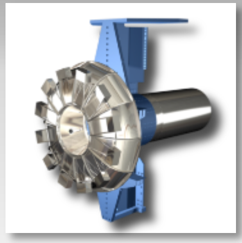
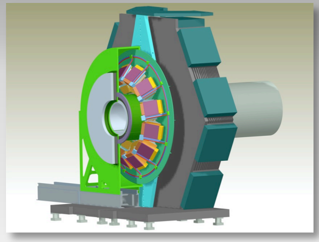
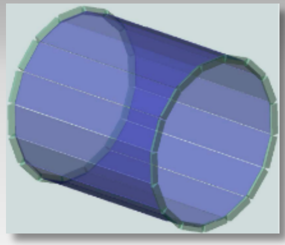
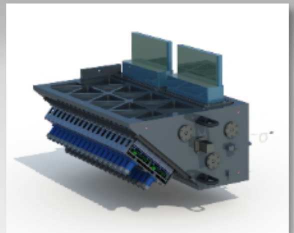
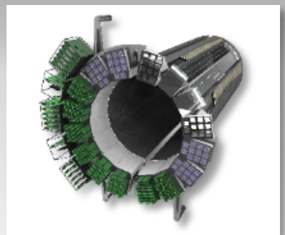
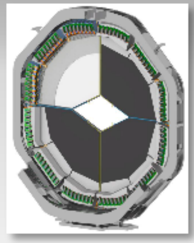
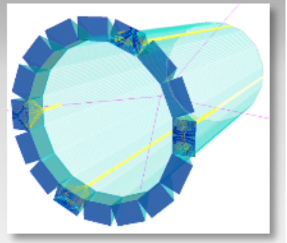








Status of DIRC Detectors

Super c-tau factory workshop, BINP, May 26-27, 2018

Jochen Schwiening

GSI Helmholtzzentrum für Schwerionenforschung GmbH

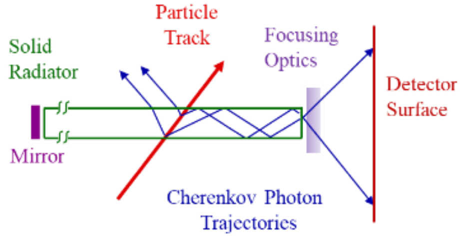
Detection of Internally Reflected Cherenkov Light

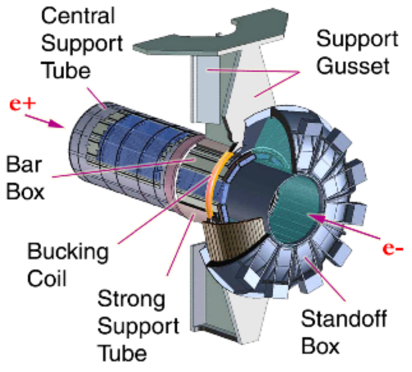
DIRC Concept

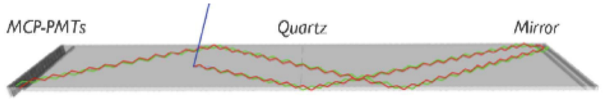
BaBar DIRC Experience

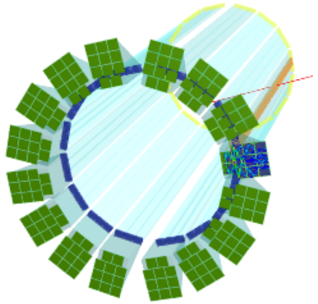
R&D for Future DIRC Counters

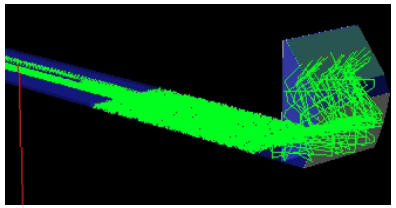
- emphasis on small pixels
- emphasis on fast timing
- future directions







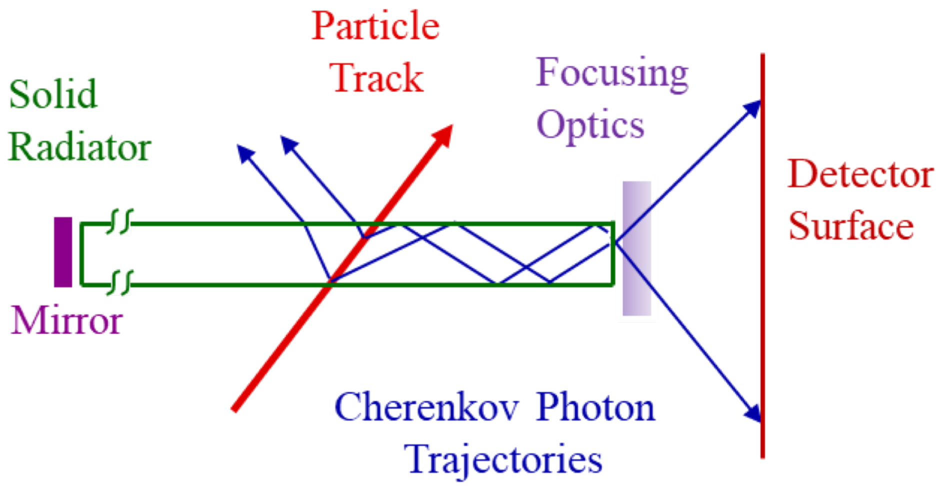




A lot of activity with many interesting results,
too much for a 30 minute talk, for more details see

- *RICH workshop series (most recent: RICH2016, Bled, Slovenia)*
- *DIRC workshop series (most recent: DIRC2017, Giessen, Germany)*

- Charged particle traversing radiator with refractive index n with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos\theta_c = 1/\beta n(\lambda)$.

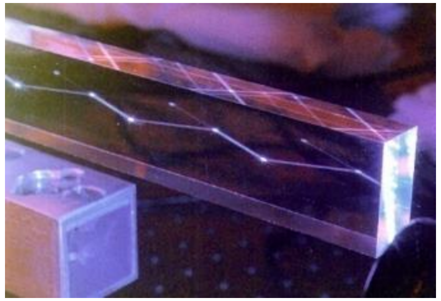


- For $n>\sqrt{2}$ some photons are always totally internally reflected for $\beta \approx 1$ tracks.

- Radiator and light guide: bar, plate, or disk made from Synthetic Fused Silica ("Quartz") or fused quartz or acrylic glass or …

- Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)

→ Major technological challenge for BaBar – is it really possible to efficiently and precisely conserve angle during up to 2000 reflections? ... and maintain that surface quality for 10+ years?

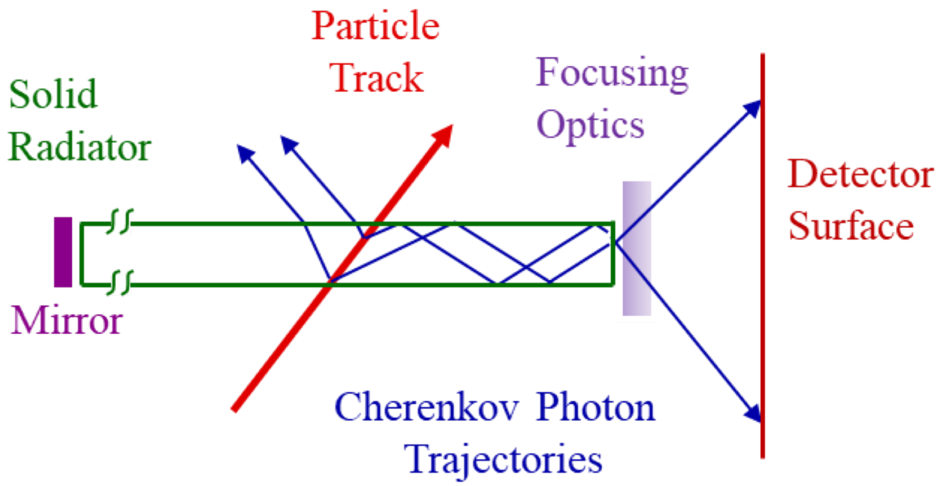


- Mirror attached to one bar end, reflects photon back to readout end.

- Photons exit radiator via optional focusing optics into expansion region, detected on photon detector array.

- DIRC is intrinsically a 3-D device, measuring: x, y, and time of Cherenkov photons, defining θ_c, ϕ_c, $t_{propagation}$.

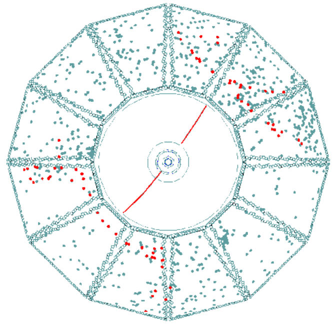
- Ultimate deliverable for DIRC: PID likelihoods.



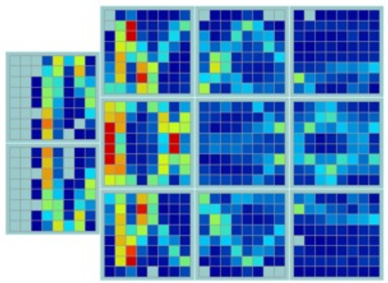
DIRC hit patterns are not typical Cherenkov rings.

Different DIRCs use different reconstruction approaches to provide likelihood for observed hit pattern (in detector space or in Cherenkov space) to be produced by e/μ/π/K/p plus event/track background.

DIRC requires momentum and position of particle measured by tracking system.



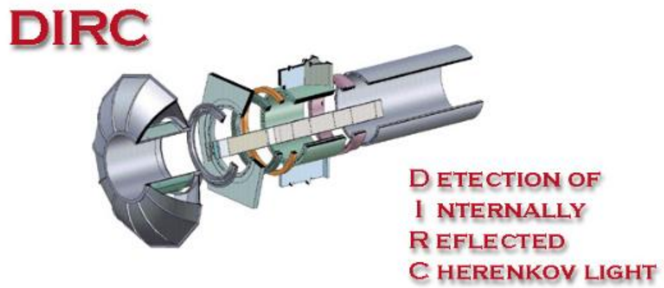
Typical event BaBar DIRC



Accumulated hit pattern PANDA Barrel DIRC

DIRC Timeline

DIRC used for the first time in BABAR as primary hadronic particle ID system, flavor tagging, π/K ID to 4 GeV/c.



- 1992: first publication of DIRC concept§.
- 1993-1996: progression of prototypes and DIRC R&D.
- Nov 1994: decision in favor of DIRC for hadronic PID for BABAR.
- Nov 1998: installed part of DIRC; start of cosmic ray run, commissioning run.
- April 1999: BABAR moves into beam line, added 4 more bar boxes.
- Nov 1999: all 12 bar boxes installed, start of first physics run.
- early 2000s: interest in DIRCs for future experiments (SuperB, Belle II, PANDA) → start of R&D.
- April 2008: last event recorded with BABAR.
- Oct 2013: call for proposals for reuse of BABAR DIRC radiator bars.
- 2016: installation of TOP counter into Belle II, first beam data expected in 2019.
- 2018: installation of DIRC counter into GlueX, first beam data expected in late 2018.

§*B. Ratcliff, SLAC-PUB-6047 (Jan. 1993)*

DIRC thickness:

8 cm radial incl. supports

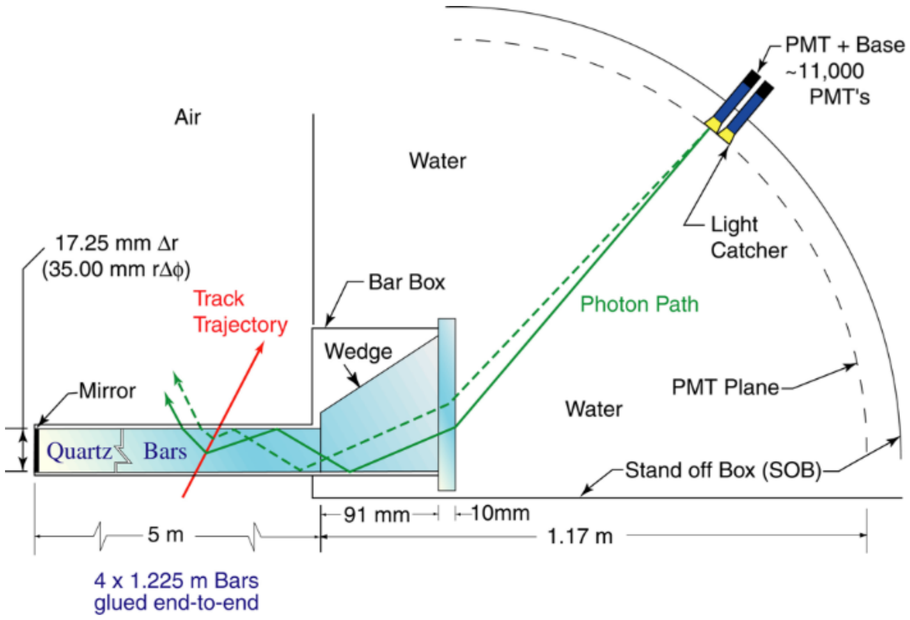
19% radiation length

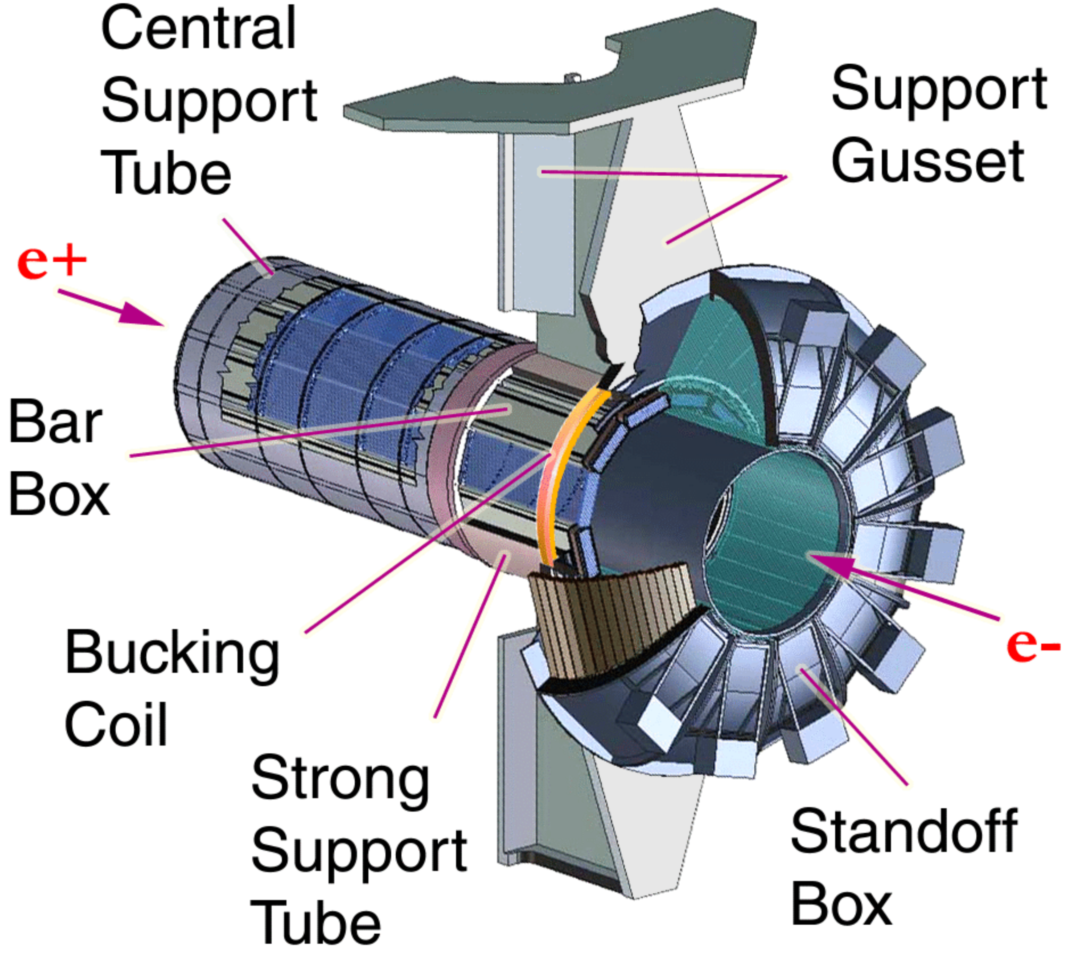
at normal incidence

DIRC radiators cover:

94% azimuth,

83% c.m. polar angle





BABAR DIRC COMPONENTS

Photon detectors:
~11,000 standard 1" PMTs with light concentrators

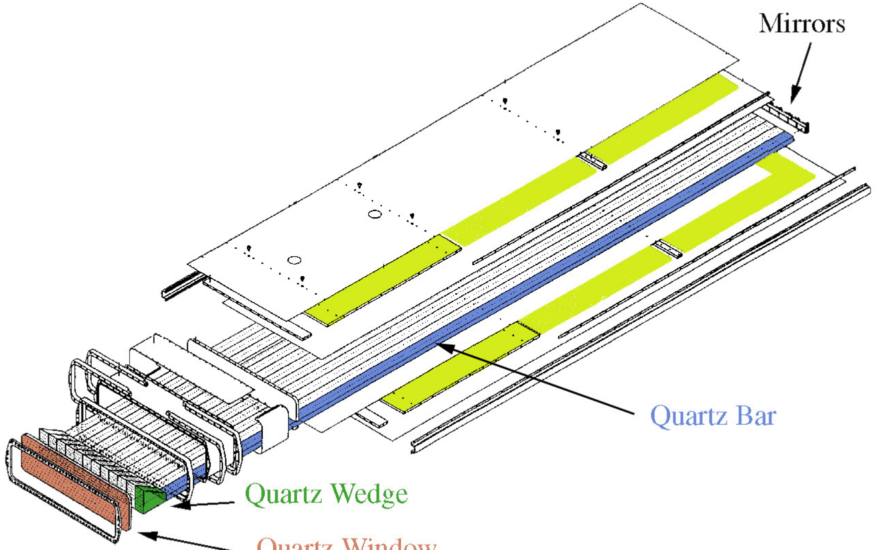
Expansion volume:
Large tank with ~6,000 liters ultra-pure water

Pinhole focusing:
Size of bar small compared to size of expansion volume

Radiators:
144 long bars, made of 576 short bars
synthetic fused silica (Spectrosil)
5A *rms* polish, square, sharp corners

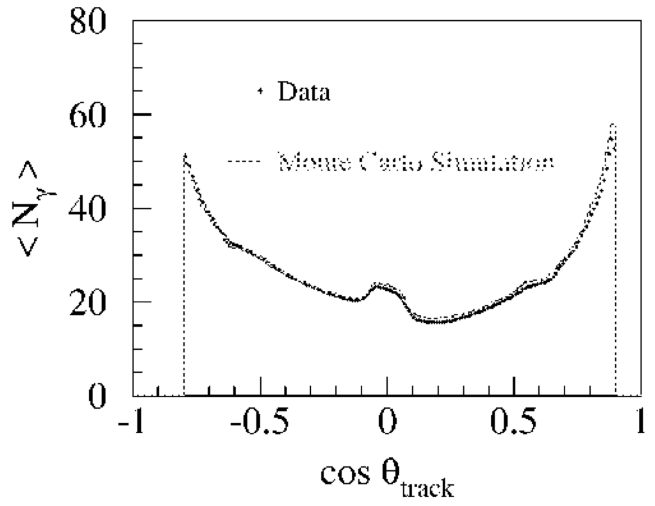
Bar box: 12 bar boxes in BABAR
12 long (4.9m) bars per box
150µm air gap between bars
dry nitrogen flow

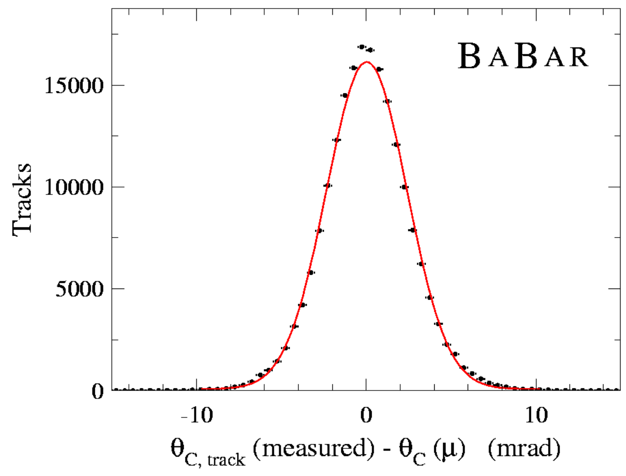
Long bar: 4 short (1.225m) bars
Mirror on forward end
Wedge on readout end

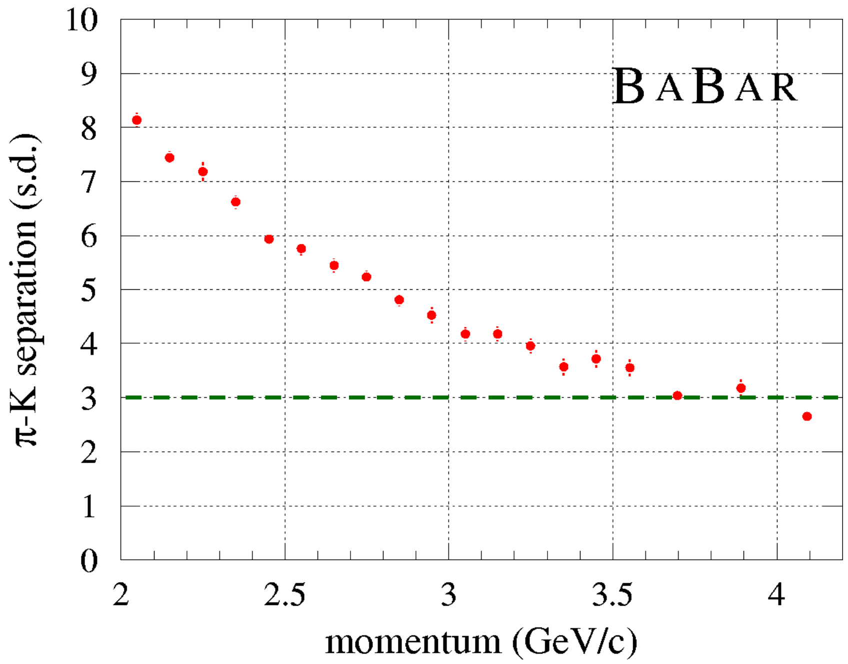


BABAR DIRC PERFORMANCE

Single photon timing resolution	1.7ns
Single photon Cherenkov angle resolution	~10mrad
Photon yield	20-60 photons per track
Track Cherenkov angle resolution	2.4mrad (di-muons)
π/K separation power	4.3σ @ 3GeV/c, ~3σ @ 4GeV/c







Excellent performance: very reliable, robust, easy to operate, significant in almost all BABAR physics results.

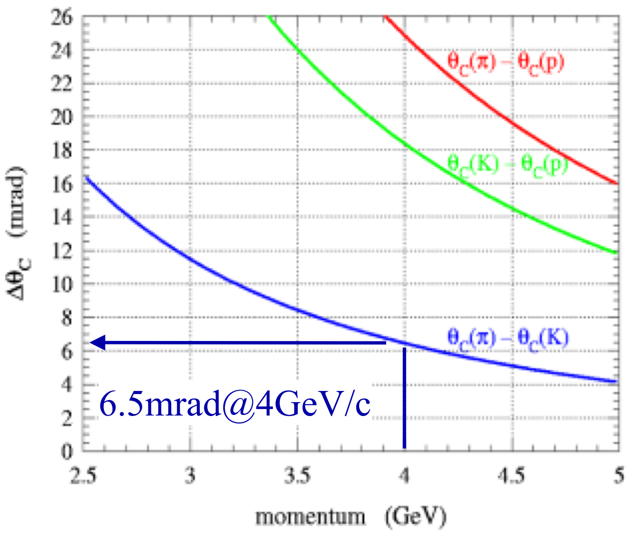
A lot of R&D steps were needed to go from the proof of the principle to a final DIRC detector

1. Penetrate iron or not ? A crucial decision contributing to DIRC success.
2. Define pin hole camera optics, and select photon detector.
3. Electronics development.
4. Transmission through Fused silica bars and optical glues.
5. Radiation hardness studies of Fused silica and various other materials.
6. Effect of pollution from various materials on the internal reflection coefficient.
7. Transmission study of water.
8. Water corrosion study of PMT glass and other materials sitting in highly purified water.
9. Effect of large photon fluxes over many years on optical epoxies.
10. Does Fused silica scintillates ?
11. Periodic variation of refraction index within Fused silica.
12. Water tightness of bar boxes.
13. Study of mechanical precision of bars.
14. Study of edge quality of bars.
15. Develop a procedure to minimize mechanical stresses on bars when in bar boxes in various positions.
16. Software: (a) data analysis and (b) MC codes.
17. DIRC background studies in BaBar.
18. How to keep bars in a clean environment for many years ?

J. Va'vra, "Development of focusing DIRC detectors", Fermilab Research Techniques Seminar, May 22, 2018.

IMPROVING ON BABAR DIRC

As early as 2000 R&D efforts underway to improve future DIRCs.



PID performance largely driven by track Cherenkov angle (θ_C) resolution.
Required resolution defined by refractive index of radiator.

Example: π/K separation in synthetic fused silica <n>≈1.473
→ 6.5 mrad π/K difference in θ_C at 4 GeV/c;
→ need ~ 2.2 mrad resolution for 3 s.d. separation.

Cherenkov angle resolution determined by single photon resolution
(scales with $1/\sqrt{N_\gamma}$) and correlated terms (mult. scattering, etc).

BABAR-DIRC Cherenkov angle resolution: 9.6 mrad per photon → 2.4 mrad per particle

Limited in BABAR by:			Improve for future DIRCs via:
▪ size of bar image	~4.1 mrad	→	▪ focusing optics
▪ size of PMT pixel	~5.5 mrad	→	▪ smaller pixel size
▪ chromaticity (n=n(λ))	~5.4 mrad	→	▪ better time resolution
	9.6 mrad	→	4-5 mrad per photon → 1–2 mrad per particle?

SUPERB, GLUEX
BELLE II &
PANDA

IMPROVING ON BABAR DIRC

As early as 2000 R&D efforts underway to improve future DIRCs.

- Push DIRC π/K separation to higher momentum by improving single-photon θ_C resolution
- Investigate alternative radiator shapes (plates, disks), possible use as endcap device.
- Make DIRC less sensitive to background (main issue in BaBar and for SuperB)
  - decrease size of expansion volume (replace pinhole focusing with lens/mirror optics);
  - use photon detectors with smaller pixels and faster timing;
  - make it possible to place photon detector inside magnetic field.

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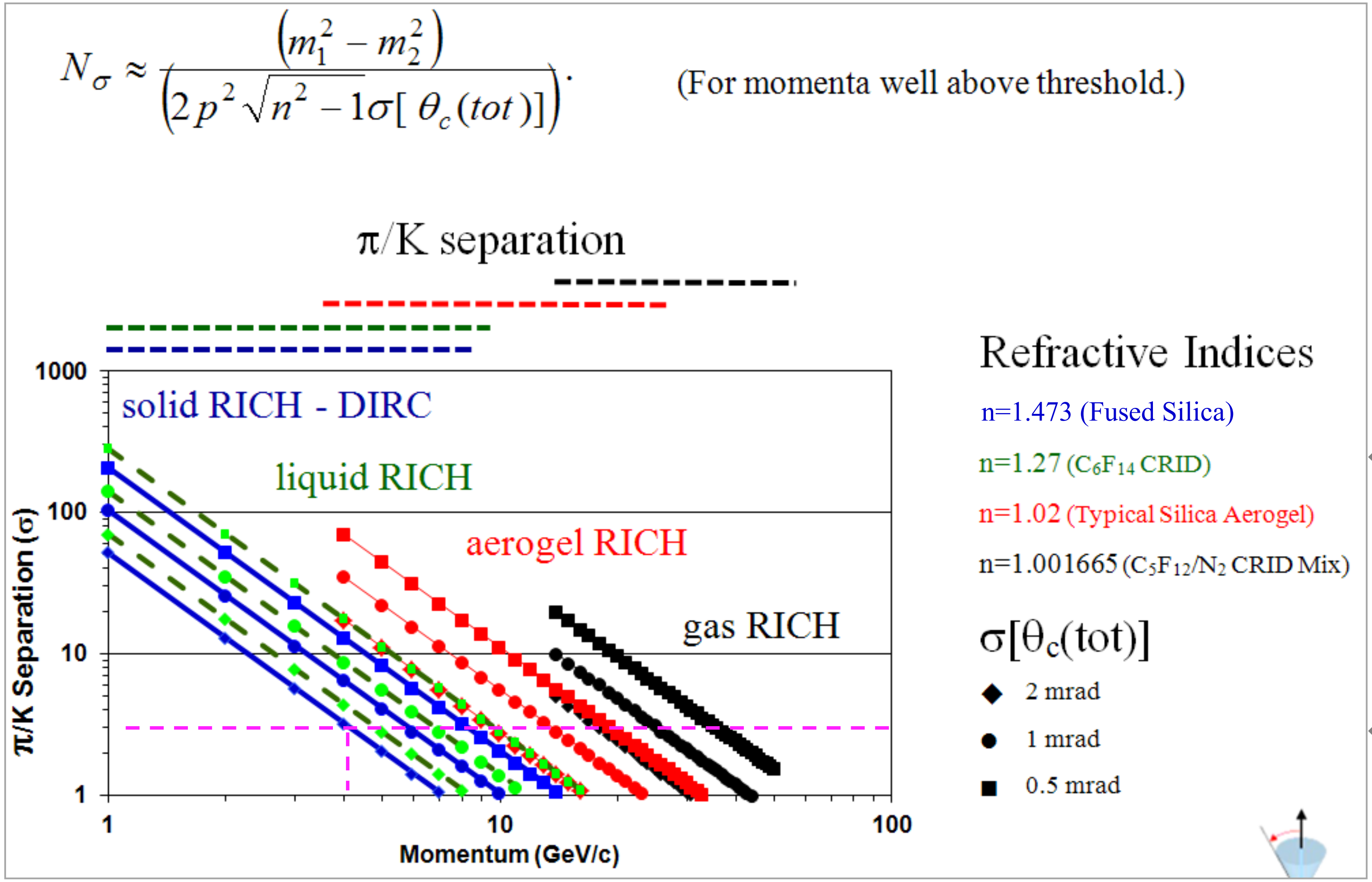
SUPERB, GLUEX
BELLE II &
PANDA

DIRC LIMITS



$$N_\sigma \approx \frac{(m_1^2 - m_2^2)}{(2p^2\sqrt{n^2-1}\,\sigma[\theta_c(tot)])}.$$

radiator materials

angular error per track

DIRC provides good π/K separation potential significantly beyond 4 GeV/c.

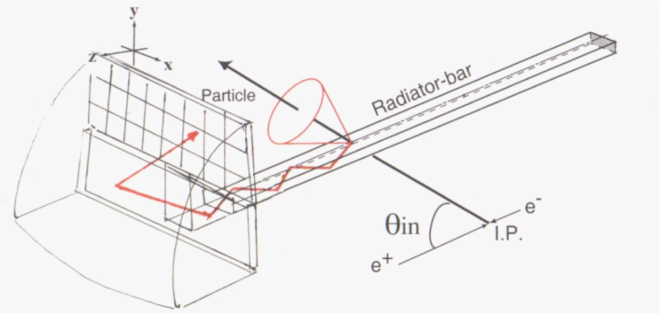
Large refractive index limits effective momentum range to below 10 GeV/c.

based on B. Ratcliff RICH2002

FUTURE DIRC COUNTERS

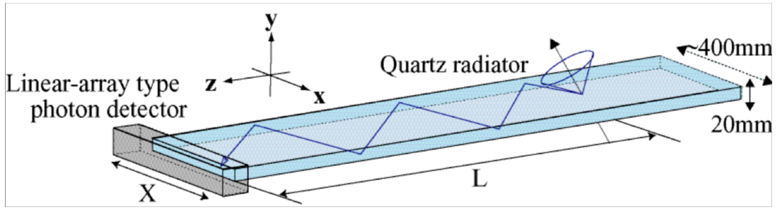
Initial next-generation DIRC R&D directions can roughly be divided into three imaging approaches using different focusing optics

- moderate timing, (very) good spatial resolution
  examples: fDIRC, GlueX DIRC, early PANDA Barrel DIRC
  100-200 ps photon timing, array of (~6mm) 2D pixels → PID primarily based on spatial imaging



Early SuperB fDIRC design

- very fast timing, moderate/poor spatial resolution
  examples: early Belle II TOP design, early PANDA Disc DIRC design
  ~50 ps photon timing, (~5mm) 1D pixels → PID primarily based on time imaging



Early Belle II TOP design

- very fast timing, very good spatial resolution
  examples: "ultimate fDIRC", EIC High-Performance DIRC
  <100 ps photon timing, large array of (~3mm) 2D pixels → PID uses full 3D imaging

Final designs for Belle II TOP and PANDA DIRCs are hybrids derived from these initial approaches.

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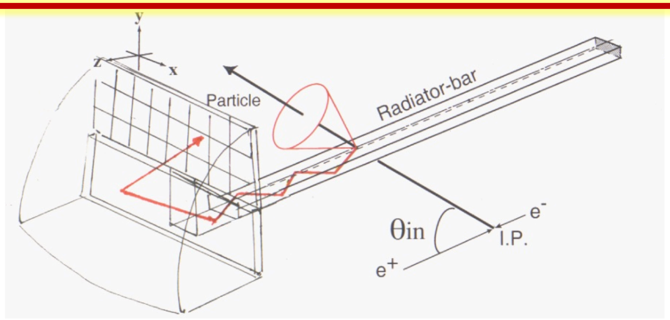

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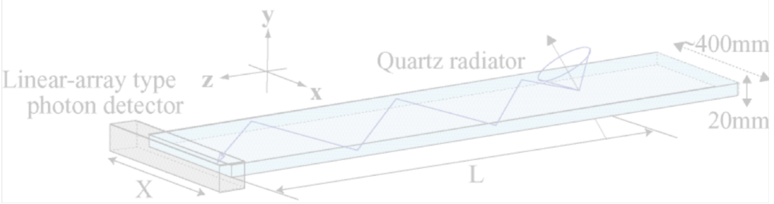

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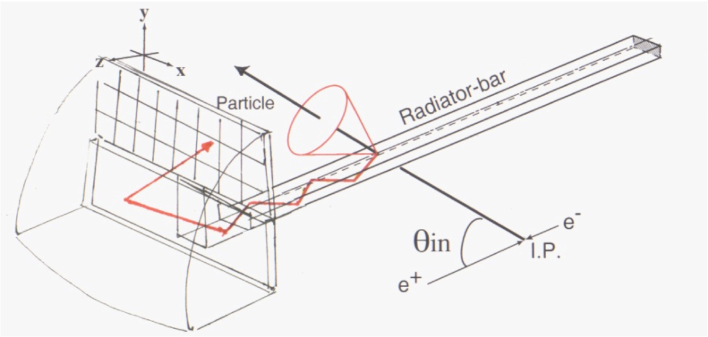
FDIRC R&D AT SLAC

Primary DIRC R&D goals for SuperB:

maintain DIRC PID performance for much higher backgrounds at 100x luminosity

reuse existing BaBar DIRC bar boxes



Main source of background in BaBar DIRC: large expansion volume (6000 l water)

→ replace water tank with compact expansion volume (25x smaller)

→ maintain angular resolution by using focusing and smaller pixels with 10x better timing precision

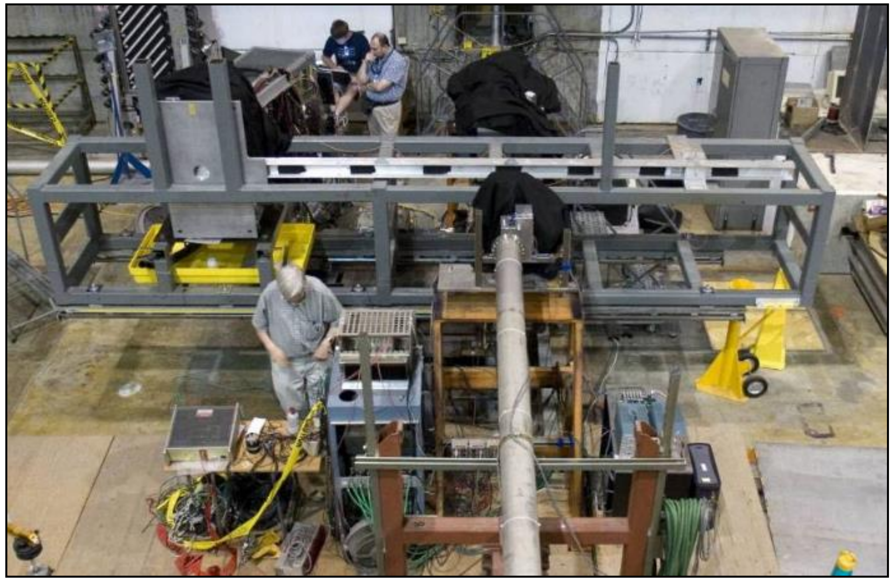
First prototype:

single 3.7 m long BaBar DIRC bar in 10 GeV electron beam
oil tank expansion volume (KamLand mineral oil)
spherical mirror (SLD CRID) for focusing
mix of multi-anode sensors (MaPMTs, MCP-PMTs)
mix of CAMAC and early waveform sampling readout

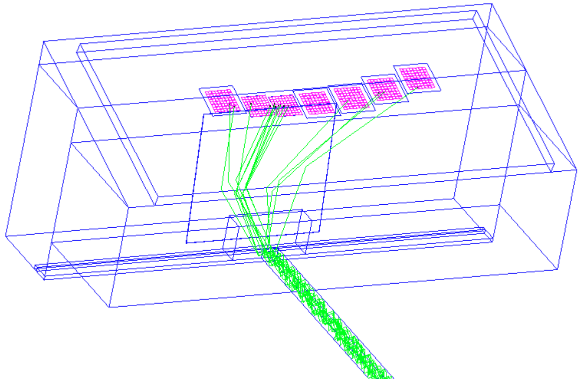
Second prototype:

complete BaBar DIRC bar box in Cosmic Ray Telescope
synthetic fused silica focusing block
cylindrical mirror (coating on block) for focusing
MaPMTs as sensors
waveform sampling electronics

For more details on fDIRC R&D see: J. Va'vra, "Development of focusing DIRC detectors", Fermilab Research Techniques Seminar, May 22, 2018.



- Single 3.7m-long BABAR-DIRC bar,
  compact, oil-filled expansion volume,
  focusing mirror (CRID),
  array of H-8500/H-9500 MaPMTs and
  Planacon 85011 MCP-PMTs,
  fast readout electronics
  (both CAMAC and early BLAB).
- Photon yield consistent with BABAR DIRC.
- Demonstrated that the chromatic error of θ_C can be corrected using fast timing.
  (Shown at RICH 2007.)
- Single-photon θ_C resolution 5.5 – 7 mrad after chromatic correction
  for long paths (consistent with G4 simulation).
- Successful proof of principle for Focusing DIRC.
- Basis for SuperB FDIRC design.



J. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, K. Suzuki, J. Schwiening, J. Uher, L.L. Ruckman, G. Varner, and J. Va'vra,

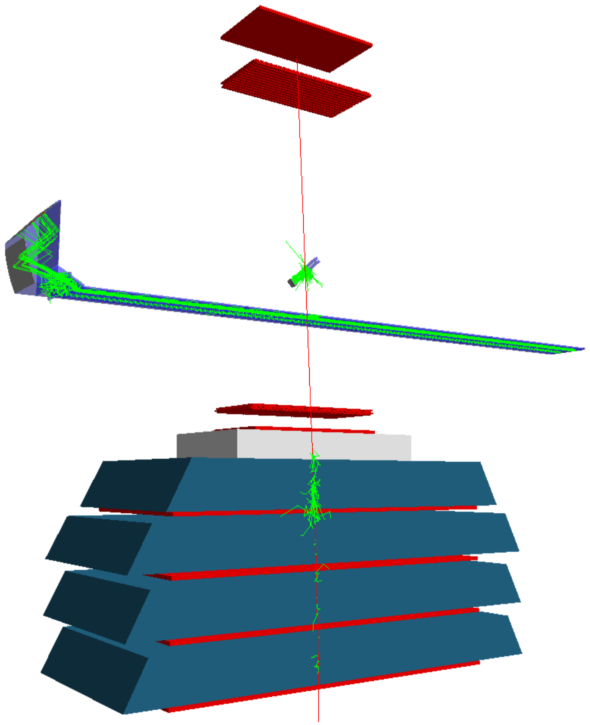
SLAC-PUB 12236 & 12803, NIMA 595 (2008) 104

SECOND FDIRC PROTOTYPE AT SLAC

D.A. Roberts et al., "Results from the FDIRC prototype", RICH 2016 and Nucl. Instr. Meth. A, 766, 2014.

Significant upgrade of optics and electronics for second prototype.

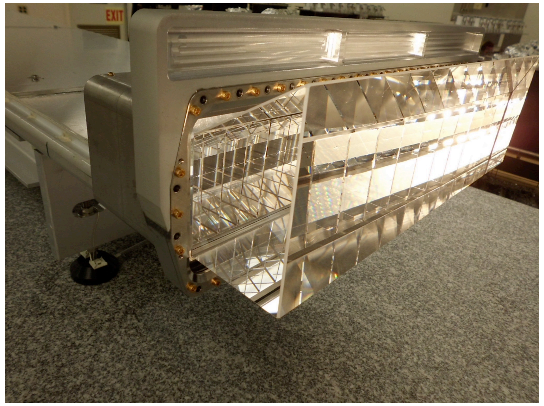
- New solid fused silica expansion volume (FBLOCK) with cylindrical focusing.
- Additional wedge to couple BaBar DIRC bar box to FBLOCK.
- Waveform sampling readout electronics (IRS2, early version of Belle II TOP readout).
- Array of 12 Hamamatsu H8500 MaPMTs (8*8 pixels, 6mm pitch, 140ps TTS).

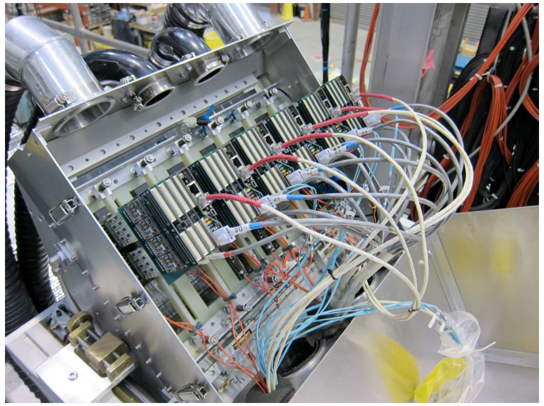


Detailed study of SuperB fDIRC phase space using hardened cosmic rays at SLAC.

Clearly demonstrated resolution improvement from chromatic correction with fast timing.

Achieved required resolution for SuperB fDIRC.





J. Va'vra, "Development of focusing DIRC detectors", Fermilab Research Techniques Seminar, May 22, 2018.

SuperB FDIRC

D.A. Roberts et al., "Results from the FDIRC prototype", RICH 2016 and Nucl. Instr. Meth. A, 766, 2014.

Focusing DIRC (FDIRC):

Intended as barrel PID system for SuperB experiment in Italy (cancelled).

Important constraint:

BABAR DIRC bar boxes to be reused, readout outside magnetic field.

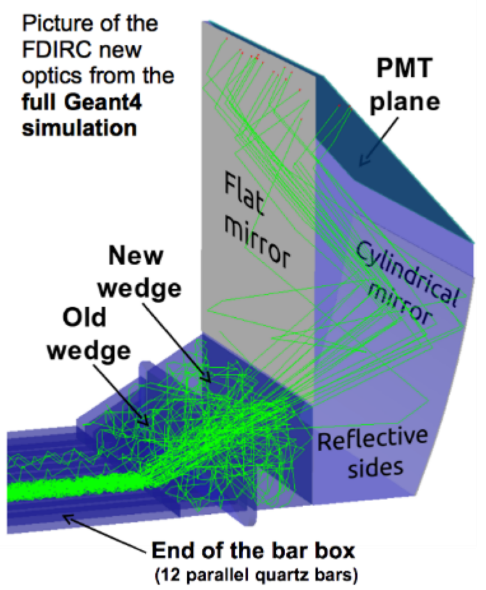
Expected much higher backgrounds at $10^{36}/cm^2 \cdot s$ (100 times BABAR luminosity)

→ decrease size of expansion volume (main source of background in BABAR DIRC).

Design based on R&D at SLAC; new optics (replace tank with 12 cameras) and electronics

Complete redesign of the photon camera (SLAC-PUB-14282)

- True 3D imaging using:
  - 25× smaller volume of the photon camera
  - 10× better timing resolution to detect single photons
- Optical design based entirely on solid fused silica to avoid water or oil as optical medium
- Array of MaPMTs (H8500) for photon detection.



In 2012 the Italian government unfortunately cancelled the SuperB project.

However, this was not the end of the story for the BaBar DIRC bar boxes or for the fDIRC optics design...

GLUEX DIRC

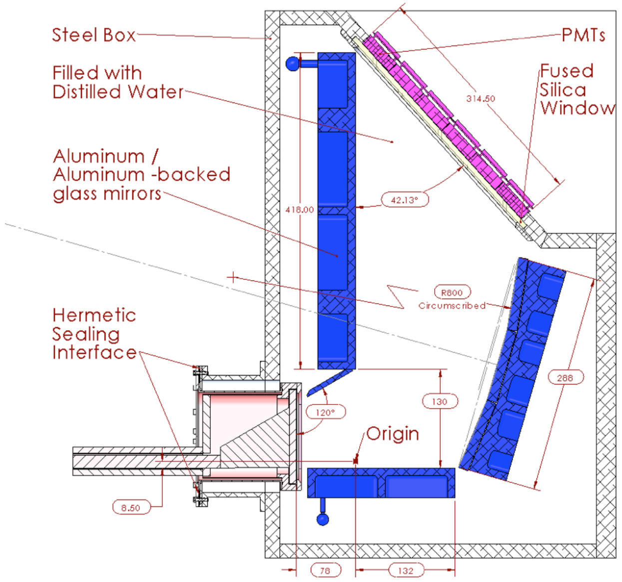
J. Stevens, DIRC2017

After cancellation of SuperB project, BaBar DIRC bars became available to other experiments.

PID upgrade for GlueX experiment in Hall D at Jefferson Lab to extend physics reach.

Future GlueX PID requirements similar to proven fDIRC/BaBar DIRC performance

goal: π/K separation with 3 s.d. up to ~4 GeV/c

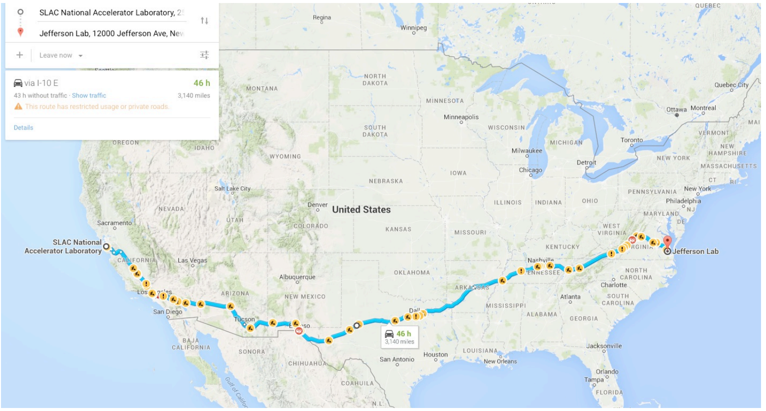


GlueX proposed plan to reuse four unmodified BaBar DIRC bar boxes

- adapt fDIRC expansion volume design (simplify, reduce cost)
- equip with new multianode sensors and readout (use CLAS12 solution)
- install as forward PID wall in GlueX for strangeness program

Major technological challenge: how do you safely transport ~20 yr old, fragile bar boxes from SLAC to JLab without risking damage to edges or glue joints?

First bar box transported successfully in the fall of 2017,
remaining three bar boxes started their journey this week

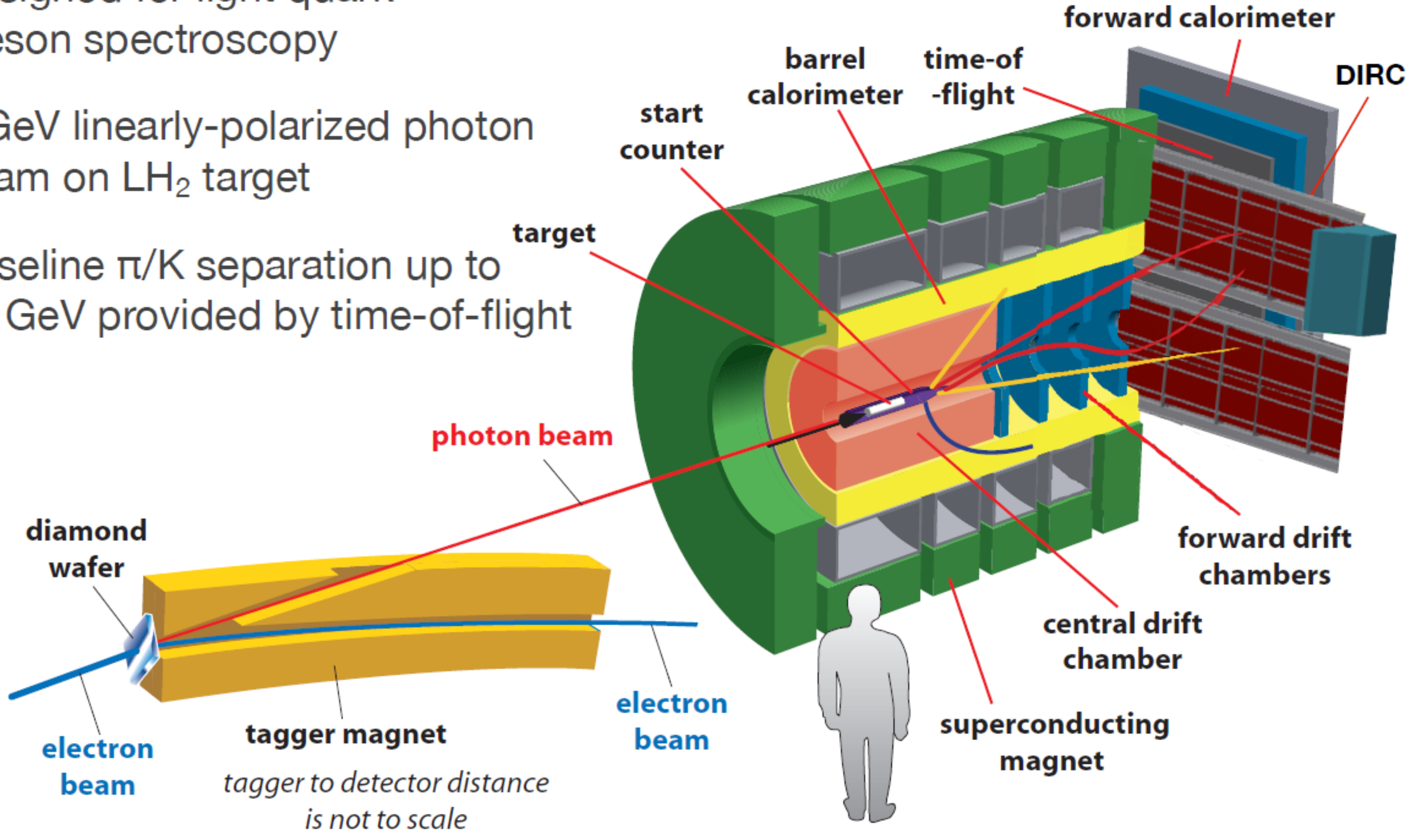


Installation into GlueX planned for this summer, first data in the fall,
first full physics run with DIRC in the fall of 2019.

J. Stevens, DIRC2017

GlueX at JLab

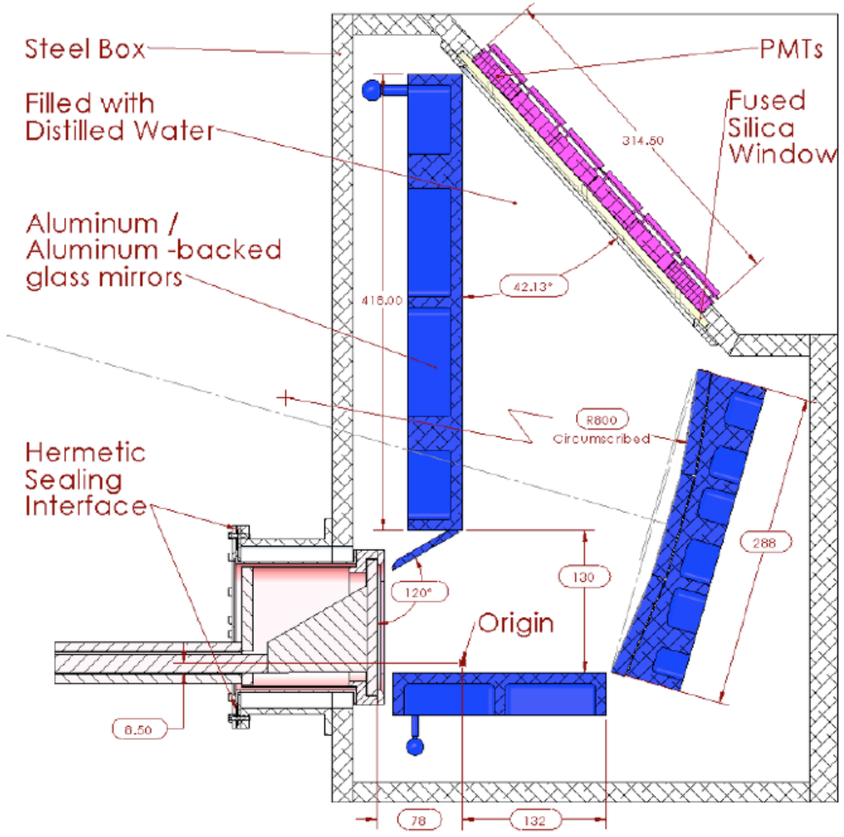
- Designed for light quark meson spectroscopy
- 9 GeV linearly-polarized photon beam on LH_2 target
- Baseline π/K separation up to ~2 GeV provided by time-of-flight



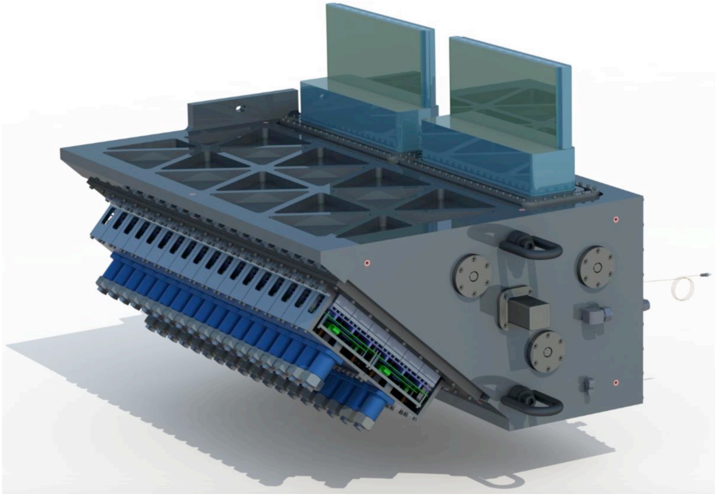
J. Stevens, DIRC2017

Optical box design

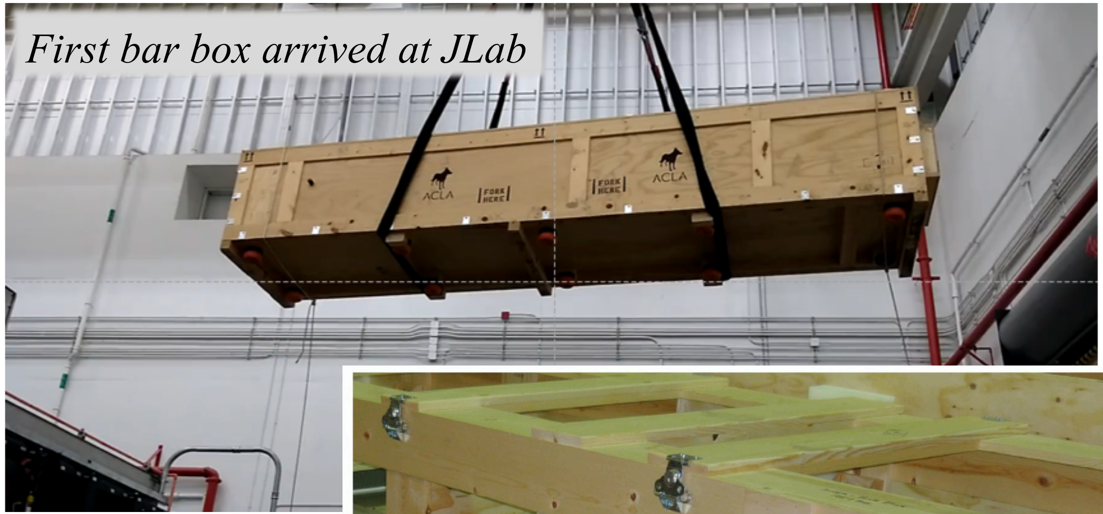
- Design based on SLAC FDIRC prototype
  - Replace fused silica block from FDIRC prototype with mirrors contained in distilled water
  - Replace of cylindrical mirror with 3-segment flat mirror
- Similar coupling of bar boxes to water volume as used at BaBar

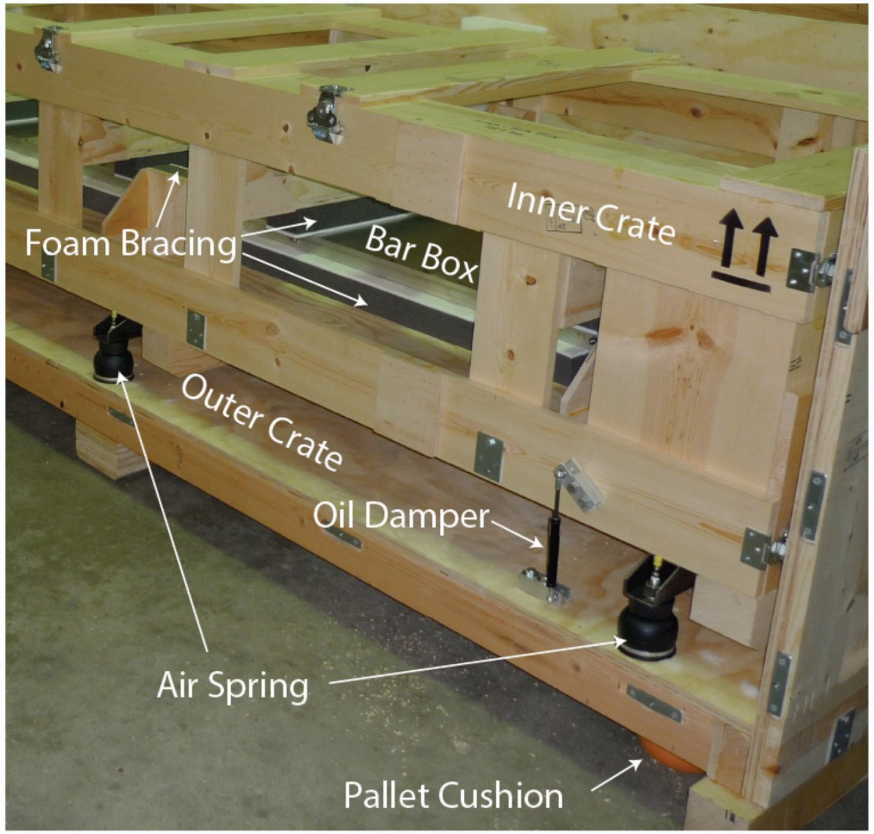


Significant design simplification and cost reduction by replacing fused silica block with DI water and cylindrical mirror with set of flat mirrors.



A. Ali, DPG 2018



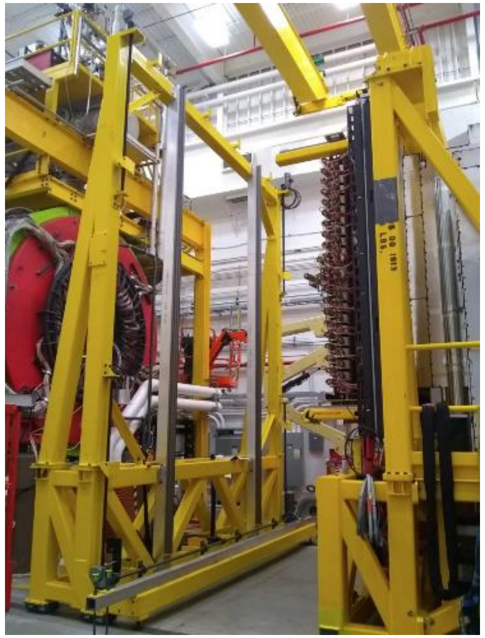


Successful transport of fragile bar box from SLAC to JLab.

Elaborate transport bar box-in-crate-in-crate design.

Very close, continuous monitoring of bar box on truck;
shock, temperature, N_2 gas flow, camera inside crate observing glue joints

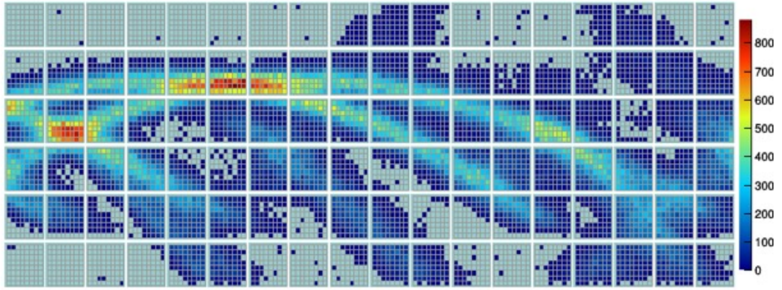
(check out the GlueX DIRC twitter feed at https://twitter.com/GlueX_DIRC for latest news on second trip)



Support structure in Hall D

A. Ali, DPG 2018
R. Dzhygadlo, priv. comm.

Sensor: Hamamatsu H12700 MaPMT, ~6mm pixel pitch coupled to fused silica window with silicone cookies.



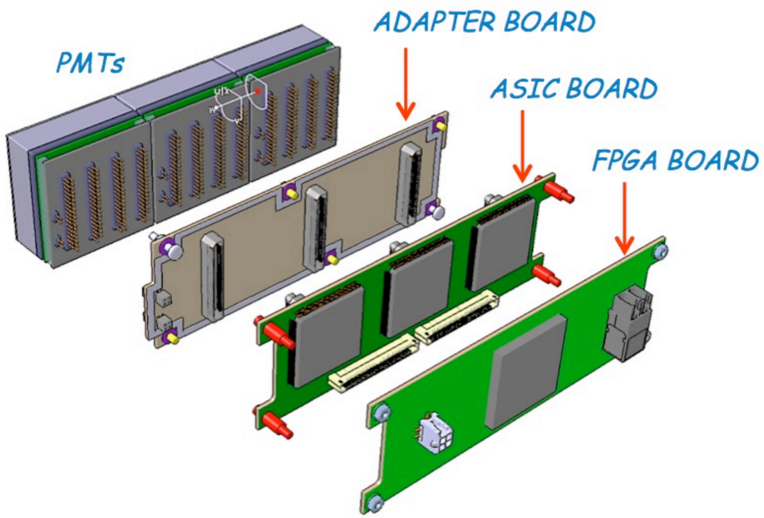
Geant4 hit pattern, 4GeV/c kaons

Readout electronics: MAROC3 ASIC, timing: 1ns/count

Reconstruction:

- BaBar-like geometric (lookup-table) algorithm using primarily spatial information, time to suppress background
- Belle II-like time-based algorithm in preparation (currently using simulation to create PDFs)

Geant4 simulation predicts performance better than BaBar DIRC and fDIRC due to higher PDE of sensor array, exceeding GlueX requirements.



Eagerly awaiting first beam data in fall of 2018.

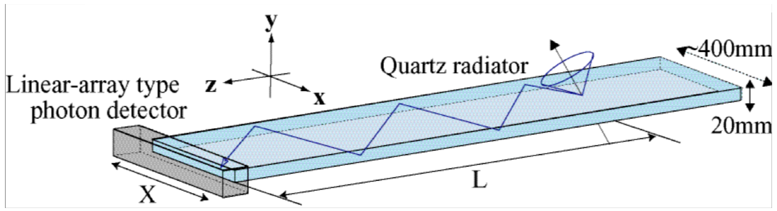
Future DIRC Counters

Initial next-generation DIRC R&D directions can roughly be divided into three imaging approaches using different focusing optics

- moderate timing, (very) good spatial resolution
  examples: fDIRC, GlueX DIRC, early PANDA Barrel DIRC
  100-200 ps photon timing, array of (~6mm) 2D pixels → PID primarily based on spatial imaging

Early SuperB fDIRC design

- very fast timing, moderate/poor spatial resolution
  examples: early Belle II TOP design, early PANDA Disc DIRC design
  ~50 ps photon timing, (~5mm) 1D pixels → PID primarily based on time imaging



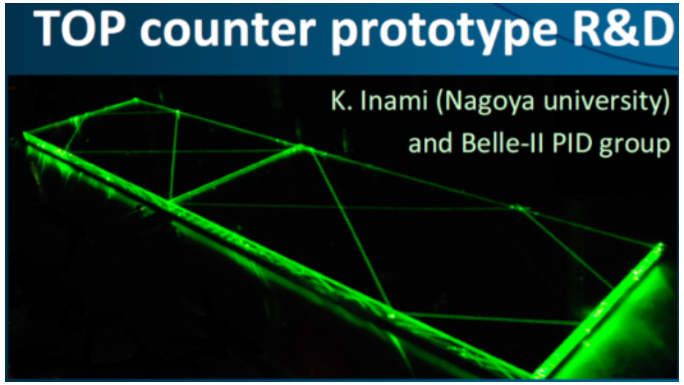
Early Belle II TOP design

- very fast timing, very good spatial resolution
  examples: “ultimate fDIRC”, EIC High-Performance DIRC
  <100 ps photon timing, large array of (~3mm) 2D pixels → PID uses full 3D imaging

Final designs for Belle II TOP and PANDA DIRCs are hybrids derived from these initial approaches.

Belle II TOP

K. Inami, RICH2010



Upgrade of Belle detector for high-luminosity Belle II experiment;

replace Aerogel Cherenkov Counter in barrel with time-of-propagation (TOP) DIRC;

design goal 4σ π/K separation up to 4 GeV/c;

use plates (~40 cm x 250 cm), synthetic fused silica.

TOP concept combines information from photon TOP with time-of-flight of particle.

→ Major technological challenge for Belle II:

Entire TOP system had to fit inside the EM calorimeter, no space for large expansion volume, tight fit, no easy access.

Initial design was pure 2D TOP detector

high precision timing + one space coordinate (linear array) – ultimately rejected.

Simulation studies and beam test resulted in alternative 3D TOP designs:

segmentation of barrel into a "TOF zone" and "TOP zone"

with focusing optics and second space coordinate (X, Y of hit, 4x4 version of SL10) – ultimately rejected;

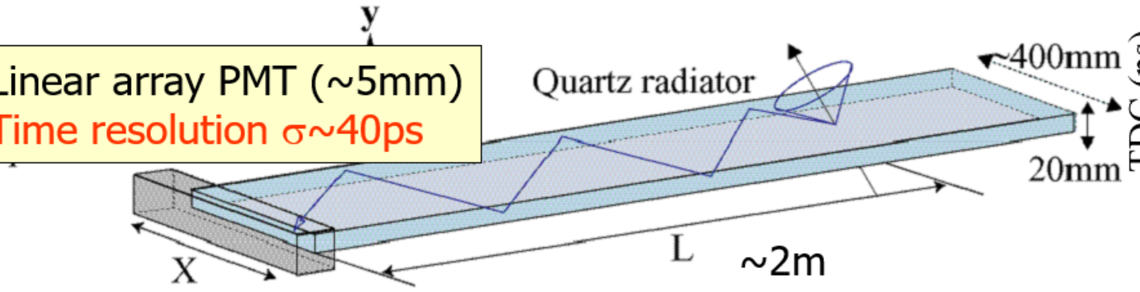
add imaging: small fused silica expansion volume with 4x4 version of SL10 – ultimately built.

K. Inami, RICH2007

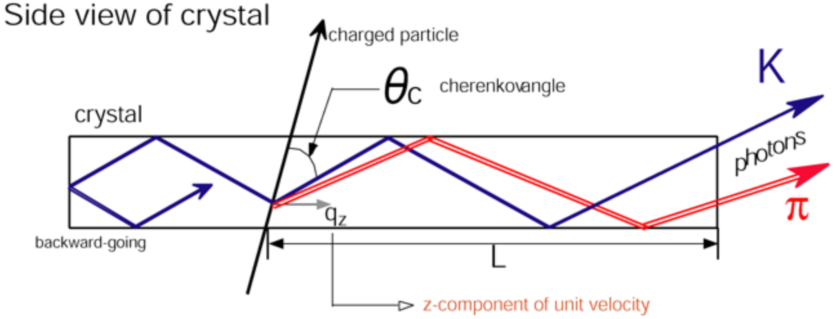
TOP counter

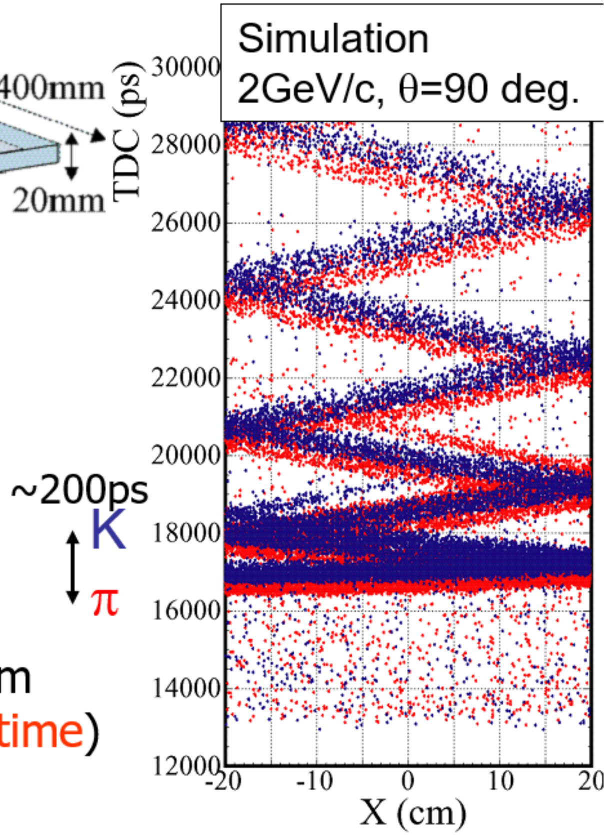
- 2D position information → Position+Time
  - Compact detector!

Linear array PMT (~5mm)
Time resolution σ~40ps



Side view of crystal





Different opening angle for the same momentum
→ Different propagation length(= propagation time)

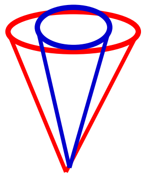
+ TOF from IP works additively.

2007/10/15-20 RICH07 4

Ring image of TOP counter

Ring image animation

Top view

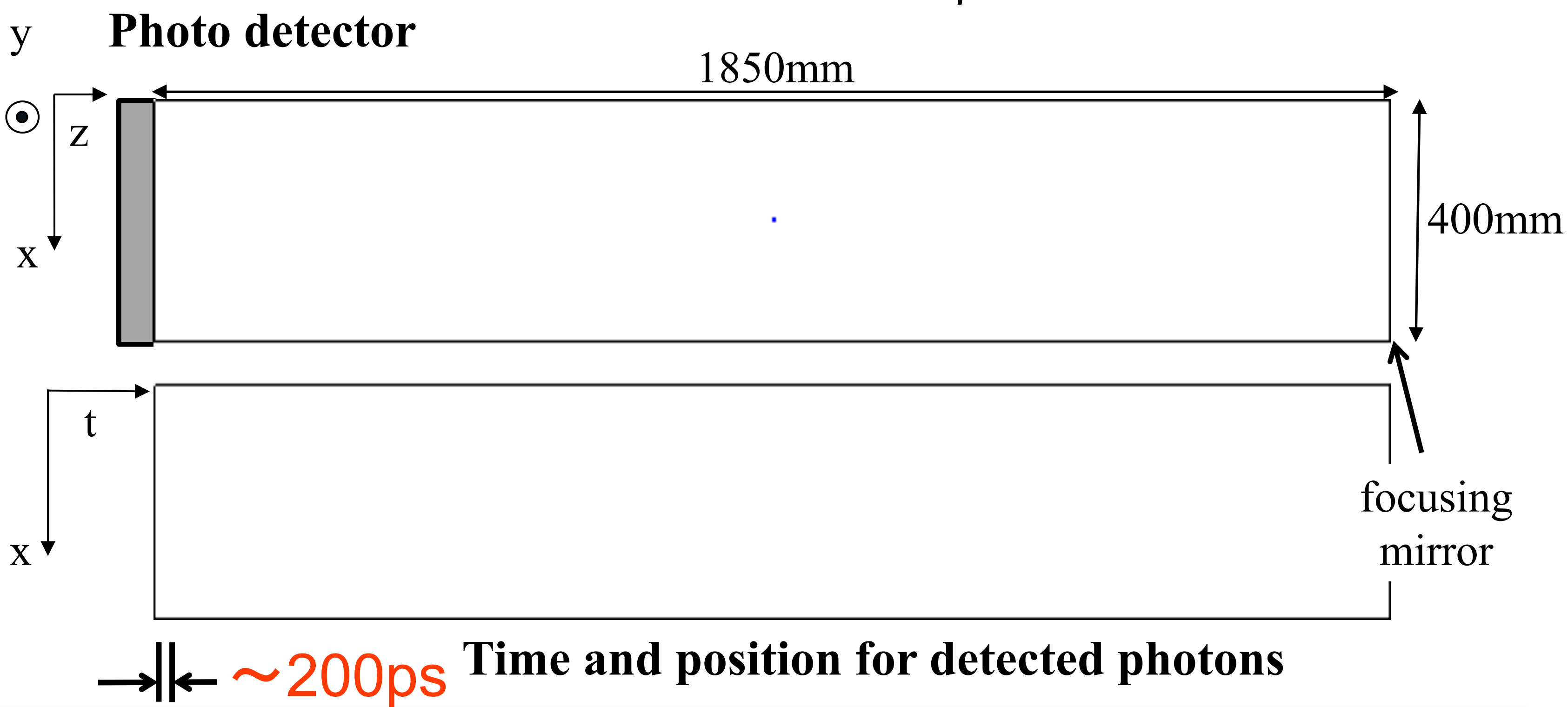


π/K

$\rightarrow \beta$ are different

$$\cos\theta_c = \frac{1}{n\beta}$$

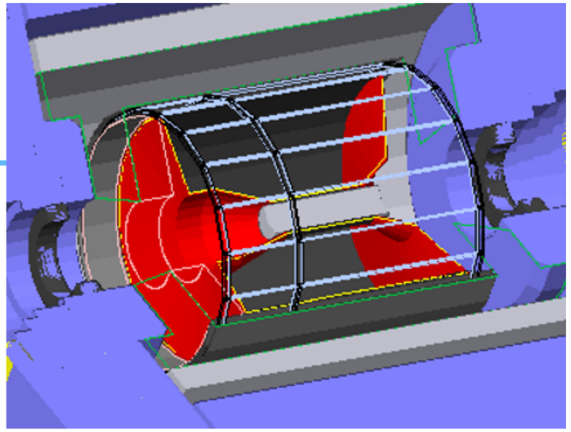
Ring image has high sensitivity to incident position and angles of particles.



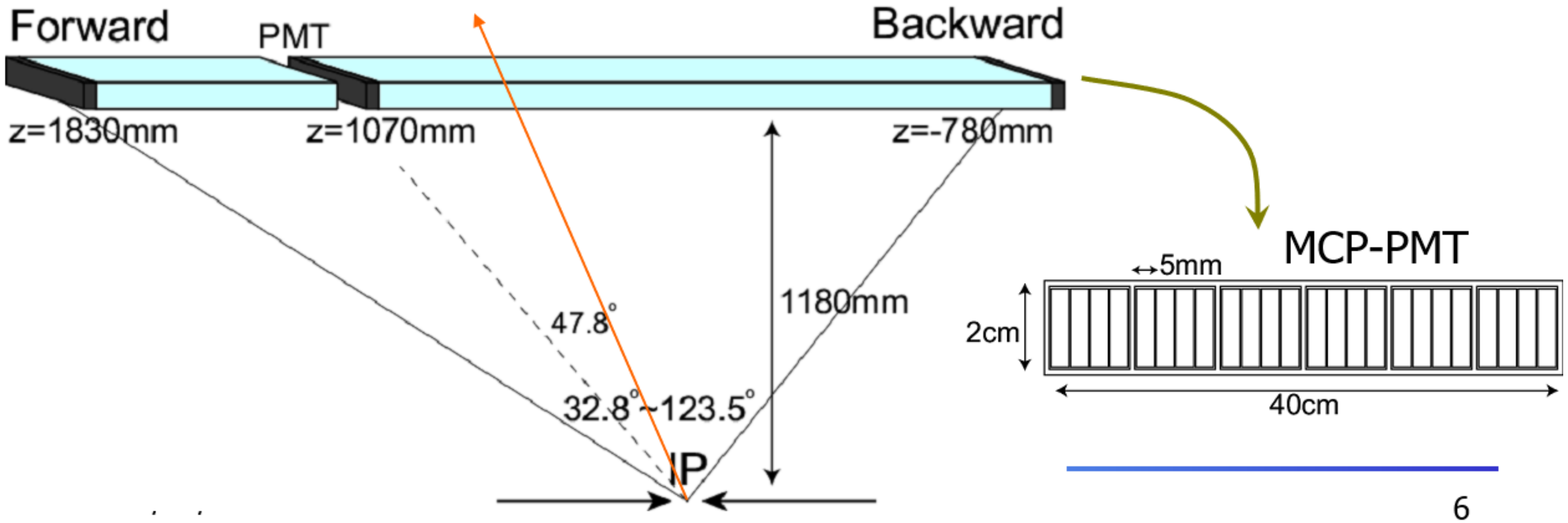
QFPU 2013 Y. Arita, *Belle II TOP counter*

K. Inami, RICH2007

Design



- Quartz: 255cm^L x 40cm^W x 2cm^T
  - Cut at 47.8deg.
    to reduce chromatic dispersion
- Multi-anode MCP-PMT
  - Good time resolution (<~40ps), Linear array (5mm pitch)
  - Three readout planes

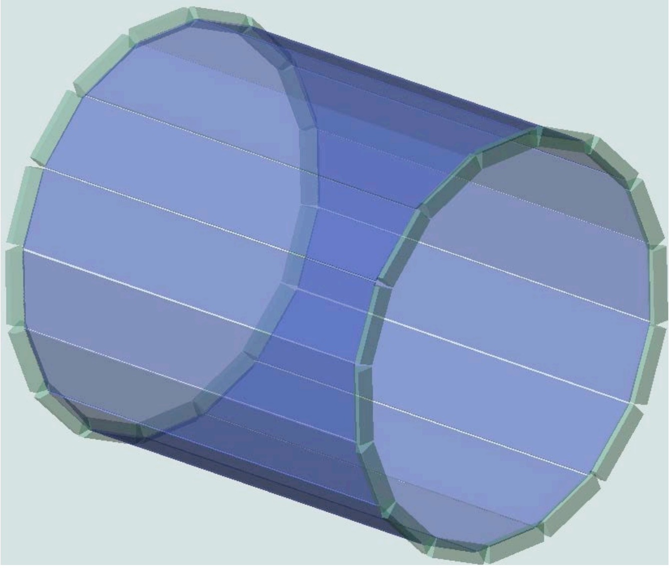


6

BELLE II TOP

P. Krizan, DIRC2013
B. Wang, TIPP2017

Design ultimately incorporated the advantages of a moderate pixel segmentation in x & y (~6mm pitch), combined it with fast timing (~100ps per photon).



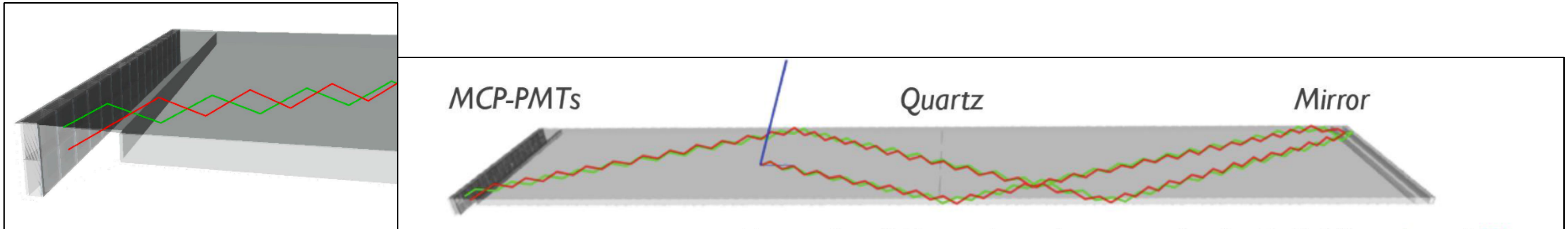
Radiator: fused silica plate 45cm wide, 2cm thick, 250cm long (2 glued pieces).
(Significantly lower fabrication cost per area than narrow bars, first plate DIRC.)

TOP barrel formed by 16 plates.

Small expansion volume (10cm depth), spherical mirror on forward end.

Photon detector: array of 32 Hamamatsu SL-10 MCP-PMTs per sector (4x4 pixels each).

Readout: IRSx waveform sampling ASIC, <100ps timing precision.



Example of Cherenkov-photon paths for 2 GeV/c $\pi^\pm$ and $K^\pm$.

Imaging design with 2D sensor array and small expansion has many advantages (redundancy, robustness, sensor lifetime).

M. Staric, RICH2010
M. Staric et al. NIMA 639 (2011) 252
R. Dzhygadlo, TIPP2017

Belle II TOP developed innovative time-based imaging concept.

Extended likelihood probability density functions (PDF):

photon time of propagation in plate, mirror, and prism

for every pixel

derived either from simulation (for prototype tests)

or analytically (required for experiment).

For each pixel with hit, compare hit time with PDF for each particle type.

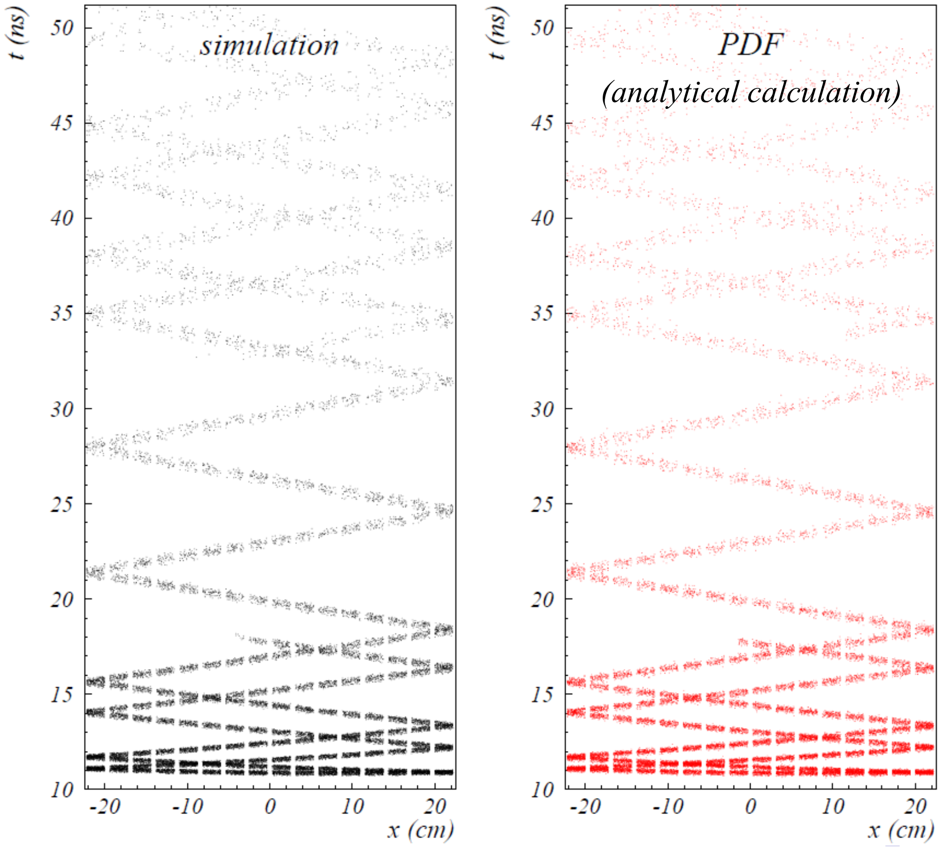
Full likelihood:

$$L_H = \prod_N \mathrm{pdf}(x_i, y_i, t_i; H) \times P_{N_0}(N)$$

Describes complex features of the hit pattern very well.

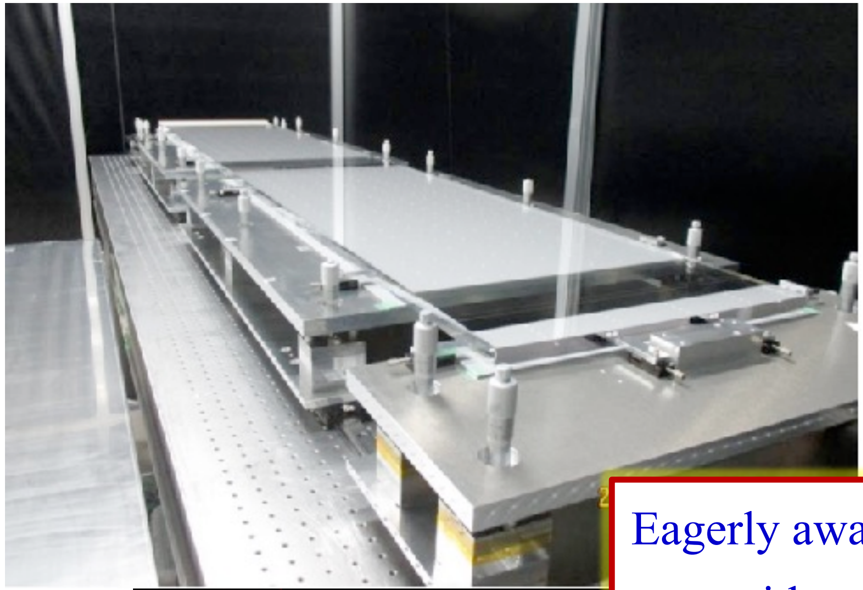
(Analytical PDFs still need to be fully validated

with experimental data, expect to see more soon (already in Elba?).)

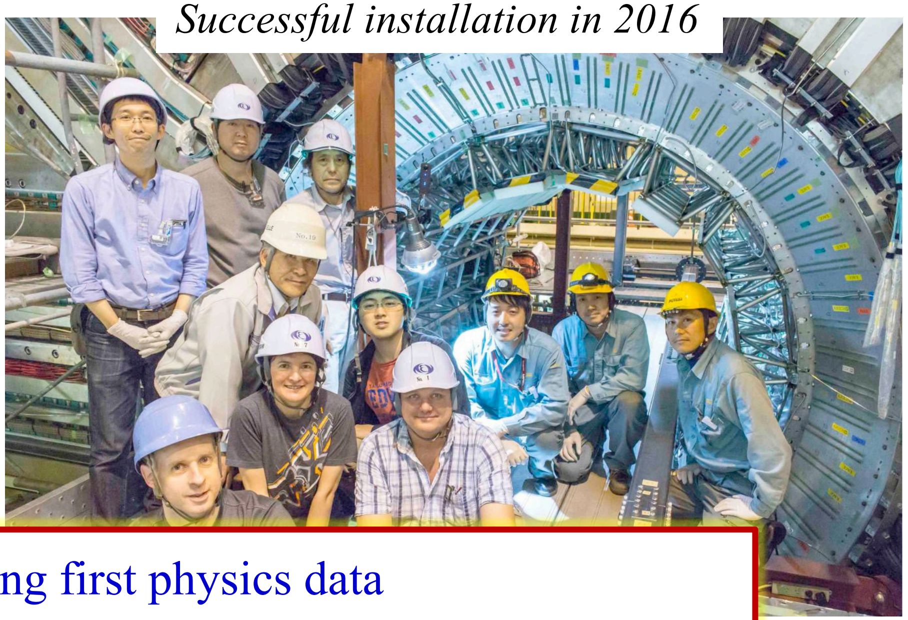


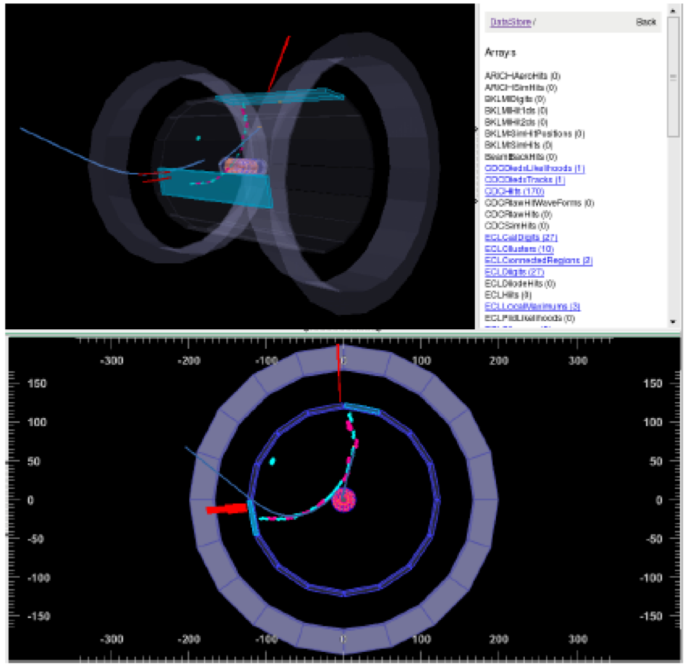
B. Wang, TIPP2017
K. Inami, DIRC2017

Optics on gluing stage



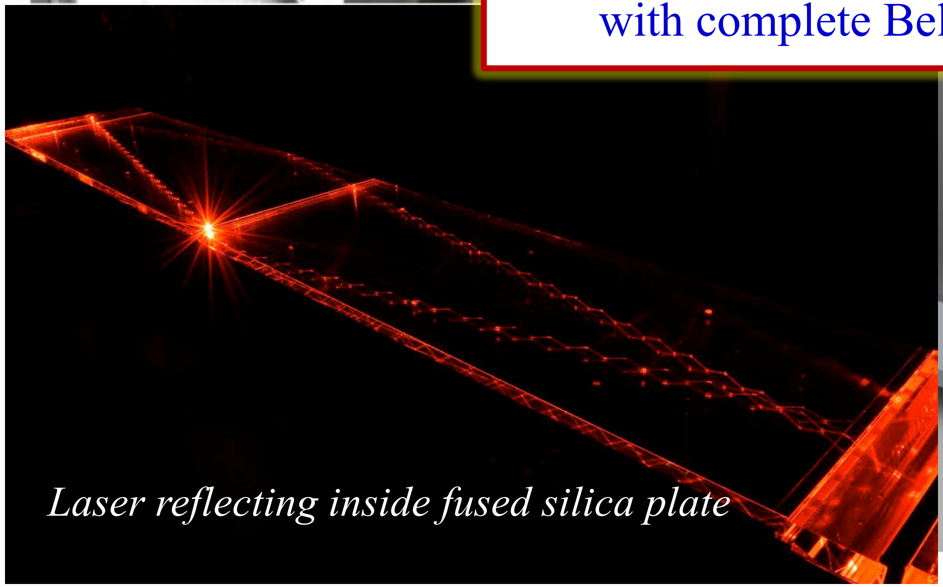
Successful installation in 2016



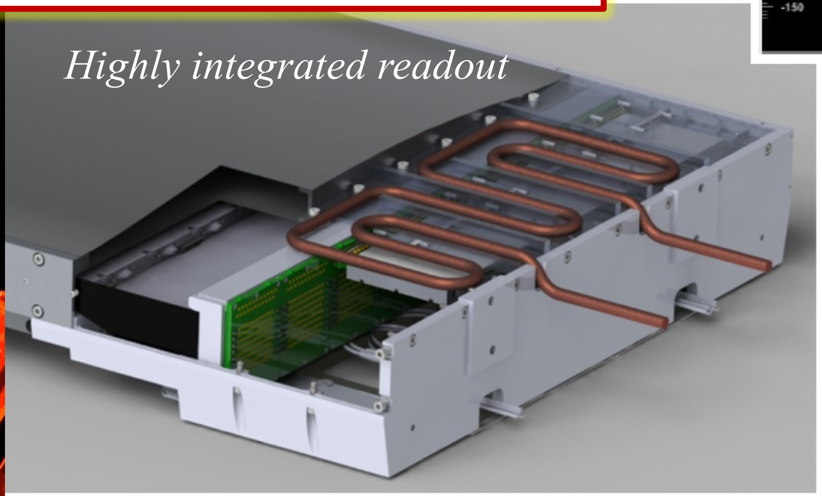


Cosmic ray test in 2017

Eagerly awaiting first physics data
with complete Belle II detector in early 2019.



Laser reflecting inside fused silica plate



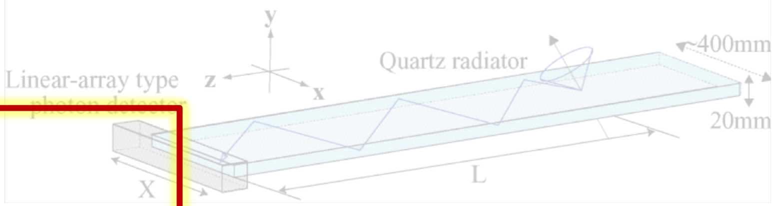
Highly integrated readout

Initial next-generation DIRC R&D directions can roughly be divided into three imaging approaches using different focusing optics

- moderate timing, (very) good spatial resolution
  examples: fDIRC, GlueX DIRC, early PANDA Barrel DIRC
  100-200 ps photon timing, array of (~6mm) 2D pixels → PID primarily based on spatial imaging

Early SuperB fDIRC design

- very fast timing, moderate/poor spatial resolution
  examples: early Belle II TOP design, early PANDA Disc DIRC design
  ~50 ps photon timing, (~5mm) 1D pixels → PID primarily based on time imaging



Early Belle II TOP design

- very fast timing, very good spatial resolution
  examples: “ultimate fDIRC”, EIC High-Performance DIRC *(via the PANDA Barrel DIRC)*
  <100 ps photon timing, large array of (~3mm) 2D pixels → PID uses full 3D imaging

Final designs for Belle II TOP and PANDA DIRCs are hybrids derived from these initial approaches.

DIRCs IN PANDA

Unless quoted specifically, all PANDA Barrel DIRC figures from
R. Dzhygadlo, TIPP2017
JS, DIRC2017

PANDA: two DIRC detectors

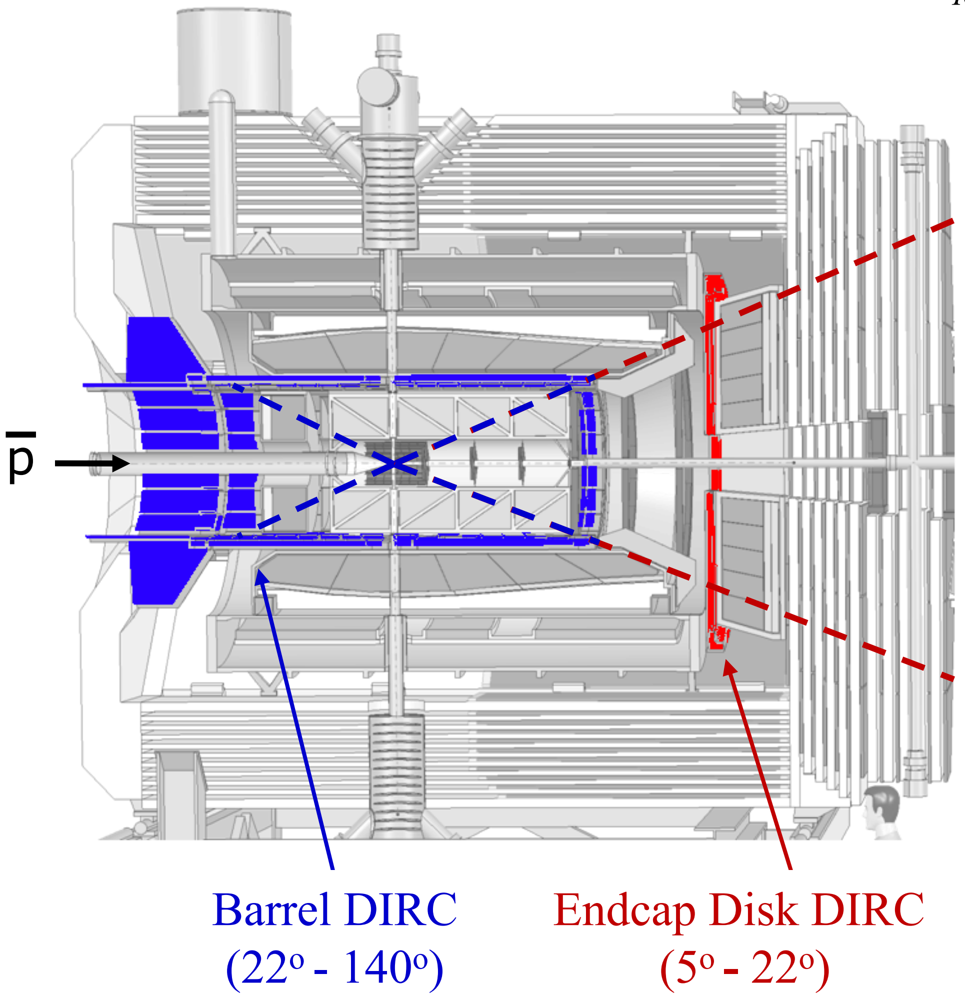
- Barrel DIRC

  PID goal: 3σ π/K separation for p<3.5 GeV/c.

- Endcap Disk DIRC

  PID goal: 3σ π/K separation for p<4 GeV/c.

  ➤ Avetik Hayrapetyan, next talk



PANDA detector environment:

- very limited space in barrel and endcap,

  EM calorimeters just outside both DIRCs.

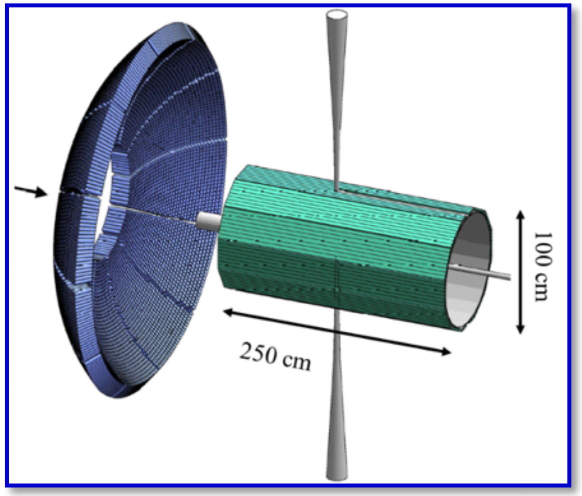
- trigger-less DAQ with average interaction rate 20MHz.

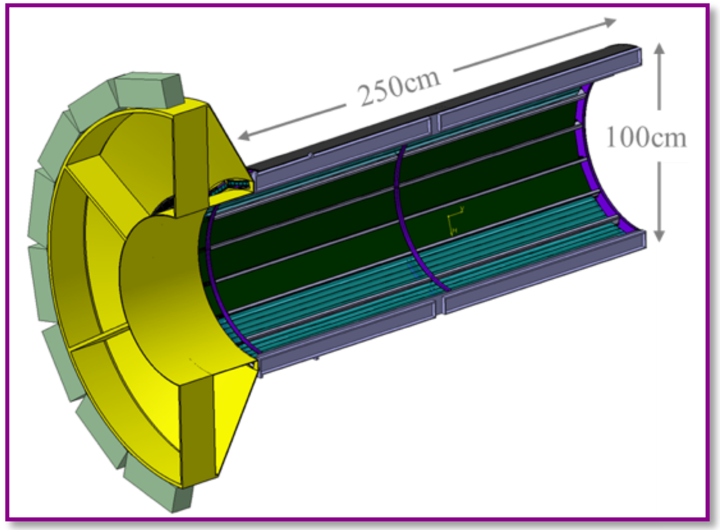
Initial approach: scaled version of BABAR DIRC

- Radiators: 96 narrow fused silica bars, 2.5m length
- Expansion volume: large water tank
- Sensors: ~ 7,000 conventional PMTs

Fast simulation: design meets PANDA PID goals.

But: increasingly complex PANDA detector design required compact imaging region inside magnet yoke





Improved design: compact photon camera

- Radiators: 80 narrow fused silica bars, 2.5m length
- Expansion volume: 30 cm-deep tank (mineral oil)
- Sensors: ~15,000 channels of MCP-PMTs
- Focusing: spherical lenses

Detailed simulation: design meets PANDA PID goals.

But: production cost ~50% over budget.

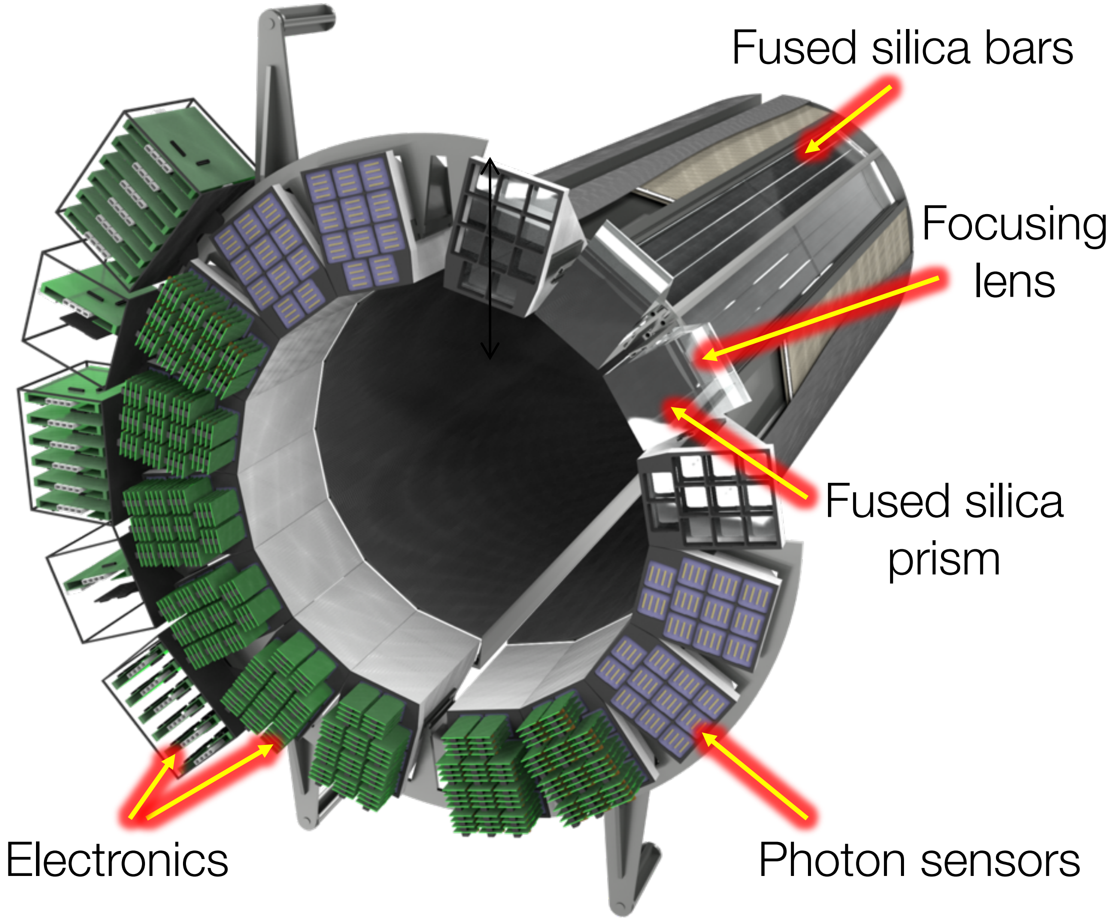
Needed additional cost/performance optimization – cost driver: fabrication of bars and MCP-PMTs.

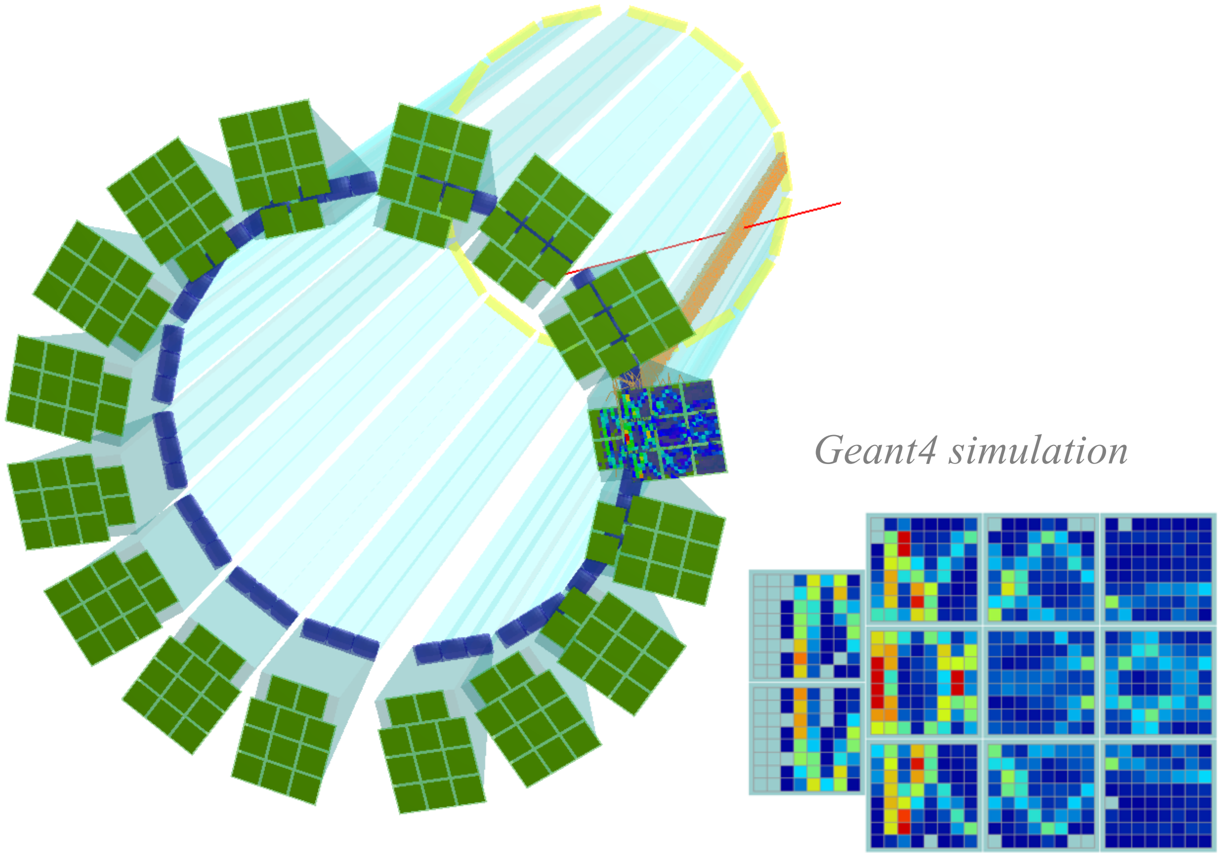
PANDA Barrel DIRC: Final Design

Main results of a comprehensive cost performance optimization in simulation:

use wider bars (3 per bar box instead of 5) and compact fused silica prisms;

40% fewer bars, 37% fewer MCP-PMTs, lower cost at no performance loss.

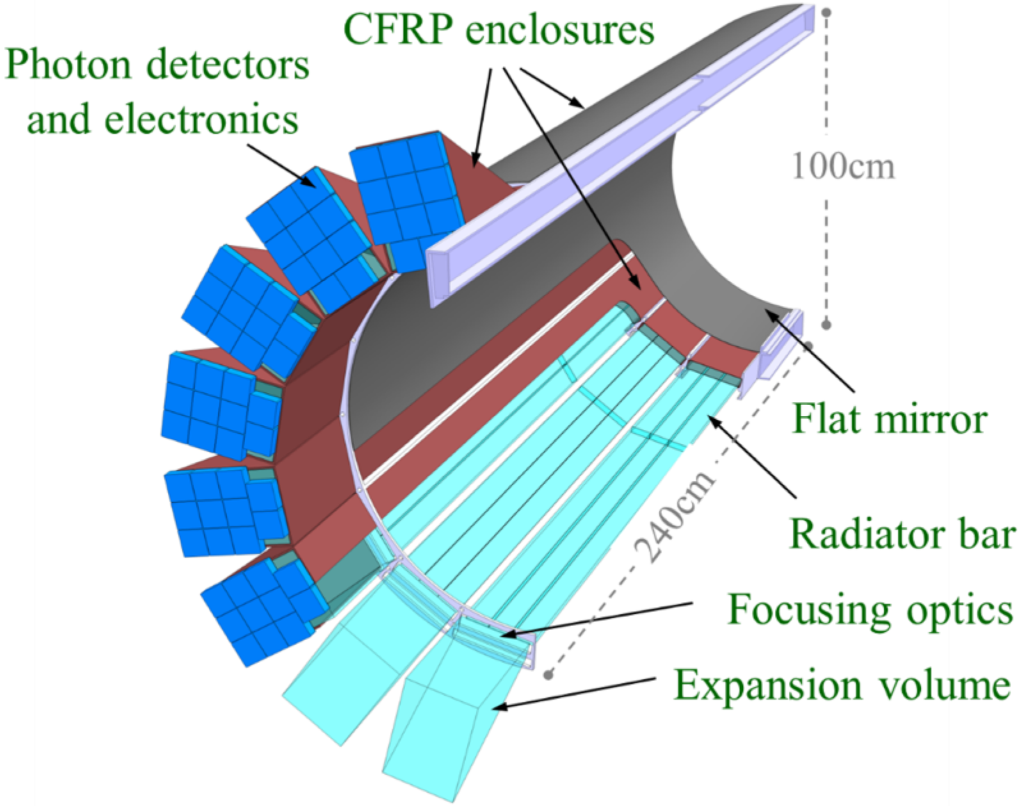




For more detail, see
PANDA Barrel DIRC TDR, arXiv:1710.00684

Compact fused silica prisms, 3 bars per bar box, 3-layer spherical lenses.

- 48 radiator bars (16 sectors), synthetic fused silica,
  17mm (T) × 53mm (W) × 2400mm (L).
- Focusing optics: 3-layer spherical lens
- Compact expansion volume:
  30cm-deep solid fused silica prisms
  ~11,000 channels of lifetime-enhanced MCP-PMTs
- Fast FPGA-based photon detection.
  ~100ps per photon timing resolution
- Expected performance (simulation and particle beams):
  better than 3 s.d. π/K separation for entire acceptance.



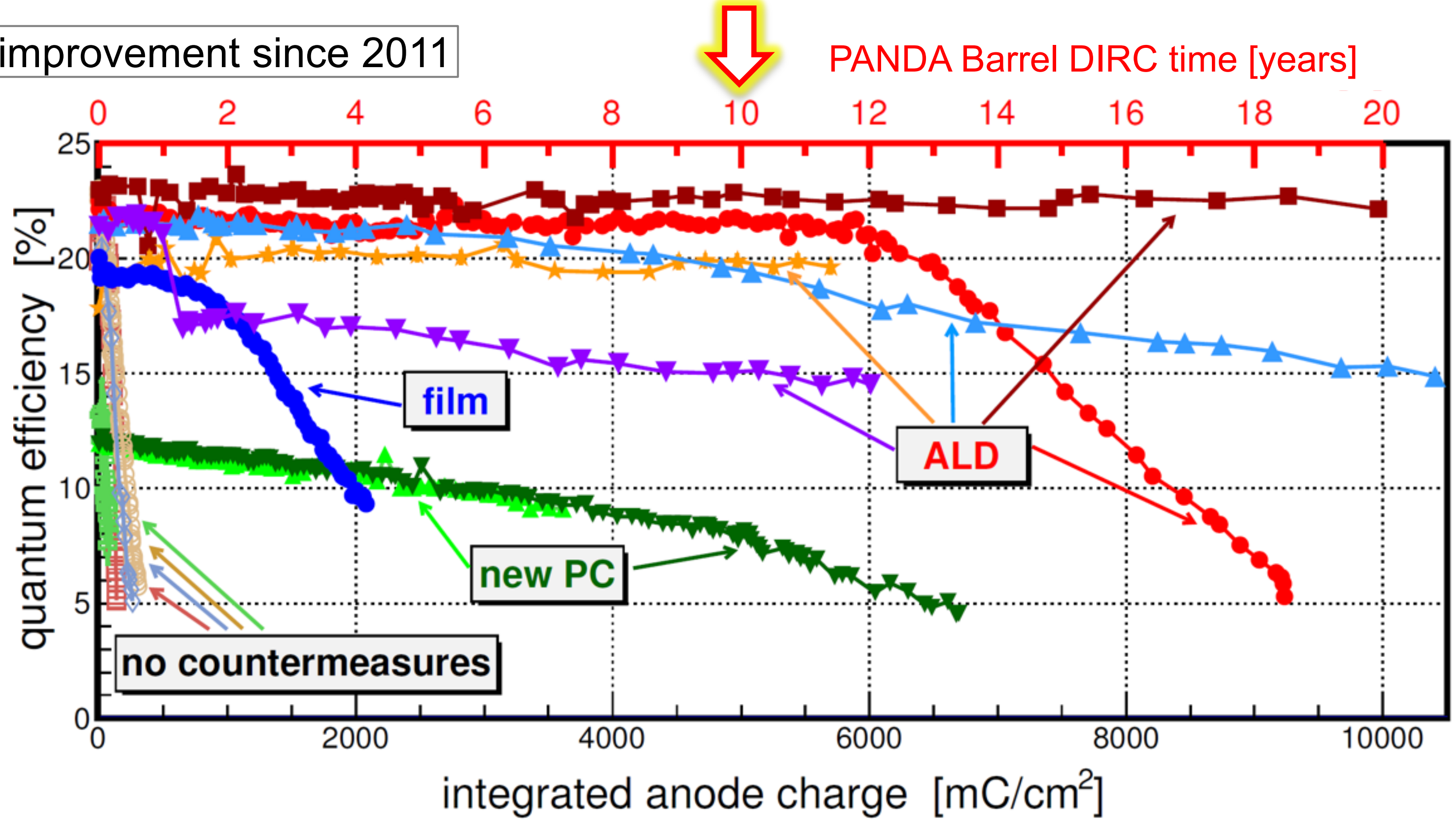
Conservative design – similar to proven BABAR DIRC, validated in particle beams in 2015.
Excellent performance, robust, little sensitivity to backgrounds and timing deterioration.
Modular design for easy access and optional staged installation of bar boxes.

PANDA Barrel DIRC: Key Technology

A. Lehmann, LIGHT14
A. Lehmann, RICH2016

Lifetime of MCP-PMTs was potential showstopper for Belle II and PANDA until a few years ago. Close collaboration with industry, issue resolved since ~2016

Factor >50 improvement since 2011



Recent MCP-PMTs with atomic layer deposition technique meet all requirements for the Belle II TOP and PANDA Barrel DIRC.

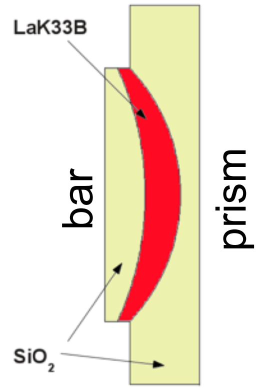
G. Kalicy, DIRC013
JS DIRC2017

Multi-layer spherical lens

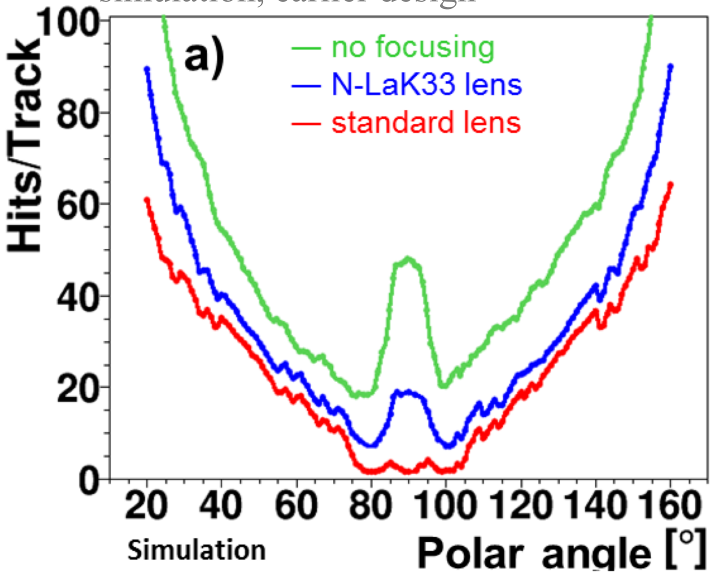
Standard fused silica lens with air gap would create large hole in DIRC acceptance for track polar angles for 75-105 deg (photon captured in lens by internal reflection).

Innovative design: use refraction at high-refractive index material to fused silica instead.

Solution for PANDA Barrel DIRC:
lanthanum crown glass (LaK33B) as middle layer in 3-layer lens,
focusing/defocusing radii inside lens designed to match prism surface



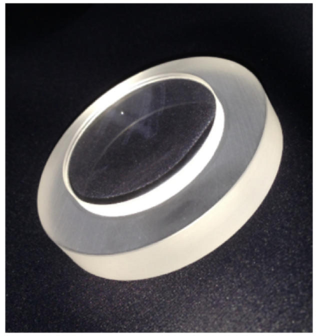
simulation, earlier design



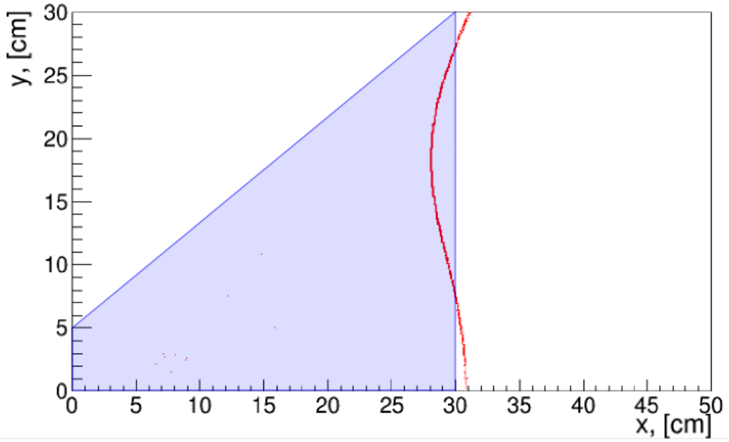
Prototype built by industry, tested with lasers in lab and with PANDA Barrel DIRC prototype using particle beams at CERN.

Photon yield, resolution, and shape of focal plane agree with simulation, hole in acceptance closed.

(Note that NLaK33B is "radiation hard enough" for PANDA [expected 10 year dose <5Gy] but not for EIC DIRC. Currently investigating alternatives: PbF_2, sapphire, ...)



simulation: focal plane of 3-layer lens



Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

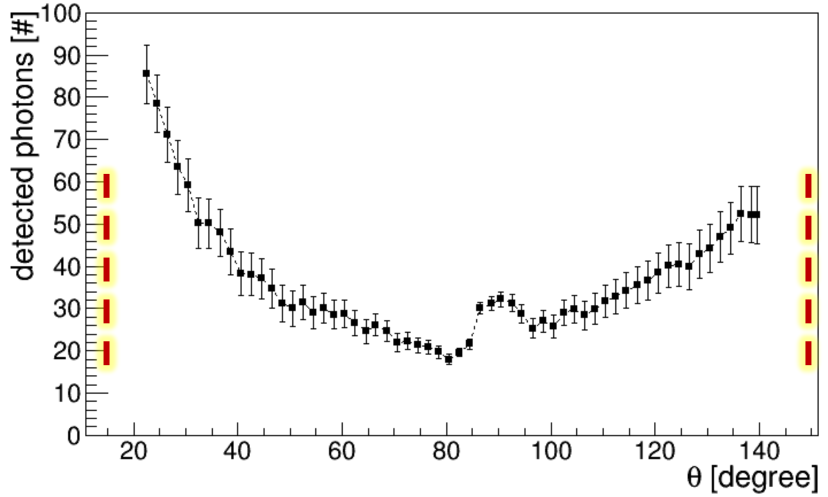
Used geometrical reconstruction (BABAR-like)
- to determine photon yield and
- single photon Cherenkov angle resolution (SPR).

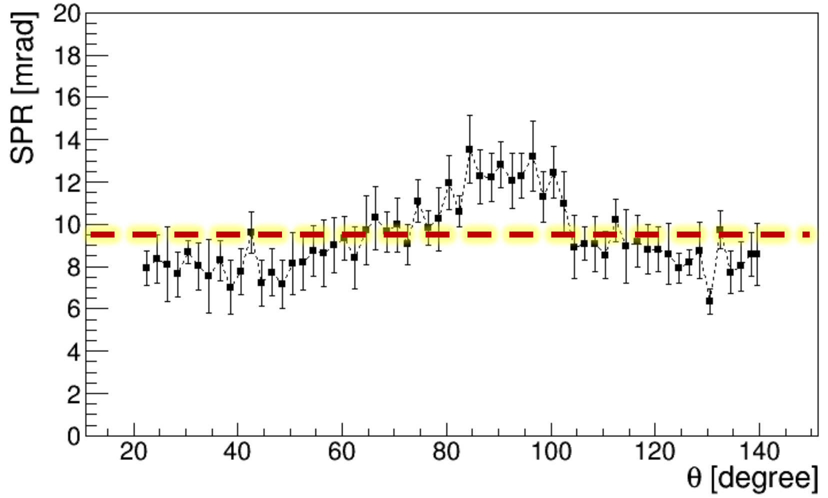
Latest generation of MCP-PMTs expected to
- further increase photon yield by up to 50%.

Yield and SPR reach performance goal.

BABAR DIRC FOMs reached or even exceeded,
- in particular for most demanding
- high-momentum forward region.

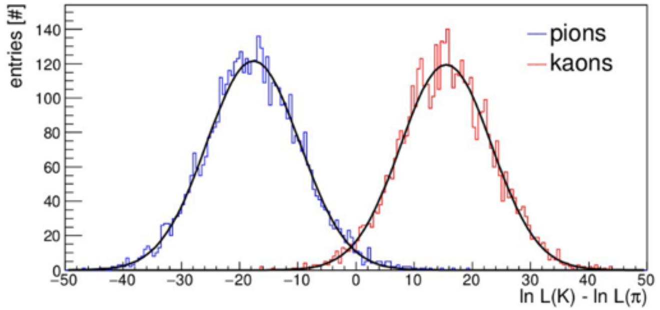
Geant simulation





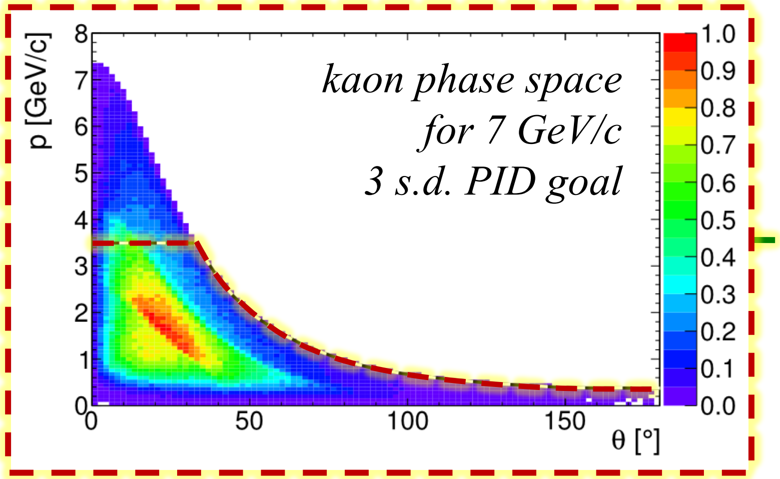
Final design, 3 bar per bar box, 3-layer spherical lens, prism

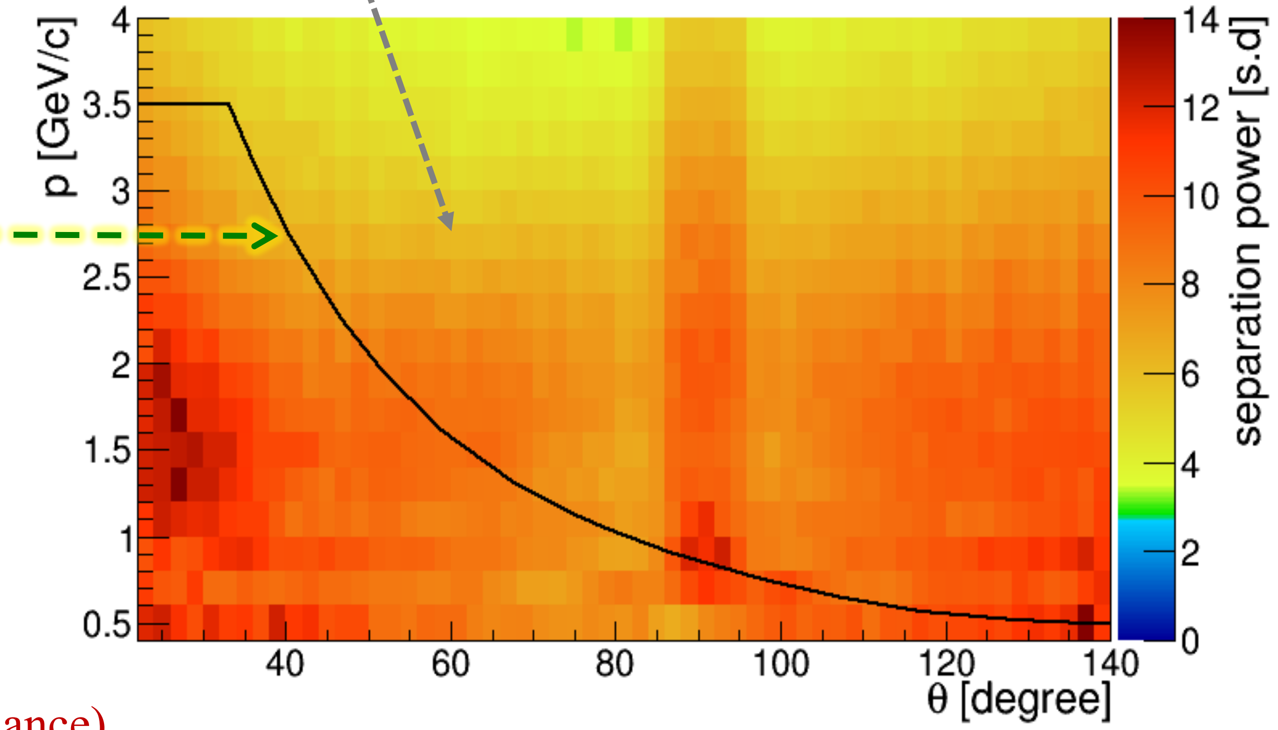
Log-likelihood difference from time-based imaging (similar to Belle II TOP)



$$N_{\text{sep}} = \frac{|\mu_1 - \mu_2|}{0.5(\sigma_1 + \sigma_2)}$$

Geant simulation, time-based imaging, σ_t=100ps

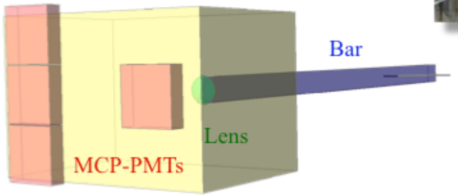




(green color: ~ 3 s.d. separation)

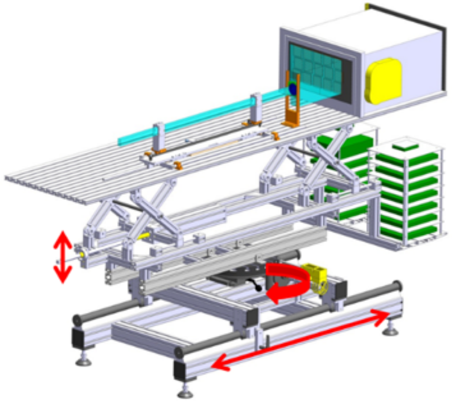
Design meets PID requirements

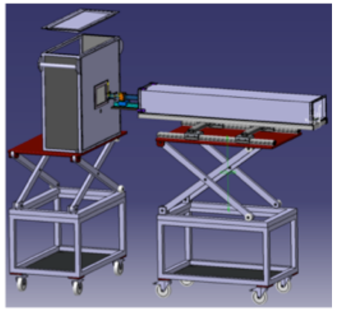
- for geometric reconstruction
- for time-based imaging (even better performance)



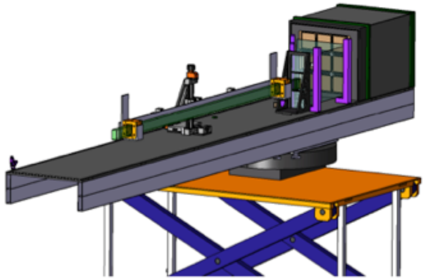
2008, 2009: GSI

2014, 2015, 2016, 2017: GSI, CERN





2011: GSI, CERN

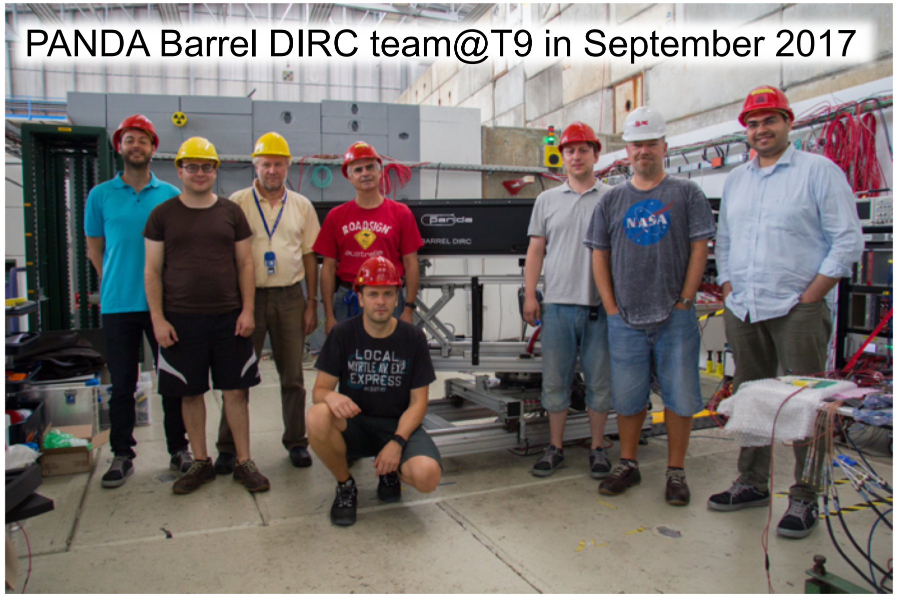


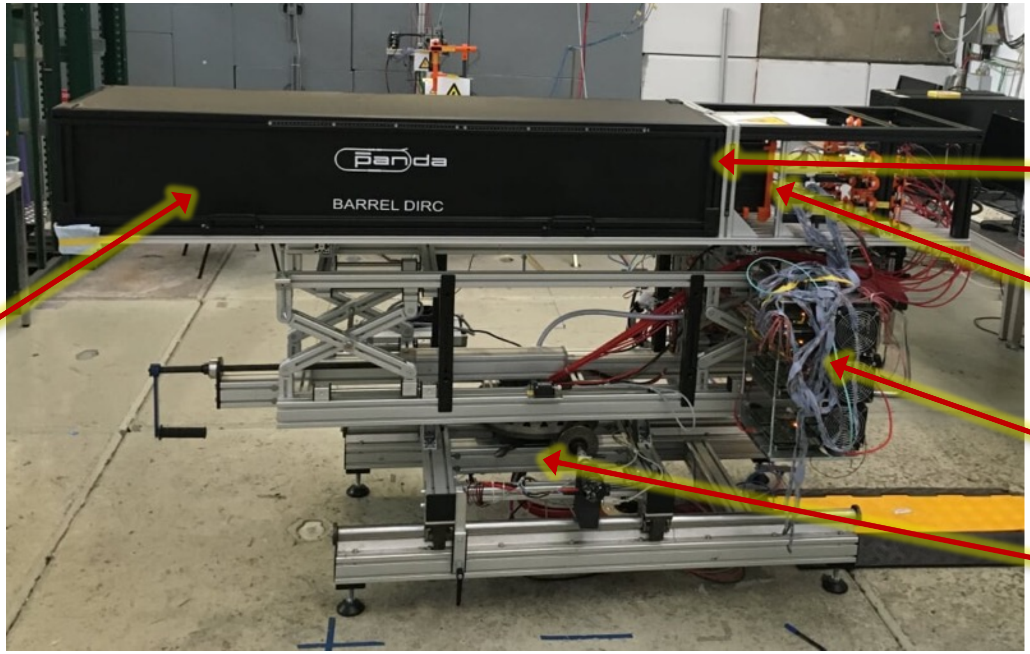
2012: CERN

2017 TESTBEAM AT CERN PS

Beam test at CERN PS/T9

- Fused silica prism as expansion volume.
- 4 x 3 array of Planacon XP85012 MCP-PMTs.
- Narrow bar and wide plate as radiator.
- 3-layer spherical and cylindrical lenses.
- Momentum and angle scans similar to PANDA phase space.
- Goal: PID validation of near-final design, test of EIC DIRC lens


PANDA Barrel DIRC team@T9 in September 2017



Dark box for optics (bar, lens, prism)

MCP-PMT array

Frontend electronics (PADIWA) (air-cooled)

DAQ boards (TRB)

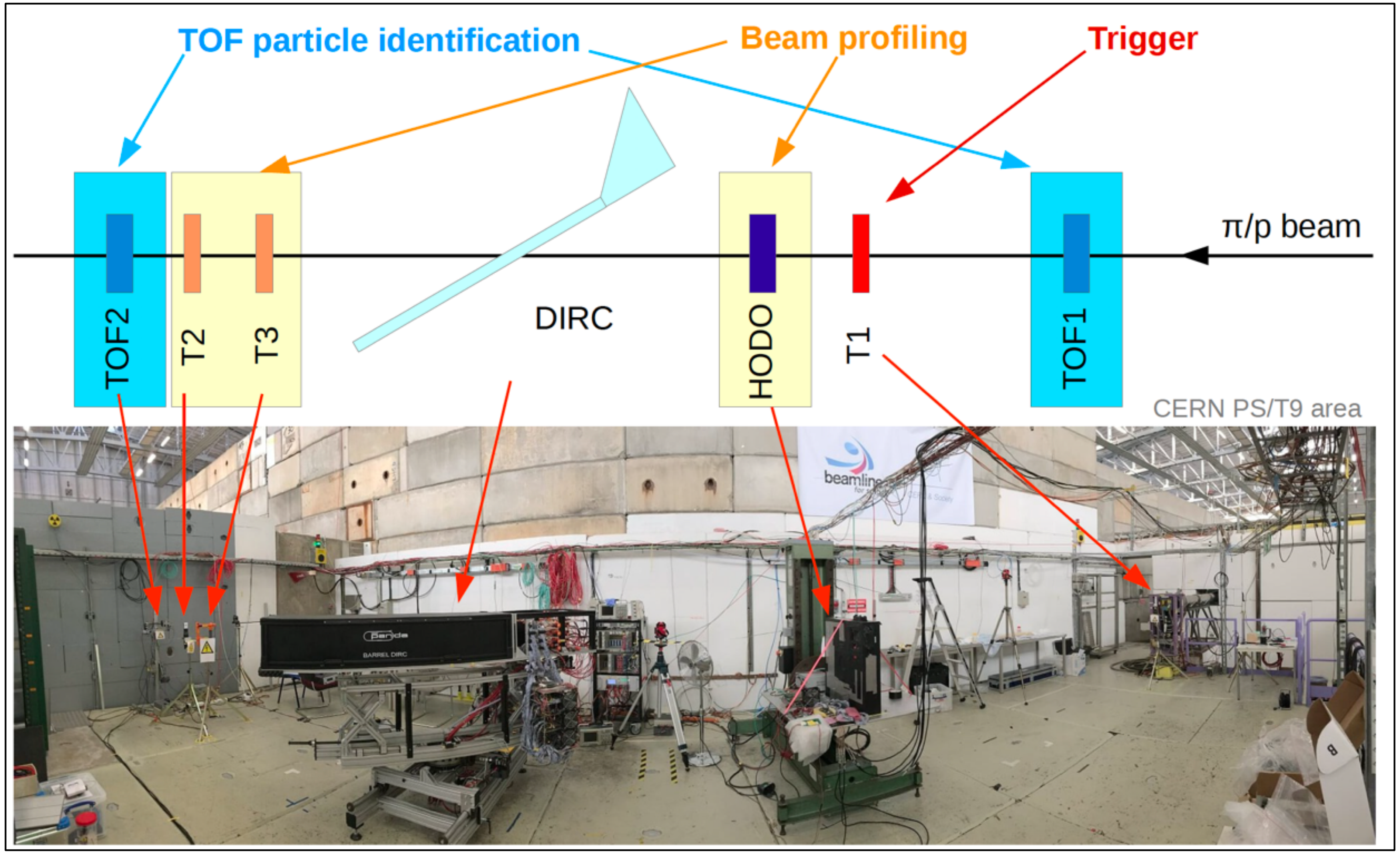
Rotation stage (remote controlled)

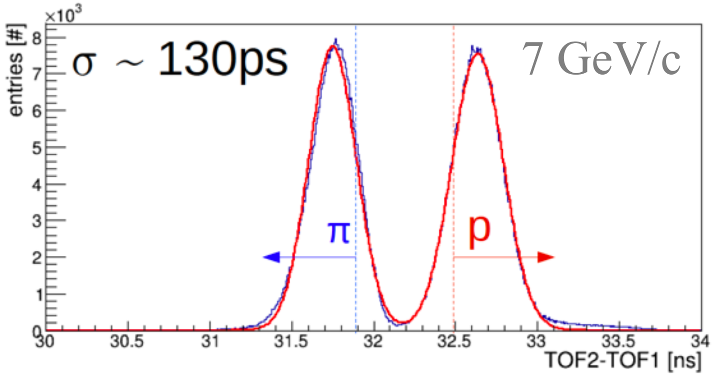
2017 TESTBEAM AT CERN PS

T9 beamline: mixed hadrons (mostly π and p), available momentum range 1.5-10 GeV/c

Most measurements at 7 GeV/c – π/p Cherenkov angle difference (8.1 mrad) approx. same as π/K at 3.5 GeV/c (8.5 mrad).

Scintillators for trigger (T1-3) and beam spot selection in combination with fiber hodoscope.





Time-of-flight system

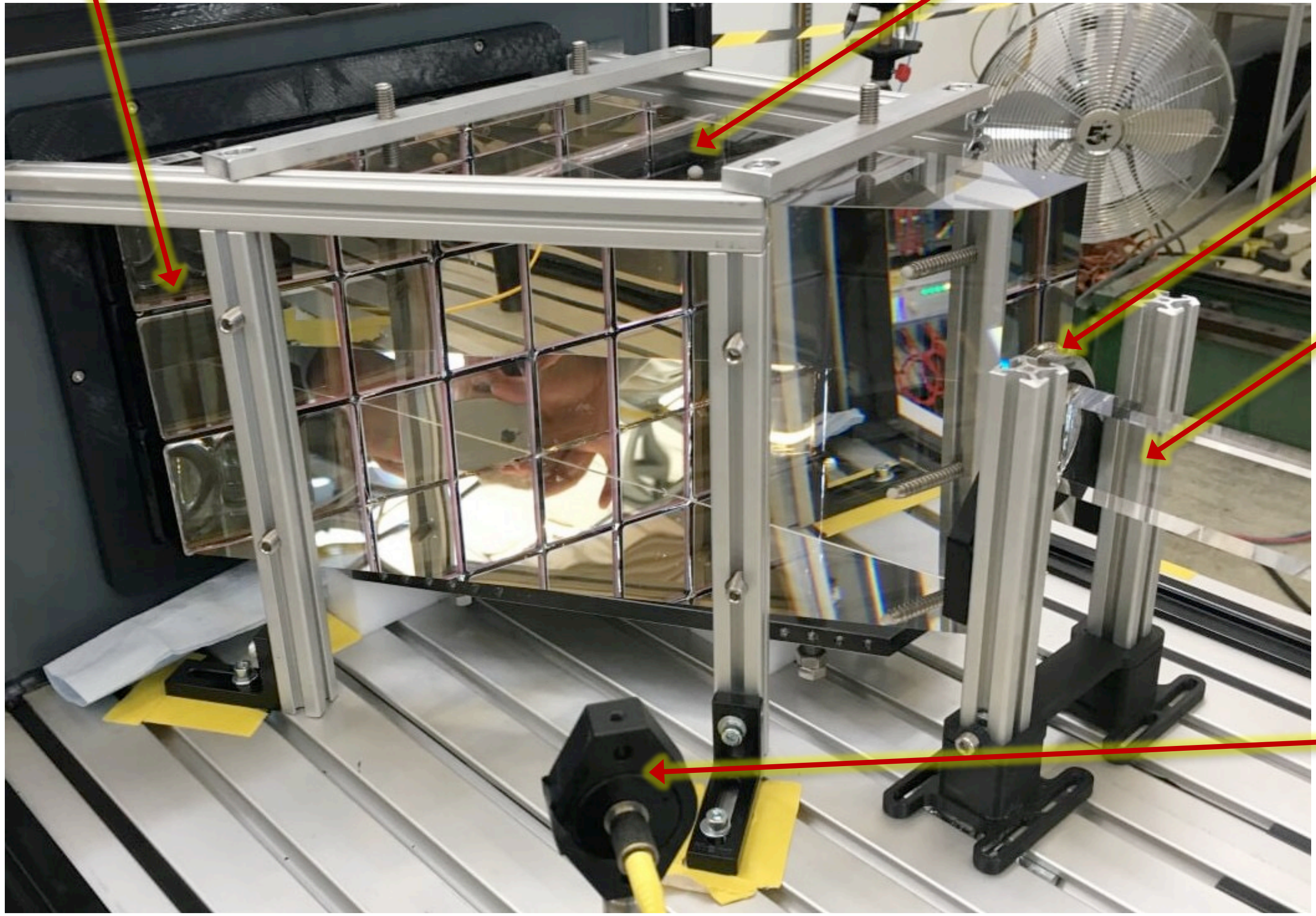
Two TOF stations, ~28m distance

Clean tag for pions and protons up to 10 GeV/c.

2017 Prototype Photos

MCP-PMT array

Fused silica prism (33deg opening angle)



Spherical 3-layer lens

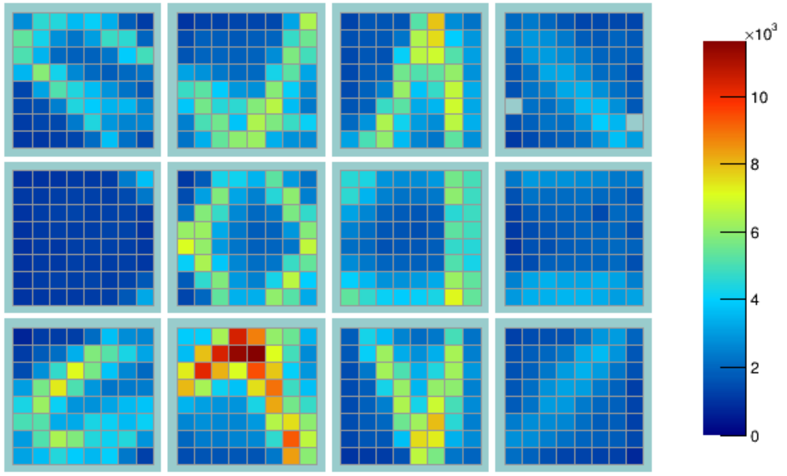
Narrow bar (35mm width)

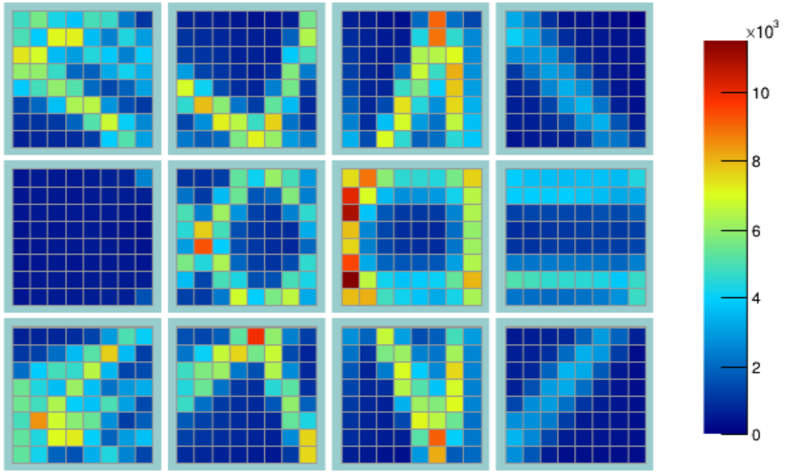
Diffuser for PiLas laser pulser

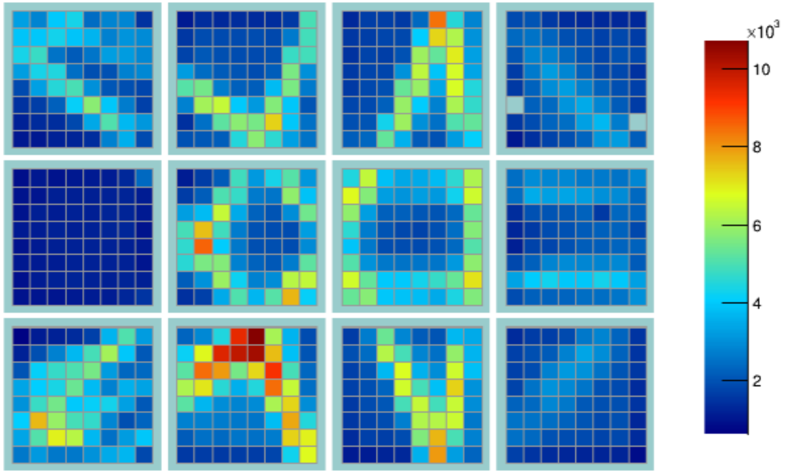
Examples of the Hit Pattern

- 20 degree polar angle
- pions and protons @ 7 GeV/c
- bar + 3 layer spherical lens

- beam data with proton tag
- beam data with pion tag
- geant simulation for pions





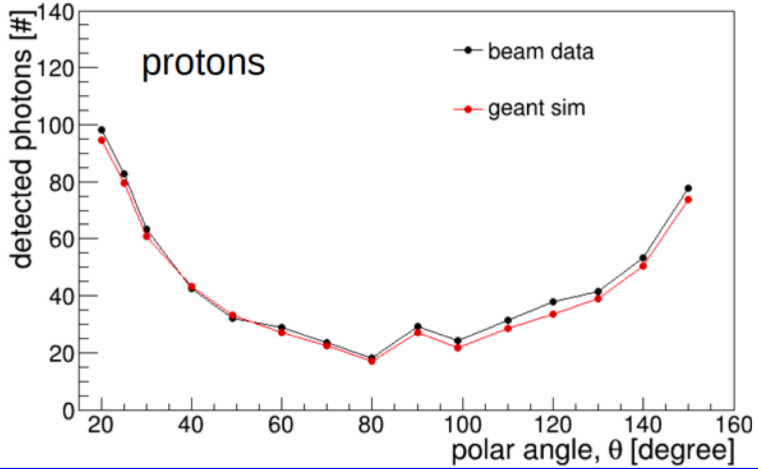


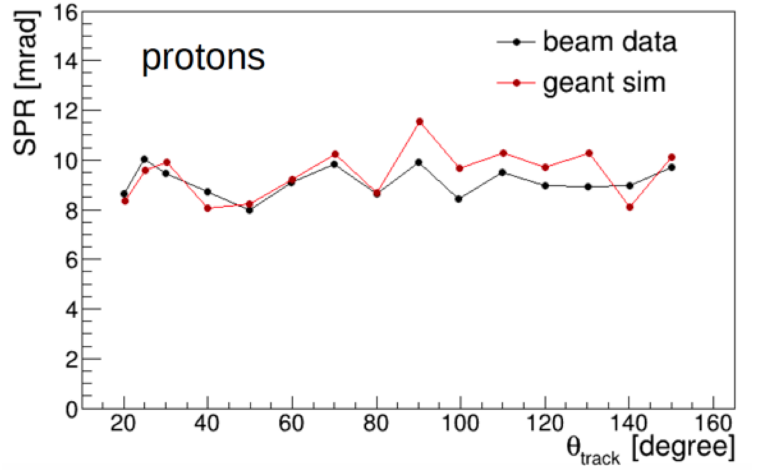
SELECTED 2017 PROTOTYPE RESULTS

Photon yield, single photon angular resolution, π/p separation

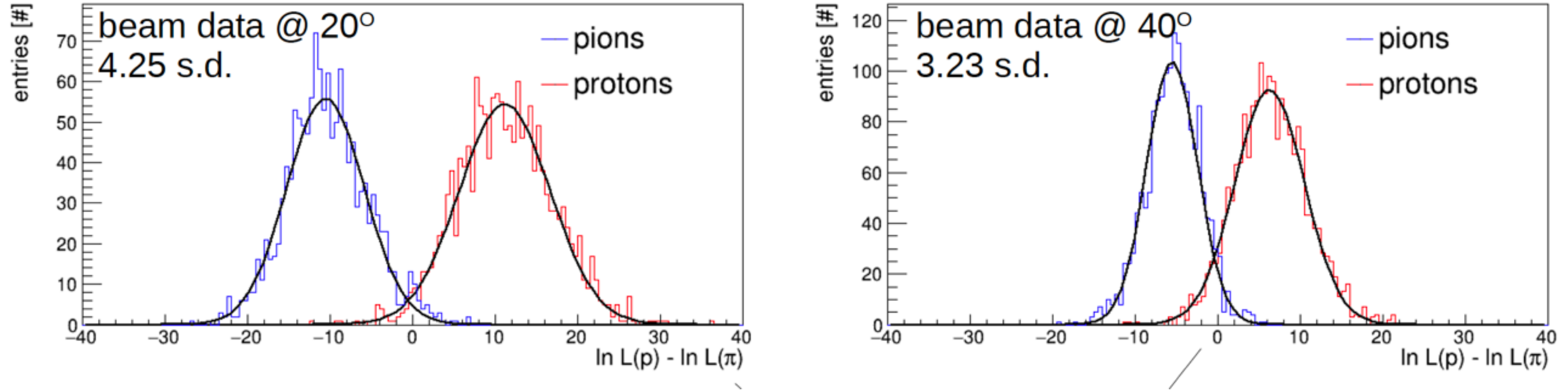
at 7 GeV/c (equivalent of 3.5 GeV/c π/K).

Calibration of data still ongoing
All results still preliminary





time-based imaging reconstruction, average time resolution ~250ps, PDFs from beam data



Simulation describes beam data well.

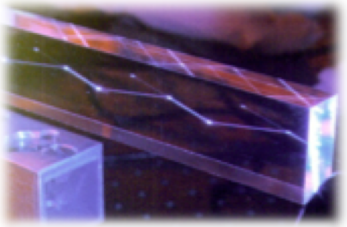
PID performance exceeds PANDA requirements,
validates the design (both geometric/spatial and time-based reco).

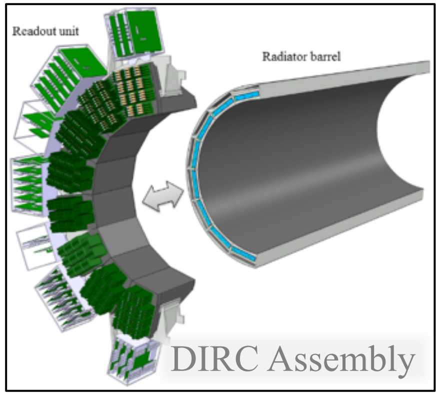
Result extrapolates to 6.6 s.d. π/K at 3.5 GeV/c, 22 deg for fully equipped PANDA Barrel DIRC (simulation with 100 ps timing).

2018-2023: Component Fabrication, Assembly, Installation.

- 2018/2019: Finalize specifications, MoUs, start tender and contracts.
- 2018-2021: Industrial fabrication of fused silica bars, lenses, and prisms.
  Industrial production of Micro-channel Plate PMTs.
- 2019-2020: Production and QA of readout electronics.
- 2018-2022: Industrial fabrication of bar containers and mechanical support frame;
  QA of bars, gluing of long bars, assembly of complete bar boxes.
  Detailed QA (scans, aging study) of MCP-PMTs.
  Assembly of readout units.
- 2022/2023: Installation of mechanical support frame in PANDA,
  insert bar boxes, mount readout modules.

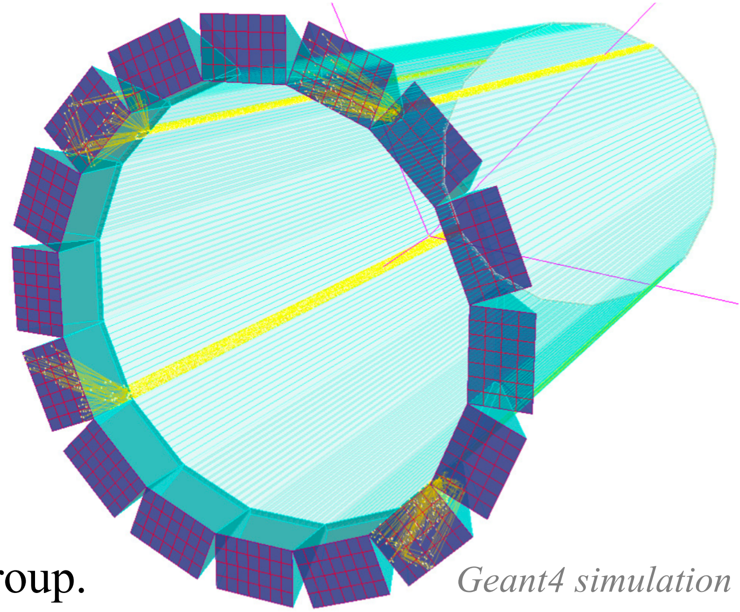
Ready as “Start Setup / Day One” detector in PANDA.


DIRC bar with laser



DIRC Assembly

G. Kalicy, DIRC2017


Geant4 simulation

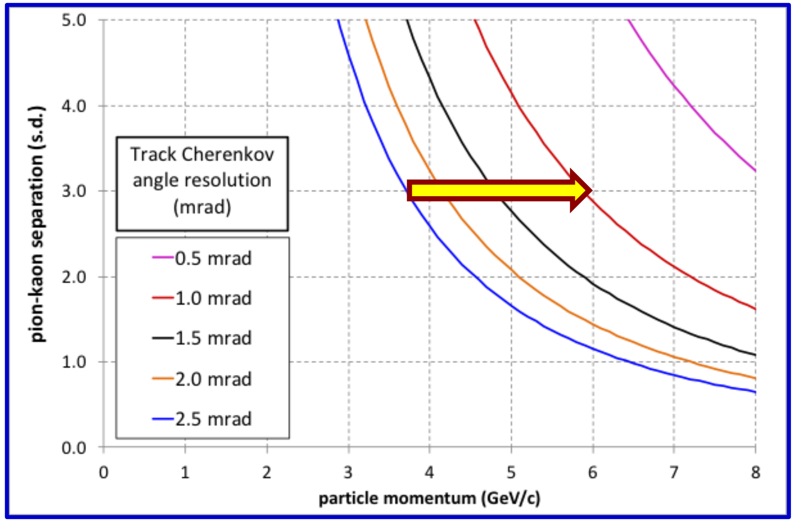
Start point for "High-Performance DIRC" for the central detector at future Electron-Ion Collider: PANDA Barrel DIRC design

16 sectors, each with 11 narrow bars (~35mm width, ~4.2m length), spherical 3-layer lens, fused silica expansion volume, array of 4*6 MCP-PMTs, inside 1-2T B field.

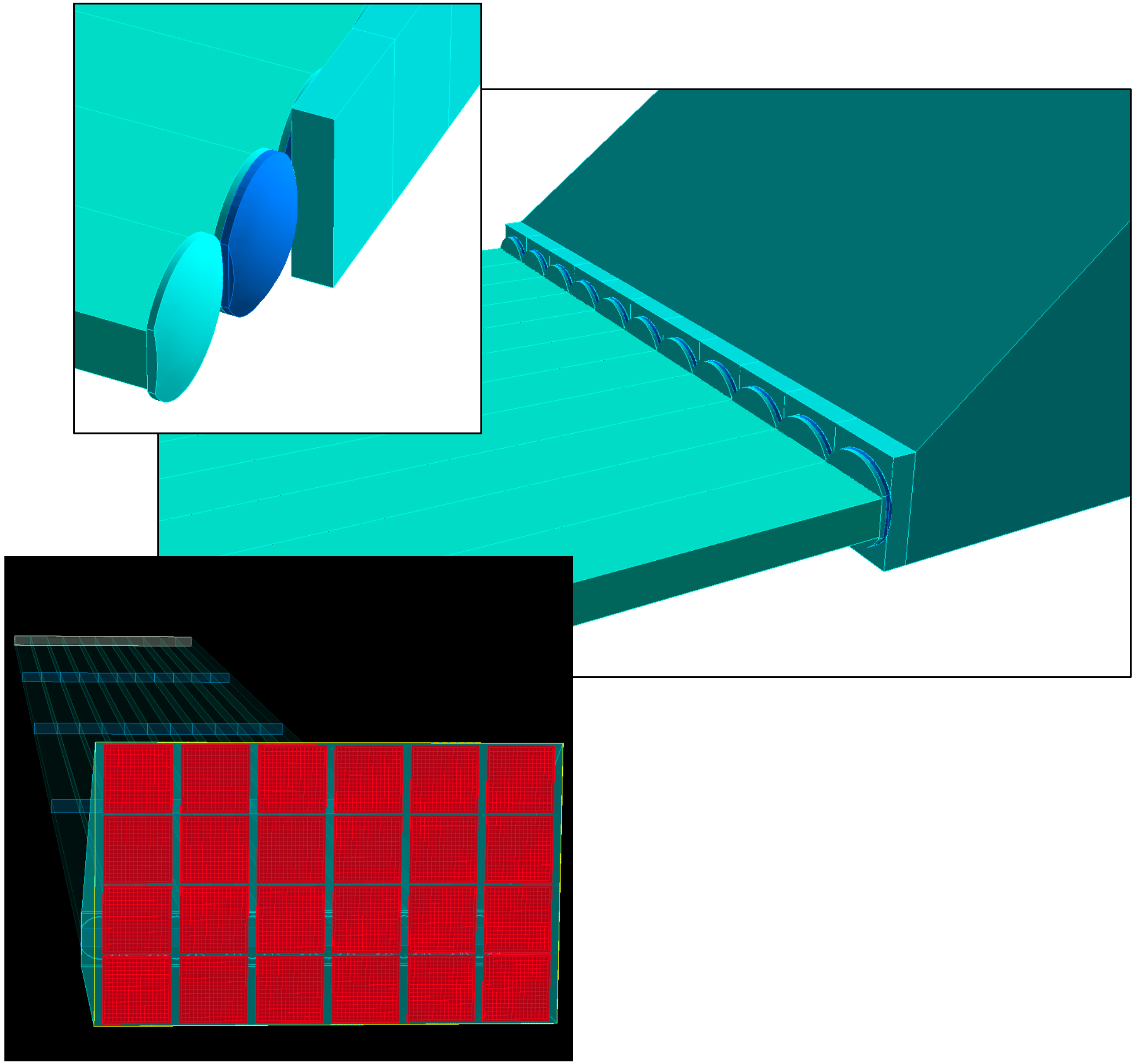
EIC DIRC R&D effort started in 2011 (eRD4, eRD14), DOE funding via BNL, consortium of universities and labs in US and Germany, including GSI PANDA group.

Goal: push Barrel DIRC performance significantly past state-of-the-art, increase range by 50% to at least 3 s.d. π/K separation at 6 GeV/c.

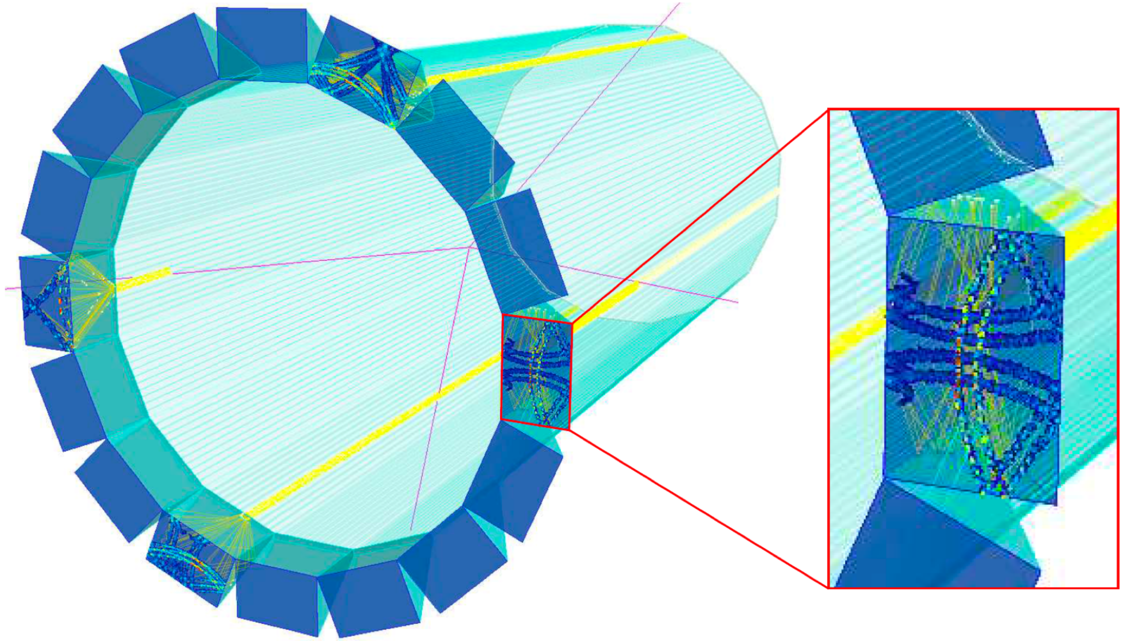
Key elements: 3-layer focusing lenses, MCP-PMTs with ~3mm pixel pitch, ~100 ps photon timing, time-based imaging reconstruction.



G. Kalicy, DIRC2017



Geant4 simulation



High-Performance EIC DIRC

G. Kalicy, DIRC2017

EIC DIRC will require smaller pixels to meet PID goal,

~2-3mm pixel pitch ideal, in line with LAPPD/ANL MCP-PMT development.

Next-generation waveform-sampling electronics (based on Belle II TOP design)

Major technological challenge: radiation hardness of lens material

NLaK33 not radiation hard enough at EIC. Currently testing alternative materials and designing new lens, goal to produce rad-hard lens by 2019.

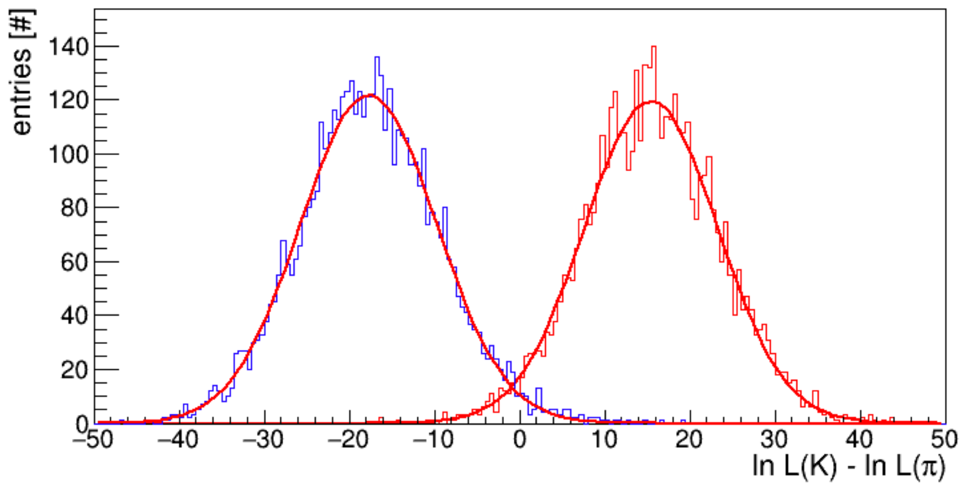
Simulation shows ~50% improvement in single photon resolution (5-6 mrad) compared to PANDA (8-10 mrad), similar photon yield.

Simulation predicts 4.2 s.d. π/K separation at 6 GeV/c for ideal tracking resolution (however, expect ~0.5-1mrad tracking@EIC).

Realistic tracking being implemented, also realistic next-gen MCP-PMTs with 50-75% higher photon detection efficiency.

DIRC being implemented into all major EIC detector simulation frameworks (BeAST, EIC-ePHENIX, JLEIC) ... stay tuned.

Geant performance example:
4.2 s.d. π/K separation at 6 GeV/c/30°,
time-based imaging, 100ps resolution,
ideal tracking assumed

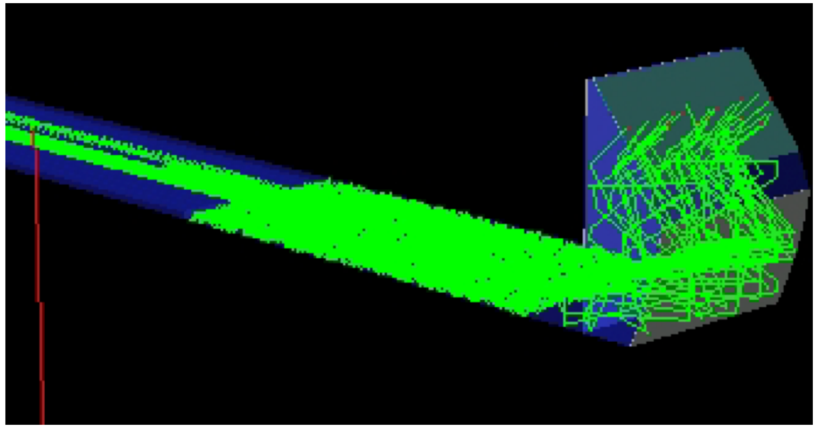


J. Va'vra, RICH2016

What about a design based on the "best of..." of DIRC R&D in recent years?

At RICH 2016 J. Va'vra showed the final optimization of fDIRC concept

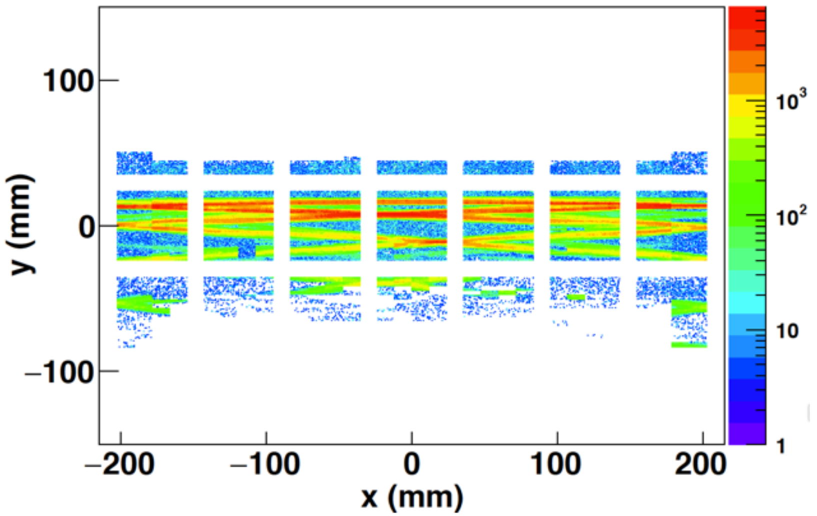
smaller fused silica block, sensors with 3mm pixel pitch, disassemble BaBar DIRC bar boxes, replace old wedges, replace bar close to wedge with one wide plate for all 12 bars in box.



This means that the plate becomes part of the expansion volume, much longer lever arm, better angular precision.

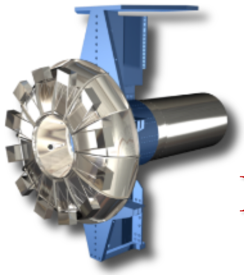
Using geometric reconstruction, using timing to resolve reconstruction ambiguities and to correct chromatic dispersion:

Cherenkov angle resolution per photon 3–5mrad (depending on optical path length) – best DIRC performance so far (in Geant).

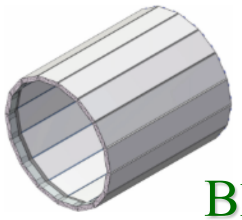


Combining this design with time-based imaging with faster sensors should lead to further improvement – on the EIC DIRC to do list...

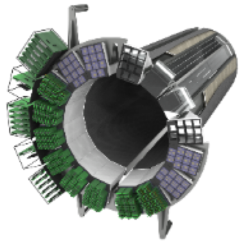
BARREL DIRC COUNTERS



BABAR DIRC



BELLE II TOP



PANDA BARREL DIRC

	BABAR DIRC	BELLE II TOP	PANDA BARREL DIRC
Radiator geometry	Narrow bars *(35mm)*	Wide plates *(450mm)*	Narrow bars *(53mm)*
Barrel radius	85cm	115cm	48cm
Bar length	490cm *(4×122.5cm)*	250cm *(2×125cm)*	240cm *(2×120cm)*
Number of long bars	144 *(12×12 bars)*	16 *(16×1 plates)*	48 *(16×3 bars)*
Expansion volume	110cm, ultrapure water	10cm, fused silica	30cm, fused silica
Focusing	None (pinhole)	Mirror (for some photons)	Spherical lens system
Photodetector	~11k PMTs	~8k MCP-PMT pixels	~11k MCP-PMT pixels
Timing resolution	~1.5ns	<0.1ns	~0.1ns
Pixel size	25mm diameter	5.6mm×5.6mm	6.5mm×6.5mm
PID goal	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 3.5 GeV/c
Timeline	1999 - 2008	Installed 2016	Installation 2022/23

SUMMARY

DIRC counters have become a popular solution for hadronic PID in recent years.

BaBar DIRC was the first DIRC, PID in barrel region, very successful, π/K up to ~4 GeV/c (1999-2008).

Prompted DIRC interest by several experiments: Belle II, SuperB, PANDA, GlueX, and others;

R&D to make DIRC readout more compact, expand momentum reach, use for endcap PID.

Key technology: multi-pixels sensors, small pixels, fast timing, tolerant of high rates and B fields.

Very active and complex R&D, applying advances in sensors, electronics, imaging, algorithms.

Main R&D directions *(with significant overlap/synergy and a lot of fruitful cooperation)*:

(a) focusing design emphasizing spatial resolution, x&y pixels (fDIRC, GlueX);

(b) focusing design emphasizing high-precision photon timing (Belle II);

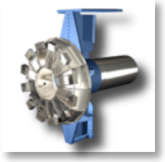
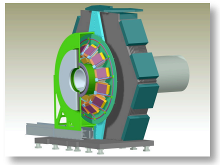
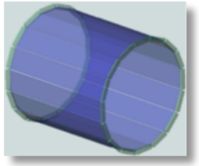
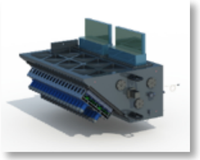
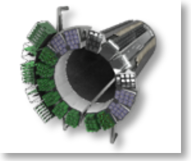
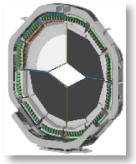
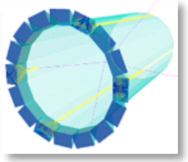
(c) focusing design with time and space coordinates with similarly high precision (PANDA, EIC).

Innovative designs completed for Belle II (installed 2016), GlueX (to be installed 2018), PANDA (2023).

Even after almost 20 years, still very active R&D, pushing the DIRC performance limits:

example: EIC PID R&D – extend PID range by 50%, 3 s.d. π/K separation to 6+ GeV/c.

Thank you all for your attention.

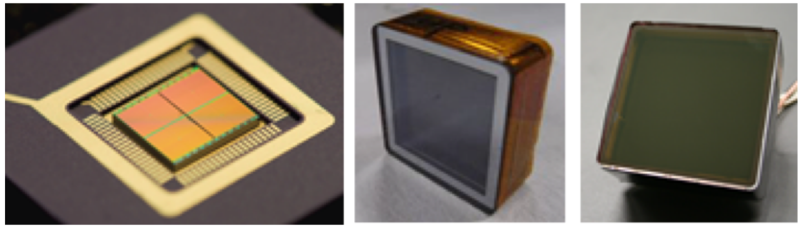
FUTURE DIRC COUNTERS

Next generation of DIRCs followed in the footsteps of successful BABAR-DIRC, making use of technological advances in

Photon detection

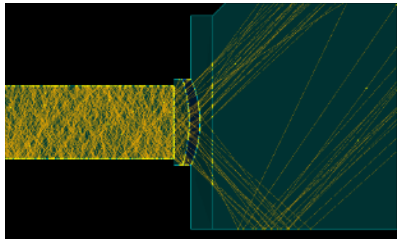
- smaller pixels
- faster timing
- longer lifetime

→ 3D imaging

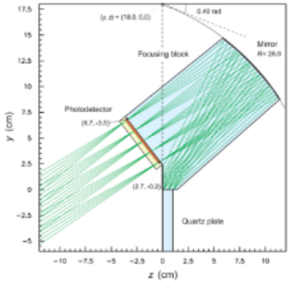


Readout electronics

PANDA



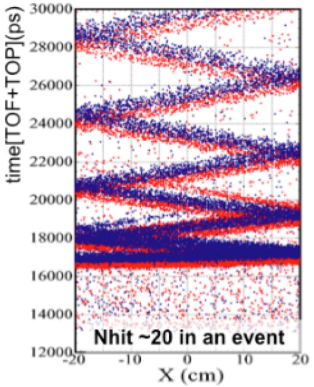
TORCH



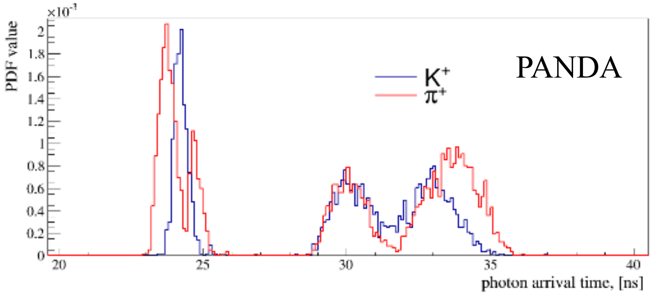
FDIRC

Focusing optics

Belle II



Time imaging



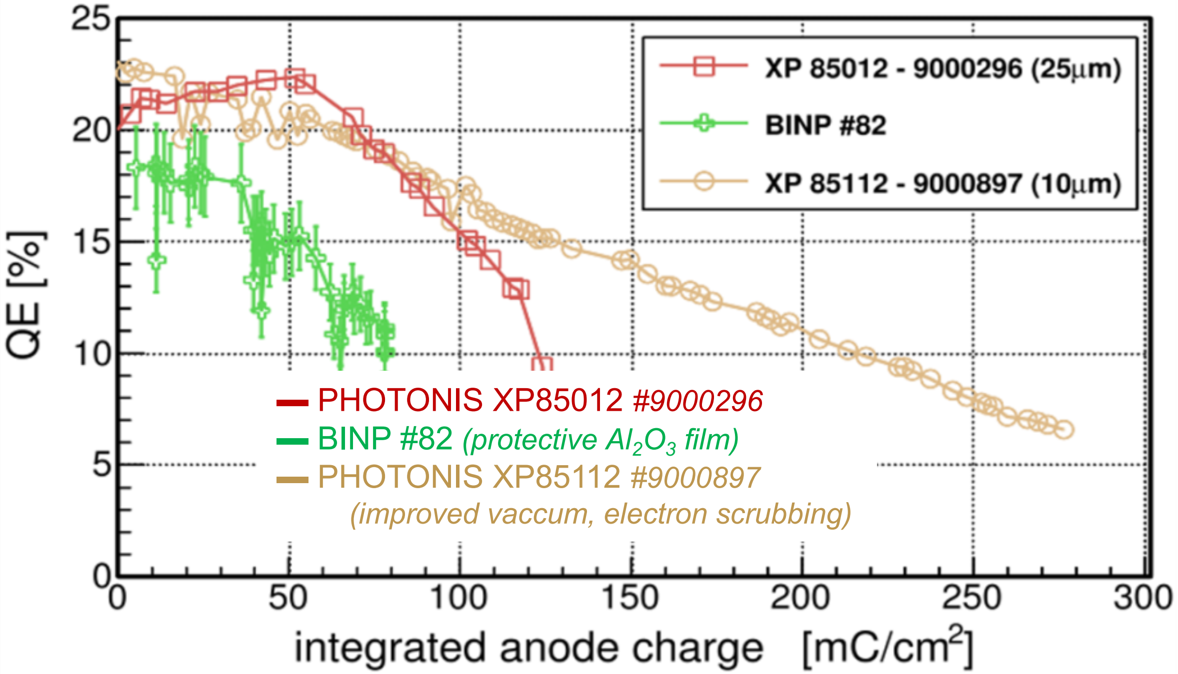
MCP-PMT Lifetime in 2011

A. Lehmann, LIGHT14
A. Lehmann, RICH2016

The main issue with using MCP-PMTs for PANDA DIRCs:

aging of photocathode, loss of quantum efficiency due to ion backflow

Status of our MCP-PMT lifetime measurements in 2011



Quantum efficiency reduced by 50% or more at only <200 mC/cm²

But: PANDA Barrel DIRC requires lifetime of ~5 C/cm² (at full luminosity)

Detailed studies at Erlangen Univ. using their aging and scanning setups, close collaboration with industry.

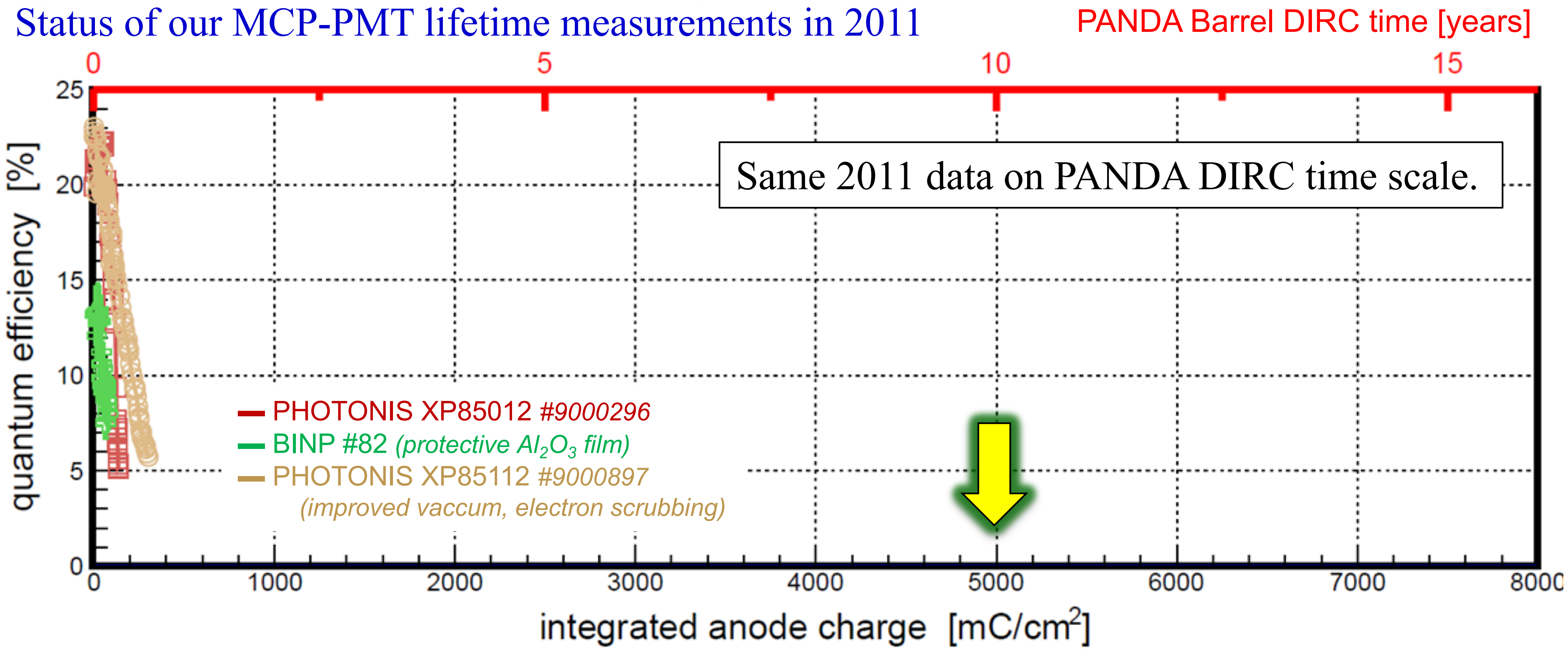
MCP-PMT LIFETIME IN 2011

A. Lehmann, LIGHT14
A. Lehmann, RICH2016

The main issue with using MCP-PMTs for PANDA DIRCs:

aging of photocathode, loss of quantum efficiency due to ion backflow

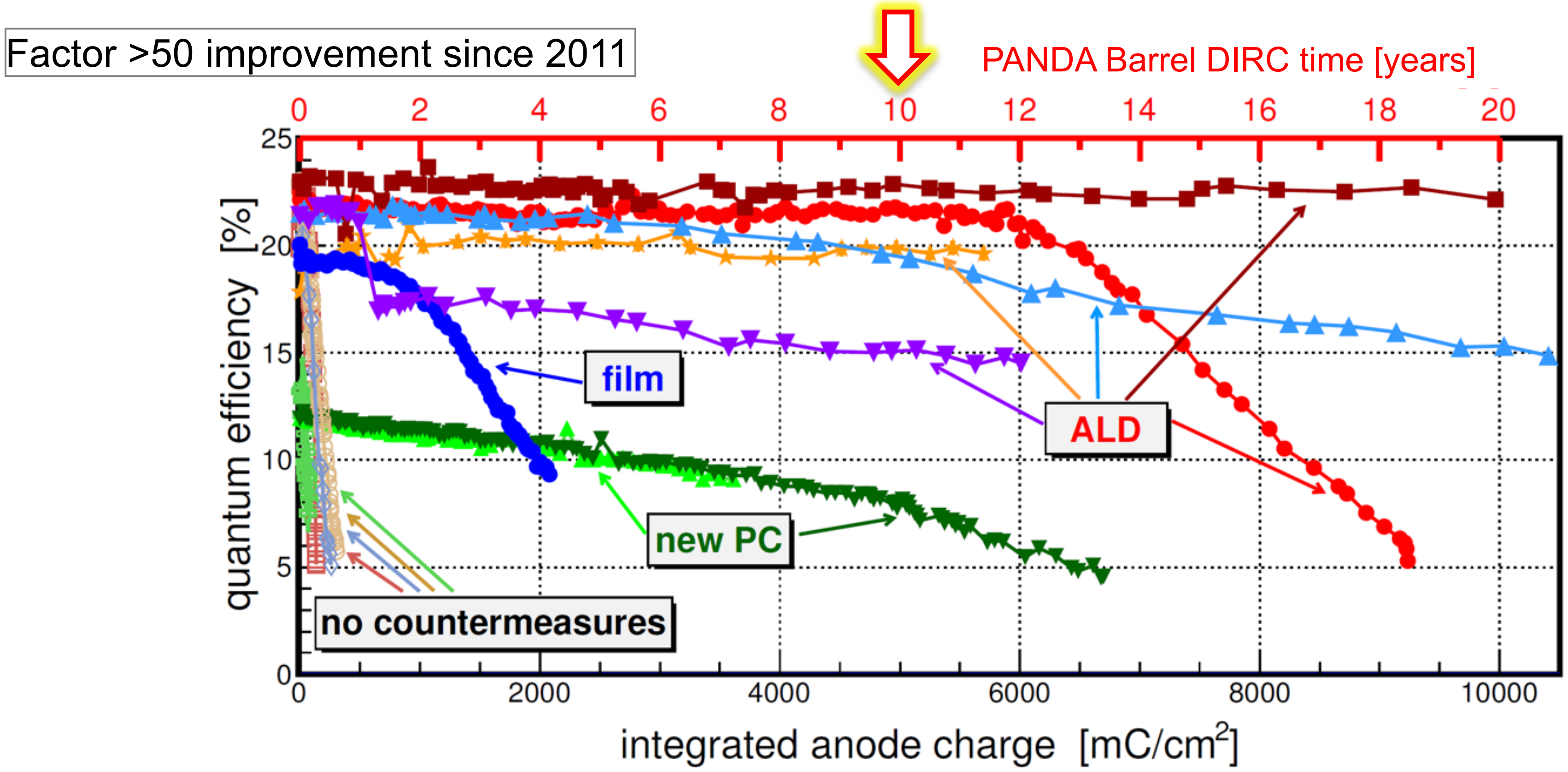
Status of our MCP-PMT lifetime measurements in 2011



None of the MCP-PMTs in 2011 would have survived for more than 2 months in PANDA.
→ needed factor ~50 (“breakthrough”) improvement in MCP-PMT lifetime

A. Lehmann, LIGHT14
A. Lehmann, RICH2016

Lifetime of MCP-PMTs was a showstopper in 2011 – solved since 2016



Recent MCP-PMTs with atomic layer deposition technique meet all requirements for the Belle II TOP and PANDA Barrel DIRC.

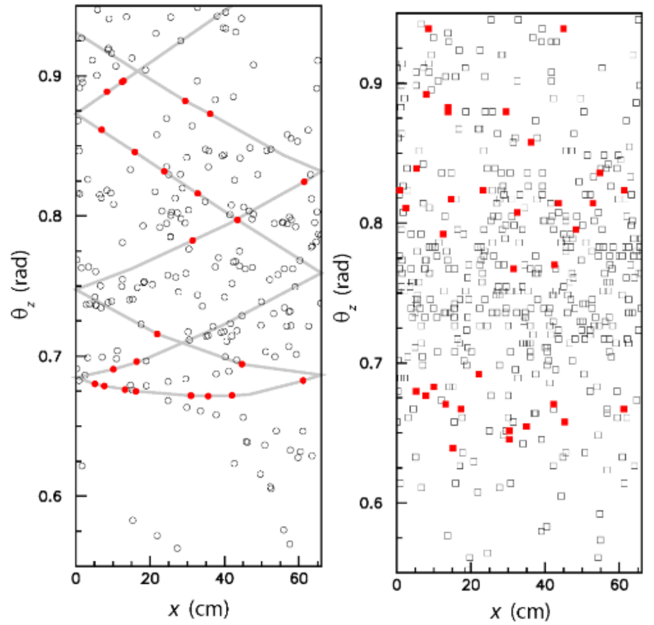
TIME-BASED IMAGING RECONSTRUCTION

Time imaging seemed imminent at RICH in 2010 with Belle II TOP and PANDA Disk DIRC were considering photon detection with only one space coordinate plus very precise timing.

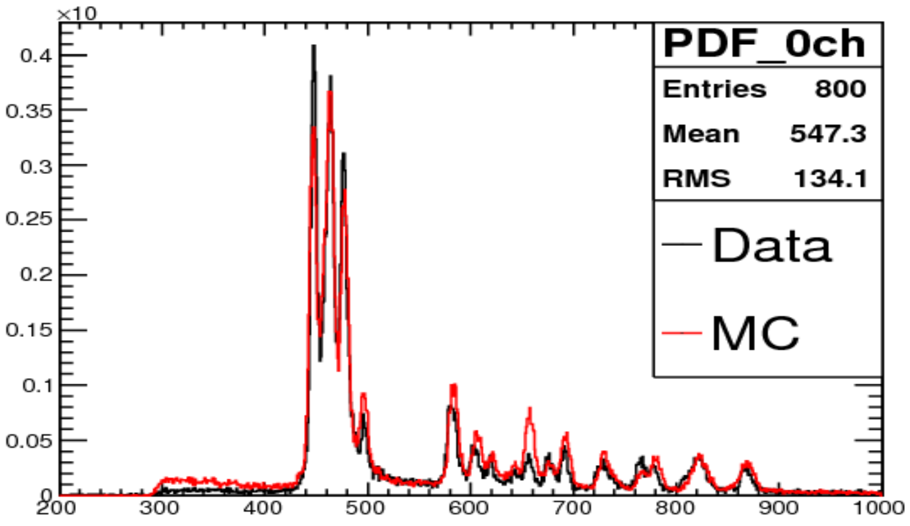
But difficult to control effects of background, alignment, PID less robust – added "Y" pixels.

But technique may be necessary to unfold complicated backgrounds that appear in geometric reconstruction approaches, certainly has potential to further improve performance.

TORCH hit pattern with and without dispersion and reflection off lower edge
R. Forty, DIRC 2013

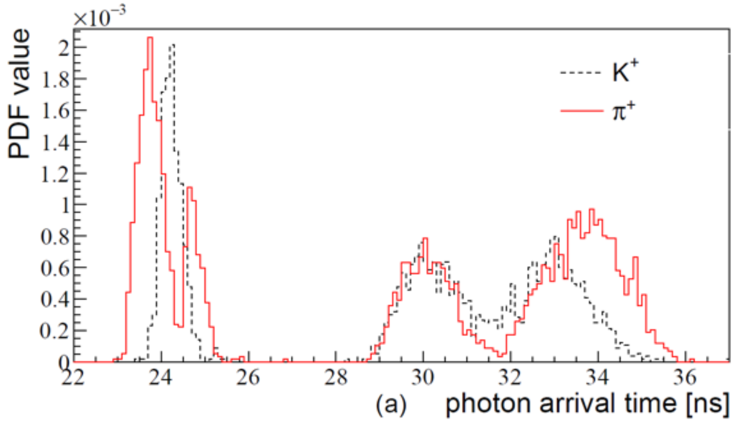


Belle II TOP time PDF, Y. Arita, QFPU 2013



M. Zuehlsdorf, IEEE2014
PANDA Barrel DIRC TDR, arXiv:1710.00684

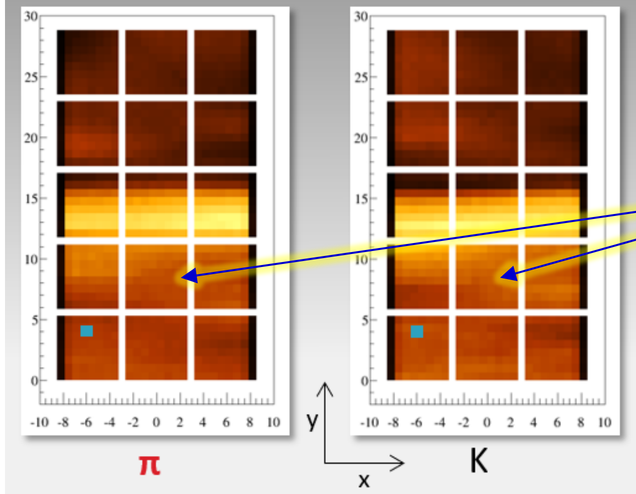
Example of time-based imaging from PANDA Barrel DIRC (older design, wide plate, no focusing, Geant4)



Another PANDA Barrel DIRC example,

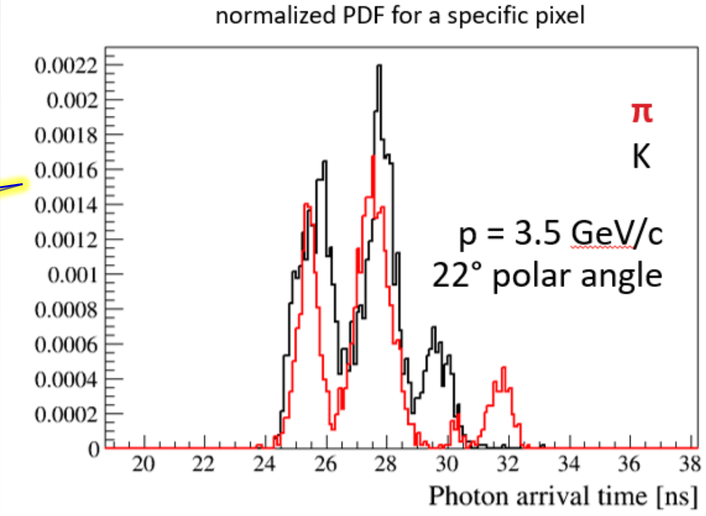
simulated PDF for one pixel,

3.5 GeV/c, 22deg polar angle, final design.



MC Simulation

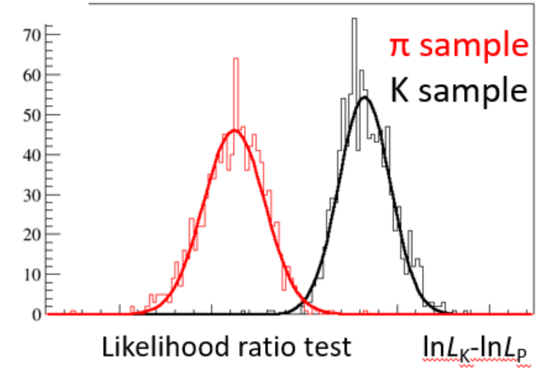
PMT map, with 5 x 3 sensors, 64 pixels each



In **3 dimensions** (x, y, t) hit patterns show **differences** between particle species

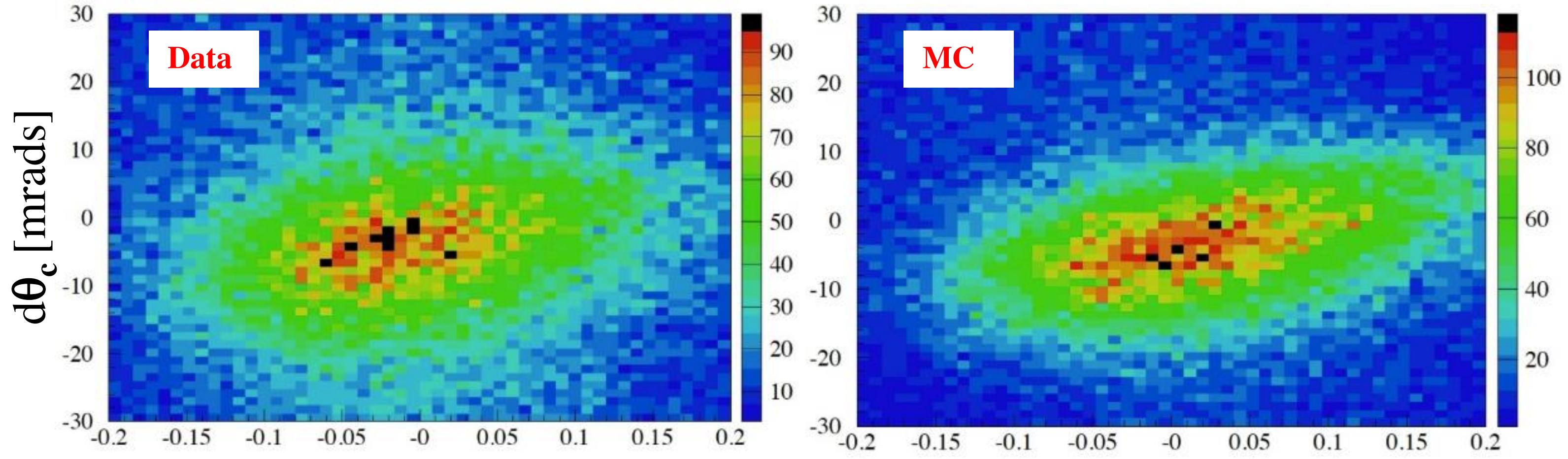
Probability density functions (**pdf**) can be generated with ~100k **Monte Carlo** tracks with same parameters and saved in histograms.

Inspired by Belle II TOP



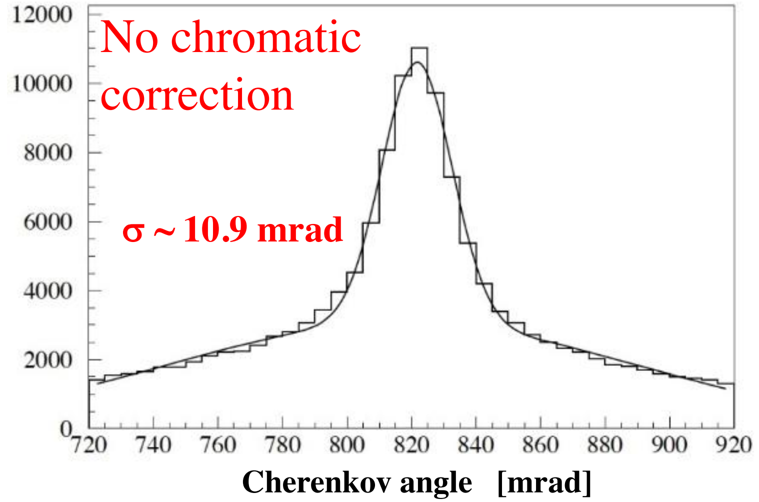
D.A. Roberts et al., "Results from the FDIRC prototype", RICH 2016 and Nucl. Instr. Meth. A, 766, 2014.

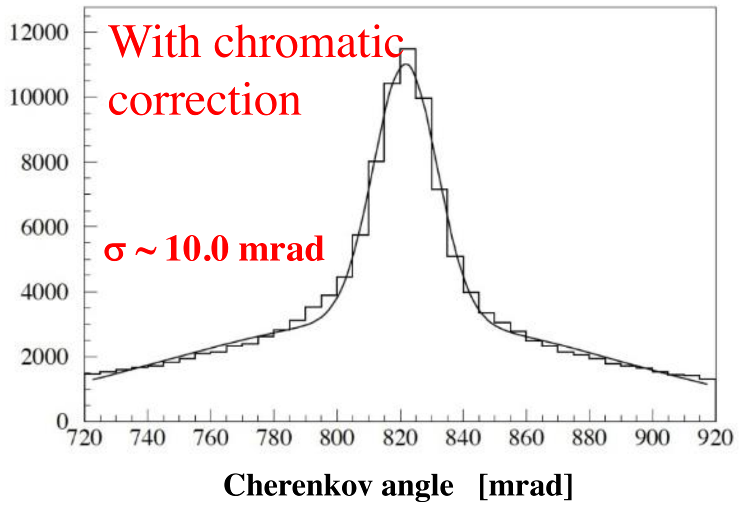
Chromatic correction using 3D tracks and real bar box in CRT.



$dTOP/L_{path} = (TOP_{measured} - TOP_{expected})/L_{path}$

Backward photons, long paths



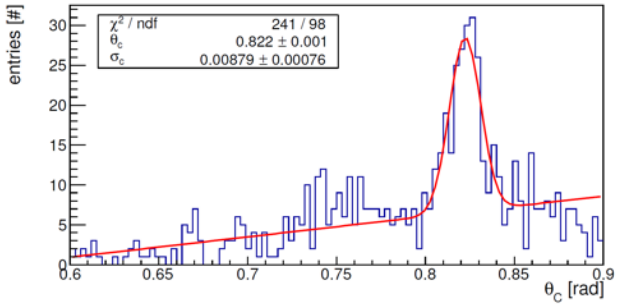


Clear improvement of single photon Cherenkov angle resolution, ~0.8 mrad, even with very modest timing precision.

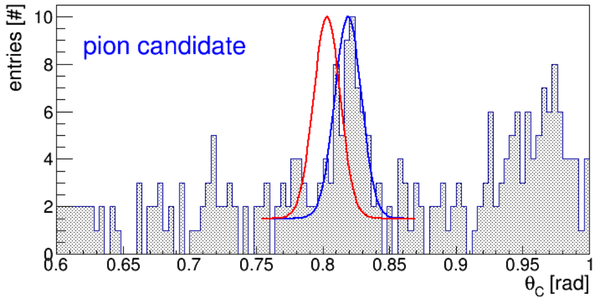
Reconstruction/PID with Narrow Bar in PANDA

Used three methods to evaluate PID performance of geometry with the narrow bar

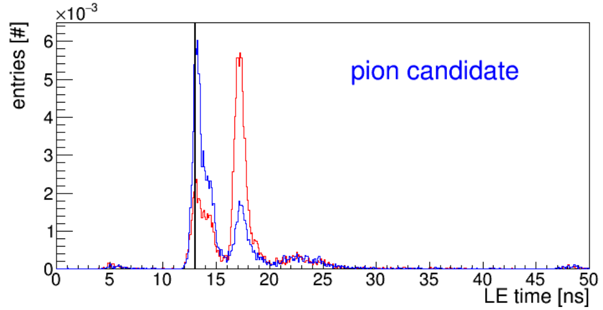
- track-by-track fit of single photon Cherenkov angle distribution to extract track Cherenkov angle (geom. reco)



- track-by-track unbinned likelihood hypothesis test to extract log-likelihood differences (geom. reco)



- time-based imaging to extract log-likelihood differences (PDFs were generated from beam data directly using time-of-flight tag, statistically independent data sets)



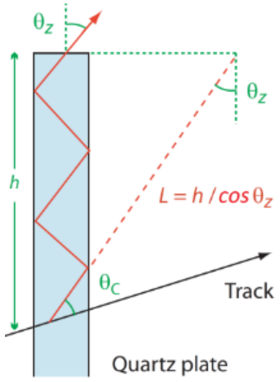
M. van Dijk, RICH2013

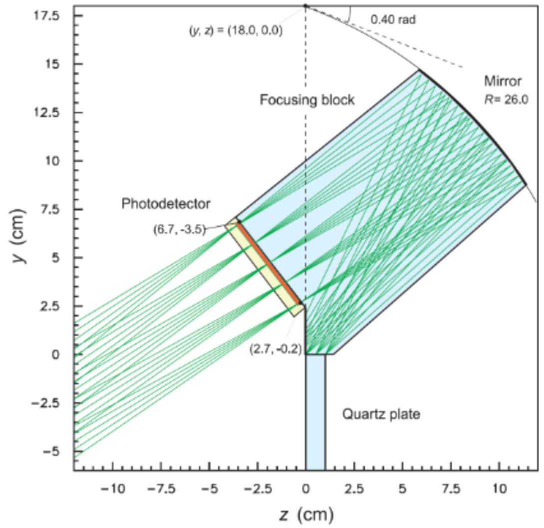
TORCH: R&D project for possible LHCb upgrade:

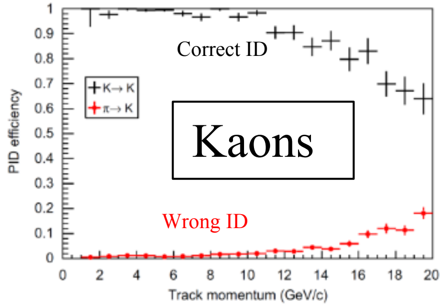
Particle ID for low/intermediate momentum (2-10 GeV/c)

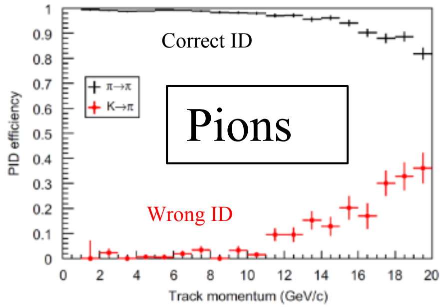
- Large quartz Cherenkov radiator plate (idealised design) with focusing block on top and bottom
- Photons extracted through total internal reflection

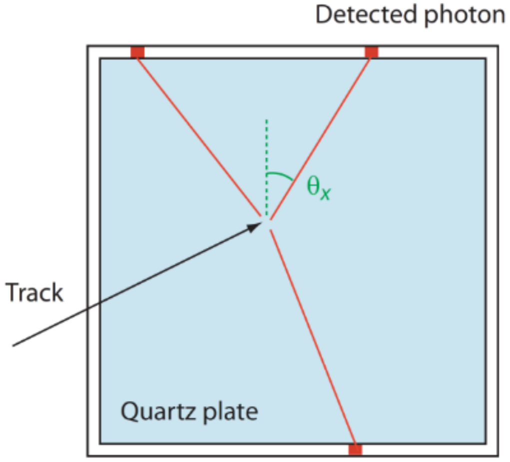
- Pions and kaons are separated in time-of-flight due to slightly different mass
- Precise time-of-flight measurement coupled to momentum information leads to identification
- Goal is to provide 3σ pion-kaon separation (needs <12.5ps per-track resolution)











LHCb TORCH

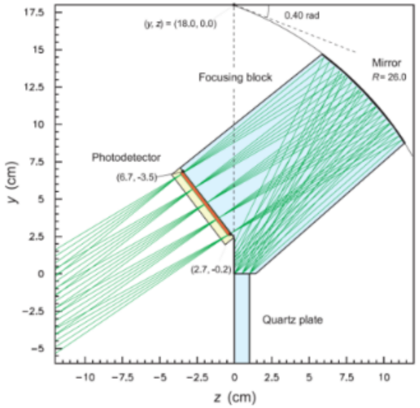
M. van Dijk, RICH2013

- Geant simulation of idealised quartz plate and focusing block
- Detector effects to be added in

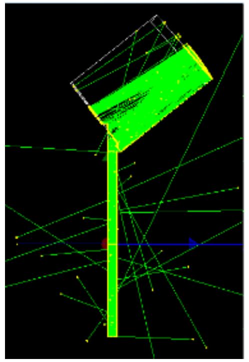
- Extra (noise) photons detected from secondary tracks (electrons) that also give of Cherenkov radiation
- Width of Cherenkov ring segment due to chromatic dispersion in quartz medium
- Simulation of accumulated photons for a thousand 10 GeV kaons

- R&D cooperation with Photek to develop high-granularity, long-lifetime, close-packing MCP-PMT.

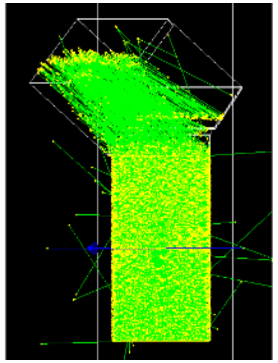
MCP-PMT matches requirement for PANDA Disk DIRC.



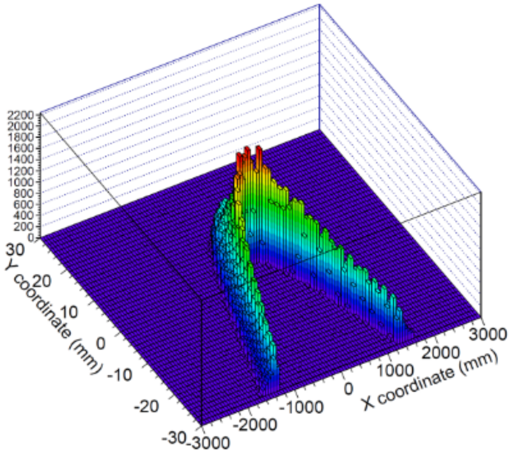
Viewpoint angles:
θ=270° φ=0°



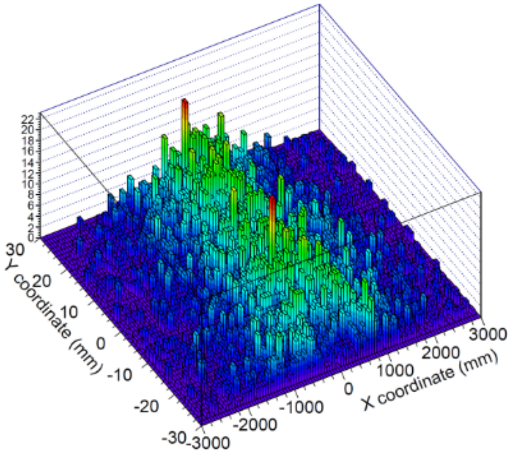
Viewpoint angles:
θ=120° φ=0°



Photons from primary track



Photons from secondary tracks



LHCb TORCH

N. Harnew, DIRC2017

- TORCH is a DIRC-type detector to achieve high-precision time-of-flight over large areas aiming to achieve K-π separation up to 10 GeV/c and beyond (with a TOF resolution of ~15 ps per track for ~30 photons)

- Ongoing R&D programme aims to produce suitable MCP-PMT, satisfying challenging requirements of lifetime, granularity, charge sharing and active area.

- Testbeam results very promising
  - Performance has been shown to be very good ~approaching 70ps time resolution per photon

- TORCH future : beam tests over the coming year
  - New optics half-sized module have been delivered
  - Phase-III MCP-PMTs are under test
  - New generation of electronics being commissioned
  - Included in future plans of the LHCb experiment

- After R&D demonstration, prepare physics case & technical proposal for LHCb

DIRC 2017, Castle Rauischholzhausen August 8, 2017 N. Harnew 23