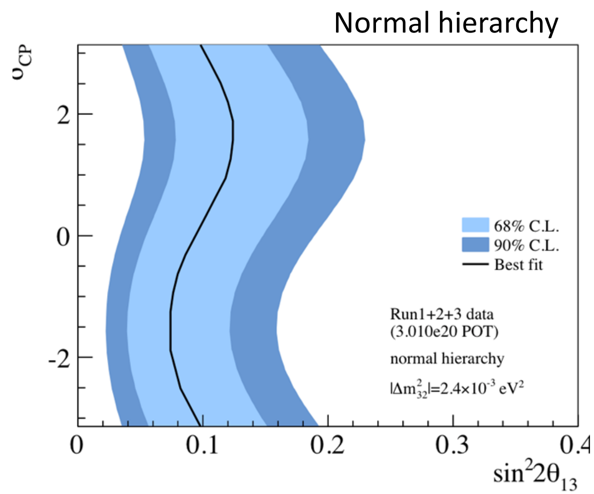


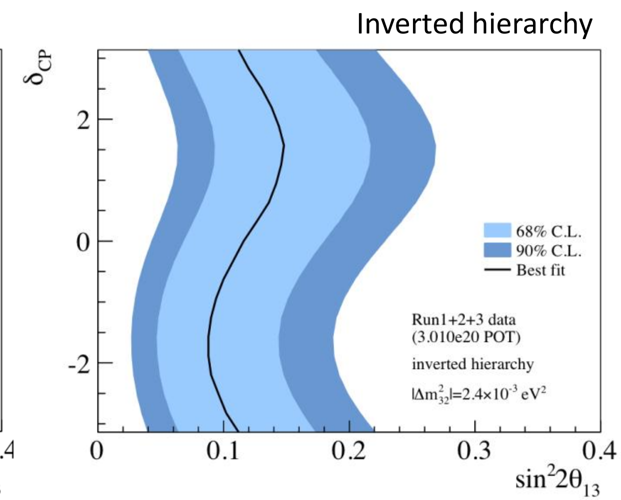
Latest Result of $\nu_\mu \to \nu_e$ from T2K

All the plots here are preliminary.

3.01×10^{20} POT

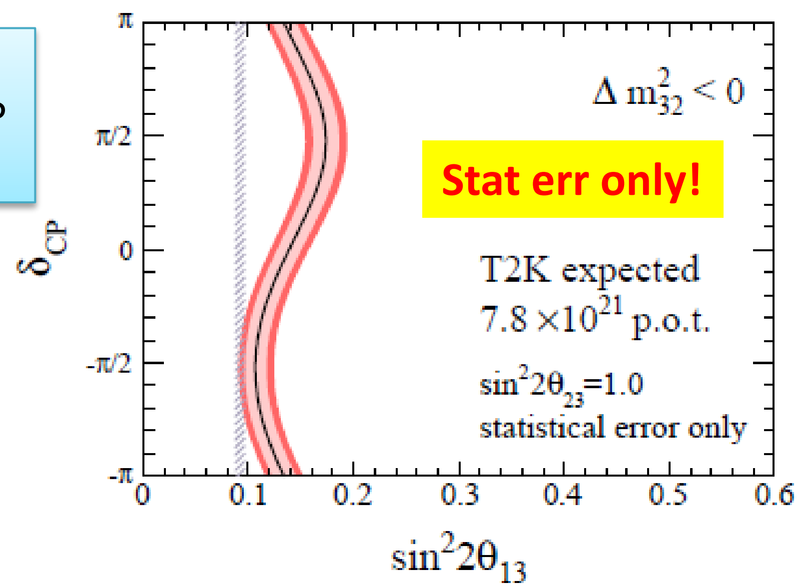






Improvement of both reactor and accelerator experiments will provide first handle on the CP violating complex phase δ_{CP}.

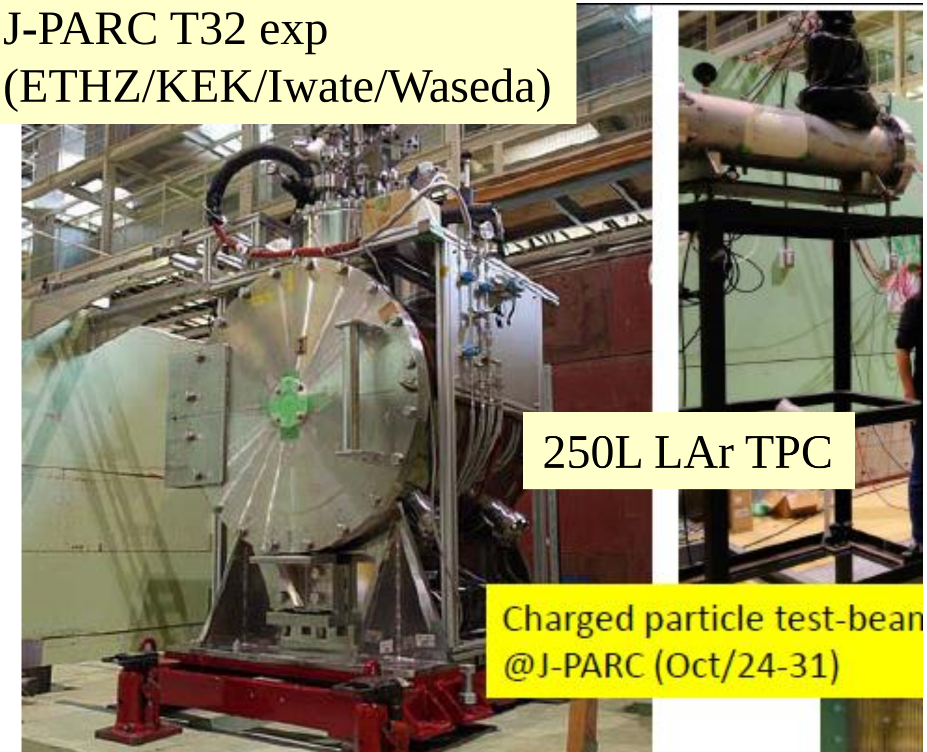
Expectation with ~50 times more data ($750\text{kW} \times 5 \times 10^7\text{s}$)

