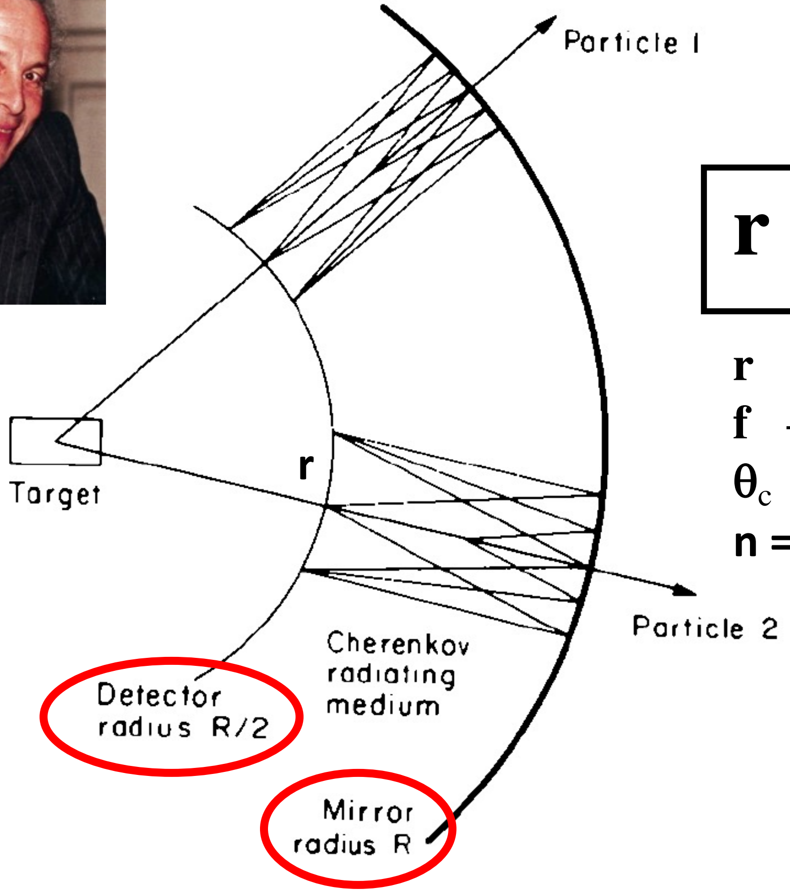
RICH for PID

J. Va'vra, SLAC

RICH proposal is a part of a larger study by:
A. Albert et al., arXiv:2203.07535v2 [hep-ex] 14 Mar 2022

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

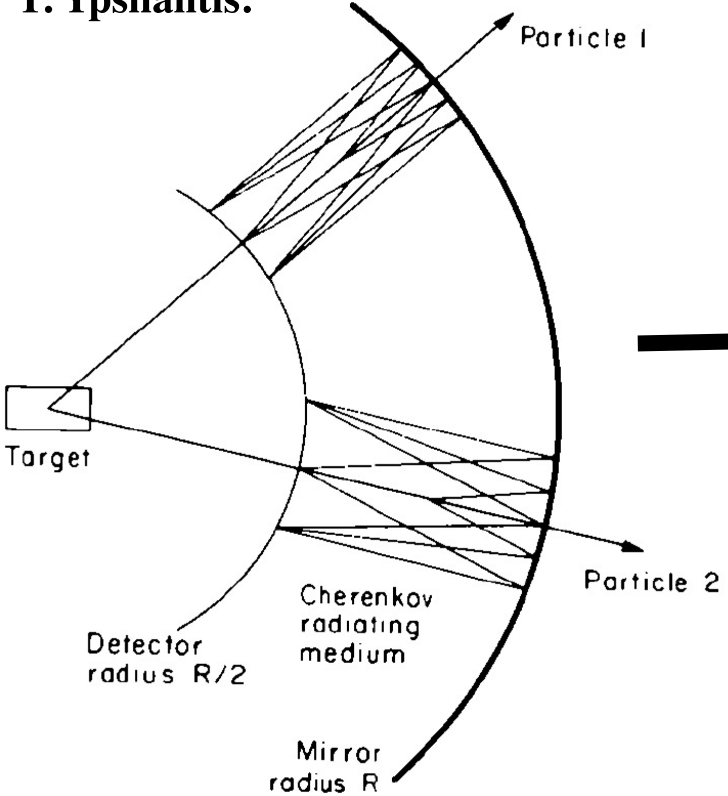
θ_c - Cherenkov angle, $\cos\theta_c = 1/(n\beta)$

n = n(λ) - refraction index

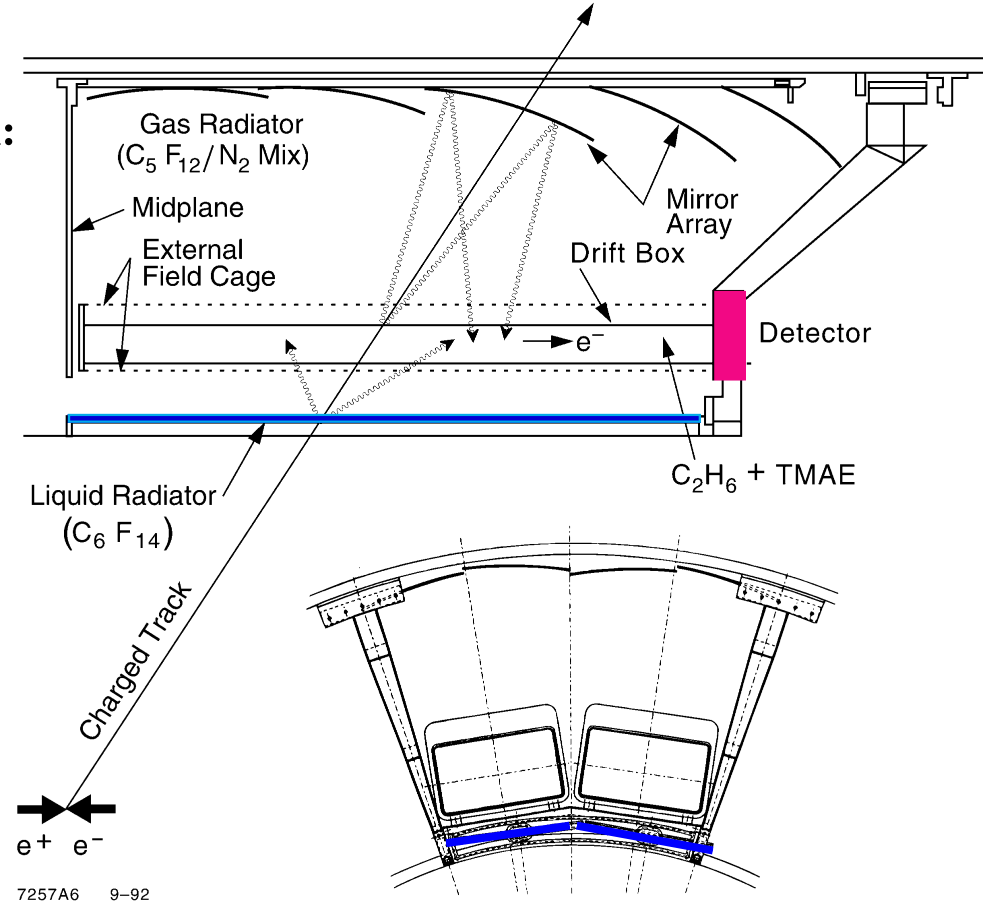
- **Ring radius measures Cherenkov angle, independently of track direction.**

Barrel CRID in SLD concept was defined around 1983-4

Optical concept of T. Ypsilantis:



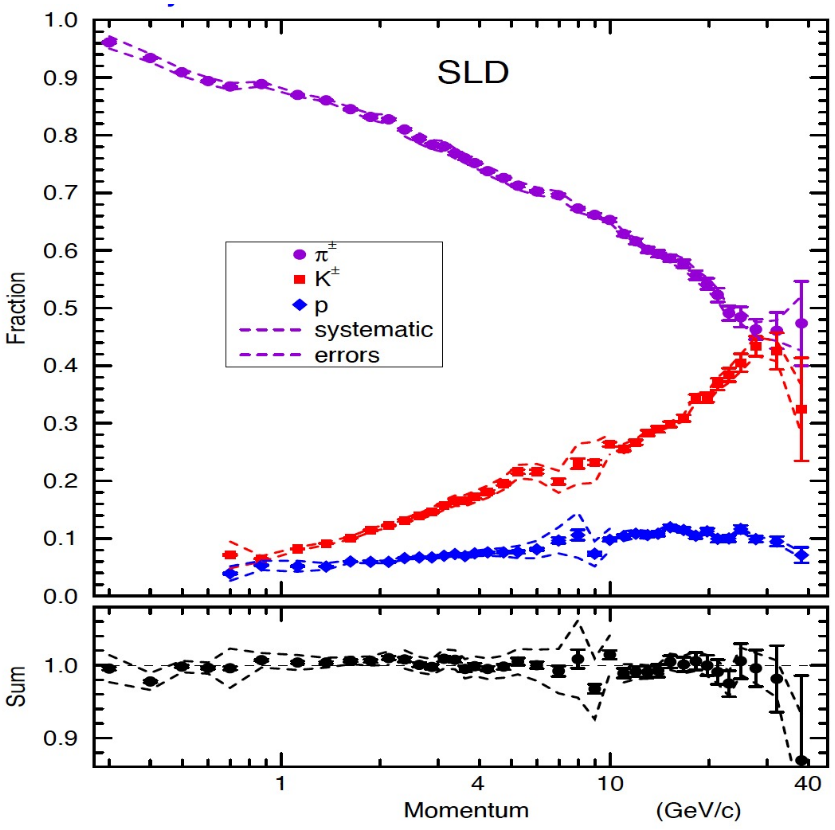
Barrel CRID implementation:

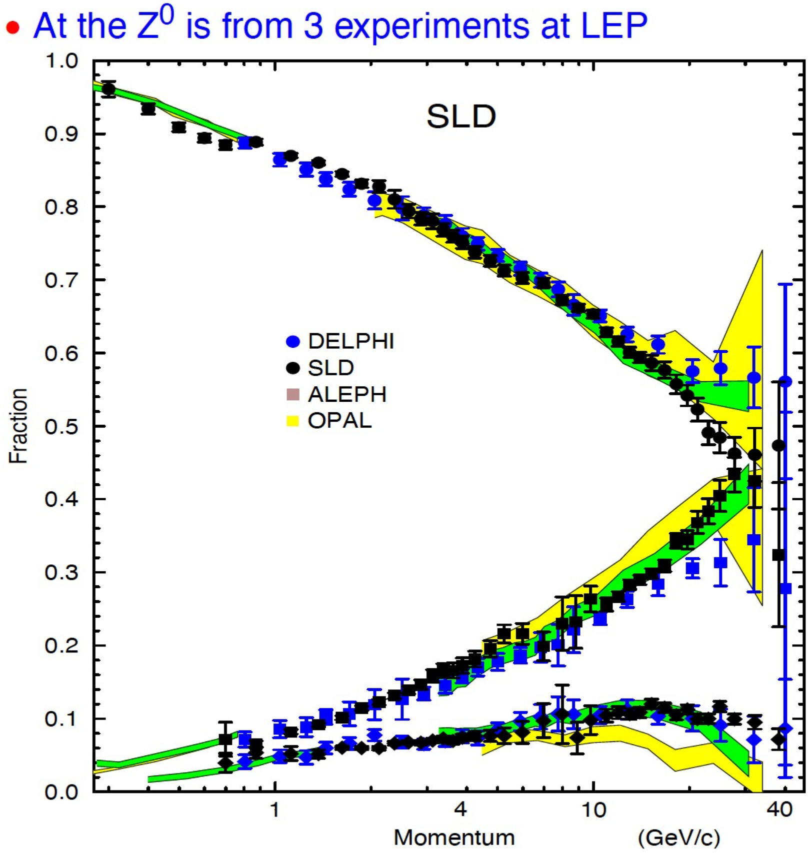


. 40 TPC's, 40 liquid radiator trays, 400 spherical mirrors
. Gas Radiator: 87% C_5F_{12} + 13% N_2 mix
. Liquid Radiator: C_6F_{14}
. Drift box gas: C_2H_6 + TMAE (~0.1 %)
. Maximum drift length: 1.2 m
. Drift field 400 V/cm; maximum voltage: -55 kV
. TMAE bubbler temperature: ~27^{o}C
. The system temperature: ~35^{o}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 al., "Inclusive hadronic production in e+e to at 91.2 GeV using the SLD CRID," talk, unpublished;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.

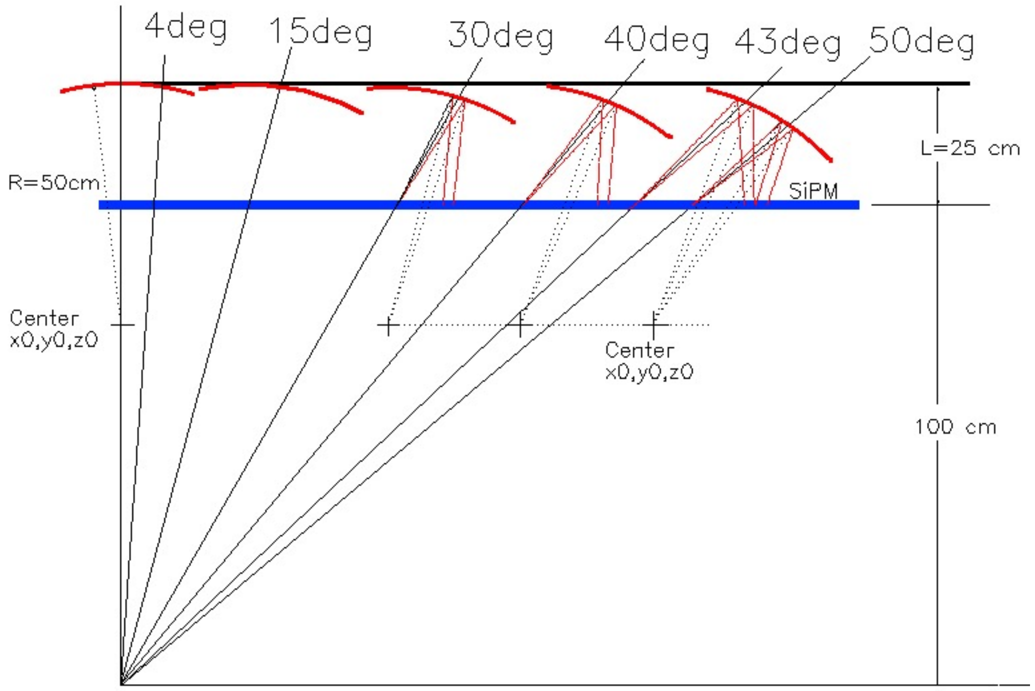




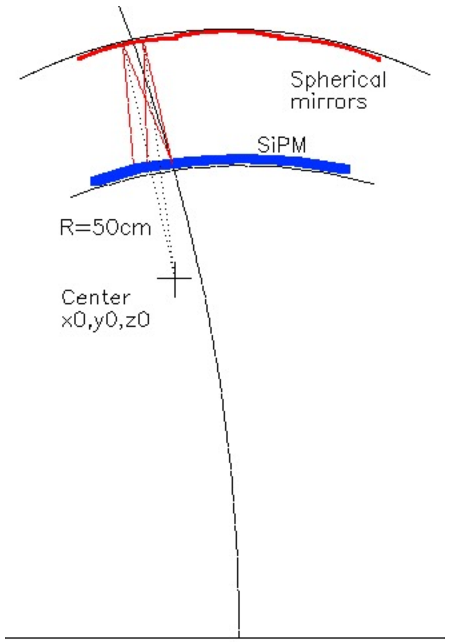
- SLD CRID and Delphi RICH pioneered this type of detector ~40 years ago.

