Development of FARICH technique for the Super Charm-Tau Factory project.

Alexander Barnyakov

on behalf of BINP PID-group of SCT-collaboration

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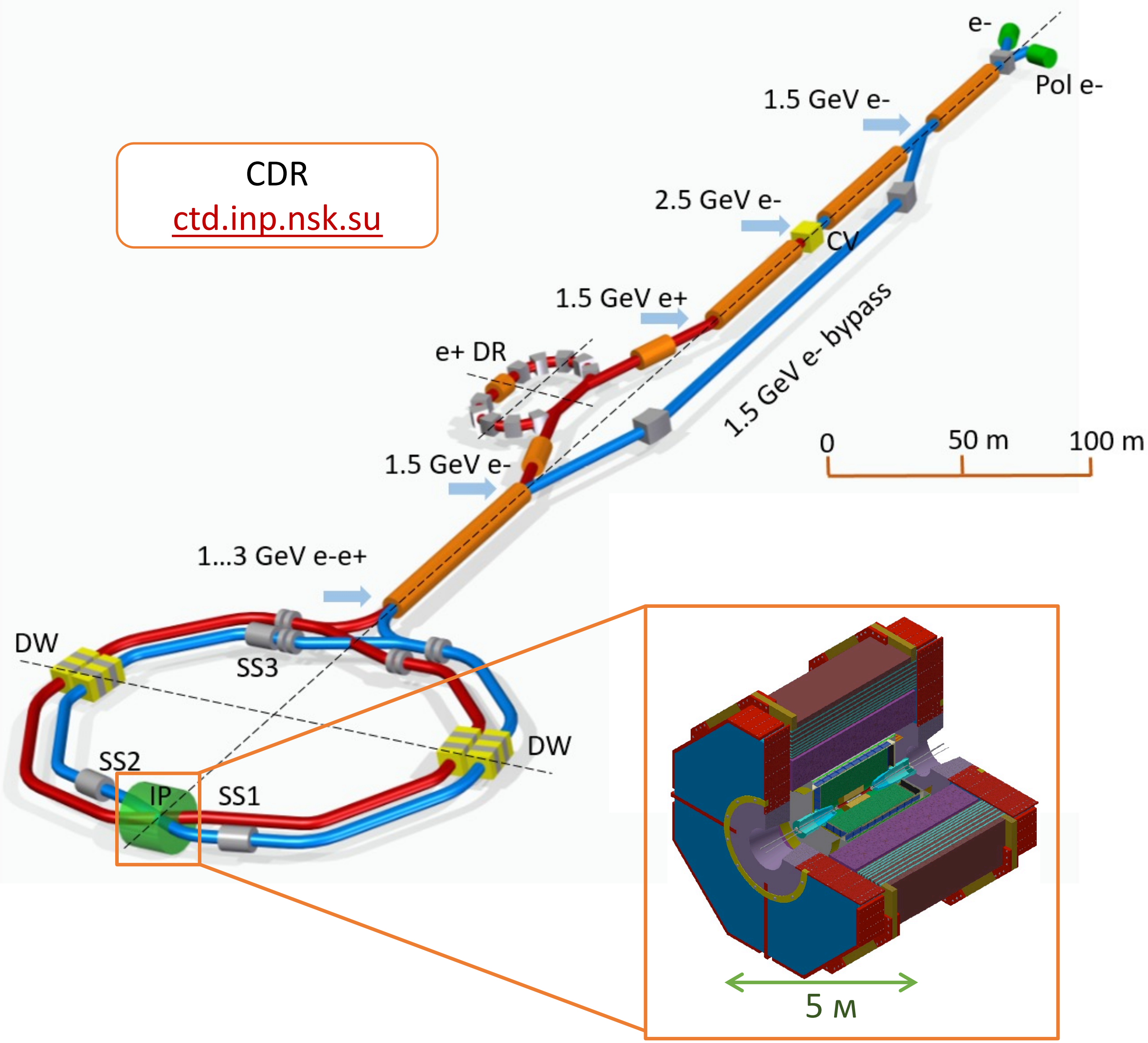
- **SCTF project overview**
- **PID system**
  - **FARICH technique progress**
  - **FARICH with dual aerogel radiator concept**
- **Summary**

4–8 September 2023

CTICC, Cape Town, South Africa

The SCT experiment

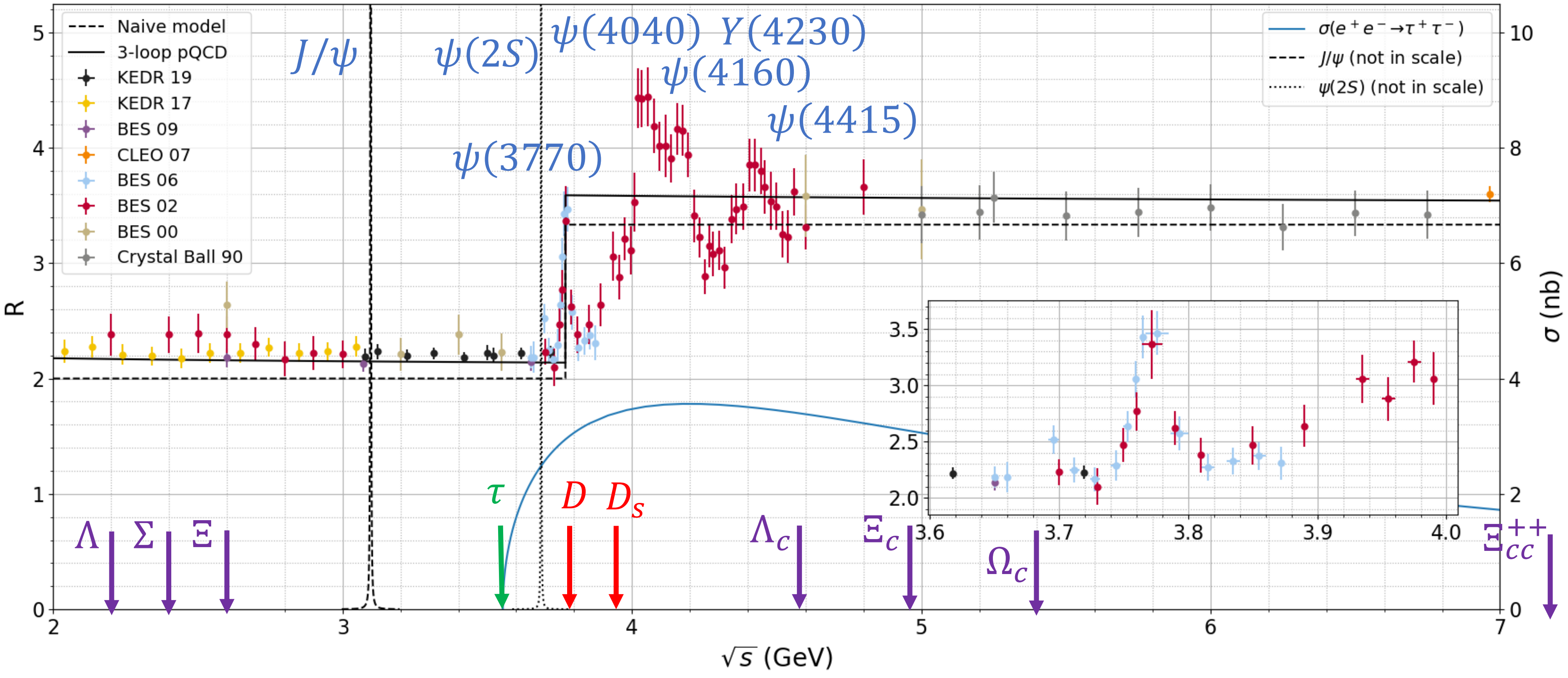
- Super charm-tau factory is $e{+}e{-}$ collider, dedicated to precision study of properties of charm-quark, τ-lepton, study of strong interactions, search of BSM physics
  - Beam energy from 1.5 (1.0) to 3.5 GeV
  - Luminosity $\mathcal{L} = 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @ 2 GeV
  - Longitudinal polarization of the e^- beams
- Experiments will be conducted using state-of- the-art general purpose detector
  - Tracking (including low p_t)
  - Calorimetry (high resolution, fast, π^0/γ sep.)
  - PID system:
    - π/K – separation up to 3.5 GeV/c
    - μ/π – separation up to 1.5 GeV/c



The SCT energy range

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma_0(e^+e^- \to \mu^+\mu^-)}$$

Threshold production of nonrelativistic particles provides best conditions for their comprehensive study



$\mathcal{L} = 10^{35}$ cm$^{-2}s^{-1}$

A one-year dataset

$2E$, GeV	Events recorded
3.1	$10^{12}\, J/\psi$
3.69	$10^{11}\, \psi(2S)$
3.77	$10^{9}\, D\bar{D}$
4.17	$10^{8}\, D_s\bar{D}_s$
3.55 ÷ 4.3	$10^{10}\, \tau\,\tau$
4.65	$10^{8}\, \Lambda_c^+\Lambda_c^-$

SCT Physics in a nutshell

charm

- ✓ Measurement of the strong phases of D decay amplitudes
- ✓ Measurement of absolute branching fractions
- ✓ Searches for rare and forbidden decays of the charm quark
- ✓ CP violation in charm
- ✓ …

Input for B meson studies at LHCb and Belle II

QCD

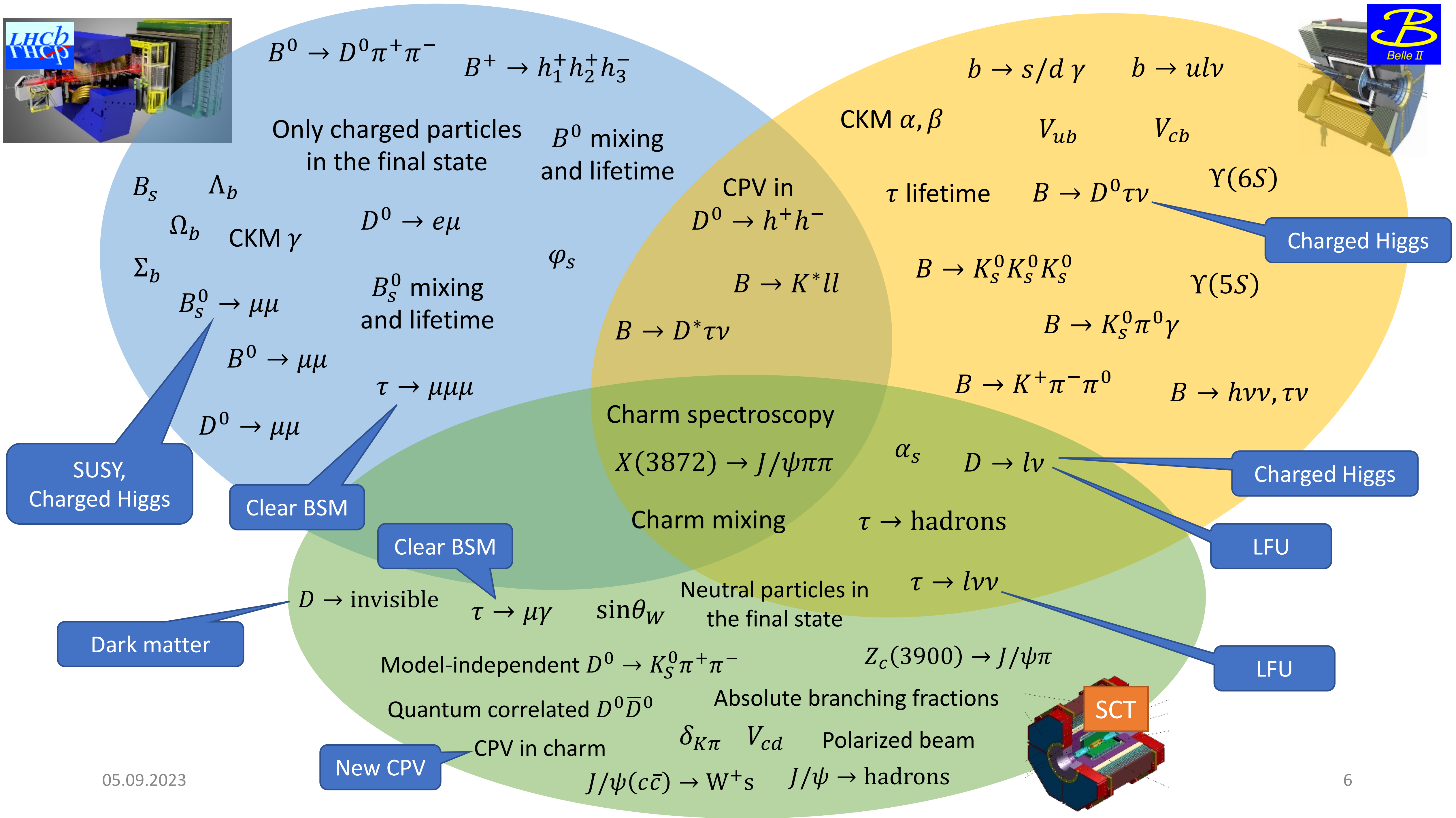
- ✓ Physics of highly-excited quarkonium
- ✓ Molecular states
- ✓ Baryon interaction at threshold
- ✓ Search for glueballs in decays of J/ψ and $\psi(2S)$
- ✓ …

