Challenges to design compact gaseous RICH with π/K PID at 50 GeV/c

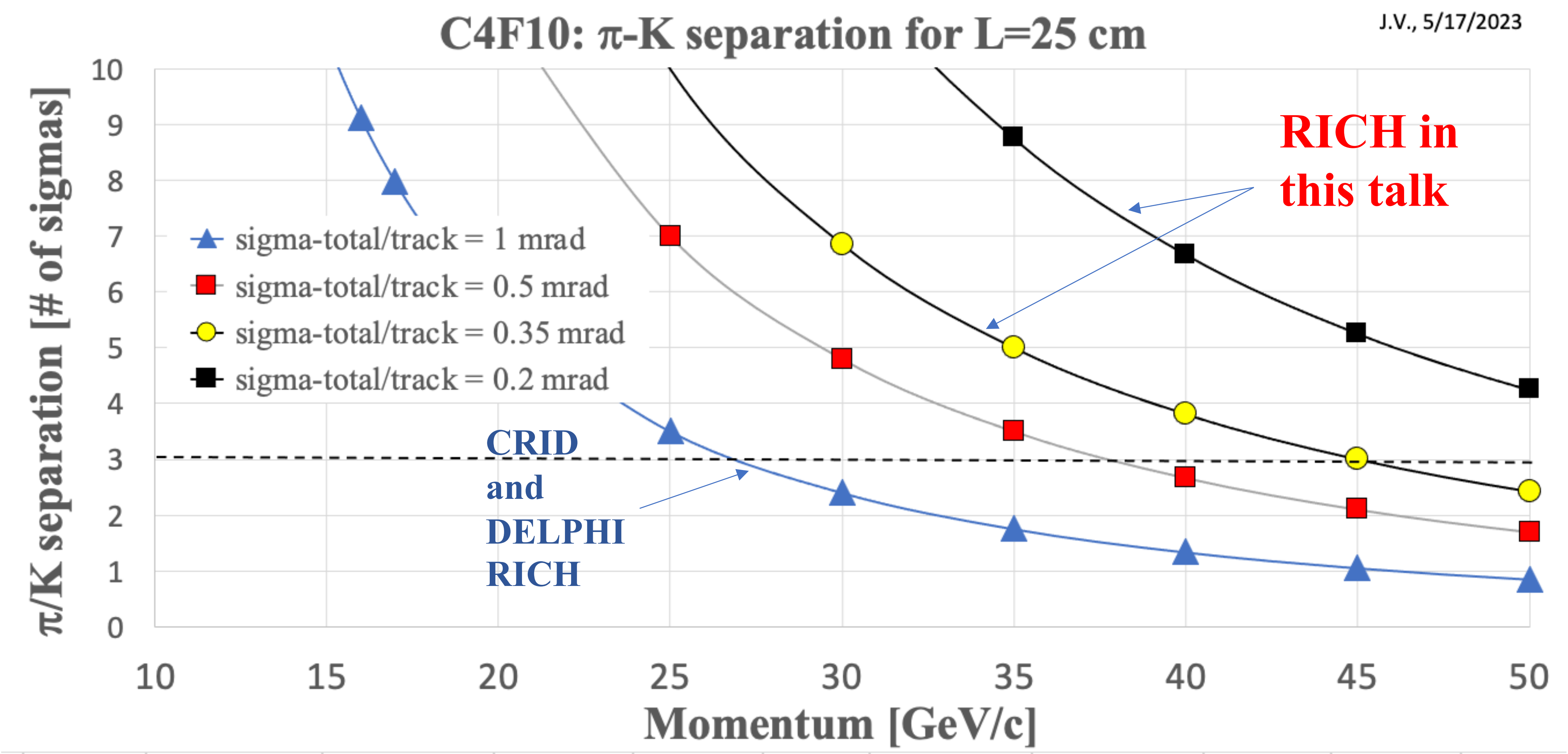
J. Va'vra, SLAC, retired

Discussions with: A. Schartzman, V. Cairo, M. Basso, Ch. Damerell, Su Dong

Motivation for this work can be found in:

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 (note: there will be a version v3 soon describing recent RICH updates).

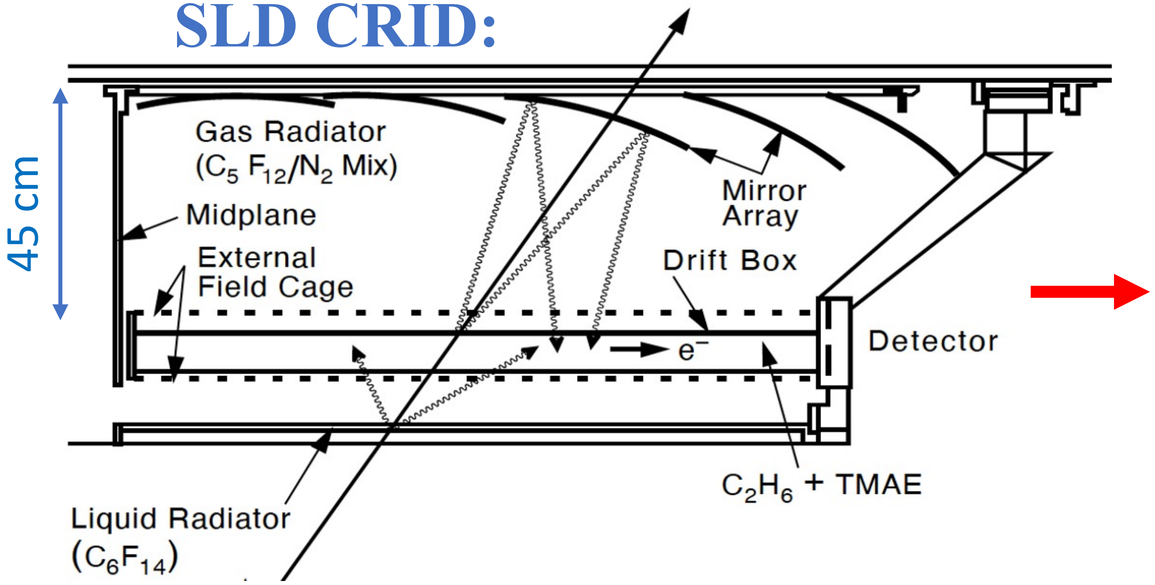
Can we achieve π/K PID at 50 GeV/c ?



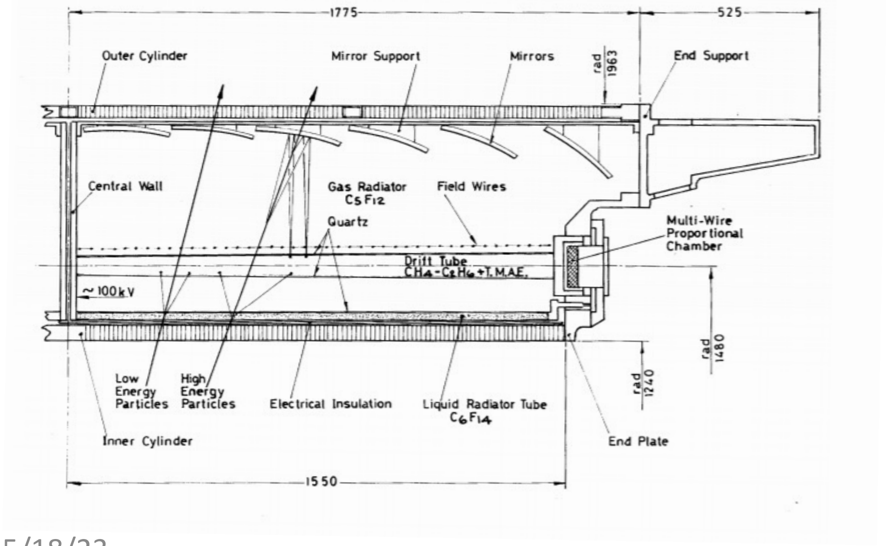
- **Goal of my talk is to convince you that it is possible.**

Our RICH design concept is derived from CRID/Delphi RICH

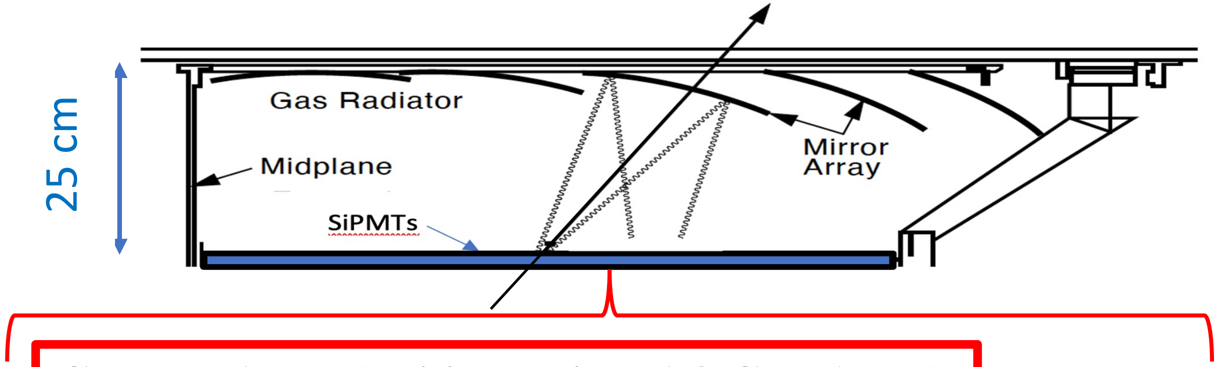
SLD CRID:



Delphi RICH:



Our proposed RICH:



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

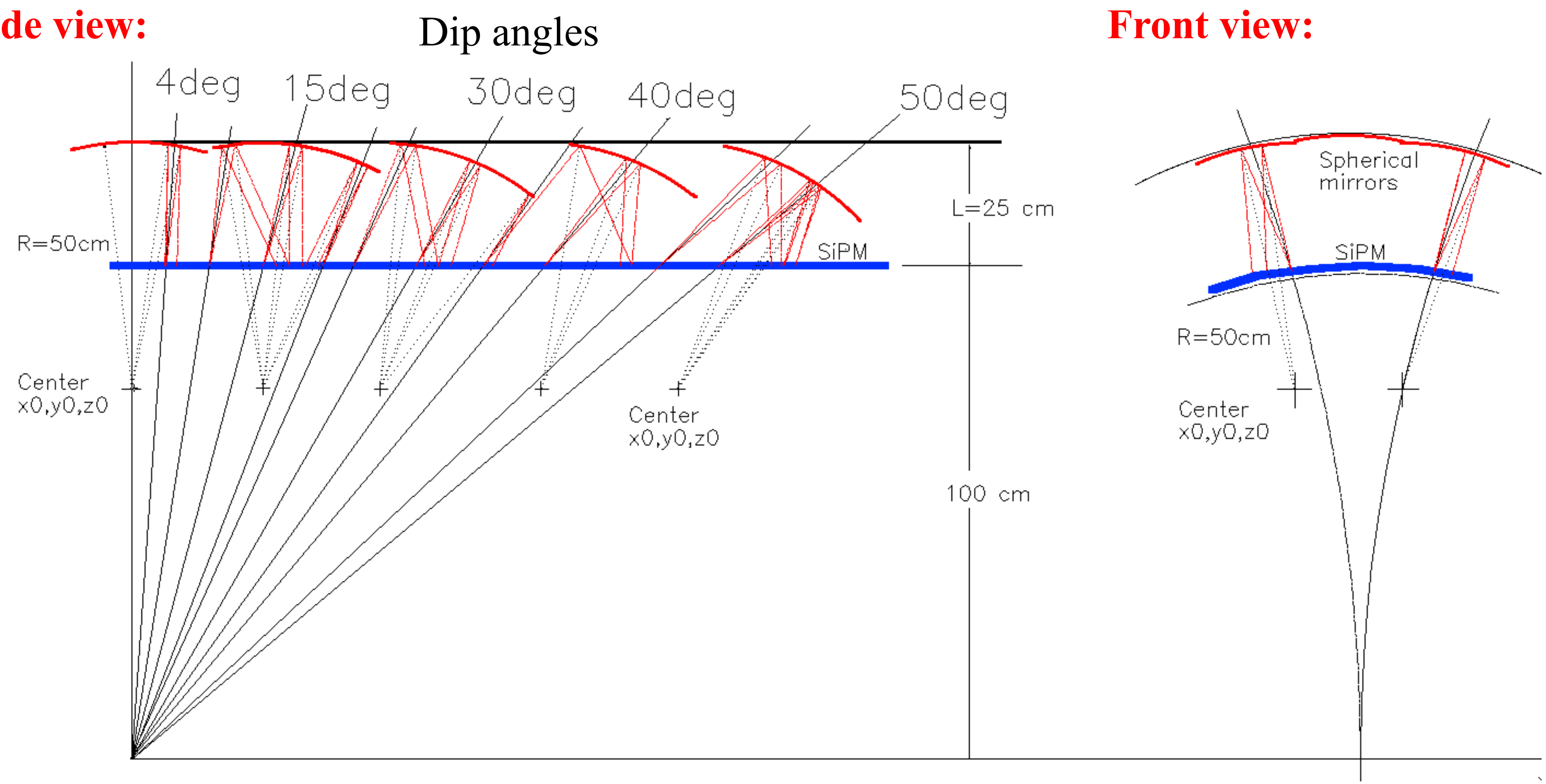
Beryllium mirrors with reflective coating

Low mass carbon-composite structure

Timing will be used to cut SiPM noise

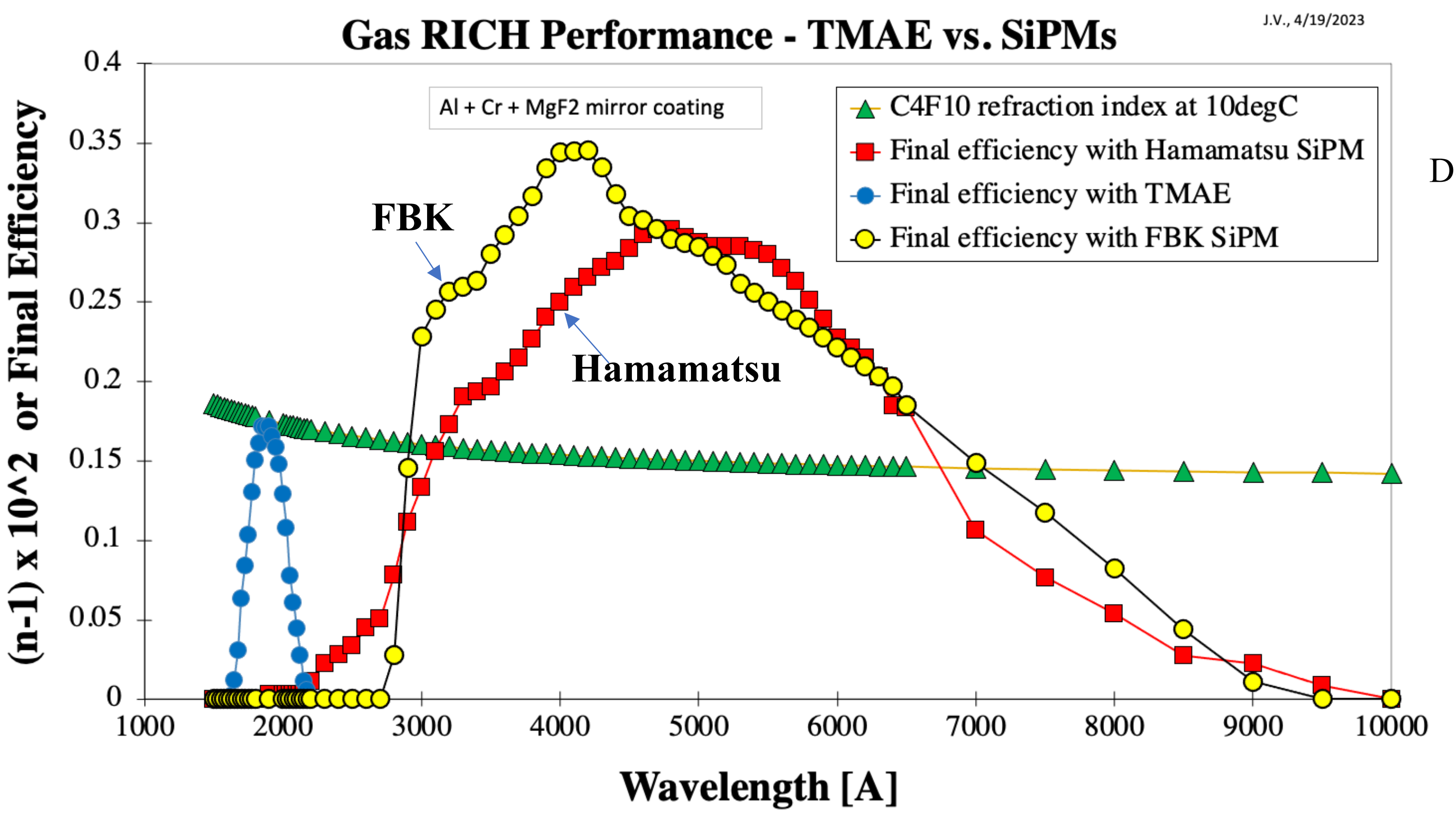
SiPM detector will run at +2-3^{o}C

To help Mathematica with mirror parameters choices, it is necessary to do ray tracing first.



