



KEK, High Energy Accelerator
Research Organization

Particle Physics in Japan

October 14, 2016

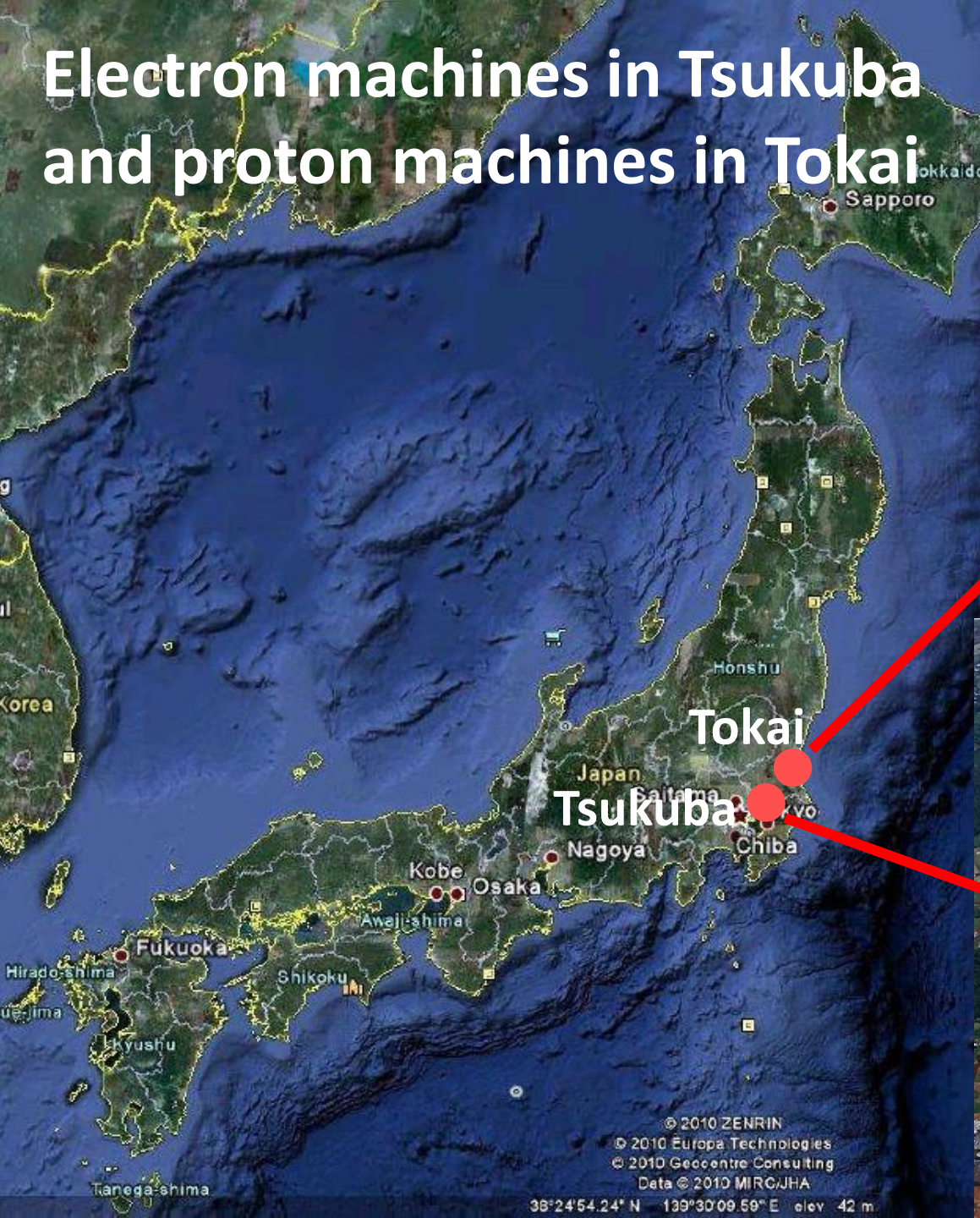
AEPSHEP 2016, Beijing

M.Yamauchi
KEK

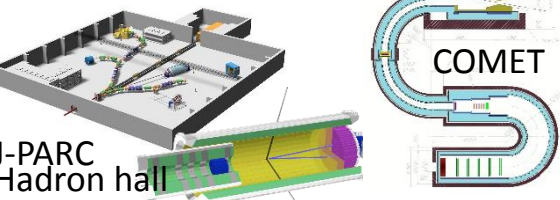
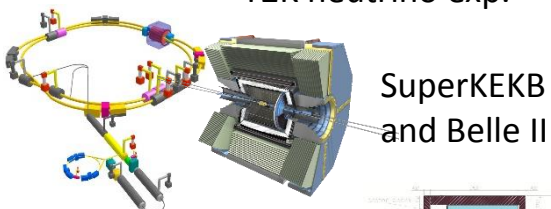
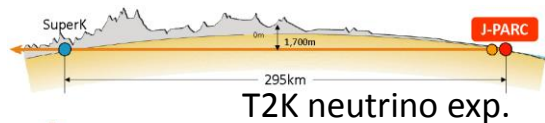
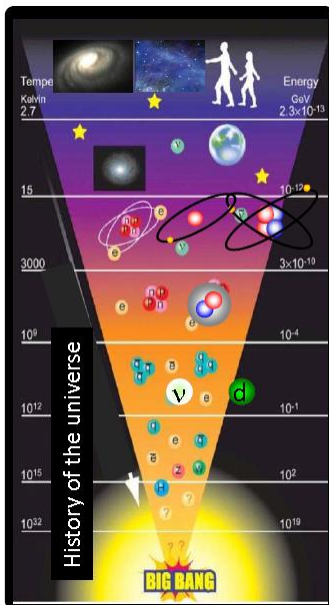
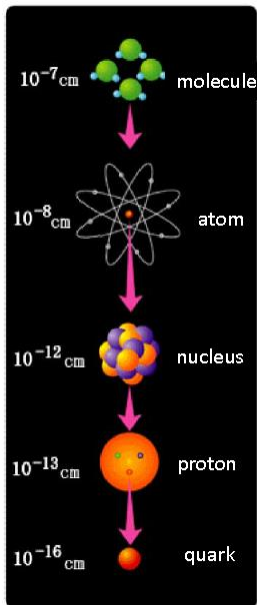
Time line of particle physics program in Japan



Electron machines in Tsukuba and proton machines in Tokai



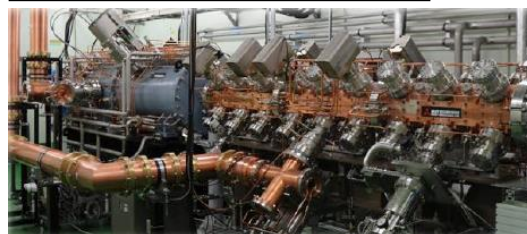
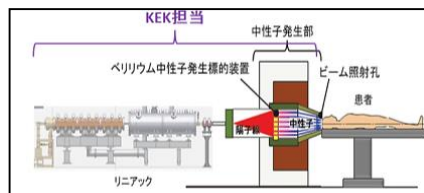
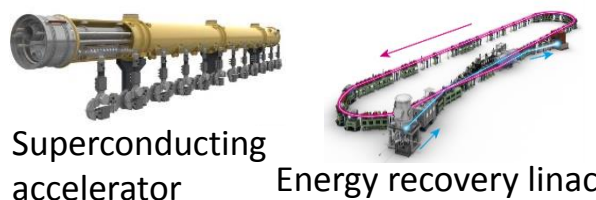
Pursuing fundamental laws of nature



Basic science Material science and its applications

KEK

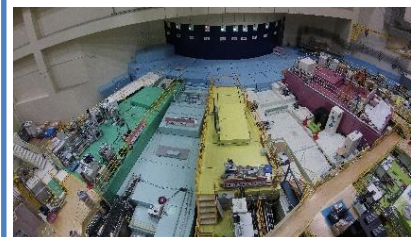
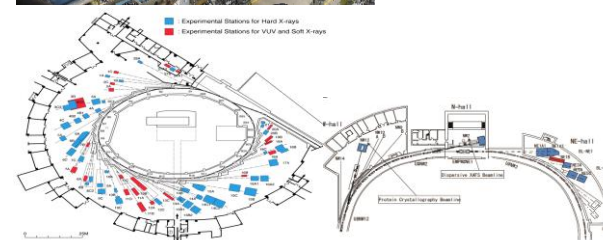
Technical development and its applications



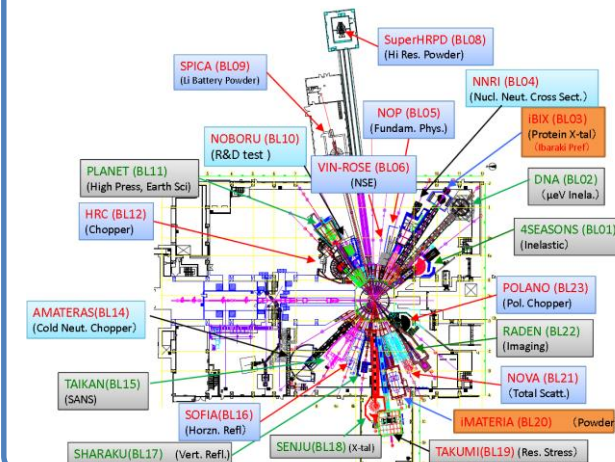
Pursuing origin of function in materials



Photon factory X-ray as a probe

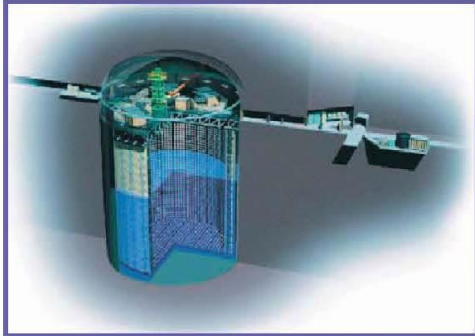


J-PARC MLF neutron and μ as a probe



T2K (Tokai to Kamioka) experiment

2010~ (Running)



Super-Kamiokande
(ICRR, Univ. Tokyo)

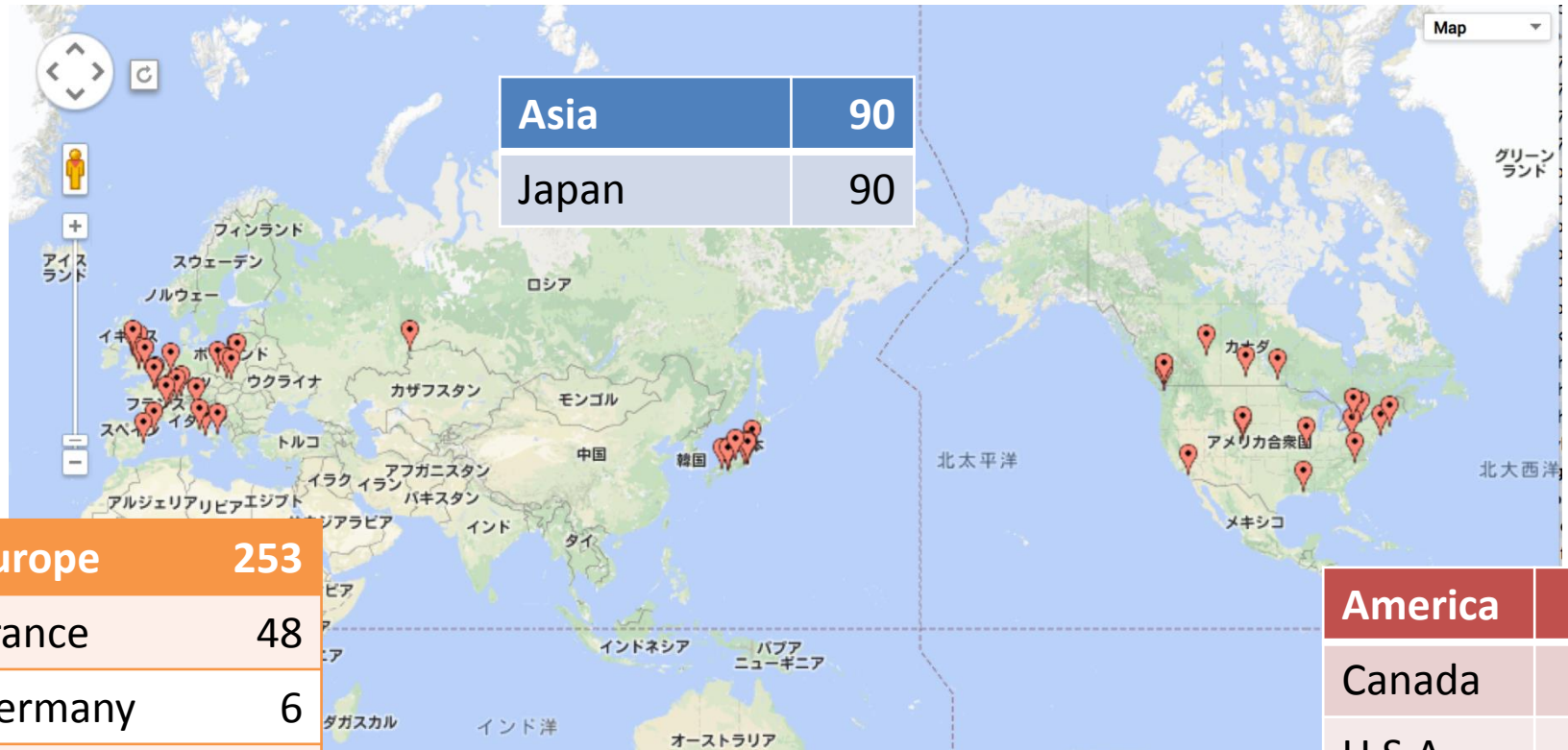


J-PARC Main Ring
(KEK-JAEA, Tokai)



- High intensity ν_μ beam from J-PARC MR to Super-Kamiokande
- Observation of $\nu_\mu \rightarrow \nu_e$ (2013)
- Updated goals
 - ▶ Precise measurement of ν_e appearance
 - ▶ Precise measurement of ν_μ disappearance
 - ➔ CPV phase, contribution to mass hierarchy determination

T2K collaboration



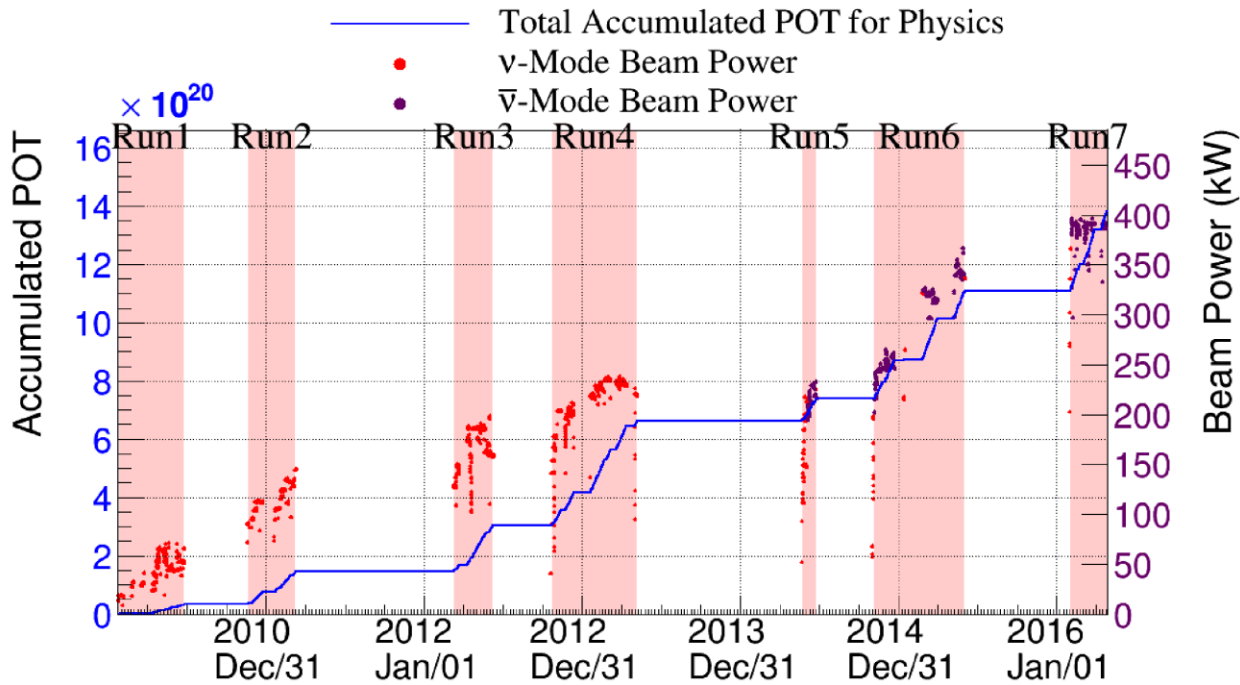
Europe	253
France	48
Germany	6
Italy	13
Poland	30
Russia	17
Spain	13
Switzerland	26
UK	100

America	147
Canada	61
U.S.A	86

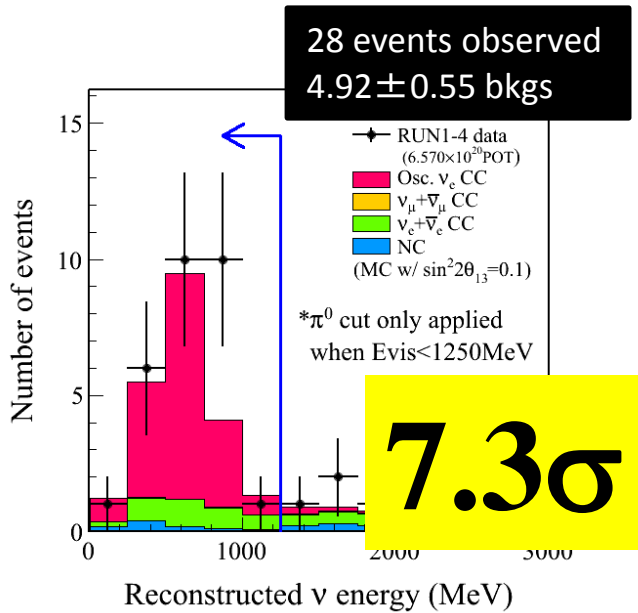


Total 490

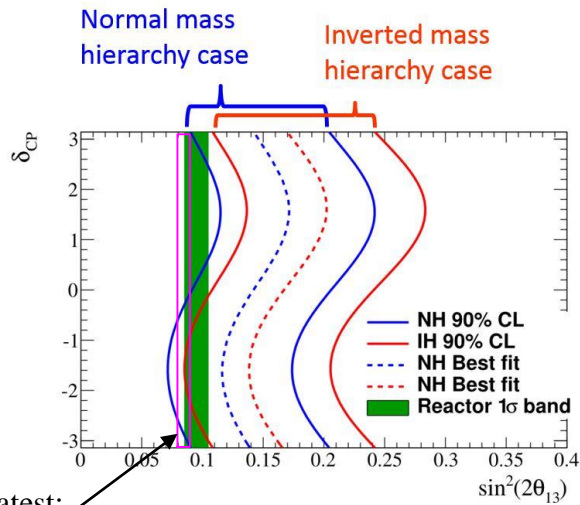
Proton delivery to T2K



- Stable operation at **390kW** achieved (first design goal: 750kW)
 - ▶ ($E_p=30\text{GeV}$) x (**200Tp/5us pulse**) x (2.48sec cycle)
 - ▶ Taking anti-neutrino beam data for CPV search
- Number of protons on target (POT)
 - ▶ 15.1×10^{20} accumulated (7.6×10^{20} for nu & 7.5×10^{20} anti-nu)
 - ▶ 7.8×10^{21} aimed as original T2K goal