tau

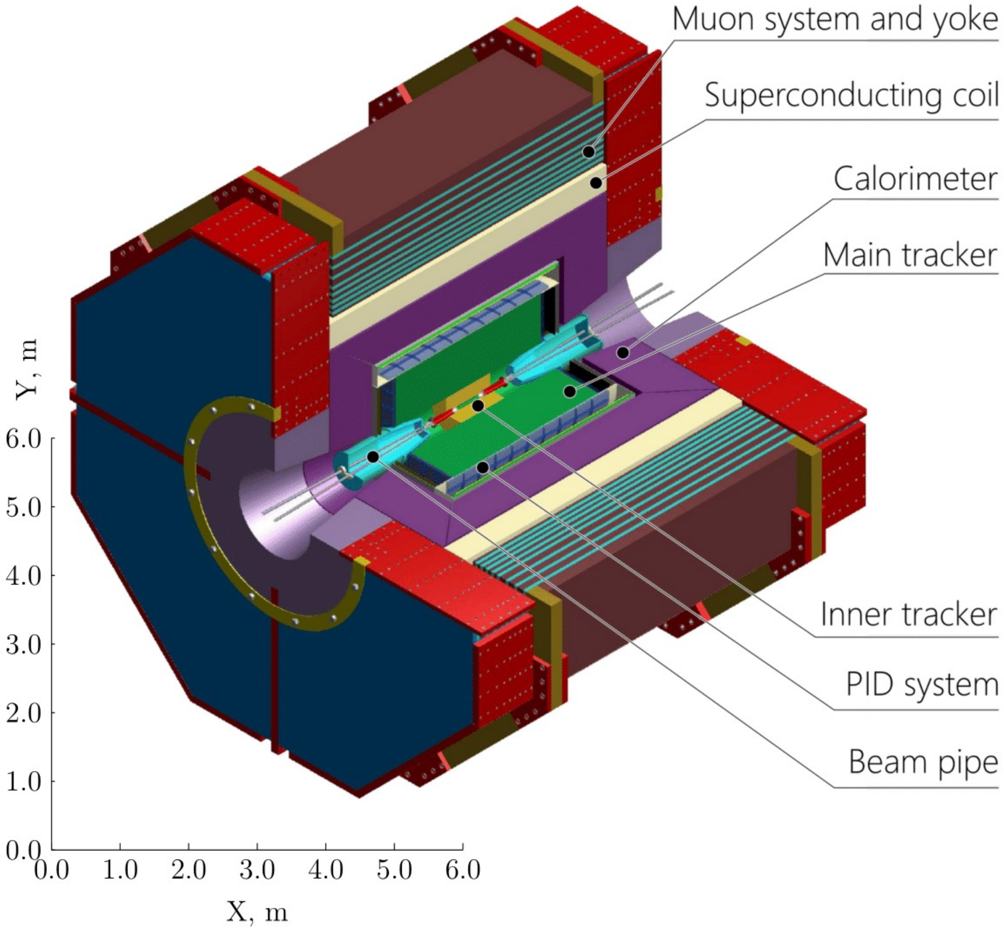
- ✓ Precision measurement of the τ lepton properties
- ✓ Michel parameters, tests of lepton universality
- ✓ Precision measurement of hadronic τ decays
- ✓ Search for CP and T violation in τ decays
- ✓ …

Test of the electroweak sector of the SM

QCD, α_s, V_{us}. Test of the electroweak model, searches for non-standard contributions


LHCb
Belle II
SCT
$B^0 \to D^0\pi^+\pi^-$
$B^+ \to h_1^+ h_2^+ h_3^-$
Only charged particles in the final state
B^0 mixing and lifetime
B_s
Λ_b
Ω_b
CKM γ
Σ_b
$D^0 \to e\mu$
φ_s
$B_s^0 \to \mu\mu$
B_s^0 mixing and lifetime
$B^0 \to \mu\mu$
$\tau \to \mu\mu\mu$
$D^0 \to \mu\mu$
SUSY, Charged Higgs
Clear BSM
$b \to s/d\,\gamma$
$b \to ul\nu$
CKM α, β
V_{ub}
V_{cb}
CPV in $D^0 \to h^+h^-$
τ lifetime
$B \to D^0\tau\nu$
$\Upsilon(6S)$
Charged Higgs
$B \to K^*ll$
$B \to K_S^0K_S^0K_S^0$
$\Upsilon(5S)$
$B \to D^*\tau\nu$
$B \to K_S^0\pi^0\gamma$
$B \to K^+\pi^-\pi^0$
$B \to h\nu\nu, \tau\nu$
Charm spectroscopy
$X(3872) \to J/\psi\pi\pi$
α_s
$D \to l\nu$
Charged Higgs
Charm mixing
$\tau \to$ hadrons
LFU
Clear BSM
$D \to$ invisible
$\tau \to \mu\gamma$
$\sin\theta_W$
Neutral particles in the final state
$\tau \to l\nu\nu$
Dark matter
LFU
Model-independent $D^0 \to K_S^0\pi^+\pi^-$
$Z_c(3900) \to J/\psi\pi$
Quantum correlated $D^0\bar{D}^0$
Absolute branching fractions
$\delta_{K\pi}$
V_{cd}
Polarized beam
New CPV
CPV in charm
$J/\psi(c\bar{c}) \to W^+s$
$J/\psi \to$ hadrons

Detector concept



Momentum resolution $\sigma_p \leq 0.4\%$ at $1 GeV/c$

Very symmetric and hermetic

Able to detect soft tracks ($p_t \geq 50\ MeV/c$)

- Inner tracker should be able to handle 104 tracks/cm2s

Very good PID: $\mu/\pi/K$

- π/K up to 3.5 GeV/c, e.g. for $D\bar{D}$ mixing
- μ/π up to 1.5 GeV/c, e.g. for $\tau \rightarrow \mu\gamma$ search
- dE/dx better than 7% for PID below 0.6 GeV/c

Able to detect γ from 10 MeV to 3.5 GeV, good π^0/γ separation

- Calorimeter energy resolution $\sigma_E \leq 1.8\%$ at 1 GeV
- Calorimeter time resolution $\sigma_t \leq 1$ ns

Efficient “soft” trigger
Ability to operate at high luminosity, up to 300 kHz at J/ψ

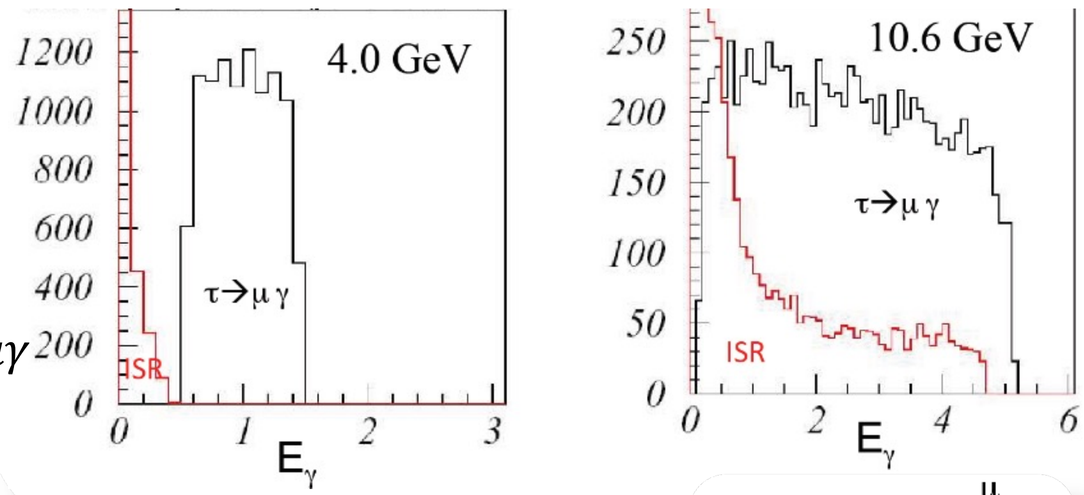
Requirements for μ/π–separation from physics program

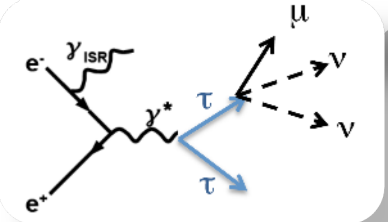
LFV with tau

$\tau \to \mu\gamma$

- Allowed in several BSM scenario, including SUSY, leptoquarks, technicolor, and extended Higgs models
- $\mathcal{O}(10^{-9})$ – reachable upper limit at SCT for the branching of $\tau \to \mu\gamma$
- Requires excellent π/μ separation from 0.5 to 1.5 GeV/c to suppress background $\tau \to \pi\pi^0\nu$

ISR photon background [arXiv:1206.1909 [hep-ex]]

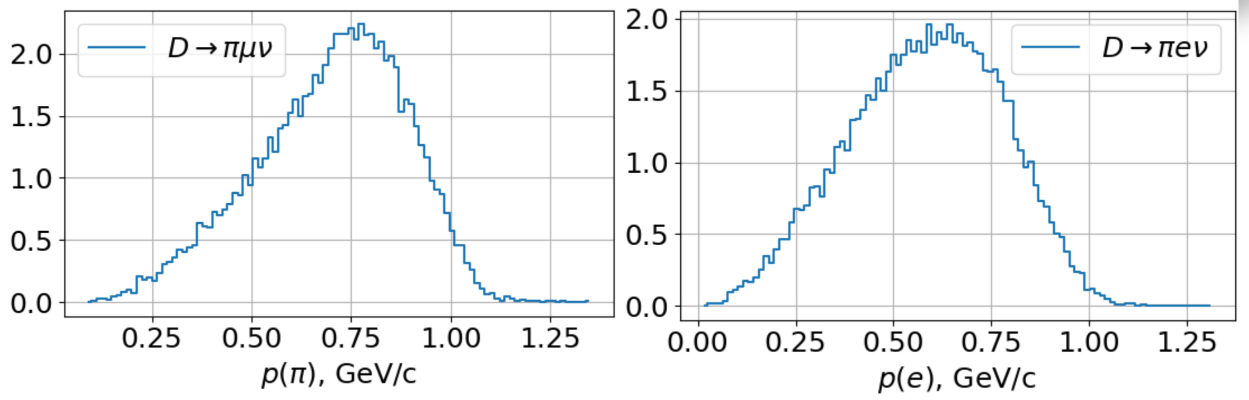




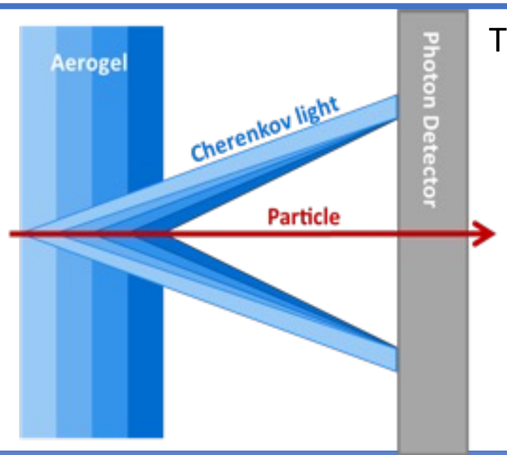
LU precise tests with D-mesons

$D \to \mu\pi\nu$, $D \to e\pi\nu$ ...

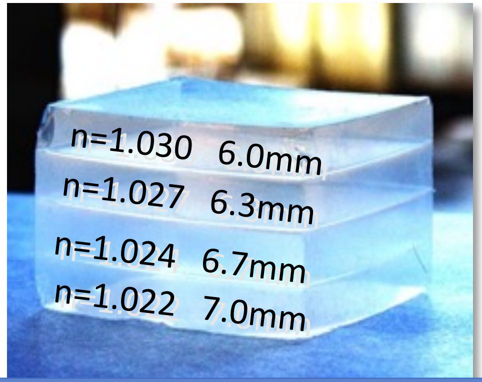
- Requires excellent π/μ separation from 0.2 to 1.0 GeV/c to suppress background $D \to \pi^+\pi^-\pi^0$ and so on.



FARICH technique



The first 4-layer monolithic sample

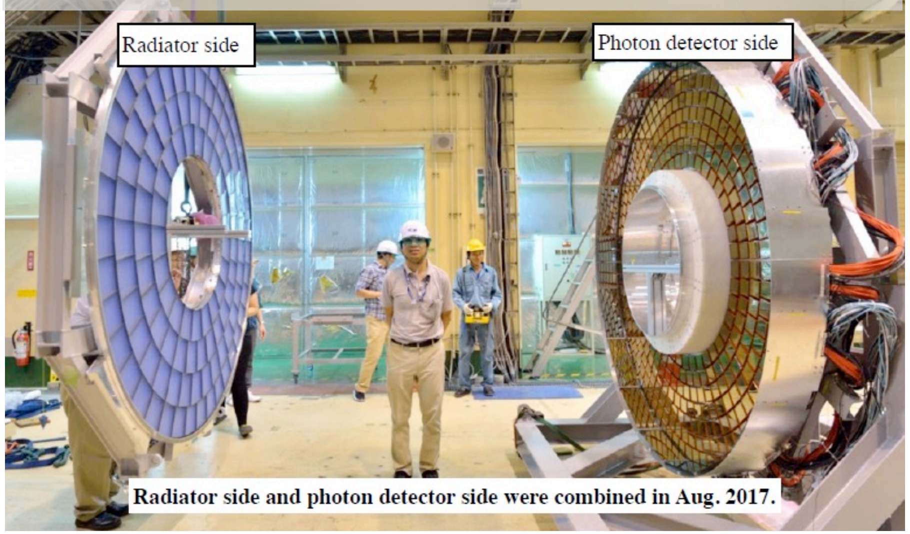


Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

T.Iijima et al., NIM A548 (2005) 383 and A.Yu.Barnyakov et al., NIM A553 (2005) 70

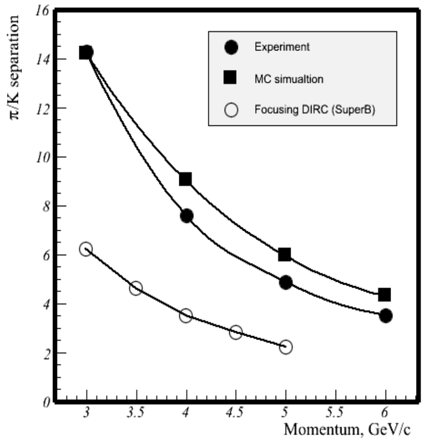
2004÷2005

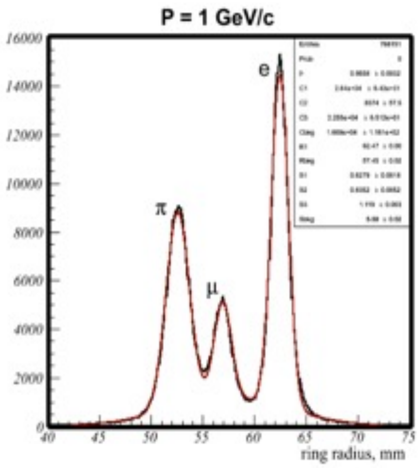
The Belle II (ARICH) is the first application of the method



