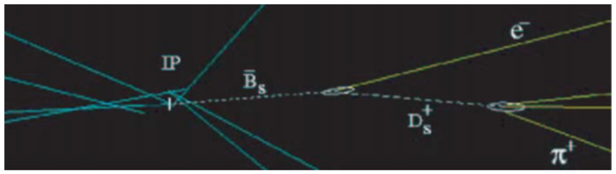
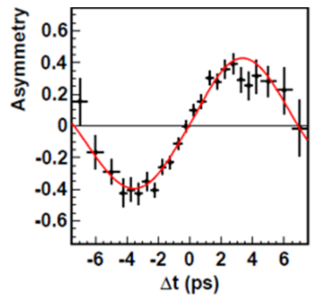
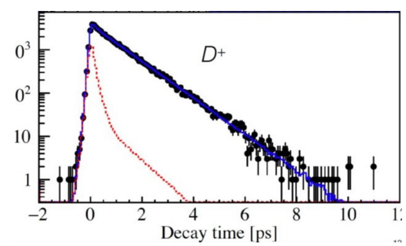
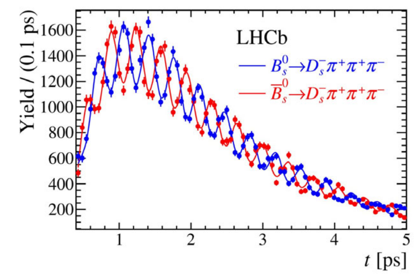
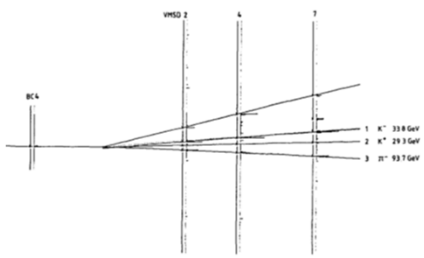
MPG HLL Inauguration Ceremony
and Semiconductor Symposium
Garching, Oct 7-8, 2024

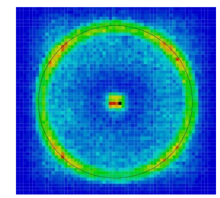




# Flavour Physics with Semiconductor Detectors

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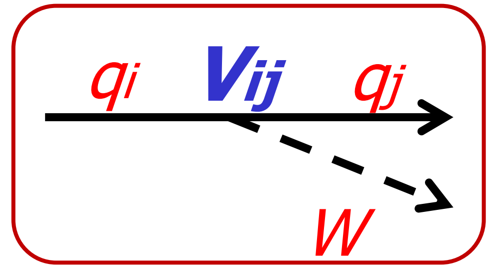
# Contents

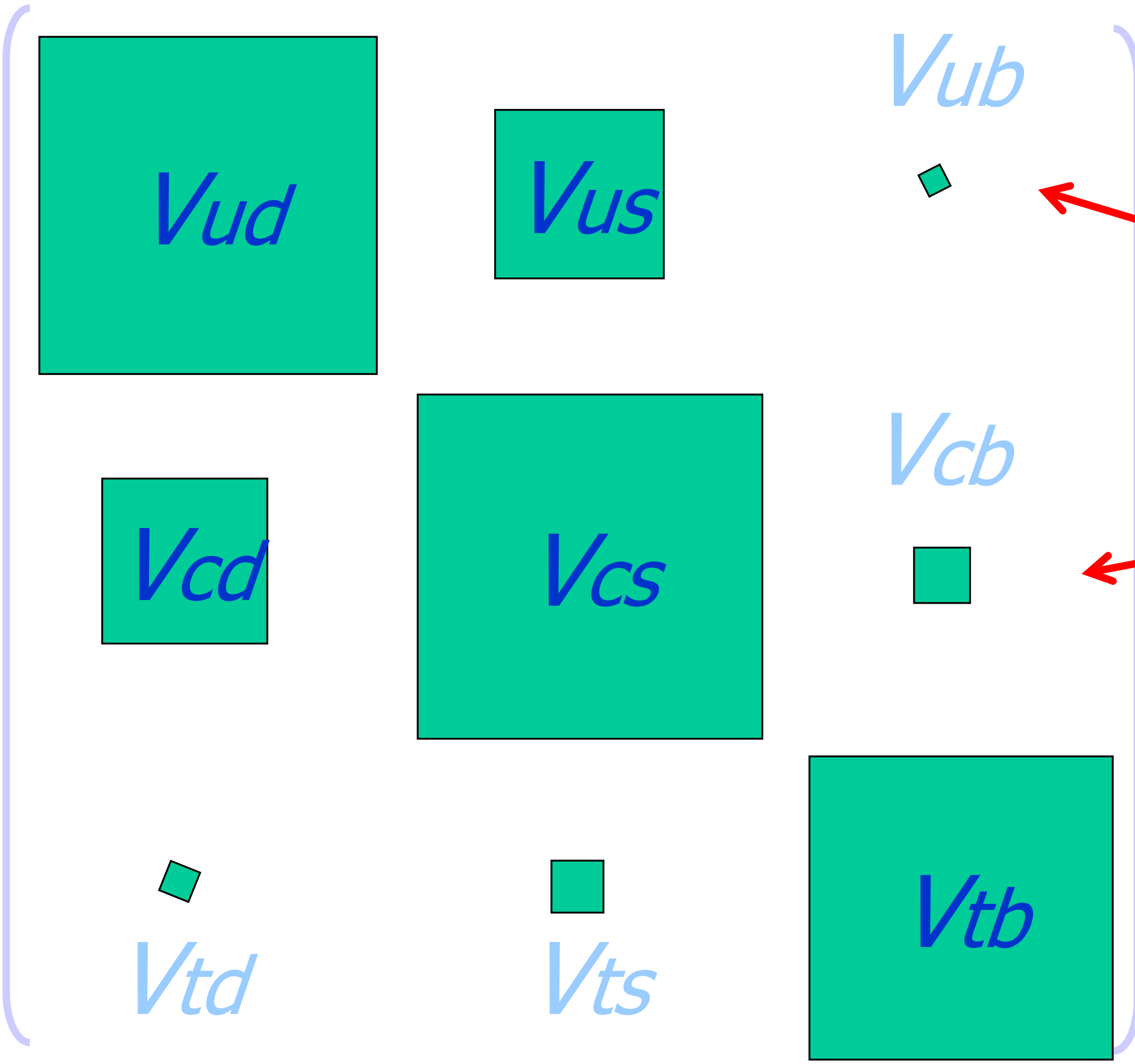
- Flavour physics
- From fixed target experiments to LEP to B factories to LHC to Belle II
- Outlook: upgrades of LHCb and Belle II

This talk: mainly on heavy flavours, b and c hadrons, and tau leptons

# CKM - Cabibbo-Kobayashi-Maskawa (quark transition) matrix:

almost real and diagonal, but not completely!




Amplitude for the b → u transition

Amplitude for the b → c transition

CKM: unitary matrix
→relations of the type

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

# Heavy flavour particles, lifetimes

Lifetimes

- B mesons: ~1.5 ps, $c\tau$: $B^0$ 456 $\mu$m, $B^+$ 453 $\mu$m, $B_s$ 453 $\mu$m
- D mesons: ~0.5-1 ps, $c\tau$: $D^0$ 123 $\mu$m, $D^+$ 312 $\mu$m, $D_s^+$ 150 $\mu$m
- $\tau$ lepton: 0.29 ps, $c\tau$: 87 $\mu$m

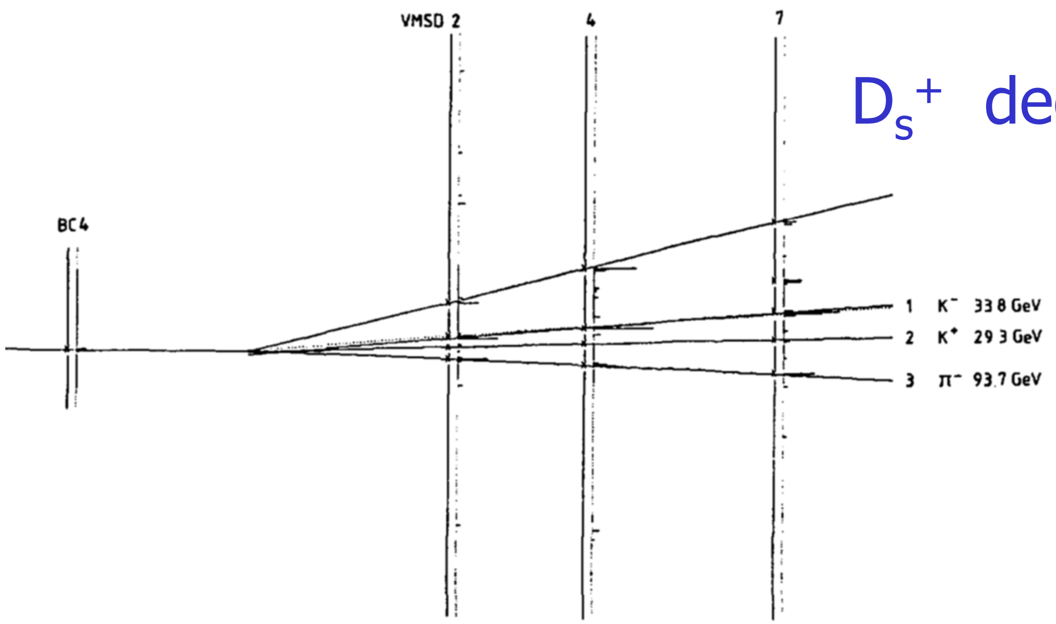
Path of order 100 $\mu$m:

- Can be used to select heavy flavour decays from others
- Measurements of time evolution in systems of heavy mesons (lifetimes, particle-anti-particle mixing, CP violation)

→ Need a detector that would measure tracks precisely enough

# Fixed target experiments at CERN

Lifetimes of charm mesons



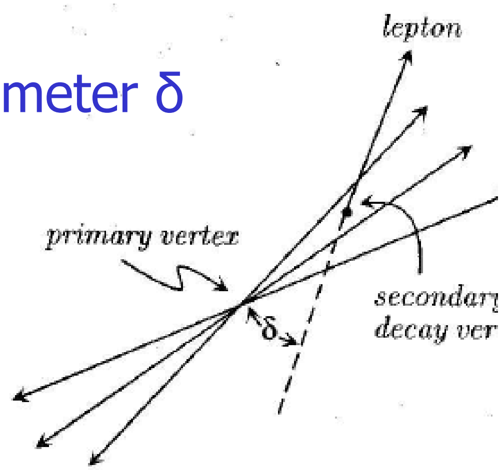

$D_s^+$ decay

NA32 ACCMOR (Amsterdam-Bristol-CERN-Cracow-Munich-Rutherford)
10μm resolution silicon vertex detector by MPI Munich

# 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

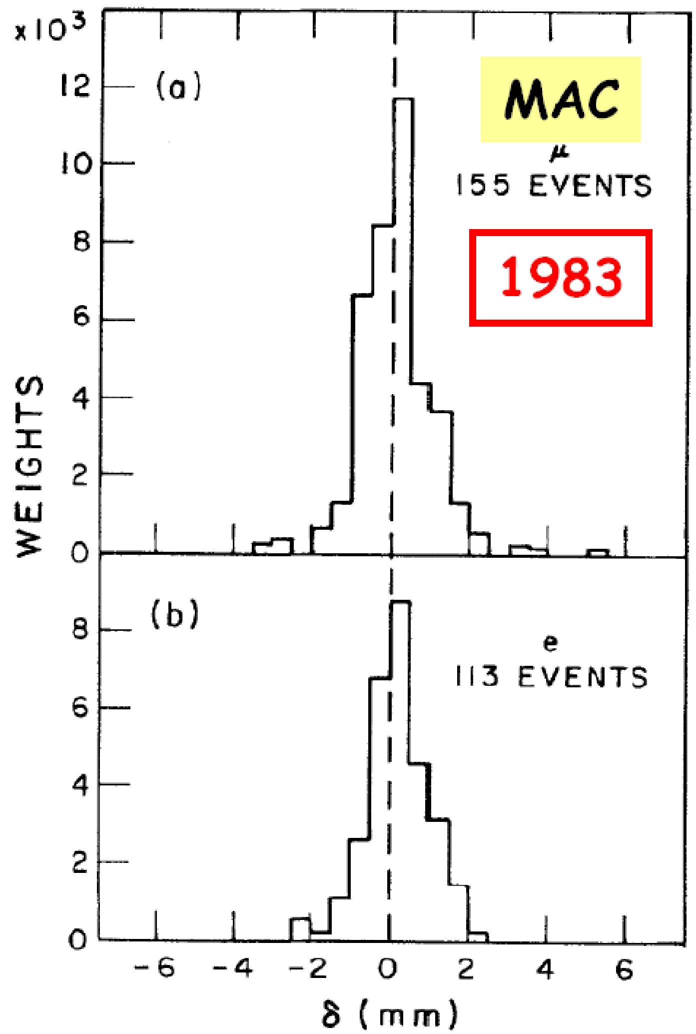



**Lifetime implies: $V_{cb}$ small**

MAC: (1.8±0.6±0.4)ps

Mark II: (1.2±0.4±0.3)ps

At **$e^+e^-$ collider with 29 GeV c.m.s. energy**: integrated luminosity 109 (92) $pb^{-1}$~3,500 bb pairs



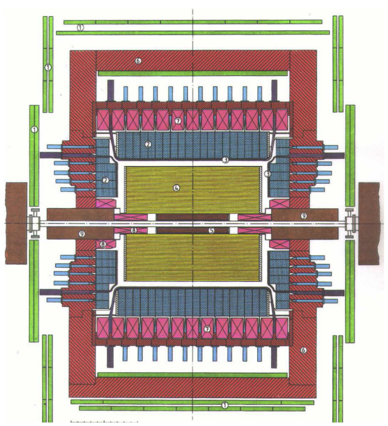

MAC, PRL **51**, 1022 (1983)
MARK II, PRL **51**, 1316 (1983)

# Systematic studies of B mesons: at $\Upsilon$(4s)
# THE discovery: mixing in the $B^0$ system

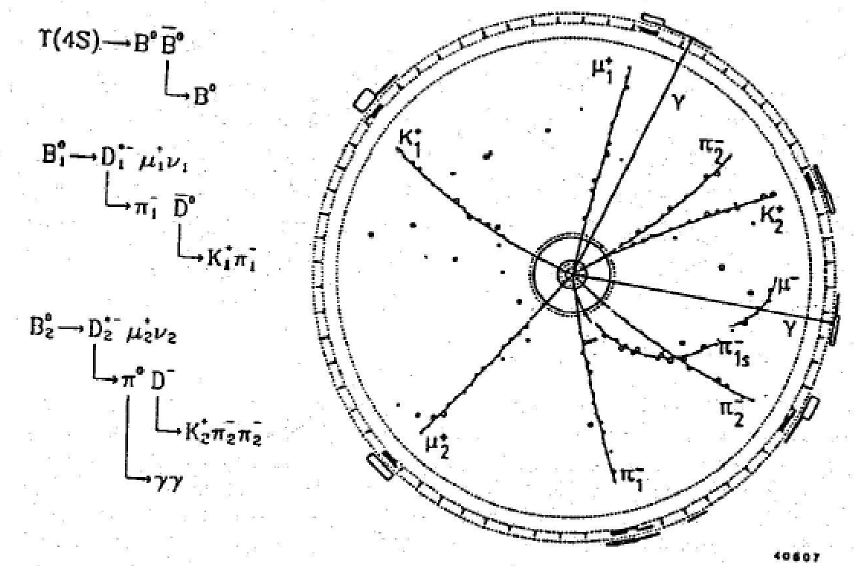
1987: ARGUS discovers $B^0$-$\bar{B}^0$ mixing: $B^0$ turns into $\bar{B}^0$

$$\chi_d = 0.17 \pm 0.05$$

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



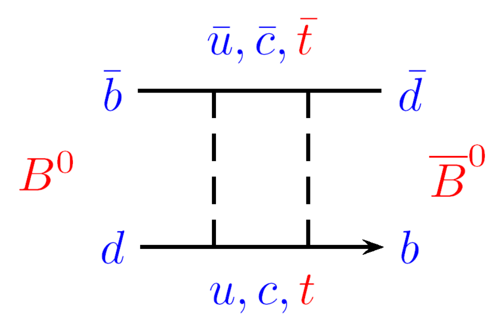
Reconstructed event




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

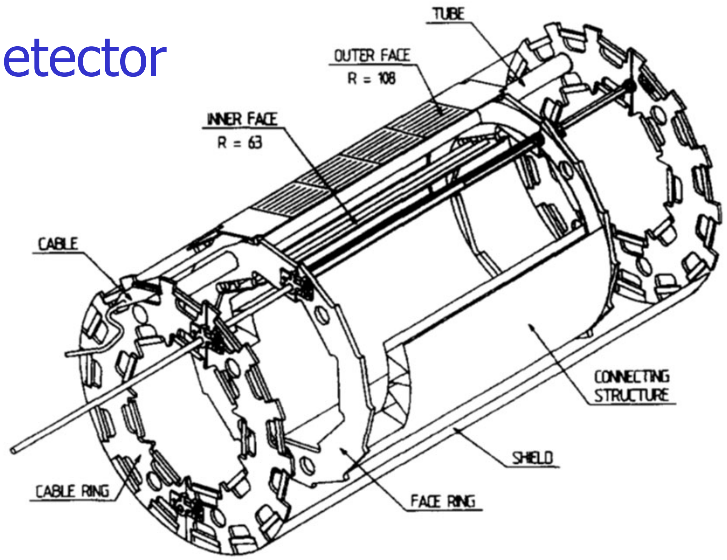
Large mixing rate → high top mass

The top quark has only been discovered seven years later!

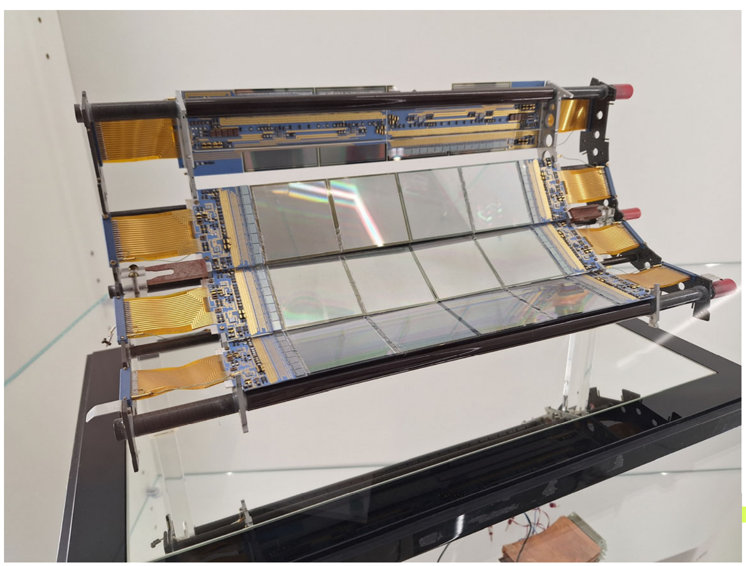


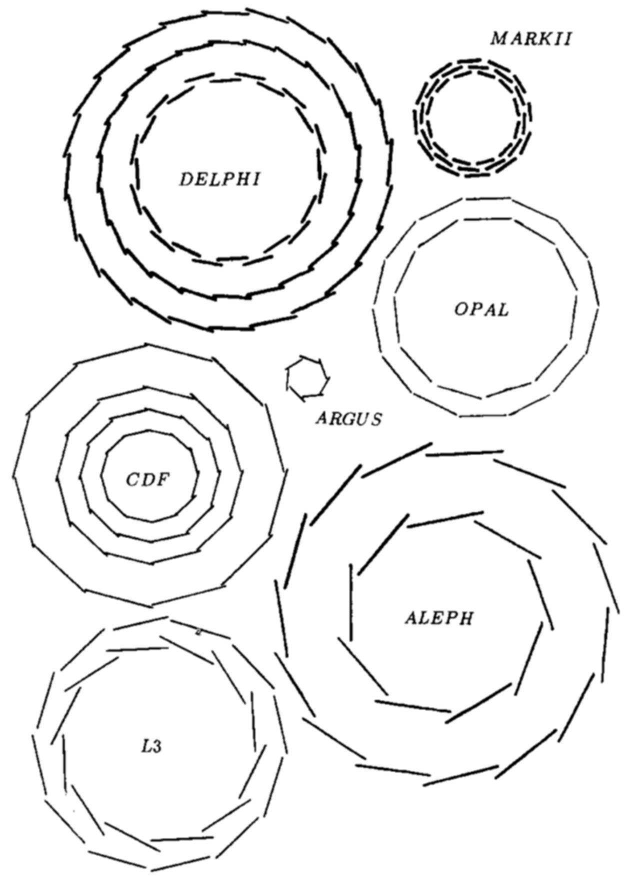
# Flavour physics at LEP: vertex detectors

ALEPH vertex detector




MPI Munich and HLL

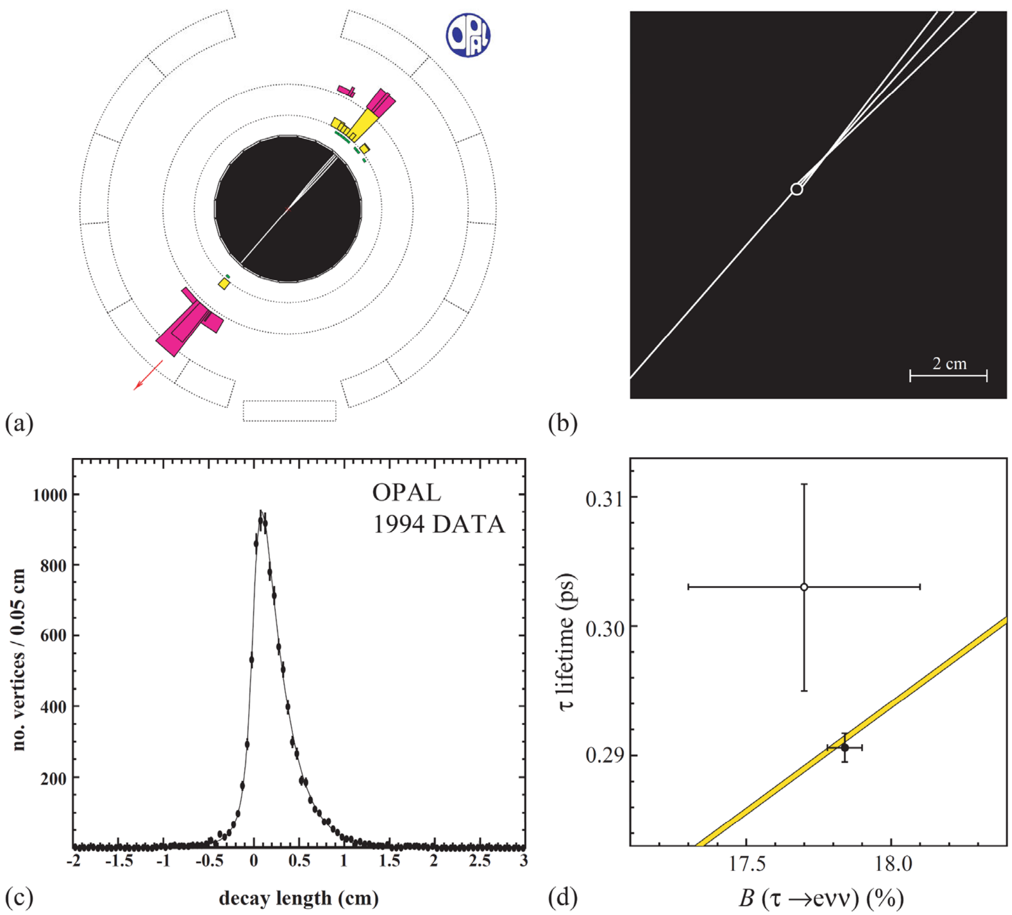





Scale common for all,
5cm = ALEPH module width

# Flavour physics at LEP

## $Z^0 \rightarrow \tau^+\tau^-$ event in the OPAL detector




Zoom on the vertex region: 3-prong decay on one side and 1-prong on the other.

The three-prong vertex is clearly displaced from the interaction point

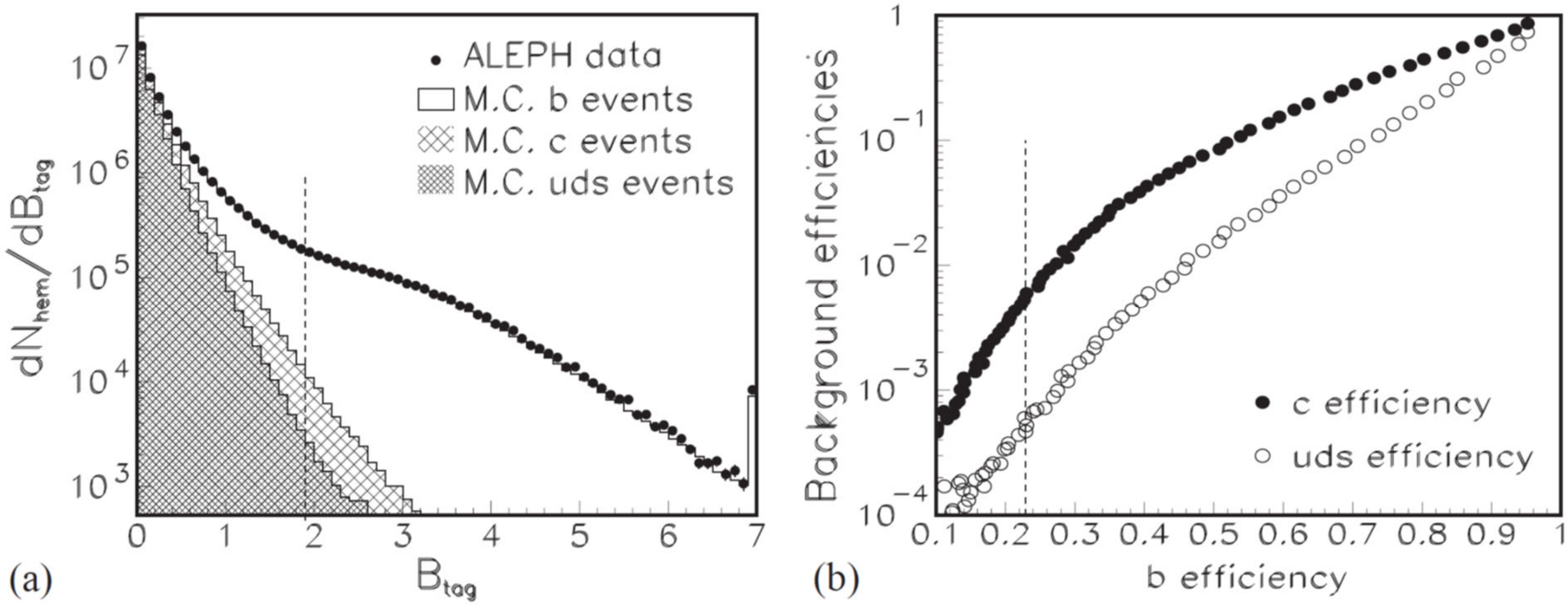
World average data for the tau lifetime vs its leptonic branching ratio (in the electron channel): from before LEP and after LEP; the theoretical expectation is indicated by the shaded band.