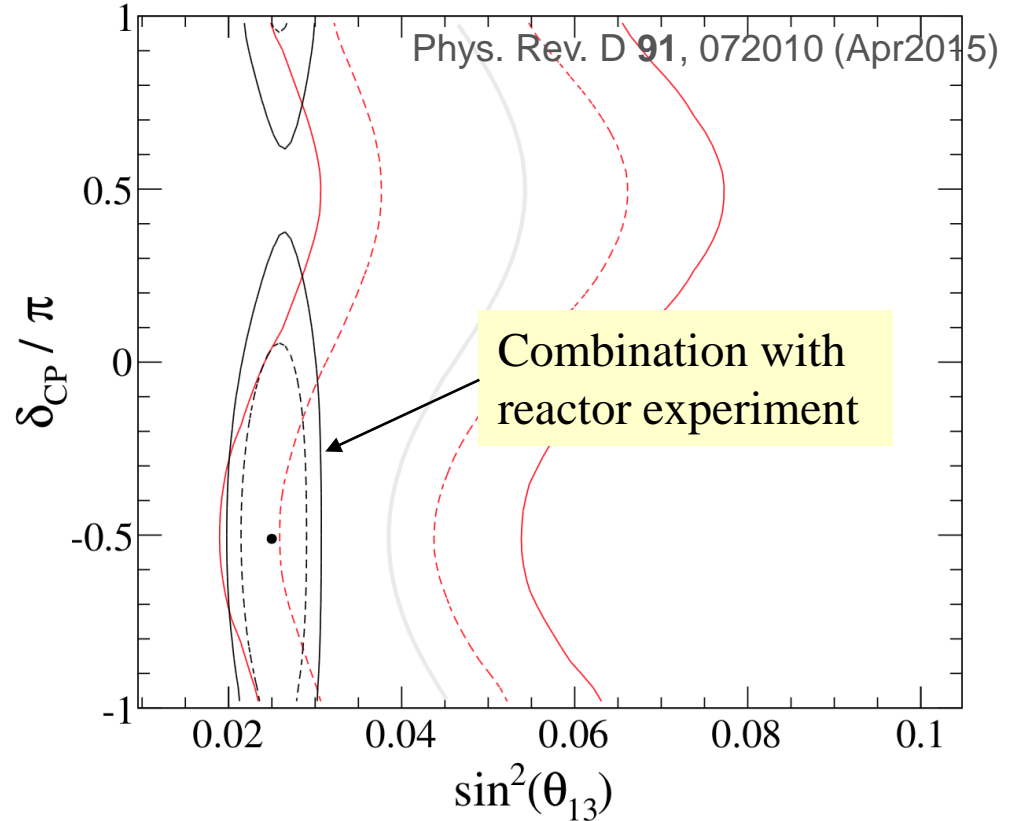


Phys. Rev. Lett. 112, 061802 (Feb.2014)



Daya Bay latest:
 $\sin^2 2\theta_{13} = 0.084 \pm 0.005$
 PRL 115, 111802 (2015)

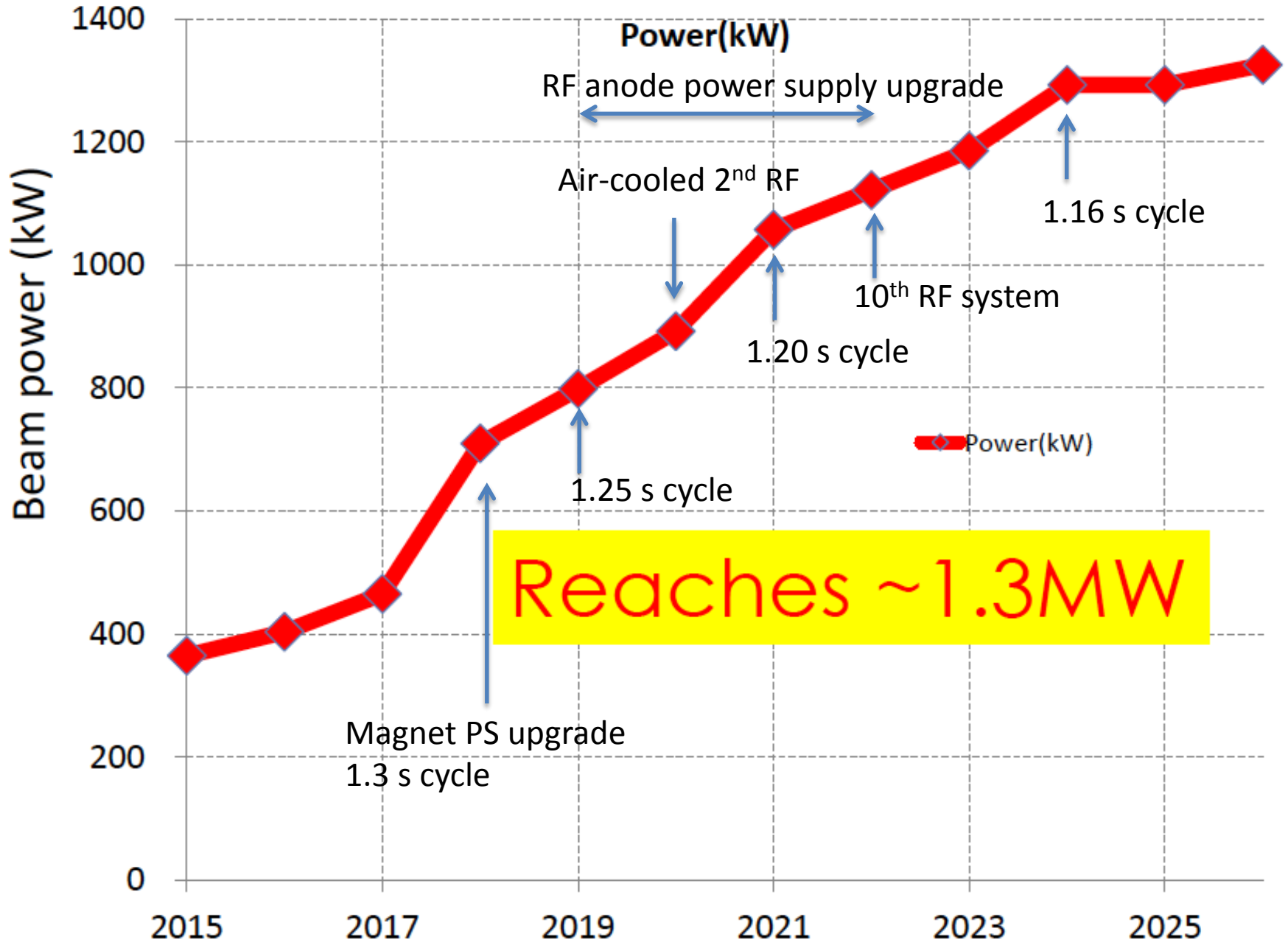
Reactor value from PDG2013
 $\sin^2 2\theta_{13} = 0.095 \pm 0.01$



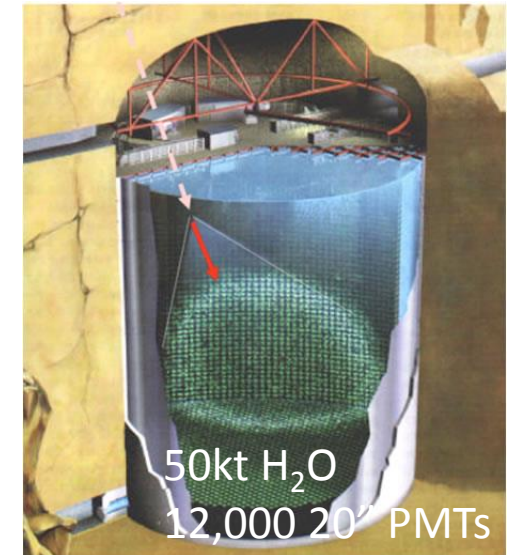
- T2K+Reactor 68% Credible Region
- T2K Only 68% Credible Region
- T2K+Reactor 90% Credible Region
- T2K Only 90% Credible Region
- T2K+Reactor Best Fit Point
- T2K Only Best Fit Line

THE FIRST CONSTRAINT ON CP PHASE!

Beam power projection

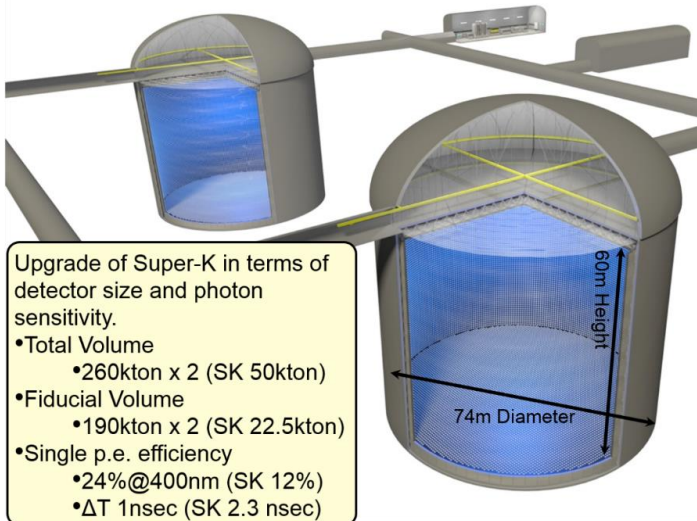


- **SK have obtained many important results**
 - ▶ Discovery of ν oscillation: atmospheric (1998), solar(2001 w/SNO), K2K (2004)
 - ▶ Discovery of $\nu_{\mu} \rightarrow \nu_e$ (2011, T2K)
- **Remaining tasks**
 - ▶ Determine Mass hierarchy, CP Violation
 - ▶ Supernova
 - ✓ 8,000 neutrino events from a SN at 10 kpc
 - ▶ Supernova Relic Neutrinos search (with Gd)
 - ▶ Solar



Hyper Kamiokande is being considered by ICRR, U. Tokyo.

- Next-generation Water Cherenkov detector
 - ▶ 260kt(190kt fid.mass) x 2
- Detector location (candidate)
 - ▶ 295km from J-PARC, @ same off-axis angle
 - ▶ 650m overburden (1755m W.E.)
- Physics goals
 - ▶ Accelerator neutrino
 - ✓ CPV in neutrino
 - ▶ Non-accelerator/Astroparticle
 - ✓ Discovery of proton decay
 - ✓ Atm-nu, solar-nu, relic nu, etc.



J-PARC ν beam + Hyper-K

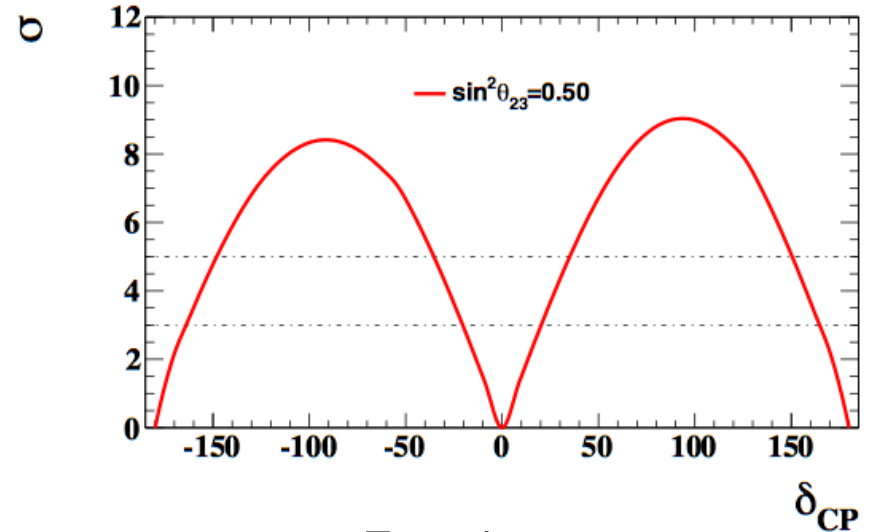
$\sin\delta_{CP}=0$ exclusion

- Exclusion of $\sin\delta_{CP}=0$

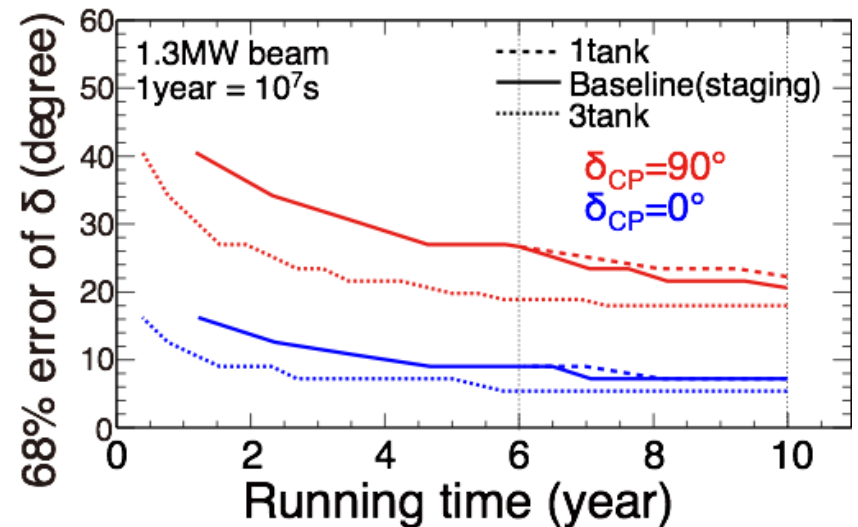
- ▶ 8σ for $\delta=-90^\circ$
- ▶ 80% coverage of δ parameter space for CPV discovery w/ $>3\sigma$

- δ_{CP} precision measurement

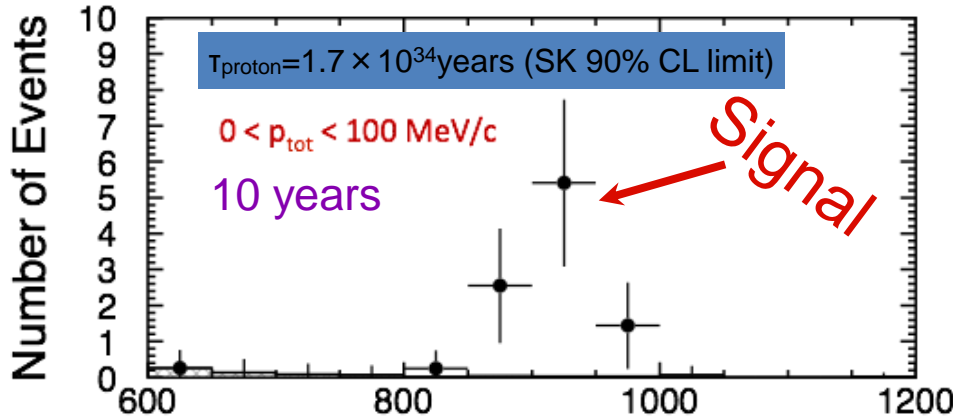
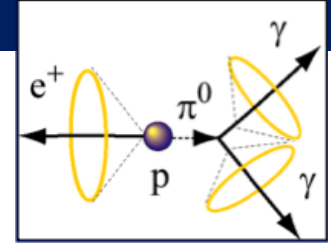
- ▶ 20° for $\delta=-90^\circ$
- ▶ 7° for $\delta=0^\circ$



δ_{CP} 1 σ error

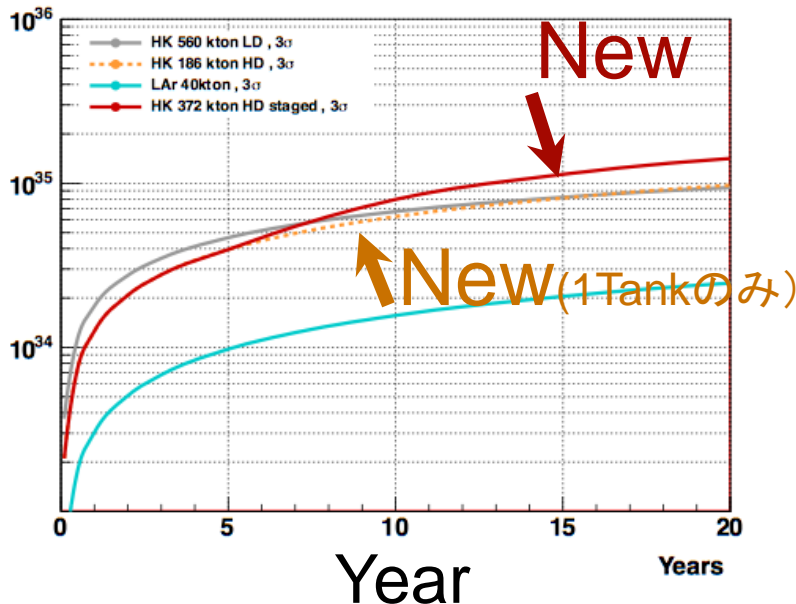


$p \rightarrow e^+ \pi^0$ search in Hyper-K



BG free by high-sensitive PMTs

For the case of
 $T_{\text{proton}} = 1.4 \times 10^{34}$ years (Super-K limit)
 ~9 σ discovery @HK



- Only realistic proposal to reach to 10^{35} years @3 σ

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

Update needed

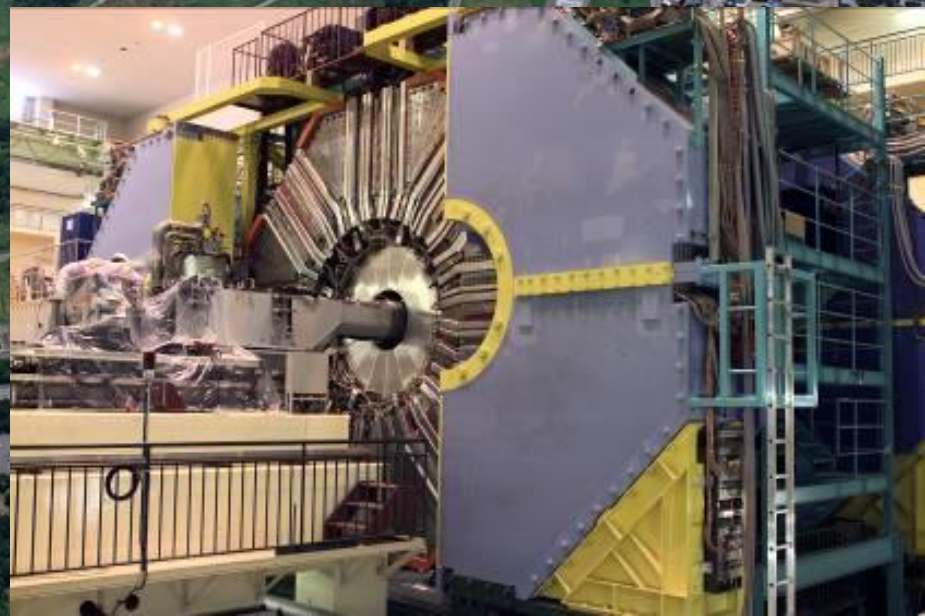
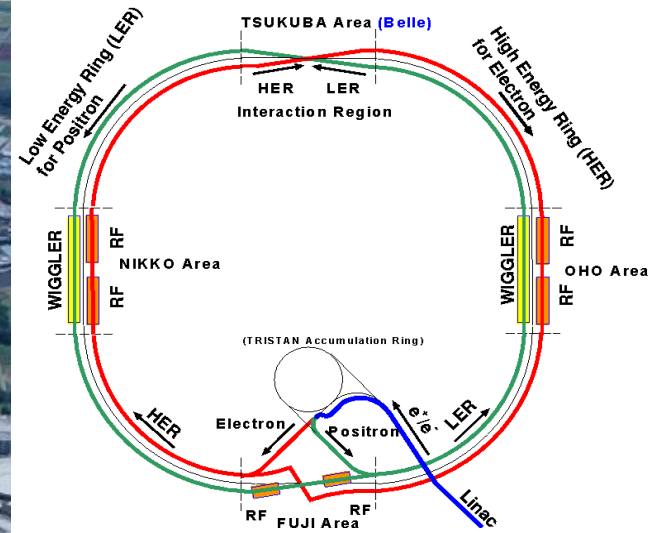
- SuperKEKB
- J-PARC
- UCN at TRIUMF

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.