2017

Excellent PID capability were shown at CERN beam test in 2012





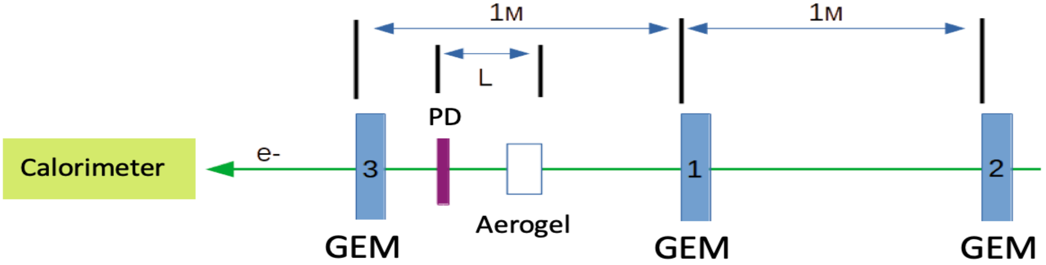
A.Yu. Barnyakov, et al., NIM A 732 (2013) 352

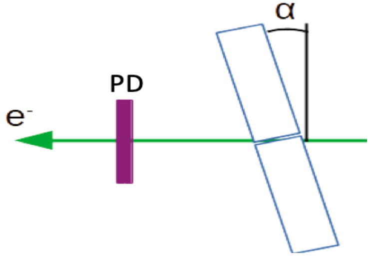
- Two layer ARICH-Belle II (n=1.045|2 cm + n=1.055|2 cm) provides exccelent π/K – separation up to 4 GeV/c
- Four layer FARICH ($thick_{total}$ =3.5 cm & n_{max}=1.05) is able to provide exccelent ($\geq 3\sigma$)

  π/K – separation up to 6 GeV/c

  μ/π – separation up to 1.5 GeV/c

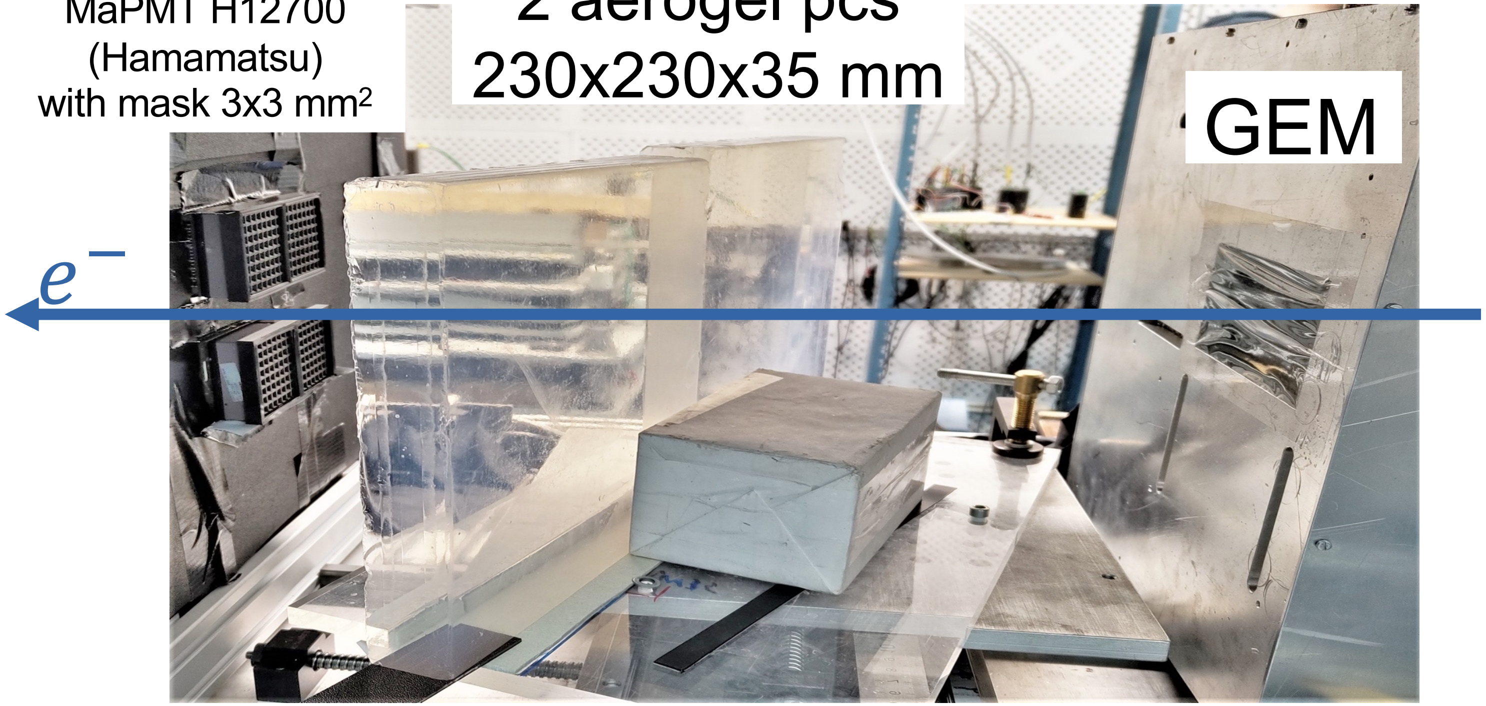
The largest focusing aerogel samples produced in 2022

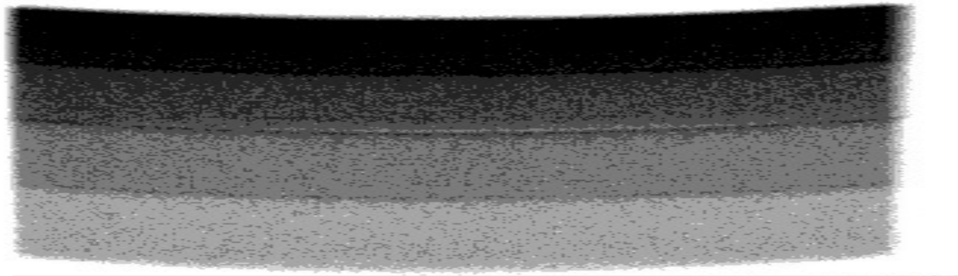




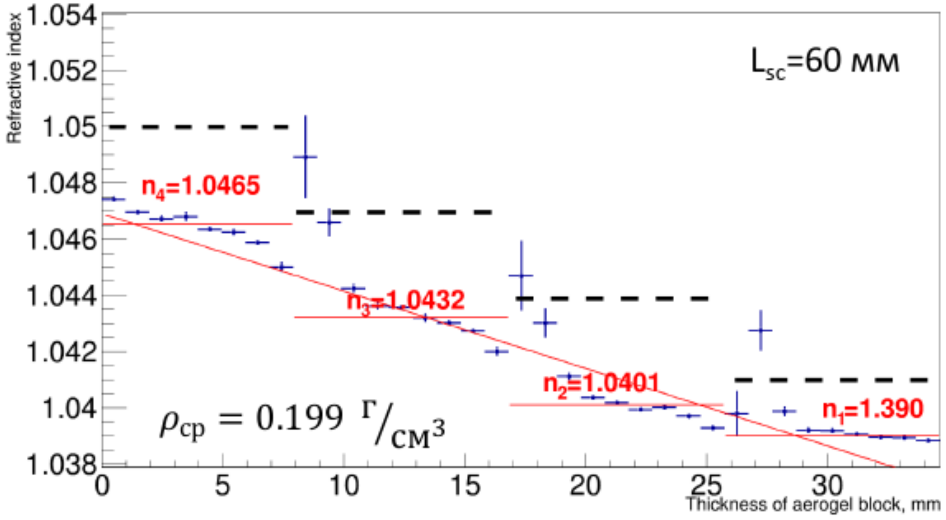
MaPMT H12700 (Hamamatsu) with mask 3x3 mm²

2 aerogel pcs 230x230x35 mm





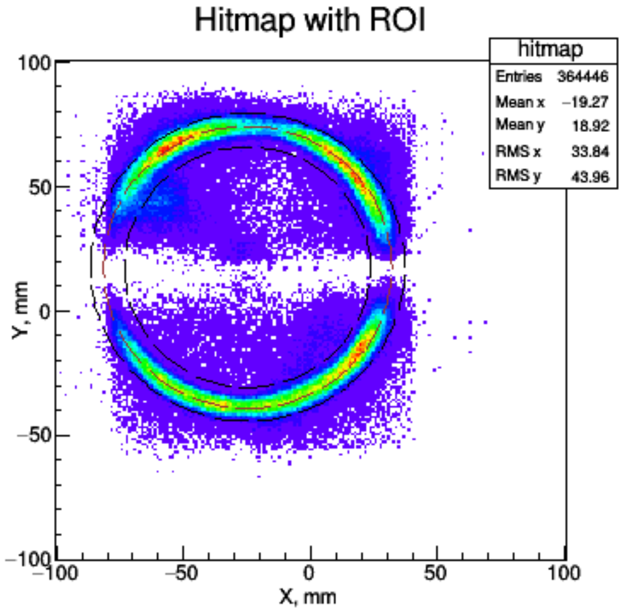
Refractive index profile is measured with help of didgital X-ray setup at the BINP.

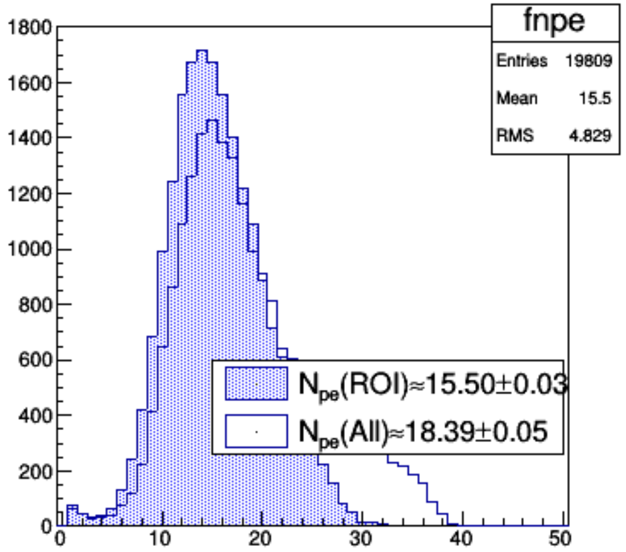


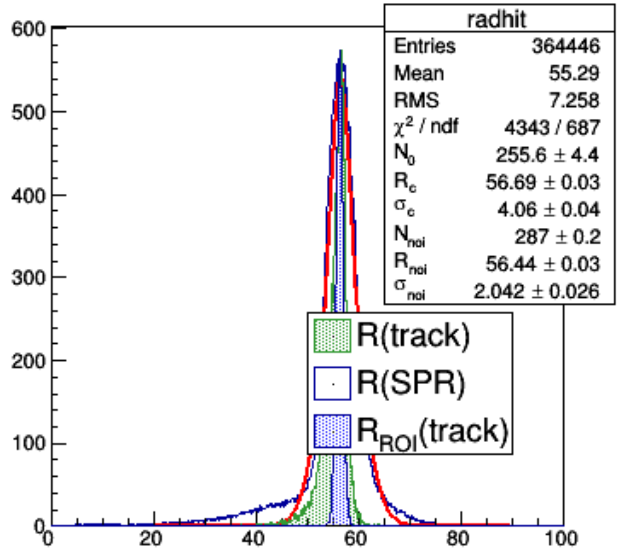
Single photon Cherenkov angle resolution is investigated with relativistic electrons at BINP beam test facilities "Extracted beams of VEPP-4M complex".

