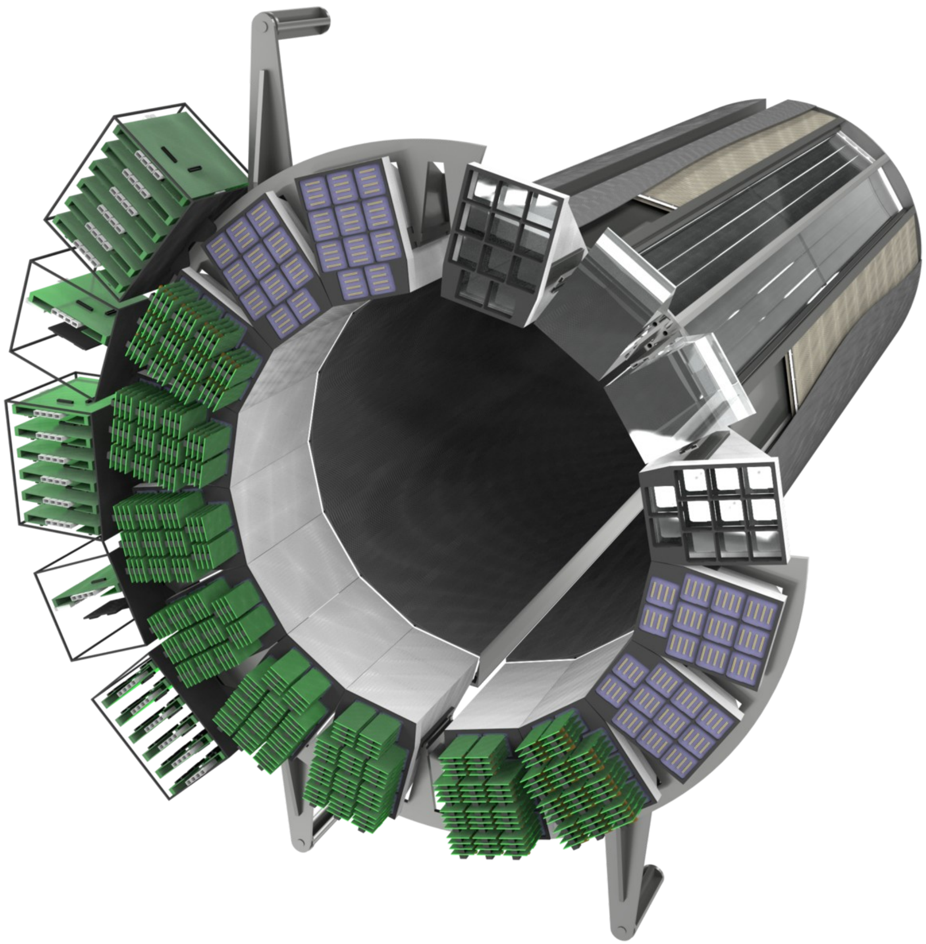
The Barrel DIRC Detector



Panda PID workshop

Roman Dzhygadlo
for the PANDA Cherenkov Group

- Barrel DIRC design
- Simulation chain
- Reconstruction methods
- Validation in beam tests
- Summary & outlook

DIRCs in PANDA

Two DIRC detectors for hadronic PID:

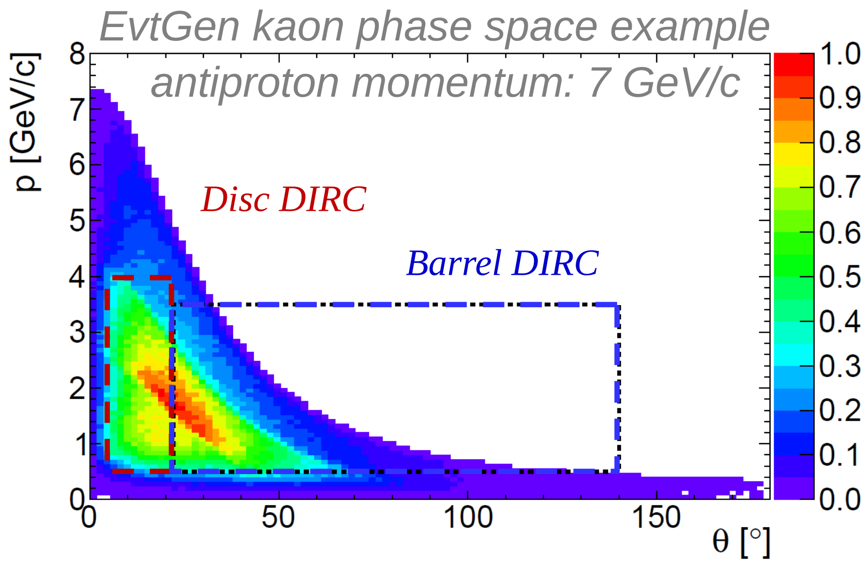
- Barrel DIRC

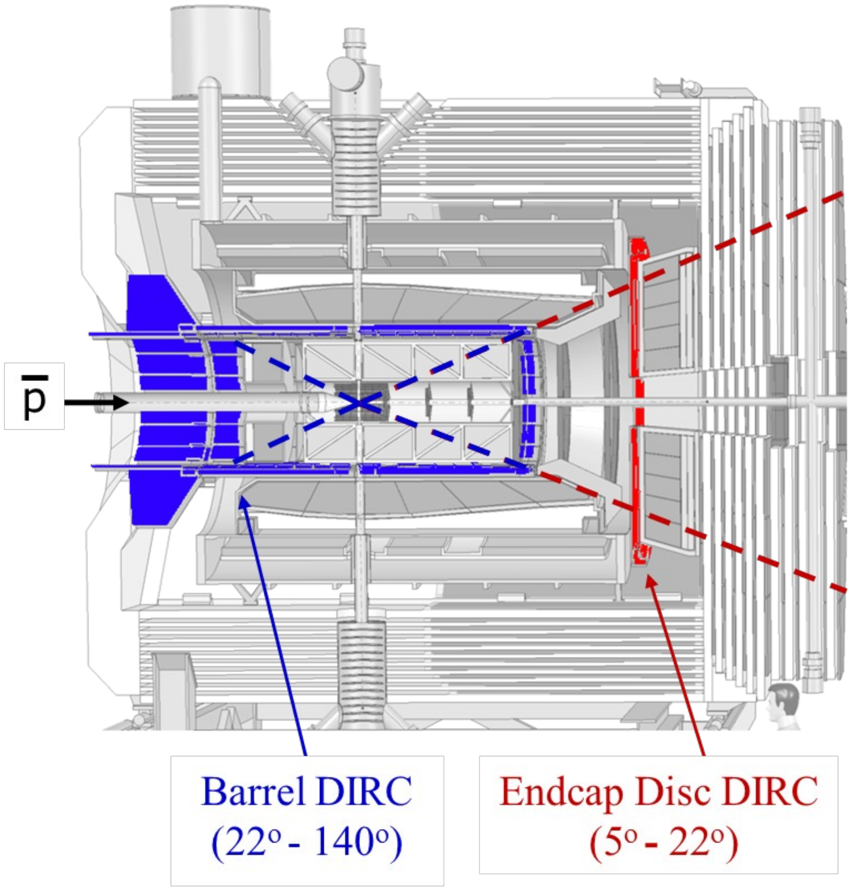
  German in-kind contribution to PANDA

  Goal: 3 s.d. π/K separation up to 3.5 GeV/c

- Endcap Disc DIRC

  Goal: 4 s.d. π/K separation up to 4 GeV/c





DIRC Principle

Detection of **I**nternally **R**eflected **C**herenkov Light

Novel type of Ring Imaging CHerenkov detector

based on total internal reflection of Cherenkov light.

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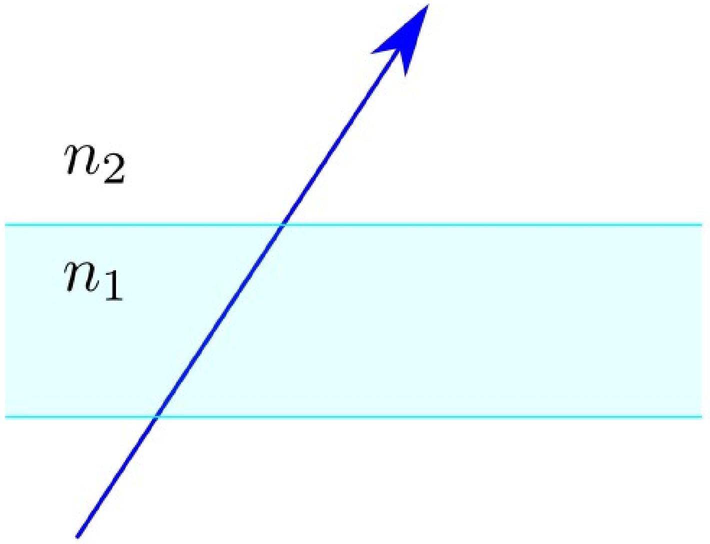
- Charged particle traversing radiator with refractive index ($n_1 \approx 1.47$) and $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos \theta c = 1/\beta n(\lambda)$.



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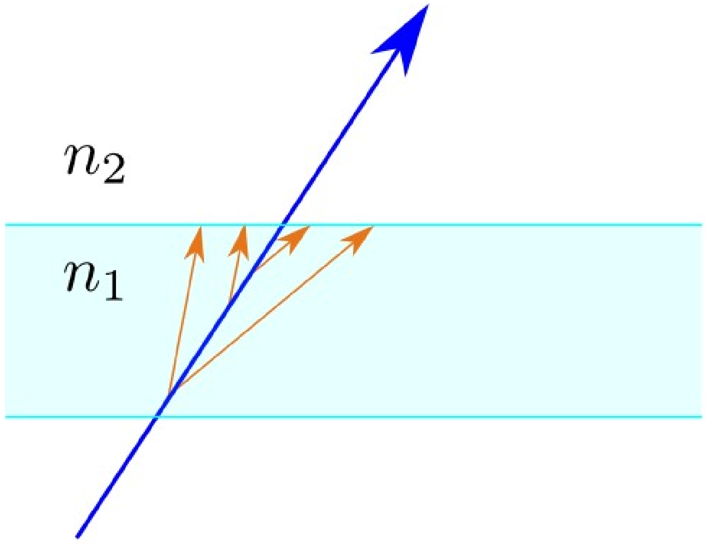

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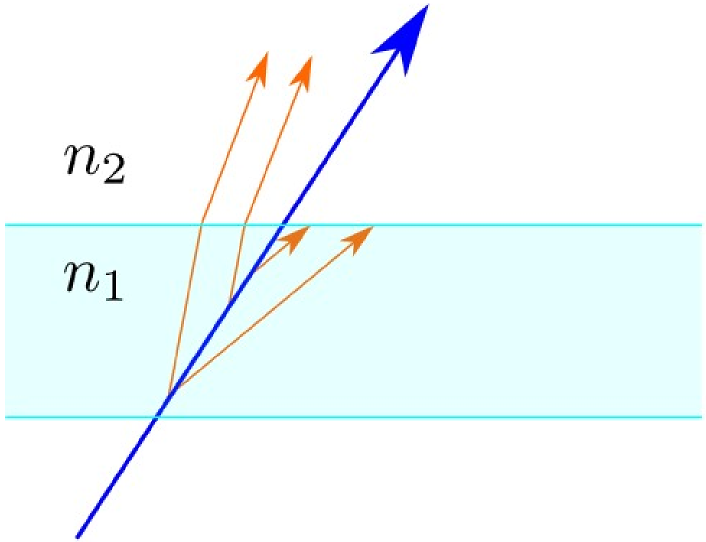

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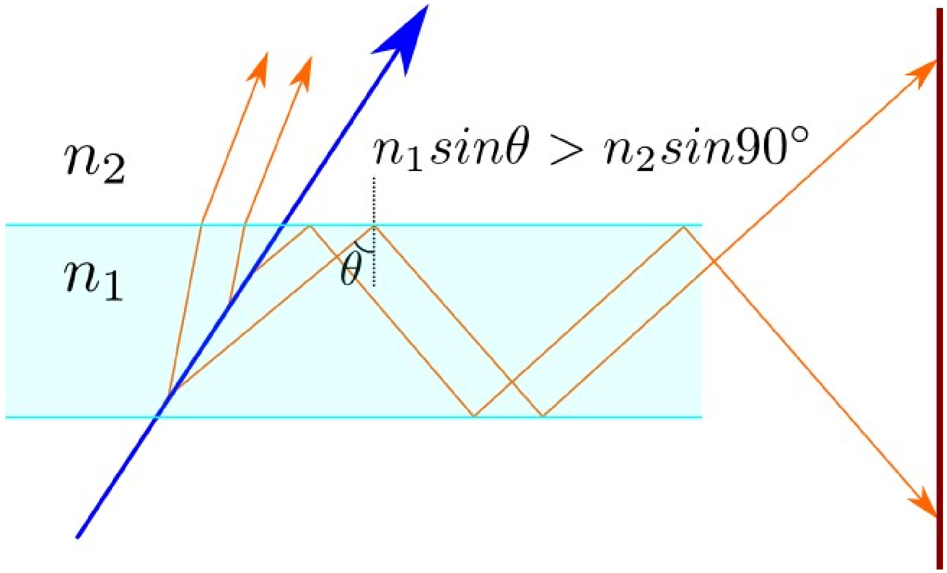

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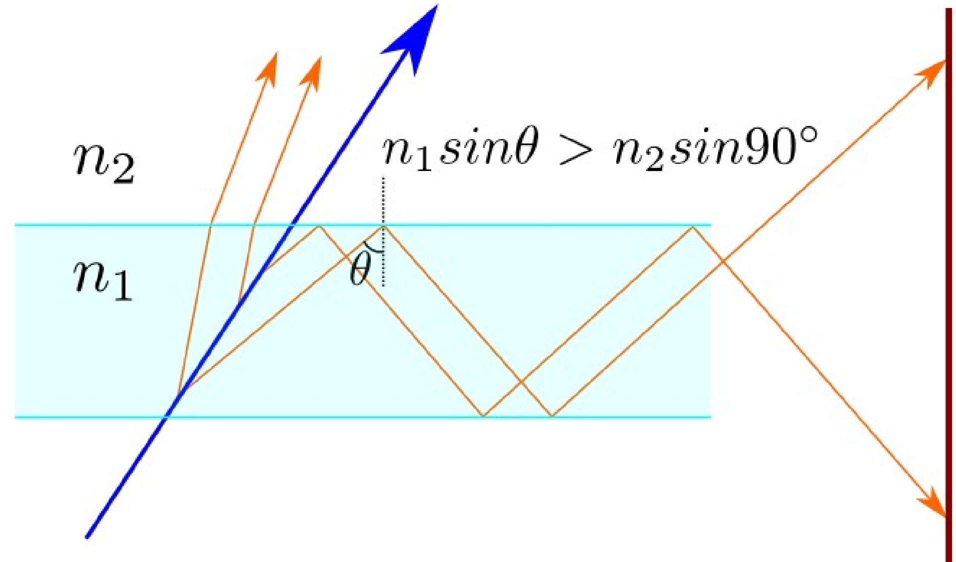

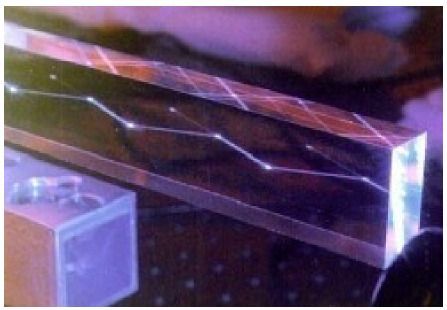

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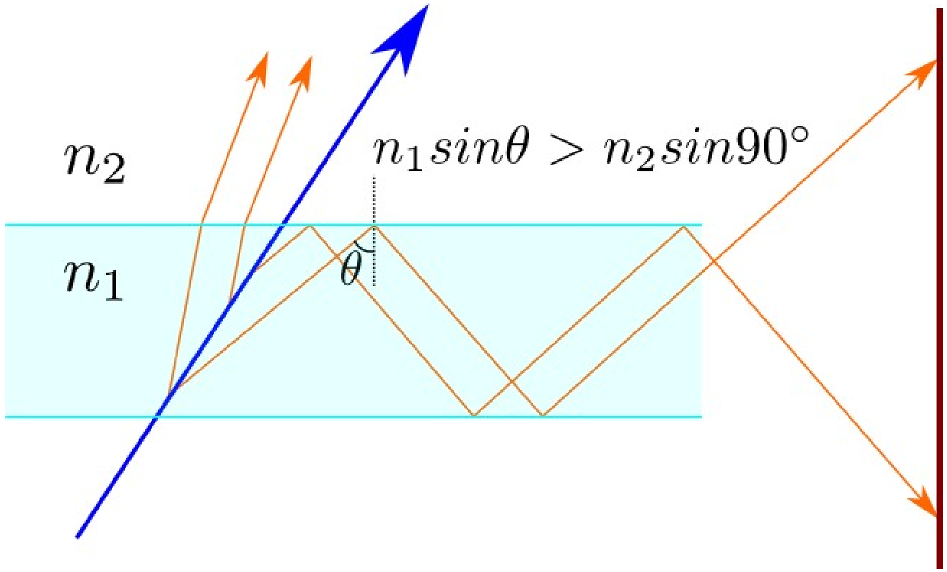

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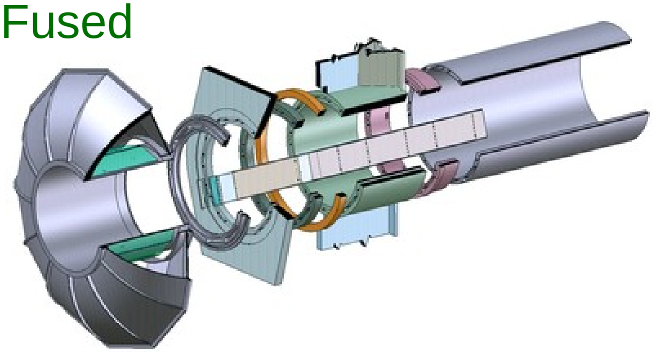
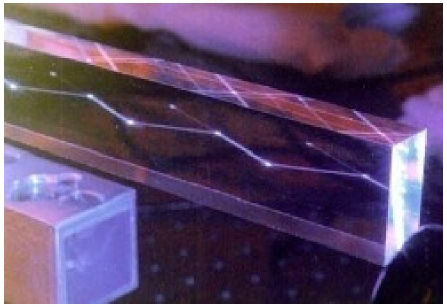
- Proven to work (BABAR-DIRC).



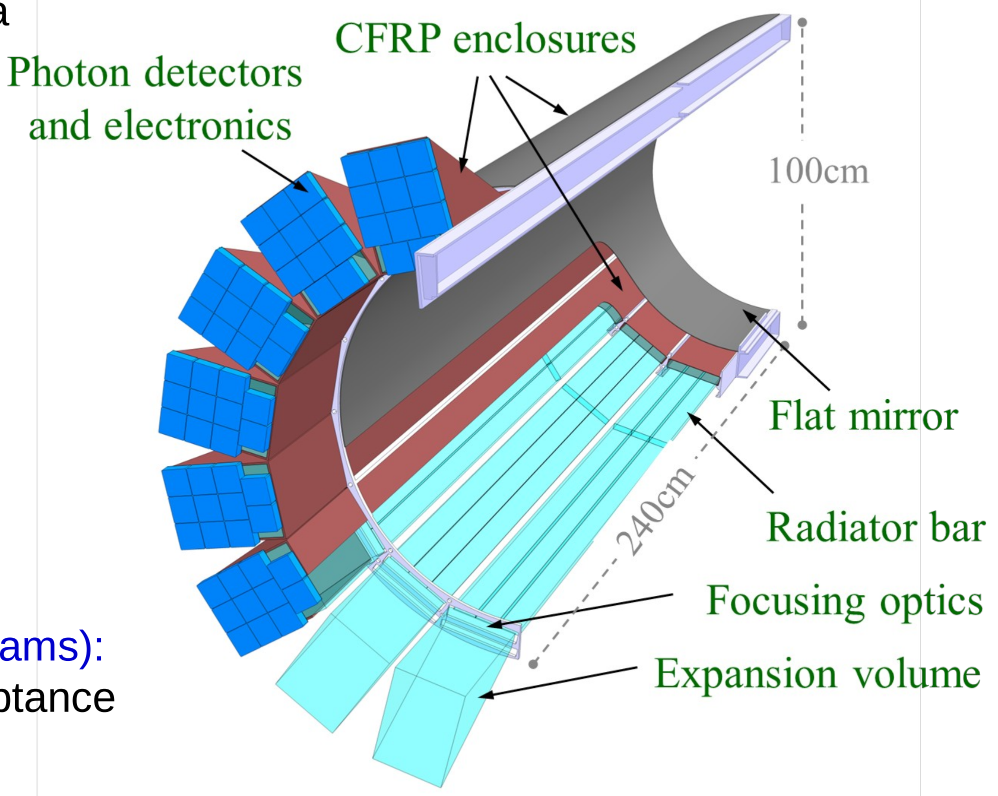


Barrel DIRC Baseline Design

Based on BABAR DIRC with key improvements

(compact fused silica prisms, spherical lenses)

- 48 radiator bars (16 sectors), synthetic fused silica
  17mm (T) x 53mm (W) x 2400mm (L)
- Focusing optics: triplet spherical lens system
- Compact expansion volume:
  30cm-deep solid fused silical prisms
  ~11,000 channels of 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



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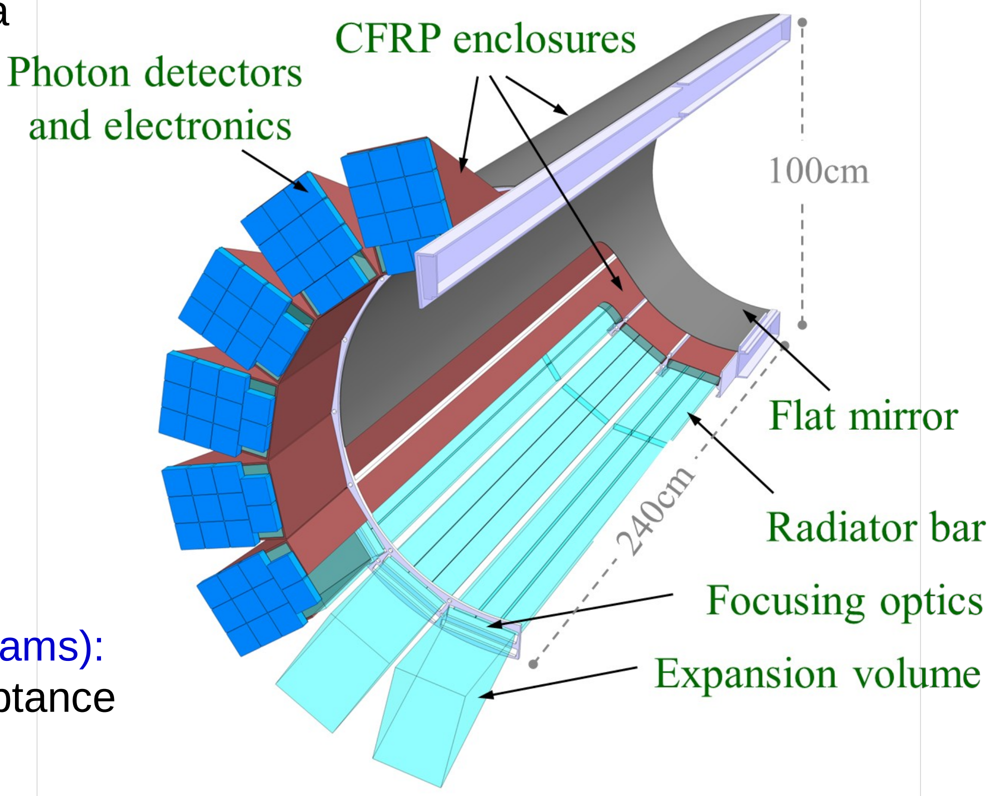


Conservative design: similar to BABAR DIRC, baseline design for TDR

Excellent performance, robust, little sensitivity to backgrounds and timing deterioration

Simulation and Reconstruction

Event generation

↓

Particle transport

↓

Digitization

↓

Hit Finder

↓

Reconstru ction

PandaRoot framework

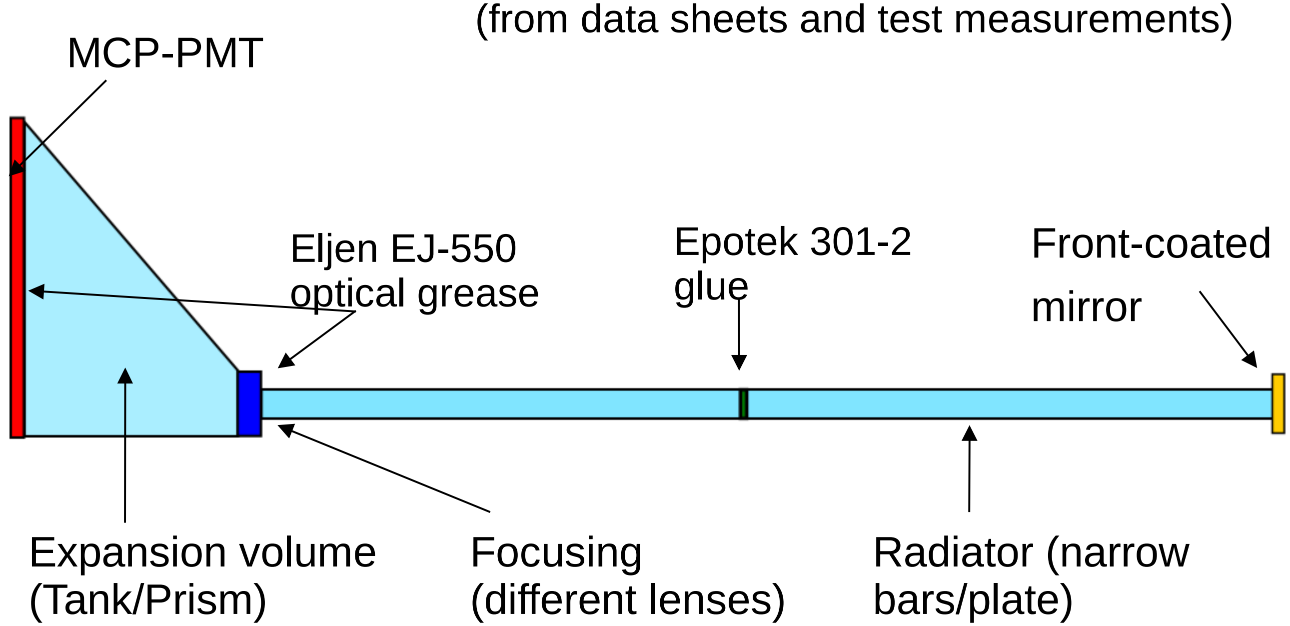
Simulation and Reconstruction

- Event generation
- Particle transport
- Digitization
- Hit Finder
- Reconstruction

~~Gean3,~~ Geant4

Geometry/material

Realistic material description
(from data sheets and test measurements)