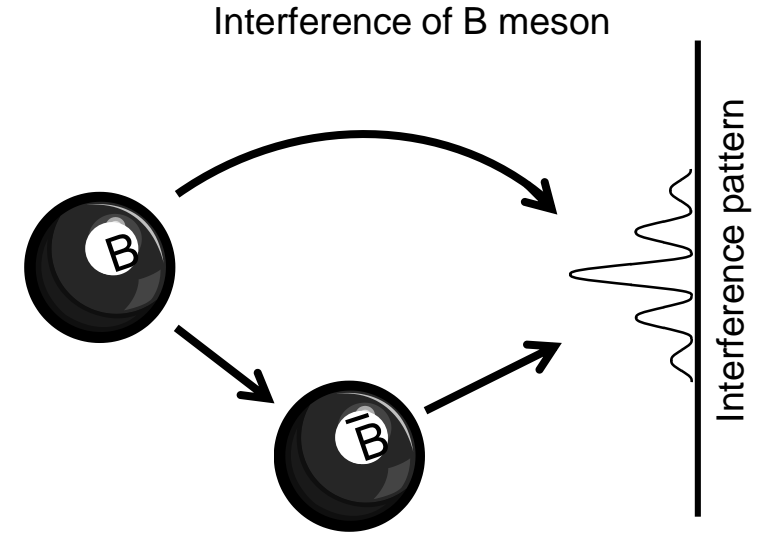
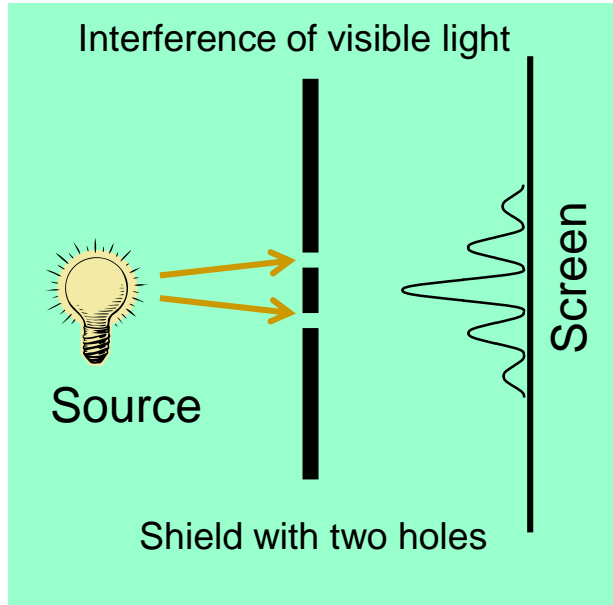
KEKB and Belle



SuperKEKB and Belle II

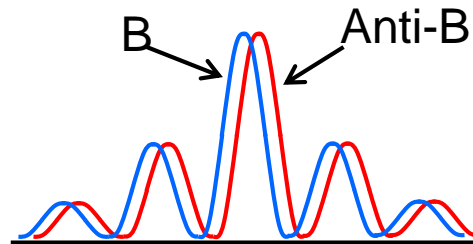


B meson interferometry



B meson decays in $\sim 10^{-12}$ second. It occasionally turns into its antiparticle before it decays.

According to K-M theory, the interference pattern should be different between B and anti-B

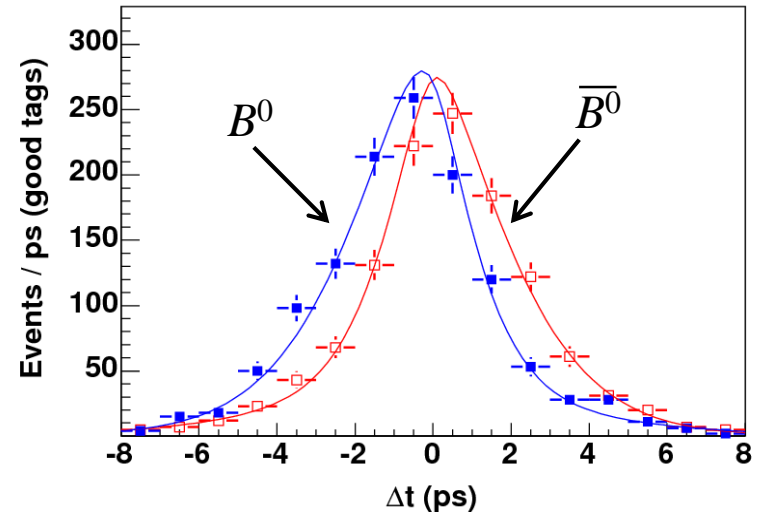
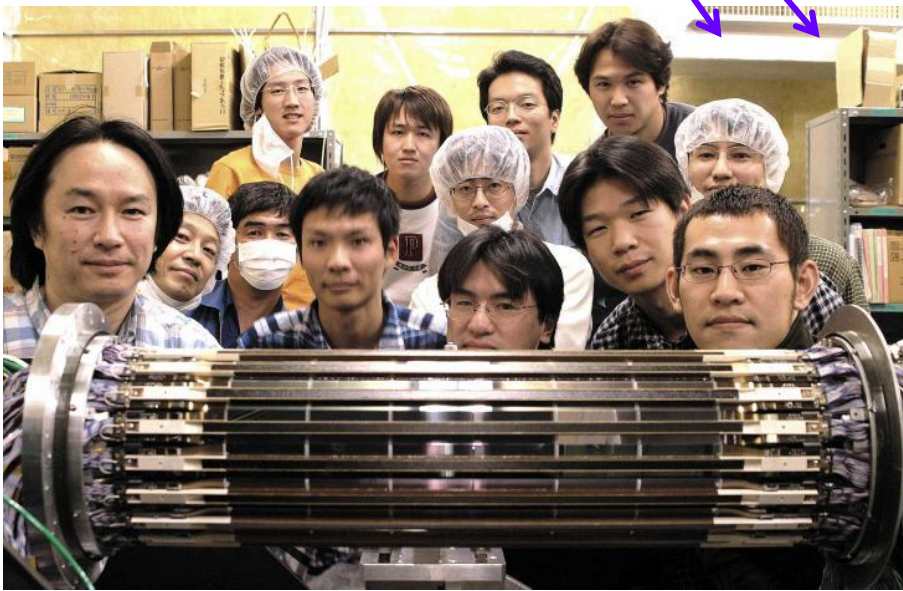
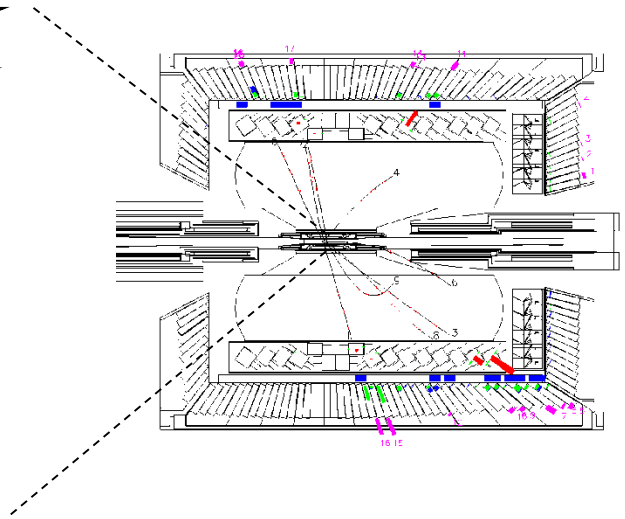
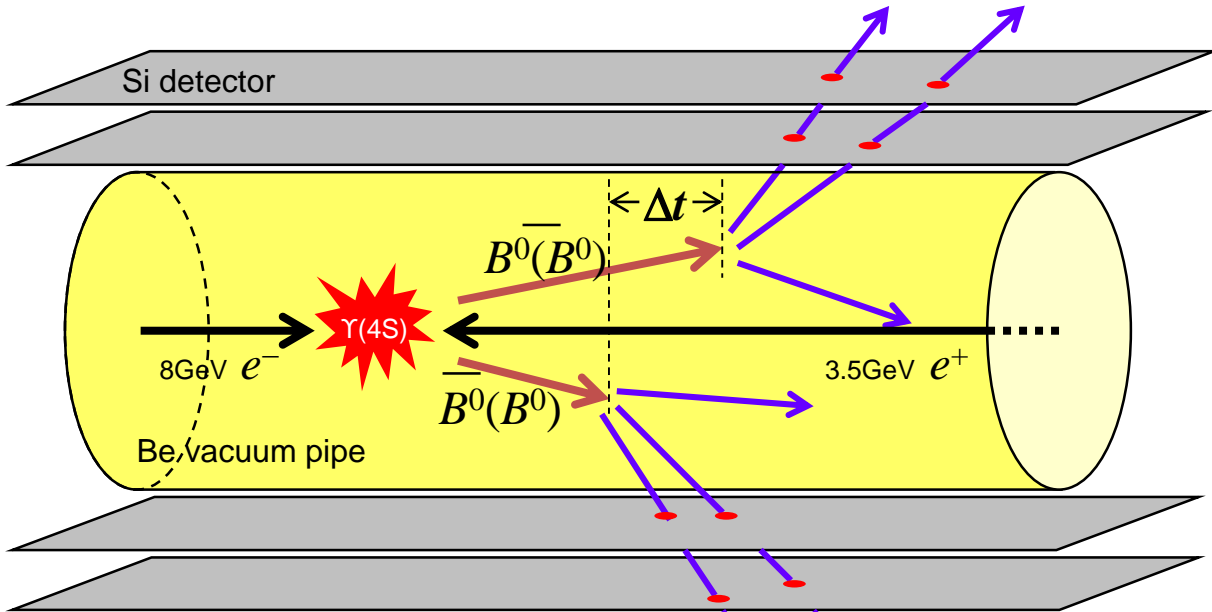


Difference between particle and anti-particle



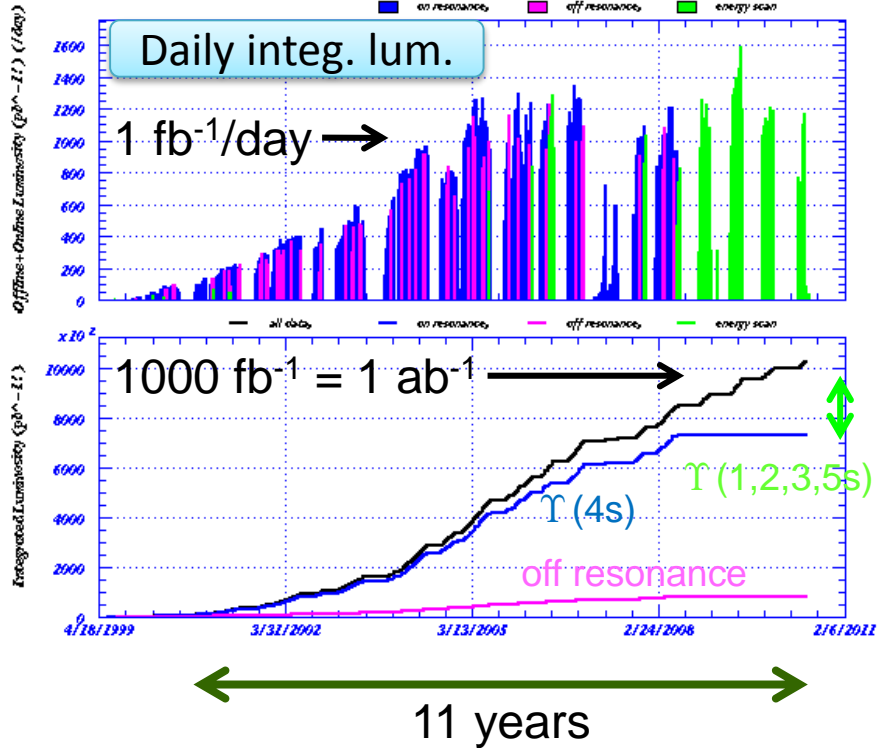
CP asymmetry

Measurement at e^+e^- B factory

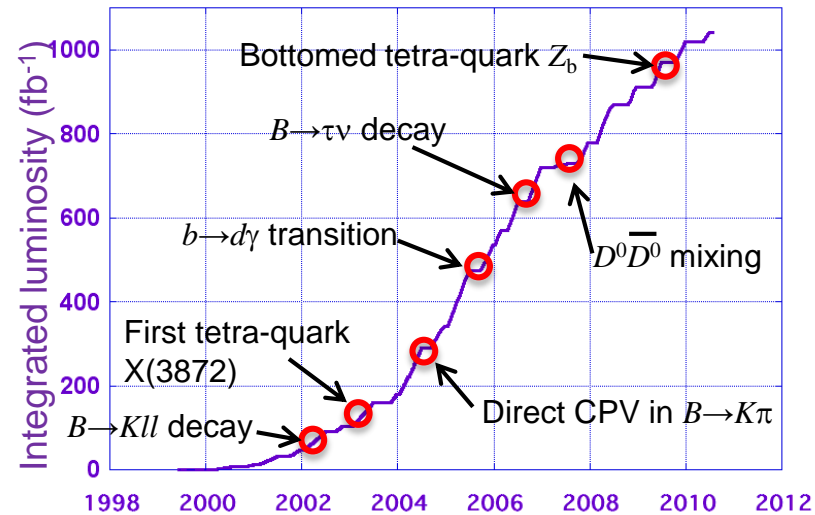
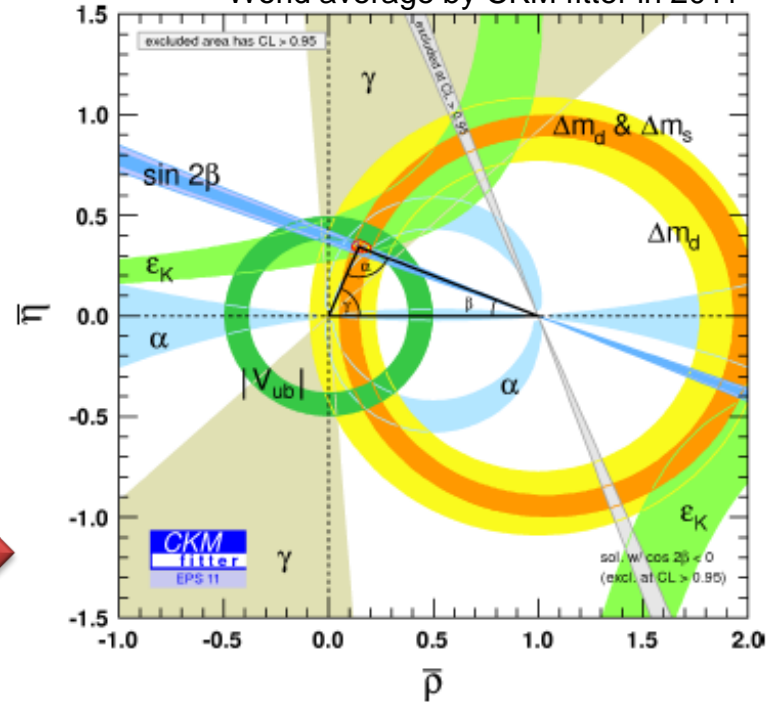


Achievements of KEKB and Belle

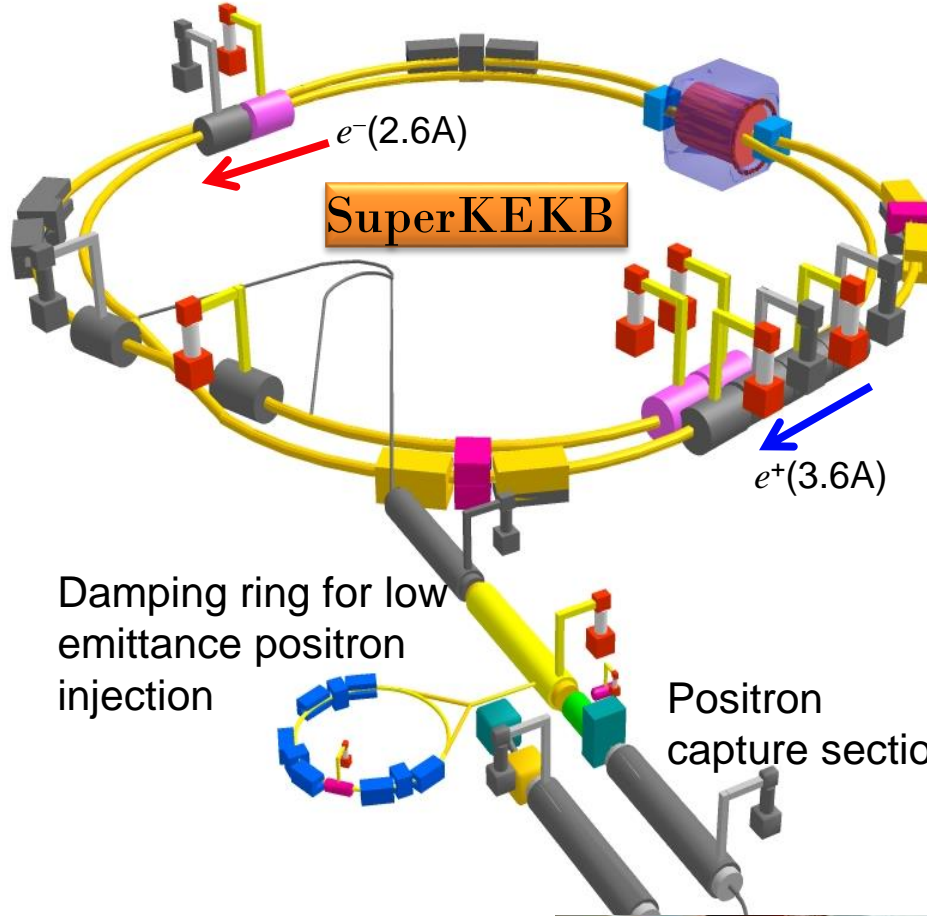
$$\mathcal{L}_{\text{peak}} = 2 \times 10^{34} / \text{cm}^2 / \text{s}$$



World average by CKM fitter in 2011



Low emittance lattice



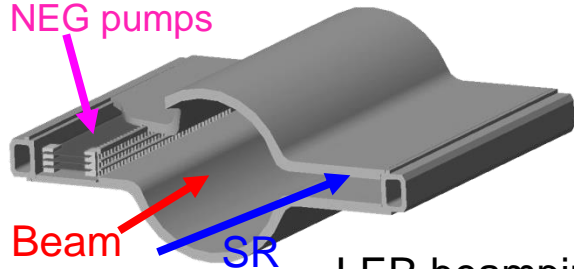
IR with $\beta_y^* = 0.3mm$
SC final focus system



