

## Search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at low momentum

- Motivation
- The experiment
- Data analysis
- Backgrounds
- Future
- Conclusion

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E787

A Search for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and Related Decays

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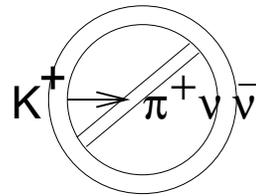
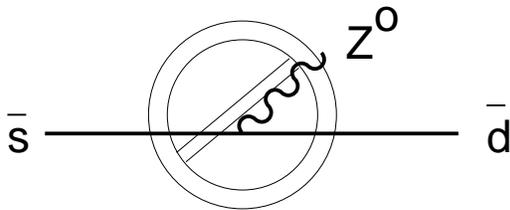
# Consequences of Cabibbo - Kobayashi - Maskawa Mixing

neutral currents:

$$(d' \quad s' \quad b') \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = (d \quad s \quad b) \underbrace{V^\dagger V}_I \begin{pmatrix} d \\ s \\ b \end{pmatrix} \Rightarrow$$

$$ddZ + ssZ + bbZ + uuZ + ccZ + ttZ$$

No “flavor-changing neutral currents”



Similarly following decays are not allowed

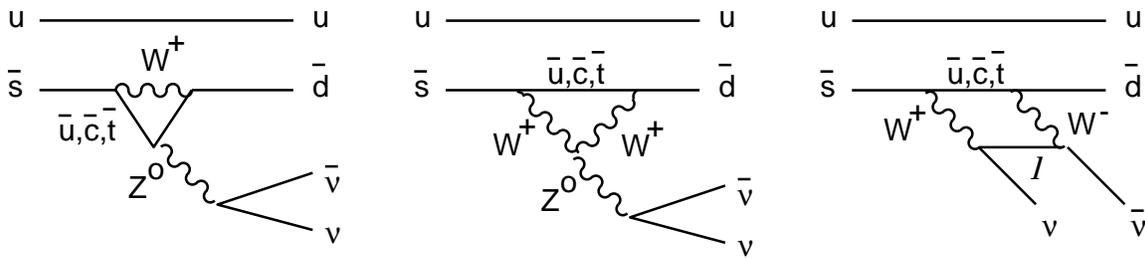
$$K_L \rightarrow \mu^+ \mu^-$$

$$K_L \rightarrow e^+ e^-$$

$$K^+ \rightarrow \pi^+ \mu^+ \mu^-$$

... etc.

... or are they? Each of these diagrams *is* allowed:



$$V_{us}^*, V_{cs}^*, V_{ts}^*$$

$$V_{ud}, V_{cd}, V_{td}$$

Unitarity of  $V \implies$  “G.I.M. mechanism”

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0$$

No flavor-changing neutral currents at all!

Loophole:  $m_u \ll m_c \ll m_t$ : the cancellation is not exact and most of the surviving rate is due to **top quarks!**

The residual rate is calculable – for three neutrino flavors:

$$\text{BR}_{\text{calc}}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.75 \pm 0.29) \times 10^{-10}$$

A.J. Buras, Preprint hep-ph/0101336

## CP and $\pi\nu\bar{\nu}$

$$K_L = \frac{K_2 + \epsilon K_1}{\sqrt{(1+|\epsilon|^2)}} \quad CP \approx -1$$
$$K_S = \frac{K_1 + \epsilon K_2}{\sqrt{(1+|\epsilon|^2)}} \quad CP \approx +1$$

$\pi^0\nu\bar{\nu}$  is CP even state

$$A(K^0 \rightarrow \pi^0\nu\bar{\nu}) = (1/\sqrt{2})A(K^+ \rightarrow \pi^+\nu\bar{\nu})$$
$$A(K_1 \rightarrow \pi^0\nu\bar{\nu}) = \text{Re}(A(K^+ \rightarrow \pi^+\nu\bar{\nu})) = R$$
$$A(K_2 \rightarrow \pi^0\nu\bar{\nu}) = i\text{Im}(A(K^+ \rightarrow \pi^+\nu\bar{\nu})) = iI$$
$$B(K_L \rightarrow \pi^0\nu\bar{\nu}) = I^2 + 2\text{Re}(-i\epsilon RI) + |\epsilon|^2 R^2 \simeq I^2$$

$$R/I \simeq \text{Re}(V_{ts}^* V_{td}) / \text{Im}(V_{ts}^* V_{td}) \simeq \frac{3.0 \times 10^{-4}}{1.4 \times 10^{-4}}$$

But the smallness of  $|\epsilon| \sim 0.0022$  makes  $K_L \rightarrow \pi^0\nu\bar{\nu}$  almost entirely through direct CP violation ( $K_2 \rightarrow \pi^0\nu\bar{\nu}$ ).

Littenberg, 1989

Measurements of  $K \rightarrow \pi\nu\bar{\nu}$  provide CKM parameters with small theoretical uncertainties, but the experiments are hard.

Extend analysis to get limit on branching ratio:

$$B(K_L \rightarrow \pi^0\nu\bar{\nu}) < 4.4 \times B(K^+ \rightarrow \pi^+\nu\bar{\nu})$$

Grossman and Nir, 1997



# Measurement at low momentum ?

- Current observation based on two events with  $P > 211 MeV/c$ .

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.57_{-0.82}^{+1.75}) \times 10^{-10}$$

S. Adler et al., Phys. Rev. Lett. 88, 041803 (2002).

- Tension between  $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  and  $B_d - \bar{B}_d$  mixing.  
Need measurement with higher statistics for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and  $\Delta M_{B_d}/\Delta M_{B_s}$
- Exotic physics possibilities such as  $K^+ \rightarrow \pi^+ X^0$  where  $X^0$  has some mass need to be examined.
- Sizable SUSY contributions to  $s \rightarrow d \nu \bar{\nu}$  allowed because  $K_L \rightarrow \mu^+ \mu^-$  and  $\epsilon'/\epsilon$  do not provide sufficient constraint. Also correlations exist with  $b \rightarrow dl^+ l^-$  and  $b \rightarrow sl^+ l^-$ .

G. D'Ambrosio and G. Isidori, hep-ph/0112135

- Other exotic physics could modify the spectrum.

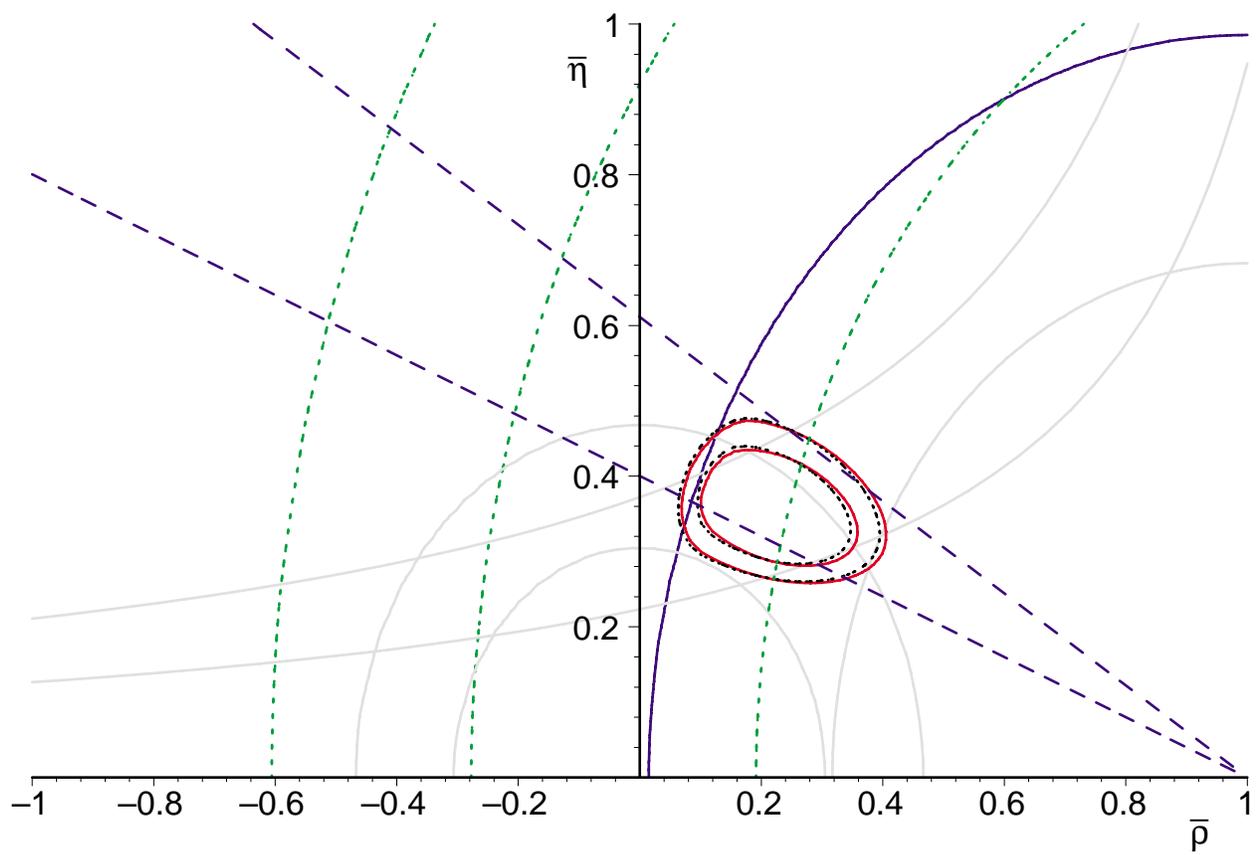
$$K^+ \rightarrow \pi^+ J J$$

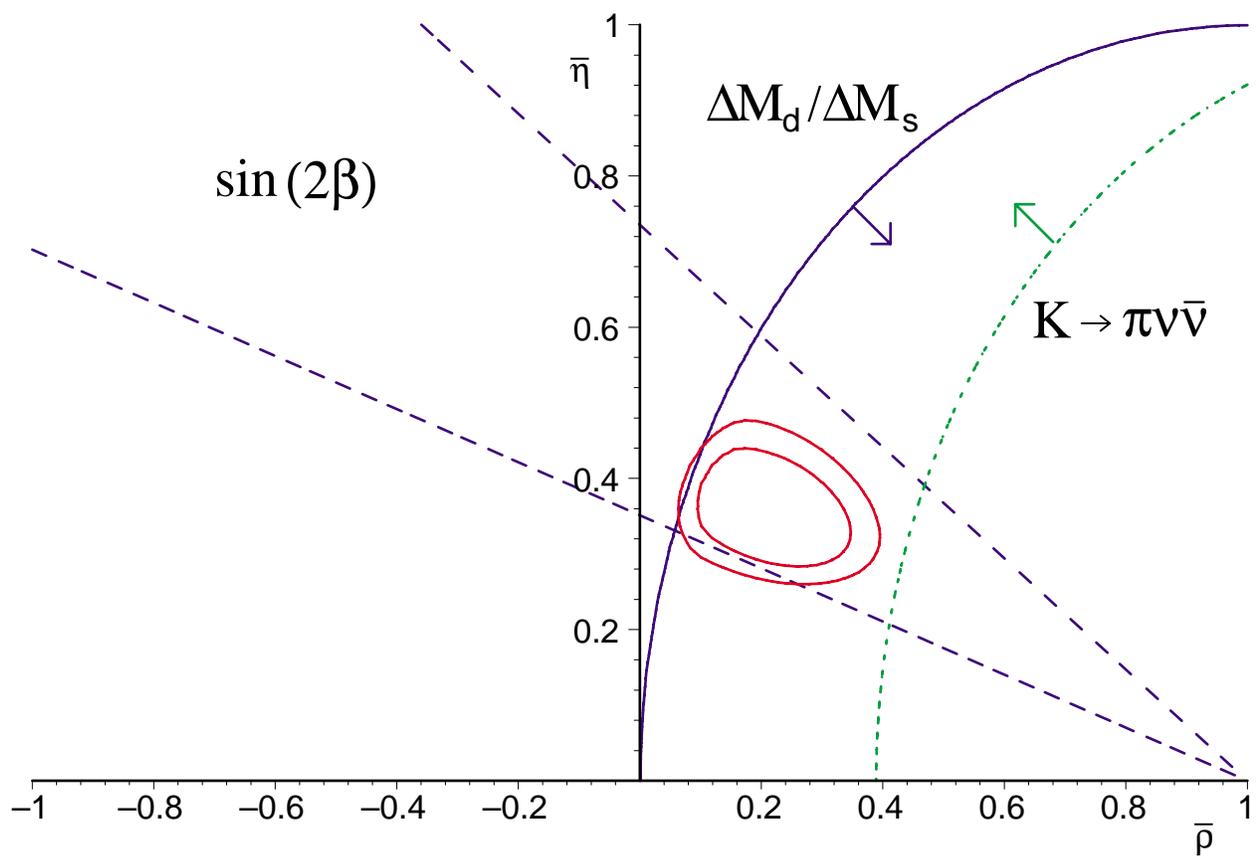
Bertolini and Sanatamaria, NP **B315**, 558 (1989).

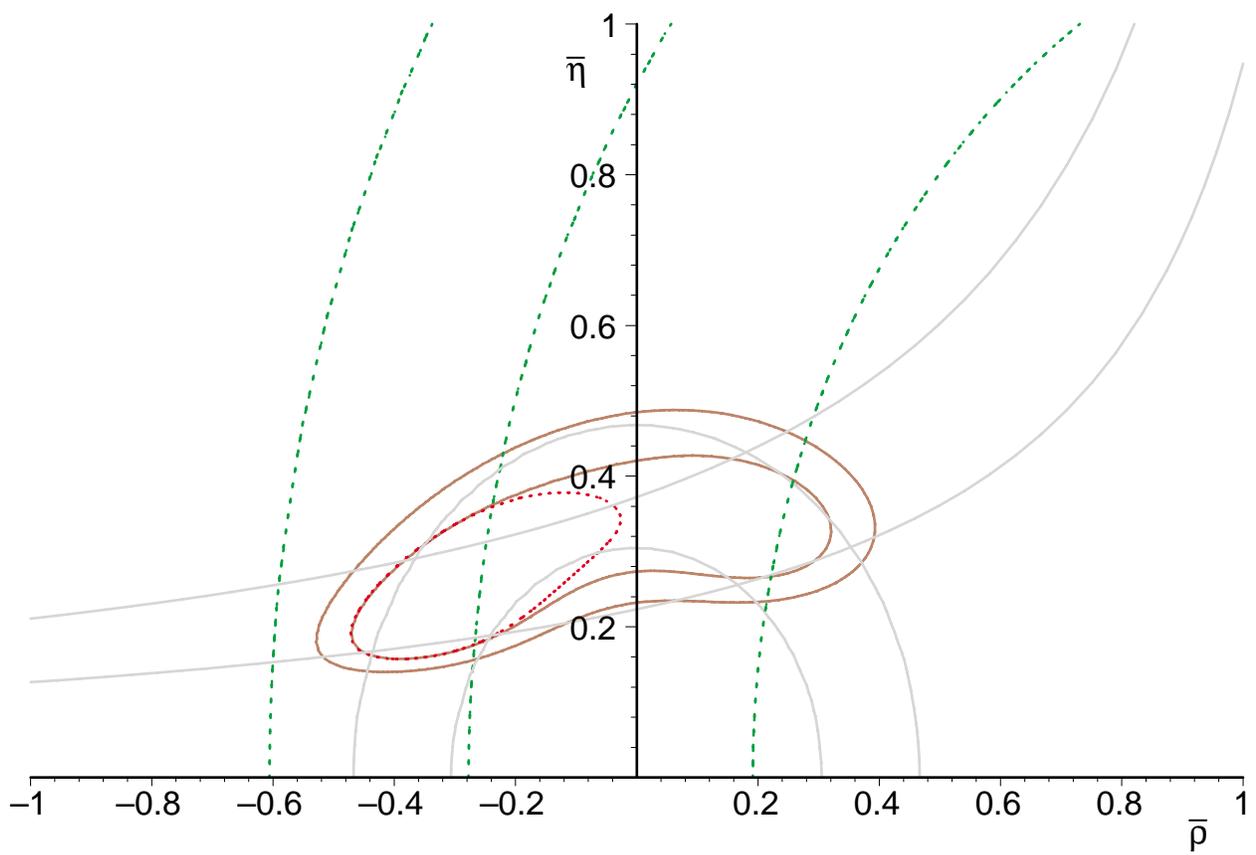
- Within SM long-distance physics ( $\sim 10^{-13}$ ) could have a distorted spectrum.

Rein and Sehgal, PRD **39**, 3325 (1989).

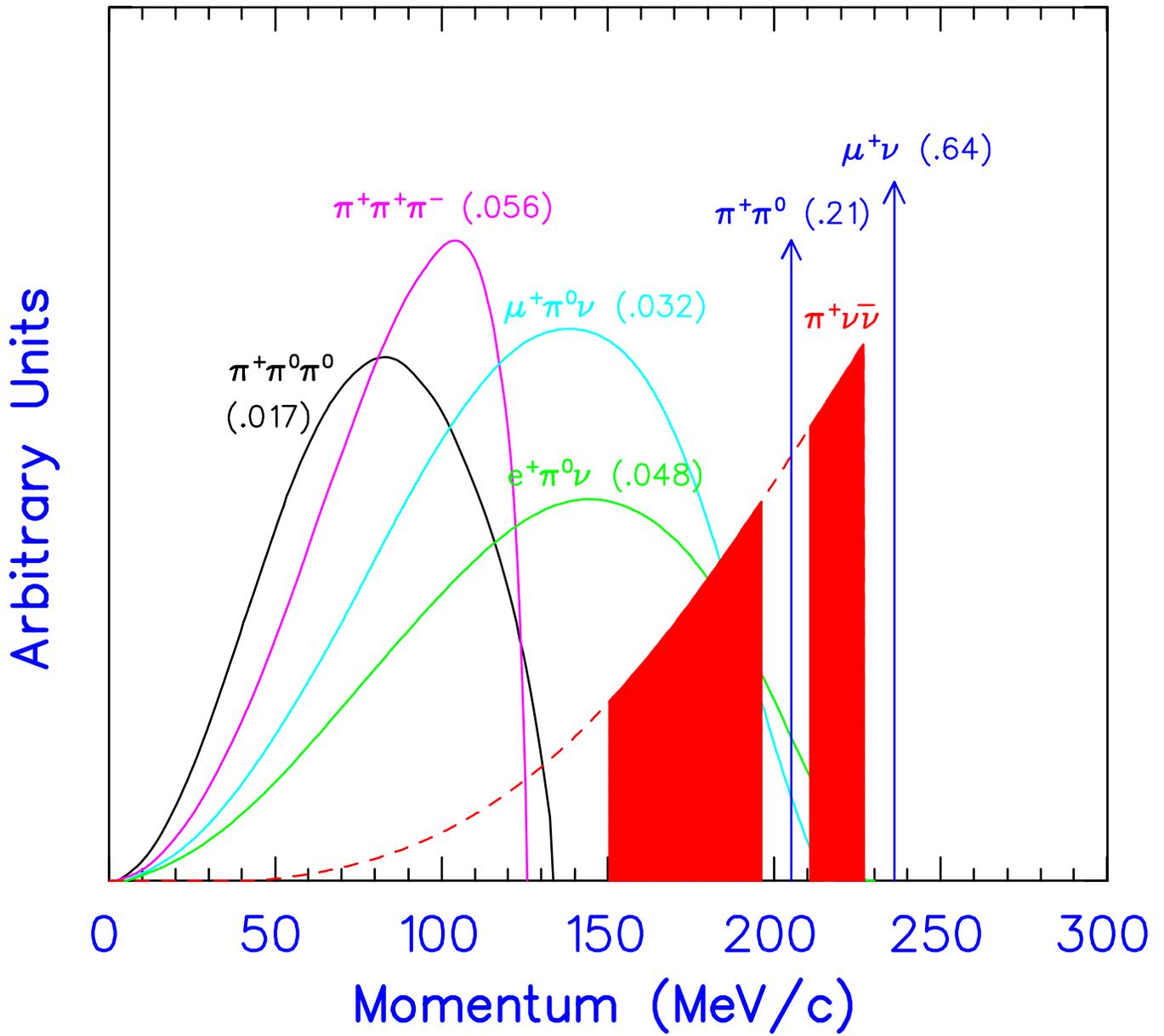
- Attempt to enhance the efficiency for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  over all phase phase-space.







# PNN backgrounds and tools



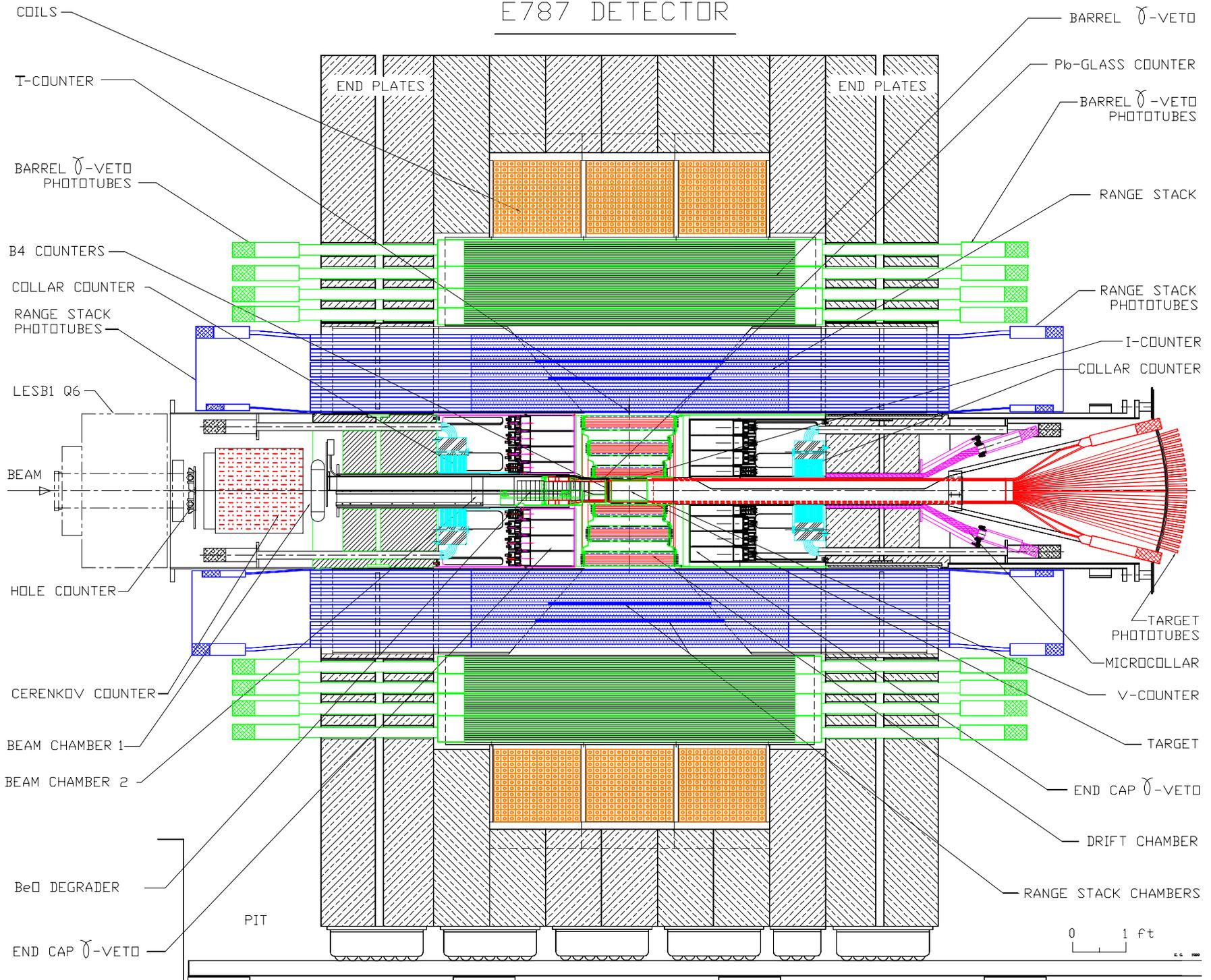
## PNN1 main backgrounds

- $K^+ \rightarrow \pi^+\pi^0$  : Two body kinematics and Photon veto
- $K^+ \rightarrow \mu^+\nu$  : Two body kinematics and  $\pi^+ \rightarrow \mu^+ \rightarrow e^+$  id.
- Scattering of  $\pi^+$  contamination:  $K^+$  decay time and Cerenkov Particle identification in the beam.

## PNN2 main backgrounds

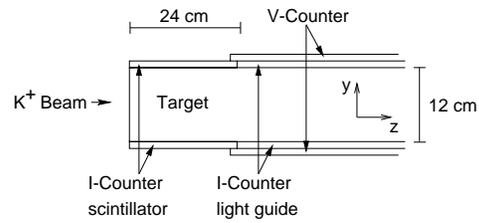
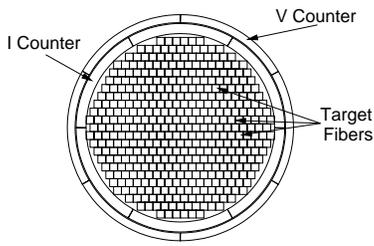
- $K^+ \rightarrow \pi^+\pi^0$  with scattering of  $\pi^+$  in the kaon stopping target: Two body kinematics, Photon veto, and Detection of  $\pi^+$  scattering in the target.
- $K^+ \rightarrow \pi^+\pi^-e^+\nu$ : Detection of  $\pi^-$  and  $e^+$  in the target.
- Scattering of  $\pi^+$  contamination in the beam:  $K^+$  decay time and Cerenkov Particle identification in the beam.
- Use CCD's to find  $\pi^+$  hits hidden under the kaon fibers. Allow long kaon decay time to help.
- Photon veto system not as effective as for PNN1 because  $\pi^0$  is not back-to-back with  $\pi^+$ .

# E787 DETECTOR



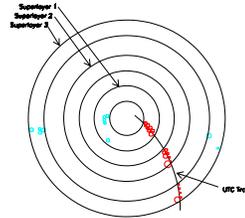
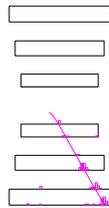
# E787 Technique

$K^+$  I.D.'d by beam counters, stop in 400-element sci-fi target



Wait 2ns for decay

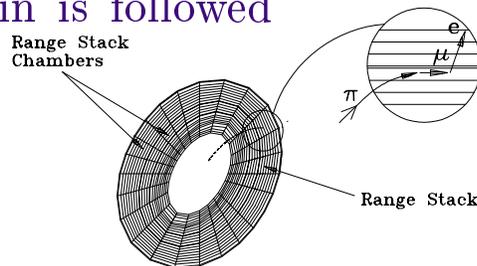
Then  $\pi^+$  tracked & momentum analyzed in UTC (B=1T)



$\pi^+$  then ranges out in an Range Stack (scint. + straw ch.)

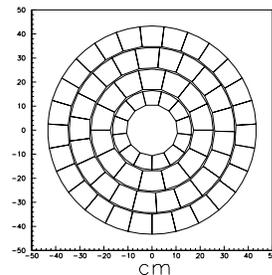
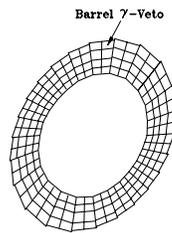
Range/energy/momentum can be compared.

Also  $\pi^+ \rightarrow \mu^+ \rightarrow e^+$  decay chain is followed



Hermetic photon vetoing via barrel Pb-scint system (BV)

+ CsI-pure endcaps (EC)

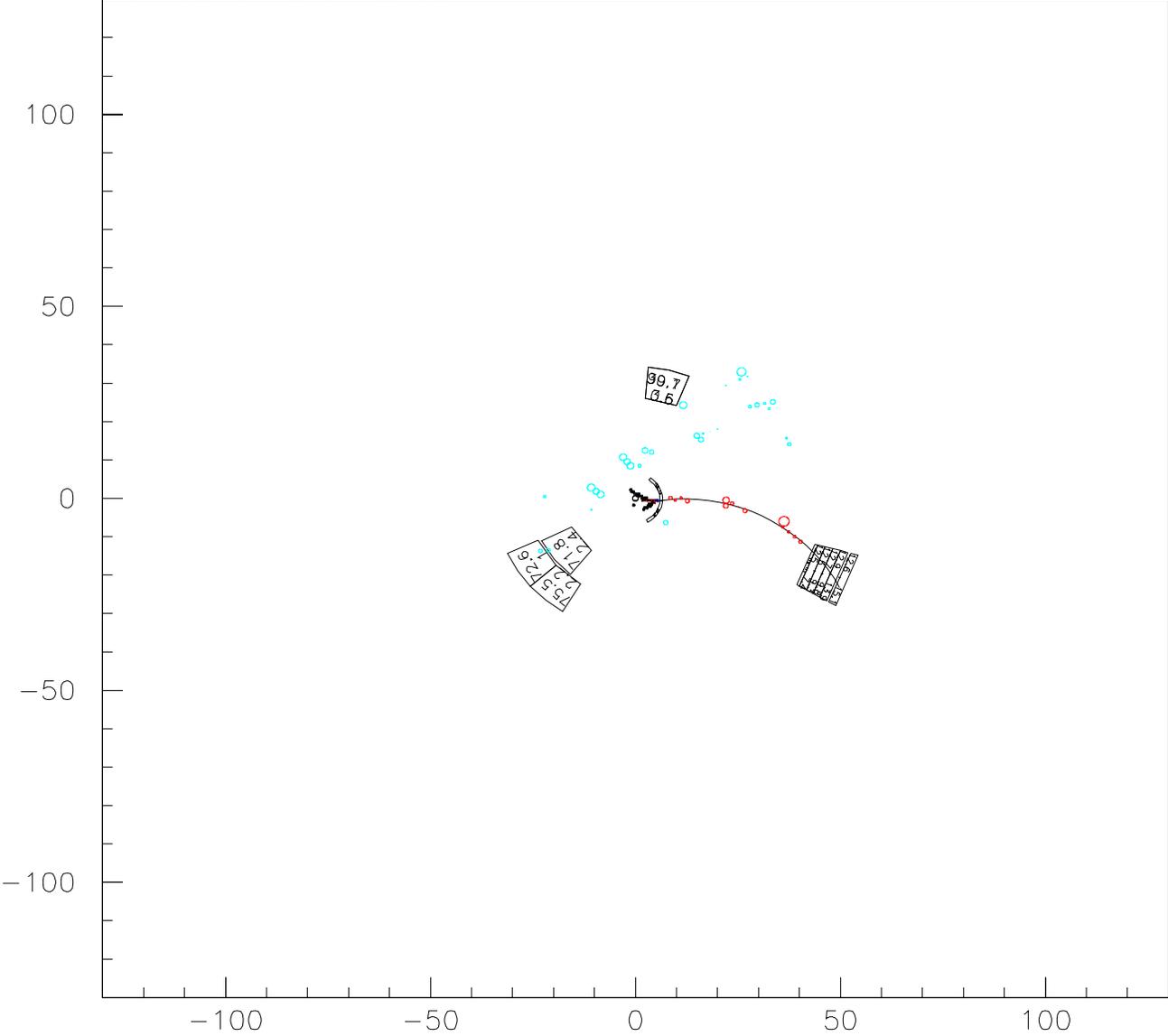


Get  $> 10^6 : 1$   $\pi^0$  rejection,  $> 10^8 : 1$   $\mu^+$  rejection

Also very good kinematic rejection of two-body decays.

CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

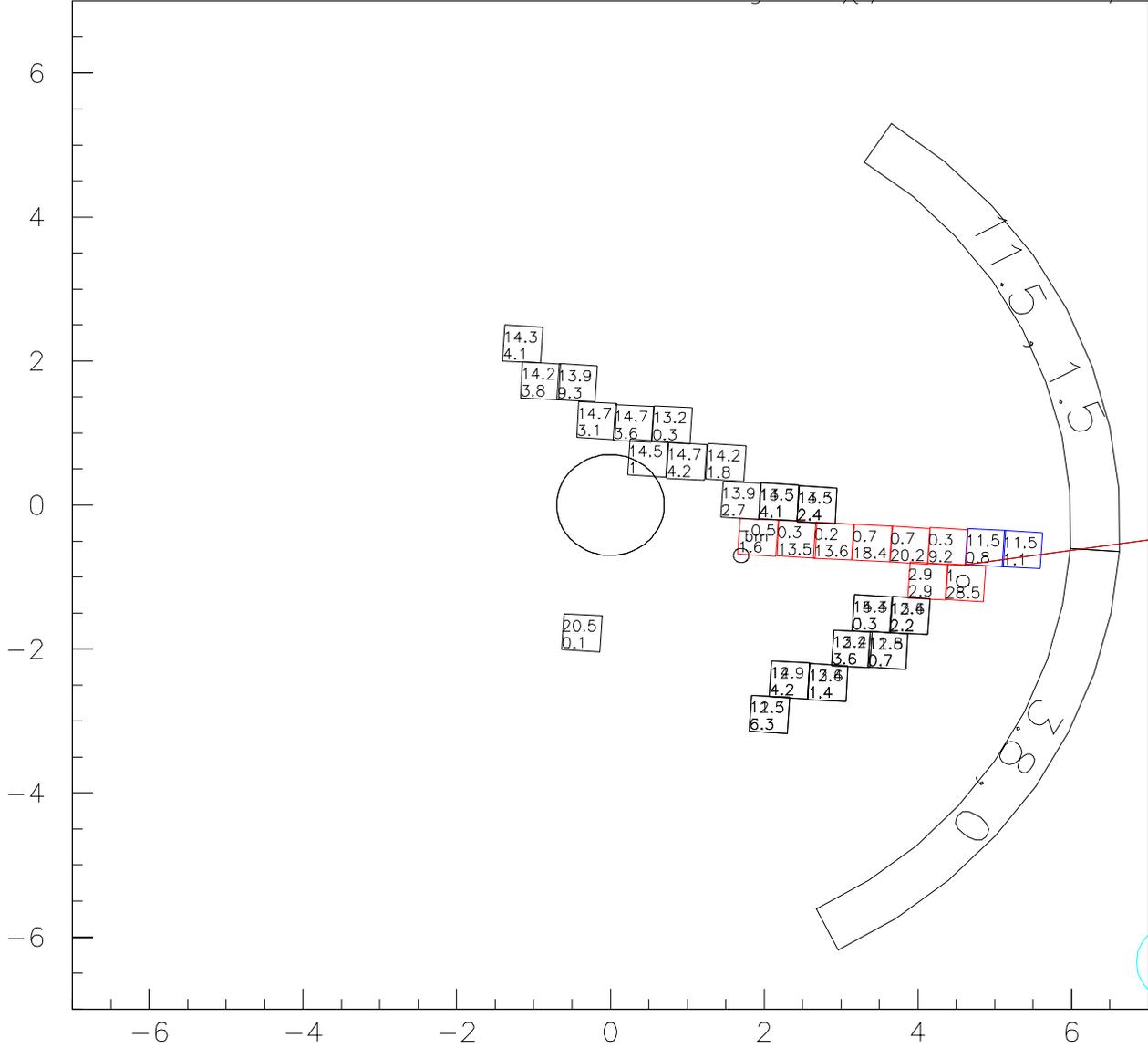
RUN 32180 Event 21029



CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

RUN 32180 Event 21029

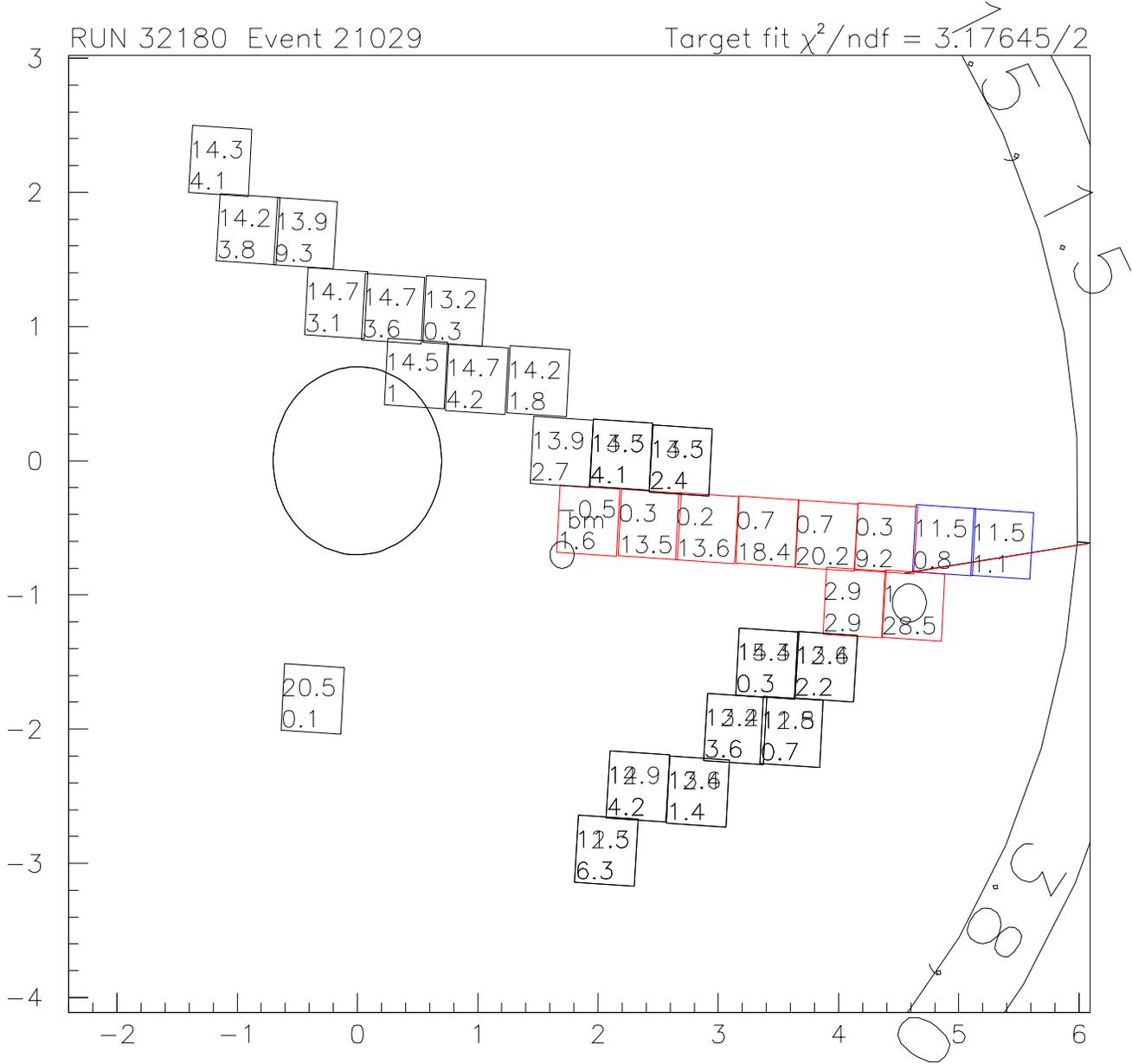
Target fit  $\chi^2/\text{ndf} = 3.17645/2$



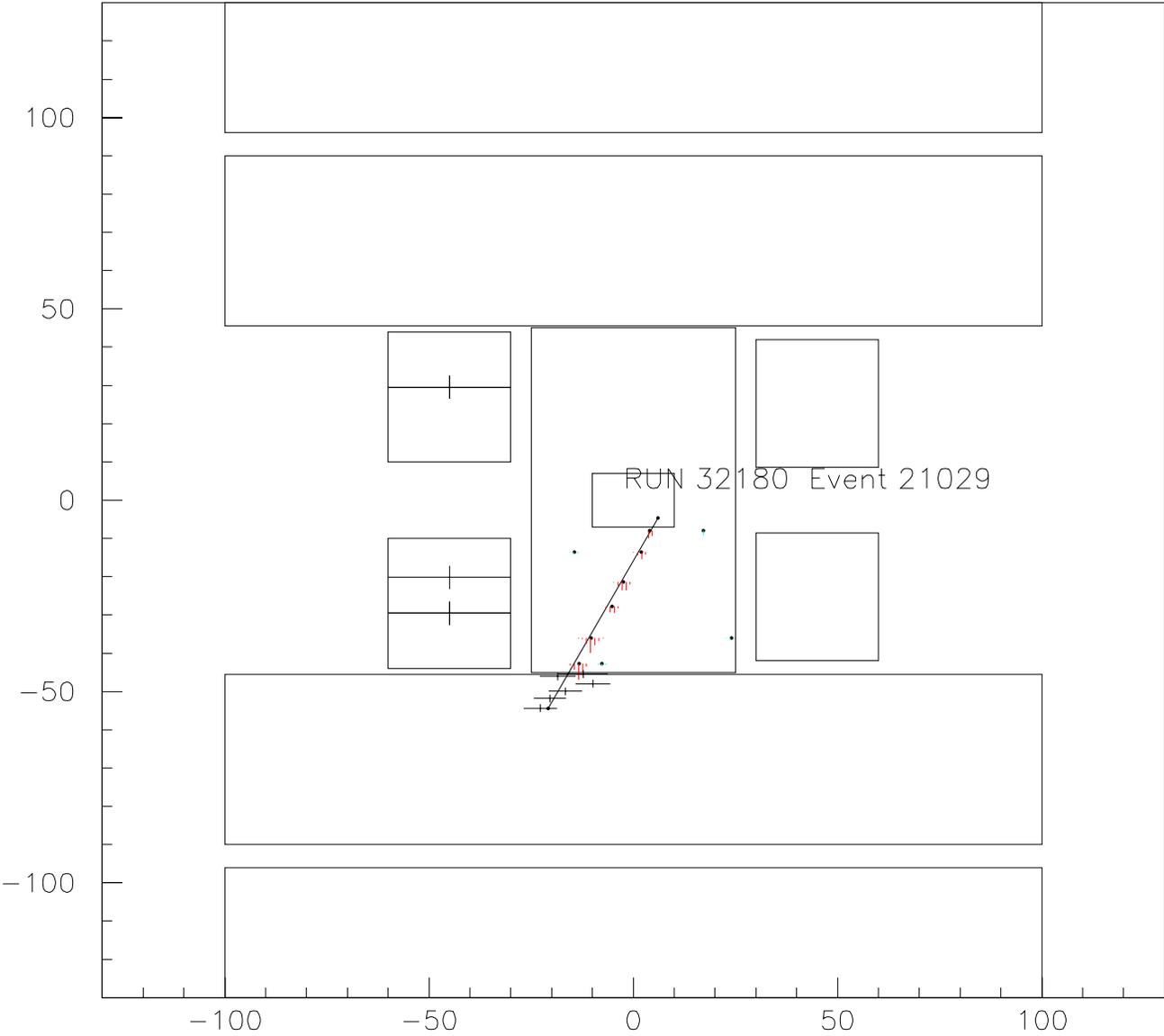
CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

RUN 32180 Event 21029

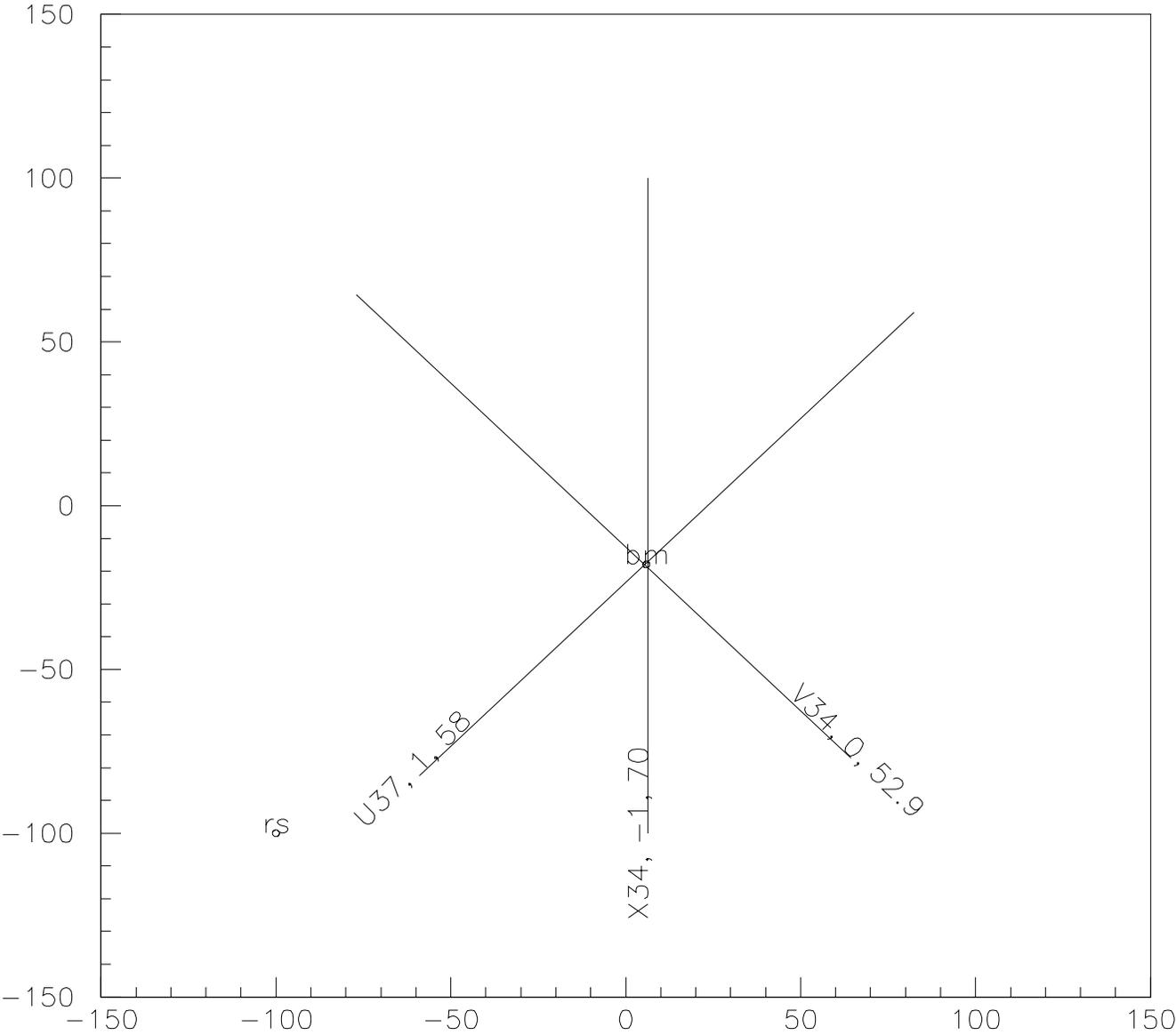
Target fit  $\chi^2/\text{ndf} = 3.17645/2$



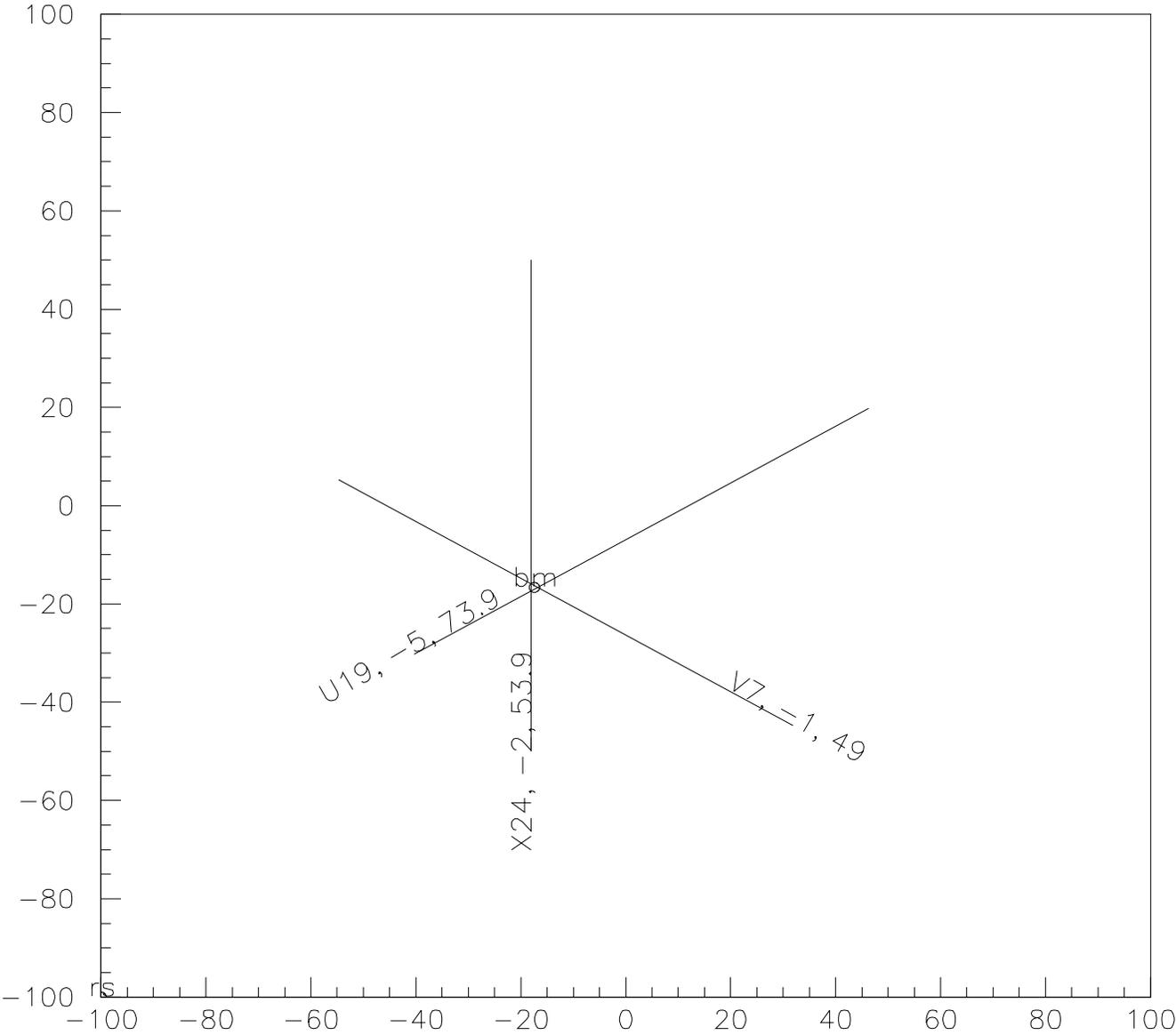
CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029



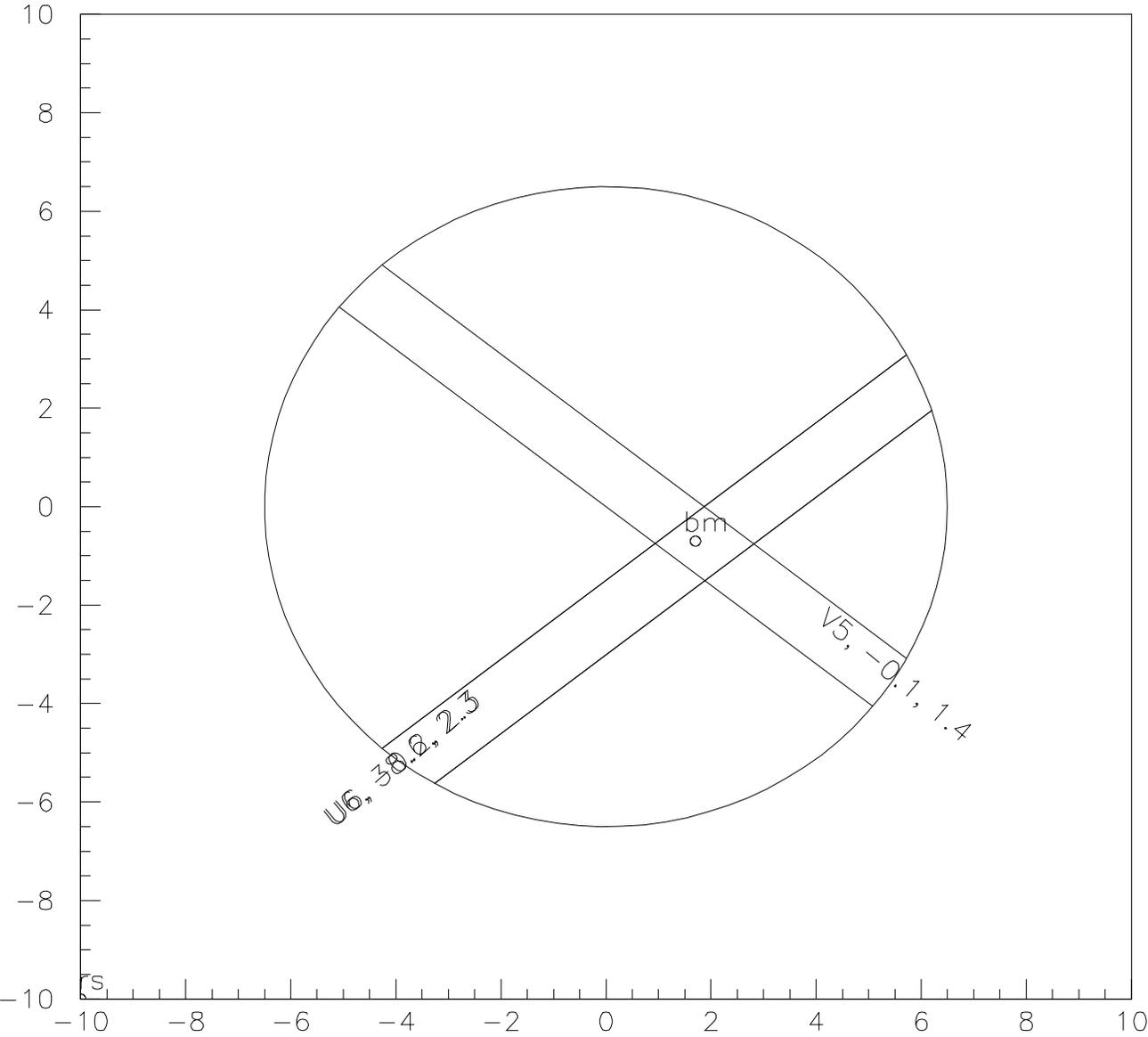
CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029



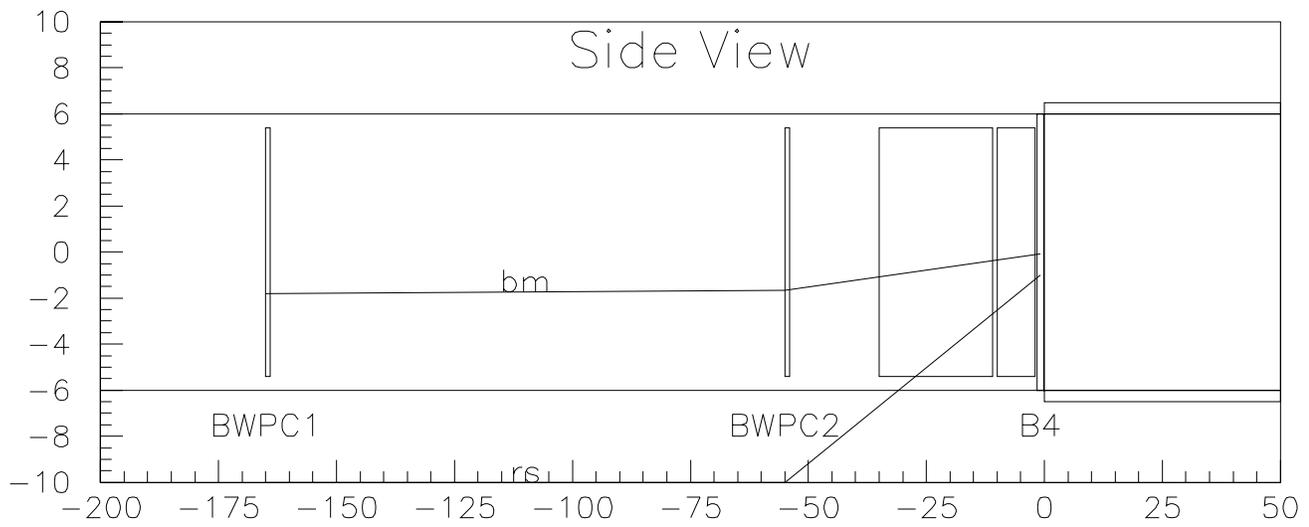
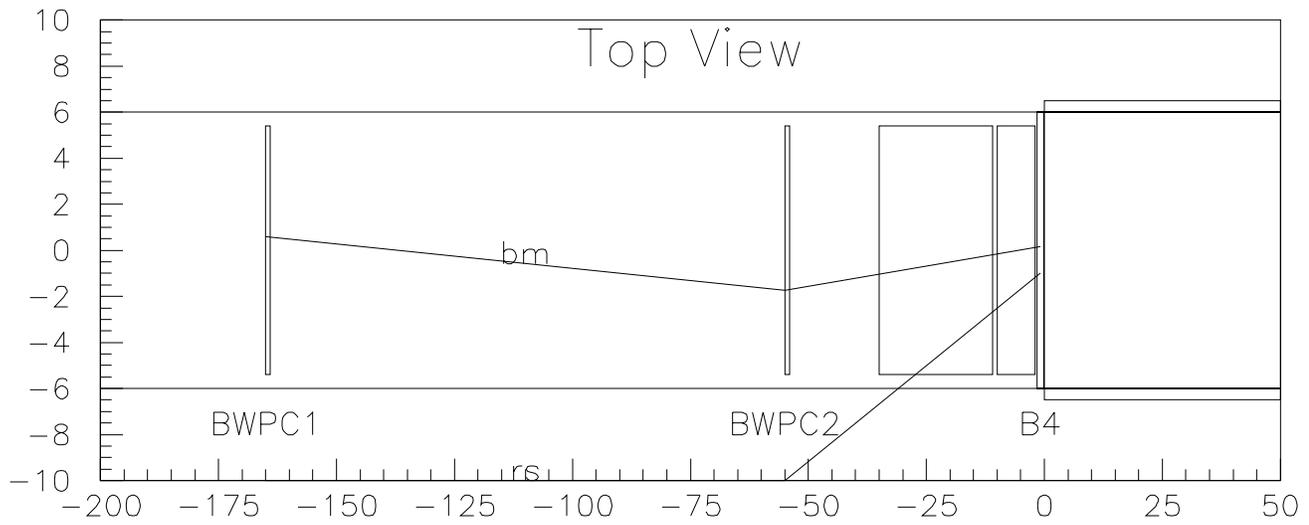
CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029



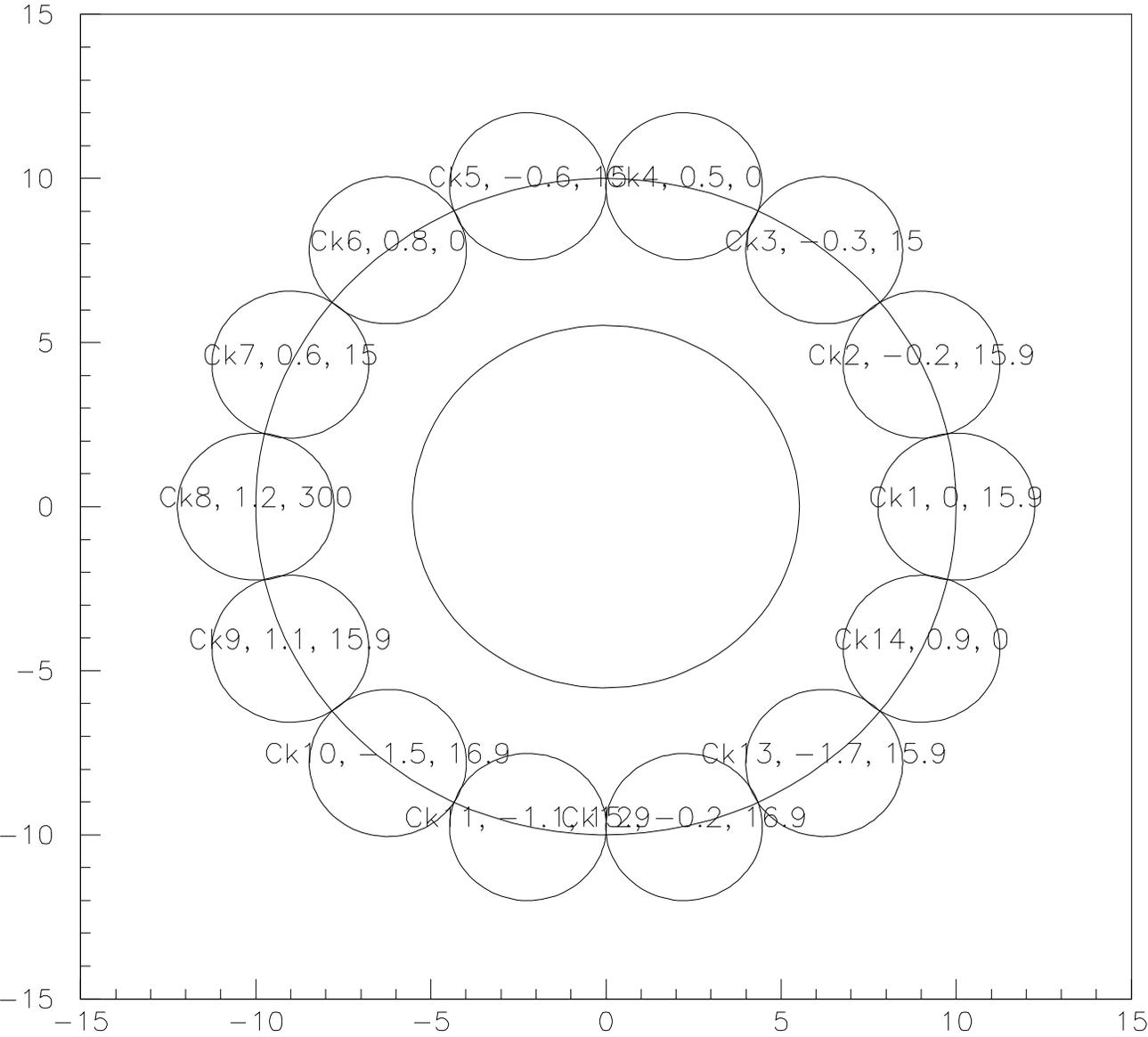
CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029



CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

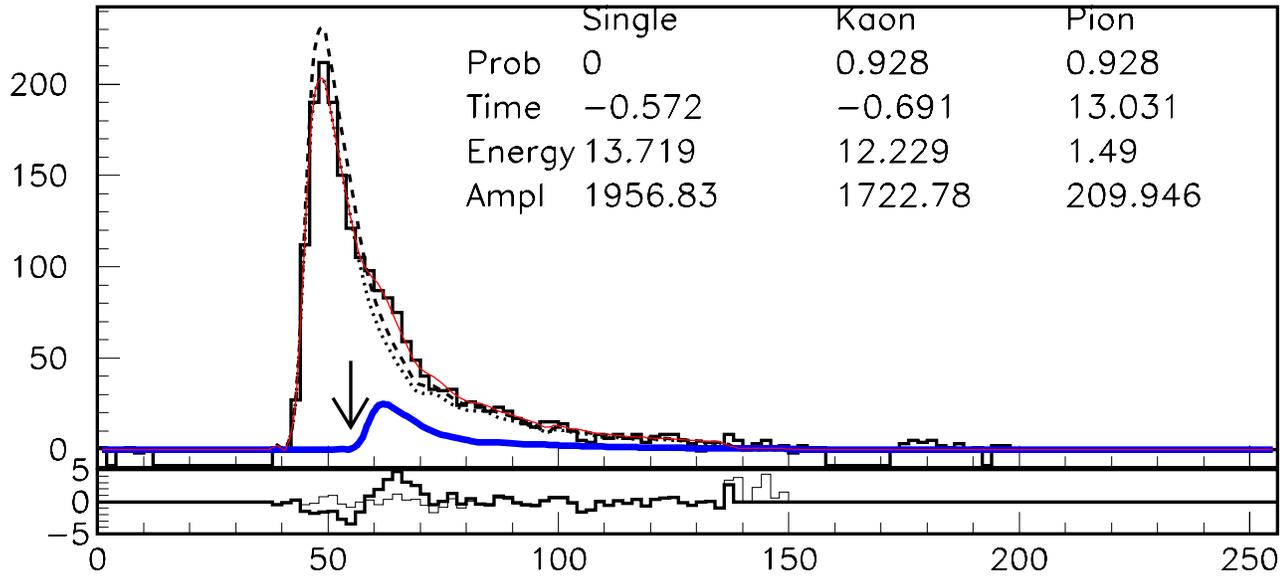


CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

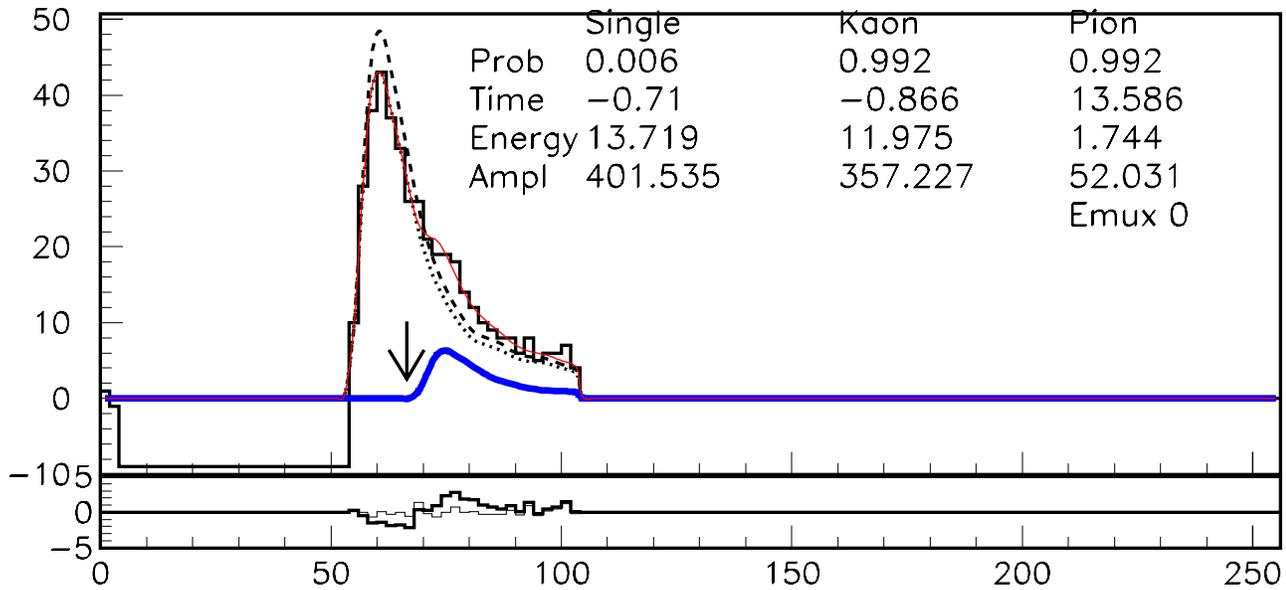


CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

Run 32180 Event 21029 EK 13.685 TK 0.234 TRS 12.746



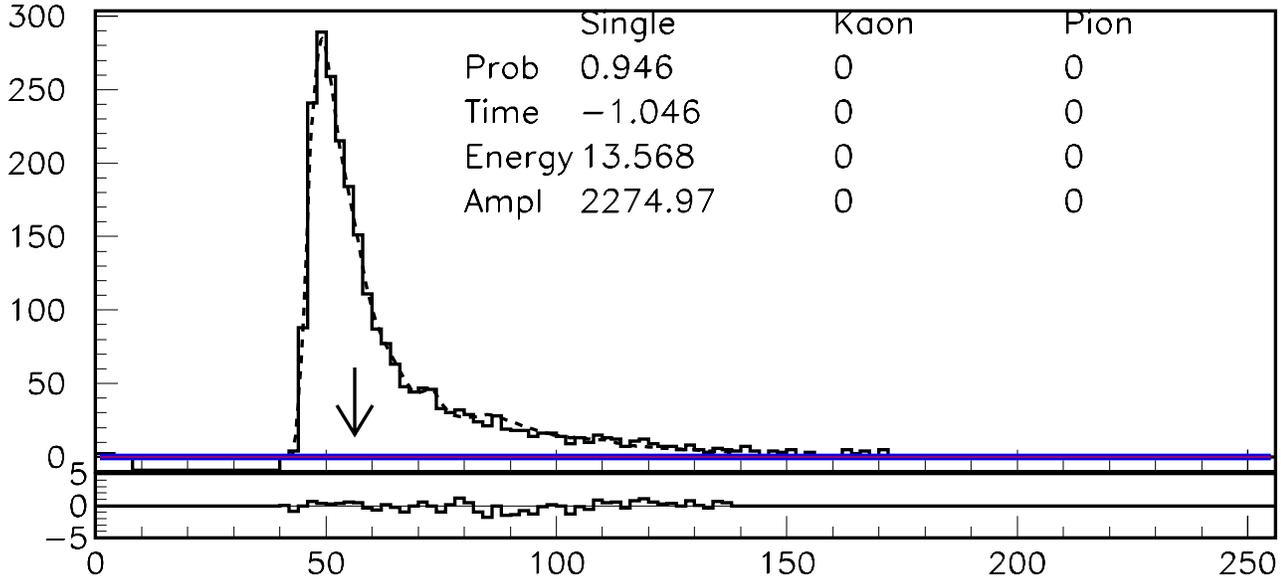
K fibre 306 Raw HighGain



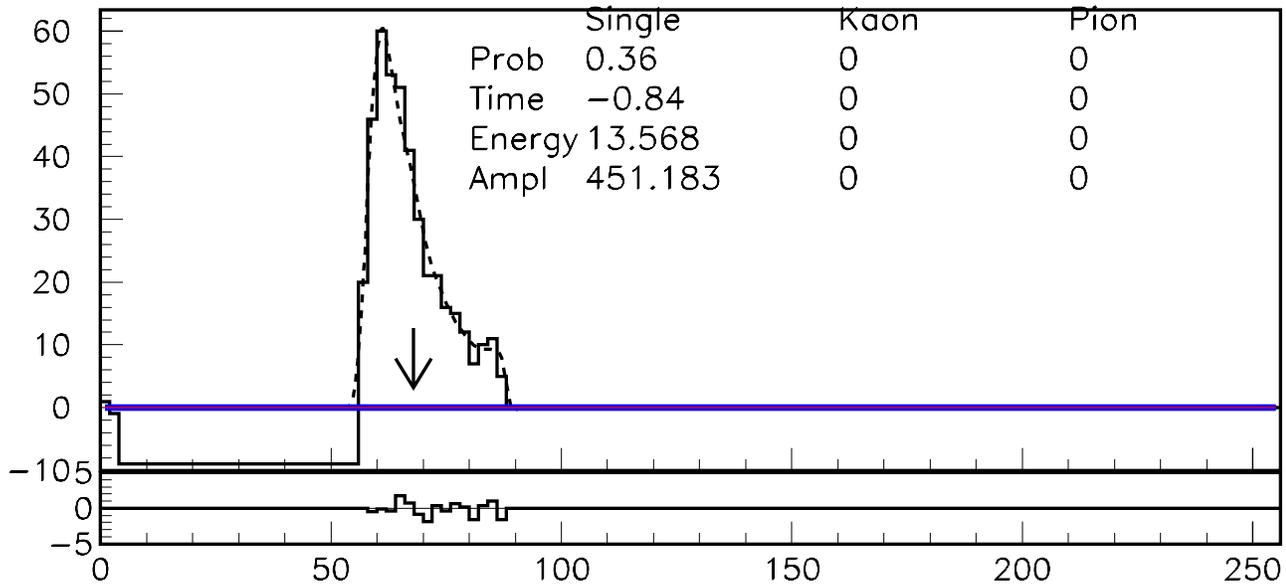
K fibre 306 Raw Low gain

CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

Run 32180 Event 21029 EK 13.587 TK 0.332 TRS 12.746



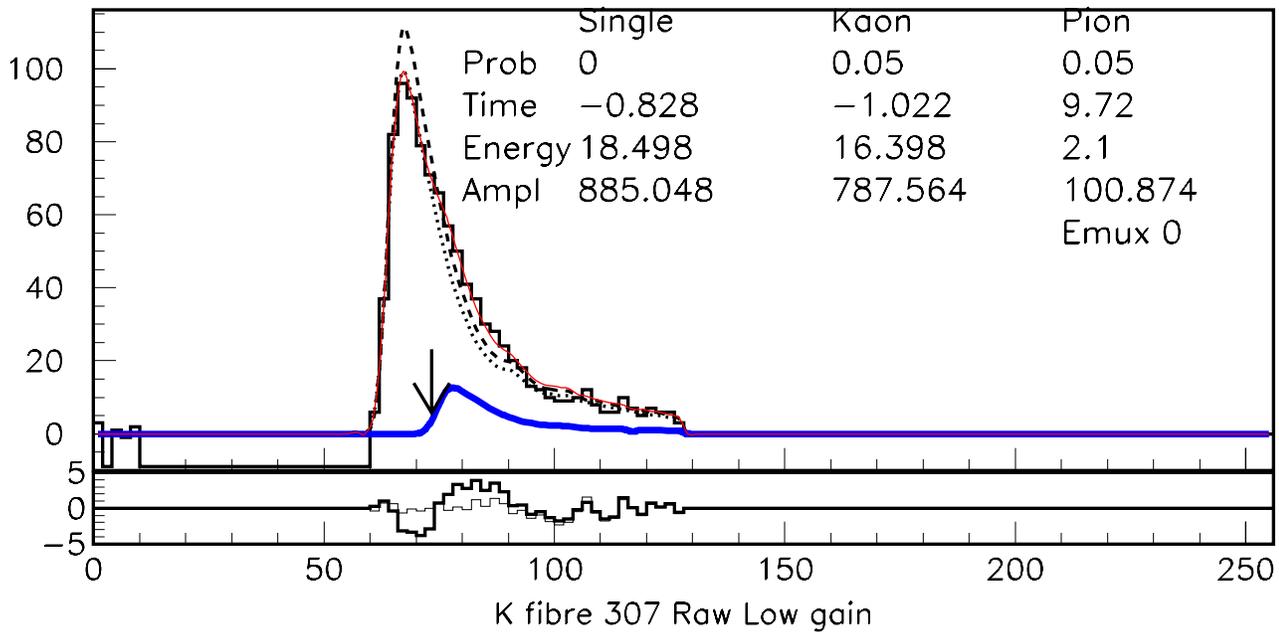
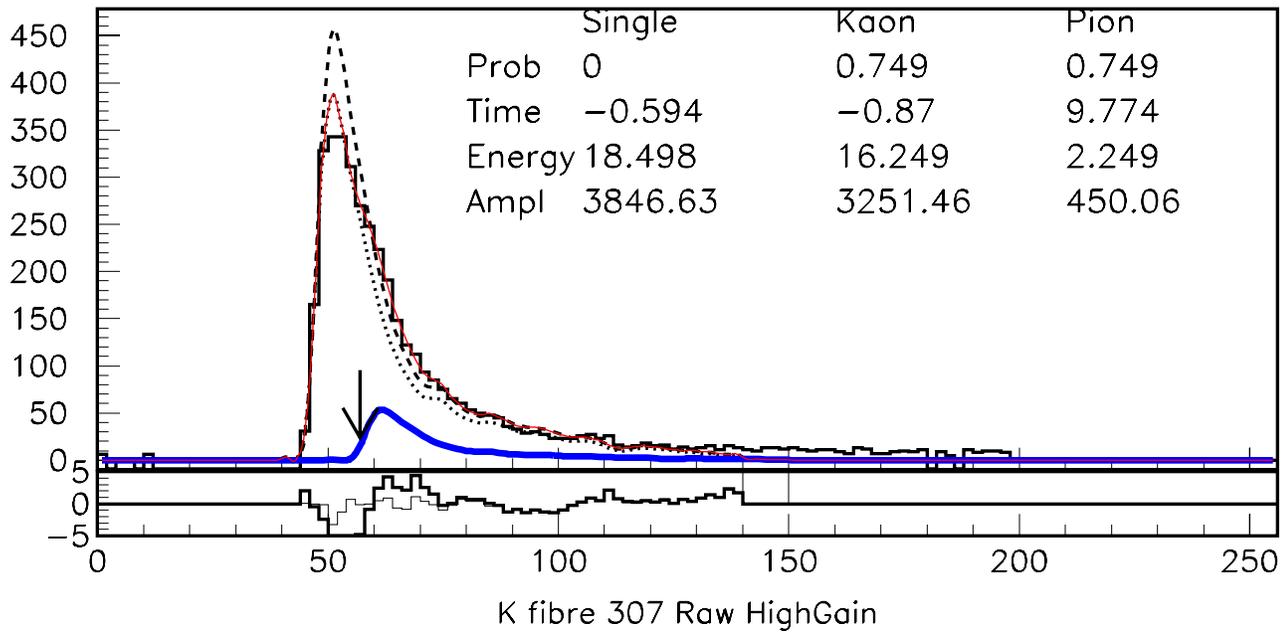
K fibre 305 Raw HighGain



K fibre 305 Raw Low gain

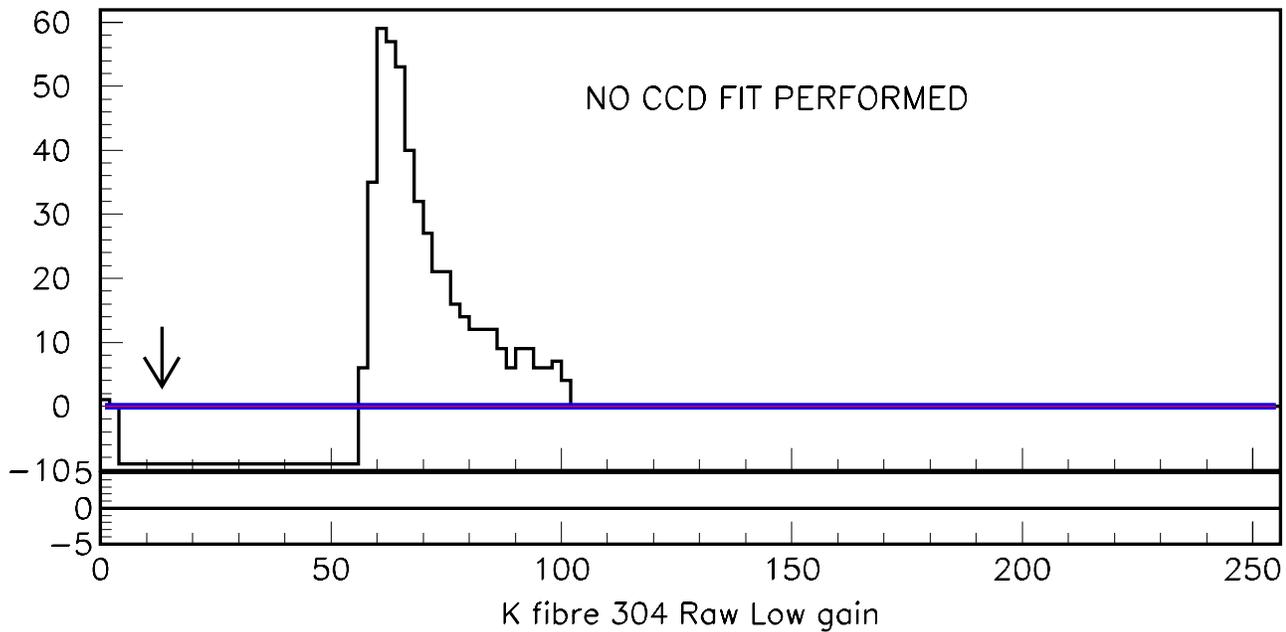
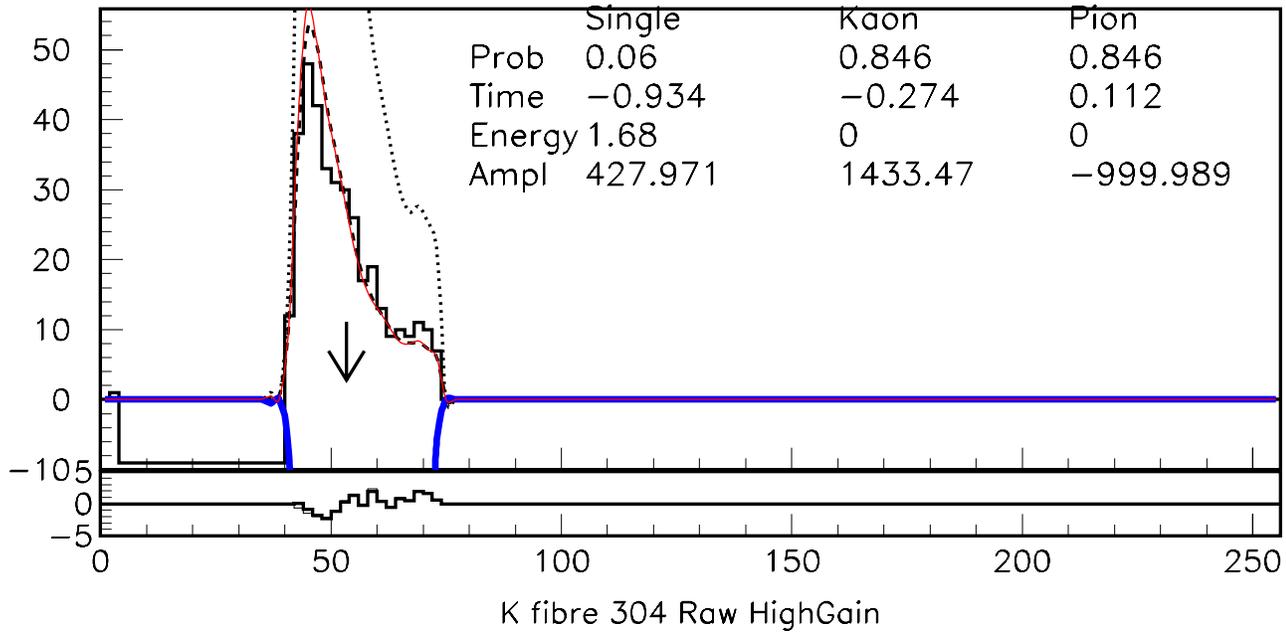
CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

Run 32180 Event 21029 EK 18.475 TK 0.723 TRS 12.746



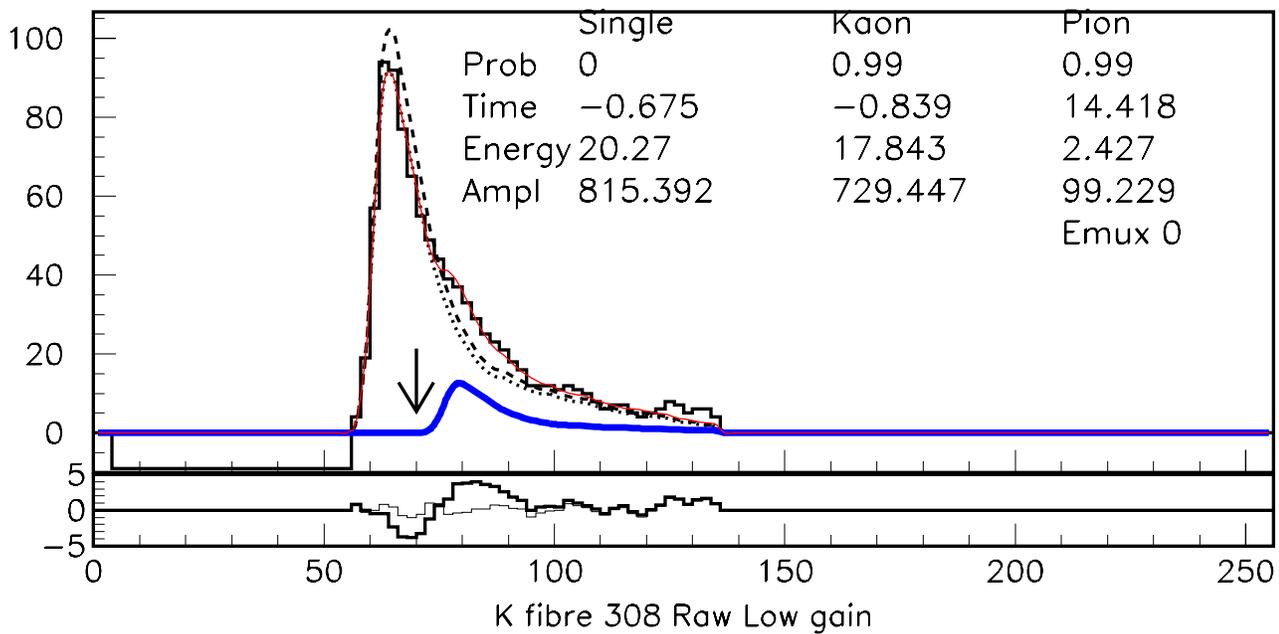
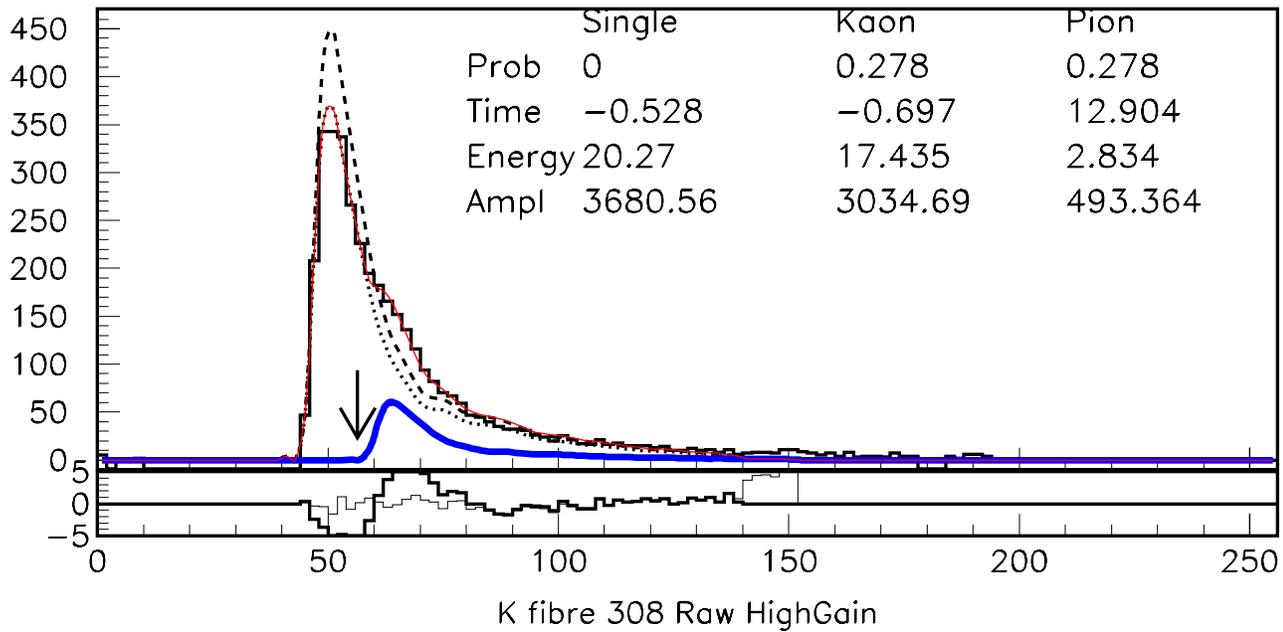
CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

Run 32180 Event 21029 EK 1.661 TK -0.547 TRS 12.746



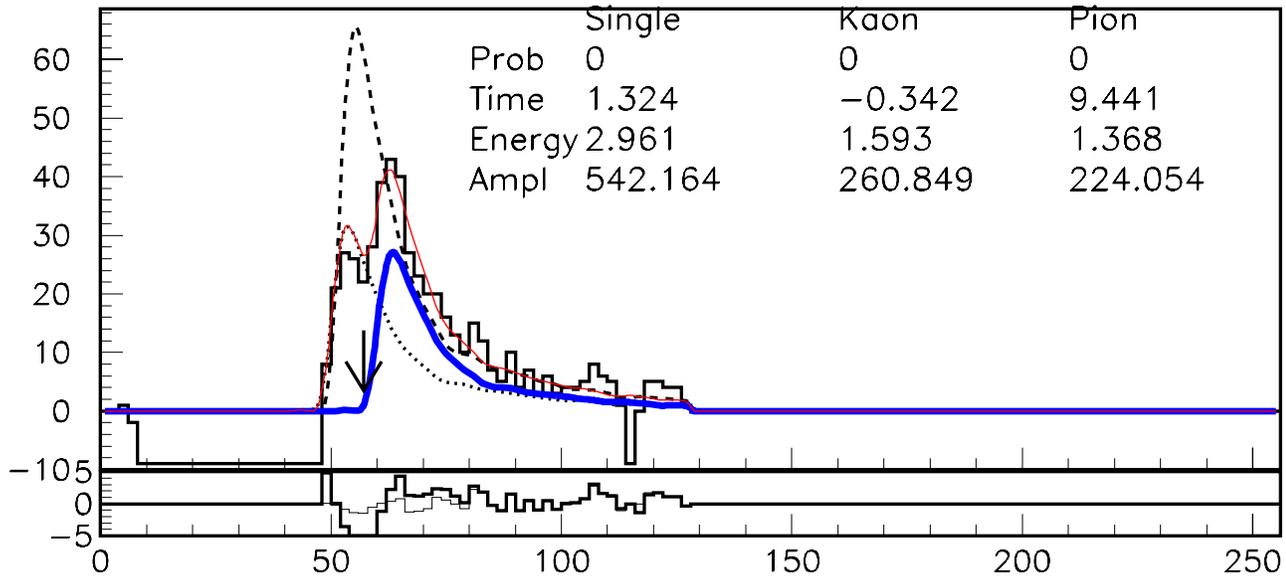
CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