Simulation and Reconstruction

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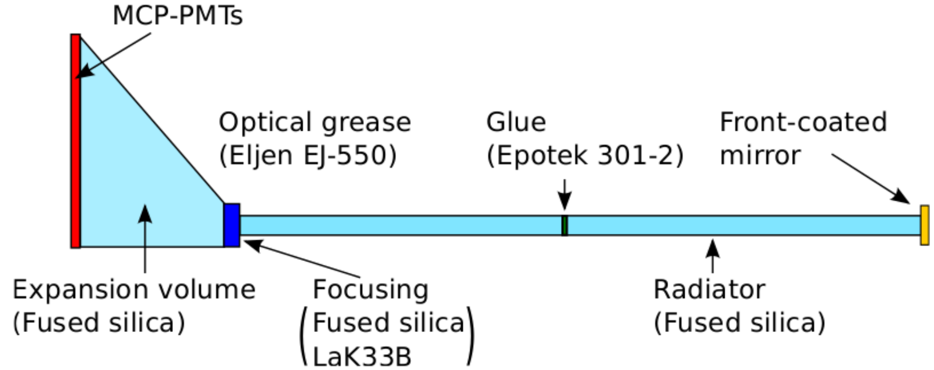
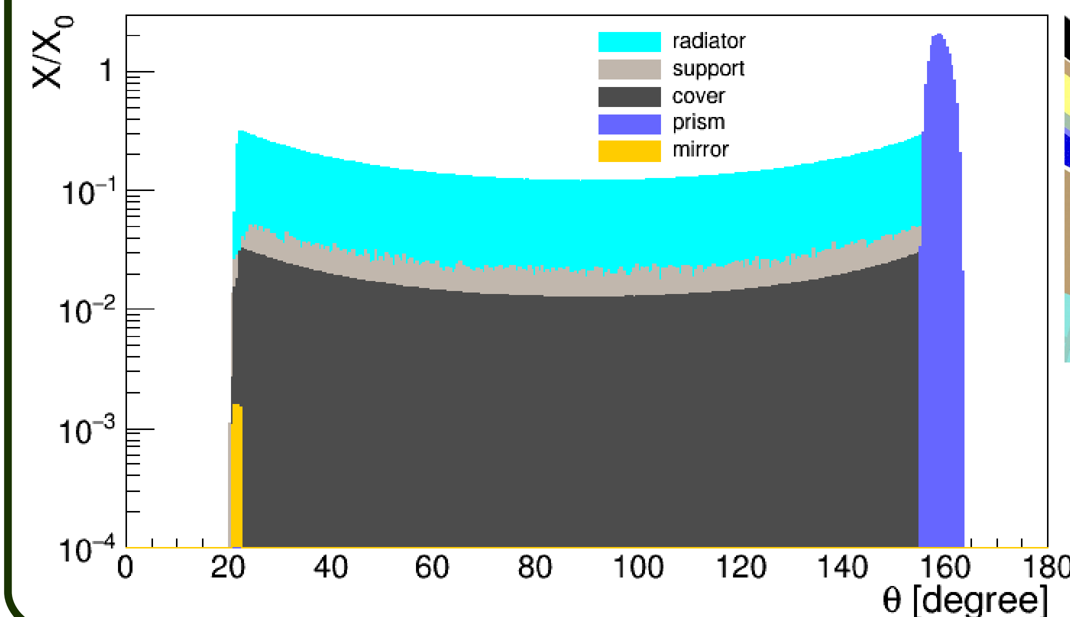
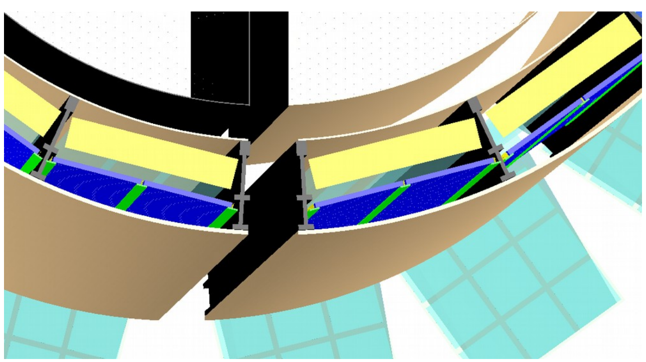


Projected radiation length:

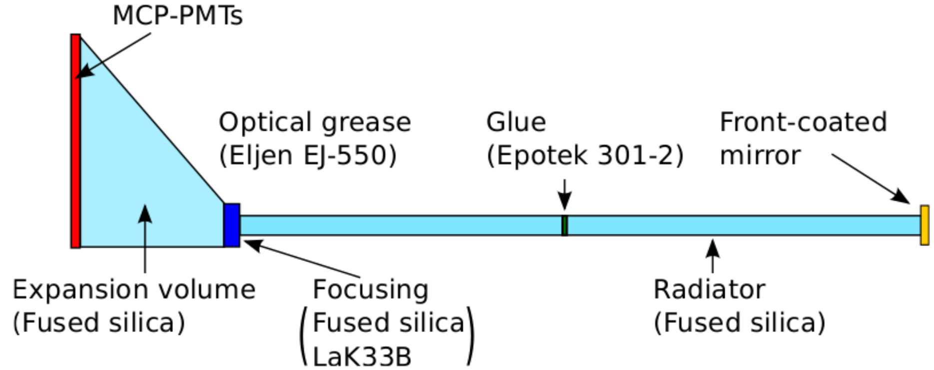




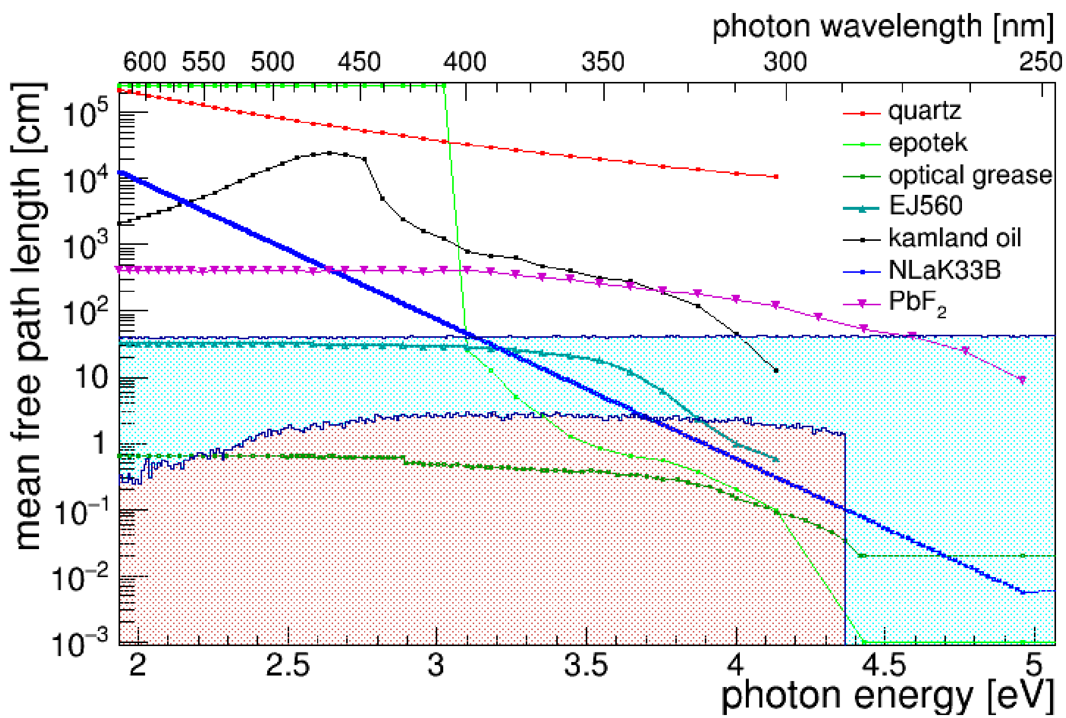
Barrel DIRC with cover (carbon fiber reinforced polymer)

Simulation and Reconstruction

Event generation → Particle transport → Digitization → Hit Finder → Reconstruction



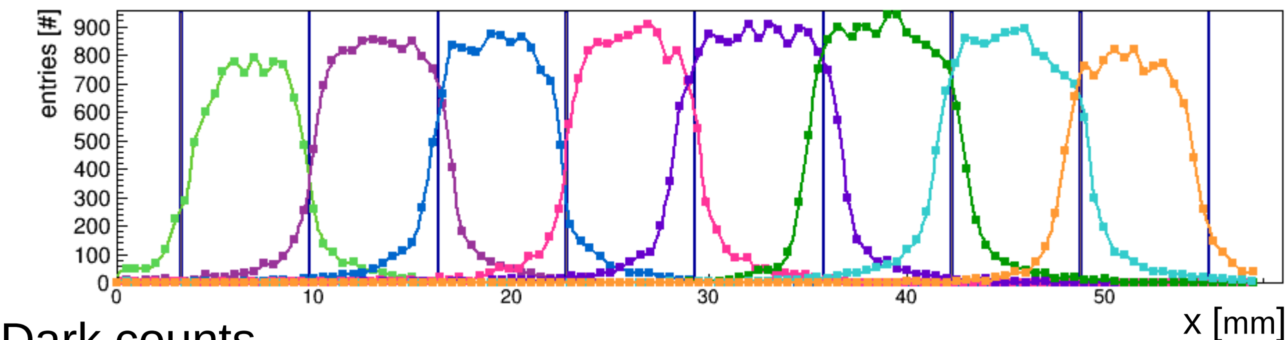
Material transmittance:



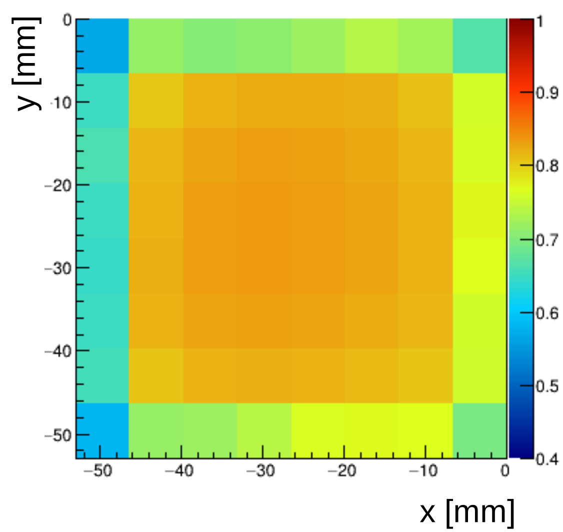
Simulation and Reconstruction

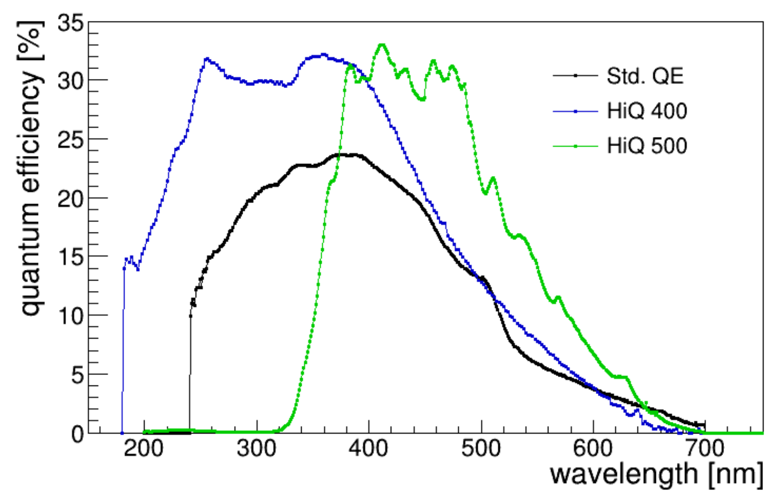
Event generation → Particle transport → Digitization → Hit Finder → Reconstruction

- Transport efficiency
- Charge sharing

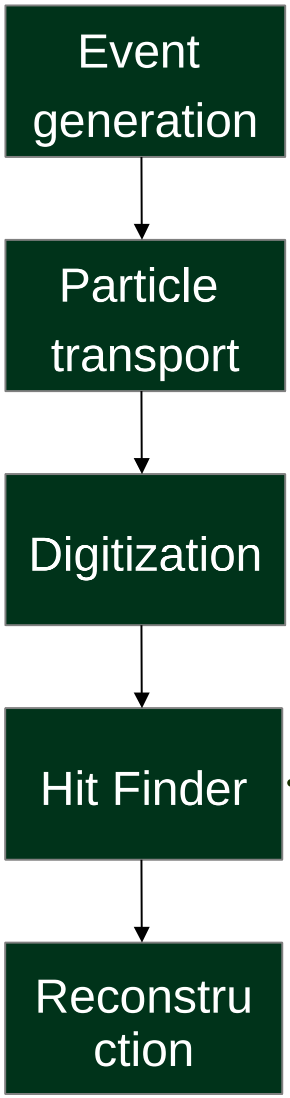


- Dark counts
- Single photon time resolution
- Quantum/collection efficiency

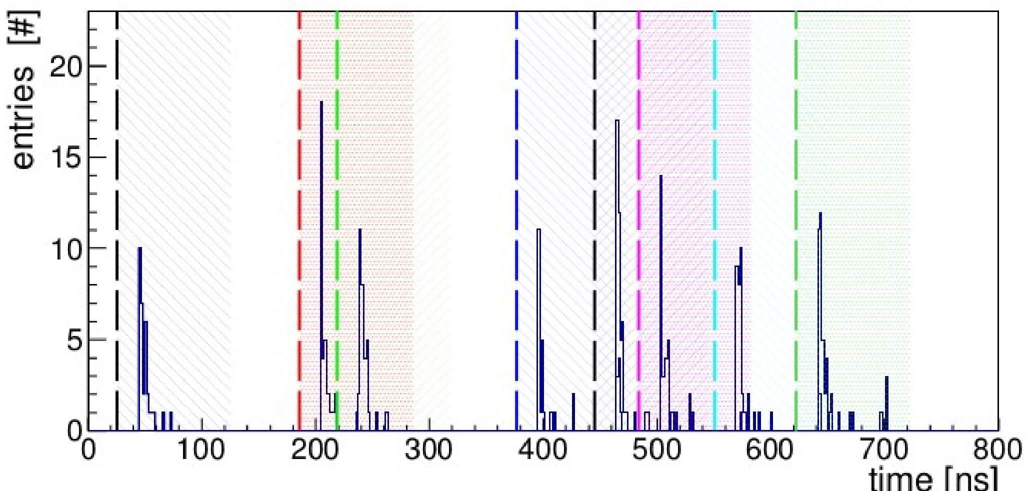




Simulation and Reconstruction

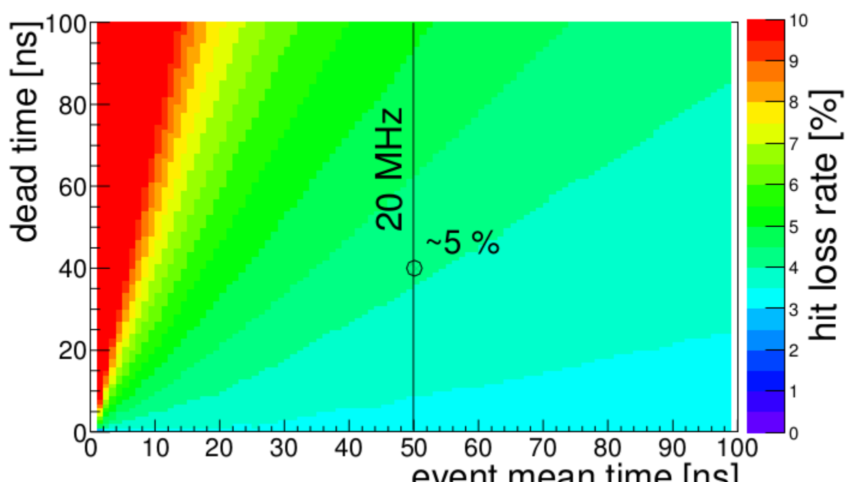


Assignment of hits to their tracks (time-based sim)



Example of the photon detection time @ 20MHz

- Lost hits due to pile-up
- Ambiguous assignment of hits to their tracks/events



- 5 charged tracks in each event
- p=[1,3] GeV/c θ=[22, 140]° φ=[0, 180]°

only 5% of photons are lost due to pileup (@20 MHz and 40 ns dead time)

Simulation and Reconstruction

Event generation

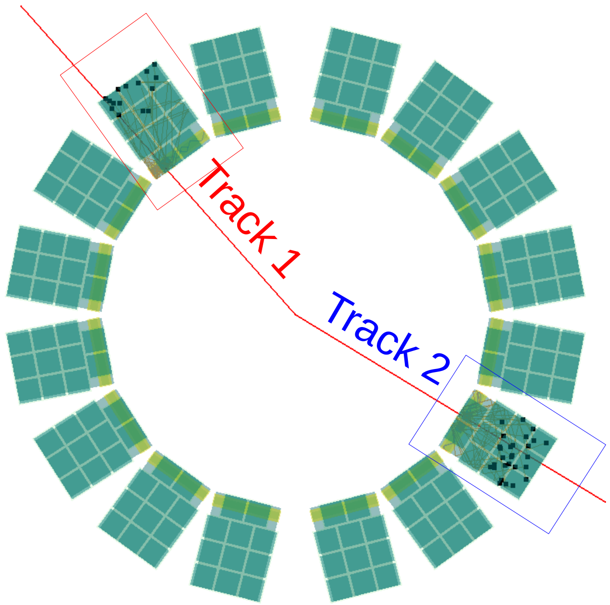
Particle transport

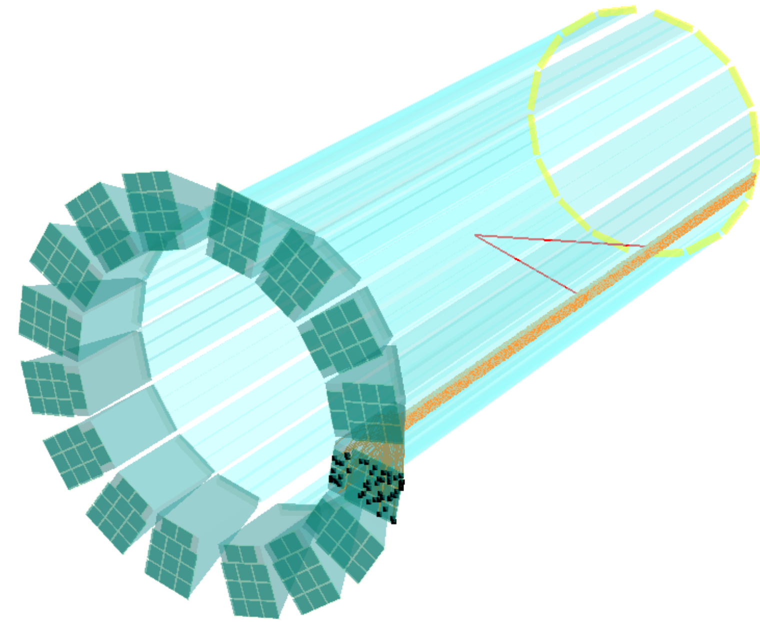
Digitization

Hit Finder

Reconstruction

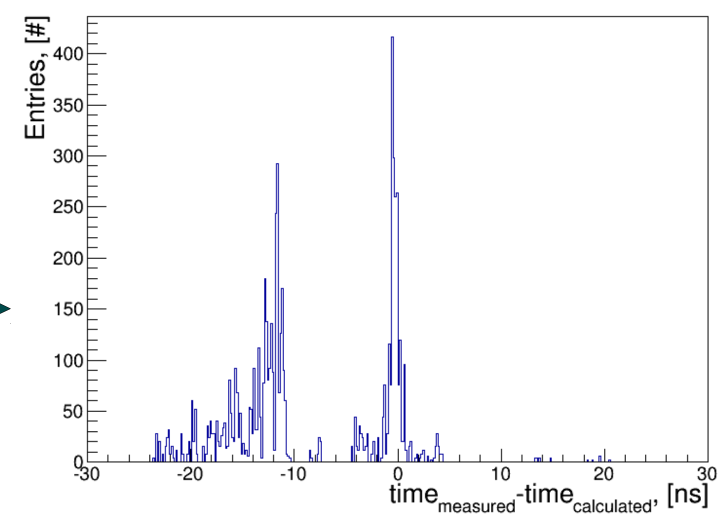
Multiple tracks





- good separation in space
- ~4 % of tracks are hit same bar box (using DPM)

- good separation in time
- 90% of 2 tracks in same bar-box still could be separated using delta timing.



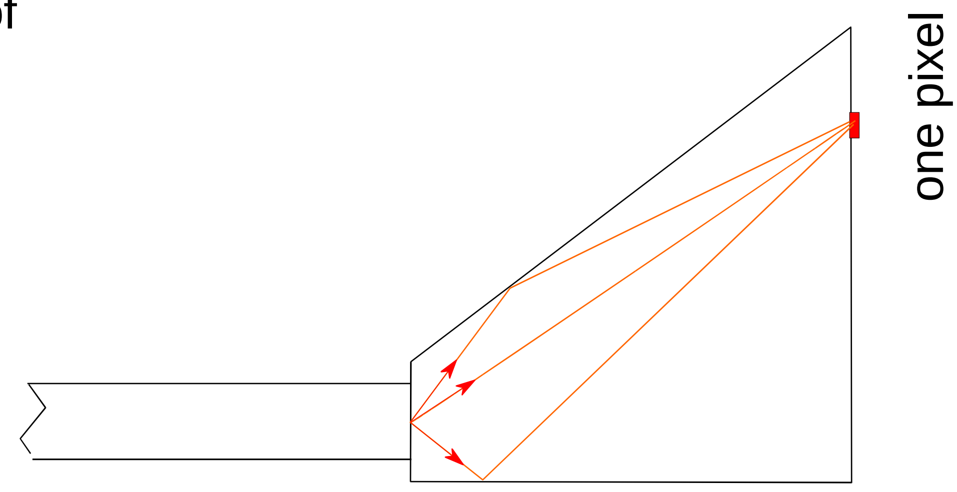
Simulation and Reconstruction

Event generation → Particle transport → Digitization → Hit Finder → Reconstruction

- Geometrical reconstruction (BABAR-like)
- Time imaging (Belle II TOP-like)

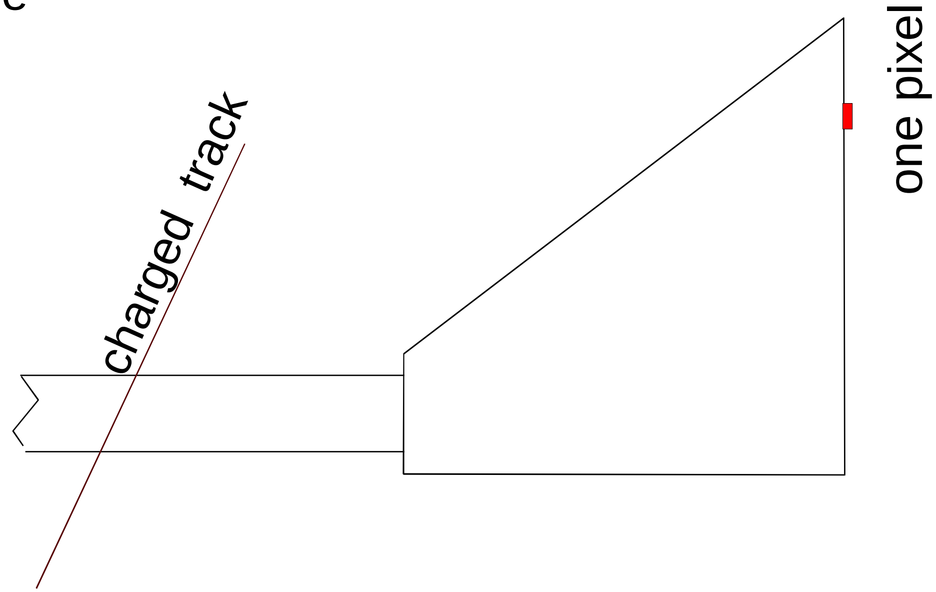
Geometrical Reconstruction

Look-Up Table creation: store direction at the end of the radiators for each hit pixel



Geometrical Reconstruction

Reconstruction: direction from LUT for hit pixels are combined with charge track direction



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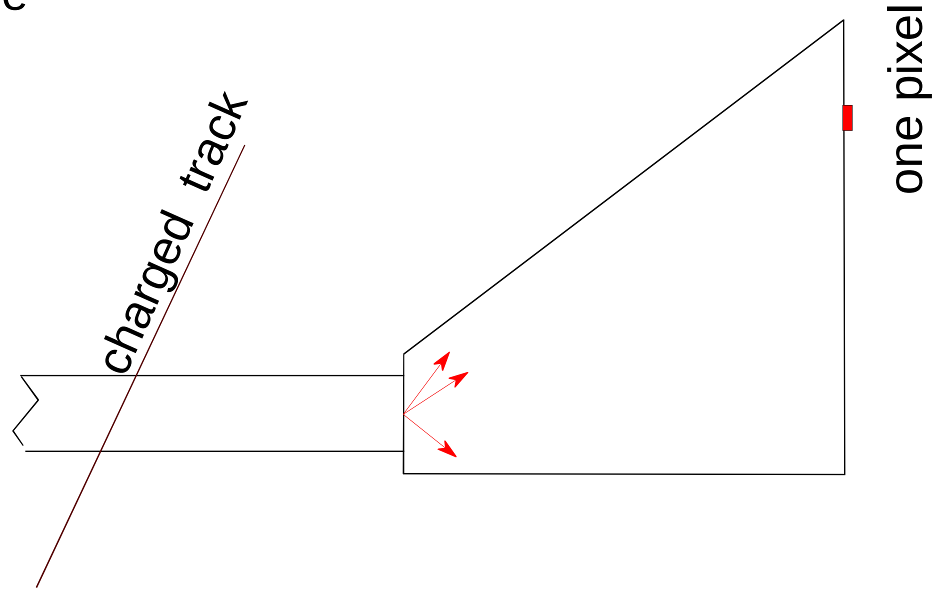

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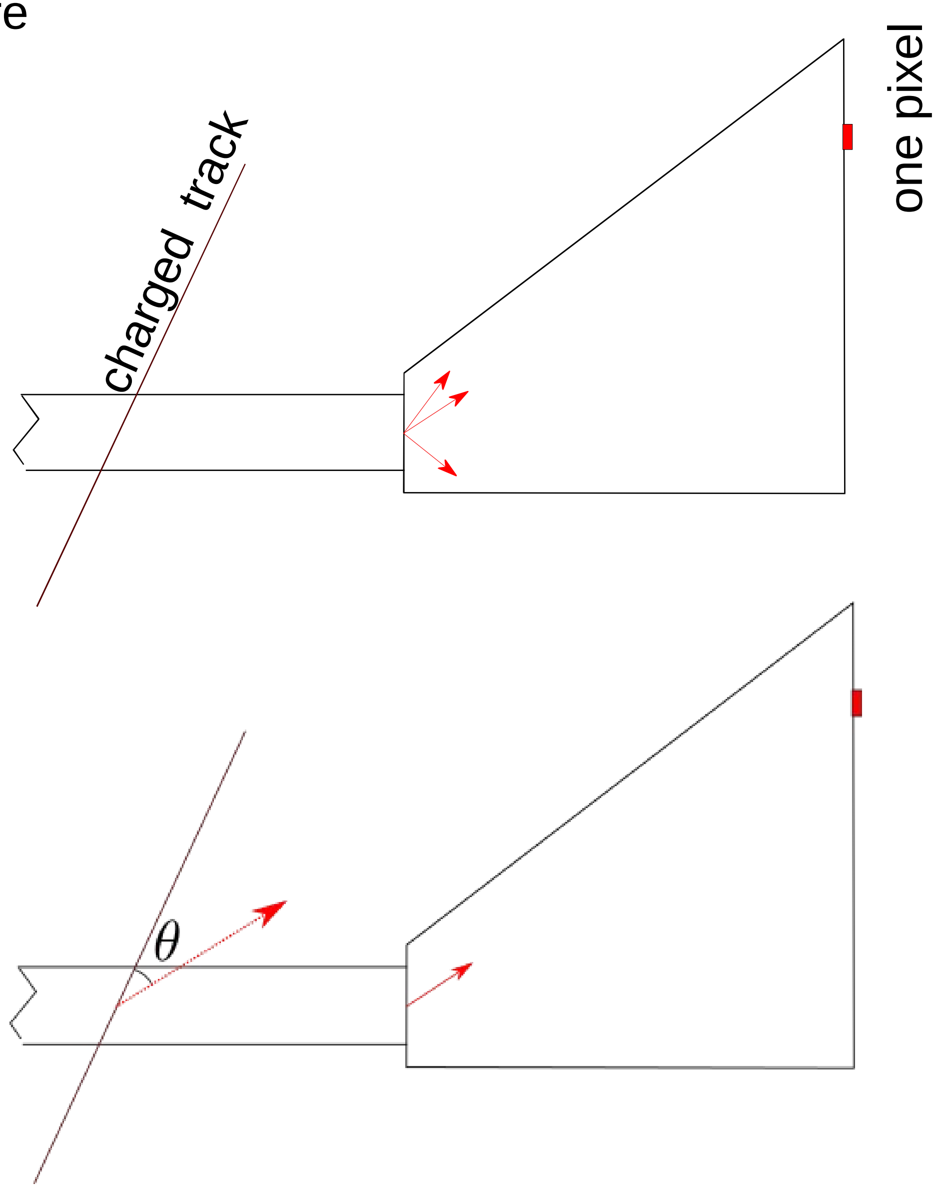

