E787/E949: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

("golden needle in micro-cosmic haystack" - BNL press release)

G. Redlinger, BNL

KAON 2005 Northwestern University 13-17 June, 2005

Outline

- Experimental overview
  - Stopped K technique
  - E787 → E949
- Background analysis
- Result from 2002 data
- Current efforts
  - “Region 2” (p < 195 MeV/c)

E949 Collaboration

University of Alberta

Brookhaven National Laboratory

Fermilab

Fukui University

IHEP, Protvino

INR,RAS

KEK

Kyoto University

National Defense Academy, Japan

Osaka University

Stony Brook State University of New York

TRIUMF

UBC

The University of New Mexico

E787 Collaboration

UNIVERSITY OF ALBERTA

UBC

BROOKHAVEN NATIONAL LABORATORY

KEK

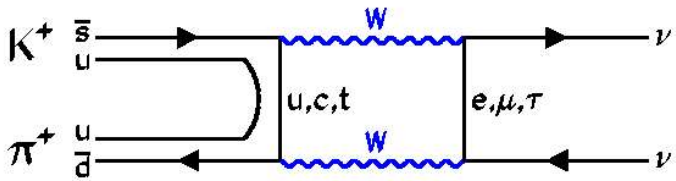
Osaka University

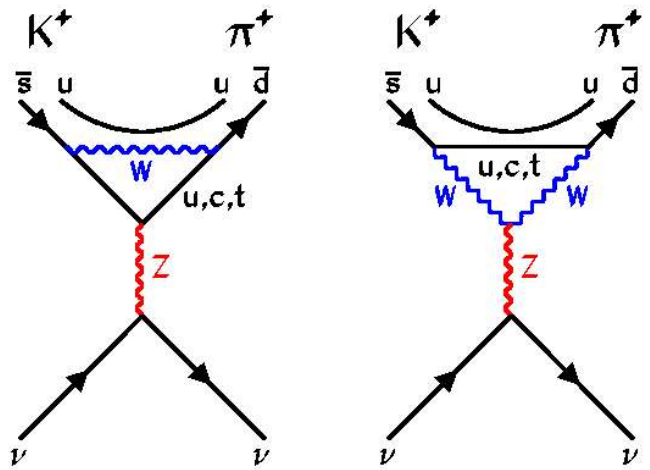
TRIUMF

Introduction

- Highly suppressed in the SM. Sensitive to new physics in the loops.
- Very clean theoretically
  - BR calculable in SM with precision of ~7%. Could be brought down to ~ 2% with NNLO QCD calculation (Buras et al, hep-ph/0405132)
- SM expectation:

  $BR = (0.78 \pm 0.12) \times 10^{-10}$
- If there is new physics in quark mixing, the effects could be different in the s → d sector compared to b → d

