BNL E949 collaboration

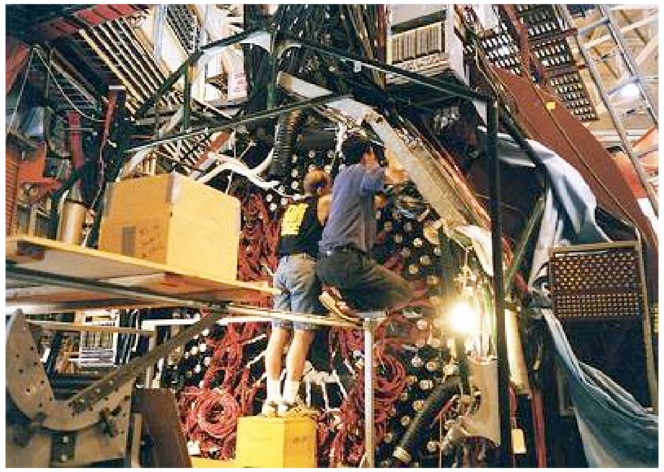
> 60 physicists, 16 institutes from Canada, China, Japan, Russia and the US.

A.V. Artamonov[1], B. Bassalleck[2], B. Bhuyan[3], E.W. Blackmore[4], D.A. Bryman[5], S. Chen[6,4], I-H. Chiang[3], I.-A. Christidi[7], P.S. Cooper[8], M.V. Diwan[3], J.S. Frank[3], T. Fujiwara[9], J. Hu[4], J. Ives[5], D.E. Jaffe[3], S. Kabe[10], S.H. Kettell[3], M.M. Khabibullin[11], A.N. Khotjantsev[11], P. Kitching[12], M. Kobayashi[10], T.K. Komatsubara[10], A. Konaka[4], A.P. Kozhevnikov[1], Yu.G. Kudenko[11], A. Kushnirenko[8], L.G. Landsberg[1], B. Lewis[2], K.K. Li[3], L.S. Littenberg[3], J.A. Macdonald[4], J. Mildenberger[4], O.V. Mineev[11], M. Miyajima[13], K. Mizouchi[9], V.A. Mukhin[1], N. Muramatsu[14], T. Nakano[14], M. Nomachi[15], T. Nomura[9], T. Numao[4], V.F. Obraztsov[2], K. Omata[10], D.I. Patalakha[1], S.V. Petrenko[1], R. Poutissou[4], E.J. Ramberg[8], G. Redlinger[3], T. Sato[10], T. Sekiguchi[10], T. Shinkawa[16], R.C. Strand[3], S. Sugimoto[10], Y. Tamagawa[13], R. Tschirhart[8], T. Tsunemi[10], D.V. Vavilov[1], B. Viren[3], Zhe Wang[6,3], N.V. Yershov[11], Y. Yoshimura[10] and T. Yoshioka[10]

1. Institute for High Energy Physics (IHEP), 2. University of New Mexico (UNM), 3. Brookhaven National Laboratory (BNL), 4. TRIUMF, 5. University of British Columbia, 6. Tsinghua University 7. Stony Brook University, 8. Fermi National Accelerator Laboratory (FNAL), 9. Kyoto University, 10. High Energy Accelerator Research Organization (KEK), 11. Institute for Nuclear Research (INR), 12. Centre for Subatomic Research, University of Alberta, 13. Fukui University, 14. Research Center for Nuclear Physics (RCNP), Osaka University, 15. Osaka University, and 16. National Defense Academy.

E949 institutes

- Japan: KEK(+Tokyo), RCNP, Fukui, Kyoto, Osaka, NDA
- US: BNL, FNAL, Stony Brook, New Mexico
- Canada: TRIUMF, Alberta, British Columbia
- Russia: IHEP, INR
- China: Tsinghua

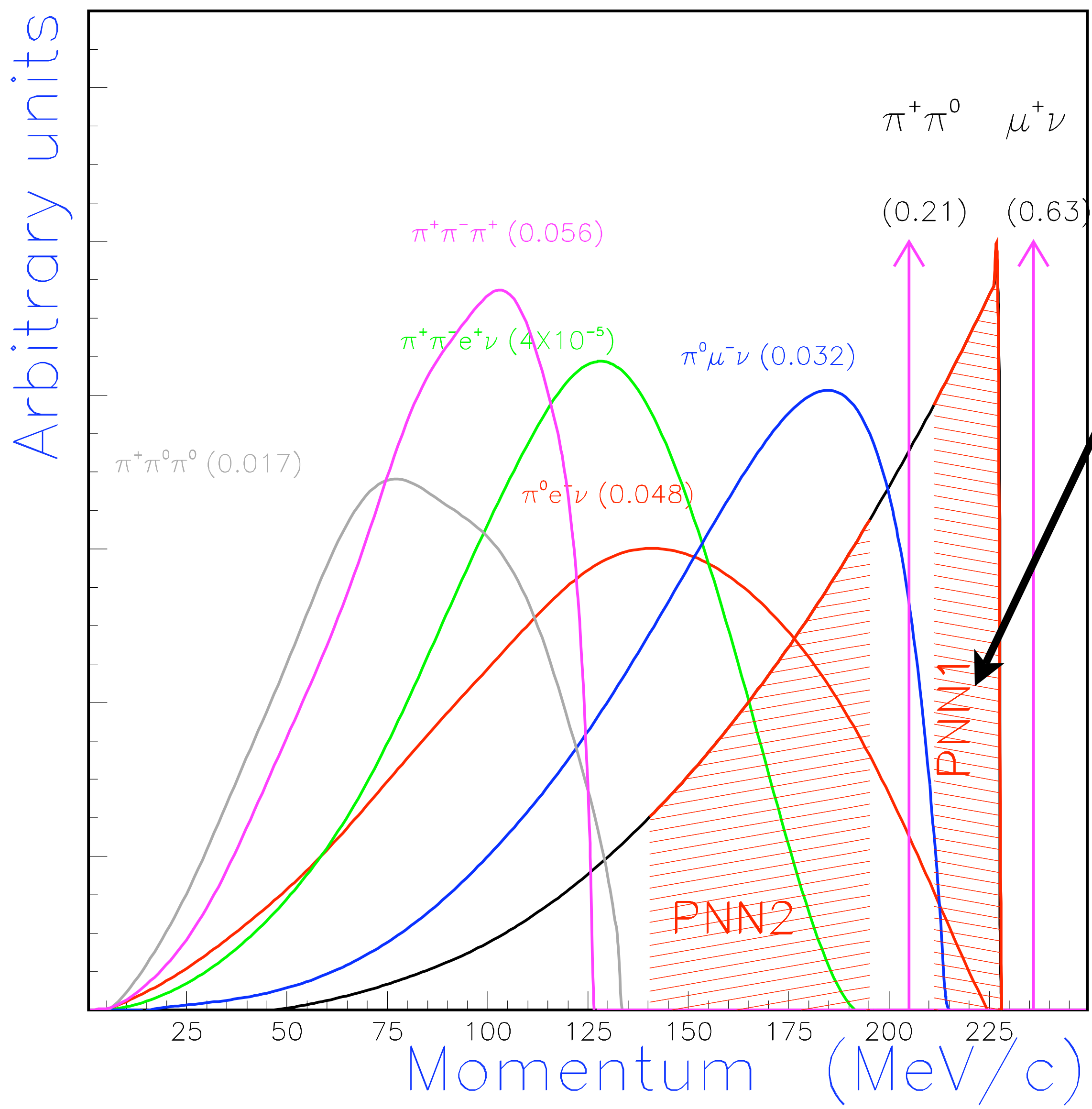


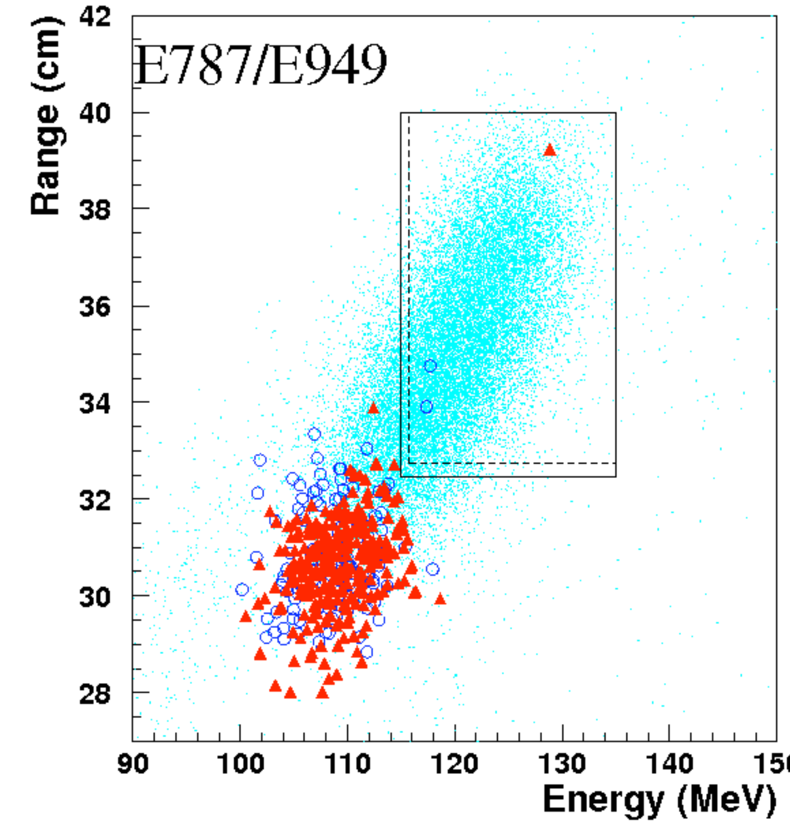
BNL-E787 (-1998)
E949 proposed (1998), approved (1999)
construction/upgrade (-2001)
engineering run (2001)
First (and last) Physics Run (2002)

First results (2004)

PNN1: above $K_{\pi 2}$

π^+ momentum from K^+ decay at rest





KEK Physics Seminar (April 7, 2004)

Phys. Rev. Lett. **93**, 031801 (2004)

Phys. Rev. **D77**, 052003 (2008)

First results (2004)

PNN1: above $K_{\pi 2}$

PHYSICAL REVIEW D **77**, 052003 (2008)

Measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio

S. Adler,[1] V. V. Anisimovsky,[2] M. Aoki,[3,*] M. Ardebili,[4] A. V. Artamonov,[5] M. Atiya,[1] B. Bassalleck,[6] A. O. Bazarko,[4] B. Bhuyan,[1,†] E. W. Blackmore,[3] D. A. Bryman,[7] S. Chen,[8,3] I-H. Chiang,[1] I.-A. Christidi,[9,‡] M. R. Convery,[4] P. S. Cooper,[10] M. V. Diwan,[1] J. S. Frank,[1] T. Fujiwara,[11] J. Haggerty,[1] J. Hu,[3] T. Inagaki,[12] M. M. Ito,[4] A. P. Ivashkin,[2] D. E. Jaffe,[1] S. Kabe,[12] M. Kazumori,[12,§] Y. Kuno,[12,*] M. Kuriki,[12,‖] S. H. Kettell,[1] M. M. Khabibullin,[2] A. N. Khotjantsev,[2] P. Kitching,[13] M. Kobayashi,[12] T. K. Komatsubara,[12] A. Konaka,[3] A. P. Kozhevnikov,[5] Yu. G. Kudenko,[2] A. Kushnirenko,[10,¶] L. G. Landsberg,[5,**] B. Lewis,[6] K. K. Li,[1] L. S. Littenberg,[1] J. A. Macdonald,[3,**] D. R. Marlow,[4] R. A. McPherson,[4] P. D. Meyers,[4] J. Mildenberger,[3] O. V. Mineev,[2] M. Miyajima,[14] K. Mizouchi,[11] V. A. Mukhin,[5] N. Muramatsu,[15] T. Nakano,[15] M. Nomachi,[16] T. Nomura,[11] T. Numao,[3] V. F. Obraztsov,[5] K. Omata,[12] D. I. Patalakha,[5] S. V. Petrenko,[5] R. Poutissou,[3] E. J. Ramberg,[10] G. Redlinger,[1] T. Sato,[12] T. Sekiguchi,[12] T. Shinkawa,[17] F. C. Shoemaker,[4] A. J. S. Smith,[4] J. R. Stone,[4] R. C. Strand,[1] S. Sugimoto,[12] Y. Tamagawa,[14] R. Tschirhart,[10] T. Tsunemi,[12,††] D. V. Vavilov,[5,‡‡] B. Viren,[1] N. V. Yershov,[2] Y. Yoshimura,[12] and T. Yoshioka[12,§§]

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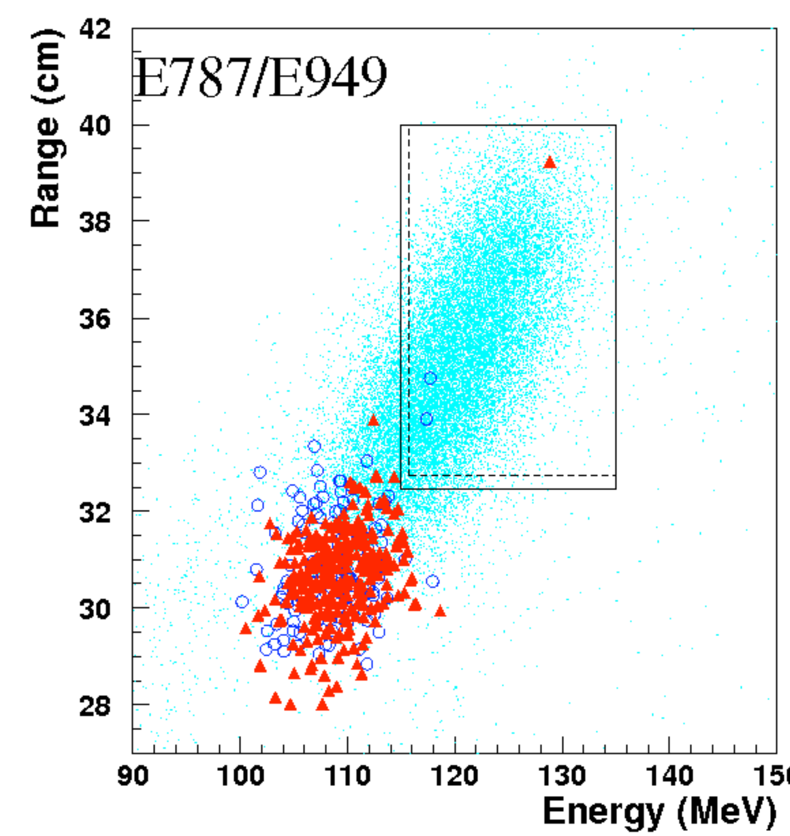
(Received 6 September 2007; published 13 March 2008)

Experiment E949 at Brookhaven National Laboratory studied the rare decay $K^+ \to \pi^+ \nu \bar{\nu}$ and other processes with an exposure of 1.77×10^{12} K^+'s. The data were analyzed using a blind analysis technique yielding one candidate event with an estimated background of 0.30 ± 0.03 events. Combining this result with the observation of two candidate events by the predecessor experiment E787 gave the branching ratio $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$, consistent with the standard model prediction of $(0.74 \pm 0.20) \times 10^{-10}$. This is a more detailed report of results previously published [V. V. Anisimovsky *et al.*, Phys. Rev. Lett. **93**, 031801 (2004)].

DOI: 10.1103/PhysRevD.77.052003 PACS numbers: 13.20.Eb, 12.15.Hh, 14.80.Mz



KEK Physics Seminar (April 7, 2004)

Phys. Rev. Lett. **93**, 031801 (2004)

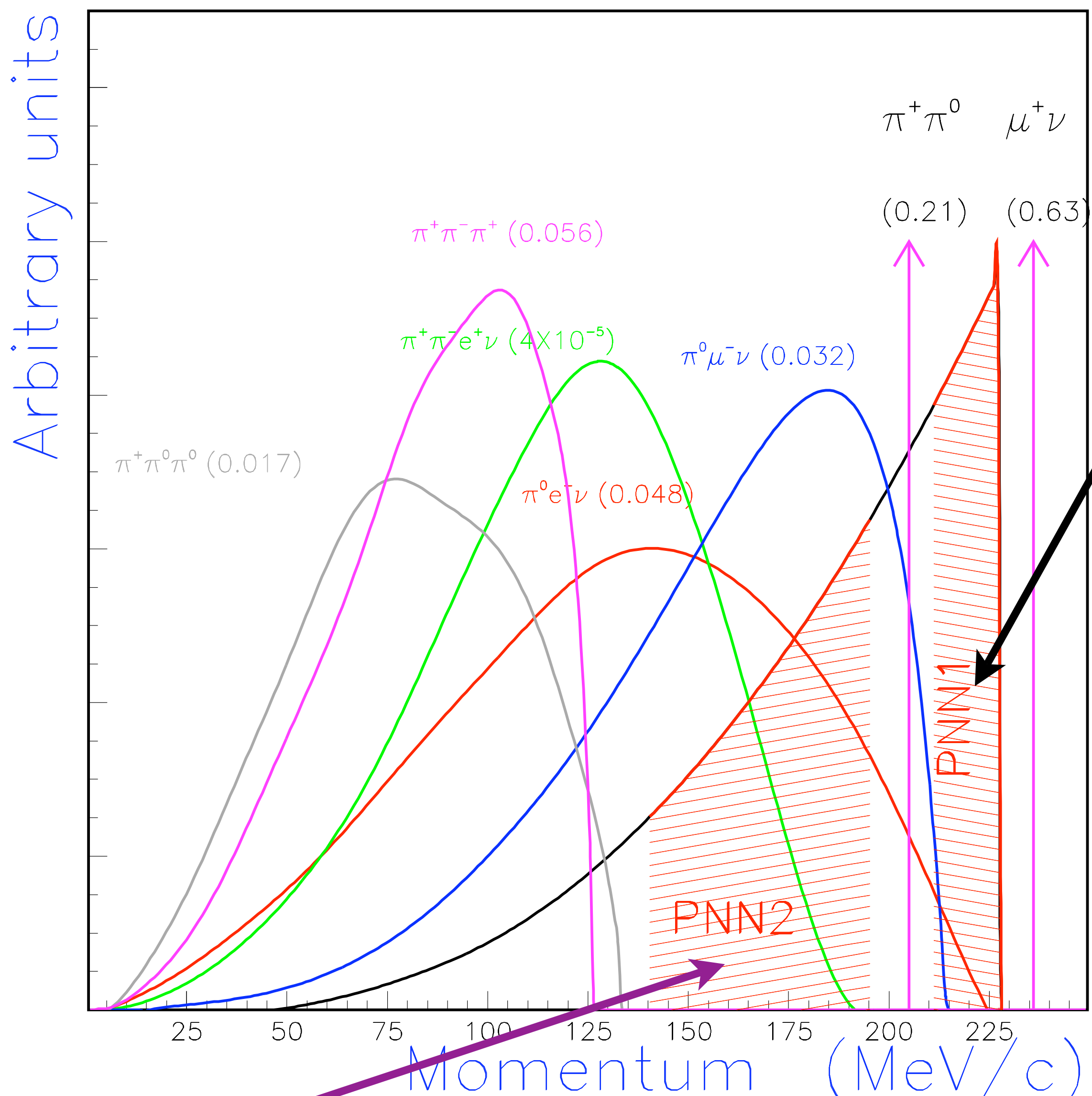
Phys. Rev. **D77**, 052003 (2008)

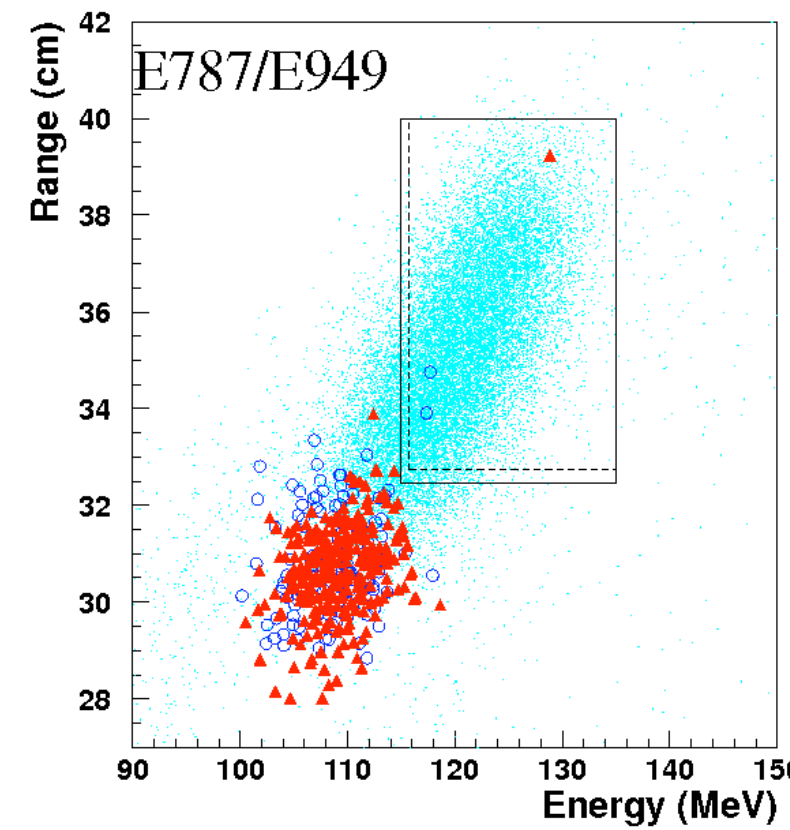
(including E787 collaborators to the authors)

First results (2004)

PNN1: above $K_{\pi 2}$

π^+ momentum from K^+ decay at rest





Final results (today)

PNN2: below $K_{\pi 2}$

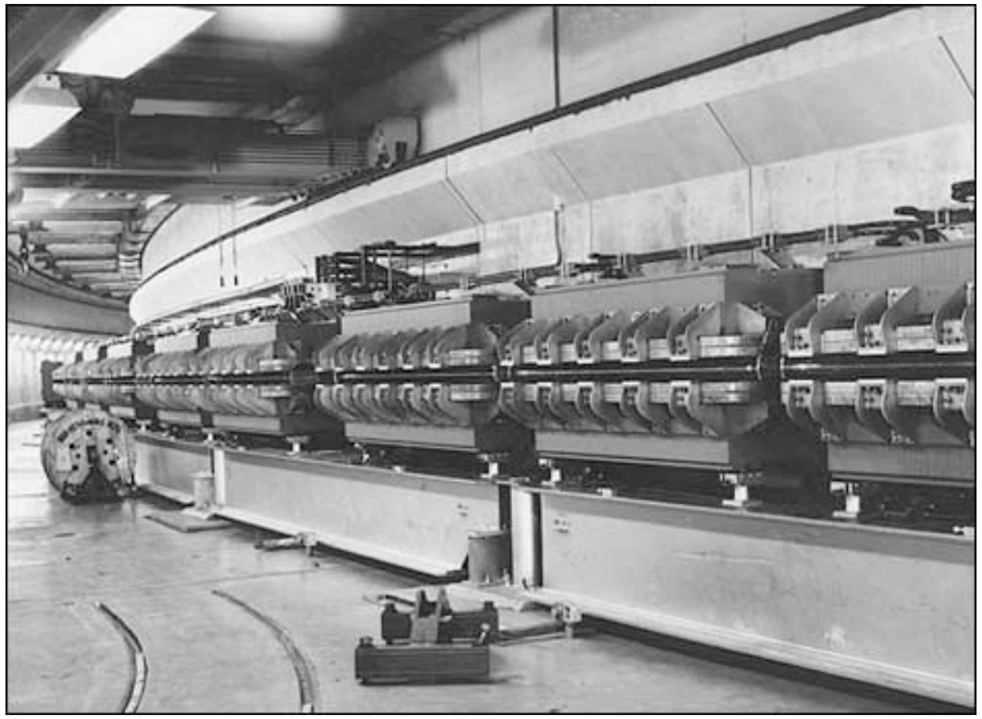
and E787+E949, PNN1 and 2, all combined

FINAL Results from BNL-E949 on the Rare Decay $K^+ \to \pi^+ \nu\bar{\nu}$

Takeshi K. Komatsubara (KEK-IPNS)

representing the E949 collaboration

- arXiv:0808:2459
- CKM2008 workshop at Roma, Sept 9-13 by D.E, Jaffe (BNL)



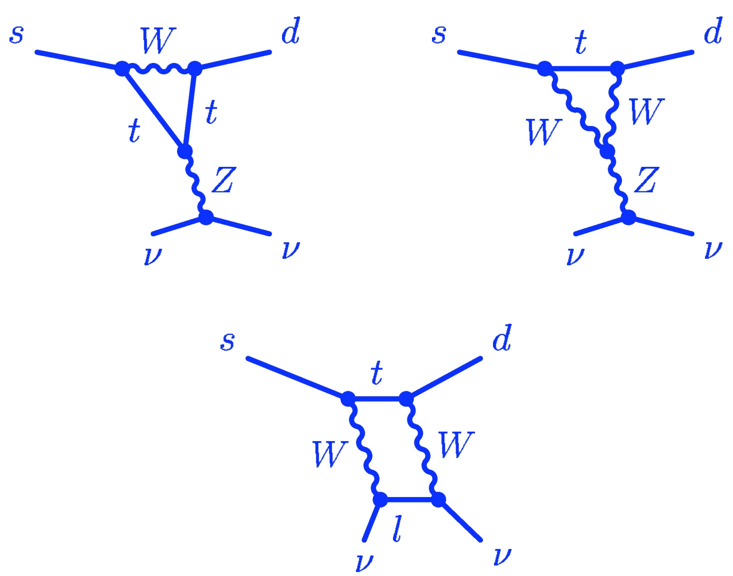
KEK Physics Seminar, September 16, 2008

[in 58 slides, 50 minutes]

outline

- introduction
- $K^+ \to \pi^+ \nu \bar{\nu}$
  in and beyond the Standard Model
- BNL AGS and E949 in 2002:
  experiment with K+ decay at rest (and the " jargons ")
- analysis for PNN2: why different and difficult ?
- results
- conclusions and future

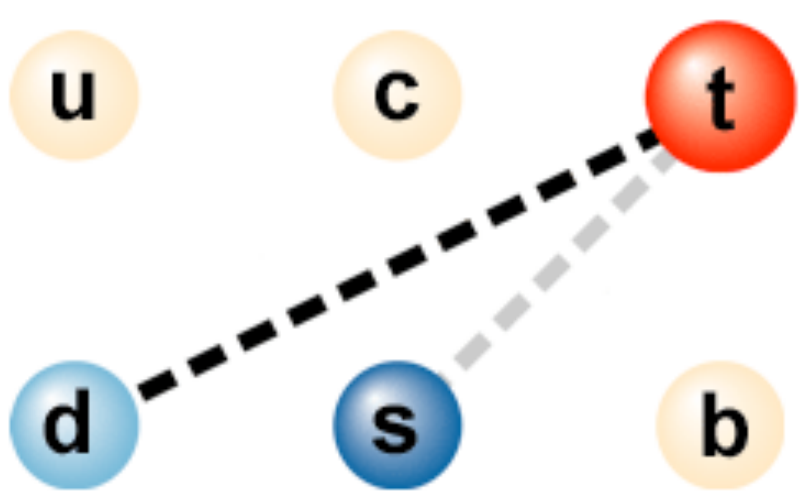
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay



- Standard Model:
  $s \rightarrow d$ FCNC loop $(W^{\pm}/Z^0)$
- top-quark (174 GeV/c^2) dominant
- $\lambda_t \equiv V_{ts}^* \cdot V_{td}$

  $= -A^2\lambda^5 \cdot (1 - \rho - i\eta)$:

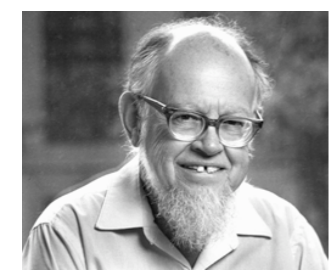
  best place to determine $|\lambda_t|$ (or $|V_{td}|$)



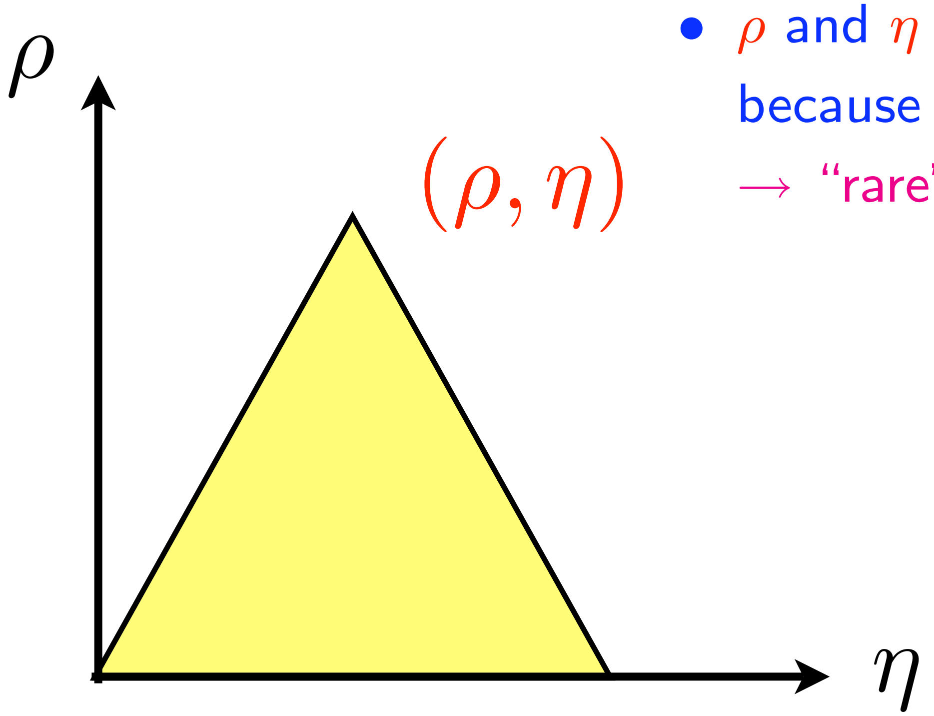
Cabibbo(1963)-Kobayashi-Maskawa(1972) matrix

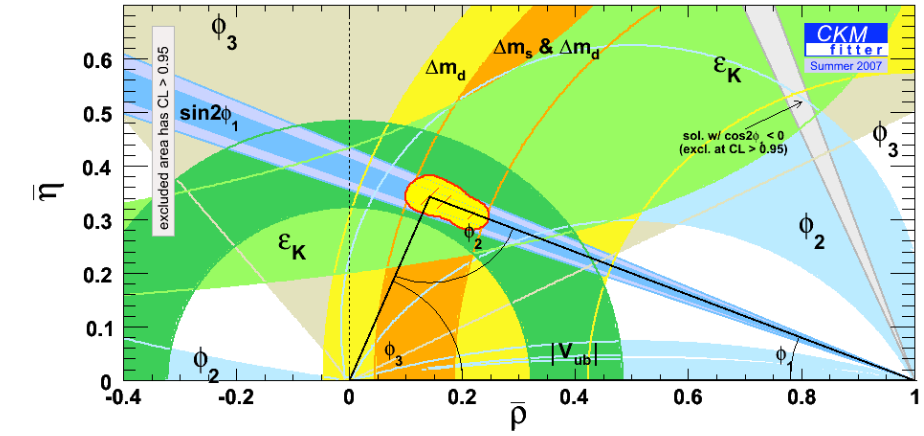
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} .975 & .22 & .002-.005 \\ .22 & .974 & .038-.044 \\ .004-.014 & .037-.044 & .999 \end{pmatrix}$$

$$\simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

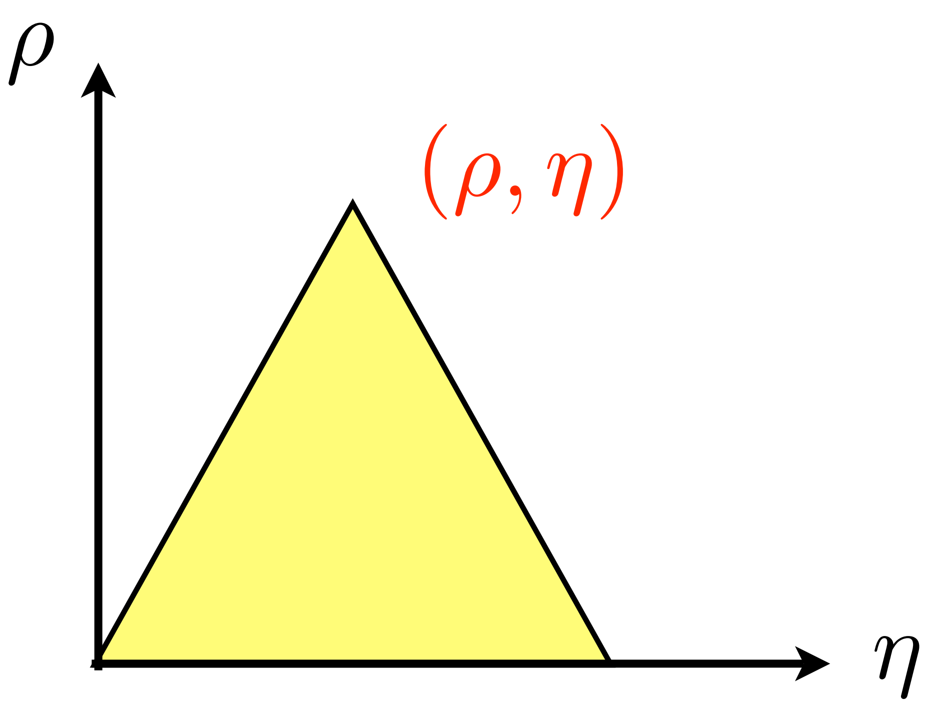


- Wolfenstein parameterization (1983) :
  $\lambda \equiv sin\theta_C = 0.22,\ A,\ \rho,\ \eta.$
- ρ and η are hard to measure,
  because they are in V_{ub} and V_{td} of $O(\lambda^3)$.
  → "rare" processes in K and B decays.

