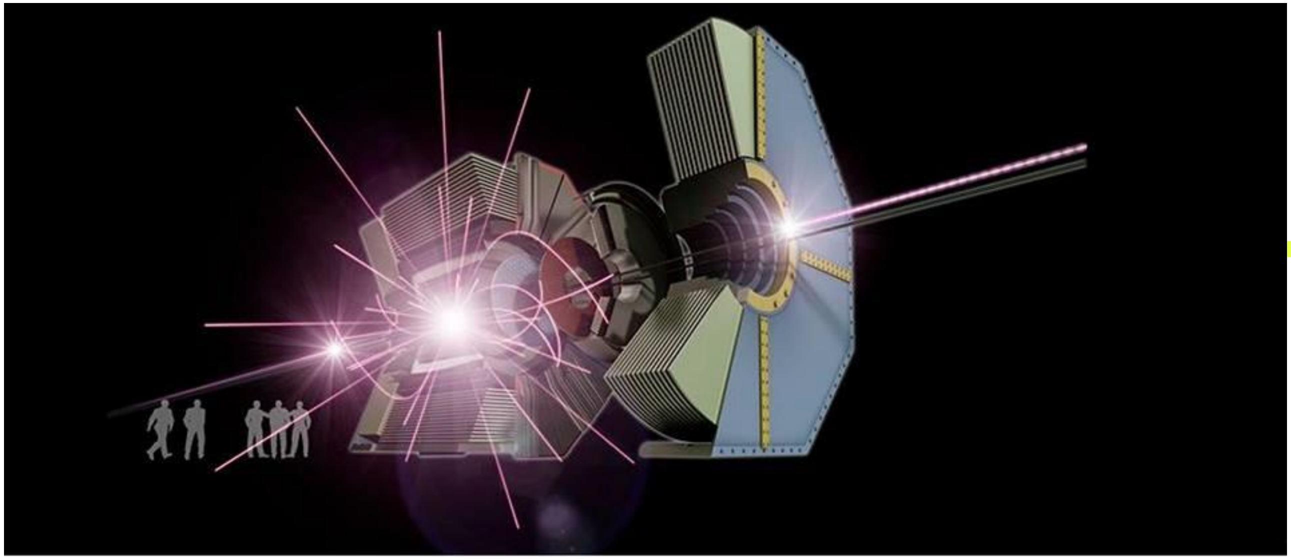


Slovenian group in the Belle and Belle II experiments at KEK

Peter Križan
University of Ljubljana and JSI

Slovenian group at Belle and Belle II

- J. Stefan Institute
- Faculty of mathematics and physics, University of Ljubljana
- Faculty of chemistry and chemical technology, University of Maribor
- Laboratory for astroparticle physics, University of Nova Gorica

Prof. B. Golob, Prof. dr. S. Korpar, Prof. P. Križan, Prof. S. Stanič, Prof. M. Starič, Dr. M. Bračko, Dr. R. Dolenec, Dr. R. Pestotnik, Dr. L. Šantelj, Dr. A. Zupanc, PhD student: L. Rizzuto + one more (starting in autumn)

Slovenian contributions to the Belle experiment

- Joined in spring 2001 by combining the Ljubljana HERA-B team (RICH and analyses) and a part of the DELPHI group (RICH and analyses)

- Hardware: detector was already there, so only limited contribution possible (R+D for the upgrade of the SVD, silicon vertex detector, installed in 2003; radiation monitoring system)

- Immediately got fully involved in the analysis →

Boštjan Golob and Anže Zupanc have been running for several years the Belle charm physics + spectroscopy group, the biggest and most productive physics working group in Belle.

Belle physics studies carried out so far (mostly PhD theses)

- U. Bitenc, D^0 mixing in semi-leptonic decays
- I. Bizjak, V_{ub} inclusive
- S. Fratina, CP violation in B → DD
- A. Zupanc, B → D_sD
- S. Starič, D^0 mixing in KK/$\pi\pi$
- S. Starič, A_{CP} in KK/$\pi\pi$
- A. Zupanc, D^0 mixing in ϕ K_S
- M. Petrič, Search for $D^0 \to \ell^+\ell^-$
- M. Petrič, B → $K\pi\pi^0$ t-integrated
- A. Zupanc, absolute measurement of D_s branching fractions
- L. Šantelj, CP violation in B → K_S η'
- P. Smerkol, CP violation in Λ_c decays
- T. Nanut, A_{CP} in D(s) → (ρ^0, K^{*0}, ϕ) γ
- J. Biswal, double charm production with DD in e^+e^- collisions
- E. Ribežl, X(3872) production in e^+e^- collisions
- M. Lubej, $B \to KK\ell\nu$

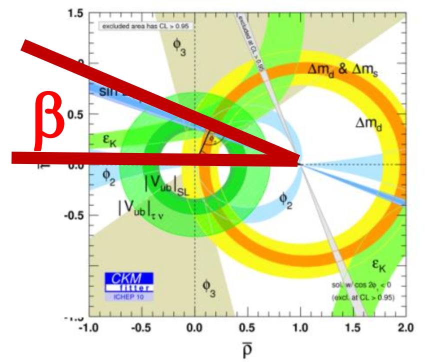
→ 11 Ph.D theses at the University of Ljubljana, another one is in preparation; one of them got the prestigious J. Stefan Golden Medal (best Slovenian Thesis).

Some selected results of Ljubljana based analyses

- V_{ub} inclusive, PRL 95, 241801 (2005); in many ways pionereed inclusive measurements of $b \to u$ at Belle, ~80 citations;
- D^0 mixing in KK/ππ; PRL 98, 211803 (2007); first evidence (together with BaBar); in a way opened the era of CP violation measurements in charm sector, >400 citations;
- A_{CP} in KK/ππ; Phys. Lett. B 670, 190 (2008); one of first high sensitivity CPV measurement in the charm sector, >100 citations;
- Search for $D^0 \to \ell^+\ell^-$; PRD 81, 091102 (2010); constraints on LQ models, ~60 citations;
- CPV in $B \to D^*D^*$; PRD 86, 071103(R) (2012); first observation;
- D_s absolute branching fractions; JHEP 09, 139 (2013); novel method for absolute measurements of charm meson branching fractions, ~60 citations

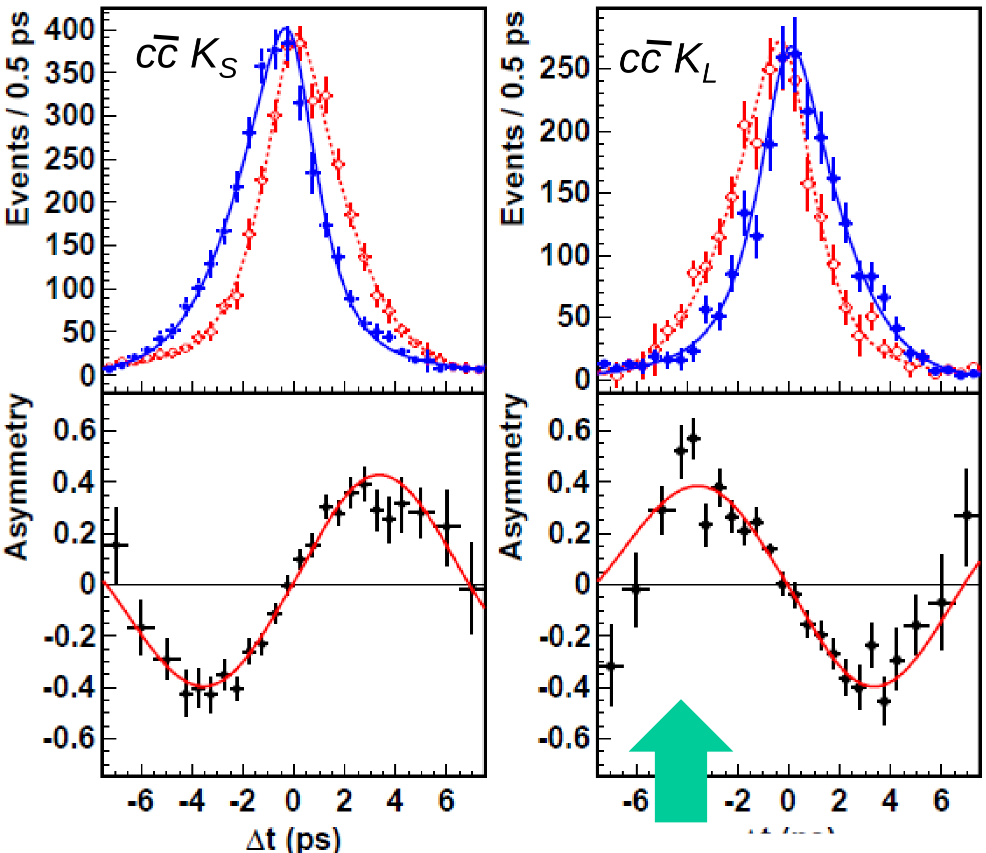
Profited a lot from an excellent collaboration with the members of the Theory department of the JSI.

CP violation in the B meson system: measurement of the CKM phase



ϕ_1 from CP violation measurements in $B^0 \rightarrow J/\psi\, K^0$

$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t) = \sin 2\phi_1 \sin(\Delta m t)$$



Opposite CP → sine wave with a flipped sign

sin2ϕ_1 (=sin2β)

Belle:	0.668 ± 0.023 ± 0.012
BaBar:	0.687 ± 0.028 ± 0.012

Belle, PRL 108, 171802 (2012)

BaBar, PRD 79, 072009 (2009)

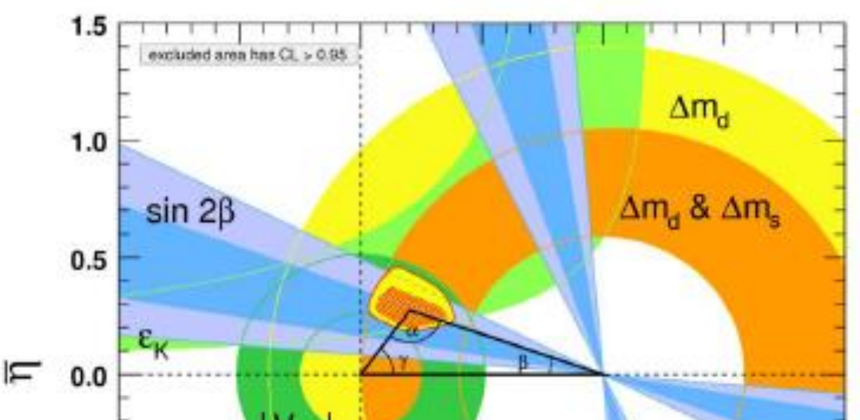
with a single experiment precision of ~4%!

$\phi_1 = \beta = (21.4 \pm 0.8)^0$

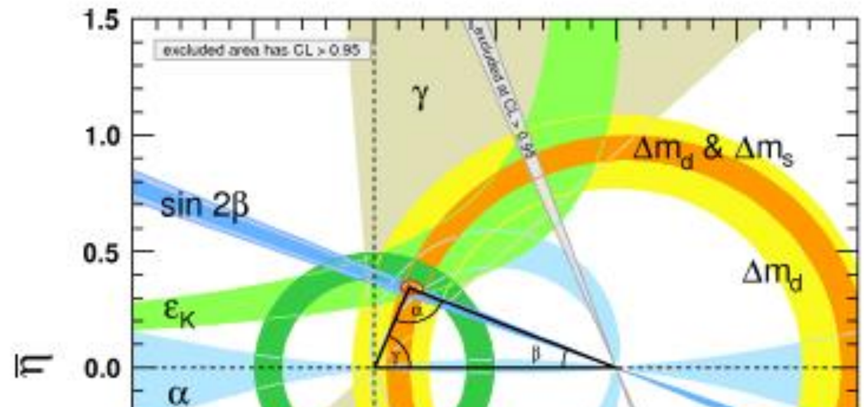
CP violation in the B system

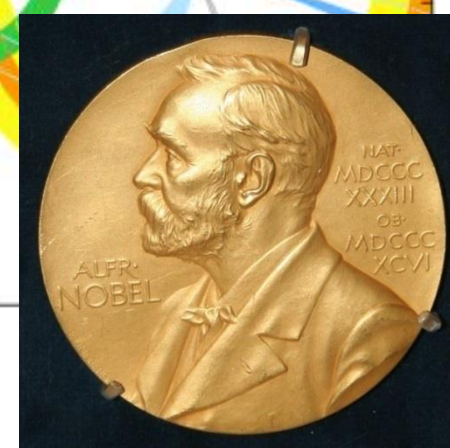
B factories: CP violation in the B system: from the discovery (2001) to a precision measurement (2011) → remarkable agreement with the Kobayashi-Maskawa prediction!

EPS 2001



EPS 2011





Part of the Slovenian group at KEK with Prof. Kobayashi, 2008 Nobel laureate

Belle and BaBar – decisive impact on particle physics 2001-2013

Numerous exciting results from B factories

Around 1000 scientific papers summarized in a 900-pages book published by Springer

Foreword: M. Kobayashi. T. Maskawa

One of the five editors:
Boštjan Golob

Authors: several members of the Slovenian team

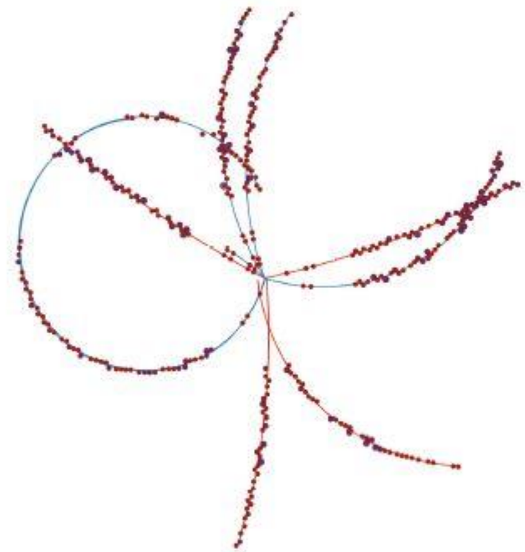
Eur. Phys. J. C (2014) 74:3026
DOI 10.1140/epjc/s10052-014-3026-9

THE EUROPEAN PHYSICAL JOURNAL C

Review

The Physics of the B Factories

Received: 29 July 2014 / Accepted: 29 July 2014



From Belle towards Belle II

Next generation: Super B factories → Looking for NP

→ Need much more data (almost two orders!)

