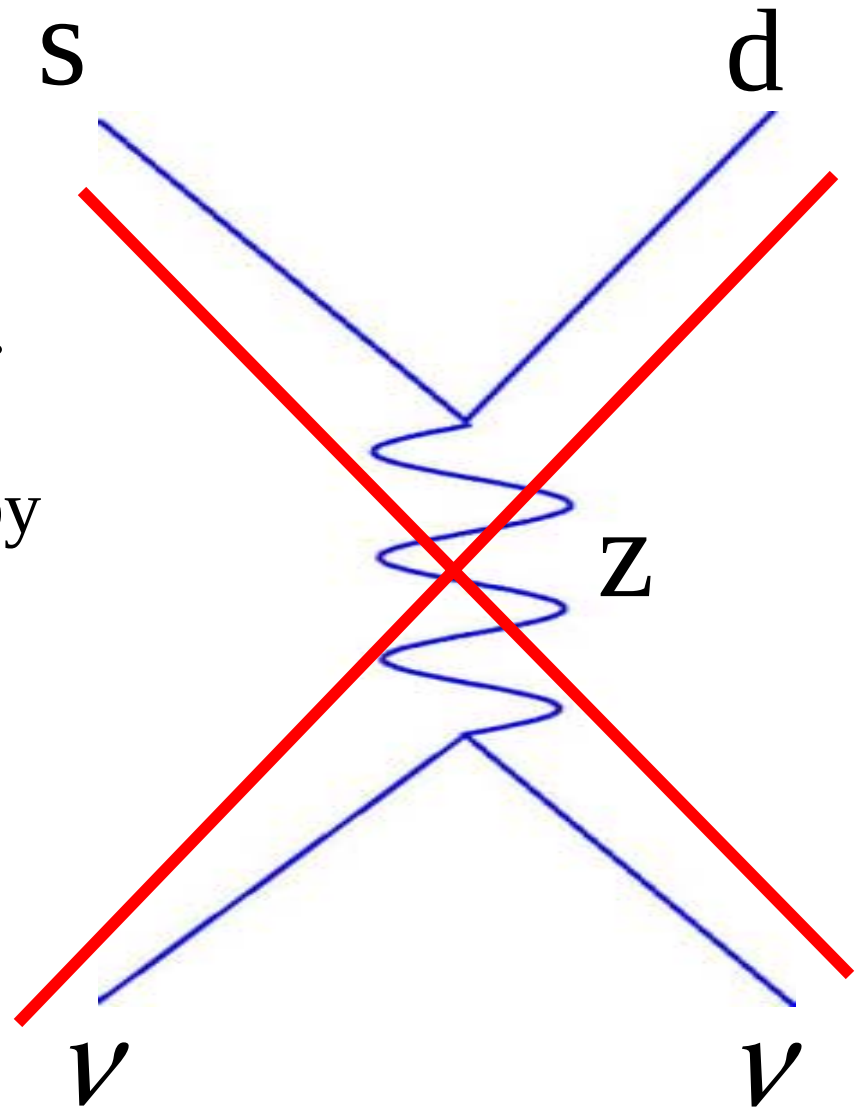
$K \to \pi \nu \bar{\nu}$
Status of Rare Kaon Decay Experiments at BNL

Toshio Numao

TRIUMF

June 9, at CAP2003

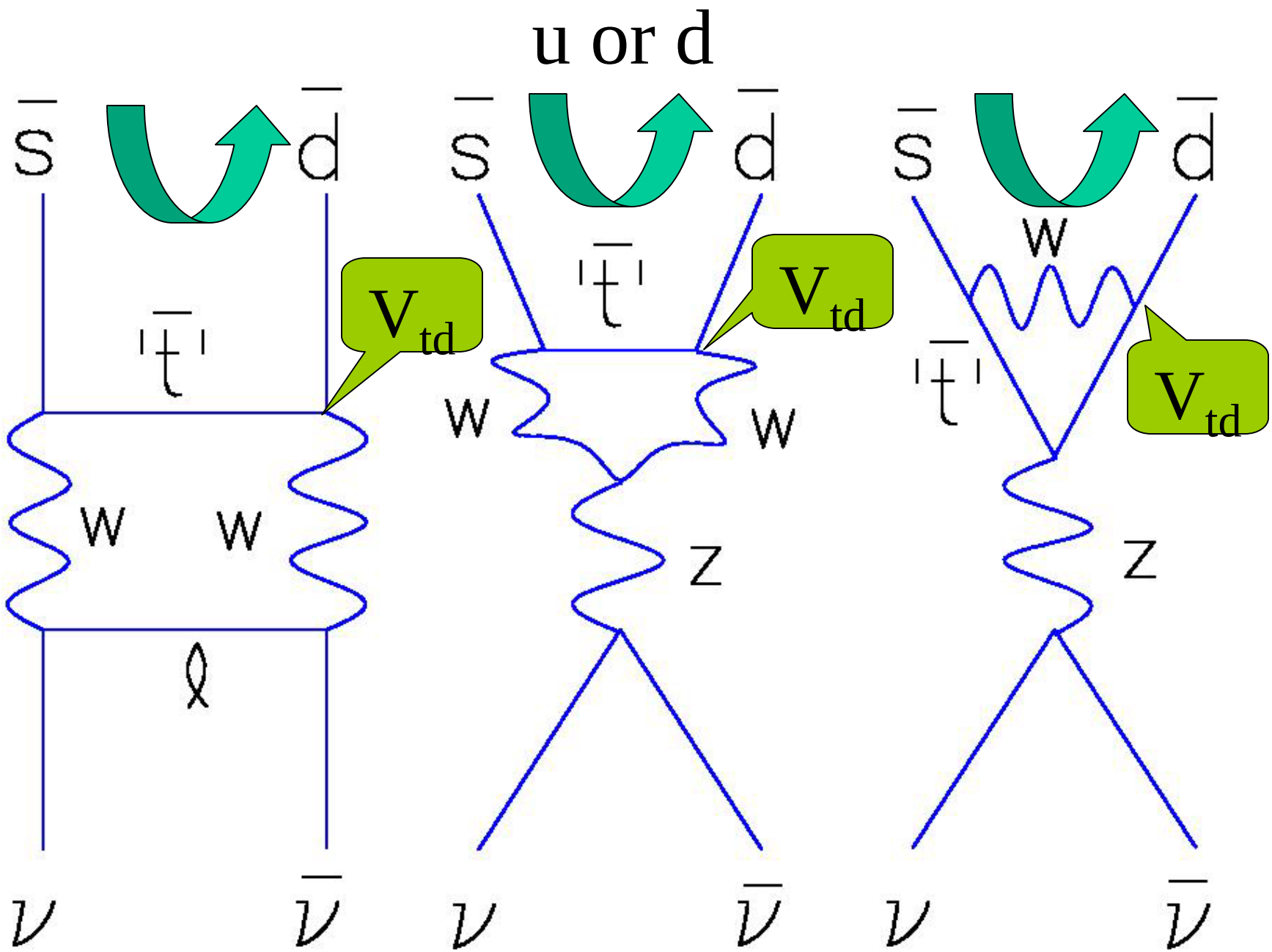
$K \to \pi \nu \bar{\nu}$



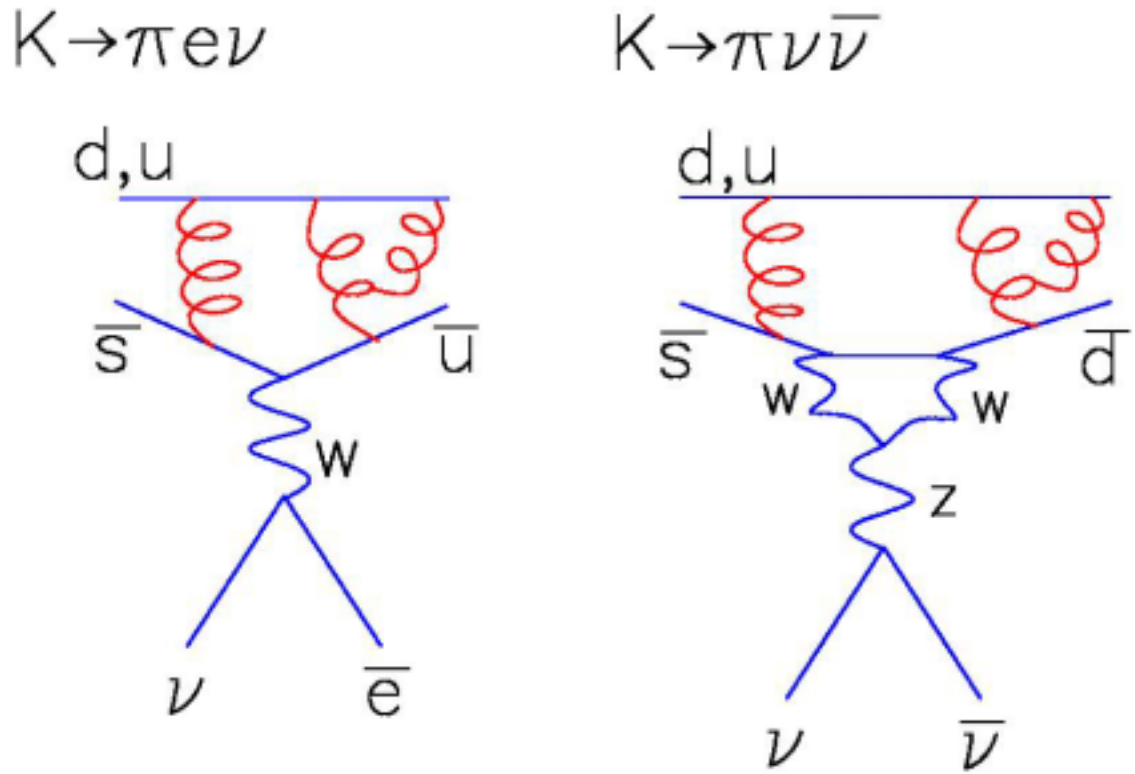
Flavor changing neutral current.

The tree diagram is prohibited by the GIM mechanism.

Second order diagrams are the lowest.


u or d
s̄
d̄
t̄
W
W
ℓ
ν
ν̄
V_td
s̄
d̄
t̄
W
W
Z
ν
ν̄
V_td
s̄
d̄
W
t̄
Z
ν
ν̄
V_td

$K \to \pi\nu\bar{\nu}$ Calculation



$$BR(K^+\to\pi^+\nu\bar{\nu}) = \kappa_+\cdot\left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5}X(x_t)\right)^2+\left(\frac{\mathrm{Re}\lambda_c}{\lambda}P_0(X)+\frac{\mathrm{Re}\lambda_t}{\lambda^5}X(x_t)\right)^2\right]$$

$$BR(K_L\to\pi^0\nu\bar{\nu}) = \kappa_L\cdot\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5}X(x_t)\right)^2$$

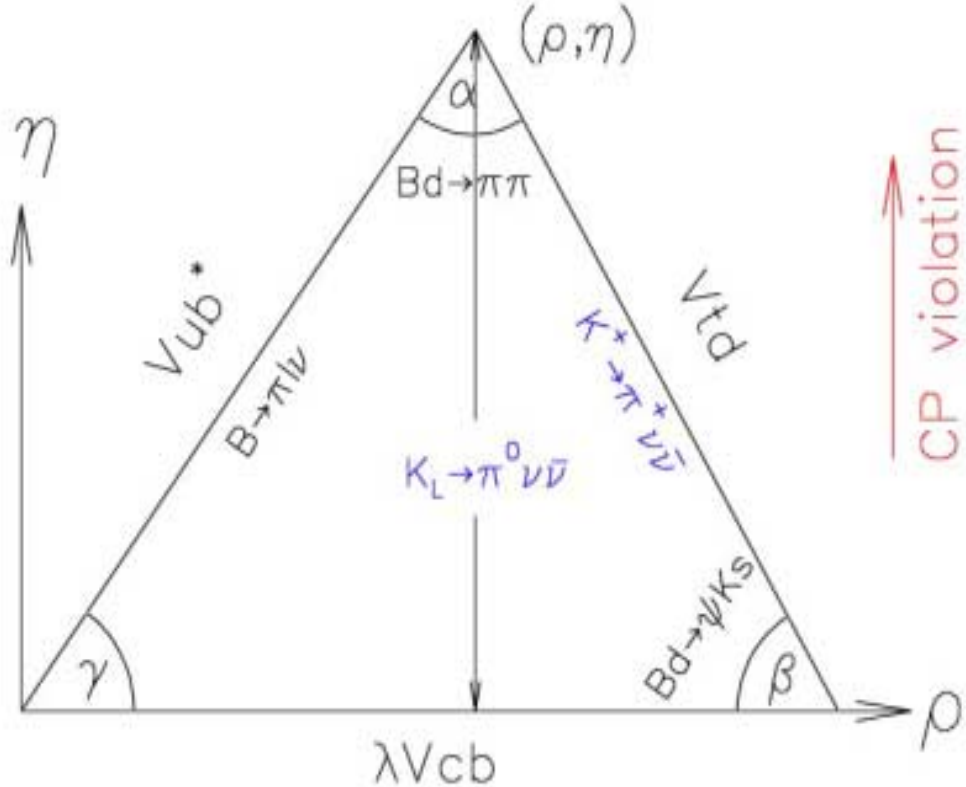
$\kappa_+,\ \kappa_L \propto BR(K^+\to\pi^0e^+\nu)$ $\quad \lambda_j = V^*_{js}V_{jd}$ $(j=u,c,t)$

CKM matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Wolfenstein parametrization

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



Clean modes:

