Measurement of the Charged Kaon Mass in MIPP

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For the Fermilab MIPP E907/P960 collaboration

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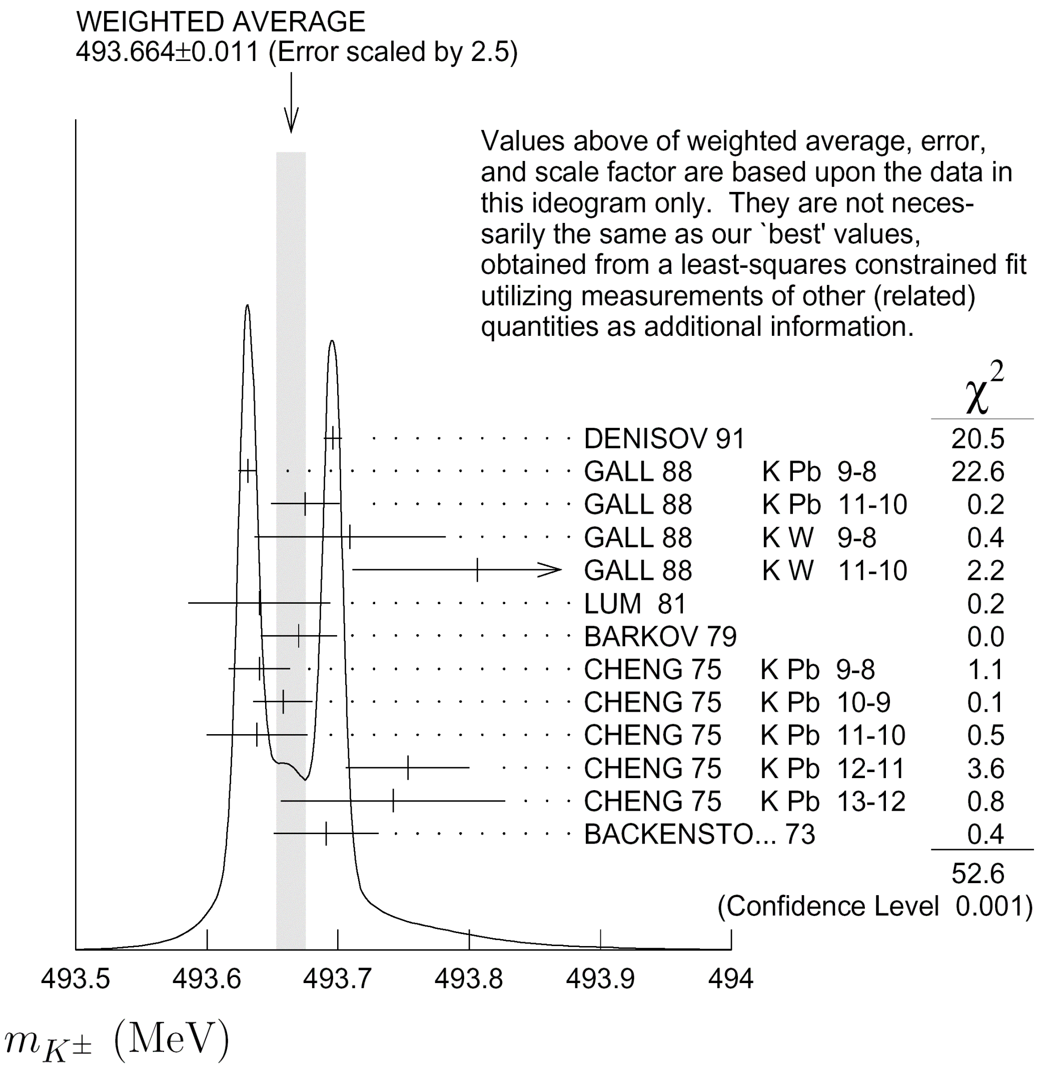
Current Value in PDG



Source: S. Bidelman et al (Particle Data Group) Phys. Lett. B **592**, 1 (2004)

m_k = 493.677 ± 0.013 MeV (26 parts per million).

Weighted average of measurements from kaonic atom x-rays.

Dominated by two recent measurements, Denisov and Gall. Precisions of 14 and 22 ppm respectively and differ by 122 ppm.

Goal is to help resolve ambiguity, not compete with these two measurements.

An improved kaon mass would impact measurements of CKM element V_{us}.

Overview of MIPP

Main Injector Particle Production (MIPP) is a fixed target experiment at Fermilab.

Large acceptance spectrometer to measure hadronic particle production.

Secondary beam of 5-85 GeV/c $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ produced by 120 GeV/c protons interacting on copper target.

Measure production off various targets such as liquid hydrogen, Be, C, Bi, and U.

Applications for data:

Improve hadron shower models in Fluka, Geant4, MARS

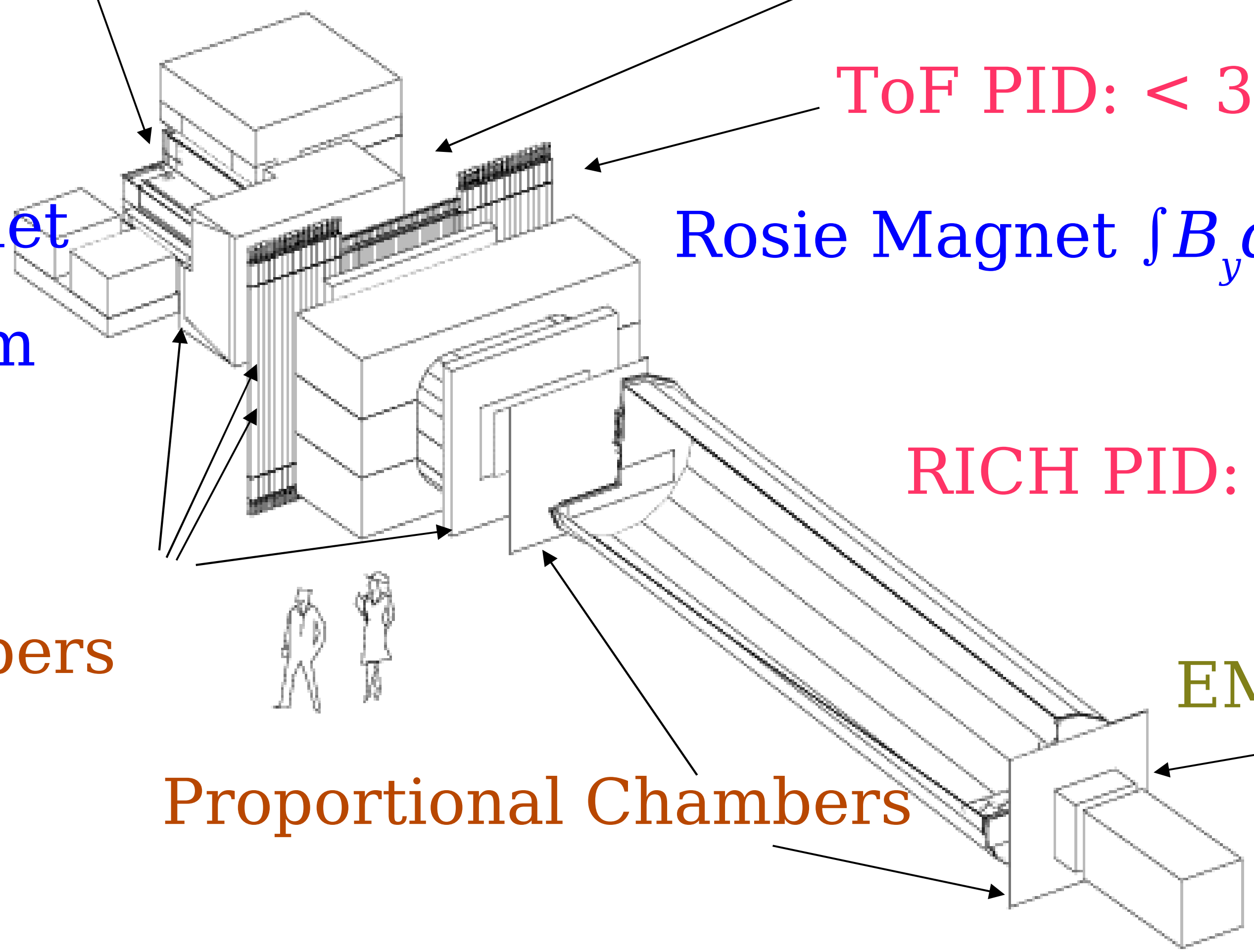
Non-perturbative QCD

Relativistic heavy ion physics

Nuclear physics

Primary 120 GeV/c beam from the Main Injector for service measurement of NuMI target.

Spectrometer Geometry

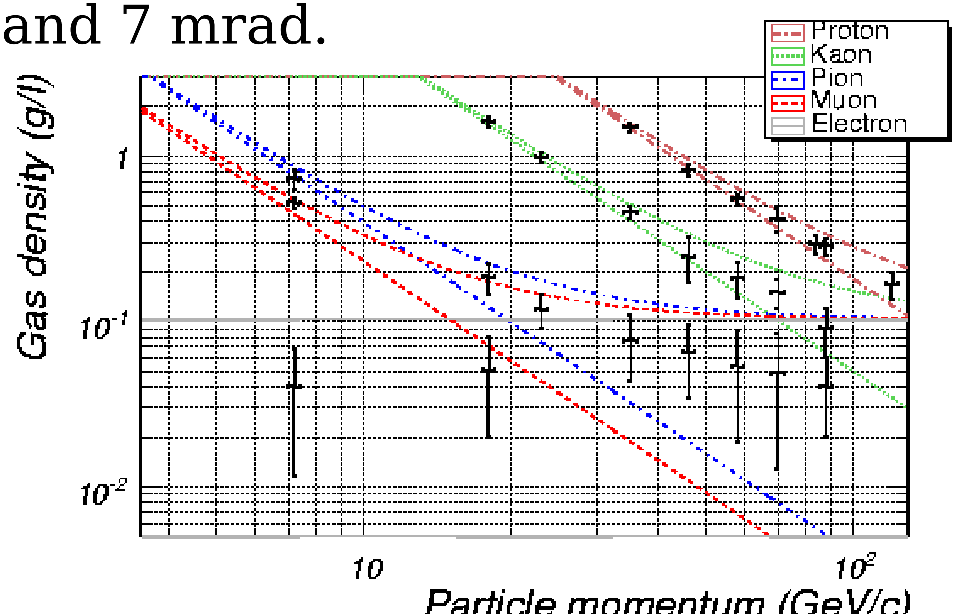


Beam Cherenkov

Two 18 in diameter, cylindrical Cherenkov counters identify beam particles.

22.9 and 12.2 m long, respectively.

Mirrors reflect light onto inner and
outer PMTs. Cutoff angles of 5 and 7 mrad.



Tune gas density so that:

$$\pi : \overline{UI} \cdot UO$$

$$K : UI \cdot \overline{UO}$$

$$p : DI \cdot \overline{DO}$$

Chambers

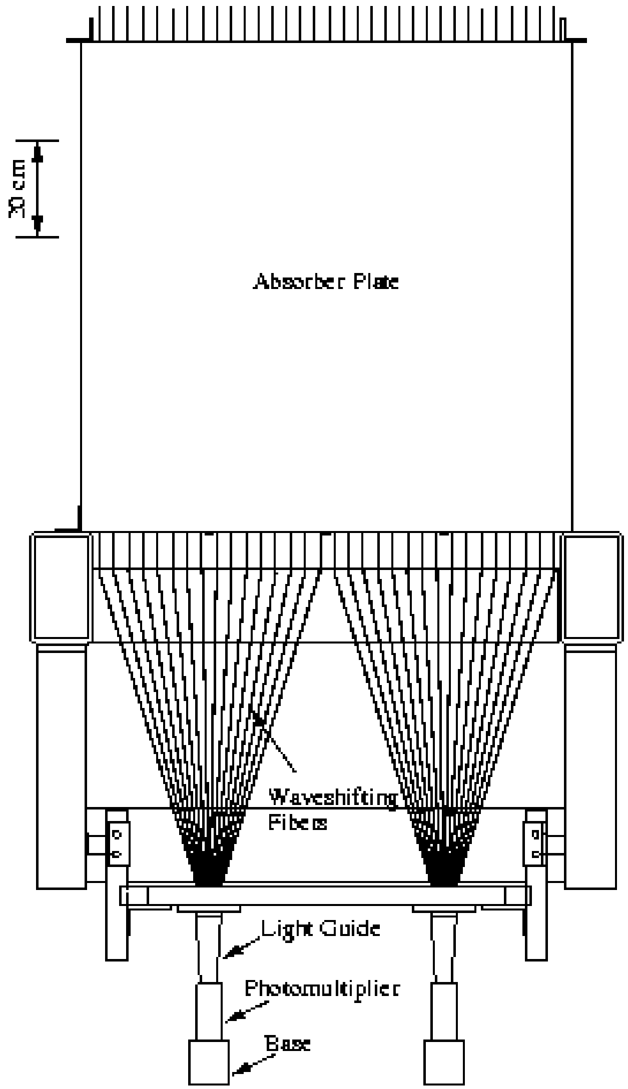
Three small drift chambers track beam to target.
1.0 mm wire spacing.
Resolution: 150 μm, 5μrad.