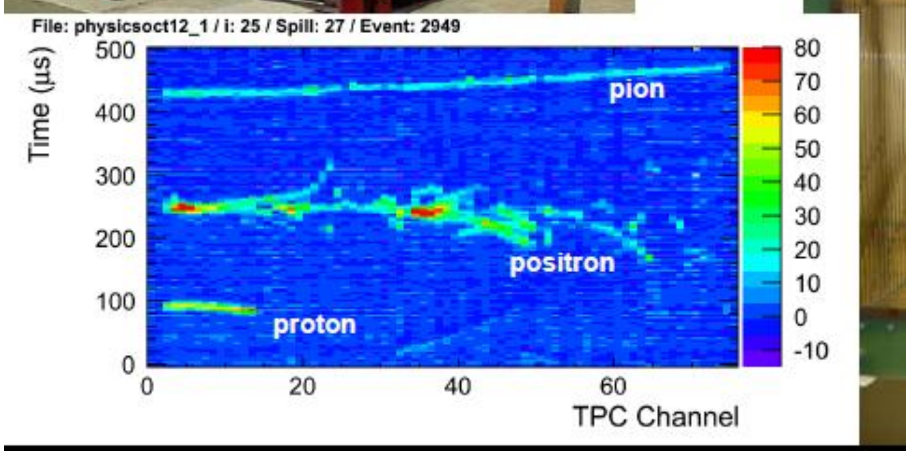


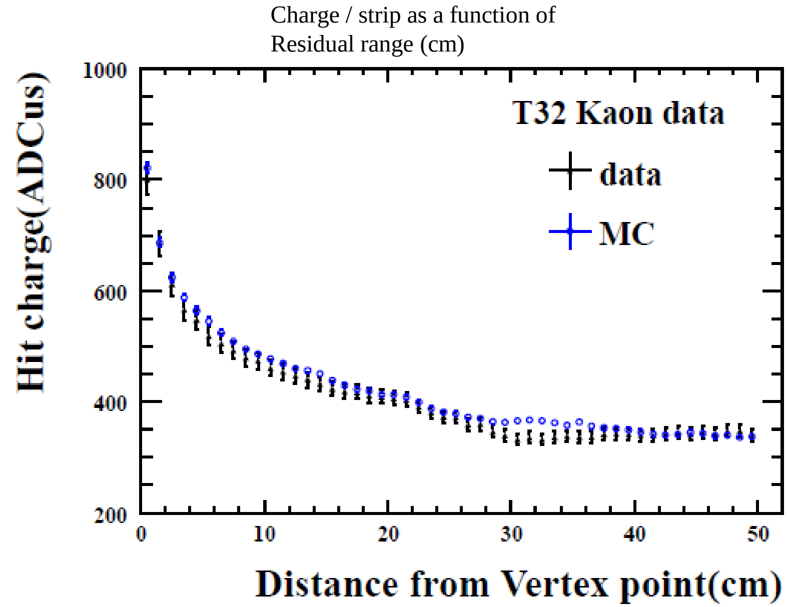
Expected beam power	May 2012	2014	2018
	190kW	300kW	750kW

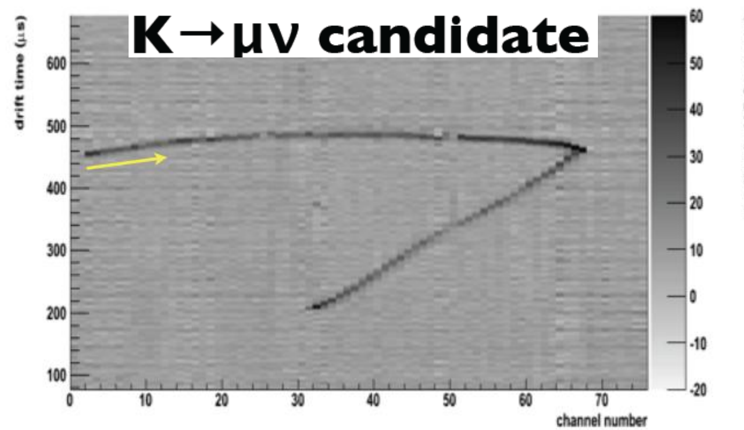
R&D toward realizing 100kt Liq. Ar TPC

J-PARC T32 exp
(ETHZ/KEK/Iwate/Waseda)