Add RF systems for higher beam current



NEG pumps



LER beampipe to suppress photoelectron instability

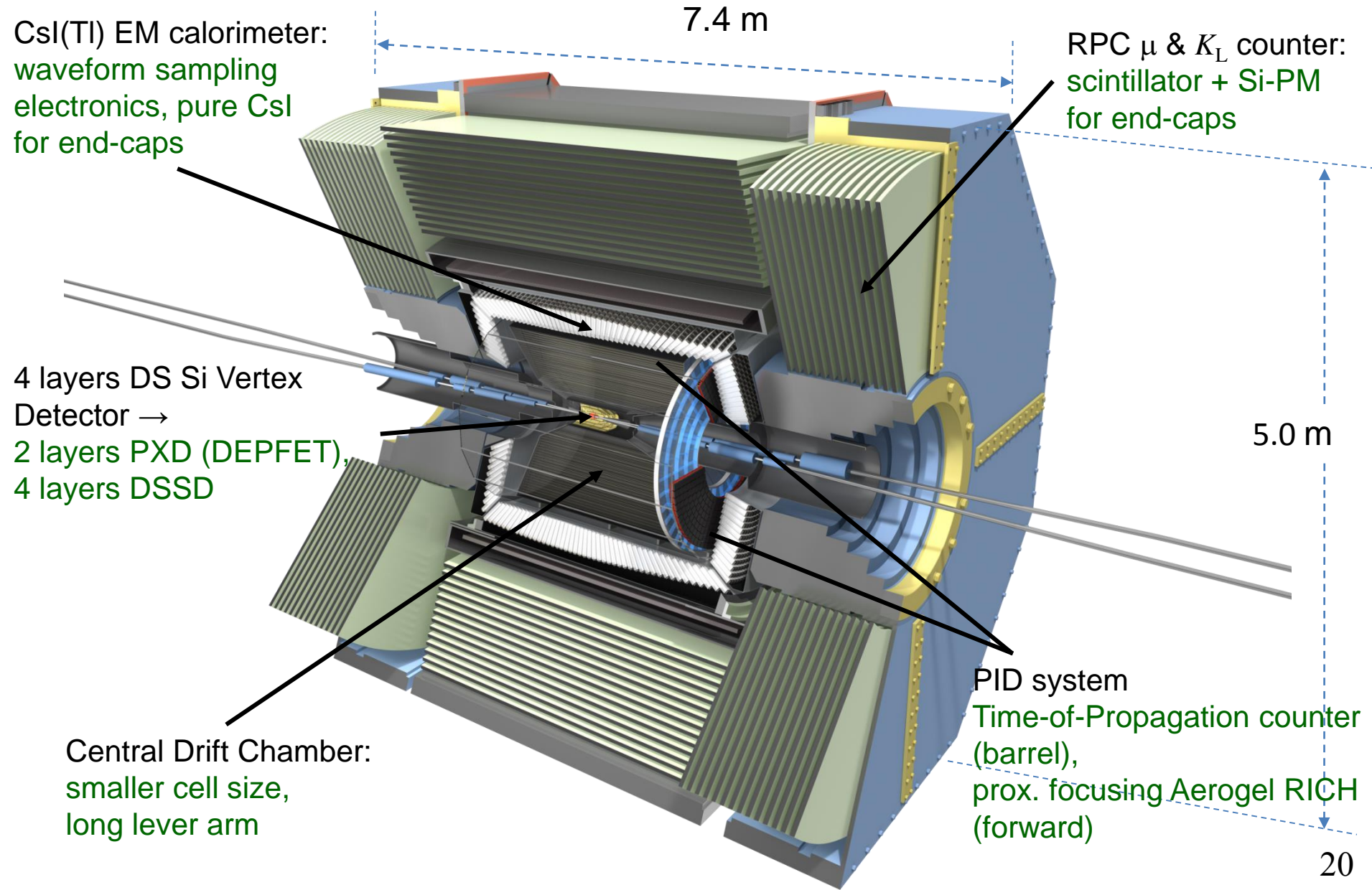


Parameter	Units	KEKB		SuperKEKB	
		HER (e^-)	LER (e^+)	HER (e^-)	LER (e^+)
Circumference	m	3016		3016	
Energy	GeV	8	3.5	7	4
Crossing angle	mrad	22		83	
β_x at IP	cm	120	120	2.5	3.2
β_y at IP	mm	5.9	5.9	0.30	0.27
ε_x (emittance)	10^{-9} m	24	18	4.6	3.2
Emittance ratio	%			0.35	0.40
σ_z	mm	6	6	5	6
Beam current	mA	1400	2000	2600	3600
σ_x at IP	10^{-6} m	150	150	11	10
σ_y at IP	10^{-9} m	940	940	62	48
ξ_x (tune shift)				0.0028	0.0028
ξ_y		0.090	0.129	0.0875	0.09
Luminosity	$\text{cm}^{-2} \text{s}^{-1}$	2×10^{34}		8×10^{35}	

Higher
beam current

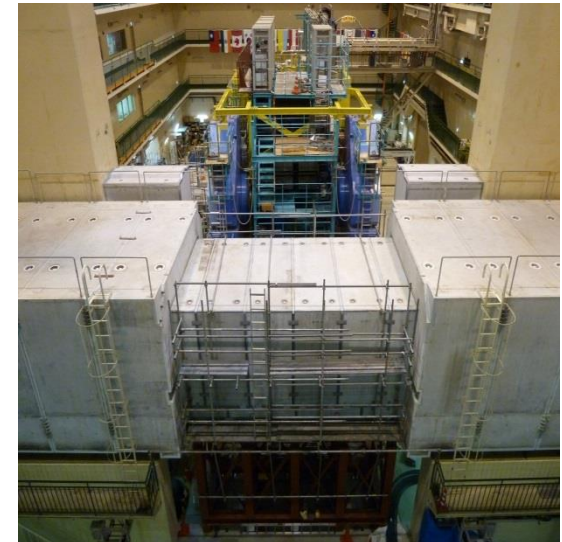
Nanobeam

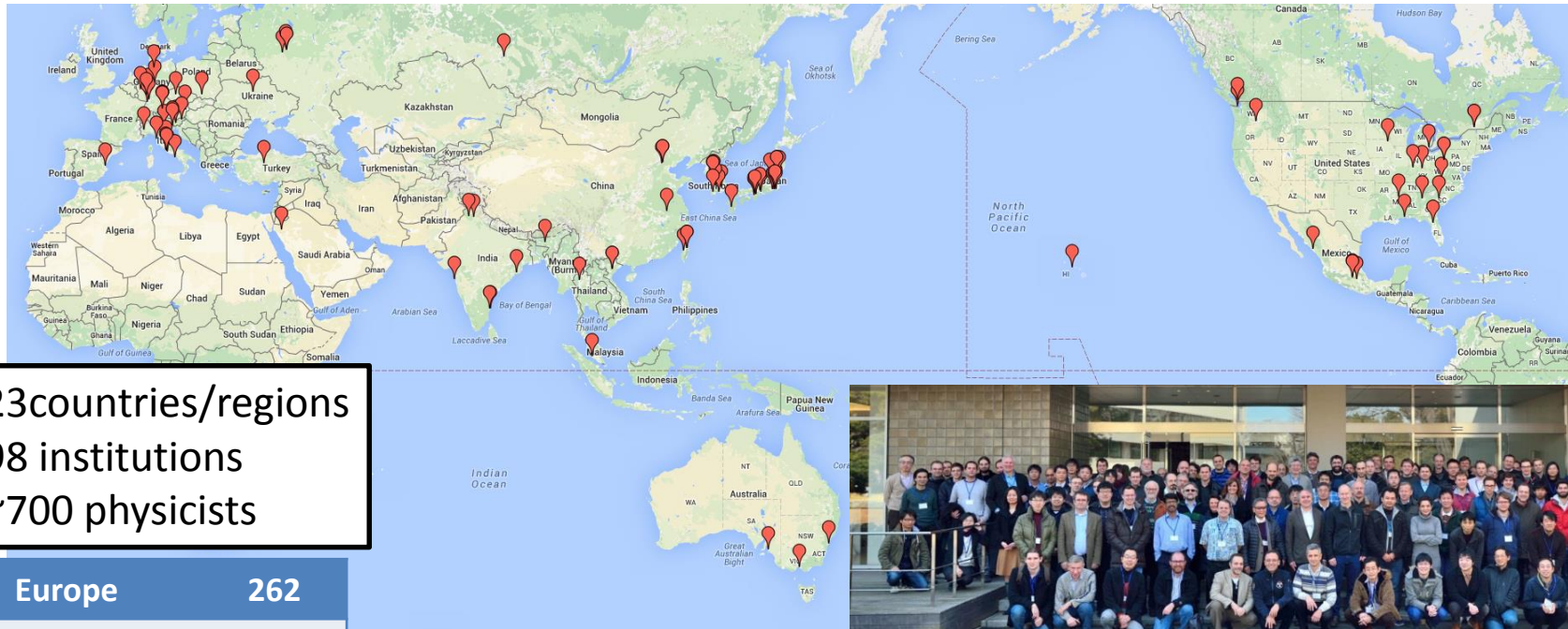
x40



Machine operation started

- Belle II still in the pit, waiting for some more sub-detectors
- BEAST (background monitors) is installed at Interaction Point (IP)
- Covered with concrete shields
- Final focus magnets (QCS) are not installed yet
- Damping Ring (DR) for positron beam not integrated yet





23 countries/regions
98 institutions
~700 physicists

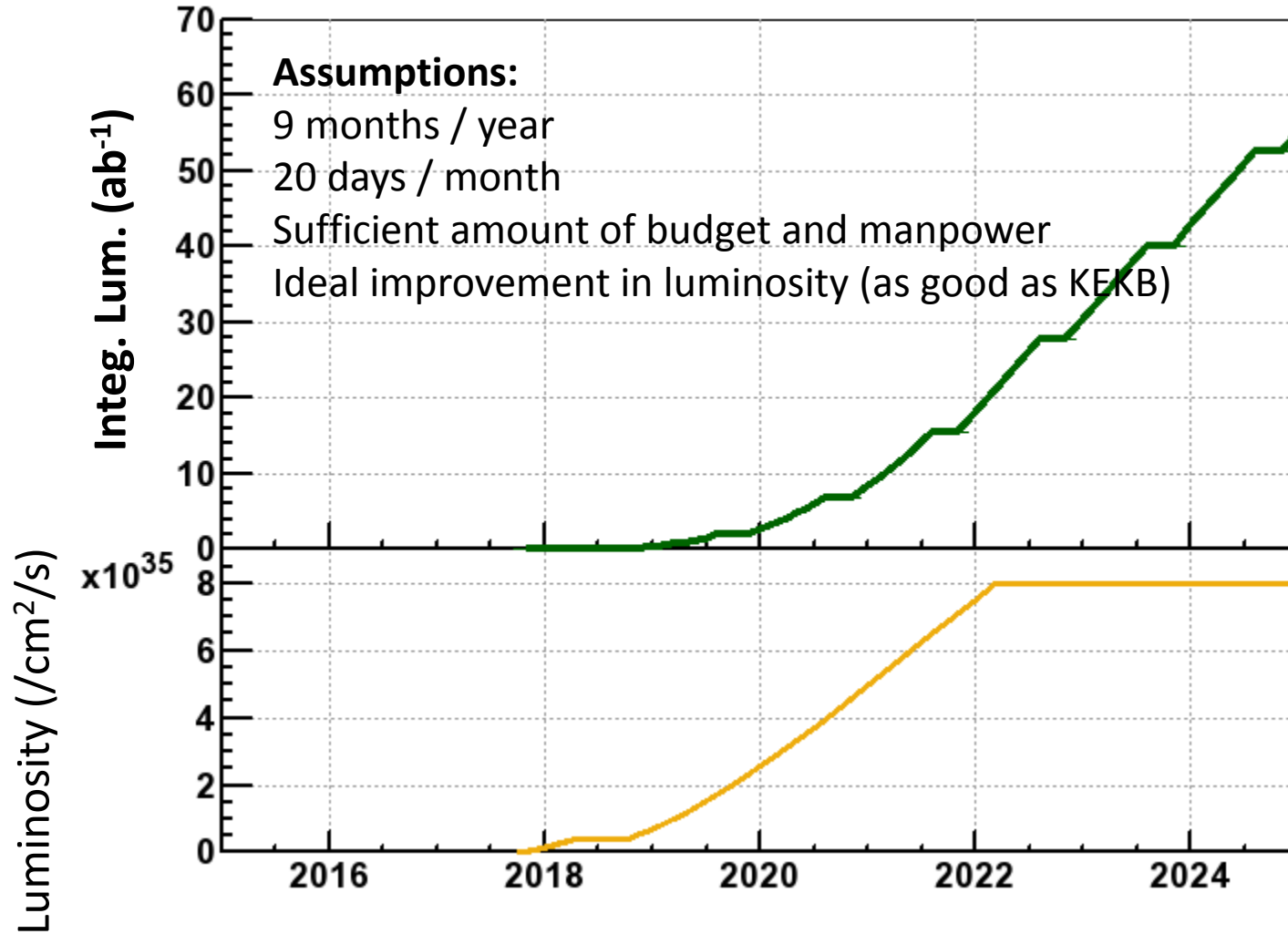
Europe	262
Austria	13
Czech	6
Germany	96
Italy	69
Poland	12
Russia	44
Slovenia	18
Spain	2
Ukraine	2

Asia	313		
Saudi Arabia	5	Korea	37
Australia	26	Malaysia	7
China	22	Vietnam	4
India	33	Taiwan	20
Japan	156	Thailand	1
		Turkey	2

America	111
Canada	26
Mexico	10
USA	75

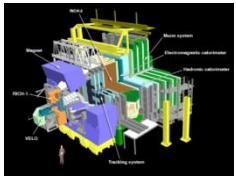


Luminosity Projection

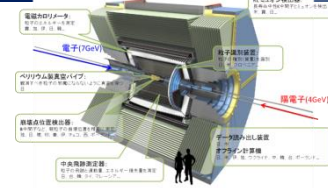


New Measurement Map

LHCb@CERN



Belle II



>>analyses LHCb is good at

>>analyses Belle II is good at

Only electrically charged particles (muons) in the final states

B_s, Λ_b
 $B_s \rightarrow \mu\mu$

SUSY,
Charged
Higgs

$B \rightarrow K^* \ell \ell$
Model-indep. NP
LUV
new CPV
 D^0 CPV

Model-indep. NP

Neutral particles (γ, ν, K_S etc.) in the final state

new CPV
 $b \rightarrow sqq$

$B \rightarrow D^* \tau \nu$ $B \rightarrow D^0 \tau \nu$

LUV

tau
 $\tau \rightarrow \mu \gamma$
LFV

Inclusive analysis

$b \rightarrow s/d \gamma$
 $b \rightarrow u \ell \nu$

$B \rightarrow K_S \pi^0 \gamma$
 $B \rightarrow h \nu \nu, \tau \nu$

SUSY,
charged
Higgs

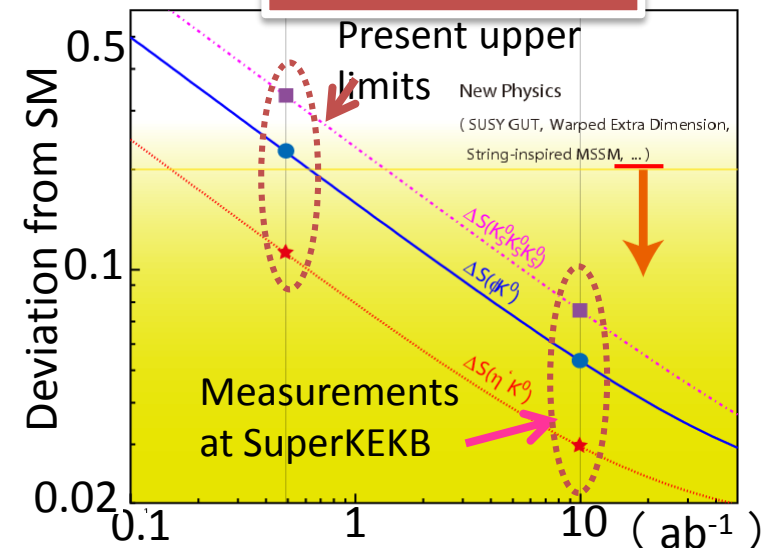
Charged
Higgs

right-
handed
weak
interaction

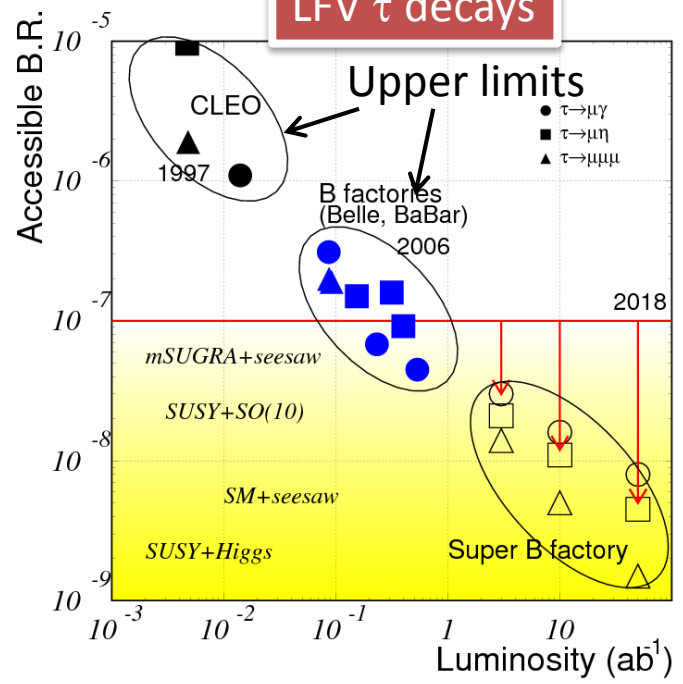
Charged
Higgs

- If New Physics scale is at TeV region,
 - It is natural to assume that the NP effects are seen in $B/D/\tau$ decays.
 - Flavor structure of new physics?
 - CP violation in new physics?
- Otherwise...
 - Search for deviations from SM in flavor physics will be one of the best ways to find new physics.

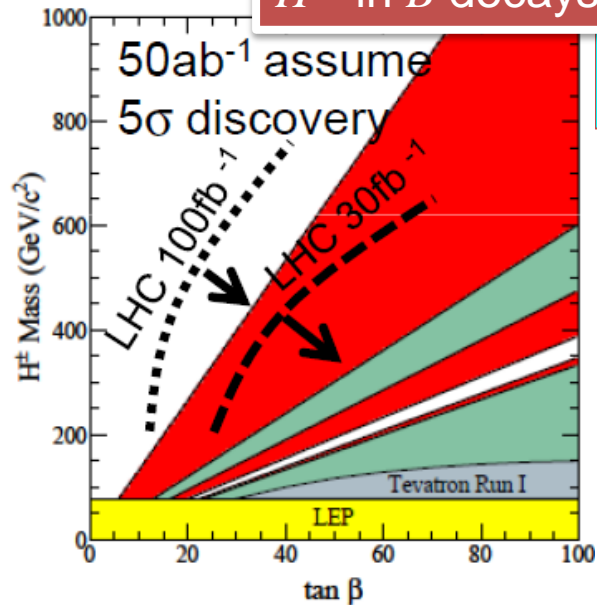
CPV in new FCNC



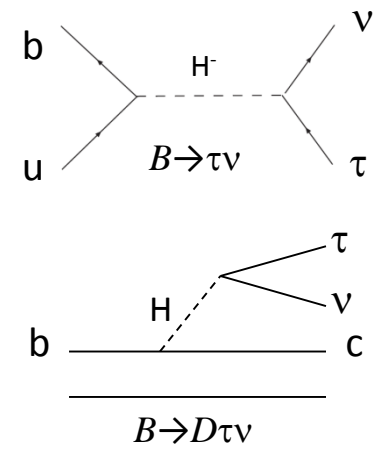
LFV τ decays



H^\pm in B decays

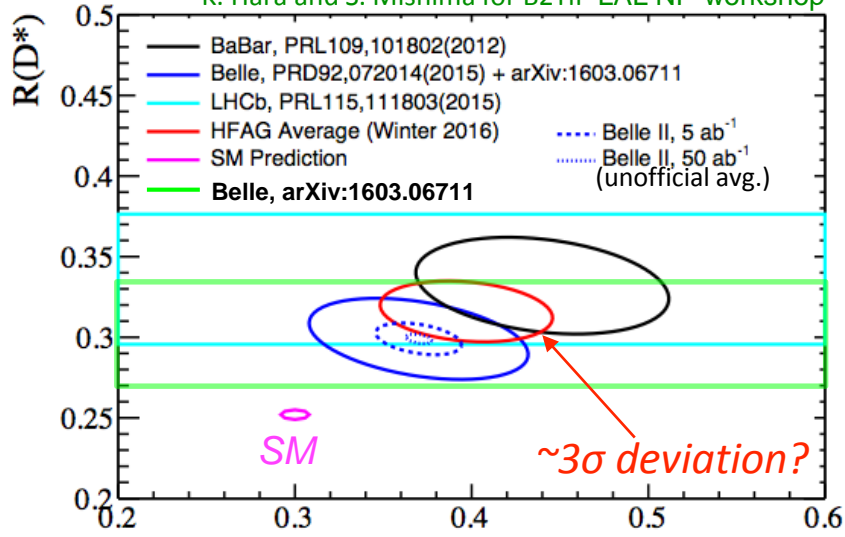


$B \rightarrow \tau \nu$: H - b - u coupling
 $B \rightarrow D \tau \nu$: H - b - c coupling