Decay length distribution for events of this type

From: R. Forty, Heavy flavor physics at LEP, Phys.Rept. 403-404 (2004) 241-254

# Flavour physics at LEP: selection of events with $b\bar{b}$ quarks

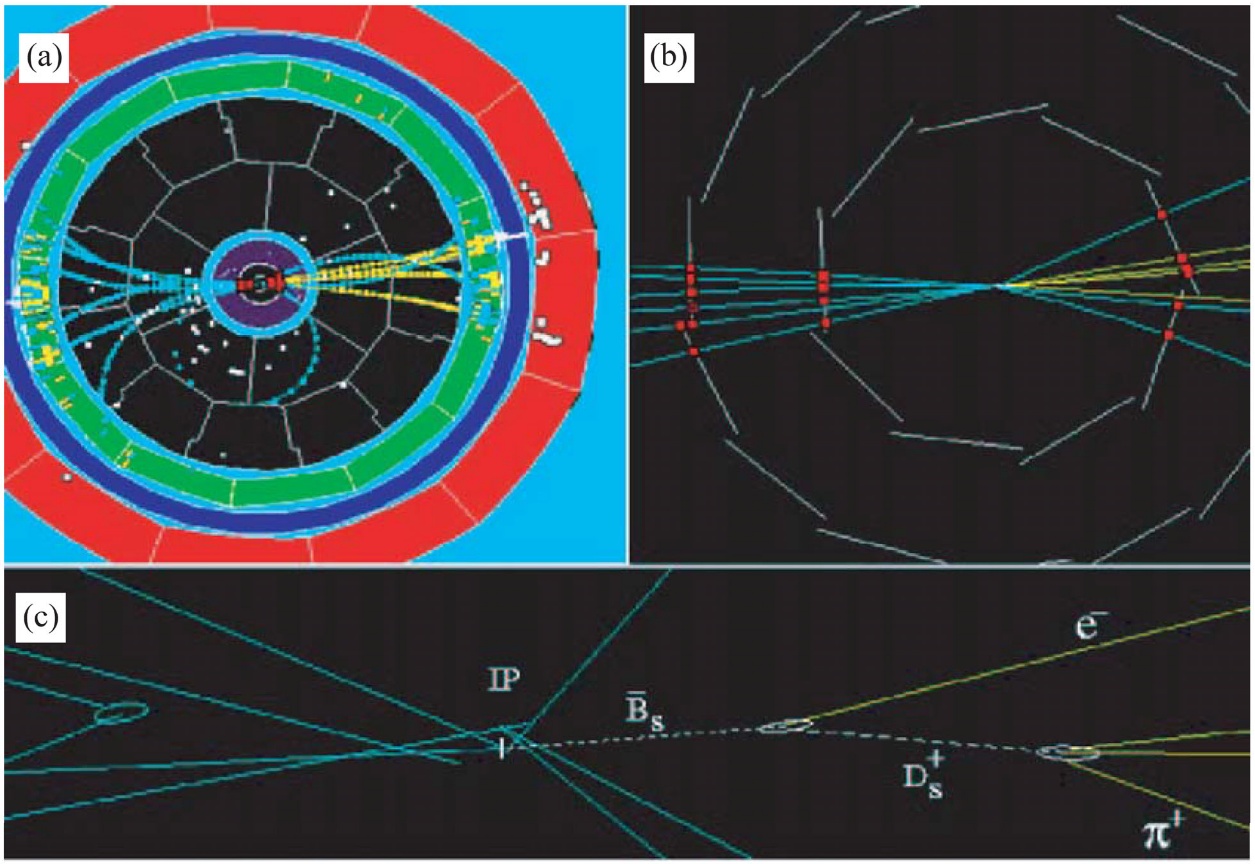
Distribution of the B tagging variable based on lifetime and mass information, data from ALEPH




Efficiency for the selection of hemispheres containing light quarks versus the efficiency for those containing b quarks.

# Flavour physics at LEP

A reconstructed $B^0_s \rightarrow D^+_s\, e^-\, \nu_e$ event in the ALEPH detector

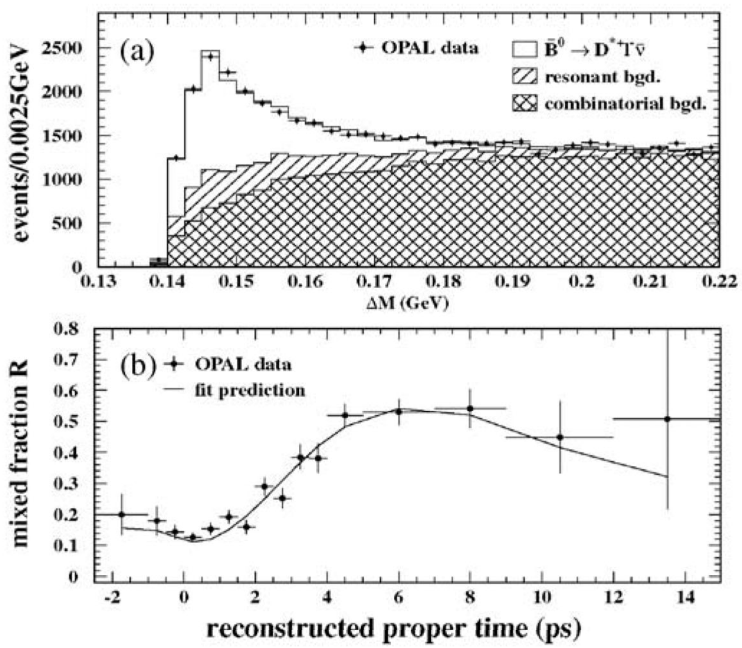



Zoom on the vertex detector, showing the hits seen in the silicon microstrips

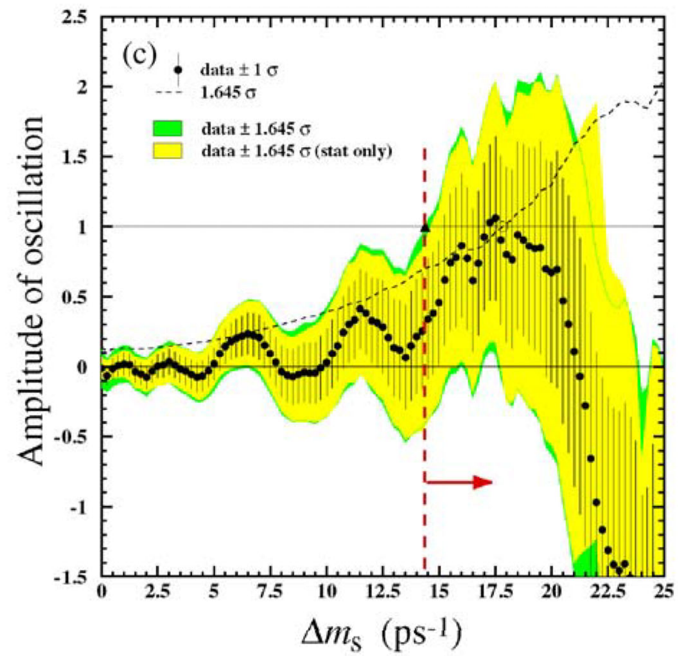
Further zoom on the region around the interaction point (IP), showing the reconstructed tracks and vertices of the event.

# Flavour physics at LEP: time evolution of the neutral B mesons

Signal for $B^0 \rightarrow D^{*-} l^+ X$ from OPAL, seen in the mass difference distribution of the $D^{*-}$ and $D^0$ candidates from the decay $D^{*-} \rightarrow D^0 \pi^-$, with a correlated lepton of the correct charge.




Time-dependence of the $B^0$ – anti-$B^0$ oscillation: mixed fraction as a function of reconstructed proper time.

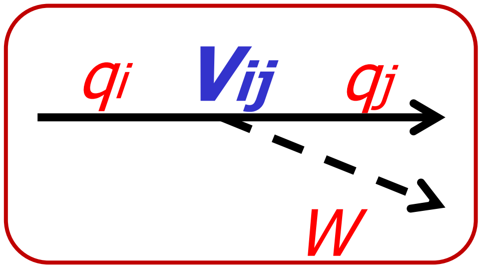



2004 world combination of the amplitude of $B^0_s$ – anti-$B^0_s$ oscillation, as a function of the test frequency $\Delta m_s$; the 2004 lower limit is indicated by the dashed line.

# 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

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

# Golden Channel: $B \rightarrow J/\psi K_S$

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

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 ($\sin2\phi_1 = \sin2\beta$)

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

Clear experimental signatures ($J/\psi \rightarrow \mu^+\mu^-$, $e^+e^-$, $K_S \rightarrow \pi^+\pi^-$)

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

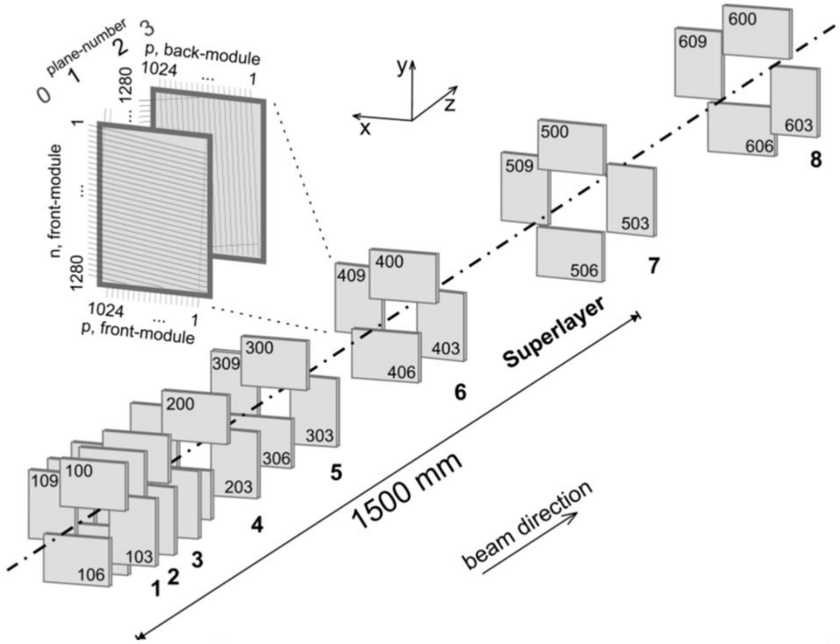
→ A lot of physicists across the world were after this holy grail

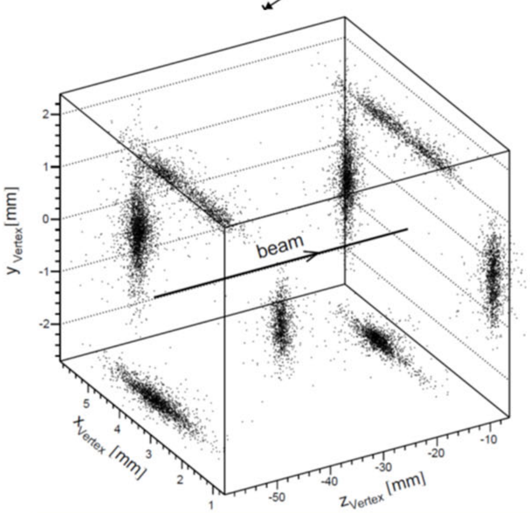
# HERA-B vertex detector

Double-sided silicon strip detectors with four stereo views.

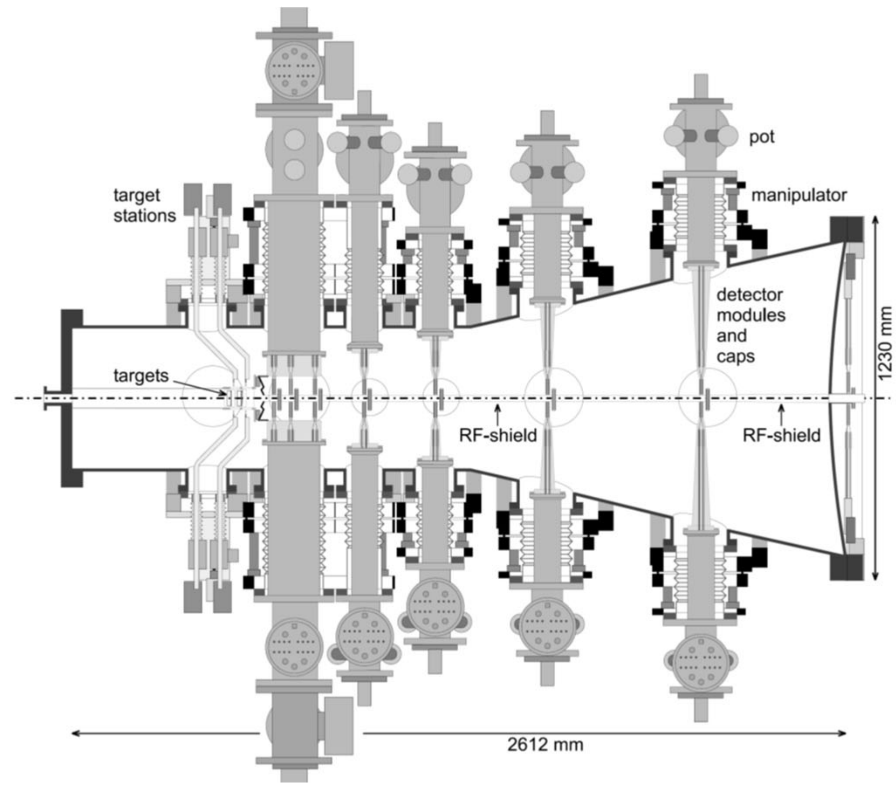
Roman pots in a vacuum vessel, retractable during injection.

MPI Heidelberg and MPI Munich, design and part of production by HLL.




Reconstructed vertex positions on 8 wire targets

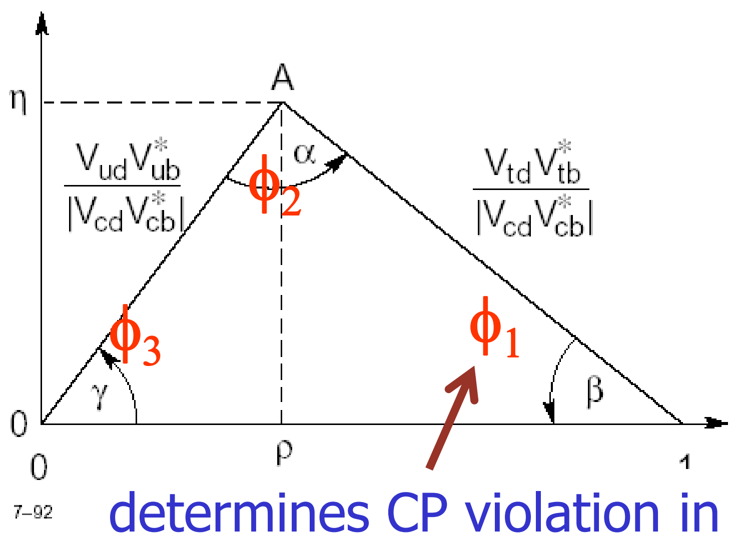



The first vertex detector successfully operating in an LHC-like environment

# CP violation: related to the angles of the unitarity triangle

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

$\mathrm{Im}(\lambda) = \sin 2\phi_1$ in $B \rightarrow J/\psi\ K_S$ decays!

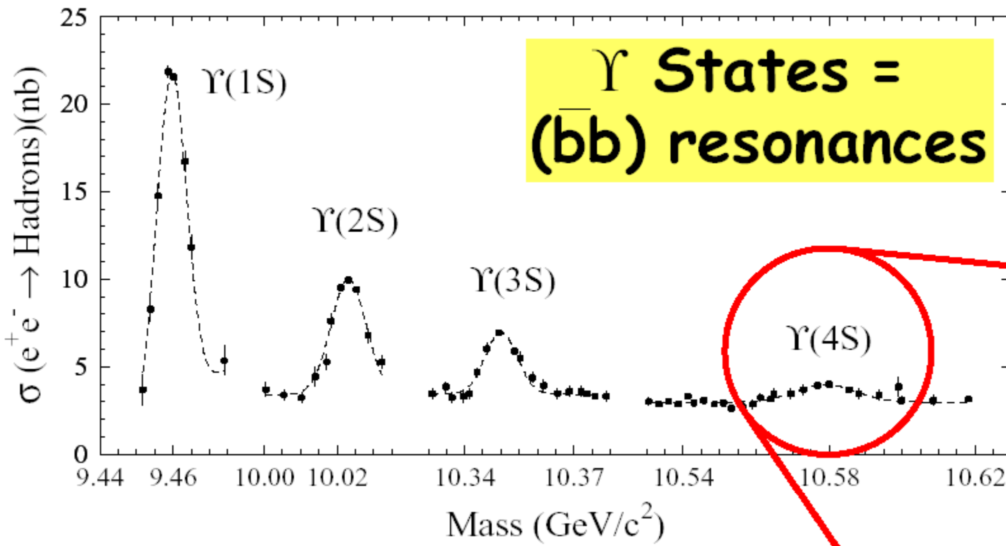


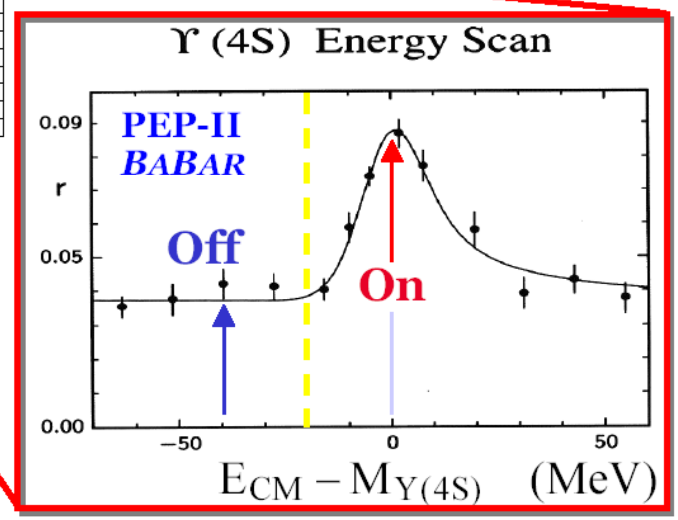

determines CP violation in $B \rightarrow J/\psi\ K_S$ decays

Unitarity condition:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

# → Back to B meson production at $\Upsilon(4s)$




**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

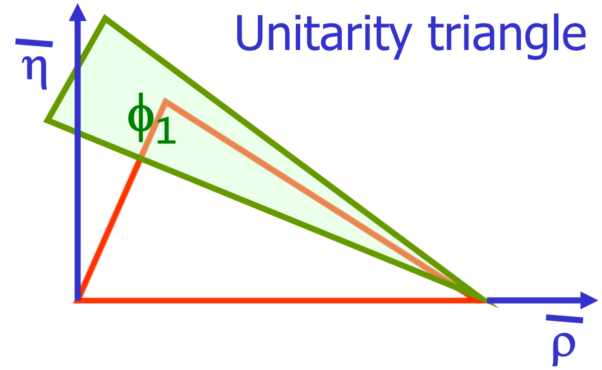
$u\bar{u} \sim 1.4$ nb

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

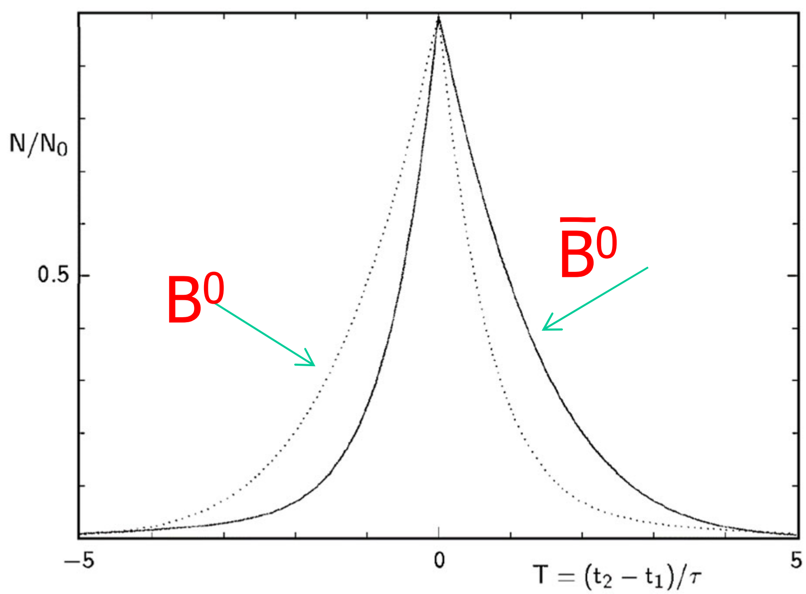
$L = 1$ state

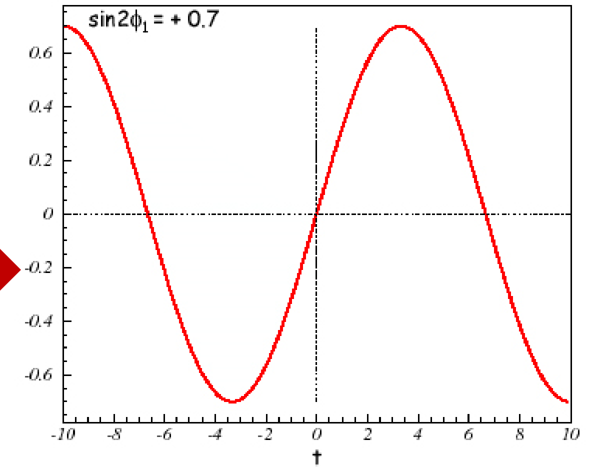
BB produced almost at rest in the e+e- system

# 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



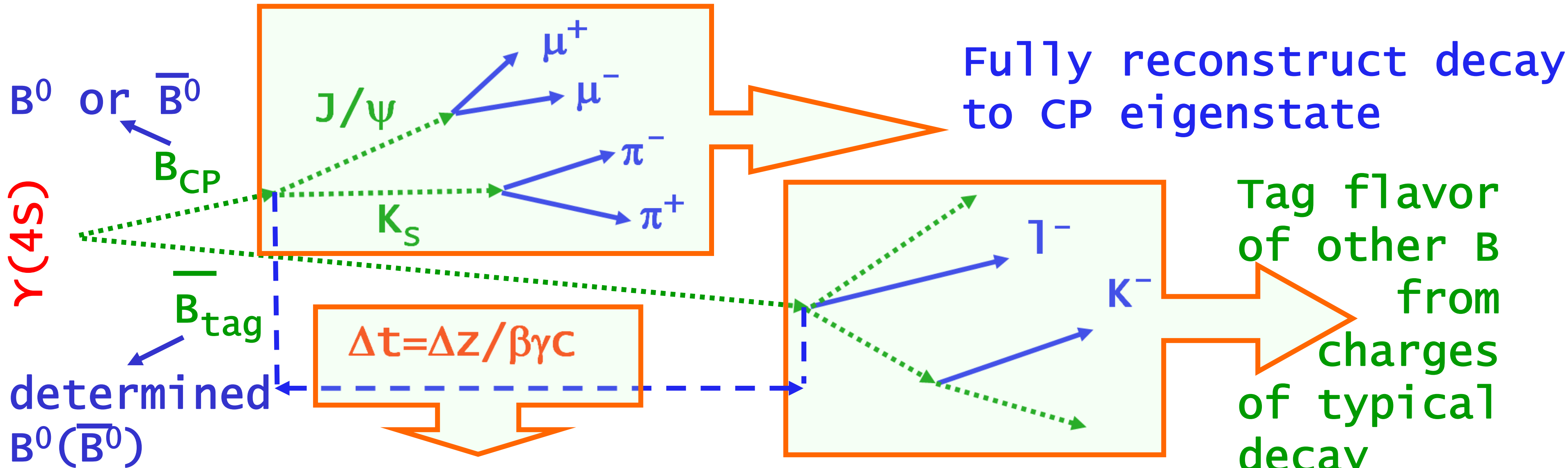




$$a_{f_{CP}} = -\frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

Time dependent decay rate difference - CP asymmetry:

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

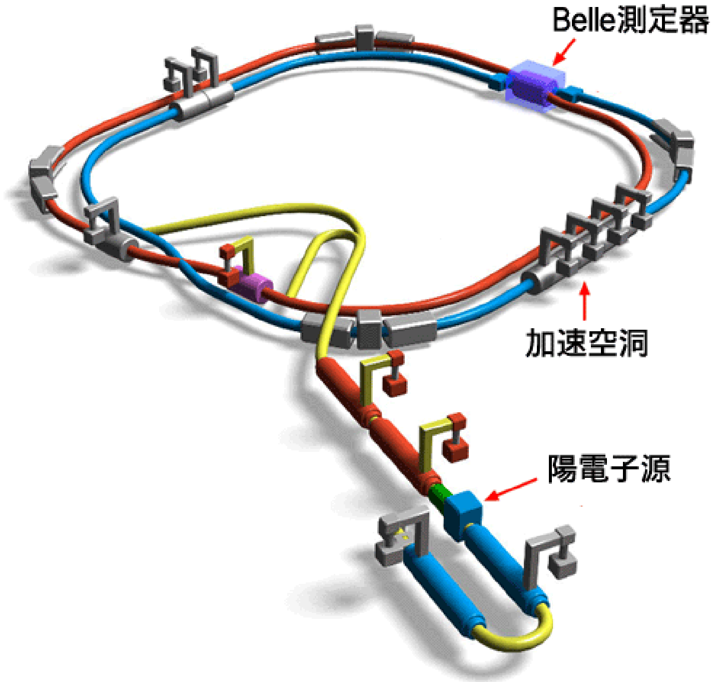
# Typical measurement

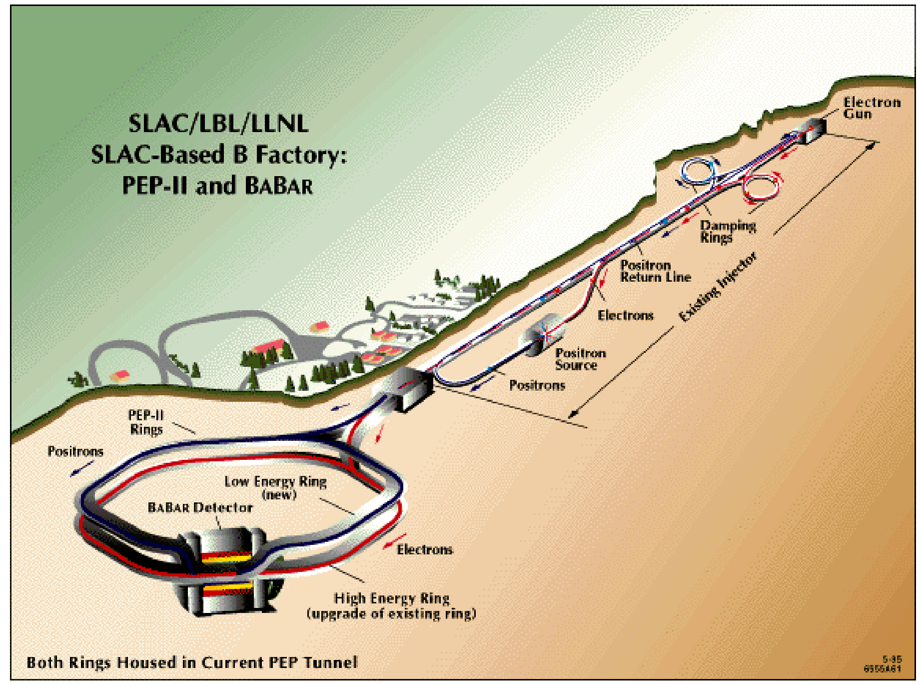



Determine time between decays

Need a boosted c.m.s. system
and excellent vertexing

# Colliders: asymmetric B factories, e+e- colliders operating at Υ(4S)




$\sqrt{s}$=10.58 GeV

$e^+$ → Υ(4s) ← $e^-$

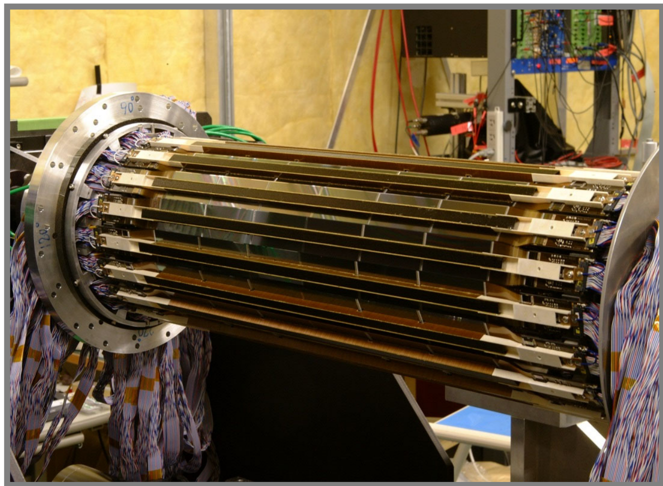
Υ(4s) → B, $\bar{B}$

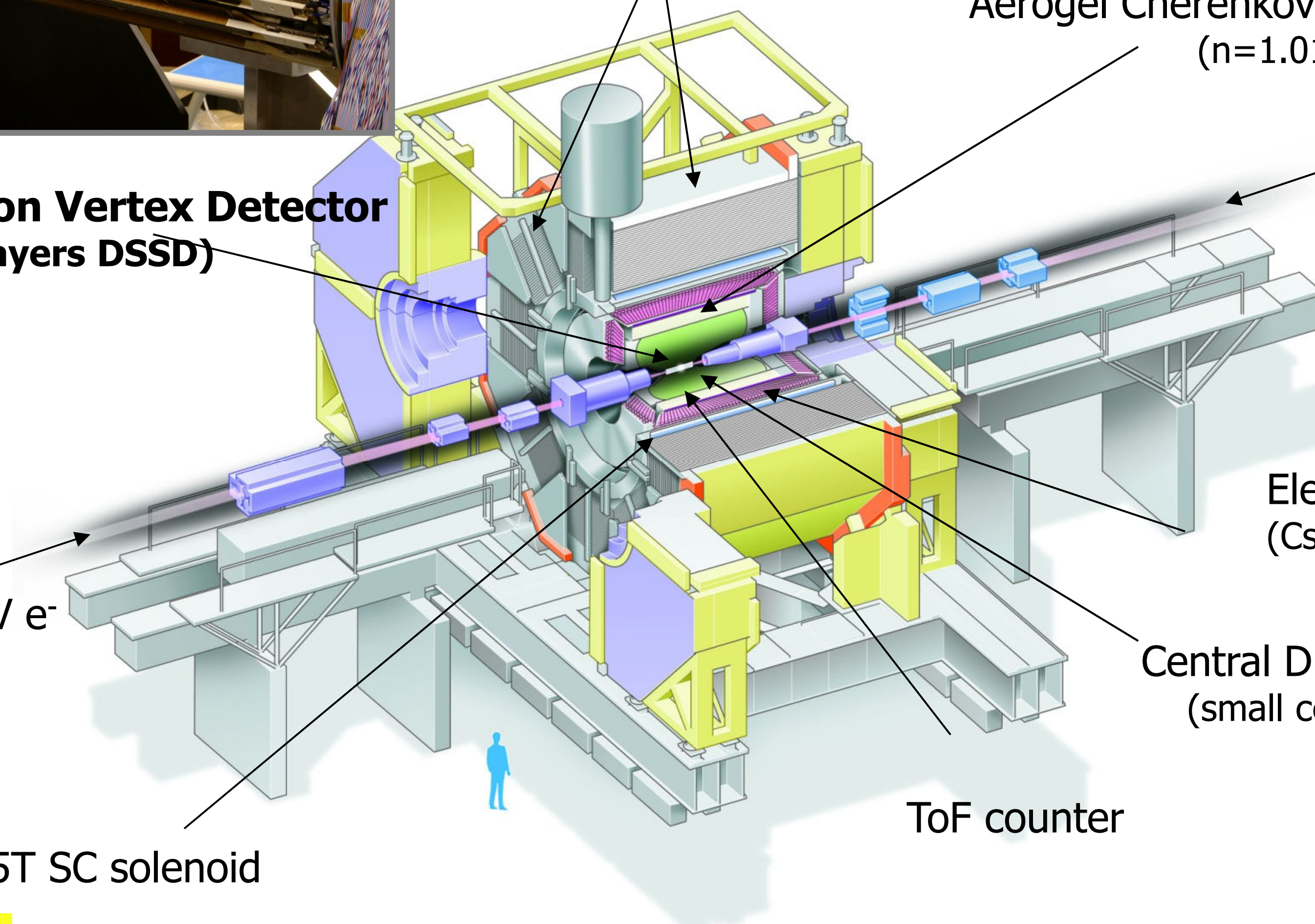
$\Delta z \sim c\beta\gamma\tau_B$

$\sim 200\mu m$

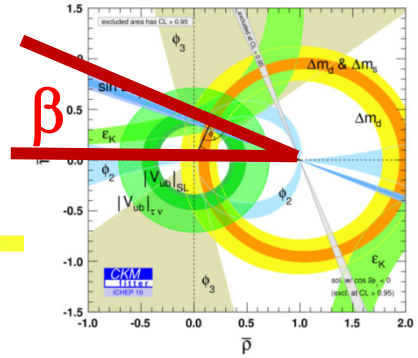
| | | | |
|---|---|---|---|
| BaBar | $p(e^-)$=9 GeV | $p(e^+)$=3.1 GeV | $\beta\gamma$=0.56 |
| Belle | $p(e^-)$=8 GeV | $p(e^+)$=3.5 GeV | $\beta\gamma$=0.42 |

# Belle spectrometer at KEK-B



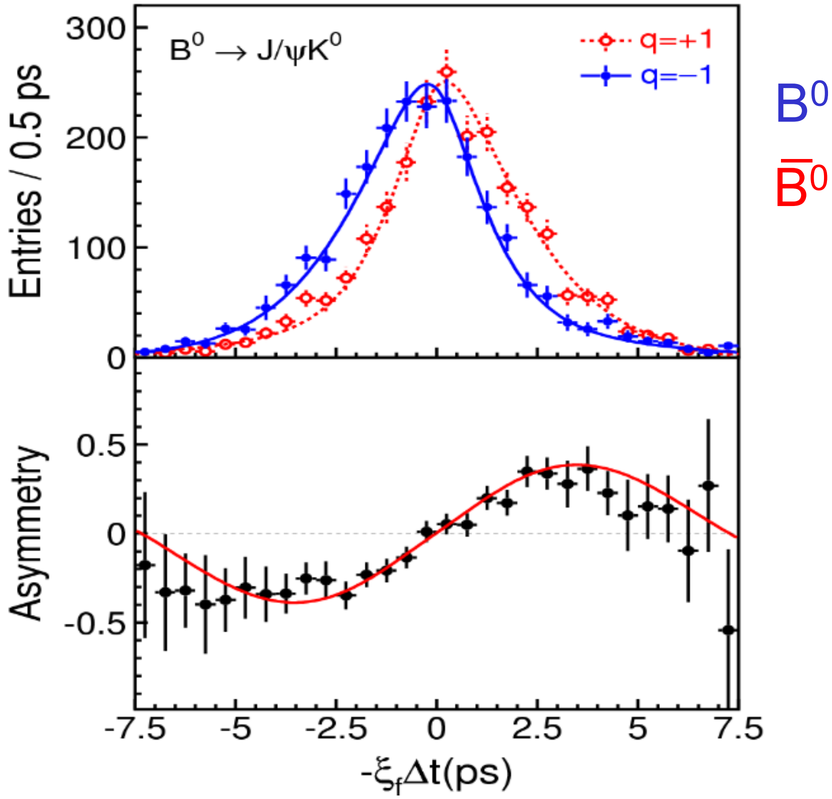


# Final measurement of $\sin 2\phi_1$ ($=\sin 2\beta$)




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

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




$\sin 2\phi_1$ ($=\sin 2\beta$)

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

Belle, PRL 108, 171802 (2012)

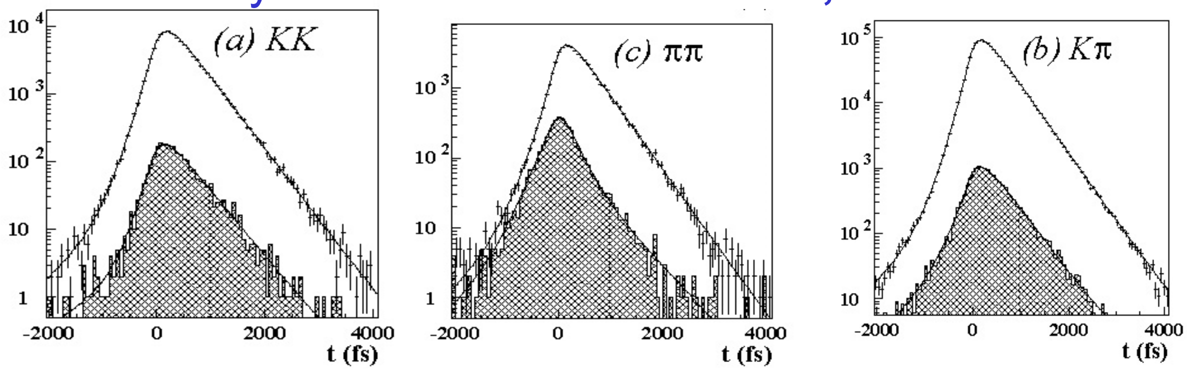
BaBar, PRD 79, 072009 (2009)

with a single experiment precision of ~4%!

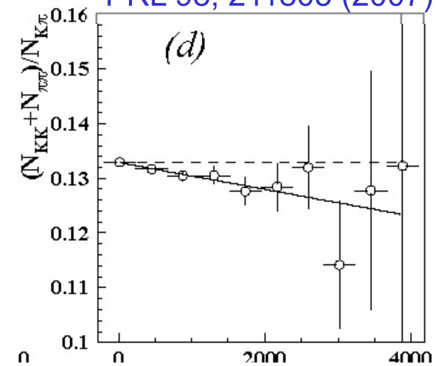
$\phi_1 = \beta = (21.4 \pm 0.8)^0$

# $D^0$ mixing in $K^+K^-$, $\pi^+\pi^-$ and $K_S\pi^+\pi^-$

Decay time distributions for $K^+K^-$, $\pi^+\pi^-$ and $K^-\pi^+$



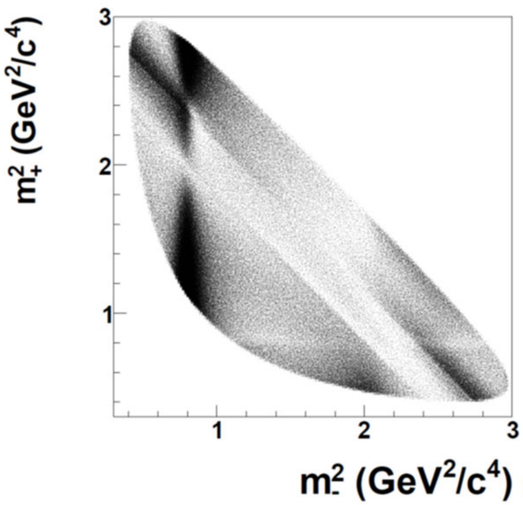

PRL 98, 211803 (2007)




ratio of $K^+K^-$, $\pi^+\pi^-$ and $K^-\pi^+$

Mixing parameter,
final result with full statistics

$$y_{CP} = (1.11 \pm 0.22 \pm 0.09)\ \%$$




From the time evolution of the Dalitz plot in the $K_S\pi^+\pi^-$ decay determine both mixing parameters

$$x = (0.56 \pm 0.19 \pm {}^{0.03}_{0.09} \pm {}^{0.06}_{0.09})\%$$
$$y = (0.30 \pm 0.15 \pm {}^{0.04}_{0.08} \pm {}^{0.06}_{0.08})\%$$

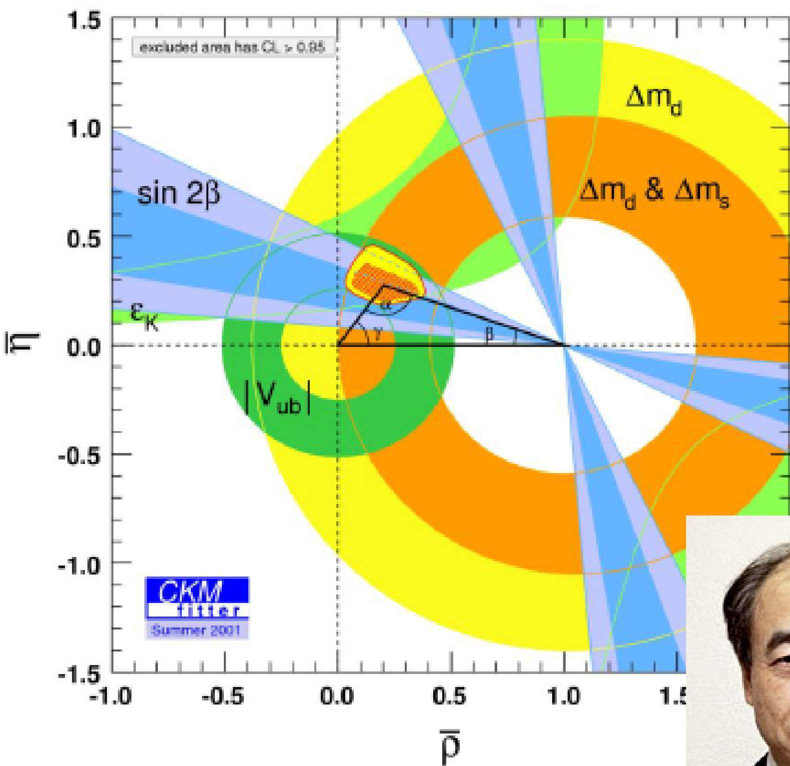
± stat. ± exp.syst. ± decay model syst.

Final result with full statistics

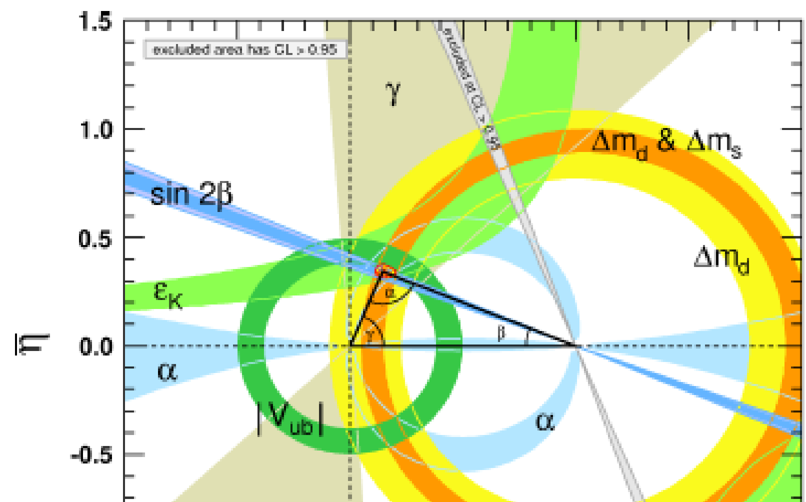
# Summary: CP violation in the B system

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

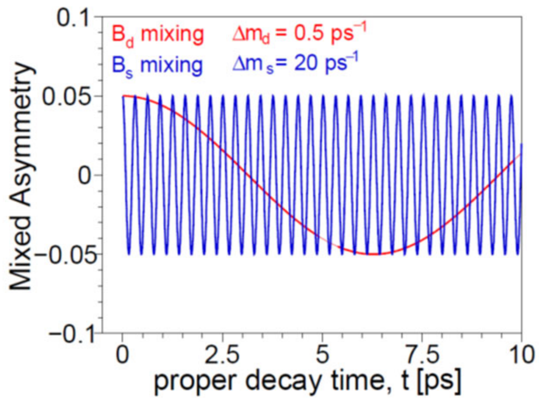
EPS 2001




EPS 2011




# $B_s$ mixing: $B_s$ ←→ anti-$B_s$

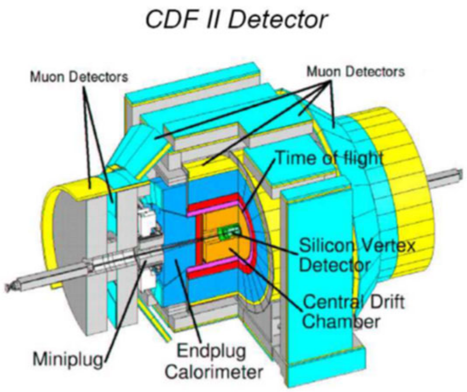



Very fast compared to $B_d$:

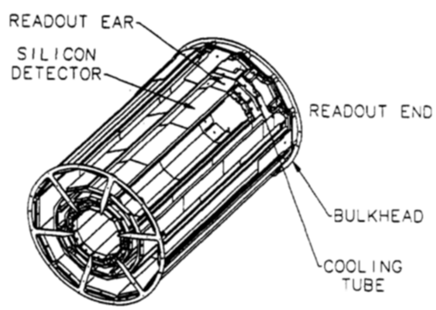
a $B_s$ turns into an anti-$B_s$ in 0.3 ps, 3 $10^{12}$ times per second

The oscillation amplitude gets diluted by $e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}}$

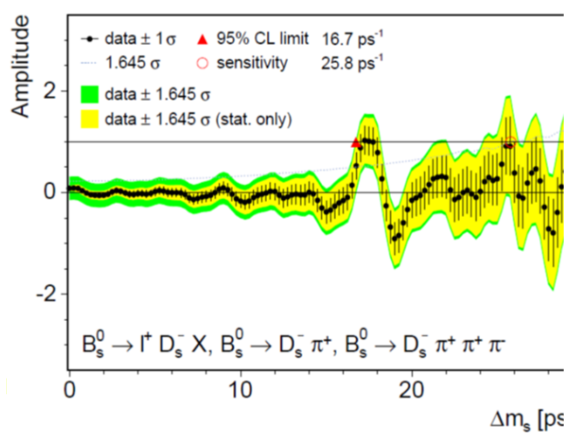
→precise vertexing is essential

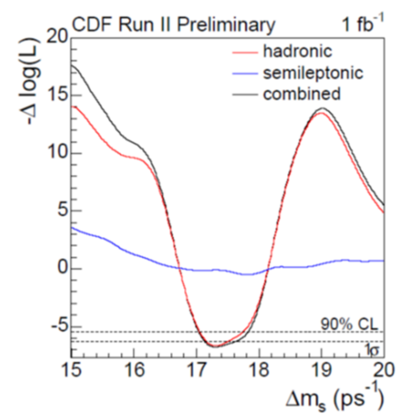



Nearly succeded at LEP – lower limit $\Delta m_s > 14.4.\ ps^{-1}$ at 95% CL




Observed at CDF II in 2006

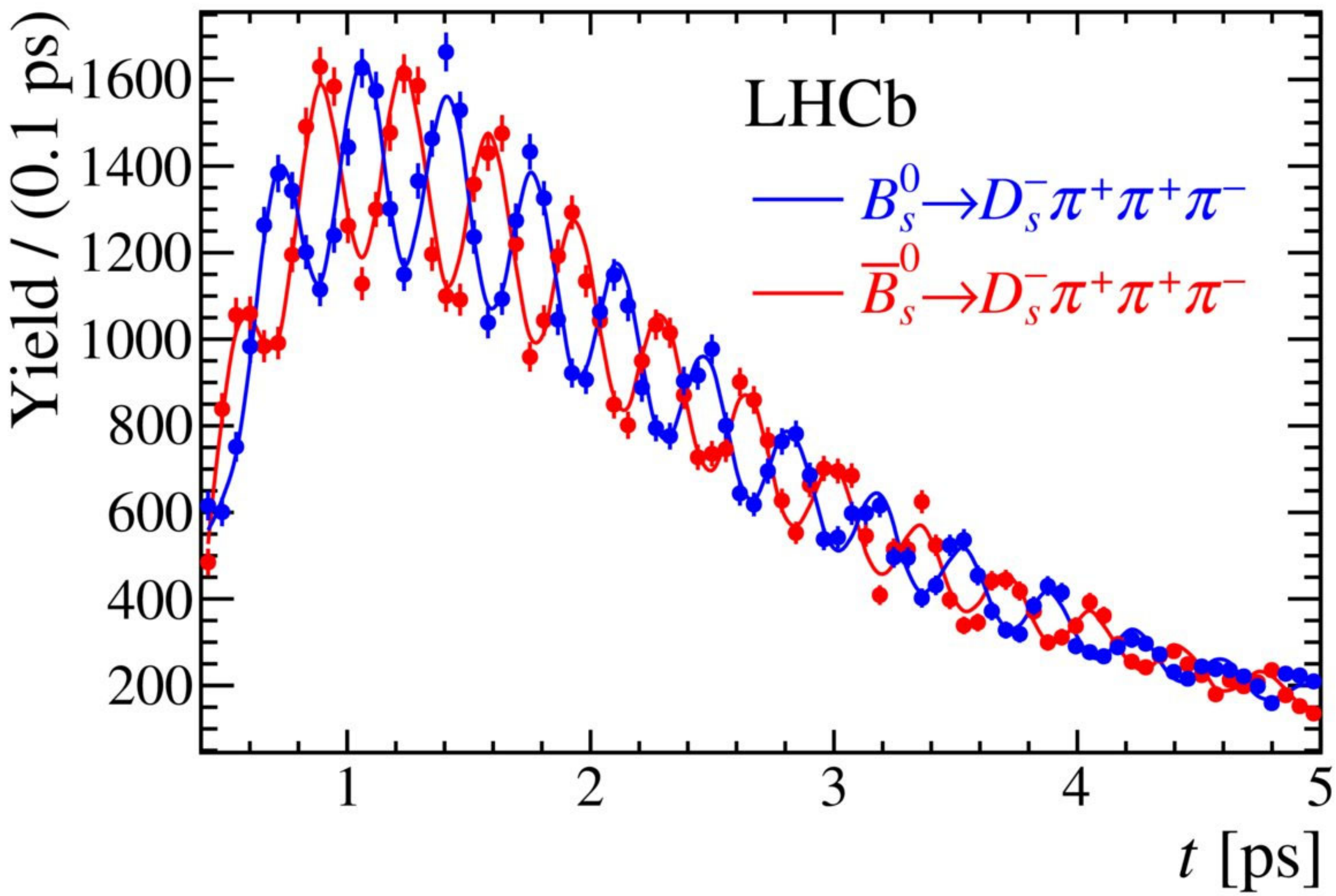



- 4 layers of single-sided sensors at 20, 43, 57, 78 mm from the IP.
- Impact parameter resolution: ~30μm at 2 GeV/c

$\Delta m_s = 17.31^{+0.33}_{-0.18}(stat.) \pm 0.07(syst.)\,ps^{-1}$

# $B_s$ mixing: $B_s$ ←→ anti-$B_s$

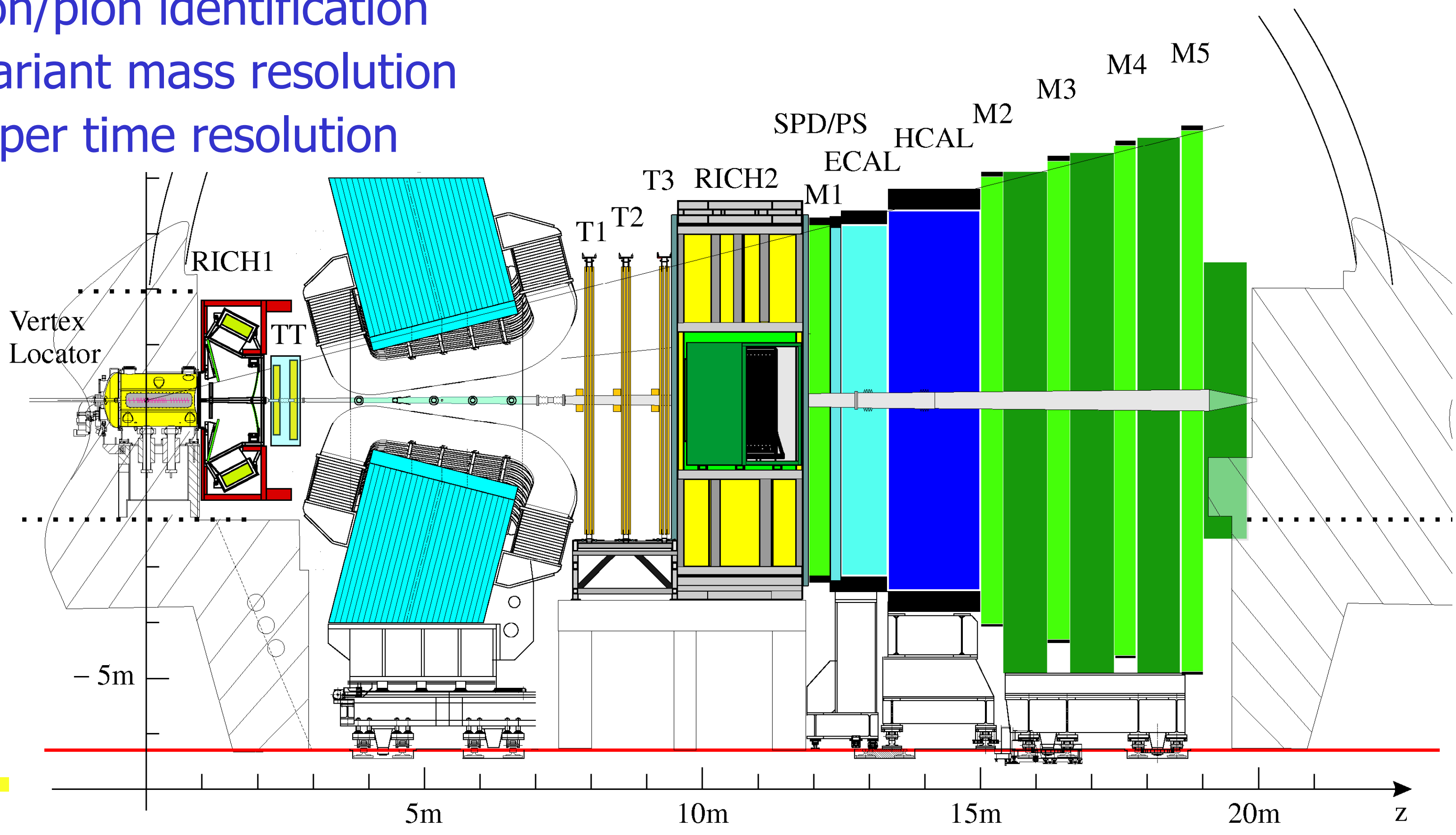



Beautiful precision measurement by LHCb: $\Delta m_s$ = (17.757 +- 0.021) $ps^{-1}$

# LHCb

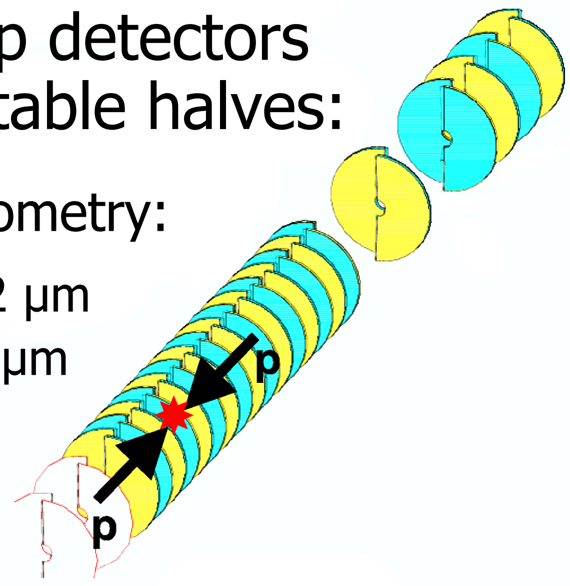
LHCb is a forward spectrometer:

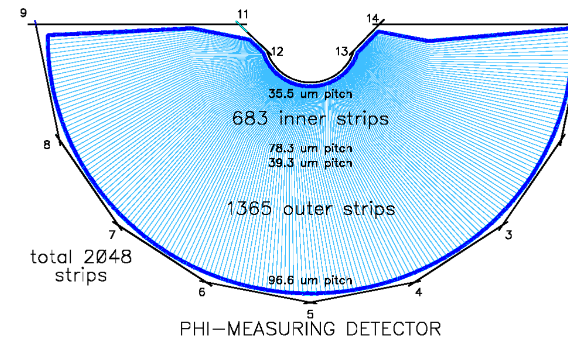
- Acceptance 10-300 mrad
- Efficient B-mesons trigger
- Good Kaon/pion identification
- Good invariant mass resolution
- Good proper time resolution

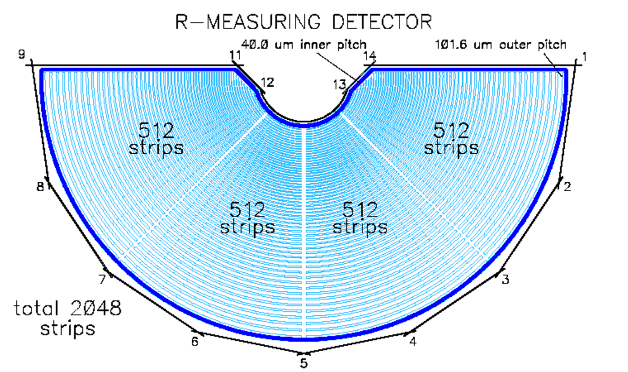


# VELO - Vertex locator

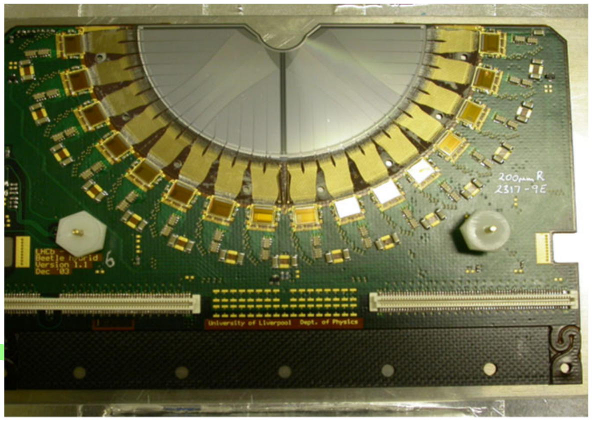
- 21 pairs of silicon strip detectors arrange in two retractable halves:
  - Strips with an R-φ geometry:
    - R strip pitch: 40-102 μm
    - φ strip pitch: 36-97 μm
  - 172k channels.