Present optical design concept with ray tracing model

Side view:

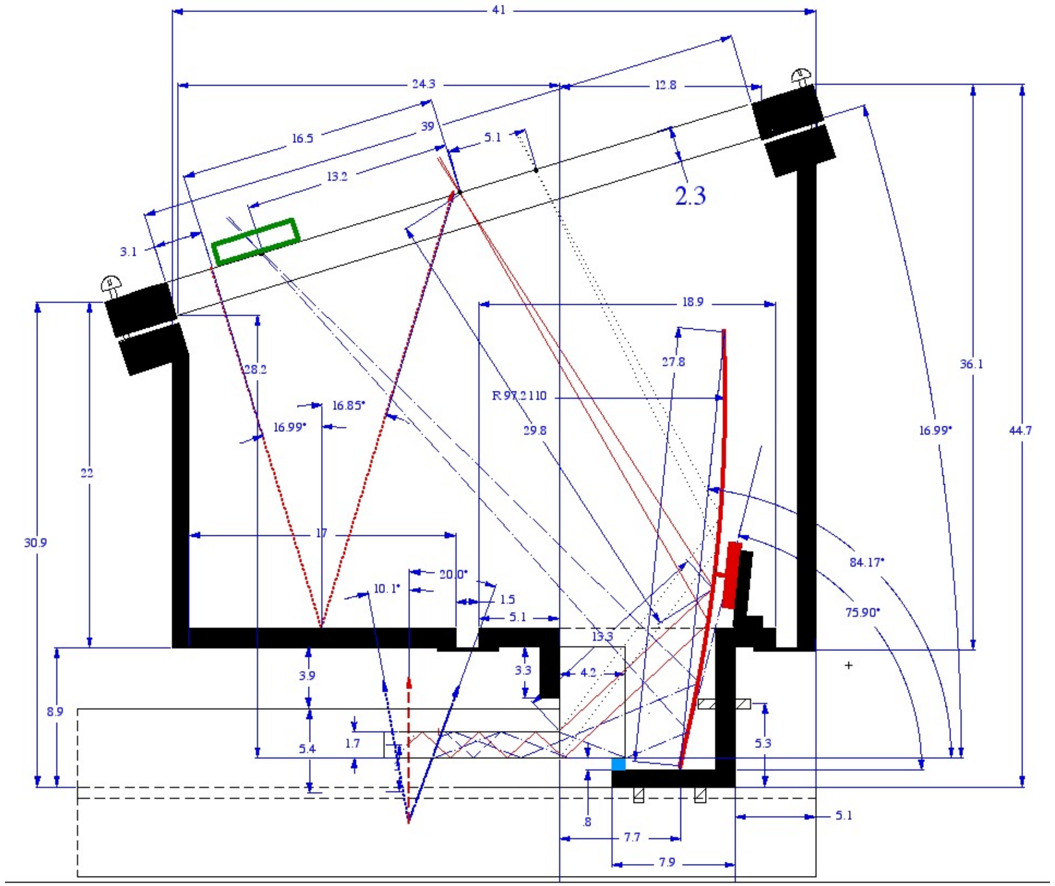


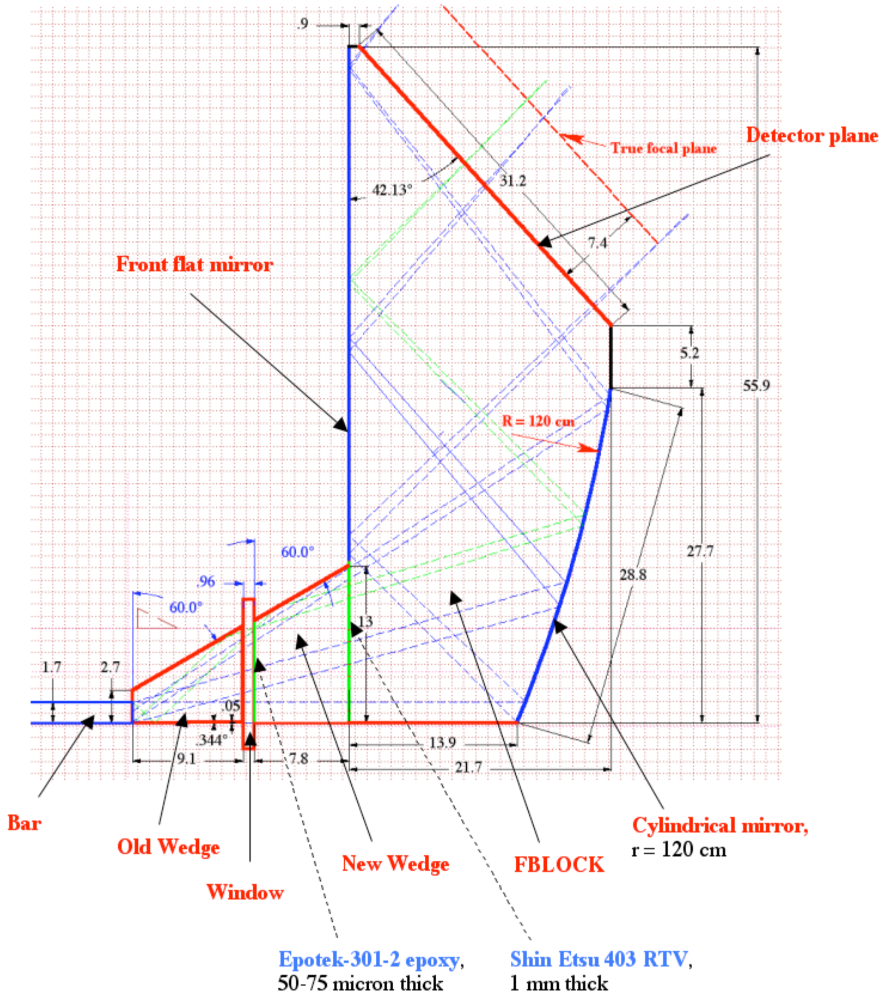
Front view:



- **Spherical mirrors with R = 50 cm, f = 25 cm.**
- **Our goal was to have <u>as low mass as possible</u> => operation at 1 bar.**
- **A full SiPM coverage. Use a track hit to reduce the SiPM noise by timing.**

Other examples ray tracing I have done previously

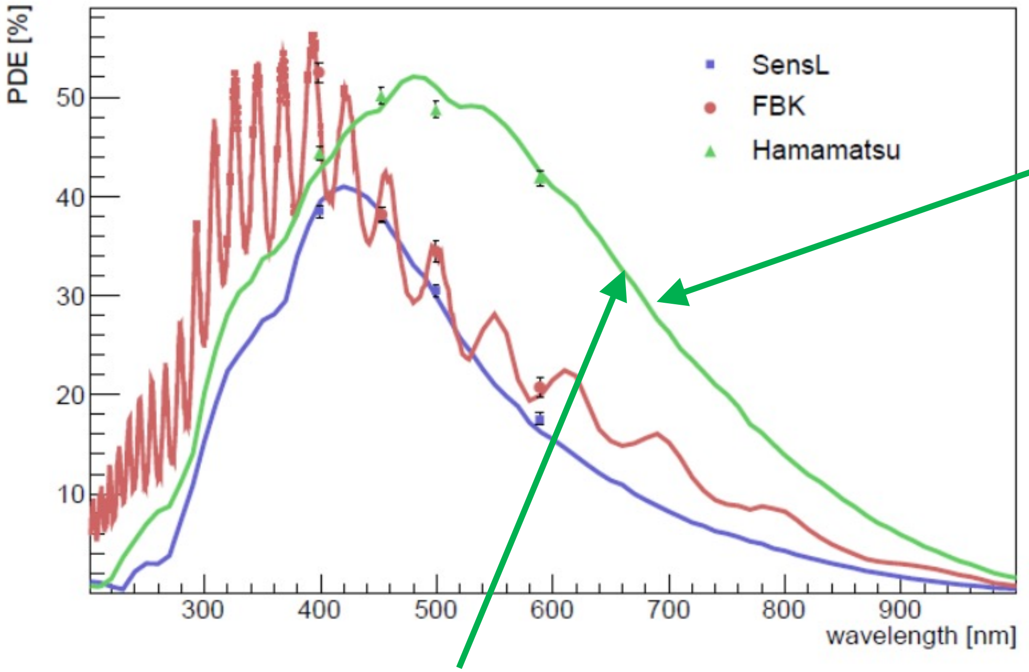




- This was done for SuperB FDIRC two prototypes.

PDE of a single SiPM

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



I used Hamamatsu single SiPM PDE in the calculation

Photon detection efficiency of single SiPM:

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

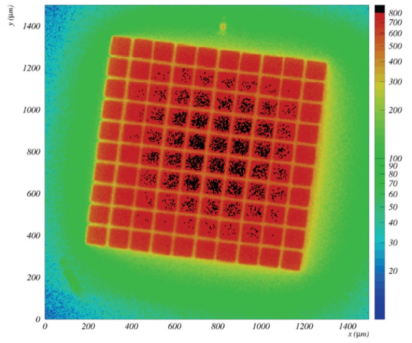
$QE(\lambda)$ – QE of Si

FF – Fill factor within one SiPMT

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

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

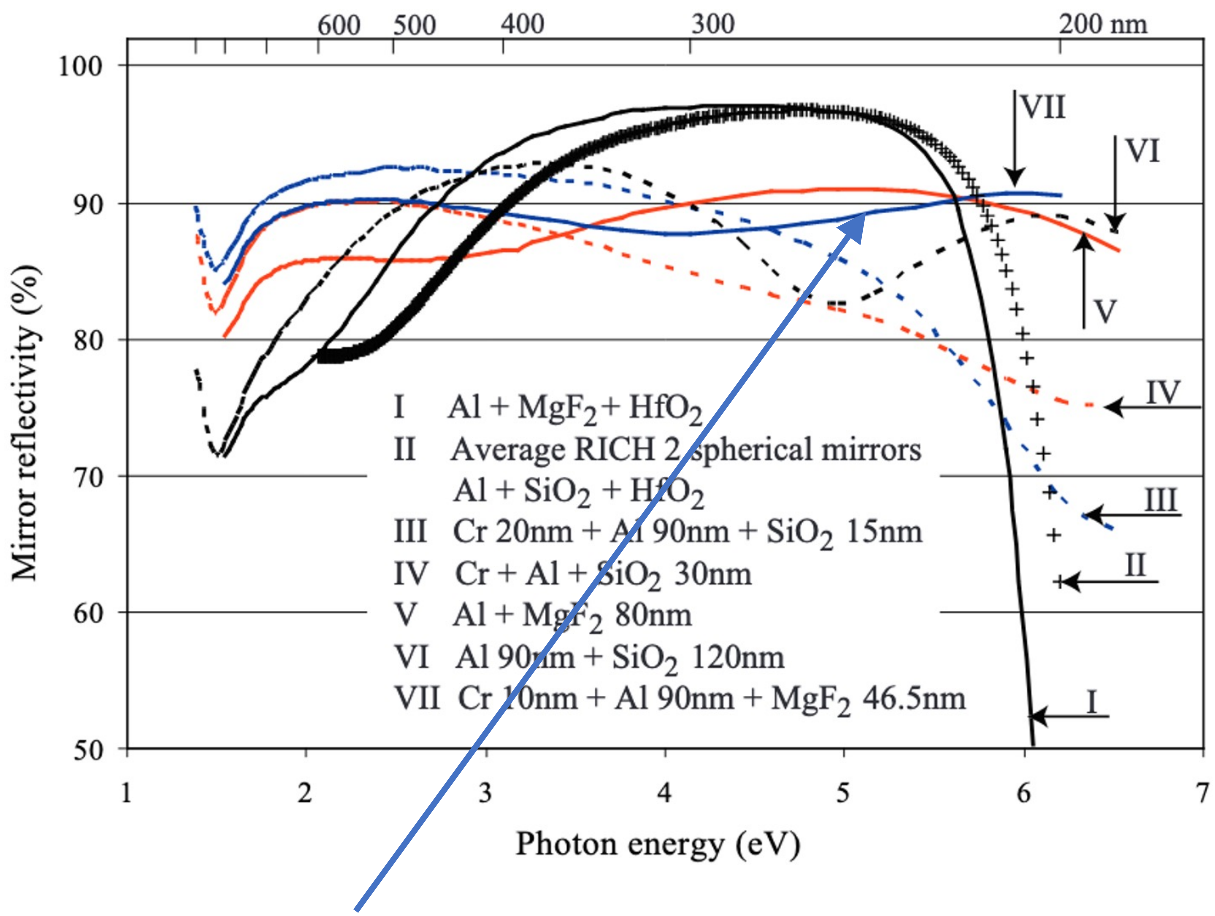
I assumed <u>array fill factor</u> of 65%:



- **<u>All this will improve in next 5-10 years !!!</u>**

Mirror reflectivity

LHCb collaboration, JINST 3 S08005, 2008



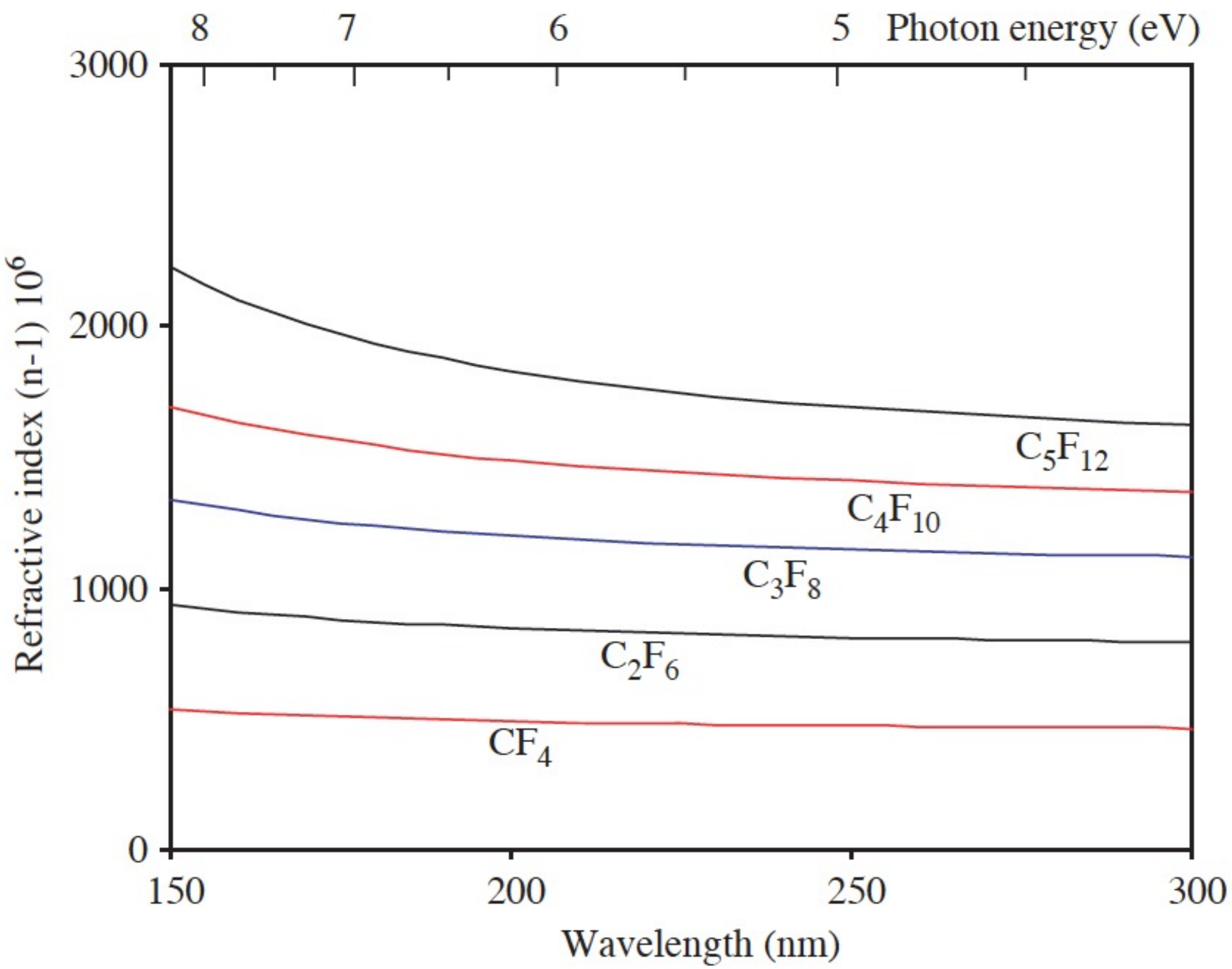
- For calculations in this note I used Al+Cr+MgF_2 mirror coating. This coating was also used by CRID.

Gas choice

- **C_5F_{12} gas** at 1 bar requires a detector temperature of 40^oC since boiling point of this gas is 31^oC at 1 bar. Not very agreeable with the SiPM noise.
- **C_4F_{10} gas** at 1 bar allows detector operation at a few degrees ^oC since boiling point of this gas is -1.9^oC at 1 bar. **This is presently our preferred choice.**
- **C_2F_6 gas** at 1 bar would allow detector operation even below 0^oC since boiling point of this gas is -70.2^oC 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. The detector PID performance will be between C_2F_6 and C_4F_{10}.

