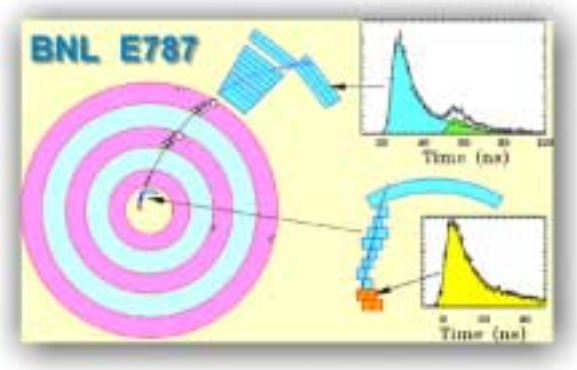


Informal HEP Seminar
Caltech
April 2, 2002

$K^+ \to \pi^+ \nu\overline{\nu}$

- $K^+ \to \pi^+ \nu\overline{\nu}$: E787/E949
- $K_L^\circ \to \pi^\circ \nu\overline{\nu}$: KOPIO

Steve Kettell
Brookhaven National Laboratory

Brookhaven Science Associates
U.S. Department of Energy

CKM Matrix and CP-Violation

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\overline{\rho}-i\overline{\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

$K \to \pi\nu\overline{\nu}$: The Golden Modes

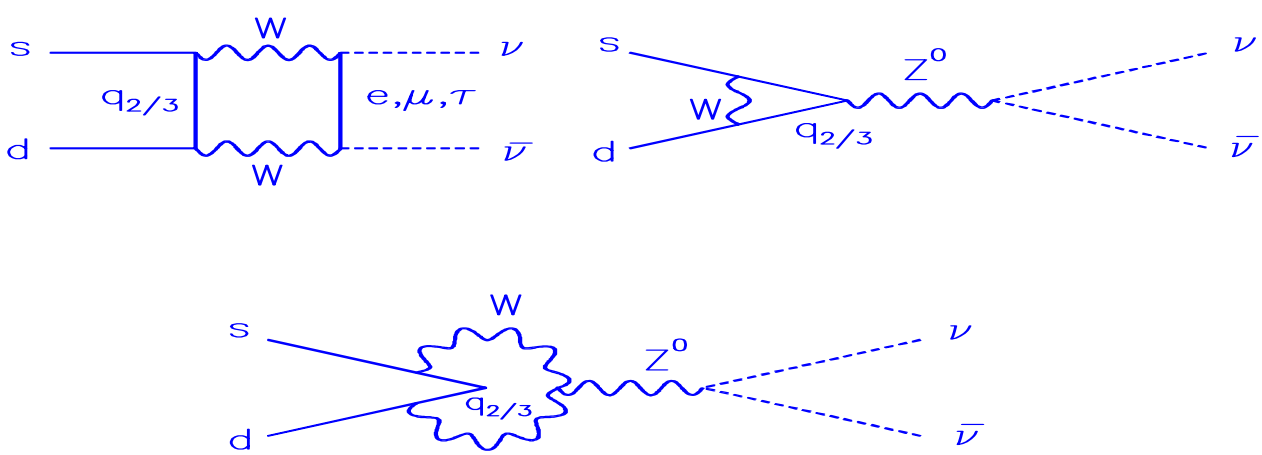
- $K^+ \to \pi^+\nu\overline{\nu}$: measure $|\lambda_t| \equiv |V_{ts}^* V_{td}\ |$.

$$\begin{aligned} B(K^+ \to \pi^+\nu\overline{\nu}\ ) &= \frac{\kappa_+ \alpha^2 B(K^+ \to \pi^\circ e^+ \nu_e\ )}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \sum_l |X_t V_{ts}^* V_{td}\ + X_c V_{cs}^* V_{cd}\ |^2 \\ &= (0.72 \pm 0.21) \times 10^{-10} \end{aligned}$$

- $K_L^\circ \to \pi^\circ\nu\overline{\nu}$: direct CP violating, measure $Im(\lambda_t) = Im(V_{ts}^* V_{td}\ )$.

$$\begin{aligned} B(K_L^\circ \to \pi^\circ\nu\overline{\nu}\ ) &= \frac{\tau_{K_L}}{\tau_{K^+}} \frac{\kappa_L \alpha^2 B(K_{e3})}{2\pi^2 sin^4\theta_W |V_{us}|^2} \sum_l |Im(V_{ts}^* V_{td}) X_t|^2 \\ &= (0.26 \pm 0.12) \times 10^{-10} \end{aligned}$$

This is the best way to measure $Im(\lambda_t)$ and the Jarlskog invariant J_{CP}.



Combining the two **Golden Kaon Modes ($K \to \pi\nu\overline{\nu}$)** with the two **Golden B Modes ($B_d^\circ \to \psi K_S^\circ$ and $\Delta M_{B_s}/\Delta M_{B_d}$)**, two important tests of SM CP violation can be made:

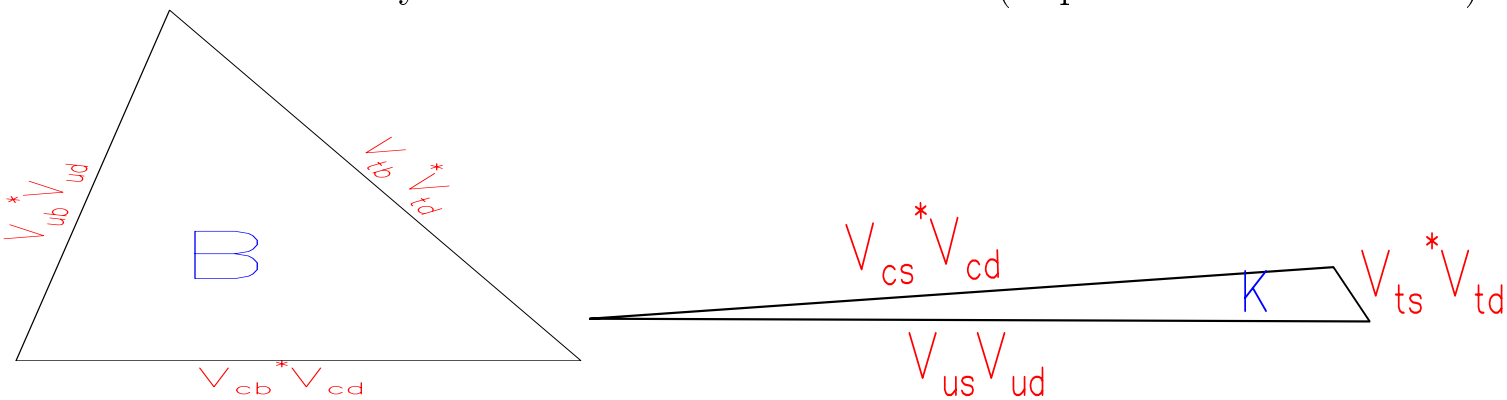
- Overconstraint of $|V_{td}|$ from $K^+ \to \pi^+\nu\overline{\nu}$ and $\Delta M_{B_s}/\Delta M_{B_d}$
- Overconstraint of β from $K_L^\circ \to \pi^\circ\nu\overline{\nu}\ /K^+ \to \pi^+\nu\overline{\nu}$ and $B_d^\circ \to \psi K_S^\circ$

B$(K^+ \to \pi^+\nu\overline{\nu}\ ) < 0.4 \times 10^{-10} \left[P_{charm} + A^2 X(x_t) \frac{r_{sd}}{\lambda} \sqrt{\frac{\Delta M_d}{\Delta M_s}}\right]^2$ with $r_{sd} = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$

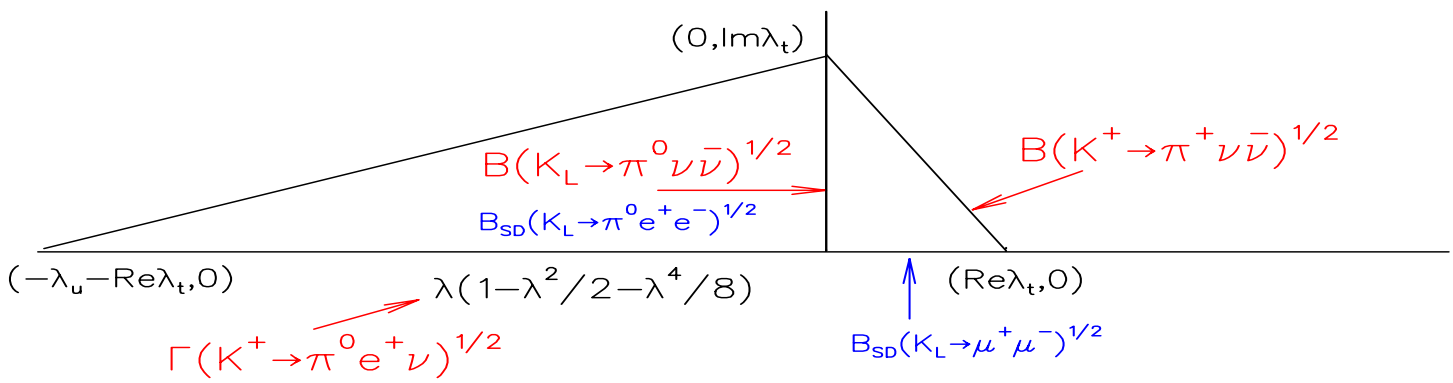
B$(K^+ \to \pi^+\nu\overline{\nu}\ ) < 1.32 \times 10^{-10}$

Rare Kaon Decays and the CKM Matrix

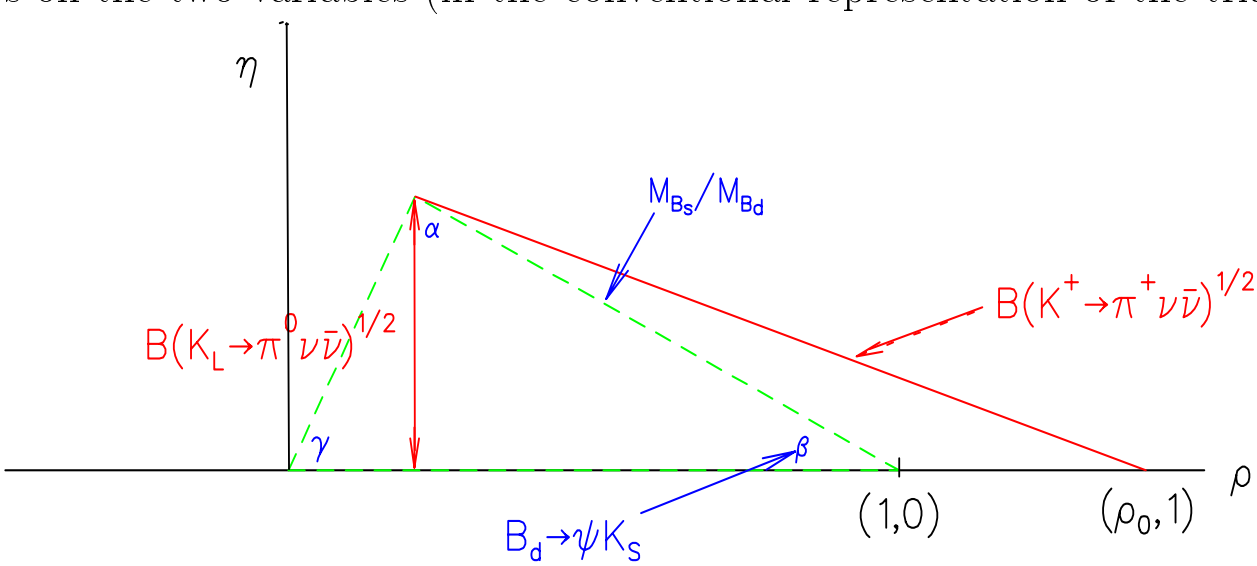
There are six unitarity relations: all should be tested (requires 3 measurements).



The fundamental measure of CP violation, J_{CP} is related to the area of the triangle and should be measured as well as possible (in as many ways as possible). In the kaon triangle, only two measurements are needed to determine the area: $K^+ \to \pi^\circ e^+ \nu_e$ and $K_L^\circ \to \pi^\circ \nu\overline{\nu}$; and we can completely determine the unitarity triangle with theoretically unambiguous measurements:.



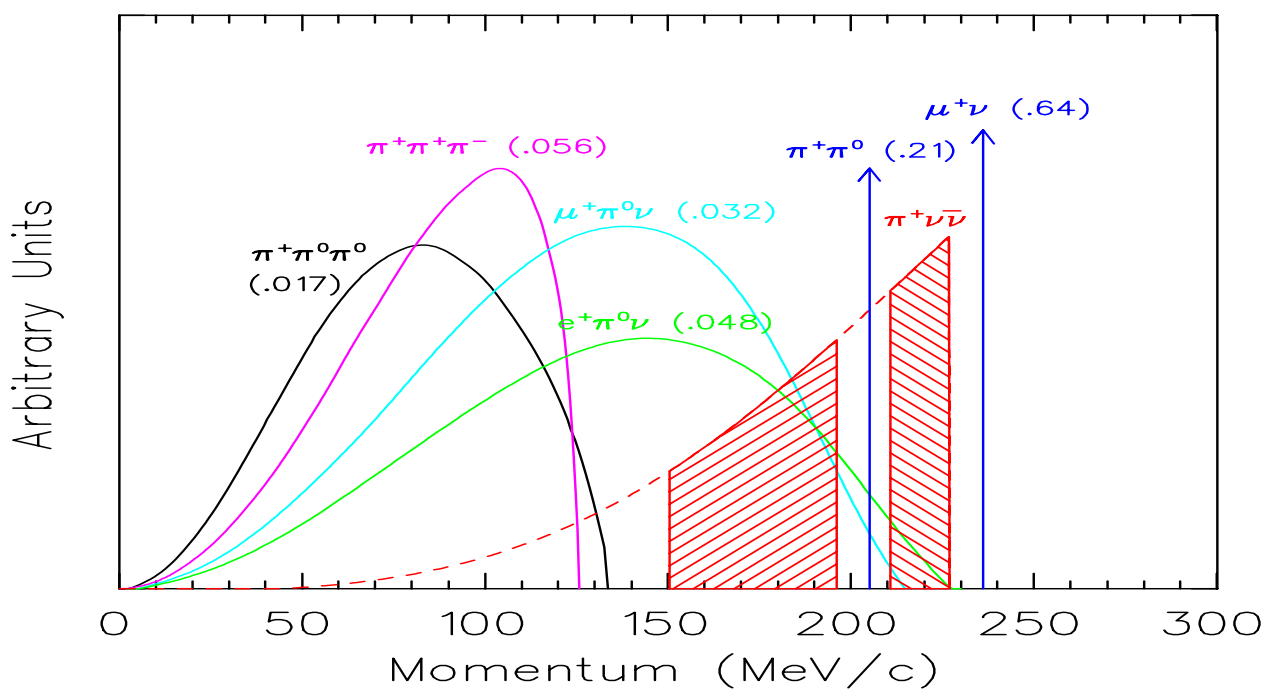
Using only those modes with little or no theoretical ambiguity there are 4 constraints on the two variables (in the conventional representation of the triangle):



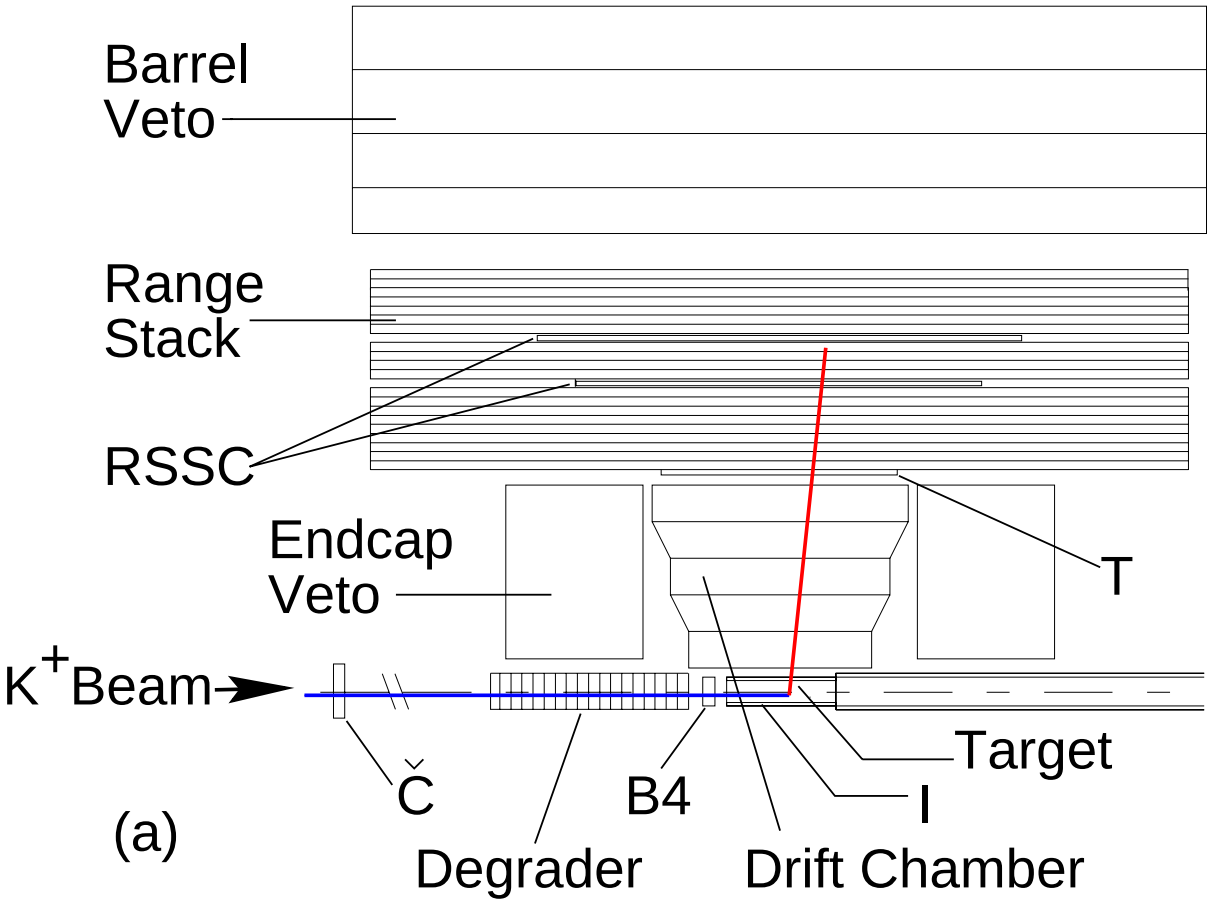
$K^+ \to \pi^+ \nu\bar{\nu}$ Experimental Strategy

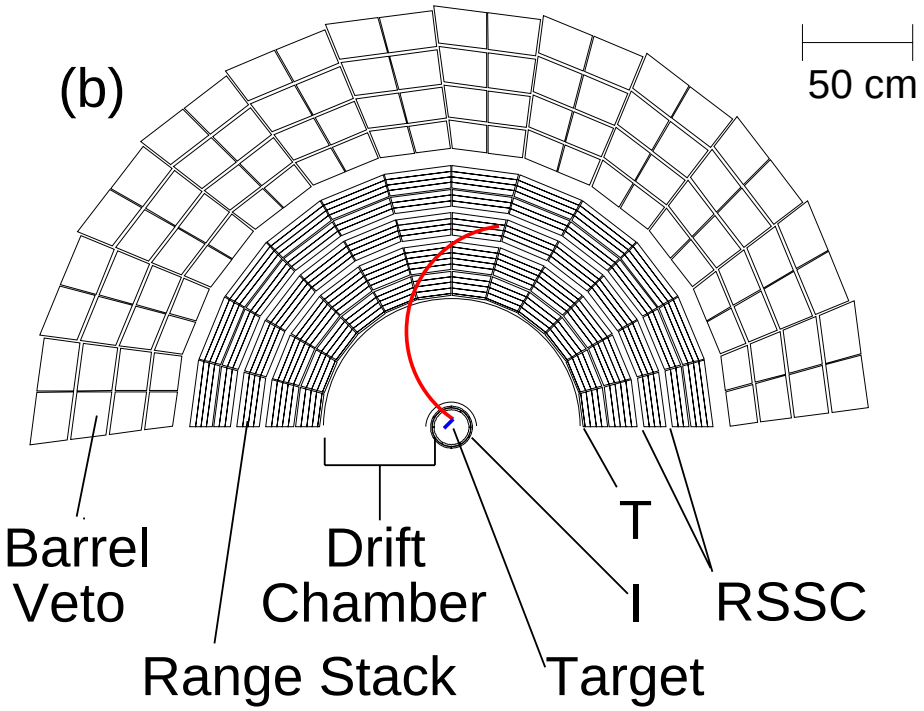
Measure everything possible

- Positively identify π^+.
- Veto extra particles.
- Measure kinematics with high resolution and redundancy.



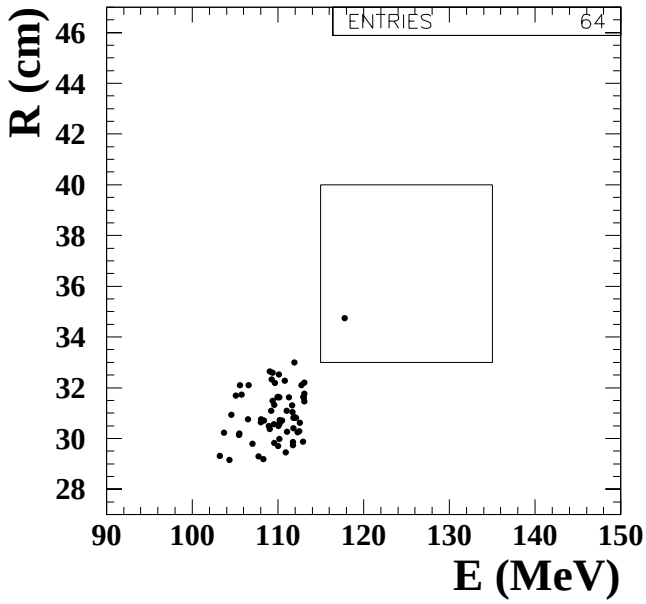
- Suppress background by 10^{11}: B/S(SM) < 0.1
- Reliably **measure** background from data.