$B \rightarrow D^{(*)} \tau \nu$ at Belle, LHCb and Belle II

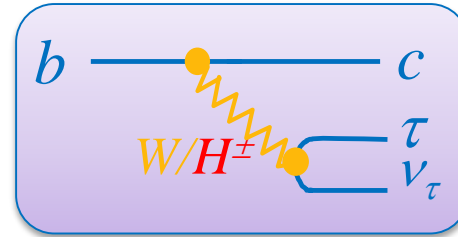
K. Hara and S. Mishima for B2TiP LAL NP-workshop



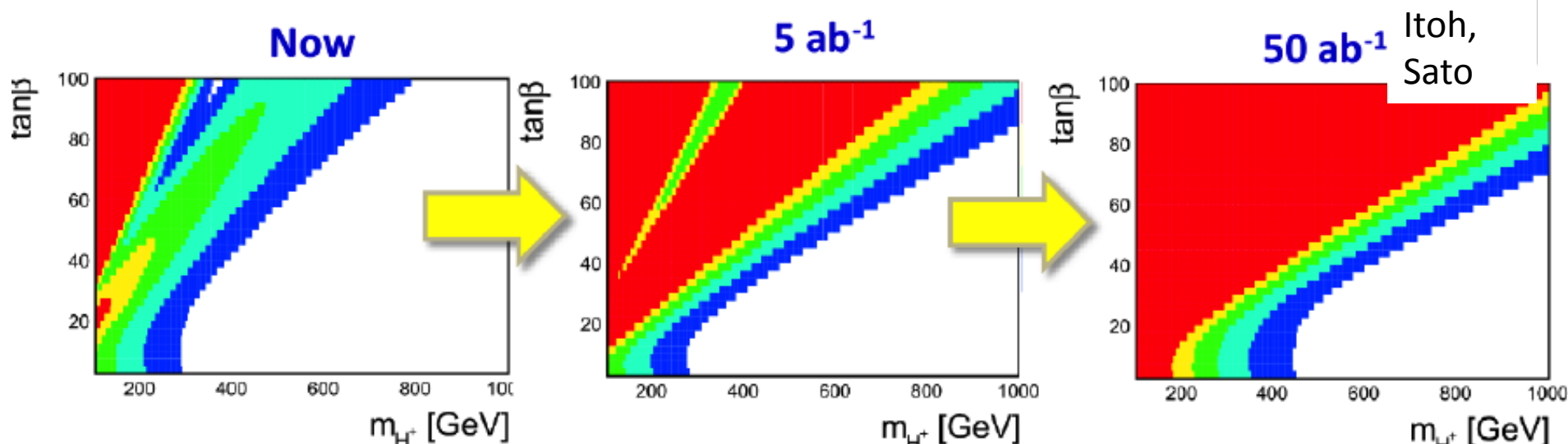
$$R(D^{*}) = \frac{\mathcal{B}(B \rightarrow D^{*} \tau \nu)}{\mathcal{B}(B \rightarrow D^{*} \ell \nu)}$$

Belle and LHCb are competitive and complementary experiments

One of important common topics : $B \rightarrow D^{*} \tau \nu$ sensitive to NP such as H^{\pm}



World average including the 2016 Belle result
 $\rightarrow \sim 3\sigma$ deviation from SM

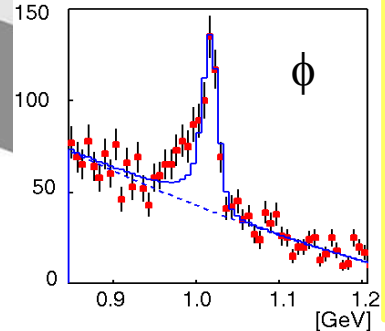
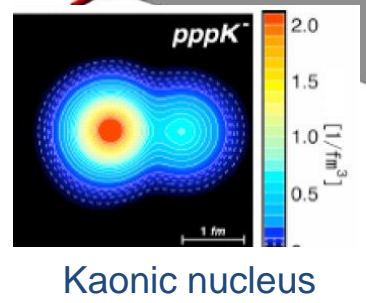
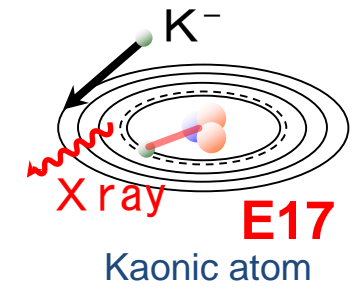
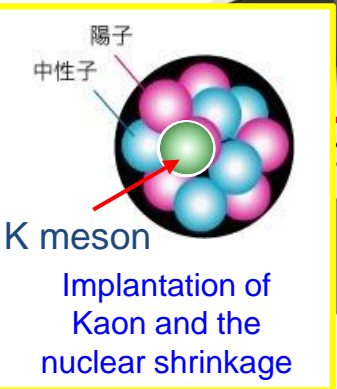
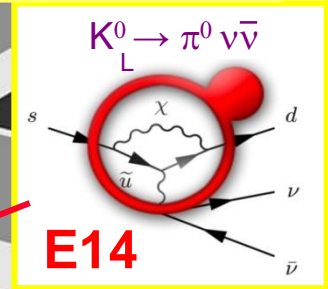
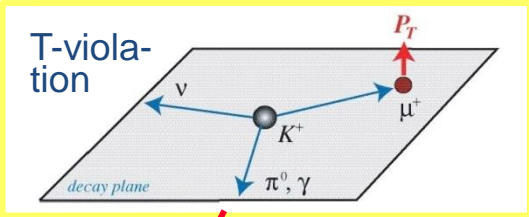
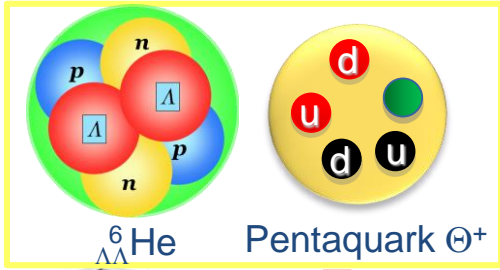
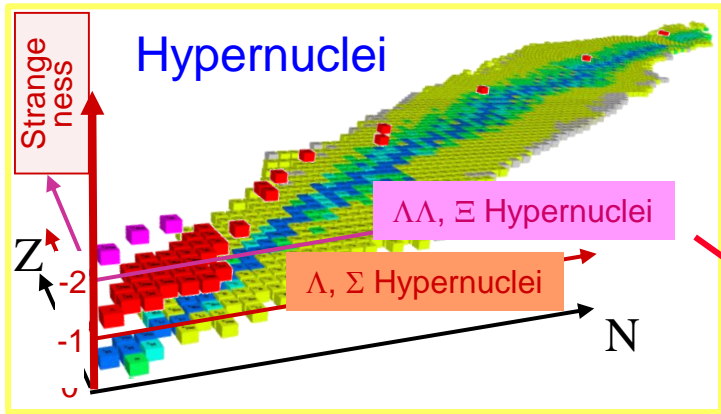


Simple message from the world's flavor physicists:

Credit: Djouadi



With apologies to Herodotus, Thucydides, Sparta, Persia...

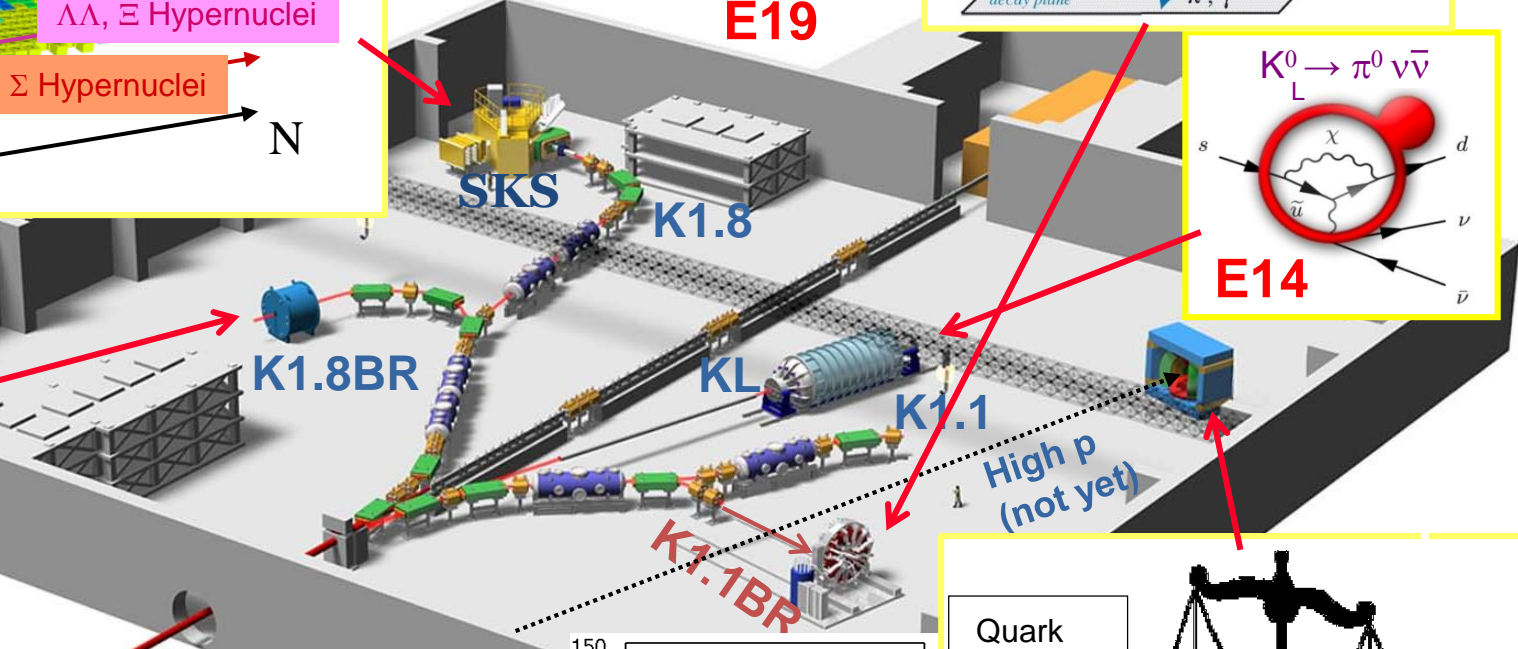


Quark

Free quarks

Bound quarks

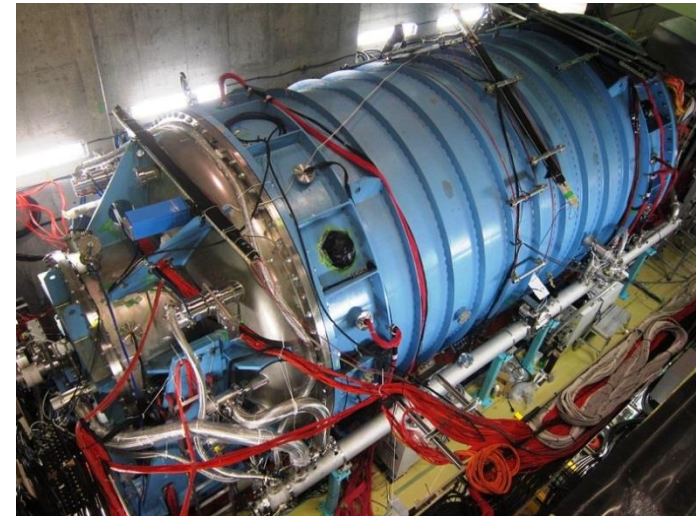
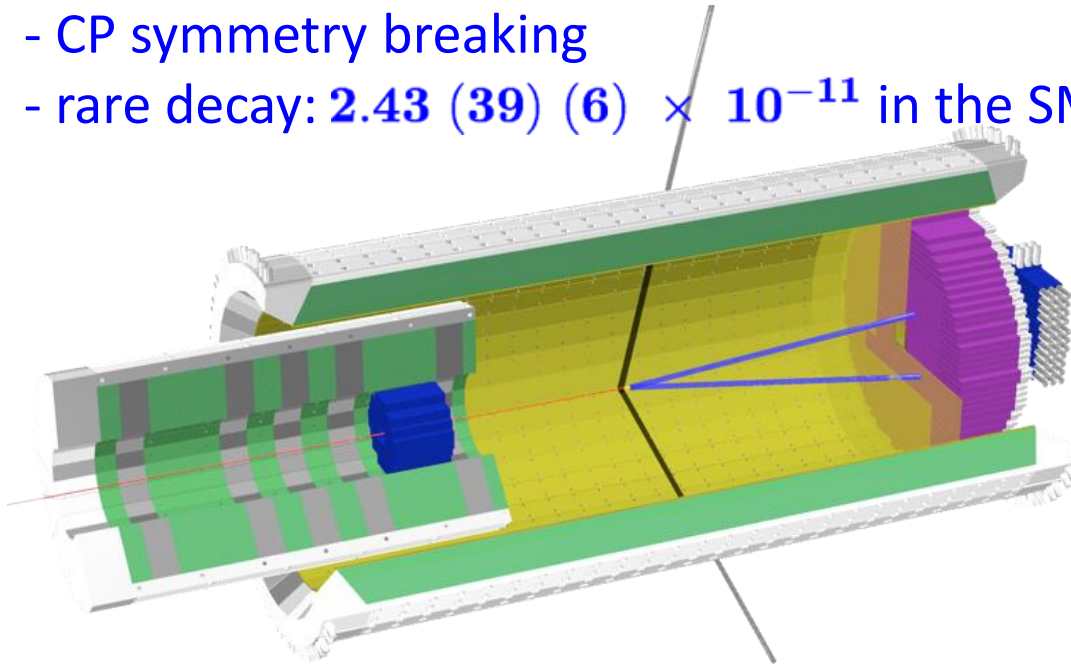
Why are bound quarks heavier?
Mass without Mass Puzzle



65 participants from Japan, US, Korea, Taiwan, Russia



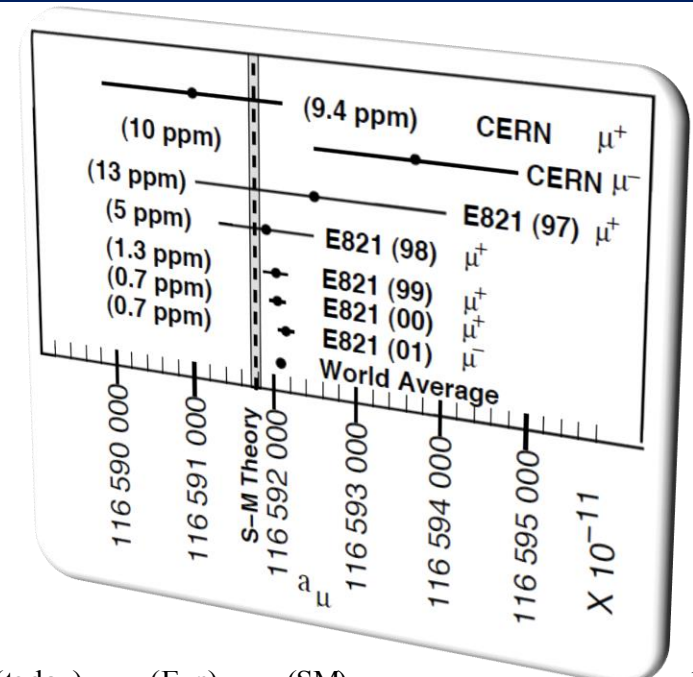
- CP symmetry breaking
- rare decay: $2.43 (39) (6) \times 10^{-11}$ in the SM



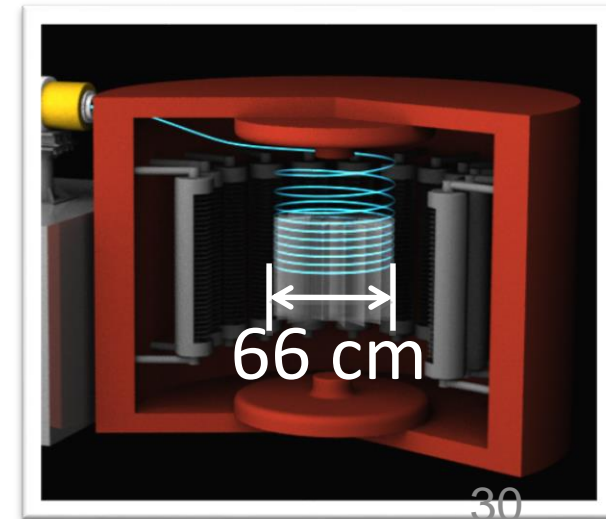
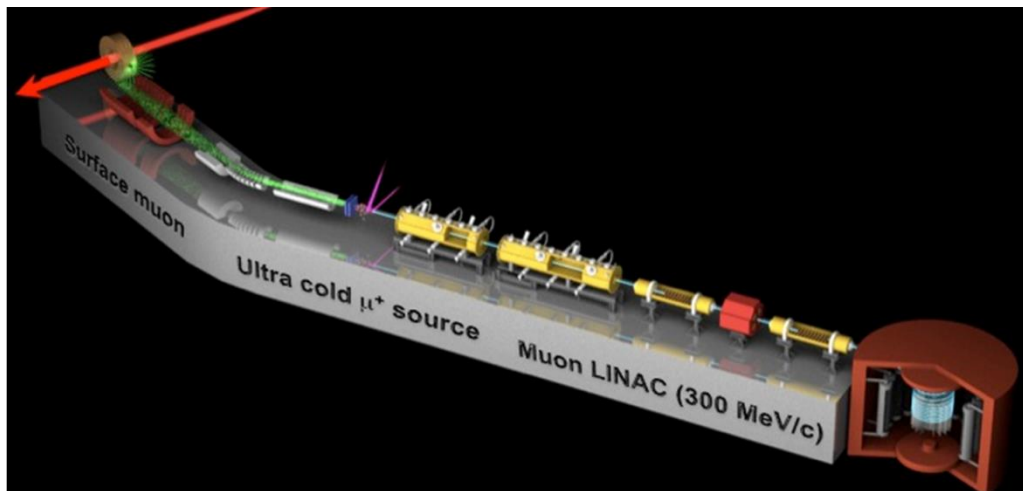
- **CsI calorimeter** to measure $\pi^0 \rightarrow \gamma\gamma$
- background rejection:
 - hermetic extra-particle detection (“veto”)
- Trigger/DAQ (37k channels):
 - waveform digitization (14bits, 125MHz ADC), pipeline readout

Muon g-2/EDM in MLF

- 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 \rightarrow 0.1 ppm
 - ▶ EDM: CP violation in the lepton sector?
 - ✓ $< 1 \times 10^{-19} \text{ e cm} \rightarrow 5 \times 10^{-21} \text{ e cm}$
- Extensive R&D on various elements are on-going