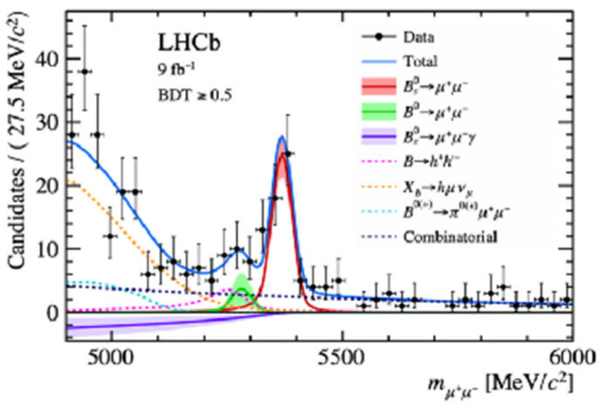




- Operated:
  - In vacuum, separated from the beam vacuum by an Al foil
  - Close to the beam line (7 mm)
  - Radiation ≤ $1.5\times10^{14}$ $n_{eq}/cm^2$ per year
  - Cooled at -5 °C

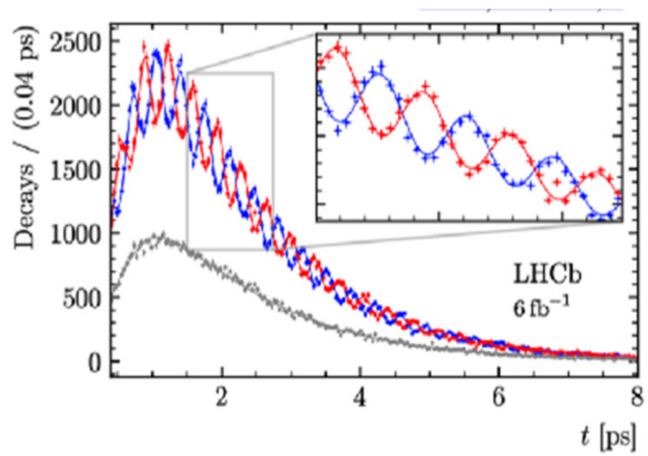


# LHCb highlights in flavour physics – some of many

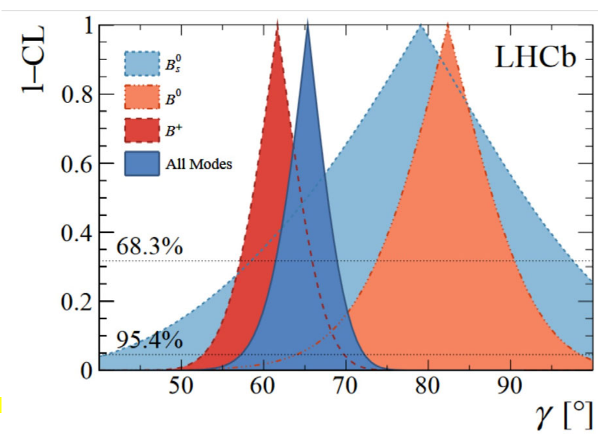
## $B_s \to \mu^+\mu^-$



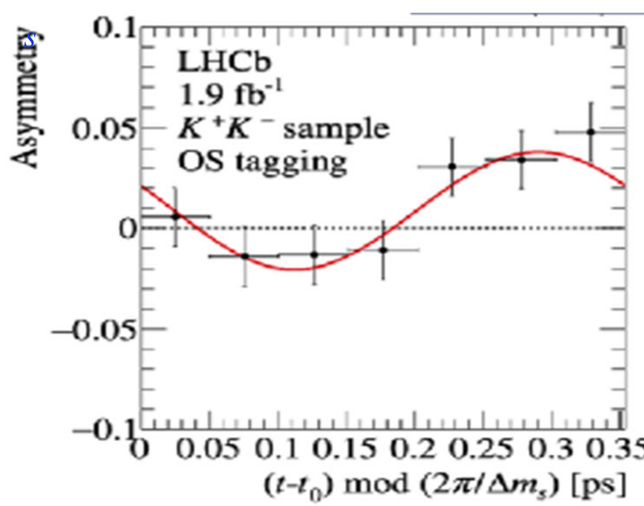

## $B_s$ mixing: $\Delta m_s$




## CKM angle γ



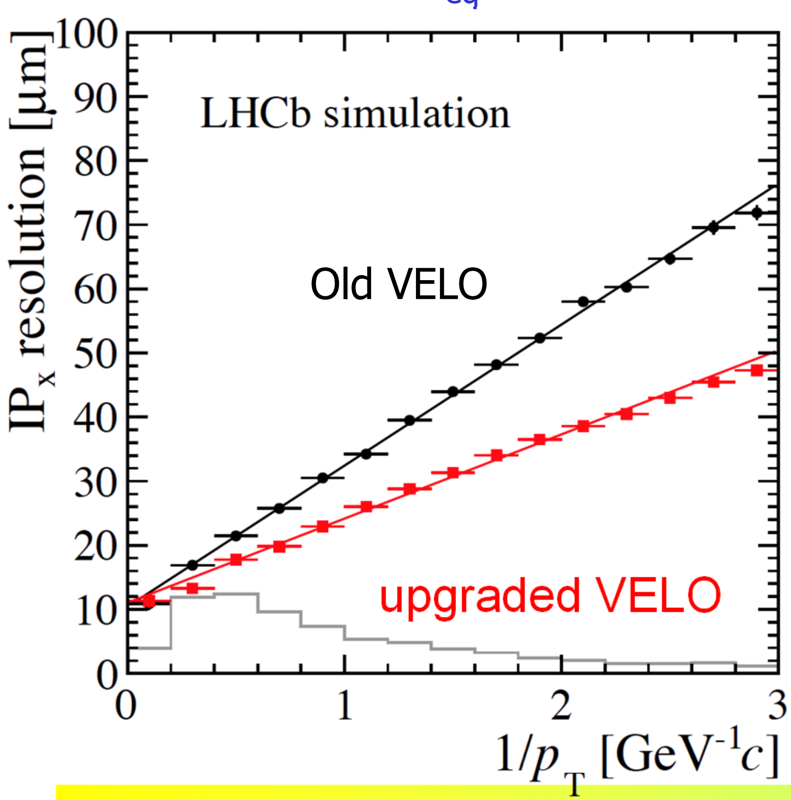

## $B_s$ time-dependent CP violation

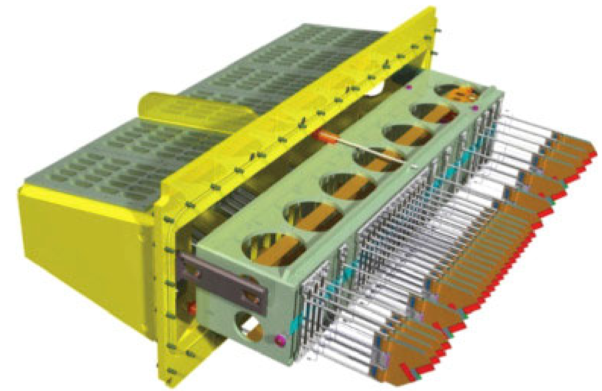


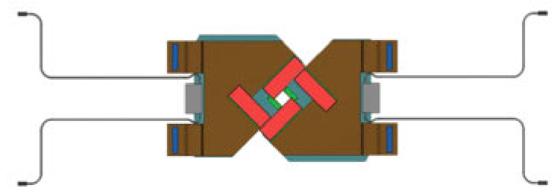
# LHCb Vertex LOcator upgrade

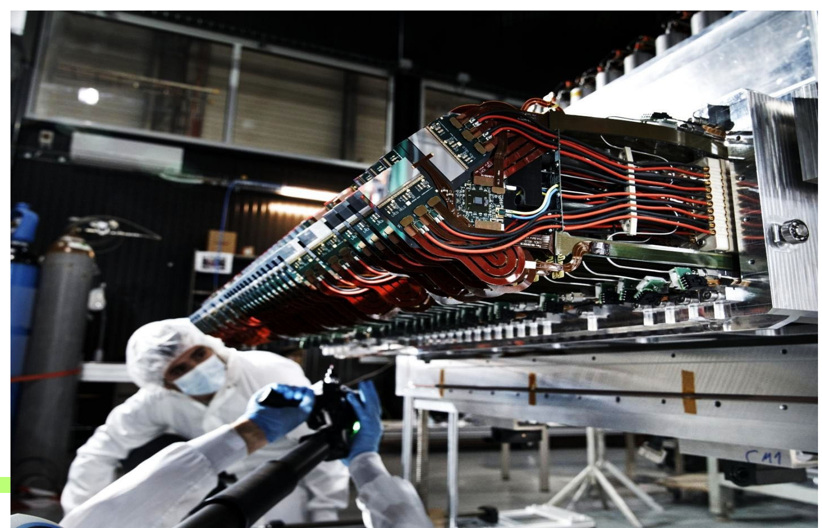
The upgraded VELO for taking data in Run III operation @

- 40 MHz and $2\text{x}10^{33}$ $cm^{-2}s^{-1}$
- at 3.5 mm from the beams,
- 2.8 Tb/s data rates,
- $8 \times 10^{15}$ 1 MeV $n_{eq}$ $cm^{-2}$ max fluence



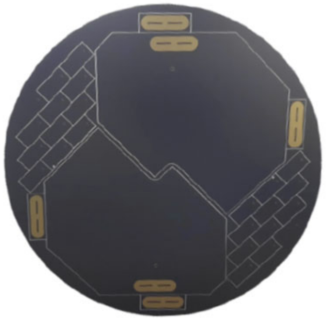


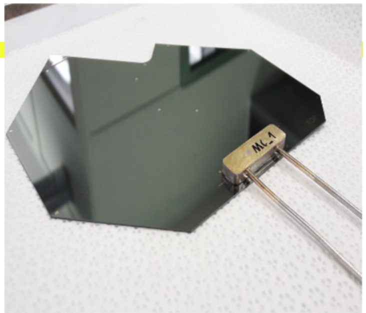


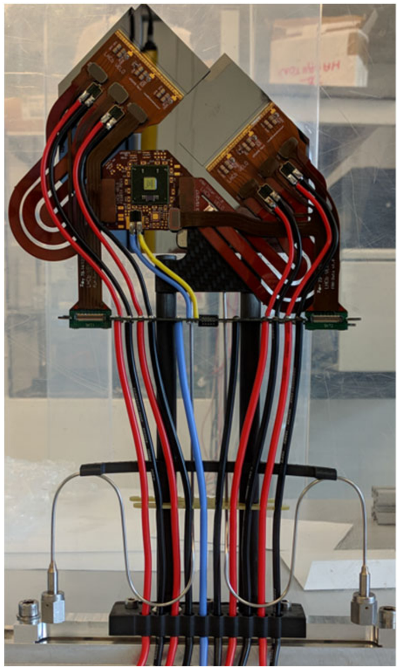
# LHCb VErtex LOcator upgrade

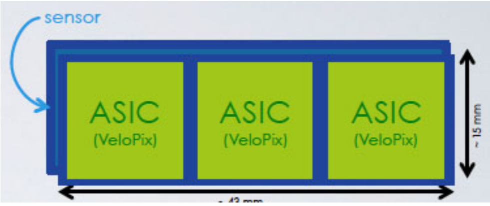
Micro-channel cooling

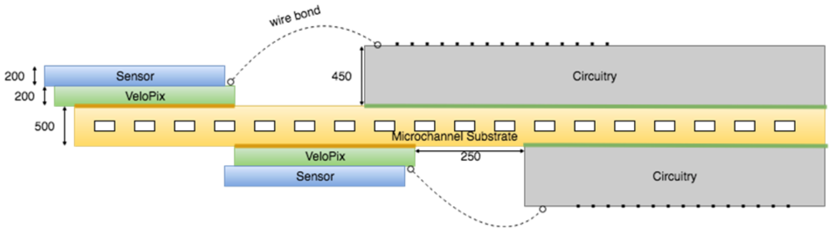
- 500 µm thick silicon substrate with integrated micro channels (70 $\mu$m x 200 $\mu$m) :
  - same thermal expansion as sensors
  - low material
  - high thermal efficiency
  - cooling power ~50 W
- pressure: 14 bar @ -30 $^{o}$C, 60 bar @ 22 $^{o}$C

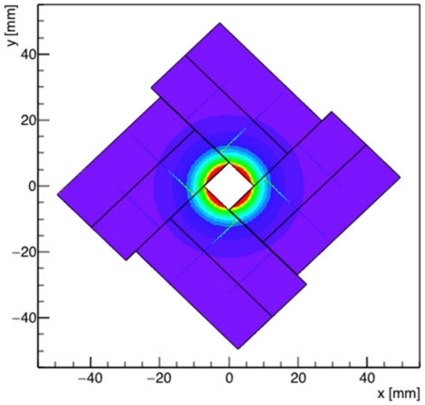






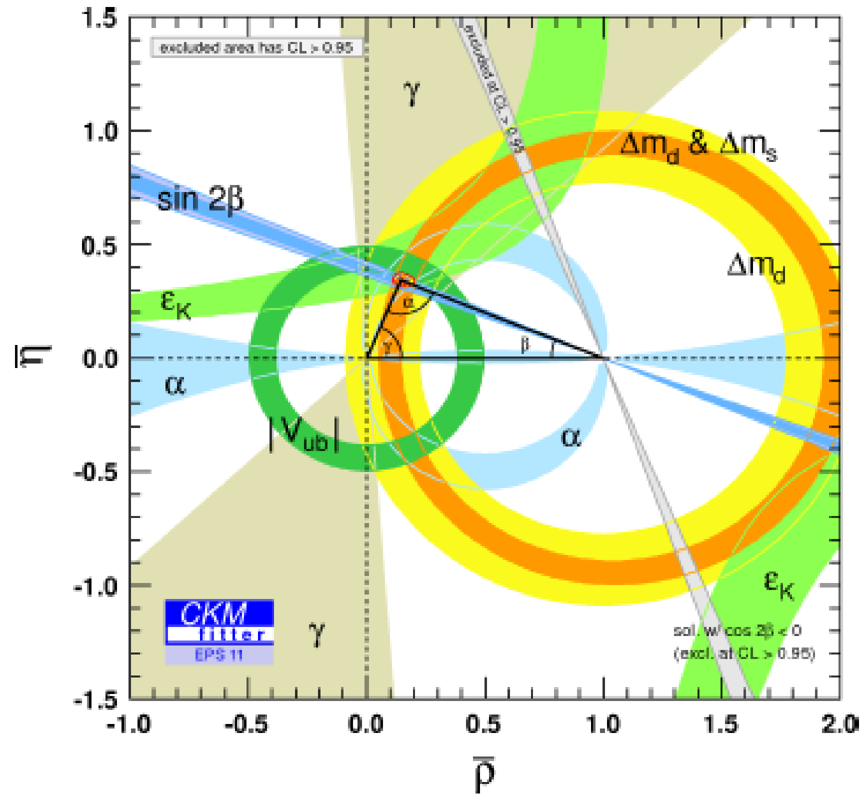


# The unitarity triangle – status

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%



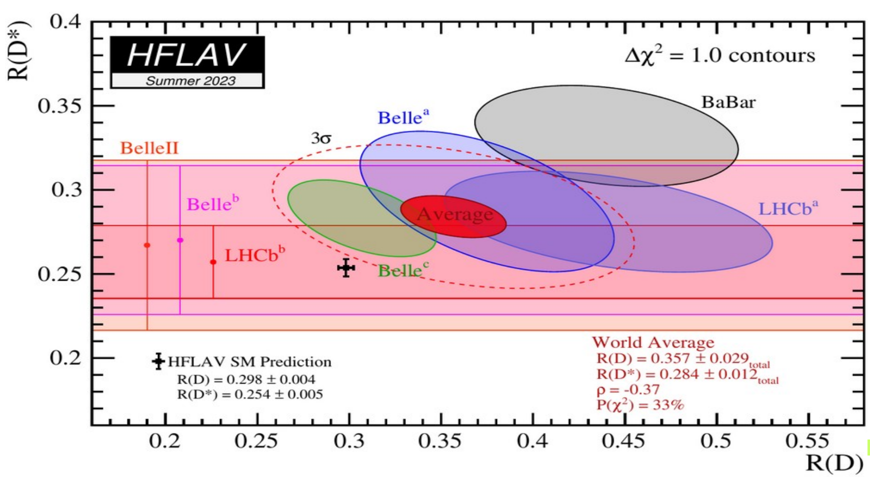

→investigate possible NP phenomena with precise measurements

→Intensity frontier (=need more data)

→ LHCb, Belle II, ATLAS and CMS

# It worked already many times!

- The smallness of $K_L \to \mu^+\mu^-$ → GIM mechanism →need one more quark – charm
- $K^0$ – 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

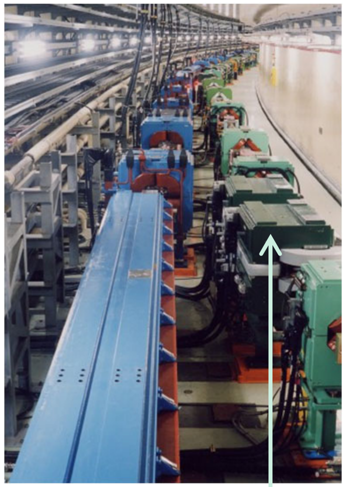



Measurements of R(D) and R(D*) compared to the SM predictions – interesting, but more data needed

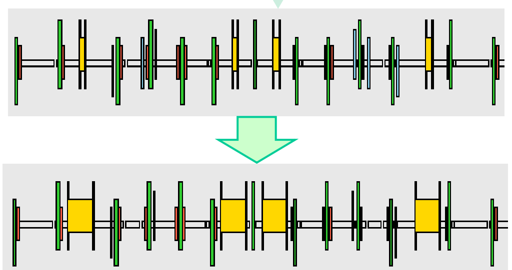
$$R(D, D^*, X) = \frac{\mathcal{B}(B \to D, D^*, X\tau\nu)}{\mathcal{B}(B \to D, D^*, X\ell\nu)}$$

with $\ell$ a light lepton

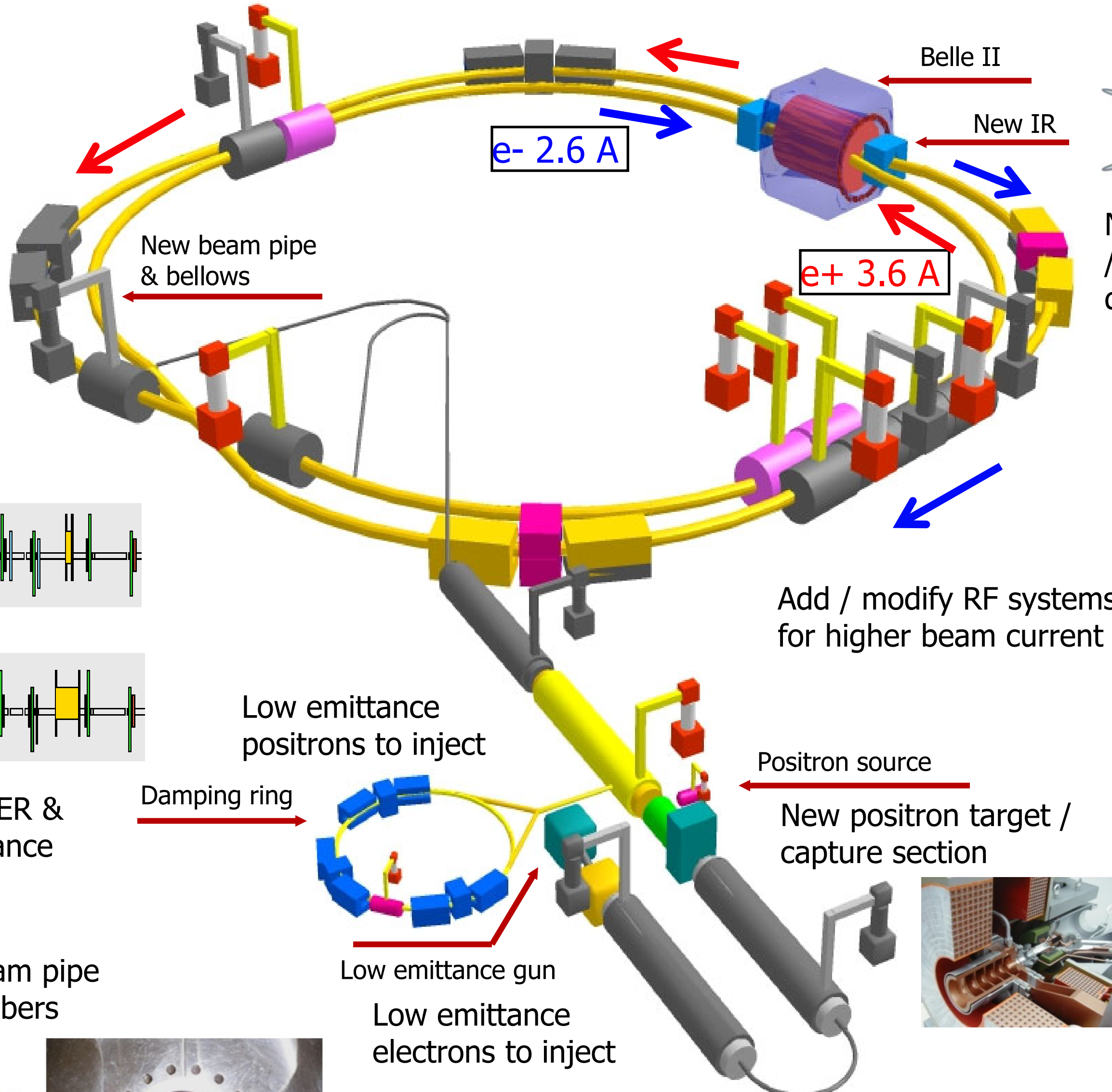
# KEKB → SuperKEKB



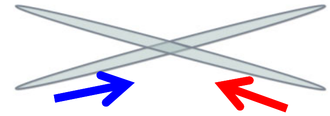
Replace short dipoles with longer ones (LER)



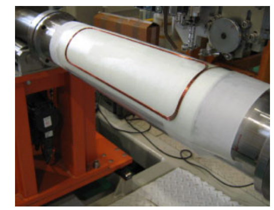
Redesign the lattices of HER & LER to squeeze the emittance



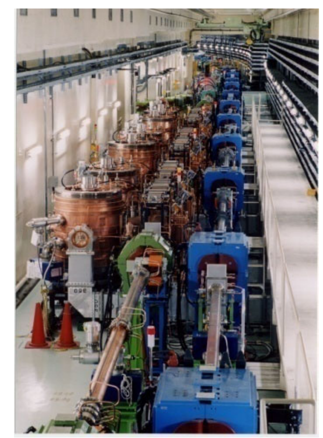

Colliding bunches



New superconducting /permanent final focusing quads near the IP

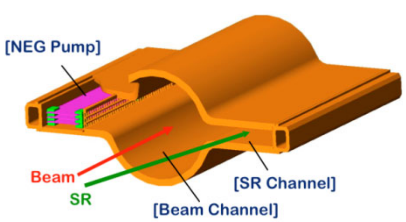


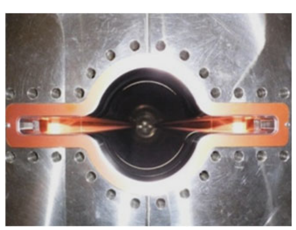
Add / modify RF systems for higher beam current