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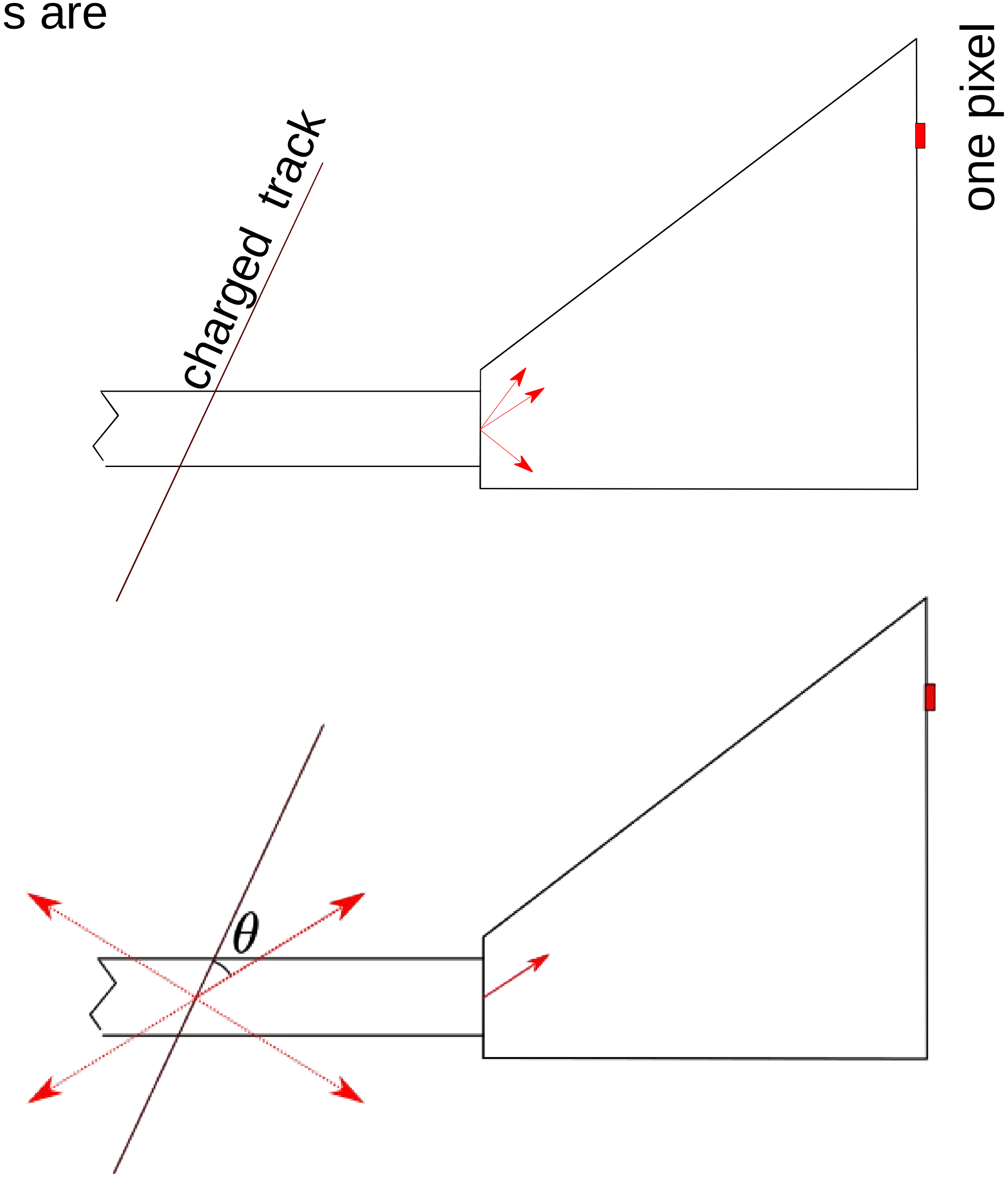

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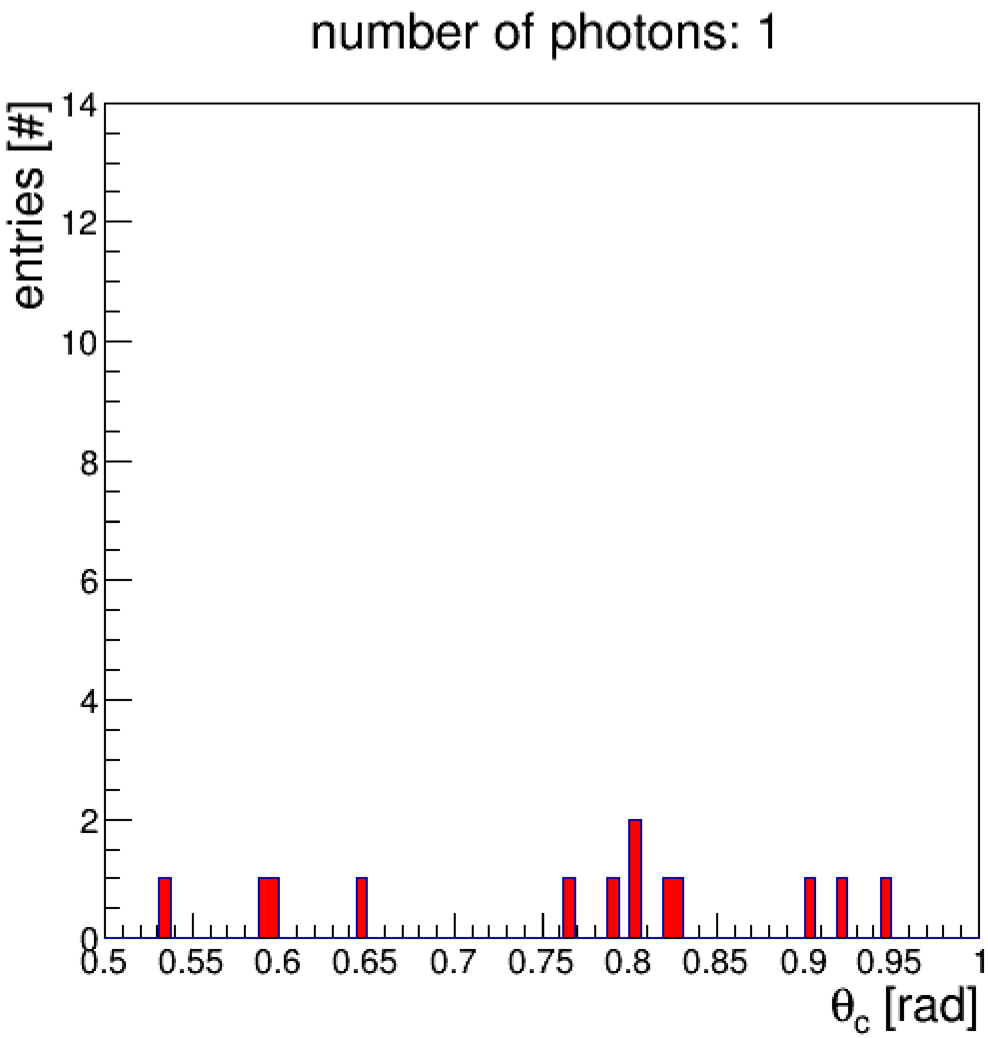

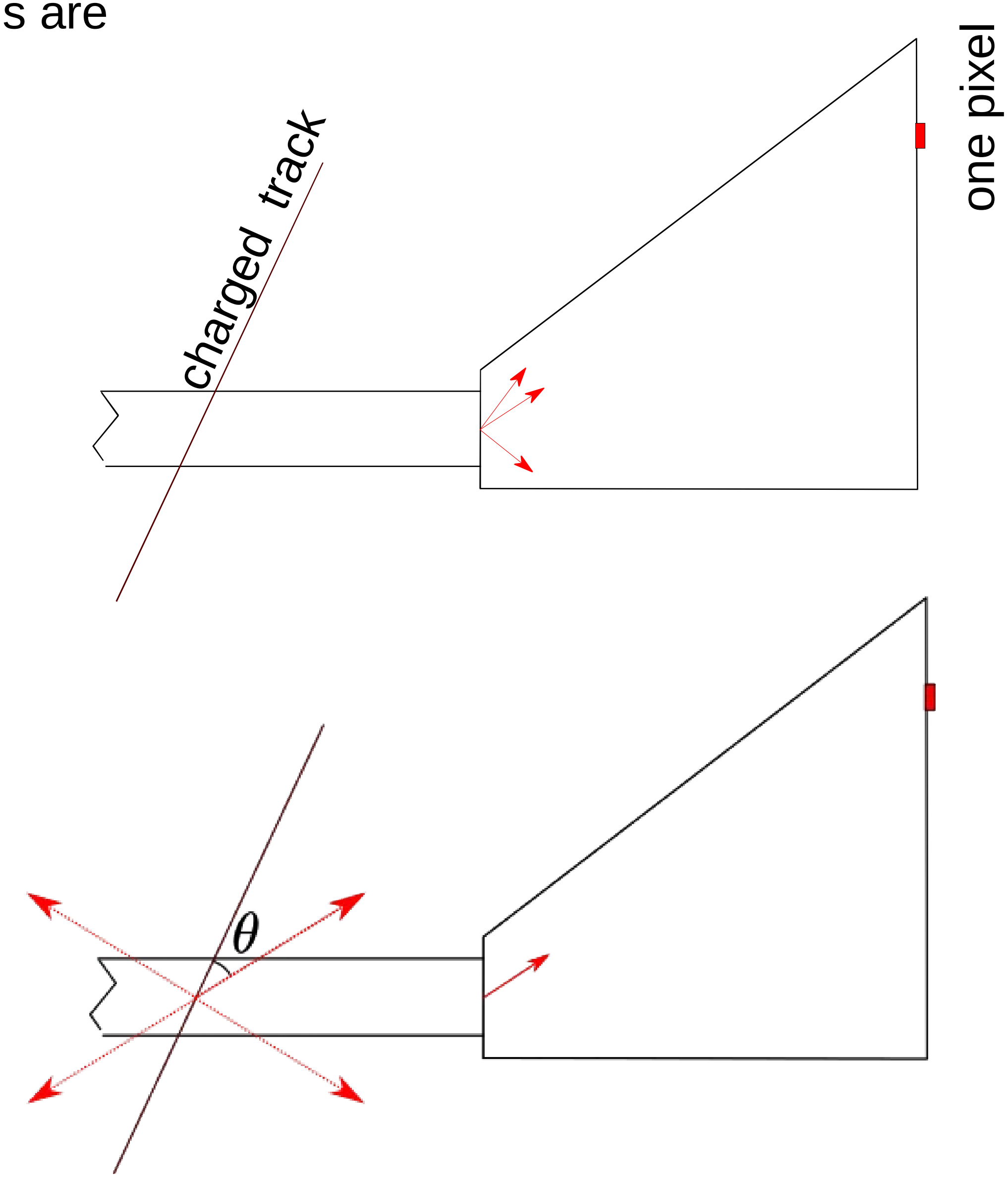

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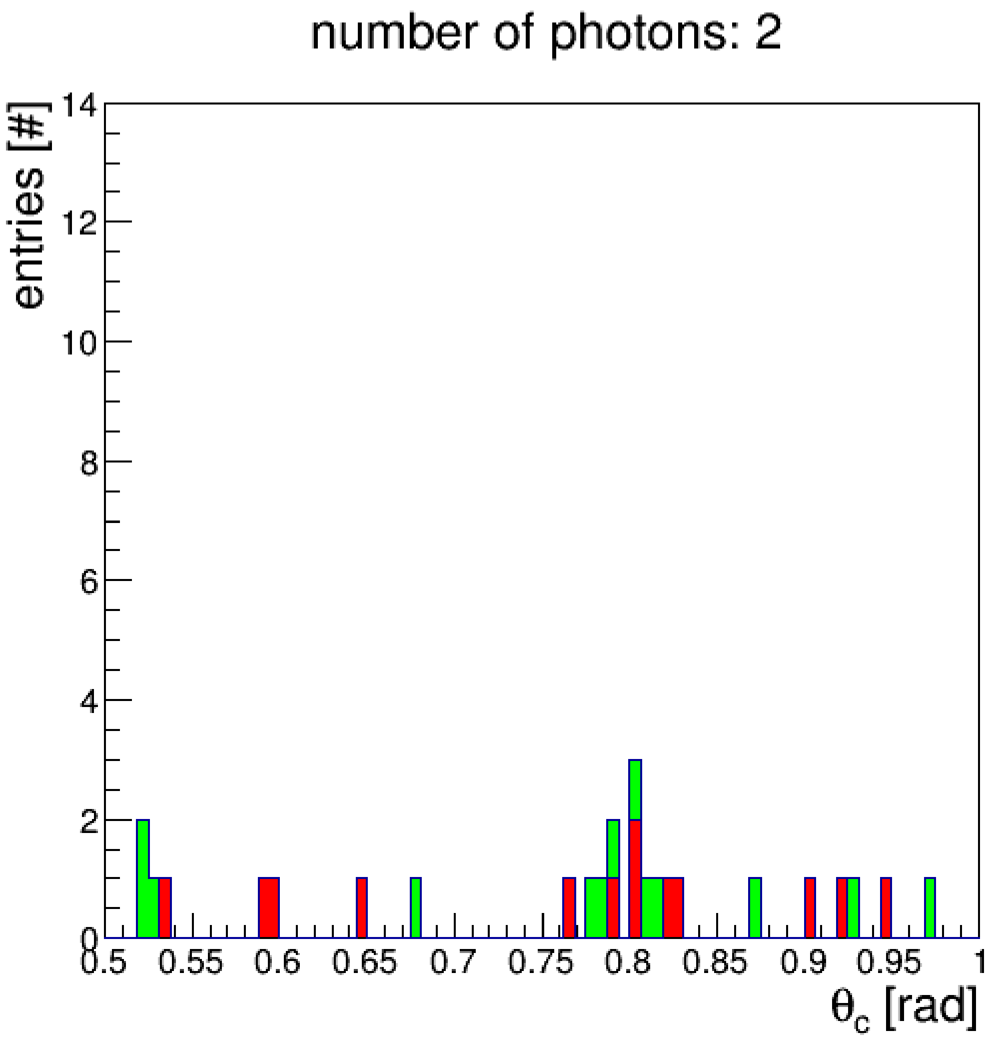

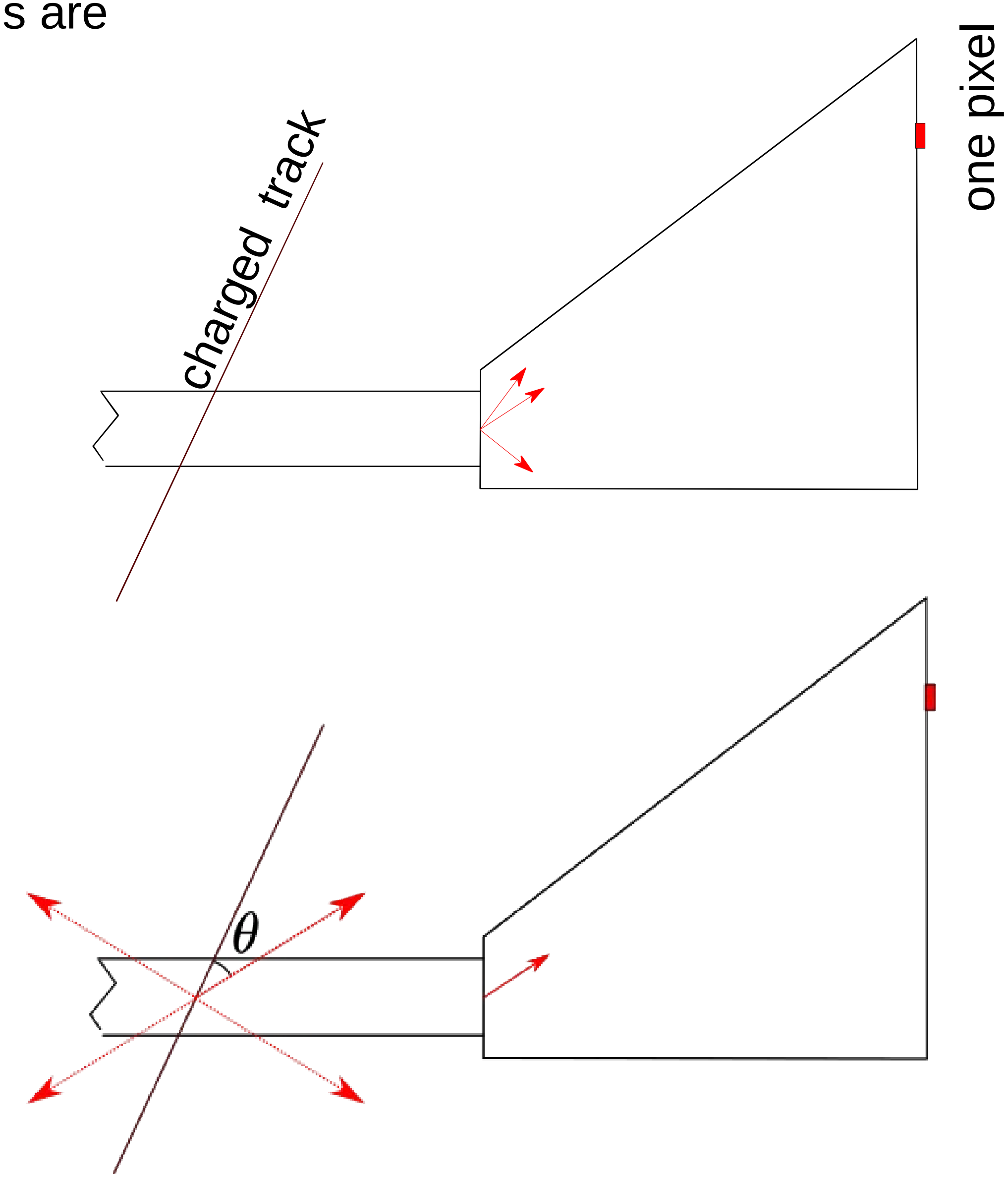

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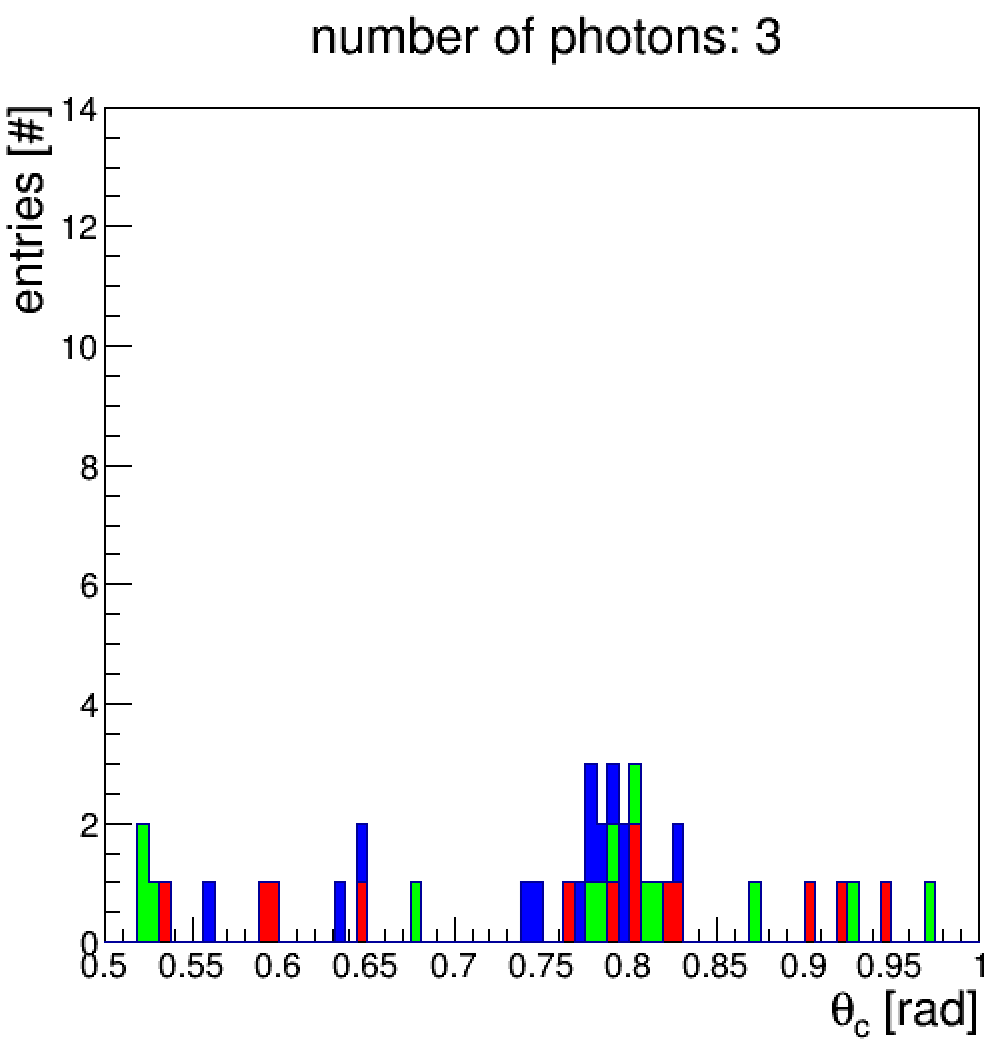

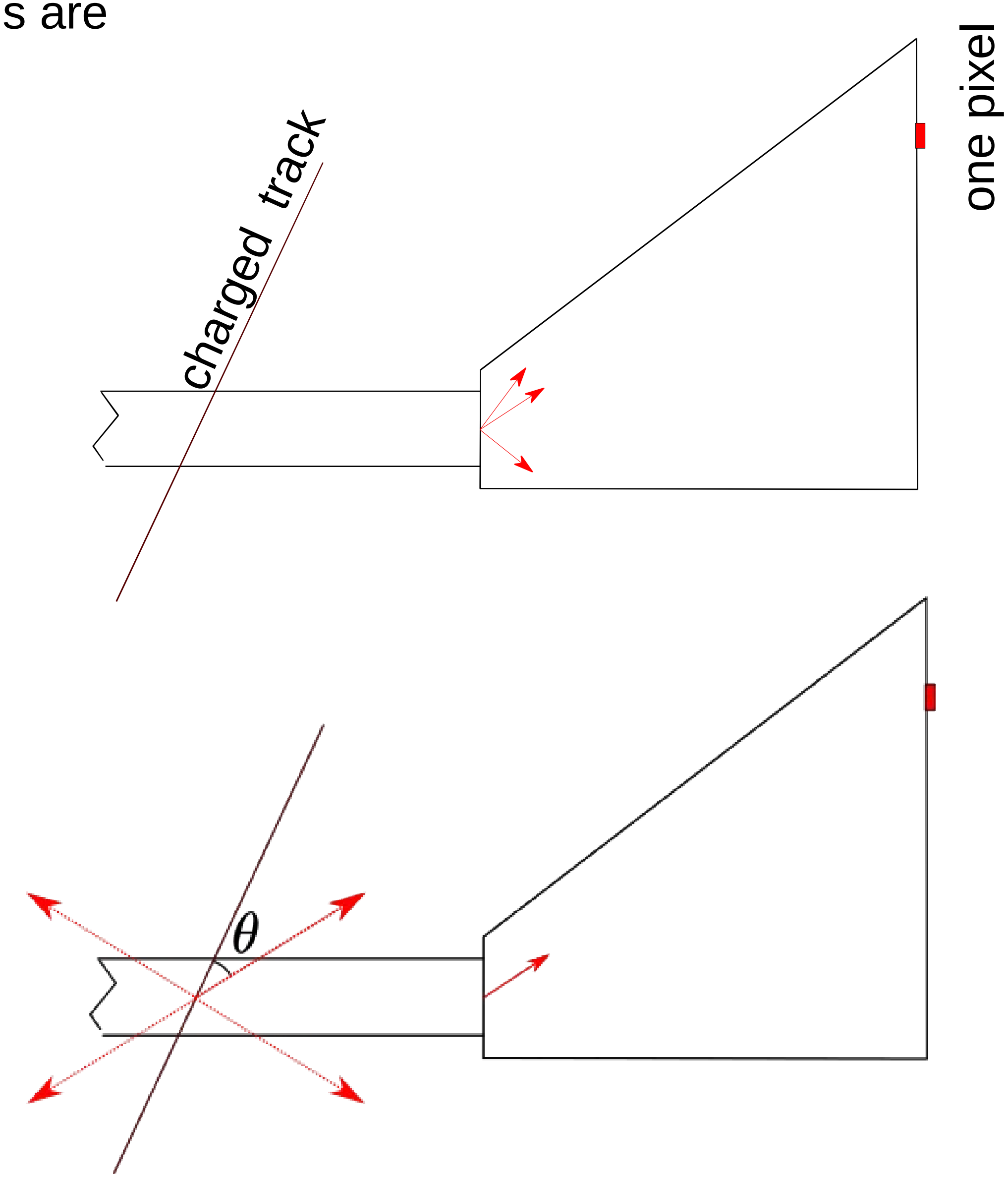

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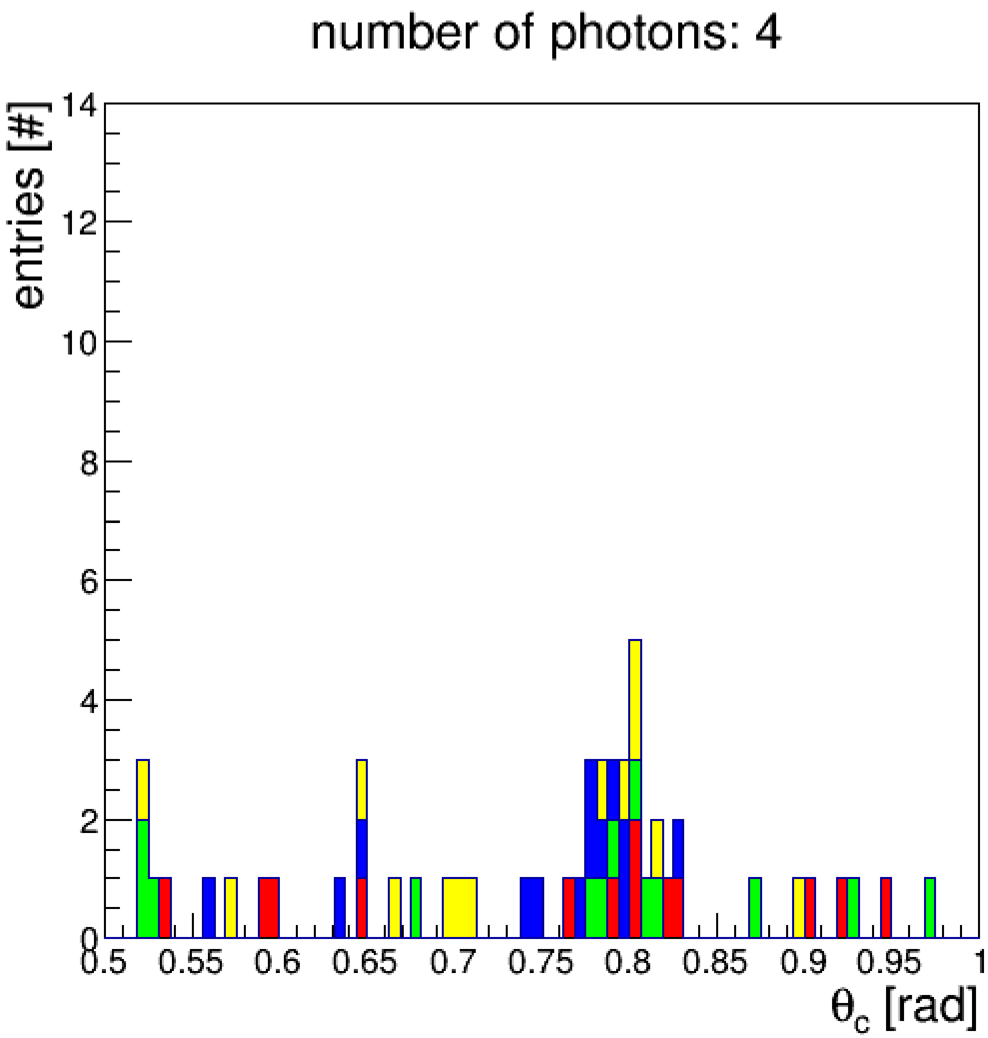