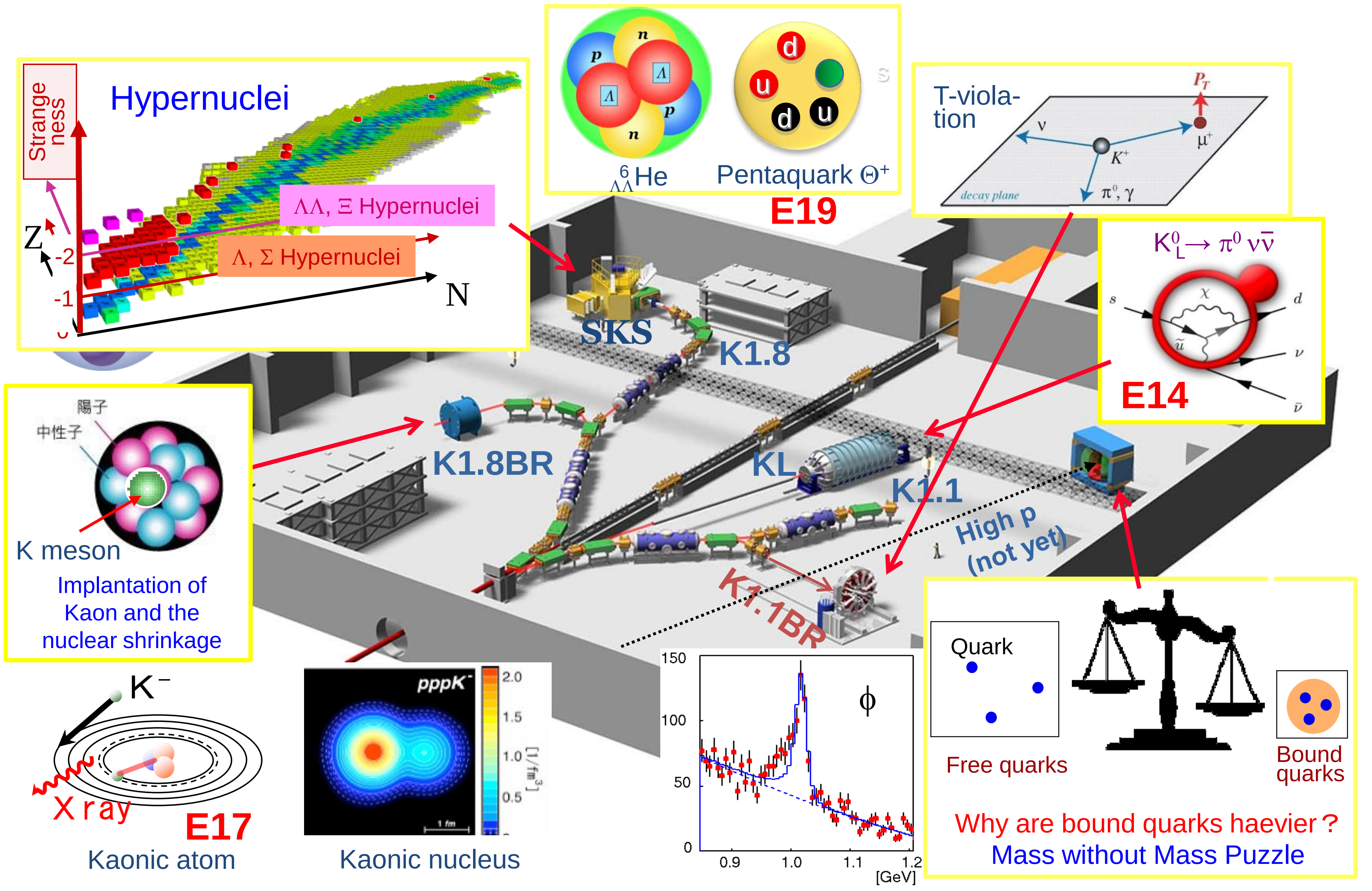








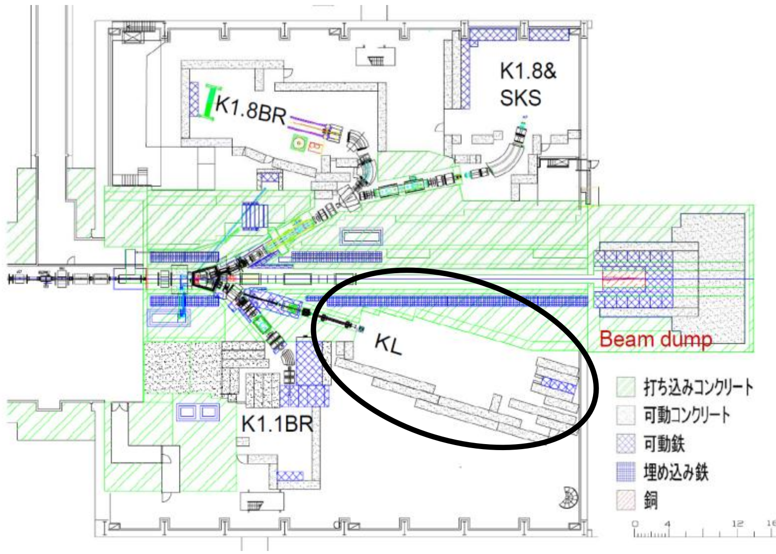
Nuclear & Particle Physics with J-PARC Hadron Beam

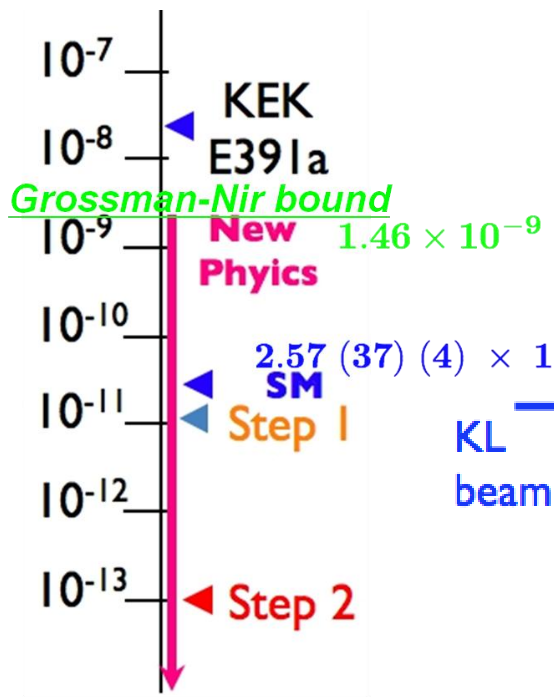


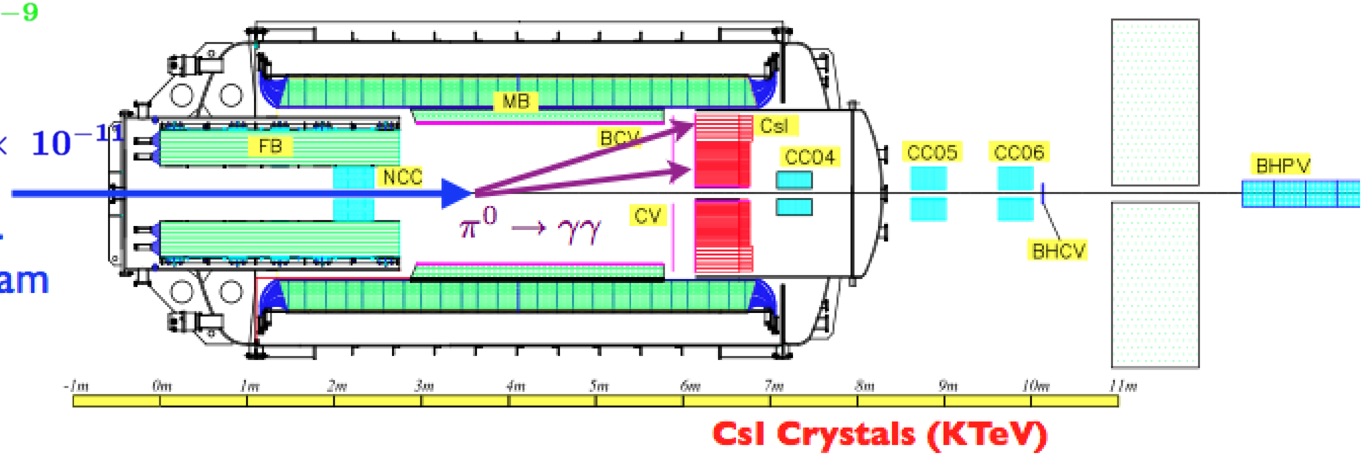
KOTO experiment

- Direct CPV rare decay for physics beyond the standard model
- Milestones
  - Before Summer 2013: Exceed GN limit (~10^{-9})
    - **10~30kW x 4weeks**
  - Final goal : 290kWx3SNyr➔1×10^{-11}
    - **Critical to have >100kW**
- Requirement for duty factor (rough estimate)
  - Duty [%] > 100% x (Power[kW]/300kW)

