Exploiting Cherenkov in Calorimetry

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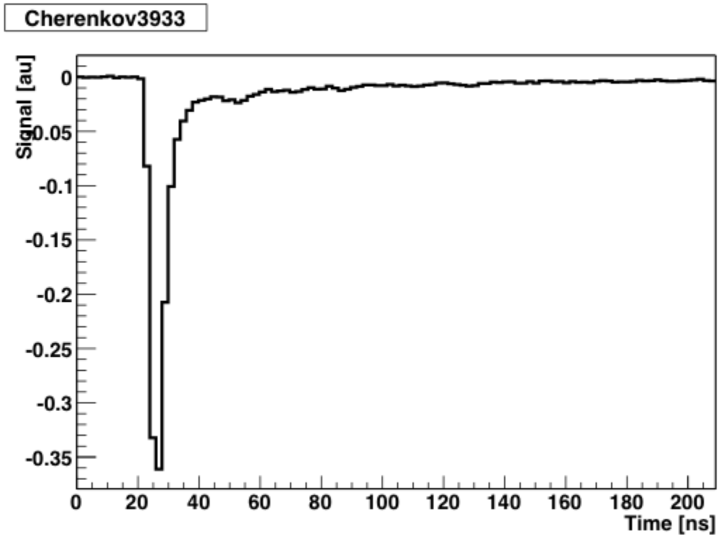
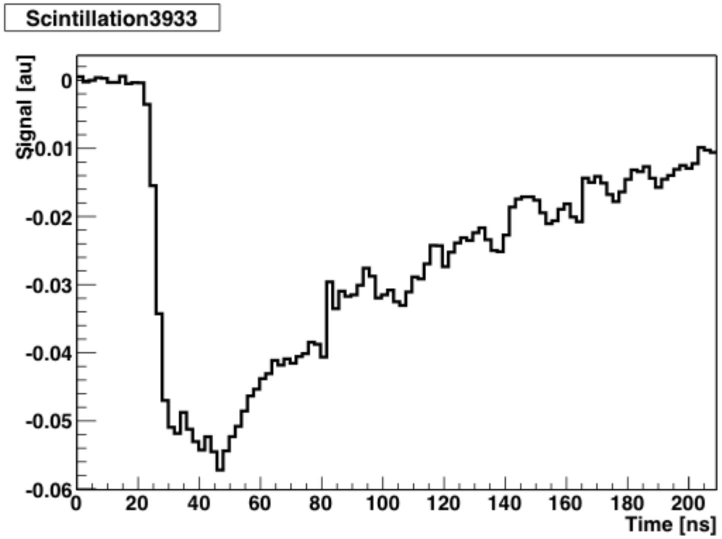
Start with an Example : BSO

Six distinct features distinguish Cherenkov radiation from scintillation:

1. Directionality (Cherenkov cone, $\theta_c = \cos^{-1}$ $(1/\beta n(\lambda)$, *vs* isotropic emission)
2. Emission/wavelength spectrum ($1/\lambda^2$ *vs* scintillator specific)
3. Cherenkov threshold ($T=(\gamma-1)mc^2$, for $n=2$ electrons:~80 keV, protons: ~140 MeV)
4. Timing (Prompt *vs* ~several ns)
5. Polarization (linearly polarized *vs* unpolarized)
6. Cherenkov light is feeble (scintillation is often not)





How (EM) Many Cherenkov Photons? (I)

We need realistic light yield estimates in order to set the scale for the calorimeter performance:

$$\frac{dE}{dx} = \frac{Z^2}{2}\left(\frac{e^2}{\hbar c}\right)\left(\frac{mc^2}{e^2}\right)\left[\frac{(hf_1)^2 - (hf_2)^2}{mc^2}\right]\sin^2\theta_C$$

$$400\,\mathrm{nm} < \lambda < 700\,\mathrm{nm} \qquad n = 1.46$$

Critical values are the following:

1. 500 eV/cm in the form of Cherenkov photons
2. Consider photon energy range from 1.7 eV to 3.0 eV
3. 160 to 250 Cherenkov photons are produced per cm
4. Minimally ionizing particle loses 4.5 MeV/cm in quartz

How (EM) Many Cherenkov Photons? (II)

Take 1 GeV electron/gamma shower in a block of quartz:

1. Assume tracks as a collection of MIPs
2. (1,000 MeV/4.5 MeV/cm) = 222 cm total track length
3. (222 cm)(~200 photons/cm) = 44,000 Cherenkov photons per GeV
4. Not all charged particles are above the Cherenkov threshold (*T*=190 keV)
5. Cuts down to ~70%, *i.e.* 31,000 photons

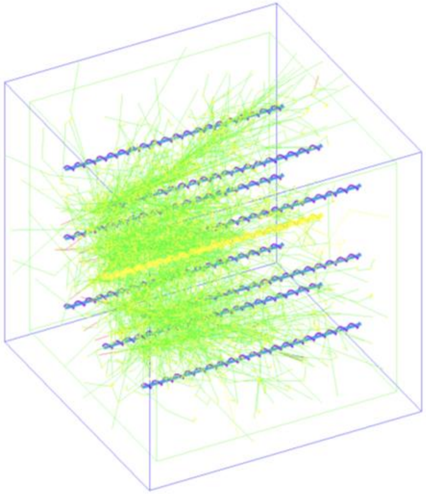
There are three other major factors if quartz fiber calorimeter is considered:

1. Packing fraction: ~1% by volume
2. Fiber trapping efficiency: typically ~1% (depending on fiber 0.5 to 3%)
3. Detection of these photons by a bi-alkaline PMT results in ~20% signal
4. Therefore, we are left with ~0.62 p.e. per GeV
5. Examples: CMS HF (copper) = 0.53 p.e./GeV; CMS HF (steel) = 0.25

QQ, QP, Plastic, and Air-clad Fibers

Optical fiber is an electromagnetic waveguide and light propagation through this waveguide is complex but can be solved for exactly. Depending on the refractive indices of the core and clad material and the geometry, the relevant features for calorimetry can be optimized. CMS HF hosts QP fibers.

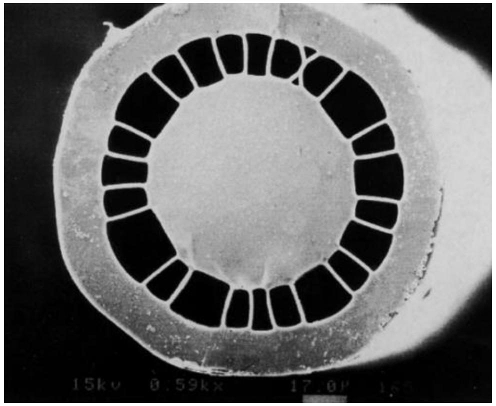
If the radiation damage were not an issue, the choice of fiber would be easy.



$$f_{\mathrm{trap}} \approx \left(\frac{\mathrm{NA}}{2n_{\mathrm{core}}}\right)^2$$

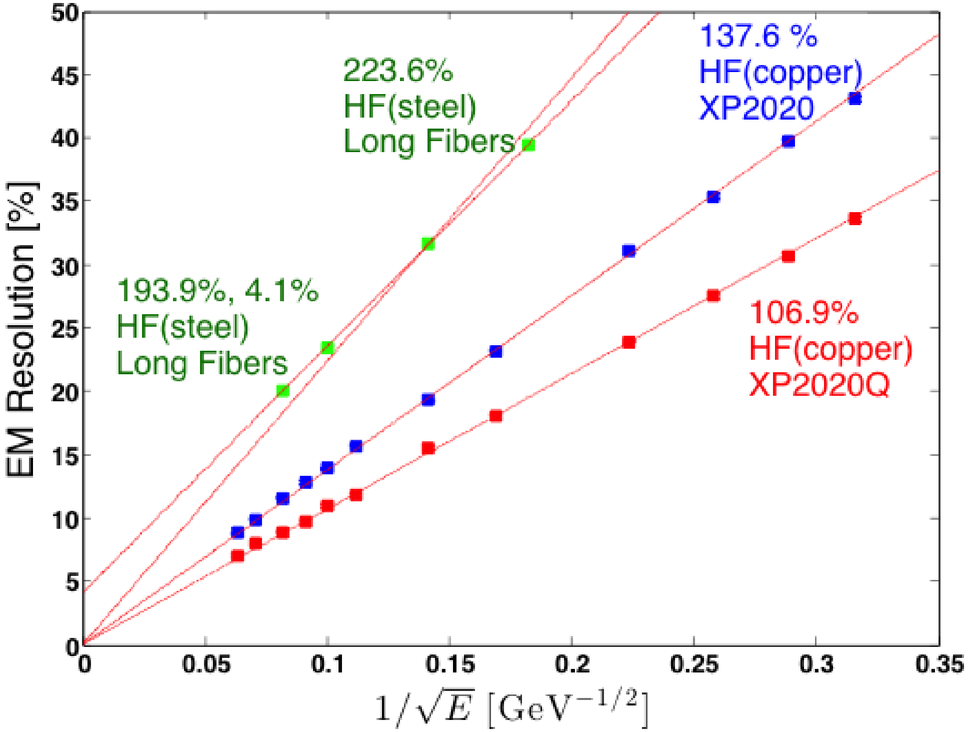
$$\mathrm{NA} \approx \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{clad}}^2}$$

	QQ	**QP**	**Plastic**	**Air-clad**
NA	0.22	0.37	0.55	~0.9
n_{core}	1.46	1.46	1.5	1.46
f_{trap}	0.57%	1.61%	3.36%	9.5%



Plastic (PS) NA = 0.72 but suffers from short attenuation length (λ_{att} ~ 3 m)

QQ, QP and Plastic Fibers and EM Energy Resolution - I



- EM energy resolution is essentially scales with 1/sqrt{E}, thus it is dominated by Poisson photoelectron statistics in quartz fiber calorimeters
- The constant term arises from non-uniformities in packing fractions (see CMS HF(steel), when summed linearly, it is ~4%)
- At 100 GeV, practically achievable energy resolutions range 10% to 23% with quartz fibers alone

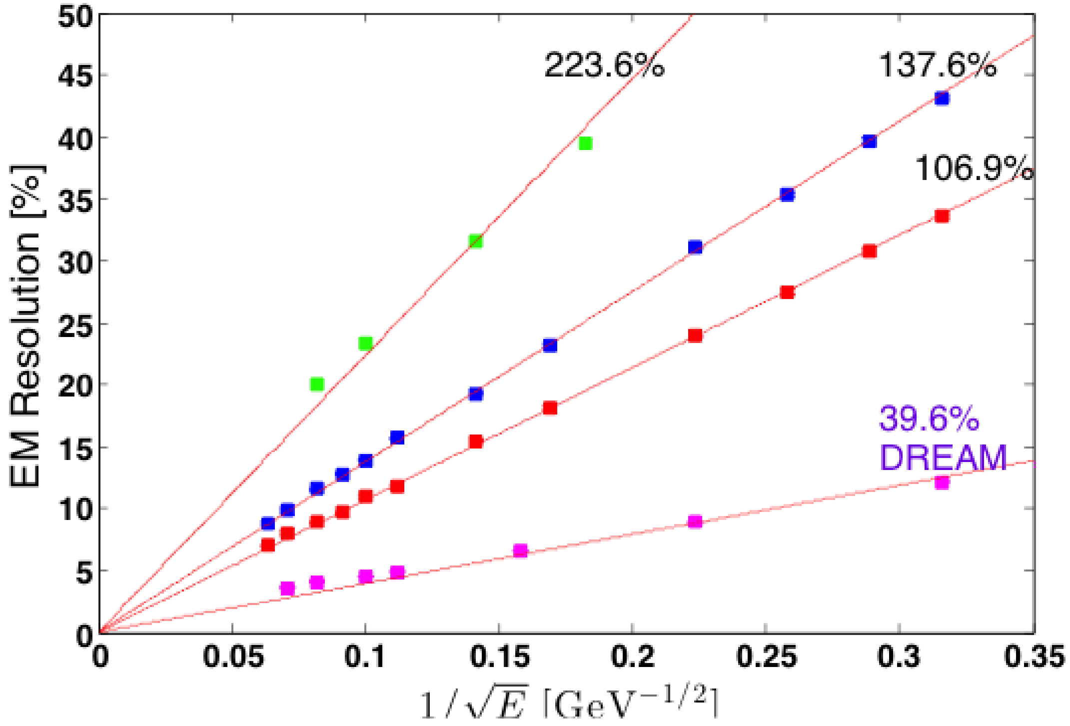
QQ, QP and Plastic Fibers and EM Energy Resolution - II