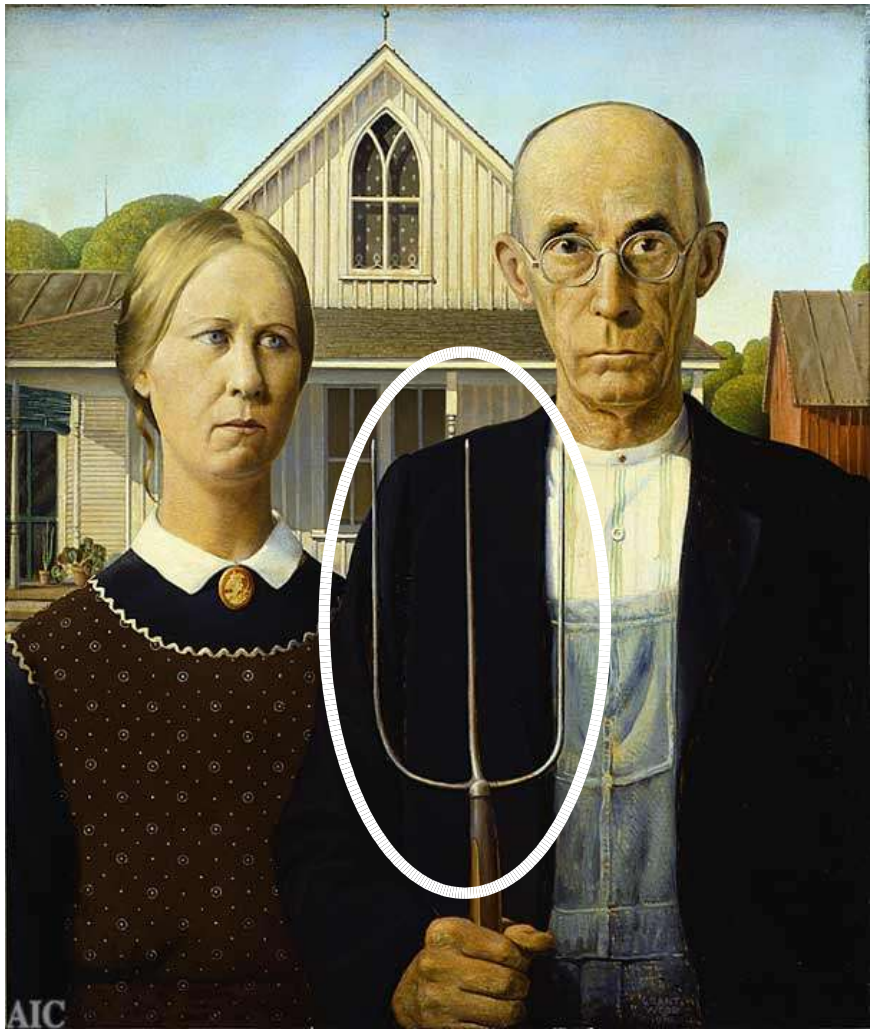




$K^+ \rightarrow \pi^+\nu\bar{\nu}$ measurement

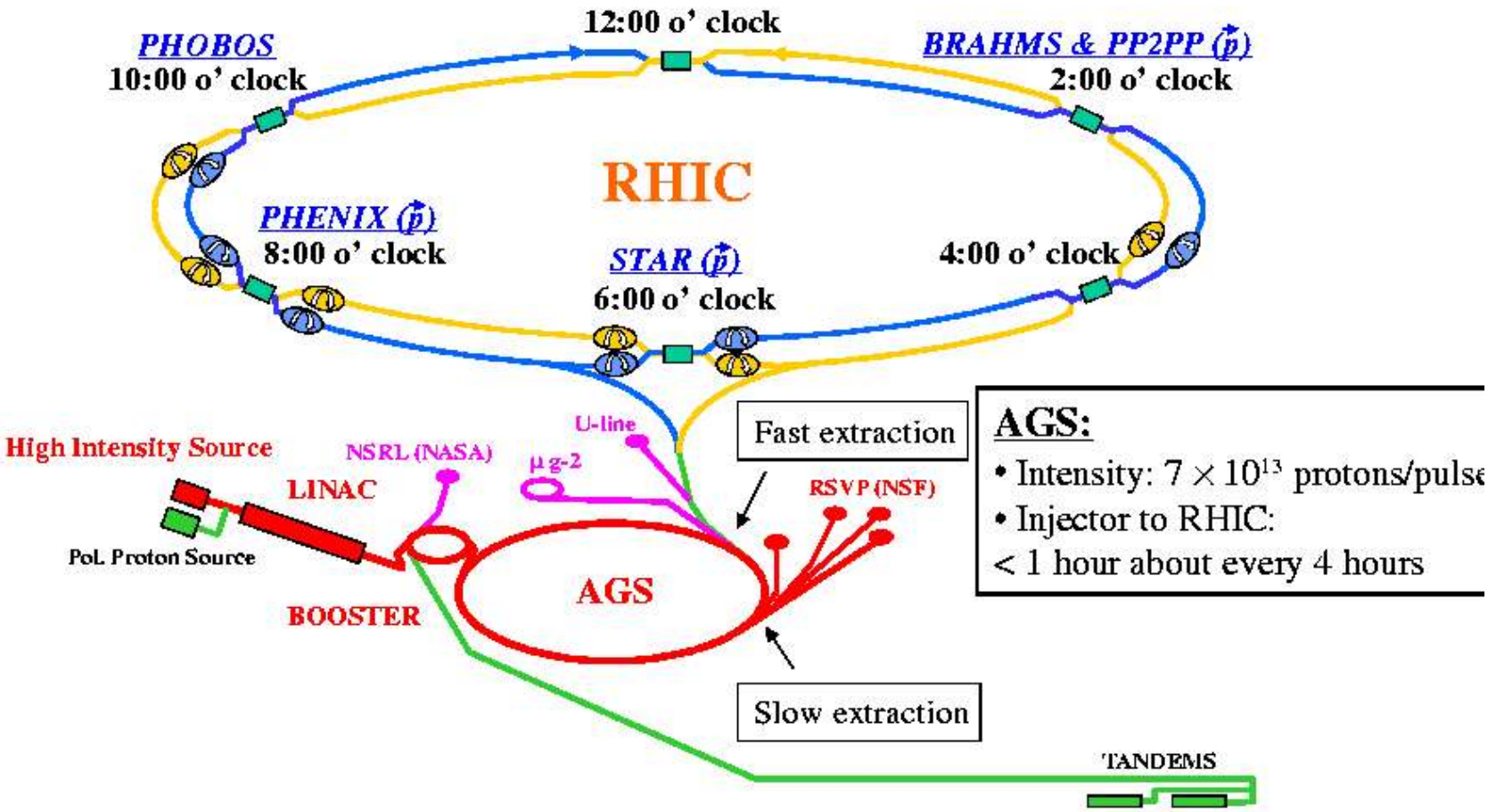
- Experimentally challenging, but do-able as shown by BNL E787.
- E787 (1995-98) observed two $K^+ \rightarrow \pi^+\nu\bar{\nu}$ candidates with a background of 0.15 ± 0.05 events
- Likelihood analysis based on additional signal/bkg discrimination yielded
  - Probability of bkg alone giving rise to these 2 (or "cleaner") events = 0.0013
  - $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 1.57\ (+\ 1.75,\ -0.82) \times 10^{-10}$ from E787
- E787 was primarily limited by proton flux from AGS on K production target
- E949 is based on "modest" upgrades to the E787 program
  - Use "entire" proton flux. 15×10^{12} protons/spill → 65×10^{12}
  - Longer AGS running during RHIC operation ($\gtrsim$ 25 weeks/yr)
  - Detector upgrades: photon veto, π^+ tracking and kinematic resolution, trigger/DAQ, K^+ tracking system
- Aimed at SES $\leq 10^{-11}$ or 5-10 SM events

Tools

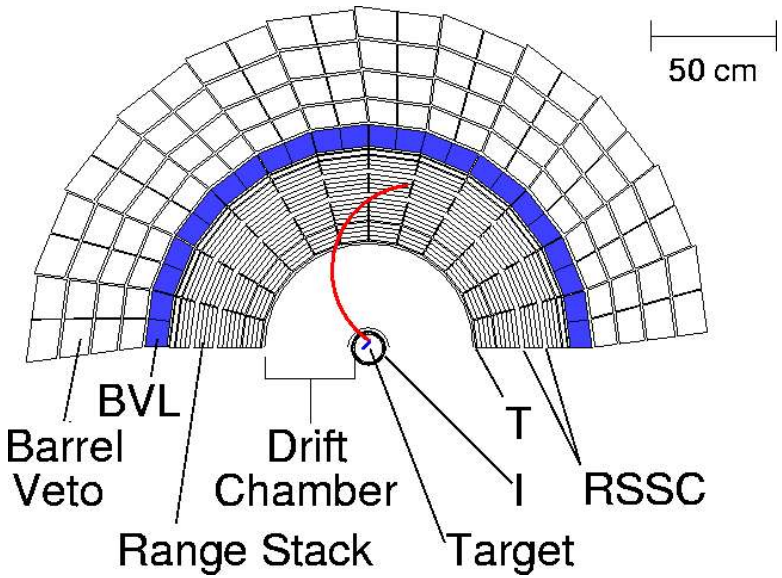


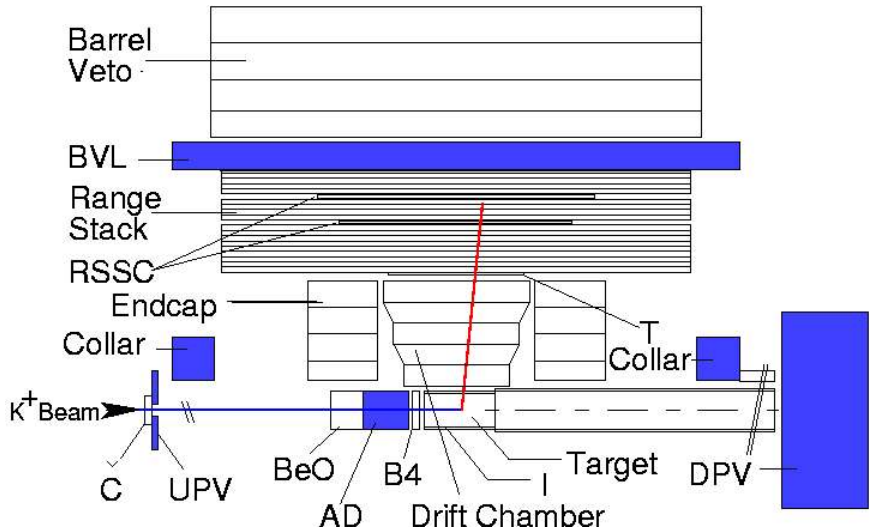
Grant Wood
American Gothic, 1930
Art Institute of Chicago