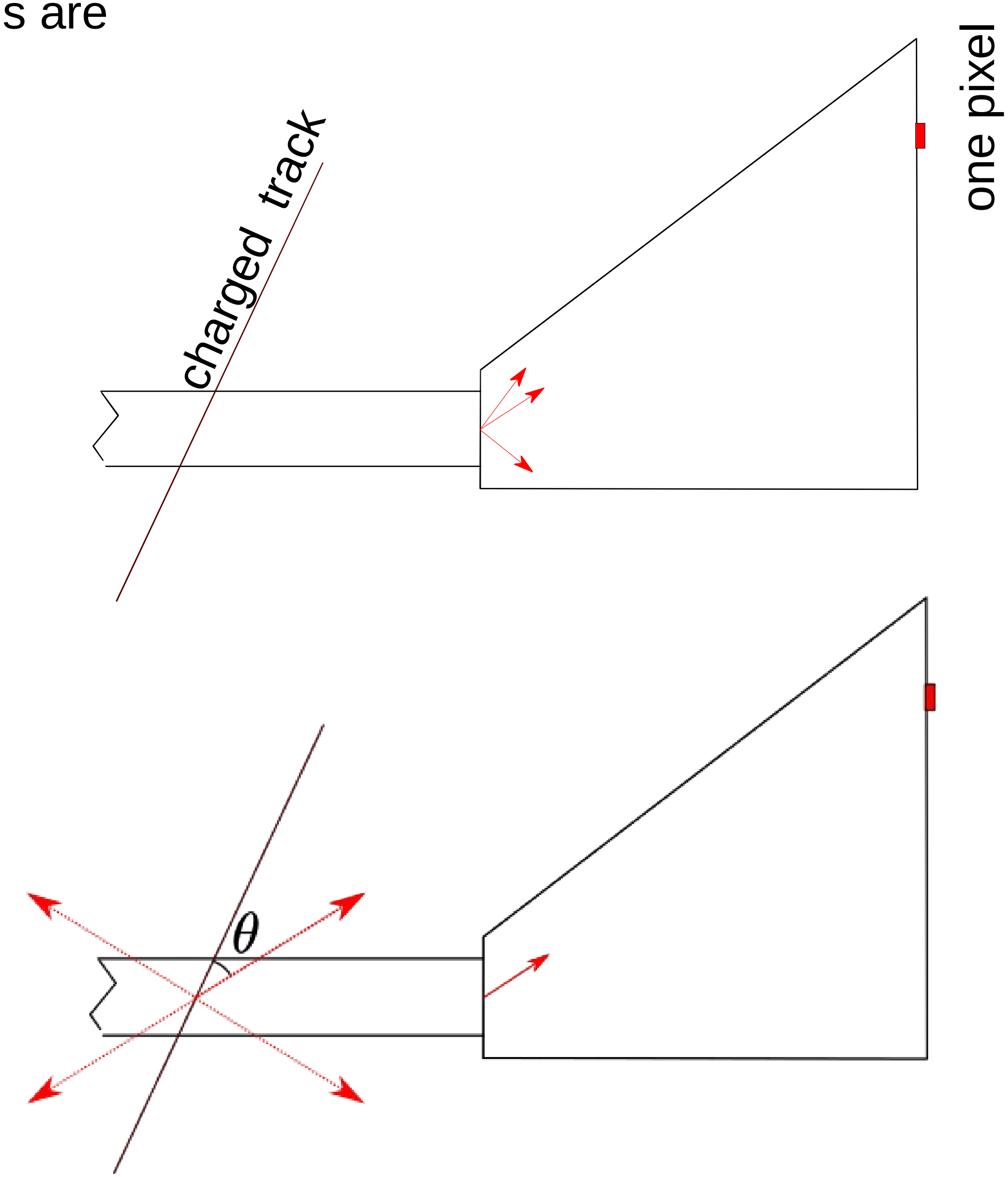

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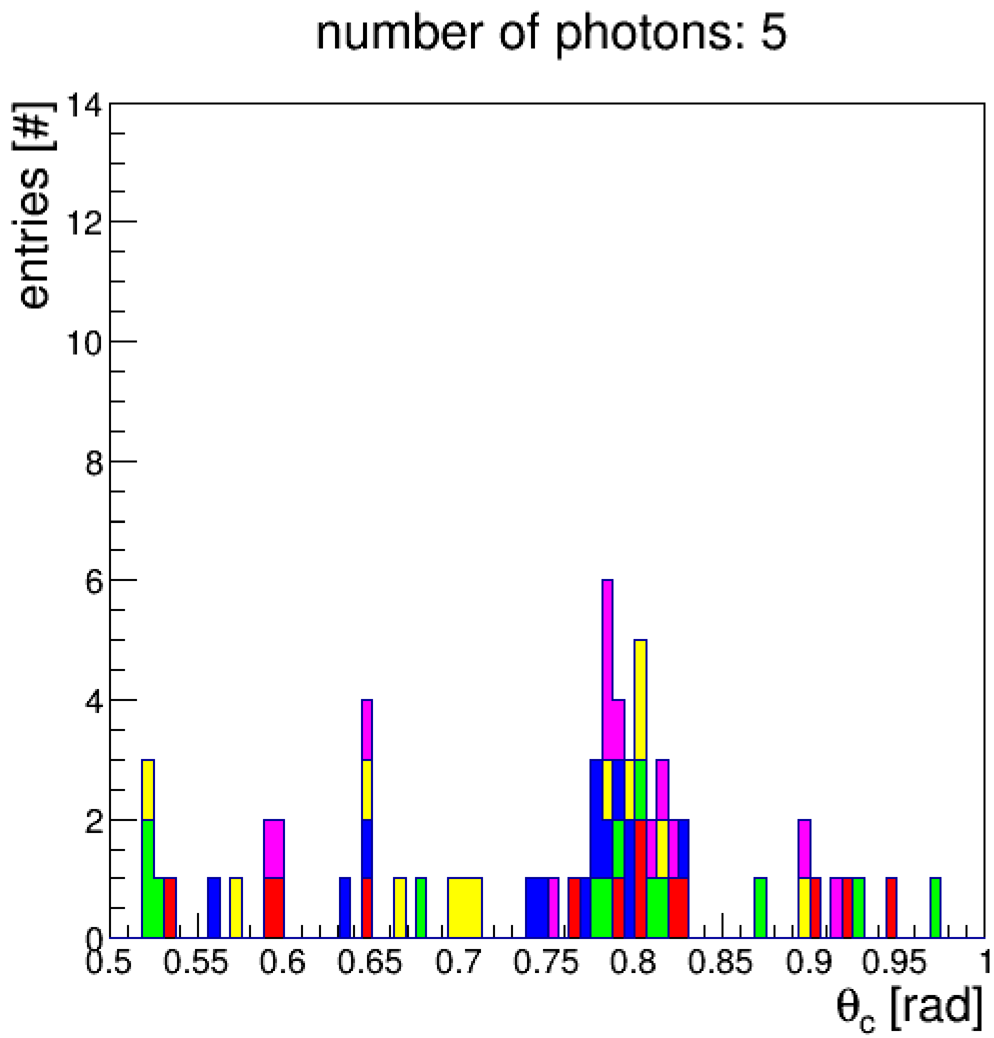

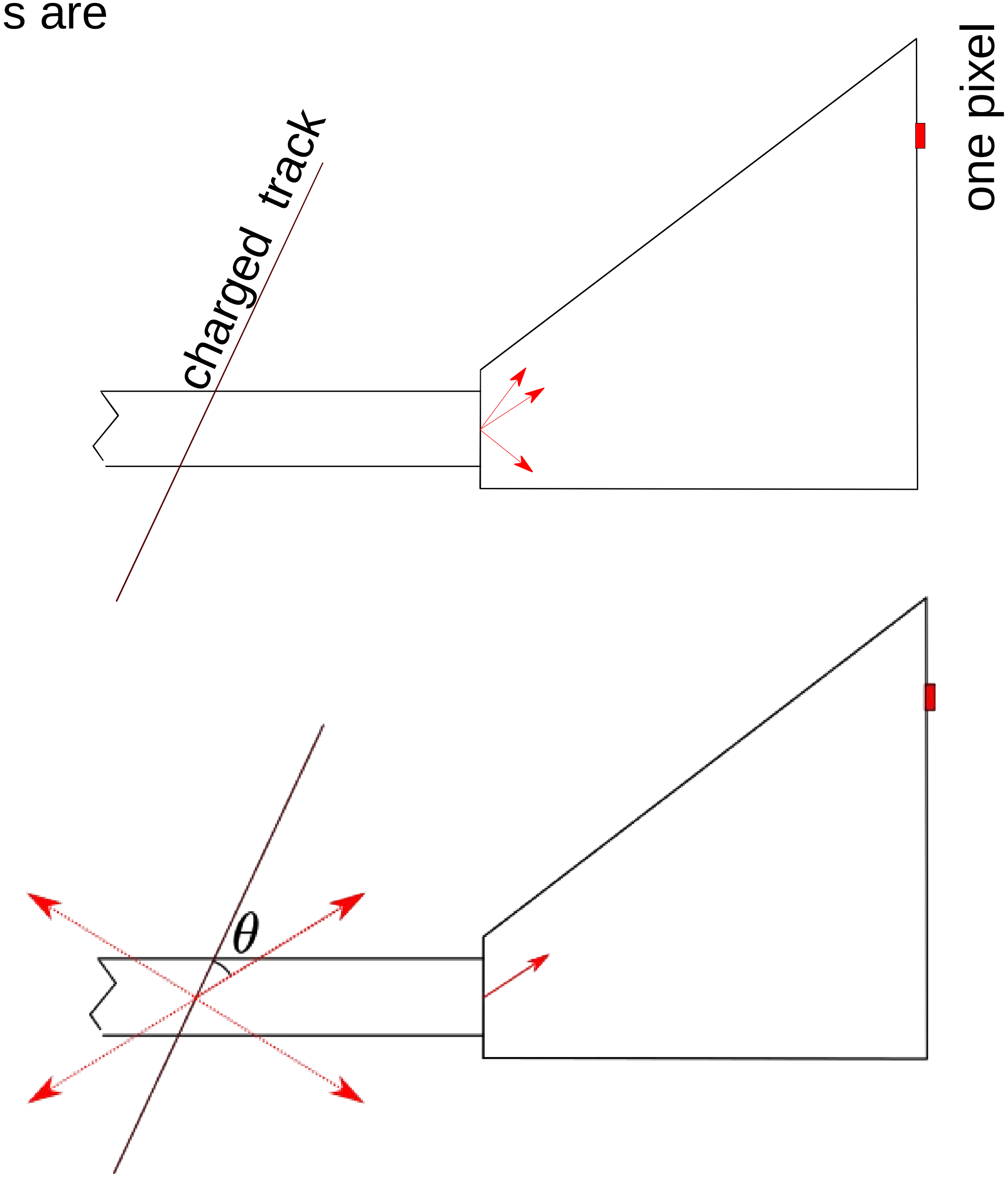

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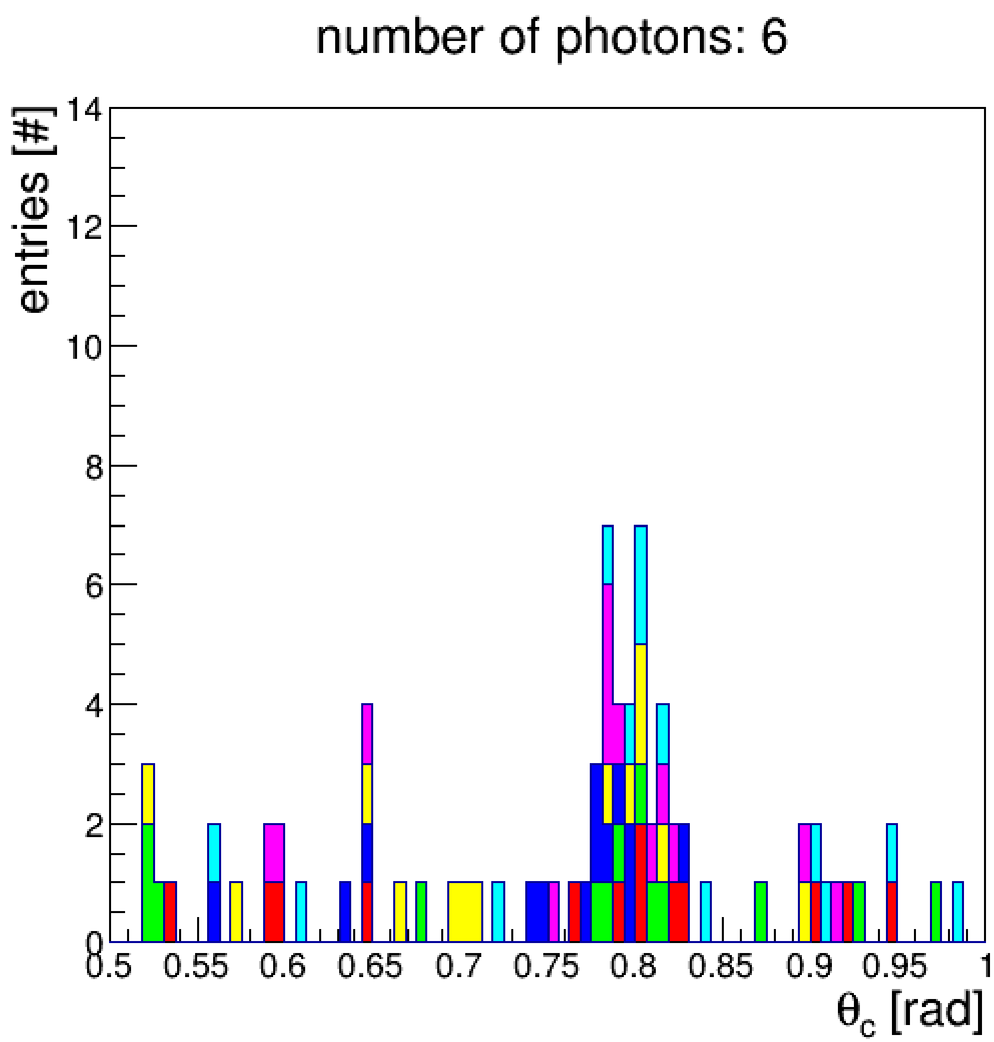

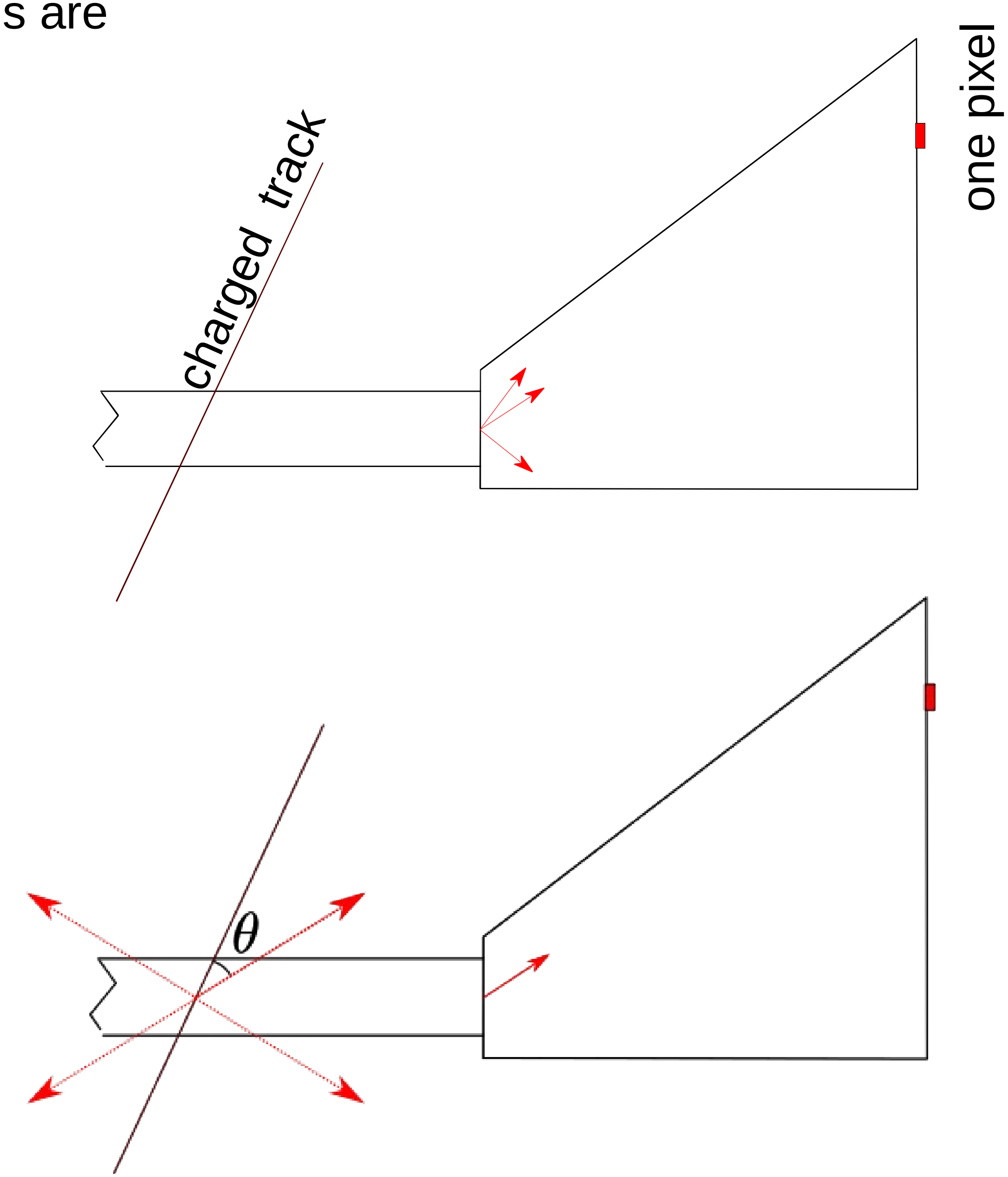

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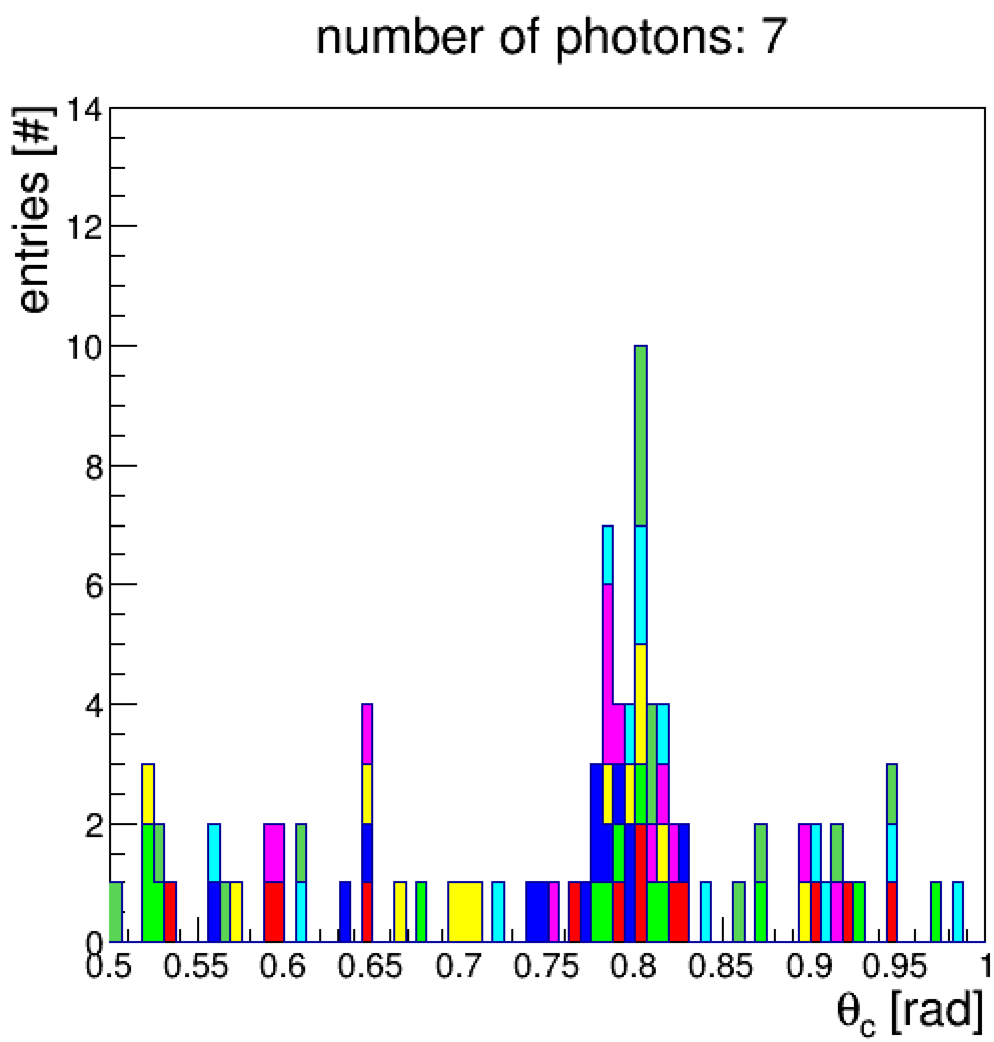

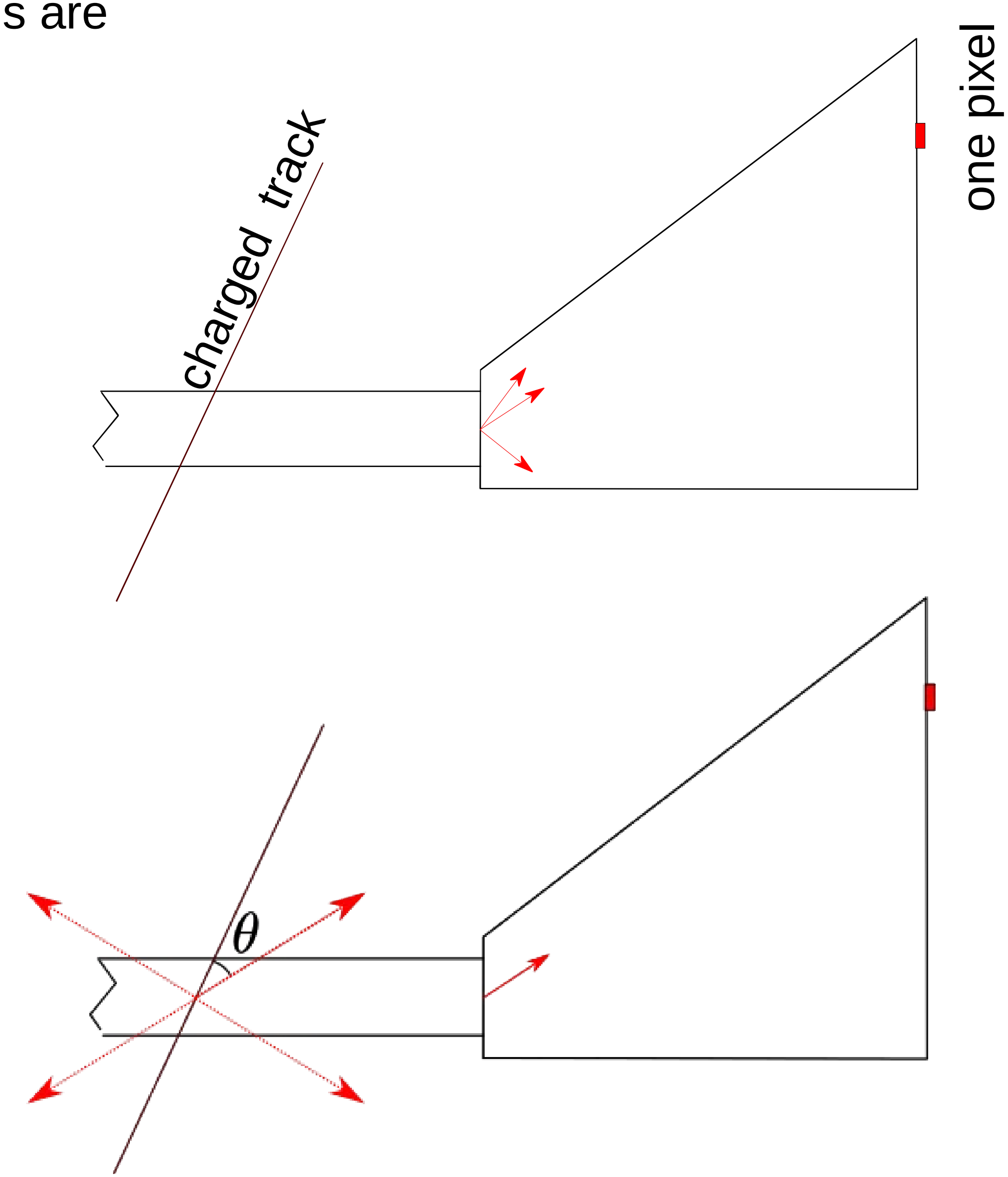

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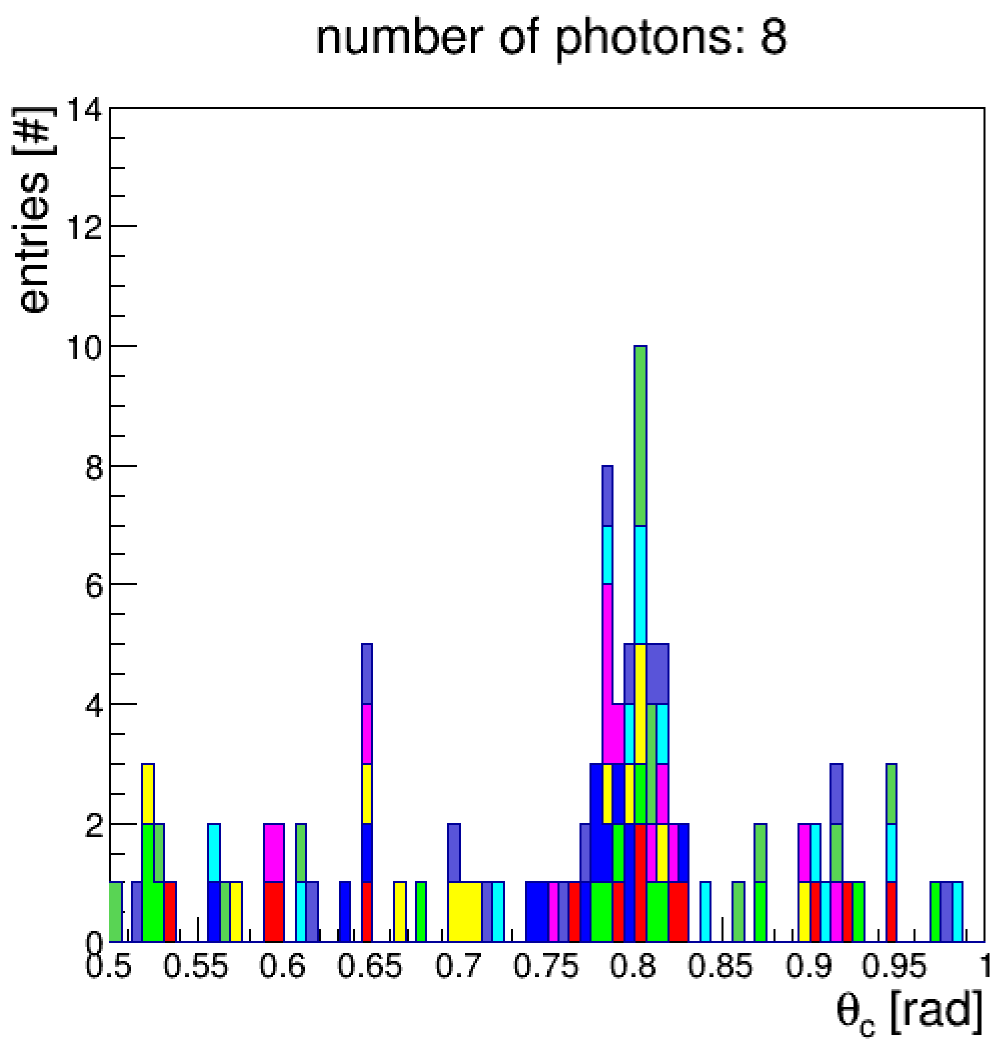

