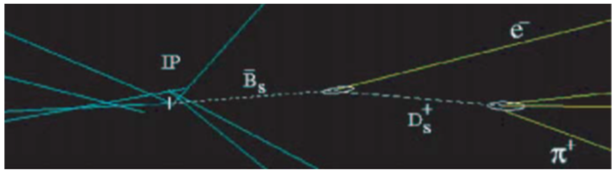
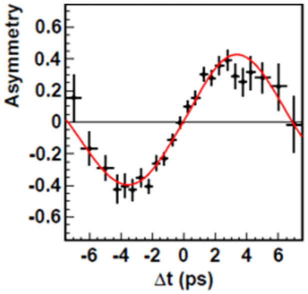
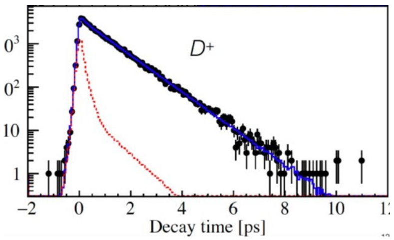
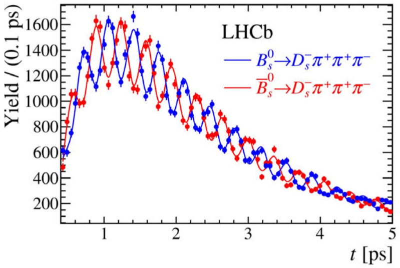
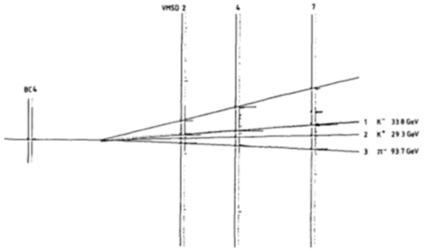
MPG HLL Inauguration Ceremony
and Semiconductor Symposium
Garching, Oct 7-8, 2024

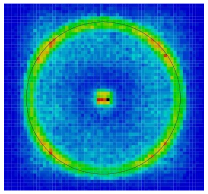












Flavour Physics with Semiconductor Detectors

Peter Križan

University of Ljubljana and J. Stefan Institute

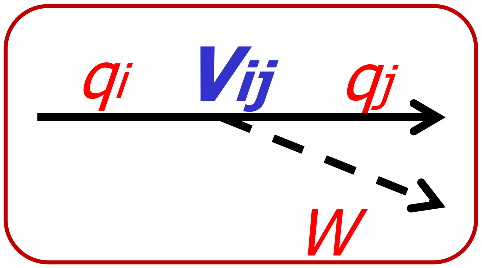
Contents

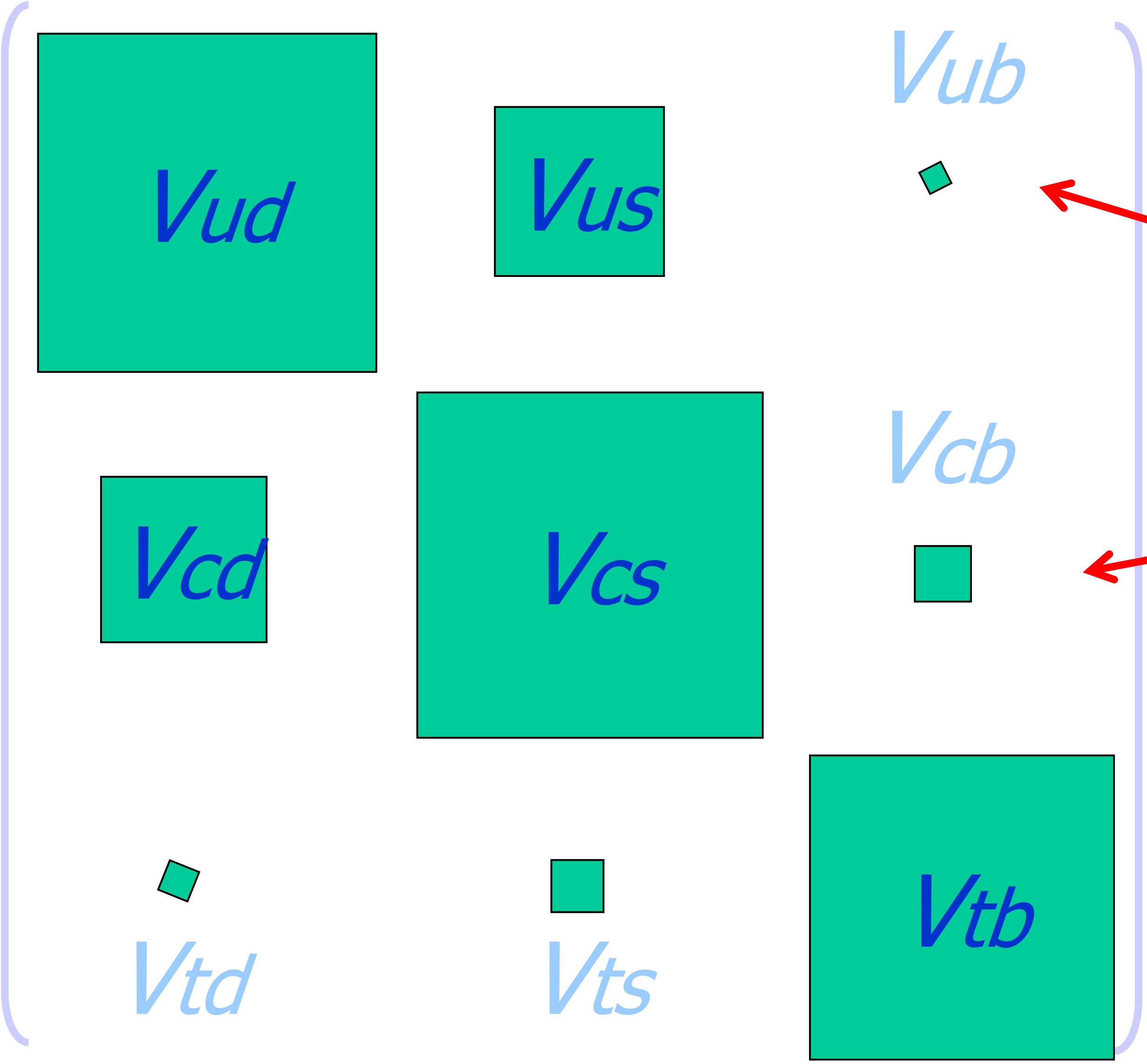
- Flavour physics
- From fixed target experiments to LEP to B factories to LHC to Belle II
- Outlook: upgrades of LHCb and Belle II

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

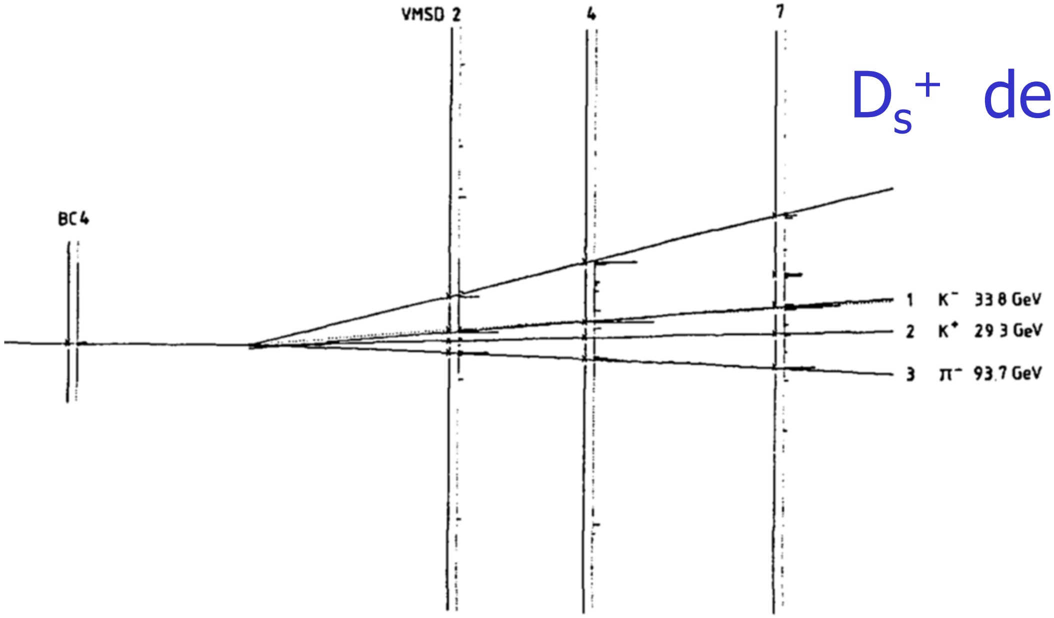
Path of order 100 μm:

- 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

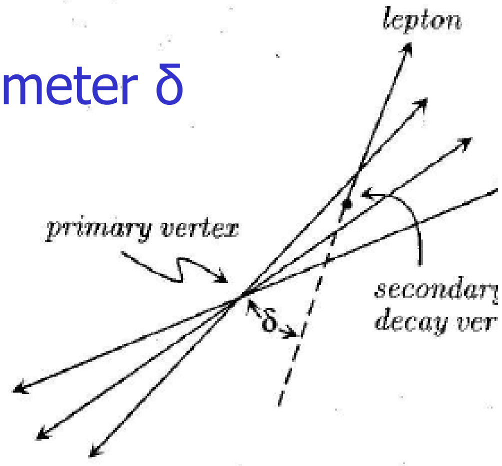
NA32 ACCMOR (Amsterdam-Bristol-CERN-Cracow-Munich-Rutherford)

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

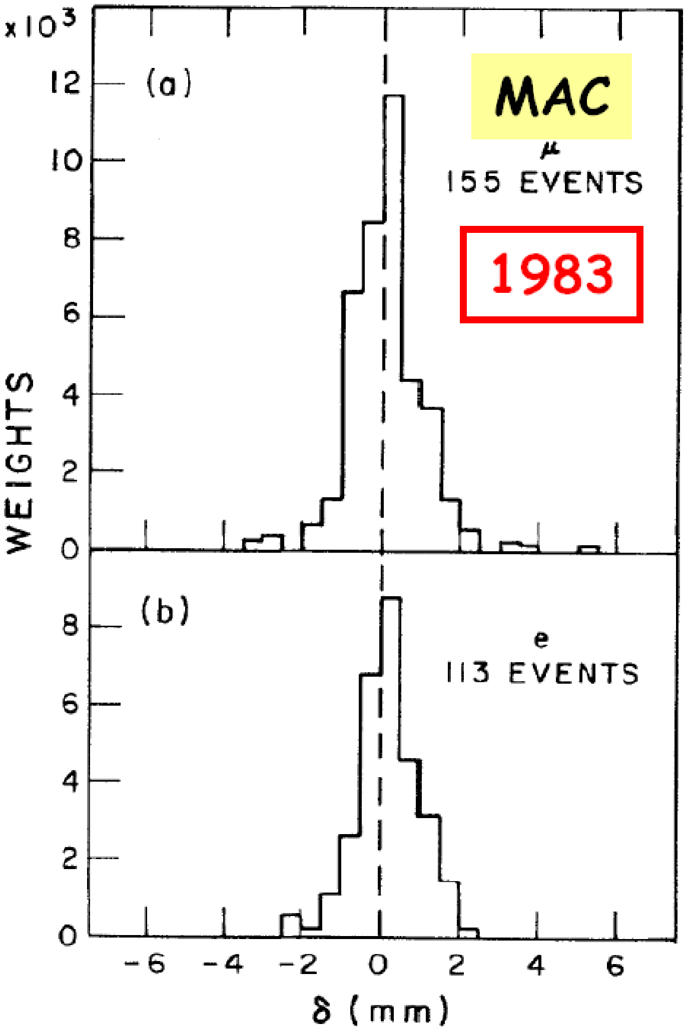


Lifetime implies: V_{cb} small

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



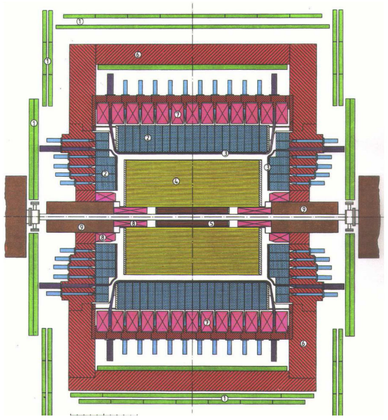
MAC, PRL **51**, 1022 (1983)
MARK II, PRL **51**, 1316 (1983)

Systematic studies of B mesons: at Υ(4s)
THE discovery: mixing in the B^0 system

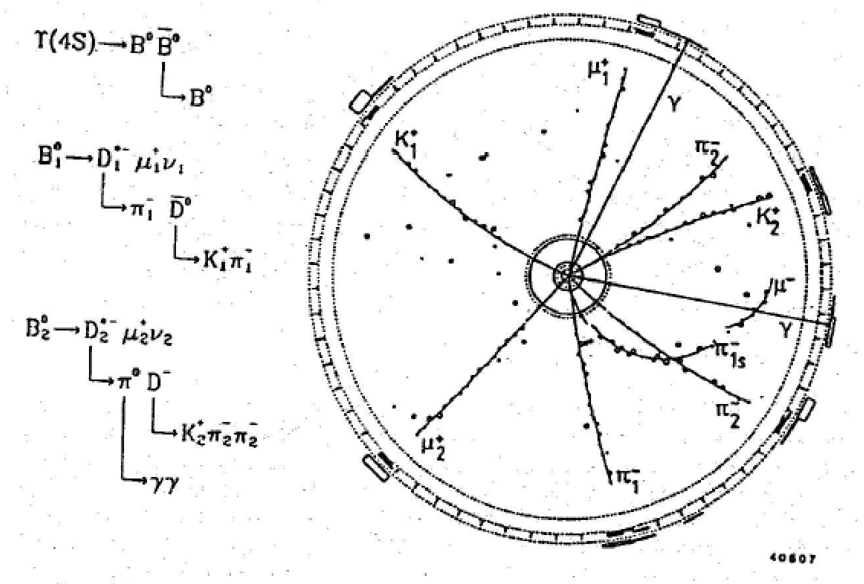
1987: ARGUS discovers B^0-$\overline{B}^0$ mixing: B^0 turns into $\overline{B}^0$

$$\chi_d = 0.17 \pm 0.05$$

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



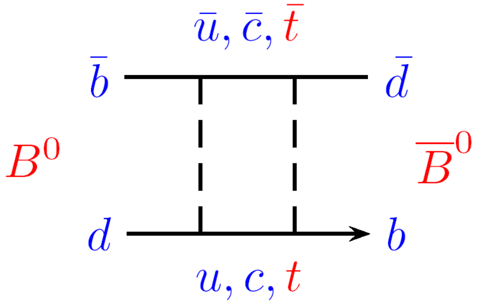
Reconstructed event



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

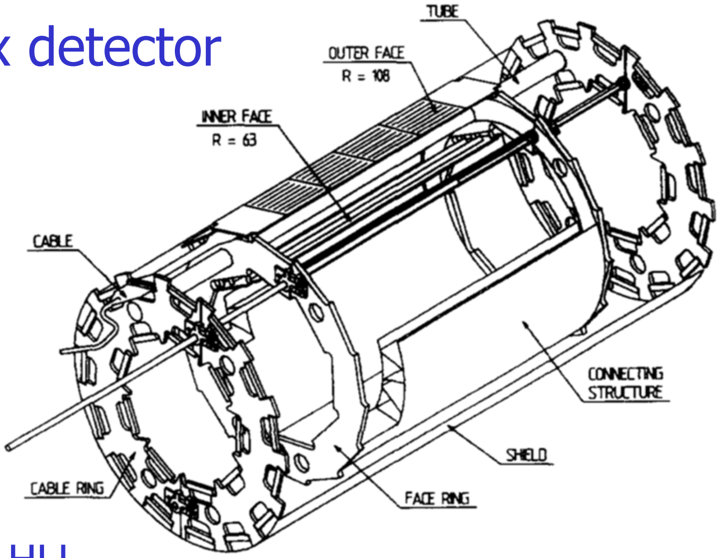
Large mixing rate → high top mass

The top quark has only been discovered seven years later!

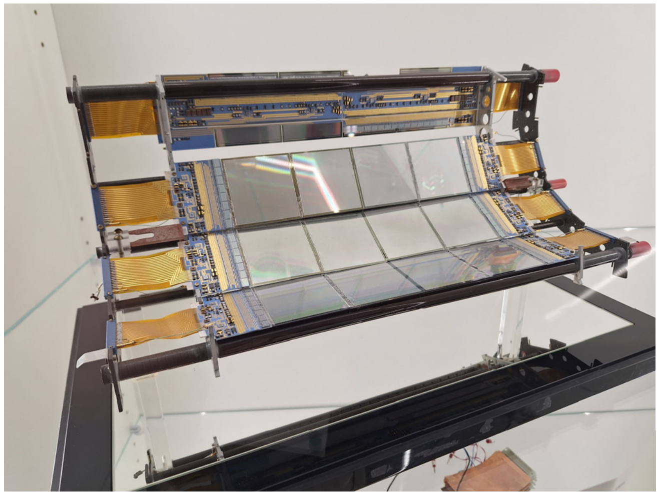


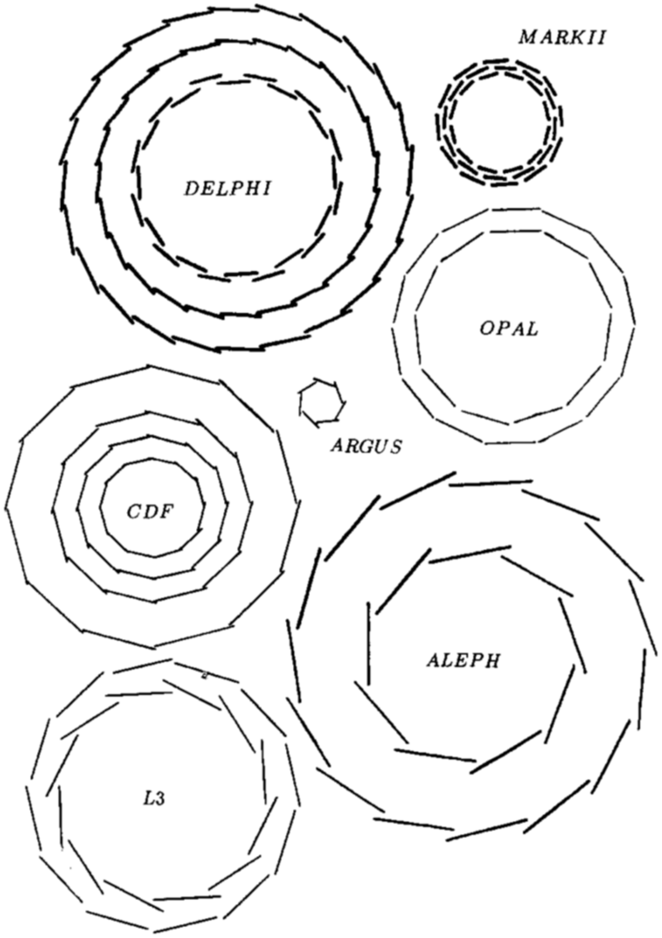
Flavour physics at LEP: vertex detectors

ALEPH vertex detector



MPI Munich and HLL



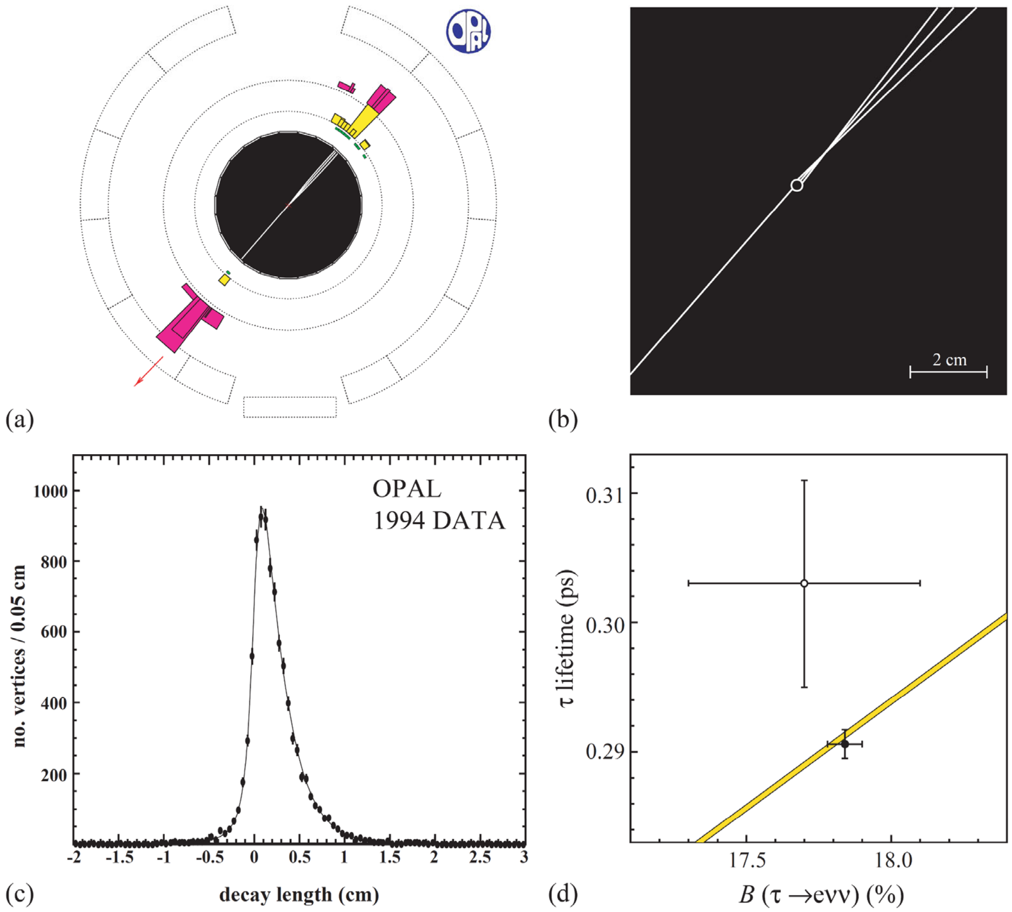


Scale common for all,
5cm = ALEPH module width

From: A. Schwarz, Heavy flavor physics at colliders with silicon strip vertex detectors, Phys. Rept. 238 (1994) 1-133

Flavour physics at LEP

$Z^0 \to \tau^+\tau^-$ 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

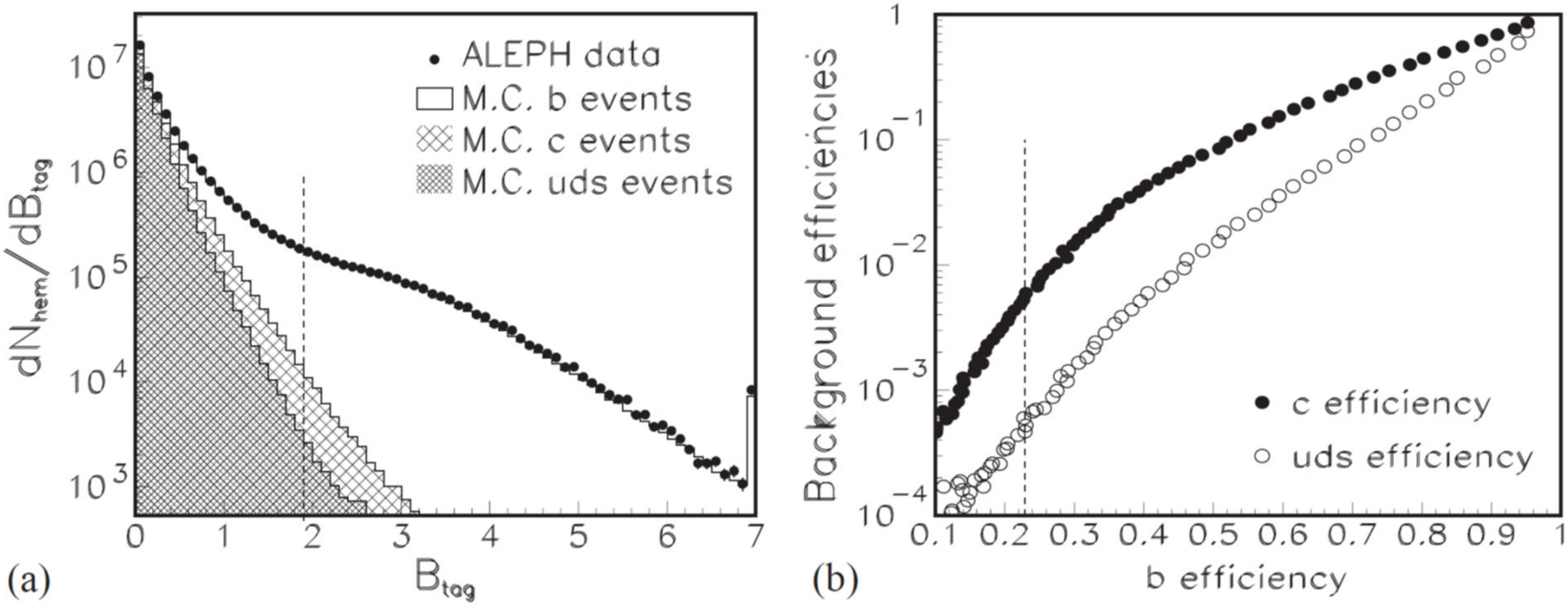
World average data for the tau lifetime vs its leptonic branching ratio (in the electron channel): from before LEP and after LEP; the theoretical expectation is indicated by the shaded band.

