Charm and Beauty in Physics

10 - 11 November 2016, Moscow

# B Physics: from the Beginnings to B Factories


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# Contents

- B physics: introduction, with a little bit of history
- B physics at ARGUS
- B physics at B factories
- Outlook: Belle II

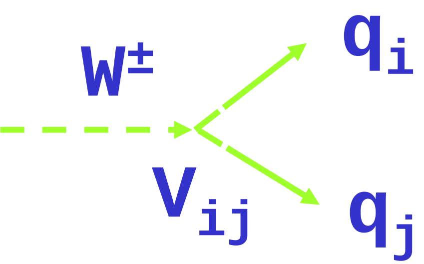
On the occasion of the 70th anniversary of Misha Danilov

# Flavour physics and CP violaton

Discovery of CP violation in $K_L \to \pi^+ \pi^-$ decays (Fitch, Cronin, 1964)

Kobayashi and Maskawa (1973): to accommodate CP violation into the Standard Model, need three quark generations, six quarks

Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix

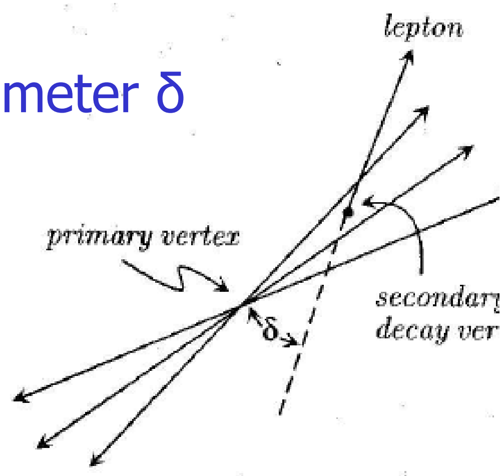



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

# First studies of B mesons: long lifetime

**Isolate samples of high-$p_T$ leptons (155 muons, 113 electrons) wrt thrust axis**

Measure impact parameter δ wrt interaction point

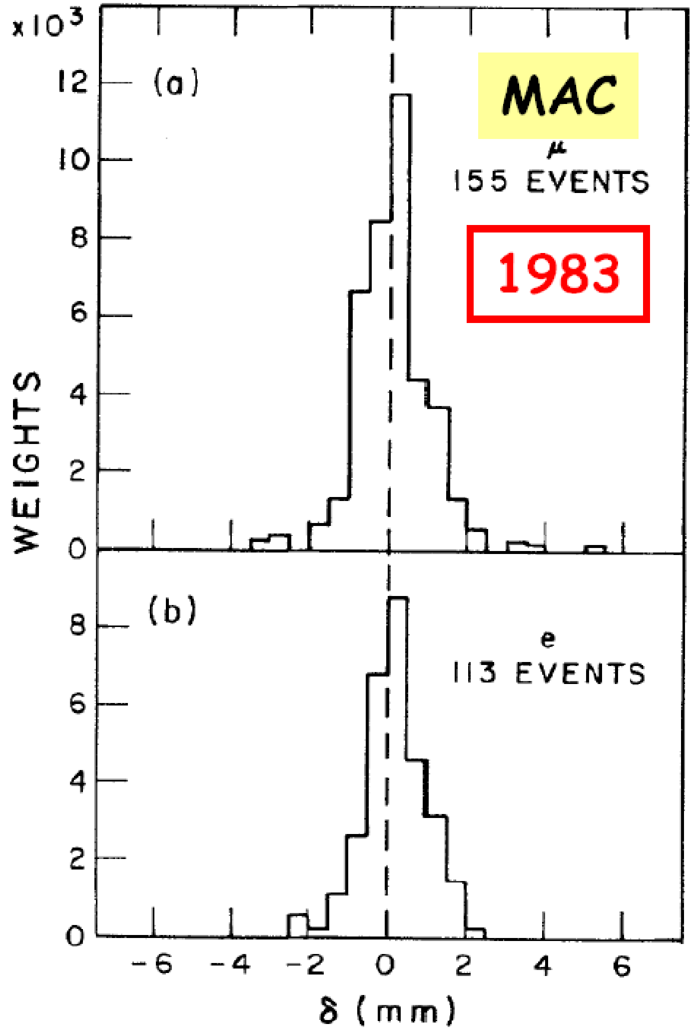



**Lifetime implies: $V_{cb}$ small**

MAC: (1.8±0.6±0.4)ps

Mark II: (1.2±0.4±0.3)ps

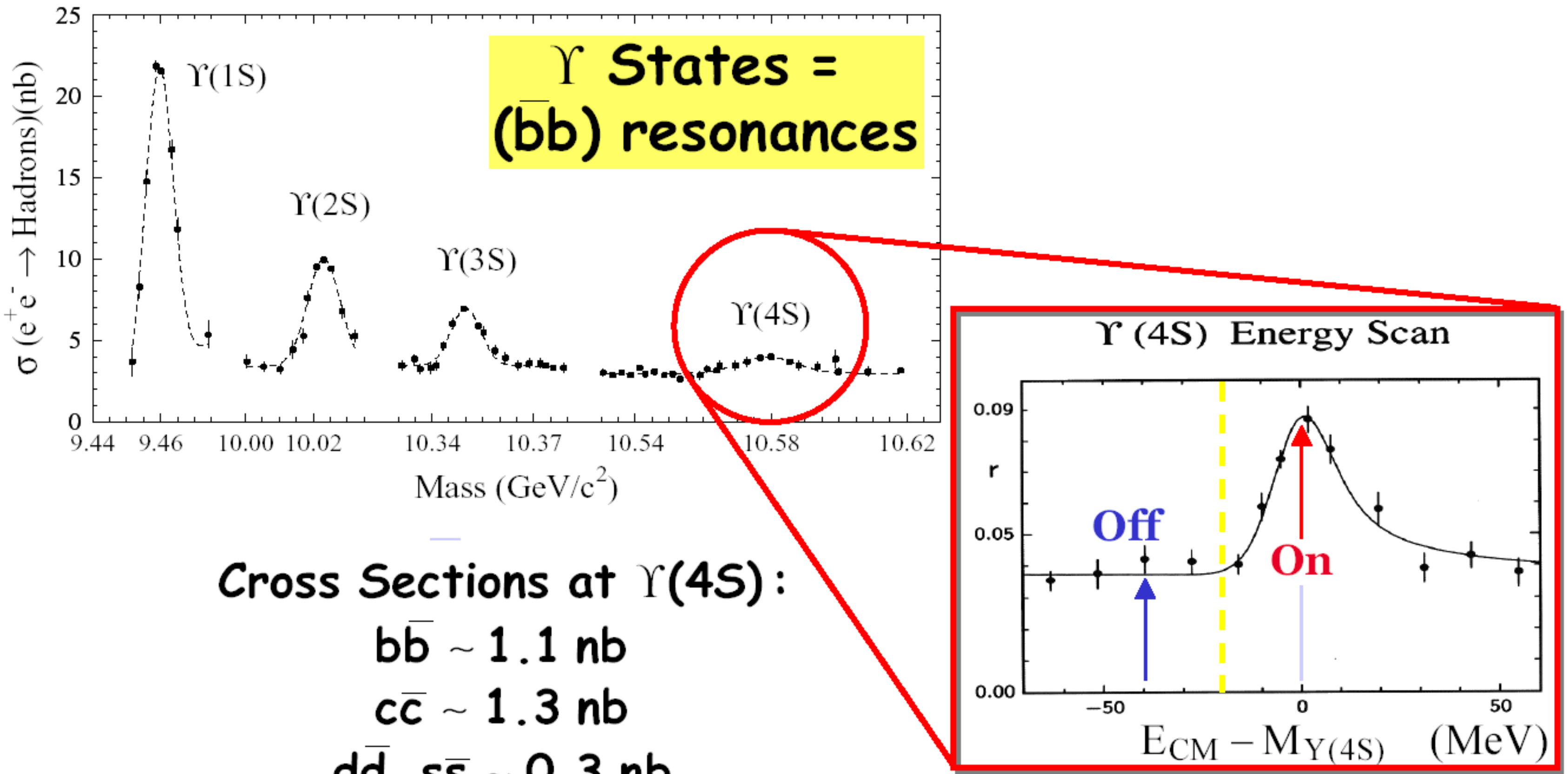
**Integrated luminosity at 29 GeV:** 109 (92) $pb^{-1}$~3,500 bb pairs




MAC, PRL **51**, 1022 (1983)

MARK II, PRL **51**, 1316 (1983)

# Systematic studies of B mesons: at Υ(4s)




**Cross Sections at Υ(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

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

$L = 1$ state

# Systematic studies of B mesons at $\Upsilon(4s)$

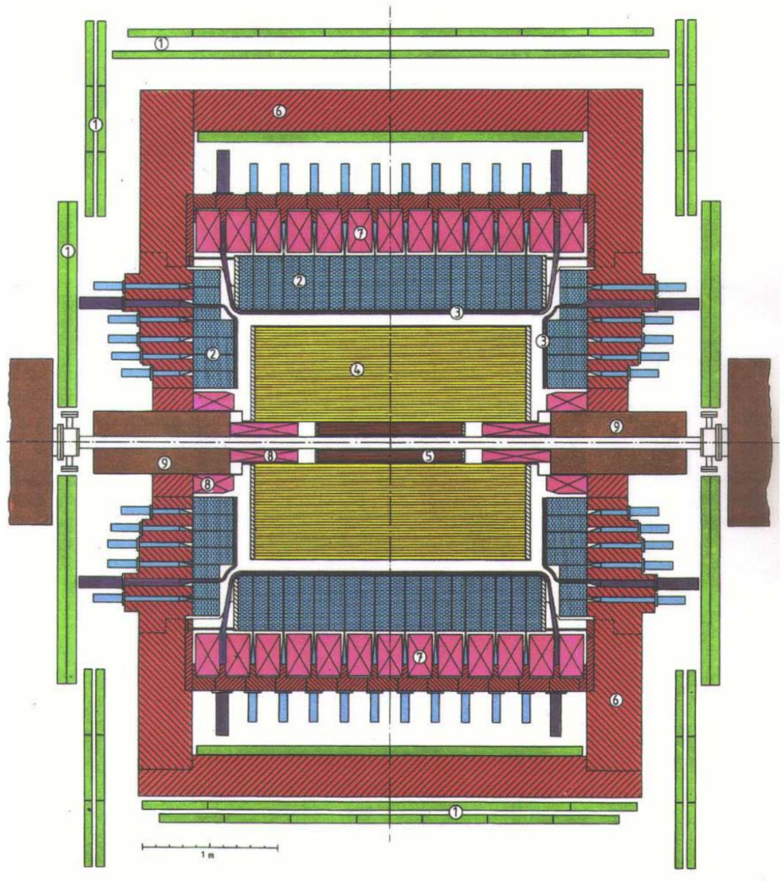
80s-90s: two very successful experiments:

•ARGUS at DORIS (DESY)

•CLEO at CESR (Cornell)

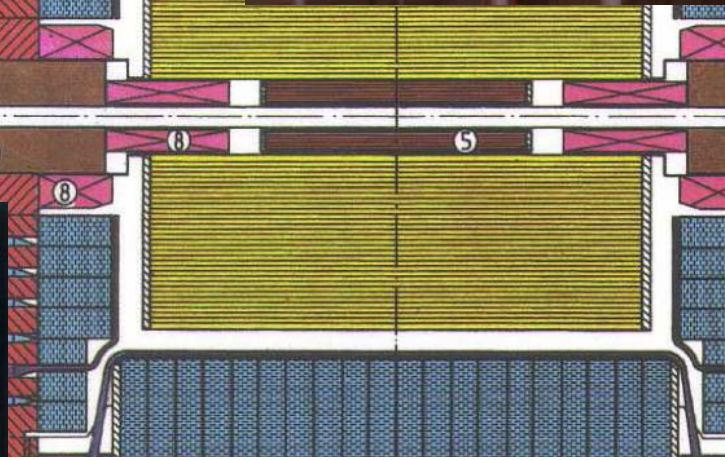
Magnetic spectrometers at $e^+e^-$ colliders (5.3GeV+5.3GeV beams)

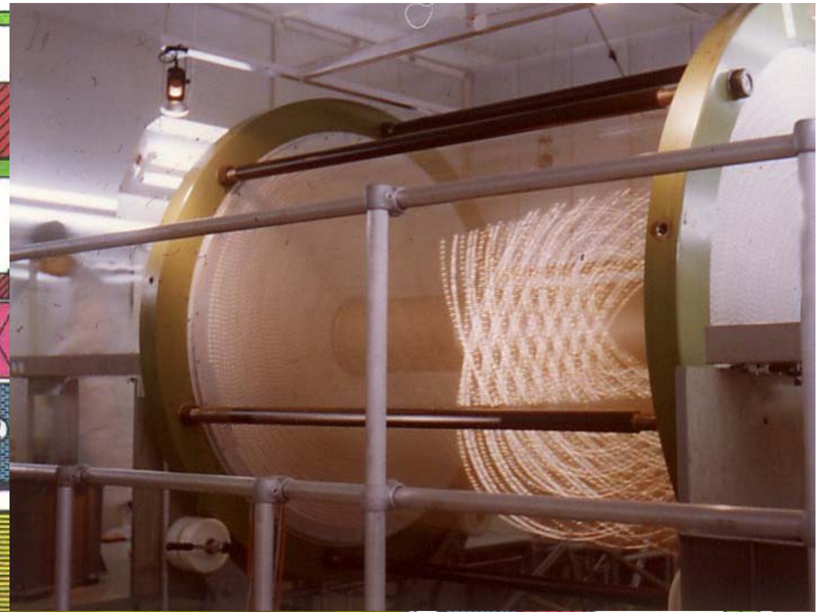
Large solid angle, excellent tracking and good particle identification (TOF, dE/dx, EM calorimeter, muon chambers).

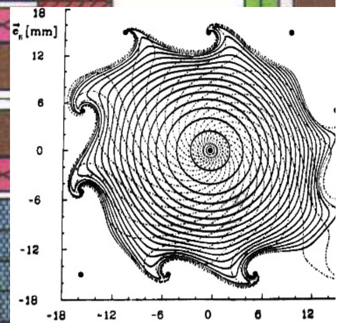


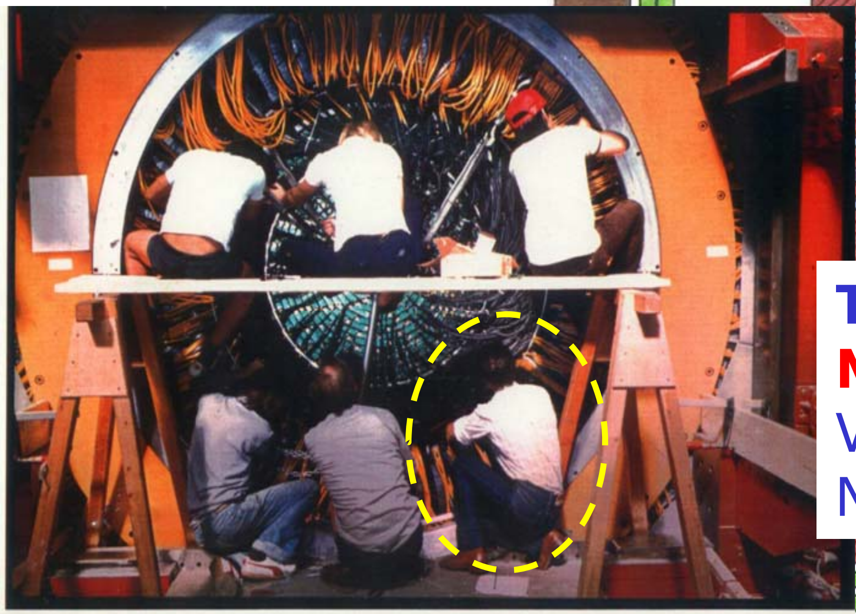
Many important discoveries and studies of properties of

- B mesons
- D mesons
- $\tau$ lepton (and even a measurement of $\nu_\tau$ mass)









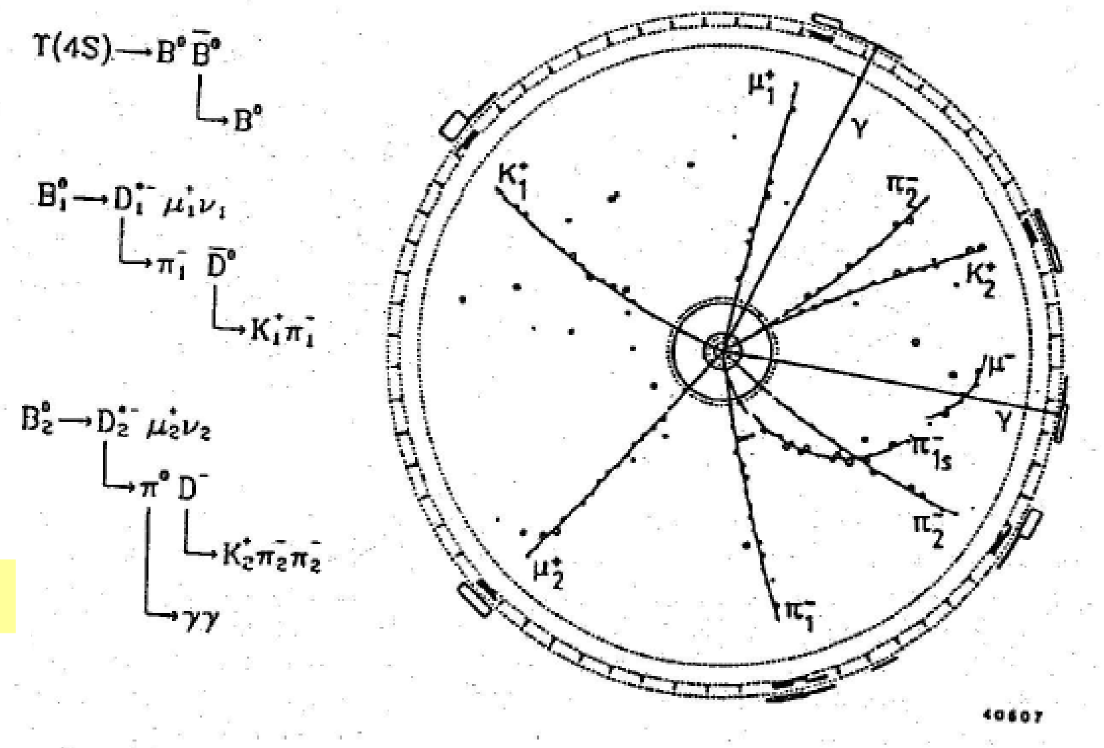
**The ARGUS drift chamber**

**M. Danilov,** H. Hasemann, P. Kim, E. Michel, V. Nagovizin, W. Schmidt-Parzefall , R. Wurth, NIMA 217 (1983) 153-159

# THE discovery: mixing in the $B^0$ system

## 1987: ARGUS discovers BB mixing: $B^0$ turns into anti-$B^0$

Reconstructed event




$$\chi_d = 0.17 \pm 0.05$$

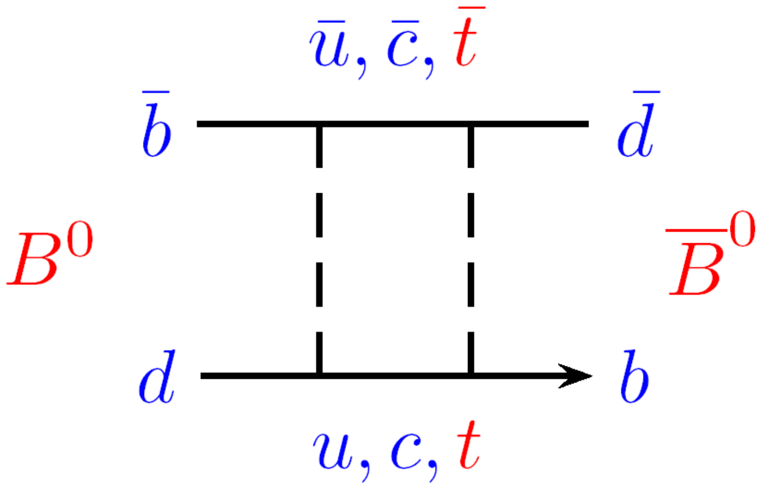
ARGUS, PL B **192**, 245 (1987)

cited >1000 times.