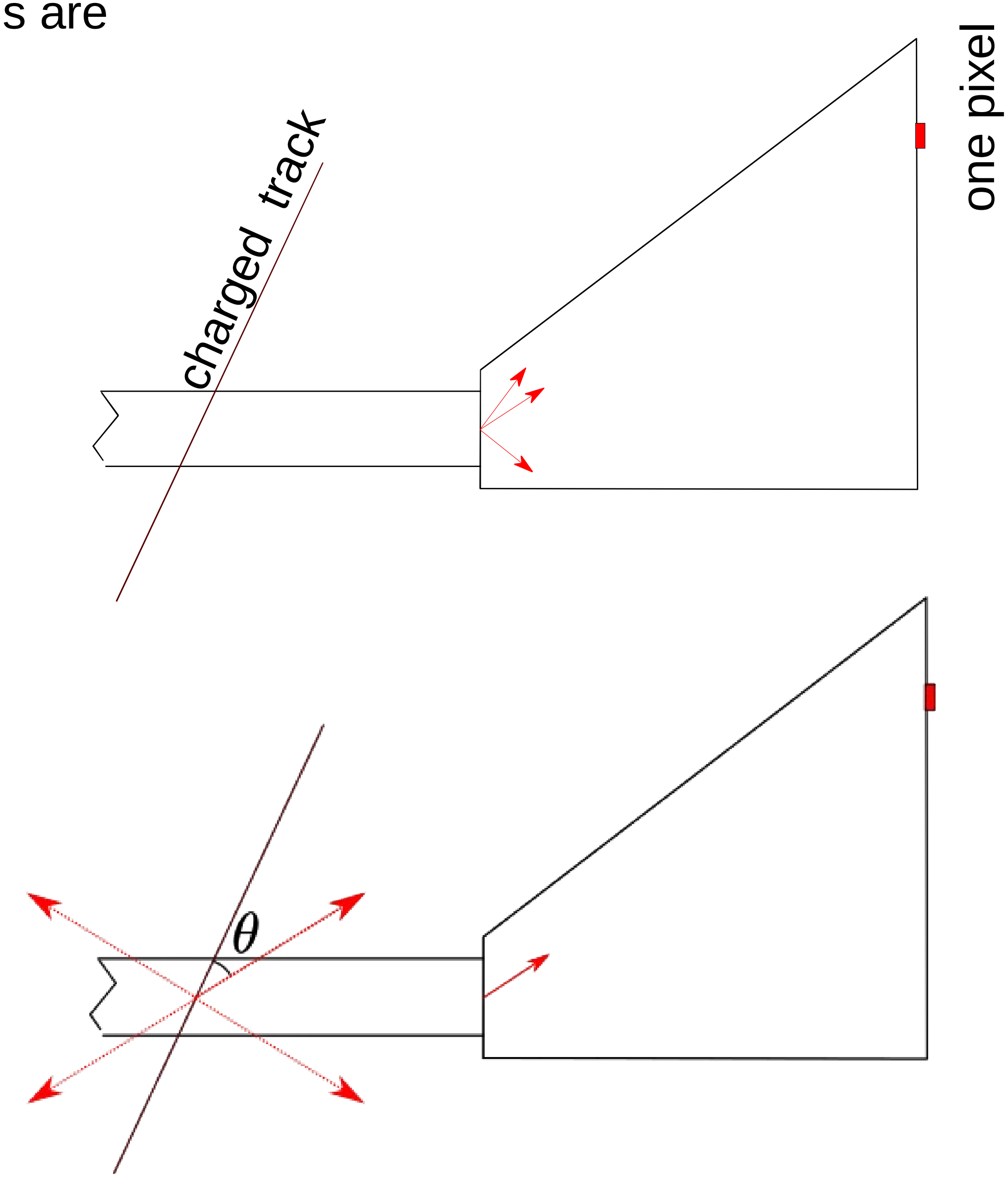

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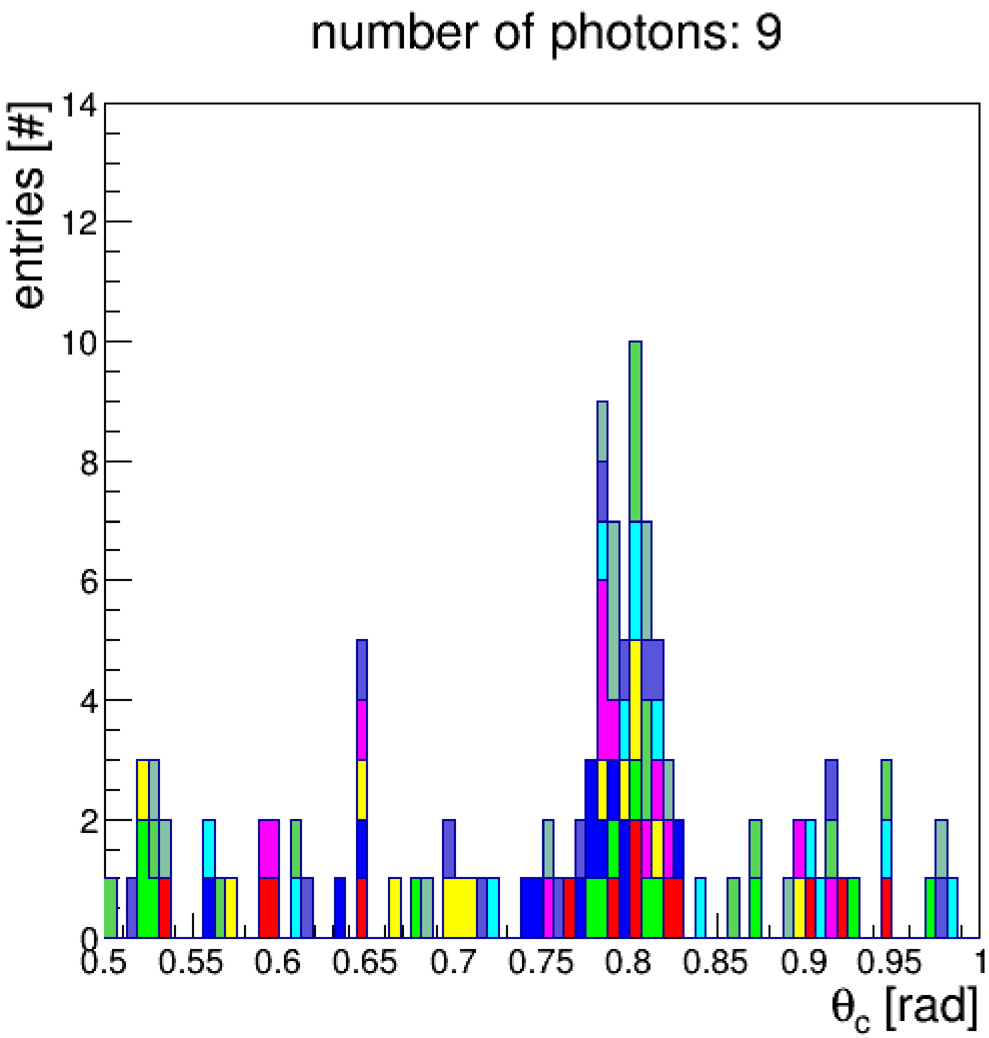

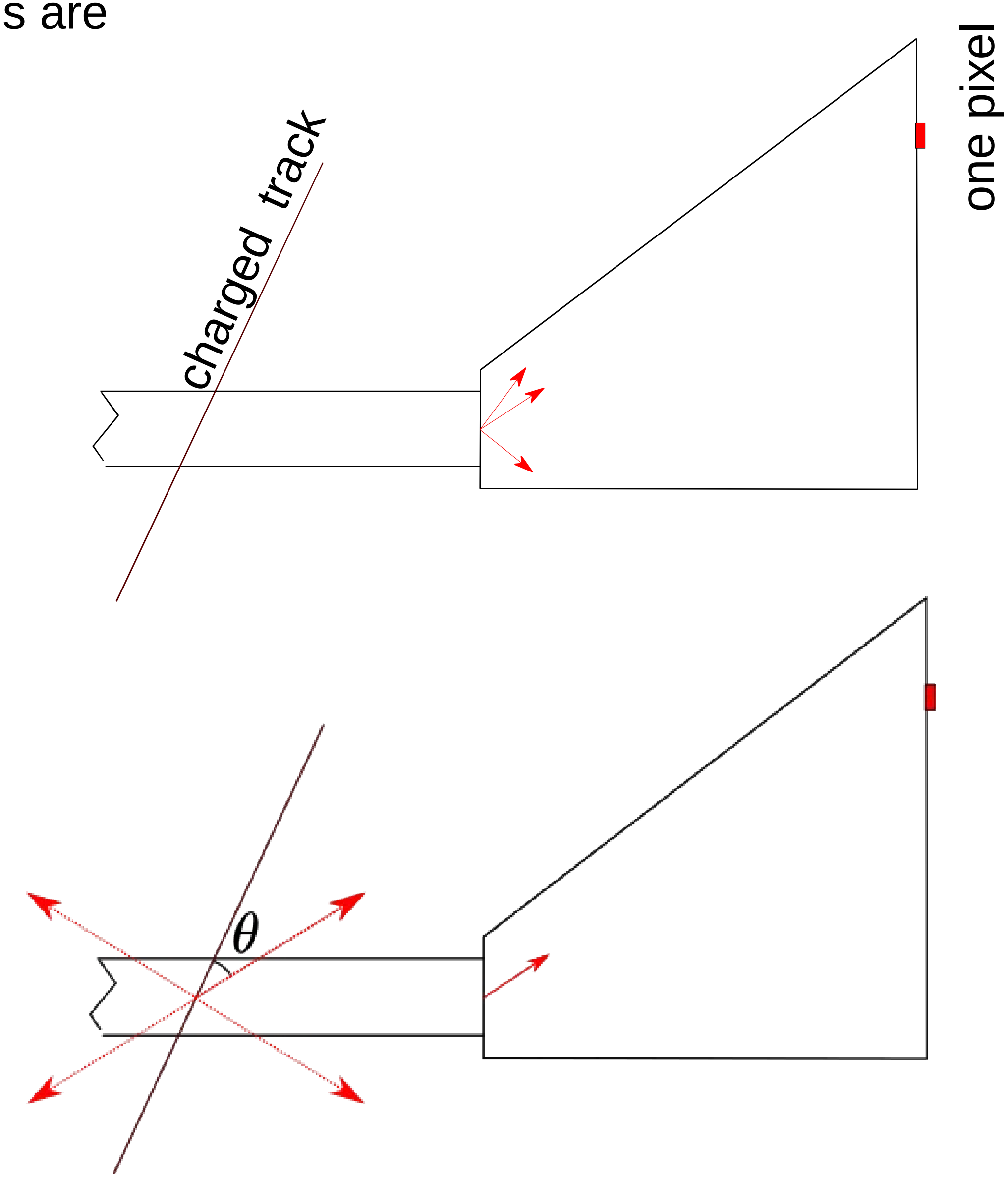

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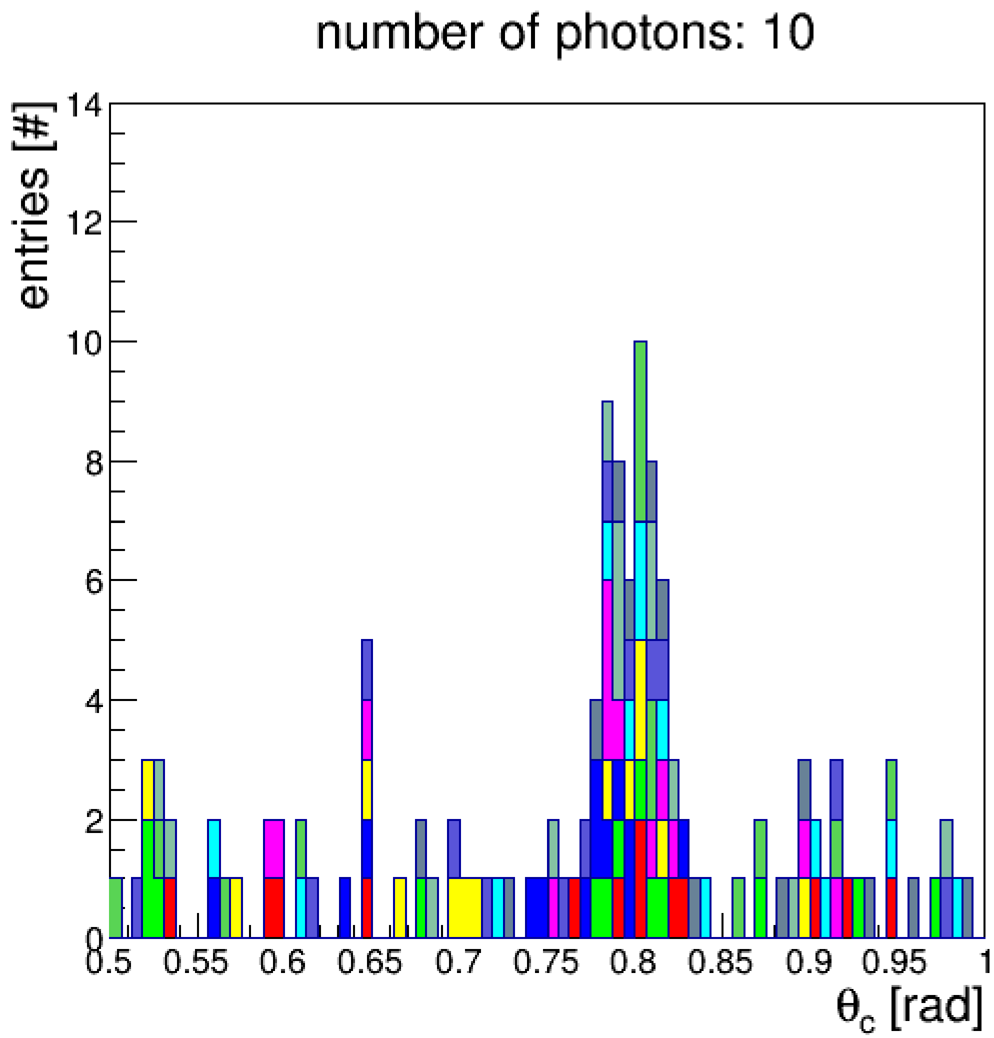

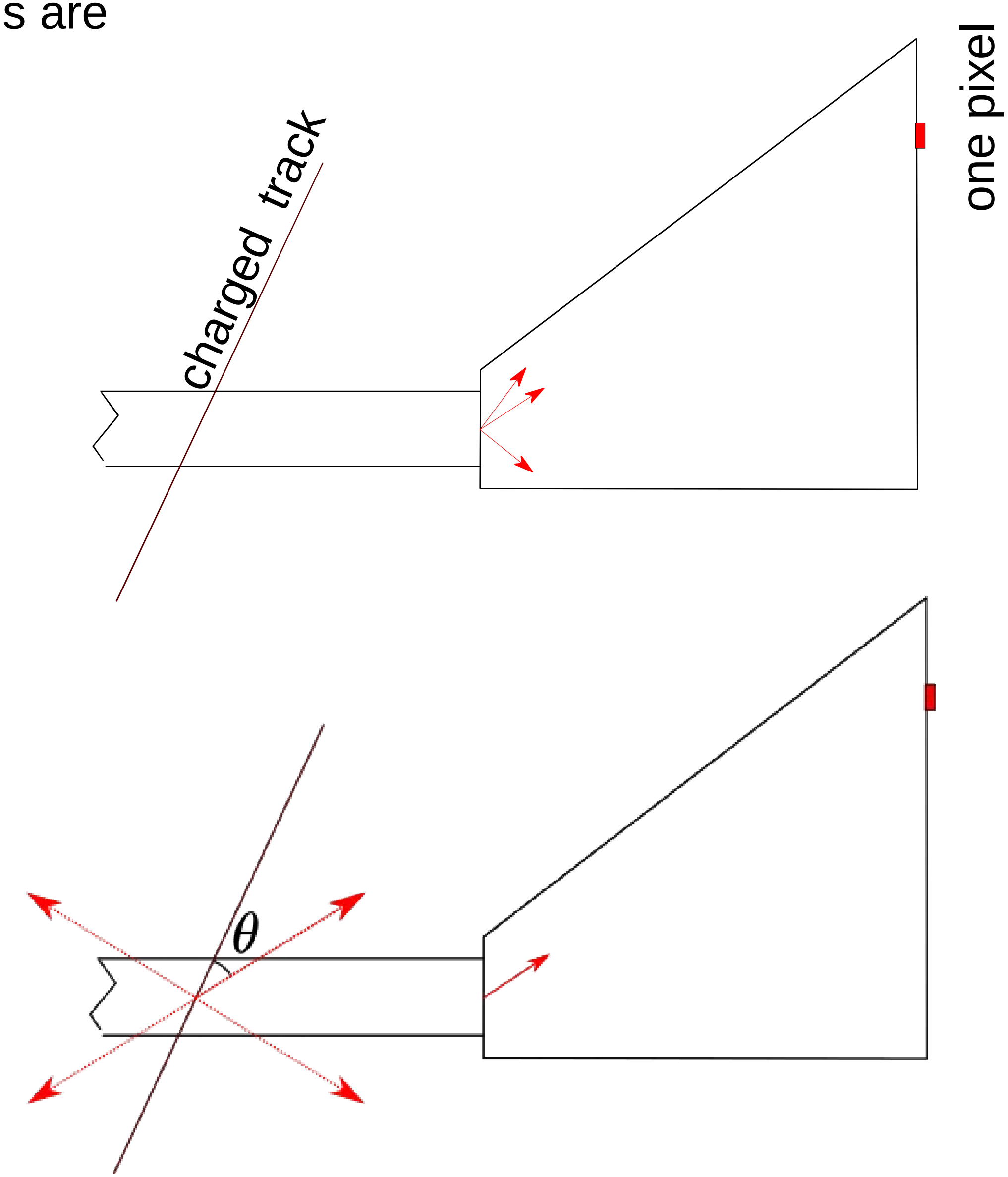

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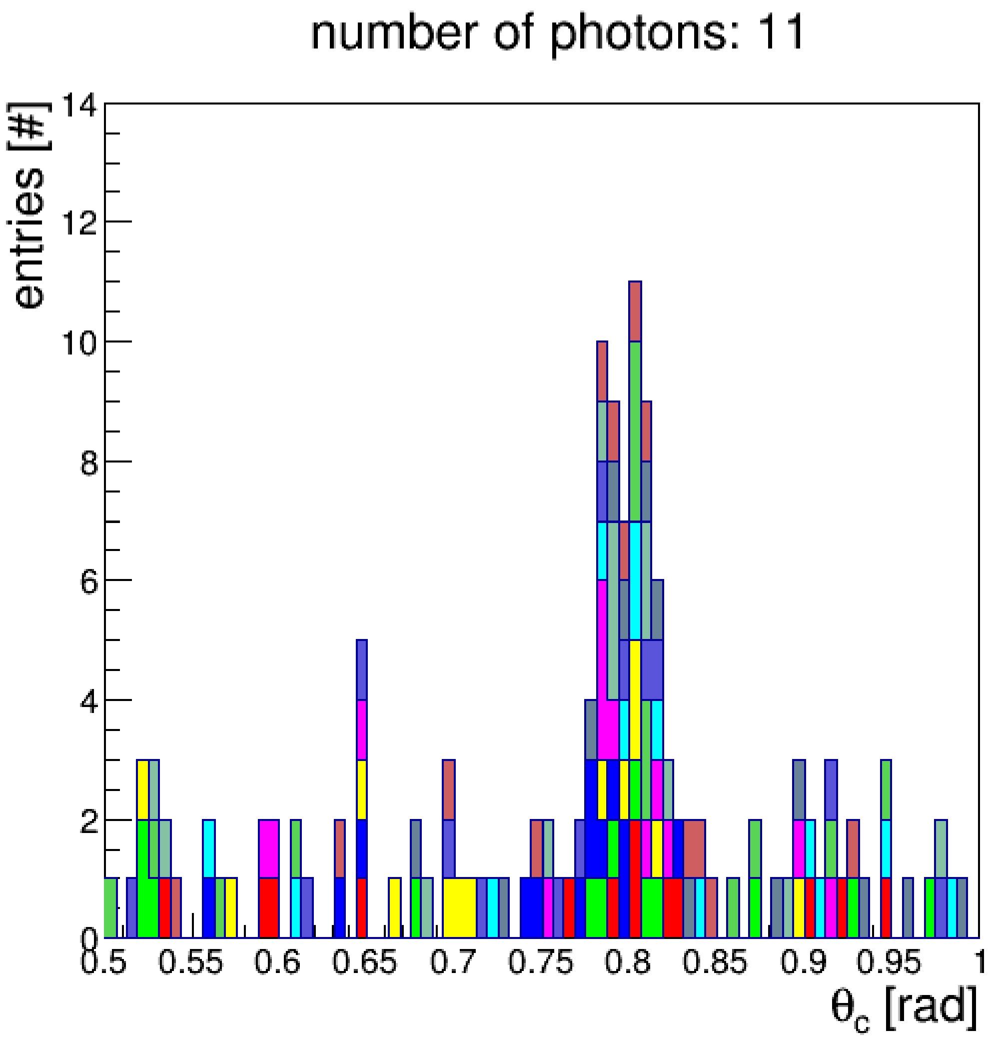