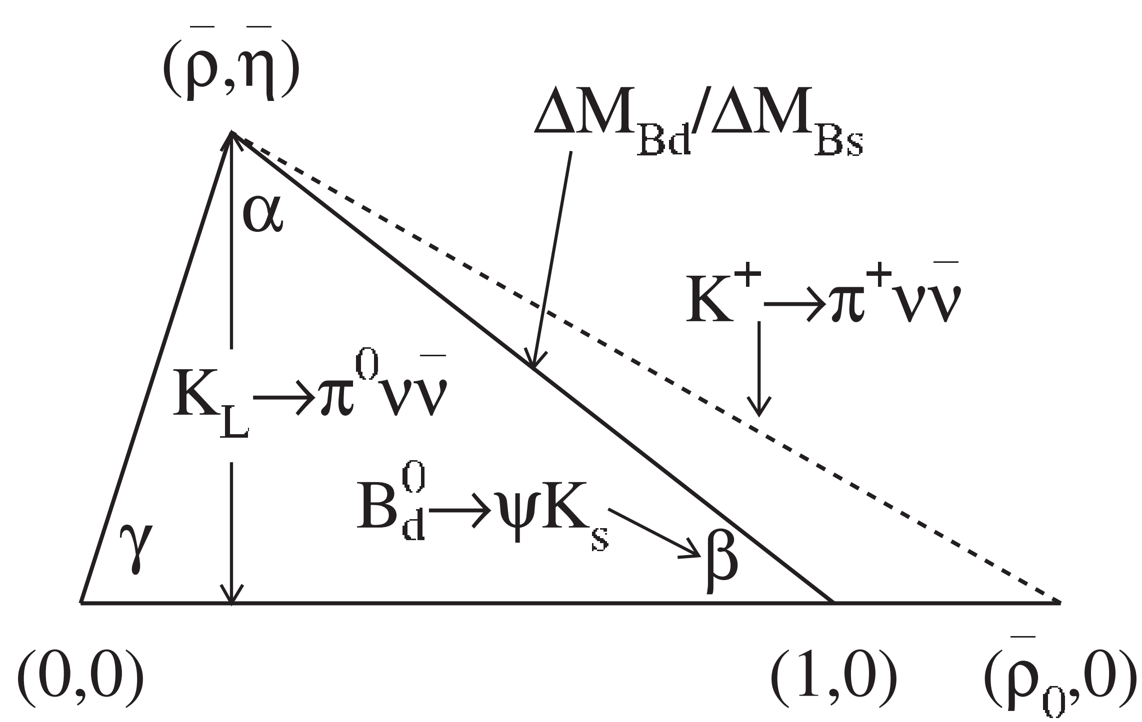




CKM fitter
Summer 2007
excluded area has CL > 0.95
sin2ϕ_1
Δm_d
Δm_s & Δm_d
ε_K
sol. w/ cos2ϕ_1 < 0
(excl. at CL > 0.95)
$|V_{ub}|$
ϕ_1
ϕ_2
ϕ_3
$\bar{\eta}$
$\bar{\rho}$

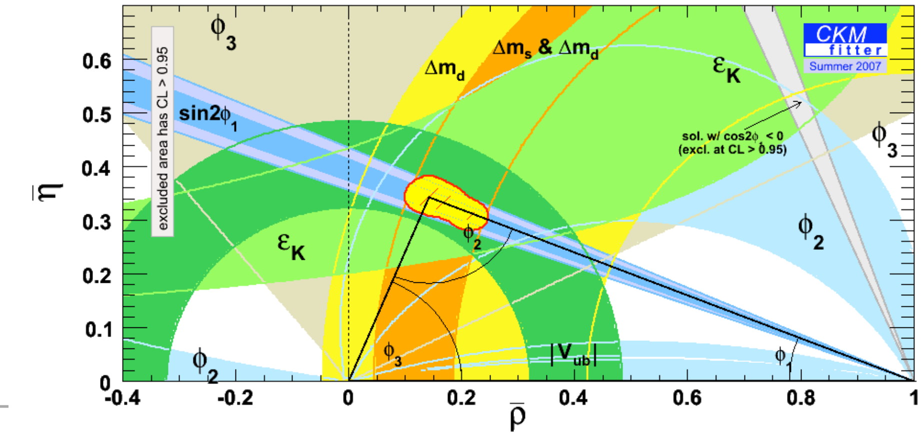


ρ
(ρ, η)
η



$(\bar{\rho},\bar{\eta})$
$\Delta M_{Bd}/\Delta M_{Bs}$
α
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$
$K_L \rightarrow \pi^0 \nu\bar{\nu}$
$B_d^0 \rightarrow \psi K_s$
γ
β
(0,0)
(1,0)
$(\bar{\rho}_0,0)$

in the SM: $K \to \pi\nu\bar{\nu}$



$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (\,5.30 \times 10^{-11}\,) \cdot C_{\pi\nu\bar{\nu}} \times [\,(\rho_0 - \rho)^2 + \eta^2\,]$$

$$\mathcal{B}(K_L^0 \to \pi^0 \nu\bar{\nu}) = (\,23.2 \times 10^{-11}\,) \cdot C_{\pi\nu\bar{\nu}} \times [\,\eta^2\,]$$

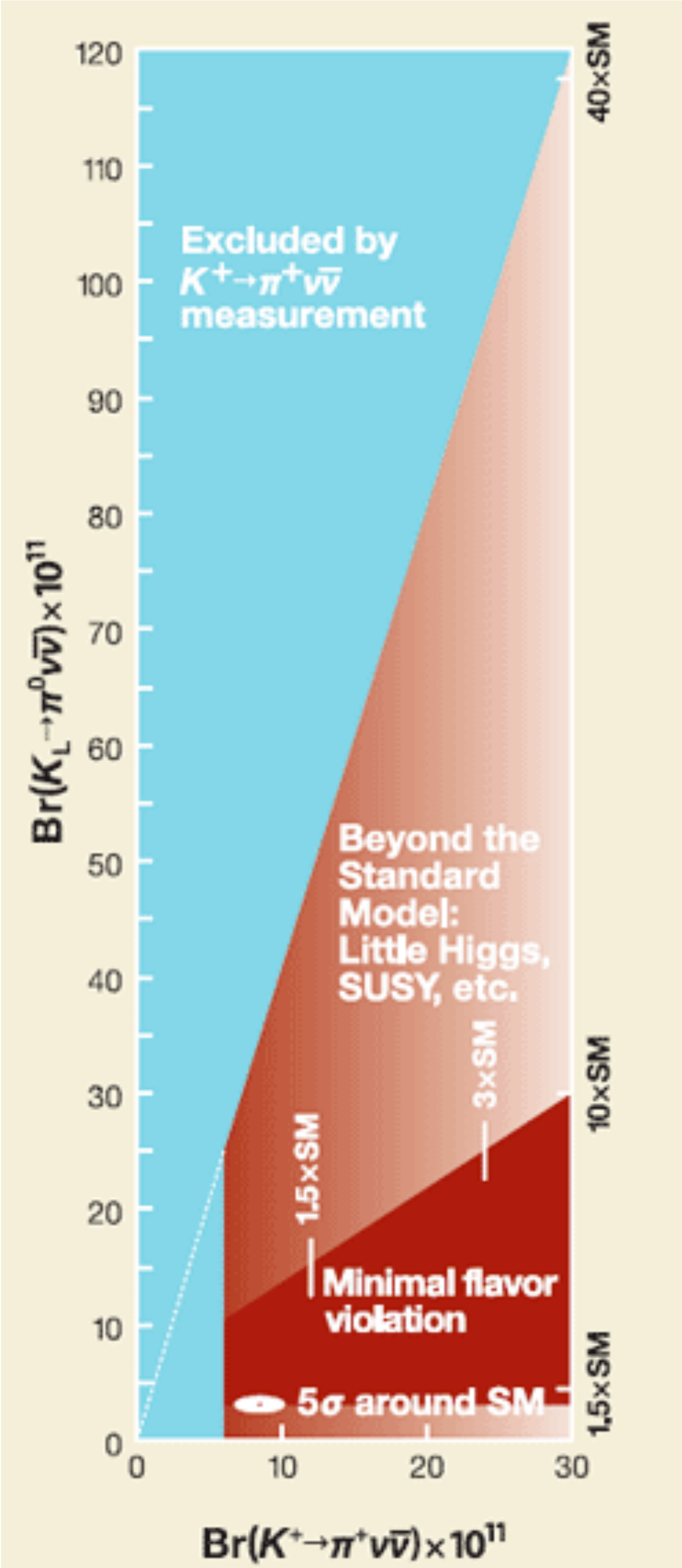
$$C_{\pi\nu\bar{\nu}} \equiv \left[\frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu)}{4.87 \times 10^{-2}}\right] \times \left[\frac{|V_{cb}|}{0.0415}\right]^4 \times \left[\frac{X(x_t)}{1.529}\right]^2$$

$\times 10^{-11}$

	2004	2008
K+	7.8 +- 1.2 (15%)	8.51 +- 0.70 (8%)
KL	3.0 +- 0.6 (20%)	2.76 +- 0.40 (14%)

- NNLO QCD calculations (Buras et al. ’05, ‘06)
- non-perturbative effects due to charm&up (Isidori et al. ’05)
- Kl3 matrix elements (Mescia-Smith ‘07)

- electroweak corrections to charm contribution (Brod-Gorbahn arXiv:0805.4119)
- a complete review by Buras, Schwab, Uhlig, Rev.Mod.Phys. 80, 965 (2008)



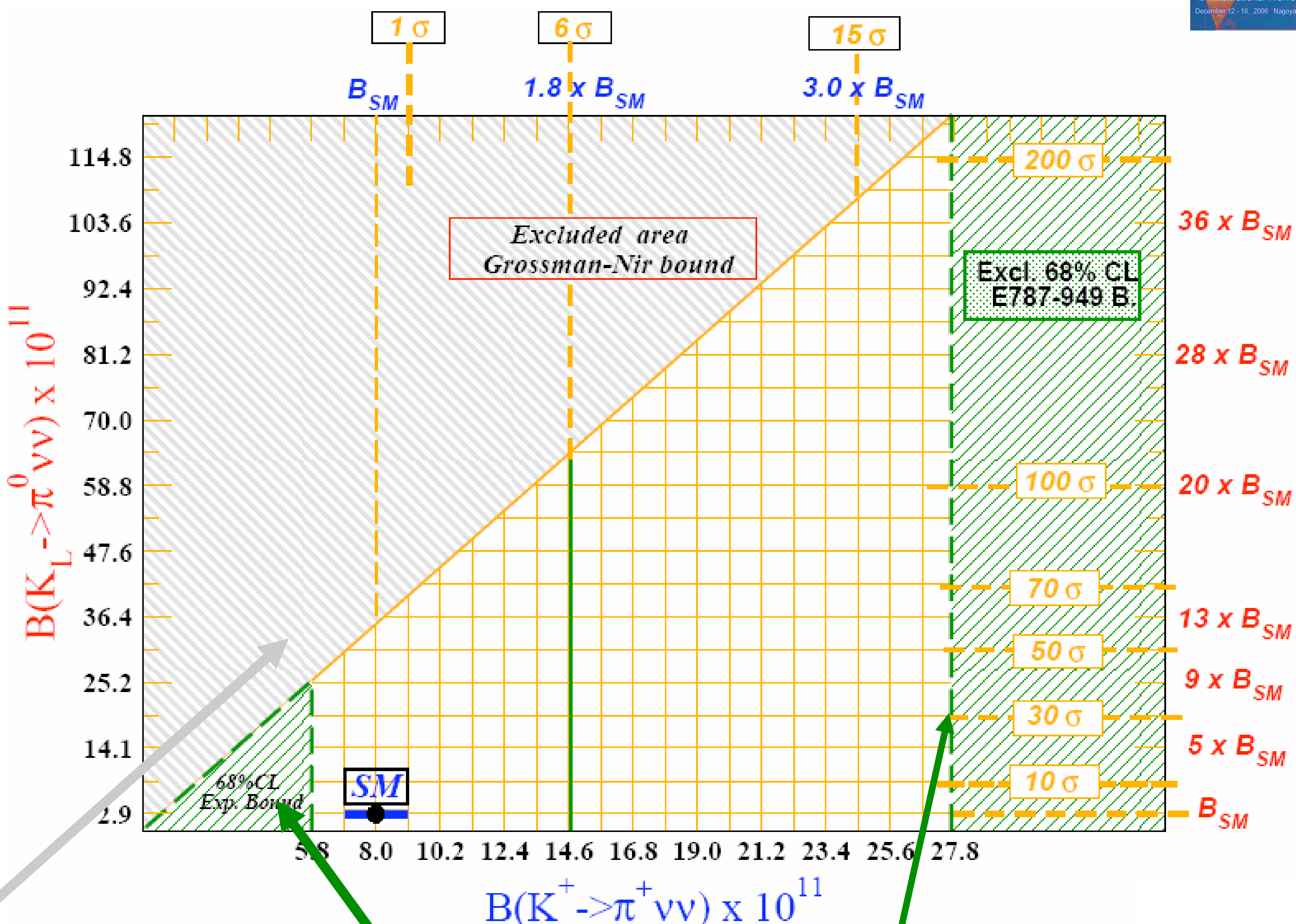
New Physics

illustrated in

Fermilab Steering Group Report (2007)

Federico Mescia @

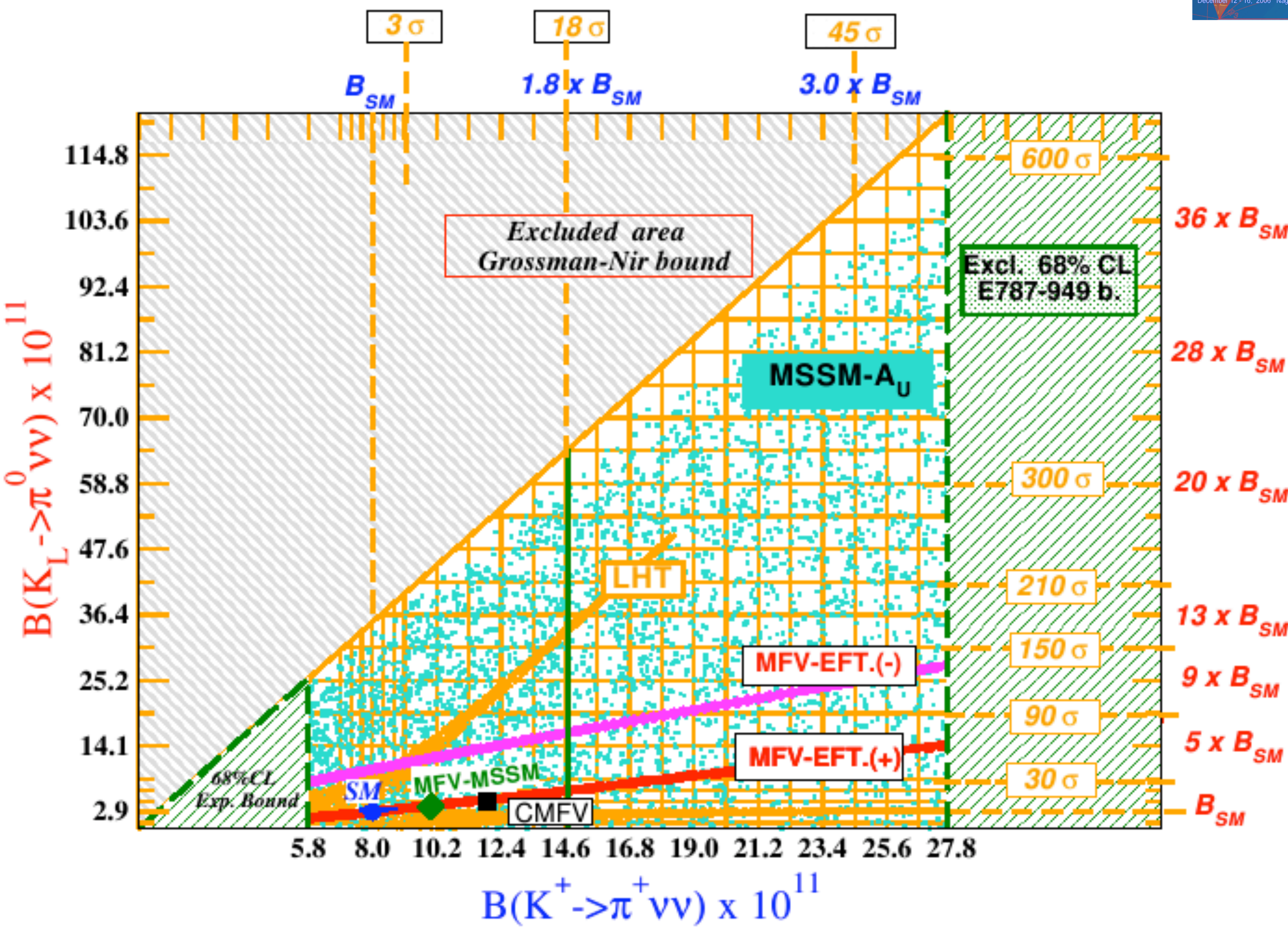
CKM 2006
4th International Workshop on the CKM Unitarity Triangle
December 12 - 16, 2006 Nagoya University, Nagoya, Japan



$B(K^+ \to \pi^+ \nu\bar{\nu}) = 14.7^{+13.0}_{-8.9} \times 10^{-11}$ [E787-E949]

$B(K_L \to \pi^0 \nu\bar{\nu}) \leq 4.4 B(K^+ \to \pi^+ \nu\bar{\nu})$ [Grosmann - Nir Bound]

Federico Mescia @

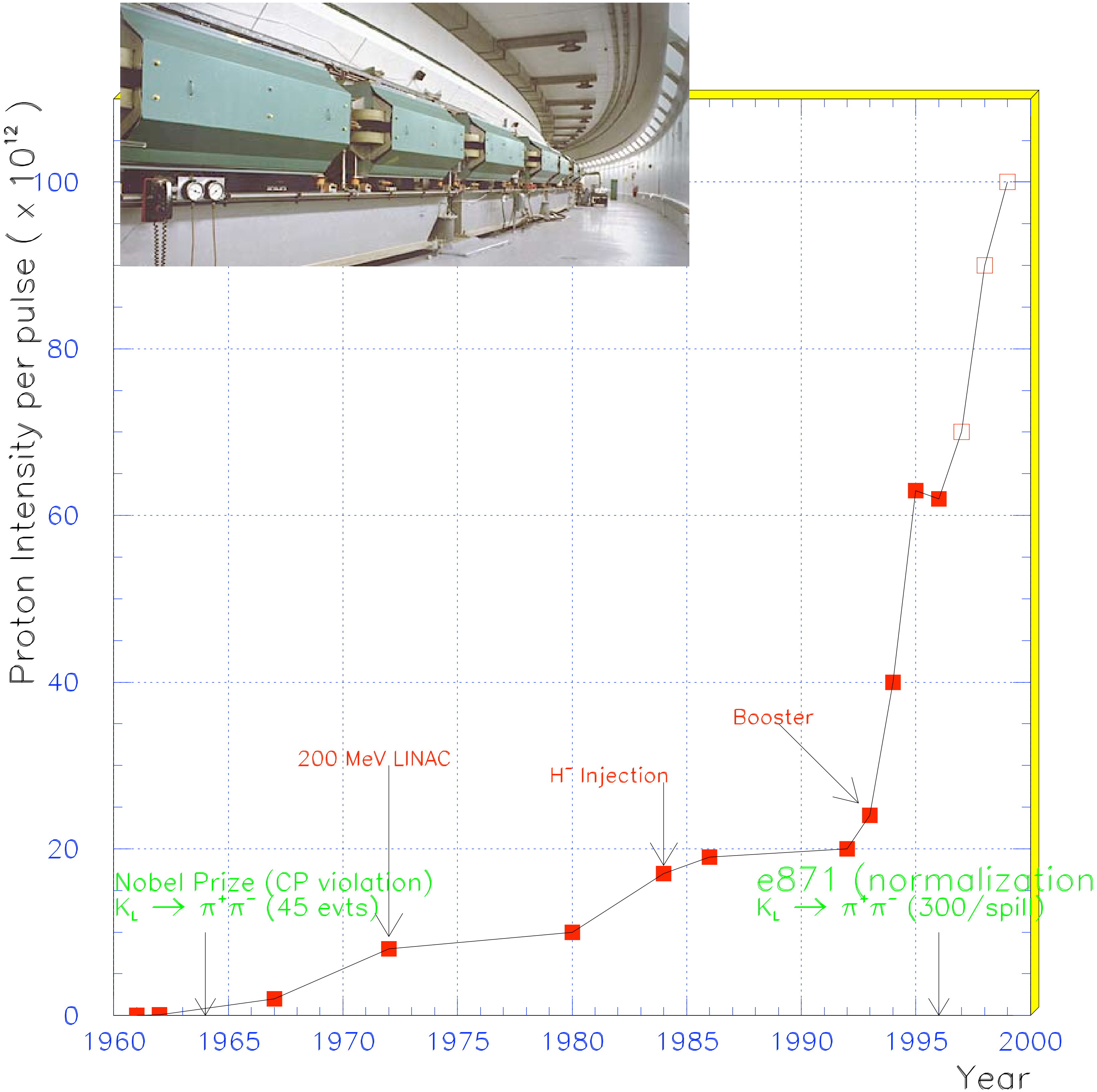


http://www.lnf.infn.it/wg/vus/content/Krare.html

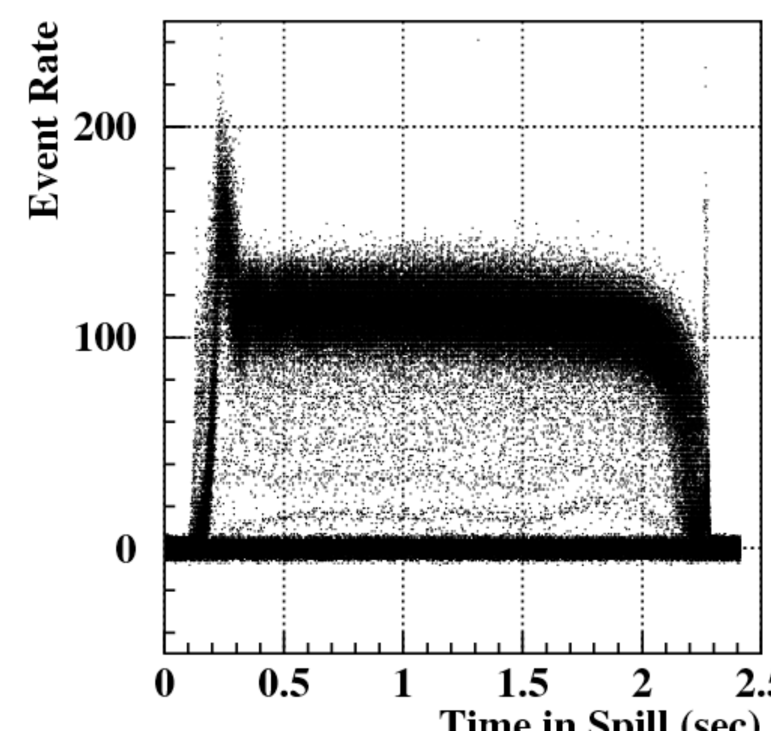
go back to E949 in 2002

That was the last time
AGS ever saw
high-intensity proton beam.

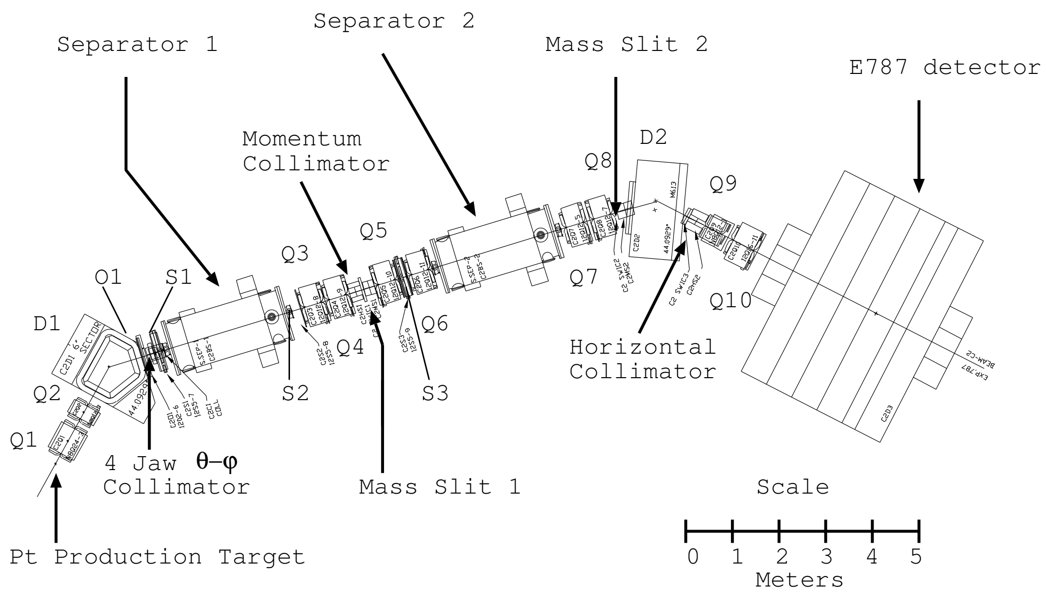
BNL-AGS: $\geq 60 \times 10^{12}$(Tera) protons per spill

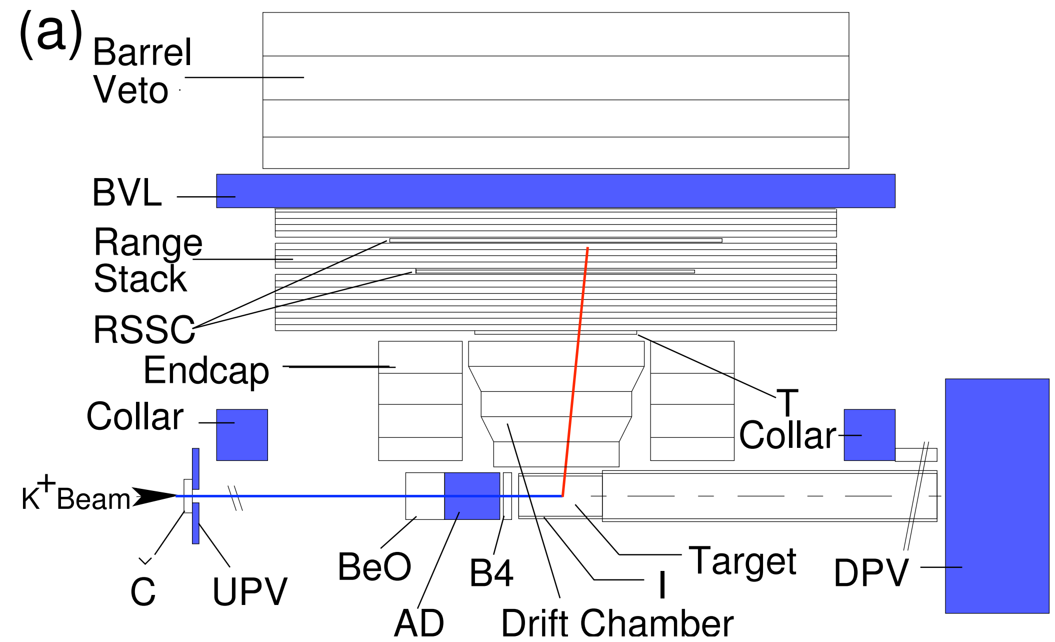


		E949-'02
protons per spill	Tp	65
AGS energy	GeV	22
beam spill	sec	2.2
cycle	sec	5.4
duty factor	%	41

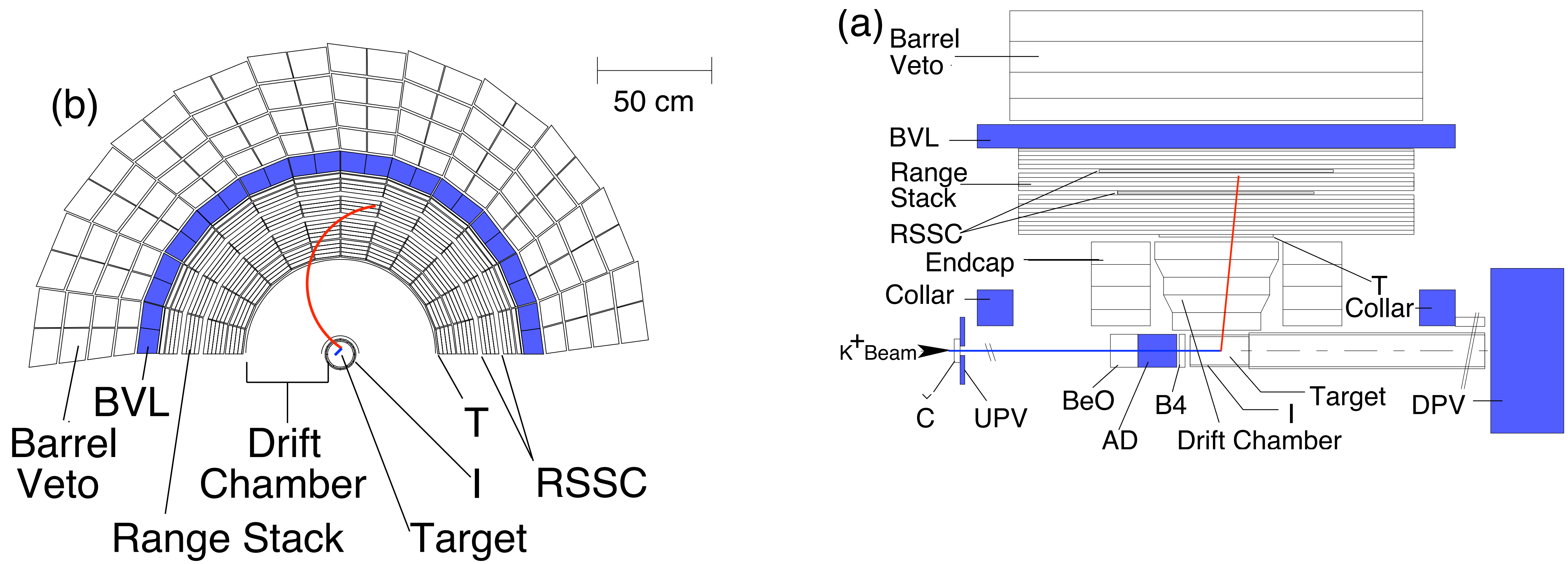


LESB3 → K^+ slowed by degrader and coming to rest





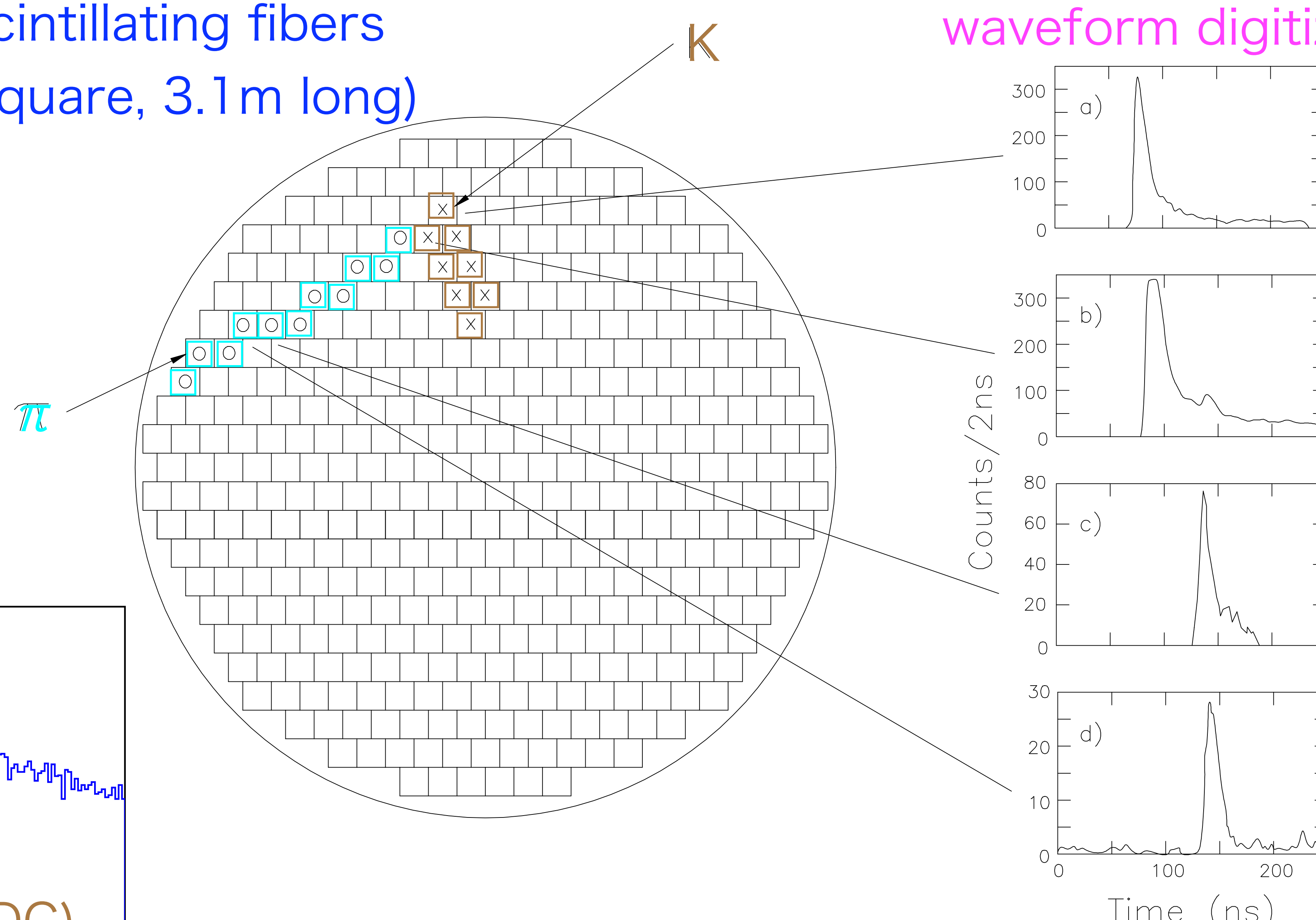
		E949-'02
K^+/π^+		3
kaon momentum	MeV/c	710
N_K in the spill	M	3.5
N_K	MHz	1.6
stopping fraction	%	28