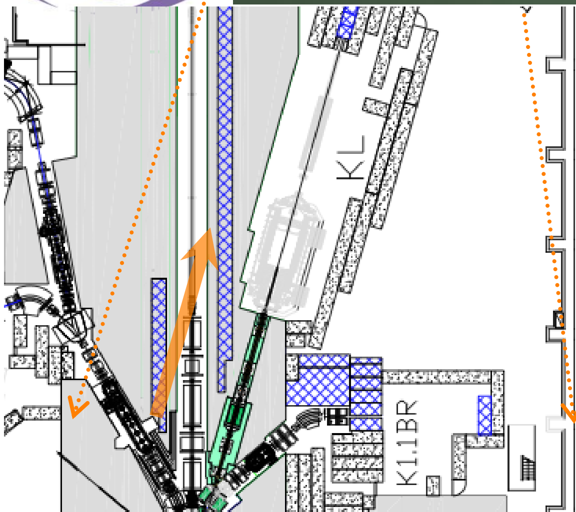
$$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$$



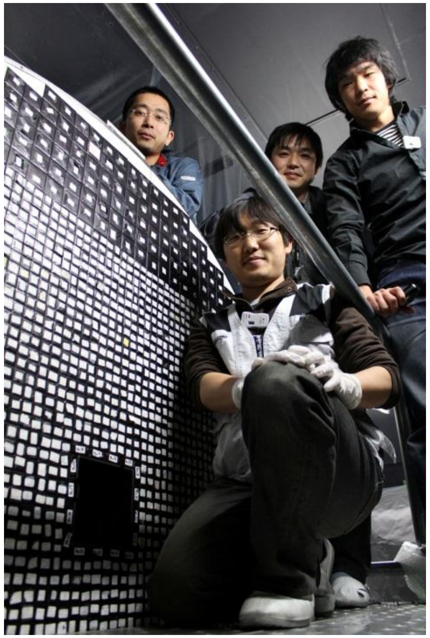




KOTO Beam Line and Detector

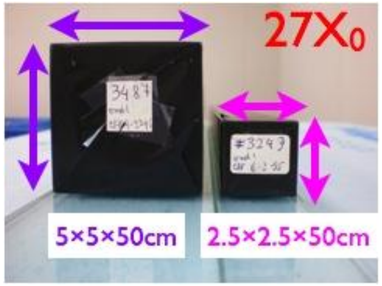


Fermilab
KTeV
CsI calorimeter
↓
KOTO CsI calorimeter