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

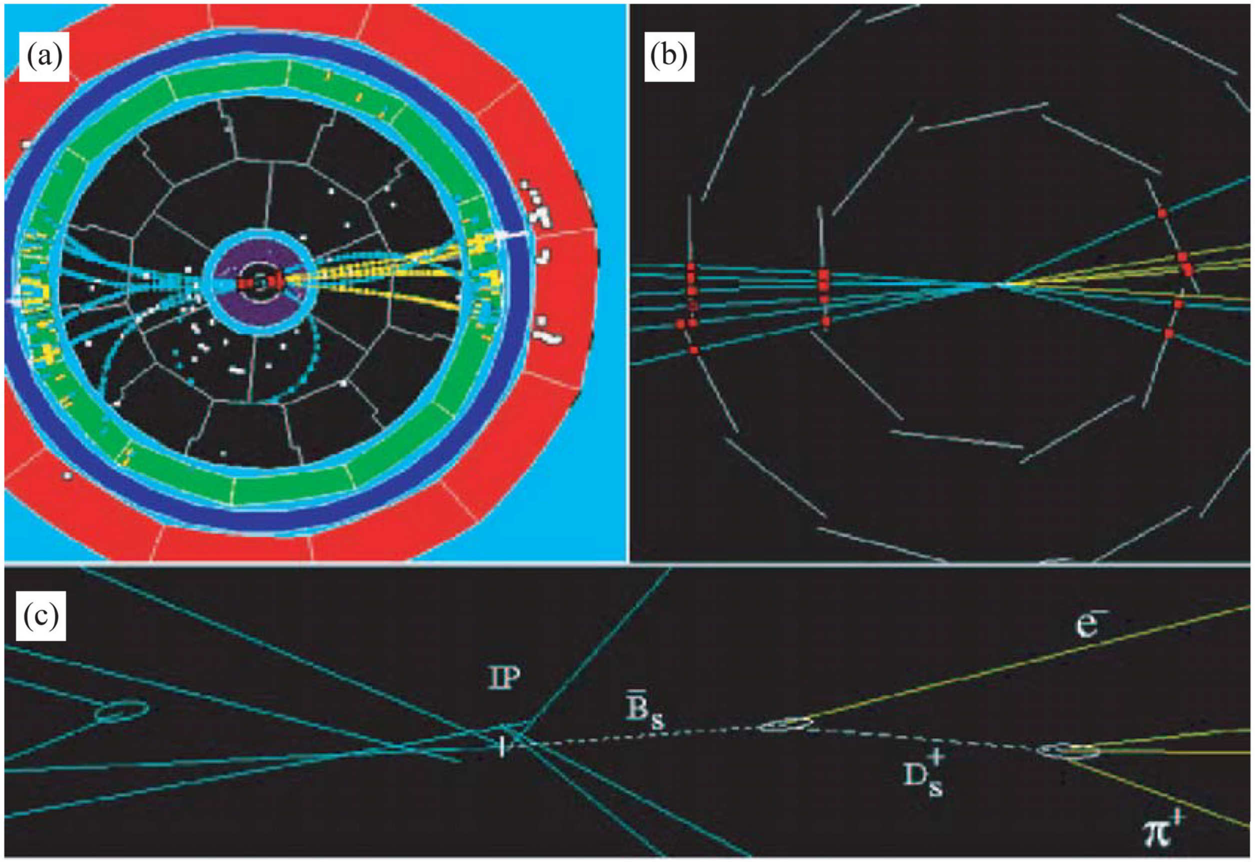
Distribution of the B tagging variable based on lifetime and mass information, data from ALEPH



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

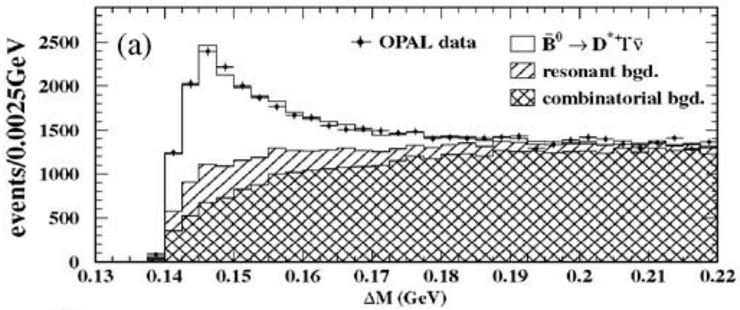


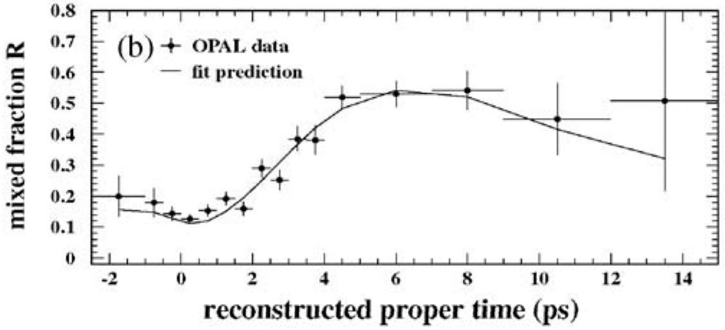
Zoom on the vertex detector, showing the hits seen in the silicon microstrips

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

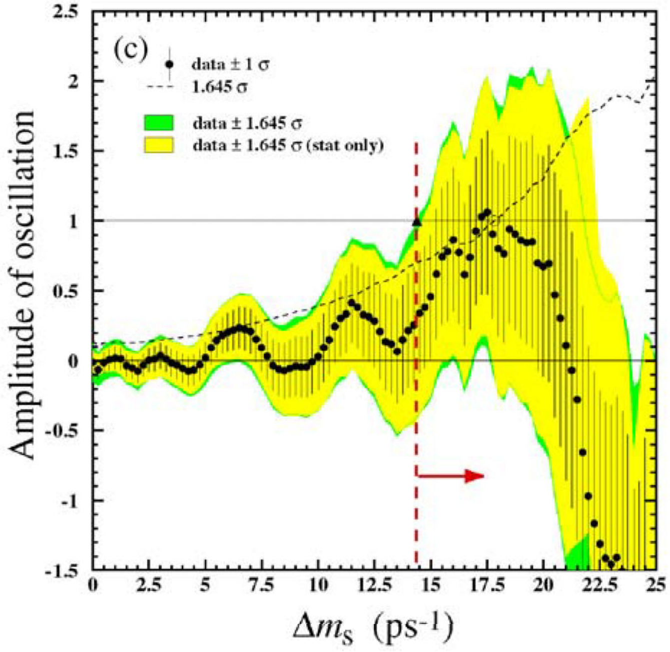
Flavour physics at LEP: time evolution of the neutral B mesons

Signal for $B^0 \to D^{*-}l^+X$ from OPAL, seen in the mass difference distribution of the D^{*-} and D^0 candidates from the decay $D^{*-} \to D^0\,\pi^-$, 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.

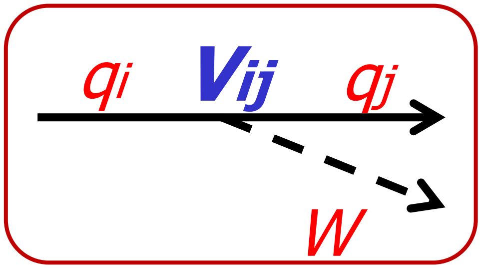


2004 world combination of the amplitude of B^0_s – anti-B^0_s oscillation, as a function of the test frequency Δm_s; the 2004 lower limit is indicated by the dashed line.

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 → $J/\psi\ K_S$

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

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→ccs ($\sim 10^{-3}$)

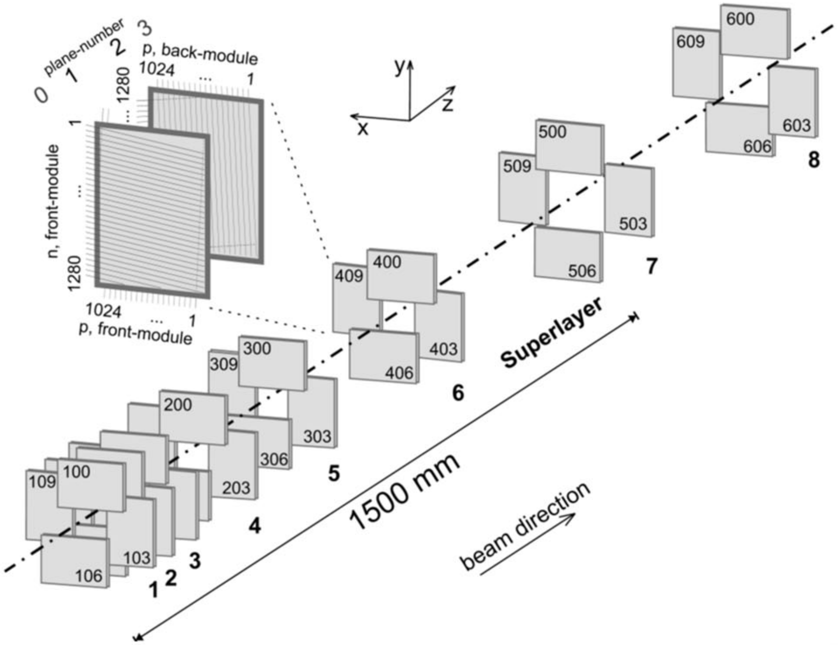
→ A lot of physicists across the world were after this holy grail

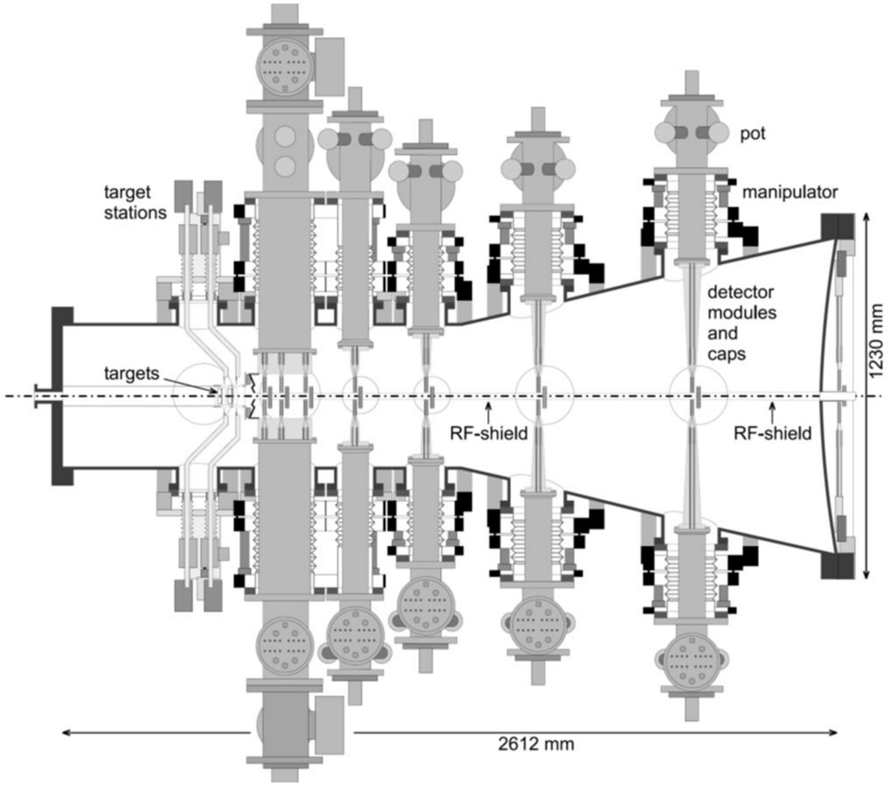
HERA-B vertex detector

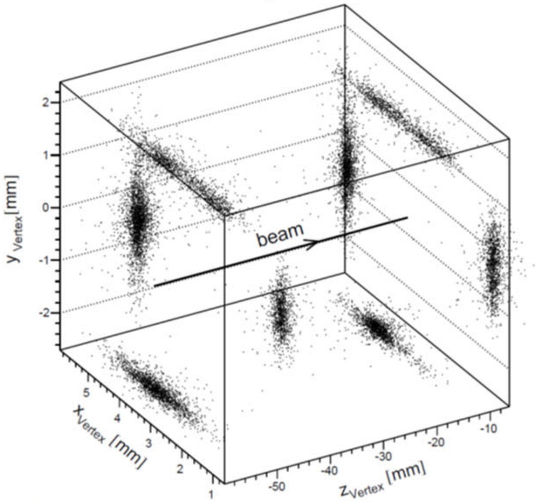
Double-sided silicon strip detectors with four stereo views.

Roman pots in a vacuum vessel, retractable during injection.

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







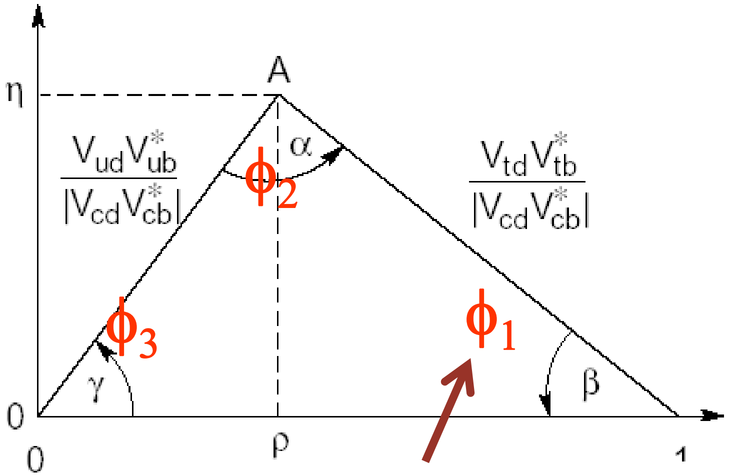
Reconstructed vertex positions on 8 wire targets

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

CP violation: related to the angles of the unitarity triangle

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

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

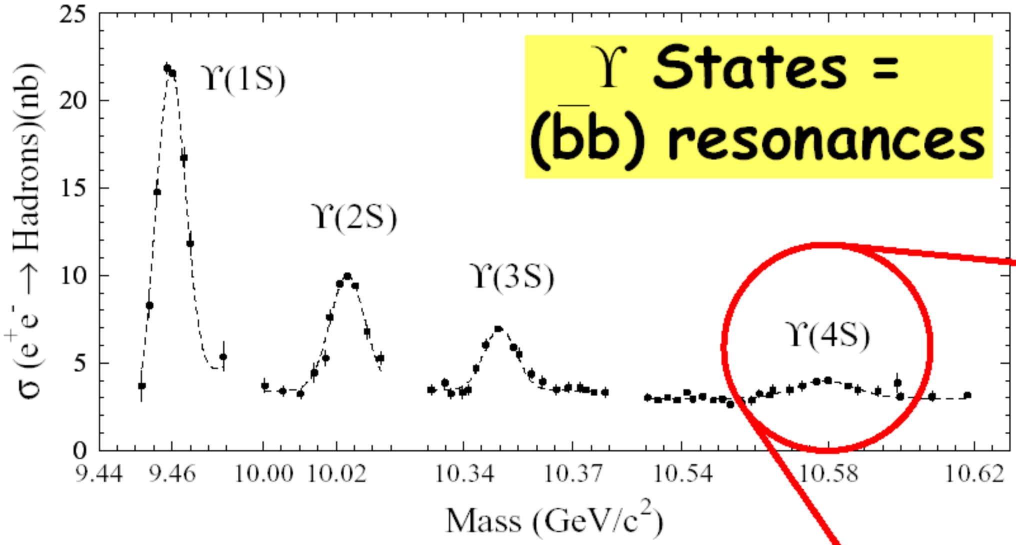


determines CP violation in $B \rightarrow J/\psi\ K_S$ decays

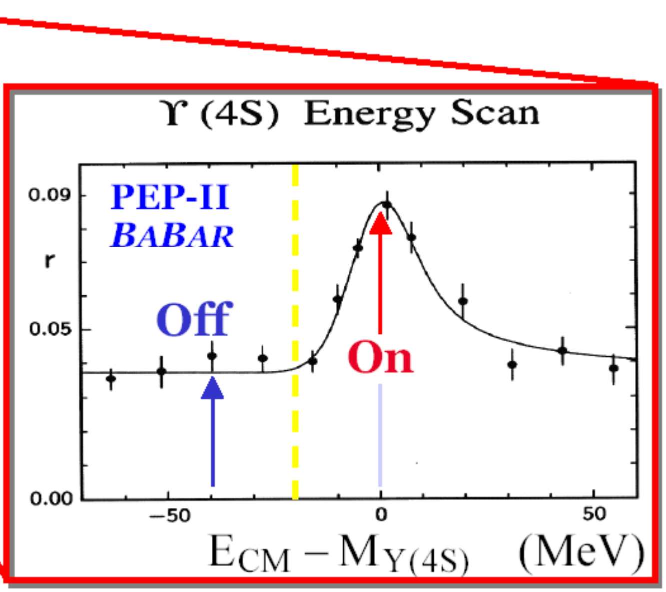
Unitarity condition:

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

→ Back to B meson production at Υ(4s)



Υ States =
($b\bar{b}$) resonances



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

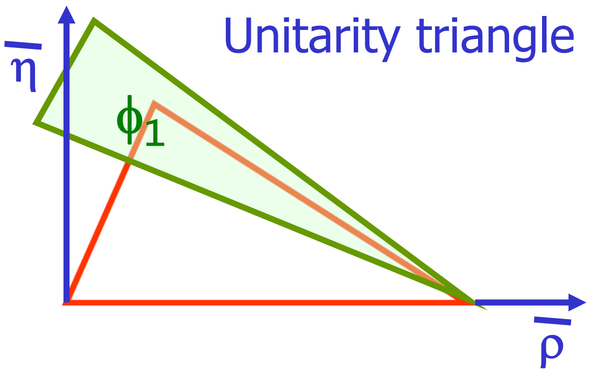
$u\bar{u} \sim 1.4$ nb

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

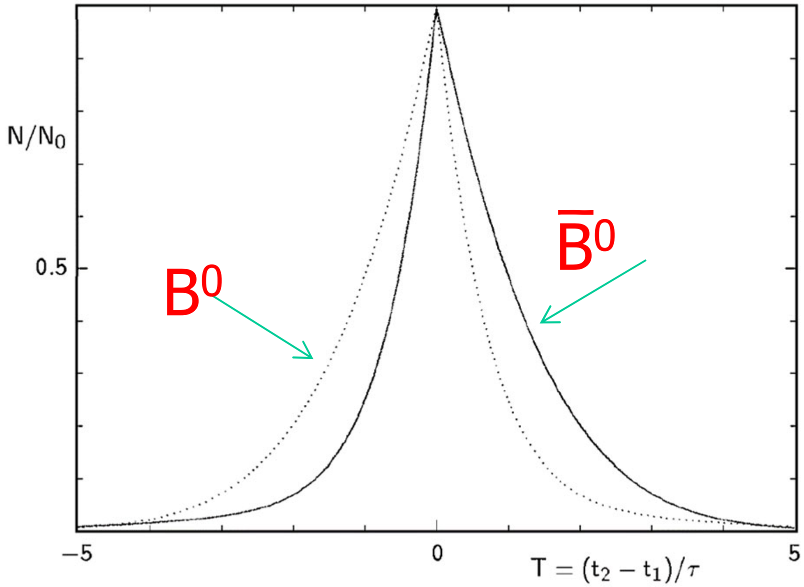
$L = 1$ state

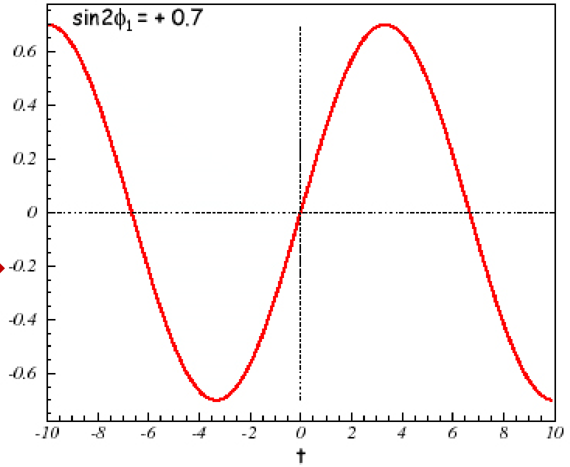
BB produced almost at rest in the e+e- system

How to measure β/ϕ_1?



To determine the angle ϕ_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



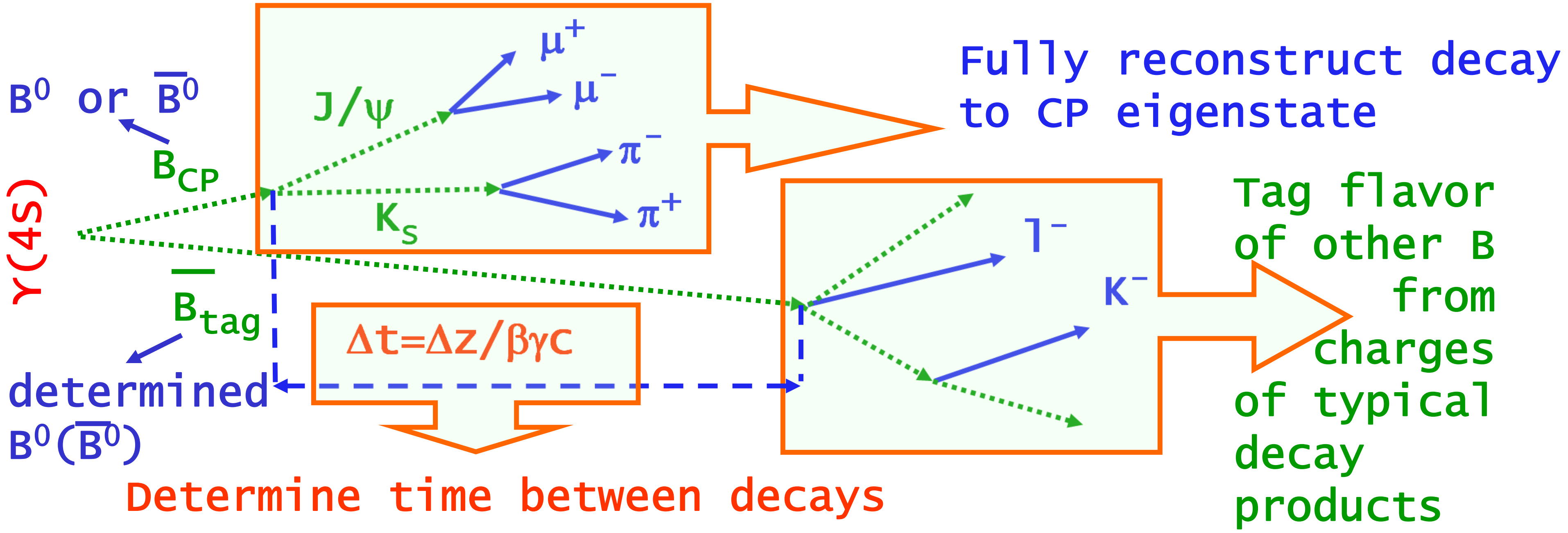


$$a_{f_{CP}} = -\frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

Time dependent decay rate difference - CP asymmetry:

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

Typical measurement



Fully reconstruct decay to CP eigenstate

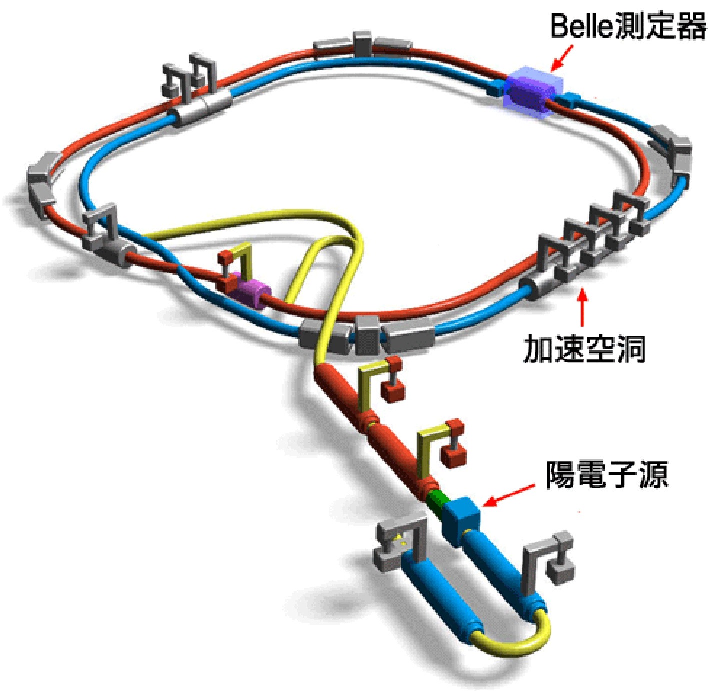
Tag flavor of other B from charges of typical decay products

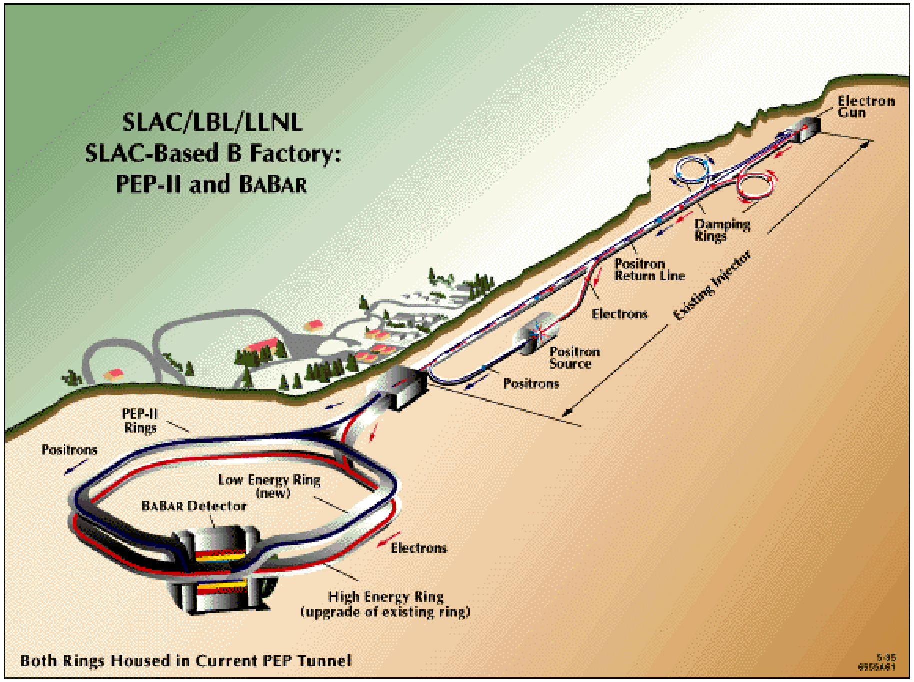
determined $B^0(\overline{B}^0)$

Determine time between decays

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

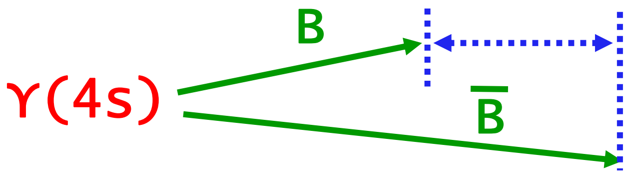
Colliders: asymmetric B factories, e+e- colliders operating at Υ(4S)