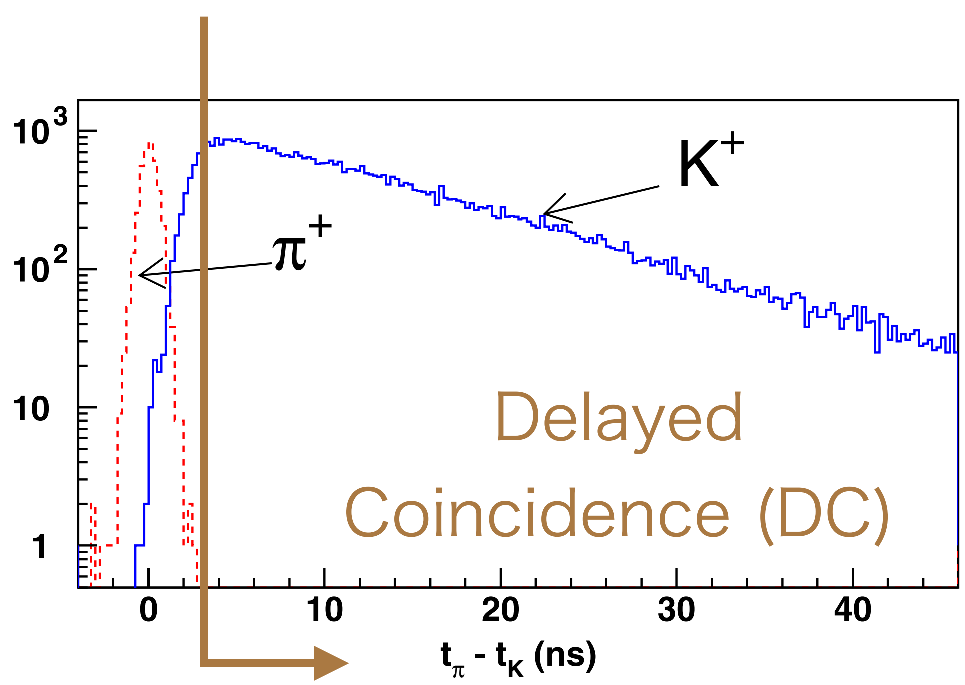

(b)
50 cm
BVL
Barrel Veto
Drift Chamber
Range Stack
Target
T
I
RSSC
(a)
Barrel Veto
BVL
Range Stack
RSSC
Endcap
Collar
T
Collar
K+Beam
C
UPV
BeO
AD
B4
Drift Chamber
I
Target
DPV

K+ decay at rest in the Target (end-view)

413 scintillating fibers
(5mm square, 3.1m long)

CCD-based 500MHz
waveform digitizers

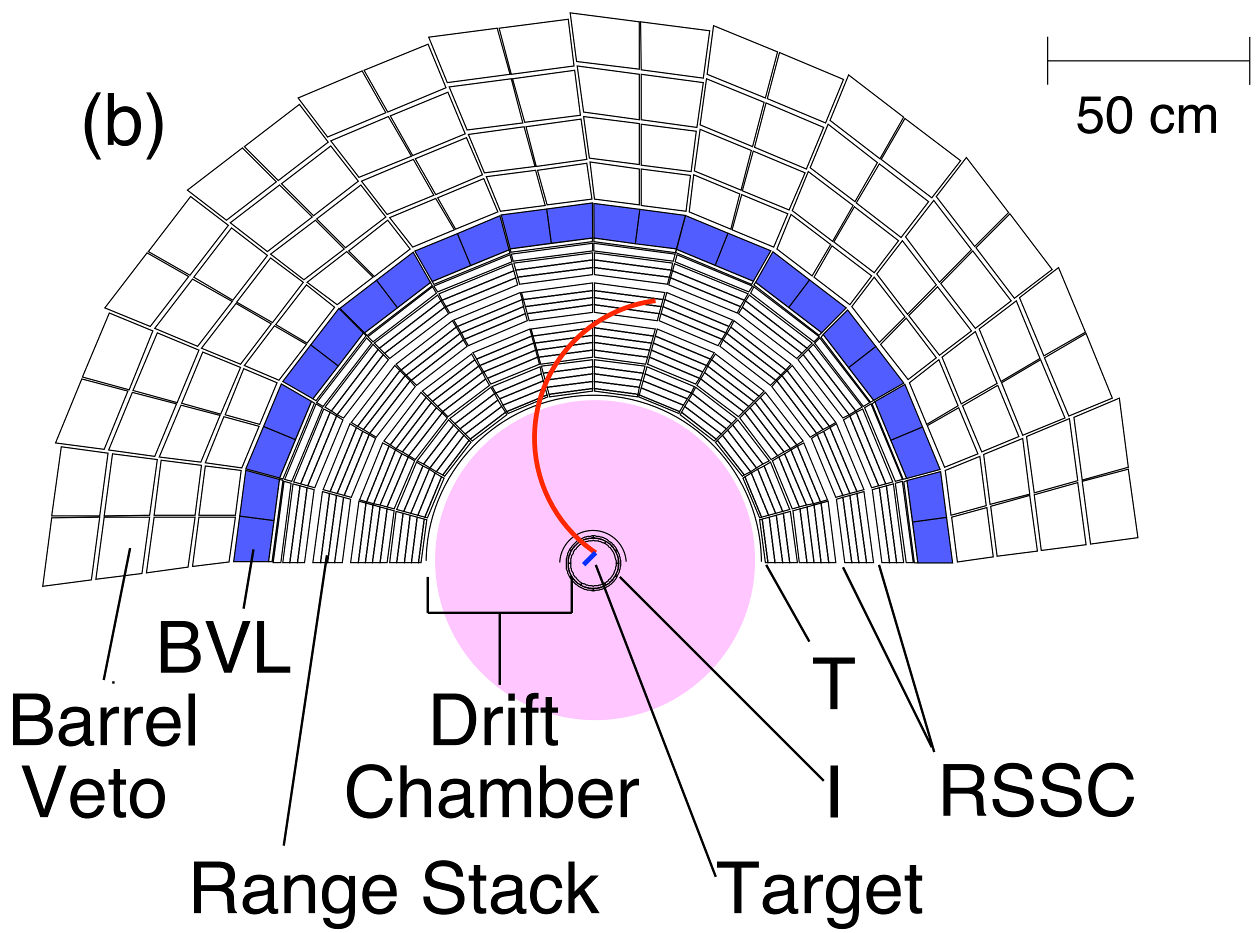


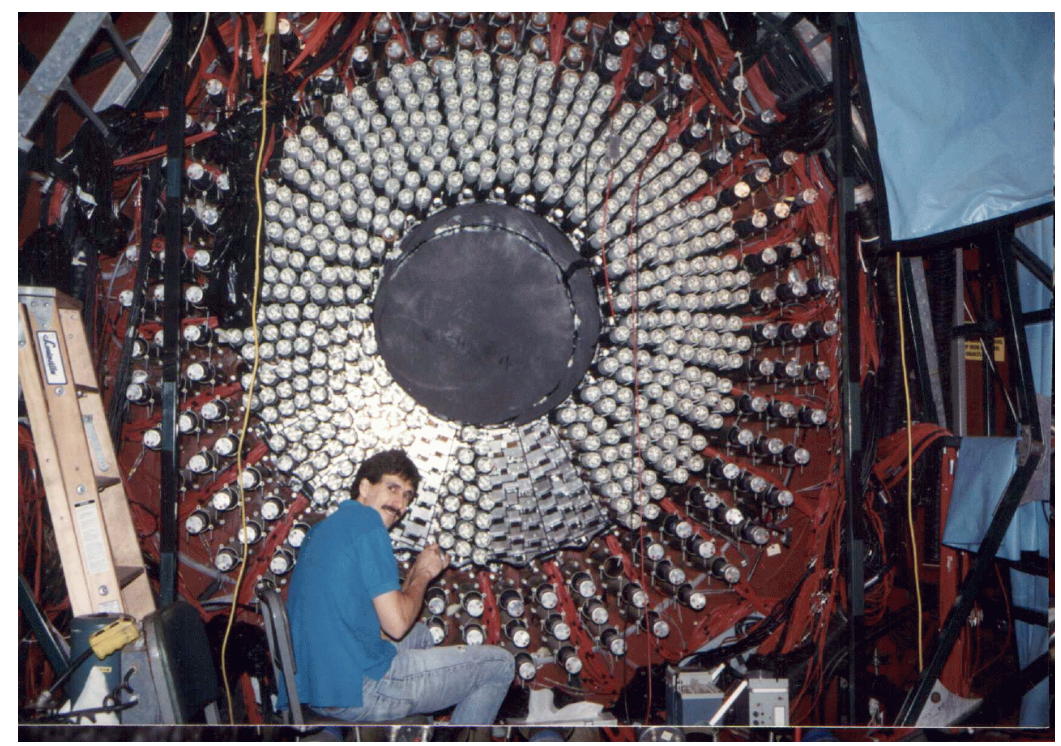


3ns in PNN2

- energy loss and path length of outgoing $\pi+$
- any "in-time" extra activity within the target

Charged track from the Target to the Range Stack





momentum and trajectory
with ultra-thin Drift Chamber

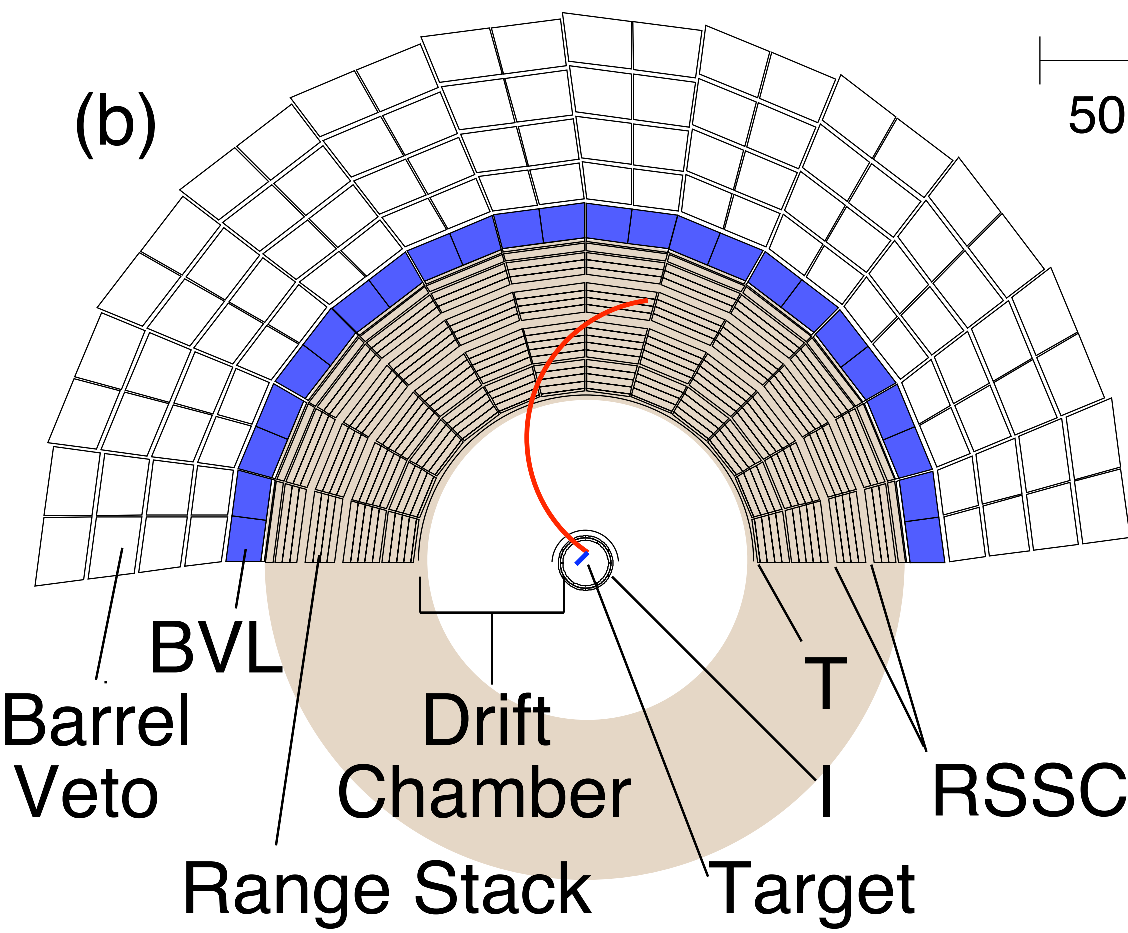
- correction with energy loss in the target

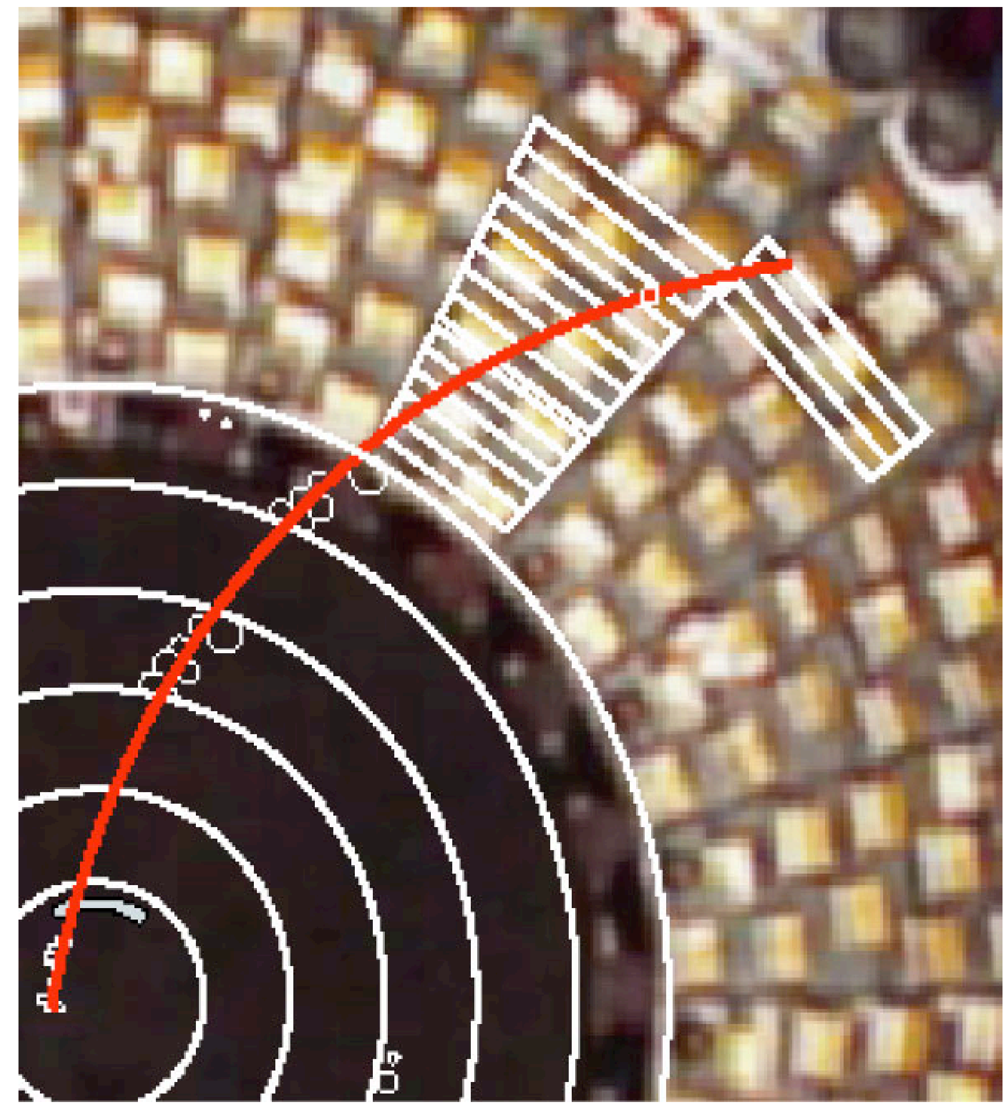
$\pi+$ loses energy, and comes to rest in the RS

sum of energy loss (= kinetic energy)

and

range in the plastic scintillator





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sum of energy loss (= kinetic energy)

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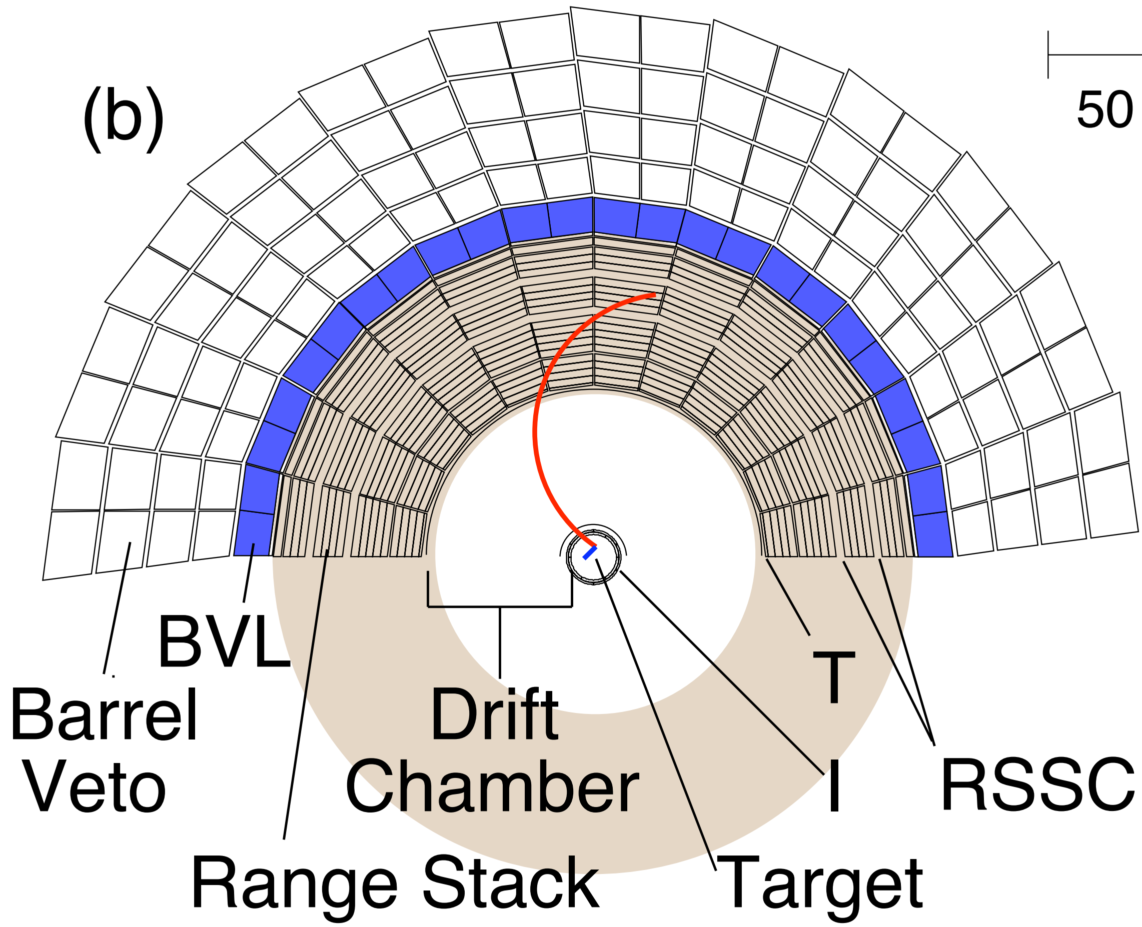
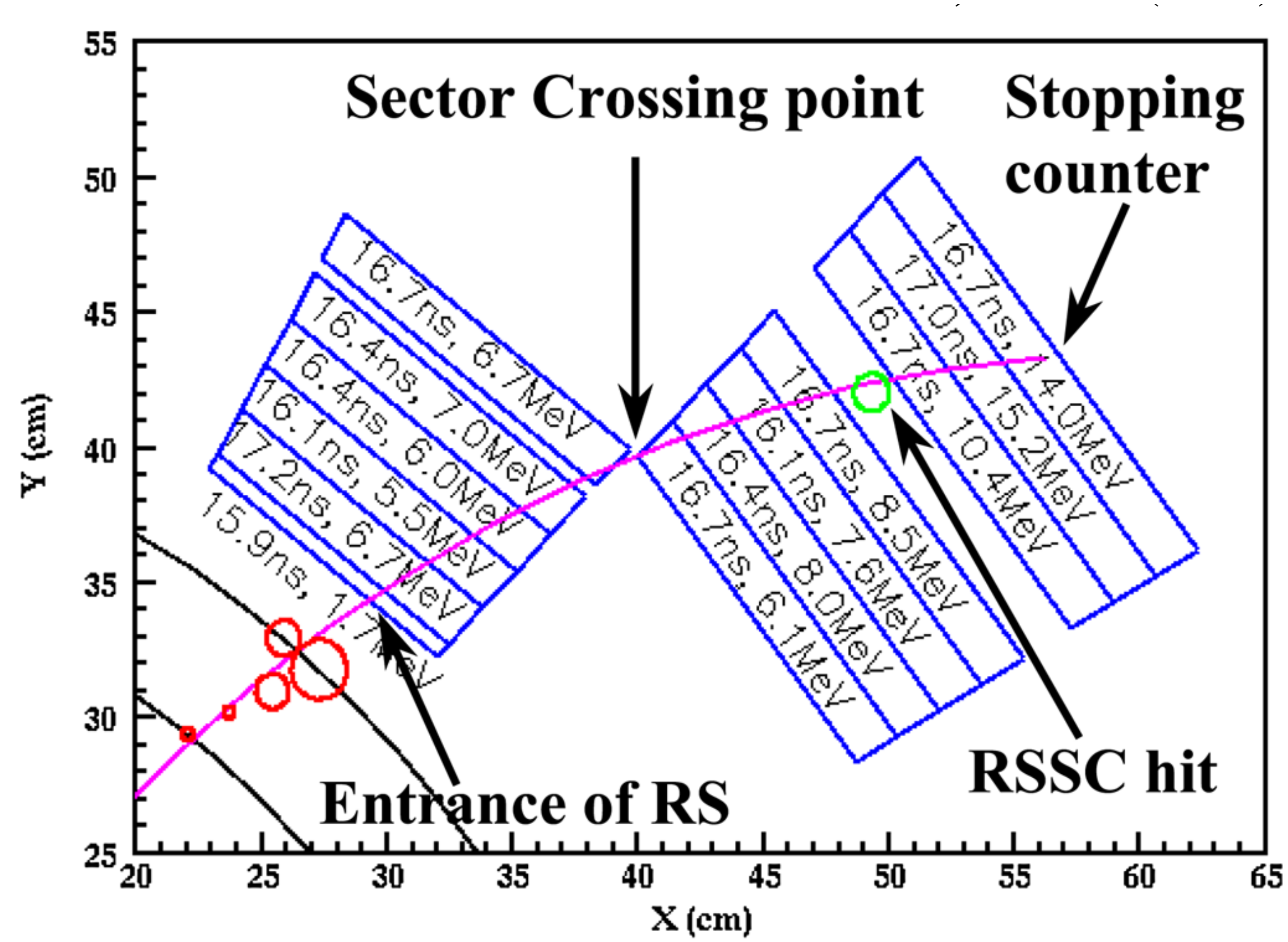
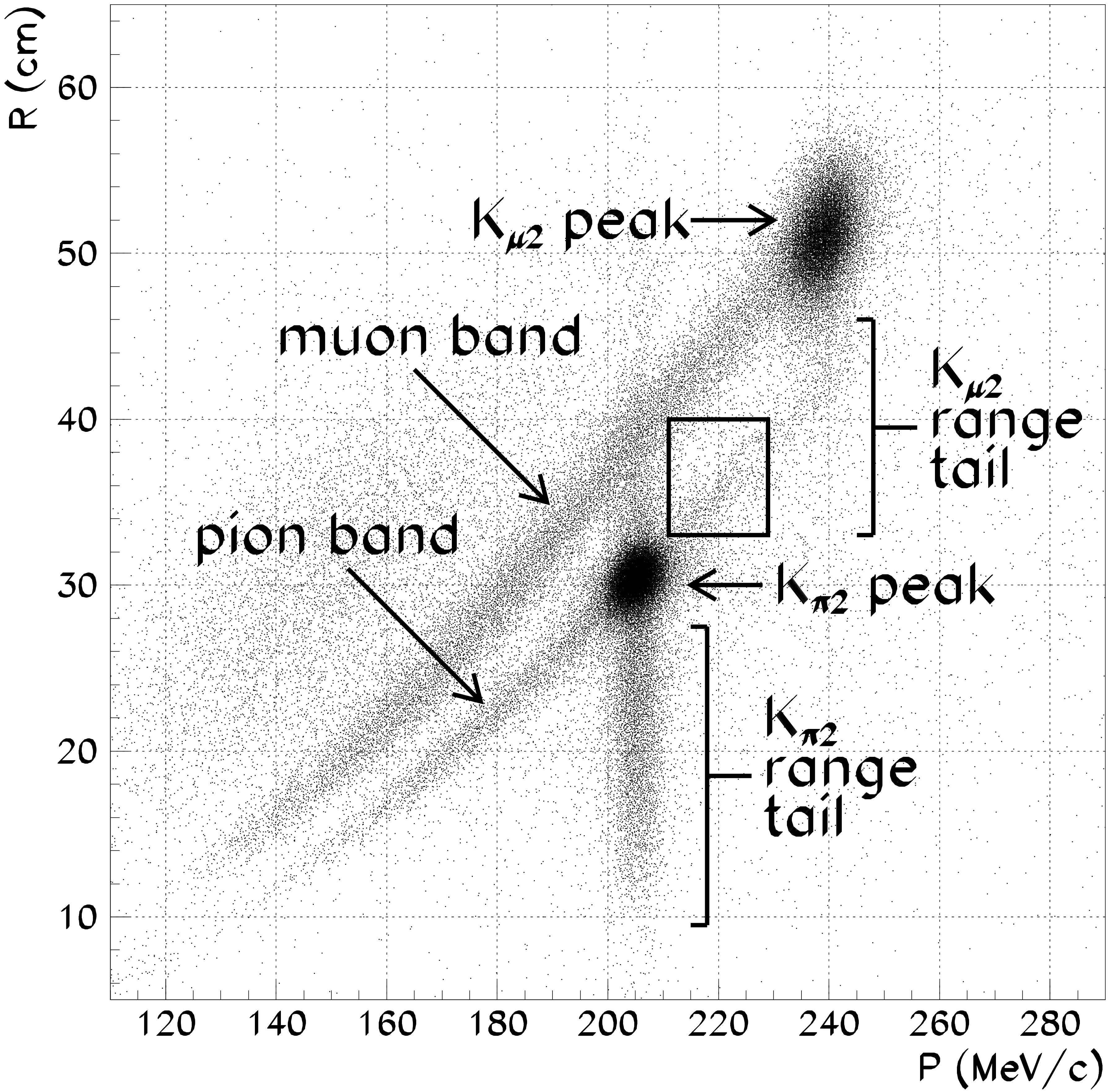




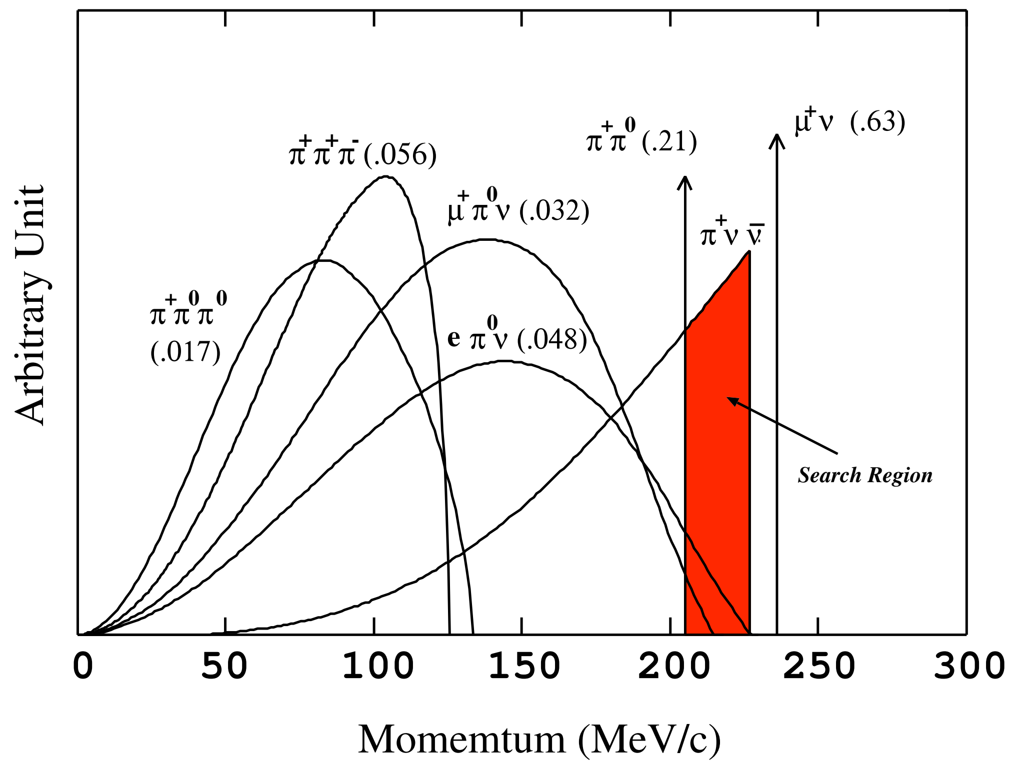
Kinematic requirements (KIN)

- correction with energy loss and path length in the target



R (cm)
60
50
40
30
20
10
120
140
160
180
200
220
240
260
280
P (MeV/c)
$K_{\mu2}$ peak
muon band
pion band
$K_{\mu2}$ range tail
$K_{\pi2}$ peak
$K_{\pi2}$ range tail