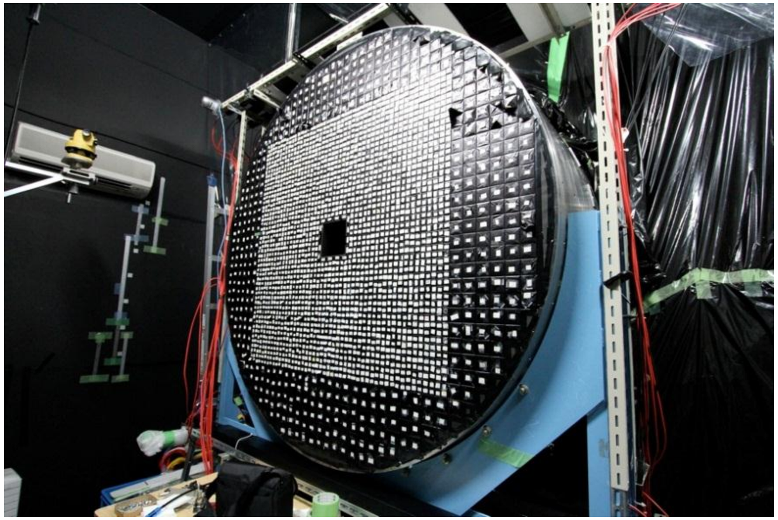


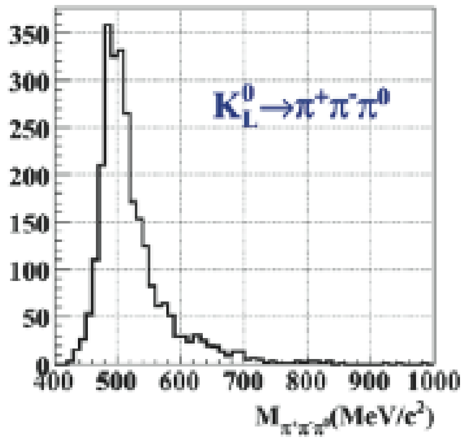
with 2716 crystals

2011.Feb.08 16:30



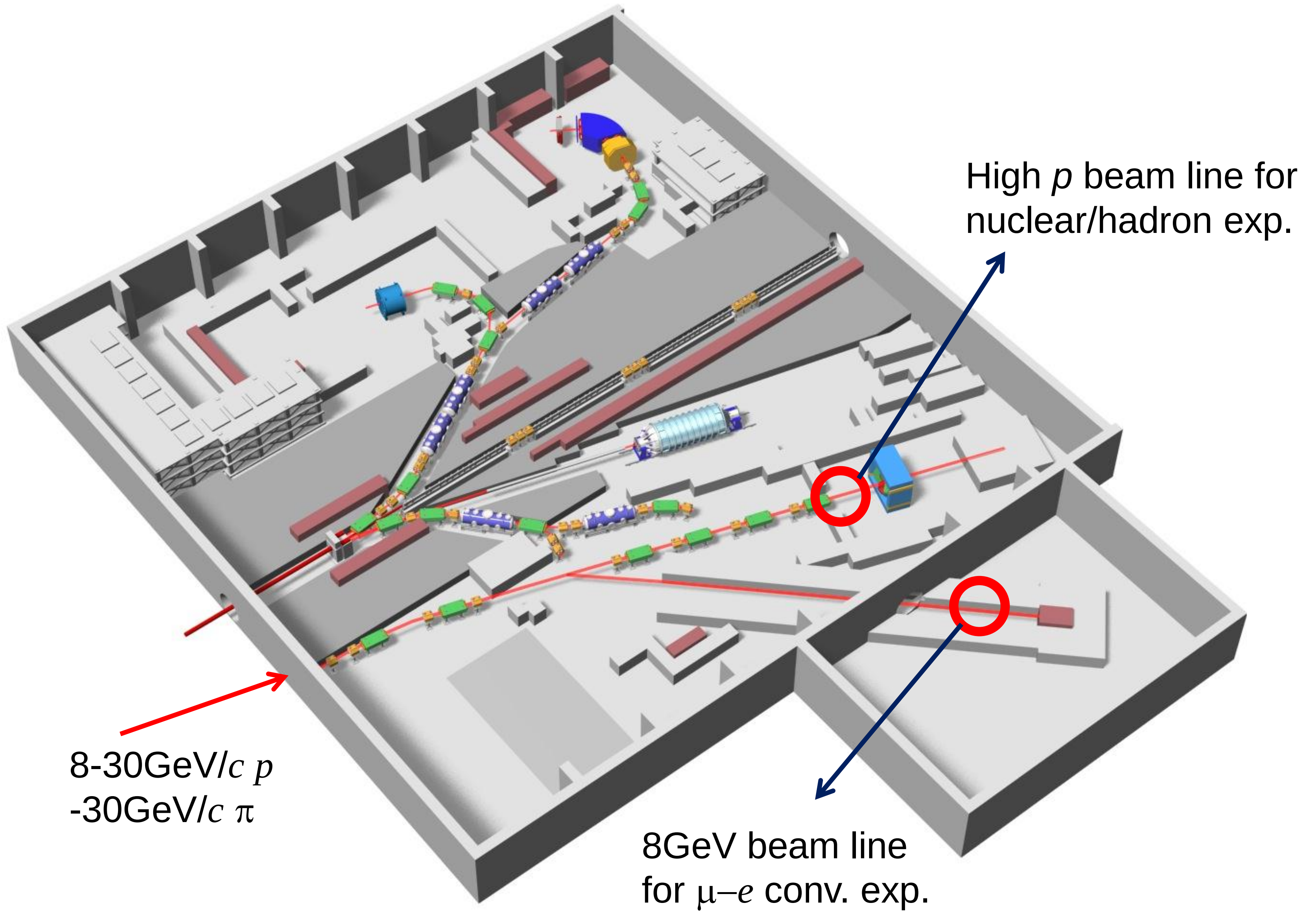
May 2011





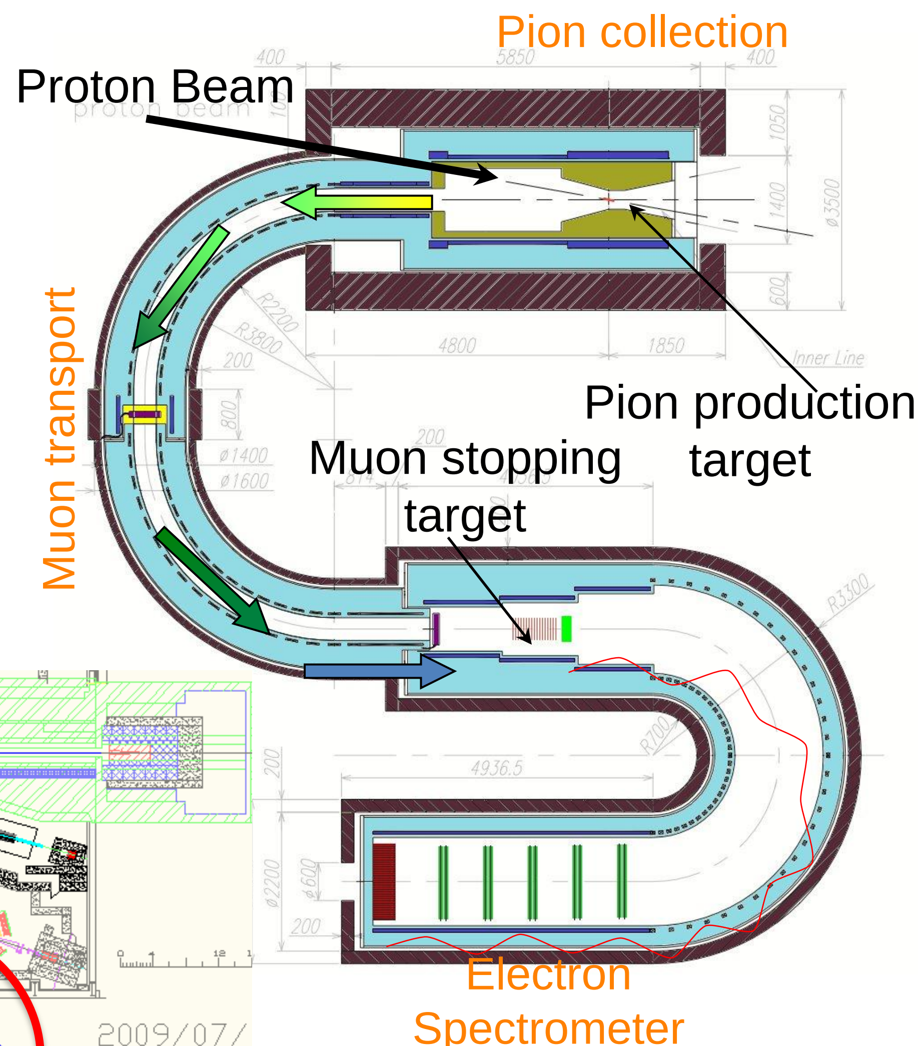
new KL beam line (south area of Hadron Hall)
confirmation of neutral kaons (December 2009)