New positron target / capture section

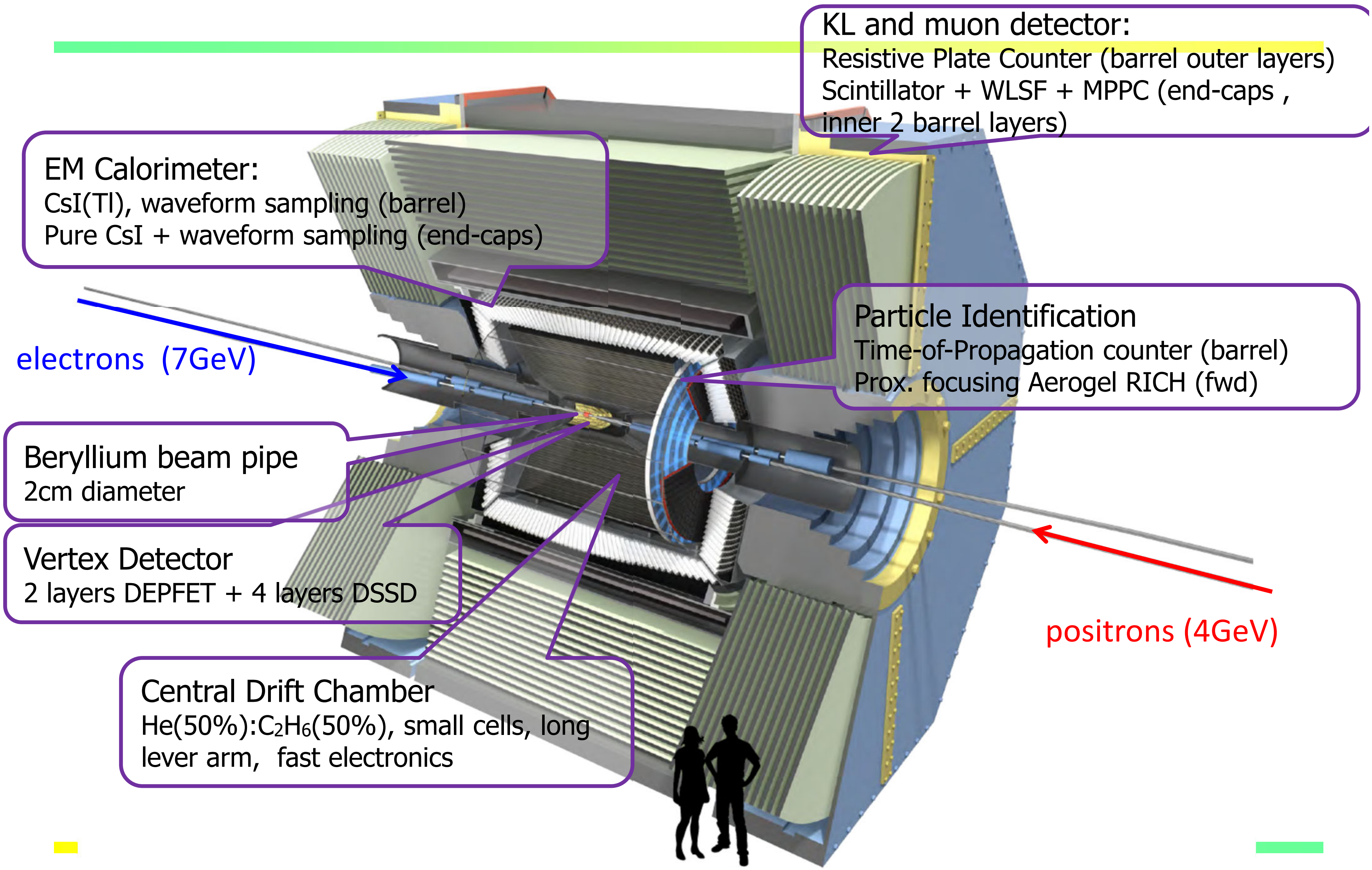
TiN-coated beam pipe with antechambers



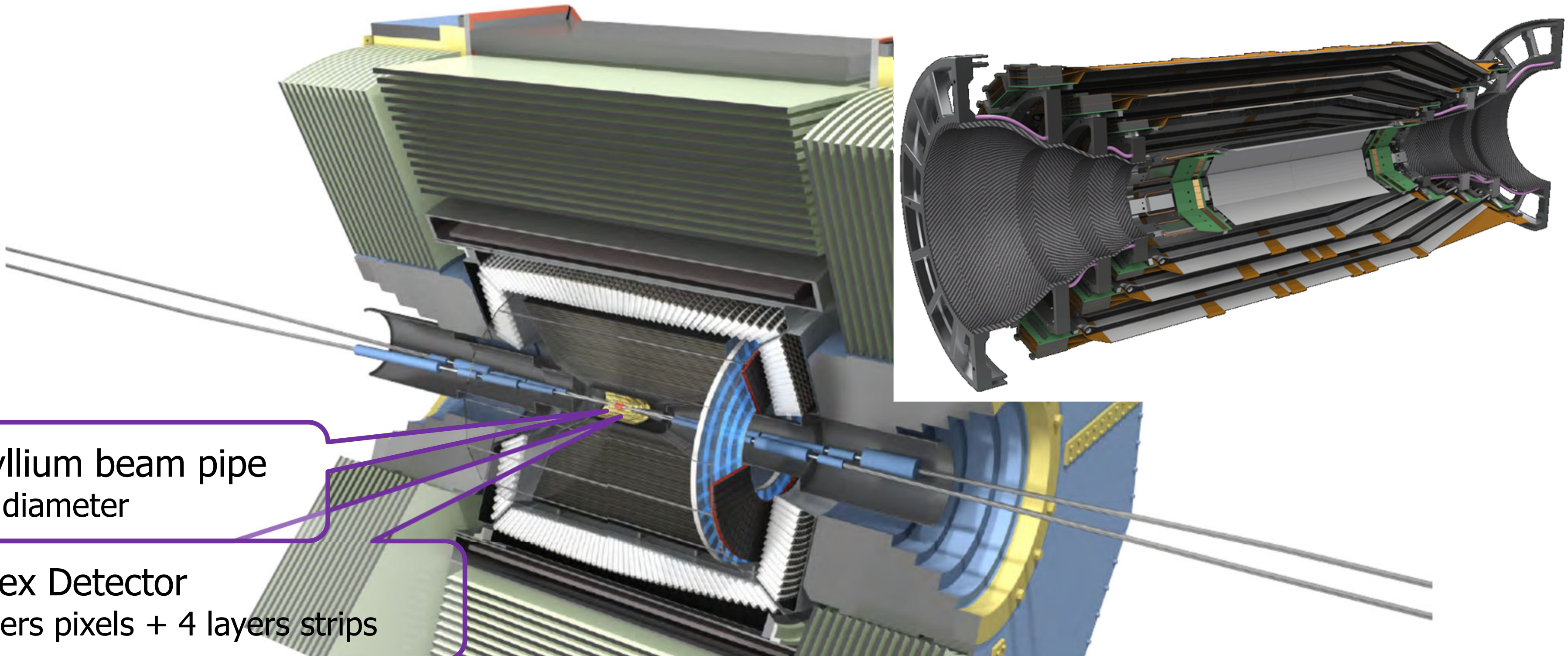
***To get x40 higher luminosity***

# Belle II Detector



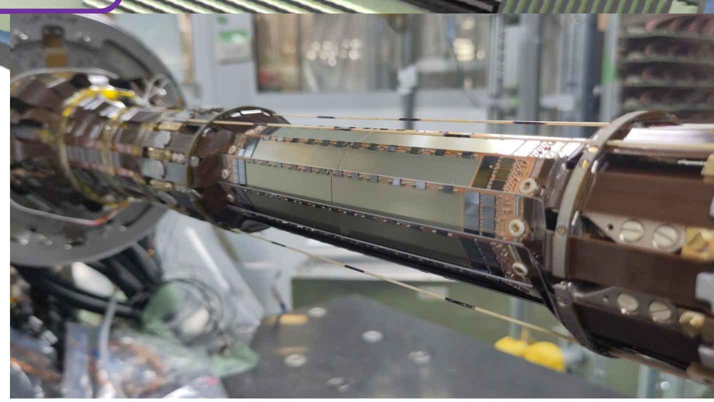
# Vertexing at Belle II

## Momenta of charged particles from B meson decays: p < 4 GeV/c



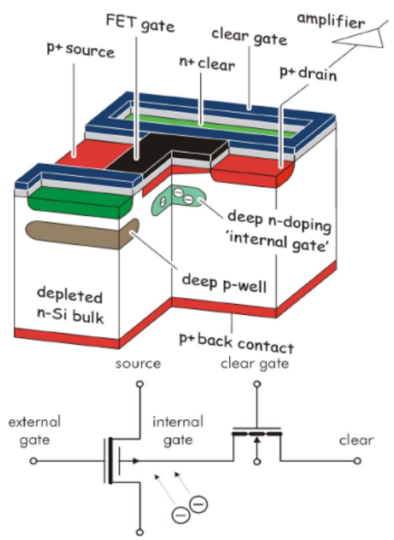
Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers pixels + 4 layers strips



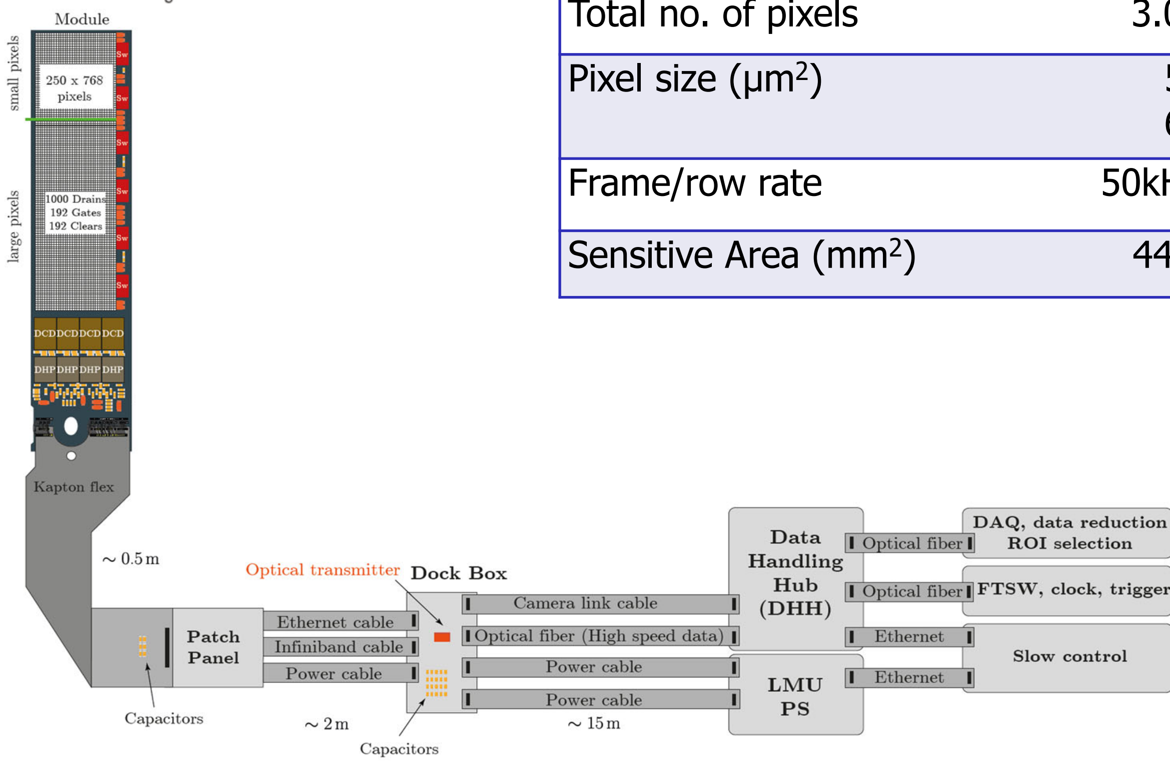
| | | |
|---|---|---|
| **Beam Pipe** | | **r = 10mm** |
| **DEPFET pixels** | | |
| | **Layer 1** | **r = 14mm** |
| | **Layer 2** | **r = 22mm** |
| **DSSD silicon strips** | | |
| | **Layer 3** | **r = 39mm** |
| | **Layer 4** | **r = 80mm** |
| | **Layer 5** | **r = 104mm** |
| | **Layer 6** | **r = 135mm** |

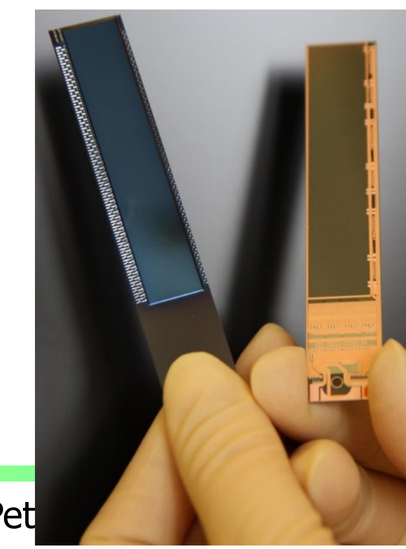
DEpleted P-channel FET




# Belle II pixel detector: 2 layers of DEPFET sensors

| | L1 | L2 |
|---|---|---|
| # ladders (modules) | 8 (16) | 12 (24) |
| Distance from IP (cm) | 1.4 | 2.2 |
| Thickness (μm) | 75 | 75 |
| #pixels/module | 768x250 | 768x250 |
| #of address and r/o lines | 192x1000 | 192x1000 |
| Total no. of pixels | $3.072 \times 10^6$ | $4.608 \times 10^6$ |
| Pixel size ($\mu m^2$) | 55x50<br>60x50 | 70x50<br>85x50 |
| Frame/row rate | 50kHz/10MHz | 50kHz/10MHz |
| Sensitive Area ($mm^2$) | 44.8x12.5 | 61.44x12.5 |



MPI Munich, HLL, DESY, Bonn, Prague, Goettingen

Pet

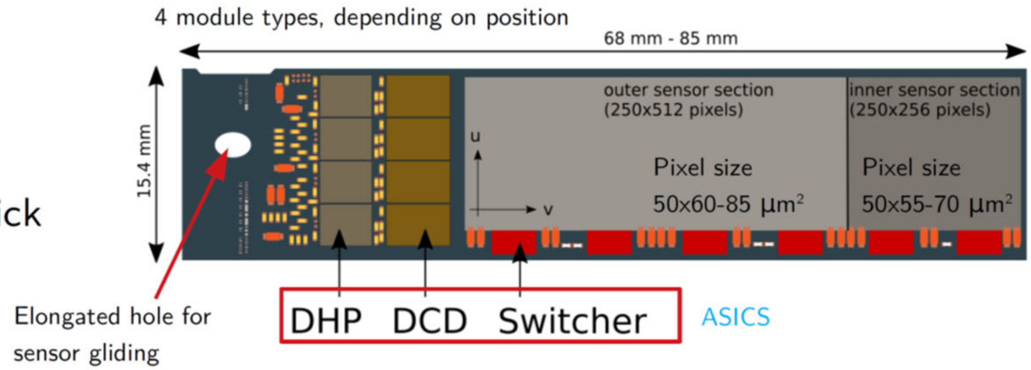
# Belle II PXD Module

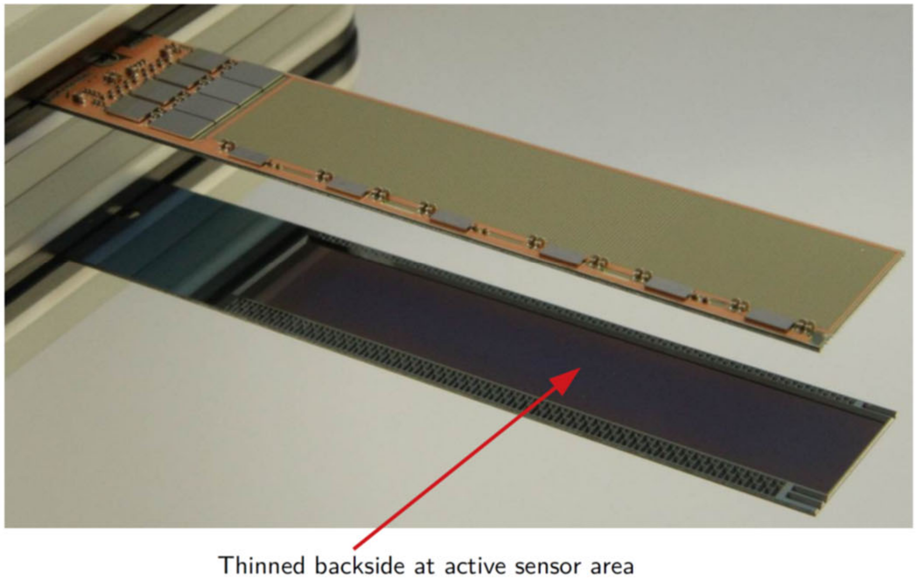
Properties:

- Self-supporting "**all-silicon**" structure
  - Support frame ~500 µm thick
  - **Monolithic** active area 75 µm thick
- **Low material budget** (~0.21% $X_0$)
- Pixel sizes 50 x 55-85 µm$^2$ (250 x 768 pixels)

Rolling Shutter Readout:

- **Switcher**: consecutive row selection for signal digitization of columns (10 MHz)
- **DCD**: 8-bit AD conversion of signal
- **DHP**: zero suppression, data formatting
- 20 µs integrated readout time (2x beam revolution)




Anselm Baur VERTEX 2023

# Belle II PXD Detector

2 Modules = 1 Ladder:

- Glued together
- In total 20 ladders

10 Ladders = 1 Half-Shell:

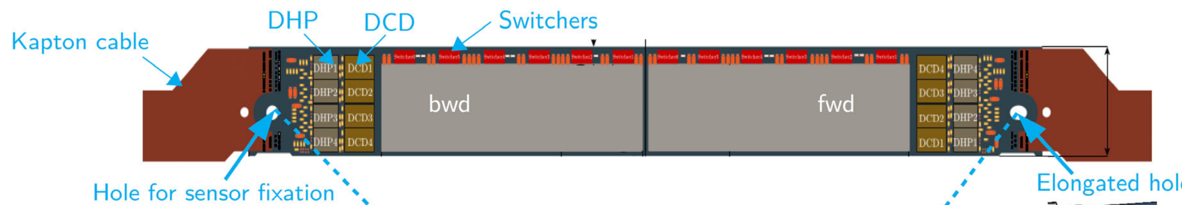
- Ladders screwed on cooling block
  - Radii: $r_{L1}$=14mm, $r_{L2}$=22mm
- Half-Shell mounted on beam pipe

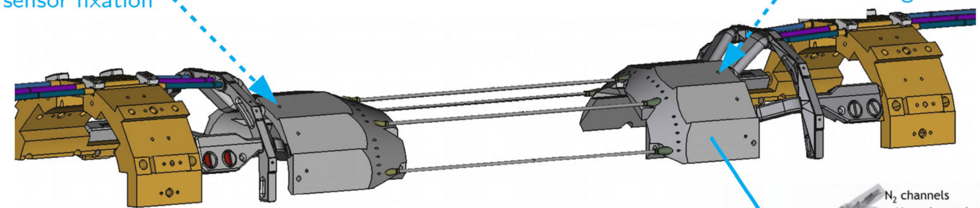
Power Consumption:

- ~9 W per module
  → ~360 W (full detector)
- Cooling
  - 2 phase $CO_2$: DHP/DCD (8W)
  - $N_2$ gas: sw.+sensor area (1W)

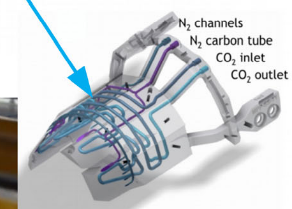
PXD1:

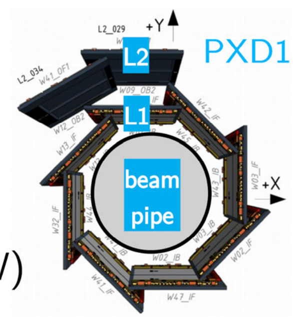
- PXD1 incomplete (effectively 1 layer)

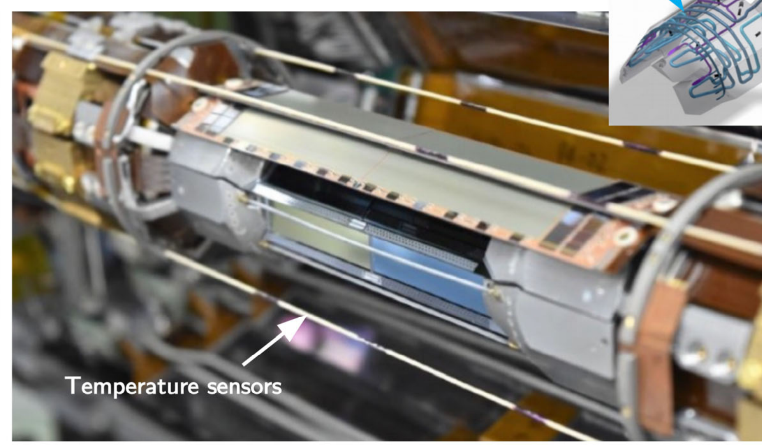


PXD half-shell support and cooling block (SCB)



# Belle II SVD: four layers of double-sided silicon strip detectors.

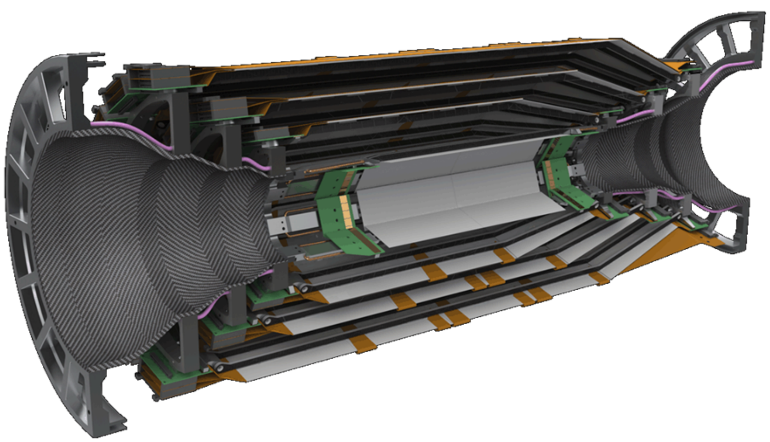
Double-sided silicon strip detectors

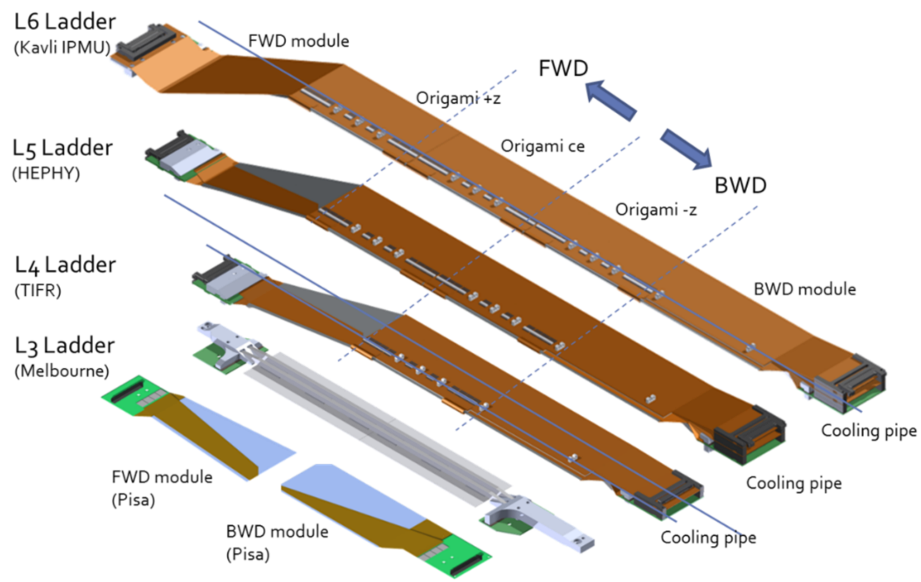
Origami chip-on-sensor concept (readout chips on top of the sensors with flex pitch adapters bent around the edge to reach the bottom sensor side) for good S/N with fast readout and moderate material budget

Excellent time resolution (~4ns) thanks to multiple recorded samples and waveform fitting

$CO_2$ dual-phase cooling

with a very strong Indian contribution



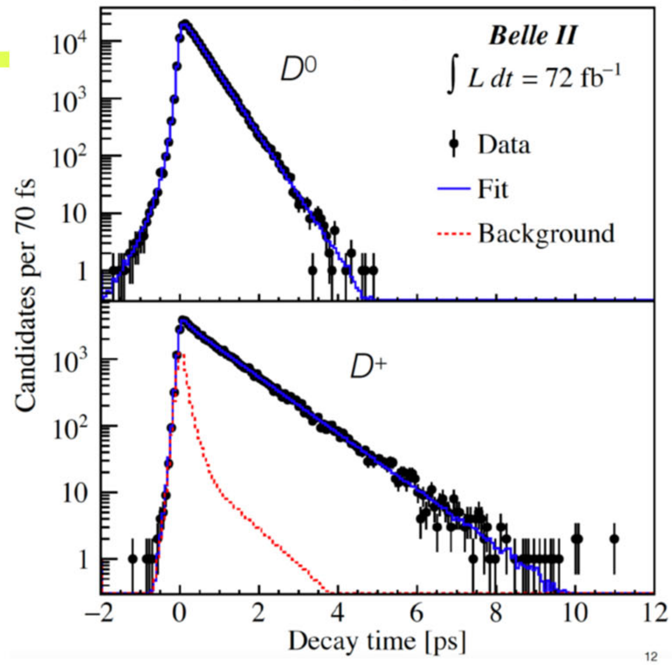


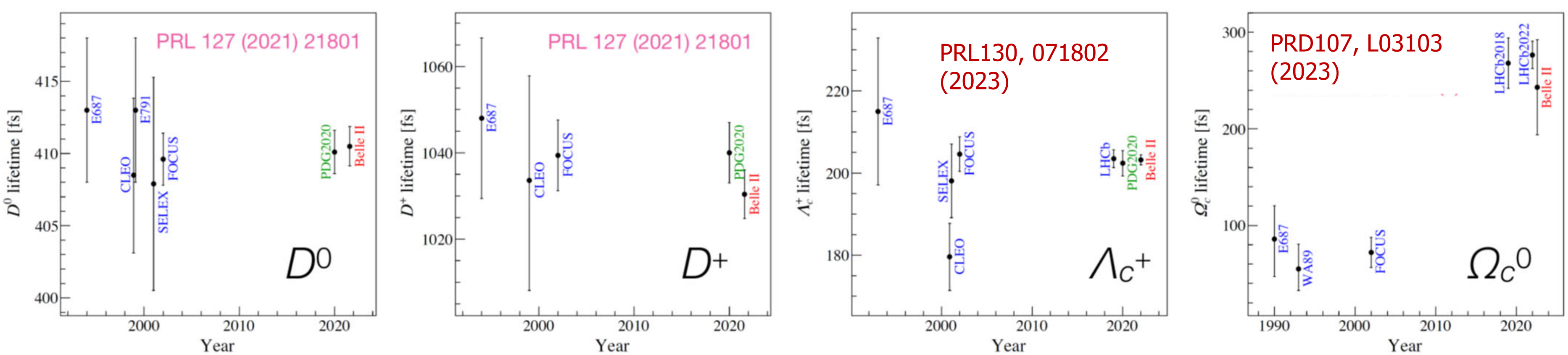
# Charmed hadrons: lifetime measurements

Example of improved performance of Belle II vs Belle: time-dependent capabilities in D lifetime measurements.