- **Spherical mirrors have radius R = 50 cm, focal length f = 25 cm nominally, except mirrors at large θ_{dip}.**

Final efficiency: TMAE vs. SiPMs



Details in appendix

- **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: $\sigma_{\theta_c}|_{\text{single photon}} \sim$ 0.4 mrad (TMAE) vs. ~0.62 mrad (SiPM).**
- **FBK SiPM QE enhances lower wavelengths.**

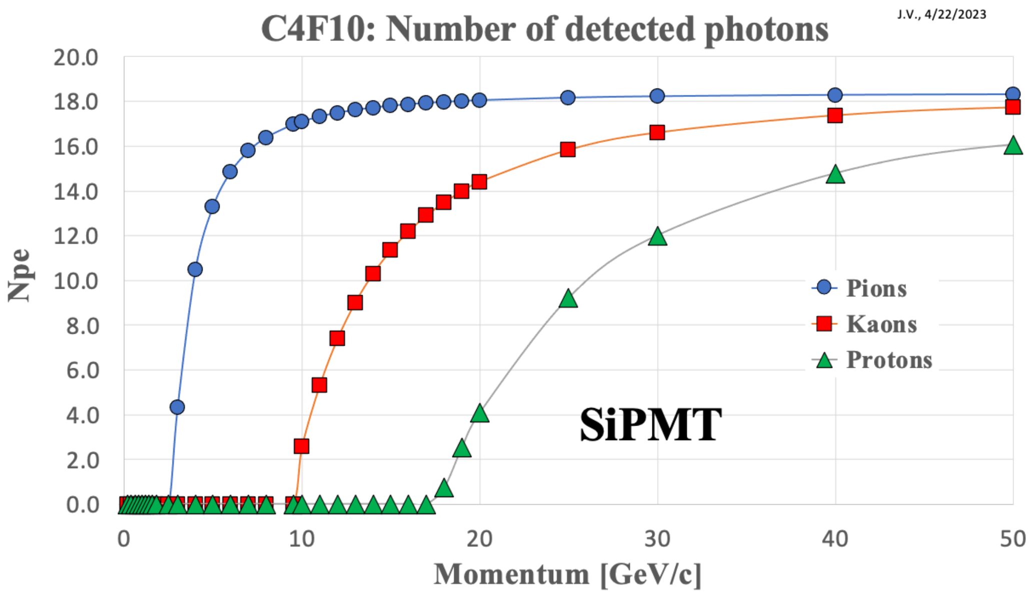
Npe and θ_c in our present design for FBK SiPM

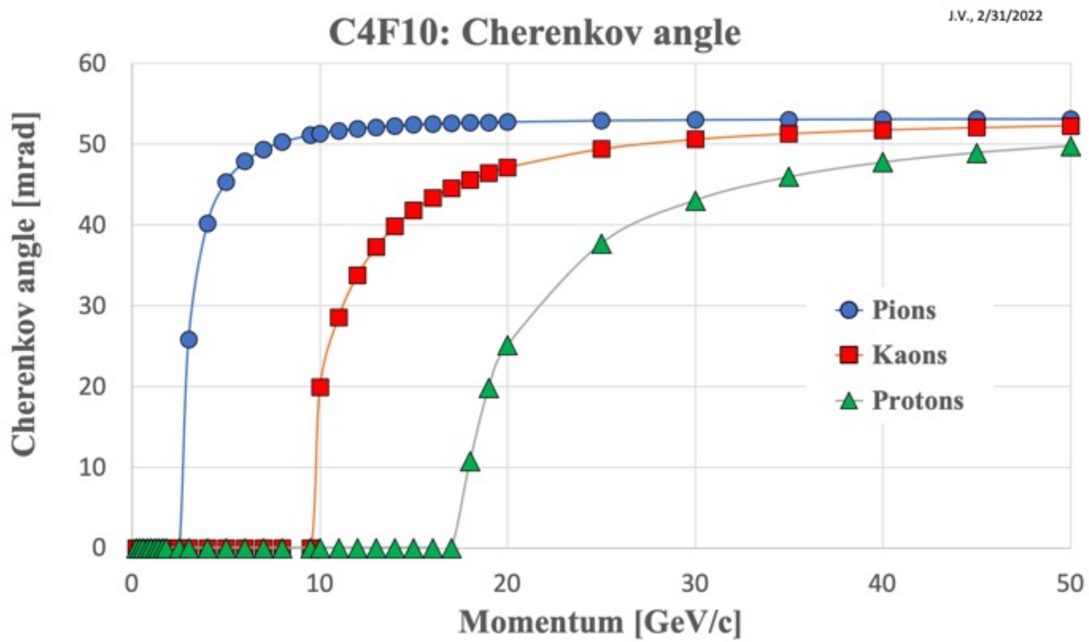
$$N_o = \frac{\left(\frac{\alpha}{hc}\right) \int \mathrm{Eff(E)}[\sin(\theta_c)]^2 dE}{[\sin(<\theta_c>)]^2} = \text{260 for FBK SiPM}$$

$$N_{pe} = N_o\, L\, [\sin <\theta_c>]^2 \quad = \text{19 for } \beta = 1 \text{ particle}$$

$<\theta_c>$ is mean Cherenkov angle

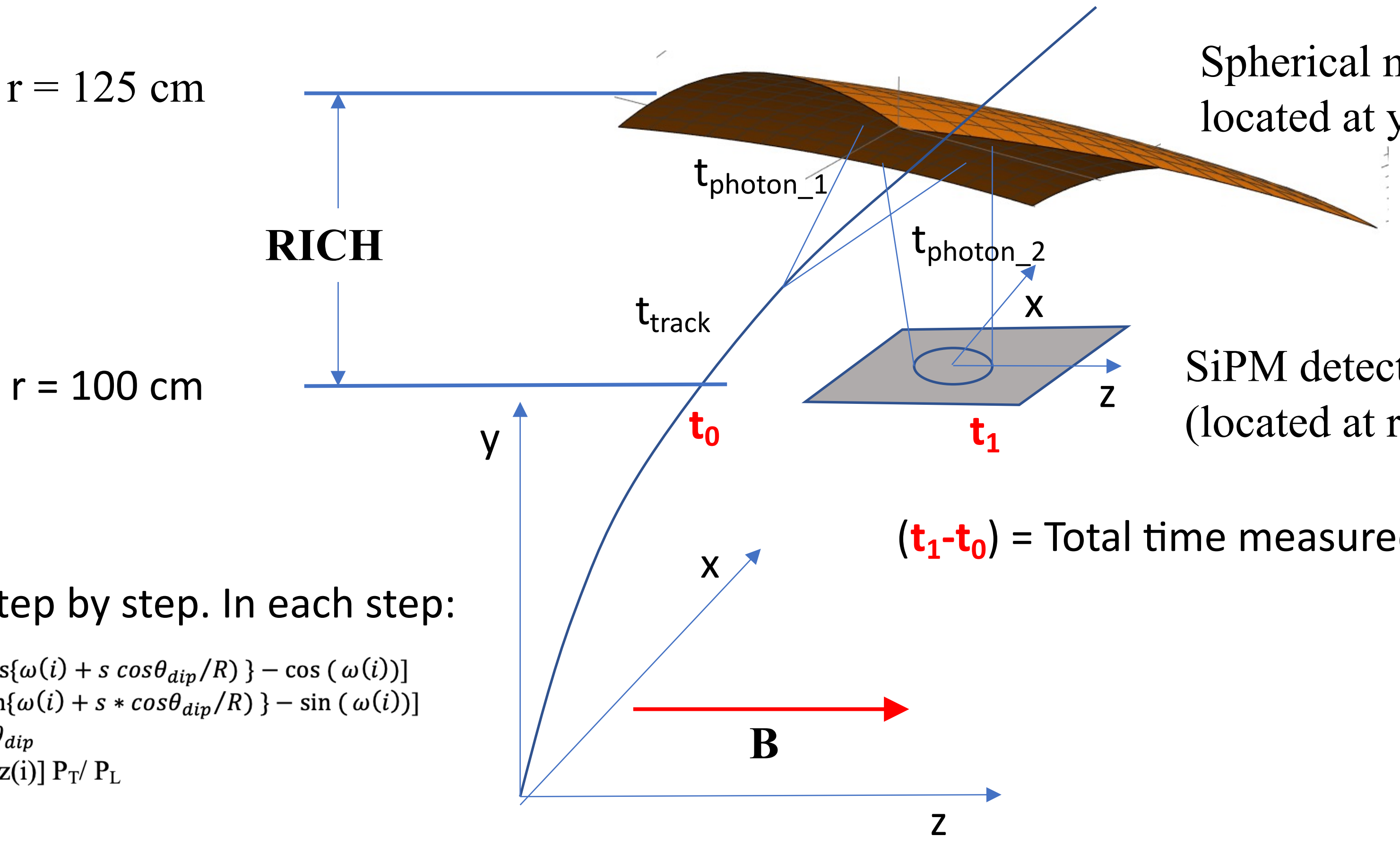
$$\cos\theta_c = 1/(<n>\beta)$$





- L = 25 cm & 1 bar.

Created tracking program in Mathematica



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

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

$(t_1 - t_0)$ = Total time measured = $t_{track} + t_{photon\_1} + t_{photon\_2}$

Follow helix step by step. In each step:

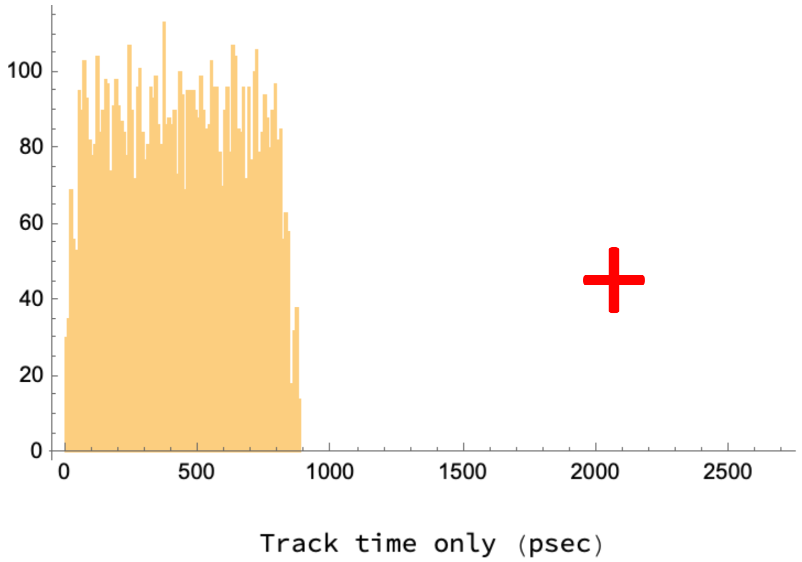
$$x(i+1) = x(i) - R[\cos\{\omega(i) + s\cos\theta_{dip}/R)\} - \cos(\omega(i))]$$
$$y(i+1) = y(i) + R[\sin\{\omega(i) + s * \cos\theta_{dip}/R)\} - \sin(\omega(i))]$$
$$z(i+1) = z(i) + \sin\theta_{dip}$$
$$s\cos\theta_{dip} = [z(i+1) - z(i)]\, P_T / P_L$$

Details in appendix

- **Time t_0 could be a special timing layer (σ_{start}= 10ps), t_1 is FBK SiPM time (σ_{stop}= 25ps).**

Time information for $\theta_{dip} = 4^o$ & 20 GeV/c & B = 5 Tesla

(Pions)



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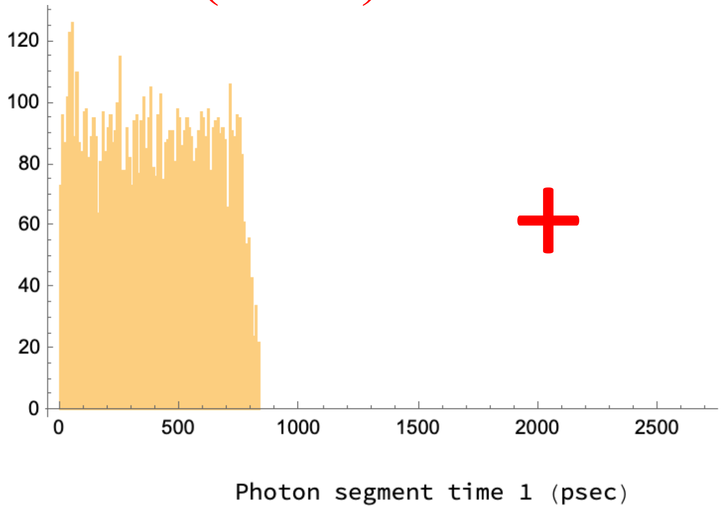

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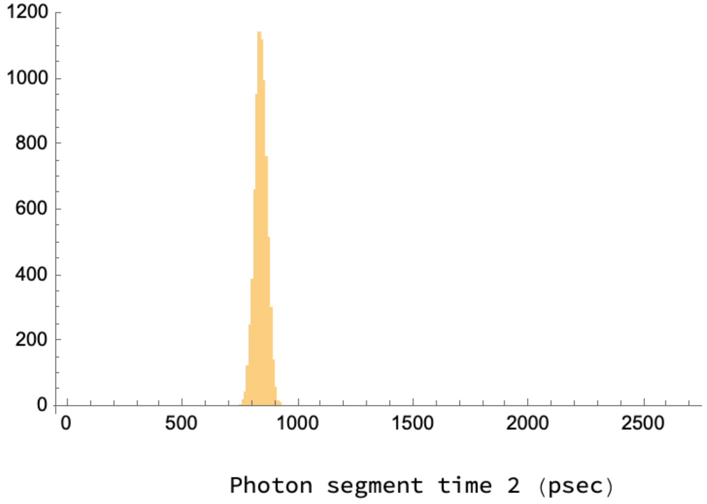

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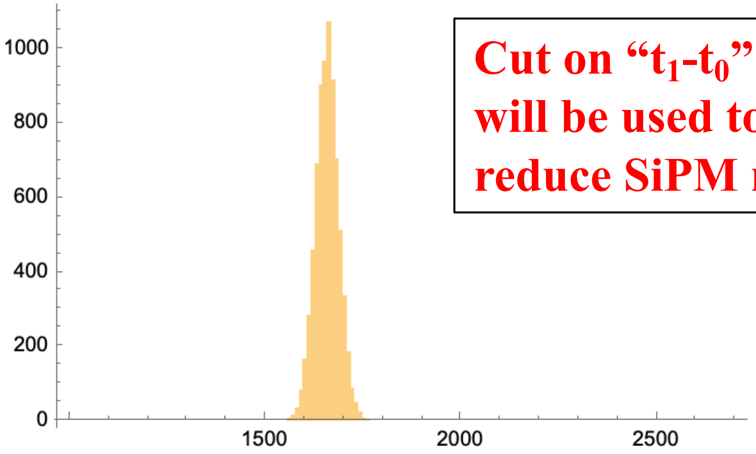


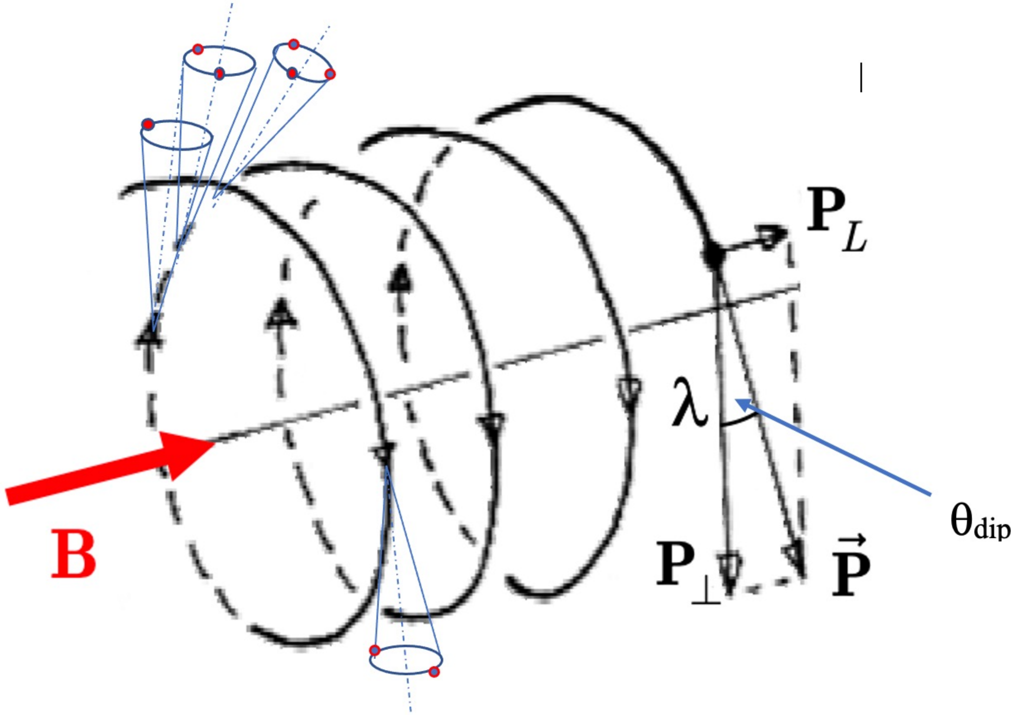
$(t_1\text{-}t_0)$ = Total time = Track time + Photon time 1 + Photon time 2 (psec)

Cut on "t_1-t_0" time will be used to reduce SiPM noise

σ_{start} = 10 ps
σ_{stop} = 25 ps

Smearing and focusing errors - which one dominates ?

Smearing effect in large magnetic field:



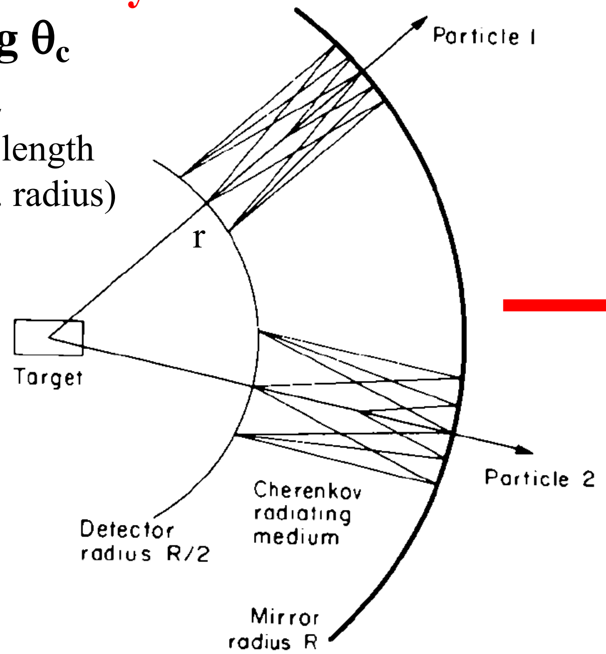
Portion of circle/ellipse can be out of focus:

Ideal geometry:

$r = f \;\; tg\, \theta_c$

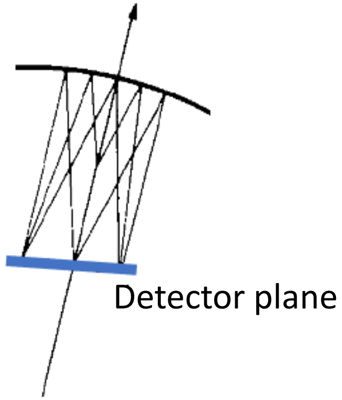
$f = R/2$

(f - focal length
r - Cher. radius)



Ring radius measures Cherenkov angle, independently of track direction.