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



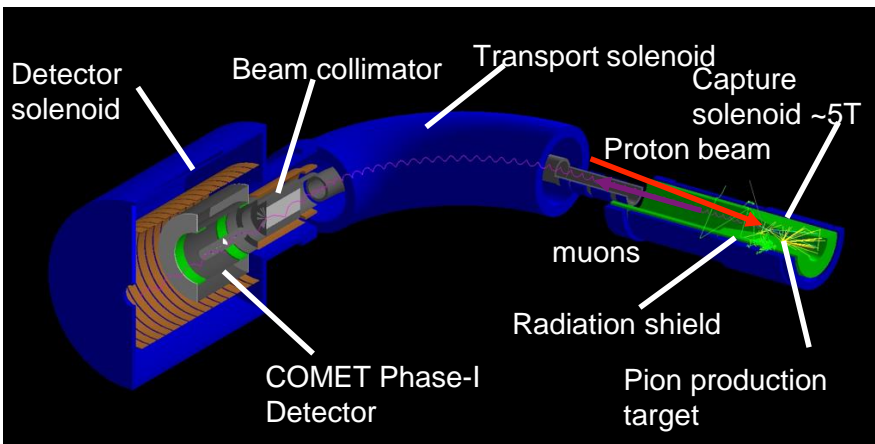
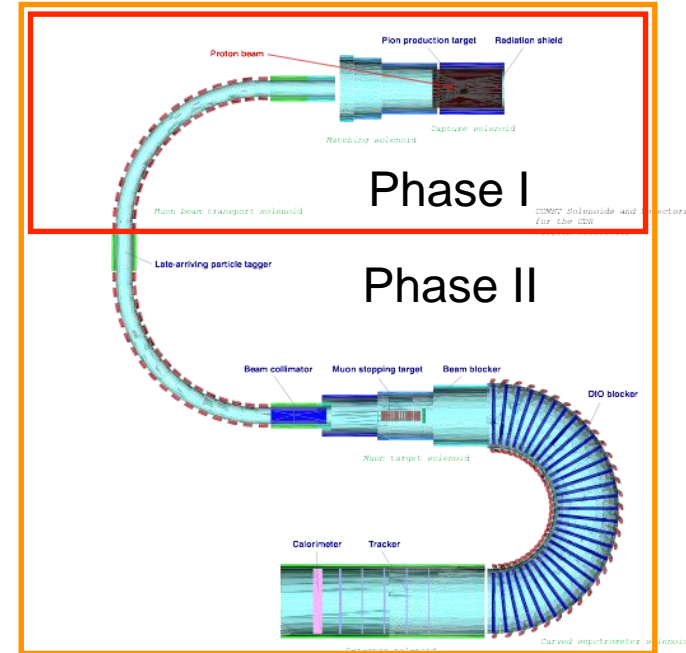
Phase I

- ▶ Detailed understanding of the beam background and achieving the sensitivity of $< 10^{-14}$ (100 better than the current limit)
- ▶ 8GeV, 3.2kW beam, ~90-days DAQ (Graphite as a primary target)

Phase II

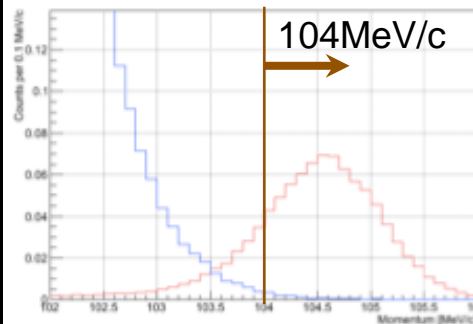
- ▶ 8GeV, 56kW beam, 1-year DAQ (Tungsten as a primary target)
- ▶ COMET final goal Sensitivity $< 10^{-16}$

- ▶ Proton beam extinction (w/o extraction) of 10^{-12} has been already achieved (Req. $< 10^{-9\sim 10}$)



Phase I background

0.03 BG expected
 In 7.8×10^6 sec running time
 BR= 3×10^{-15}



Phase I

2013-2015

Facility construction

2013-2016

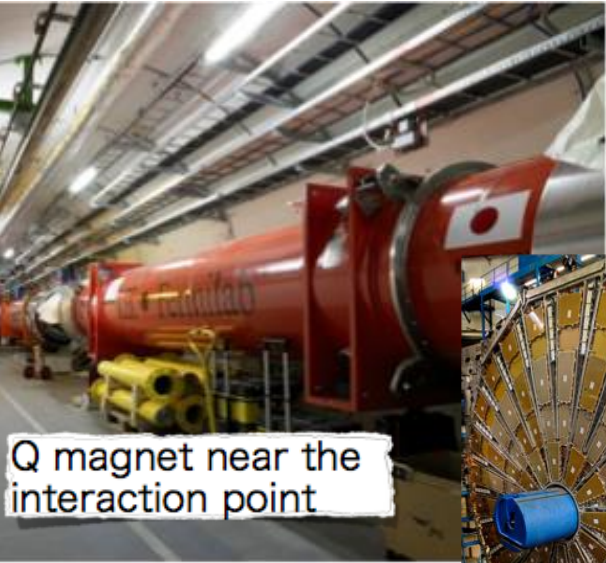
Magnet construction & installation

2016-2017

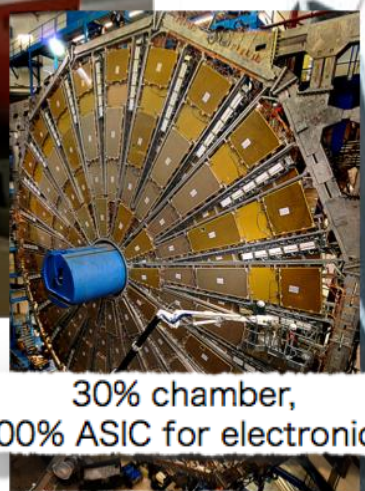
Eng. run & Physics run

Phase II

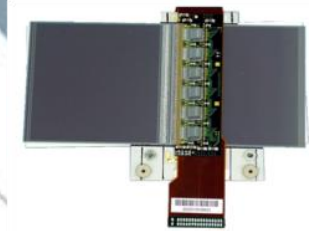
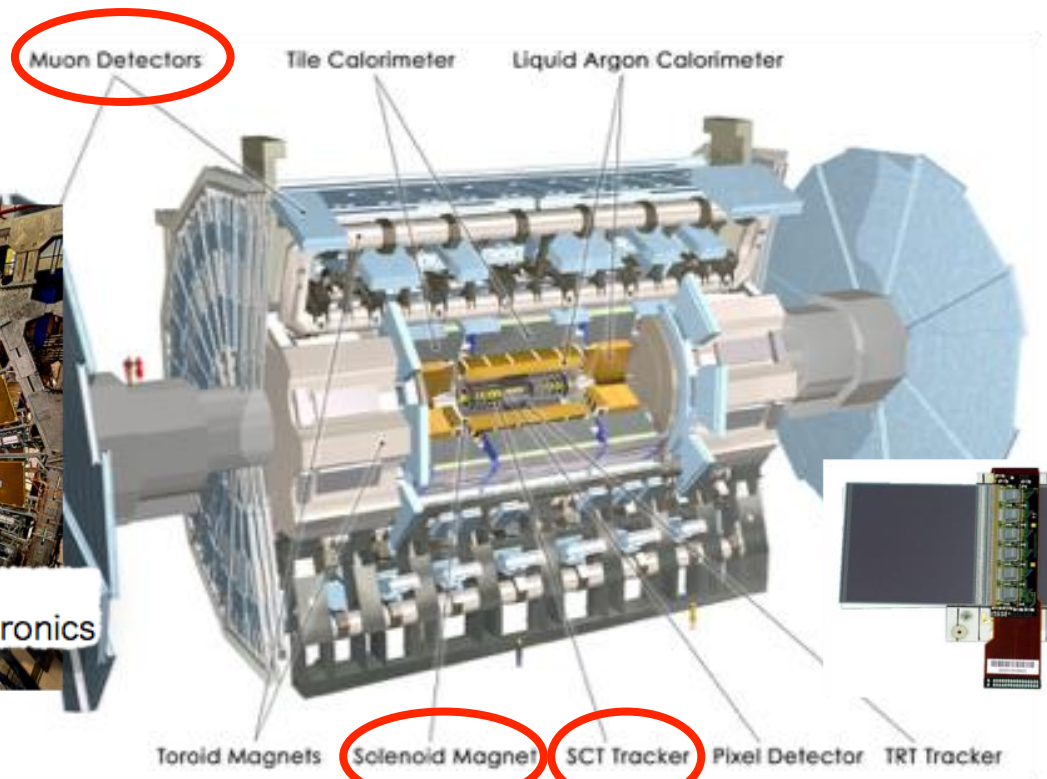
Eng. run in 2020(?)



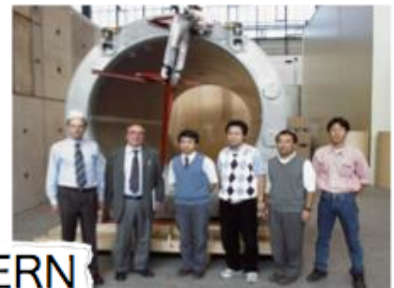
Q magnet near the interaction point



30% chamber, 100% ASIC for electronics

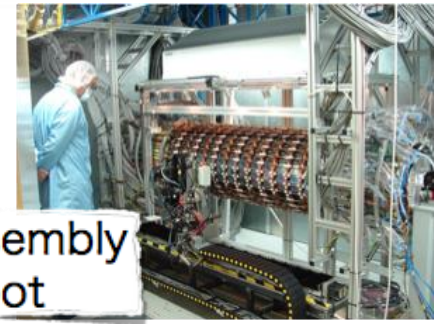


- Critical contributions
- pixel/SCT operation
 - muon trigger responsibility
 - computing
 - physics analysis
 - trigger coordinator
 - collaboration board chair



Solenoid at CERN before installation

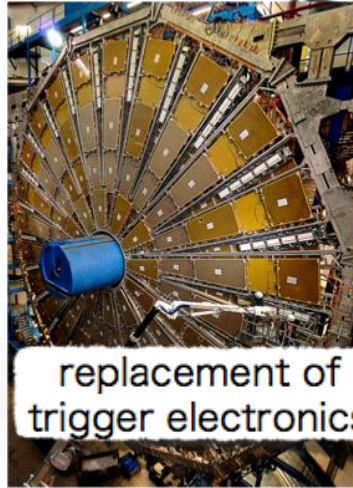
100% 20%



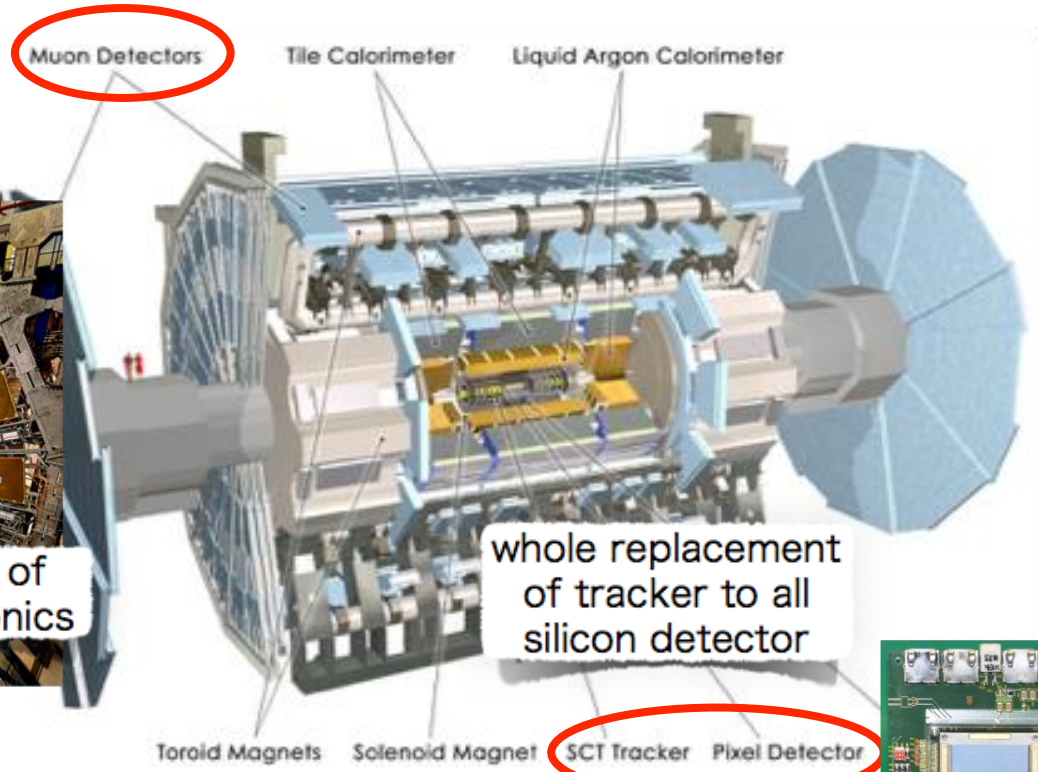
module assembly by KEK robot



beam separation Q magnet
1st prototype under test



replacement of trigger electronics

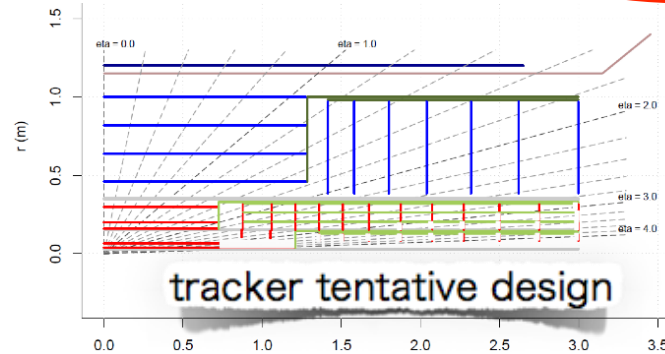


whole replacement of tracker to all silicon detector



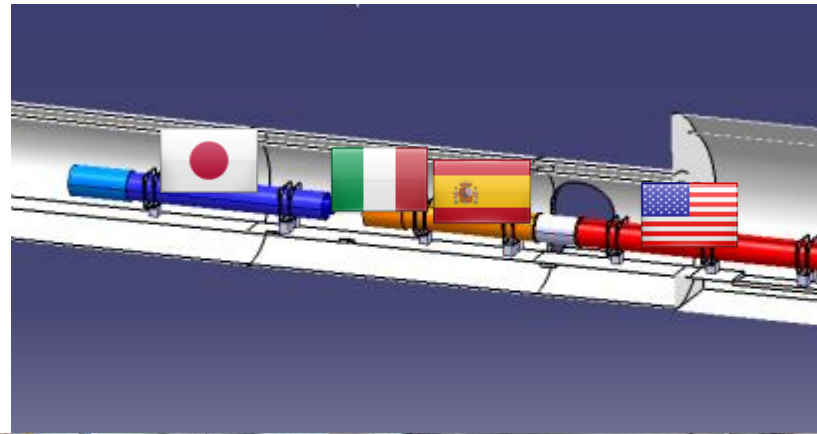
Critical contributions

- beam separation magnet
- silicon pixel/strip detector
- muon trigger electronics
- computing

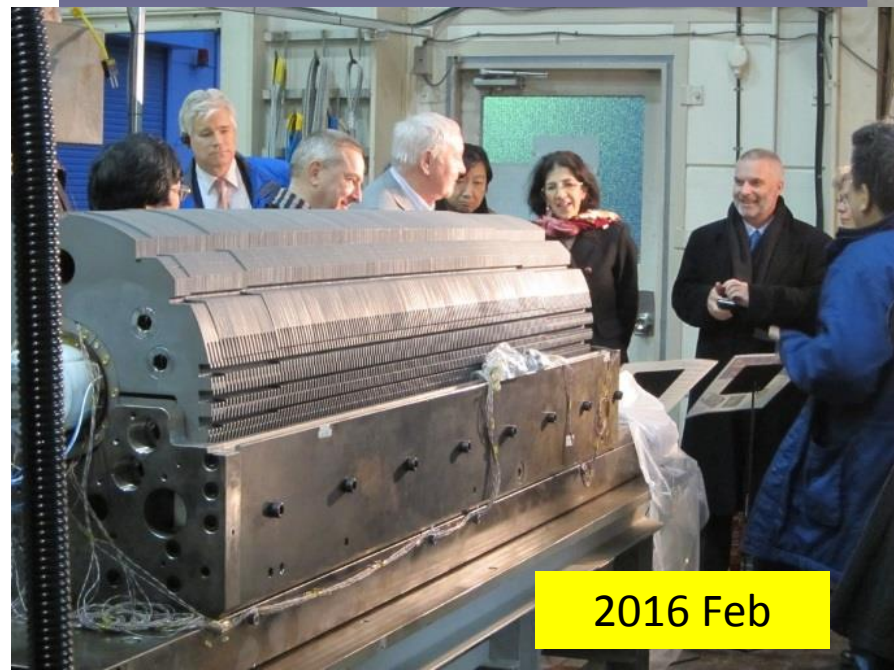


tracker tentative design

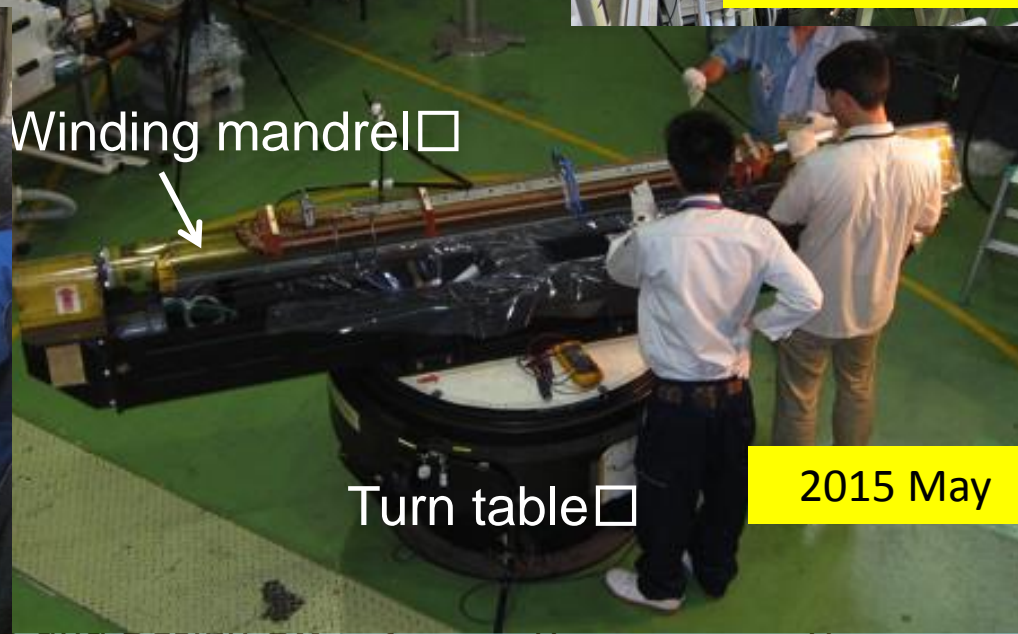
2m Model coil production and test at KEK



2016 May

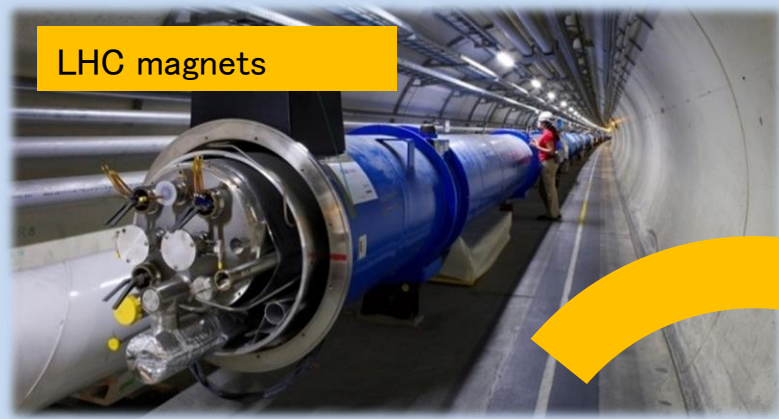


2016 Feb



2015 May

Very fruitful collaboration with CERN



LHC magnets



J-PARC neutrino beamline



PSB: cavities



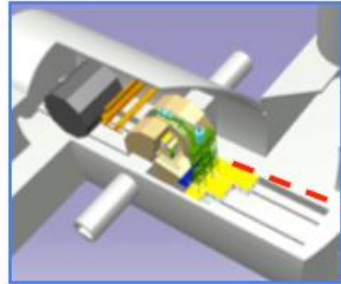
J-PARC New RF cavities



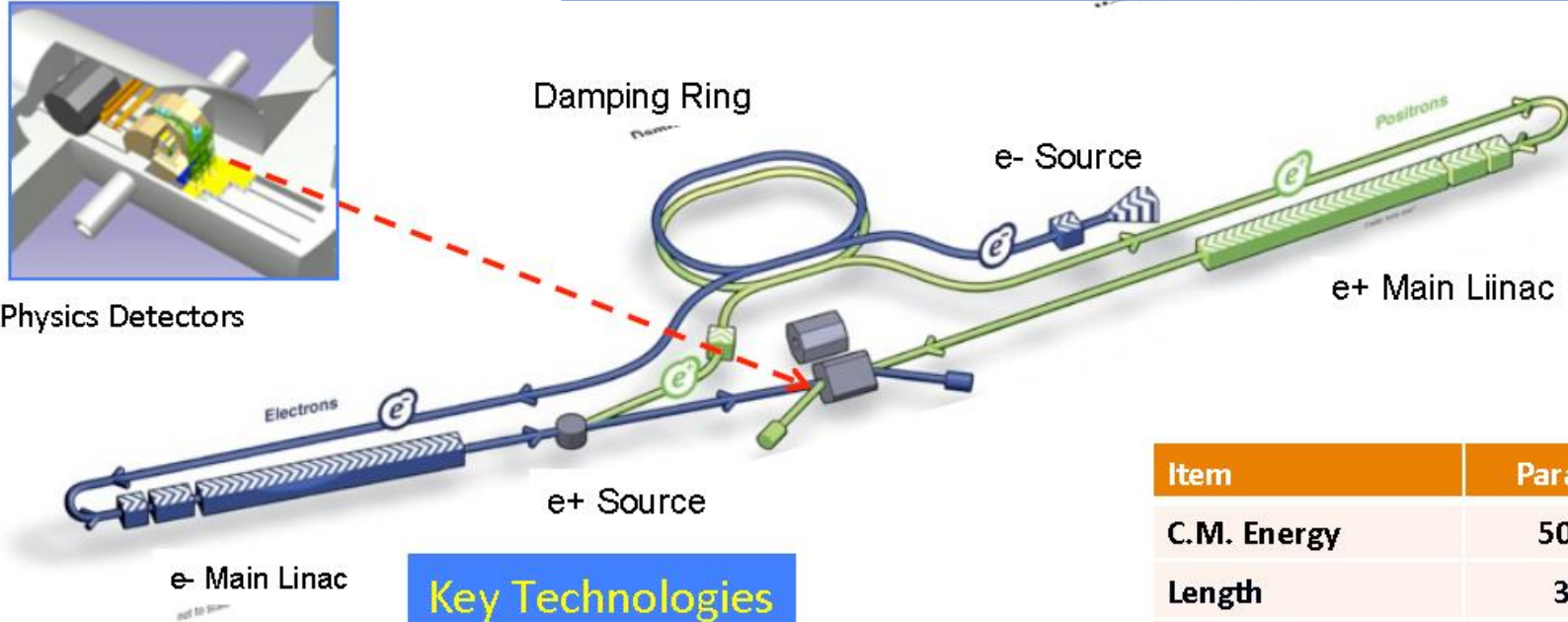
KEK: Contribution to LIU:
132 Finemet Core production:
(~0.4MCHF) in 2016.