Four drift chambers track through ROSIE.
DC1: Four planes of 512 wires.
Spacing is 3.5 mm.
DC2-4: Four planes of 448 wires.
Spacing is 3.2 mm.
Previously used by FNAL 690.

Two MWPCs straddle RICH.
Four planes of 640 wires, spacing of 3.0 mm.
Only two planes in chamber 5 active.
Previously used by NA24 and SELEX.

Hadron Calorimeter

Previously used by HyperCP.



Measure forward going neutron production. Also functions as beam dump.

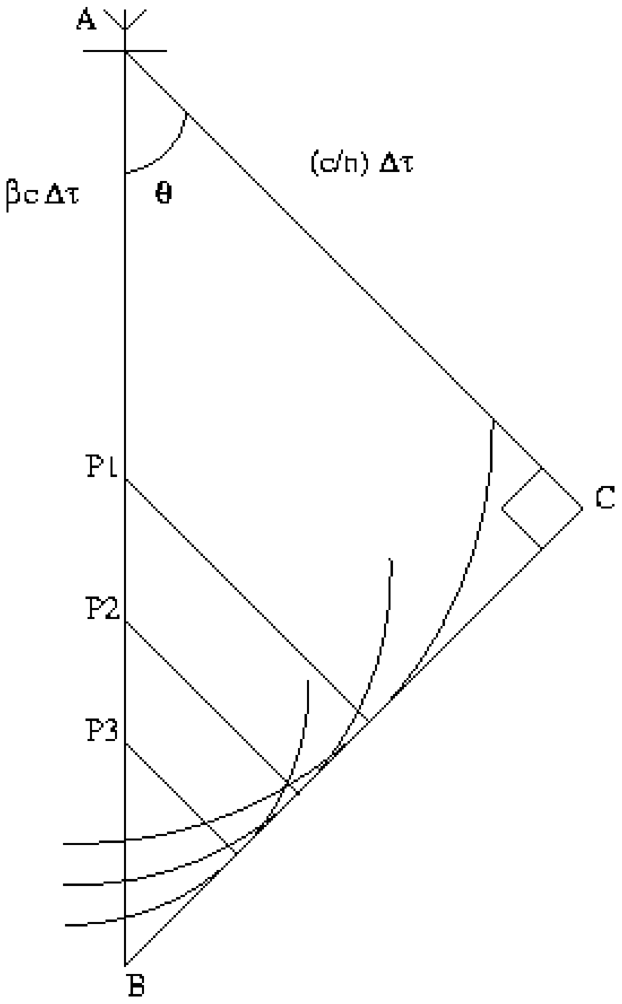
Sum energy deposition of hadronic shower in lead sheets.

Four scintillator plates sandwiched between lead sheets.

Each plate has two cells readout by phototubes.

Help cut out downstream interactions and decays.

Cherenkov Effect



Charged particle traveling near speed of light in medium: asymmetric polarization.

Wavelets coherent when speed exceeds that of light in medium.

Some properties:

$$\cos(\theta) = \frac{1}{(n\beta)}$$

$$\beta_{thr} = \frac{1}{n}$$

$$\theta_{max} = \cos^{-1}(1/n)$$

$$\frac{\partial^2 N_{ph}}{\partial\lambda\,\partial x} = \frac{2\pi\alpha}{\lambda^2}\sin^2(\theta)$$

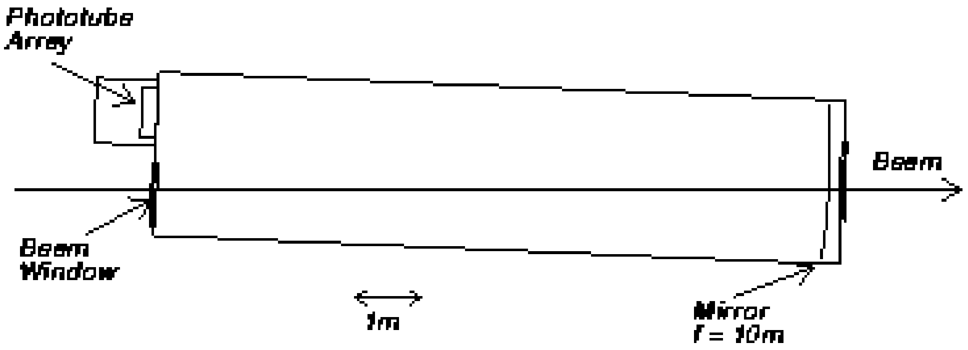
R I C H

Built for Selex experiment at FNAL.

Cylindrical steel vessel is 10.22 m long, with a diameter of 93 in.

LED array for calibration.

Pressure, upstream and downstream temperature monitored every 10 min.



Beam windows made of Kevlar, Al, and Tedlar layers.

Radiator is CO_2 at just above 1 atm.

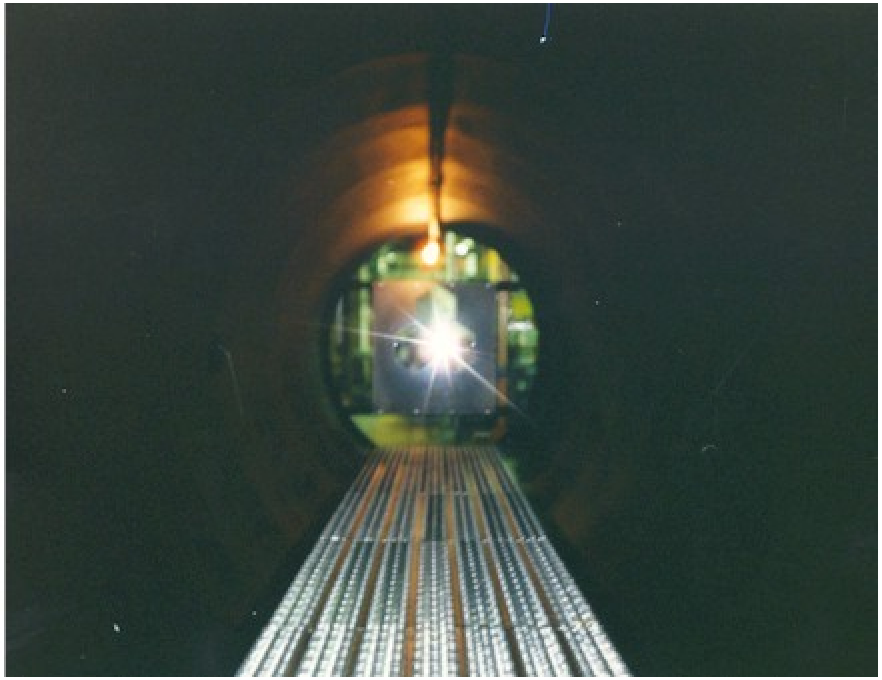
Thresholds: 4.5 GeV/c for pions, 17 GeV/c for kaons, 31 GeV/c for protons.

Max. radius: ~29.5 cm

PID: 3σ π/K up to 80 GeV/c

3σ p/K up 120 GeV/c

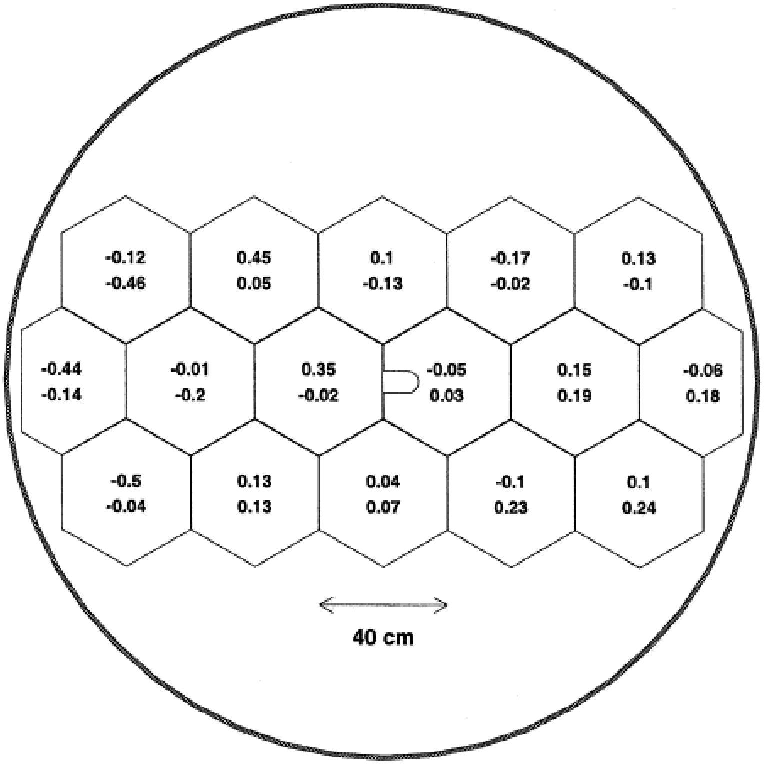
RICH Mirrors



Array of 16 hexagonally shaped spherical mirrors.

Cover area of 2.4 m X 1.2 m.

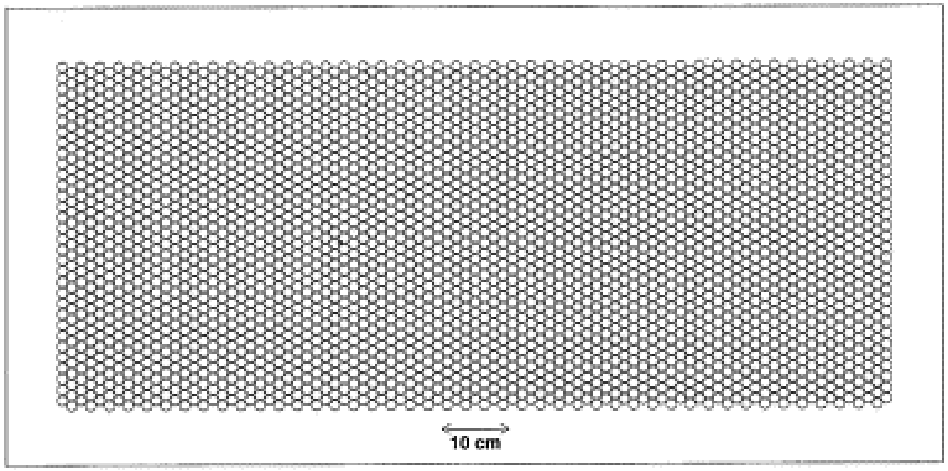
6.8 cm X 11 cm cutout for beam

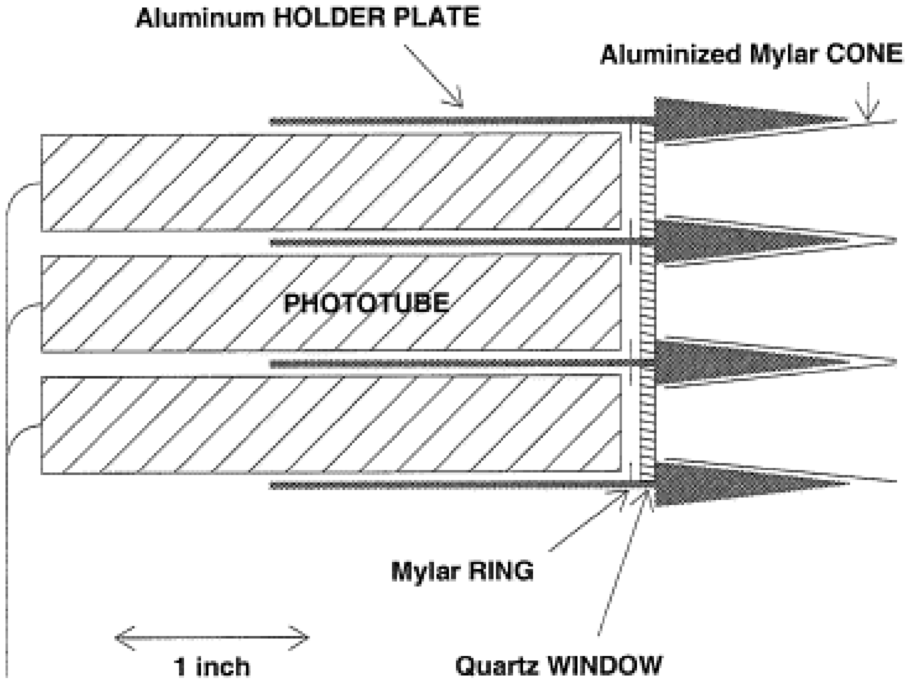


Radius ~990 cm. Deviation of less than 5 cm.