Barrel
Veto
Range
Stack
RSSC
Endcap
Veto
T
K+Beam
Target
Č
B4
I
(a)
Degrader
Drift Chamber

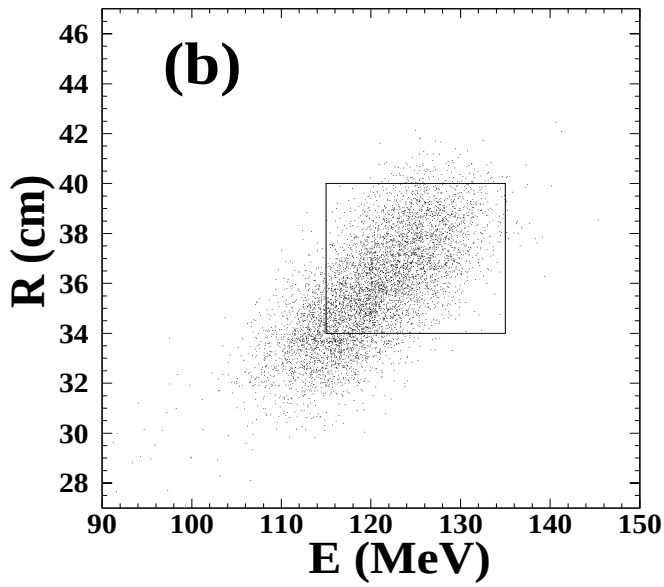

(b)
50 cm
T
Barrel
Veto
Drift
Chamber
I
RSSC
Range Stack
Target

$K^+ \to \pi^+ \nu\overline{\nu}$ Event

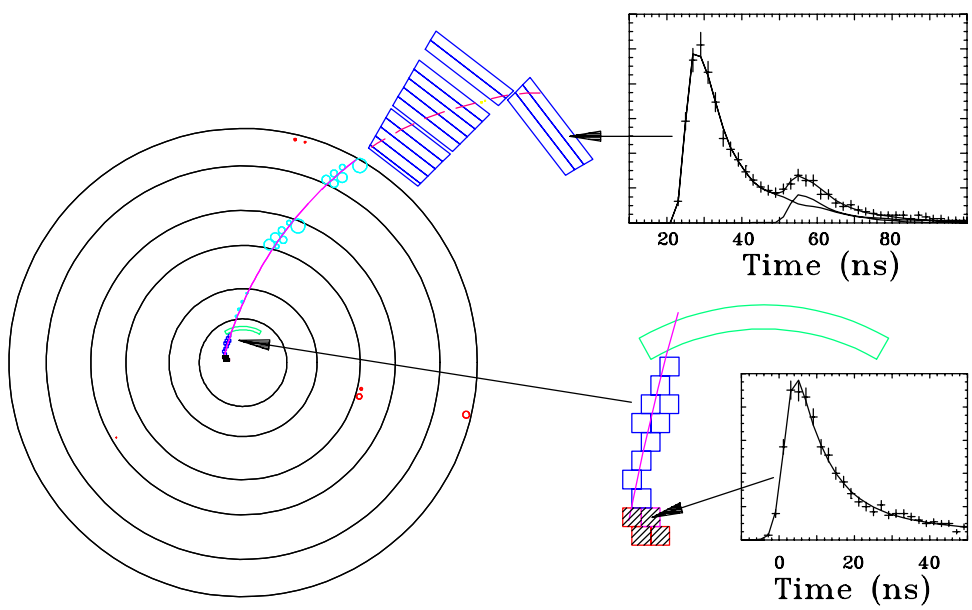
1995–97 Data



Monte Carlo



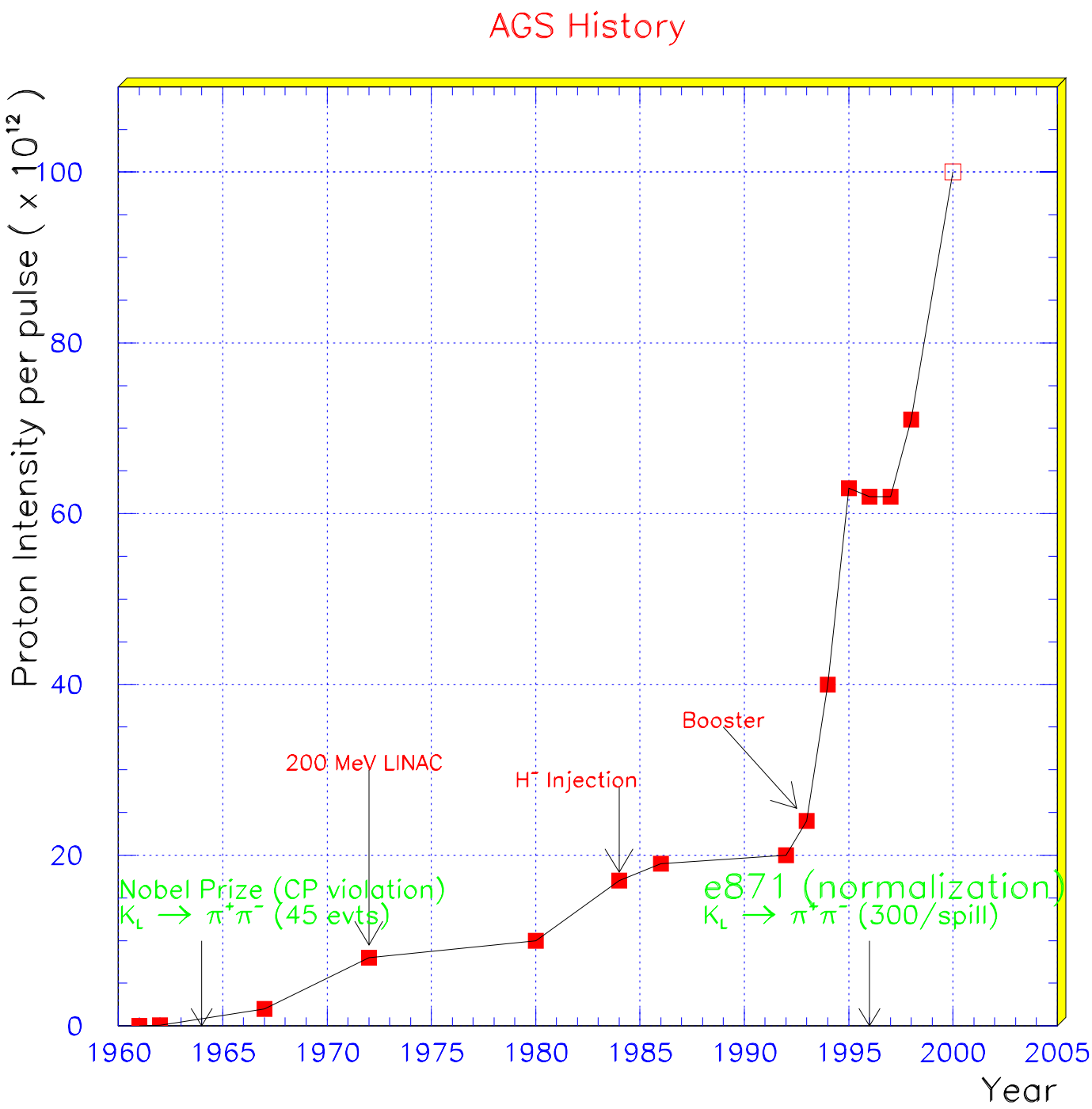
Event Display

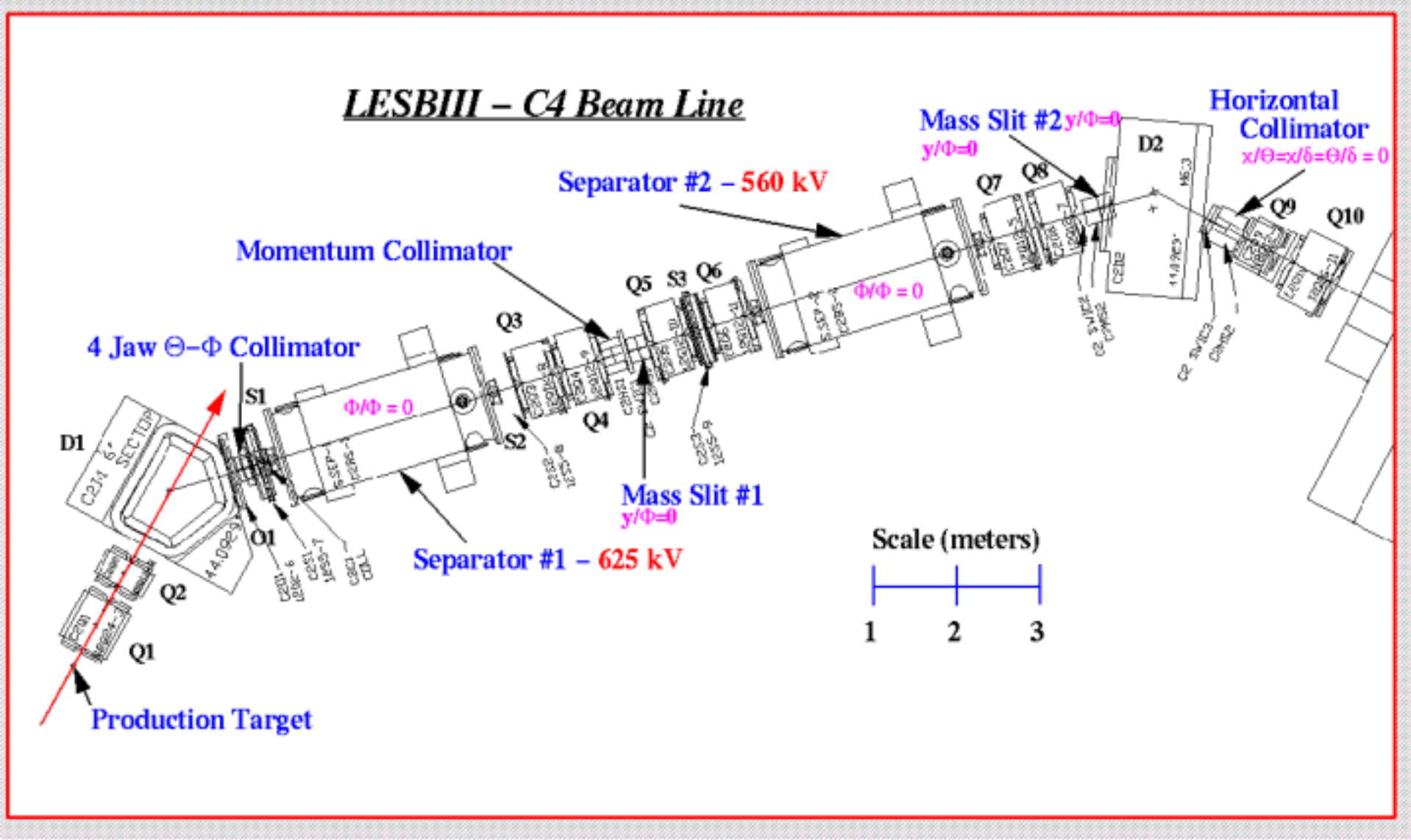


$$\mathbf{BR}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = 1.5^{+3.4}_{-1.2} \times 10^{-10}$$

SM: BR($K^+ \to \pi^+ \nu\overline{\nu}$) $= 0.72 \pm 0.21 \times 10^{-10}$ (from CKM fits)

[1995: PRL **79**, 2204 (1997), 1995–7: PRL **84**, 3768 (2000)]

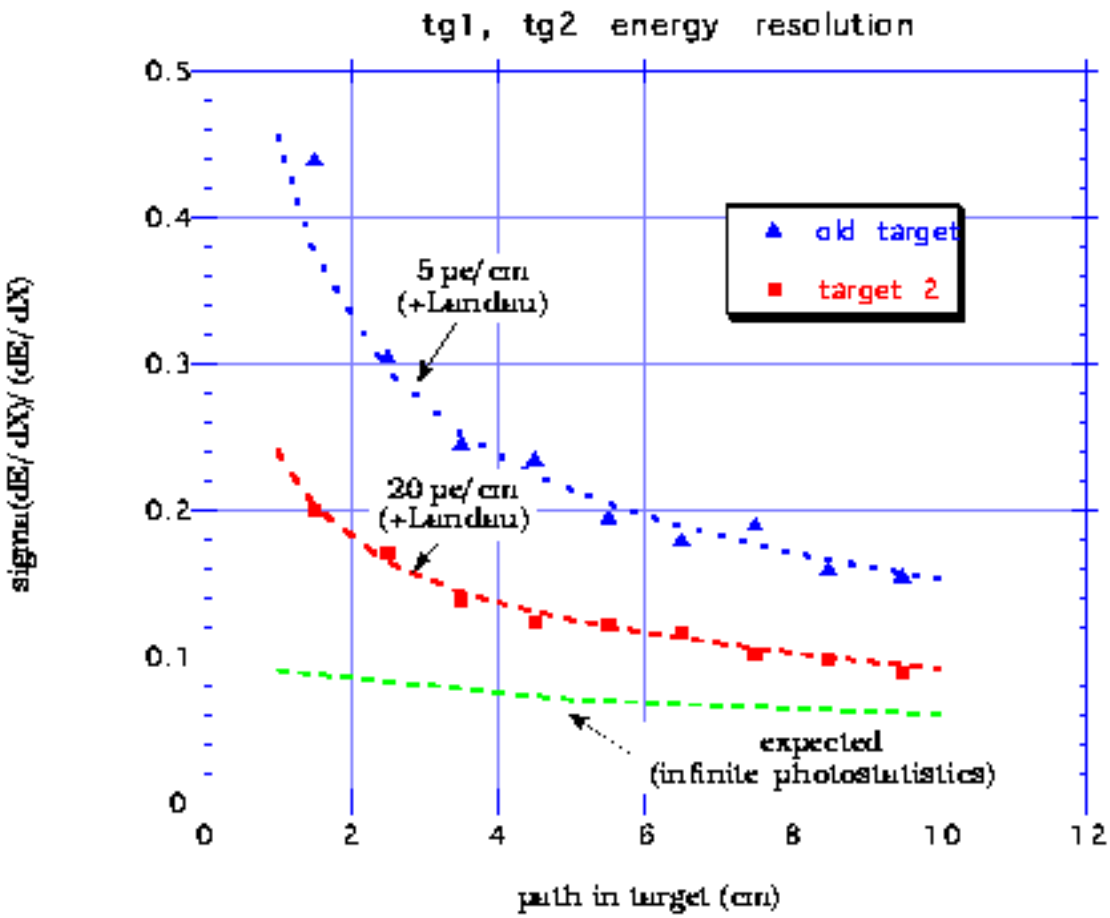

AGS History
Proton Intensity per pulse (x 10^12)
0
20
40
60
80
100
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Nobel Prize (CP violation)
K_L → π+π- (45 evts)
200 MeV LINAC
H- Injection
Booster
e871 (normalization)
K_L → π+π- (300/spill)


LESBIII – C4 Beam Line
Horizontal Collimator
x/Θ=x/δ=Θ/δ = 0
Mass Slit #2 y/Φ=0
y/Φ=0
Separator #2 – 560 kV
Momentum Collimator
4 Jaw Θ–Φ Collimator
Φ/Φ = 0
Φ/Φ = 0
D1
D2
Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8
Q9
Q10
S1
S2
S3
O1
Mass Slit #1
y/Φ=0
Separator #1 – 625 kV
Production Target
Scale (meters)
1
2
3

Scintillating Fiber Target (TT)

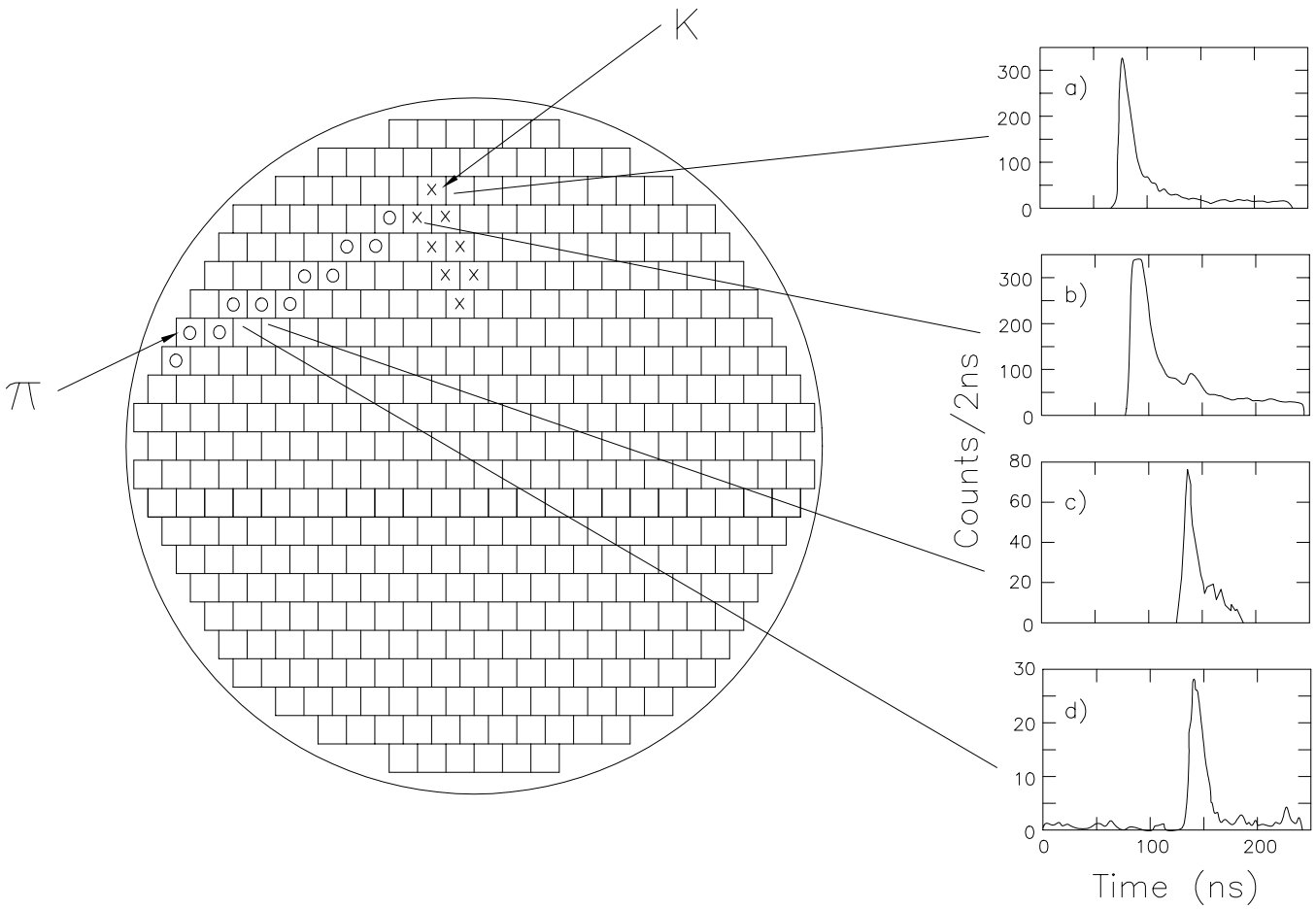
- 413 fibers 0.5 × 0.5×310 cm
- BCF10, τ=2.7ns, atten. length = 2 m
- cladding 0.009 cm (n=1.49; fiber n=1.59)
- bench tests give 30 p.e./MeV
- PMT: 429 HPK R1635-02, ϕ=3/8", τ_r=0.8ns

$\Rightarrow$ ×4 brighter



$K^+ \longrightarrow \pi^+$ Decay

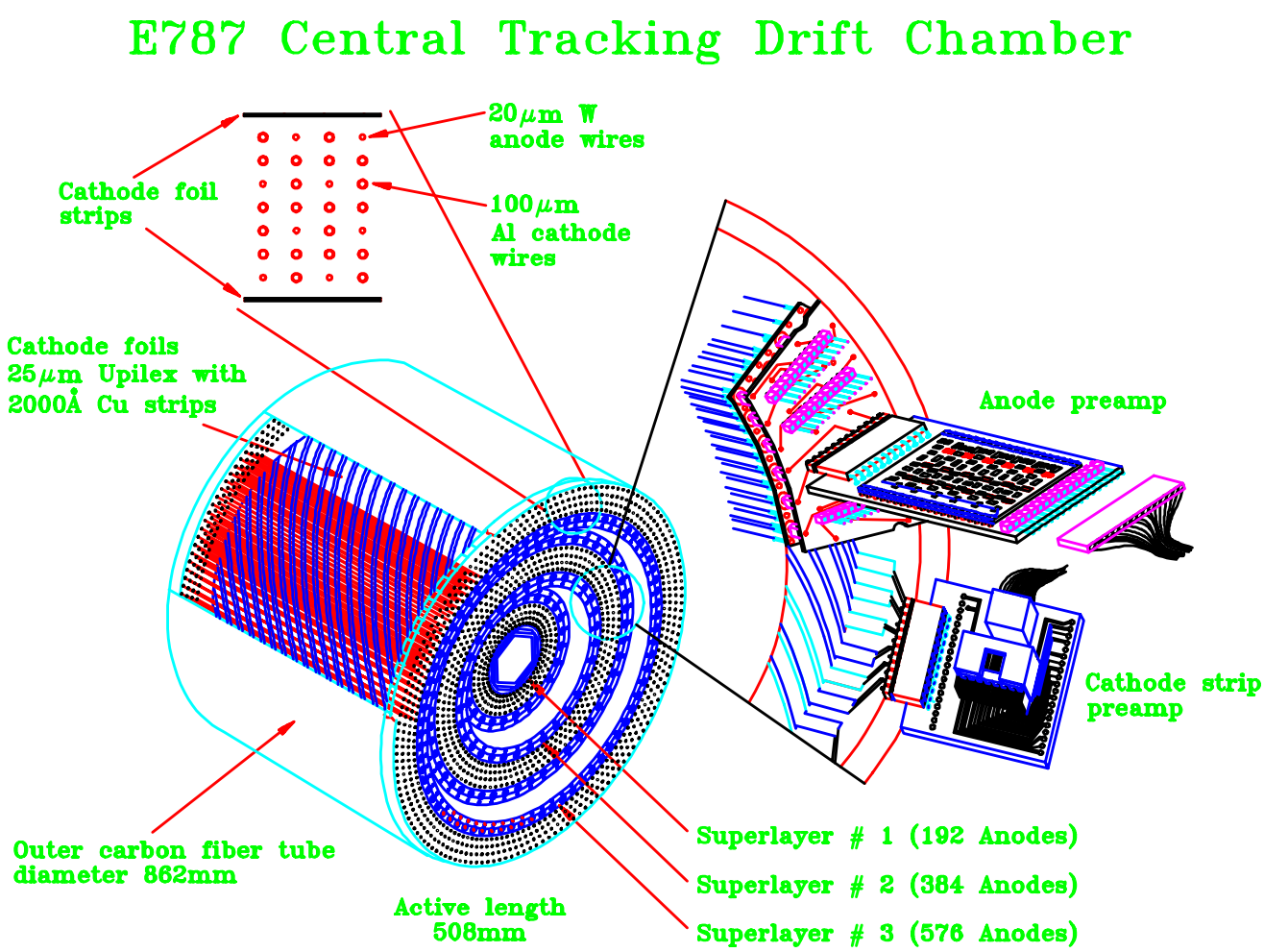
- 5 mm × 5 mm scintillating fibers
- 500 MHz GaAs CCD digitizers



Ultra Thin Chamber (UTC)

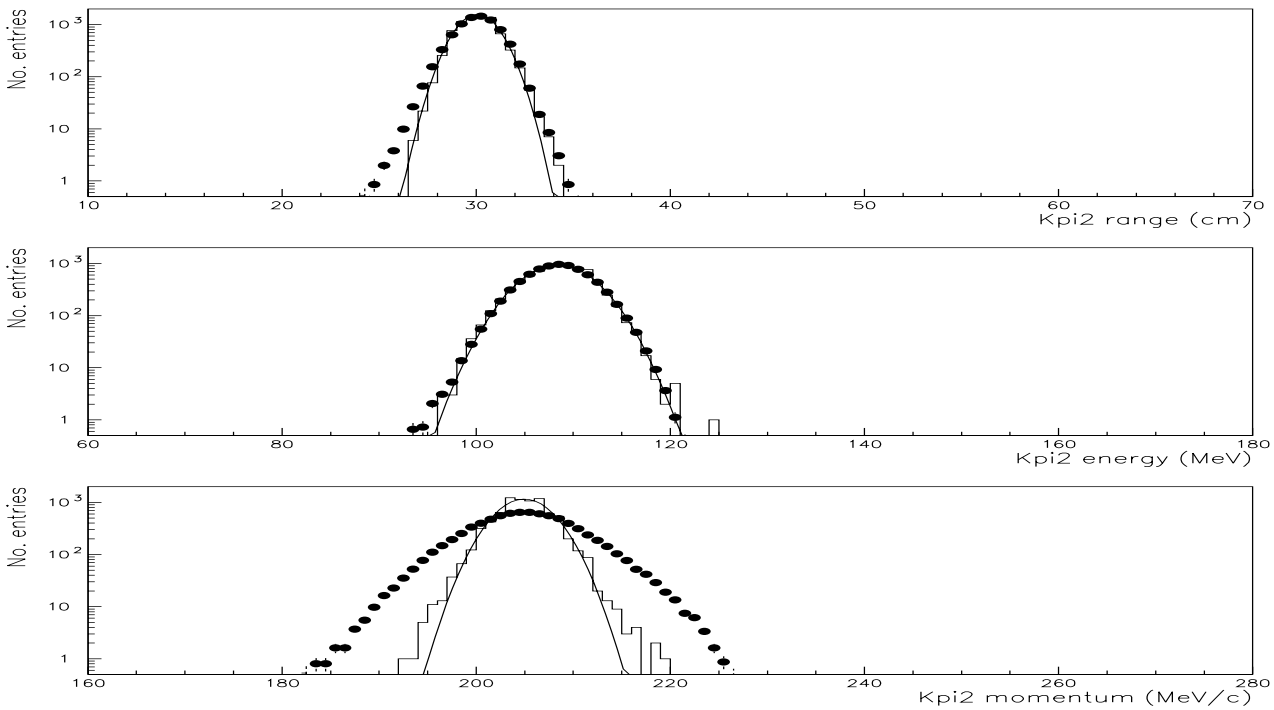
- buffer layers with N_2
- active region material $2\times10^{-3}X_0$ (total $= 3\times10^{-2}X_0$) [$\times5$]
- Z from helical cathode strips. $\sigma \sim 0.1$ cm [$\times2$]
- $\delta P/P \sim 1.4\%$ [$> \times2$]
  - $\Delta X \sim 110\mu$m