$\sqrt{s}=10.58$ GeV

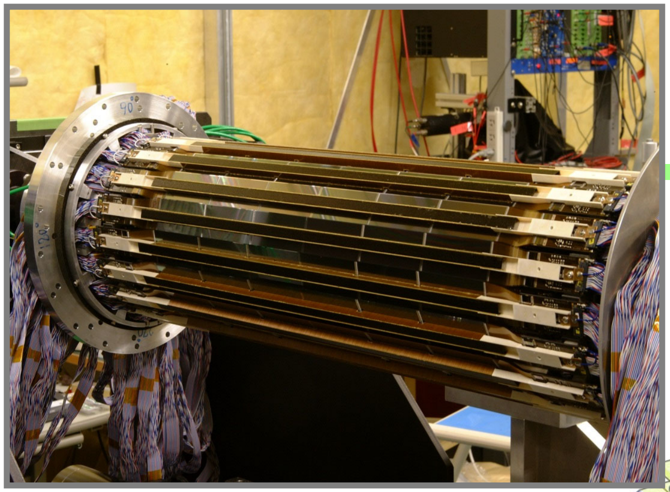
$$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$$

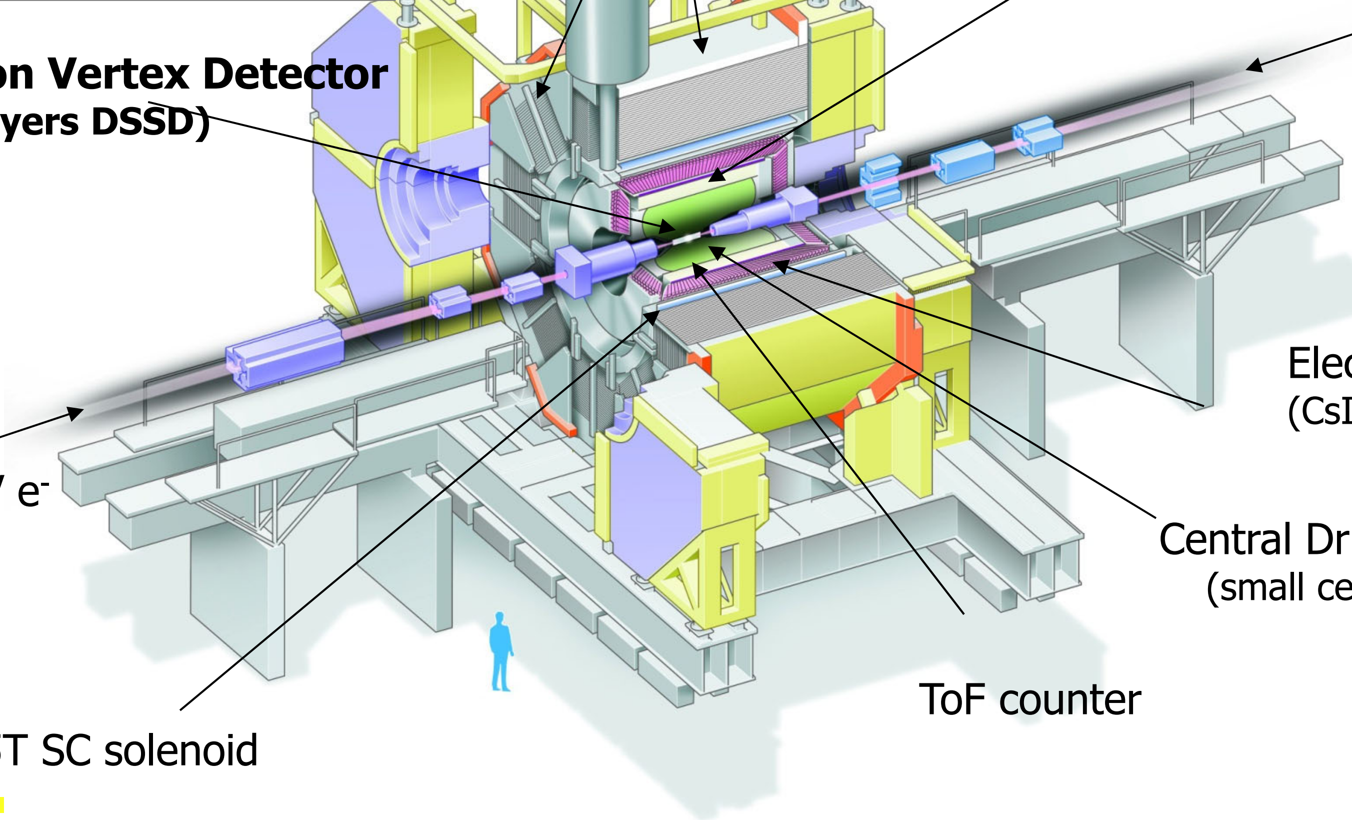


$\Delta z \sim c\beta\gamma\tau_B$
$\sim 200\mu m$

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

Belle spectrometer at KEK-B





μ and K_L detection system
(14/15 layers RPC+Fe)

Aerogel Cherenkov Counter
(n=1.015-1.030)

3.5 GeV e^+

Silicon Vertex Detector
(4 layers DSSD)

Electromag. Cal.
(CsI crystals, $16X_0$)

8 GeV e^-

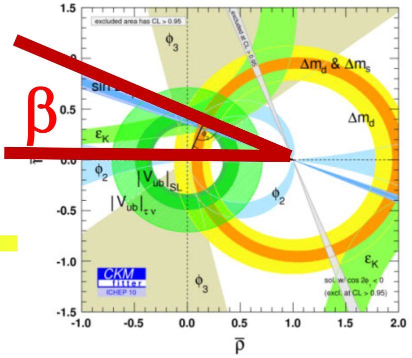
Central Drift Chamber
(small cells, He/C_2H_6)

ToF counter

1.5T SC solenoid

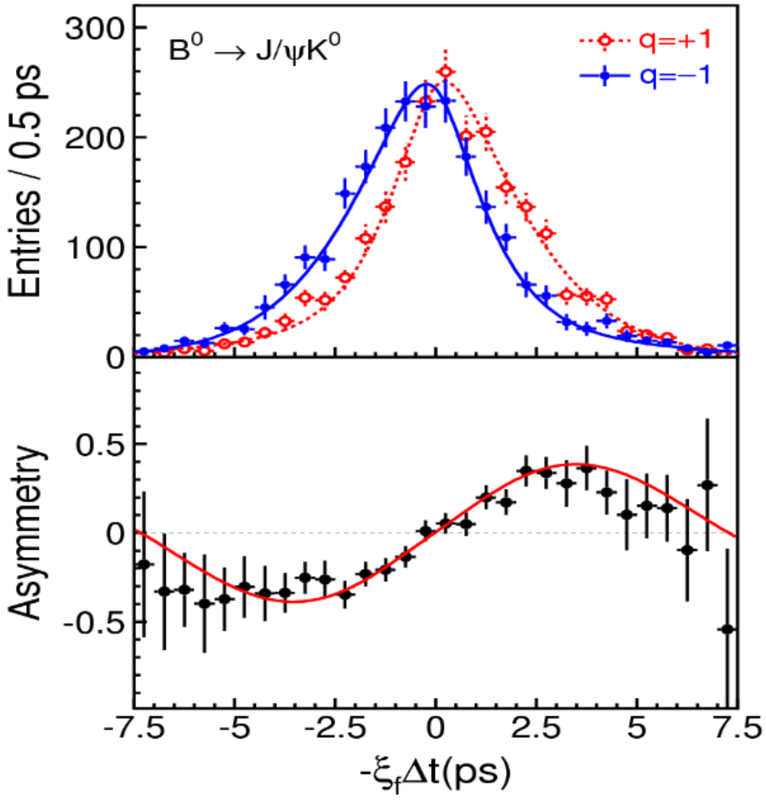
Peter Križan, Ljubljana

Final measurement of sin2ϕ_1 (=sin2β)



β/ϕ_1 from CP violation measurements in $B^0 \to J/\psi K^0$

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



B^0

$\bar{B}^0$

sin2ϕ_1 (=sin2β)

Belle: 0.668 ± 0.023 ± 0.012

BaBar: 0.687 ± 0.028 ± 0.012

Belle, PRL 108, 171802 (2012)

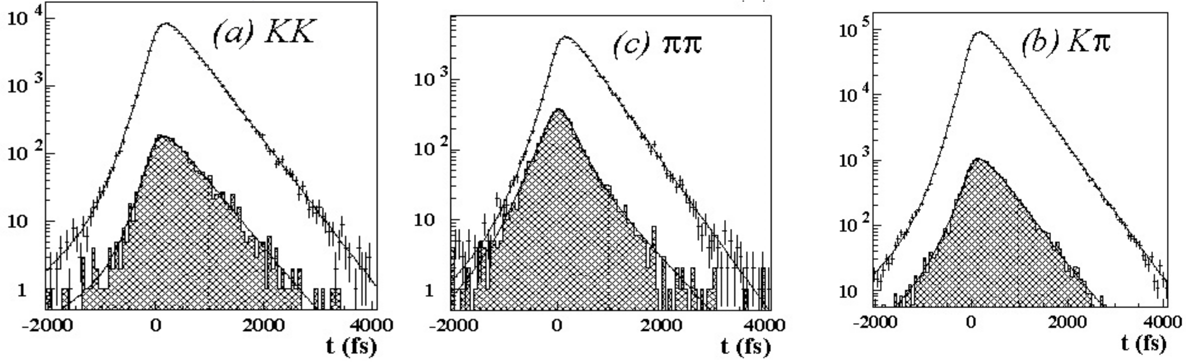
BaBar, PRD 79, 072009 (2009)

with a single experiment
precision of ~4%!

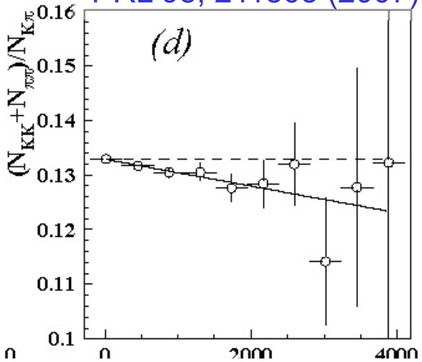
$\phi_1 = \beta = (21.4 \pm 0.8)^0$

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

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



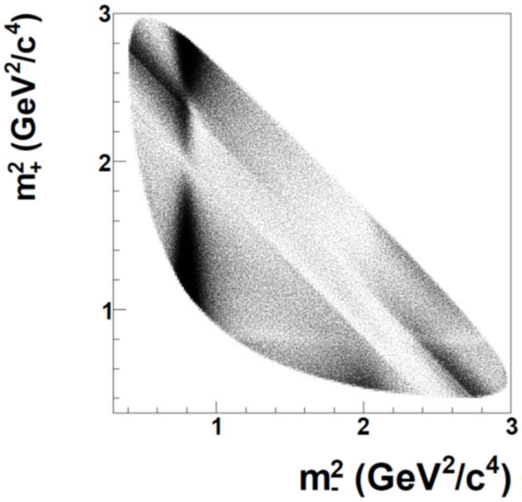
PRL 98, 211803 (2007)



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

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

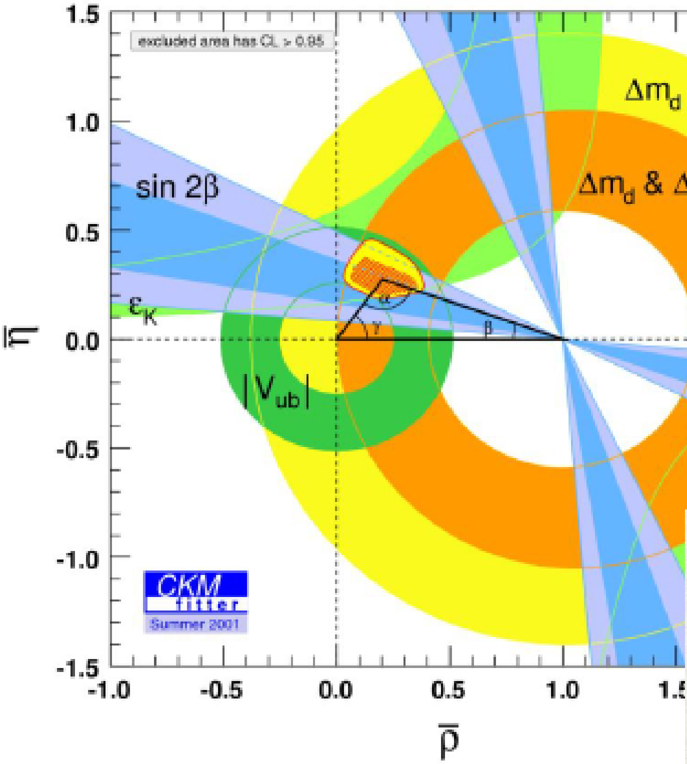
± stat. ± exp.syst. ± decay model syst.

Final result with full statistics

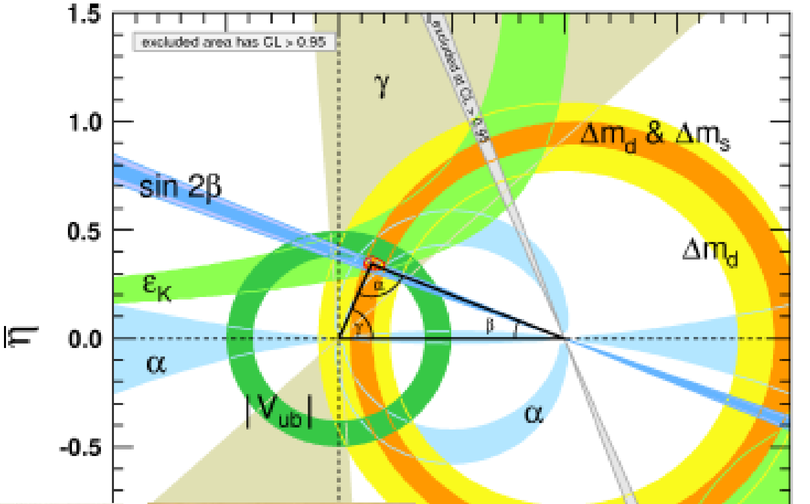
Summary: CP violation in the B system

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

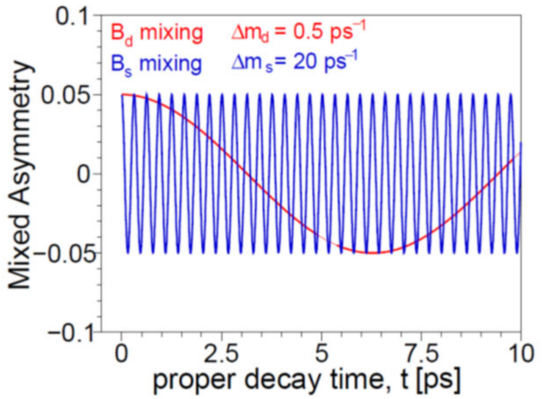
EPS 2001



EPS 2011



B_s mixing: B_s ←→ anti-B_s



Very fast compared to B_d:

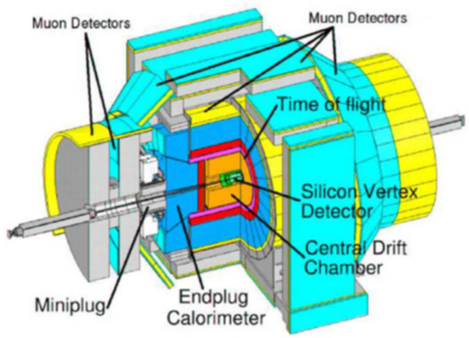
a B_s turns into an anti-B_s in 0.3 ps, 3 10^{12} times per second

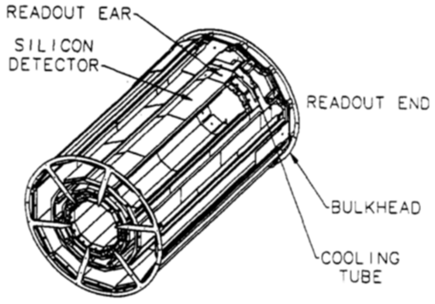
The oscillation amplitude gets diluted by $e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}}$

→precise vertexing is essential

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

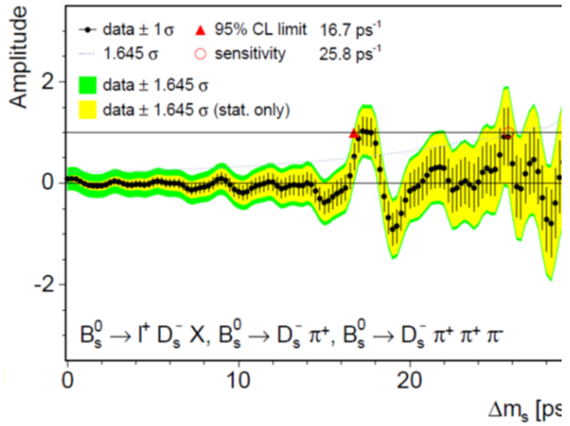
CDF II Detector

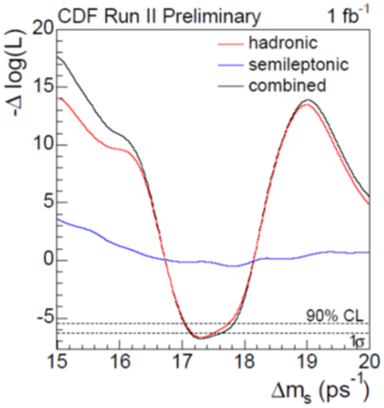




- 4 layers of single-sided sensors at 20, 43, 57, 78 mm from the IP.
- Impact parameter resolution: ~30μm at 2 GeV/c

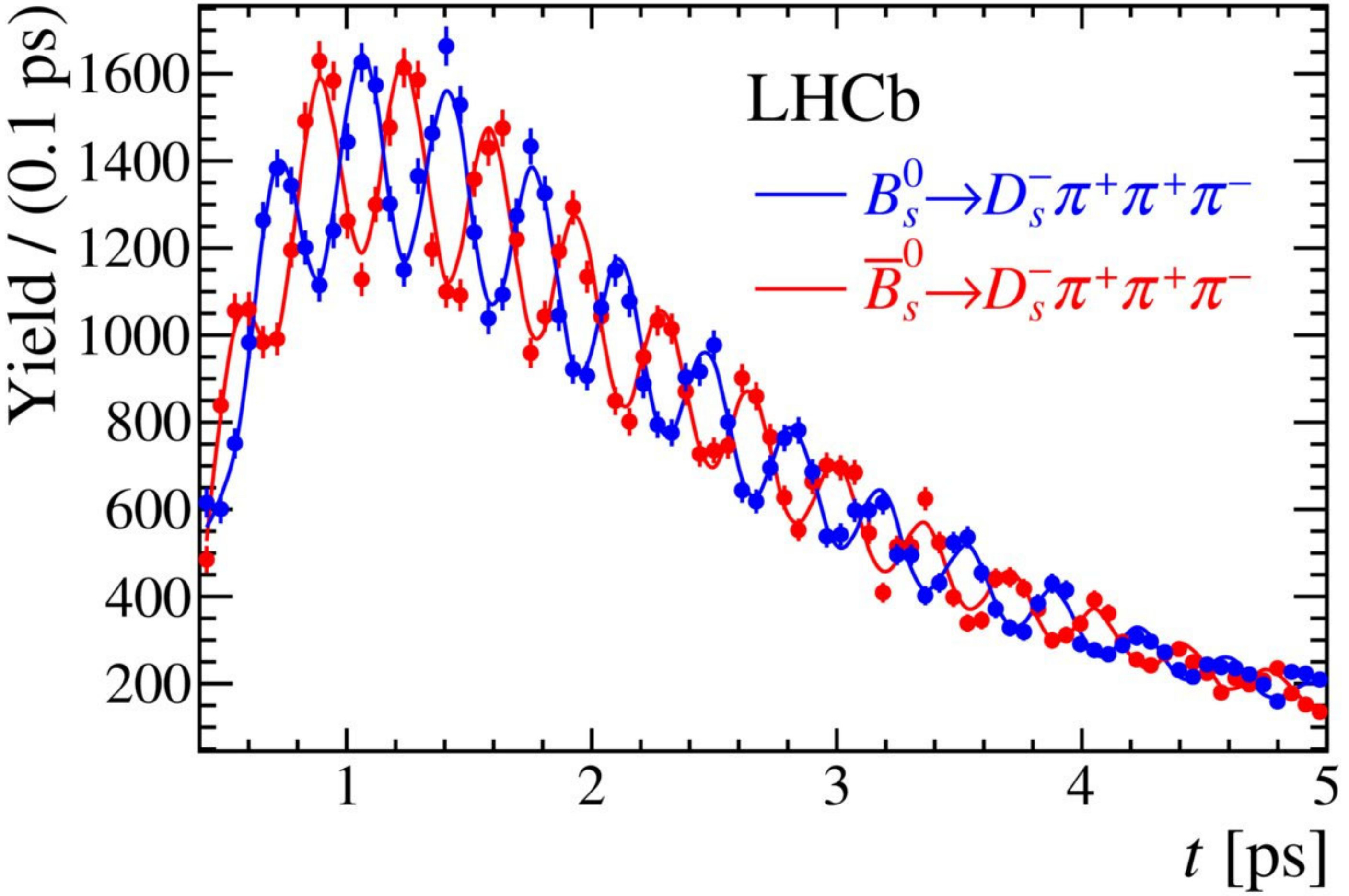
Observed at CDF II in 2006





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

B_s mixing: B_s ←→ anti-B_s

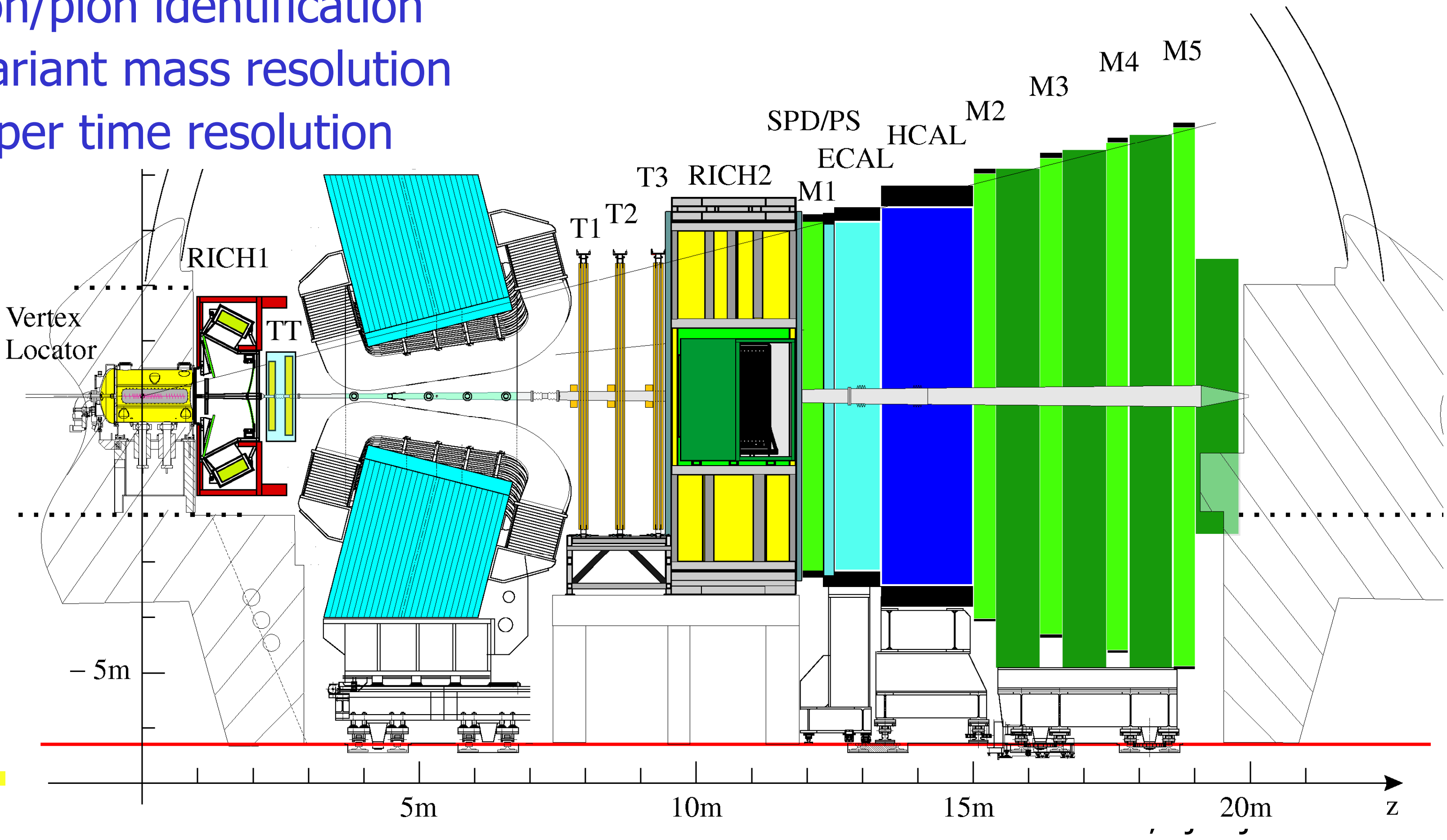


Beautiful precision measurement by LHCb: Δm_s = (17.757 +- 0.021) ps^{-1}

LHCb

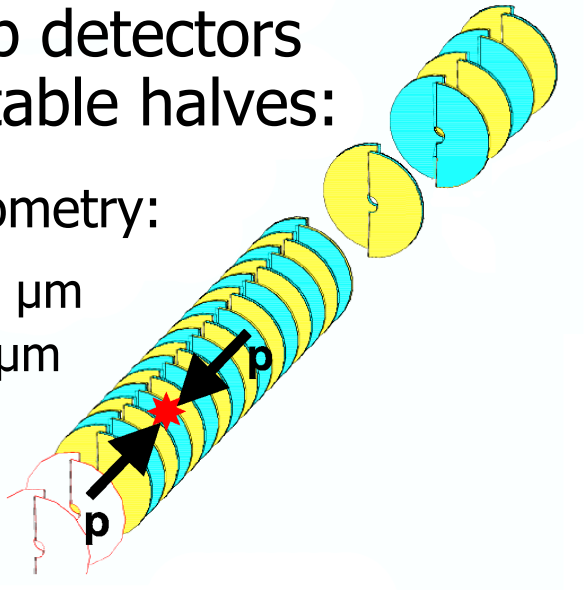
LHCb is a forward spectrometer:

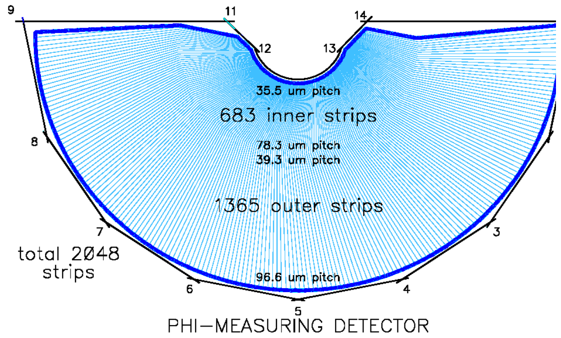
- Acceptance 10-300 mrad
- Efficient B-mesons trigger
- Good Kaon/pion identification
- Good invariant mass resolution
- Good proper time resolution

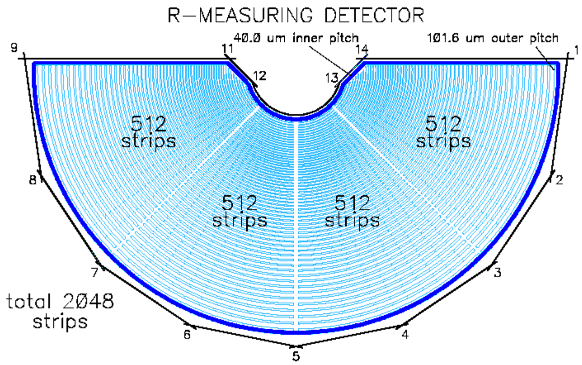


VELO - Vertex locator

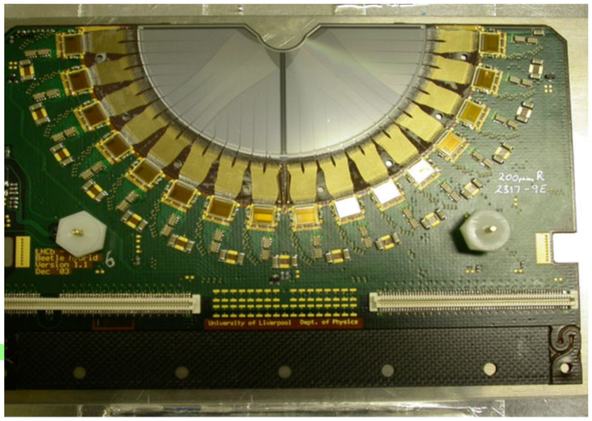
- 21 pairs of silicon strip detectors arrange in two retractable halves:
  - Strips with an R-φ geometry:
    - R strip pitch: 40-102 µm
    - φ strip pitch: 36-97 µm
  - 172k channels.