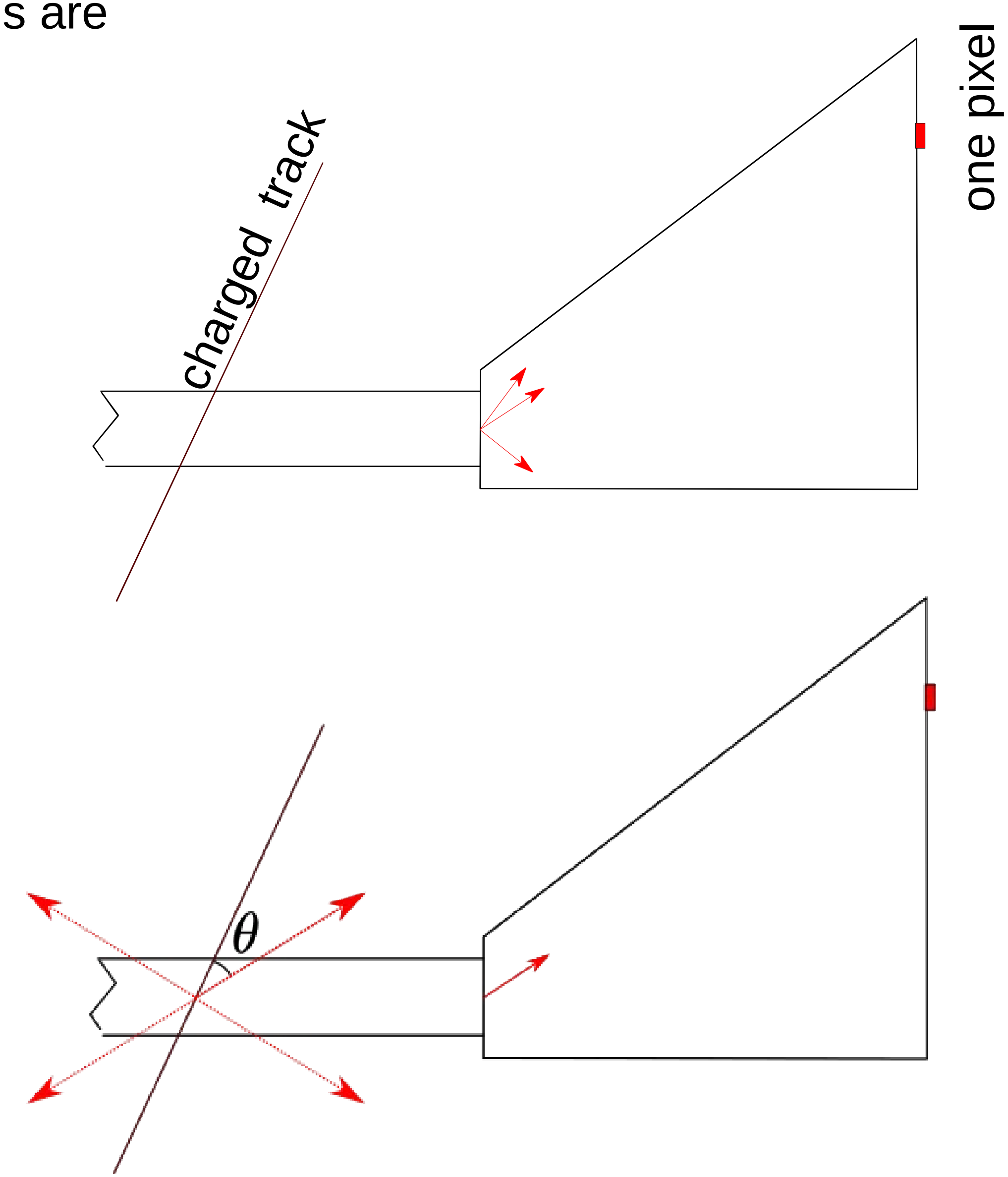

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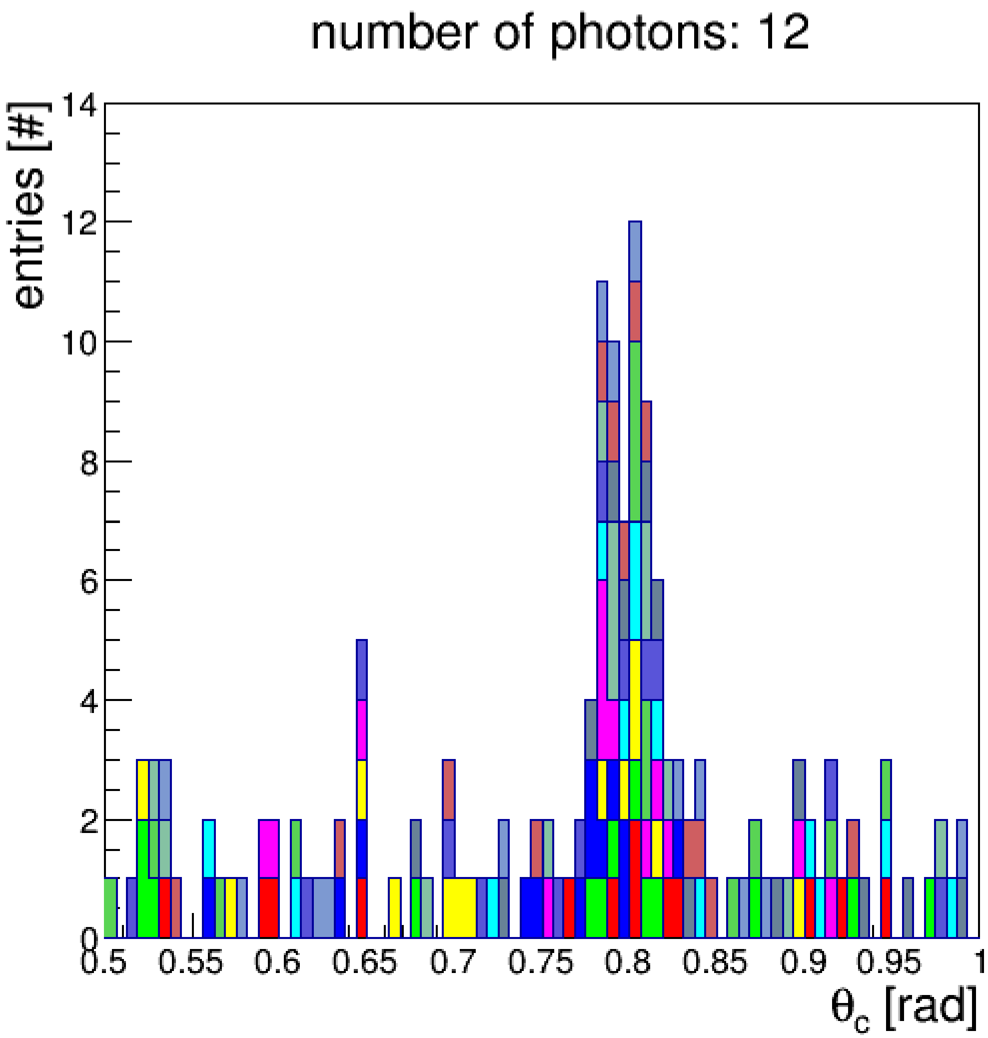
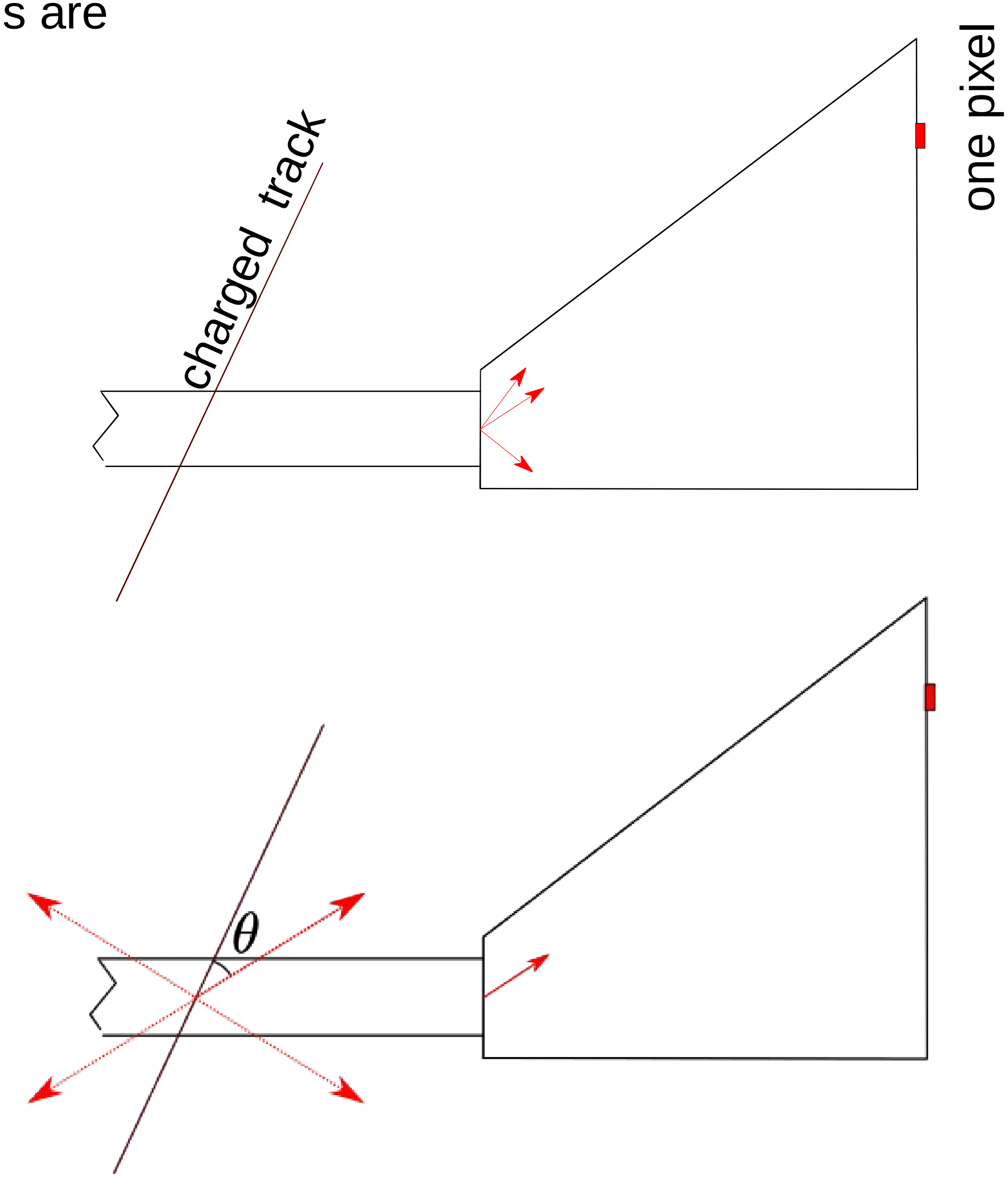
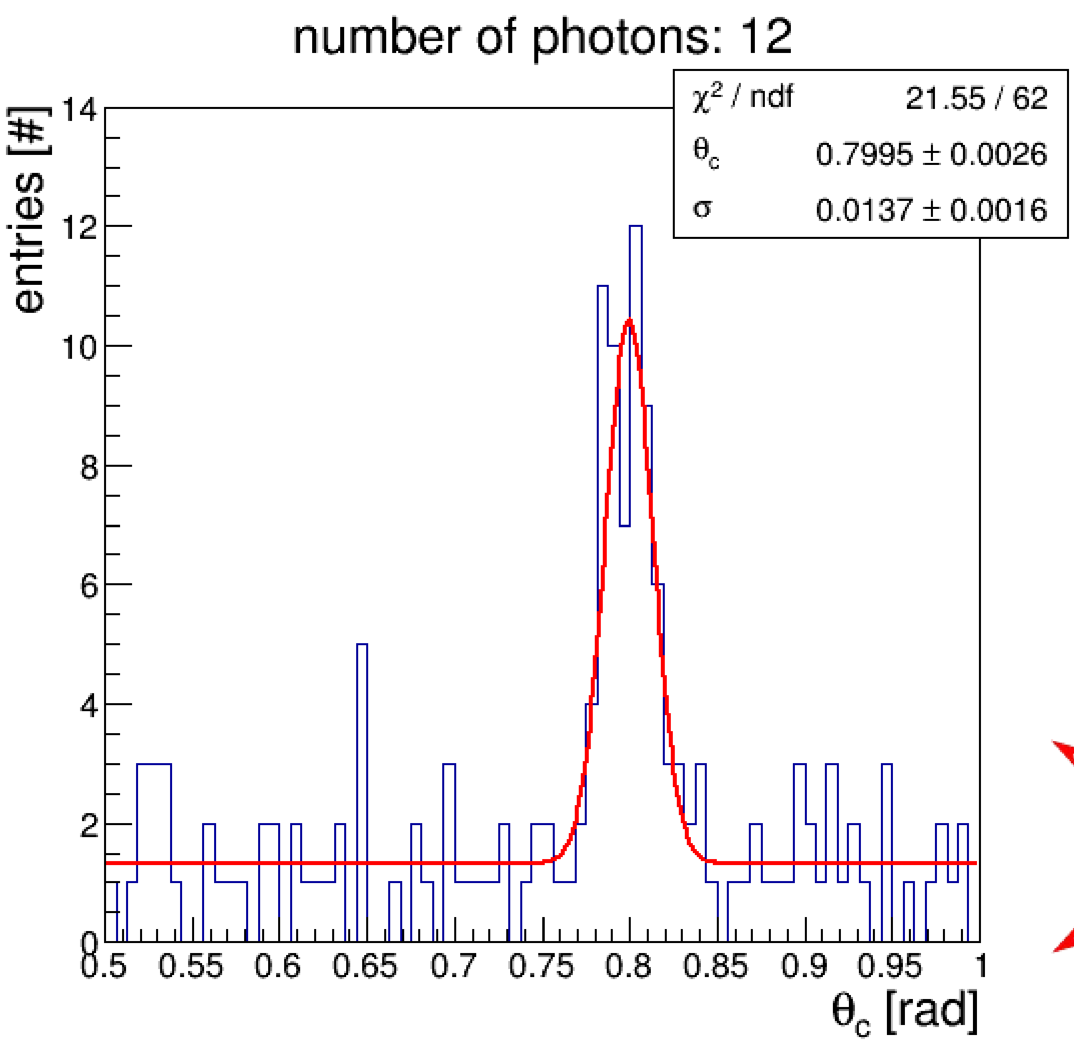
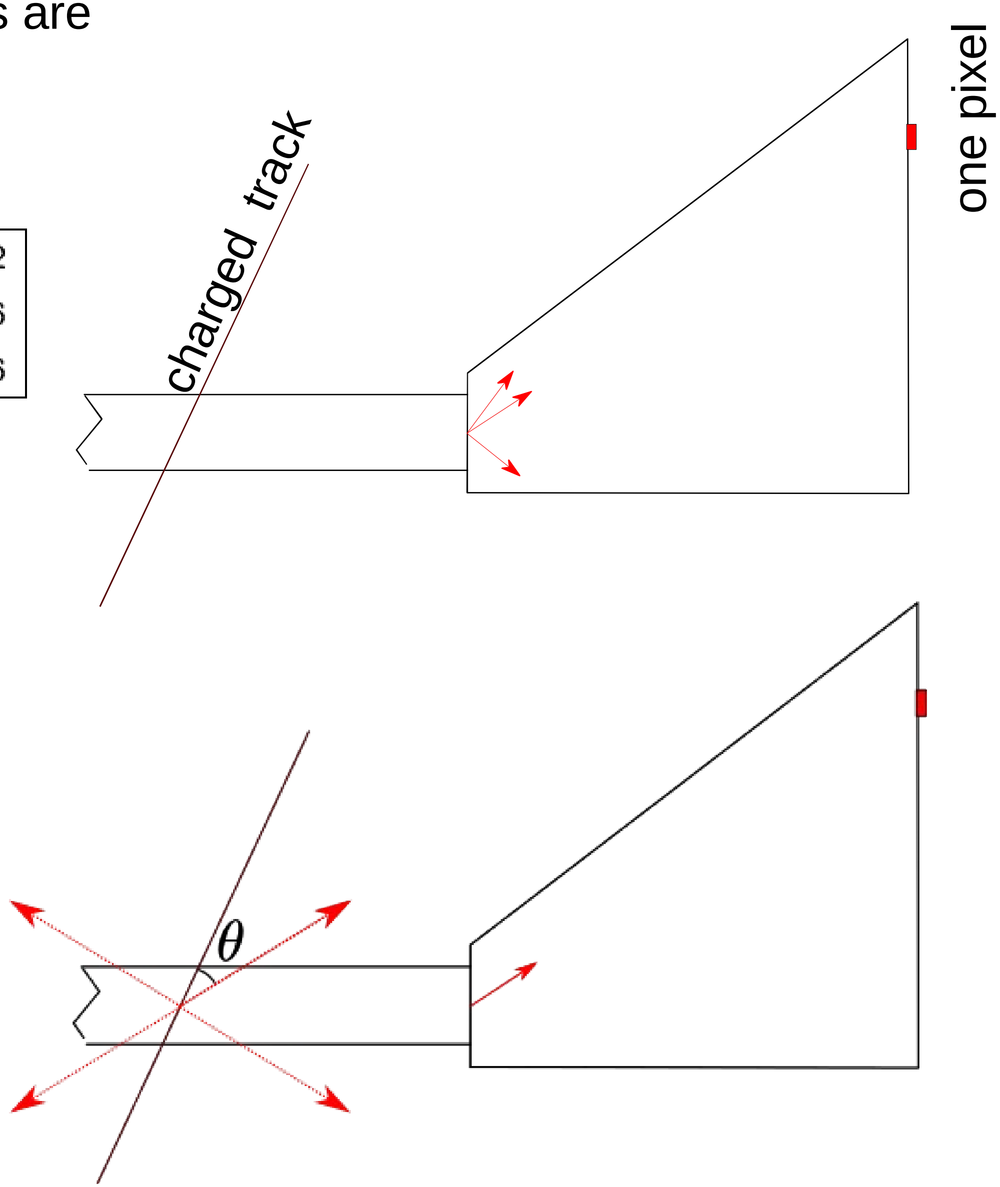




Geometrical Reconstruction

Reconstruction: direction from LUT for hit pixels are combined with charge track direction



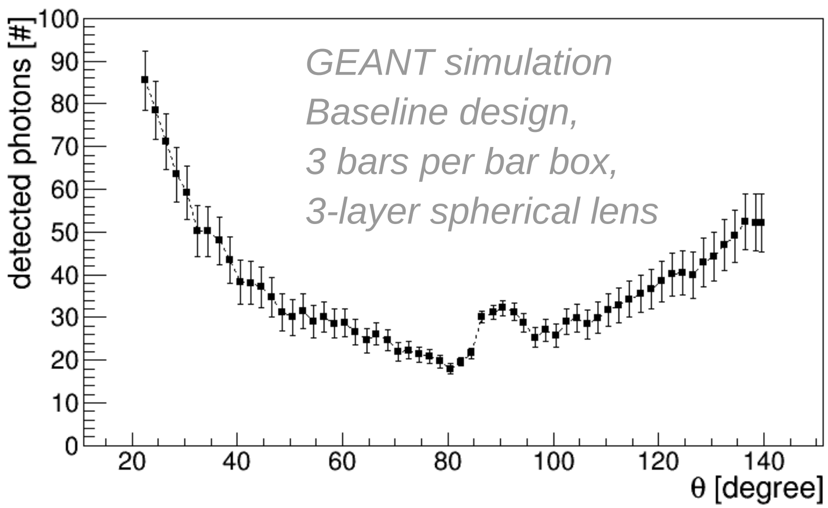


Geometrical Reconstruction

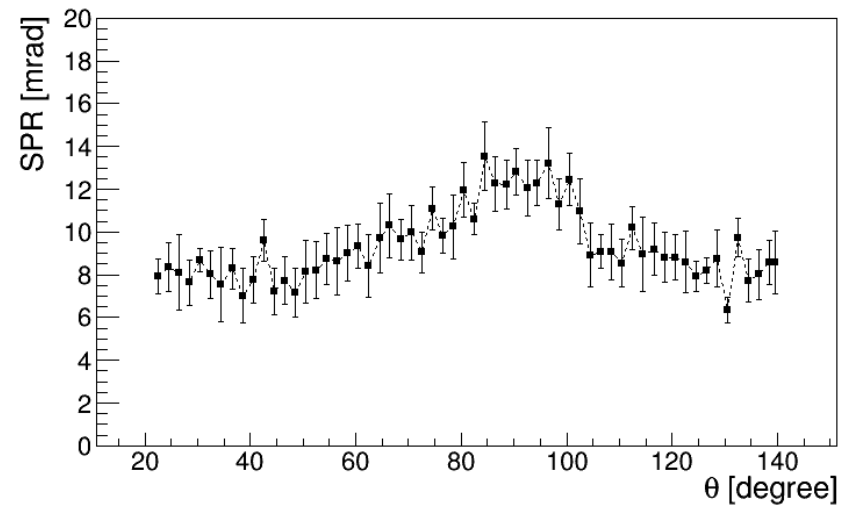
Cherenkov track resolution: $\sigma_{\theta_C}^{\text{track}} = \sqrt{\left(\frac{\sigma_{\theta_C}^{\text{photon}}}{\sqrt{N_{\text{photons}}}}\right)^2 + (\sigma^{\text{correlated}})^2}$

tracking resolution
2-3 mrad

Photon yield



Single Photon Cherenkov angle resolution (SPR)



Geometrical Reconstruction

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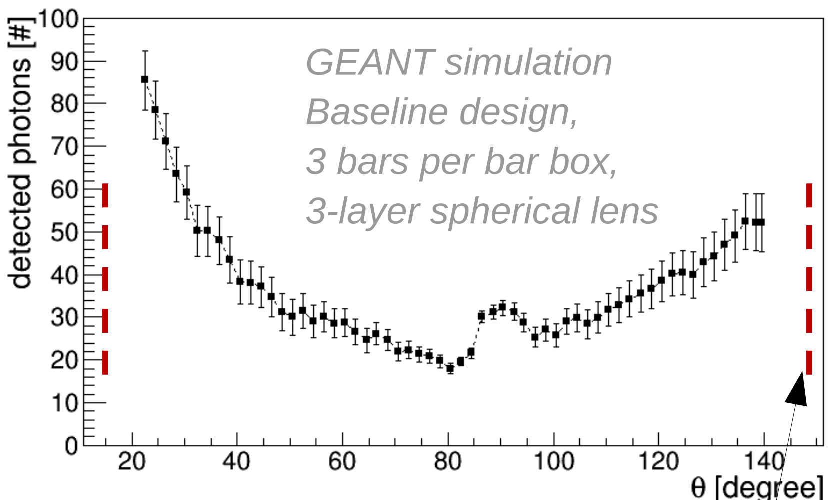
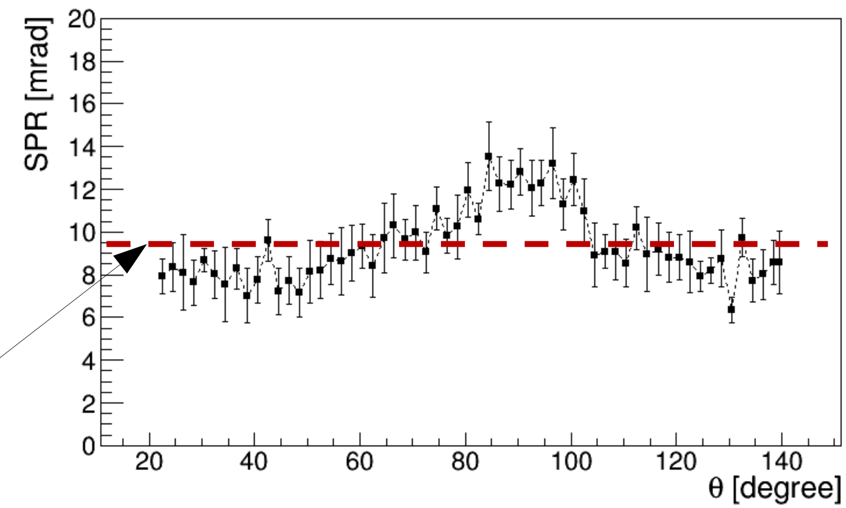
tracking resolution
2-3 mrad

Photon yield



Single Photon Cherenkov angle resolution (SPR)

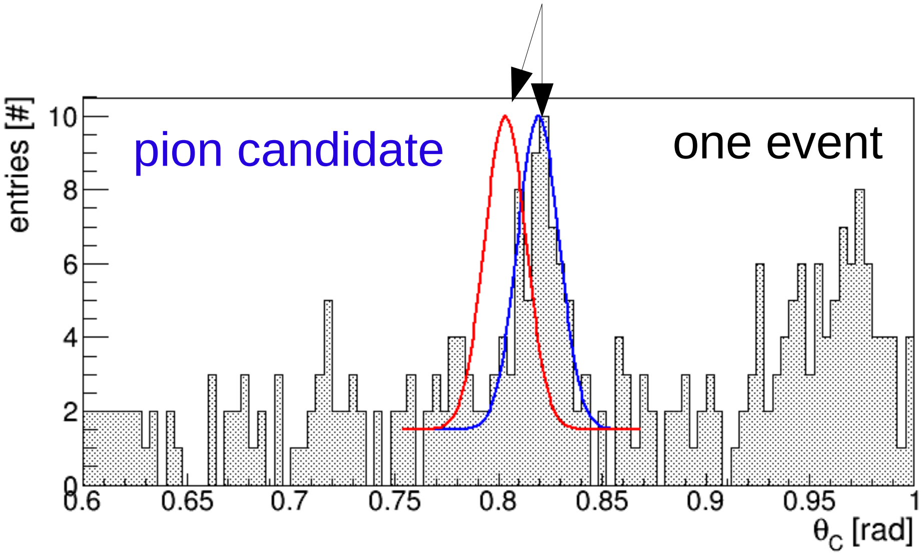


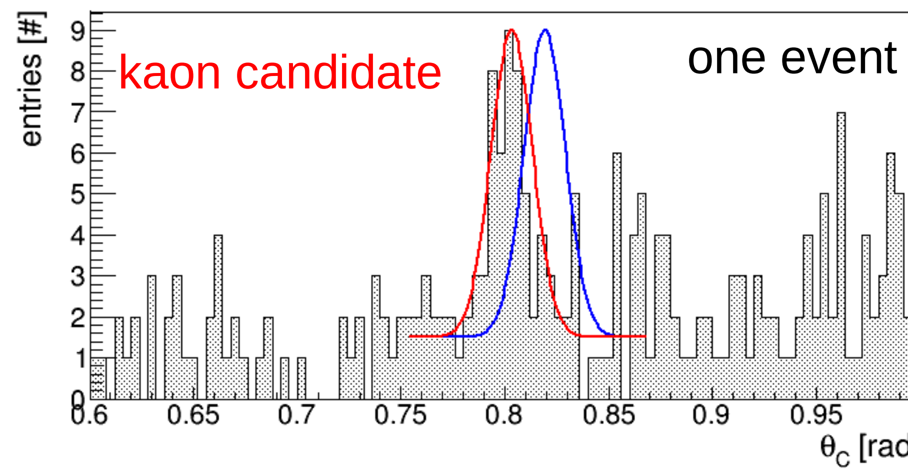
Yield and SPR reach performance goal

Geometrical Reconstruction

Likelihood calculation:

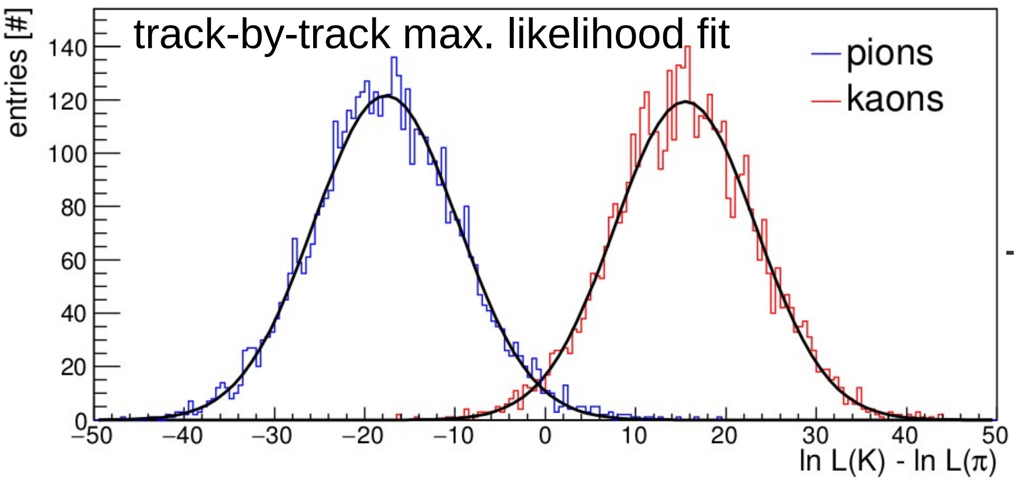
particle hypothesis





$$\log\mathcal{L}_h = \sum_{i=1}^{N} \log\left(\frac{S_h(x_i,y_i,t_i)+B(x_i,y_i,t_i)}{N_e}\right) + \log P_N(N_e)$$