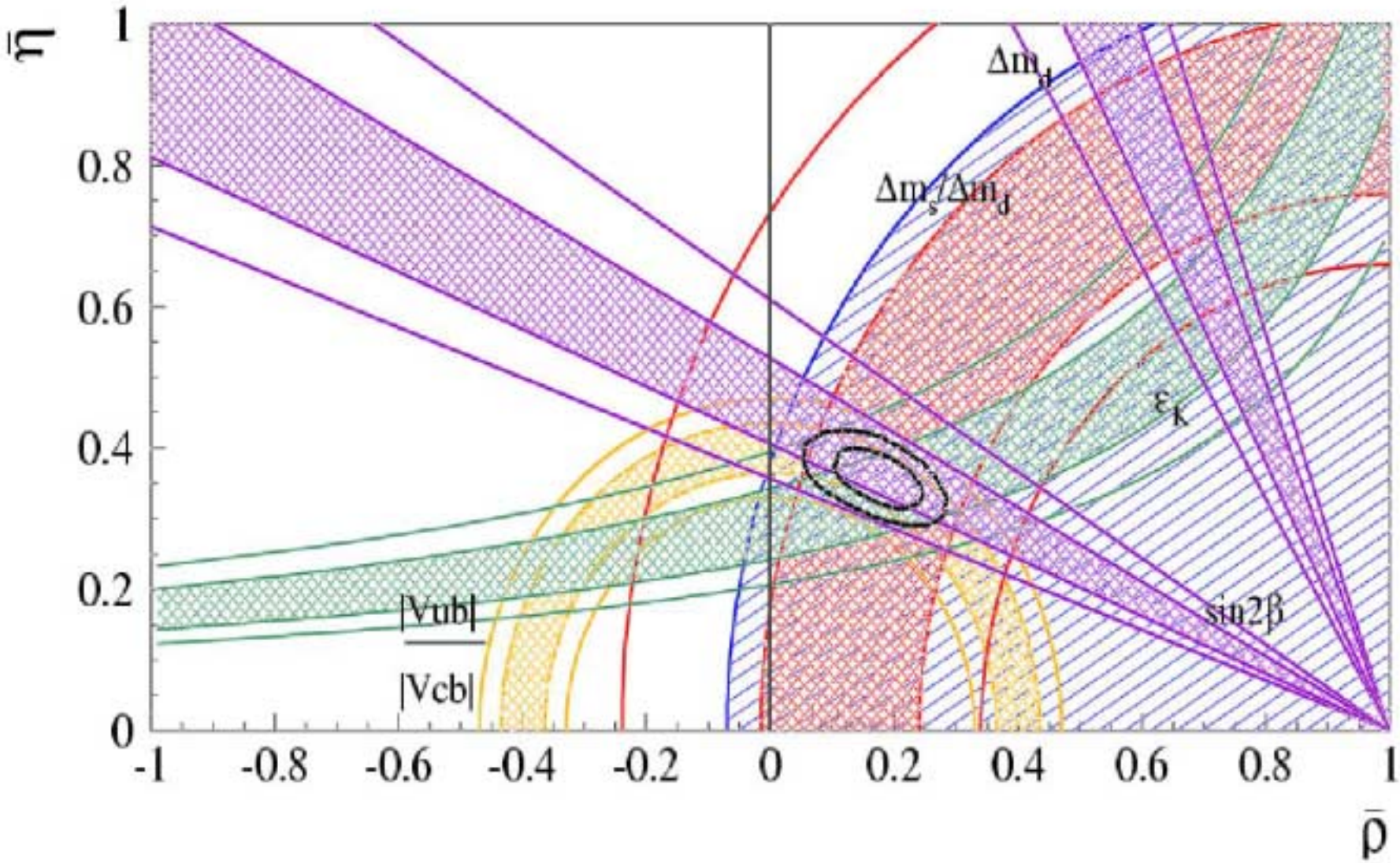
$K^+ \to \pi^+ \nu\bar{\nu}$ *

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

$B_d \to \Psi K_s$ **

$\Delta M_{Bs}/\Delta M_{Bd}$ *

Unitarity triangle in 2002 by Isidori



Param.	$K \to \pi \nu \bar{\nu}$	$B_{factory}$	LHC_B
$\lvert V_{td} \rvert$	10 %	5.5 %	5.0 %
ρ	0.16	0.03	0.01
η	0.04	0.04	0.01
$\sin 2\beta$	0.05	0.06	0.02
$\mathrm{Im}\,\lambda_t$	5 %	14 %	10 %

$\|\|$

$\mathrm{Im}(V^*_{ts} V_{td})$: $J = 2 \cdot \Delta = -\mathrm{Im}(V_{ud} V^*_{us} V^*_{ts} V_{td})$

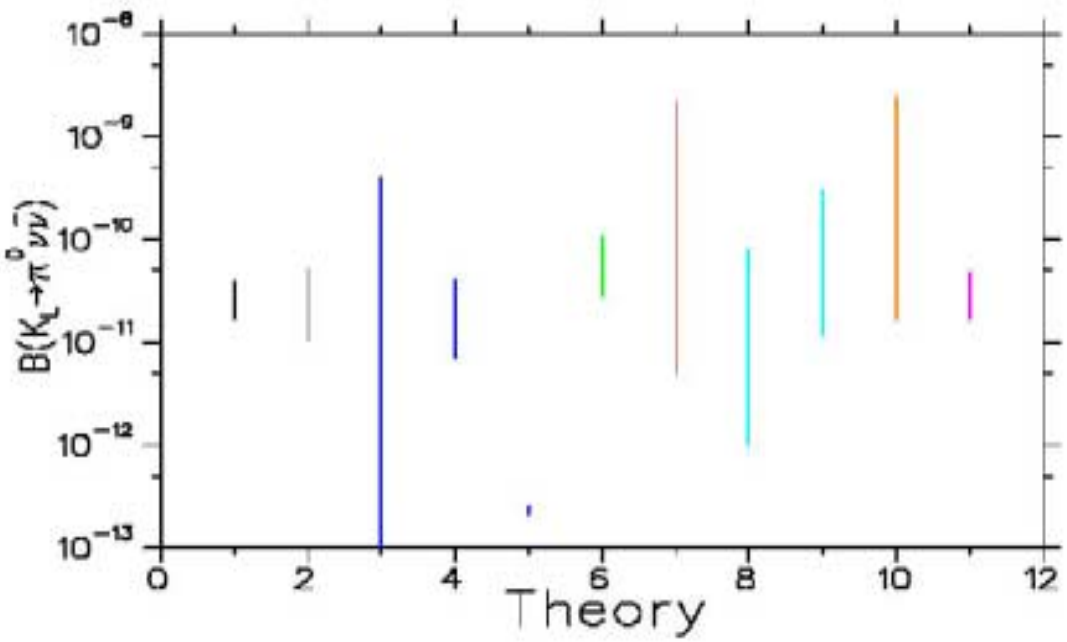
(Jarlskog invariant)

A.J. Buras, hep-ph/9905437

$K_L \to \pi^0 \nu\bar{\nu}$ Beyond the Standard Model

	Who	What	$10^{11} B(K_L \to \pi^0 \nu\bar{\nu})$
1	Buchalla	Standard Model CKM fit	2.8 ± 1.1
2	Plaszczynski/Schune	Conservative SM fit	$1-5$
3	Buras, *et al.*	Generic SUSY w/min. part. content	$0-40$
4	Buras, *et al.*	MSSM w/o new flavor or CP viol.	$(0.41-1.03)\times$ SM
5	Brhlik, *et al.*	all CP-viol. due to SUSY	$\sim .023$
6	Chanowitz	$SU(2)_L \times SU(2)_R$ Higgs	$2.8-10.6$
7	Hattori, *et al.*	4th generation	$0.5-220$
8	Xiao, *et al.*	top-color assisted technicolor	$0.1-8$
9	Xiao, *et al.*	multiscale walking technicolor	$1.2-30$
10	Grossman/Nir	Extra "vector-like" quarks	$1.7-240$
11	Kiyo, *et al.*	seesaw L-R model†	$(1-1.2)\times$ SM

† predicts spectrum will be altered.



Collaborations

E787

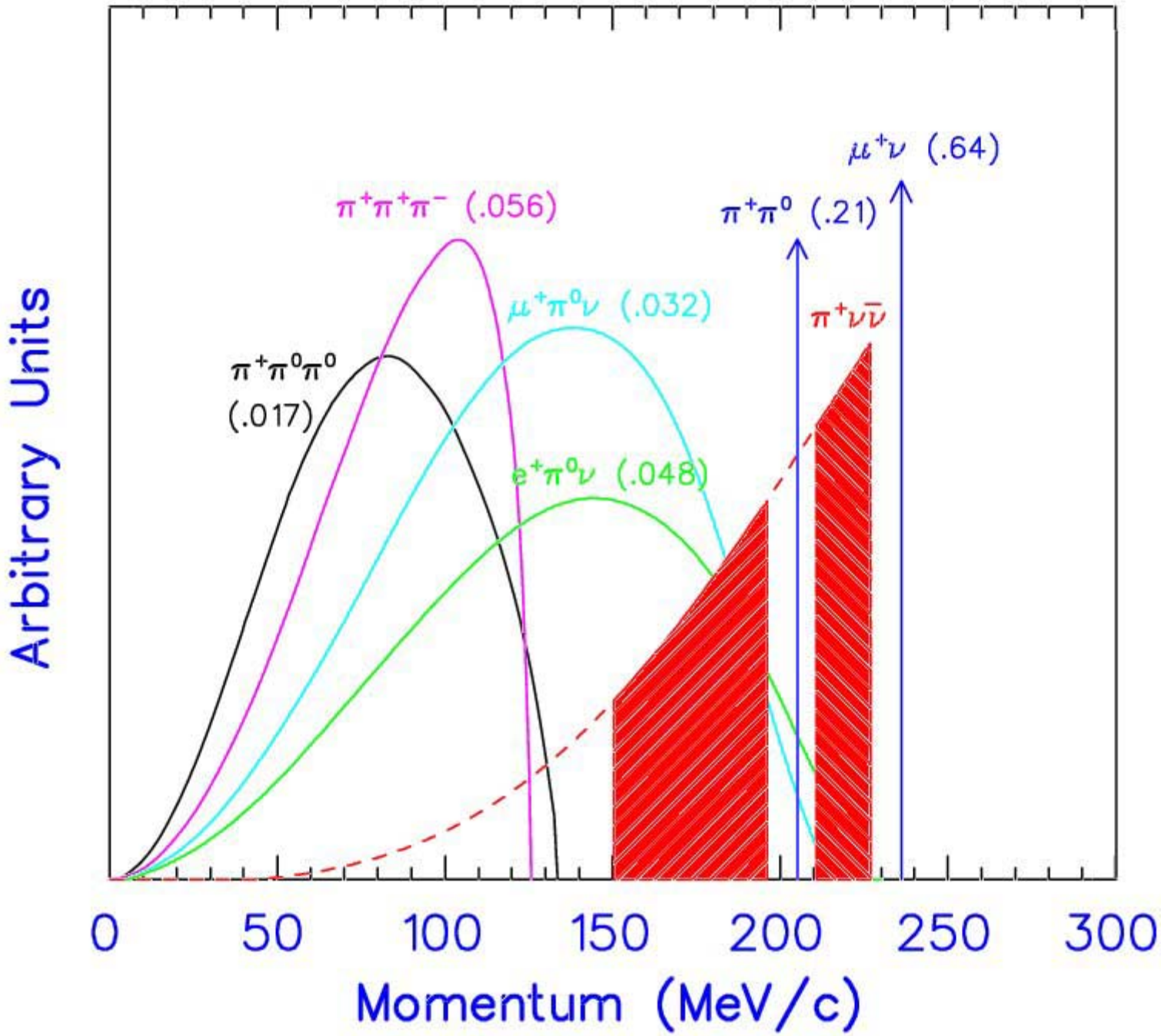
BNL, Fukui, KEK, Osaka,
Princeton, TRIUMF

E949

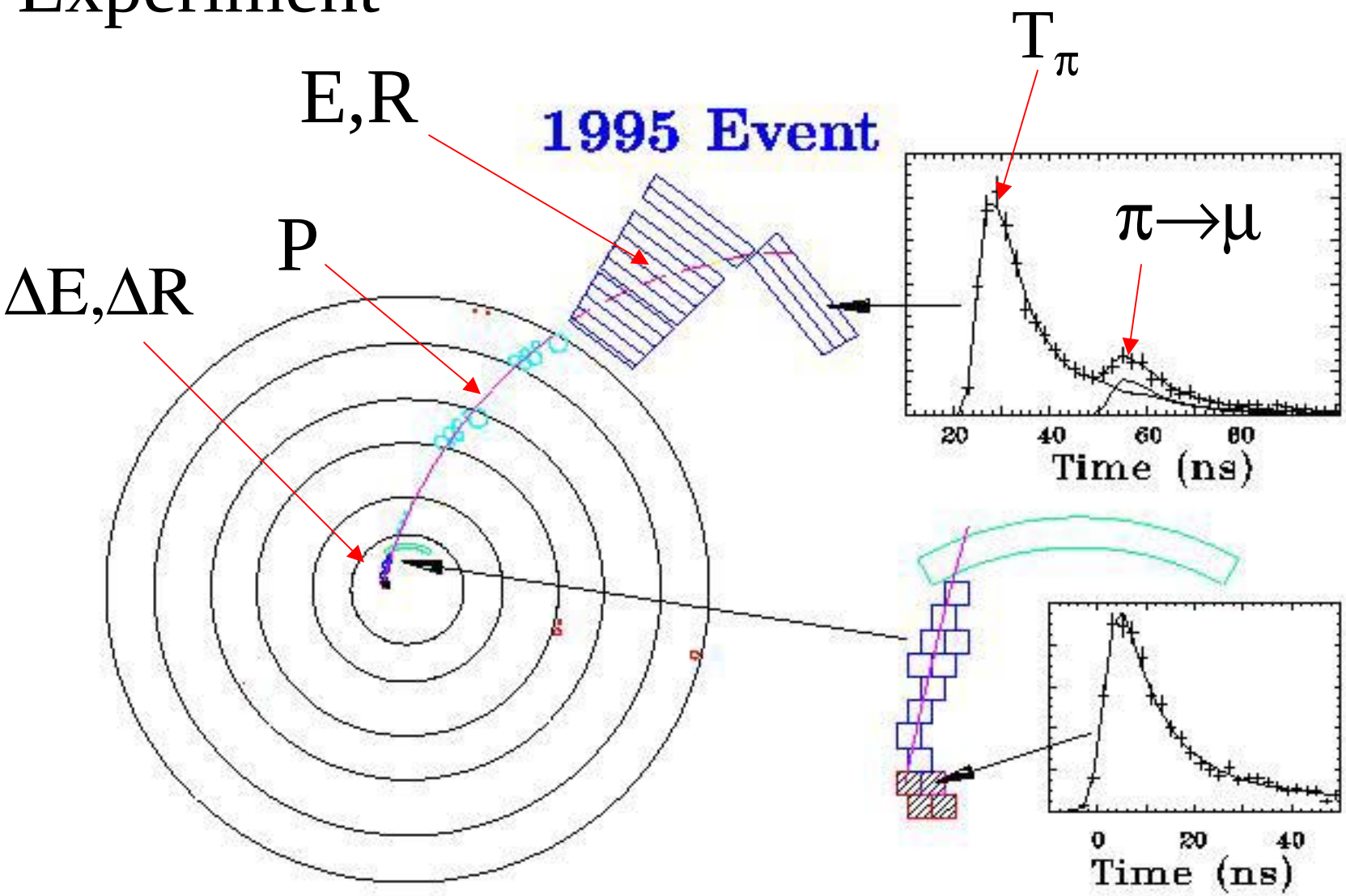
BNL, Fukui, FNAL, INR, KEK,
Kyoto, NM, Osaka, TRIUMF