Real geometry:

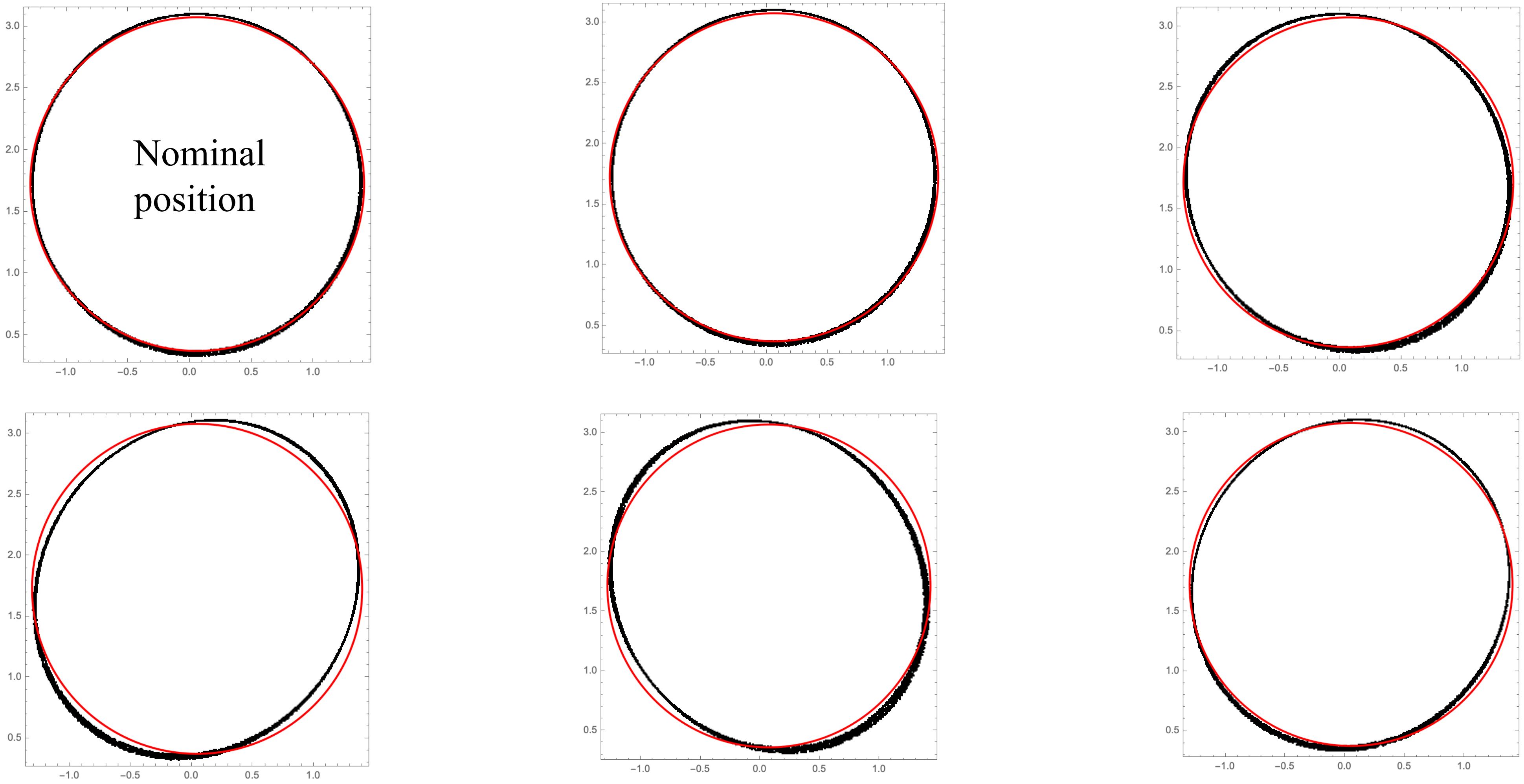


Ring can become ellipse and portion of it out of focus.

(See next slide)

- **Both effects make rings slightly fuzzy at certain Cherenkov angle azimuths ϕ_c.**
- **The focusing error is larger than the smearing error for p > 20GeV/c** – see appendix.

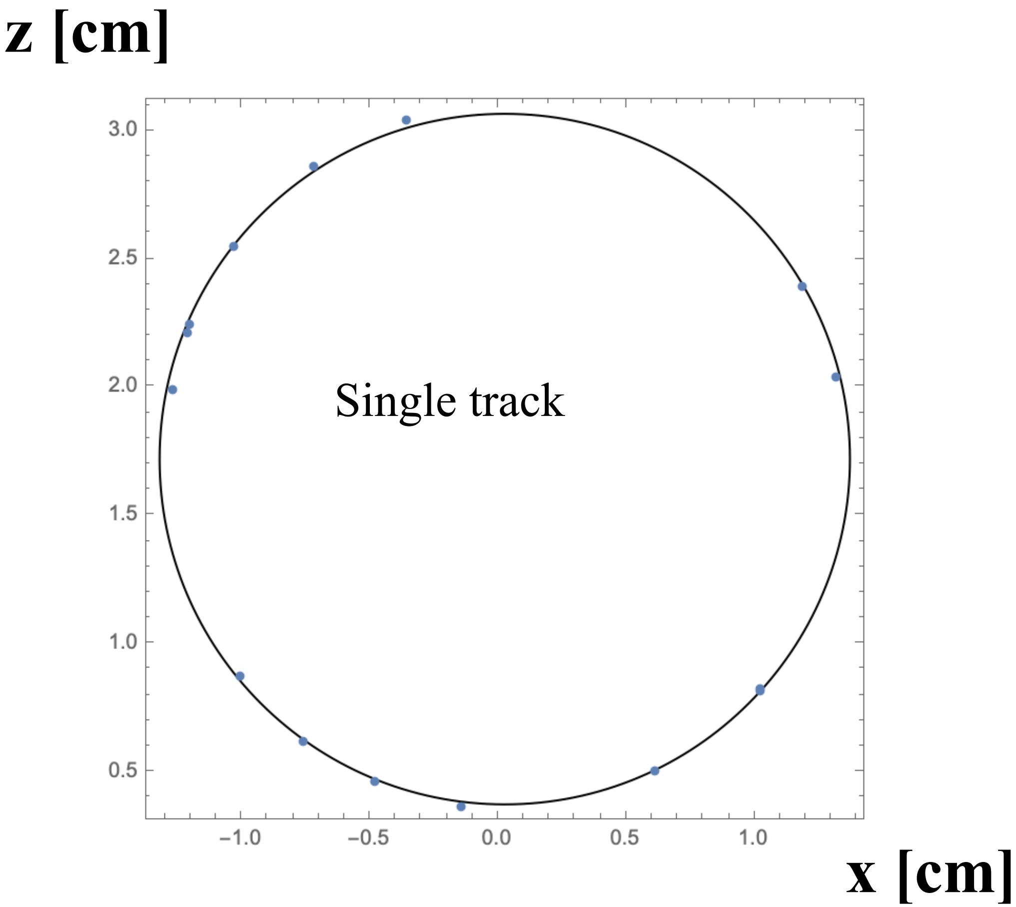
Illustration of ring distortions at $\theta_{dip} = 4^{o}$ & 20 GeV/c & B = 5 Tesla

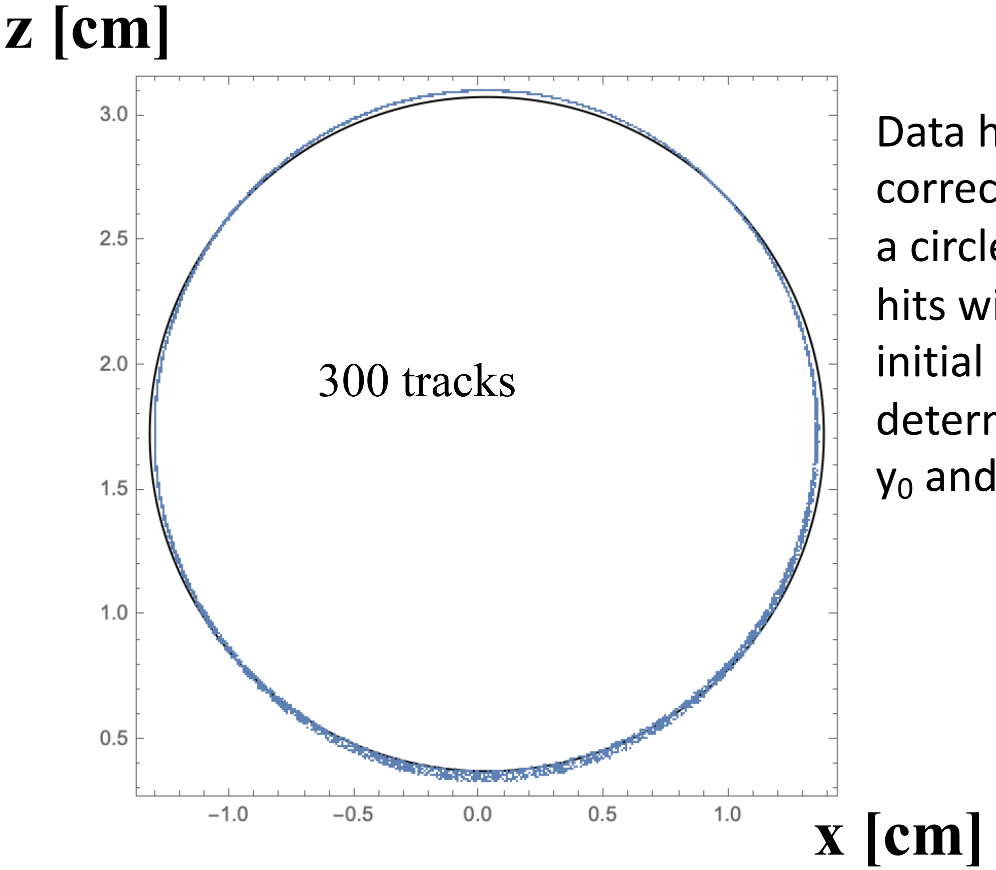


- **I rotated detector plane arbitrarily. Images are ellipses with fuzzy edges.**

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

(Nominal geometry)



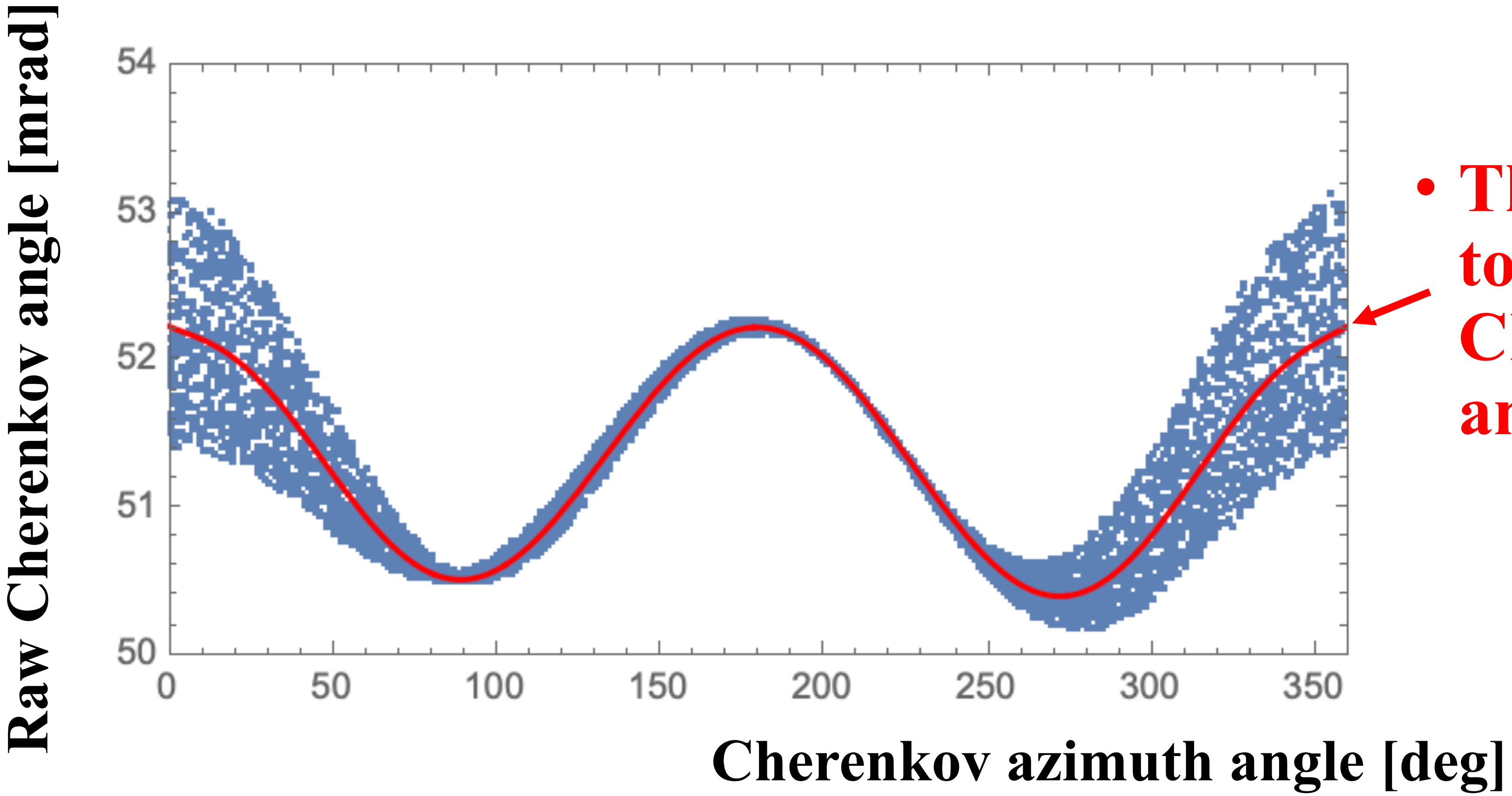


Data have no corrections. Fit a circle to raw hits without any initial guess. Fit determines x_0, y_0 and radius.

- **Based on one event, one does not recognize any distortion. However, it is clear in a sample of 300 tracks. The final image is an ellipse.**

Correction for ellipse distortion at $\theta_{dip} = 4^o$ at 50 GeV/c with B = 5 Tesla

(Nominal geometry)



- **This fit is used to correct raw Cherenkov angle.**

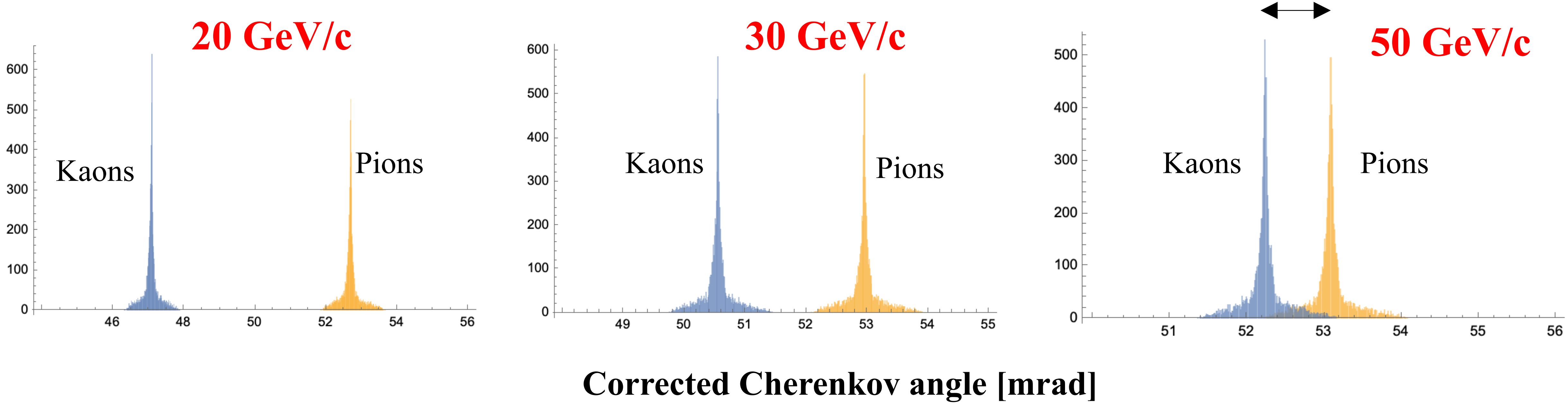
- **Raw ring radius:** CherRadius = Sqrt[$(z_{final}[i] - z_0)^2 + (x_{final}[i] - x_0)^2$] ($x_0$, z_0 - see previous page).
- **Raw Cherenkov angle: θ_c-raw** = CherRadius/(Focallength); (have to supply $x_{0,}$ $z_{0,}$ Focallength)

Results of the correction for $\theta_{dip} = 4^o$ & <u>B = 5 Tesla</u>

(Focusing/smearing errors only)

Typical rms error = 0.25 mrad per single hit (includes tails)