Time-integrated mixing rate: 25 like sign, 270 opposite sign dilepton events

Integrated Y(4S) luminosity 1983-87: 103 $pb^{-1}$ ~110,000 B pairs

# Mixing in the $B^0$ system




$$\Delta m \propto$$

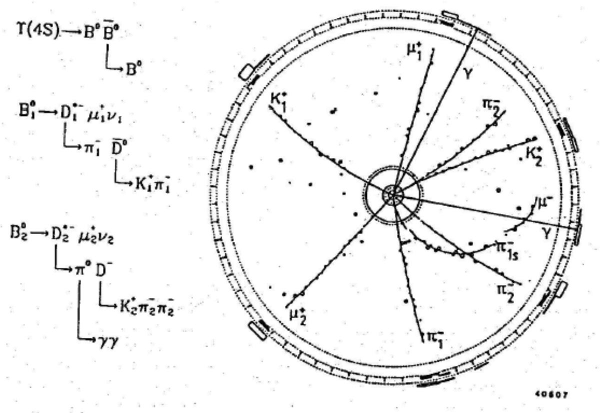
$$|V_{tb}^* \, V_{td}|^2 m_t^2 \;\propto\; \lambda^6 m_t^2$$

$$|V_{cb}^* \, V_{cd}|^2 m_c^2 \;\propto\; \lambda^6 m_c^2$$

Large mixing rate → high top mass (in the Standard Model)

The top quark has only been discovered seven years later!

*Multae sunt cause…*



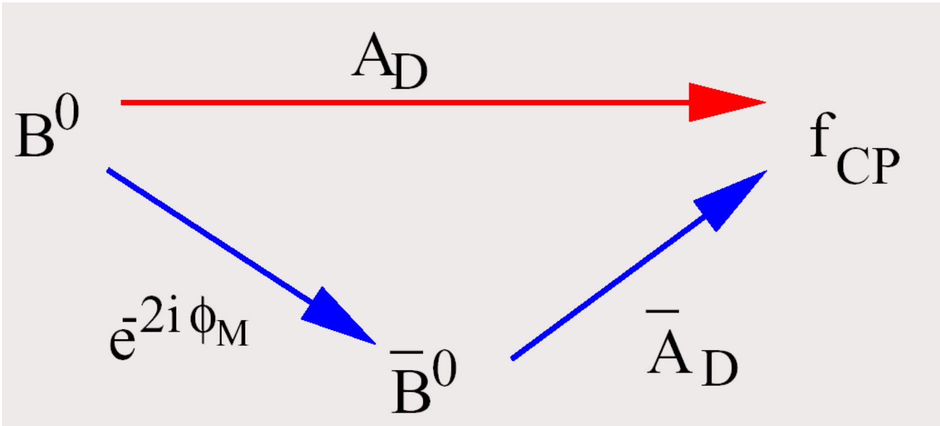


# ... and 20 years later

# CP violation in the B System

Large B mixing → expect sizeable CP violation (CPV) in the B system

CPV through interference between
mixing and decay amplitudes




Directly related to CKM parameters in case of a single amplitude

# Golden Channel: B → J/ψ $K_S$

Soon recognized as the best way to study CP violation in the B meson system (I. Bigi and T. Sanda 1987)

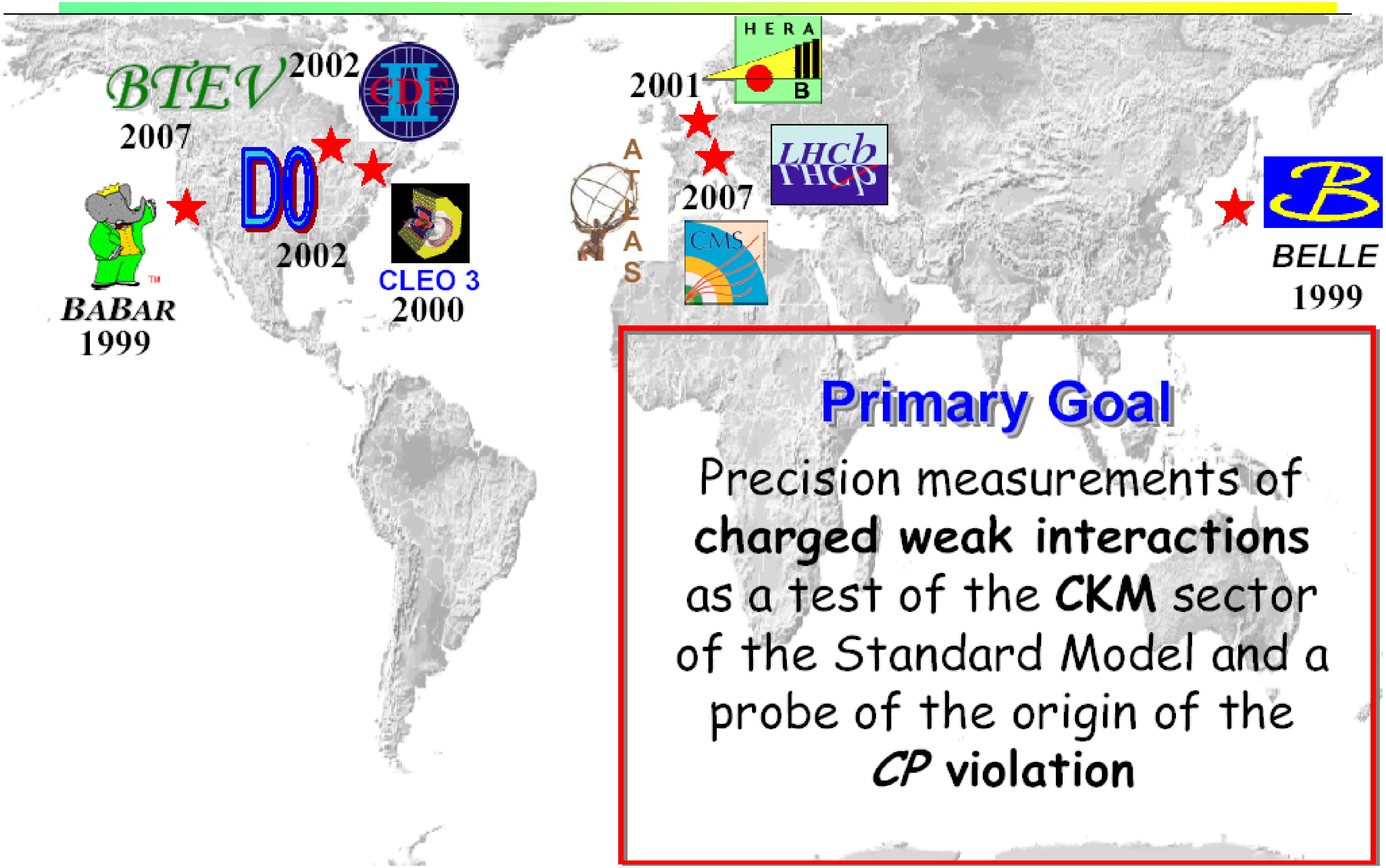
Theoretically clean way to one of the parameters ($\sin 2\phi_1 = \sin 2\beta$)

Use boosted BBbar system to measure the time evolution (P. Oddone)

Clear experimental signatures (J/ψ → $\mu^+\mu^-$, $e^+e^-$, $K_S \to \pi^+\pi^-$)

Relatively large branching fractions for b→ccs ($\sim 10^{-3}$)

→ A lot of physicists were after this holy grail




## Primary Goal

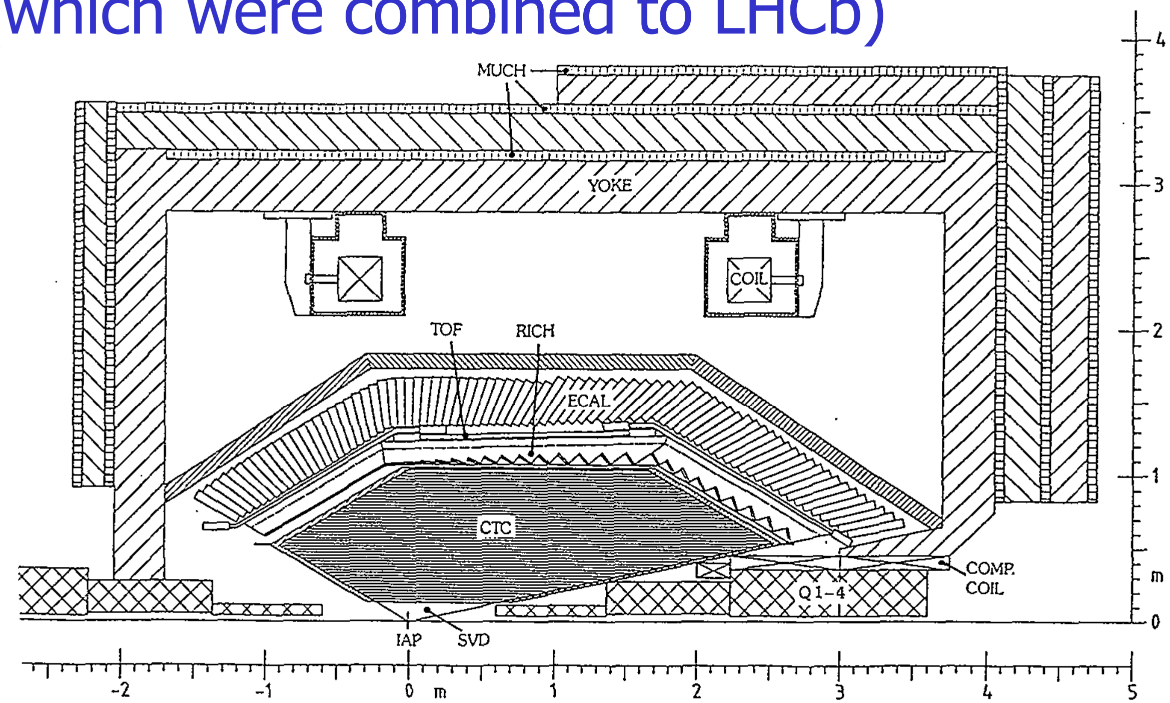
Precision measurements of **charged weak interactions** as a test of the **CKM** sector of the Standard Model and a probe of the origin of the ***CP* violation**

# Genesis of Worldwide Effort 2

In late 80s and early 90s there were several proposal which were not approved:

- symmetric $e^+e^-$ in PSI (Villigen, Switzerland), 1988
- Helena, asymmetric $e^+e^-$ collider at DESY, 1992
- 3 proposals at LHC (which were combined to LHCb)

Helena @ DESY
9.3 GeV + 3 GeV

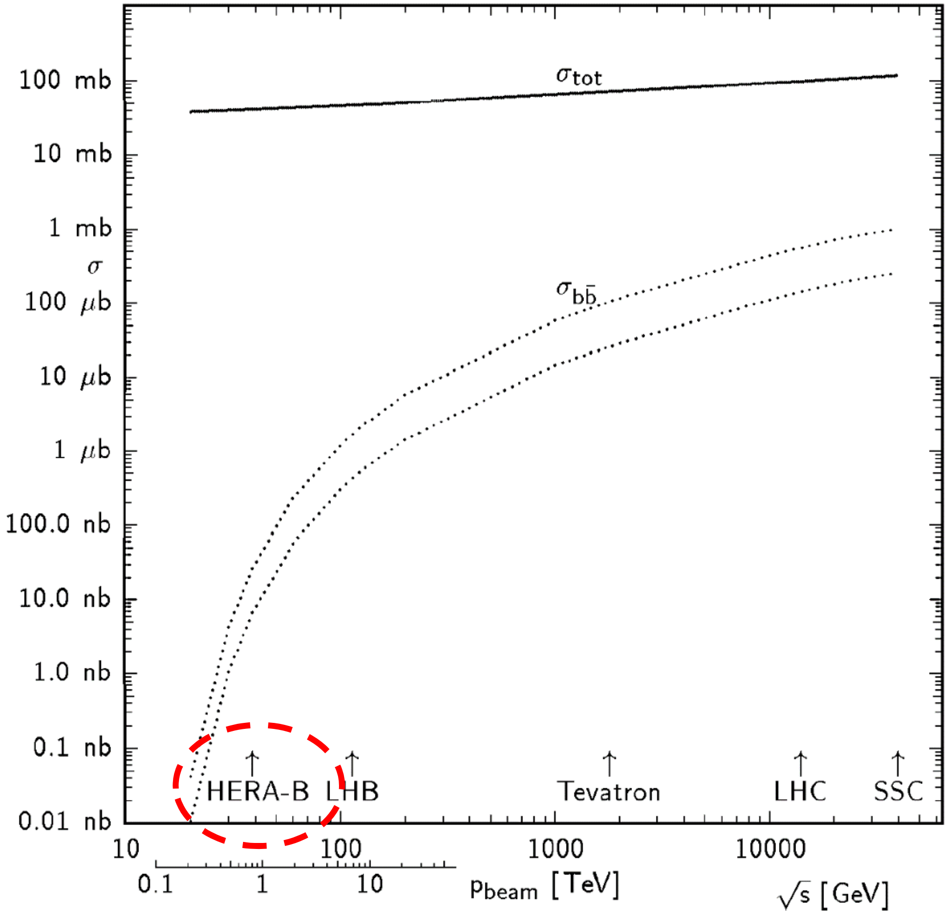


# B physics at a hadron machine?

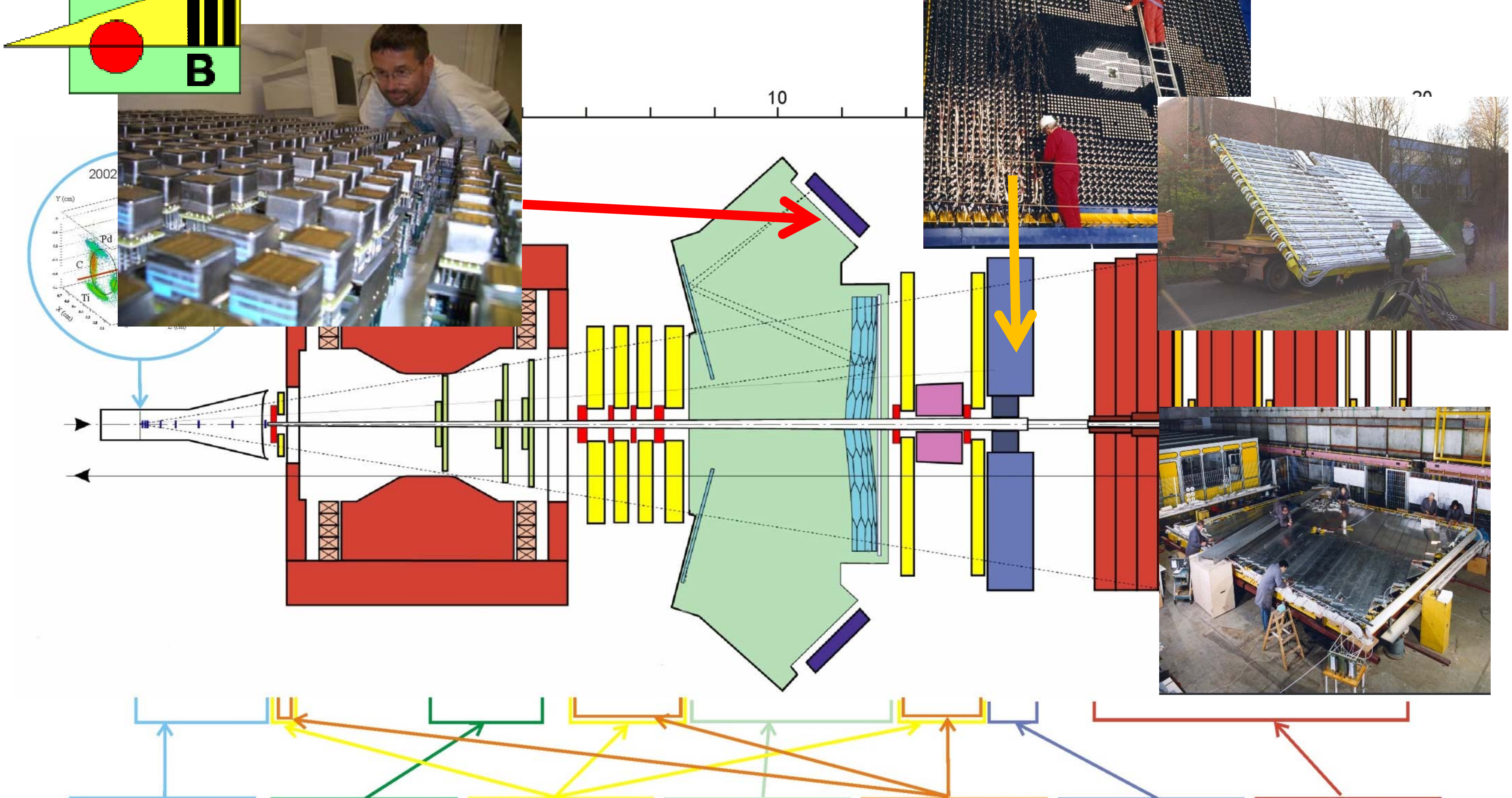
- larger bb production rates - compare to 1.1nb at Y(4s)
- large boosts → <L> = <βγ> 480 μm
- in addition to $B^0/B^{+-}$ also $B_s$, $B_c$, $\Lambda_b$,..