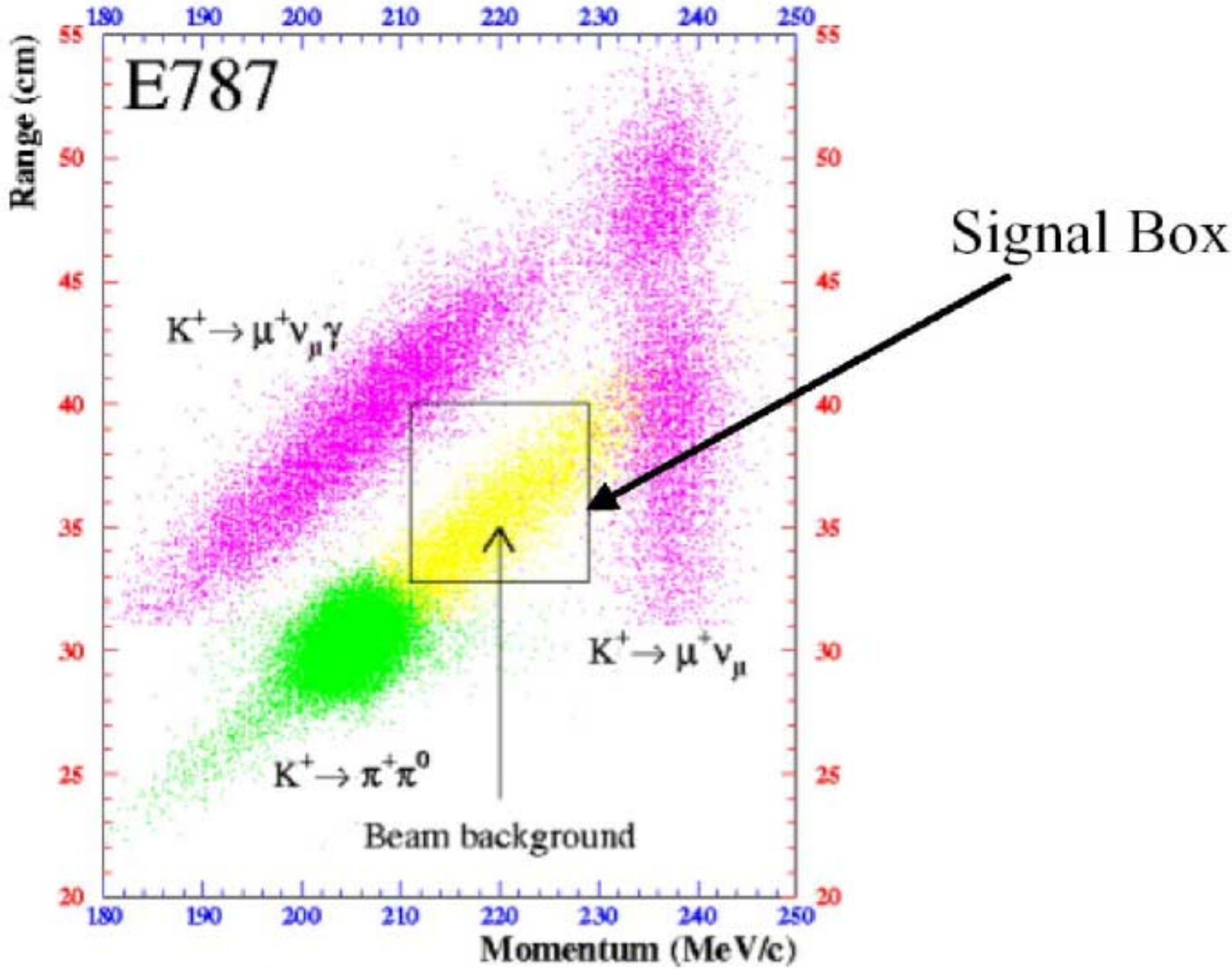
KOPIO

BNL, INR, Kyoto, NM, Perugia,
SUNY, TJNAF, TRIUMF, VPI, Yale


$\mu^+\nu$ (.64)
$\pi^+\pi^+\pi^-$ (.056)
$\pi^+\pi^0$ (.21)
$\mu^+\pi^0\nu$ (.032)
$\pi^+\nu\bar{\nu}$
$\pi^+\pi^0\pi^0$
(.017)
$e^+\pi^0\nu$ (.048)
Arbitrary Units
0
50
100
150
200
250
300
Momentum (MeV/c)

Experiment




E787
Range (cm)
Momentum (MeV/c)
$K^+ \to \mu^+ \nu_\mu \gamma$
$K^+ \to \mu^+ \nu_\mu$
$K^+ \to \pi^+ \pi^0$
Beam background
Signal Box

Analysis strategy

To avoid a bias:

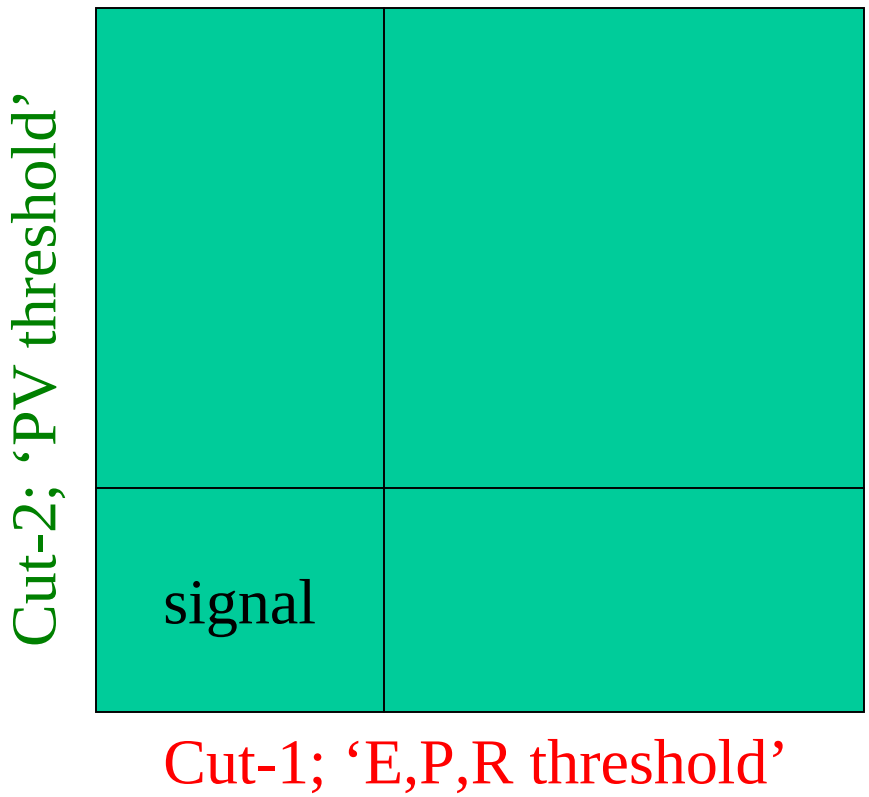
First, fix the cuts and estimate the background.

Use data as much as possible in the background estimates.

Bifurcated BG analysis.

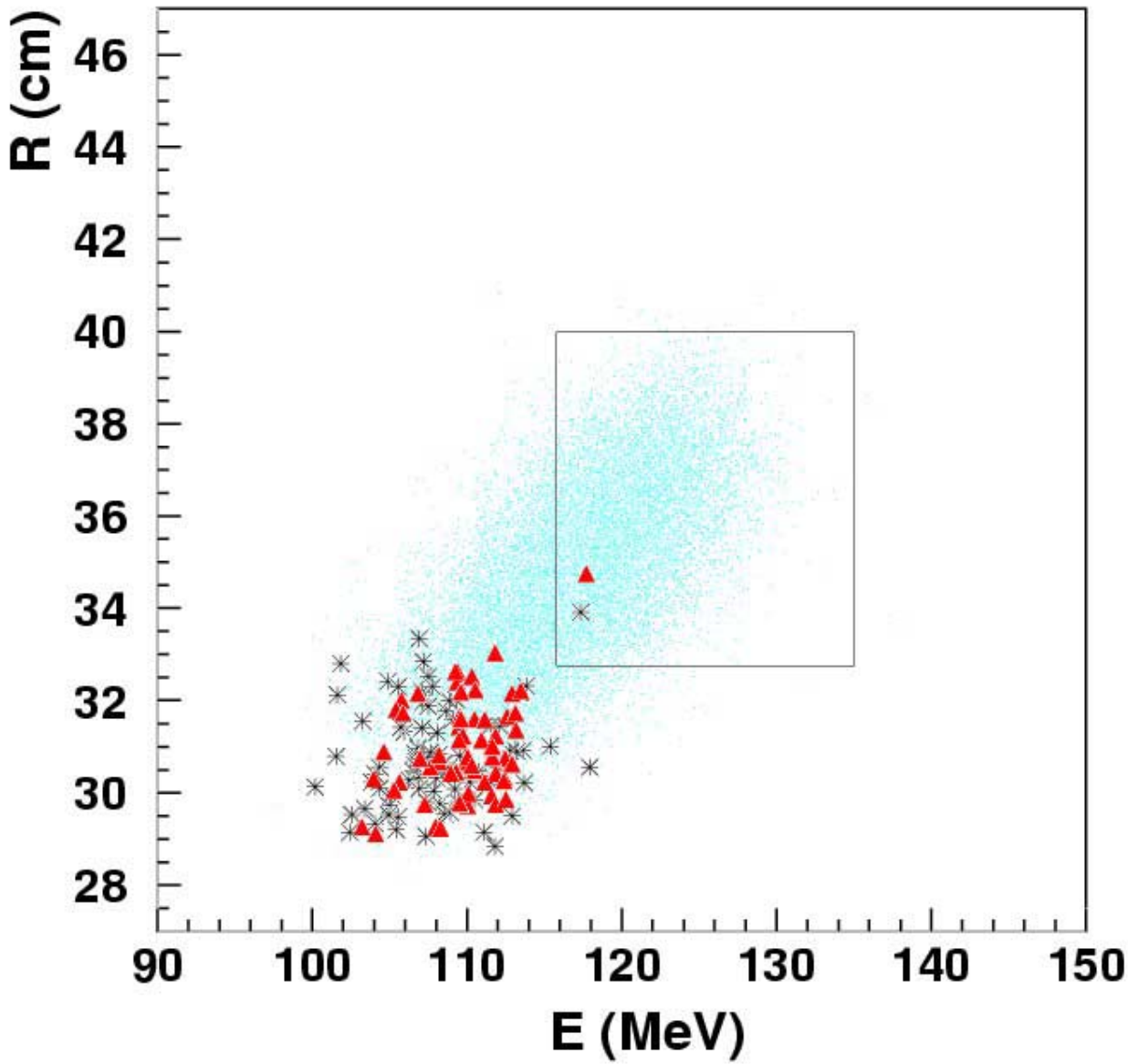
Study the correlation.

Open the “box”.



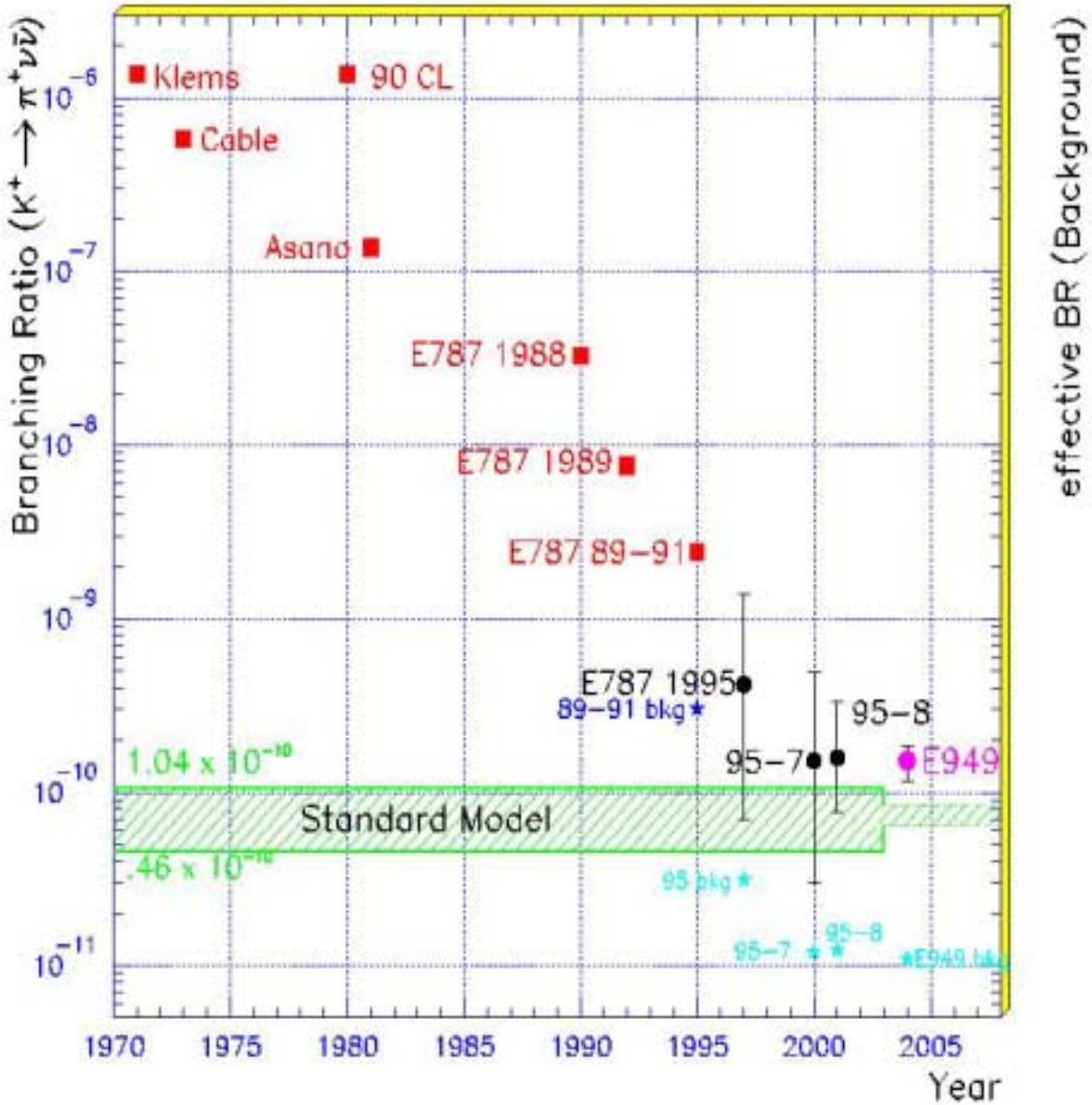
$K_{\pi 2}$: 1=Kinematics 2=photon veto

BG Proc.	95–97	98
$K_{\pi 2}$	0.03	0.034
$K_{\mu 2}$	0.02	0.012
Beam	0.02	0.004
$K^+ \to K_L$	0.01	0.016
ϵ (%)	0.21	0.20
$K^+ (10^{12})$	3.2	2.7



final result: $1.57^{+1.72}_{-0.82} \times 10^{-11}$

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



E949 Improvements

More protons

Beam duty factor

Faster trigger decision

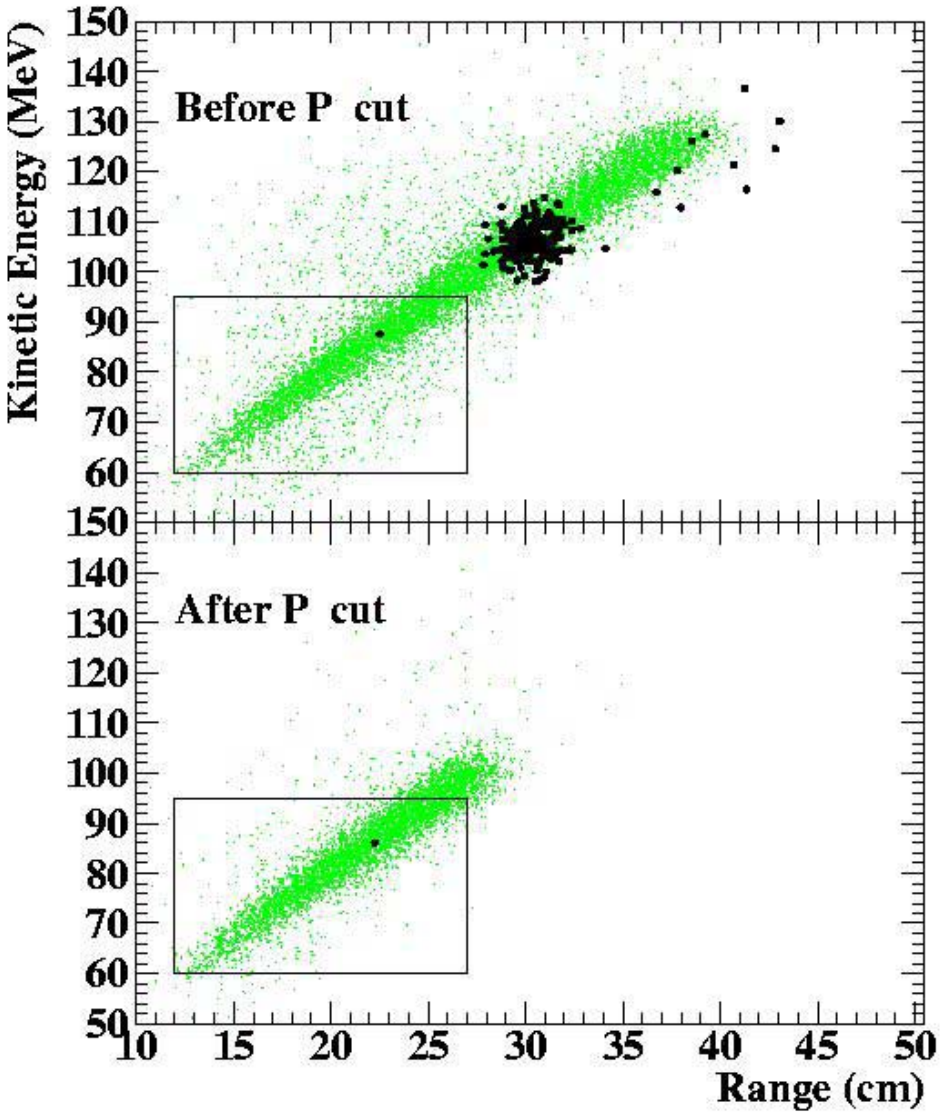
Move PV capability

for the region below $K_{\pi 2}$

Better Z resolutions

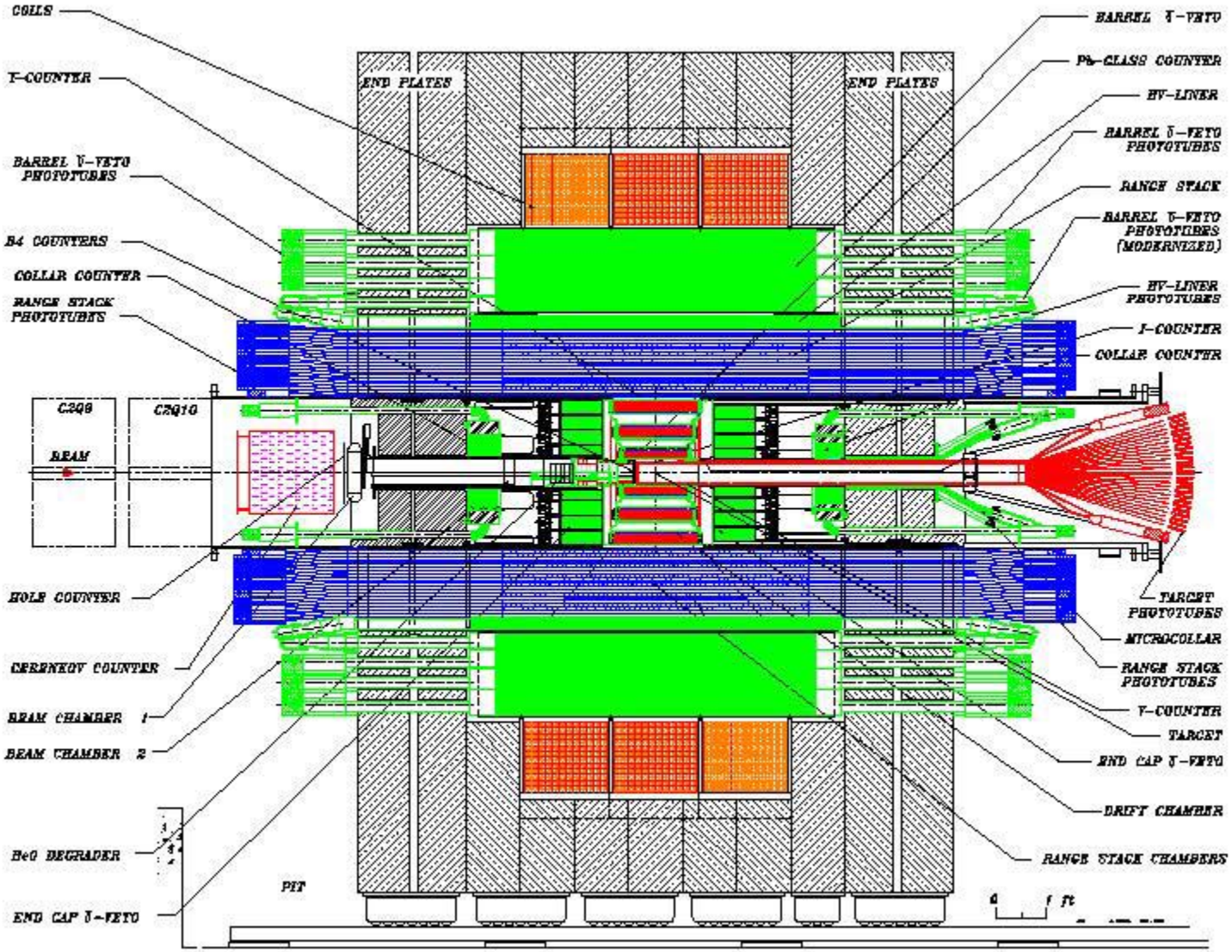
New beam counters

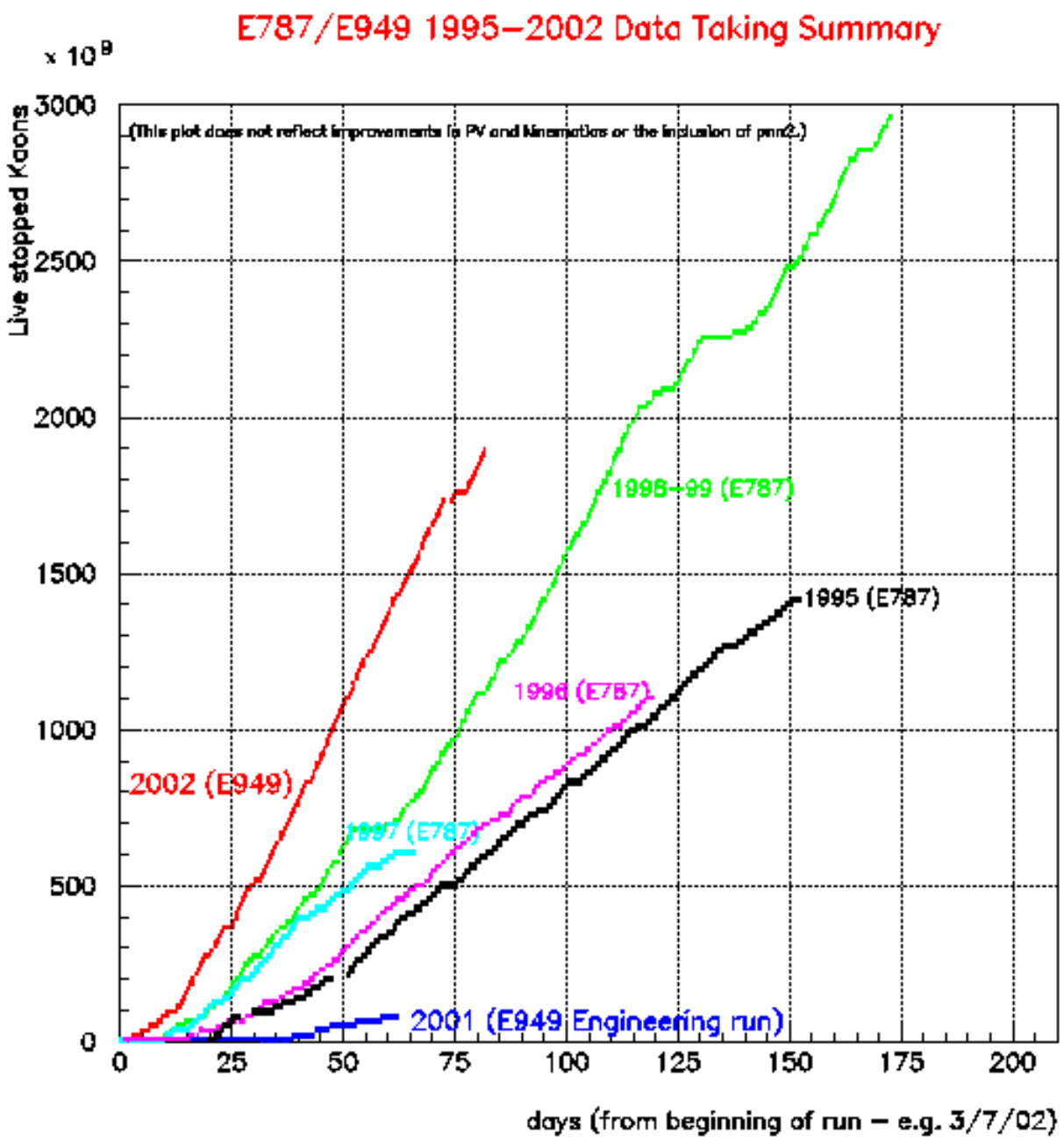
LED monitor



Total improvement factor: 6-12

E949 Detector



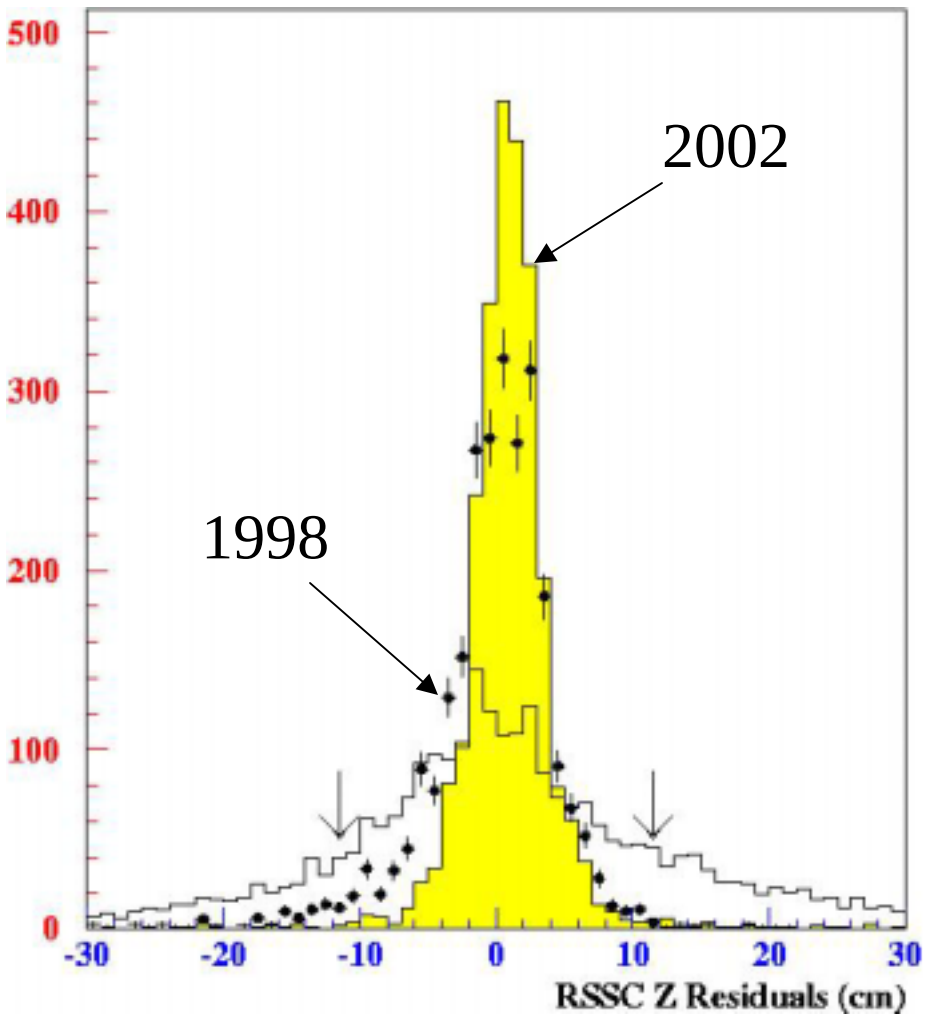

E787/E949 1995–2002 Data Taking Summary
x 10^9
Live stopped Kaons
(This plot does not reflect improvements to PV and kinematics or the inclusion of pnn2.)
3000
2500
2000
1500
1000
500
0
0
25
50
75
100
125
150
175
200
1998–99 (E787)
1995 (E787)
1996 (E787)
2002 (E949)
1997 (E787)
2001 (E949 Engineering run)
days (from beginning of run – e.g. 3/7/02)

Run Summary

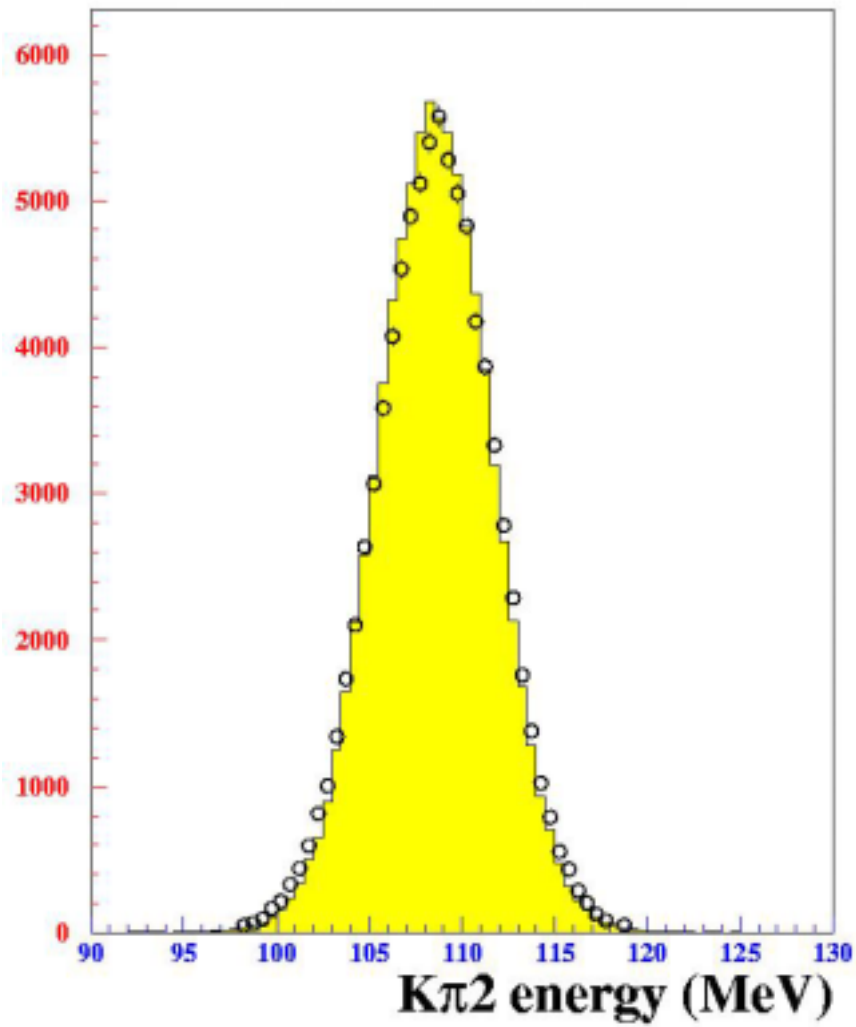
	1995	1998	2002	E949
AGS(GeV)	24	24	21.5	24
spill(s)	1.4	2.2	2.2	4.1
DF(%)	41	49	41	64
P_K(MeV/c)	790	710	710	~710
K/s(MHz)	0.81	0.97	1.57	~1.6
K/π	3.8	4.0	3.1	4.0
LT	0.76	0.81	0.74	0.85
$N_K/y(10^{12})$	1.55	2.90	1.90	~10

Improvements

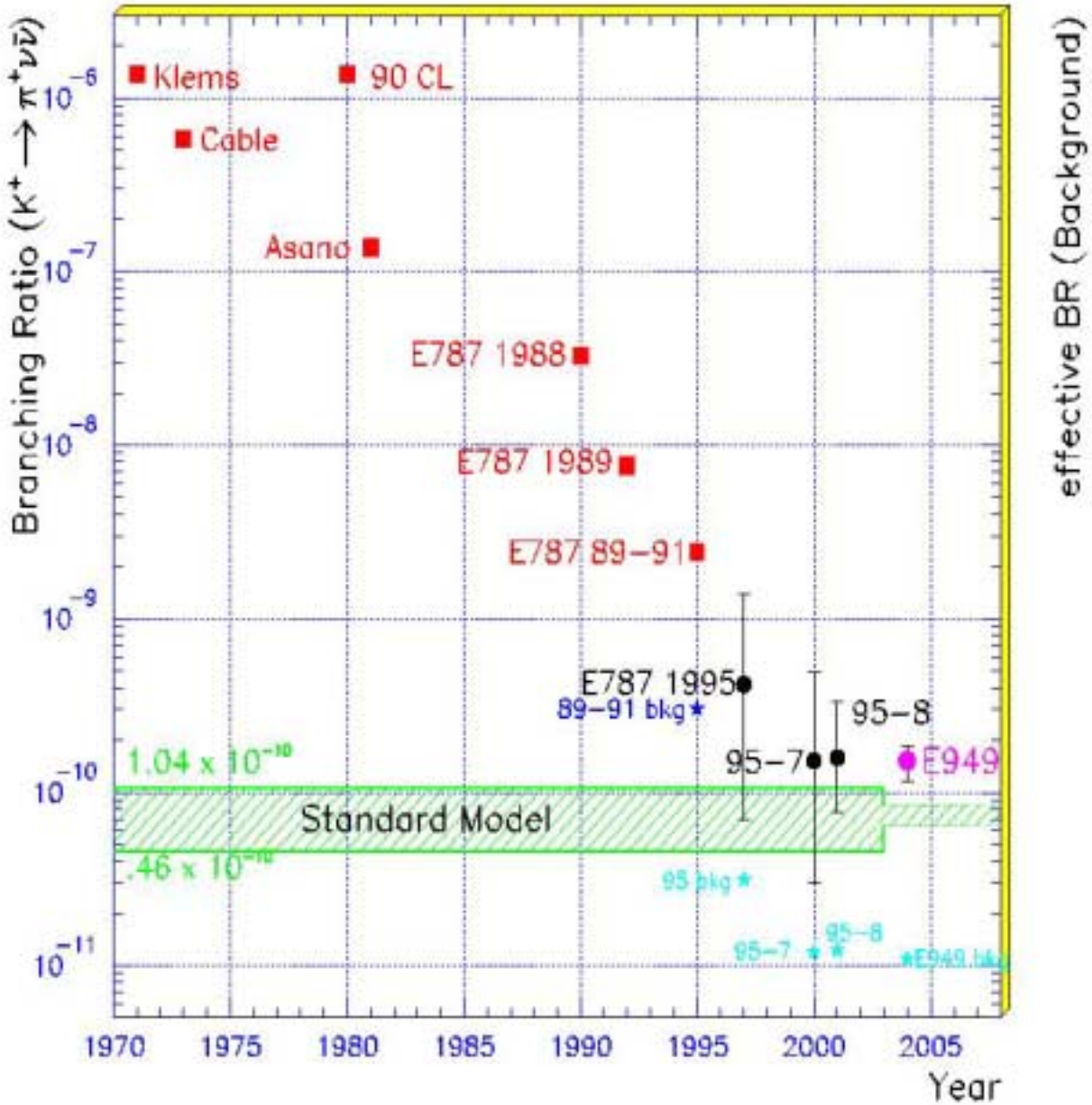
RS chamber Z resolution



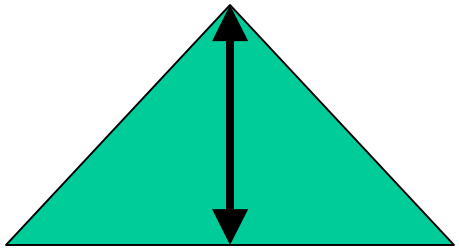
Energy resolution



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



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



cp $\quad - \quad + \quad\quad +$

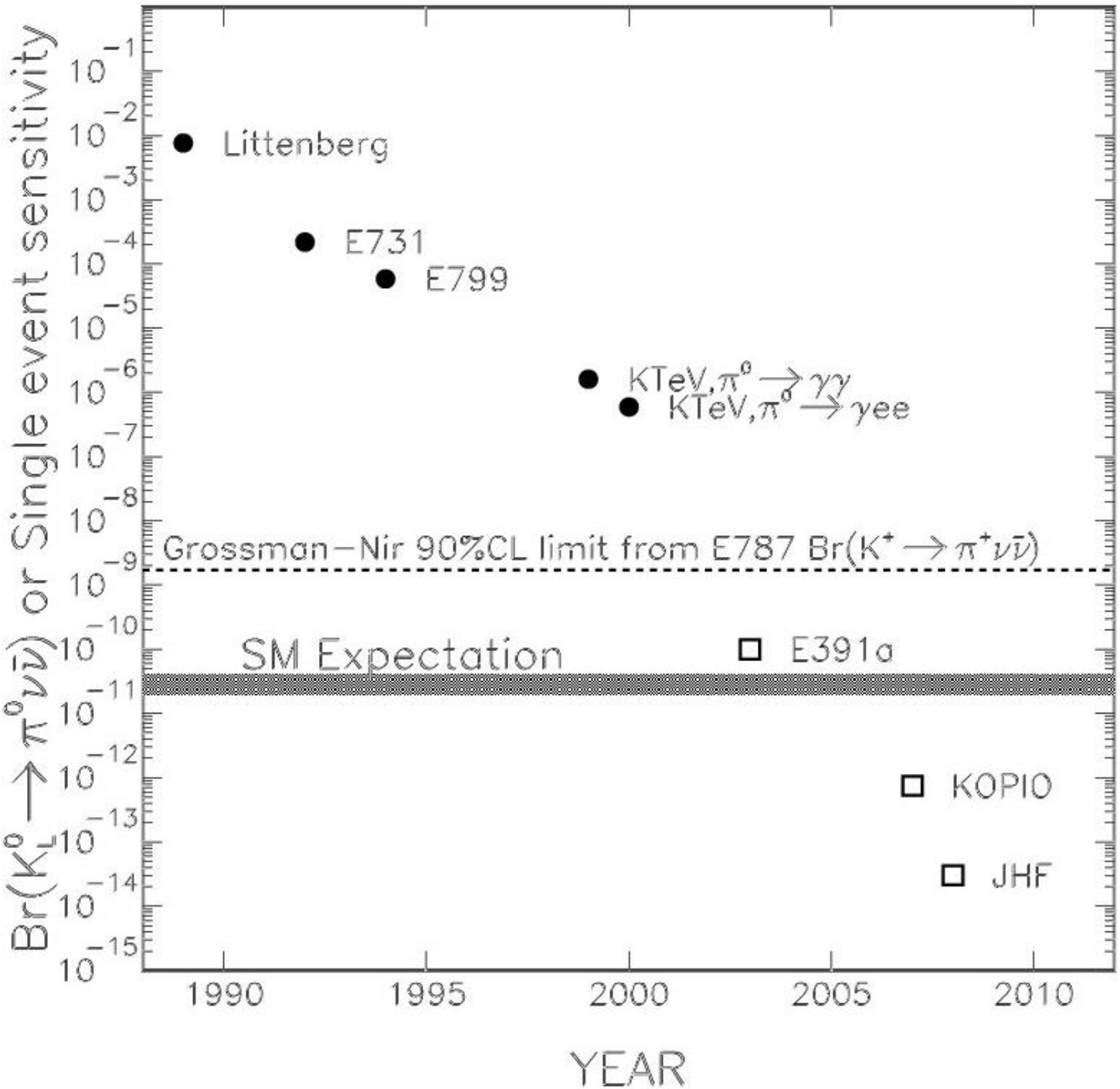
$$K_L = K_2 + \epsilon K_1 \to \pi^0 \nu \bar{\nu}$$