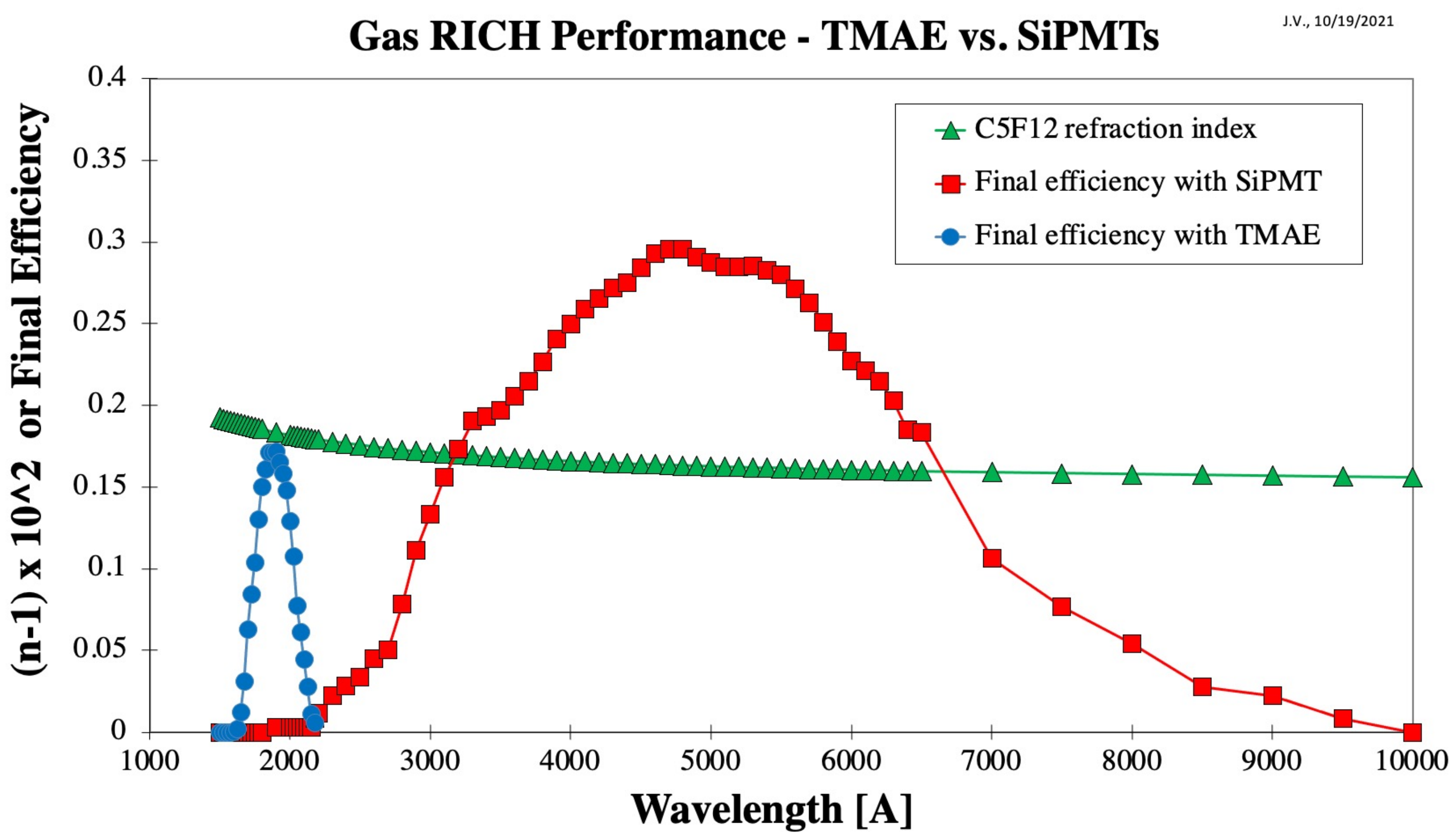
Refraction index of Freons

O. Ullaland, NIM A 553(2005)107



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

Final efficiency: TMAE vs SiPMs



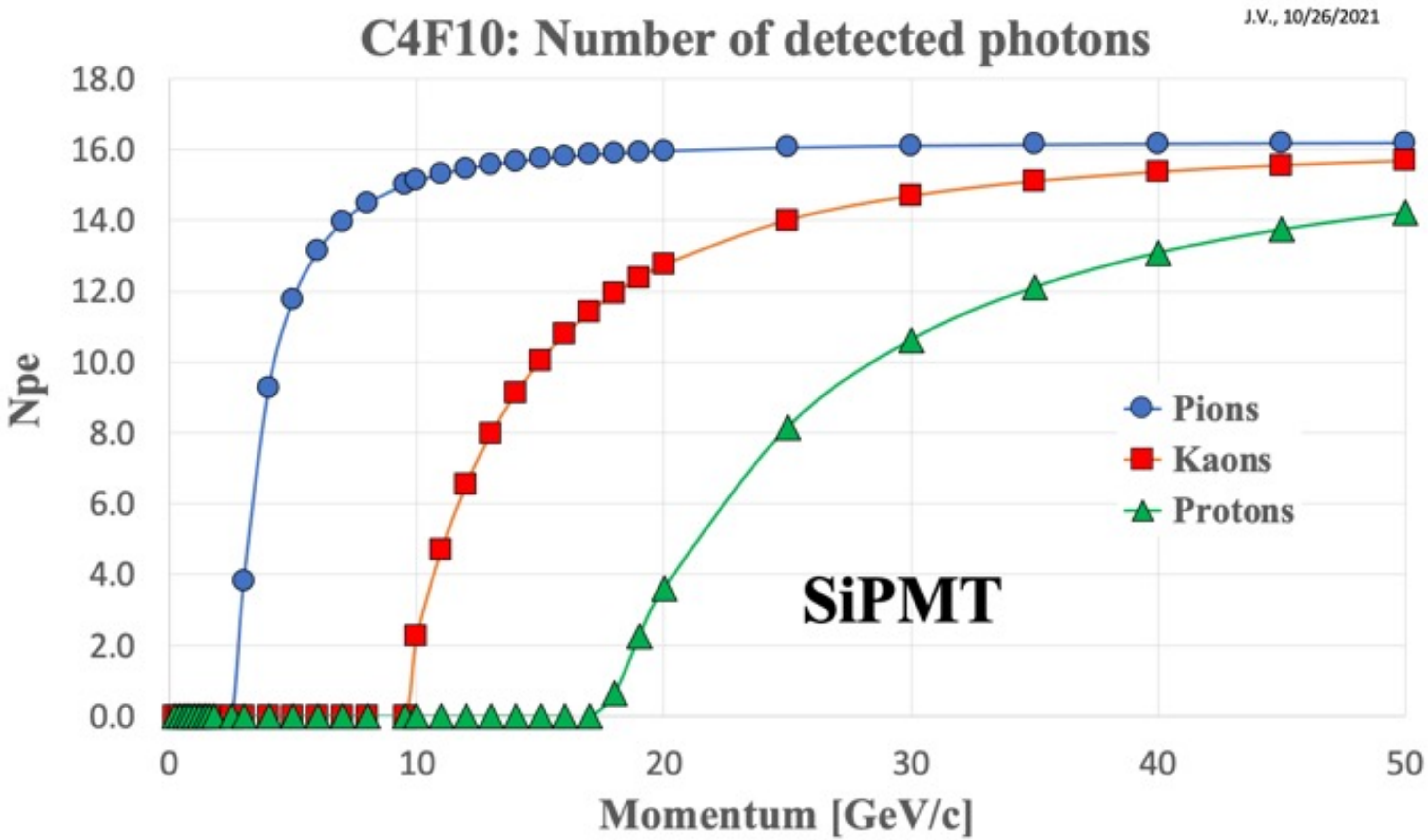
- **Although CRID operated in a region where refraction index changed more rapidly, its wavelength acceptance was very narrow and therefore the chromatic error was smaller: ~0.4 mrad vs. ~0.85 mrad (SiPM).**

PID near threshold using Npe

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

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

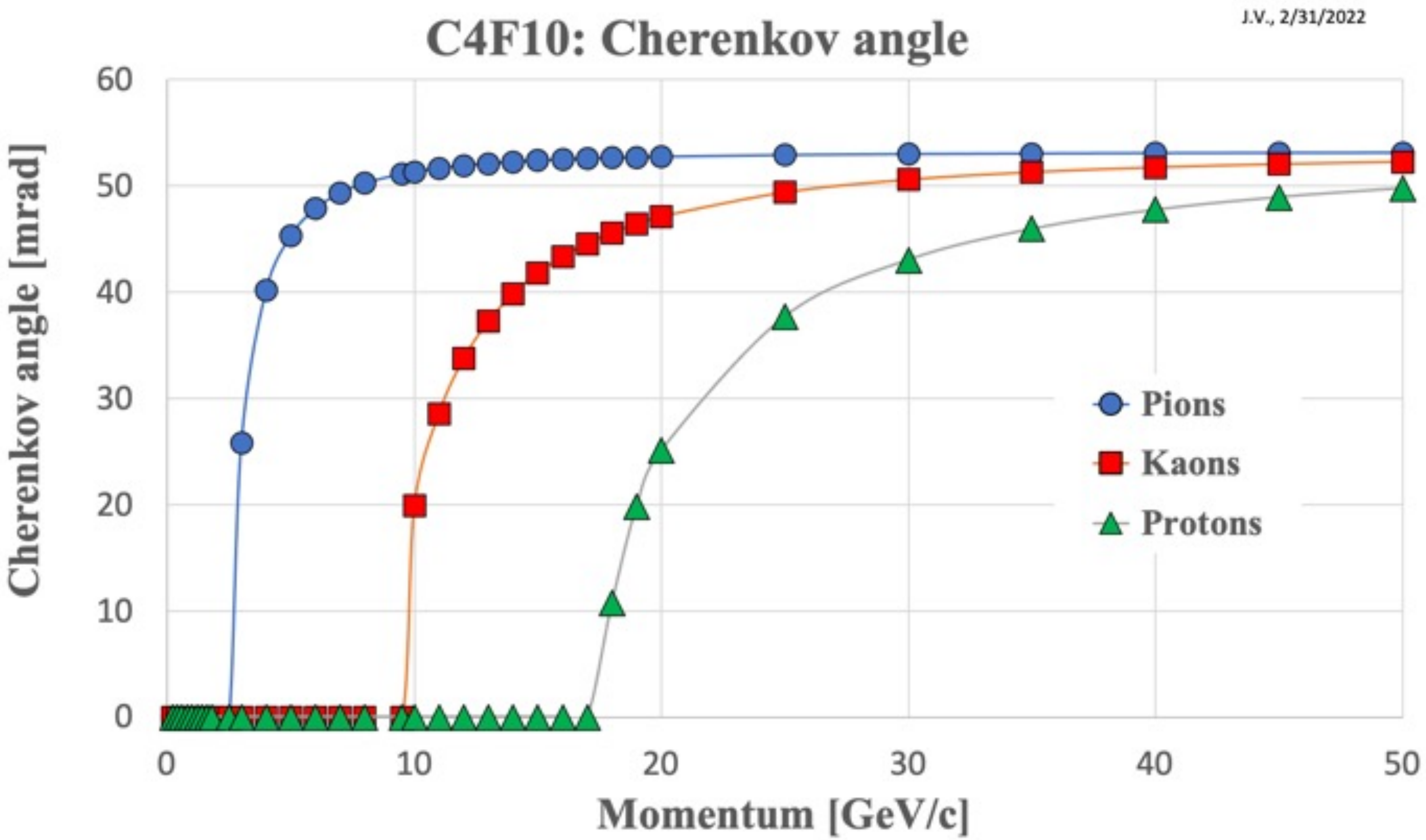
$< \theta_c >$ is mean Cherenkov angle



- L = 25 cm & 1 bar.
- Below ~9 GeV/c Kaons do not produce light, Pions do, etc.
- Between 10 and 15 GeV/c Kaons produce small number of photoelectrons.

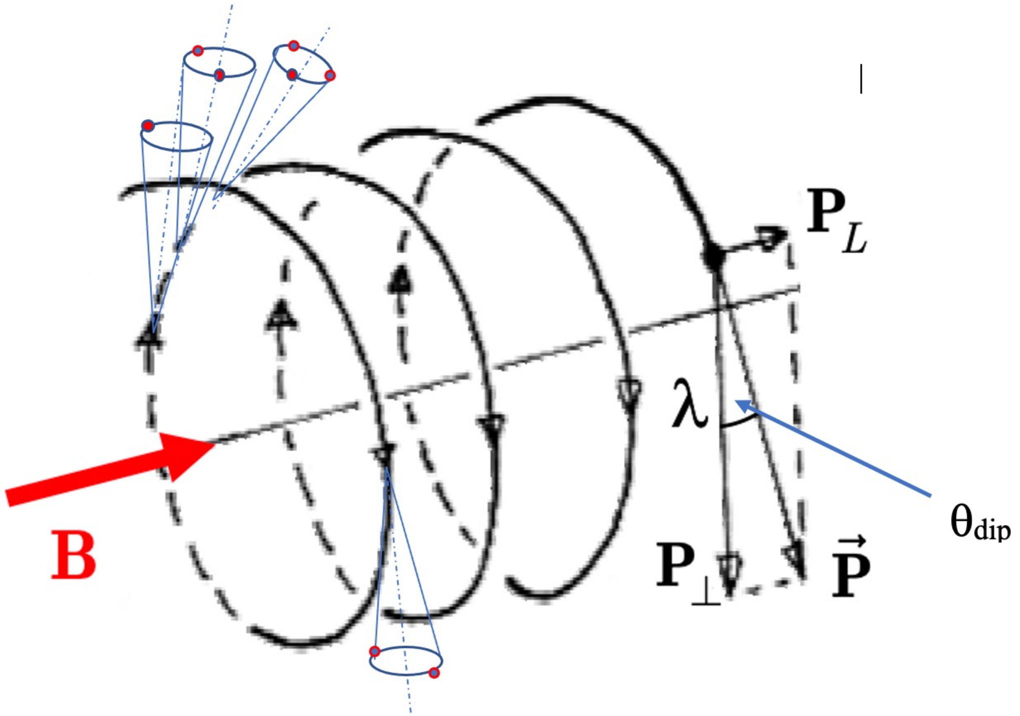
PID near threshold using θ_c

$\cos \theta_c = 1/(\langle n \rangle \beta)$



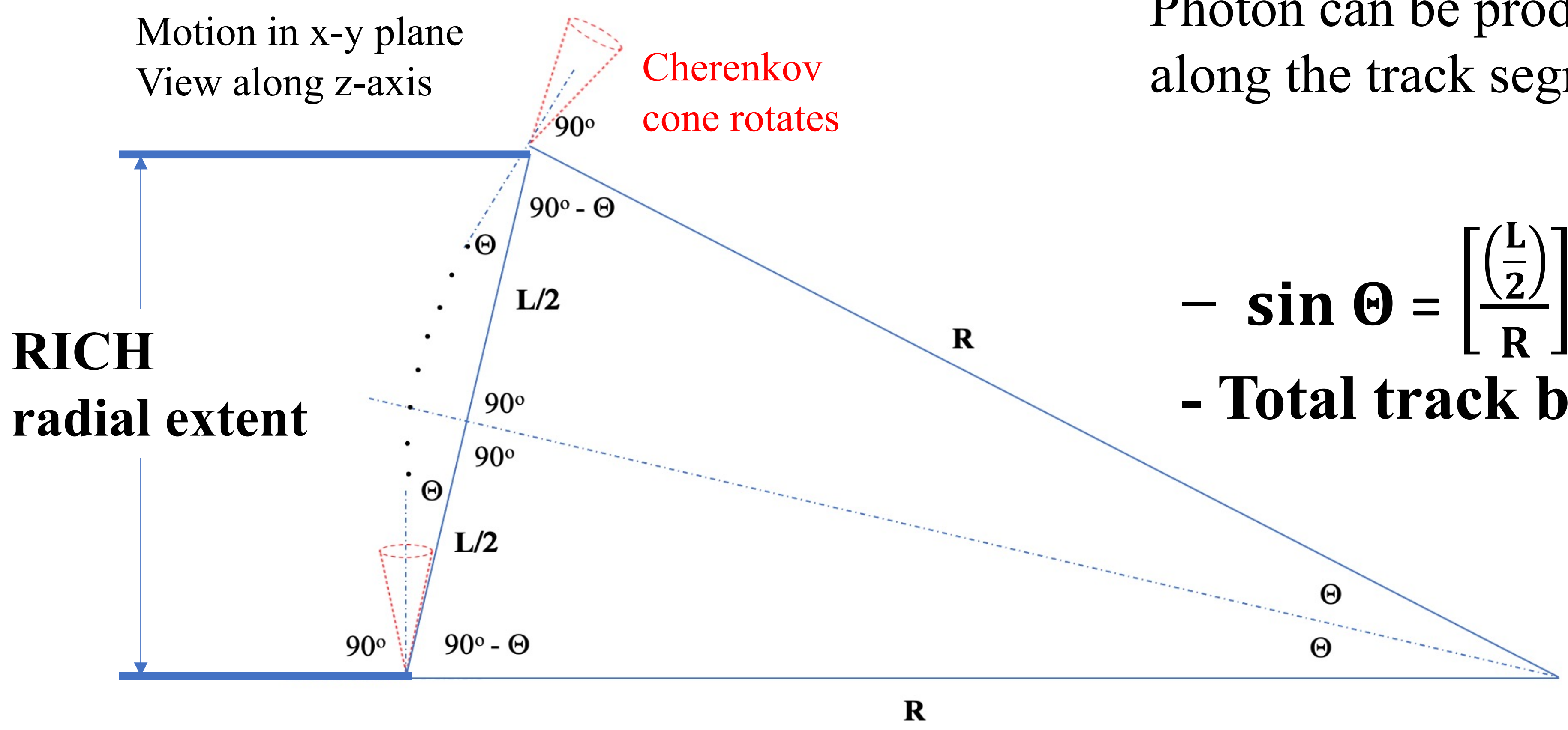
- **Near threshold it is relatively easy, at 40-50 GeV/c it is tricky.**