AGS in the RHIC era



E949 detector





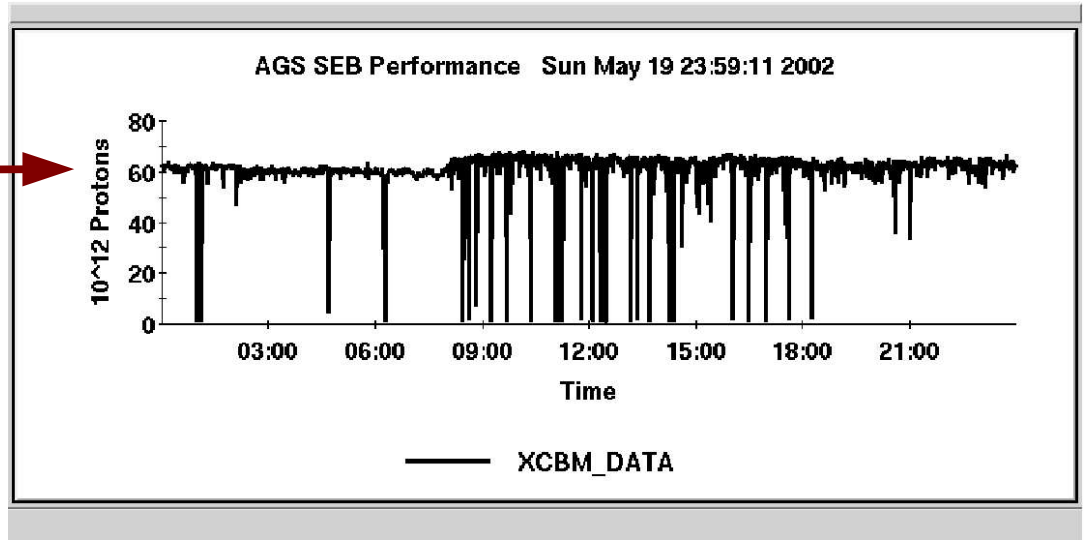
- Incoming beam (~700 MeV/c) tagged by Cerenkov, dE/dx counters
- Stopped kaon beam. Wait ~2ns for K decay (reject beam π). High geometrical acceptance.
- Stopped decay pion. Redundant measurements of kinematics (R,E,P). Observation of π → μ → e decay sequence for μ rejection.
- Photon veto counters surround everything (E949 PV upgrades shown in blue).
- Minimize inactive material.

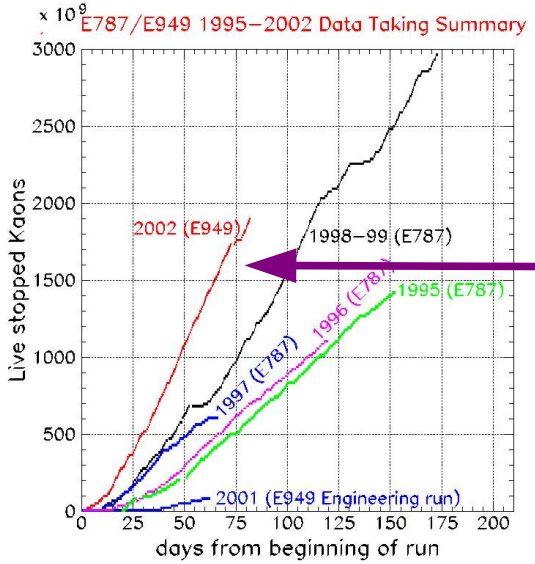
E949: Beam

Proton intensity:
- 76 x 10^{12}/spill (peak)
- 65 x 10^{12}/spill (typical)

Kaons:
- Incoming: 6–7 MHz
- "Stopping": ~2 MHz

E949 (2002) protons on target (typical day)

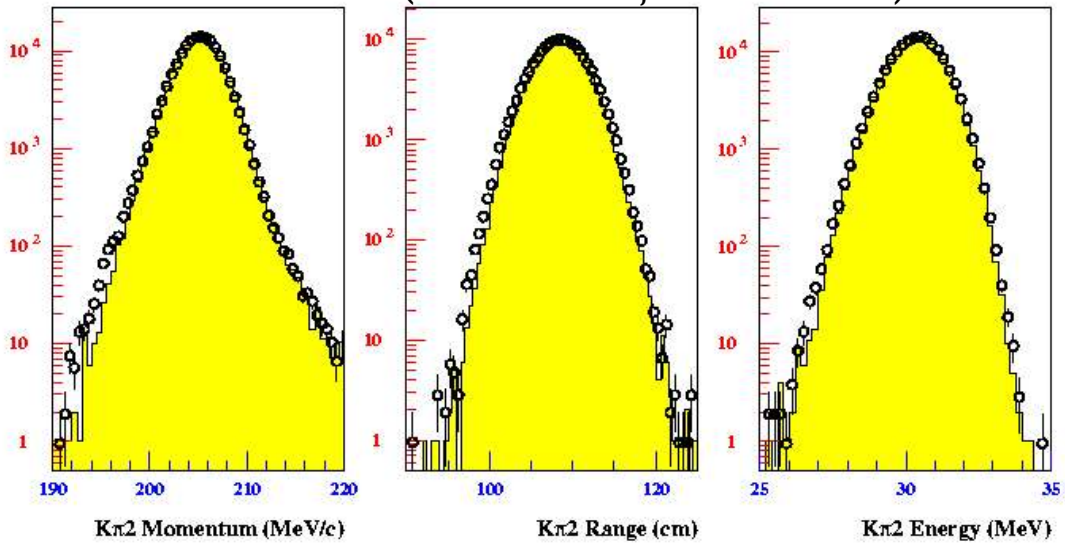




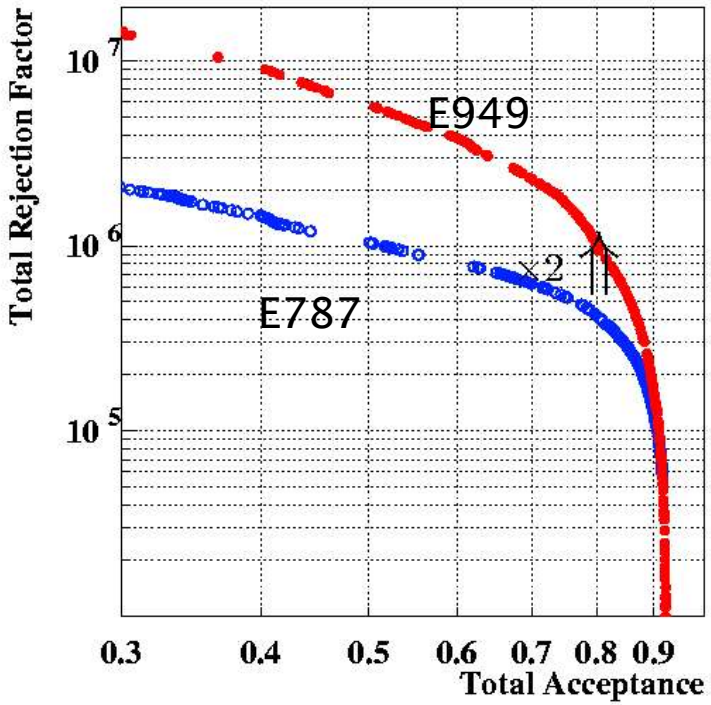
Not optimal in 2002:
- Short run
- AGS main power supply problem. 20% worse duty factor cf. E787. Lower proton momentum ⇒ ~10% in K flux.
- K/π separator problems

E949: Detector upgrades

Kinematic resolution (dots: E787, solid: E949)