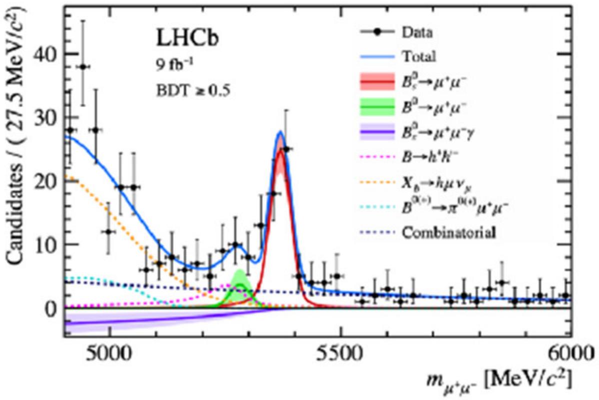


- Operated:
  - In vacuum, separated from the beam vacuum by an Al foil
  - Close to the beam line (7 mm)
  - Radiation ≤ 1.5×10^{14} n_{eq}/cm^2 per year
  - Cooled at -5 °C

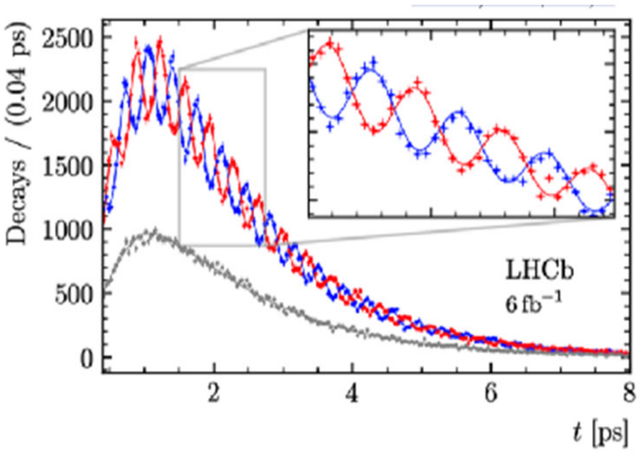


LHCb highlights in flavour physics – some of many

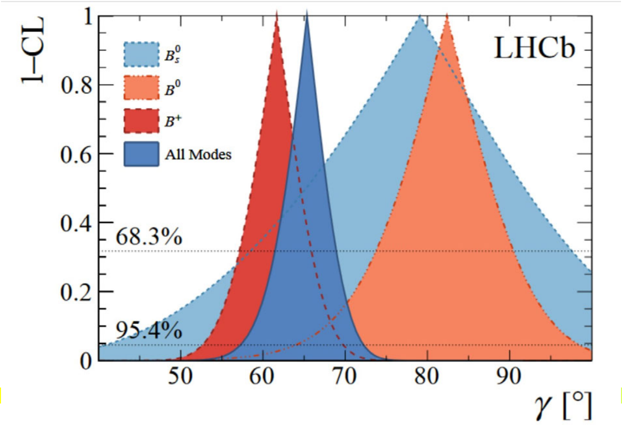
$B_s \rightarrow \mu^+\mu^-$



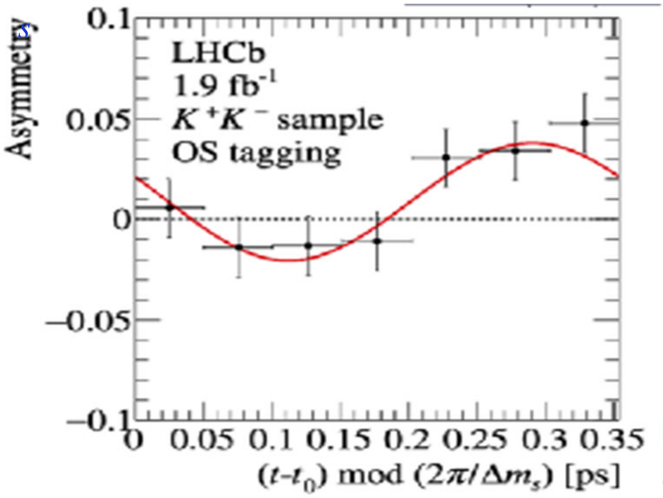
B_s mixing: Δm_s



CKM angle γ



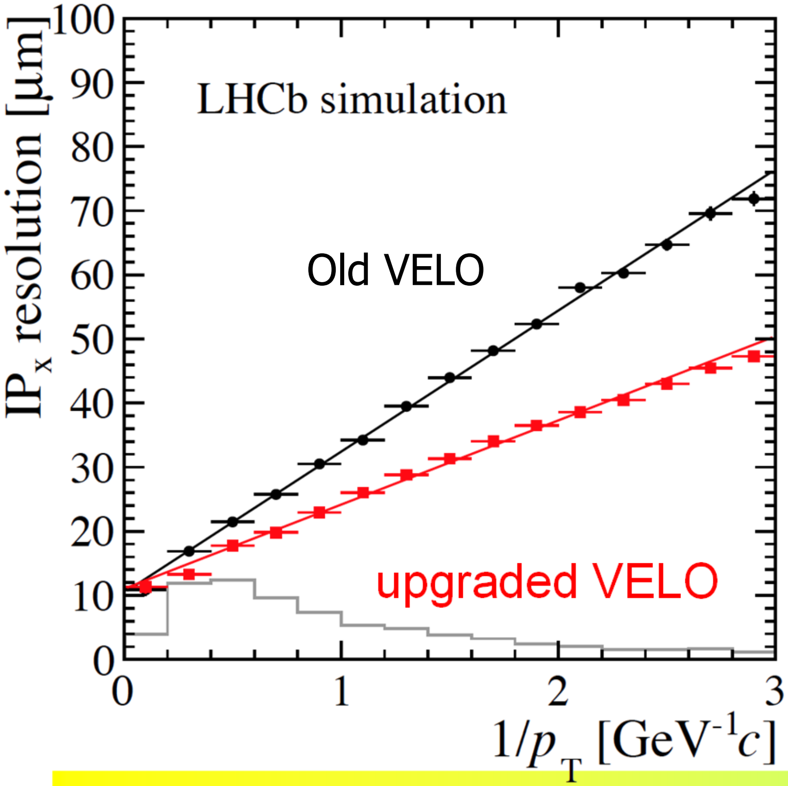
B_s time-dependent CP violation

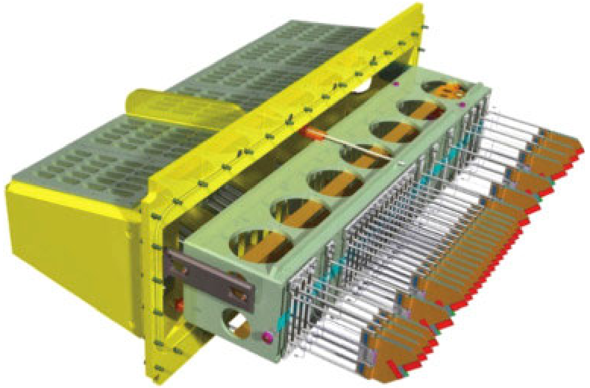


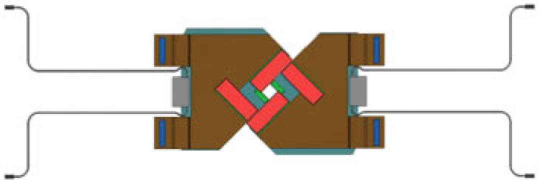
LHCb Vertex LOcator upgrade

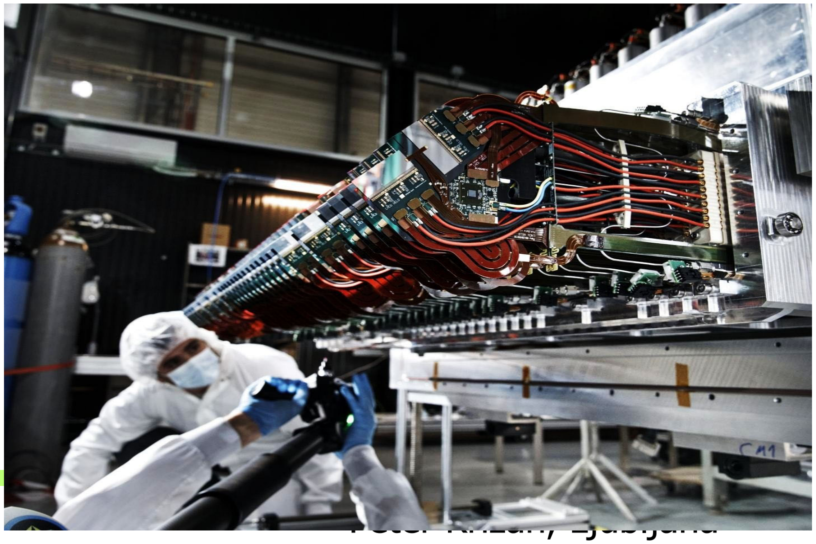
The upgraded VELO for taking data in Run III operation @

- 40 MHz and $2x10^{33}$ $cm^{-2}s^{-1}$
- at 3.5 mm from the beams,
- 2.8 Tb/s data rates,
- 8 x 10^{15} 1 MeV n_{eq} cm^{-2} max fluence

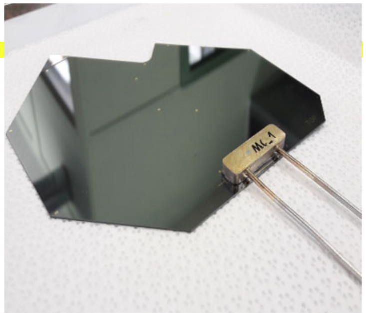






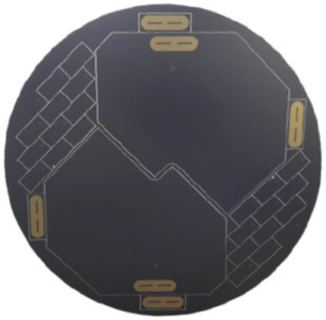


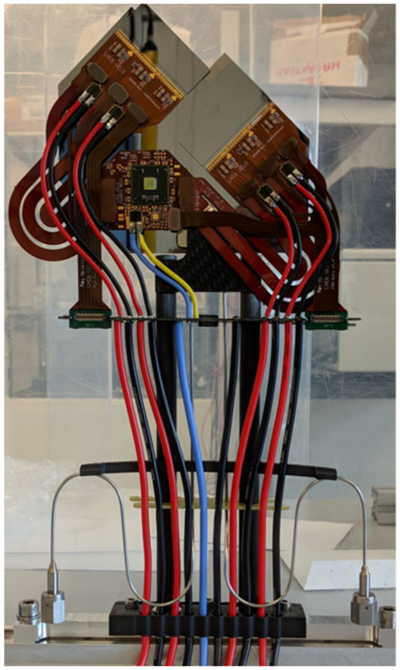
LHCb VErtex LOcator upgrade

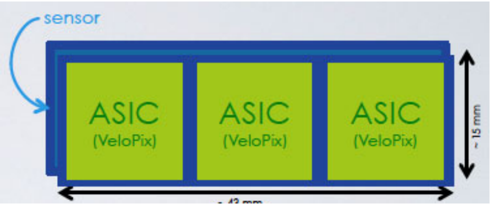


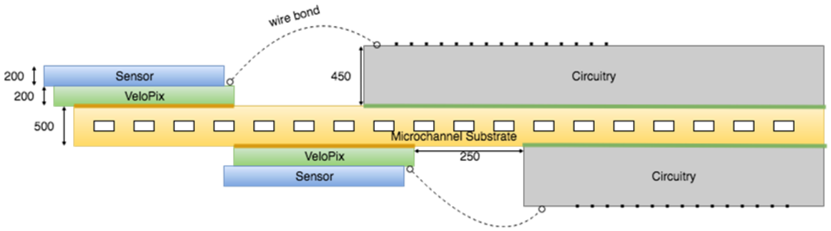
Micro-channel cooling

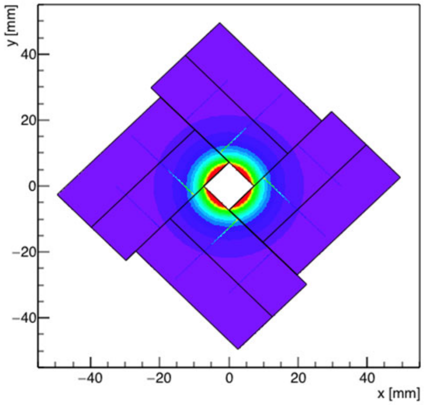
- 500 µm thick silicon substrate with integrated micro channels (70 μm x 200 μm) :
    - same thermal expansion as sensors
    - low material
    - high thermal efficiency
    - cooling power ~50 W
- pressure: 14 bar @ -30 °C, 60 bar @ 22 °C





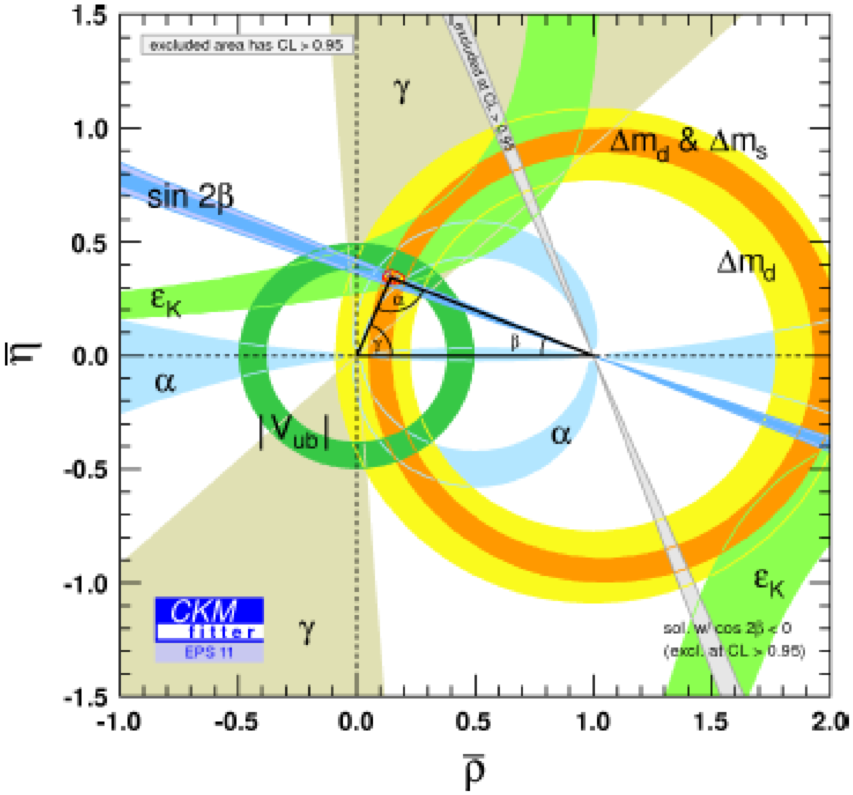






The unitarity triangle – status

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%



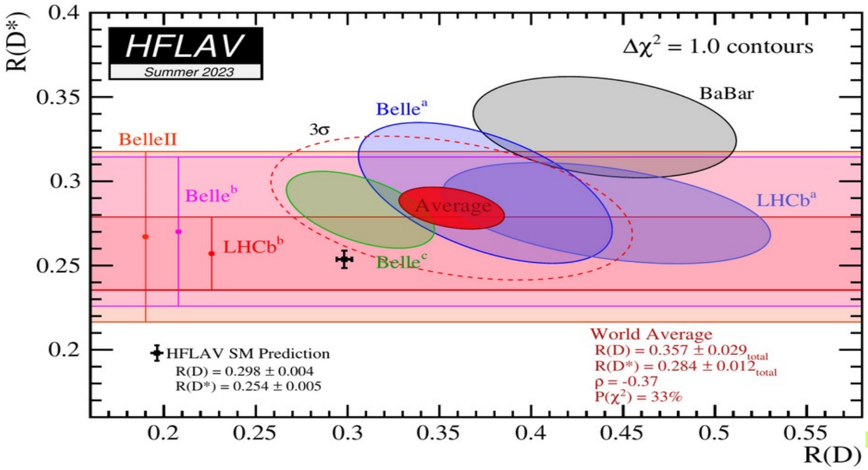
→investigate possible NP phenomena with precise measurements

→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 Δm_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

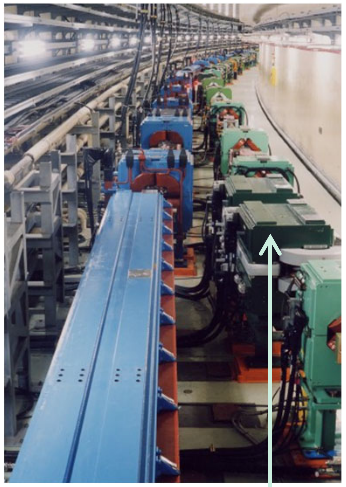


Measurements of R(D) and R(D*) compared to the SM predictions – interesting, but more data needed

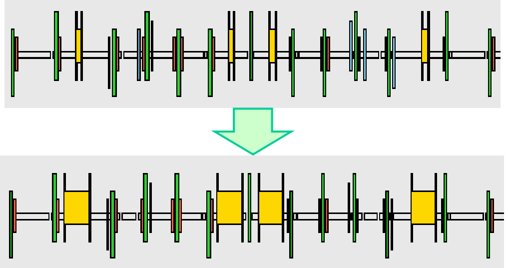
$$R(D, D^*, X) = \frac{\mathscr{B}(B \to D, D^*, X\tau\nu)}{\mathscr{B}(B \to D, D^*, X\ell\nu)}$$

with ℓ a light lepton

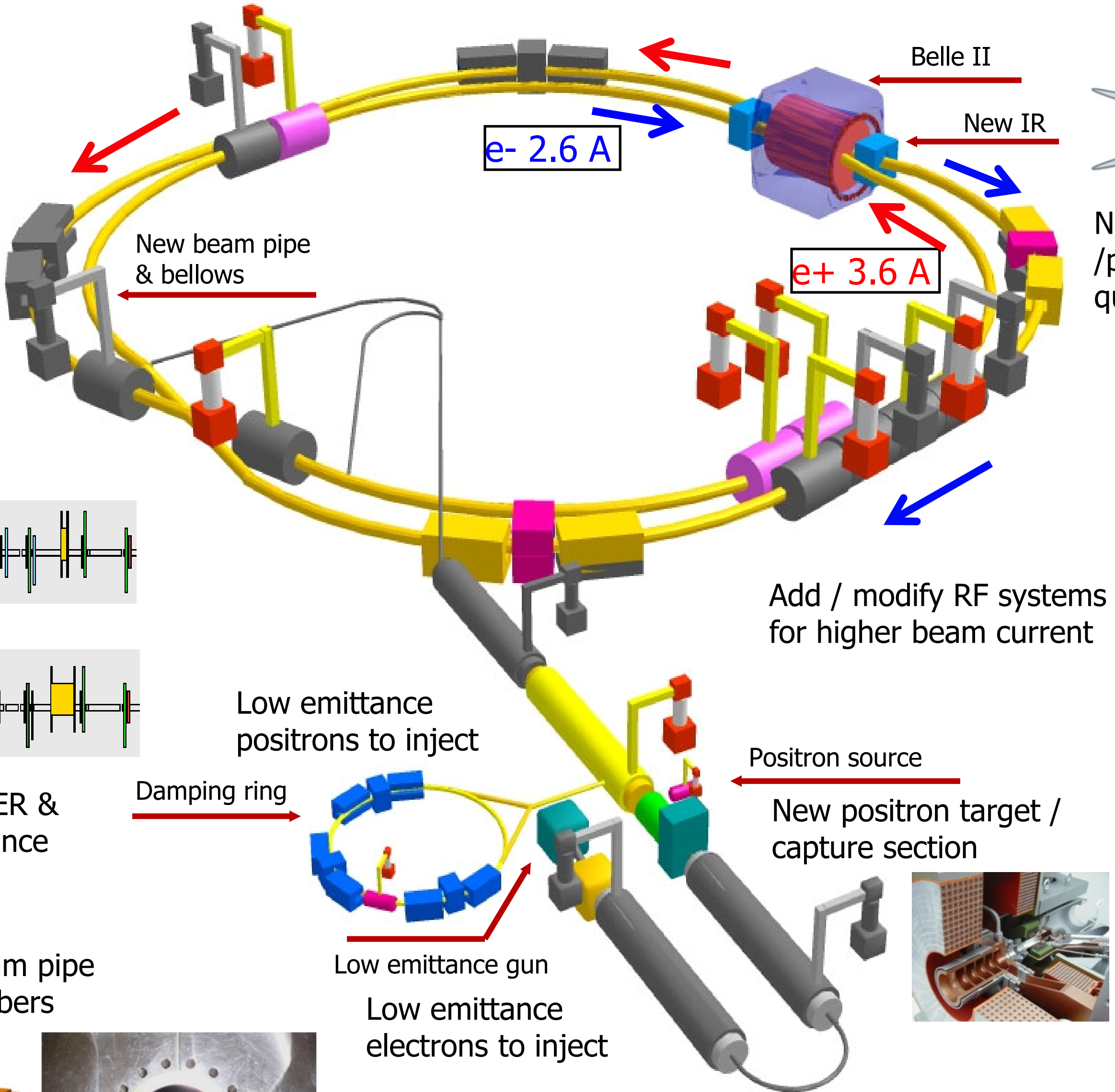
KEKB → SuperKEKB



Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance



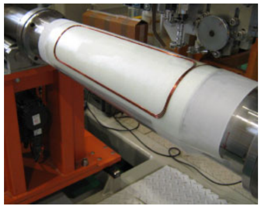
Low emittance positrons to inject

Low emittance electrons to inject

New positron target / capture section

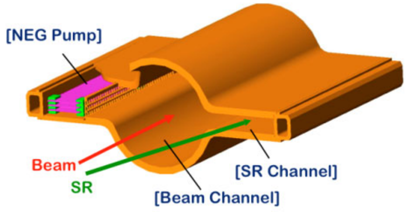
Colliding bunches

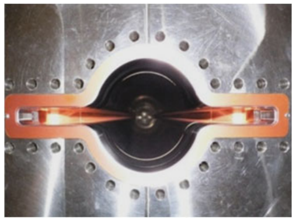
New superconducting /permanent final focusing quads near the IP