Cherenkov ring is smeared at large magnetic field



- **This effect was about ~0.5 mrad for SLD CRID operating at 0.5 Tesla. It is larger in large magnetic field and large RICH detector radial extent.**
- **Two methods to estimate it: (a) Analytical formula, (b) Mathematica code.**

Smearing effect estimate due to track bending



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

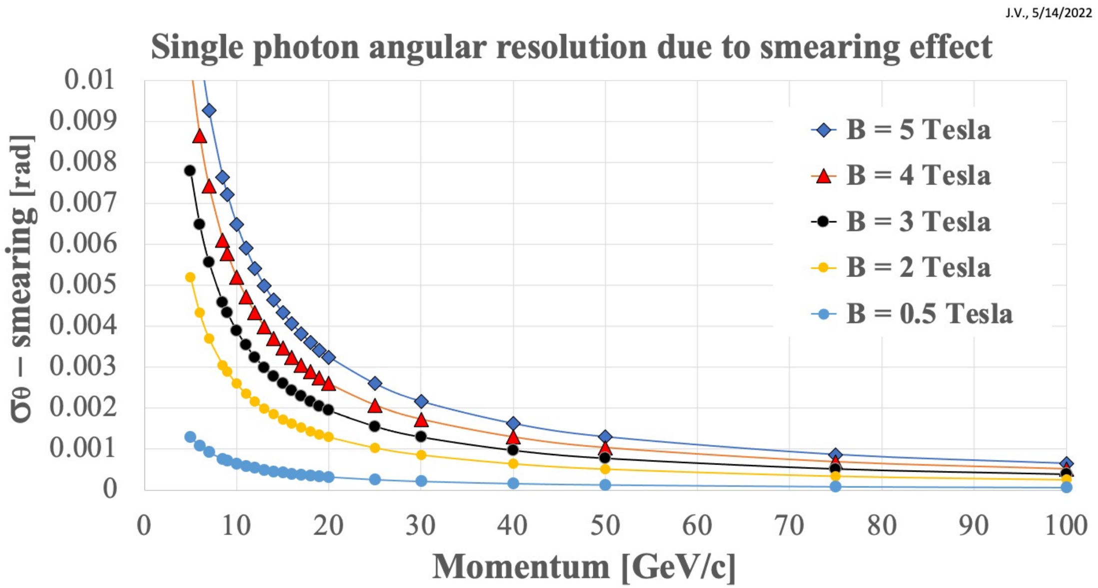
- $\sin\Theta = \left[\frac{\left(\frac{L}{2}\right)}{R}\right]$
- Total track bend angle: 2Θ

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

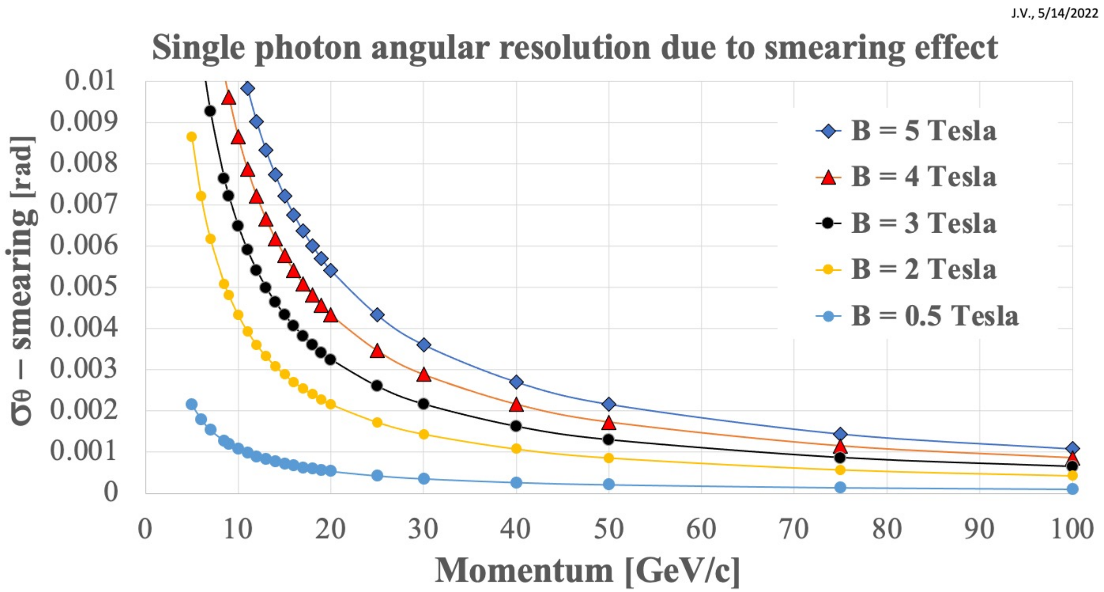
Smearing effect due to track bending = f(B)

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



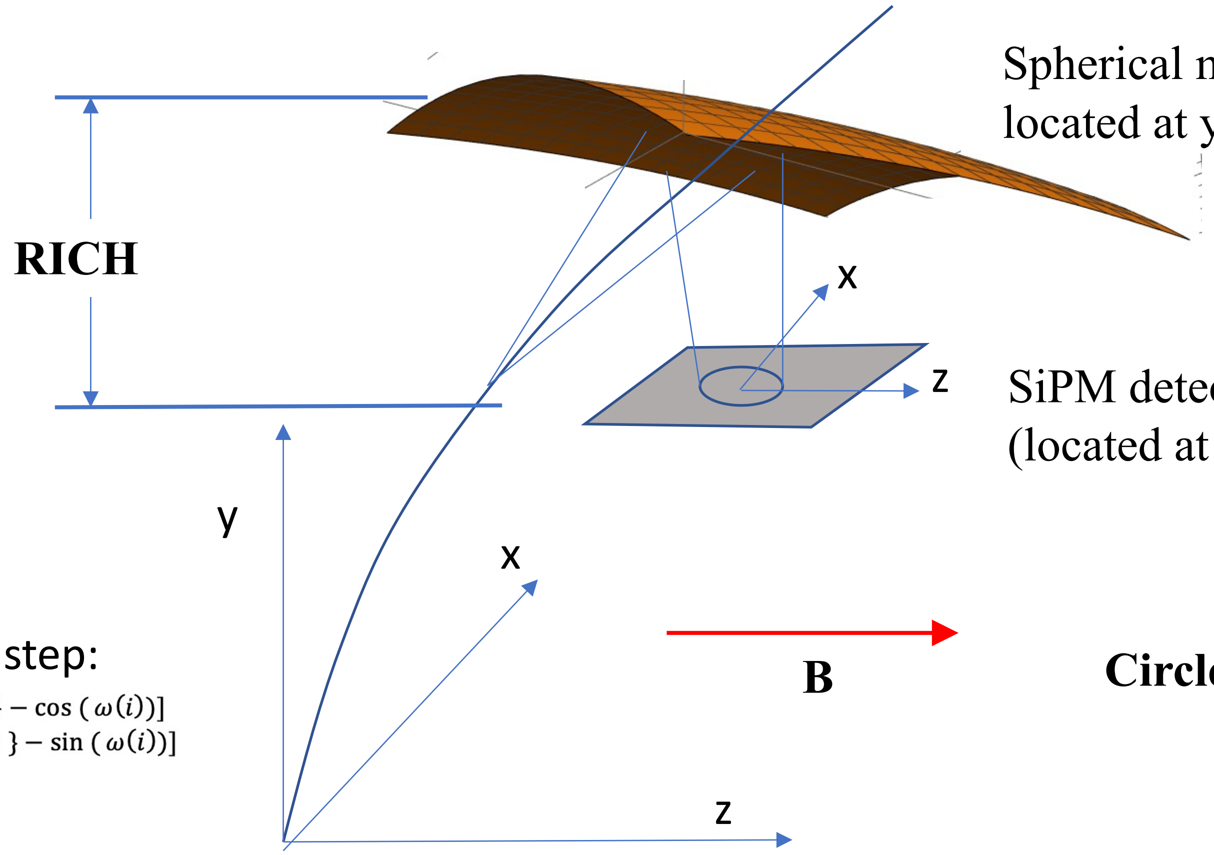
L = 25 cm



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

Simple model in Mathematica program

Schematic picture:



Spherical mirror with **Radius** = 50 cm, located at y = 125 cm

SiPM detector in **focal plane** (located at r = 100 cm)

Circle is in x-y plane

Move step by step. In each step:

$x(i+1) = x(i) - R[\cos\{\omega(i) + s\, cos\theta_{dip}/R)\} - \cos(\omega(i))]$

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

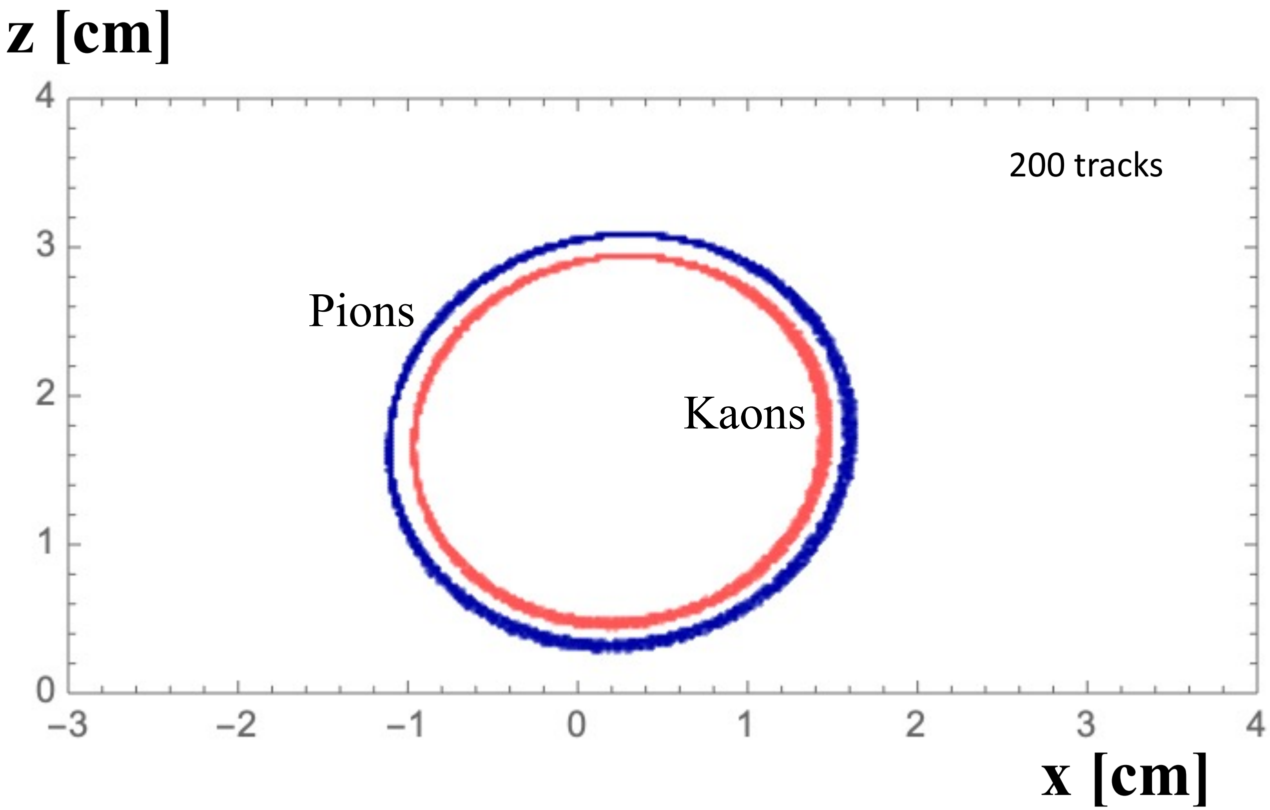
$z(i+1) = z(i) + \sin\, \theta_{dip}$

$s \cos \theta_{dip} = [z(i+1) - z(i)]\, P_T / P_L$

- **Step through the field, radiate Cherenkov photons when 100< r <125, reflect them from spherical mirror and find their intersection with a detector plane.**

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

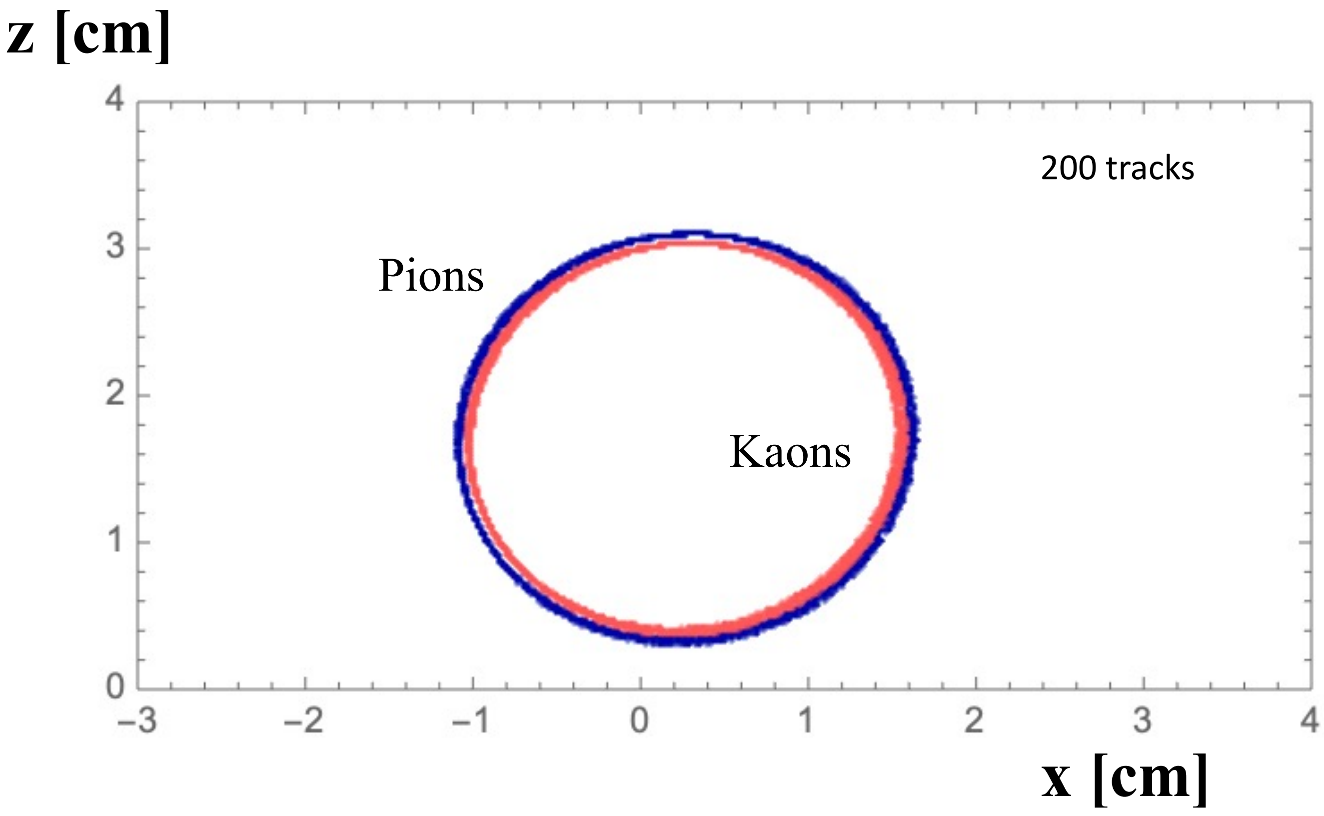


Smearing error only

- **Smearing effect varies as a function of $\boldsymbol{\Phi}_c$.**
- **Plot all {x_{final}[i] & z_{final}[i]} 2D-hits in detector plane, no cuts, no fitting.**
- **One could determine a weighting function dependent on $\boldsymbol{\Phi}_c$. Not yet done.**

