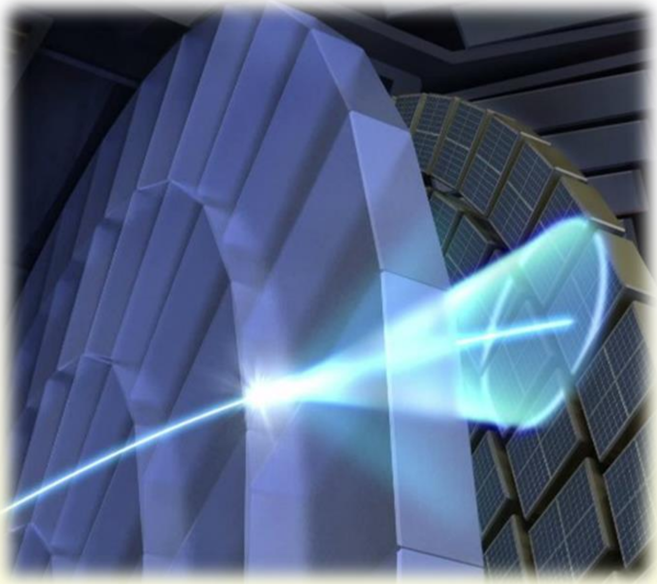
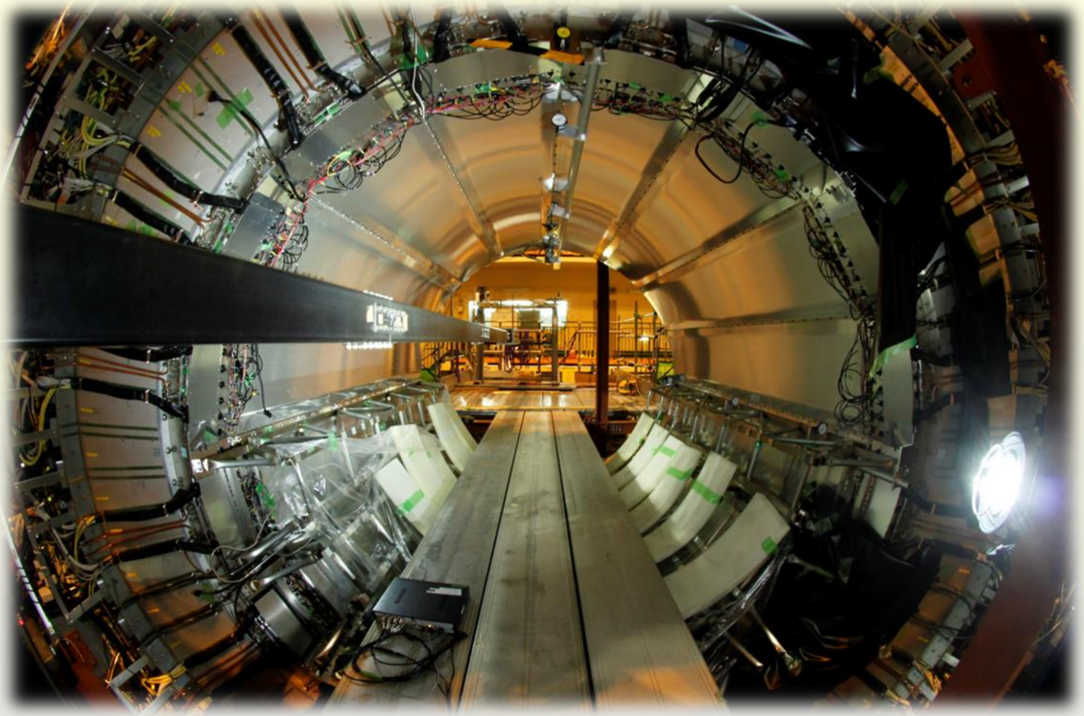


Cherenkov detectors at Super B factory

Pavel Pakhlov

Lebedev Physical Institute of RAS



18th Cherenkov's reading

LPI RAS

April 18, 2017

Flavor physics in the SM …

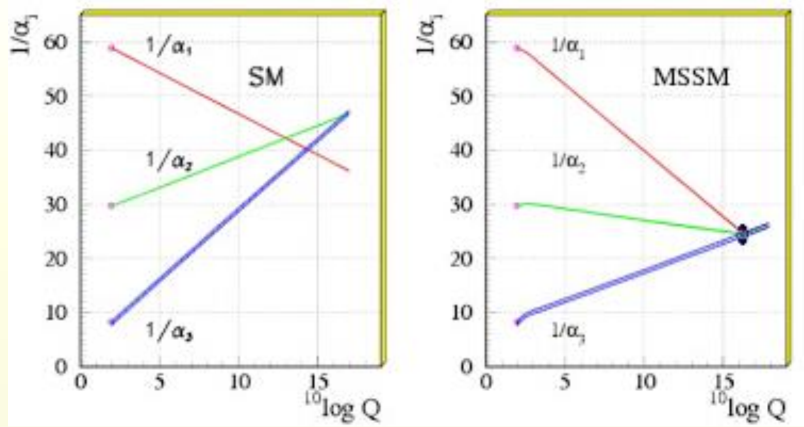
bosonic sector of the SM:

5 free parameters:

one defines the scale

+ 4 dimensionless coupling constants

$$@1\text{GeV}: g' \sim 0.3,\quad g \sim 0.6,\ g_s \sim 0.6,\ \lambda \sim 1$$



Ideally, we have to accept one scale parameter, and expect that dimensionless parameters are some geometrical constants; there is a hint that three gauge constants are related to each other...

fermionic (flavor) sector (without neutrino):

3 Yukawa constants for charged leptons:

6 Yukawa constants for quarks

4 quark-mixing parameters

$$Y_t \sim 10^0,\quad Y_b \sim 10^{-2}, Y_c \sim 10^{-2},$$
$$Y_s \sim 10^{-3}, Y_u \sim 10^{-5}, Y_d \sim 10^{-5},$$
$$Y_\tau \sim 10^{-2}, Y_\mu \sim 10^{-3}, Y_e \sim 10^{-6},$$
$$|V_{ud}| \sim 1, |V_{us}| \sim 0.2, |V_{cb}| \sim 0.04,$$
$$|V_{ub}| \sim 0.004, \delta_{KM} \sim 1$$

This is a really miraculous part of the SM.
There is no idea

- why do we have many (3) generations?
- why are these 13 constants such as they are?
- why is there a hierarchy & smallness structure?
- why is the mixing matrix almost unit, but not exactly?

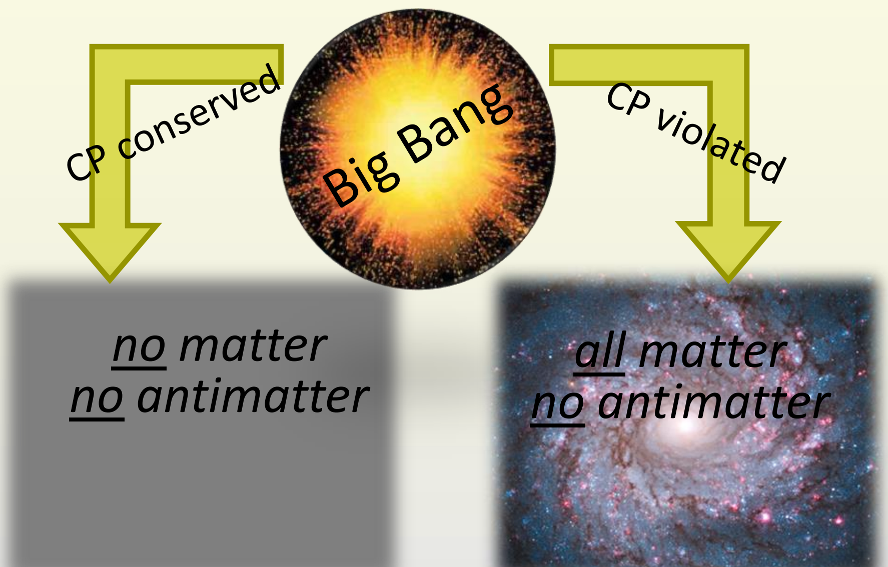
All these "W*hys?*": <u>The SM flavor puzzle</u>

CP violation: Tiny effect ⇒ BIG RESULT

Why do we care about 0.2% discrepancies for W bosons and strange quarks?

Need:
CP violation
+ baryon number nonconservation
+ thermal nonequilibrium

A.D. Sakharov, 1968



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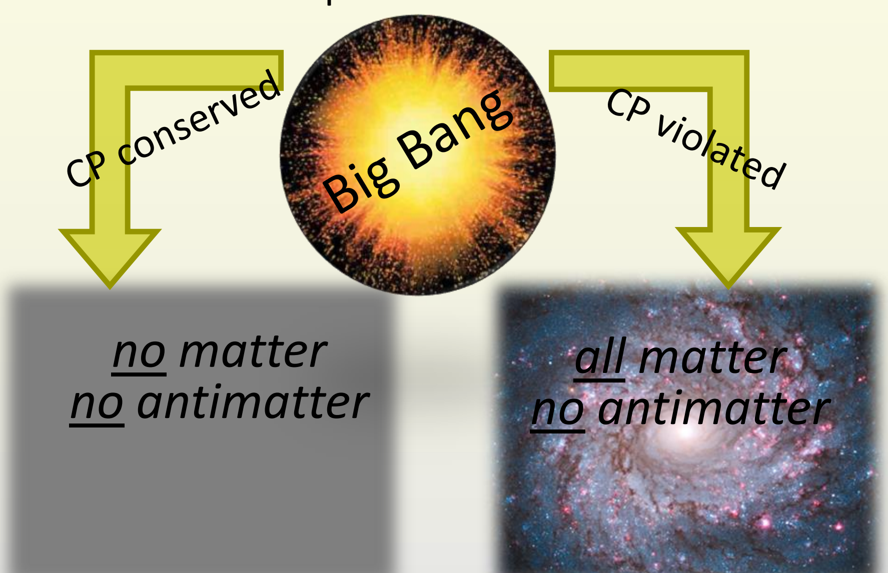


… and beyond

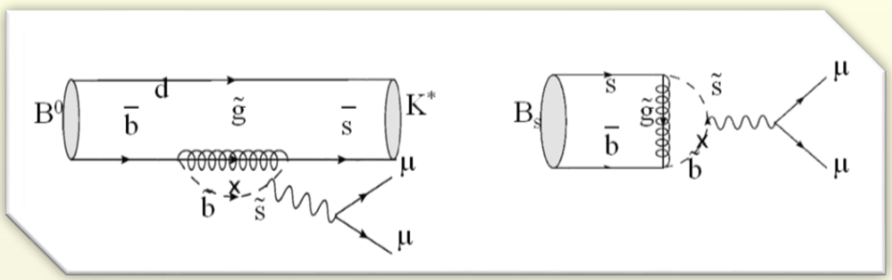
Beyond SM:

13 parameters are too many for a fundamental theory, but not too many to check consistency of the SM predictions for decay/oscillation/CP violation patterns:

500 decays modes (Br's and UL's) for B

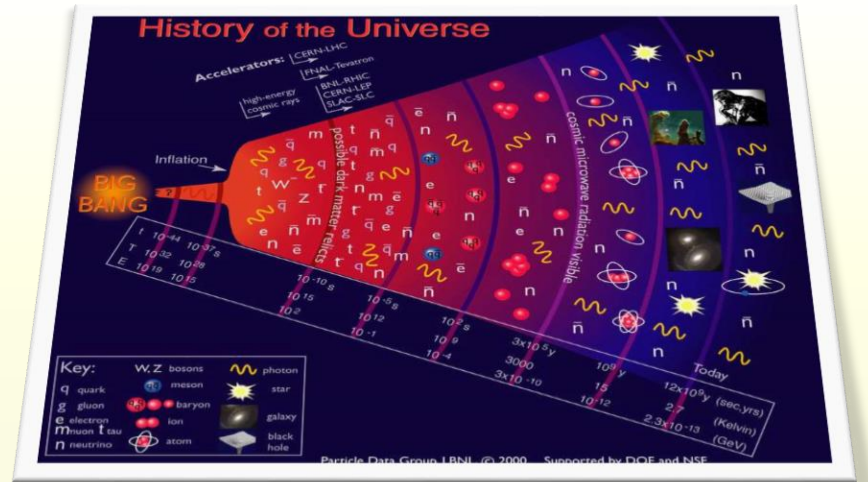
200 decays for D

non-SM particles run around in loops



Cosmology:

needs CP-violation



to produce baryonic asymmetry of the Universe; the only known source of CPV is flavor sector

$$\frac{N_B - N_{\bar{B}}}{N_\gamma} \approx \frac{(m_t^2 - m_c^2)\times(m_t^2 - m_u^2)\times(m_c^2 - m_u^2)\times(m_b^2 - m_s^2)\times(m_b^2 - m_d^2)\times(m_s^2 - m_d^2)\times J_{CP}}{M^{12}}$$

It is too small: if M assumed to be the electroweak scale gives ~10^{-17}

Flavor physics:
SM: in the heart of quark interactions
Cosmology: related to matter-antimatter asymmetry
Beyond SM: measurements are sensitive to New particles

What's required to discover CPV at e^+e^- collider?

Produce B mesons! Need accelerator…

it's not enough…

well, produce moving B-mesons, thus asymmetric energy accelerator

still not enough…

Produce a huge number of B mesons!

Need asymmetric accelerator with record luminosity!

Reconstruct B mesons, tag the flavor and measure vertices

more required…

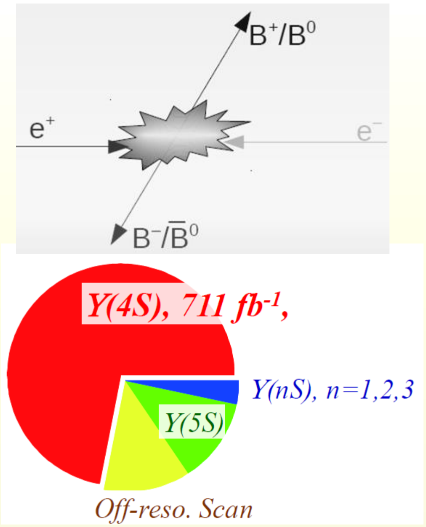
Reconstruct B mesons with maximum efficiency in all possible decays

Correctly determine the flavor of the second B-meson in the event

Precisely reconstruct two decay vertices

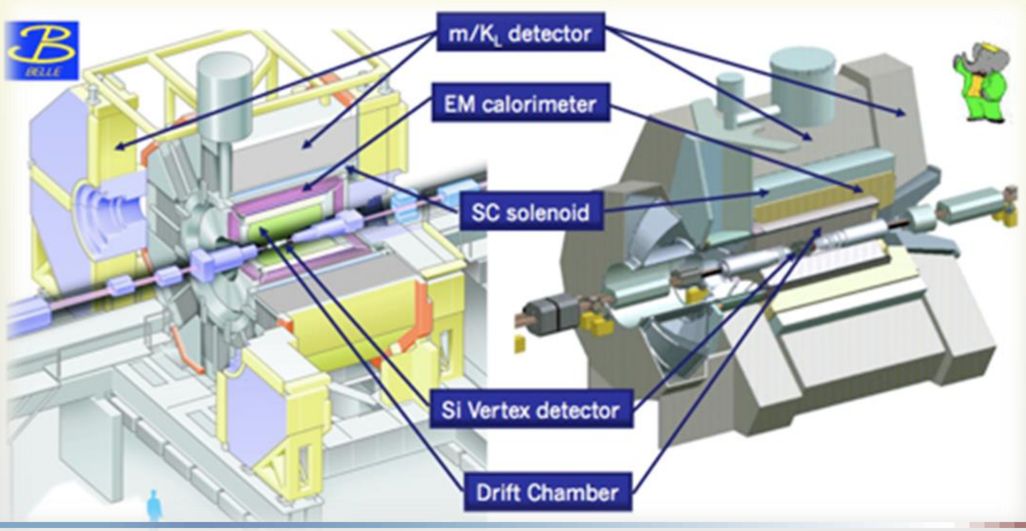
Need very good detector with efficient subdetectors for all types of particles, excellent particle identification…

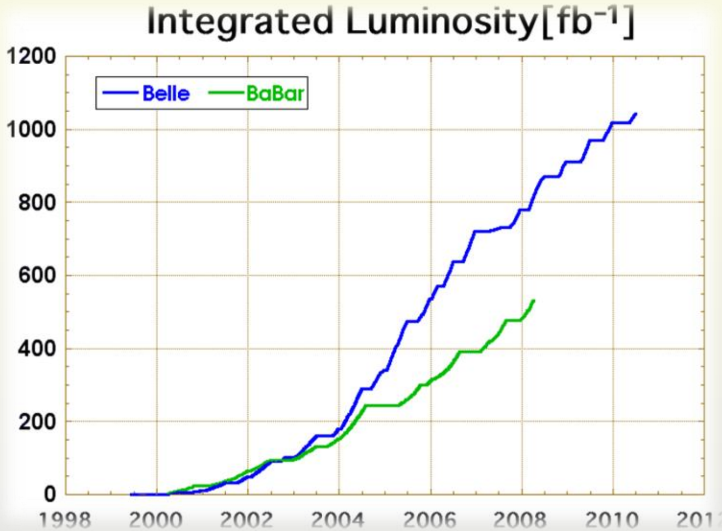
e^+e^- asymmetric B-factories
world highest luminosities