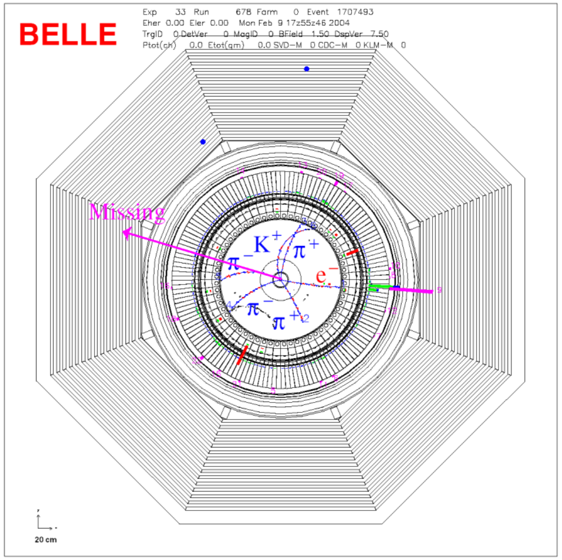
A joint & complementary effort at the intensity frontier with LHCb, BESIII,...

An e^+e^- machine running at (or near) Υ(4s) will have considerable advantages in several classes of measurements, and will be complementary in many more

→ Physics at Super B Factory, arXiv:1002.5012 (Belle II)
→ SuperB Progress Reports: Physics, arXiv:1008.1541 (SuperB)
→ Physics at B Factories, Eur. Phys. J. C74 (2014) 3026
→ Belle II Theory Interface Platform (B2TiP), Belle II Physics Book, arXiv:1808.10567, to be published in PTEP

Advantages of a super B factory in the LHC era

$$B^+ \to D^0\pi^+$$
$$(\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$



Unique capabilities of B factories:

→ Exactly two B mesons produced

one B meson reconstructed, study decays of the other (especially with Emiss, at low bkgs.)

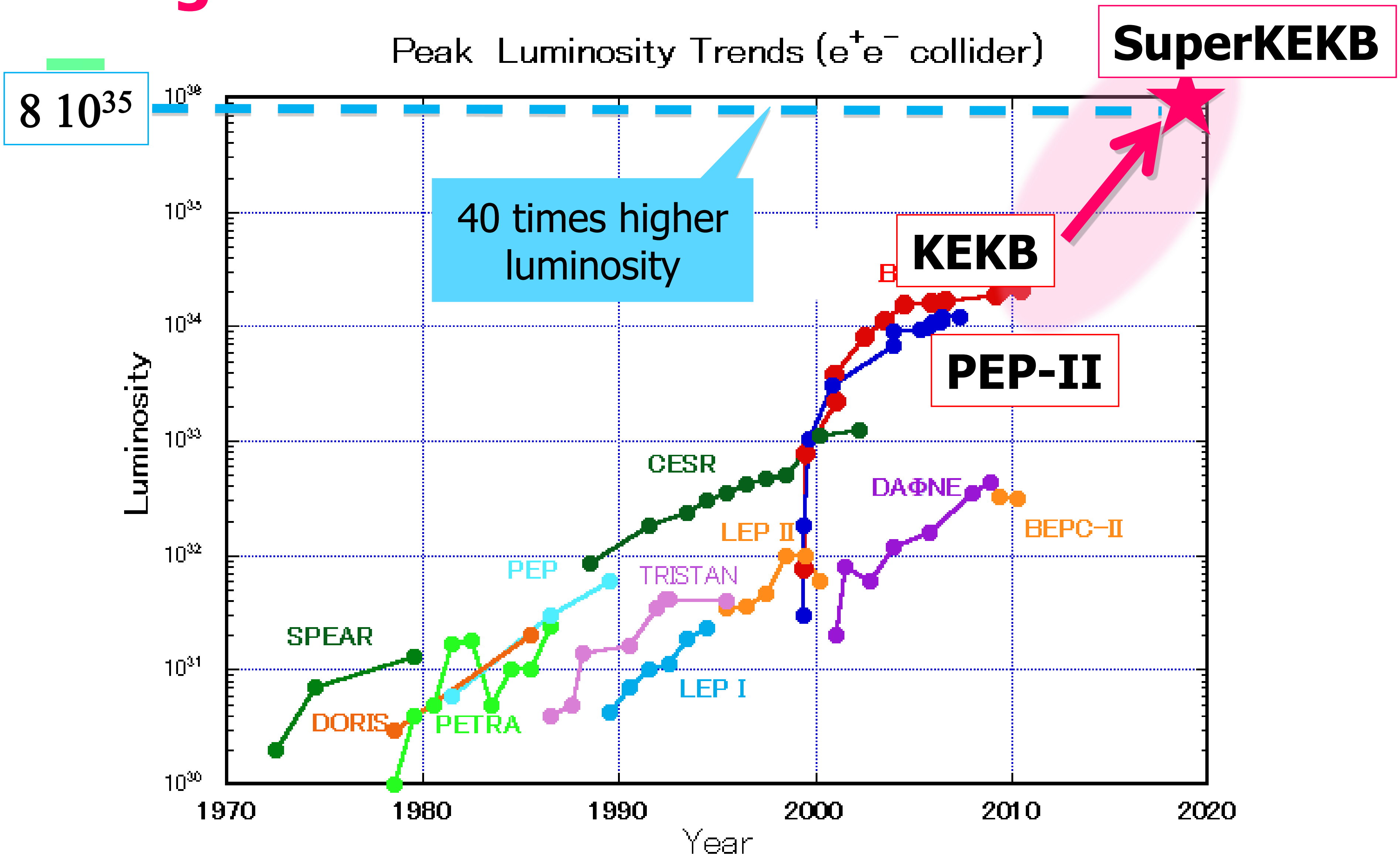
→ High flavour tagging efficiency

→ Detection of gammas, π^0s, K_Ls

→ Very clean detector environment (can observe decays with several neutrinos in the final state!)

However, need a two-orders-of-magnitude larger data sample!

Need O(100x) more data →Next generation B-factories



N.B. KEKB peak L: 2.11 10^{34} cm^{-2} s^{-1}

How to increase the luminosity?

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

- Lorentz factor ($\gamma_{e\pm}$)
- Classical electron radius (r_e)
- Beam size ratio@IP (σ_y^*/σ_x^*): 1 - 2 % (flat beam)
- Beam current ($I_{e\pm}$)
- Beam-beam parameter ($\xi_y^{e\pm}$)
- Vertical beta function@IP (β_y^*)
- Lumi. reduction factor (crossing angle)& Tune shift reduction factor (hour glass effect) (R_L/R_{ξ_y}): 0.8 - 1 (short bunch)

(1) Smaller β_y^*

(2) Increase beam currents

(3) Increase ξ_y

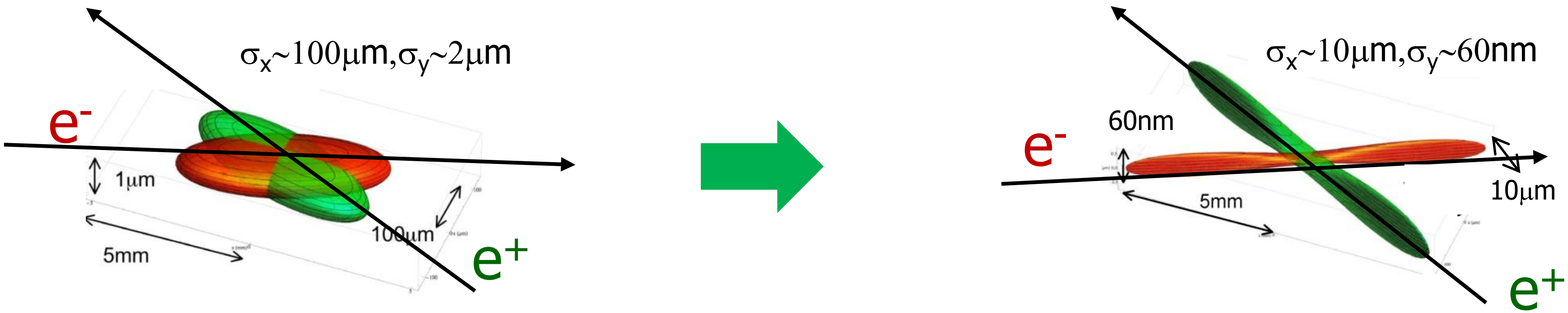
← **"Nano-Beam" scheme**

Collision with very small spot-size beams

How big is a nano-beam ?

How to go from an excellent accelerator with world record performance – KEKB – to a 40x times better, more intense facility?

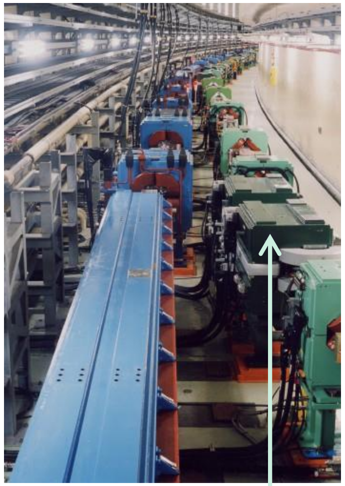
In KEKB, colliding electron and positron beams were already much thinner than a human hair...



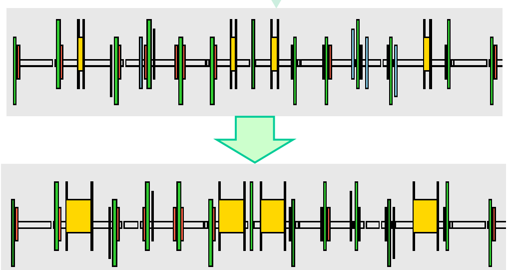
... For a 40x increase in intensity you have to make the beam as thin as a few x100 atomic layers!

Invented by Pantaleo Raimondi for the SuperB project

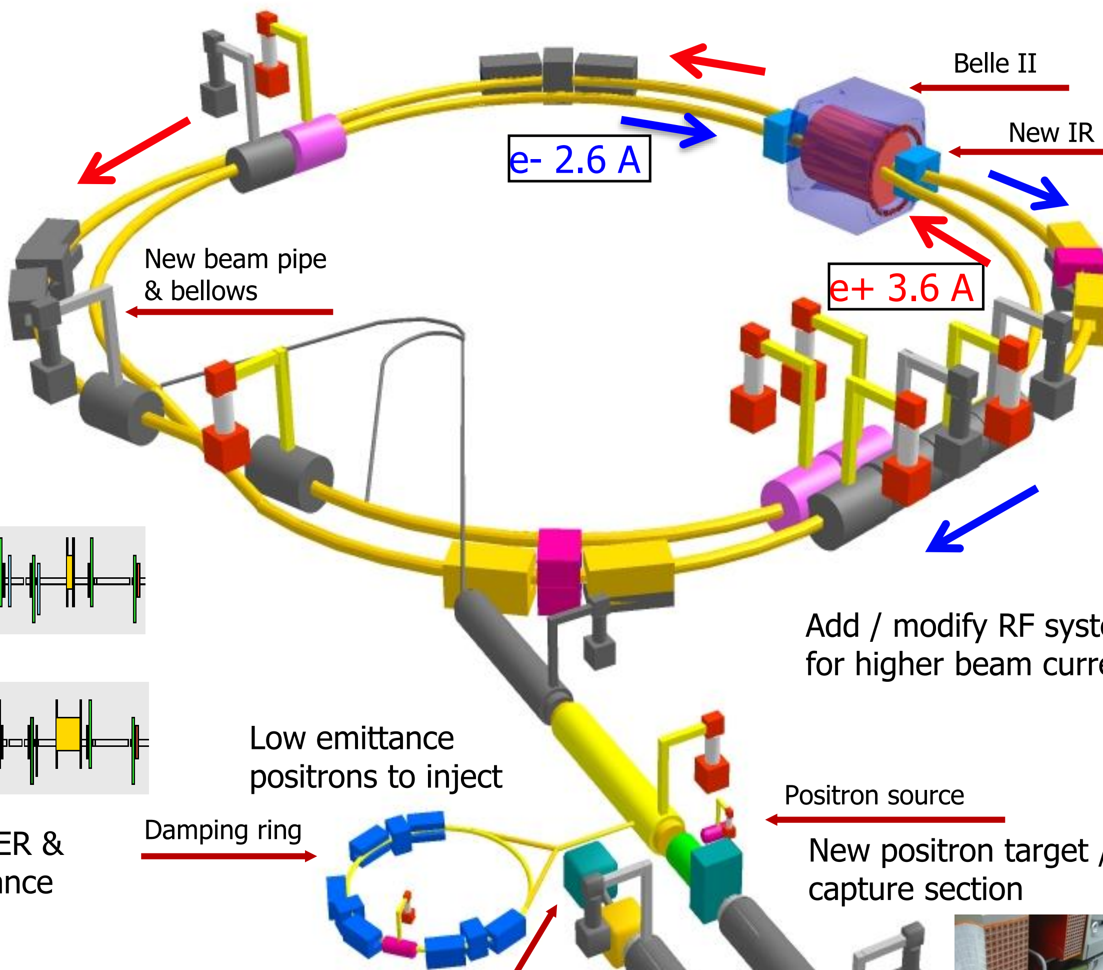
KEKB → SuperKEKB

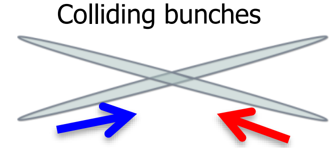


Replace short dipoles with longer ones (LER)