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.**

Final performance for nominal design

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

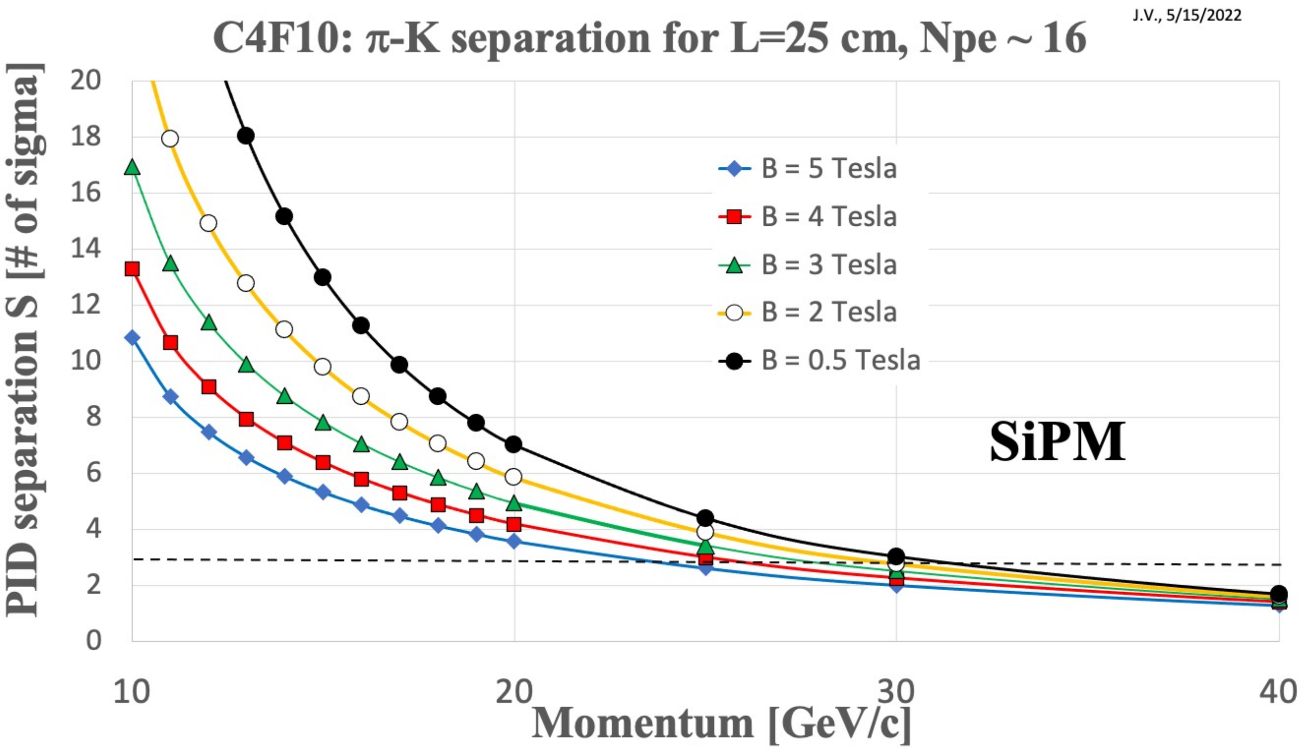
$\sigma_{smearing}$ = **analytical formula** , $\sigma_{chromatic}$ ~ **0.85 mrad**, pixel size: **3 mm**, $\sigma_{tracking}$ ~ **0.5 mrad**, L = **25cm**, **1 bar**

S [# of sigma]

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

σ_θ is total photon angle resolution, which includes:

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



- **3 σ limit: ~25-30 GeV/c at 2-3 Tesla.**

Reduce pixel size, higher PDE and better tracking

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

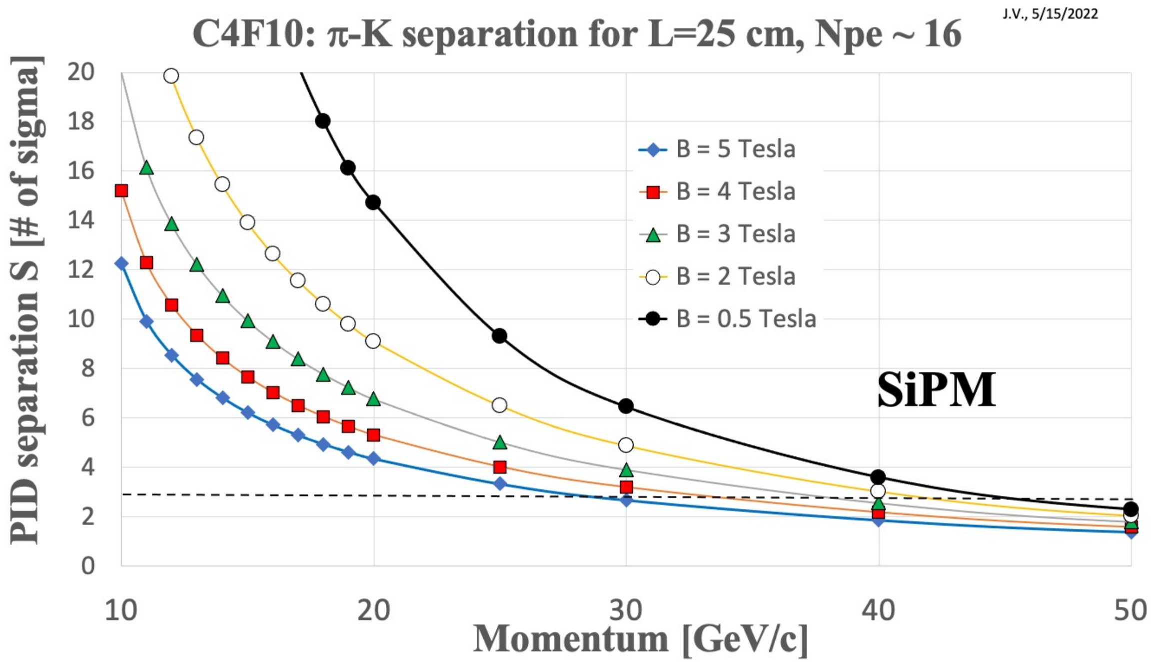
$\sigma_{smearing}$ = **analytical formula** , $\sigma_{chromatic}$ ~ **0.85 mrad**, **pixel size: 0.5 mm**, $\sigma_{tracking}$ ~ **0.3 mrad**, **increase PDE by 20%**

S [# of sigma]

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

σ_θ is total photon angle resolution, which includes:

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



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

Can it be improved further ?

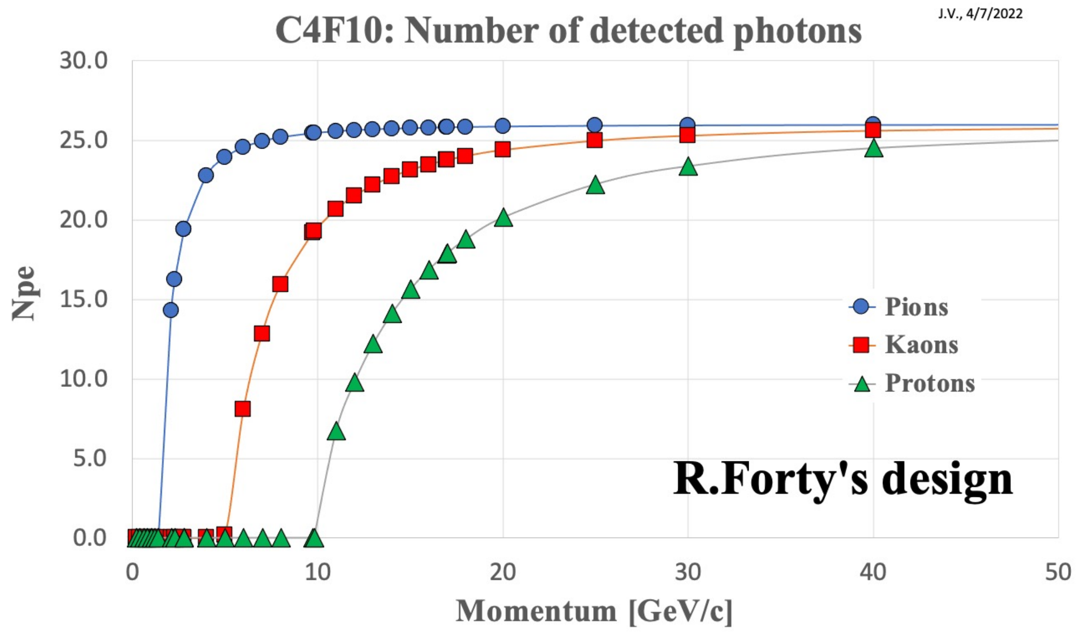
R. Forty & C. Gargiulo RICH design

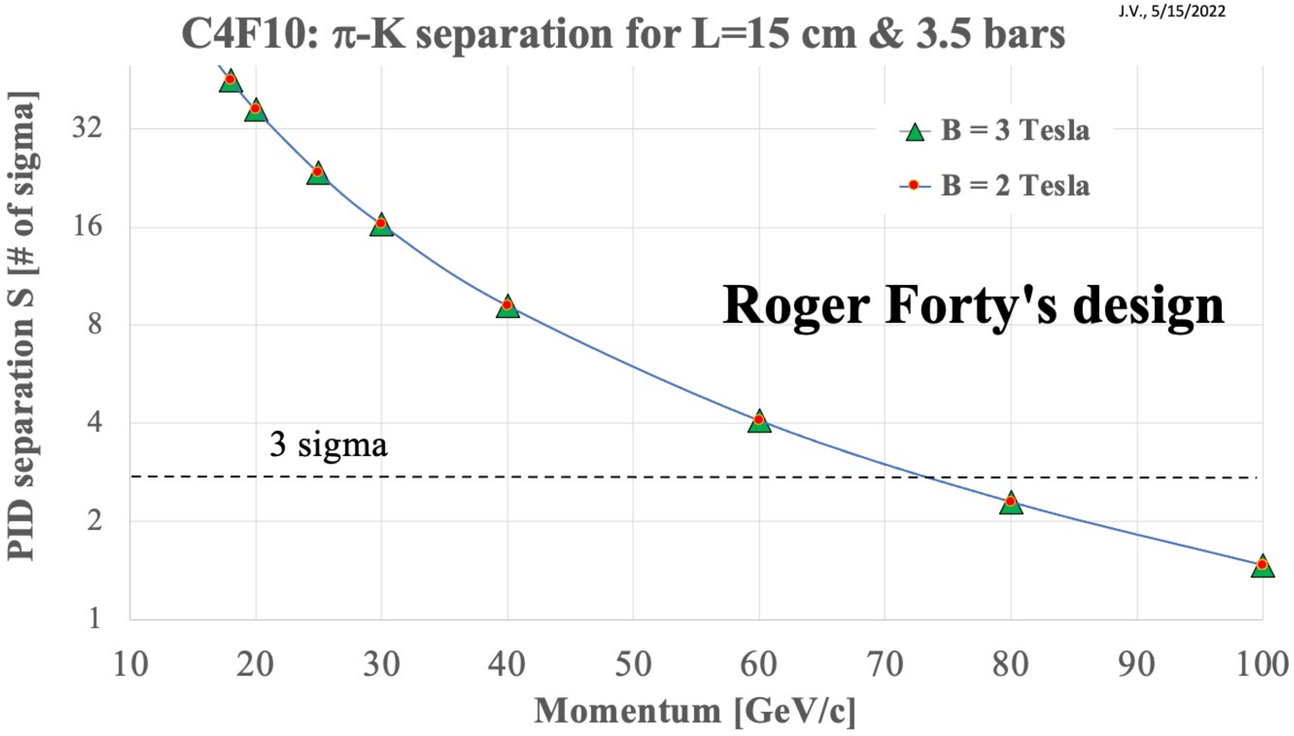
(I used their design parameters, but did my independent calculation)

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%.**

Conclusion

- 1 bar design limits Npe to ~16 pe's/ring in C_4F_{10} gas at 1 bar.
- 3 sigma π/K PID at 40 GeV/c is possible for fields at 2-3 Tesla.
- Preliminary results justify a full-scale simulation by Geant 4.
- The goal:

  a) Bring tracking error to ~0.3 mrad.

  b) Use pixel size of 0.5 mm x 0.5 mm.

  c) Create a clever weighting algorithm to minimize the smearing effect.

  e) To do the SiPM noise reduction by timing, one needs a full coverage by SiPM detectors area to provide a track hit. If tracking will have fast timing layer, SiPM RICH coverage does not have to be complete.

  f) X/Xo ~ 3-4%.

  g) SiPM technology is developing very fast. In 5 years, all this will be obsolete, and the detector design can be improved.

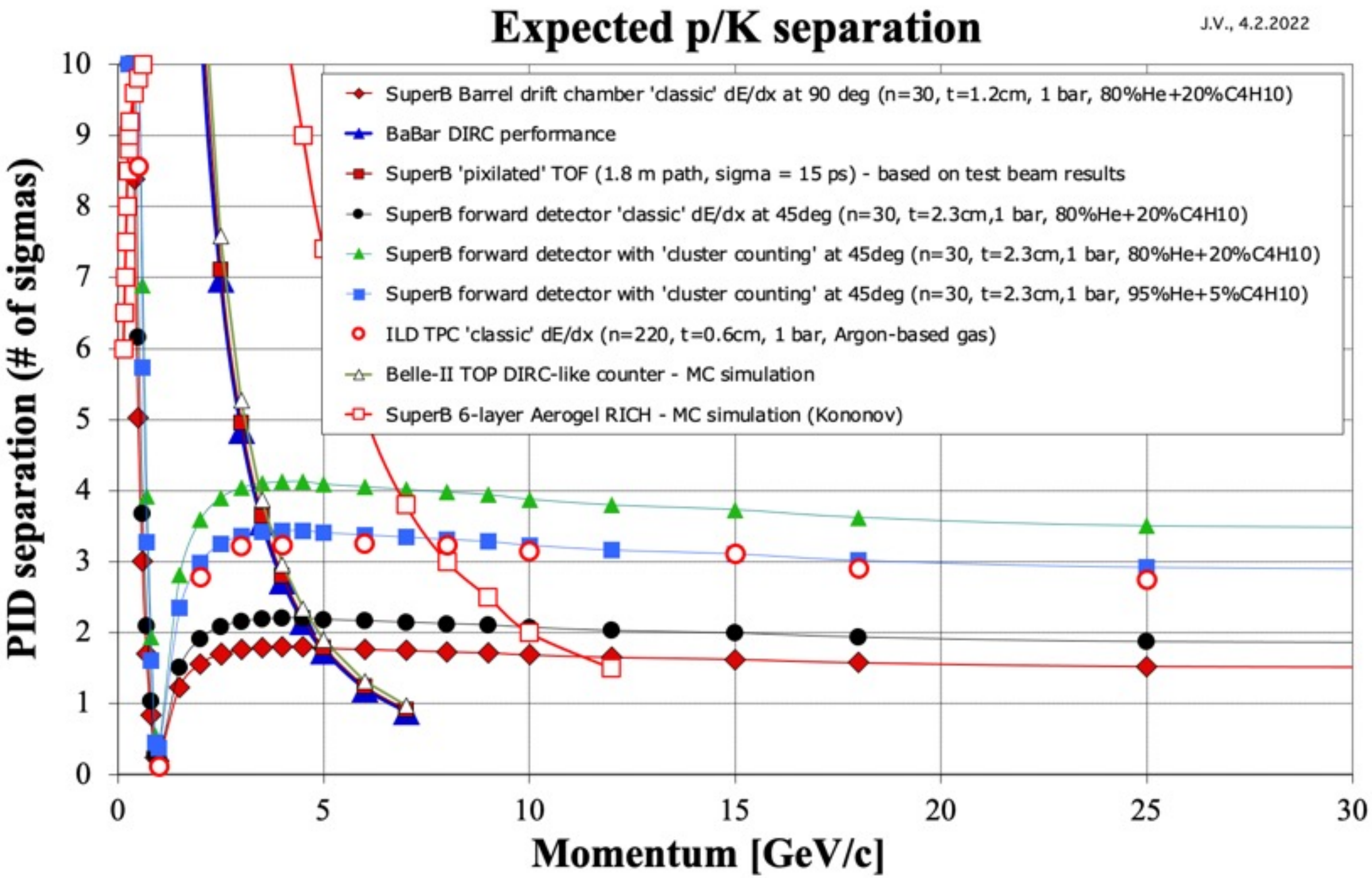
Appendix

Summary of our design

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	1.5 - 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]