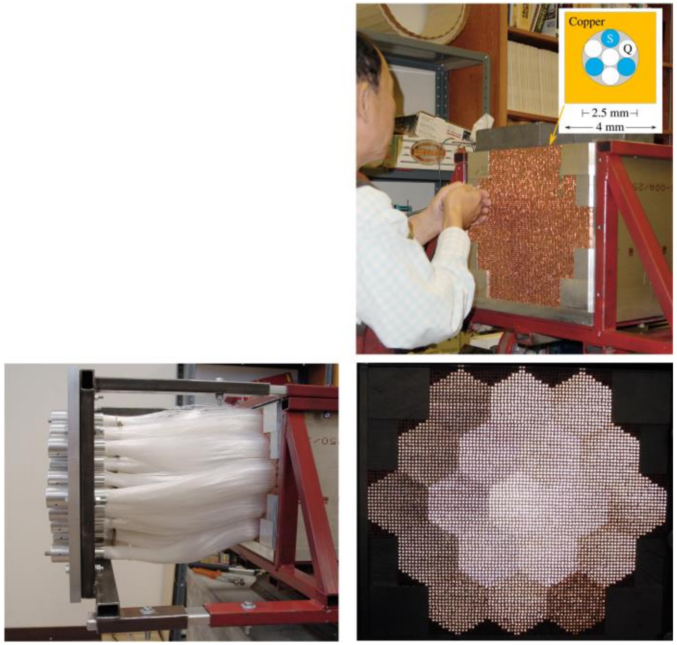
Calorimeter	Fiber	Packing	Fiber-to-fiber dist (mm)	Fiber core dia (um)	Light yield (p.e./GeV)
CMS HF(copper)	QQ	1.5%	2.3	300	0.53
CMS HF(steel-L)	QP	0.57%	~7.1	600	0.25
DREAM	QP	12.6%	~4	600	8
	P	12.6%	~4	600	18

Scaling approximately holds (ignore other contributions for now). For example,

CMS HF(copper) to DREAM QP: (12.6/1.5)(1.61/0.57)(0.53)=12 *vs* 8
CMS HF(steel-L) to DREAM QP: (12.6/0.57)(0.25)=6 *vs* 8

QQ, QP and Plastic Fibers and EM Energy Resolution - III

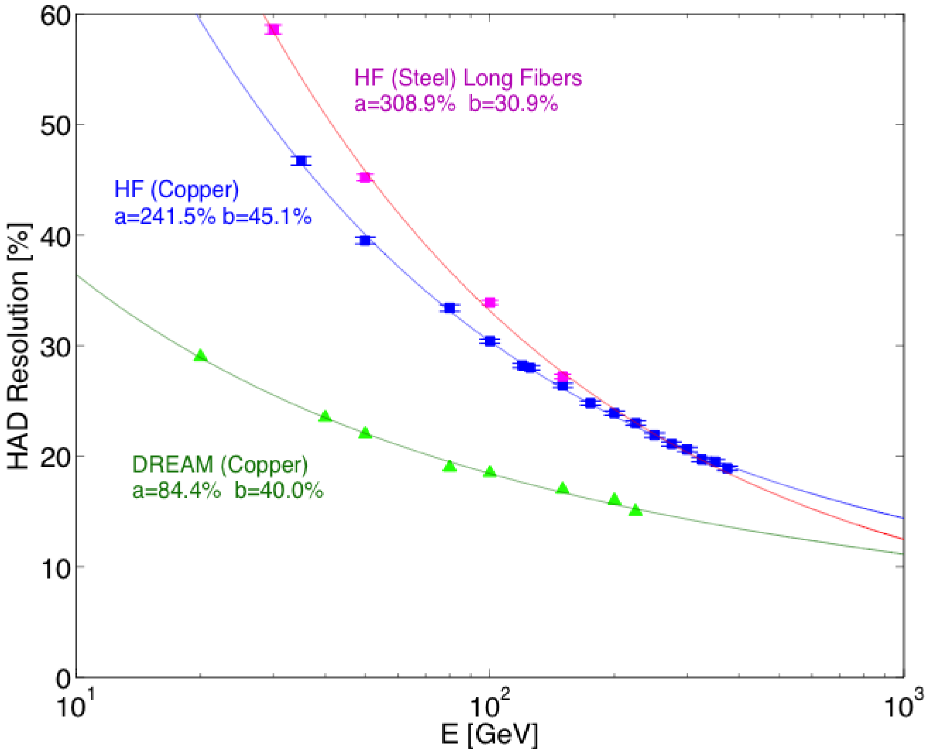




40%/sqrt{E} EM resolution is clearly achievable with Cherenkov photons and can be further improved (perhaps 15-20%/sqrt{E}) in several ways:

1. Improve NA or f_{trap} (~2x) [new optical structures…]
2. Improve QE (~2x) [SiPMs vs PMTs …]
3. Increase packing fraction (see RD52 prototypes)
4. Improve sampling frequency

Quartz Fiber/Cherenkov Hadronic Energy Resolution



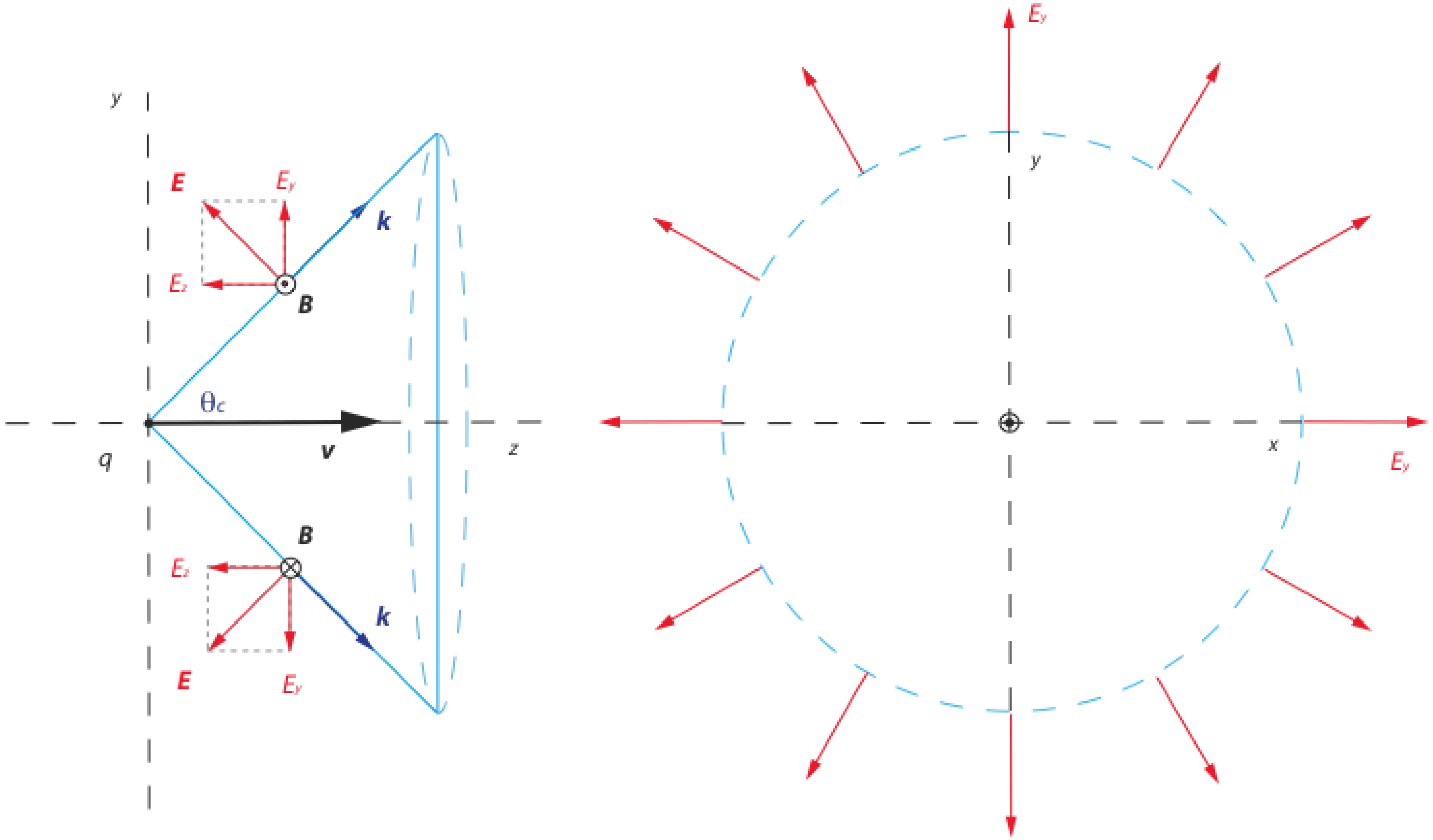
$$\left(\frac{\sigma}{E}\right) = \frac{a}{\sqrt{E}} \oplus b\left(\frac{E}{E_0}\right)^c$$

For illustration purposes, assume c = -0.18-19 and E_o= 0.7 GeV

- Hadronic energy resolution of highly non-compensating calorimeters behaves significantly differently than typical scintillation-based calorimeters

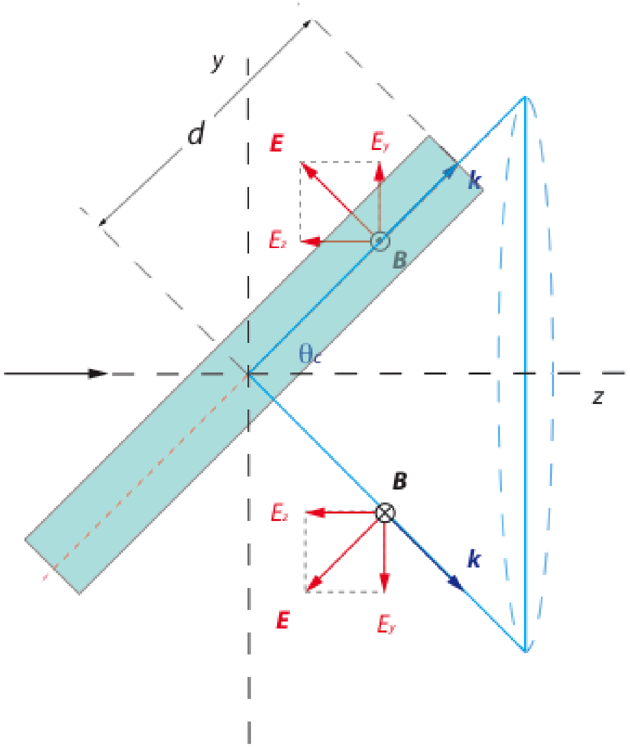
- At high energies (~1 TeV), most quartz Cherenkov calorimeters will perform similarly but at low energies, the situation is more complicated