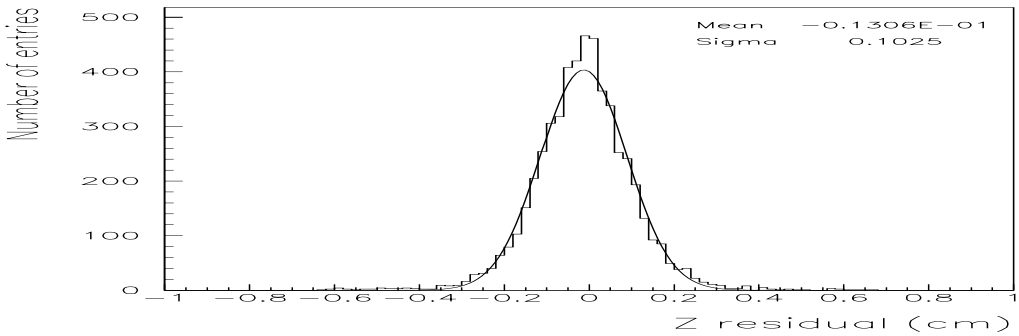
$\Rightarrow$ Less multiple scattering, much better z tracking



Kinematic resolution

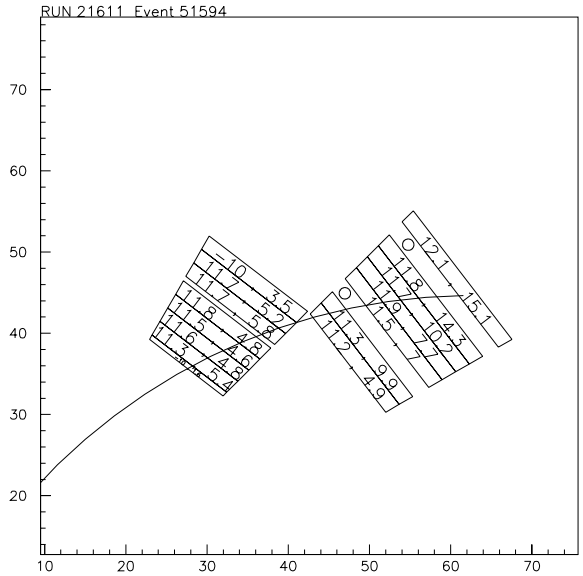
- $K_{\pi 2}$ kinematic resolution (1991 and 1995)
  - momentum (1.25%)
  - energy (3.2%)
  - range (3.4%)
  - z (1 mm)

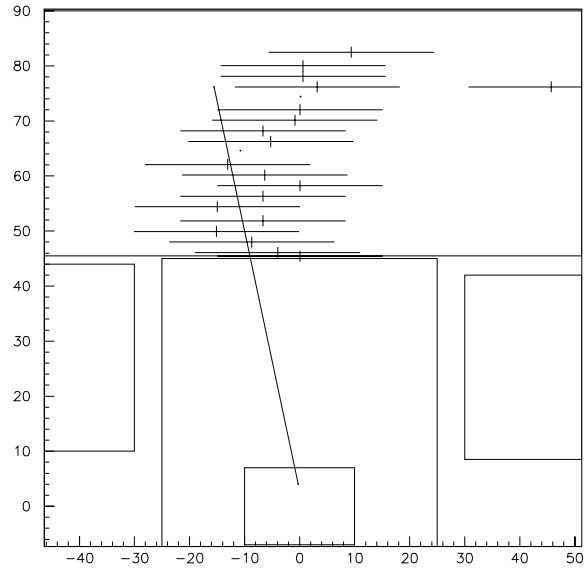




Range Stack

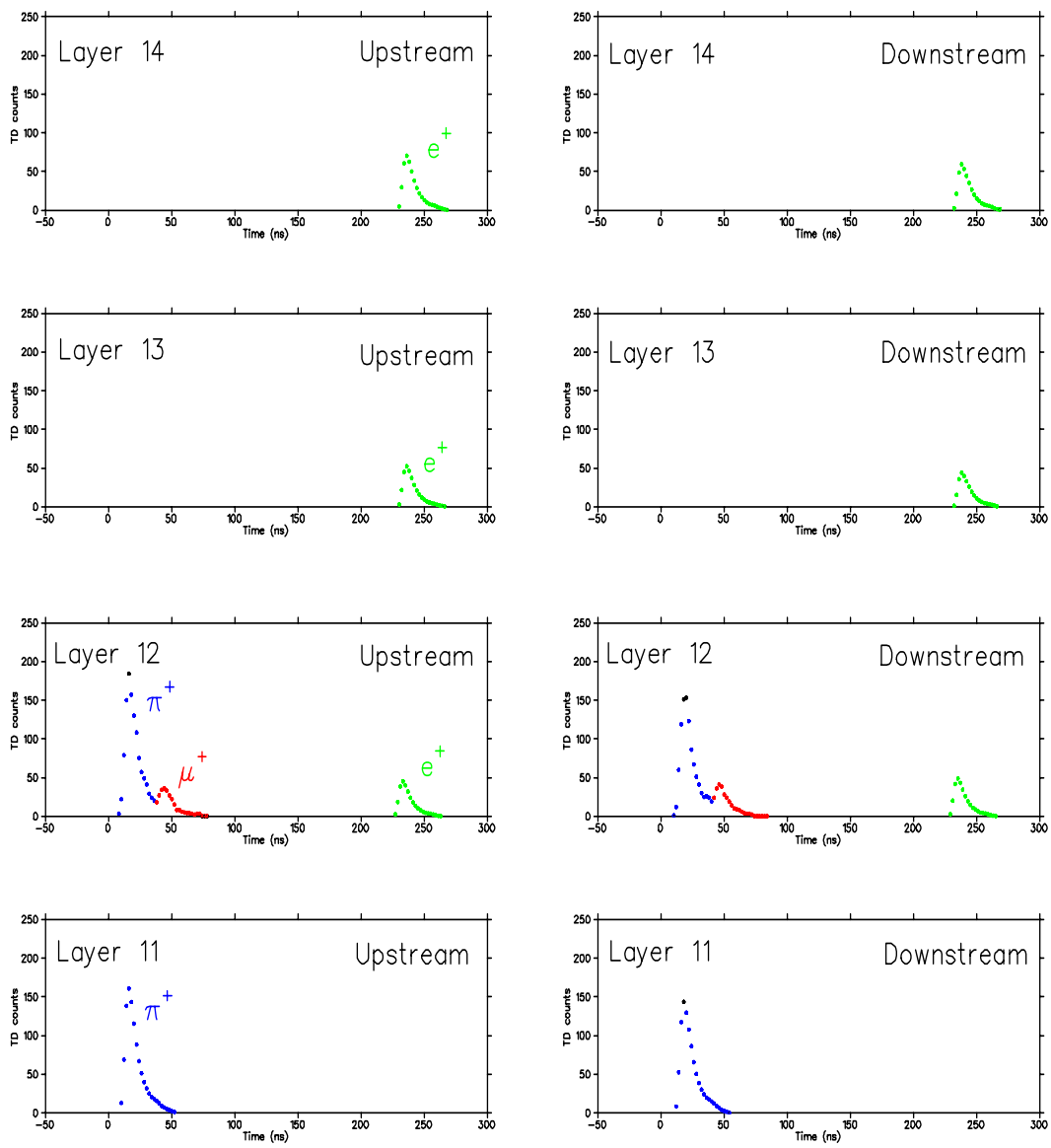
- RS
  - Demultiplexed to 2 PMT's / layer (21 instead of 15)
  - Replaced bad PMT's, repaired glue joints
- RSSC
  - Low mass Straw chambers
  - z-resolution $\sim$ 1.5 cm





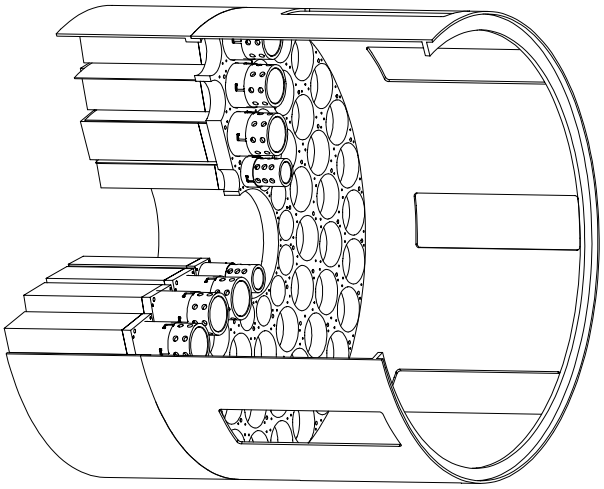
Pion Identification: $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ Tagging

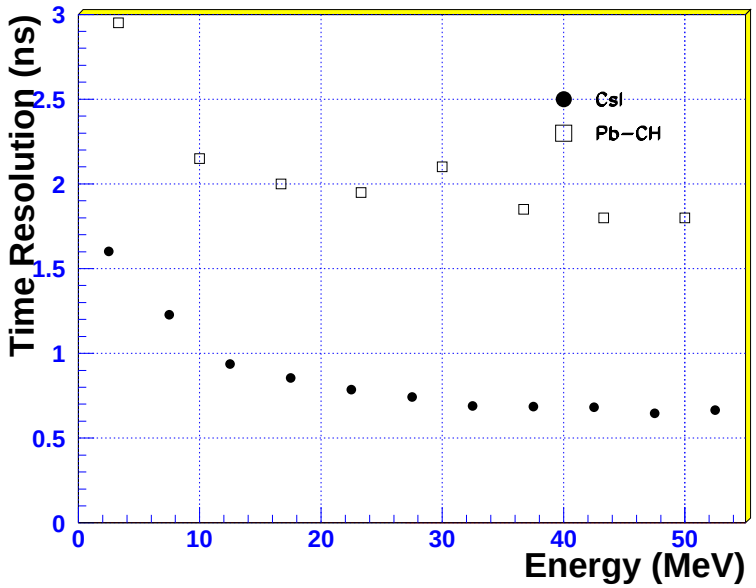
- Sample pulse height every 2 nsec for 4.5 μsec
- π^+ stops in Range Stack Scintillator (each layer is 2cm thick)
- $\pi^+ \longrightarrow \mu^+ \nu_\mu$: $E_{\mu^+} = 4.1$ MeV, $R_{\mu^+} \sim 1$ mm, $\tau_{\pi^+} = 26.0$ nsec.
- $\mu^+ \longrightarrow e^+ \nu_e \overline{\nu_\mu}$: $E_{e^+} \leq 53$ MeV, $\tau_{\mu^+} = 2.20$ μsec.



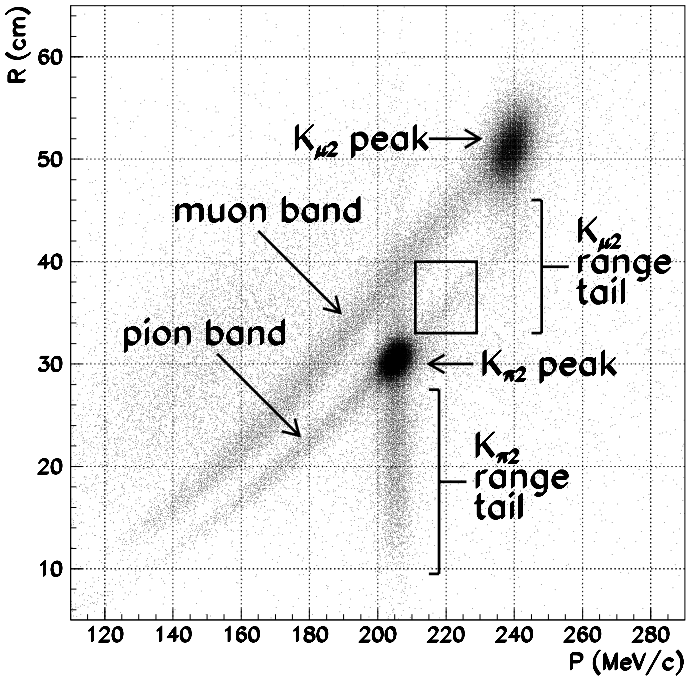
CsI (undoped) Endcap

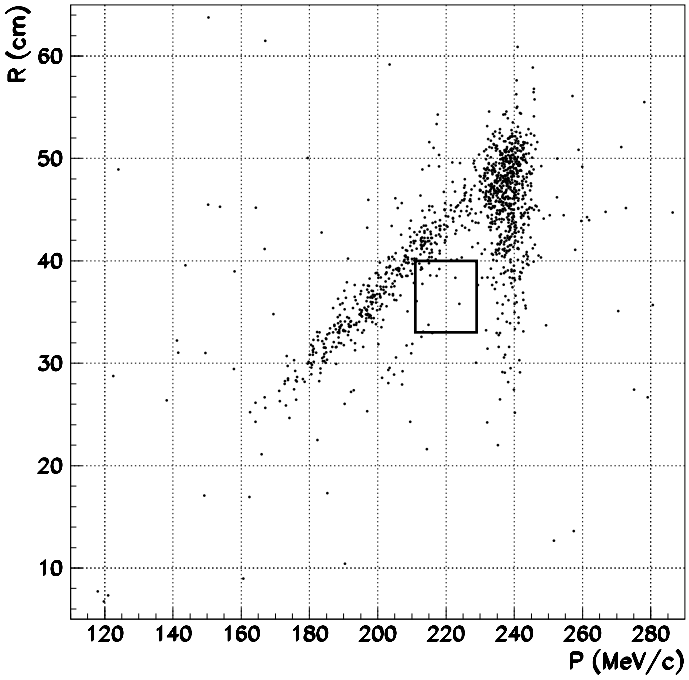
- fully active (fewer photonuclear losses)
- $\sim \times 10$ more light
- 143 xtals $\sim 75\text{cm}^2 \times 25$ cm
- High field (10kG) PMTs
- CCD transient digitizers; 500MHz, 512ns



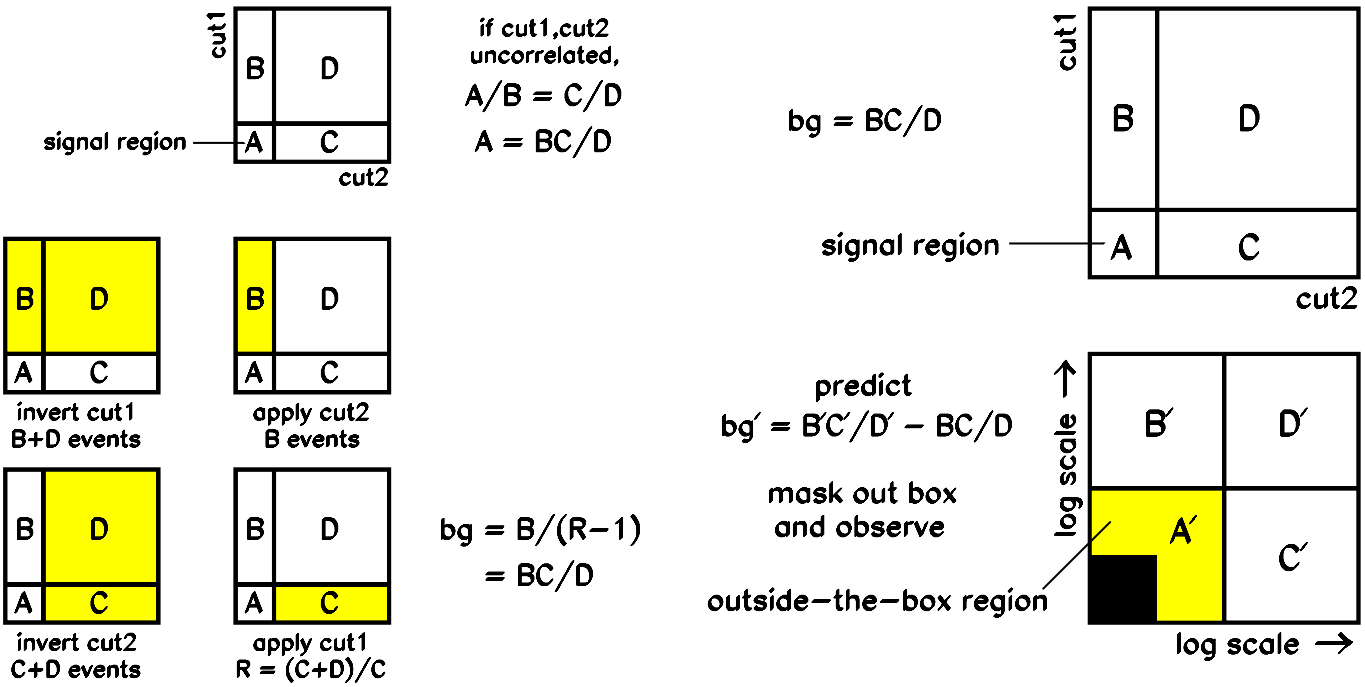


The E787 Data





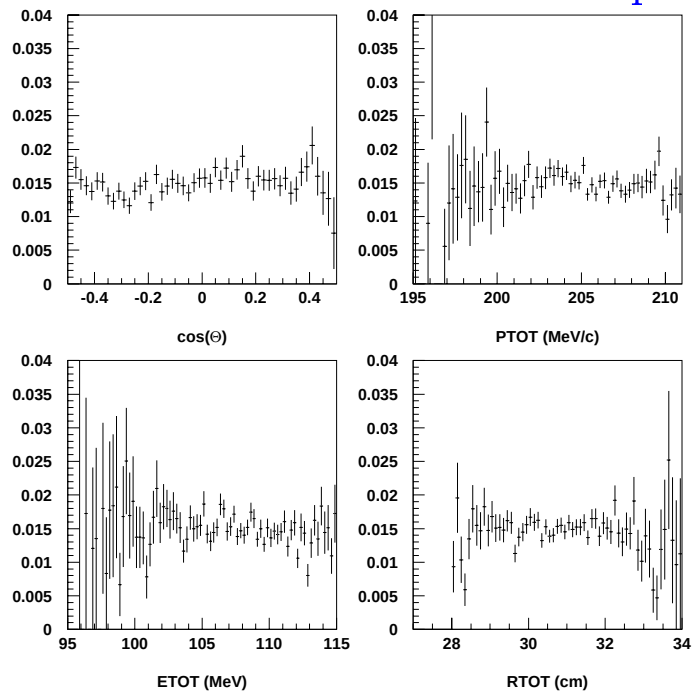
Bifurcated Analyses



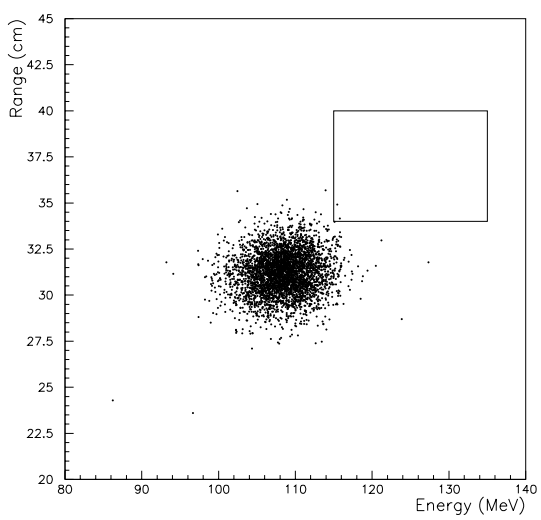
Background	Normalization or crosscheck	Rejection
$K_{\pi 2}$	$\bar{\gamma}$ tagged	Kinematic tagged
$K_{\mu 2}$	TD tagged	Kinematic tagged
Single beam	TG Del. coin. tagged	B4 dE/dx tagged
Double beam	BWPC tagged	B4 2-hit tagged
$K^+ \to K^0$ CEX	CEX cuts tagged	K_S-based M.C.

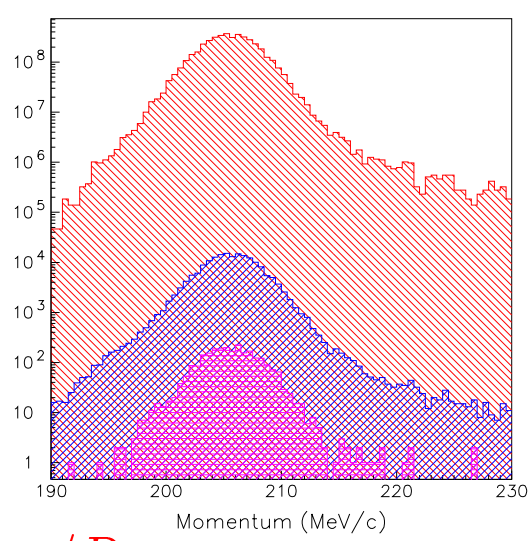
Example: $K^+ \to \pi^+\pi^0$

Check $\bar{\gamma}$ for correlations with kinematics quantities



Bring 2 branches together to make b.g. prediction:





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

So far: We *think* we know how much background is "inside the box", assuming:

- Bifurcated cuts are not correlated
- All of the backgrounds are accounted for

Construct background probability functions by relaxing and tightening cuts on the different backgrounds:

- $K_{\pi 2}$: adjust kinematics cuts, photon veto parameters
- $K_{\mu 2}$: adjust kinematics cuts, TD cuts
- Beam: adjust coincidence timing windows

Two results:

1. Testable prediction outside the box before looking inside.
2. *A priori* (i.e **unbiased**) evaluation function inside the box for interpretation of events, if any found.

Results from 1995–98 $\pi\nu\bar{\nu}(1)$ data sets

Background	1995–97	1998
$K_{\pi 2}$	0.03 ± 0.01	$0.012^{+0.003}_{-0.004}$
$K_{\mu 2}$	0.02 ± 0.01	$0.034^{+0.043}_{-0.024}$
Beam (1 + 2)	0.02 ± 0.02	0.004 ± 0.001
CEX	0.01 ± 0.01	$0.016^{+0.005}_{-0.004}$
Total background	0.08 ± 0.02	$0.066^{+0.044}_{-0.025}$

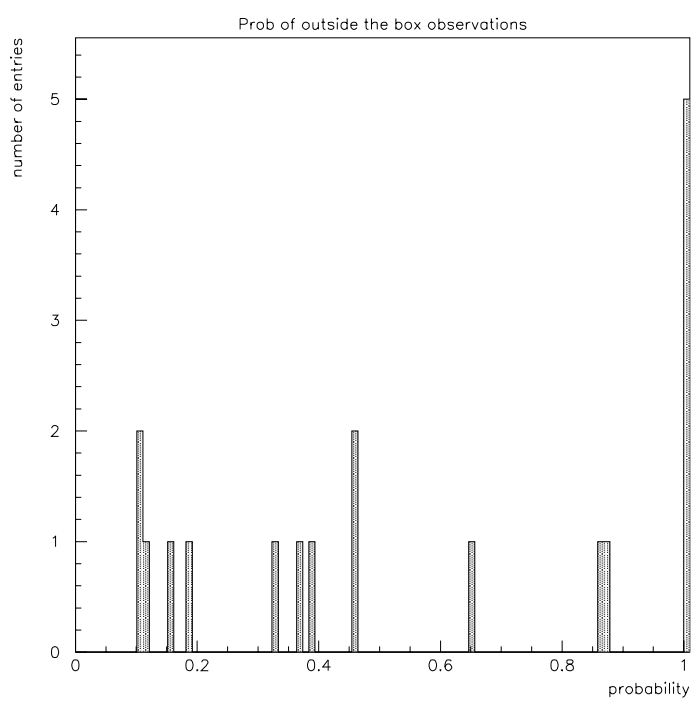
Acceptance factors	1995–97	1998
K^+ stop efficiency	0.704	0.702
K^+ decay after 2 ns	0.850	0.851
$K^+ \to \pi^+\nu\bar{\nu}$ phase space	0.155	0.136
Solid angle acceptance	0.407	0.409
π^+ nucl. int., decay-in-flight	0.513	0.527
Reconstruction efficiency	0.959	0.969
Other kinematic constraints	0.665	0.554
$\pi - \mu - e$ decay acceptance	0.306	0.392
Beam and target analysis	0.699	0.706
Accidental loss	0.785	0.751
Total acceptance	0.0021	0.00196

Summary	1995–97	1998
N_K	3.2×10^{12}	2.7×10^{12}
Acc.	0.0021(1)(2)	0.00196(5)(10)
Sensitivity	1.5×10^{-10}	1.89×10^{-10}
Background	0.08 ± 0.03	$0.066^{+0.044}_{-0.025}$

Examination "outside the box"

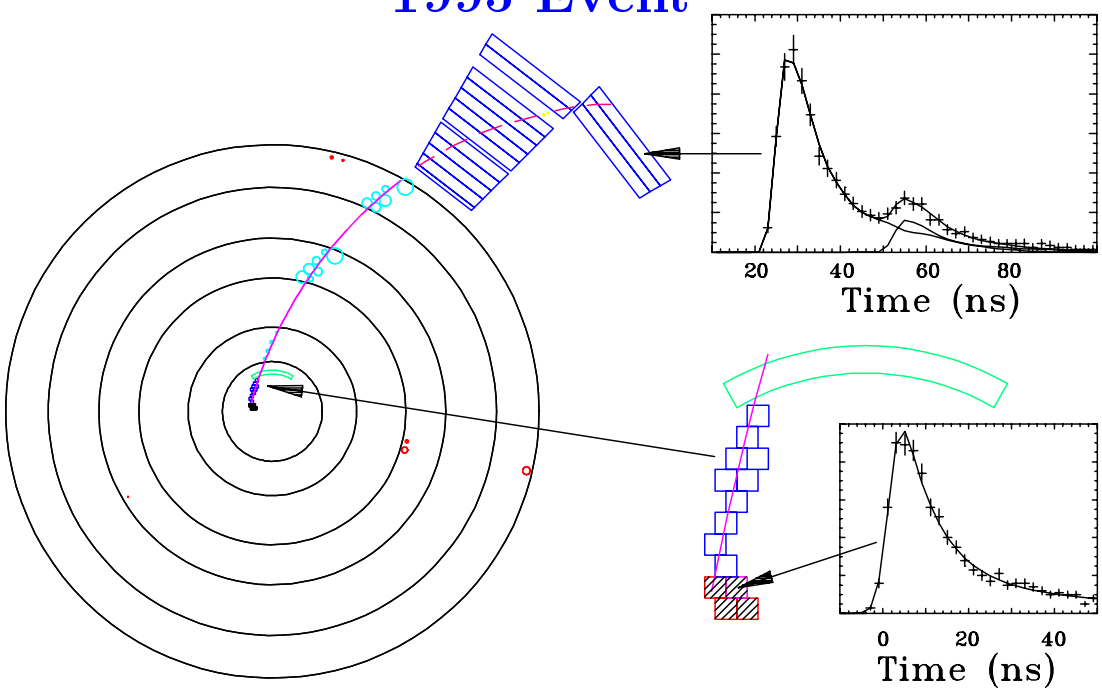
To confirm the validity of the background estimation technique, predicted background outside the signal region is compared to observation by loosening the primary cuts for each background.