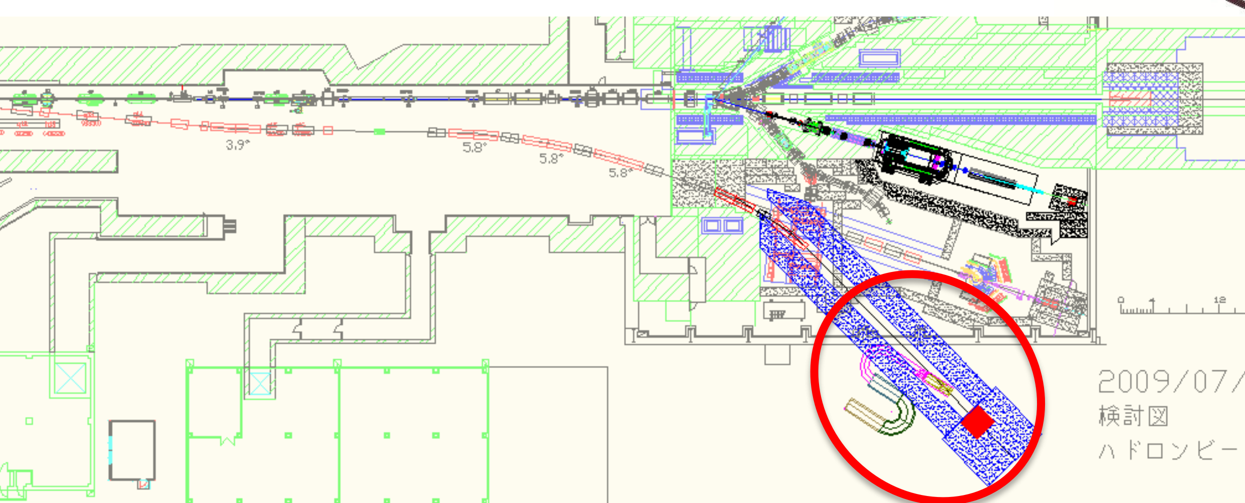
New primary beam line for e-μ conversion search



COMET μ-e conv. search

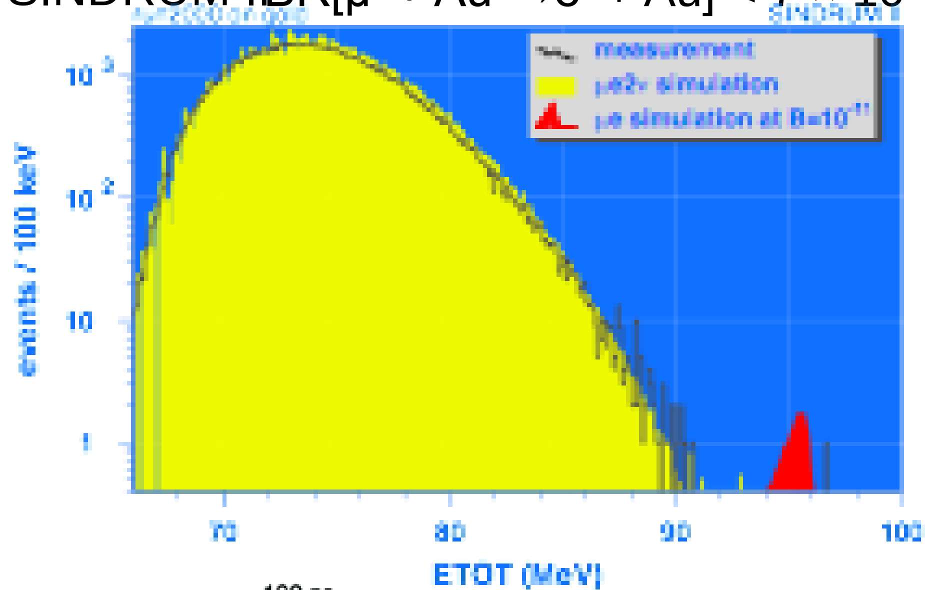
- Search for cLFV mu-e conv.
  - **10^{-16}** sensitivity (Target S.E.S. 2.6 × 10^{-17})
  - Improve **O(10^4)** than present upper bound such as SINDRUM-II BR[μ^- + Au → e^- + Au] < 7 × 10^{-13}
- Signature: 105MeV monochromatic electron
- Beam requirement
  - 8GeV bunched slow extraction
  - 8.5x10^{20} pot needed to reach goal
  - 7 uA (56kW) x 2 SN year (2x10^7sec)
  - Extinction <10^{-9}





Principle of Measurement

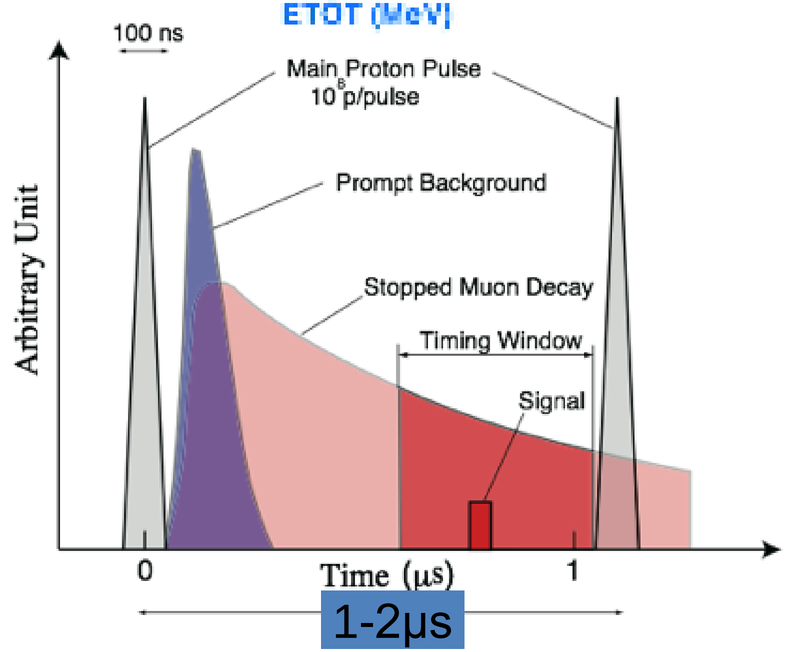
SINDRUM II BR[$\mu^- + Au \rightarrow e^- + Au$] < 7×10^{-13}



- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
- A single mono-energetic electron
  - $E_{\mu e}(Al) \sim m_\mu - B_\mu$:105 MeV
  - Delayed : ~1μS

- No accidental backgrounds
- Physics backgrounds
- Muon Decay in Orbit (DIO)
  - $E_e > 102.5$ MeV (BR:10^{-14})
  - $E_e > 103.5$ MeV (BR:10^{-16})
- Beam Pion Capture
- $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$

  $\gamma \rightarrow e^+ e^-$

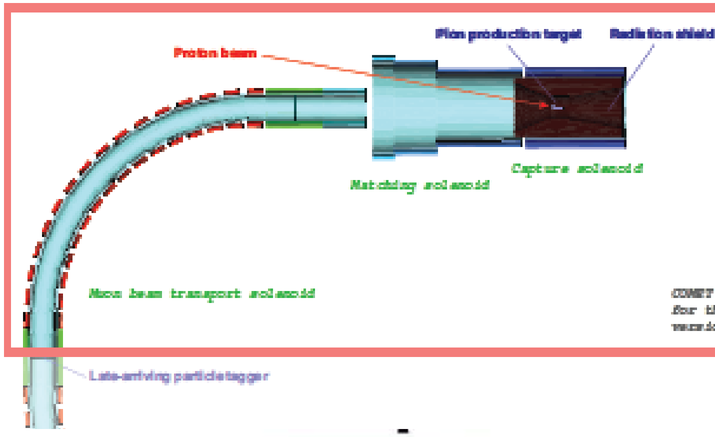


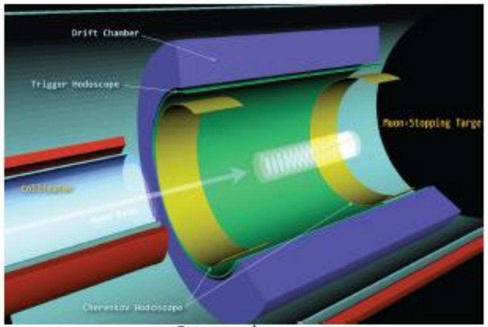
$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$

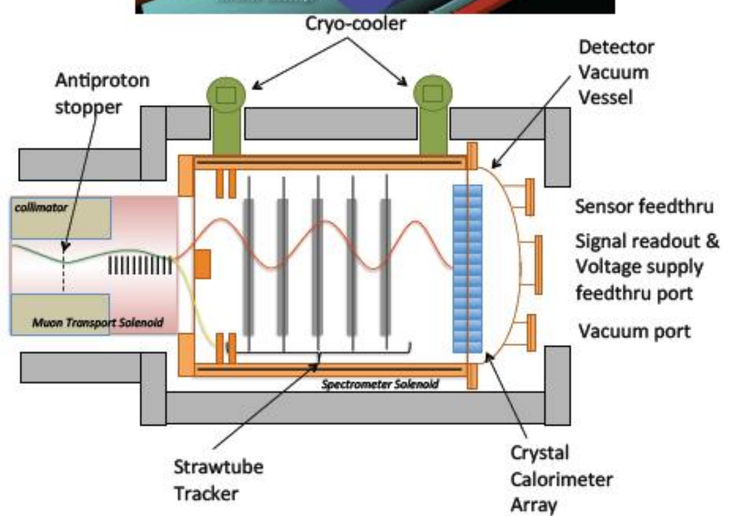
COMET staging approach (phase1)

- Construct proton beamline, upstream 90deg part of COMET beam line
  - (+ effort to realize detectors w/ external funding)
- Goals
  - Understand beam
    - Verify pion collection
    - Radiation environment
    - Background studies for COMET
    - ➔ Feedback to COMET
  - μ-e conversion search
    - 10^6s (12days) of 3.2kW 8GeV beam
    - B(μ-+Al→e-+Al) < 7.2x10-15 (90%)
    - 2 order improvement from present upper bound of

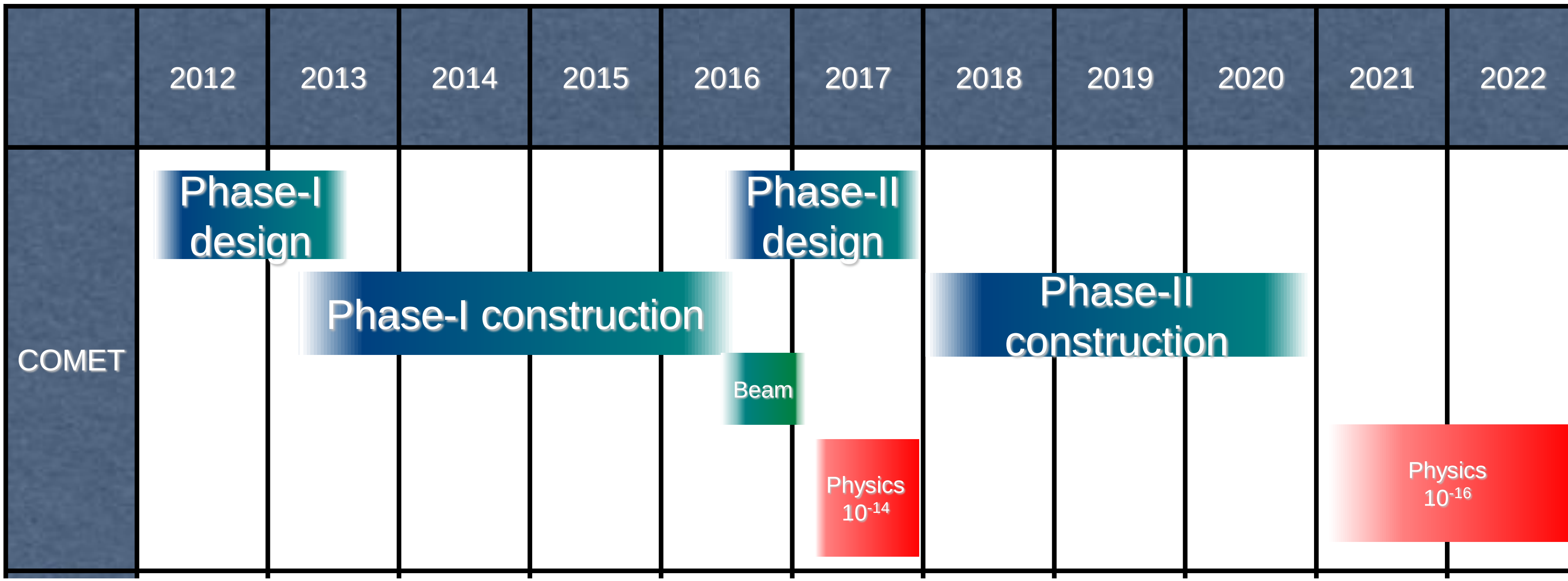
      $BR[\mu^- + Au \rightarrow e^- + Au] < 7 \times 10^{-13}$