Photon Veto: x2 more rejection at nominal acceptance

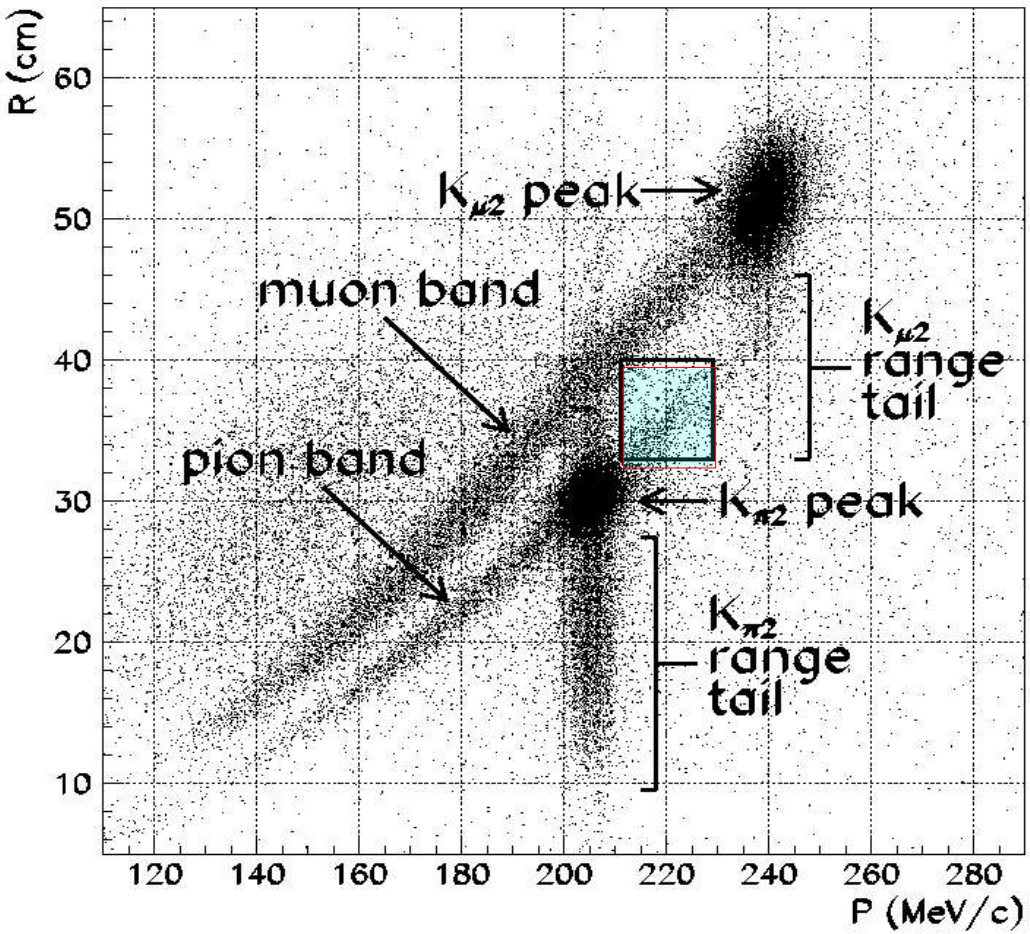


Comparable kinematic resolution at x2 instantaneous rate.

σ(P) ~ 2.3 MeV/c
σ(R) ~ 0.9cm
σ(E) ~ 3.0 MeV

Jackson Pollock, Greyed Rainbow, 1953. Art Institute of Chicago

Backgrounds to $K^+ \to \pi^+\nu\bar{\nu}$



$K^+ \to \mu^+\nu(\gamma)$, $(\mu^+\pi^0\nu)$
- Wrong kinematics
- Mis-ID of μ as π
- (Photon(s) undetected)

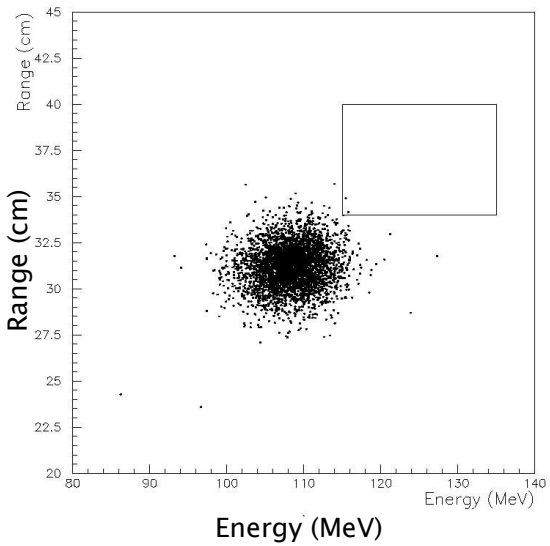
$K^+ \to \pi^+\pi^0$
- Wrong kinematics
- π^0 undetected

Scattered beam π
- Incoming π mis-id as K
- π fakes K-decay at rest (timing)
- K decay-in-flight mismeasured (timing)
- Two beam particles (segmentation)

$K^+n \to K^0p$, $KL \to \pi^+l^-\nu$
- KL decays in K-stopping target
- Lepton missed
- No gap between K^+ and KL

Key: Reliable estimate of backgrounds suppressed to the 0.1 evt level

Background estimation: Kπ2



Full data set

Remove non-Kπ2 backgrounds

Photon tag

Kinematic tag (R,P,E)

Signal region blinded

All other cuts (except PV!)

All other cuts except PV and R,P,E

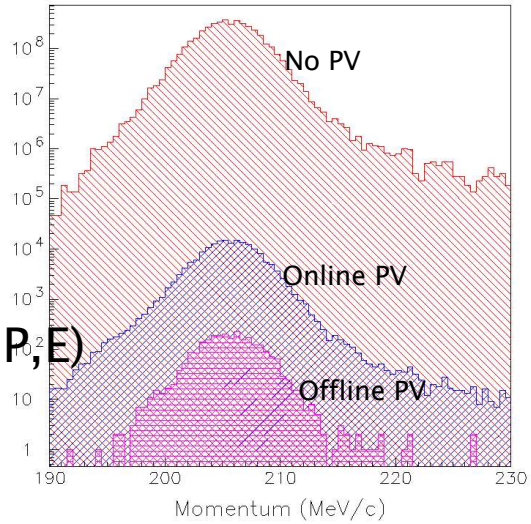
N_1

N_0

Photon veto cuts

N_2

$R(PV) = N_1/N_2$



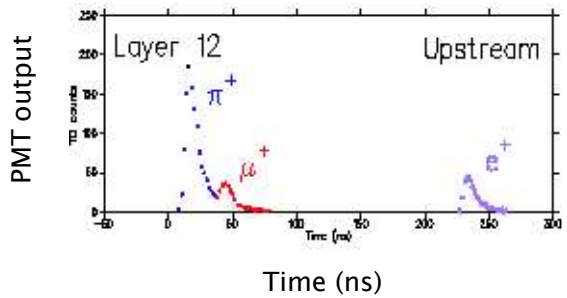
Cuts tuned on 1/3 of the data.

Cut performance measured (unbiased) on 2/3 of data. Cut positions are not changed.