LHC →

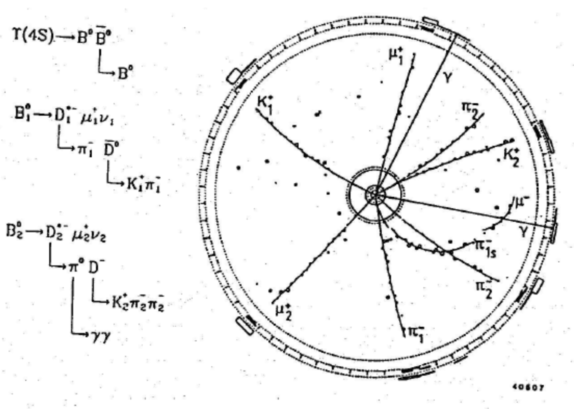
Y(4s) →



# HERA-B spectrometer

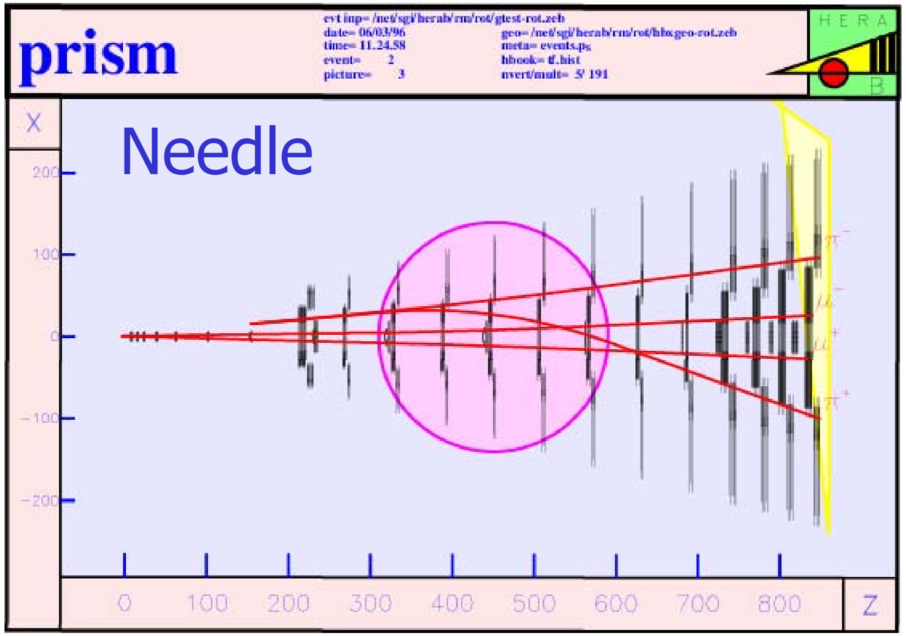


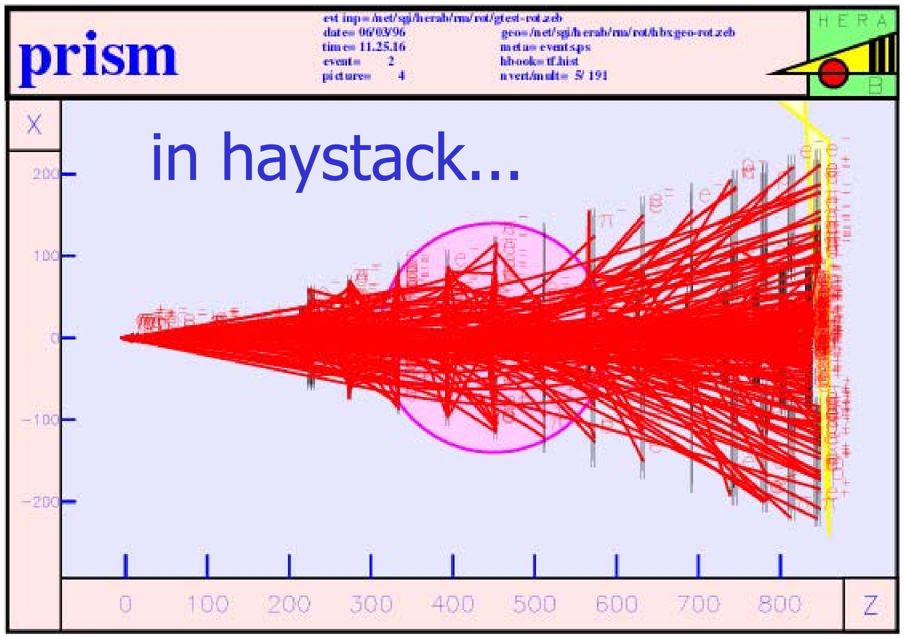

| Target & Vertex | High $p_T$ | Outer Tracker | RICH | Inner Tracker | Electromagnetic Calorimeter | Muon System |
|---|---|---|---|---|---|---|
| 8 layers of double-sided Si-microstrips, movable on Roman-Pots; 8 wire-target (see above) | 3 superlayers gas, pixel and pad chambers; pre-trigger for high $p_T$ tracks | 7 superlayers of honeycomb drift chambers, 5 and 10mm cells | Spherical mirror inside $C_4F_{10}$ radiator, Lens-enhanced multianode PMT focal plane. | 7 superlayers of Micro Strip Gas Chambers with GEM-foil | W/Pb scintillator sandwich, shashlik WLS readout with PMTs; energy-cluster pre-trigger | 4 superlayers of gas-pixel, tube & pad chambers; pad-coincidence pre-trigger |




# bb event at an $e^+e^-$ machine

## bb event at HERA-B:




B → J/ψ Ks

and the rest

# HERA-B summary

•First LHC like experiment before the LHC

•Designed with a very ambitious goal

•Many components behaved very well (e.g. SVD – silicon vertex detector, RICH, calorimeter and muon system)

•Several critical components were less successful (tracking)

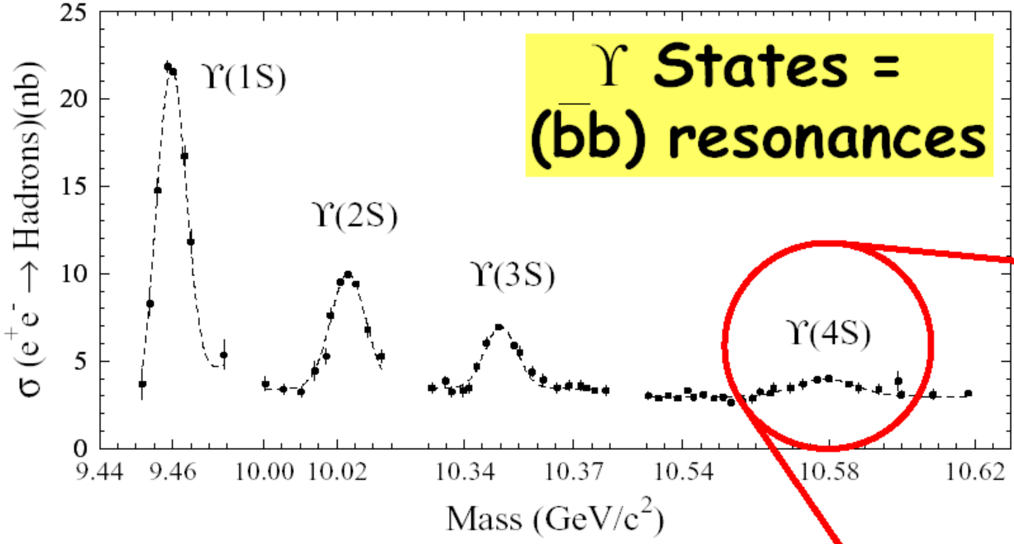
•Trigger efficiency (which heavily relied on the tracking system efficiency) was >10x lower than expected…

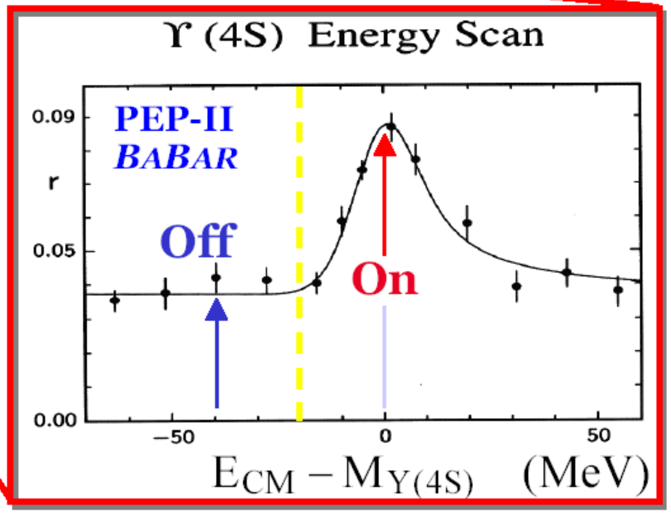
→No precision tests in B physics were possible

•Still: a solid physics program could be carried out (i.e. bb and cc production cross sections, a limit on $D \to \mu\mu$, pentaquark searches)

•HERA-B experience: An important input for LHC experiments

# → Back to B meson production at Υ(4s)




**Cross Sections at Υ(4S):**

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

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

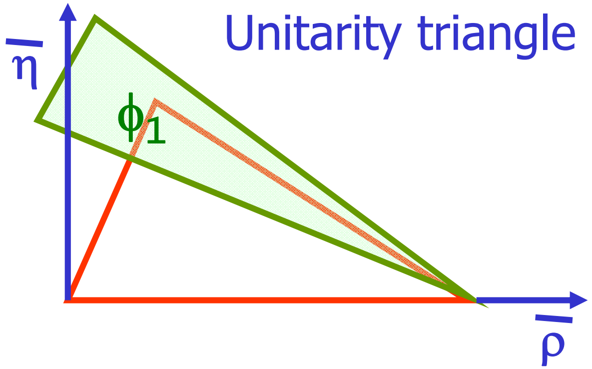
$d\bar{d}$, $s\bar{s} \sim 0.3$ nb

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

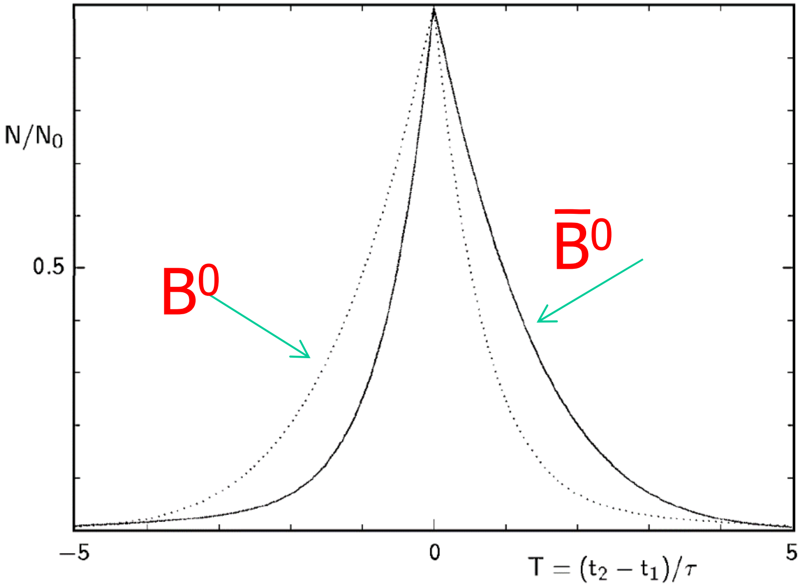
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

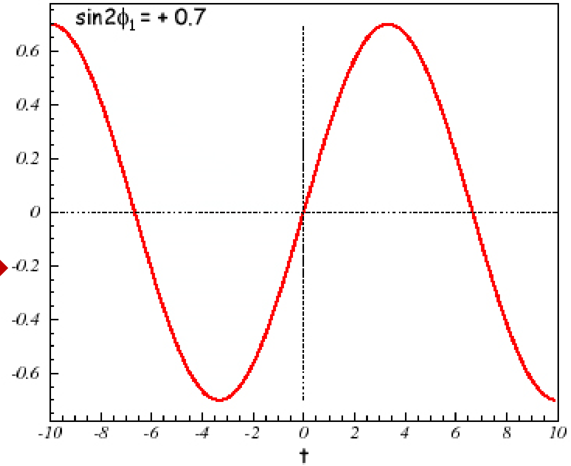
$L = 1$ state

# How to measure $\beta/\phi_1$?




To determine the angle $\phi_1$ of the unitarity triangle, we have to measure the time dependence of the difference in $\overline{B}^0 \to J/\Psi K_s$ and $B^0 \to J/\Psi K_s$ decays



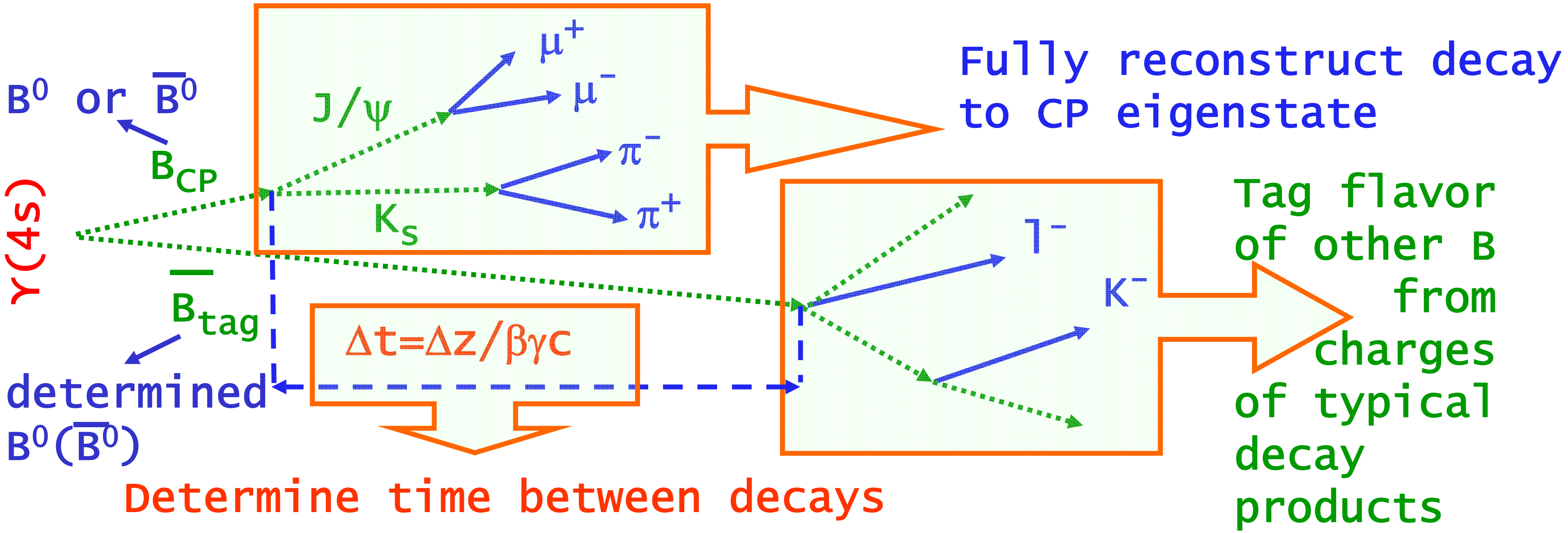




$$a_{f_{CP}} = -\frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

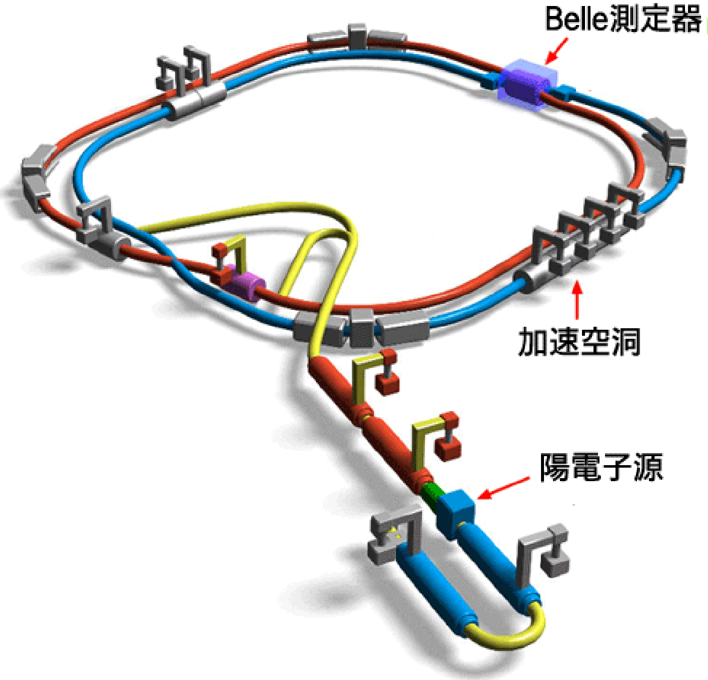
Time dependent decay rate difference - CP asymmetry:

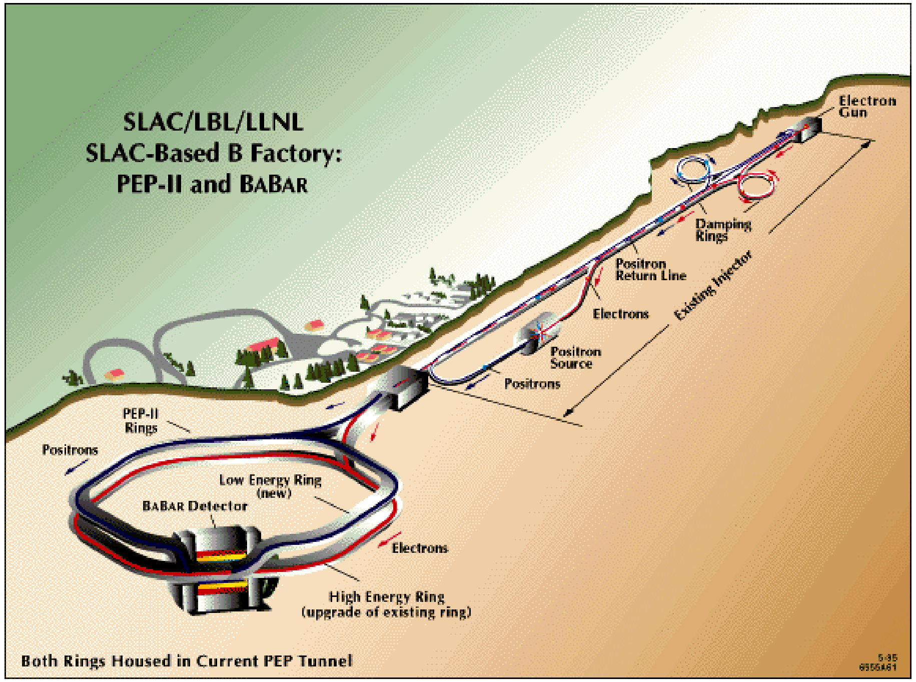
$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t) = \sin 2\phi_1 \sin(\Delta m t)$$

# Principle of measurement



# Colliders: asymmetric B factories




$\sqrt{s}=10.58$ GeV

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

$\Upsilon(4s) \rightarrow B\,\bar{B}$

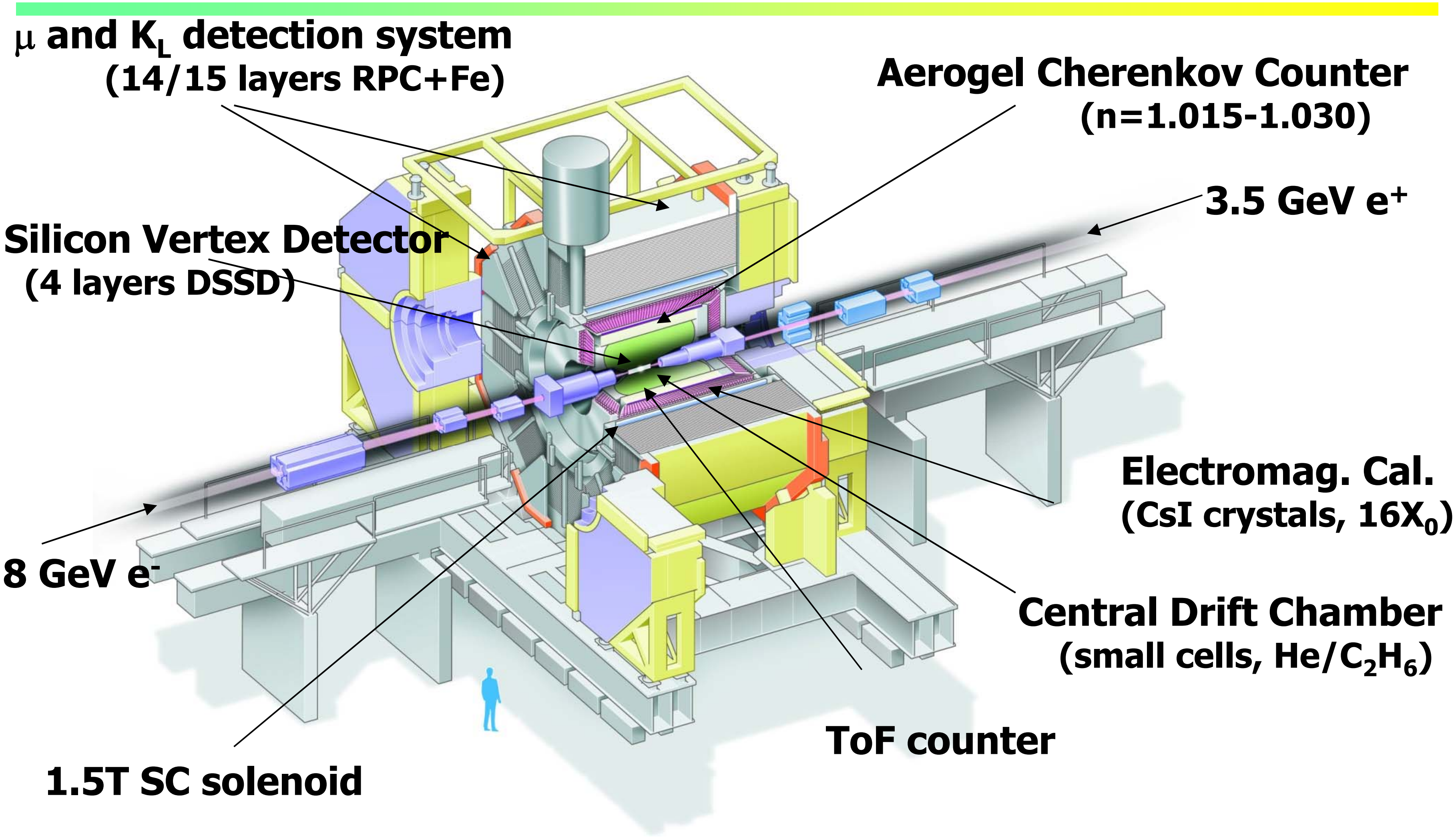
$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$

**BaBar** $p(e^-)=9$ GeV $p(e^+)=3.1$ GeV $\beta\gamma=0.56$

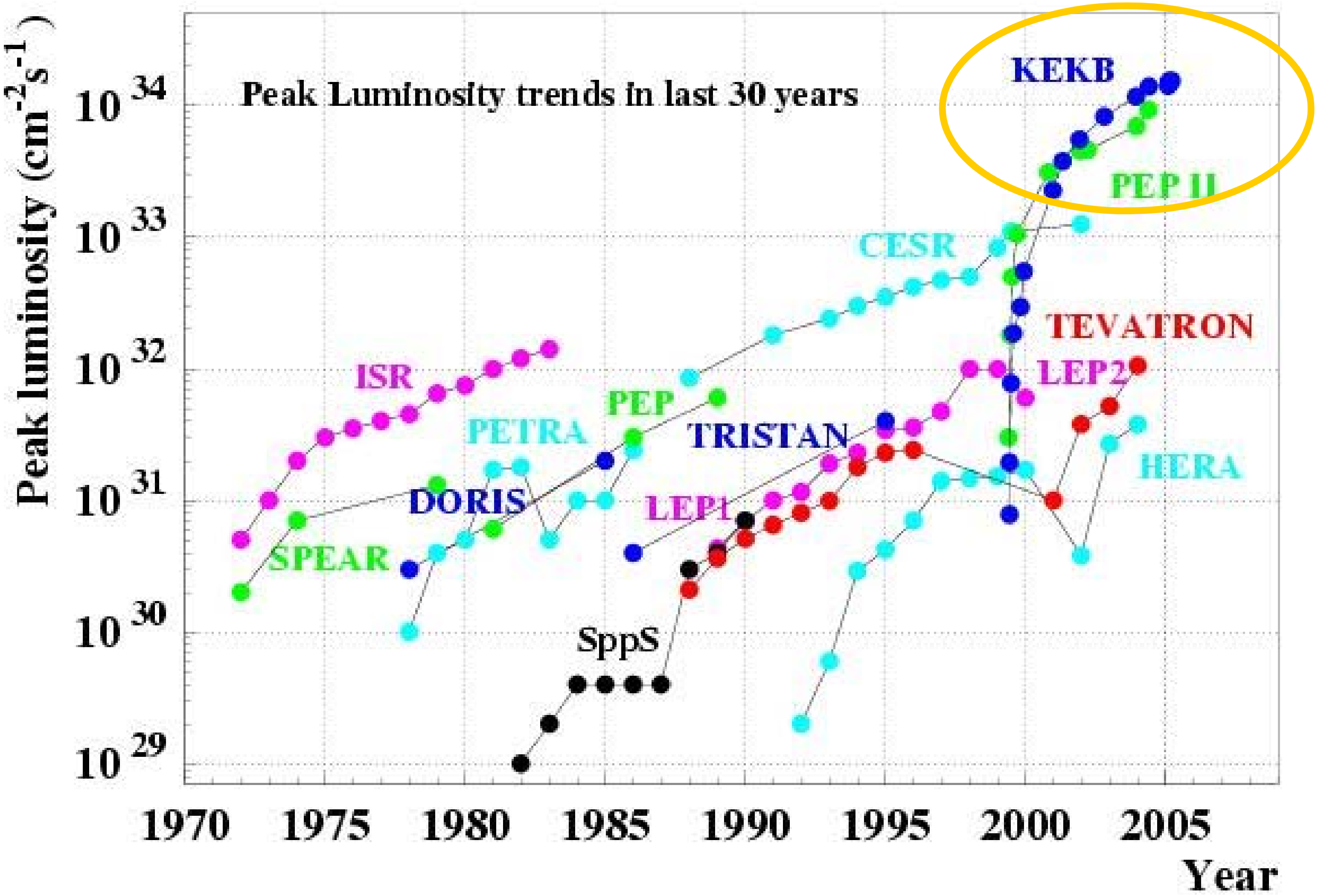
**Belle** $p(e^-)=8$ GeV $p(e^+)=3.5$ GeV $\beta\gamma=0.42$


BELLE

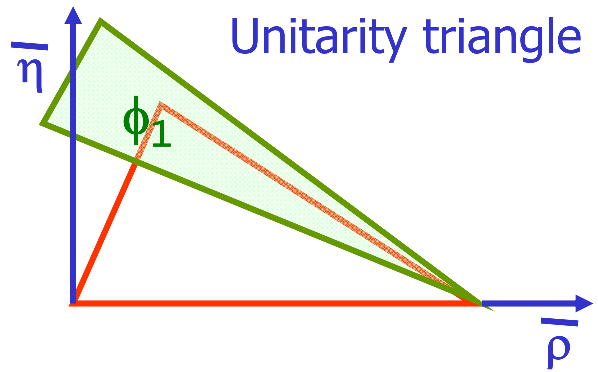
# Belle spectrometer at KEK-B



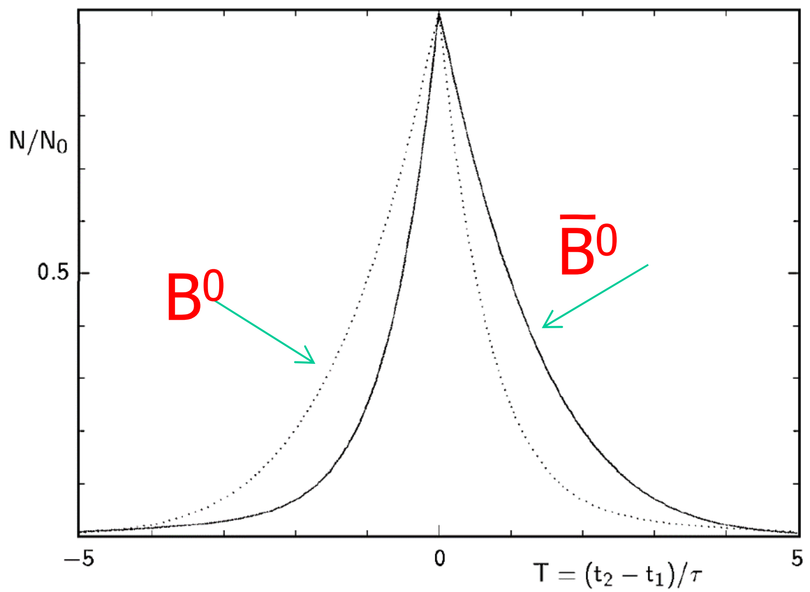
# Accelerator performance

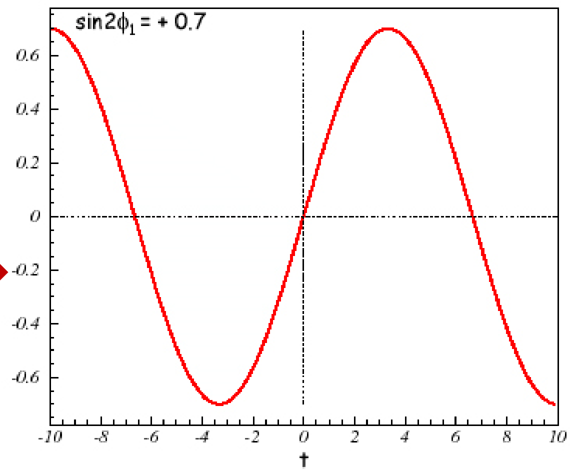


# How to measure $\beta/\phi_1$?




To determine the angle $\phi_1$ of the unitarity triangle, we have to measure the time dependence of the difference in $\bar{B}^0 \to J/\Psi\ K_s$ and $B^0 \to J/\Psi\ K_s$ decays



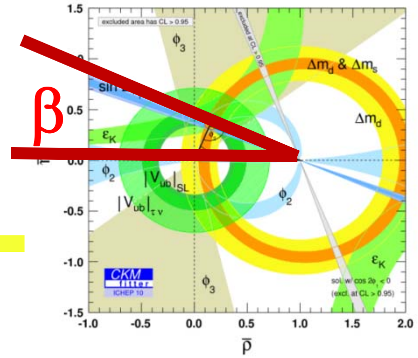




$$a_{f_{CP}} = -\frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

Time dependent decay rate difference - CP asymmetry:

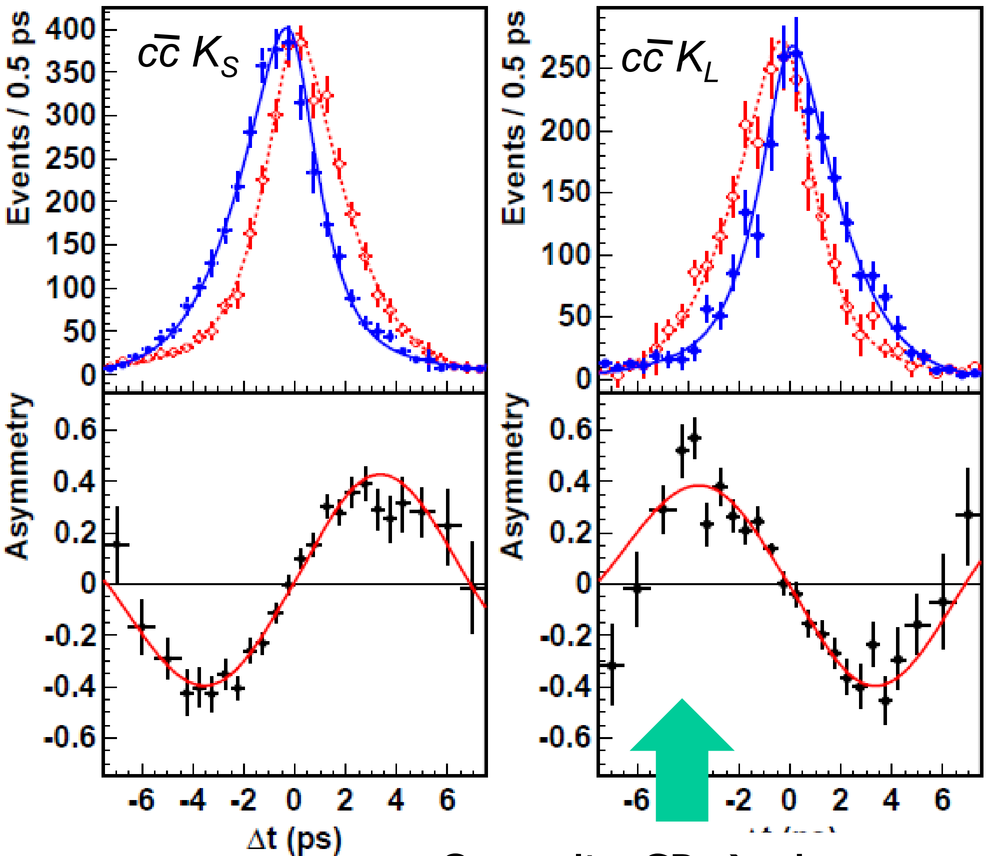
$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t) = \sin 2\phi_1 \sin(\Delta m t)$$

# Final measurement of $\sin 2\phi_1$ (=sin2β)



## $\phi_1$ from CP violation measurements in $B^0 \to J/\psi K^0$

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




Opposite CP → sine wave with a flipped sign

$\sin 2\phi_1$ (=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%!

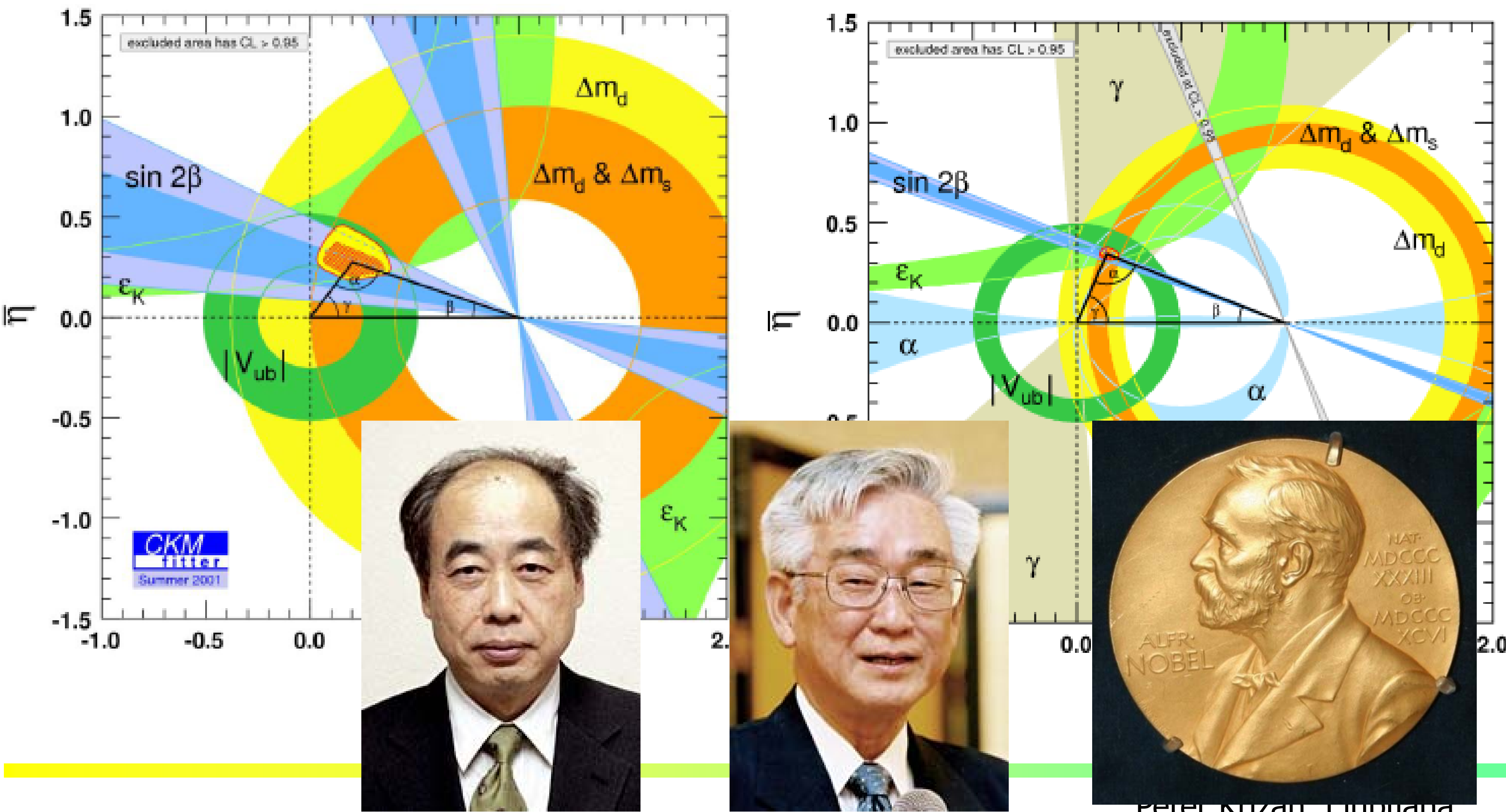
$\phi_1 = \beta = (21.4 \pm 0.8)^0$

# Summary: 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 KM

EPS 2001

EPS 2011

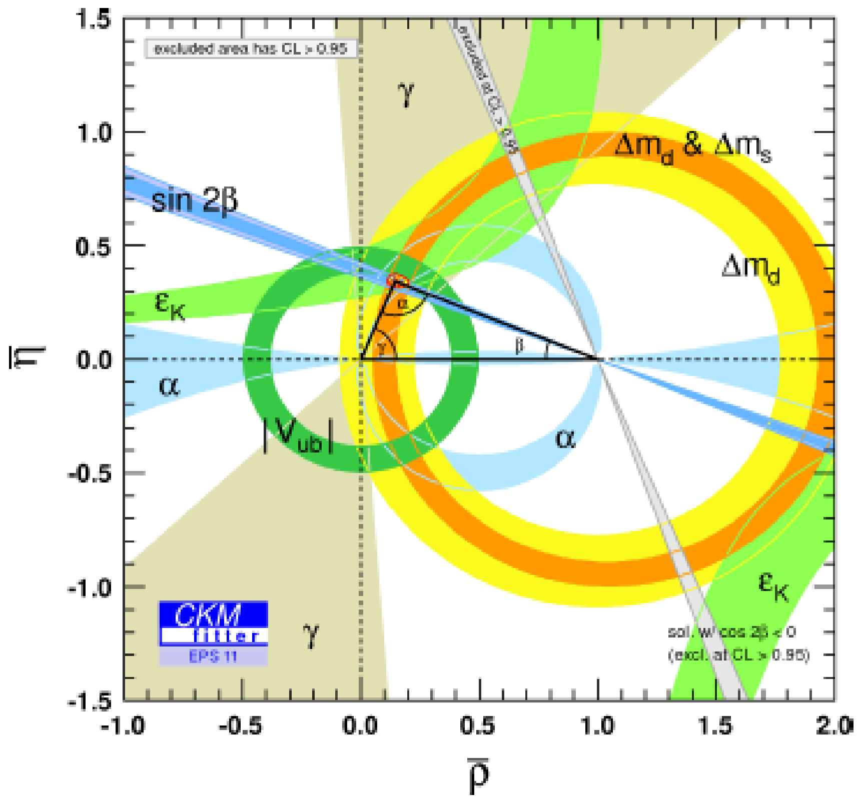


# B factories: a success story

- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g., $B \rightarrow \tau\nu$, $D\tau\nu$)
- $b \rightarrow s$ transitions: probe for new sources of CPV and constraints from the $b \rightarrow s\gamma$ branching fraction
- Forward-backward asymmetry ($A_{FB}$) in $b \rightarrow sl^+l^-$
- Observation of D mixing
- Searches for rare $\tau$ decays
- Discovery of exotic hadrons including charged charmonium- and bottomonium-like states

# The unitarity triangle – status

Constraints from measurements of angles and sides of the unitarity triangle → remarkable agreement, but contributions of New Physics could be as high as 10-20%

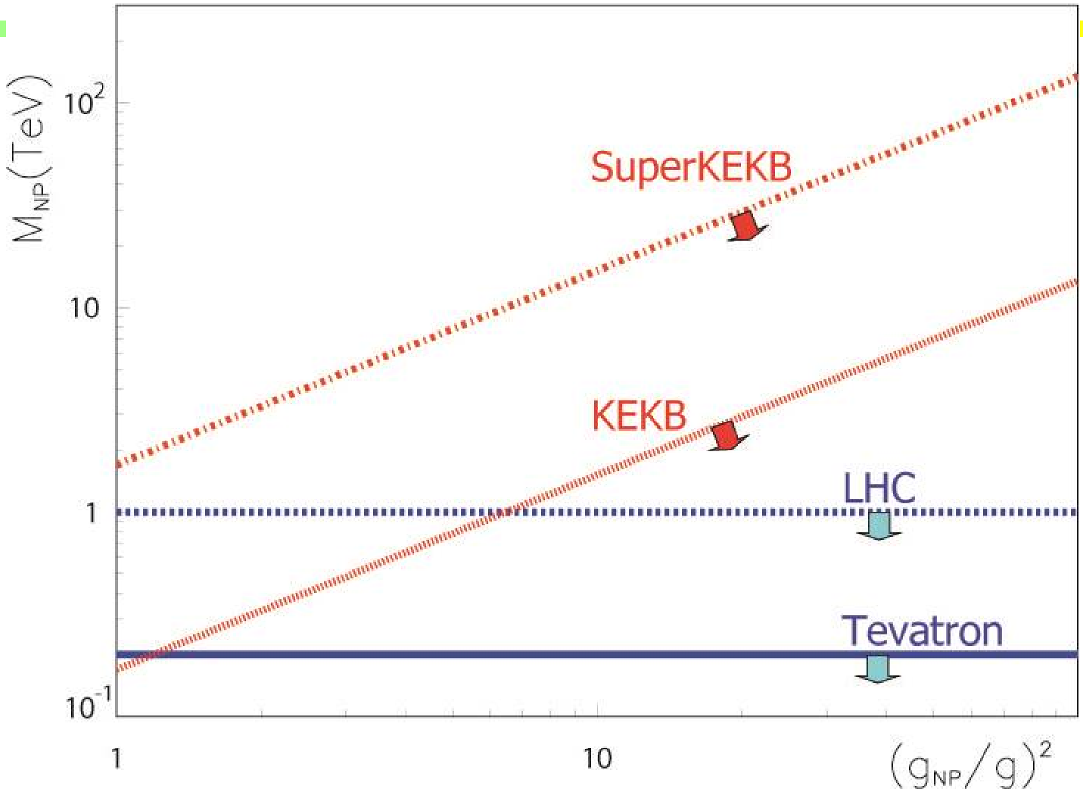



→investigate possible NP phenomena with precise measurements

→Intensity frontier

# Intensity Frontier vs Energy Frontier

Reach in mass of New Physics particles



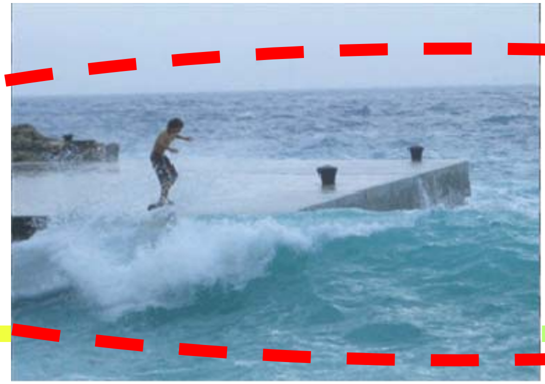

New Physics coupling vs standard model

→ A very interesting complementarity of the two approaches

# 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)**

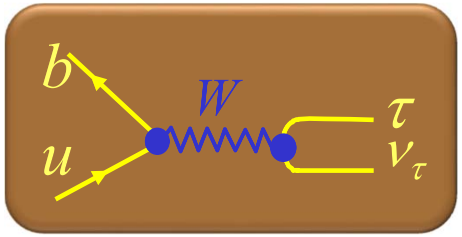
**Luminosity frontier - (super) B factories**

# It worked already many times!

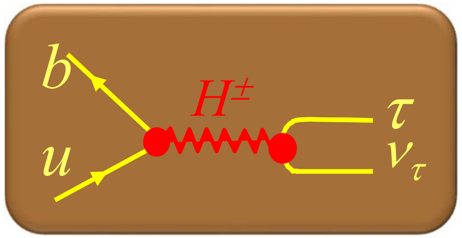
- The smallness of $K_L \to \mu^+\mu^-$ → GIM mechanism →need one more quark – c
- $K^0$ – anti-$K^0$ mixing frequency $\Delta m_K$ → estimate the charm quark mass
- Mixing in the $B^0$ system: large mixing rate → high top mass; top quark has only been discovered seven years later!
- CP violation in K decays (1964) → KM mechanism (1973) → need three more quarks, discovered later in 1974, 1977, 1995

# An example: Hunting the charged Higgs in the decay $B^- \to \tau^- \nu_\tau$

In addition to the Standard Model Higgs discovered at the LHC, in New Physics (e.g., in supersymmetric theories) there could be another – a charged Higgs.




The rare decay $B^- \to \tau^- \nu_\tau$ is in SM mediated by the W boson



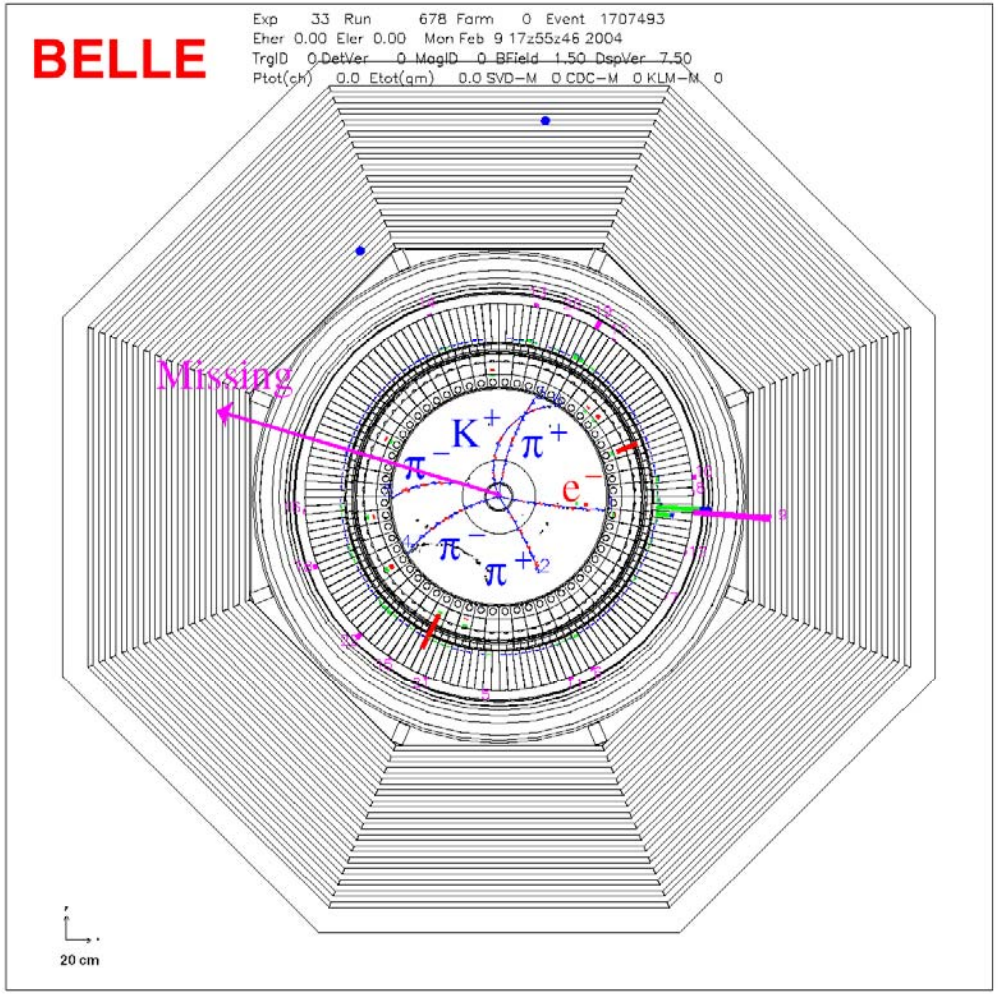

In some supersymmetric extension it can also proceed via a charged Higgs

The charged Higgs would influence the decay of a B meson to a tau lepton and its neutrino, and modify the probability for this decay.

# $B^- \rightarrow \tau^- \nu_\tau$

Example of a $B^- \rightarrow \tau^- \nu_\tau$ decay as measured at Belle

$$
\begin{aligned}
B^+ &\rightarrow D^0\pi^+ \\
&\qquad (\rightarrow K\pi^-\pi^+\pi^-) \\
B^- &\rightarrow \tau(\rightarrow e\nu\bar{\nu})\nu
\end{aligned}
$$

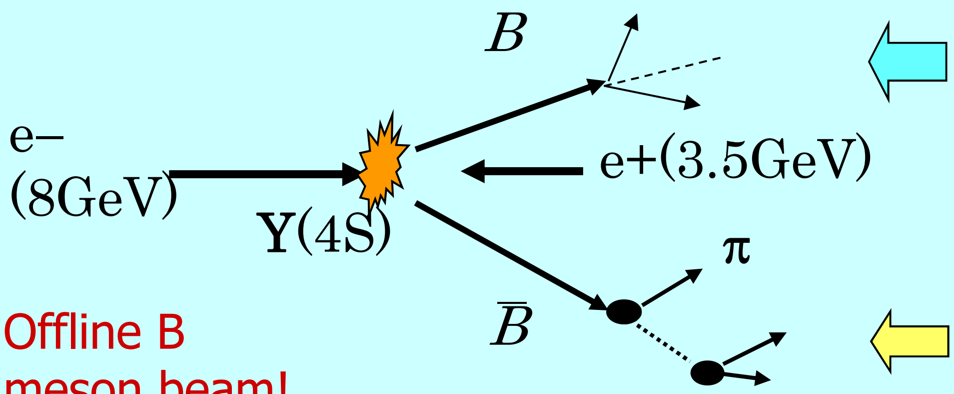



Tough to tackle experimentally: three neutrinos in the final state and only one charged particle from the B decay.

Can be carried out at B factories! →

# Full reconstruction tagging

Idea: fully reconstruct one of the B's to tag B flavor/charge, determine its momentum, and exclude decay products of this B from further analysis




Decays of interest

- $B \rightarrow X_u\, l\, \nu$,
- $B \rightarrow K\, \nu\, \nu$
- $B \rightarrow D\tau\nu$, $\tau\nu$

full reconstruction
$B \rightarrow D\pi$ etc. (0.1-0.3%)

Offline B meson beam!

Powerful tool for B decays with neutrinos

→unique feature at B factories

# What next?

Next generation: Super B factories → Looking for NP

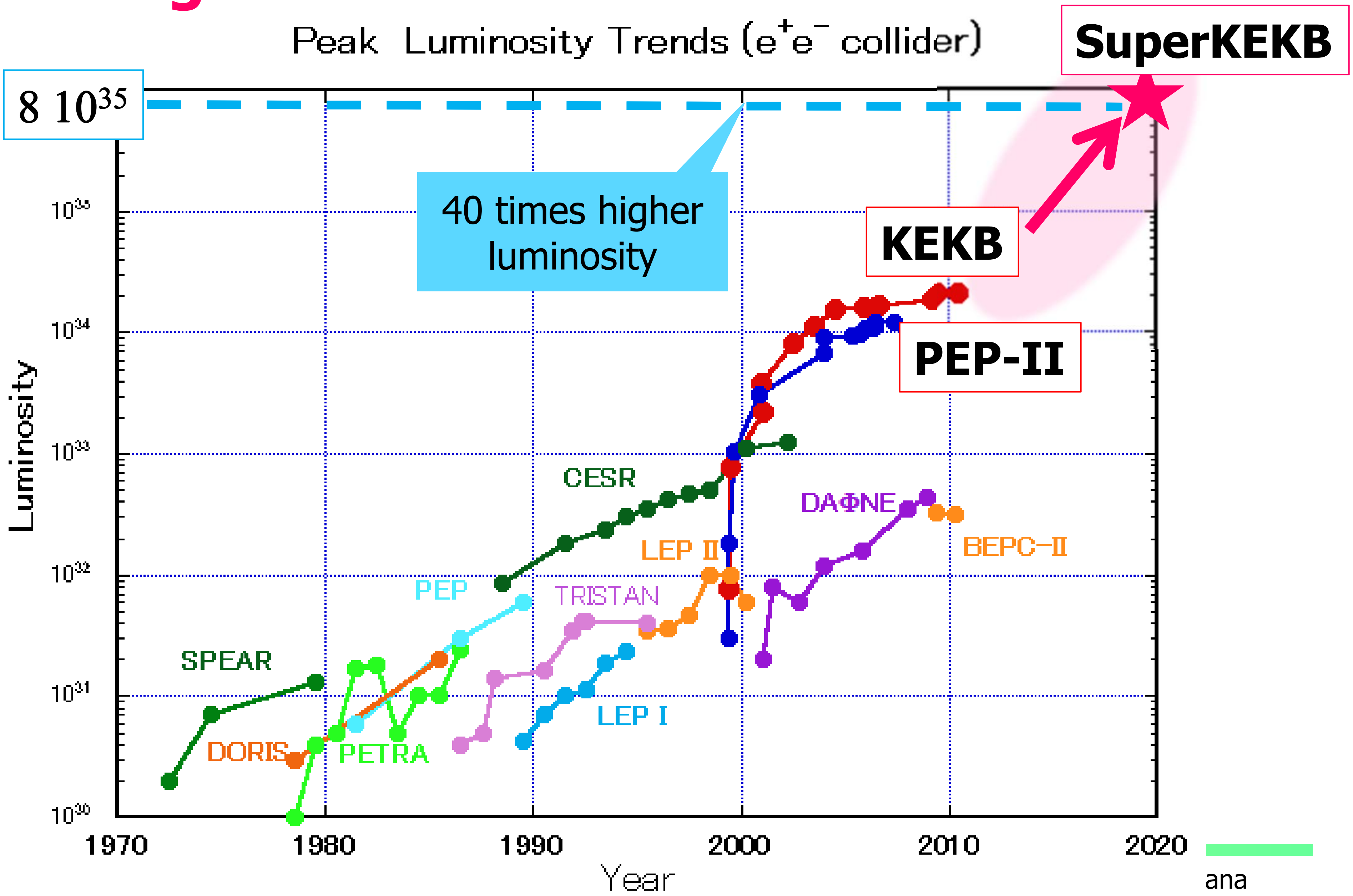
→ Need much more data (almost two orders!)

However: it will be a different world in two years, there is a hard competition from LHCb and BESIII

Still, a $e^+e^-$ 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)

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



# How to increase the luminosity?

Super KEKB Quest for BSM

Beam-beam parameter

Lorentz factor

Beam current

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

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 $b_y^*$**
**(2) Increase beam currents**
(3) Increase $x_y$

**"Nano-Beam" scheme**

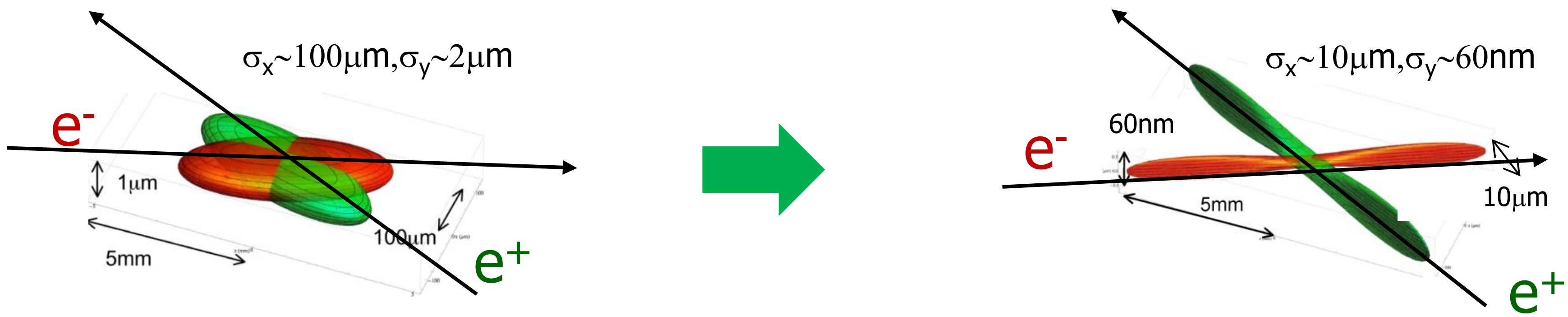
***Collision with very small spot-size beams***

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?

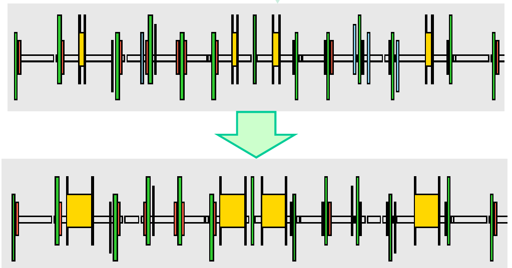
In KEKB, colliding electron and positron beams were already much thinner than a human hair...



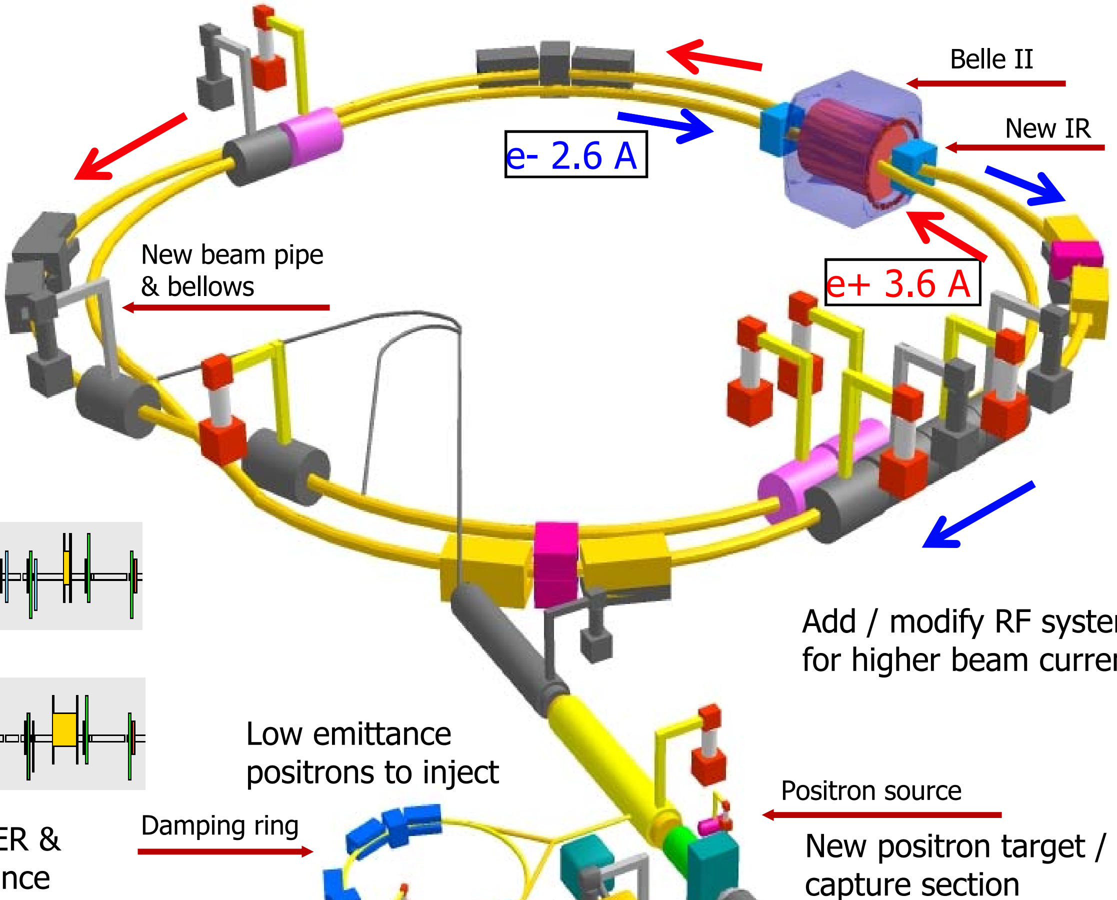

... For a 40x increase in intensity you have to make the beam as thin as a few x100 atomic layers!

# KEKB → SuperKEKB

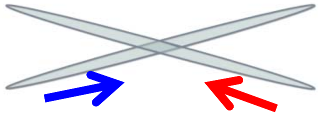
Replace short dipoles with longer ones (LER)



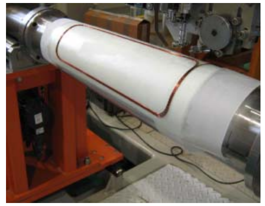
Redesign the lattices of HER & LER to squeeze the emittance




Colliding bunches

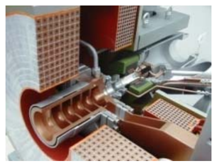


New superconducting /permanent final focusing quads near the IP

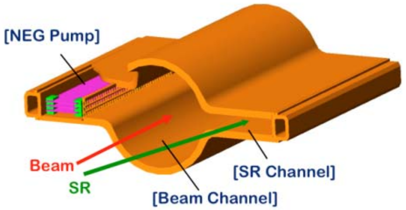


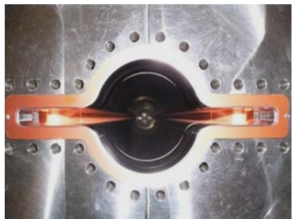
Add / modify RF systems for higher beam current

New positron target / capture section



TiN-coated beam pipe with antechambers



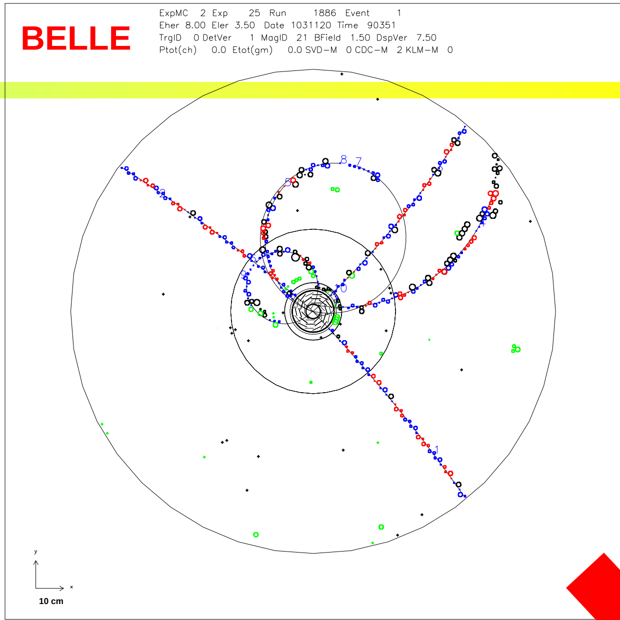



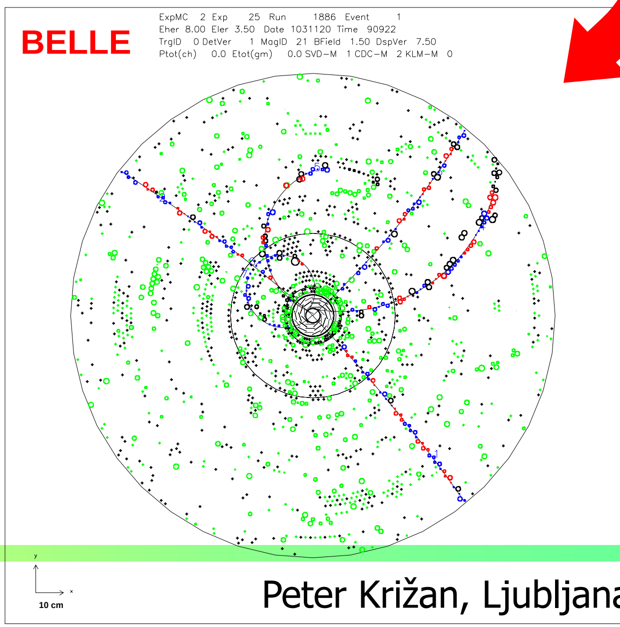
***To get x40 higher luminosity***

# Requirements for the Belle II detector

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

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



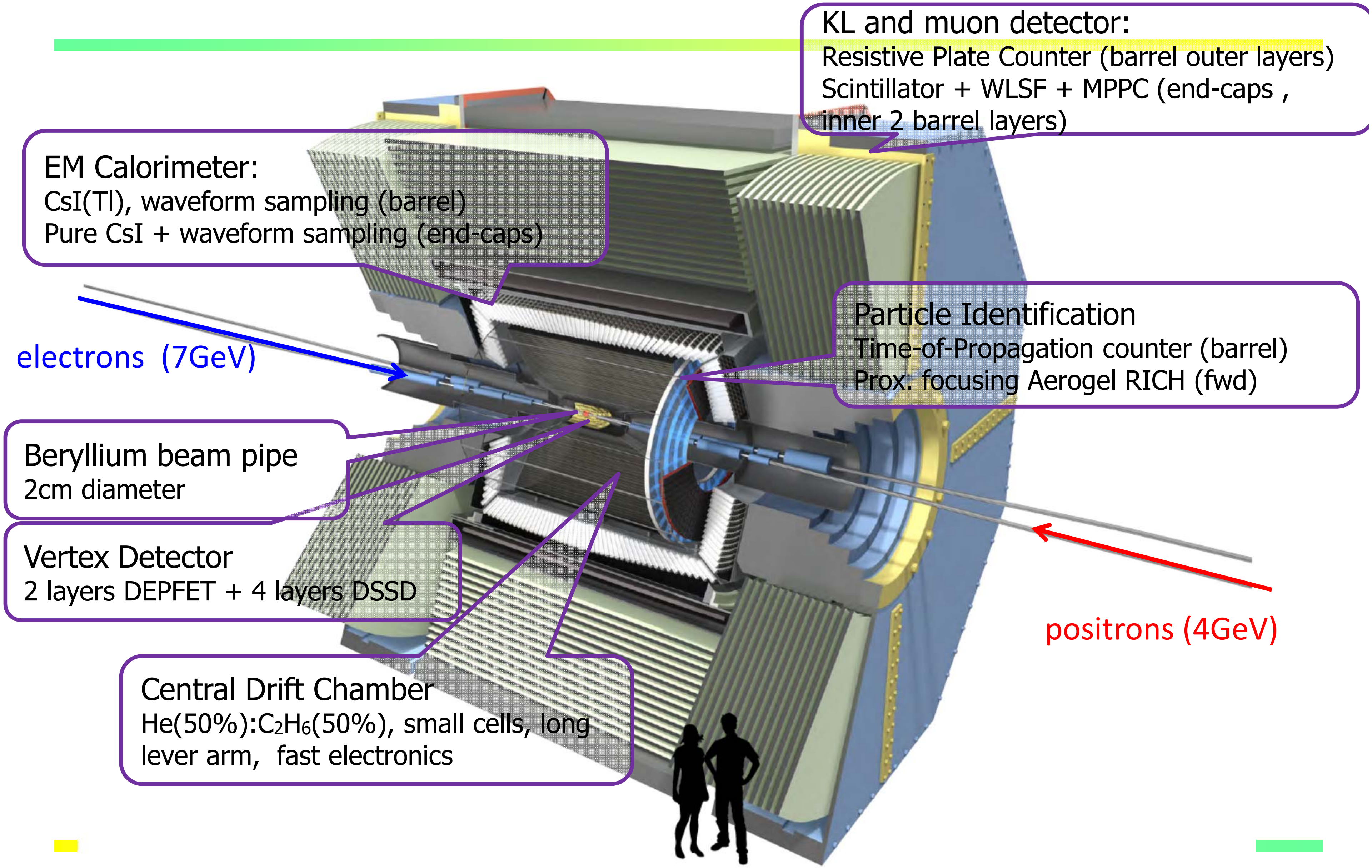




Solutions:

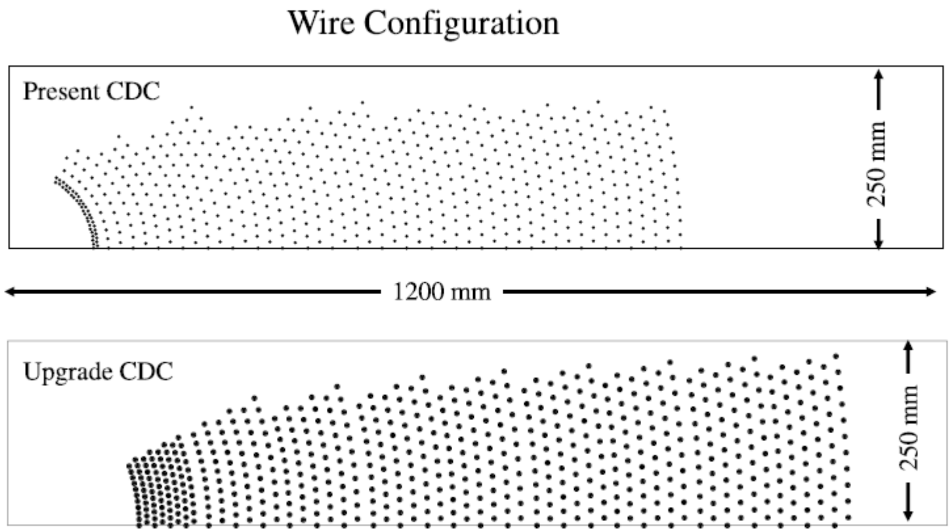
- Replace inner layers of the vertex detector with a pixel detector.
- Replace inner part of the central tracker with a silicon strip detector.
- Better particle identification device
- Replace endcap calorimeter crystals
- Faster readout electronics and computing system.

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

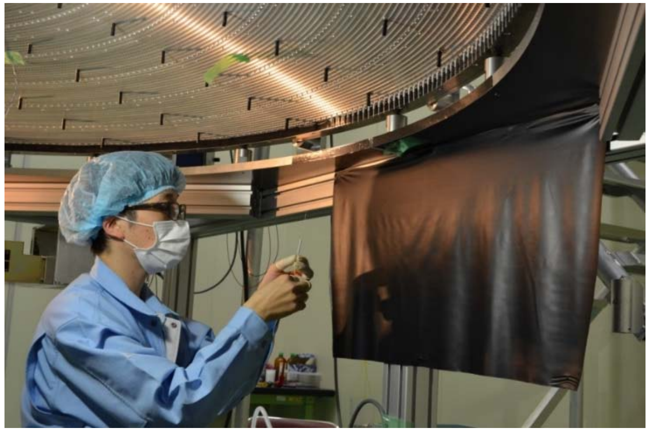
# Belle II Detector



# Belle II CDC

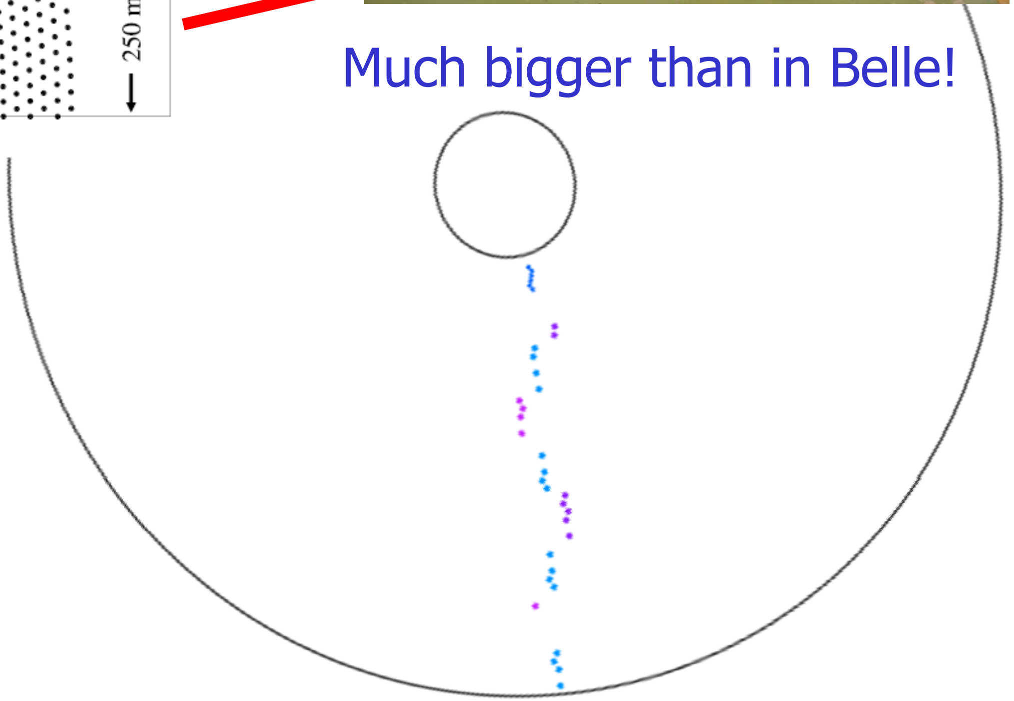



Much bigger than in Belle!



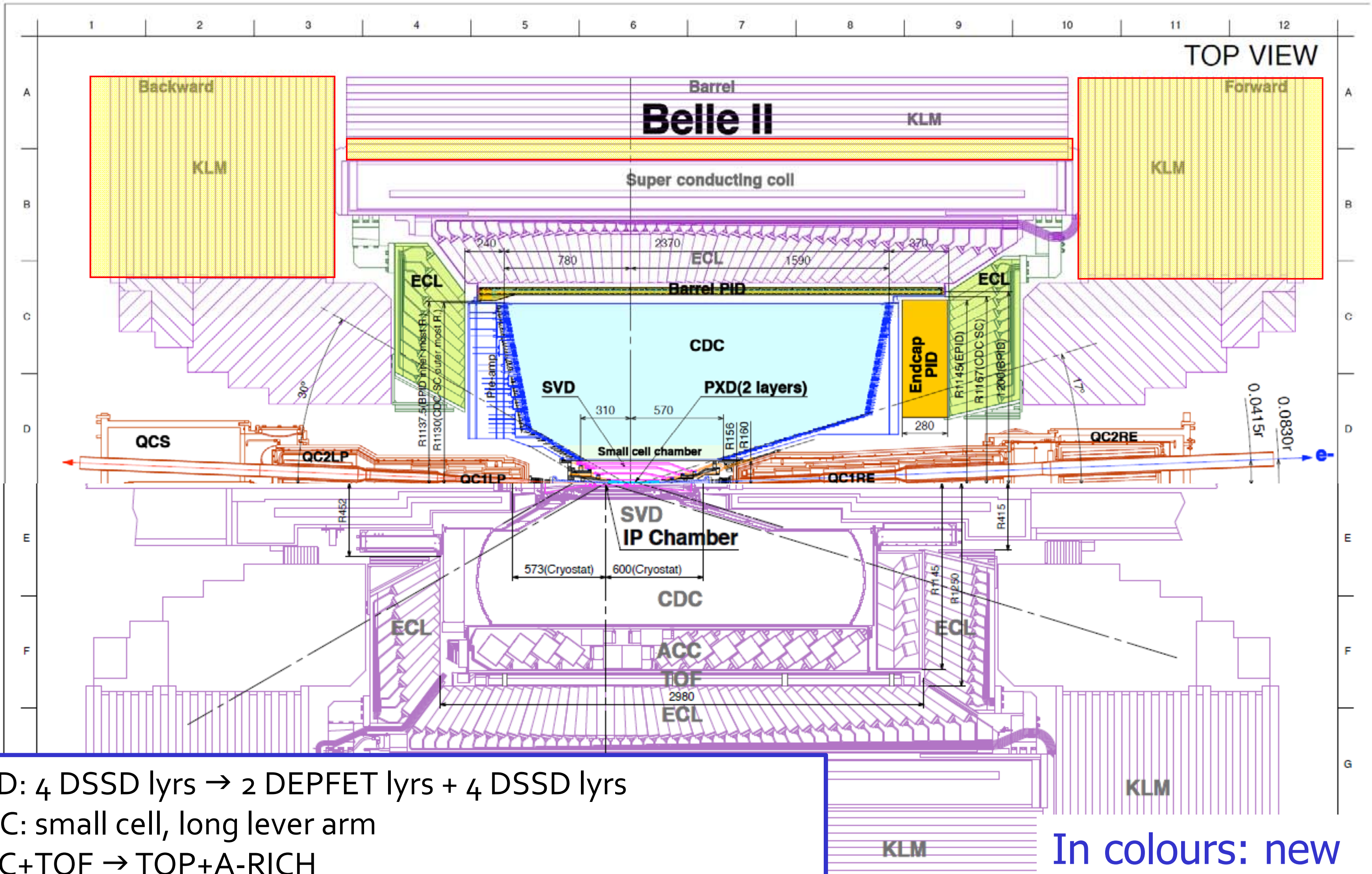
Wire stringing in a clean room

- thousands of wires,
- 1 year of work...



Being commissioned with cosmic rays.

# Belle II Detector (in comparison with Belle)

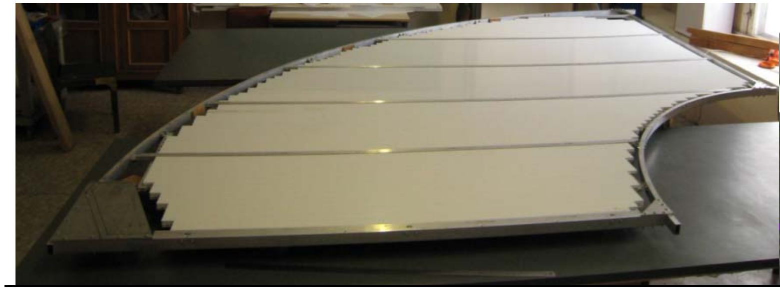


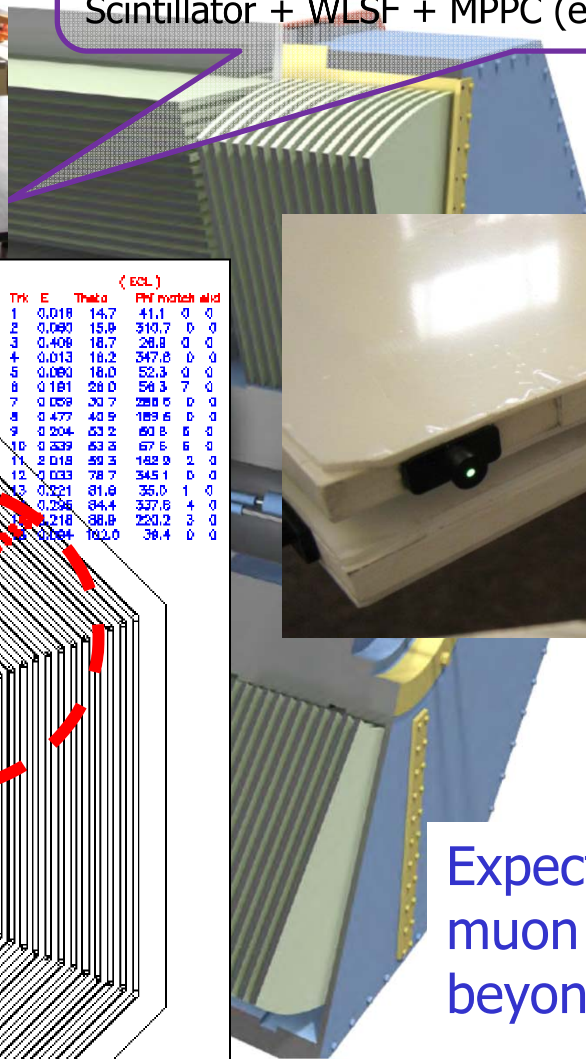

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

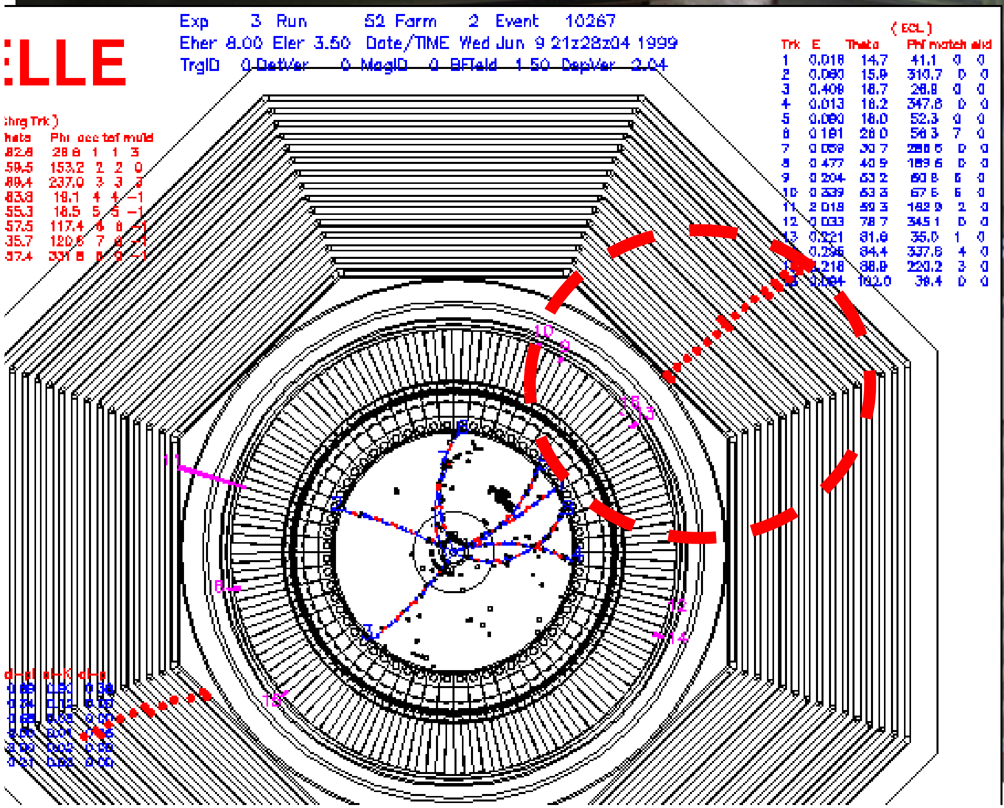
In colours: new components

Detection of muons and $K_L$s: a sizable part of the present RPC system have to be replaced to handle higher backgrounds (mainly from neutrons).

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



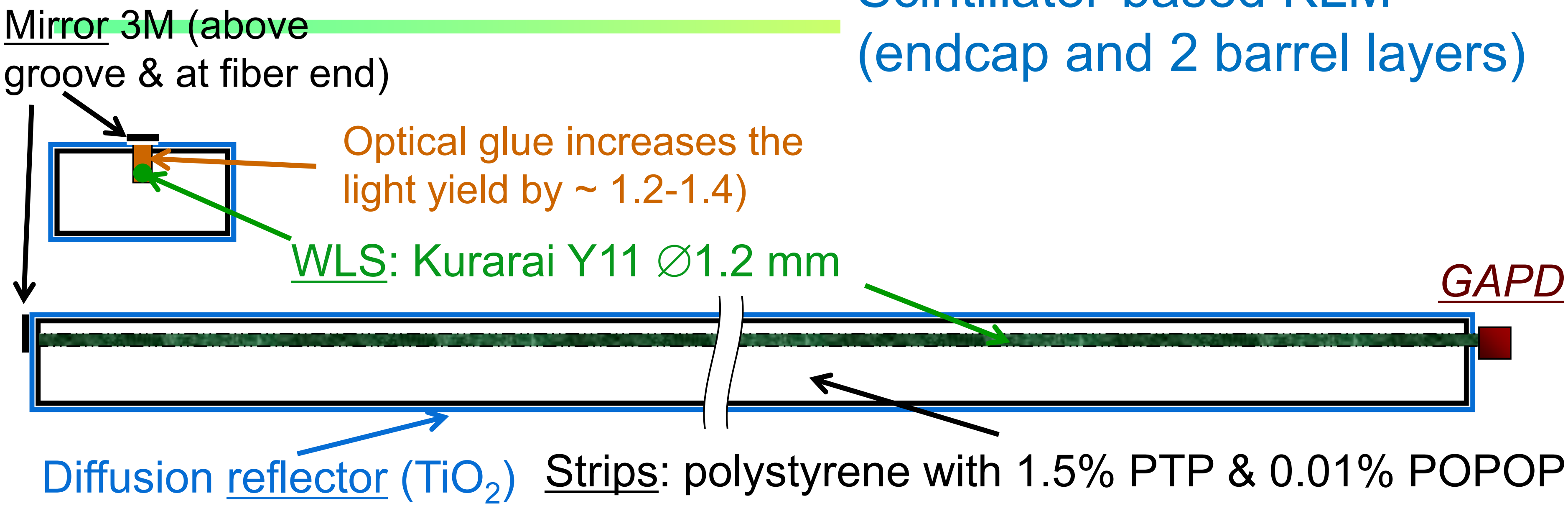




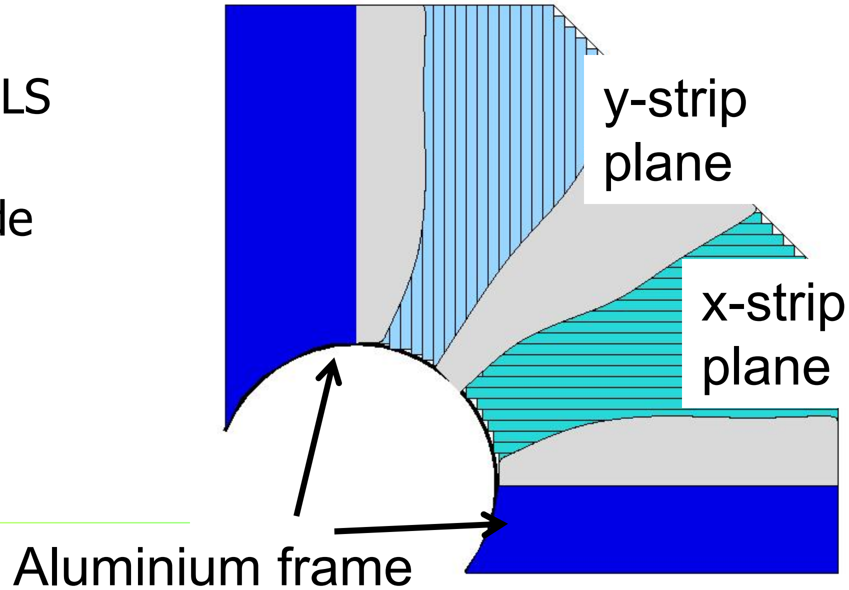

Expected to improve $K_L$ and muon detection efficiency beyond Belle performance.

# Muon detection system upgrade

## Scintillator-based KLM (endcap and 2 barrel layers)

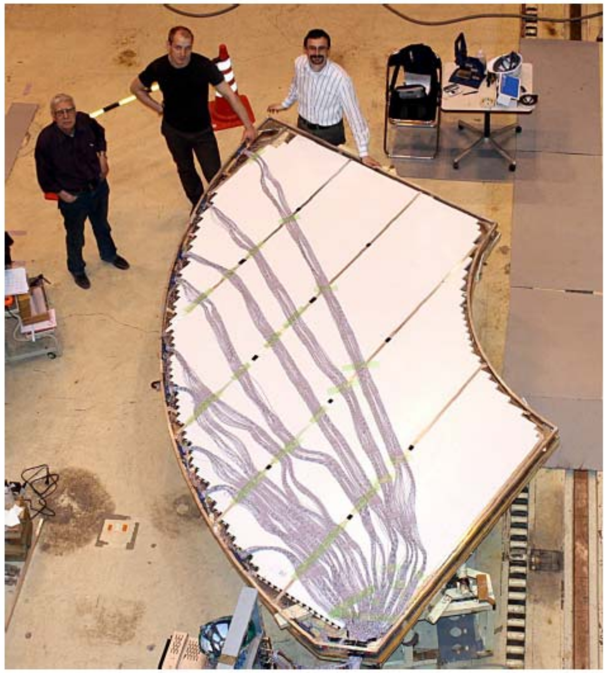


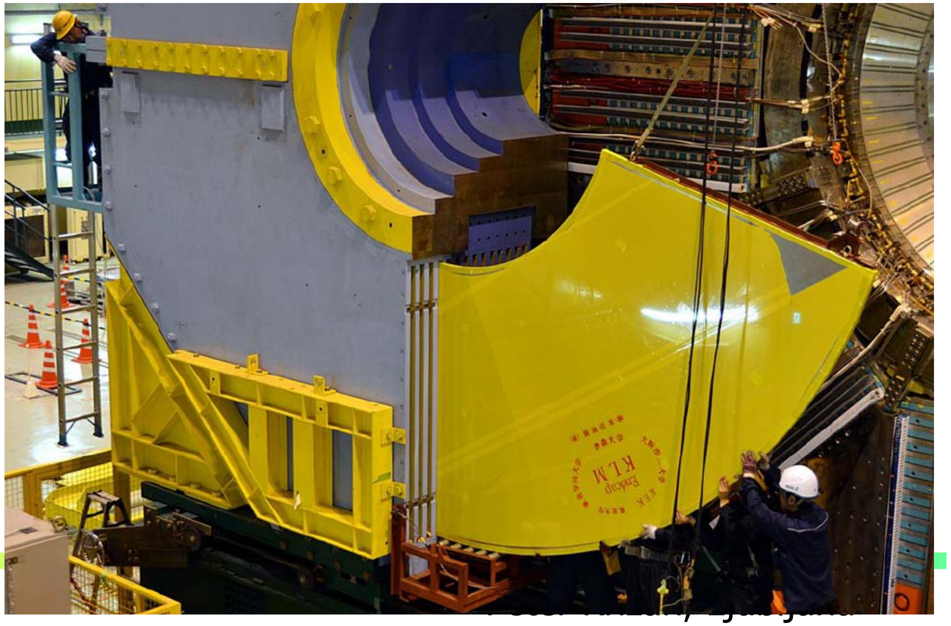

- Two independent (x and y) layers in one superlayer made of orthogonal strips with WLS read out
- Photo-detector = SiPM (avalanche photodiode in Geiger mode)
- ~120 strips in one 90º sector (max L=280cm, w=25mm)
- ~30000 read out channels
- Geometrical acceptance > 99%



# Muon detection system upgrade

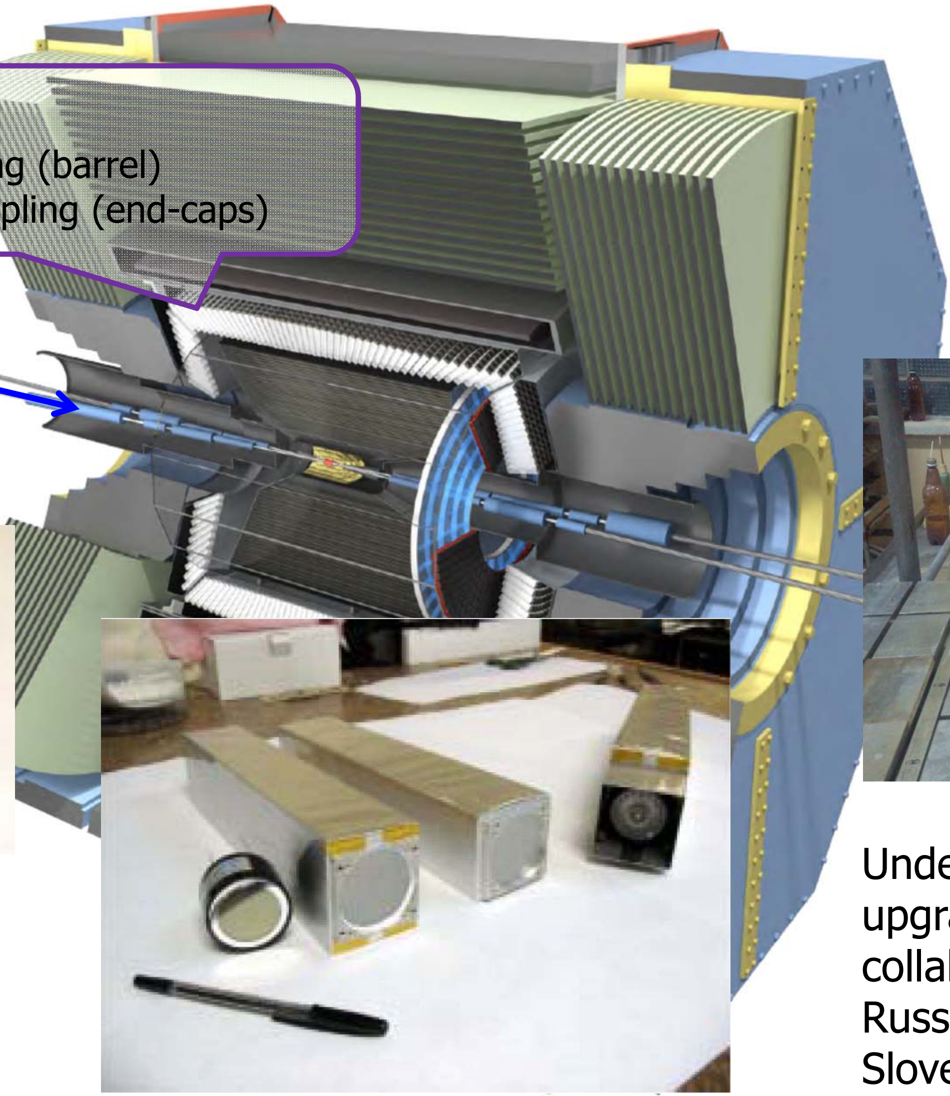
Scintillator-based KLM:
•design and construction of modules at ITEP, Moscow
•installation of final modules in the Belle II detector – the first Belle II component to be ready!

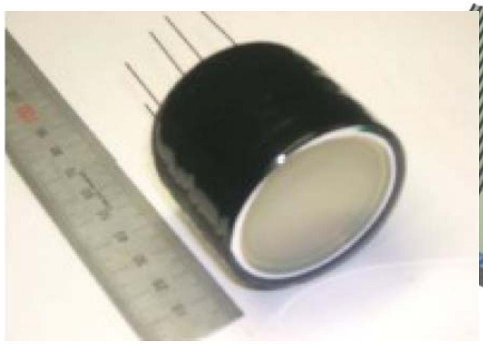




EM calorimeter: upgrade needede because of higher rates (barrel: electronics, endcap: electronics and CsI(Tl) → pure CsI) and radiation load (endcap: CsI(Tl) → pure CsI)

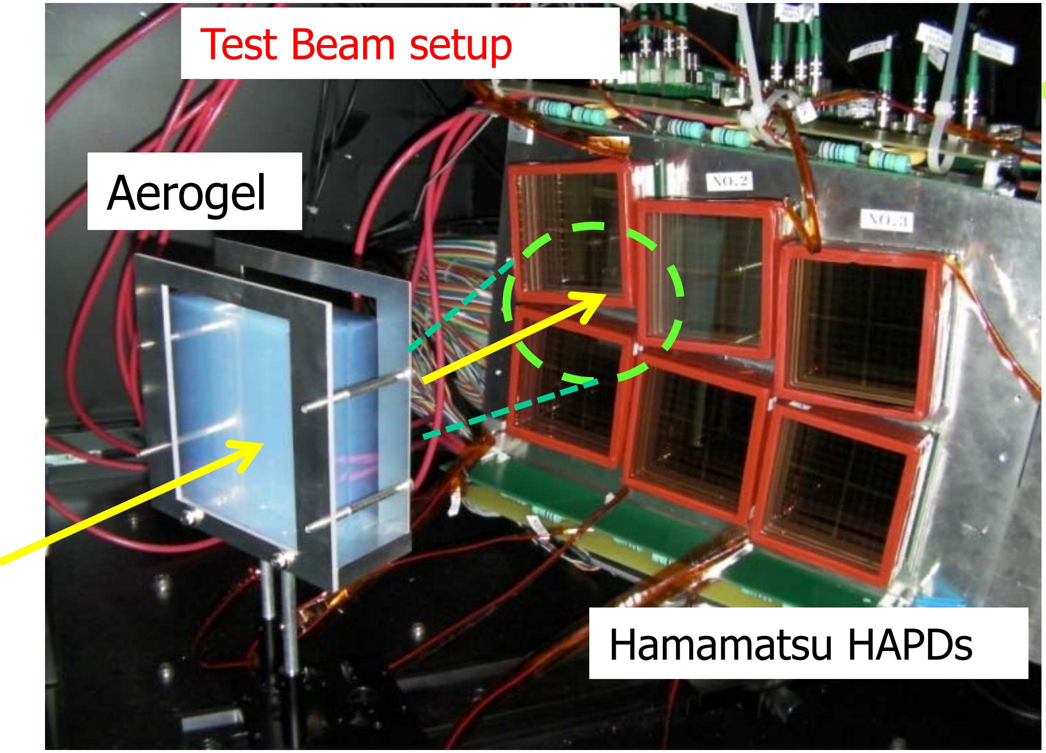
EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

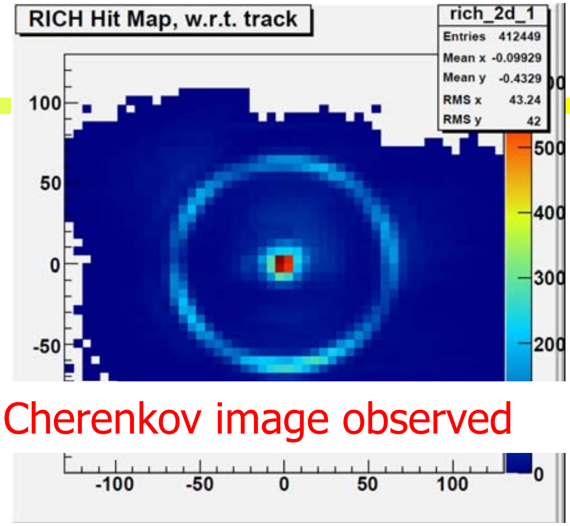




Under discussion: an upgrade to pure CsI, a collaborative effort of Russia, Canada, Italy, Japan, Slovenia

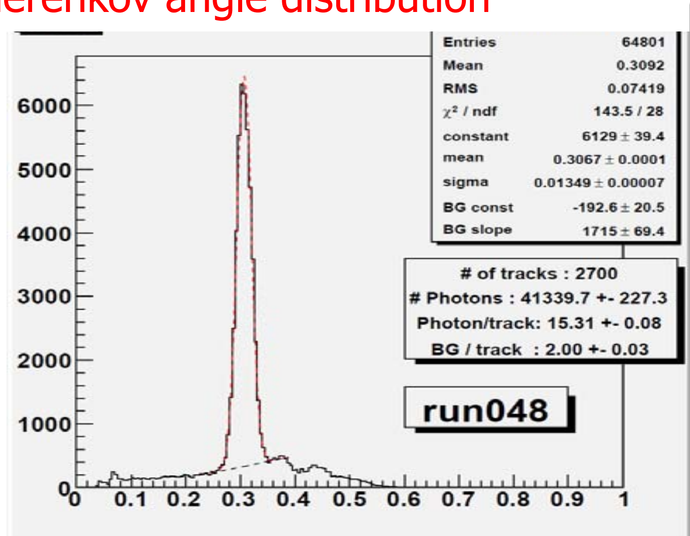
# Aerogel RICH (endcap PID)



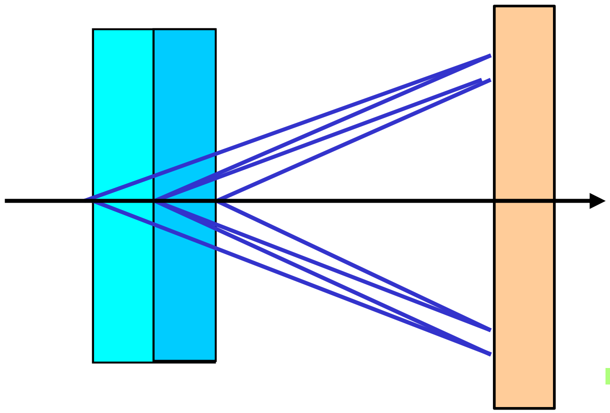

Clear Cherenkov image observed

Cherenkov angle distribution




**6.6 σ π/K at 4GeV/c !**

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



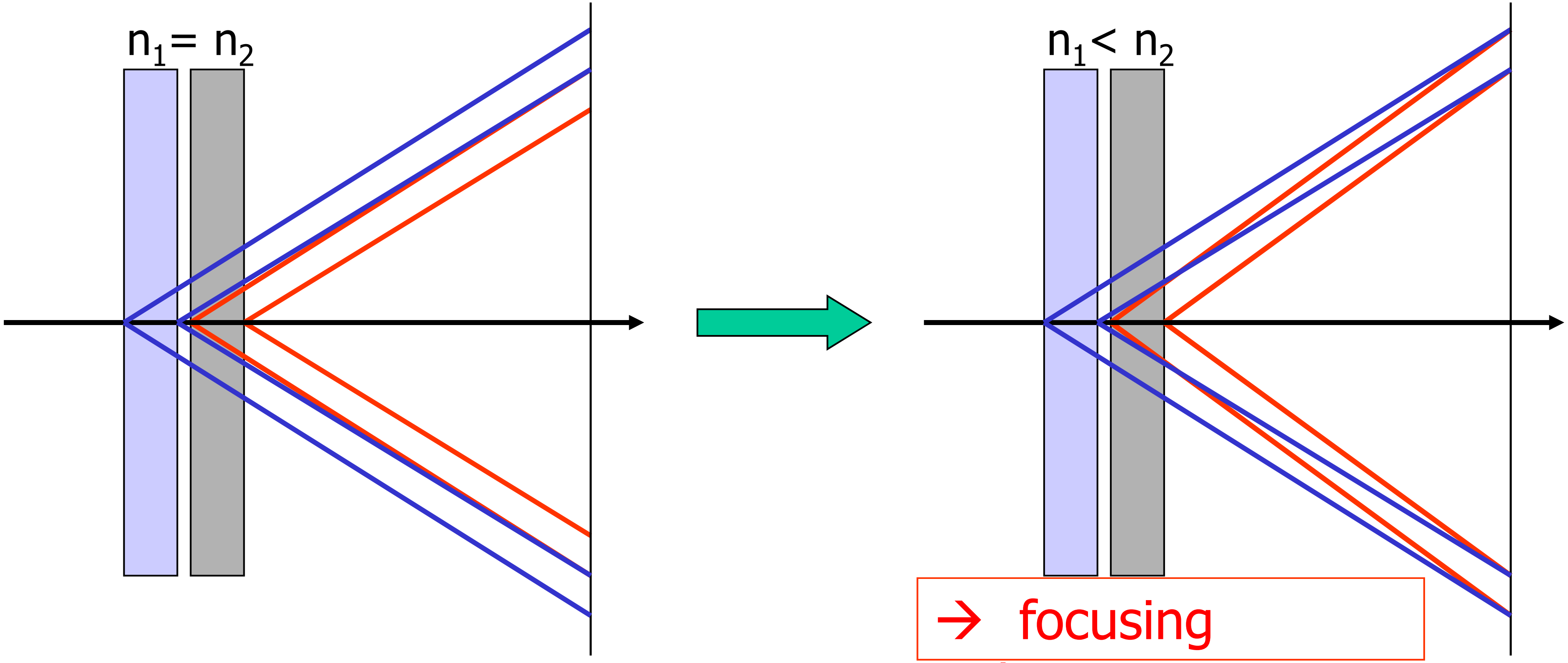
Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.

# Radiator with multiple refractive indices

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

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

normal

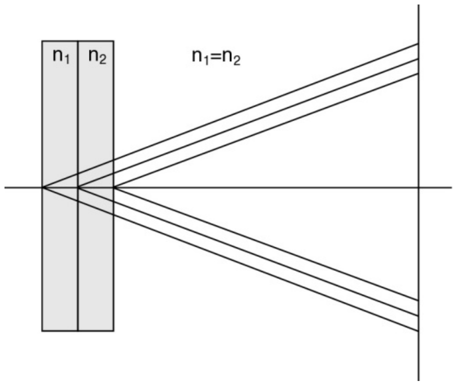



Such a configuration is only possible with aerogel (a form of $Si_xO_y$) – material with a tunable refractive index between 1.01 and 1.13.

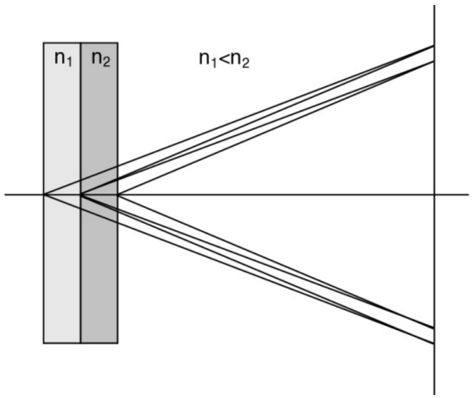
# Focusing configuration – data

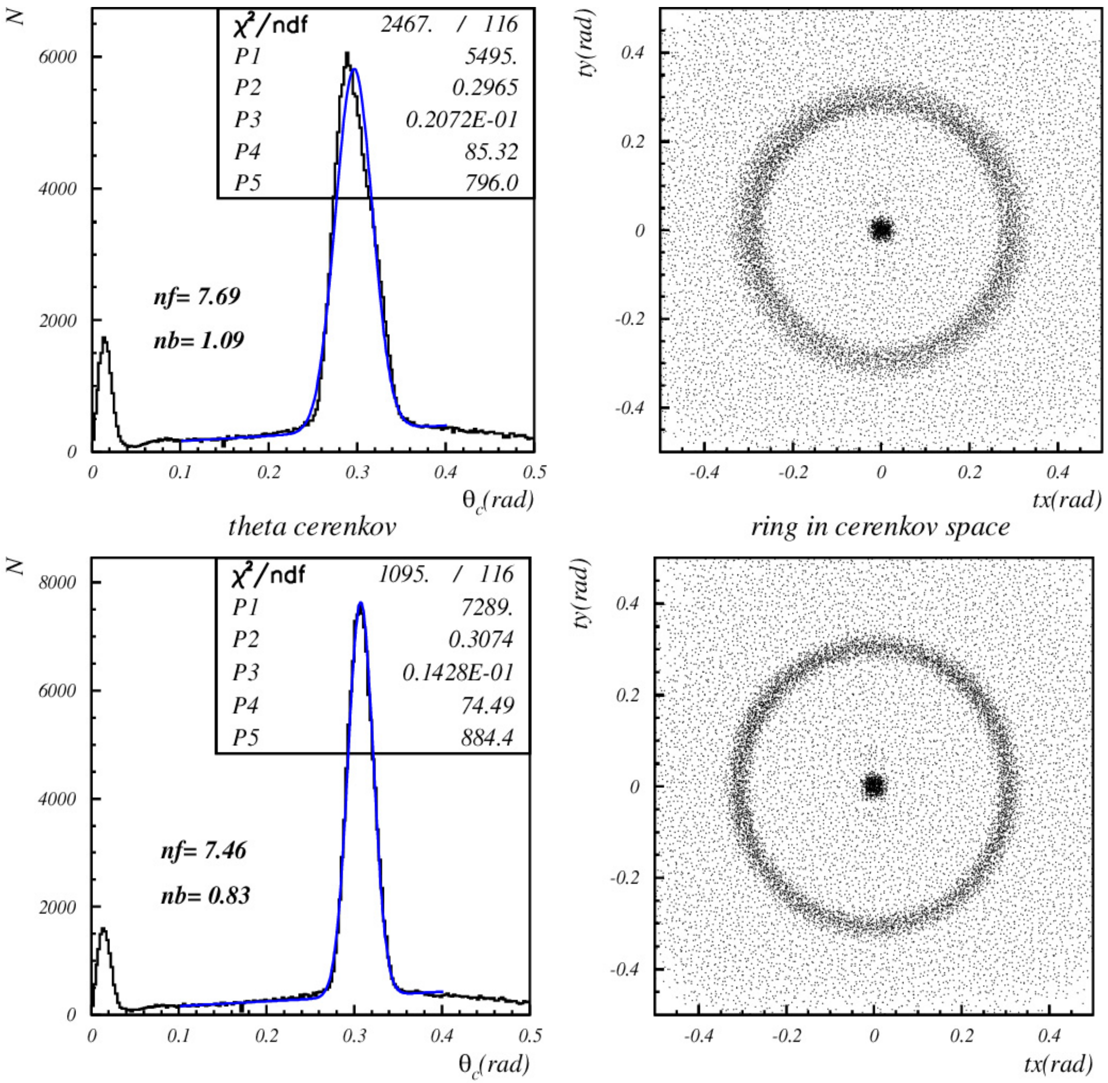
Increases the number of photons without degrading the resolution

## 4cm aerogel single index




## 2+2cm aerogel



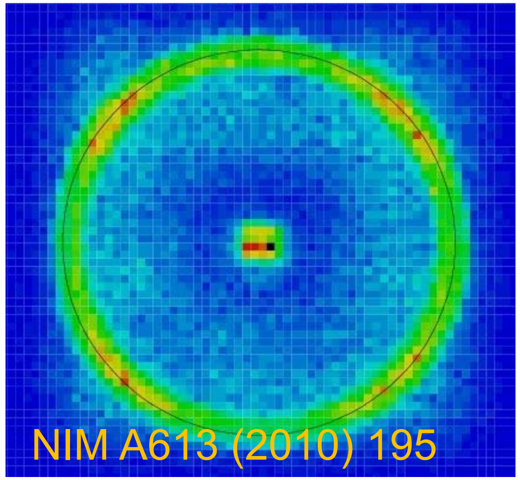




→NIM A548 (2005) 383

# SiPMs as single photon detectors for RICH counters?

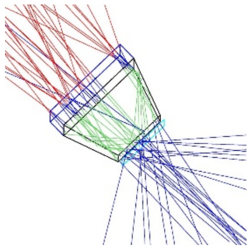
SiPMs have excellent properties (low operation voltage, high gain, high PDE, excellent time resolution, work in high magnetic field) but also have serious drawback - dark counts ~ few 100 kHz/mm$^2$ .

→Challenge in a RICH counter where we have to detect single photons (dark counts have single photon pulse heights, rates 0.1-1 MHz/mm$^2$).

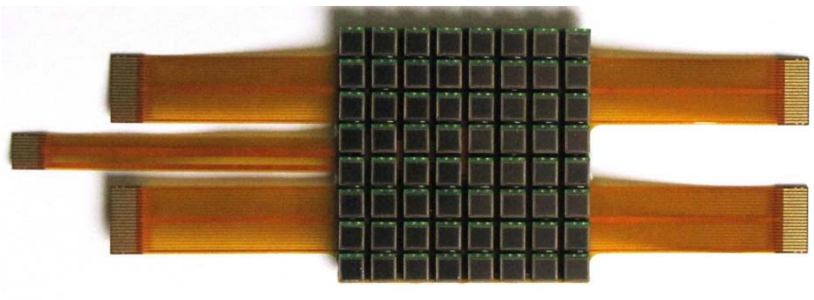


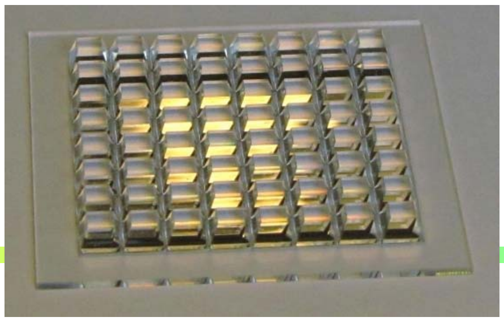

Improve the signal-to-noise ratio:

- Reduce the noise by a narrow (<10ns) time window
- Increase the number of signal hits per sensor by using pyramidal light collectors



→S. Korpar et al., NIM A594 (2008) 13





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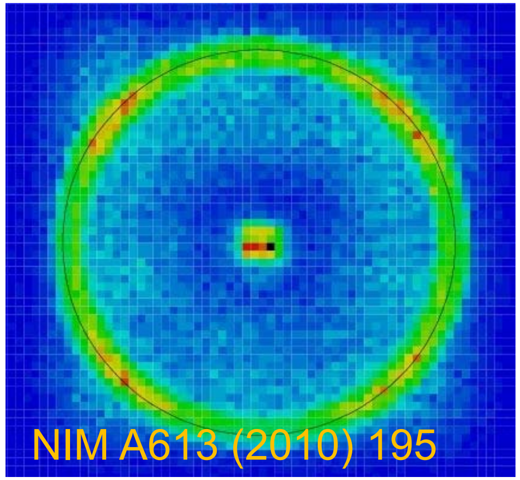


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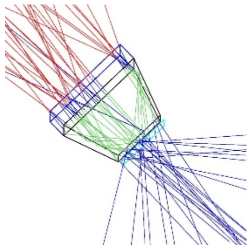

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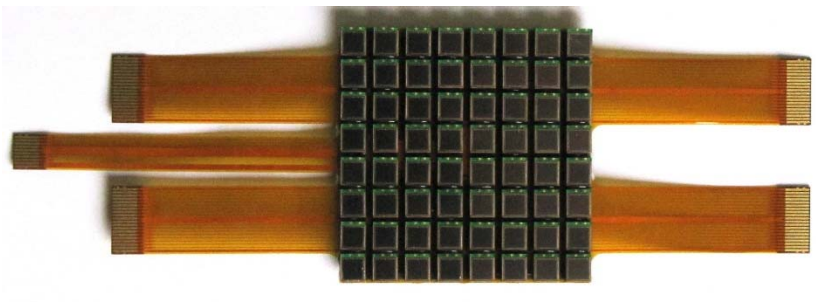
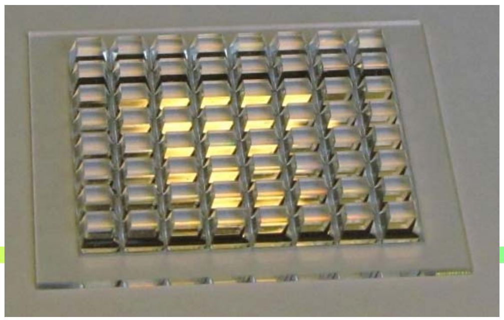


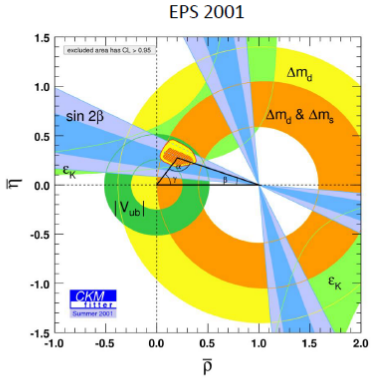


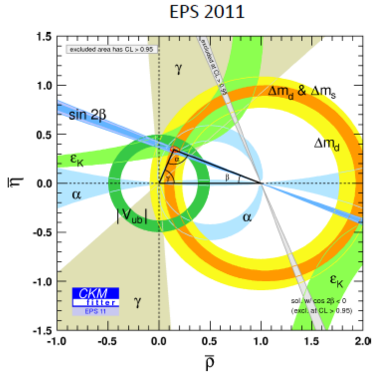
# SuperKEKB/Belle II Status

- Commisioning (Phase 1) of the main ring (without final quads) successfully carried out from Feb 1, 2016 – end of June! Interaction point detector: instead of Belle II, a commissioning detector – Beast II.

- Add final quads in until end of 2016
- Belle II: installation of outer detectors: early summer – december 2016
- Belle II (without the vertex detector) roll in March 2017, cosmic rays
- Phase 2 commissioning Nov 2017 – spring 2018 (+ first physics runs)
- Install vertex detector summer 2018
- Full detector operation by the end 2018 (Phase 3)

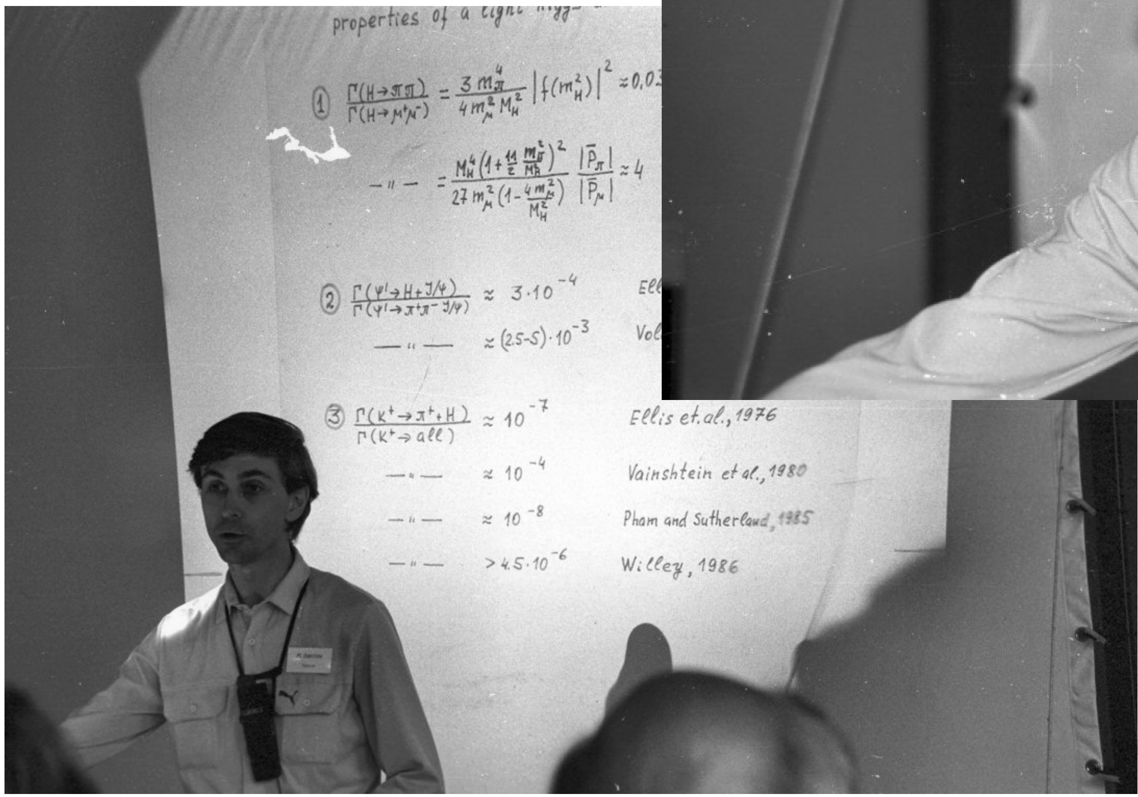
# Summary




- Physics of B mesons has made a tremendous leap forward since ealry 80s
- ARGUS measurements of sizable mixing revolutionized the field
- B factories have proven to be an excellent tool for flavour physics as well for searches for new hadronic states, with reliable long term operation, constant improvement of the performance, achieving and surpassing design performance
- Super B factory at KEK under construction → SuperKEKB+Belle II, L x40, construction at full speed
- Expect a new, exciting era of discoveries, and a friendly competition and complementarity of Belle II, LHCb and BESIII

# In all these endeavors, Misha played a decisive role




You are as young at heart

as are the people you are able to inspire


MICHAEL
DANILOV
HAPPY
BIRTHDAY


Michael DANILOV