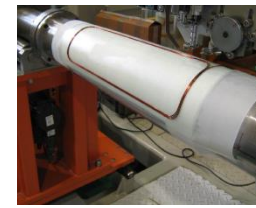


Redesign the lattices of HER & LER to squeeze the emittance





New superconducting /permanent final focusing quads near the IP



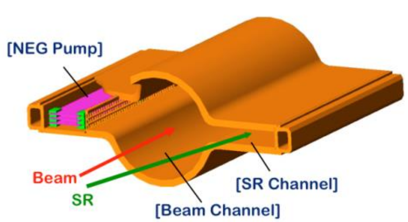
Add / modify RF systems for higher beam current

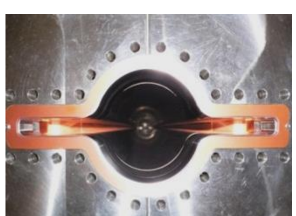
Low emittance positrons to inject

New positron target / capture section

Low emittance electrons to inject

TiN-coated beam pipe with antechambers



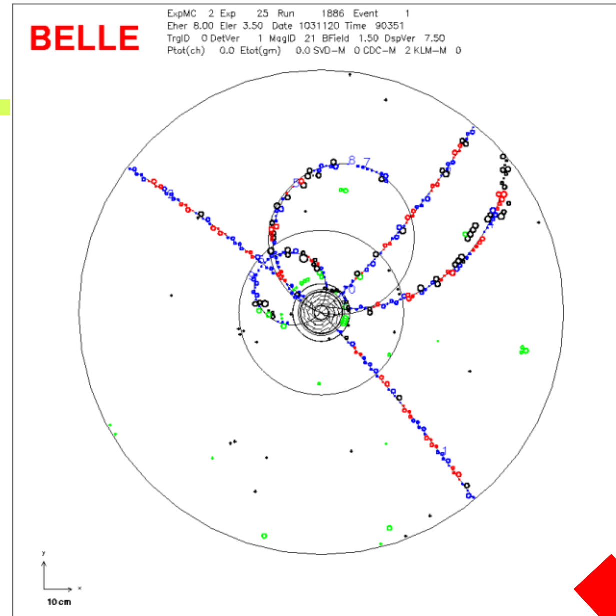


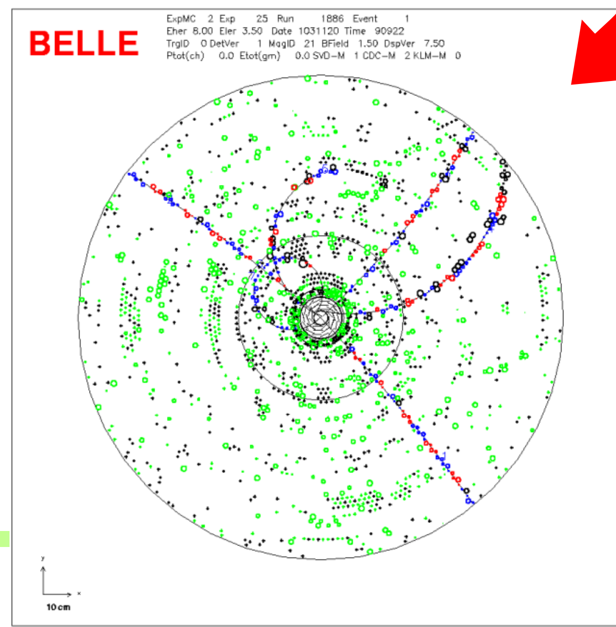
To get x40 higher luminosity

Requirements for the Belle II detector

Critical issues at L= 8 x 10^{35}/cm^2/sec

- **Higher background (×10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing
- **Require special features**
  - low *p* μ identification ← $s\mu\mu$ recon. eff.
  - hermeticity ← ν "reconstruction"



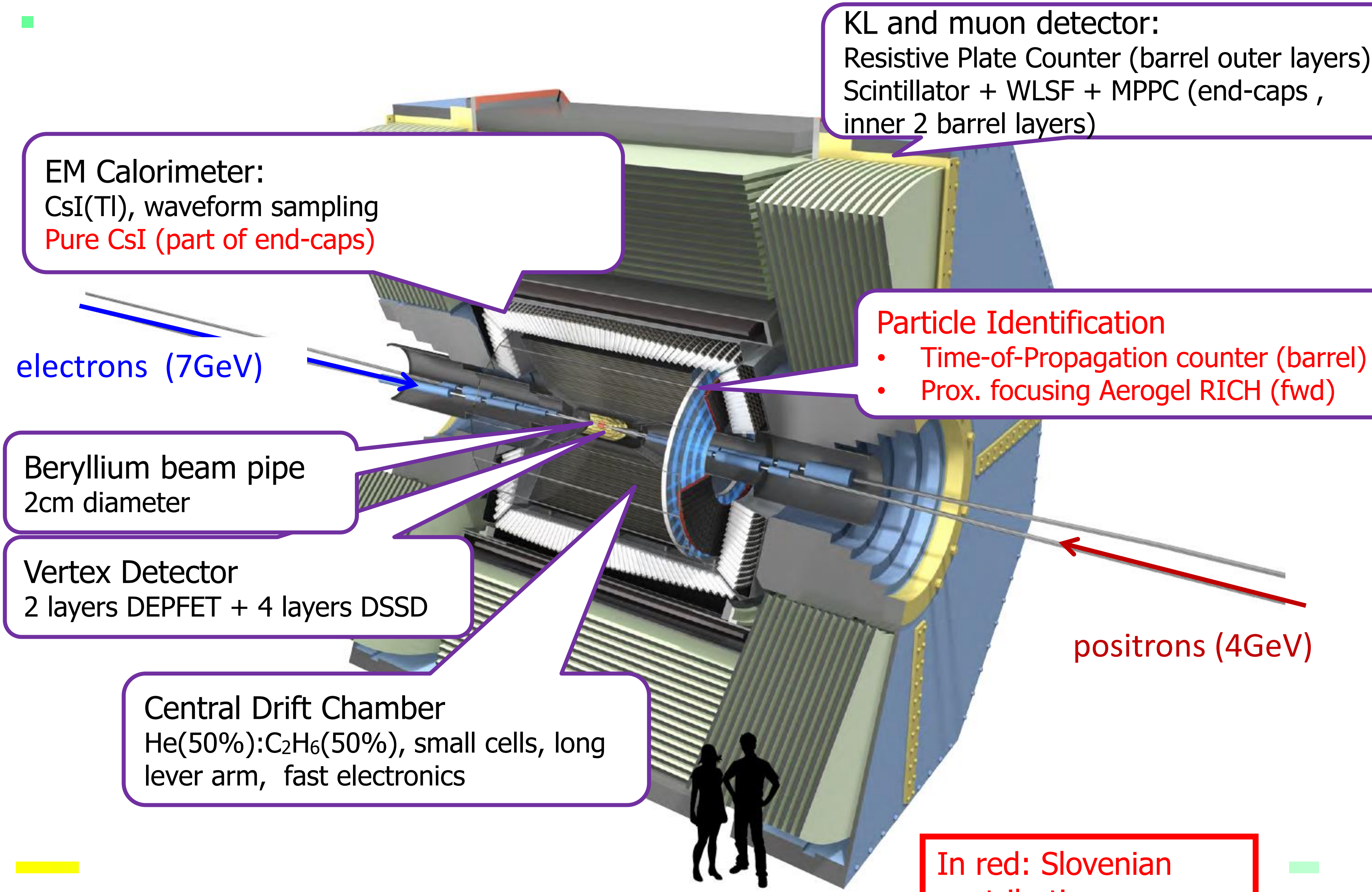


Solutions:

- Replace inner layers of the vertex detector with a pixel detector.
- Replace inner part of the central tracker with a silicon strip detector.
- Better particle identification device
- Replace part of endcap calorimeter crystals
- Faster readout electronics and computing system.

Belle II TDR, arxiv:1011.0352v1[physics.ins-det]

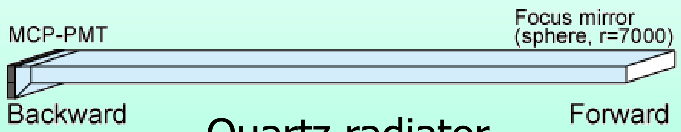
Belle II Detector



In red: Slovenian contributions

Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)



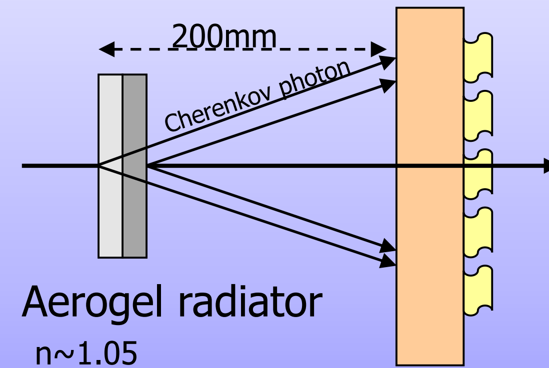
Quartz radiator

Focusing mirror

Small expansion block

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

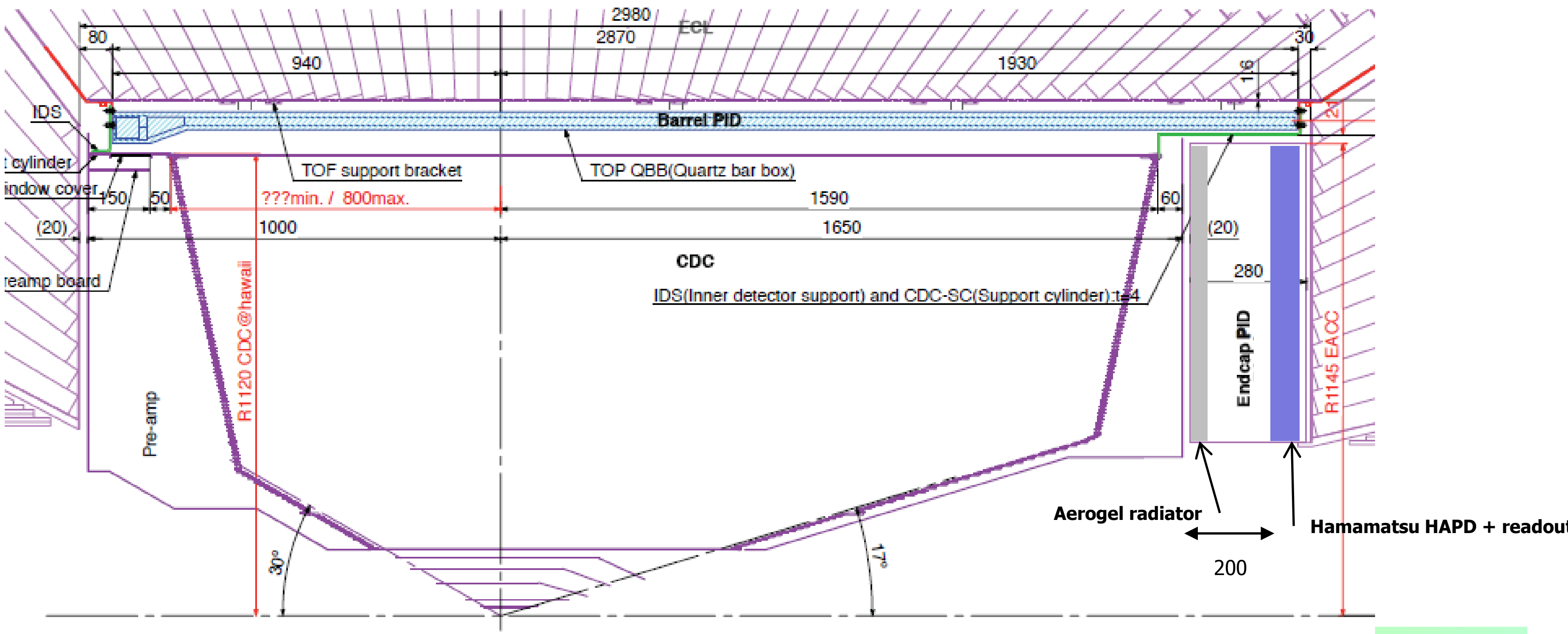
Endcap PID: Aerogel RICH (ARICH)