mixing $\sim 10^{-15}$

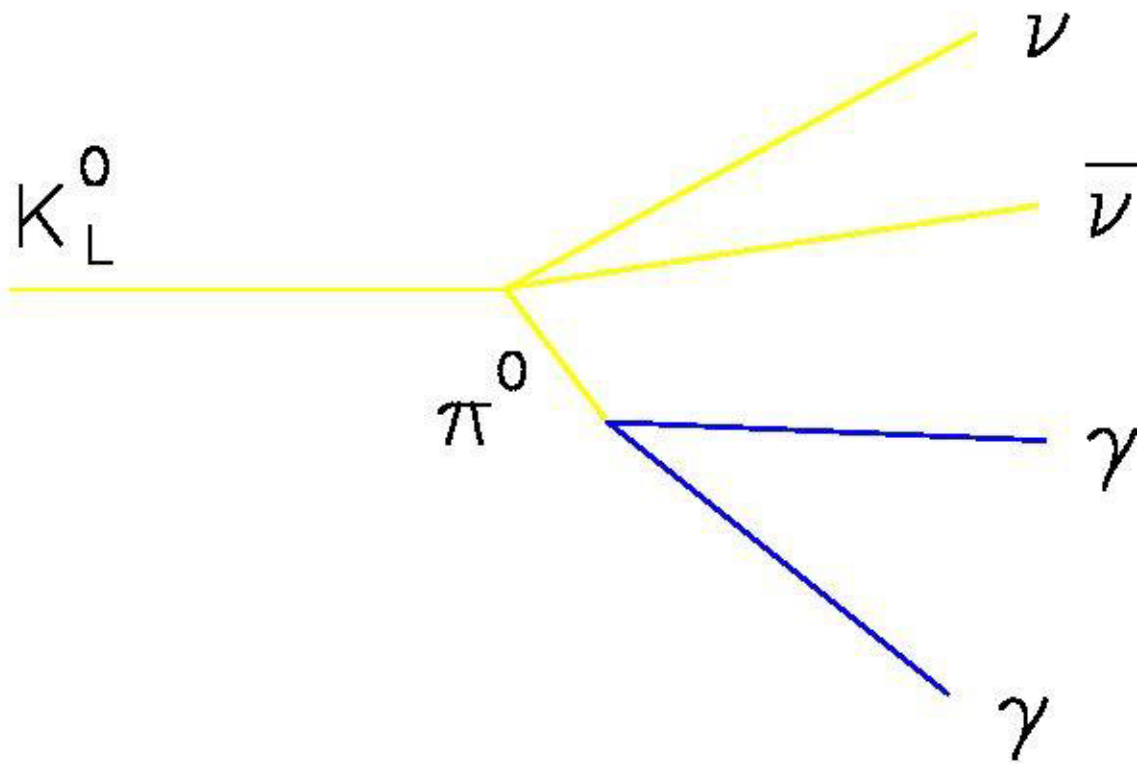
decay $\sim 3 \times 10^{-11}$

Previous search: 5.9×10^{-7}

KOPIO goal: 10^{-12} s.e.s, >50 events

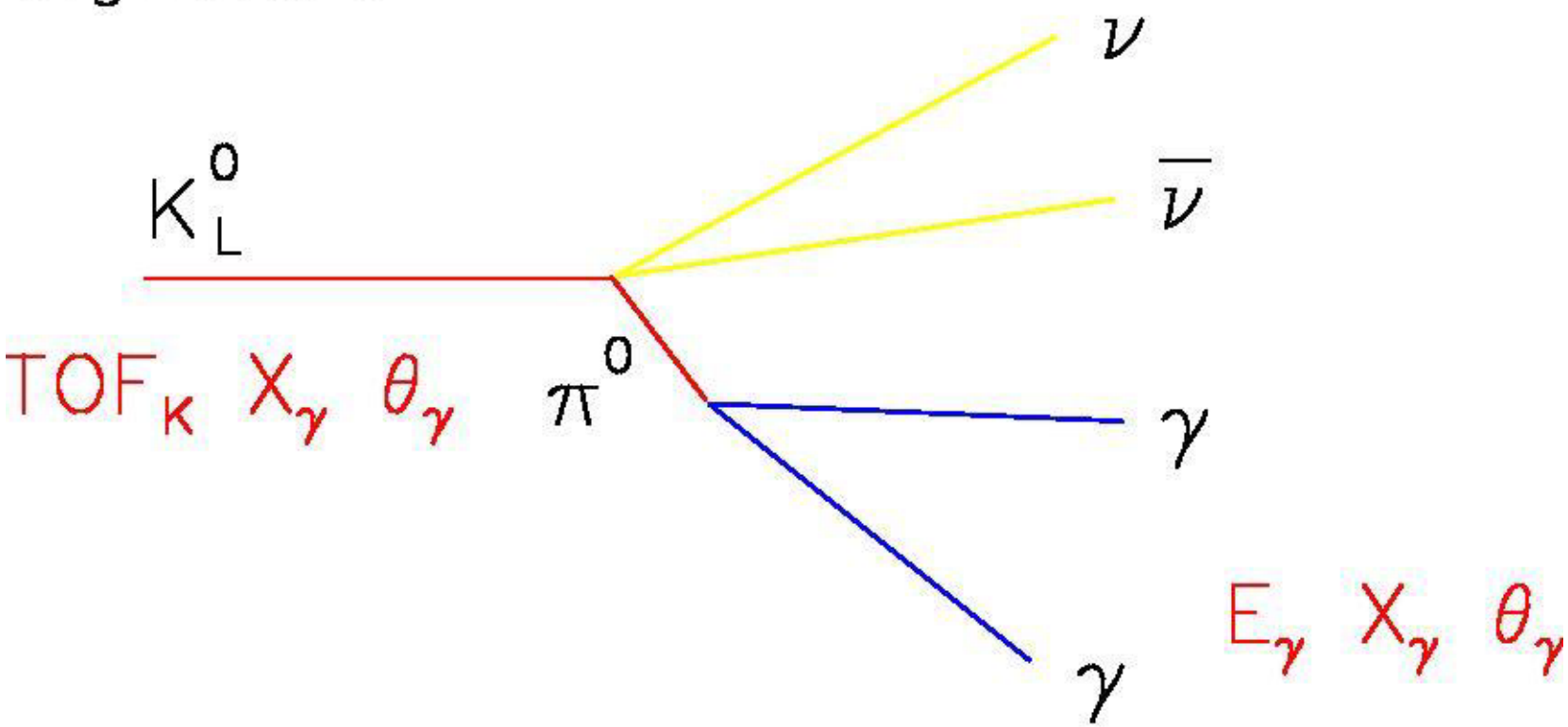

Br($K_L^0 \to \pi^0 \nu\bar{\nu}$) or Single event sensitivity
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
Littenberg
E731
E799
KTeV, $\pi^0 \to \gamma\gamma$
KTeV, $\pi^0 \to \gamma ee$
Grossman−Nir 90%CL limit from E787 Br($K^+ \to \pi^+ \nu\bar{\nu}$)
SM Expectation
E391a
KOPIO
JHF
1990
1995
2000
2005
2010
YEAR

Signature



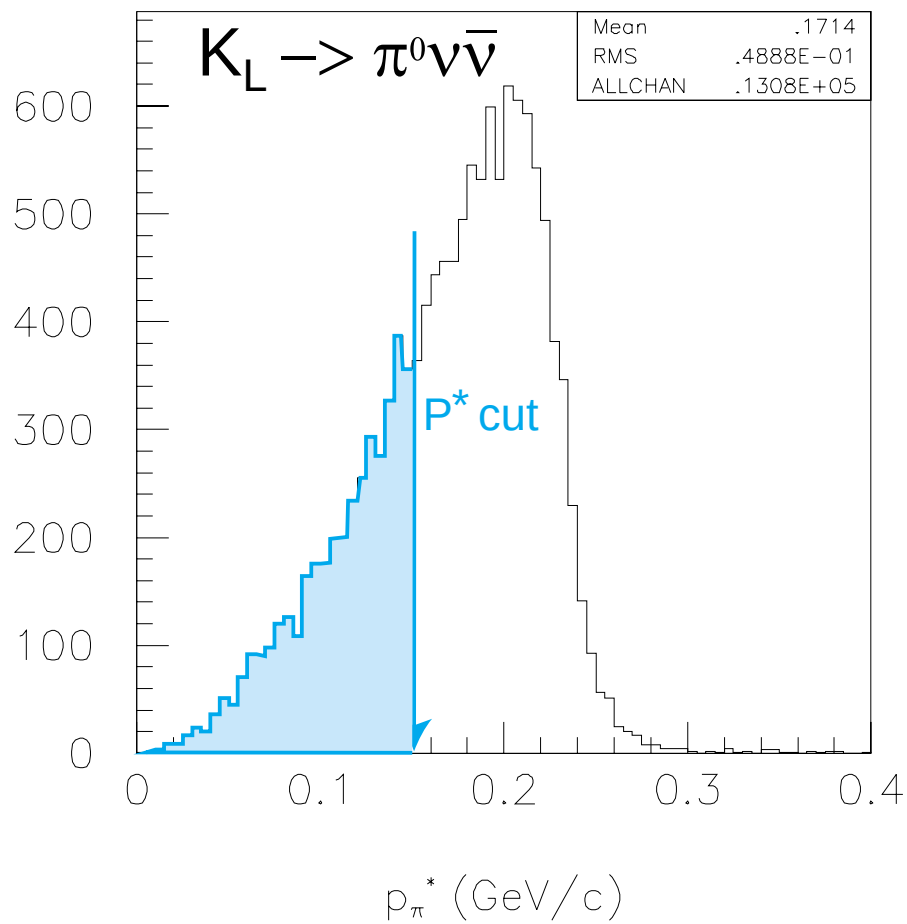
- 2 γ's
- No other activity

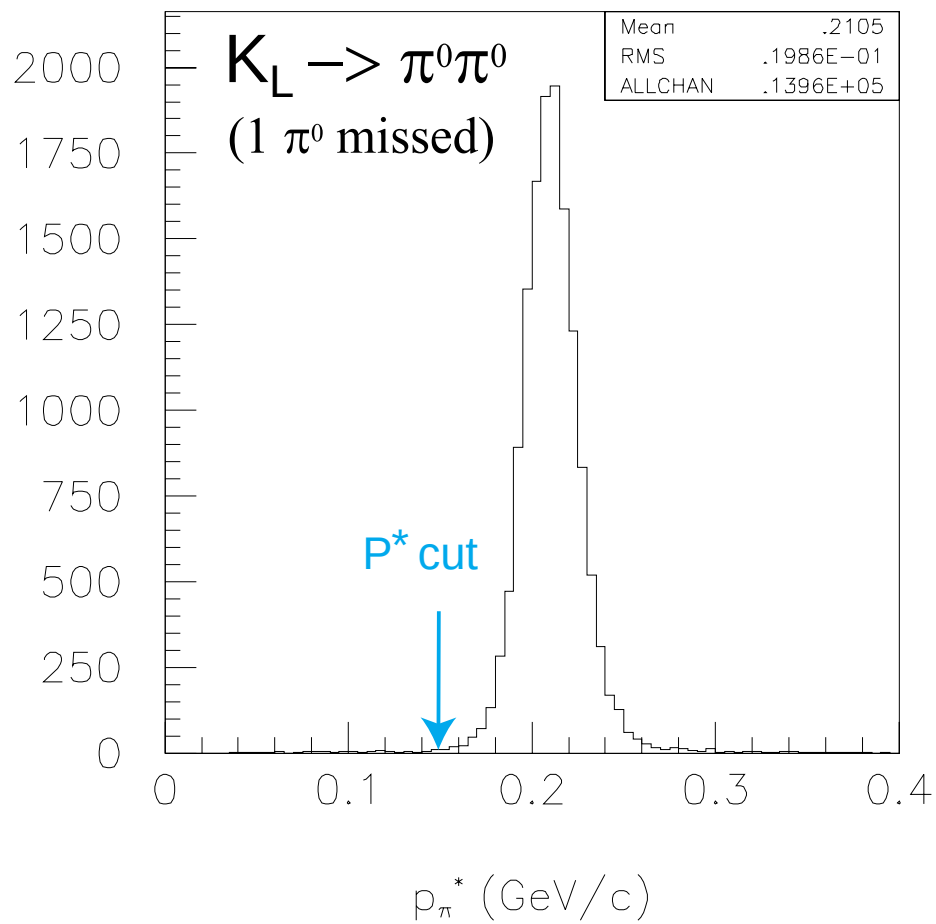
Signature



- 2 γ's
- No other activity

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

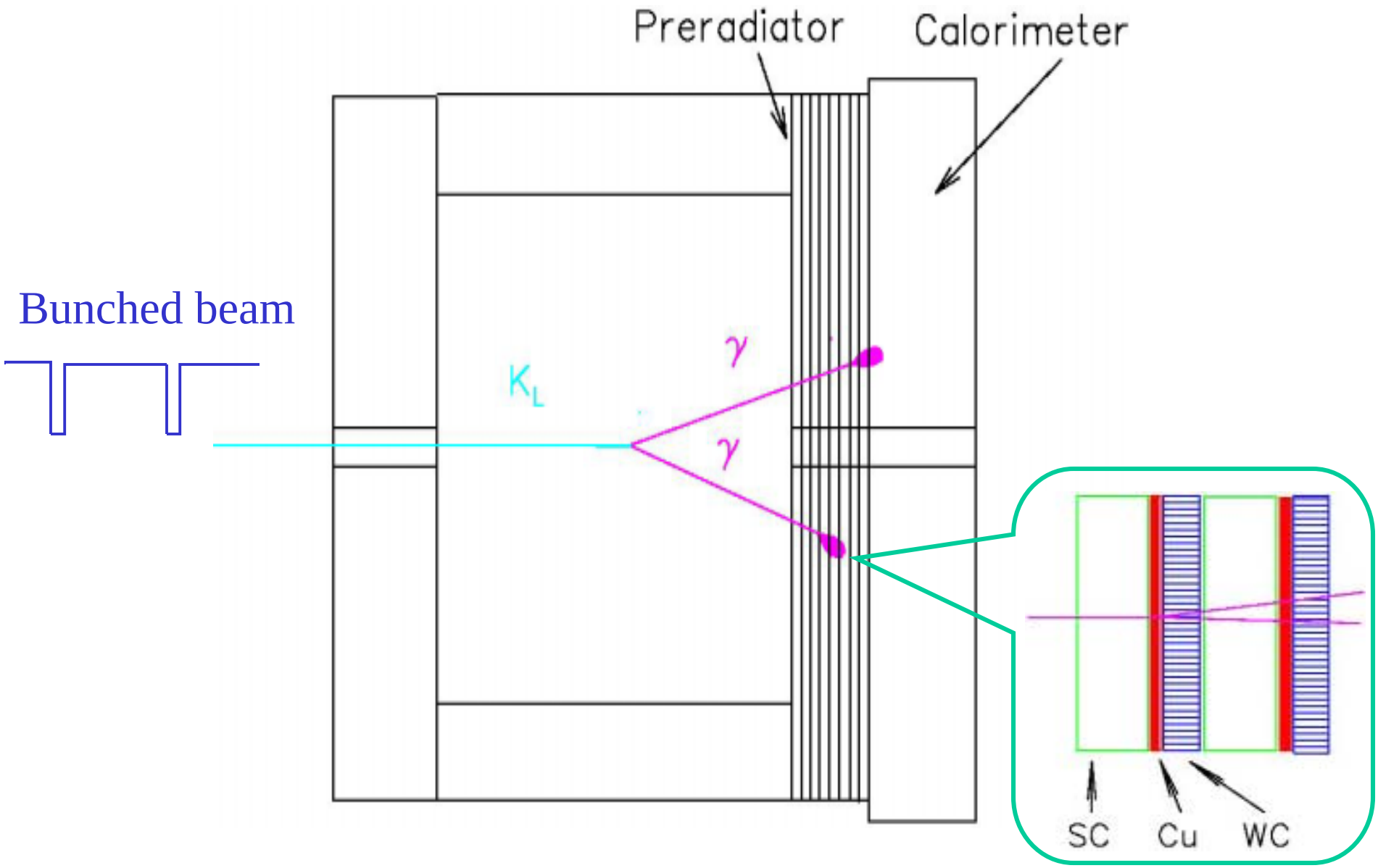




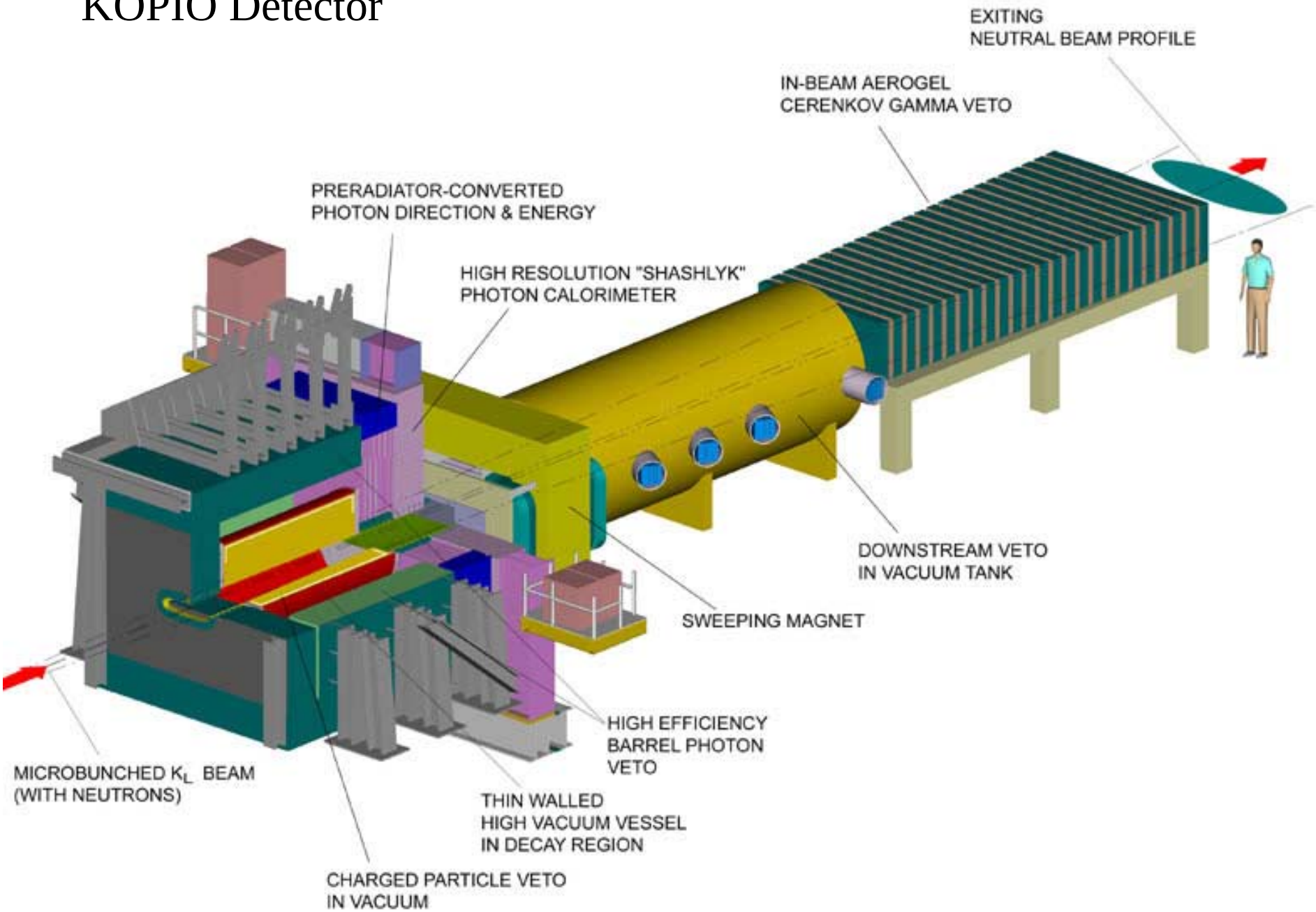
KOPIO Requirements

Parameters	Req.	Expected
ΔE_γ $(E_\gamma^{-1/2})$	3.5 %	2.7 %
$\Delta\theta_\gamma$ (250MeV)	25−30 mr	23 mr
Δt_γ $(E_\gamma^{-1/2})$	100 ps	50 ps
$\Delta x_\gamma, \Delta y_\gamma$	1.0 cm	<0.1 cm
Bunch width	300 ps	200 ps
$\bar{\gamma}$ ineff.	$\bar{\epsilon}_{E787}$	$0.3 \cdot \bar{\epsilon}_{E787}$