FARICH beam test 2023 results

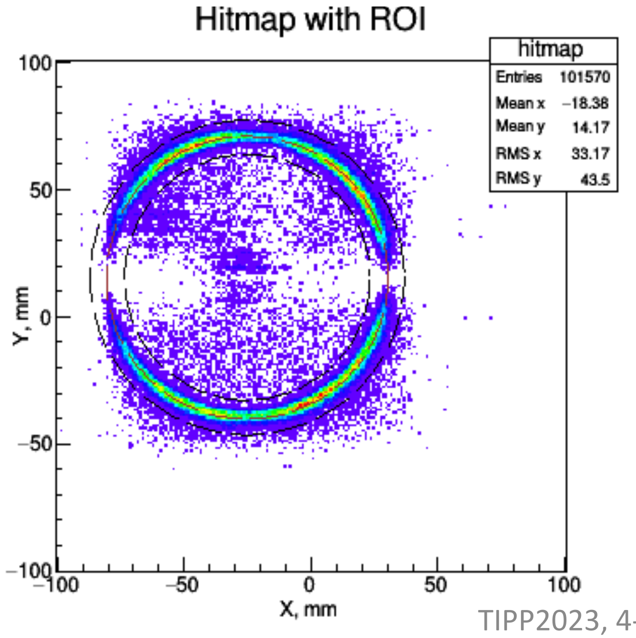
Pixel 6x6 mm
Geom.Eff. ~ 80%

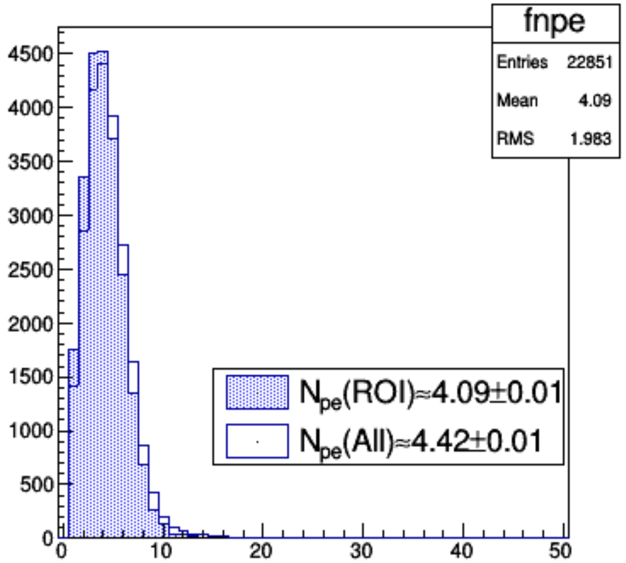


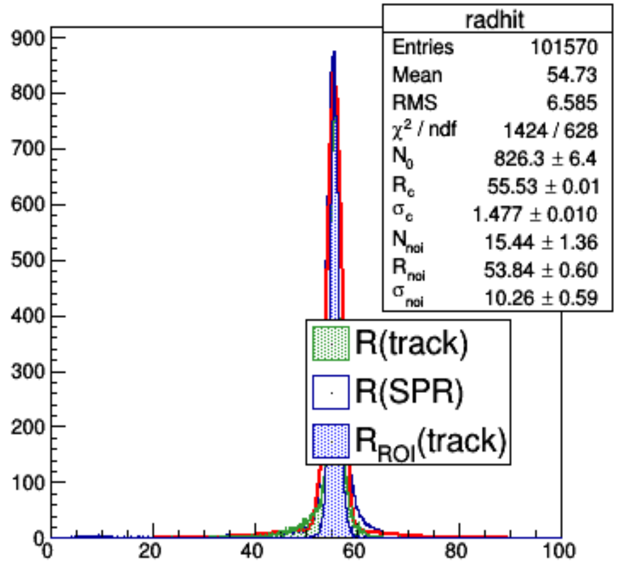




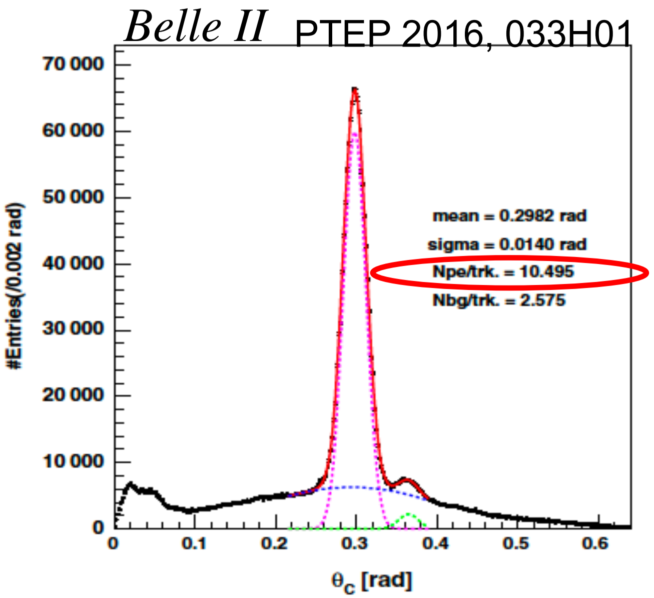
Pixel 3x3 mm
Geom.Eff. ~ 20%

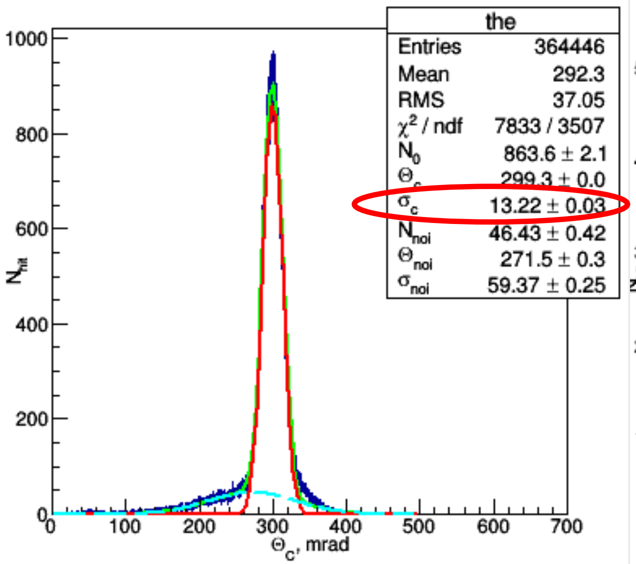


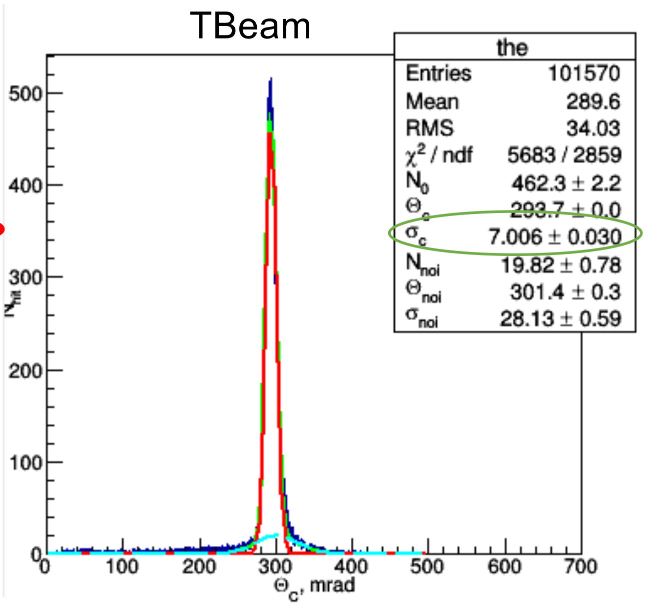


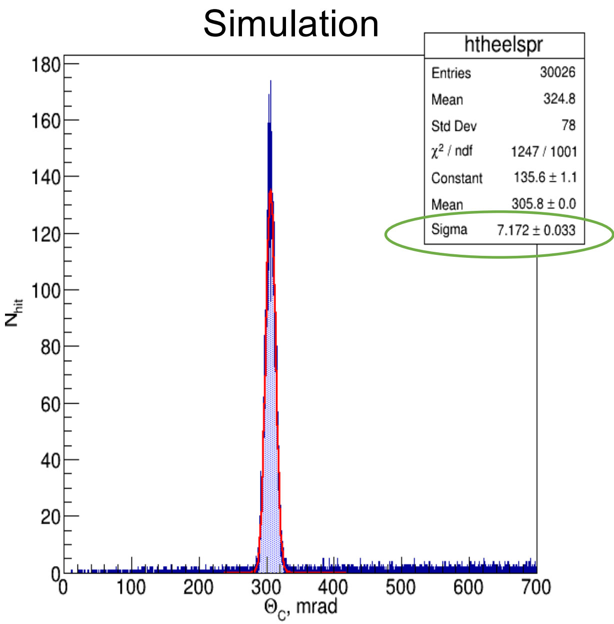


TBeam results consideration









	Belle II	4-layers (Novosibirsk)	TBeam	Simulation
Aerogel:	20+20 mm (Chiba Univ.)	4-layers (Novosibirsk) –>	–	4-layers (ideal profile)
n(400nm):	1.045 +1.055	1.039 ÷ 1.046	–	1.041 ÷ 1.050
Pixel:	5x5 mm	6x6 mm	3x3 mm	3x3 mm

Geom.Eff. ~ 90%	Geom.Eff. ~ 80%	Geom.Eff. ~ 20%
$N_{pe} \approx 10.5$	$N_{pe} \approx 16$	$N_{pe} \approx 4$

SPE resolution ~7÷8 $mrad$ is able to provide:

- π/K @ 8.0 GeV/c $> 3\sigma$ if ($N_{PE} = 16$) and π/K @ 6.0 GeV/c $> 3\sigma$ if ($N_{PE} = 8$)
- μ/π @ 1.5 GeV/c $> 3\sigma$ if ($N_{PE} = 16$) and μ/π @ 1.3 GeV/c $> 3\sigma$ if ($N_{PE} = 8$)

Dimensions of focusing aerogels 23x23x3.5 cm allow us to design the full-scale FARICH systems for the future particle physis experiments.

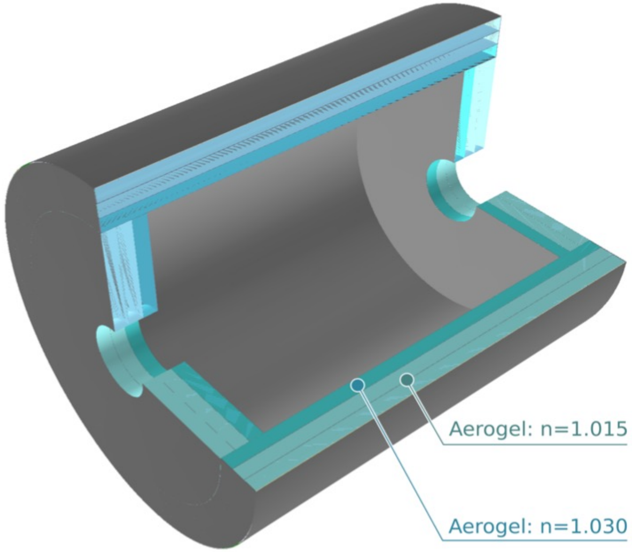
PID options for π/K – separation

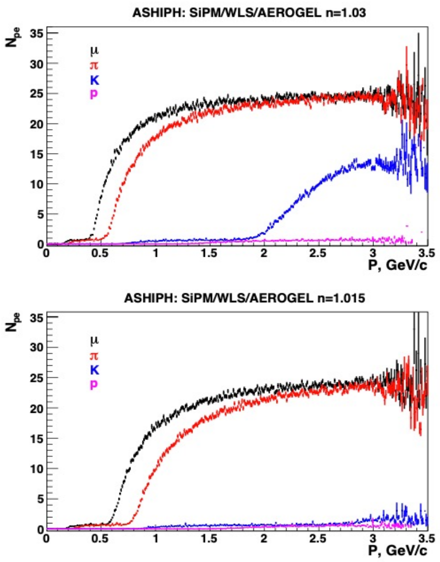
- $^{dE}/_{dx}$
    - $\frac{\sigma_{dE/dx}}{\langle dE/dx \rangle} \leq 7\% \rightarrow \geq 3\sigma$ up to 0.6 GeV/c
    - $\frac{\sigma_{N_{cl}/dx}}{\langle N_{cl}/dx \rangle} \leq 4\% \rightarrow \geq 3\sigma$ up to 0.9 GeV/c
- Focusing Aerogel RICH (FARICH)

(4 layer @ n_{max}=1.05) → $\geq 3\sigma$ from 0.5 to 6 GeV/c

- ASHIPH@SiPM (n_1=1.03 and n_2=1.015) → $\geq 3\sigma$ from 0.6 to 3.5 GeV/c

EPJ Web of Conferences **212**, 01012 (2019),
A.Yu. Barnyakov *et al* 2020 *JINST* **15** C04032





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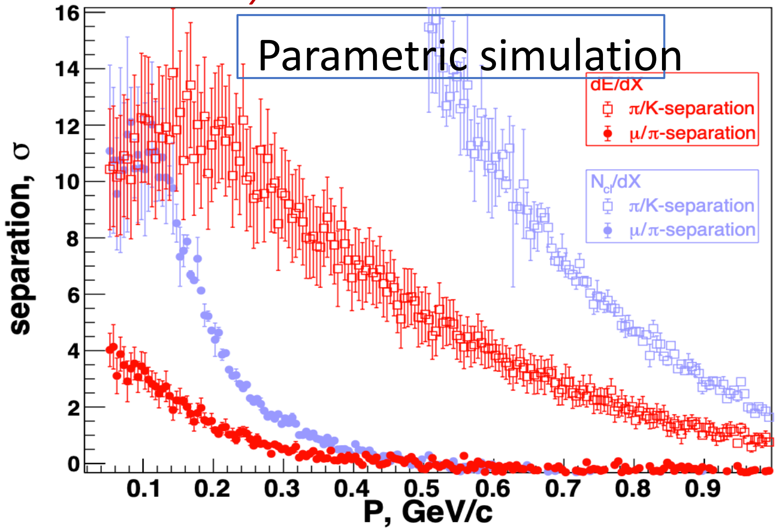
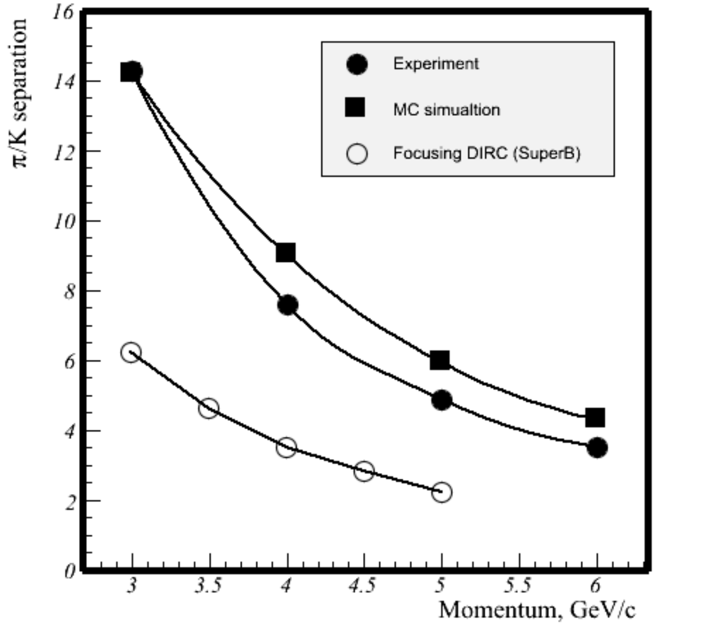
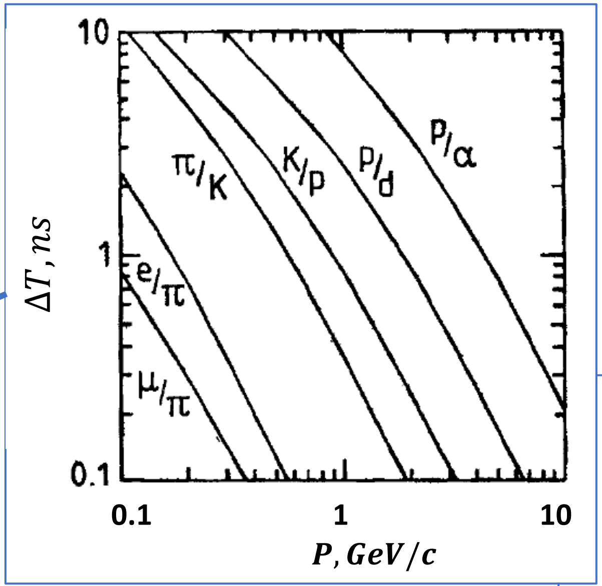