The addition of a pixel vertex detector (with a 1cm radius beam pipe) gives a *factor of two improvement* in proper time resolution for charm lifetime measurements compared to Belle. Alignment systematics are much improved.

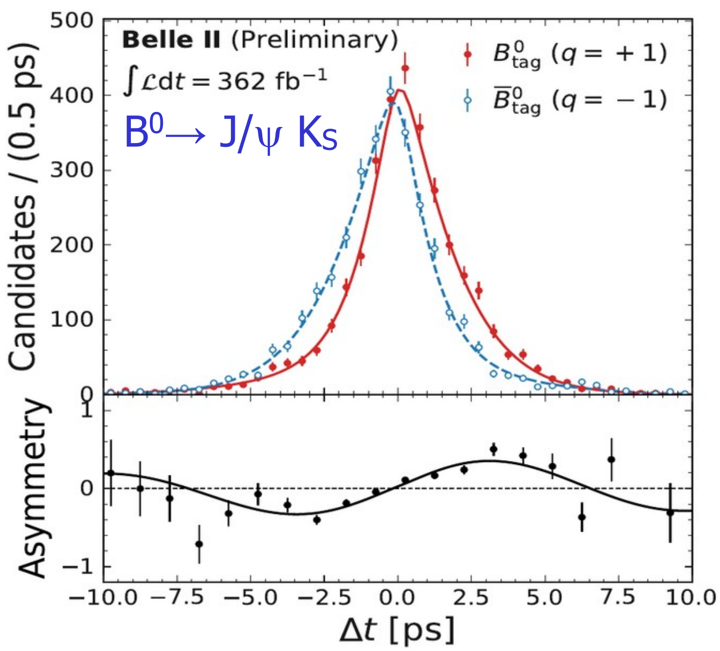
PRL 127 (2021) 21801

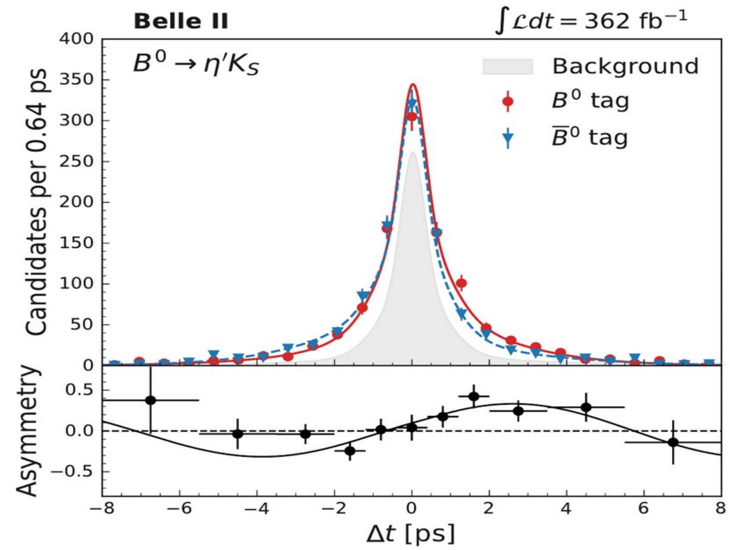


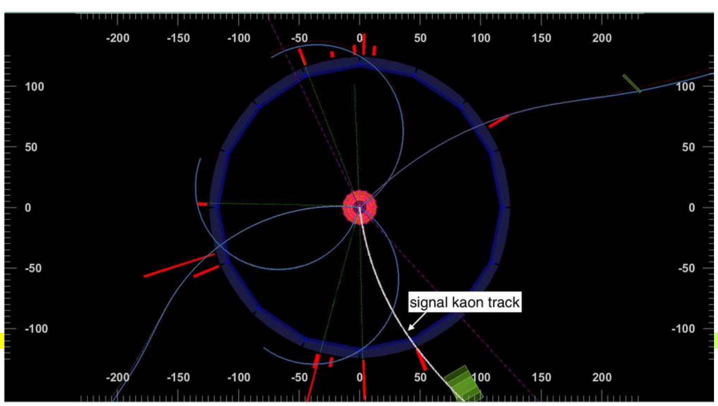

Tiny systematic uncertainties (e.g., 2‰ for $D^0$) demonstrate excellent performance and understanding of the Belle II detector, never achieved at previous B factories

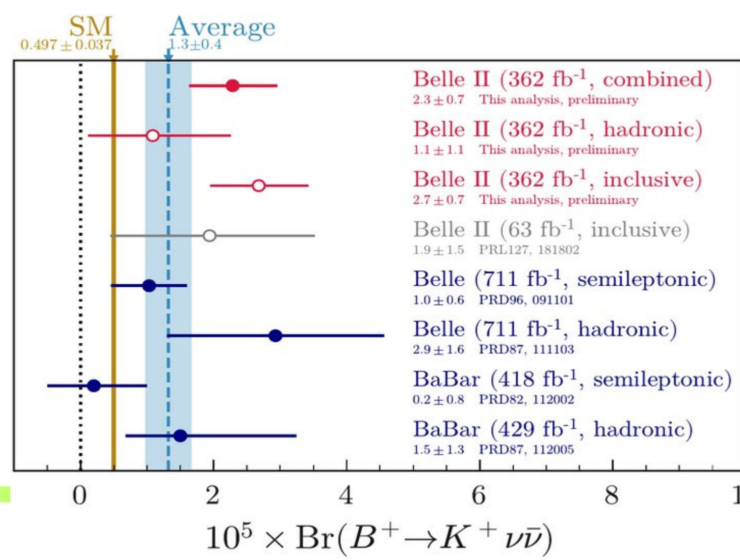
# … many results published, and many more too come




$B^+ \to K^+ \nu\, \nu$



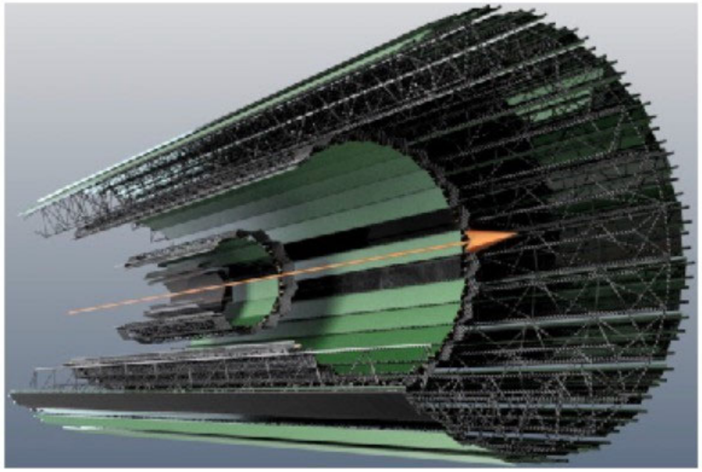
# Belle II VXD Upgrade for LS2: requirements

Motivations:

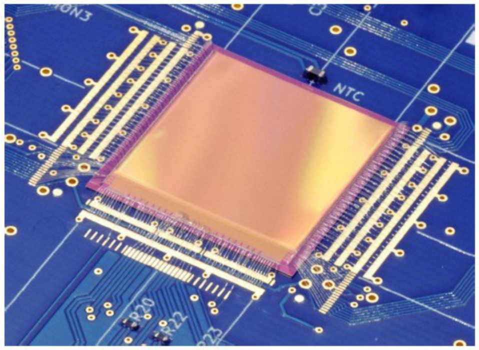
- Cope with larger background rates
- Improve momentum and impact parameter resolution at low $p_T$
- Simplify vertex system (pixels + strips → pixels)
- Operation without data reduction
- Be safe in case of accident

Concept:

- 5 layers with high space-time granularity & low material budget
  - Robustness against high radiation environment (innermost layer) - occupancy < $\mathcal{O}(10^{-4})$
  - Higher vertexing precision
  - Lighter services and simpler design
  - adaptable to potential change of interaction region



Max radius 14 cm & length 70 cm → 1 $m^2$



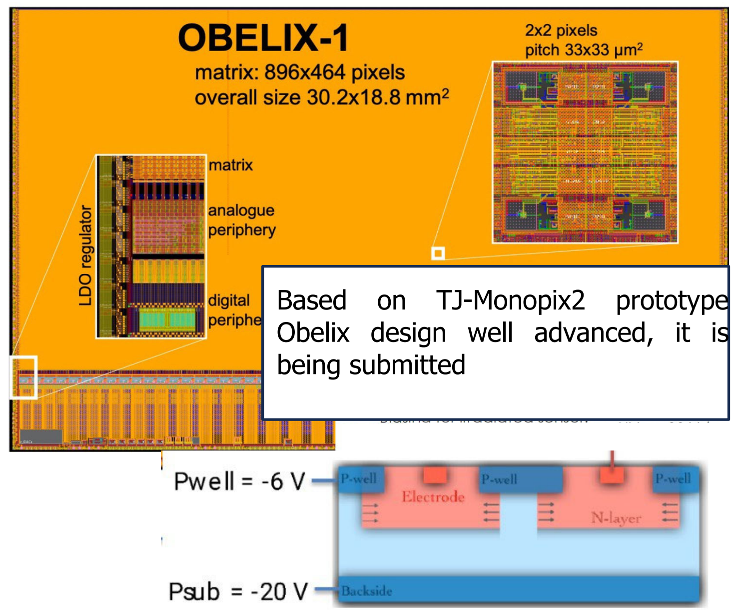
Claudia Cecchi - FPCP 2024

# Belle II VTX Upgrade Specifications

- Depleted monolithic active CMOS pixels
- Sensitive layer thickness < 30 μm (~2500e from MIPs vs. 200-250e threshold)
- Sensor thickness < 50 μm
- iVTX: innermost 2 layers, self-supported, cooling under study
- oVTX: outer 3 layers, CF structure, single-phase coolant
- Prototype (TJMonopix2, developed for ATLAS) has largely met these specifications, including irradiation tests
- New OBELIX DMAPS sensor, targeting Belle II specific application, now in the final design phase

## OBELIX-1 specifications & layout

| | |
|---|---|
| Pitch | 33 μm |
| Signal ToT | 7 bits |
| Integration time | 50 To 100 ns |
| Time stamping | ~5 ns for hit rate < 10 MHz/cm² |
| Hit rate max for 100% eff. | 120 MHz/cm² |
| Trigger handling | 30 KHz with 10 μs delay |
| Trigger output | ~10 ns resolution with low granularity |
| Power (with hit rate) | 120 to 200 mW/cm² (1 to 120 MHz/cm2) |
| Bandwidth | 1 output 320 MHz |

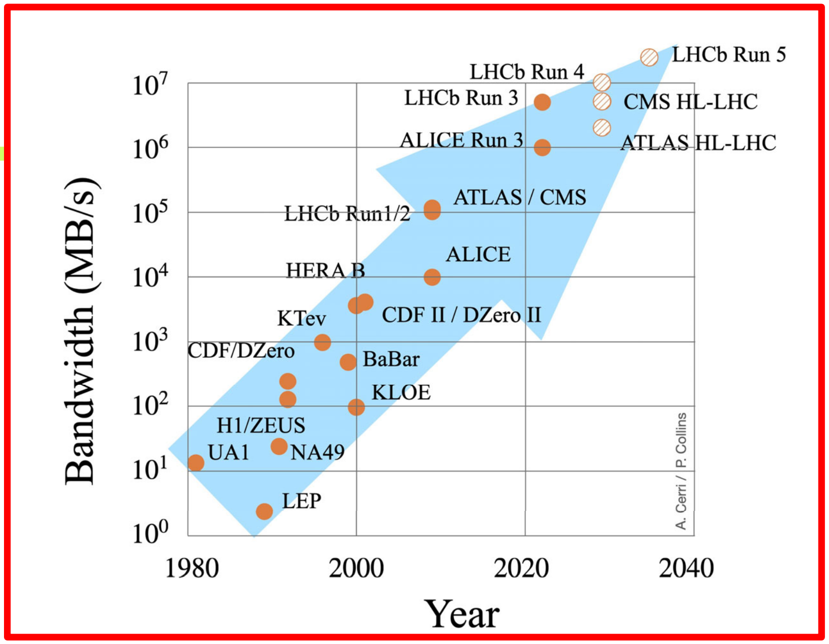



Based on TJ-Monopix2 prototype Obelix design well advanced, it is being submitted

# LHCb Upgrade II

Upgrade II performance must equal or surpass that of Upgrade I, with

- Pile-up reaching values of 40
- 200 Tb/s of produced data
- charged particle densities up to ✖ $10^{12}\,/\mathrm{cm}^2$

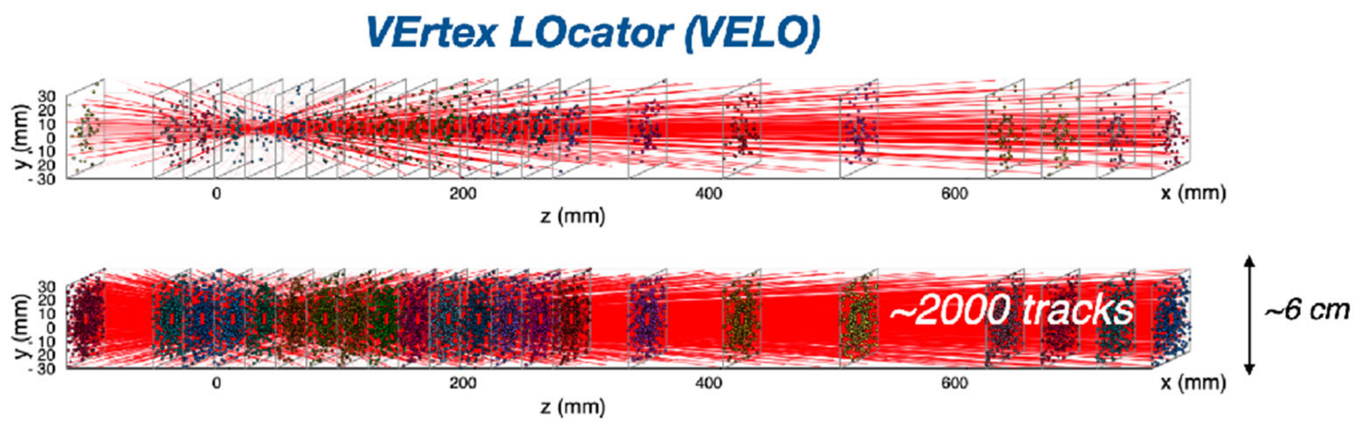



This is the **intensity frontier**! New, lightweight technologies with high granularity, timing, radiation resistance and innovative data processing all necessary to go to ✖ $10^{34}\,\mathrm{sec}^{-1}\mathrm{cm}^{-2}$

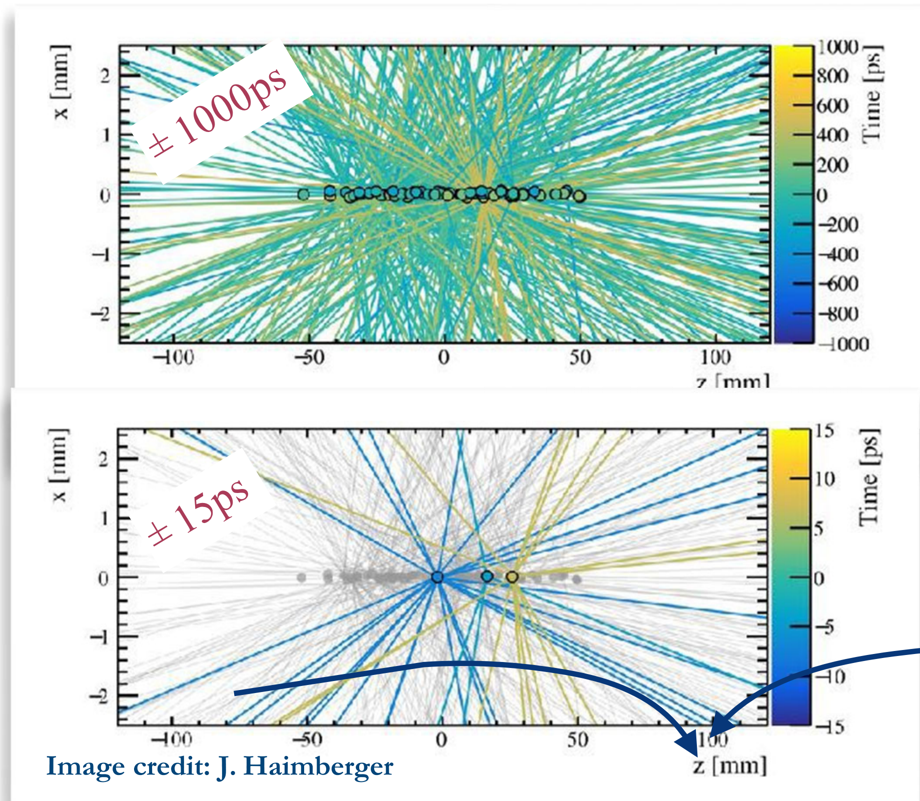
Image credit: Tim Evans

Run 3: pile-up ~5

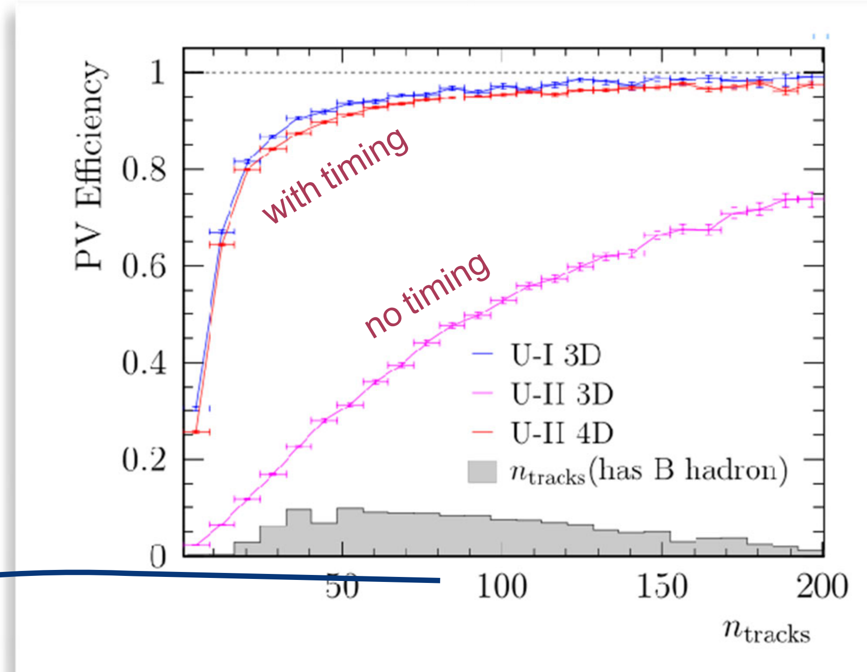
Upgrade II: pile-up ~40



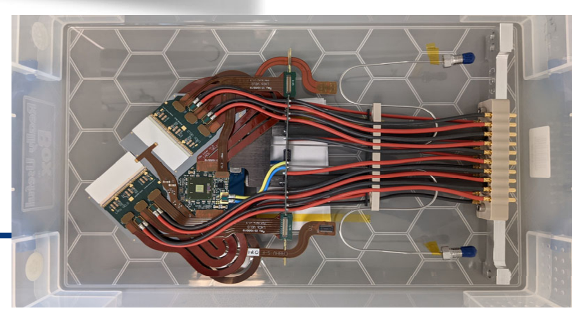
# LHCb Upgrade II




## Timing to the Rescue



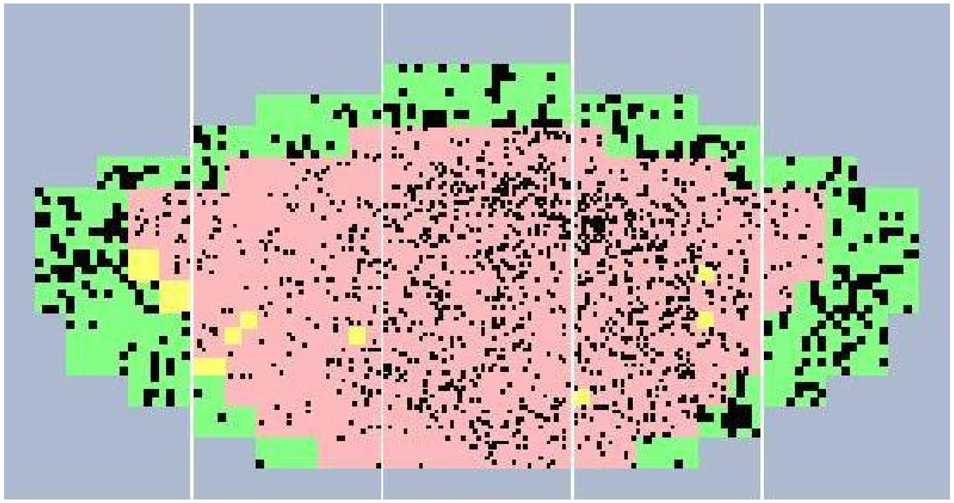

**Sensors** to be replaced with timestamping, radiation hard solution (3d, thin planar…)



**ASICS** to be replaced with ultra high rate, radiation hard, timestamping, low pitch ++ solution

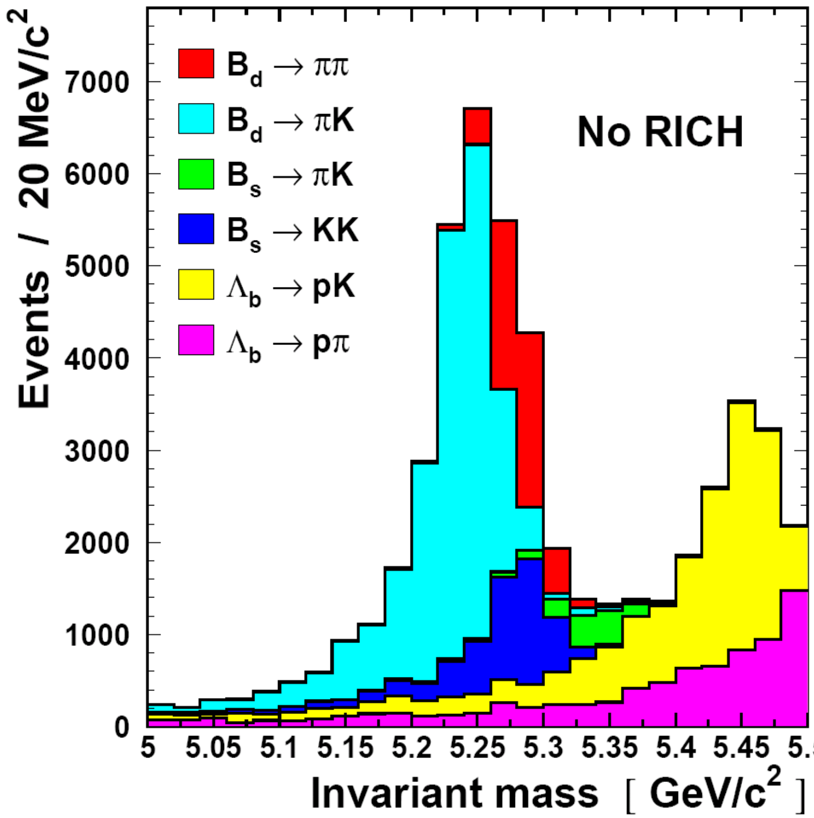
# The next frontier for semiconductor detectors: single photon detection for RICH counters

… in LHC or LHC-like environments

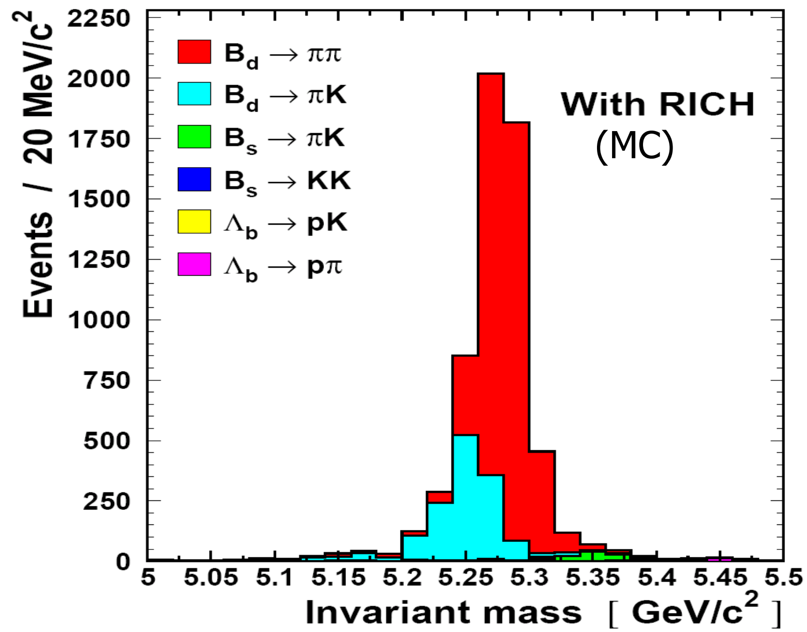


It works with multianode PMTs, but can we make it with semiconductor detectors?