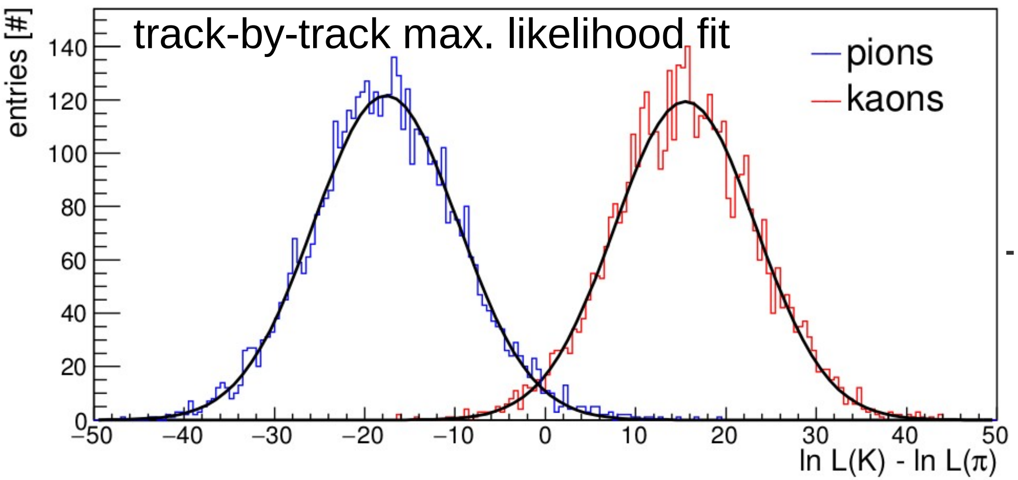
Geometrical Reconstruction



Baseline design with geometrical reconstruction

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

Geometrical Reconstruction

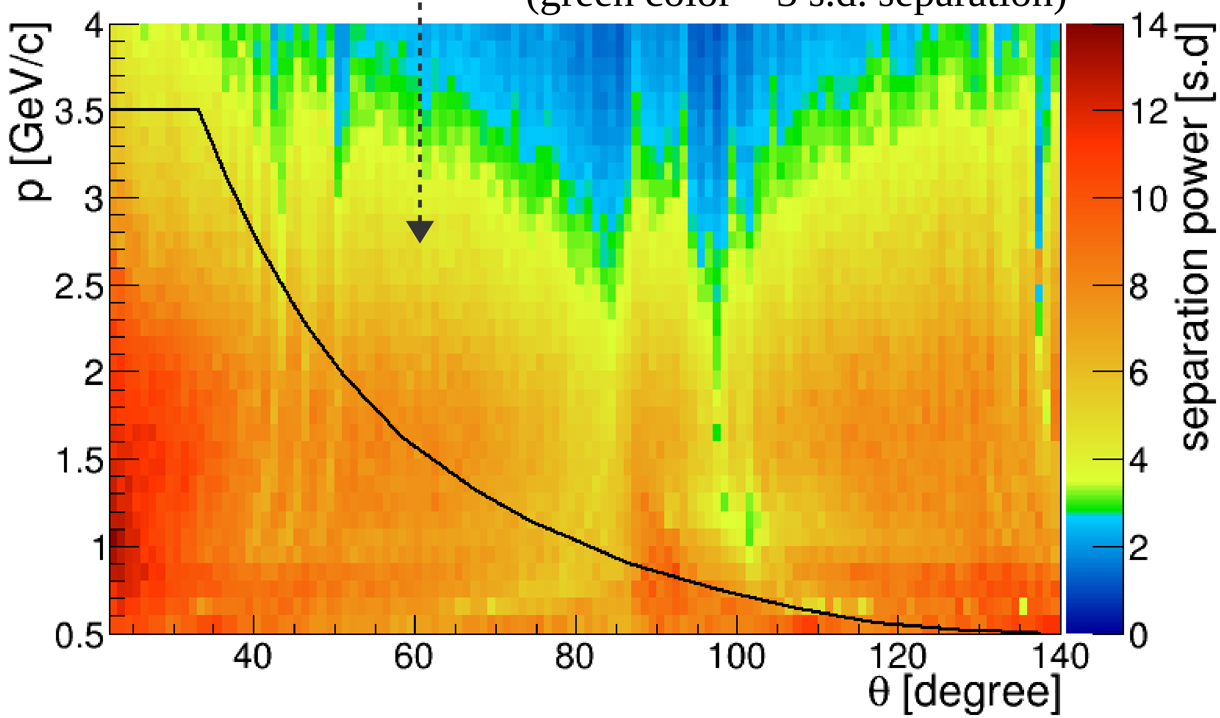


Baseline design with geometrical reconstruction

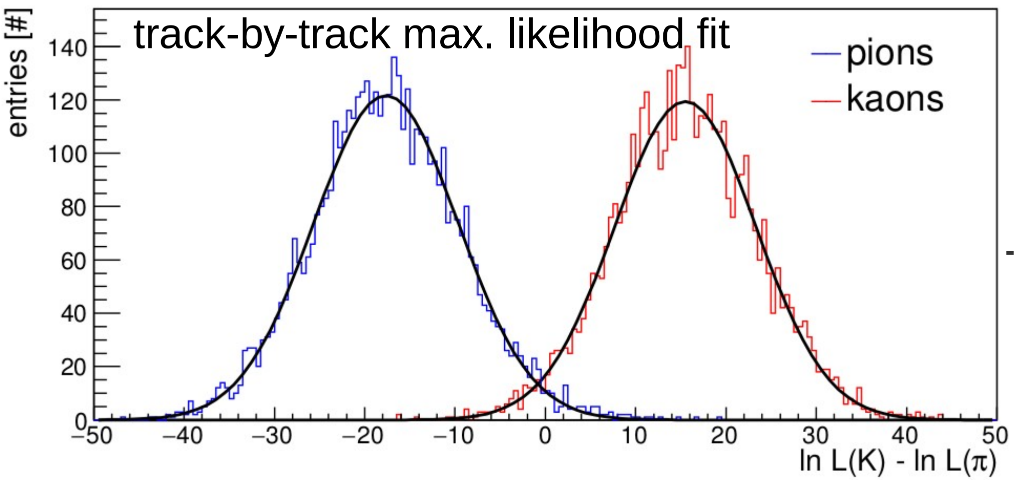
$$N_{\mathrm{sep}} = \frac{|\mu_1 - \mu_2|}{0.5(\sigma_1 + \sigma_2)}$$

Geant simulation

(green color ~ 3 s.d. separation)



Geometrical Reconstruction



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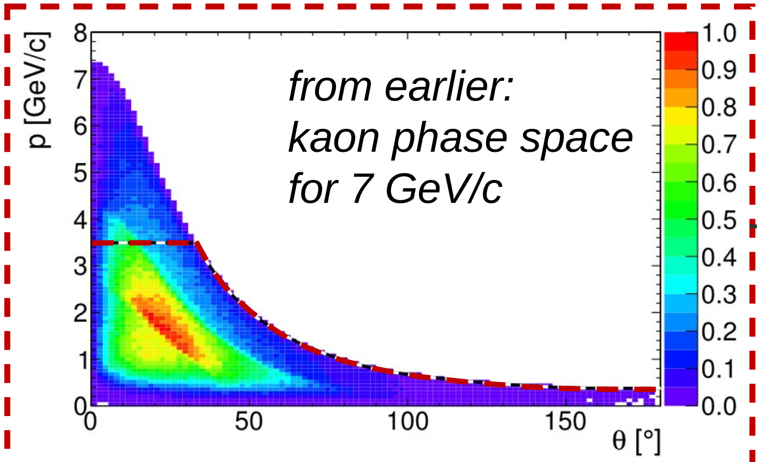
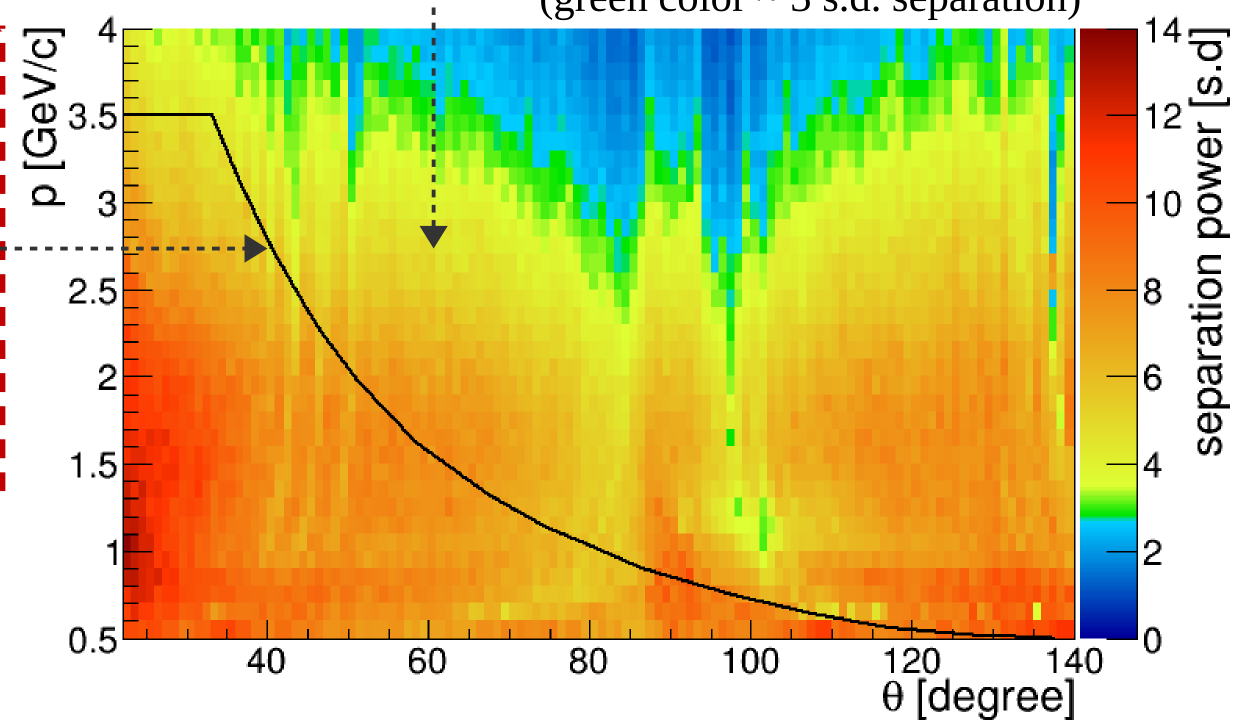


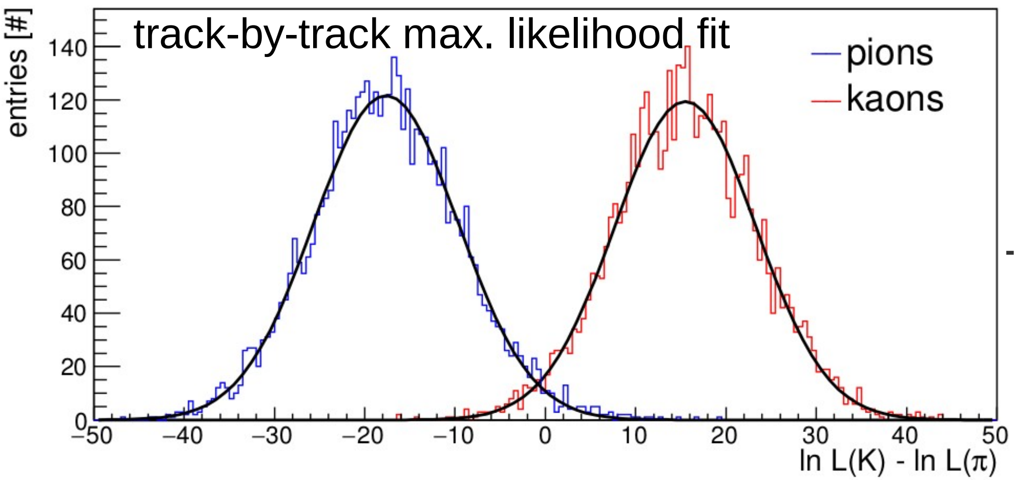
Barrel DIRC PID 3 s.d. goal

Geant simulation

(green color ~ 3 s.d. separation)



Geometrical Reconstruction



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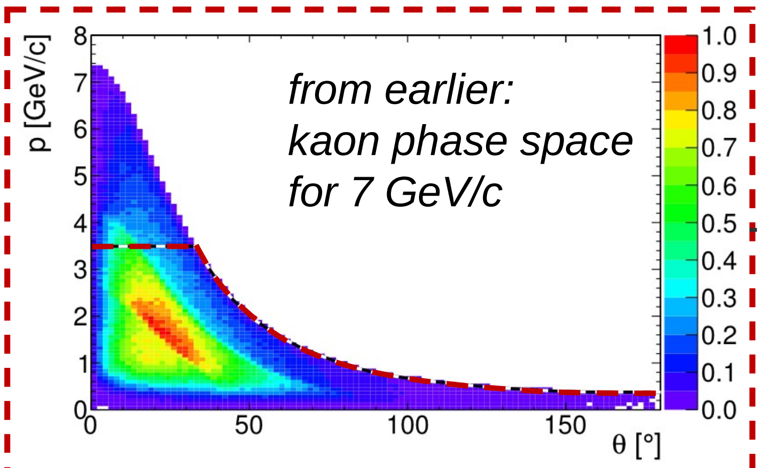
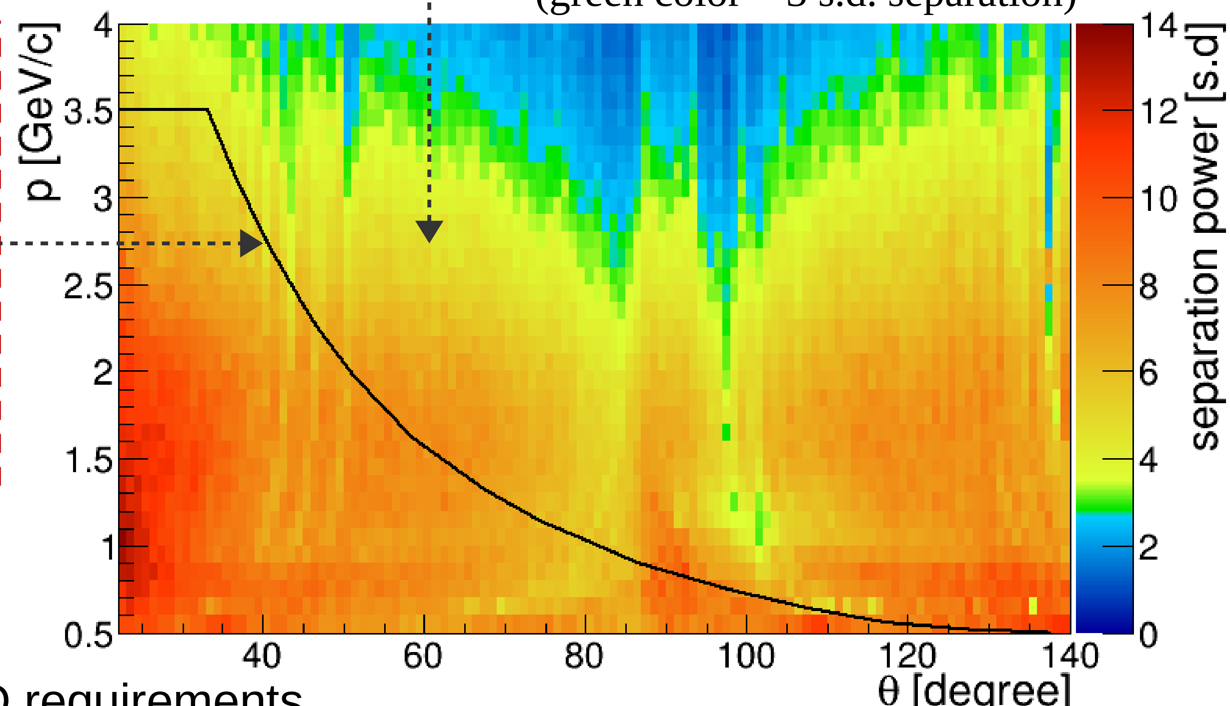


Barrel DIRC PID 3 s.d. goal

Geant simulation

(green color ~ 3 s.d. separation)

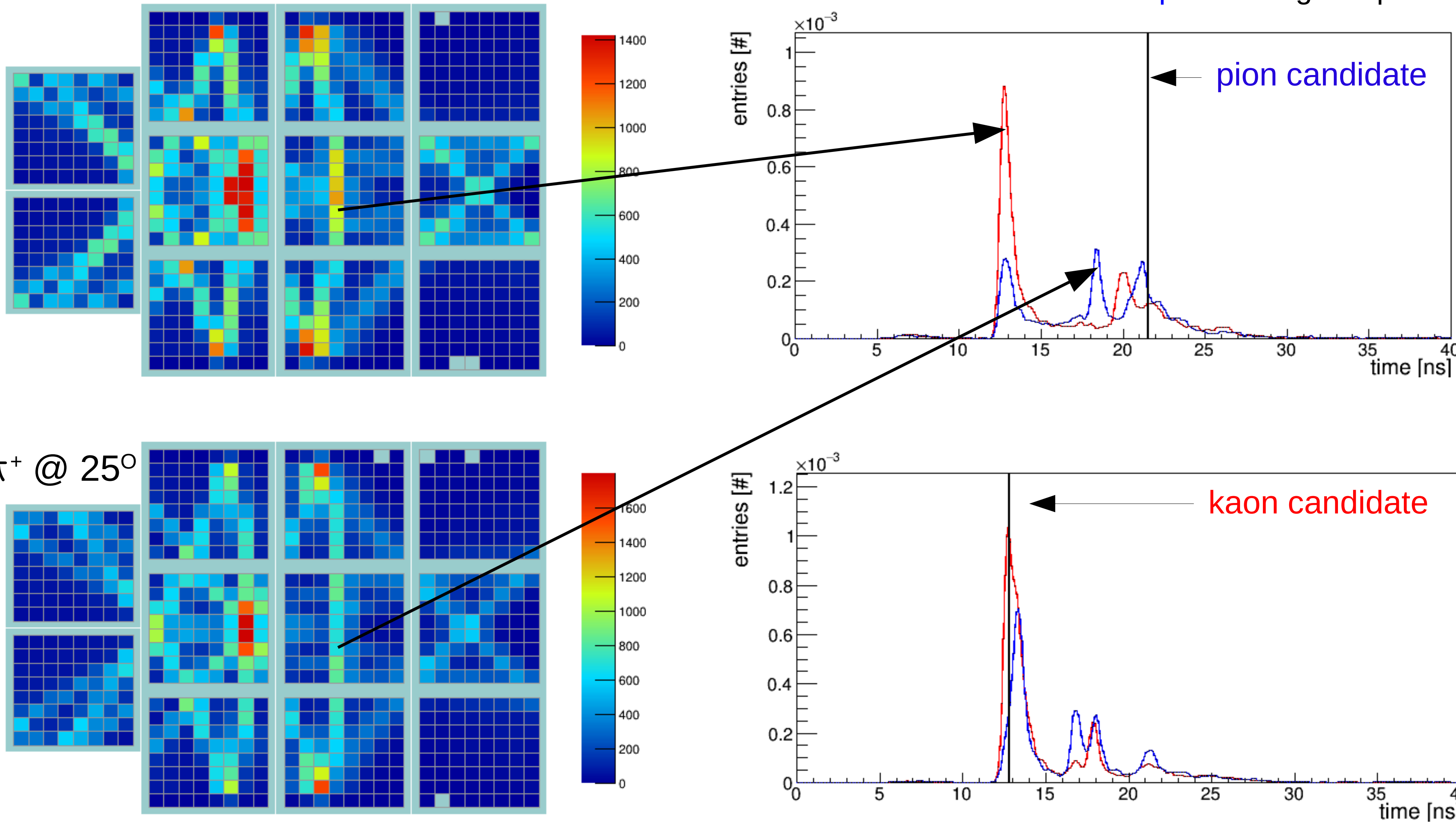


➡ Design meets or exceeds PID requirements

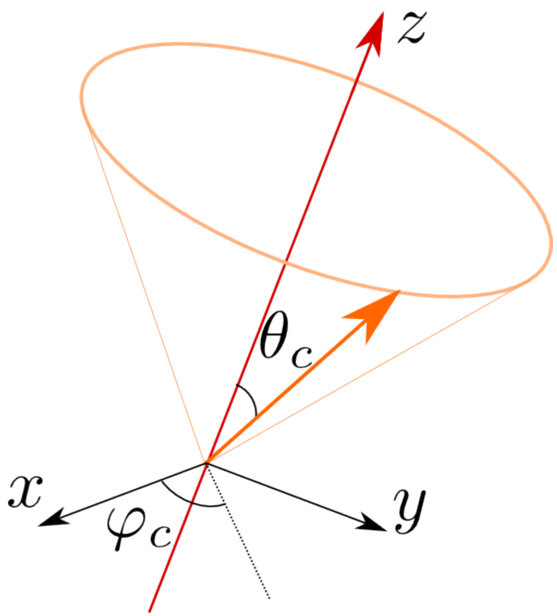
Time Imaging

K^+ @ 25° @ p = 3.5 GeV

PDFs of kaon and pion for a given pixel

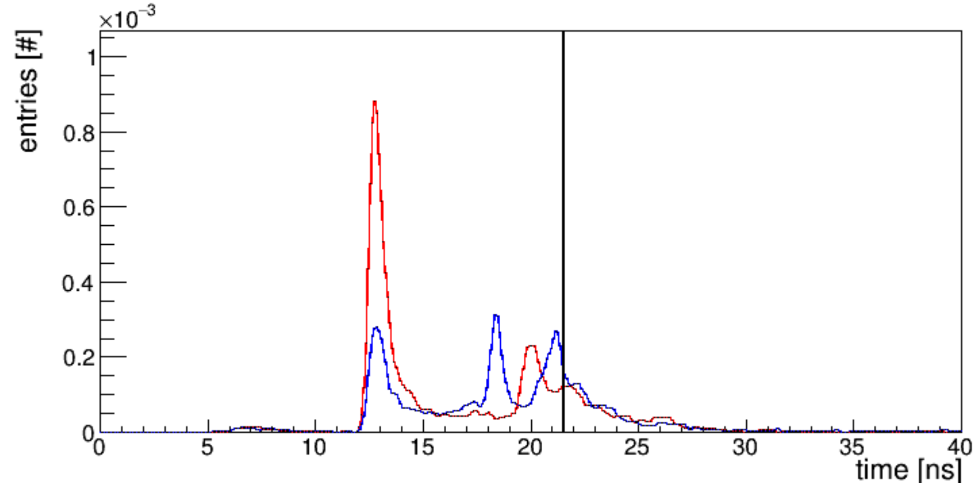


Time Imaging



Analytical PDF (Belle II TOP):

PDFs of kaon and pion for a given pixel:



peak position:

$$t_{kj} = \frac{z_D - z_0}{(\cos\theta\cos\theta_c - \sin\theta\sin\theta_c\cos\phi_c^{kj})}\frac{n_g}{c_0} + t_{\mathrm{TOF}}$$

peak width:

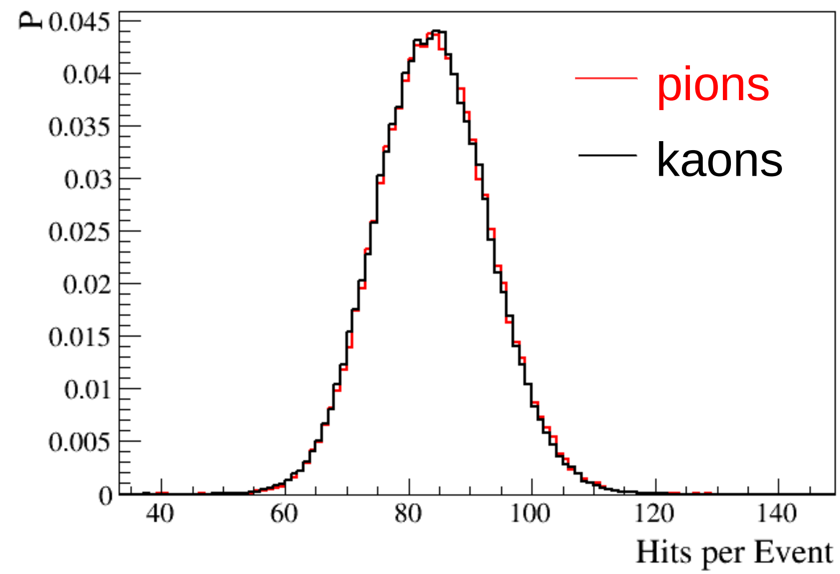
$$\sigma_{kj}^{\mathrm{disp}} = (t_{kj} - t_0)\left| f_{kj}\frac{1}{n}\frac{\mathrm{d}n}{\mathrm{de}} + \frac{1}{n_g}\frac{\mathrm{d}n_g}{\mathrm{de}} \right| \sigma_e$$

number of photons in peak:

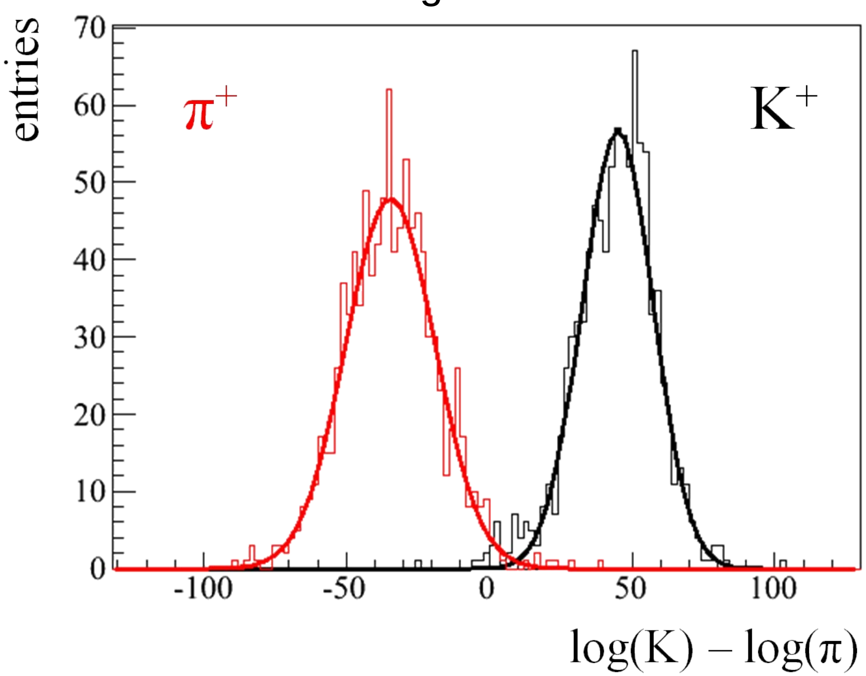
$$n_{kj} = N_0 \ell \sin^2\theta_c \frac{\Delta\phi_c^{kj}}{2\pi}$$

Time Imaging

Reconstruction: arrival time of each photon from given track is compared with PDF to calculate time-based likelihood for the photon to originate from a given particle



