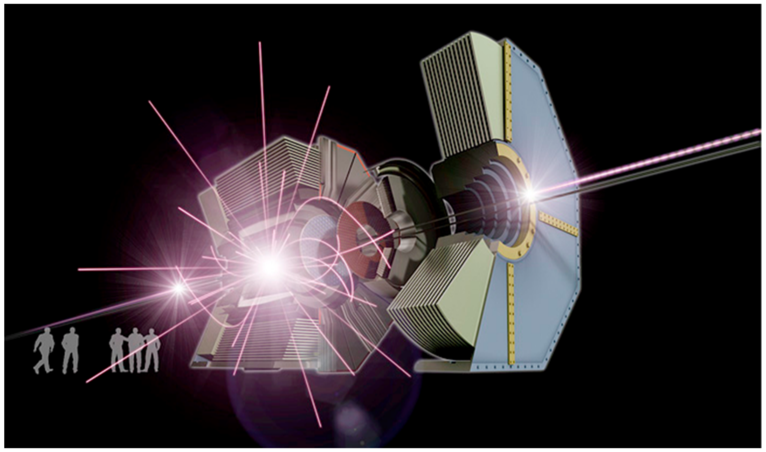
Kolokvij, FMF, April 20, 2020



FAIME – hunt for anomalies in particle physics

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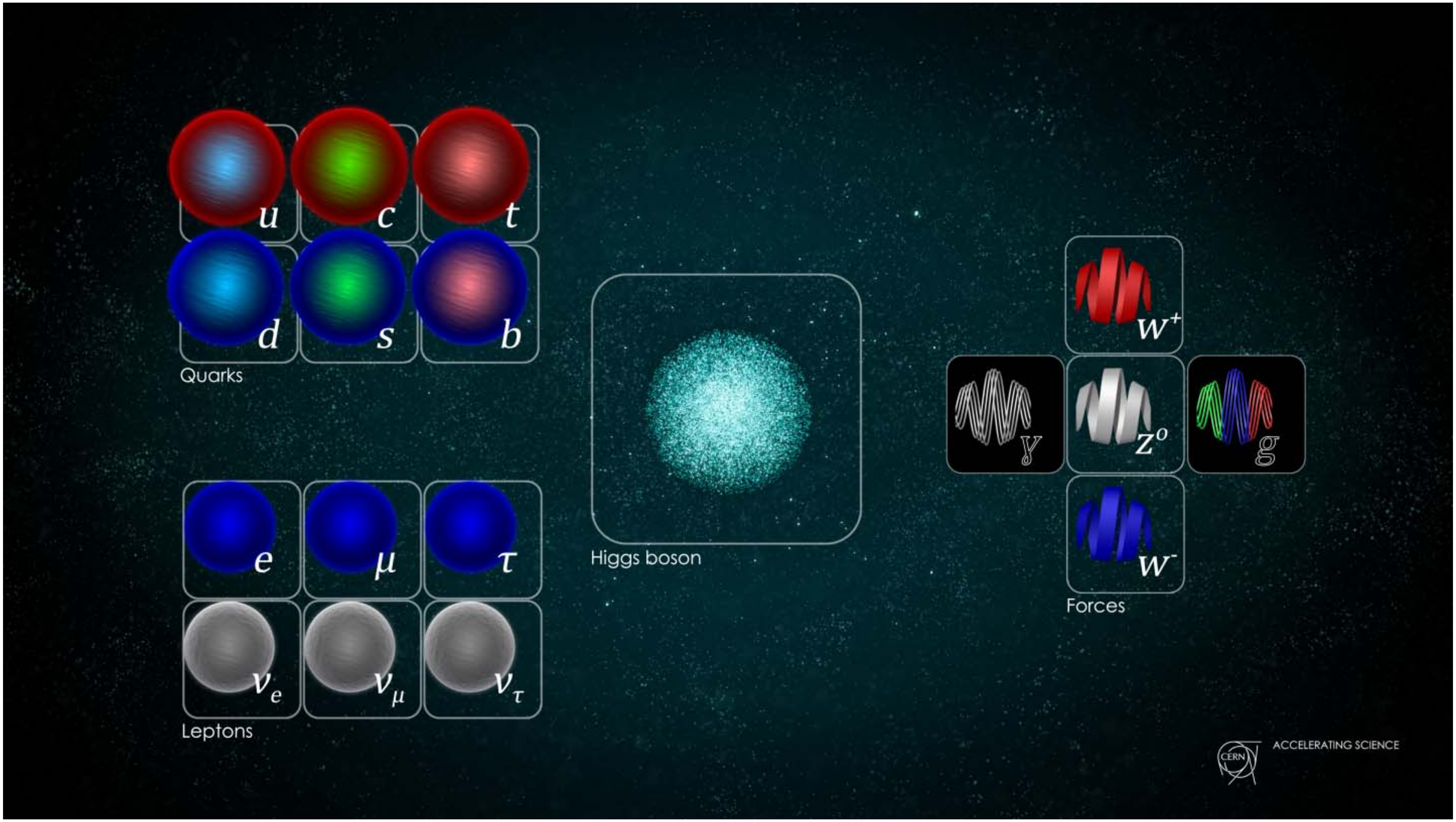
- Introduction: flavour anomalies
- FAIME, aims
- SuperKEKB and Belle II
- Advanced particle identification
- Outlook

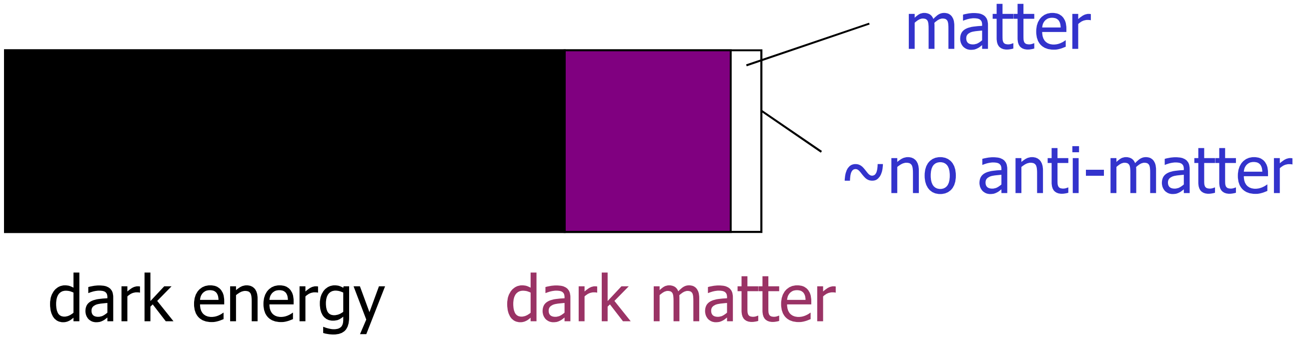
Standard Model



An incredibly successful theory to describe elementary particles and their interactions

However…

- However, the CP violation mechanism of the Standard model is by far too small to account for the asymmetry between matter and anti-matter in the Universe (falls short by 10 orders of magnitude !)
- SM does not contain the fourth fundamental interaction, gravitation
- Most of the Universe is made of stuff we do not understand...



Two complementary approaches to study shortcomings of the Standard Model and to search for the so far unobserved processes and particles (so called New Physics, NP). These are the **energy frontier** and the **intensity frontier** .

Energy frontier : direct search for production of unknown particles at the highest achievable energies.

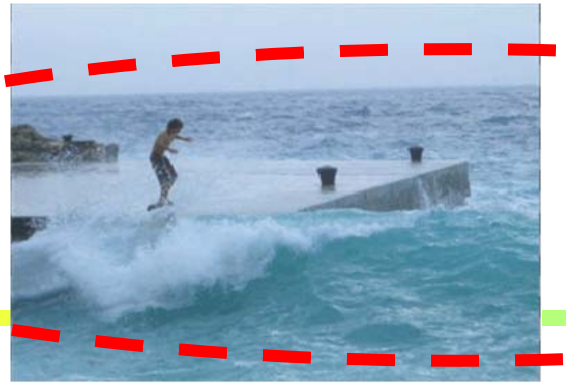
Intensity frontier : search for rare processes, deviations between theory predictions and experiments with the ultimate precision.

→for this second kind of studies, one has to investigate a very large number of reactions (˝events˝) → need accelerators with ultimate **intensity** (˝luminosity˝)

Comparison of **energy** /**intensity** frontiers

To observe a large ship far away one can either use **strong binoculars** or observe **carefully the direction and the speed of waves** produced by the vessel.

Energy frontier (LHC)



Luminosity frontier - (super) B factories

Standard Model: particles

Elementary particles	1st family	2nd family	3rd family
quarks	u,d	s,c	b,t
leptons	e^-,ν_e	μ^-,ν_μ	τ^-,ν_τ

One of the cornerstones of the Standard model (verified by experiments): Lepton Flavour Universality (LFU) - interactions of leptons do not depend on their flavour

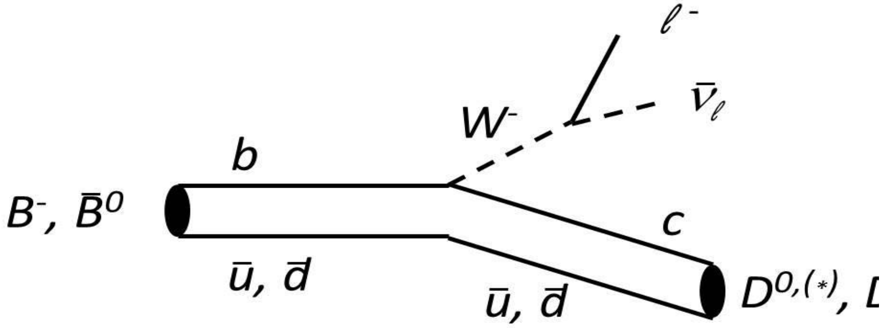
= e^-, μ^-, τ^- should behave in the same way

Flavour anomalies

Recent results from B physics experiment: hints that Lepton Flavour Universality is violated

Anomalies in $B \to D(*)\tau\nu$

Diagrams for the transition, mediated
by the charged SM weak interaction



LFU → the rate for the transition (corrected for available phase space) should not depend on the lepton flavour

→ Same for electrons, muons and tau leptons

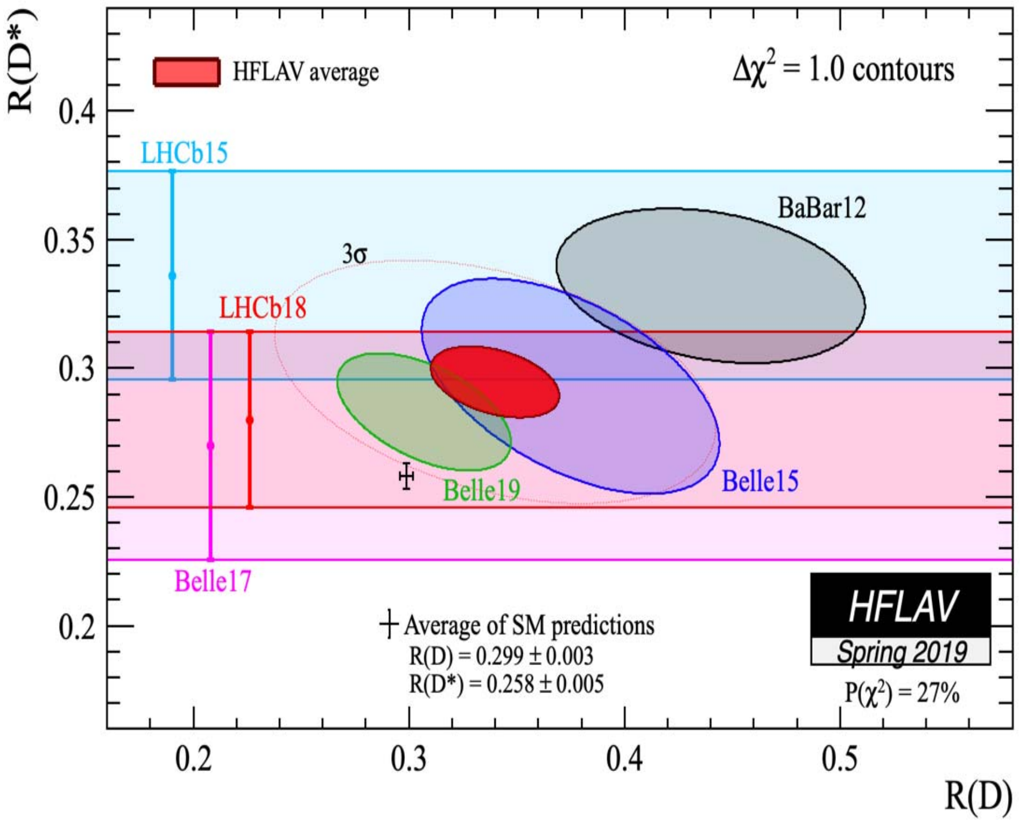
Check the ratio $R(D(*)) = Br(B \to D(*)\tau\nu)/Br(B \to D(*)l\nu)$

SM: $R(D^*) = 0.258 \pm 0.005$ and $R(D) = 0.299 \pm 0.003$

Experiment: $R(D^*)= 0.295 \pm 0.011 \pm 0.087$ and $R(D)=0.340 \pm 0.027 \pm 0.013$

(combined value of measurements of BaBar, Belle and LHCb collaborations)

Anomalies in $B \to D(*)\tau\nu$ decays

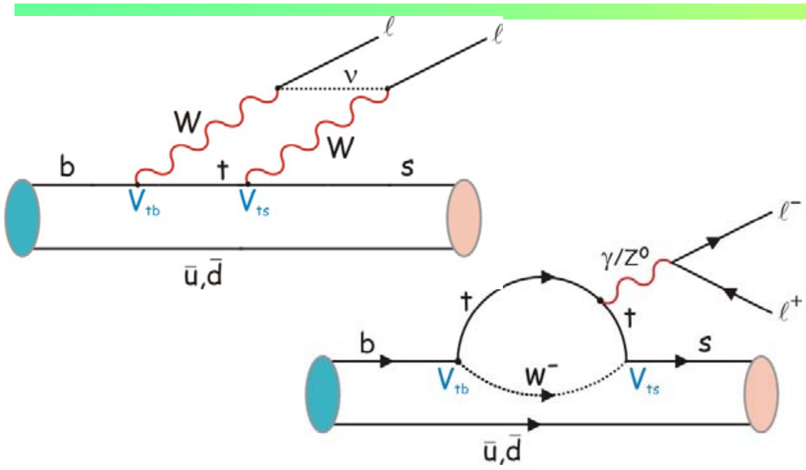


Measurements of R(D) and R(D*) compared to the SM predictions

SM: R(D*) = 0.258±0.005 and R(D) = 0.299±0.003

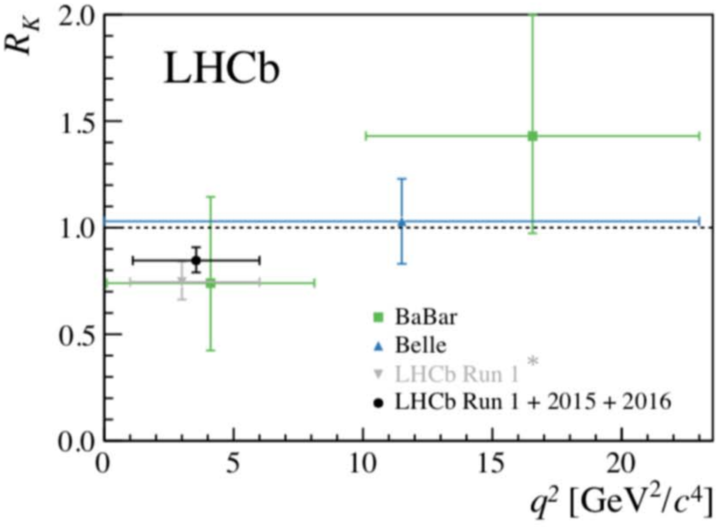
Experiment: R(D*)= 0.295±0.011±0.087 and R(D)=0.340±0.027±0.013