		Looser cuts $\longrightarrow$			
$K^+ \to \pi^+\pi^0$	predict observe	1.18 3	4.74 5	33.00 36	225.00 233
$K^+ \to \mu^+\nu$ "tail"	predict observe	0.33 0	23.67 30	66.44 66	204.00 205
$K^+ \to \mu^+\nu$ "band"	predict observe	0.21 1	5.64 7	32.82 36	118.00 118
1-beam K	predict observe	0.029 0	0.578 2	4.188 8	
2-beam K	predict observe	0.007 0	0.059 0	0.398 0	

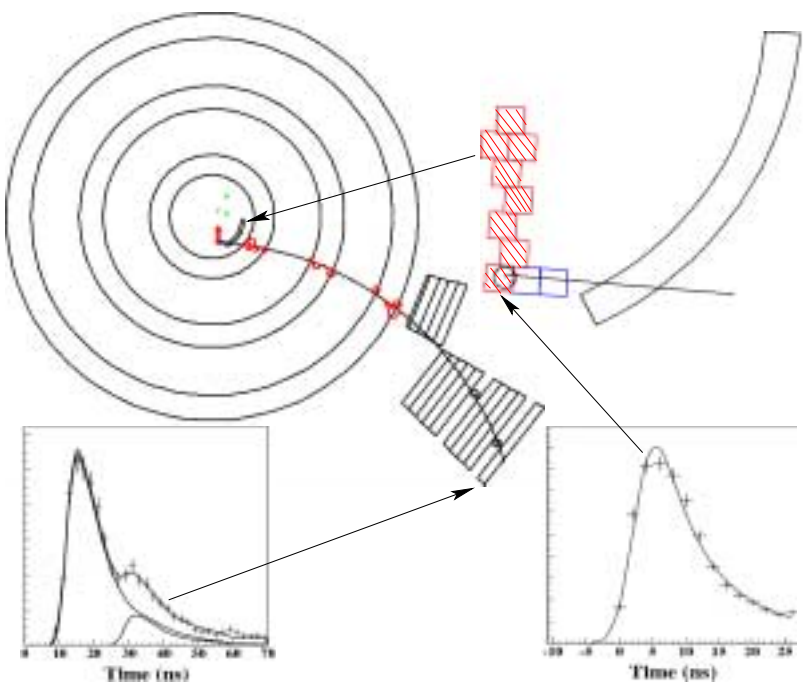


The Two E787 $K^+ \to \pi^+ \nu\overline{\nu}$ Events

1995 Event



1998 Event



$$\mathbf{BR}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

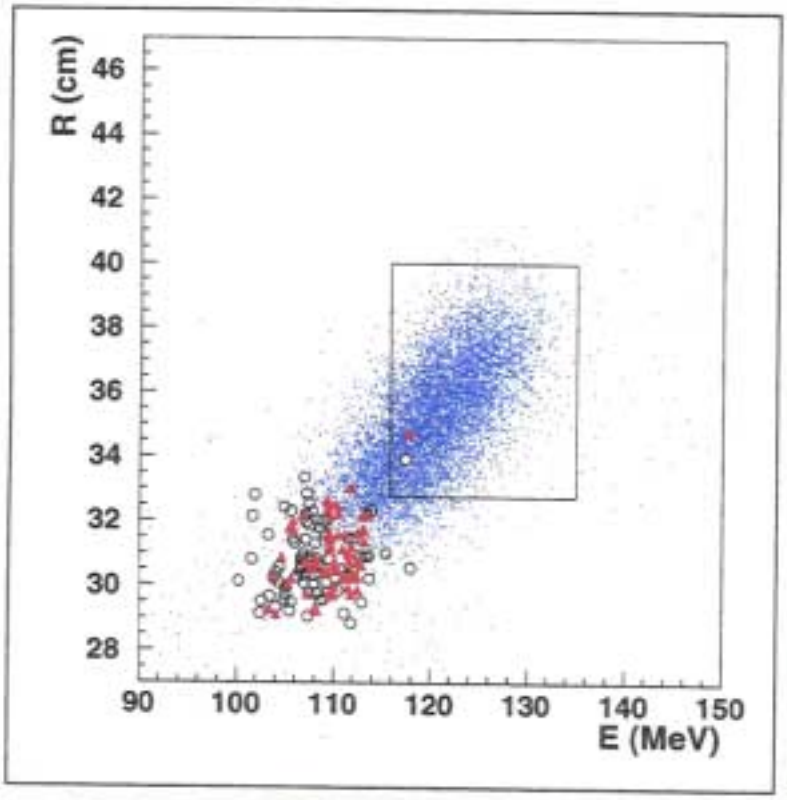
[1995–8: PRL **88**, 041803 (2002),
1995–7: PRL **84**, 3768 (2000),
1995: PRL **79**, 2204 (1997)]

JAN 31 2002

PHYSICAL REVIEW LETTERS

28 January 2002

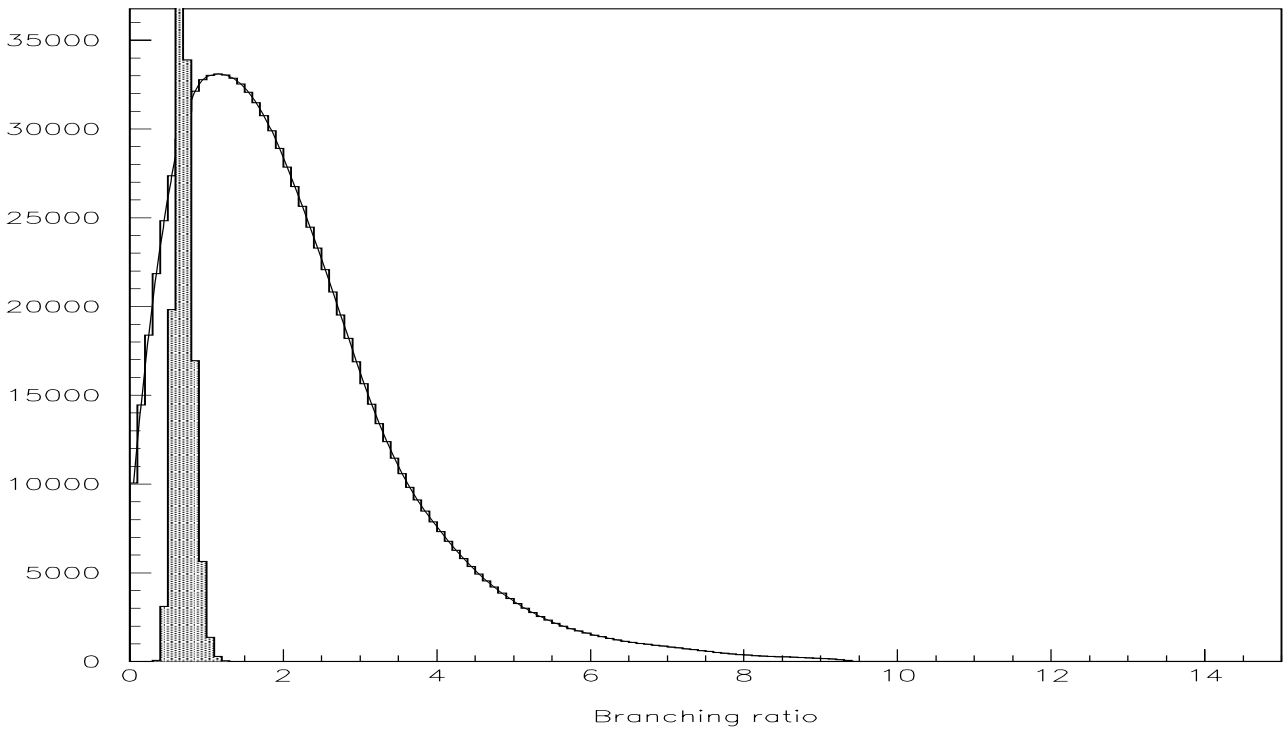
Volume 88, Number 4



APS Published by The American Physical Society

Comparison of B($K^+ \to \pi^+ \nu\overline{\nu}$) to SM

Event	Kinematic quantities $P(MeV/c)$	$R(cm)$	$E(MeV)$	S/N	Bkg	Rel. acc
1995	218.2	34.8	117.8	35	0.008	0.55
1998	213.8	33.9	117.1	3.6	0.022	0.84
B2(98)	224.9	37.1	125.5	0.7	0.11	1.24



E787 Summary

- 2 events found consistent with $K^+ \to \pi^+ \nu\bar{\nu}$
- BR($K^+ \to \pi^+ \nu\bar{\nu}$) $= 1.57^{+1.75}_{-0.82} \times 10^{-10}$ (SM: $0.75 \pm 0.29 \times 10^{-10}$)

84% CL limits (68% CL int.)	90% CL limits (80% CL int.)	95% CL limits (90% CL int.)	99% CL limits (98% CL int.)
[0.749,3.323]	[0.560,3.886]	[0.366,4.694]	[0.132,6.452]

- $P_b \sim 0.02\%$
- $B(K^+ \to \pi^+ X^0) < 0.59 \times 10^{-10}$ (90% CL)
- already has non-trivial impact on CKM fits [hep-ph/0112135]

CERN–TH/2001–355
hep-ph/0112135

arXiv:hep-ph/0112135 v1 10 Dec 2001

$K^+ \to \pi^+ \nu\bar{\nu}$: a rising star on the stage of flavour physics*

Giancarlo D'Ambrosio[a†] and Gino Isidori[b]

[a] *INFN, Sezione di Napoli and Dipartimento di Scienze Fisiche, Università di Napoli, I-80126 Napoli, Italy*

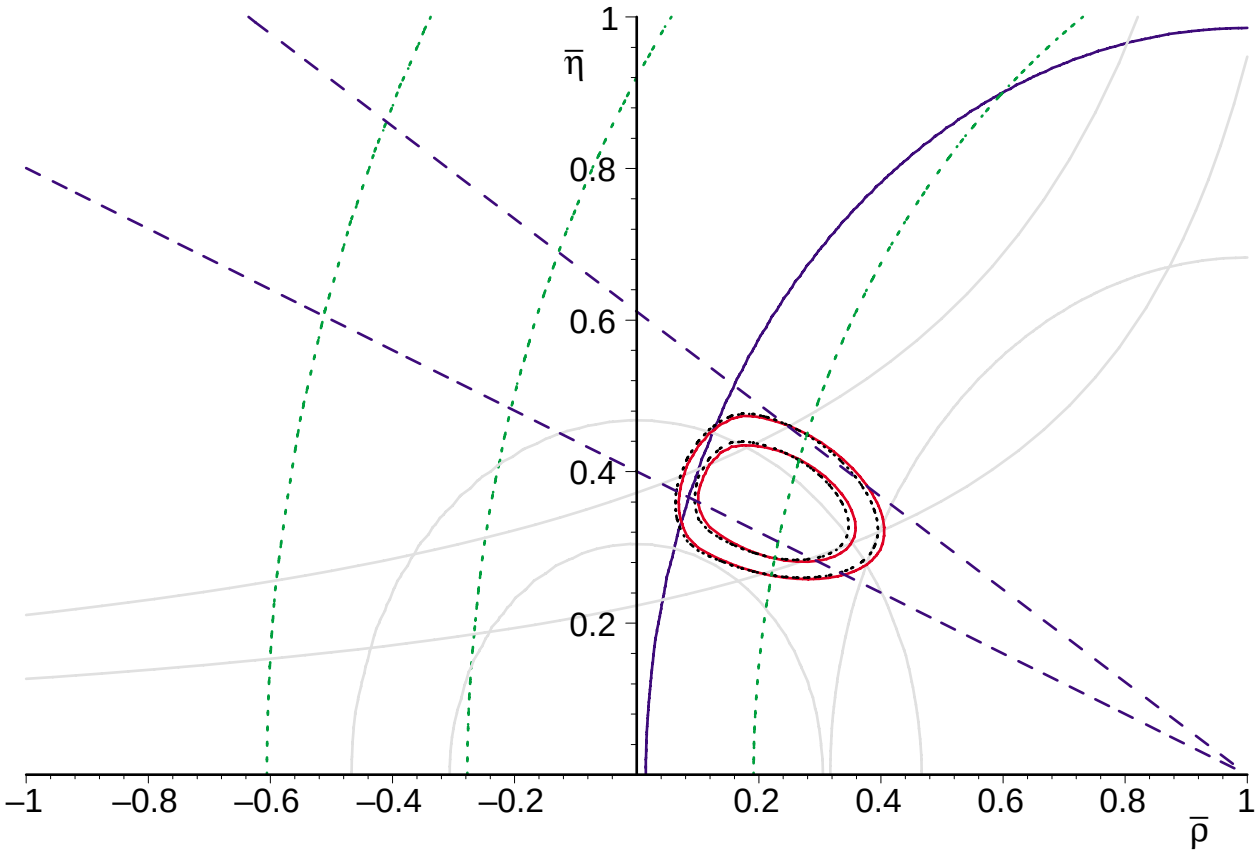
[b] *Theory Division, CERN, CH-1211 Geneva 23, Switzerland and INFN, Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*

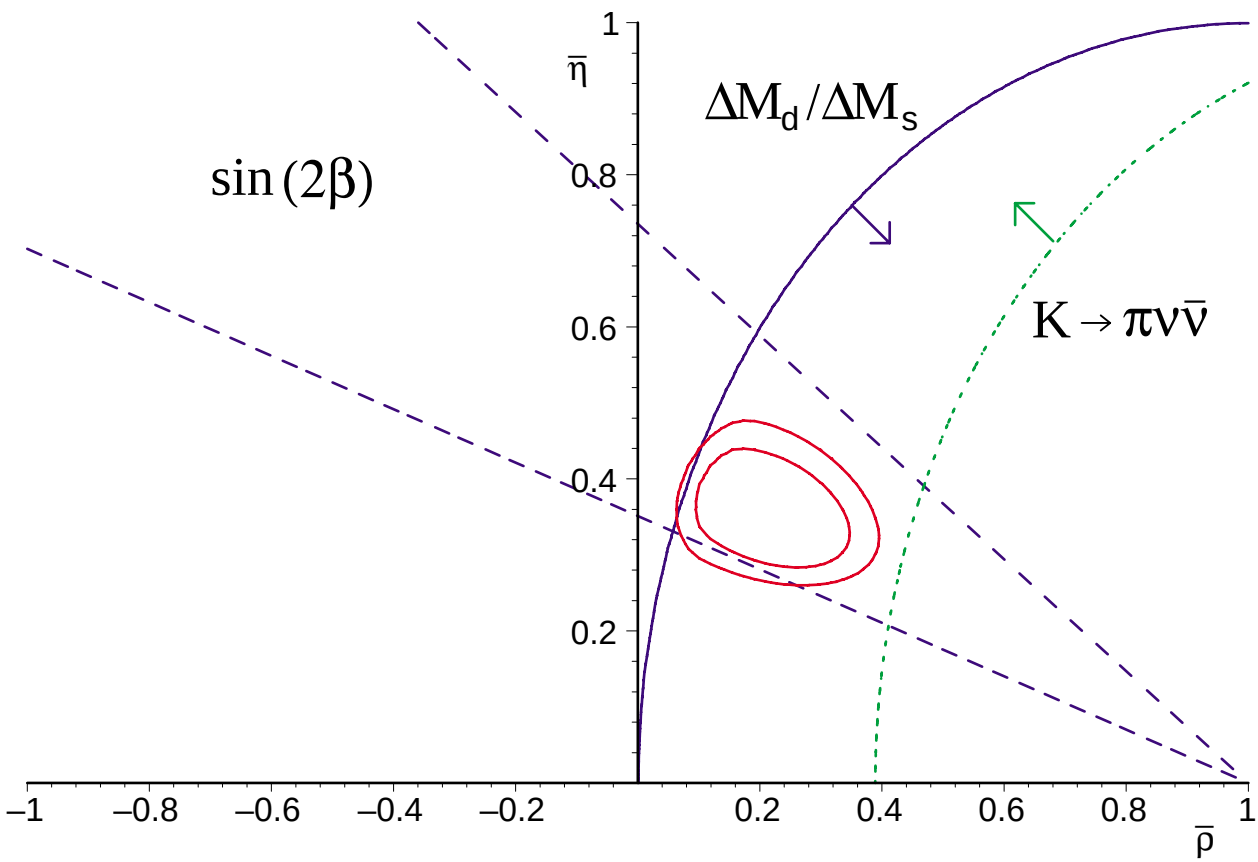
Abstract

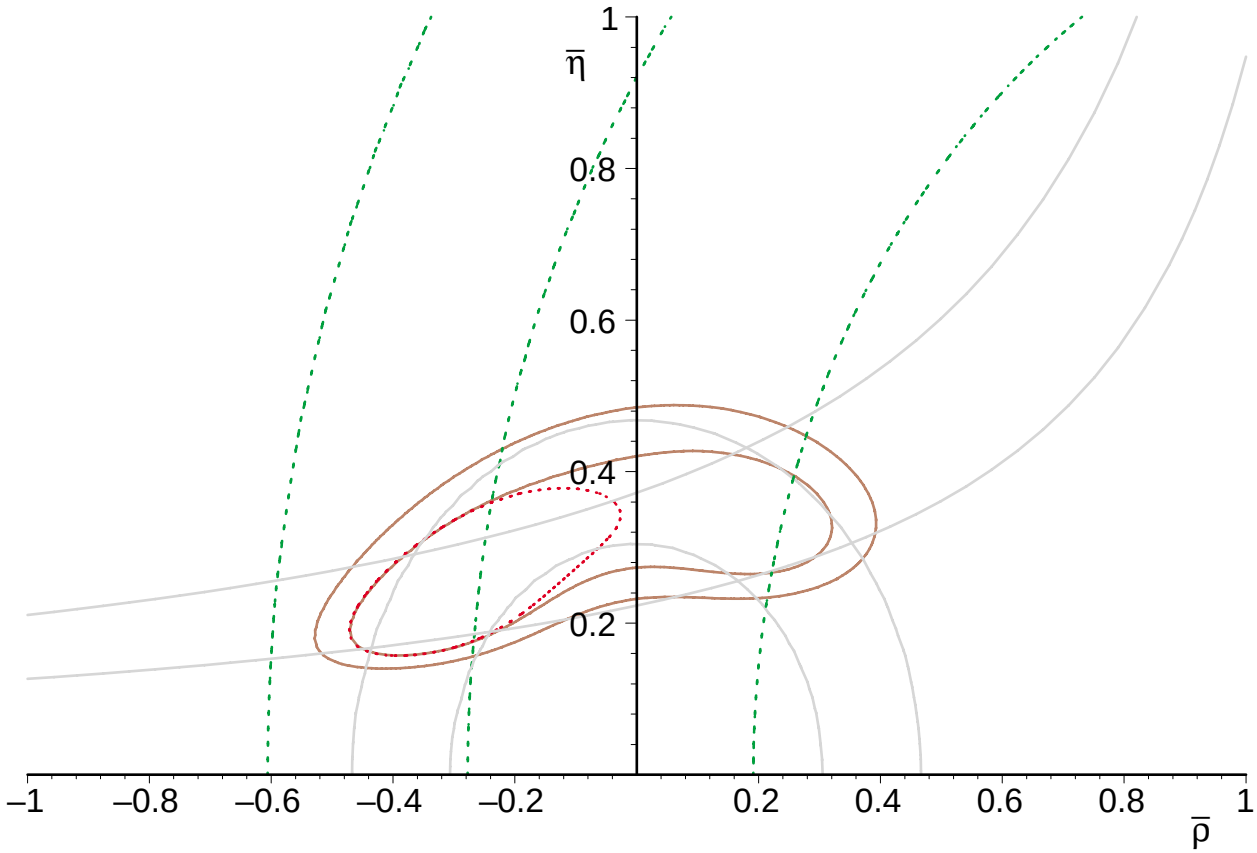
Motivated by the new experimental information reported by the BNL–E787 Collaboration, we analyse the present impact and the future prospects opened by the measurement of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$. Although still affected by a large error, the BNL–E787 result favours values of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ substantially larger than what expected within the Standard Model. As a result, this data already provide non-trivial constraints on the unitarity triangle, when interpreted within the Standard Model framework. We stress the importance of the clean relation between $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, $\sin 2\beta$ and $\Delta M_{B_d}/\Delta M_{B_s}$ that in the next few years could provide one of the deepest probes of the Standard Model in the sector of quark-flavour dynamics. A speculative discussion about possible non-standard interpretations of a large $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ is also presented. Two main scenarios naturally emerge: those with direct new-physics contributions to the $s \to d\nu\bar{\nu}$ amplitude and those with direct new-physics effects only in B_d–$\bar{B}_d$ mixing. Realistic models originating these two scenarios and possible future strategies to clearly identify them are briefly discussed.