Example: momentum = 3 GeV/c
angle = 22°

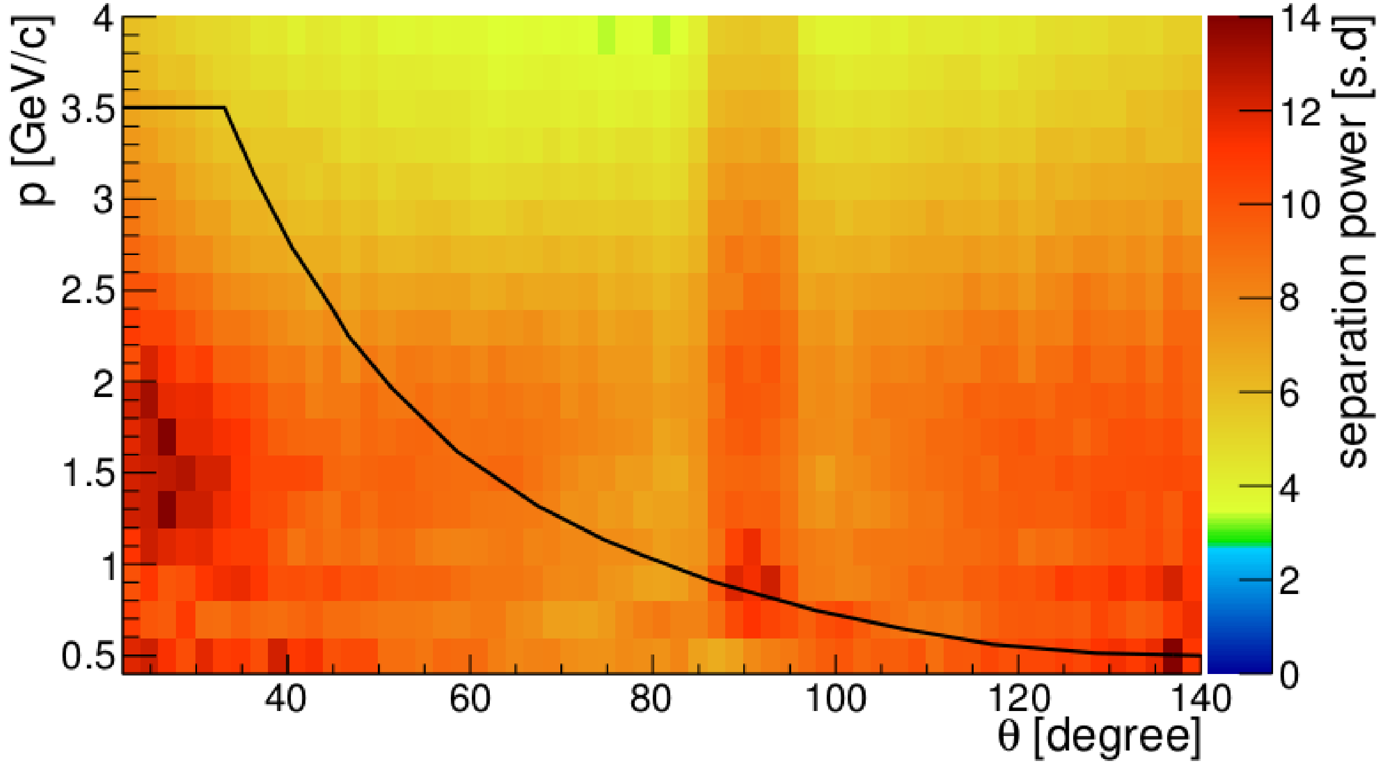


Full likelihood:

$$\log\mathcal{L}_h = \sum_{i=1}^{N} \log\left(\frac{S_h(x_i,y_i,t_i)+B(x_i,y_i,t_i)}{N_e}\right) + \log P_N(N_e)$$

Time Imaging

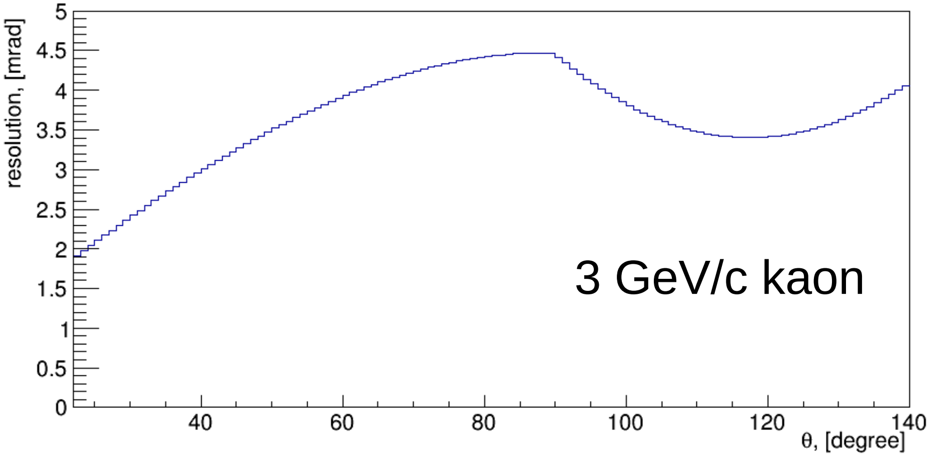
π^+/K separation map for Barrel DIRC:

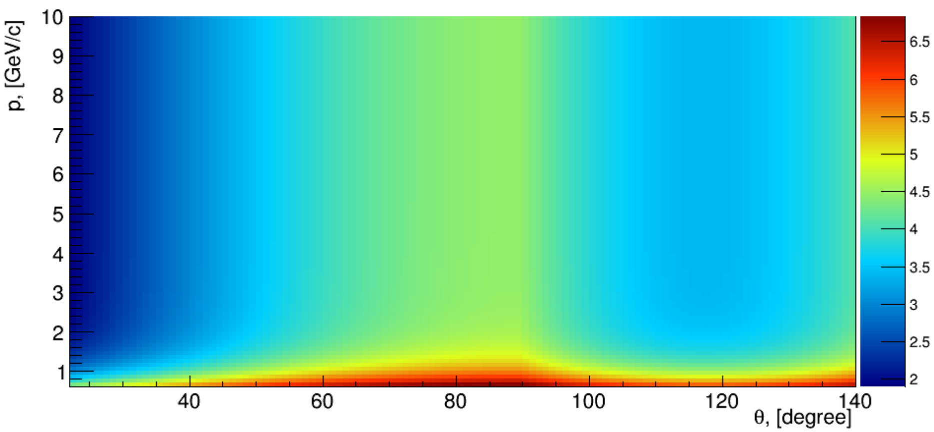


➡ Design meet/exceed PID requirements for entire acceptance range

Fast Simulation/Reconstruction

- Simulation with Cherenkov light is 10-50 times slower
- Output file is bigger (10-30MB per 1k tracks)

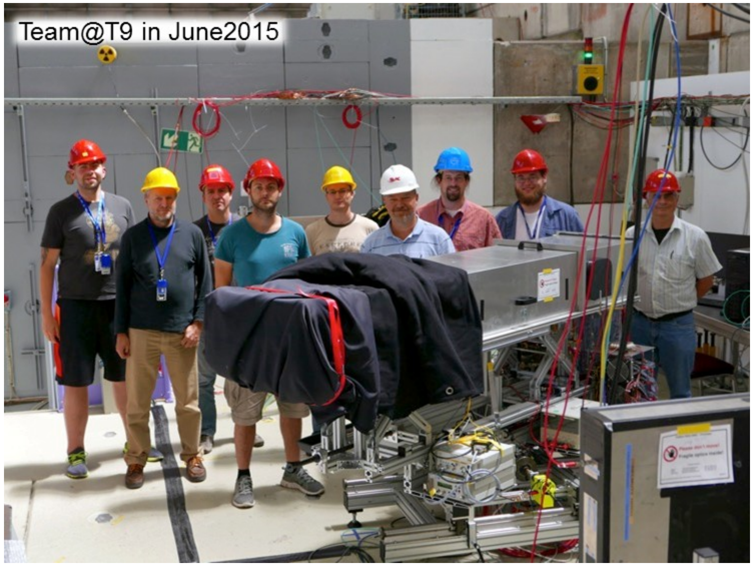




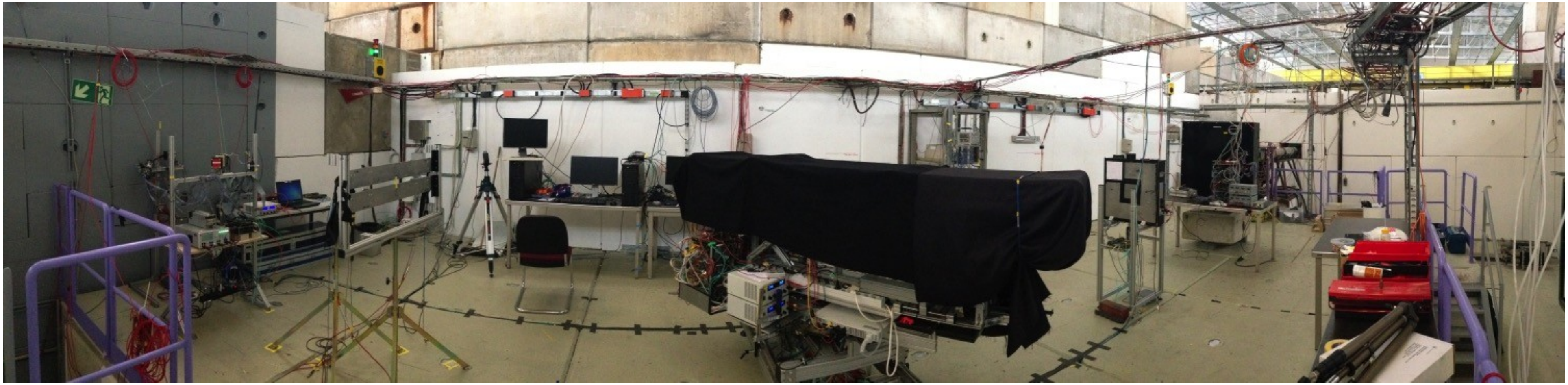
- Cherenkov track resolution is parametrized with track momentum and polar angle
- Cherenkov track resolution is used to calculate PID probabilities
- Parametrization is done based on test-beam data and data from different experiments

Beam Test at CERN 2015

- Fused silica prism as expansion volume
- 5 x 3 array of Planacon MCP-PMTs
- Narrow bar as radiator
- Many different imaging/lens configurations
- Momentum and angle scans
- ~500M triggers during 34 days of data taking



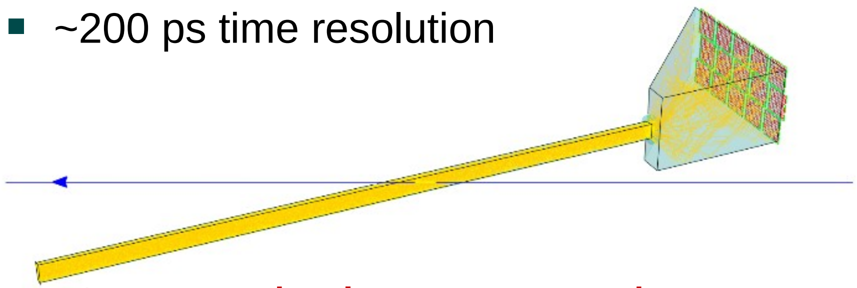
Goal: validation of PID performance of baseline design (narrow bars)



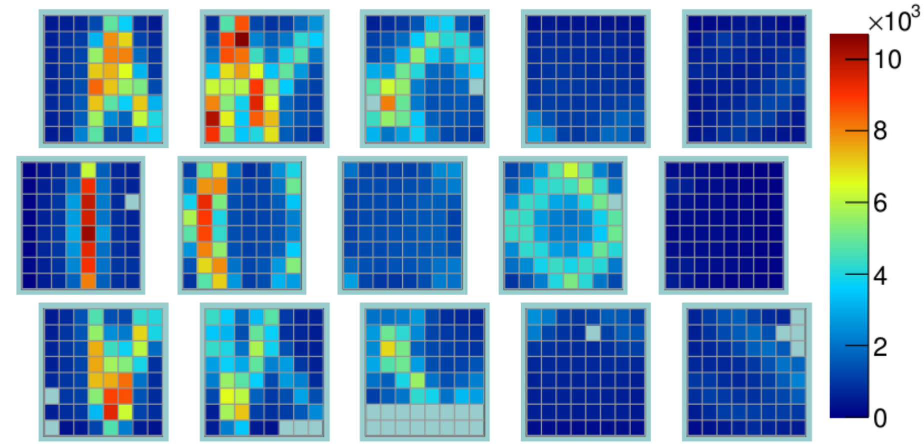
Beam Test at CERN 2015: Narrow Bar

- Goal: validate PANDA Barrel DIRC design and test components for DIRC@EIC

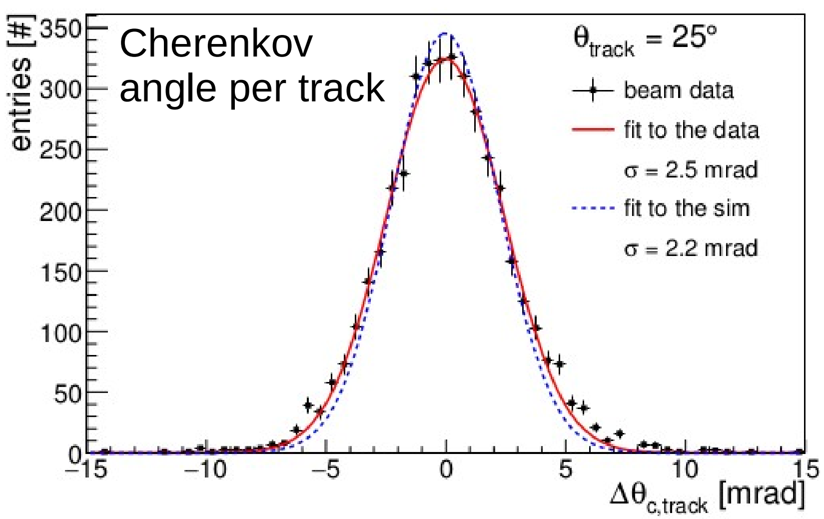
- Narrow bar (17x32x1250 mm³)
- Fused silica prism
- Focusing with 3-layer spherical lens
- ~200 ps time resolution



Hit patterns, proton tag:

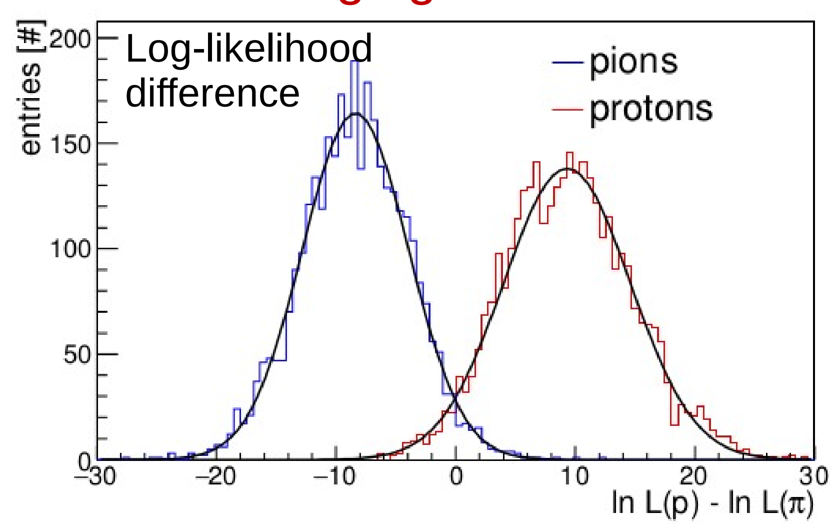


- Geometrical reconstruction:



➡ ~3.4 s.d. π/K @ 3.5 GeV/c

- Time imaging:



➡ ~3.6 s.d. π/K @ 3.5 GeV/c

Summary and Status

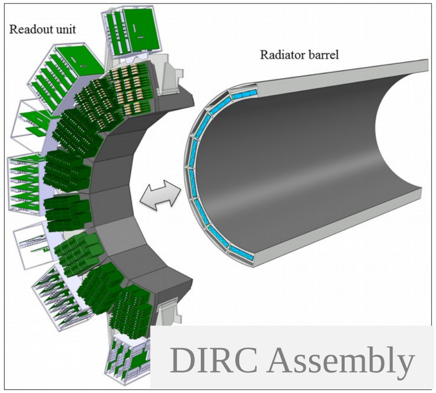
- The PANDA Barrel DIRC is a key component of the PANDA PID system
  - Simulations predict 3 s.d. π/K separation up to 3.5 GeV/c
  - Successfully validated PID performance in particle beams
  - Technical Design Report: arXiv:1710.00684
- Implementation in PandaRoot
  - Geometry: all materials are included in realistic way
  - Digitization: all relative effects are included
  - Reconstruction: geometrical and time imaging
  - Open point: T0 determination; analytical PDF for time imaging

Barrel DIRC Timetable

- 2018-2021: Industrial fabrication of fused silica bars and prisms
  Industrial production of MCP-PMTs

DIRC bar with laser

- 2018-2019: Production and QA of readout electronics
- 2018-2022: Industrial fabrication of bar containers and mechanical support frame, gluing of bars/plates, construction of complete bar boxes
  Detailed scans of all sensors
  Assembly of readout units
- 2023: Installation of mechanical support frame in PANDA, insert bar boxes, mount readout modules



DIRC Assembly

Barrel DIRC Timetable

- 2018-2021: Industrial fabrication of fused silica bars and prisms
  Industrial production of MCP-PMTs
- 2018-2019: Production and QA of readout electronics
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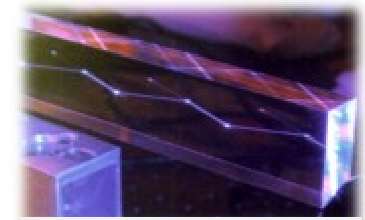
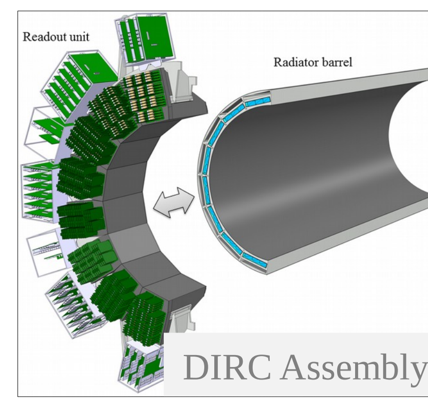


DIRC bar with laser



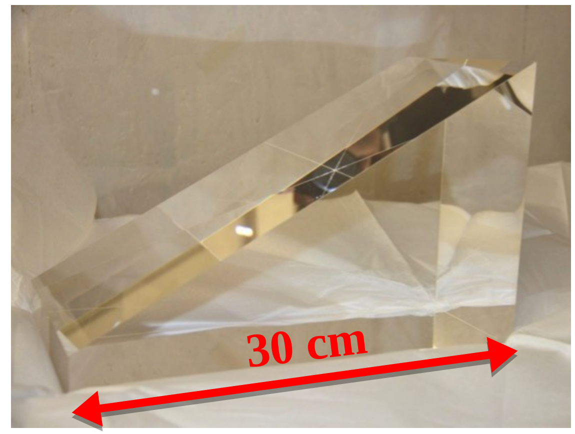
DIRC Assembly

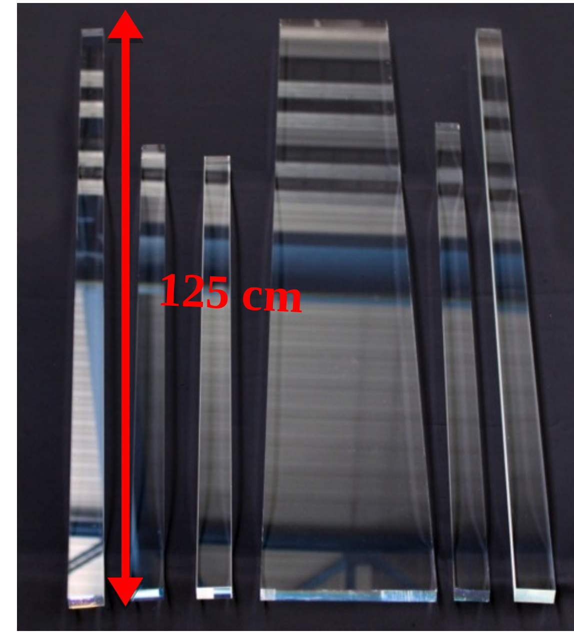
Thank you for the attention

Backup slides

Key components

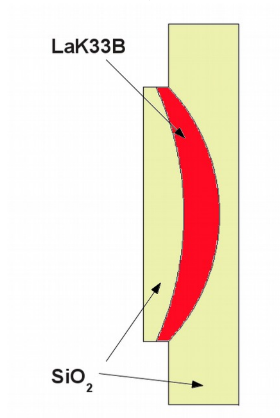
- Radiators
  ~30 bars/plates produced by 8 companies
  (AOS/Okamoto, InSync, Nikon, Zeiss, Zygo;
  Heraeus, Lytkarino LZOS, Schott Lithotec)

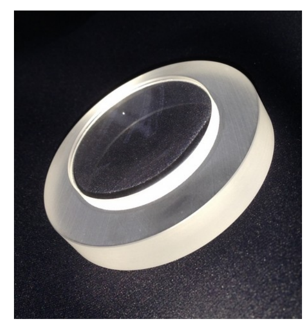


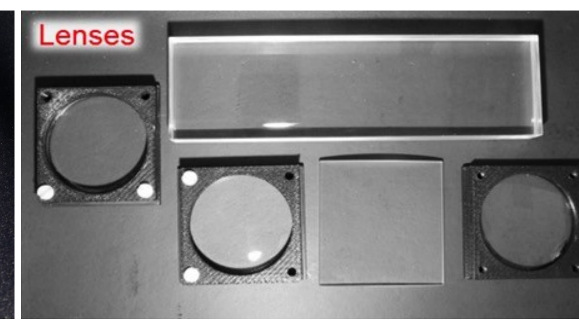


- Several solid fused silica prism prototypes (30° - 45° top angle) built by industry

- Focusing system
  Designed several
  spherical and cylindrical lenses,
  with and without air gap,
  several prototypes built by industry

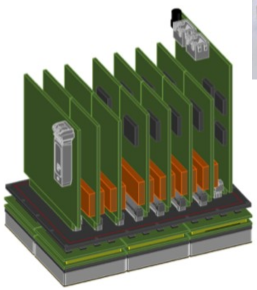


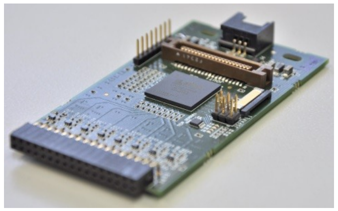




- Micro-channel Plate Photomultipliers (MCP-PMTs)
  excellent timing and magnetic field performance
  used to have issues with rate capability and aging, now solved;
  sensors of choice for Belle II TOP, LHCb TORCH, PANDA DIRCs

Readout and Mechanical Design





DiRICH, PADIWA, and TRB3

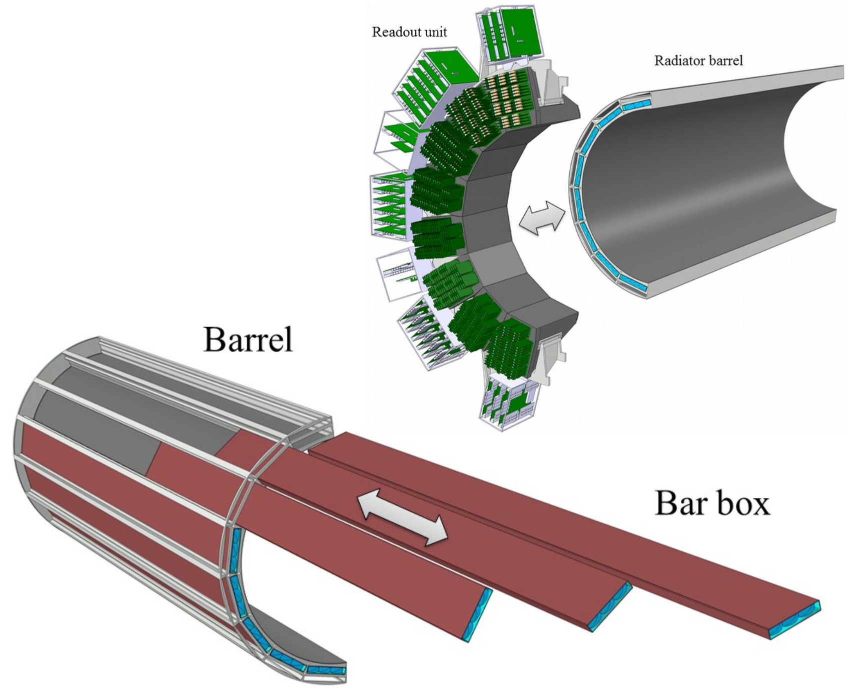
Readout Electronics

~100ps timing per photon for small MCP-PMT pulses – amplification and bandwith optimization

20MHz average interaction, trigger-less DAQ

Current approach: HADES TRBv3 board with PADIWA amplifier/discriminator

Near future: DiRICH, integrated backplane, joint development with HADES/CBM RICH



Mechanical Design

Light-weight and modular, allows staged bar box installation, access to inner detectors

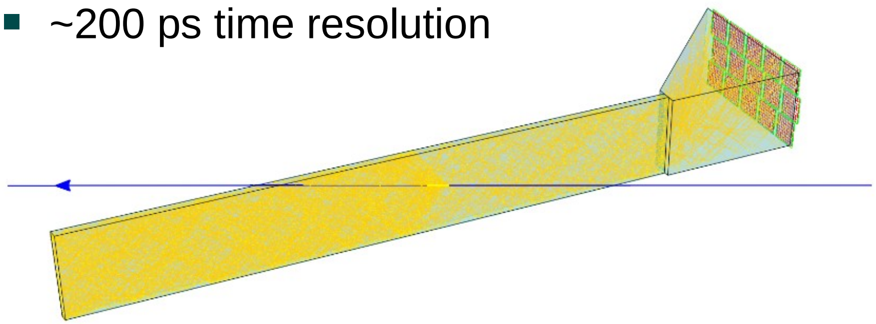
Mechanical support elements made from aluminum alloy or carbon fiber (CFRP)

Boil-off nitrogen flush for optical surfaces

Beam Test at CERN 2016: Wide Plate

- Goal: validate plate as cost saving option for PANDA Barrel DIRC and DIRC@EIC

- Plate (17x175x1225 mm^3)
- Fused silica prism
- Focusing with 2-layer cylindrical lens
- ~200 ps time resolution



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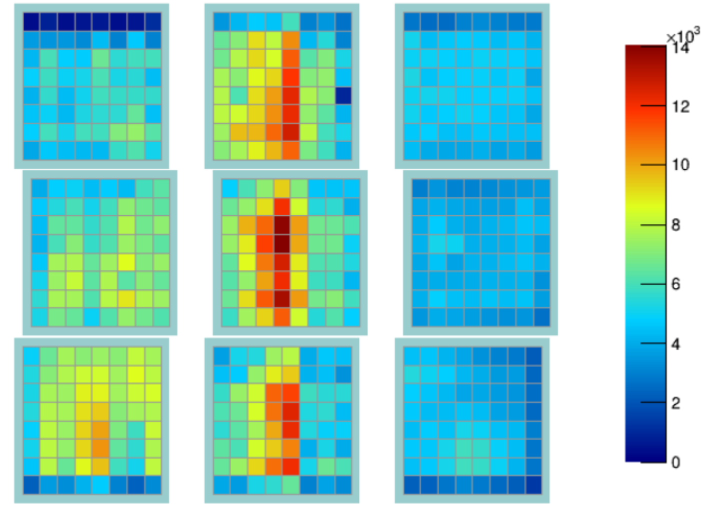
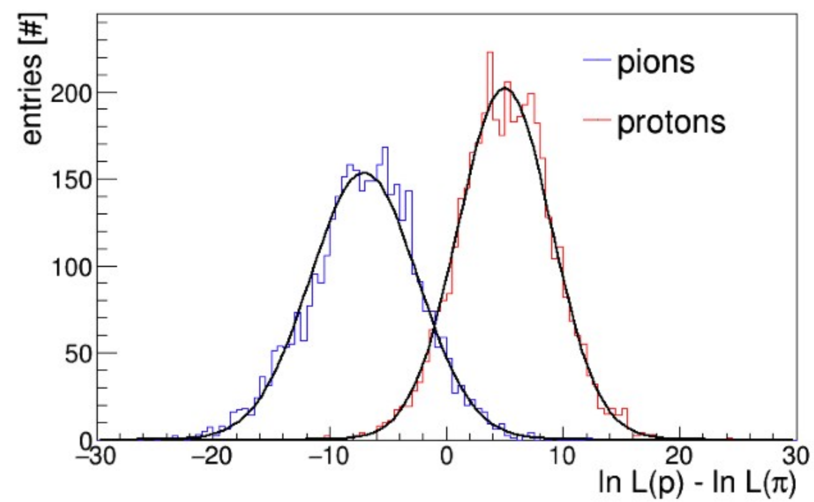


Time imaging:



➡ ~3.2 s.d. π/K @ 3.5 GeV/c