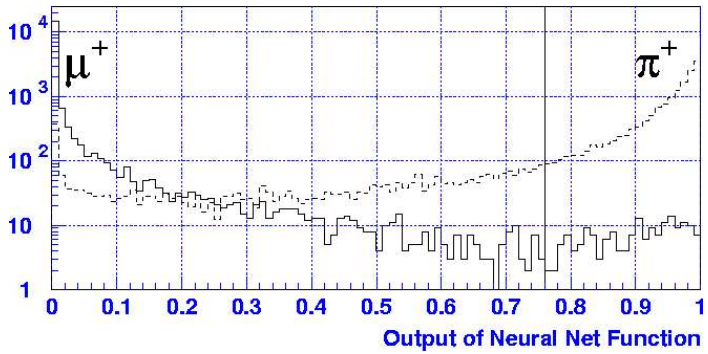
$$N(K\pi 2) = N_0/(R-1)$$

Kμ2 background

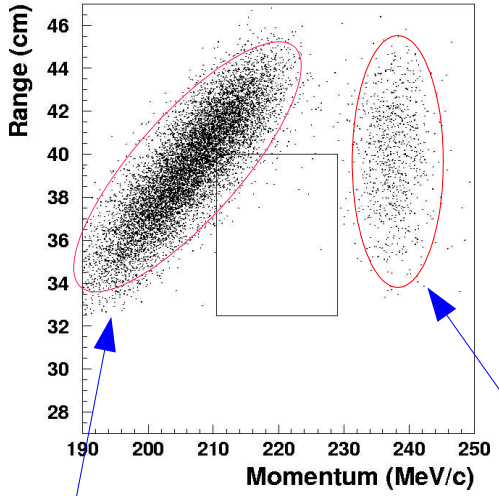
Waveform digitizer analysis (π → μ → e) in pion stopping counter:

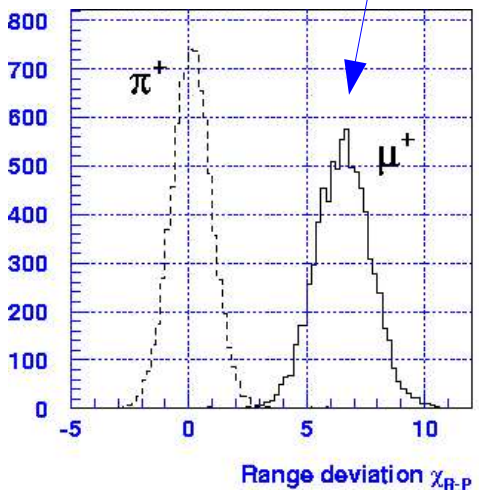


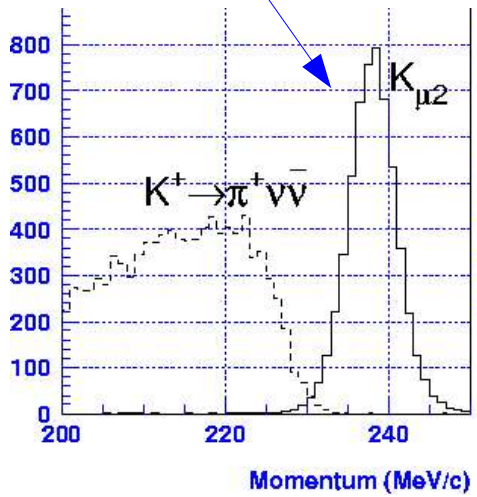
Neural net function



Kinematics







Background summary & verification

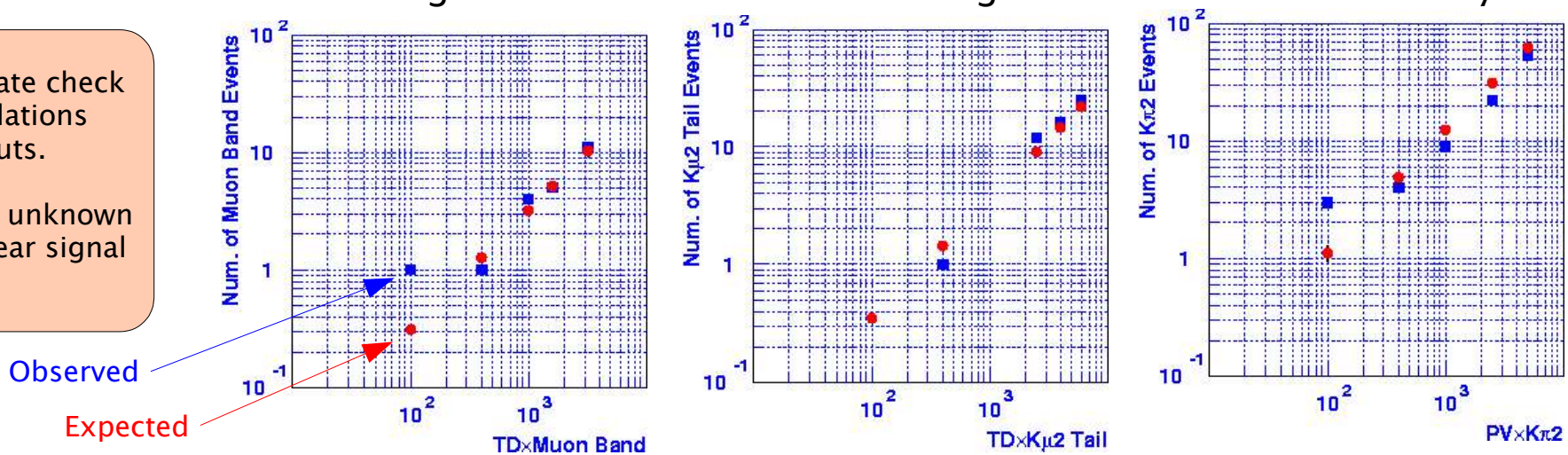
Background	Number of events
Kπ2	0.216 ± 0.023
Kμ2	0.044 ± 0.005
Kμ2γ, Kμ3	0.024 ± 0.010
1-Beam	0.0060 ± 0.0022
2-Beam	0.0028 ± 0.0021
Chg. Exch	0.0045 ± 0.0005
Total	0.30 ± 0.03

- Signal region expanded to let in more background cf. E787
  - Rely on likelihood analysis for further discrimination inside the signal region
  - 30% gain in acceptance

Background verification. Loosening "dual cuts" simultaneously

Serves as ultimate check of lack of correlations between dual cuts.

Also checks for unknown backgrounds near signal region.