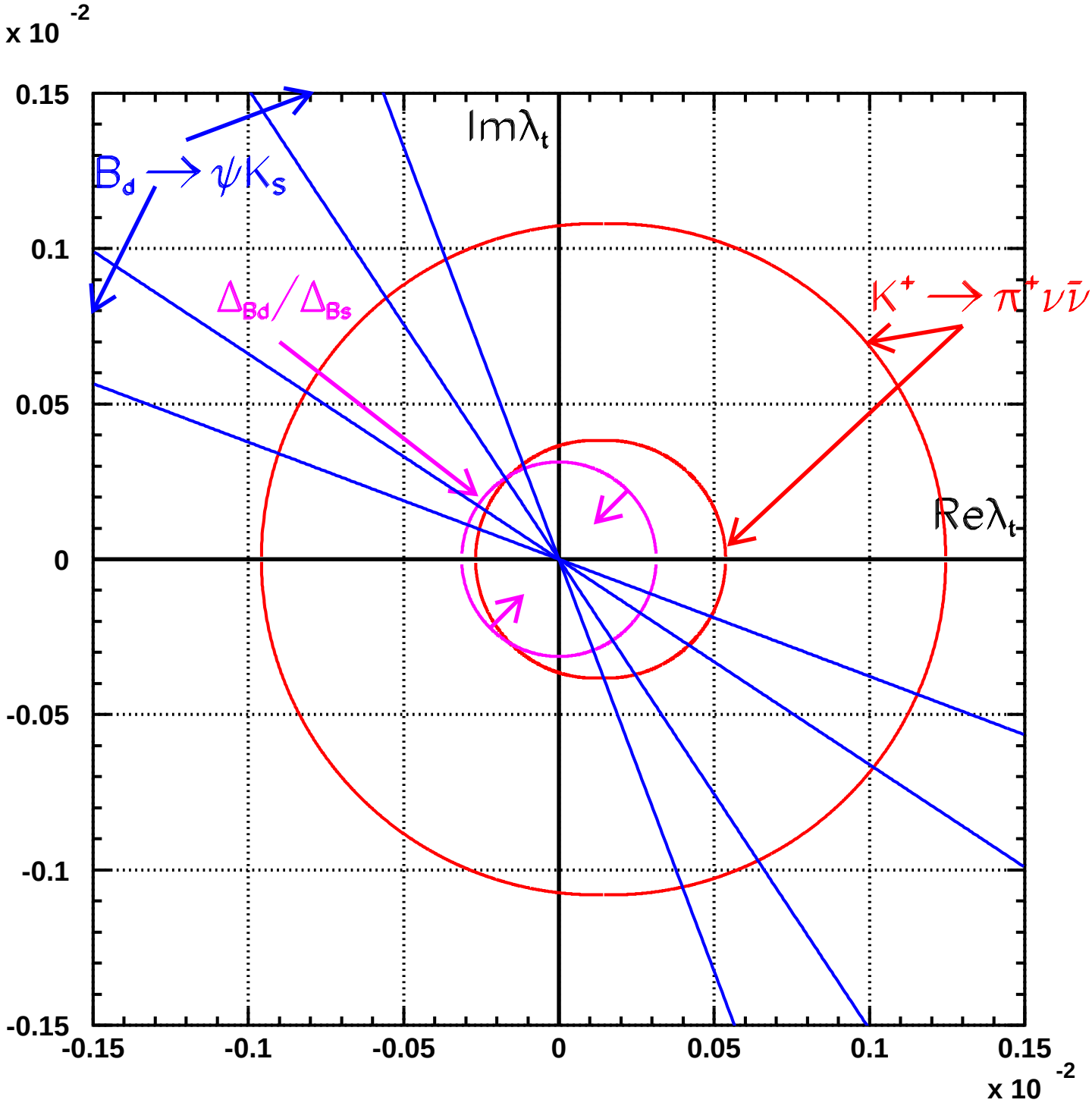
† On leave of absence at *Theory Division, CERN, CH-1211 Geneva 23, Switzerland.*

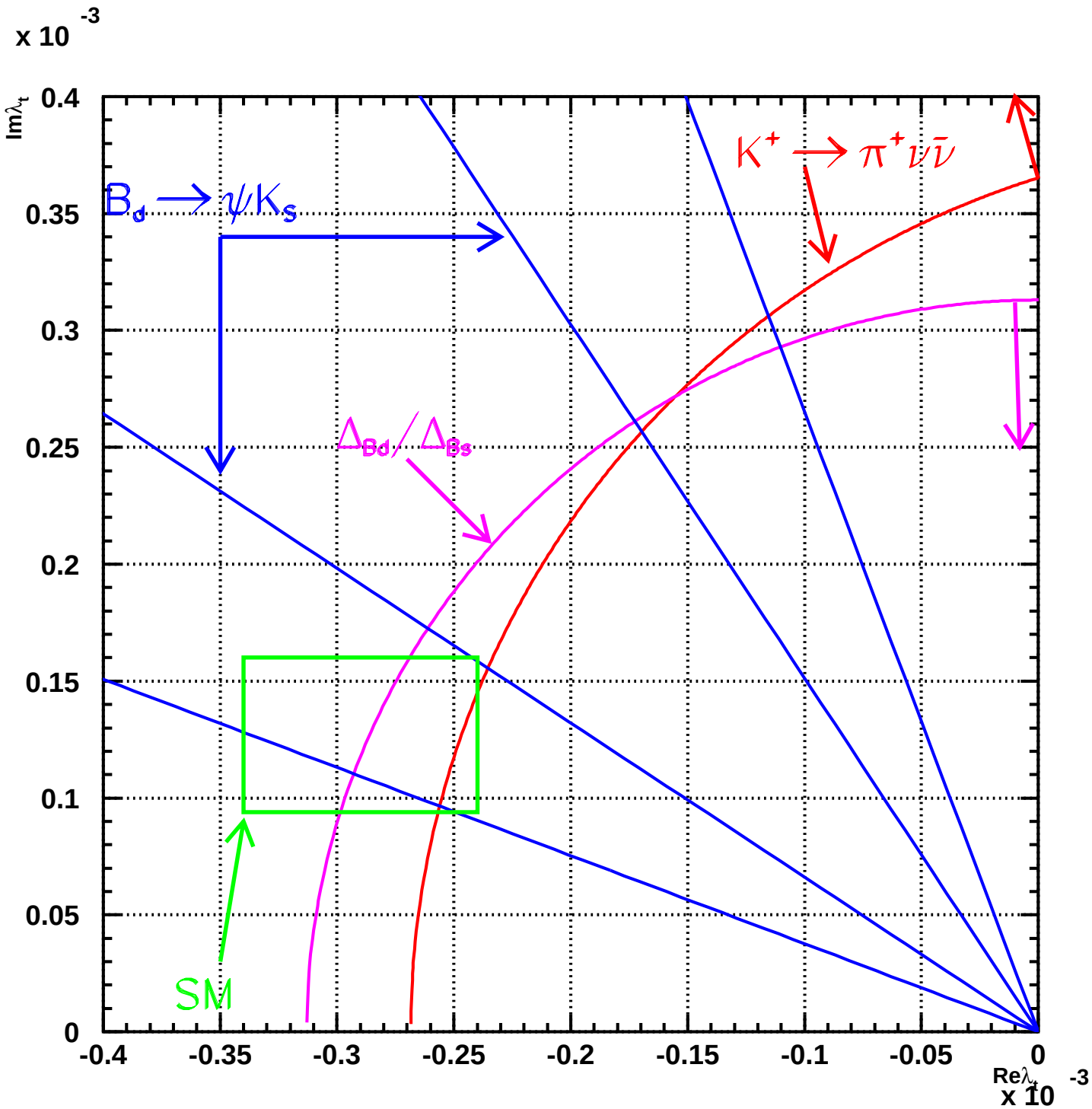
* Work supported in part by TMR, EC–Contract No. ERBFMRX-CT980169 (EURODAΦNE).


1
$\bar{\eta}$
0.8
0.6
0.4
0.2
–1
–0.8
–0.6
–0.4
–0.2
0.2
0.4
0.6
0.8
1
$\bar{\rho}$


$\sin(2\beta)$
$\Delta M_d / \Delta M_s$
$K \to \pi\nu\bar{\nu}$
$\bar{\eta}$
$\bar{\rho}$
1
0.8
0.6
0.4
0.2
–1
–0.8
–0.6
–0.4
–0.2
0.2
0.4
0.6
0.8
1


1
η̄
0.8
0.6
0.4
0.2
–1
–0.8
–0.6
–0.4
–0.2
0.2
0.4
0.6
0.8
1
ρ̄

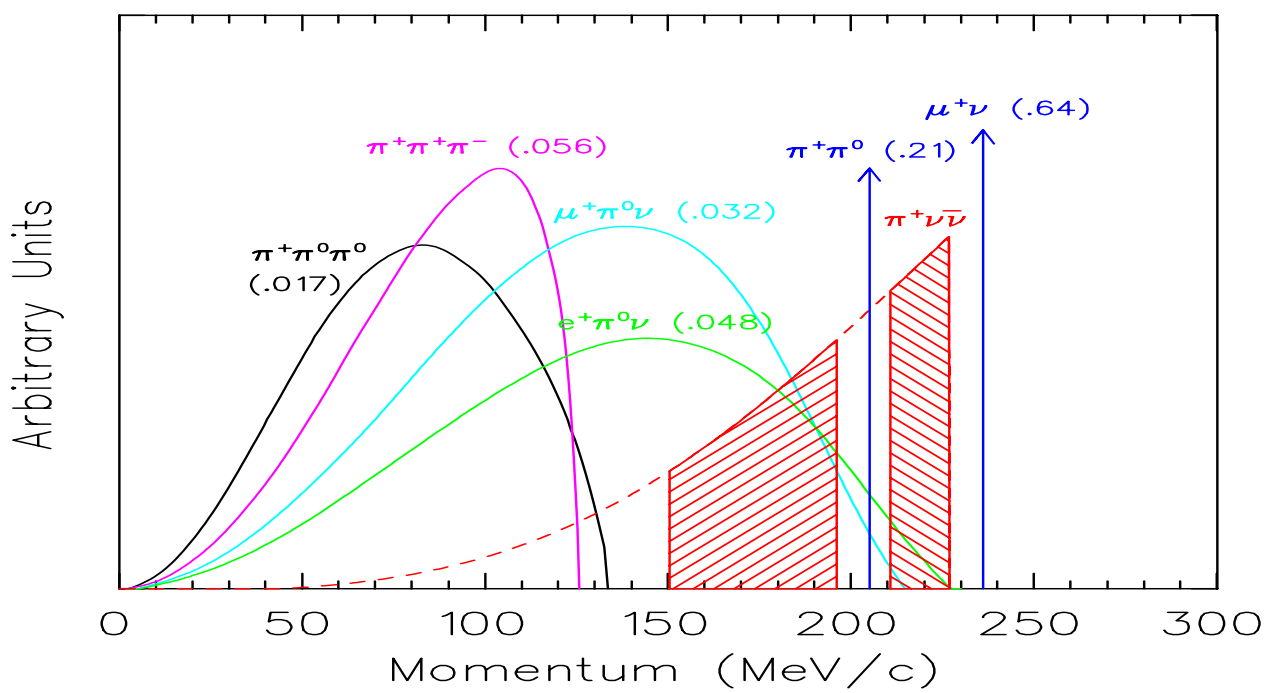

x 10 -2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
x 10 -2
Imλt
Reλt
Bd → ψKs
Δ_Bd/Δ_Bs
K+ → π+νν̄


x 10 -3
Imλt
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.4
-0.35
-0.3
-0.25
-0.2
-0.15
-0.1
-0.05
0
Reλt
x 10 -3
B_d → ψK_S
K+ → π+νν̄
Δ_Bd/Δ_Bs
SM

$K^+ \to \pi^+ \nu\bar{\nu}$ Experimental Strategy

Measure everything possible

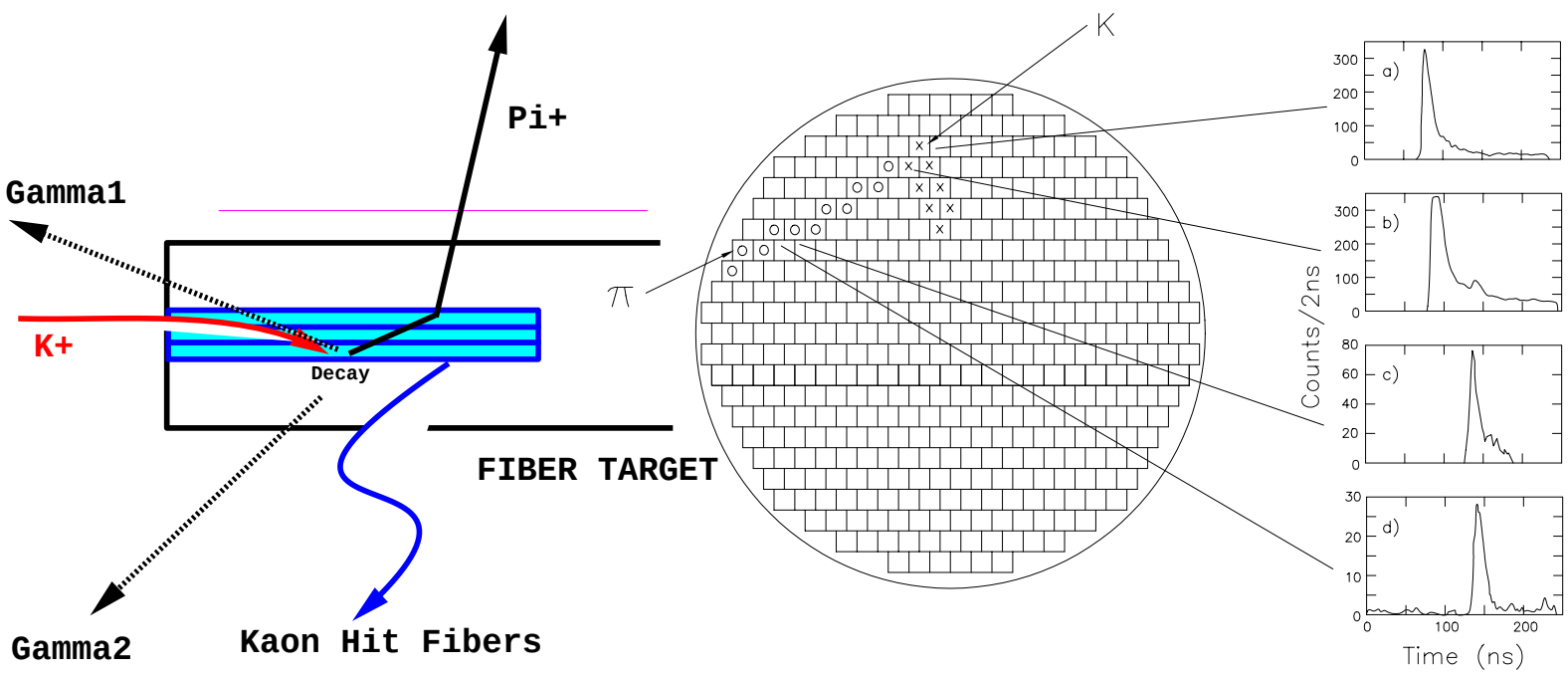
- Positively identify π^+.
- Veto extra particles.
- Measure kinematics with high resolution and redundancy.

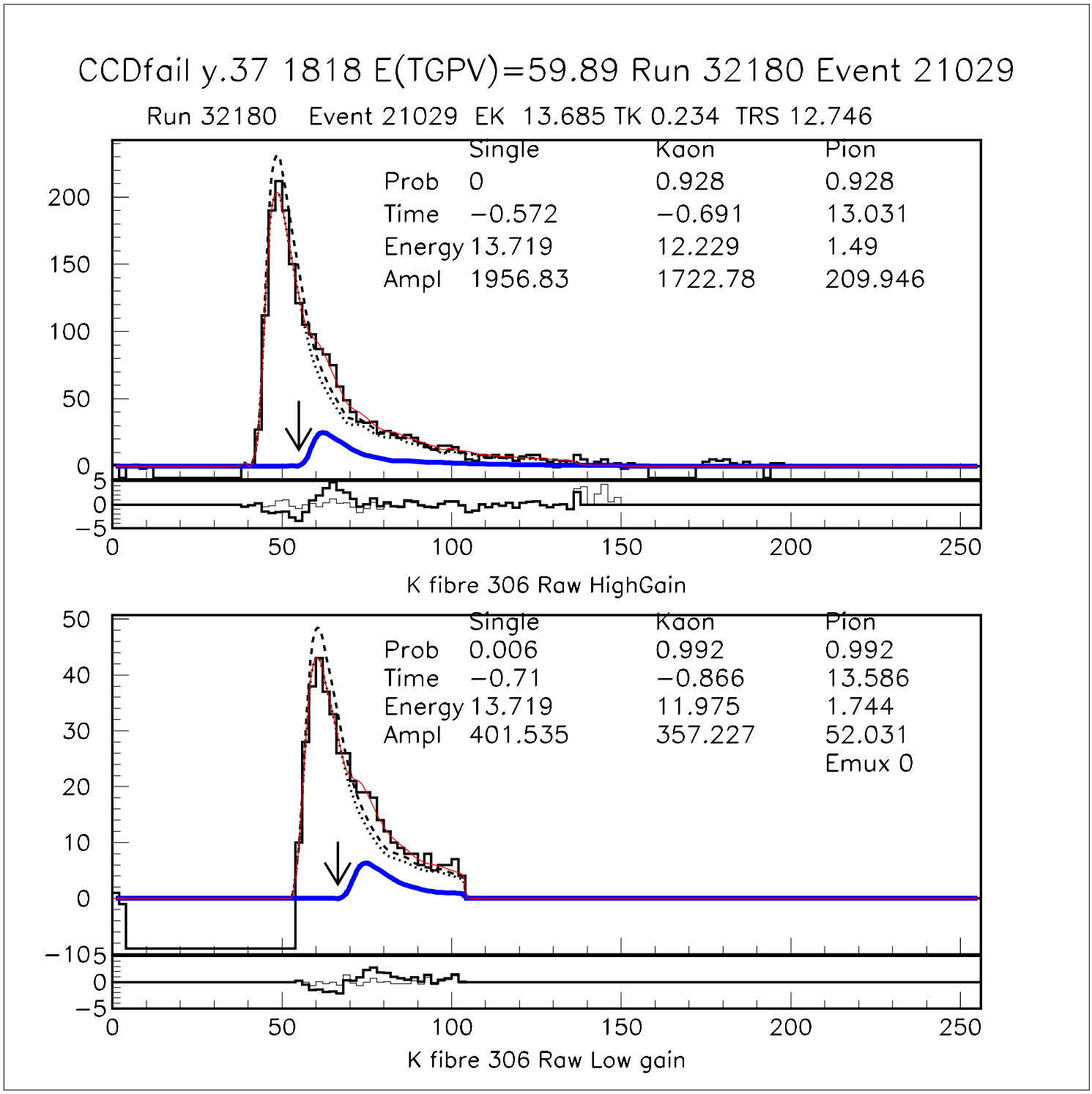


- Suppress background by 10^{11}: B/S(SM) < 0.1
- Reliably **measure** background from data.

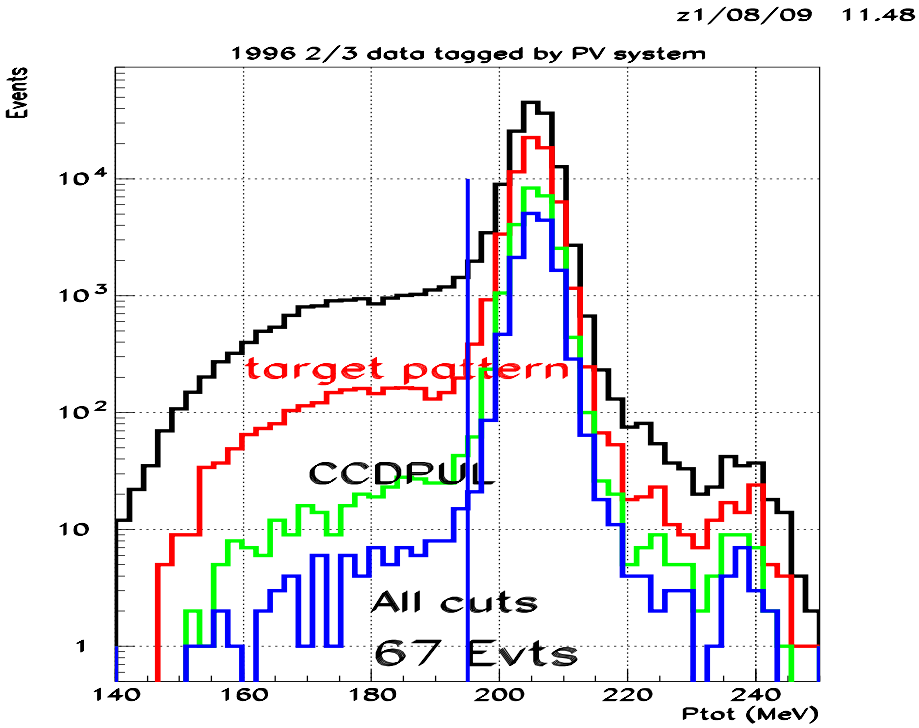
$\pi\nu\overline{\nu}(2)$ (below $K^+ \to \pi^+\pi^\circ$) data analysis

- Much larger phase space acceptance below $K_{\pi 2}$ peak.
- Large background from $K^+ \to \pi^+\pi^\circ$ in which π^+ undergoes interaction in the scintillator fiber target.
- 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.

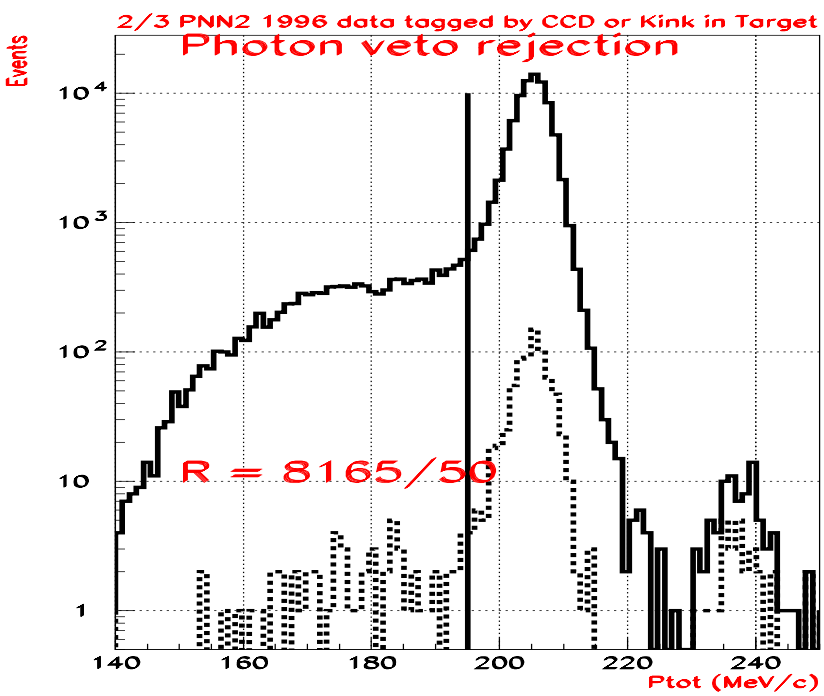



CCDfail y.37 1818 E(TGPV)=59.89 Run 32180 Event 21029
Run 32180 Event 21029 EK 13.685 TK 0.234 TRS 12.746
Single Kaon Pion
Prob 0 0.928 0.928
Time −0.572 −0.691 13.031
Energy 13.719 12.229 1.49
Ampl 1956.83 1722.78 209.946
K fibre 306 Raw HighGain
Single Kaon Pion
Prob 0.006 0.992 0.992
Time −0.71 −0.866 13.586
Energy 13.719 11.975 1.744
Ampl 401.535 357.227 52.031
Emux 0
K fibre 306 Raw Low gain

$K_{\pi 2}$ background



$$\mathbf{N} = \mathbf{67}$$



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

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

$K^+ \to \pi^+\pi^-e^+\nu$

Key steps in background determination

- Branching ratio: 4×10^{-5}.

  No photons.

  π^- can disappear by absorption.

  e^+ can disappear by annihilation.

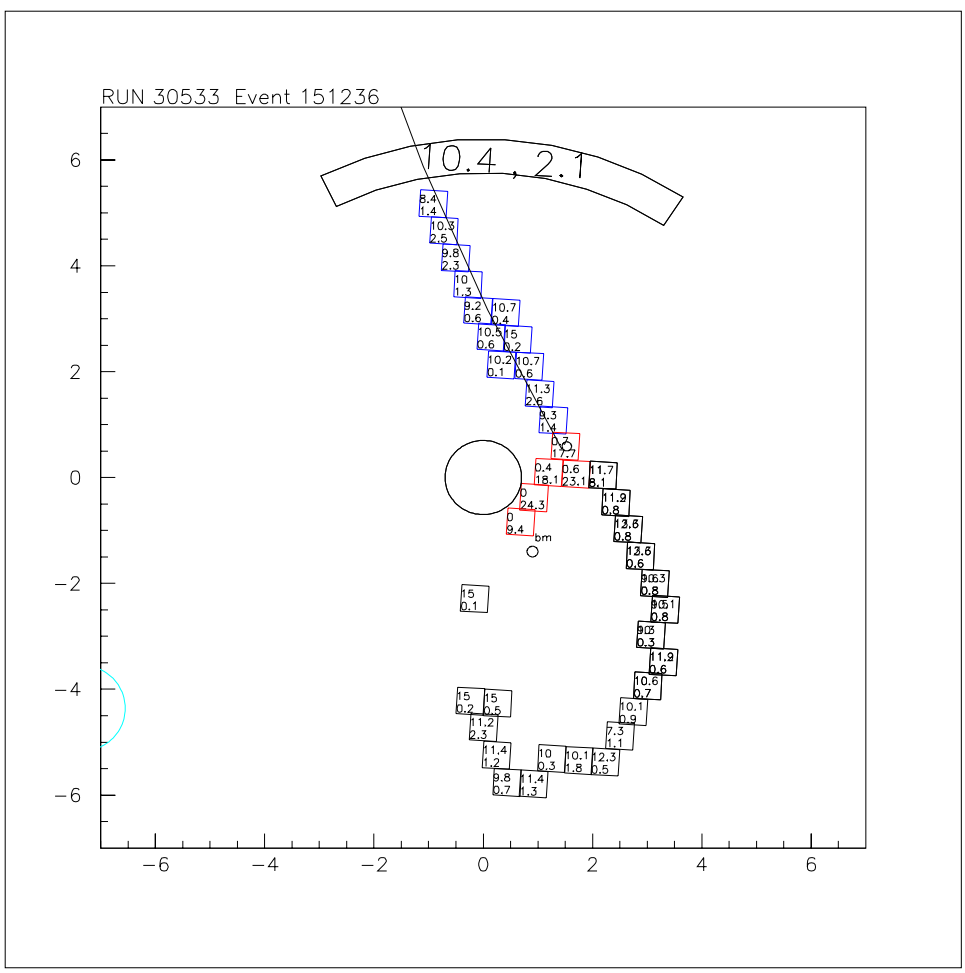
  π^+ momentum falls in the range of 150 to 190 MeV.

