Compact RICH for PID

J. Va'vra, SLAC

This RICH proposal is a part of a larger study by:

A. Albert, M.J. Bass, S.K. Bright-Thonneya, V.M. M. Cairoc, Ch. Damerell, D. Ega~na-Ugrinovic, U. Einhaus, U. Heintz, S. Homiller, S. Kawada, J. Luoh, C. Mantel, P. Meade, J. Monroy, M. Narain, R. S. Orr, J. Reichert, A. Ryd, J. Strube, Dong Su, A. G. Schwartzman, T. Tanabe, J. Tian, E. Usai, J. Va'vra, C. Vernieri, C. C. Young, and R. Zou, ArXiv:2203.07535v2 [hep-ex] 14 Mar 2022

Physics motivation π/K/p particle identification

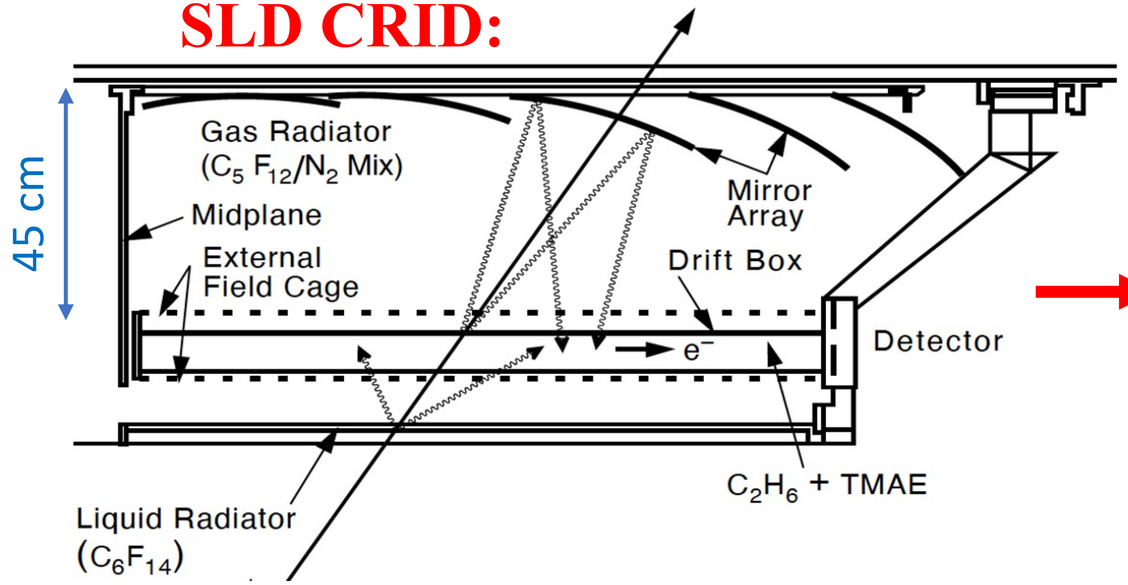
- **General point:** **What is the origin of flavor ? Why we have three families ?**
- **Higgs physics**: need to test Higgs coupling to lighter quarks. Use π/K PID to separate strange-initiated jets from u/d (ArXiv: 2203.07535v2, Mar.2022)
- **Flavor physics:** requires excellent hadron particle identification (separation of π, K, p) to resolve combinatorics + separate decay modes
- **SM physics:** Plenty of Z, W, top produced! Measure $Z \rightarrow s\bar{s}$, $Z \rightarrow qq$, $e^+e^- \rightarrow s\bar{s}$, $W \rightarrow cs$, etc.

- **Additional references:**

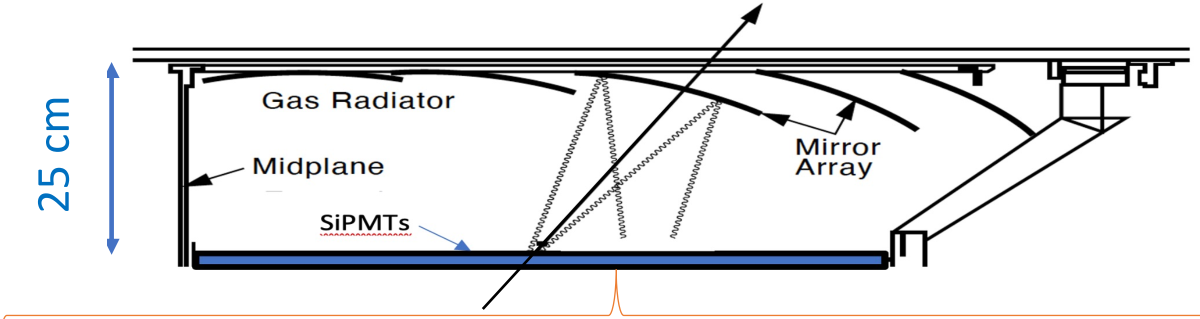
- Wolfgang Altmannshofer: SSI2021 lectures on "Roles of Higgs Sector in Generation & Flavor Problem". Lecture 1: slides, video; Lecture 2: slides, video
- Patrick Meade: SSI 2022 lectures on "Fermion Generations". Lecture 1: slides, video; Lecture 2: slides, video
- Su Dong: SLAC Snowmass Higgs WG Mar/2020: Higgs Yukawa Couplings & Fermion Generation Puzzle

Our present RICH design concept

SLD CRID:



Our proposed FCC RICH:



C_4F_{10} at 1 bar (boiling point -1.9 C at 1 bar)

Beryllium mirrors with reflective coating

Low mass carbon-composite structure

SiPM detector covering barrel

- **SiPM temperature will be reduced to +2-3°C to reduce the SiPM noise somewhat. The second reduction comes from timing. This requires a good timing resolution at a 100 ps level. From a known trajectory, photon azimuth on Cherenkov ring, track and photon hit times one form a difference: timing between calculated "photon hit & measured photon hit". One may also attempt to correct the smearing effect.**

SiPM single photon timing resolution

Gundacker et al. "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET."*Physics in Medicine & Biology*64.5 (2019): 055012
A. Gola, FBK Foundation Co., Italy, "Status and Perspectives of SiPM", RICH 2022, Edinburgh

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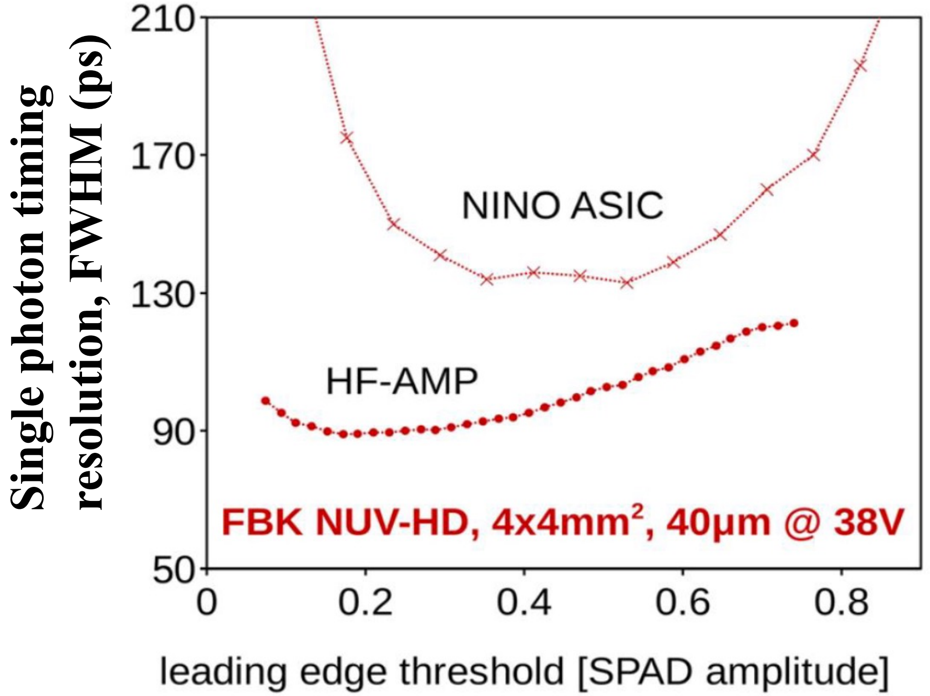
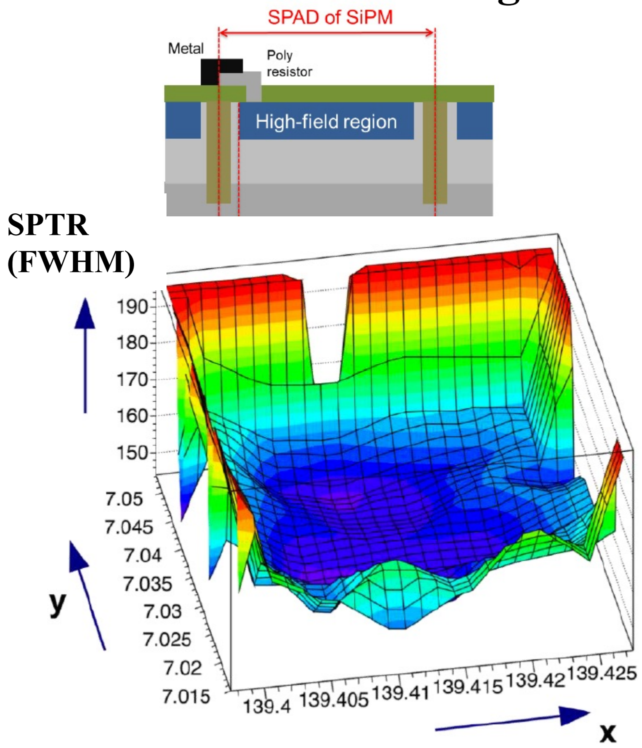
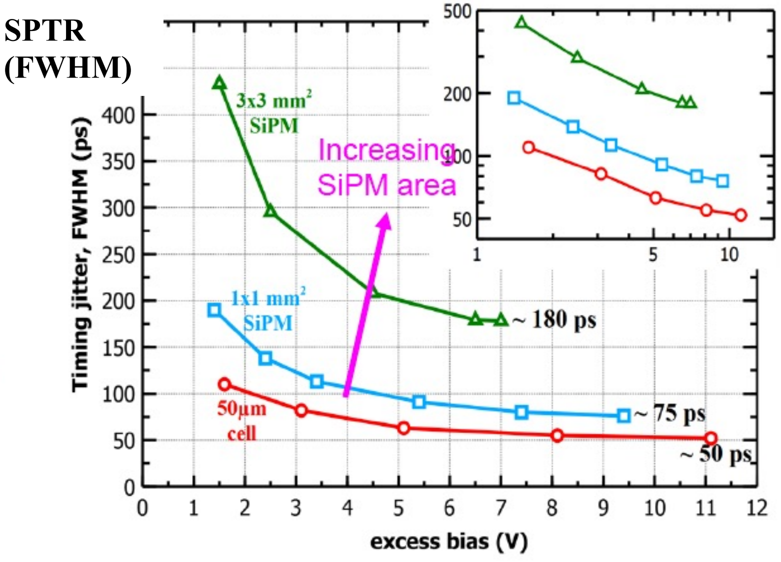
Single pixel timing resolution is excellent:



Each SPAD element has edge effects:

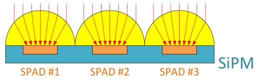


Large arrays have slightly worse timing resolution:



Gola's suggestion:
Organize array differently to improve timing

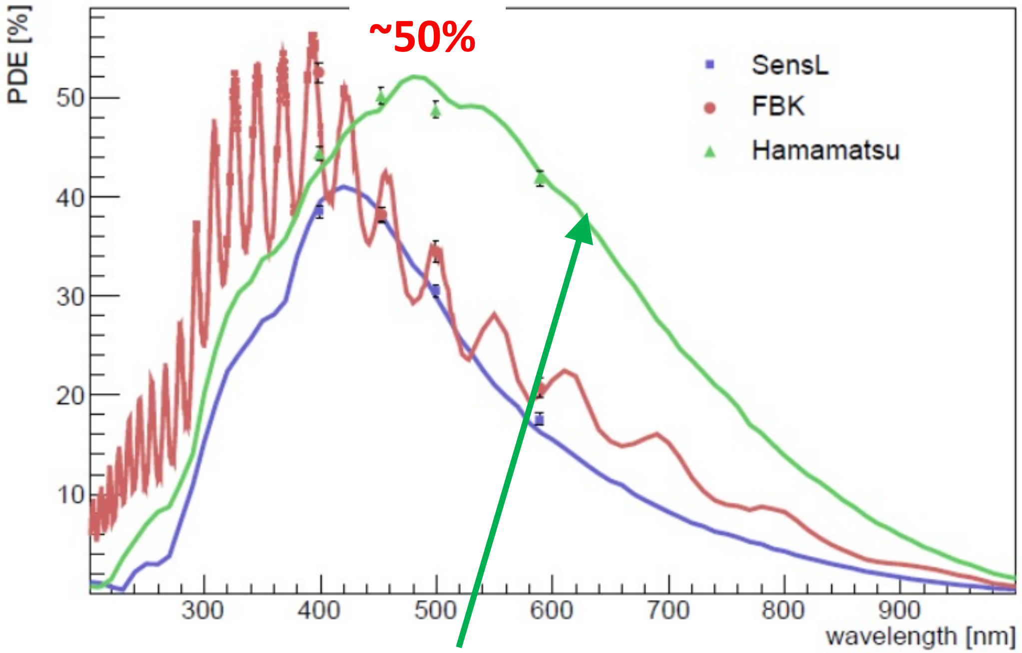
Gola's suggestion:
Use micro-lenses to remove edge effect:



- **SiPM can reach average single photon timing resolution/pixel of σ ≲100 ps.**
- SPTR = single photon timing resolution, SPAD = Single photon avalanche diode, an element of SiPM

Photon Detection Efficiency (PDE) of a single SiPM

A.N. Otte et al., NIM A 864(2017)106



Photon detection efficiency of single SiPM:

$$PDE = FF \times QE(\lambda) \times P_T(V_{bias}, \lambda)$$

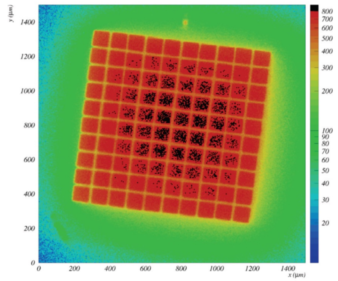
$QE(\lambda)$ – QE of Si

FF – Fill factor within one SiPM

$P_T(V_{bias}, \lambda)$ – Trigger efficiency

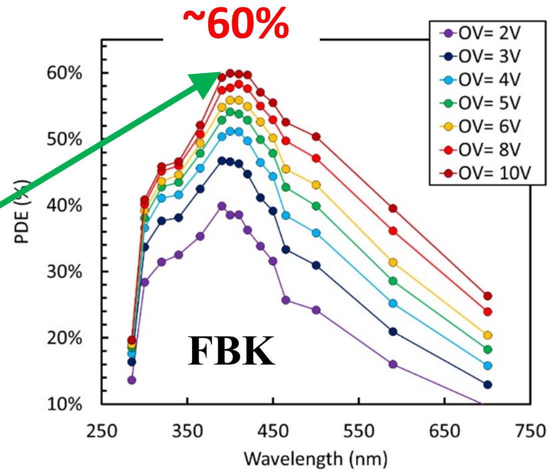
SiPM array has additional losses due to gaps between pixel elements !