# Why particle ID?

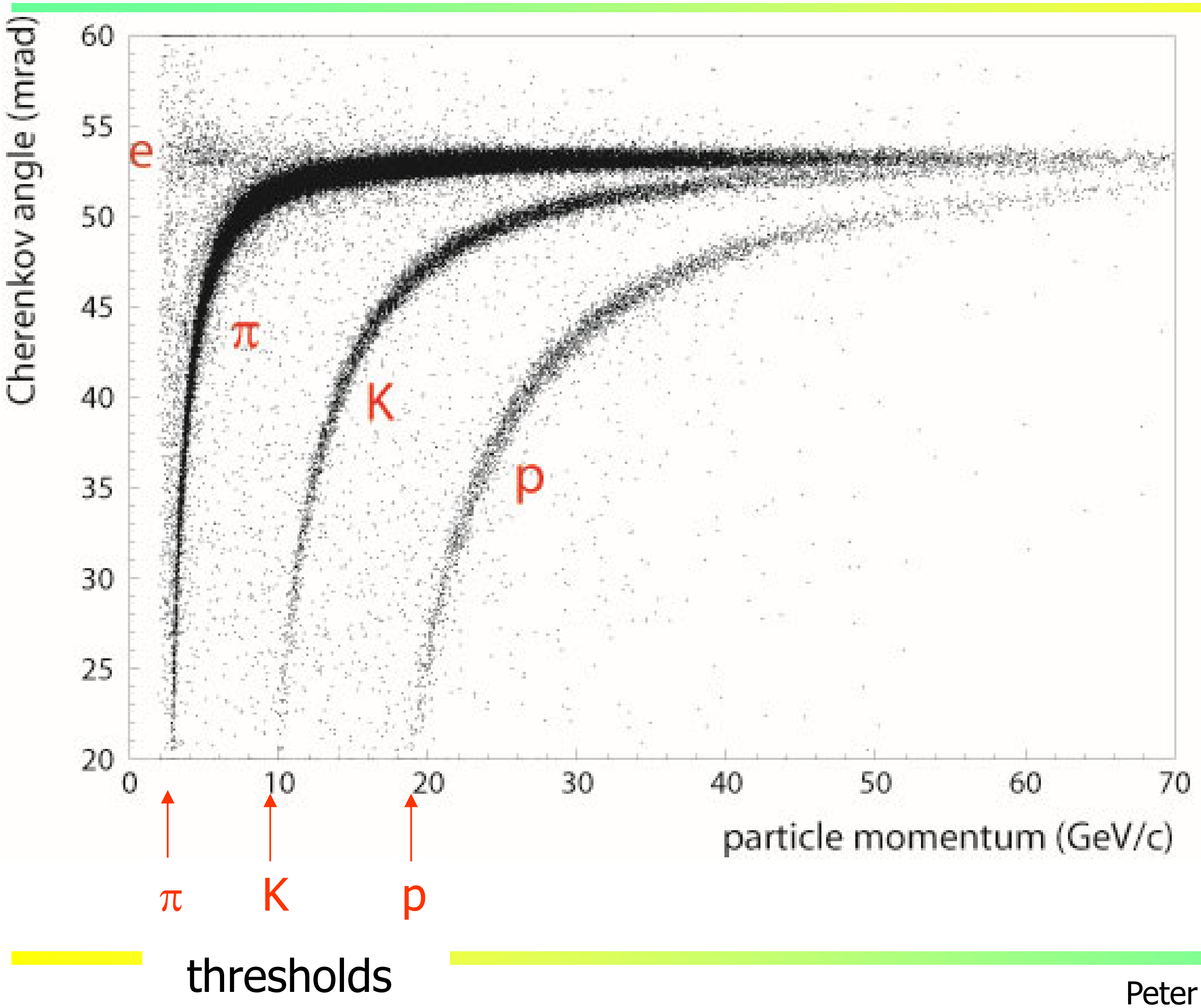



Example: LHCb



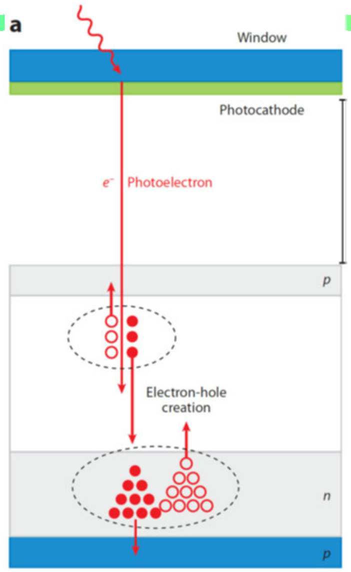

Need to distinguish $B_d \rightarrow \pi\pi$ from other similar topology 2-body decays and to distinguish B from anti-B using K tag.

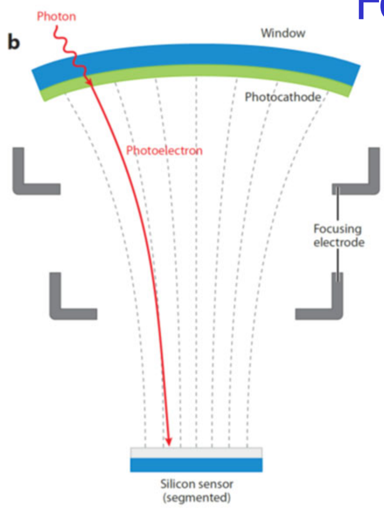
# PID at high momenta: measure Cherenkov angle in a RICH detector




Radiator:
$C_4F_{10}$ gas

# Hybrid photodetectors (HPD, HAPD)




Focusing and proximity-focusing configurations

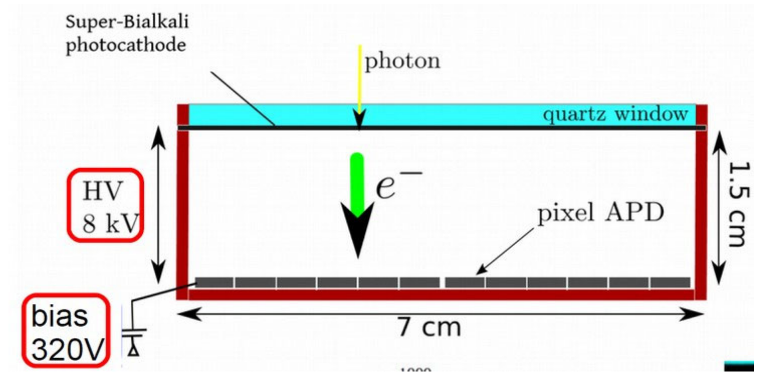


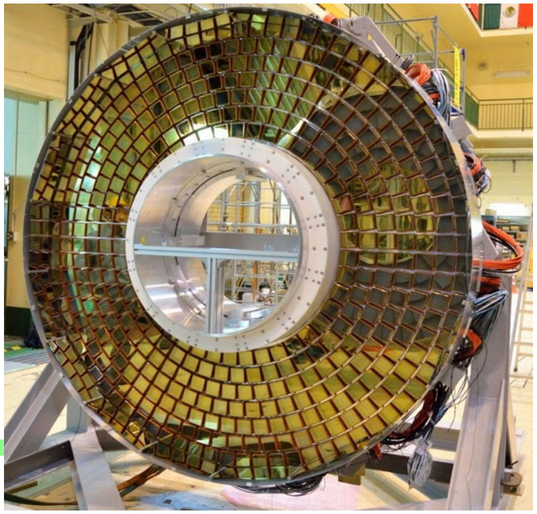

Photo-electron acceleration in a static electric field (8kV to 25 kV)

Photo-electron detection with

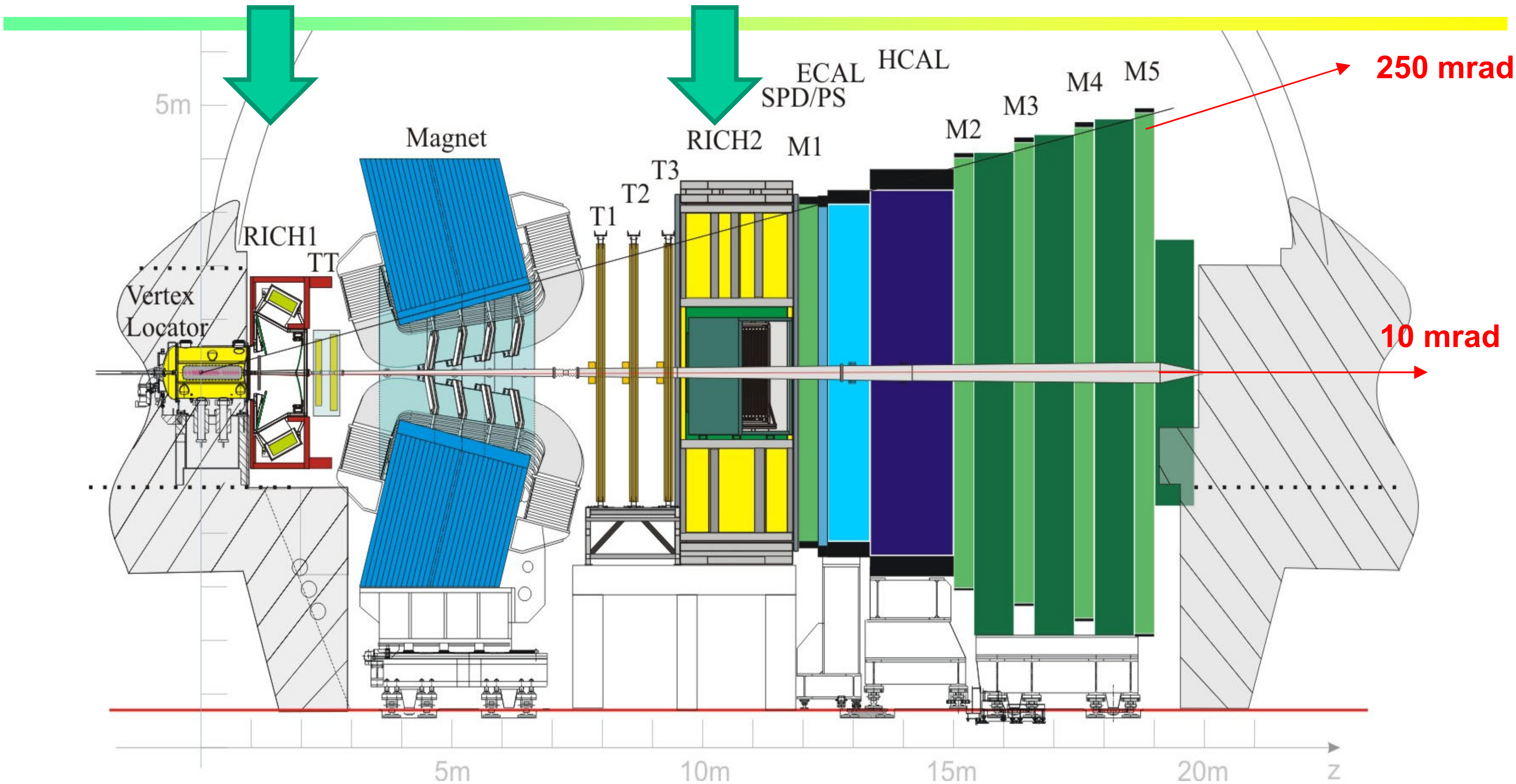
- Segmented PIN diode (HPD)
- Avalanche photo diode (HAPD)
- Silicon photomultiplier (VSiPMT)

Employed on a large scale:

- HPD: RICH1+RICH2 of LHCb (Run 1+2), CMS HCAL
- HAPD: Aerogel RICH detector of Belle II



# The LHCb RICH counters




**Vertex reconstruction:**
**VELO**

**Trigger:**
**Muon Chambers**
**Calorimeters**
**Tracker**

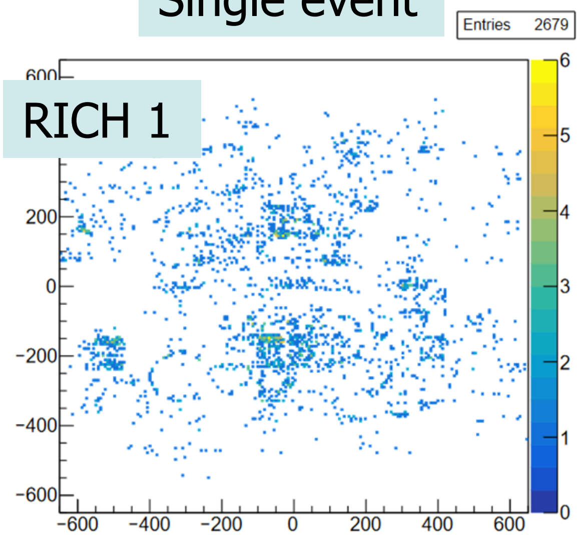
**PID:**
**RICHes**
**Calorimeters**
**Muon Chambers**

**Kinematics:**
**Magnet**
**Tracker**
**Calorimeters**

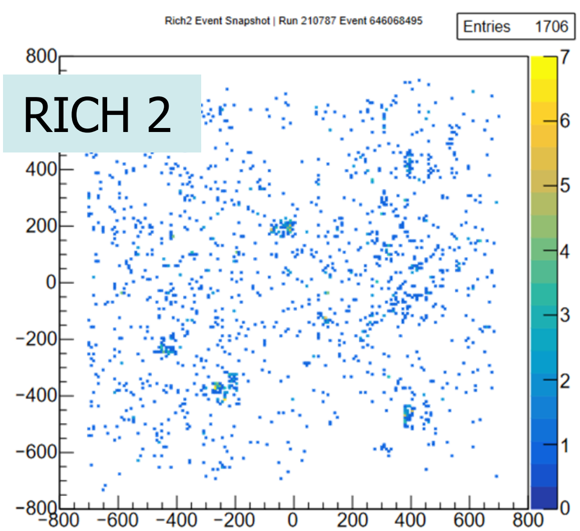
# Performance of LHCb RICHes

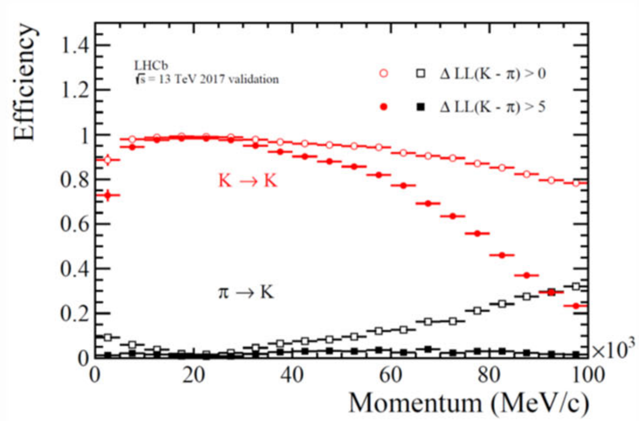
Single event

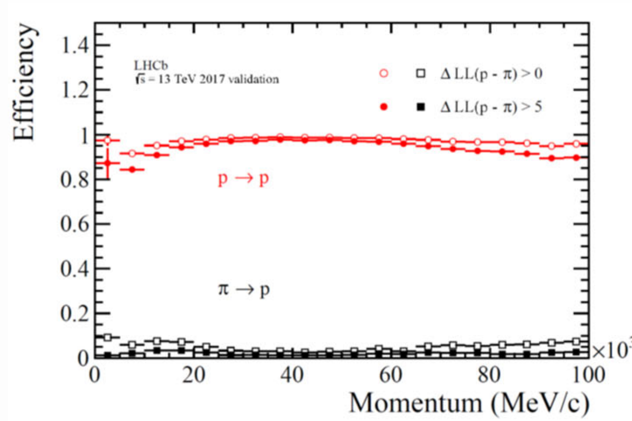
RICH 1

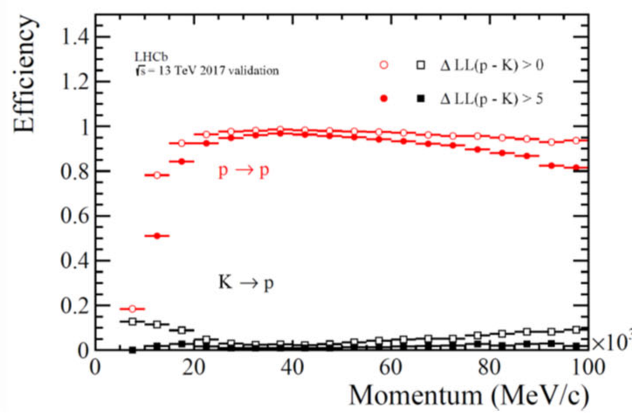



RICH 2

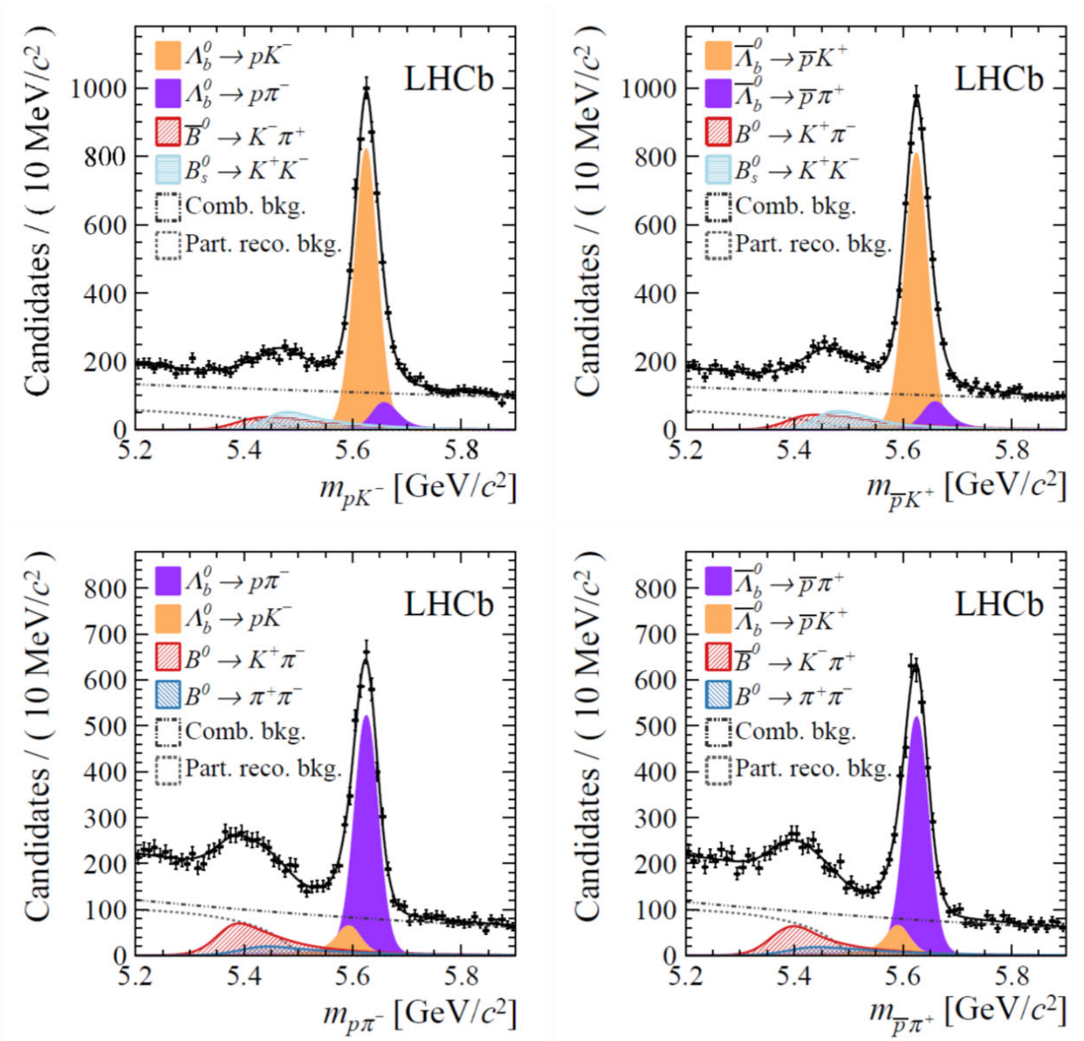


# LHCb RICHes: performance

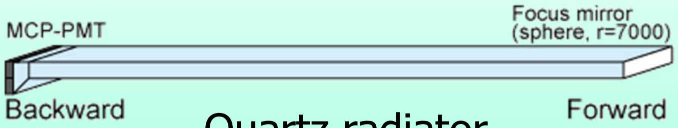



"Search for CP violation in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays"

[LHCb-PAPER-2018-025]

# Belle II Cherenkov detectors

## Barrel PID: Time of Propagation Counter (TOP)



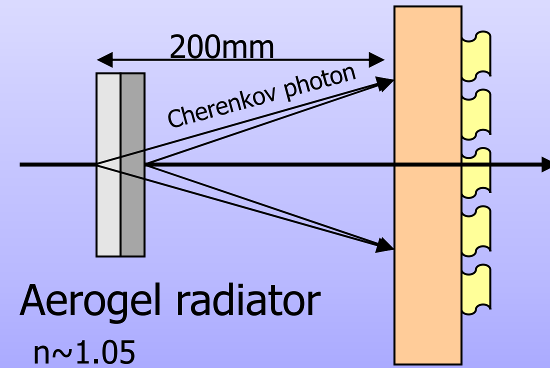

Quartz radiator

Focusing mirror

Small expansion block

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

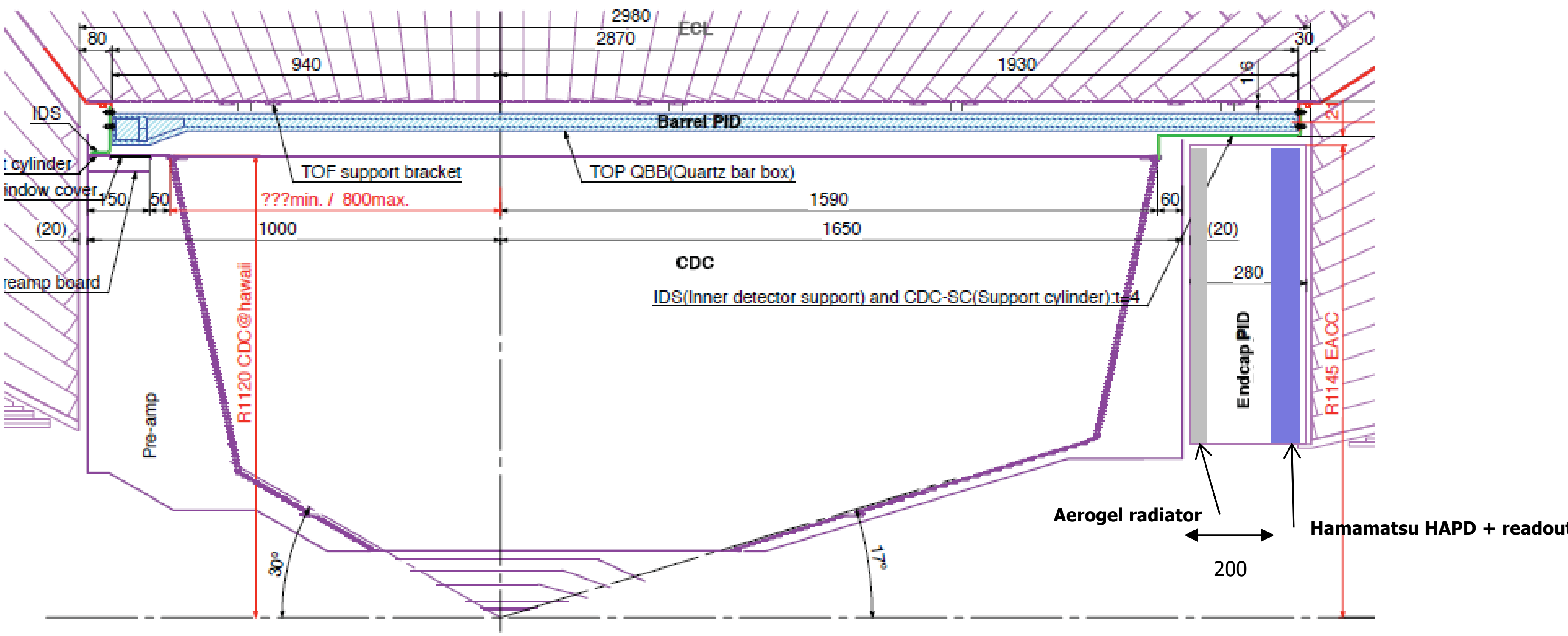
## Endcap PID: Aerogel RICH (ARICH)