A.Yu. Barnyakov, et al., NIM A 732 (2013) 35



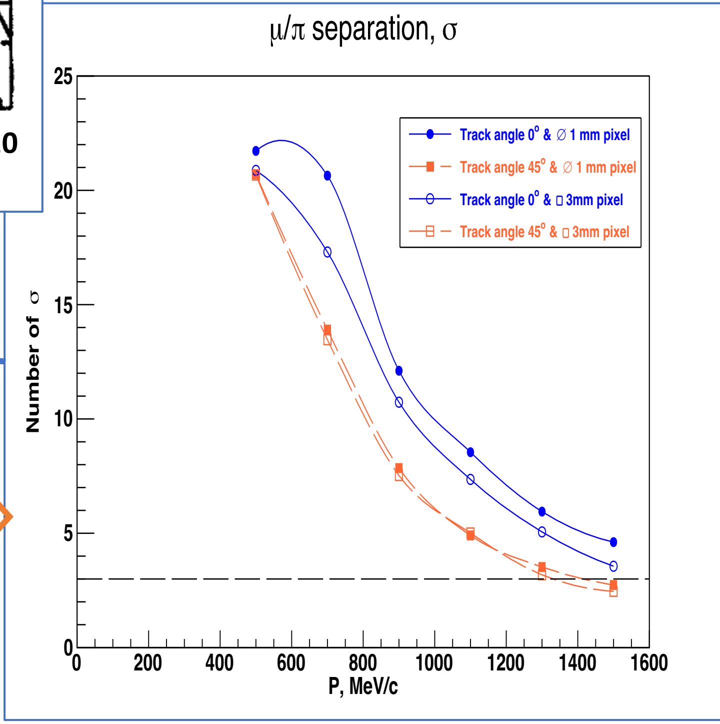
PID options for μ/π – separation

- $^{dE}/_{dx}$
  - $\frac{\sigma_{dE/dx}}{\langle dE/dx \rangle} \approx 7\% \rightarrow \geq 3\sigma$ up to 0.15 GeV/c
  - $\frac{\sigma_{N_{cl}/dx}}{\langle N_{cl}/dx \rangle} \approx 4\% \rightarrow \geq 3\sigma$ up to 0.25 GeV/c
- **TOF** with σ_t ≈100 ps $\rightarrow \geq 3\sigma$ up to 0.2 GeV/c, e.g. Chernkov light from entrance window of MCP-PMT
- **FARICH** (4-layer, n_{max}=1.05) $\rightarrow \geq 3\sigma$ from 0.5 to 1.5 GeV/c



FARICH with dual aerogel radiator is proposed to extend down μ/π – separation from 0.5 to 0.2 GeV/c

Results of parametric simulation tuned with results of beam test :
– SPR(β = 1, ■3 mm)= 1.63 mm
– SPR(β = 1, ø1 mm)= 1.36 mm

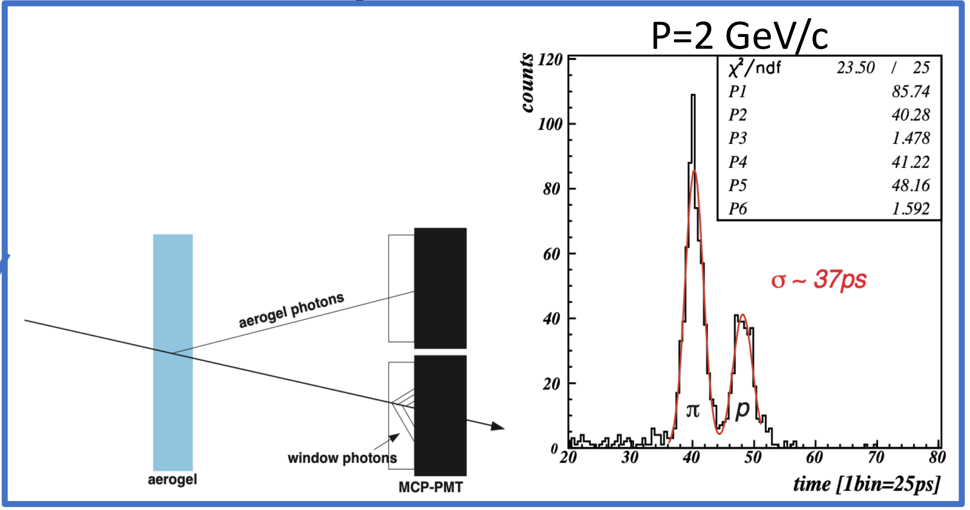


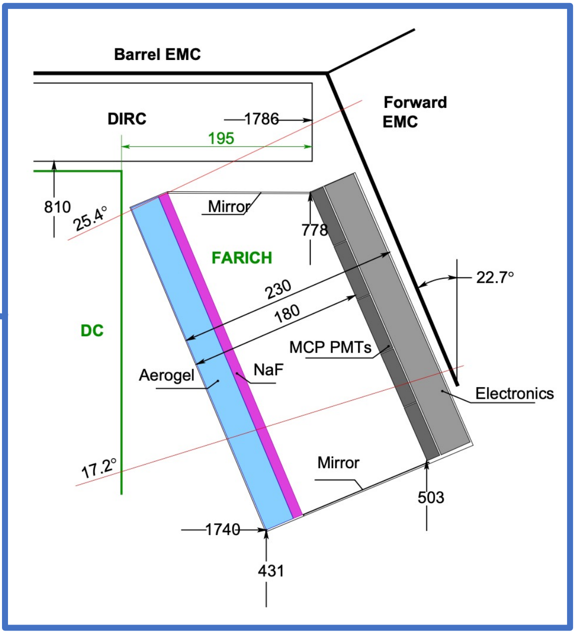
A.Yu.Barnyakov et al., NIMA 1039 (2022) 167044

RICH with dual radiators is not very new idea!

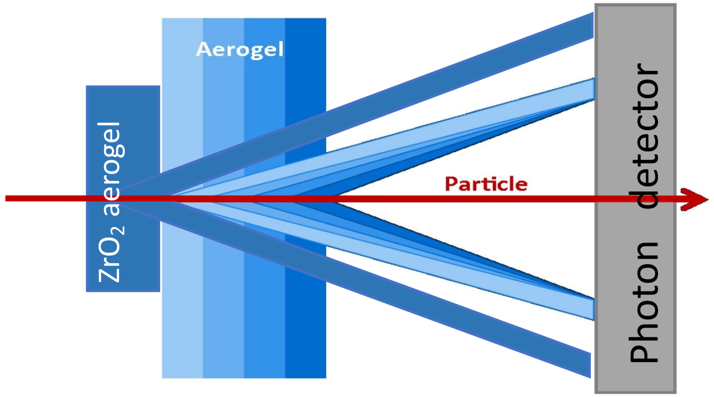
- Liquid + Gas:
  - RICH – DELPHI
  - CRID – SLD
    - C_6F_{12}(n=1.278@190nm) + C_5F_{10}(n=1.00174@190nm)
- Aerogel + Gas:
  - HERMES
  - RICH1 – LHCb
    - Aer.(n=1.03@400nm) + C_4F_{10}(n=1.00137@400nm)
- Aerogel + Crystal:
  - RICH+ToF – SuperB:
    - Aer.(n=1.05@400nm) + Quartz (n=1.47@400nm)
  - FARICH – SuperB:
    - 3-layer aer. n_{max}=1.07@400nm + NaF (n=1.33@400nm)
- Aerogel + Aerogel:
  - FARICH – SCTF:
    - 4-layer aer. n_{max}=1.05@400nm + aer (n=1.12@400nm)

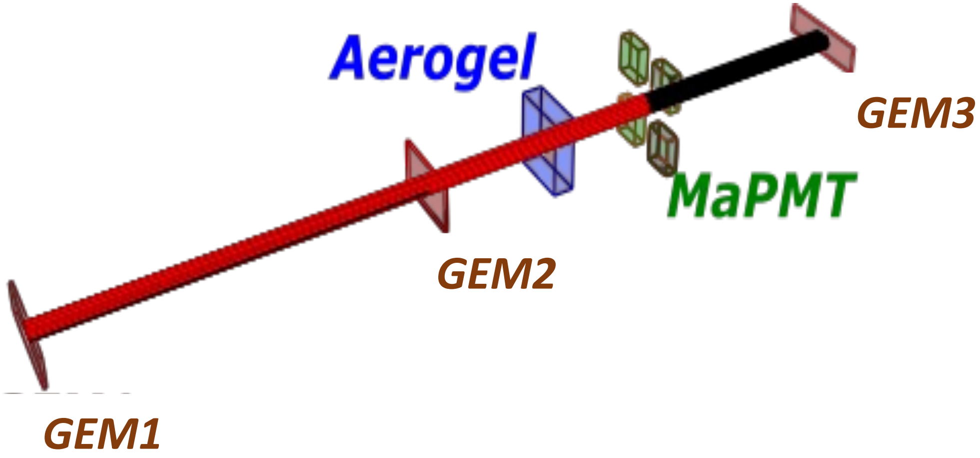
Aerogel is material with easy tunnable refractive index!

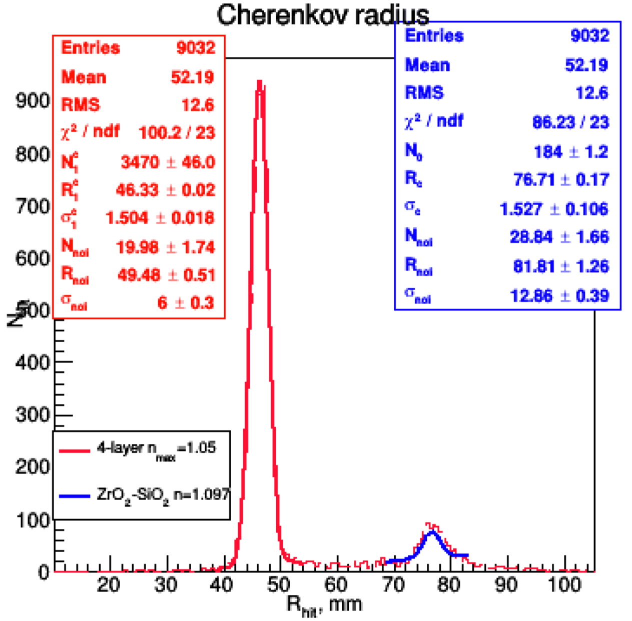


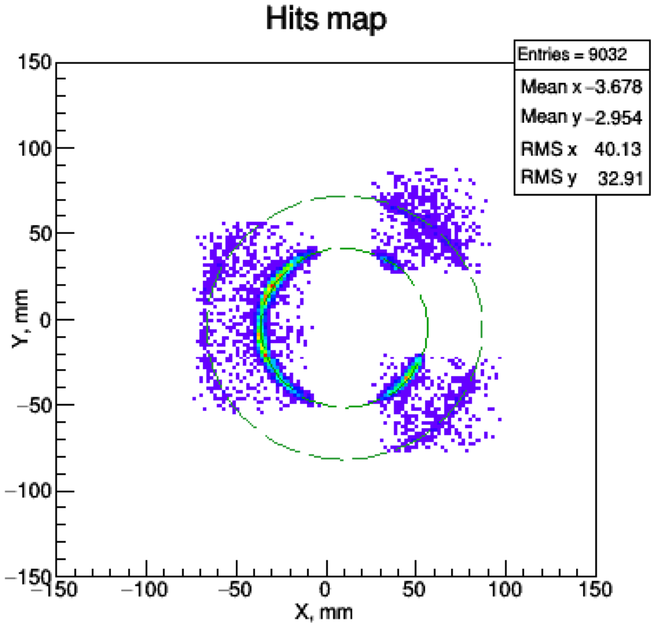


Beam tests results of FARICH with dual radiator









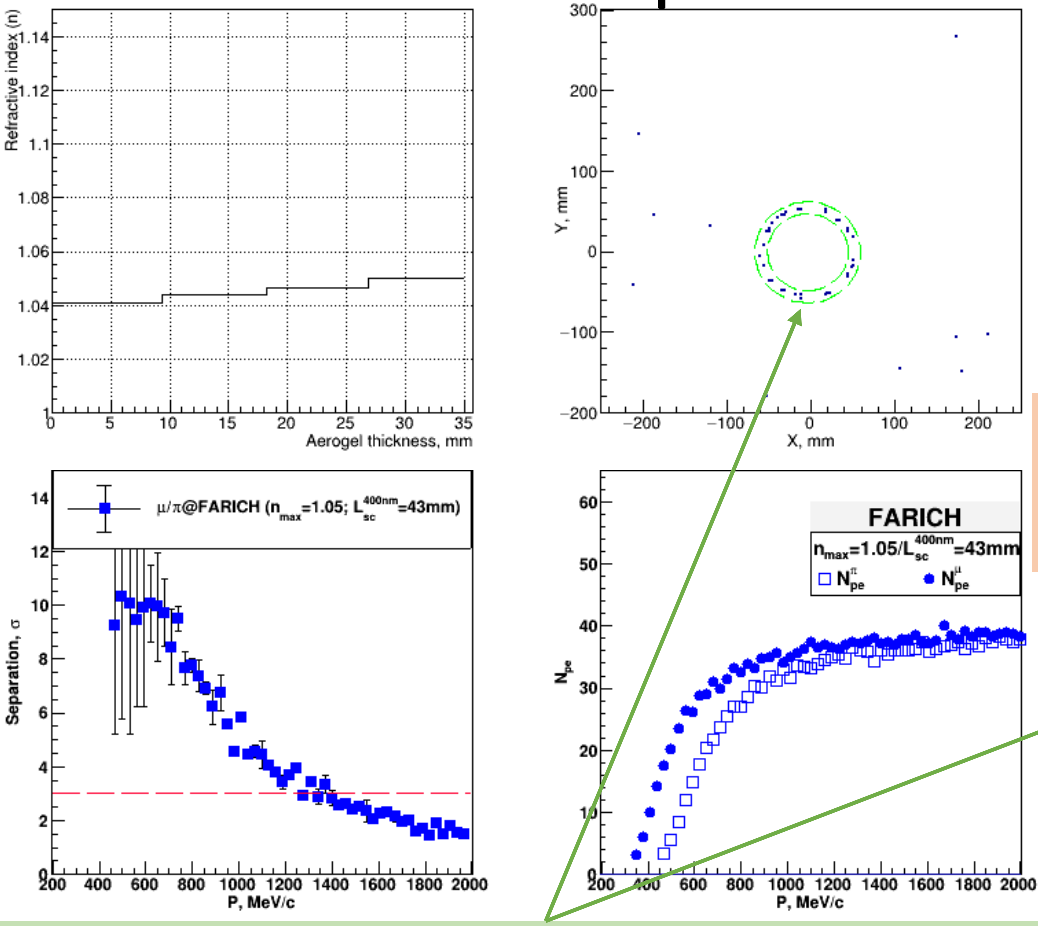
ZrO$_2$–SiO$_2$ aerogel:
Thickness 12 mm & ø20 mm;
L_{sc}(400nm)=21±0.5 mm;