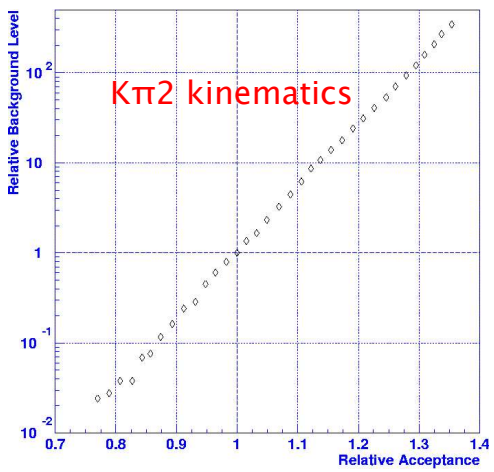
Likelihood functions

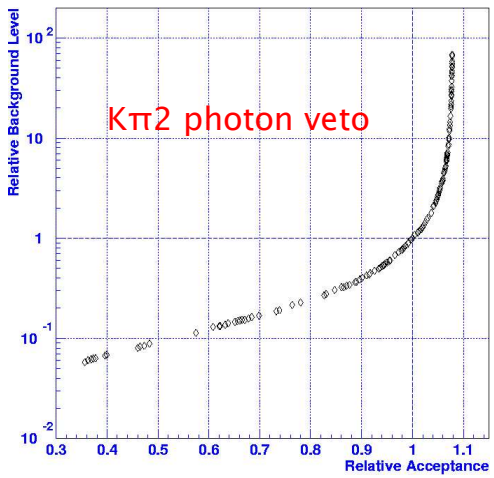
The same dual cut technique is used. Background level and signal acceptance are measured for an ensemble of cut positions.

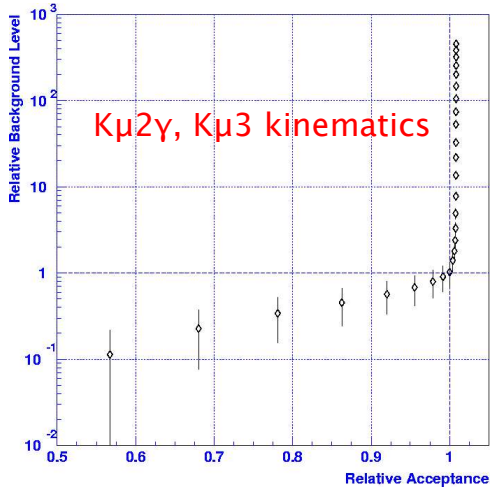
Quantities used for discrimination:

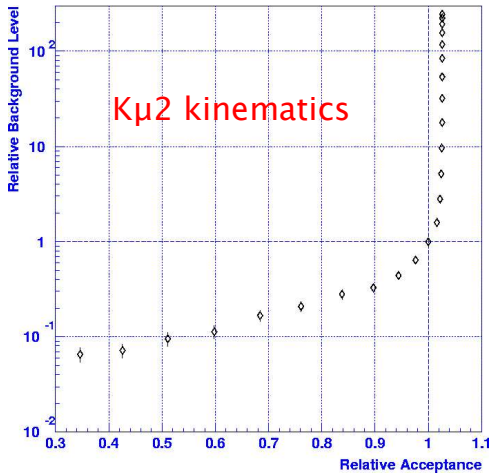
- Muon background
  - Momentum (Kμ2)
  - Range vs momentum correlation (Kμ2γ + Kμ3)
  - Neural net for π → μ → e
- Kπ2 background
  - Range, Energy, Momentum
  - Photon veto
- Beam background
  - t(π) – t(K) for 1-beam bkg and chg exch
  - Veto extra tracks in beamline for 2-beam bkg

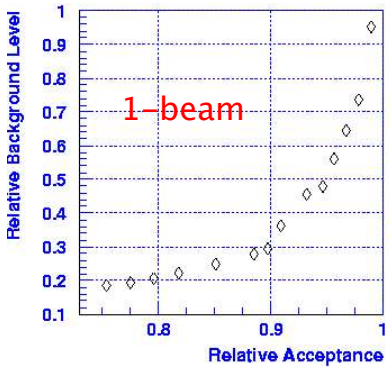
Likelihood functions (2)

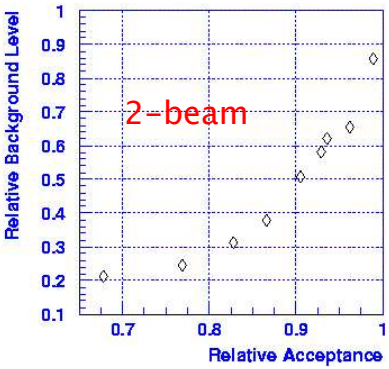


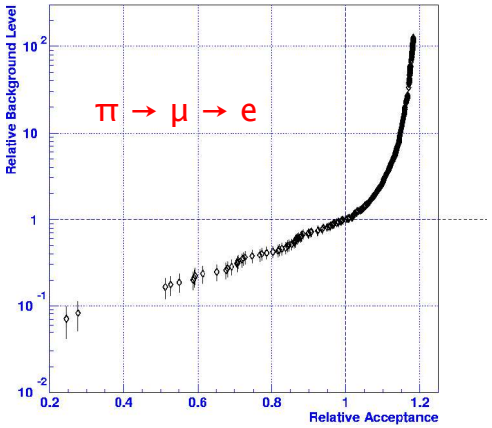








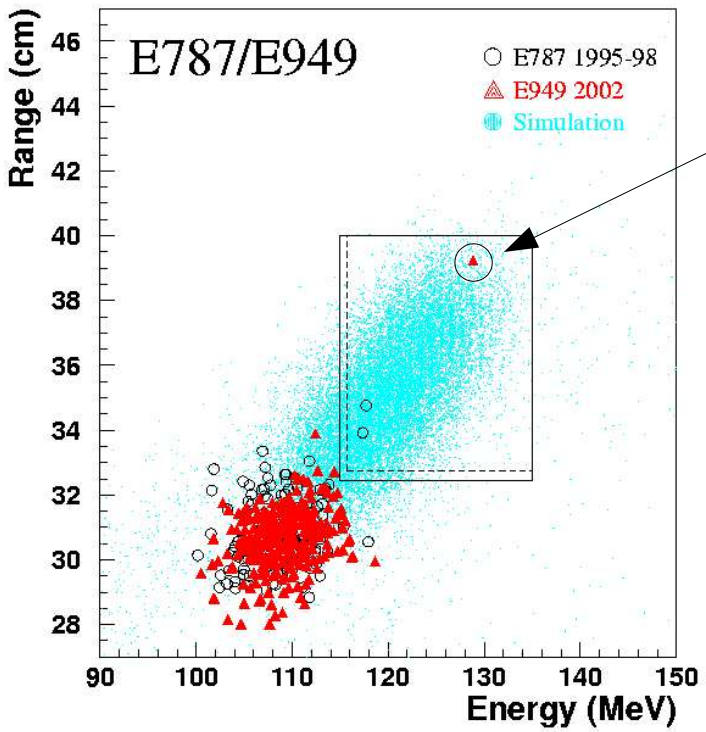




Result

Pierre-Auguste Renoir
Young Woman Sewing, 1879
Art Institute of Chicago

$K^+ \to \pi^+\nu\bar{\nu}$. First result from E949



Single event seen. Not as clean as the previous two events from E787. Effectively contributes half an event to the total sample.

	E787	E949
No. kaons	5.9×10^{12}	1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002	0.0022 ± 0.0002
Total Background	0.14 ± 0.05	0.30 ± 0.03
S/B	50, 7	0.9
Weight	0.98, 0.88	0.48
Background prob.	0.006, 0.02	0.07

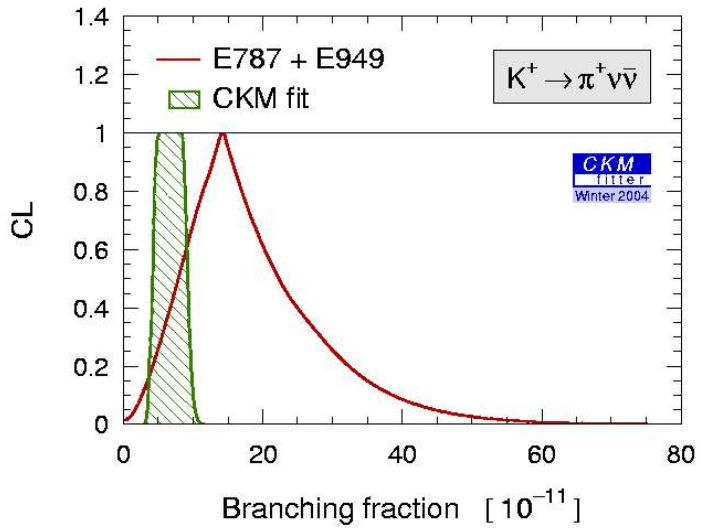
$BR(K^+ \to \pi^+\nu\bar{\nu}) = 1.47\ (+1.30, -0.89) \times 10^{-10}$

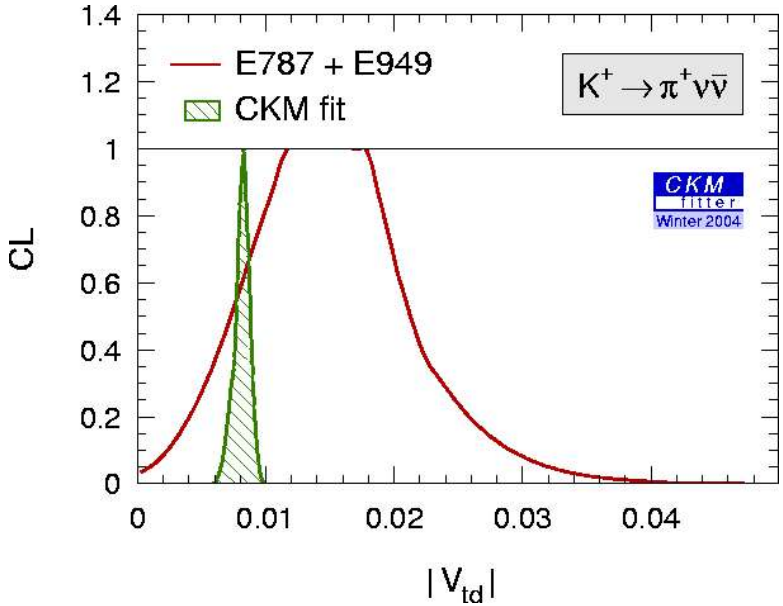
combined E787,E949

PRL **93** (2004) 031801

Impact on unitarity triangle

CKM fitter: hep-ph/0406184

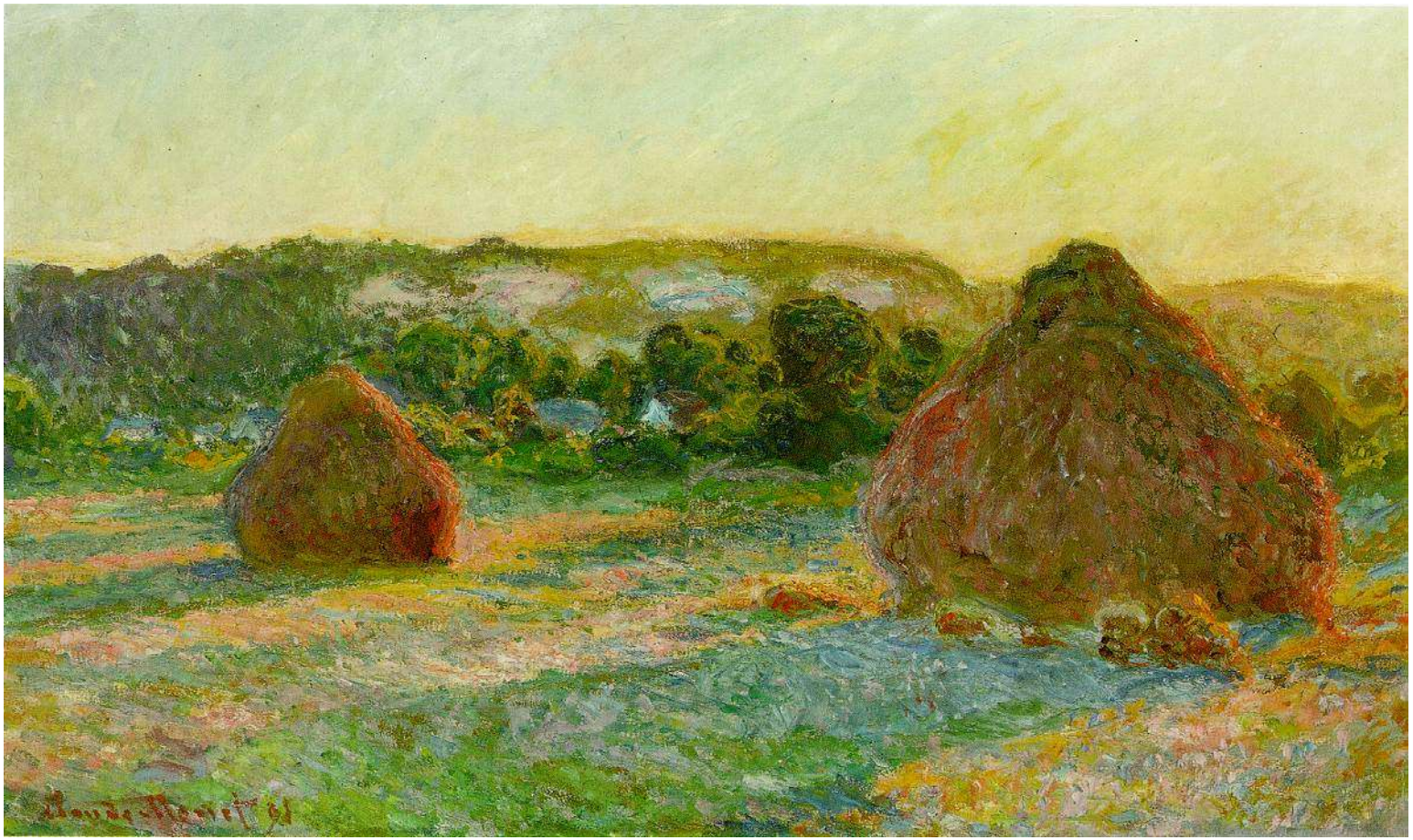




Still room for new physics to appear in ΔF=1 kaon decays.

Needs more data.

“Region 2” $p(\pi) < 195$ MeV/c



Claude Monet
Wheatstacks (End of Summer), 1890
Art Institute of Chicago

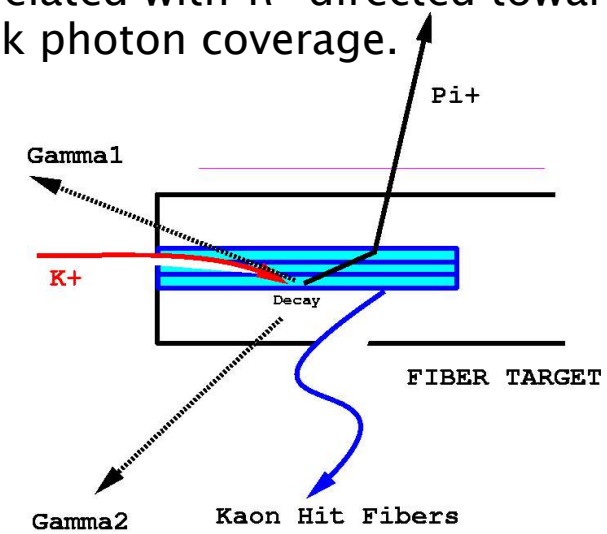
"Region 2" p(π) < 195 MeV/c

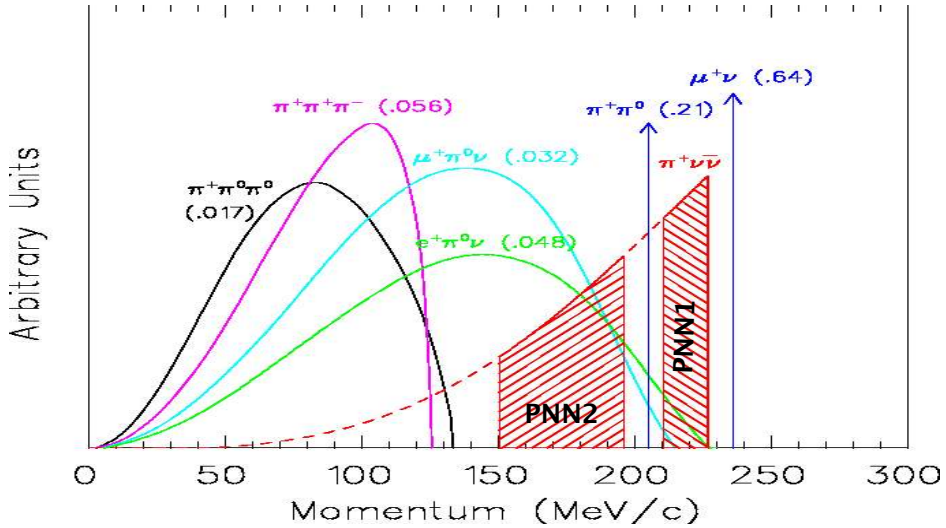
Potentially big gains to be had:

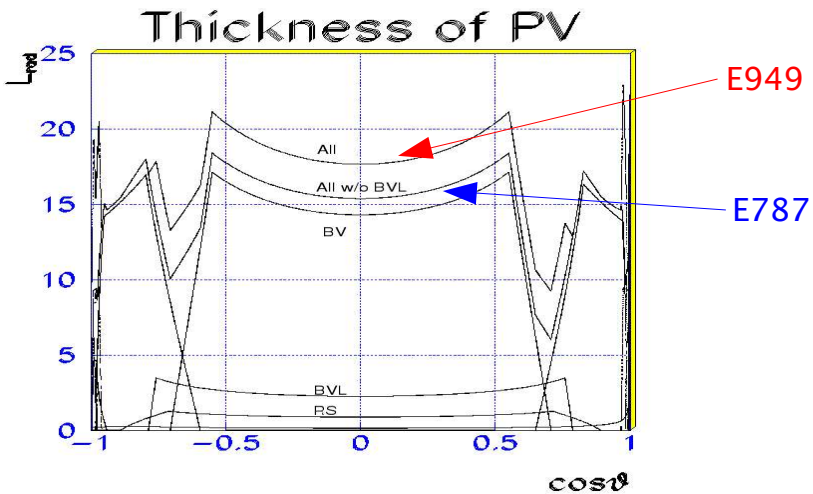
- x2 phase space
- x1.5 fewer pions disappearing (via interactions) before stopping

Gives access to π spectrum shape.

However, very severe background from Kπ2: pion scattering in target (downshift in R,E,P) correlated with π^0 directed towards area of weak photon coverage.

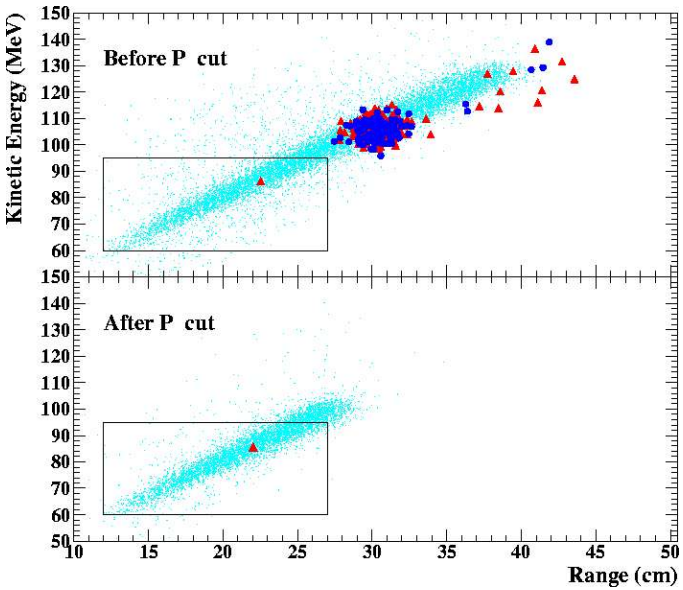






"Region 2" $p(\pi) < 195$ MeV/c

Region 2 analysis of E787 1997 data
(PRD **70** (2004) 037102)



	E787 (1996)	E787 (1997)
N(K)	1.12×10^{-12}	0.61×10^{-12}
Total acceptance	7.65×10^{-4}	9.7×10^{-4}
Total background	0.73 ± 0.18	0.49 ± 0.16
# events seen	1	0

$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) < 2.2 \times 10^{-9}$ @ 90%CL
E787 1996+1997 combined

Need x2 in acceptance and x5 in bkg rejection in E949 to reach S/N=1 with comparable sensitivity to region 1.

Analysis in progress. Focused on photon veto and target scattering.

Future and conclusion

Georgia O'Keefe
Black Cross, New Mexico, 1929
Art Institute of Chicago

Conclusion

- E949 upgrade successful. Detector performed well at higher rates.
- Backgrounds well understood. Likelihood analysis extended to regions of higher background than E787, giving more signal acceptance.
- All E787and E949 data in region 1 ($p(\pi)>211$ MeV/c) have been analyzed. $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 1.47\ (+1.30, -0.89) \times 10^{-12}$ based on 3 candidates. There is a tension with the CKM fits from B decays, but more data is needed.
- Highly likely that E949 would have reached its goal if run to completion. But alas, E949 only ran for 20% of the approved running time.
- Analysis of region 2 ($p(\pi)<195$ MeV/c) is in progress. Hoping to achieve S/N ~ 1 in this region.
- More running of E949? NSF proposal...

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Q: "Are you an optimist?"
A: "I remain a willing prisoner of hope." – Bishop Desmond Tutu