- 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 π^- and e^+ goes to 0.



$\pi\nu\bar{\nu}$(2) Background Estimate

Table of Backgrounds for PNN2 data

Background	
$K_{\pi 2}$ scatter (target)	0.62 ± 0.17
$K_{\pi 2}$ scatter (RS)	0.007 ± 0.006
$K^+ \to \pi^+ \pi^\circ \gamma$	0.027 ± 0.004
$K^+ \to \mu^+ \nu_\mu \gamma$	0.007 ± 0.007
1-beam	0.0003 ± 0.0003
2-beam	0.033 ± 0.033
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	0.026 ± 0.032
Charge Exchange	0.011 ± 0.011
Total	0.731 ± 0.177

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 ± 0.14 in the 2-6 ns region.

Acceptance

Acceptance factors	PNN1	PNN2
K^+ stop efficiency	0.702	0.670
K^+ decay after 6 ns	0.851	0.591
$K^+ \to \pi^+ \nu\bar{\nu}$ phase space	0.155	0.345
Geometry	0.409	0.317
π^+ 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	1.96×10^{-3}	7.65×10^{-4}

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

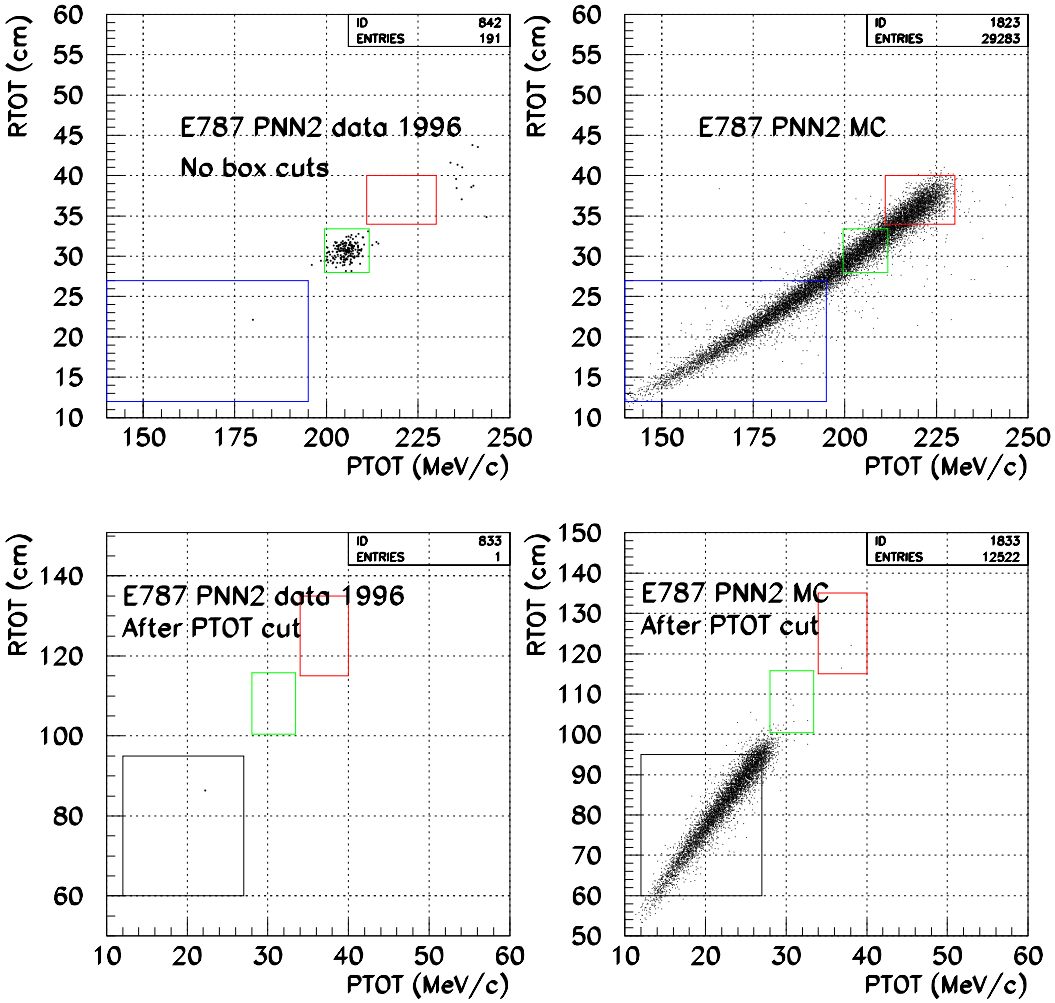
The large loss due to CCD and tighter photon vetos will be improved the analysis of remaining data as well as E949.

Total Analysed Exposure:

PNN1: 5.9×10^{12} kaons

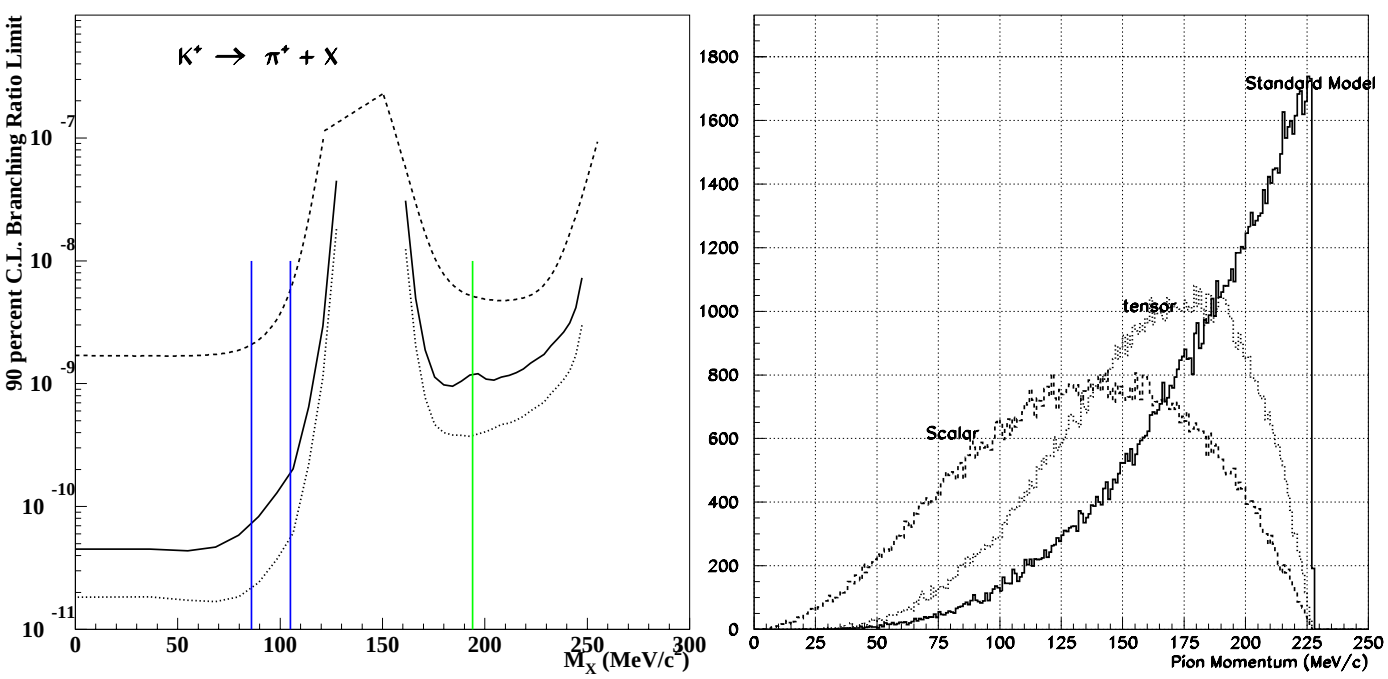
PNN2: 1.12×10^{12} kaons

Distribution in Signal box



Limits, etc.

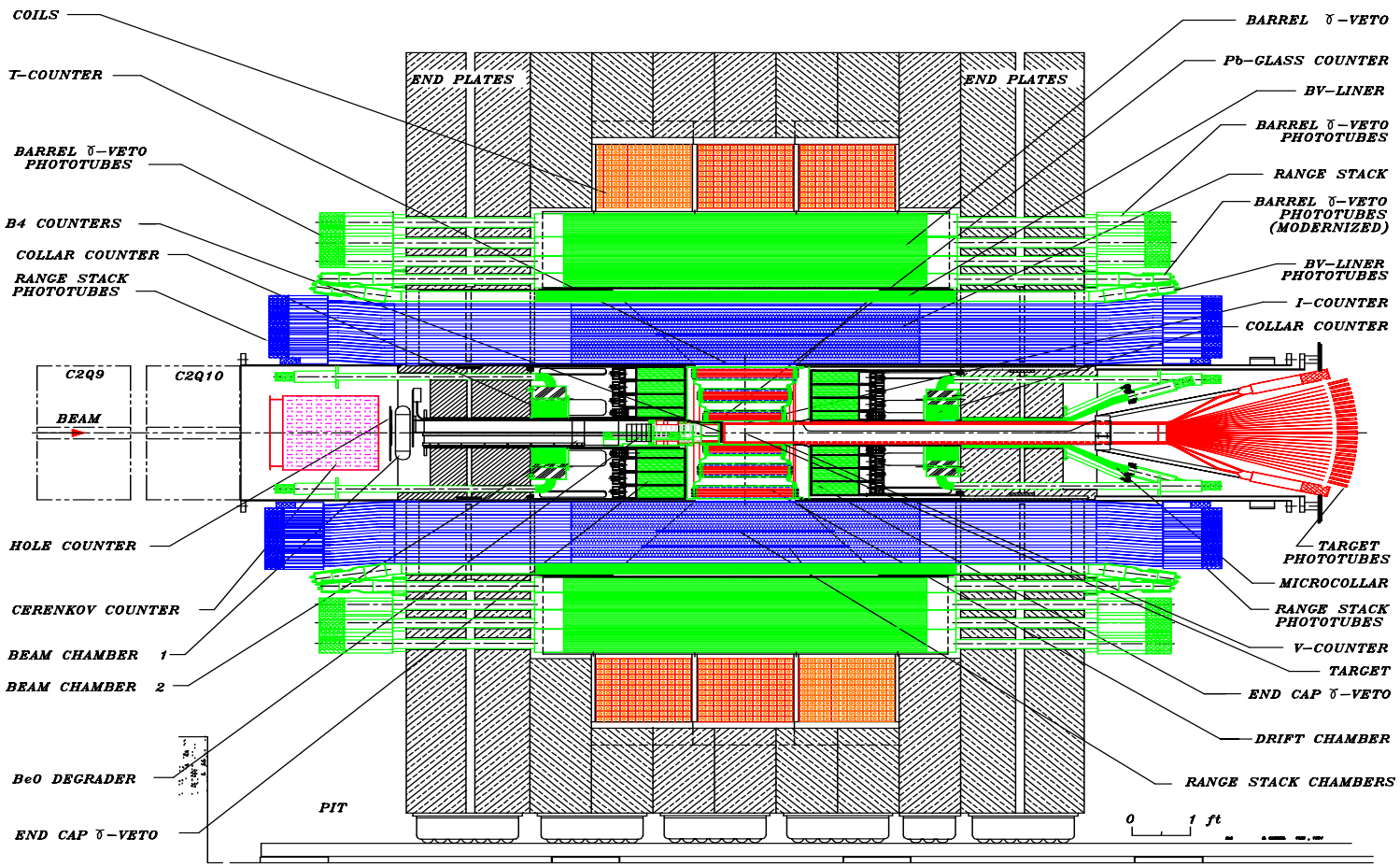
- Previous 90% C.L. limit using the low momentum region: 1.7×10^{-8}
  M.S. Atiya et al., PR**D 48**, R1 (1993).
- E787 measurement using 2 events in high momentum region:
  $\mathrm{B}(K^+ \to \pi^+ \nu \overline{\nu}\ ) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$
  S. Adler et al., PRL 88, 041803 (2002).
- This measurement: S.E.S $= 1.17 \times 10^{-9}$ S. Adler et al., hep-ex/0201037
- 1 event observed with background of 0.73 ± 0.18.
  $\mathrm{B}(K^+ \to \pi^+ \nu \overline{\nu}\ ) < 4.2 \times 10^{-9}$
- Assume Scalar spectrum: $\mathrm{B}(K^+ \to \pi^+ \nu \overline{\nu}\ )_S < 4.7 \times 10^{-9}$
- Assume Tensor spectrum: $\mathrm{B}(K^+ \to \pi^+ \nu \overline{\nu}\ )_T < 2.5 \times 10^{-9}$



- 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.**

E949: Measurement of B($K^+ \to \pi^+ \nu\overline{\nu}$)

Alberta/BNL/FNAL/Fukui/IHEP/INR/KEK/Kyoto/UNM/Osaka/TRIUMF



Sensitivity improvement with respect to E787 (1995):

- Increased spill length ($\times 1.56$)
- Lower Momentum ($\times 1.38$)
- Increased efficiency (trigger,DAQ,analysis) ($\times 3.2$)
- Acceptance below $K_{\pi 2}$ peak [$\times 2$]
- Total gain of $\times 7$ – [14] (per hour of running)

$\Longrightarrow$ **Will observe 5–10 SM events in 2 years.**

E949

An experiment to measure the branching ratio $B(K^+ \to \pi^+ \nu\overline{\nu})$

B. Bassalleck[10], E.W. Blackmore[12], D.A. Bryman[2,12]a, S. Chen[12], I-H. Chiang[3], P.S. Cooper[4], M.V. Diwan[3], D.E. Fields[10], J.S. Frank[3], T. Fujiwara[9], J.S. Haggerty[3], M.P. Grigoriev[7] T. Inagaki[8], A.P. Ivashkin[7], S. Kabe[8], S.H. Kettell[3]a, M.M. Khabibullin[7], A.N. Khotjantsev[7], P. Kitching[1], M. Kobayashi[8], T.K. Komatsubara[8], A. Konaka[12], A. Kozjevnikov[6], Y.G. Kudenko[7], Y. Kuno[8], L. Landsberg[6], K.K. Li[3], X. Li[2], L.S. Littenberg[3], J. Lowe[10], J.A. Macdonald[12], J. Mildenberger[12], O.V. Mineev[7], M. Miyajima[5], V. Mukhin[6], N. Muramatsu[8], T. Nakano[11], J. Nishide[5], M. Nomachi[11], T. Nomura[9], T. Numao[12], V. Obraztsov[6], K. Omata[8], S. Petrenko[6], J.-M. Poutissou[12], R. Poutissou[12], E. Ramberg[4], G. Redlinger[3], V. Rykalin[6], T. Sato[8], K. Shimada[5], T. Shinkawa[8], T. Shimoyama[5], R.C. Strand[3], S. Sugimoto[8]a, Y. Tamagawa[5], T.L. Thomas[10], T. Toshinao[8], R.S. Tschirhart[4], V. Victorov[6], Y. Yoshimura[8] and T. Yoshioka[8].

[1]Centre for Subatomic Research, University of Alberta, Edmonton, Alberta T6G 2N5, Canada
[2]University of British Columbia, Vancouver V62 1Z2, Canada
[3]Brookhaven National Laboratory (BNL), Upton, NY 11973, United States
[4]Fermi National Accelerator Laboratory, Batavia, IL 60510, United States
[5]Fukui University, Bunkyo, Fukui 910-8507, Japan
[6]Institute for High Energy Physics (IHEP), Protvino, Moscow region, 142 284, Russia
[7]Institute for Nuclear Research RAS, 60 October Revolution Pr. 7a, 117312 Moscow, Russia
[8]High Energy Accelerator Research Organization (KEK), Oho, Tsukuba, Ibaraki 305-0801, Japan
[9]Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
[10]University of New Mexico, Albuquerque, NM 87131, United States
[11]Research Center for Nuclear Physics, Osaka University, Mihogaoka, Ibaraki, Osaka 567-0047, Japan
[12]TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada

beam: LESB3, low energy (600-800 MeV/c) separated K^+ beam. The beam conditions are expected to be a 730 MeV/c K^+ beam with a K^+/π^+ ratio of >3:1 with 65 Tp on the C-target. The expected spill length is ~4.1 sec and a Duty Factor of 64%.

detector: Solenoidal magnetic spectrometer, with 4π calorimetric detection of all decay products except neutrinos.

hours: Request 6,000 hours. This should represent 2 years of running in the RHIC era. Expect to be ready for data collection during the fall of 2000.

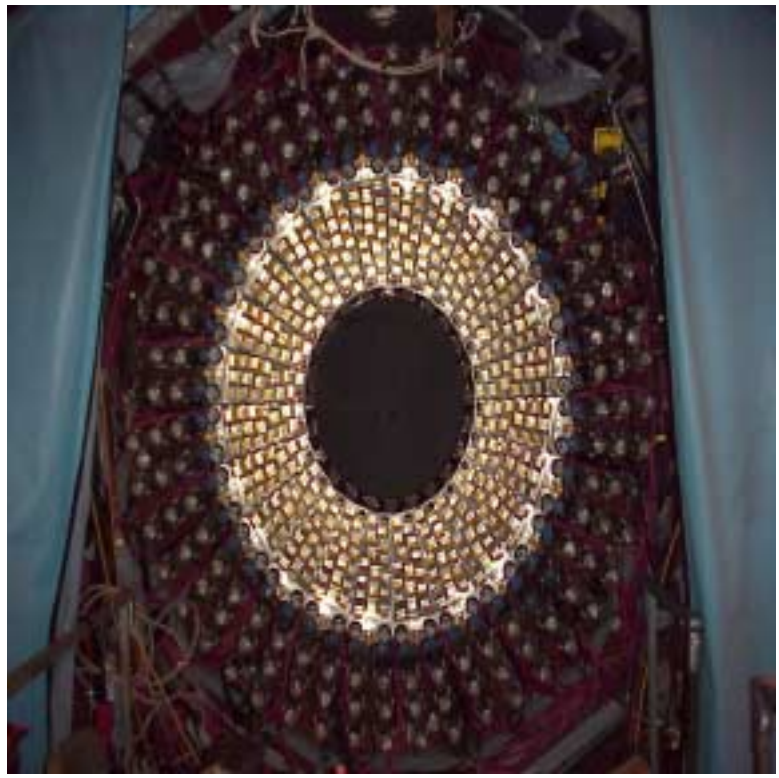
Abstract

A new, more precise measurement of the $K^+ \to \pi^+ \nu\overline{\nu}$ branching ratio is proposed. Improvements to the E787 apparatus and running mode will be made to reach a sensitivity of $(8\text{–}15)\times 10^{-12}$, an order of magnitude below the Standard Model prediction. This will result in a determination of $|V_{td}|$ to better than 30%.

[a]spokespersons:
Douglas Bryman, doug@triumf.ca, (604)222-7338;
Steve Kettell, kettell@bnl.gov, (631)344-5323; and
Shojiro Sugimoto, shojiro.sugimoto@kek.jp, (+81)424-69-9548.

E949 Upgrades

- AGS remains the world's highest intensity proton synchrotron
- 6.5×10^{13} protons/spill to increase duty factor and lower kaon momentum
- Proven technique and background rejection from E787.
- Detector and beam upgrades to improve efficiency and bkg rej.
- Beam upgrades to improve reliability and cope with large flux

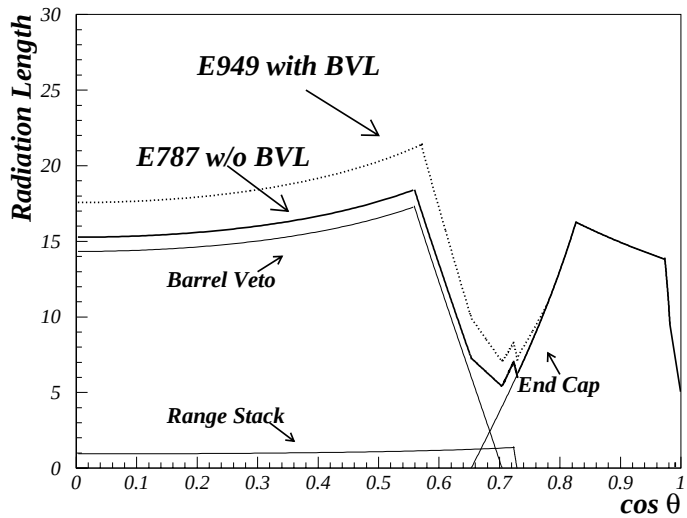


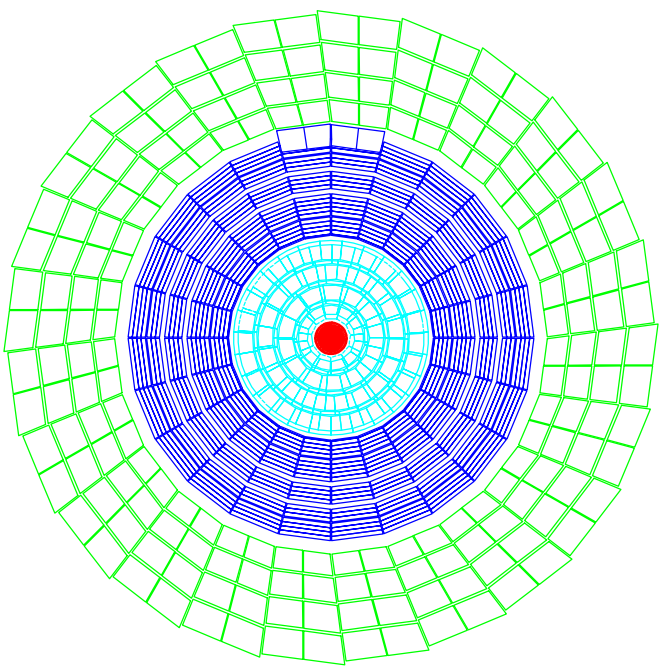
- Photon Veto (access low p_π phase space)
  - Barrel Veto Liner (additional 2.3 $X_\circ$) *Completed*
  - Live degrader upgrade *Completed*
  - Additional upstream vetoes 11/01
  - Thicken collar counter downstream *Completed*
  - Downstream veto *Completed*
- UTC (tracking efficiency increase) *Completed*
- Range stack upgrades
  - Replace T-counters (better trigger, tracking efficiency) *Completed*
  - Replace Layer 2-5 (better dE/dx resolution, timing) *Completed*
  - Repair dead RSSCs (better tracking efficiency) *Completed*
  - Upgrade RSSC electronics (muon rejection) 11/01
  - Monitor system (reliability and energy resolution)
    - LEDs on RS *Completed*
    - Voltage monitor *Completed*
- Trigger upgrade (reduce deadtime and improve rejection) mostly completed
- DAQ upgrade (reduce deadtime, increase rate capability) mostly completed
- Beam counter upgrade (increase background rejection) 11/01
- Separator Upgrade *Completed*
- New targets 6/01, ongoing

Barrel Veto Liner (BVL)

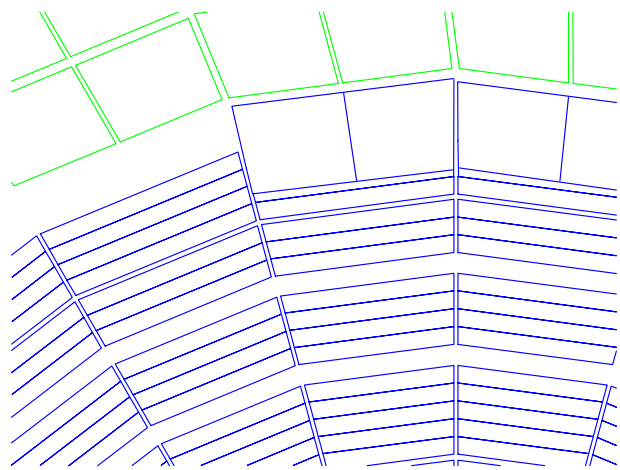
Thickens barrel veto by 2.3 X_0
Plugs 45° thin spot
Gives factor 2-3 in π^0 rejection