Completed data taking on June, 2010
to start SuperKEKB/Belle II upgrade

Stopped in 2008

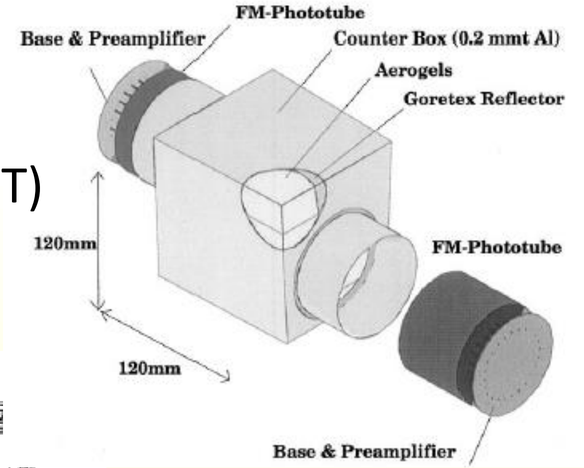


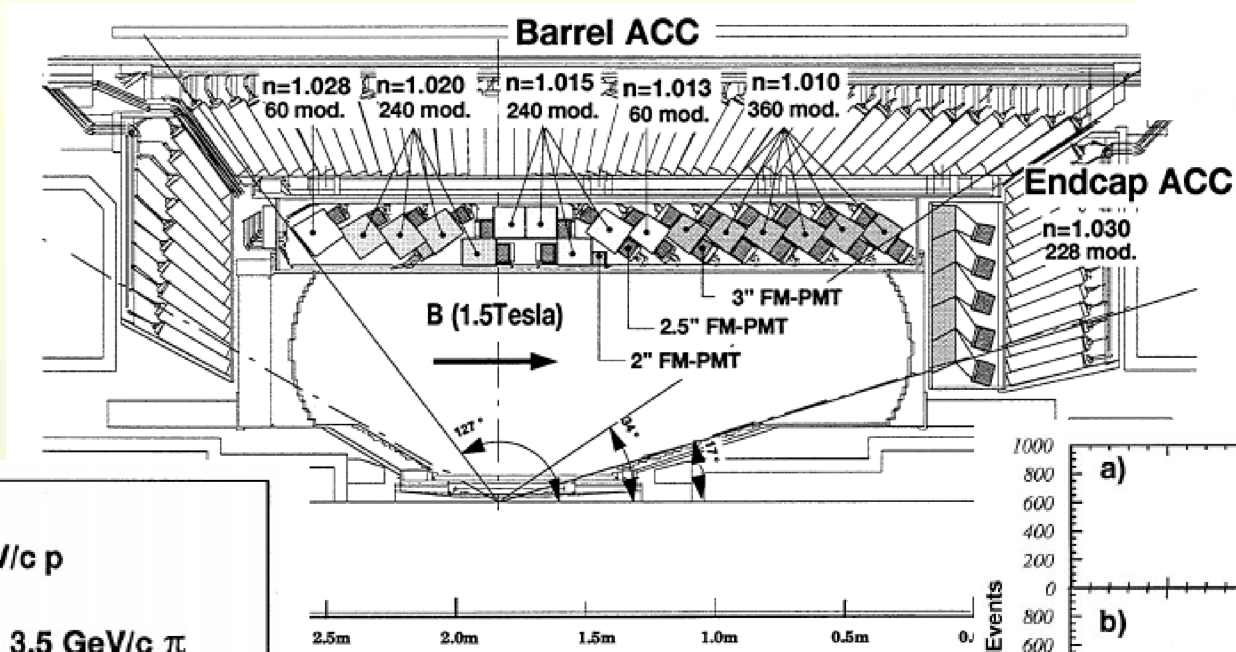


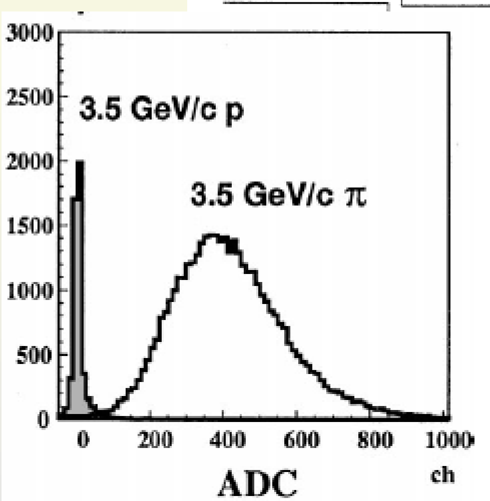
Particle identification at Belle

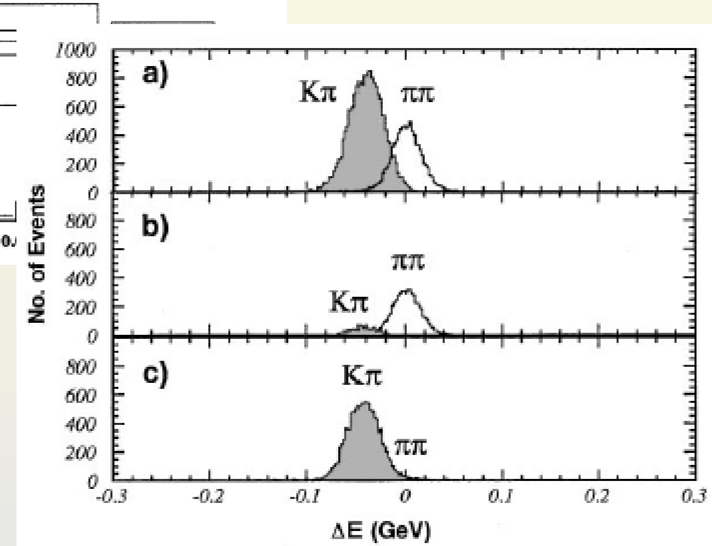
- Radiator: low-refractive index silica aerogel
- Photodetector: fine-mesh PMT (operating in strong B ~ 1.5 T)

→ Threshold-type Cherenkov counters



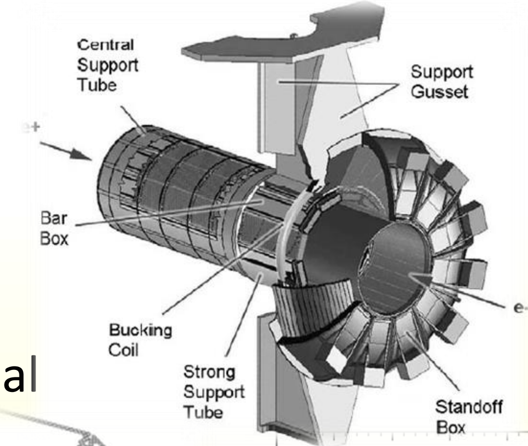


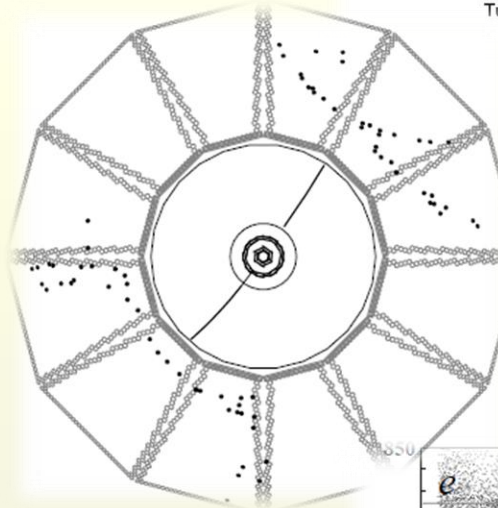


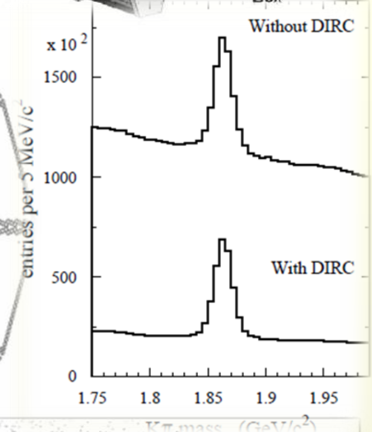


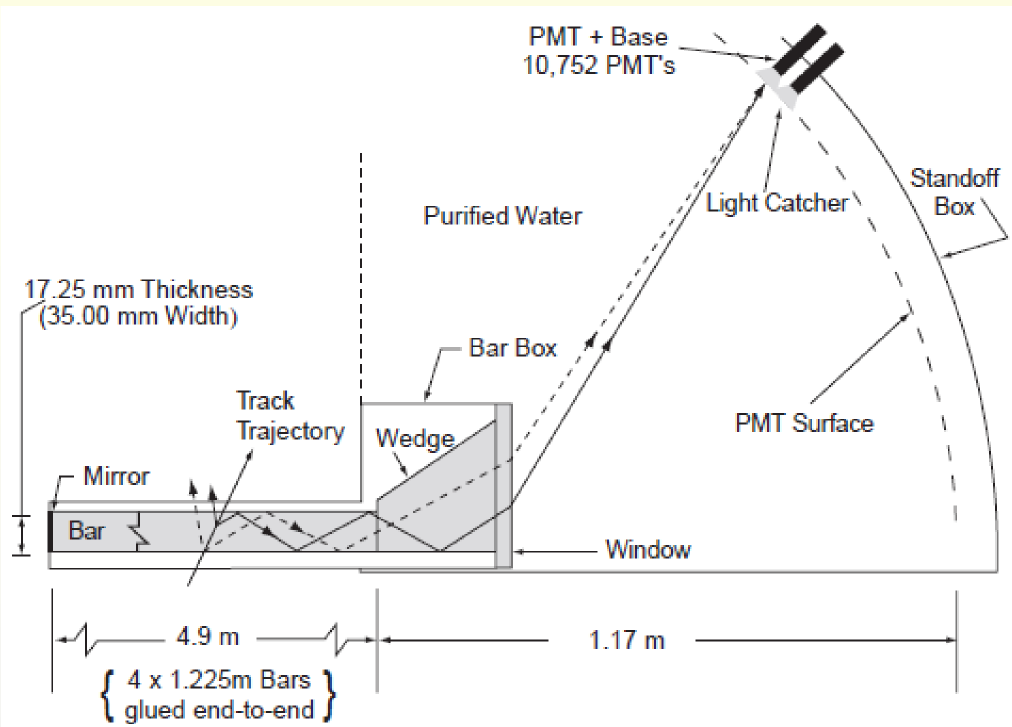
Particle identification at BaBar

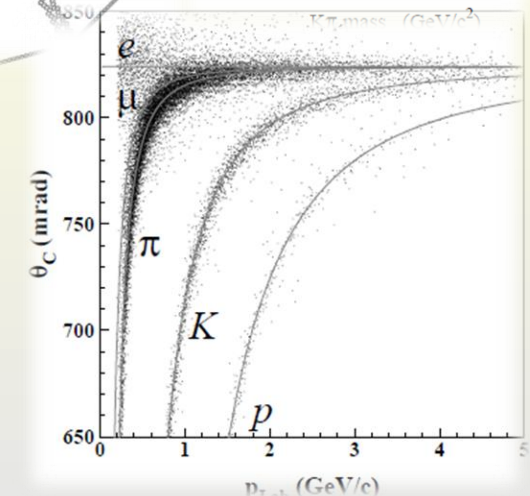
- DIRC = Detection of Internally Reflected Cherenkov (Light)
- utilizes the optical material of the radiator in two ways, simultaneously: as the Cherenkov radiator; as a light guide for the Cherenkov light trapped in the radiator by total internal refection.



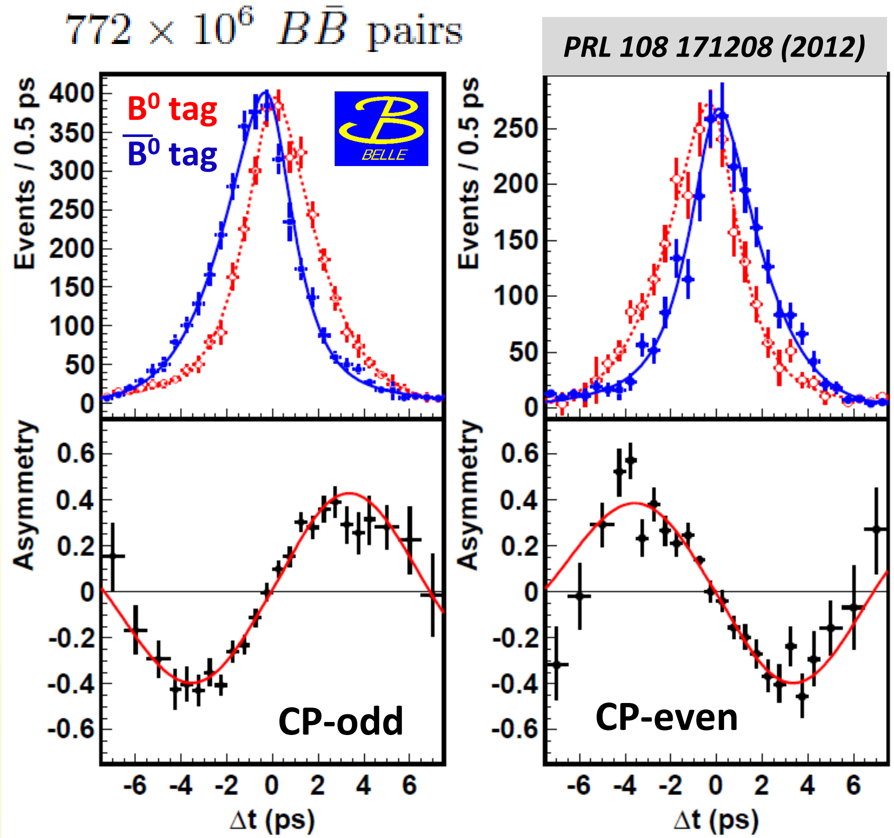




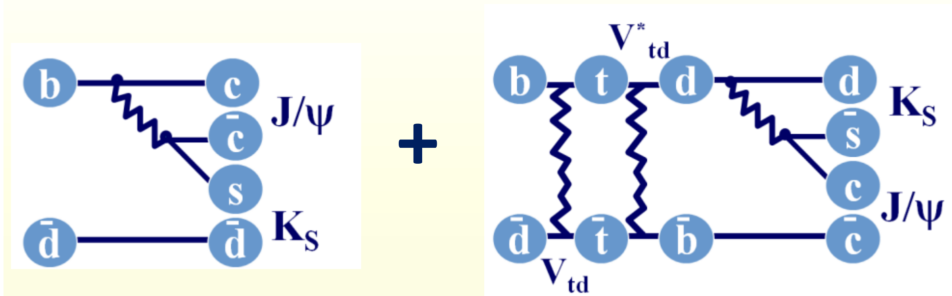




Precise measurement of sin(2β) in $B^0 \to c\bar{c}K^0$



$\Upsilon(4S) \to B^0\bar{B}^0 \to f_{CP} f_{tag}$



Need flavor tag: the most powerful tag is provided by charged kaons via b → c → s

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 + q\left[\mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t)\right]\right\}$$

SM: S = −ξ sin(2β) and A = 0

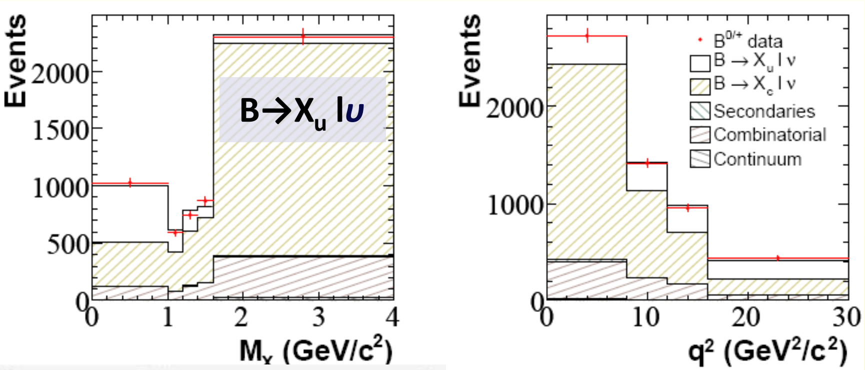
<u>Belle 2012</u>: $B \to J/\psi K^0_s$, $\psi(2S)K^0_s$, $\chi_{c1}K^0_s$ & $B \to J/\psi K^0_L$

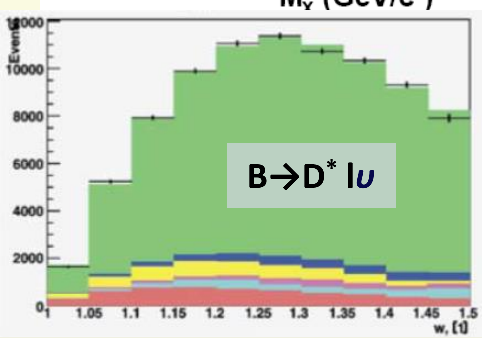
sin(2β) = 0.667 ± 0.023 ± 0.012 (0.9°)