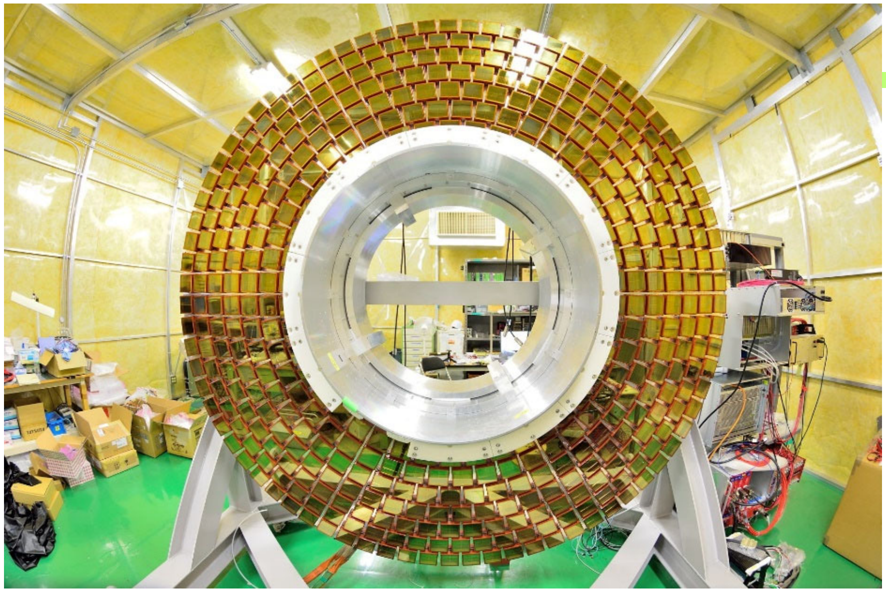

Aerogel radiator

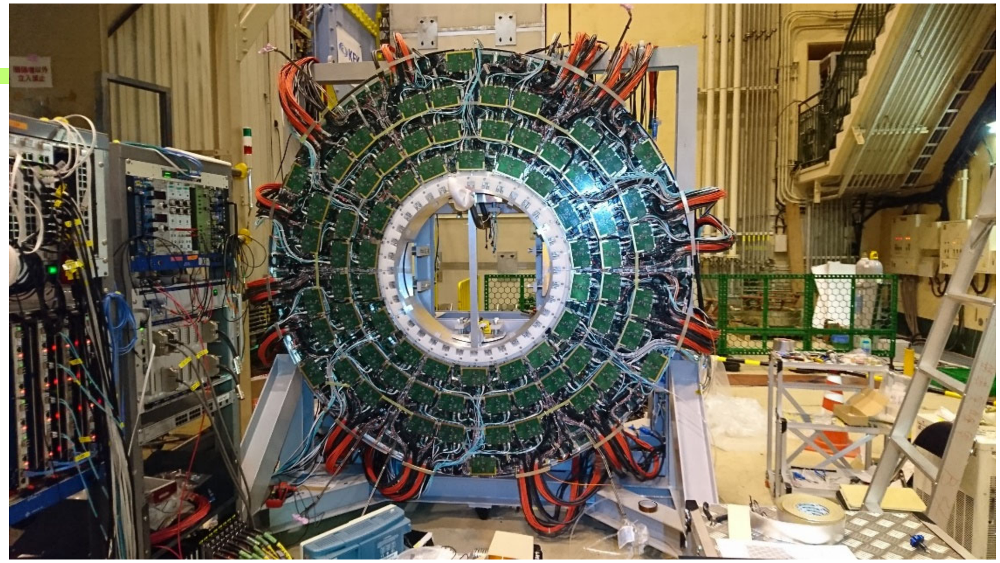
n~1.05

Hamamatsu HAPD
+ new ASIC

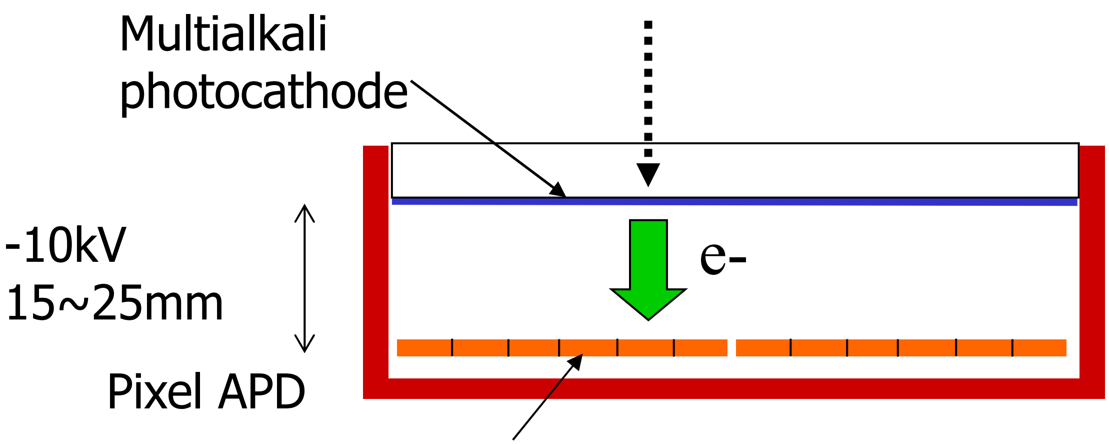


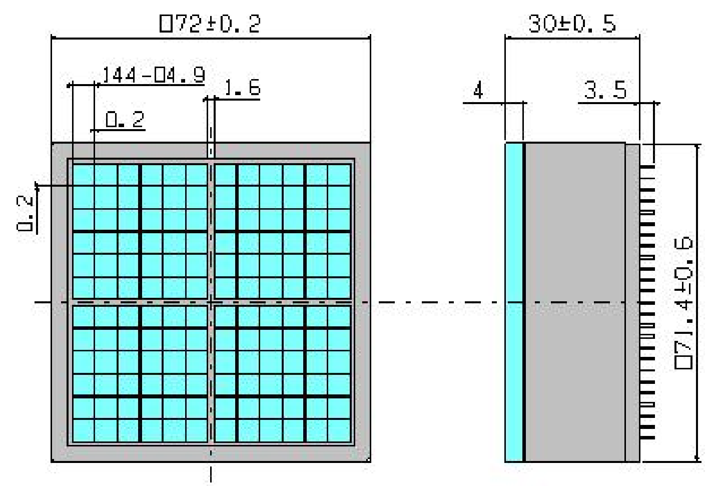
# The big eye of ARICH – 420 HAPDs





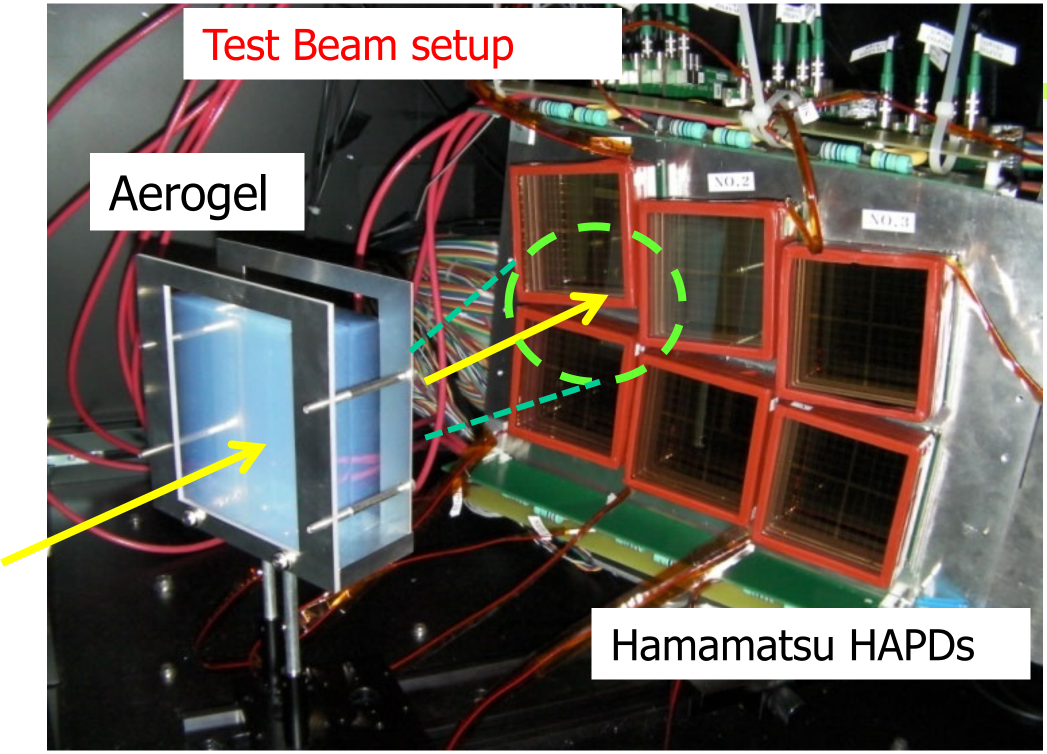
## Sensor: Hybrid APD - HAPD

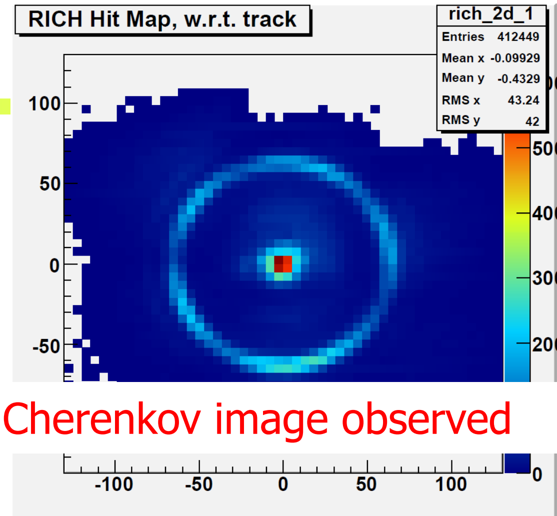



HAPD R&D project in collaboration with HPK.

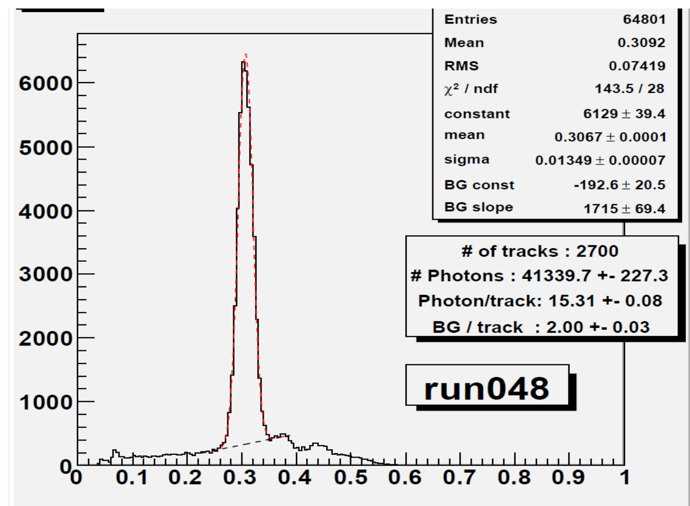
# Aerogel RICH (endcap PID)



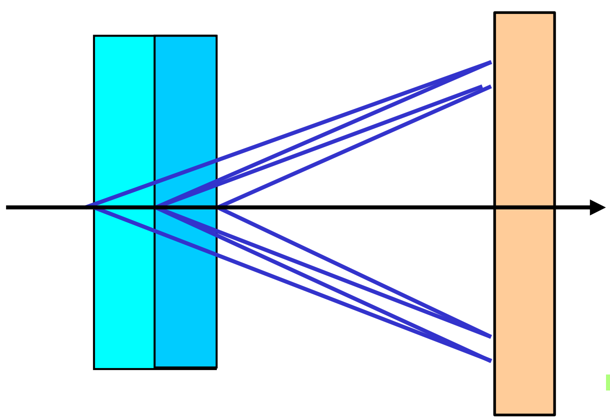




Clear Cherenkov image observed

Cherenkov angle distribution




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



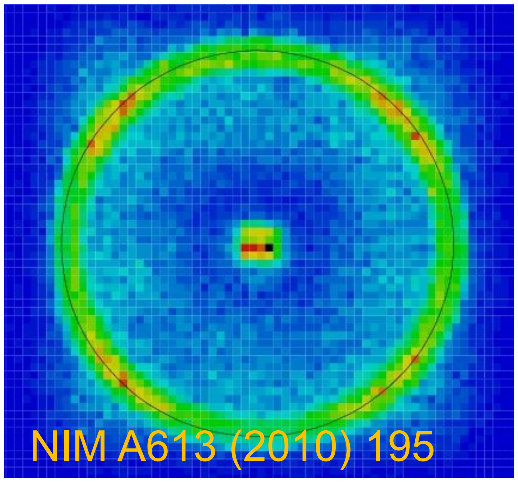
Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.

**6.6 σ π/K at 4GeV/c !**

# SiPMs as single photon detectors for RICH counters?

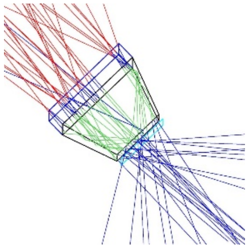
SiPMs have excellent properties (low operation voltage, high gain, high PDE, excellent time resolution, work in high magnetic field) but also have serious drawback - dark counts ~ few 100 kHz/mm$^2$.

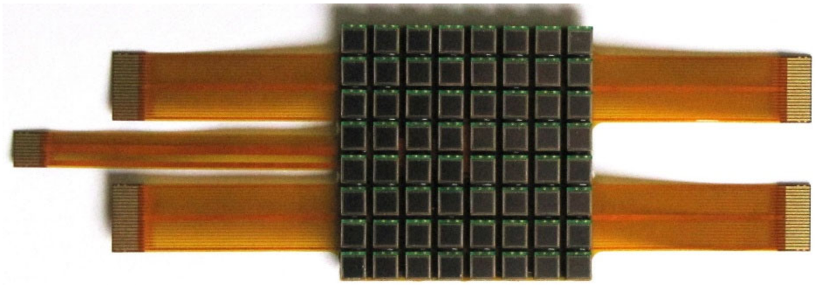
→Challenge in a RICH counter where we have to detect single photons (dark counts have single photon pulse heights, rates 0.1-1 MHz/mm$^2$).

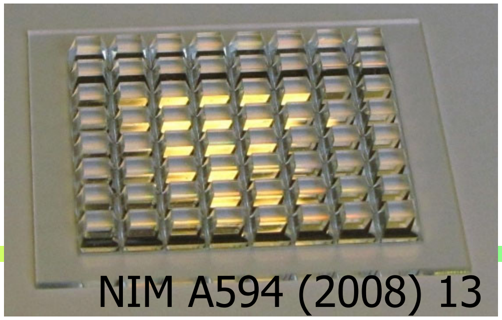



Improve the signal-to-noise ratio:

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



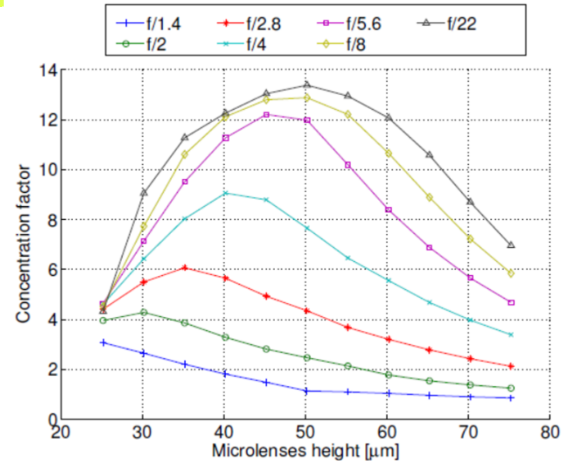


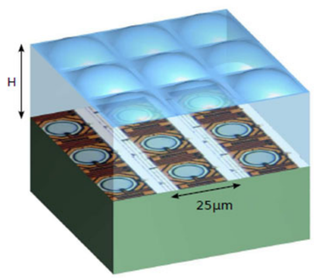


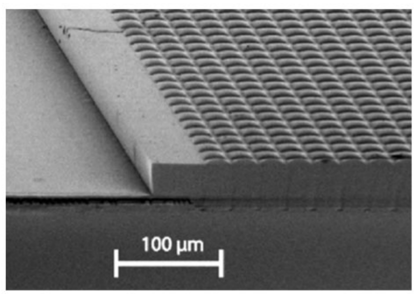

# Microlenses

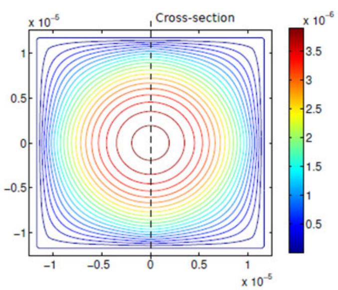
## Micro-lens array coupled to SPAD array

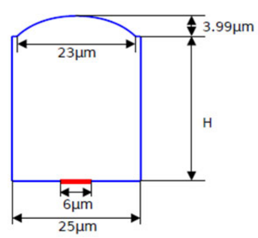
- CMOS SPAD array, 128x128 $6\mu m$ diameter @25 $\mu m$ pitch – 5% fill factor
- matching polymer plano-convex micro-lens array

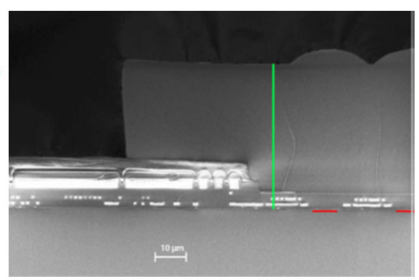


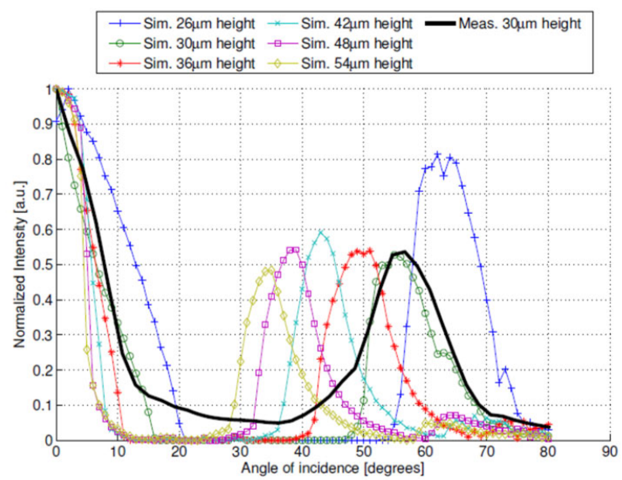



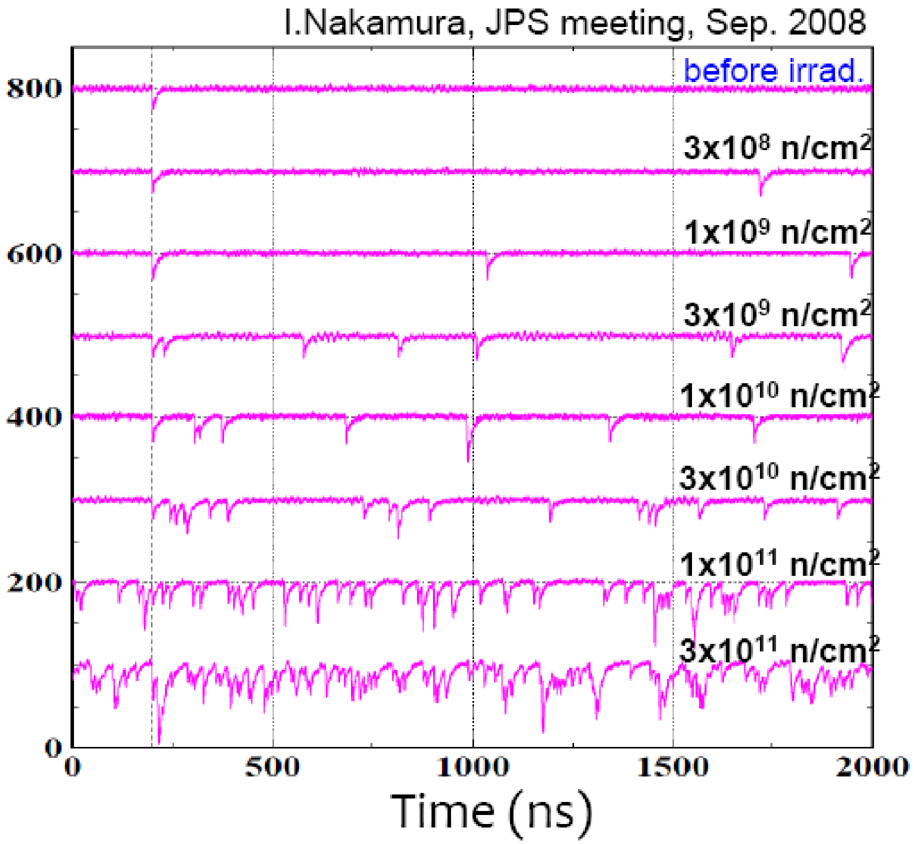






J.M. Pavia et al. Opt.Exp. 22-4(2014)4202

# SiPMs: Radiation damage




Expected fluence at 50/ab at Belle II:
2-20 $10^{11}$ n $cm^{-2}$

→ Worst than the lowest line

Single photon sensitivity required!

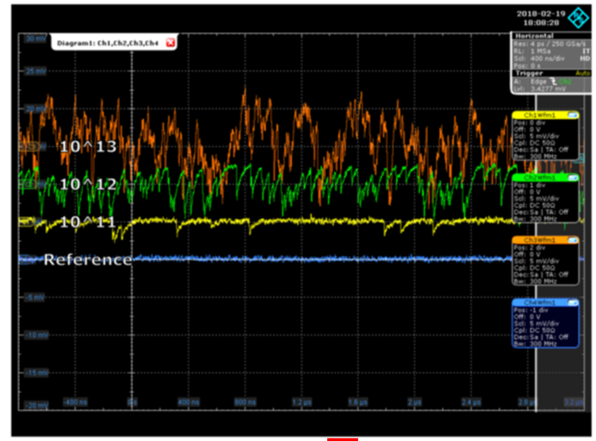
→Need cooling of sensors and wave-form sampling readout electronics

→Annealing?

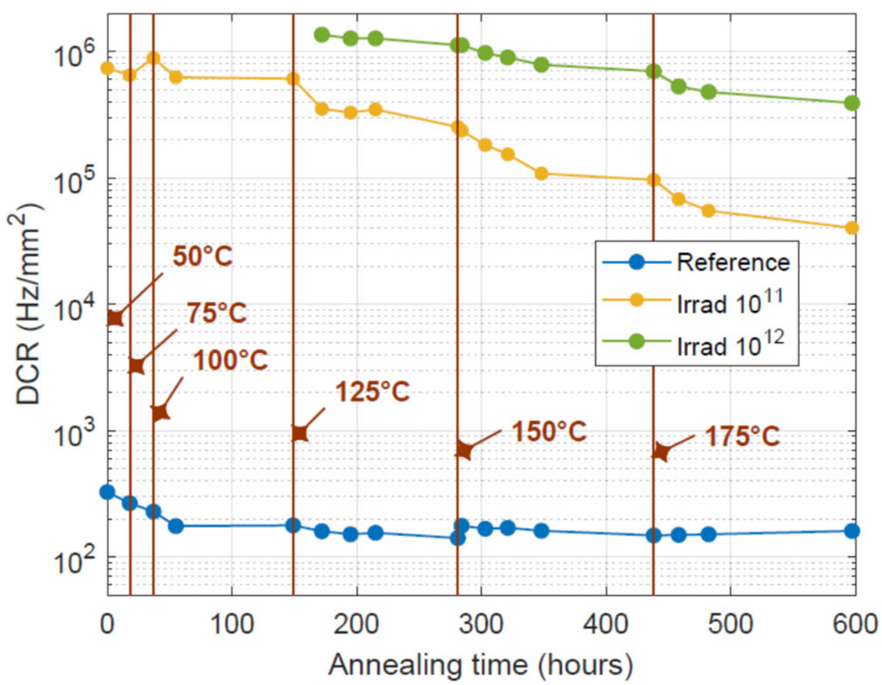
… and more radiation resistant SiPMs…

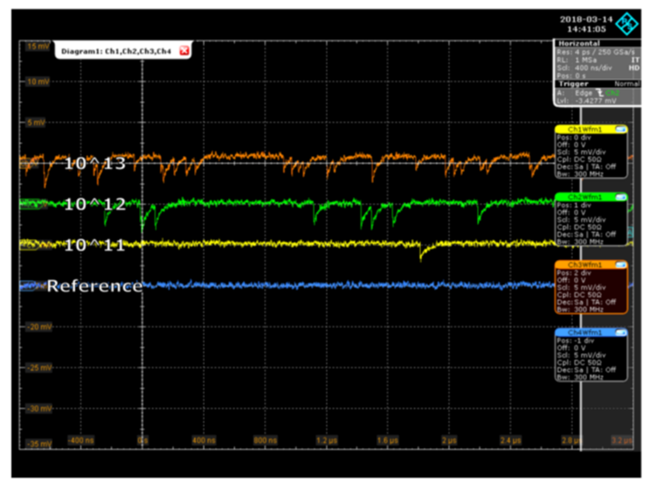
# SiPMs: Radiation damage, annealing at elevated temperatures

Dark counts at -30C of a Hamamatsu S13360-1350CS SiPMs: non irradiated (blue) and irradiated up to $10^{11}$ (yellow), $10^{12}$ (green) and $10^{13}$ (orange) $n_{eq}/cm^2$




annealing




M. Calvi et al., NIMA 922 (2019) 243-249

# SiPMs after irradiation; annealing

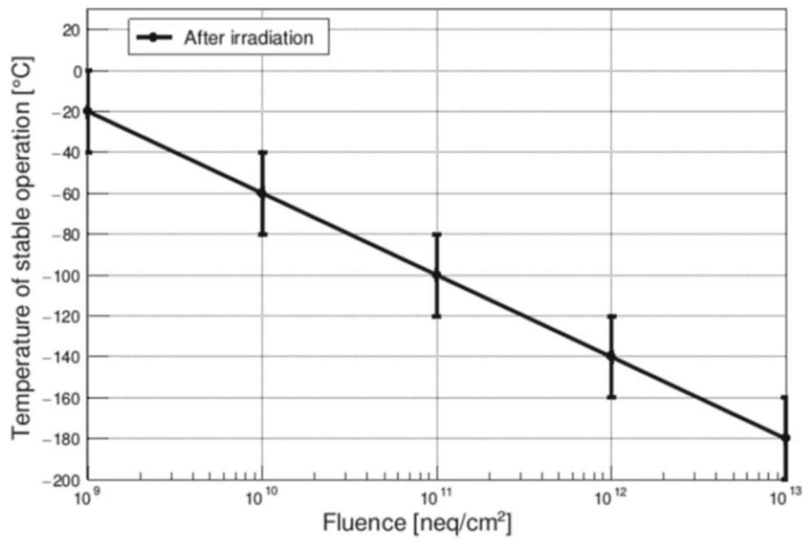



**Fig. 13** The temperatures at which single photon can be resolved at an overvoltage of 9 V vs. different irradiation levels. The error bars indicate the 40°C steps in which the measurements were carried out in this work

D. Consuegra Rodrigez et al, Eur. Phys. J. C (2024) 84:970

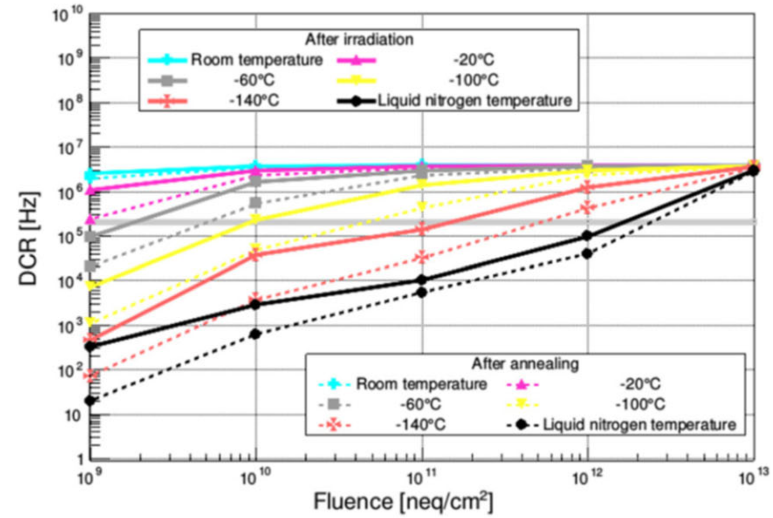



**Fig. 17** DCR vs. fluence at different temperatures before and after the annealing and an overvoltage of 9 V. Dashed lines were used to plot data after the annealing, while the gray line indicates the DCR at room temperature and an overvoltage of 9 V measured with the non-irradiated SiPM

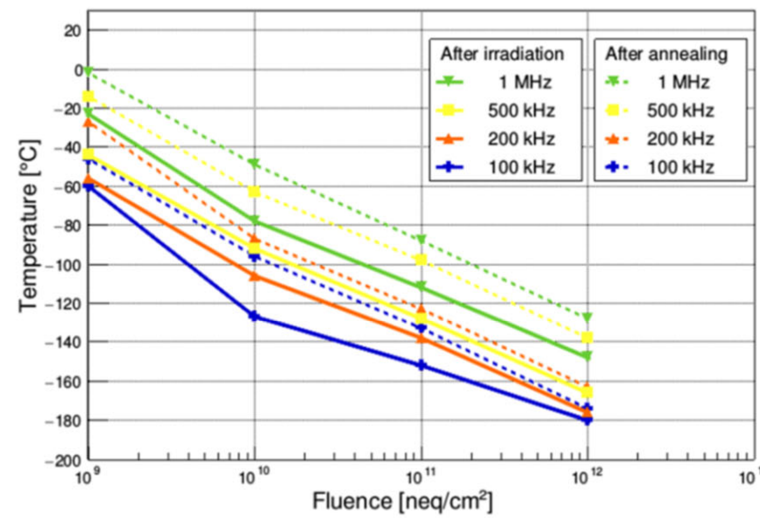
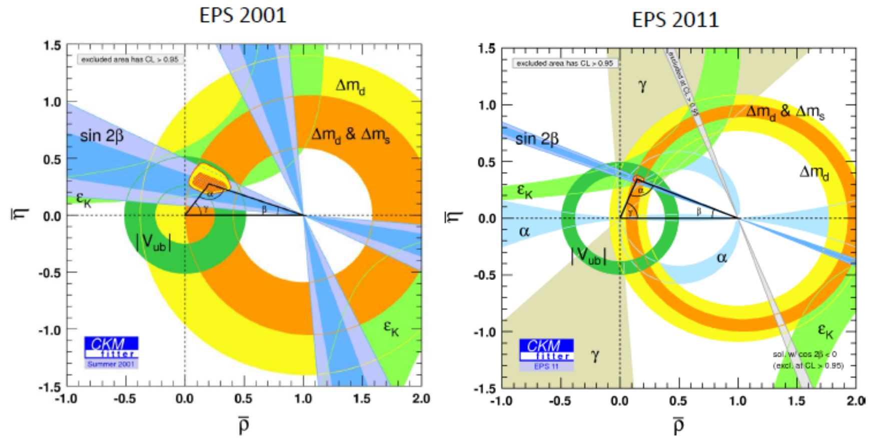



**Fig. 18** Temperature required to reach different DCR levels at different fluences. Dashed lines were used to plot data after the annealing. At fluence of $10^{13}$ neq/cm$^2$, the DCR never reaches the levels included in this plot (Fig. 16)

# Summary




- Physics of b and c hadrons and tau leptons has made a tremendous leap forward since early '80s
- Semiconductor detectors have been an indispensable tool in this effort, and have been essential for (almost) all important discoveries
- Expect a new, exciting era of discoveries in flavour physics, with the next generation of semiconductor sensors for charged particles and for single/few photons at Belle II, LHCb, ATLAS, and CMS
- HLL has played a pioneering role in this field, and has a sizable share of fame
- All the best for the many years to come!