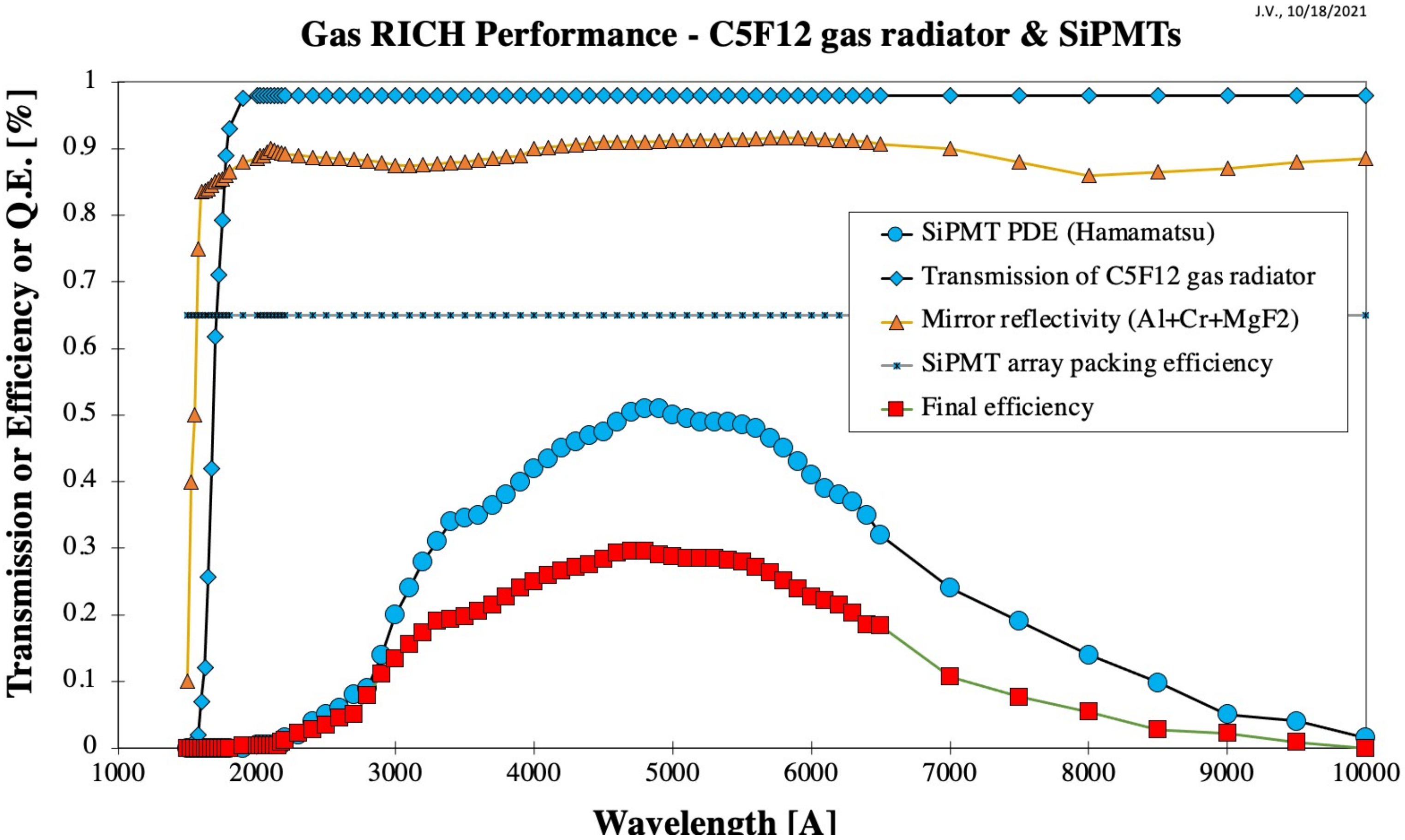
- **At 2-3 Tesla the smearing error is smaller.**
- **Results are interesting enough to justify the full Geant4 simulation.**

Examples of PID detectors



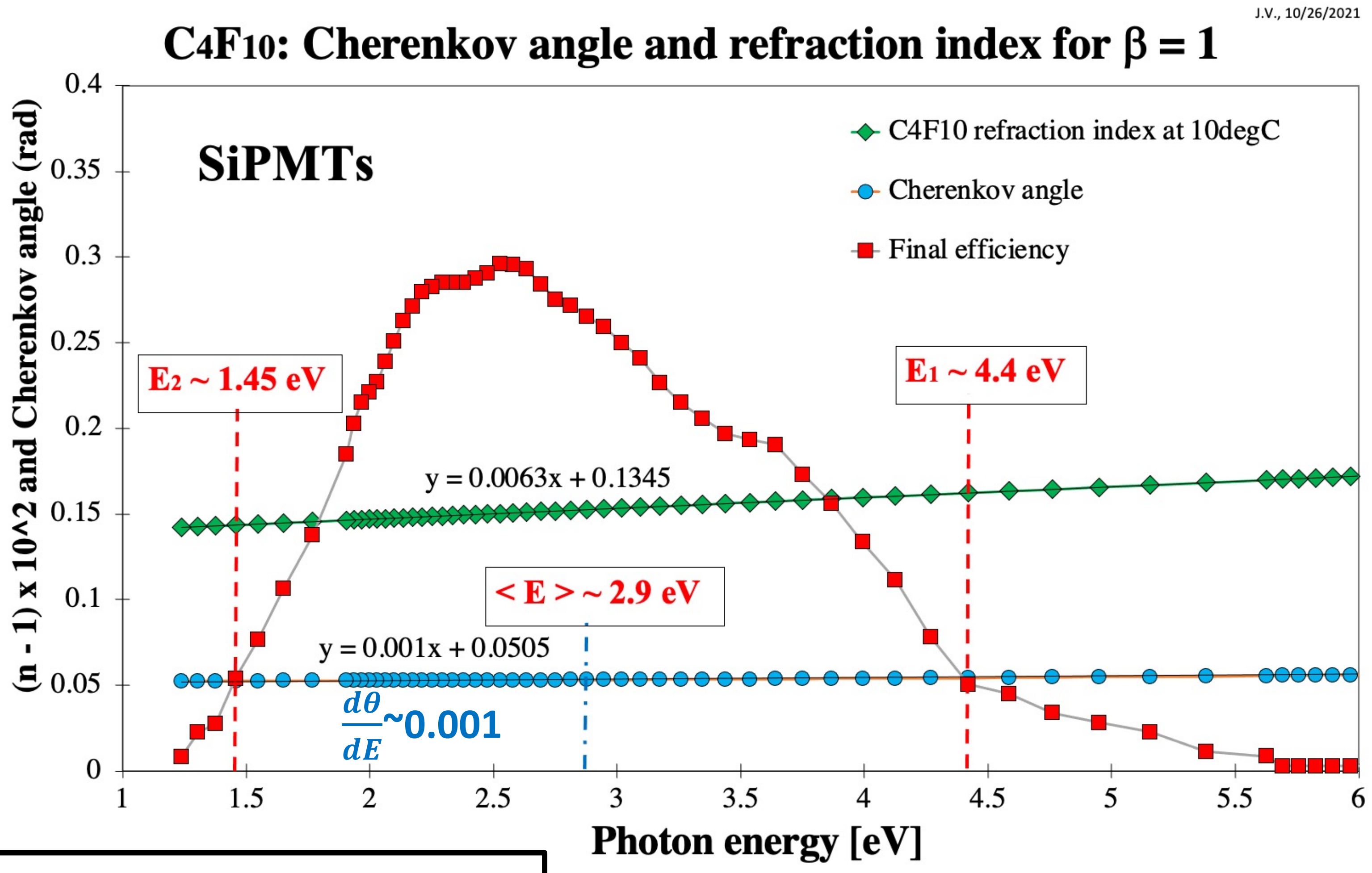
- Present ILD TPC design separates p/K's at ~30 GeV/c at a level of ~3 σ.

Overall efficiency of SiPM array in this calculation



- For now, I assume that SiPM packing efficiency is 65% !

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.

PID performance = f(momentum,σ_θ)

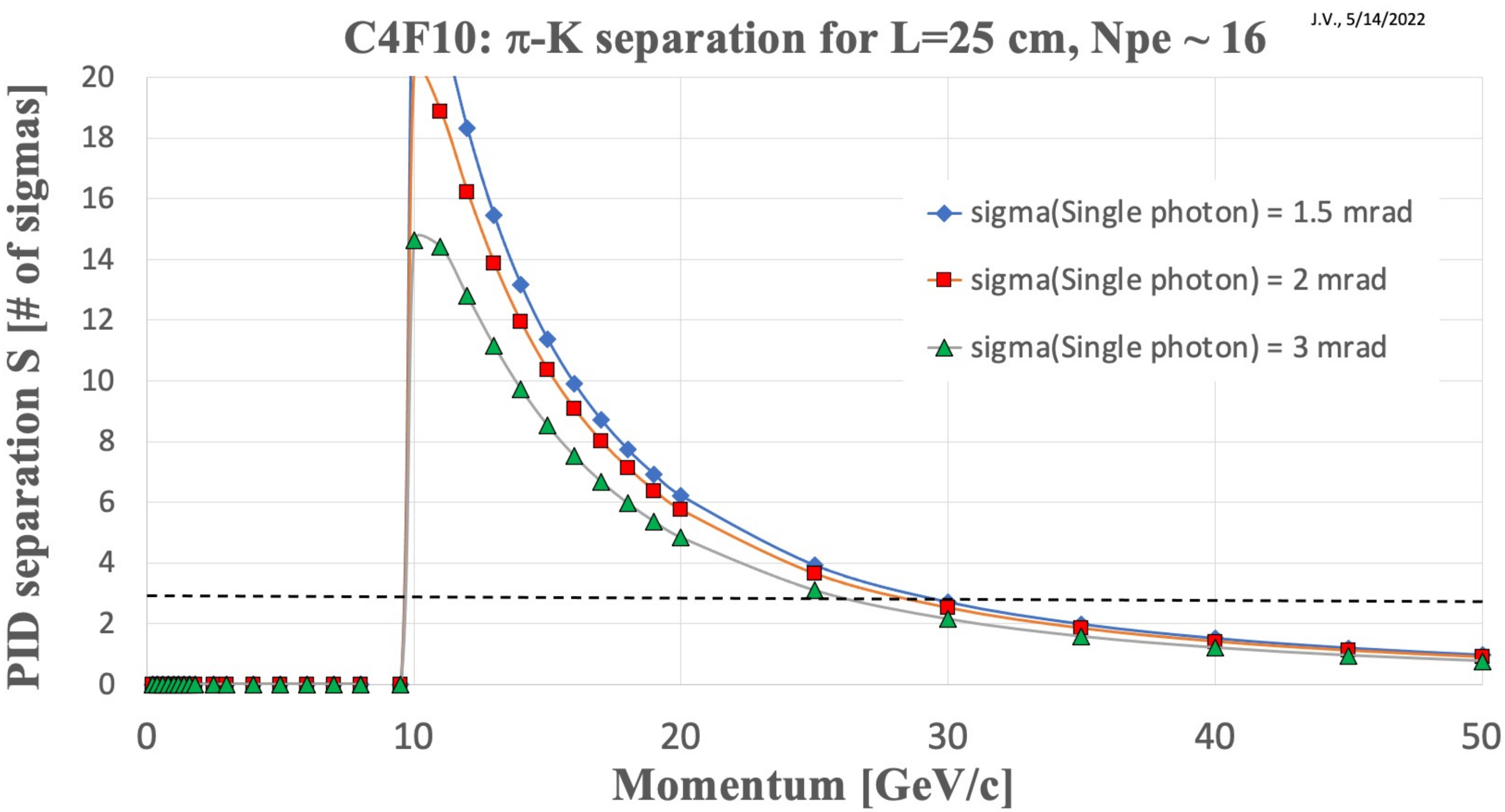
$\sigma_\theta = \sigma_{single\ photon} / \surd Npe \otimes \sigma_{tracking} = \surd\{\sigma_{chromatic}^2 + \sigma_{pixel}^2 + \sigma_{smearing\ effect}^2\} / \surd Npe \otimes \sigma_{tracking}$

S [# of sigma]

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

$\boldsymbol{\sigma_\theta}$ is total single photon angle resolution, which includes:

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



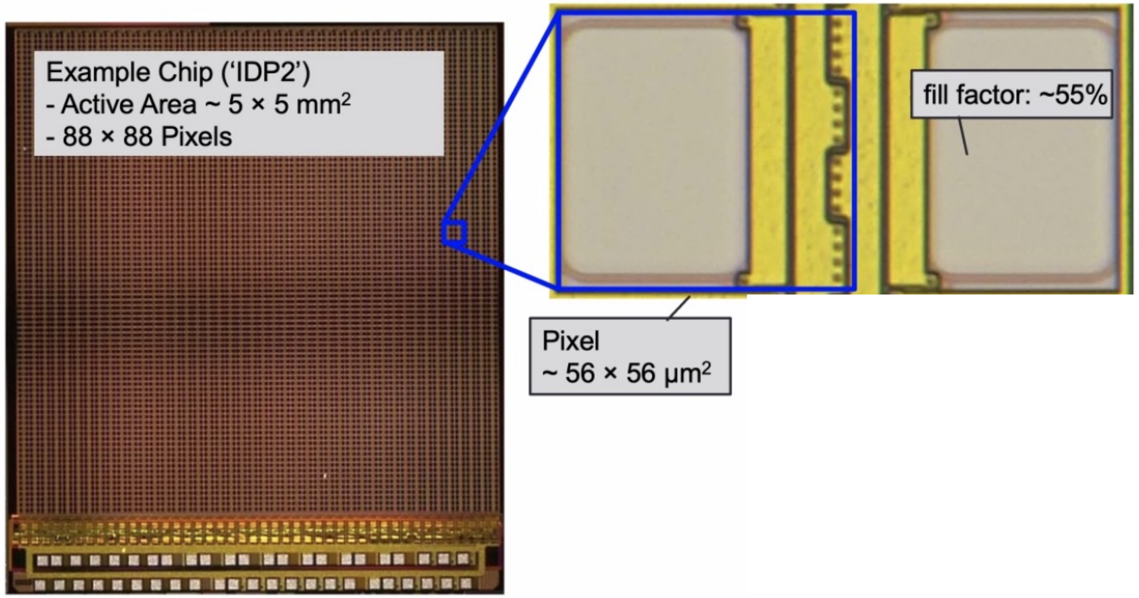
- **Limited by Npe at 1 bar; assume $\sigma_{tracking}$ ~0.5 mrad.**

Are digital SiPMs a good choice in future ?