International Linear Collider

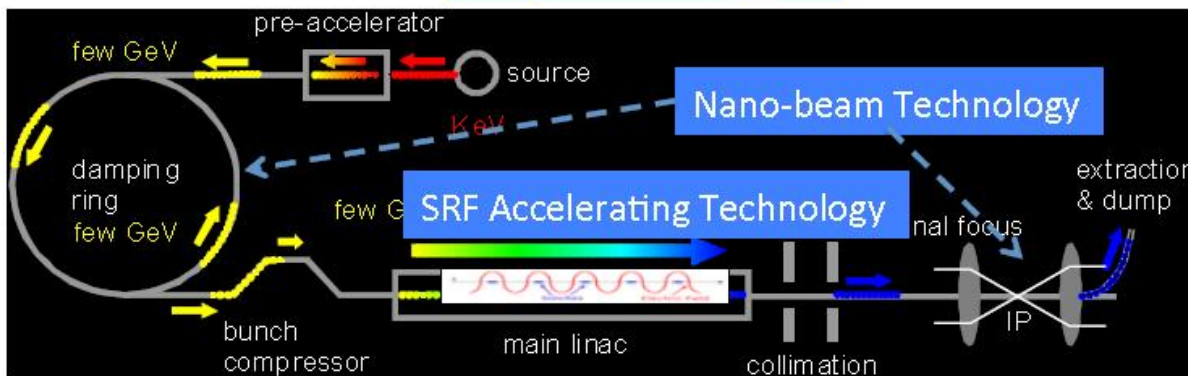
ILC has been proposed by the international HEP community and recommended by European strategy, US P5, etc. Its studies are conducted by the initiative of ICFA.



Physics Detectors

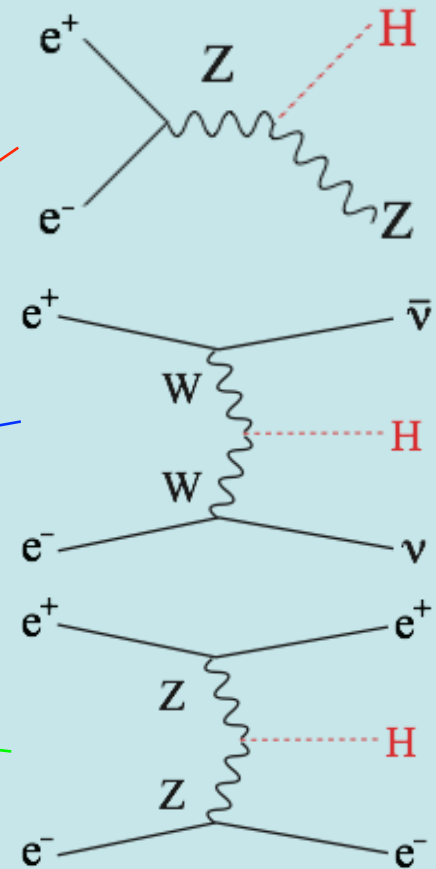
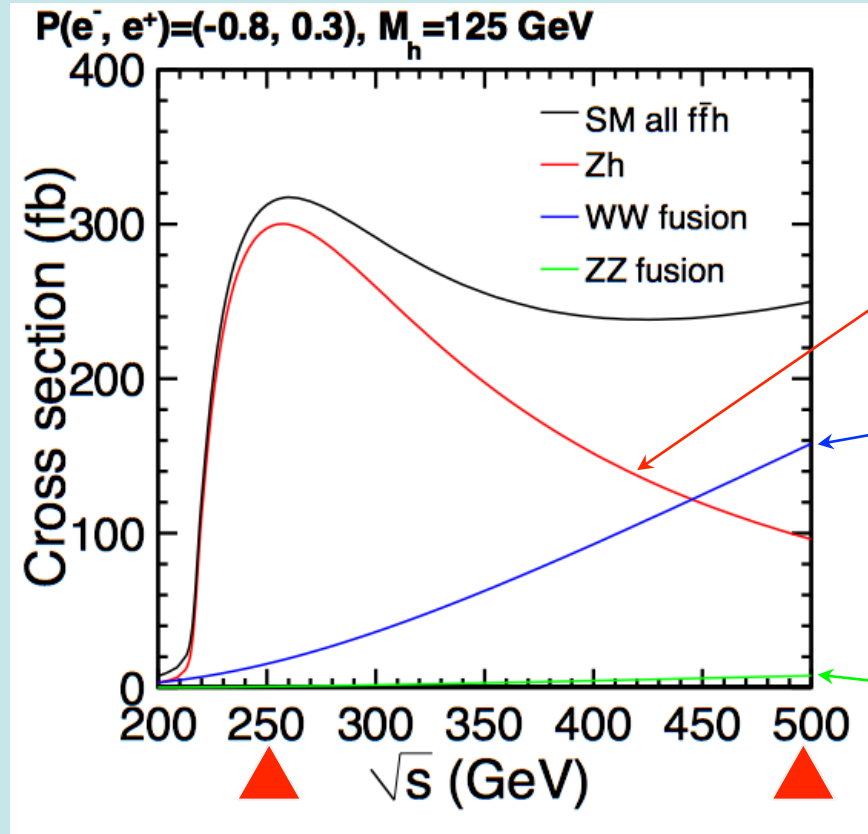


Key Technologies



Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	$1.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA
Beam size (y) at FF	5.9 nm
SRF Cavity G.	31.5 MV/m
Q_0	$Q_0 = 1 \times 10^{10}$

Production cross section



ZH dominates at 250 GeV
 (~80k ev: 250 fb⁻¹)

$\nu\nu H$ takes over at 500 GeV
 (~125k ev: 500 fb⁻¹)

$$\chi^2 = \sum_{i=1}^{35} \left(\frac{Y_i - Y'_i}{\Delta Y_i} \right)^2$$

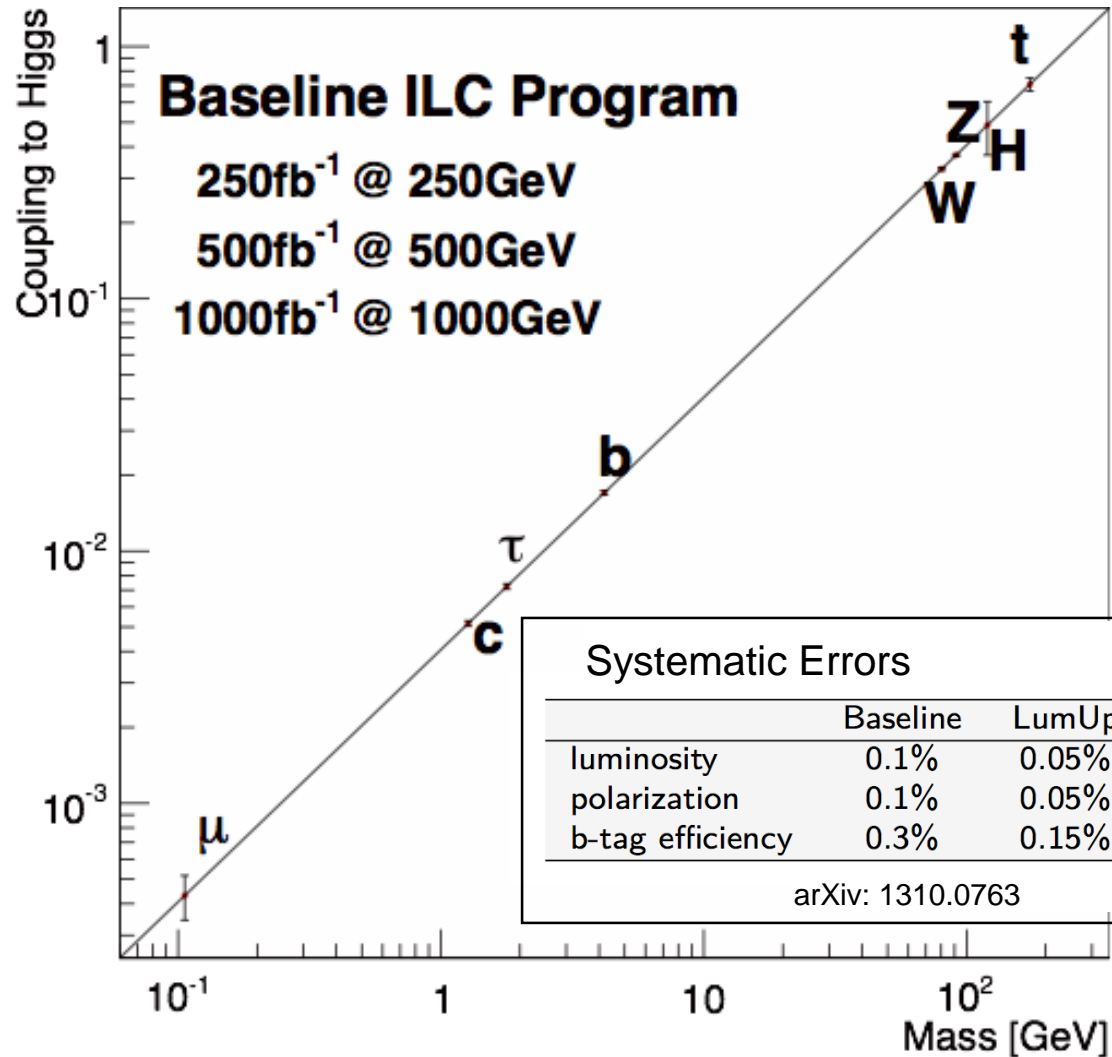
$$Y'_i = F_i \cdot \frac{g_{HA_iA_i}^2 \cdot g_{HB_iB_i}^2}{\Gamma_0}$$

$(i = 1, \dots, 33)$
 $(A_i = Z, W, t)$
 $(B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$

$$F_i = S_i G_i$$

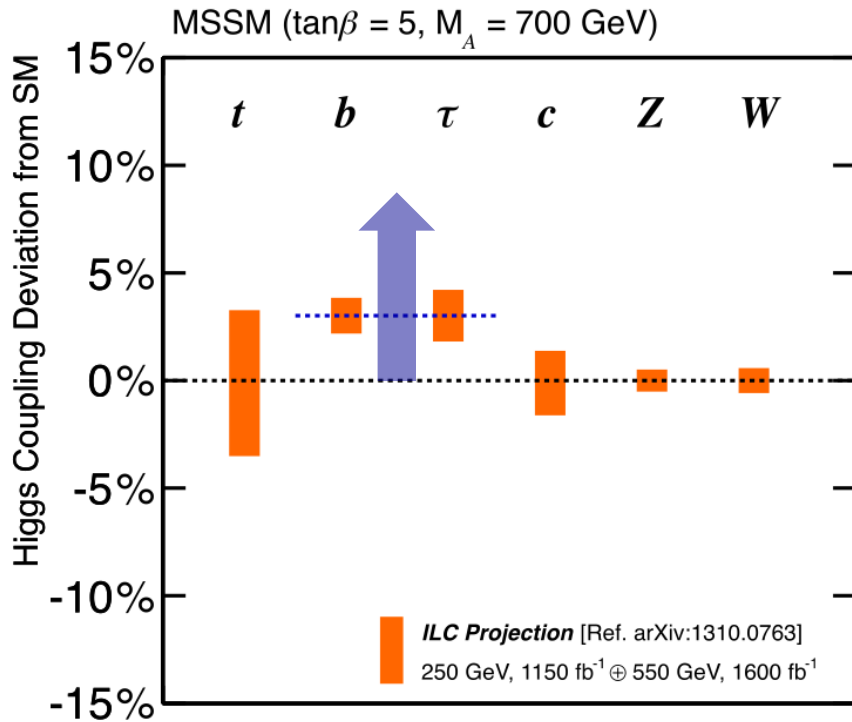
$G_i = \left(\frac{\Gamma_i}{g_i^2} \right)$

$$S_i = \left(\frac{\sigma_{ZH}}{g_{HZZ}^2} \right), \left(\frac{\sigma_{\nu\bar{\nu}H}}{g_{HWW}^2} \right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g_{Htt}^2} \right)$$

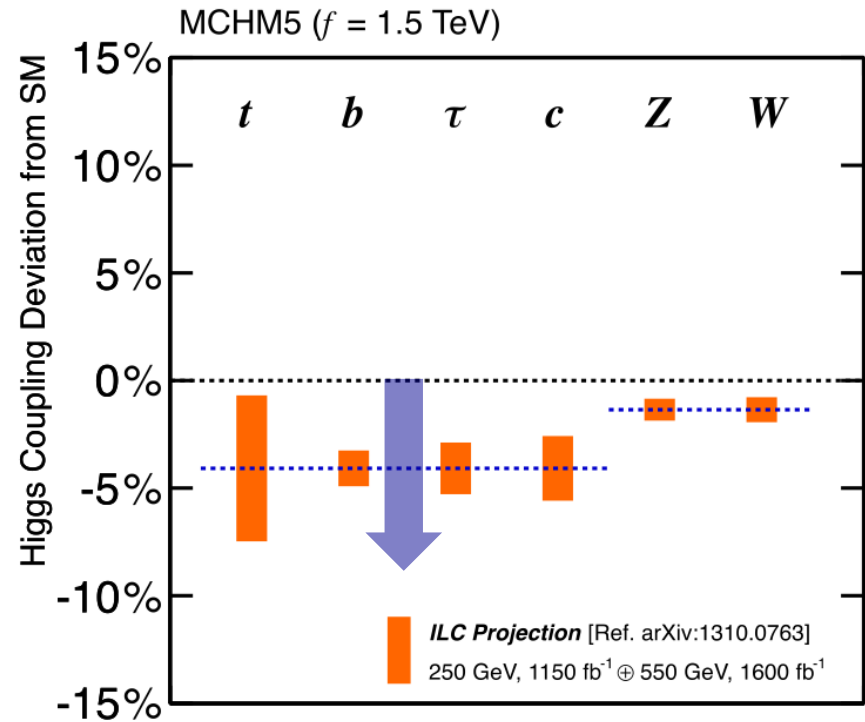


ILC's precisions will eventually reach sub-% level!

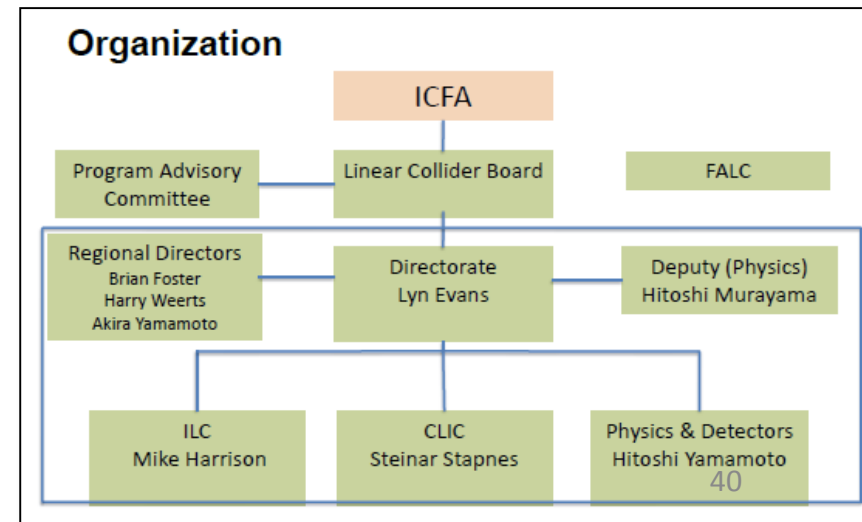
Supersymmetry (MSSM)



Composite Higgs (MCHM5)



- R&D for a future e+e- linear collider was started more than 20 years ago in three regions.
- By early 2000's , it became a consensus among the world HEP community that an e+e- linear collider with the CM energy of about 500 GeV should be the next collider beyond the LHC.
- ICFA chose the cold technology for LC as a global project, and set up a global team (GDE) for design and coordination of R&D for the ILC.
- After eight years of works, the TDR of the ILC was published in June 2013 . ICFA set up the Linear Collider Collaboration for engineering design phase.



- In October 2012, after the discovery of the Higgs boson at LHC, Japanese HEP community proposed to host the ILC in Japan as a global project.
- This proposal was welcomed by worldwide HEP communities.