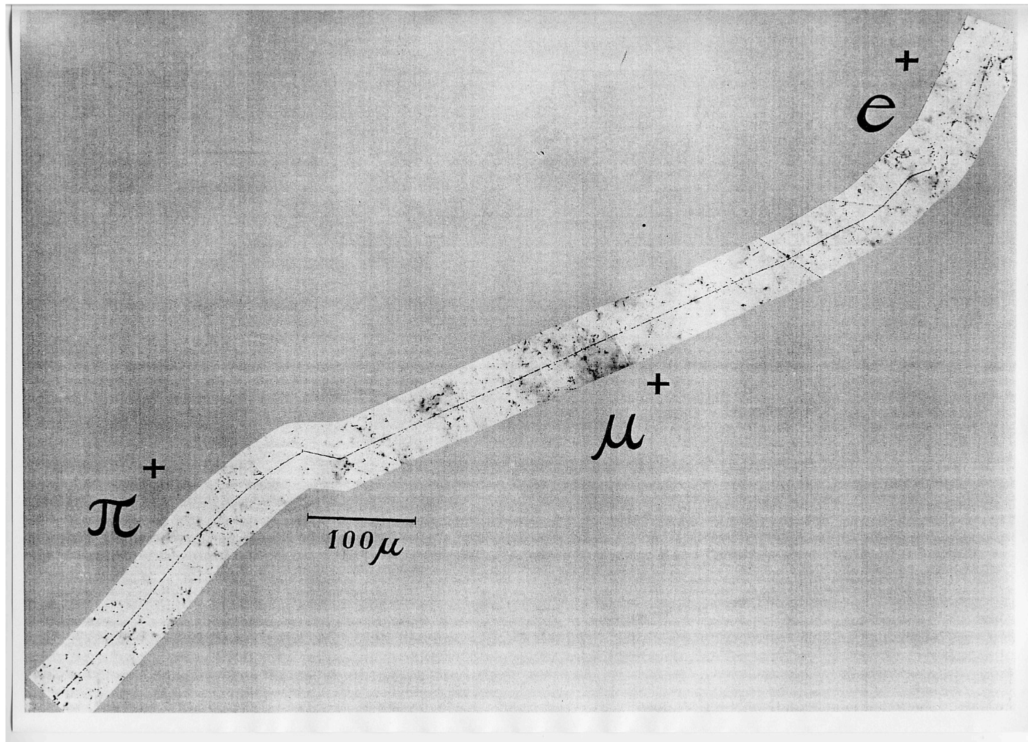
K^+decay at rest $\rightarrow \pi^+ +$ "nothing"

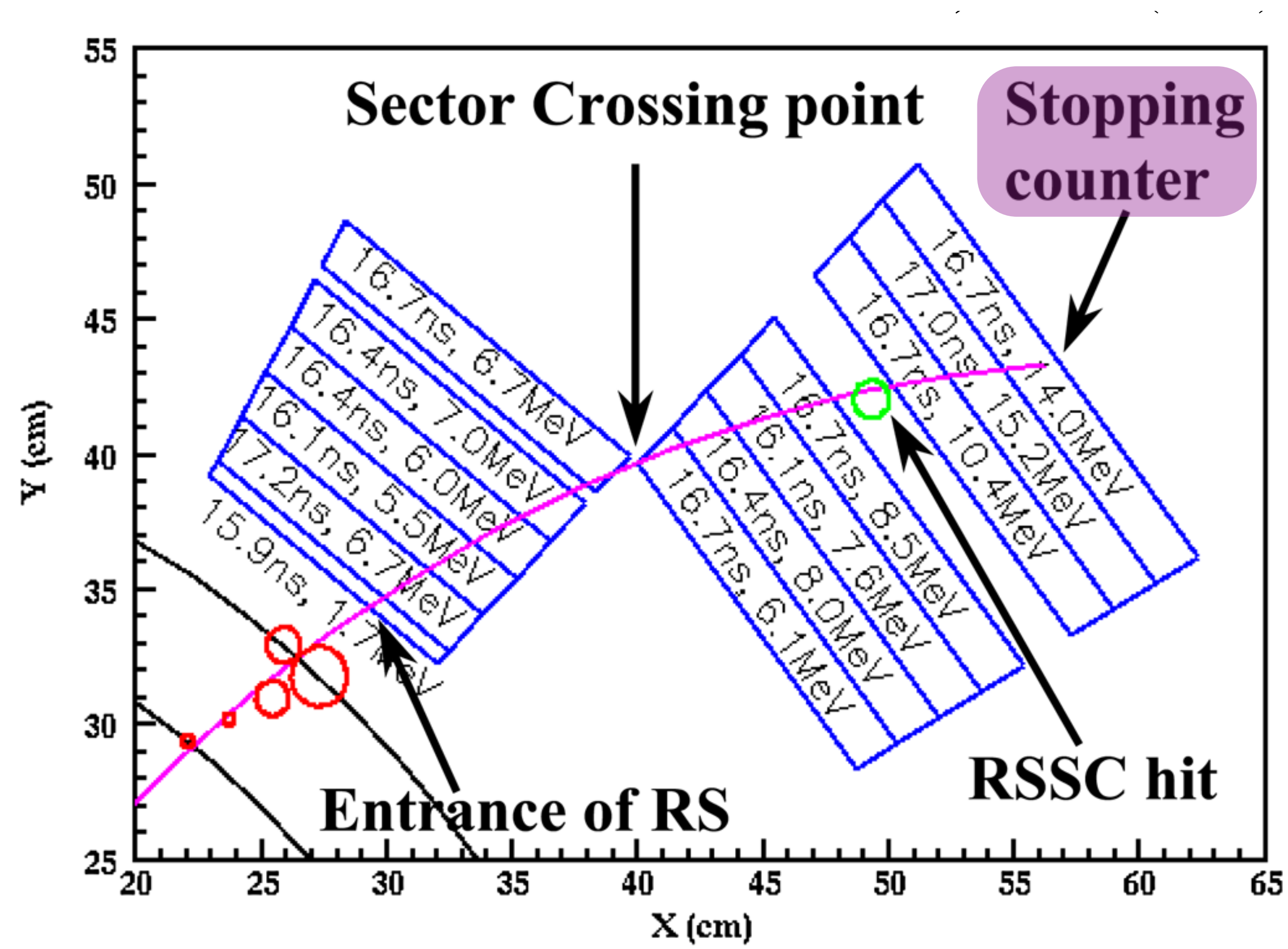


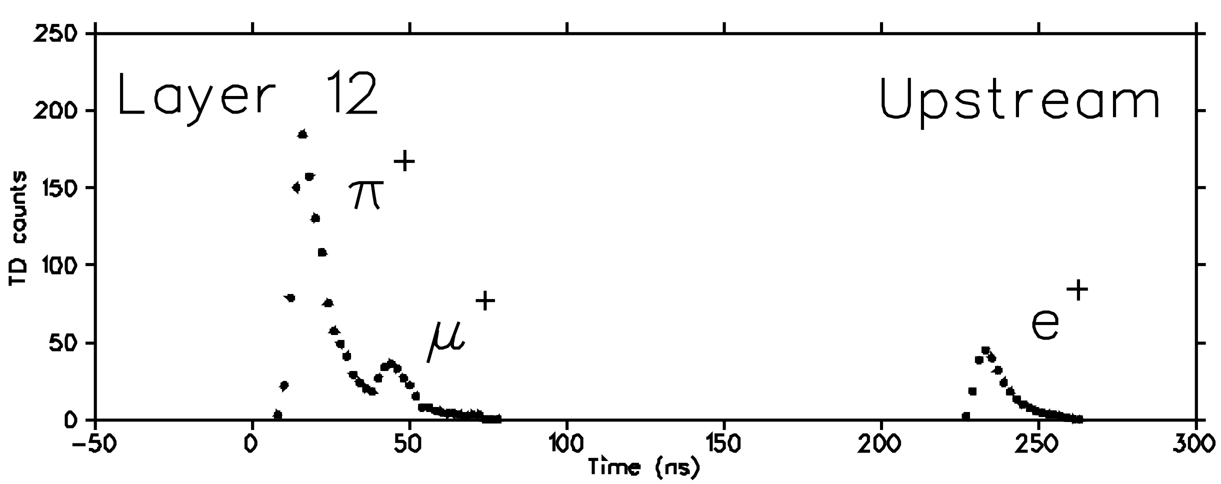
Background Rejection

- Kinematics of π^+
  - Momentum
  - Kinetic Energy
  - "Range" in plastic scintillators
- π^+/μ^+ separation
  $\Longleftrightarrow K^+ \rightarrow \mu^+\nu$
- extra particles (γ, ..)
  $\Longleftrightarrow K^+ \rightarrow \pi^+\pi^0$

each weapon should have rejection of $\underline{10^6 \sim 10^7}$



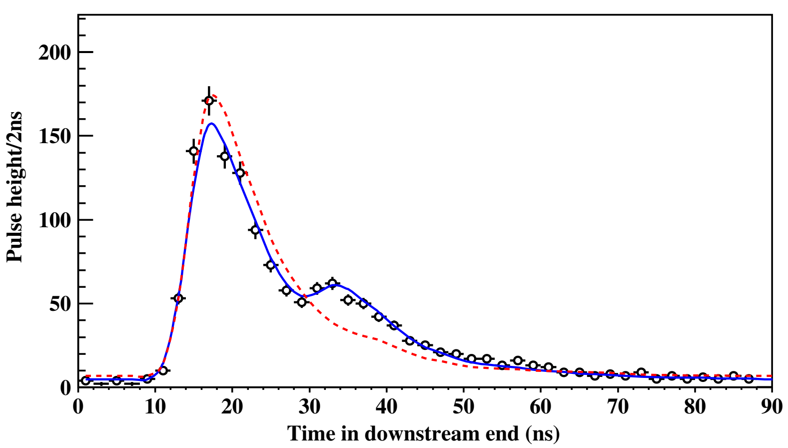


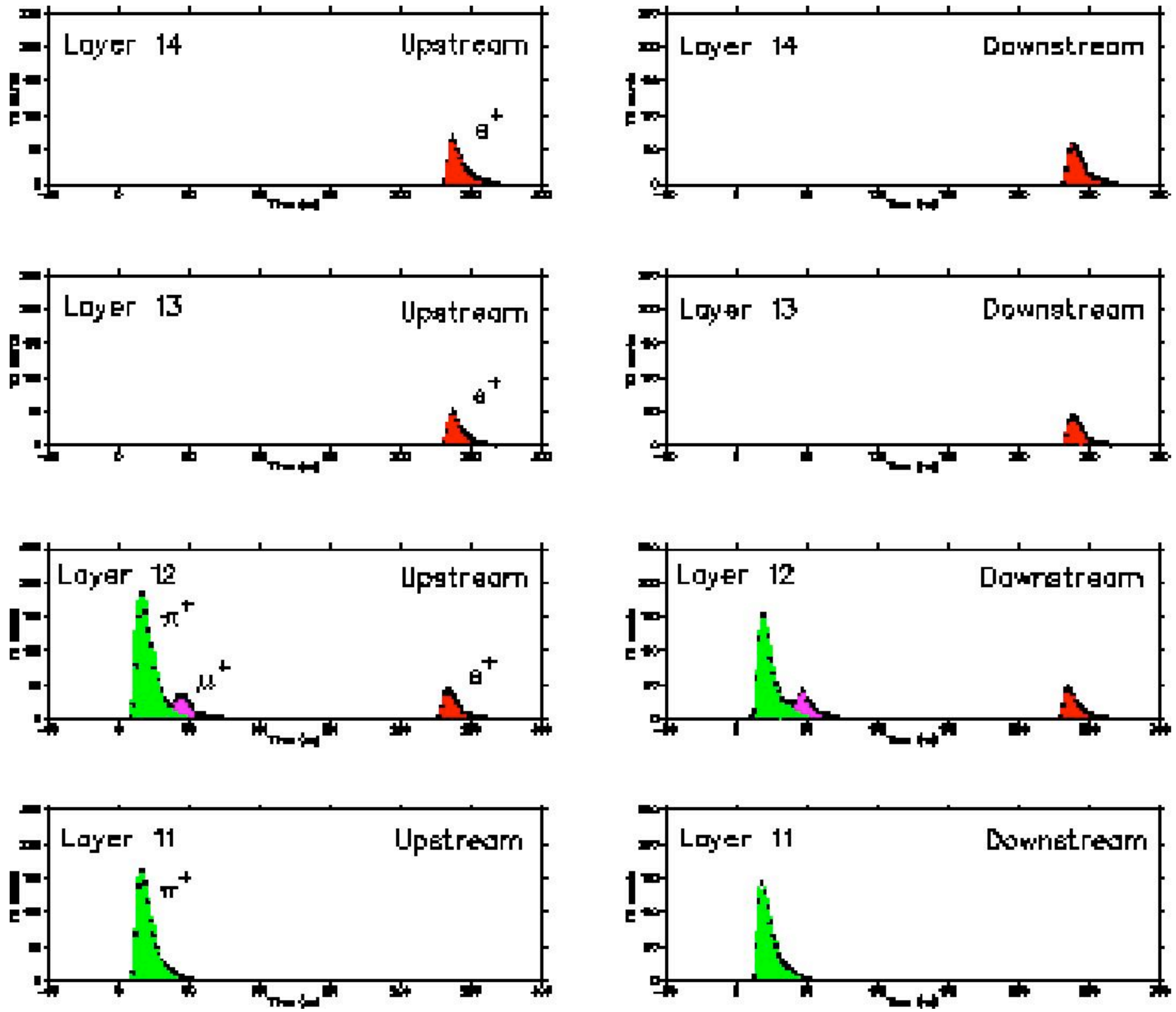


output pulse shape in each end of the stopping counter

Transient Digitizer (TD)

$\pi^+ \to \mu^+ \to e^+$ **recorded by 500-MHz waveform digitizer**



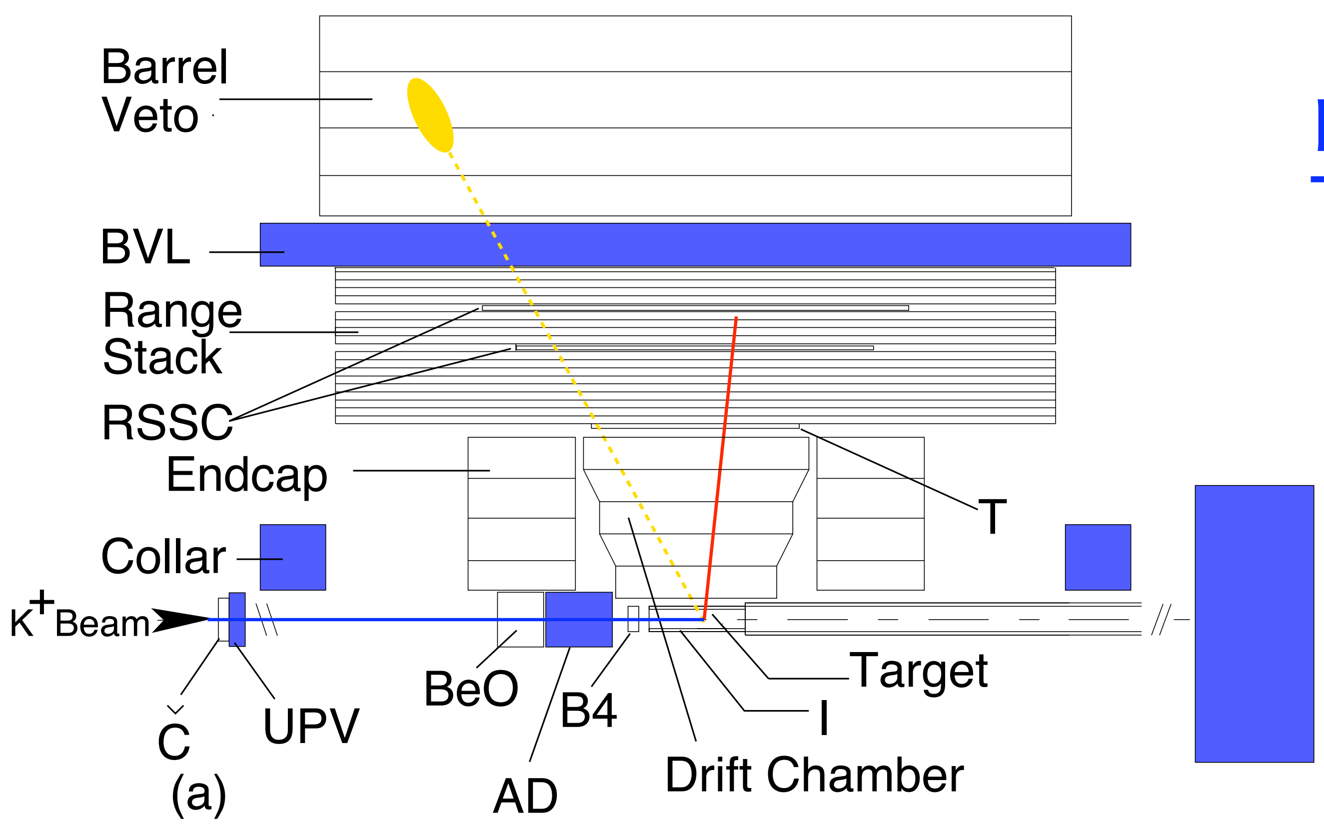


Online + Offline μ^+ rejection ($> 10^5$)

“Photon Veto” (PV)

γ detection by the hermetic Calorimetry

any in-time detector activity
with Barrel, Endcap, Range Stack, Target



new calorimeters (in blue)

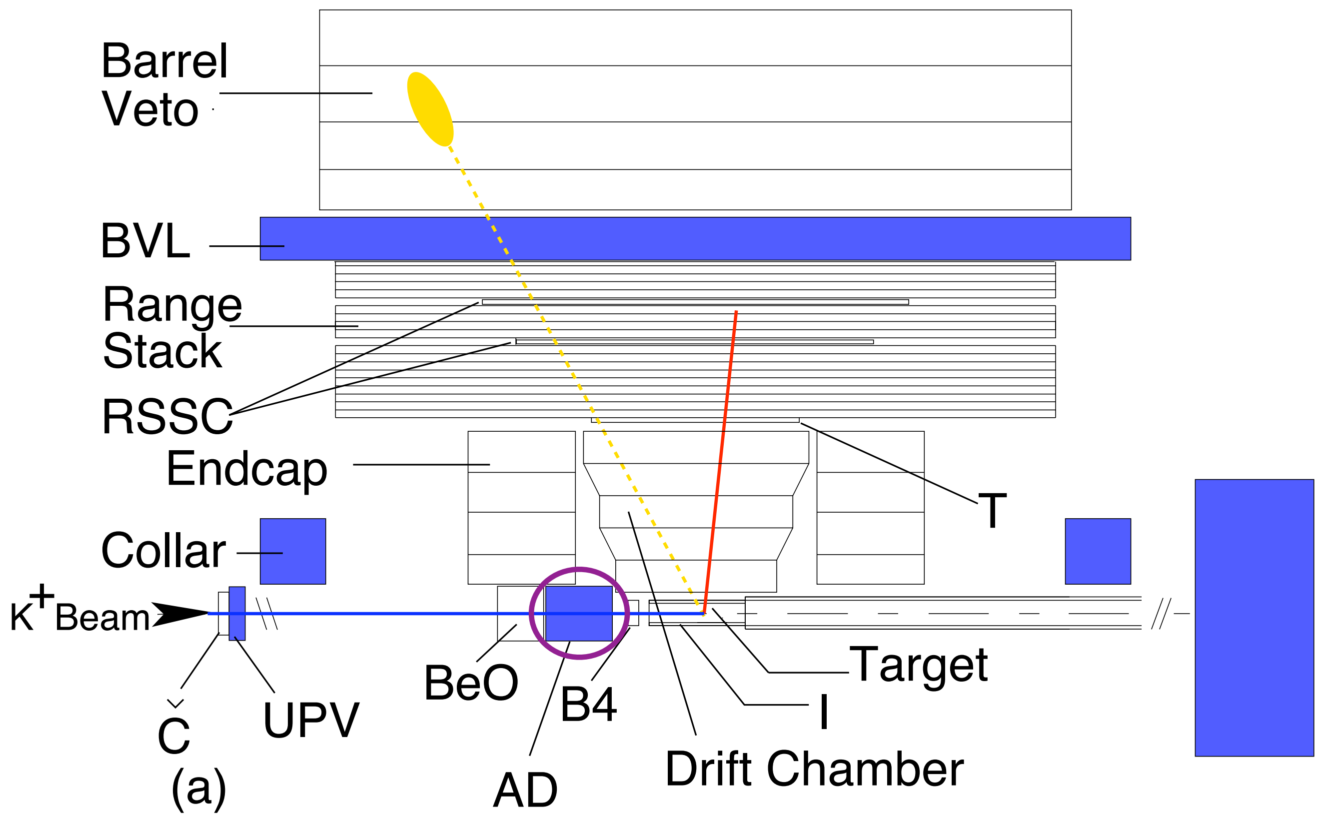
- barrel part (add 2.3 X_0)
- minor openings along the beam direction

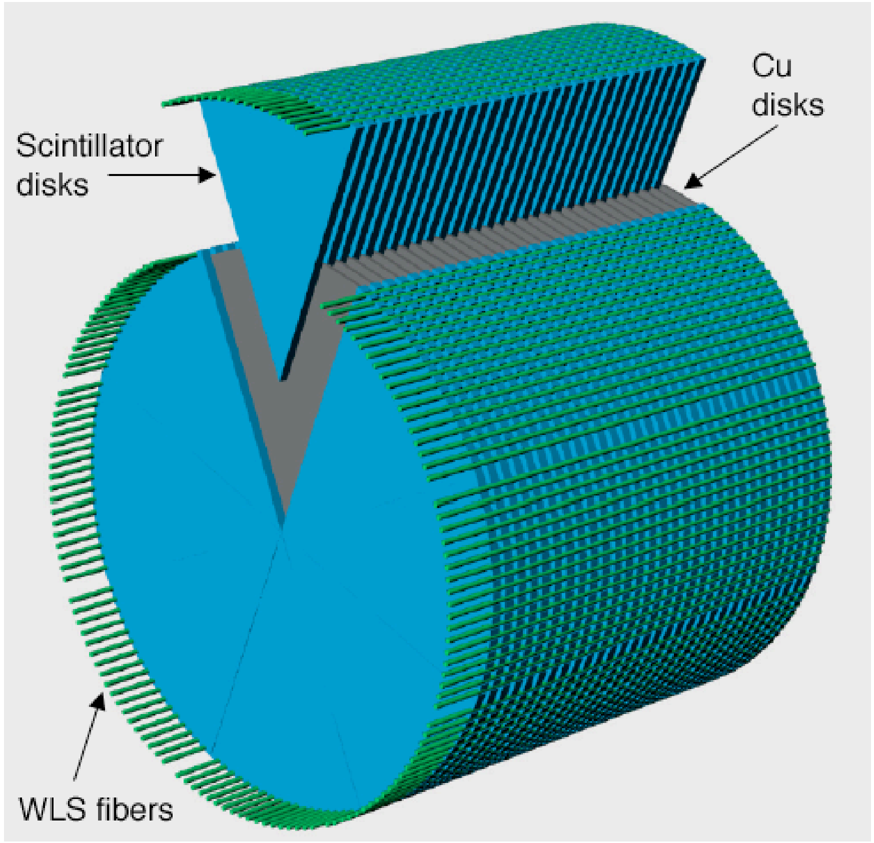
  - segmented Active Degrader
  - new Collar detectors
  - Upstream and Downstream PV

“Photon Veto” (PV)

γ detection by the hermetic Calorimetry

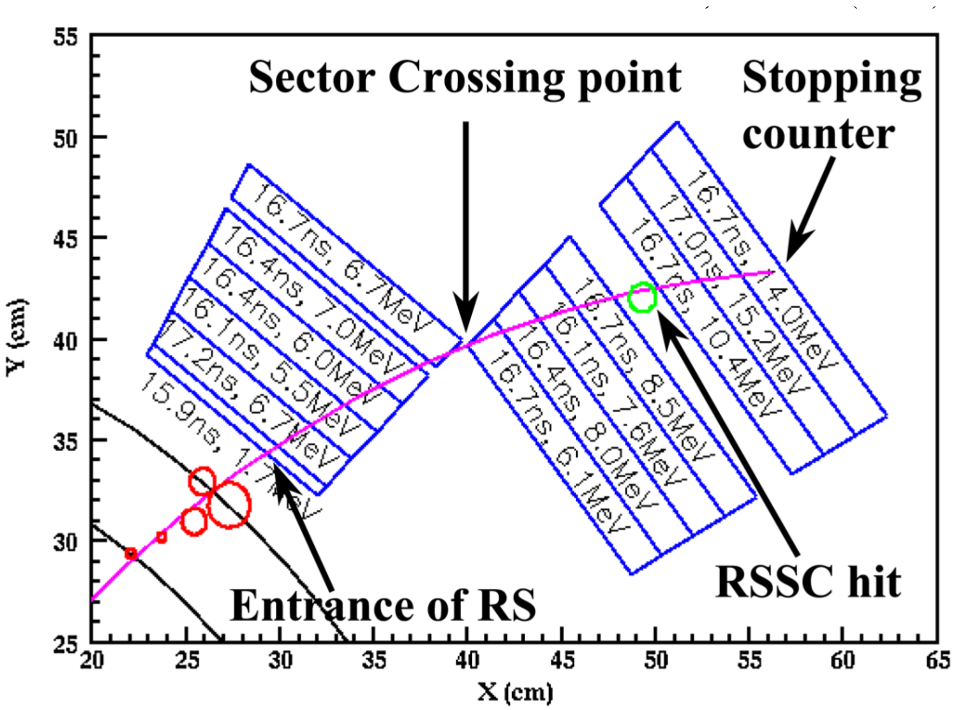
any in-time detector activity
with Barrel, Endcap, Range Stack, Target

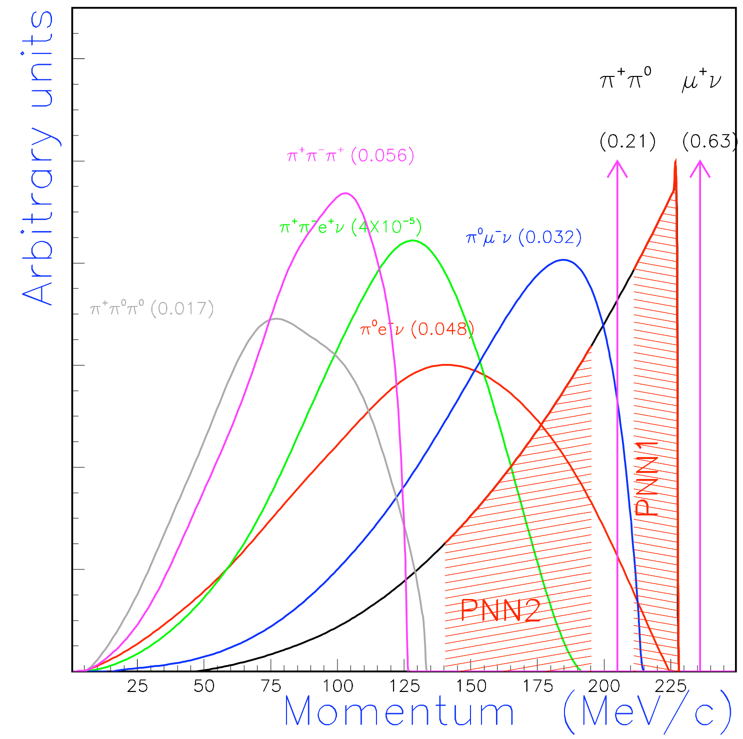




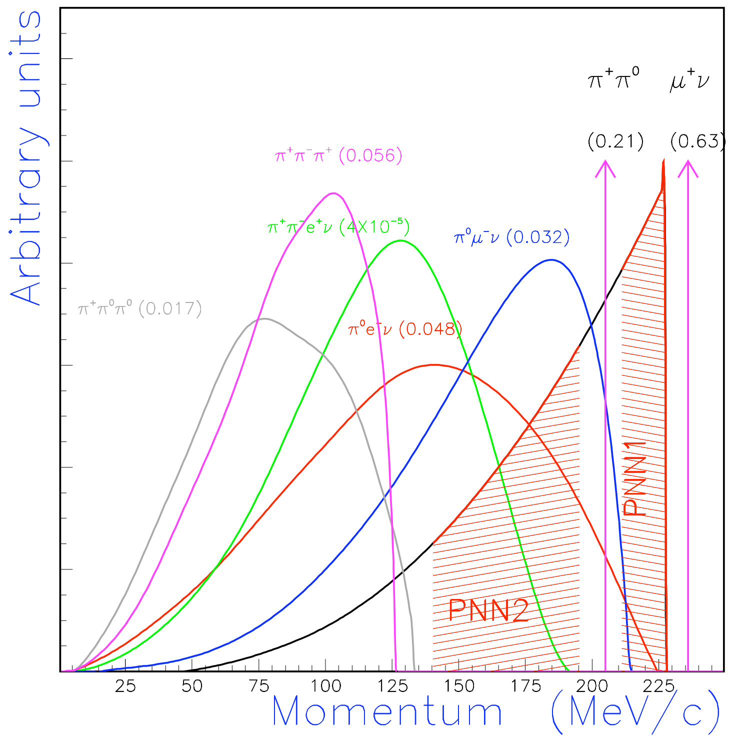
Active Degrader (AD)
14cm diameter, 17cm long,
12 azimuthal segments
6.1 radiation lengths

Trigger requirements for π^+ "above/below" the $K_{\pi 2}$ peak





	E949-$\pi^+\nu\bar{\nu}(2)$	E949-$\pi^+\nu\bar{\nu}(1)$
Beam	K^+ at rest in the target to decay	
	no incoming π^+	
charged track to RS	I-counters and T-counters	
RS stopping layer (π^+ range)	from 6 to 12	from 11 to 18
π^+ identification	$\pi^+ \to \mu^+$ in the stopping counter	
γ	no shower in RS, Barrel, Endcap	
K^+ exposure	1.7×10^{12}	1.8×10^{12}
# of triggered events	9.3×10^7	9.0×10^7

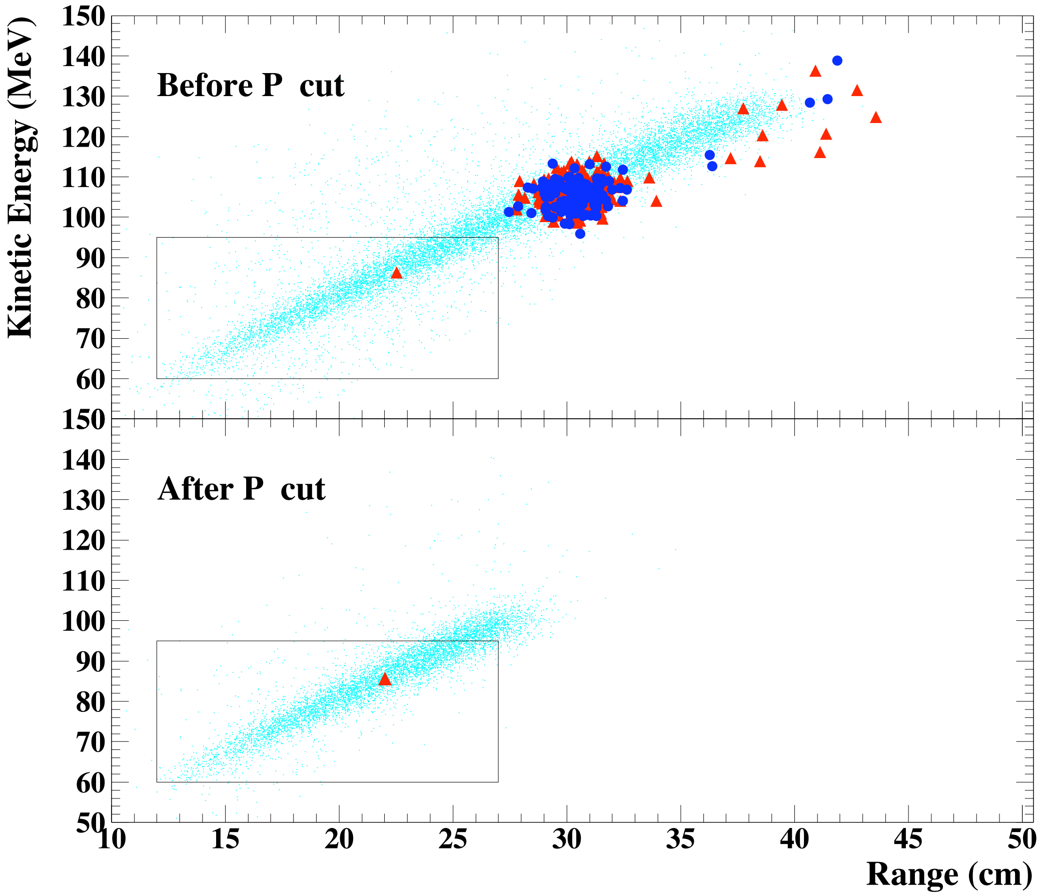


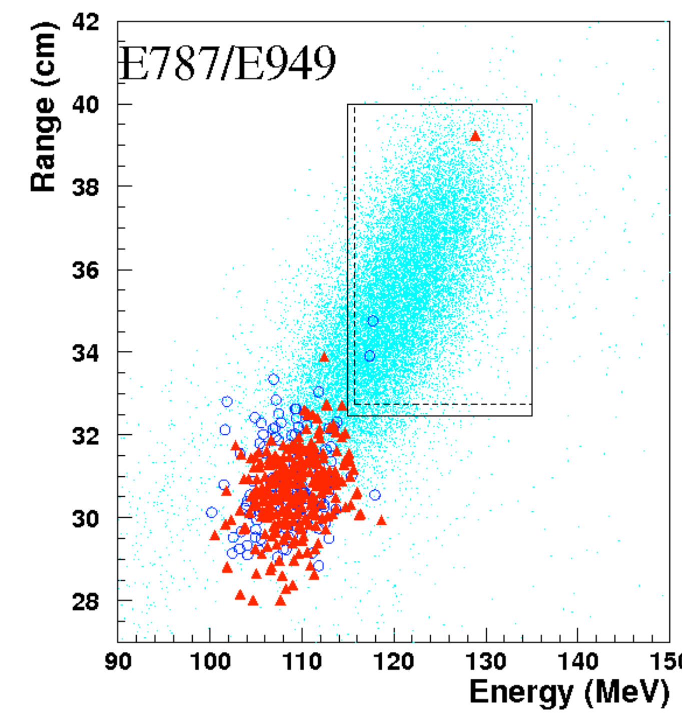
analysis for PNN2

why different and difficult ?