Cherenkov Radiation and Polarization - I

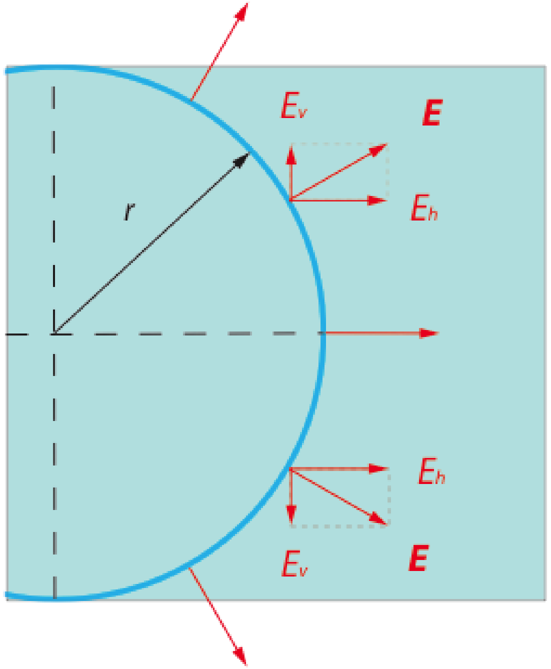


Cherenkov Radiation and Polarization - II

$$r = d \sin \theta_C$$

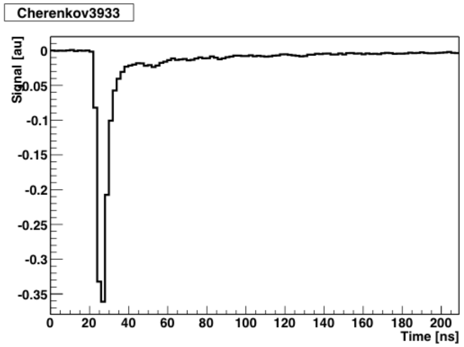


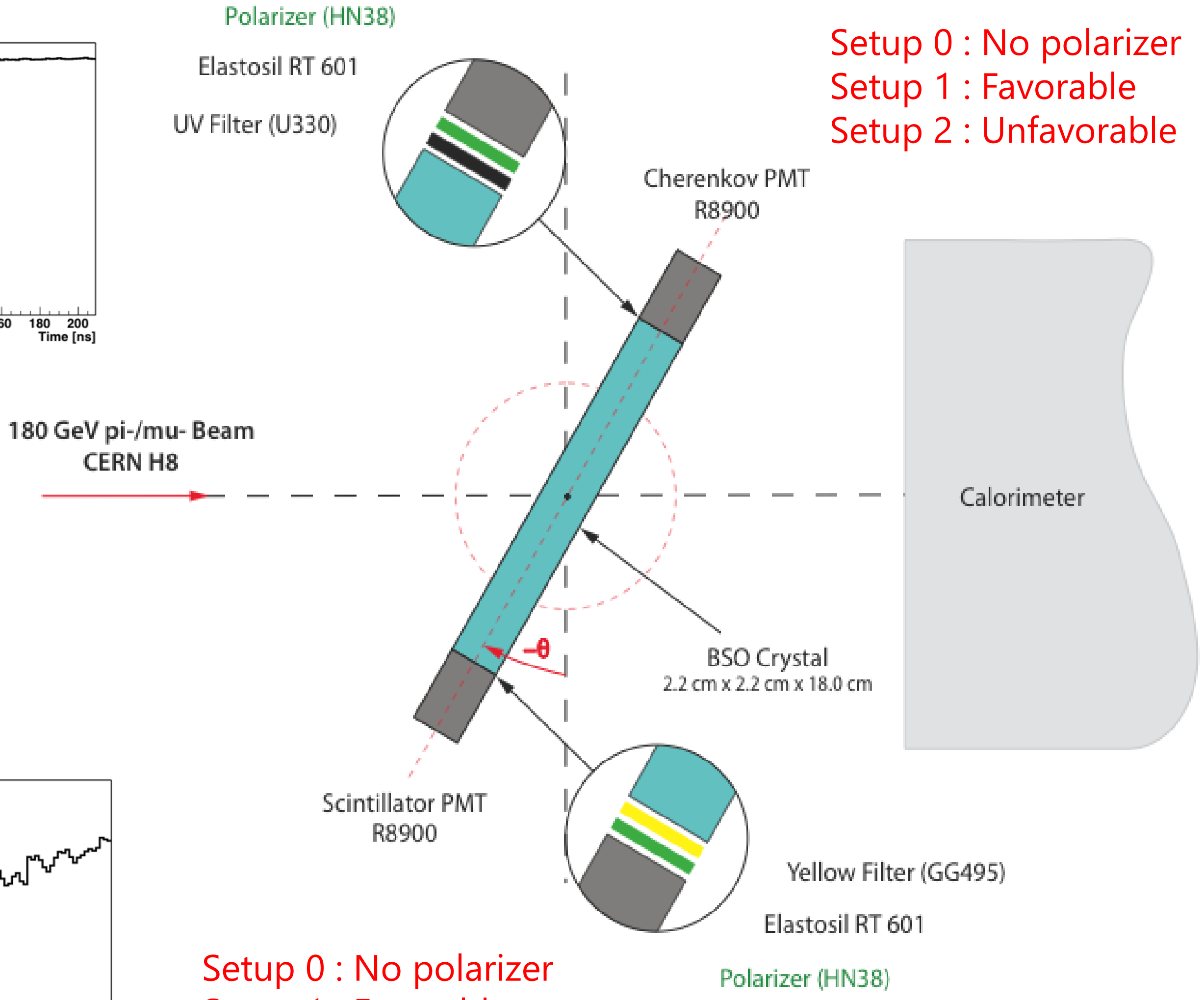
TOP VIEW



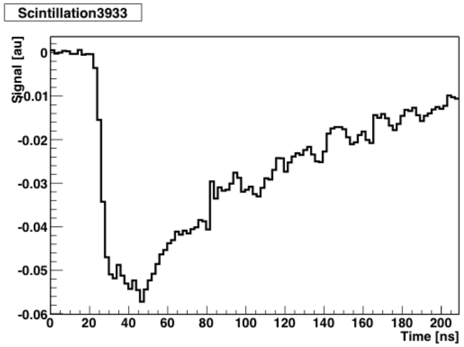
END VIEW
"As PMT views it"

Measuring Cherenkov Polarization in Three Steps





Setup 0 : No polarizer
Setup 1 : Favorable
Setup 2 : Unfavorable



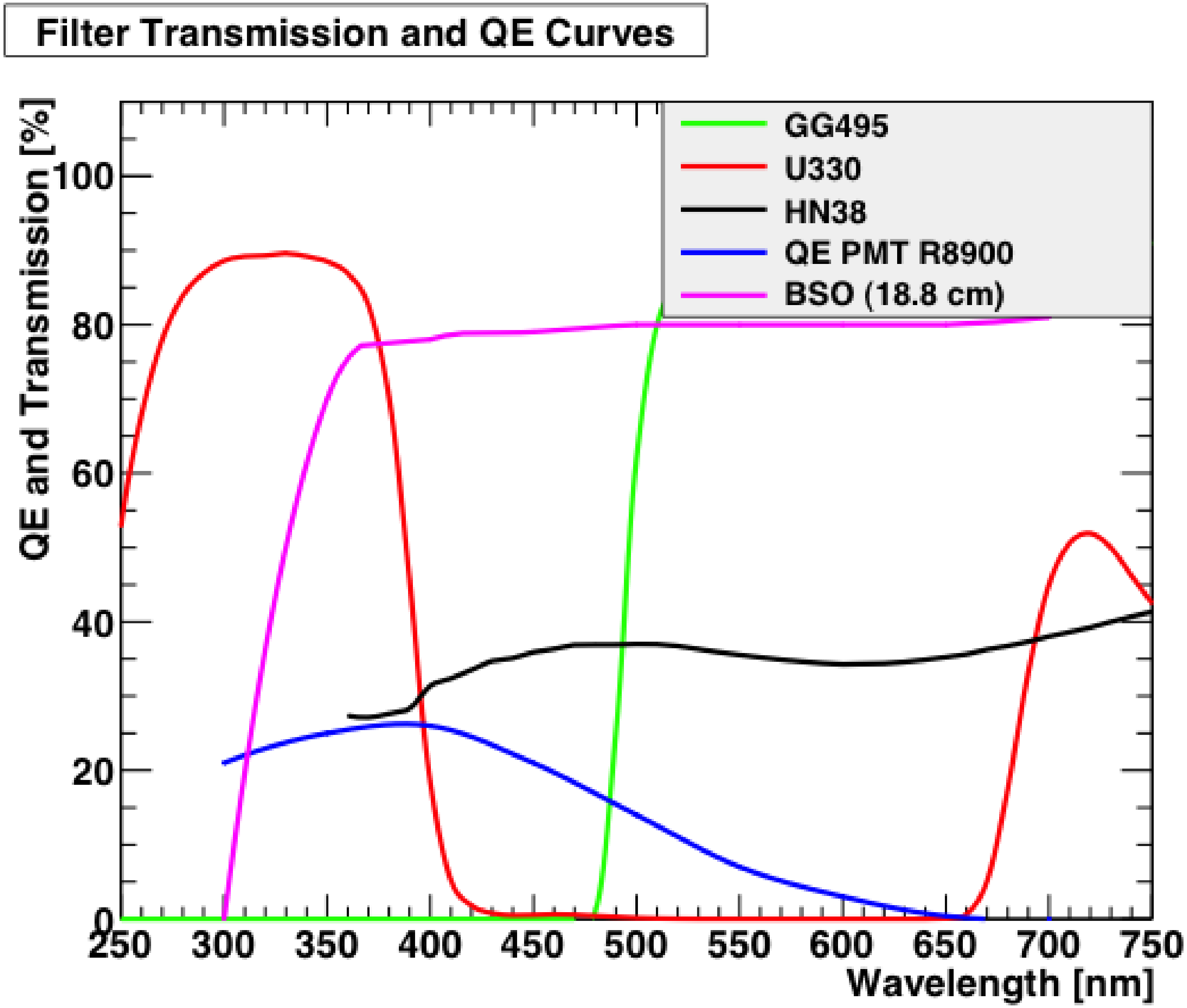
Setup 0 : No polarizer
Setup 1 : Favorable
Setup 2 : Favorable

BSO ($Bi_4Si_3O_{12}$) Crystal - I

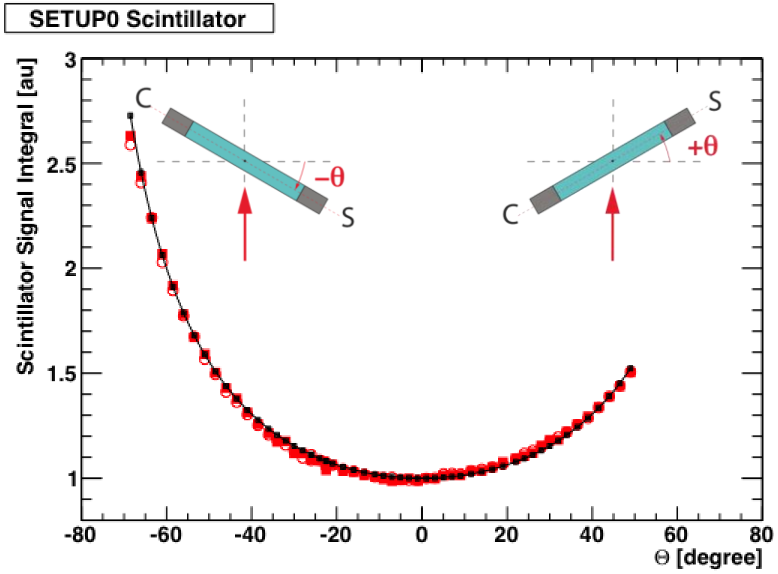
	BSO	**BGO**	**PWO**
Density (g/cm^3)	6.80	7.13	8.28
Radiation length (mm)	11.5	11.2	8.9
Decay time (ns)	~100	~300	~10
Peak emission (nm)	480	480	410-500
Relative light output	0.04	0.1	0.01
Refractive index	2.06	2.15	2.20
Cherenkov angle (^{o})	61	62	63

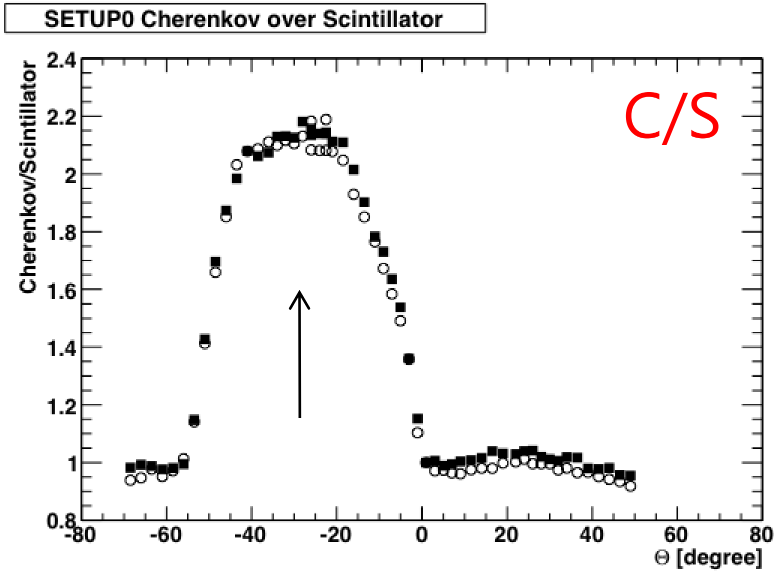
Any transparent medium with a refractive index will generate Cherenkov light when a relativistic charged particle traverses it. BSO crystal is used as an example because the spectral characteristics proved convenient.