Add / modify RF systems for higher beam current

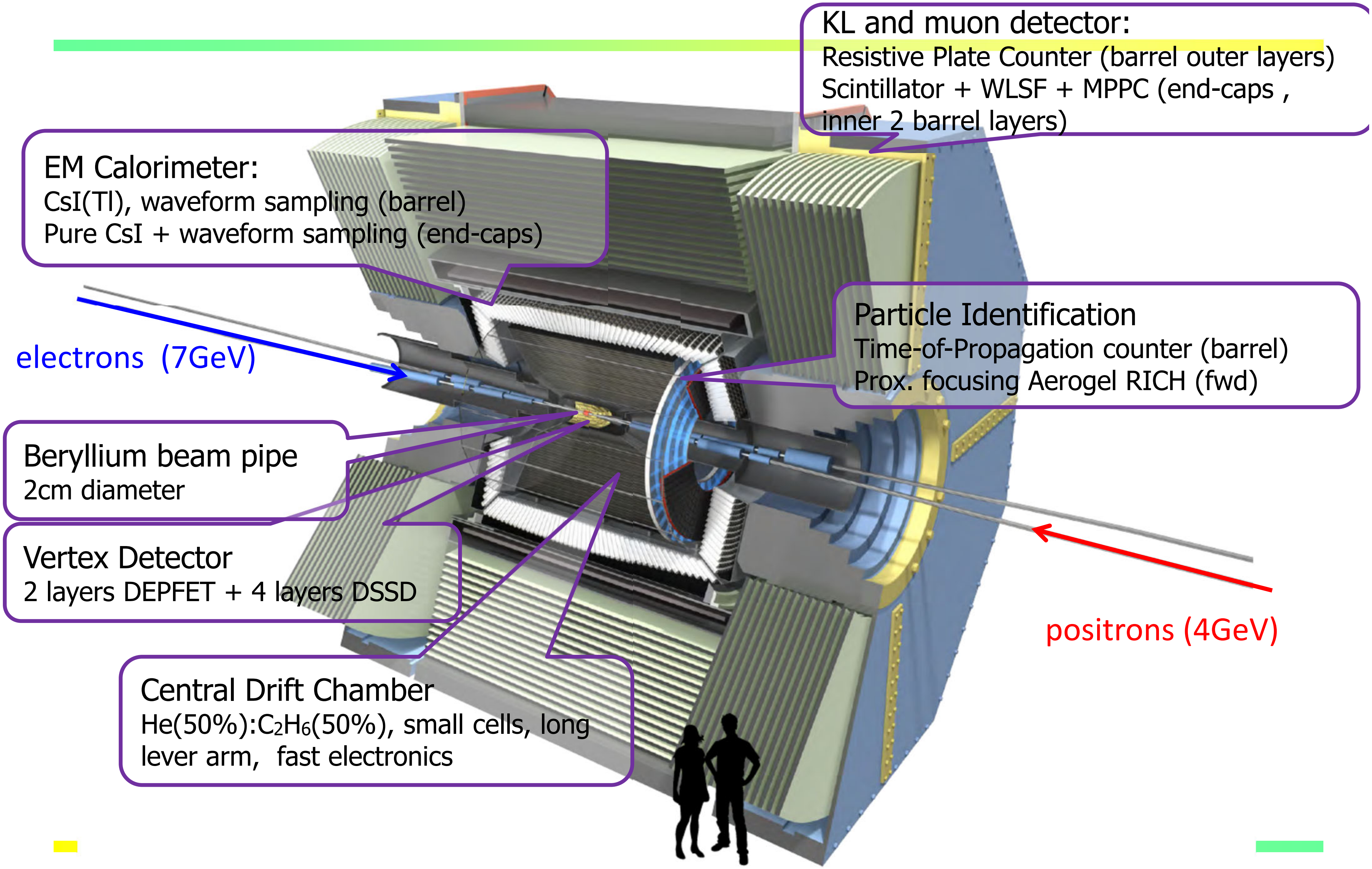
TiN-coated beam pipe with antechambers





To get x40 higher luminosity

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 (barrel)
Pure CsI + waveform sampling (end-caps)

electrons (7GeV)

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

Beryllium beam pipe
2cm diameter

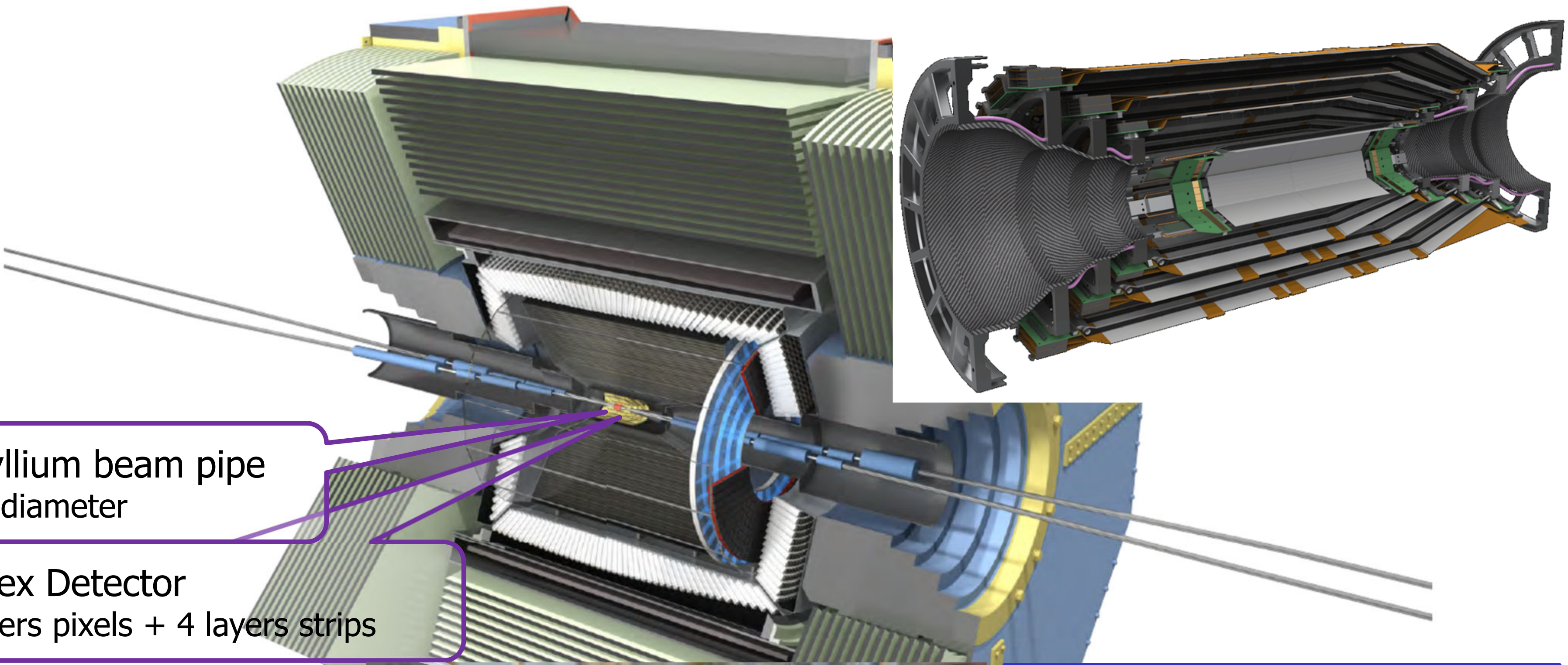
Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4GeV)

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

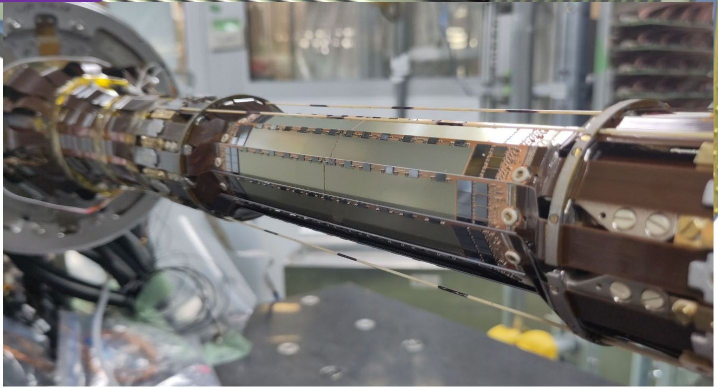
Vertexing at Belle II

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



Beryllium beam pipe
2cm diameter

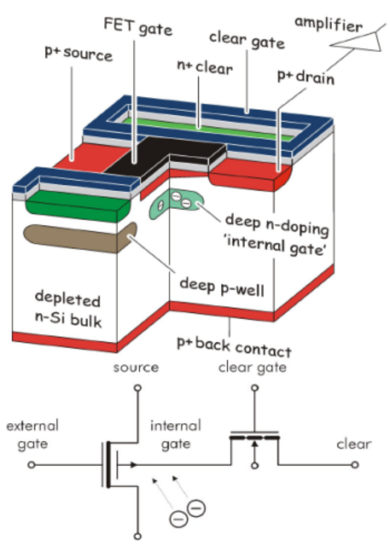
Vertex Detector
2 layers pixels + 4 layers strips



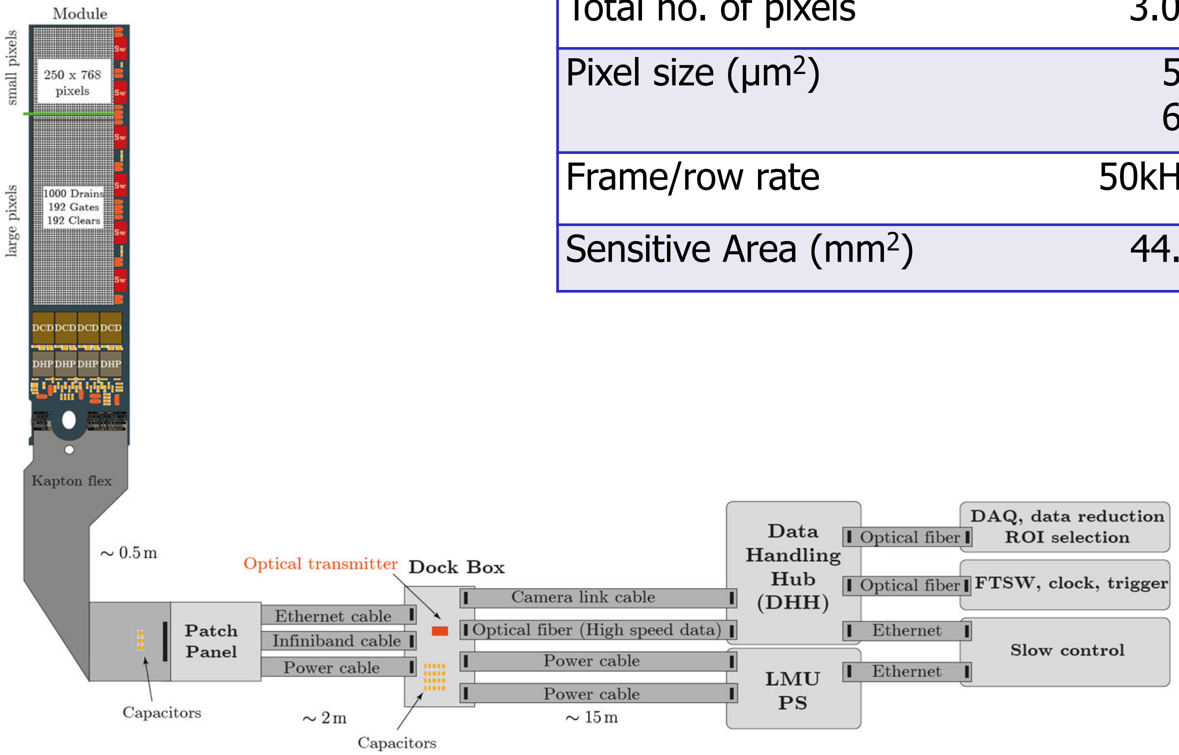
Beam Pipe		**r = 10mm**
DEPFET pixels		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD silicon strips		
	Layer 3	**r = 39mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 104mm**
	Layer 6	**r = 135mm**

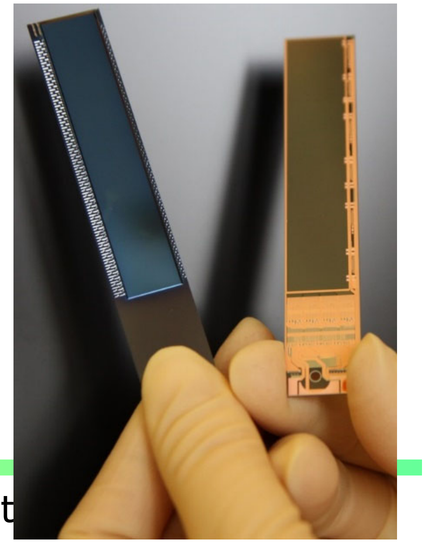
Belle II pixel detector: 2 layers of DEPFET sensors

DEpleted P-channel FET



	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	3.072x10^6	4.608x10^6
Pixel size (μm^2)	55x50 60x50	70x50 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

Belle II PXD Module

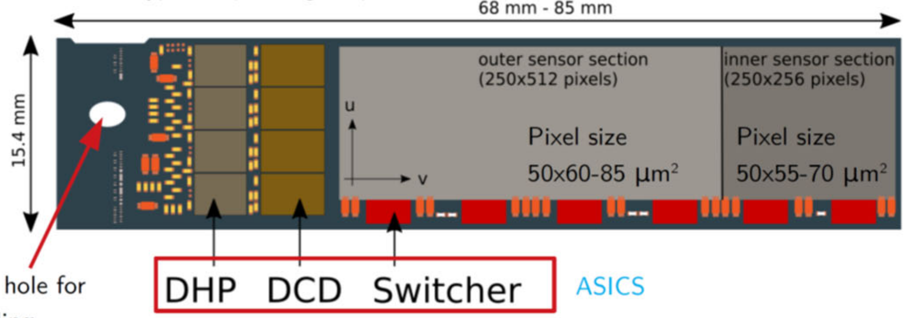
Properties:

- 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 μm²
  (250 x 768 pixels)

Rolling Shutter Readout:

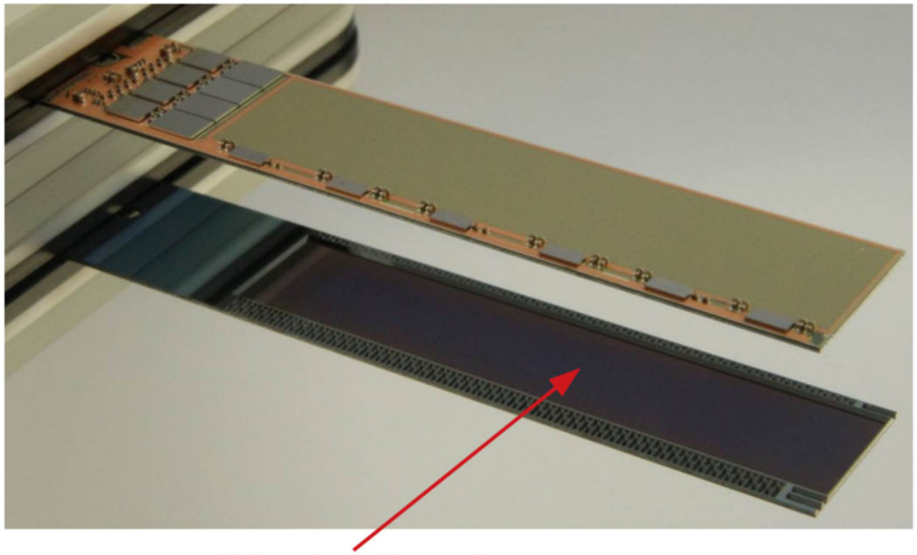
- **Switcher**: consecutive row selection for signal digitization of columns (10 MHz)
- **DCD**: 8-bit AD conversion of signal
- **DHP**: zero suppression, data formatting
- 20 μs integrated readout time
  (2x beam revolution)

4 module types, depending on position



Elongated hole for sensor gliding

ASICS



Thinned backside at active sensor area

Anselm Baur VERTEX 2023

Belle II PXD Detector

2 Modules = 1 Ladder:

- Glued together
- In total 20 ladders

10 Ladders = 1 Half-Shell:

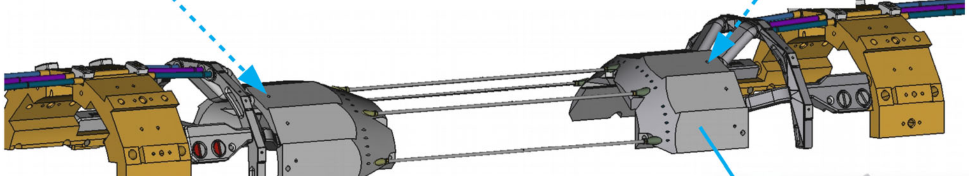
- Ladders screwed on cooling block
  - Radii: r_{L1}=14mm, r_{L2}=22mm
- Half-Shell mounted on beam pipe

Power Consumption:

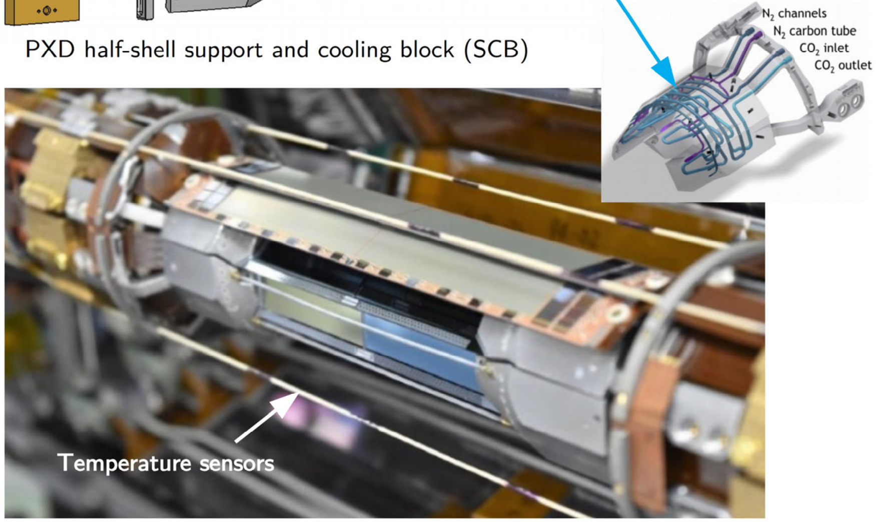
- ~9 W per module
  → ~360 W (full detector)
- Cooling
  - 2 phase CO_2: DHP/DCD (8W)
  - N_2 gas: sw.+sensor area (1W)

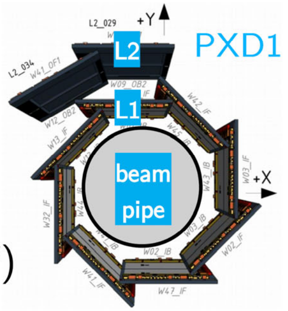
PXD1:

- PXD1 incomplete (effectively 1 layer)



PXD half-shell support and cooling block (SCB)





Anselm Baur VERTEX 2023

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

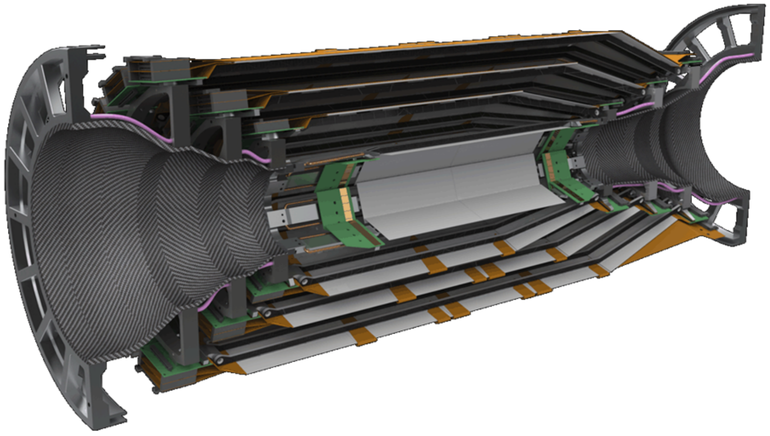
Double-sided silicon strip detectors

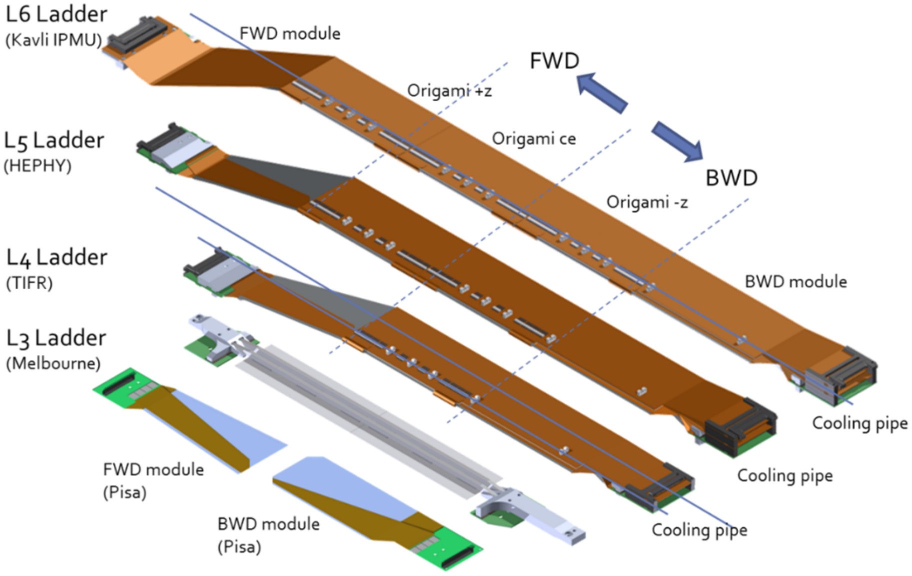
Origami chip-on-sensor concept (readout chips on top of the sensors with flex pitch adapters bent around the edge to reach the bottom sensor side) for good S/N with fast readout and moderate material budget

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

CO_2 dual-phase cooling

with a very strong Indian contribution



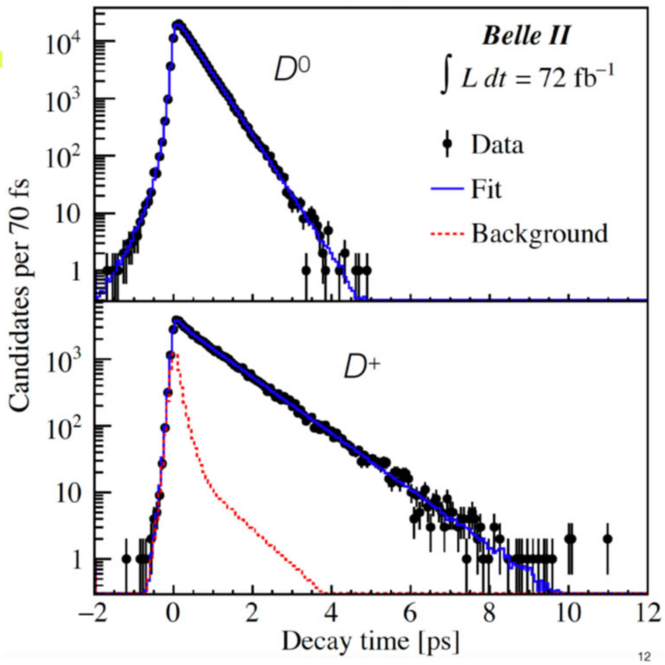


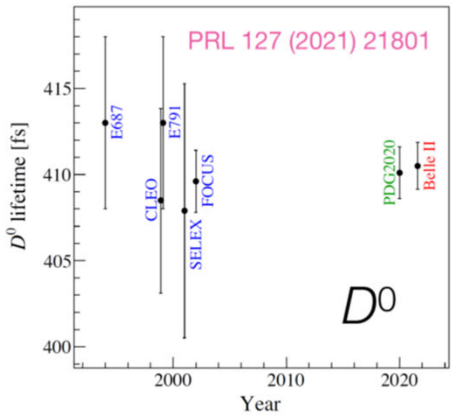
Charmed hadrons: lifetime measurements

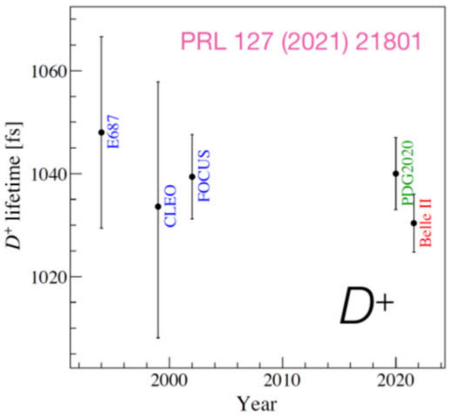
Example of improved performance of Belle II vs Belle: time-dependent capabilities in D lifetime measurements.

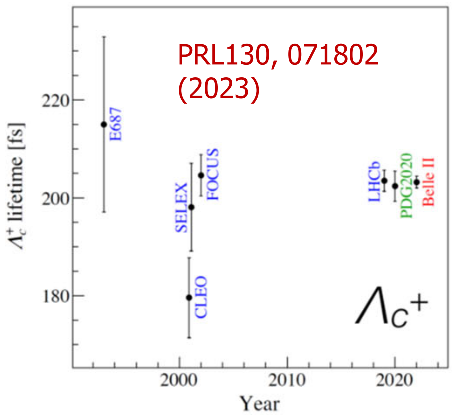
The addition of a pixel vertex detector (with a 1cm radius beam pipe) gives a *factor of two improvement* in proper time resolution for charm lifetime measurements compared to Belle. Alignment systematics are much improved.