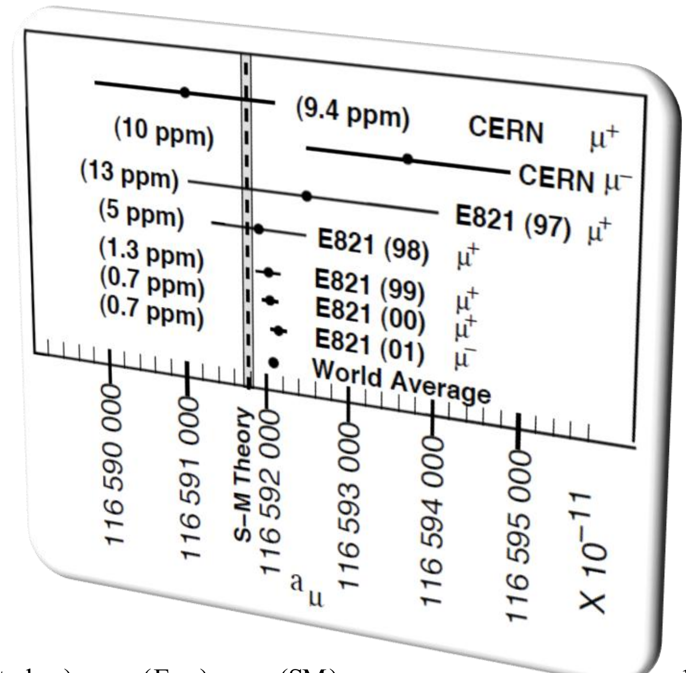


COMET Schedule – staging scenario

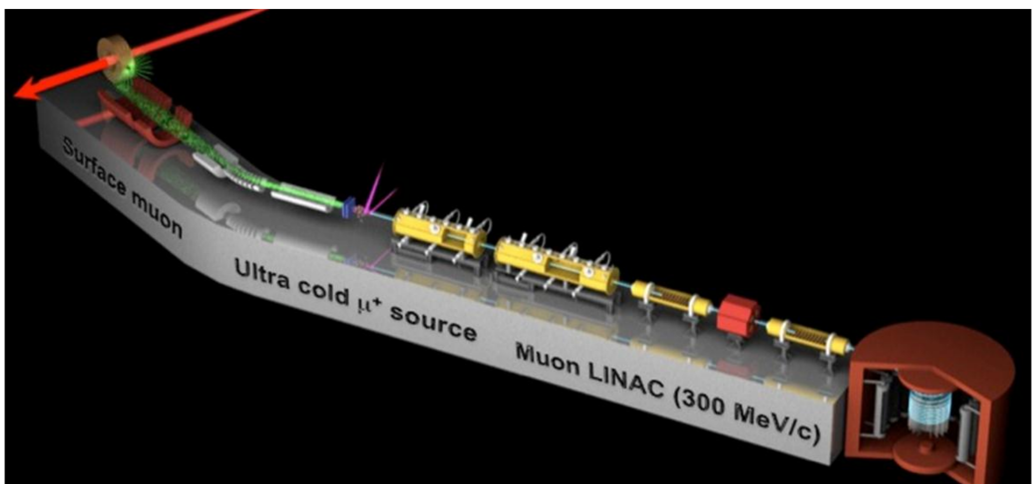


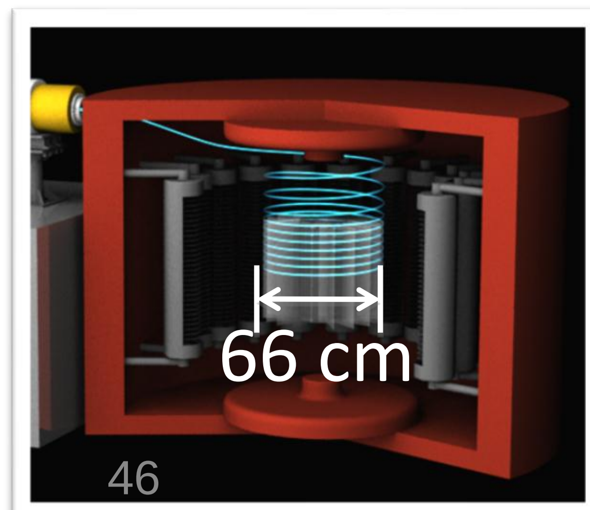
Muon g-2/EDM at J-PARC

- proposed at H-line in MLF
- New idea to avoid "magic" momentum by eliminating electric field
- Ultra cold μ^+ accelerated to 300MeV/c
- Goals
  - g-2 : 3.4 sigma away from the SM
    - 0.5 ppm→ 0.1 ppm
  - EDM: CP violation in the lepton sector?
    - < 1 x 10 $^{-19}$ e cm → 5 x 10 $^{-21}$ e cm
- Extensive R&D on various elements are on-going



$$\Delta a_\mu^{(\text{today})} = a_\mu^{(\text{Exp})} - a_\mu^{(\text{SM})} = (295 \pm 88) \times 10^{-11}$$





Summary

- SuperKEKB and Belle-II
  - Third year of construction
  - Machine commissioning is expected in JFY2014 to be followed by Belle-II roll-in after careful background studies.
- J-PARC also has a flavor physics program.
  - T2K: continue data taking to improve ν_e appearance measurement. $\rightarrow \delta_{CP}$
  - KOTO will be ready soon to start search for $K_L \rightarrow \pi^0 \nu\nu$.
  - New program: COMET search for μ-e conversion
  - New g_μ-2 measurement