4-layer SiO$_2$ aerogel:
100x100x35 mm;
L_{sc}(400nm)=37±0.3 mm;

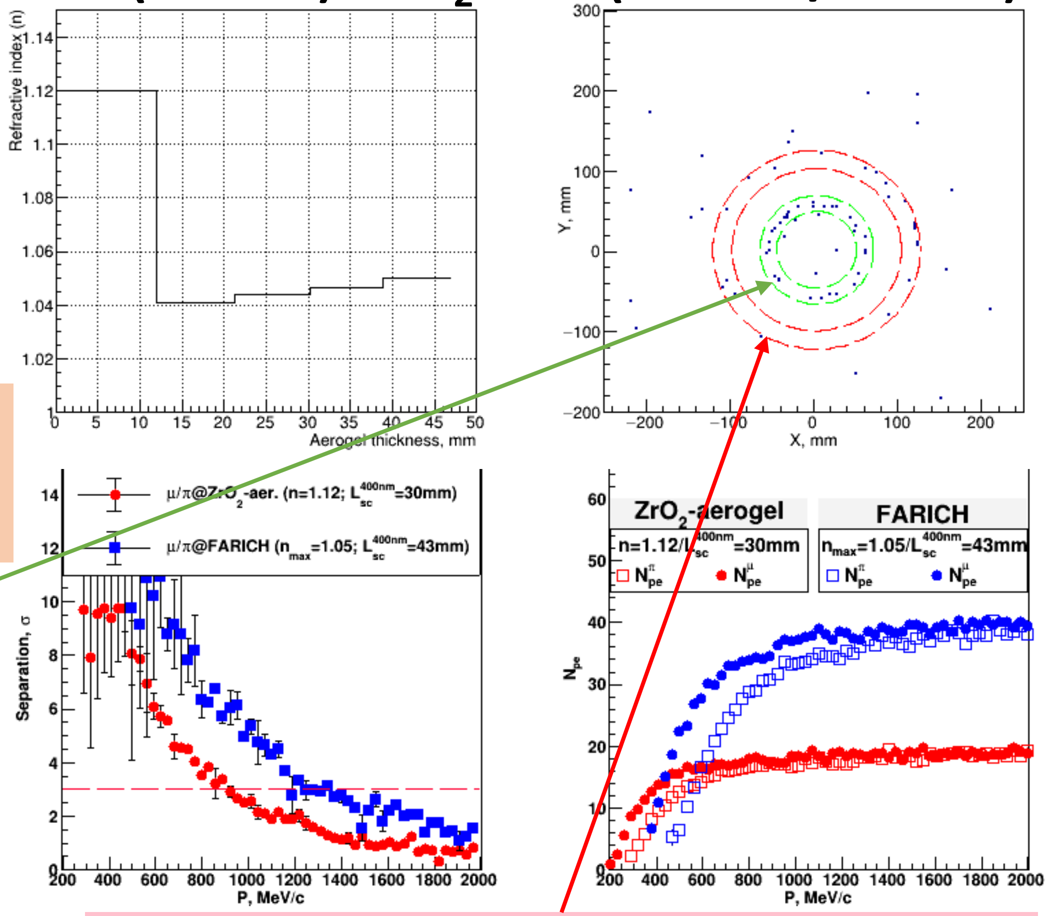
Photon detector
4 MaPMT H12700 (Hamamatsu);
256 pixels with 3x3 mm size;

μ/π-separation via G4 simulation

FARICH: "ideal" n profile



FARICH ("ideal")+ZrO_2–aer. (n =1.12/12 mm)

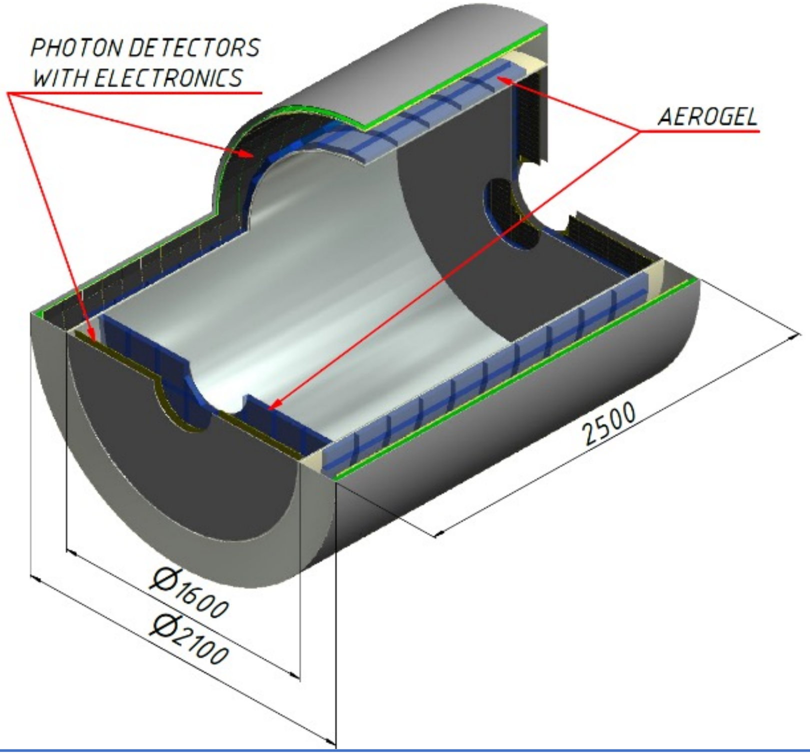


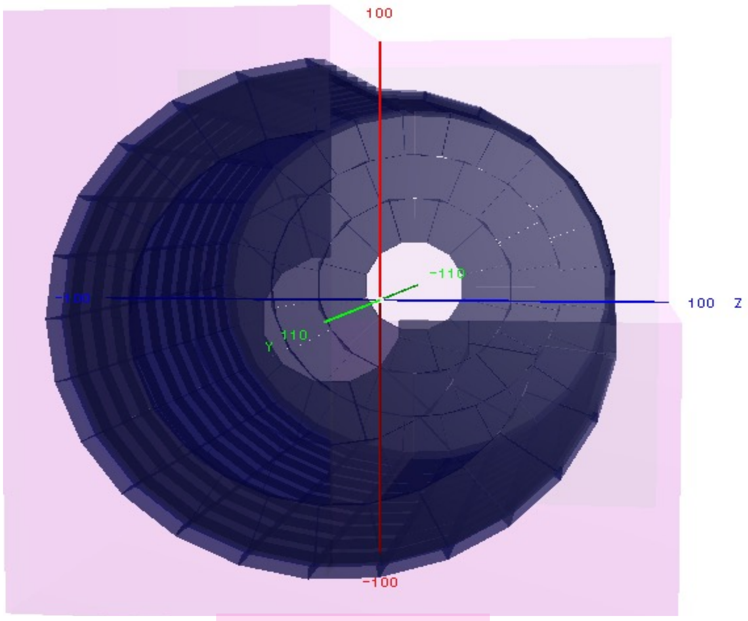
$$N_\sigma = \frac{\bar{R}_C^{\mu} - \bar{R}_C^{\pi}}{\left(\sigma_R^{\pi} + \sigma_R^{\mu}\right)/2}$$

$$(\mathbf{L_f} - \mathbf{t_{Zr}} - \mathbf{t_{Fa}}) \cdot \frac{\sqrt{\left(\mathbf{n}_{\mathbf{Fa}}^{min\,2} - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\frac{\mathbf{m}^2}{p^2} + 1}} \leq \mathbf{R_{Fa}} \leq (\mathbf{L_f} - \mathbf{t_{Zr}}) \cdot \frac{\sqrt{\left(\mathbf{n}_{\mathbf{Fa}}^{\mathbf{max}\,2} - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\left(\mathbf{n}_{\mathbf{Fa}}^{\mathbf{max}\,2} - 2\right) + \frac{\mathbf{m}^2}{\mathbf{p}^2}}}$$

$$(\mathbf{L_f} - \mathbf{t_{Zr}}) \cdot \frac{\sqrt{\left(n_{Zr}^{2} - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\frac{\mathbf{m}^2}{\mathbf{p}^2} + 1}} \leq \mathbf{R_{Zr}} \leq \mathbf{L_f} \cdot \frac{\sqrt{\left(n_{Zr}^{2} - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\left(n_{Zr}^{2} - 2\right) + \frac{m^2}{\mathbf{p}^2}}}$$

FARICH system concept for the SCTF

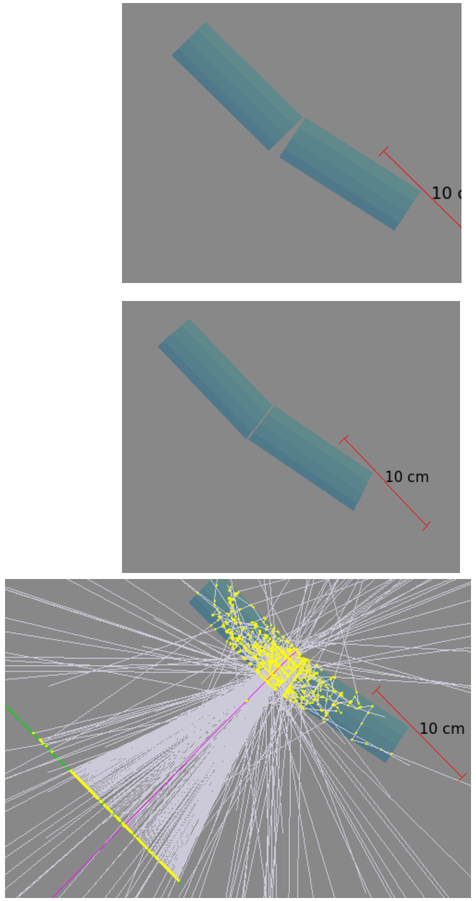




Aerogel layout

275 tiles 200x202x35 in barrel part
2x55 trapezoidal tiles in end caps:
- 2x12 – inner radius
- 2x18 – medium radius
- 2x25 – outer radius

GEANT4 simulation of edge effects



- Proximity focusing RICH
- 4-layer focusing aerogel
  - n_{max} = 1.05 (1.07?), total thickness 35 mm
  - $S_{aer} = 15\ m^2$
- 21 m^2 – total area of photon detectors
  - SiPMs – barrel part (16 m^2)
  - MCP-PMT – endcap parts (4 m^2)
- ~10^6 pixels 3x3 mm^2 with pitch 4 mm

SHAPE	Δ, mm	Aerogel size, mm			
		200	100	75	50
Parallelepiped	6	0.86	0.74	0.62	0.5
Trapezoidal	1	0.96	0.94	0.92	0.9

Summary

- In 2020-2023 the essential progress in FARICH technique development was achieved in Novosibirsk:
  - The 4-layer focusing aerogel sample with 20x20x3.5 cm size were produced for the first time in the world –> the possibility to create full-scale systems based on 4-layer focusing aerogel Cherenkov radiators was demonstrated
  - The measured SPR (~7 mrad) of FARICH based on 4-layer focusing aerogel is in good agreement with simulation and expectation
  - Recent progress in high opticaly dense aerogel production with help of ZrO_2 dope allows us to consider new design of FARICH detector with dual aerogel radiator which able to provide exccelent μ/π – separation from 0.2 up to 1.5 GeV/c
- For further progress of the FARICH option the development of position-sensetive photon detectors and compatible R/O electronics are highly required

Back up slides

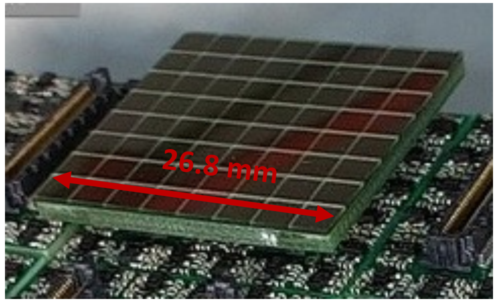
Photon detector options

Due to axial magnetic field the SiPM is only one possible candidate for the cylindrical part of the FARICH system!!!

For the endacp regions there are three options of photon detectors.