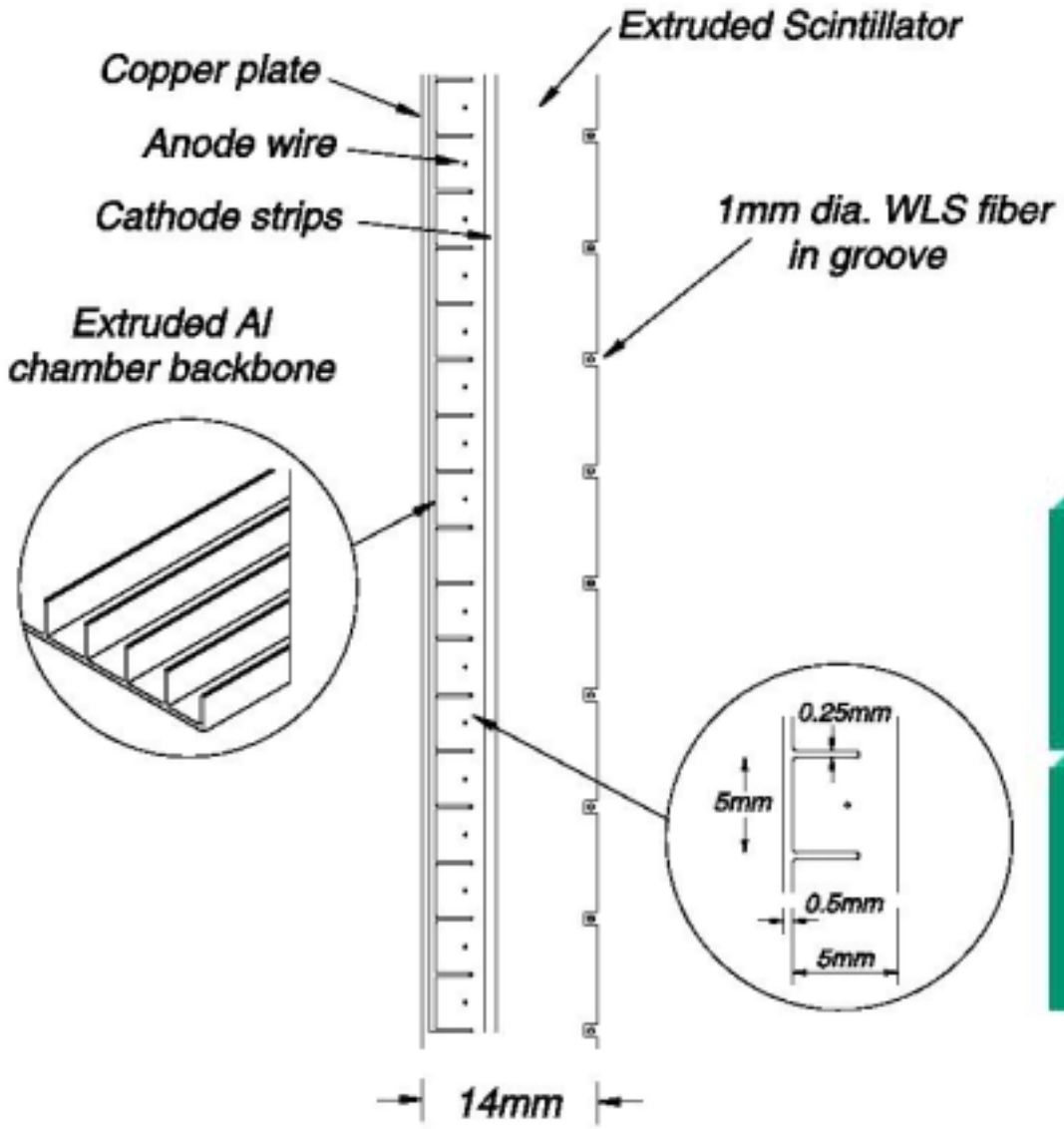
Detection concept

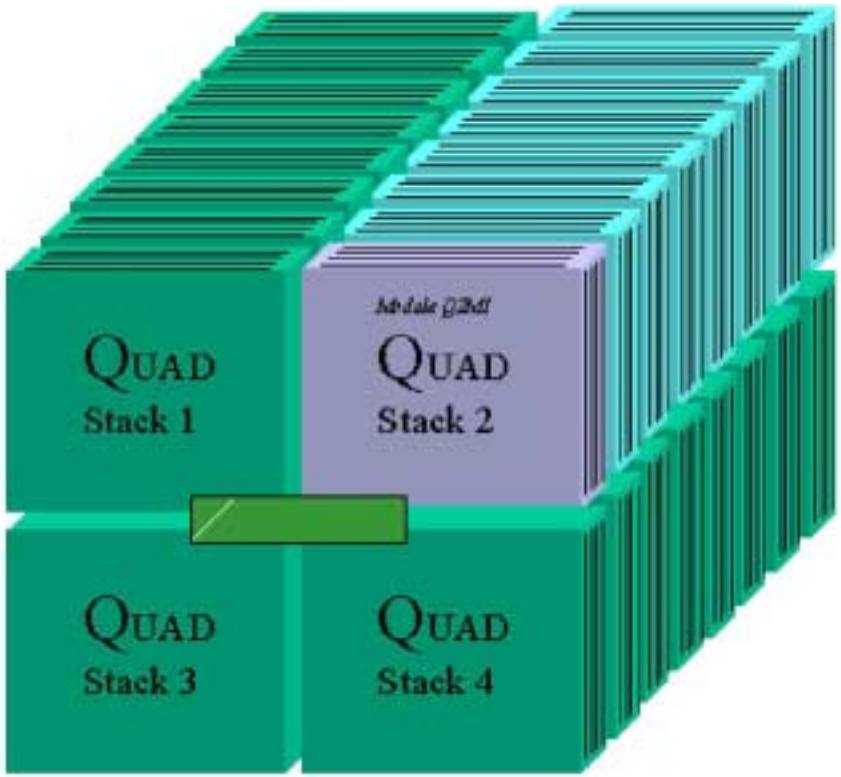


KOPIO Detector



Pre-radiator





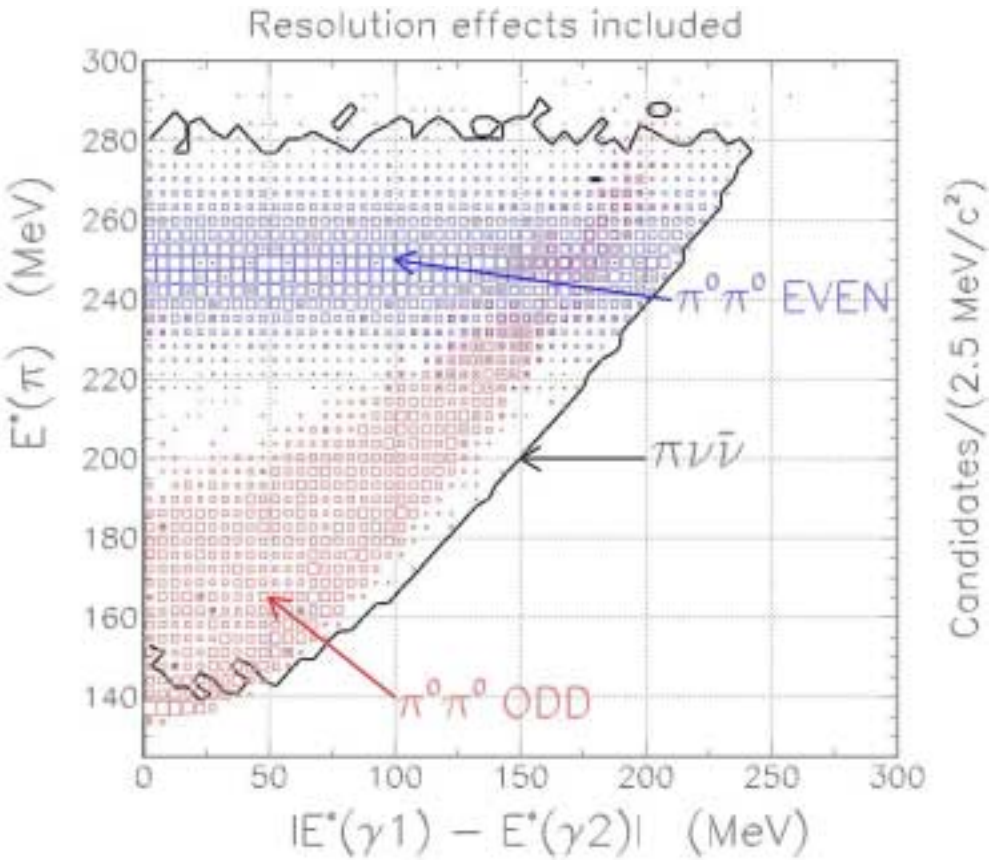
Background sources from K decays

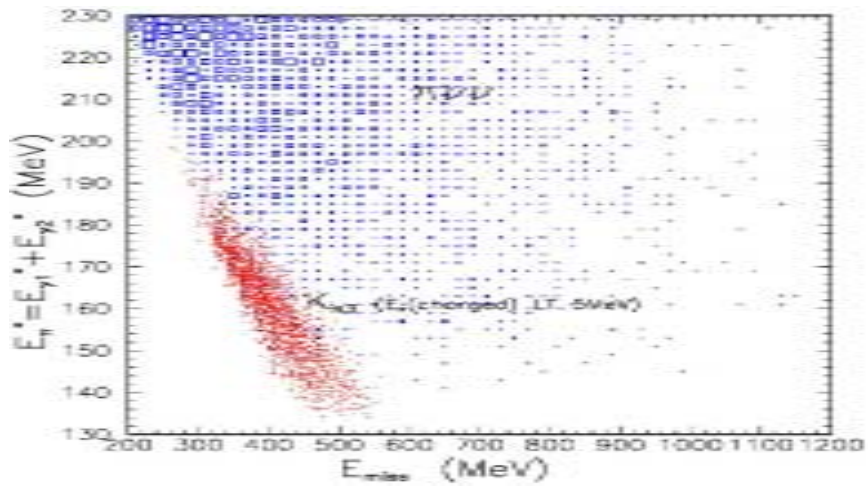
K_L^0 Decay	$\mathcal{B}/3\times10^{-11}$	Kinematic	Photon veto	Charged veto
$\pi^0\pi^0$ even	3.1×10^7	E_π^*	$\surd\surd$	
$\pi^0\pi^0$ odd	3.1×10^7	$\lvert E_{1\gamma}^* - E_{2\gamma}^*\rvert$, $M_{\gamma\gamma}$	$\surd\surd$	
$\pi^\pm e^\mp \nu\gamma$	1.2×10^8	$M_{\gamma\gamma}$, χ^2	$\surd$	$\surd$
$\pi^+\pi^-\pi^0$	4.2×10^9	E_π^*, E_{MISS}		$\surd\surd$
$\pi^0\pi^\pm e^\mp \nu$	1.7×10^6	E_π^*		$\surd\surd$
$\pi^0\pi^0\pi^0$	7.0×10^9	E_π^*	$\surd\surd\surd$	
$\pi^0\gamma\gamma$	5.6×10^4		$\surd\surd$	
$\gamma\gamma$	2.7×10^7	$M_{\gamma\gamma}$, E_π^*		

even $\equiv$ both γ from same π^0

odd $\equiv$ γ from different π^0

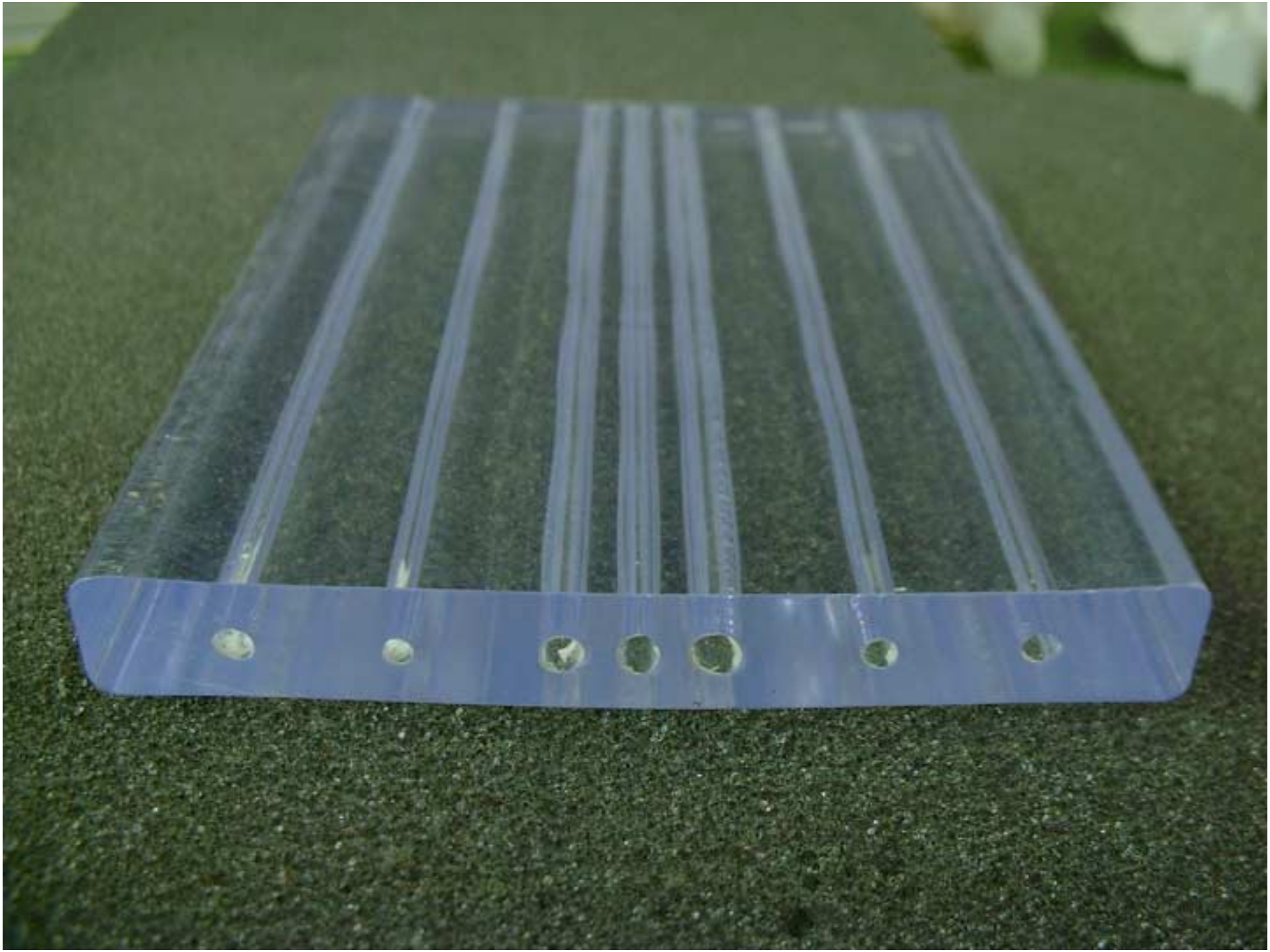
Background distributions



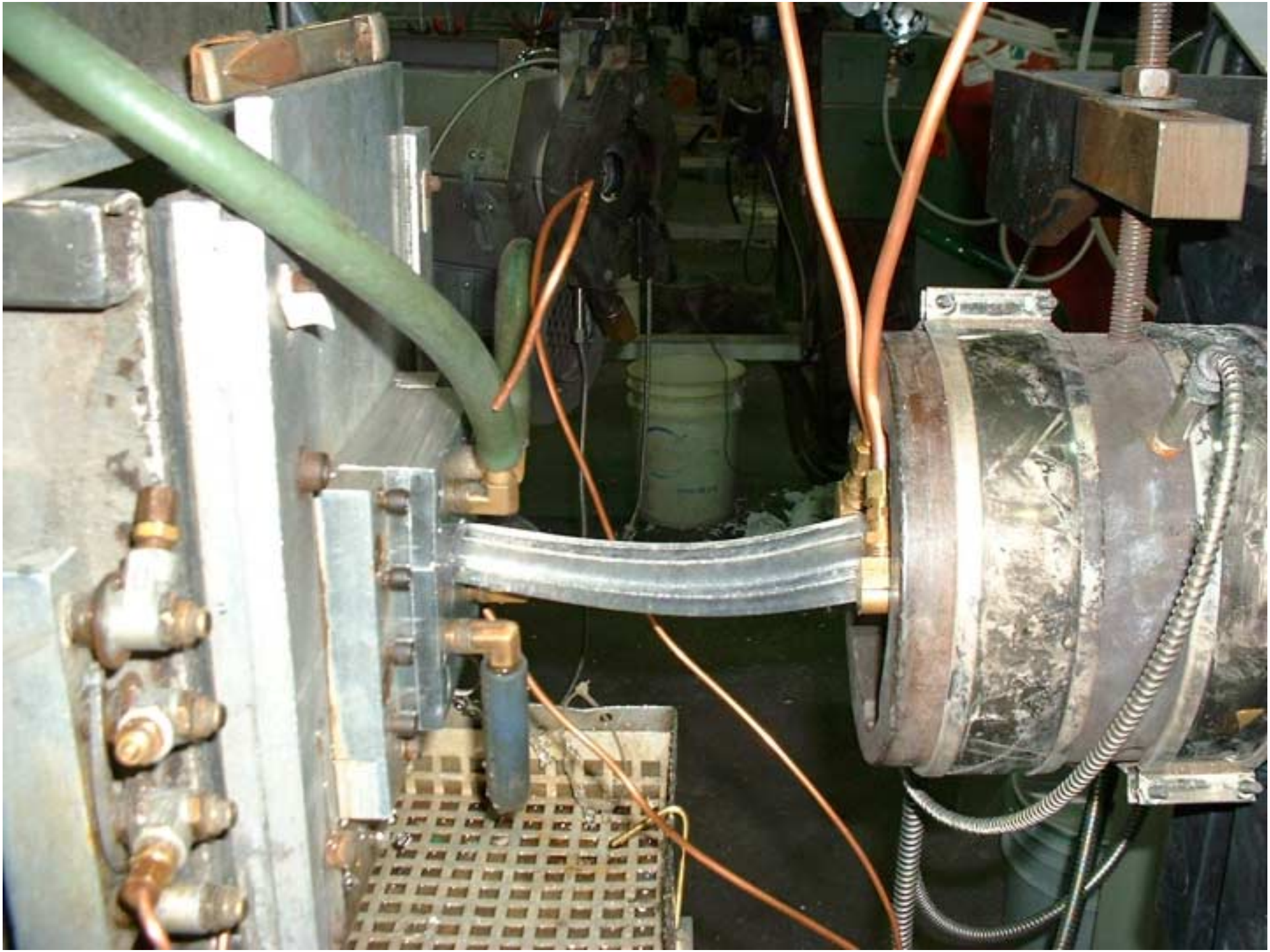


KOPIO background

Process	level
$\pi^0\pi^0\pi^0, \pi^0\pi^0 \ldots$	0.31
$\pi^- e^+ \nu\gamma$	0.11
$\pi^+\pi^-\pi^0$	0.04
accidental (γ,n,K...)	0.015
$n \rightarrow \pi^0$	0.005

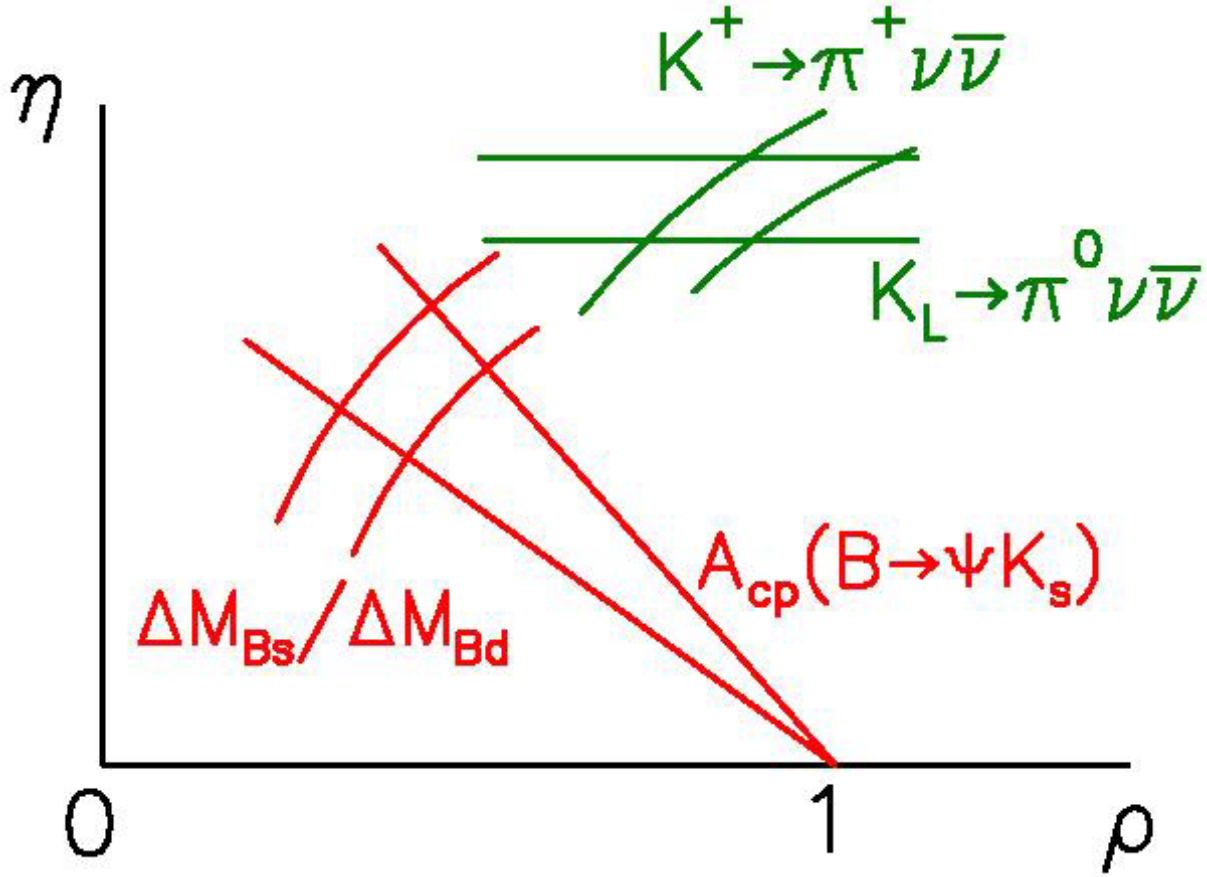


SEPT 13/02



Goodman
CAUTION
KEEP HANDS
CLEAR
CAUTION
READ INSTRUCTIONS
BEFORE OPERATING
CAUTION
-DO NOT-
OPERATE
WITHOUT GUARD
Goodman

Conclusion



Challenging but interesting physics is waiting for us.