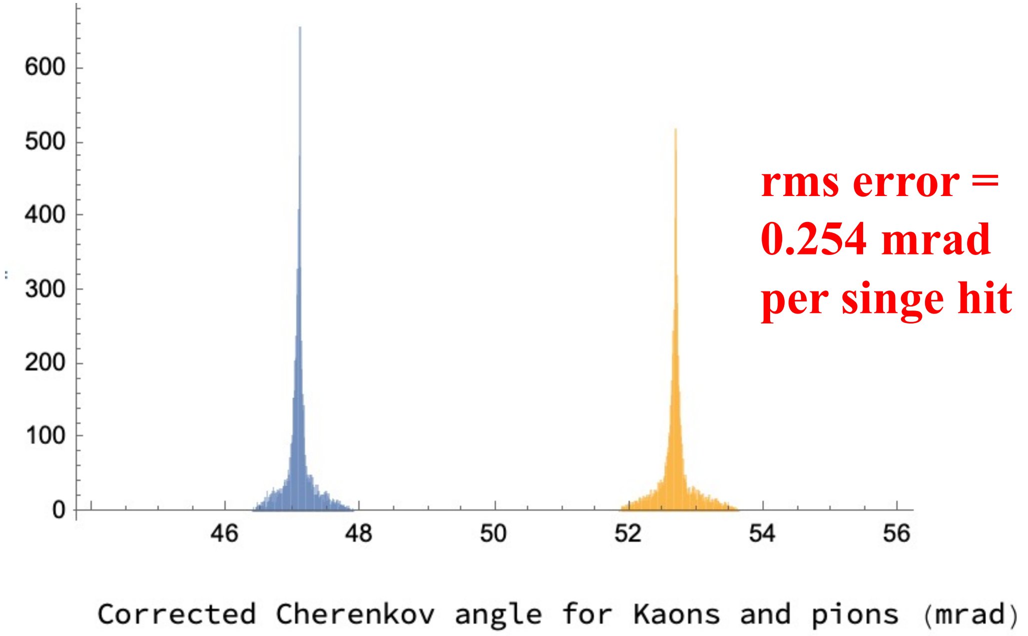
$\Delta\theta_c = \theta_c(\text{pion}) - \theta_c(\text{Kaon}) = 0.85$ mrad



- **Cherenkov angle distribution dramatically improves after the correction for ring distortion. At this point we consider focusing & smearing error only.**

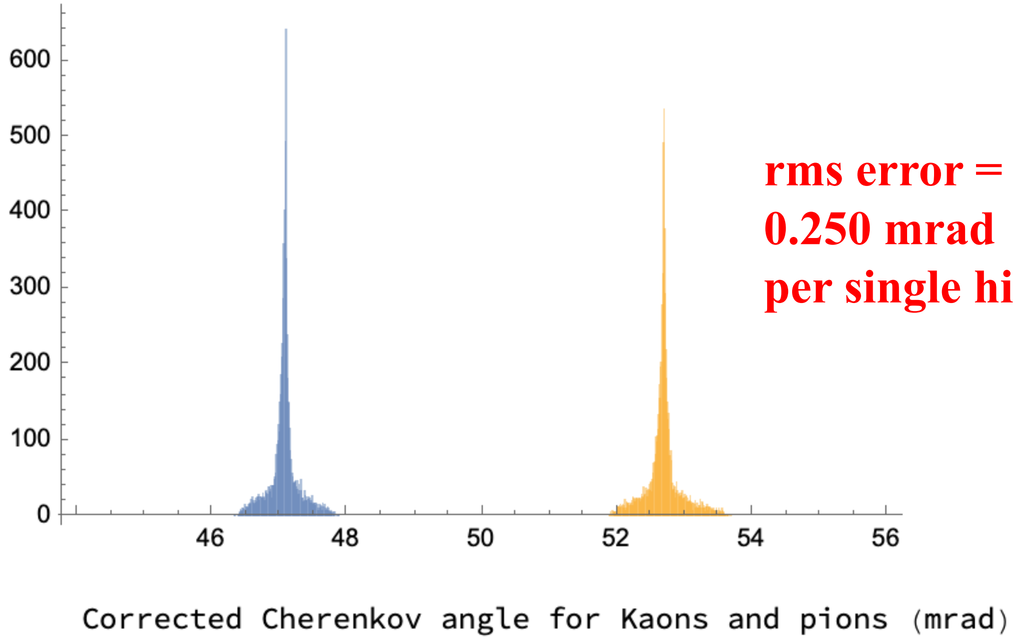
PID for $\theta_{dip} = 4^{o}$ & 20 GeV/c

2 Tesla



rms error =
0.254 mrad
per singe hit

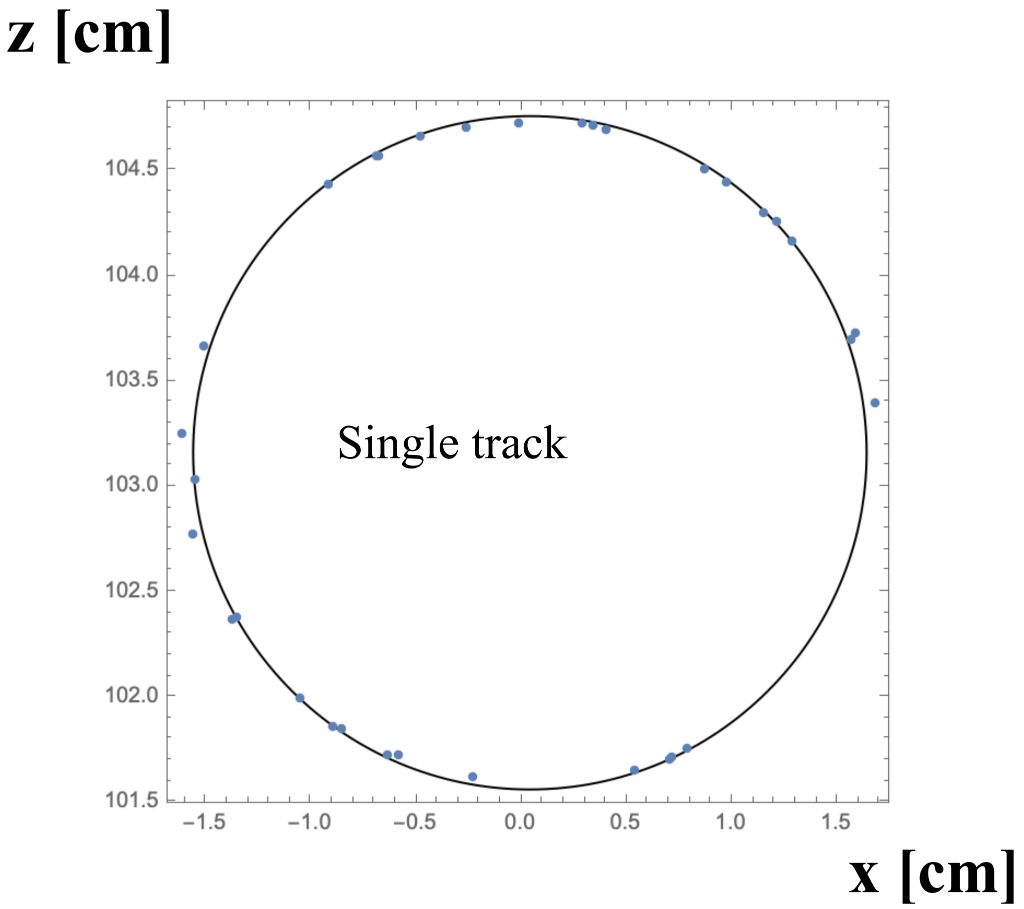
5 Tesla

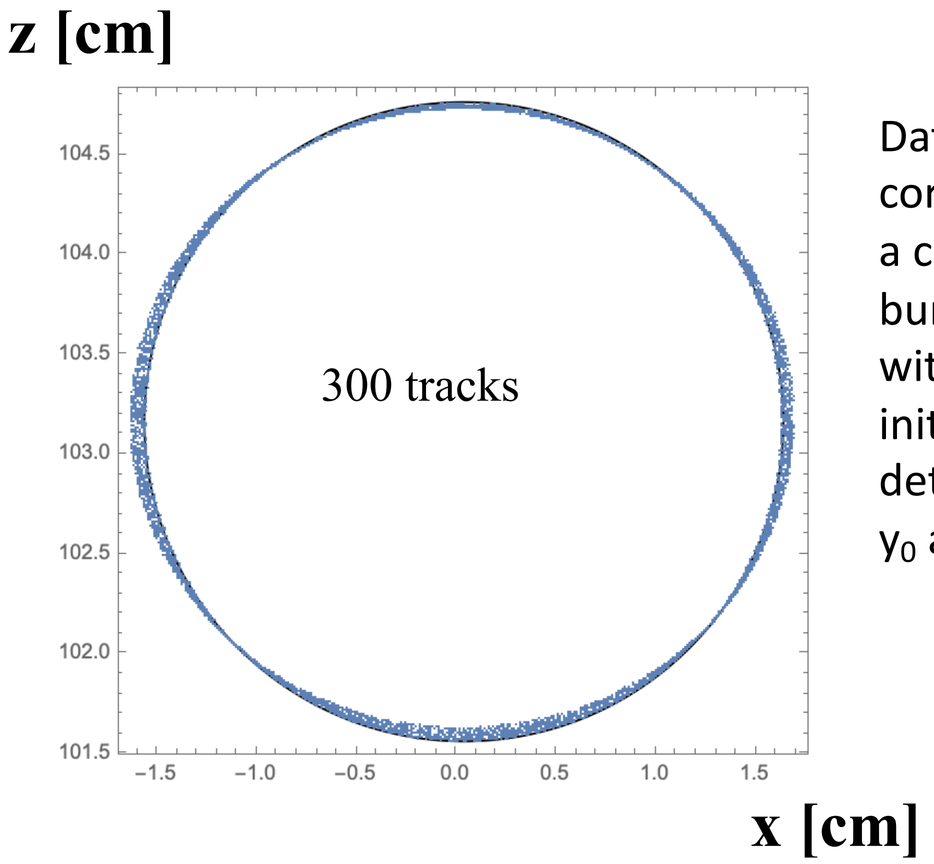


rms error =
0.250 mrad
per single hit

- **Do not see much difference in the corrected Cherenkov angle distribution.**

Cherenkov rings for $\theta_{dip} = 40^o$ & 50 GeV/c & B = 5 Tesla





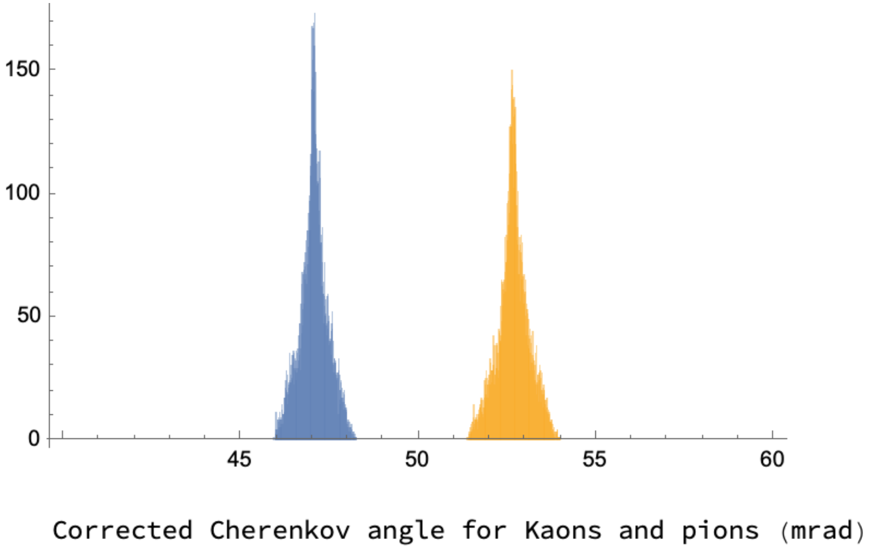
Data have no corrections. Fit a circle to a bunch of points without any initial guess. Fit determines x_0, y_0 and radius.

- **Image is a bit fuzzy in four spots around the azimuth and ellipse.**

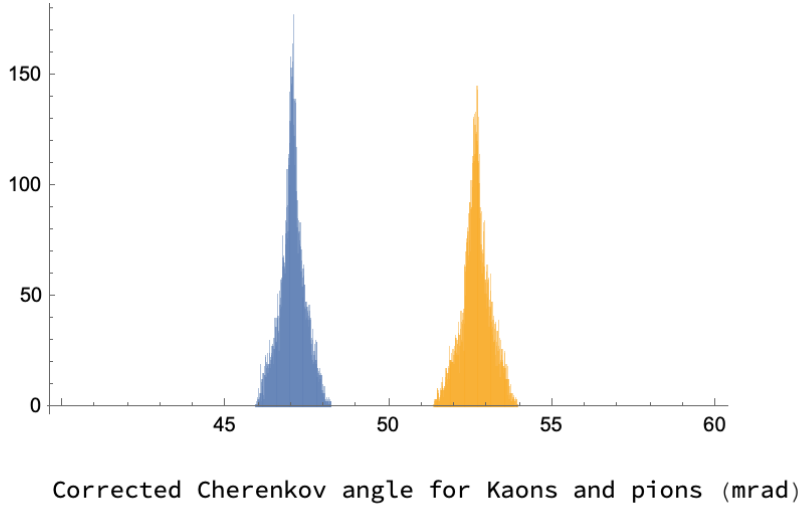
PID for $\theta_{dip} = 40^{o}$

Typical rms error (pion) ~ 0.43 mrad per single hit

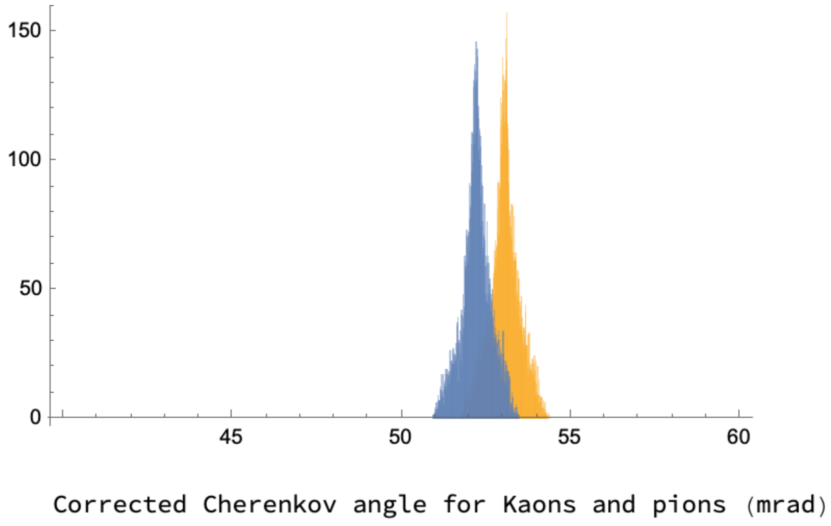
20 GeV/c, 2 Tesla



20 GeV/c, 5 Tesla



50 GeV/c, 5 Tesla



- **Focusing & smearing errors and ring distortion correction only.**
- **Larger dip angles have larger rms error.**

L=25 cm

Total error in our RICH design

Npe ~18 for θ_{dip} =4°, and **24** for θ_{dip} =40°, both at 50 GeV/c

Errors per single photon: $\boldsymbol{\sigma}_{\textbf{single photon}} = \sqrt{}(\boldsymbol{\sigma}_{\textbf{chromatic}}{}^2 + \boldsymbol{\sigma}_{\textbf{pixel}}{}^2 + \boldsymbol{\sigma}_{\textbf{smearing/focusing}}{}^2)|_{\text{single photon}}$

$\sigma_{\text{smearing/focusing}}$ ~ **0.25-0.4** mrad; depends on momentum and dip angle

$\sigma_{\text{chromatic}} = 0.0009*(4.3-1.9)/\sqrt{12}$ ~ **0.62** mrad – see appendix

σ_{pixel} ~ [pixel size $/\sqrt{12}$]/$<L_{\text{photon}}>$ ~ **0.3-0.4** mrad; $<L_{\text{photon}}>$ is average photon path length (for 0.5 mm pixels size)

Common error: σ_{tracking} ~ **0.3** mrad or **0.1** mrad in case of SiD

Total error: $\boldsymbol{\sigma_\theta}$ **/track** = $\boldsymbol{\sigma}_{\textbf{single photon}}/\sqrt{\textbf{Npe}} \otimes \boldsymbol{\sigma}_{\textbf{tracking}}$ ~ **0.35** mrad or ~ **0.2** mrad (SiD)

- **PID performance: 2.5 σ limit or 4.0 σ limit (SiD) at ~50 GeV/c.**

L=25 cm

Error contribution for final error with FBK SiPMs

(Use the overall standard deviation errors for each distribution, i.e., do not use fitted results)

P [GeV/c]	θ_{dip} [deg]	Npe per track for pions	Chromatic error per photon hit [mrad]	Chromatic error per track [mrad]	**0.5mm** pixel error per photon hit [mrad]	**0.5mm** pixel error per track [mrad]	Focusing/ smearing error per photon hit [mrad]	Focusing/ smearing error per track after correction [mrad]	Track error [mrad]	**Total θ_c error per track [mrad]**	PID pi/K separation in number of sigma
20	4	**18**	0.62	**0.143**	0.38	**0.09**	0.25	**0.058**	**0.3**	**0.35**	**16.0**
30	4	**18**	0.62	**0.143**	0.38	**0.09**	0.25	**0.057**	**0.3**	**0.35**	**6.9**
50	4	**18**	0.62	**0.143**	0.38	**0.09**	0.25	**0.057**	**0.3**	**0.35**	**2.4**
50	40	**24**	0.62	**0.125**	0.29	**0.06**	0.44	**0.089**	**0.3**	**0.34**	**2.5**

- **After tracking error, chromatic error is the largest at present.**
- **In blue are parameters we can tune to influence RICH design.**

L=25 cm

Error contribution for final error with FBK SiPMs

(Use the overall standard deviation errors for each distribution, i.e., do not use fitted results)

