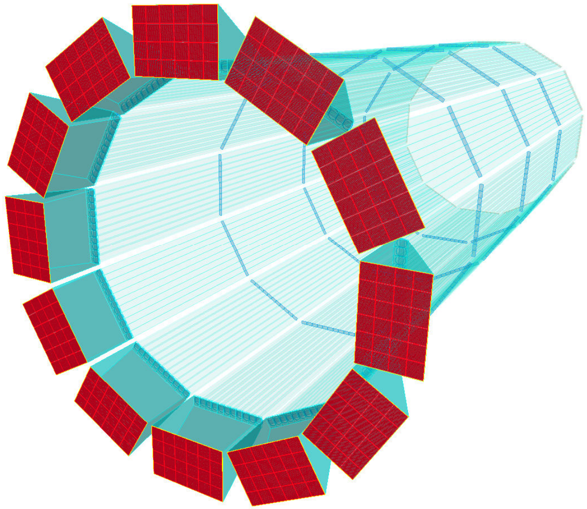
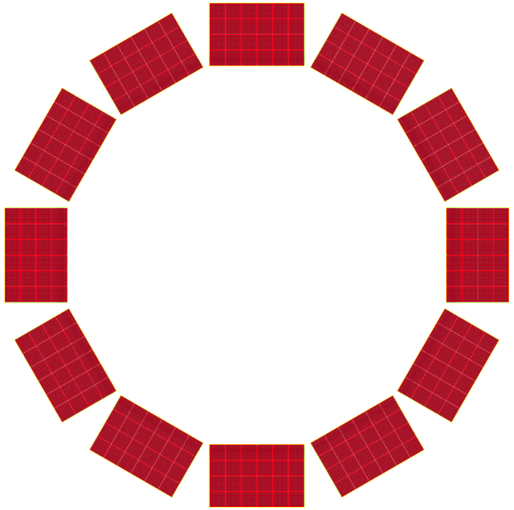
The High-Performance DIRC





Greg Kalicy — CUA

Joe Schwiening — GSI

- DIRC threshold mode
- Special DIRC aspects
- Potential performance
- Next steps

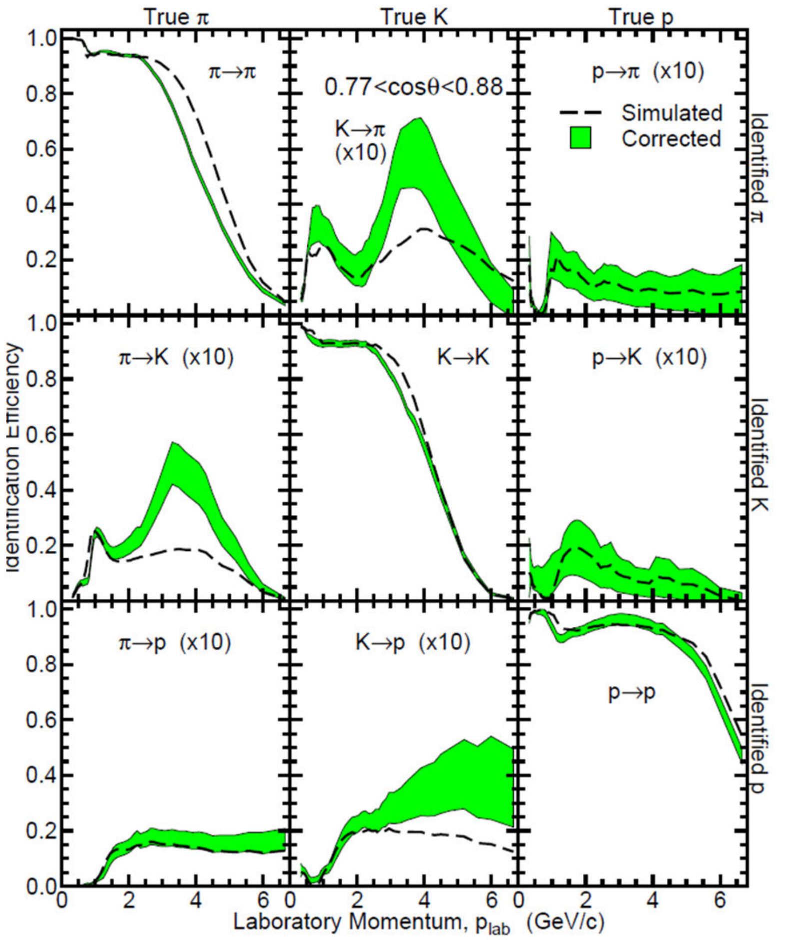
DIRC Counters in Threshold Mode

Initial request: presentation about experience with DIRC threshold mode

Experience? I am not aware of any studies of DIRC performance
in threshold/veto mode from BaBar, Belle II, GlueX, or PANDA

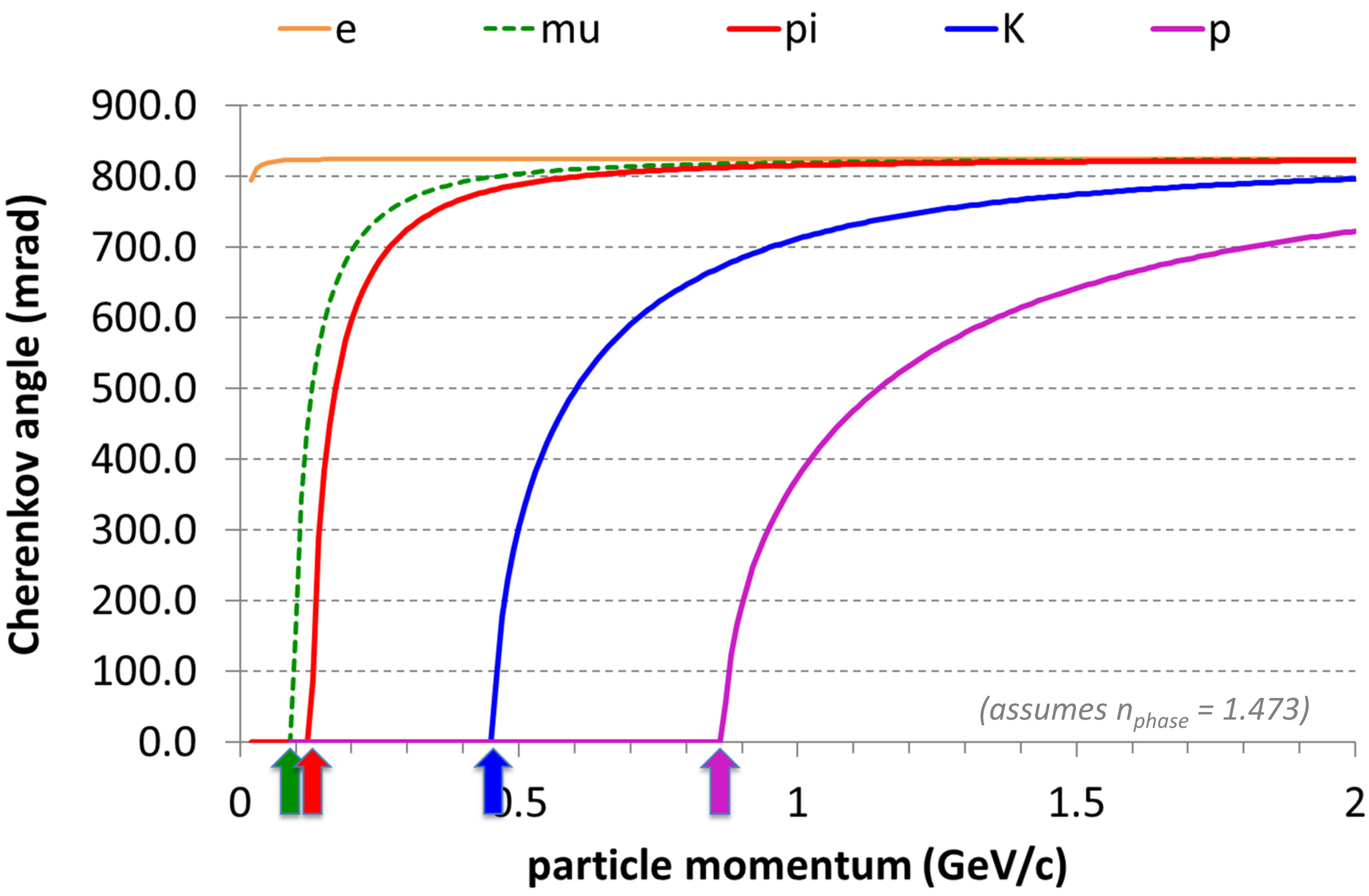
Those experiments have/had dedicated lower-momentum PID systems
(dE/dx and/or TOF), published their DIRC PID studies for
positive ID, both particles above threshold

Example: BaBar charged hadron effi/mis-ID (2013),
DIRC contributes for wide momentum range but dE/dx from
vertex detector and drift chamber dominate at lower momentum,
no separate discussion of DIRC impact



Today: discuss special threshold mode features for hpDIRC,
examples from PANDA-based Geant simulation photon yield study

BaBar Collaboration, J. P. Lees et al.,
Production of charged pions, kaons and protons
in e+e- annihilations into hadrons at sqrt{s} = 10.54 GeV
arXiv:1306.2895, Phys.Rev. D88 (2013) 032011,
doi:10.1103/PhysRevD.88.032011



Particle Cherenkov angle vs momentum in fused silica

$$\beta_{thresh} = \frac{v_{thresh}}{c} = \frac{1}{n(\lambda)}$$

$$\cos\theta_c = \frac{1}{\beta\, n(\lambda)}$$

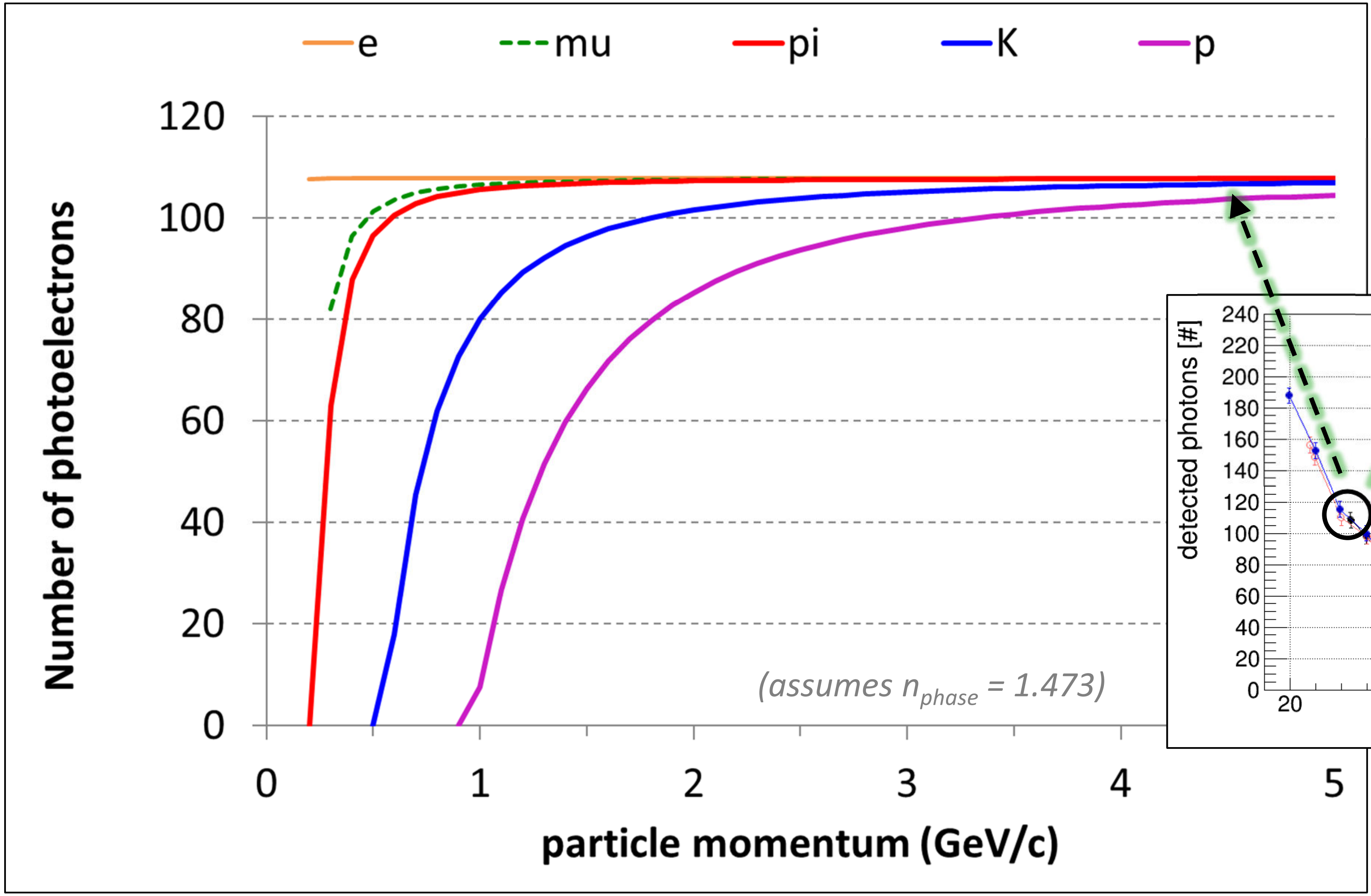
For n=1.473: β_{thresh}=0.679

→ pions start at ~130MeV/c,

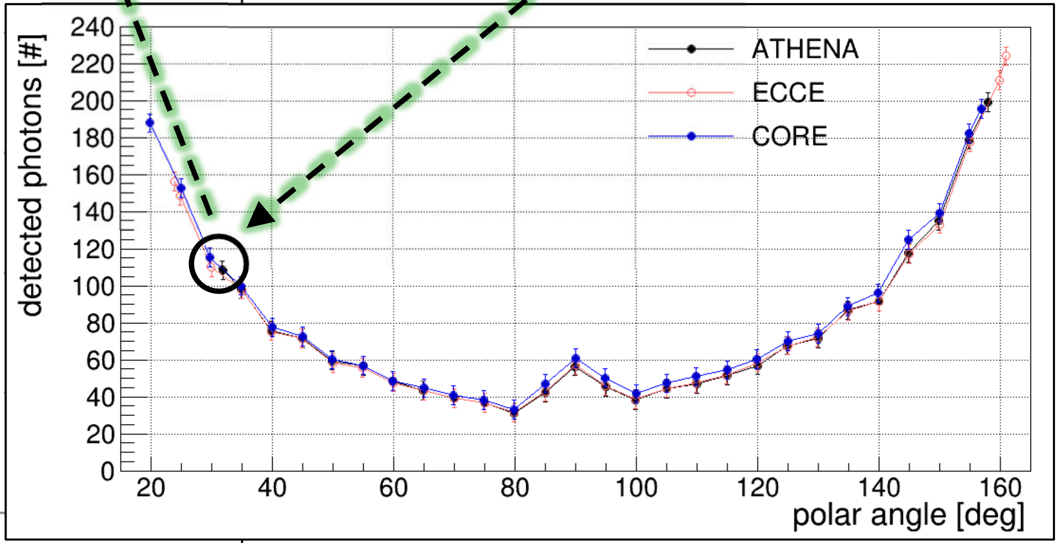
kaons at ~450 MeV/c,

protons at ~870 MeV/c

Photoelectron Yield (fused silica)



Similar thresholds for detected photon yield



$$N_{\text{photons}} = L \frac{\alpha^2 z^2}{r_e m_e c^2} \int \sin^2\theta_c(E)\, dE$$

Excel calculation scaled to expected hpDIRC Geant4 photon yield (30° polar angle, β≈1)

DIRC Threshold Mode Aspects

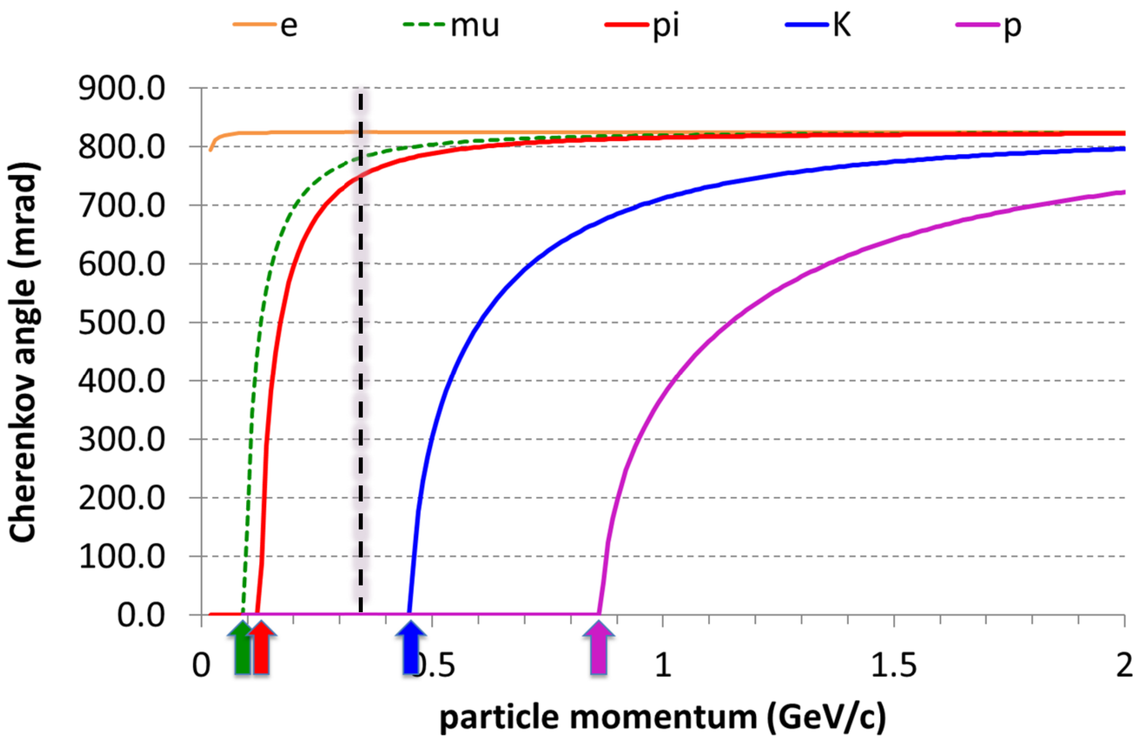
Due to high refractive index, detected number of photons in hpDIRC is large, robust against backgrounds

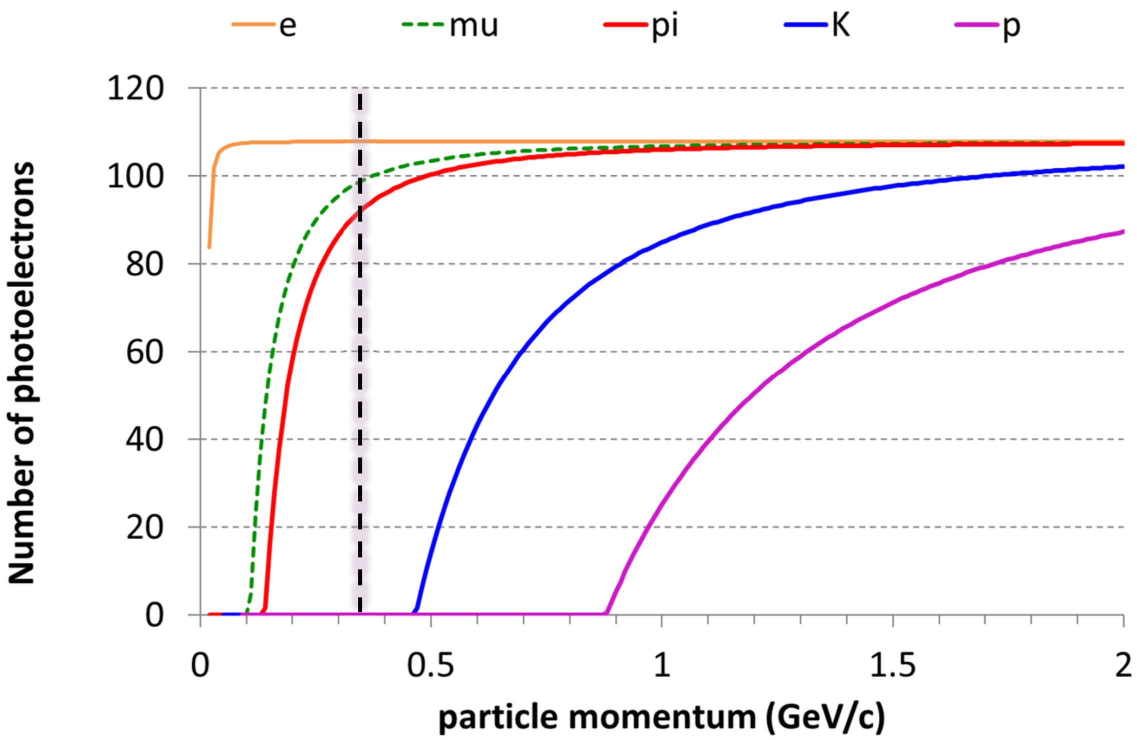
Example: charged track at 30 deg polar angle, 350 MeV/c momentum

~90 photoelectrons for pion, zero (plus background) for kaon and proton

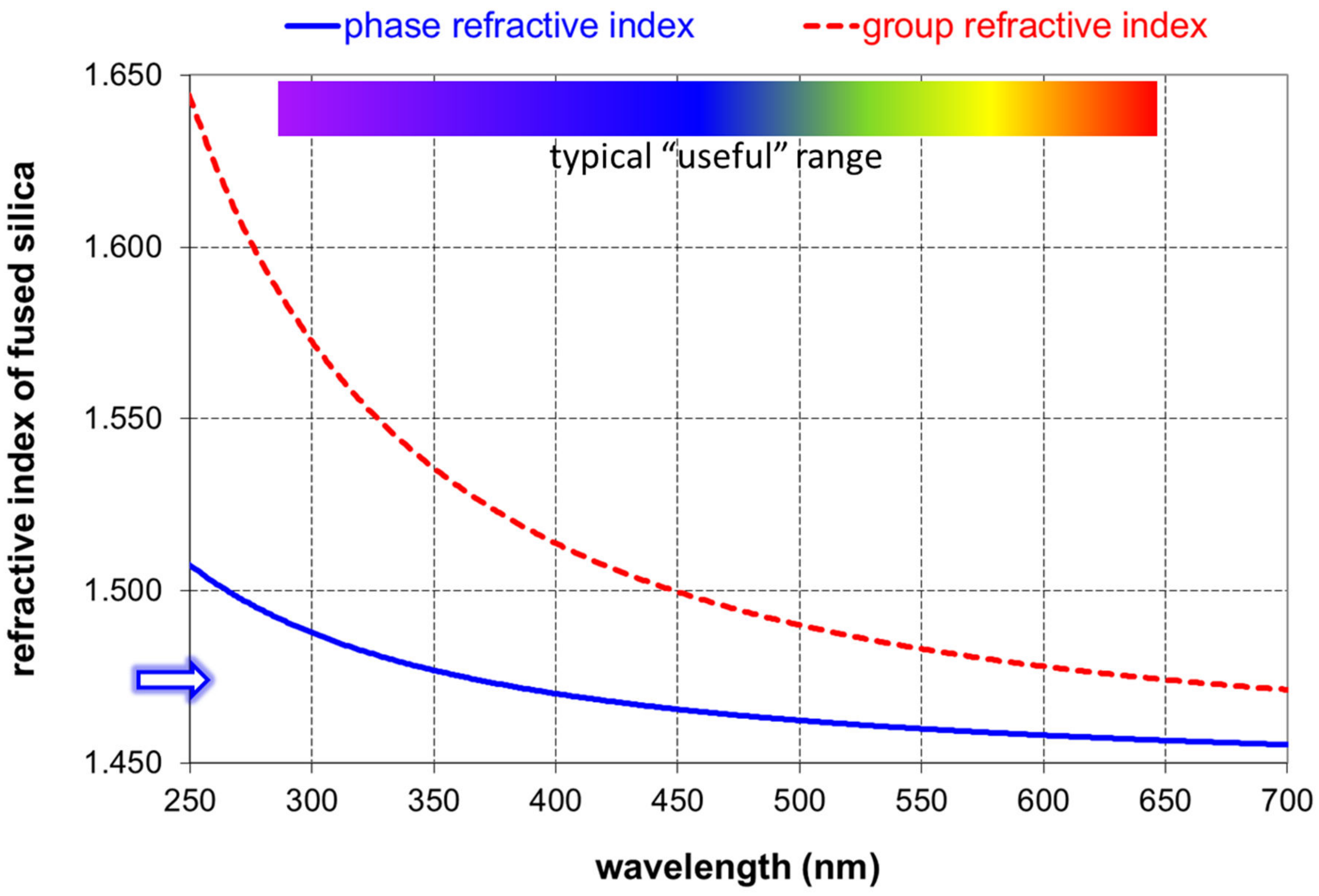
hpDIRC timing will be very powerful tool to deal with background from MCP-PMT noise and other tracks.

Note that the real hpDIRC geometry in Detector-1 needs to be well understood to reliably predict the expected photon yield





Dispersion: refractive index of fused silica varies significantly for sensitive sensor range



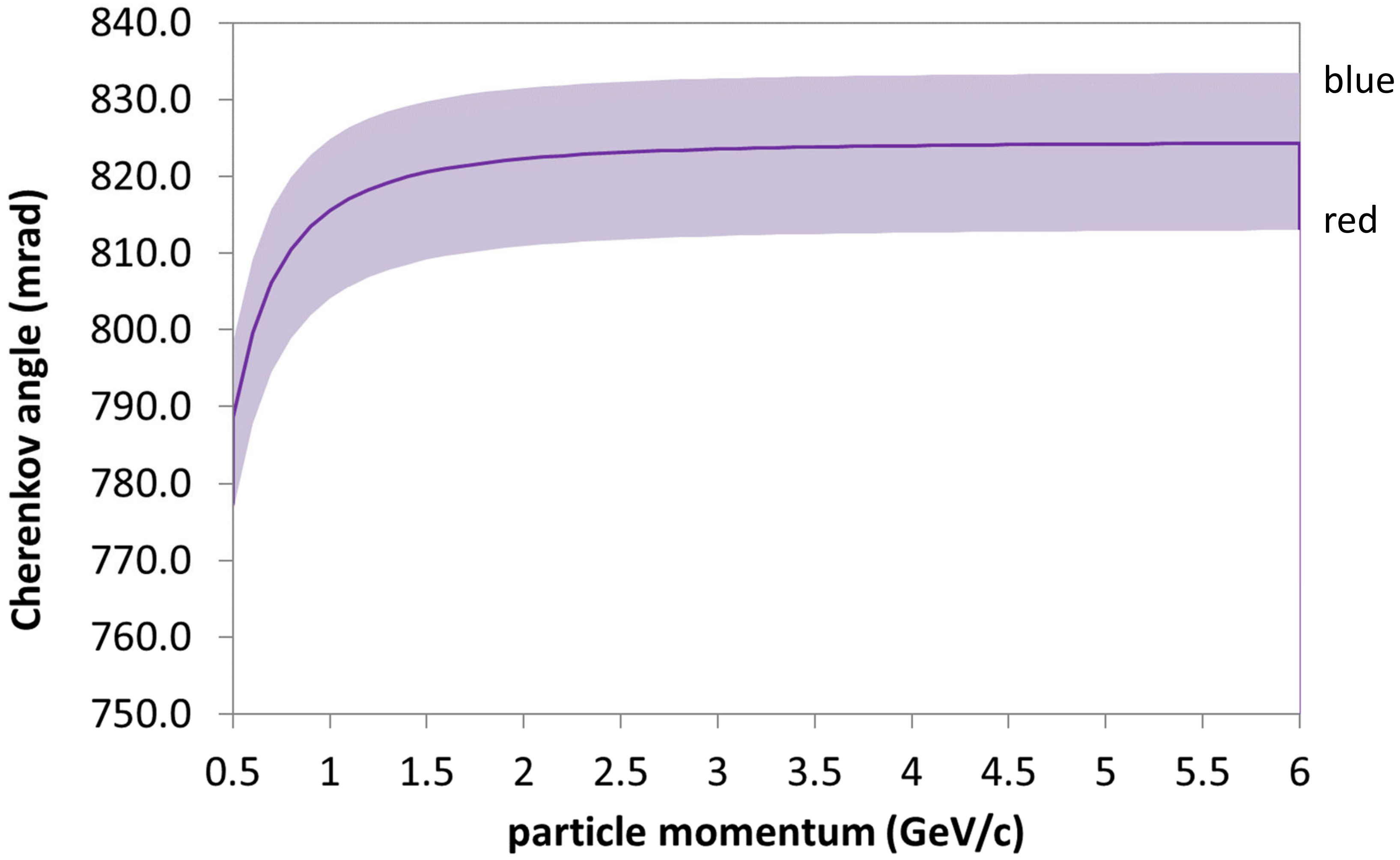
Useful range defined by sensor acceptance and glue properties

(Epotek 301-2 cuts at ~280nm)

phase index → photon angle/location

group index → photon velocity/timing

Cherenkov angle per photon for charged pions in fused silica (example: 300nm-650nm wavelength range)

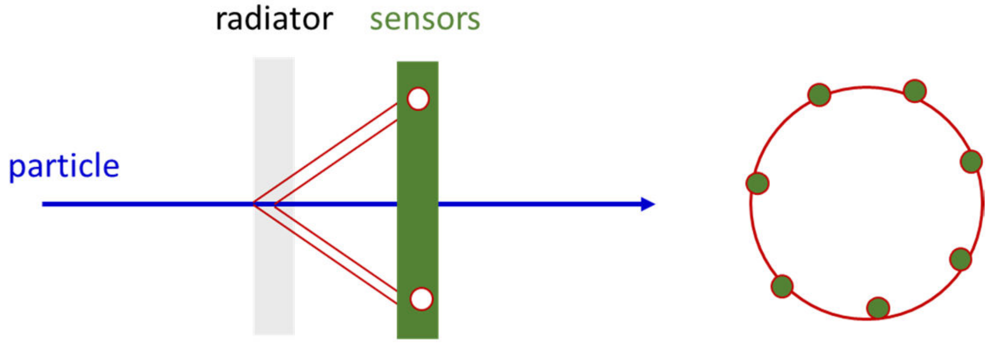


Not all wavelengths may always be totally internally reflected in hpDIRC

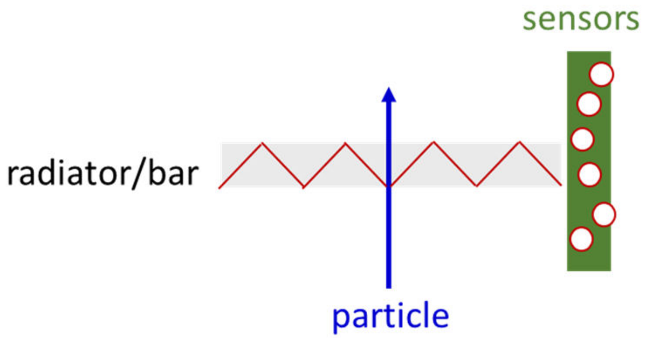
Due to critical angle for total internal reflection, a particle above threshold may be "invisible" in hpDIRC

→ hpDIRC threshold mode more complicated than in gaseous or aerogel RICHes

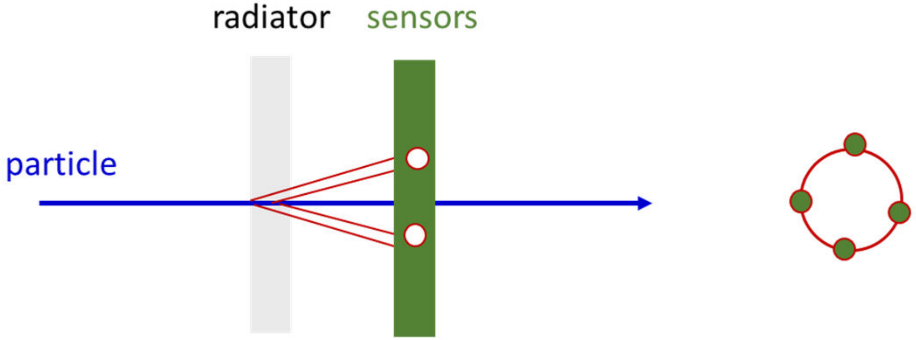
gaseous or aerogel RICH, $p >> p_{thresh}$



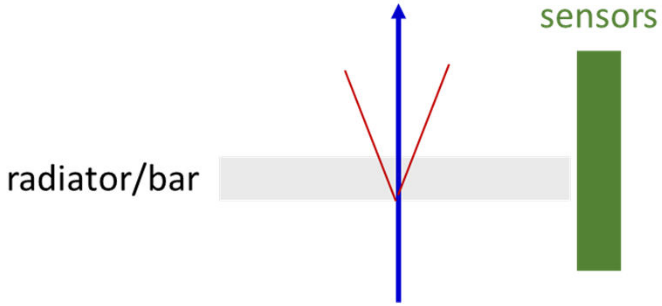
DIRC, $p >> p_{thresh}$



gaseous or aerogel RICH, $p = p_{thresh} + \Delta p$



DIRC, $p = p_{thresh} + \Delta p$



HPDIRC VETO MODE

We do not have real studies of the expected hpDIRC threshold performance yet.

This is on our to do list, once hpDIRC reconstruction in Detector-1 framework (currently Fun4All) is fully operational

Today: Photon yield examples from standalone Geant4 simulation

(simulation, plots: Roman Dzhygadlo)

Number of detected photons as a function of particle type, polar angle, and momentum

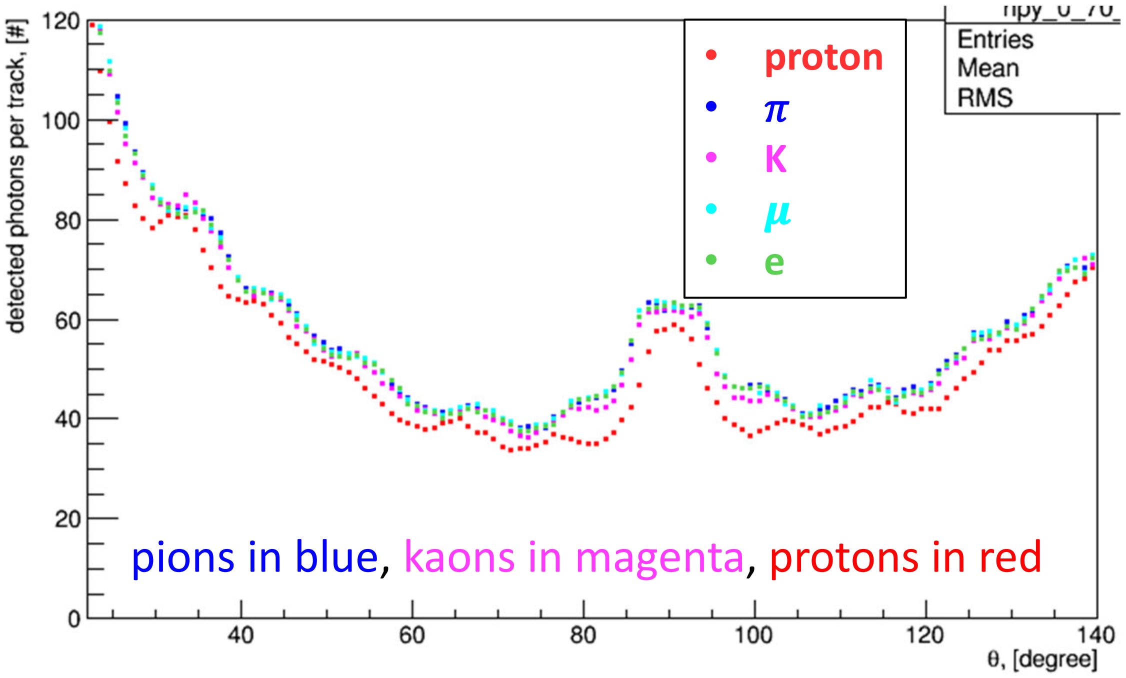
→ Familiar shape, but detailed photon yield a lot more complex than scaled excel plot due to total internal reflection limits

Note:

PANDA DIRC Geant4 configuration (shorter bars/plates, lower PDE)

Single particles, track perpendicular to plate in azimuth, no lens, no magnetic field, no noise/backgrounds

high-momentum example: p=3.5 GeV/c



(illustrative qualitative examples, details will be different at EIC)

hpDIRC Veto Mode

Useful π/K threshold mode contribution (with gap) possible

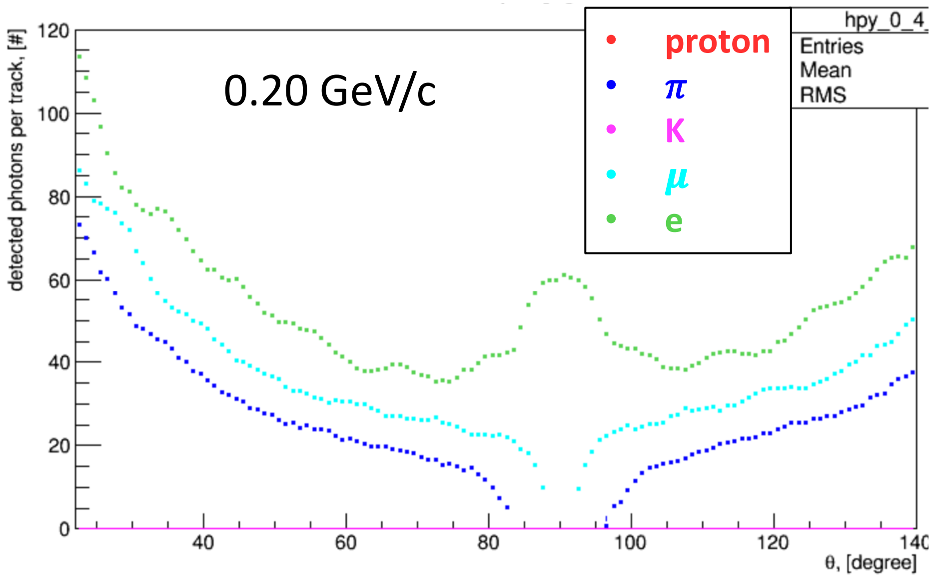
as low as 0.2 GeV/c

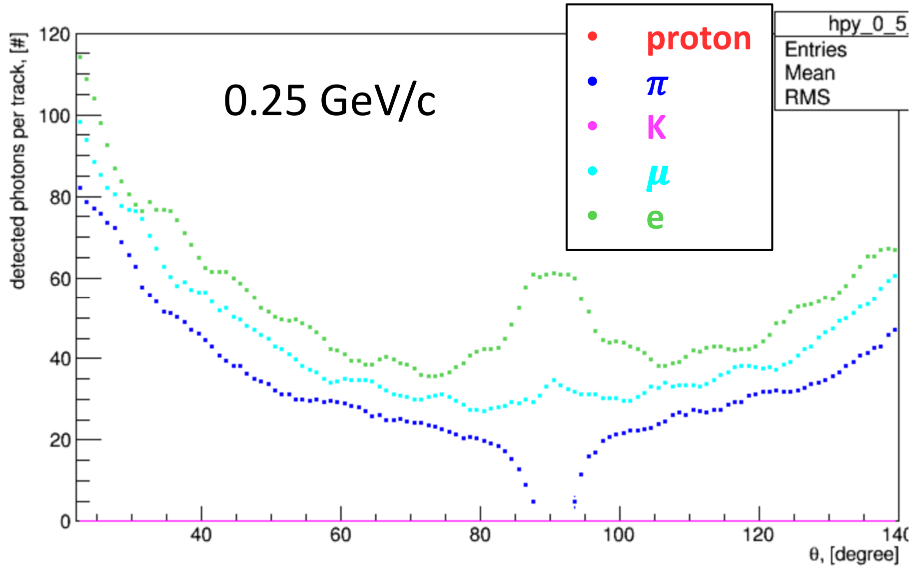
pion N_{pe}>10 for polar angles <80° and >100°

π/K coverage gap at 0.25 GeV/c: pseudorapidity –0.15 … +0.15

Please remember that this simulation was performed

without a magnetic field, all tracks can reach the DIRC radius



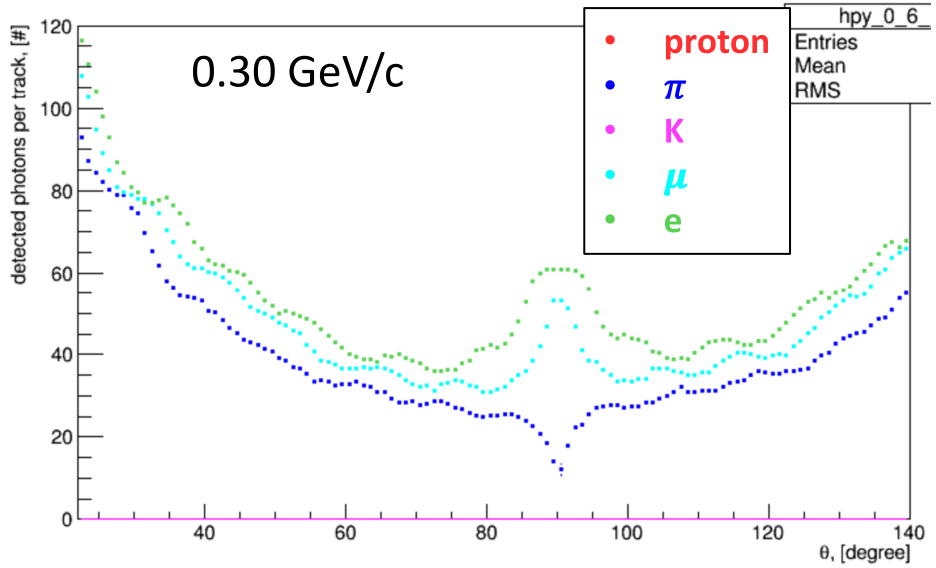


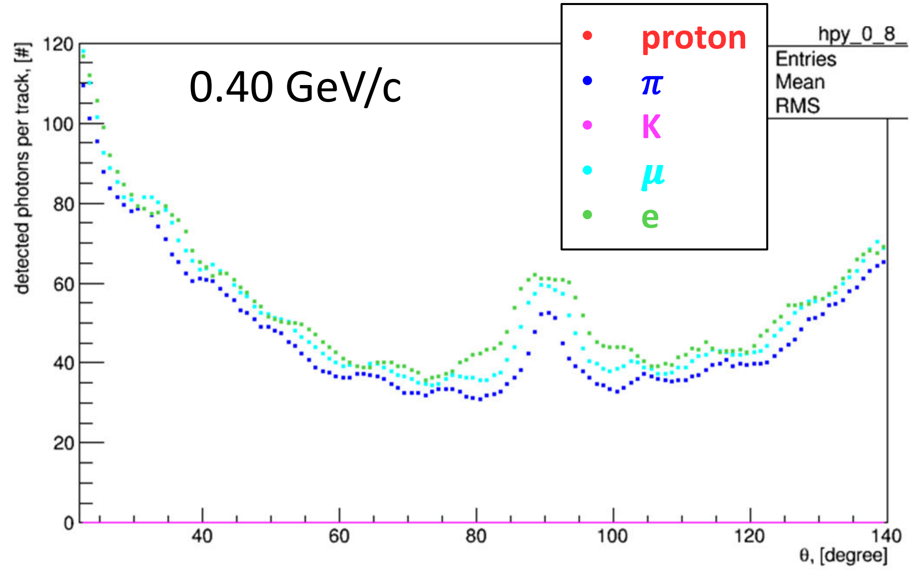
HPDIRC VETO MODE

For 0.3-0.4 GeV/c: Robust pion photon signal (N_{pe}>10)

for full polar angle/pseudorapidity range

while kaons are still below threshold

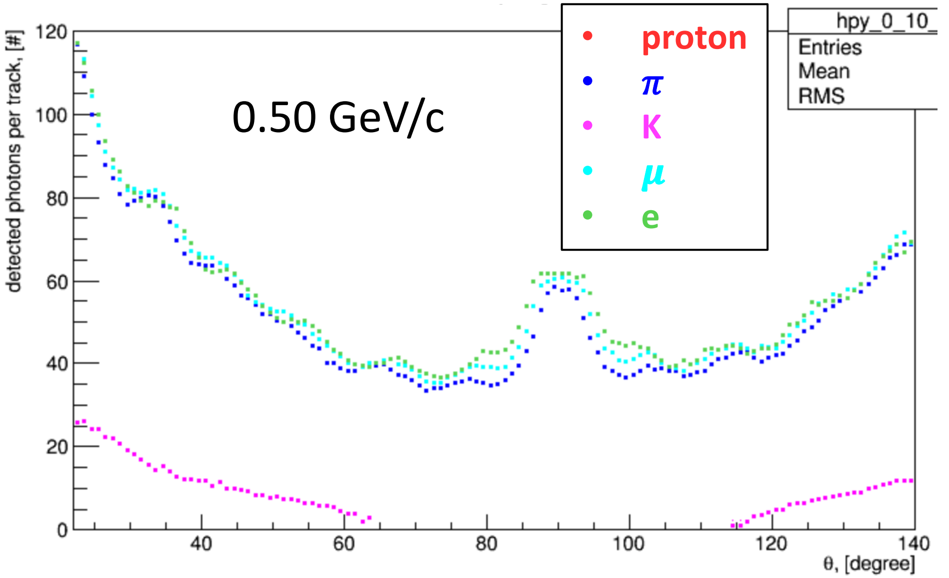


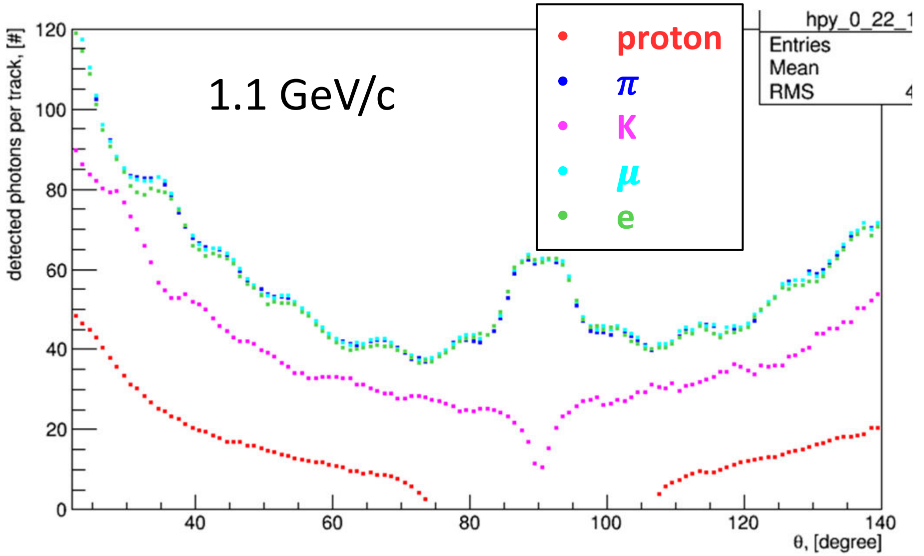


hpDIRC Veto Mode

At 0.5 GeV/c: Photon yield for kaons starts to become significant at steep polar angles, though photons from kaons still not internally reflected for most polar angles

Above 1.1 GeV/c: Robust kaon photon signal (N_{pe}>10) for full polar angle/pseudorapidity range, protons photon yield significantly smaller





hpDIRC Veto Mode

At 1.5 GeV/c: Photon yield gap for protons closing but still significant

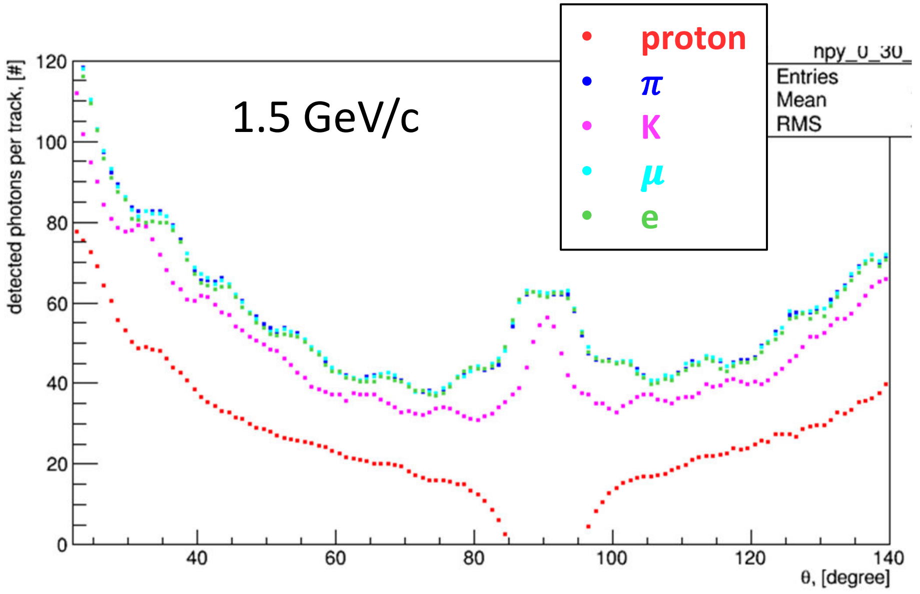
Above 2.15 GeV/c: Robust proton photon signal (N_{pe}>10)

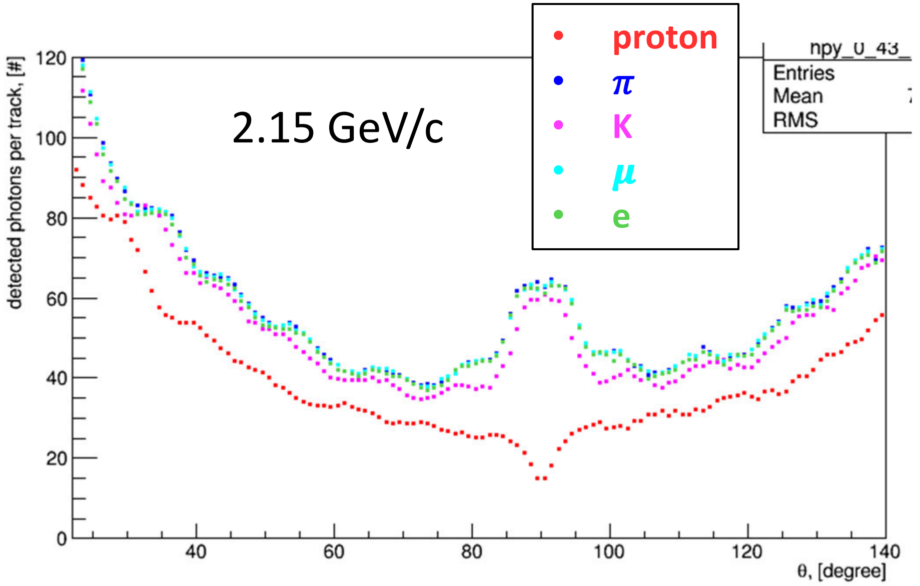
for full polar angle/pseudorapidity range

→ “standard” RICH reconstruction domain

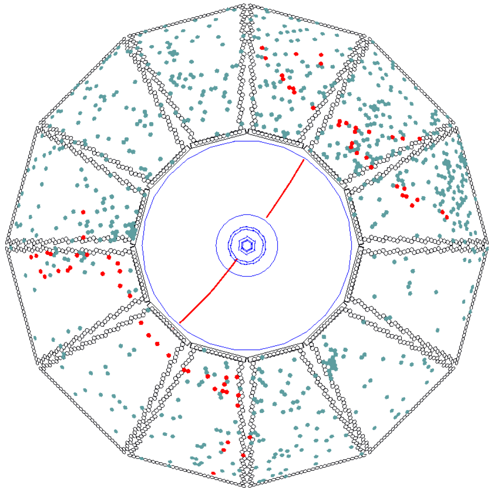
Please note that “standard” reconstruction for DIRC counters

looks different, less “ring” fitting, more pattern matching





Single 3.5 GeV/c pion event, GlueX DIRC beam data



Single dimuon event, BABAR beam data

DIRC hit patterns do not look like your typical RICH "rings"

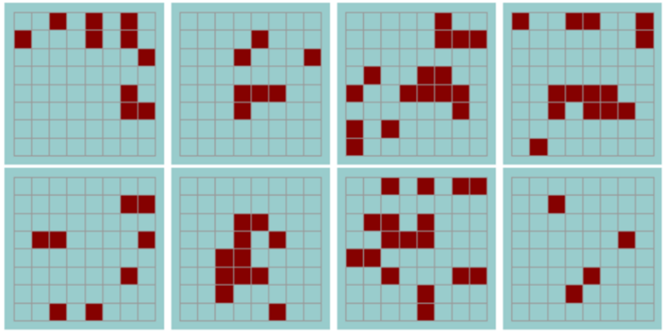
Patterns complicated by internal reflections inside bar/plate,
mirror, expansion volume, shape of sensor plane.

Detector space is often not the best space for DIRC reconstruction,
no simple ring fits

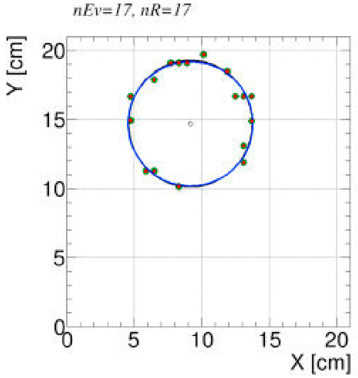
Performing reconstruction and PID in Cherenkov space instead

Input: track momentum, photon location and time – plus photon yield

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

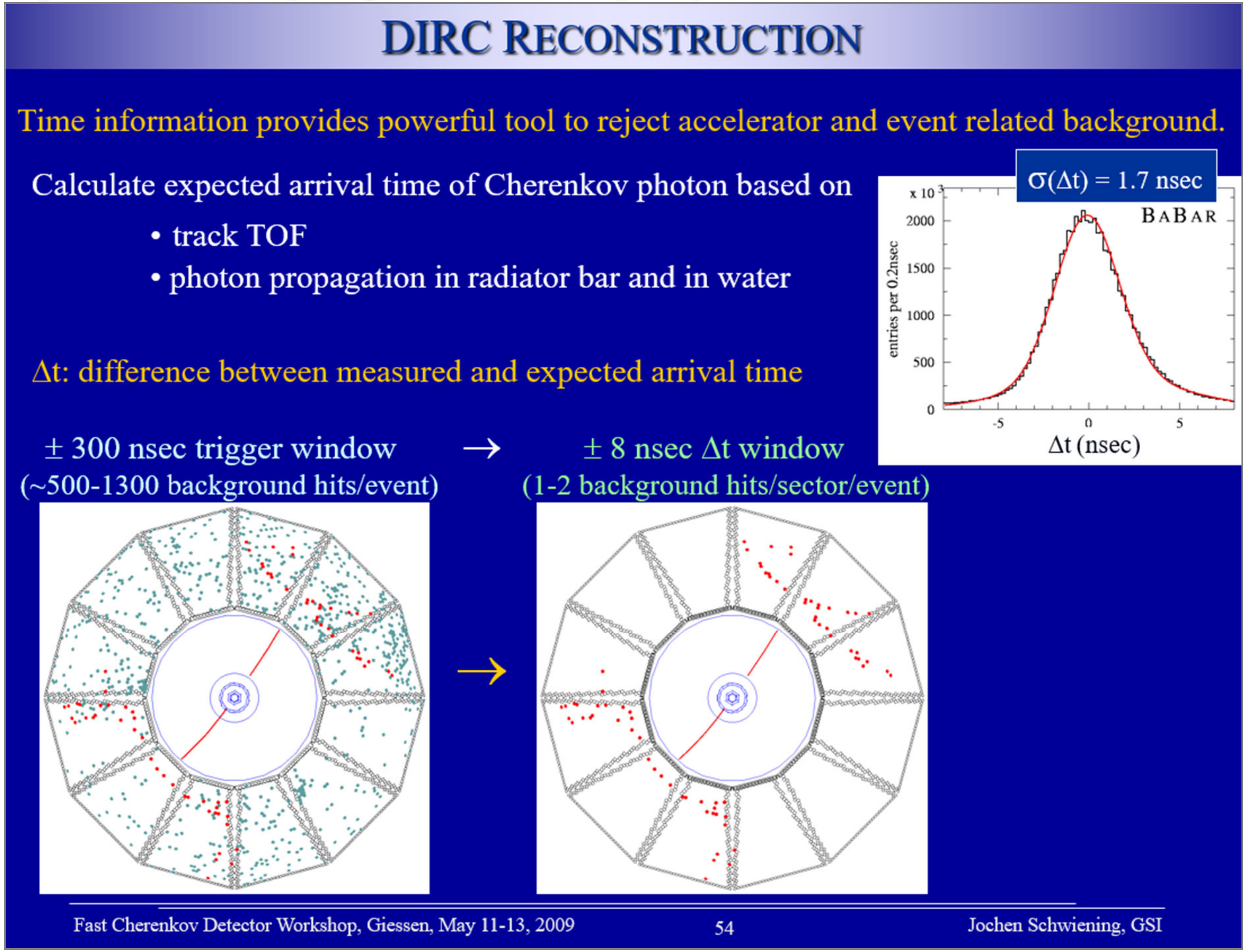


Single 3.5 GeV/c pion event,
PANDA Barrel DIRC prototype



For comparison:
Single event in
CMB RICH (CO_2) prototype

BaBar DIRC Photon Timing

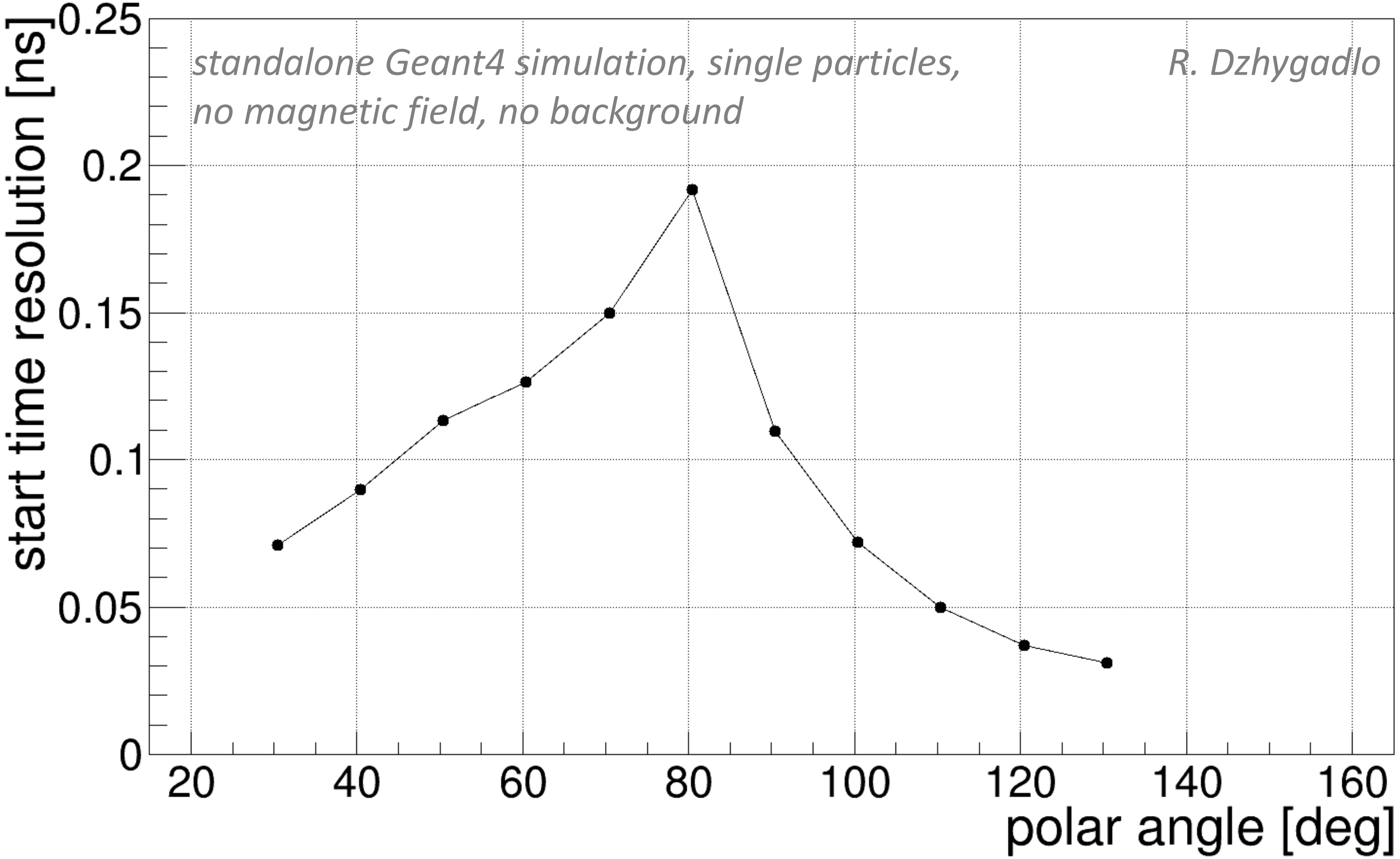


- Timing information not used for PID but crucial in dealing with accelerator-induced background
- Powerful DIRC timing variable: difference between measured and calculated photon arrival time (can provide "DIRC t_0 event time")
- Backgrounds from other tracks can be efficiently suppressed
- hpDIRC sensor timing factor >10 better than BaBar

J.S., DIRC2009

hpDIRC Start Time Resolution

"Start time" means time of emission of Cherenkov photons for particle – can be used as TOF "stop time" if event T_0 is known



Summary

Detailed standalone Geant simulation predicts significant potential for hpDIRC
to contribute to low-momentum π/K and K/p identification below DIRC threshold

Caveat: simulation shown today performed without magnetic field, without backgrounds

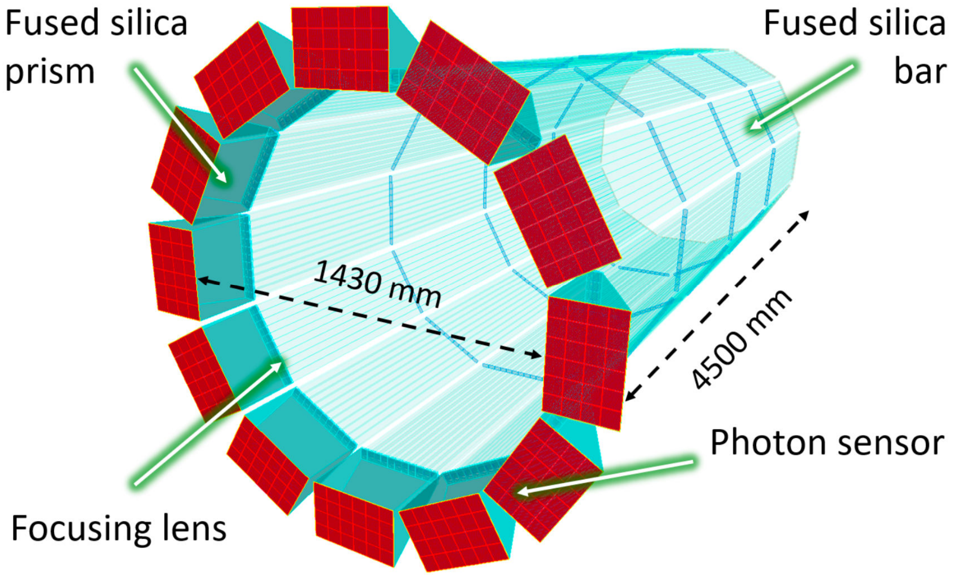
For particles with robust photon yield hpDIRC PID likelihoods will include
photon yield per particle, as well as DIRC-based TOF contribution

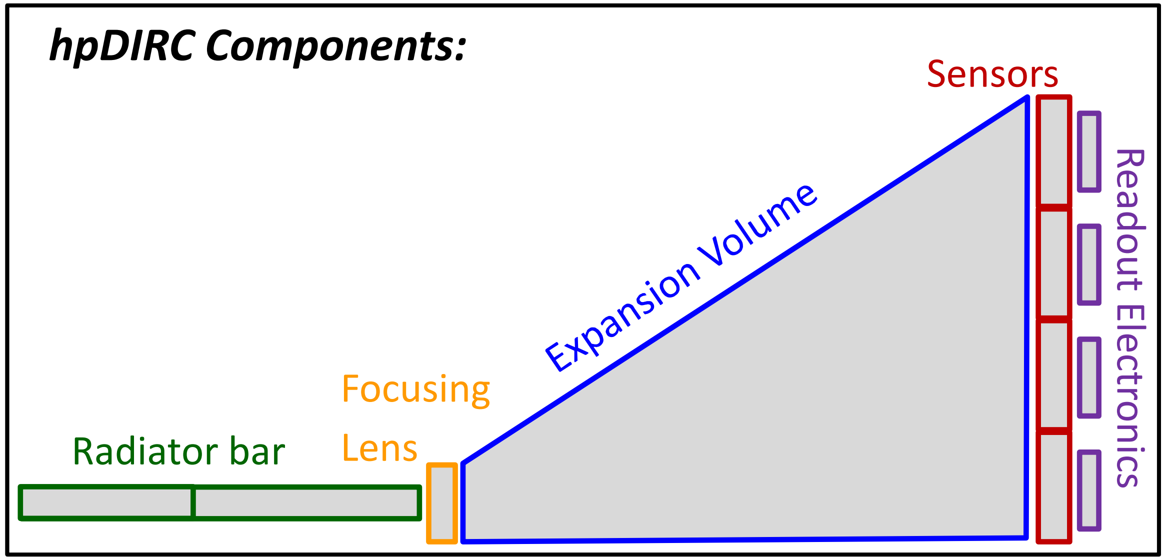
We plan to investigate hpDIRC threshold mode in Fun4All, with Detector-1 B-field and
physics events, once DIRC reconstruction in framework is fully operational

Thank You For Your Attention

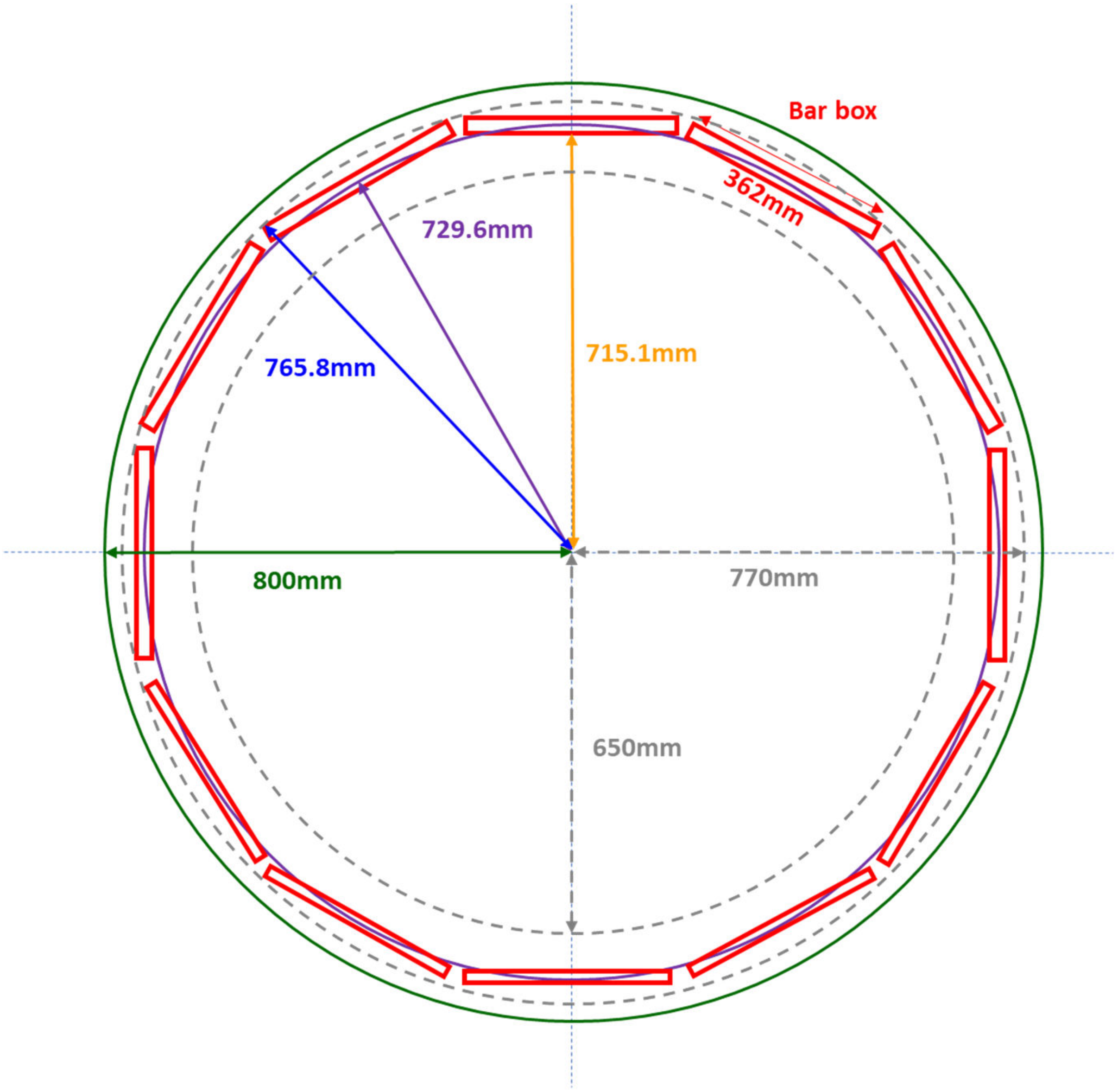
Extra Material

- Barrel hpDIRC with 72cm radius
- Radiator bars:
  - 420cm bar length (baseline: reused BaBar DIRC bars)
  - 12 bar boxes, 10 long bars side-by-side in a bar box
    long bar: 3 BaBar DIRC bars;
    additional lightguide section (bars or plate) to couple to lens/prism
- Focusing optics:
  Radiation-hard 3-layer spherical lens
- Expansion volume:
  Solid fused silica prism: 24 x 36 x 30 cm^3 (H x W x L)
- Readout baseline:
  PHOTONIS MCP-PMT Sensors + NALU's ASIC-based Electronics





Detector-1 hpDIRC Baseline Design



ECCE proposal hpDIRC configuration

- 10 bars side by side per bar box
- 12 bar boxes
- 20mm rib width between bar boxes
- Barbox width: 362mm
- Barbox thickness: 29mm

- Middle hpDIRC radius: 729.6mm
- Minimum hpDIRC radius: 715.1mm
- Maximum hpDIRC radius: 765.8mm
- hpDIRC total radial thickness 50.7mm
- Azimuthal coverage 91.6%

hpDIRC Photon Yield Expectation

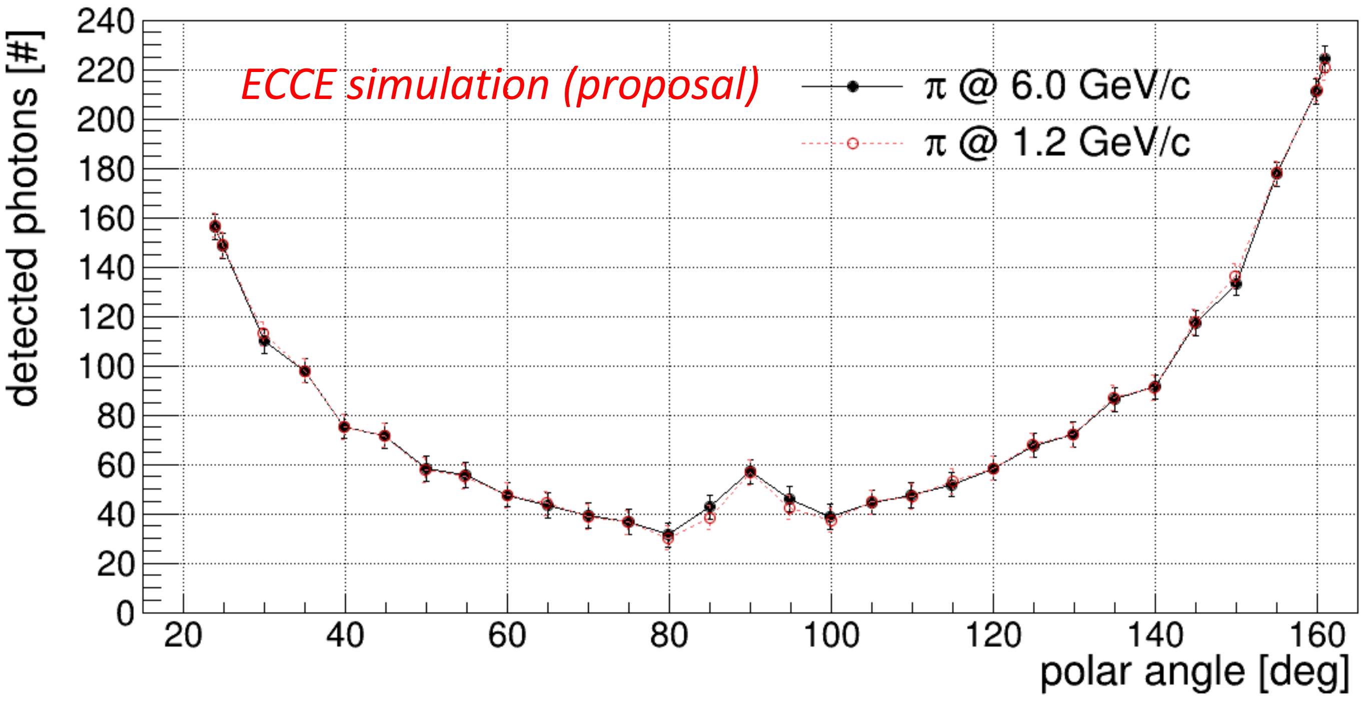
Figures for PANDA Geant study of the expected photon yield (right) look quite different from ECCE Geant simulation (left)

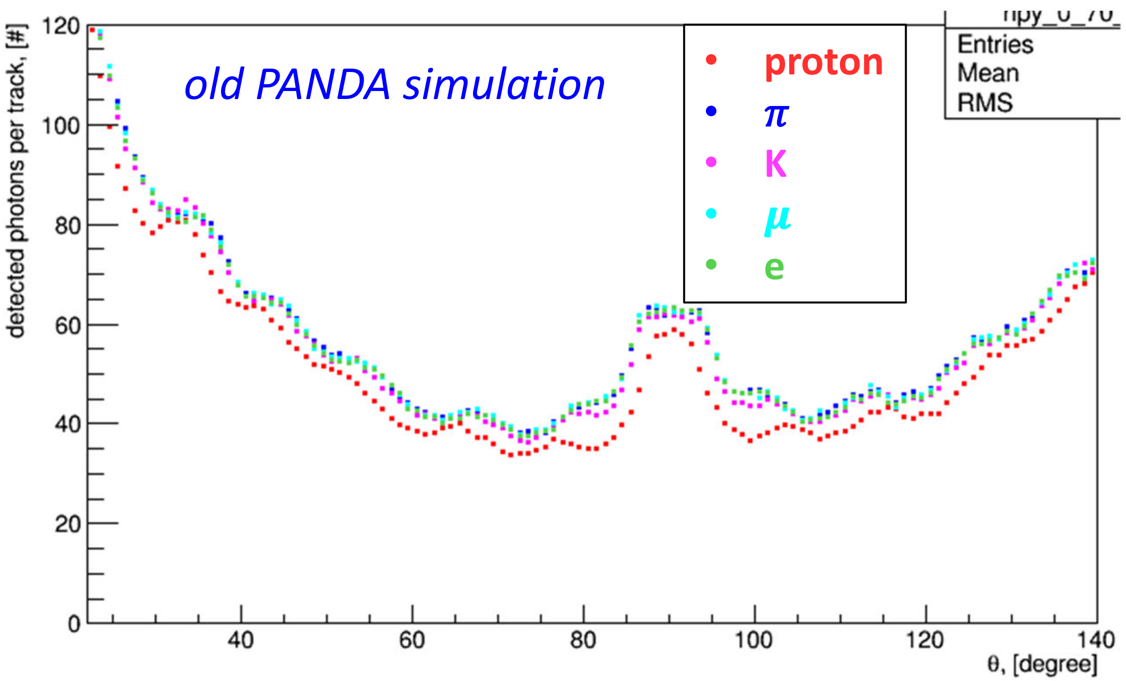
One trivial reason: prism and mirror sides are flipped in our definition of the polar angle

(30° tracks point to prism end in PANDA, to mirror end in Detector-1)

Other reasons: ECCE sim used narrow bars, spherical 3-layer lens, and current commercial MCP-PMT properties;

this particular PANDA sim used a wide plate without any lens and older MCP-PMT specs (lower CE and QE)





HPDIRC PHOTON YIELD EXPECTATION

Figures for PANDA Geant study of the expected photon yield (right) look quite different from ECCE Geant simulation (left)

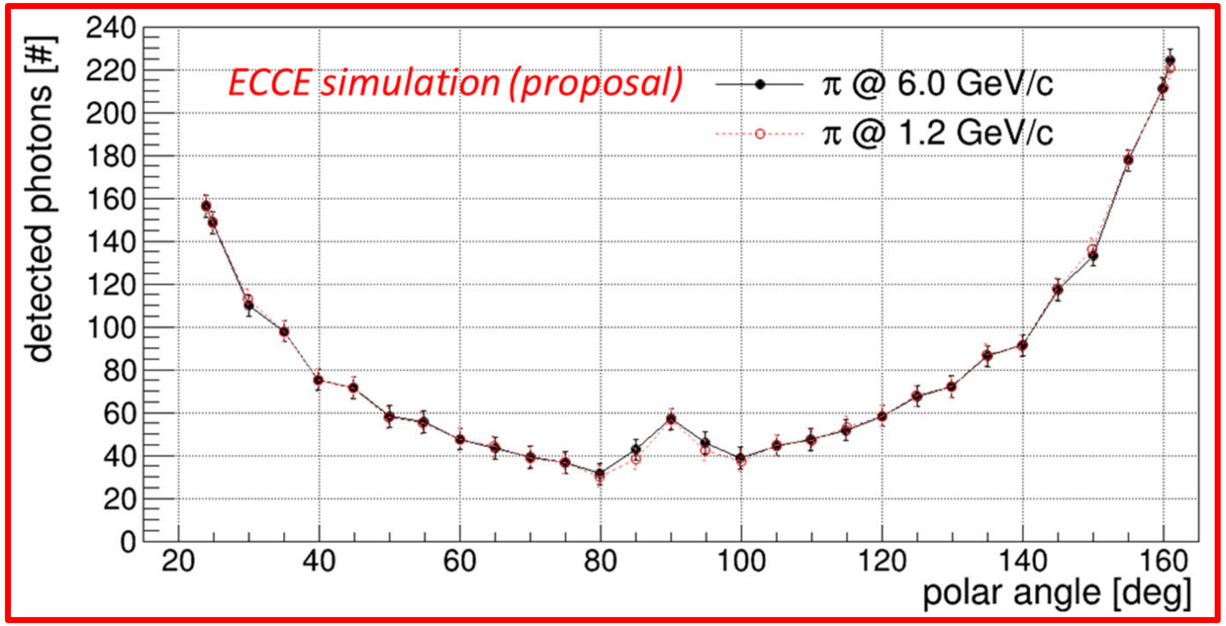
One trivial reason: our definition of the polar angle, prism and mirror sides are flipped

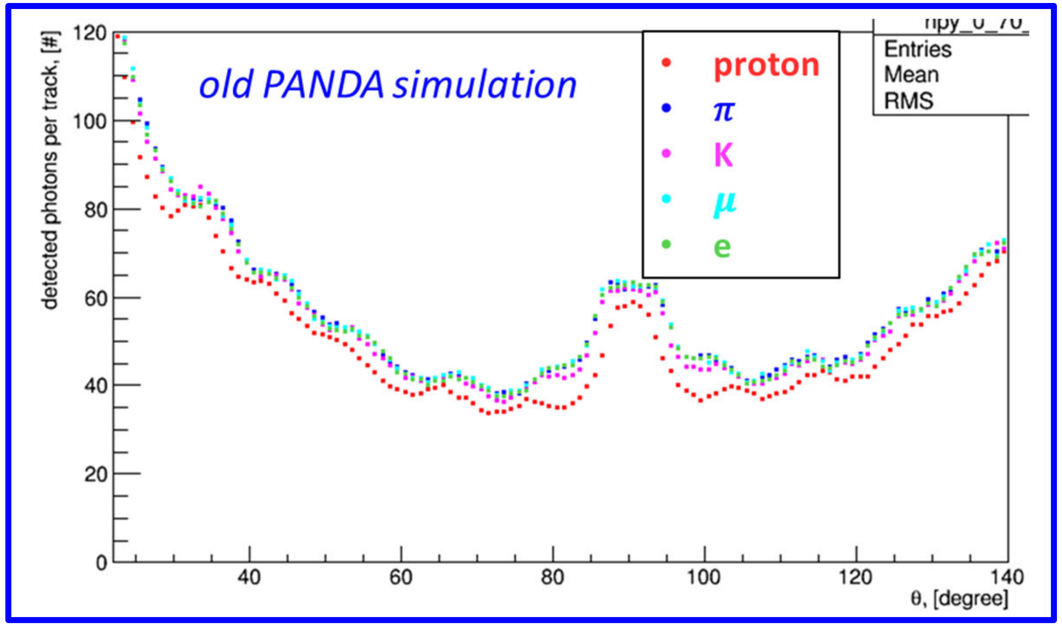
(30° tracks point to prism end in PANDA, to mirror end in ECCE)

Main issue: ECCE sim used narrow bars, spherical 3-layer lens, and current commercial MCP-PMT properties;

this particular PANDA sim used a wide plate without any lens and older MCP-PMT specs (lower CE and QE)

Difference results in higher yield at steep forward/backward angles in ECCE and smaller yield near perpendicular incidence

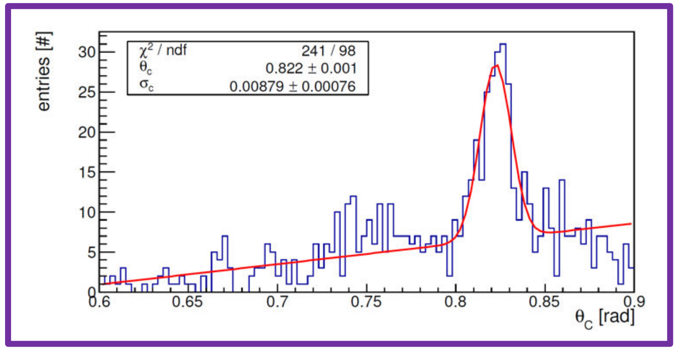




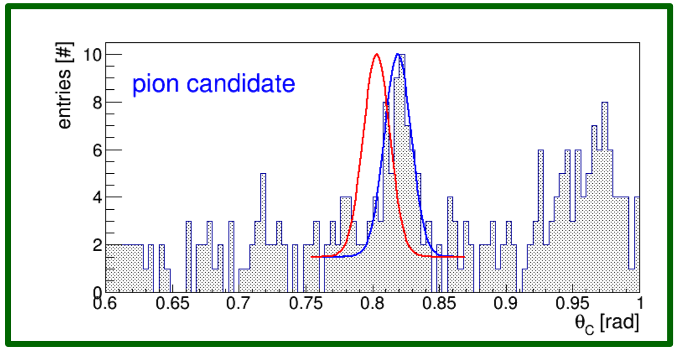
R. Dzhygadlo, CHEP2019

Examples of reconstruction/PID methods from PANDA Barrel DIRC

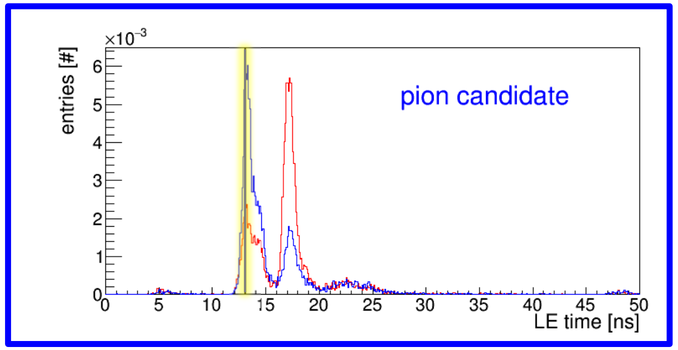
- track-by-track fit of single photon Cherenkov angle distribution based on look-up tables to extract track Cherenkov angle ("BABAR-like")



- track-by-track unbinned likelihood hypothesis test to determine log-likelihood differences ("geometrical reconstruction")



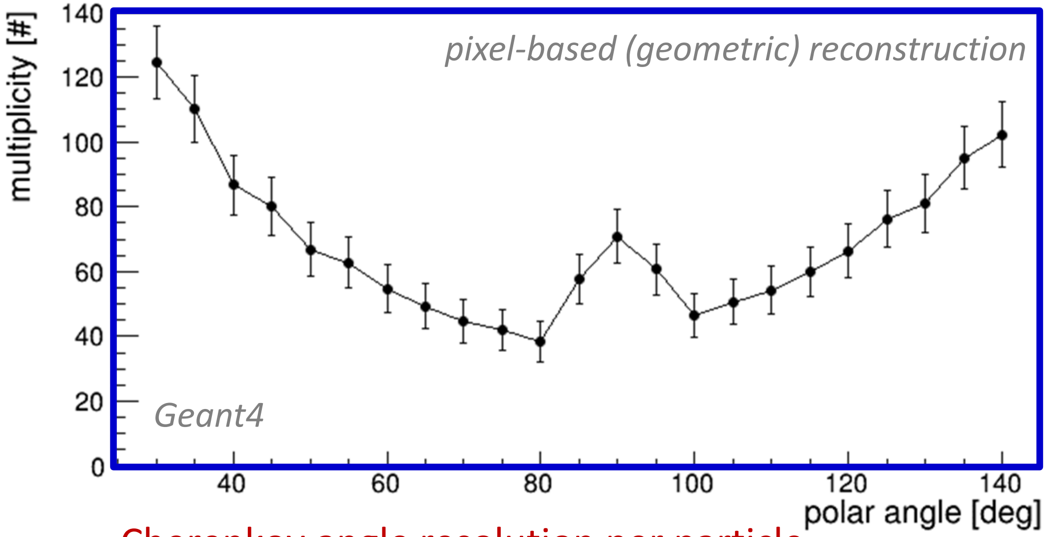
- "Belle II-like" time imaging to extract log-likelihood differences (PDFs were generated either analytically or from beam data directly using time-of-flight tag, statistically independent data sets)



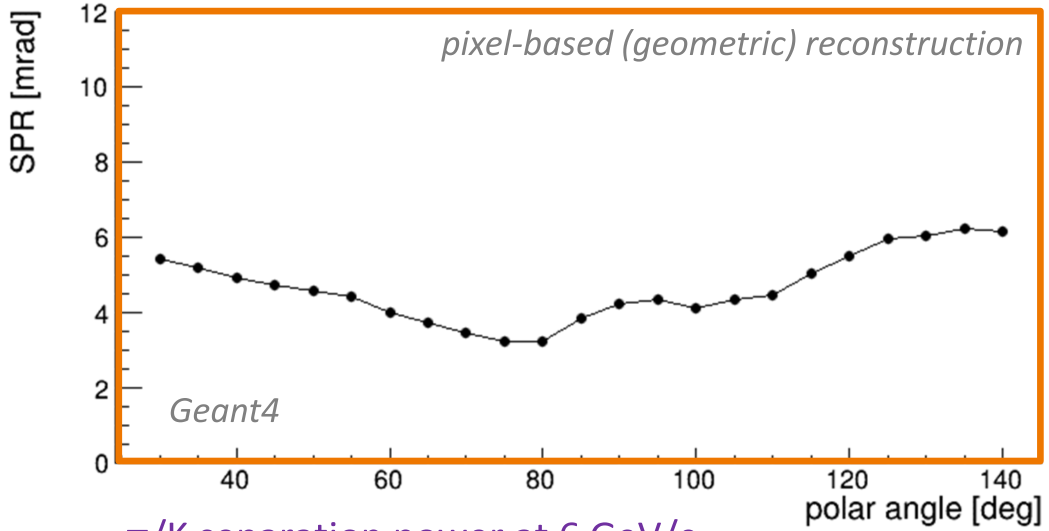
- development of PID methods using advanced AI/ML techniques underway

EIC High-Performance DIRC

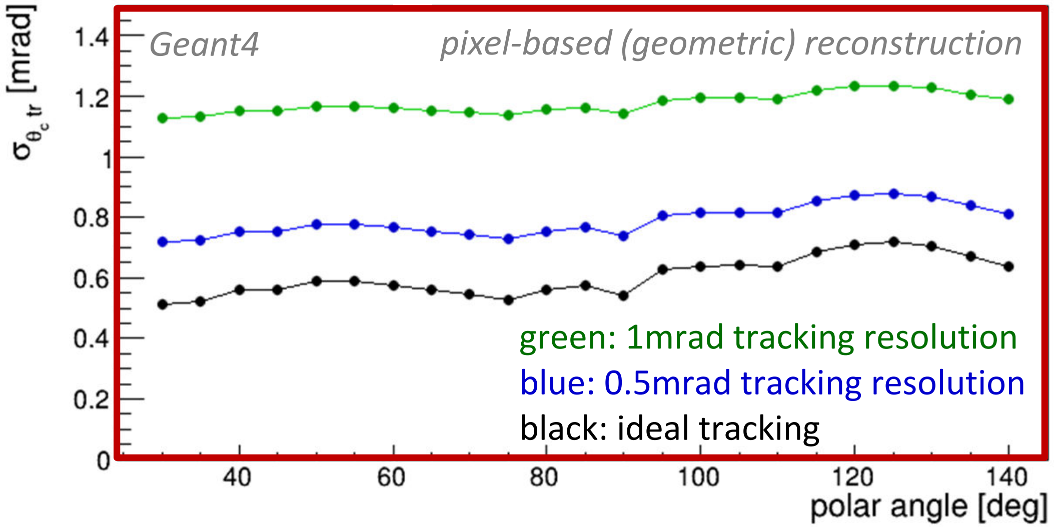
Photon yield per particle



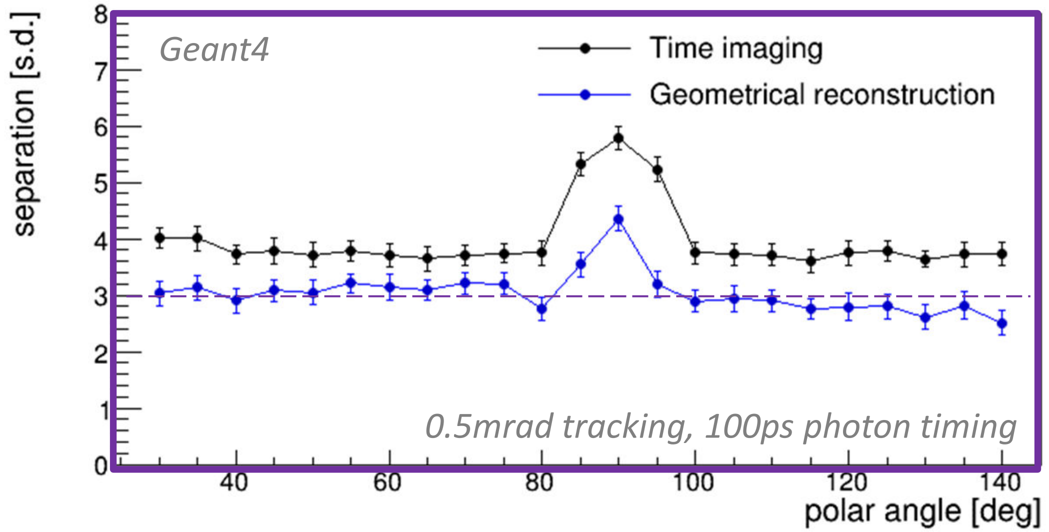
Cherenkov angle resolution per photon (SPR)



Cherenkov angle resolution per particle



π/K separation power at 6 GeV/c



→ 3 s.d. π/K separation at 6 GeV/c and 1 mrad Cherenkov angle resolution seems to be in reach

JS, eRD14 report, BNL, Mar 2021

Impact of photon timing precision on DIRC performance (generic design, status summer 2020)

π/K separation power at 6 GeV/c