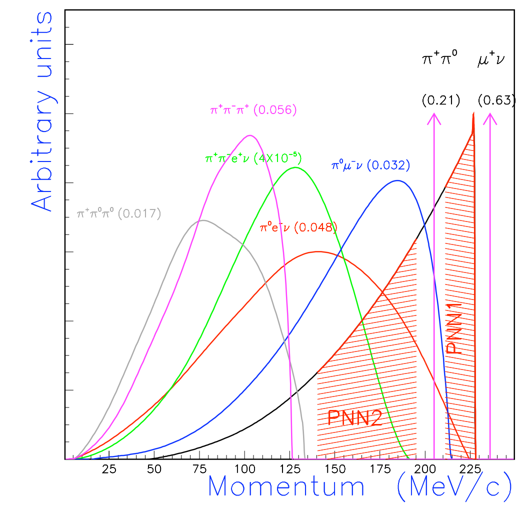
previous $K^+ \to \pi^+\nu\bar{\nu}$ results

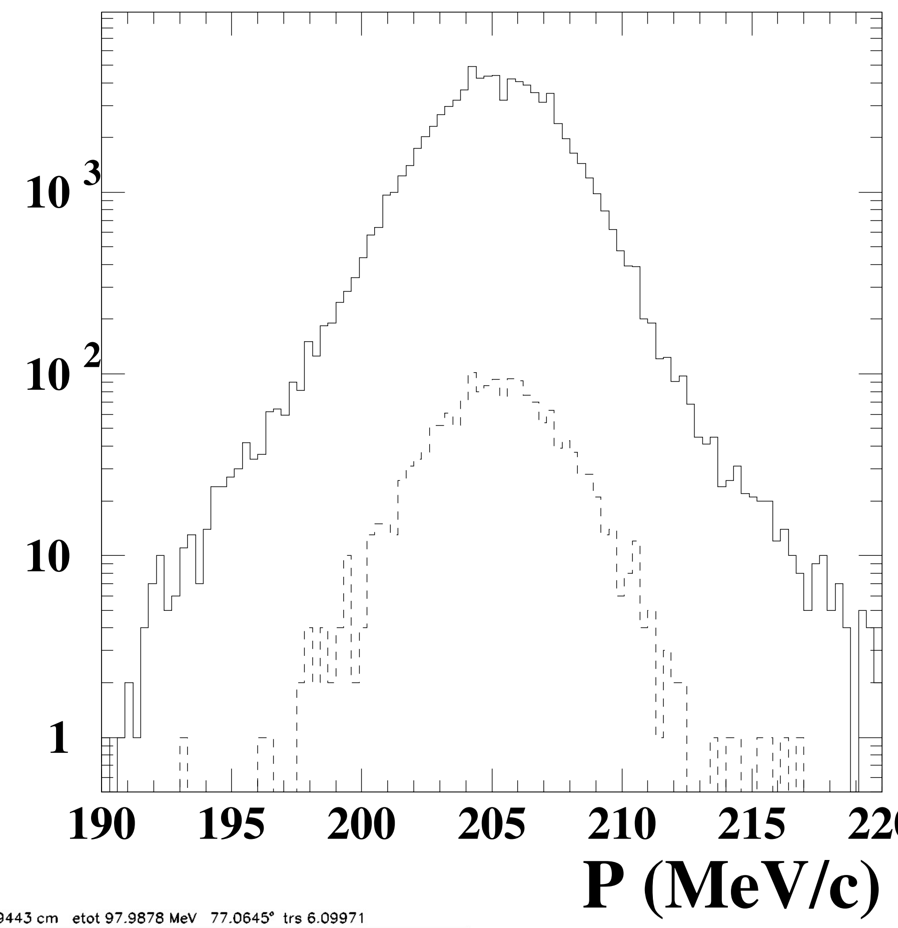
Region	**“PNN2”**	**“PNN1”**
P_{π^+} (MeV/c)	[140,195]	[211,229]
Years	E787 96-97	E787(95, 96-97,98) E949
Ref:	PR **D70**, 037102 (2004)	PRL **93**, 031801 (2004)
Stopped K^+	1.73×10^{12}	7.7×10^{12}
Acceptance	0.084%	0.2%
SES	6.9×10^{-10}	0.63×10^{-10}
Background	1.22 ± 0.24	0.44 ± 0.05
Candidates	1	3
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$

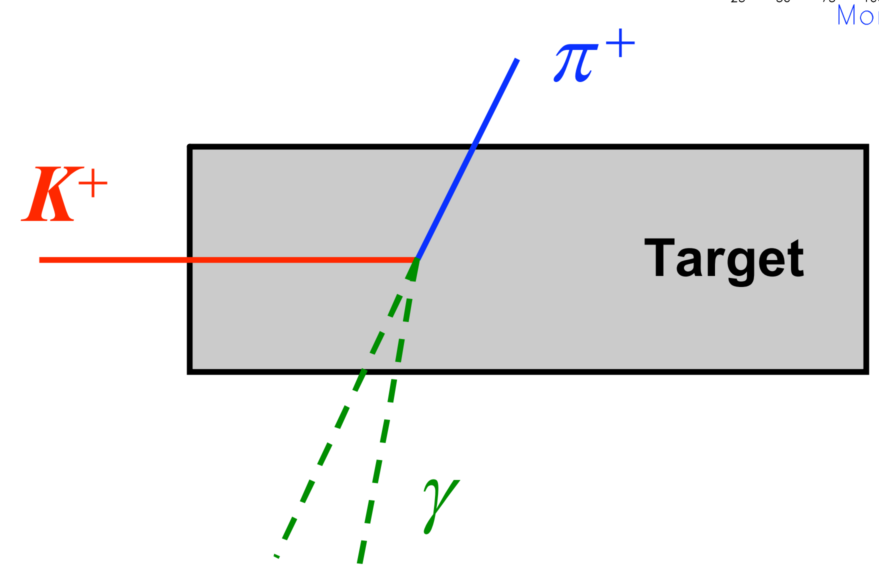


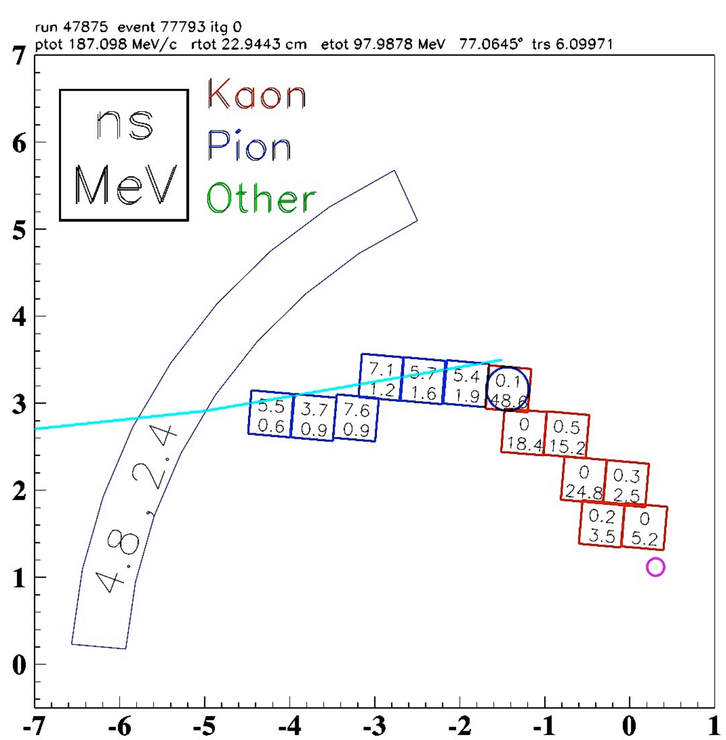


Kπ2 background in PNN1



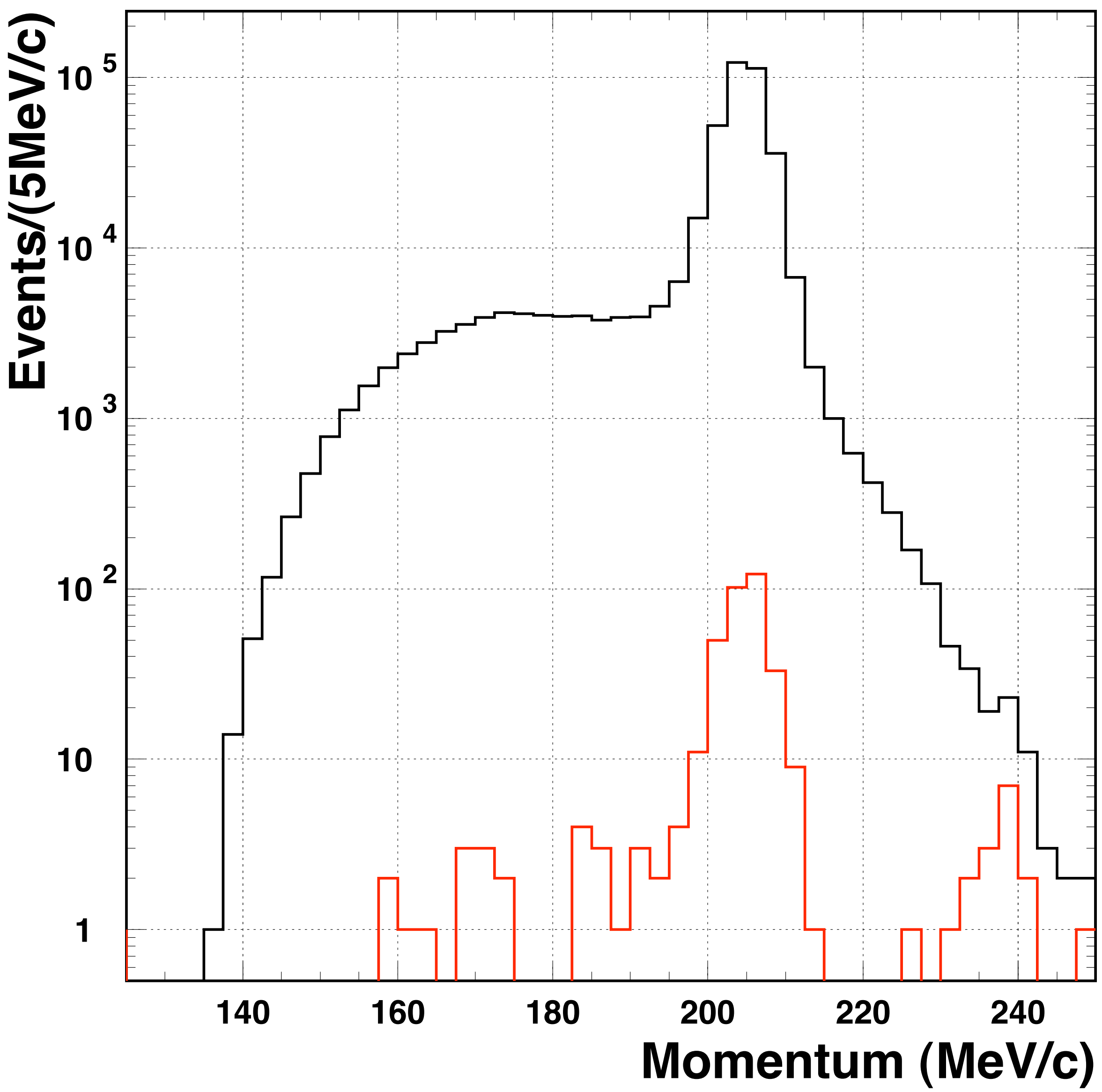


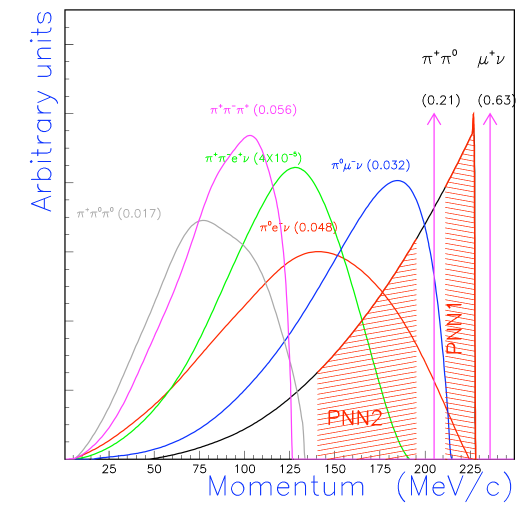


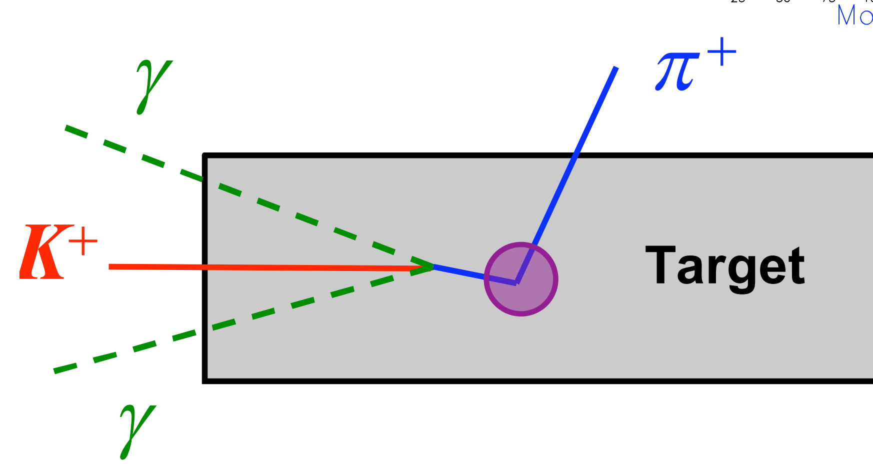


- π^+ P/E/R get larger only due to mis-measurement.
- π^+ triggered by RS ensures π^0 in the opposite direction (and γ's are covered by Barrel and Endcap).

Kπ2 background in PNN2



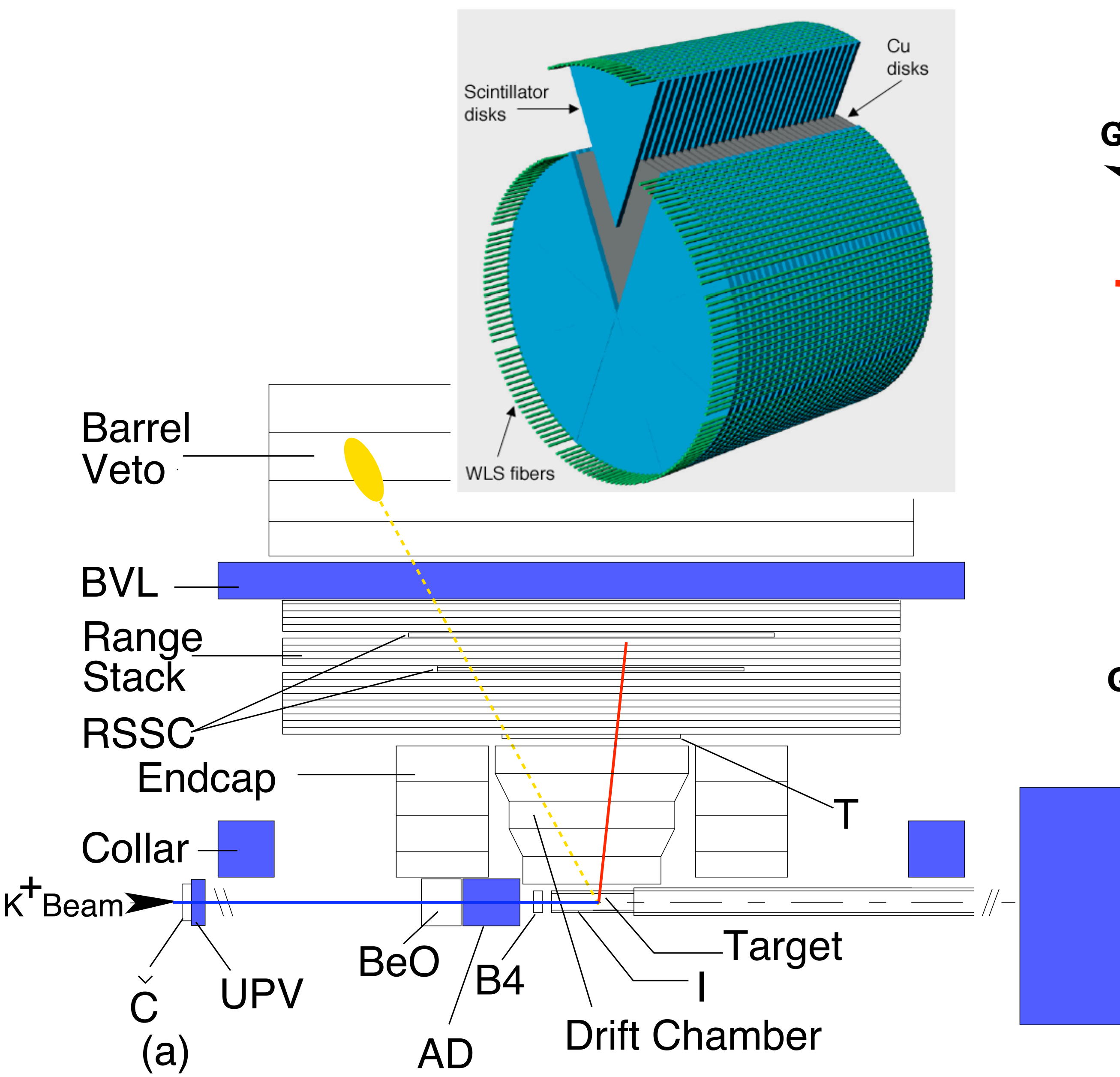


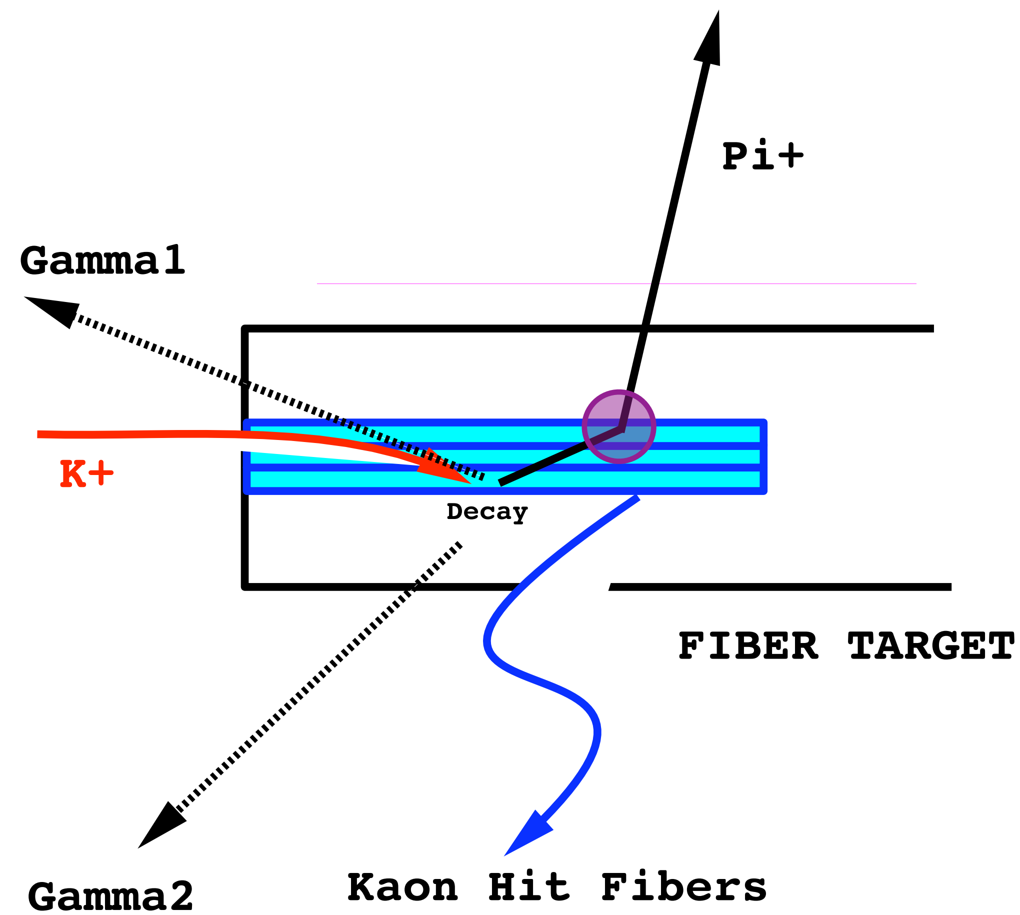


- π^+ P/E/R can get smaller due to scattering (and energy loss) in the Target.
- π^0 (and γ's) may go to the beam region whose coverage is weak.

$K\pi 2$ background in PNN2

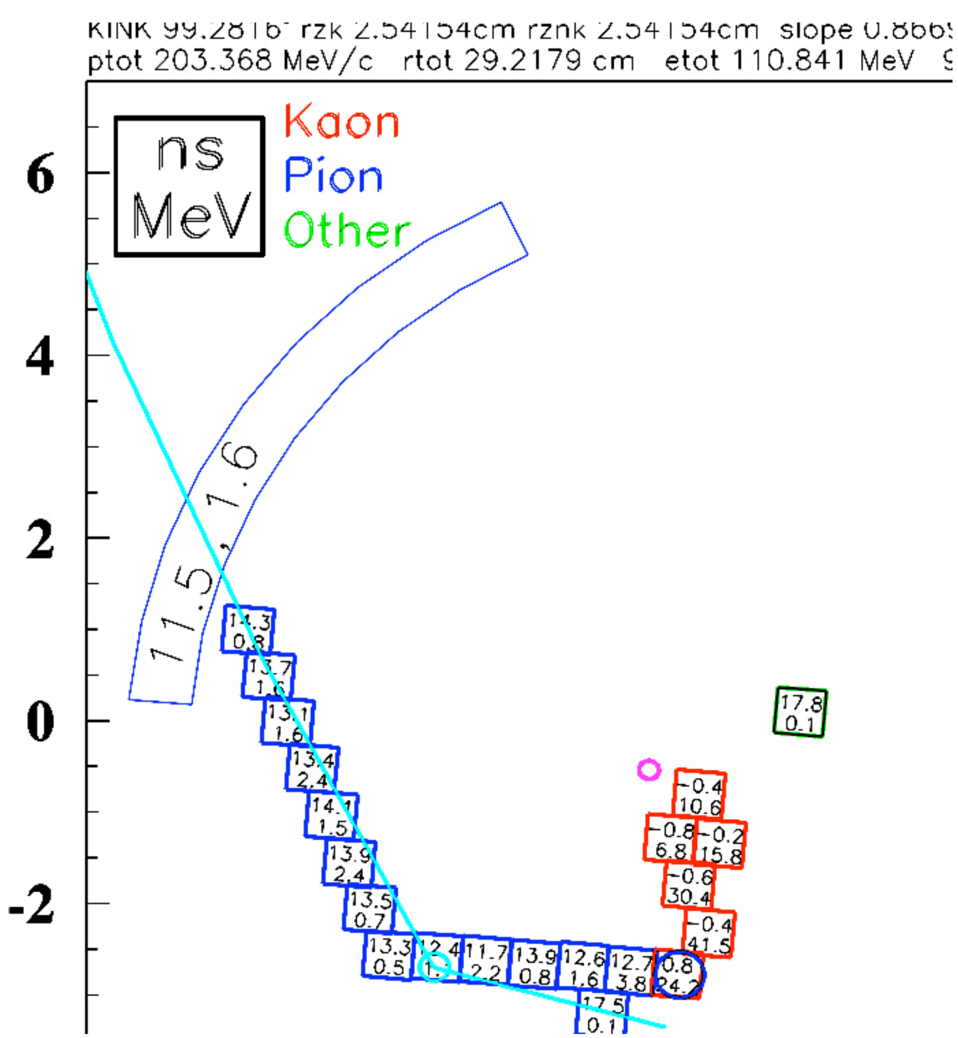
- γ detection in the beam region

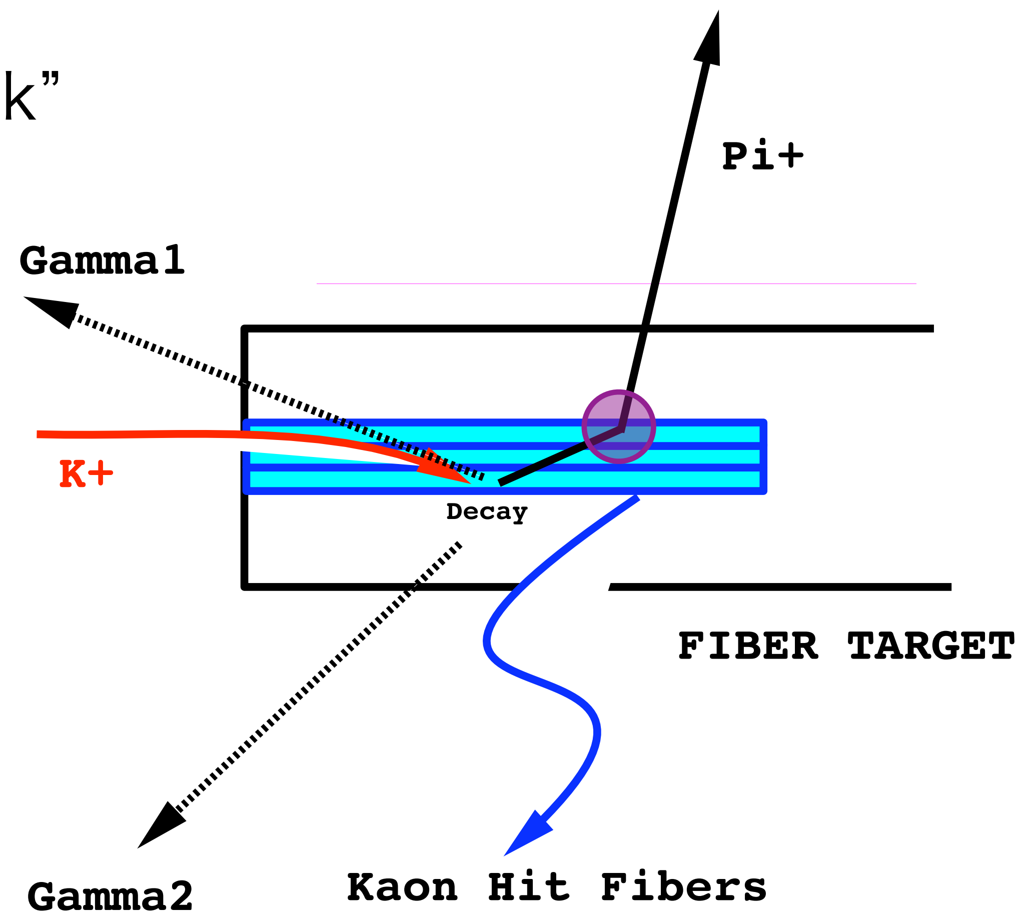




$K\pi 2$ background in PNN2

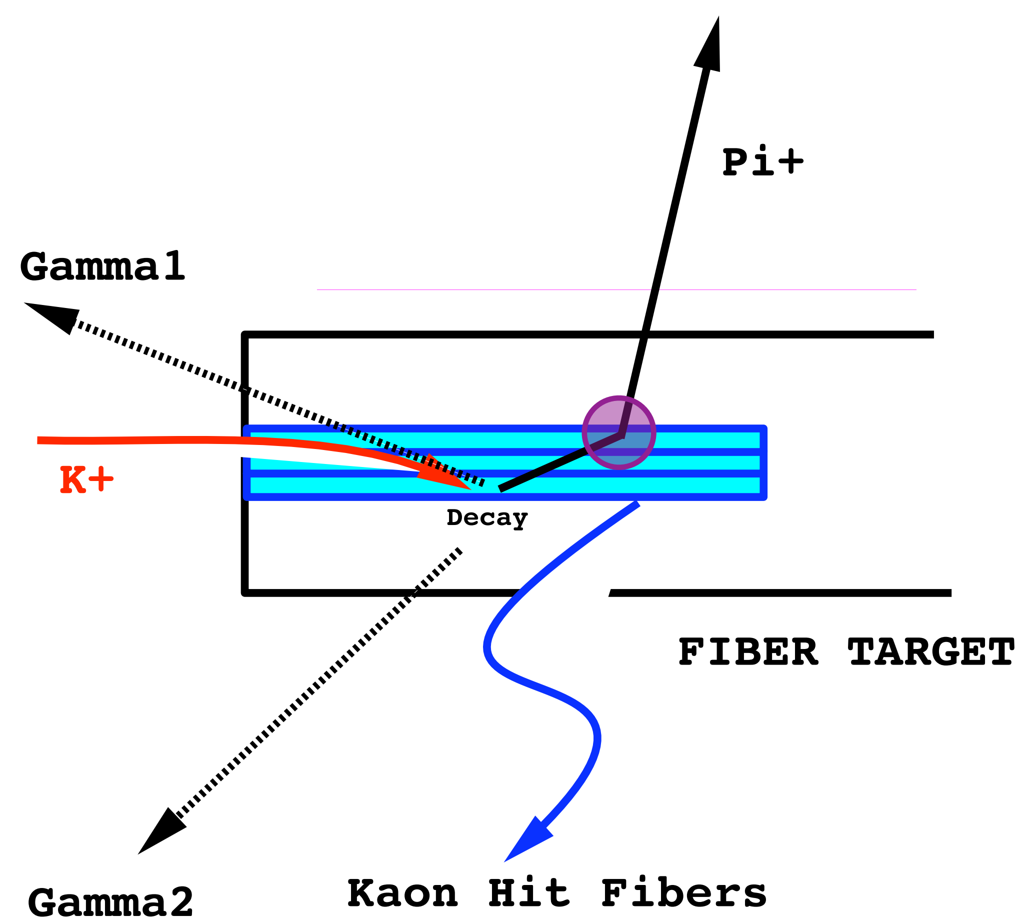
- Identification of $\pi +$ scattering in the Target fibers:
  - "kink" in the XY pattern of fibers
  - $\pi +$ track that does not "point back" to the K+ decay point.