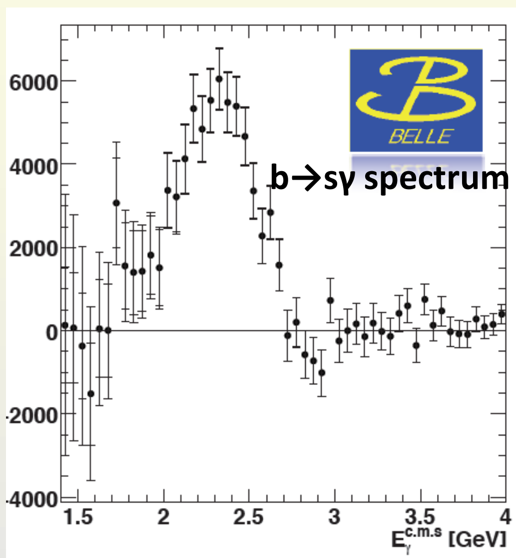
A_f = 0.006 ± 0.016 ± 0.012 (direct CPV)

From CPV observation to precise KM test

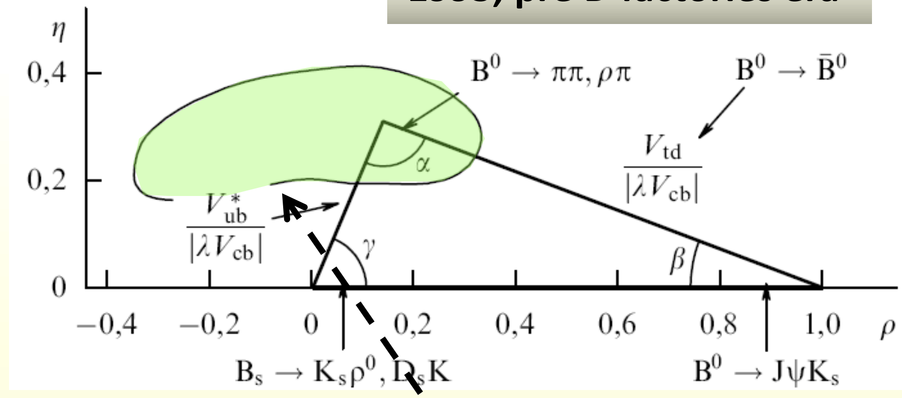
- Angle β is measured with <1° accuracy; angles α and γ ~ 3-10° accuracy
- Accuracies for V_{cb} ~ 3%; V_{ub} ~ 10%; V_{td} ~ 7%; V_{ts} ~ 6%; V_{td}/V_{ts} ~ 3% (Δm_s)





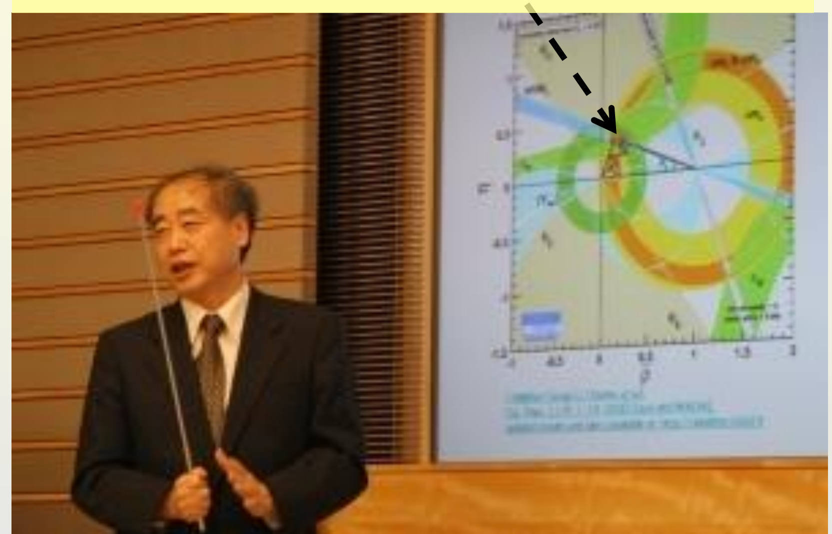


1995, pre B-factories era



The allowed area for upper apex is squeezed by almost 2 orders of magnitude

Belle & BaBar + LHCb + Tevatron + huge contribution from theory



One more physics result

- Direct CP violation in penguin B-decays

- Need good Kaon identification to suppress background from **$B \to \pi^+\pi^-$**

- CP violation is observed! Opposite sign of CP asymmetry in charged and neutral B – long lasting puzzle.

- Published in Nature.

- + ~400 papers on rare B-decays, CP violation, charm and tau-leptons. Almost all of the analysis utilize information from Cherenkov detector.

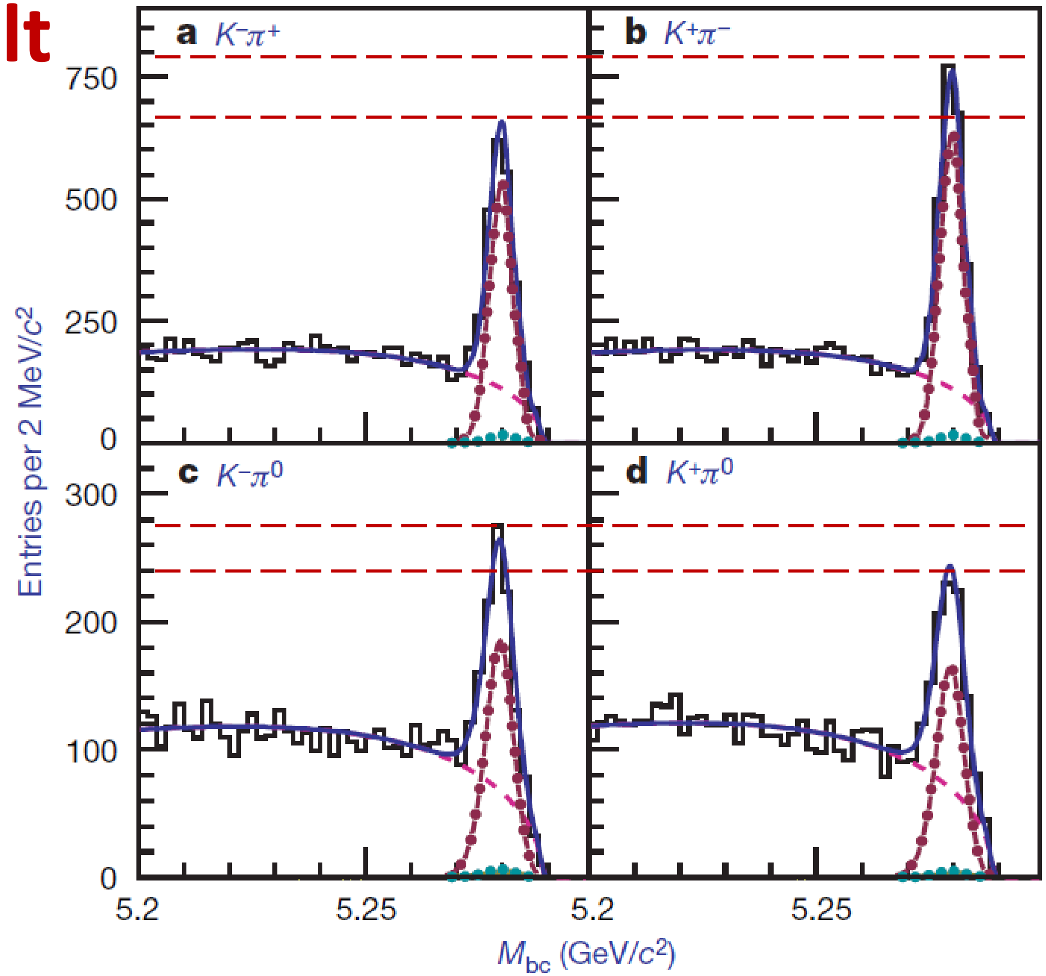
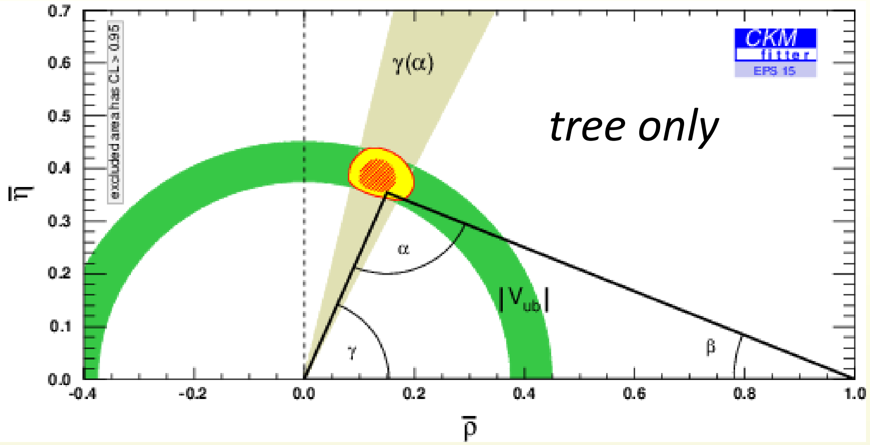
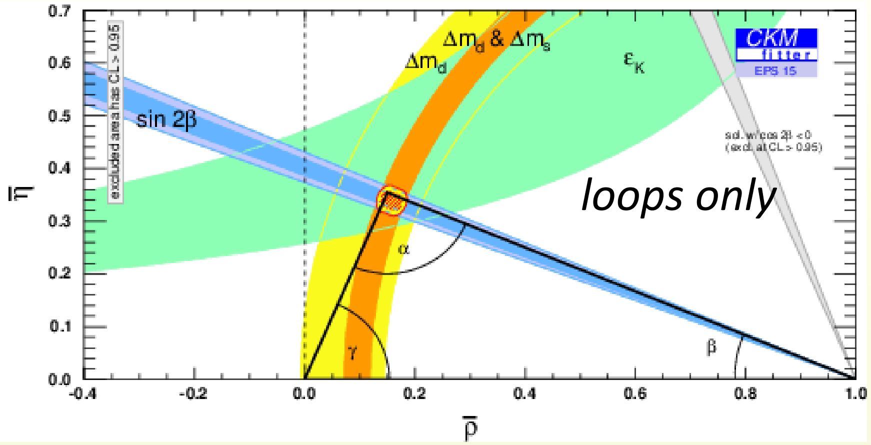


Figure 2 | M_{bc} projections for $K^-\pi^+$ (a), $K^+\pi^-$ (b), $K^-\pi^0$ (c) and $K^+\pi^0$ (d). Histograms are data, solid blue lines are the fit projections, point-dashed lines are the signal components, dashed lines are the continuum background, and grey dotted lines are the $\pi^\pm\pi$ signals that are misidentified as $K^\pm\pi$. The M_{bc} projections are made by requiring $|\Delta E| < 0.06$ GeV for $K^\pm\pi^\mp$ and $-0.14 < \Delta E < 0.06$ GeV for $K^\pm\pi^0$.

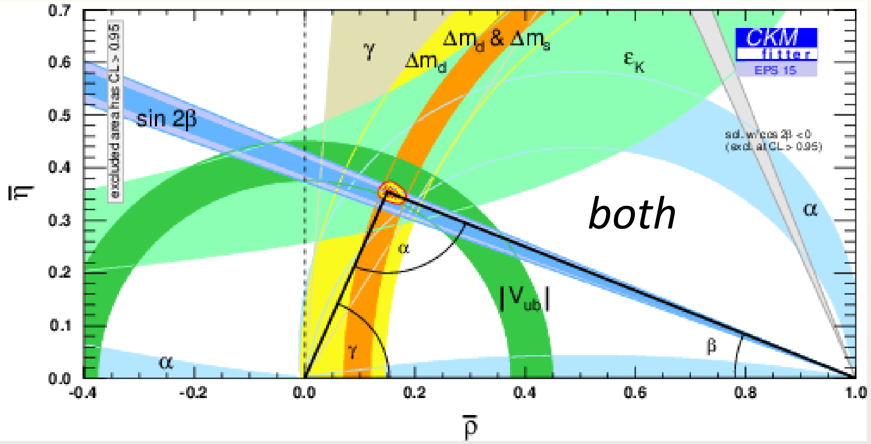
10 years of running of two B-factories provided high statistics (10^9 B) + three years of operation of LHCb (even more than 10^9 B/year). We have measured UT precisely.





Can play a game: compare
tree only measurements (NO NEW PHYSICS CONTRIBUTION expected) and
loop measurement (NEW heavy particles can contribute)

NO anomaly seen with the current precision



Extending the SM

SUSY

Technicolor

Extra dimensions

Composite Higgs

Multi-Higgs

Left-right symmetry

4th generation

Extending the SM: Introduce new fields/interactions according to certain rules; check that they don't break the agreement of the existing measurements with the SM predictions

New Physics enters at higher scale,

the SM should be valid as an effective low-energy theory

4th generation: add another fermion generation
- CKM for three generations is no more unitary;
- experimentally seen as violation of UT

2HDM: No restrictions on number of the Higgs fields; extend to 2 doublets
- get 3 neutral and 2 charged Higgs;
- to avoid too large CPV and FCNC impose "flavor conservation"
- $\tan\beta$ – ratio of v.e.v's for two doublets
- enhance some rare B-decays

SUSY: symmetry for spin *s* and *s*±½ particles;
- solve hierarchy problem and UV divergence;
- need SUSY breaking to match with experiment;
- breaking term introduce huge number of free parameters, including new CP violation phases;
- heavy superpartners enter loop and box diagrams in B-decay and change the CPV pattern

Physics reach with 50 ab^{-1} (~ 5 years with $8\times10^{35}/cm^2/s$)

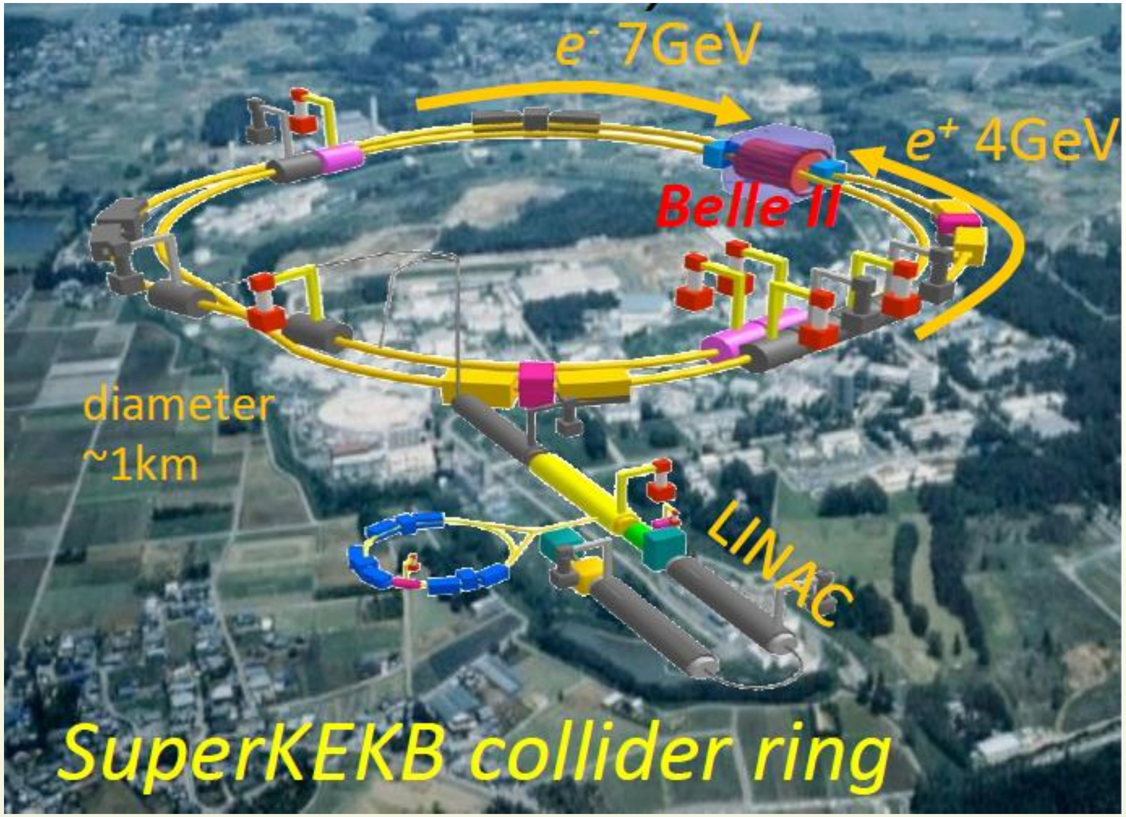
- Increasing accuracy of flavor related measurements we can test Physics at ~ 1 – 10 TeV scale
- Which physics will we done at Super B-factories?

Basically the same we did at B-factories:

- Measure UT (angles & sides) *with much better precision*. If new phases contribute to any measurable → inconsistency of UT.
- CPV in $b \to sqq$ *vs* $b \to ccs$: Extra new phases in the penguin loop makes CPV parameters different. Typical accuracy in ΔS $\sigma \approx 0.02 – 0.03$ for $B \to K^0 \phi$ ($K^0 \eta'$).
- search for CPV in radiative decays $B \to K^{*0}(K_S^0 \pi^0) \gamma$ is a test of right-handed current in the penguin loop.
- Rare decays $b \to sg(\gamma)$, $B \to \tau\nu$. Even Br's constrain mass of NP (provided CKM matrix elements and FF are known precisely).
- Electro-weak penguins $b \to s\mu\mu$, see, $s\nu\nu$: Br's, Q^2 -distribution, FB asymmetry are sensitive to NP
- \+ many new decay channels hardly / not seen with the present statistics.
- \+ New ideas.