BSO ($Bi_4Si_3O_{12}$) Crystal - II

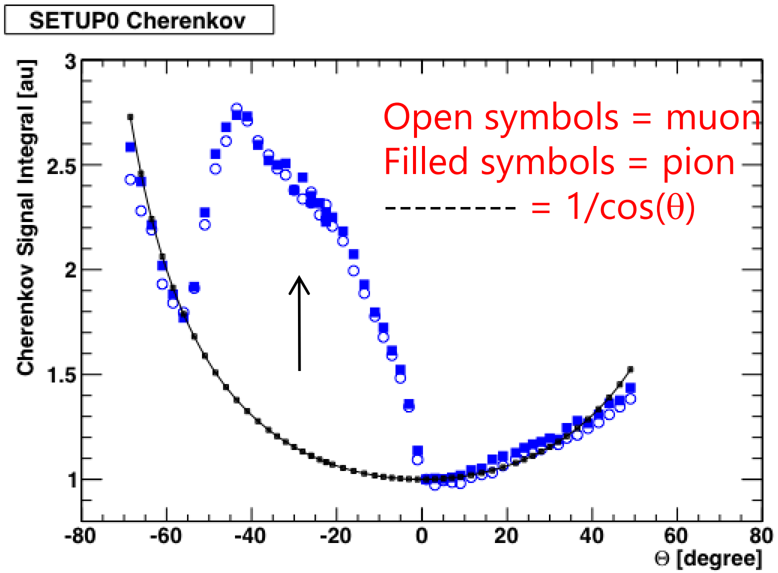


Setup 0 : No Polarizers

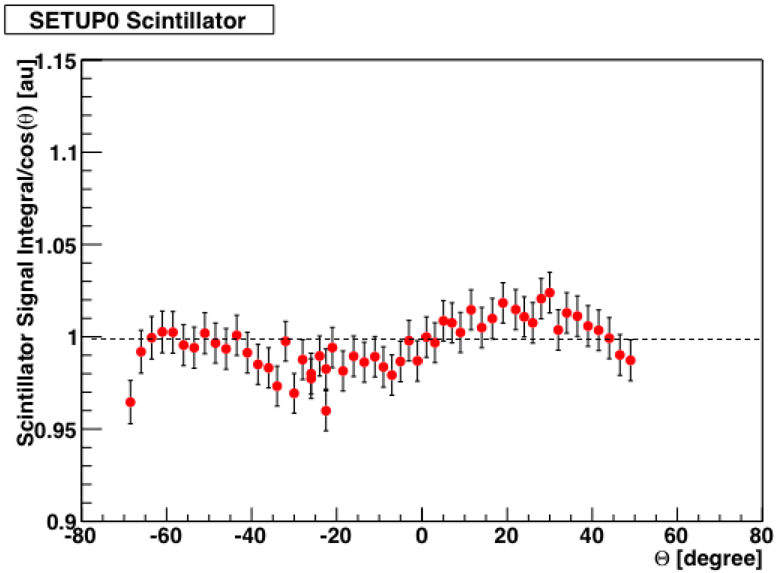

SETUP0 Scintillator


SETUP0 Cherenkov over Scintillator

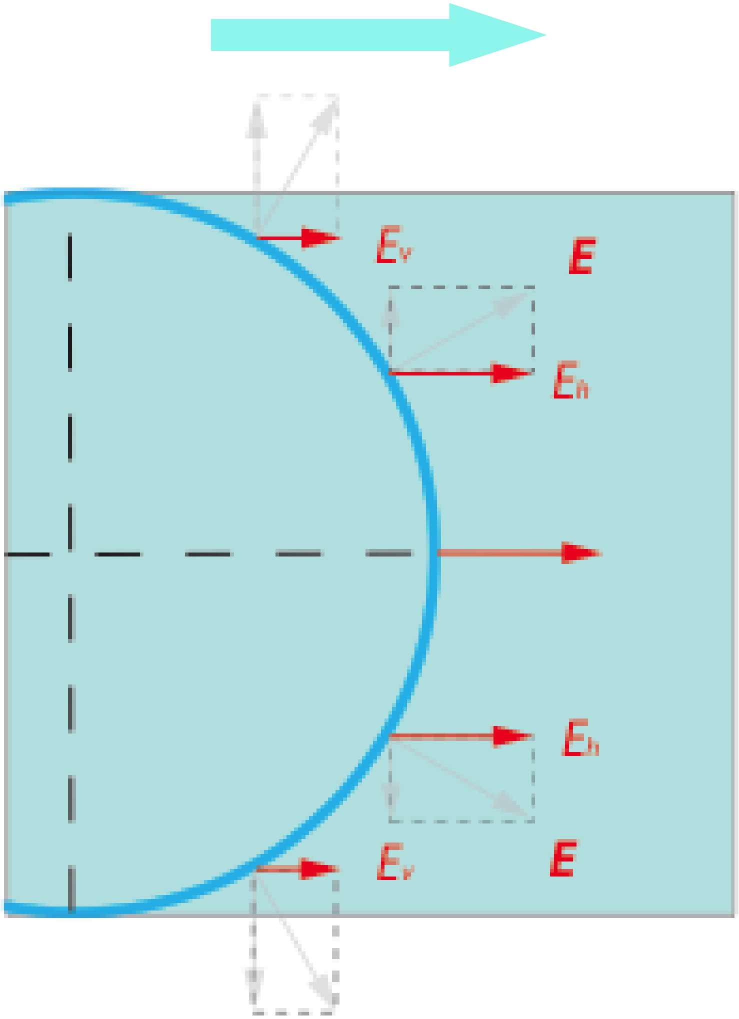
C/S


SETUP0 Cherenkov

Open symbols = muon
Filled symbols = pion
-------- = 1/cos(θ)


SETUP0 Scintillator

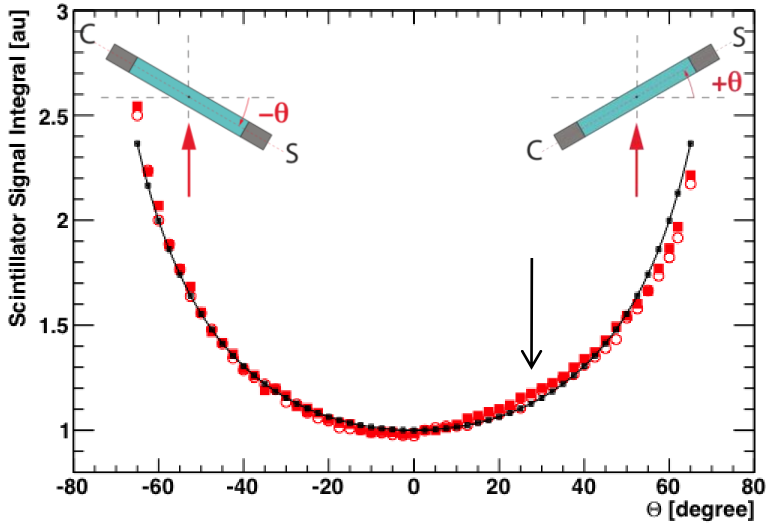
Setup 1 : Favorable Polarization Selection

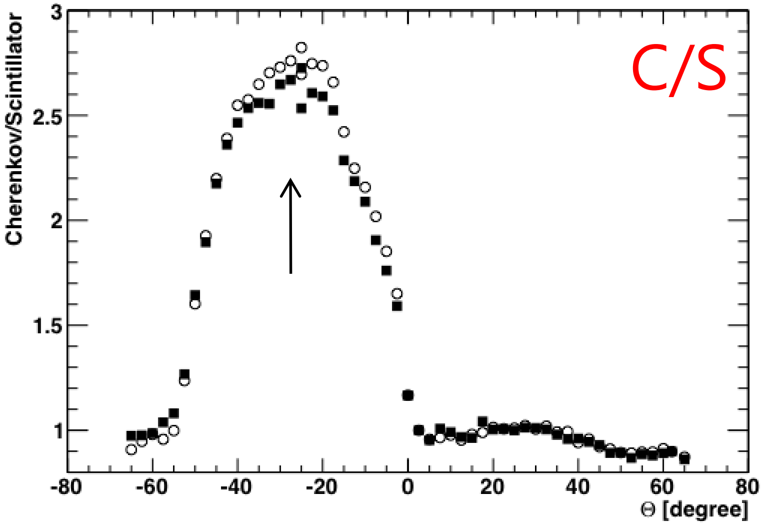


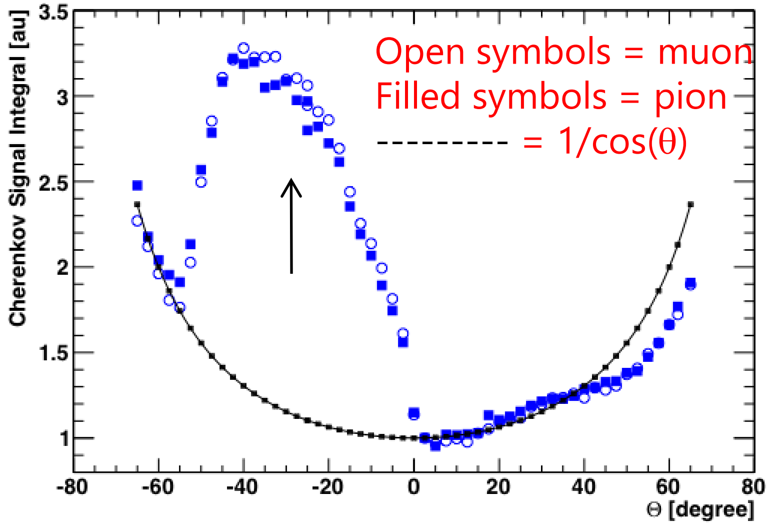
The polarizers at both Cherenkov and scintillation side are oriented such that the horizontal components are transmitted as shown on the right.

The vertical components are blocked.

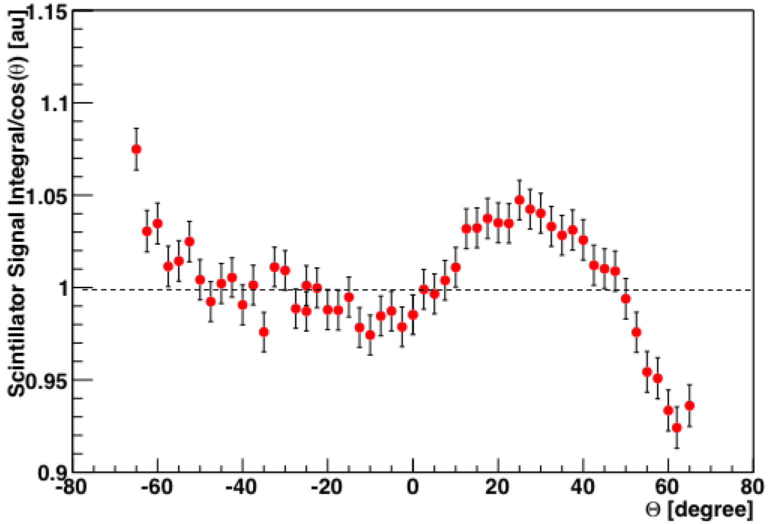
Setup 1 : C (Favorable) & S (Favorable)


SETUP1 Scintillator


SETUP1 Cherenkov over Scintillator


SETUP1 Cherenkov

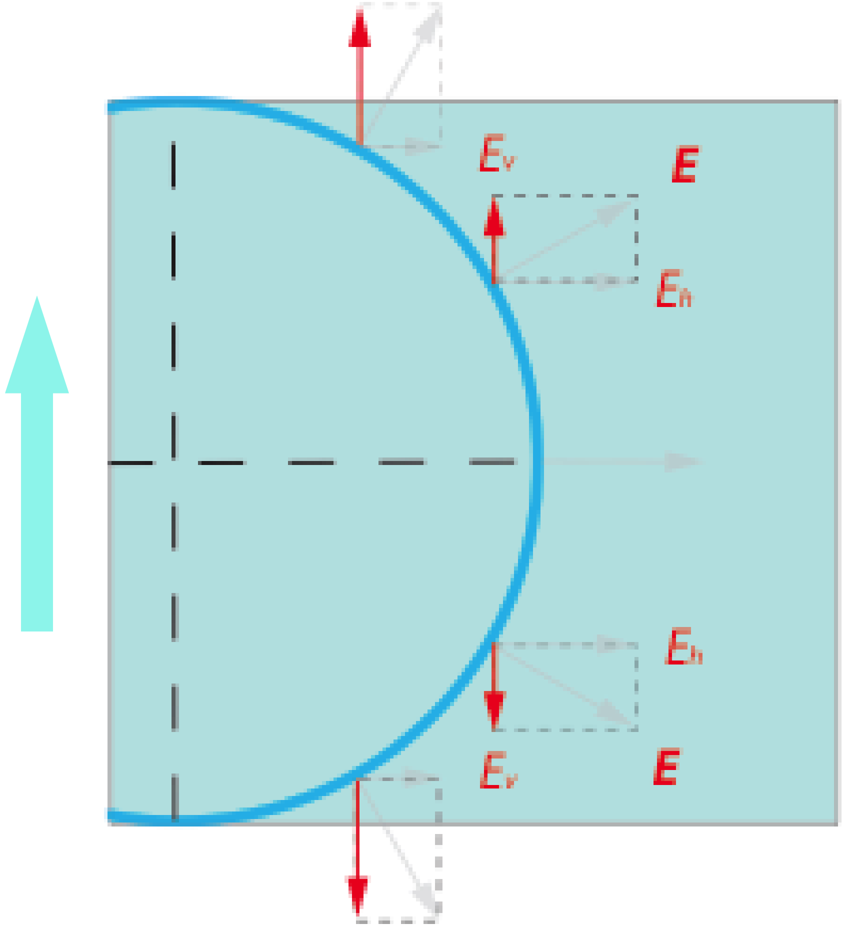
Open symbols = muon
Filled symbols = pion
-------- = 1/cos(θ)


SETUP1 Scintillator

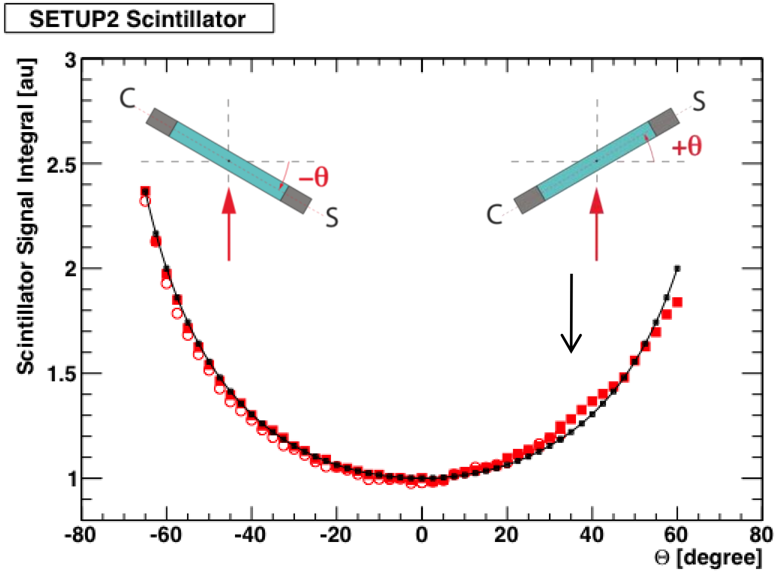
Setup 2 : Unfavorable Polarization Selection

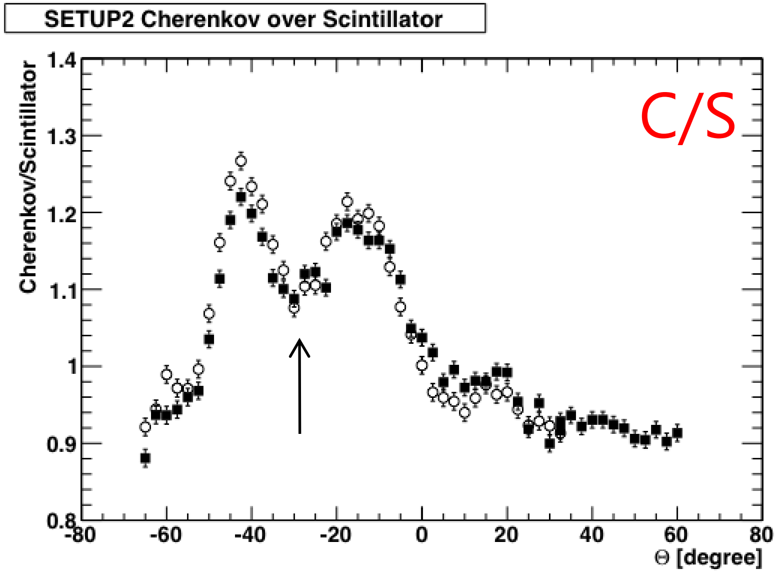
The polarizer at Cherenkov side is oriented such that the vertical components are transmitted which on average add to zero as shown on the right.