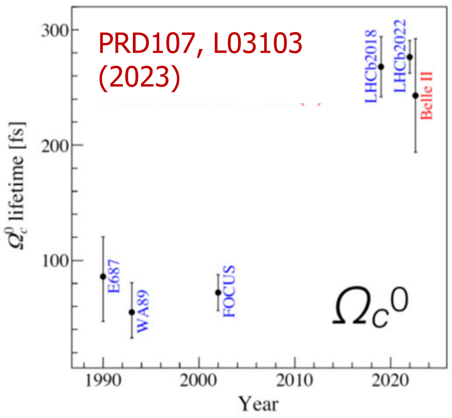
PRL 127 (2021) 21801




PRL 127 (2021) 21801

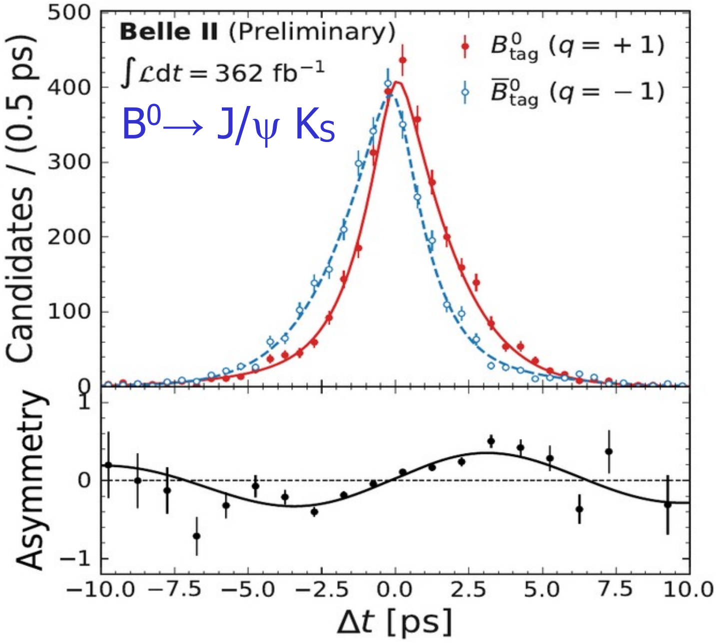

PRL 127 (2021) 21801

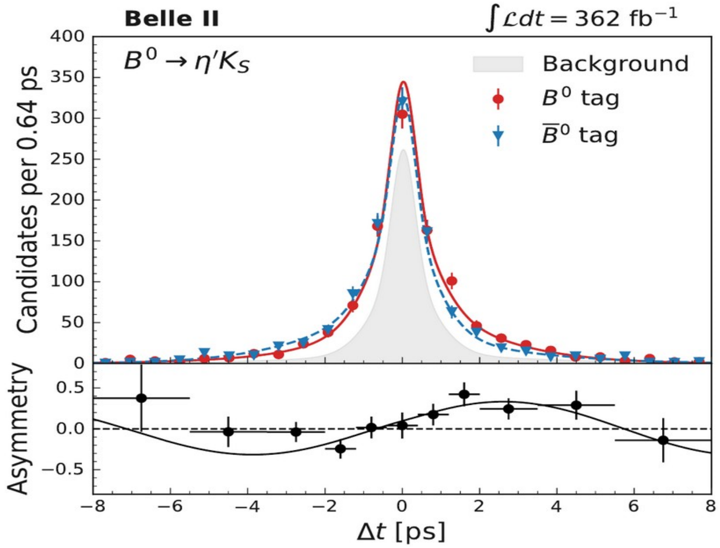

PRL130, 071802 (2023)


PRD107, L03103 (2023)

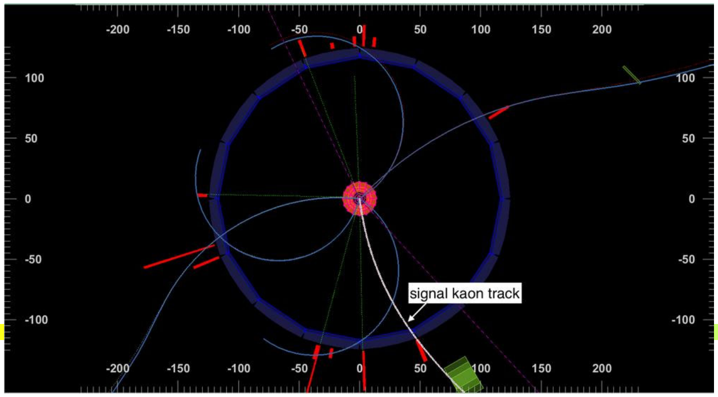
Tiny systematic uncertainties (e.g., 2‰ for D^0) demonstrate excellent performance and understanding of the Belle II detector, never achieved at previous B factories

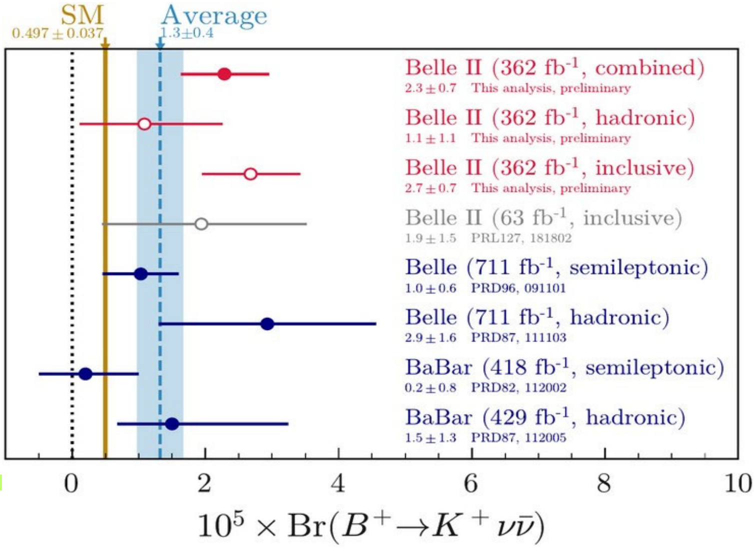
… many results published, and many more too come





B+→ K+ ν ν





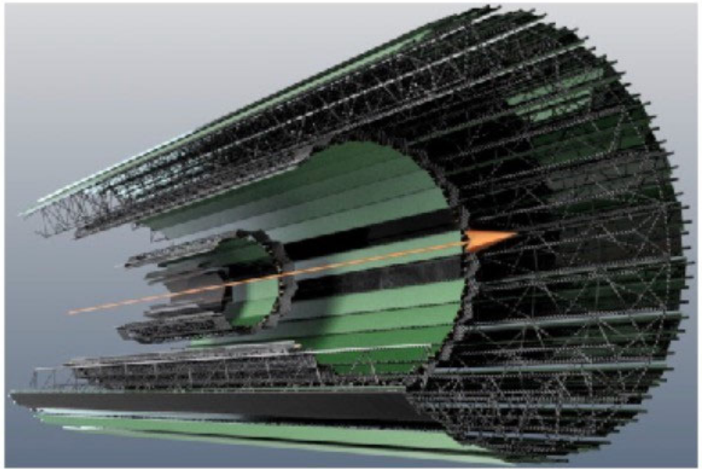
Belle II VXD Upgrade for LS2: requirements

Motivations:

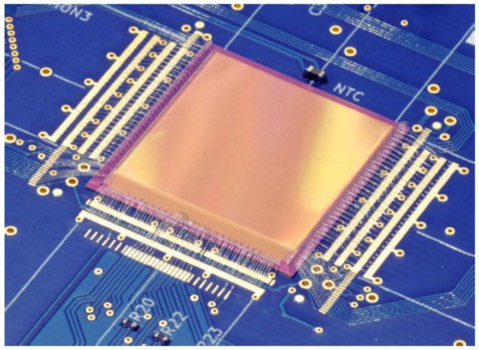
- Cope with larger background rates
- Improve momentum and impact parameter resolution at low p_T
- Simplify vertex system (pixels + strips → pixels)
- Operation without data reduction
- Be safe in case of accident

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



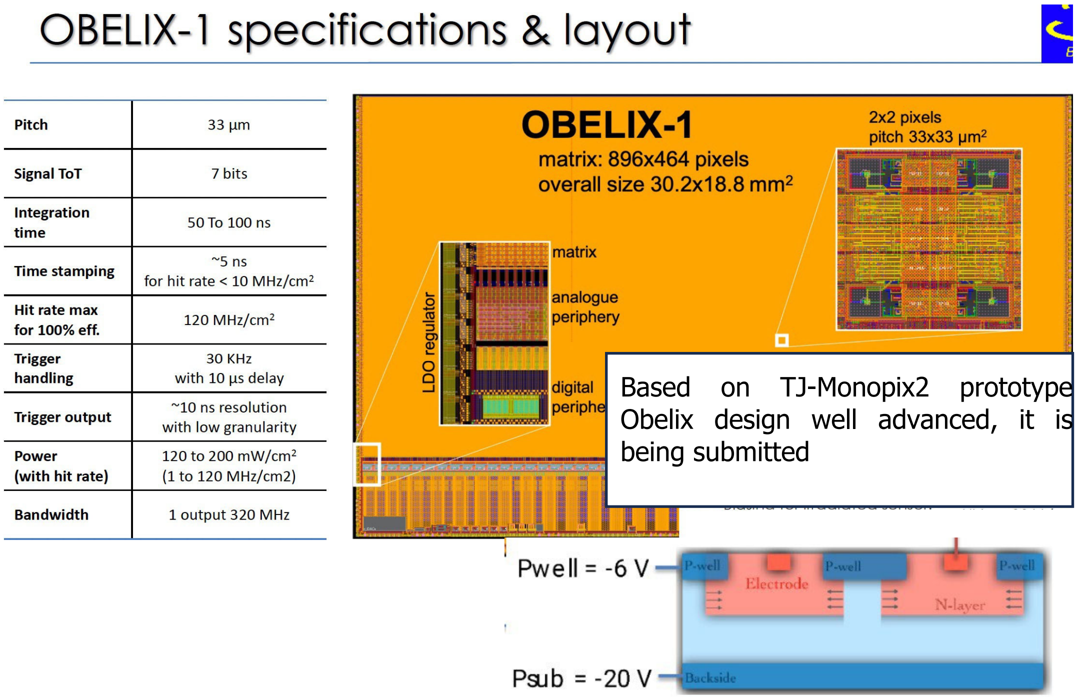
Max radius 14 cm & length 70 cm → 1 m^2



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

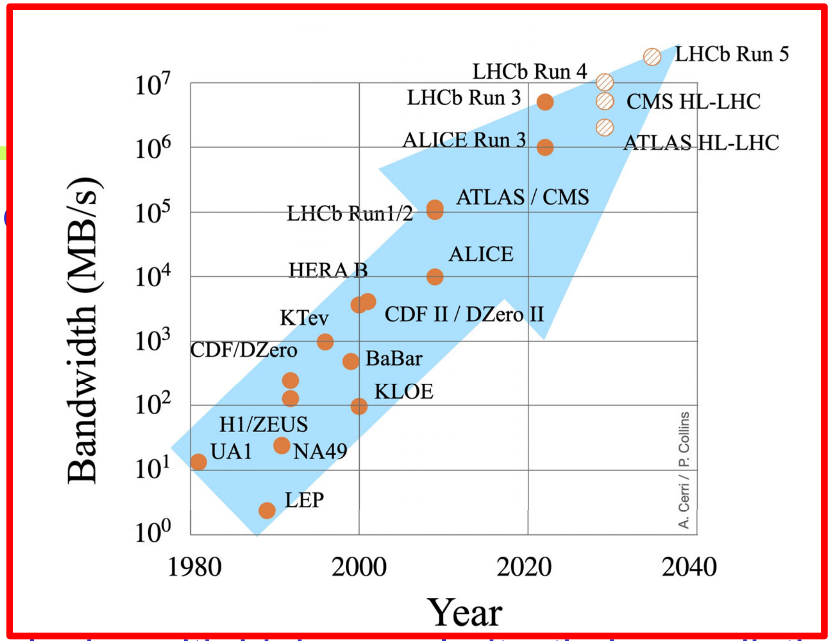
Pitch	33 µm
Signal ToT	7 bits
Integration time	50 To 100 ns
Time stamping	~5 ns for hit rate < 10 MHz/cm²
Hit rate max for 100% eff.	120 MHz/cm²
Trigger handling	30 KHz with 10 µs delay
Trigger output	~10 ns resolution with low granularity
Power (with hit rate)	120 to 200 mW/cm² (1 to 120 MHz/cm2)
Bandwidth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

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

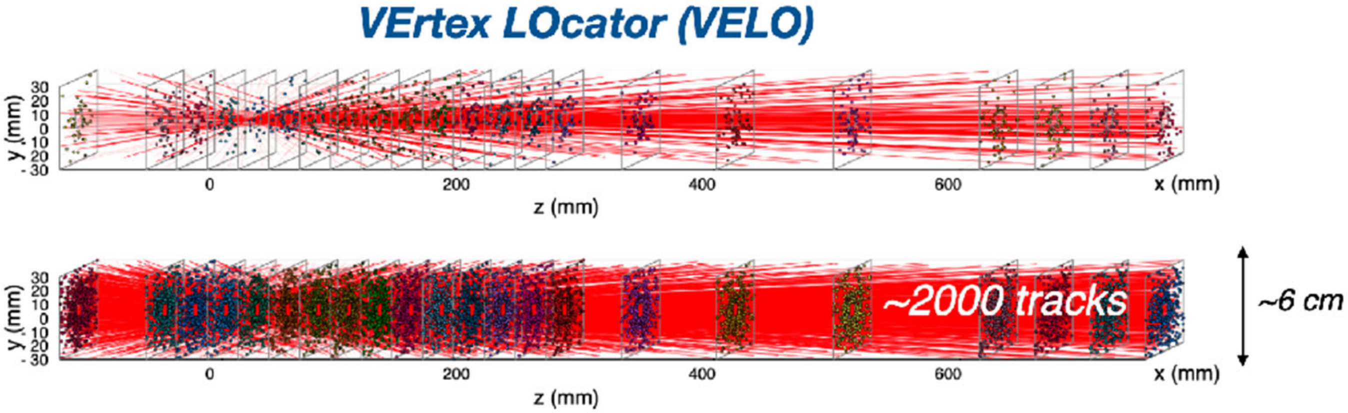


This is the **intensity frontier**! New, lightweight technologies with high granularity, timing, radiation resistance and innovative data processing all necessary to go to ✖ 10^{34} sec^{-1}cm^{-2}

Image credit: Tim Evans

Run 3: pile-up ~5

Upgrade II: pile-up ~40



LHCb Upgrade II

Timing to the Rescue

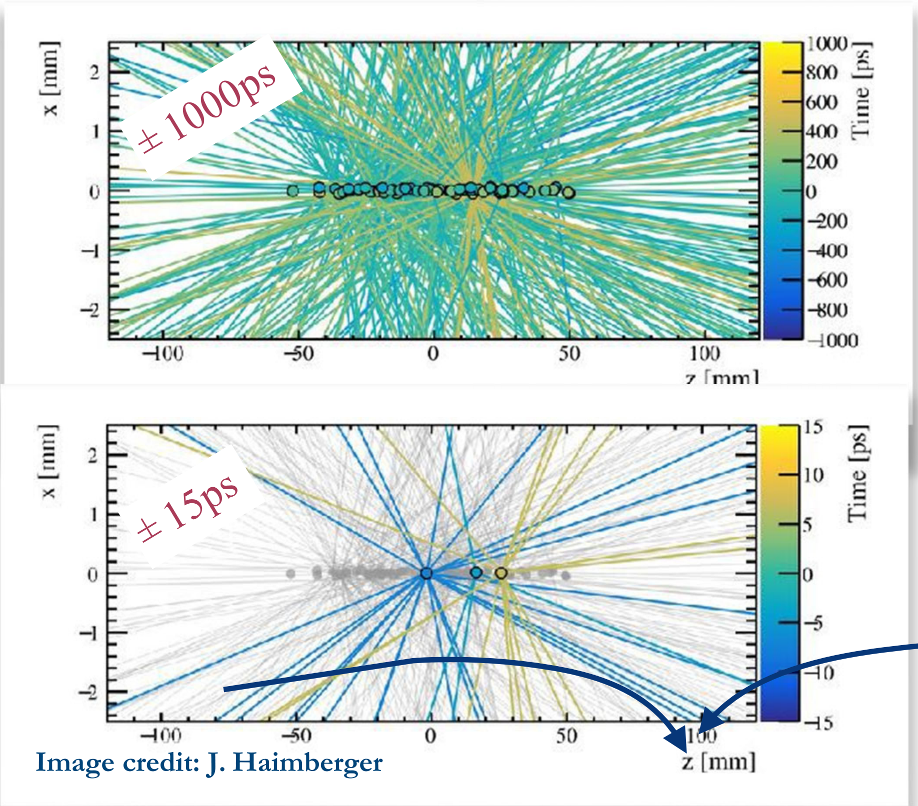
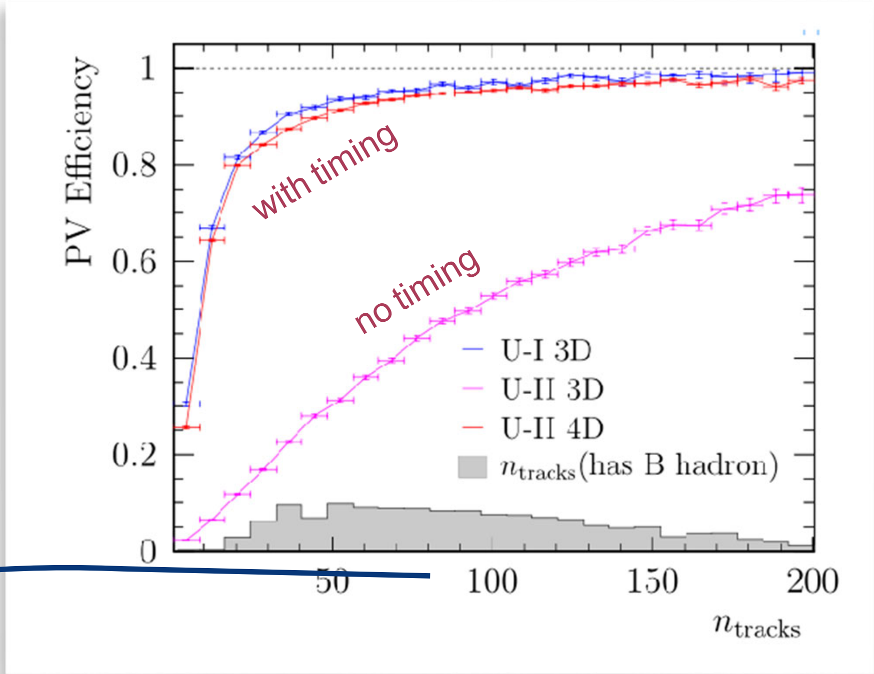
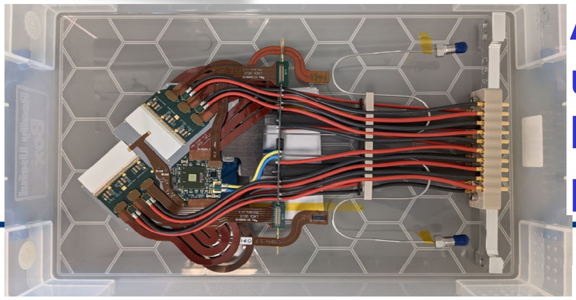


Image credit: J. Haimberger



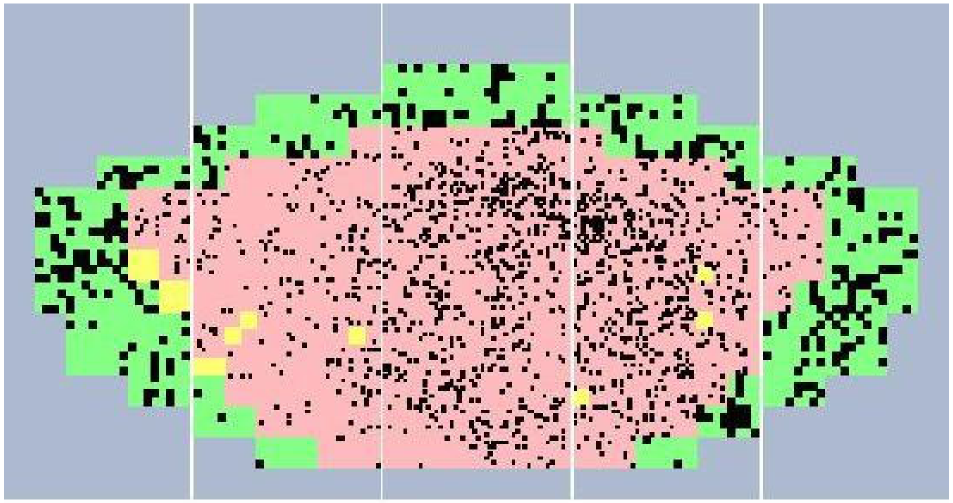
Sensors to be replaced with timestamping, radiation hard solution (3d, thin planar…)



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

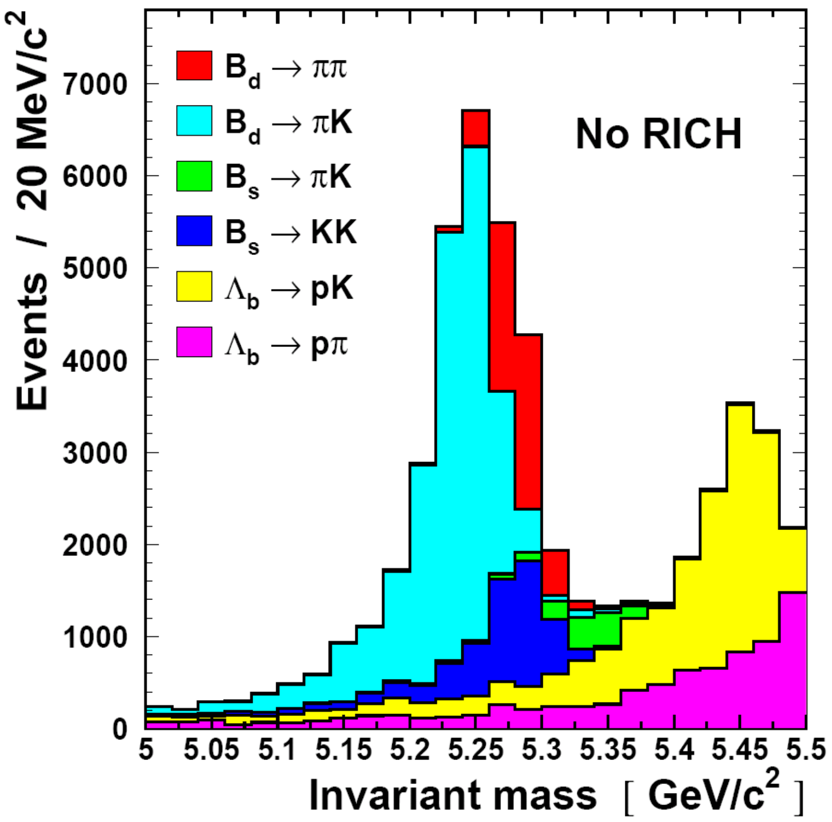
… in LHC or LHC-like environments

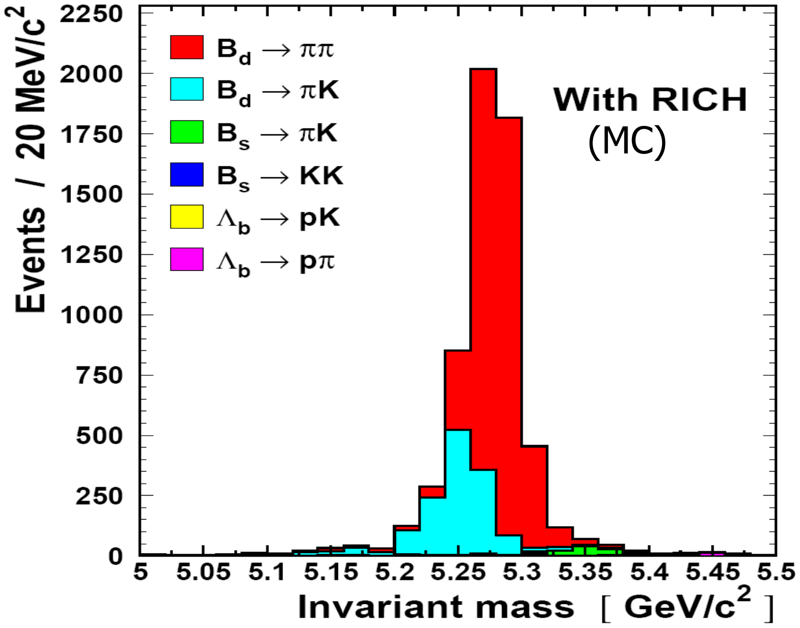


It works with multianode PMTs, but can we make it with semiconductor detectors?

Why particle ID?

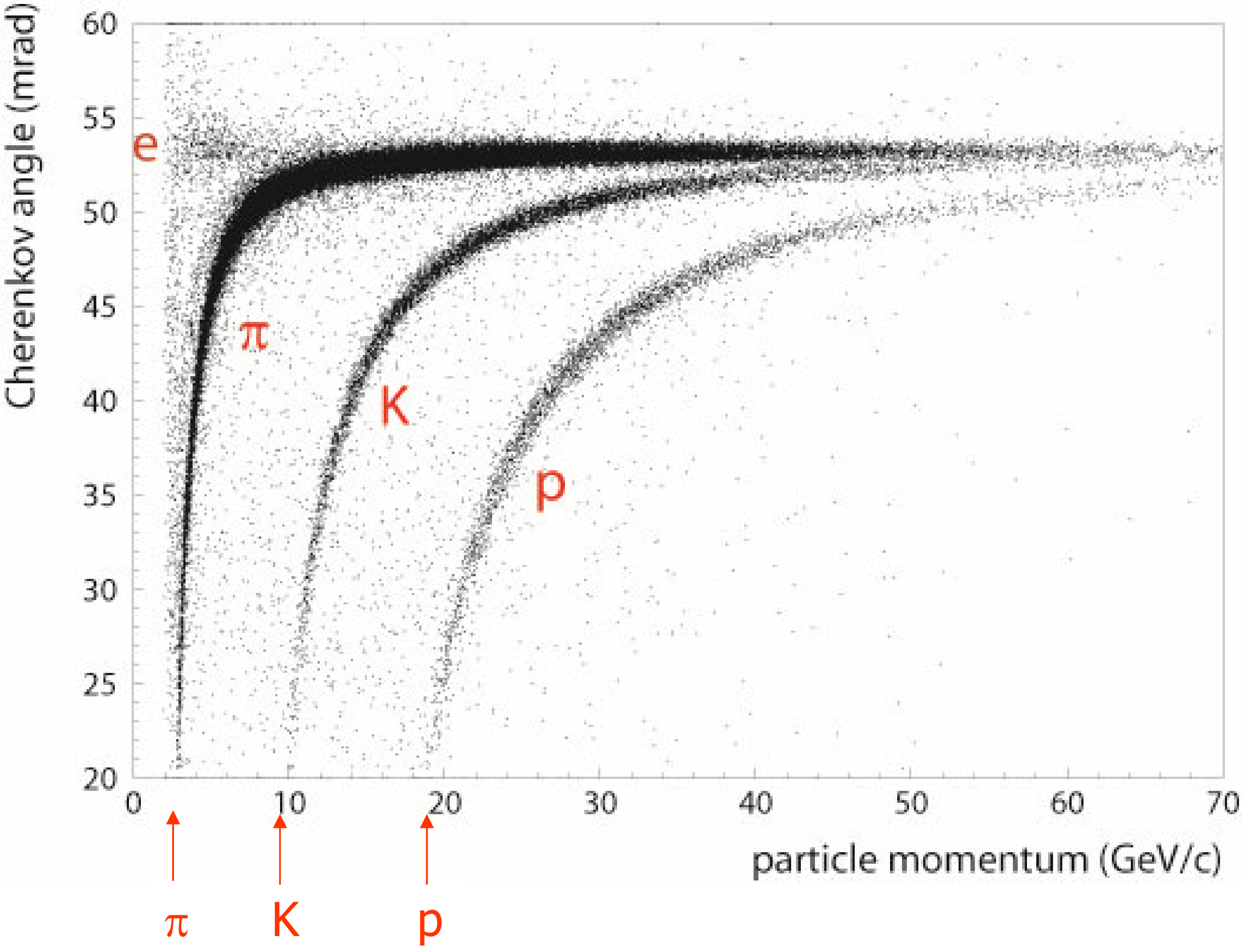
Example: LHCb





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

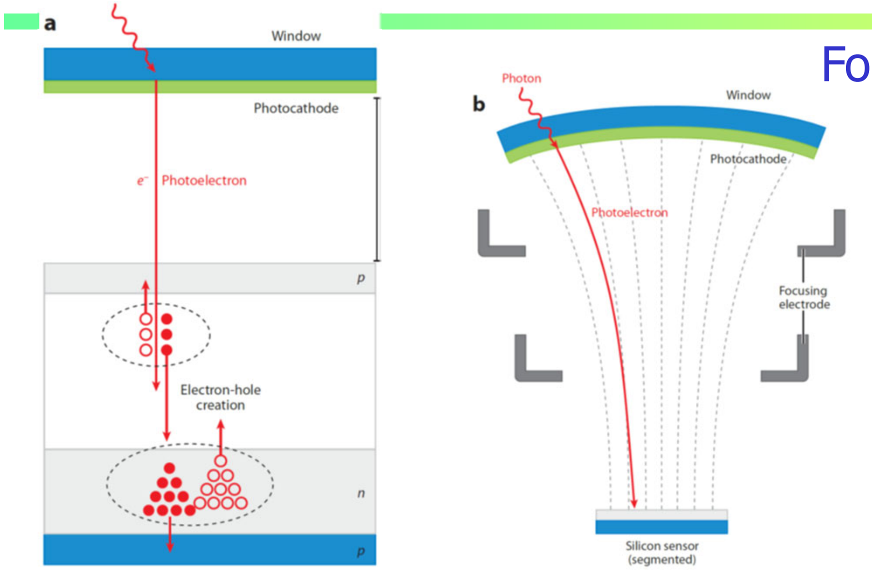


thresholds

Radiator:
C_4F_{10} gas

Hybrid photodetectors (HPD, HAPD)

Focusing and proximity-focusing configurations



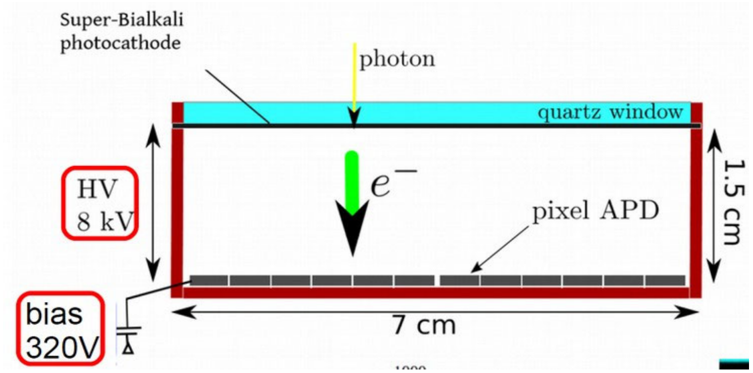


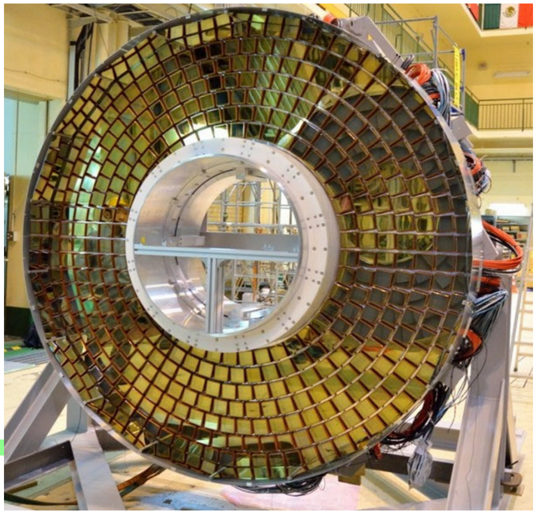
Photo-electron acceleration in a static electric field (8kV to 25 kV)

Photo-electron detection with

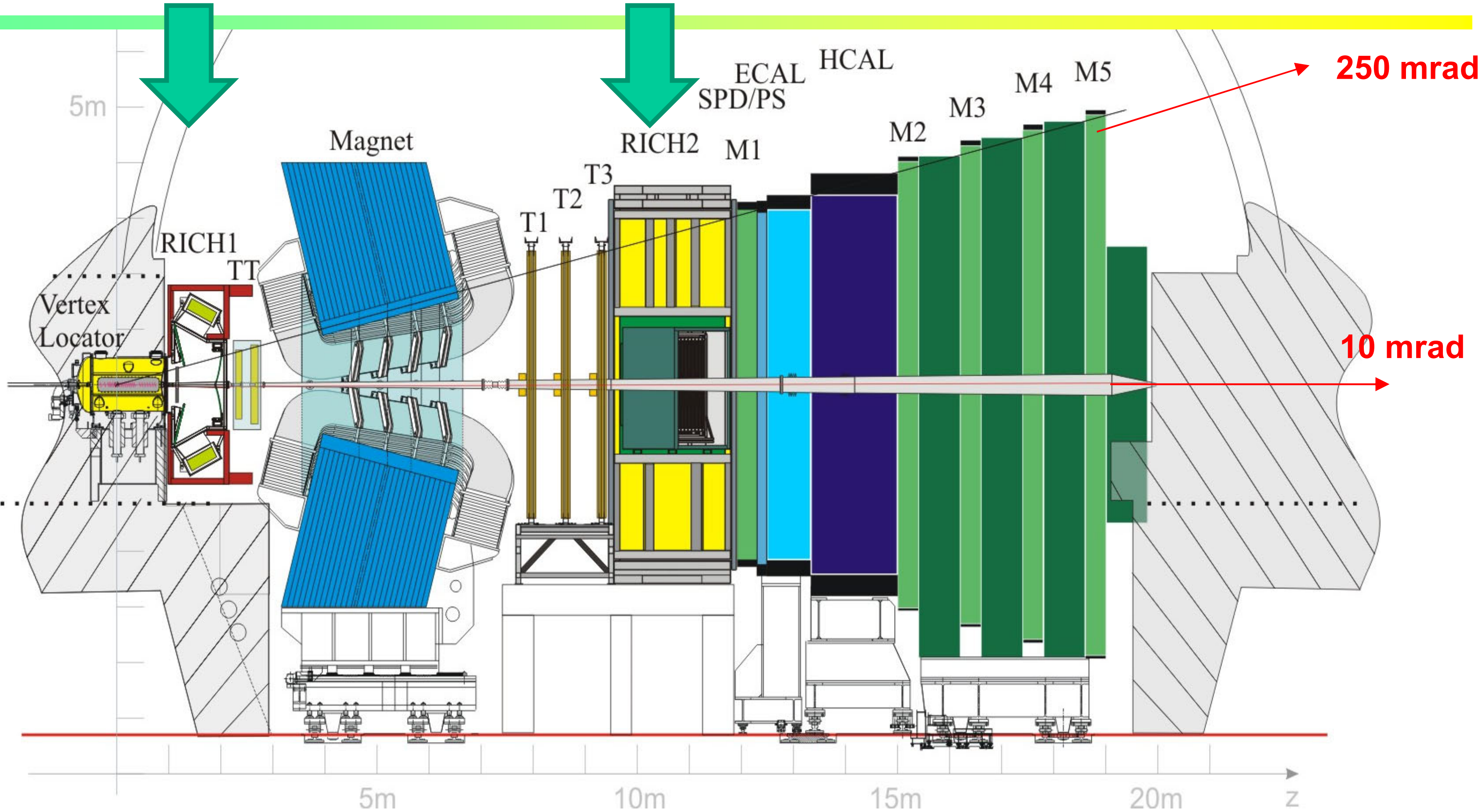
- Segmented PIN diode (HPD)
- Avalanche photo diode (HAPD)
- Silicon photomultiplier (VSiPMT)

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

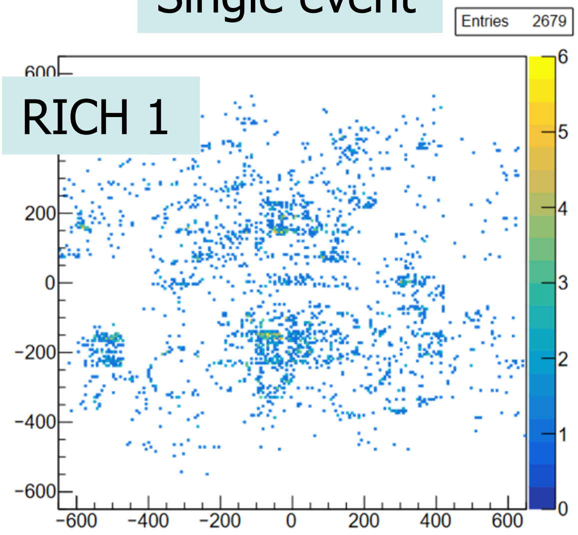
PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

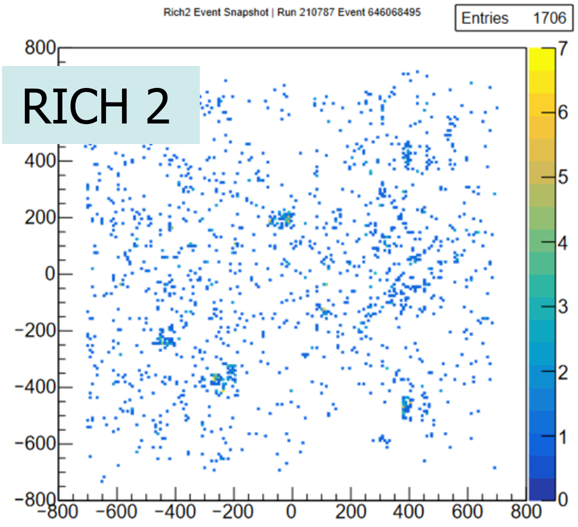
Performance of LHCb RICHes

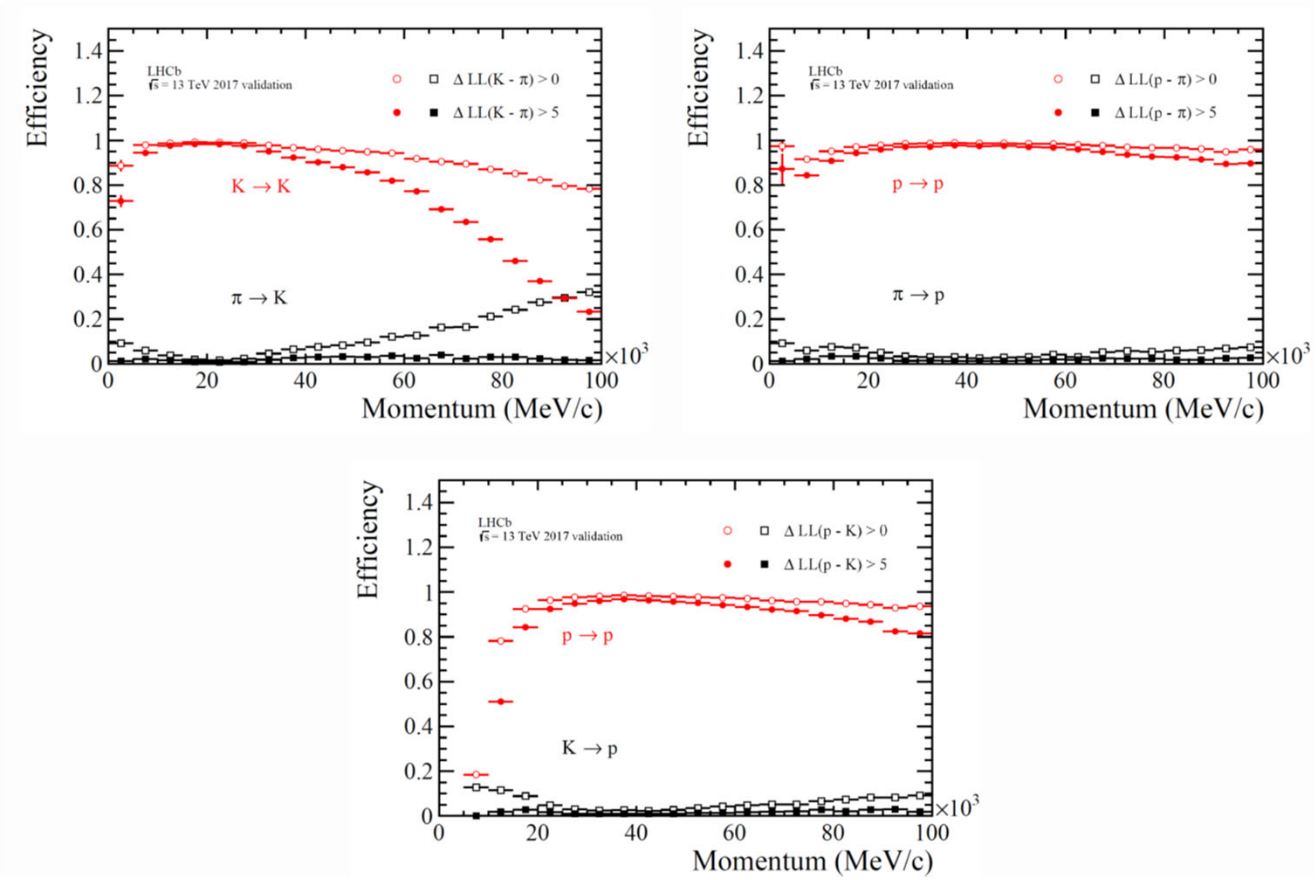
Single event

RICH 1

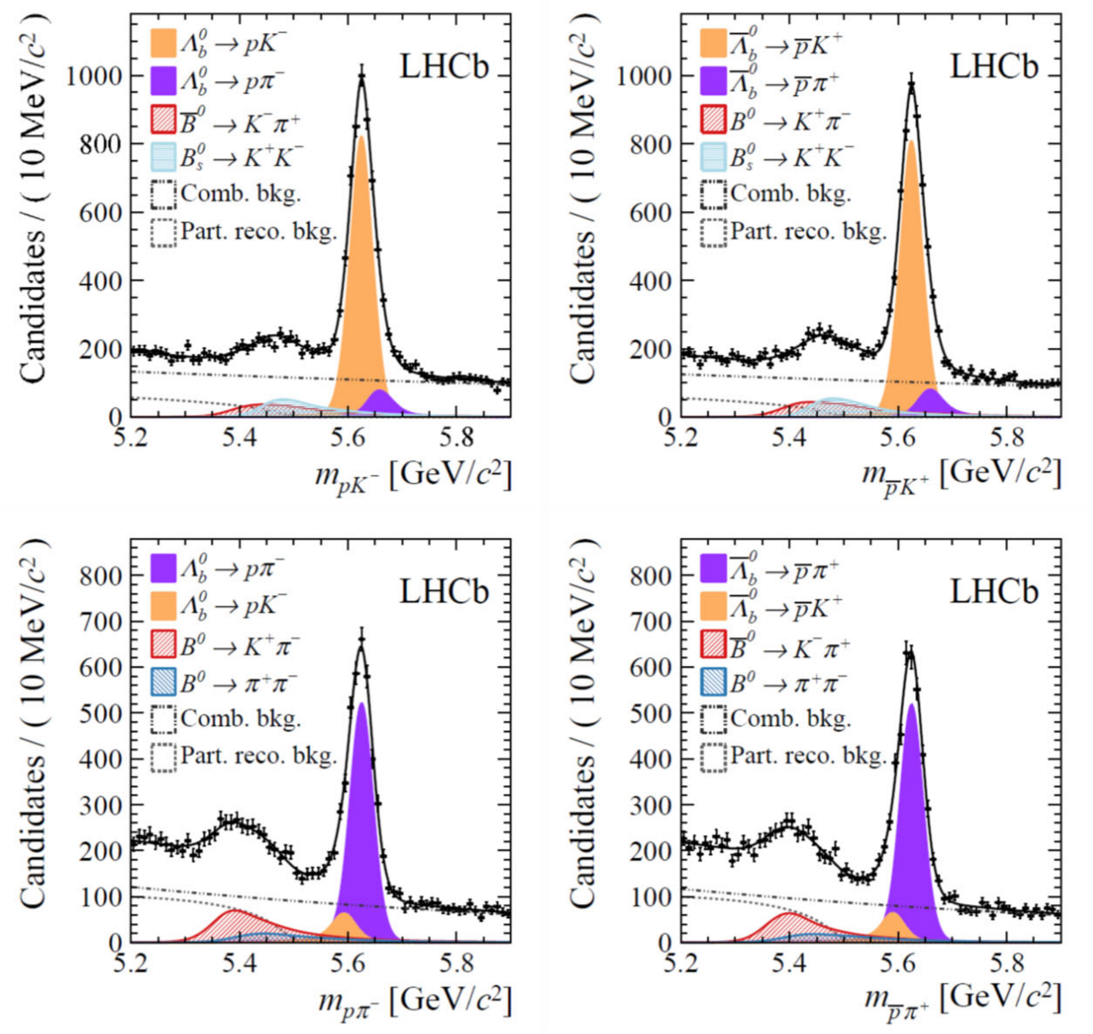


RICH 2





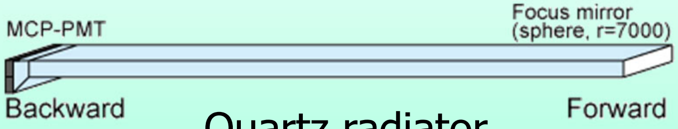
LHCb RICHes: performance



"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)



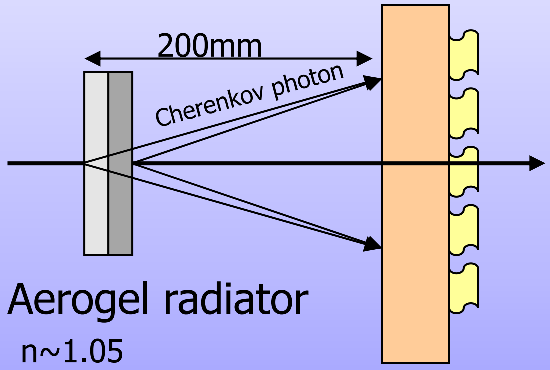
Quartz radiator

Focusing mirror

Small expansion block

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

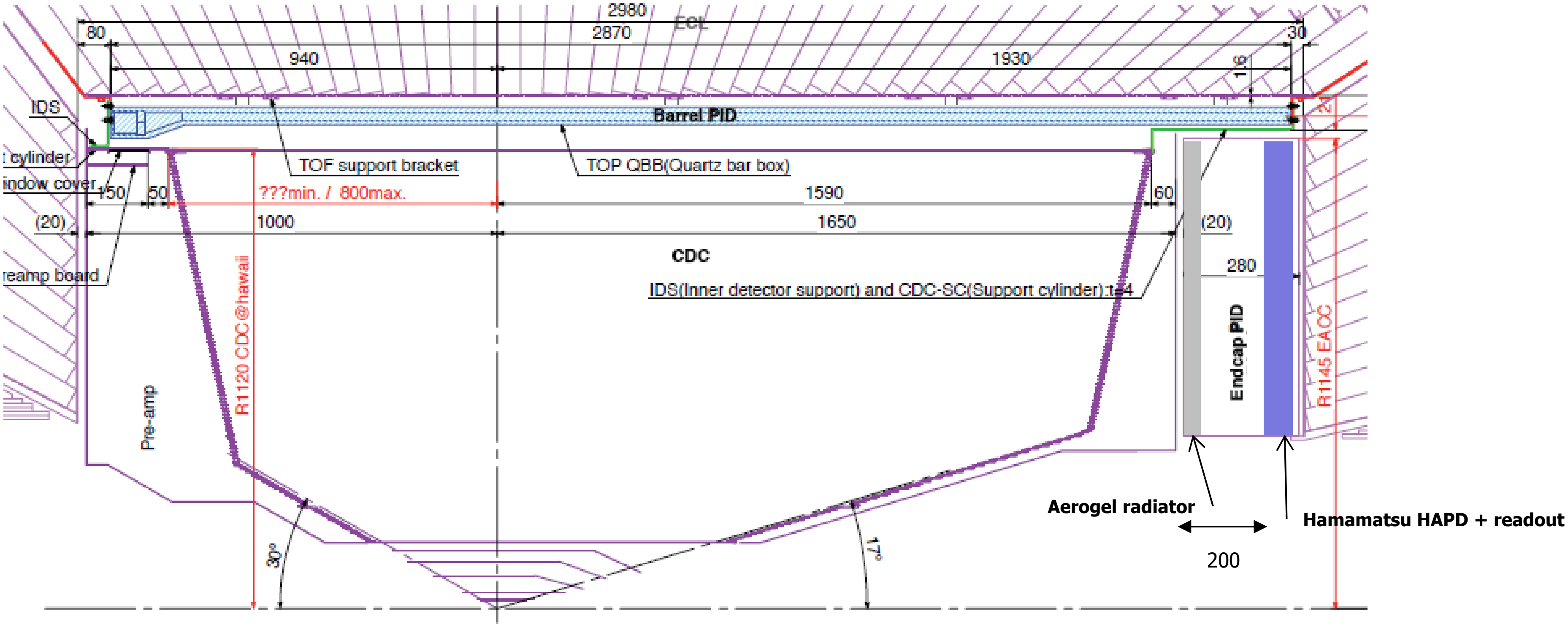
Endcap PID: Aerogel RICH (ARICH)



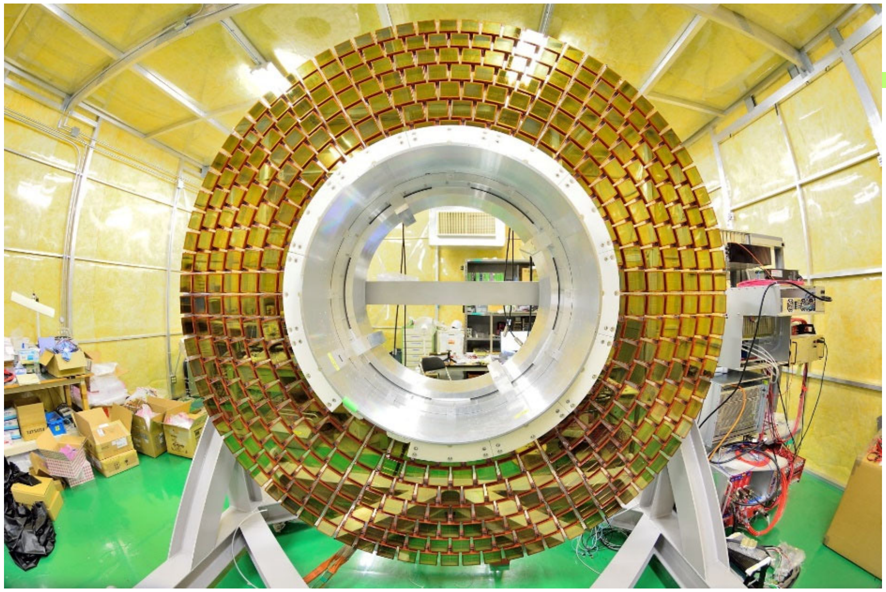
Aerogel radiator

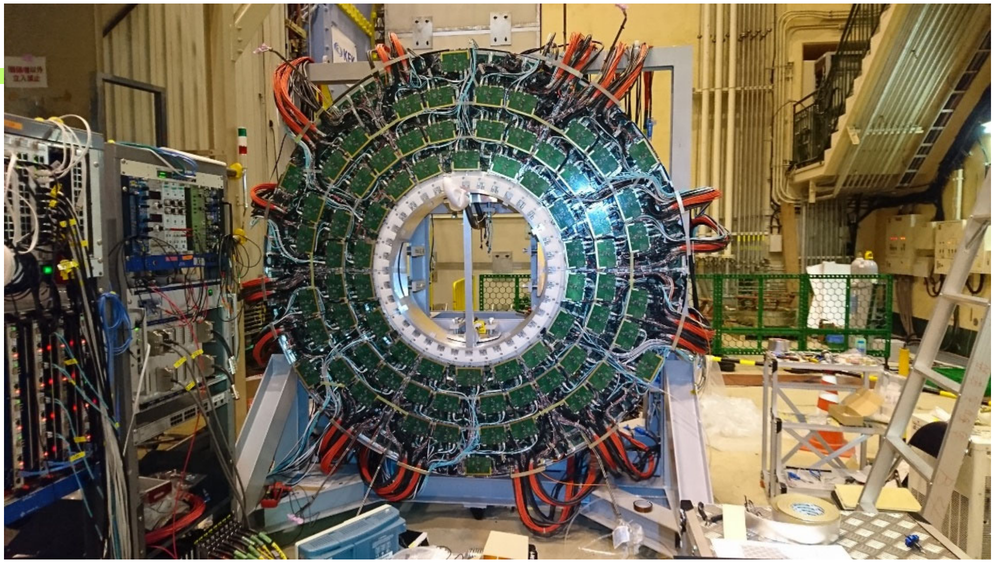
n~1.05

Hamamatsu HAPD
+ new ASIC

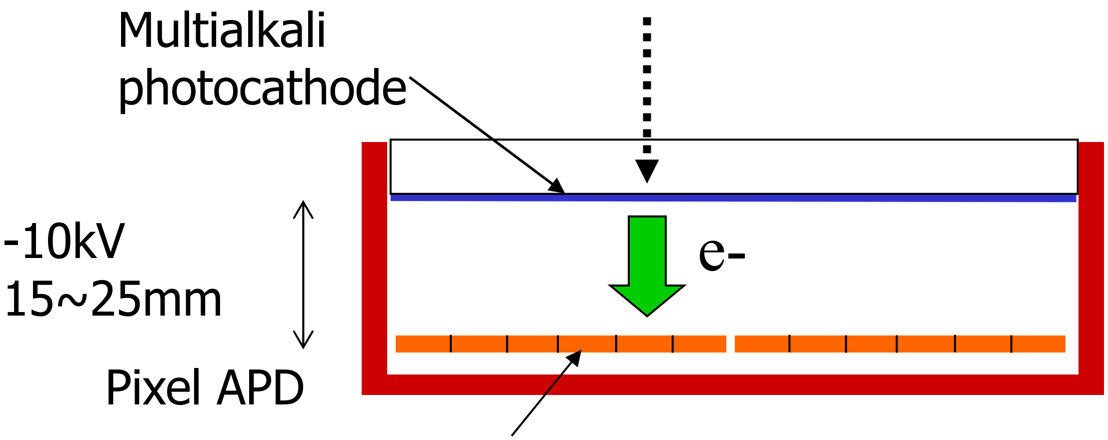


The big eye of ARICH – 420 HAPDs





Sensor: Hybrid APD - HAPD

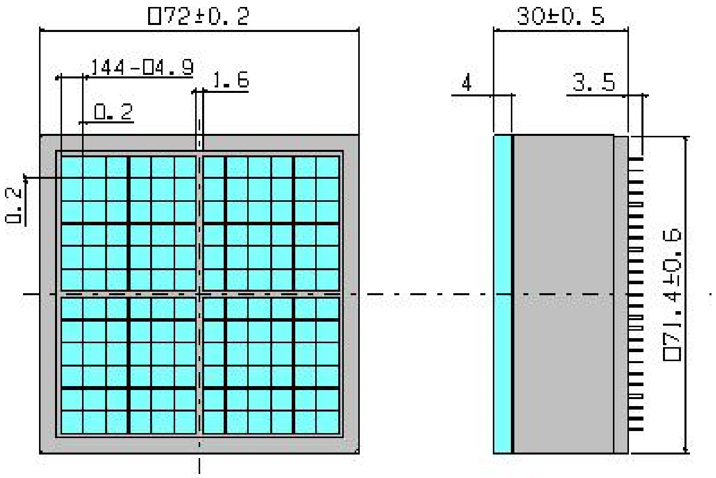


Multialkali
photocathode

e-

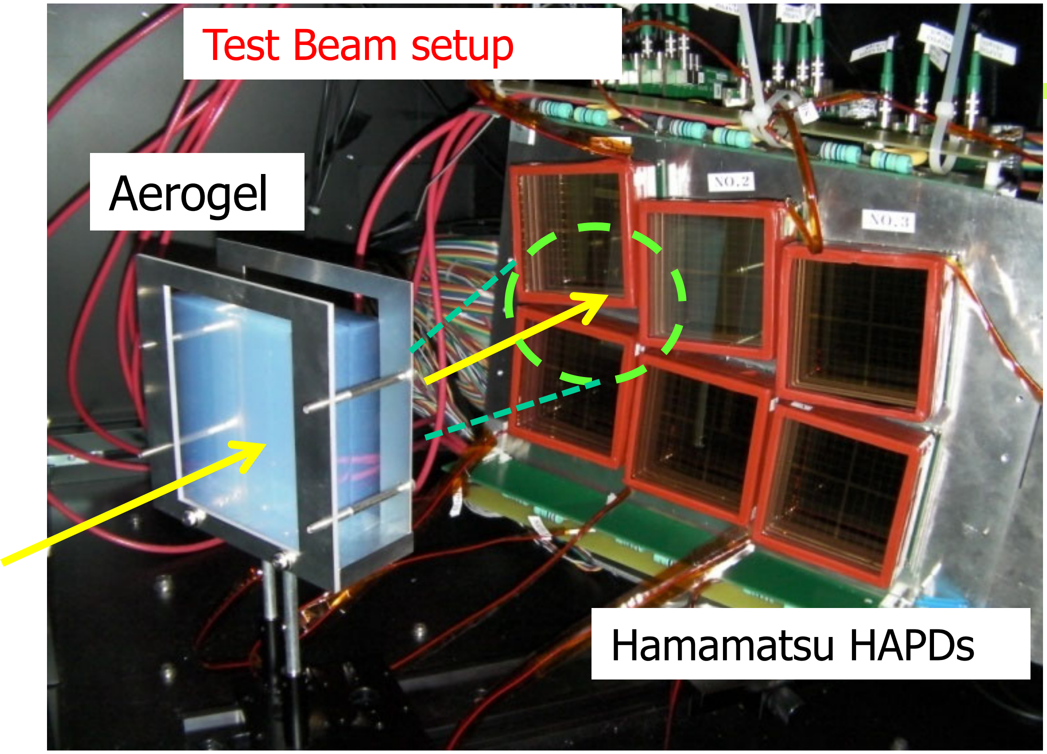
-10kV
15~25mm

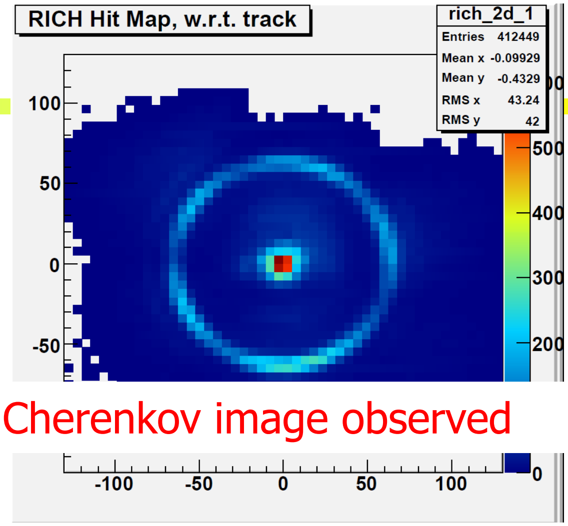
Pixel APD



HAPD R&D project in
collaboration with HPK.

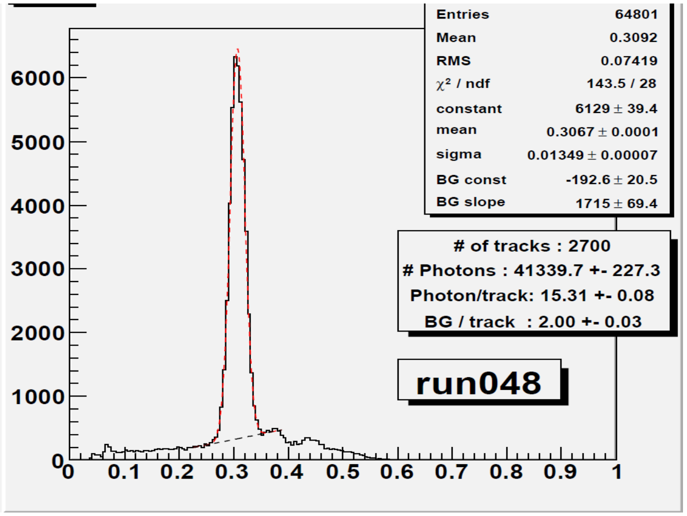
Aerogel RICH (endcap PID)





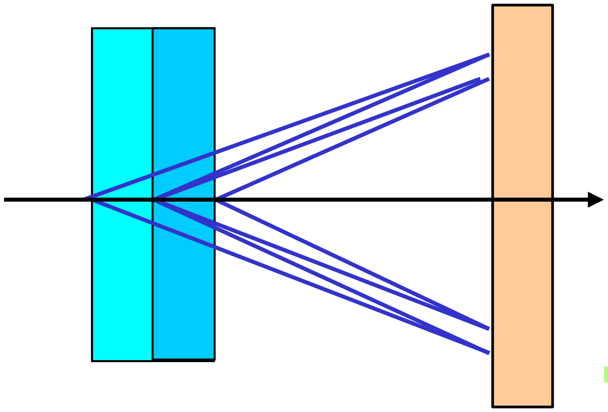
Clear Cherenkov image observed

Cherenkov angle distribution



6.6 σ π/K at 4GeV/c !

RICH with a novel “focusing” radiator – a two layer radiator



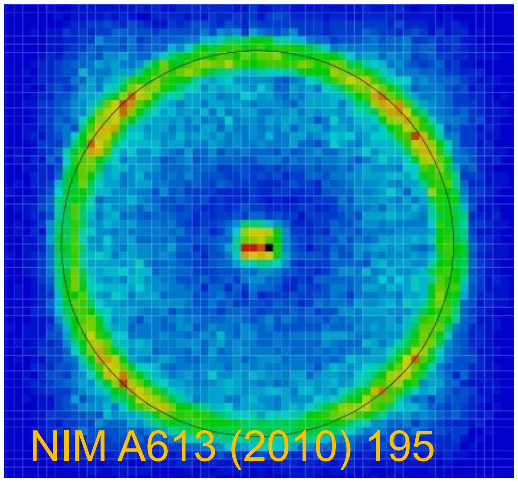
Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.

Peter Križan, Ljubljana

SiPMs as single photon detectors for RICH counters?

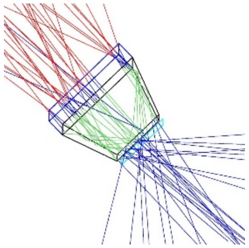
SiPMs have excellent properties (low operation voltage, high gain, high PDE, excellent time resolution, work in high magnetic field) but also have serious drawback - dark counts ~ few 100 kHz/mm^2 .

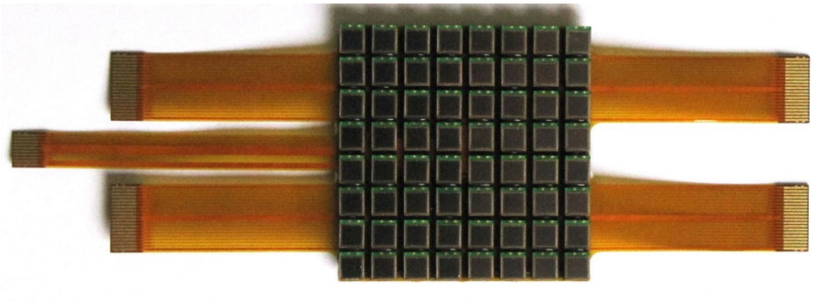
→Challenge in a RICH counter where we have to detect single photons (dark counts have single photon pulse heights, rates 0.1-1 MHz/mm^2).

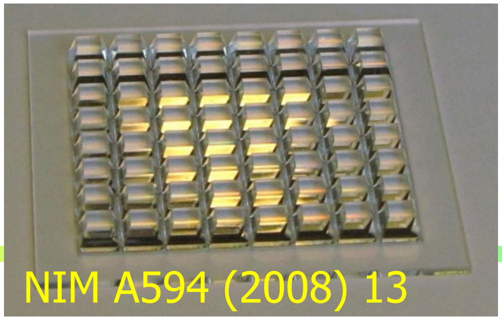

NIM A613 (2010) 195

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



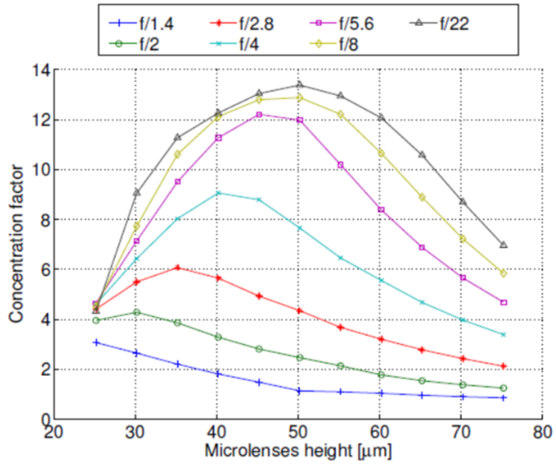


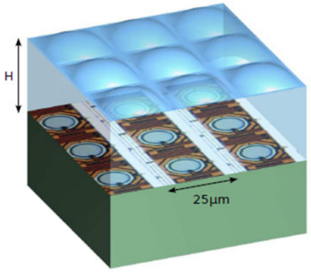

NIM A594 (2008) 13

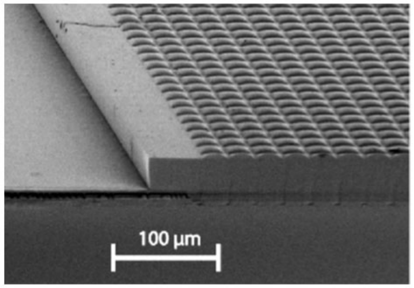
Microlenses

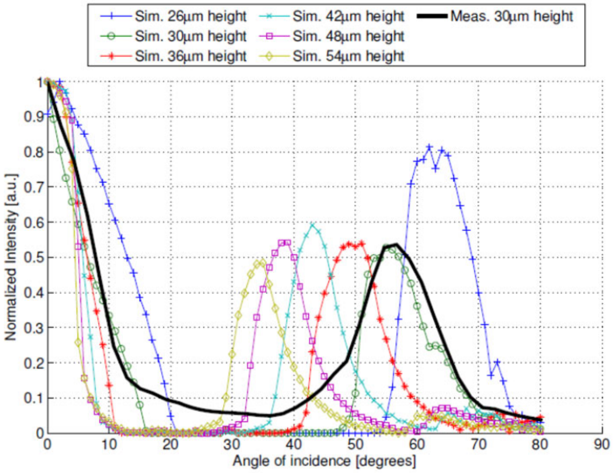
Micro-lens array coupled to SPAD array

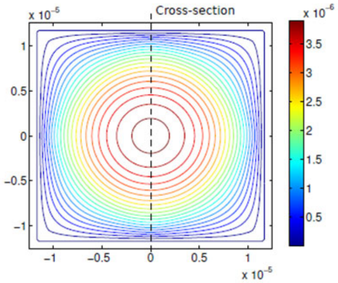
- CMOS SPAD array, 128x128 $6\mu m$ diameter @25 μm pitch – 5% fill factor
- matching polymer plano-convex micro-lens array

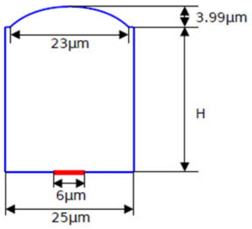


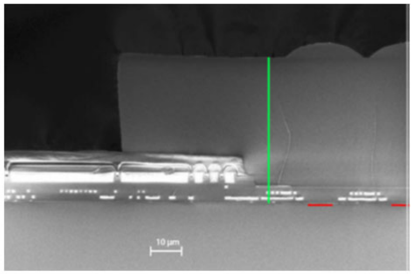






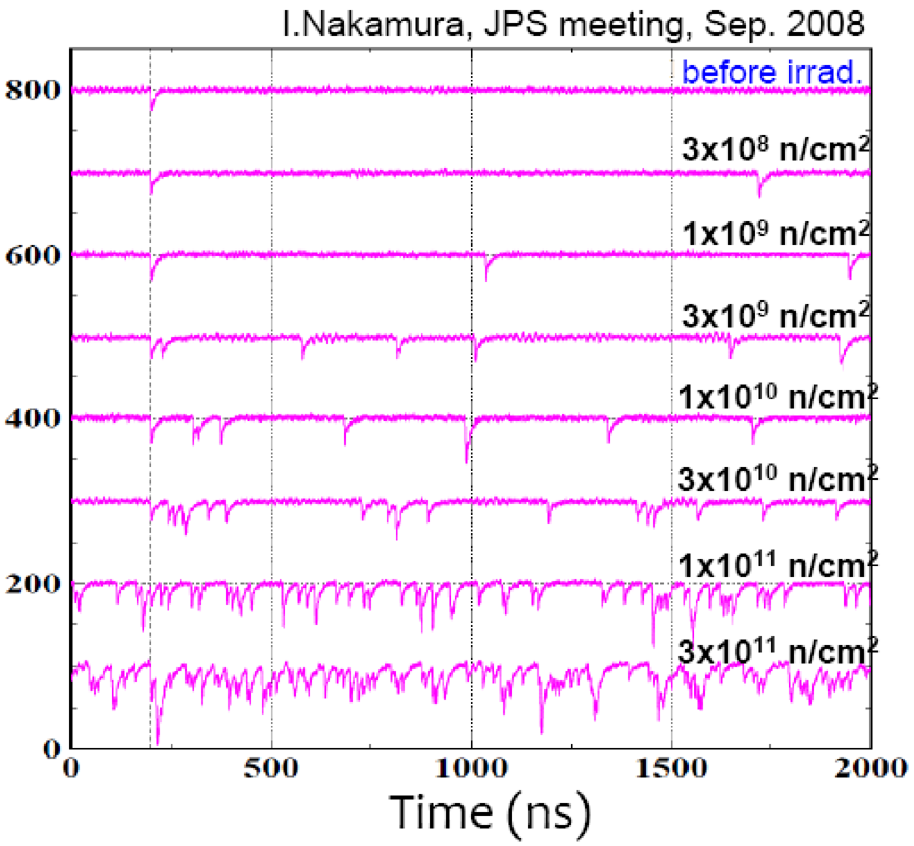






J.M. Pavia et al. Opt.Exp. 22-4(2014)4202

SiPMs: Radiation damage



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

→ Worst than the lowest line

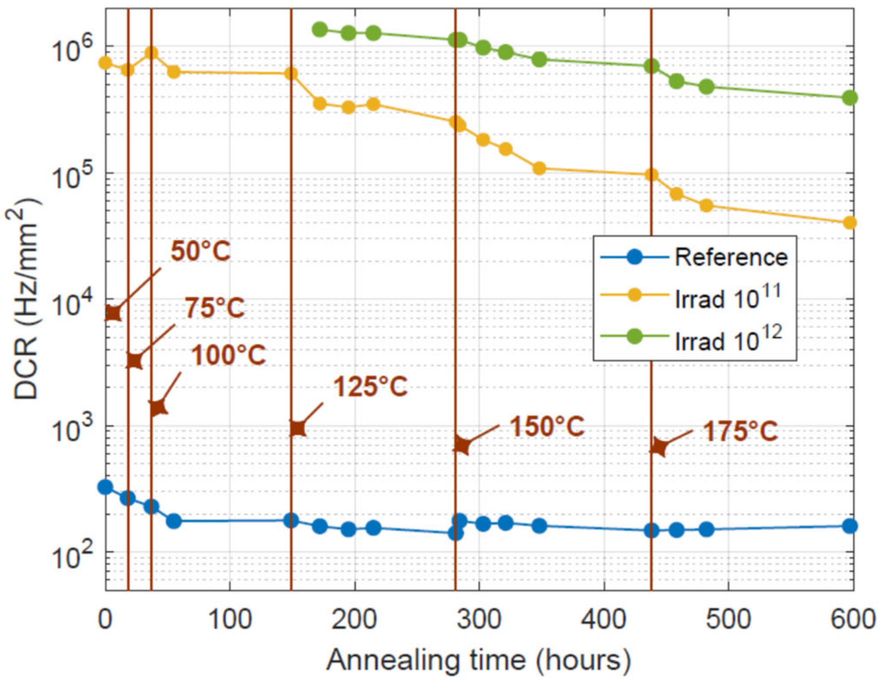
Single photon sensitivity required!

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

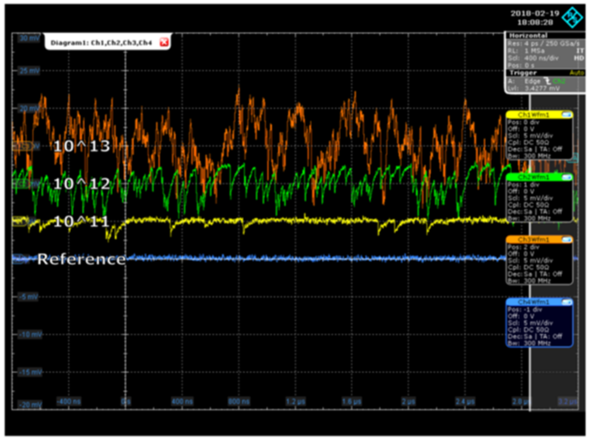
… and more radiation resistant SiPMs…

SiPMs: Radiation damage, annealing at elevated temperatures

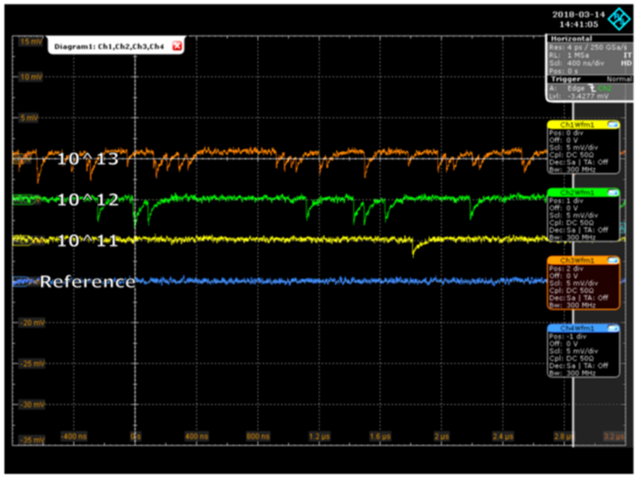
Dark counts at -30C of a Hamamatsu S13360-1350CS SiPMs: non irradiated (blue) and irradiated up to 10^{11} (yellow), 10^{12} (green) and 10^{13} (orange) n_{eq}/cm^2



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



annealing



SiPMs after irradiation; annealing

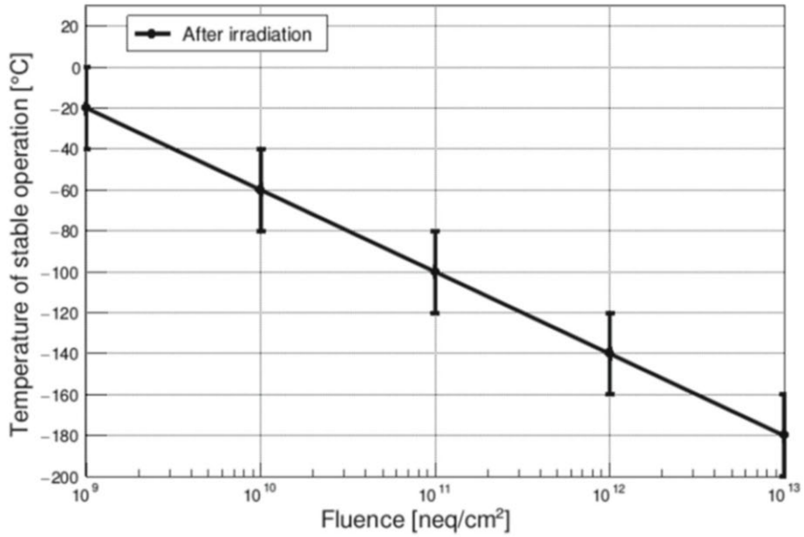


Fig. 13 The temperatures at which single photon can be resolved at an overvoltage of 9 V vs. different irradiation levels. The error bars indicate the 40°C steps in which the measurements were carried out in this work

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

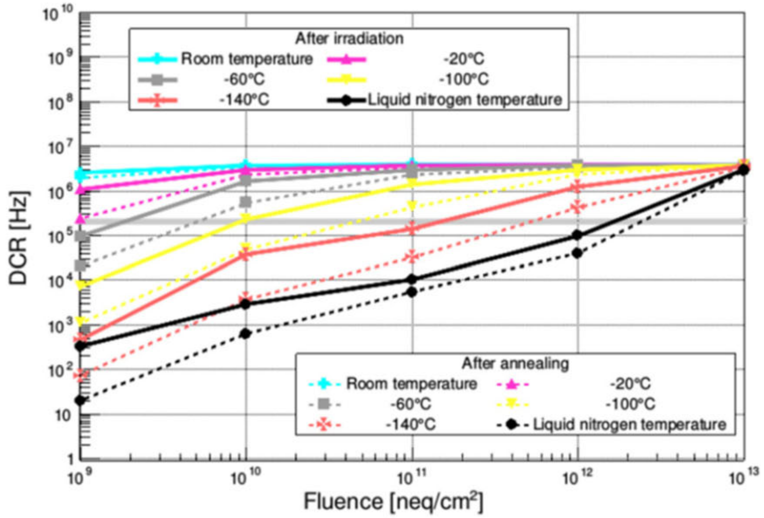


Fig. 17 DCR vs. fluence at different temperatures before and after the annealing and an overvoltage of 9 V. Dashed lines were used to plot data after the annealing, while the gray line indicates the DCR at room temperature and an overvoltage of 9 V measured with the non-irradiated SiPM

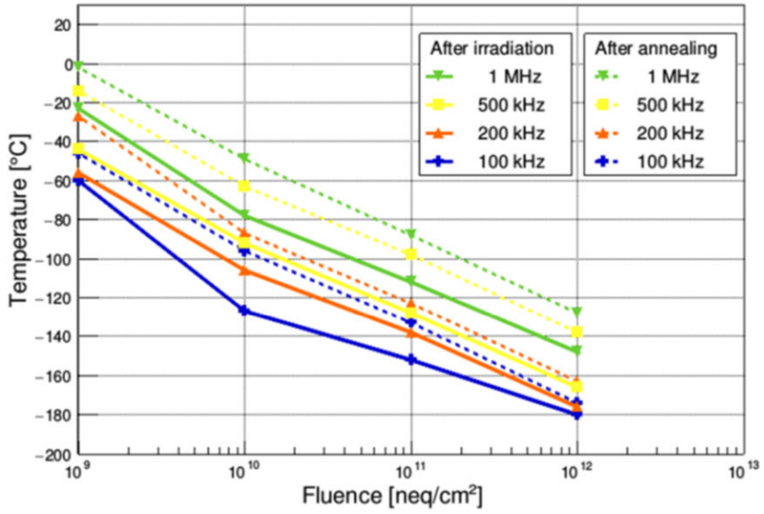
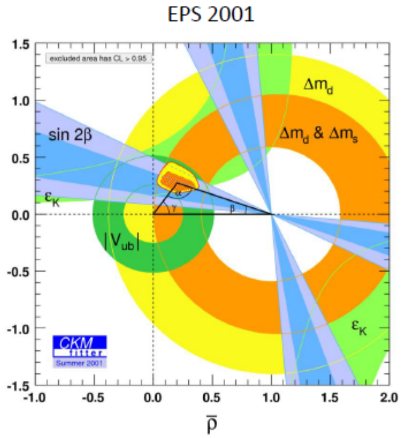
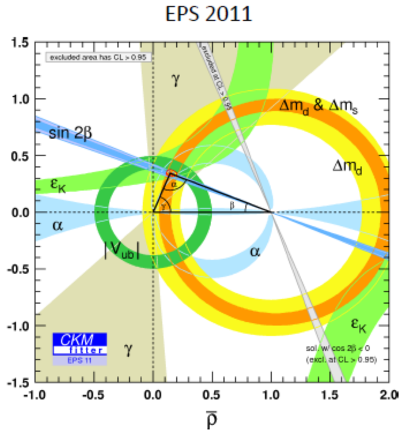


Fig. 18 Temperature required to reach different DCR levels at different fluences. Dashed lines were used to plot data after the annealing. At fluence of 10^{13} neq/cm^2, the DCR never reaches the levels included in this plot (Fig. 16)

Summary


EPS 2001


EPS 2011

- 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!