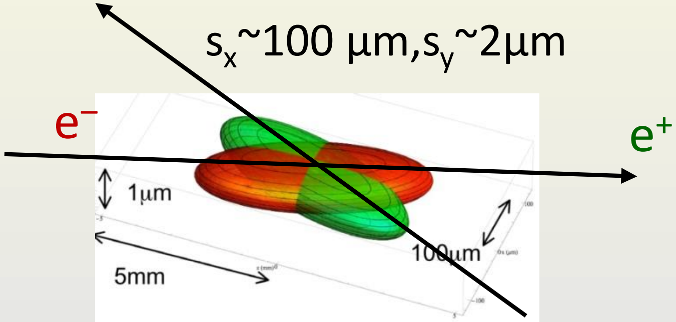
Not technical updates of the previous analyses:
need to reduce model dependence and systematic uncertainties

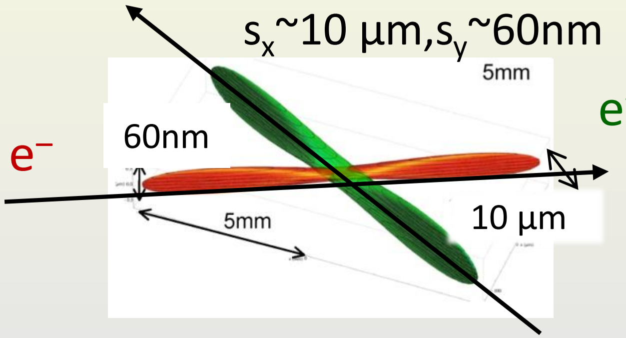
KEKB upgrade → SuperKEKB (nano-beam)



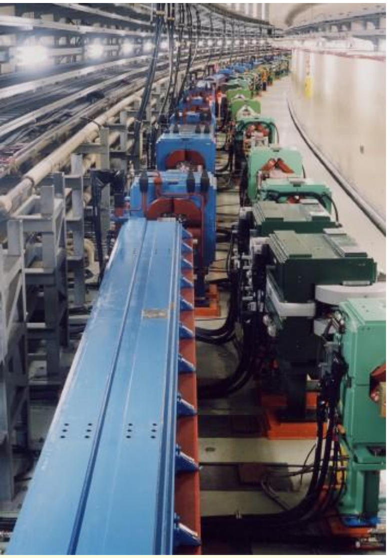
In KEKB, colliding electron and positron beams were already much thinner than a human hair...
... for a 40x increase in intensity one have to make the beam as thin as a few hundreds atomic layers!

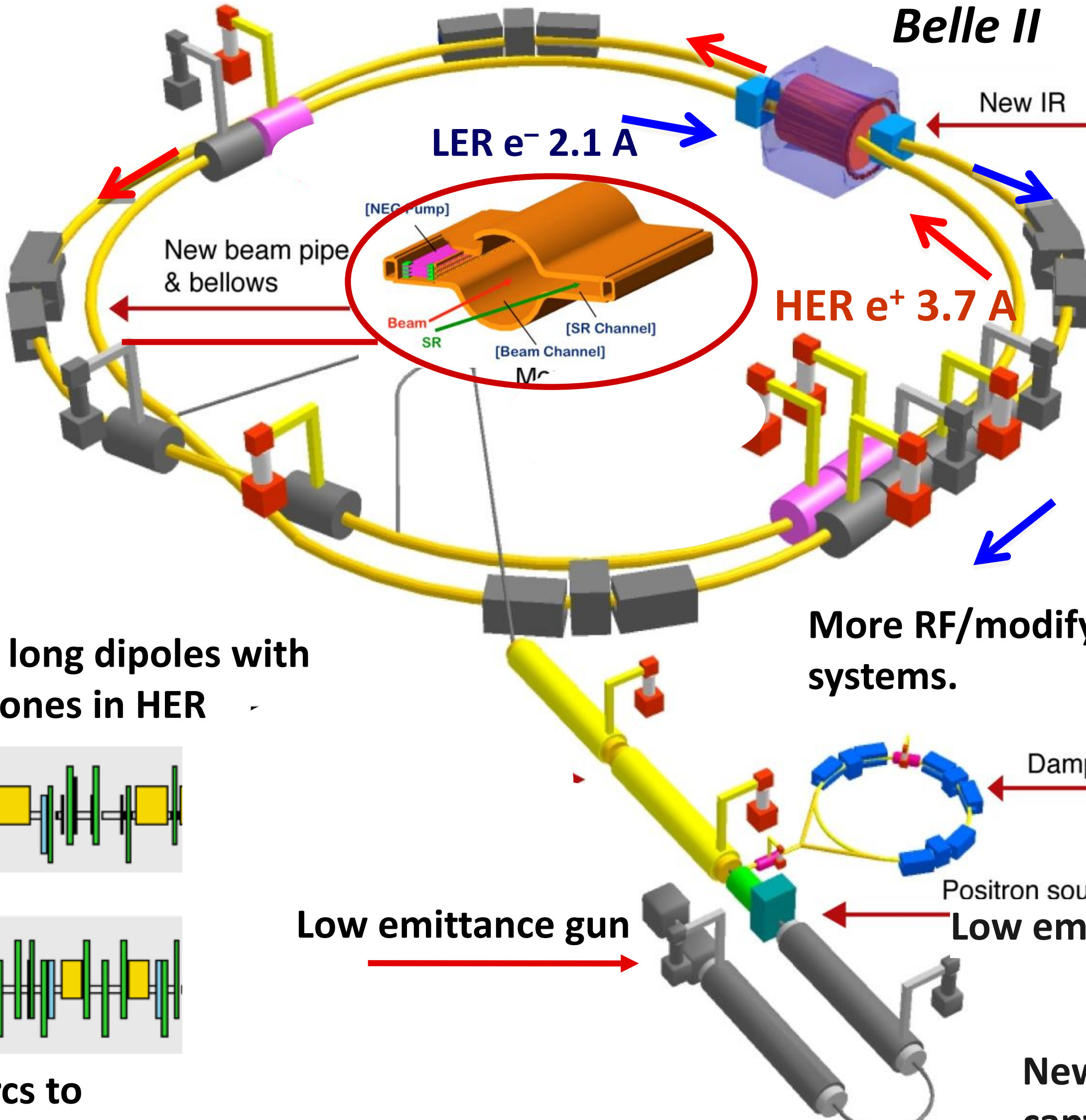
Nano-beams and a factor of two more beam current to increase luminosity





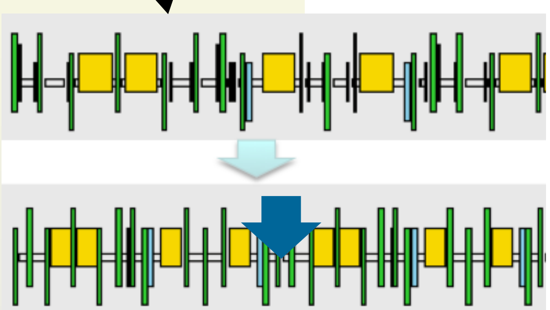
KEKB upgrade → SuperKEKB(nano-beam)





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

Replace long dipoles with shorter ones in HER



Redesign the HER arcs to reduce the emittance

More RF/modify RF systems.

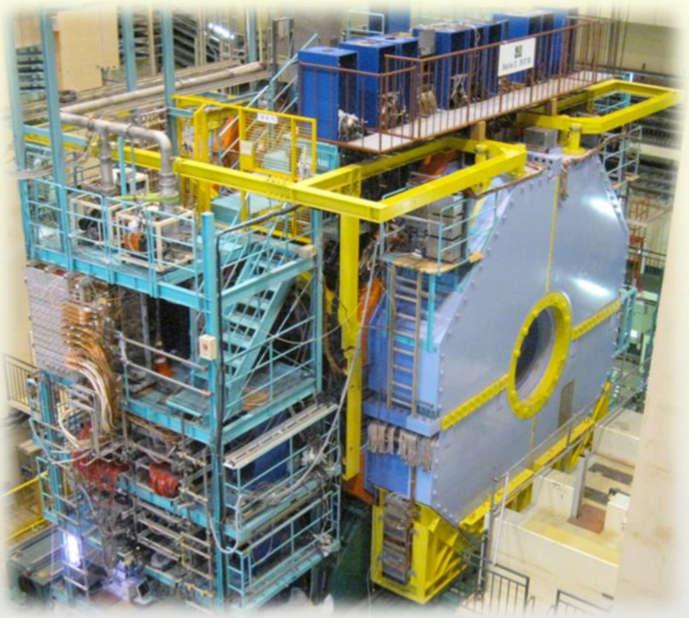
Low emittance gun

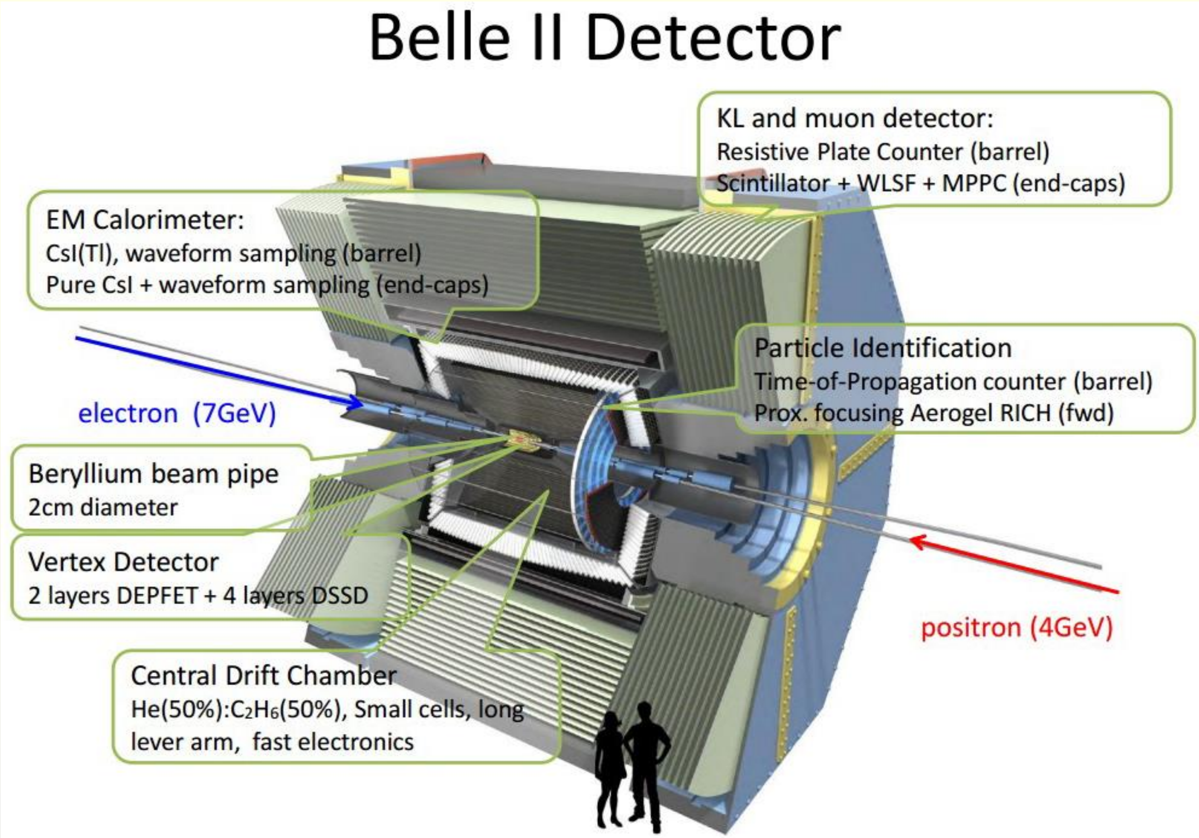
Low emittance positrons

New positron target / capture section

Belle II at SuperKEKB B factory

- ***Precision measurements of rare B, D and τ decays***
- ***SuperKEKB will deliver 40 times higher event rates than KEKB.***
- ***Belle II will collect 50ab^{-1} by 2022 (> 10^{10} B mesons)***
    - *Higher rates*
    - *Much higher backgrounds*





Detector upgrade

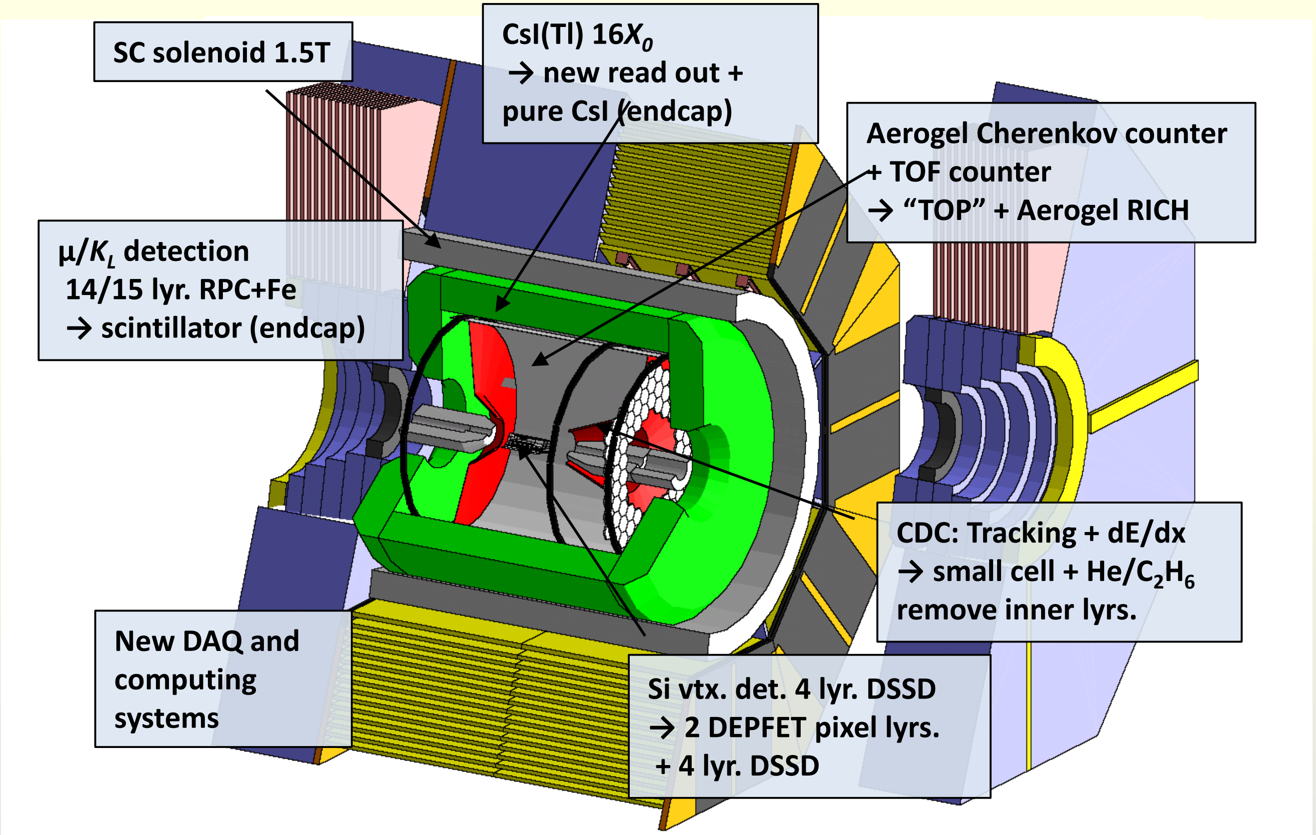
Critical issues at
$L = 8 \times 10^{35}/cm^2/sec$

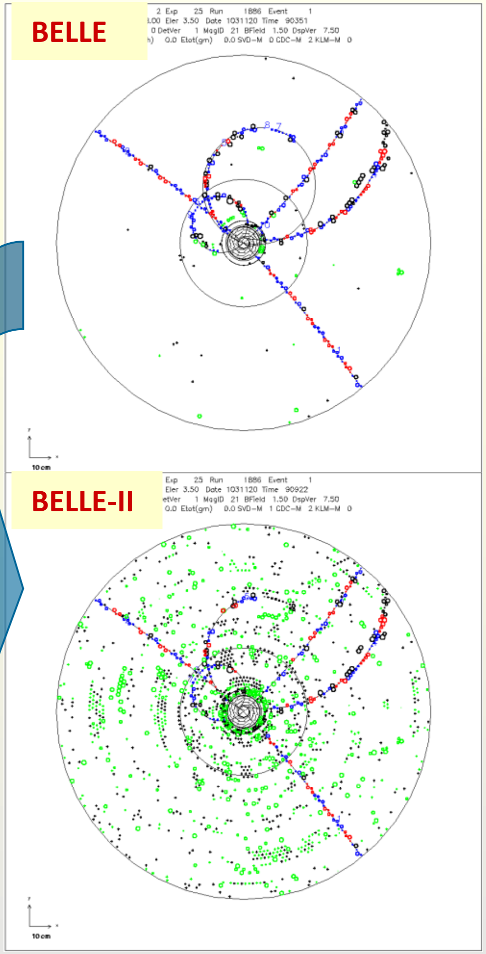
- **Higher event rate**
  - higher rate trigger, DAQ and computing

+

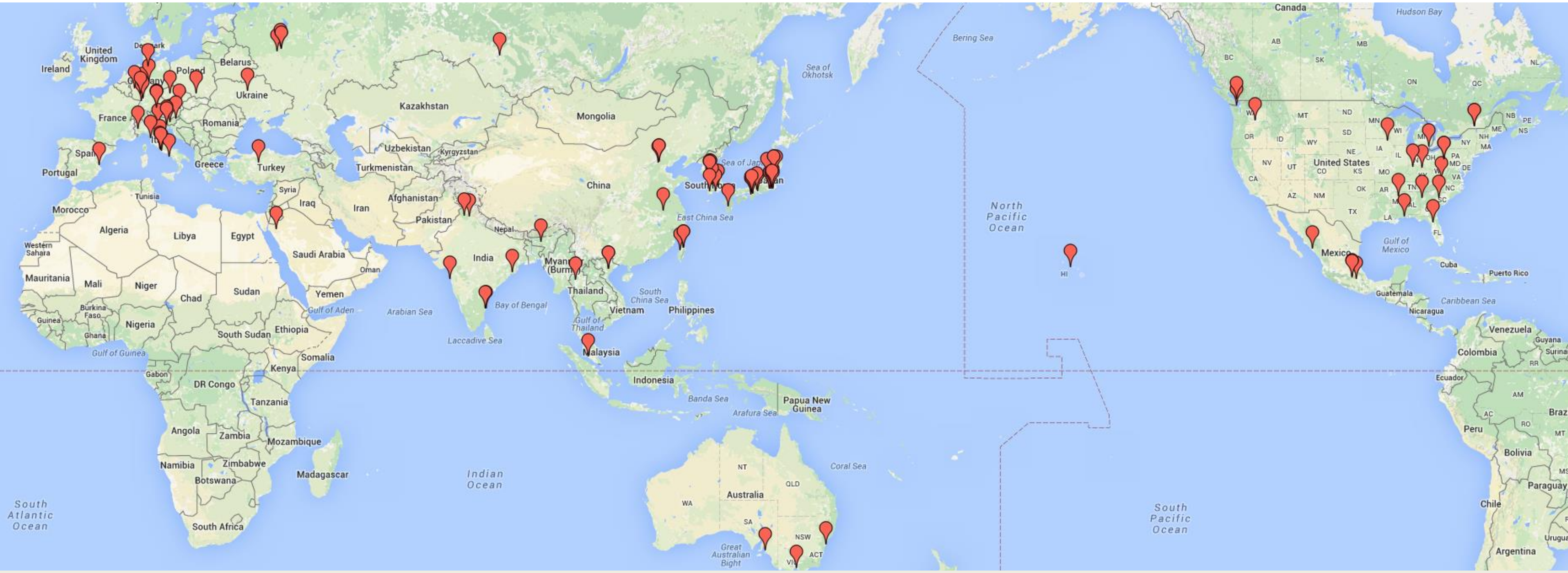
- **Improve performance**
  - try better PID options
  - low p μ identification for b → sμμ efficiency
  - hermeticity → missing E "reconstruction"

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





Belle II collaboration

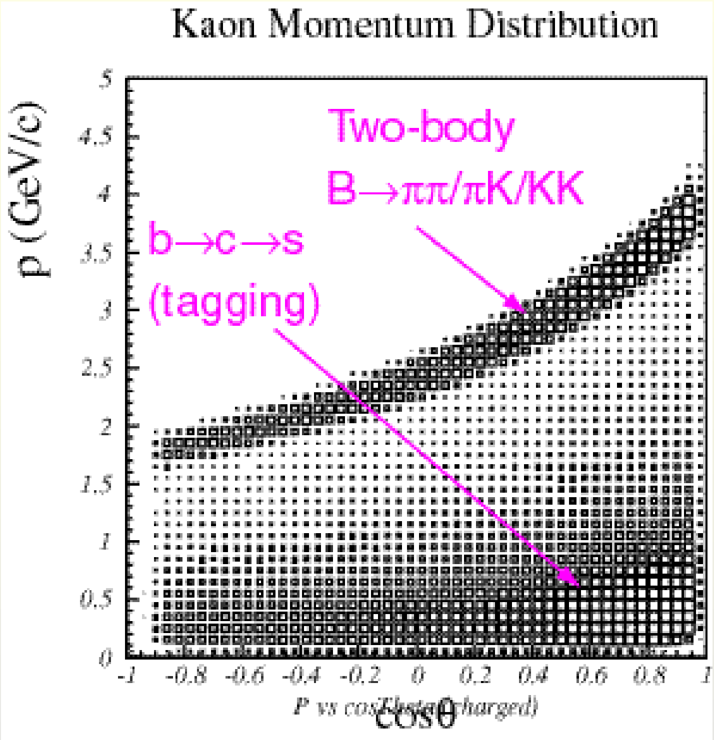


23 countries/regions, ~100 institutions, ~700 collaborators

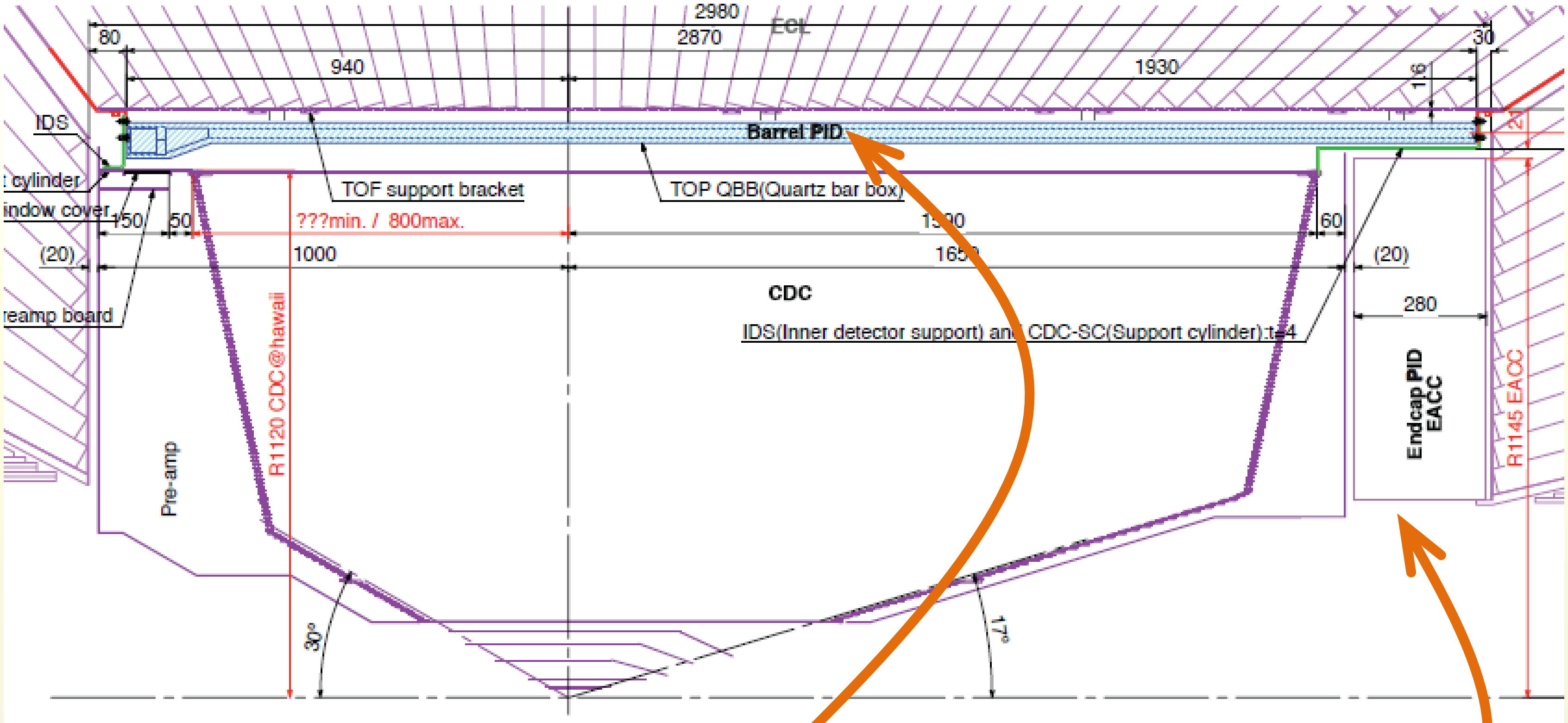
Particle identification at Belle II

- Highly efficient π/K separation for momentum range up to 4GeV/c is needed to identify particles from various B, D, and τ decays, and for flavor tagging

  - Very limited available space & constrains by the existing frame;
  - Minimal radiation length (otherwise PID detector deteriorates the electromagnetic calorimeter performance);
  - Radiation tolerance (n, γ);
  - Strong magnetic field (B ~ 1.5 T).



Particle Identification at Belle II



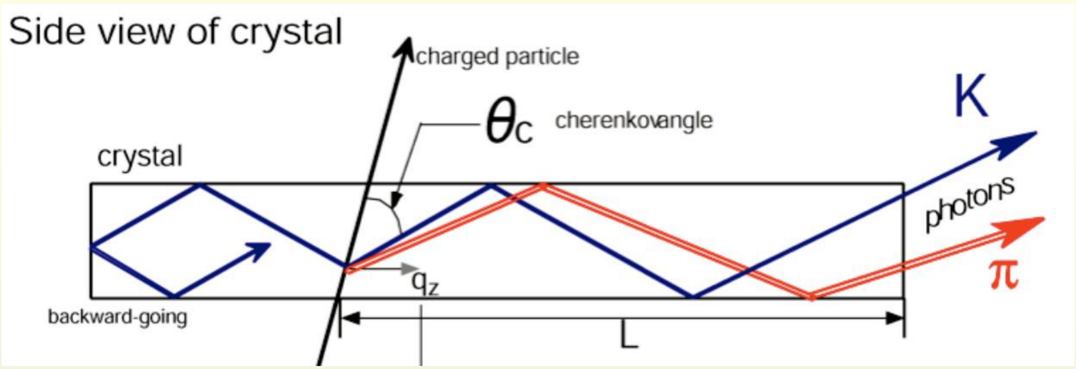
Two dedicated particle ID devices: both RICHes → designed to fit into available space

- Barrel: Time-Of-Propagation (TOP)
- End-cap: Proximity focusing Aerogel RICH (ARICH)

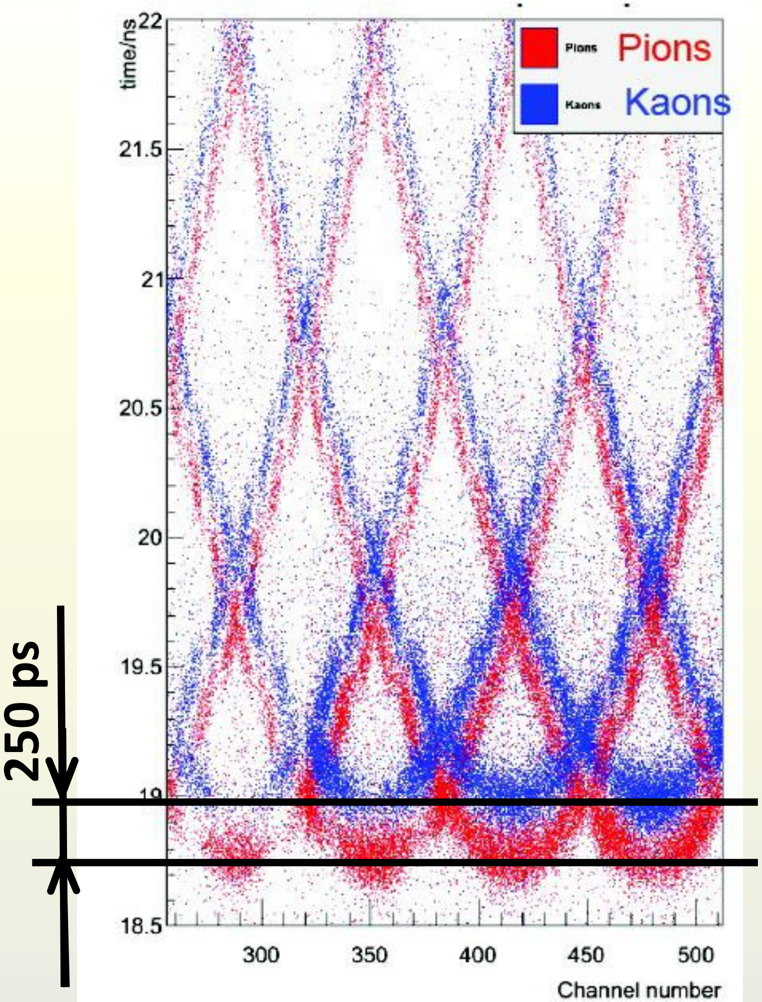
Photo detectors → operation in magnetic field 1.5T

iTOP detector

Main idea: Cherenkov photons emitted in the quartz radiator
→ internally reflected
→ registered at the end of the bar by a fast position sensitive detector of single photons.



K/π → Different θ_c (according to $\cos \theta_c = 1/n\beta$) → Different path length → Different Time Of Propagation
θ_c reconstructed from: hit position (x,y) and Time Of Propagation of photon.



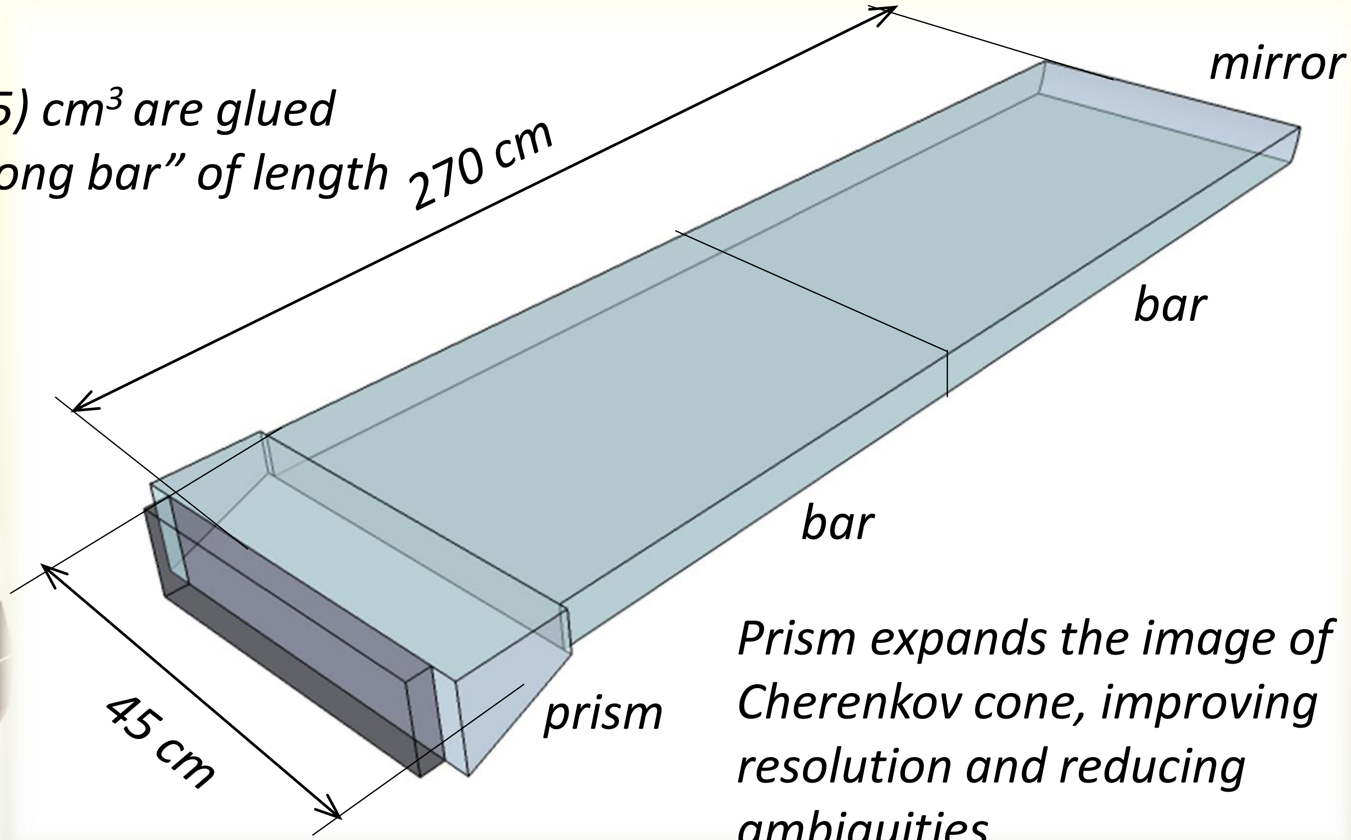
Reflector

High quality quartz bar:

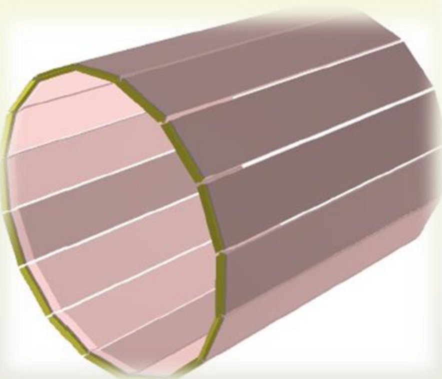
- Flatness < 6.3 μm
- Roughness < 0.5 nm (RMS)
- Perpendicularity S1 to S3, S4 < 20 arcsec
- Parallelism S1|| S2 < 4 arcsec

Spherical mirror: to focus Cherenkov photons onto PMTs to improving imaging.