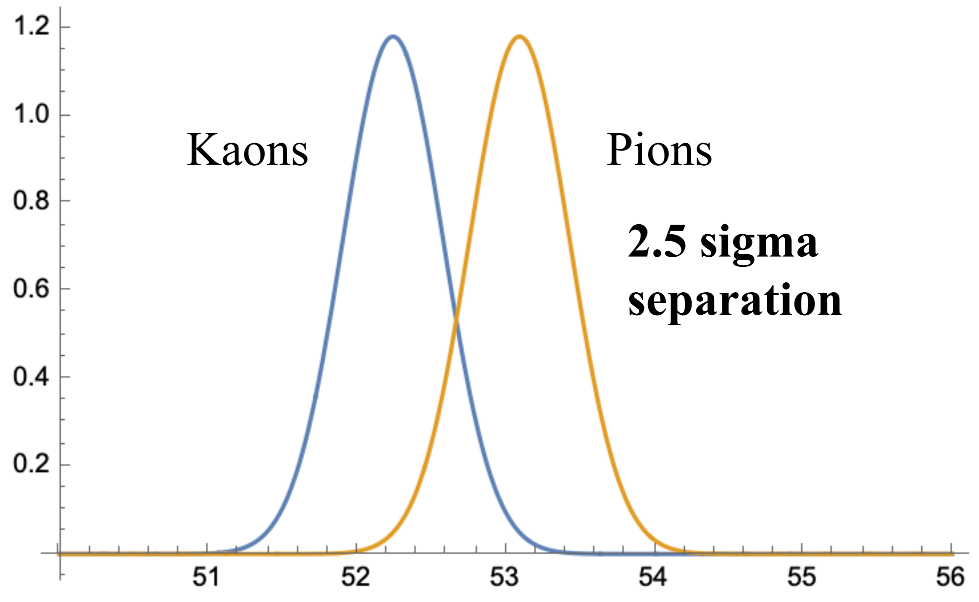
P [GeV/c]	θ_{dip} [deg]	Npe per track for pions	Chromatic error per photon hit [mrad]	Chromatic error per track [mrad]	**0.5mm** pixel error per photon hit [mrad]	**0.5mm** pixel error per track [mrad]	Focusing/ smearing error per photon hit [mrad]	Focusing/ smearing error per track after correction [mrad]	Track error [mrad]	**Total θ_c error per track [mrad]**	PID pi/K separation in number of sigma
20	4	**18**	0.62	**0.143**	0.38	**0.09**	0.25	**0.058**	**0.1**	**0.21**	**26.5**
30	4	**18**	0.62	**0.143**	0.38	**0.09**	0.25	**0.057**	**0.1**	**0.21**	**11.4**
50	4	**18**	0.62	**0.143**	0.38	**0.09**	0.25	**0.057**	**0.1**	**0.21**	**4.0**
50	40	**24**	0.62	**0.125**	0.29	**0.06**	0.44	**0.089**	**0.1**	**0.18**	**4.6**

- **After tracking error, chromatic error is the largest at present.**
- **Now it really makes sense to reduce chromatic & pixel errors.**

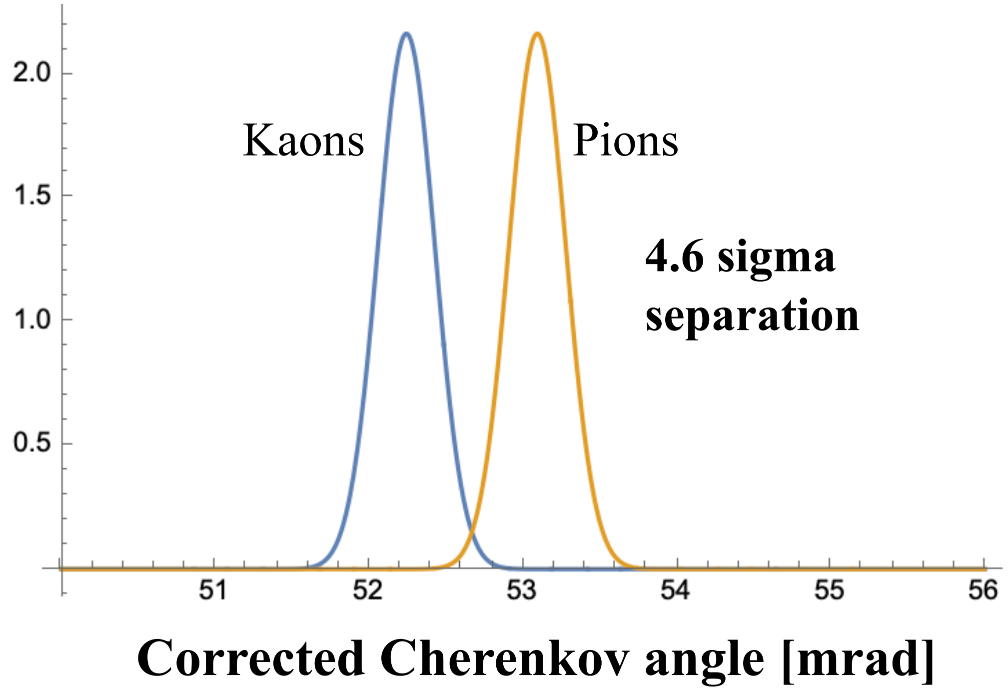
SiD ?

Expected PID for $\theta_{dip} = 40^{o}$ at 50 GeV/c & B = 5 Tesla

$\sigma_{tracking} \sim$ **0.3** mrad



$\sigma_{tracking} \sim$ **0.1** mrad



- **Tracking error really makes a difference.**
- **In this plot we consider all contributions to the final error.**

Conclusion

- **We have demonstrated that π/K separation of 4.6σ is possible at 50 GeV/c & 5 T,**

  if tracking direction error will be ~ 0.1 mrad.

- **We find that the focusing effect error is <u>larger</u> than the magnetic smearing error for momenta larger than 20 GeV/c.**

Next:

- Introduce a realistic SiPM noise to verify that timing cuts work.

Down the road challenges:

- Optimize optical design of the entire system considering all tracks.

- MC simulation of the entire system

Appendix

FBK 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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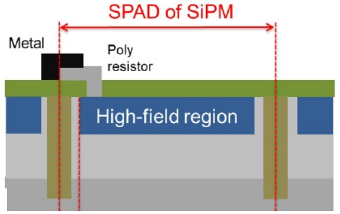
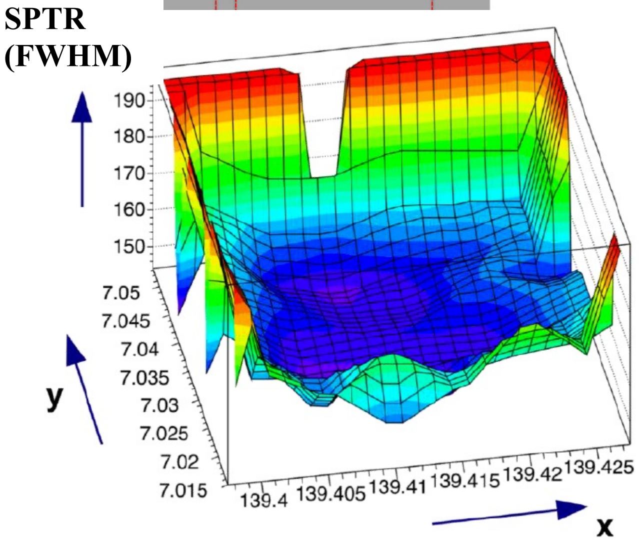
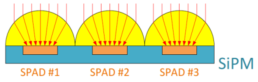
Each SPAD element has edge effects:

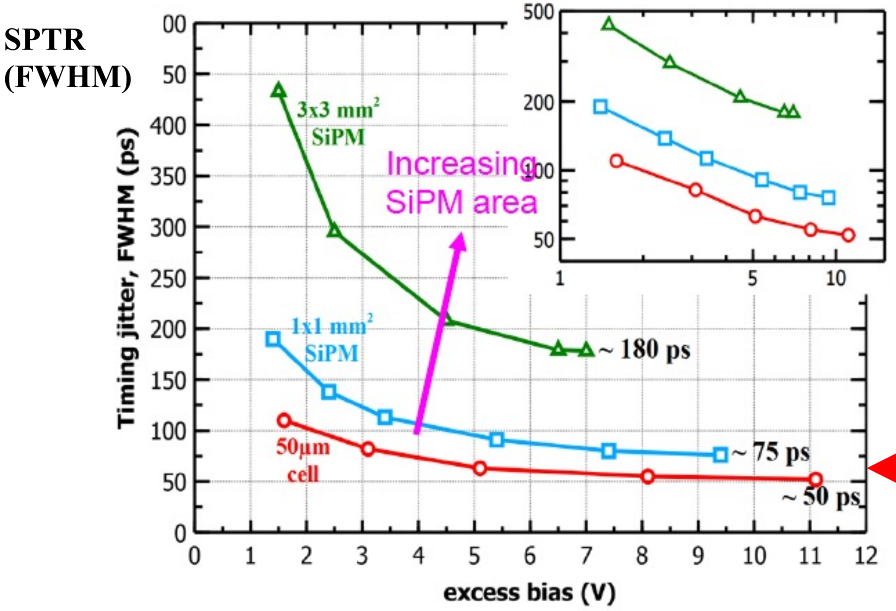




Gola’s suggestion:
Use micro-lenses to remove edge effect:



Large arrays have slightly worse timing resolution:



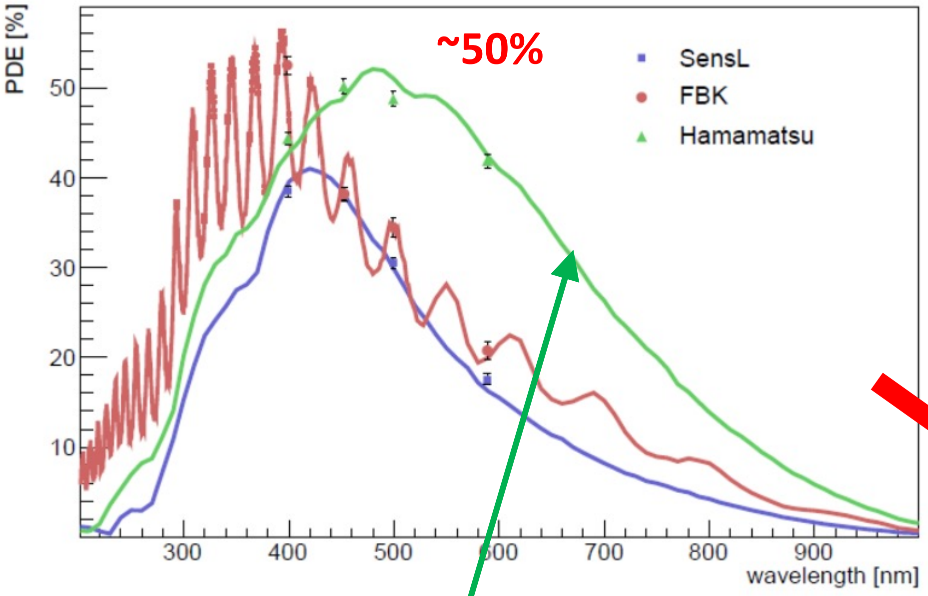
σ ~25 ps

Gola’s suggestion:
Organize array differently to improve timing

- **0.5mm pixel SiPM can reach single photon timing resolution/pixel of σ ~25 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, Gola et al. (2019). *Sensors*, *19*(2), 308.



Photon detection efficiency of single SiPM:

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

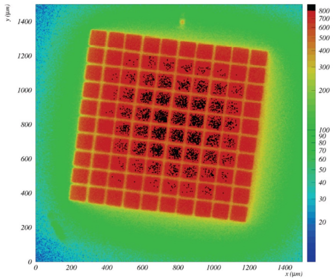
$QE(\lambda)$ – QE of Si

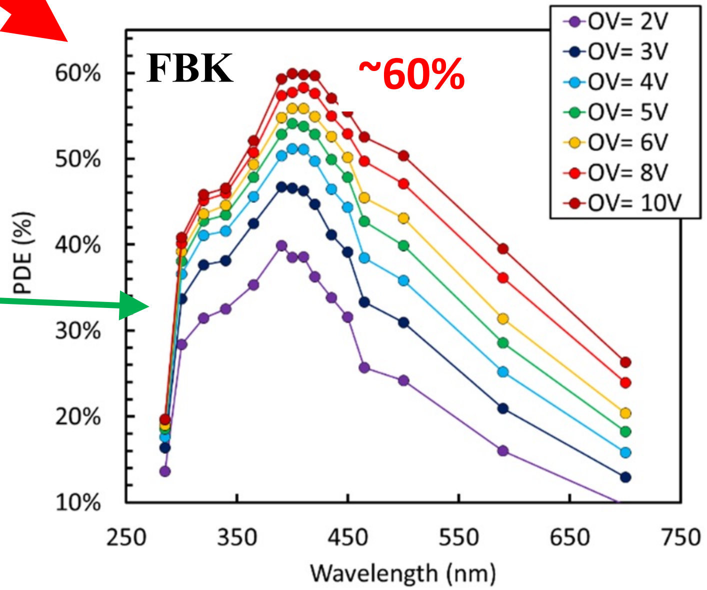
FF – Fill factor within one SiPM

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

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

I assume 65%:



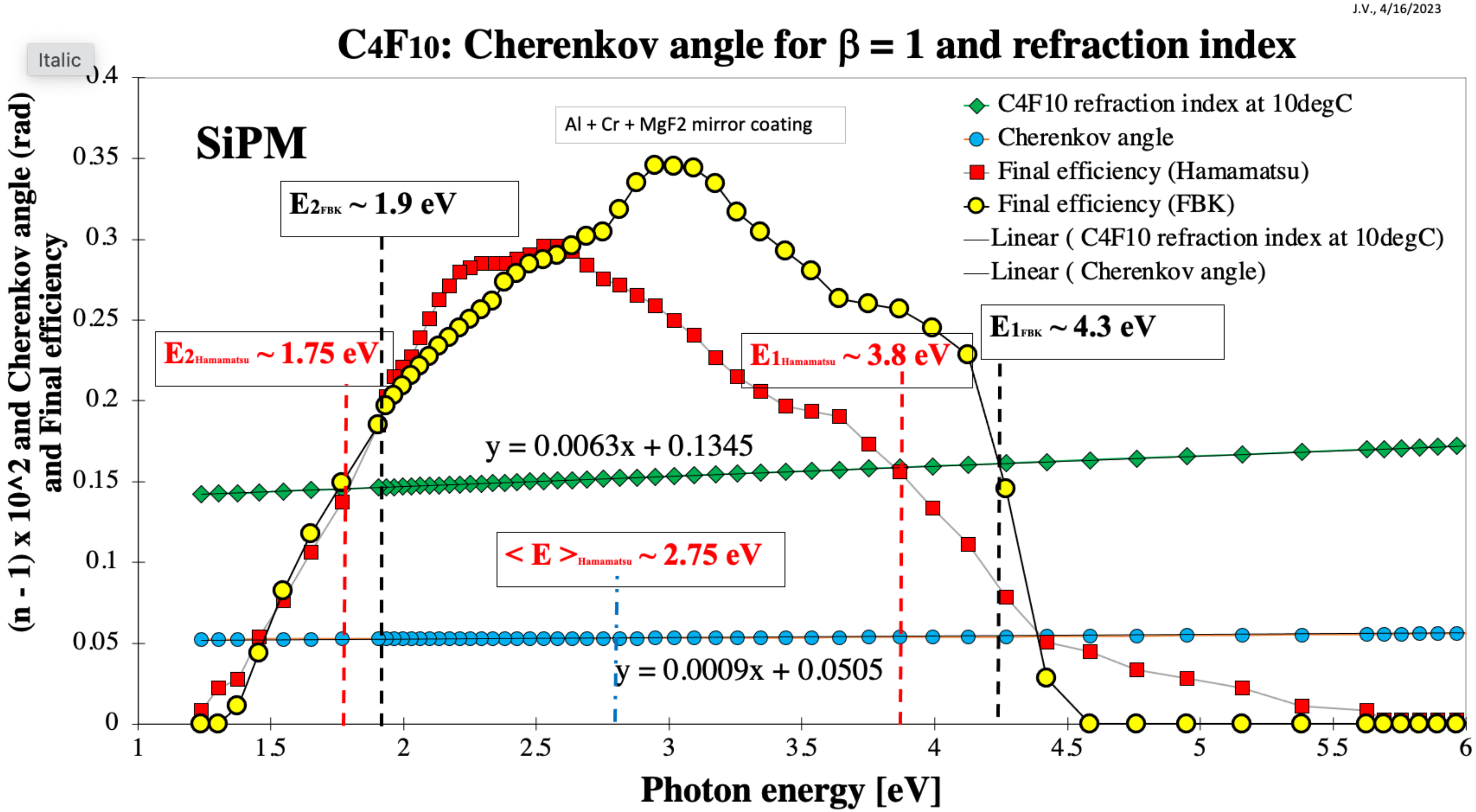


- **We switched from Hamamatsu SiPM PDE in the calculation to FBK SiPM PDE.**

This gives us a few photoelectrons extra !

Chromatic error: FBK vs. Hamamatsu

J.V., 4/16/2023

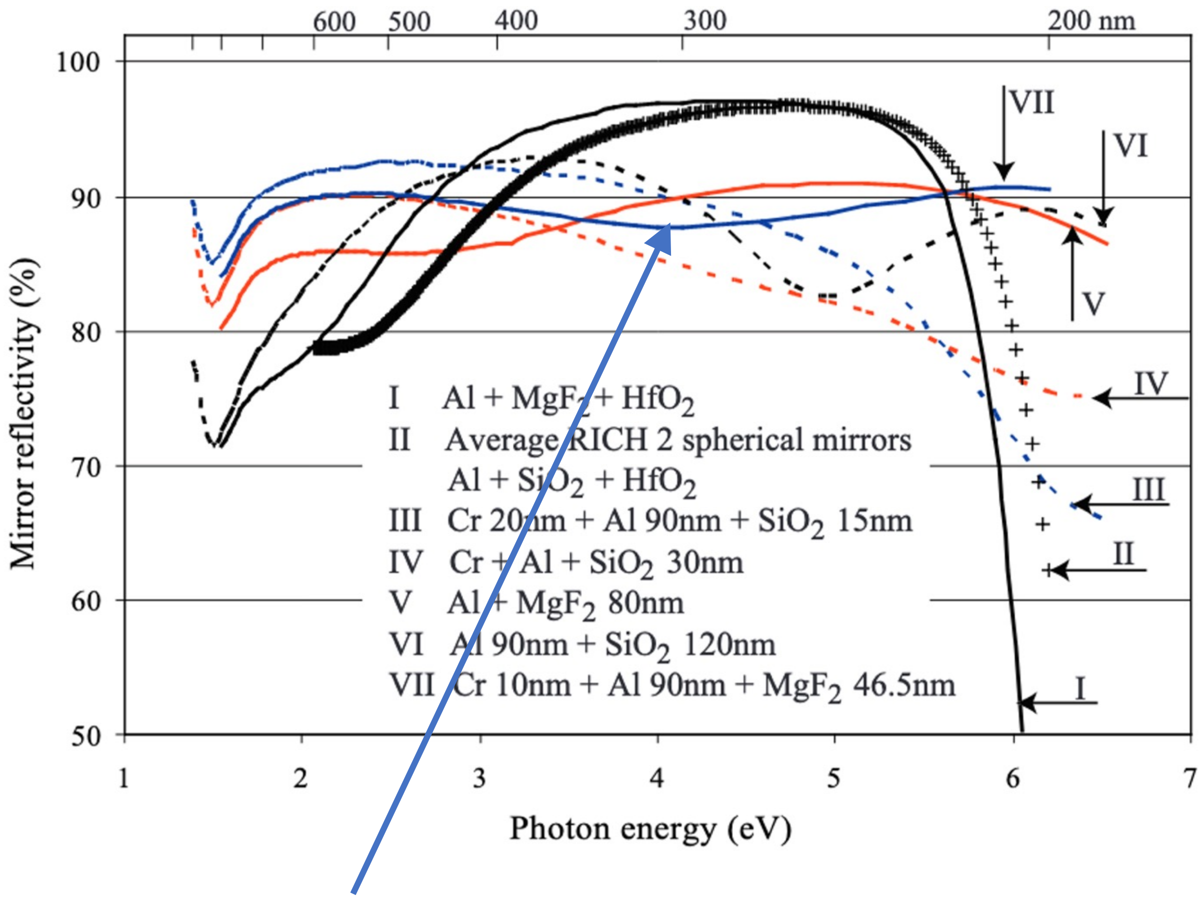


C4F10: Cherenkov angle for β = 1 and refraction index

- **FBK SiPM:** $\sigma_{\theta_c}\big|_{\text{single photon}} \sim \frac{d\theta_c}{dE}(E_2 - E_1)\frac{1}{\sqrt{12}} = 0.0009*(4.3-1.9)\frac{1}{\sqrt{12}} = 0.62$ mrad => $\sigma_{\theta_c}\big|_{18\ \text{photons}} \sim 0.14$ mrad

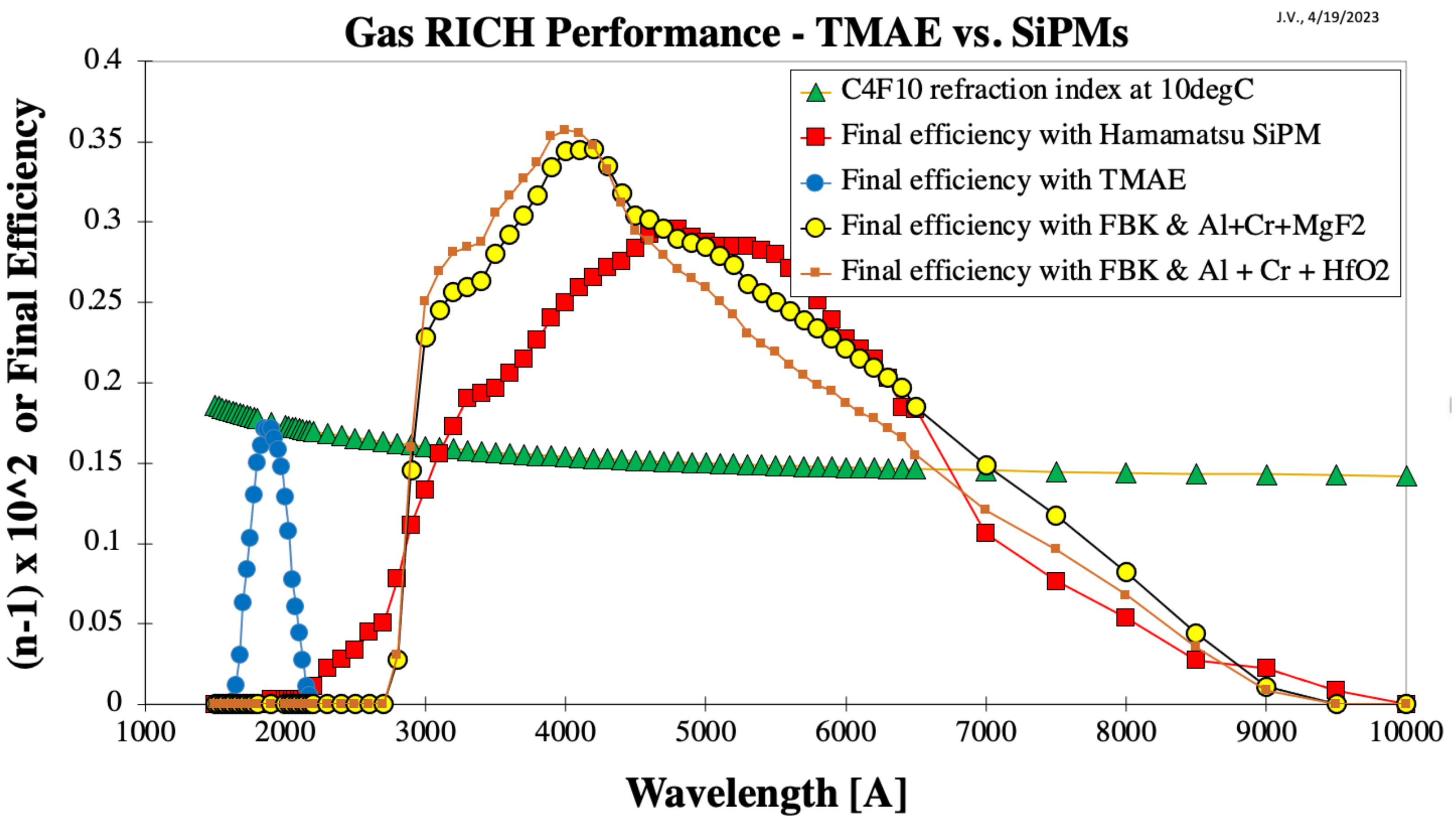
Mirror choice for FBK SiPM

The LHCb Collaboration, J. Instrum. 3, S08005 (2008).



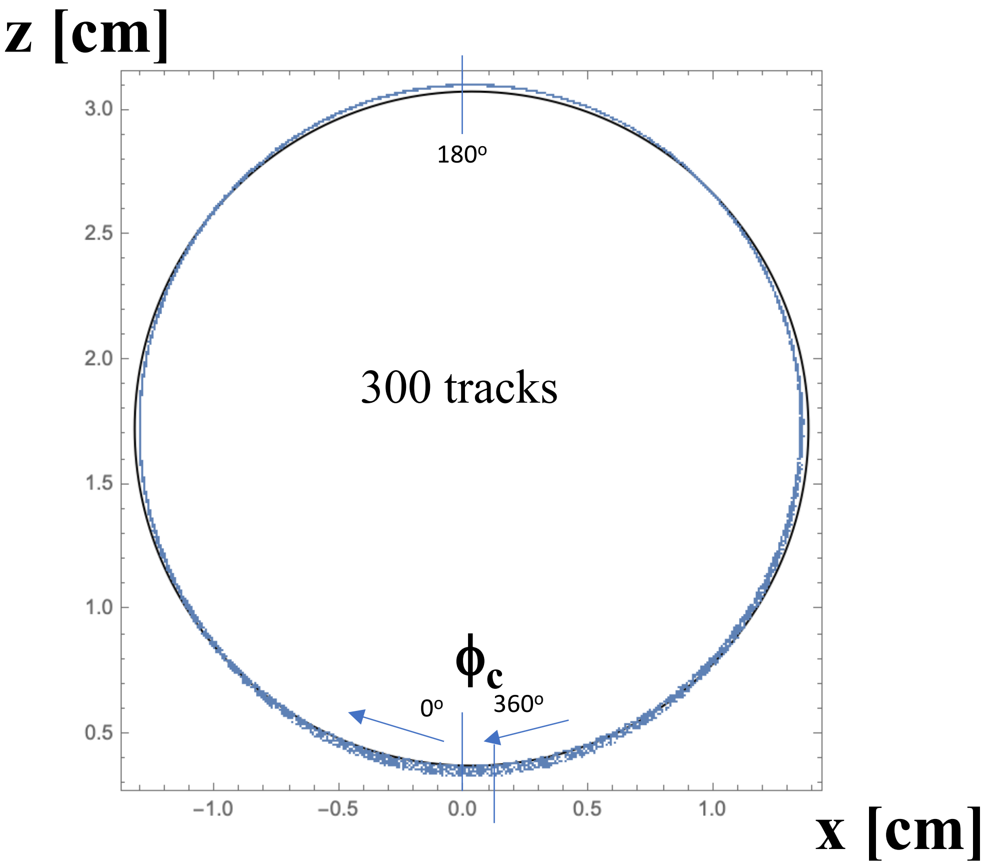
- **So far, I kept a classical Al + MgF$_2$ + Cr coating. This coating was used by CRID.**
- **N$_{pe}$ is about the same for Cr + Al + HfO$_2$ coating; perhaps tiny reduction of chromatic error.**

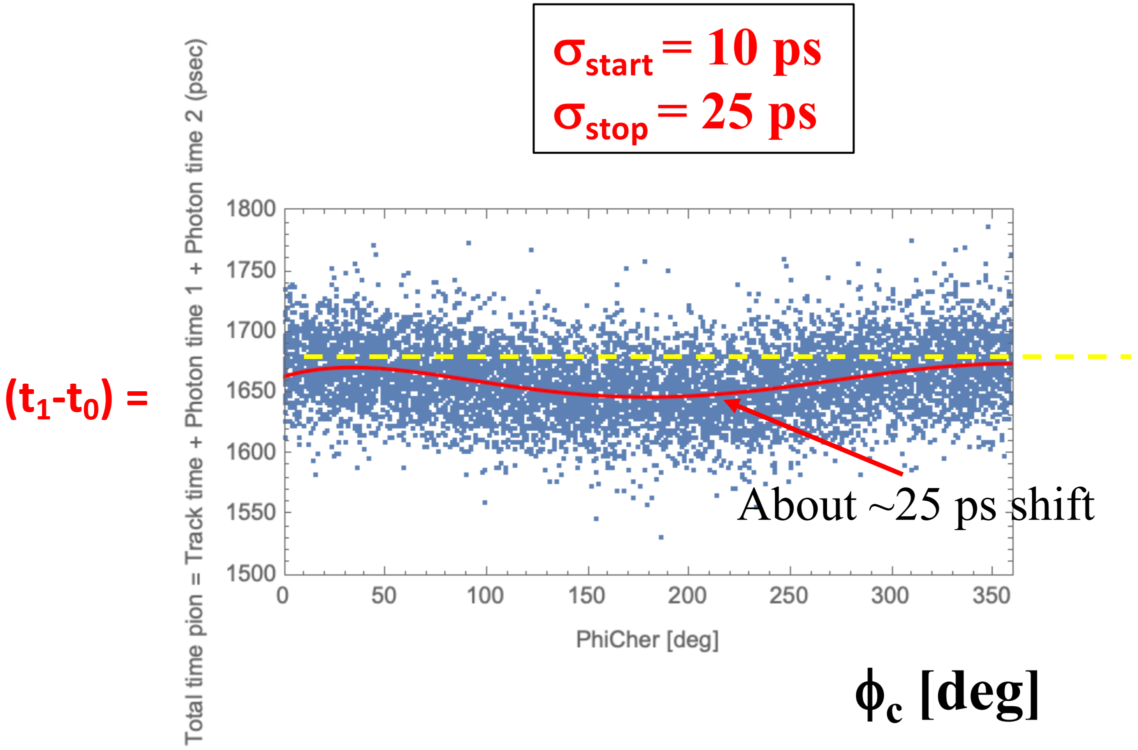
Final efficiency: FBK vs. Hamamatsu



- Al+Cr+HfO$_2$ coating helps in UV region, but it makes it worse in red region.
- It reduces chromatic error from 0.62 to 0.60 per photon hit. May consider it in future.

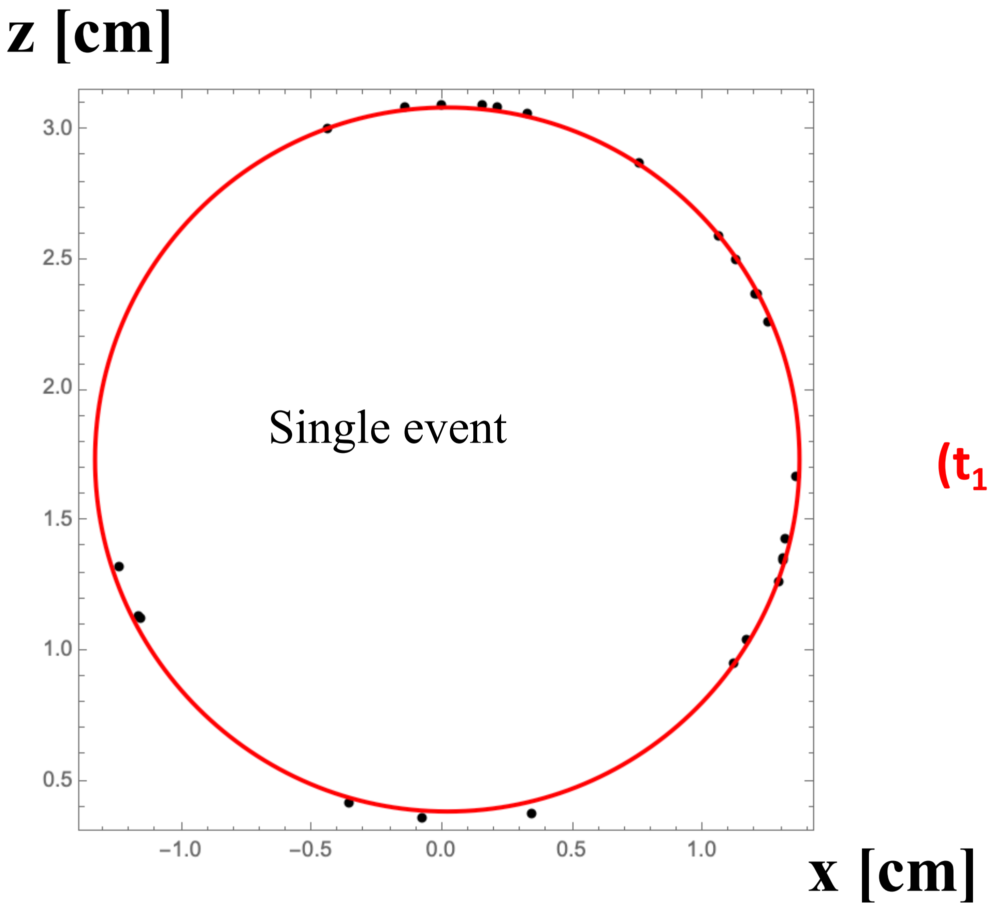
Timing for $\theta_{dip} = 4^o$ & 20 GeV/c & B = 5 Tesla



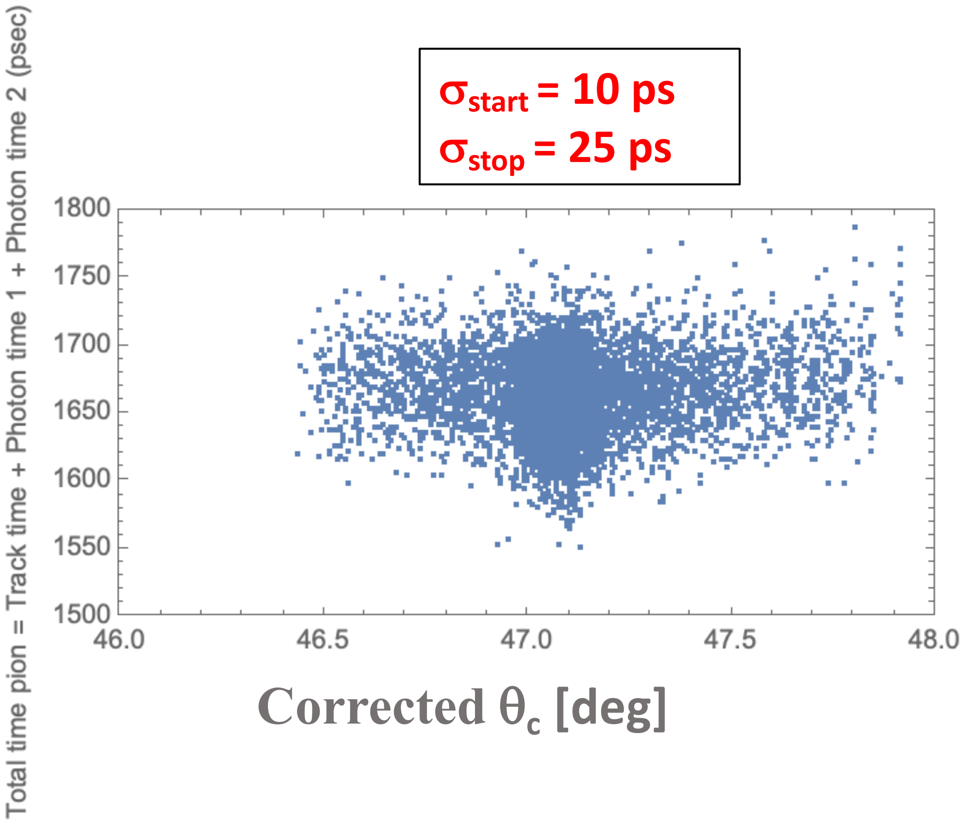


- **Points near $\phi_c = 180^o$ have small time shift of ~25 ps.**
- Note: This time correction was not used in this analysis.

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



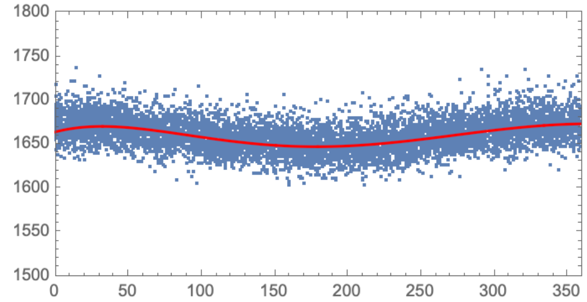
$(t_1 - t_0) =$


σ_{start} = 10 ps
σ_{stop} = 25 ps

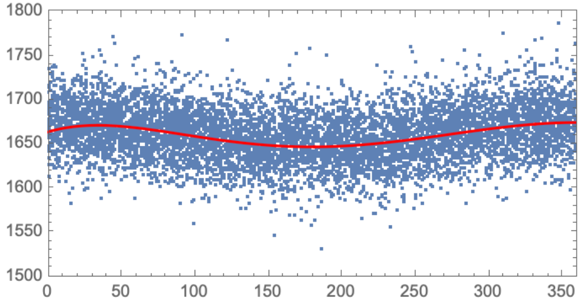
- ”t_1-t_0” timing has almost no effect on the <u>corrected</u> Cherenkov angle.

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

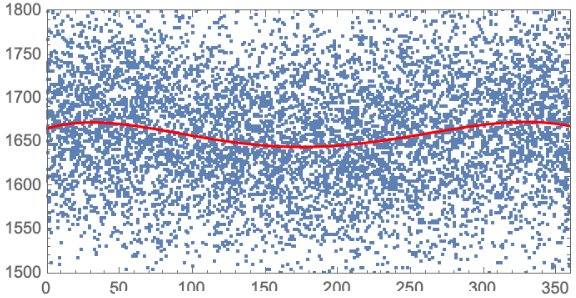
(t$_1$-t$_0$) = [ps]



σ_{start} = 10 ps
σ_{stop} = 10 ps



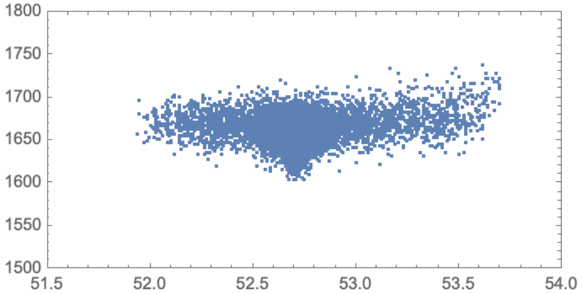
σ_{start} = 10 ps
σ_{stop} = 25 ps



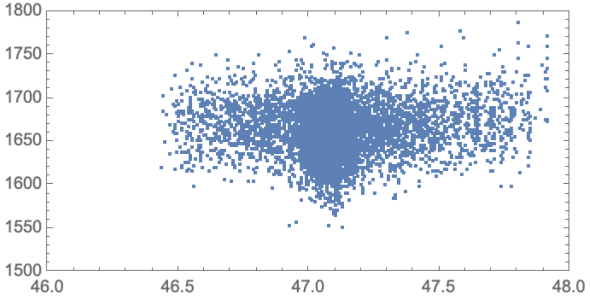
σ_{start} = 50 ps
σ_{stop} = 50 ps

$\phi_{azimuth}$ [deg]

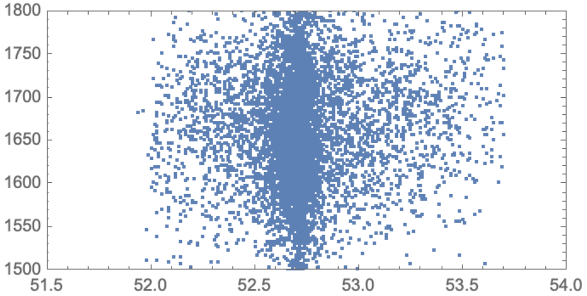
(t$_1$-t$_0$) = [ps]



σ_{start} = 10 ps
σ_{stop} = 10 ps



σ_{start} = 10 ps
σ_{stop} = 25 ps

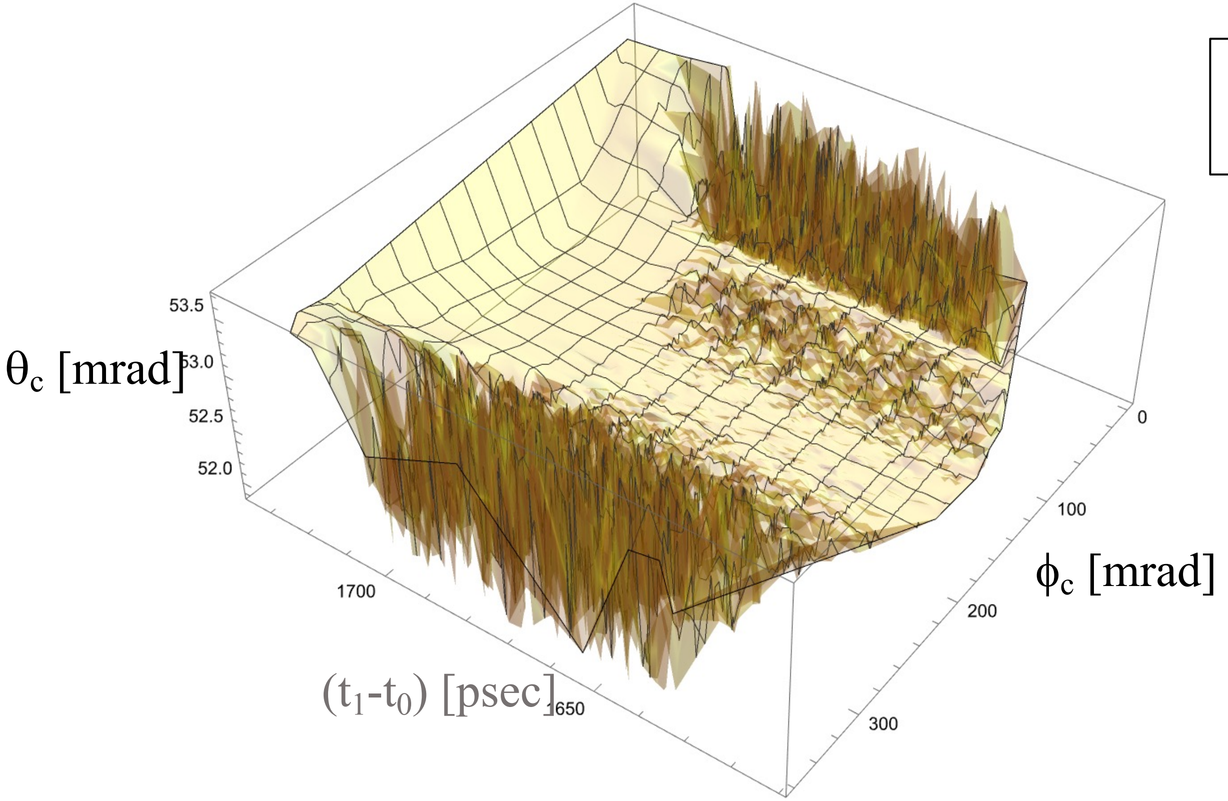


σ_{start} = 50 ps
σ_{stop} = 50 ps

Corrected θ_c [deg]

- ϕ_c depends on time ”t_1-t_0”, but corrected θ_c does not.

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



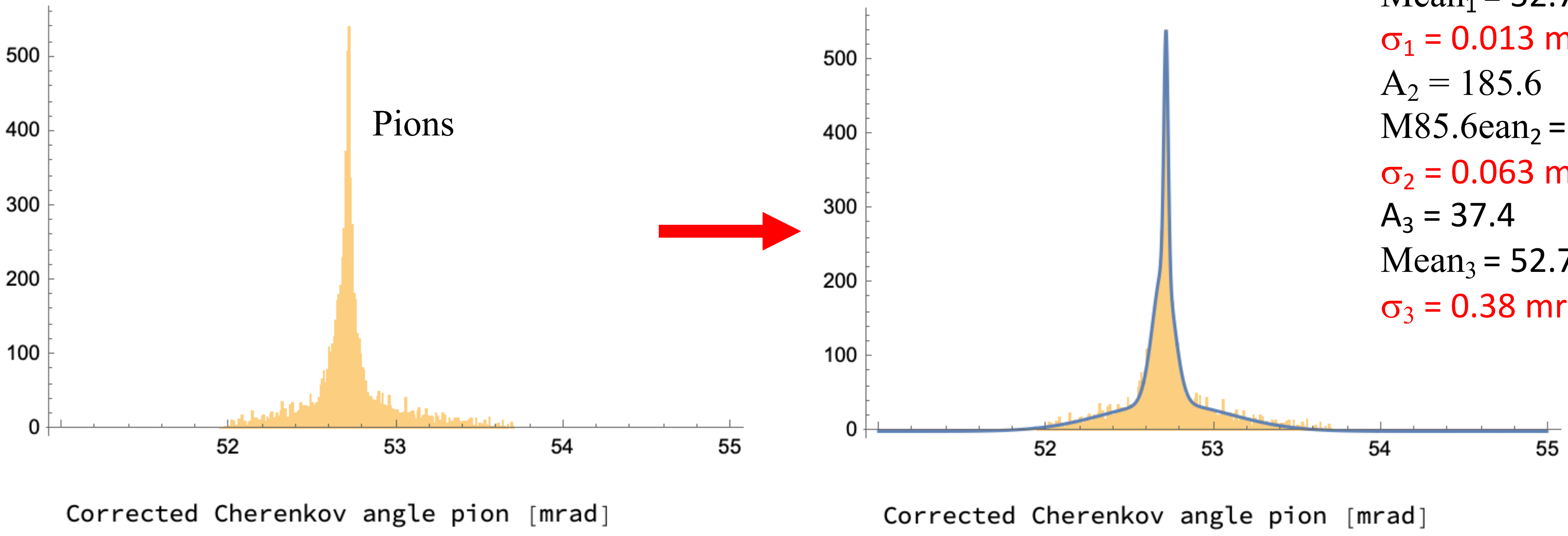
σ_{start} = 10 ps
σ_{stop} = 25 ps

- **3D views of Cherenkov angle including "t_1-t_0" timing.**

Cherenkov angle distribution for 20 GeV/c & θ_{dip} = 4^{o} & B = 5 Tesla

Note: I started to get "help" from AI computer (https://chat.openai.com/auth/login); he knows more about Mathematica than any person I know.

rms error = 0.25 mrad per single hit



A_1 = 323.7
Mean$_1$ = 52.7 mrad
σ_1 = 0.013 mrad
A_2 = 185.6
M85.6ean$_2$ = 52.7 mrad
σ_2 = 0.063 mrad
A_3 = 37.4
Mean$_3$ = 52.7 mrad
σ_3 = 0.38 mrad

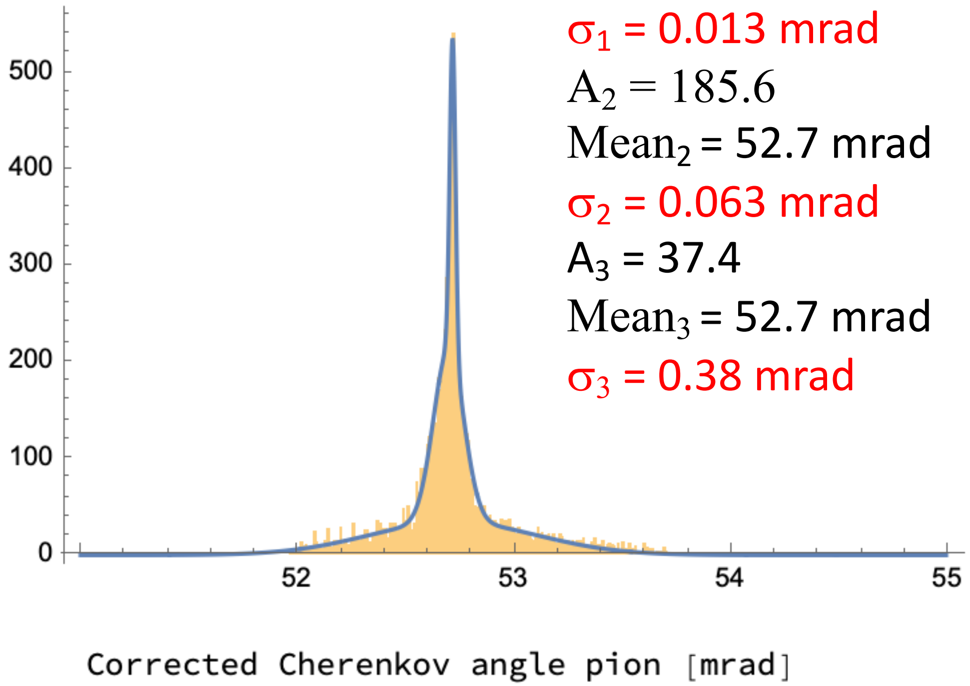
- **Fit histogram with 3 Gaussian distributions.**
- **σ_3 error dominates; σ_1 and σ_2 errors are smaller than rms error.**

Magnetic field on & off for 20 GeV/c & $\theta_{dip} = 4^{o}$

rms error = 0.25 mrad per single hit

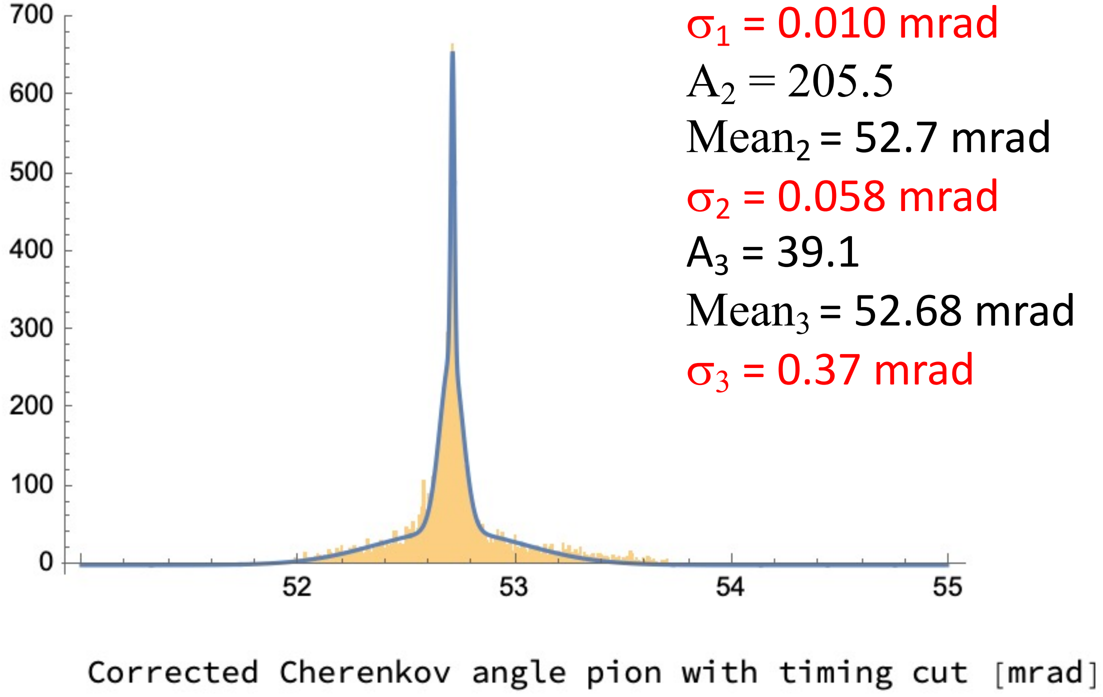
B = 5 Tesla

A_1 = 323.7
$Mean_1$ = 52.7 mrad
σ_1 = 0.013 mrad
A_2 = 185.6
$Mean_2$ = 52.7 mrad
σ_2 = 0.063 mrad
A_3 = 37.4
$Mean_3$ = 52.7 mrad
σ_3 = 0.38 mrad



B = 0.001 Tesla

A_1 = 323.9
$Mean_1$ = 52.7 mrad
σ_1 = 0.010 mrad
A_2 = 205.5
$Mean_2$ = 52.7 mrad
σ_2 = 0.058 mrad
A_3 = 39.1
$Mean_3$ = 52.68 mrad
σ_3 = 0.37 mrad



- **"Magnetic field off" errors are smaller.**

Smearing vs. focusing error at 20 GeV/c & $\theta_{dip} = 4^{o}$ & B = 5 Tesla

Smearing error

$\sigma_1 = 0.008$ mrad
$\sigma_2 = 0.024$ mrad
$\sigma_3 = 0.09$ mrad

(Result of subtraction of square of errors)

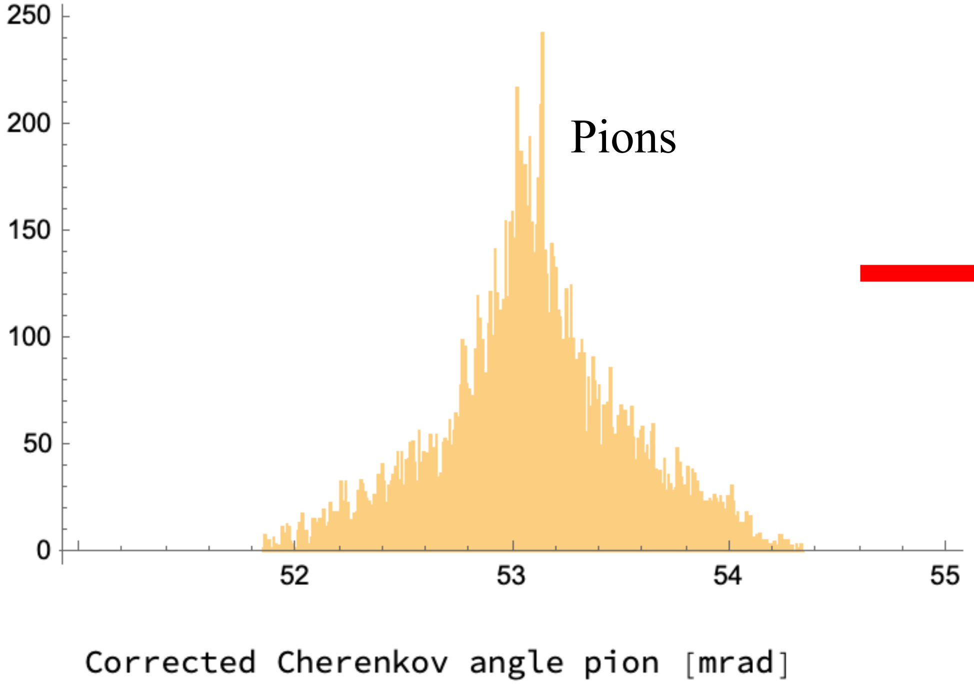
Focusing error

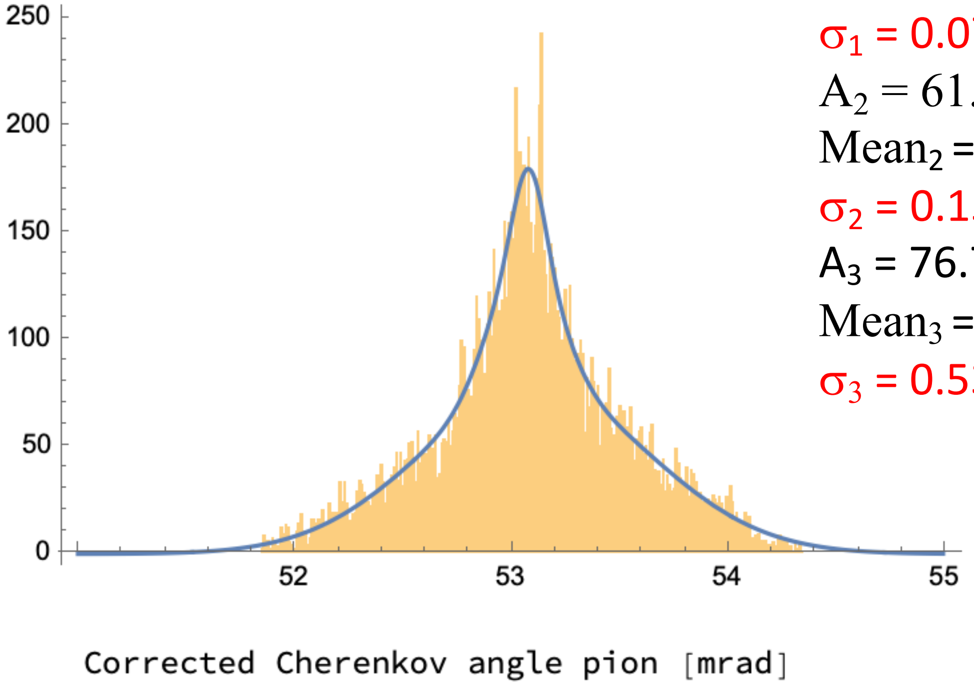
$\sigma_1 = 0.010$ mrad
$\sigma_2 = 0.058$ mrad
$\sigma_3 = 0.37$ mrad

- **We conclude that the focusing error is larger than the smearing error.**

Cherenkov angle distribution for 50 GeV/c & $\theta_{dip} = 40^o$ & B = 5 Tesla

rms error (pion) ~ 0.43 mrad





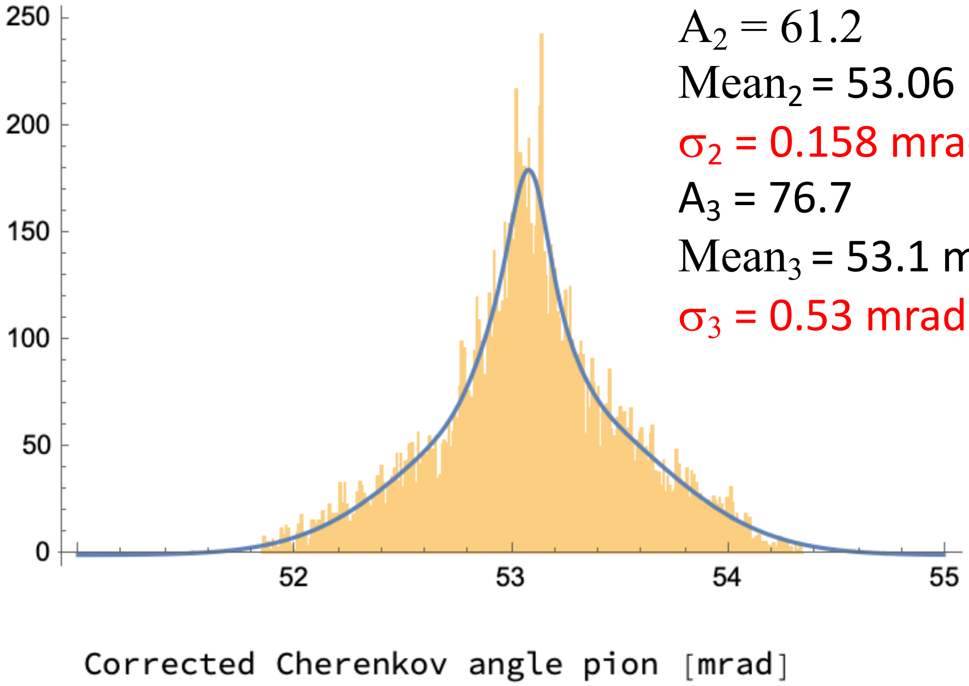
A_1 = 42.5
Mean_1 = 53.08 mrad
σ_1 = 0.073 mrad
A_2 = 61.2
Mean_2 = 53.06 mrad
σ_2 = 0.158 mrad
A_3 = 76.7
Mean_3 = 53.1 mrad
σ_3 = 0.53 mrad

- σ_3 error dominates; σ_1 and σ_2 errors are smaller than rms error.
- **Analyzing magnetic field off data ,we again conclude that the focusing effect error is larger than the smearing effect error.**

Magnetic field on & off for 50 GeV/c & $\theta_{dip} = 40^o$

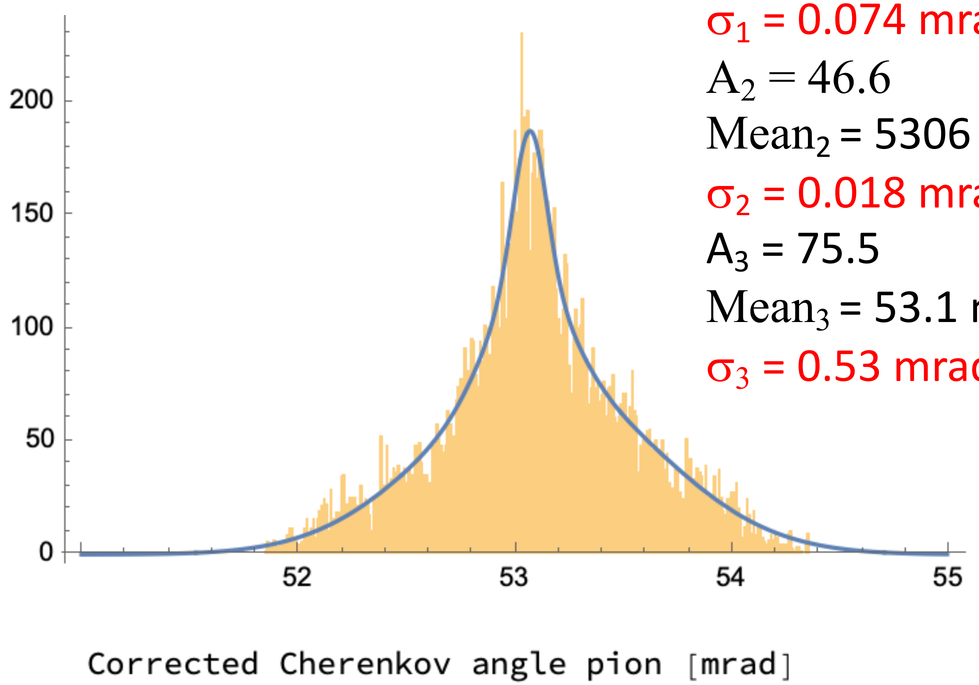
B = 5 Tesla

A_1 = 42.5
Mean_1 = 53.08 mrad
σ_1 = 0.073 mrad
A_2 = 61.2
Mean_2 = 53.06 mrad
σ_2 = 0.158 mrad
A_3 = 76.7
Mean_3 = 53.1 mrad
σ_3 = 0.53 mrad



B = 0.001 Tesla

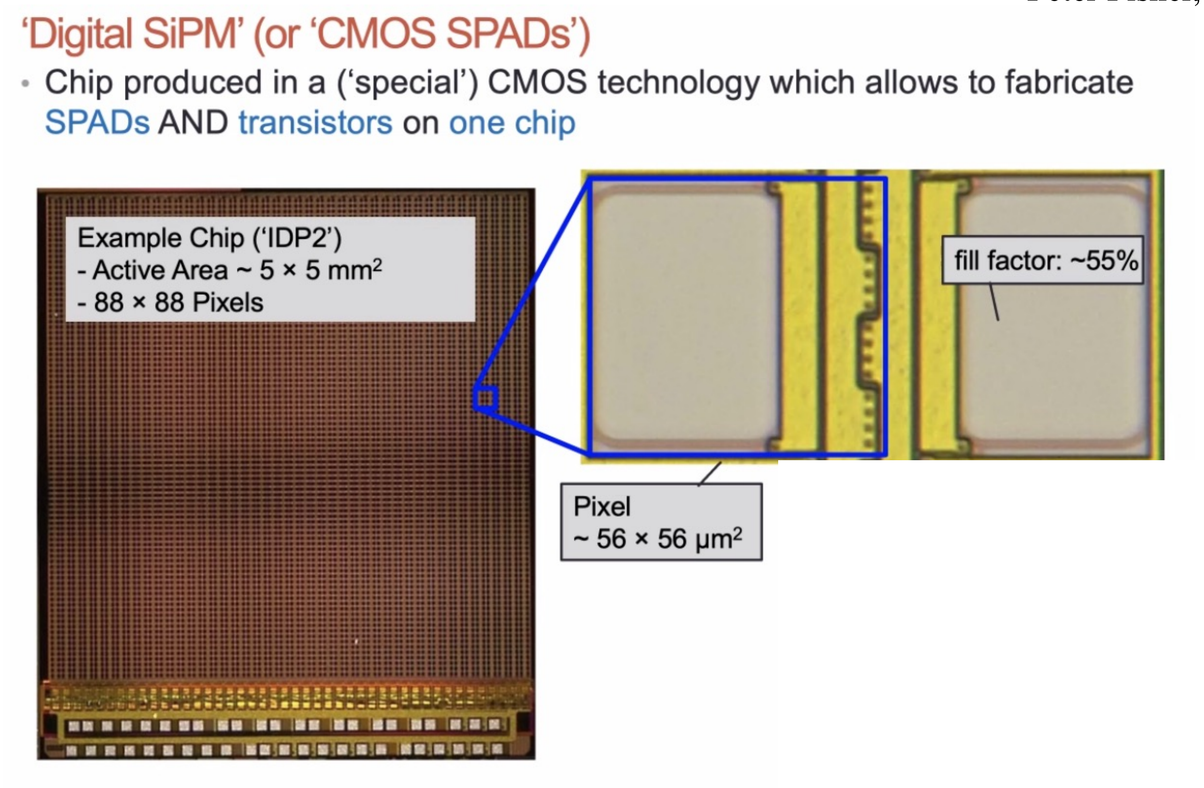
A_1 = 65.9
Mean_1 = 53.06 mrad
σ_1 = 0.074 mrad
A_2 = 46.6
Mean_2 = 5306 mrad
σ_2 = 0.018 mrad
A_3 = 75.5
Mean_3 = 53.1 mrad
σ_3 = 0.53 mrad



- **Note: Errors are about the same for magnetic field off.**
- **We again conclude that the focusing effect error is larger than the smearing effect error.**

Are digital SiPMs a good choice in future ?

Peter Fisher, Heidelberg



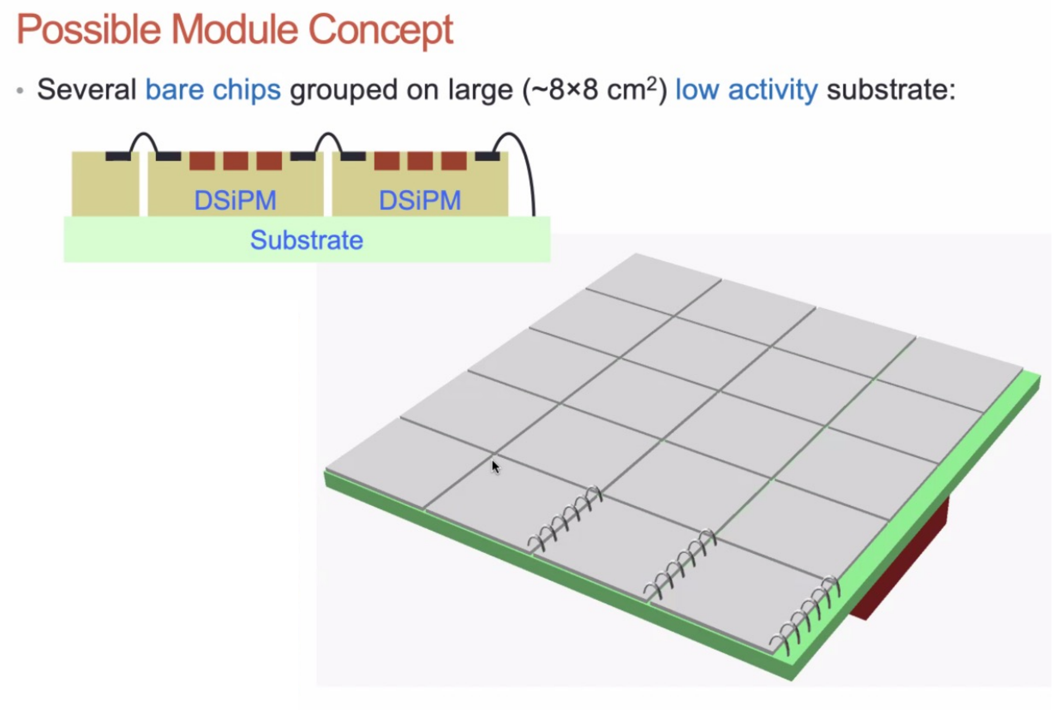
'Digital SiPM' (or 'CMOS SPADs')

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

Example Chip ('IDP2')
- Active Area ~ 5 × 5 mm²
- 88 × 88 Pixels

fill factor: ~55%

Pixel
~ 56 × 56 μm²

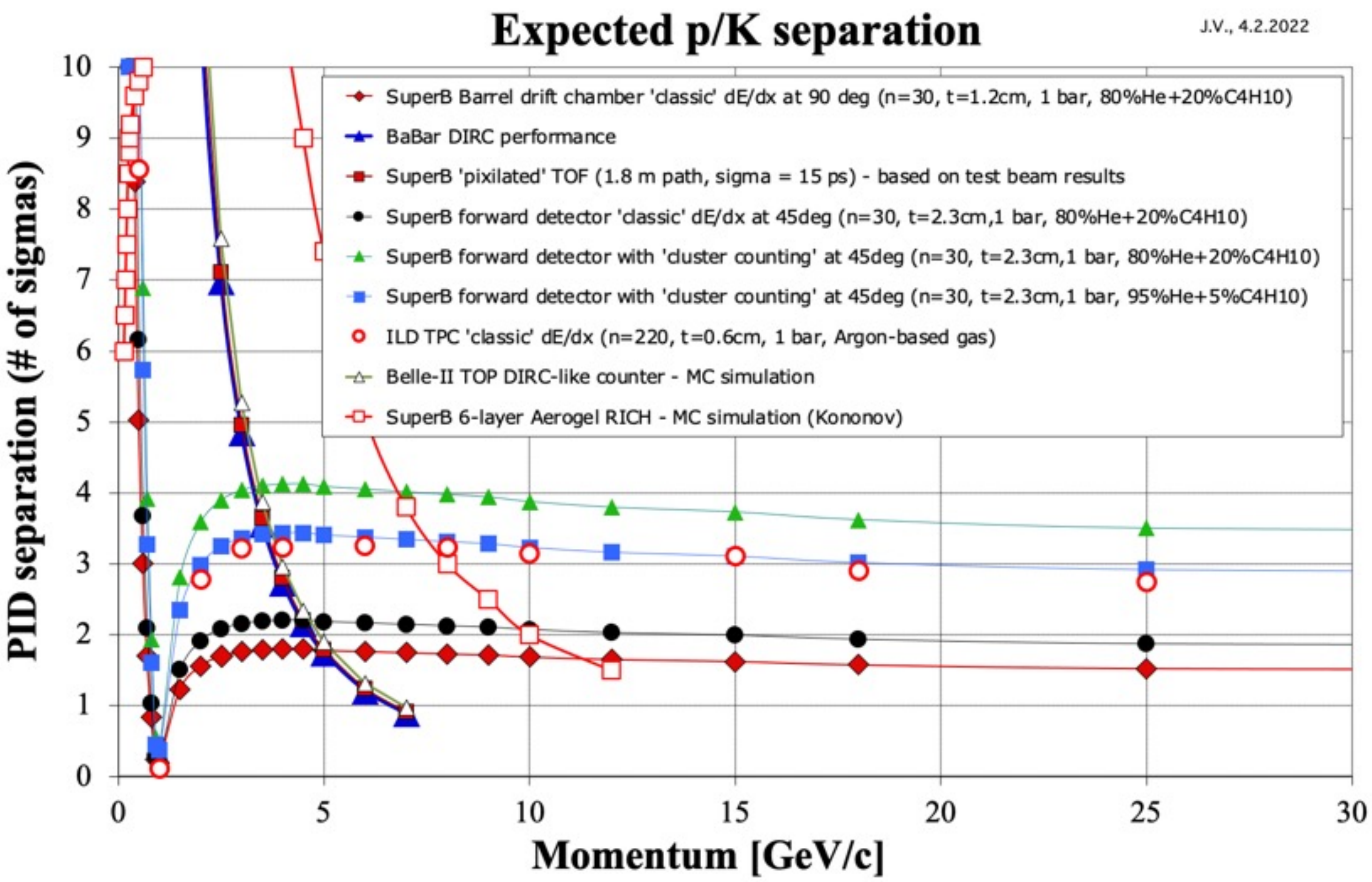


Possible Module Concept

- 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.**

PID using other methods



- **Cherenkov imaging with our gaseous RICH is vastly superior.**

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