Largest single E949 project
Fabrication complete
>75% installed





End view with 2 sectors installed



Closer view of end configuration

E949

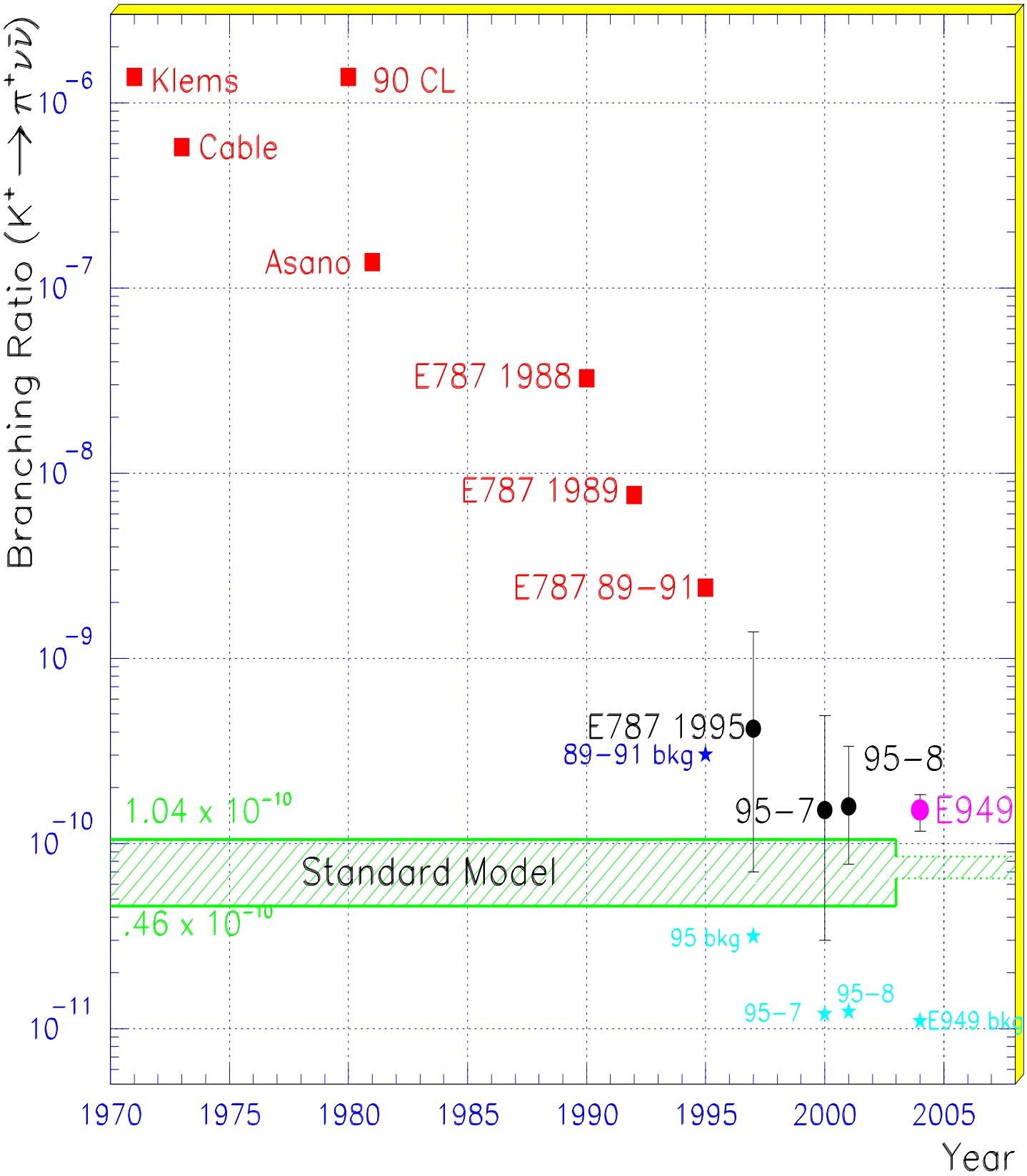
Goals

- Solid projection of sensitivity gain from E787
- Sensitivity for B($K^+ \to \pi^+ \nu \overline{\nu}$) of 9–16$\times 10^{-12}$, an order of magnitude below the SM $\longrightarrow$ observe 6-11 SM events.
- Background small and well understood.
- Background $\sim$10% of SM signal. Benefit from extensive E787 measurements.

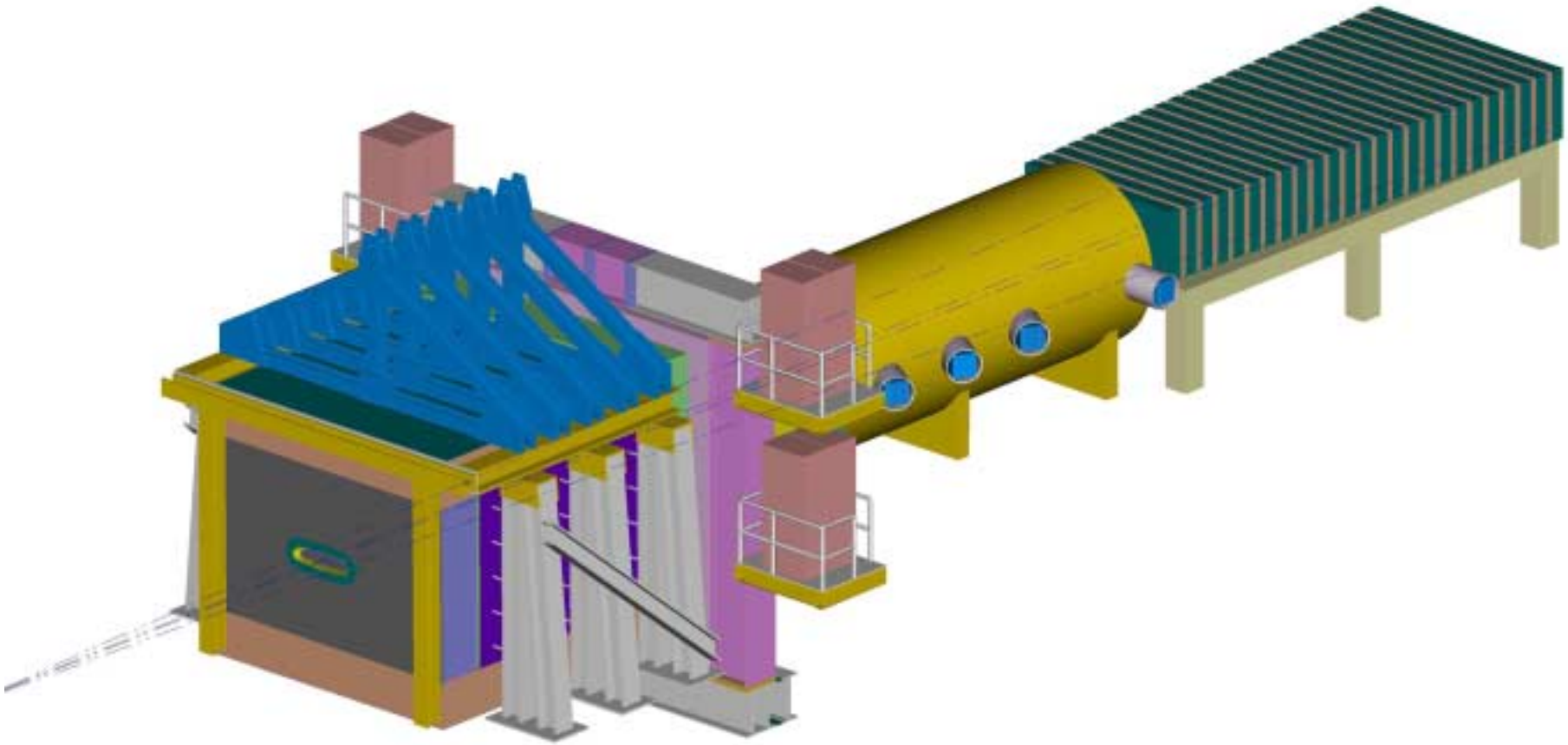
Status

- Scientific Approval (BNL) in 1998
- Full Approval (DOE) in 1999 (construction/operations funding FY01–03 with 60 weeks of running)
- Construction essentially complete in FY01
- Comissioning run for 4 weeks with 1/10 pulse from $\underline{g-2}$ in April '01
- Engineering run with RHIC/MEP (low intensity) for 8 weeks in Sep–Oct '01
- First major data collection run at full intensity Feb '02
  - **Problem #1** Reduced DOE funding, increased cost of running w/o RHIC: 25 weeks $\longrightarrow$ 8 weeks
  - **Problem #2** Separator HV breakdown $\longrightarrow$ postpone '02 startup by $\sim$1 month
- To get 60 weeks need to run during FY01–**04**.
  - **Problem #3** DOE approval apparently does not mean much. FY03 funding in Presidental budget is \$0 $\longrightarrow$ need help from Congress and HEP community.

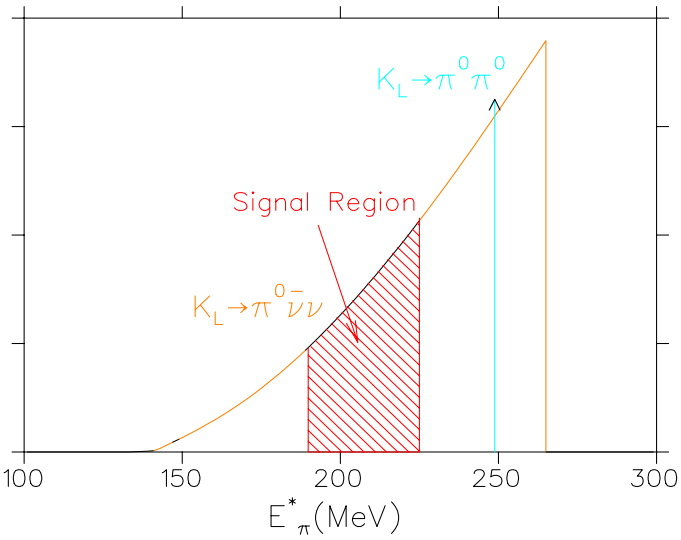
History of the Search for $K^+ \to \pi^+ \nu\bar{\nu}$

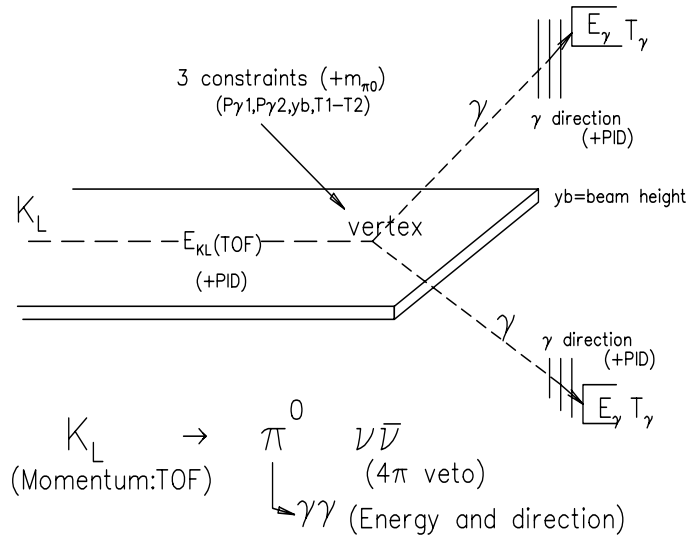


BNL, Cinncinnati, INR-Moscow, KEK, Kyoto, INFN-Perugia, Stony Brook, TJNAF, TRIUMF, British Columbia, New Mexico, Virginia, Virginia Tech, Yale, Zurich

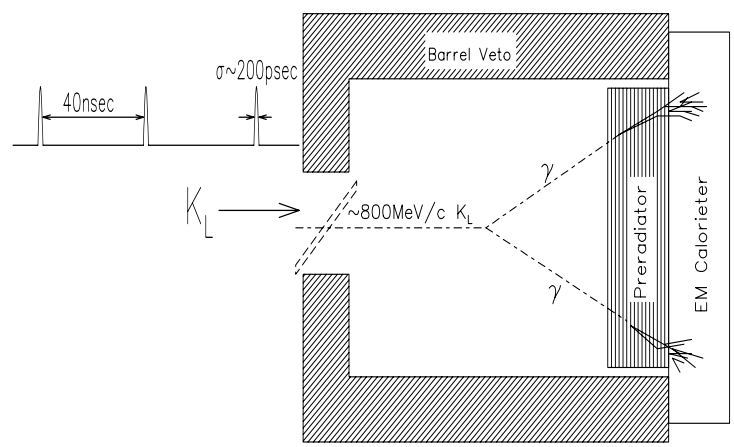


KOPIO Principles and Technique





- Measure all initial & final state quantities.
  - Work in the K_L center of mass: Bunched, large angle (low $\vec{p}$) beam.
  - Preradiator to measure γ directions.
  - Calorimeter for energies and times.
- *Measure* backgrounds.
- Hermetic photon veto ('beam catcher').



- Bunched beam
  $\longrightarrow$ kinematically reduce $K_L^\circ \to \pi^+\pi^-$ by ~40, most neutrons and accidental K° out of time, measure π° momentum spectrum (consistent with $K_L^\circ \to \pi^\circ \nu\overline{\nu}$).
- Low momentum beam
  $\longrightarrow$ neutrons below π° threshold, no hyperons, neutrons and photons out of time.
- Determine decay vertex
  $\longrightarrow$ 4C fit to π°, decay vertex in plane, reduce adcidentals.

KOPIO $K_L \to \pi^0 \nu\bar{\nu}$

Proposal recommended by National Science Board
- NSF-funded R&D has begun

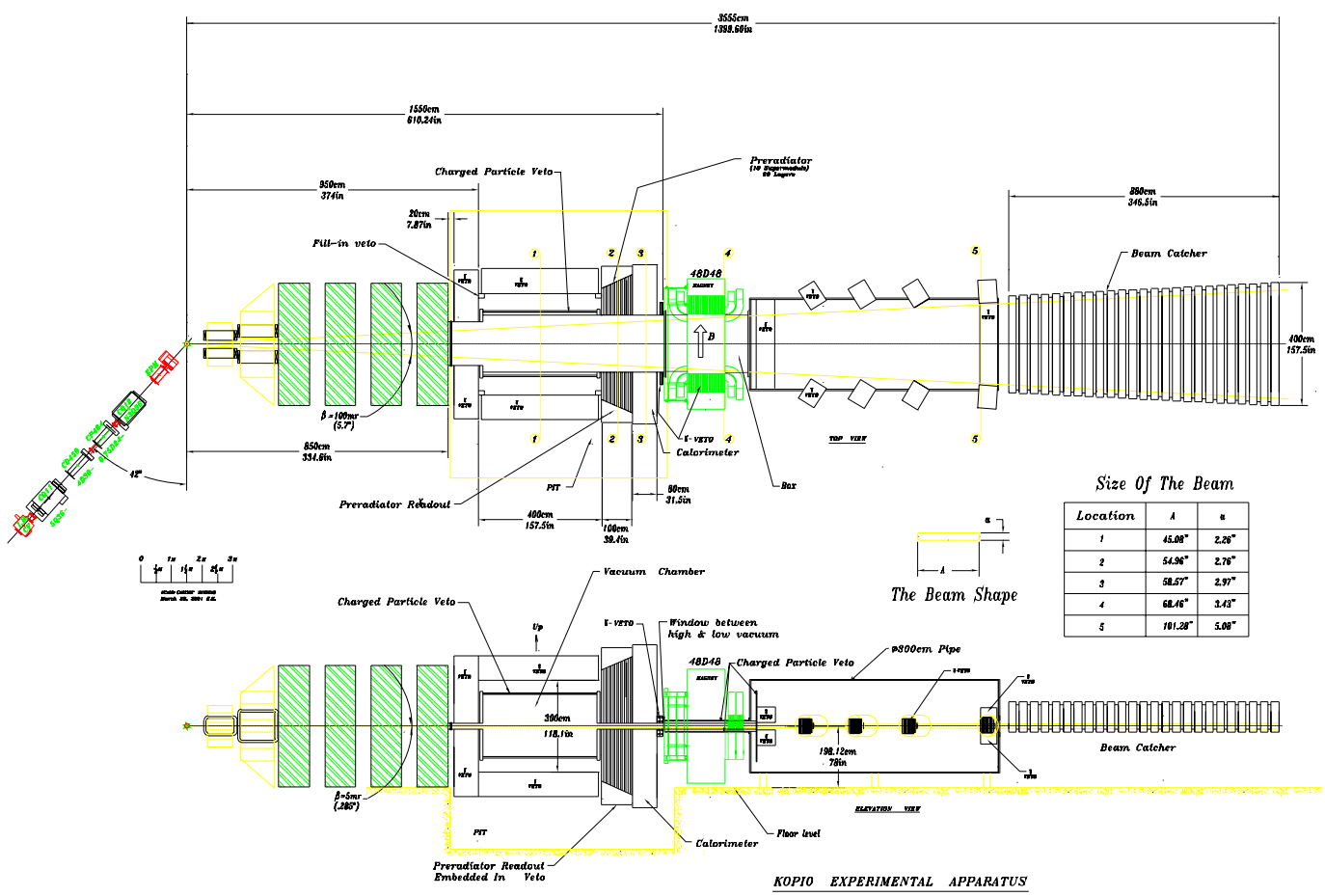
Uses the BNL AGS ~ 20 hrs/day it's not serving RHIC

Microbunched, low energy beam allows TOF determination of p_K

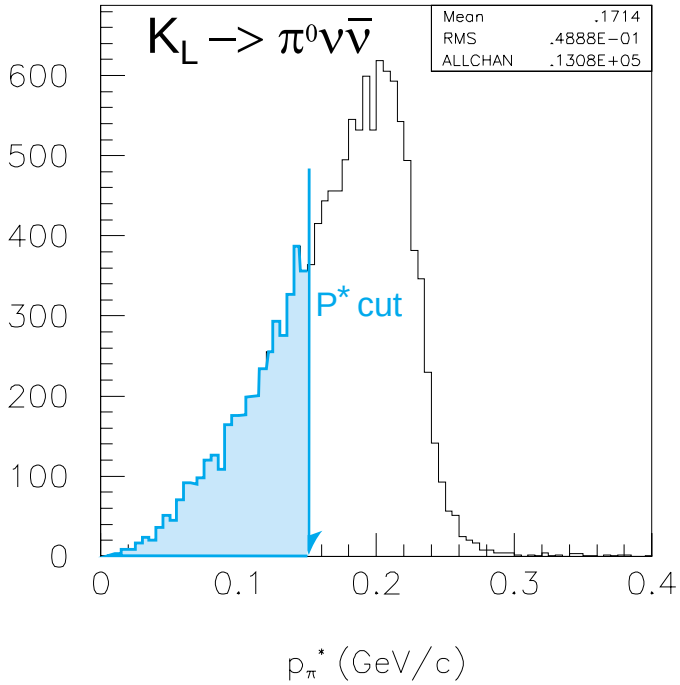
Measures photon direction as well as energy, time, position

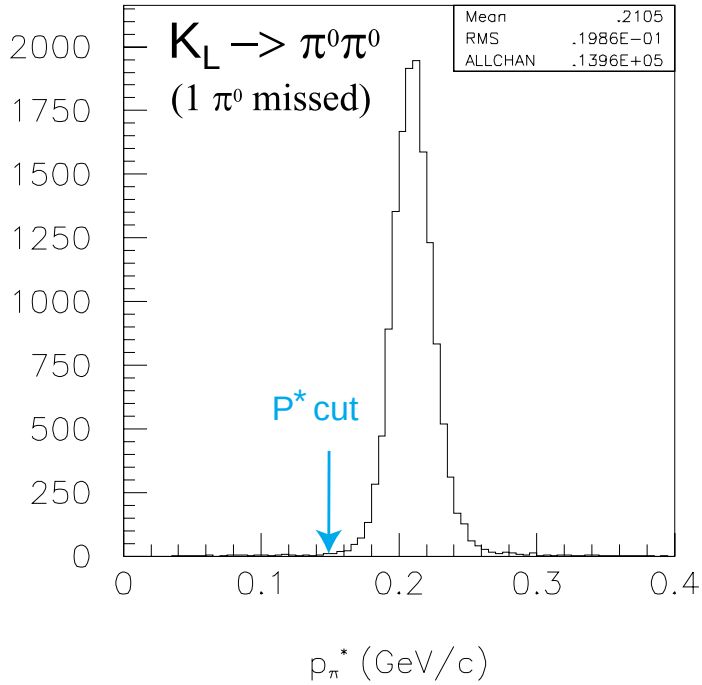
Hermetic veto with proven level of inefficiency

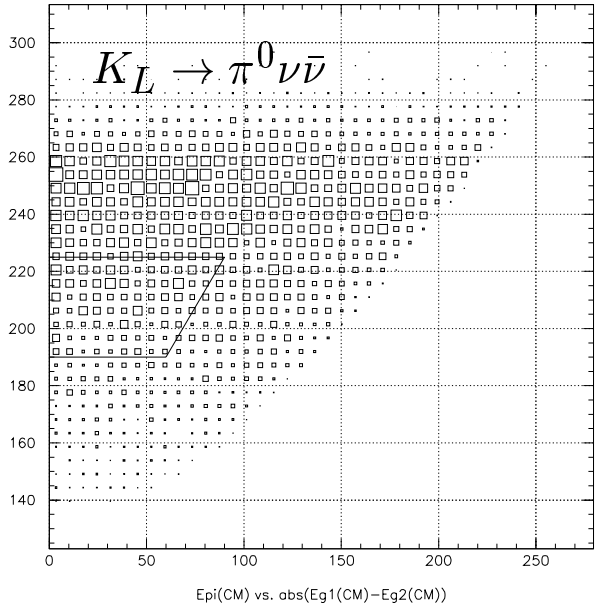
~ 50 events, S:B $\sim 2:1$

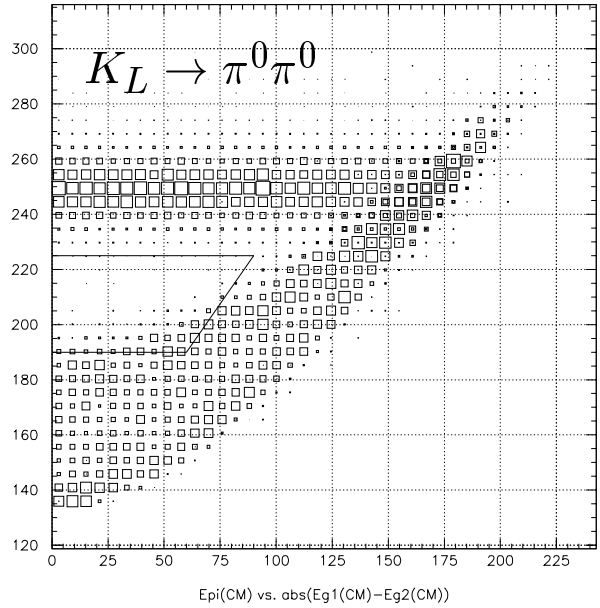


$K_L \to \pi^0\nu\bar{\nu}$ and $K_L \to \pi^0\pi^0$ identification



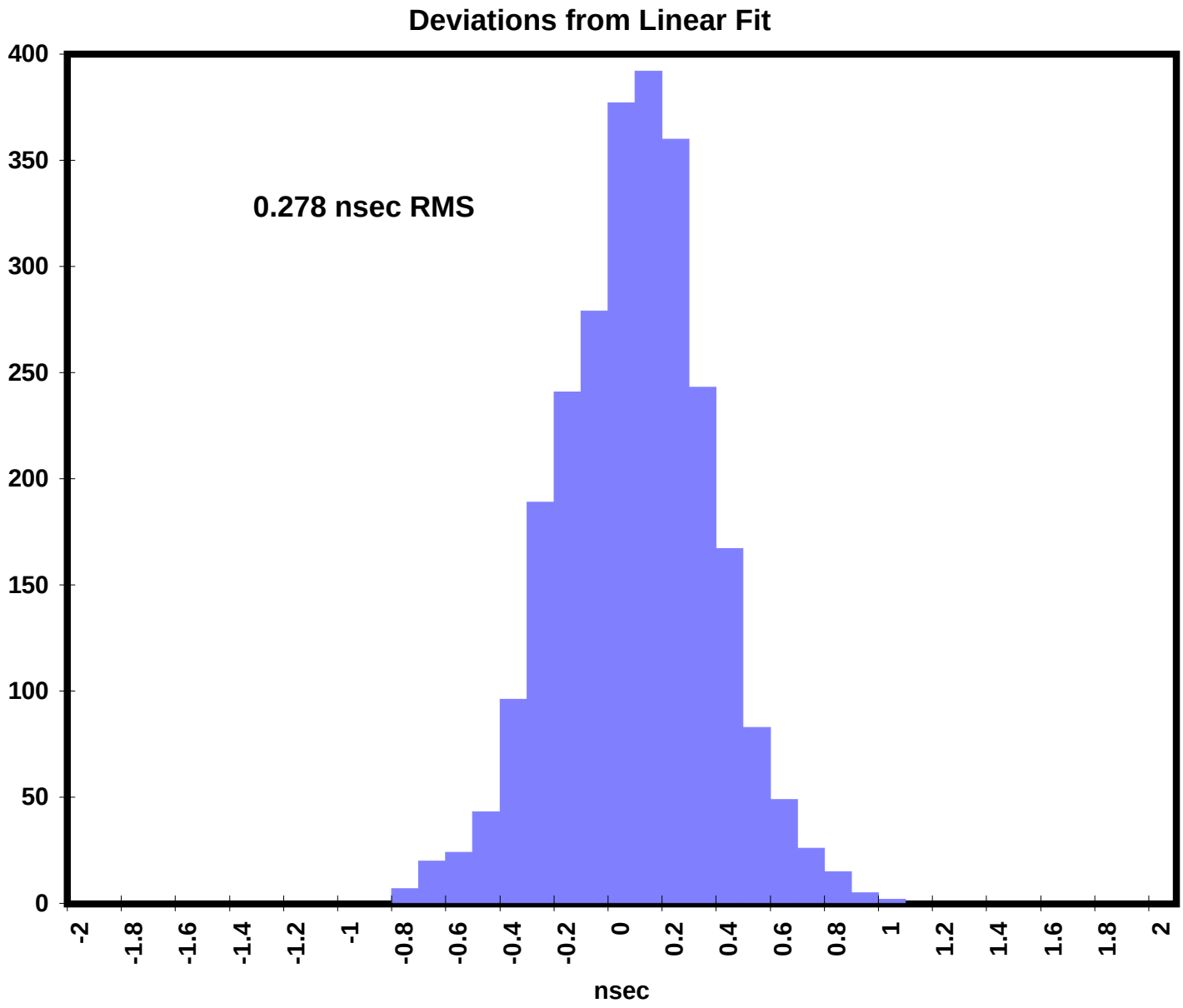






Energy of the purported π^0 (vertical) vs absolute value of the difference of the energies of the two detected γ's (horizontal) both in the K_L cm system.