Reflectivity of about 90% at wavelengths above 200 nm.

RICH Phototubes





Two types of ½ inch PMTs: Hamamatsu R760 and Russian FEU60, with digital readout.

Efficiency: 25% at 350 nm (R76)

FEU60: ~42% as efficient. Coated with wavelength shifter.

Aluminum holder plate is 55 in X 27 in X 3 in.

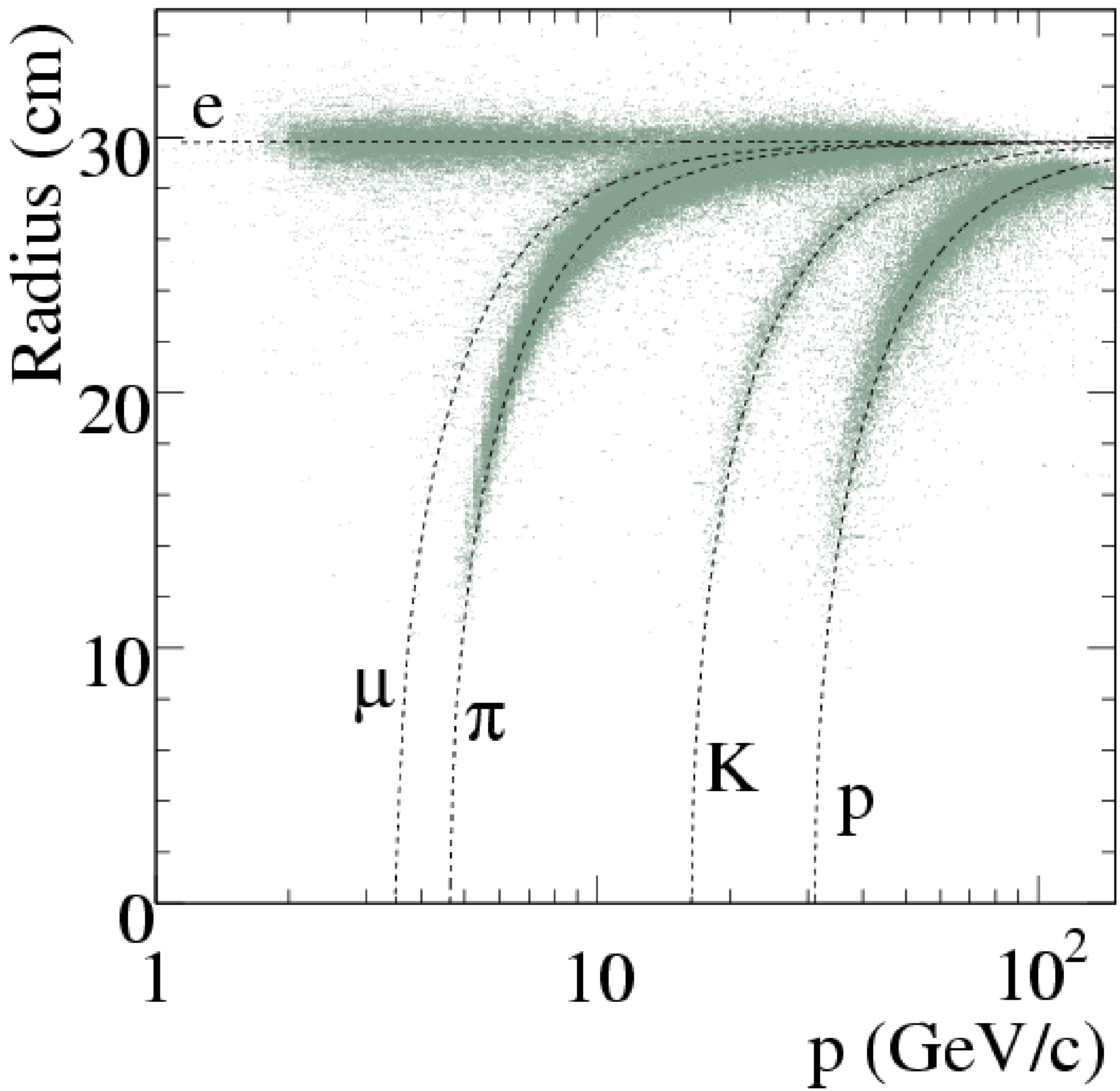
Aluminized mylar cones for nearly 100% coverage.

Quartz window provides gas seal.

Tubes are packed in columns of 32 each.

Originally 89 columns for a total of 2848 tubes.

Basic Concept



Use mono-energetic π/K/p beam.
Cherenkov angle is:

$$\theta = \frac{R}{L} = \sqrt{2\left(1 - \frac{1}{n\beta}\right)}$$

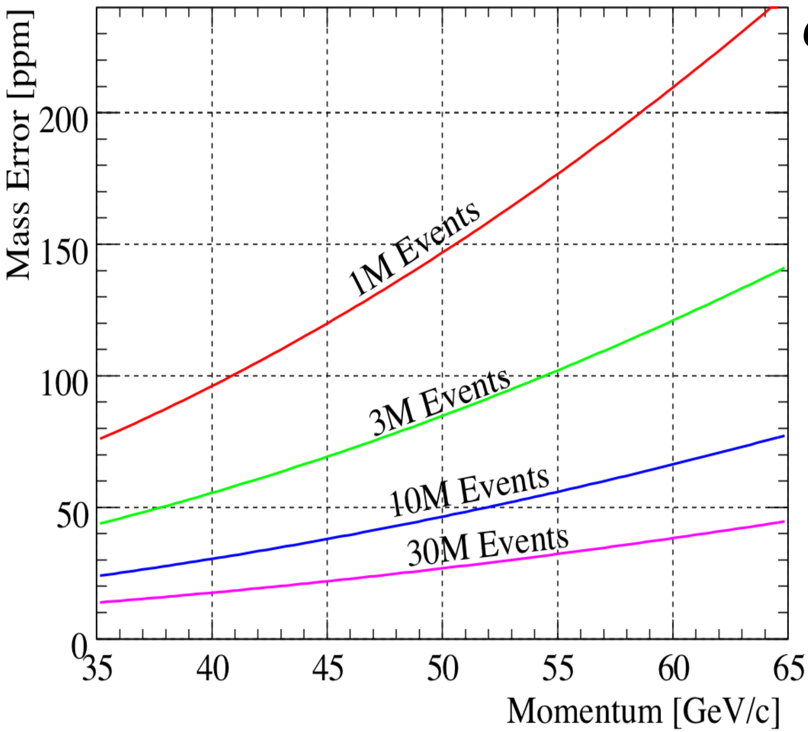
Relate two angles by eliminating n

$$\theta_i^2 - \theta_j^2 = \frac{m_j^2 - m_i^2}{p^2}$$

Eliminate momentum p and relate masses, angles

$$m_K^2 = m_\pi^2 + (m_p^2 - m_\pi^2)\left(\frac{\theta_\pi^2 - \theta_K^2}{\theta_\pi^2 - \theta_p^2}\right)$$

Estimated Statistical Error



$$\sigma_{m_K} \sim p^2 \longrightarrow$$

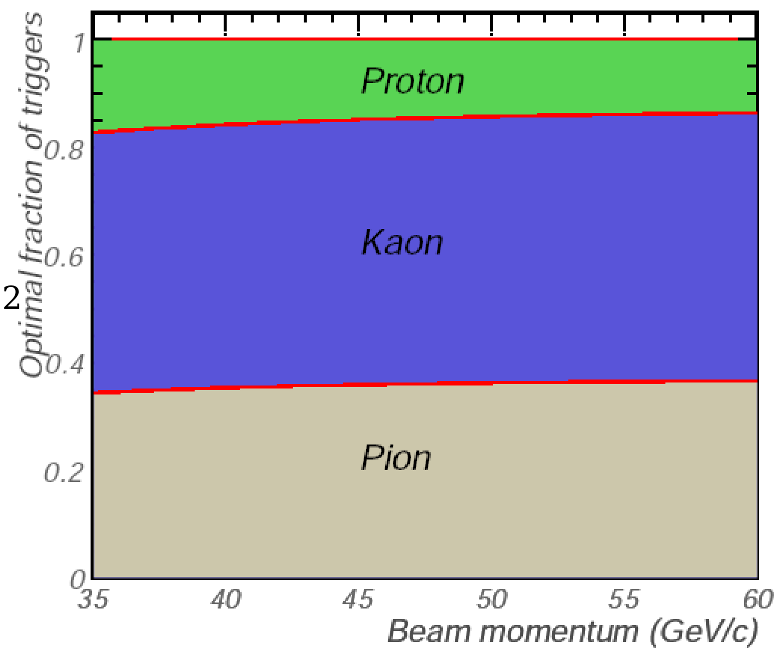
Need to run with momentum as low as possible. 40 GeV/c is still above proton threshold.

Largest contributions to width of ring are:

Dispersion in radiator $\Delta_n \sim 7 x 10^{-6}$

Spread in beam momentum $\frac{\sigma_p}{p} \sim 0.01$

$$\frac{\sigma_{m_K}^2}{m_K^2} = [0.6^2 + 0.9^2 + \frac{31.0^2}{N_\pi} + \frac{44.1^2}{N_K} + \frac{18.1^2}{N_p}][ppm]^2$$



Optimal fractions are 35% pions, 45% kaons, and 20% protons. Estimate 30 ppm statistical error with 10 million events at 40 GeV/c.

Data Totals

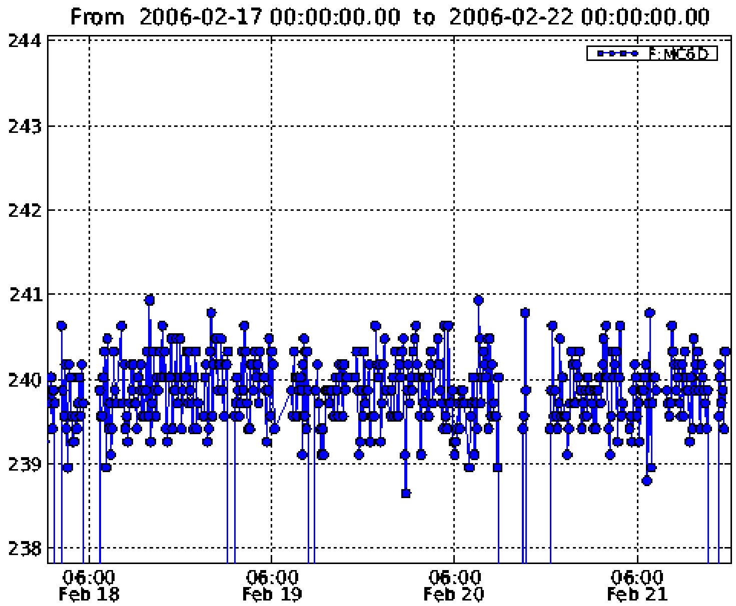
Data for charged kaon mass measurement was taken opportunistically during times in which the analysis magnets were down. As a result there are different momentum settings.

Beam Momentum Setting	**Proton Triggers**	**Kaon Triggers**	**Pion Triggers**	**Total**
37 GeV/c	0.64	0.77	0.81	2.22
40 GeV/c	1.10	1.04	1.20	3.34
42 GeV/c	0.41	0.34	0.34	1.09
56 GeV/c	0.18	0.12	0.16	0.46
60 GeV/c Field Of	1.19	0.52	0.95	2.67
60 GeV/c Field On	0.90	0.38	0.69	1.97
63 GeV/c	0.13	0.05	0.08	0.26
Total	4.56	3.22	4.22	12.00

Numbers are millions of events

A total of 12 million events with a clear PID from the beam Cherenkov counters were taken. An additional 2.3 million events without a clear PID were taken.

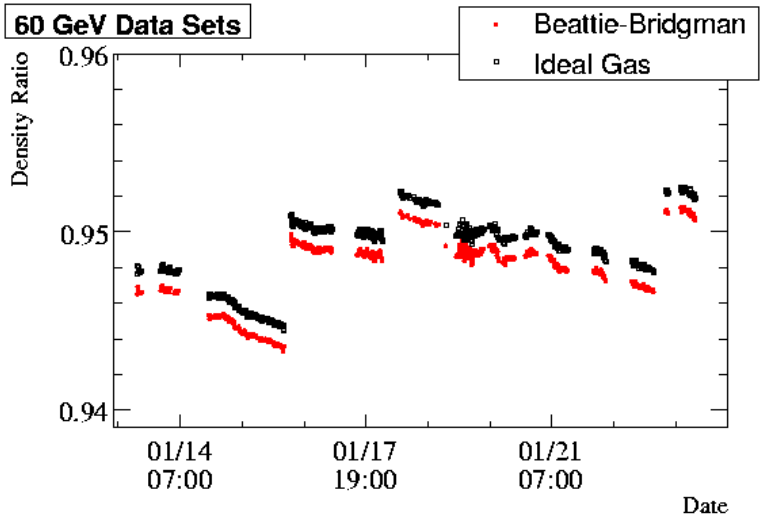
Running Conditions

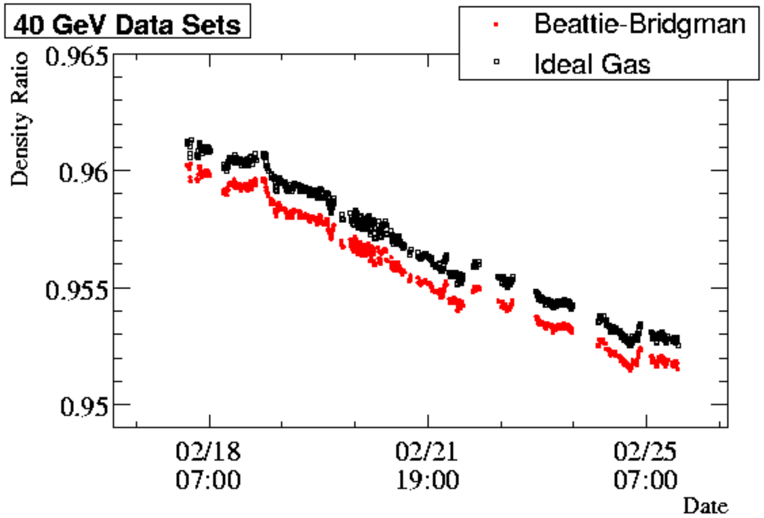


Chambers, RICH, HCAL active.
TPC would limit rate to 30 Hz.
Actual rate about 20x greater.

Current of momentum selecting magnet varied by less than 1%. Low values are missed spills.

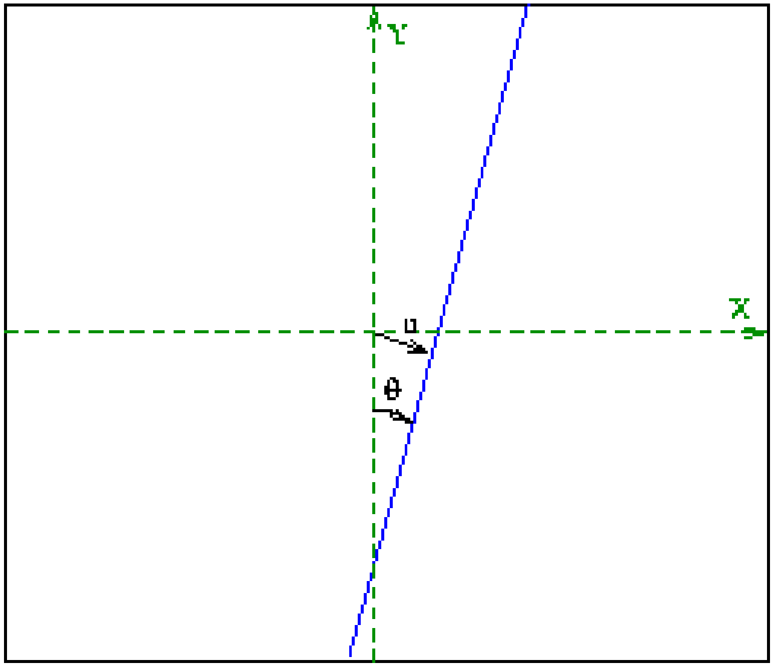
Density ratio decreases by 0.01 per week. That's a gas leak rate of 3.0e-8 g/m^3/s.





Vertical axis is current density divided by density at STP.

Event Reconstruction



Track reconstruction
Define views for different chamber plane orientations
Restrict to wires near the beam axis
Group hit wires into clusters
Find wire crosses to form 3D points
Fit straight line to points

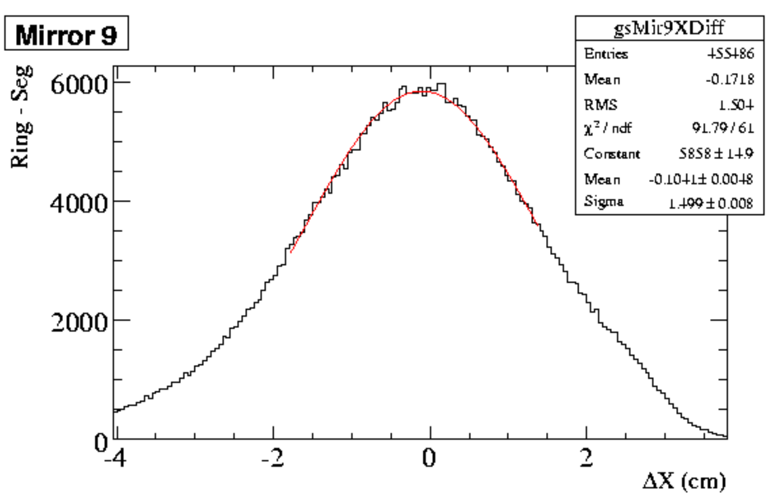
Attempt to use only three most downstream chambers in fit. If fit fails, include next most downstream chamber.

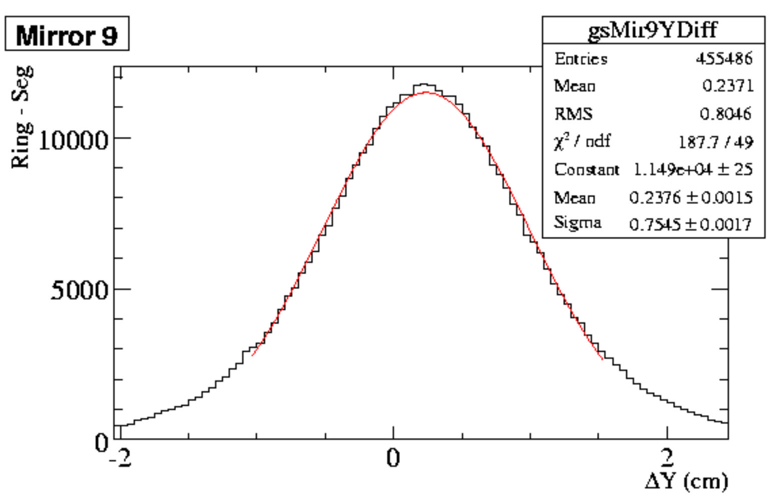
RICH ring fitting
Use Hough transformation of PMT hits to find ring candidates
Iteratively fit all points to a circle, waiting down hits far from the center at each step

Mirror Alignment

Ring can be split in half between two central mirrors, 8 and 9. Need to align each separately.

Procedure:
Introduce global horizontal and vertical position offsets to ring fits.
Run ring fitter twice, first allowing only mirror 9 hits to move, then only mirror 8 hits.
Select good rings: at least 10 hits for protons, 15 for pions/kaons.
Also cut on radius.





Constants determined on a per run basis. Runs with less than 20,000 events were combined.

Data Selection

Select only events which meet the following criteria:
Clear PID from beam Cherenkov counters.
Pass through both front and rear RICH windows.
Reconstructed track segment using clusters in at least 2 of 3 most downstream chambers (field off).
Require clusters in all 3 most downstream chambers (field on).
Cut on HCAL ADC sum to reduce interactions and decays.
Tight cut on reconstructed track χ^2 to select only well reconstructed tracks.
Tight cuts on angle of reconstructed track trajectory to ensure only straight forward-going tracks are used.
~50% of data remains after cuts.

Final Data Totals

Final data totals after applying all cuts.

Beam Momentum Setting	Proton Triggers	Kaon Triggers	Pion Triggers	Total
37 GeV/c	0.33	0.40	0.42	1.15
40 GeV/c	0.57	0.54	0.64	1.75
42 GeV/c	0.21	0.17	0.17	0.55
56 GeV/c	0.08	0.05	0.07	0.20
60 GeV/c Field Of	0.59	0.27	0.48	1.34
60 GeV/cField On	0.29	0.12	0.23	0.64
63 GeV/c	0.07	0.03	0.04	0.13
Total	2.14	1.57	2.05	5.76

Total of 5.76 million events is just over half the goal of 10 million. Most events are lost from HCAL cut and track χ^2 cut, which each reduce the dat set by about 20%. Exception is the field on set, which is reduced to nearly half from stricter cluster requirement.

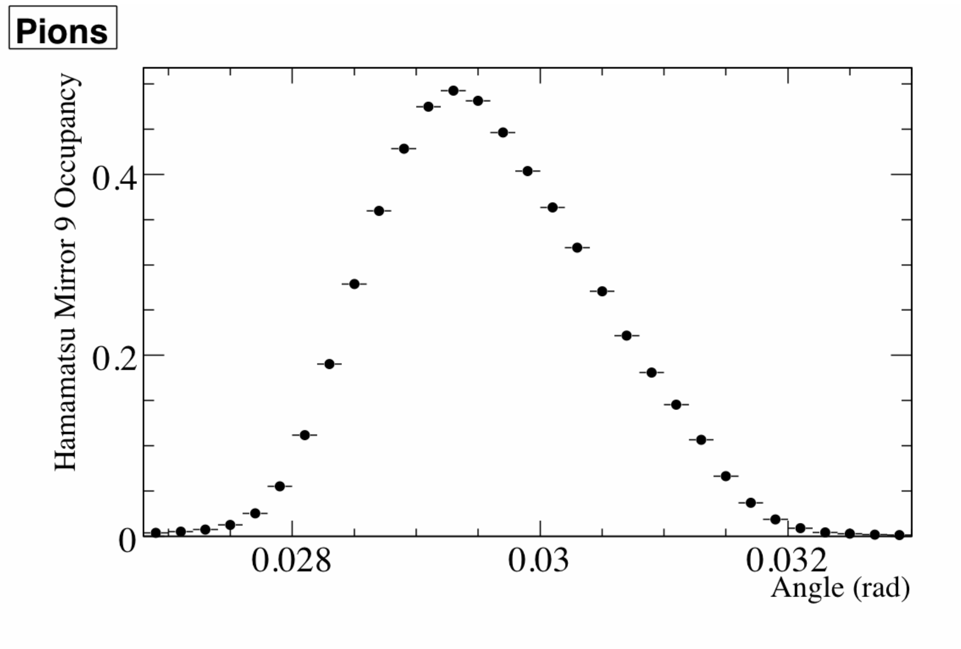
Fractions are 37% proton, 27% kaon, and 36% pion.

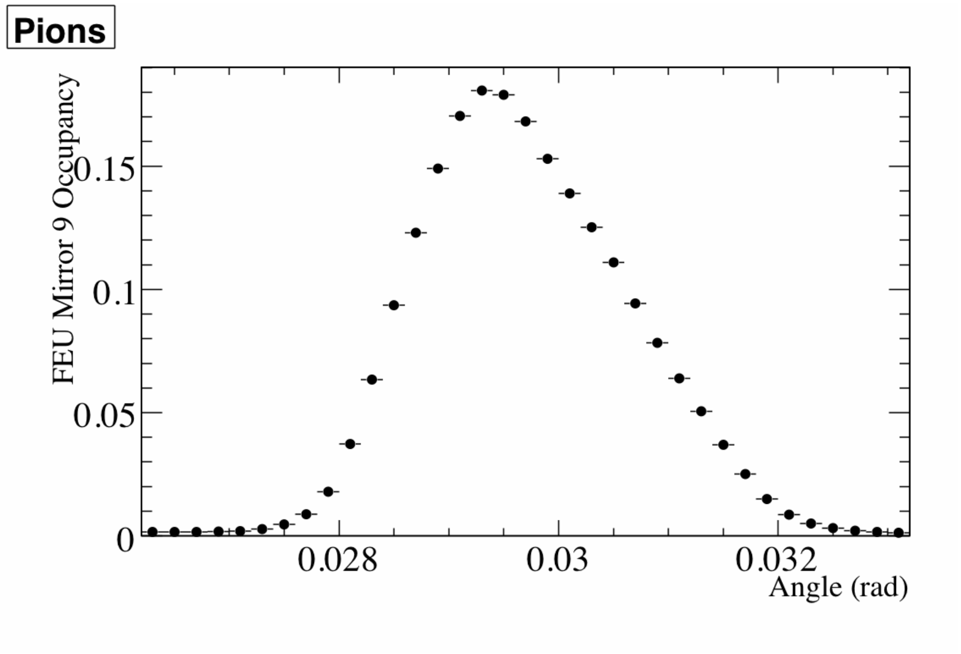
Data Occupancy

PMT occupancy vs. angle is accumulated for each data set. It is broken up by:
Particle ID
Phototube type
Mirror (8 or 9)

Angle: $\theta = \tan^{-1}(R_0 / F_L)$

R_0 is the distance between predicted ring center from track and PMT center. F_L is the mirror focal length. Bin size is 0.2 mrad.





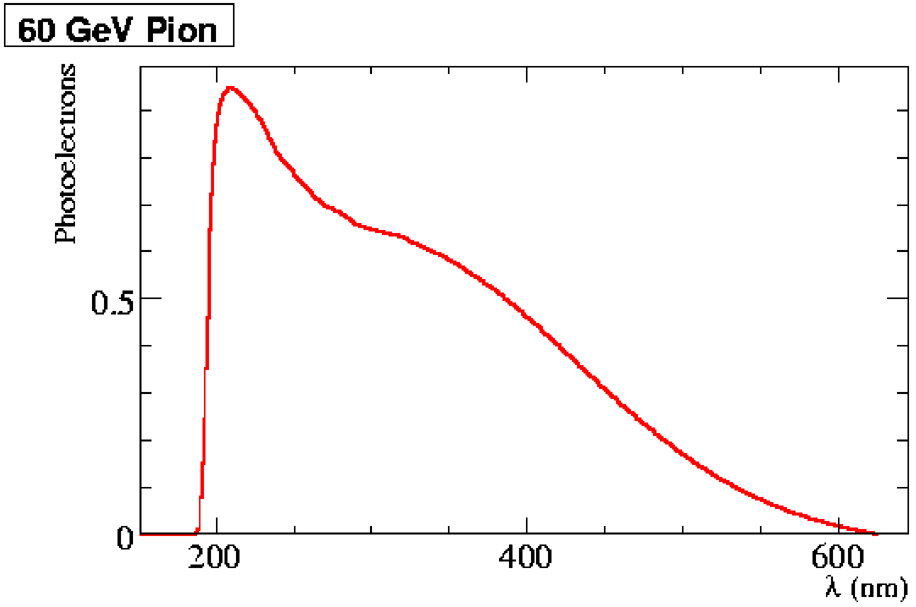
Light Yield In More Detail

Light yield for a track passing through the RICH:

$$N_{ph} = \int_0^L \int_{\lambda_1}^{\lambda_2} 2\pi \frac{\alpha}{\lambda^2} \left(1 - \frac{1}{n^2(\lambda)\beta^2}\right) e^{-\mu(\lambda)(F_L + x)} \epsilon(\lambda)\, d\lambda\, dx$$

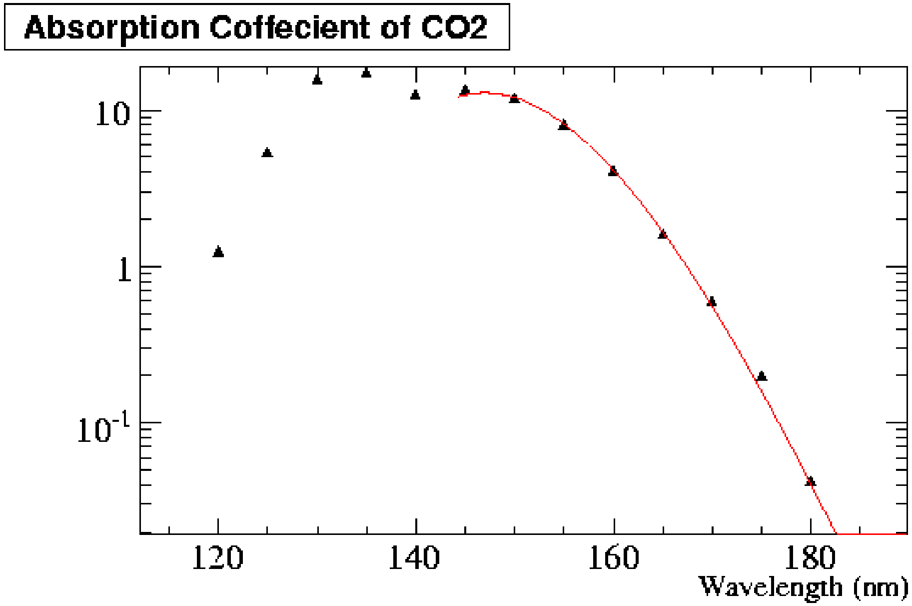
Where $\mu(\lambda)$ is the absorption coefficient of carbon dioxide, L is the path length of the track, F_L is the focal length of the mirror, and $\varepsilon(\lambda)$ is the product of all efficiency factors:

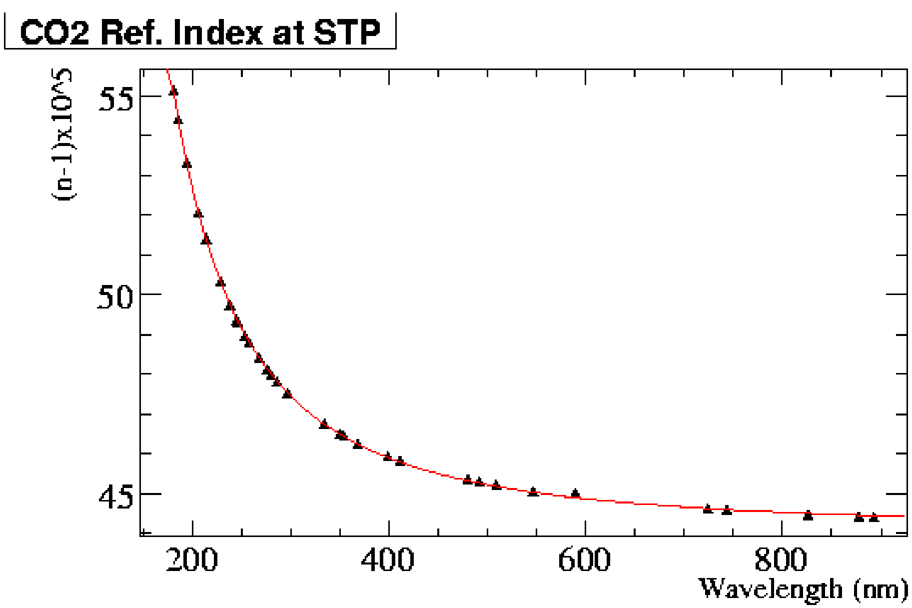
Mirror reflectivity
Cone reflectivity
Quartz window transmission
PMT efficiency

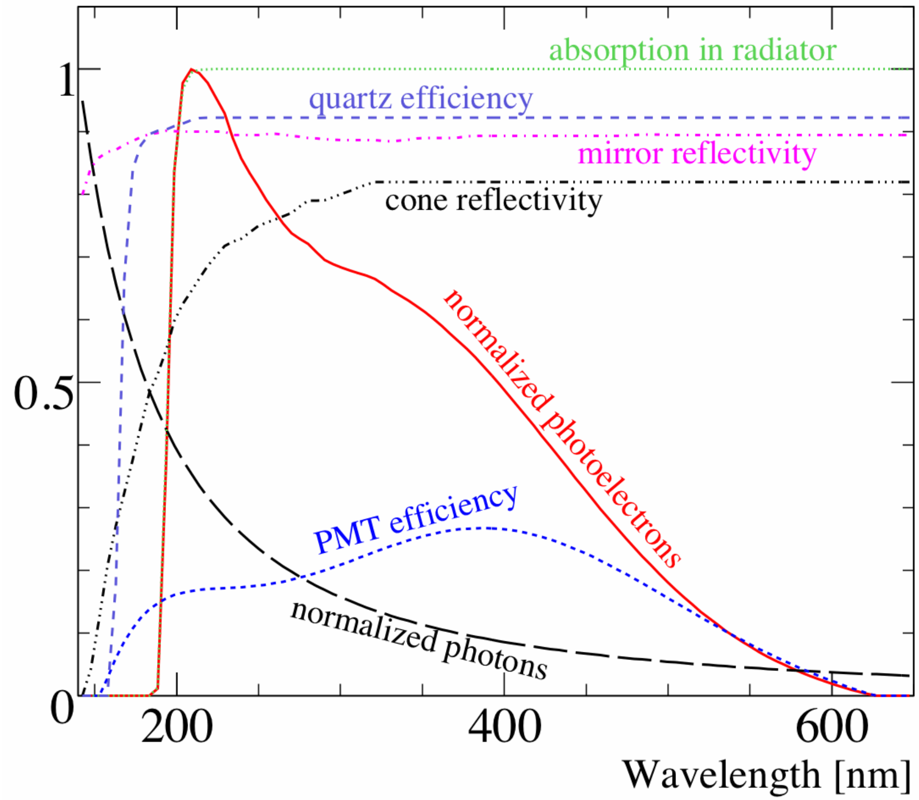


Right: Expected number of photoelectrons vs. wavelength for a 60 GeV pion at STP.

Shaping Functions







Refractive index data and parameterization from:

A. Bideau-Mehu, Y. Guern, R. Abjean, and A. Johannin-Gilles. Interferometric determination of the refreactive index of carbon dioxide in the ultraviolet region. *Optics Communications*, September 1973.

Light Smearing

Smearing of light is modeled as a Gaussian. Three sources:

Intrinsic detector smearing width, σ_0

Dispersive scattering width, σ_N

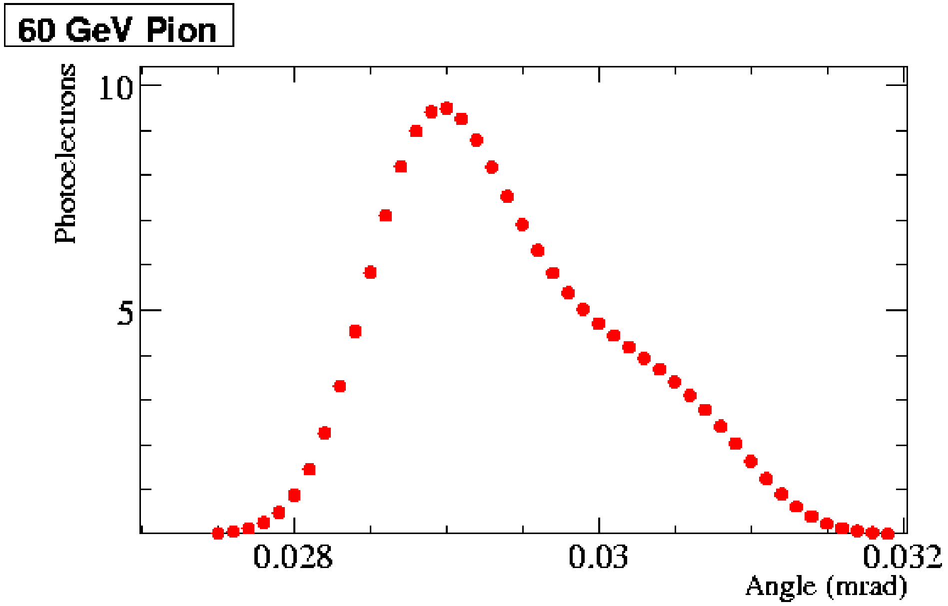
Multiple scattering of track

$$\sigma_{ms} = \frac{13.6\,MeV}{\beta p} z \sqrt{(x/X_0)}[1 + 0.038 \ln(x/X_0)] = \frac{0.00286\,GeV}{\beta p}$$

Where x/X_0 is thickness in radiation lengths. For MIPP RICH this is 1023 cm / 18310 cm. Multiple scattering is an order of magnitude smaller than other widths.

Total width:

$$\sigma(\theta_c) = \sqrt{(\sigma_0^2 + \frac{\sigma_N^2}{\tan^2(\theta)} + \sigma_{ms}^2)}$$



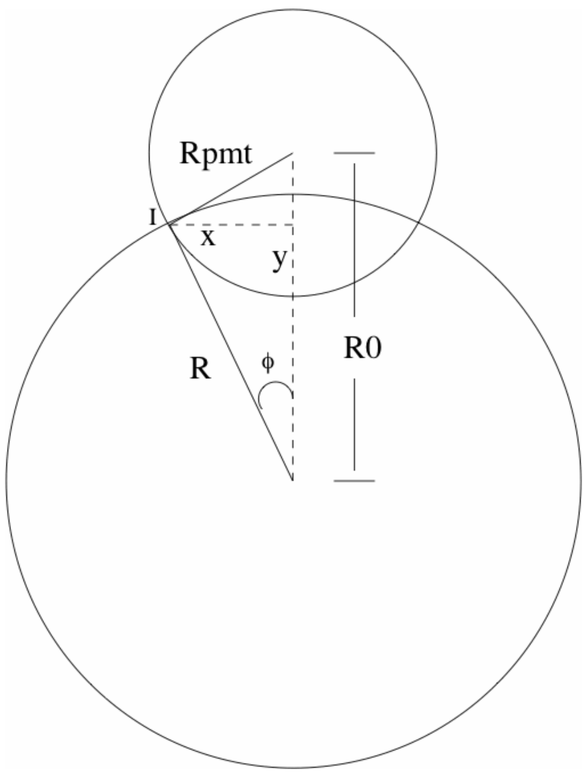
Predicting PMT Occupancy

Integrate N_{pe} expression over angular width for each PMT:

$$N_{pe}^{i}=\int_{0}^{L}\int_{\theta_1}^{\theta_2}\int_{\lambda_1}^{\lambda_2} 2\pi\frac{\alpha}{\lambda^2}\left(1-\frac{1}{n^2(\lambda)\beta^2}\right)e^{-\mu(\lambda)(F_L+x)}S(\theta,\theta_c(\lambda))\epsilon(\lambda)G_i(\theta)\,d\lambda\,d\theta\,dx$$

Where G_i is the geometric acceptance for the i[th] PMT:

$$G_i=\frac{1}{\pi}\arccos\left(\frac{R^2+R_0^2+R_{PMT}^2}{2\mathrm{R}_0 R}\right)$$



Account for light sharing between mirrors.
Calculate probability of firing from Poisson statistics, weighted by bad fraction:

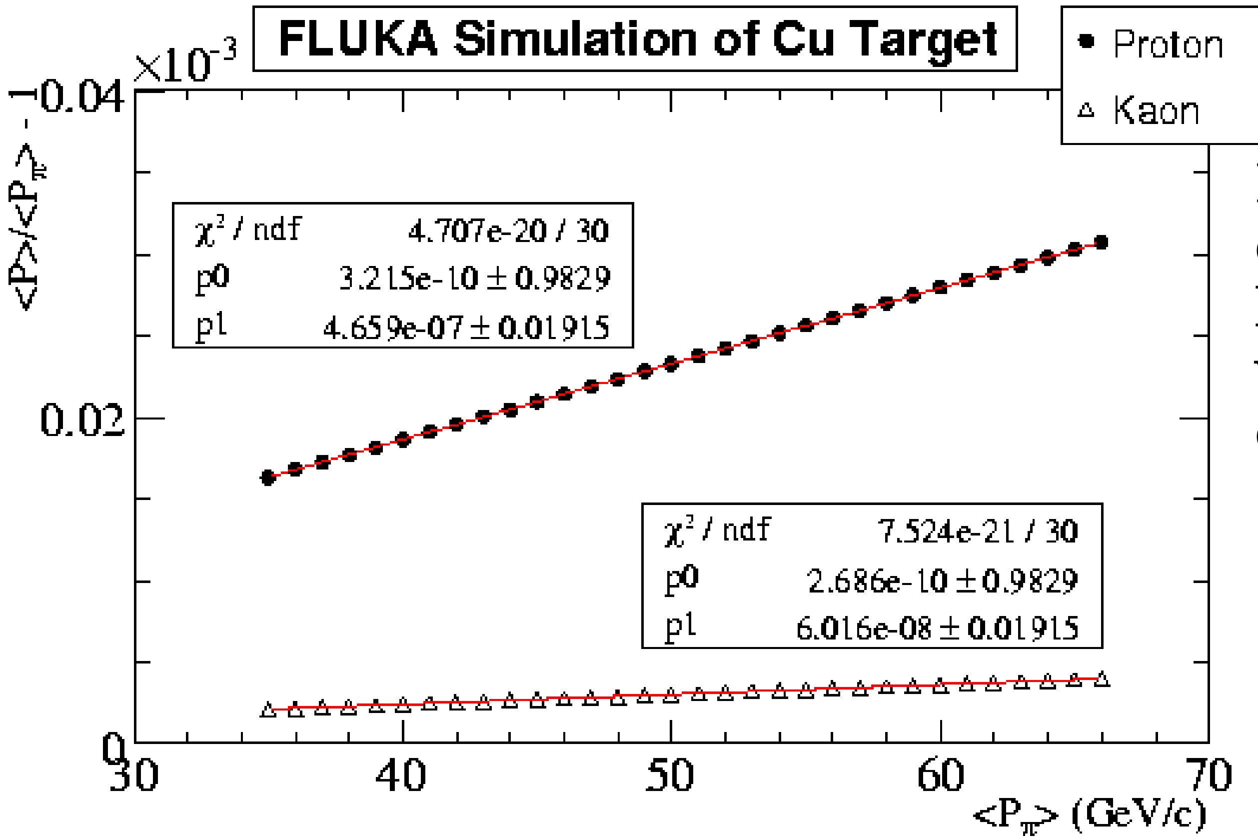
$$P=1-\exp(-N_{pe}-bg)$$

Noise term

Need to integrate over
Gas Density
Ring center position
Pion momentum spread (assumed to be Gaussian)

FLUKA Results

Model momentum spectra of π/K/p production off primary copper target using 30 million POT FLUKA simulation.



Integrate momentum distributions weighted by a Gaussian for mean values from 35-65 GeV/c in steps of 1GeV/c.

Relative difference from pion momentum is linear. Use in prediction.

Fitting Procedure

Fit prediction to data by varying:	Initial Seed:
Intrinsic scattering width: σ_0	2.0e-4 mrad
Dispersive scattering width: σ_N	9.0e-6 rad
Density ratio scale factor: DensSf	0.97
Density ratio offset: DensOS	0.008
Air contamination: AirFrac	100 ppm
Central pion momentum P_π	0.98 of nominal
Momentum width: σ_p	0.5%
Kaon mass: m_k	493.677 MeV

Normalize prediction to data by scaling to match N_{pe} areas.

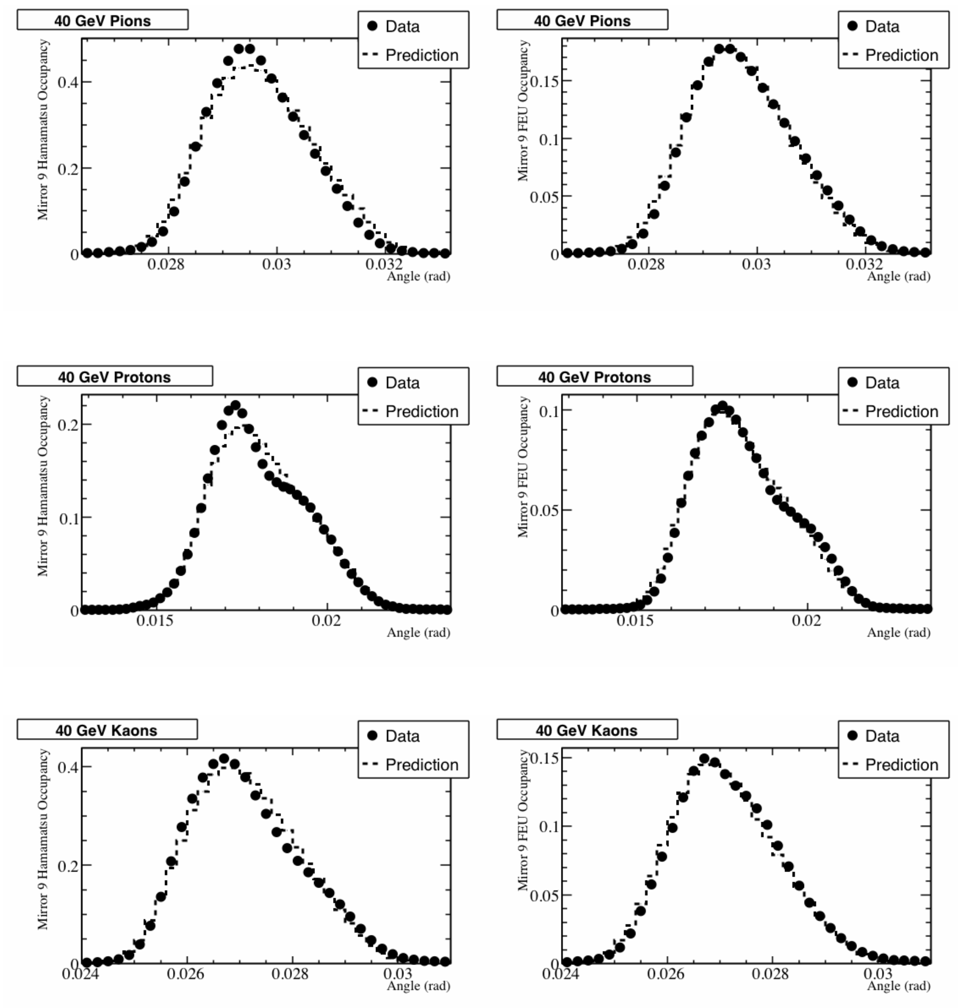
Calculate χ^2 and minimize using TMinuit.

Hold kaon mass fixed for 200 iterations.