Run 32180 Event 21029 EK 20.234 TK 0.723 TRS 12.746

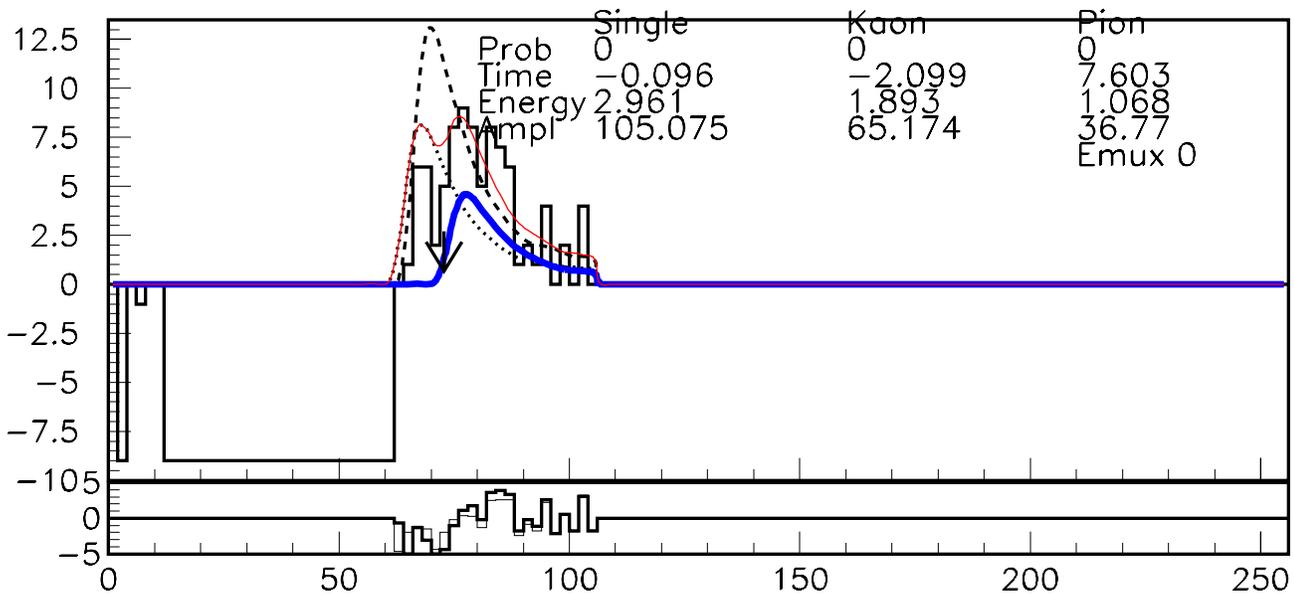


CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

Run 32180 Event 21029 EK 2.932 TK 2.971 TRS 12.746



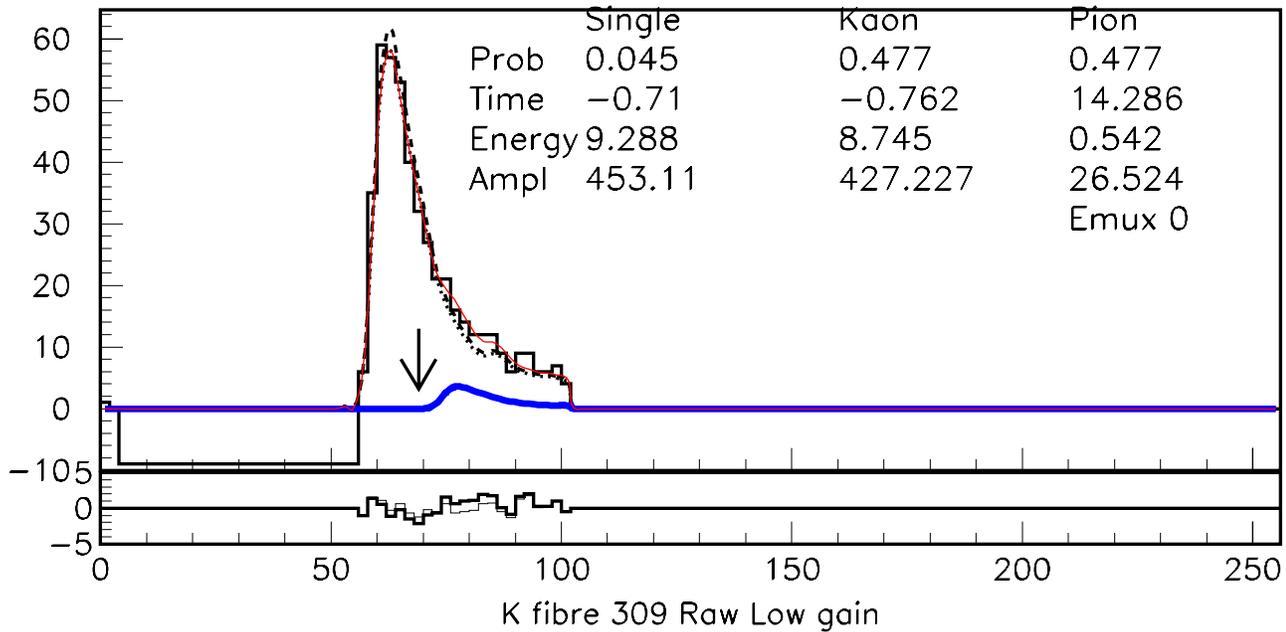
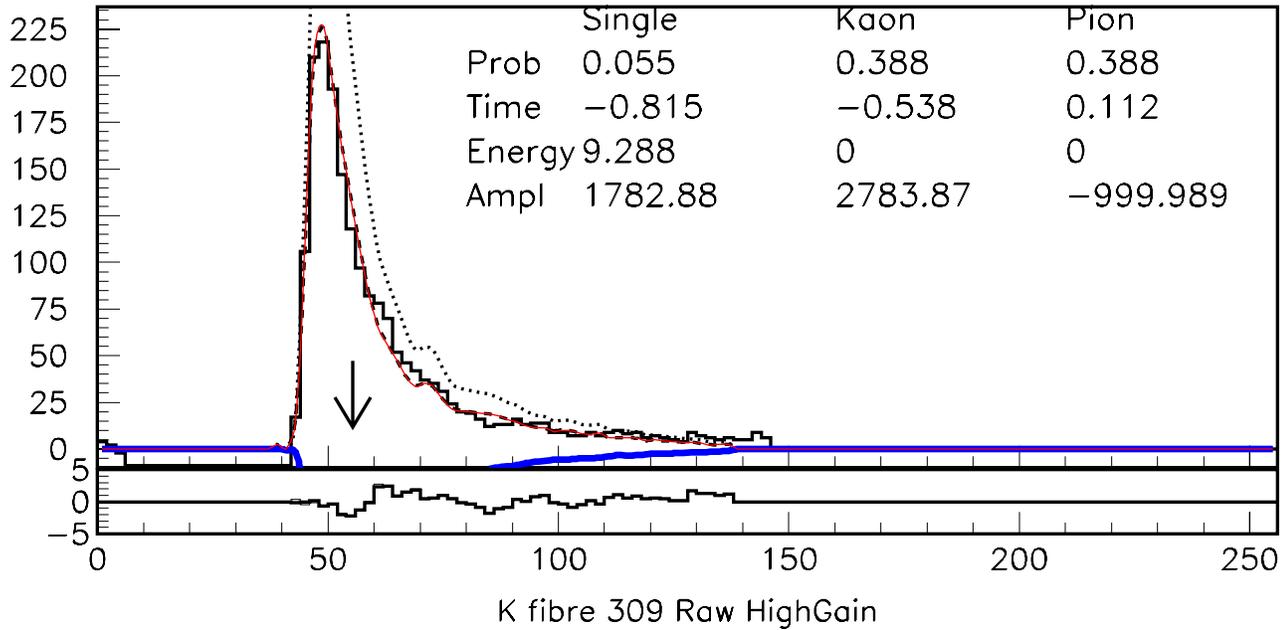
K fibre 285 Raw HighGain



K fibre 285 Raw Low gain

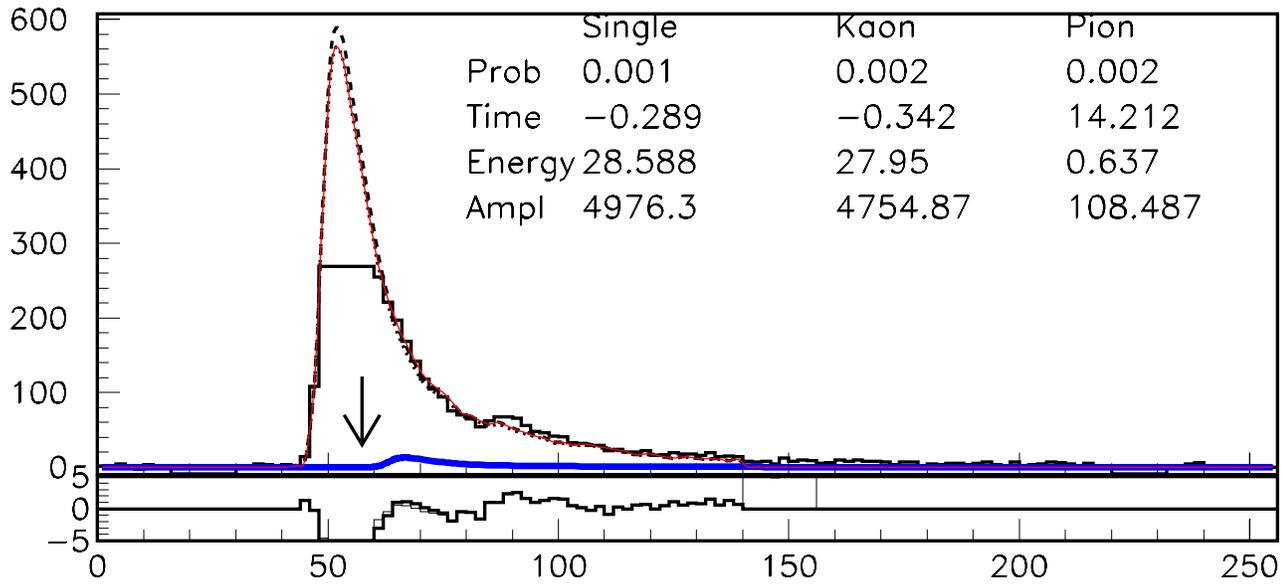
CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

Run 32180 Event 21029 EK 9.286 TK 0.332 TRS 12.746

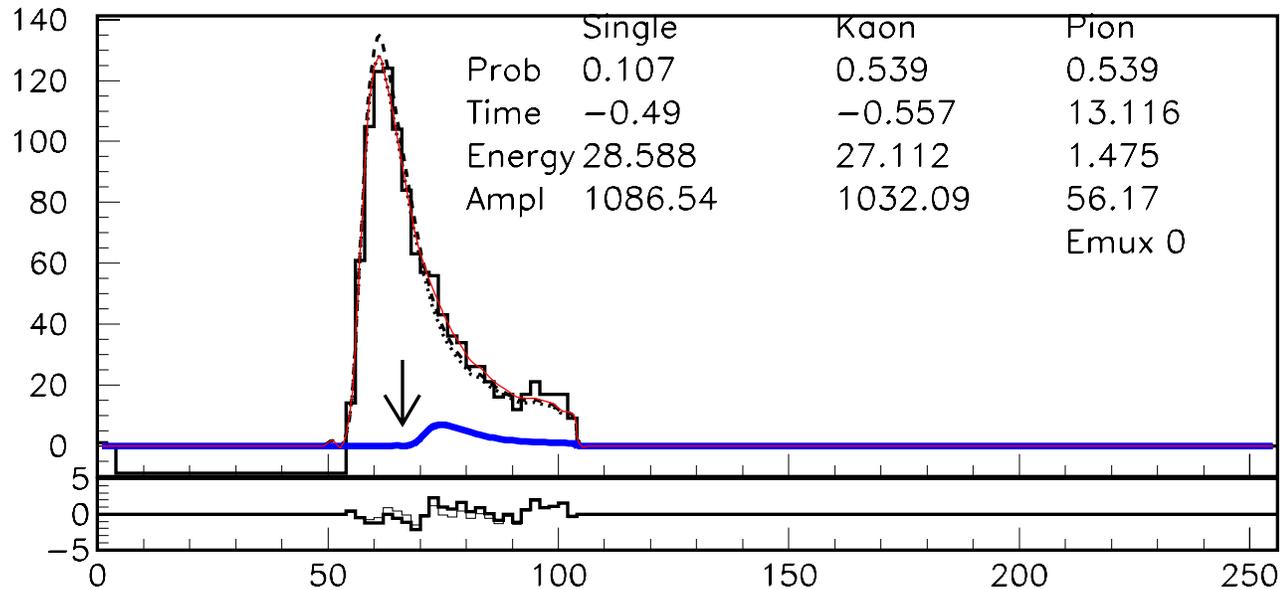


CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029

Run 32180 Event 21029 EK 28.543 TK 1.016 TRS 12.746



K VXfib 286 Raw HighGain



K VXfib 286 Raw Low gain

**Experiment 787**  
**Technical Note No. 374**

**An algorithm to fit pulses in target CCD data**

Milind Diwan, Jim Frank, Vivek Jain

**Abstract**

This technote describes an algorithm for fitting Kaon fiber pulses in the target CCD data. The code, which was originally written to run on PASS3 ntuples, has been adapted to run as part of KOFIA. Both high gain and low gain CCD pulses are fit, and the results are stored in the PASS3 ntuples. A routine, which runs on these ntuples, has been written to choose between high gain and low gain results, depending on the Kaon energy in a given fiber,  $E_K(\text{fiber})$ , and  $(T_\pi - T_K)$ .

The performance of the pulse fitter is studied using a “Monte Carlo”. We have also run the fitter on 1996 Skim5 data. Some preliminary results are presented.

## 1 Introduction

The main background in the PNN2 region is believed to be due to  $K \rightarrow \pi^+ \pi^0$ , where the  $\pi^+$  scatters in the target, loses energy and falls in the kinematic box [1]. One signal for this background can be the presence of a second pulse in a Kaon fiber. It is, therefore, imperative to fit pulses in Kaon fibers and veto events whenever a second pulse, above a given threshold, is found.

We have chosen to use the calibrated pulse shapes (for each fiber) to fit the data rather than the analytical approach used by Joe and Toshio. Results are stored in the PASS3 ntuples and are subsequently used in the PNN2 analysis. We then choose between high gain and low gain results, depending on the Kaon energy in the given fiber,  $E_K(\text{fiber})$ , and  $(T_\pi - T_K)$ .

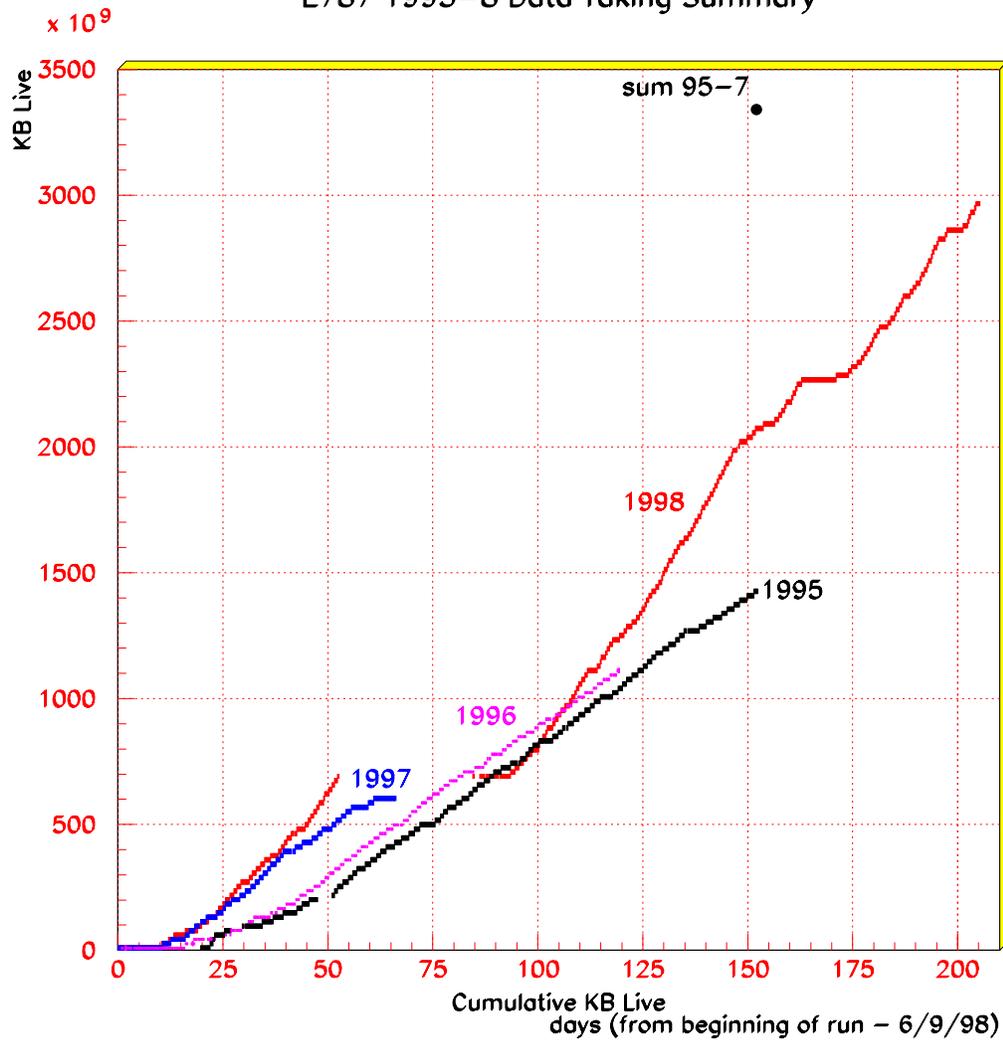
The performance of this fitter has been studied using a “Monte Carlo”. We take pulses in Kaon fibers which have a very good single pulse fits (probability  $\geq 80\%$ ), and add a second pulse, with amplitude varying between 0 and 5 MeV, at different values of  $(T_\pi - T_K)$ . This is done in bins of  $E_K(\text{fiber})$ .

## 2 Fitting algorithm

We first describe the fitting algorithm. The main routines, shpfit2-hg and shpfit2-lg, are called from setup-pass2. Each pulse is fitted with an average pulse shape determined separately for each fiber. Pulse shapes and the error (in each time bin) associated with the shapes are stored in CFM, separately for high gain and low gain.

The pulse shapes were determined as follows. Firstly, all other target CCD calibrations were done (using KM21 monitors). From a set of ntuples, pulses for both high gain and low gain were chosen to be included in the calibration if (a)  $E_K(\text{fiber})$  was greater than 4 MeV, (b) pulse had not overflowed, and (c) the time was within 3 ns of 0. The events also had to have passed a target

## E787 1995–8 Data Taking Summary



- $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  in PNN1 region sensitivities

- '95 :  $4.2 \times 10^{-10}$
- '95-'97 :  $1.5 \times 10^{-10}$
- '95-'98 :  $\sim 0.8 \times 10^{-10}$

- $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  in PNN2 region sensitivities

- Only 96 data analysed so far.
- $1.12 \times 10^{12}$  kaons
- 6M kaons in 1.6 sec at 730 MeV/c (24% pion cont.)
- Known hardware problem in PBG detector.

## PNN2 after pass1

Data reduction cuts ONLINE

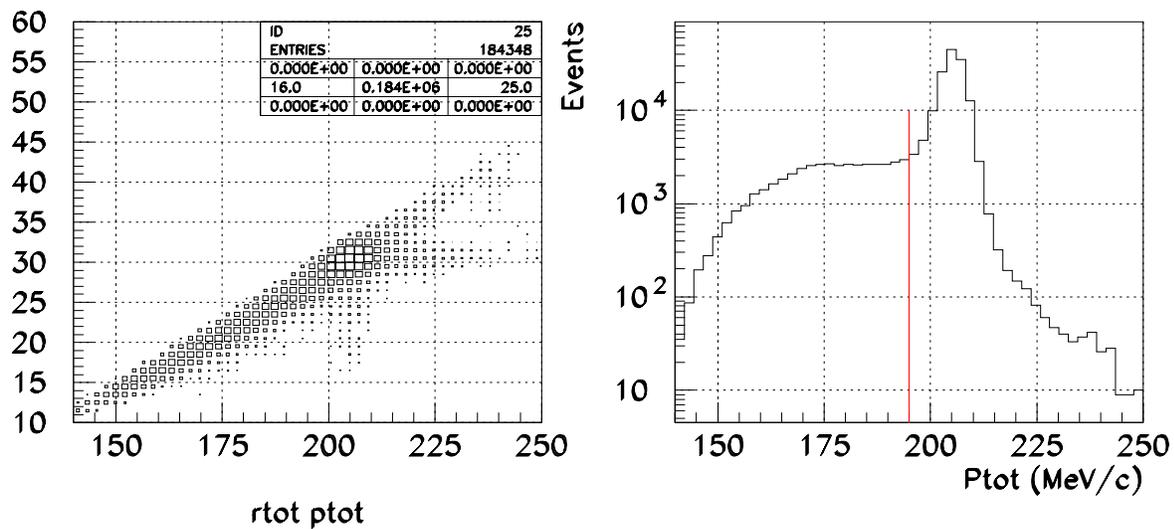
- Require single kaon using Cerenkov.
- Require single charged decay product after 1.5 ns delay.
- Require charged particle to penetrate range stack between layers 6-18.
- Require target and range stack hit pattern consistent with PNN.
- Require  $\pi \rightarrow \mu$  decay using TD/ASIC system.
- Require no photon hit in Barrel and endcap ( $> 20MeV$ ).

Data reduction at PASS1

- Reconstruct kaon, pion, photon hits and calculate range, momentum, energy, and time of all hits.
- Further veto on photons in range stack.
- Reconstruct  $\pi \rightarrow \mu$  decay with detailed fit to pulse shape and make a cut.

Offline signal and background streams.

- KPI2: Cut on range versus momentum to select pions. Cut on beam instrumentation to eliminate scattered beam-particles.
- Muons: Veto on photons to eliminate KPI2.
- Cut on everything except allow extra particles in target.



KPI2 background stream. Plot on left has logarithmic Z-scale.

Blindness: Define 1/3 and 2/3 streams and block out the signal region.

1/3 for tuning cuts

2/3 for measuring background

Open signal region after defining all cuts.

Signal region

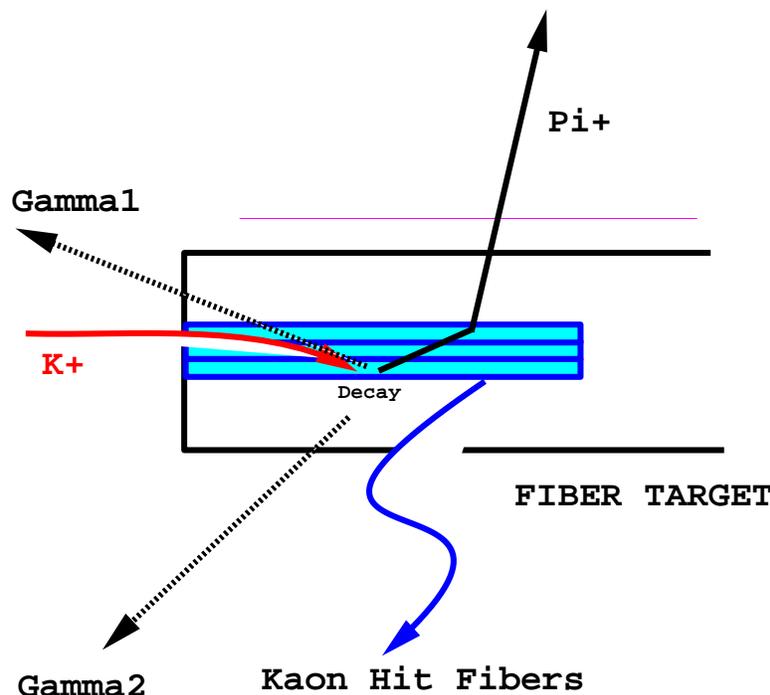
$$140 < PTOT < 195$$

$$12 < RTOT < 27$$

$$60 < ETOT < 95$$

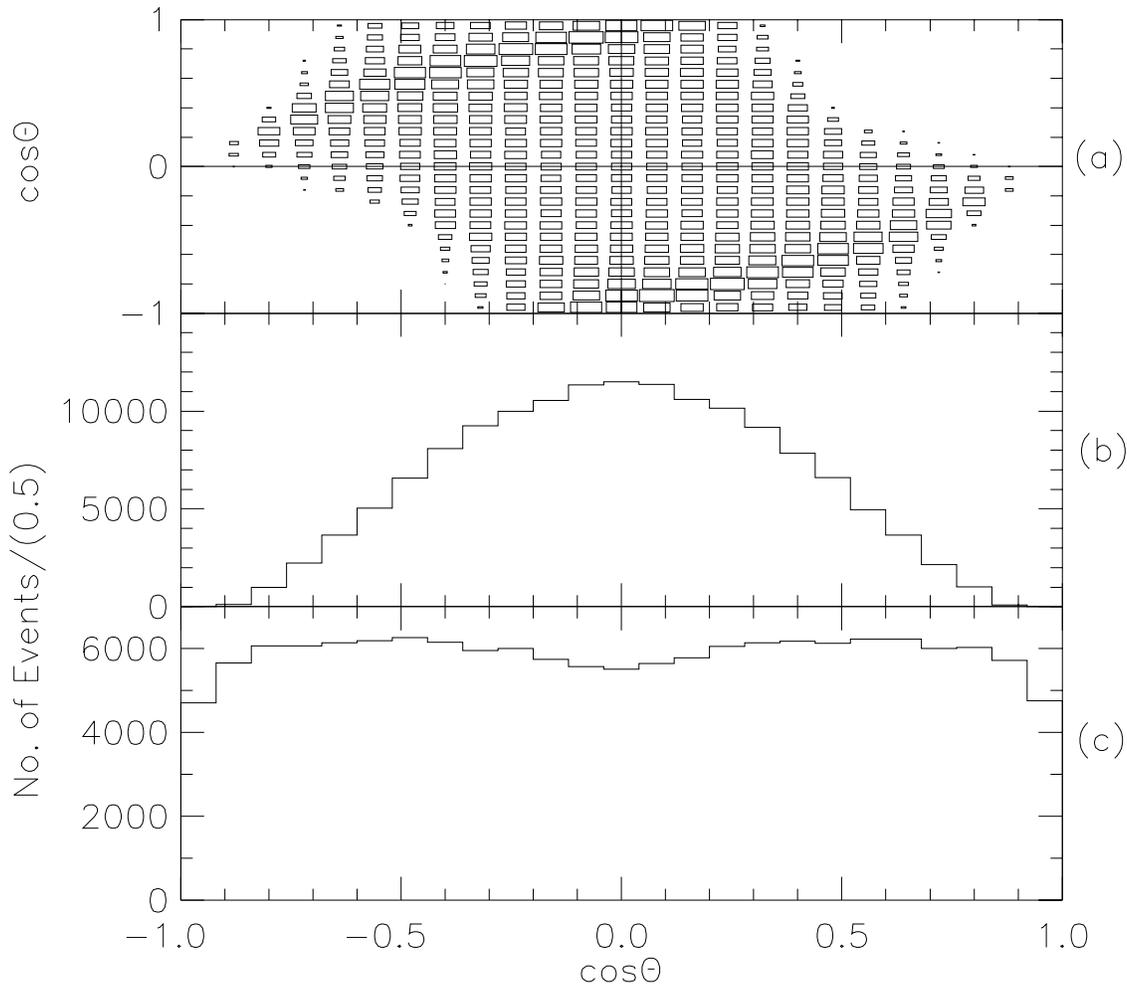
# PNN2 data analysis

- Good news: Much larger phase space acceptance below Kpi2 peak.
- Bad news: Huge background from  $K^+ \rightarrow \pi^+\pi^0$  in which  $\pi^+$  undergoes interaction in the scintillator fiber target.
- Not possible to simulate all details of the main background. Must be measured from data using two independent cuts and blind analysis techniques.
- After reconstruction of pion and kaon, make fits to all CCD pulses for kaon fibers.
- Find second pulses at pion time overlapping kaon fibers. Cut at 1 MeV threshold.
- Measure rejection of CCD cut by using events tagged by photons.
- Measure Photon veto rejection by using events tagged by CCD second pulses as well as kinks in the track.

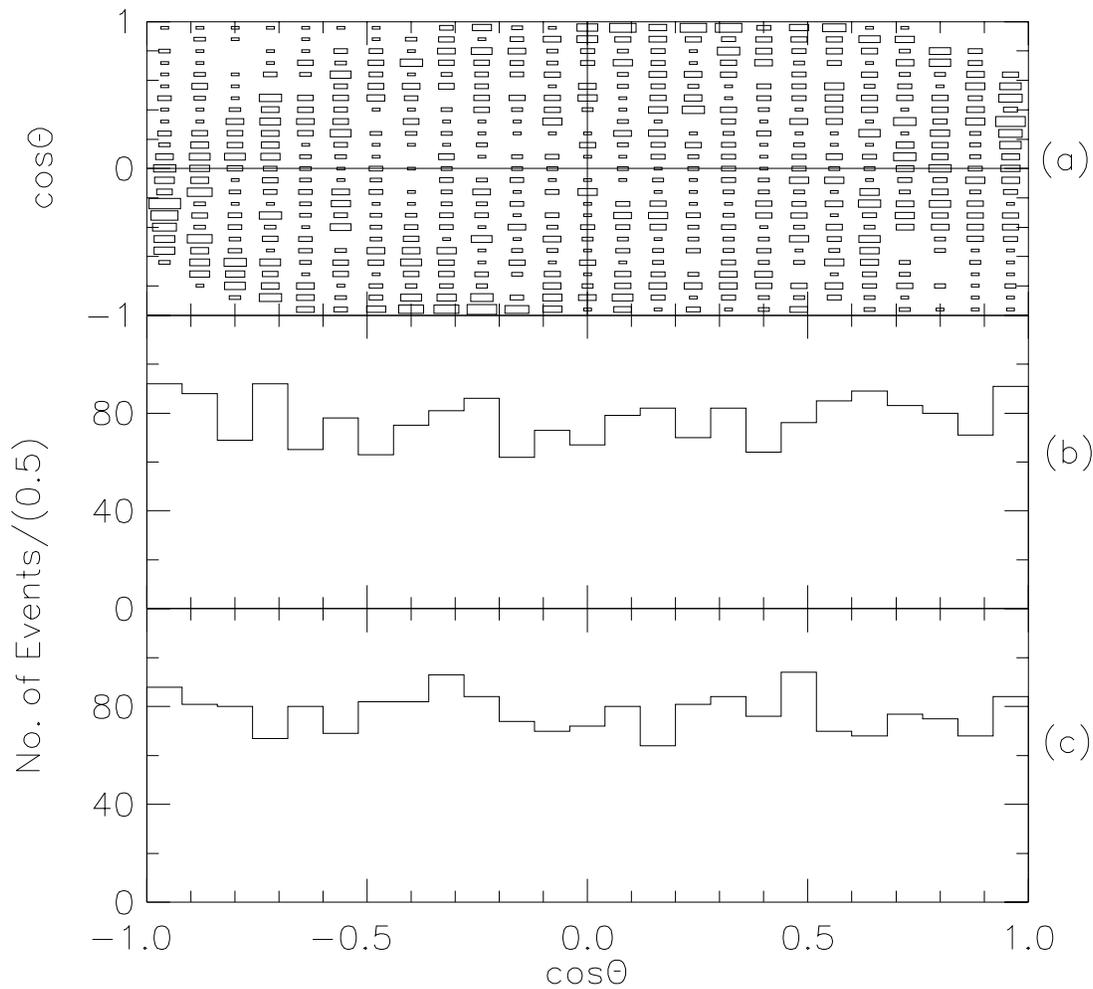


## PNN2 background picture

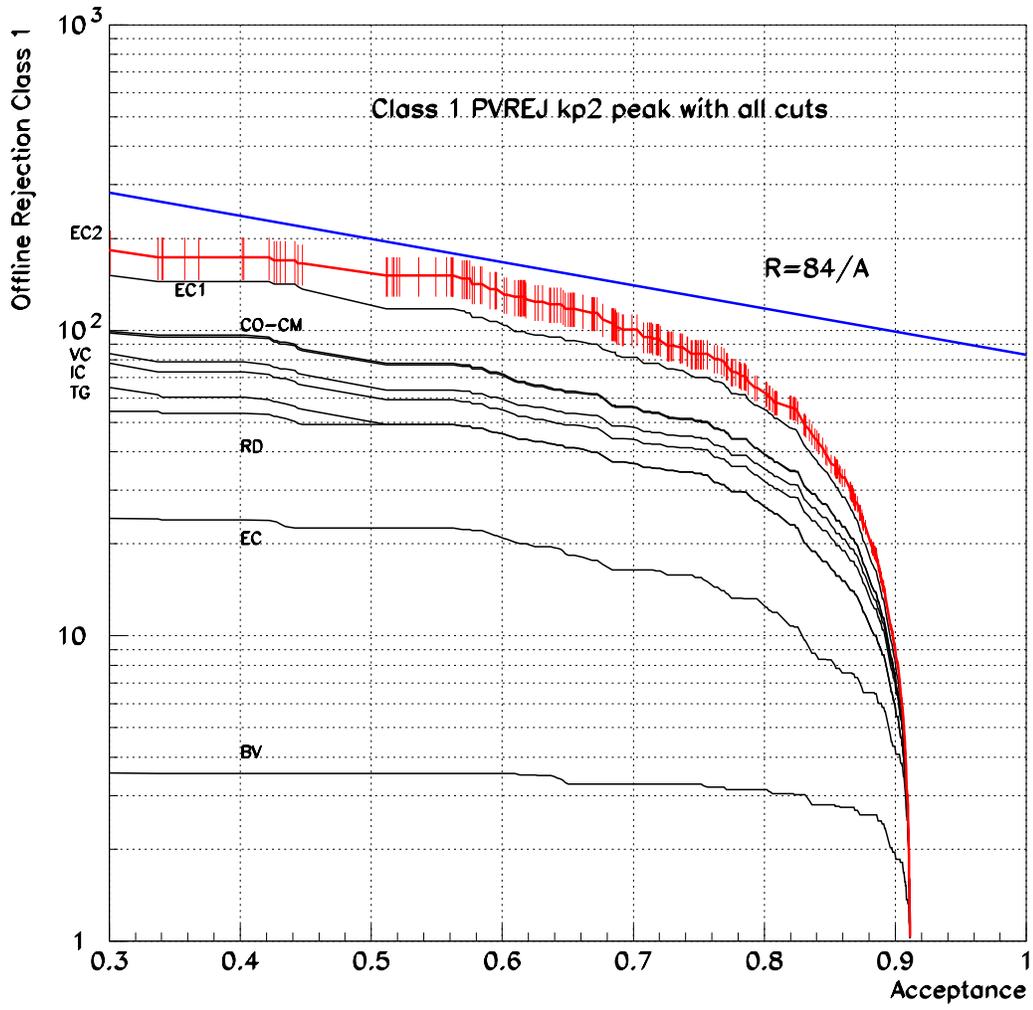
- Need to confirm the background model.  
Scanned many samples of events  
Changed selection criteria to study background  
Monte Carlo of  $K^+ \rightarrow \pi^+ \pi^0$  scattering.
- Special problem: Final few events remaining in the background sample may have contamination from  $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$  or other reactions.



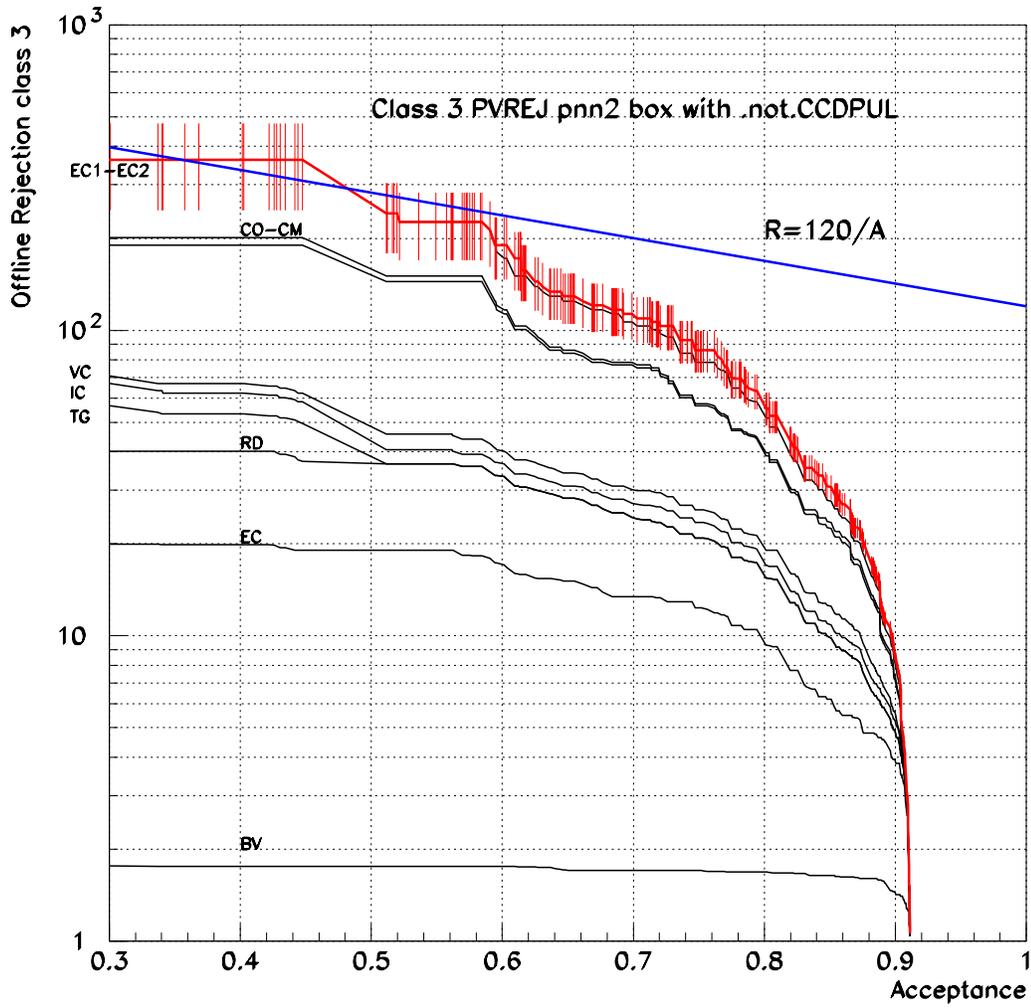
Monte Carlo simulation.  $\theta$  is the angle of a photon from  $K^+ \rightarrow \pi^+ \pi^0$  decay. Angle of the smaller energy photon versus the larger energy photon is plotted for events in which the  $\pi^+$  was accepted in the E787 geometry. The  $\pi^+$  momentum is in the 205 MeV/c peak.



Monte Carlo simulation.  $\theta$  is the angle of a photon from  $K^+ \rightarrow \pi^+\pi^0$  decay. Angle of the smaller energy photon versus the larger energy photon is plotted for events in which the  $\pi^+$  was accepted in the E787 geometry. The  $\pi^+$  momentum is below 195 MeV/c because of scattering.



OFFLINE photon veto rejection on KPI2 peak data.



OFFLINE photon veto rejection on data in PNN2 box (below KPI2 peak) that has failed the CCD cut.

## Total photon veto rejection

Type	HEX $R_{HEX}$	BV-EC-RDP1 $R_{BEP}$	Offline $R_{OFF}$	Total $\times 10^5$ $R_{PV}$
KPI2BOX	$2.62 \pm 0.04$	$13000 \pm 156$	$147 \pm 21$	$50.1 \pm 7.0$
PNN2BOX	$1.66 \pm 0.15$	$942 \pm 29$	$241 \pm 62$	$3.77 \pm 1.10$

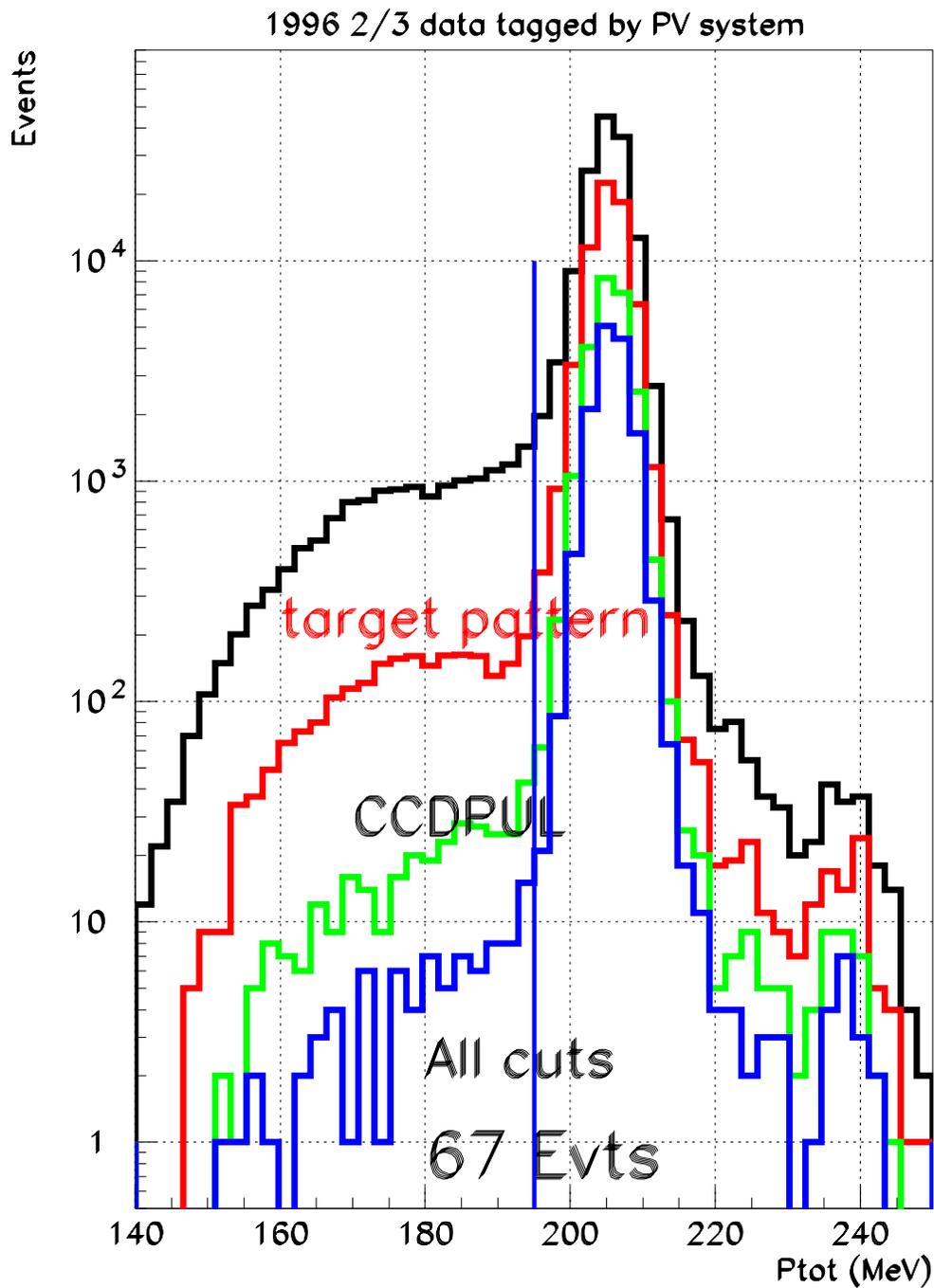
The online and offline photon veto rejections for KPI2 peak and PNN2 box type events.

### Important cuts

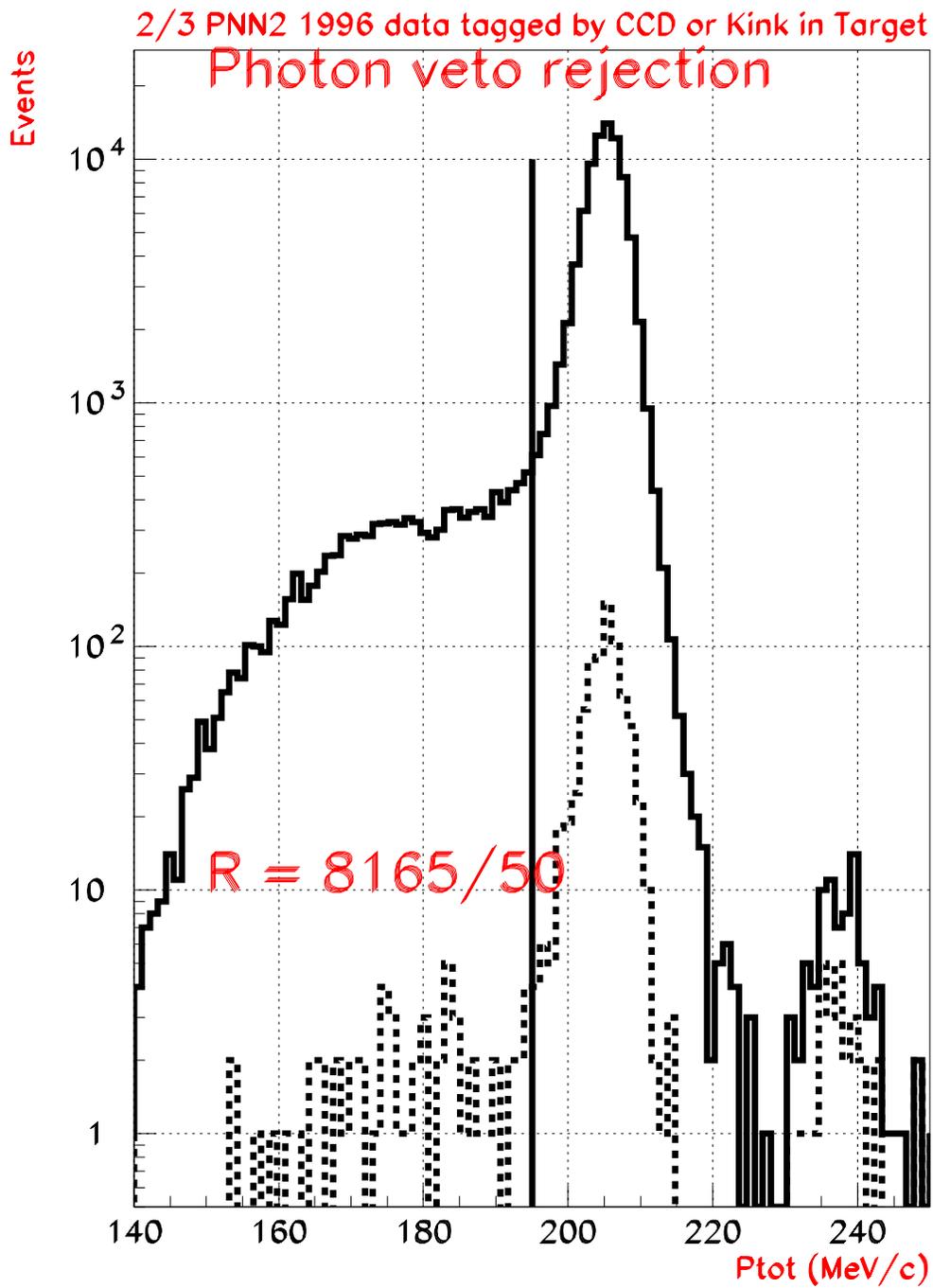
- Charged track kinematics consistent with pion mass.
- Photon veto.
- Track fitting in the fiber-target. No kinks. Pion points back to kaon vertex fiber.
- CCD pion-time energy less than 1 MeV.
- Kaon decay time  $> 6ns$ .
- No extra particles in the fiber-target.
- No extra particles entering along with the kaon.

# PNN2 Kpi2 background

z1/08/09 11.48



$N = 67$



$$Rej(\bar{\gamma}) = 163 \pm 23$$

$$N_{b.g.} = 1.5 \times N_{Kin.}/R_{\bar{\gamma}} = 0.62$$

# PNN2 Final Background Estimate

Table of Backgrounds for PNN2 data

Background	1/3	2/3
KPI2-sct-in-target	$0.35 \pm 0.12$	$0.62 \pm 0.17$
RS-KPI2-sct-in-target	$0.004 \pm 0.004$	$0.007 \pm 0.006$
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	$0.021 \pm 0.004$	$0.027 \pm 0.004$
$K^+ \rightarrow \mu^+ \nu \gamma$	$0.011 \pm 0.011$	$0.007 \pm 0.007$
1-beam	$0.0009 \pm 0.0009$	$0.0003 \pm 0.0003$
2-beam	$0.056 \pm 0.056$	$0.033 \pm 0.033$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.051 \pm 0.062$	$0.026 \pm 0.032$
Charge Xng	$0.011 \pm 0.011$	$0.011 \pm 0.011$
Total	$0.506 \pm 0.147$	$0.731 \pm 0.177$

Total background estimates from the 1/3 and 2/3 1996 analysis. The background estimate in both columns are for the entire 1996 data set. Explicitly, the 1/3 data set has already been corrected by factor of 3 and the 2/3 column has been corrected by factor of 1.5.

3 events in the background region just outside the signal. All of them consistent with background estimate.

1 event at 4.2 ns kaon decay time consistent with background estimate of  $0.45 \pm 0.14$  in the 2-6 ns region.

# Total photon veto rejection

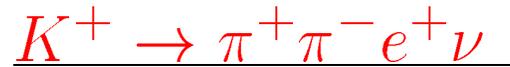
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Type	HEX $R_{HEX}$	BV-EC-RDP1 $R_{BEP}$	Offline $R_{OFF}$	Total $\times 10^5$ $R_{PV}$
KPI2BOX	$2.62 \pm 0.04$	$13000 \pm 156$	$147 \pm 21$	$50.1 \pm 7.0$
PNN2BOX	$1.66 \pm 0.15$	$942 \pm 29$	$241 \pm 62$	$3.77 \pm 1.10$

The online and offline photon veto rejections for KPI2 peak and PNN2 box type events.

## Important cuts

- Charged track kinematics consistent with pion mass.
- Photon veto.
- Track fitting in the fiber-target. No kinks. Pion points back to kaon vertex fiber.
- CCD pion-time energy less than 1 MeV.
- Kaon decay time  $> 6ns$ .
- No extra particles in the fiber-target.
- No extra particles entering along with the kaon.



Key steps in background determination

- Branching ratio:  $4 \times 10^{-5}$ .

No photons.

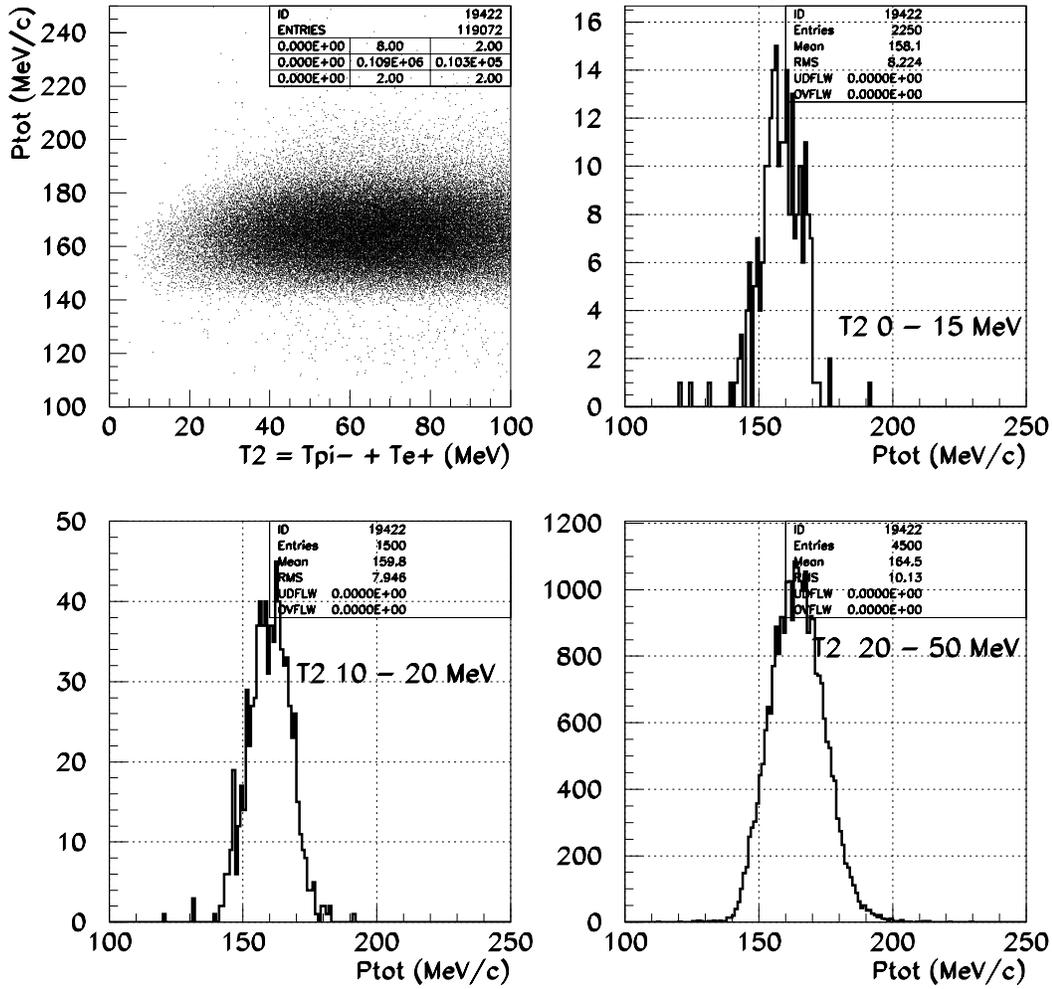
$\pi^-$  can disappear by absorption.

$e^+$  can disappear by annihilation.

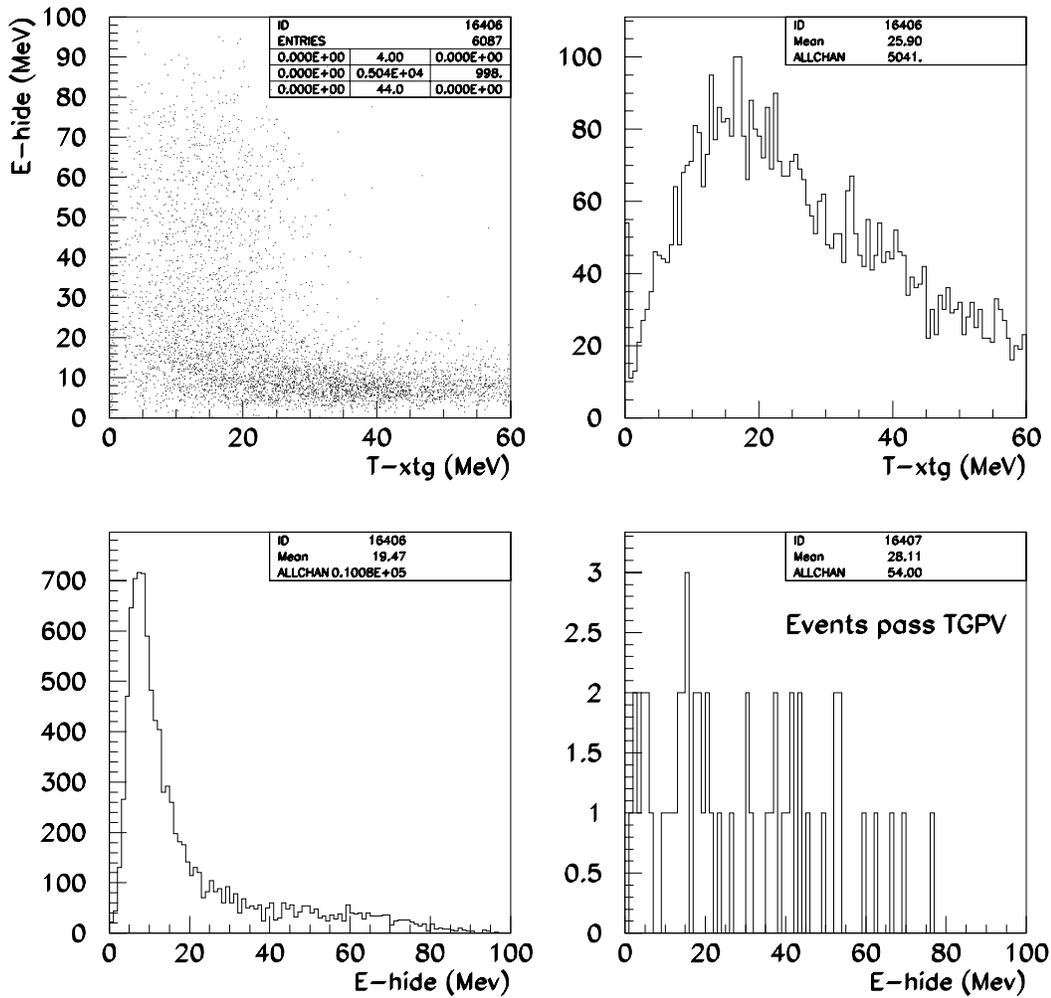
$\pi^+$  momentum falls in the range of 150 to 190 MeV.

- Identify events in the data.
- Determine effect of CCD cut and target veto cuts.
- Use Monte Carlo and data to estimate background and error.
- Luck factor: no phase space for decay as kinetic energy for  $\pi^-$  and  $e^+$  goes to 0.

Monte Carlo Ke4 Kinematic cuts only



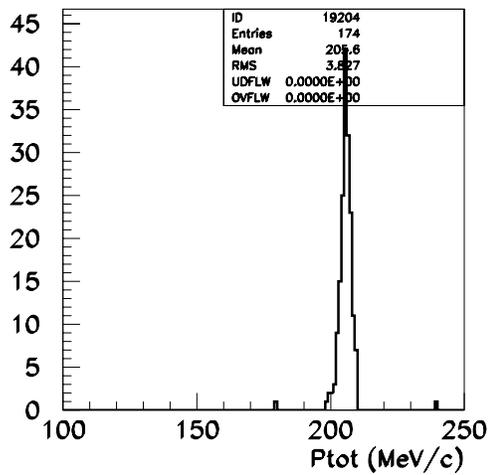
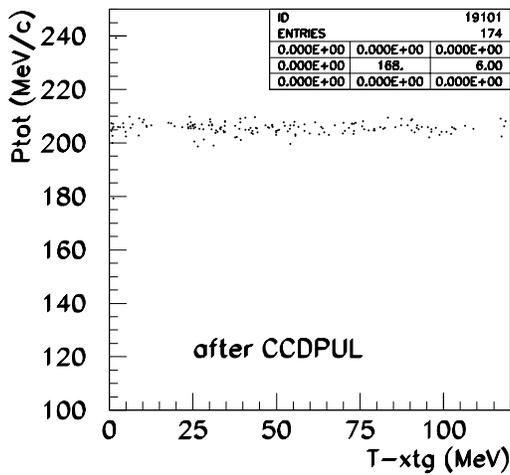
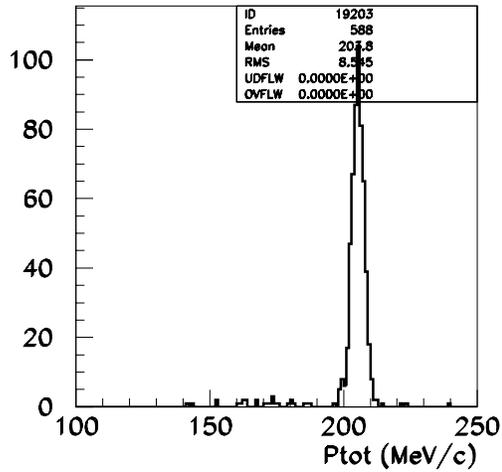
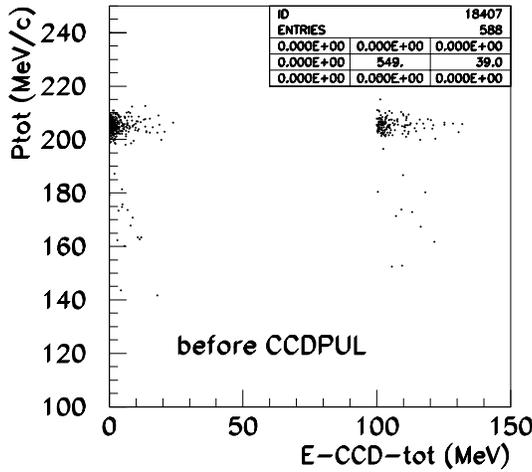
Monte Carlo of  $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ . Reconstructed momentum of  $\pi^+$  versus the kinetic energy of  $\pi^-$  and  $e^+$ .



Monte Carlo of  $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ . This plot with simulation of  $\pi^-$  absorption and  $e^+$  annihilation.  $T - xtg$  is the extra energy deposited in the target by  $\pi^-$  or  $e^+$ .  $E - hide$  is the extra energy at  $\pi^+$ -time hidden under the kaon. In real data it is found by the CCDs.

Signal cut is a  $1 \text{ MeV} \times 1 \text{ MeV}$  box. Based on this plot we estimate the rejection of cutting on  $T - xtg$  to be  $58 \pm 41$  for this background.

reverse TGPVCUT

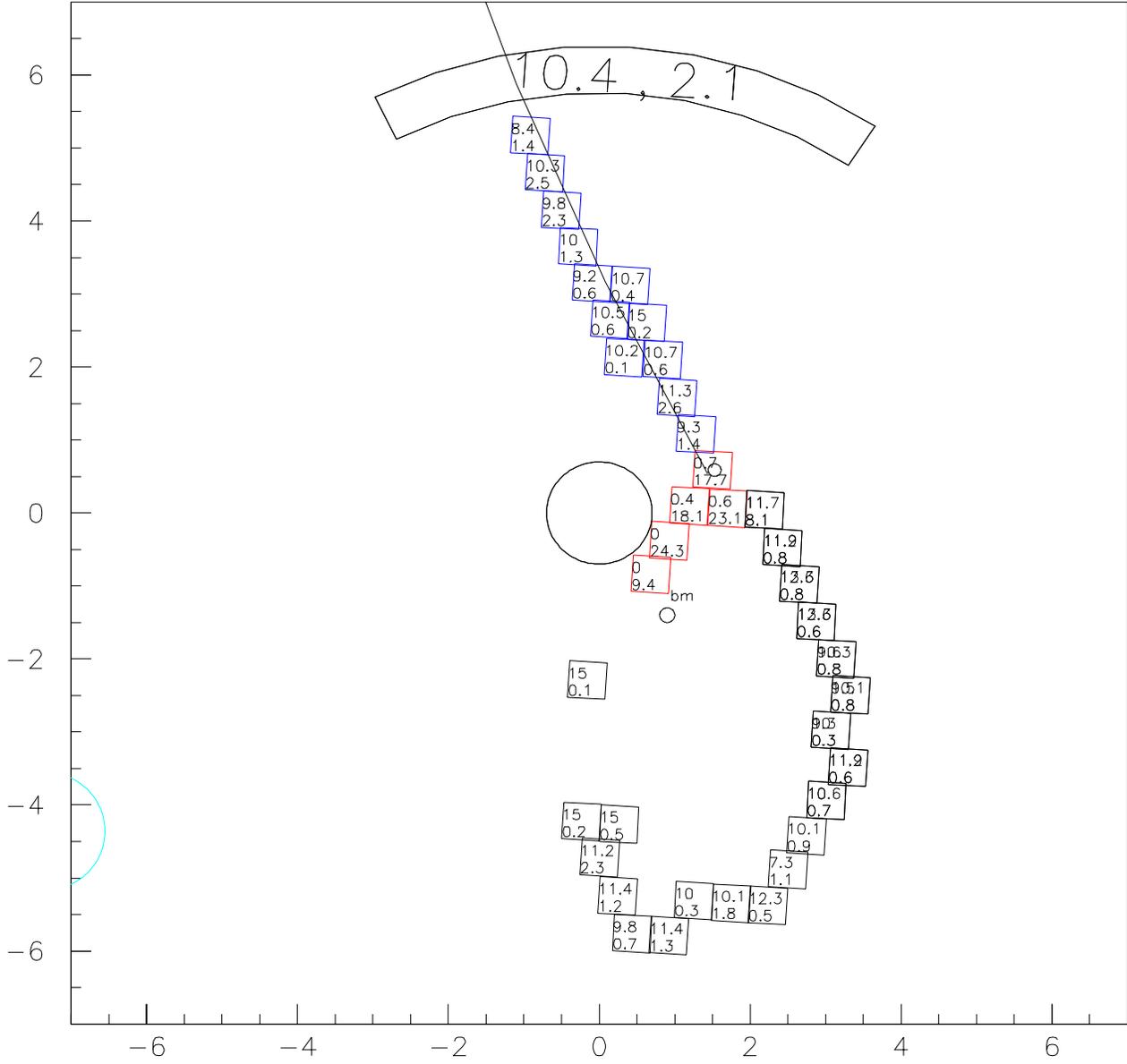


2/3 ke4 background stream data. With  $T - xt_g > 1MeV$ . 31 events fail both  $T - xt_g$  and CCD cut. 1 Event left after all cuts.

Background estimate:  $1.5 \times \frac{1.0}{58 \pm 41}$

Estimate double checked with other methods. Background small so does not contaminate other estimates !

RUN 30533 Event 151236



# PNN2 Final Background Estimate

Table of Backgrounds for PNN2 data

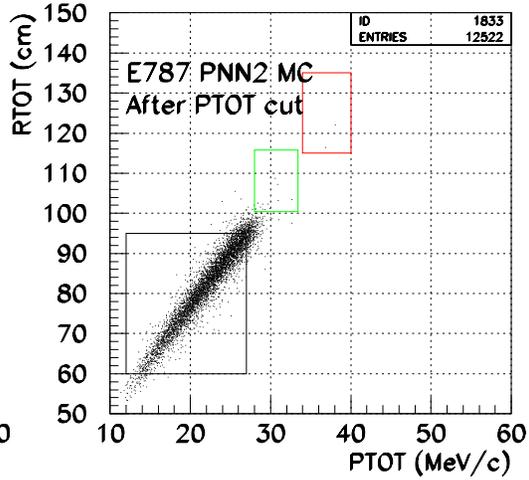
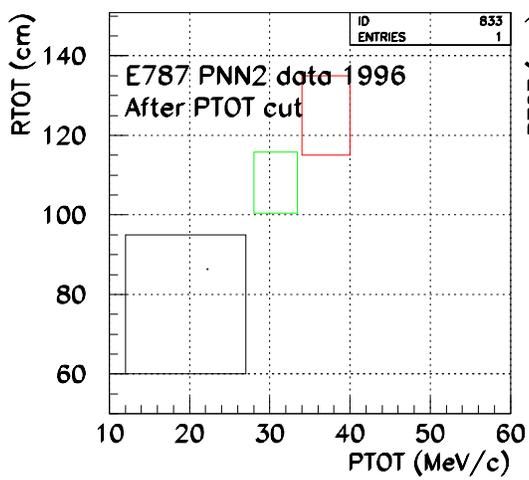
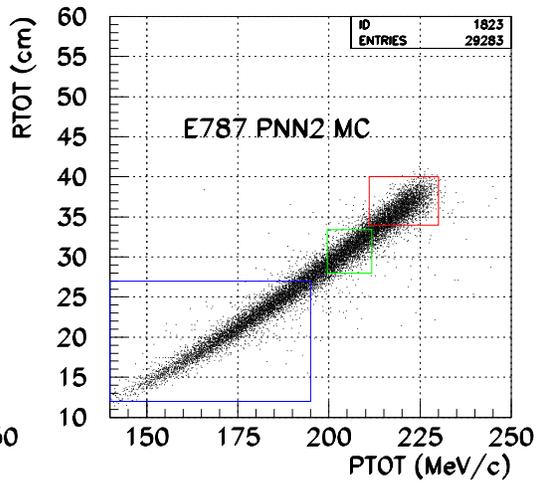
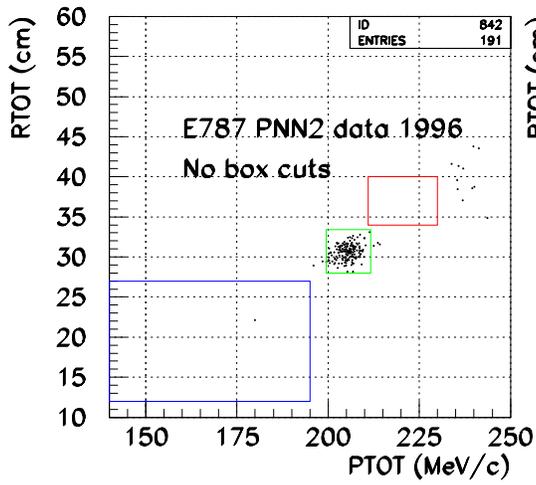
Background	1/3	2/3
KPI2-sct-in-target	$0.35 \pm 0.12$	$0.62 \pm 0.17$
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1-beam	$0.0009 \pm 0.0009$	$0.0003 \pm 0.0003$
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$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.051 \pm 0.062$	$0.026 \pm 0.032$
Charge Xng	$0.011 \pm 0.011$	$0.011 \pm 0.011$
Total	$0.506 \pm 0.147$	$0.731 \pm 0.177$

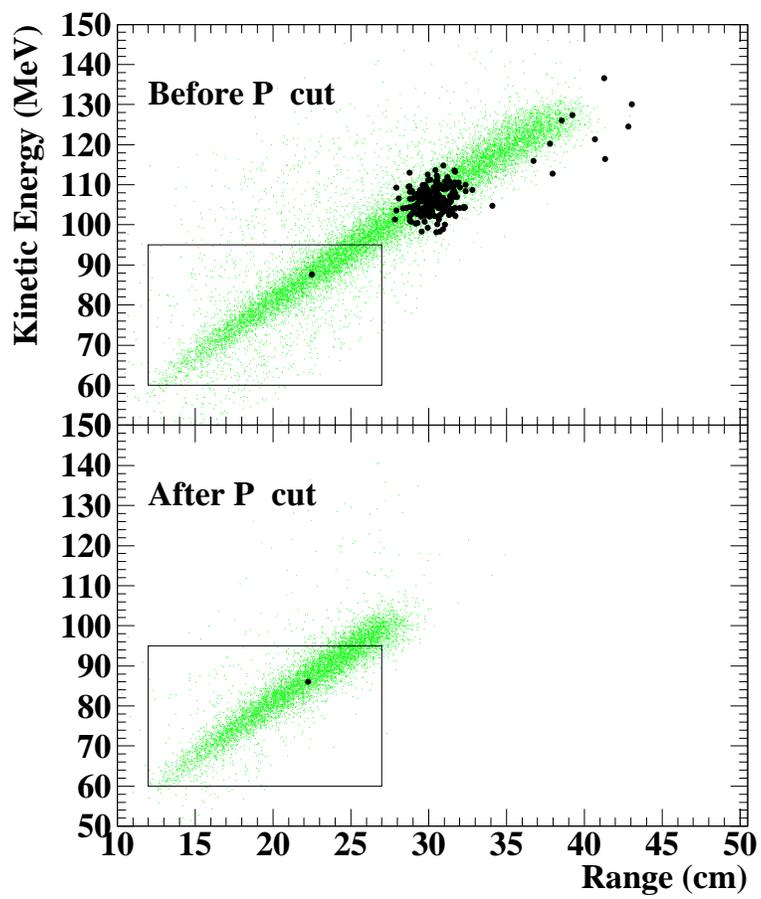
Total background estimates from the 1/3 and 2/3 1996 analysis. The background estimate in both columns are for the entire 1996 data set. Explicitly, the 1/3 data set has already been corrected by factor of 3 and the 2/3 column has been corrected by factor of 1.5.

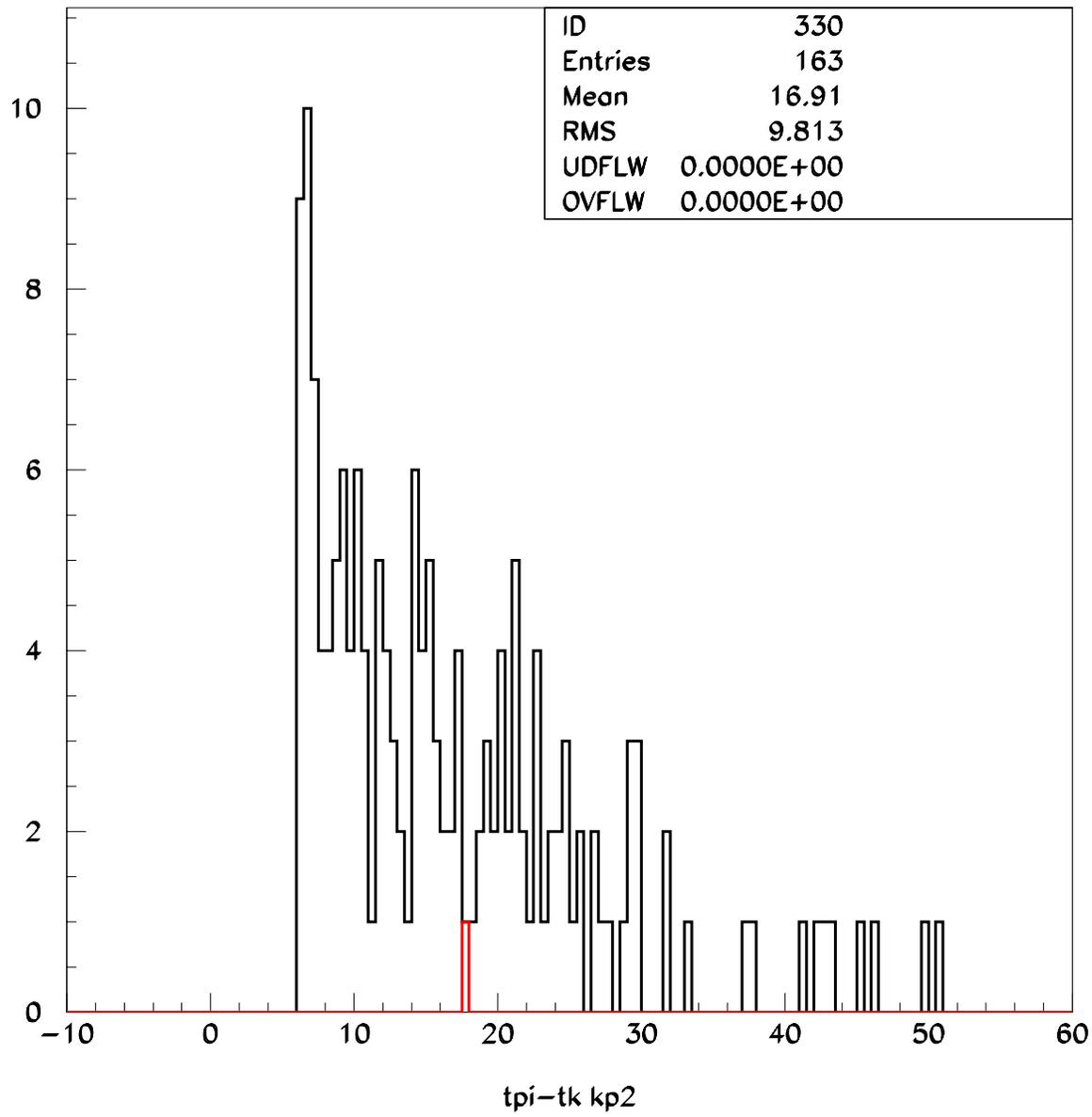
3 events in the background region just outside the signal. All of them consistent with background estimate.

1 event at 4.2 ns kaon decay time consistent with background estimate of  $0.45 \pm 0.14$  in the 2-6 ns region.

# Distribution in Signal box

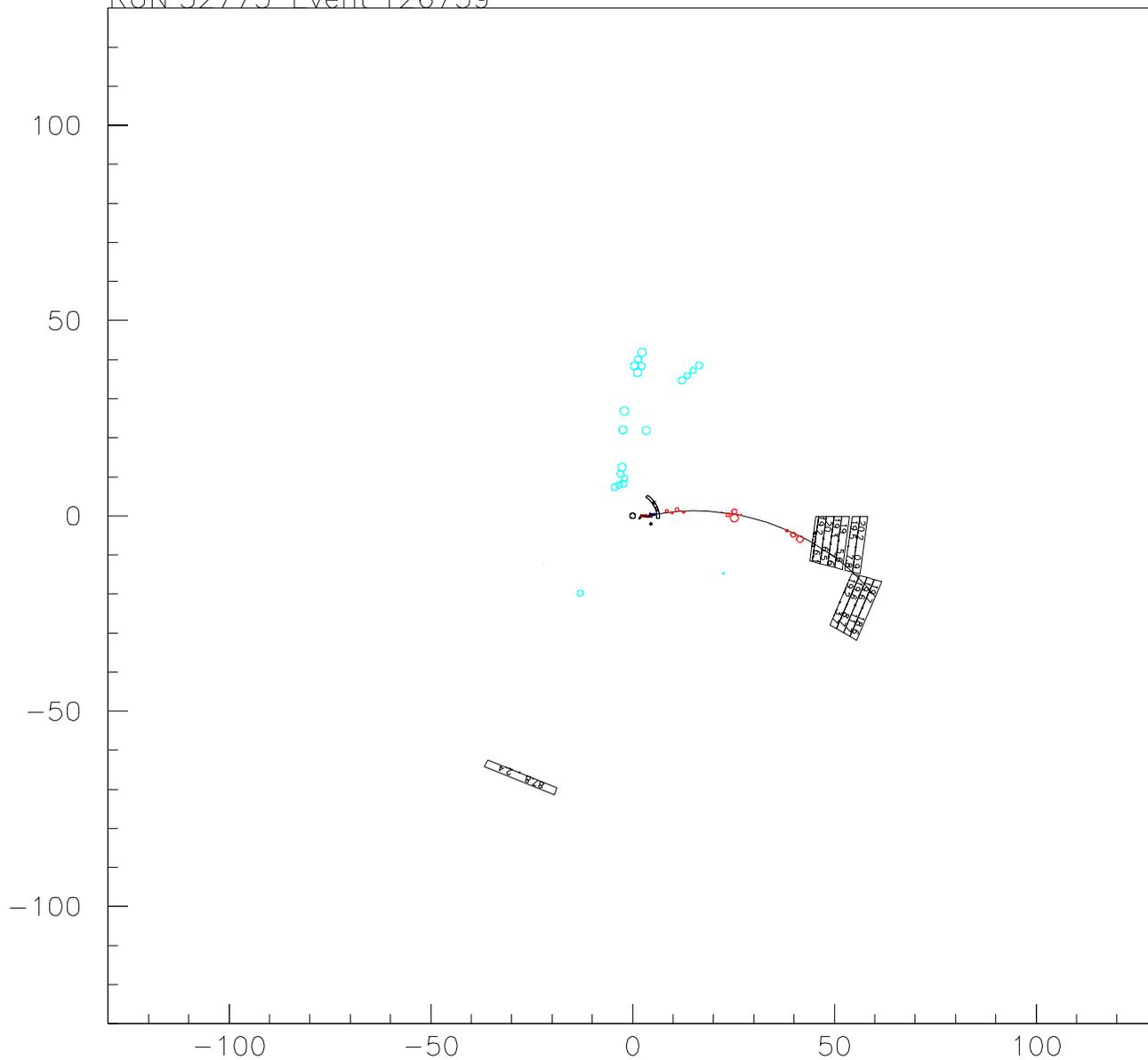






# m.88 627 InTheBox

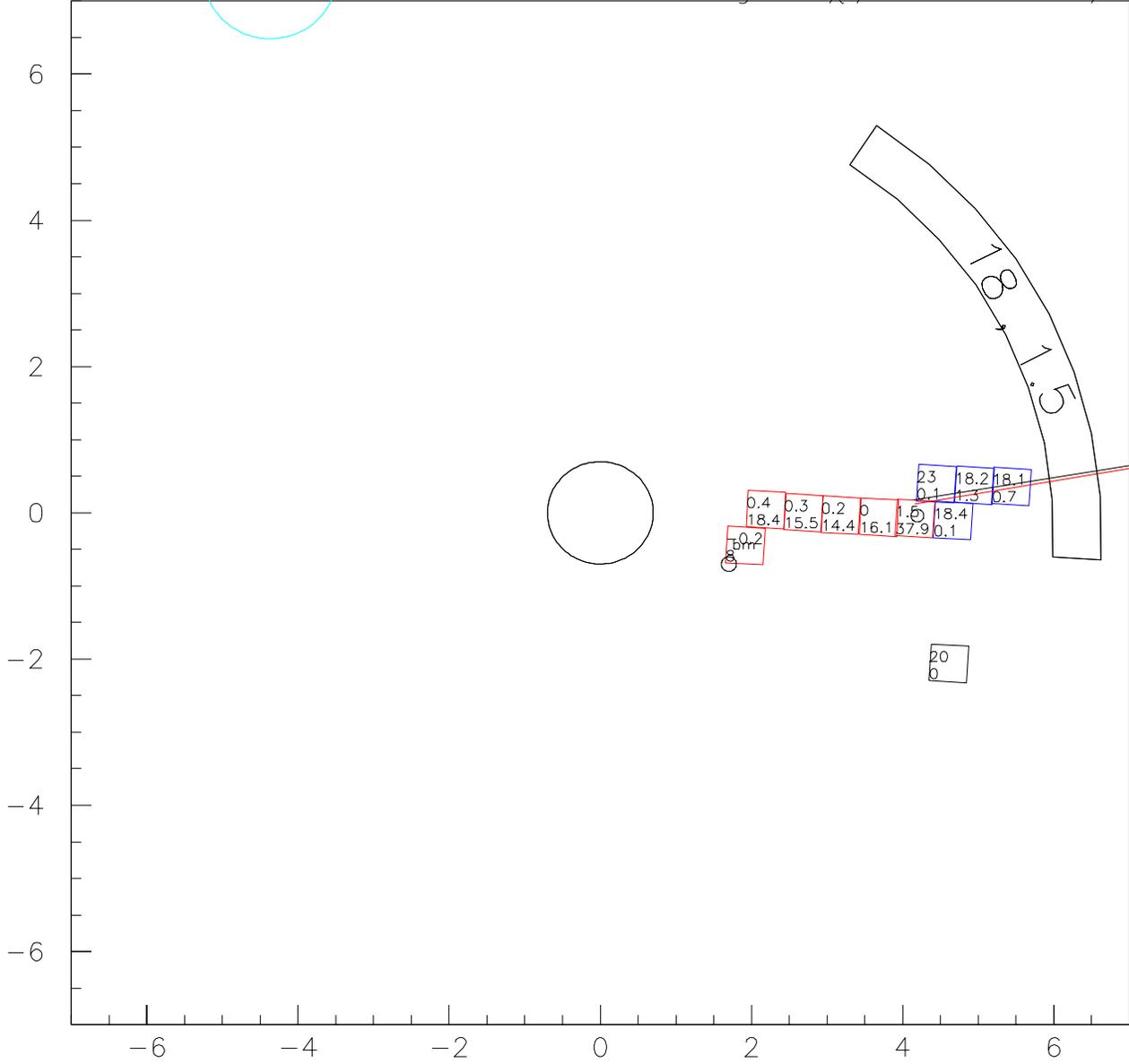
RUN 32775 Event 126739



# m.88 627 InTheBox

RUN 32775 Event 126739

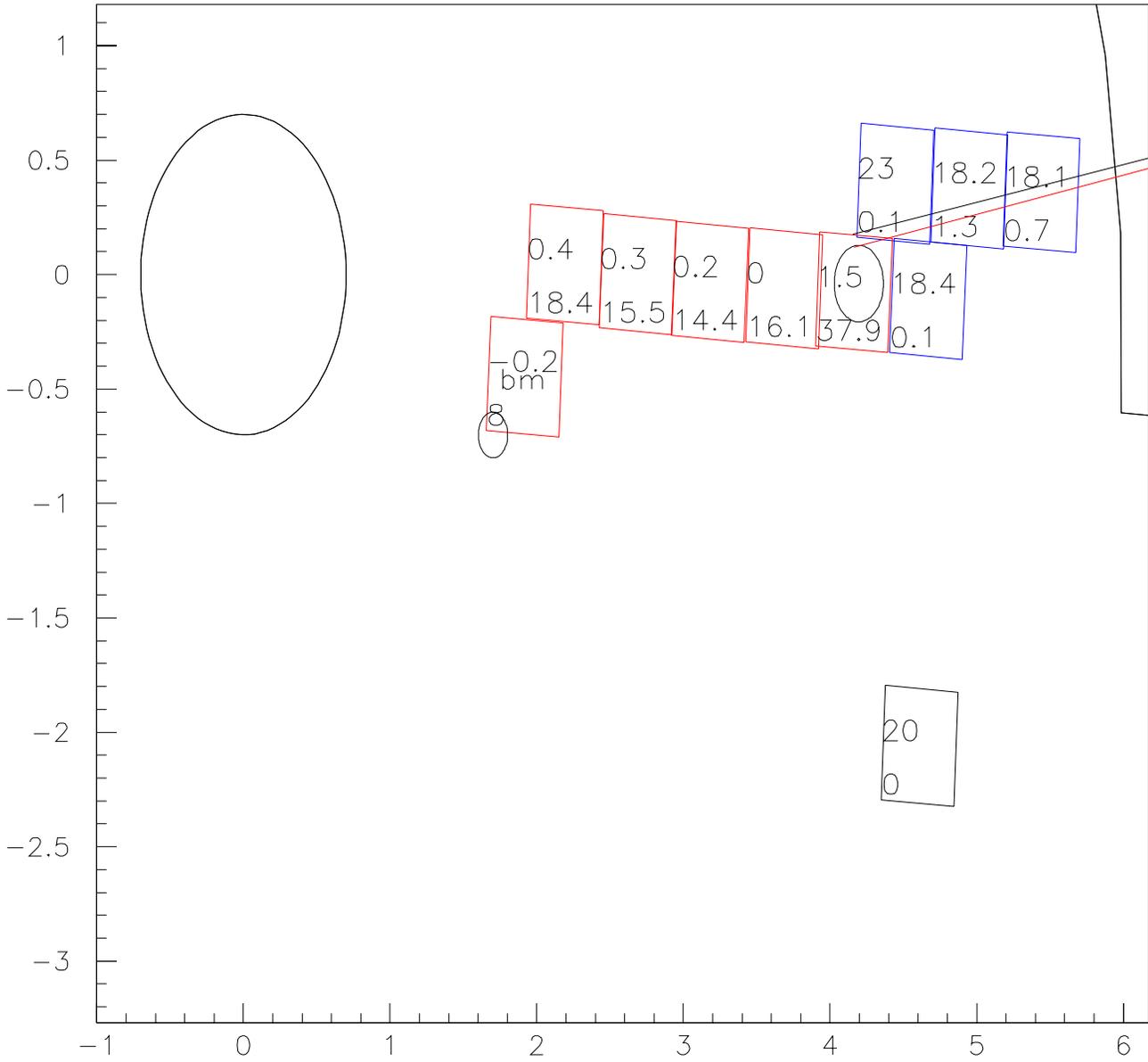
Target fit  $\chi^2/\text{ndf} = 4.52679/4$



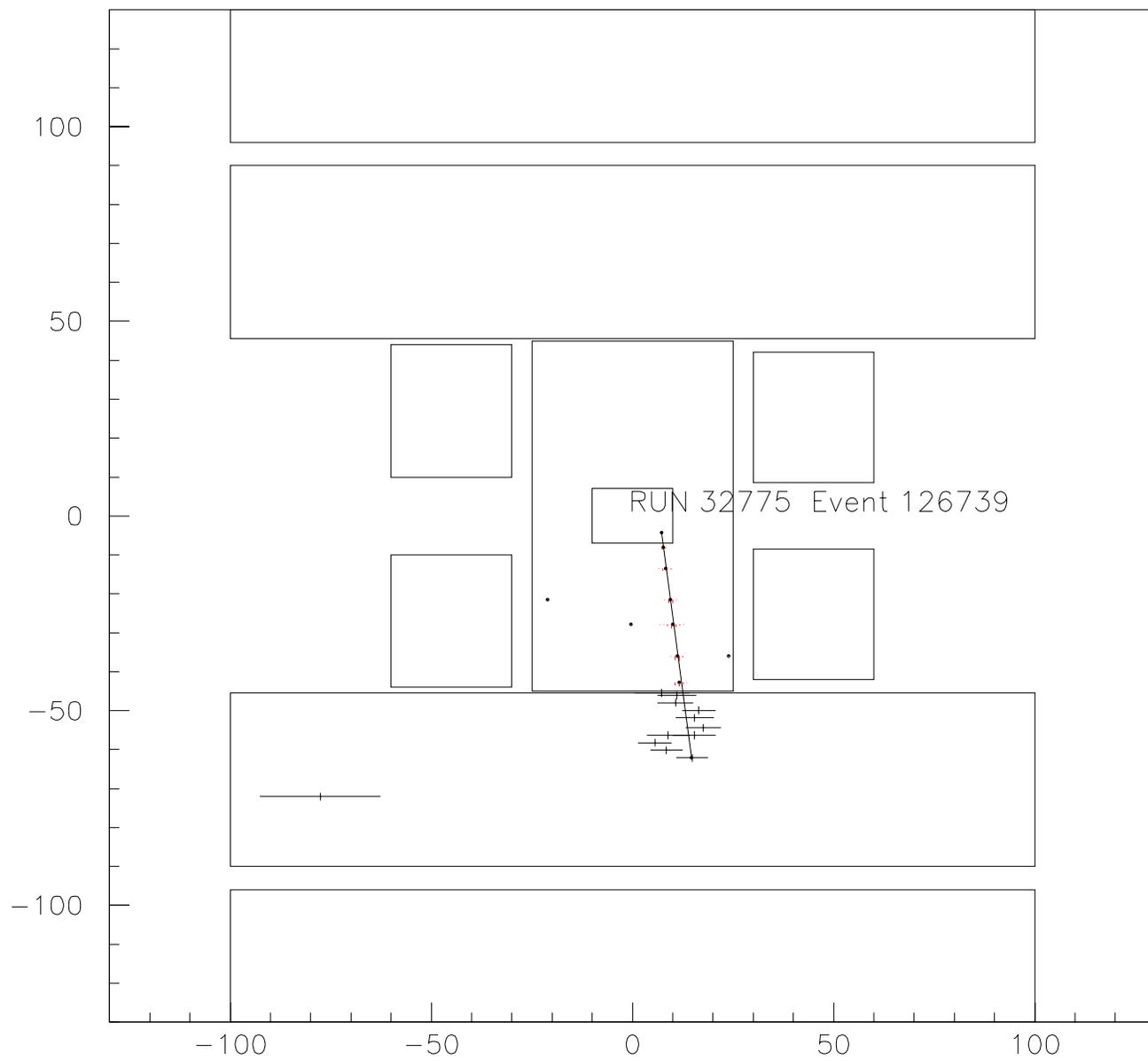
# m.88 627 InTheBox

RUN 32775 Event 126739

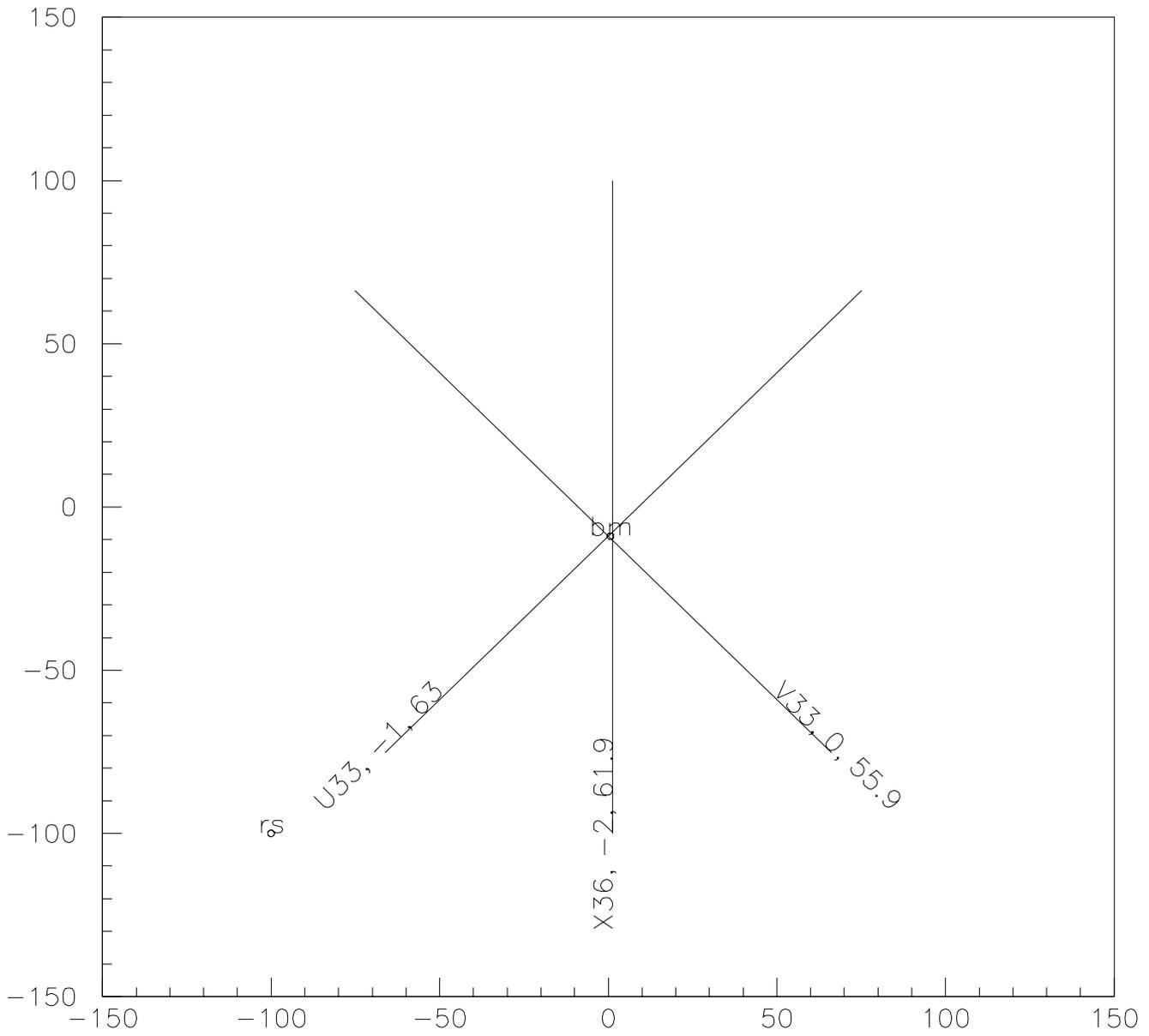
Target fit  $\chi^2/\text{ndf} = 4.52679/4$



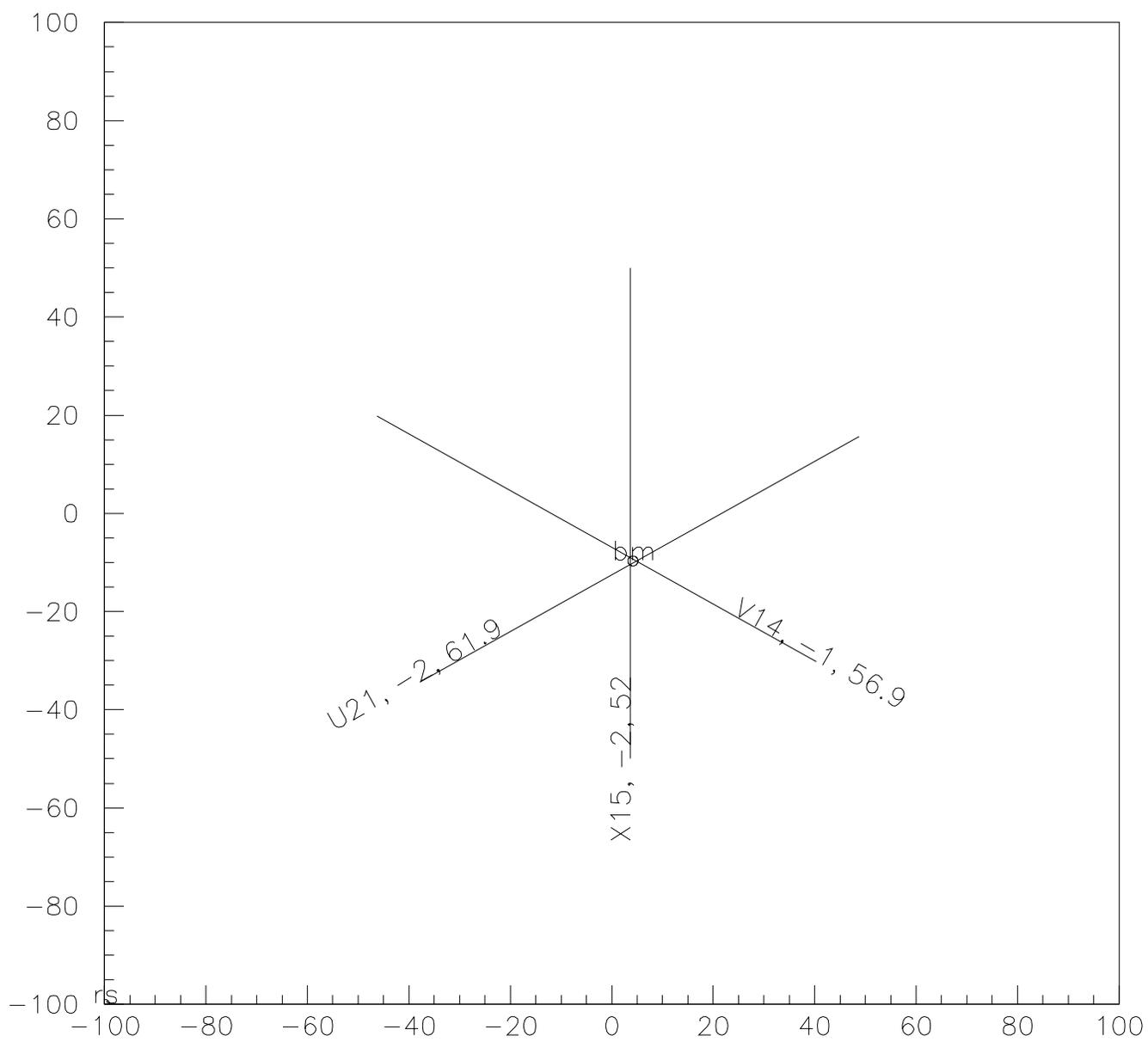
# m.88 627 InTheBox



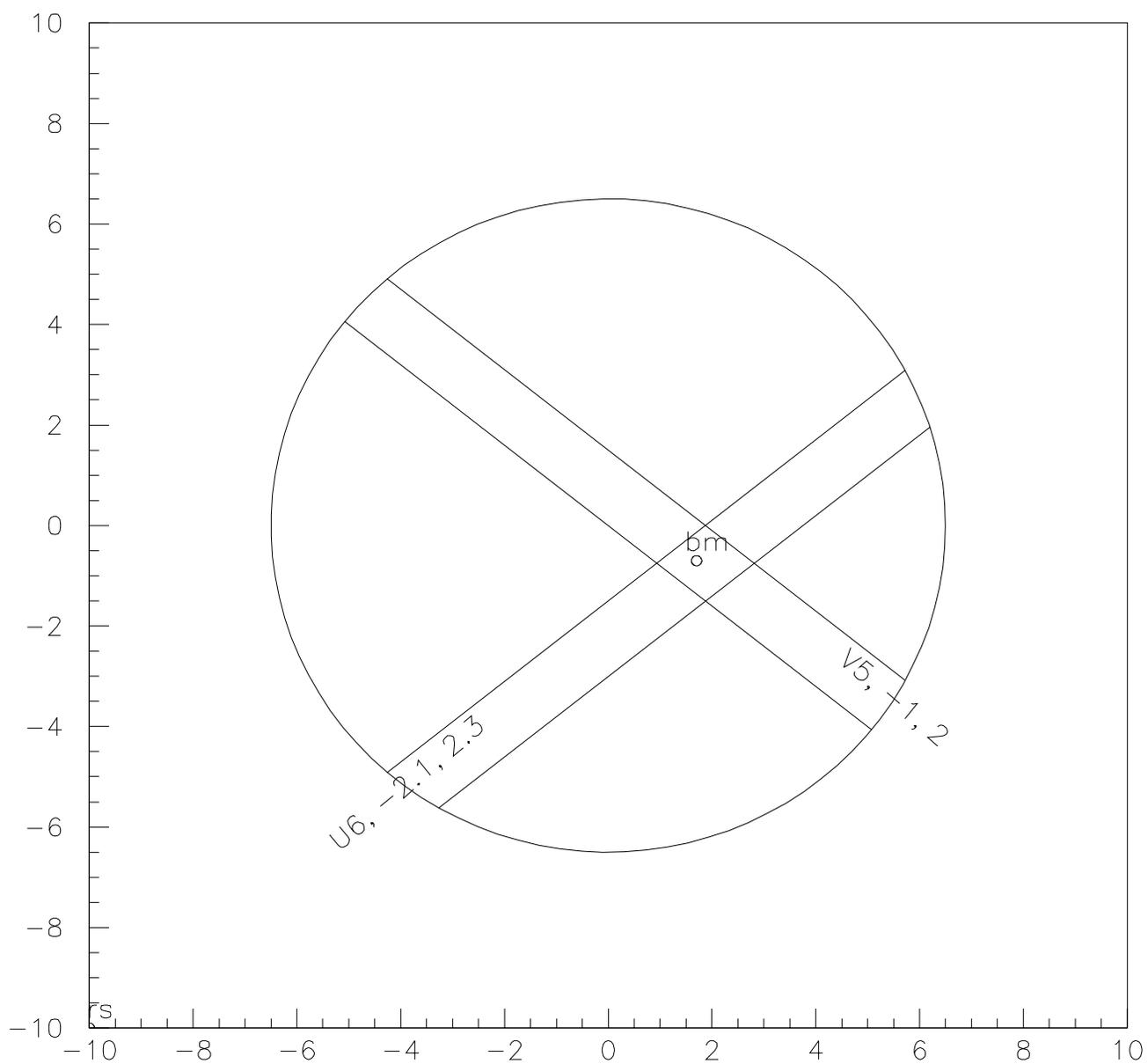
# m.88 627 InTheBox



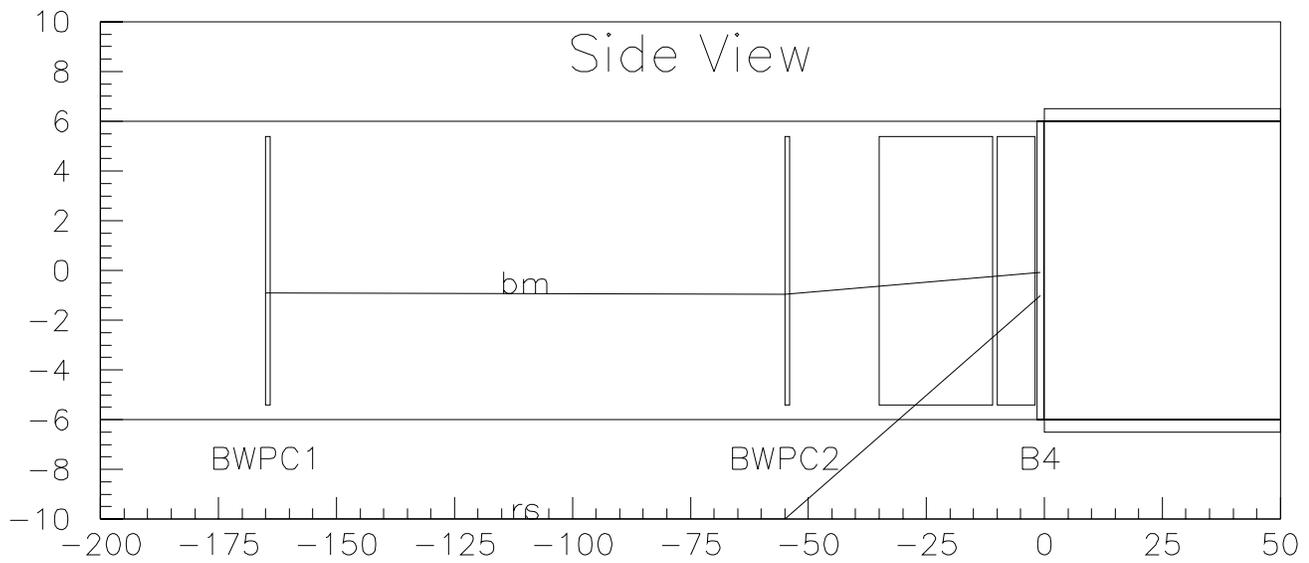
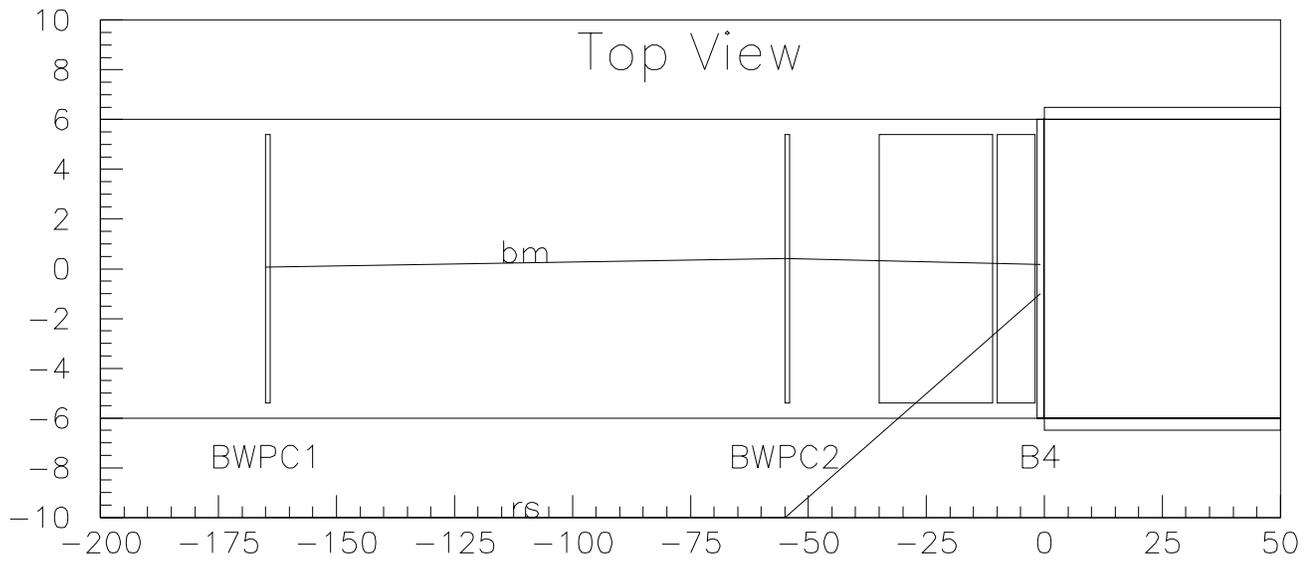
# m.88 627 InTheBox



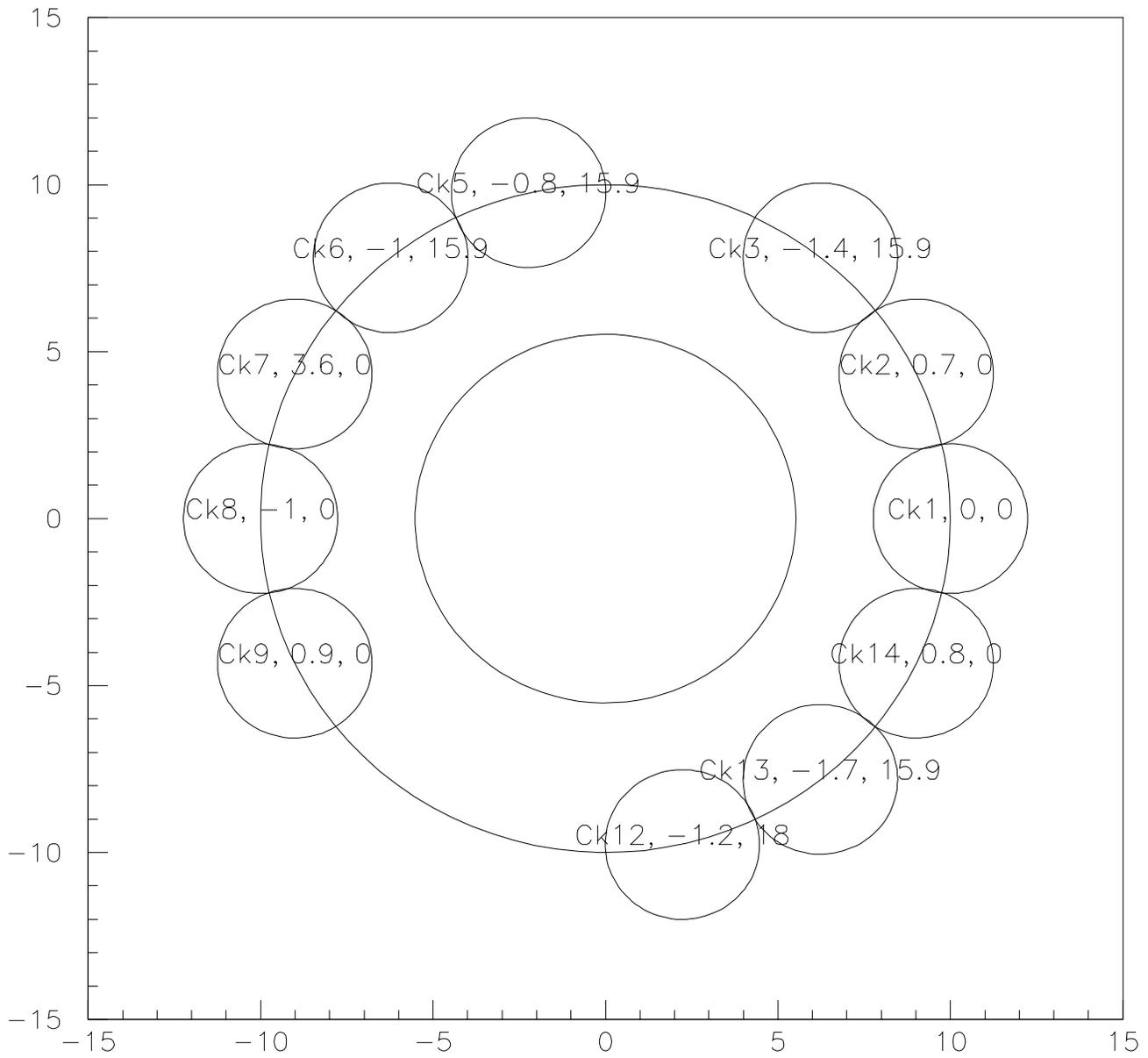
# m.88 627 InTheBox



# m.88 627 InTheBox

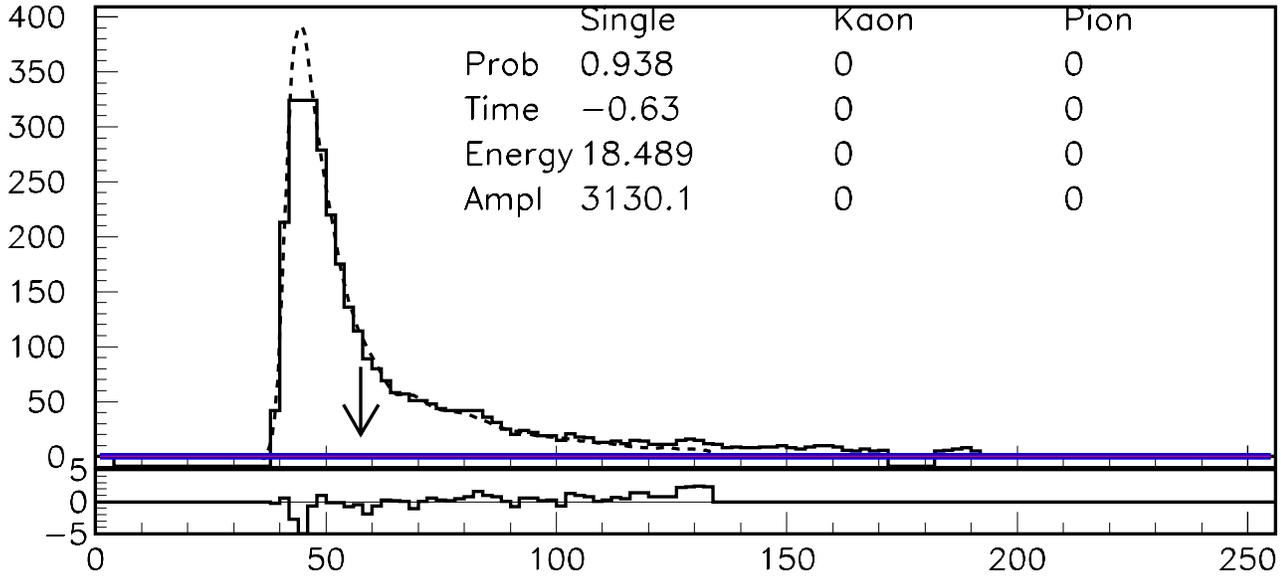


# m.88 627 InTheBox

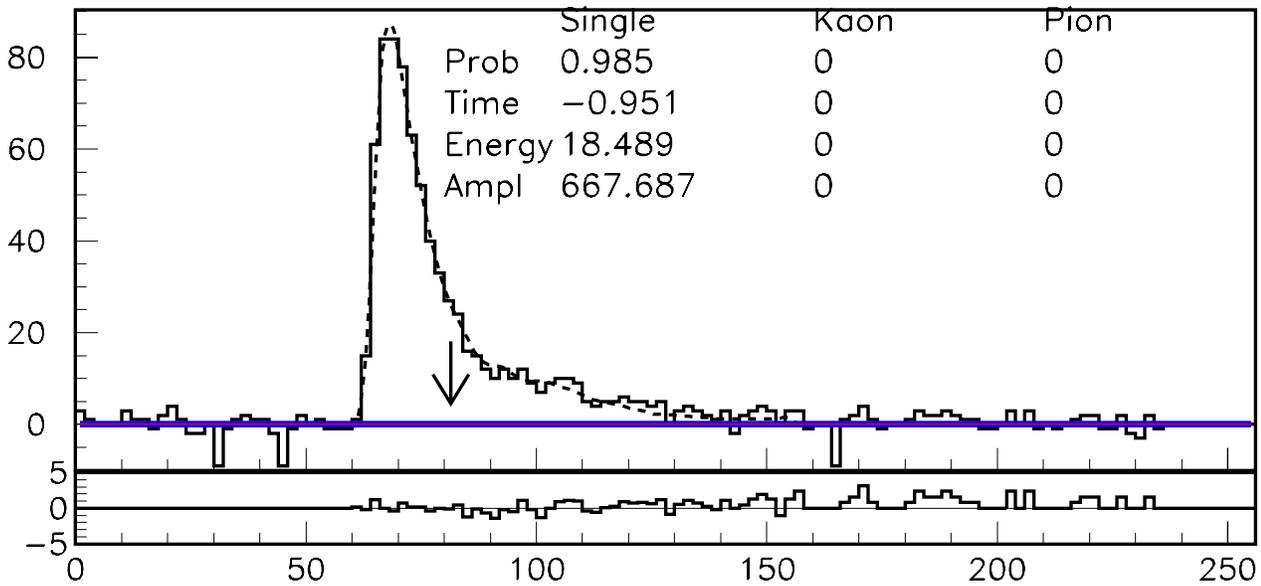


# m.88 627 InTheBox

Run 32775 Event 126739 EK 18.475 TK 0.43 TRS 19.491



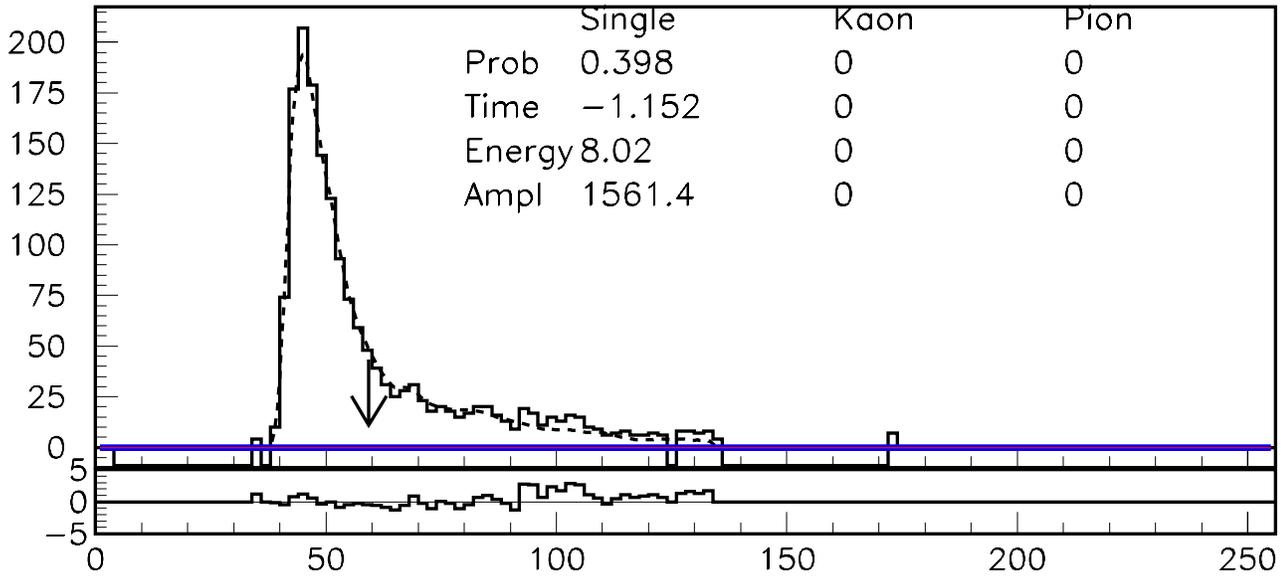
K fibre 329 Raw HighGain



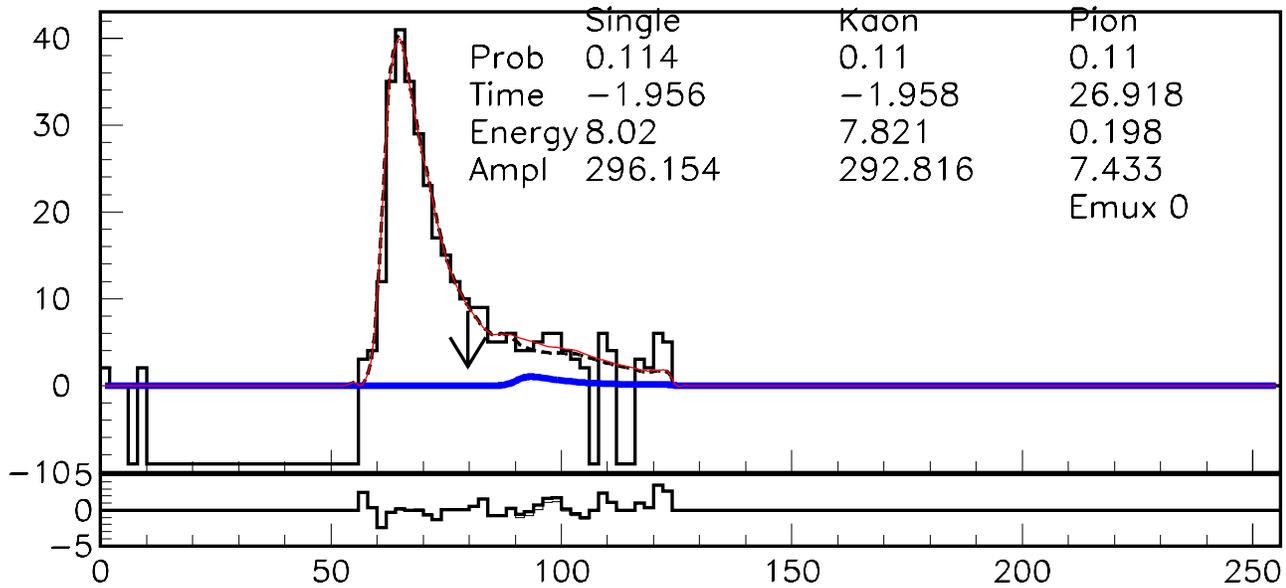
K fibre 329 Raw Low gain

# m.88 627 InTheBox

Run 32775 Event 126739 EK 8.015 TK -0.254 TRS 19.491



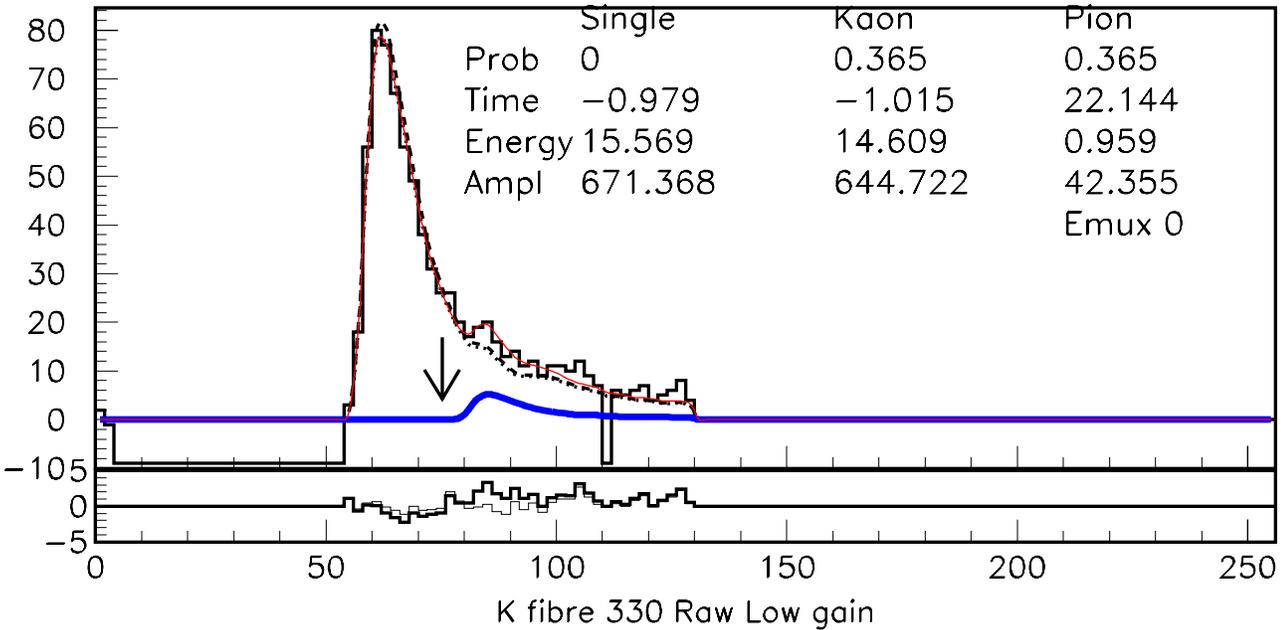
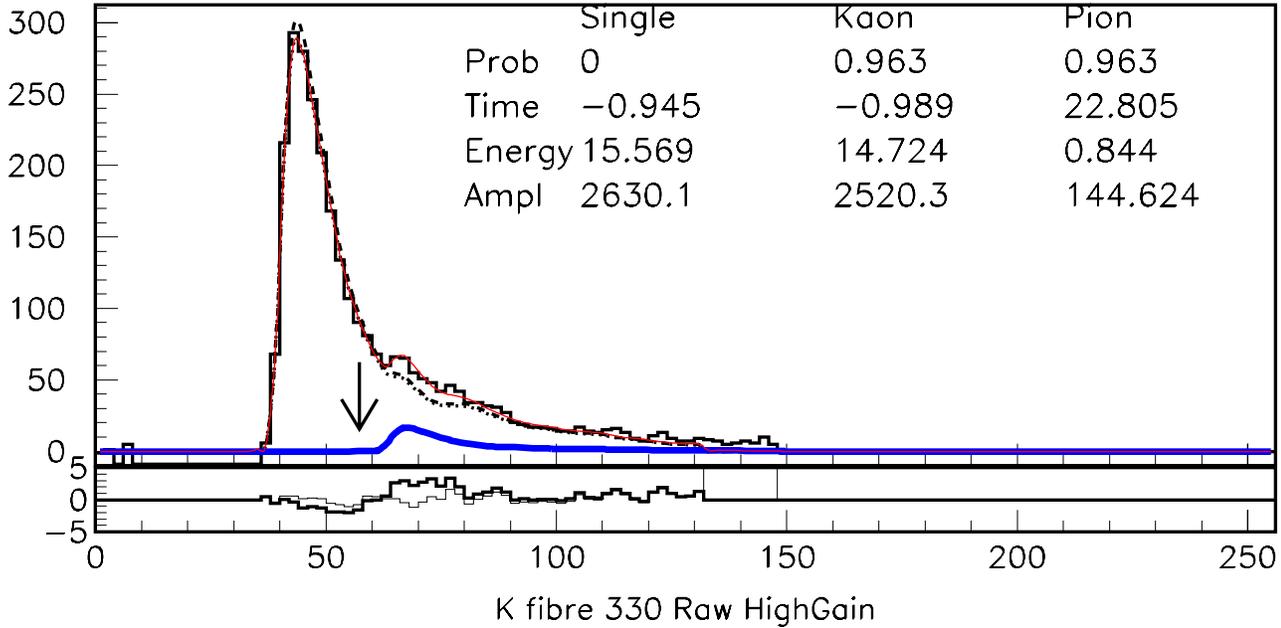
K fibre 304 Raw HighGain



K fibre 304 Raw Low gain

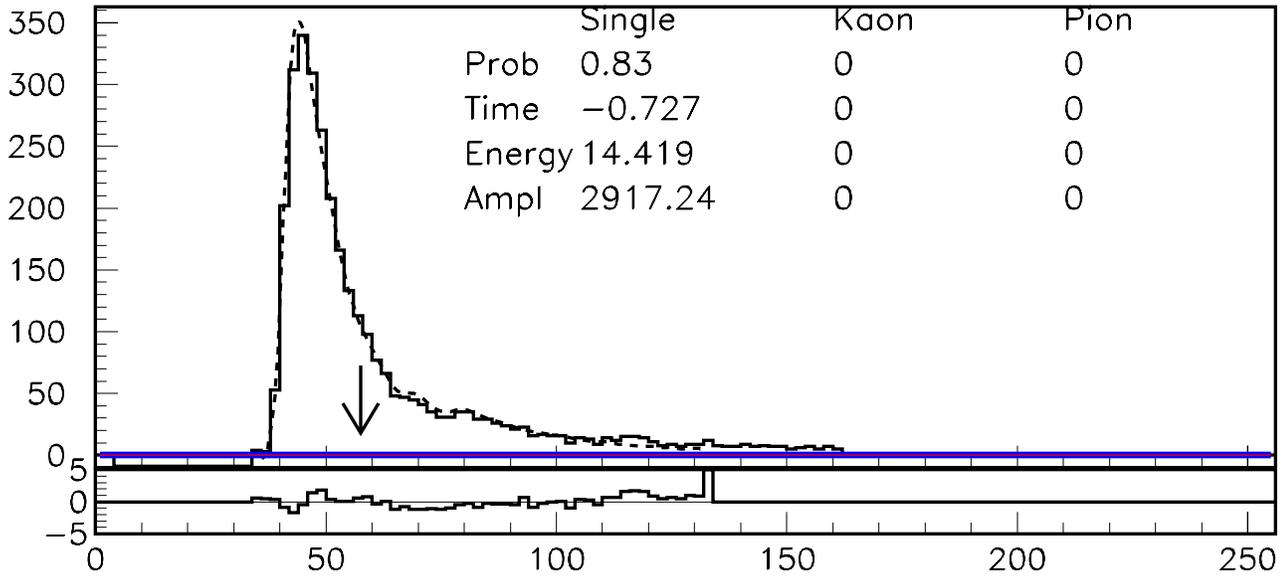
# m.88 627 InTheBox

Run 32775 Event 126739 EK 15.542 TK 0.332 TRS 19.491

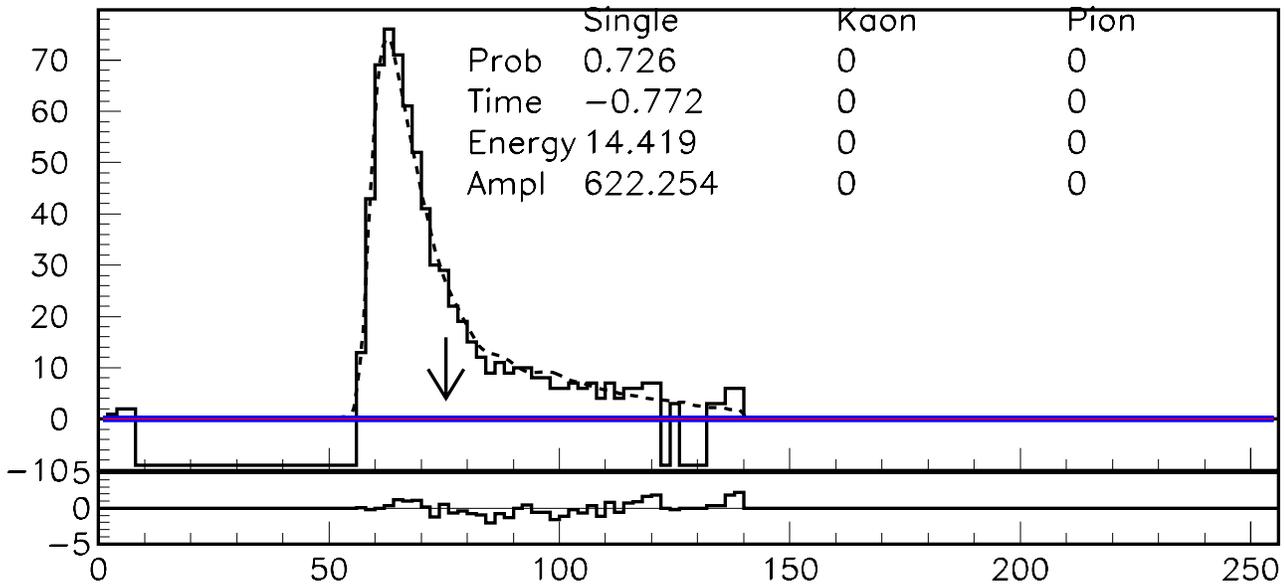


# m.88 627 InTheBox

Run 32775 Event 126739 EK 14.467 TK 0.234 TRS 19.491



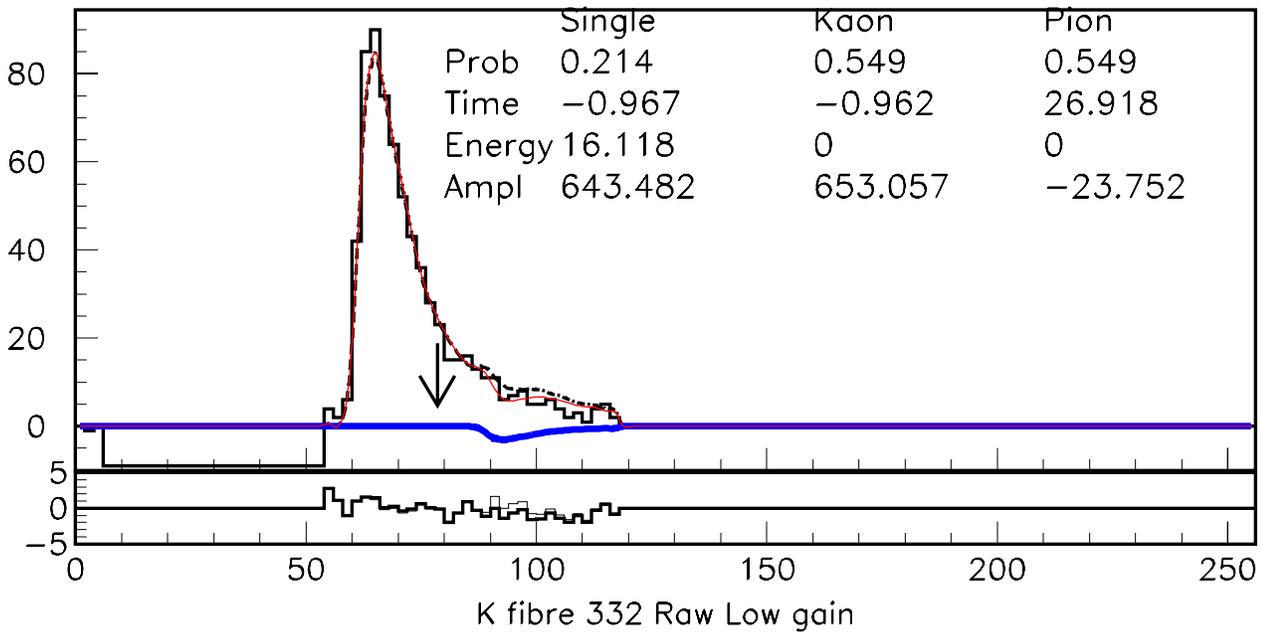
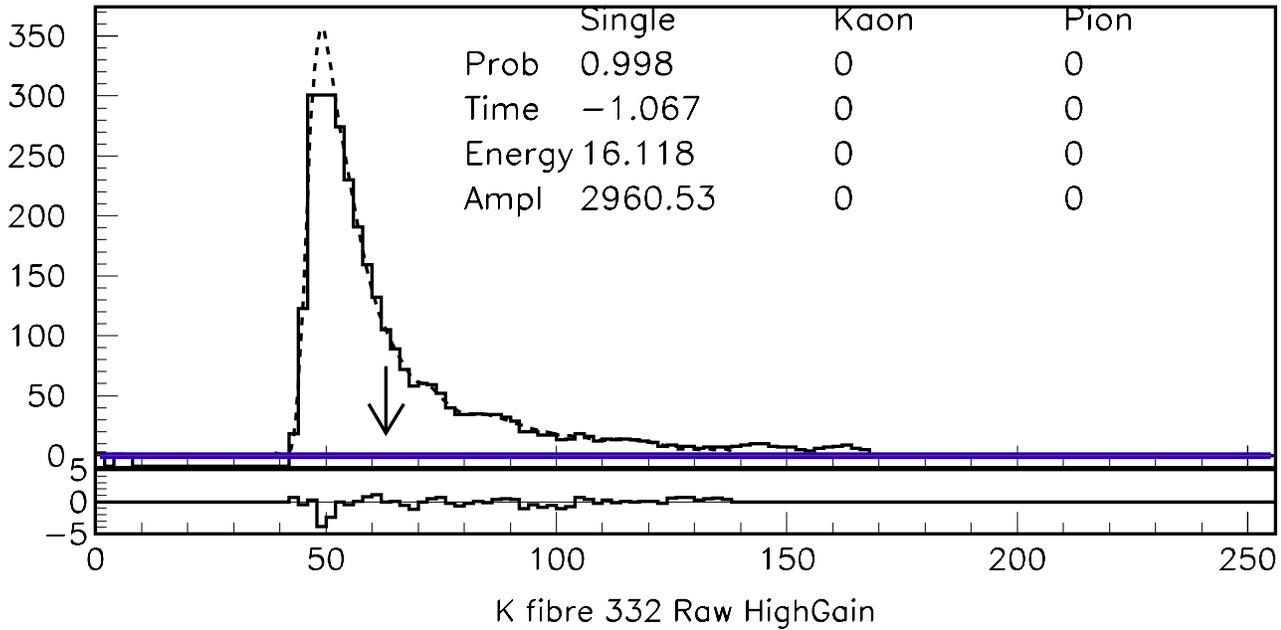
K fibre 331 Raw HighGain



K fibre 331 Raw Low gain

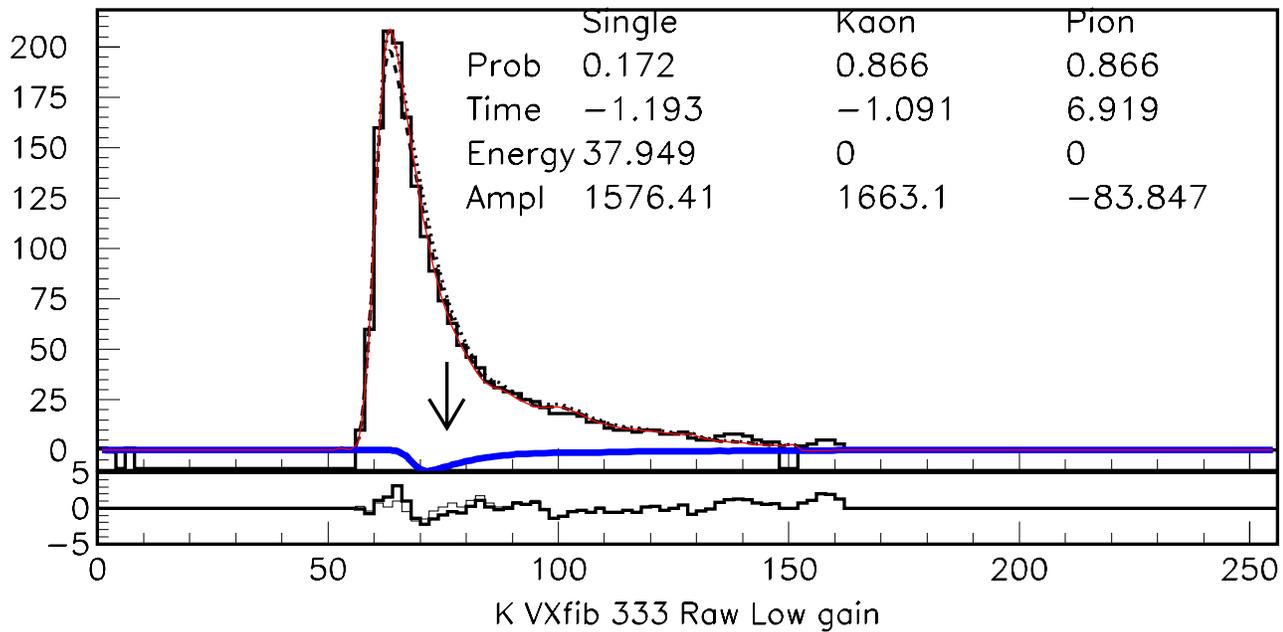
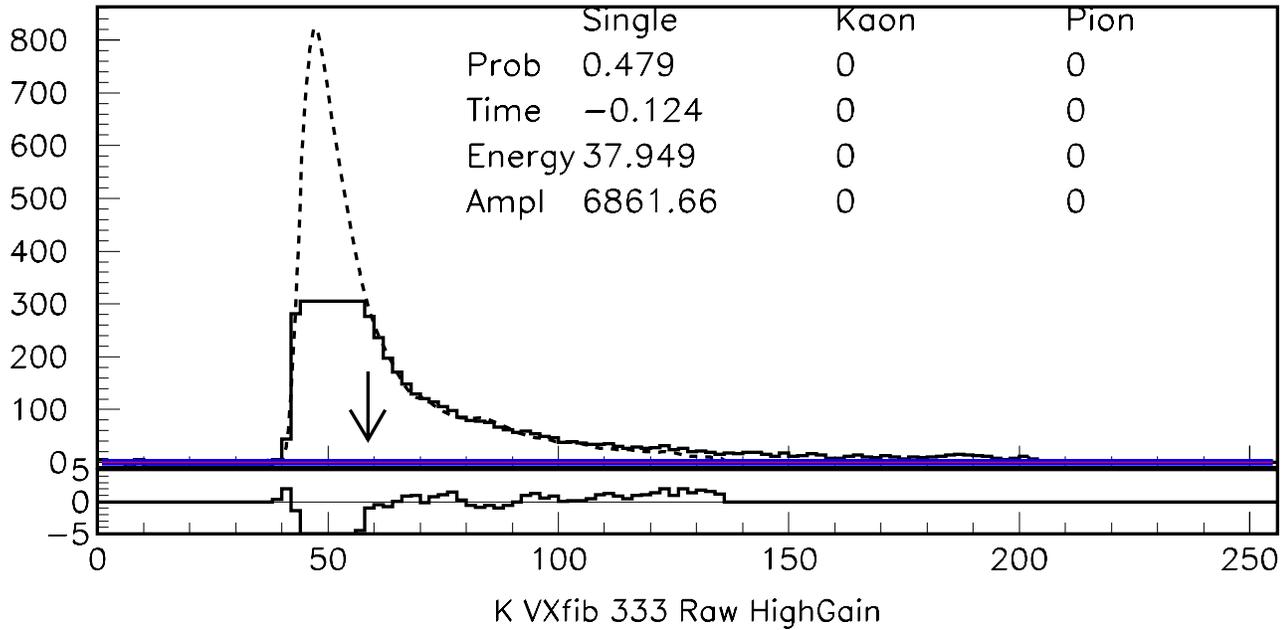
# m.88 627 InTheBox

Run 32775 Event 126739 EK 16.129 TK 0.039 TRS 19.491



# m.88 627 InTheBox

Run 32775 Event 126739 EK 37.927 TK 1.505 TRS 19.491



# Acceptance

Acceptance factors	PNN1	PNN2
$K^+$ stop efficiency	0.702	0.670
$K^+$ decay after 6 ns	0.851	0.591
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ phase space	0.155	0.345
Geometry	0.409	0.317
$\pi^+$ nucl. int. and decay in flight	0.527	0.708
Reconstruction efficiency	0.969	0.957
Other kinematic cuts	0.554	0.686
$\pi - \mu - e$ decay chain	0.392	0.545
Beam and target analysis	0.706	0.479
CCD acceptance	1.0	0.401
Accidental loss	0.751	0.363
Total acceptance	$1.96 \times 10^{-3}$	$7.65 \times 10^{-4}$

Acceptance factors used in the measurement of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  in Region 2. The “ $K^+$  stop efficiency” is the fraction of kaons entering the TG that stopped. “Other kinematic constraints” include particle identification cuts.

Total Analysed Exposure:

PNN1:  $5.9 \times 10^{12}$  kaons

PNN2:  $1.12 \times 10^{12}$  kaons

## Limits, etc.

- Previous 90% C.L. limit using the low momentum region:  $1.7 \times 10^{-8}$   
M.S. Atuya et al., Phys. Rev. D 48, R1 (1993).

- E787 measurement using 2 events in high momentum region:

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.57_{-0.82}^{+1.75}) \times 10^{-10}$$

S. Adler et al., Phys. Rev. Lett. 88, 041803 (2002).

- This measurement

$$S.E.S = 1.17 \times 10^{-9}$$

- 1 event observed with background of  $0.73 \pm 0.18$ .

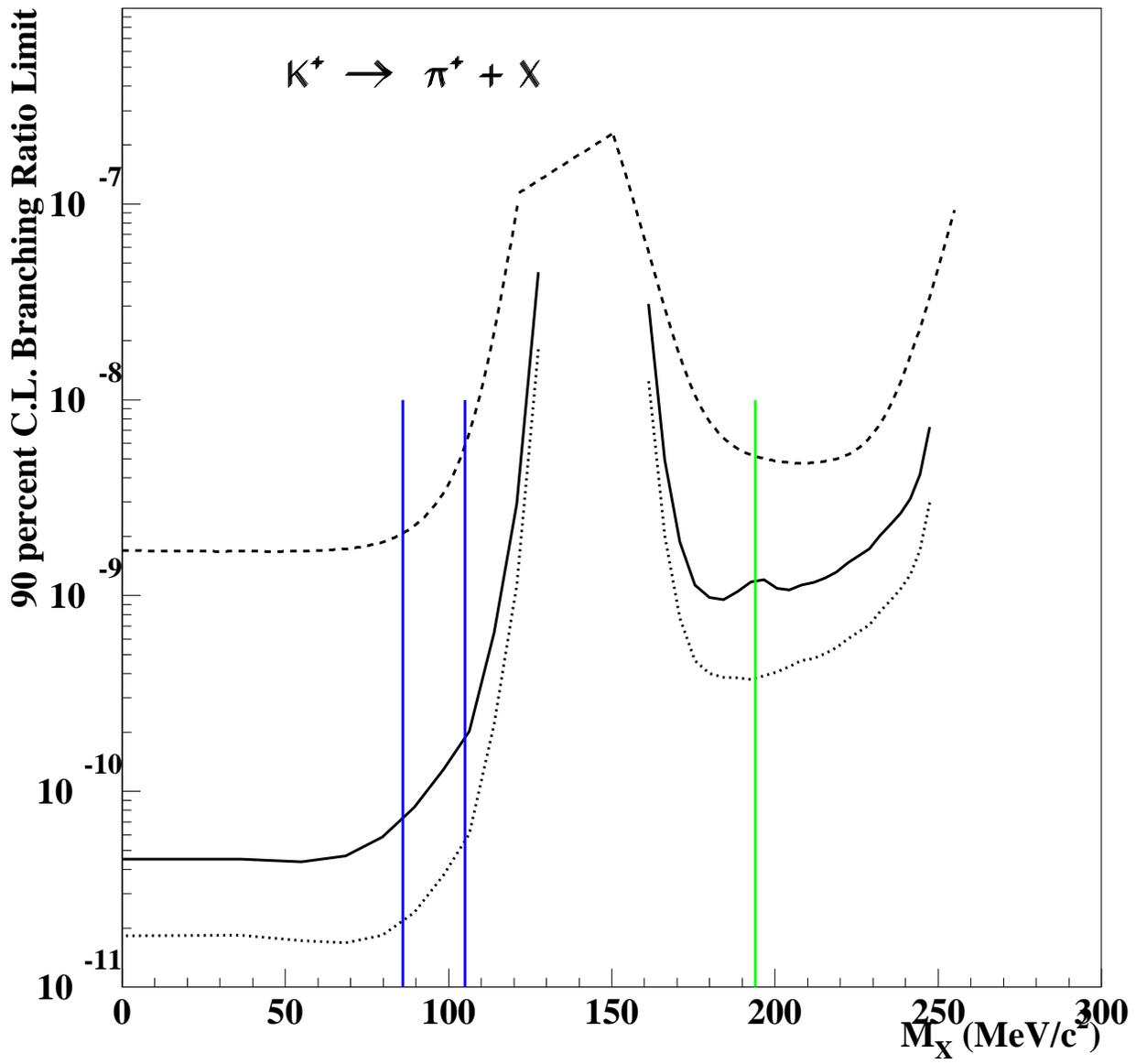
$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 4.2 \times 10^{-9}$$

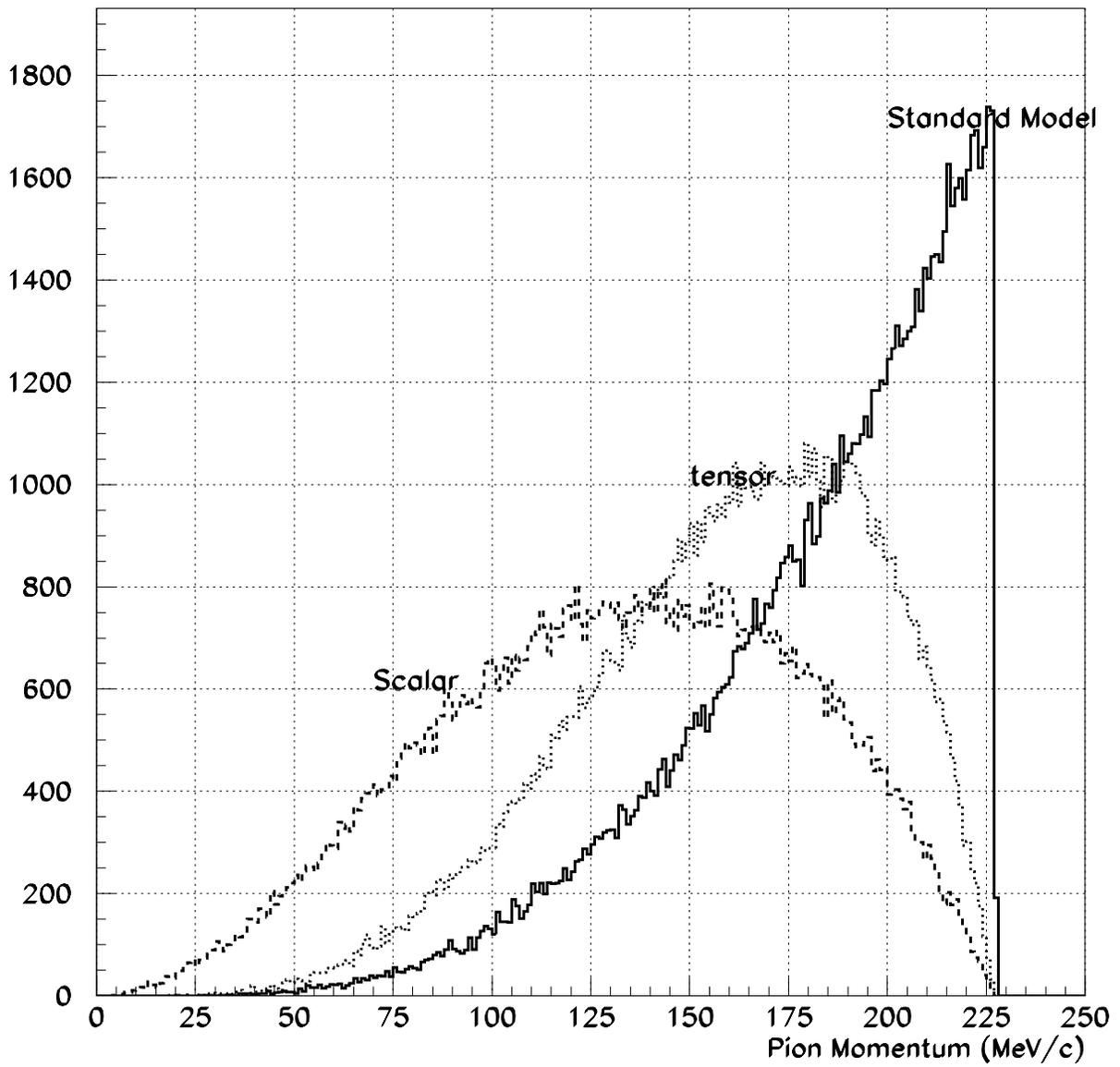
- Assume Scalar spectrum:

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})_S < 4.7 \times 10^{-9}$$

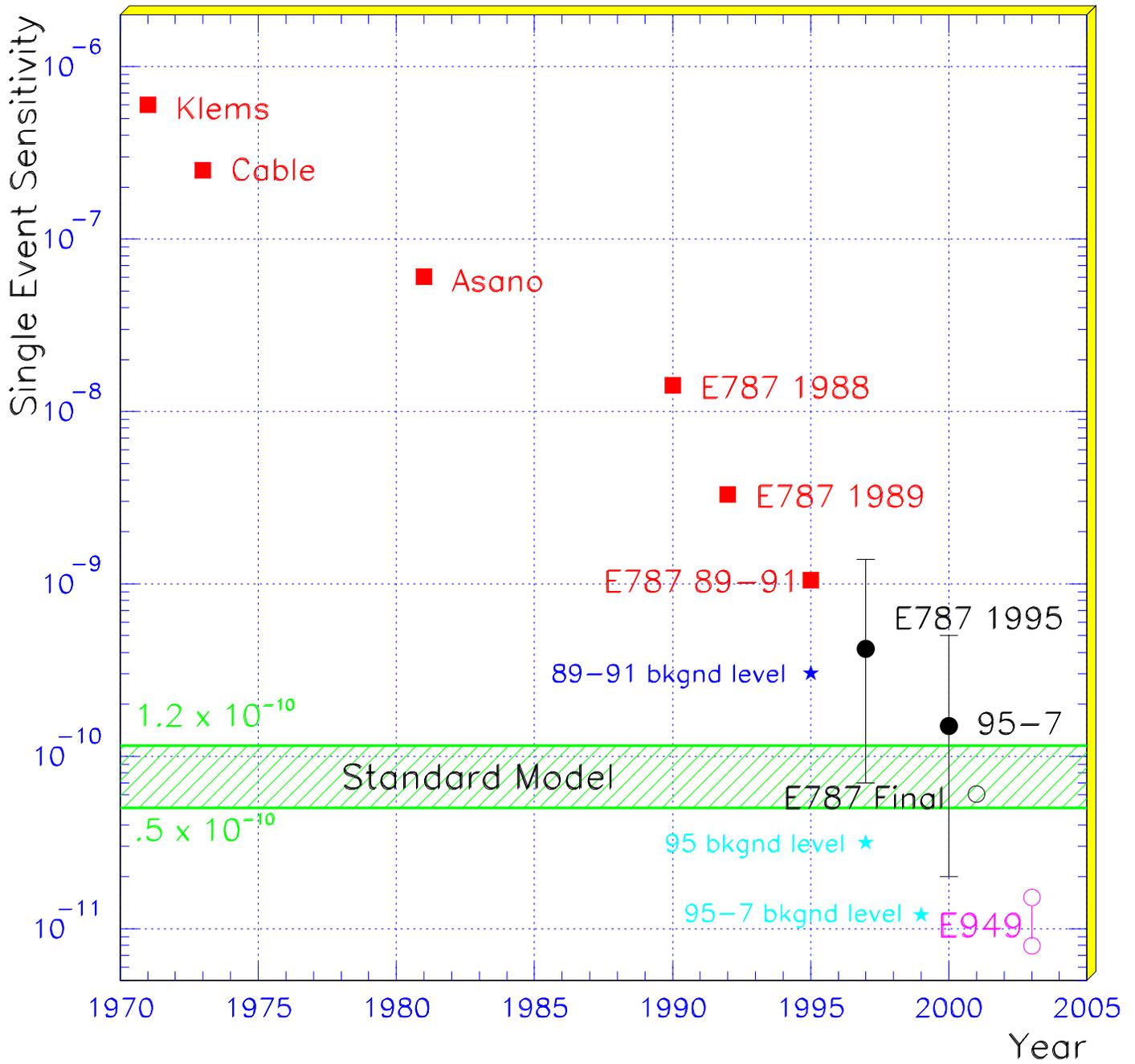
- Assume Tensor spectrum:

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})_T < 2.5 \times 10^{-9}$$





# Progress in $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



## Conclusion

- Analysis of E787 PNN1 data from 95-98 complete with result of

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.57_{-0.82}^{+1.75}) \times 10^{-10}$$

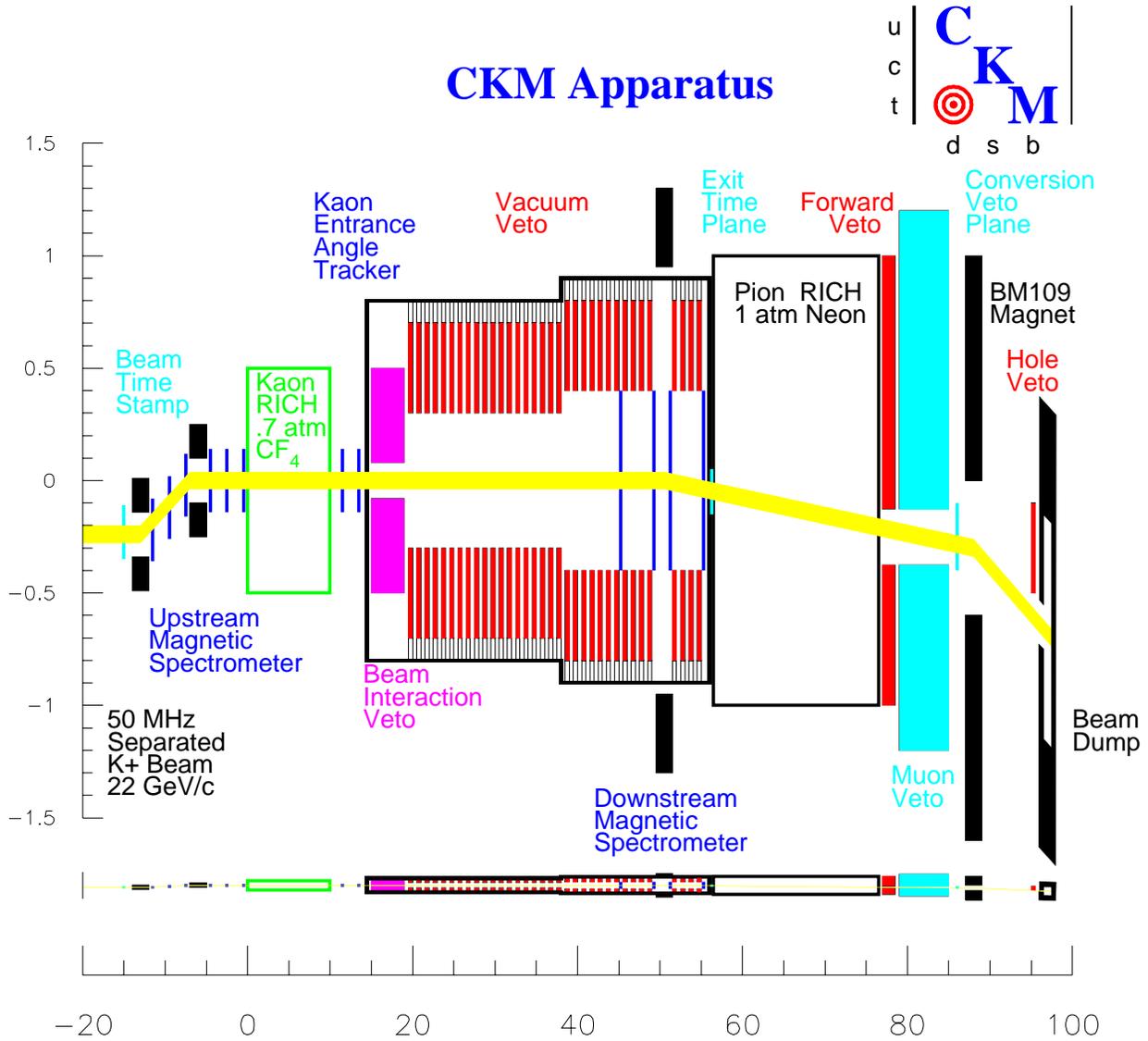
- Major new effort on analysis of PNN2 (below the Kpi2 peak) concluded.  
1 event observed with background of  $0.73 \pm 0.18$ .

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 4.2 \times 10^{-9}$$

- New techniques using the fiber-target and CCDs allow background determination in PNN2 region.  
No evidence of major background other than KPI2.
- The PNN2 measurement appears to be limited by photon veto.
- E949 with major upgrades to photon veto system and many other improvements on schedule to take  $\times 10$  data.
- FNAL experiment CKM may have no scattering background. Could be best place to do low momentum measurement.



# CKM in brief



CKM Experiment Sensitivity and Backgrounds