I assumed 65%:

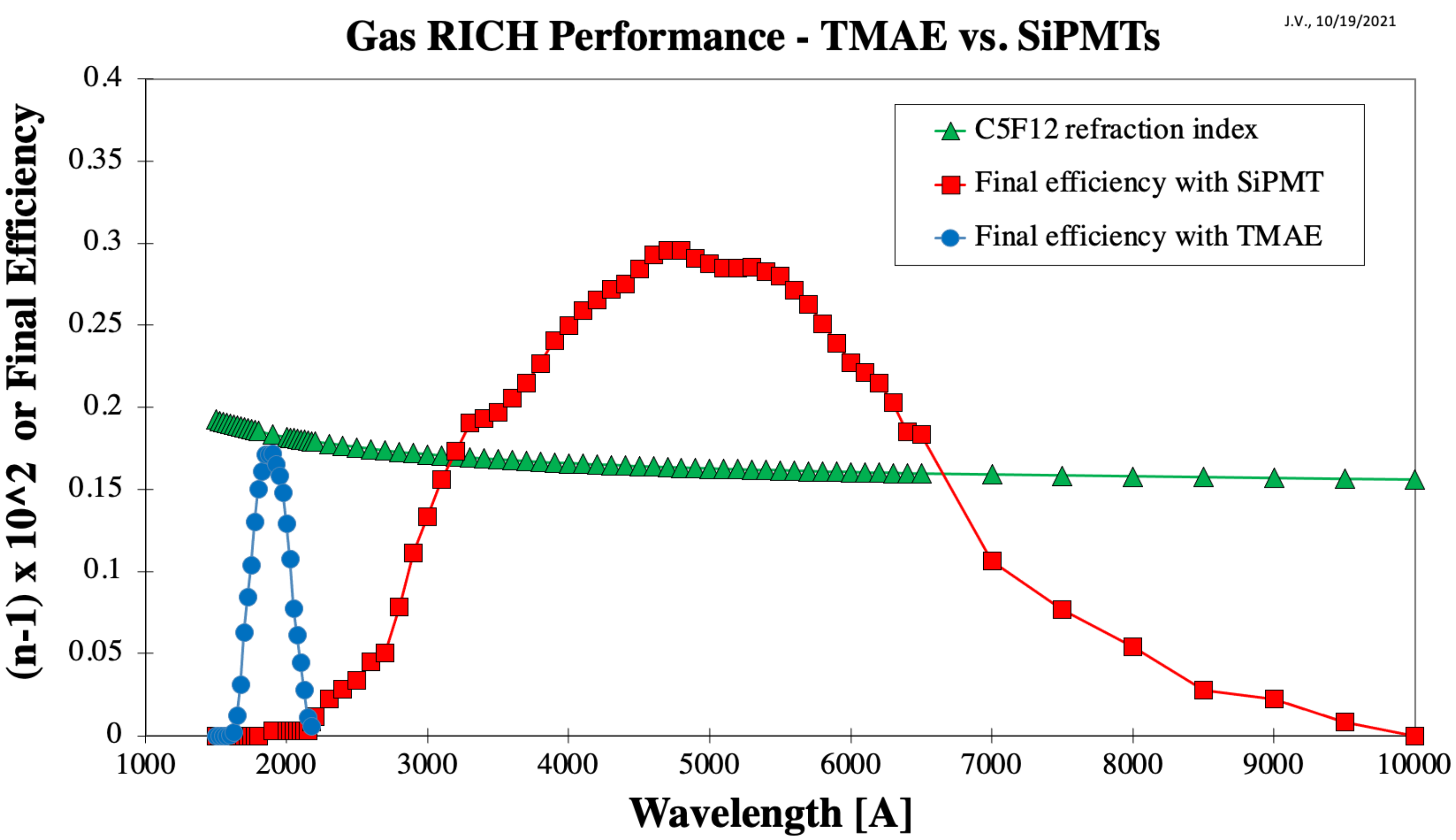


- **I used Hamamatsu SiPM PDE in my calculation**
- **<u>All this will improve in next 5-10 years !</u>**
- **Already now there are better SiPMs with higher PDE**

(Gola et al. (2019). *Sensors*, *19*(2), 308.)



Final efficiency: TMAE vs. SiPMs



- **Although CRID operated in a region where refraction index changed more rapidly, its wavelength acceptance was very narrow and therefore the chromatic error was smaller: ~0.4 mrad (TMAE) vs. ~0.85 mrad (SiPM).**

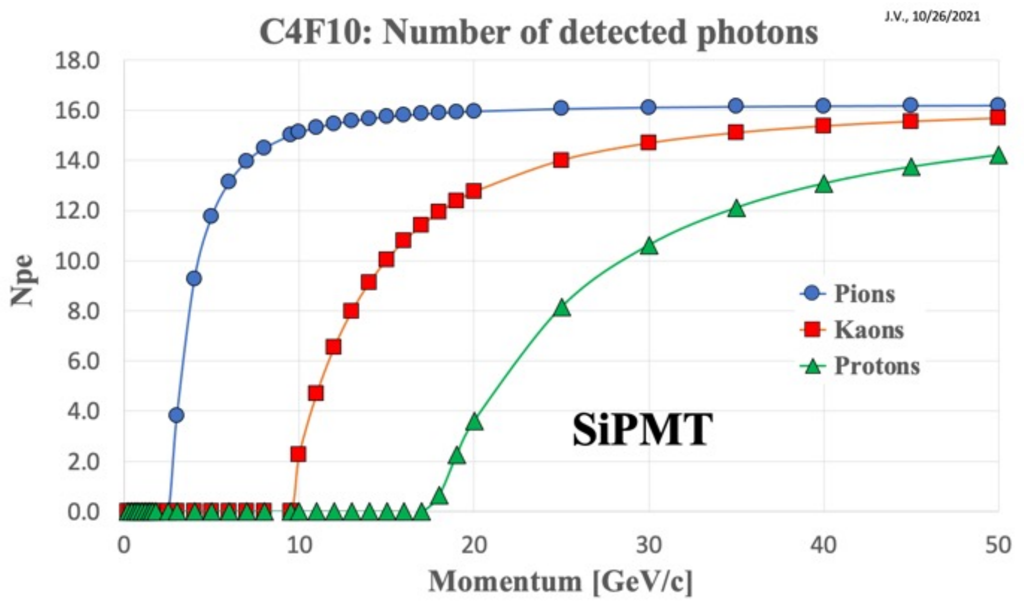
PID using Npe and θ_c in our design

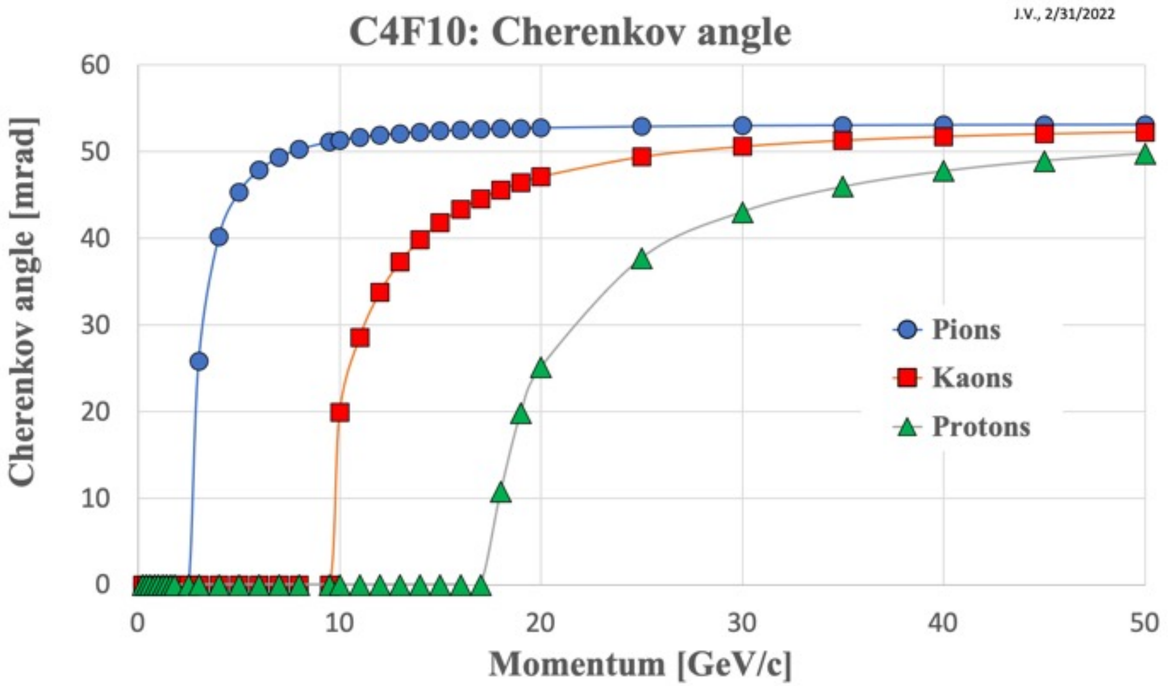
$$N_o = \frac{\left(\frac{\alpha}{hc}\right) \int \mathrm{Eff}(E)[\sin(\theta_c)]^2 dE}{[\sin(<\theta_c>)]^2}$$

$$N_{pe} = N_o \, L \, [\sin <\theta_c>]^2$$

$< \theta_c >$ is mean Cherenkov angle

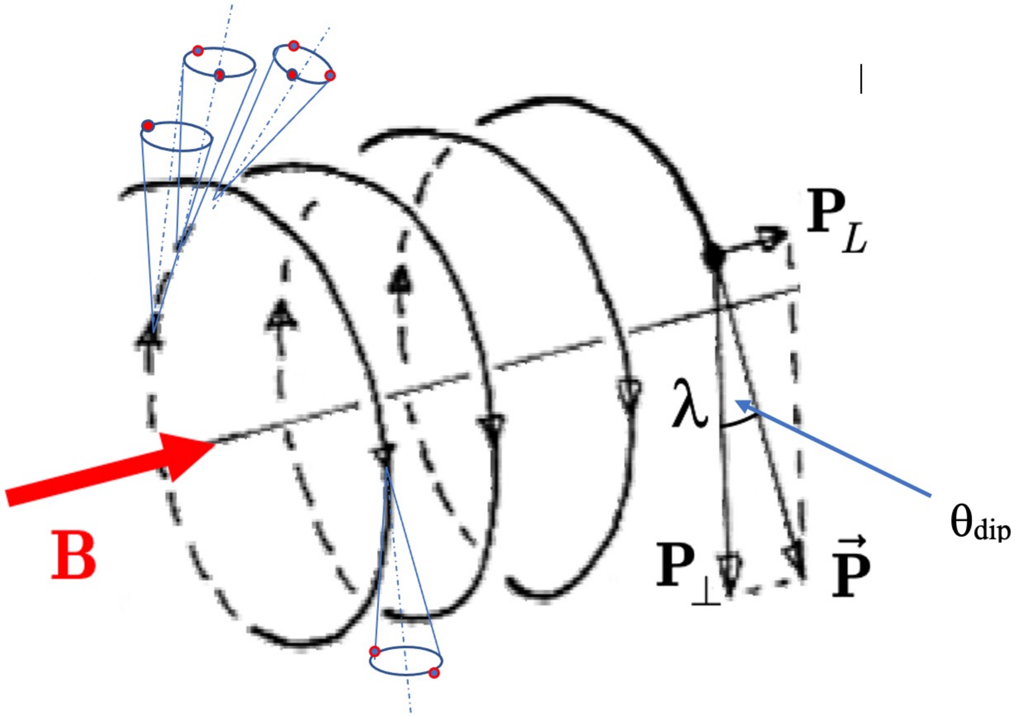
$$\cos\theta_c = 1/(<n>\beta)$$





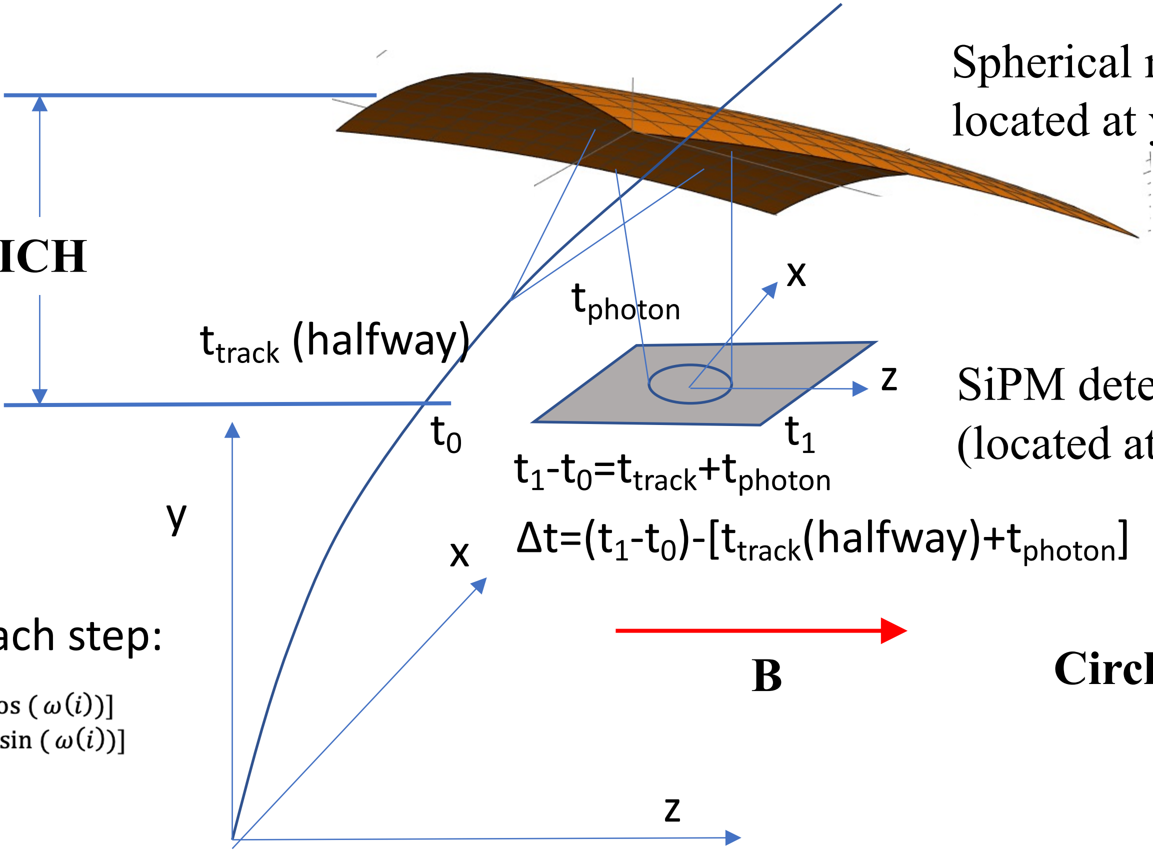
- **L = 25 cm & 1 bar.**
- **p/K PID is trivial below 25 GeV/c, becomes more difficult above 30 GeV/c.**

Smearing effect in magnetic field



- **This effect was small for SLD CRID operating at 0.5 Tesla (~0.5 mrad). It is significant at 5 Tesla for RICH detector with a large radial extent.**
- **I used two methods to estimate it: (a) Analytical formula, (b) Mathematica code.**

I wrote a simple tracking program in Mathematica



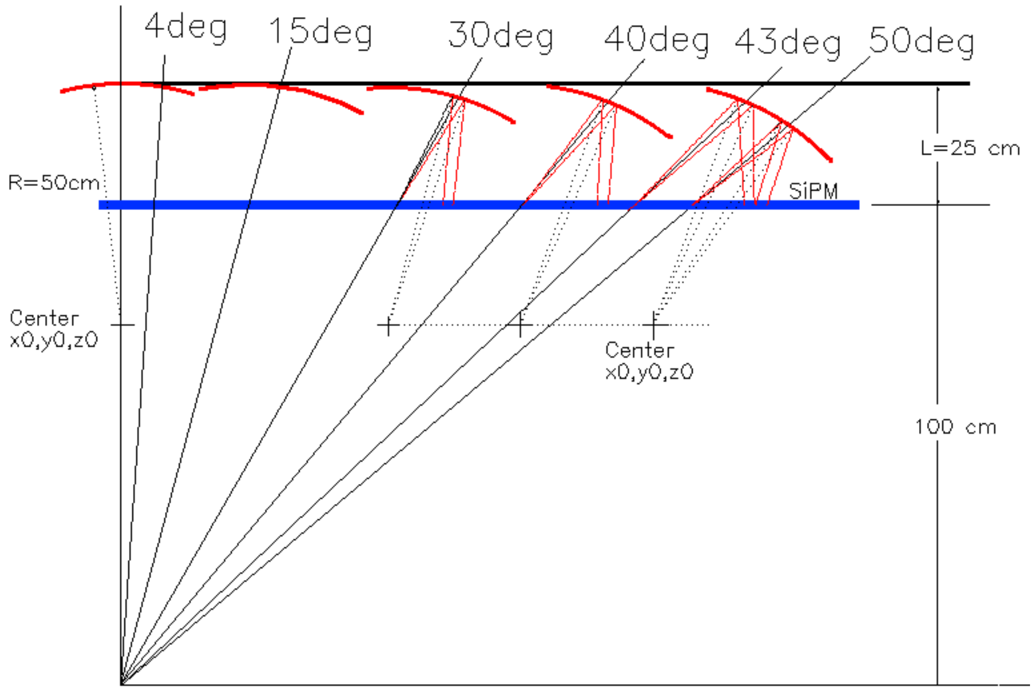
Follow helix step by step. In each step:

$$x(i+1) = x(i) - R[\cos\{\omega(i) + s\cos\theta_{dip}/R)\} - \cos(\omega(i))]$$
$$y(i+1) = y(i) + R[\sin\{\omega(i) + s * \cos\theta_{dip}/R)\} - \sin(\omega(i))]$$
$$z(i+1) = z(i) + \sin\theta_{dip}$$
$$s\cos\theta_{dip} = [z(i+1) - z(i)]\, P_T/P_L$$

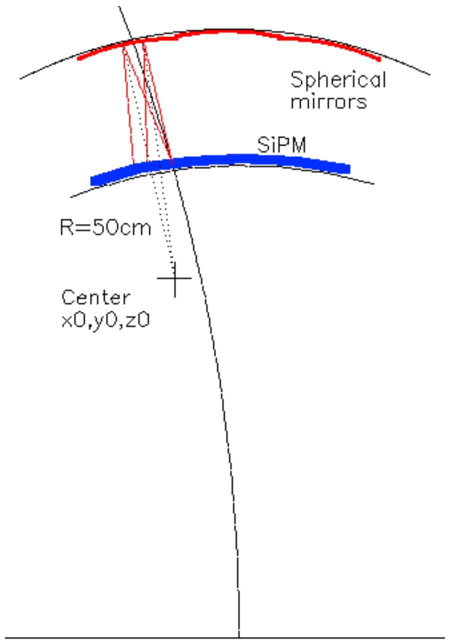
- **Step through the field, radiate Cherenkov photons when in radiator (100< r <125), reflect them from spherical mirror and find their intersection with a detector plane.**
- **Use trajectory, ring radius (Cherenkov angle) , track hit t_0, photon hit t_1 times to reject background photons, and one may work out algorithm to reduce the smearing effect (?).**

To do a calculation I have created a ray tracing model

Side view:



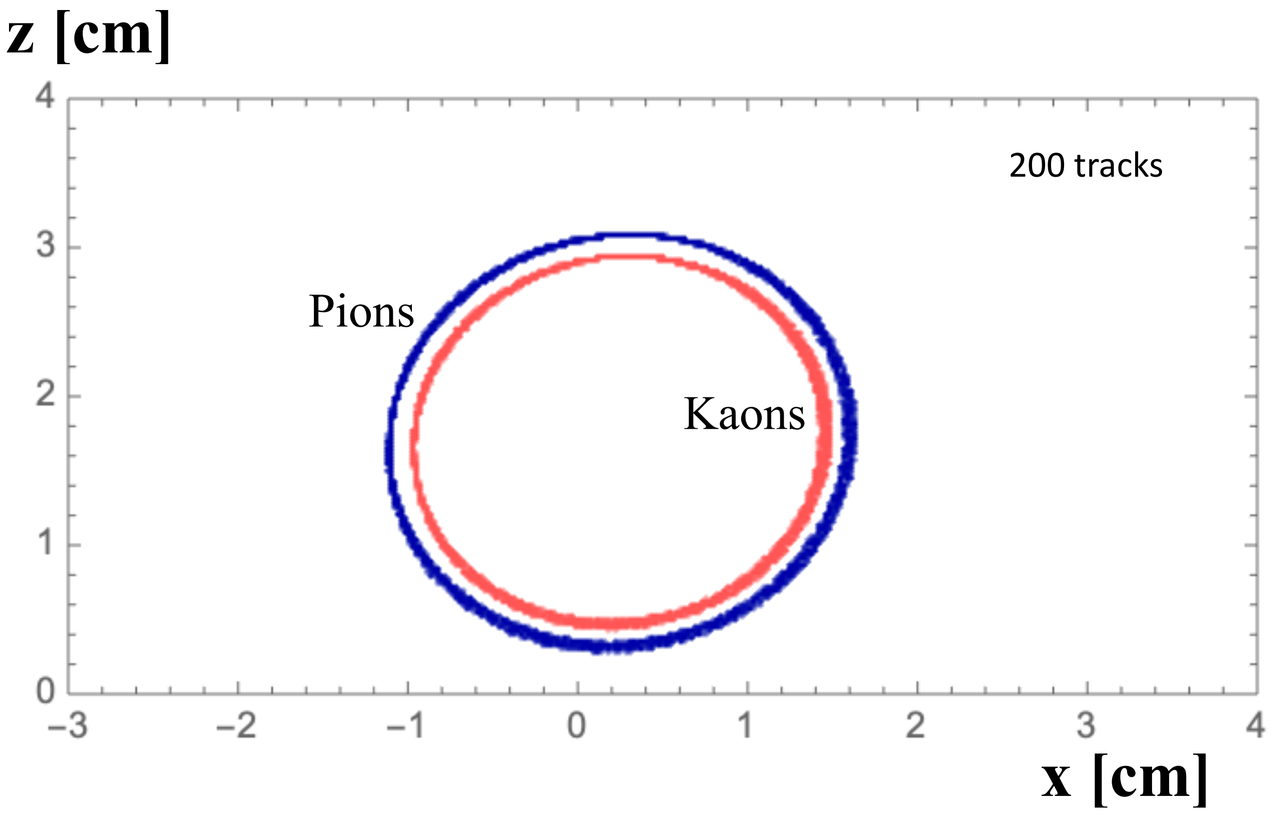
Front view:



- **Spherical mirrors with R = 50 cm, f = 25 cm.**
- **Goal of ray tracing was to rotate mirrors, so that the image comes reasonably perpendicularly to SiPM plane.**

Cherenkov rings for $\theta_{dip} = 4^o$ at 20 GeV/c with B = 5 Tesla

B = 5 Tesla,
P = 20 GeV/c pions
Pt = 19.951 GeV/c
Pz = 1.3973 GeV/c
Theta = $86^o = 90^o - \theta_{dip}$
Phi = 90^o
R-helix=13.3 meters
θ_C (Pions)= 53.2 rad
θ_C (Kaons)= 47.1 mrad
Npe (Pions) ~ 16
Npe (Kaons) ~ 12-13
C_4F_{10} gas
$\mathbf{L_{radiator} = 25\ cm}$



Smearing error only in this plot

- **Smearing effect varies as a function of Cherenkov angle azimuth Φ_c.**

Cherenkov rings for θ_{dip} = 4° at 20 GeV/c with B = 5 Tesla

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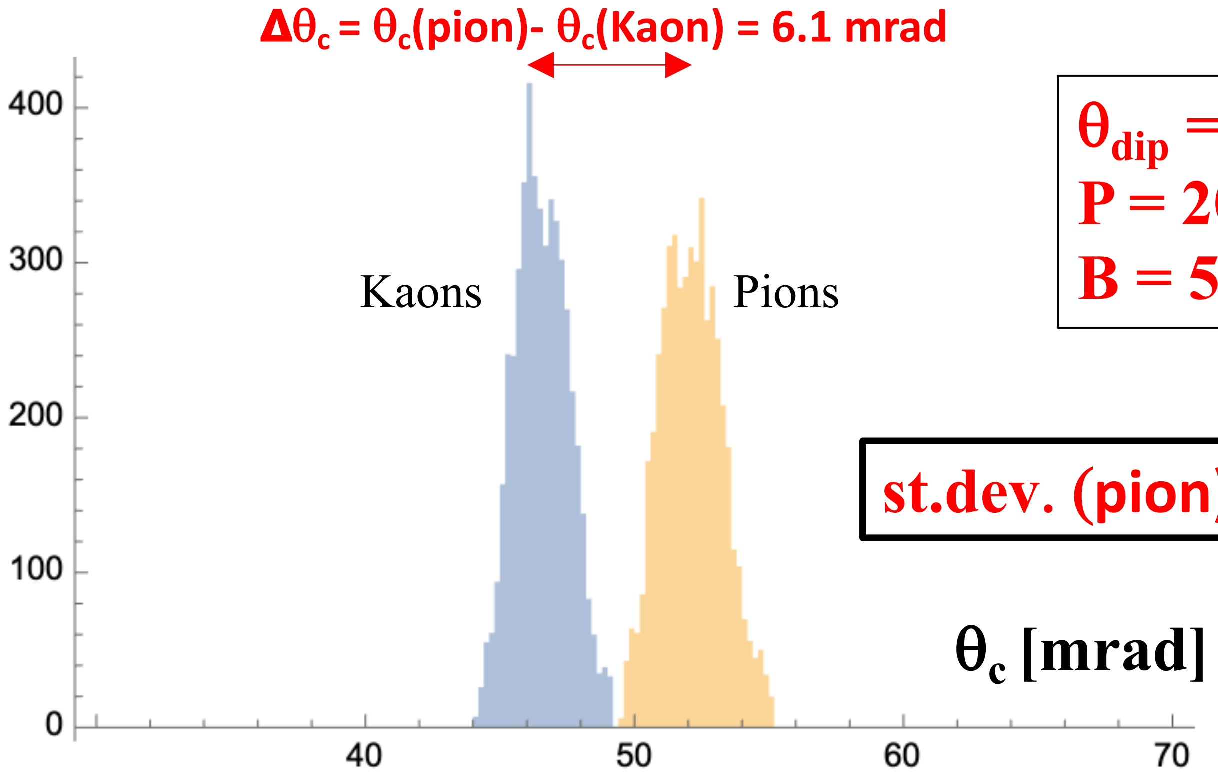


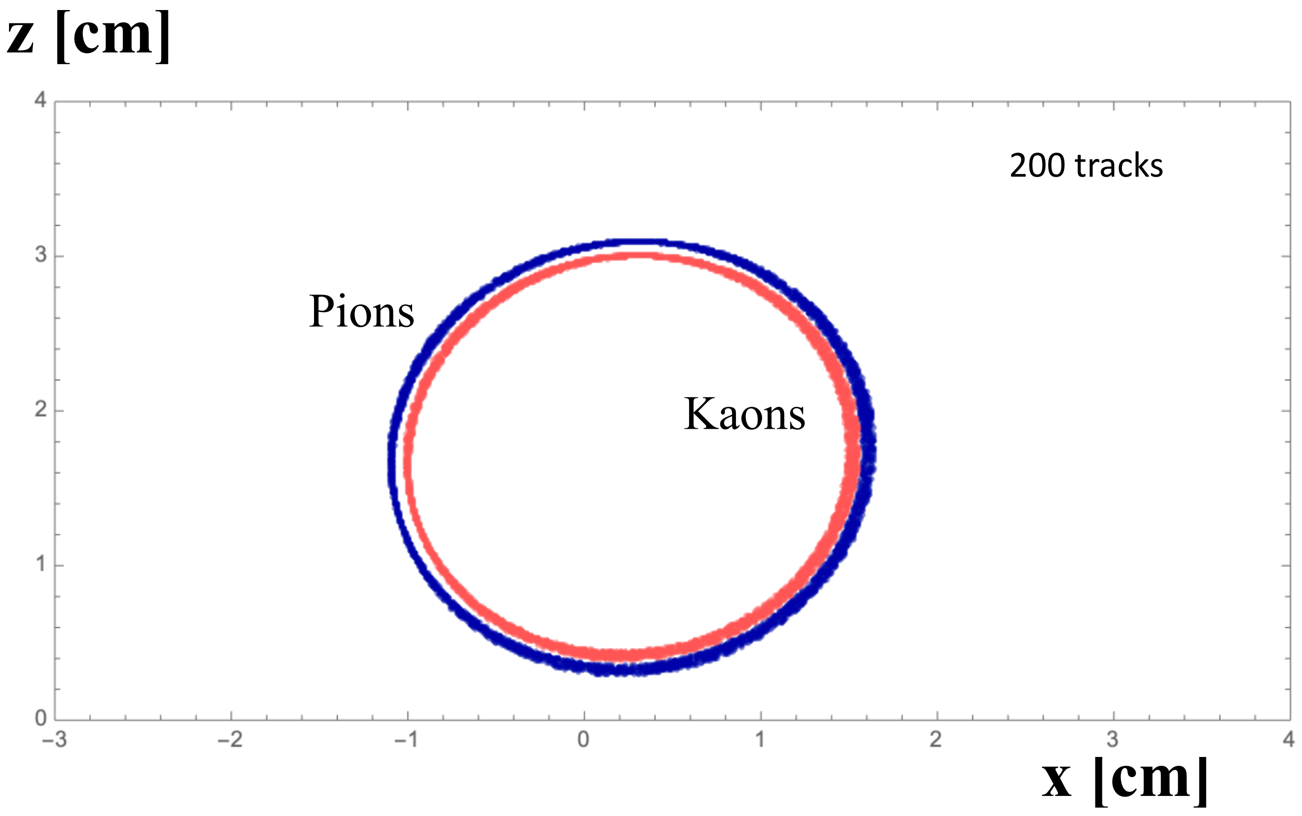
θ_{dip} = 4°
P = 20 GeV/c
B = 5 Tesla

st.dev. (pion) = 1.1 mrad

- **Ring radius:** CherRadius = Sqrt[$(z_{final}[i] - z_0)^2 + (x_{final}[i] - x_0)^2$]
- **Cherenkov angle:** θ_c = CherRadius/(Focallength)

Cherenkov rings for $\theta_{dip} = 4^o$ at 25 GeV/c with B = 5 Tesla

B = 5 Tesla,
P = 25 GeV/c pions
Pt = 24.939 GeV/c
Pz = 1.7467 GeV/c
Theta = 86^o = 90^o- θ_{dip}
Phi = 90^o
R-helix=16.63 meters
θ_C (Pions)= 52.9 rad
θ_C (Kaons)= 49.4 mrad
Npe (Pions) ~ 16
Npe (Kaons) ~ 14-15
C_4F_{10} gas
$L_{radiator}$ = 25 cm



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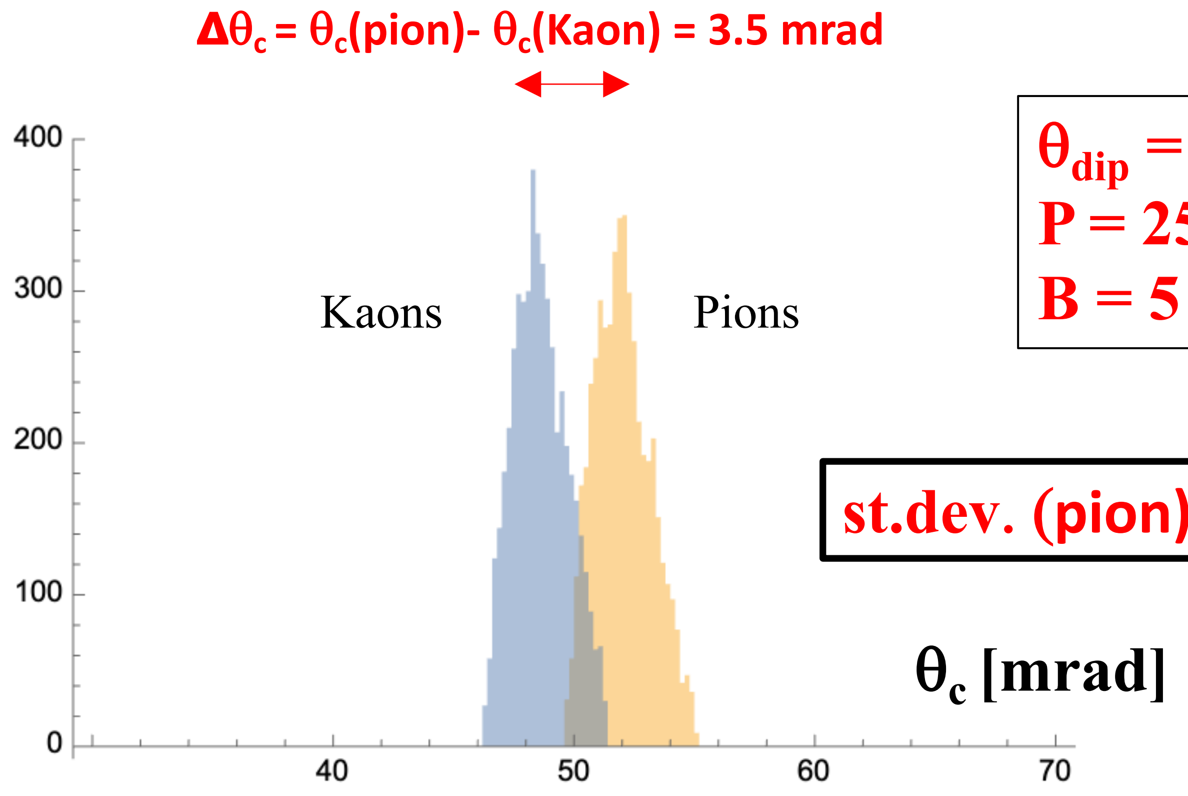


θ_{dip} = 4^o
P = 25 GeV/c
B = 5 Tesla

st.dev. (pion) = 1.2 mrad

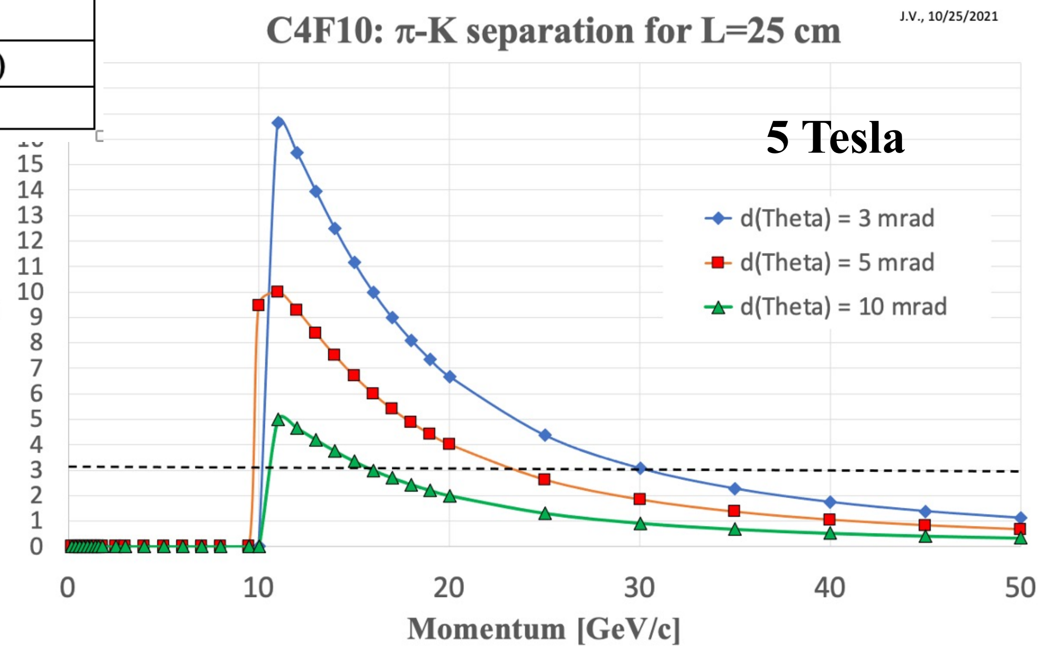
- **Ring radius:** CherRadius = Sqrt[$(z_{final}[i] - z_0)^2 + (x_{final}[i] - x_0)^2$]
- **Cherenkov angle:** θ_c = CherRadius/(Focallength)

Errors in our design vs. SLD CRID

Single photon error source	SiD/ILD RICH detector @ 5 Tesla [mrad]	SLD CRID detector @ 0.5 Tesla [mrad]
Chromatic error	~0.85	~0.4
Pixel size (0.5mmx0.5mm - 3mmx3mm)	0.4 - 2.3	~0.5
Smearing effect due to magnetic field	1.2 - 2.5	~0.5
Mirror alignment	<< 1	~1 (?)
Other systematic errors	<<1	a few mrad
Total single photon error σ_{photon}	**1.8 – 3.5**	**~ 3.4**
Total error including systematic effects	-	**~ 4.3**
Tracking angular error	~0.5	~0.8 [9]
Other variables:		
Npe/ring for β~1	~16	~10 (in gas)
X/Xo	3-4%	>15%

Chromatic, pixel and smearing effect errors contribute to final error as $1/\sqrt{N_{pe}}$, the rest don't !!

PID performance worsens rapidly with increasing total error:



# of sigmas = $\frac{\theta_\pi - \theta_K}{\sigma_\theta/\sqrt{N}}$

σ_θ is total Cherenkov angle resolution

- **Designing a good RICH detector at high momentum is a question of minimizing errors.**
- **Smearing effect and pixels size are the most crucial contribution in this design.**

Final performance for our design

$\sigma_\theta = s_{single\ photon}/\sqrt{Npe} \otimes \sigma_{tracking} = \sqrt{\{\sigma_{chromatic}^2 + \sigma_{pixel}^2 + \sigma_{smearing\ effect}^2\}} / \sqrt{Npe} \otimes \sigma_{tracking}$

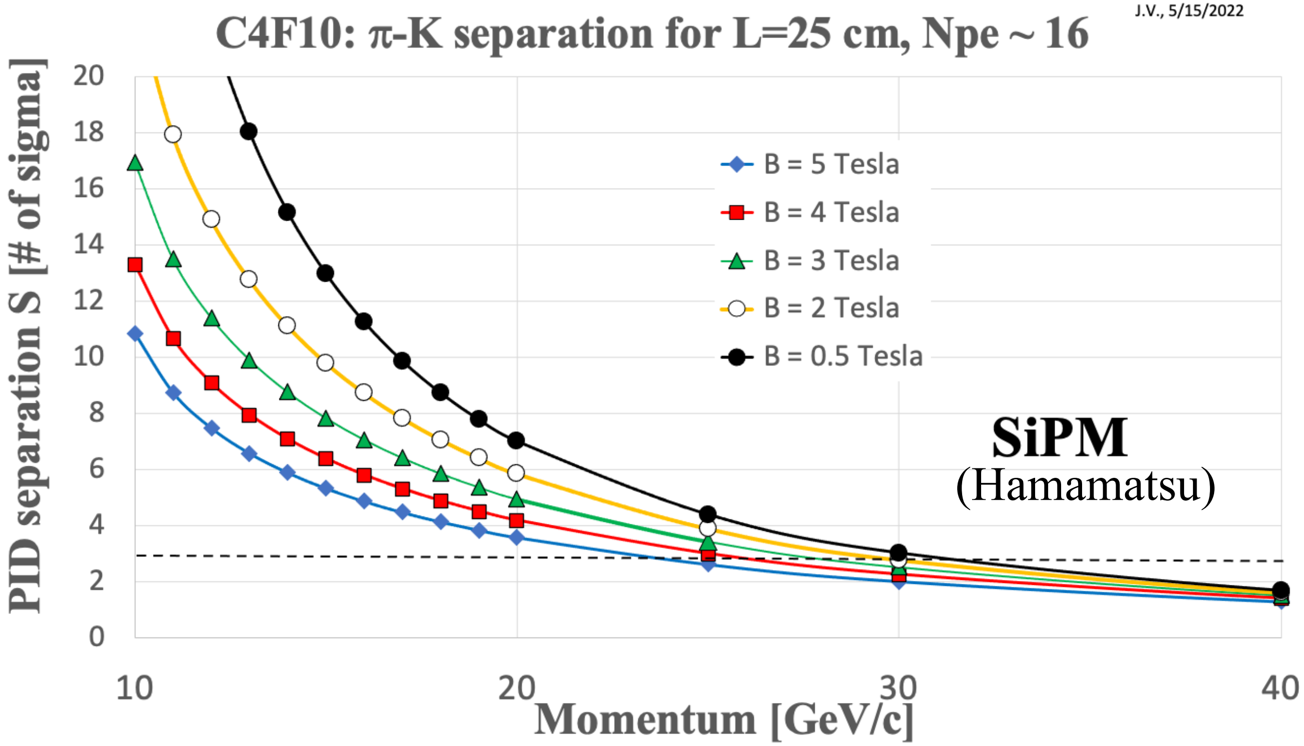
$\sigma_{smearing}$ = **analytical formula**, $\sigma_{chromatic}$ ~ **0.85 mrad**, pixel size: **3 mm**, $\sigma_{tracking}$ ~ **0.5 mrad**, L = **25cm**, **1 bar**

S [# of sigma]

$$= \frac{\theta_\pi - \theta_K}{\sigma_\theta}$$

σ_θ is total photon angle resolution, which includes:
$\sigma_{single\ photon}/\sqrt{Npe} \otimes \sigma_{tracking}$

$Npe = (N_{Pion} + N_{Kaon})/2$



- **3σ limit: ~26-28 GeV/c at 2-3 Tesla, and ~22-24 GeV/c at 5 Tesla.**

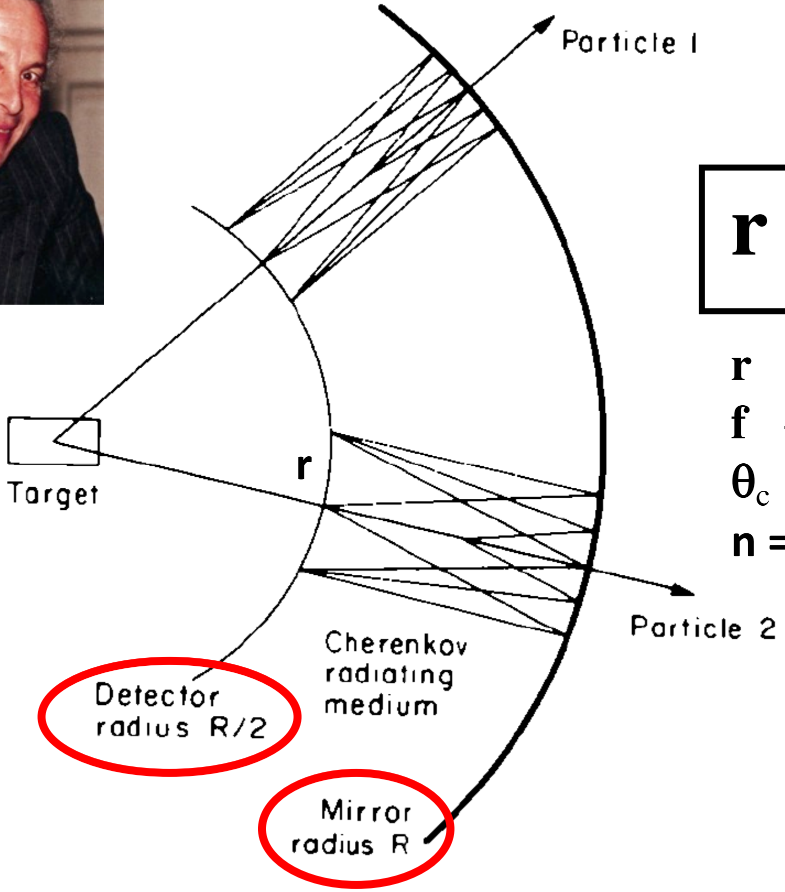
Conclusion

- **Our compact RICH design competes well with much larger SLD CRID design.**
- **3 sigma π/K PID at ~30 GeV/c is possible at 2-3 Tesla, and at ~25 GeV/c at 5 Tesla.**
- **Very low mass design: X/Xo ~ 3-4%. Much better than CRID.**
- **SiPM technology is developing very fast, driven by medical research. In 5 years, all this will be obsolete, and the detector design will improve. This can be used either for reducing radial length, or for improving performance.**
- **Measuring time to 100 ps will open a new exciting possibilities for analysis of rings.**
- **Roger Forty produced a design with a better performance, however, assuming 3.5 bar gas pressure. Using his assumptions, I confirmed his result. However, his design may prove to be more difficult to sell to calorimeter people because of higher mass.**

Appendix

RICH optical concept was known early

T. Ypsilantis and J. Sequinot, Nucl. Instr. & Meth., 142 (1977) 377



$$r = f \ \mathrm{tg}\ \theta_c$$

r - radius of the ring on the inner sphere

f - focal length of the mirrored outer sphere = R/2

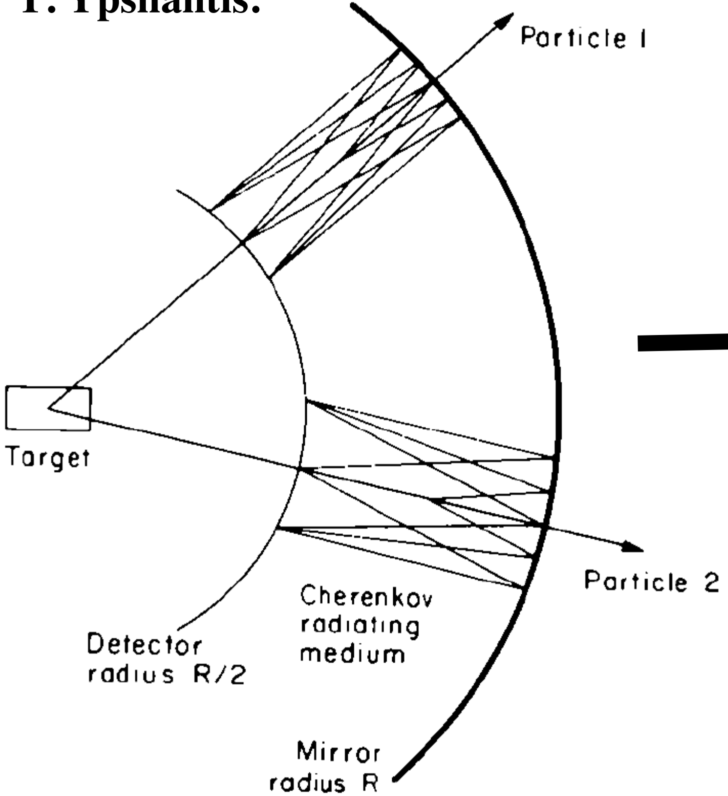
θ_c - Cherenkov angle, $\cos\theta_c = 1/(n\beta)$

$n = n(\lambda)$ - refraction index

- **Ring radius measures Cherenkov angle, independently of track direction.**

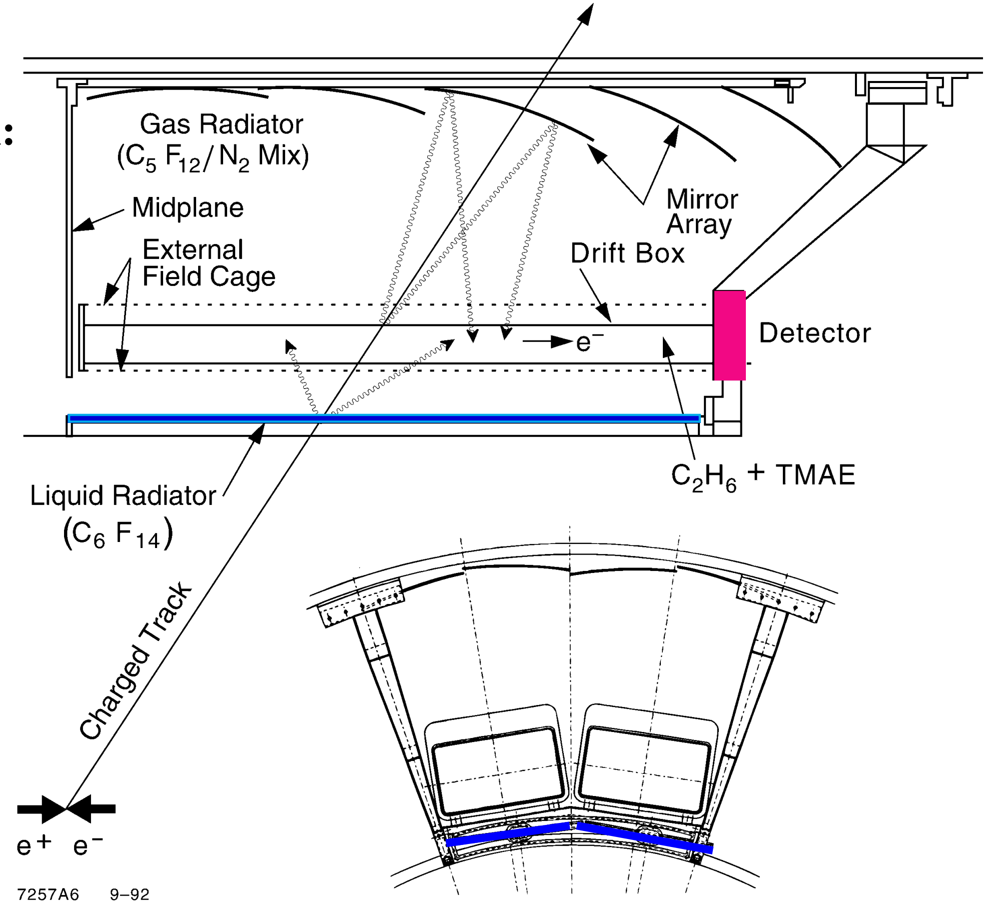
Barrel CRID in SLD concept was defined around 1983-4

Optical concept of T. Ypsilantis:



$$r = f \ \mathrm{tg}\ \theta_c$$

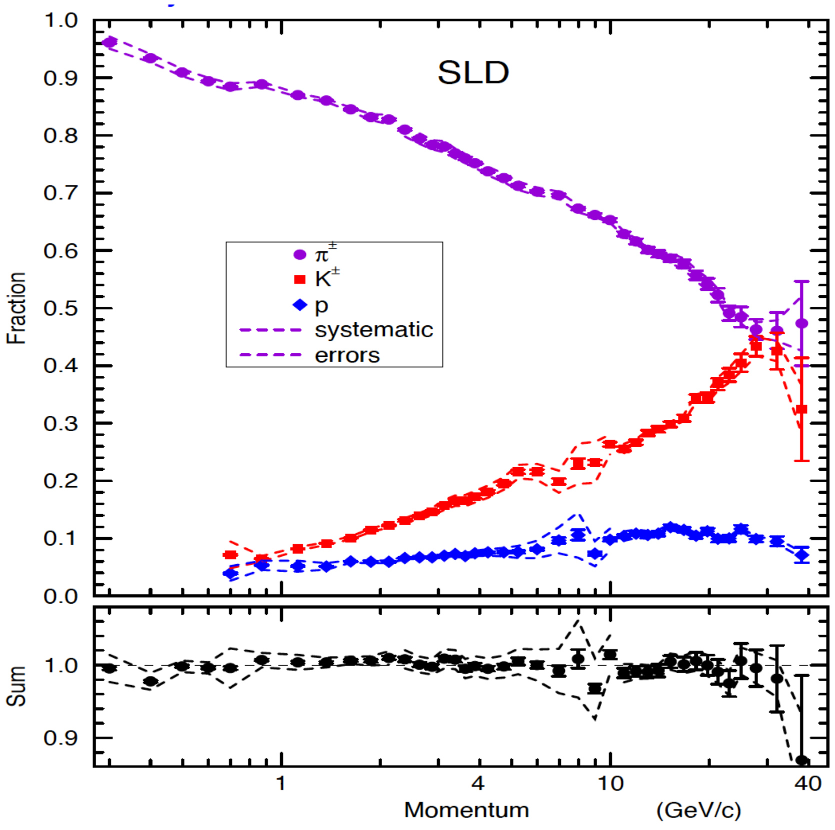
Barrel CRID implementation:



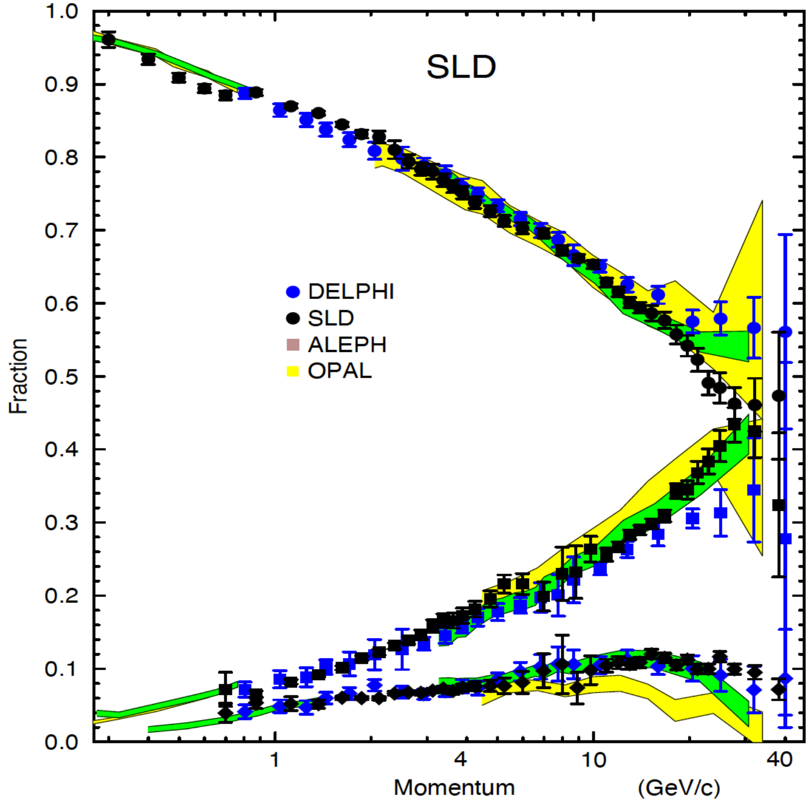
. 40 TPC's, 40 liquid radiator trays, 400 spherical mirrors
. Gas Radiator: 87% C_5F_{12} + 13% N_2 mix
. Liquid Radiator: C_6F_{14}
. Drift box gas: C_2H_6 + TMAE (~0.1 %)
. Maximum drift length: 1.2 m
. Drift field 400 V/cm; maximum voltage: -55 kV
. TMAE bubbler temperature: ~27°C
. The system temperature: ~35°C

Gaseous RICH – SLD and DELPHI

D. Muller et. al., "Inclusive hadronic production in e+e to at 91.2 GeV using the SLD CRID," talk, unpublished;
The SLD collaboration, "Production of p, K, K^{o}, K^{*o}, f, p, & L^{o} in hadronic Z^{o} decays, SLAC-PUB-7766, 1998.



- At the Z^0 is from 3 experiments at LEP



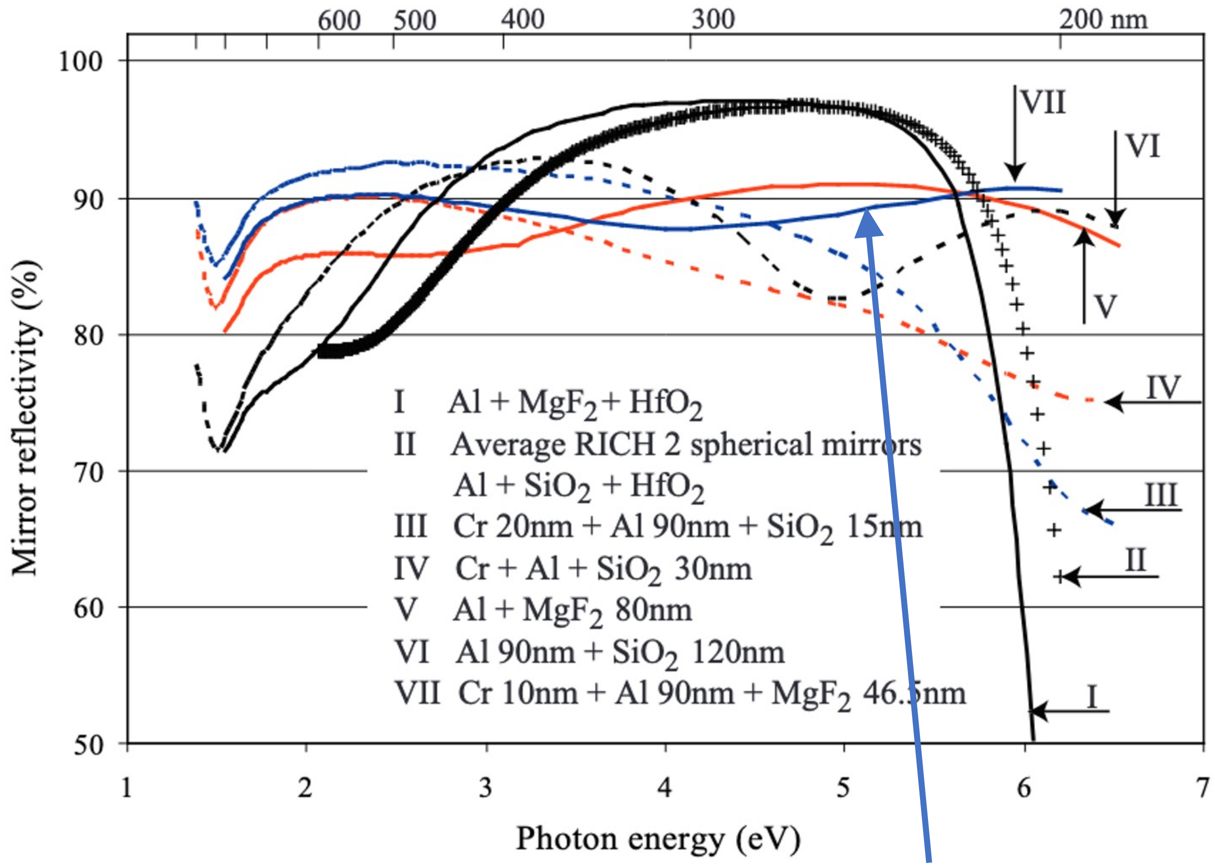
- SLD CRID and Delphi RICH pioneered this type of detector ~40 years ago.

Gas choice

- **C_5F_{12} gas** at 1 bar requires a detector temperature of 40^{o}C since boiling point of this gas is 31^{o}C at 1 bar. Not very agreeable with the SiPM noise.
- **C_4F_{10} gas** at 1 bar allows detector operation at a few degrees ^{o}C since boiling point of this gas is -1.9^{o}C at 1 bar. **This is presently our preferred choice.**
- **C_2F_6 gas** at 1 bar would allow detector operation even below 0^{o}C since boiling point of this gas is -70.2^{o}C at 1 bar. However, this gas would deliver insufficient number of photoelectrons.
- **C_3F_8 gas** at 1 bar would allow detector operation at -30 deg C since the boiling point of C_3F_8 is -37 deg C. Still worse performance than C_4F_{10}.

Mirror reflectivity

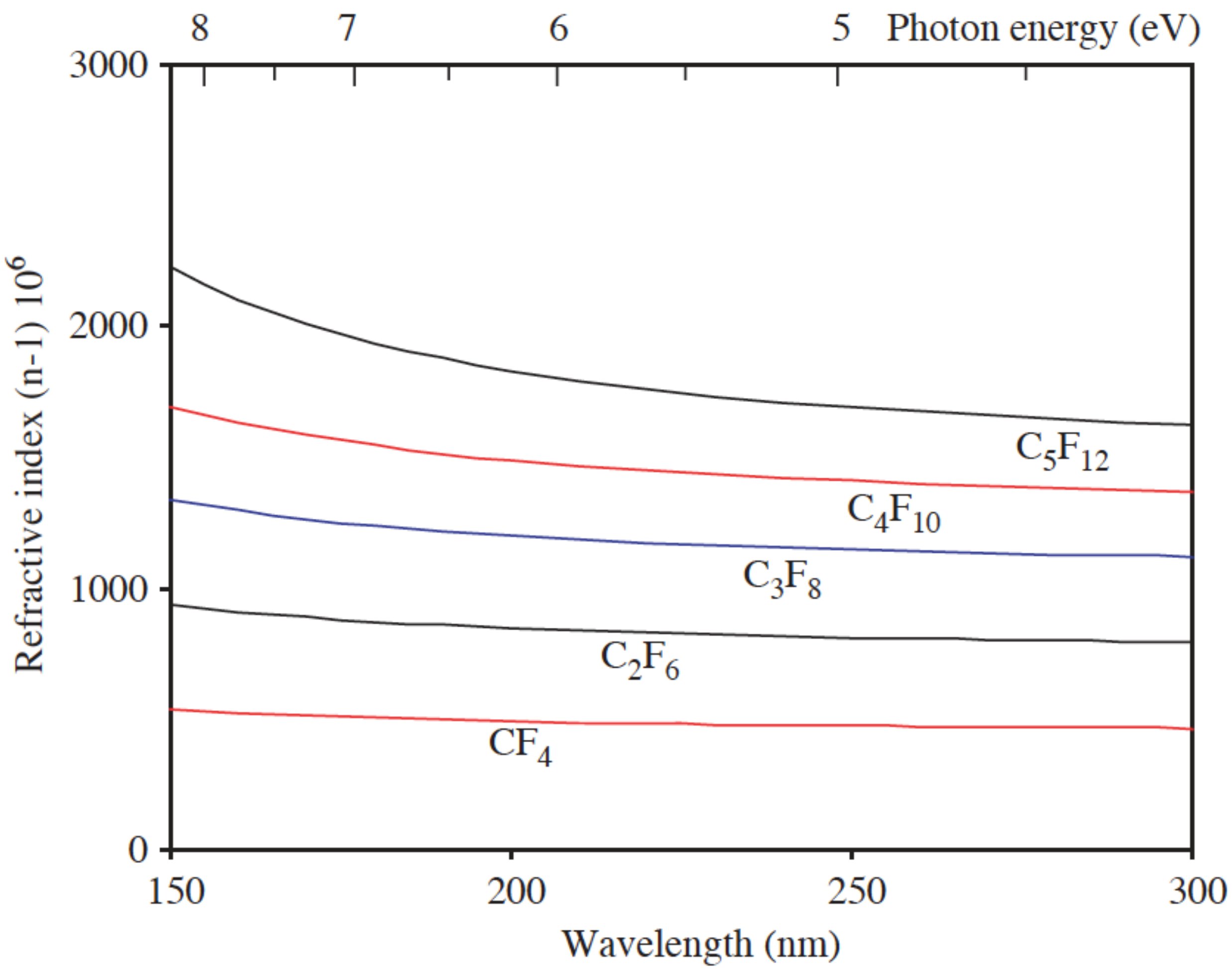
LHCb collaboration, JINST 3 S08005, 2008



- For calculations in this work, I used Al+Cr+MgF_2 mirror coating.
- This coating was also used by CRID.

Refraction index of Freons

O. Ullaland, NIM A 553(2005)107

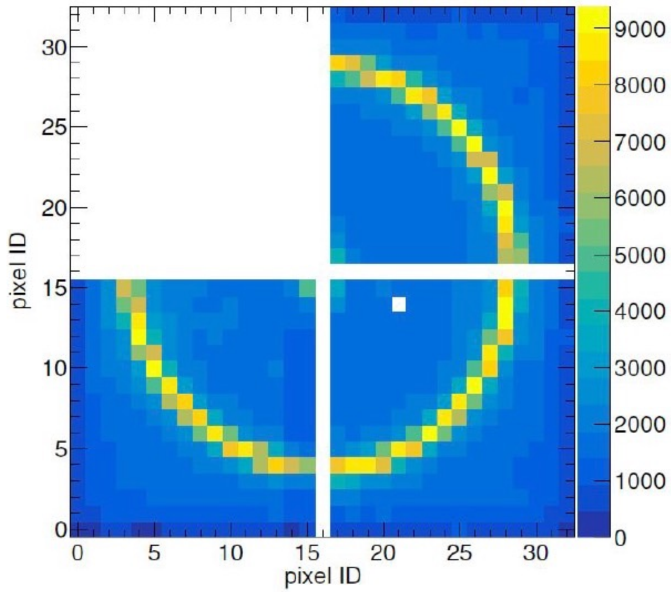


- **Refraction index of these Freon gas candidates is well understood.**

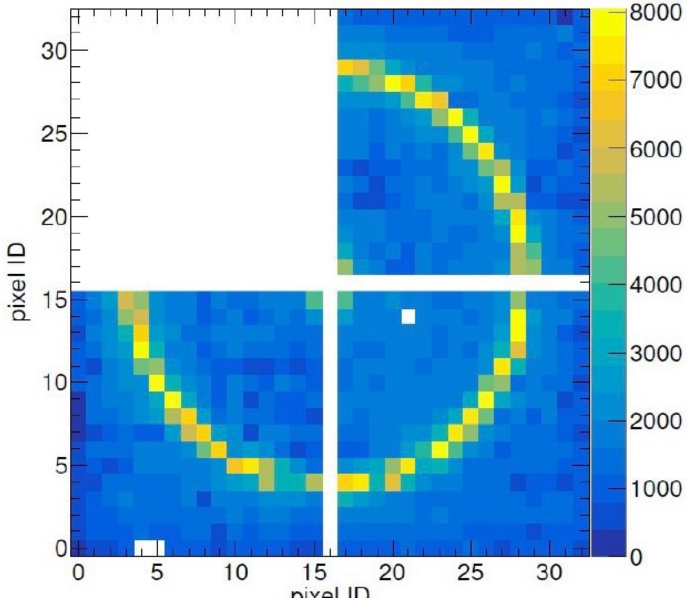
EIC mRICH –SiPM noise

C.P. Wong et. al., NIM A 871, 13 (2017)

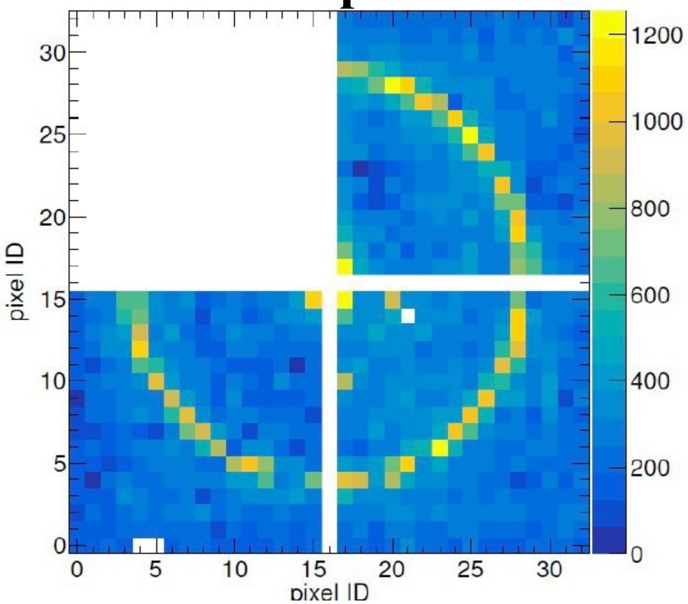
-30 ^{o}C:



-20 ^{o}C:



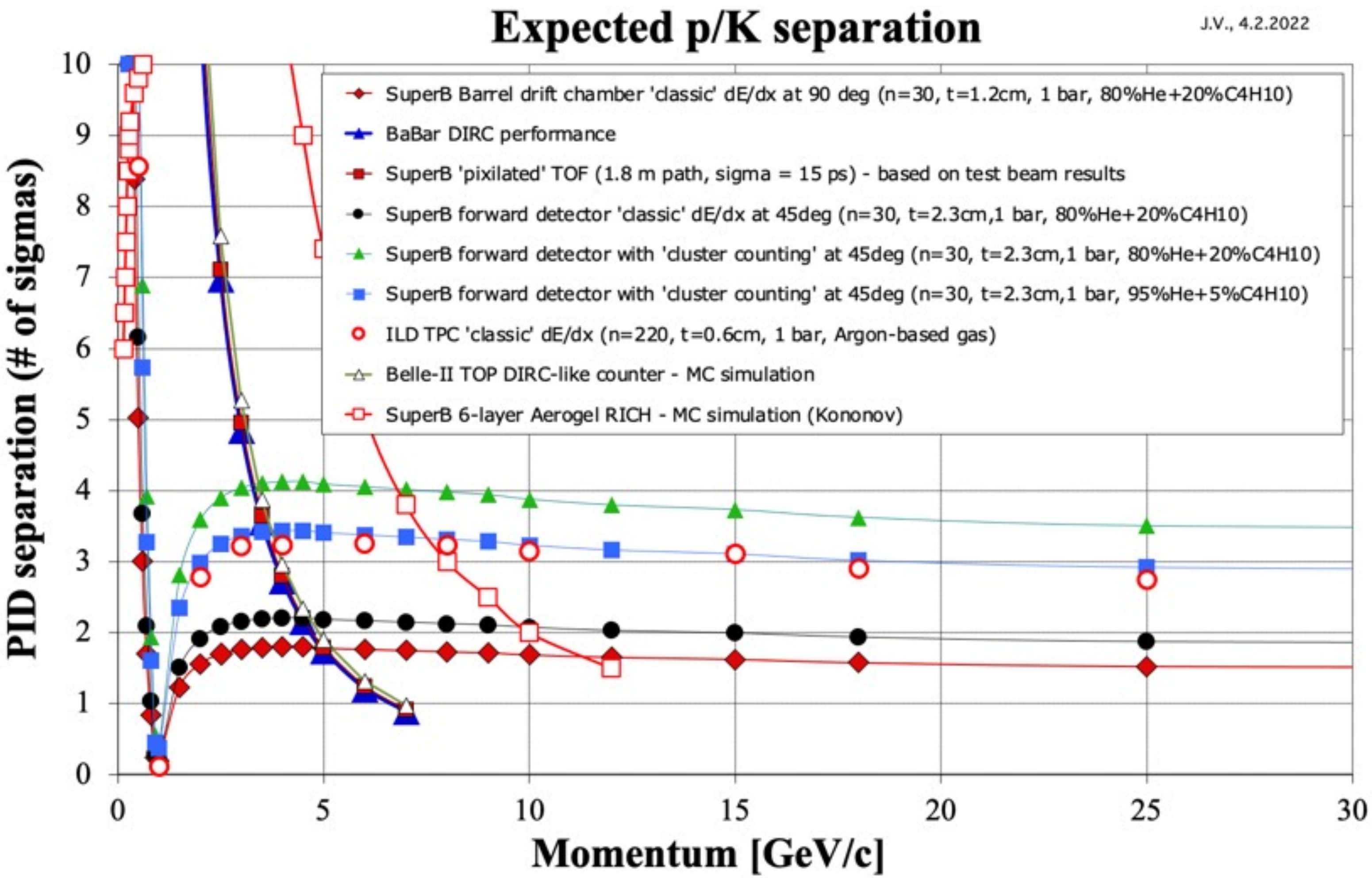
Room temperature:



- They used Aerogel radiator and SiPM readout, and temperature to reduce the noise.
- **Our idea:**

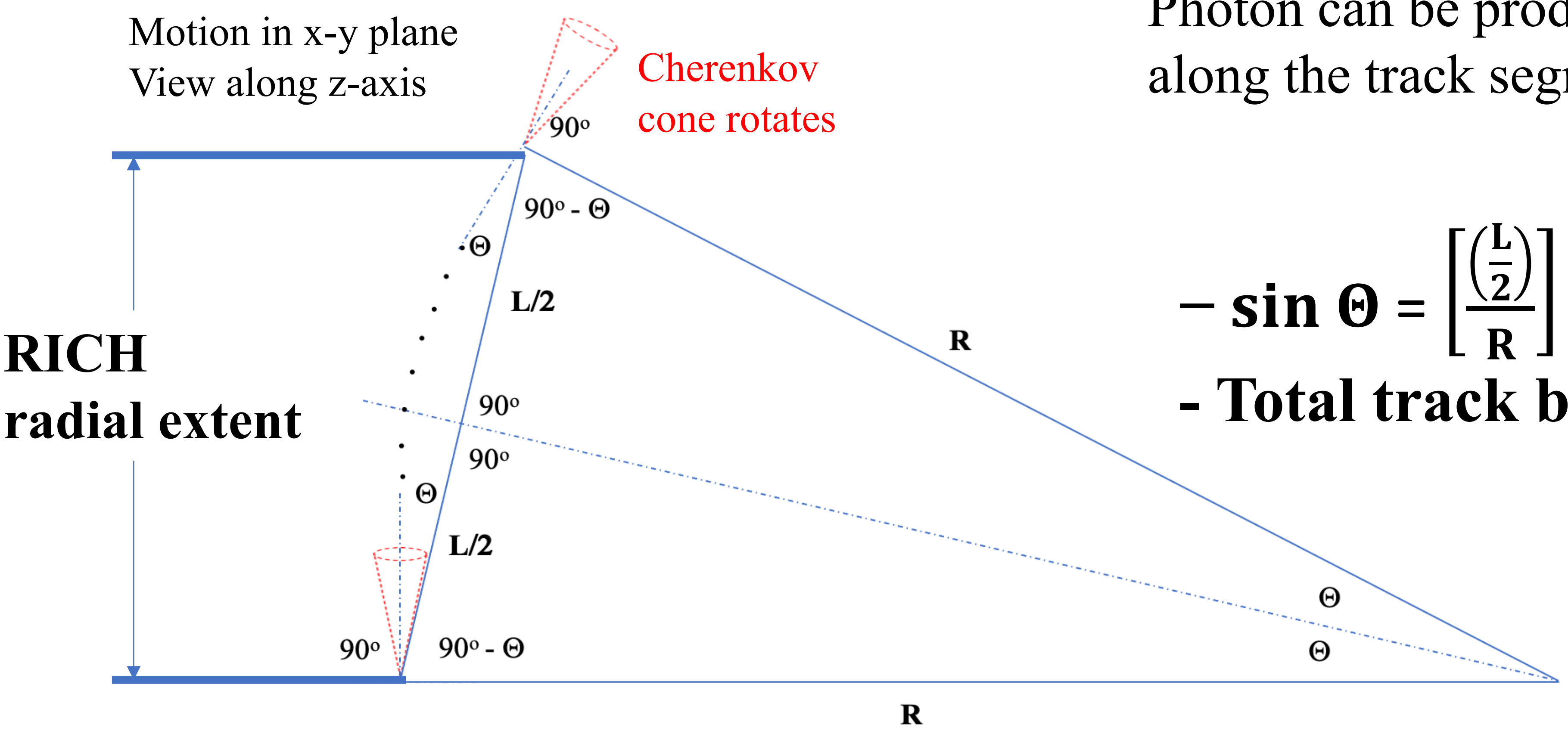
  Use a <u>track hit</u> & <u>photon hit</u> to make a timing window. Need ~100 ps resolution.

Examples of PID detectors



- Present ILD TPC design separates p/K's at ~20 GeV/c at a level of ~3 σ.

Analytical formula to estimate the smearing effect



Photon can be produced anywhere along the track segment along path L

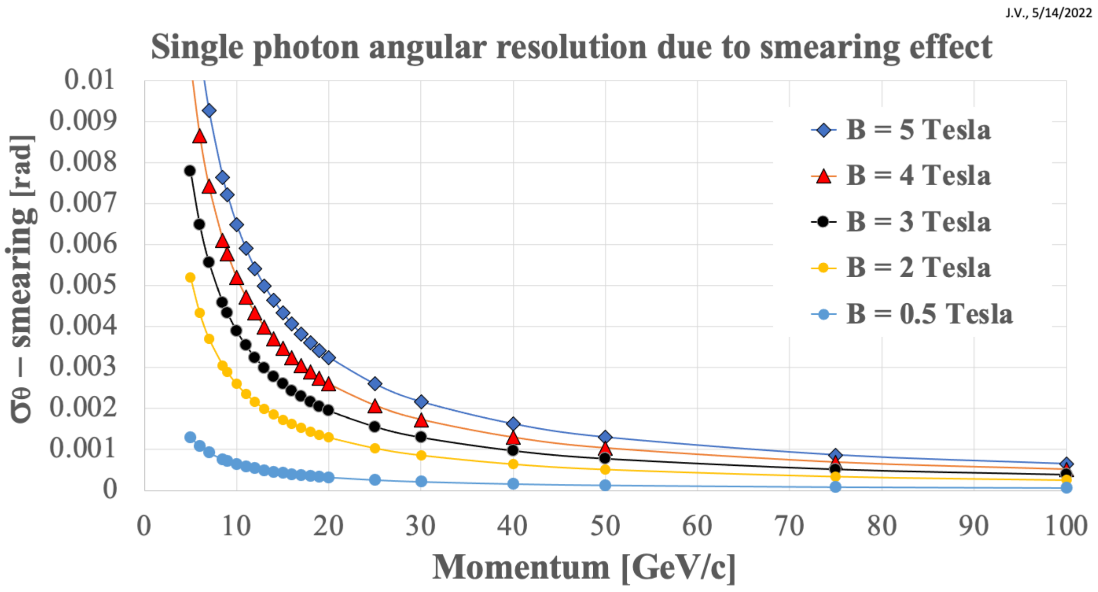
- $\sin\Theta = \left[\frac{\left(\frac{L}{2}\right)}{R}\right]$
- Total track bend angle: 2Θ

$$\sigma_{\theta c} \sim \frac{2\,\Theta}{\sqrt{12}} \sim \left\{2\ \mathrm{arsin}\left[\frac{\left(\frac{L}{2}\right)}{R}\right]\right\}\frac{1}{\sqrt{12}}\ ,\ R = \frac{p}{300\ B},\ L = 0.25\ \mathrm{m},\ p\ [\mathrm{MeV/c}],\ R\ [\mathrm{m}]$$

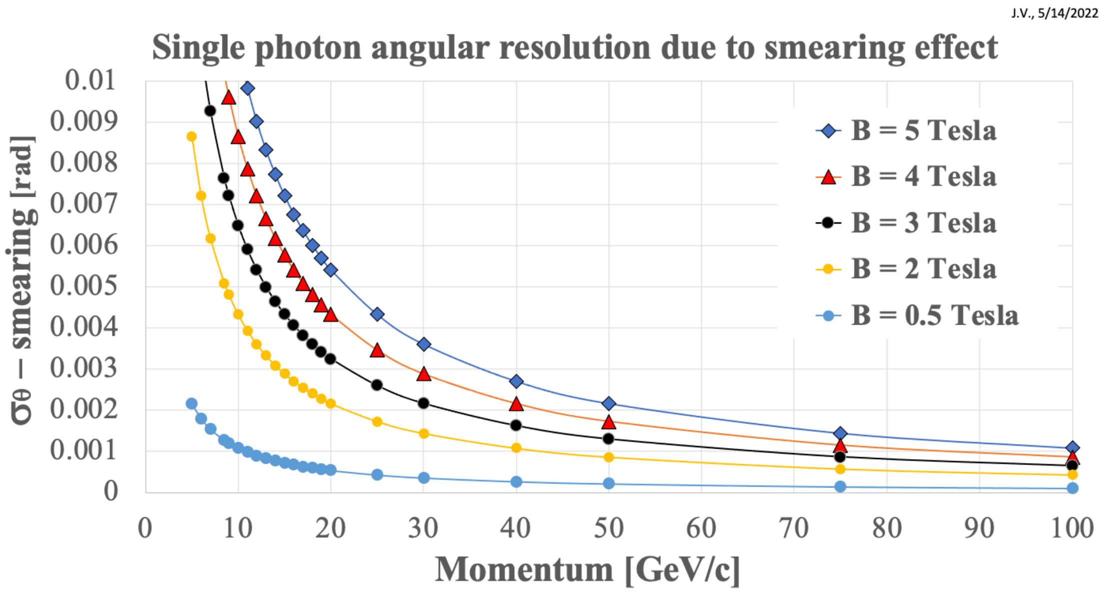
Smearing effect due to track bending = f(B)

Analytical formula: $\sigma_\theta \sim \frac{2\,\Theta}{\sqrt{12}} \sim [2\,\mathrm{arsin}[\frac{(\frac{L}{2})}{R}]\,\frac{1}{\sqrt{12}}$

L = 15 cm

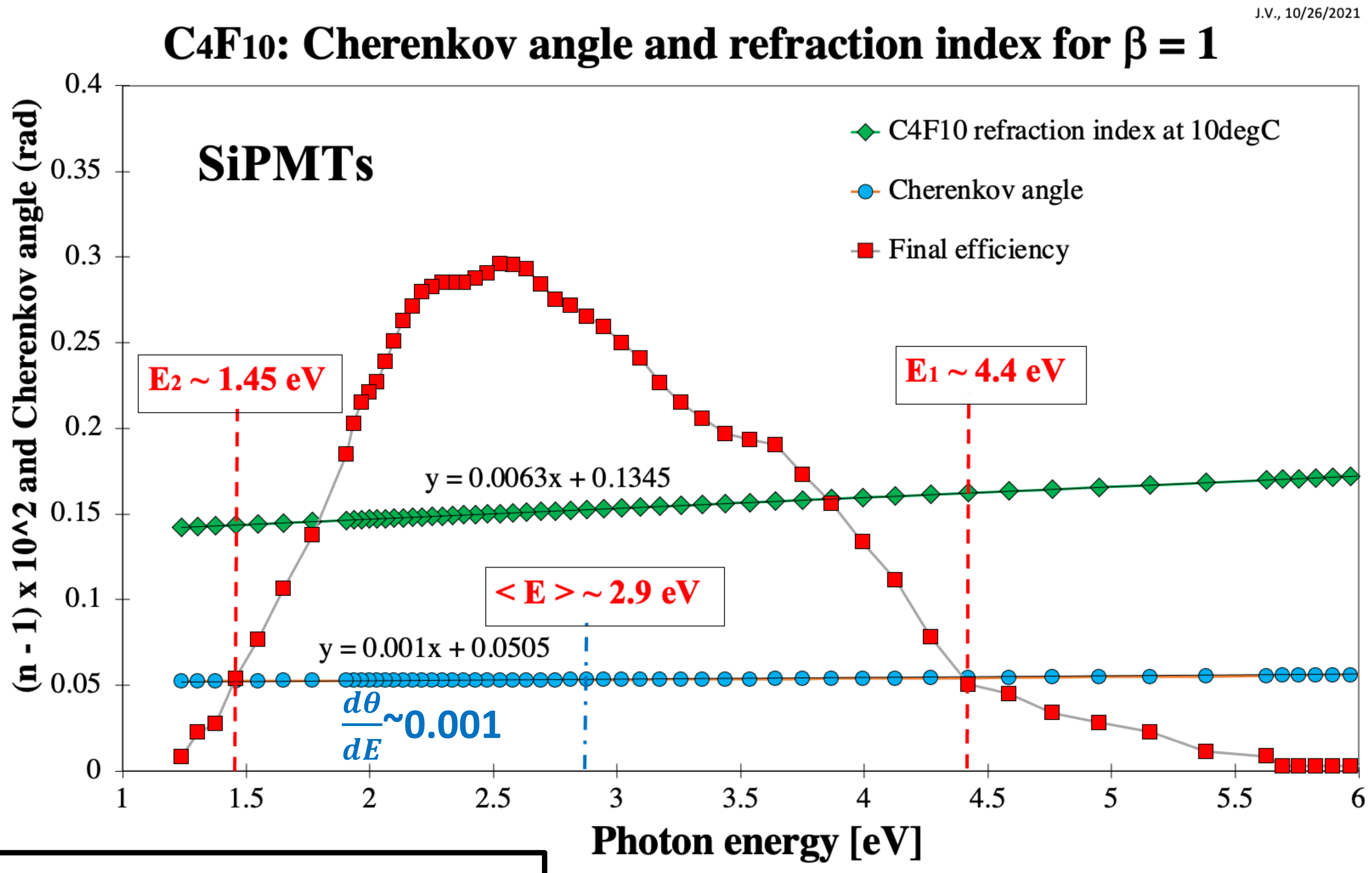


L = 25 cm



- **A subsequent study with Mathematica code has showed that it is more complicated as smearing error depends on Cherenkov angle azimuth angle.**

Chromatic error error = f(n(E))

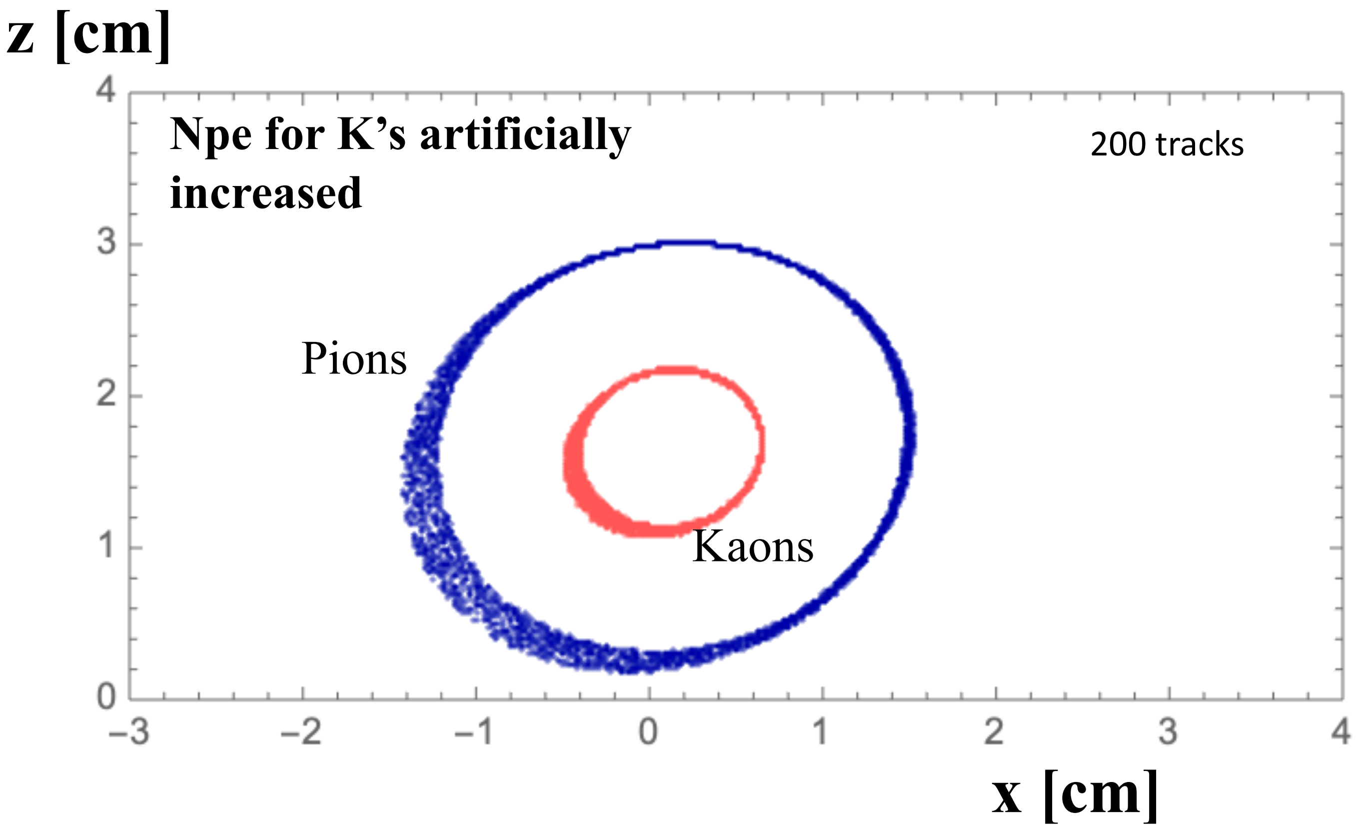


$\sigma_{\theta_c} \sim \frac{d\theta_c}{dE}(E_2 - E_1)\frac{1}{\sqrt{12}} \sim$ **0.85 mrad**, no filter to reduce BW at present.

More on smearing effect

Cherenkov rings for θ_{dip} = 4^o at 10 GeV/c & 5 Tesla

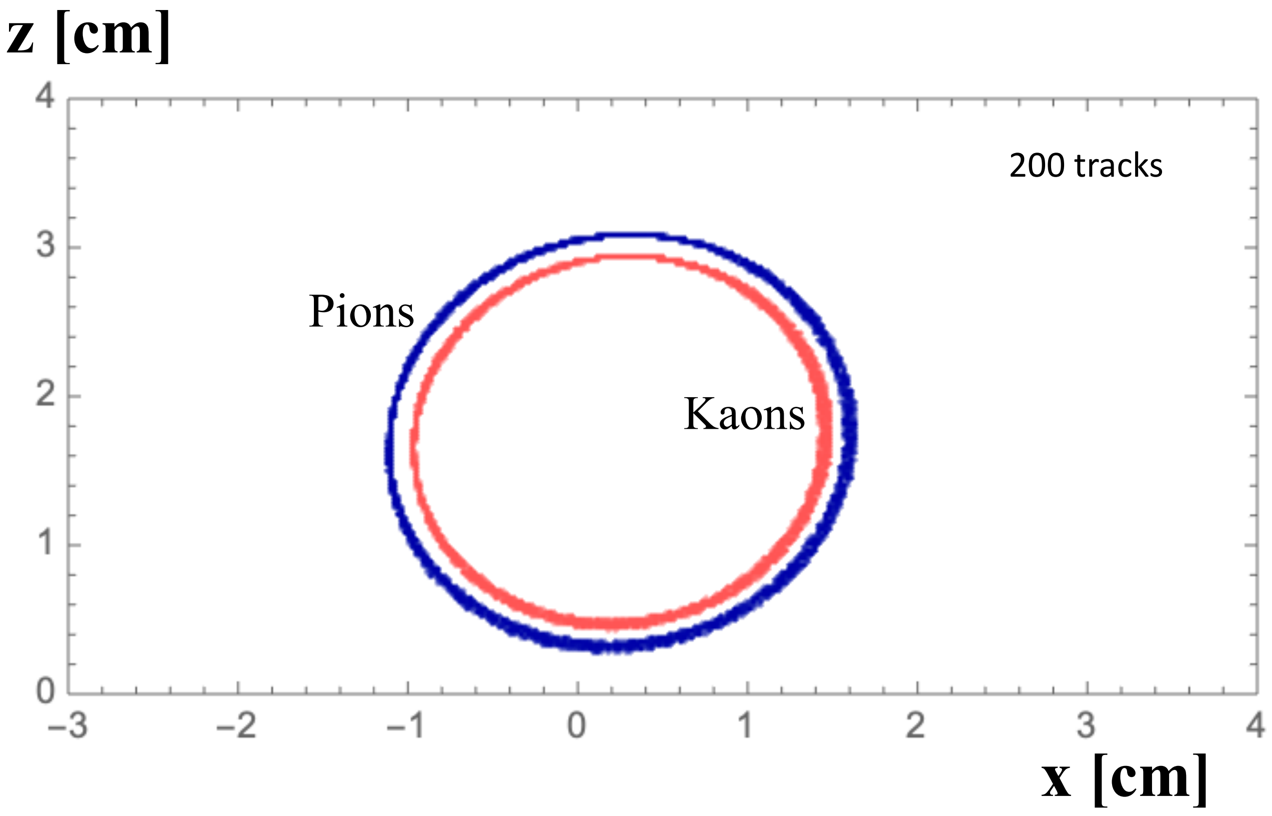
B = 5 Tesla,
P = 10 GeV/c pions
Pt = 9.976 GeV/c
Pz = 0.699 GeV/c
Theta = 86^o = 90^o- θ_{dip}
Phi = 90^o
R-helix=6.65 meters
θ_C (Pions)= 0.0513 rad
θ_C (Kaons)= 0.0198 rad
Npe (Pions) ~ 15
Npe (Kaons) ~ 2-3
C_4F_{10} gas
$L_{radiator}$ = 25 cm



- One can still do PID because Cherenkov angles are very different.
- N_{pe} for Kaons is small between 10 and 12 GeV/c.

Cherenkov rings for θ_{dip} = 4^{o} at 20 GeV/c with B = 5 Tesla

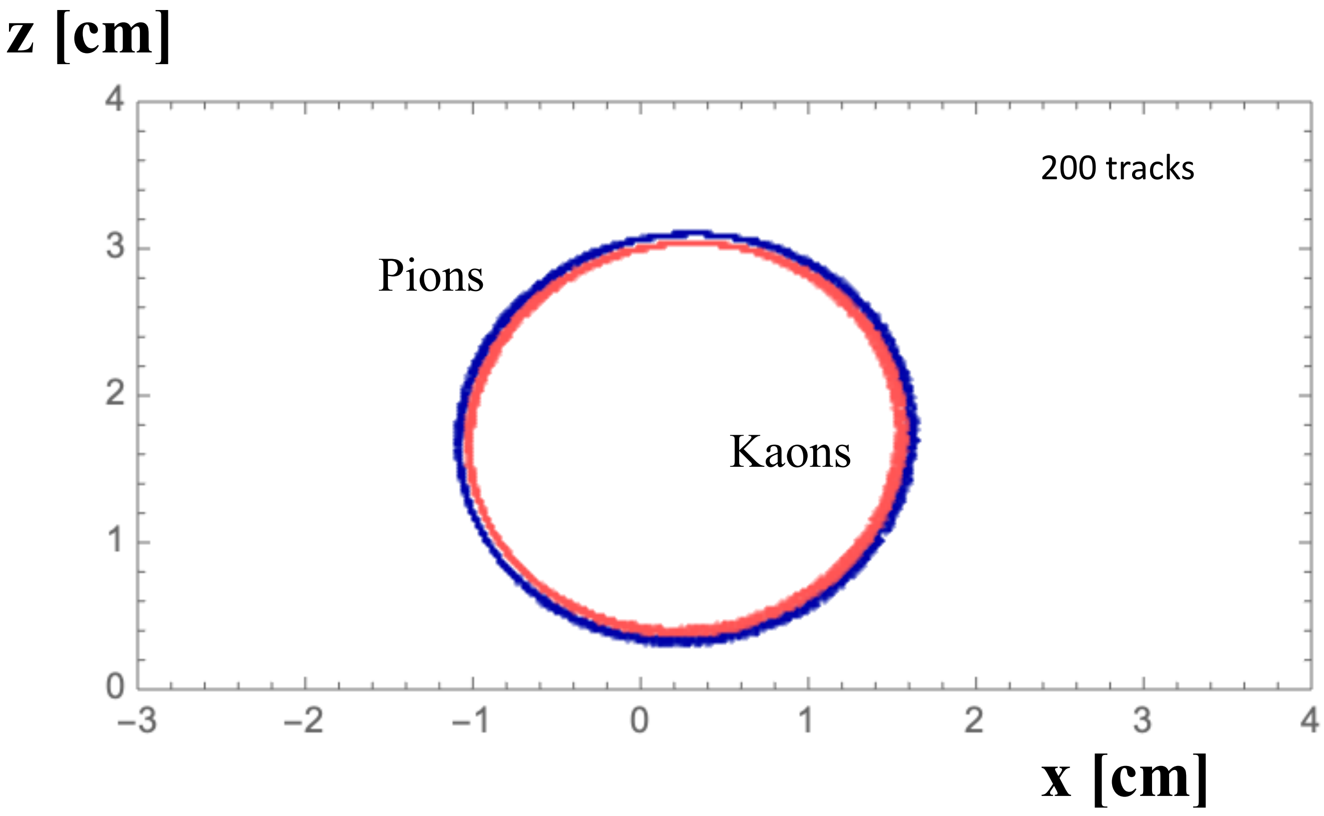
B = 5 Tesla,
P = 20 GeV/c pions
Pt = 19.951 GeV/c
Pz = 1.3973 GeV/c
Theta = 86^{o} = 90^{o}- θ_{dip}
Phi = 90^{o}
R-helix=13.3 meters
$\boldsymbol{\theta}_C$ (Pions)= 53.2 rad
$\boldsymbol{\theta}_C$ (Kaons)= 47.1 mrad
Npe (Pions) ~ 16
Npe (Kaons) ~ 12-13
C_4F_{10} gas
$L_{radiator}$ = 25 cm



- **Plot all {xfinal[i] & zfinal[i]} 2D-hits in detector plane, no cuts, no fitting.**
- **We determine center of the circle x_0 & z_0.**

Cherenkov rings for θ_{dip} = 4^o at 30 GeV/c & 5 Tesla

B = 5 Tesla,
P = 30 GeV/c pions
Pt = 29.927 GeV/c
Pz = 2.896 GeV/c
Theta = 86^o = 90^o- θ_{dip}
Phi = 90^o
R-helix=19.95 meters
θ_C (Pions)= 53.0 mrad
θ_C (Kaons)= 50.6 mrad
Npe (Pions) ~ 16.1
Npe (Kaons) ~ 14.7
C_4F_{10} gas
$L_{radiator}$ = 25 cm



Smearing error only

- **Smearing effect will limit the resolution at large magnetic field.**

Can we improve our design ?

Reduce pixel size, higher PDE and better tracking

$\sigma_\theta = \sigma_{single\ photon}/\sqrt{Npe} \otimes \sigma_{tracking} = \sqrt{\sigma_{chromatic}^2 + \sigma_{pixel}^2 + \sigma_{smearing\ effect}^2} / \sqrt{Npe} \otimes \sigma_{tracking}$

$\sigma_{smearing}$ = **analytical formula**, $\sigma_{chromatic}$ ~ **0.85 mrad**, **pixel size: 0.5 mm**, $\sigma_{tracking}$ ~ **0.3 mrad**, **increase PDE by 20%**

(Probably not doable)

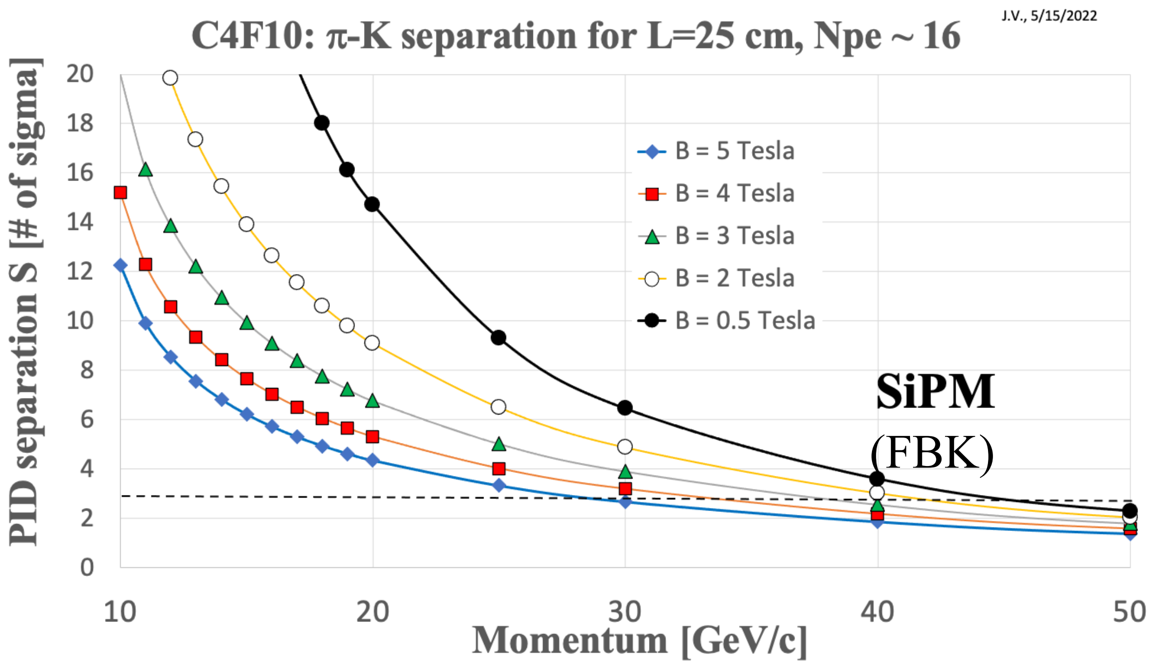
S [# of sigma]

$$= \frac{\theta_\pi - \theta_K}{\sigma_\theta}$$

σ_θ is total photon angle resolution, which includes:

$\sigma_{single\ photon}/\sqrt{Npe} \otimes \sigma_{tracking}$

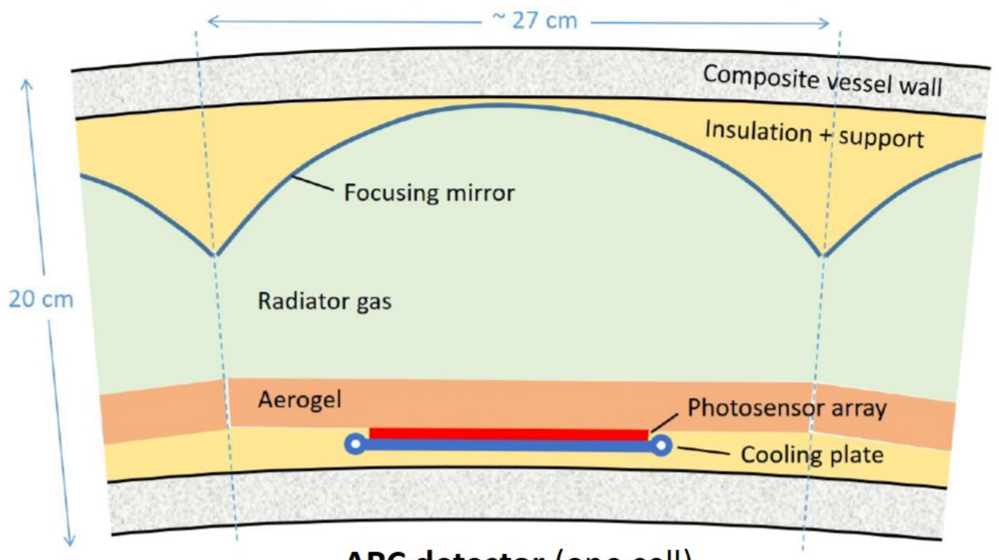
Npe =(N_{Pion} + N_{Kaon})/2



- **3σ limit: ~40-45 GeV/c at 2-3 Tesla, and ~30 GeV/c at 5 Tesla.**
- **Could be improved further with a clever algorithm for the smearing effect and by reducing the chromatic error using filters or mirror reflectivity.**

Two designs

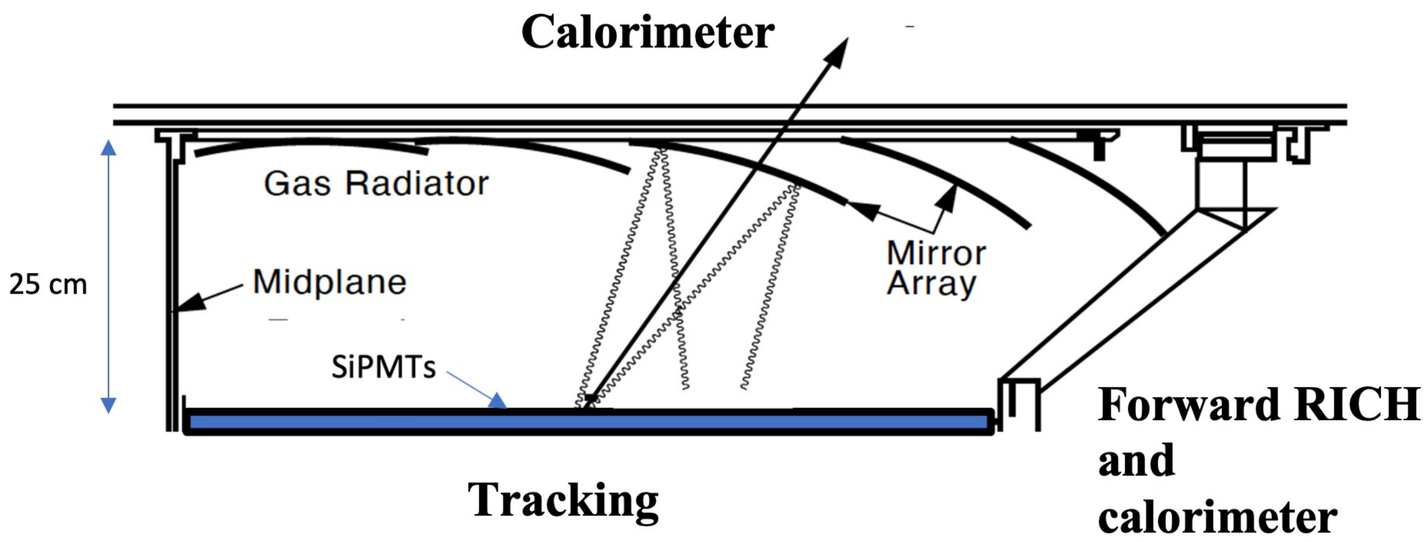
Roger Forty's design:



ARC detector (one cell)

C4F10 gas at 3.5 bars
His SiPM PDE is 20% higher than ours
N = 1.0049
X/X_o ~ 10%
N_{pe} ~ 25 for β =1

Schematic picture of our design:



C4F10 at 1 bar
N = 1.001415
X/X_o ~ 4%
N_{pe} ~ 16 for β =1

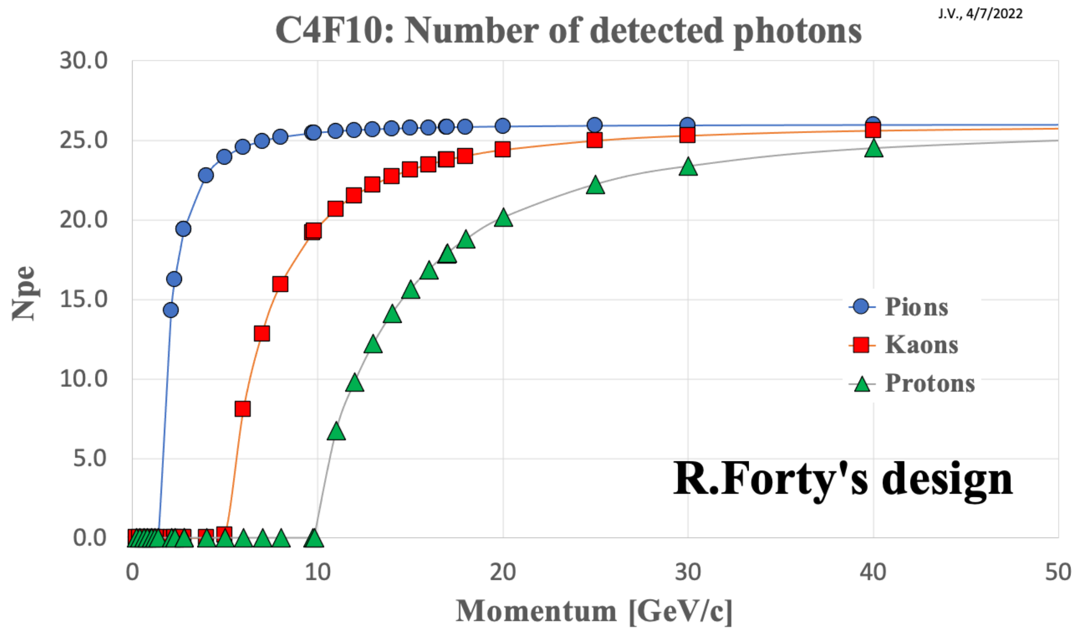
R. Forty & C. Gargiulo RICH design

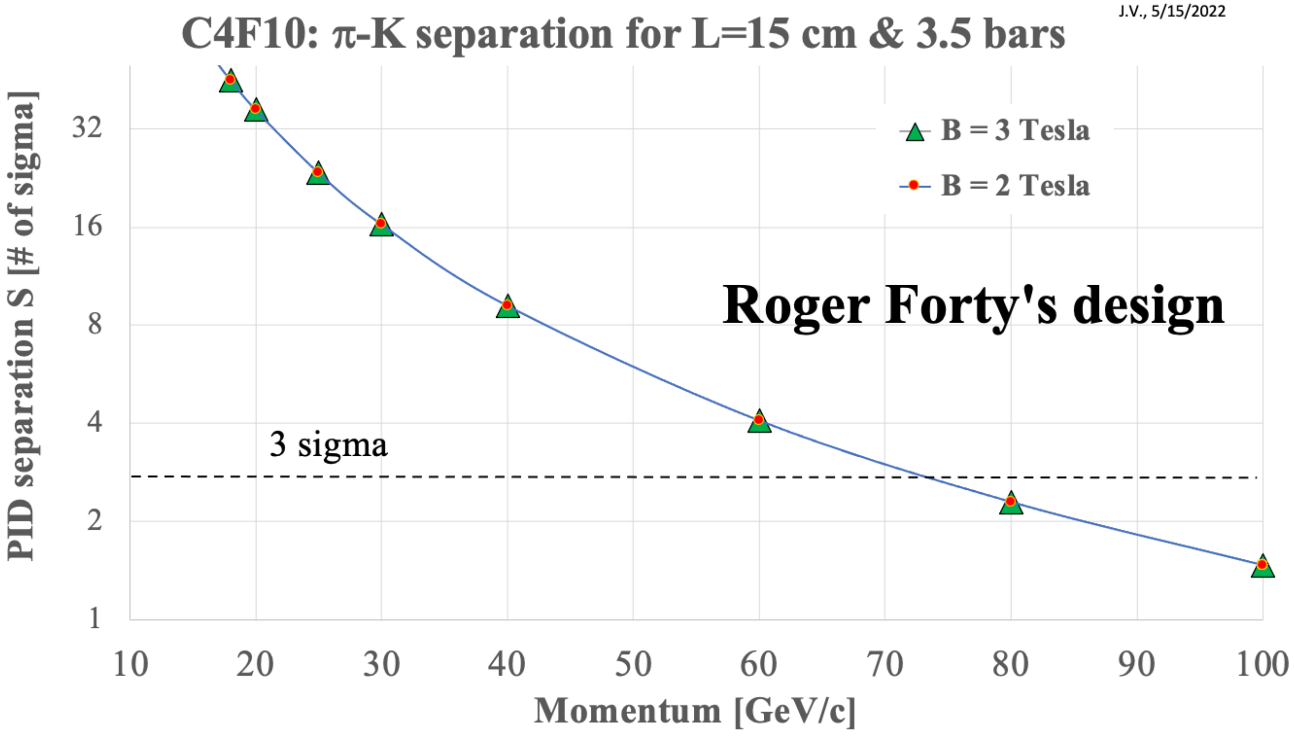
(I used their design parameters, but did my independent calculation)

FCC week,
1 July 2021
CERN

$\sigma_\theta = \sigma_{single\ photon}/\sqrt{Npe} \otimes \sigma_{tracking} = \{\sigma_{chromatic} \otimes \sigma_{pixel} \otimes \sigma_{smearing\ effect} \otimes \sigma_{other\ syst.\ errors}\}/\sqrt{Npe} \otimes \sigma_{tracking}$

$\sigma_{smearing}$ ~ **1 mrad**, $\sigma_{chromatic}$ ~ **0.5 mrad**, pixel size: **0.5 mm**, $\sigma_{tracking}$ ~ **0.3 mrad**, **20%** **higher PDE**, **3.5 bars**, **L = 15 cm**





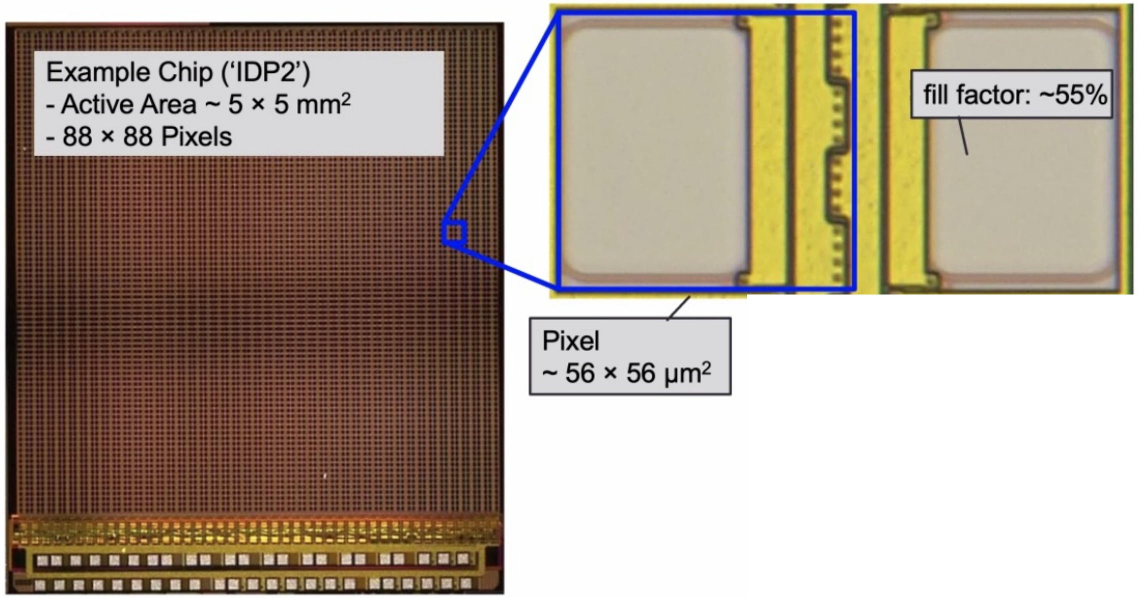
- **3 σ limit: ~75 GeV/c.** **Price for this performance: 3.5 bars and X/X_o ~ 10%.**

Are digital SiPMs a good choice in future ?

Peter Fisher, Heidelberg

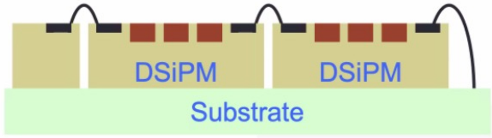
'Digital SiPM' (or 'CMOS SPADs')

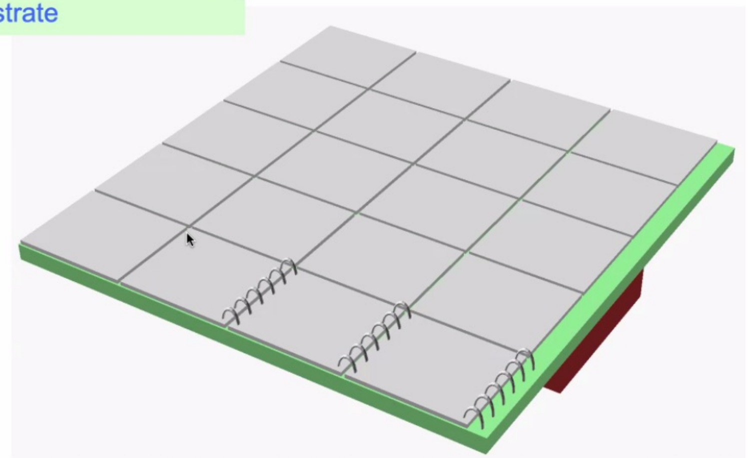
- Chip produced in a ('special') CMOS technology which allows to fabricate SPADs AND transistors on one chip



Possible Module Concept

- Several bare chips grouped on large (~8×8 cm²) low activity substrate:





- **Can have very small pixel sizes.**
- **Combine electronics and photosensor together on one chip. Fill factor: 55%.**
- **Can switch off the cell which is too noisy.**
- **Can daisy chain different segments.**