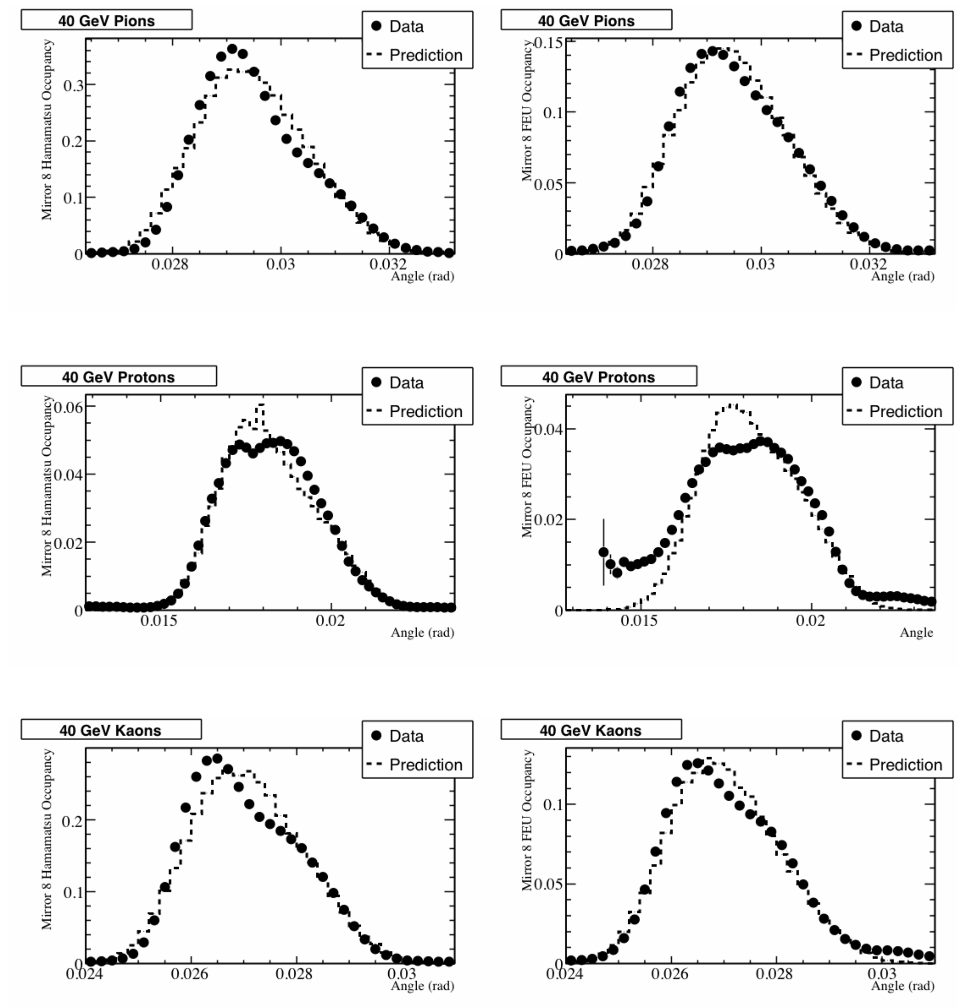
Release and minimize for 1000 iterations.

Occupancy Fits – 40 GeV

Mirror 9

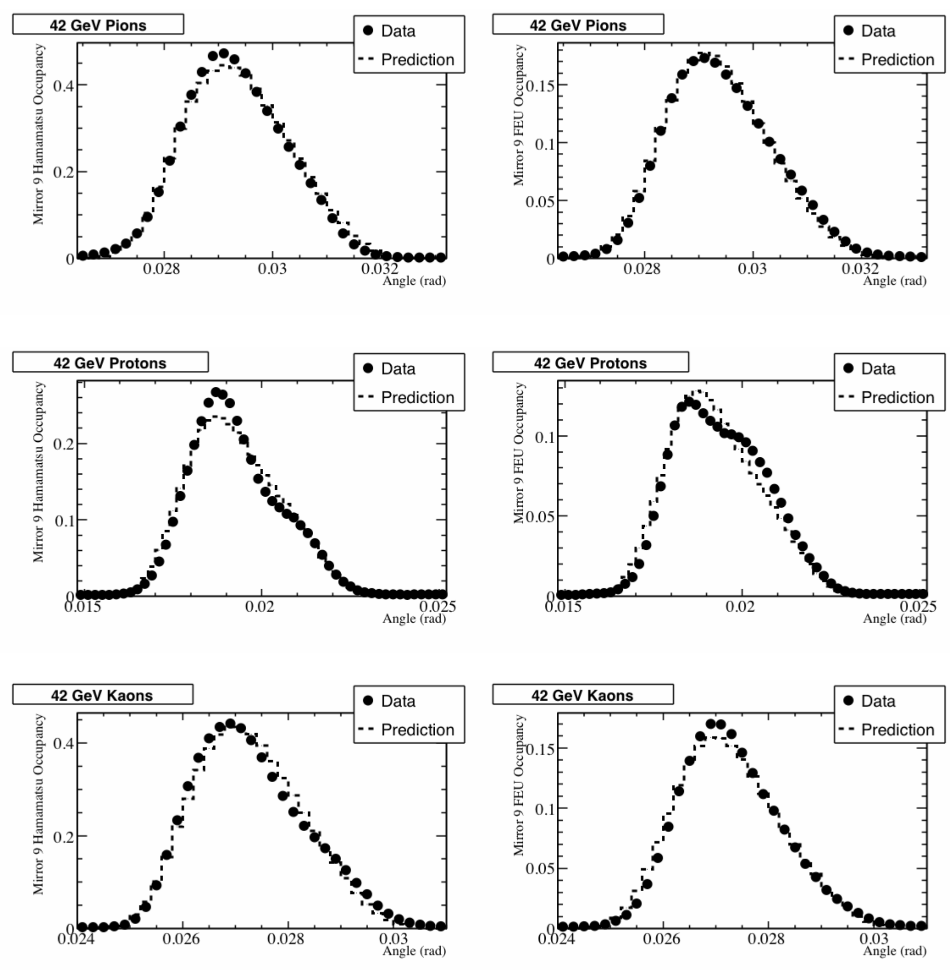


Mirror 8

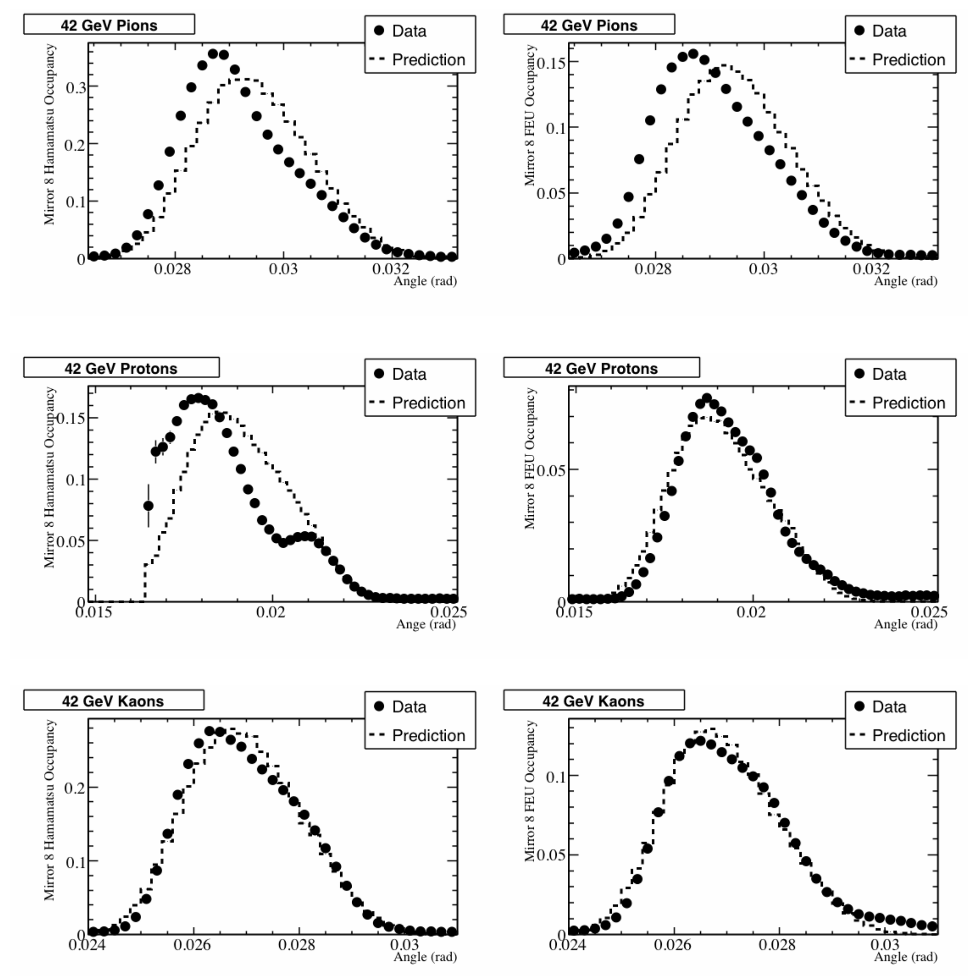


Occupancy Fits – 42 GeV

Mirror 9

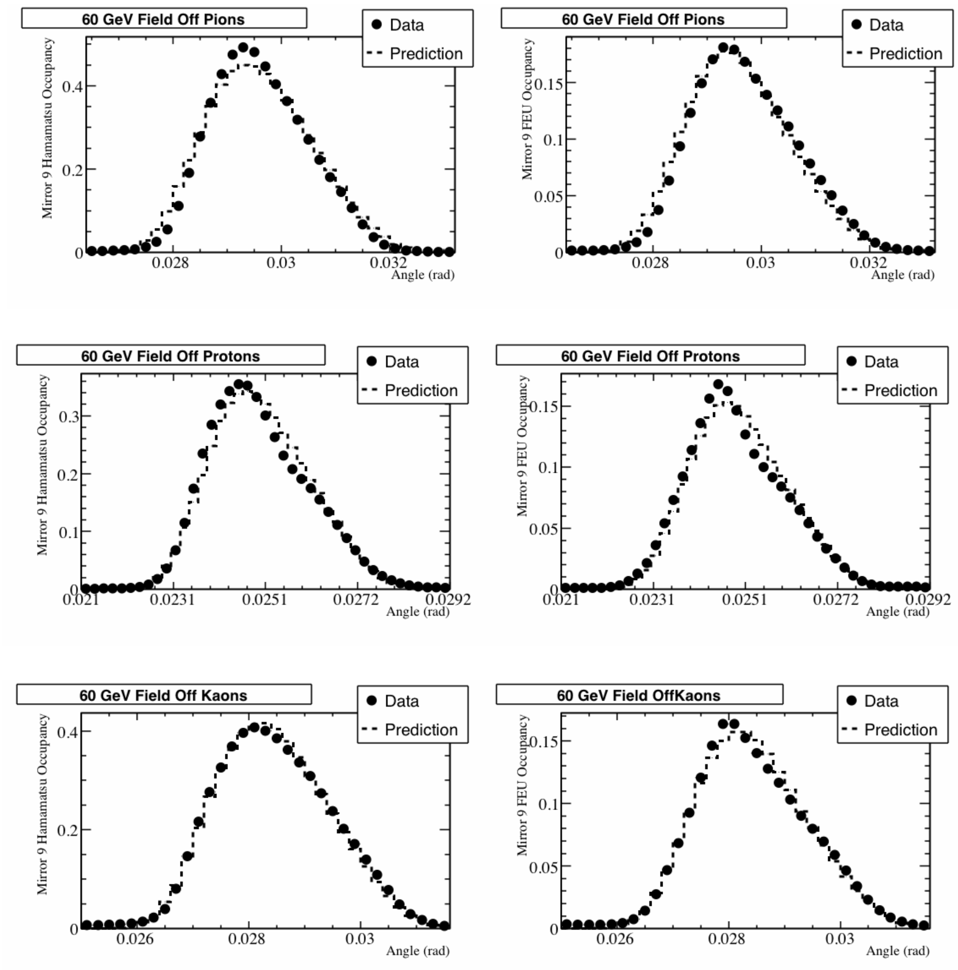


Mirror 8

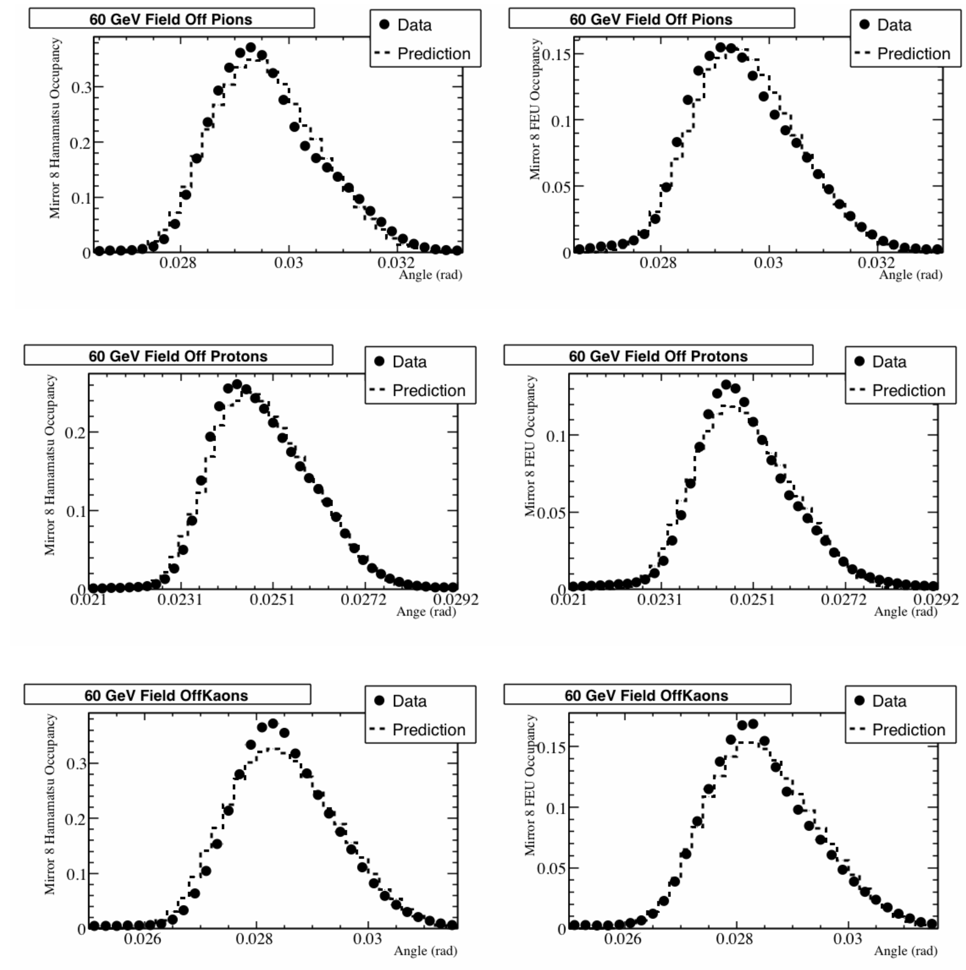


Occupancy Fits – 60 GeV Off

Mirror 9



Mirror 8



Error Bar Scaling

Error bars are scaled so that χ^2/NDF = 1

Momentum	Mirror	χ^2	NDF	Scale Factor
37 GeV/c	8	7.513E+05	135	74.6
37 GeV/c	9	8.047E+05	154	72.3
40 GeV/c	8	1.363E+06	144	97.3
40 GeV/c	9	1.396E+06	144	98.5
42 GeV/c	8	7.372E+05	156	68.7
42 GeV/c	9	5.574E+05	156	59.8
56 GeV/c	8	1.892E+05	144	36.2
56 GeV/c	9	1.853E+05	144	35.9
60 GeV/c Field Of	8	9.232E+05	146	79.5
60 GeV/c Field Of	9	1.208E+06	146	90.9
60 GeV/cField On	8	4.964E+05	144	58.7
60 GeV/cField On	9	5.752E+05	144	63.2
63 GeV/c	8	1.028E+05	144	26.7

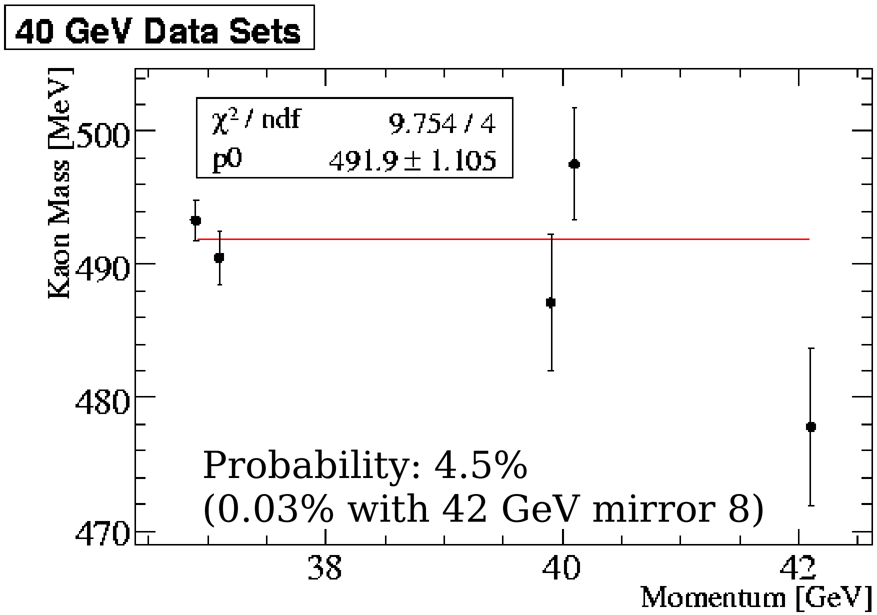
Statistical error is overwhelmed by systematics.

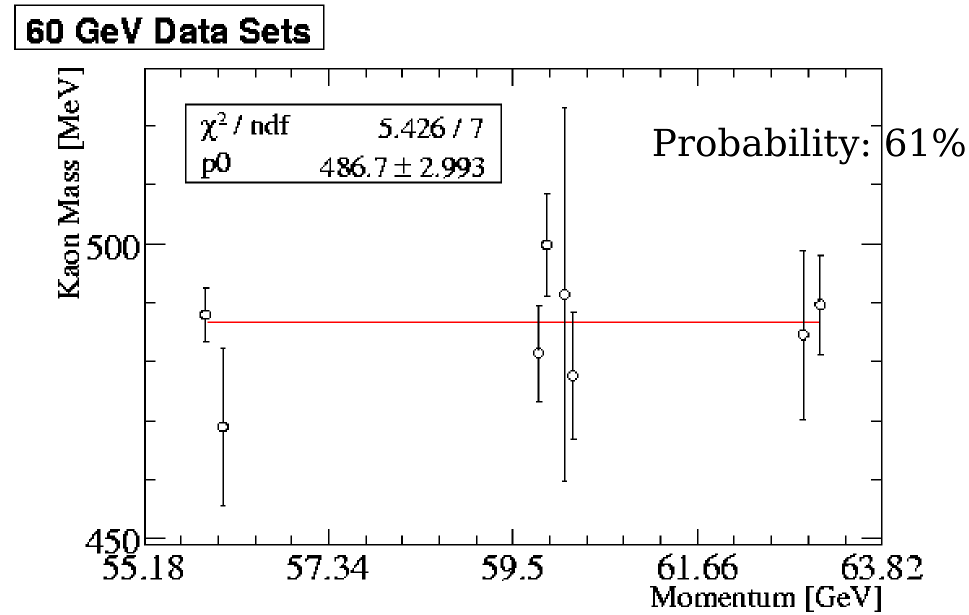
Kaon Mass Fit Results

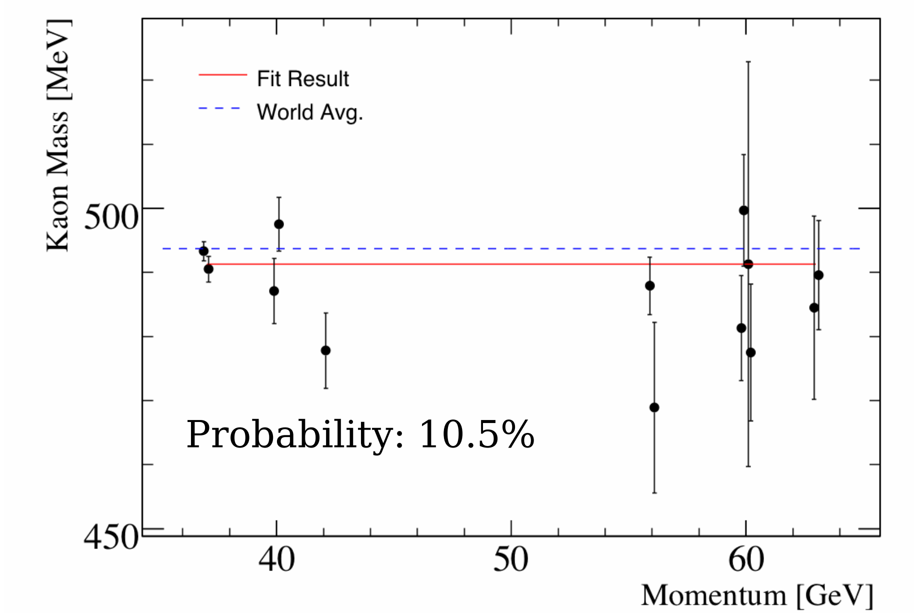
Momentum	Mirror	Mass (MeV)	Error (MeV)
37 GeV/c	8	493.3	1.5
37 GeV/c	9	490.5	2.0
40 GeV/c	8	487.1	5.1
40 GeV/c	9	497.5	4.2
42 GeV/c	8	510.8	6.3
42 GeV/c	9	477.8	4.5
56 GeV/c	8	487.9	4.5
56 GeV/c	9	469	13
60 GeV/c Field Of	8	481.3	8.2
60 GeV/c Field Of	9	499.7	8.7
60 GeV/cField On	8	491	32
60 GeV/cField On	9	477	11
63 GeV/c	8	485	14
63 GeV/c	9	489.6	8.5

Fit Low/High Momentum Sets

Points offset to the left are mirror 8, points offset to the right are mirror 9.





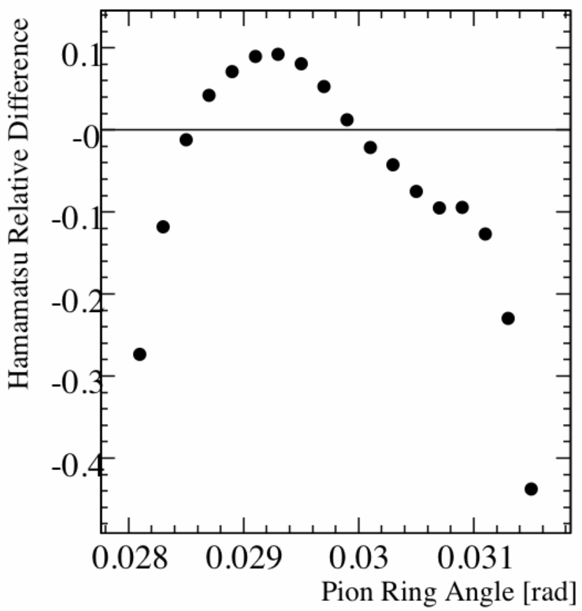


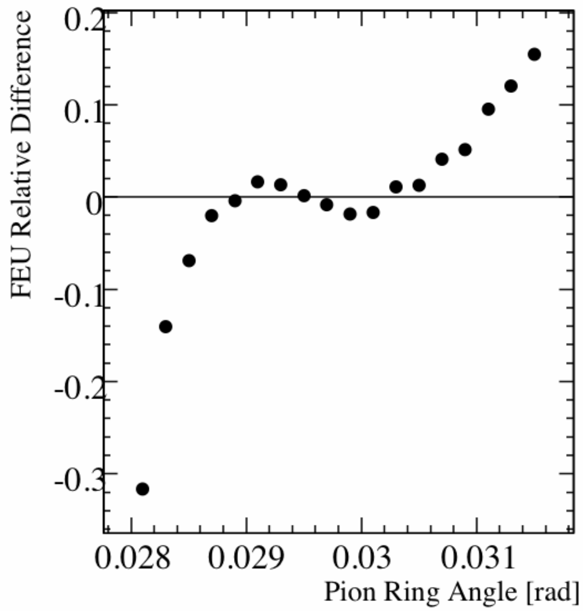
As per the PDG convention, error bars are scaled when combining measurements.

Final Result:

m_k = 491.3 ± 1.7 MeV (3500 ppm)

Systematic Errors





Prediction deviates from data by ~10% near the peak regions.

To improve measurement by a factor of 100, need to improve predictions to 1% level.

Sources of systematic error with estimates from error matrix:
Index of refraction: ~500 ppm
Momentum: ~50 ppm
Tracking/Mirror Focusing: ~50 ppm
Remaining systematics from understanding of PMT response and efficiencies.

Need MC studies to understand these better.

Conclusion

What's the real lesson: You can't just make a precision measurement with the equipment you have lying around. It takes careful study and planning.

Still, there is hope for this method with a dedicated experiment.
Some suggestions:
Channel-by-channel measurements of photodetector response.
Improved electronics.
Aerogel radiator maintained at a uniform temperature.
Single focusing mirror (or none at all?).
Well understood narrow band beam. Possibly track-by-track momentum measurement.
More finely segmented detector, perhaps using hybrid photodetectors.
Reliable photoelectron counts, not just on/off.
Perhaps likelihood fits to data.