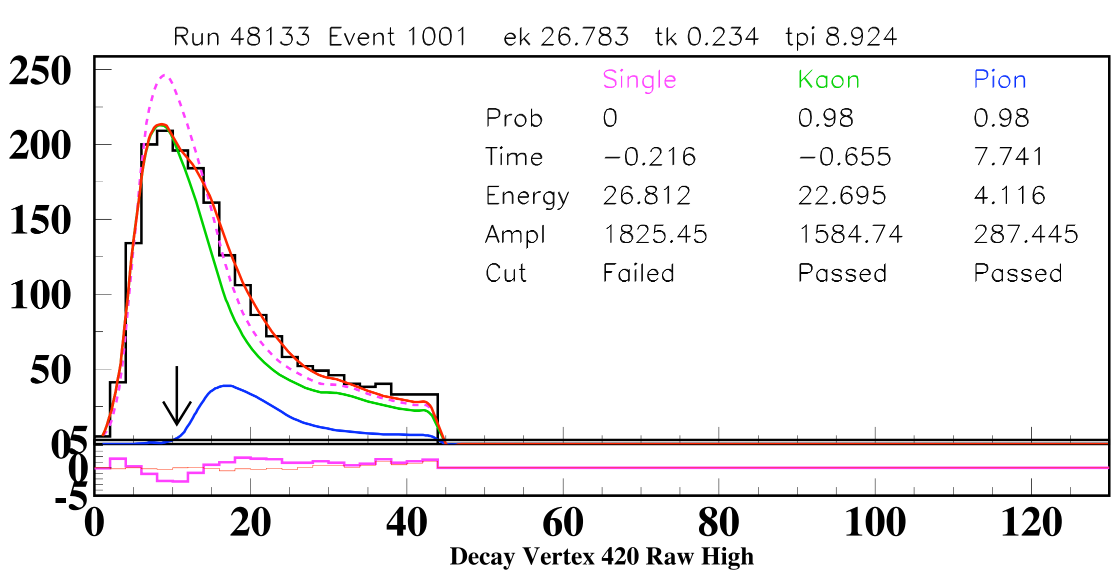


Kπ2 background in PNN2

- Identification of π+ scattering in the Target fibers:
  - large energy deposit hidden in the Kaon Hit Fibers
  - extra energy deposit inconsistent with outgoing π+

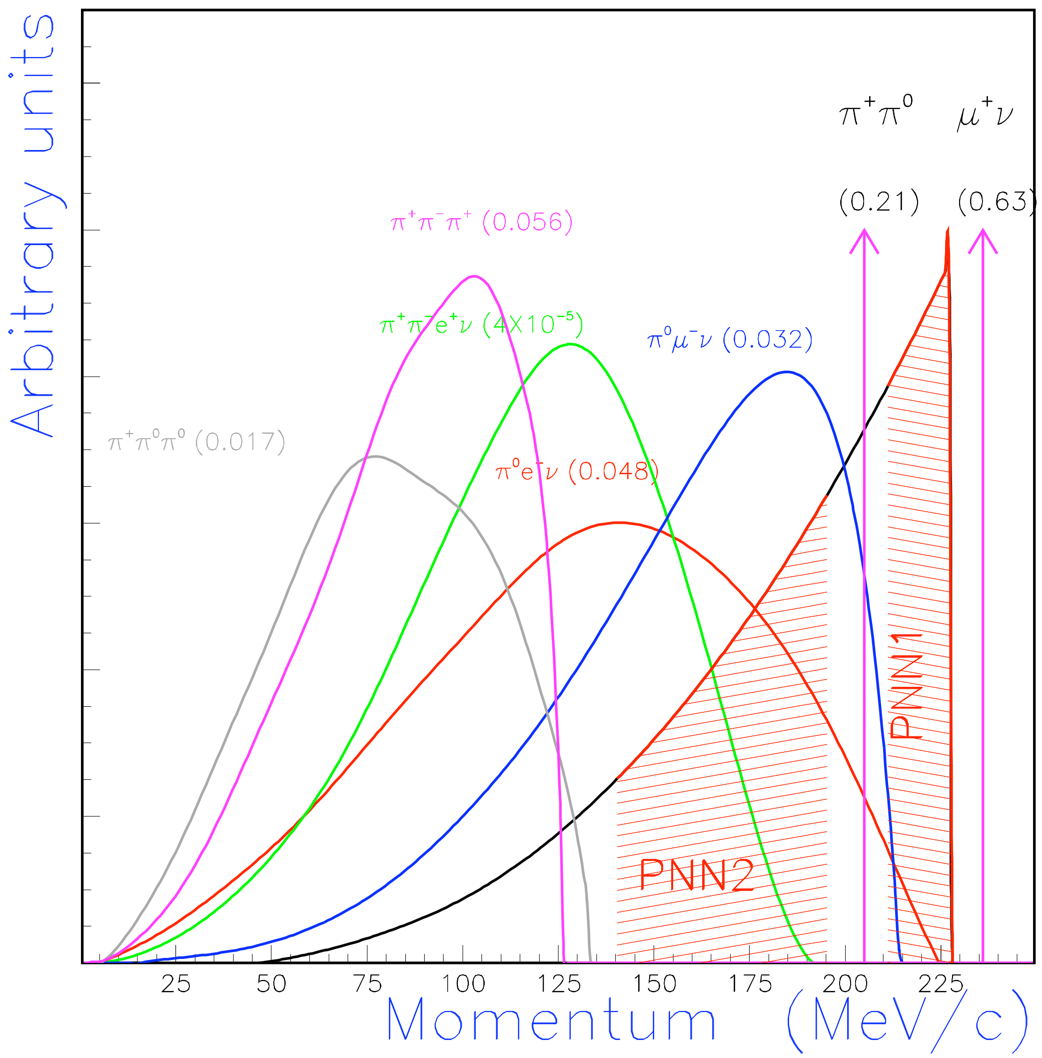


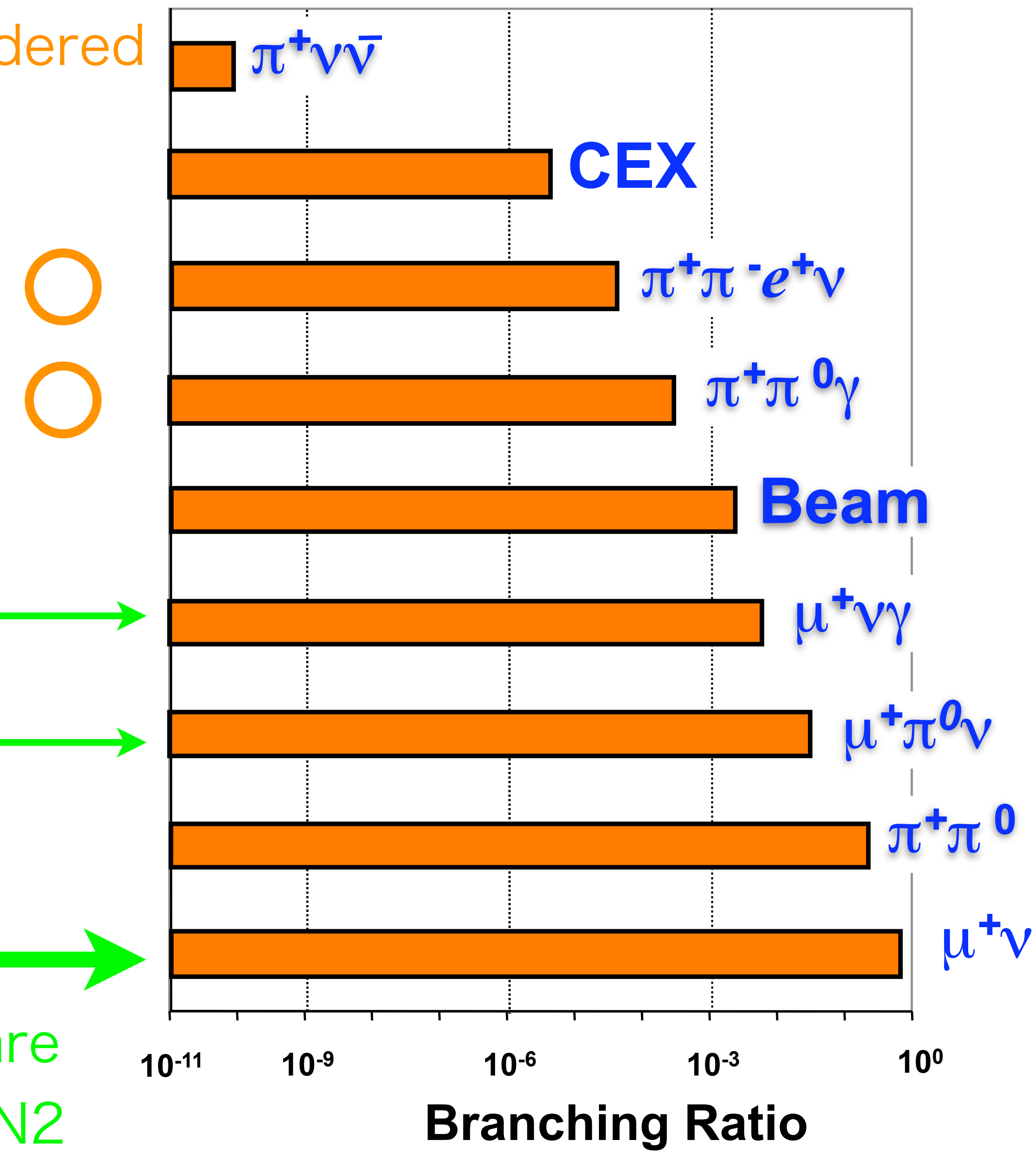
CCD pulse fitting in kaon fibers



background sources in PNN2

more sources should be considered



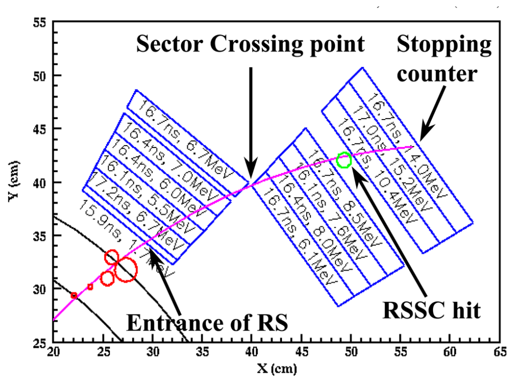


μ backgrounds are not serious in PNN2 (in particular $\mu+\nu$)

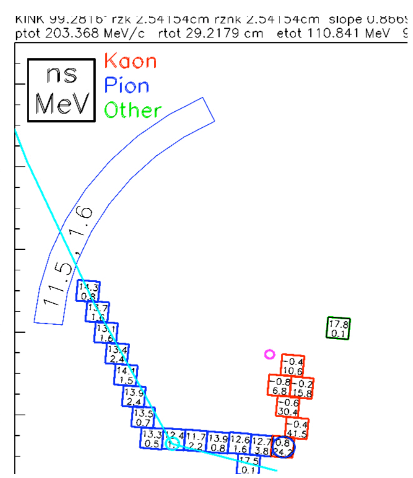
selection criteria (cuts)

- signal region:
  140 < P < 199 MeV/c
  Range: R, Kinetic Energy: E

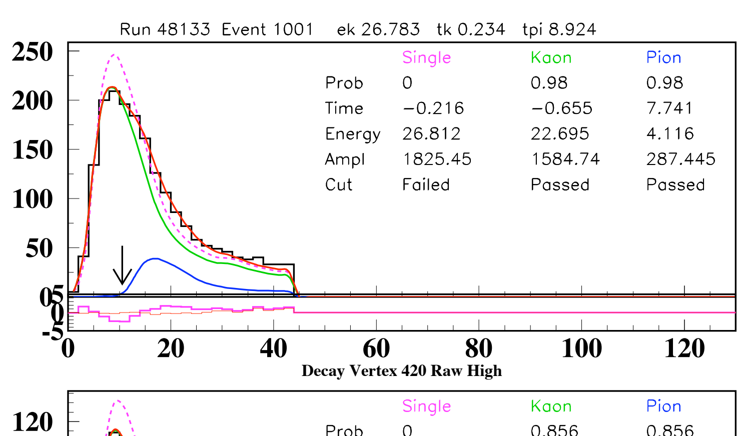
- Kinematic cuts (KIN)



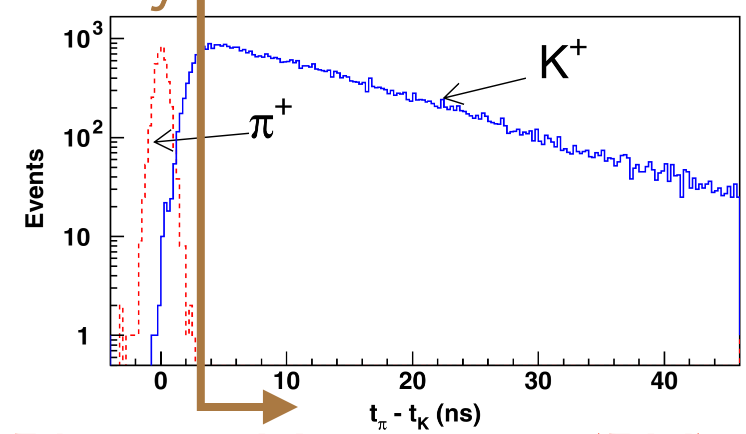
- Target cuts (TARGET)



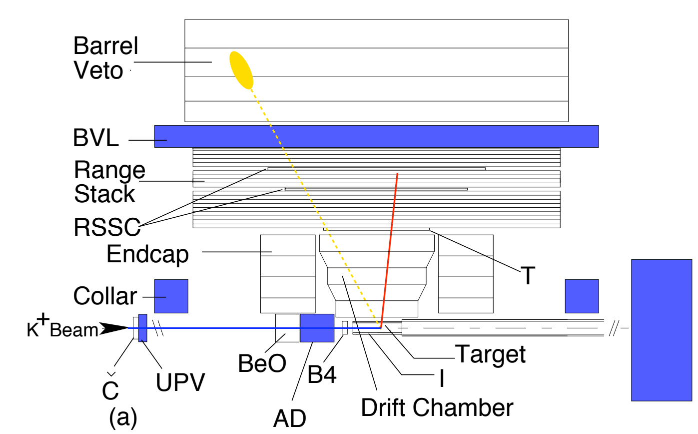
- CCD pulse cuts (CCDPUL)



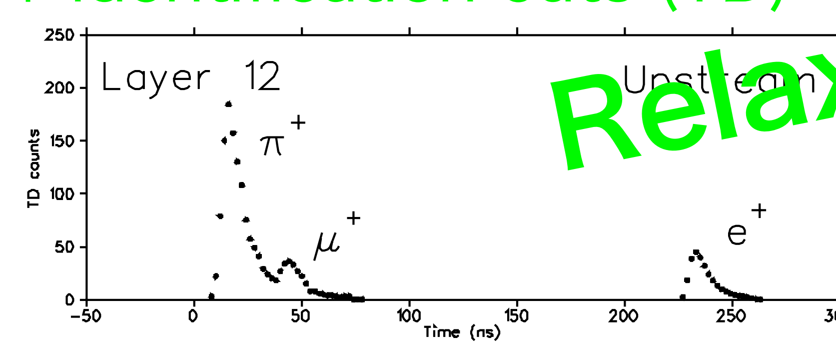
- Beam cuts (BEAM) and
  Delayed Coincidence cuts (DC)



- Photon Veto cuts (PV)



- $\pi+$ identification cuts (TD)



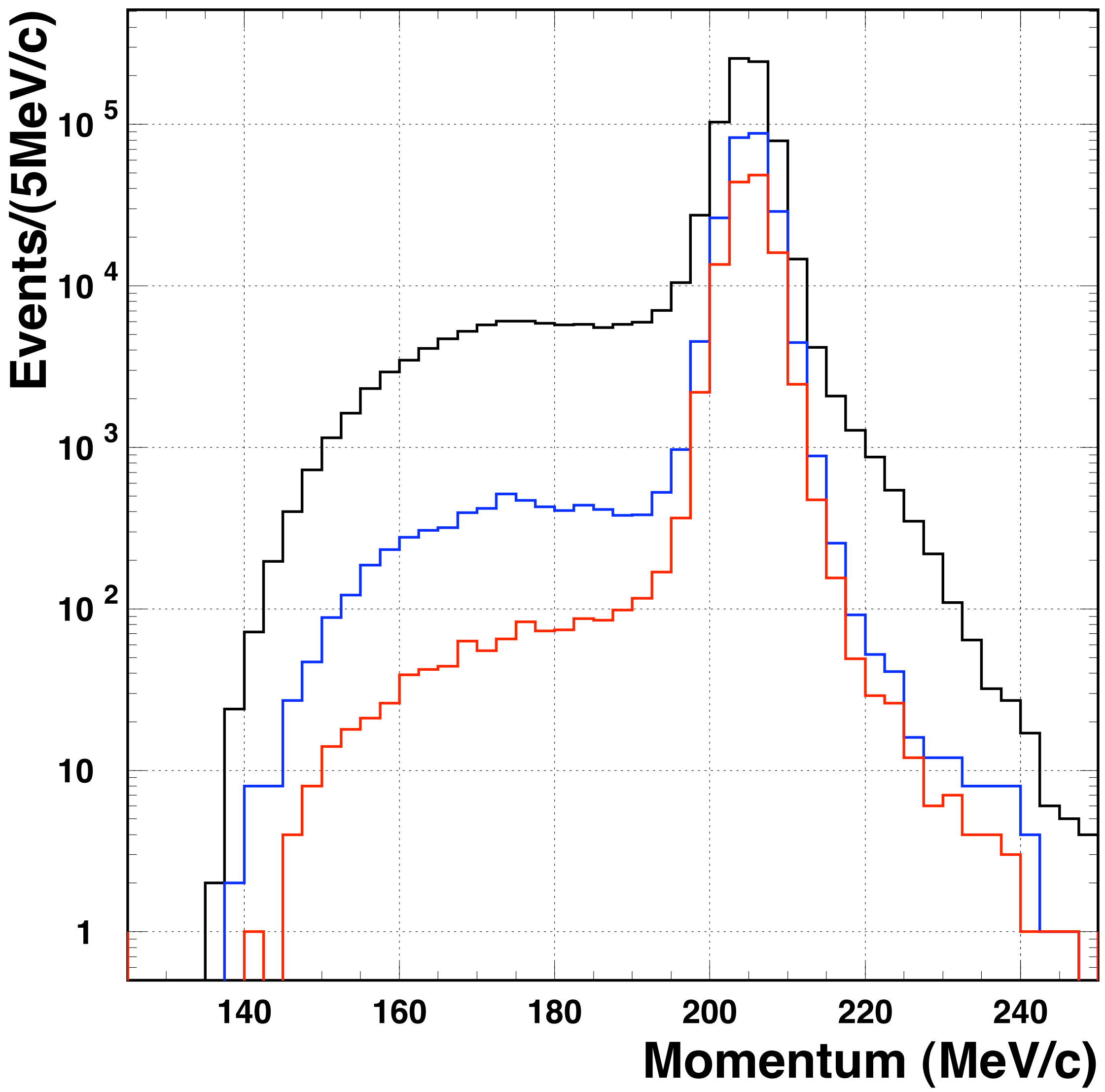
Relaxed

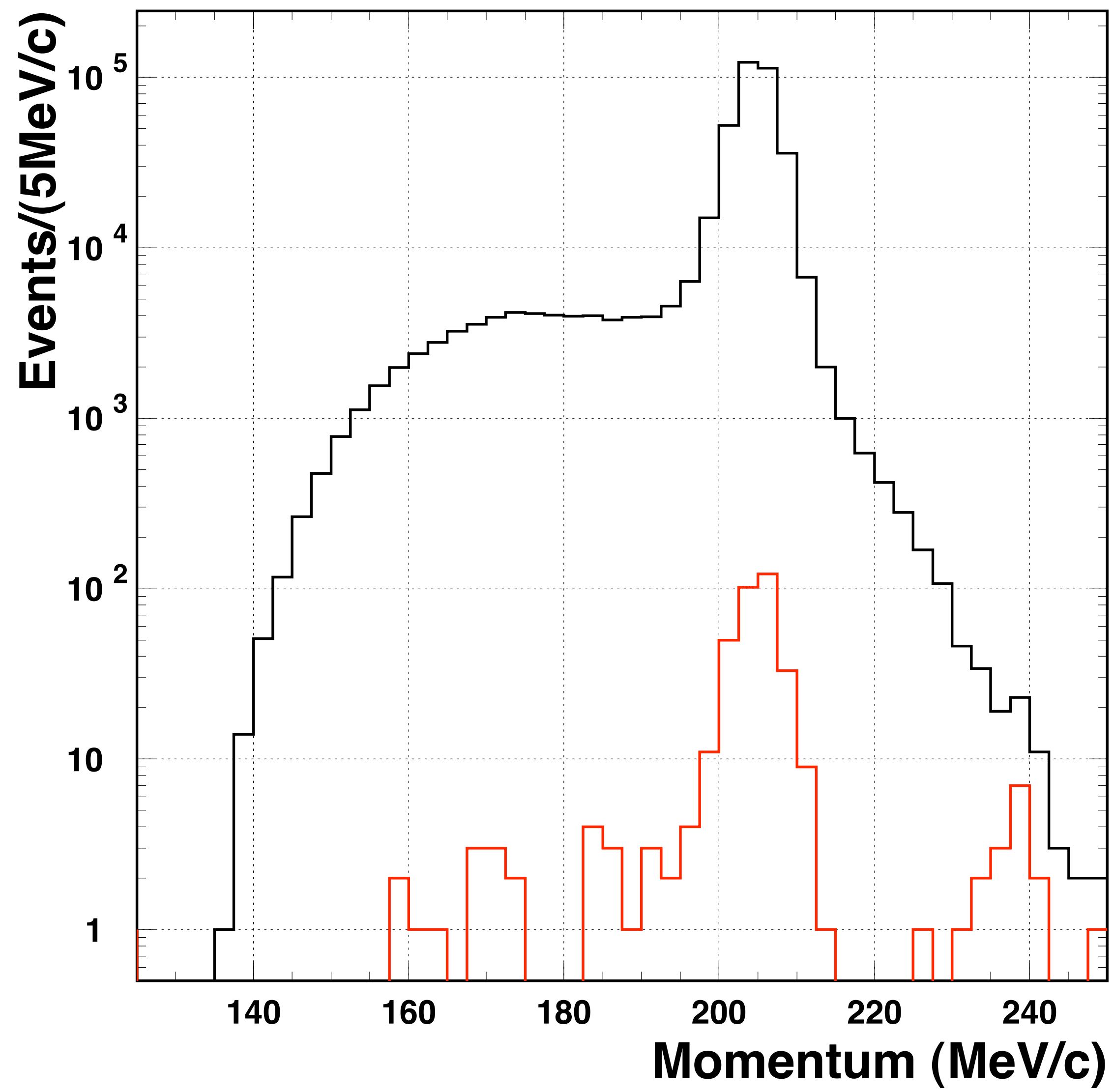
- “Pathology” cuts

Background studies: our policy and philosophy

- To avoid bias due to small statistics,
  - 1/3 of sample: for study
  - 2/3 of sample: (keep untouched)
- **invert** at least one of the cuts to:
  - enhance the backgrounds collected by the trigger
  - prevent candidate events from being examined ("Blind Analysis" even at the event selection)
- Cuts were **frozen** with the 1/3 sample.
- Then measure the background levels in the search region with the remaining (independent) 2/3 sample.

Kπ2 background in PNN2





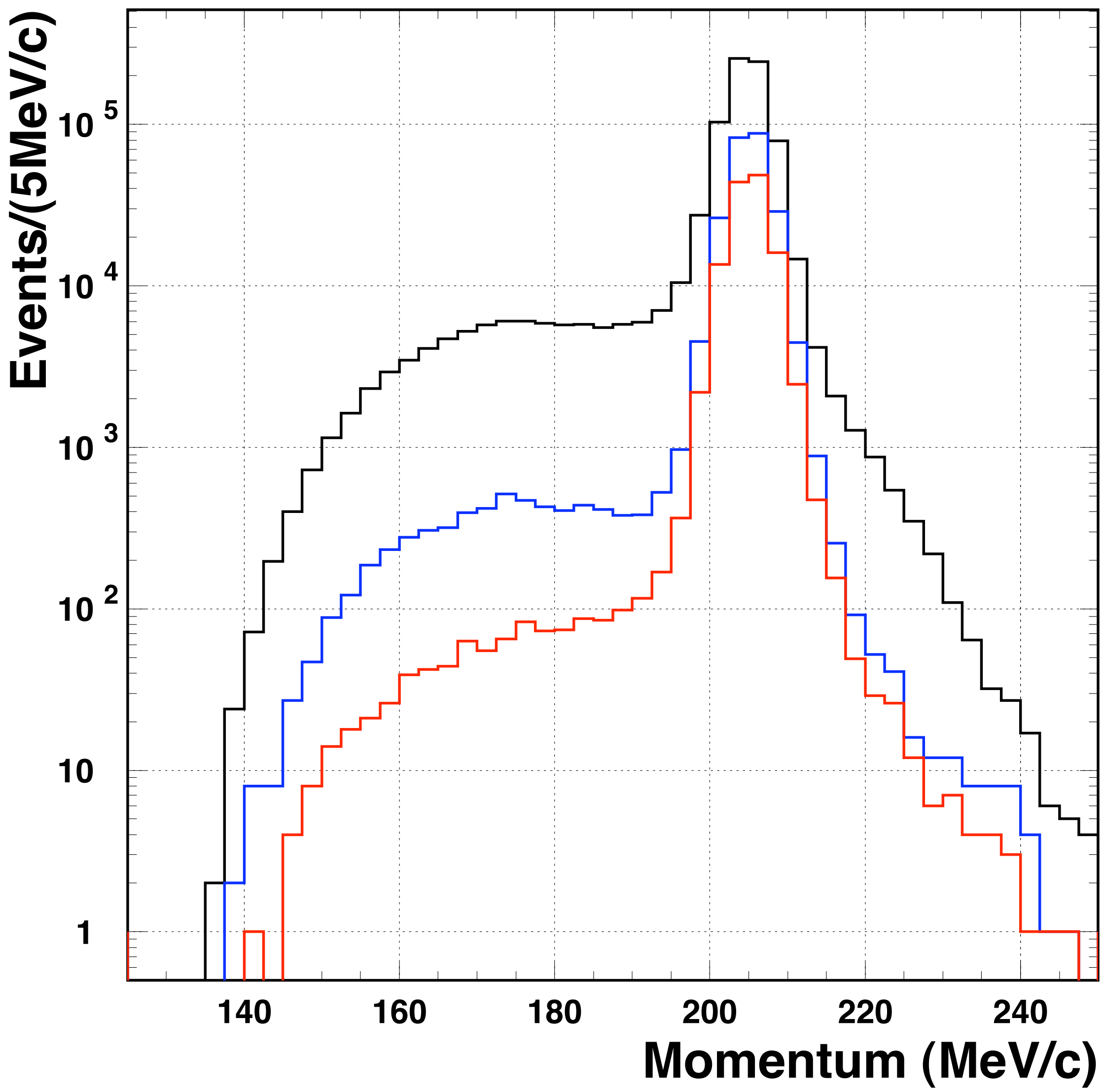
photon tagged sample

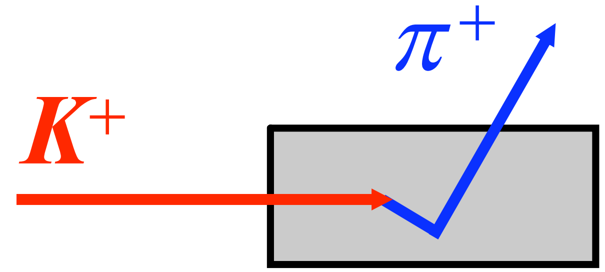
- imposing TARGET cuts
- imposing CCDPUL cuts

π+scatter tagged sample

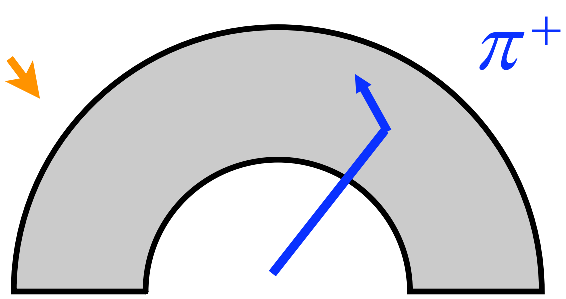
- imposing PV cuts

$K\pi 2$ background in PNN2

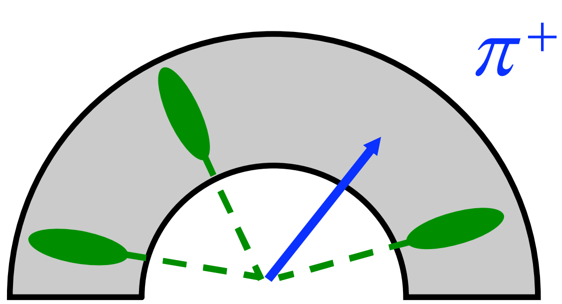




Process	Background events
$K_{\pi 2}$ TG-scatter	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi 2}$ RS-scatter	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2 \gamma}$	$0.076 \pm 0.007 \pm 0.006$



photon tagged sample

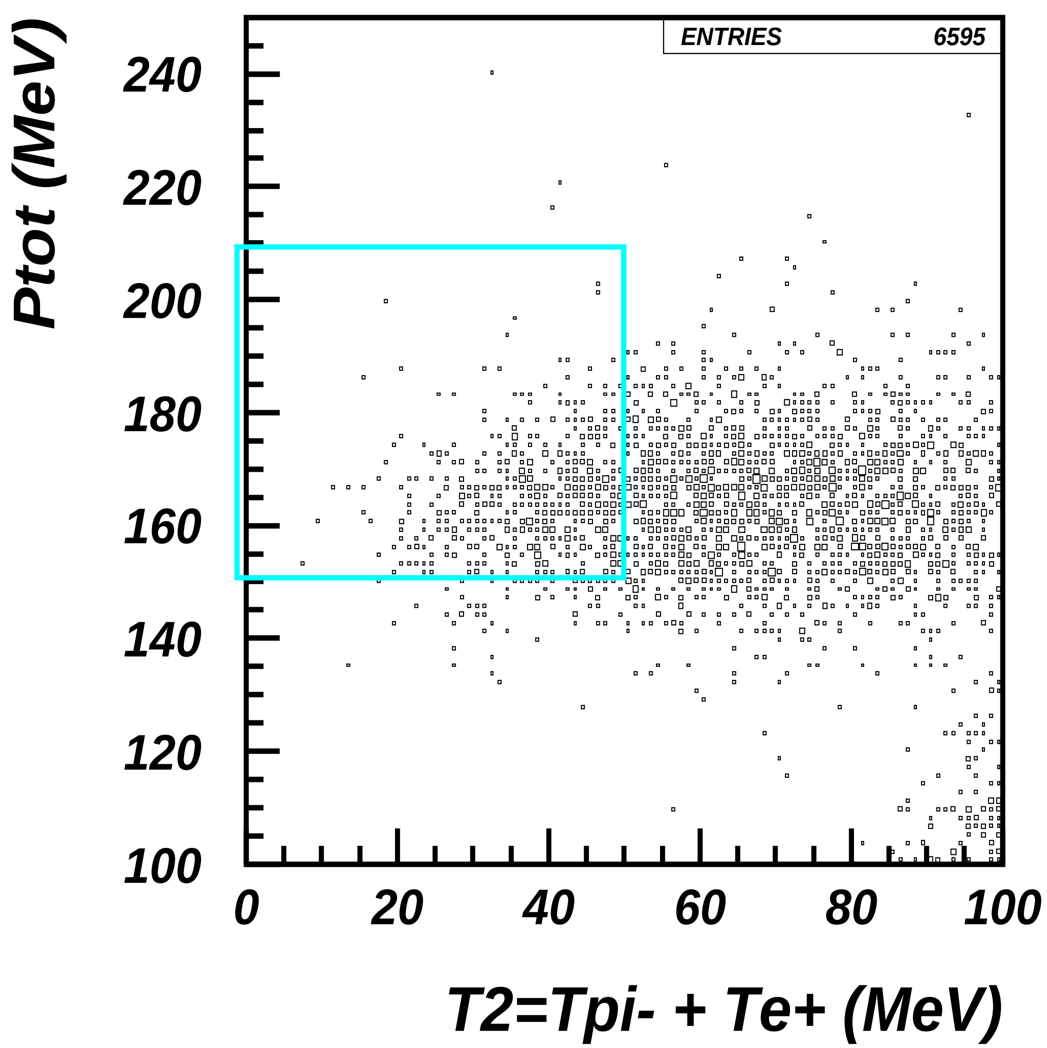


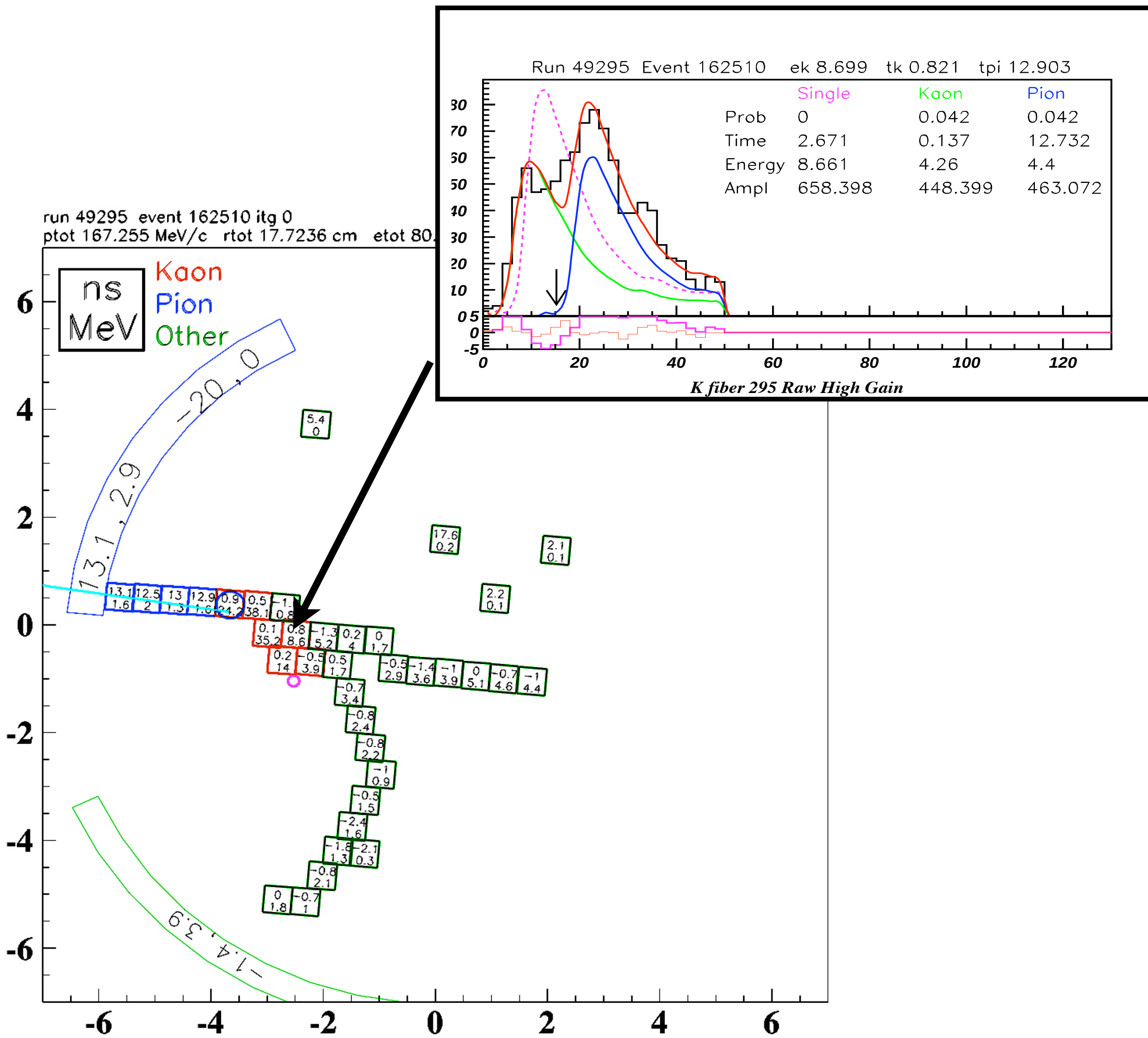
no photon in the final state

$$K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e \quad (K_{e4}) \qquad 4.09 \times 10^{-5} \quad P_{\pi^+\ max} = 203 MeV/c$$