Peter Fisher, Heidelberg

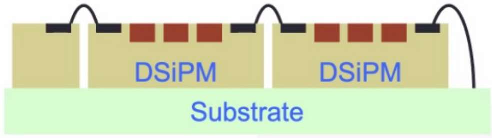
'Digital SiPM' (or 'CMOS SPADs')

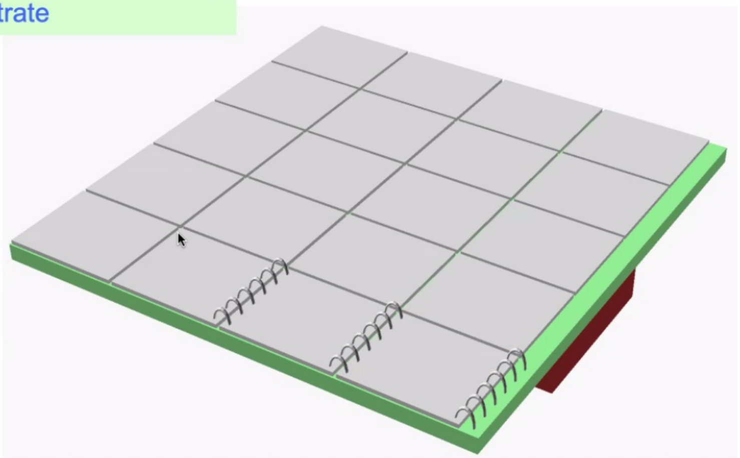
- Chip produced in a ('special') CMOS technology which allows to fabricate SPADs AND transistors on one chip



Possible Module Concept

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



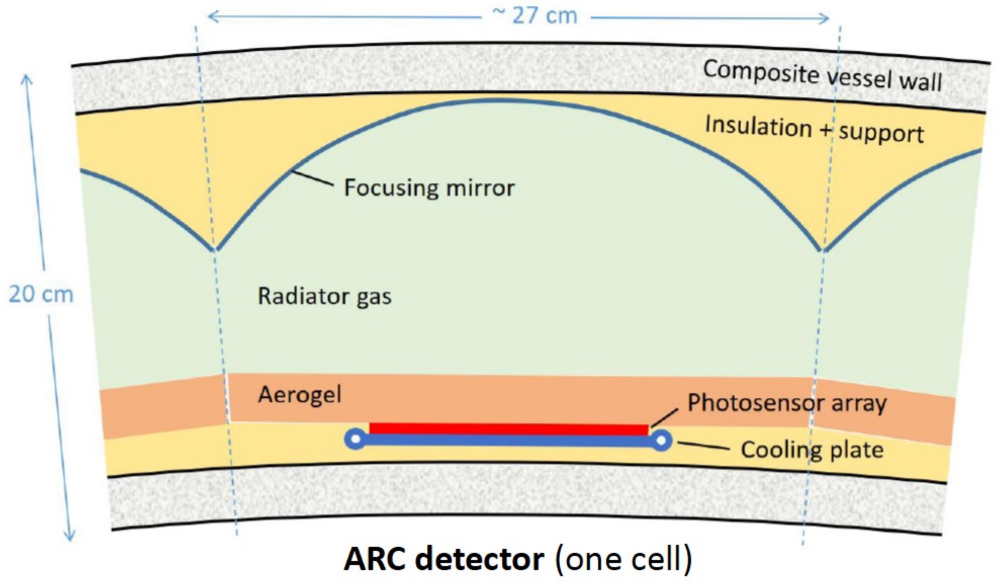


- **Can have very small pixel sizes.**
- **Combine electronics and photosensor together on one chip. Fill factor: 55%.**
- **Can switch off the cell which is too noisy.**
- **Can daisy chain different segments.**

Comparison to Roger Forty

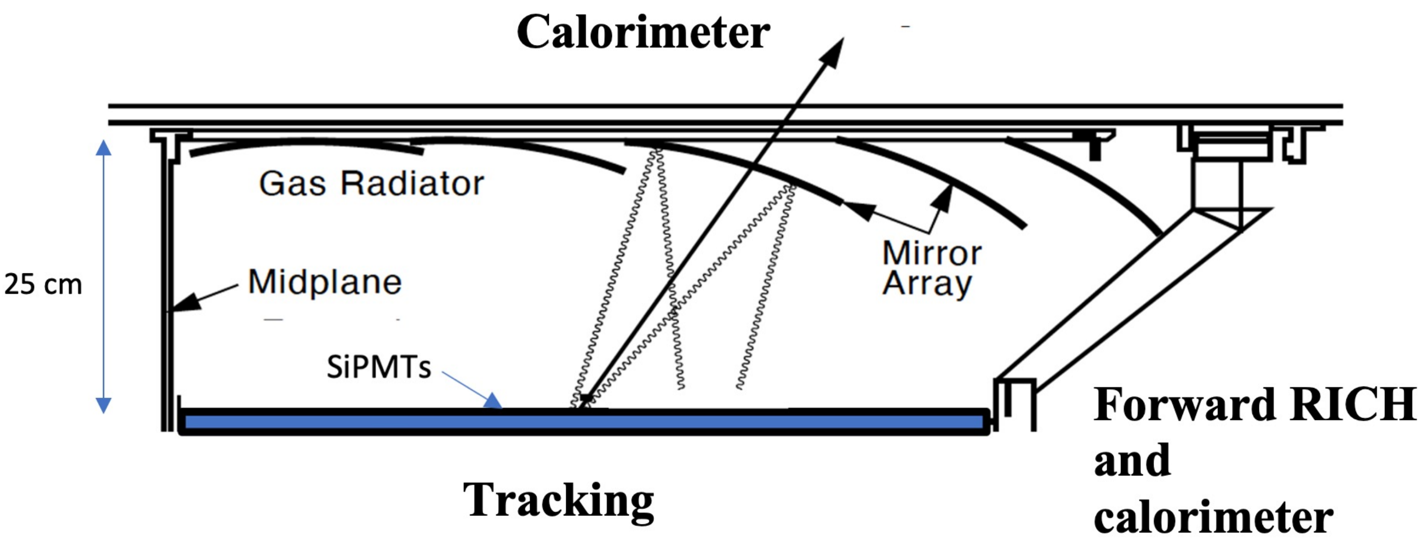
Two designs

Roger Forty's design:



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:

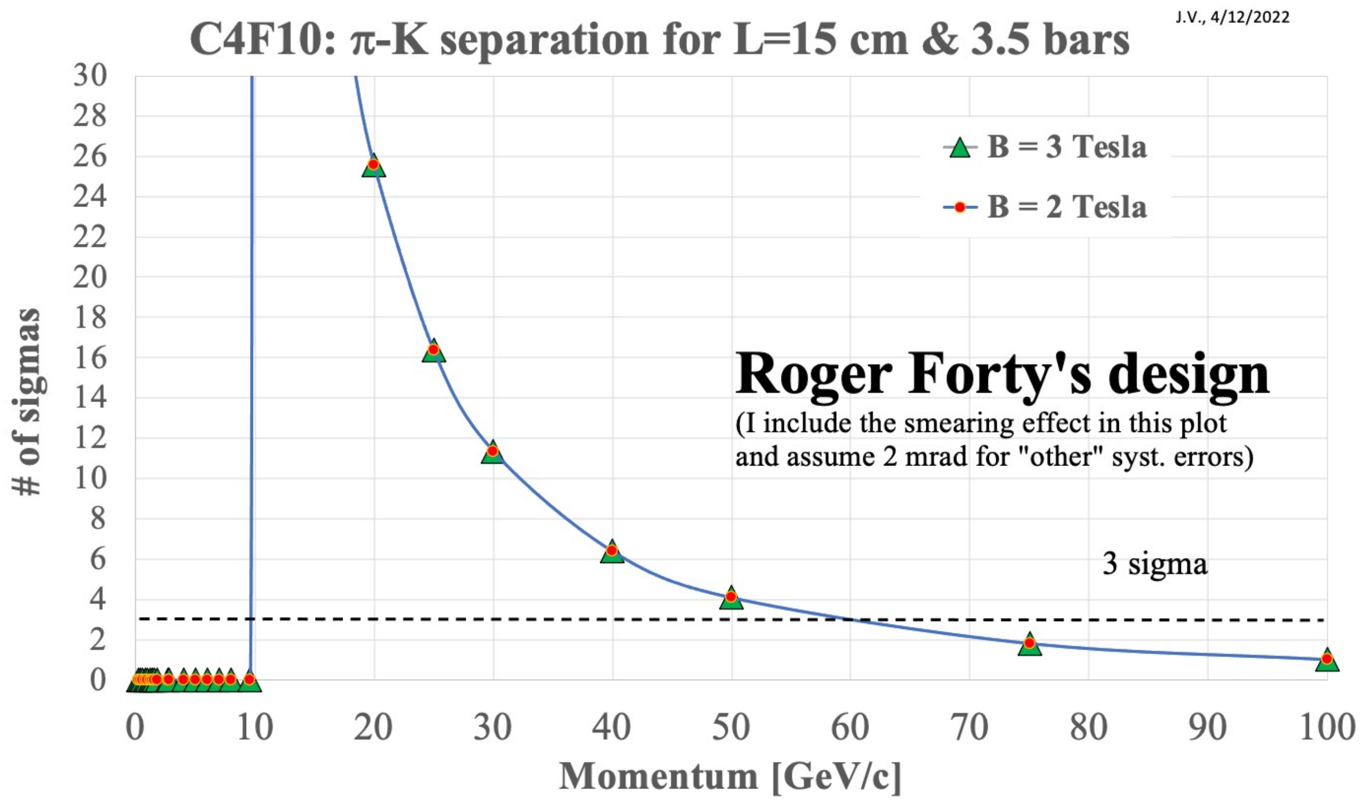


C4F10 at 1 bar
N = 1.001415
X/X_o ~ 4%
N_{pe} ~ 16 for β =1

Roger's slightly more realistic design

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

2. $\sigma_{smearing}$ = **calculate**, $\sigma_{chromatic} \sim$ **0.5 mrad**, pixel size: **1 mm**, $\sigma_{tracking} \sim$ **0.3 mrad**, $\sigma_{other\ syst,}$ **~2 mrad**

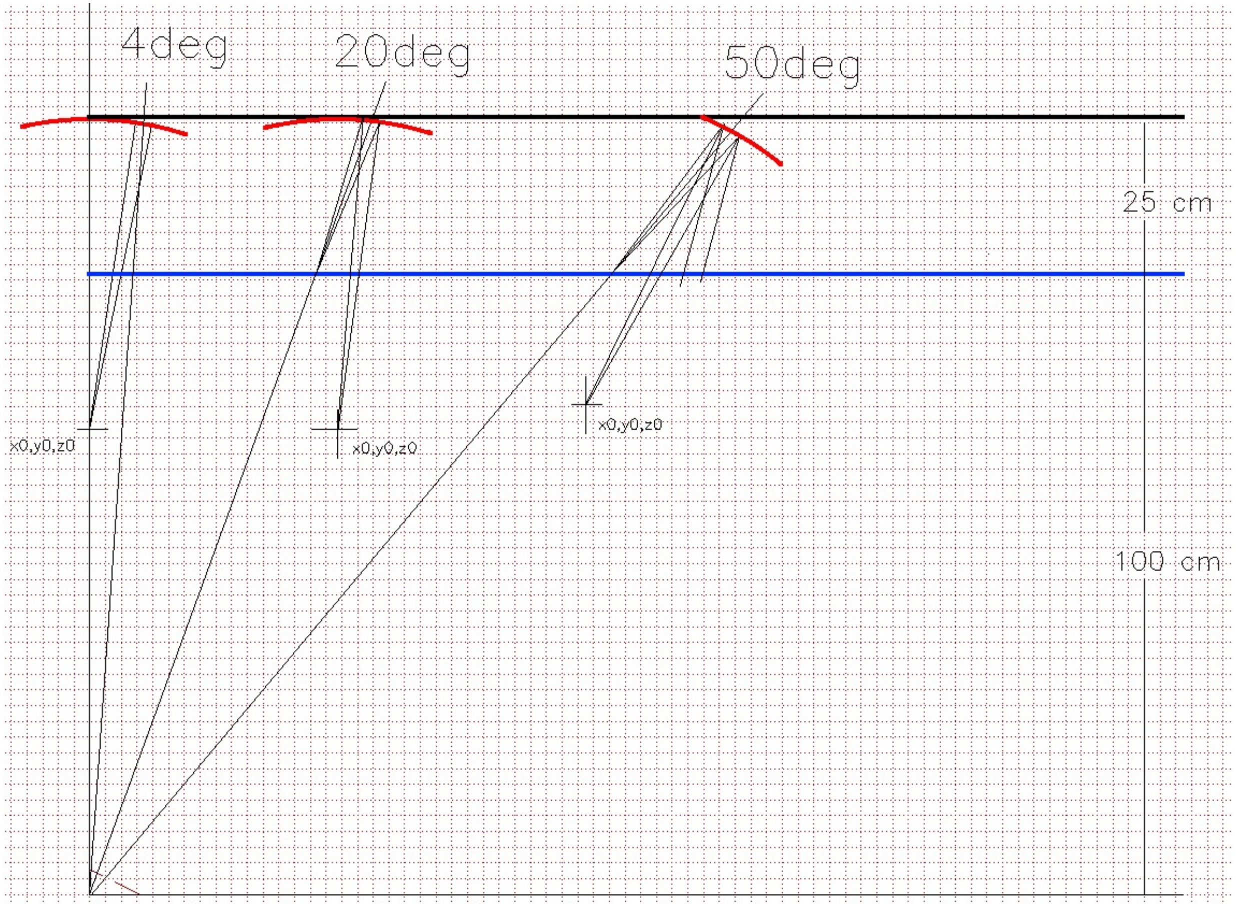


- **3 σ limit: ~60 GeV/c.**

More on smearing effect

Dip angle dependence

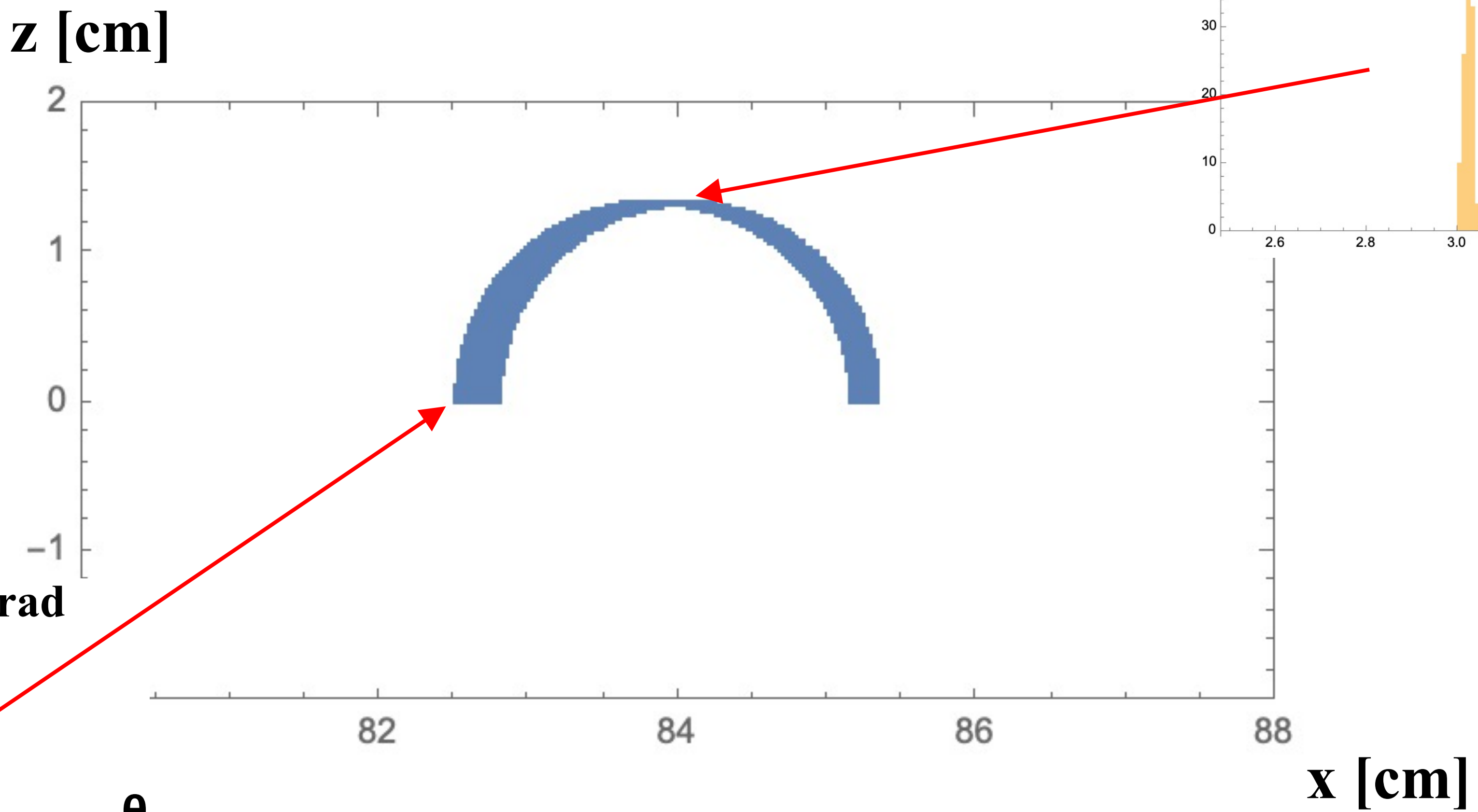
Ray tracing:

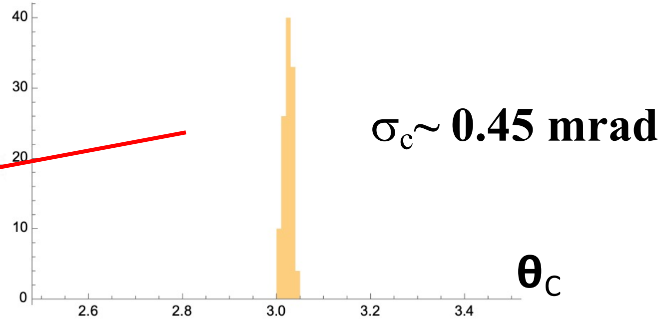


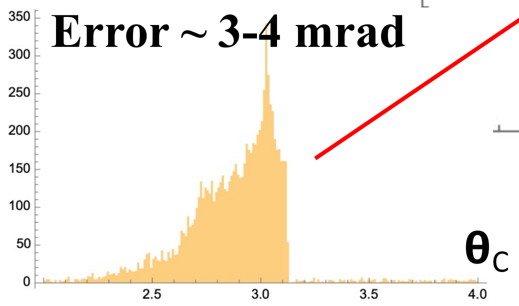
- **Aim is to compare these three cases: θ_{dip} = 4^o, 20^o and 50^o.**
- **For each dip angle I had to move mirror.**