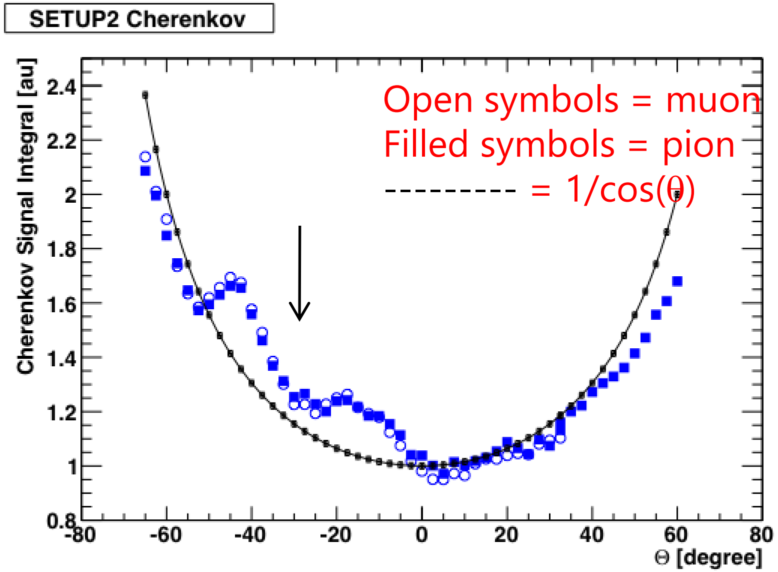
The horizontal components are blocked.



Setup 2 : C (Unfavorable) & S (Favorable)

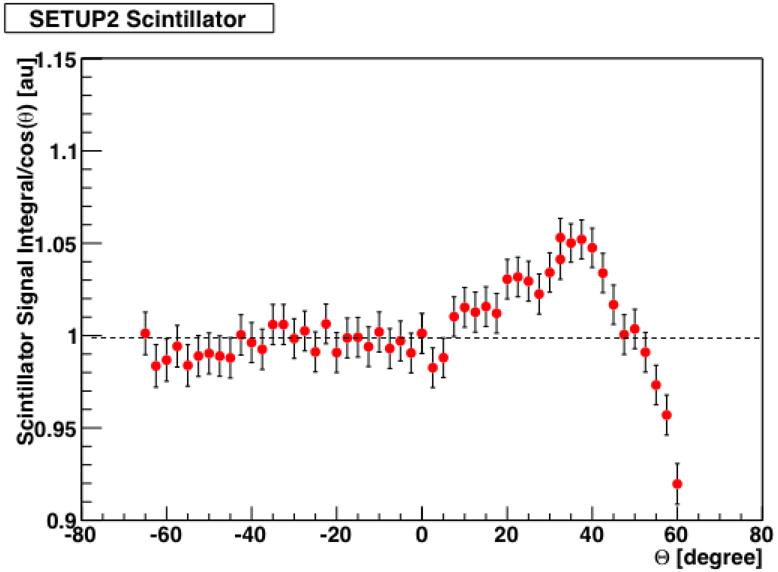



C/S

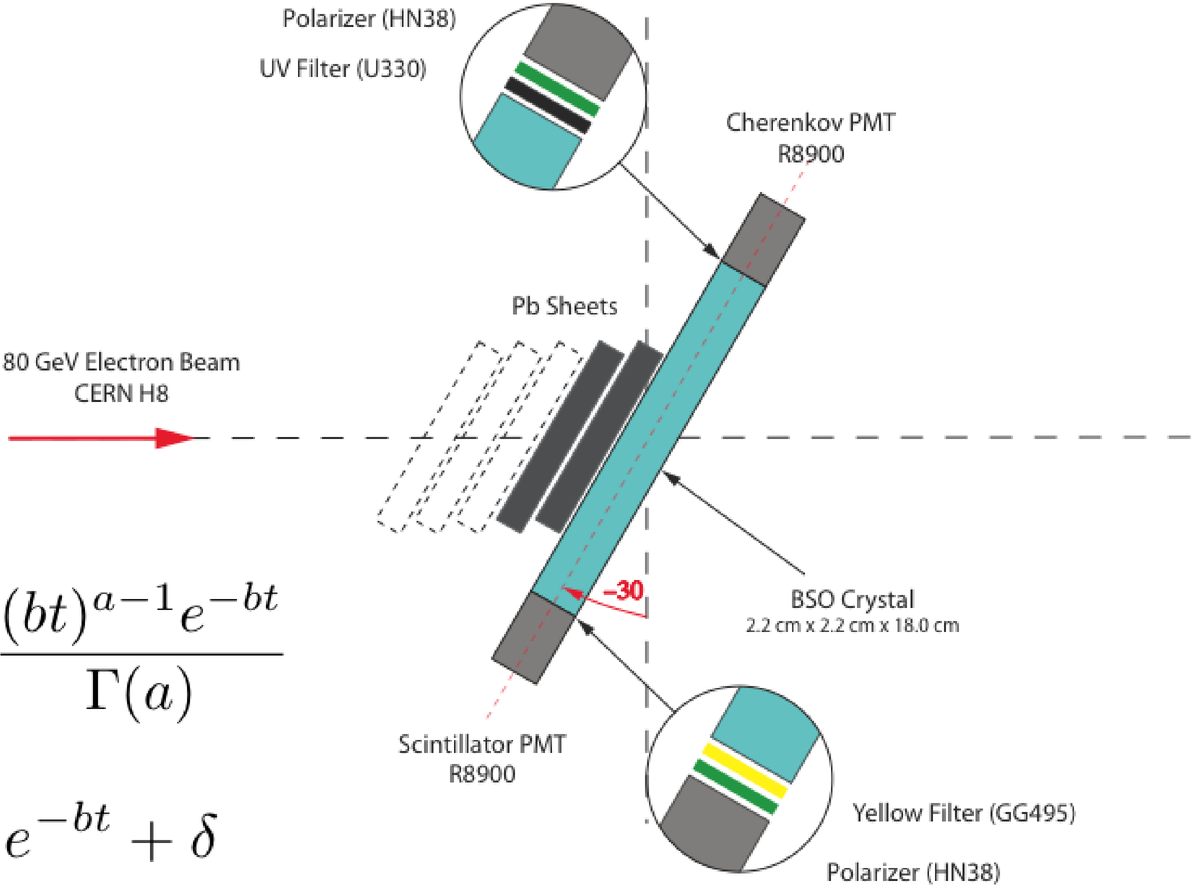

Open symbols = muon

Filled symbols = pion

--------- = 1/cos(θ)



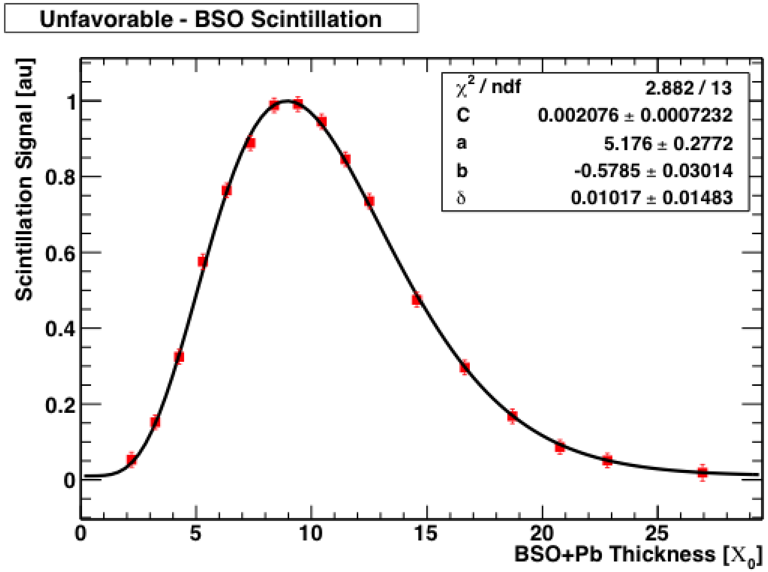
Polarization Profile in EM Showers

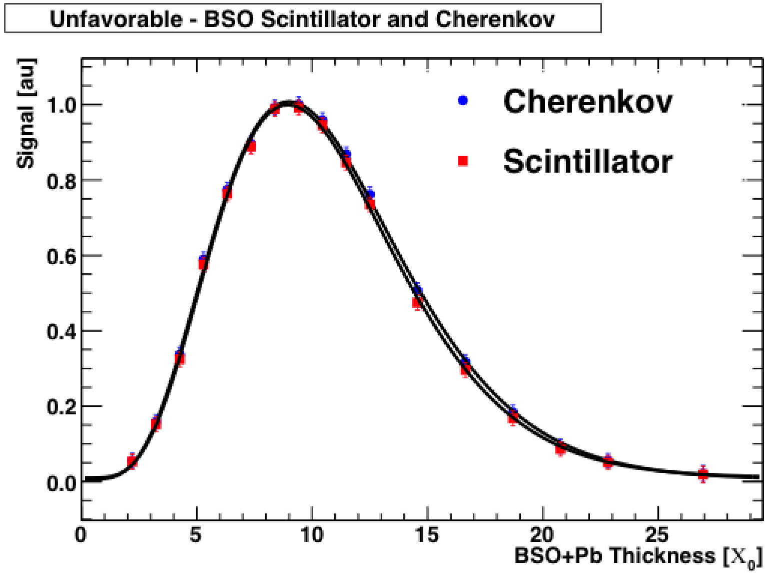


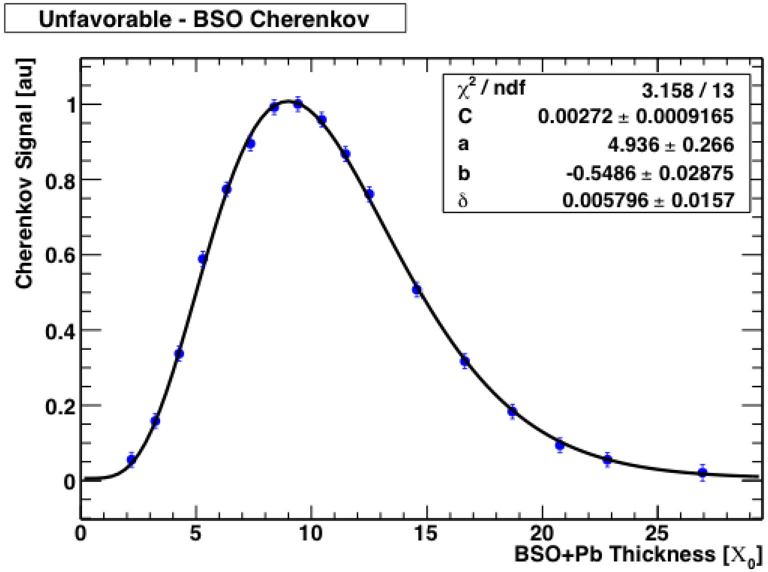
$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

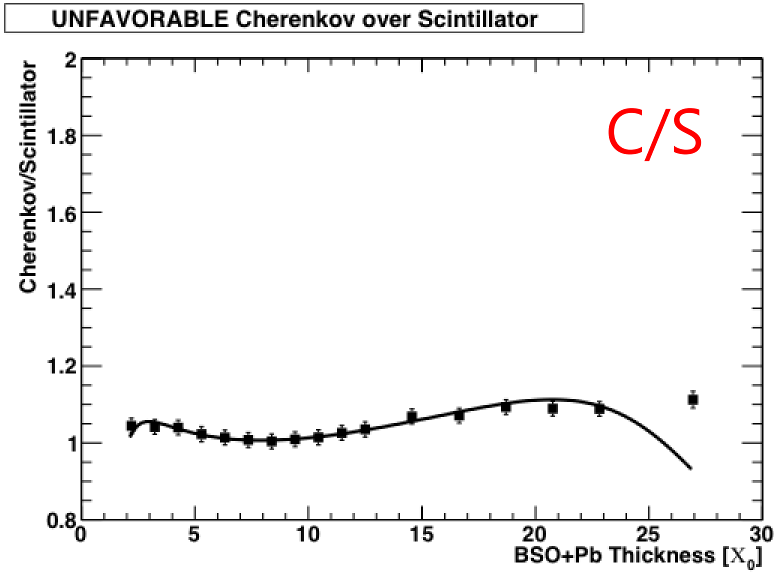
$$\frac{dE}{dt} = C t^a e^{-bt} + \delta$$

Unfavorable Polarizer Orientation


Unfavorable - BSO Scintillation

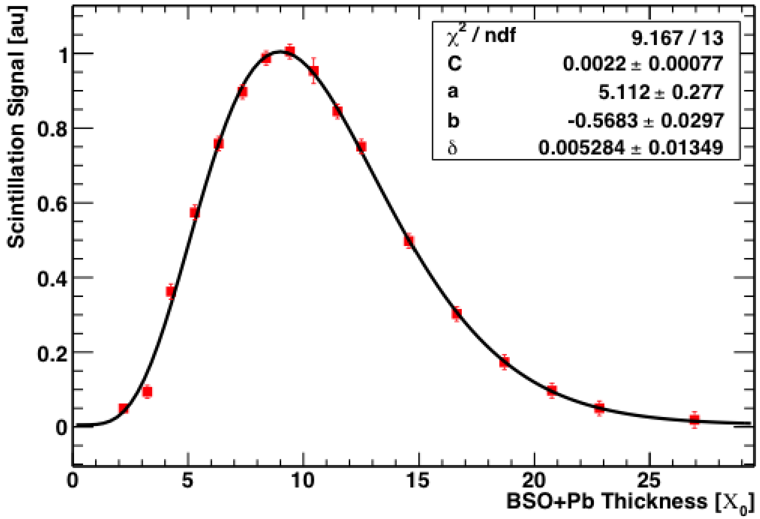

Unfavorable - BSO Scintillator and Cherenkov


Unfavorable - BSO Cherenkov

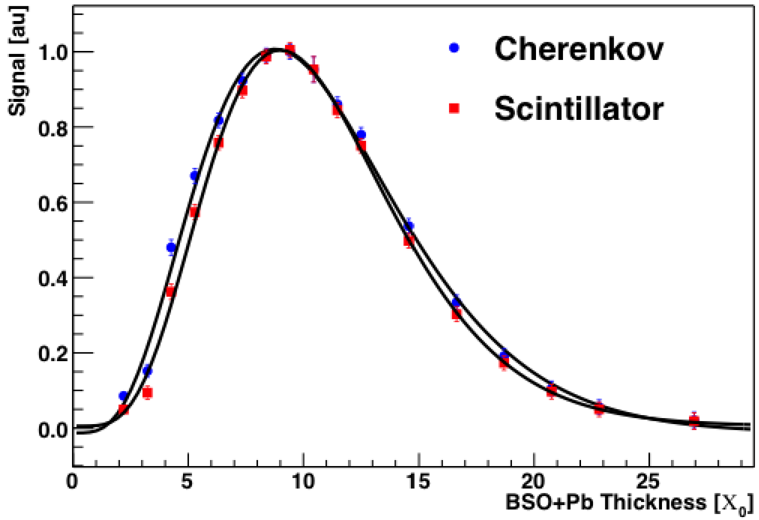

UNFAVORABLE Cherenkov over Scintillator

Favorable Polarizer Orientation

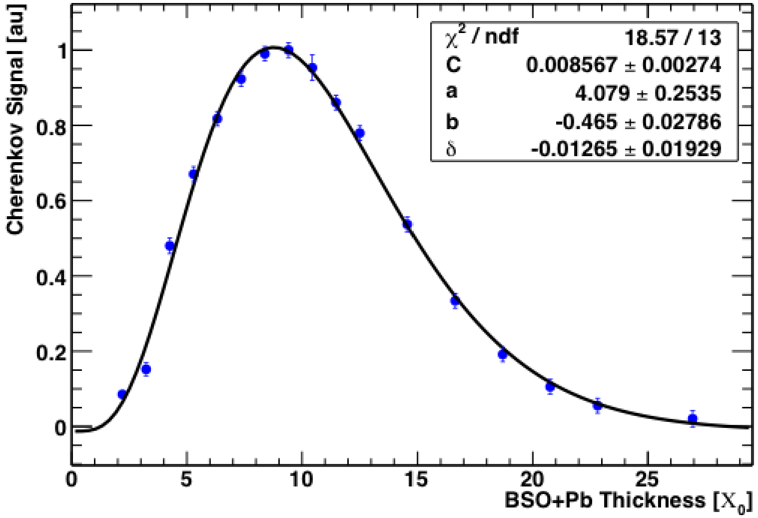
Favorable - BSO Scintillation



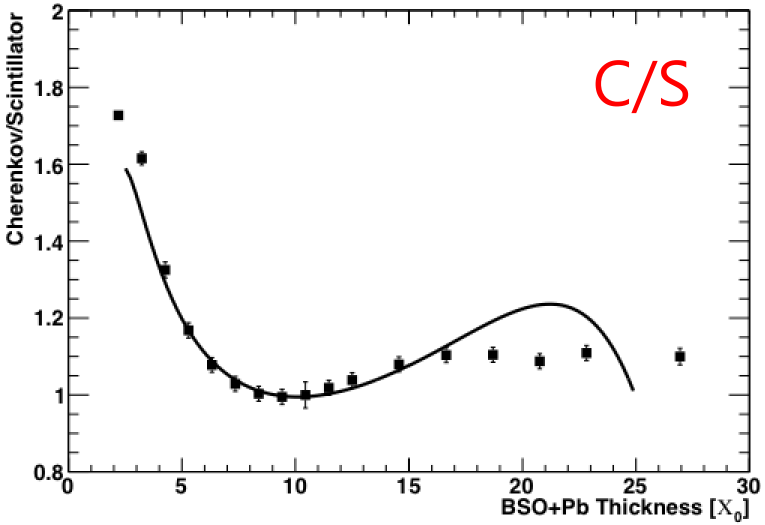
Favorable - BSO Scintillator and Cherenkov



Favorable - BSO Cherenkov



FAVORABLE Cherenkov over Scintillator



Longitudinal Cherenkov Polarization Profile

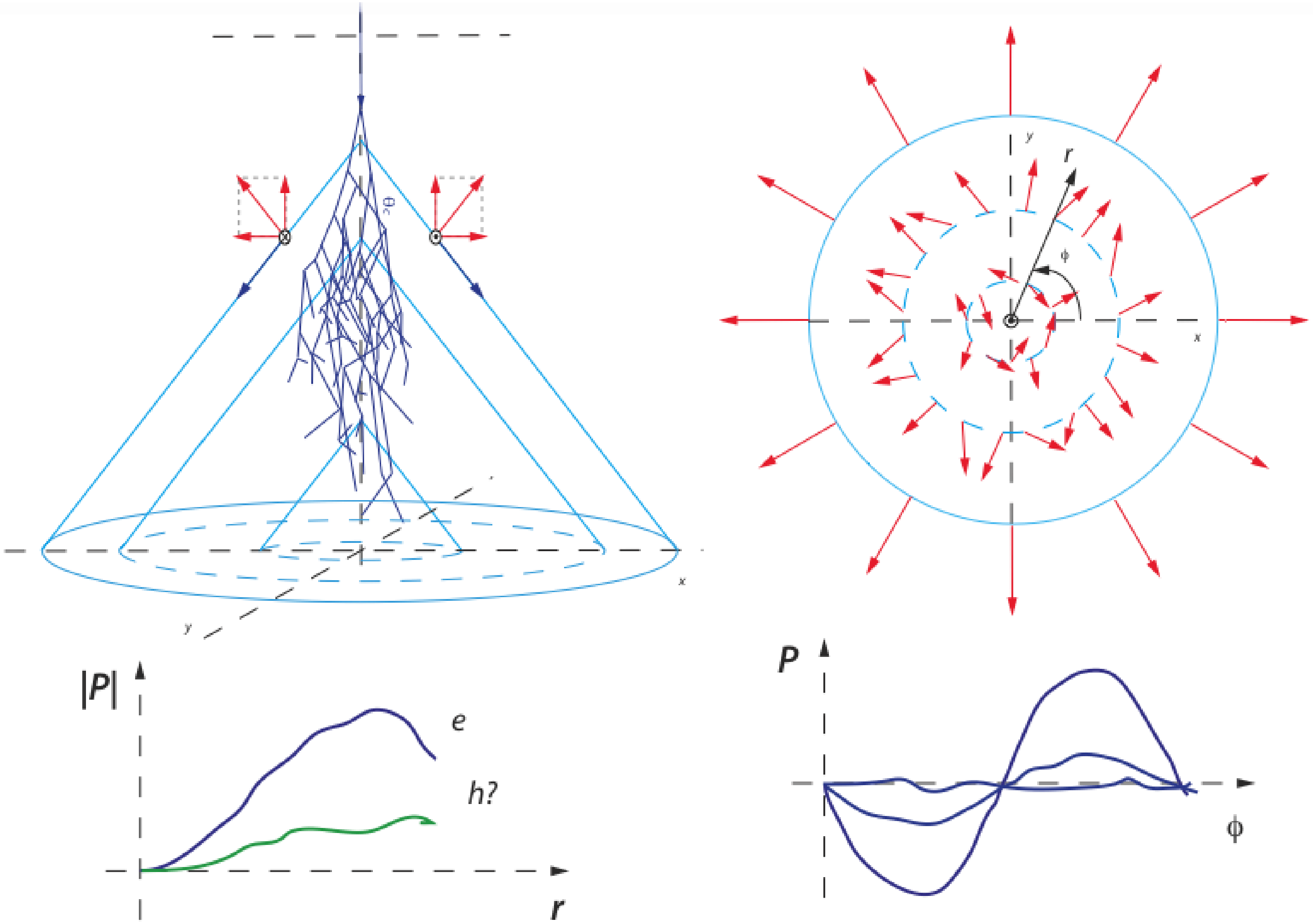
	a	***b***
Favorable (Sci)	5.11 ± 0.28	0.568 ± 0.029
Favorable (Che)	4.08 ± 0.25	0.465 ± 0.028
Unfavorable (Sci)	5.18 ± 0.28	0.579 ± 0.030
Unfavorable (Che)	4.94 ± 0.27	0.549 ± 0.029

Polarization of Cherenkov light in the earlier stages of the em shower development ($<7\ X_o$) is preserved and the effect is relatively large

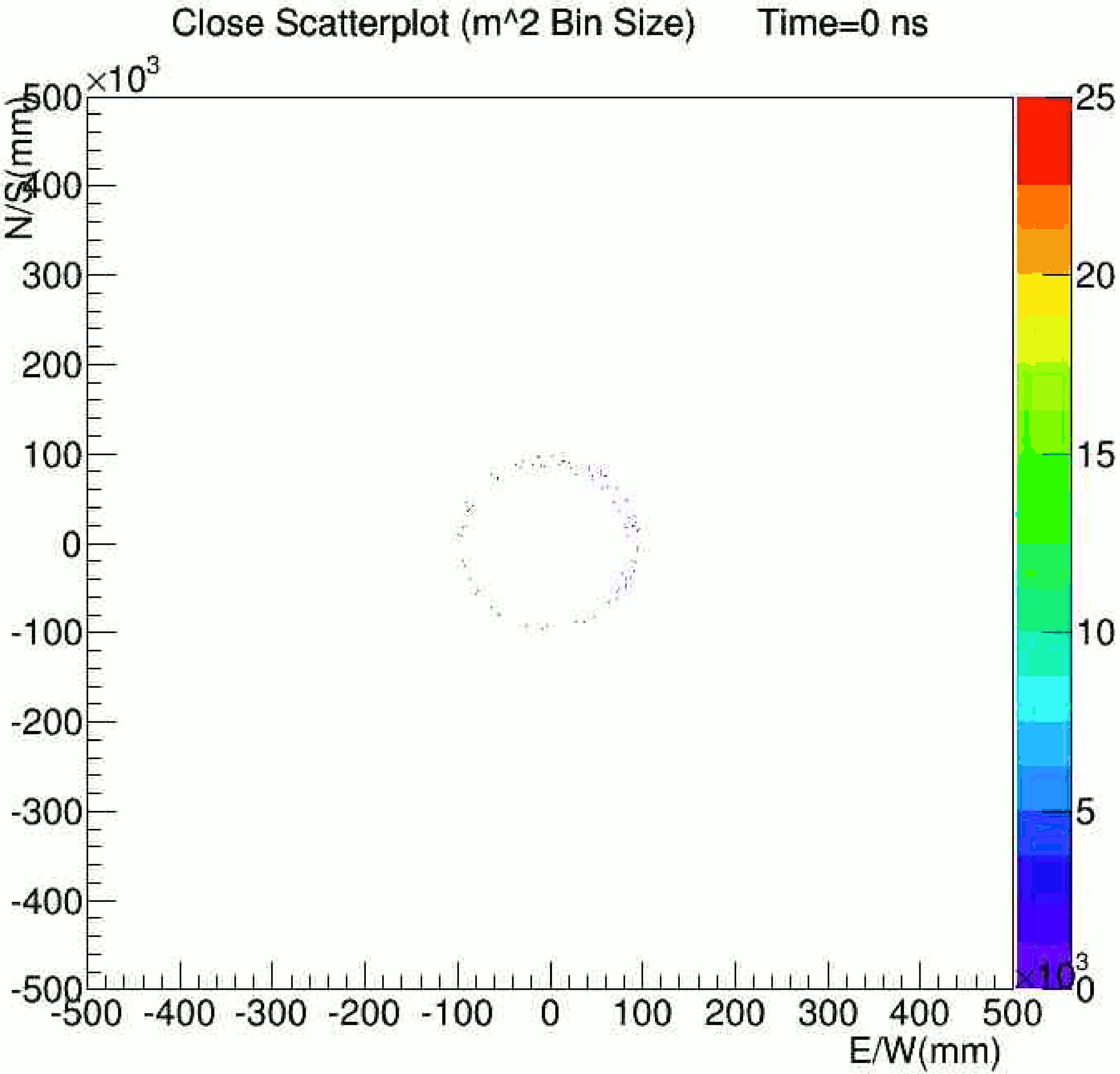
After the shower maximum, as expected Cherenkov polarization has no unique orientation

This aspect of Cherenkov radiation maybe useful in different applications in calorimetry if polarization can be measured per event, *etc*.

A Possible Application – Air Calorimeter Example ?

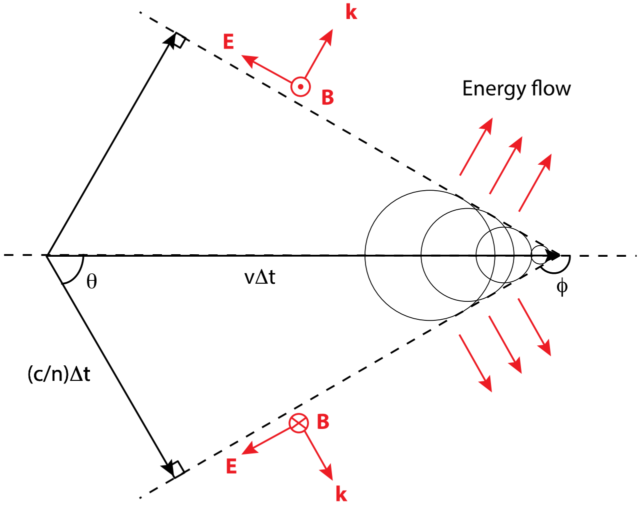


It may be possible to perform this measurement in fully sampling large media (*e.g.* air, ice, big crystals). The polarization component of Cherenkov light adds another (independent) feature that is worth exploring. This approach will enable us to measure the early part of the shower and effectively longitudinally segment the early part of the shower (by polarization).

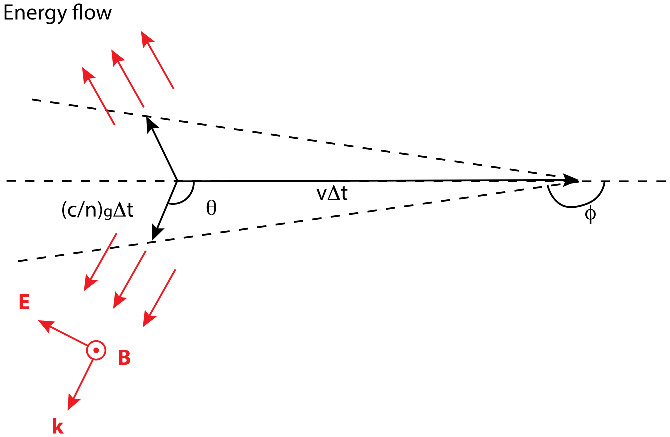

Close Scatterplot (m^2 Bin Size)
Time=0 ns
×10^3
N/S(mm)
500
400
300
200
100
0
-100
-200
-300
-400
-500
-500
-400
-300
-200
-100
0
100
200
300
400
500
E/W(mm)
25
20
15
10
5
0
×10^3

Flipped Cherenkov Radiation - I

“Normal” Cherenkov



“Flipped” Cherenkov



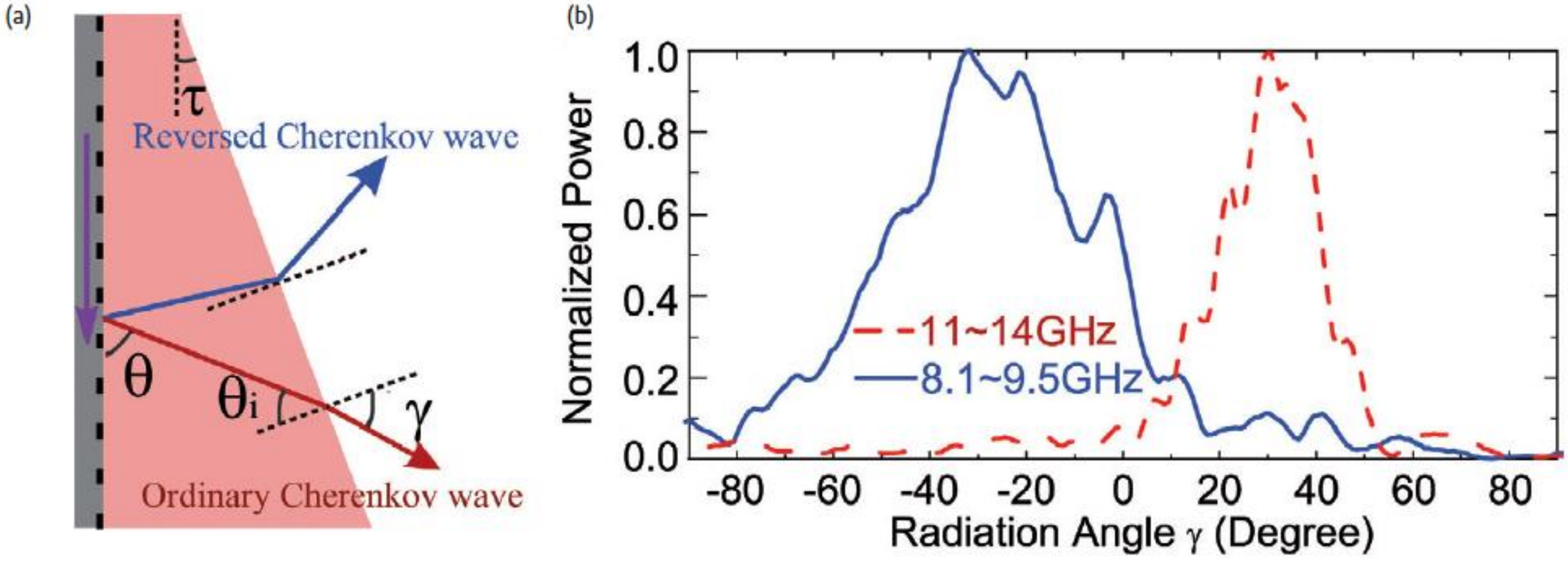
In normal Cherenkov radiation, the real part of the refractive index is positive ($n=2$ above, $\theta \sim 60^o$, *e.g.* BSO) and the group and phase velocities of the wave coincide

If the refractive index is negative (LHM), the Cherenkov angle ($\theta \sim 115^o$ above) is large and the photons and charged particles go in opposite directions. In such dispersive media, the phase and group velocities are different ($n=c/(\omega/k)= -\mathrm{sqrt}(\mu_r\varepsilon_r) \sim -2.38$) and $n_g=c/(d\omega/dk) \sim 6.57$ and the energy flows with the group velocity

φ satisfies the condition $\tan(180-\varphi)=[(n/n_g)\sin\theta \cos\theta]/[1-(n/n_g)\cos^2\theta]$

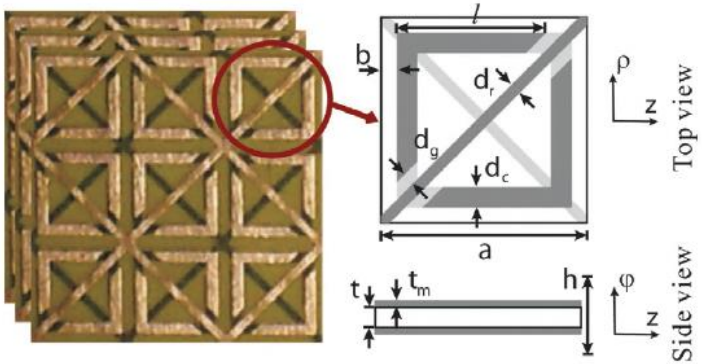
Flipped Cherenkov Radiation - II

S. Xi et al PRL 103 194801 (2009)



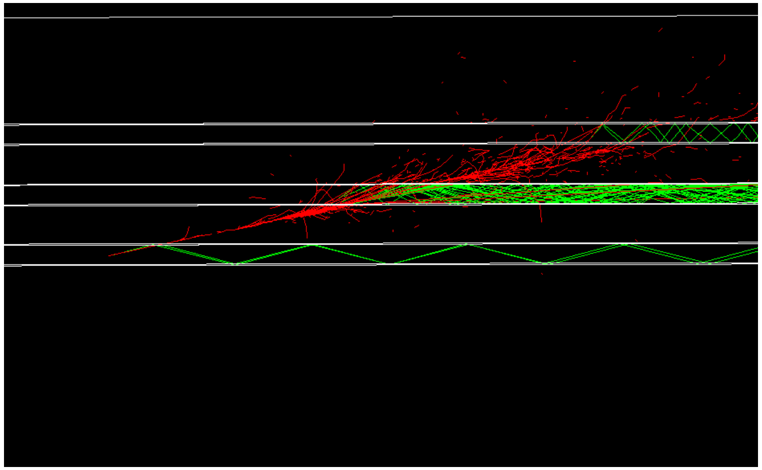
H. Chen et al Materials Today 14 1-2 (2011)

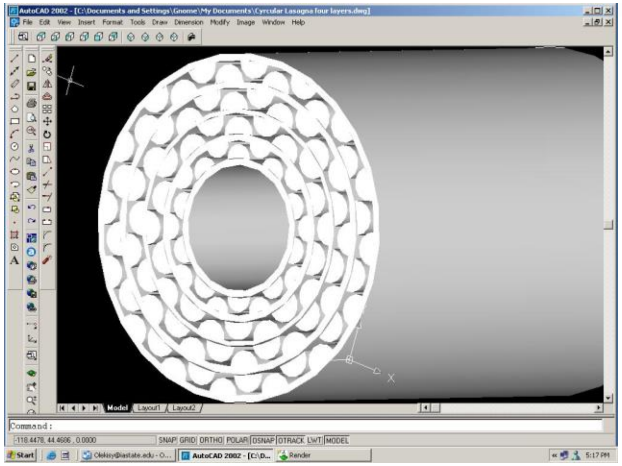
- The effect is demonstrated in microwaves (~8-12 GHz) with metamaterials where the feature size is measured in mm (much smaller than the wavelength). In the optical region where Cherenkov photons are more abundant and potentially useful in HEP, the feature size needs to be in nm
- If such metamaterials are realized, flipped Cherenkov effect might prove useful for calorimetry (readout upstream)



Cherenkov Light in Gas

O. Atramentov et al ALCW (2003)

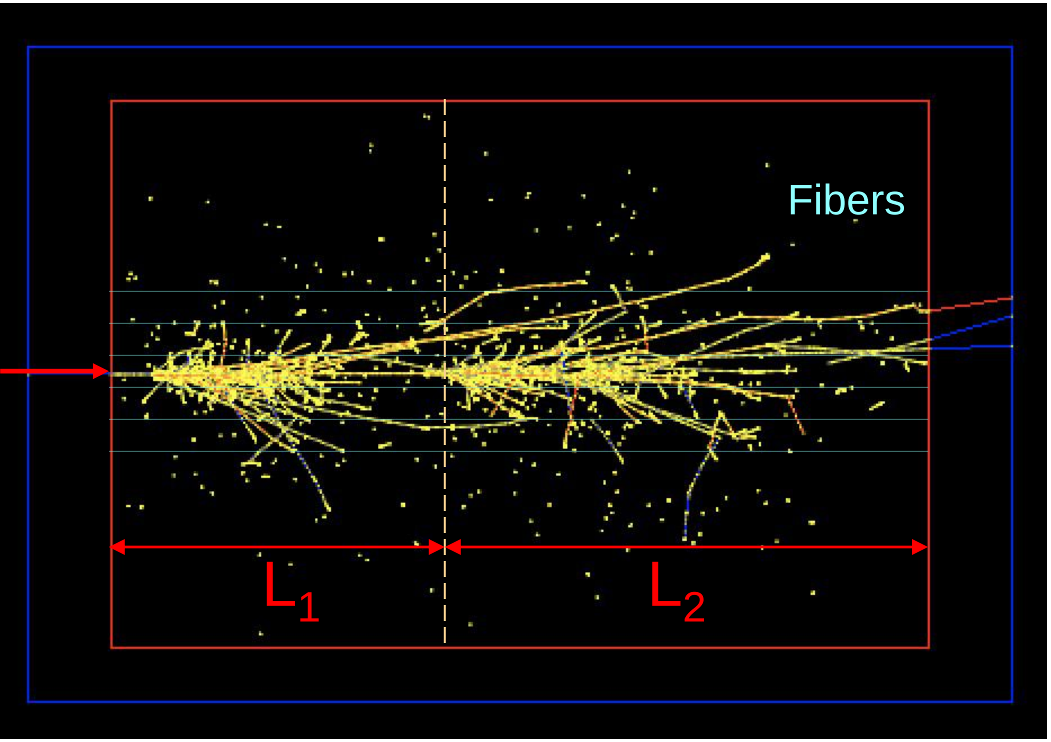




- Index of refraction for gasses is in general small $n=1+\delta$ ($\delta \sim 10^{-3}$). Example: $\delta_{C4H8}=0.00258$. This has the following consequences:
  1. Cherenkov angle is small: $\sin\theta_c \sim \mathrm{sqrt}(2\delta) \sim 0.05$ which means particles and light come out of the detector at the ~same time and time spread is small
  2. The Cherenkov threshold is high: $E_{th} \sim m_e/\mathrm{sqrt}\{2\delta\} \sim 11.2$ MeV which means decay products from radioactivation do not generate signal/noise
- If high quality (>95%?) reflective surfaces can be made (a few meters long) for UV+VIS, a calorimeter based on gas Cherenkov would be very radiation hard (indestructible?)

Longitudinal Segmentation with Timing

Fibers generate and efficiently transport fast Cherenkov radiation. With appropriate timing (sampling), it may be possible to effectively segment the calorimeter in depth



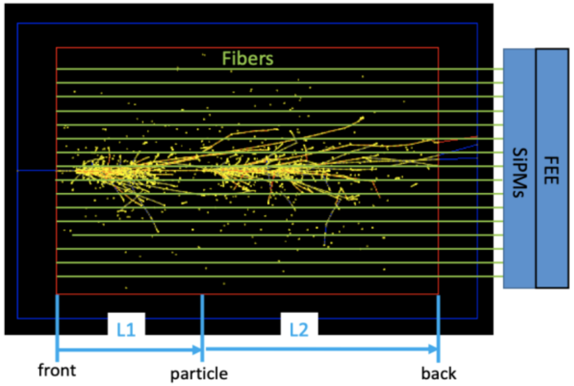
Signal time = $L_1/c + L_2/(c/n)$,

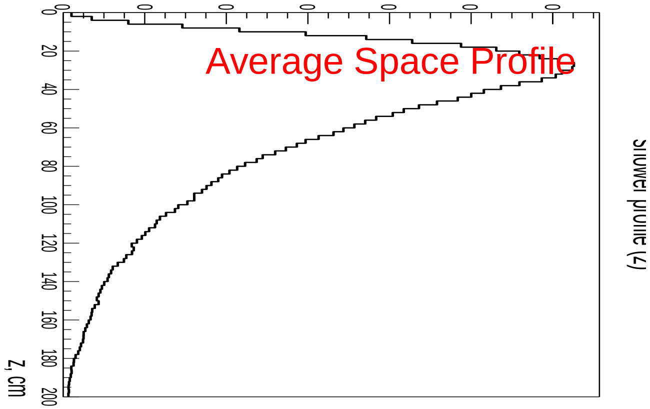
(c/n) = velocity of light in fiber (n~1.45)

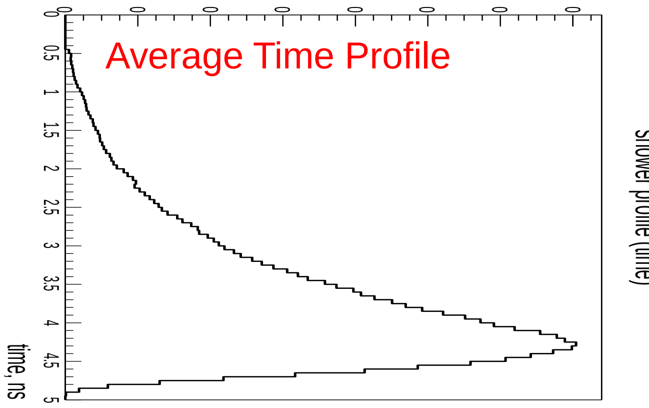
~20 cm/ns or ~1 cm/50 ps

There is significant savings in channel count (and calibration) as one fiber represents many channels along the depth of calorimeter.

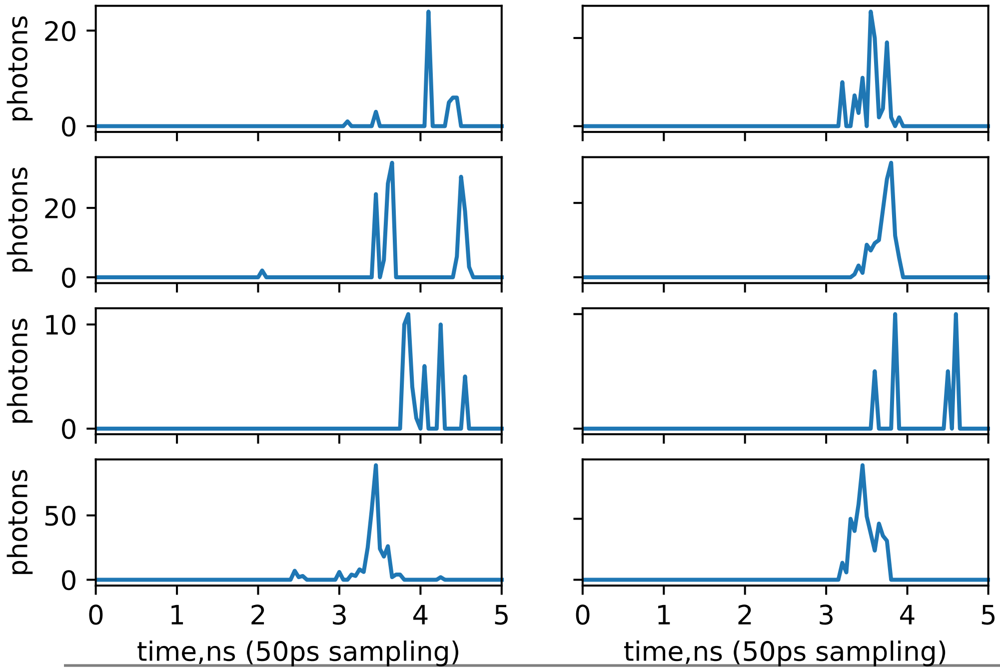
Simulations/Estimates with Cherenkov Photons







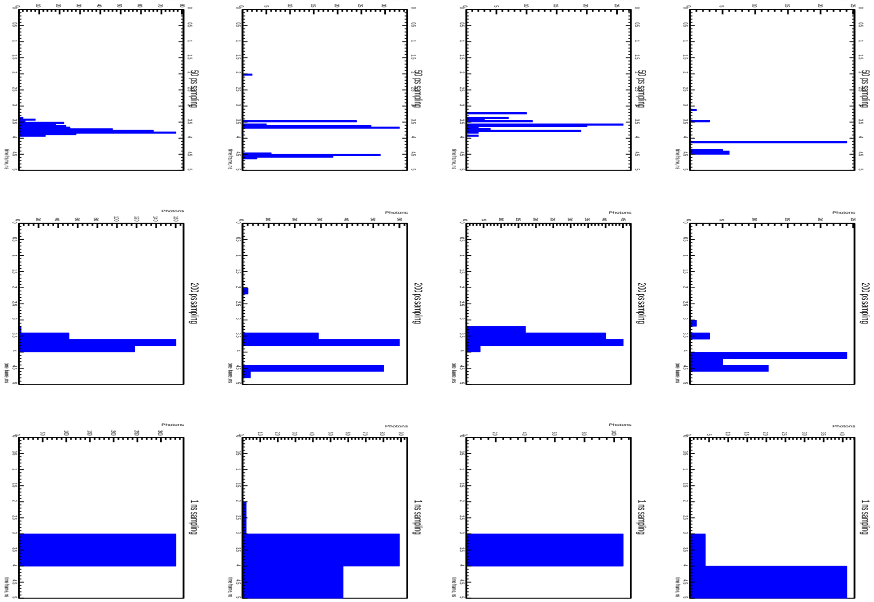
50 GeV π^+ in 1.2 cm x 1.2 cm tower



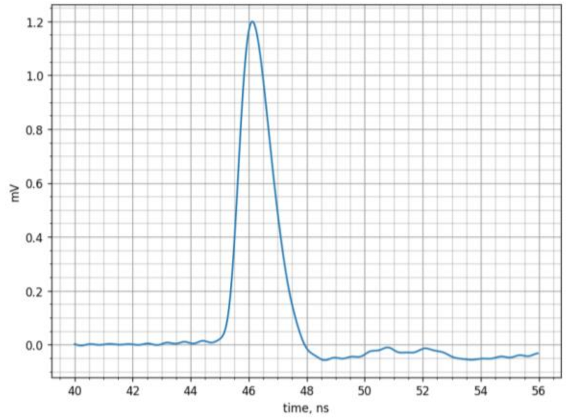
0.05 ns (1 cm)

0.2 ns (4 cm)

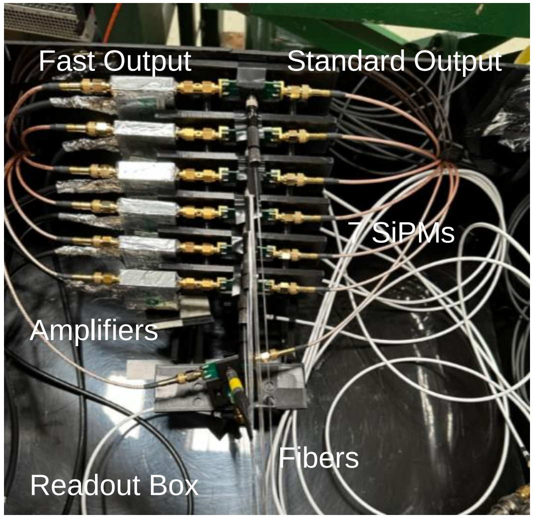
1 ns (20 cm)

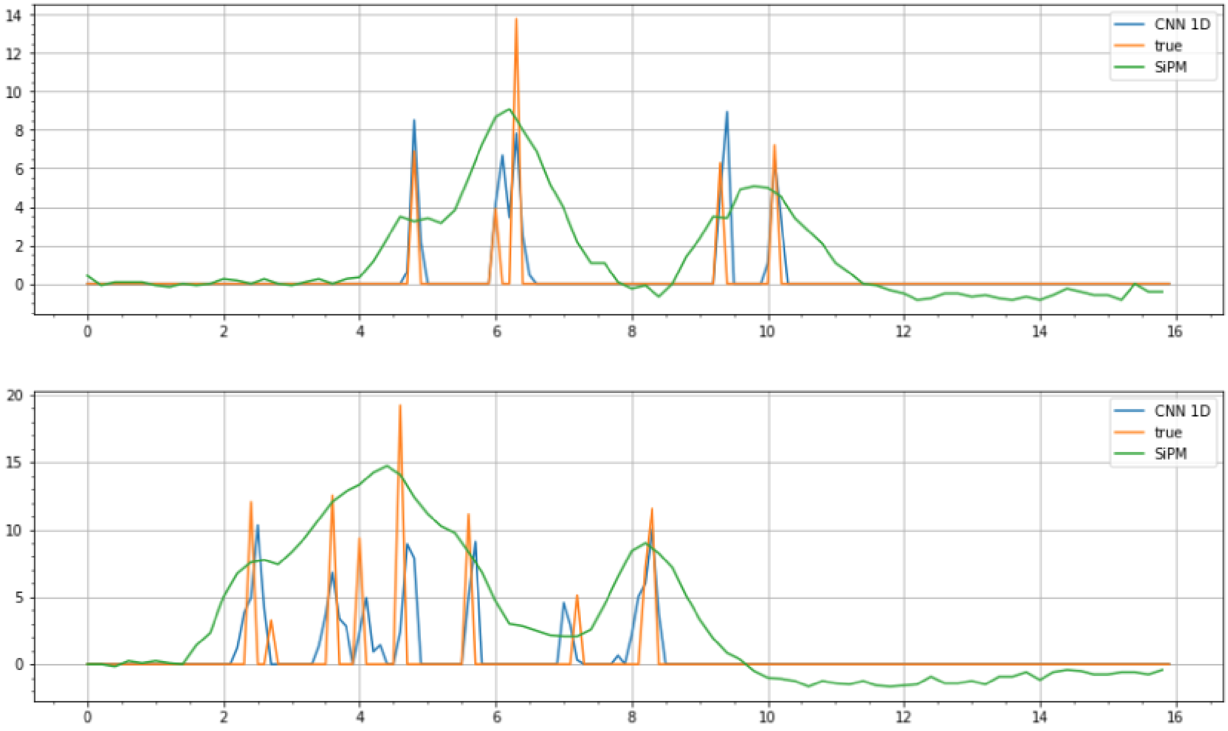


Deconvolution of Cherenkov Pulse Train with CNN



Single Cherenkov photon SiPM pulse obtained in 2023 beam test





It seems possible to deconvolve overlapping SiPM (Cherenkov) pulses to reveal the true distribution of shower components using CNN:

Green: Convoluted SiPM pulse train

Blue: Deconvoluted SiPM pulse train

Orange: True pulse train

Conclusions

Cherenkov radiation is rich in interesting features, and many can be exploited for calorimetry

- Polarization adds another interesting one but need to figure out how to take advantage of it for HEP calorimetry
- Fast signals lend themselves for effective longitudinal segmentation, and better energy and timing resolution
- Metamaterials might open new possibilities in calorimetry