Two bars (2 x 45 x 125) cm³ are glued together to make a "long bar" of length 2.5 m.



Prism expands the image of Cherenkov cone, improving resolution and reducing ambiguities.

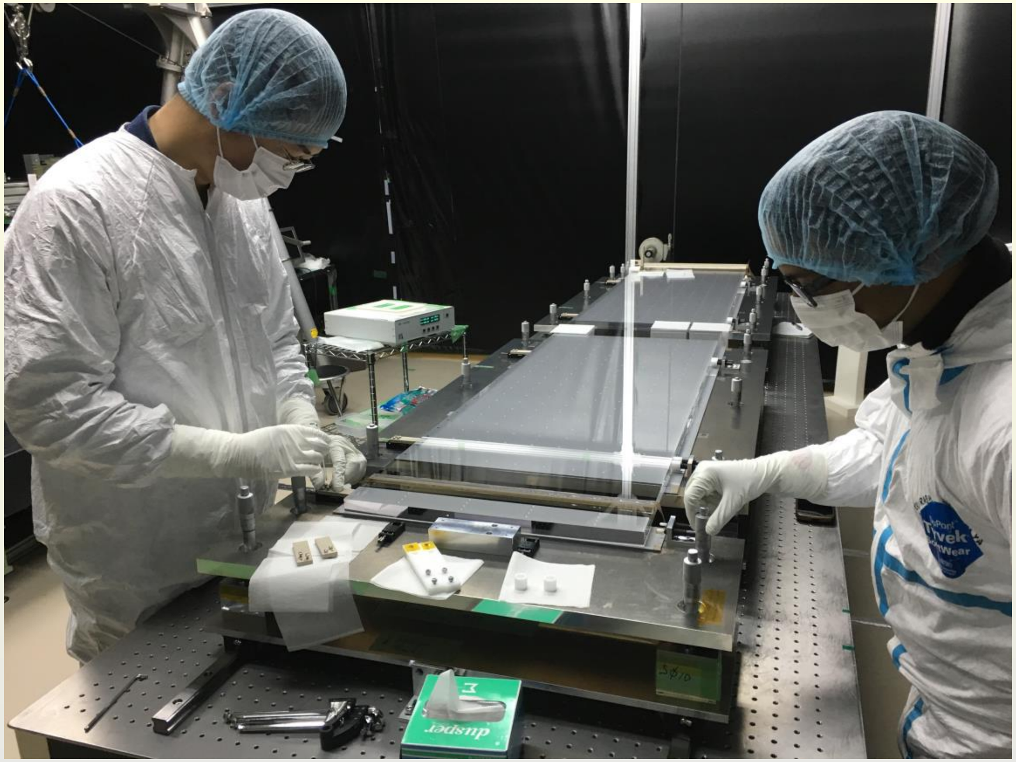


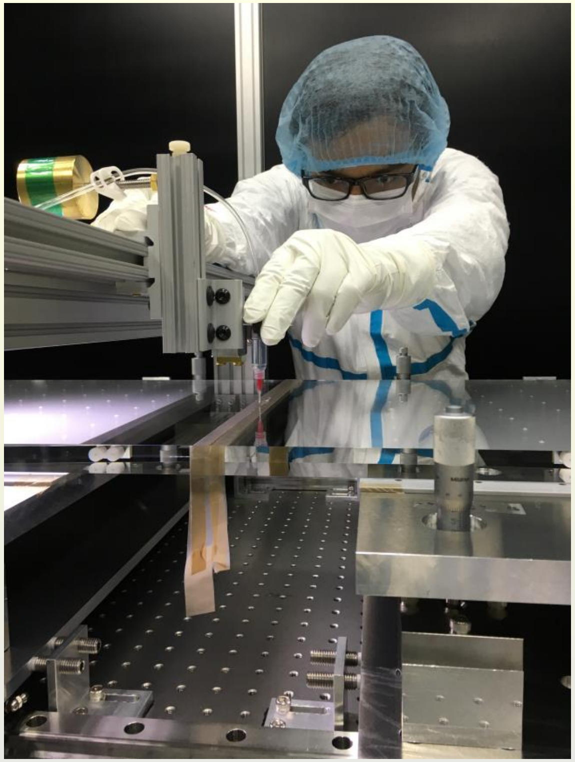
Gluing Optics

- bar to bar
- bar to prism
- bar to mirror

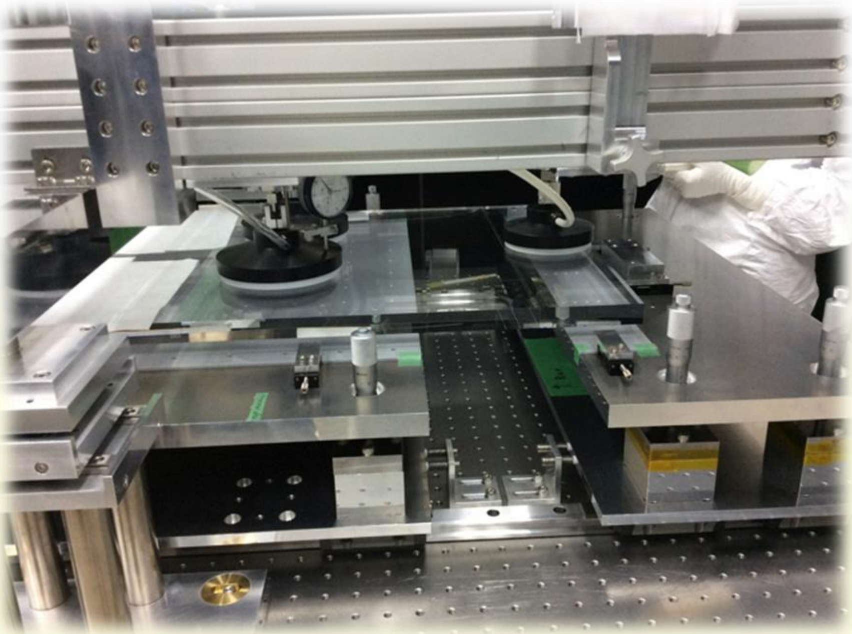
Alignment and Gluing:

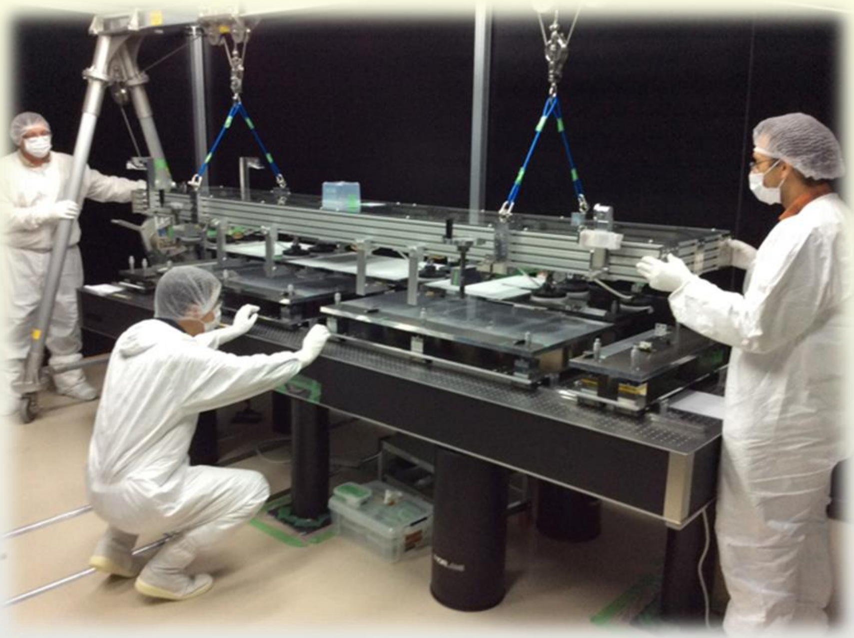
- adjust surfaces positions using laser displacement sensor and micrometers
- adjust surfaces angles using autocollimator and micrometers
- insert shims, tape joint and repeat steps 1, 2
- apply epoxy (EPOTEK 301-2) to joint

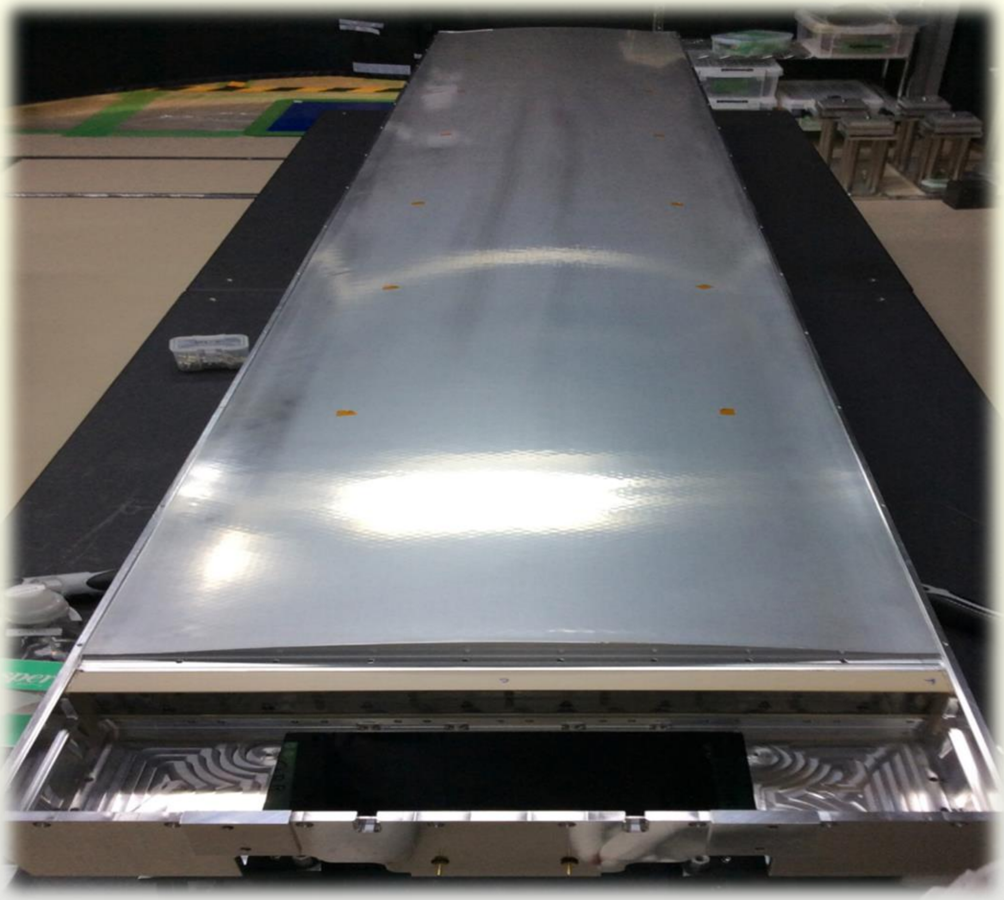




Quartz Bar Box Assembly



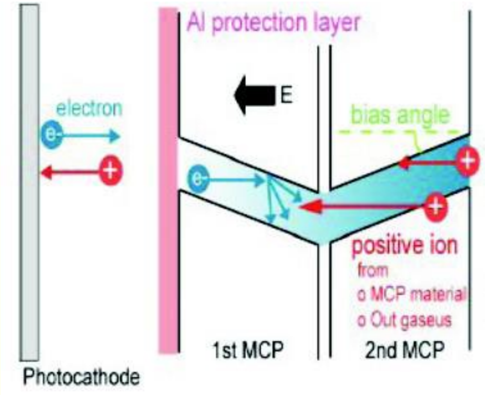


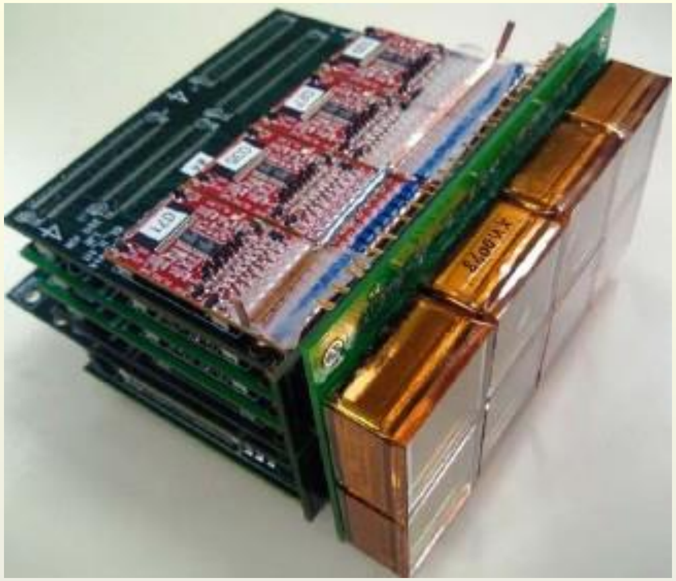


Photon Detection: Hamamatsu MCP-PMTs

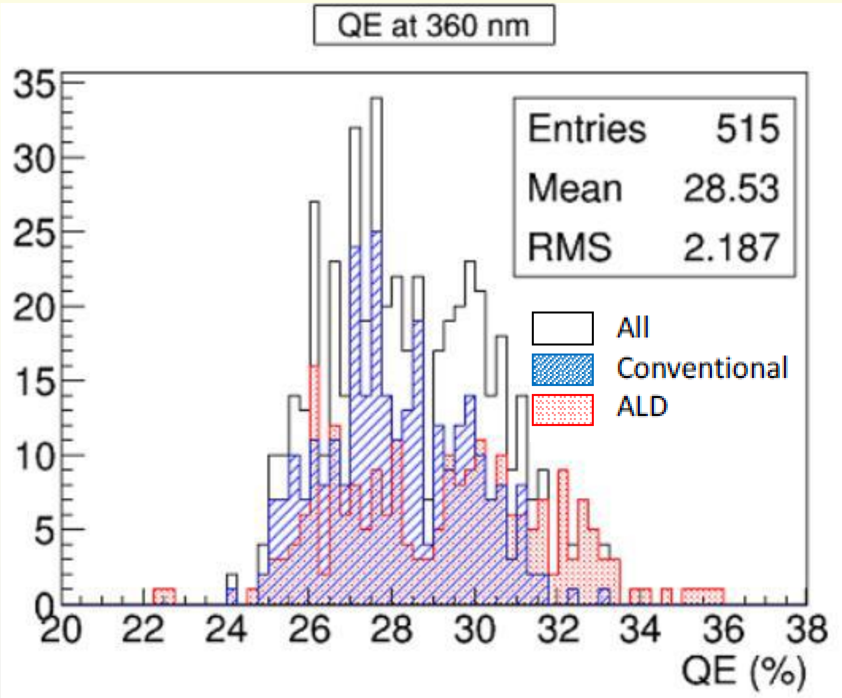
Hamamatsu SL-10 Multi-Channel-Plate PMTs:

- >5-year R&D effort at Nagoya University
- high gain to detect single photons
- excellent timing: < 50 ps
- good QE: 28% on average
- good segmentation: 16 anodes/tube
- works in a 1.5 T magnetic field

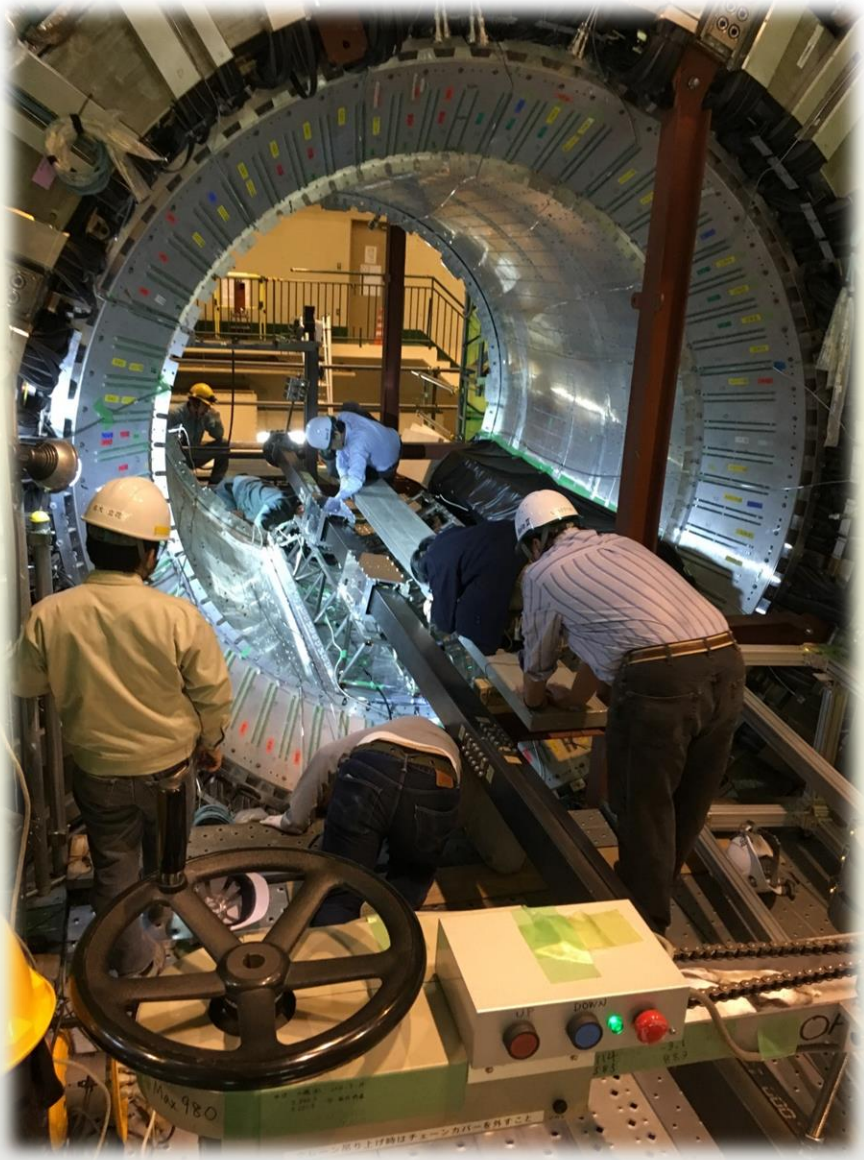




32 tubes/module x 16 modules = 512 tubes needed (8192 channels)



Installing Modules in the detector



All 16 modules installed:

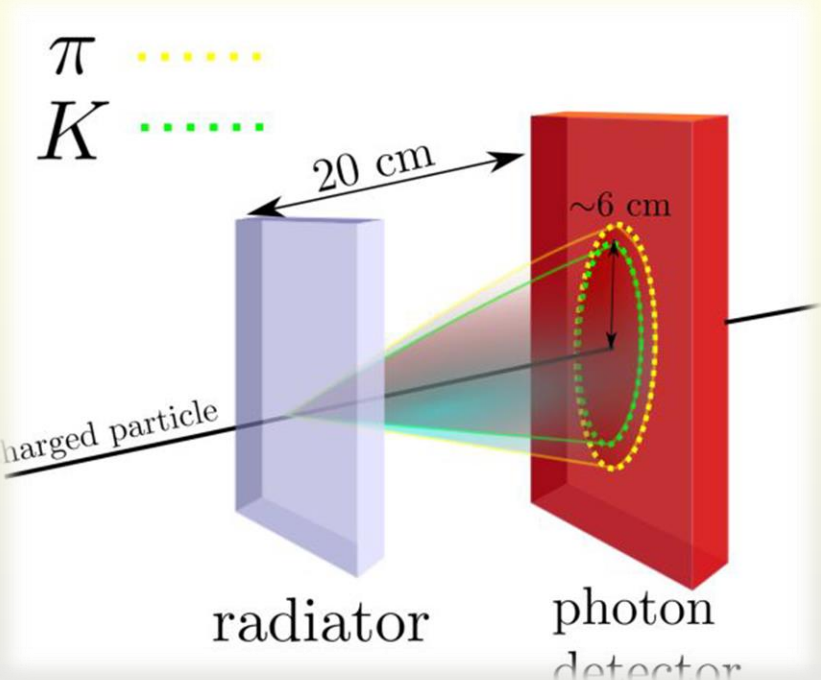
Endcap PID: ARICH

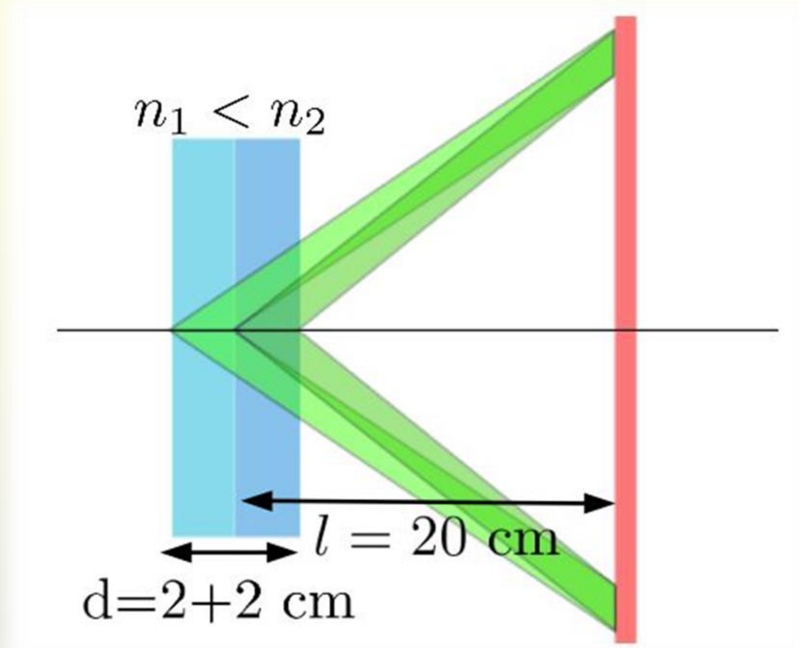
- π threshold: 0.4 GeV/c
- *K threshold: 1.5 GeV/c*
- $\theta_C(\pi)$*: 307 mrad @ 3.5GeV/c*
- $\theta_C(\pi)-\theta_C(K)$*: 30 mrad @ 3.5GeV/c*

Goal:
4σ separation K-π, at 1.0 - 3.5 GeV

Constraints:
- in 1.5 T magnetic field.
- limited available space ~ 28 cm.

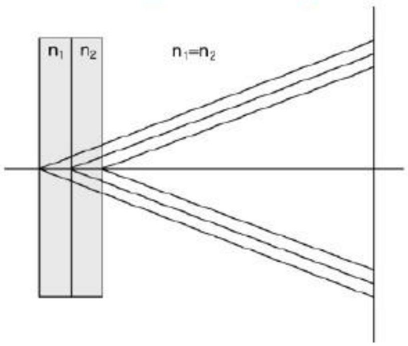
Two aerogel layers in focusing configuration:
n1=1.045, n2=1.055
Overlapping rings from 1st and 2nd layer
High transmission length is required (>30 mm).



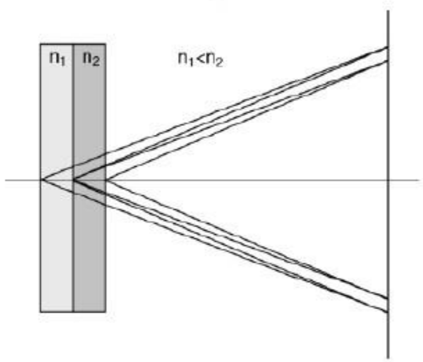


ARICH: focusing configuration

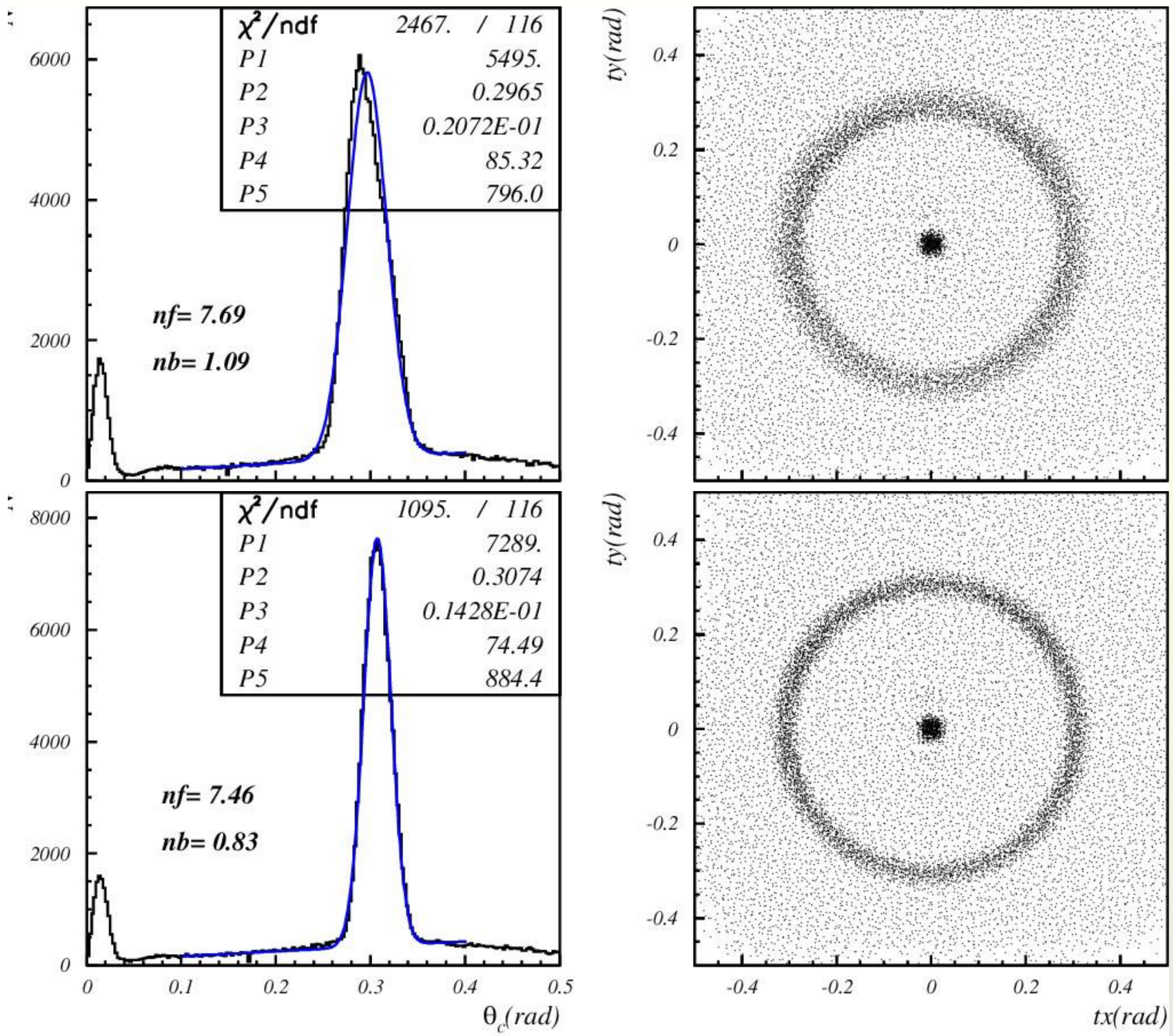
4cm aerogel single index



2+2cm aerogel

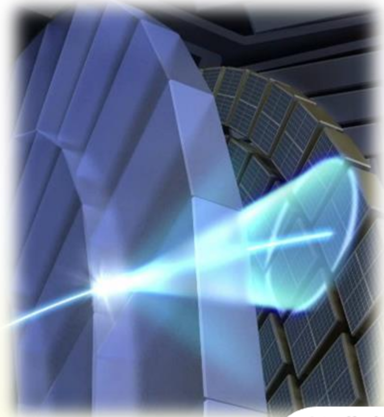


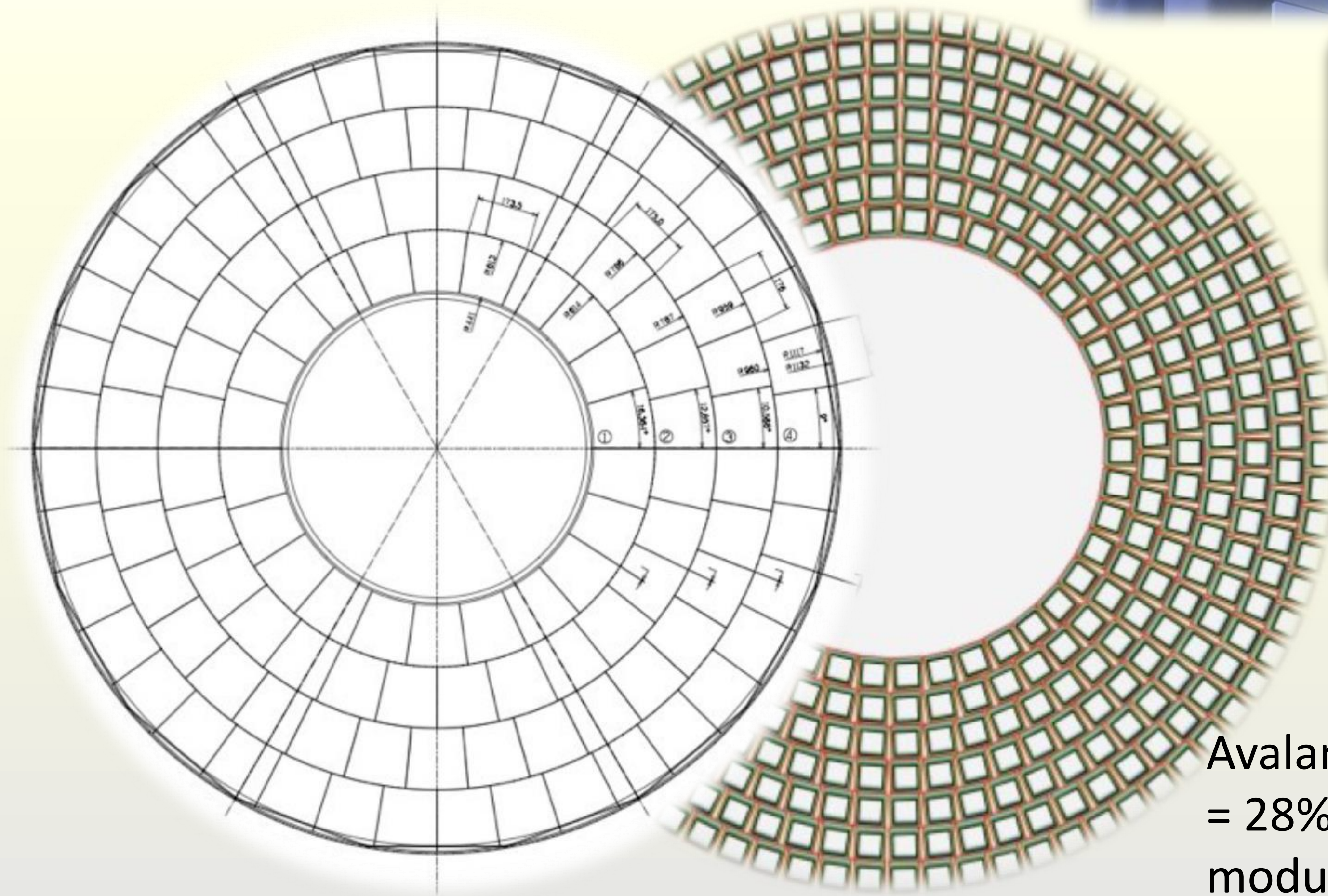
→NIM A548 (2005) 383

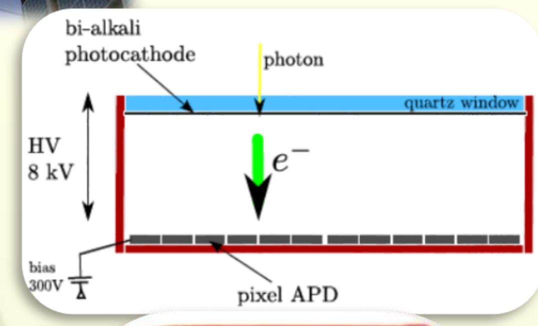


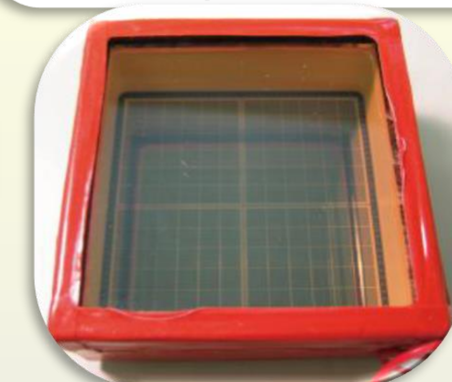
ARICH

Aerogel: 124x2 pieces
- wedge shape, each layer 20mm thick
- 4 types depending on radius
- Cut out from square tile ~175 mm in side



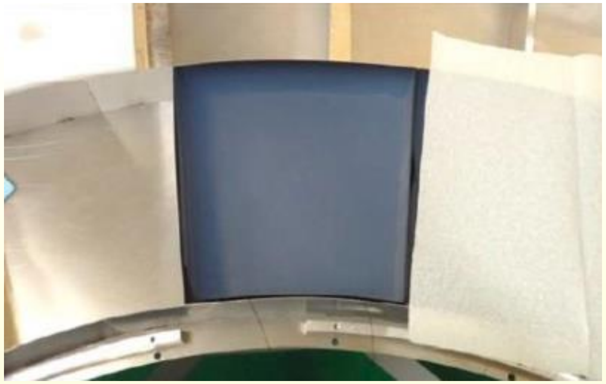


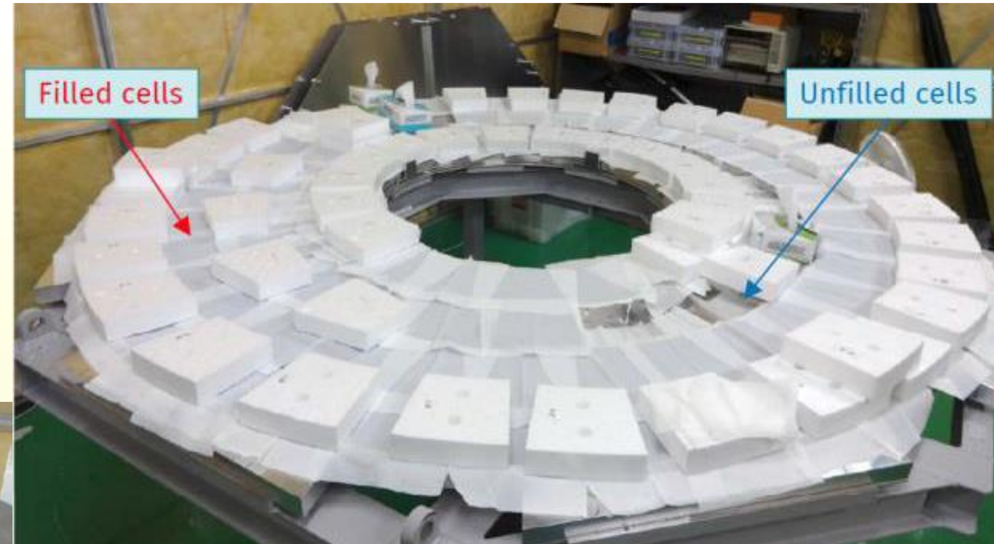


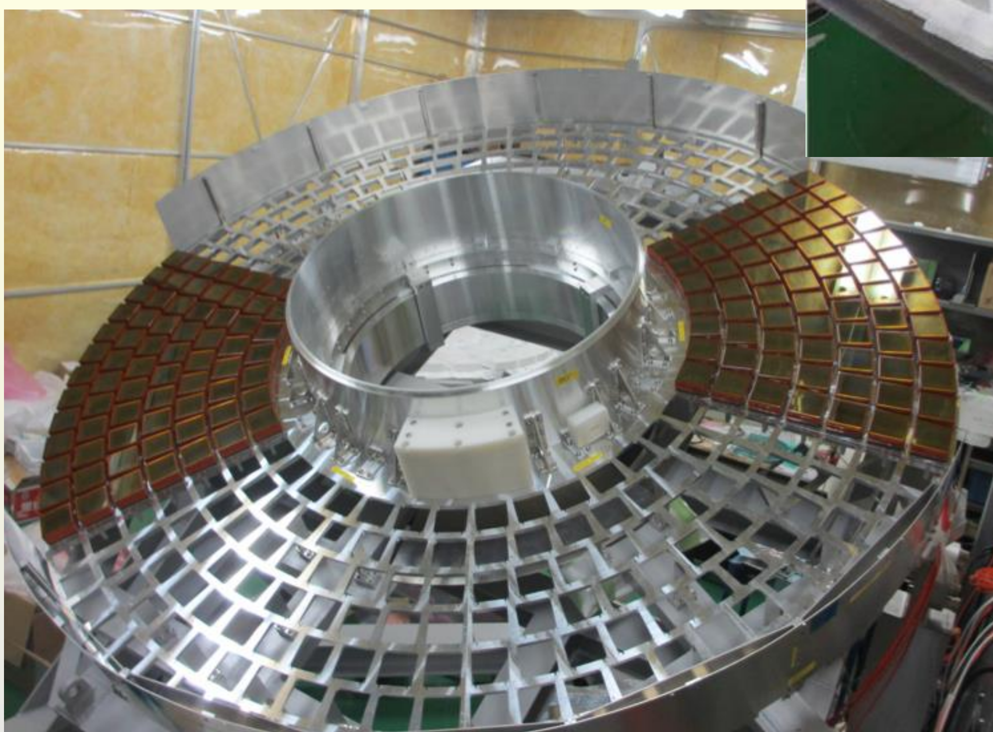


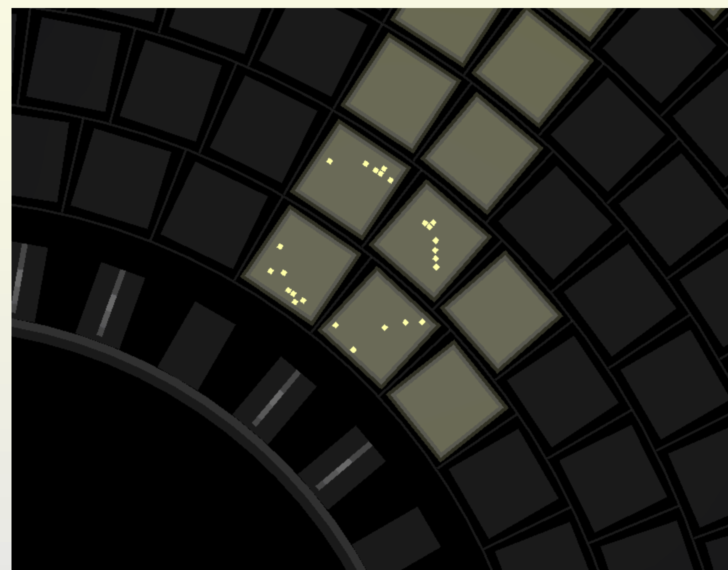
420 HAPD (Hybrid Avalanche Photo Detector QE = 28% at 400 nm, gain ~ 10^5) modules in 7 rings

ARICH manufacturing

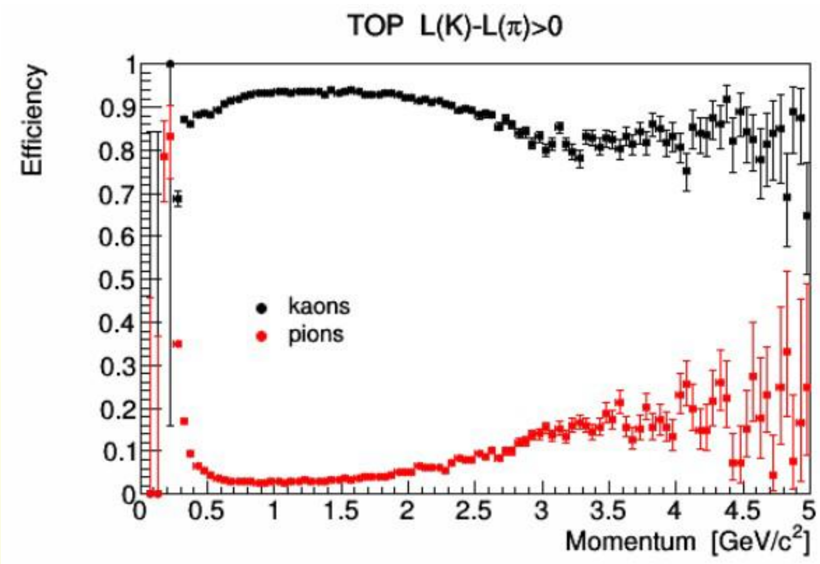


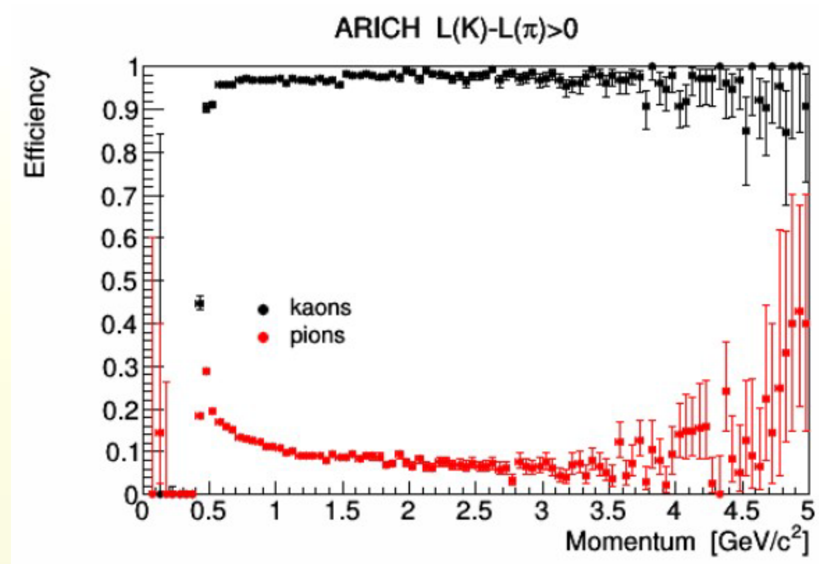






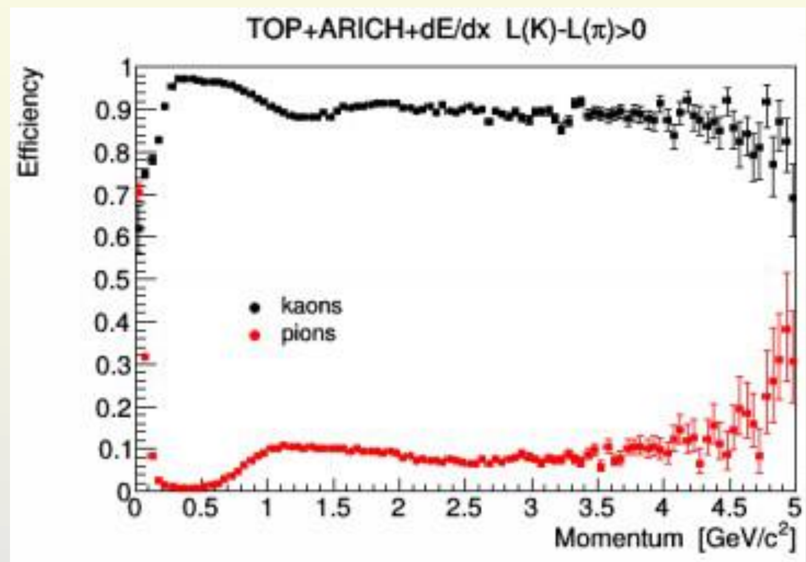
Expected performance



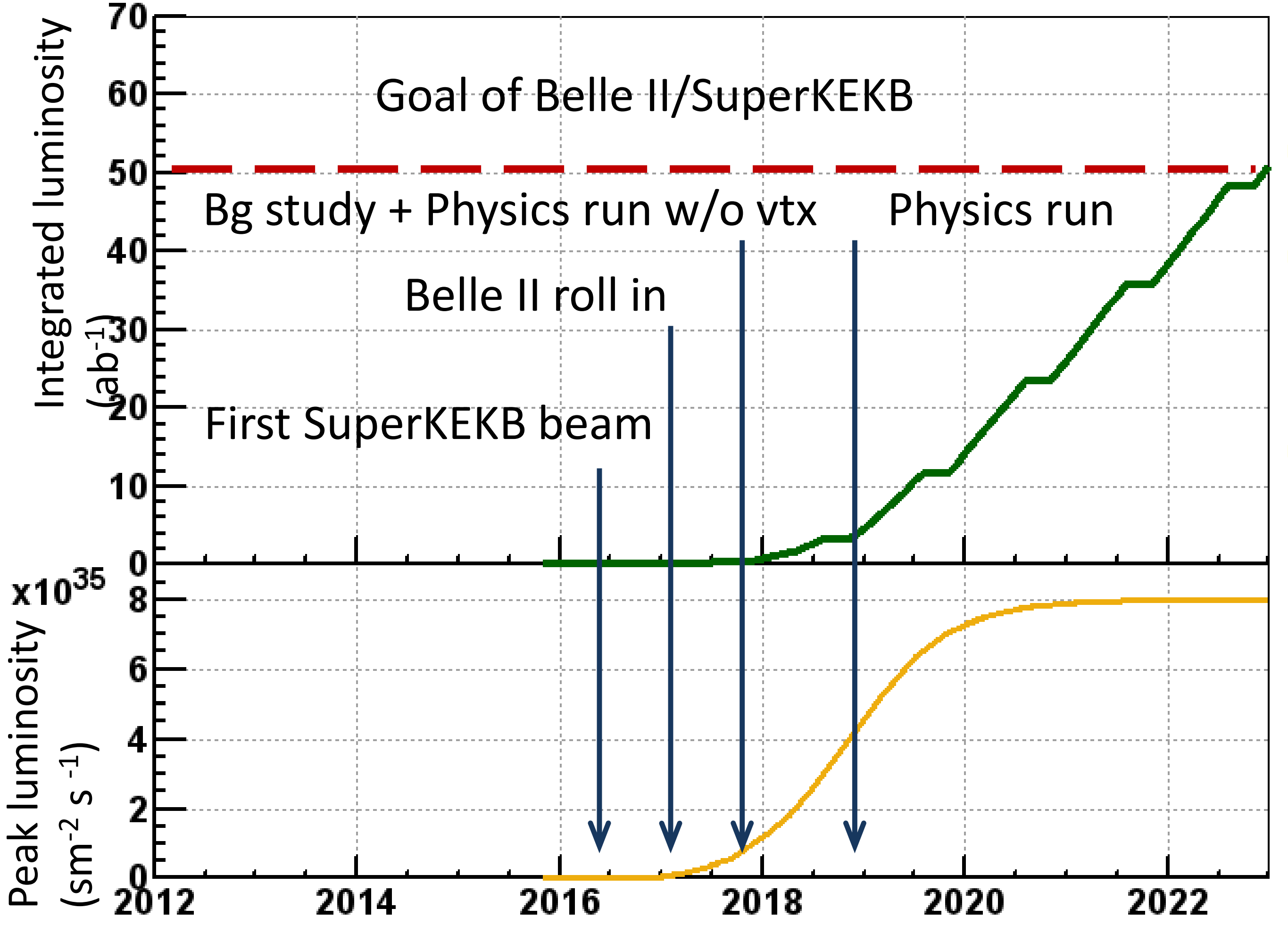


Excellent K identification efficiency over wide momentum range:
→ Belle II: **93%, 4% π misidentification probability**

Compare to:
→ Belle : 88%, 9%



SuperKEKB luminosity projection



- **phase-1 (done)**
  - Beam commissioning
- **phase-2 (Jan. 2018)**
  - Beam BG measurement
  - Belle II detector with partial vertex sensors
- **phase-3 (Dec. 2018)**
  - Physics running
  - Full Belle II detector

Expected numbers of produced particles at 50 ab^{-1}

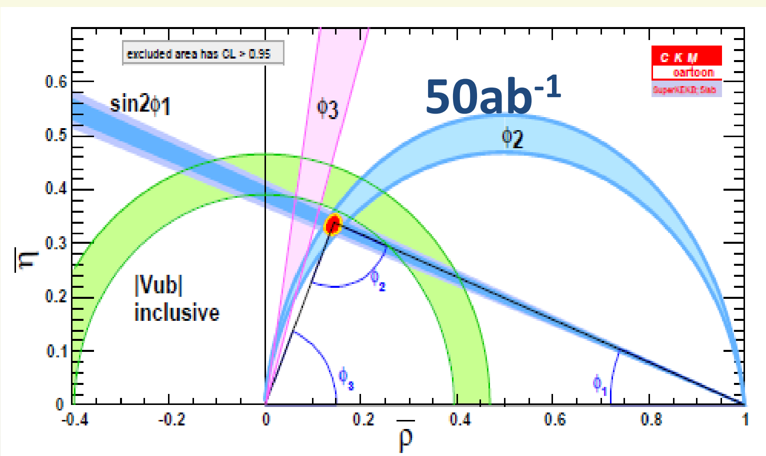
Process	$\sigma[nb]$	No. events $[\times 10^9]$
$B\bar{B}$	1.1	55
$q\bar{q}$ $(q=u,d,s)$	2.52	185.45
$\tau^+\tau^-$	0.92	45.95

Summary

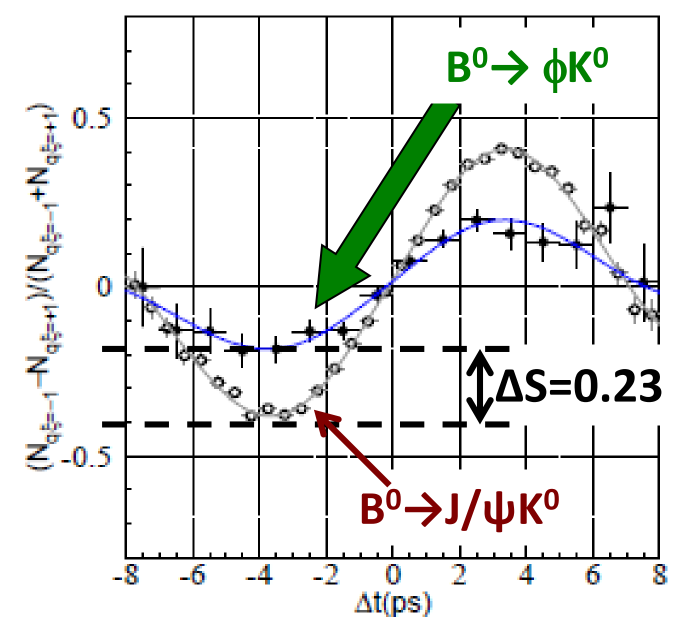
Physics beyond the Standard Model has successfully avoided detection up to now. But we are sure it is somewhere nearby.

Up to now the sensitivity of Flavor experiments to New Physics amplitude was ~10% of those from the SM; in 5-10 years it will be improved by an order of magnitude.

- **Rich physics program for Belle II**
- **Belle II will start data taking in 2018**
- **Belle II goal of 50/ab will provide great sensitivity and complimentary to LHCb information in many areas of flavor, CP and related fields**



- **We hope to observe something like THIS in 5-7 years**
- **Cherenkov detectors are of key importance for this!**



UT 2014		Belle II
α	4° (WA)	**1°**
β	0.8° (WA)	**0.2°**
γ	8.5° (WA) 14°(Belle)	**1-1.5°**

T H A N K   Y O U !