with small energy, and if undetected in the Target

Monte Carlo with PNN2 trigger





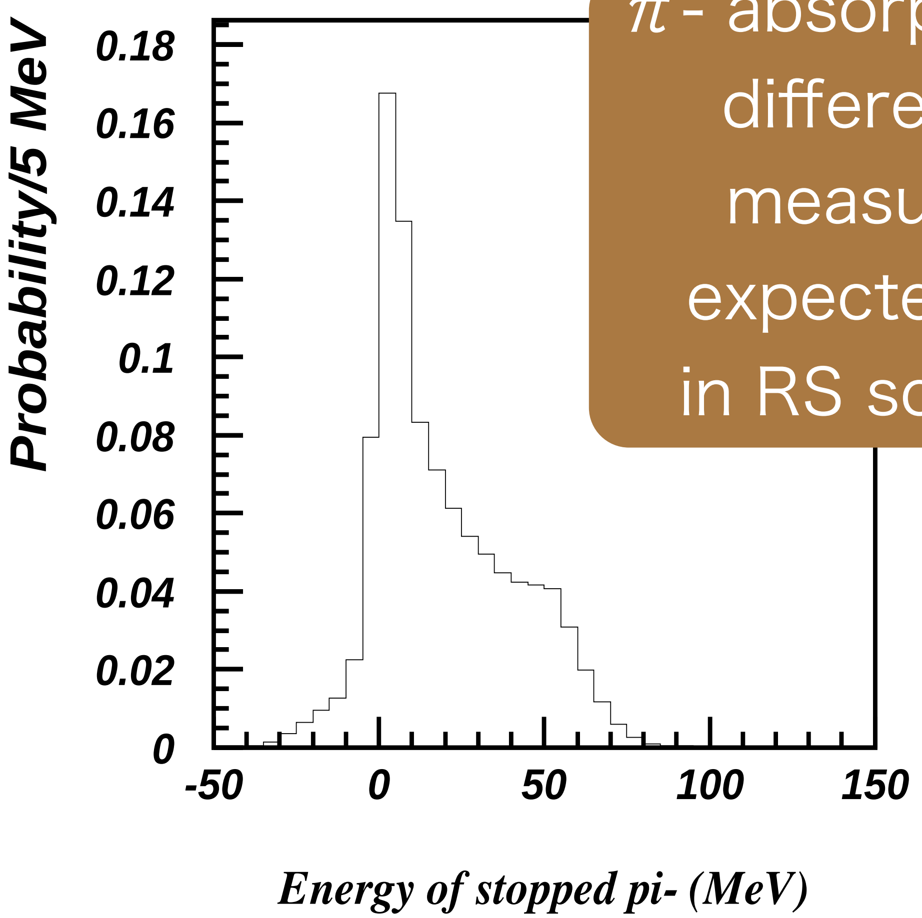
a Ke4 candidate event, tagged by CCDPUL

$$K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e \quad (K_{e4}) \qquad 4.09 \times 10^{-5}$$

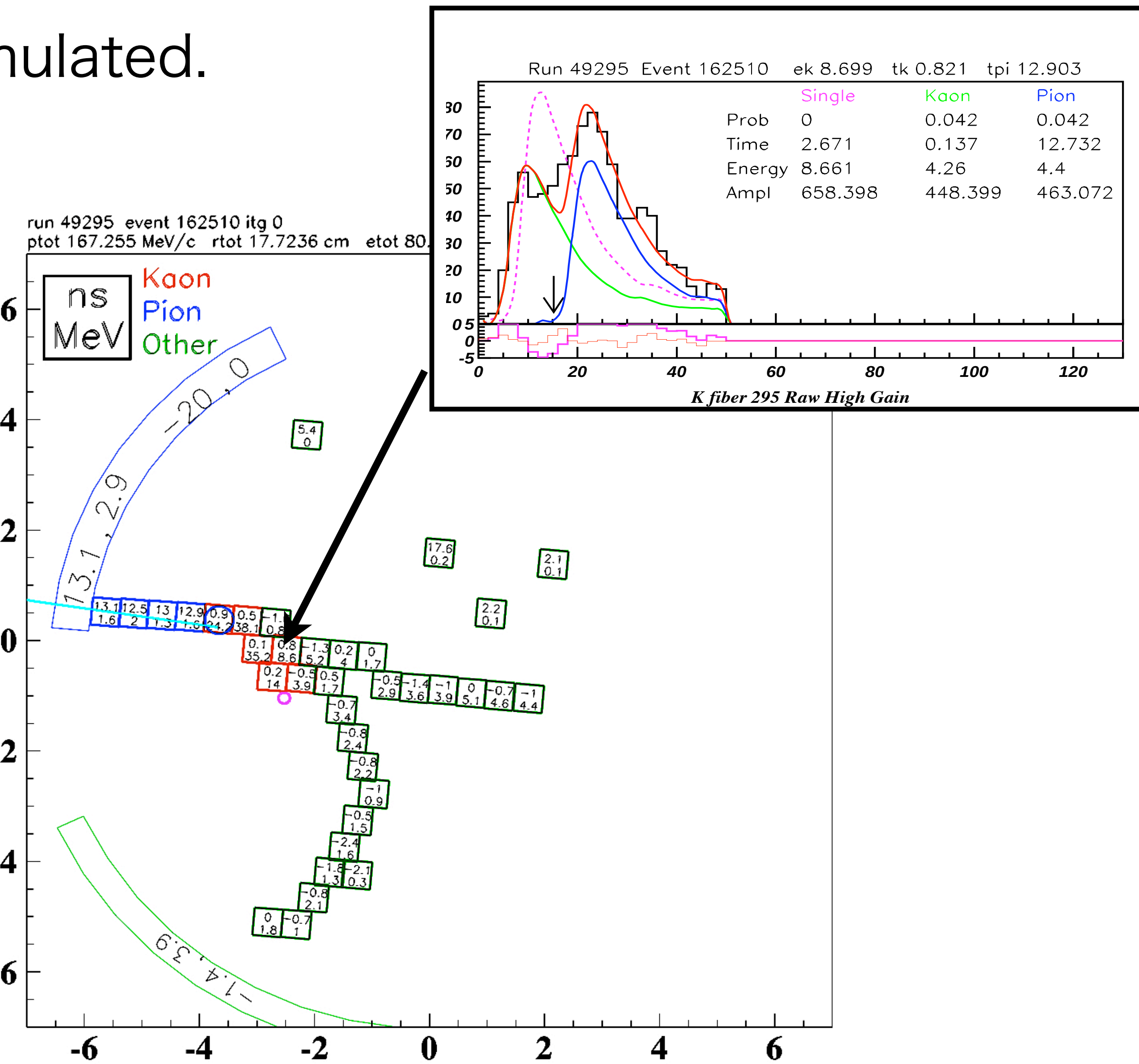
$$P_{\pi^+ \ max} = 203 MeV/c$$

Target pattern recognition:

energy deposit of charged tracks are simulated.



π- absorption (data): difference bet. measured and expected energy in RS scintillators



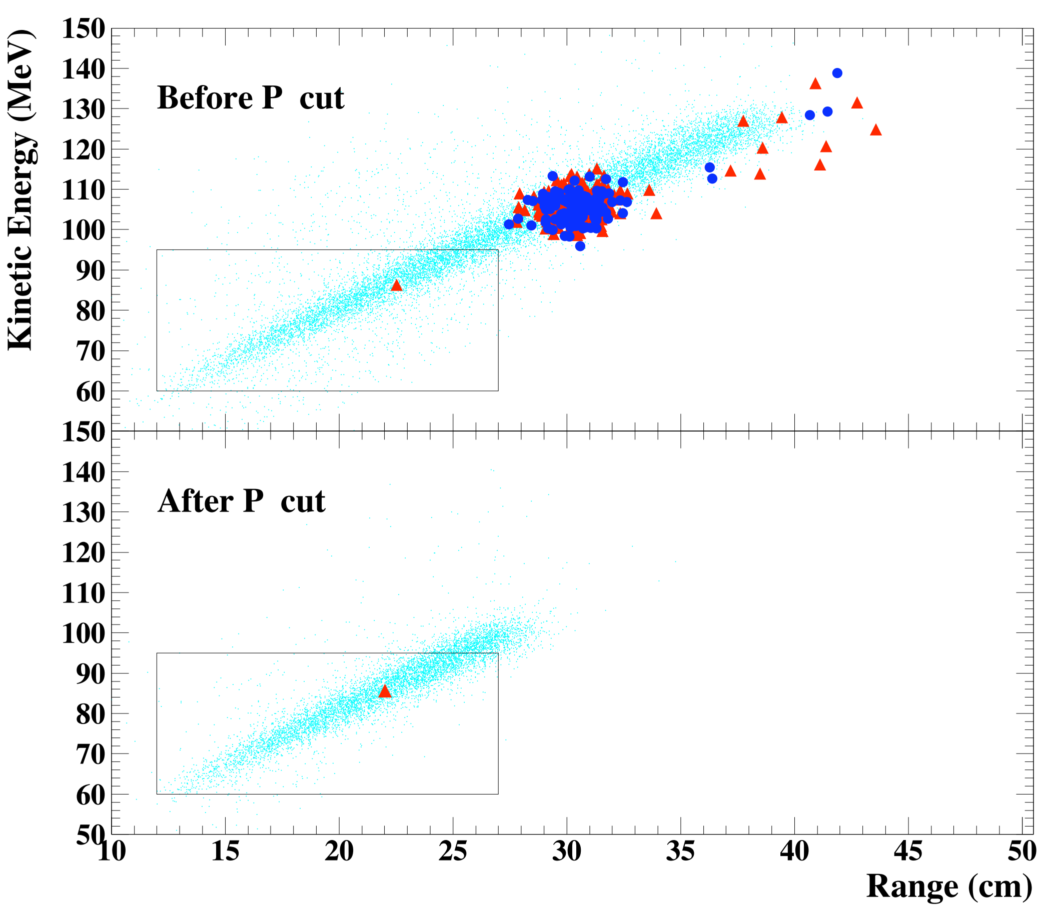
e+ interaction (in EGS4)

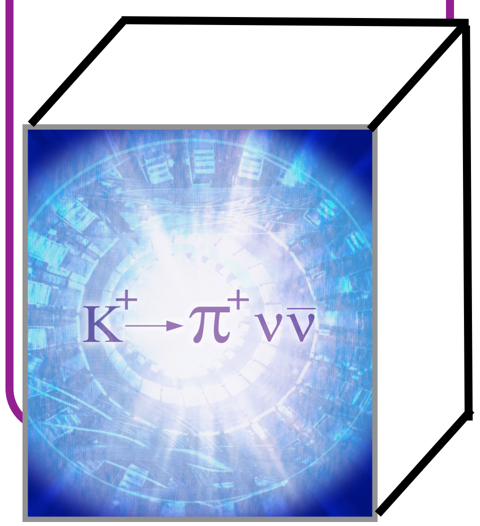
a K_{e4} candidate event, tagged by CCDPUL

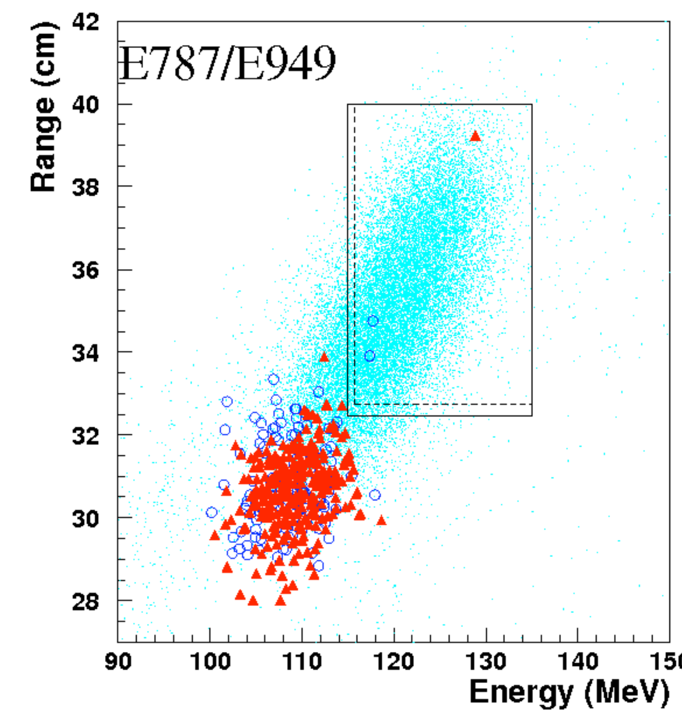
total background in PNN2

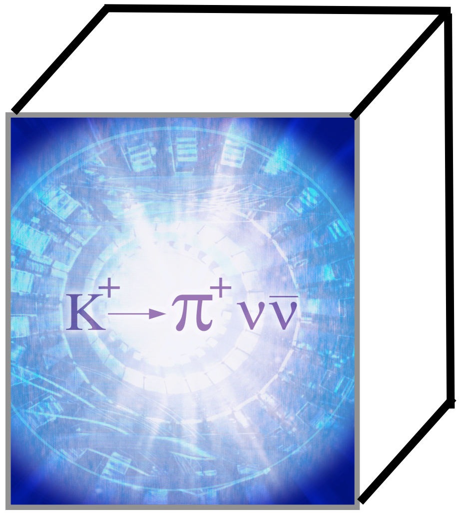
Process	Bkgd events (E949)	Bkgd events (E787)
$K_{\pi 2}$-scatter	$0.649 \pm 0.150^{+0.067}_{-0.100}$	1.030 ± 0.230
$K_{\pi 2 \gamma}$	$0.076 \pm 0.007 \pm 0.006$	0.033 ± 0.004
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$	0.052 ± 0.041
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$	0.024 ± 0.017
Muon	0.011 ± 0.011	0.016 ± 0.011
Beam	0.001 ± 0.001	0.066 ± 0.045
Total bkgd	$0.93 \pm 0.17^{+0.32}_{-0.24}$	1.22 ± 0.24

Region	"PNN2"		"PNN1"
P_{π^+} (MeV/c)	[140,195]	[140,199]	[211,229]
Years	E787 96-97	E949	E787(95, 96-97,98) E949
Ref:	PR **D70**, 037102 (2004)	arXiv:0808.2459	PRL **93**, 031801 (2004)
Stopped K$^+$	1.73×10^{12}	1.71×10^{12}	7.7×10^{12}
Acceptance	0.084%	0.137%	0.2%
SES	6.9×10^{-10}	4.3×10^{-10}	0.63×10^{-10}
Background	1.22 ± 0.24	$0.93 \pm 0.17^{+0.32}_{-0.24}$	0.44 ± 0.05
Candidates	1		3
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$< 22 \times 10^{-10}$		$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$









results

By further tightening four of the cuts, Signal region (in multi-dimensional “cut” space) was divided into 9 cells.

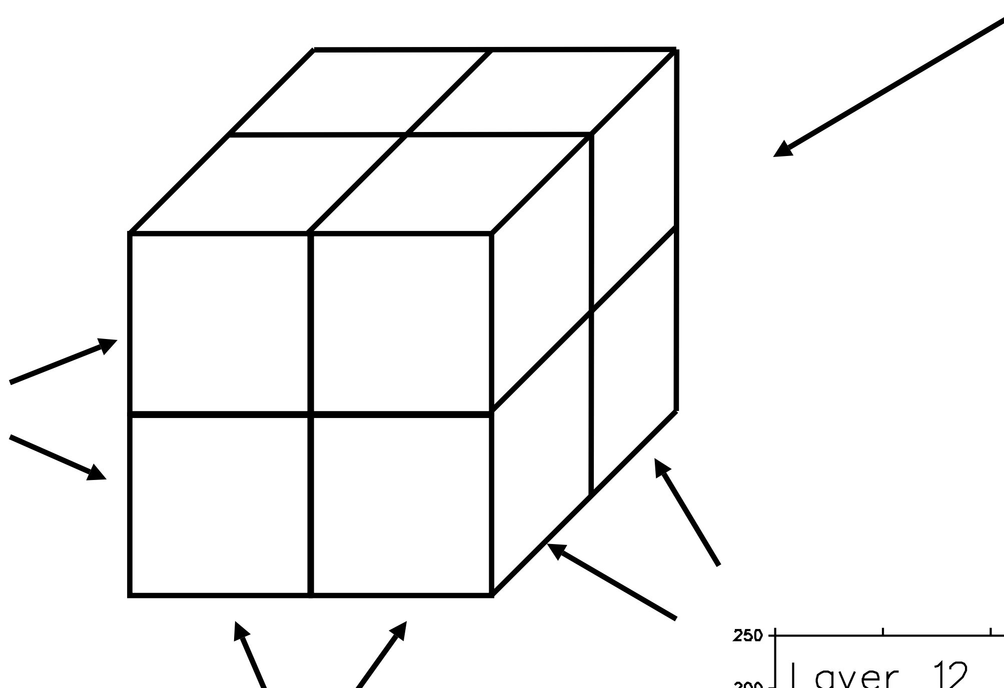
tight-”signal region”

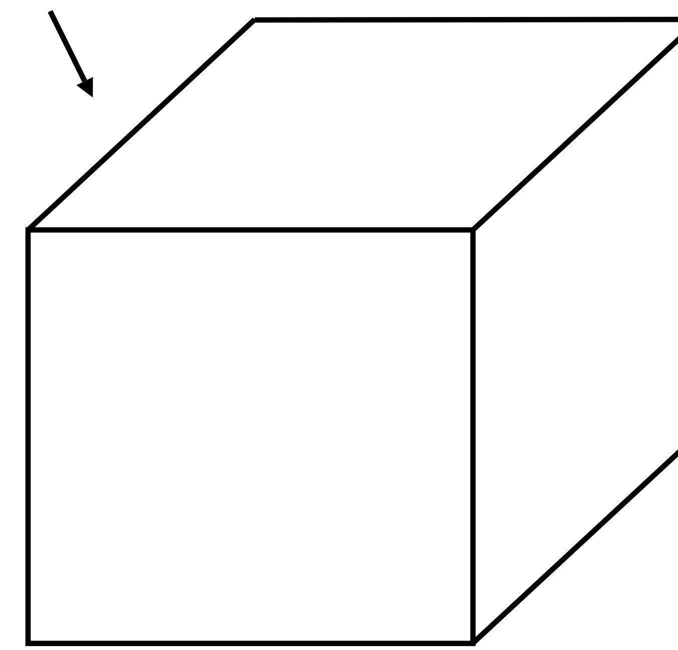
165 < P < 197 MeV/c
17<R<28cm, 72<E<100MeV

”Signal region”

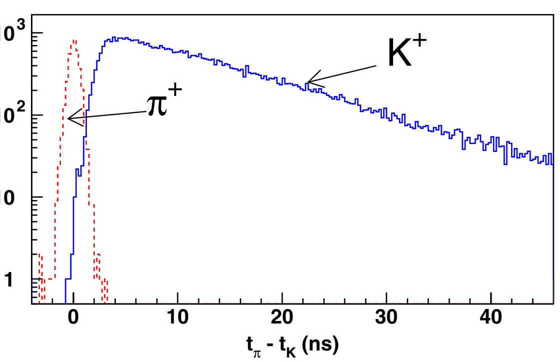
140 < P < 199 MeV/c
12<R<28cm, 60<E<100.5MeV

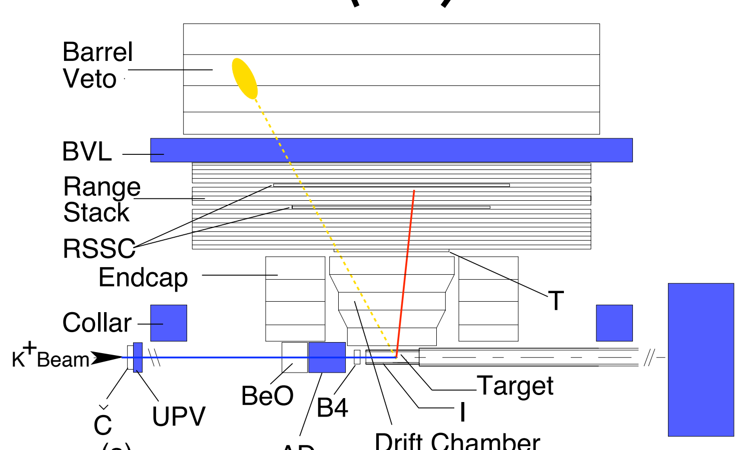
excluding the tight region



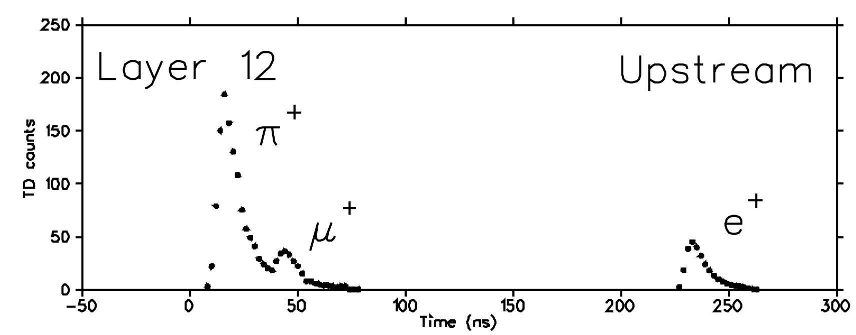


Delayed Coincidence (DC)





Photon Veto (PV)



$\pi+$ identification (TD)

By further tightening four of the cuts, Signal region (in multi-dimensional "cut" space) was divided into 9 cells.

Acc = 0.137%

	rel. Acc	bkg	Acc/bkg
	0.314	0.152	2.065
	0.073	0.038	1.921
	0.031	0.019	1.653
	0.007	0.005	1.559
	0.287	0.243	1.183
	0.066	0.059	1.135
	0.028	0.027	1.036
	0.006	0.007	0.998
	0.188	0.379	0.496
sum	1	0.93	

By further tightening four of the cuts, Signal region (in multi-dimensional “cut” space) was divided into 9 cells.

Acc = 0.137%

	rel. Acc	bkg	Acc/bkg
	0.314	0.152	2.065
	0.073	0.038	1.921
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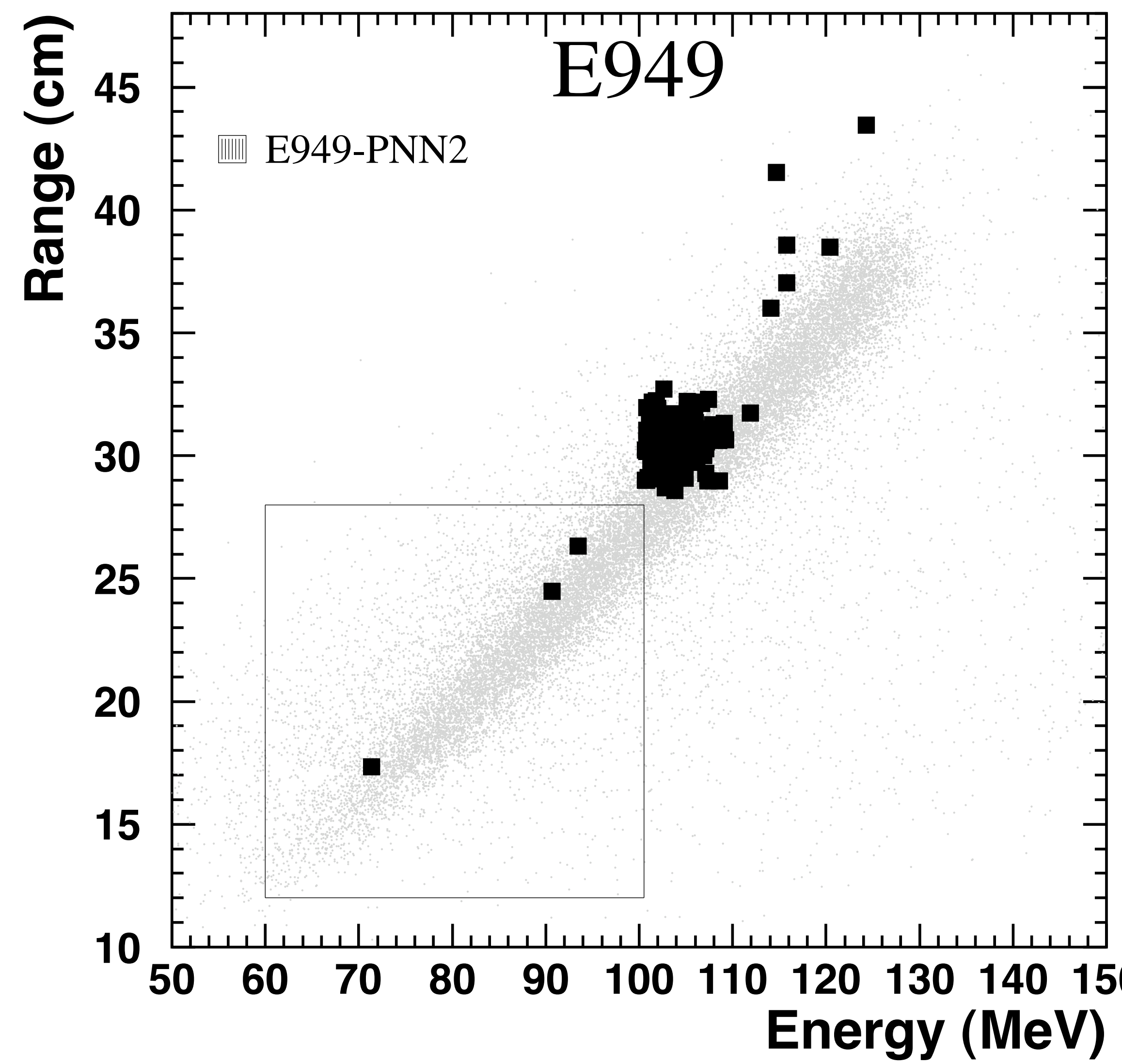
	0.028	0.027	1.036
	0.006	0.007	0.998
	0.188	0.379	0.496
sum	1	0.93	

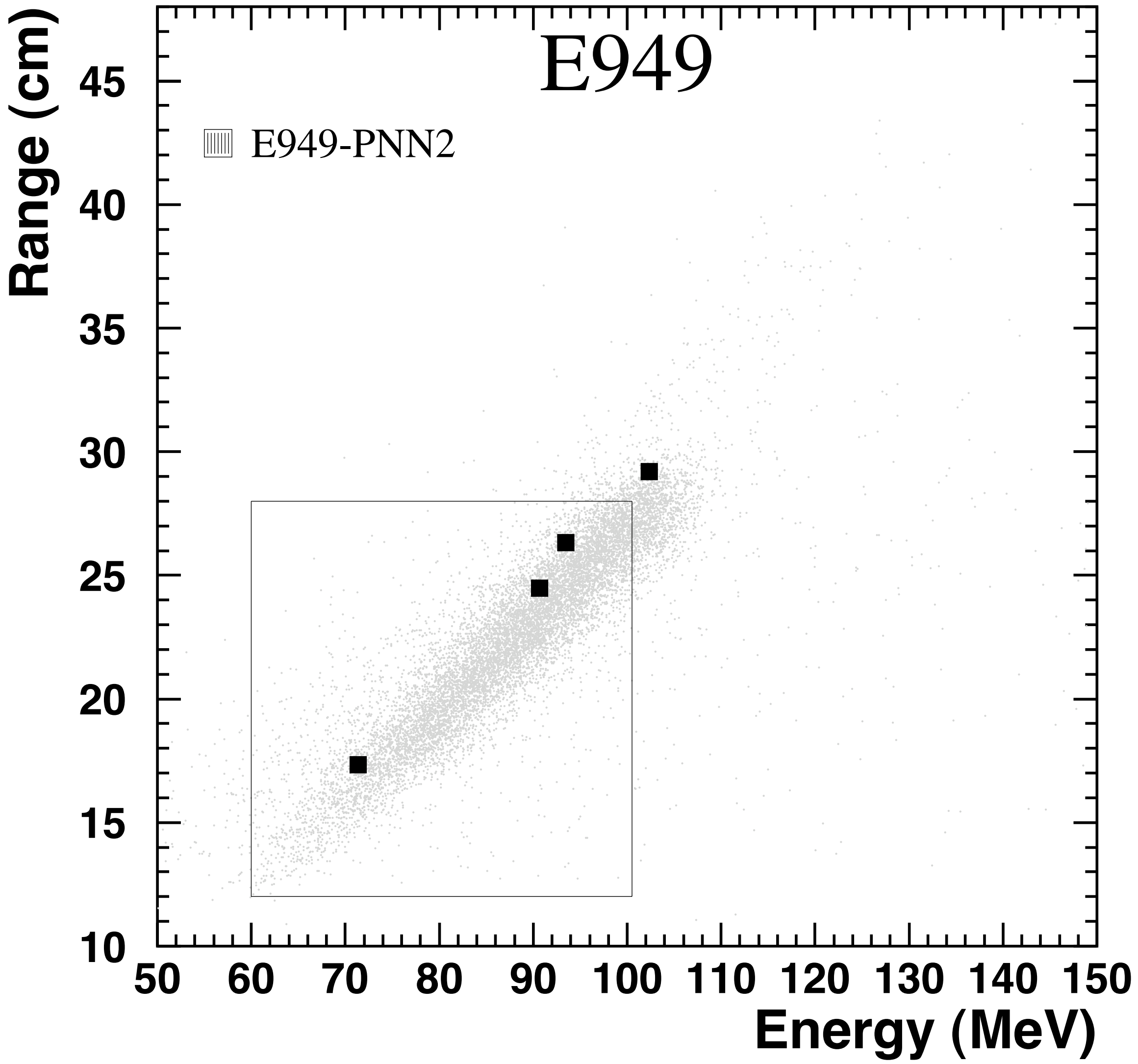


all the cuts
except for 140 < P < 199 MeV/c

By further tightening four of the cuts, Signal region (in multi-dimensional “cut” space) was divided into 9 cells.

Acc = 0.137%

	rel. Acc	bkg	Acc/bkg
	0.314	0.152	2.065
	0.073	0.038	1.921
	0.031	0.019	1.653
	0.007	0.005	1.559
	0.287	0.243	1.183
	0.066	0.059	1.135
	0.028	0.027	1.036
	0.006	0.007	0.998
	0.188	0.379	0.496
sum	1	0.93	

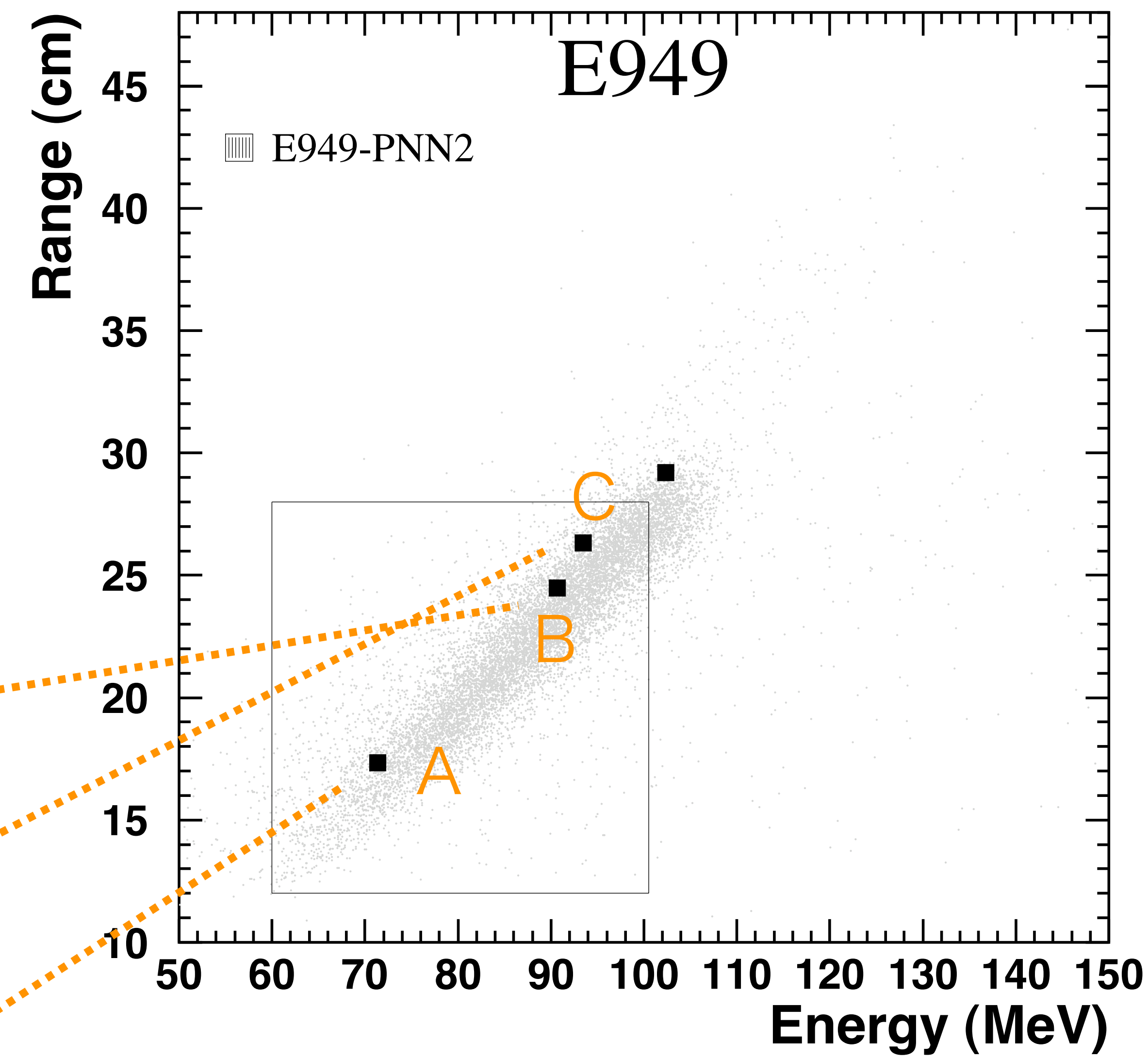


after imposing 140 < P < 199 MeV/c

By further tightening four of the cuts,
Signal region (in multi-dimensional "cut" space)
was divided into 9 cells.

Acc = 0.137%

	rel. Acc	bkg	Acc/bkg	data
	0.314	0.152	2.065	0
	0.073	0.038	1.921	0
	0.031	0.019	1.653	0
	0.007	0.005	1.559	0
	0.287	0.243	1.183	1
	0.066	0.059	1.135	0
	0.028	0.027	1.036	1
	0.006	0.007	0.998	0
	0.188	0.379	0.496	1
sum	1	0.93		

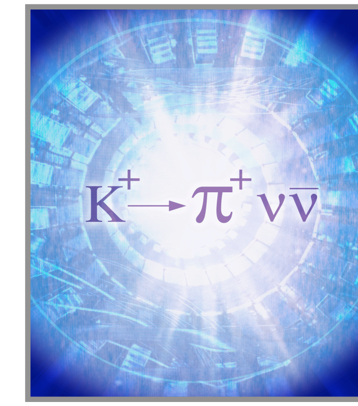


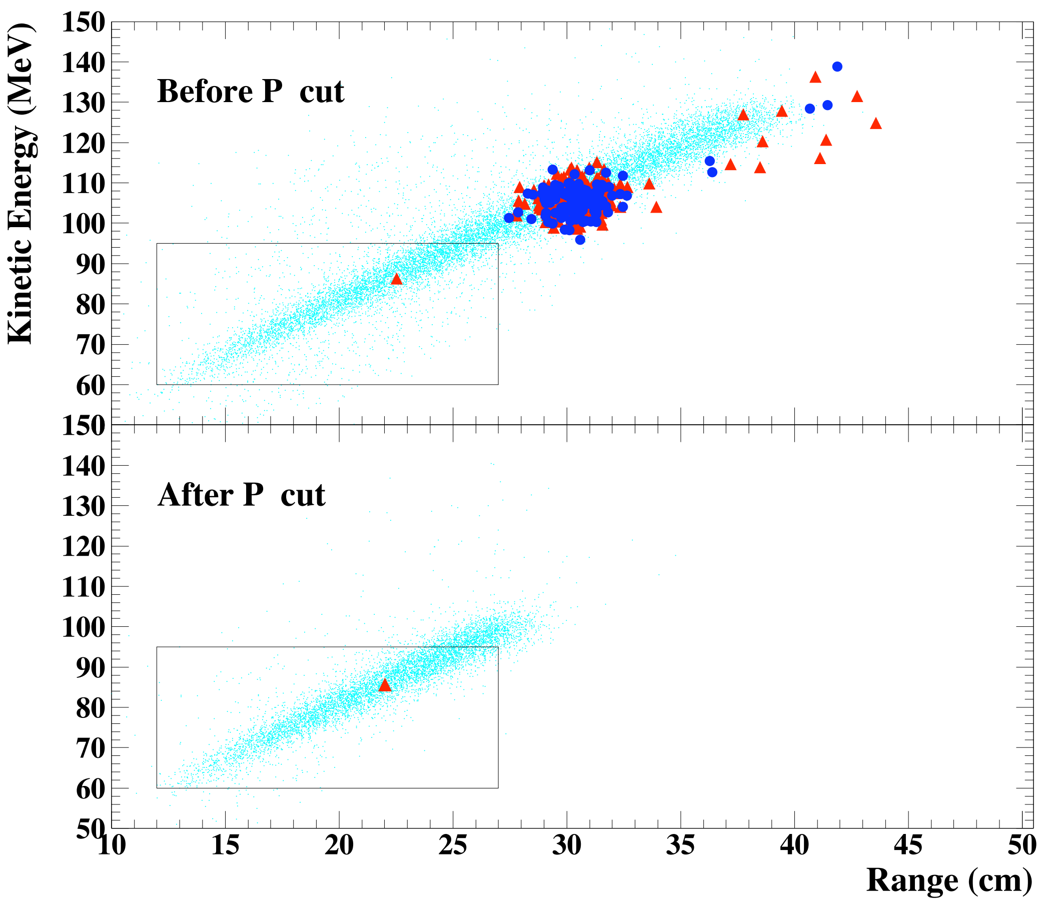
after imposing 140 < P < 199 MeV/c

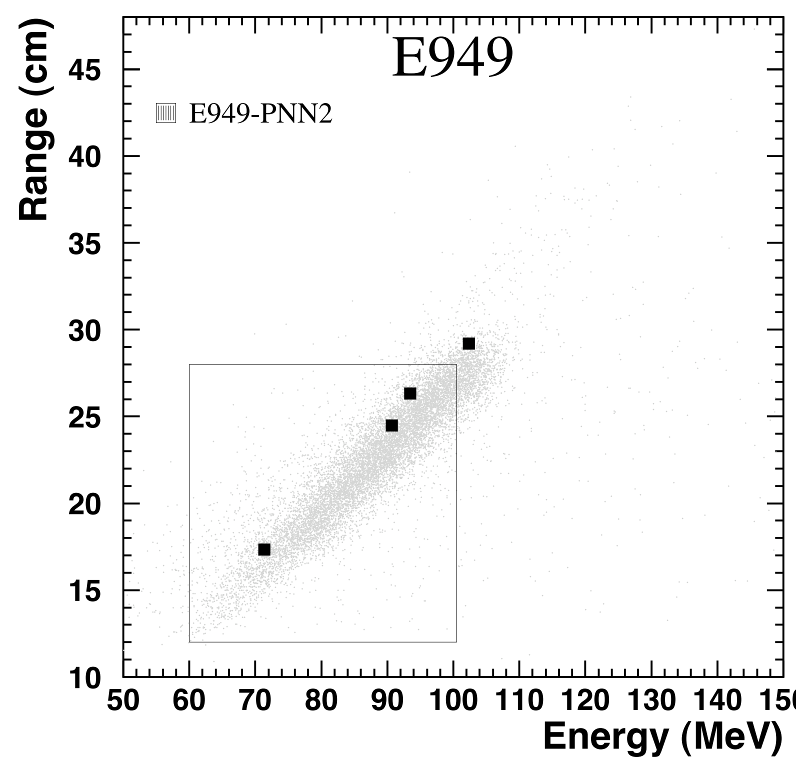
The probability that the 3 events were due to background only is 3.7%.

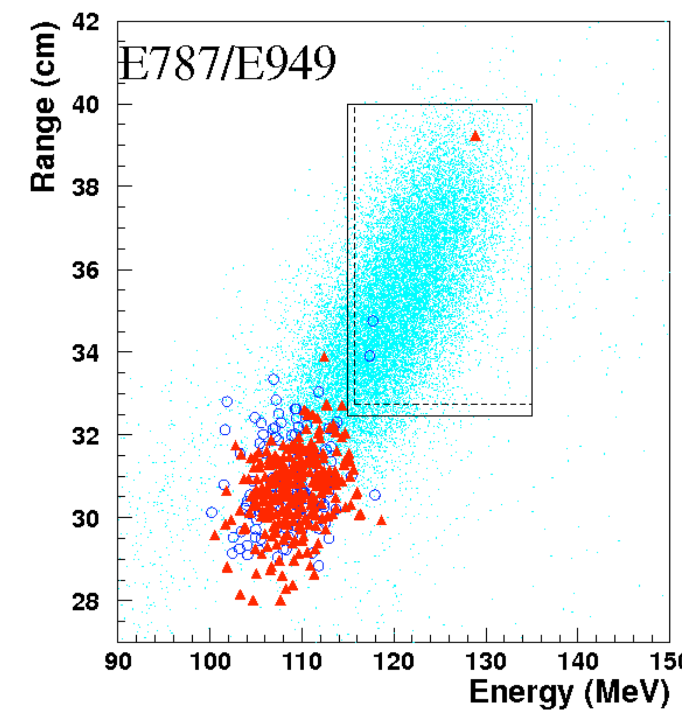
named as	A	B	C
P (MeV/c)	161.46	188.40	191.30
R (cm)	17.29	24.16	26.10
E (MeV)	76.07	95.57	97.94
tight Box	fail	pass	pass
K+ decay time (ns)	3.70	15.74	5.14
$\pi+$ decay time (ns)	22.4	16.7	10.2
$\mu+$ decay time (ns)	5959	2271	9508
tight DelCo	fail	pass	fail
tight PhotonVeto	pass	fail	fail
tight TD	pass	pass	pass

Region	"PNN2"		"PNN1"
P_{π^+} (MeV/c)	[140,195]	[140,199]	[211,229]
Years	E787 96-97	E949	E787(95, 96-97,98) E949
Ref:	PR **D70**, 037102 (2004)	arXiv:0808.2459	PRL **93**, 031801 (2004)
Stopped K$^+$	1.73×10^{12}	1.71×10^{12}	7.7×10^{12}
Acceptance	0.084%	0.137%	0.2%
SES	6.9×10^{-10}	4.3×10^{-10}	0.63×10^{-10}
Background	1.22 ± 0.24	$0.93 \pm 0.17^{+0.32}_{-0.24}$	0.44 ± 0.05
Candidates	1	3	3
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(7.89^{+9.26}_{-5.10}) \times 10^{-10}$	$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$







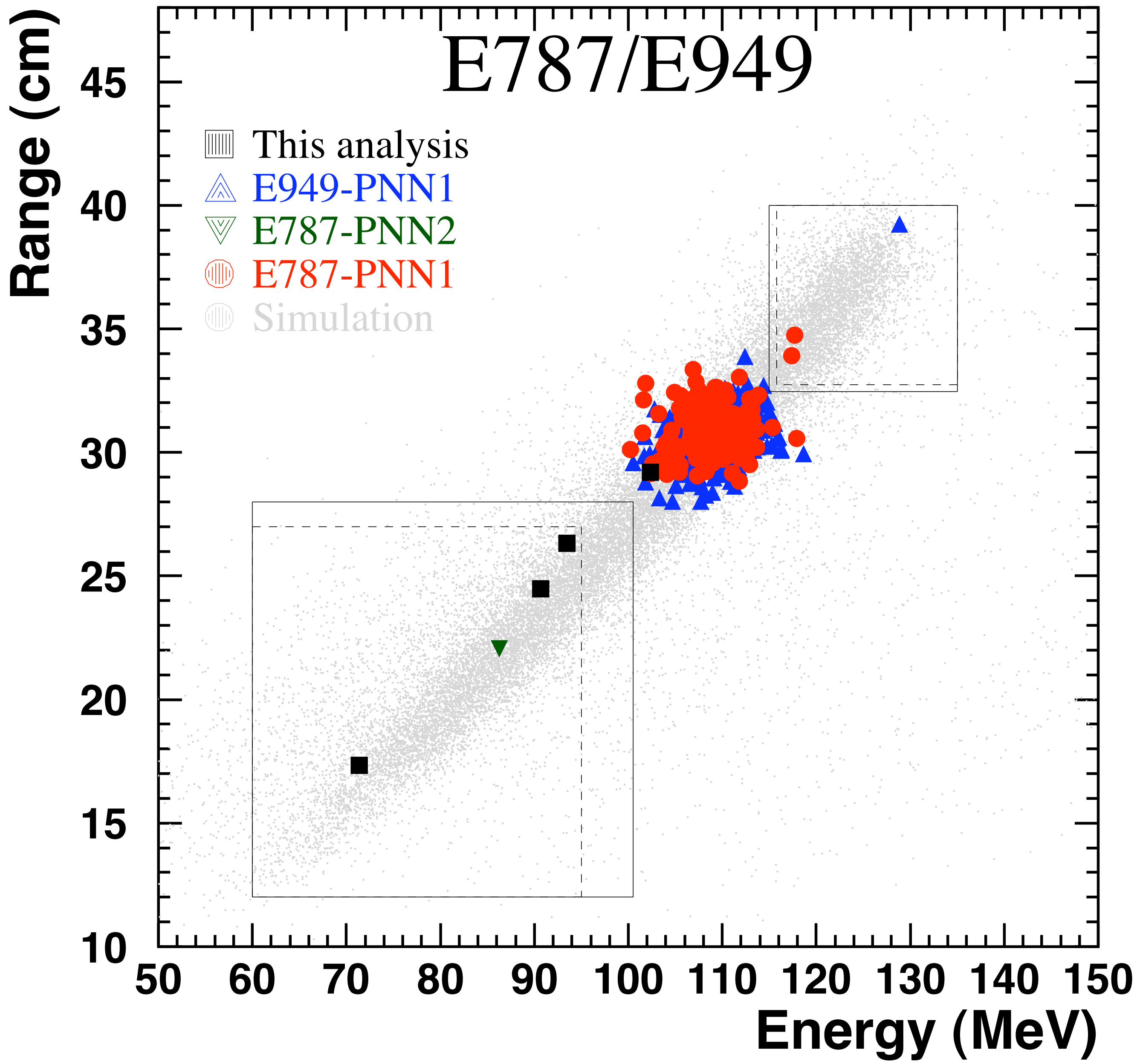


with $S_i(BR) \equiv BR \bullet \mathrm{N}_K \bullet A_i$

$$A_i \;/\; b_i \;\Longrightarrow\; S_i \;/\; b_i$$

d_i

FIG. 1 in arXiv:0808.2459



$S_i \;/\; b_i$

E787-PNN1 95	59
E787-PNN1 98	8.2
E949-PNN1 02	1.1
E787-PNN2 96	0.2
E949-PNN1 02A	0.20
E949-PNN1 02B	0.47
E949-PNN1 02C	0.42

with $BR = 1.73 \times 10^{-10}$

The probability that
all 7 events were due to background
is 0.1% (3σ).

$$B.R.(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (\ 1.73^{+1.15}_{-1.05}\ ) \times 10^{-10}$$

68%C.L. interval

90%C.L. interval upper limit

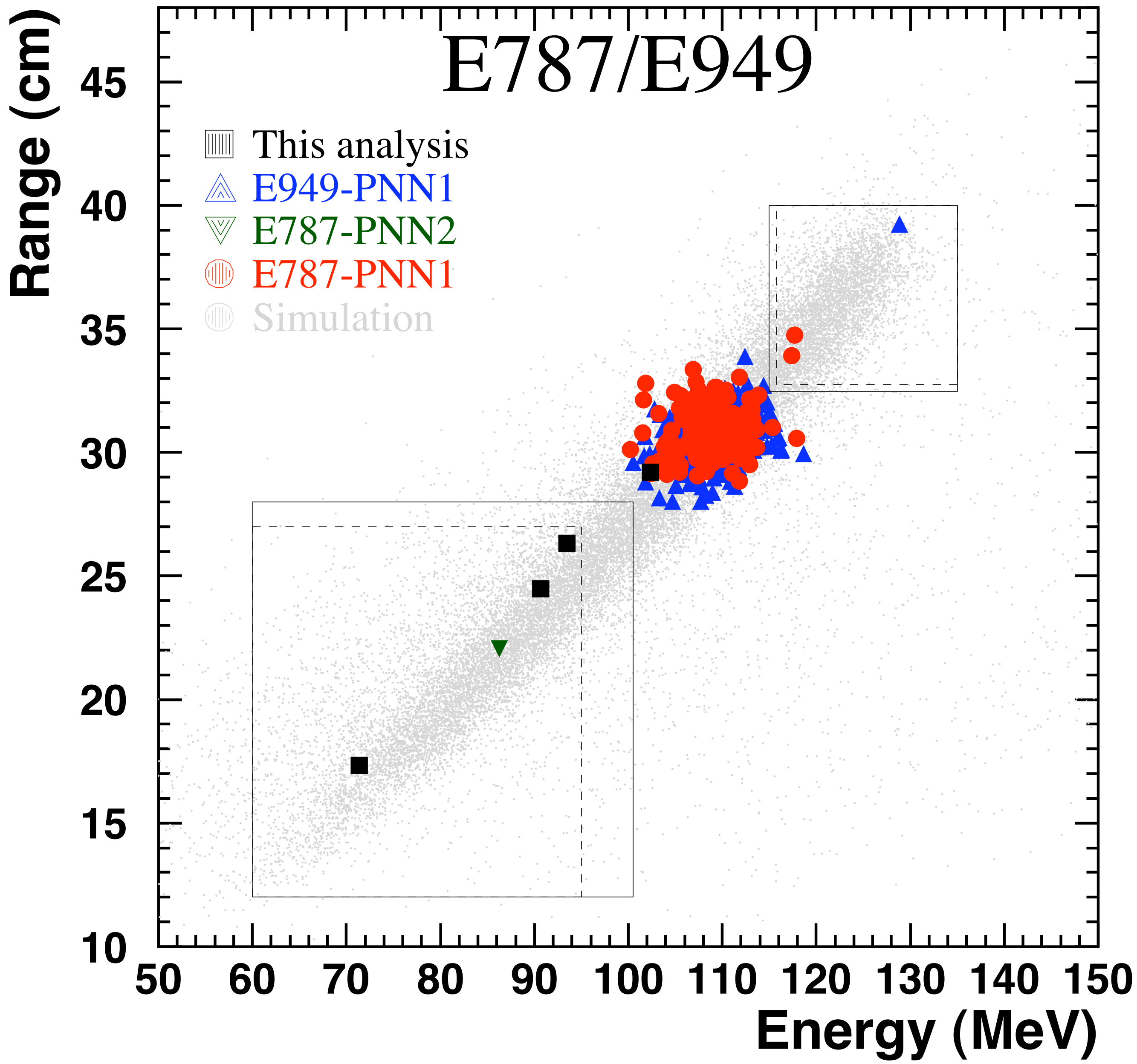
$$3.35 \times 10^{-10}$$

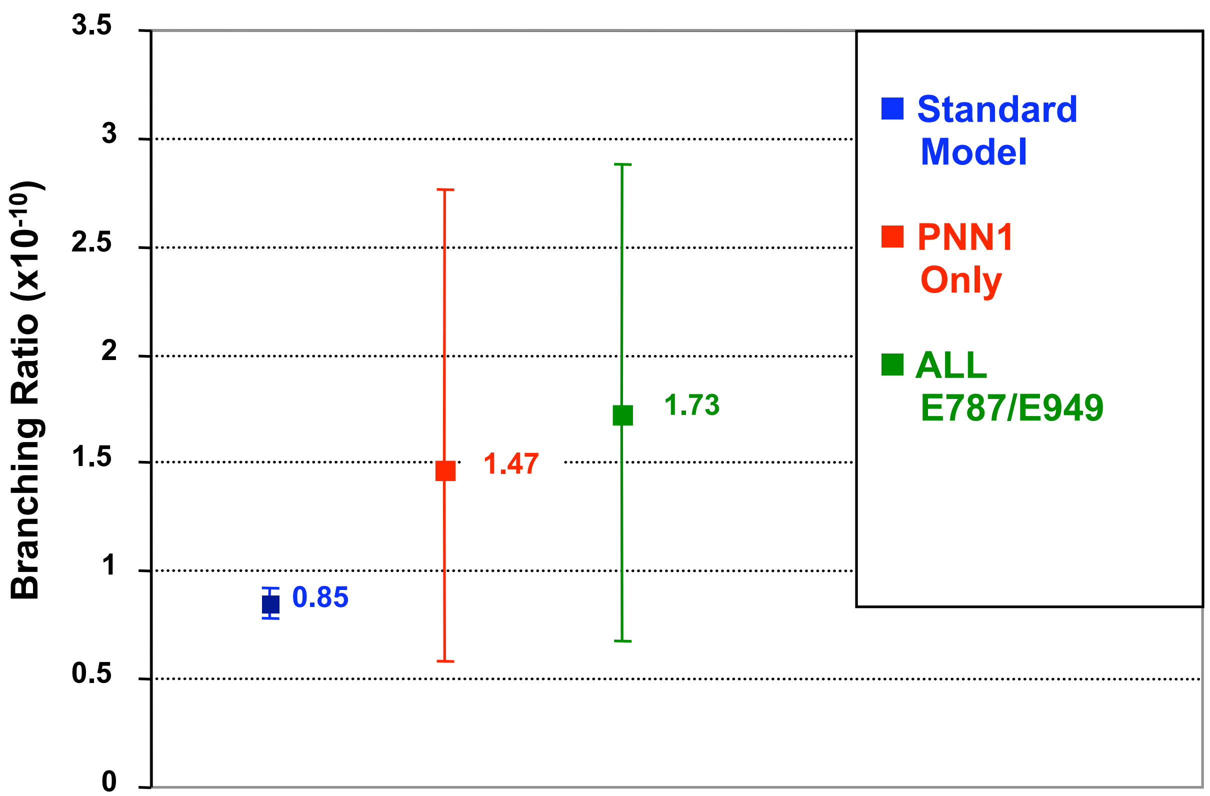
☞ Upper limit on B.R.($K_L^0 \to \pi^0 \nu \bar{\nu}$) by Grossman-Nir(1997):

$$1.4 \times 10^{-9}$$

unchanged

FIG. 1 in arXiv:0808.2459





consistent with the SM prediction

$$B.R.(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

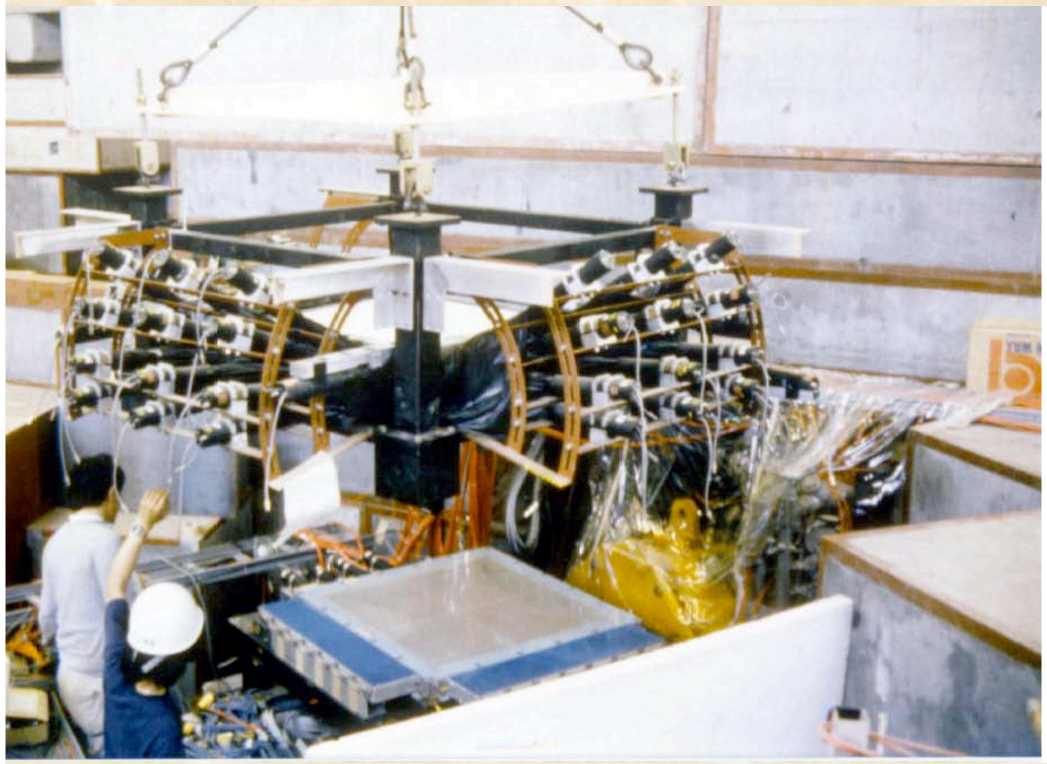
$$B.R._{SM} = (0.85 \pm 0.07) \times 10^{-10}$$

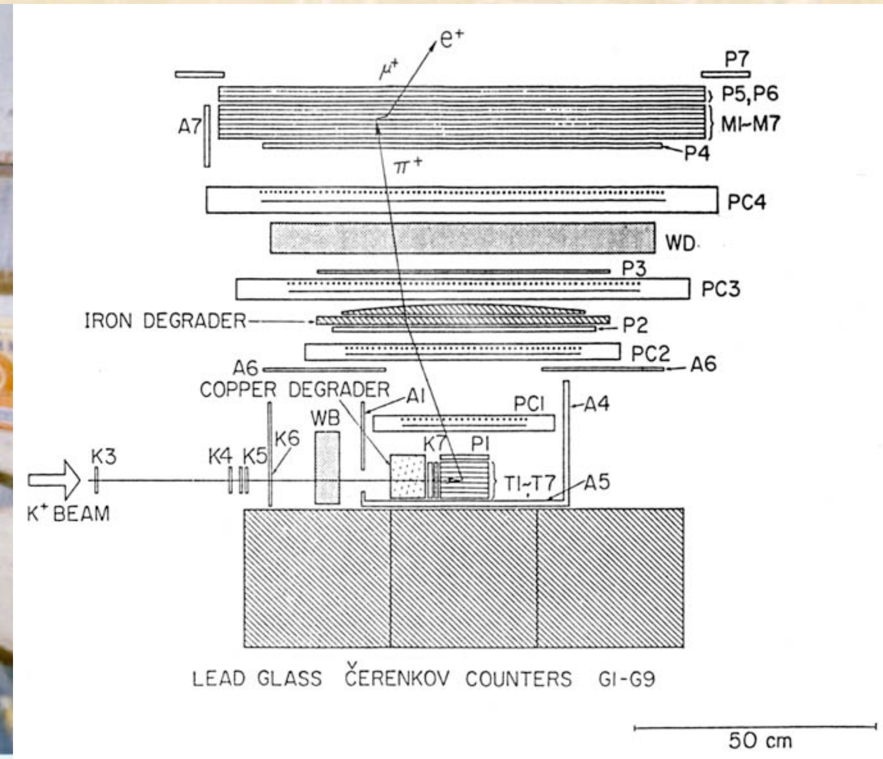
conclusions and future

An Example of Decay Experiments

E10 Y.Nagashima: $K^+ \to \pi^+ \bar{\nu}\nu$

$K^+ \to \pi^+ + axion$





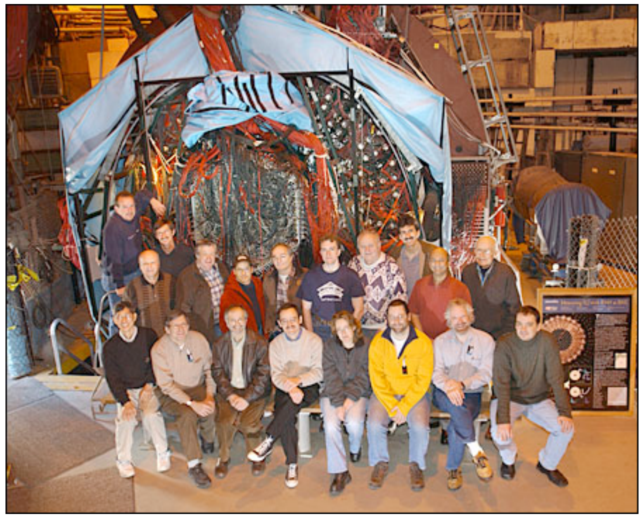
A Table–top experimrnt

: An extinct species of HEP apparatus

$$< \ 1.4 \times 10^{-7}$$

KEK-E10, PL B107, 159-162 (1981)

conclusions and future



- After the efforts of many people for 25 years and with the sophisticated (and state-of-the-art) hardware and software, E949/E787 at BNL-AGS succeeded in measuring the rare decay.

$$B.R.(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \ = \ (\ 1.73^{+1.15}_{-1.05} \ ) \times 10^{-10}$$

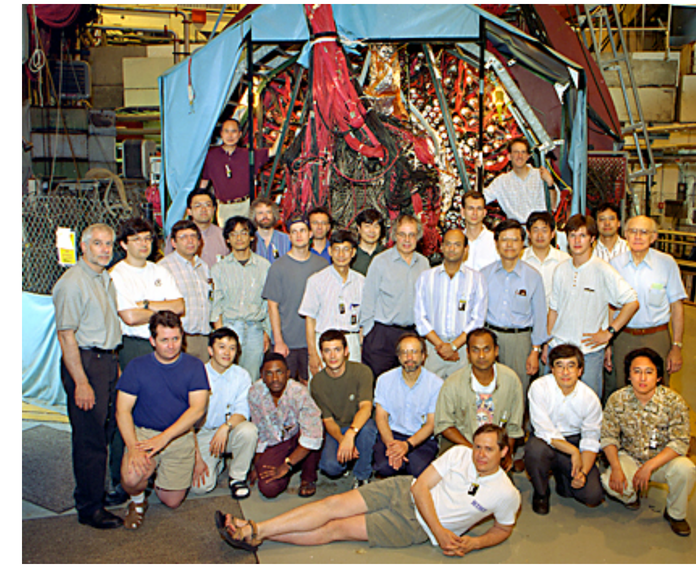
consistent with SM

- Proton operation at AGS halted.

- Analyses of E949/E787 for other K+ decay modes still continue.

- The show must go on;
  the task of precise measurement (and beyond_the_SM study)
  is passed to:
  - K+ decay in flight @ CERN NA62 (in preparation)
  - K+ decay at rest @ J-PARC (LoI)

acknowledgments



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  - Japan-U.S. Cooperative Research Program in HEP (1992-2005)
  - Grant-in-Aids for Scientific Research,
    for Encouragement of Young Scientists and for JSPS Fellows

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  who launched the Japan-US project in the early 1990's.