Measuring the masses of the charged hadrons using a RICH as a precision velocity spectrometer

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Abstract

The Selex experiment measured several billion charged hadron tracks with a high precision magnetic spectrometer and high precision RICH velocity spectrometer. We have analyzed these data to simultaneously measure the masses of all the long lived charged hadrons and anti-hadrons from the π to the Ω^- using the same detectors and techniques. The statistical precision achievable with this data sample is effectively unlimited.

We have used these measurements to develop and understand the systematic effects of a RICH as a precision velocity spectrometer with the goal of measuring all 16 masses with precision ranging from 100 KeV for the lightest to 1000 KeV for the heaviest. This requires controlling the radius measurement of RICH rings to the $\Delta R/R \sim 10^{-4}$ level. Progress in the mass measurements and the required RICH analysis techniques developed will be discussed.

Outline

- Introduction
- Quick Selex RICH review
- Measurement technique
- Systematics
- Results and issues so far
- Summary and conclusions

Introduction

Measure mass with $M=P/(\beta\gamma)_{RICH}$

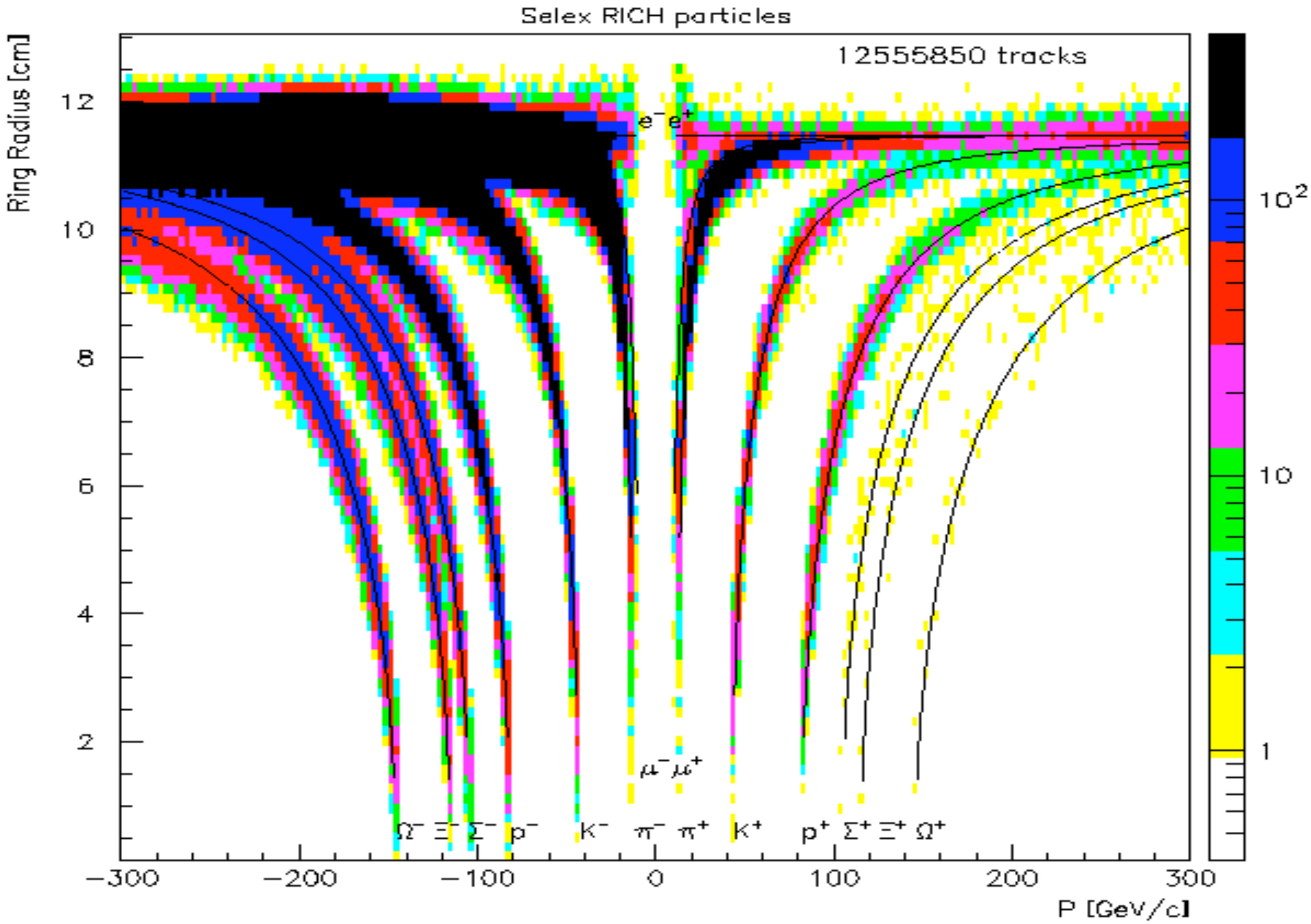
- This idea began with MIPP's suggestion to resolve the ~100ppm discrepancy in the latest charge kaon x-ray mass measurements
  Charged Kaon Mass Measurement using the Cherenkov Effect., MIPP, NIM. A615 (2010) 27-32 arXiv:0909.0971
- They now have the Selex RICH (with CO_2 instead of Ne) but not anywhere near enough data for 100 ppm.
- How about <1000ppm = <0.1% level with data we already have first?

Selex has all *stable* states from Ω^+ to Ω^- with unlimited statistics

- Use the same detectors and the same techniques for all states
  - Precision Magnetic momentum spectrometry $\Delta p/p$ ~ 1%,
  - Precision RICH velocity spectrometry $\Delta(\beta\gamma)/\beta\gamma$ ~ 1%
  - Common systematics for all states from 0.140-1.672 GeV/c^2
- Will this improve measurements in the PDG - NO, but we can beat the hell out of RICH spectrometer systematics at the <0.1% (1/10 σ) level.

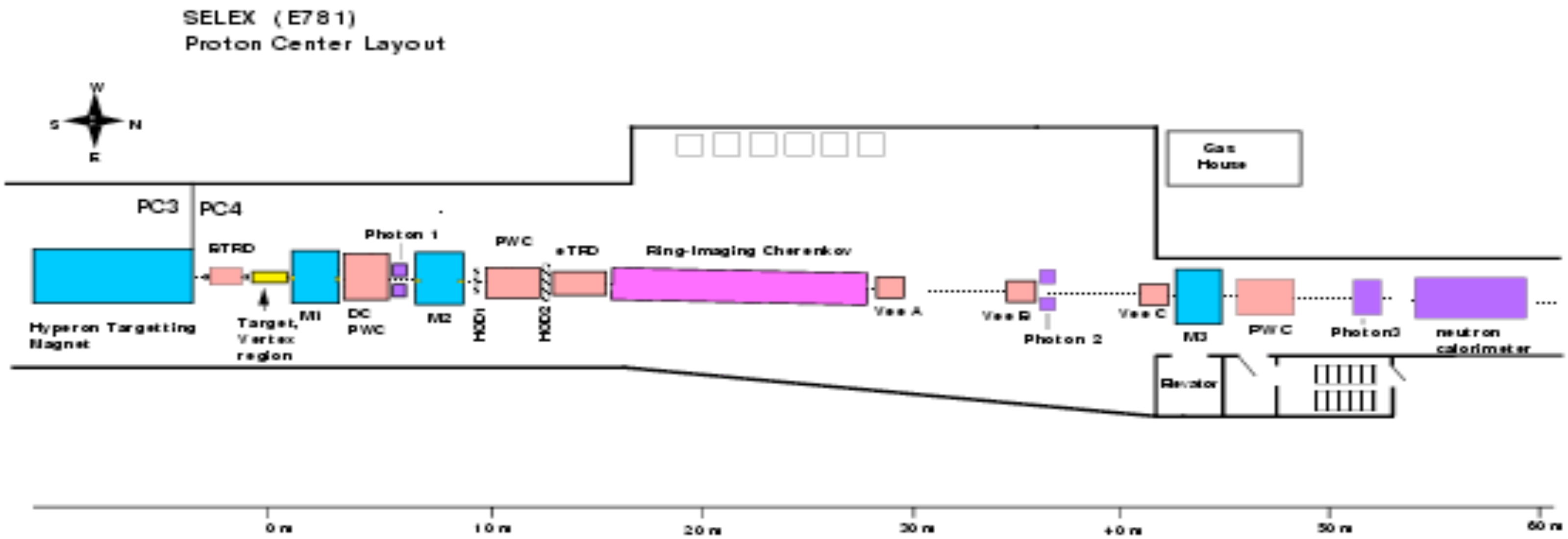
What are the systematic limitations of a RICH velocity spectrometer?

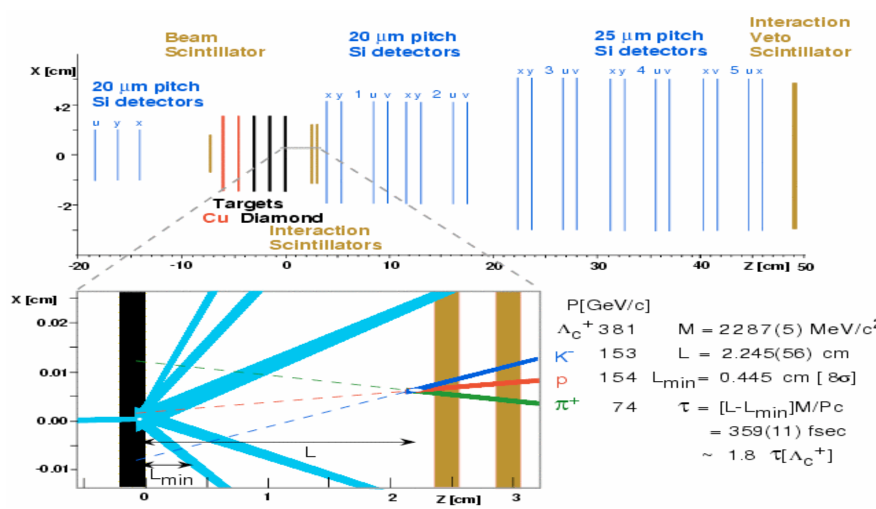
18 particles at the same time



SELEX Experiment at Fermilab

Data taken 1996-7 in P-center @ FNAL

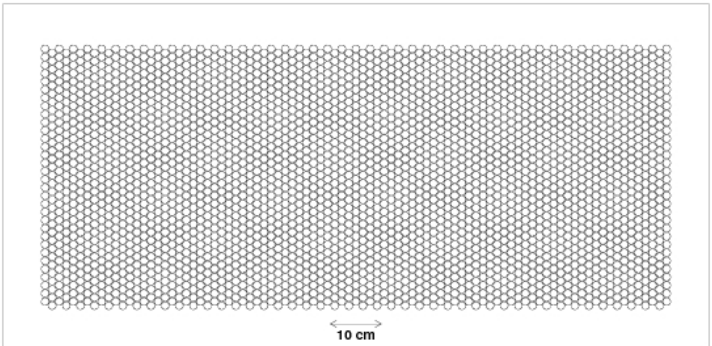


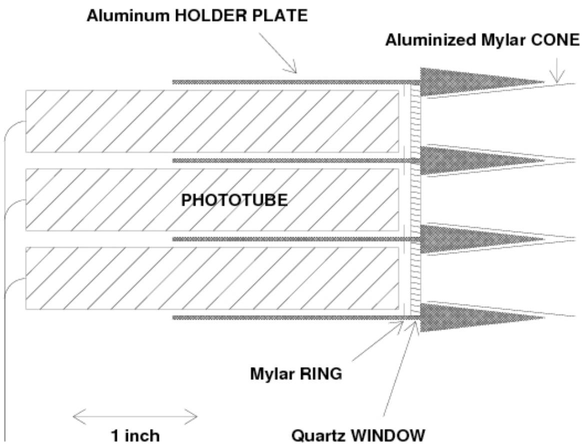


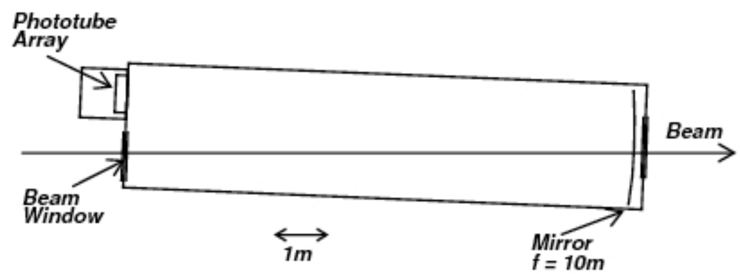
SELEX Experiment

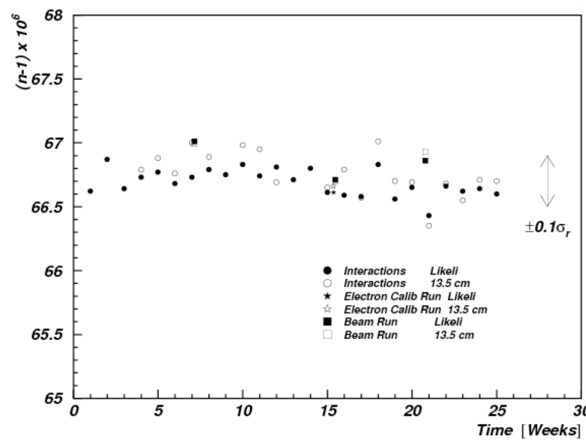
- Forward charm production $x_F>0.1$
- π^- p and Σ^- beams @ 600 GeV
- Typical boost ~100
- RICH PID above 22 GeV
- 20 plane Si vertex tracker - $\sigma>4\ \mu$
- two segmented magnet-MWPC downstream trackers

Selex RICH









One of the first multi-pixel PMT RICHes
2848 12 mm tubes @ 16mm, 10m radiator, 1 atm Neon
γ threshold = 88, Θ_c^{max} = 11.5 mRad, R_c^{max} = 113 mm
Sealed Volume, n-1 very stable (ΔR<±150 mm)
RICH PID above 22 GeV/c, (~11 GeV/c)
for β=1 <Nhits>~13, σ_R/R=1%

Measurement Technique

(Selex RICH values)

$\cos(\Theta_c) = 1/\beta n$ $\quad \delta = n-1$ (67×10^{-6}) Cherenkov equation

$\Theta_c = \sqrt{[2\delta - 1/\gamma^2]}$ good to 50 ppm after small angle and Relativistic approximations

$\Theta_c^{max} = \sqrt{[2\delta]}$ (11.5 mrad) ($\gamma_{th} = 88$)

$R(p) = F\sqrt{[(\Theta_c^{max})^2 - (m/p)^2]}$ Ring radius

$m(p,R) = p\sqrt{[(\Theta_c^{max})^2 - (R/F)^2]}$ mass

Three calibrations

- momentum scale (from K^0_s decays)
- Mirror focal lengths (F) (989-992 cm - varies by mirror)
- Θ_c^{max} (11.5 mrad)

Ring Fitting

Select tubes on a ring

- Start with angles from tracking
- Cut around predicted R(m,p)
- require at least 5 tubes

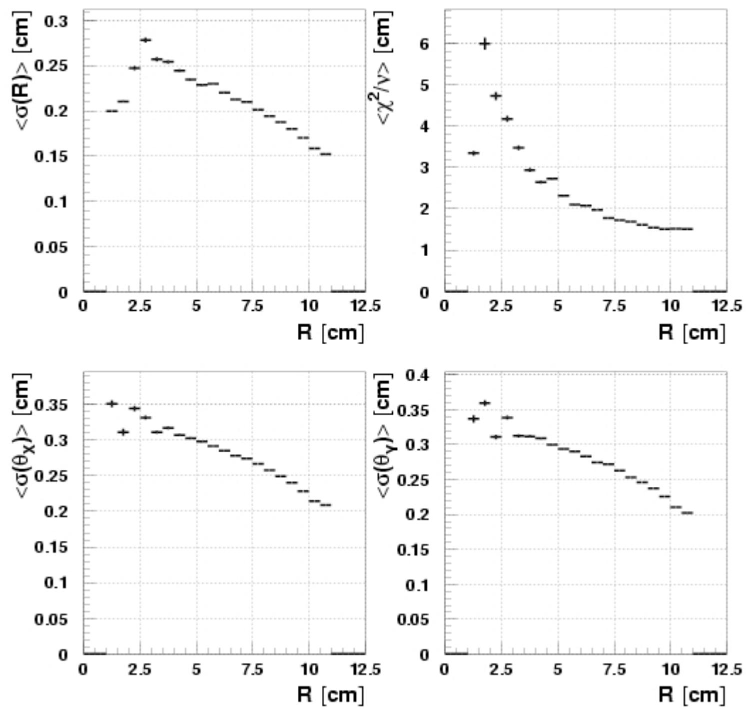
Fit for ring radius (R) and center (X,Y)

$$\chi^2 = \sum_{i=1}^{n} [R^2 - (x_i - X)^2 - (y_i - Y)^2]^2$$

$$R = \sqrt{\frac{1}{n} \sum_{i=1}^{n} [(x_i - X)^2 - (y_i - Y)^2]}$$

$$w = 1/(2R\sigma)^2$$

[NIM 211, 233, 1983.]



Results from generic ring fits

Pattern recognition

- Tube noise
- Hits from other rings

Momentum measurement

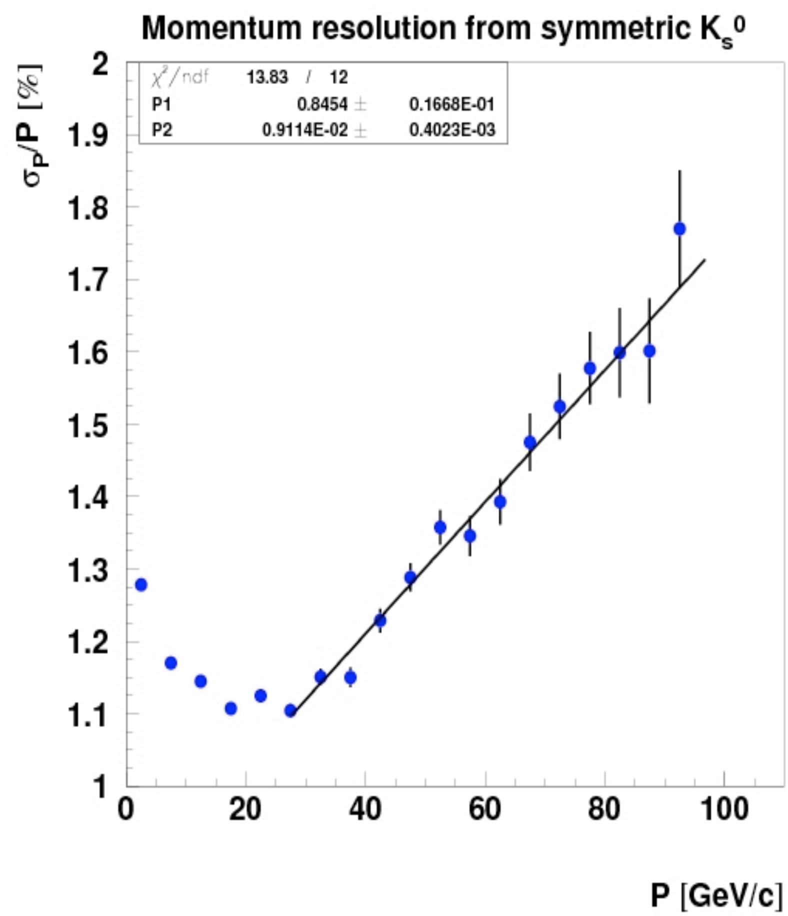
Mass scale is proportional to momentum

- $m(p,R) = p\sqrt{[(\Theta_c^{max})^2 - (R/F)^2]}$
- Precision of the momentum scale matters

Selex Momentum Spectrometer

- Si strip vertex + 2 magnets with MWPCs
- For RICH tracks $\sigma_p/p \sim 0.8\% + 0.1\%[p/10\ \mathrm{GeV/c}]$
- Momentum scale is fixed with the K^0_S mass
- Momentum scale precision is ~0.01%

We'll divide this out by fixing the proton mass at the PDG value.

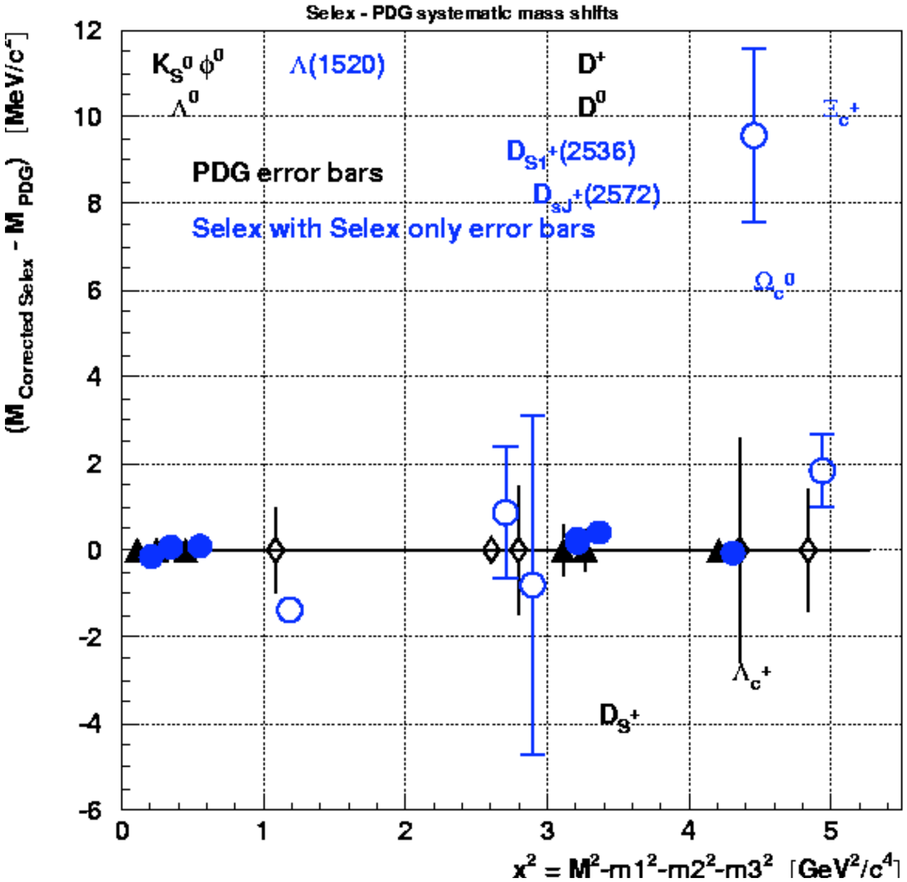


The Selex Mass and Momentum Scale

Having fixed the momentum scale we reconstruct a large number of states masses from decays with good agreement with the PDG

We spent much time and effort to make the Λ_c^+ come out at the PDG value of 2284.9 MeV/c^2 only to learn from Babar the the 2287 MeV/c^2 we got was - in fact - correct.

There is a small (2σ) correction most likely due to angular rather than momentum effects.



A first look at masses

Use Cross-section data set (9%)

- Low statistics / low rate / low multiplicity
- One magnet off (P_{min}=11 GeV/c)

First try at F and Θ_c^{max} calibration

- F(mirror 8) 988.9 → 991.34(36)
- F(mirror 9) 989.0 → 991.00(28)
- Θ_c^{max} 11.563(6) mRad

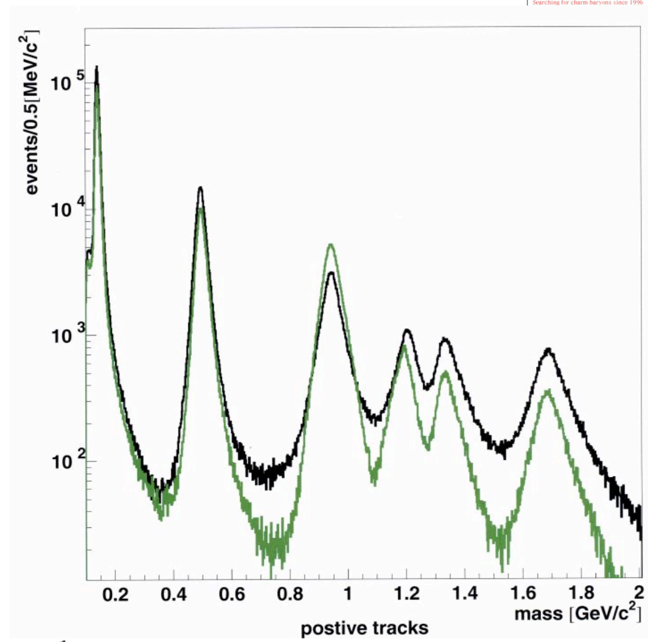
Cuts

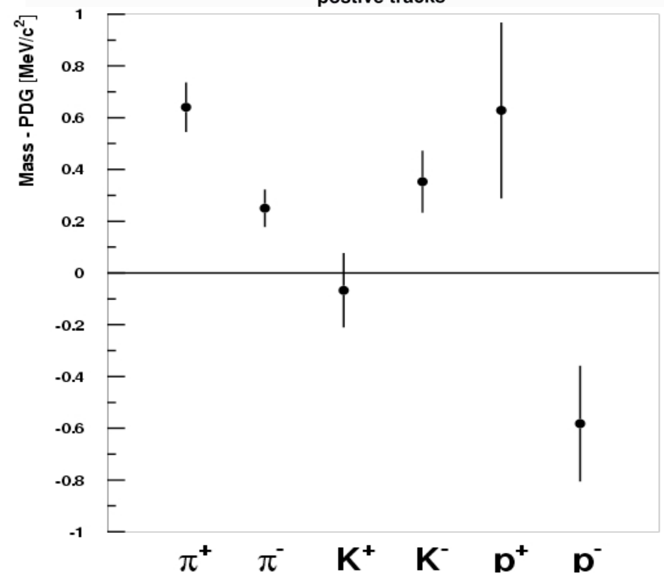
- 50 < R[mm] < 80
- Ring fits on one mirror (8 or 9)

Mass Fits

- Gaussian fits in 2 mm R bins
- Average (poor χ^2's 3-13)
- All masses within 1 MeV/c^2 of PDG
- stat errors: 70 keV (π), 160 keV (K), 350 keV (p)

Let the fun begin



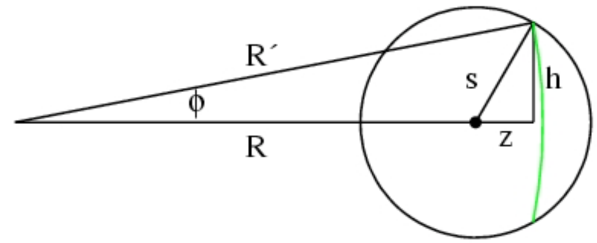


Systematics

Pixel photocathode is all geometry - BUT

Radial bias

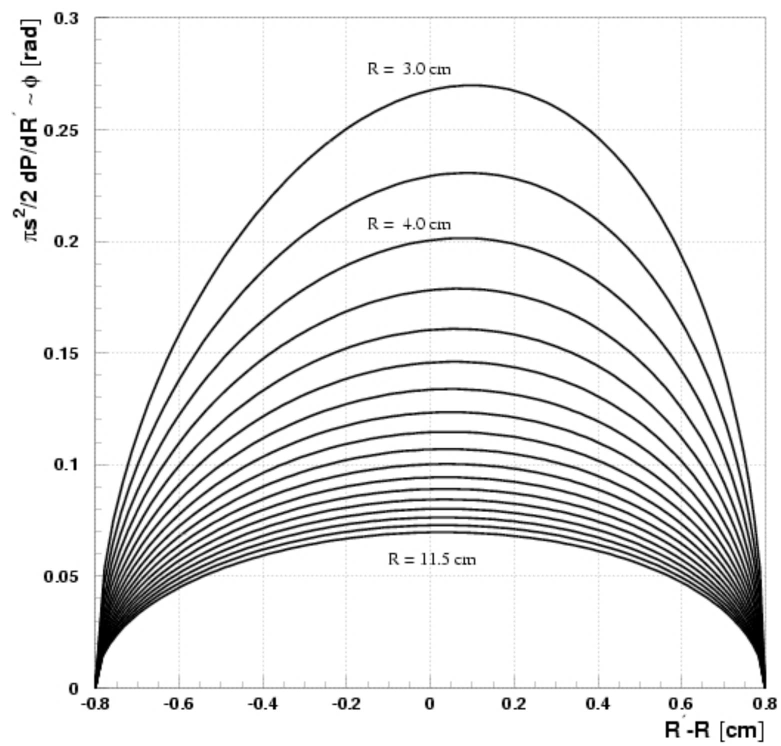
- Intersection of a ring with a tube isn't symmetric
- Acceptance is biased to R beyond the tube center



$$\phi = atan[\sqrt{s^2 - z^2}/(R+z)]$$

$$\frac{dP}{dz} = \frac{2}{\pi s^2} atan[\sqrt{s^2 - z^2}/(R+z)]$$

- This get out of hand for small rings
- Can induce large mass shifts if uncontrolled



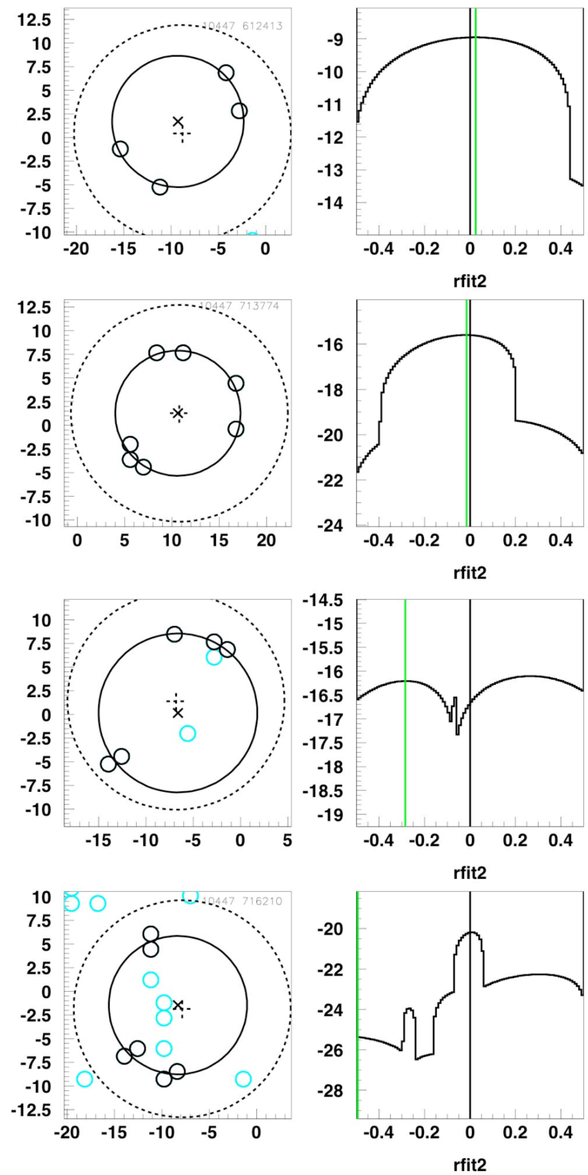
Build a likelihood ring fitter out of these probability distributions to include this

- Maximize log $\mathcal{L}$(R) = Σ log[dP/dz(z_i)]

Likelihood Ring Fitting

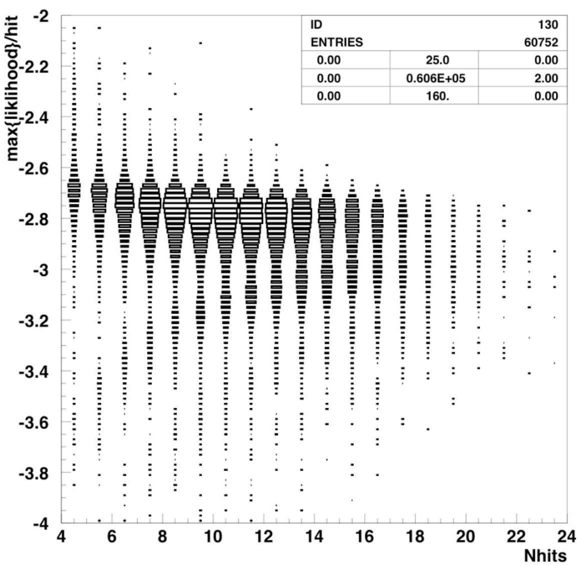
Procedure naturally deals with pattern recognition

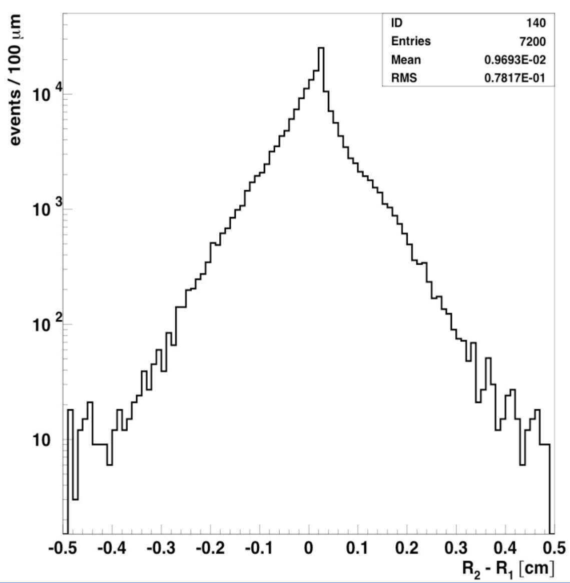
- Tubes not intersected by the ring are assigned a “noise” probability of 0.002: a combination of actual tube noise and hits from other rings
- Ambiguous cases are clear with multiple maxima



Fit properties

- Likelihood/hit well behaved
- ΔR = +100(9) μm (~0.1%) as expected



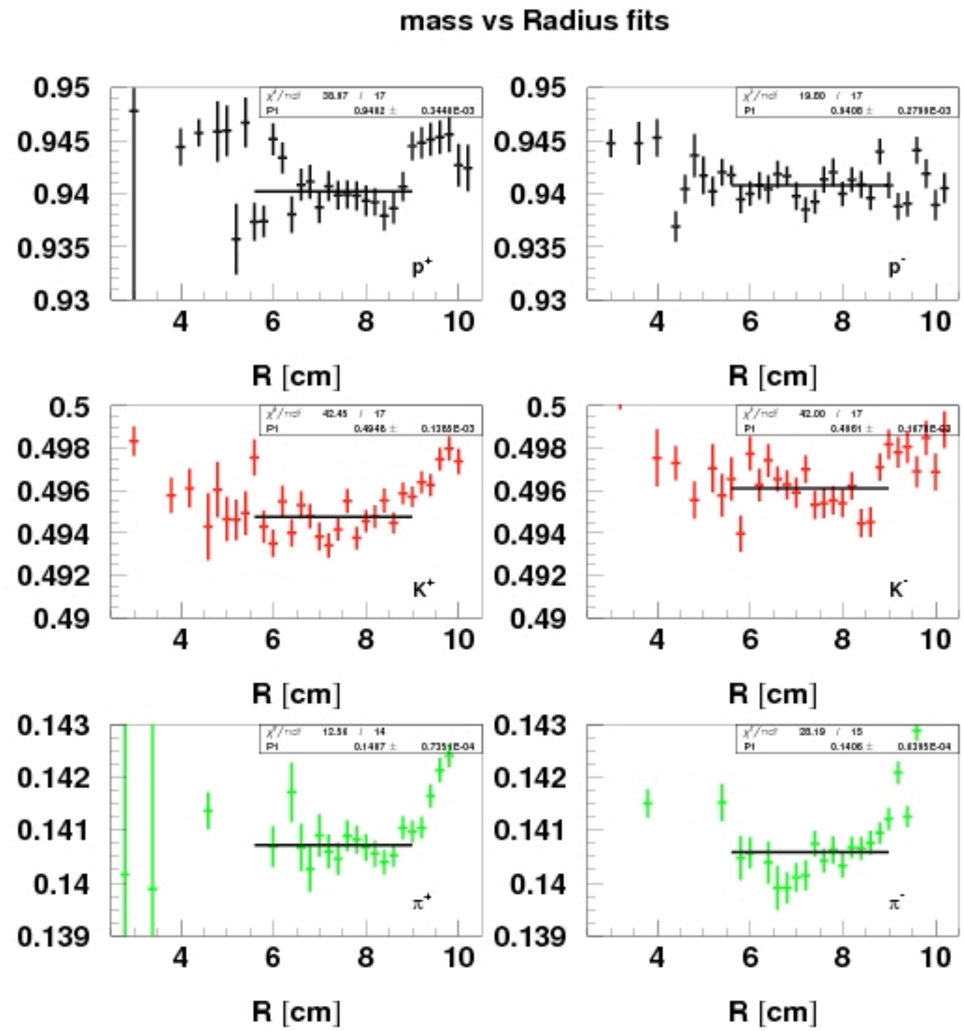


Current mass fits

Analysis using likelihood fitter

- Start with all tubes within 8mm of track center
- 5.5 < R[cm] < 9.0
- All tubes on one mirror
- <3 likelihood maxima
- Recalibrate

χ^2/ν of mass vs radius fits are now better - progress



Current mass status

Proton and anti-proton now agree

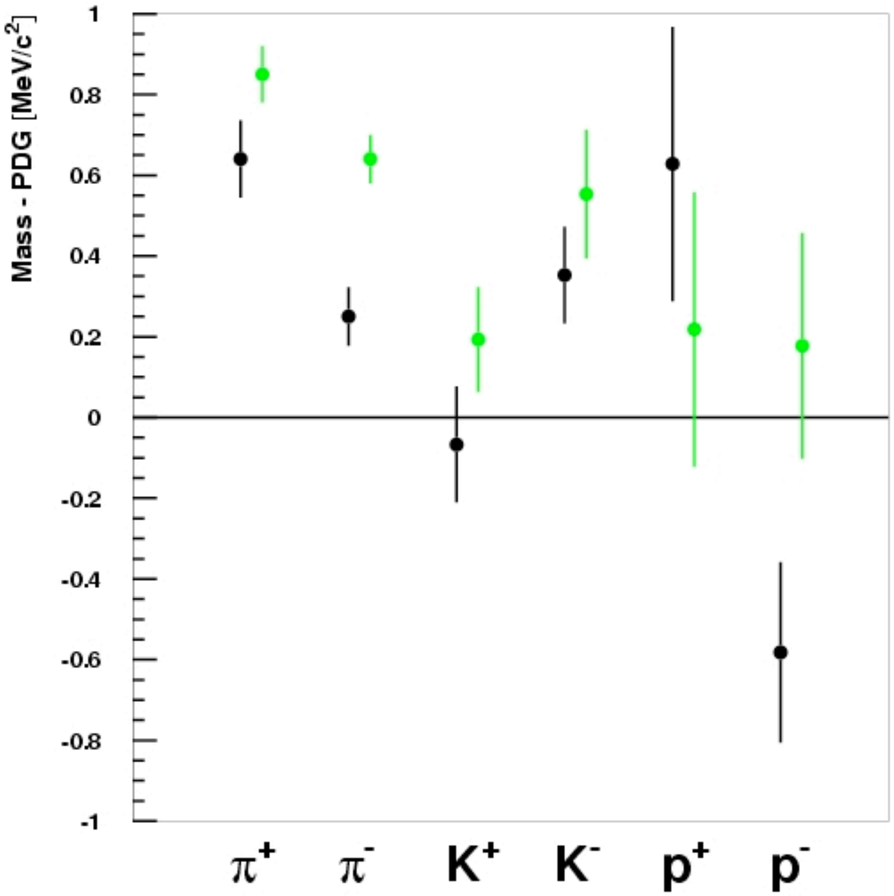
- Momentum scale shift required to make these agree with PDG is +0.02(0.02)%

Kaons are still close

Pions need work

- Muons are close by
- shouldn't these lower the mass?

Hyperons - later



Summary - work list

We’re not done yet

- Simulation
- Better pattern recognition and selection cuts
- Larger statistics sample for the hyperons (Σ^+ anti-Σ^- is hopeless)

Questions

- Why are the pions high?
- Why don’t the kaons agree with each other?
- Can the calibration be cross-checked?
  - Measured mirror focal lengths
  - Θ_c^{max} from high momentum tracks
- Other systematics?
- What and where are the ultimate limitations?

Jürgen and I got sidetracked by another Selex analysis issue

- We’re back now

Conclusions

A multi-pixel RICH is a potentially serious velocity spectrometer

- Once controlled the resolution is dominated by geometry - just like MWPC's
- Systematic control at the 1/10σ level is achieved. (This just dropped out.)
- The 1/100 σ level or better remains to be demonstrated.
- Serious calibration is hard. (So what else is new?)

Cherenkov counters began as single PMT digital (yes/no, PID) detectors

- The advent of multi-pixel detectors with >10^3 channels were (are) used in the same way (by Selex and many others)
- There's more information available in these measurements
  - e.g. the angular track resolution from the Selex RICH is only ~3x worse than the MWPC tracker in front of it. The momentum resolution is yet to be seriously studied.

Experiments are hard. Precision measurements are too valuable to go unused.