SiPM arrays

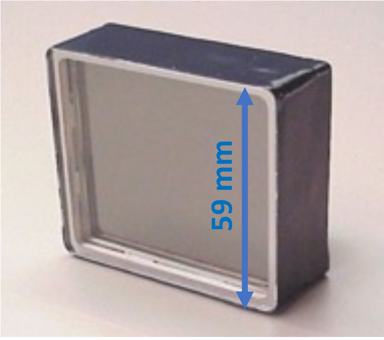
- There are several manufacturer in the world.
- It is required to develop and produce special R/O electronics and cooling system to operate with SiPMs in detector conditions



KETEK PA3325-WB-0808 (BroadCom, USA)

MCP-PMT

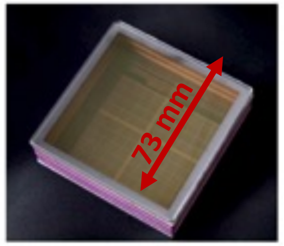
- There are several manufacturers in the world.
- PDE is not so high, it is limited by photoelectron collection efficiency (~60%) and geometrical efficiency is worse than for SiPM option. Severl vendors suggest MCP-PMT with CE=90%
- There is no such a big problem with intrinsic noise rejecion in comparison with SiPM option
- Specialised R/O elctronics is already developed for other experiments and could be adopted for the SPD experiment requirements

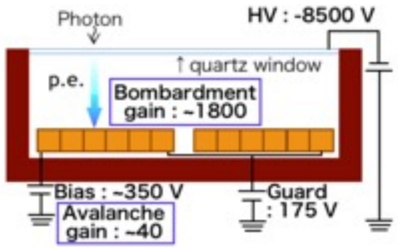


Planacon XP85112
8x8 pixels with 6x6 mm
Cost: 15 k\$

HAPD

- Only Hamamtsu produced such devices for the Belle II experiment and now it doesn't produced anymore!
- Expected PDE of such devices will less than for SiPM option but signficantly (1.5 times) higher than for MCP-PMT option.
- Expected gain is about $1 \div 2 \cdot 10^5$
- Development of specialised R/O elctronics is needed. It is possible to adopt some Belle II ARICH system expirience.
- The S/N-ratio is about 1000, it means that only thermostabilization system to operate at the room temperature will enough for this option.





R/O electronics cost estimation

There are two modern approaches in development of specialised R/O electronics:

- ASIC (Application Specialised Integrated Circuits)
- FPGA (Field Programable Gate Arrays)

The differences in performance, power consumption and costs are not sufficient today!!!

FPG-TDC (GSI)

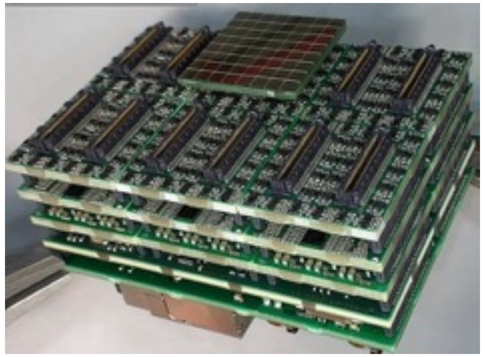
Unit	Article	Price per unit	Total price
2	DiRICH	4.917,00 €	9.834,00 €
	Additionally the export duty from Germany		150,00 €
	Total price		9.984,00 €

$\frac{9\,834€}{2\times384} \approx 13€/chan$ if N_{ch}<1000 (2019)

A system with 30kChannel (HADES):

$170k€/30k \approx 6€/chan$ (2017)

Power consumption: ~55mW/chan

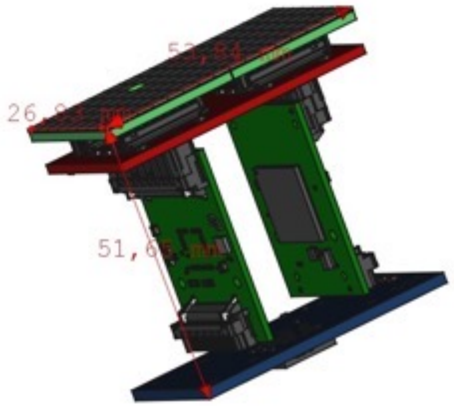


05.09.2023

TOFPET-II (PetSys)

The price of what you list (if based on ASIC_2,c) is

1	DAQ		8'000
1	clk&trg		5'000
1	FEB/D		5'376
8	FM128	1'579	12'632
TOT			31'008



$\frac{31\,008€}{8\times128} \approx 30€/chan$ if $N_{ch} \leq 1000$

A system with 100kChannel:

$5€/chan$ (2020)

Power consumption:

15mW/chan (ASIC) + DAQ (FPGA)~60mW/chan

Advantages of the SCT factory

1. Threshold production of τ leptons and charmed hadrons
   - Well-defined initial state
   - Low multiplicity of particles
   - Kinematic constraints

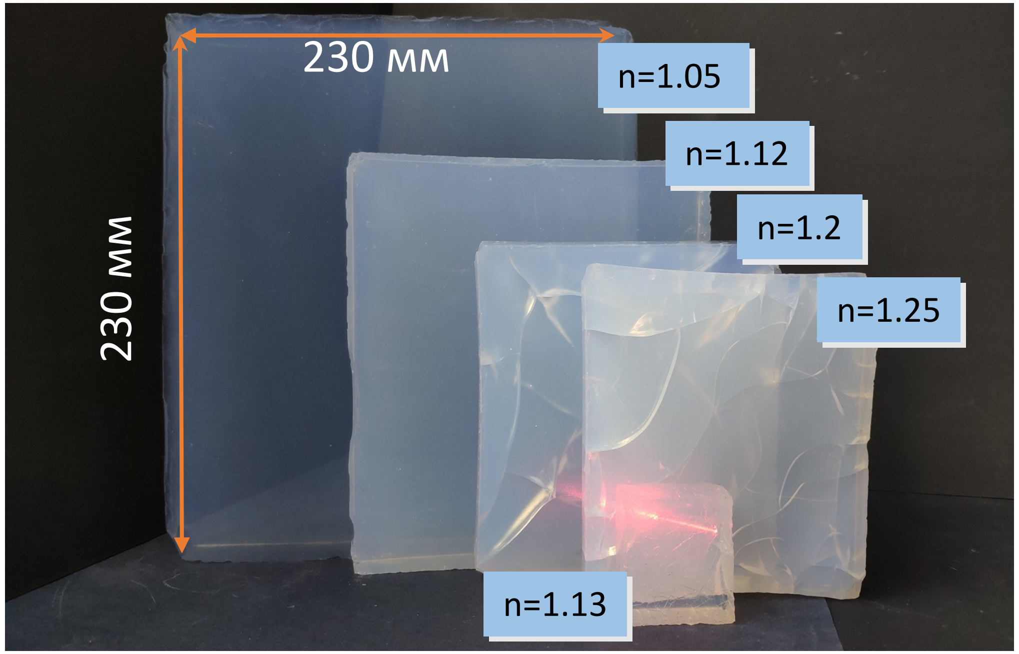
2. Longitudinal polarization of the electron beam
   - Boosted sensitivity to $\mathcal{CP}$ violation in baryons and τ leptons
   - Measuring the Weinberg angle

3. Coherent $D^0\overline{D}^0$ pairs
   - Measuring charm mixing and $\mathcal{CP}$ violation with unique techniques
   - Measuring phases of the decay amplitudes

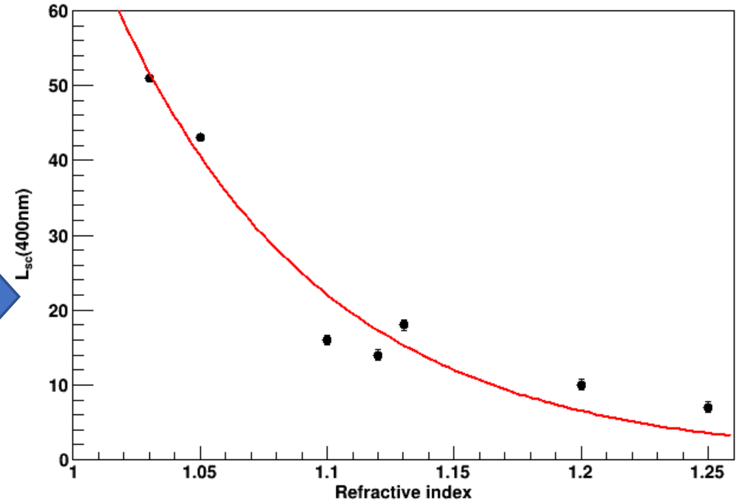
4. Full event reconstruction
   - Superior background suppression
   - Measuring absolute branching fraction of charmed hadrons

Aerogels with high optical density

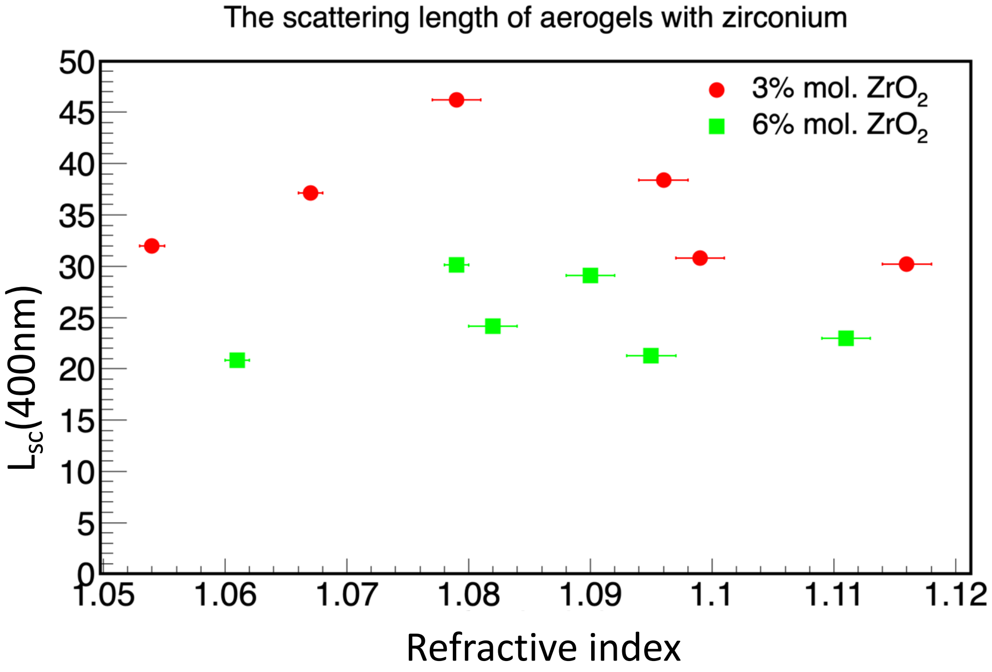
Sintering approach

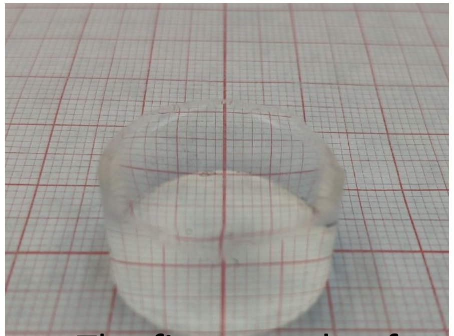


The main flaw of this approach



ZrO_2 addition approach





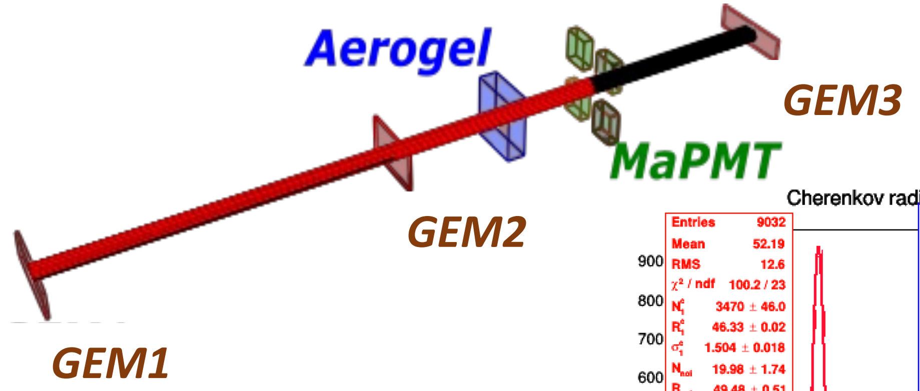
The first sample of SiO_2–ZrO_2 aerogel

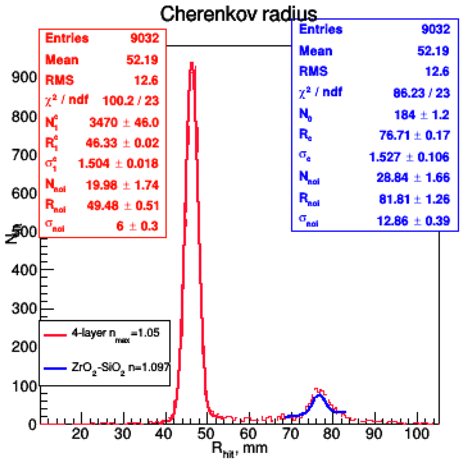
The addition of small amount (0.03÷0.06 mol) of ZrO_2 in SiO_2 based aerogel alow us to produce highly transperant aerogels with high optical density:

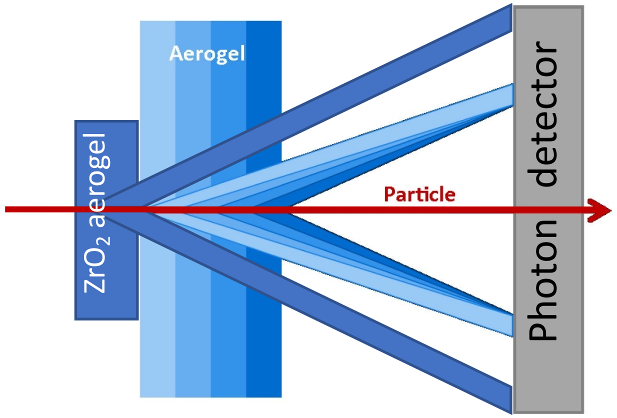
- Refractive index up to n=1.12
- Rayleigh light scattering length L_{sc}(400nm) up to 30 mm

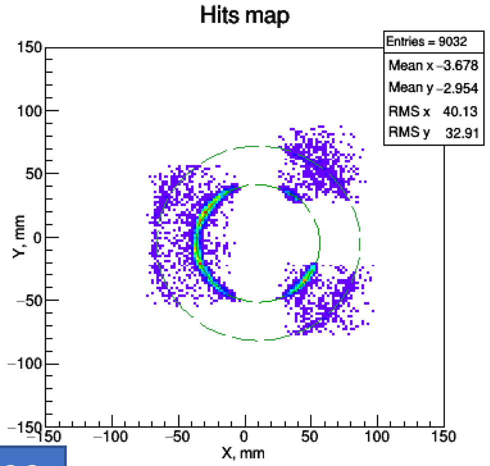
Beam tests with FARICH in 2021-2022 at BINP

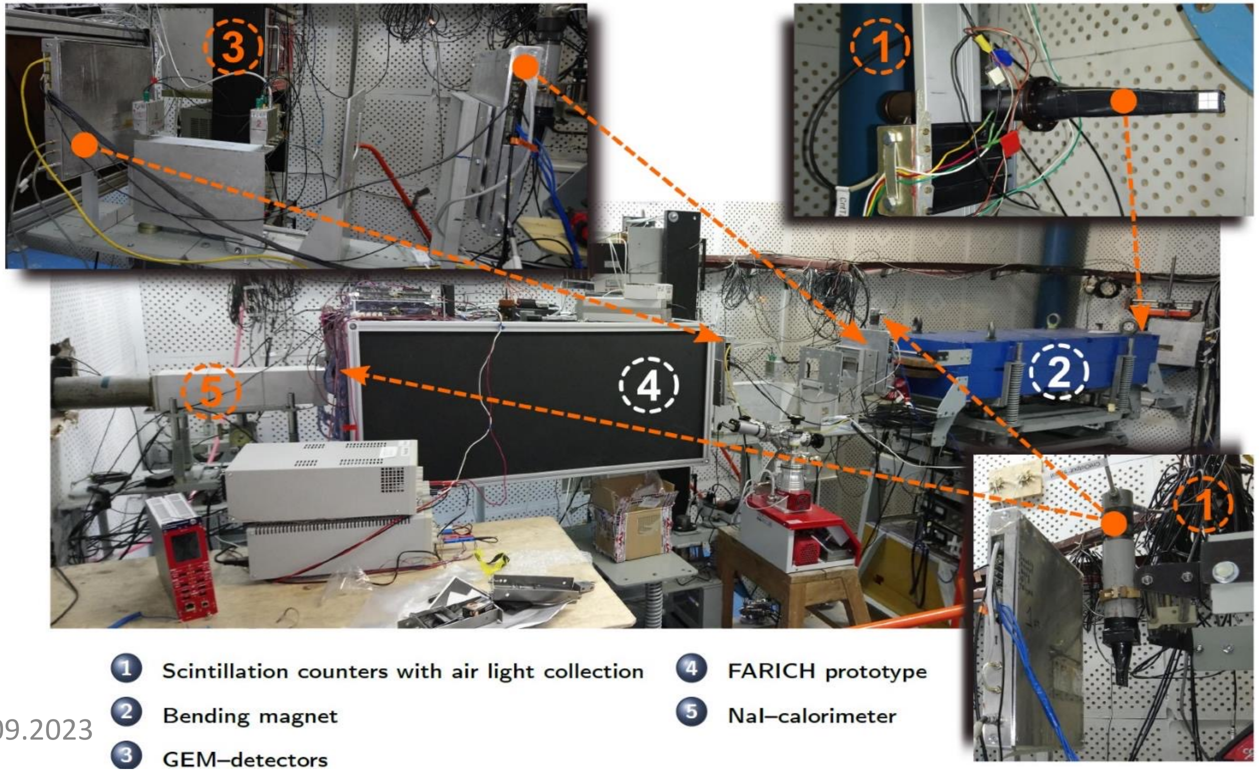
- Electrons with E=2 GeV are used
- 4 MaPMTs (H12700 from Hamamatsu with pixel 6x6 mm) were used with different masks to reduce effective pixel size:
  - Ø1 mm to investigate contribution from aerogel itself
  - 3x3 mm to measure realistic Single Photon Resoulution (SPR)
- Three GEMs are used at beamline:
  - ✓ Two before aerogel sample and one behind
  - ✓ It allows us to restore Chernekov angle for each detected photon and mitigate multiple scattering affects at beam-line.







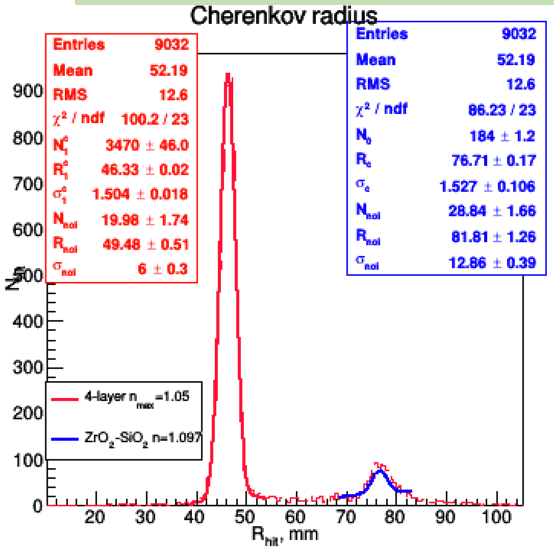


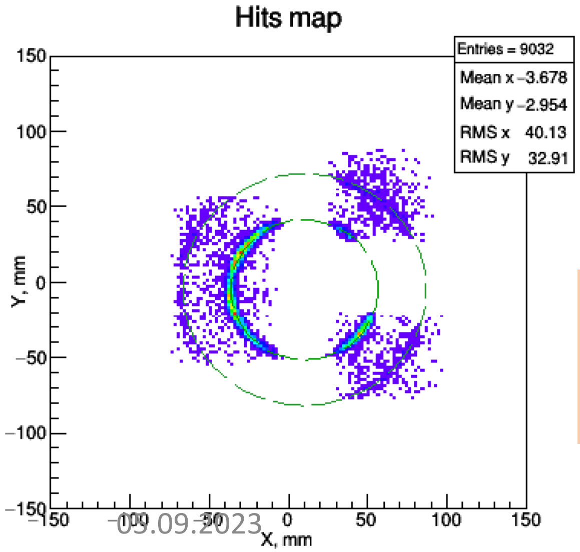


G N Abramov et al 2014 JINST 9 C08022

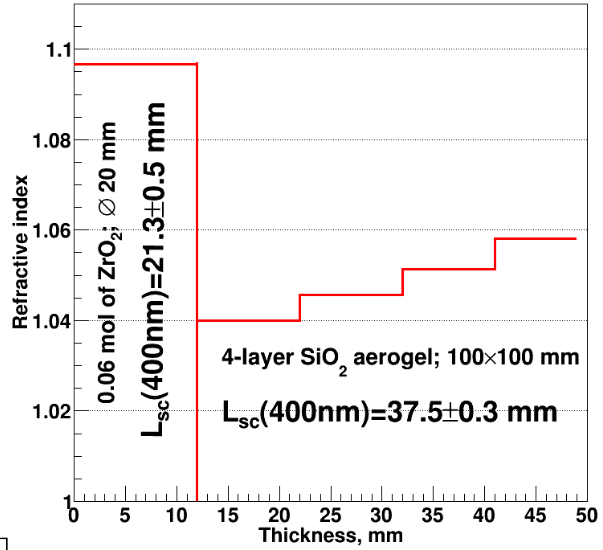
G4 simulation vs beam test results

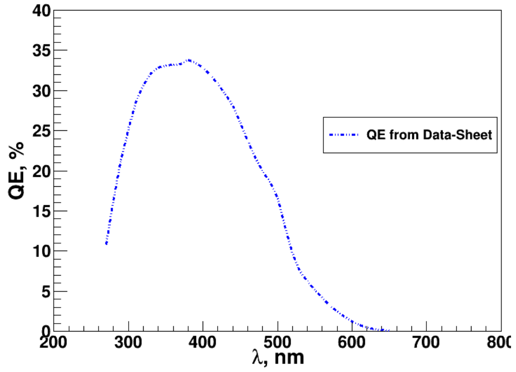
TBeam results





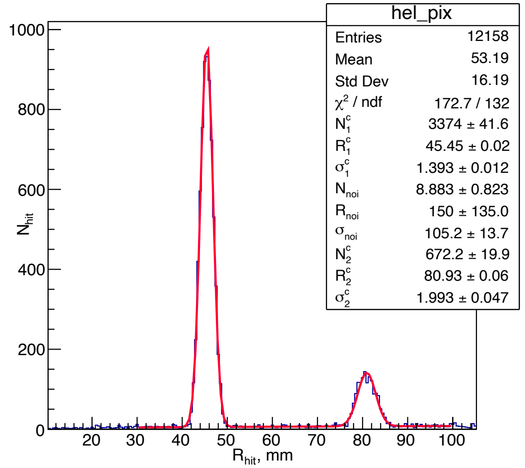
Optical parameters for G4 simultion

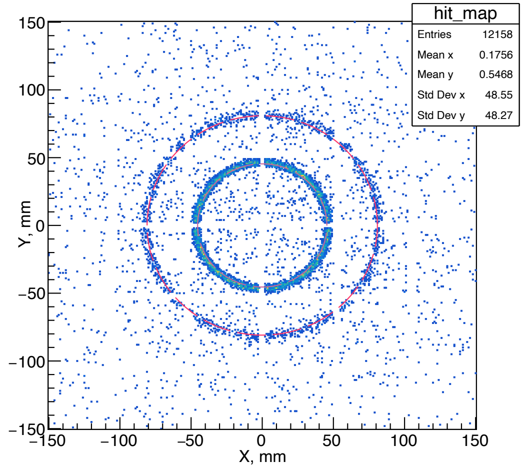




- PDE for H12700 from data-sheet
- Pixel 3x3 mm with pitch 6mm
- Focal distance L=172 mm

G4 simulation results

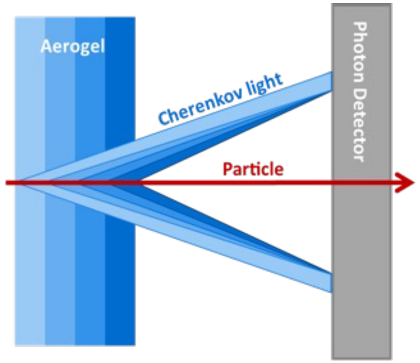




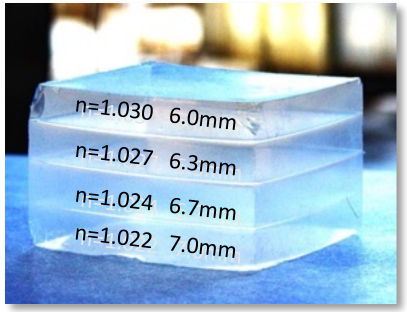
The main difference between G4sim and TBeam is a photon small angle scattering effect on aerogel surfaces and inside. These effects have not implemented in G4sim yet.

FARICH system concept for SCTF project

Focusing Aerogel RICH approach



First 4-layer aerogel



Variable n allows to increase N_{pe} using thicker radiator without compromising σ_{Θ_c}

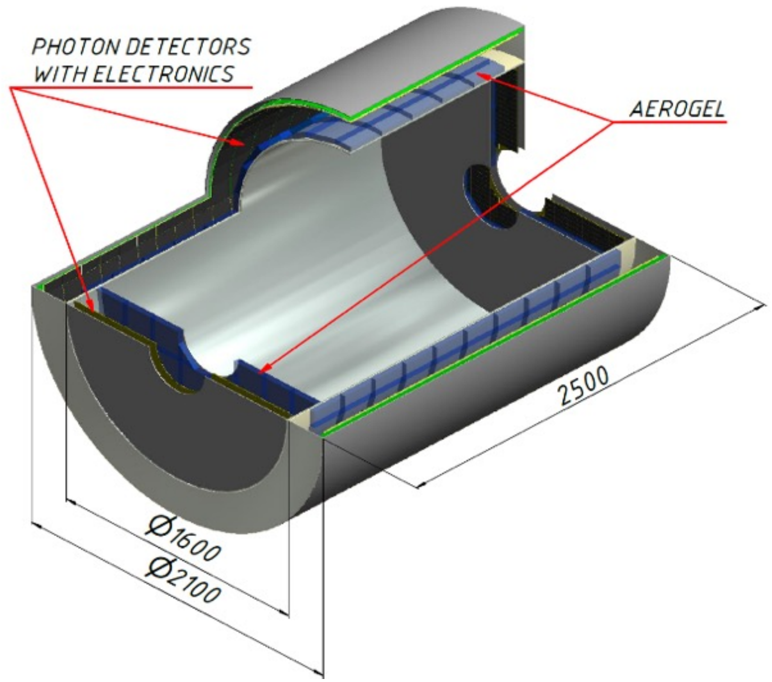
T.Iijima et al., NIM A548 (2005) 383
A.Yu.Barnyakov et al., NIM A553 (2005) 70

2012 test beam: μ/π separation >3σ at P=1 GeV/c was demonstrated
A.Yu. Barnyakov, et al., NIM A 732 (2013) 35

Main requirements for PID system:

- π/K separation $> 4\sigma$ up to 3.5 GeV/c
- μ/π suppression $\sim 1/40$ for $0.5 \div 1.2\ GeV/c$
- Below 0.2 GeV/c μ/π separation could be performed with help of tracking system by means dE/dx technique (cluster counting mode) or with ToF technique using Cherenkov light from entrance window of fast photon detectors ($TTS \leq 100\ ps$)
- FARICH with dual radiator was considered to provide π/K separation in momentum range $0.2 \div 0.5\ {}^{GeV}/_{c}$

FARICH system for SCTF project



- Proximity focusing RICH
- 4-layer or gradient aerogel radiator
  n_{max} = 1.05 (1.07?), 35 mm thickness
- 21 m^2 total photon detector area
  - SiPMs in barrel (16 m^2)
  - MCP PMTs in endcaps (5 m^2)
- $\sim 10^6$ pixels with 4 mm pitch & 3x3 mm^2 sensitive area