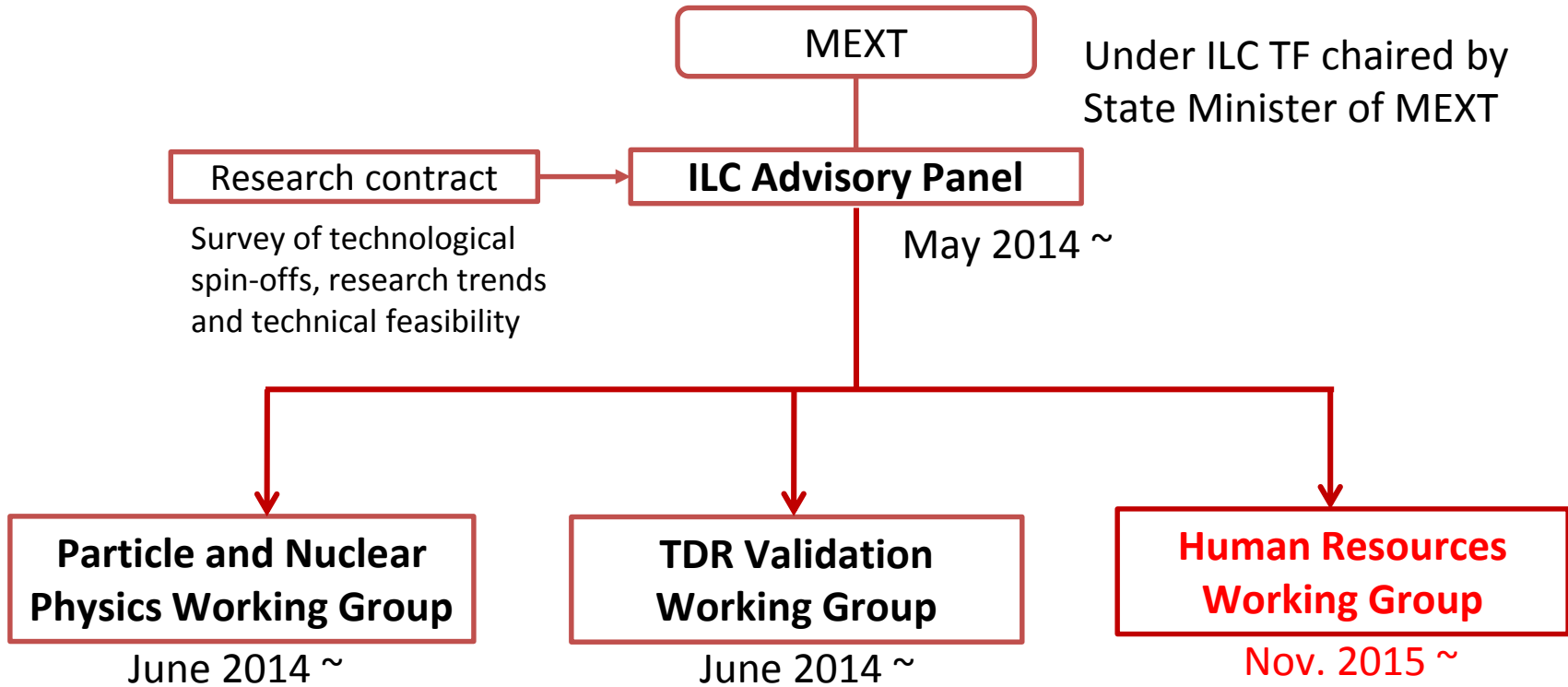
The European Strategy for Particle Physics Update 2013

US P5 report (May 2014)

ICFA statements (January and July 2014)

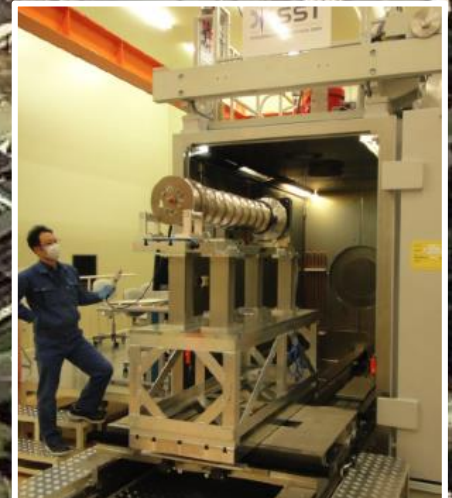
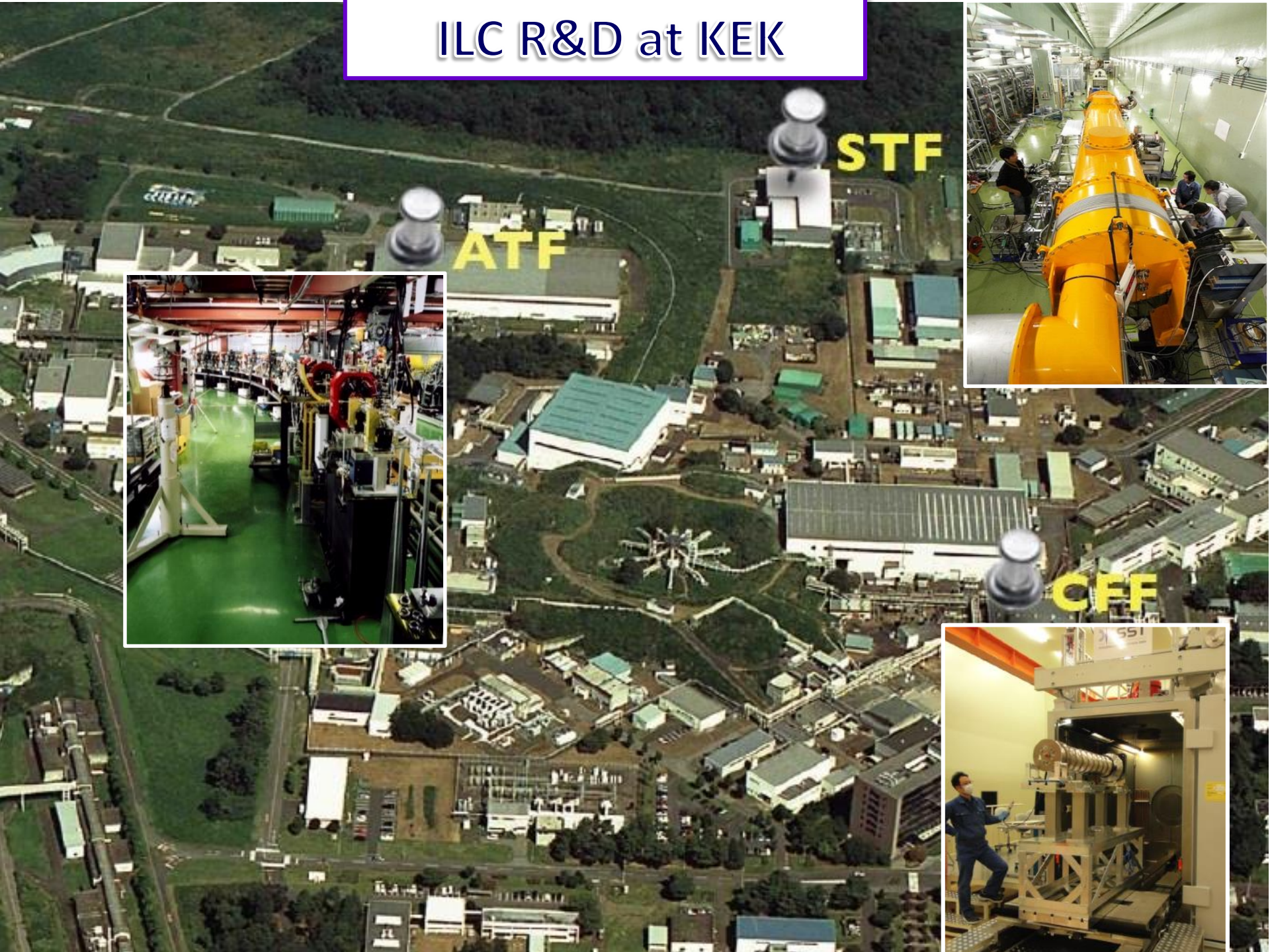
ACFA/AsiaHEP Statement on the ILC (September 2013)

- In May 2013, Science Council of Japan (SCJ) set up a special committee for the ILC Project as a response to the MEXT's request for deliberation of the ILC project from an academic point of view.



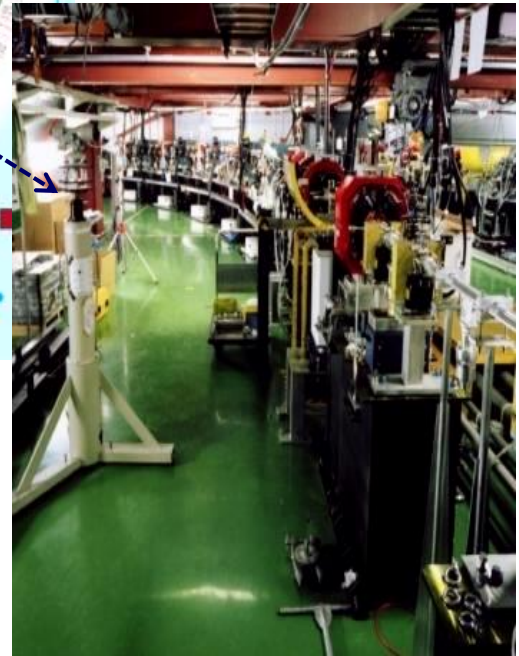
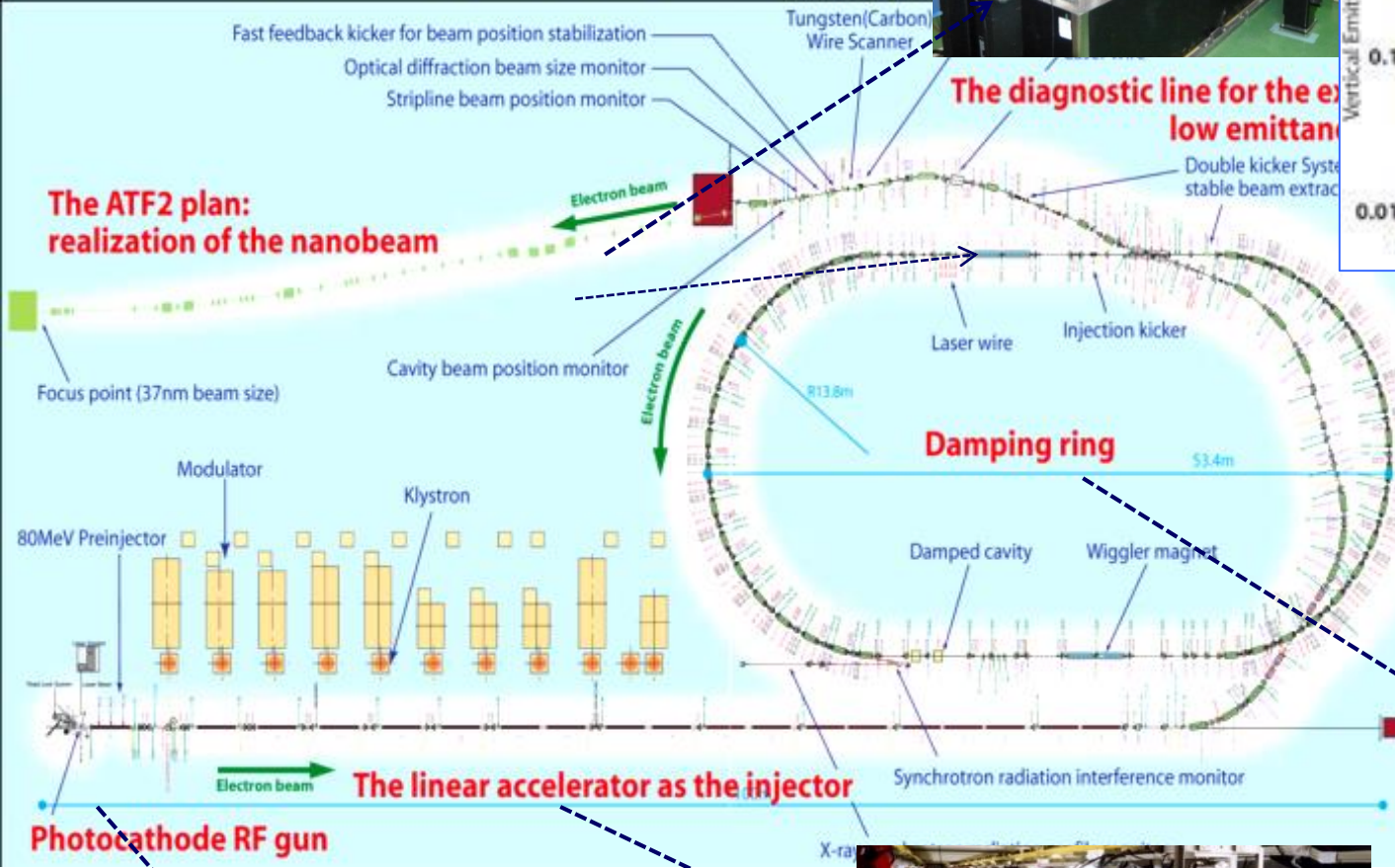
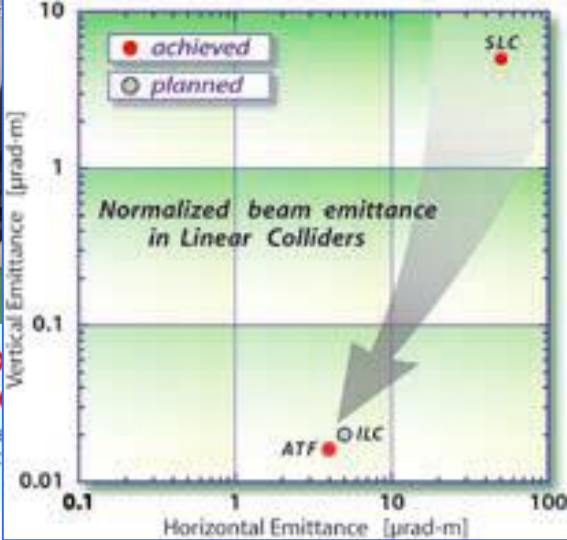
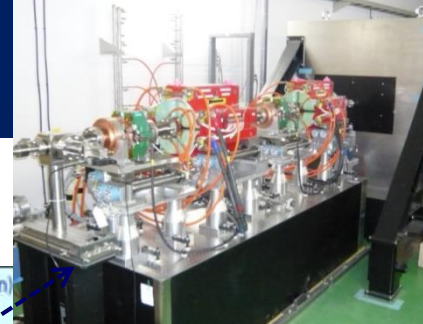
- “Summary of Discussions” released by the ILC Advisory Panel (August 2015)
 - ▶ Recommendation 1: **Share the cost internationally** and **Find a clear vision on the discovery potential of new particles.**
 - ▶ Recommendation 2: **Closely monitor and analyze the development of the LHC experiments** and **Mitigate cost risk.**
 - ▶ Recommendation 3: **Obtain general understanding by the public and science communities.**

ILC R&D at KEK



ATF

- Generate Low Emittance Beams
- Handle Nano-Size Beams



ILC Recent progress of KEK-ATF

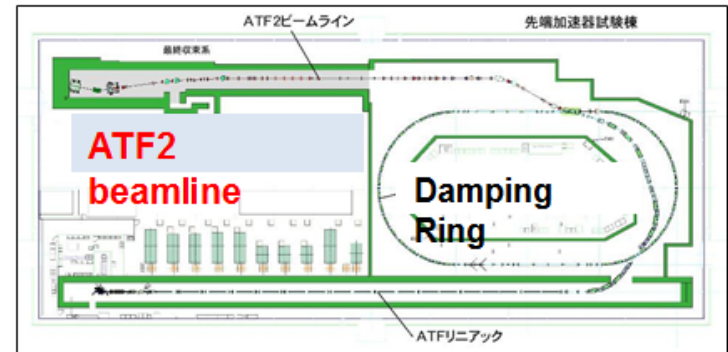
ATF2: Final focus Test beamline

Goal-1: Develop final focus system for ILC

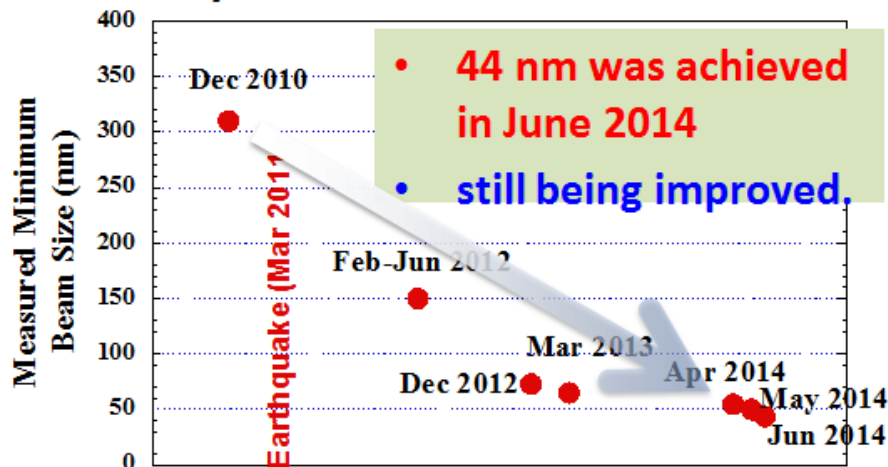
→ 37 nm vertical beam size at IP

Goal-2: Develop beam position stabilization in a few nm

→ Study of Intra-train feedback has been started.

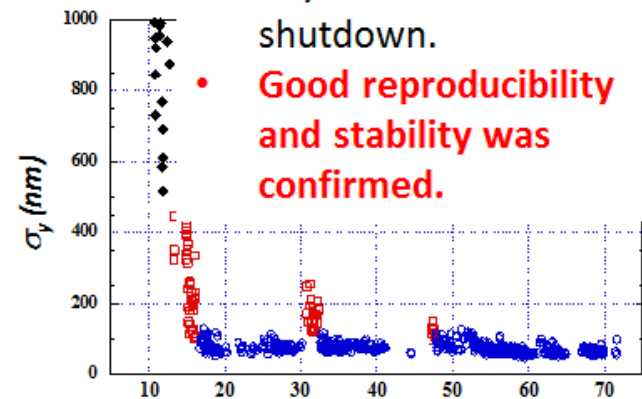


History of measured minimum beam size



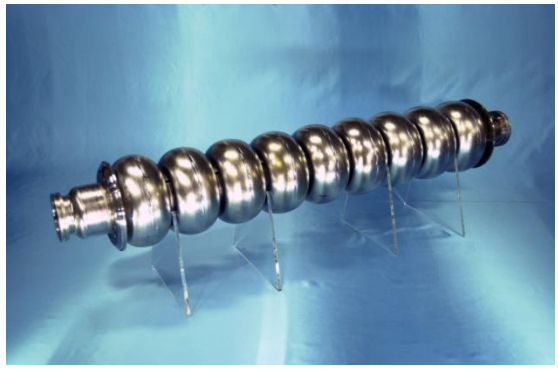
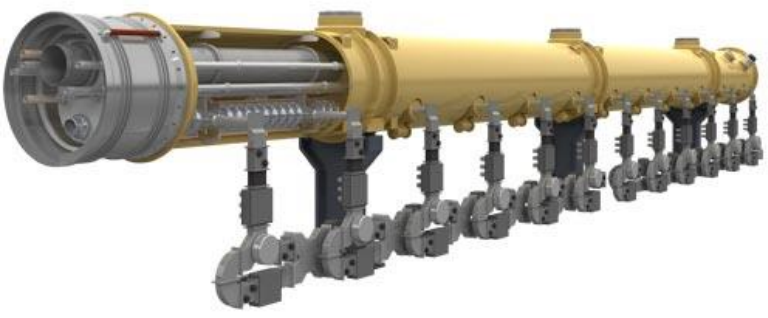
Presented by K.Kubo at IPAC2014

- Small beam size (<50 nm) was recovered in a day from an accelerator shutdown.



Time (hours) from operation start after 3 days shutdown

- Good reproducibility and stability was confirmed.



- KEK has diverse program in particle physics.
 - ▶ Long baseline neutrino experiment T2K continues data taking with >400kW beam power.
 - ▶ Future of neutrino experiment: HyperKamiokande (U. of Tokyo) + J-PARC upgrade to 1.3MW. → ν CPV
 - ▶ Flavor physics at SuperKEKB
 - ✓ Machine commissioning has started, and construction of Belle II is almost on schedule.
 - ✓ Belle II is competitive and complementary with LHCb and other LHC experiments in B physics.
 - ▶ Flavor physics at J-PARC: $K \rightarrow \pi^0 \nu \nu$, $g_{\mu} - 2$, $\mu - e$ conversion.
 - ▶ Contributions of KEK and Japanese groups to ATLAS/LHC will continue. We hope to play important roles in HL-LHC.

- Hosting ILC is being intensively studied by the Japanese Government. KEK will provide all the possible help to have them reach conclusion in timely manner together with the world ILC community.