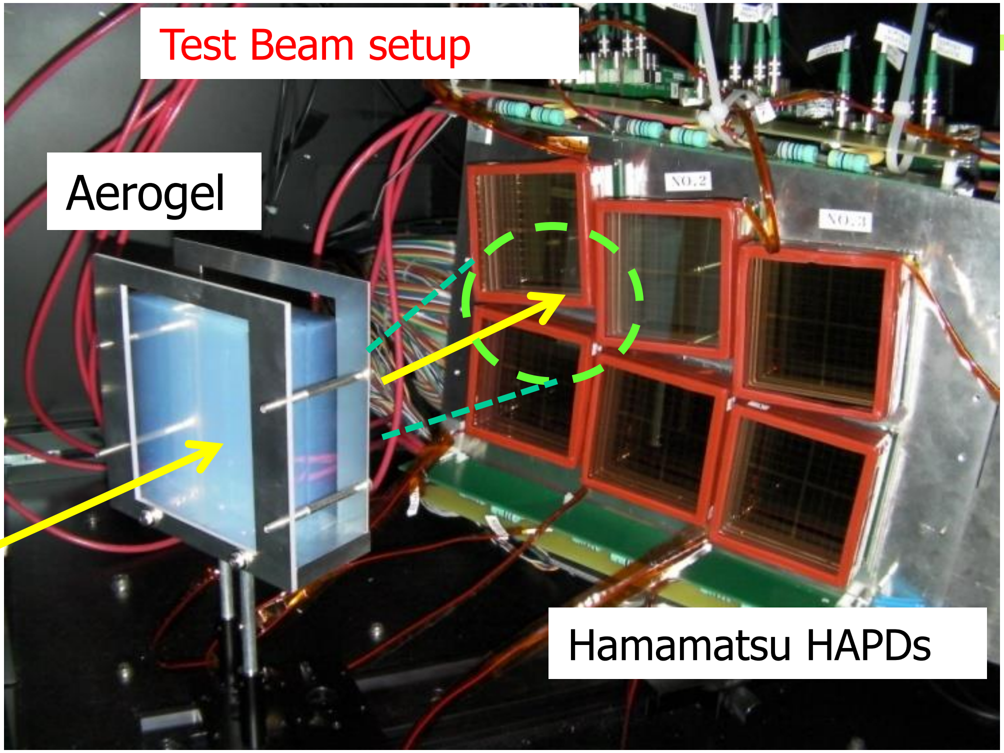
Aerogel radiator

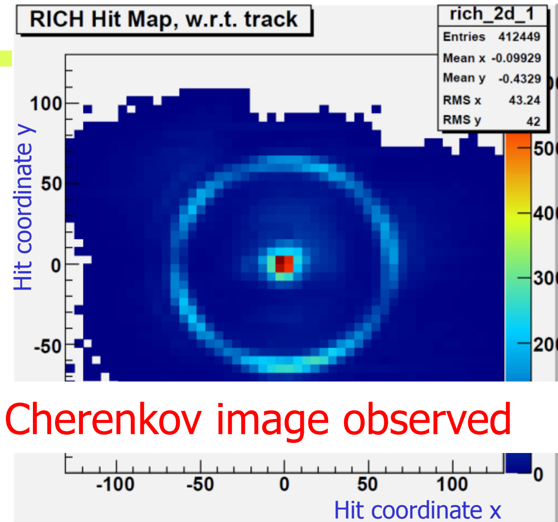
n~1.05

Hamamatsu HAPD



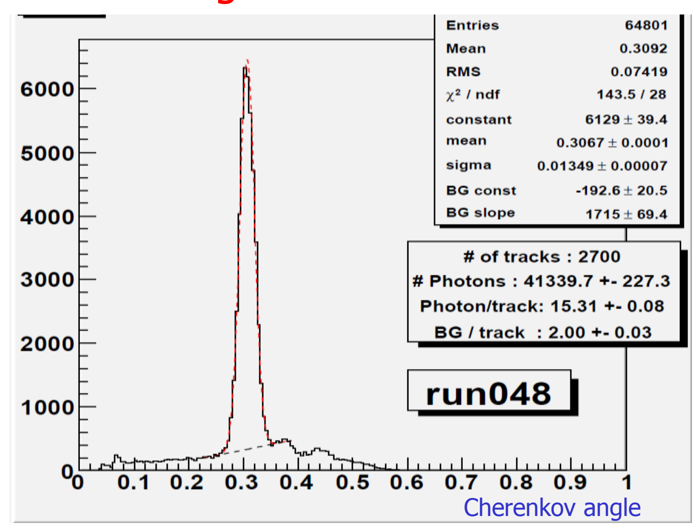
Aerogel RICH (endcap PID)



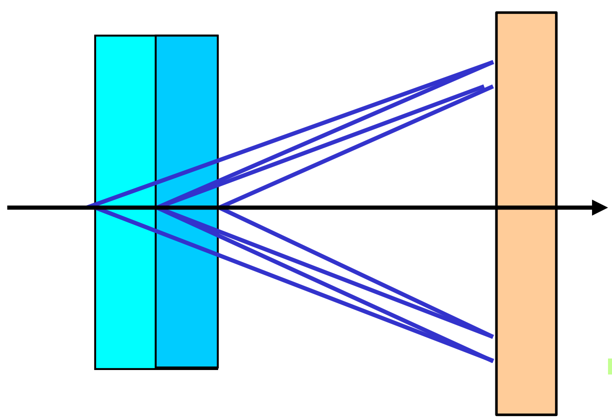


Clear Cherenkov image observed

Cherenkov angle distribution



RICH with a novel "focusing" radiator – a two layer radiator



Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.

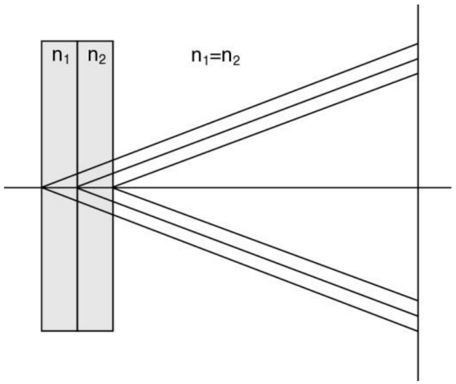
6.6 σ π/K at 4GeV/c !

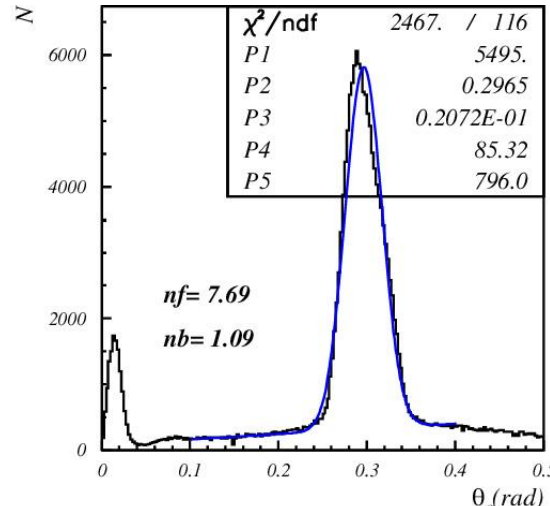
Peter Križan, Ljubljana

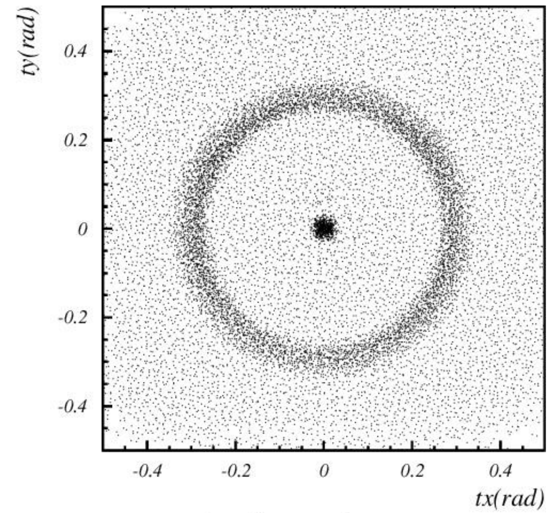
Focusing configuration – data

Increases the number of photons without degrading the resolution

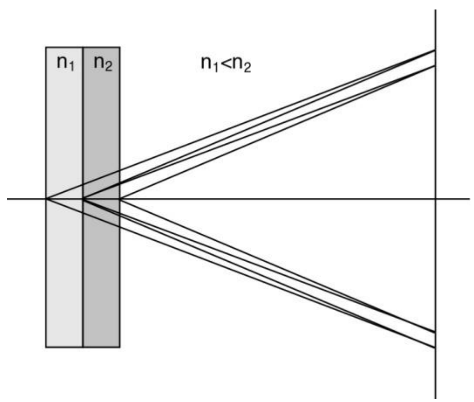
4cm aerogel single index

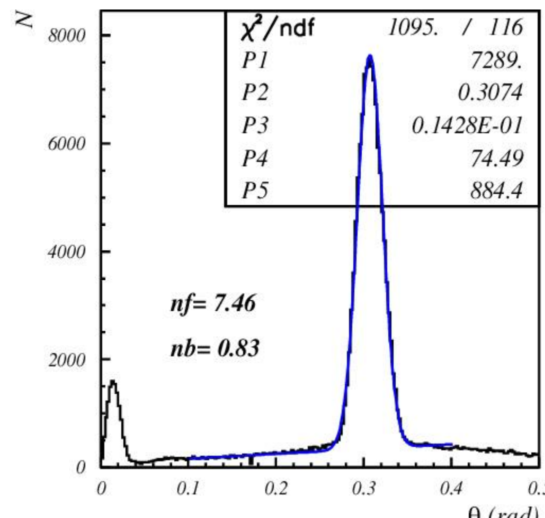


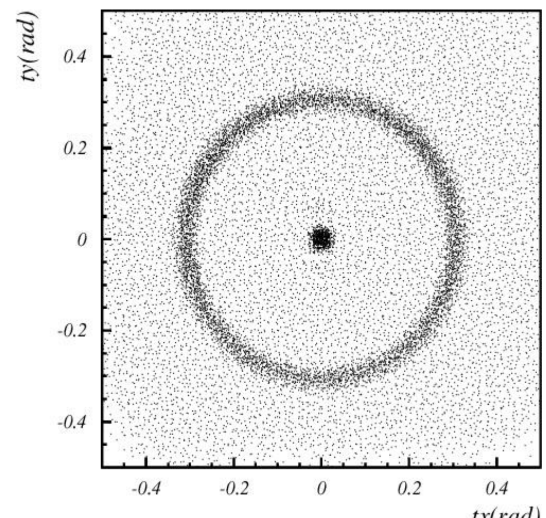




2+2cm aerogel



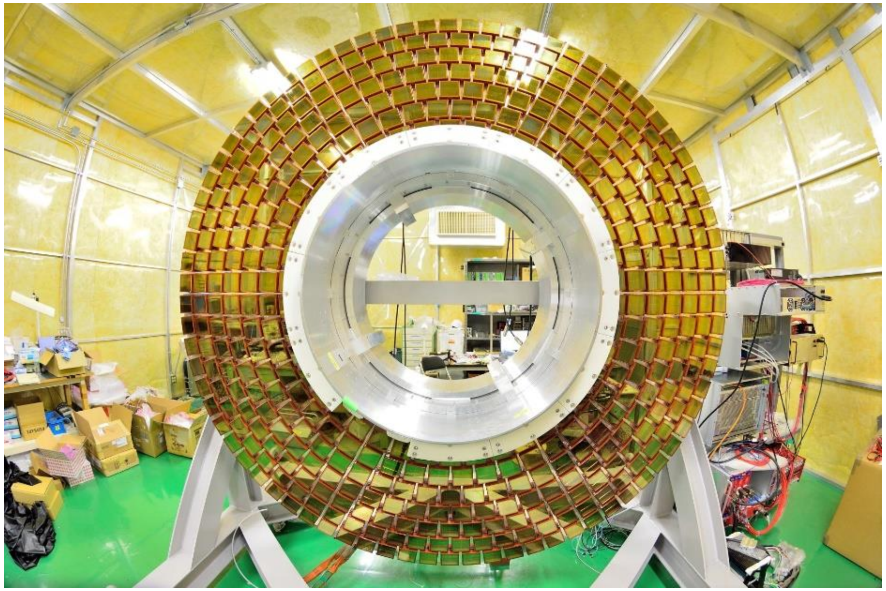
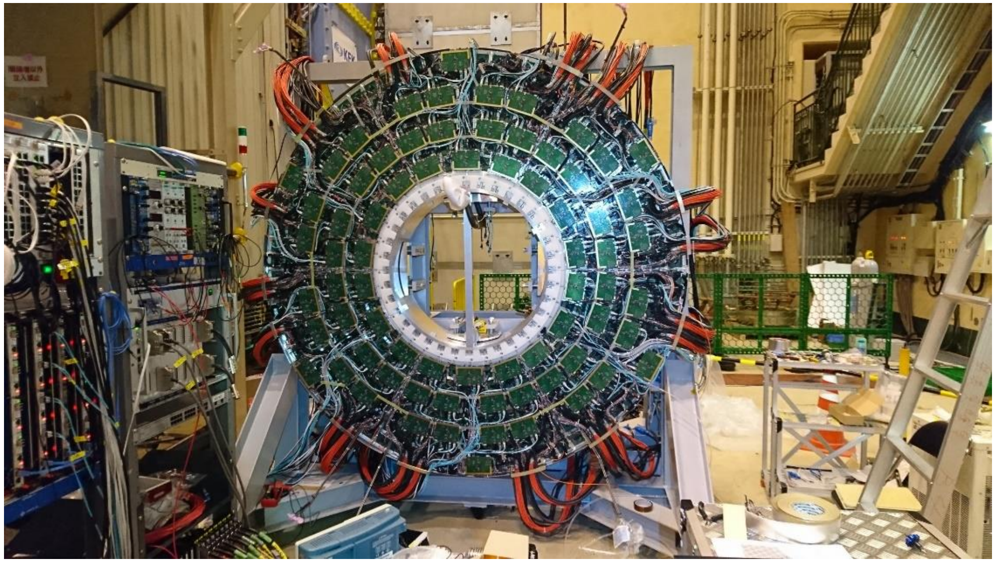
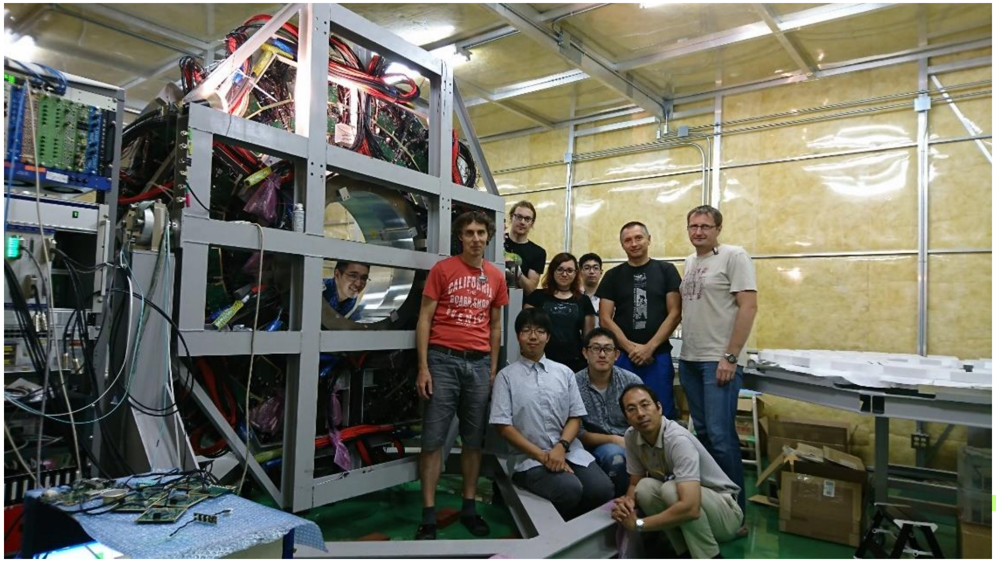
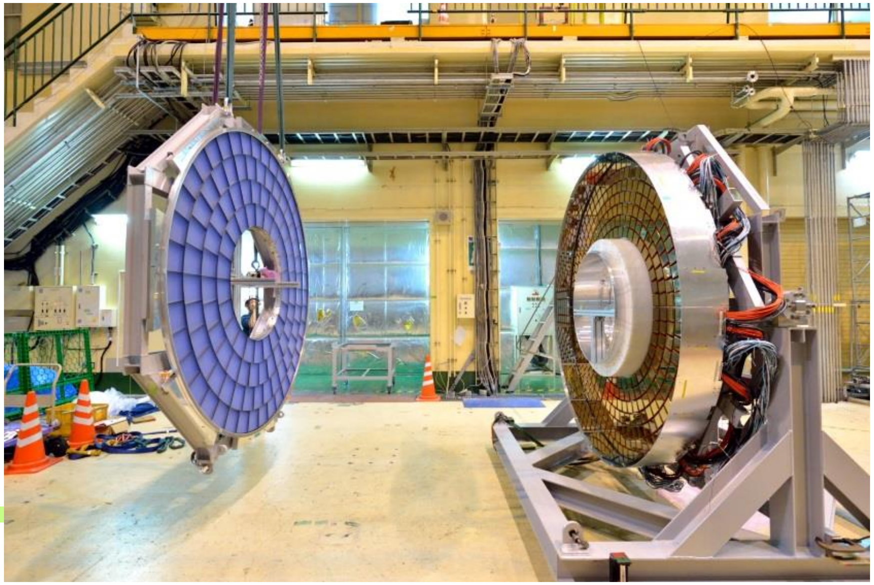




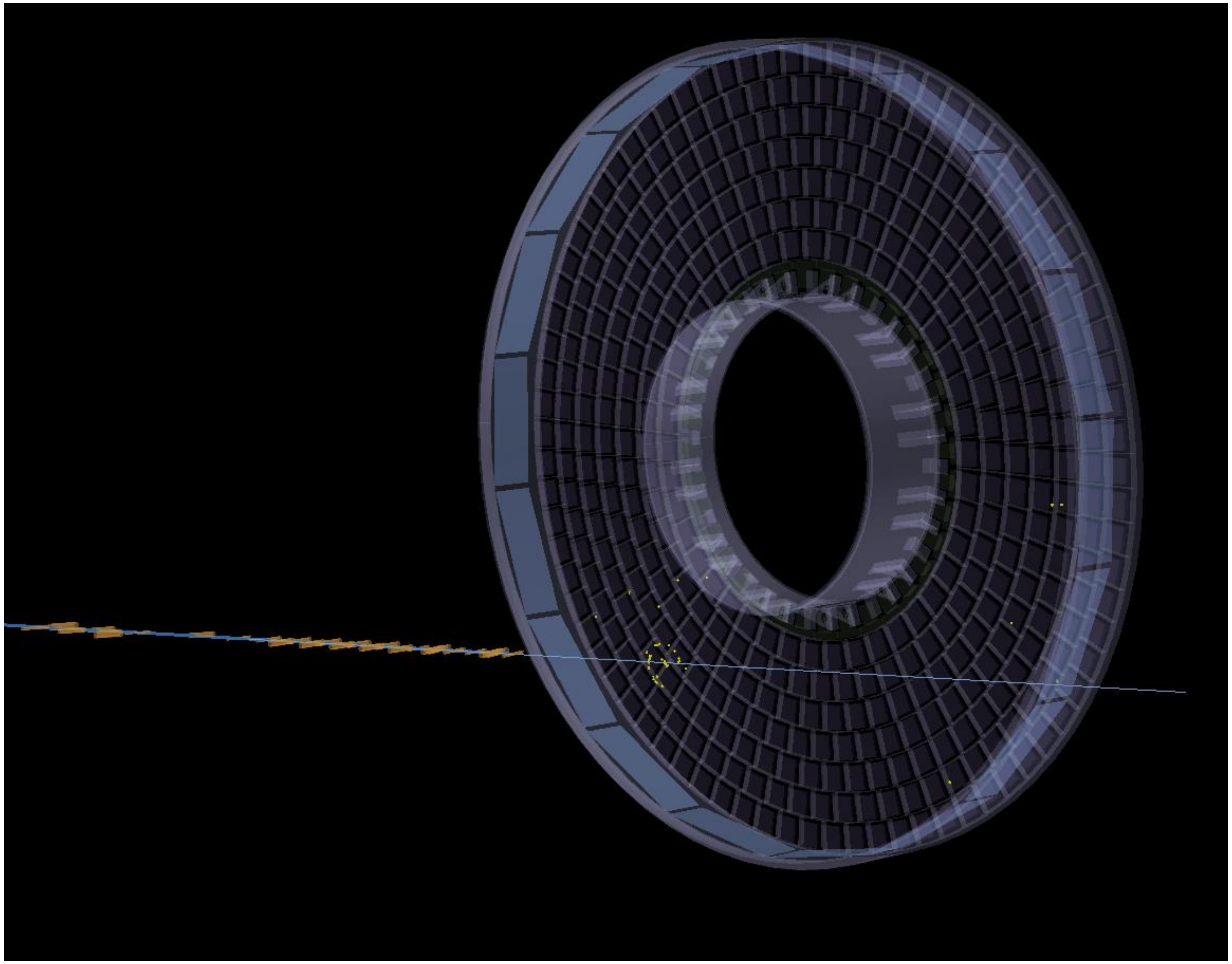
→NIM A548 (2005) 383

Focusing scheme invented by S. Korpar and I . Iijima

The big eye of ARICH

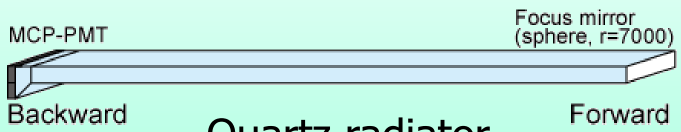
ARICH: Rings from cosmic ray muons



First events recorded in the fully instrumented ARICH.

Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



Quartz radiator

Focusing mirror

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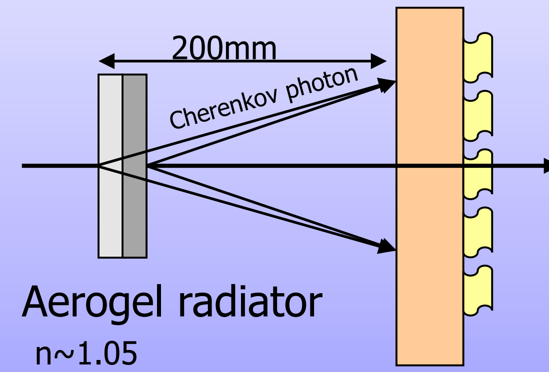
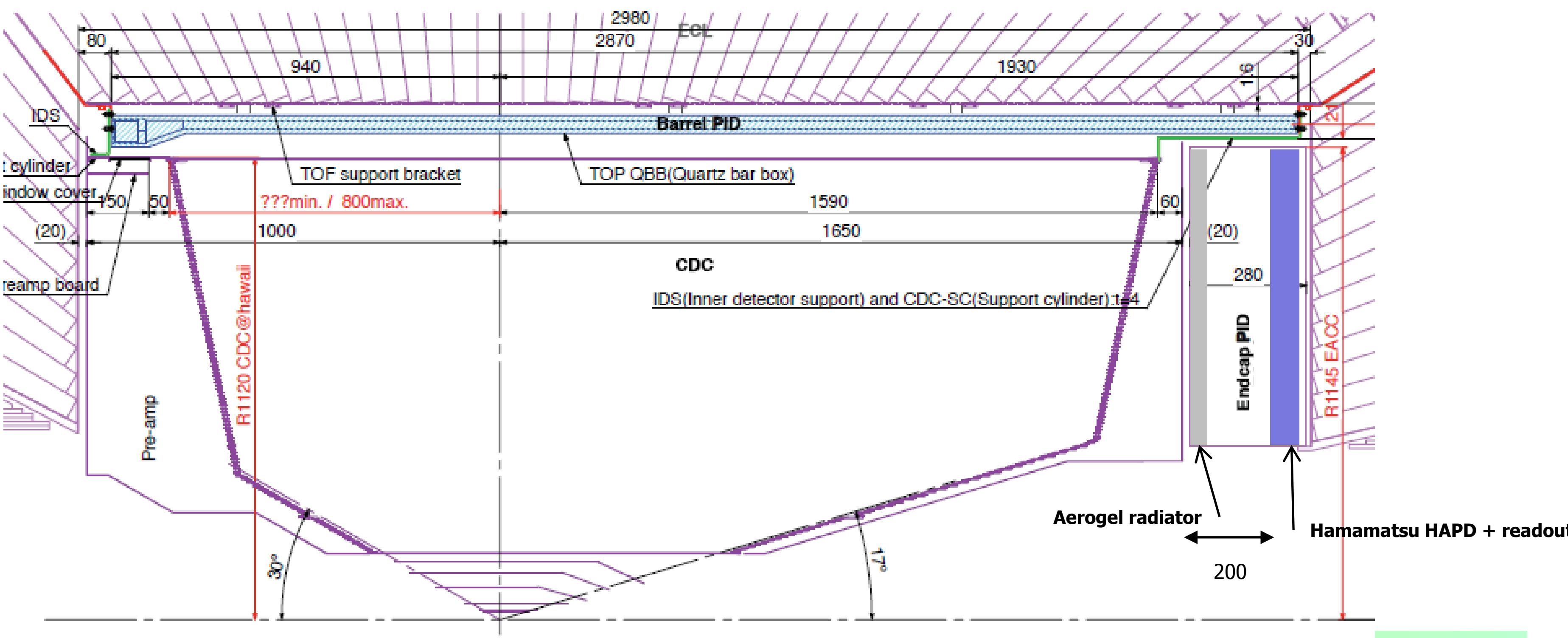
Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)

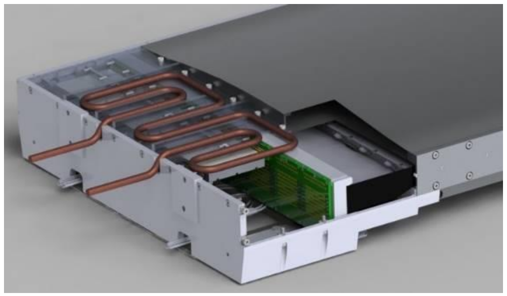


Hamamatsu HAPD
+ new ASIC

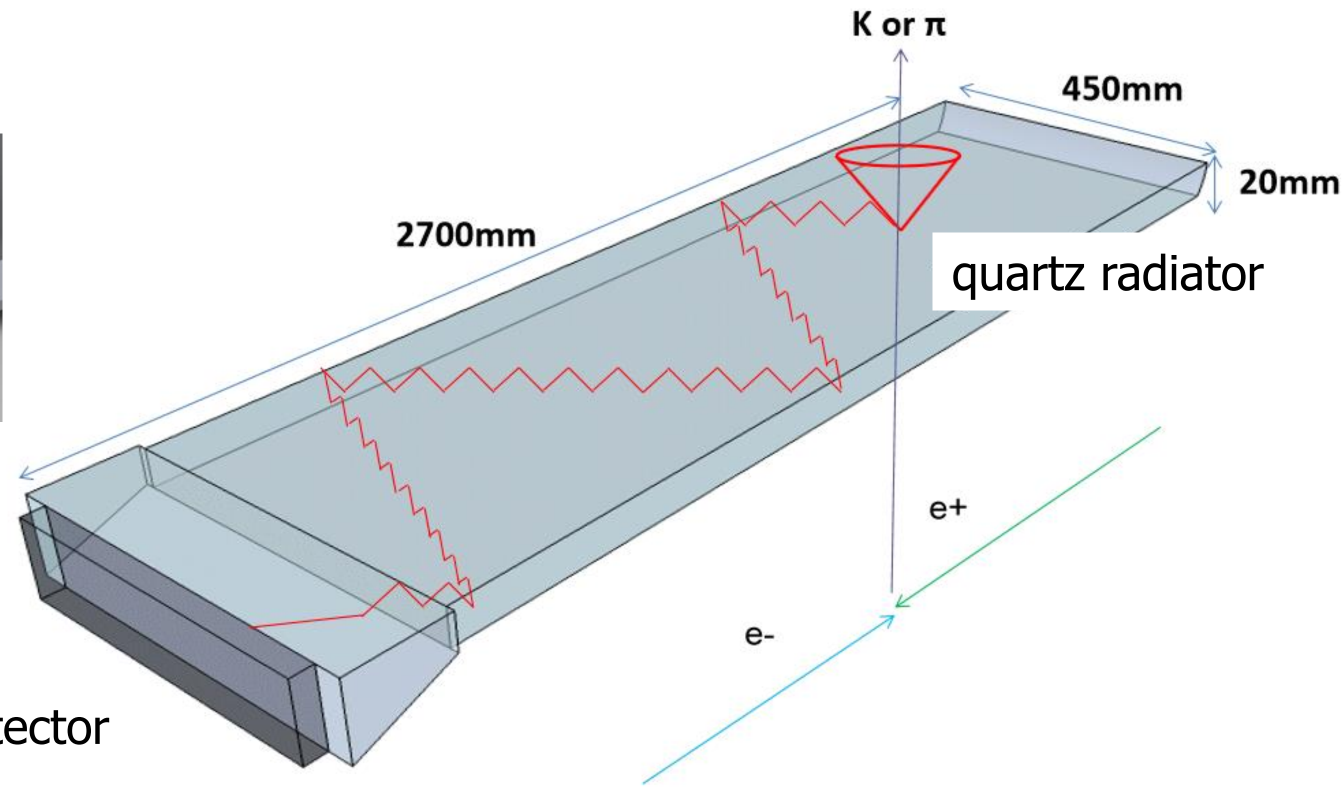


Peter Križan, Ljubljana

Barrel PID: Time of propagation (TOP) counter

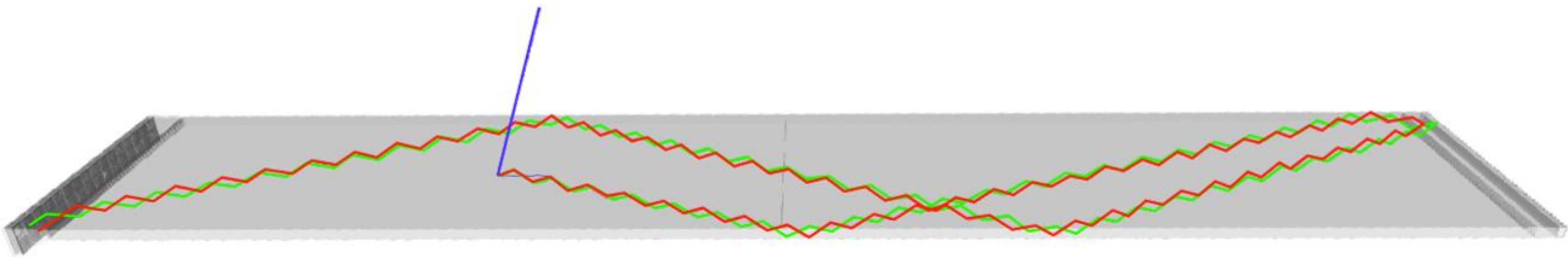


Photon detector

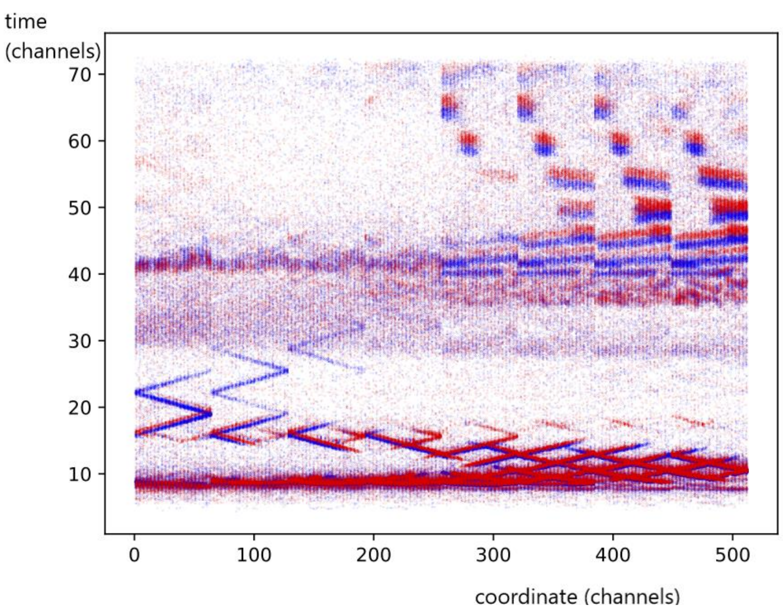


- Cherenkov ring imaging with precise time measurement.
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm thick)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity in 1.5 T

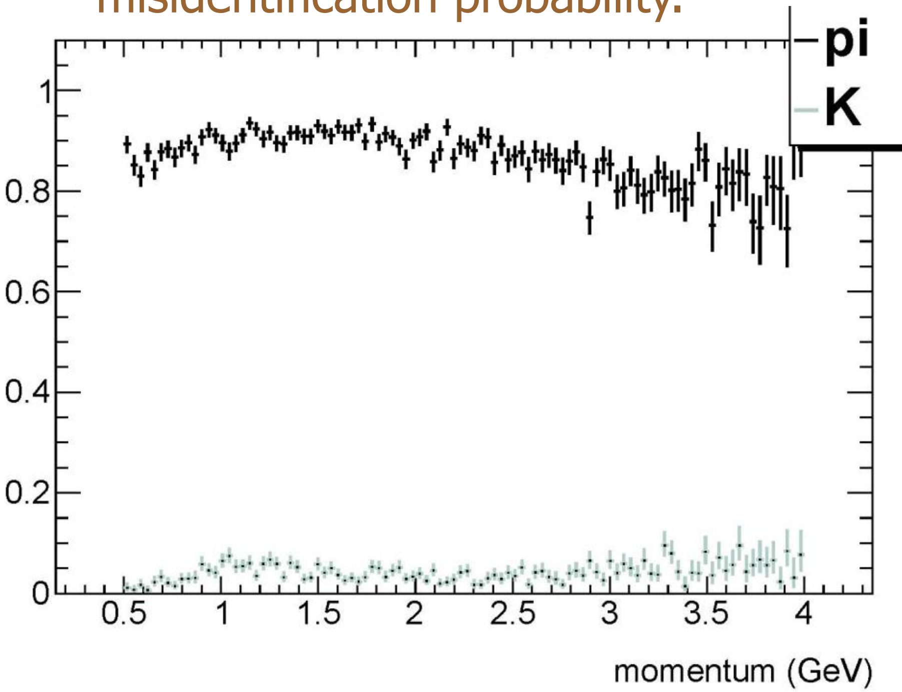
Separation of kaons and pions



Pions vs kaons in TOP:
different patterns in the time vs PMT impact point coordinate

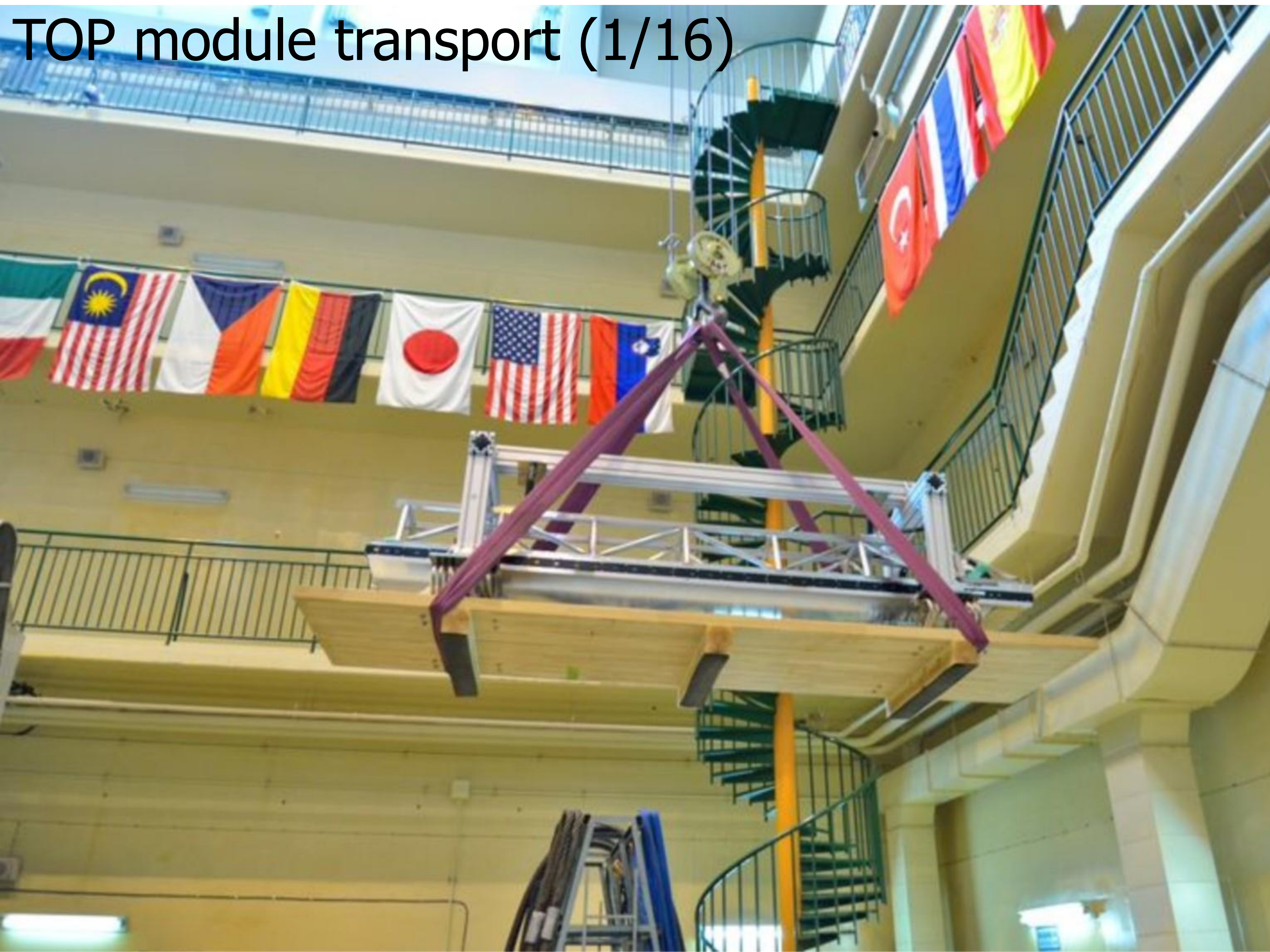


Pions vs kaons:
Expected PID efficiency and misidentification probability.



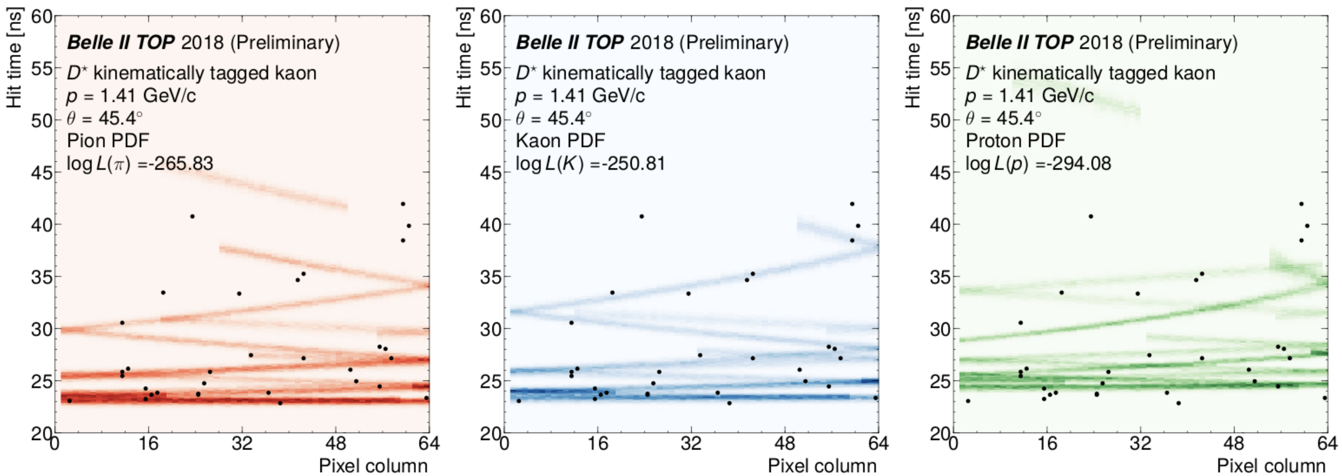
The name of the game: analytic expressions for the likelihood functions – M. Starič

TOP module transport (1/16)



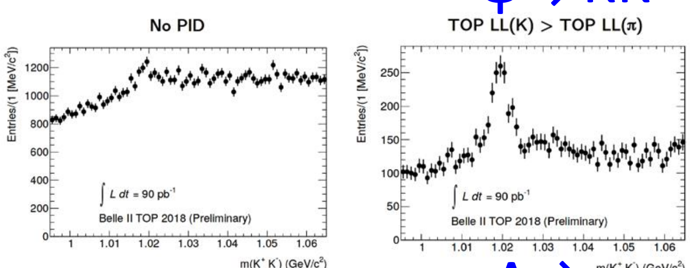
TOP in Phase 2

The phase 2 data demonstrates that the TOP principle is working



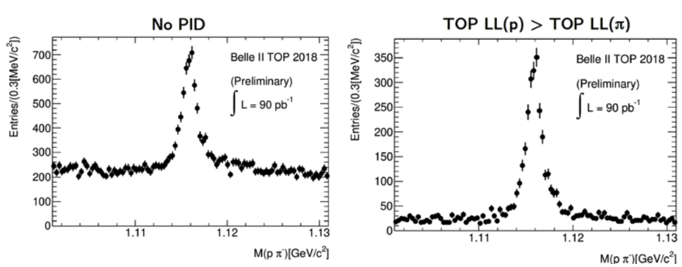
$\phi \to K^+K^-$ with both the tracks in the TOP acceptance

$\phi \to KK$

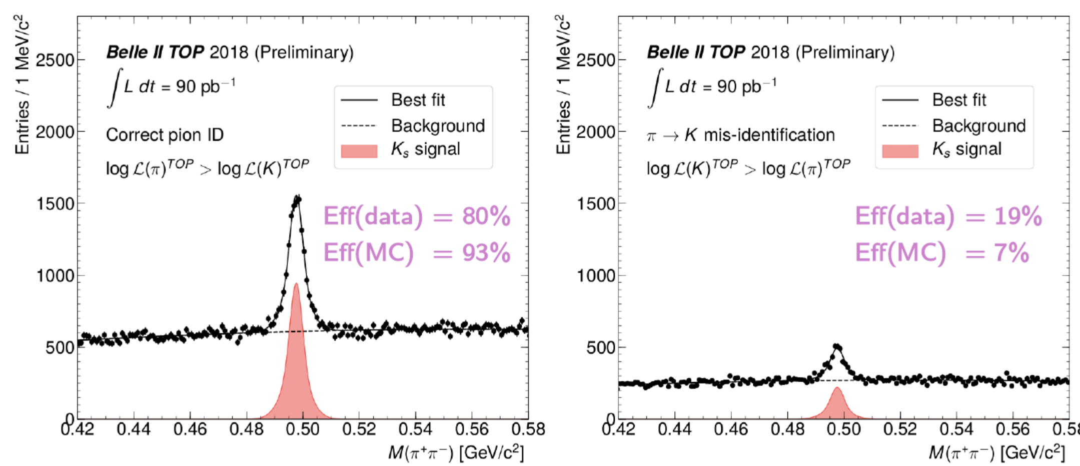


$\Lambda \to p\pi$ with the **proton candidate** in the TOP acceptance

$\Lambda \to p\pi$

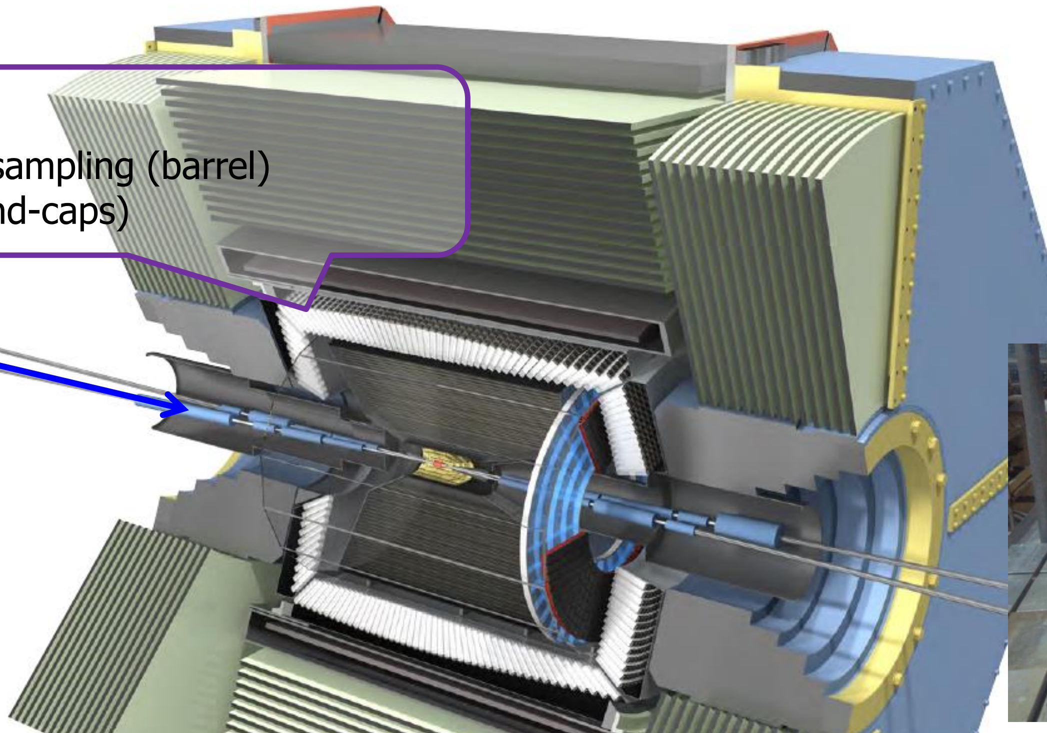


$K_s \to \pi\pi$

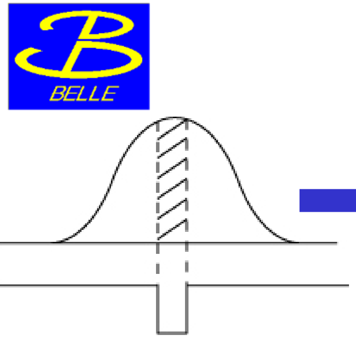


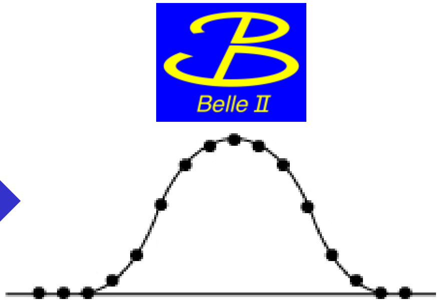
EM calorimeter: upgrade needed because of higher rates (electronics → waveform sampling) and radiation load (endcap, replace some fraction of crystals, CsI(Tl) → pure CsI, photosensor PD → photopentode or APD)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI (part of end-caps)



New read-out: waveform sampling





Further Slovenian contributions

Software:

- TOP and ARICH simulation and reconstruction
- Background overlay
- Database development and implementation
- Belle-to-Belle II format data transformation (Belle II software can now be used to analyze the Belle data)

Computing

- GRID, one of the coordinators for European sites

Slovenian contribution in managing the Belle II project

We have also played an important role in the planning and preparation of the Belle II project

- KEK Super B Factory Steering Committee chair 2008 (Peter Križan)
- Spokesperson 2009-2013 (Peter Križan)
- Physics coordinator 2009-2013 (Boštjan Golob)
- ARICH detector co-coordinator 2009→ (Samo Korpar)
- Technical coordinator 2015→ (Peter Križan)
- Leaders of working groups and task forces (Marko Starič, Marko Bračko and Anže Zupanc)

Belle II Status Summary

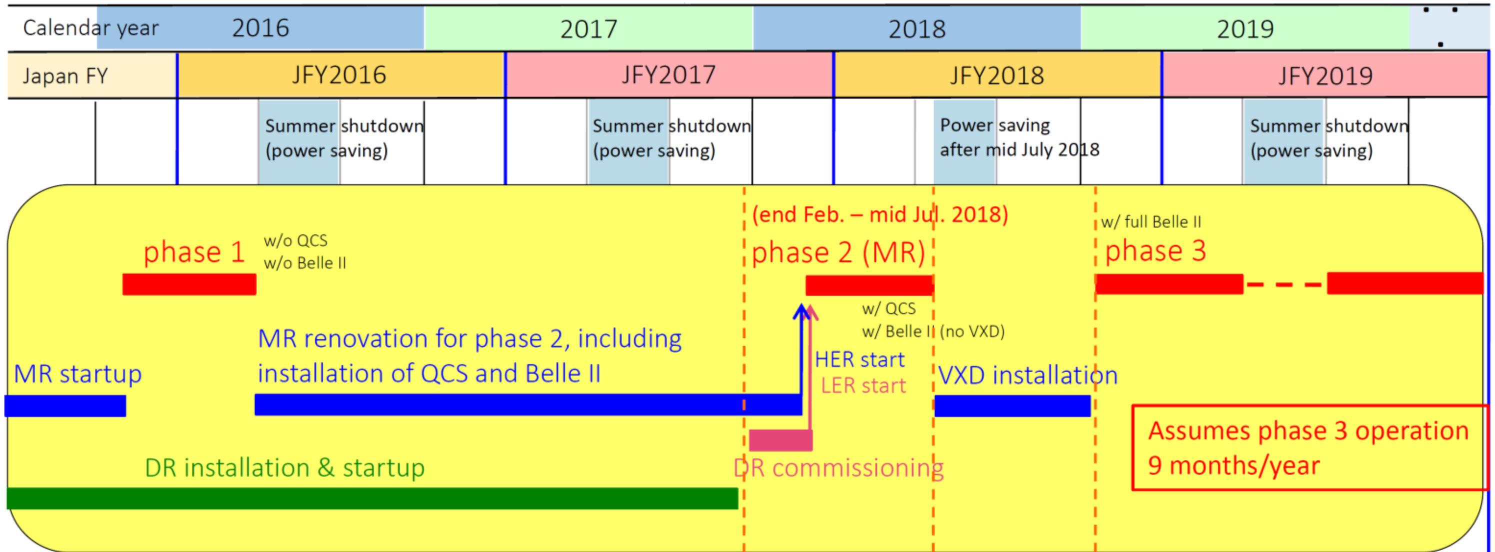
Spring 2018: First data taking with the almost complete Belle II detector (Phase 2) →

The Belle II detector is ready, the final missing piece, the full vertex detector → installed and commissioned.

All systems were debugged to improve on issues we have seen in Phase 2.

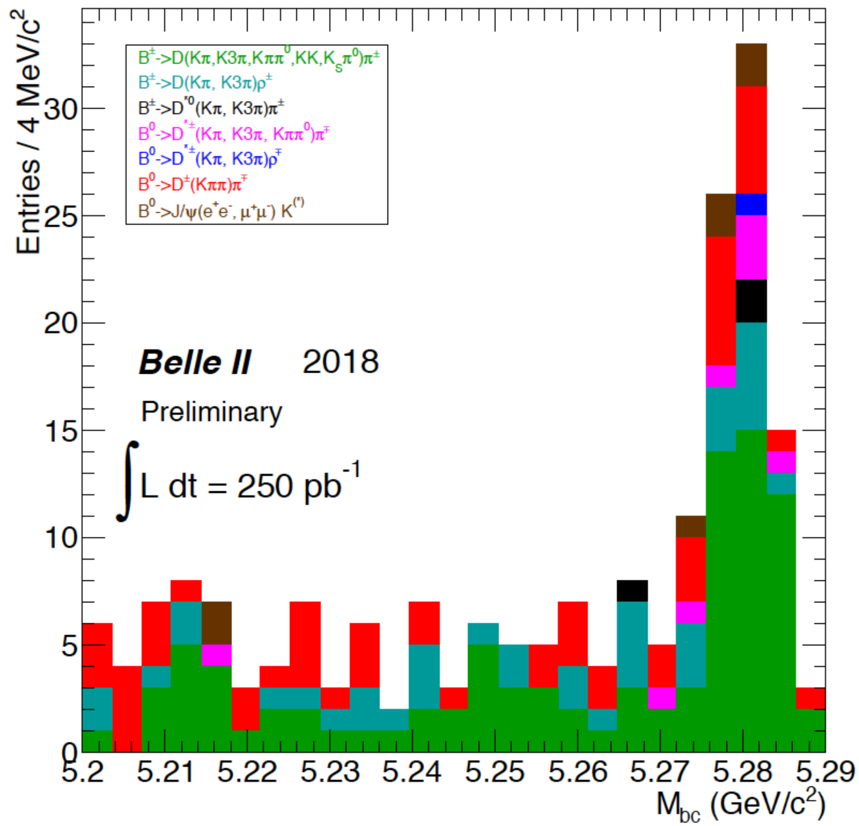
Beam operation in Phase 3 from March 11, first collisions on March 25, this week transition to low beta* (3mm).

The baseline plan: run for 9 months/year, with a target integrated luminosity of 50/ab.



In June 2018, we found our first peak in the beam-constrained mass distribution.

We have *rediscovered* the B meson ! :-)



Belle II: one of the essential methods for studies of rare deys is the reconstruction of one of the B mesons using the FEI (Full Event Interpretation) technique based on boosted decision trees (BDTs, a machine learning technique).

ε_{had} ~ 0.5%

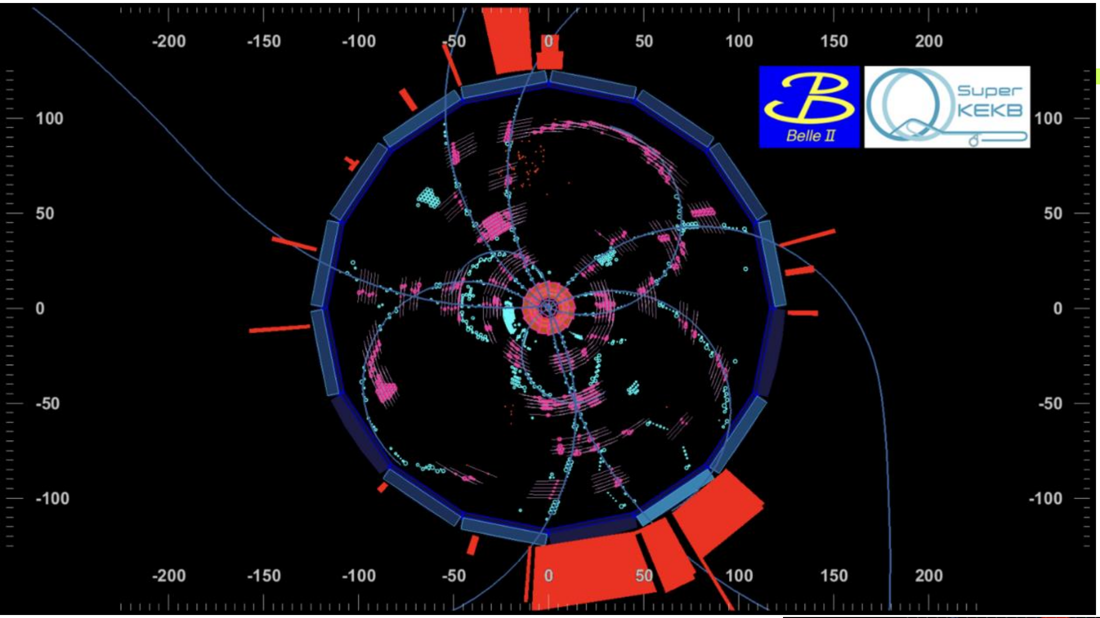
$\varepsilon_{semilept}$ ~1.3%

→ enables reconstruction of B decays with E_{miss} ($D(*)\tau\nu$, $\tau\nu$, $K\nu\nu$, ...)

The next step: getting ready for real running ("Phase 3")

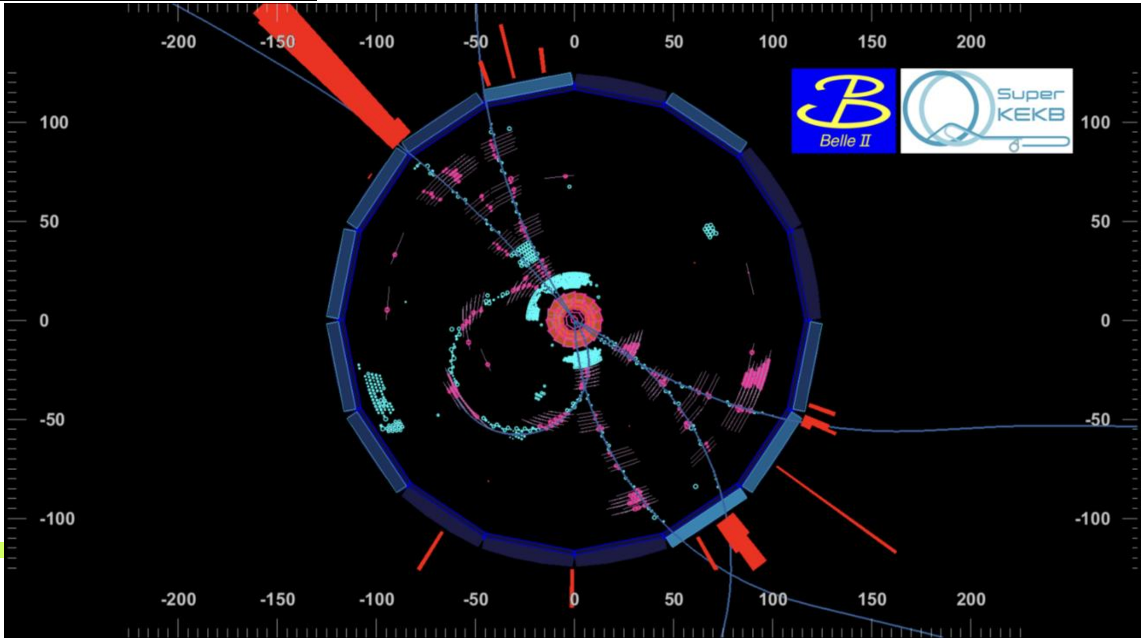
VXD: pixel detector (PXD) and silicon strip (SVD) assembled, waiting for installation

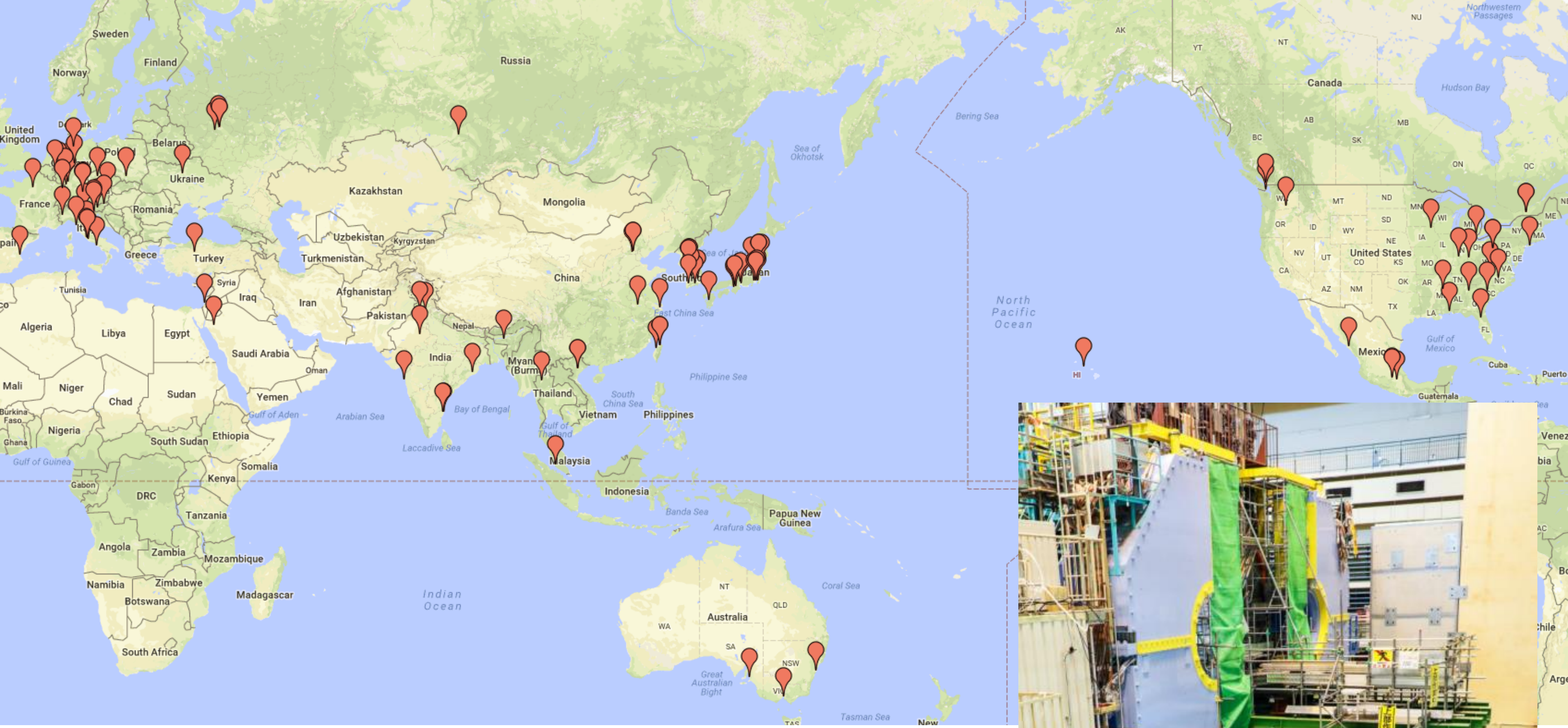
Belle II is back to business: Phase 3 (physics run)



First collisions in Phase 3 on March 25, 2019

First B-antiB event candidate (top)





Belle II: a strong group of ~933 highly motivated scientists!

- ~ 40% from European institutions!
- largest region in Belle II
- one of the largest European involvements in a non-European project
- Recognized experiment RE20 @ CERN

Detector upgrades: photo-sensors for the Cherenkov detectors

ARICH: The present photo-sensor (HAPD) is a very sensitive device. While in principle it should survive until the end of the experiment, we should investigate backup photo-sensor options

TOP: Background levels from SuperKEKB are considerably higher than anticipated, the observed light load on the photo-sensors (large number of Čerenkov photons from background, low energy gammas converted to electrons in the quartz plate), MCP PMTs might not last until the end of the experiment.

In addition,...

Discussions have started on a possible Belle II upgrade (luminosity x5)
- need photosensors for ARICH and TOP to operate at even higher rates

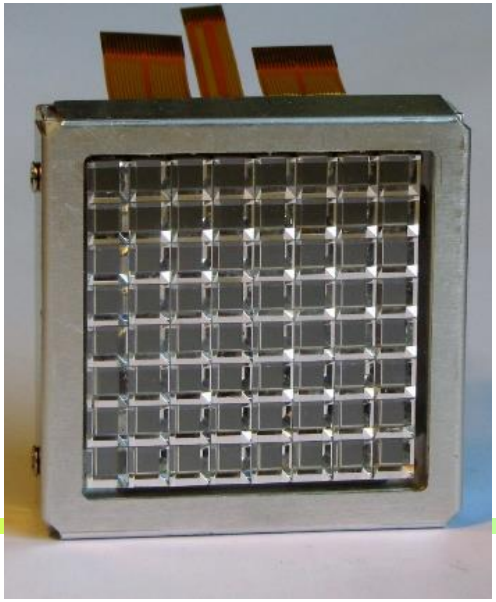
→ Photo-sensor R+D

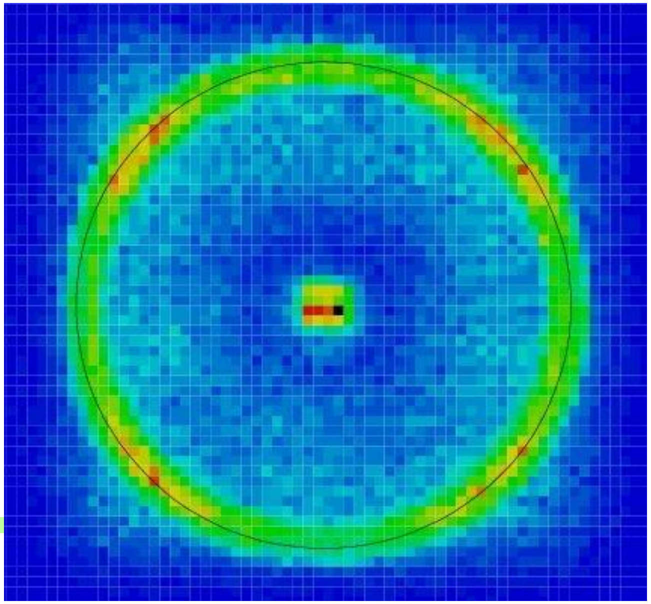
Detector upgrades: photo-sensors for the Cherenkov detectors

SiPMs, silicon photomultipliers (Geiger mode APDs) studied for both cases

JSI has pioneered the use of SiPMs in a RICH detector, first rings in 2007
A module of 64 SiPMs + pyramidal light guides

→ S. Korpar, Detector R+D talk



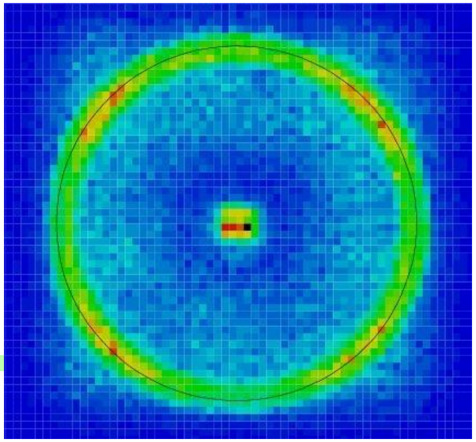


Photosensor R+D for the LHCb RICH upgrade

LHCb upgrade II (presently under discussion to fully exploit the HL LHC potential, upgraded detectors to be installed during LS4)

- RICH upgrade, development of a single photon detector with very fine granularity
- Sensor under study: SiPM, same as for Belle II upgrades
- Considering group's expertise & labs @ JSI: decided to participate in the photosensor R+D, synergy of activities
- JSI is a Technical associate member since 2018

(with R. Pestotnik as the JSI team leader)



This has the additional benefit of being a very interesting option for the very long term future flavour physics programme in Slovenia.

Where did our PhD students go?

- U. Bitenc → postdoc in Freiburg → software/computing company
- I. Bizjak → postdoc at UCL London → investment banking
- S. Fratina → postdoc at U. Pennsylvania
- A. Zupanc → postdoc in Karlsruhe → staff at JSI+UL → software company
- M. Petrič → postdoc at CERN
- L. Šantelj → postdoc at KEK, Strasbourg → staff at JSI+UL
- P. Smerkol → computing in weather forecast
- A. Seljak → postdoc at U Hawaii → FBK Trento
- T. Nanut → postdoc at EPFL
- J. Biswal → postdoc at U. Tel Aviv
- E. Ribežl → nuclear safety administration
- M. Lubej → software company

Summary, Slovenian group in the Belle and Belle II experiments at KEK

Slovenian groups in both energy and intensity frontiers

A strong Slovenian contribution to a high profile experiment, in physics analyses, detector hardware, software and computing

Considerable impact in both experiments in spite of a modest group size and resources

Attracted very good students – with interesting careers