Smearing effect at $\theta_{dip} = 0^o$, 5 Tesla and 20 GeV/c

B = 5 Tesla,
P = 20 GeV/c pions
Pt = 20 GeV/c
Pz = 0 GeV/c
Theta = 90^o
Phi = 90^o
R-helix=13.3 meters
$\boldsymbol{\theta}_C$ = 0.0532 rad
Npe = 16
C_4F_{10} gas



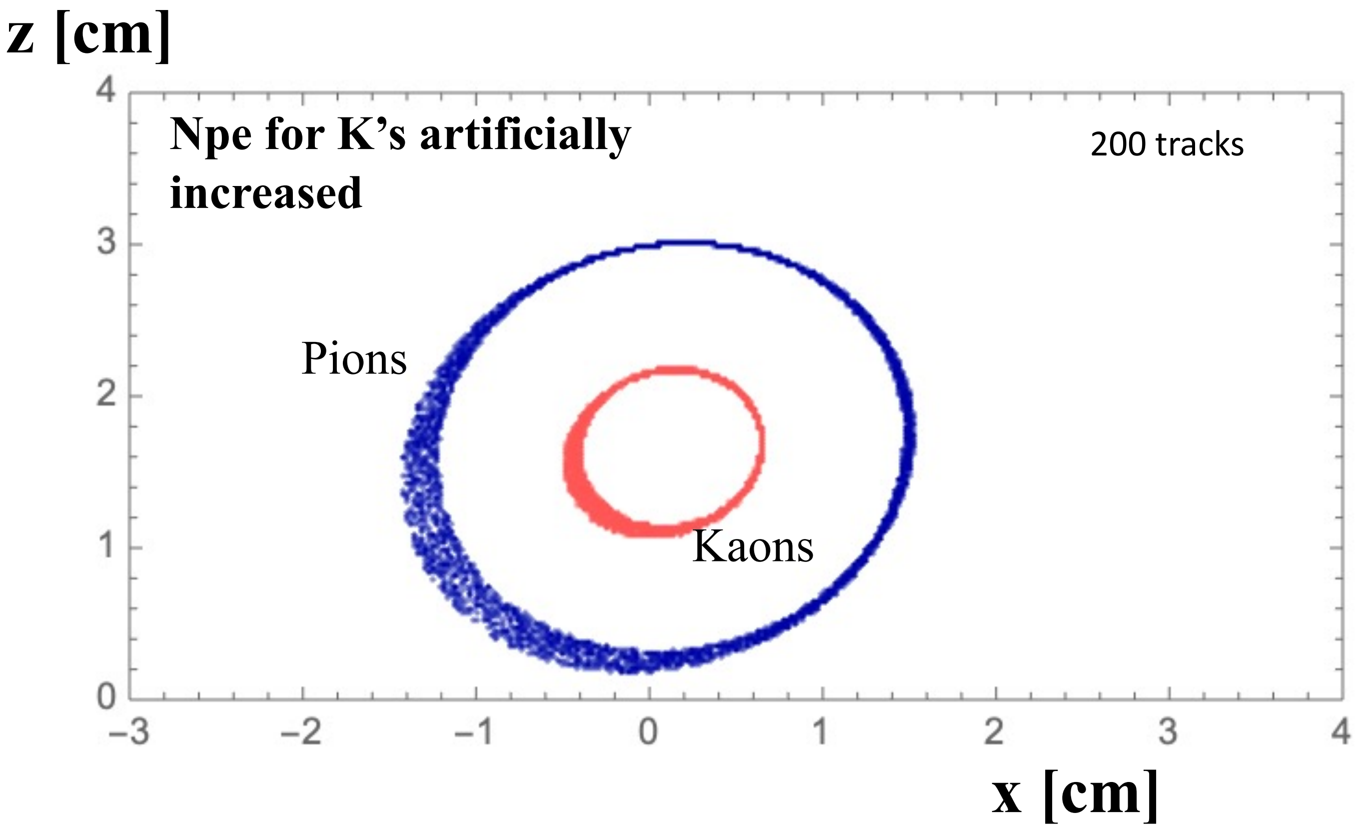




- **Smearing effect varies as a function of $\boldsymbol{\Phi}_c$. One should be able to find a weighting algorithm to improve on the analytical formula.**

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

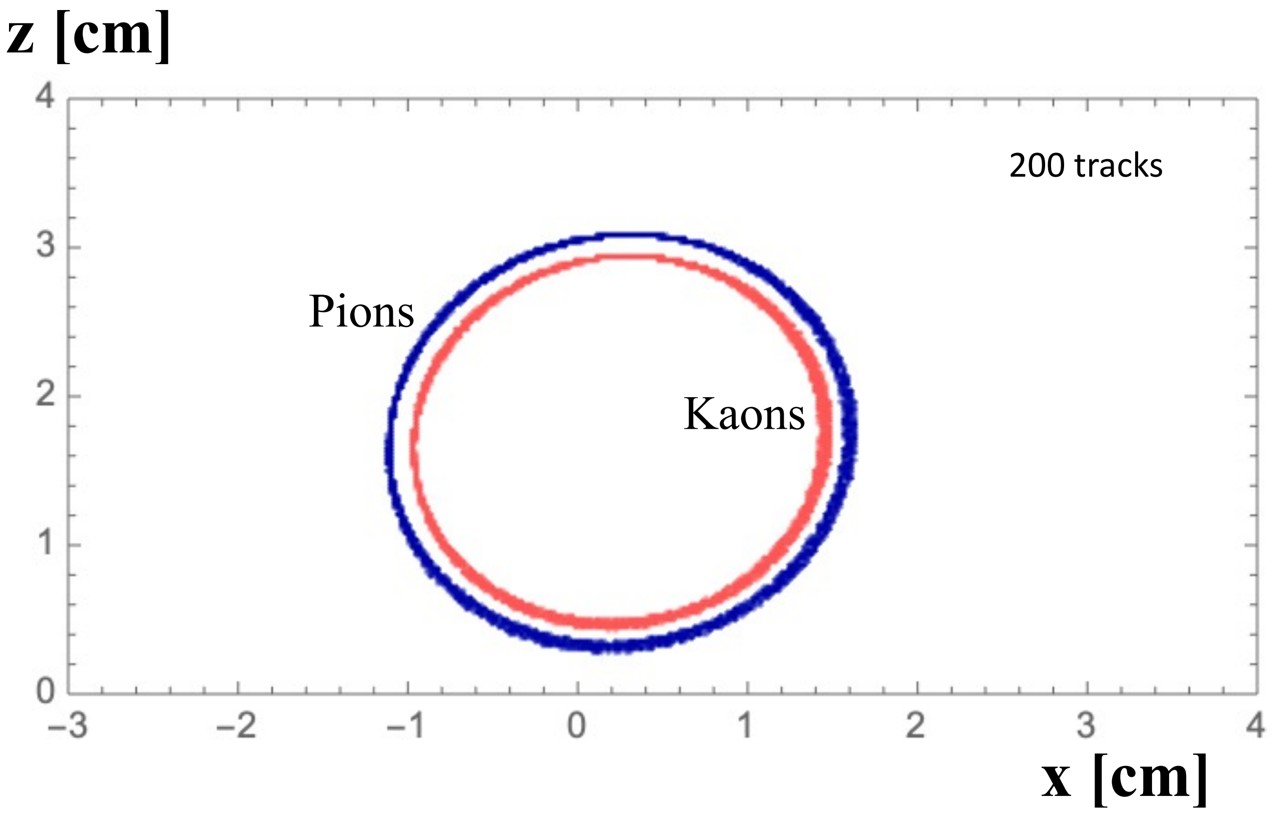
B = 5 Tesla,
P = 10 GeV/c pions
Pt = 9.976 GeV/c
Pz = 0.699 GeV/c
Theta = 86^{o} = 90^{o}- θ_{dip}
Phi = 90^{o}
R-helix=6.65 meters
$\boldsymbol{\theta}_{C}$ (Pions)= 0.0513 rad
$\boldsymbol{\theta}_{C}$ (Kaons)= 0.0198 rad
Npe (Pions) ~ 15
Npe (Kaons) ~ 2-3
C_4F_{10} gas
$L_{radiator}$ = 25 cm



- **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

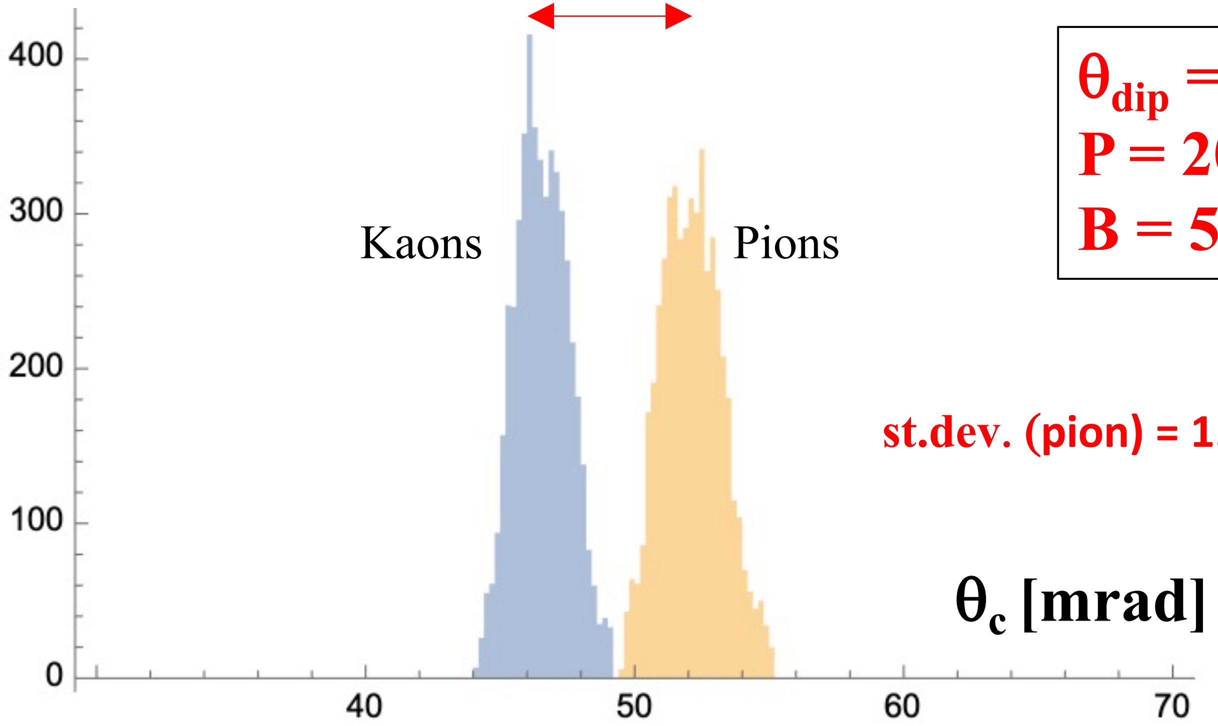


- **Plot all {xfinal[i] & zfinal[i]} 2D-hits in detector plane, no cuts, no fitting.**
- **We determine center of the circle x_0 & z_0.**

Cherenkov rings for θ_{dip} = 4° 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° = 90°- θ_{dip}
Phi = 90°
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
$L_{radiator}$ = 25 cm

$\Delta\theta_c = \theta_c$(pion)- θ_c(Kaon) = 6.1 mrad



θ_{dip} = 4°
P = 20 GeV/c
B = 5 Tesla

st.dev. (pion) = 1.1 mrad

- CherRadius = Sqrt[$(z_{final}[i] - z_0)^2 + (x_{final}[i] - x_0)^2$]; θ_c = CherRadius/(Focallength);
- **I tune x_0 & z_0 to obtain smallest possible standard deviation.**
- **Distributions are not Gaussian.**

Cherenkov rings for θ_{dip} = 4° 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° = 90°- θ_{dip}
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R-helix=13.3 meters
$\boldsymbol{\theta}_C$ (Pions)= 53.2 rad
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Npe (Pions) ~ 16
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C_4F_{10} gas
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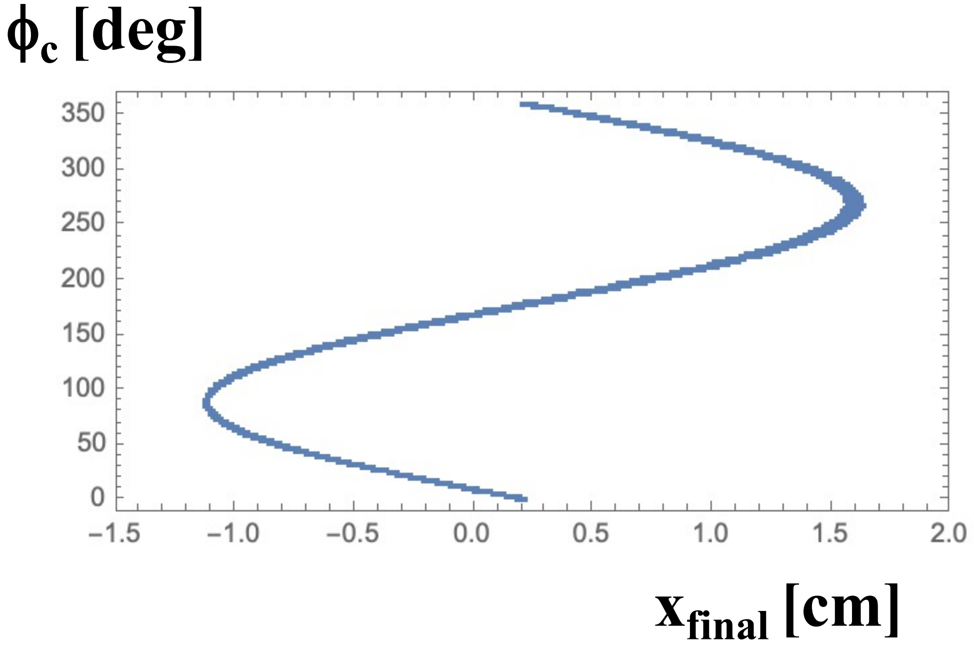

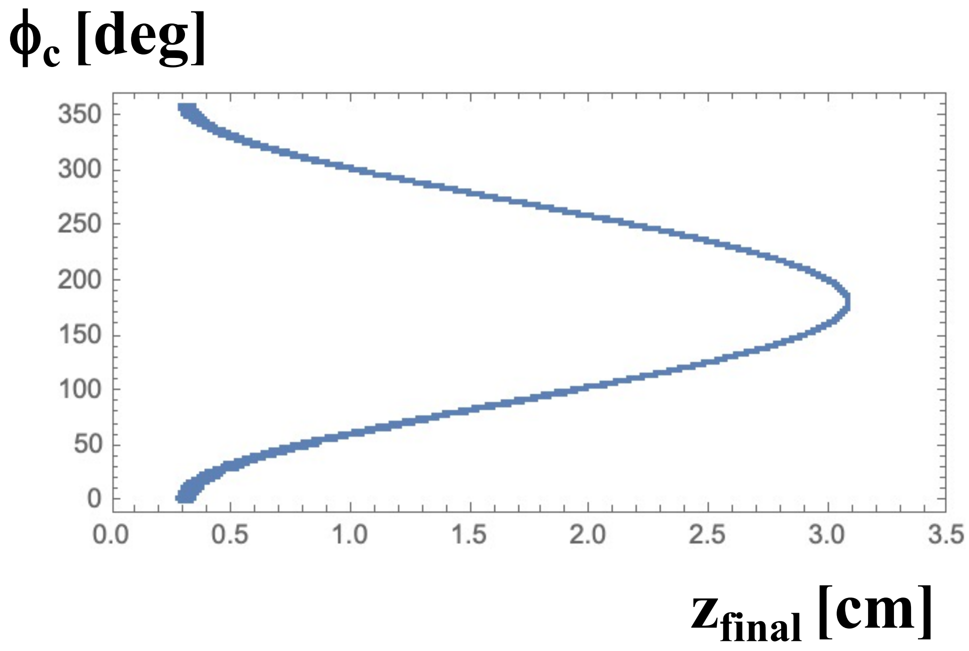

- **Error in x and z varies as a function ϕ_c.**
- **A final analysis will have to take this into account.**