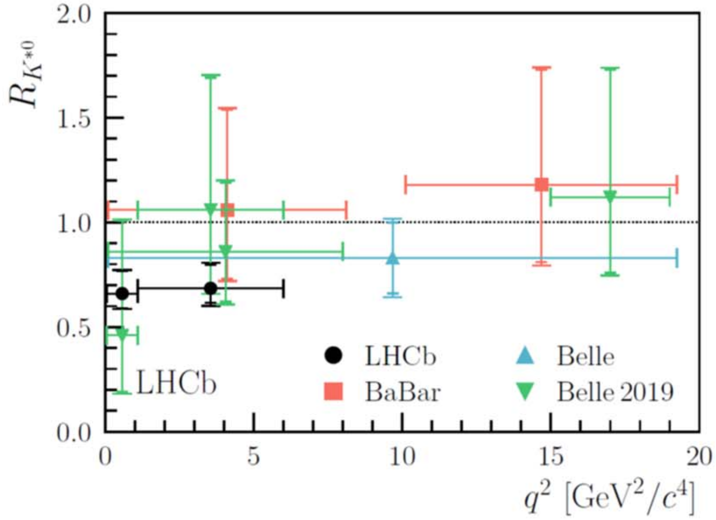
Anomalies in $B \rightarrow K(^*)e^+e^-$ and $B \rightarrow K(^*)\mu^+\mu^-$



SM: the ratio of the $B \rightarrow K(^*)e^+e^-$ *and* $B \rightarrow K(^*)\mu^+\mu^-$ should be equal to 1

Experiment (mainly dominated by LHCb) : below 1



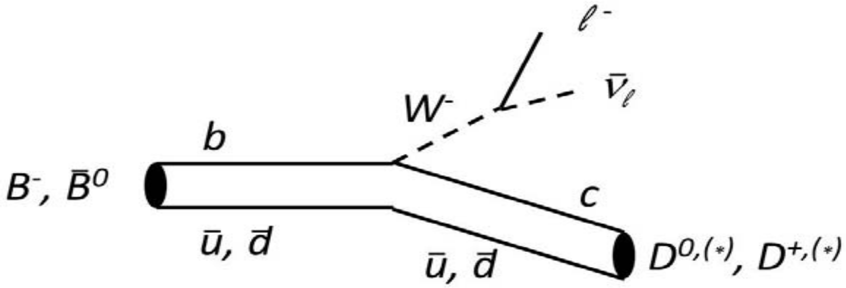


q^2 : $q^2 = (p(\ell) + p(\bar{\ell}))^2$ Lorentz invariant mass squared of lepton pair

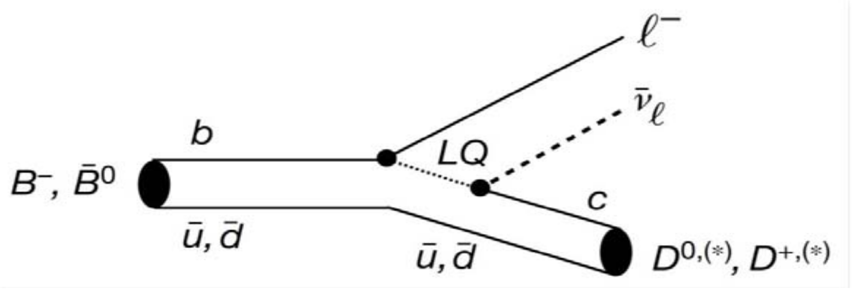
If true, what are possible interpretations?

Diagrams for the $B \rightarrow D(*)\tau\nu$ transition:

mediated by the charged SM weak interaction



a non-SM decay process involving leptoquarks



I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik & N. Kosnik, Phys. Rep. 641, 1–68 (2016).
I. Dorsner, S. Fajfer, D.A. Faroughy, N. Kosnik, arXiv:1706.07779.

Other possibilities: an additional charged Higgs meson, and others

The FAIME project

Investigate flavour anomalies on a large sample
of data collected by the Belle II spectrometer.

Of particular interest for this project are measurements of processes that satisfy the following conditions:

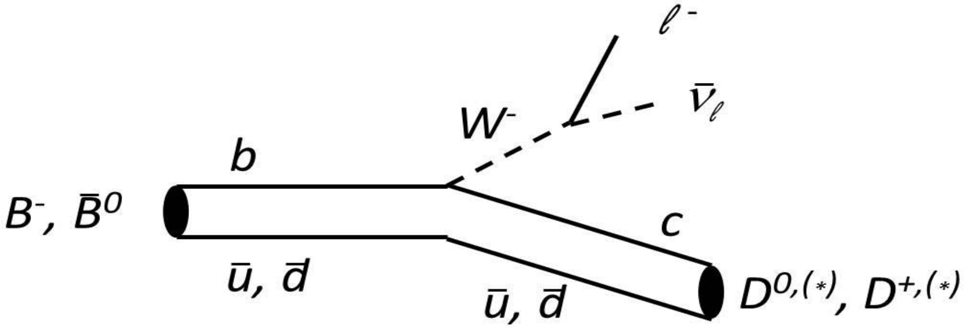
- Possibility of relatively large NP contribution to the process;
- Current experimental accuracy not enabling a clear answer on (dis)agreement with the SM prediction;
- Clear theoretical prediction;
- Complementarity in NP searches to other experimental efforts

In this project, we plan to examine several processes that satisfy these criteria to systematically study the properties of NP effects.

We = Marko Bračko, Boštjan Golob, Samo Korpar, Peter Križan, Rok Pestotnik, Marko Starič, Luka Šantelj + 2 postdocs + 4 PhD students

Research plan of FAIME (detailed)

1) Measurement of $R(D)$ and $R(D^*)$ with improved precision, determine the polarisation of the τ lepton in the $B \to D^*\tau\nu$ decay



2) Inclusive measurement of rates $B \to X_c\ \tau\ \nu$ and $B \to X_c\ \mu\ \nu$, where X_c represents any hadronic system containing the charm quark - smaller theoretical uncertainties than the exclusive modes such as $B \to D^{(*)}\tau\nu$.

(∗)

3) The ratio of branching fractions $B \to \rho\ (\pi)\ \tau\ \nu$ and $B \to \rho\ (\pi)\ \mu\ \nu$ – these decays proceed through a $b \to u$ transition (instead of $b \to c$).

4) Measurements of $D_s \to \tau\ \nu$ and $D_s \to \mu\ \nu$ rates; in these decays the initial quark is a c instead of a b quark (as in a B meson) - test of LFU with a different initial quark content.

Research plan of FAIME (detailed, part 2)

5) Ratio of rates of $B^{0(+)} \to K^{*0(+)} \mu^+ \mu^-$ and $B^{0(+)} \to K^{*0(+)} e^+ e^-$; test of universality between electrons and muons.

6) Measurements of the $B^{0(+)} \to K^{*0(+)} \tau^+ \tau^-$ decays – complementary to 5.

7) Measurement of the rate of $B \to K^{(*)} \nu \nu$ decays; this yet unobserved decay mode is not directly related to tests of LFU, but would importantly constrain possible ranges of parameters attempting to describe the LFU violation.

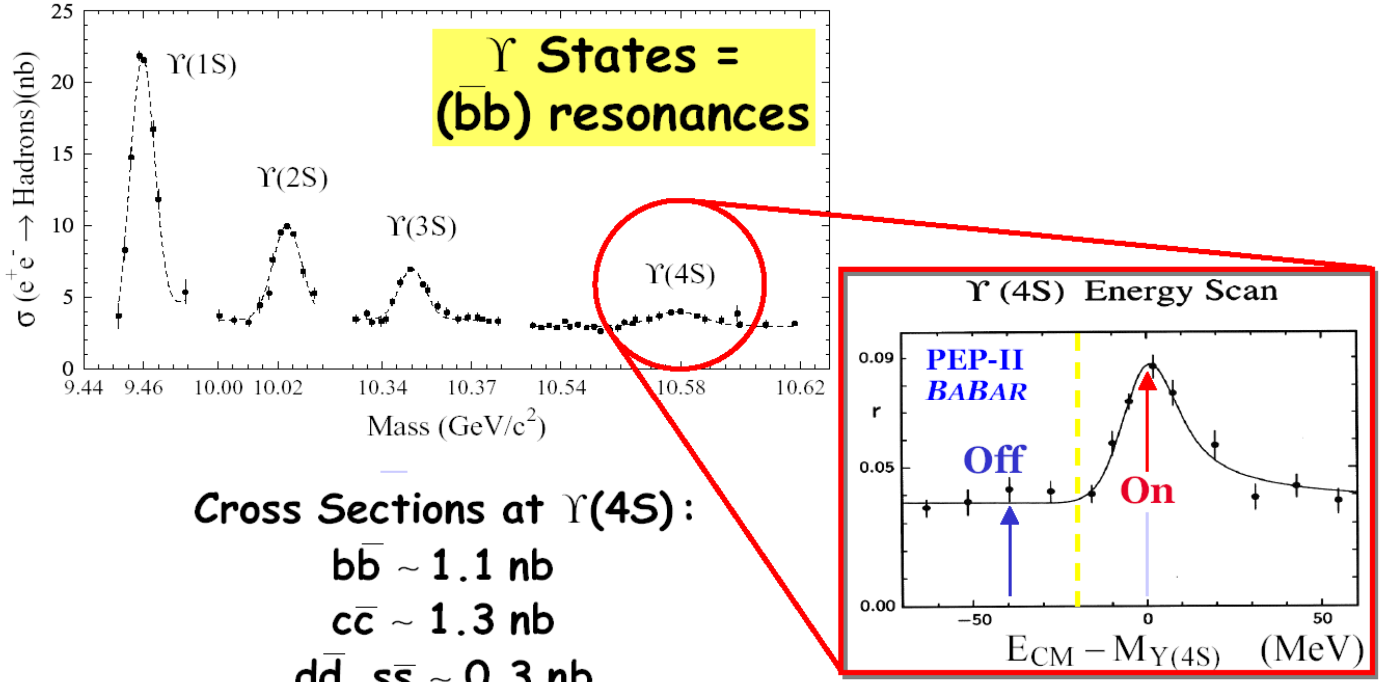
An integral part of the effort is also the developemnt of advanced particle identification methods that are compulsory for a successfull completion of the project – will be discussed later in my talk.

SuperKEKB and Belle II

Need a source of B mesons: collide electrons and positrons at the center-of-mass energy of the Υ(4S) resonance, exactly two particles produces, a B and an anti-B.

Precision measurements of rare decays of B mesons:

→ need a very very large sample.



Υ States = $(b\bar{b})$ resonances

Cross Sections at $\Upsilon(4S)$:

$b\bar{b} \sim 1.1$ nb

$c\bar{c} \sim 1.3$ nb

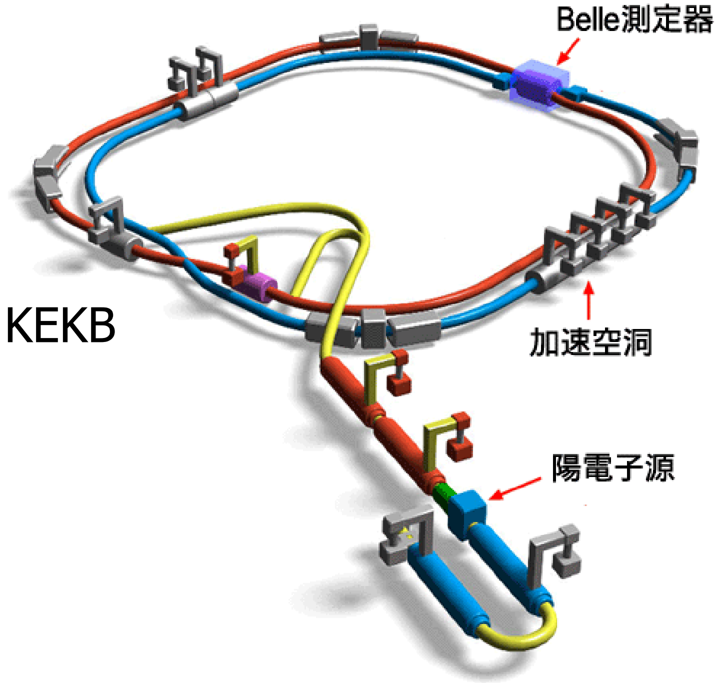
$d\bar{d}$, $s\bar{s} \sim 0.3$ nb

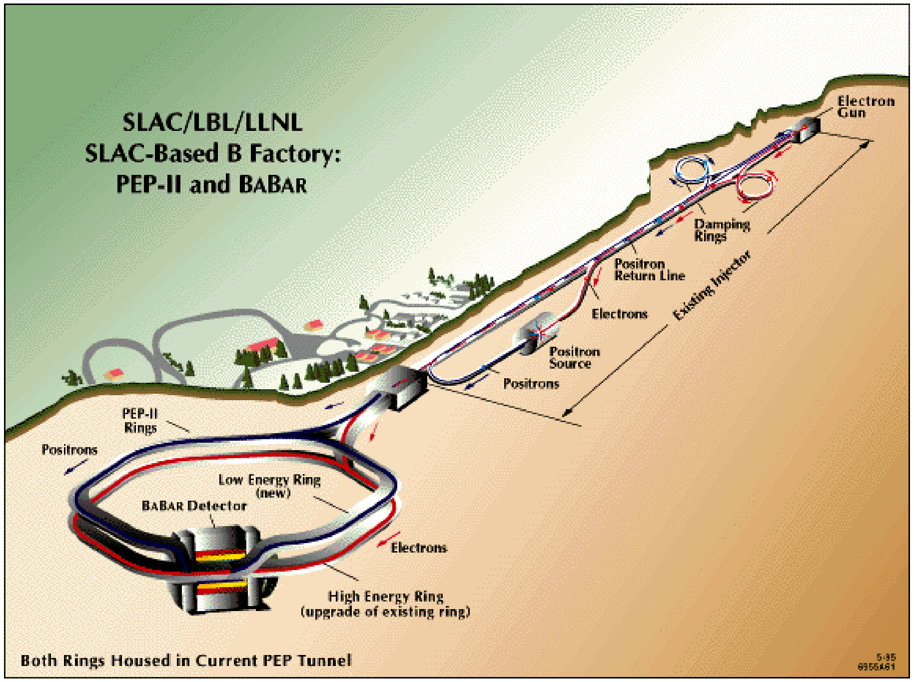
$u\bar{u} \sim 1.4$ nb

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

$L = 1$ state

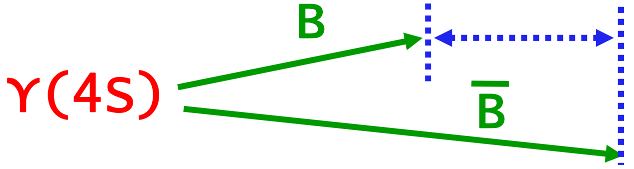
Flavour physics at the luminosity frontier with asymmetric B factories





$\sqrt{s}=10.58$ GeV

$e^+ \rightarrow \Upsilon(4S) \leftarrow e^-$

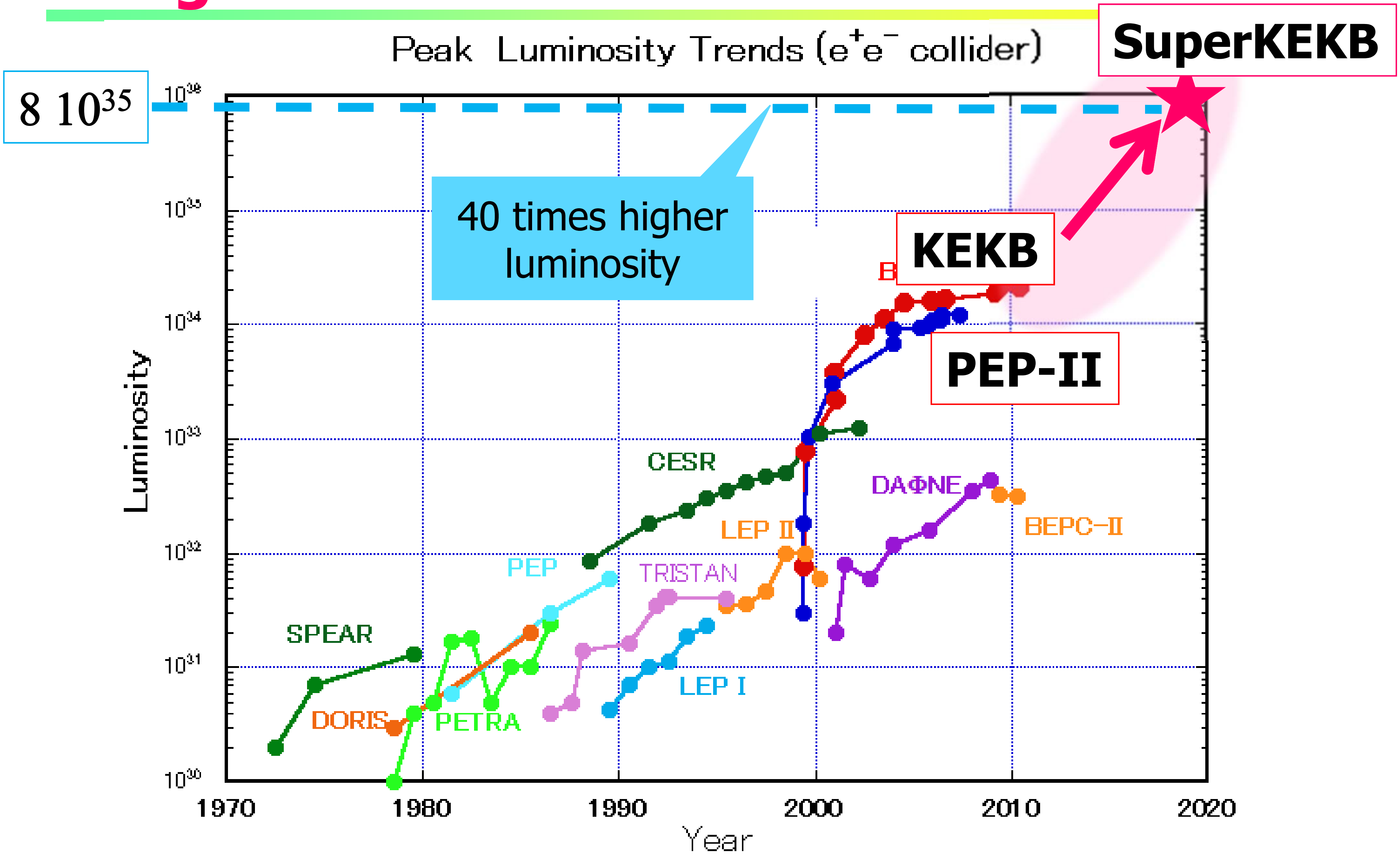


$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$

BaBar	$p(e^-)=9$ GeV	$p(e^+)=3.1$ GeV	$\beta\gamma=0.56$
Belle	$p(e^-)=8$ GeV	$p(e^+)=3.5$ GeV	$\beta\gamma=0.42$

To a large degree shaped flavour physics in the previous decade

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



$8\ 10^{35}$

40 times higher luminosity

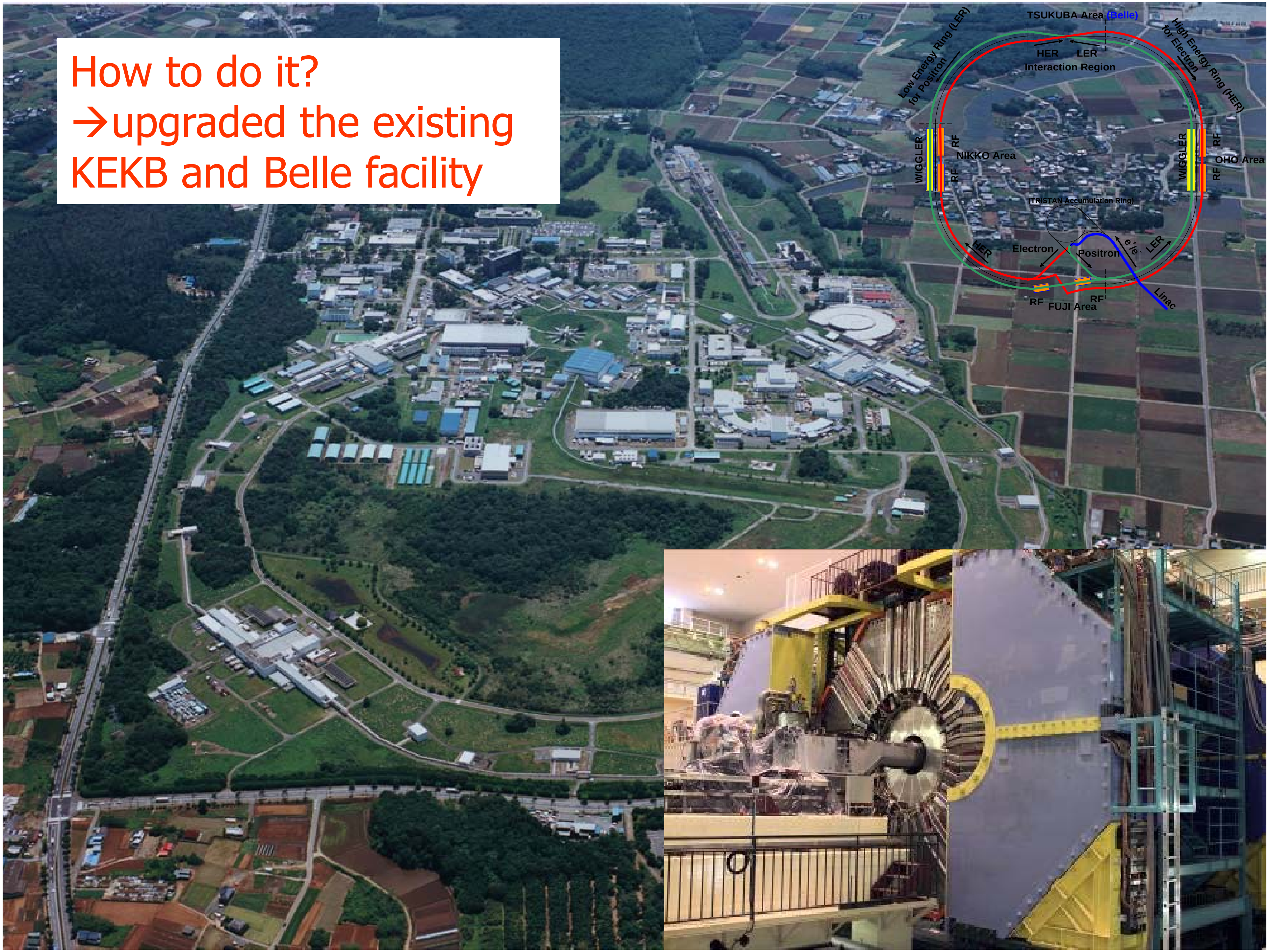
SuperKEKB

KEKB

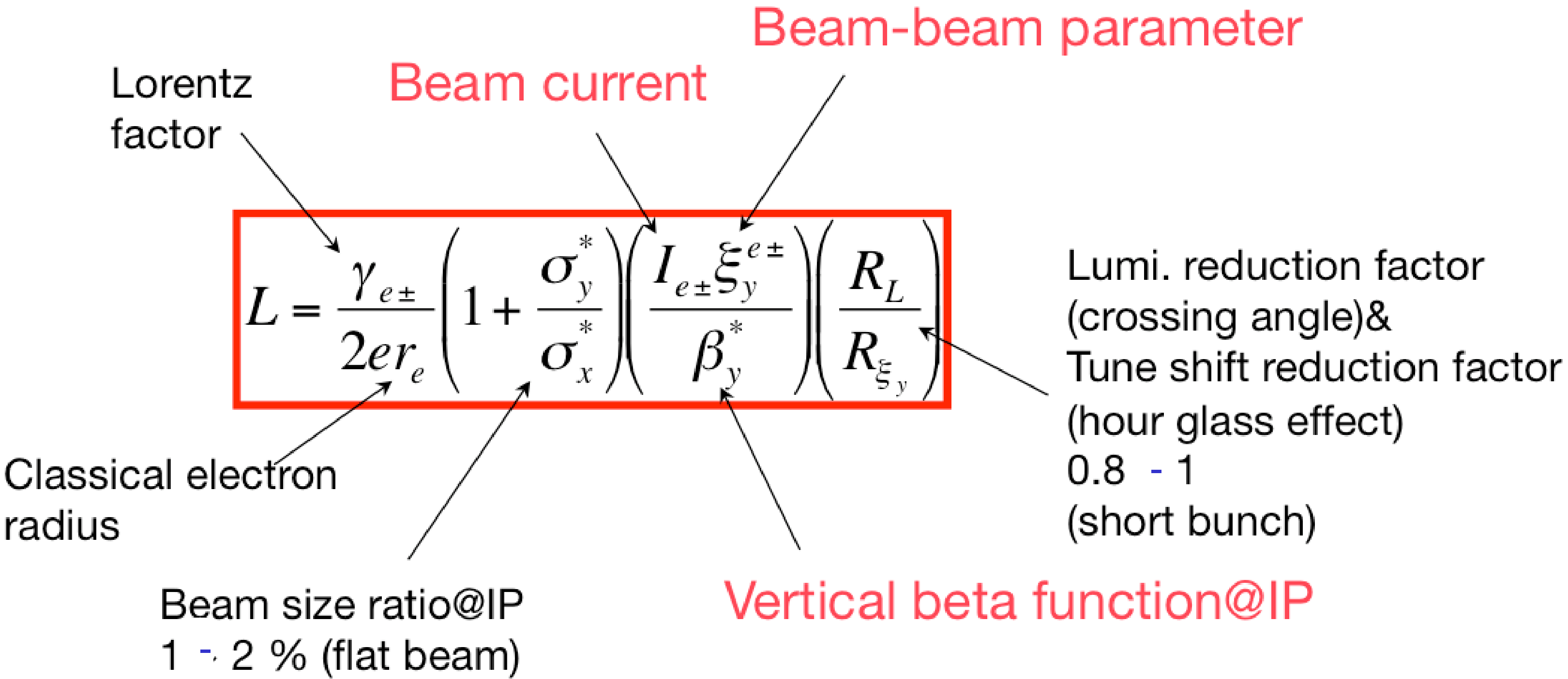
PEP-II

N.B. KEKB peak L: 2.11 10^{34} cm^{-2} s^{-1} , LHC peak L: 2.06 10^{34} cm^{-2} s^{-1}

How to do it?
→upgraded the existing KEKB and Belle facility



How to increase the luminosity?



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

Beam-beam parameter

Lorentz factor

Beam current

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 - 1
(short bunch)

Classical electron radius

Beam size ratio@IP
1 - 2 % (flat beam)

Vertical beta function@IP

(1) Smaller β_y^*

(2) Increase beam currents

(3) Increase ξ_y

← **“Nano-Beam” scheme**

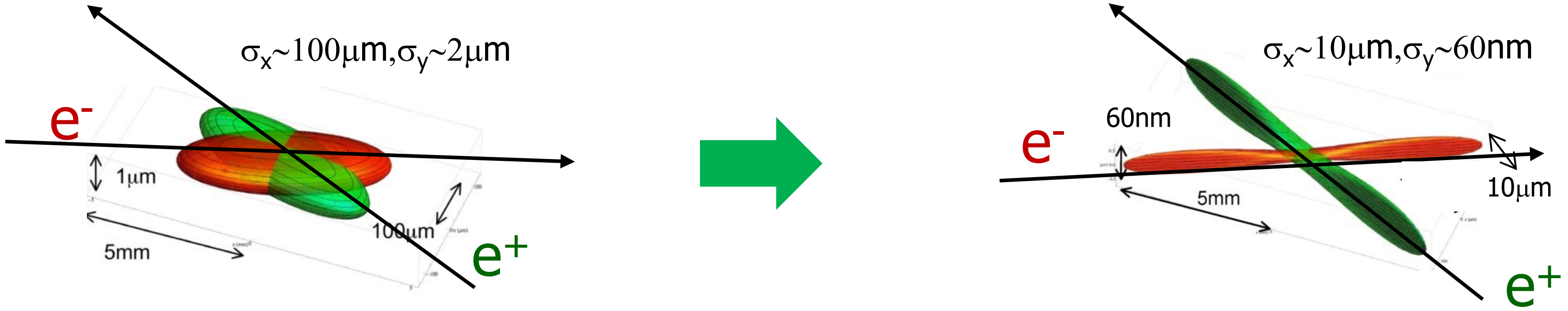
Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB

How big is a nano-beam ?

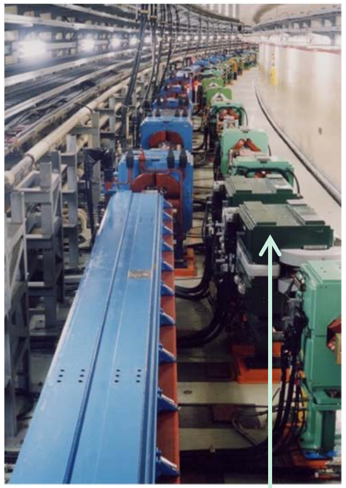
How to go from an excellent accelerator with world record performance – KEKB – to a 40x times better, more intense facility?

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

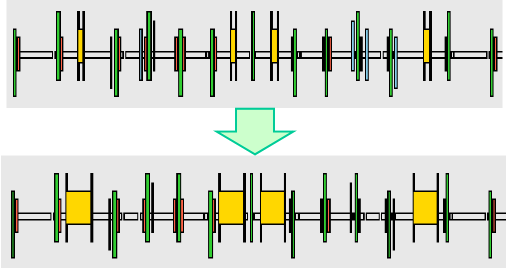


... For a 40x increase in intensity you have to make the beam as thin as a few x100 atomic layers!

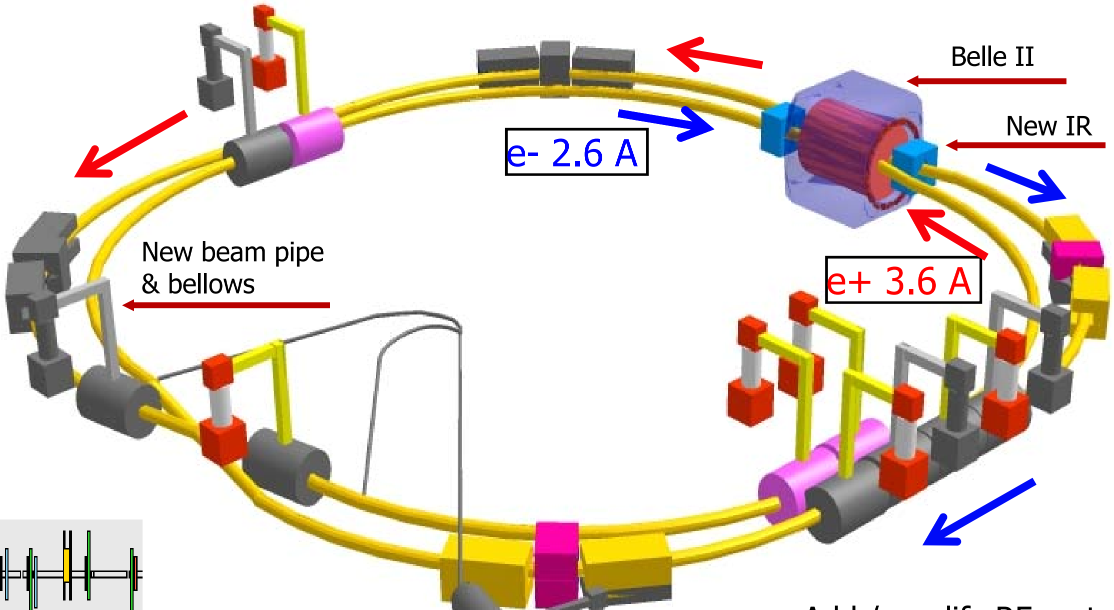
KEKB → SuperKEKB

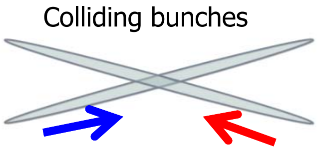


Replace short dipoles with longer ones (LER)

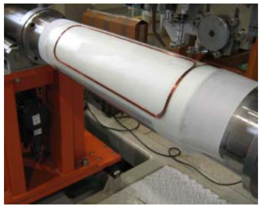


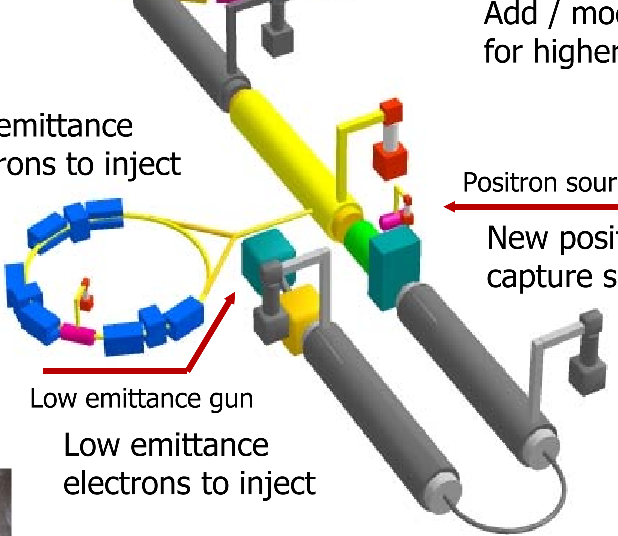
Redesign the lattices of HER & LER to squeeze the emittance





New superconducting /permanent final focusing quads near the IP



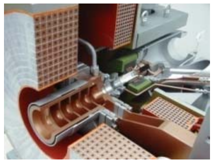


Low emittance positrons to inject

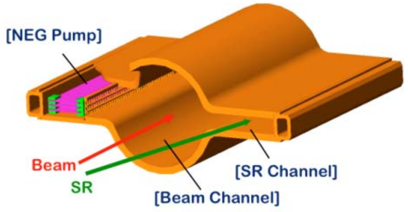
Low emittance electrons to inject

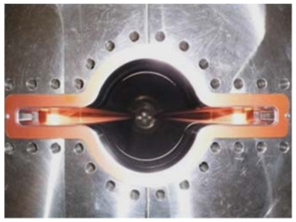
Add / modify RF systems for higher beam current

New positron target / capture section



TiN-coated beam pipe with antechambers



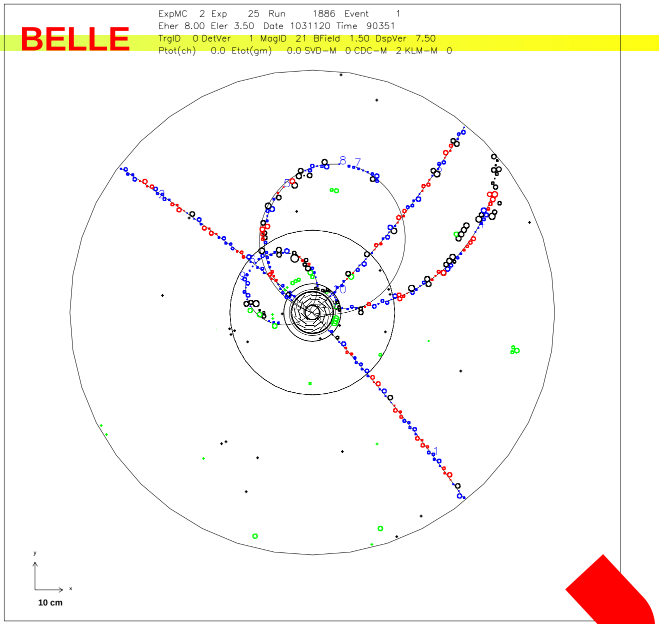


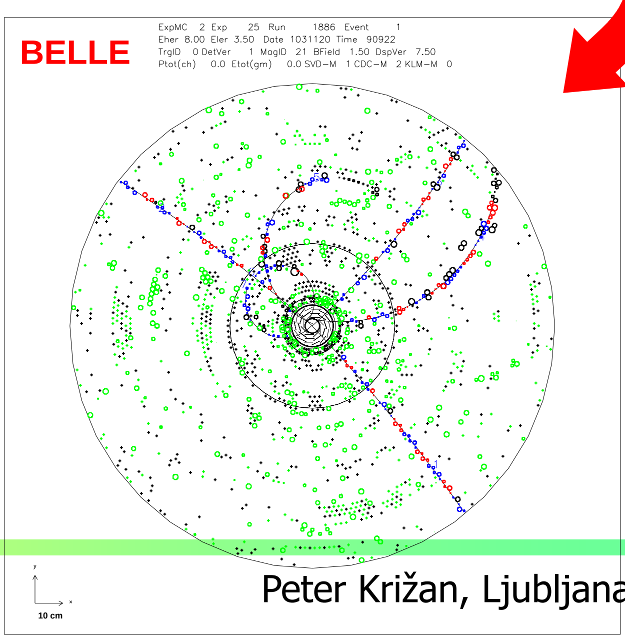
To get x40 higher luminosity

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 ← sμμ recon. eff.
  - hermeticity ← ν "reconstruction"



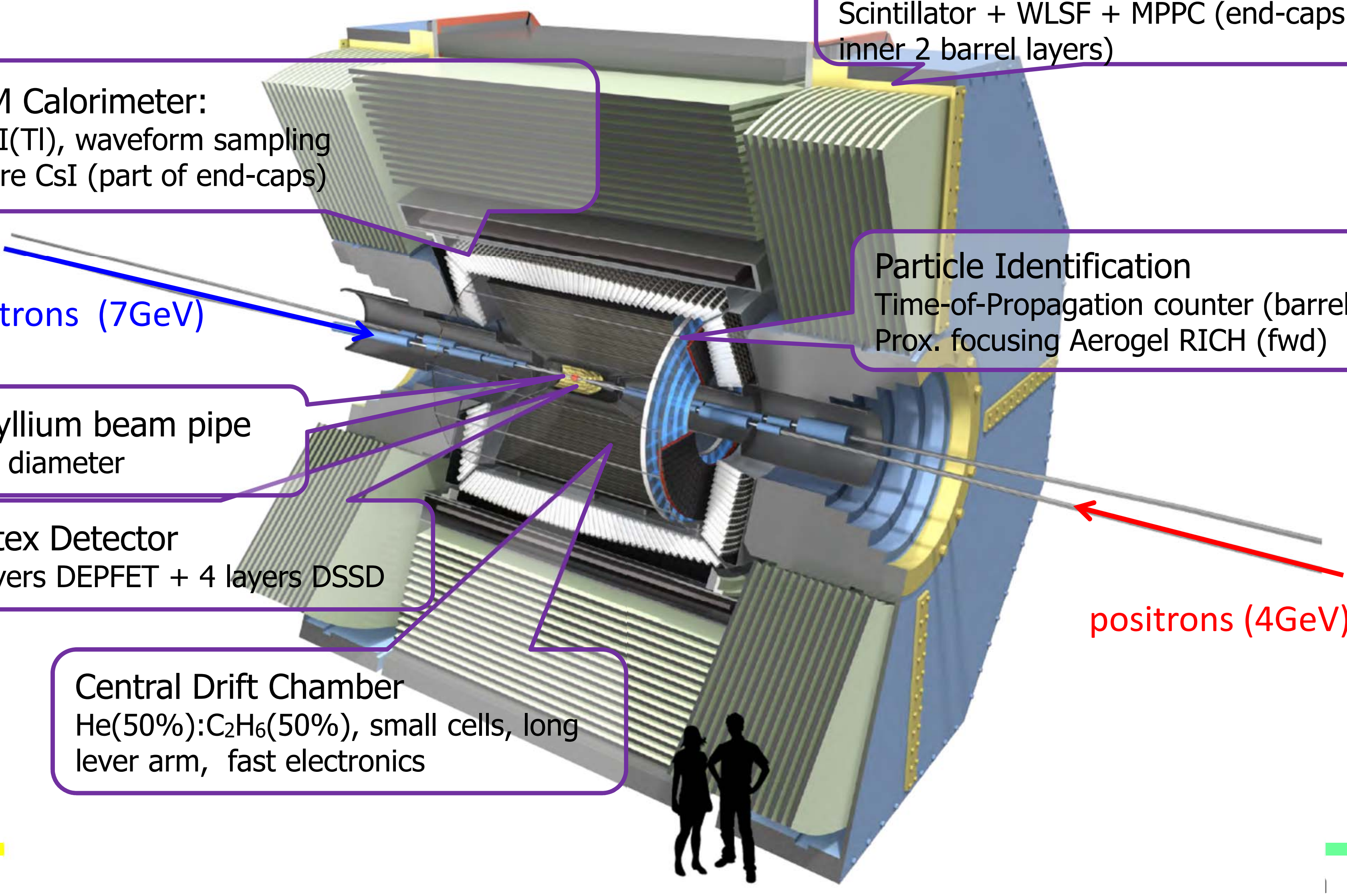


Solutions:

- 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



KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

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

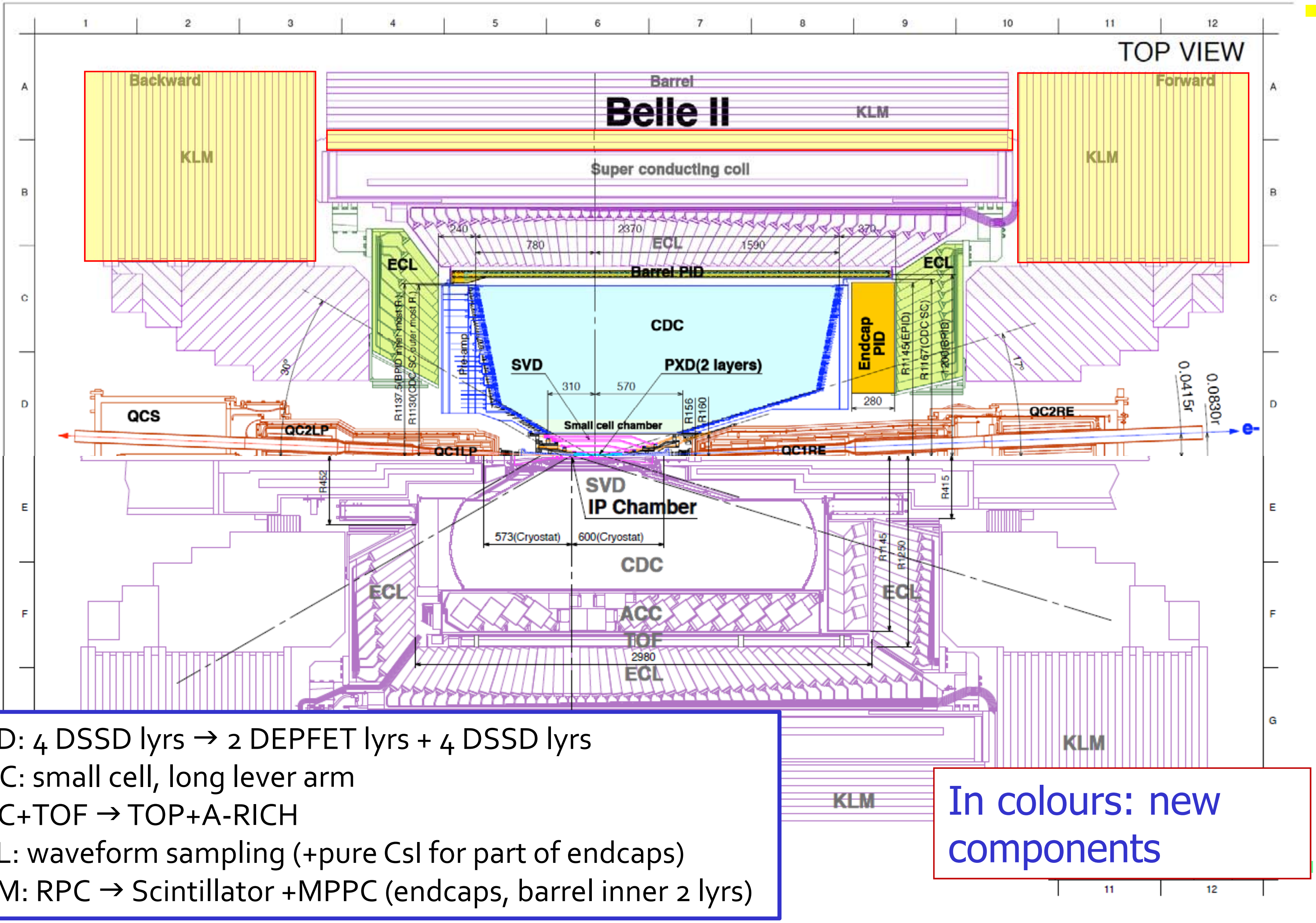
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

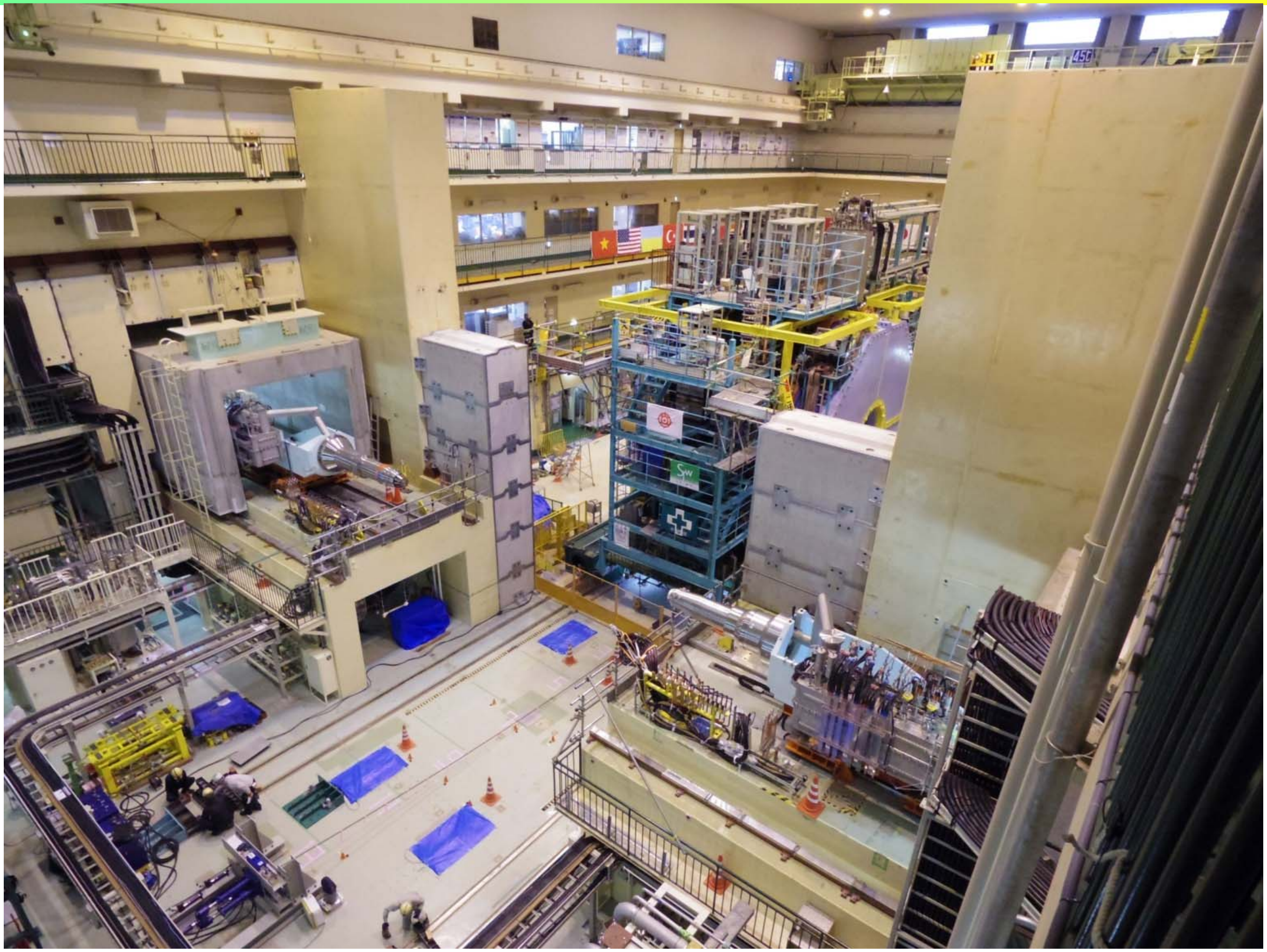
Belle II Detector (in comparison with Belle)



SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for part of endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours: new components

Belle II Roll-in



Belle II rolled-in to the beam line on April 11th, 2017

One of the most significant milestones in the construction phase

Getting ready…

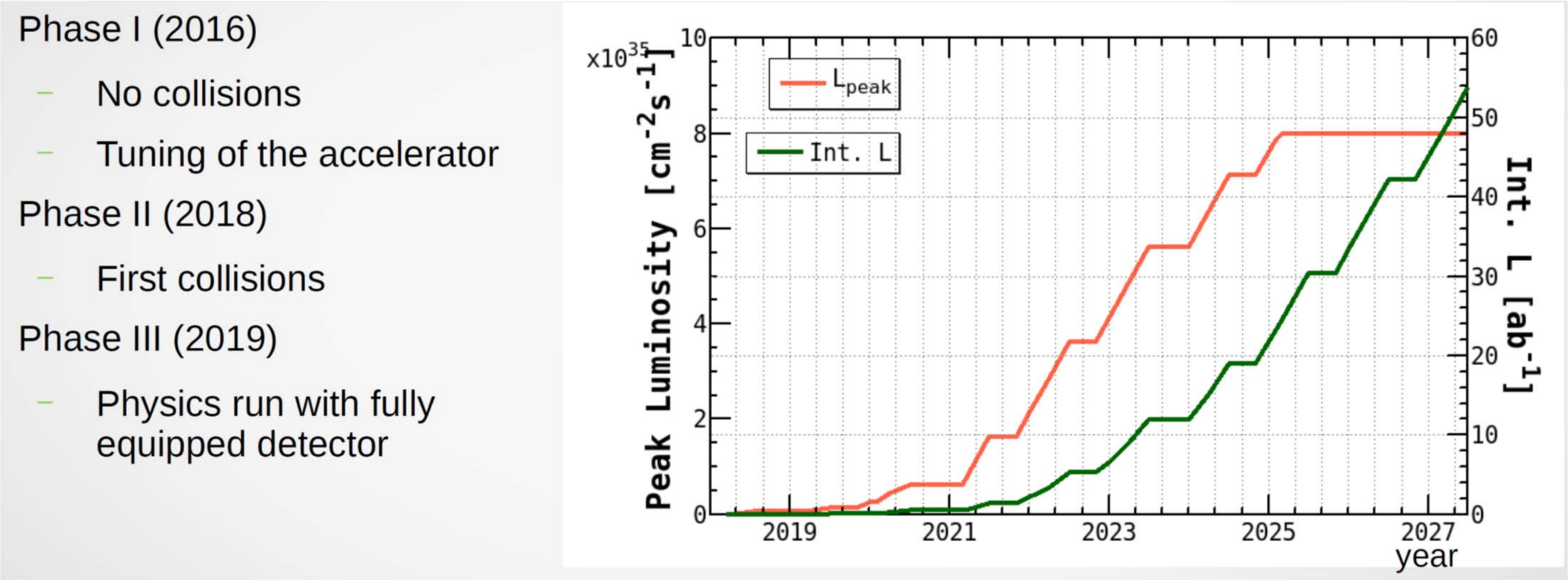
ARICH and forward endcap calorimeter transport and installation

Installation of final quads

Installation of the commissioning vertex detector

Peter Križan, Ljubljana

SuperKEKB phases and luminosity projection



Phase I (2016)

- No collisions
- Tuning of the accelerator

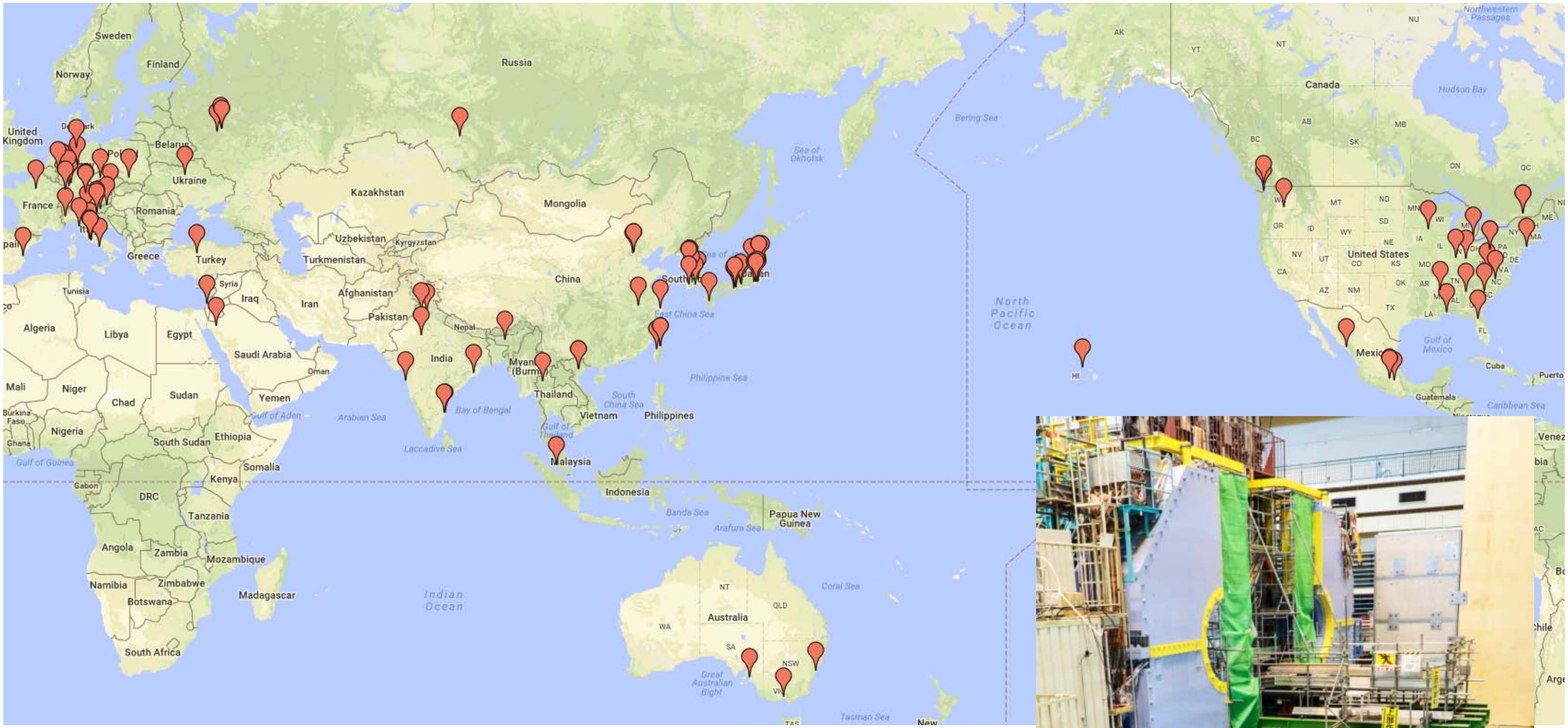
Phase II (2018)

- First collisions

Phase III (2019)

- Physics run with fully equipped detector

After 10 years of hard work in designing, testing prototypes, constructing, installing and commissioning – we are ready to go!



A very strong group of ~1000 highly motivated scientists!

Advanced particle identification

Critical for rare decays to separate our signal events from the much more copius background.

Identification: particles are identified by their mass

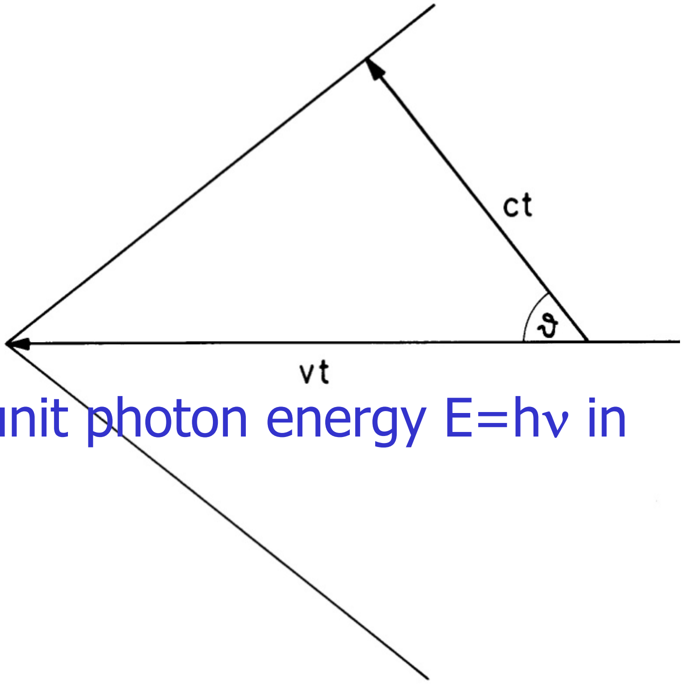
Measure velocity, combine with momentum measurement (curvature in 1T mag. field), determine mass from $p = \gamma m v$

A major fraction of particle identification in Belle II is based on the Cherenkov effect

Cherenkov radiation

A charged track with velocity v=βc exceeding the speed of light c/n in a medium with refractive index n emits polarized light at a characteristic (Cherenkov) angle (for **β > 1/n** - above threshold)

cosθ = c/nv = 1/βn

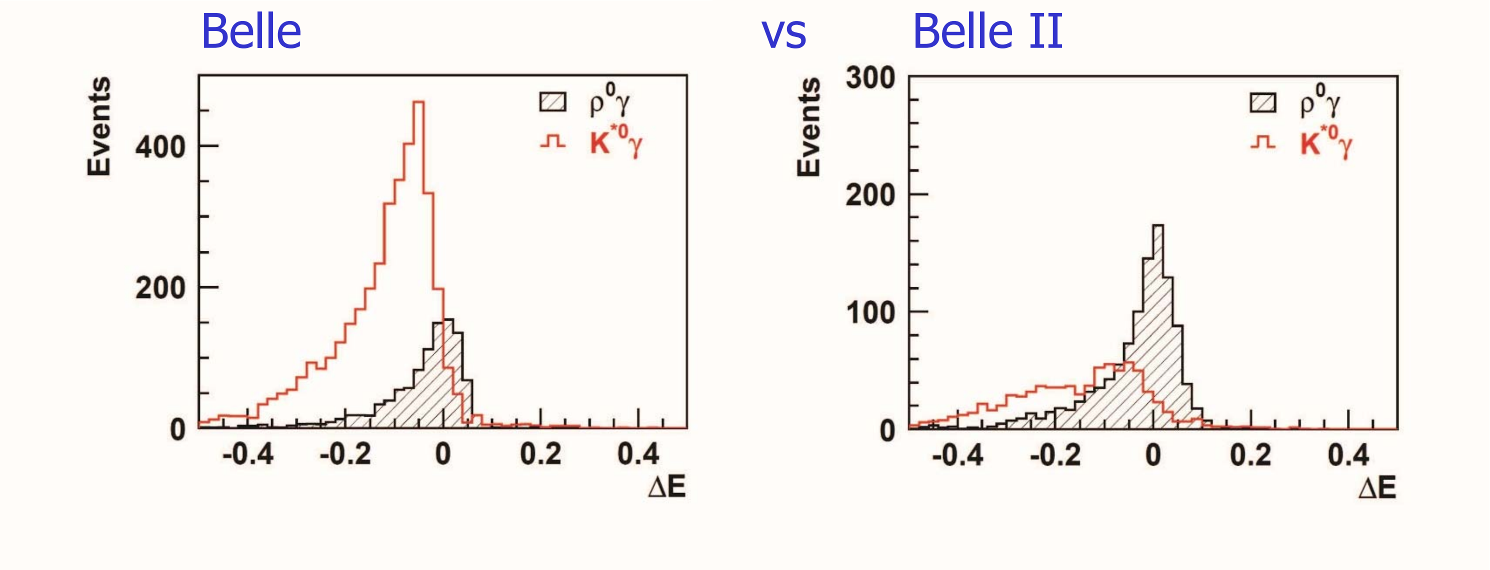


The number of Cherenkov photons emitted over unit photon energy E=hν in a radiator of length ***L***:

$$\boxed{\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2\theta = 370 (cm)^{-1} (eV)^{-1} L \sin^2\theta}$$

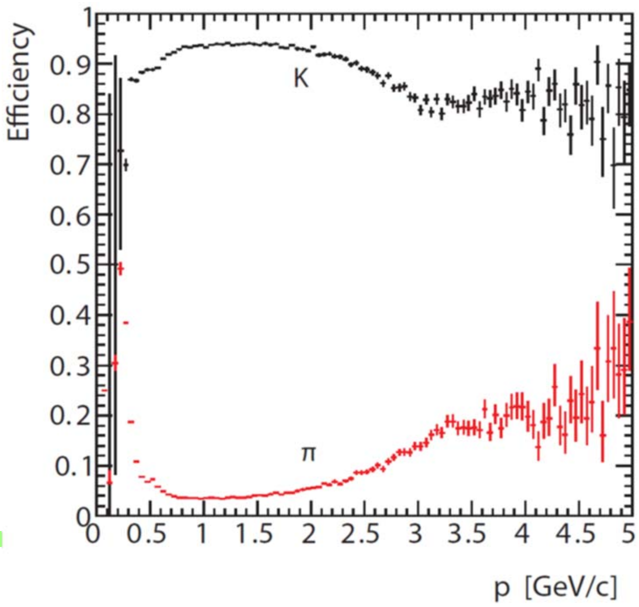
→Few detected photons

Pion and kaon identification

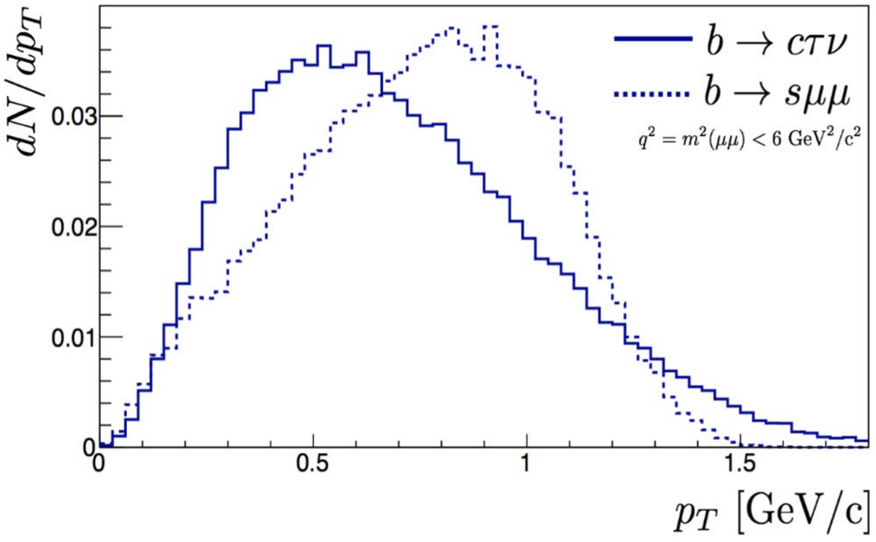


The experiment requires excellent particle identification: illustrated on an example of a very rare decay B → ρ γ , ρ → ππ, vs its main background, a much more copious decay B → K* γ , K* → K π.

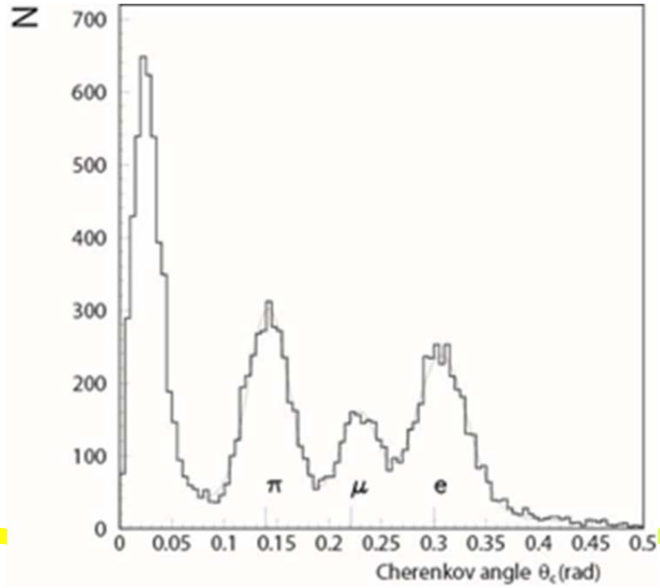
Expected performance of the particle identification system



Muon and electron identification at low momenta



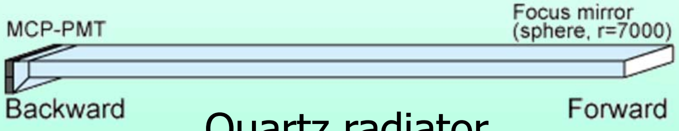
Spectrum of muons from $b \to c\tau\nu$ and $b \to s\mu\mu$ transitions.



Cherenkov angle for single Cherenkov photons from pions, muons, and electrons as measured in a 0.5 GeV/c test beam by a ring imaging Cherenkov detector prototype; with typically about 10 photons per muon as expected in such a counter, the muon and pion peaks would be well separated.

Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)



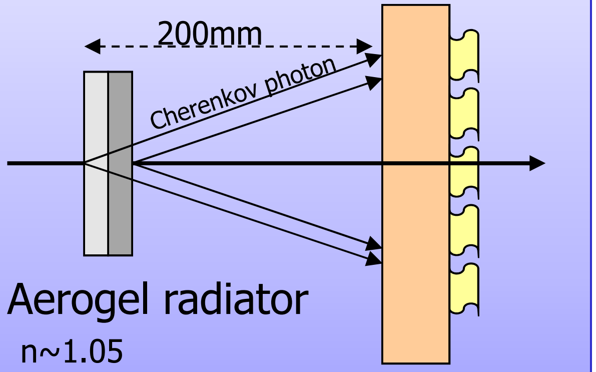
Quartz radiator

Focusing mirror

Small expansion block

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

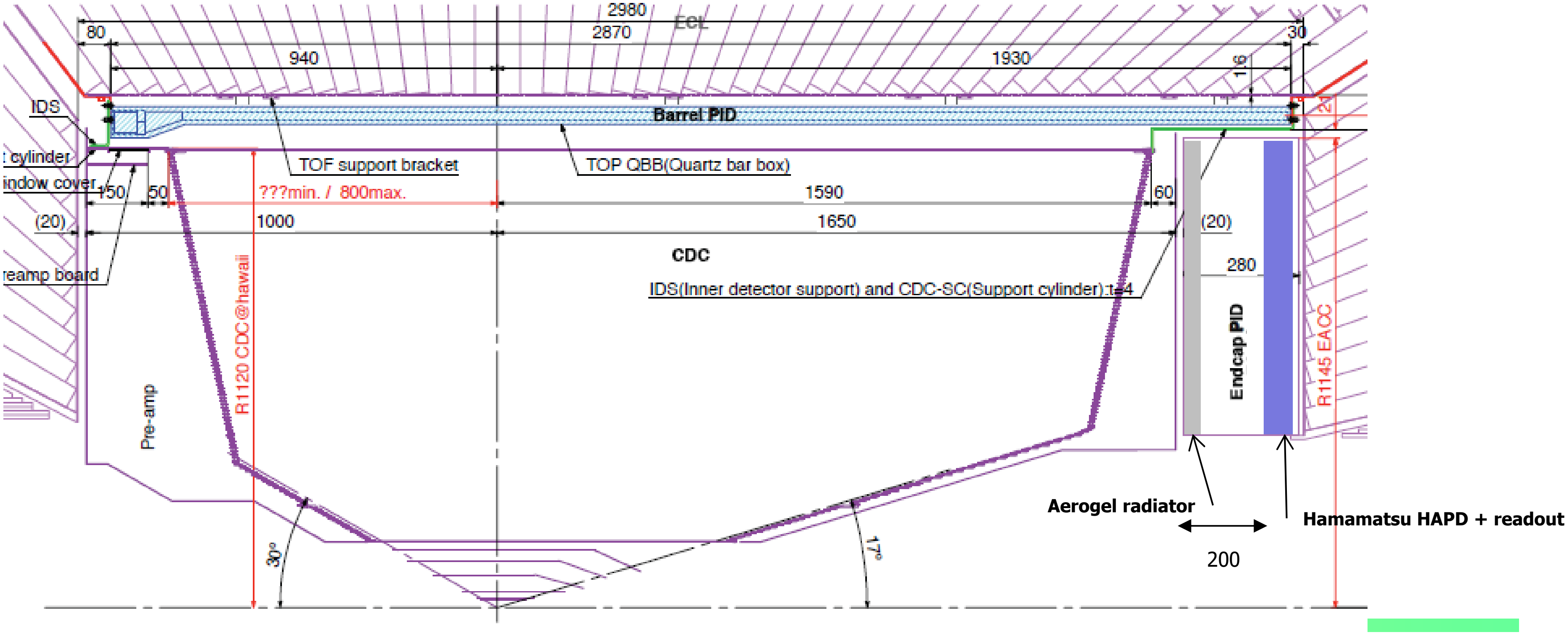
Endcap PID: Aerogel RICH (ARICH)



Aerogel radiator

n~1.05

Hamamatsu HAPD



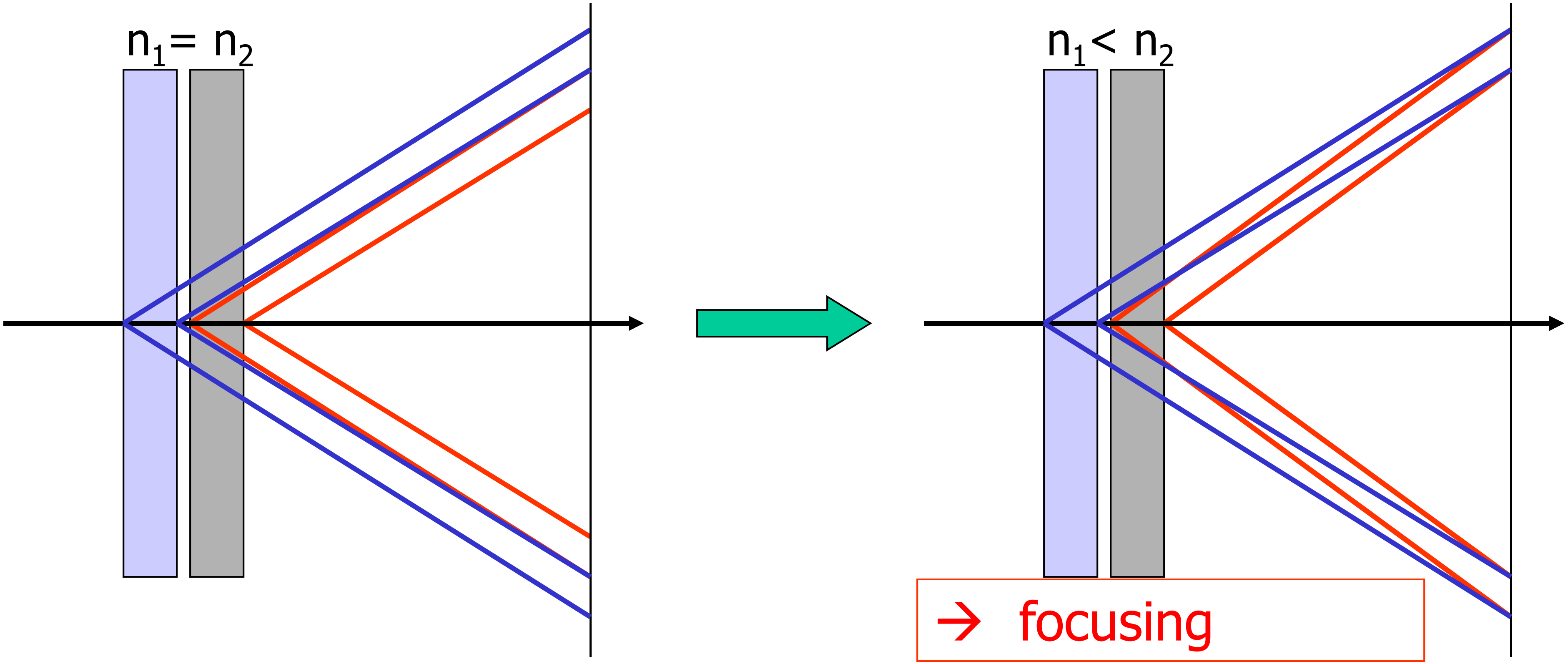
Peter Križan, Ljubljana

Radiator with multiple refractive indices: focusing configuration

How to increase the number of photons without degrading the resolution?

normal

→ stack two tiles with different refractive indices: "focusing" configuration



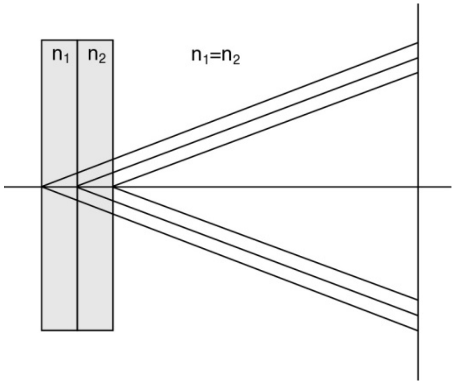
→ focusing

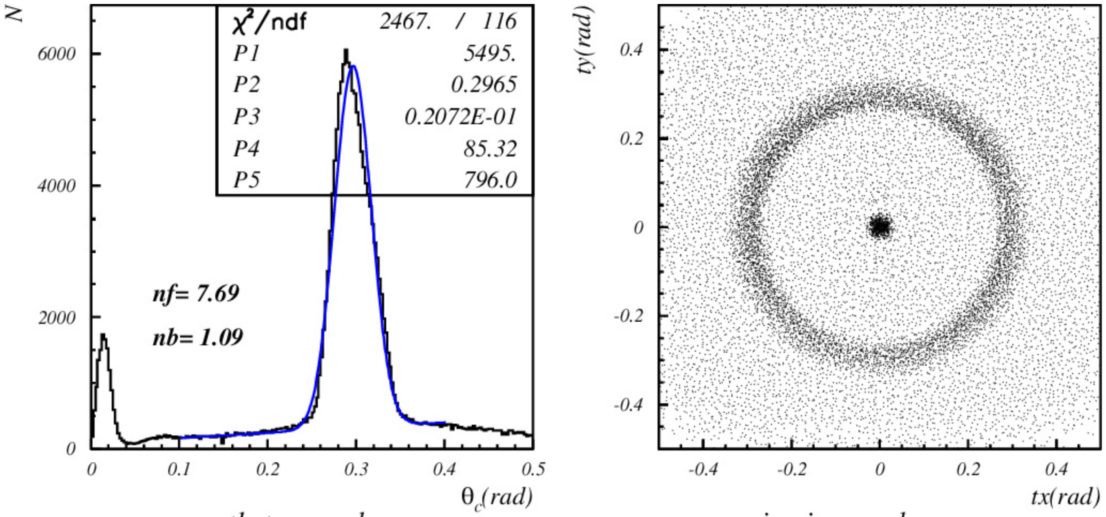
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

Focusing configuration – data

Increases the number of photons without degrading the resolution

4cm aerogel single index

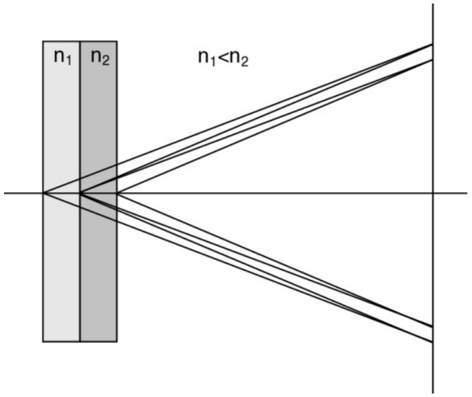


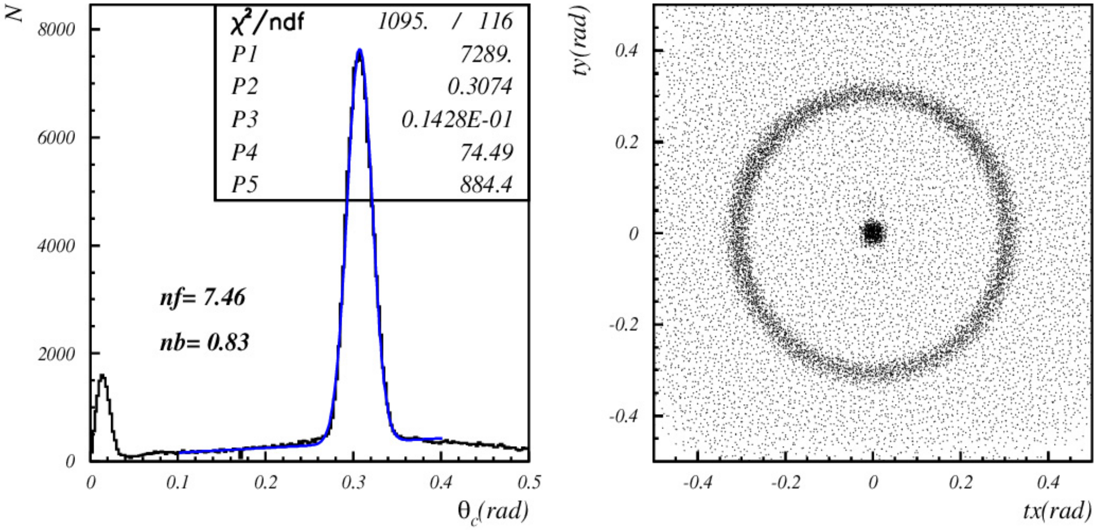


theta cerenkov

ring in cerenkov space

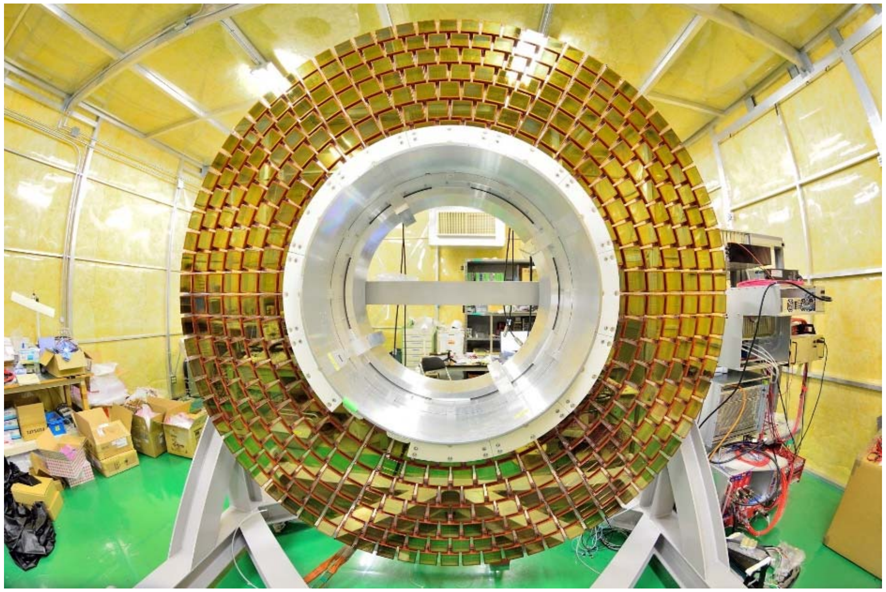
2+2cm aerogel

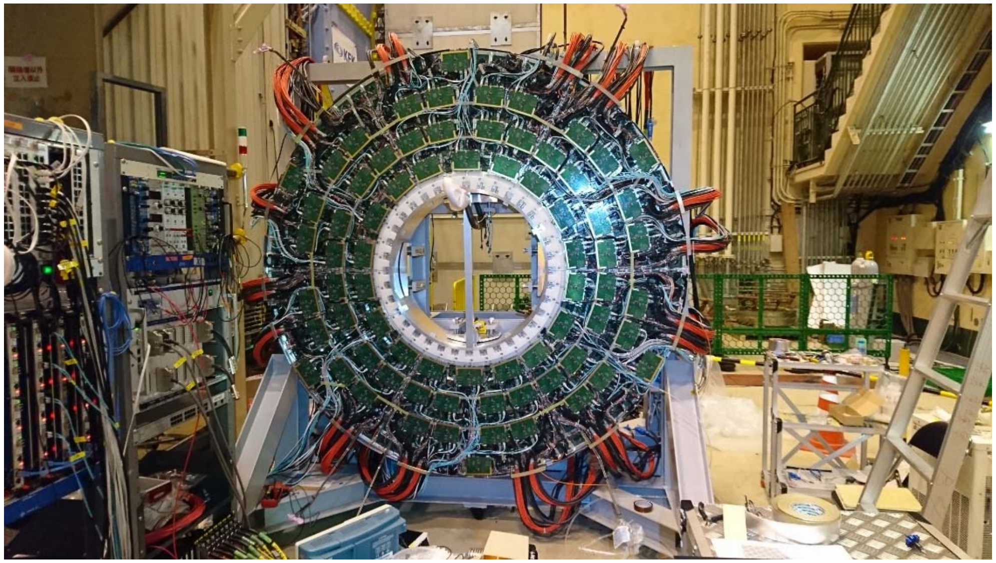


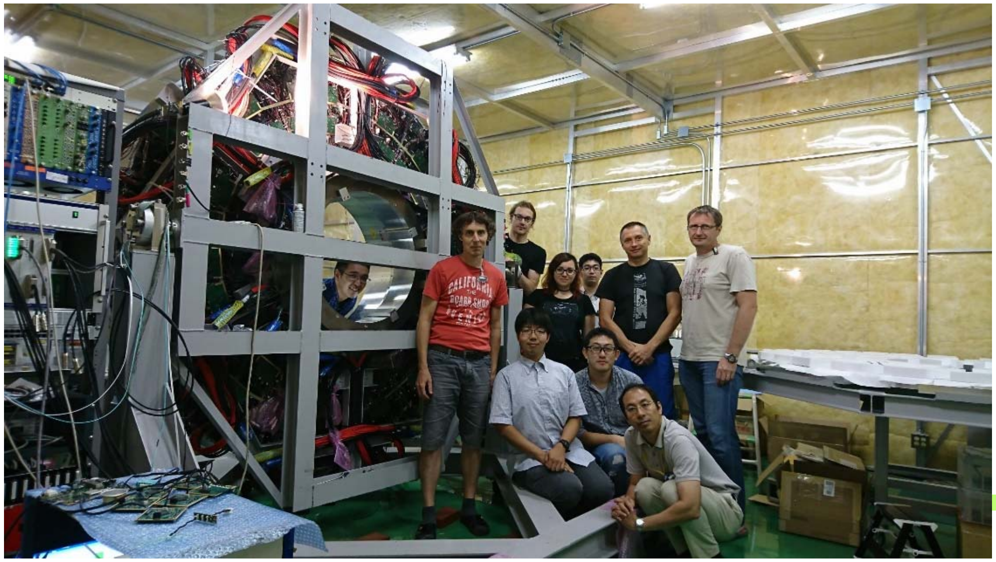


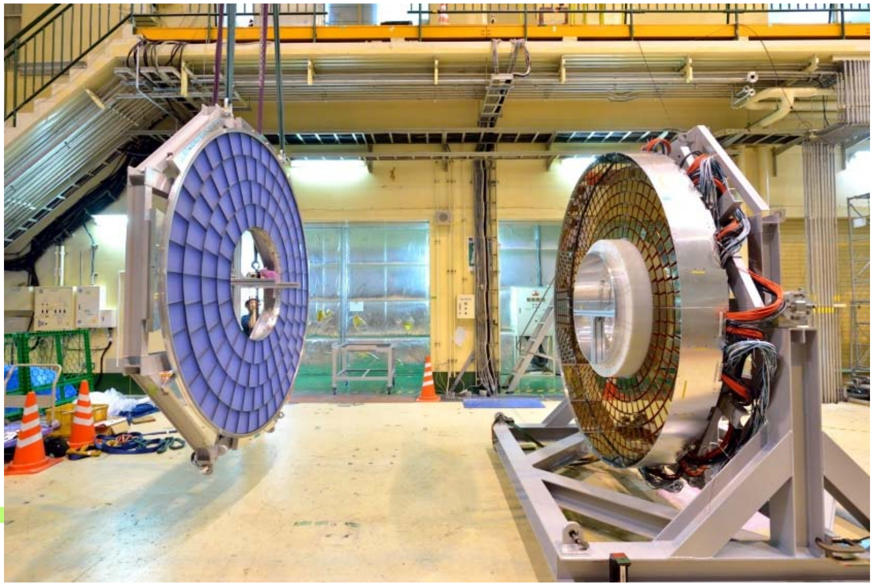
→NIM A548 (2005) 383

The big eye of ARICH

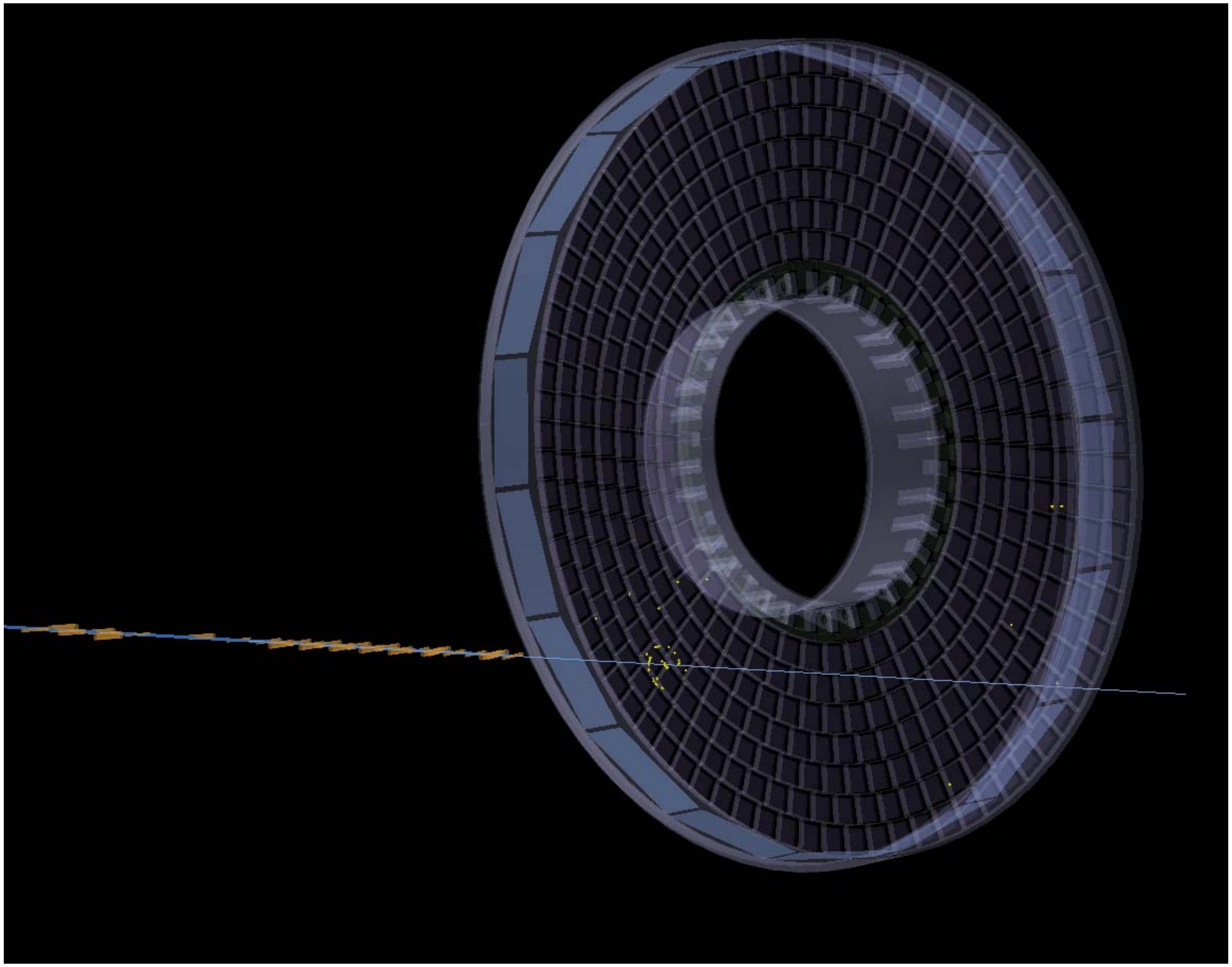








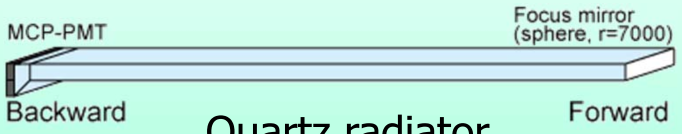
ARICH: Rings from cosmic ray muons



First events recorded in the fully instrumented ARICH.

Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



Quartz radiator

Focusing mirror

Small expansion block

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

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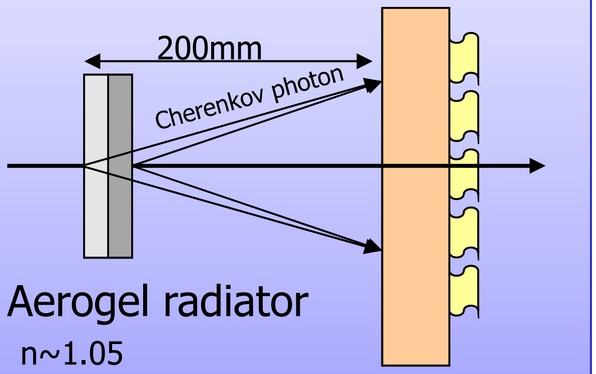
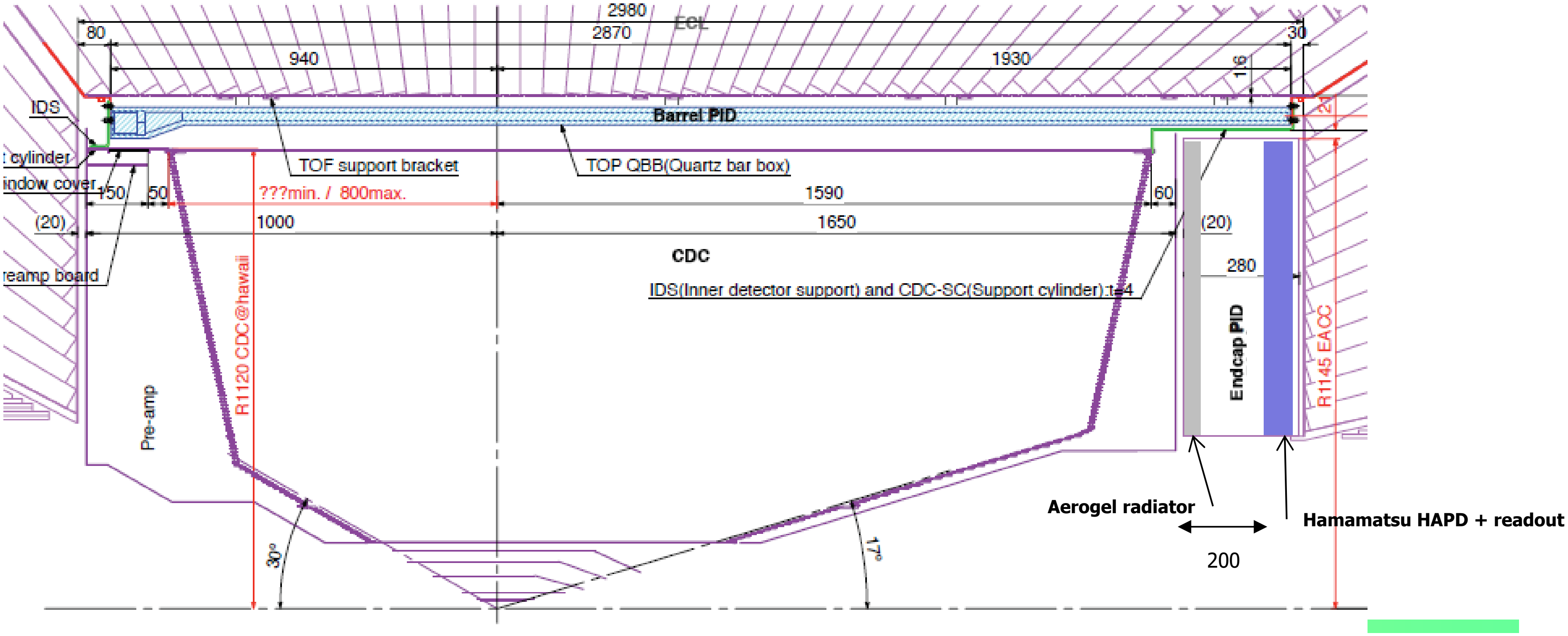


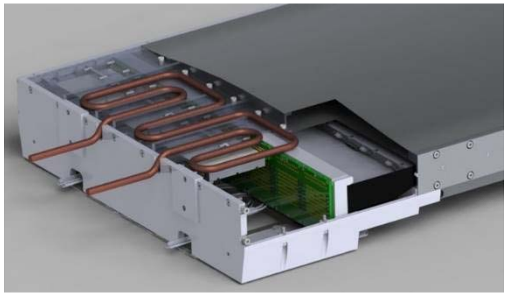
Aerogel radiator

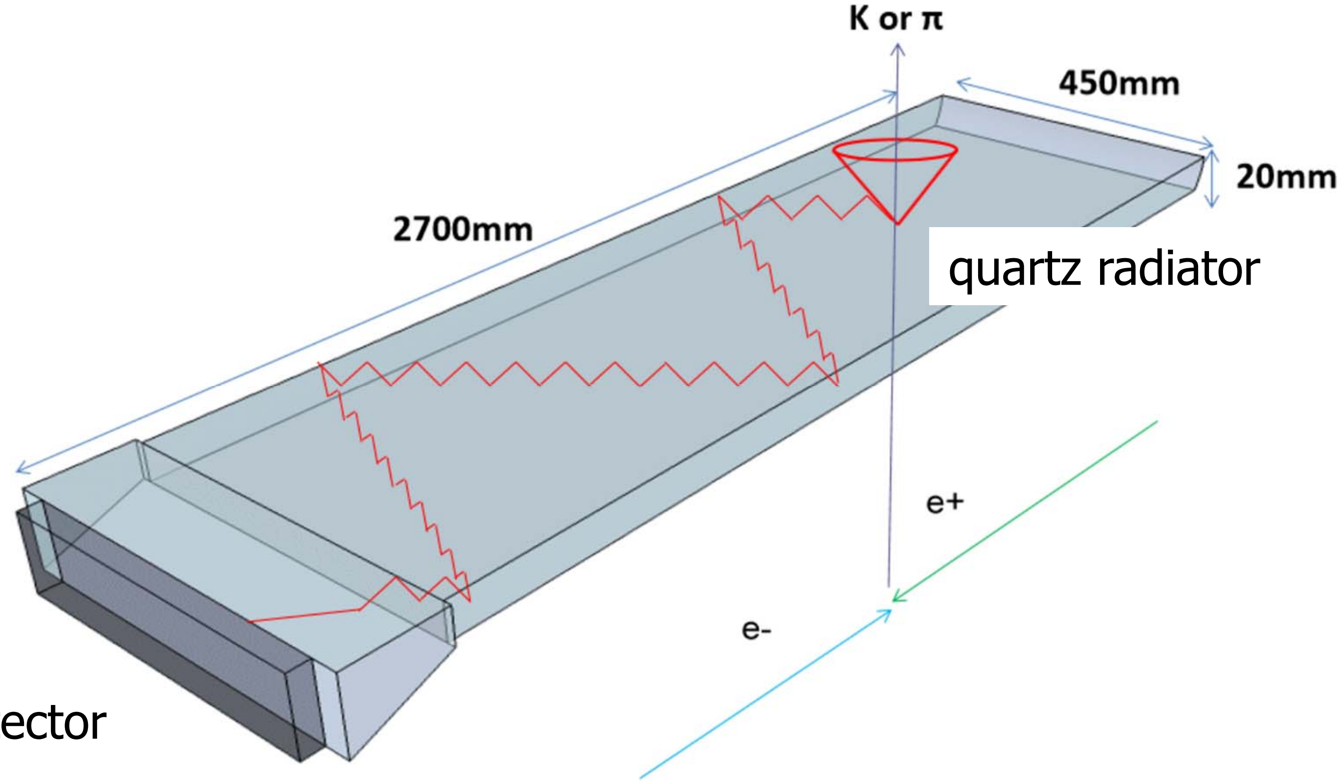
n~1.05

Hamamatsu HAPD
+ new ASIC



Barrel PID: Time of propagation (TOP) counter

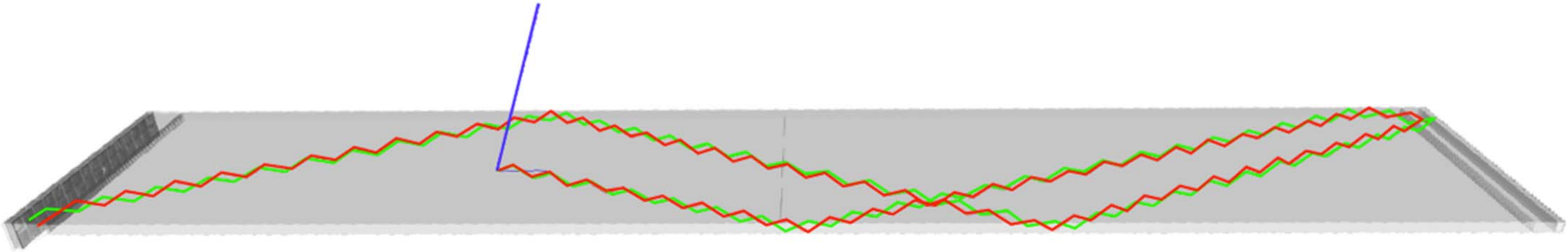




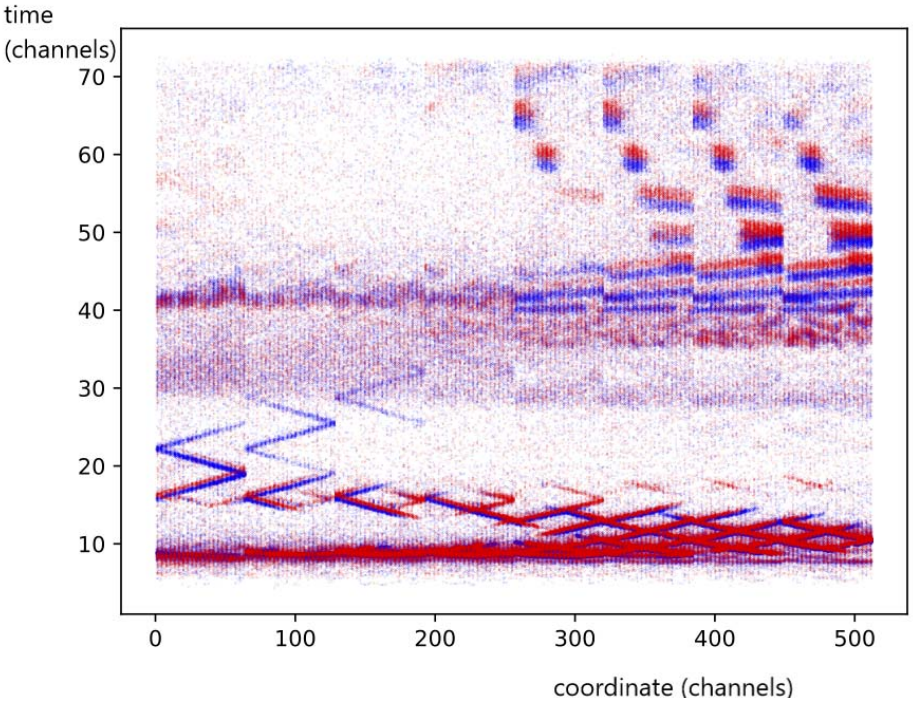
Photon detector

- 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

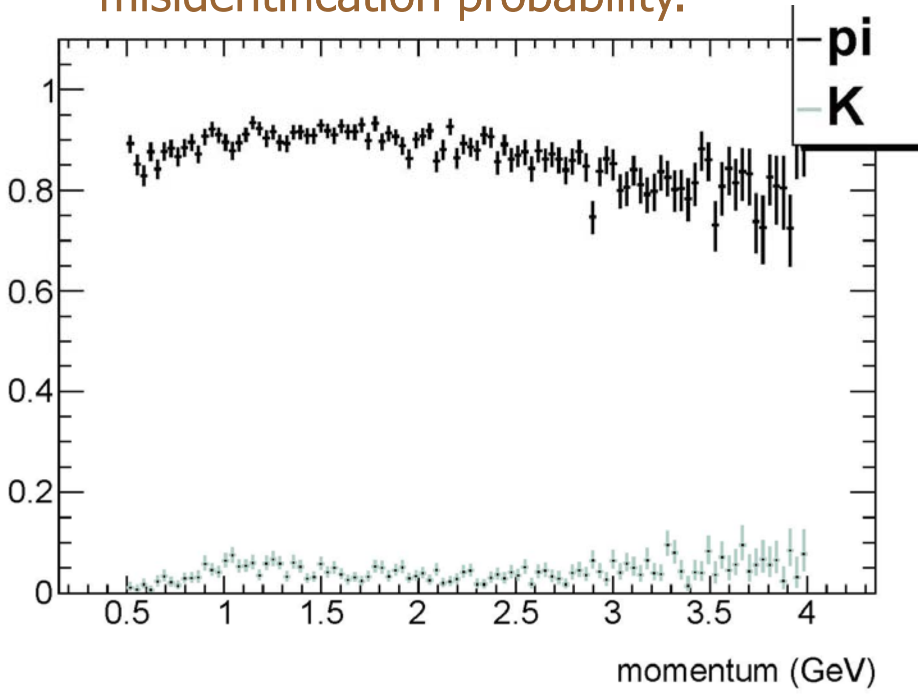
Separation of kaons and pions



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

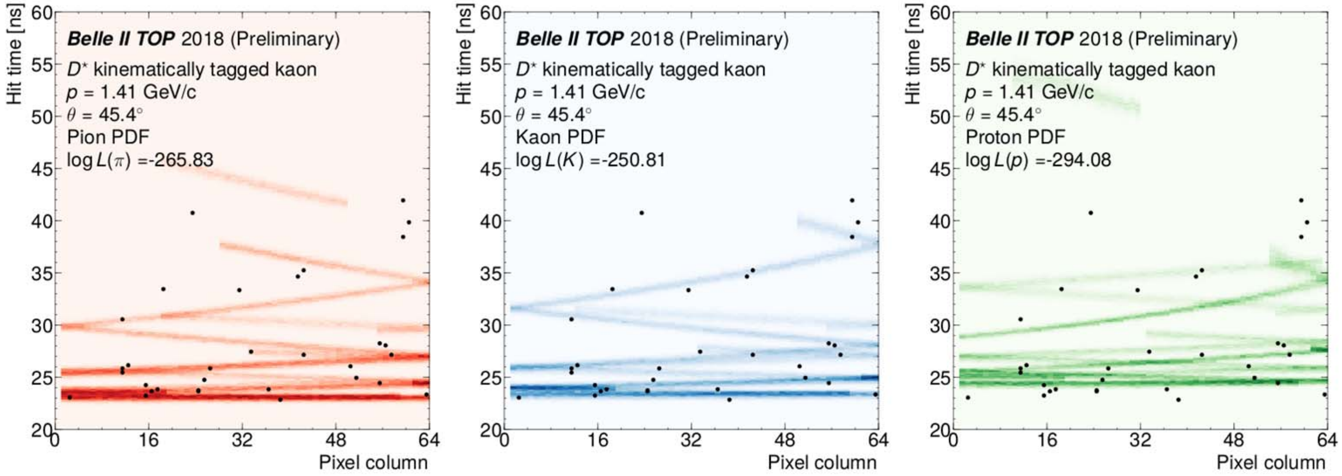


Pions vs kaons:
Expected PID efficiency and
misidentification probability.

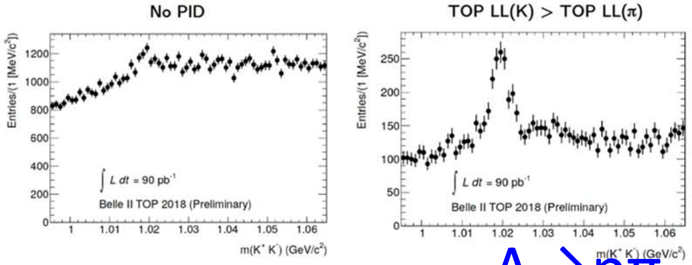


TOP patterns

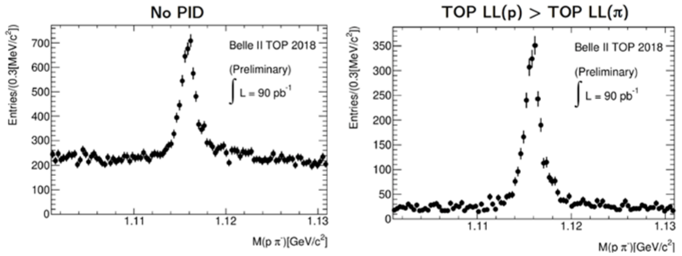
Demonstraion of the TOP principle



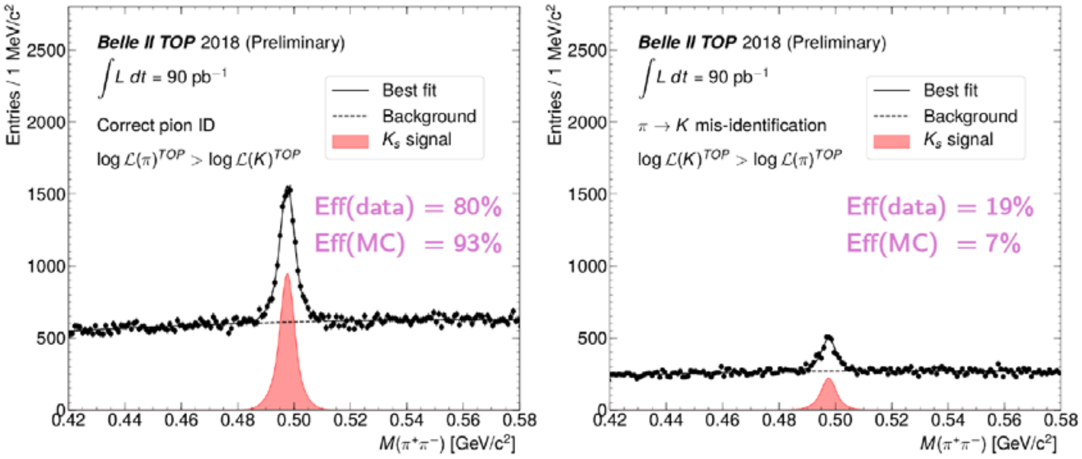
φ → K⁺K⁻ with both the tracks in the TOP acceptance **φ→KK**



Λ → pπ with the **proton candidate** in the TOP acceptance **Λ→pπ**



K_s →ππ



Summary

- Physics of B mesons has contributed substantially to our present understanding of elementary particles and their interactions
- The hints of anomalies as seen in some B meson decays are a very promising window in searches for new physics
- Our projects aims at exploring several interesting processes with high precision
- To get there, advanced particle identification methods will be developed and employed
- Expect exciting five years!

Additional slides