Test of microbunching on extraction at AGS



Technique now well established
Very successfully used to smooth AGS spill

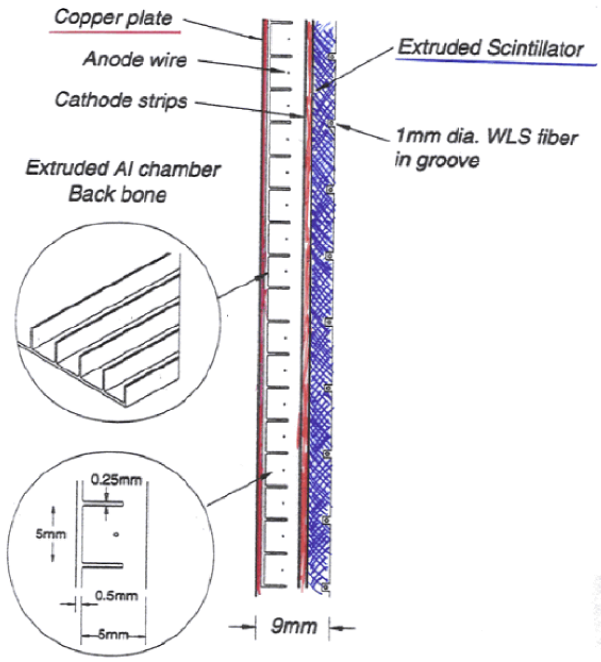
Photon angle measurement

Principle: track 1st converted pair in low-density preradiator

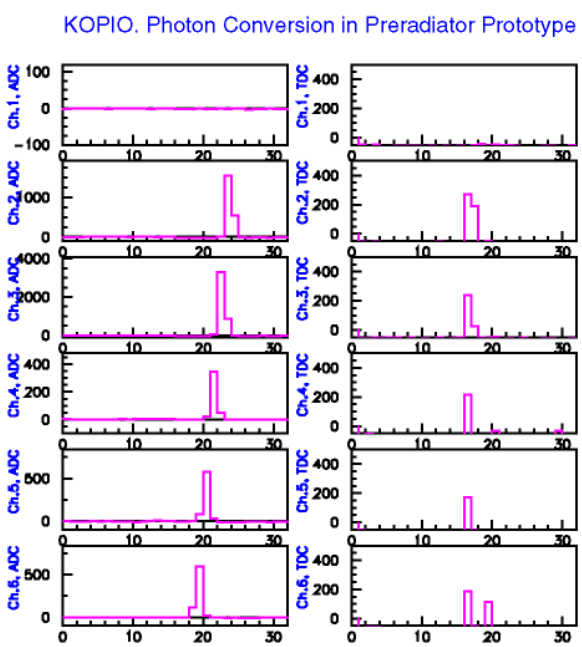
64 layers of chamber + scintillator
- each station $0.03X_0$

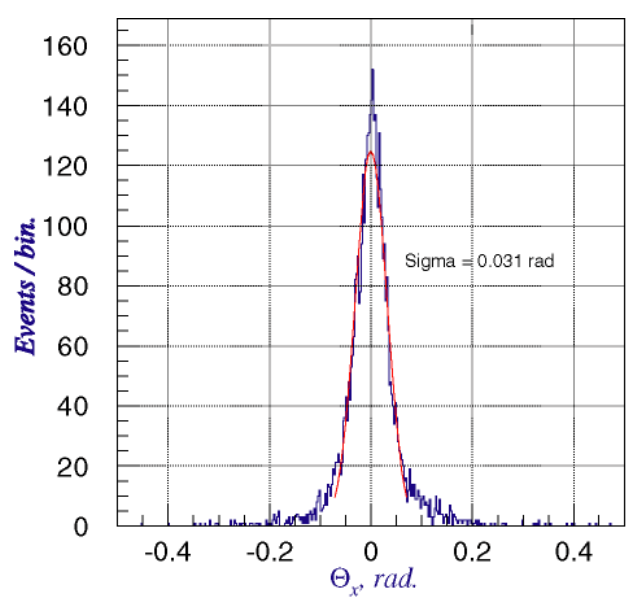
We will need $\sigma_\theta \sim 30$mr

MC indicates this can be done



Prototype tests in the LEGS tagged γ beam at the BNL NSLS confirmed this:





Θ_x distribution of detected photons. E_γ = 150 MeV.

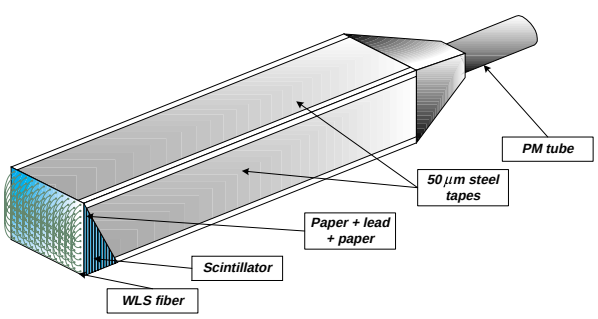
Calorimeter

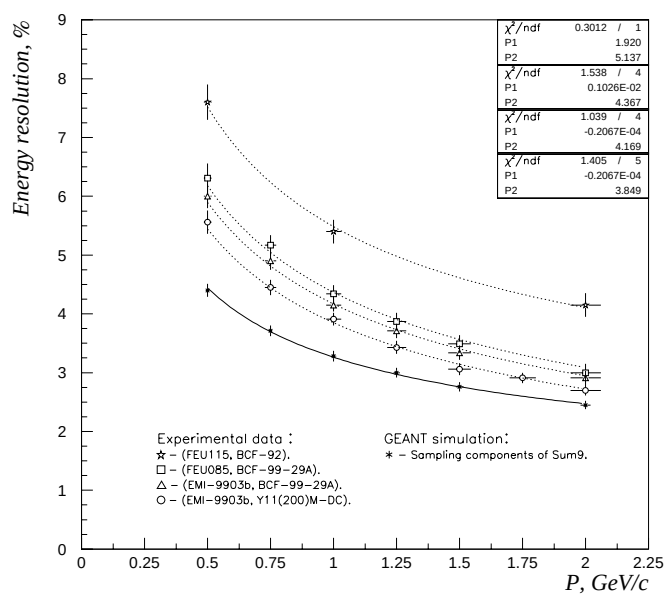
Need $\sigma_E/E \propto 0.03/\sqrt{E}$

Use well-understood shashlik technology

Better than $0.04/\sqrt{E}$ already demonstrated

MC indicates goal can be straightforwardly reached



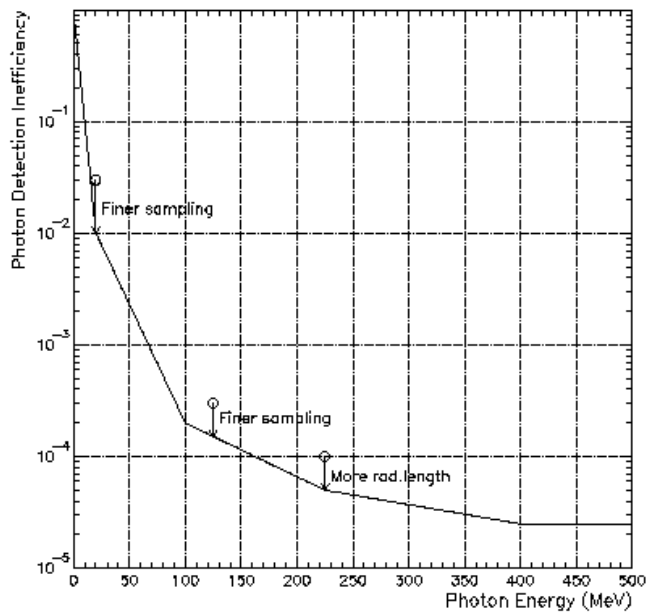


Note that **overall** σ_E depends strongly on preradiator

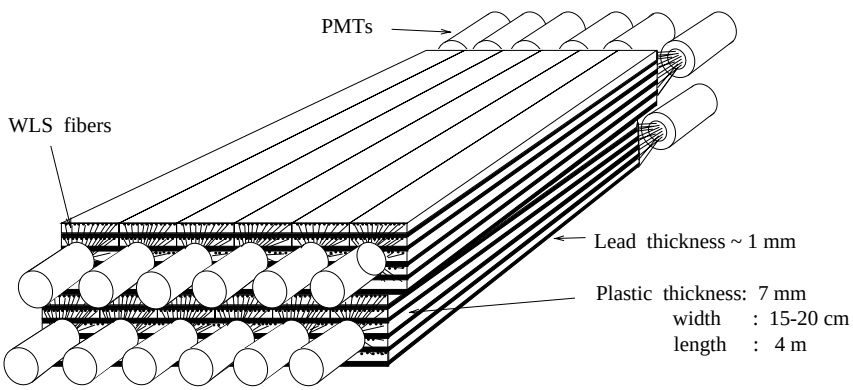
- MC of latest configuration indicates $\sigma_E/E \sim 0.027/\sqrt{E}$

KOPIO Photon Veto

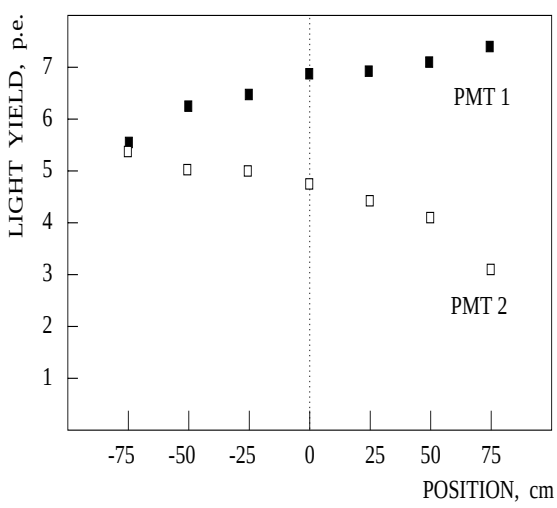
Require photon veto inefficiency only a little better than that already demonstrated in E787.

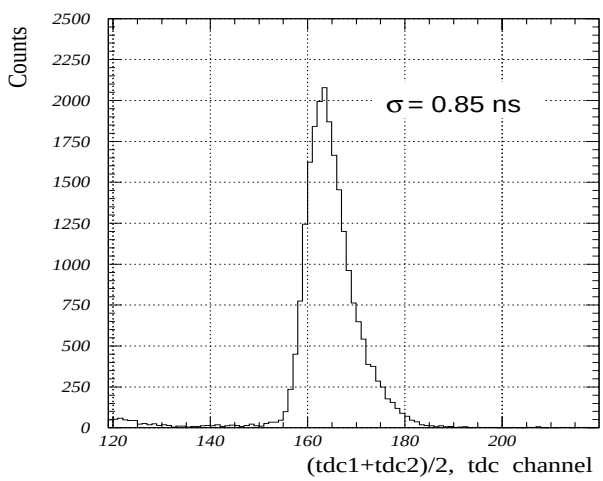


Technology similar, but wls readout gives better uniformity, brightness, and KOPIO will have more radiation lengths.

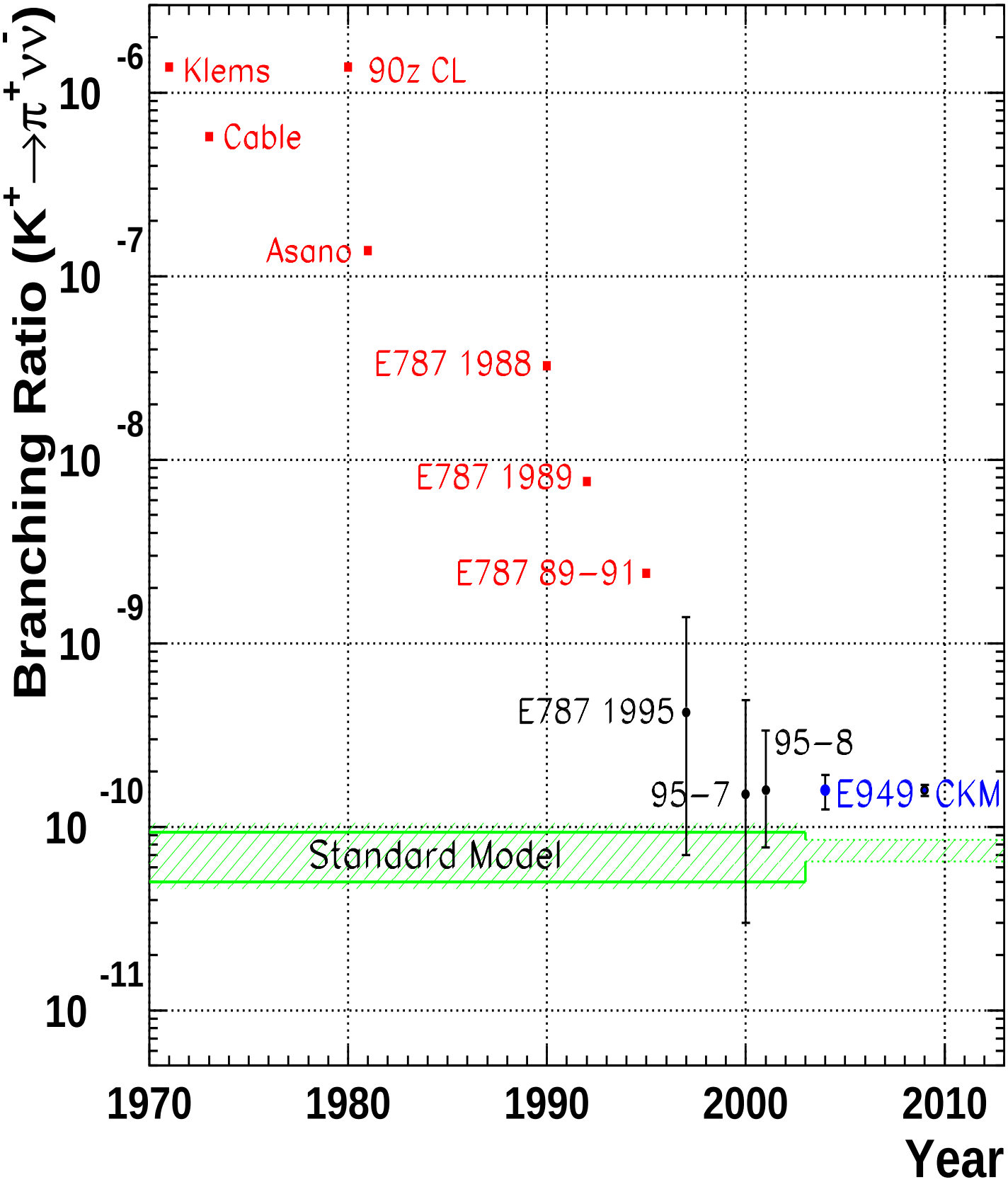


Prototype scintillators show required brightness, uniformity and time resolution:





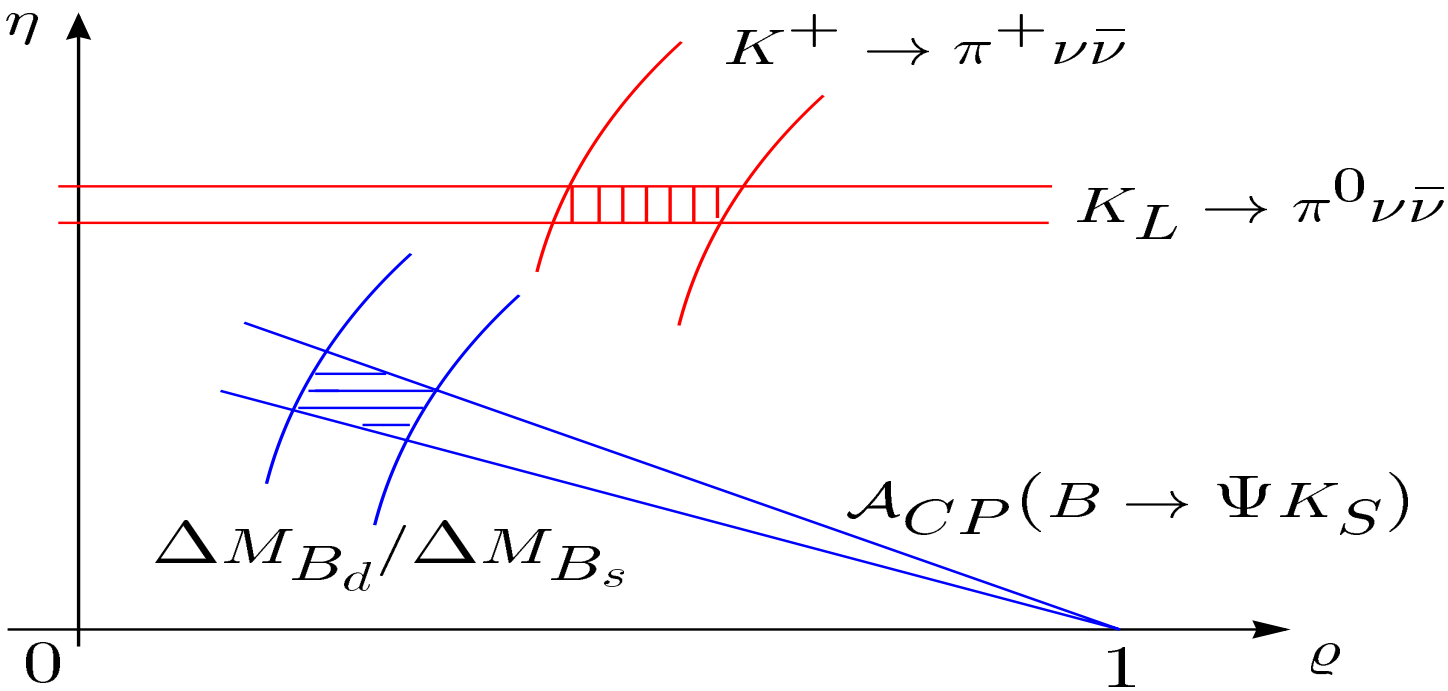
History of the Search for $K^+ \to \pi^+ \nu\bar{\nu}$



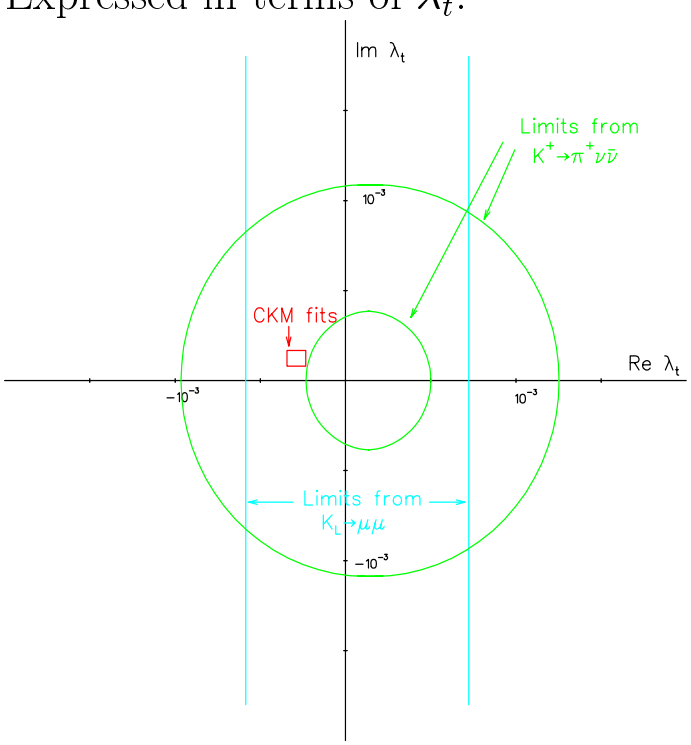
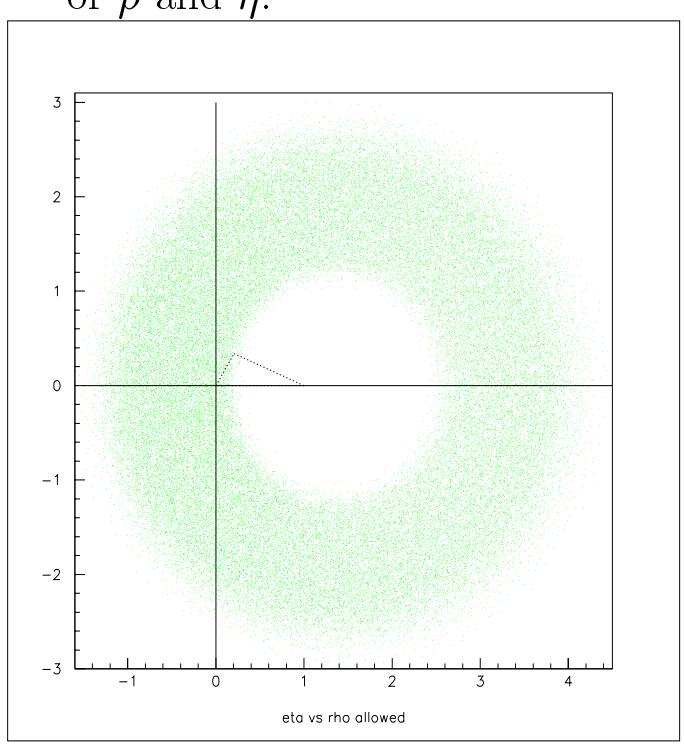
Future Kaon contribution to the CKM Matrix

Measurements and tests of the Standard Model:

- Determine $Im(\lambda_t)$ and J_{CP} to 7–8% (now 22% and ~40%)
- **Overconstrain β from $B_d^\circ \to \psi K_S^\circ$ and $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ / $K^+ \to \pi^+ \nu\overline{\nu}$**
- **Overconstrain $|V_{td}|$ from $\Delta M_{B_s}/\Delta M_{B_d}$ and $K^+ \to \pi^+ \nu\overline{\nu}$**



Expressed in terms of λ_t:



or ρ and η: