Rare Kaon (and Pion) Decay

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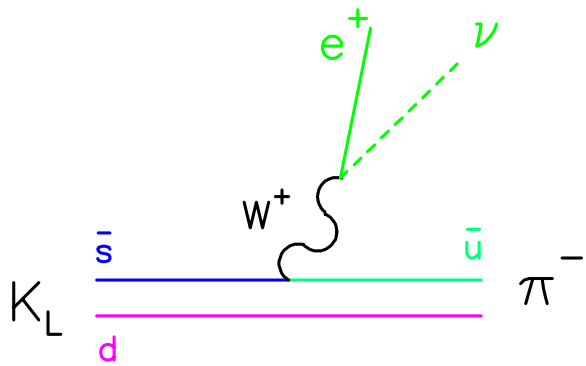
PSI Summer School - Zuoz, Switzerland, August 2002

Organization

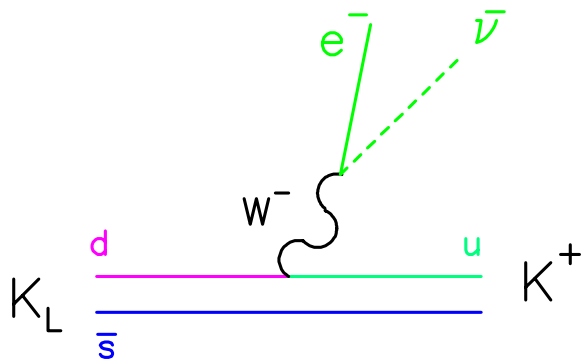
- Introduction & general motivation
- Lepton Flavor Violation
- Unitarity Triangle
- $K_L \to \ell^+\ell^-$ & $\pi^0 \to e^+e^-$
- $K^+ \to \pi^+\nu\bar{\nu}$
- $K^+ \to \pi^+X^0$
- $K_L \to \pi^0\nu\bar{\nu}$
- $K_L \to \pi^0\ell^+\ell^-$
- $K^+ \to \pi^+\ell^+\ell^-$
- $K^+ \to \pi^+\pi^0\nu\bar{\nu}$
- $\pi^+ \to \pi^0e^+\nu_e$
- $K^+ \to \ell^+\nu\ell^+\ell^-$
- Summary

What makes decays rare?

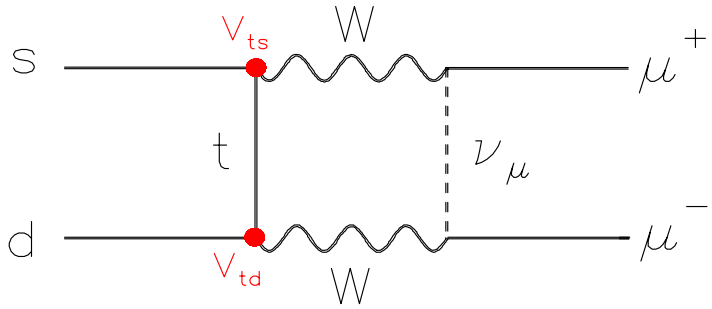
Common decay:



Rare by virtue of kinematics:



Rare since suppressed to 2nd order:



Motivation for Rare Decay Experiments

Forbidden

S.M. forbids (or greatly inhibits) many kinematically possible modes (esp. K's)

A number of these are allowed (or enhanced) by alternative approaches

Accessible sensitivity to these processes corresponds to very high mass scales

Discouraged

Certain very inhibited processes cleanly sensitive to S.M. parameters

Tolerated

Suppressed processes are a good area for testing chiral perturbation theory and other approaches to understanding the low energy structure of the S.M.

Rare K and π decay modes studied recently

$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \mu^+ \mu^-$
$K^+ \to \pi^+ \mu^+ \mu^-$
$K_L \to \mu^+ \mu^-$
$K^+ \to \pi^+ e^+ e^- \gamma$
$K_L \to e^\pm e^\mp \mu^\pm \mu^\mp$
$K_L \to \pi^+ \pi^- \gamma$
$K^+ \to \pi^+ \pi^0 e^+ e^-$
$K_L \to \pi^0 \gamma\gamma$
$K^+ \to \mu^+ \nu\gamma$
$K^+ \to \mu^+ \nu e^+ e^-$
$K_L \to e^+ e^- \gamma$
$K_L \to e^+ e^- \gamma\gamma$
$K_L \to e^+ e^- e^+ e^-$
$K^+ \to \pi^+ \mu^+ e^-$
$K_L \to \mu^\pm e^\mp$
$K^+ \to \pi^- e^+ e^+$
$K^+ \to \pi^+ X^0$
$K^+ \to \pi^+ \gamma$

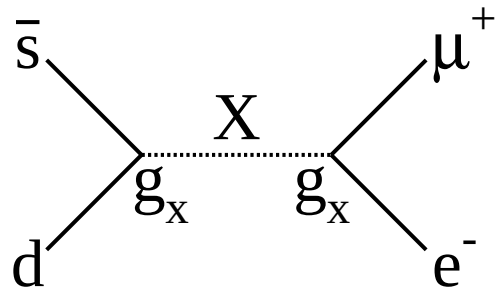
$K_L \to \pi^0 \nu\bar{\nu}$
$K_L \to \pi^0 e^+ e^-$
$K^+ \to \pi^+ e^+ e^-$
$K_L \to e^+ e^-$
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$
$K^+ \to \pi^+ \pi^0 \gamma$
$K_L \to \pi^+ \pi^- e^+ e^-$
$K^+ \to \pi^0 \mu^+ \nu\gamma$
$K^+ \to \pi^+ \gamma\gamma$
$K^+ \to e^+ \nu e^+ e^-$
$K^+ \to e^+ \nu \mu^+ \mu^-$
$K_L \to \mu^+ \mu^- \gamma$
$K_L \to \mu^+ \mu^- \gamma\gamma$
$K_L \to \pi^0 e^+ e^- \gamma$
$K_L \to \pi^0 \mu^\pm e^\mp$
$K^+ \to \pi^- \mu^+ e^+$
$K^+ \to \pi^- \mu^+ \mu^+$
$K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$

$\pi^+ \to \pi^0 e^+ \nu_e$
$\pi^+ \to e^+ \nu_e \gamma$
$\pi^+ \to e^+ \nu_e \nu\bar{\nu}$
$\pi^0 \to e^+ e^- e^+ e^-$
$\pi^0 \to \gamma\nu\bar{\nu}$
$\pi^0 \to \mu e$

$\pi^+ \to e^+ \nu_e$
$\pi^+ \to e^+ \nu_e e^+ e^-$
$\pi^0 \to e^+ e^-$
$\pi^0 \to \nu\bar{\nu}$
$\pi^0 \to 3\gamma$

Lepton Flavor Violation

Poster child for sensitivity to BSM processes such as $\longrightarrow$
Attainable sensitivity corresponding to $M_X \gtrsim 100$TeV, clean signatures



Most BSM theories predict *some* LFV in K decays:
- extended technicolor
- SUSY
- heavy neutrinos
- horizontal gauge bosons

Necessary to study both two and three body decays
- check Lorentz structure of any new interaction
- generation number sensitivity

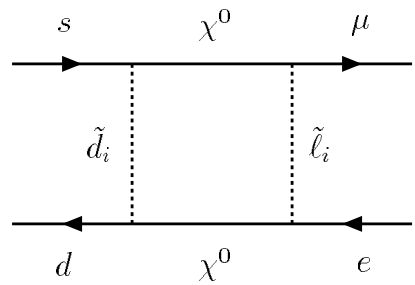
Current status:

Process	90% CL Limit	Experiment	Reference
$K_L \to \mu e$	4.7×10^{-12}	AGS-871	PRL 81:5734
$K^+ \to \pi^+\mu^+e^-$	2.8×10^{-11}	AGS-865	PRL 85:2450
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	AGS-865	PRL 85:2877
$K_L \to \pi^0\mu e$	3.3×10^{-10}	KTeV	Bellavance/DPF2002

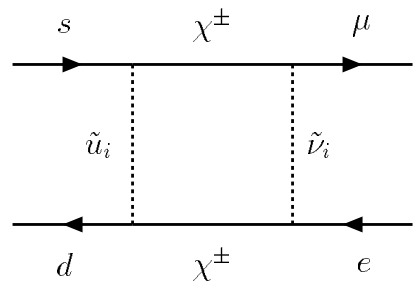
$K_L \to \pi^0\mu e$ result preliminary.
More $K^+ \to \pi^+\mu^+e^-$ data under analysis.

LFV in SUSY

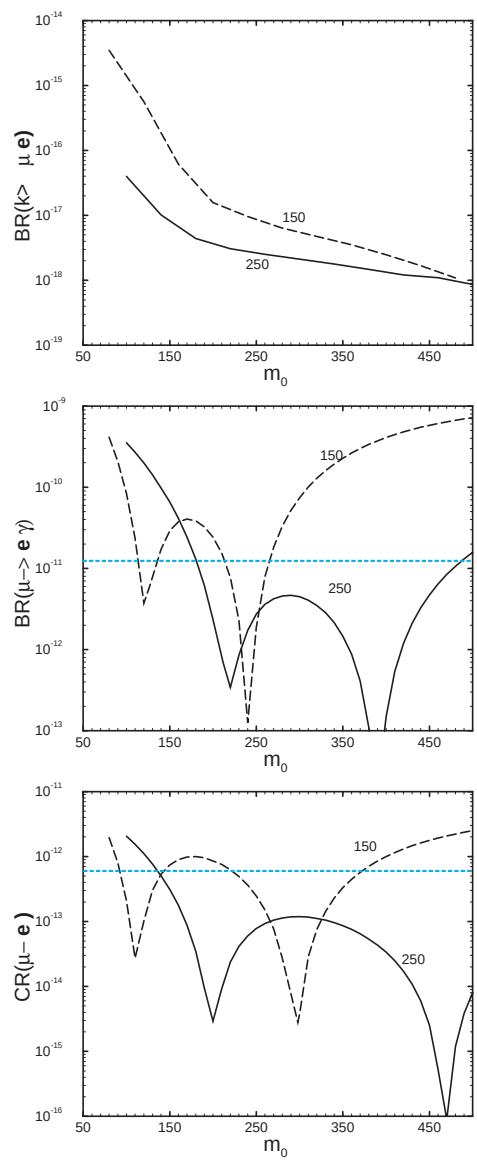
Lepton flavor violation in K decay is allowed in the MSSM by diagrams like those at right (See A. Belyaev *et al.*, hep-ph/0008276.



But the rate from such diagrams is very suppressed with respect to current experimental senstivity. The effects in K decay are also suppressed relative to those in rare muon processes such as $\mu \to e\gamma$ and $\mu^- \to e^-$ conversion in the field of a nucleus

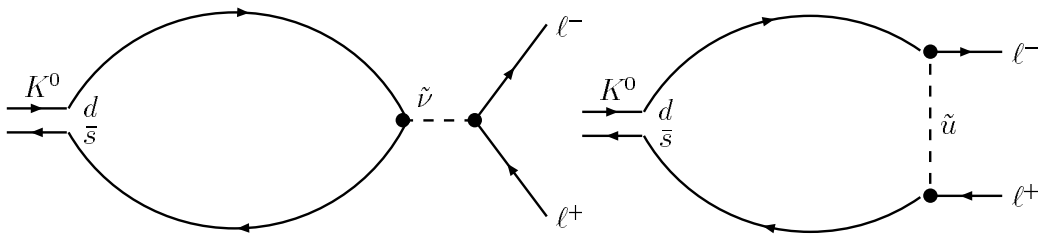


This can be seen in the plots at right which show the predictions for $K_L \to \mu e$, $\mu \to e\gamma$ and $\mu^- \to e^-$ conversion assuming the same values of SUSY parameters ($\mu < 0$, $tan\beta = 20$, $m_{1/2} = 150$ & $250\,\mathrm{GeV}$, vs m_0). The dotted horizontal lines indicate the current upper limits on $\mu \to e\gamma$ and $\mu^- \to e^-$ conversion. There are proposals to push the sensitivity of both muon processes by more than three orders of magnitude.



LFV in SUSY-2

Once R-parity is relaxed, LFV effects in SUSY can be large:



Quark/sfermion diagrams involving R-violating couplings that yield $K^0 \to \ell^\pm \ell^\mp$ *decays.*

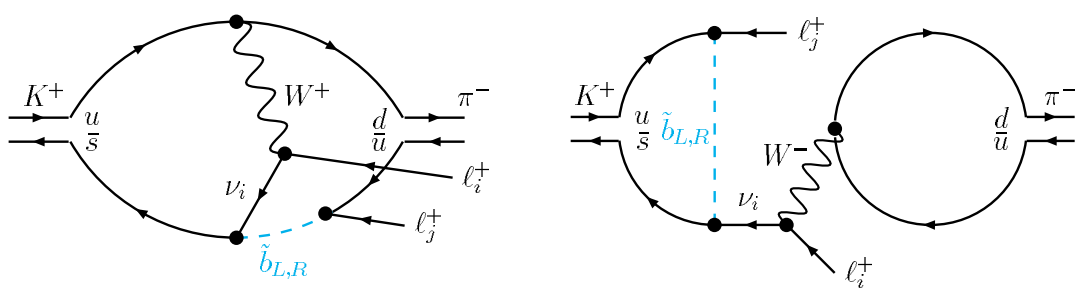
Current LFV data itself gives strictest limits on the couplings.

e.g. $B(K_L \to \mu e) < 4.7 \cdot 10^{-12}$ gives -

$$\lambda_{i21}\lambda'_{i12} \text{ and } \lambda_{i12}\lambda'_{i21} \leq 6.2 \cdot 10^{-9} \times (\frac{m_{\tilde{\nu}}}{100\text{GeV}})^2$$

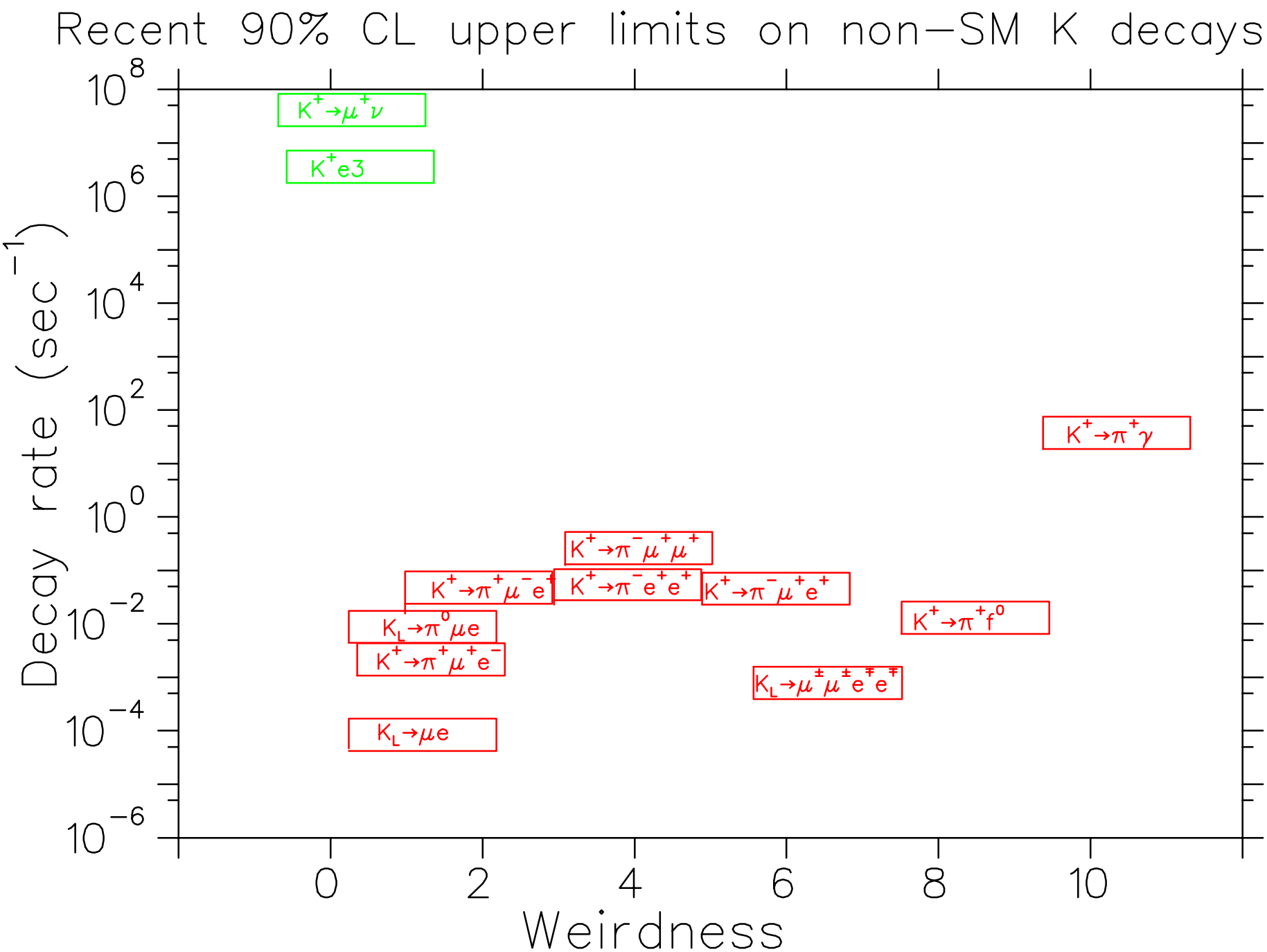
$$\& \qquad \lambda'_{2i1}\lambda'_{1i2} \text{ and } \lambda'_{1i1}\lambda'_{2i2} \leq 1.9 \cdot 10^{-7} \times (\frac{m_{\tilde{\mu}}}{100\text{GeV}})^2$$

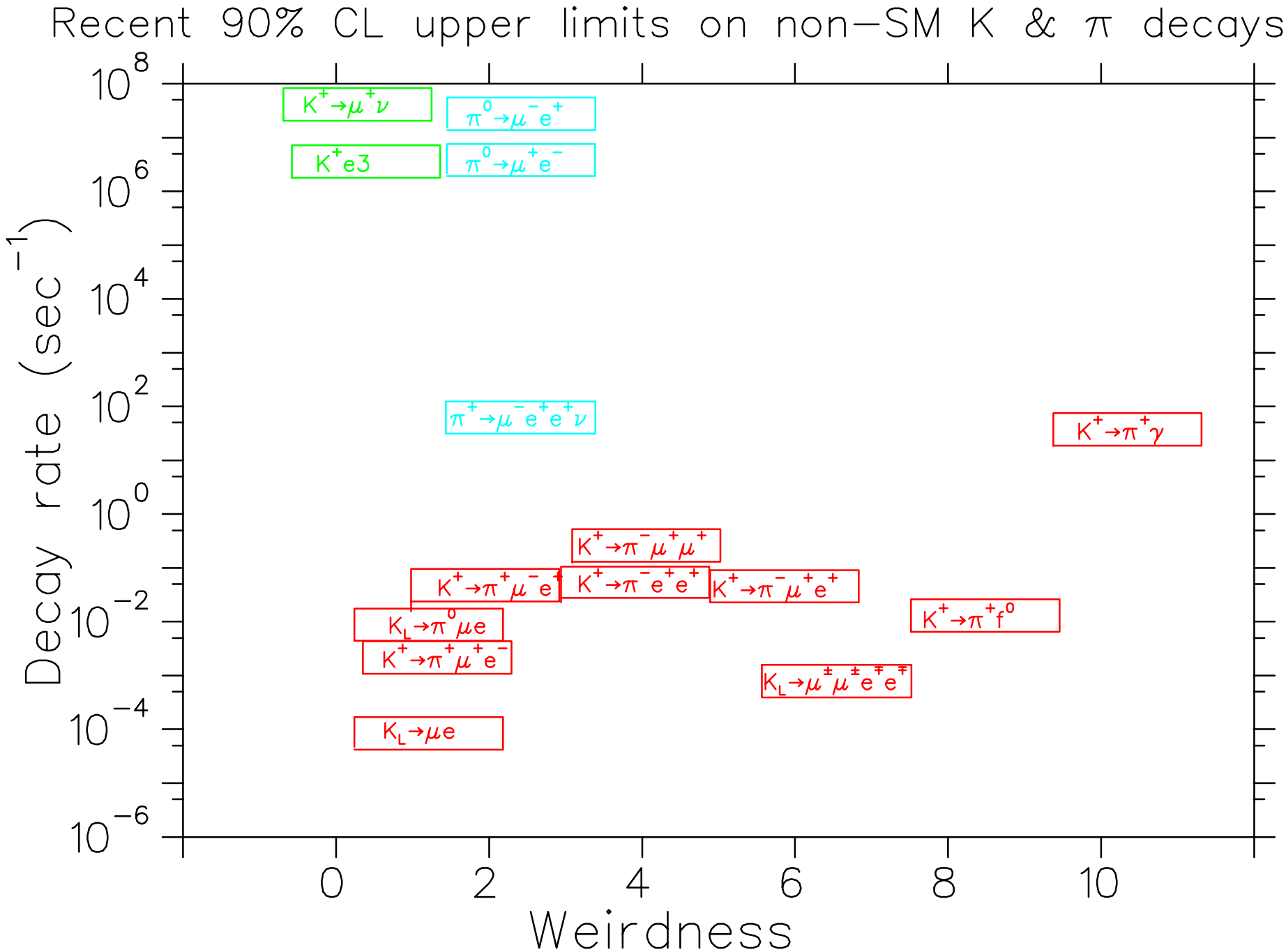
SUSY can also give like-sign lepton decays like $K^+ \to \pi^- \mu^+ e^+$ through $\tilde{b}$ mixing, *e.g.*:



However the senstivity for these is much reduced.
Even setting the $\tilde{b}$ mixing matrix element to 1,
current limit $B(K^+ \to \pi^- \mu^+ e^+) < 5 \cdot 10^{-10}$ would give -

$$\lambda'_{2k2}\lambda'_{11k} \leq 10 \times (\frac{m_{\tilde{d}_k}}{100\text{GeV}})^2$$


Recent 90% CL upper limits on non−SM K decays
Decay rate (sec^{-1})
Weirdness
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
0
2
4
6
8
10
$K^+\to\mu^+\nu$
K^+e3
$K^+\to\pi^+\gamma$
$K^+\to\pi^-\mu^+\mu^+$
$K^+\to\pi^+\mu^-e^+$
$K^+\to\pi^-e^+e^+$
$K^+\to\pi^-\mu^+e^+$
$K_L\to\pi^0\mu e$
$K^+\to\pi^+f^0$
$K^+\to\pi^+\mu^+e^-$
$K_L\to\mu^\pm\mu^\pm e^\mp e^\mp$
$K_L\to\mu e$


Recent 90% CL upper limits on non−SM K & π decays
Decay rate (sec^{-1})
Weirdness
10^{8}
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$K^+\to\mu^+\nu$
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$K^+\to\pi^+\gamma$
$K^+\to\pi^-\mu^+\mu^+$
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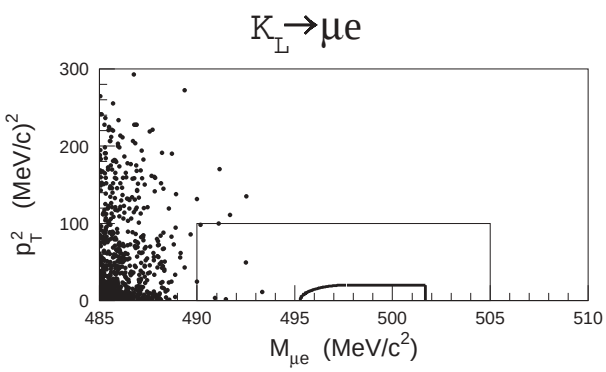
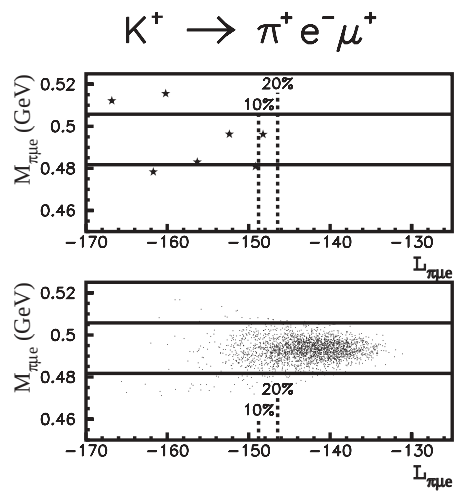
$K^+\to\pi^-\mu^+e^+$
$K^+\to\pi^+f^0$
$K_L\to\pi^0\mu e$
$K^+\to\pi^+\mu^+e^-$
$K_L\to\mu^\pm\mu^\pm e^\mp e^\mp$
$K_L\to\mu e$

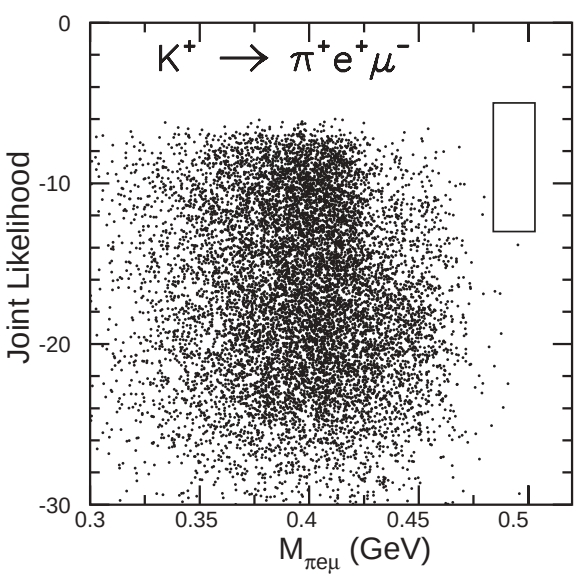
Prospects for LFV

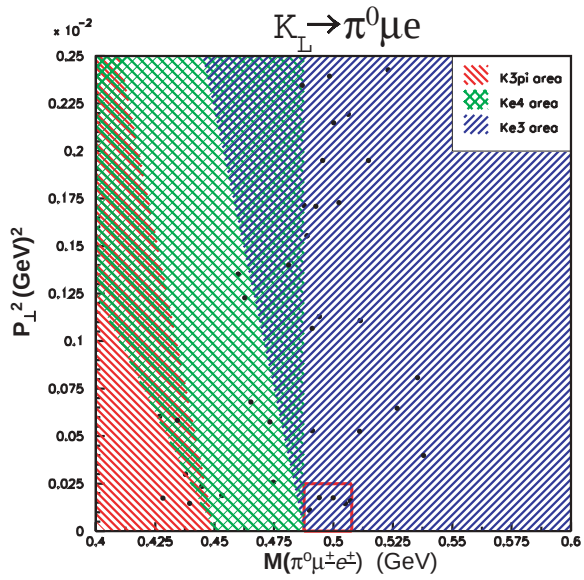
Current experiments have already helped kill the most promising approaches that predicted finite effects. Theorists now predicting more accessible levels of LFV in rare muon processes.

Future progress on LFV in kaon decays likely to be slow. No dedicated experiments on the near horizon, and background getting harder to fight:









Probably no significant progress at least until JHF or other new facility turns on.

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

Unitary matrix connecting weak with mass quark eigenstates:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Parameterization of Wolfenstein and Maiani:

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

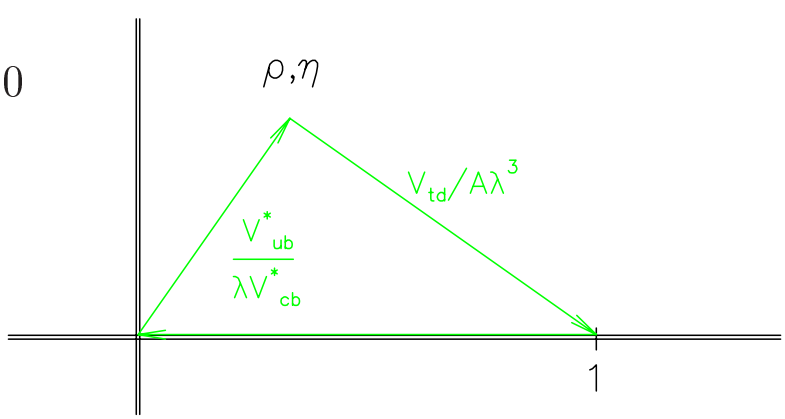
$\lambda = sin(\theta_{Cabibbo}) = 0.22$	(from $Ke3$ decay)
$A \approx 0.83$	(from semi-leptonic B decay, etc.)
$\rho \approx 0.2$	(from V_{ub}/V_{cb}, $\bar{B}-B$ mixing,
$\eta \approx 0.3$	ϵ_K, etc.)

Unitarity relation -

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$$V_{ub}^* - \lambda V_{cb}^* + V_{td} = 0$$

$$\frac{V_{ub}^*}{\lambda V_{cb}^*} - 1 + \frac{V_{td}}{A\lambda^3} = 0$$



Wolfenstein Parameterization to Higher Order

W-M parameterization of the CKM matrix only approximate
At $\mathcal{O}(\lambda^4)$ and beyond, W-M not unique
Buras, Lautenbacher & Ostermaier (PR **D50** (1994) 3433) introduced a version that is unitary to all orders.

At the moment, don't need to go above $\mathcal{O}(\lambda^5)$:

$$\begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5(\frac{1}{2}-\rho)-A^2\lambda^5 i\eta & 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}-\frac{1}{2}A^2\lambda^4 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2+A\lambda^4(\frac{1}{2}-\rho)-i\eta A\lambda^4 & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

Where $\bar{\rho} \equiv \rho(1-\frac{\lambda^2}{2})$ & $\bar{\eta} \equiv \eta(1-\frac{\lambda^2}{2})$

Main effect is to move vertex of unitary triangle to $(\bar{\rho}, \bar{\eta})$

In terms of $\lambda_i \equiv V_{id}V_{is}^*$:

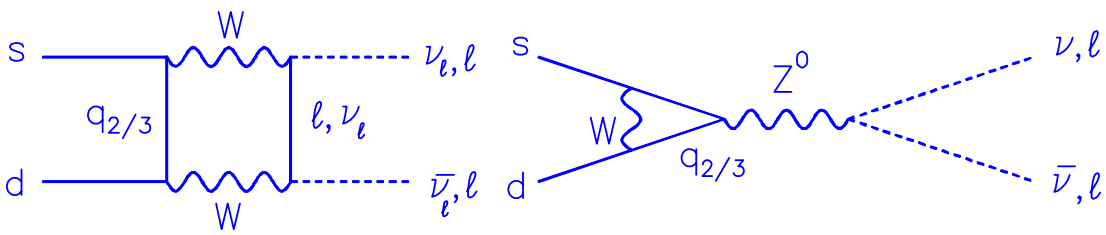
$$Im\lambda_t = -Im\lambda_c = \eta A^2\lambda^5$$
$$Re\lambda_c = -\lambda(1-\frac{\lambda^2}{2})$$
$$Re\lambda_t = -(1-\frac{\lambda^2}{2})A^2\lambda^5(1-\bar{\rho})$$

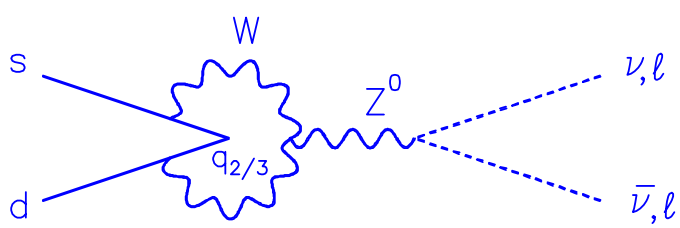
Note that the area of any unitarity triangle $= \frac{1}{2}J_{CP}$,
where $J_{CP} = -Im(V_{ts}^*V_{td}V_{us}^*V_{ud}) = \lambda\sqrt{1-\lambda^2}Im(\lambda_t)$

Thus, a measurement of $Im(\lambda_t)$ would determine the area of all 6 UT's.

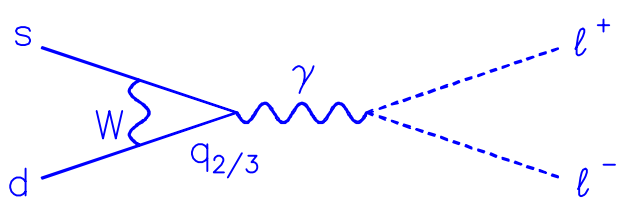
One-loop K Decays

Short-distance contributions to K decays. These decays include $K_L \to \pi^0 \nu\bar{\nu}$, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \mu^+\mu^-$, $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+ \mu^-$, etc. The hadronic matrix elements involved are known from common decays such as $K^0 \to \pi^+ e^- \bar{\nu}$. These contributions can be cleanly calculated in terms of m_t, m_c and the product of CKM elements $V_{ts}^* V_{td} \equiv \lambda_t$.





But there's a Murphy's Law for these processes:
The same interactions that allow charged final state leptons to be detected, mediate long-distance contributions. E.g.:



To avoid this one must exploit decays containing a $\nu\bar{\nu}$ pair.

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

$V_{ts}^* V_{td}$

$$B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \frac{r_{K^+}\alpha^2 B(K^+ e3)}{V_{us}^2 2\pi^2 sin^4\theta_W} \sum_l |\lambda_c X_{NL}^{\ell} + \lambda_t X\left(x_t\right)|^2 \approx 10^{-10}$$

contains QCD corr.
has been calc'd to NLLA

$X \approx 1.57\left(m_t/170\right)^{1.15}$

$$= 4.1 \times 10^{-11} A^4 X^2\left(x_t\right)\left[\eta^2 + \frac{2}{3}\left(\rho_o^e - \rho\right)^2 + \frac{1}{3}\left(\rho_o^\tau - \rho\right)^2\right]$$

where $\rho_o^\ell \equiv 1 + \frac{X_{NL}^\ell}{A^2\lambda^4 X(x_t)}$; $r_{K^+} = 0.9$

calc. uncertainty only a few %

In leading order in Wolfenstein parameters,
$B\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$ determines a circle in the ρ, η plane with center $(\rho_o, 0)$; $\rho_o \equiv \frac{2}{3}\rho_o^e + \frac{1}{3}\rho_o^\tau$ and radius $\approx \frac{1}{A^2}\sqrt{\frac{B(K^+\to\pi^+\nu\bar{\nu})}{10^{-10}}}$

Going beyond leading order the circle gets slightly squashed
BR formula becomes:

$$4.1 \times 10^{-11} A^4 X^2\left(x_t\right)\frac{1}{\sigma}\left[\left(\sigma\bar{\eta}\right)^2 + \left(\rho_o - \bar{\rho}\right)^2\right]$$

where $\sigma \equiv \left(1 - \frac{\lambda^2}{2}\right)^{-2}$ & $\rho_0 \equiv 1 + \frac{2X_{NL}^e + X_{NL}^\tau}{3\lambda^4 A^2 X(x_t)} \approx 1.4$

The ellipse departs from a circle by only a factor σ
It is 5% wider than it is tall

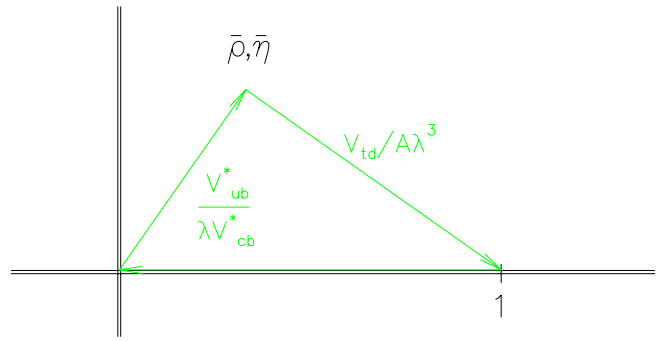
Uses of CKM Unitarity

Usual Use of Unitarity

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$$(1 - \frac{\lambda^2}{2}) V_{ub}^* - \lambda V_{cb}^* + V_{td} = 0$$

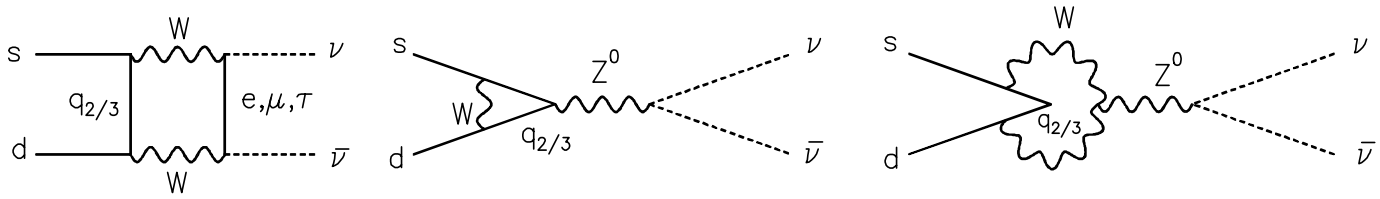
$$\frac{(1-\lambda^2/2) V_{ub}^*}{\lambda V_{cb}^*} - 1 + \frac{V_{td}}{A\lambda^3} = 0$$



Unusual Use of Unitarity

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

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

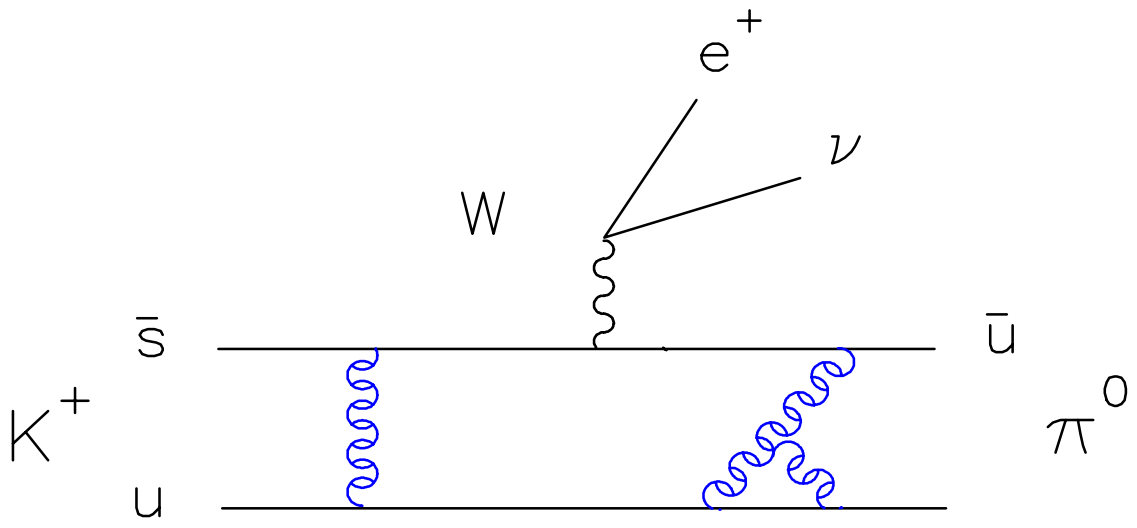


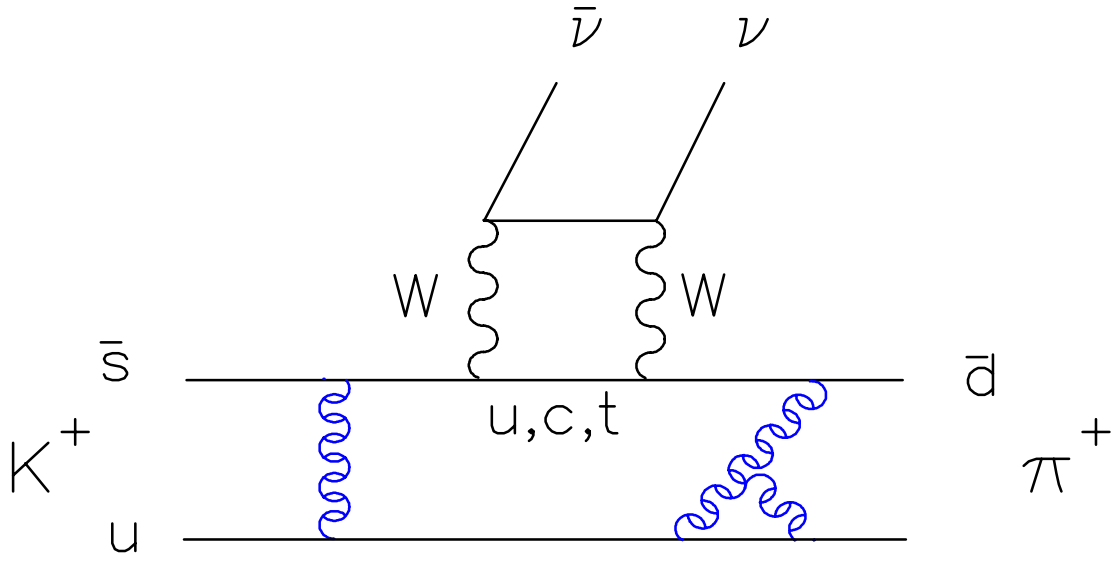
$$A(K \to \pi\nu\bar{\nu}) \propto V_{us}^* V_{ud} X(m_u) + V_{cs}^* V_{cd} X(m_c) + V_{ts}^* V_{td} X(m_t)$$

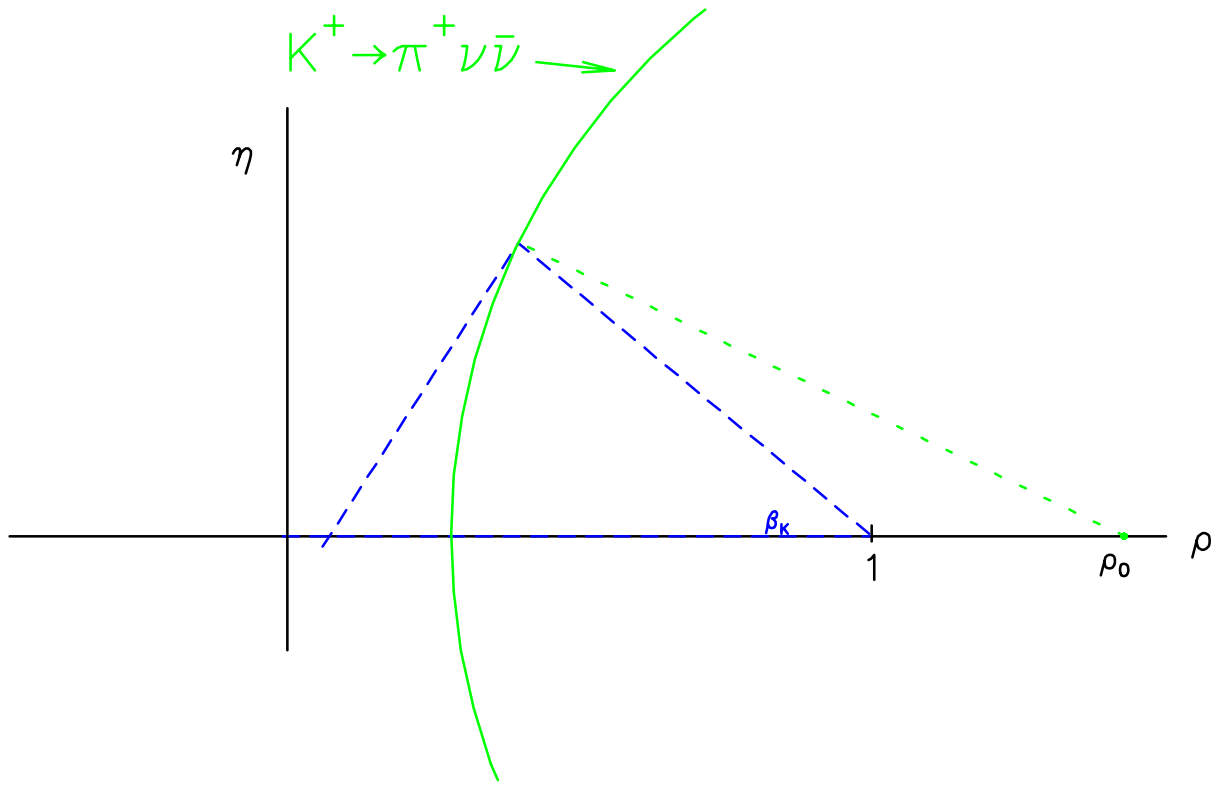
$$= V_{cs}^* V_{cd} [X(m_c) - X(m_u)] + V_{ts}^* V_{td} [X(m_t) - X(m_u)]$$

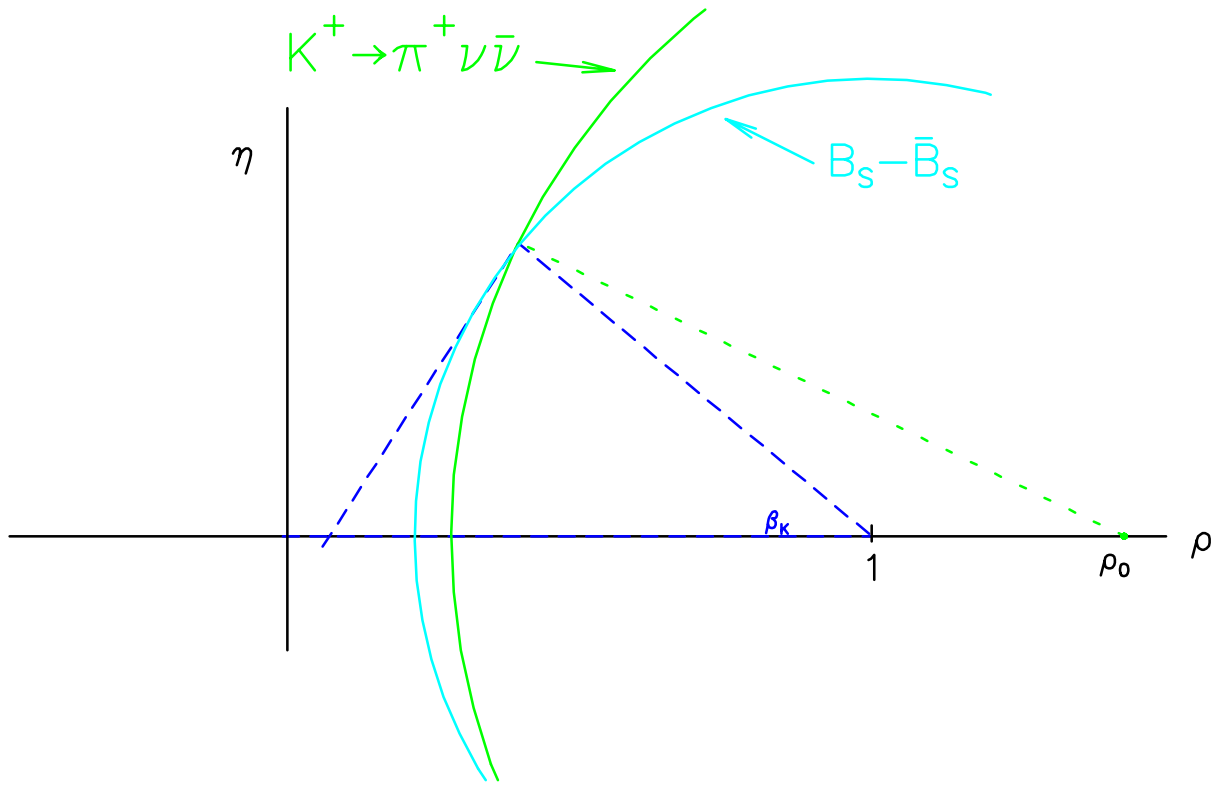
Hard to calculate parts subtract away.

K Hadronic Matrix Element

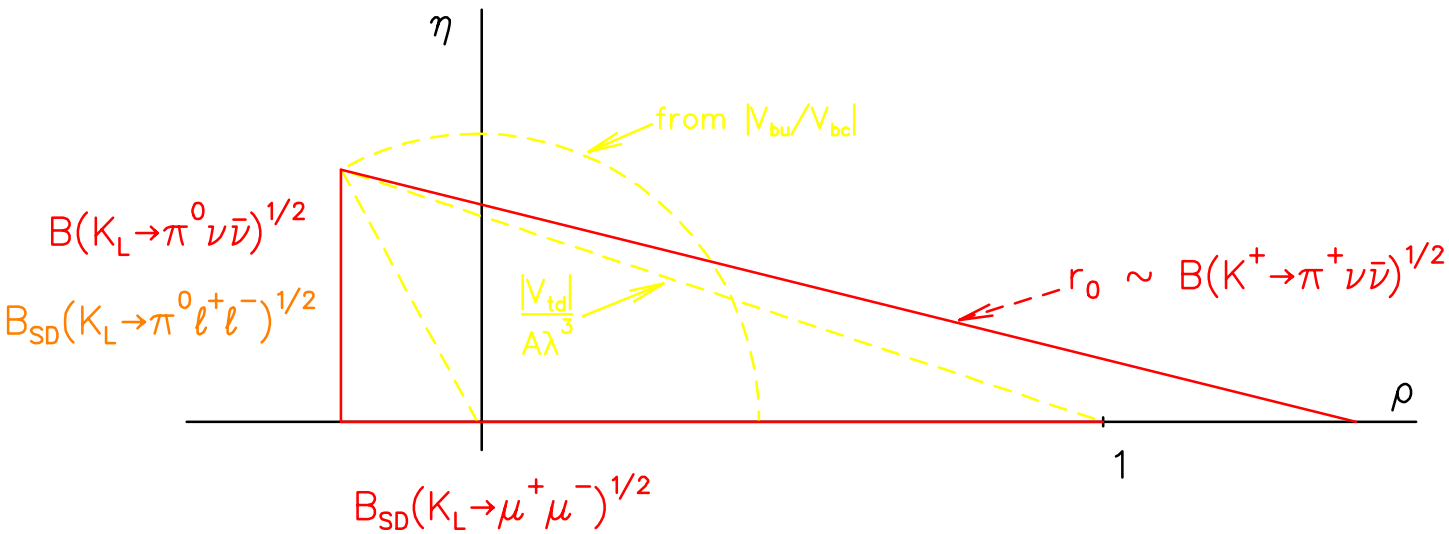





$K^+ \to \pi^+ \nu \bar{\nu}$
η
β_K
1
ρ_0
ρ


$K^+ \to \pi^+ \nu\bar{\nu}$
$B_s - \bar{B}_s$
η
ρ
β_K
1
ρ_0

Rare K Decay and the Unitarity Triangle



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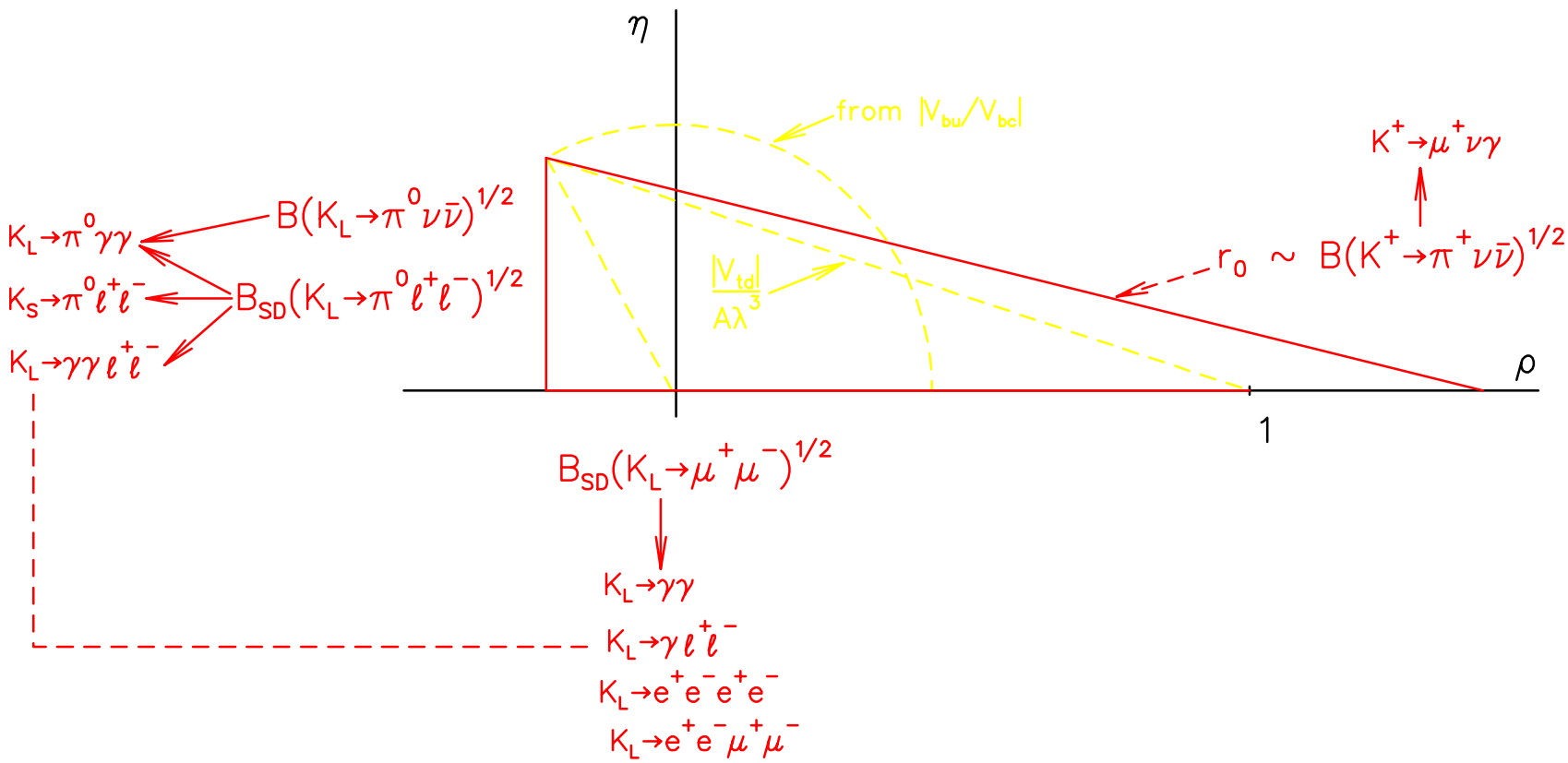


$K_L \to \mu^+\mu^-$

The **short distance** part of $B\left(K_L \to \mu^+\mu^-\right)$ given by:

$$B^{SD}_{\mu\mu} = \frac{\tau_{K_L}\alpha^2 B_{K^+\mu\nu}\xi}{\tau_{K^+}V^2_{us}\pi^2 sin^4\theta_W}\left[Re\left(\lambda_c\right)Y_{NL} + Re\left(\lambda_t\right)Y\left(x_t\right)\right]^2 \approx \mathcal{O}\left(10^{-9}\right)$$

where $Re\left(\lambda_c\right) = \lambda\left(\frac{\lambda^2}{2} - 1\right)$; $\lambda \equiv sin\theta_{Cabibbo}$; kinematic factor $\xi \approx 1$

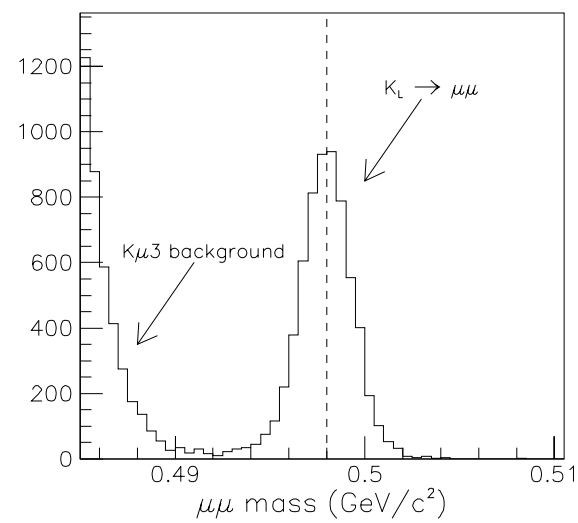
To a good approximation $Y\left(x_t\right) = 1.02\left(m_t/170\right)^{1.56}$, $Y_{NL} \approx 3 \times 10^{-4}$

$$= 1.75 \cdot 10^{-9} A^4 Y^2\left(x_t\right)\left(\bar{\rho}_0 - \bar{\rho}\right)^2 \quad = \quad \left(0.93 \pm 0.23\right) \cdot 10^{-9}$$

where $\bar{\rho}_0 \approx 1.2$

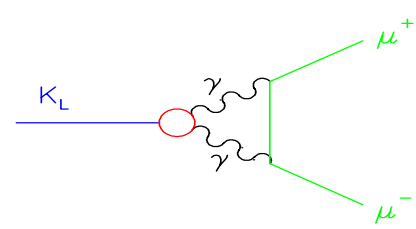
So could potentially measure $\bar{\rho}$ or be sensitive to BSM physics

Moreover there's a
Very good measurement
by AGS-871 (6000 evts!)



But there are a number of roadblocks to be overcome

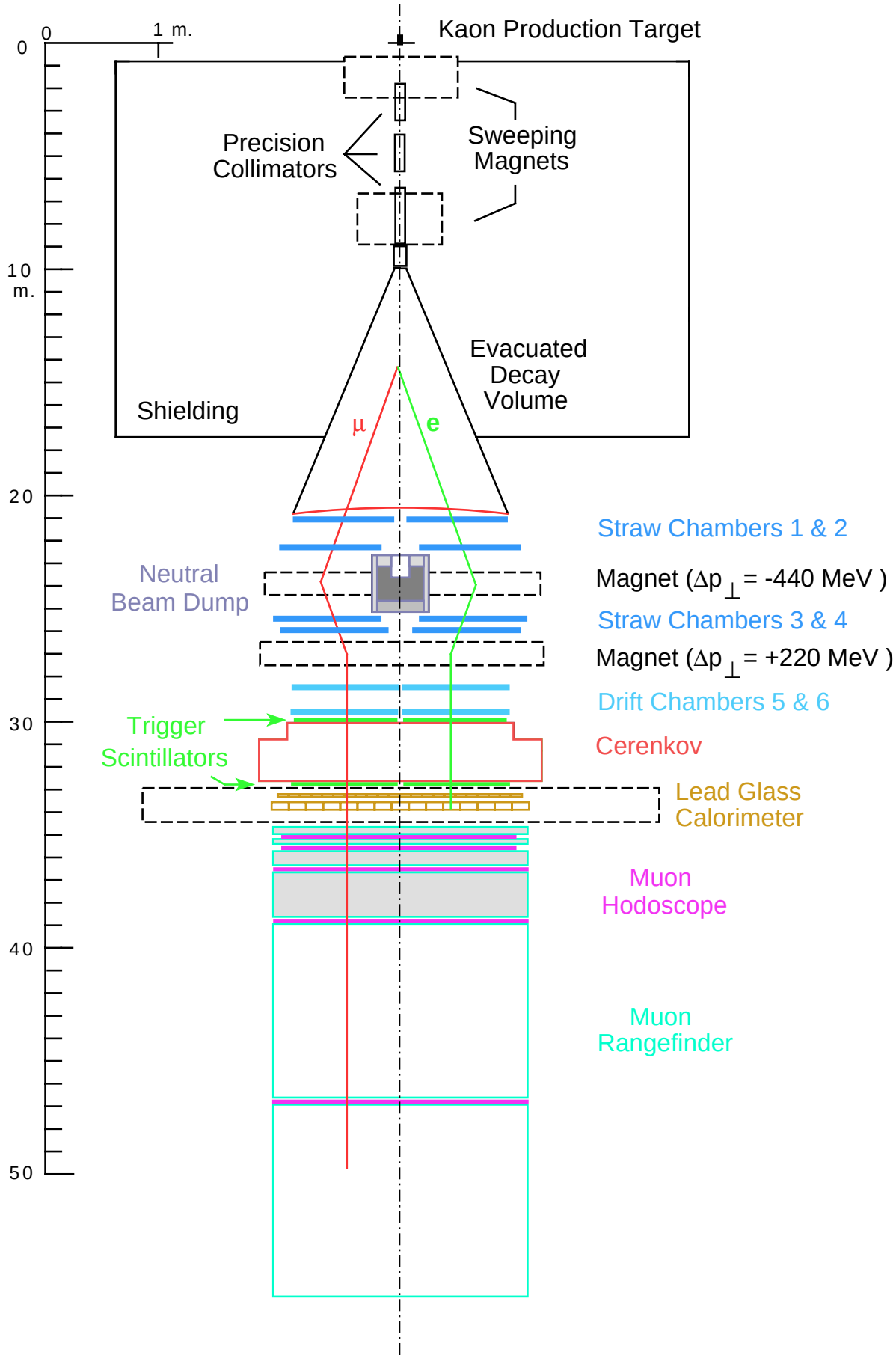
First $B\left(K_L \to \mu^+\mu^-\right)$ is dominated by an absorptive contribution from intermediate $K_L \to \gamma\gamma$:



Much larger than the dispersive part which contains $B^{SD}_{\mu\mu}$!

If precise measurements are made, this can be subtracted.

BNL Experiment 871 - The Search for $K_L^0 \rightarrow \mu e$



$K_L \to \mu^+\mu^-$ - 2

Actual quantity measured is

$$\frac{B(K_L\to\mu\mu)}{B(K_L\to\pi^+\pi^-)} = (3.48 \pm 0.05)\cdot 10^{-6} \qquad \text{(PDG average)}$$

So best to compare to:

$$\frac{B^{abs}_{\gamma\gamma}(K_L\to\mu\mu)}{B(K_L\to\pi^+\pi^-)} = \underbrace{\frac{B^{abs}_{\gamma\gamma}(K_L\to\mu\mu)}{B(K_L\to\gamma\gamma)}}_{\text{calculated}} \underbrace{\frac{B(K_L\to\gamma\gamma)}{B(K_L\to\pi^0\pi^0)}}_{\text{last measured by NA31 in 1987}} \overbrace{\frac{B(K_S\to\pi^0\pi^0)}{B(K_S\to\pi^+\pi^-)}}^{\text{Recently measured by KLOE}} \overbrace{\left(1 - 6Re\frac{\epsilon'}{\epsilon}\right)}^{\frac{B(K_L\to\pi^0\pi0)}{B(K_L\to\pi^+\pi^-)}}$$

$$1.195\cdot 10^{-5} \qquad 0.632 \pm 0.009 \qquad (2.236 \pm 0.015)^{-1} \qquad 1 - 6\,(16.6 \pm 1.6)\cdot 10^{-4}$$

$$= (3.344 \pm 0.053)\cdot 10^{-6}$$

$$\frac{B^{disp}(K_L\to\mu\mu)}{B(K_L\to\pi^+\pi^-)} = (0.136 \pm 0.073)\cdot 10^{-6}$$

Then multiply by $B\left(K_L \to \pi^+\pi^-\right) = (2.084 \pm 0.032)\cdot 10^{-3}$ (PDG fit)

To get $B^{disp}\left(K_L \to \mu\mu\right) = (0.283 \pm 0.151)\cdot 10^{-9}$
i.e.

$$B^{disp}\left(K_L \to \mu\mu\right) < 0.47\cdot 10^{-9} \text{ at } 90\% \text{ c.l.}$$

Disagrees with $B^{SD}_{\mu\mu} = (0.93 \pm 0.23)\cdot 10^{-9}$ by 2.4σ.

Why haven't we been hearing about this?

$K_L \to \mu^+\mu^-$ - 3

Problem is long distance contribution to $B^{disp}(K_L \to \mu\mu)$
This can interfere with the short distance amplitude
To untangle, must know $A(K_L \to \gamma\gamma)$ with γs off mass-shell
- size, calculability controversial:

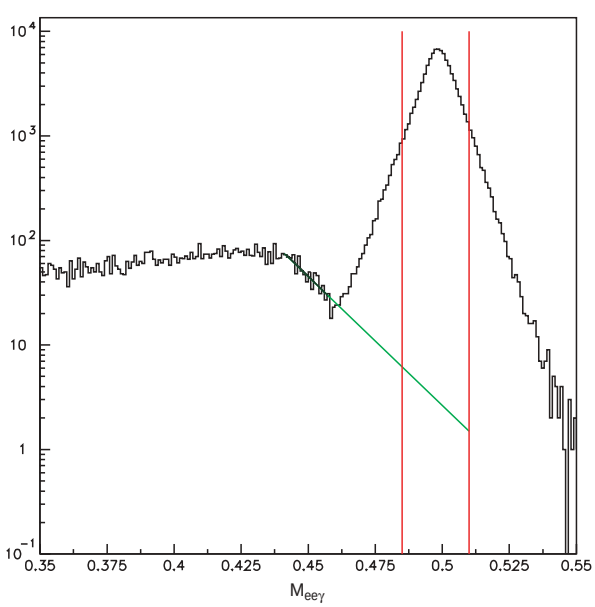
Pro	Con
Gomez-Dumm *et al.*, PRL **80** (1998) 4633	Valencia NP B **517** (1998) 339
D'Ambrosio *et al.*, PL B **423** (1998) 385	Knecht *et al.*, PRL **83** (1999) 5230

Can one **measure** this?

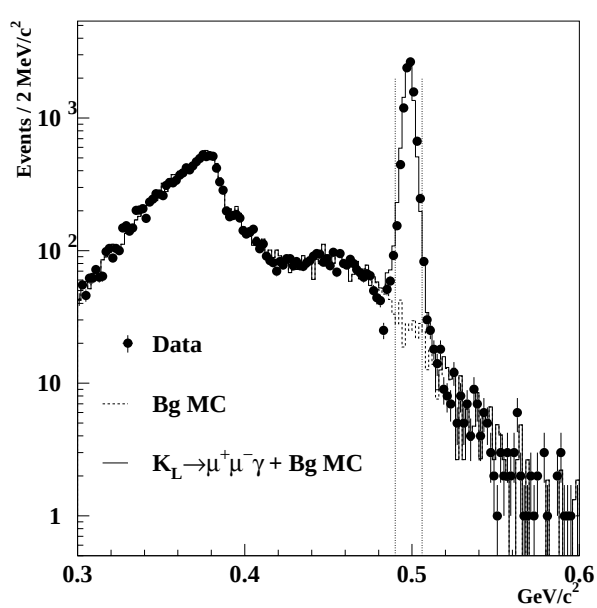
There are recent results on:

$K_L \to ee\gamma$	KTeV, NA48
$K_L \to \mu\mu\gamma$	KTeV
$K_L \to eeee$	KTeV, NA48
$K_L \to ee\mu\mu$	KTeV, NA48

People have used fits to some of these to put a limit on ρ,
- how legitimate this is is still unclear

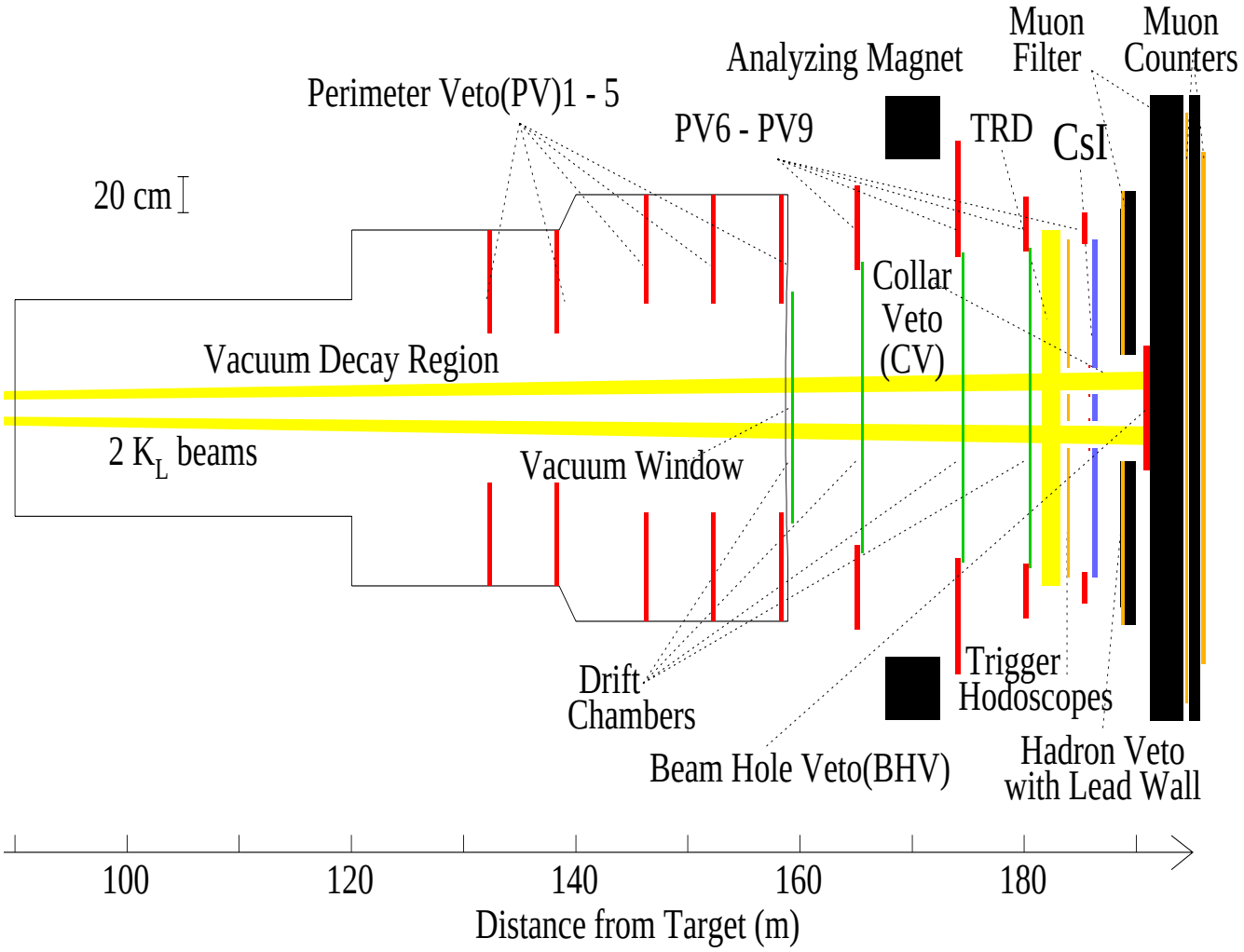


$ee\gamma$ mass from KTeV

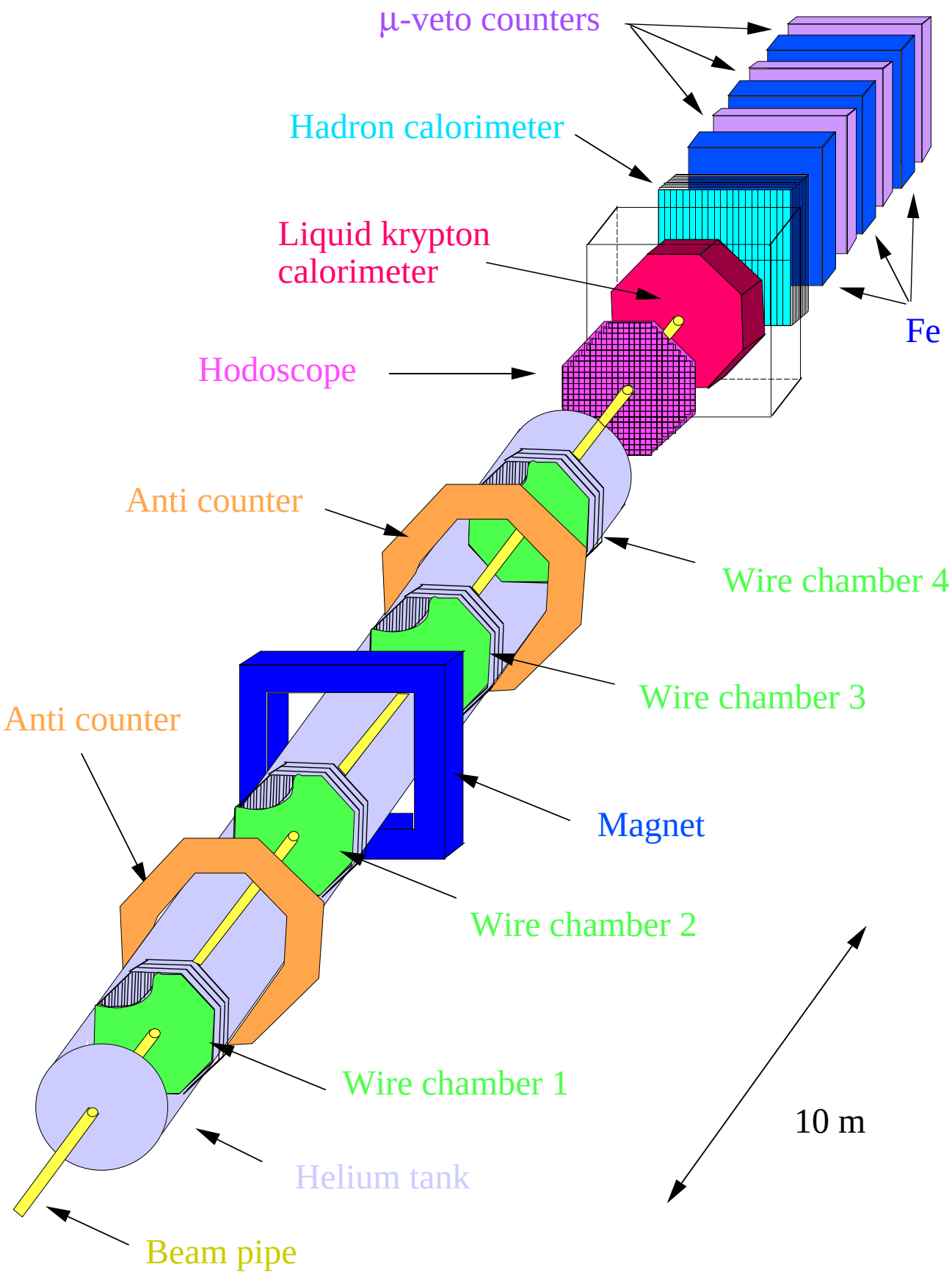


$\mu\mu\gamma$ mass from KTeV

E799-II (KTeV) Detector



The NA48 Detector

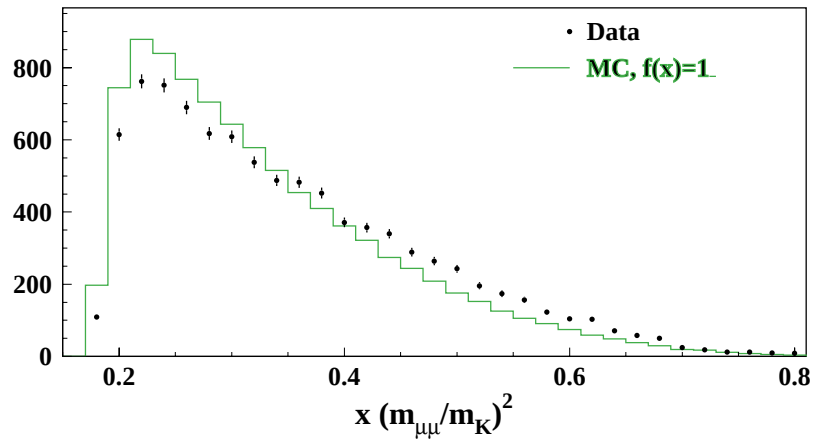


Virtual photon form factors

Virtual photon form factors are needed to calculate the long-distance dispersive contribution to $K_L \to \mu^+\mu^-$.

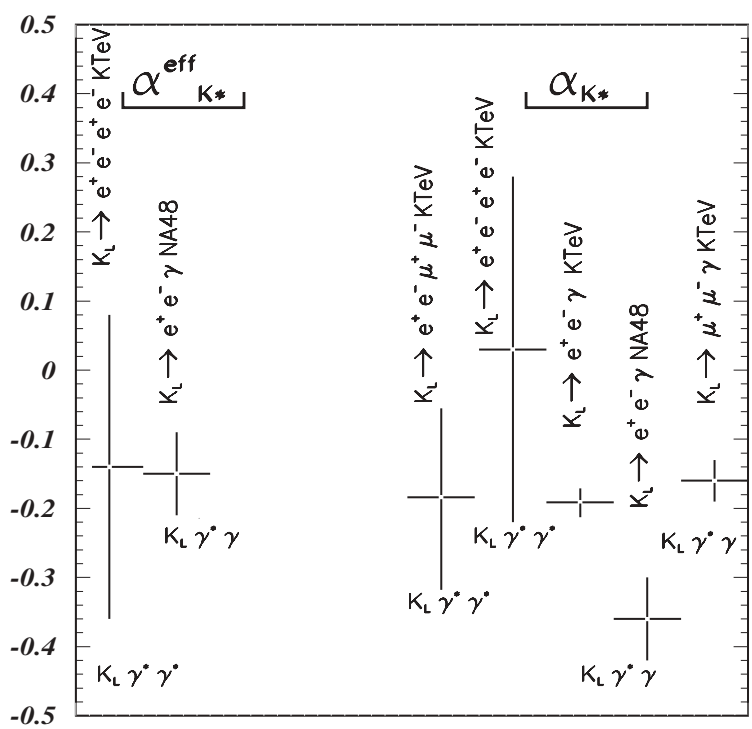
That these processes not pointlike, now clear:

Data at right from KTeV $m_{\mu\mu}$ dist. in $K_L \to \mu^+\mu^-\gamma$



There are a couple of form factor parameterizations on the market; the traditional one is Bergström, Massó, & Singer (BSM), with parameter α_{K^*}

Figure at right shows α_{K^*} from recent experiments. (Adapted from E. Halkiadakis thesis)



Agreement not inspiring but proper radiative corrections may help.

+ some issues not apparent in figure

Finally, different parameterizations give different results, *e.g.* from KTeV $K_L \to \mu\mu\gamma$:

$|ReA_{LD}^{BMS}| < 3.6 \times 10^{-5}$ but $|ReA_{LD}^{DIP}| < 2.07 \times 10^{-5}$

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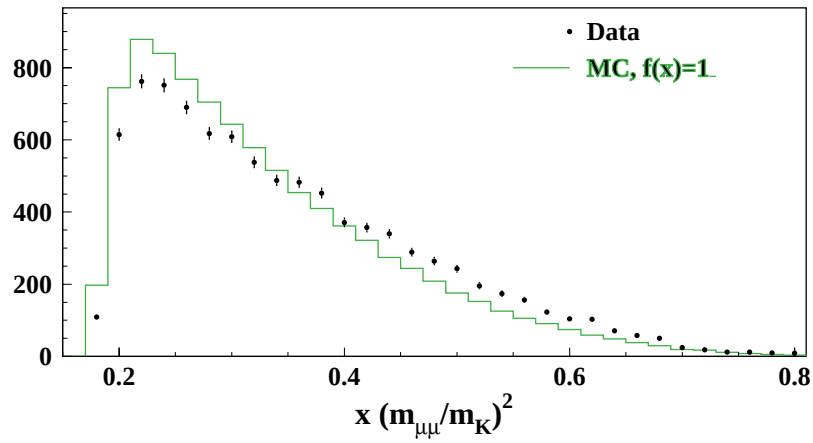

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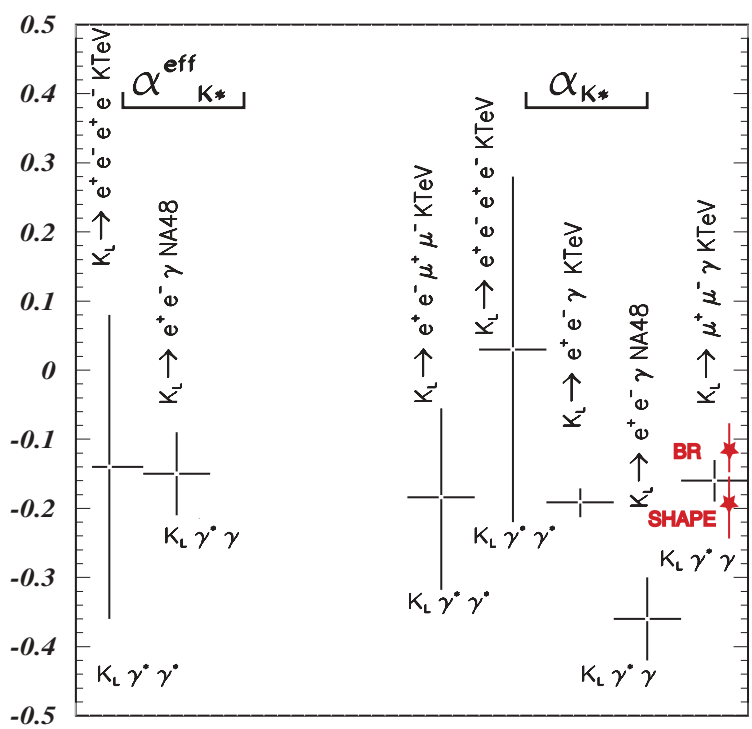

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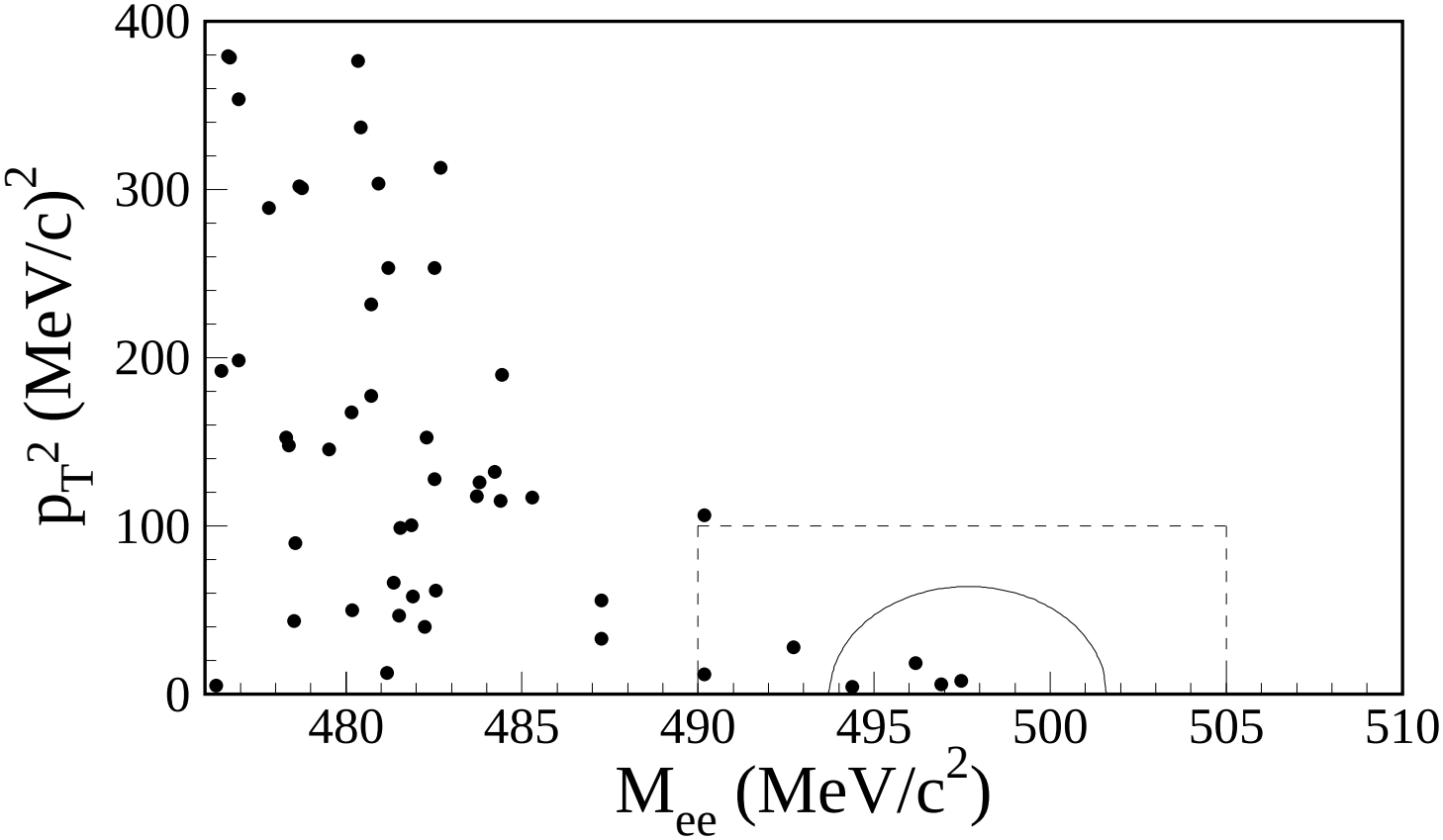
E871 Measurement of $K_L \to e^+e^-$



AGS-871 observed four $K_L \to e^+e^-$ candidates
with expected background 0.17 ± 0.10 events

They obtain $B(K_L \to e^+e^-) = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$

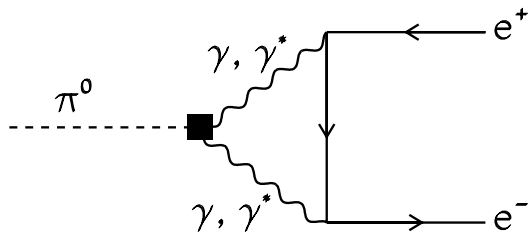
Lowest BR ever measured

Unfortunately can't be used to get short distance information.
- ironically, long-distance real part reliably calculable.
- just too big!

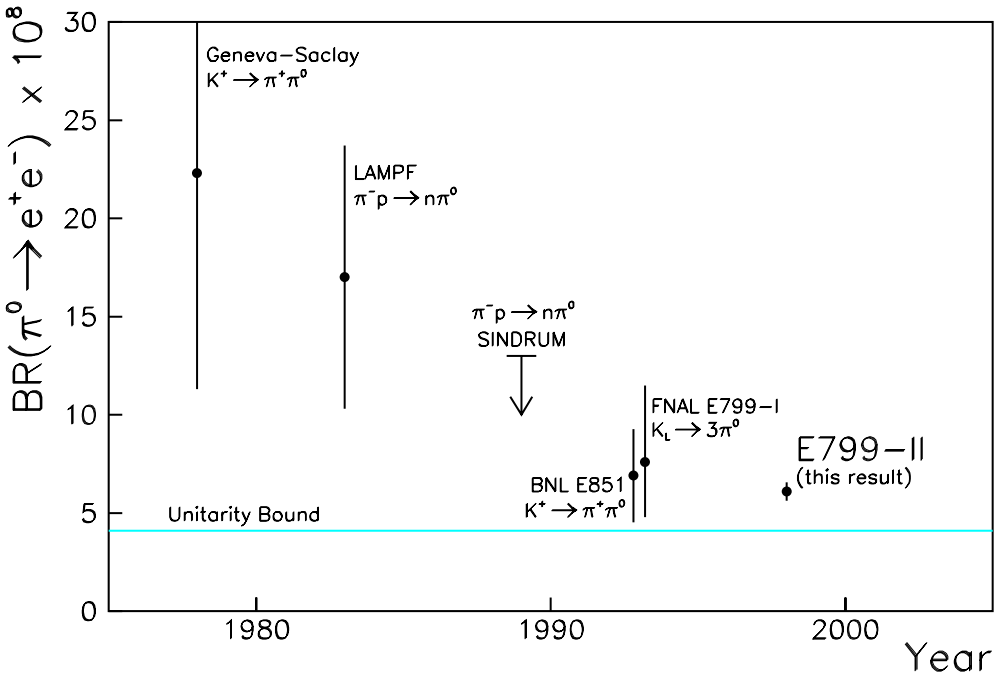
Existence proof of observation of a K decay at $< 10^{-11}$.

$\pi^0 \to e^+e^-$

Differs from $K_L \to \ell^+\ell^-$ in that there's no weak component
"Unitarity" contribution is 4.75×10^{-8}

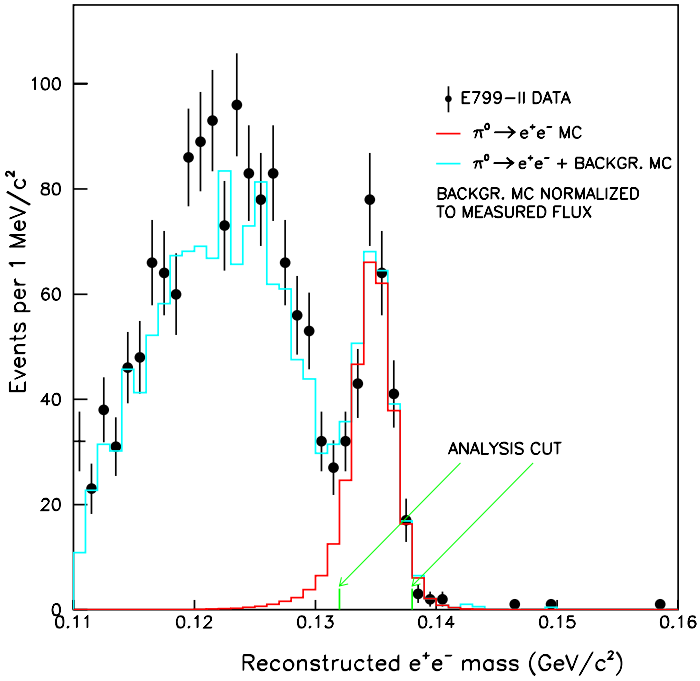


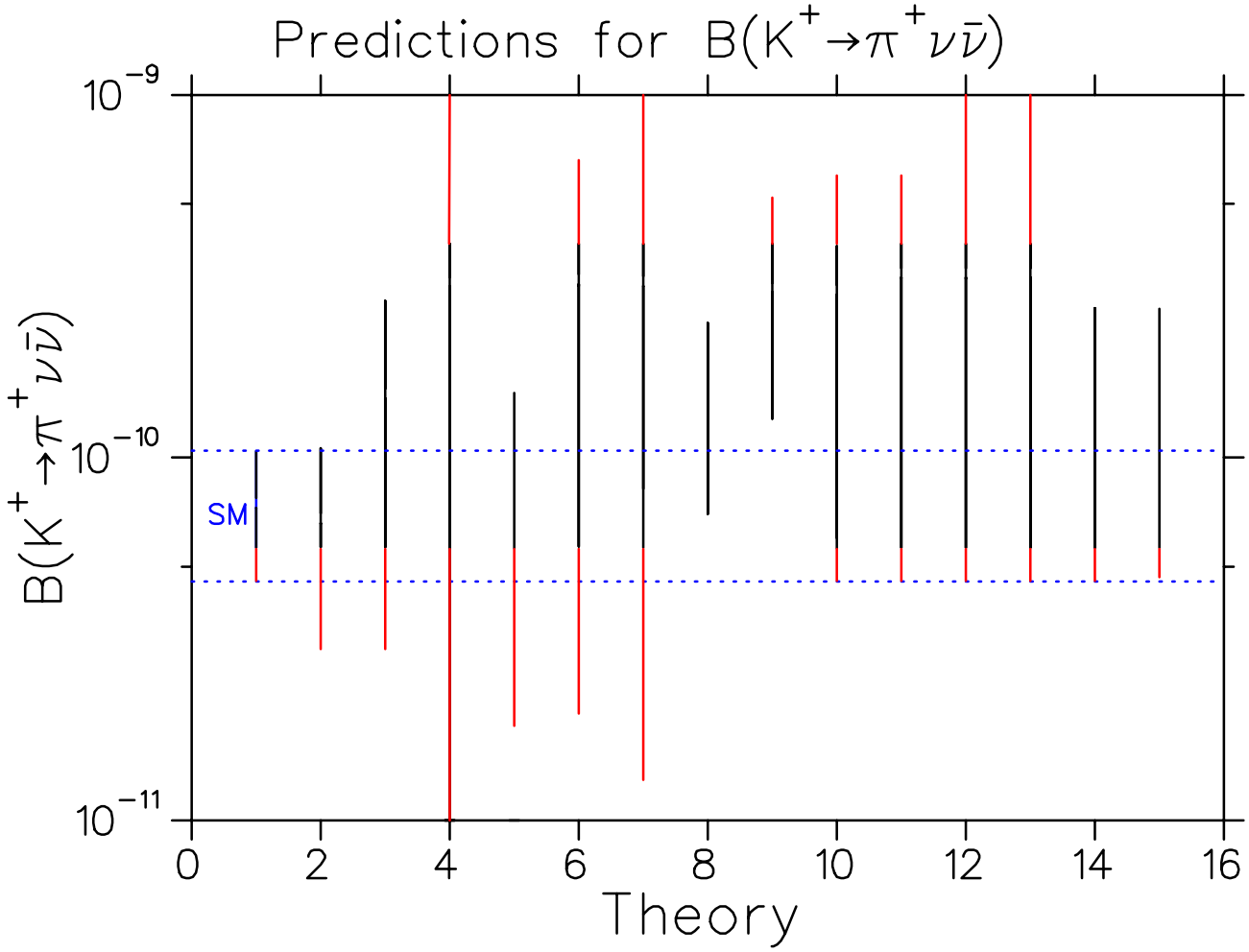
Chequered history:



Finally seen clearly in **KTeV** experiment, using tagged π^0's from $K_L \to \pi^0\pi^0\pi^0$.

Theorists can finally get to work!




Predictions for $B(K^+ \to \pi^+ \nu\bar{\nu})$
10^{-9}
10^{-10}
10^{-11}
$B(K^+ \to \pi^+ \nu\bar{\nu})$
SM
0
2
4
6
8
10
12
14
16
Theory

Predictions for $K^+ \to \pi^+ \nu\bar{\nu}$

1 Standard Model
A. J. Buras, hep-ph/0101336

2 MSSM with no new sources of flavor- or CP-violation
A.J. Buras et al., hep-ph/0007313 Nucl.Phys.B592:55,2001

3 "Generic" SUSY with minimal particle content
A.J. Buras et al., hep-ph9908371 Nucl.Phys.B566:3,2000

4 Upper limit from Z' limit given by K mass difference
H.N. Long et al., hep-ph/0104007

5 Topcolor
G. Buchalla et al., hep-ph/9510376 Phys.Rev.D53:5185,1996

6 Topcolor-assisted Technicolor models
Z. Xiao et al., hep-ph/9903348 Eur.Phys.J.C10:51,1999

7 Multiscale Walking Technicolor Model
Z. Xiao et al., hep-ph/9903347 Eur.J.Phys.C7:487,1999

8 $SU(2)_L \times SU(2)_R$ Higgs
M. Chanowitz, hep-ph/9905478

9 Four generation model
H. Hattori et al., hep-ph/9908447

10 Lepto-quarks
K. Agashe & M. Graesser, hep-ph/9510439
Phys.Rev.D54,4445,1996

11 R-parity-violating SUSY
G. Bhattacharyya & A. Raychaudhuri hep-ph/9712245
Phys.Rev.D57:3837,1998

12 Extension of SM to gauge theory of J=0 mesons
B. Machet, hep-ph/9907306 Mod.Phys.Lett.A15:579-586,2000

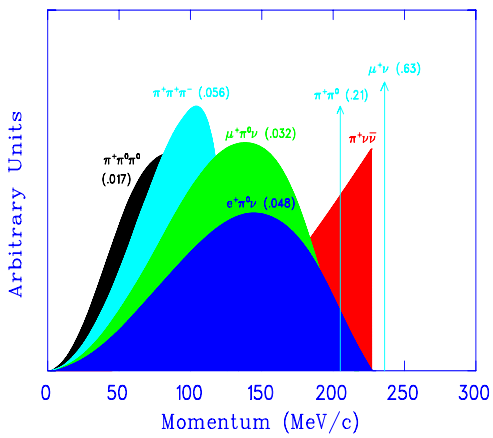
13 Multi Higgs Multiplet Model
Y. Grossman, Nucl. Phys. B426, 355 (1994)

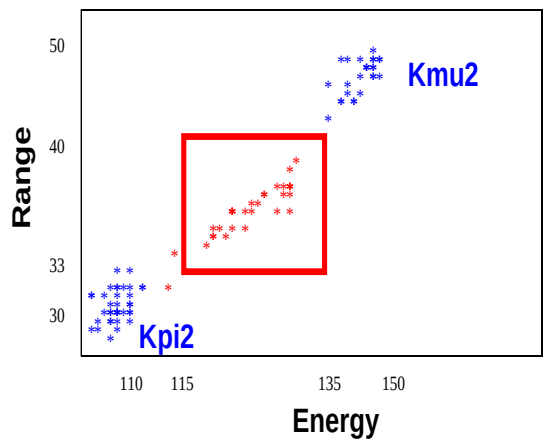
14 Light sgoldstinos
D.S.Gorbunov & V.A. Rubakov, hep-ph/0012033
Phys.Rev.D64:054008,2001

15 Familon
F. Wilczek, Phys.Rev.Lett.49,1549,1982

Experimental Considerations for $K^+ \to \pi^+ \nu\overline{\nu}$

- **3 BODY DECAY:**
  2 missing particles
  no kinematic constraints on the π^+ $(0 \leq p_{\pi^+} \leq 227 MeV/c)$
  must veto to $\leq 10^{-3}$ / extra particle
  particle identification is essential.





Note: For $p \geq 205 MeV/c$: no π^+ from other (significant) decay modes other than $\pi\nu\overline{\nu}$!

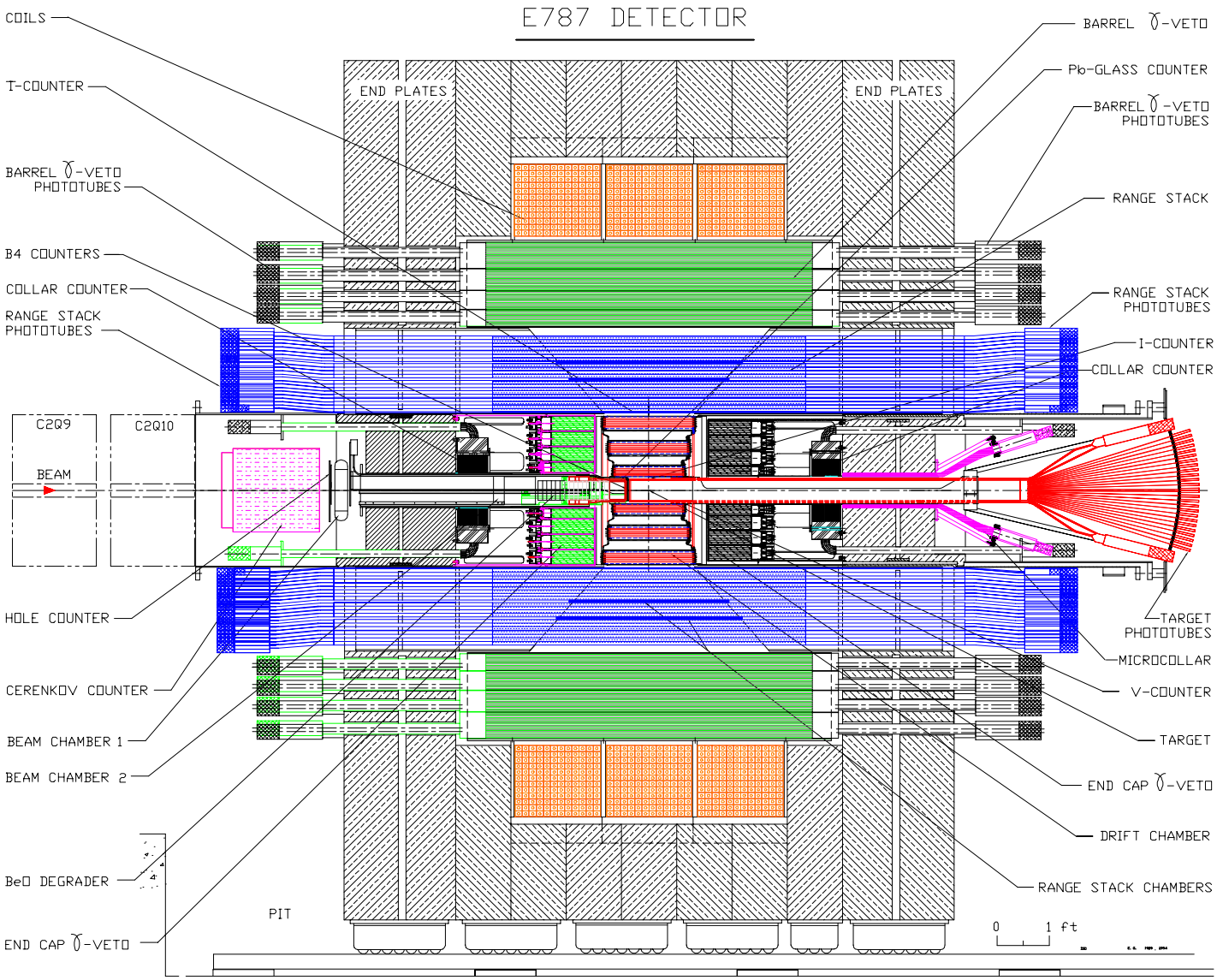
- **Backgrounds:**

decay mode	BR [%]	particle id	γ veto	extra tracks	kinematic suppression
$K^+ \to \pi^+\pi^0$	**0.21**	-	$\surd\surd$	-	$\surd$
$K^+ \to \mu^+\nu$	**0.63**	$\surd$	-	-	$\surd$
$K^+ \to \mu^+\nu\gamma$	$5 \cdot 10^{-3}$	$\surd$	$\surd$	-	-
$K^+ \to \pi^0\mu^+\nu$	**0.032**	$\surd$	$\surd\surd$	-	-
$K^+ \to \pi^0 e^+\nu$	**0.048**	$\surd$	$\surd\surd$	-	-
$K^+ \to \pi^+\pi^-\pi^+$	**0.056**	-	-	$\surd$	$\surd\surd$

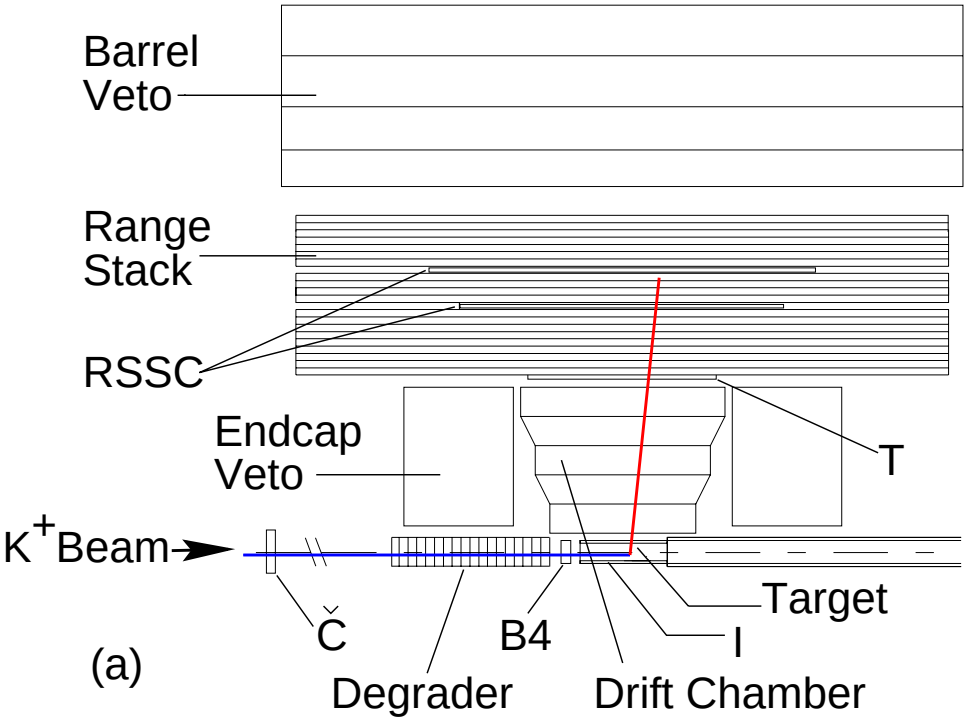
E787

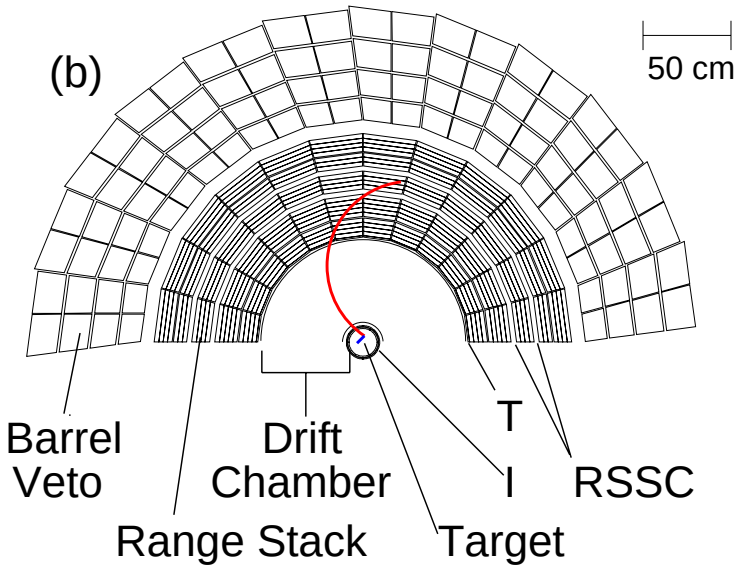
Study of $K^+ \to \pi^+ \nu\bar{\nu}$ and related processes

BNL/Fukui/KEK/Kyoto/Osaka/Princeton/TRIUMF



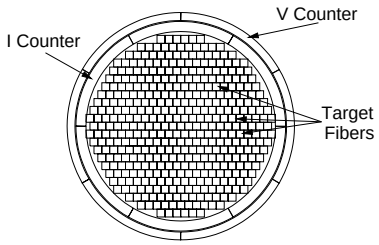
E787 Spectrometer

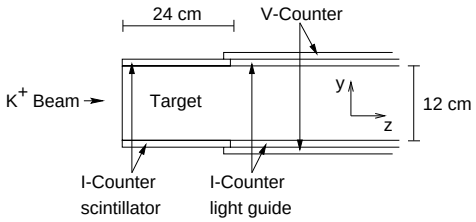




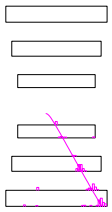
E787 Technique

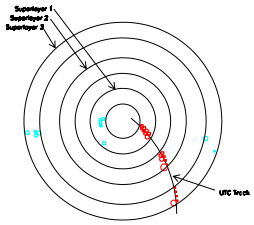
K^+ I.D.'d by beam counters, stop in 400-element sci-fi target



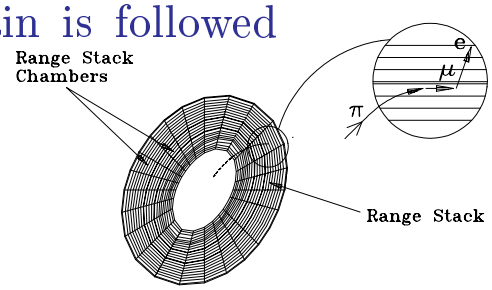


Wait 2ns for decay
Then π^+ tracked & momentum analyzed in UTC (B=1T)

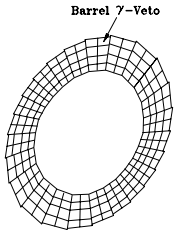


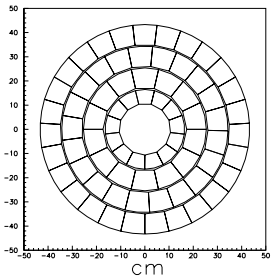


π^+ then ranges out in an Range Stack (scint. + straw ch.)
Range/energy/momentum can be compared.
Also $\pi^+ \to \mu^+ \to e^+$ decay chain is followed



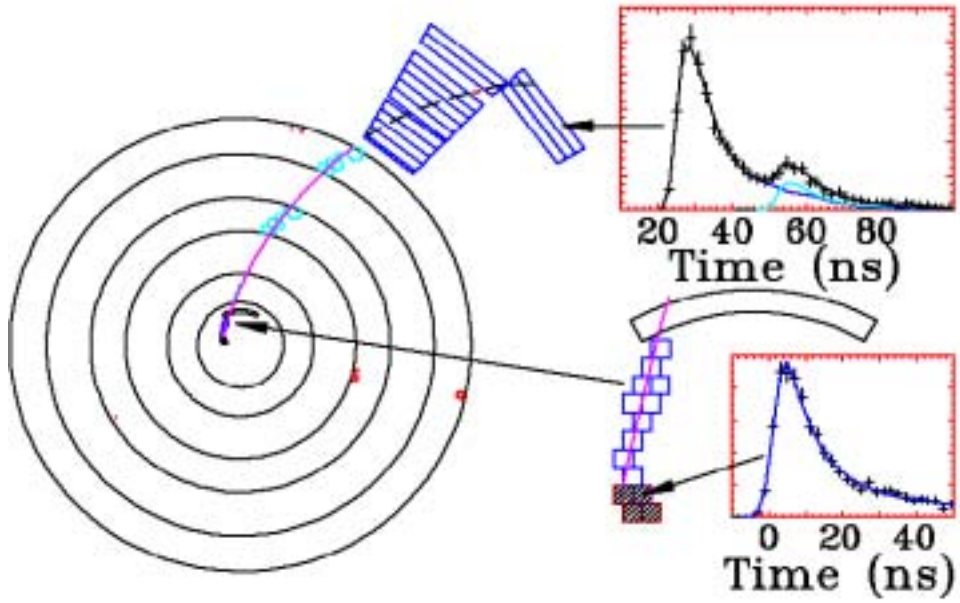
Hermetic photon vetoing via barrel Pb-scint system (BV)
+ CsI-pure endcaps (EC)



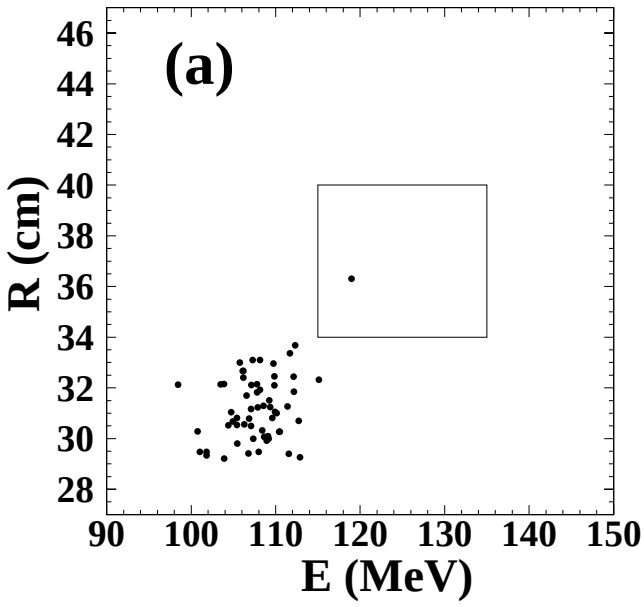


Get $> 10^6 : 1$ π^0 rejection, $> 10^8 : 1$ μ^+ rejection
Also very good kinematic rejection of two-body decays.

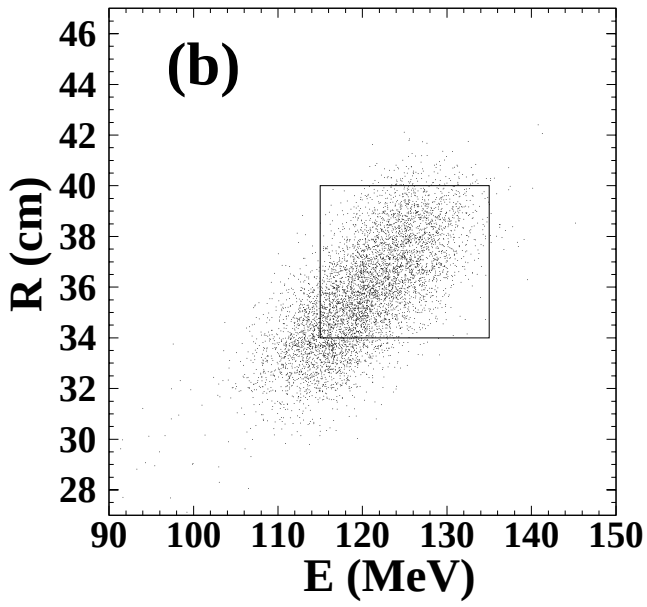
$K^+ \to \pi^+ \nu\bar{\nu}$ event



Data



Monte Carlo

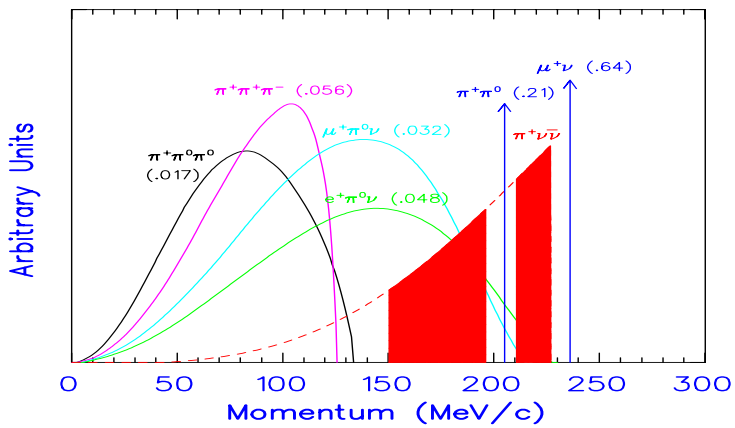


- Probability for the event to be one of the known backgrounds is very low.

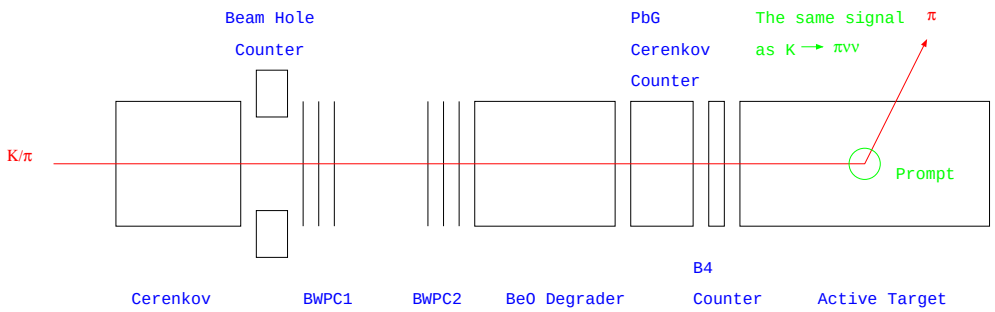
Collecting K^+ decays

Triggering E787, one encounters -

K^+ decays:

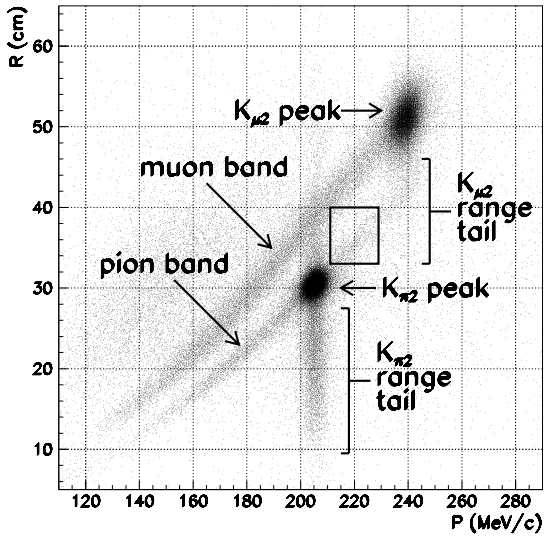


& beam scatters:

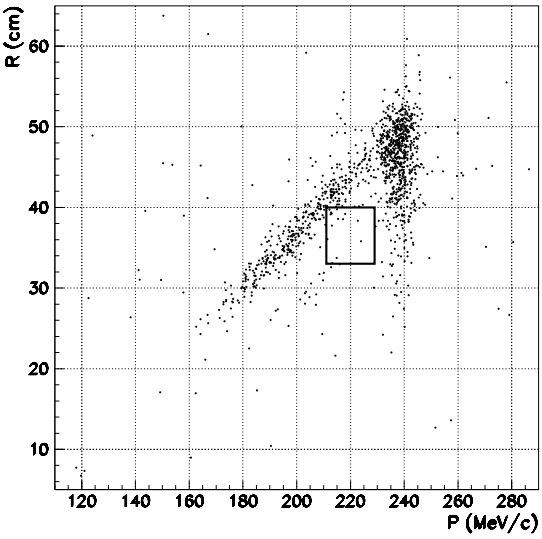


One collects -

With 1-chgd tk trigger:



With E787 trigger:



E787 Analysis

To establish a $K^+ \to \pi^+ \nu \bar{\nu}$ signal at $\sim 10^{-10}$
- must *measure* background at 10^{-11} level.

"Blind" analysis
- signal region hidden (by inverting cuts) while cuts developed
- cuts developed on $\frac{1}{3}$ of the data, but consequent background levels measured in an unbiased fashion on the remaining $\frac{2}{3}$

Bifurcated background calculation
- *A priori* identification of background sources
- same data set for backgound studies & signal search
- 2 "orthogonal" cuts with high rejection for each background
- measurement of residual background @ $10^{-3} - 10^{-2}$ event level

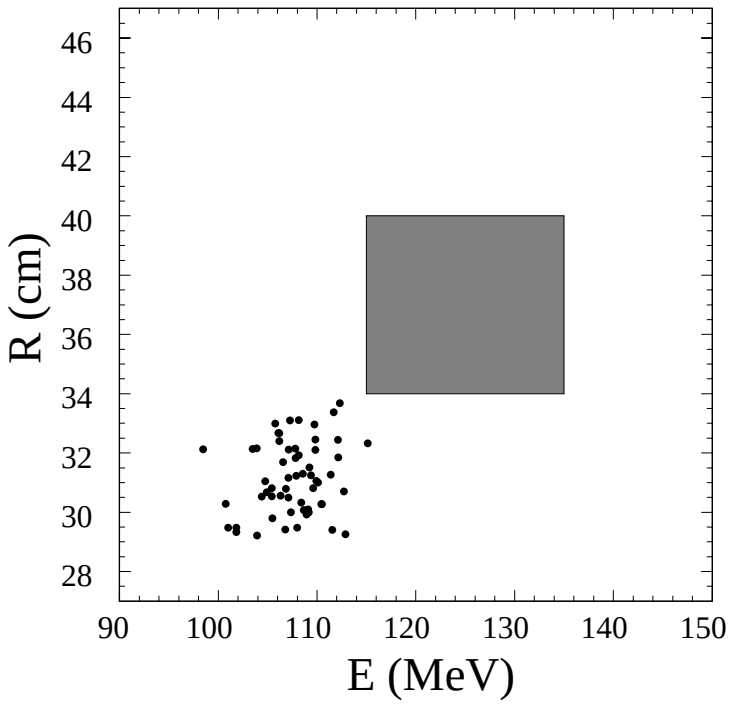
Acceptance measurement based primarily on data
- MC used only for trigger, solid angle & phase space
- crosscheck by measuring $B\left(K^+ \to \pi^+ \pi^0\right)$

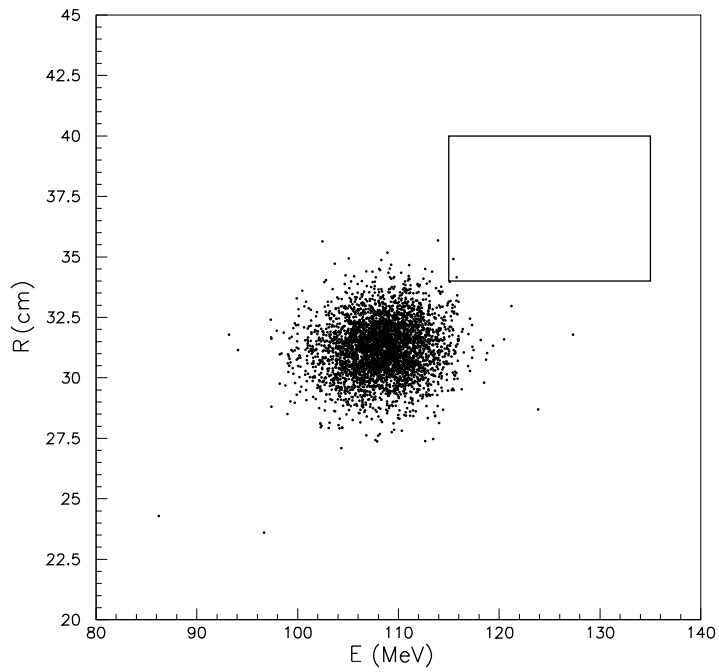
Correlation studies
- loosen cuts to uncover correlations
- move correlated cuts to setup

Background calculation checks near signal region
- predict levels & compare with observation

Likelihood analysis for assessing candidate events
- use predetermined likelihood functions

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





Method of orthogonal cut sets (works if no correlations)

- Look at $K\pi 2$ kinematic peak after all other cuts.
- From this, given the resolution function, can predict the $K\pi 2$ background in the signal region.
- Get resolution function from events *with* photons; events from primary data stream. automatically takes many effects into account
- Develop cuts on limited fraction of available data.
- Check background estimates on remainder of data, assures that estimate is unbiased.
- Confirm orthogonality by loosening cut sets

Results from 1995–98 data sets

Background	#events in signal region	
	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

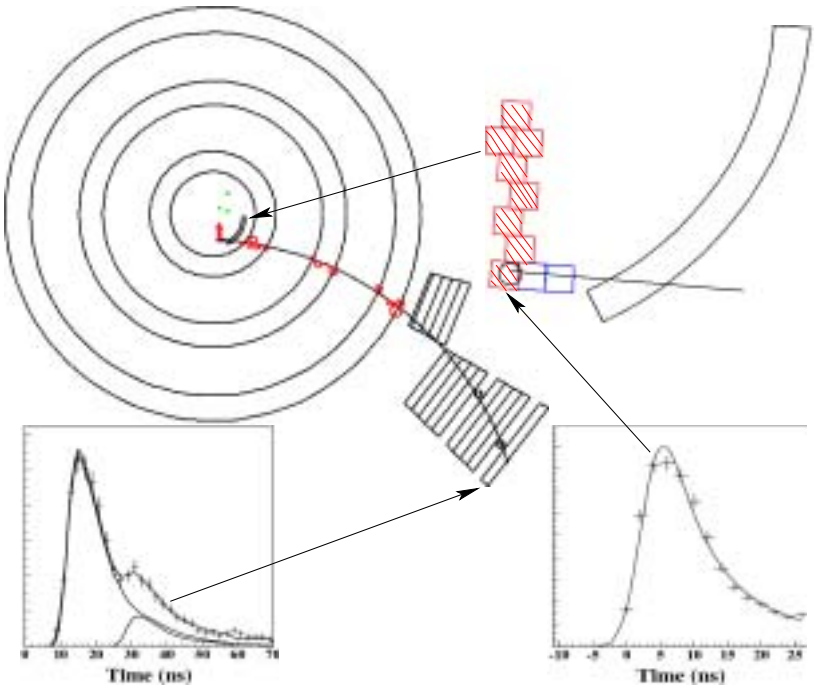
K^+ stops recorded:

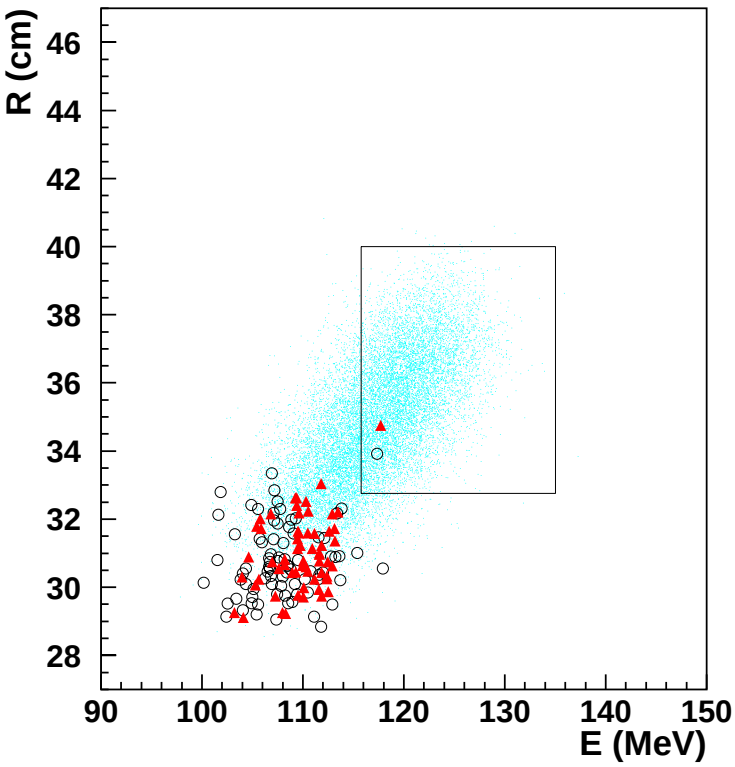
3.2×10^{12} (1995–97)

2.7×10^{12} (1998)

Test by measuring BR($K^+ \to \pi^+ \pi^0$)

Further Evidence for the Decay $K^+ \to \pi^+ \nu \bar{\nu}$





The $K^+ \to \pi^+ \nu\bar{\nu}$ candidates

Event	Kinematic quantities P(MeV/c)	R(cm)	E(MeV)	$f_i^\dagger$	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

† f_i are relative S/B measures here computed under the assumption of SM branching ratio for $K^+ \to \pi^+ \nu\bar{\nu}$. The extracted results do not depend on this assumption.

New event is not as clean as the first one, but background integrated to its position is only 0.022 events. There is a small amount of excess energy in the target, far below the cut threshold. Also K^+ decay time is earlier than for first event.

Event B2 is interesting, although since it is outside the signal region, it is not considered in the final, published, branching ratio measurement.

- Looks very good, fails only $\pi \to \mu$ cut, mainly due to small t_π
- Consistent with bkg expectations, but could be "signal contamination" of background sample.
- Can't post-analyze in our method, but with reasonable assumptions, adding it in raise the BR or at least leave it unchanged.
- Suggests the observed BR is not an upward fluctuation.

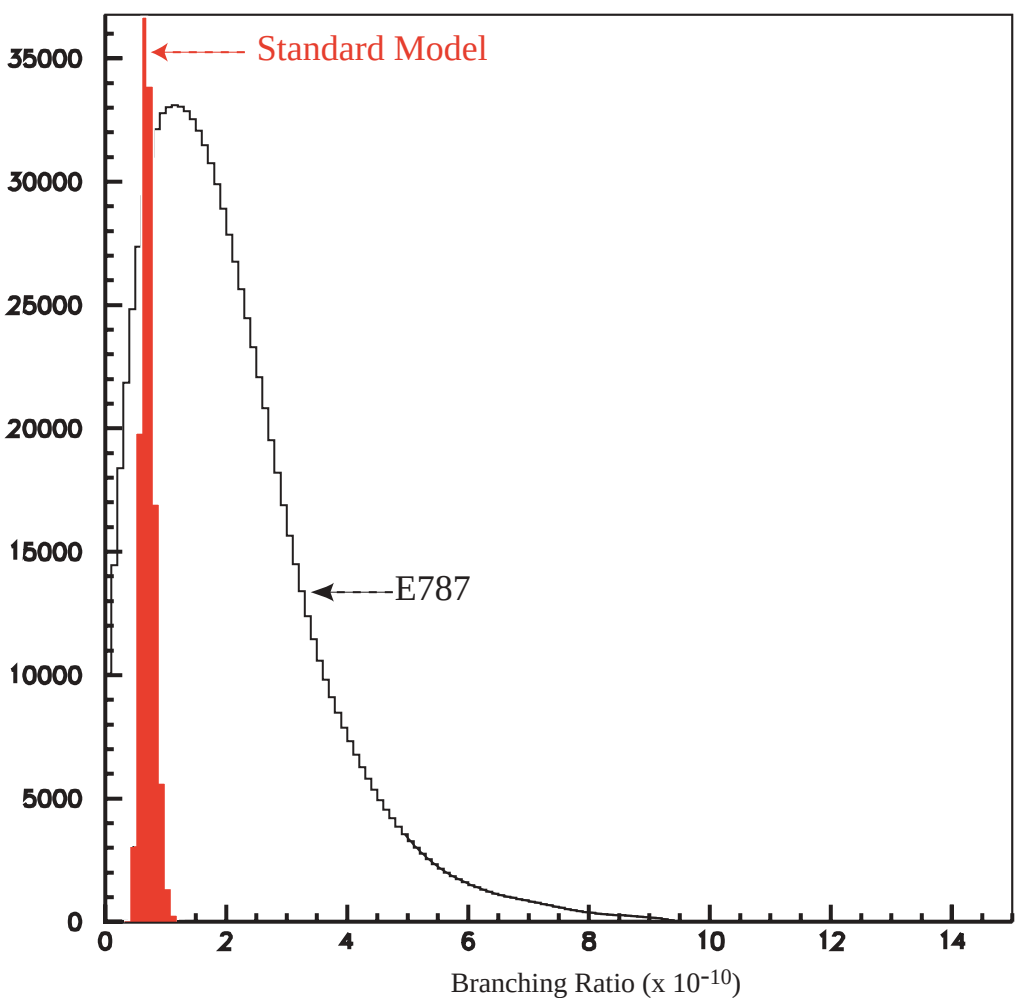
Branching ratio

We obtain $B(K^+ \to \pi^+ \nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$ @ 68% CL

c.f. SM phenomenological fit $(0.75 \pm 0.29) \times 10^{-10}$

84% CL limits (68% CL int.)	90% CL limits (80% CL int.)	95% CL limits (90% CL int.)	9% CL limits (95% CL int.)
[0.75, 3.32]	[0.56, 3.89]	[0.37, 4.69]	[0.13, 6.45]

Probability observed signal due entirely to background is 0.02%



Result agrees with S.M. at the $\sim 20\%$ level

Constraints on V_{td}

Can extract constraints on V_{td} from this result.

Assuming unitarity and taking $\bar{m}_t(m_t) = 166 \pm 5\text{GeV}/c$, $V_{cb} = 0.041 \pm 0.002$, but assuming **nothing** about V_{ub} or ϵ_K,

E787 result implies:

$0.007 < |V_{td}| < 0.030$ at 68% CL

$0.005 < |V_{td}|$ at 90% CL

$|V_{td}| < 0.033$ at 90% CL

$-0.022 < |ReV_{td}| < 0.030$ at 68% CL

$|ImV_{td}| < 0.028$ at 90% CL

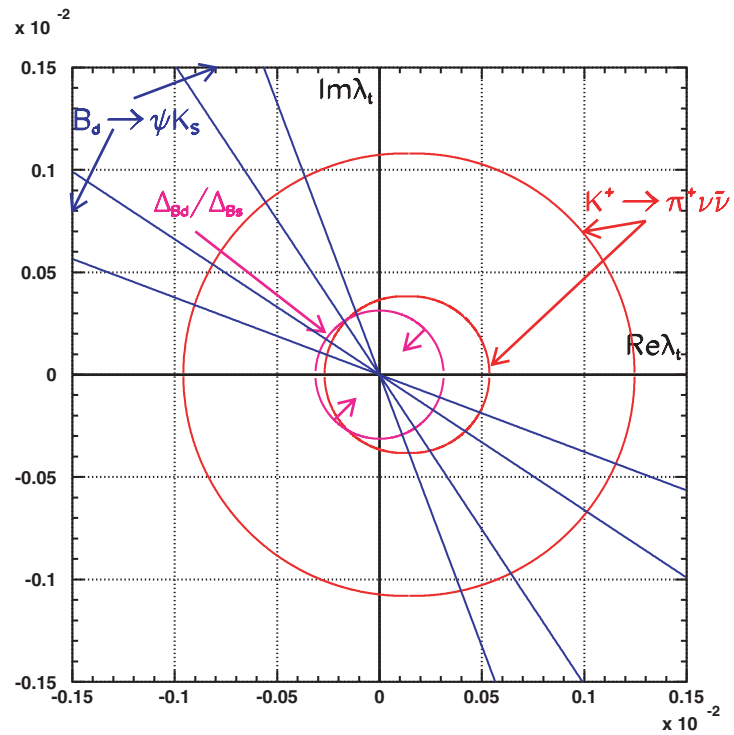
These limits are about an order of magnitude looser than the current phenomenology ($V_{td} = 0.0071 - 0.0032i$ in the 2002 PDB) but assume less.

Constraints on λ_t from E787

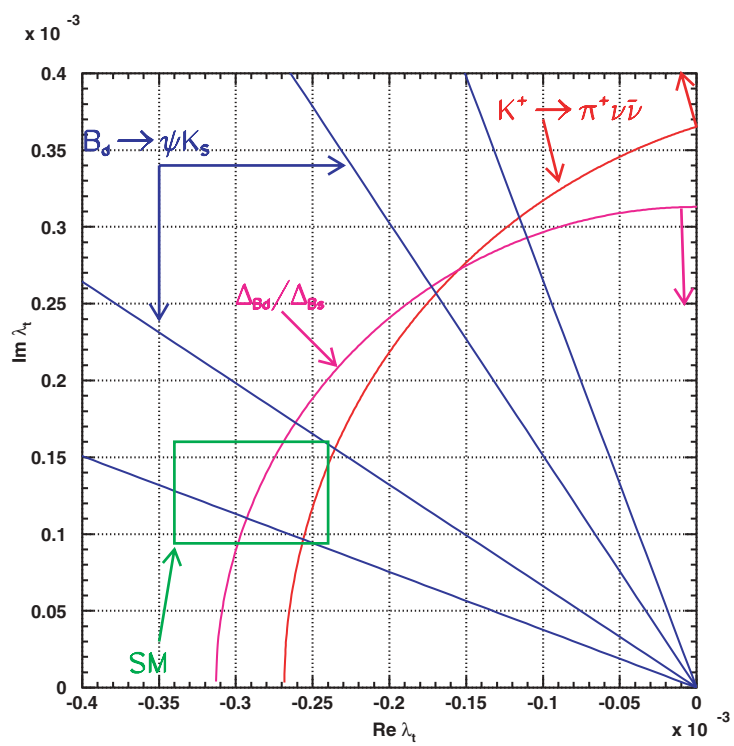
With **no** input from B system, ϵ_K or ϵ'/ϵ can get limits on $\lambda_t \equiv V_{ts}^* V_{td}$:

$$2.9 \times 10^{-4} < |\lambda_t| < 1.2 \times 10^{-3} \text{ at } 68\% \text{ CL}$$
$$-0.88 \times 10^{-3} < Re(\lambda_t) < 1.2 \times 10^{-3} \text{ at } 68\% \text{ CL}$$
$$Im(\lambda_t) < 1.1 \times 10^{-3} \text{ at } 90\% \text{ CL}$$

Allowed region is roughly a torus



$K^+\pi^+\nu\bar{\nu}$ pulls outward, while $\bar{B} - B$ mixing pulls inward



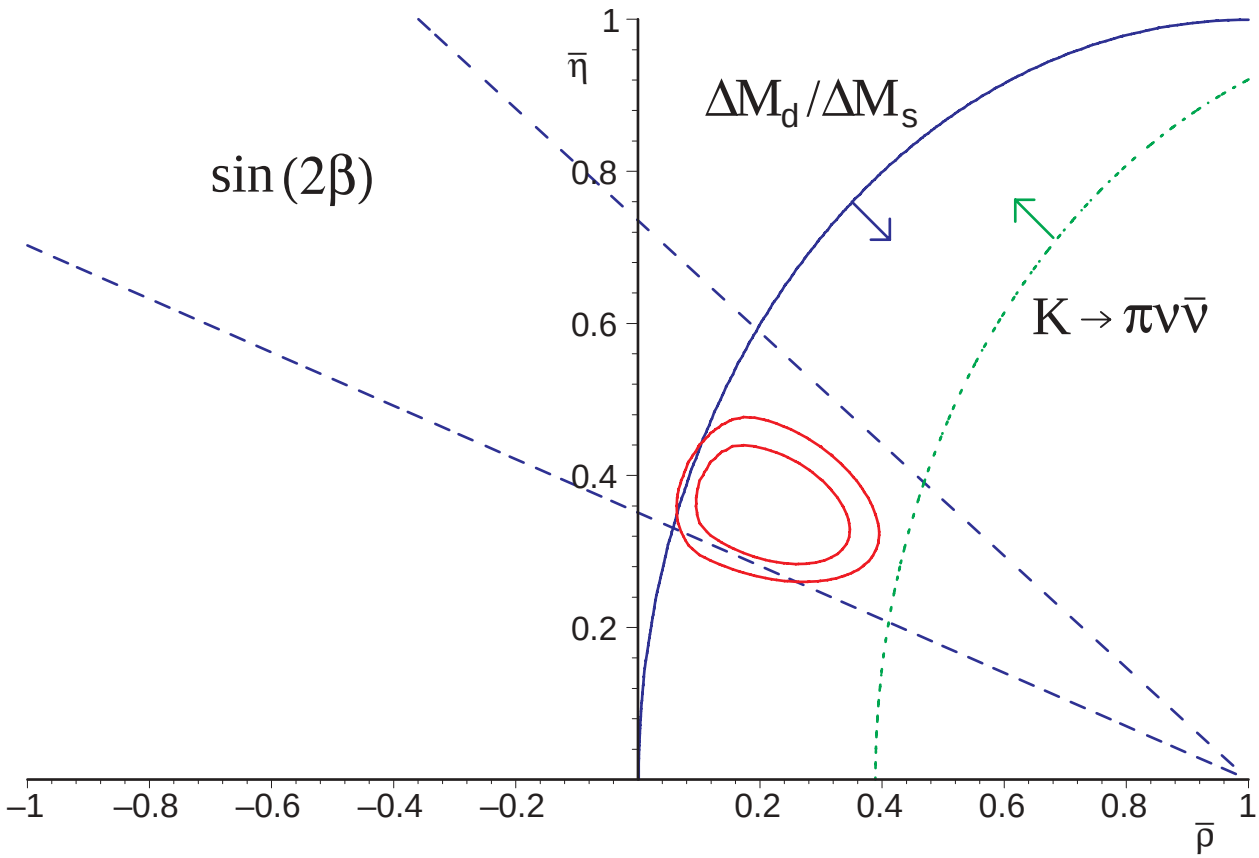
Unitarity plane with "clean" input only

Instructive to look at the unitarity plane information from clean variables only:

Ratio of $\bar{B}_d - B_d$ mixing to $\bar{B}_s - B_s$ mixing

$sin(2\beta)$ from B-factories

New E787 result

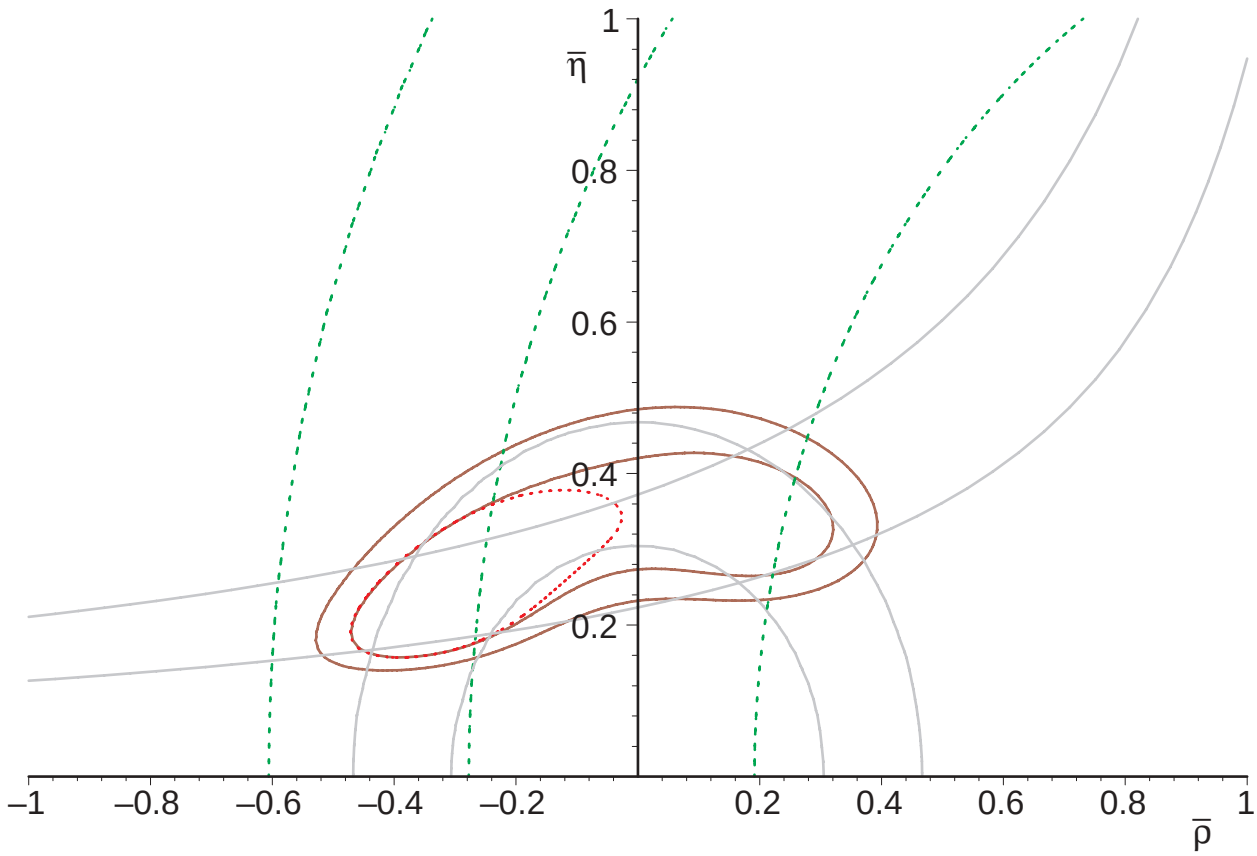


90% CL limits from quantities with very small theoretical uncertainty. 68% and 90% contours from usual unitarity fit shown in red. (From G. D'Ambrosio & G. Isidori hep-ph/0112135)

Unitarity plane without $\bar{B} - B$ mixing

Another exercise excludes $\bar{B} - B$ mixing
Input is

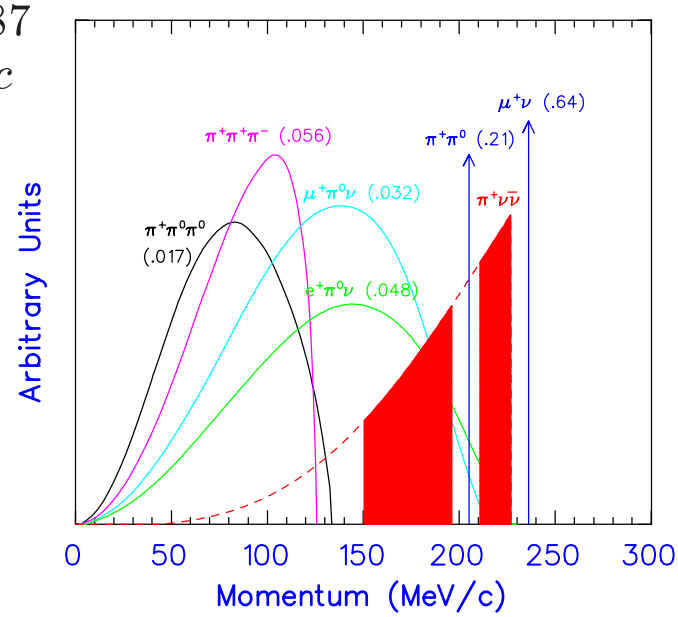
ϵ_K
$|V_{ub}/V_{cb}|$
New E787 result

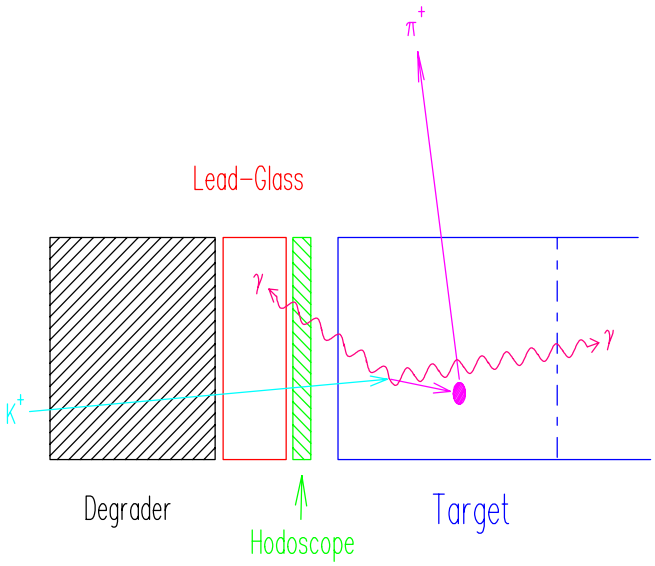


68% and 90% contours shown in red.
Dashed contour from improvement of E787 by factor two.
(From G. D'Ambrosio & G. Isidori hep-ph/0112135)

$K^+ \to \pi^+ \nu\bar{\nu}$ "below the $K\pi 2$"

$\approx$ all $K^+ \to \pi^+ \nu\bar{\nu}$ sensitivity in E787 in kinematic region $P_{\pi^+} > 205\text{MeV}/c$
Softer p_{π^+} region suffers from $K^+ \to \pi^+ \pi^0$ downshift + correlated γ inefficiency:





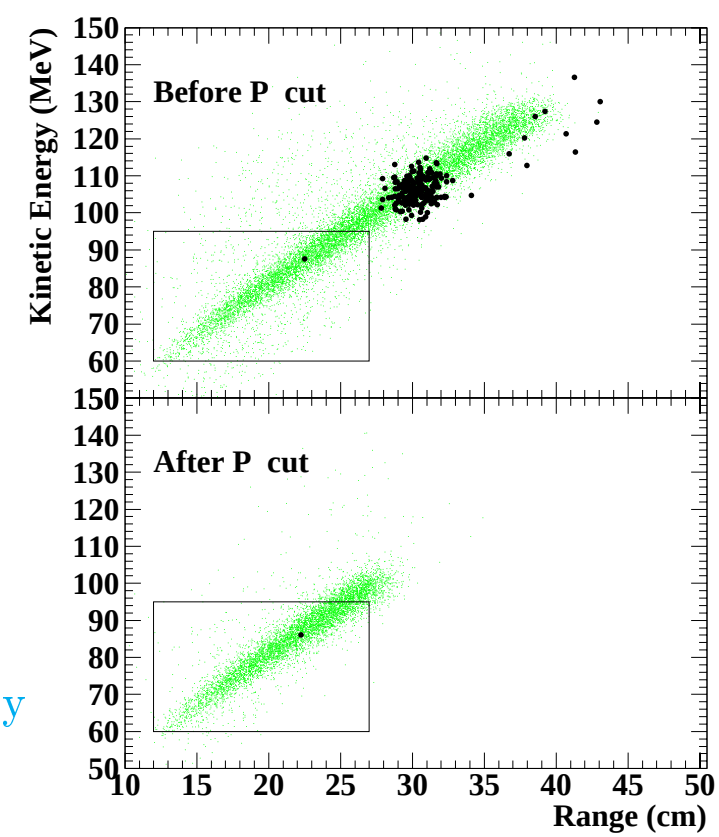
Correlation between photon veto and nuclear interactions

Analysis more difficult than for "above the $K\pi 2$", but acceptance potentially larger. New techniques developed in analysis of 1996 pnn2 data allowed s.e.s of $\sim 10^{-9}$, with calc'd. bckgnd of 0.73 evts.

One event is observed, consistent with background. Need factor ~ 10 additional rejection to get S:B = 1:1.

E949: factor 3 from BV liner, Similar factor from new vetoes.

First look at 1997 data - beam veto a little better, gave 60% more rejection. Shows rejection responds quickly to improvements near beam.



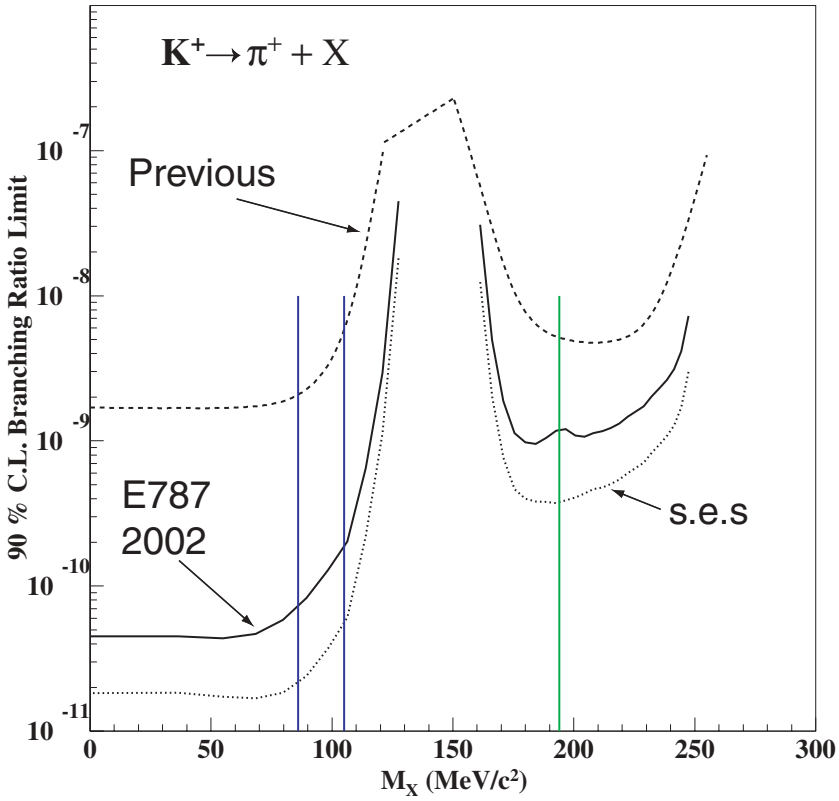
$K^+ \to \pi^+ \nu\bar{\nu}$ and Global Family Symmetry

[Wilczek(1982), Gelmini et al. (1983), Feng et al. (1998)]

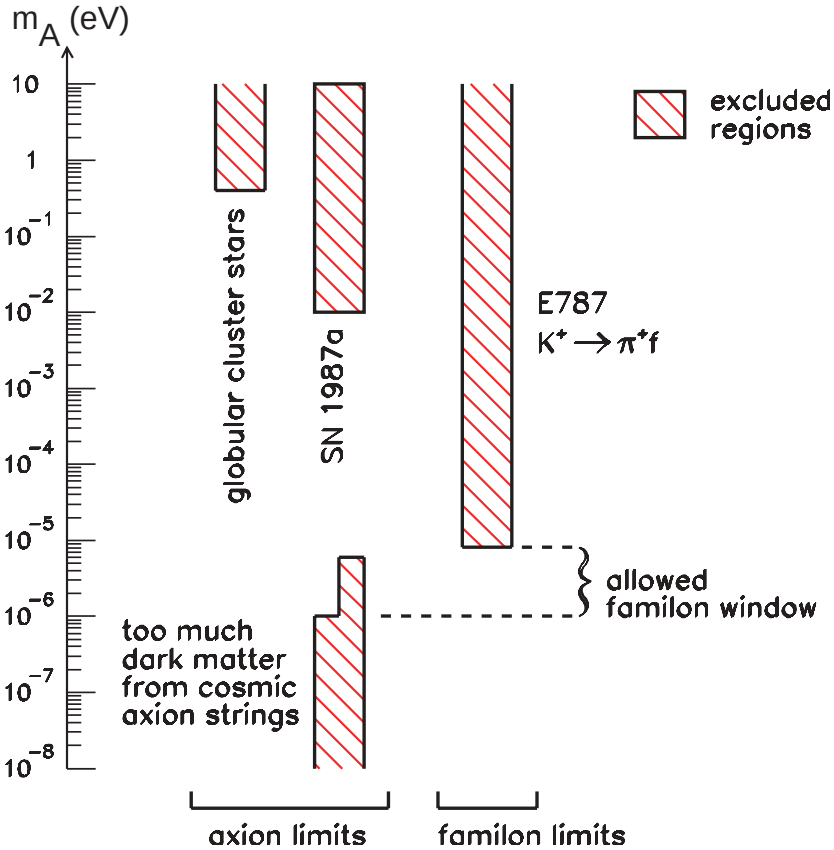
Motivation: Explain the replication of families
Postulate: Global Family Symmetry spontaneously broken at large mass scale (F) $\to$ Goldstone Boson "familon" (f)
$L_{eff} = \frac{1}{F}\partial_\mu f^\alpha J^{\mu\alpha}$: $\mu \to e + f$, $s \to d + f$, etc.

Process	**BR U. L.**	**Limit on** F (GeV)
$K^+ \to \pi^+ \nu\bar{\nu}$ (E787 2002)	5.9×10^{-11}	$F^V_{sd} > 7.7 \times 10^{11}$
$\mu^+ \to e^+ f$ (Jodidio 1986)	2.6×10^{-6}	$F^V_{\mu e} > 5.5 \times 10^9$
$\mu^+ \to e^+ \gamma f$ (Bolton 1988)	1.1×10^{-9}	$F_{\mu e} > 3.1 \times 10^9$
$\tau^- \to e^- f$ (ARGUS 1995)	2.6×10^{-3}	$F_{\tau e} > 3.2 \times 10^6$
$\tau^- \to \mu^- f$ (ARGUS 1995)	4.6×10^{-3}	$F_{\tau\mu} > 4.4 \times 10^6$
$B^\pm \to h^\pm f$ (CLEO 2001)	4.9×10^{-5}	$F^V_{bs(d)} > 6.4 \times 10^7$
$B^0 \to K^0_S f$ (CLEO 2001)	5.3×10^{-5}	$F^V_{bs} > 1.3 \times 10^8$
Cosmology		$10^9 < F < 10^{12}$

Limits on $K^+ \to \pi^+ X$

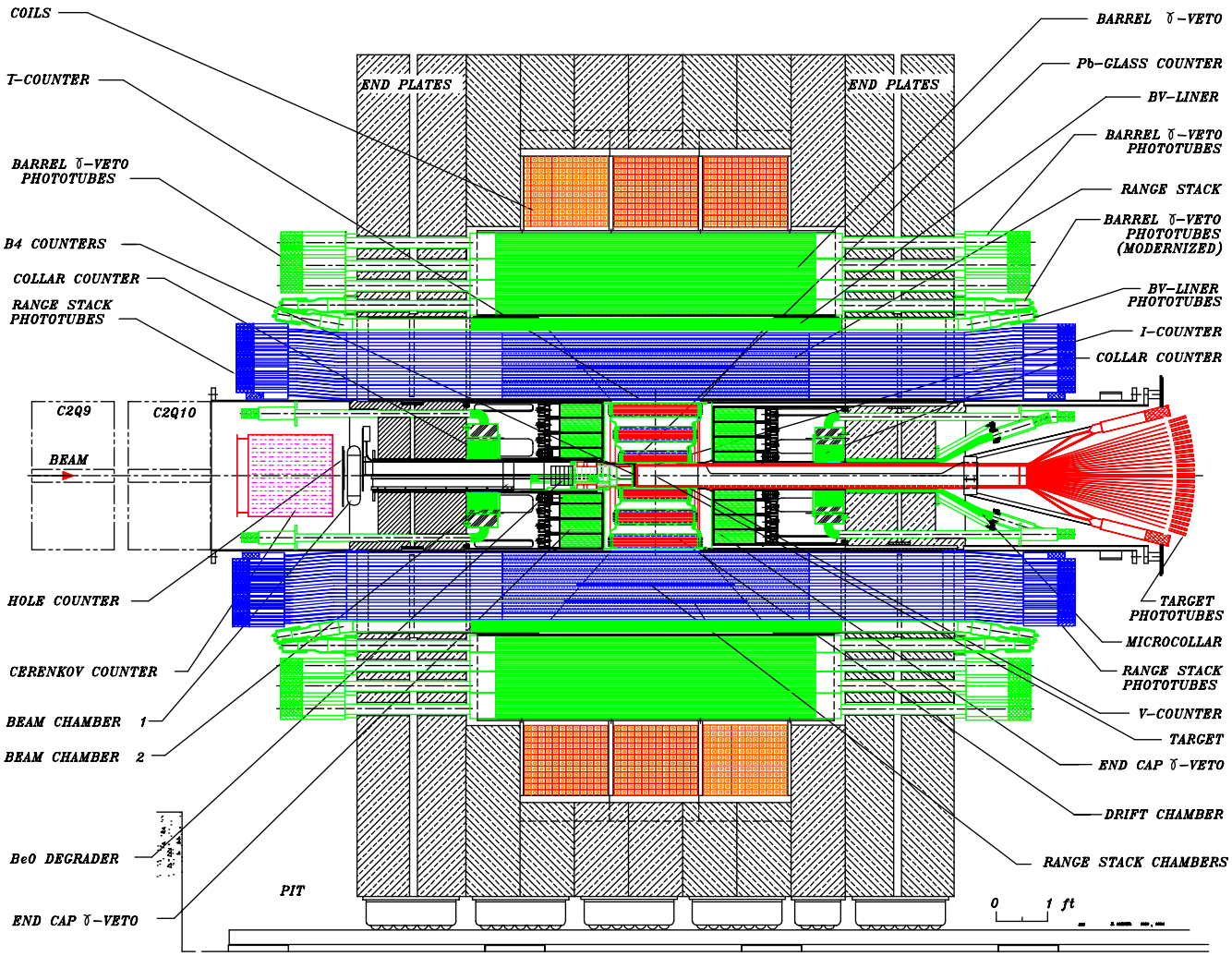


Familon / Axion mass



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

Albera, UBC, BNL, FNAL, Fukui, IHEP, INR, KEK, JAERI, Kyoto, NDAJ, New Mexico, Osaka, RCNP, TRIUMF



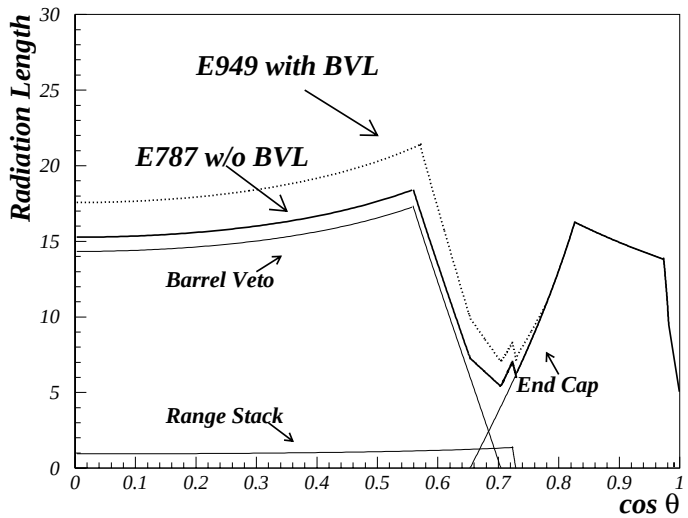
Upgrade of BNL AGS 787 -

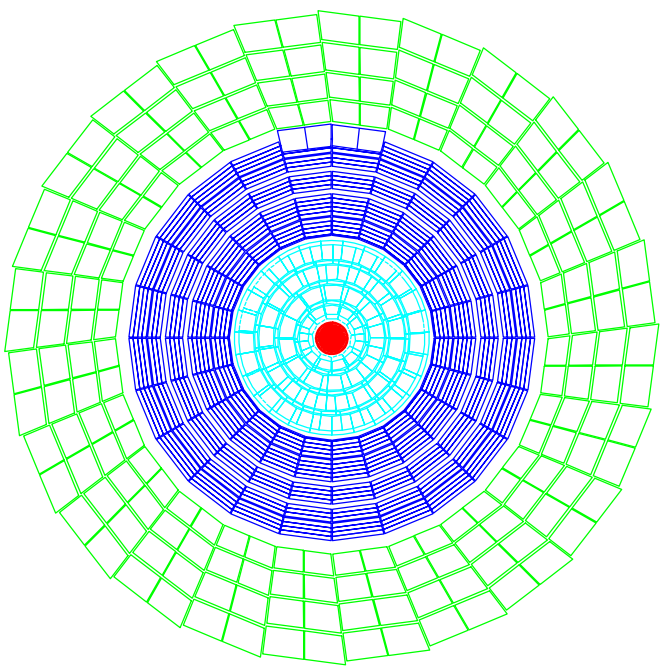
- Run with RHIC, get entire AGS proton production
- Optimize AGS spill, other conditions
- Barrel Veto Liner (BVL) shower counter
- New/improved photon veto counters around beamline
- New beam hodoscope (B4), active degrader
- Better trigger: programmable Level 0, mean-timers
- RS TDC readout (tag $\mu^+ \to e^+$ w/o transient digitizer)
- RS & BV monitoring system using LEDs
- Crate voltage monitoring system
- Terabyte disk towers to minimize tape changing

Barrel Veto Liner (BVL)

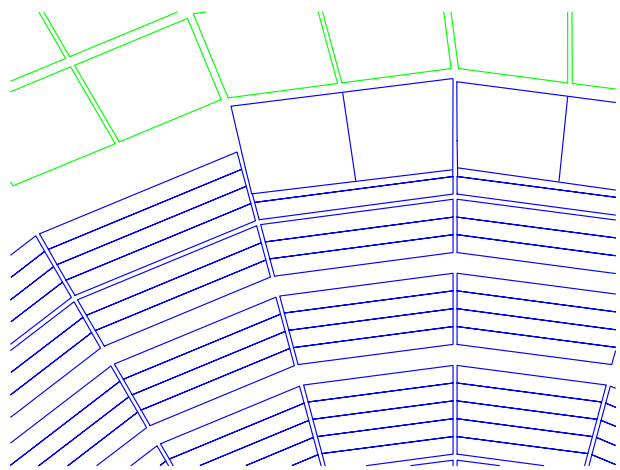
Thickens barrel veto by 2.3 X_0
Plugs 45° thin spot
Gives factor 2-3 in π^0 rejection

Largest single E949 project
Fabrication complete in 2000
Installed & tested in 2001



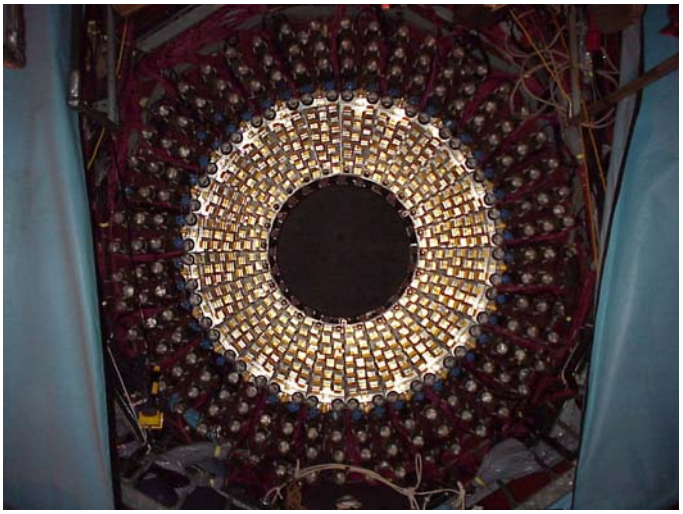


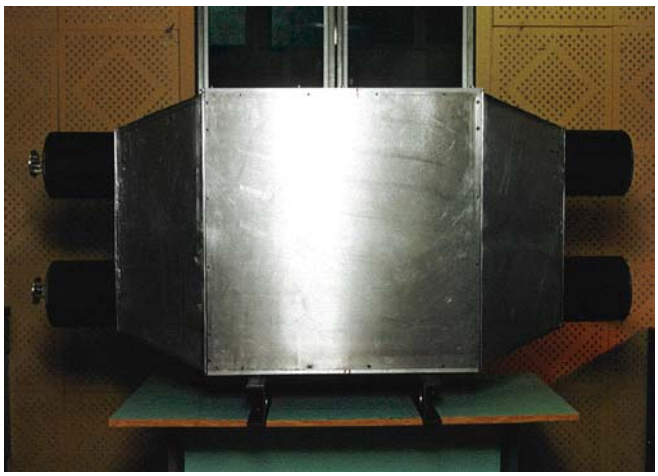
End view with 2 sectors installed



Closer view of end configuration

Status of E949





All hardware upgrades completed & installed

Commissioning run completed

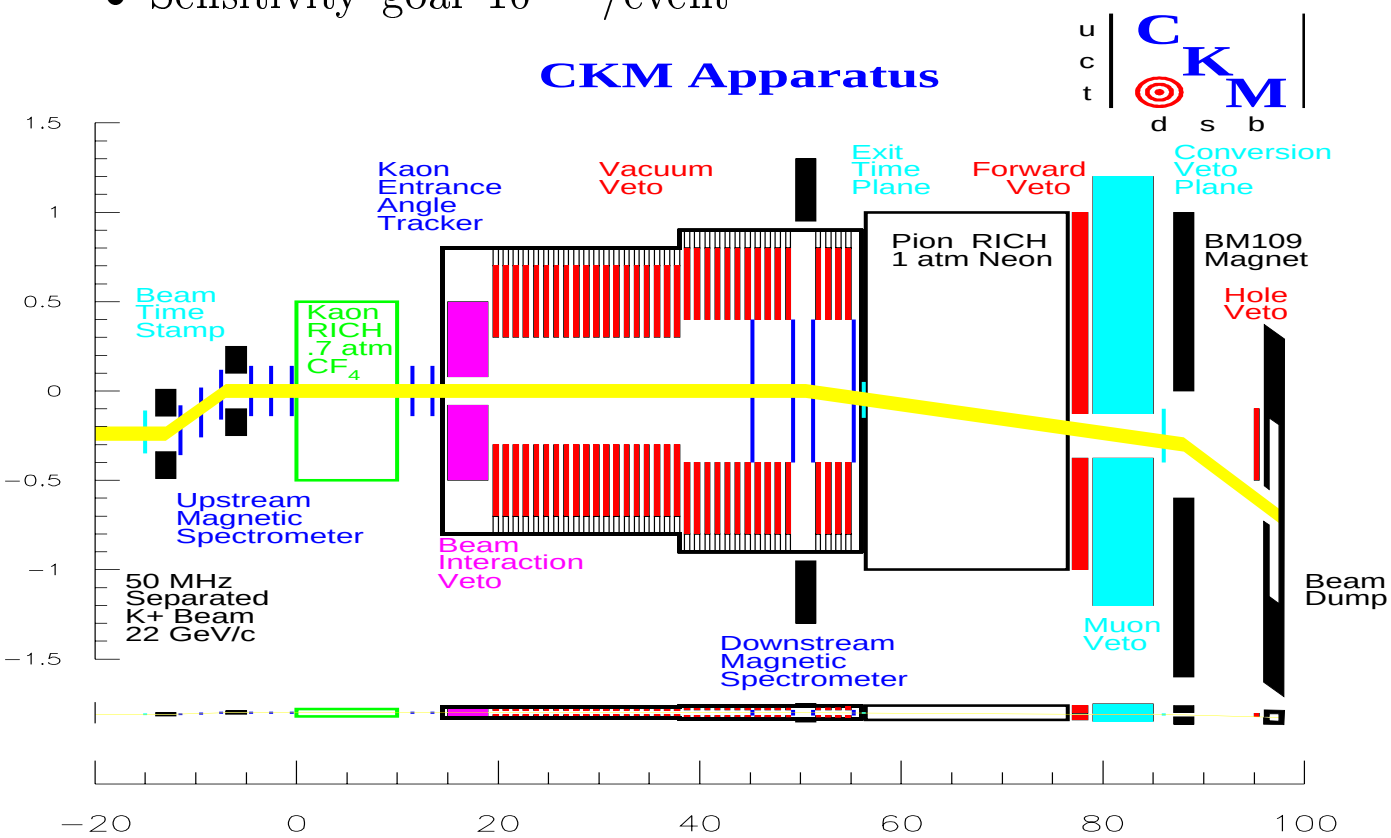
Technique for heavy ions/protons switch tested

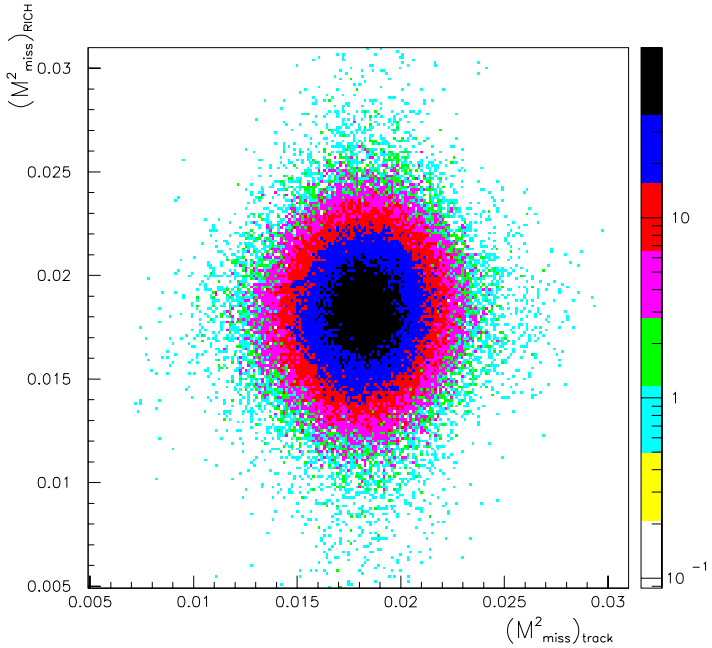
12 week data run (w/o RHIC) in Mar-June 2002

Waiting for funding of the remaining 48 weeks

CKM $K^+ \to \pi^+ \nu\bar{\nu}$ Experiment

- New in-flight decay technique
- Particle ID: RICH vs spectrometer measurement of p
- Sensitivity goal 10^{-12}/event





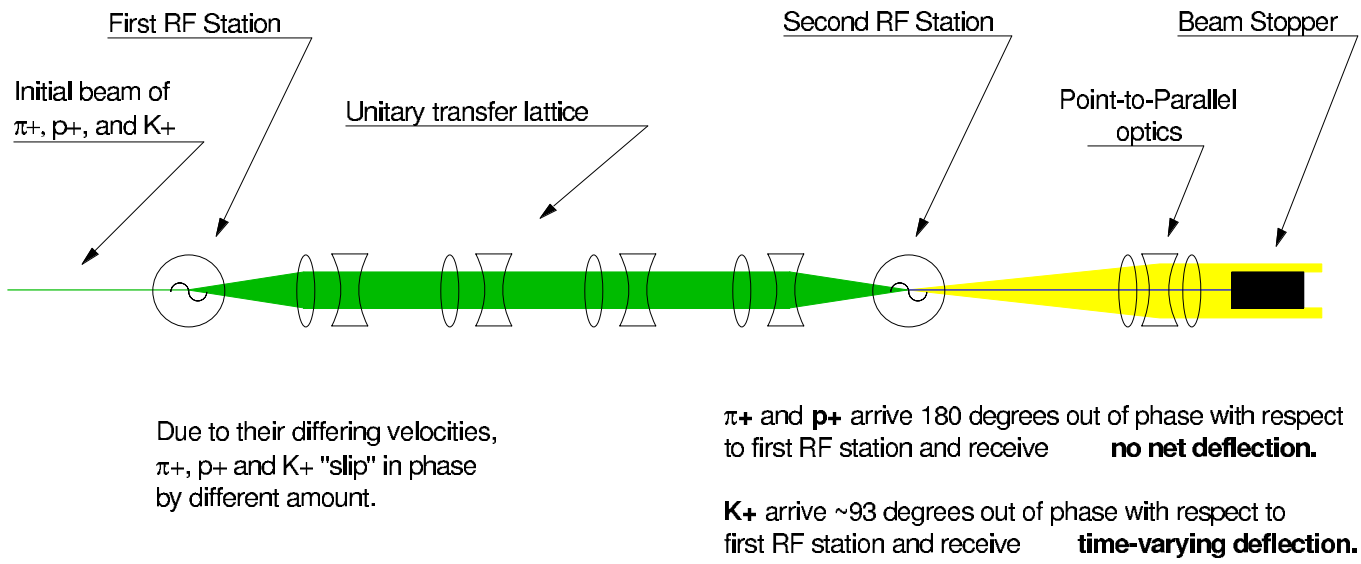
Plot shows GEANT simulation of RICH (velocity) vs spectrometer (momentum) measurement of $K^+ \to \pi^+\pi^0$ decays

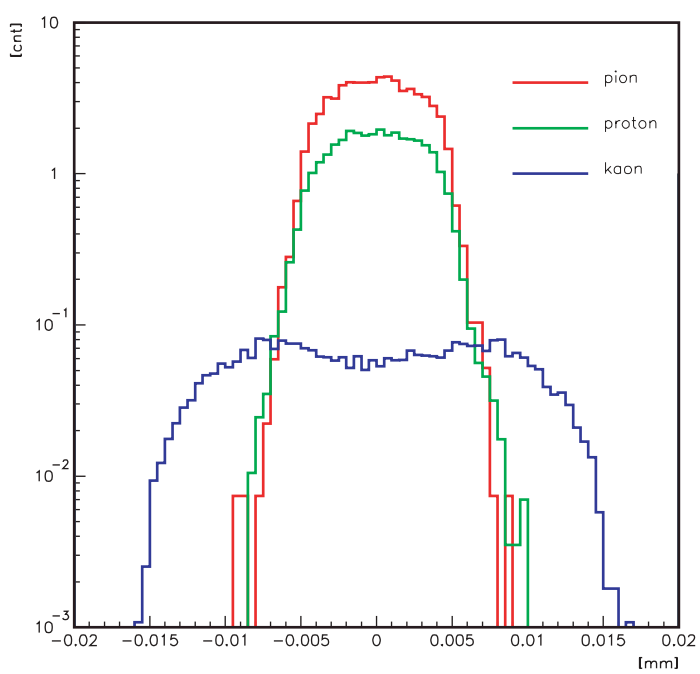
CKM RF-separated K^+ beam

Required:

- 30 MHz of 22 ± 0.4 GeV/c K^+
- debunched beam
- total rate ≤ 50 MHz

Pushes technology of RF-separation





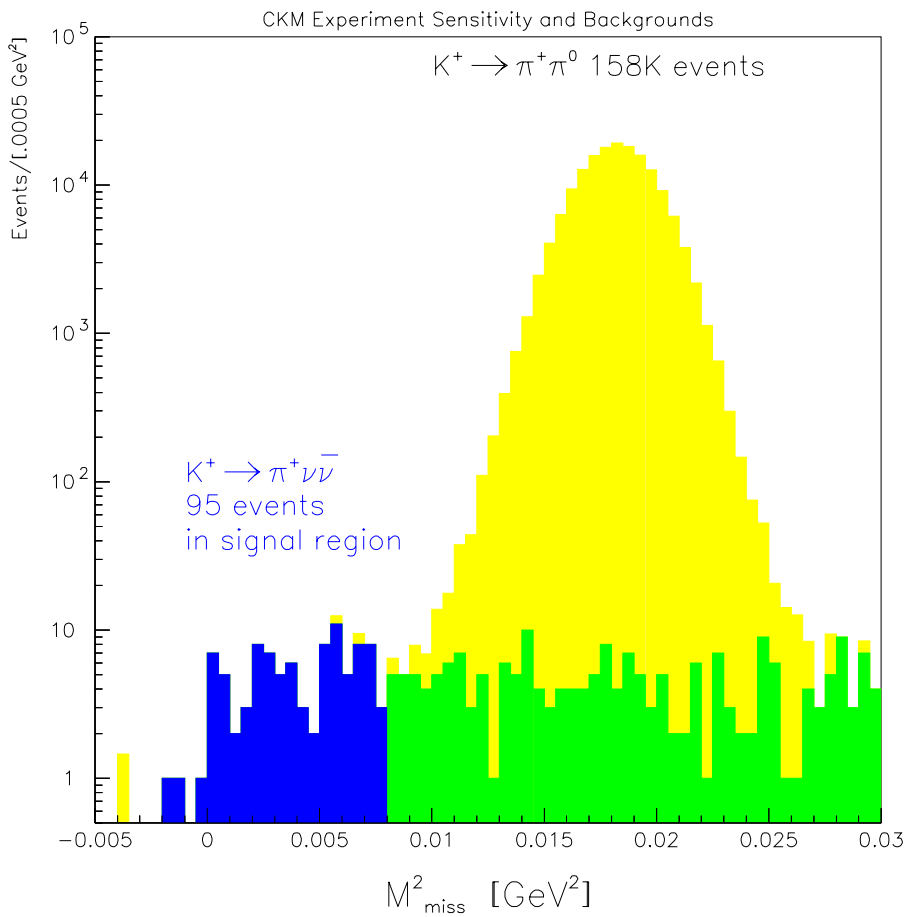
Requires length of 86m, frequency of 3.9GHz

Beam stop removes center of dist. leaving a beam $\sim 2/3$ K^+

Good progress on RF cavities

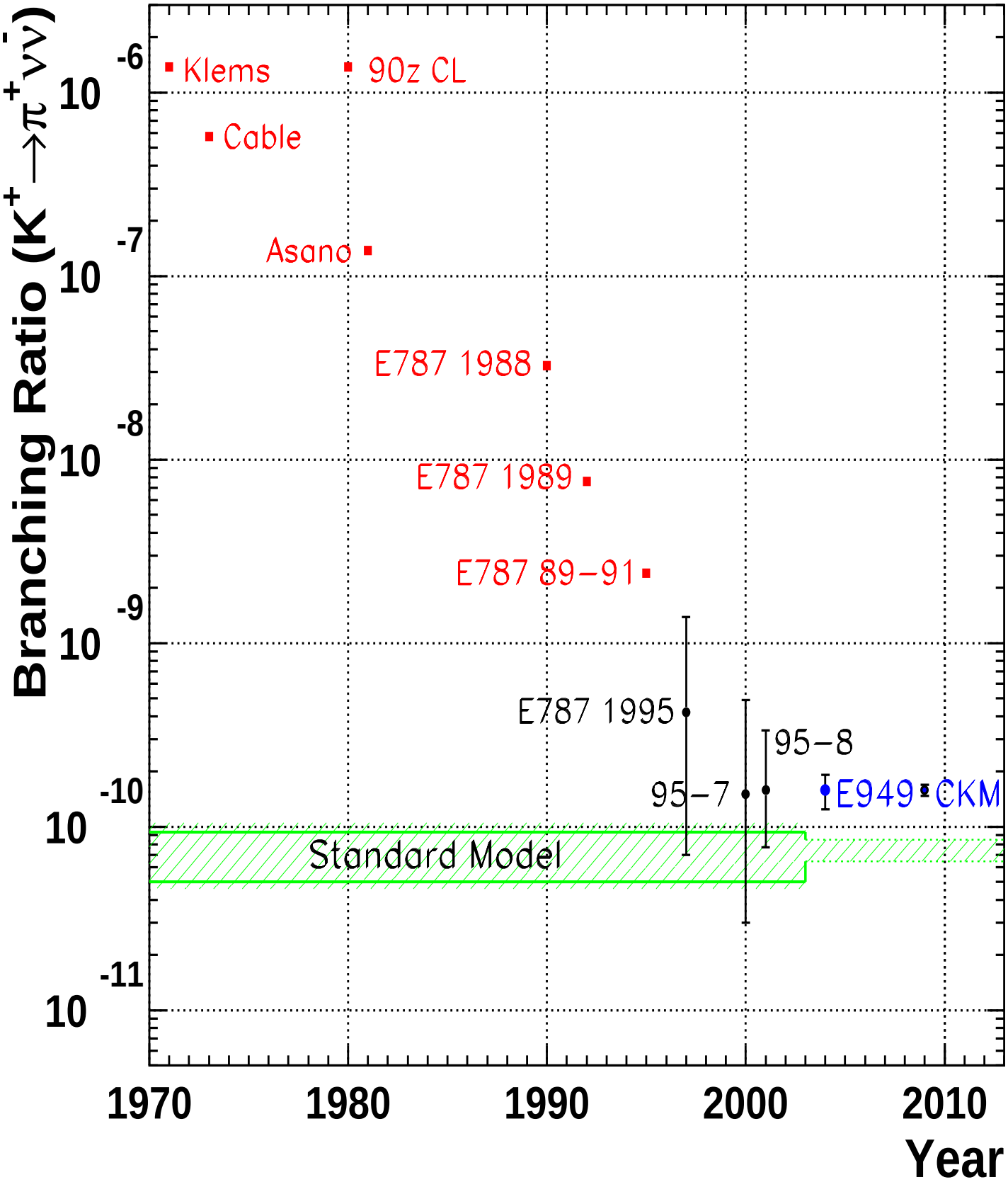
CKM Goal

100 events with S/N > 7



Background source	Effective BR ($\times 10^{-12}$)
$K^+ \to \mu^+\nu_\mu$	< 0.04
$K^+ \to \pi^+\pi^0$	3.7
$K^+ \to \mu^+\nu_\mu\gamma$	< 0.09
$K^+A \to K_L X;\ K_L \to \pi^+e^-\bar{\nu}_e$	< 0.14
$K^+A \to K_L X$ in trackers	< 4.0
$K^+A \to K_L X$ in residual gas	< 2.1
Accidentals (2 K^+ decays)	0.51
Total	< 10.6

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



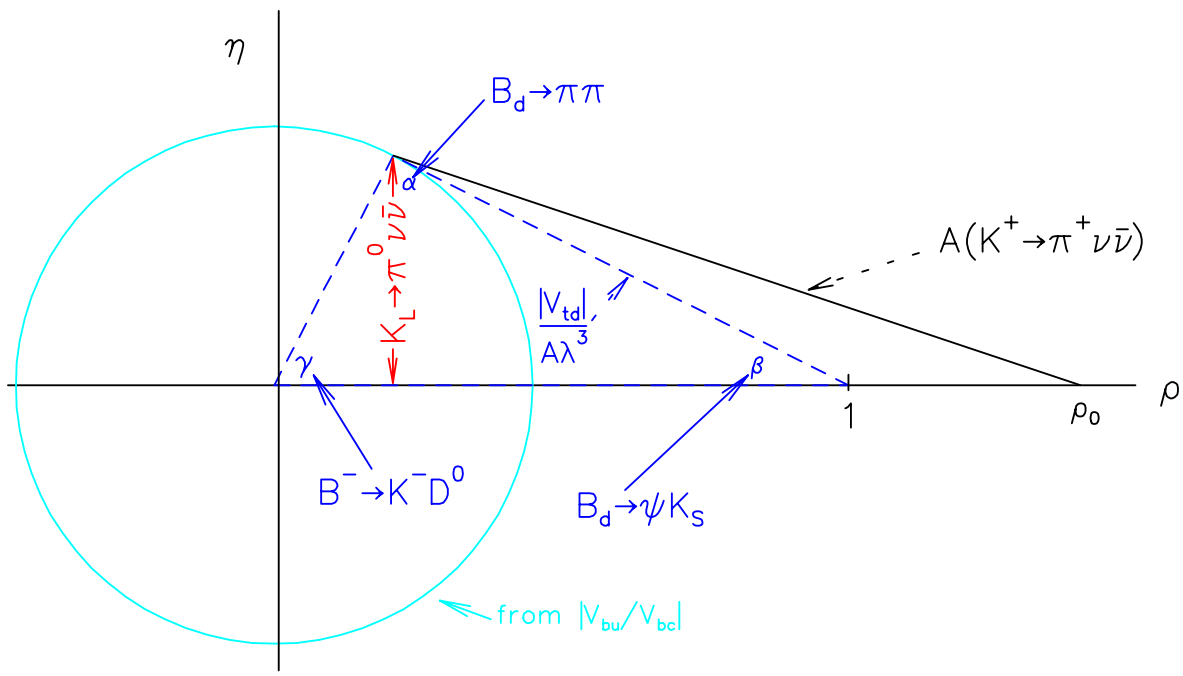
$K_L \to \pi^0 \nu\bar{\nu}$ in the Standard Model

Pure direct CP-violating (state-mixing very small)

Calculation in terms of fundamental parameters good to $\lesssim 2\%$

In terms of usual unitarity triangle parameterization:

$$B(K_L \to \pi^0 \nu\bar{\nu}) = 4 \cdot 10^{-10} A^4 \eta^2$$



Gives height of UT without triangulation

- with $K^+ \to \pi^+ \nu\bar{\nu}$ can determine ρ as well

Also note that

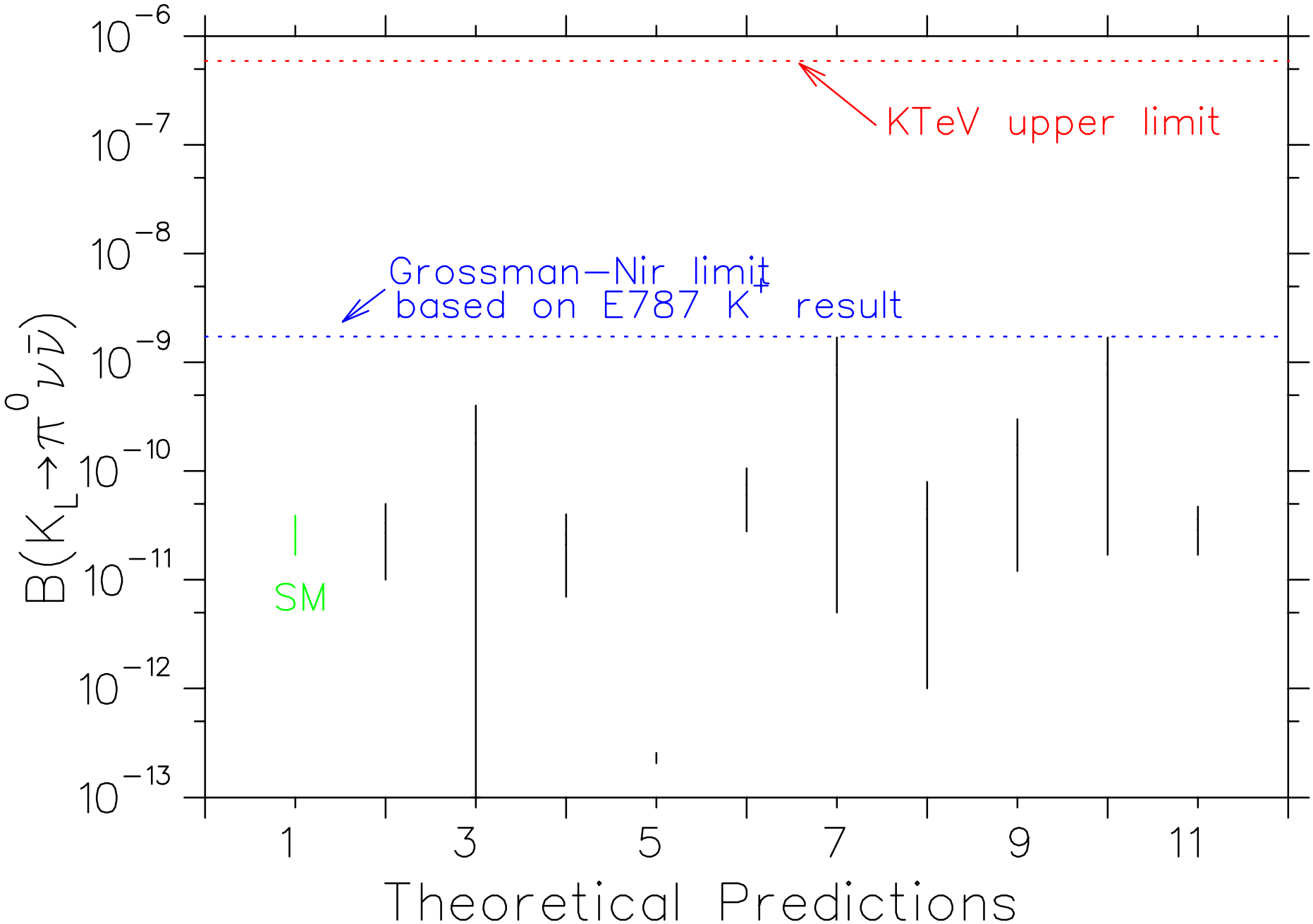
$$B(K_L \to \pi^0 \nu\bar{\nu}) = 1.56 \cdot 10^{-4} [Im(V_{ts}^* V_{td})]^2 \equiv 1.56 \cdot 10^{-4} [Im\lambda_t]^2$$

$Im\lambda_t$ presently triangulated to $\sim 20\%$,

- A dedicated experiment could directly measure it to 10%

There are only a few solid measurements on the UP

- none is better!


KTeV upper limit
Grossman–Nir limit
based on E787 K+ result
SM
B(K_L → π^0 ν ν̄)
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
10^−12
10^−13
1
3
5
7
9
11
Theoretical Predictions

A Model Independent Limit on $B(K_L \to \pi^0 \nu\bar{\nu})$

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

Proposed by Y. Grossman & Y. Nir

- Phys. Lett. **B398**, 163 (1997)

A consequence of $\Delta I = \frac{1}{2}$ rule

- trivial in SM

- true in for almost any short-distance interaction
  even if that interaction conserves CP

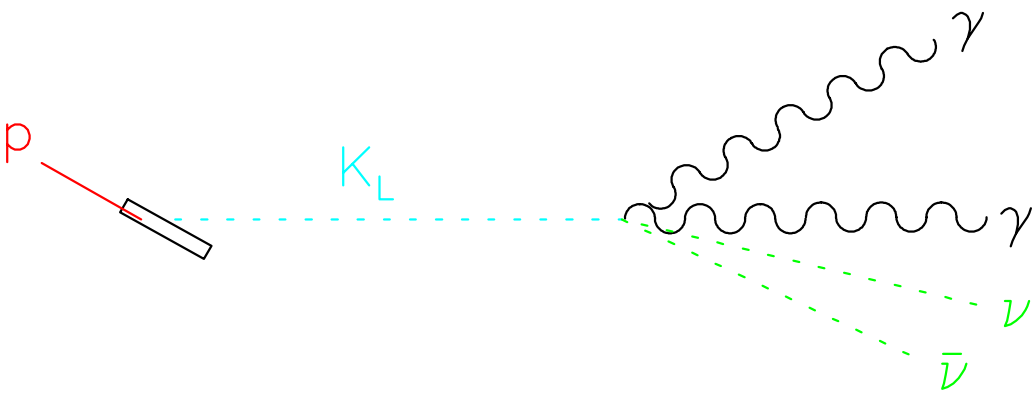
'95-8 E787 result is $B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(1.57^{+1.75}_{-0.82}\right) \times 10^{-10}$

This leads to $B\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 1.7 \times 10^{-9}$ at 90% c.l.

Far better than any other current limit

- but still 50 times larger than SM expectation

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



All neutral initial & final state, γ's make π^0

Expected branching ratio 3×10^{-11}
- need high flux of K_L

Largest background $K_L \to \pi^0\pi^0$, BR $\sim 10^{-3}$
- need excellent vetoing, other handles if possible

Background from neutron-produced π^0's, η's
- requires vacuum of 10^{-7}
- need to make sure decay vertex was in beam

Potential backgrounds from hyperon decay π^0's
- could use a clever way of getting rid of them

Present status: $B(K_L \to \pi^0\nu\bar{\nu}) < 5.9 \times 10^{-7}$
- from KTeV, using Dalitz-converted π^0's

KEK391A is first dedicated experiment
- shooting for $\sim 3 \times 10^{-10}$/evt

KTeV $K_L \to \pi^0 \nu\bar{\nu}$ using $\pi^0 \to e^+e^-\gamma$

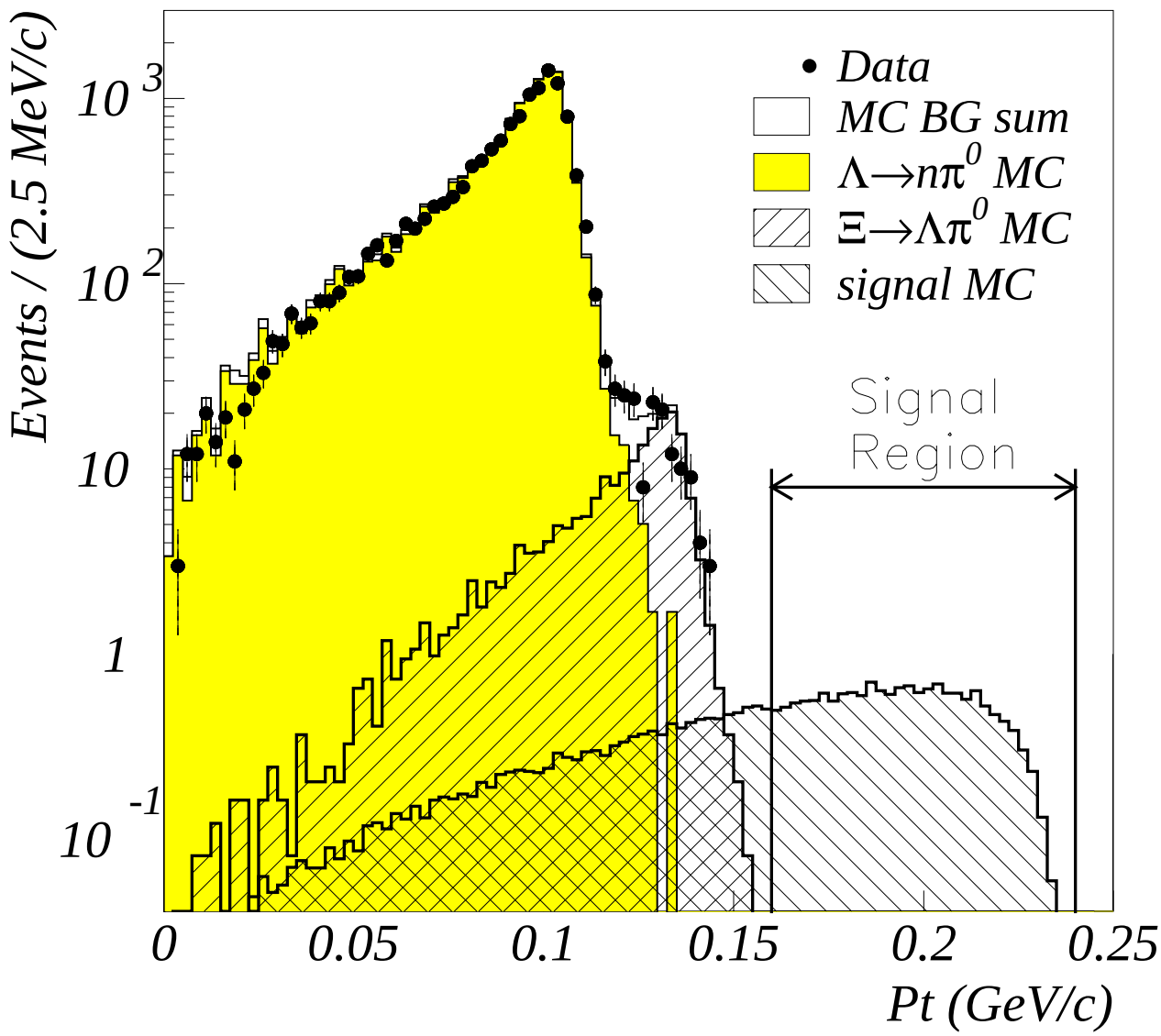
To be published in PRD (hep-ex/9907014).

Technique allows a vertex to be determined.

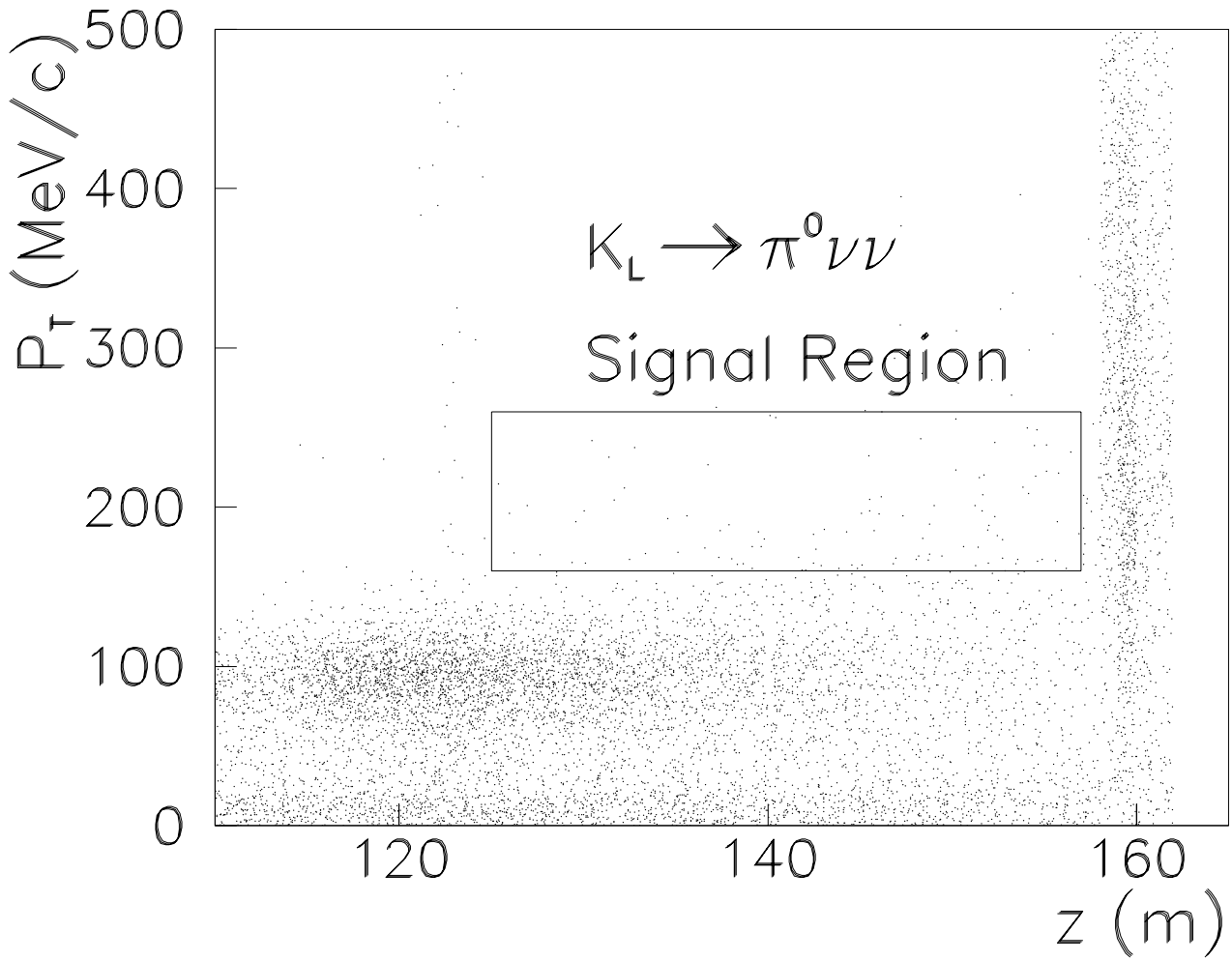
No events observed, $B\left(K_L \to \pi^0\nu\bar{\nu}\right) < 5.9 \times 10^{-7}$ at 90% c.l.

Calculated background 0.04 events.

Estimate of ultimate reach $\sim 10^{-9}$.



FNAL E799 Search for $K_L \to \pi^0 \nu\bar{\nu}$



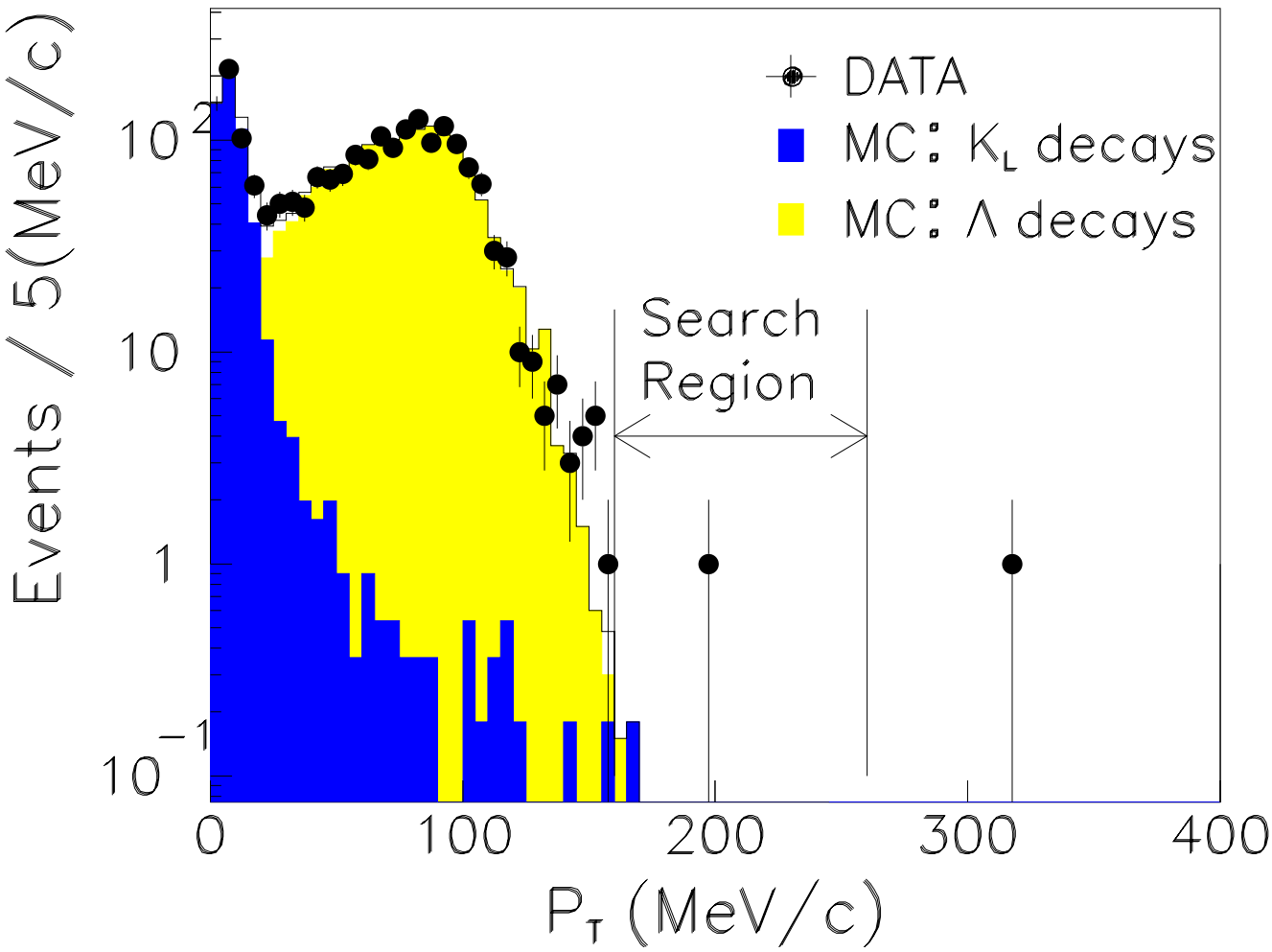
p_T vs z_V for single-π^0 events

Band at $z_V \approx 160\,\mathrm{m}$ due to n ints. in vacuum window

Band near $p_T = 100\,\mathrm{MeV/c}$ due to $\Lambda \to n\pi^0$

Events with $p_T \approx 0$ due to $K_L \to \gamma\gamma$

FNAL E799 Search for $K_L \to \pi^0 \nu\bar{\nu}$



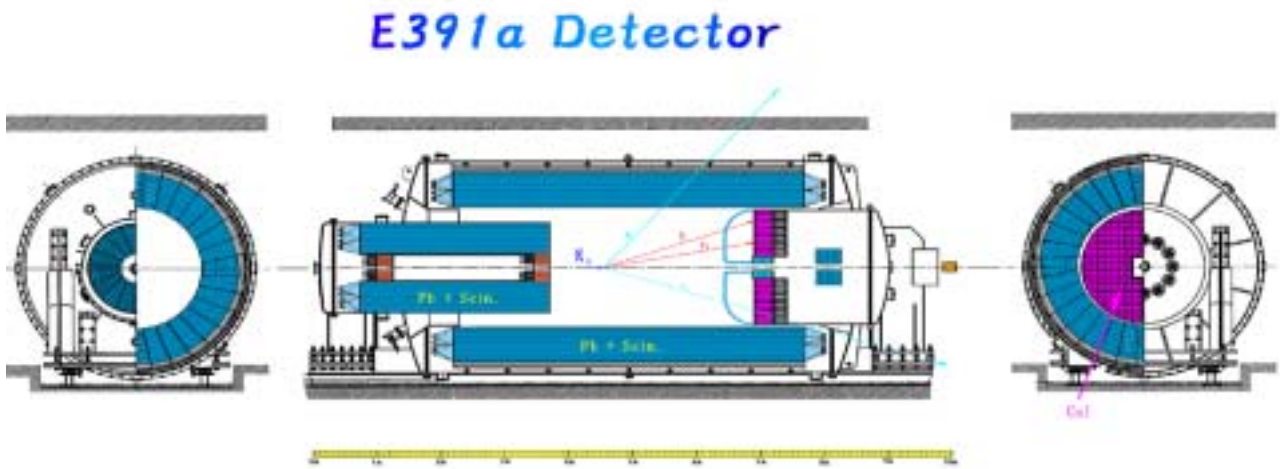
Result of one-day run in special configuration.

P_T distribution with all other cuts
- calculated backgrounds overlaid.

Residual background consistent with neutron interactions

Yields $B\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 1.6 \times 10^{-6}$ at 90% c.l.

KEK E391a search for $K_L \to \pi^0 \nu\bar{\nu}$



Carefully designed "pencil" beam, compact detector

Entire apparatus in vacuum

Very high performance photon veto

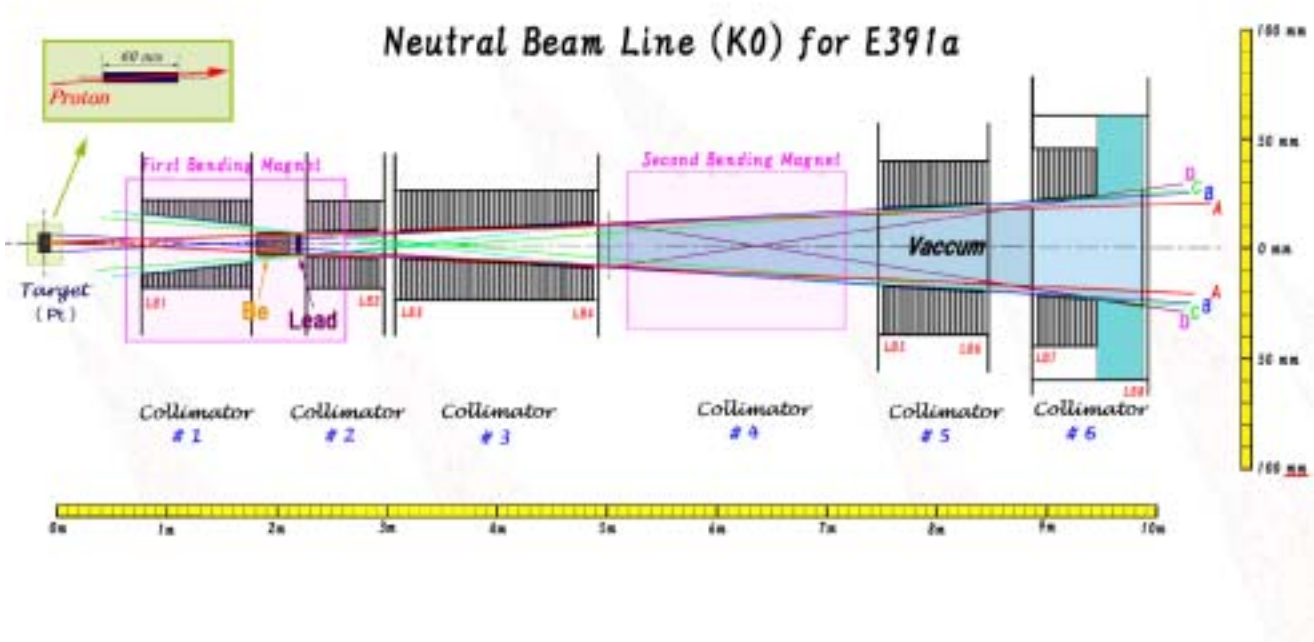
Expected to reach $\sim 3 \times 10^{-10}$ single event sensitivity
- *i.e.* w/i an order of magnitude of S.M. prediction

Beamline construction & tuning begun in March 2000

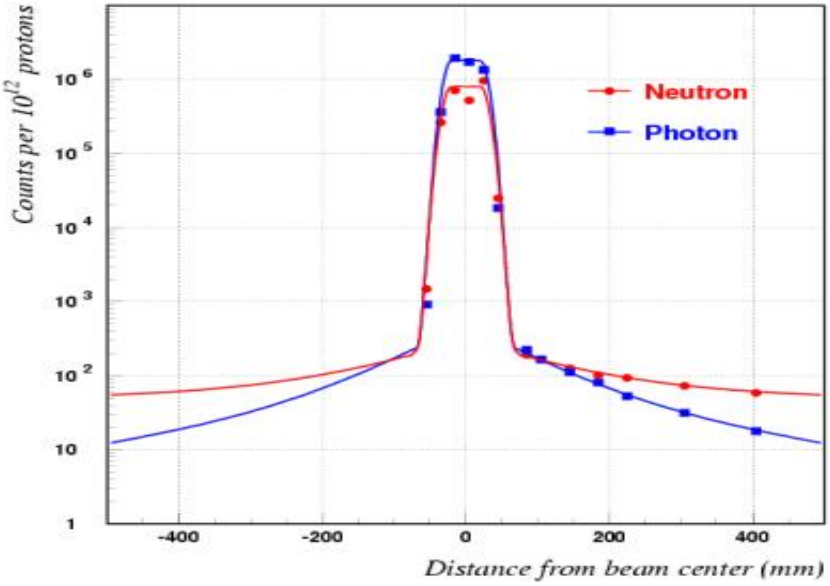
Run start scheduled for Fall, 2003

Test bed for JHF experiment

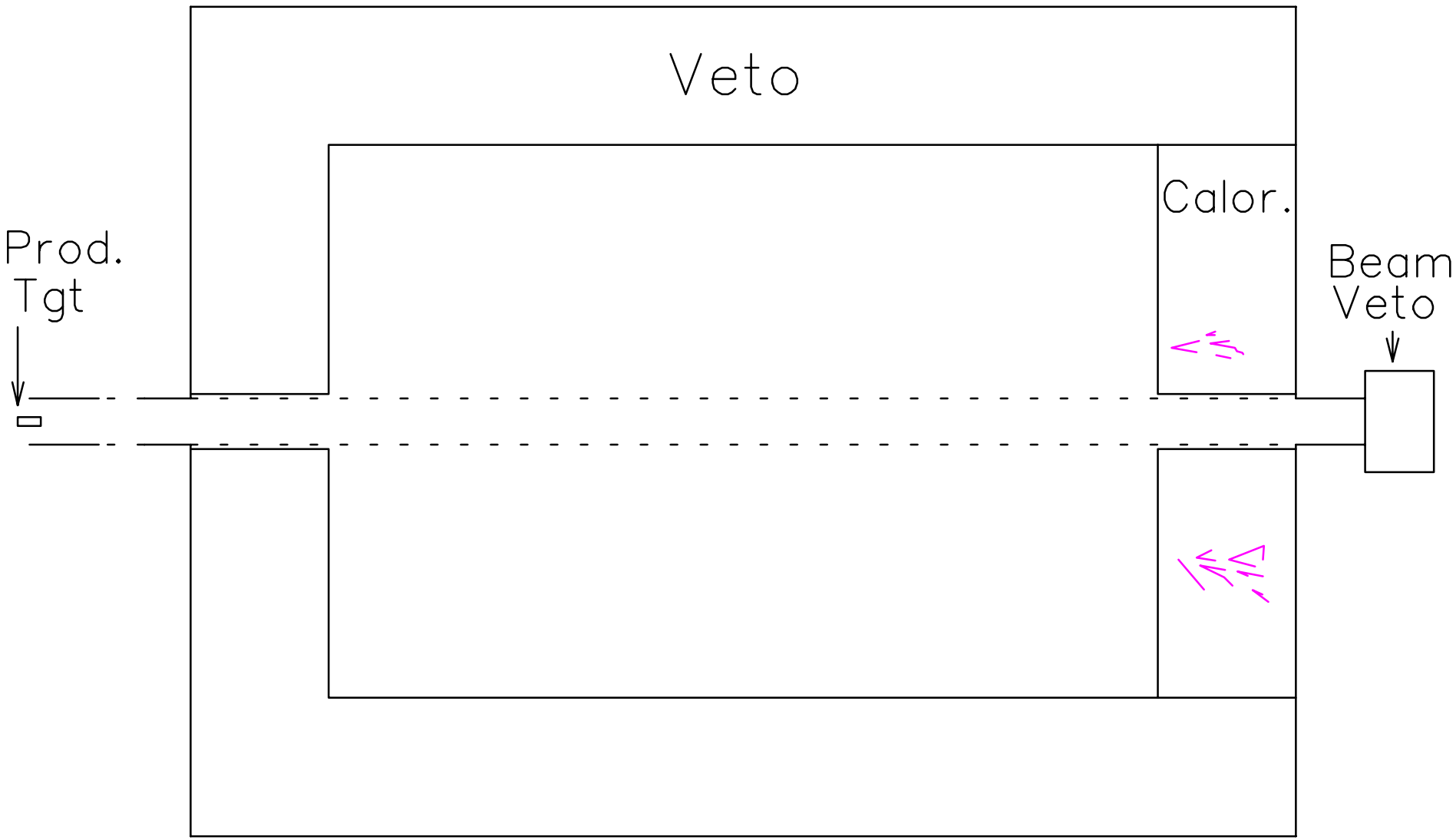
KEK E391a Beamline



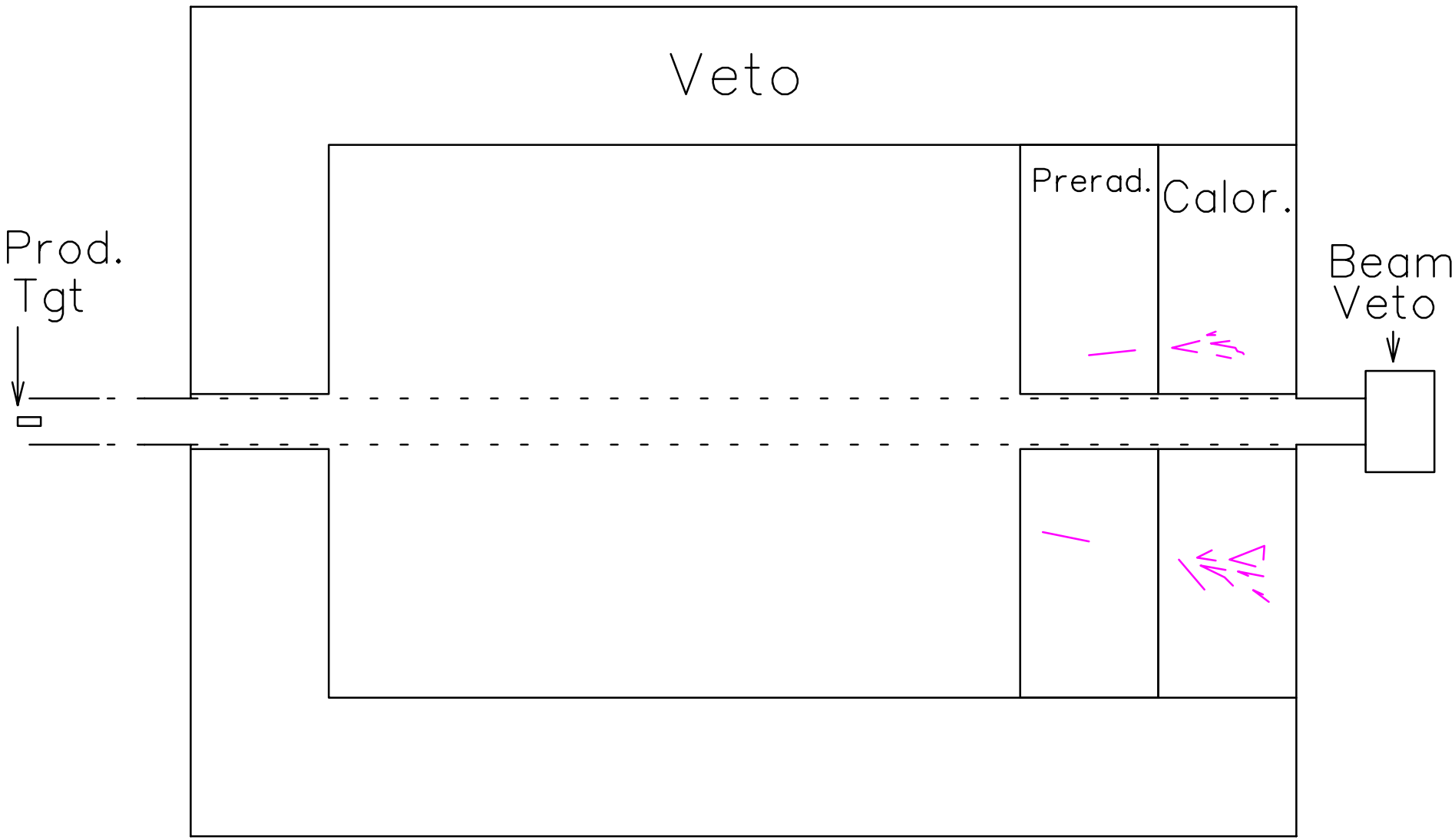
Critical to reduce the beam halo. Tests encouraging:



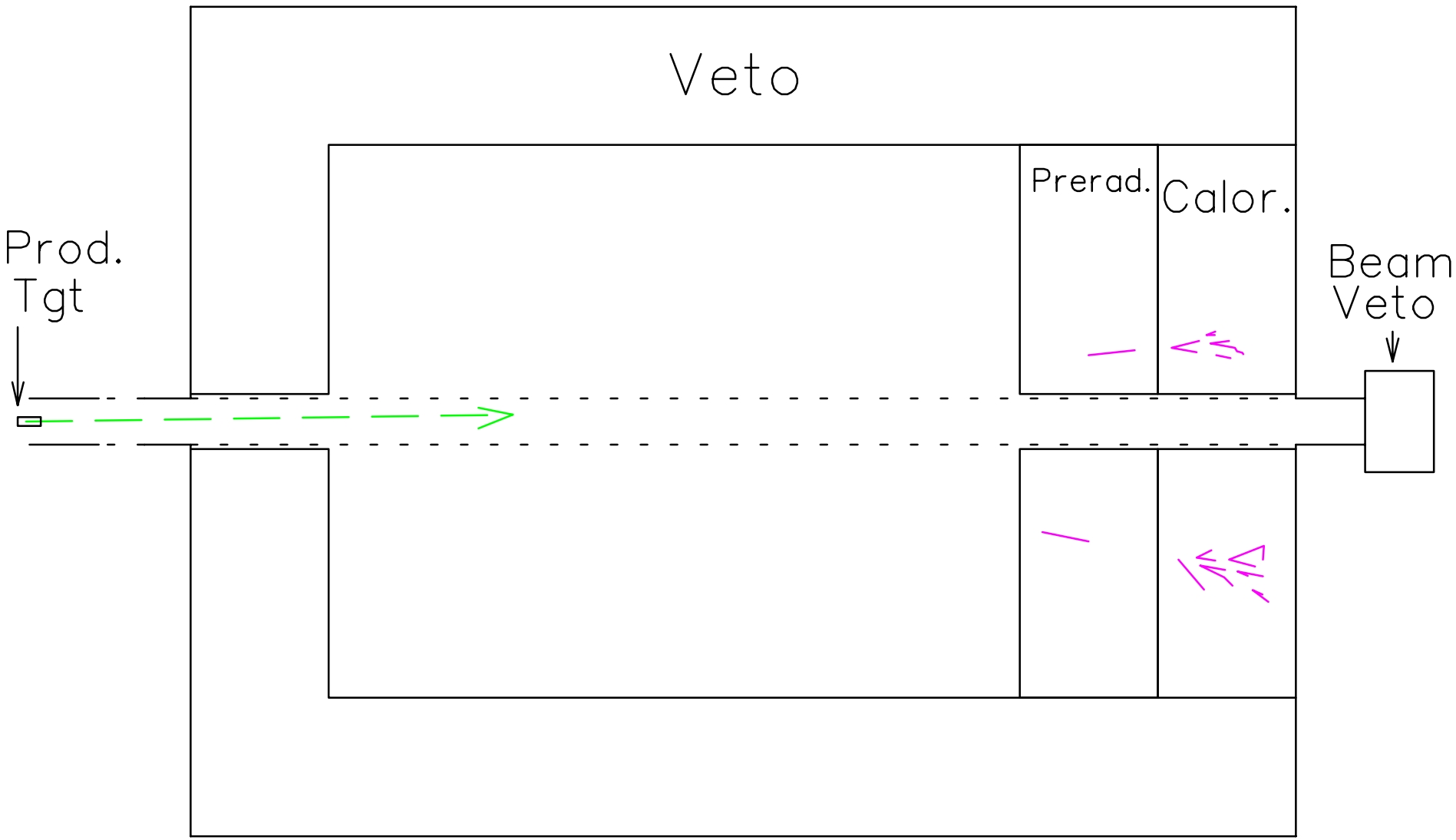
$K_L \to \pi^0 \nu \bar{\nu}$ Experiment



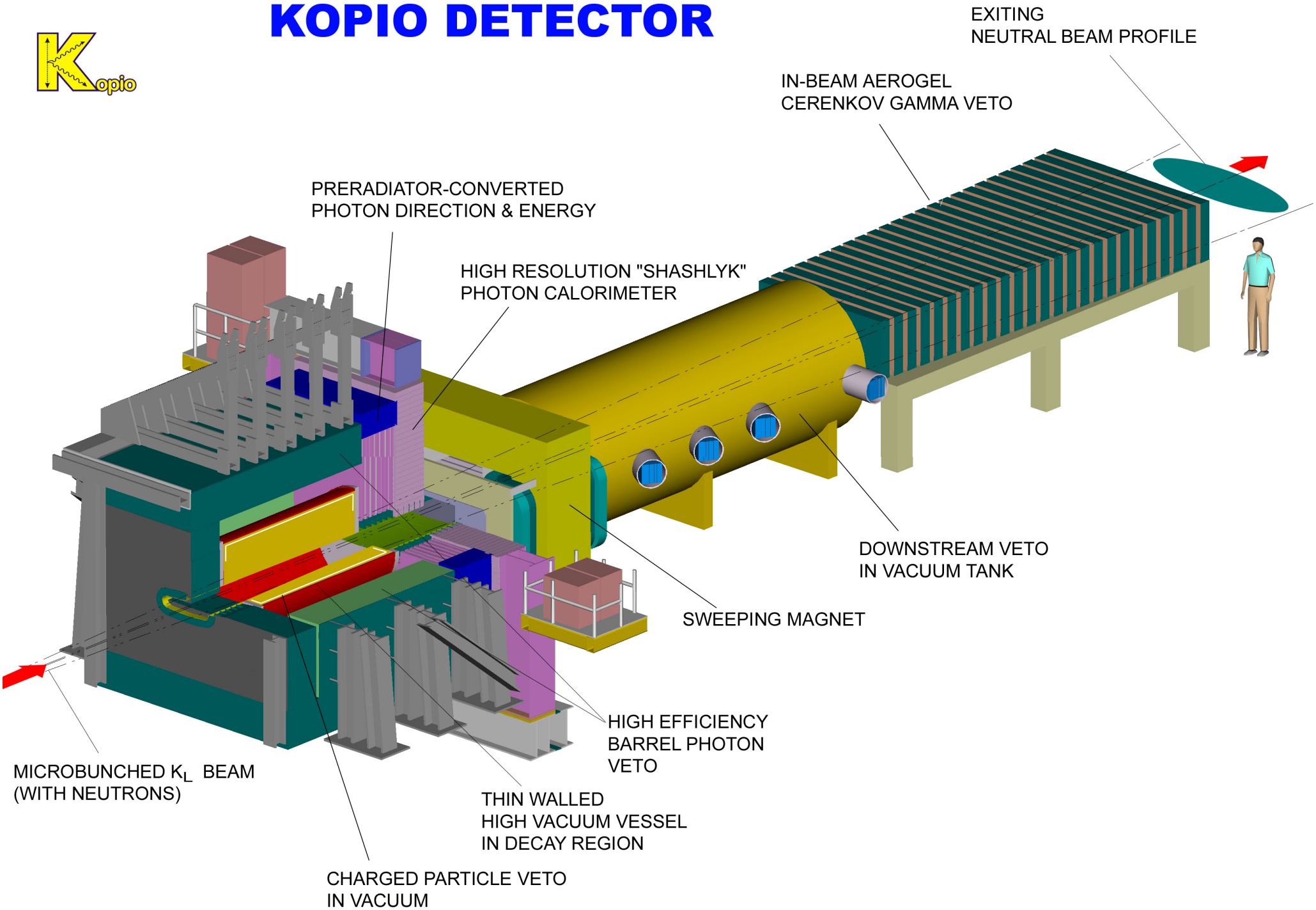
$K_L \to \pi^0 \nu \bar{\nu}$ Experiment



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



KOPIO DETECTOR



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

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

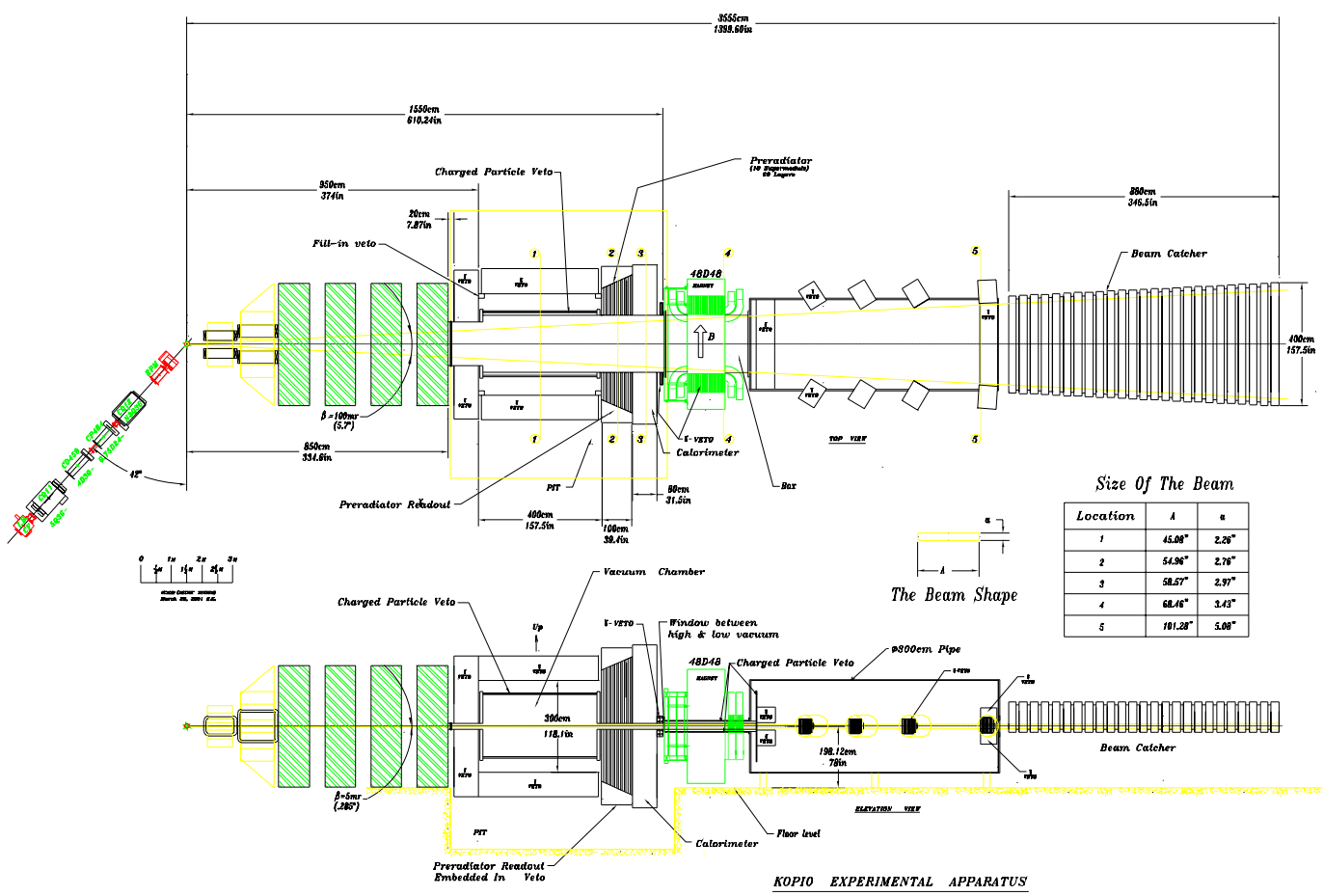
Uses the BNL AGS ~ 20 hrs/day it's not serving RHIC

Microbunched, low energy beam allows TOF determination of p_K

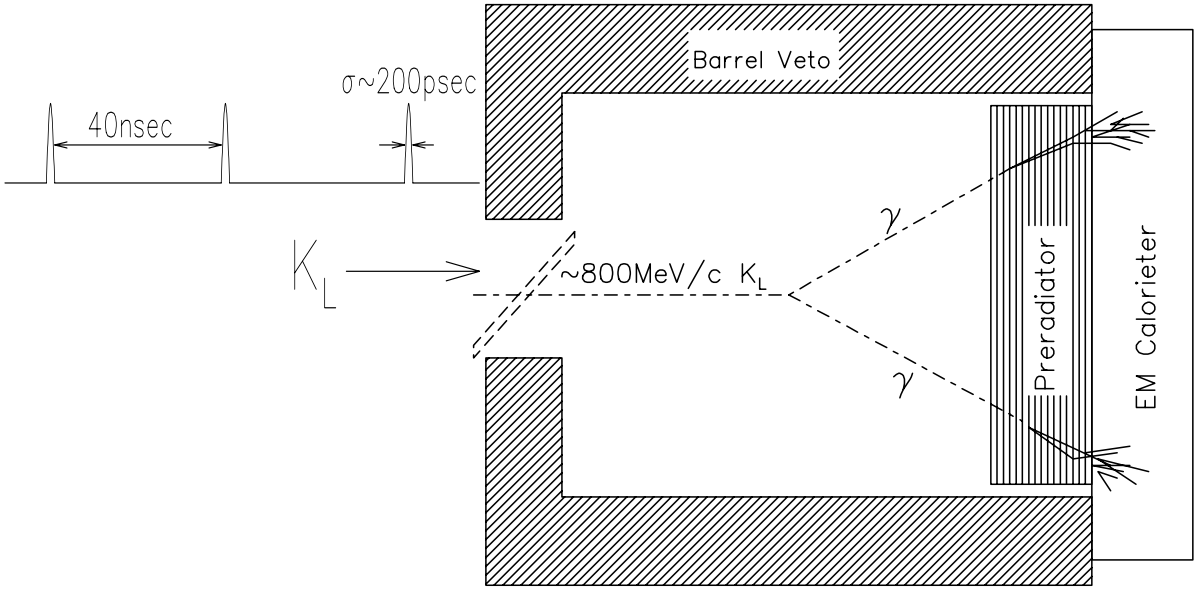
Measures photon direction as well as energy, time, position

Hermetic veto with proven level of inefficiency

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



Principles of KOPIO



Veto hermetically

E787-type veto + beam "catcher"

All possible initial & final state quantities measured

$\mu-$bunched, large $\angle$ (low p) beam for K_L TOF

Preradiator to measure γ directions (gives vertex)

+ calorimeter, get energies, times

Work in the K_L center of mass system

K_L TOF makes this possible

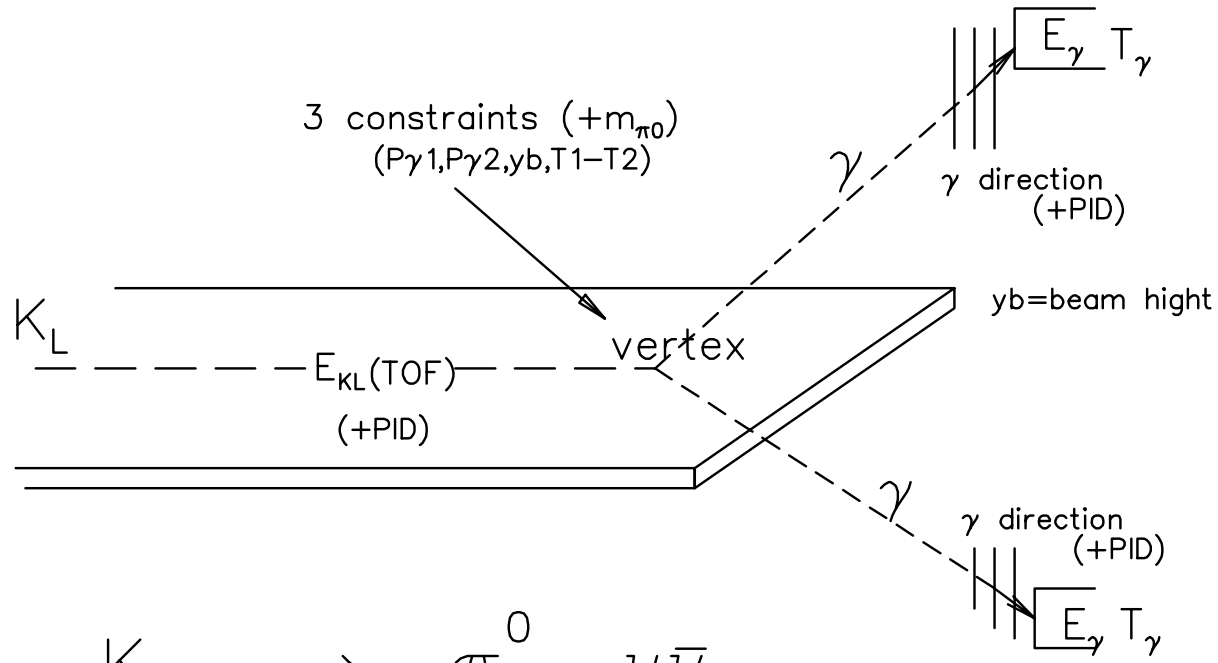
This allows kinematic suppression of backgrounds

Measure backgrounds

Kinematic handle allows one to do this

Very hard to *simulate* background at 10^{-11} level

KOPIO Beam and Constraints

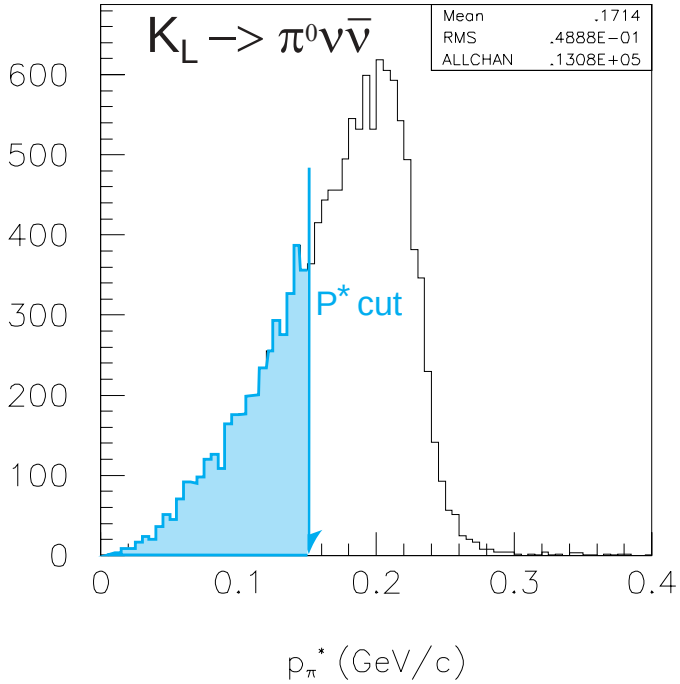


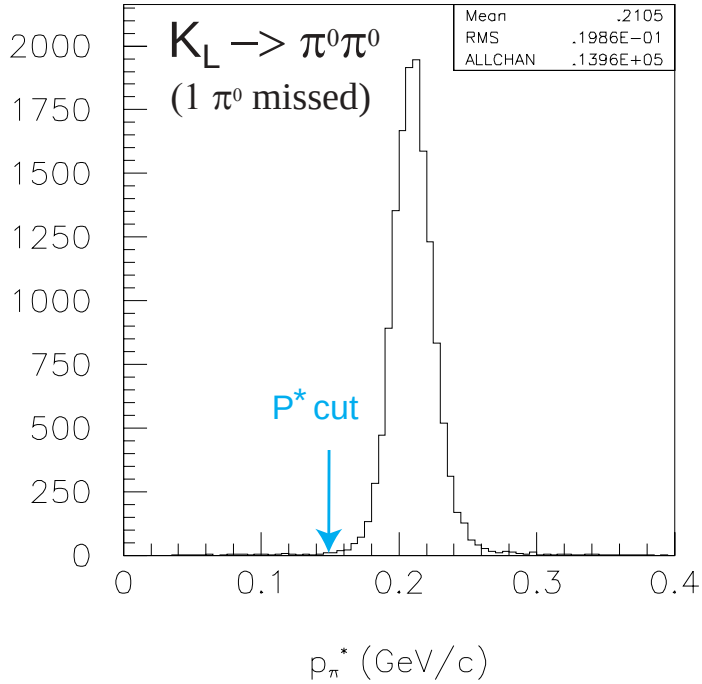
$K_L \rightarrow \pi^0 \; \nu\bar{\nu}$

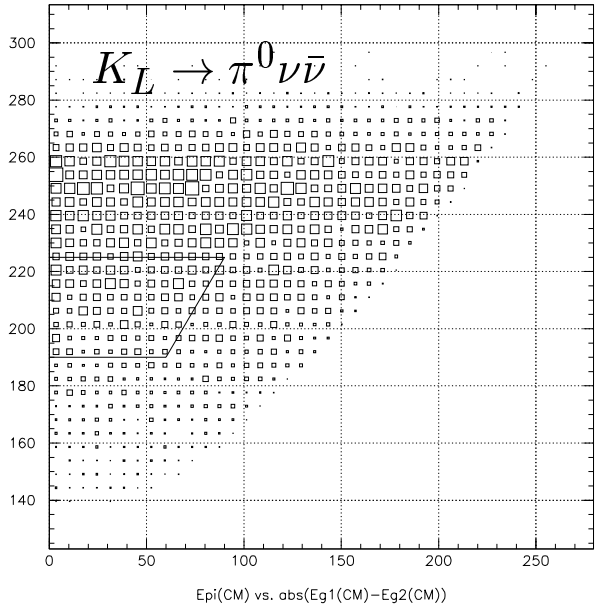
(Momentum:TOF) (4π veto)

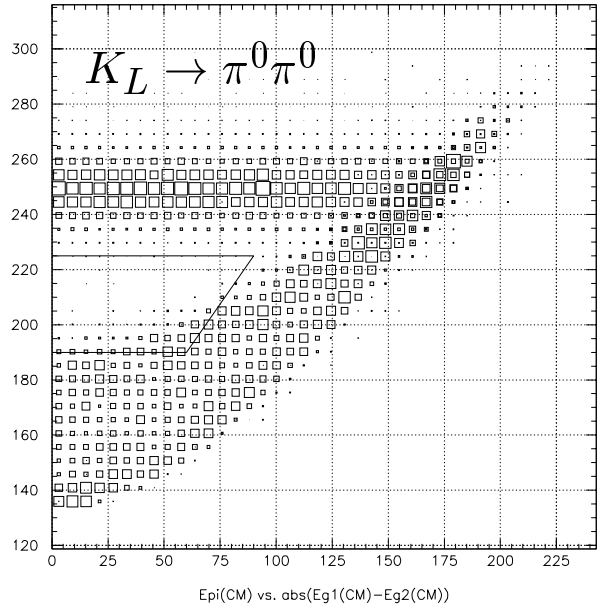
$\pi^0 \rightarrow \gamma\gamma$ (Energy and direction)

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





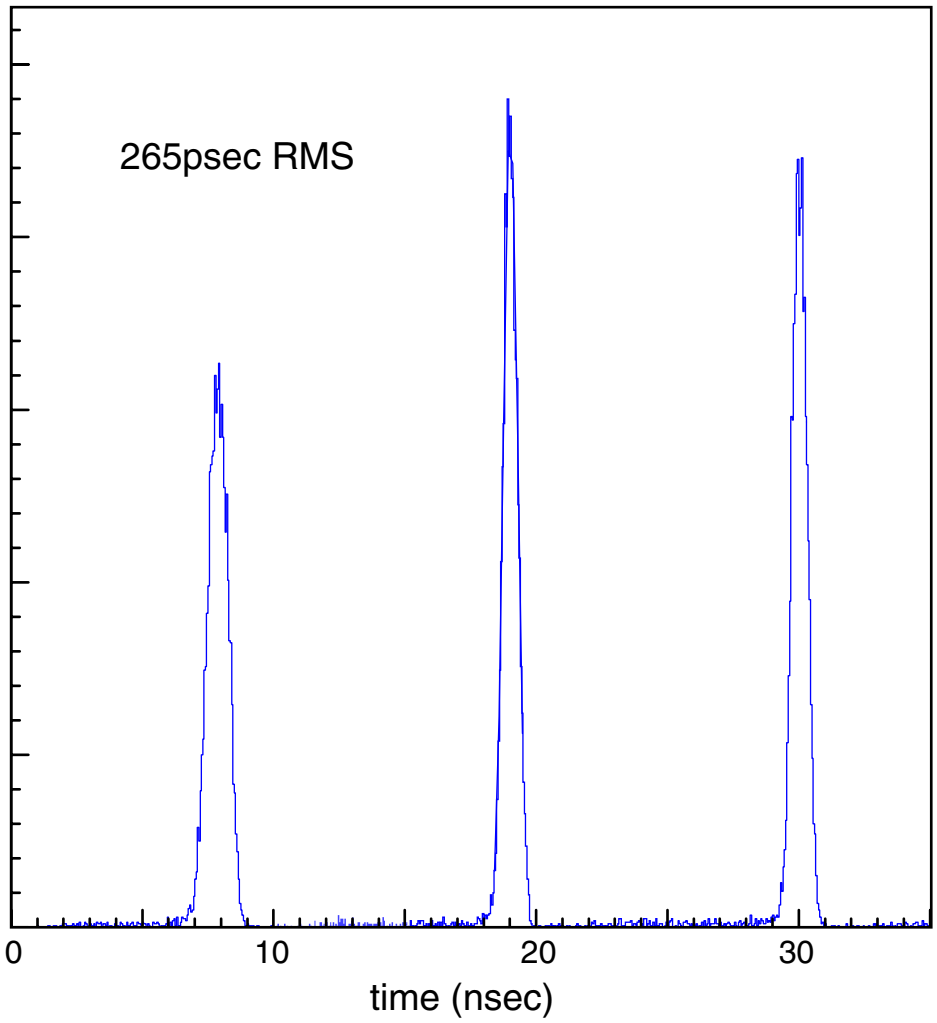




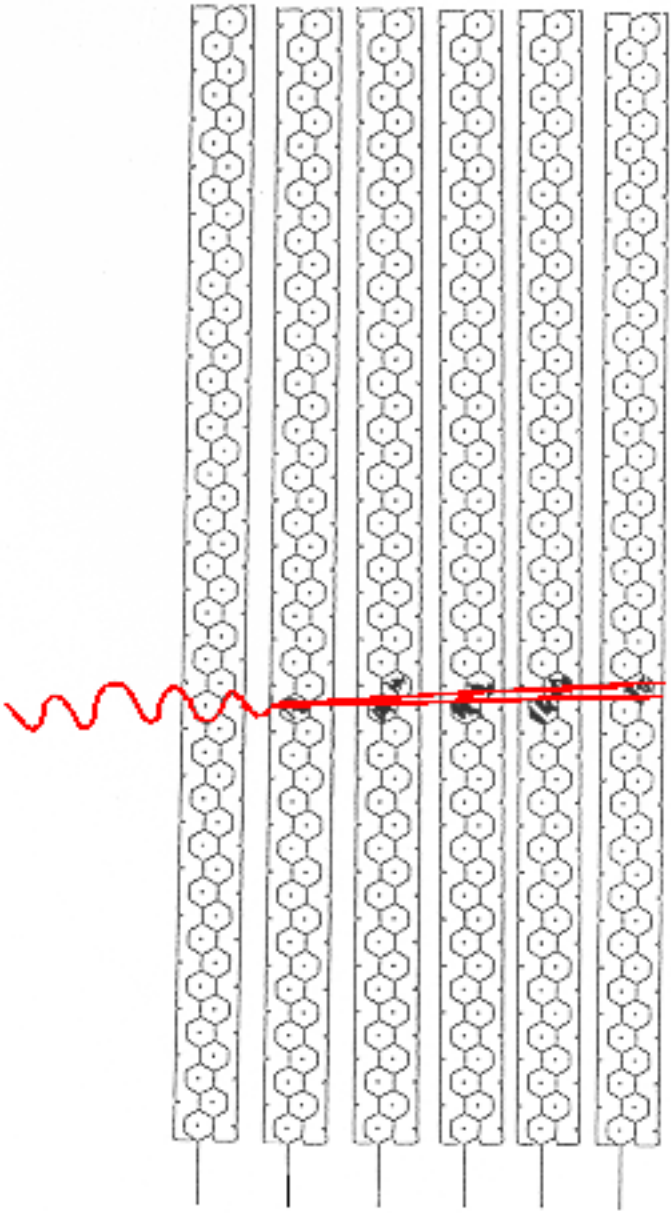
Energy of the purported π^0 (vertical) vs absolute value of the difference of the energies of the two detected γ's (horizontal) both in the K_L cm system.

Test of beam microbunching at the AGS

Technique now well established
Very successfully used to smooth AGS spill



Microbunch structure of the beam produced
by a 93 MHz cavity operating at 22 kv



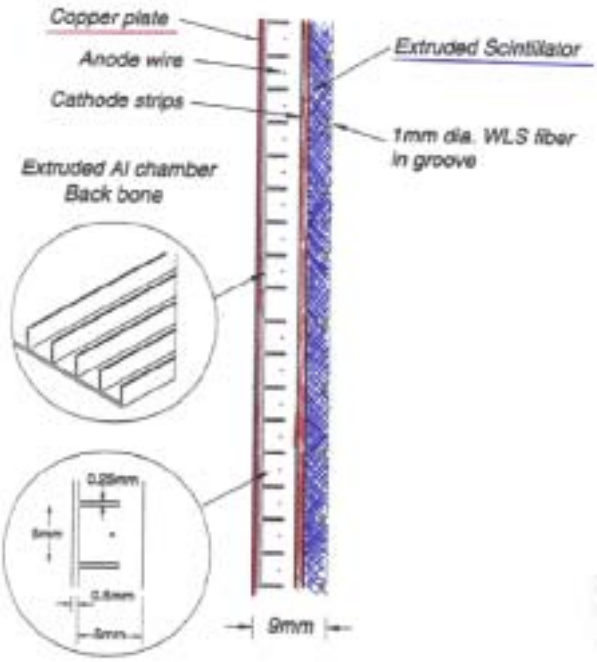
Photon angle measurement

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

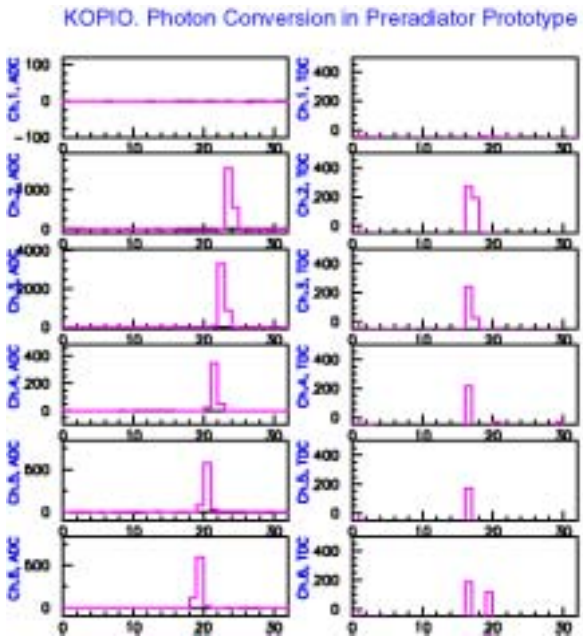
64 layers of chamber + scintillator
- each station $0.03X_0$

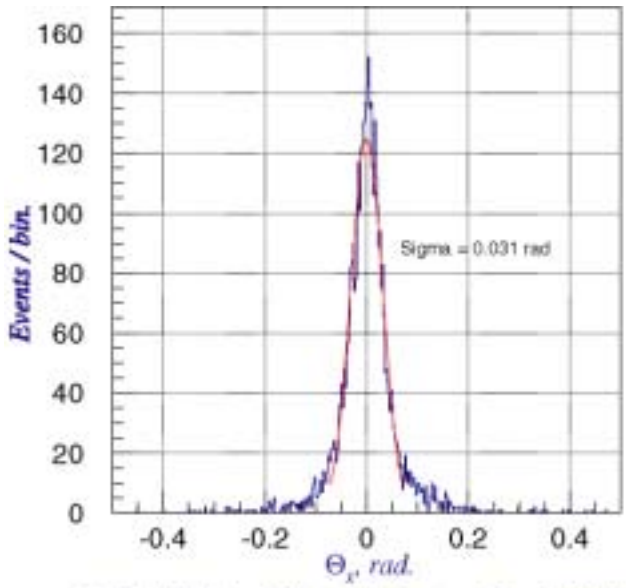
We will need $\sigma_\theta \sim 30$mr

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.

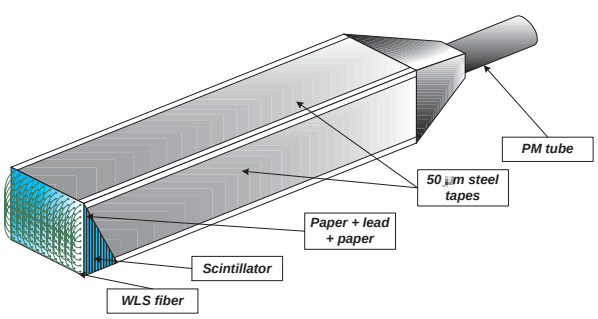
Calorimeter

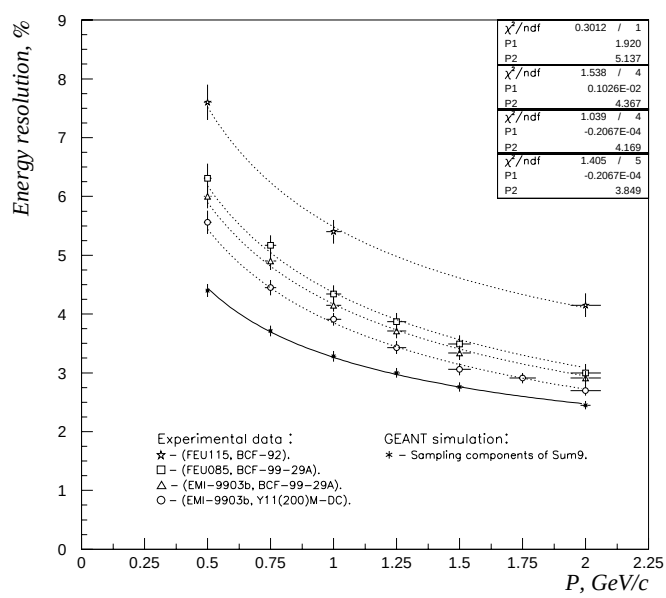
Need $\sigma_E/E \propto 0.03/\sqrt{E}$

Use well-understood shashlik technology

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

MC indicates goal can be straightforwardly reached



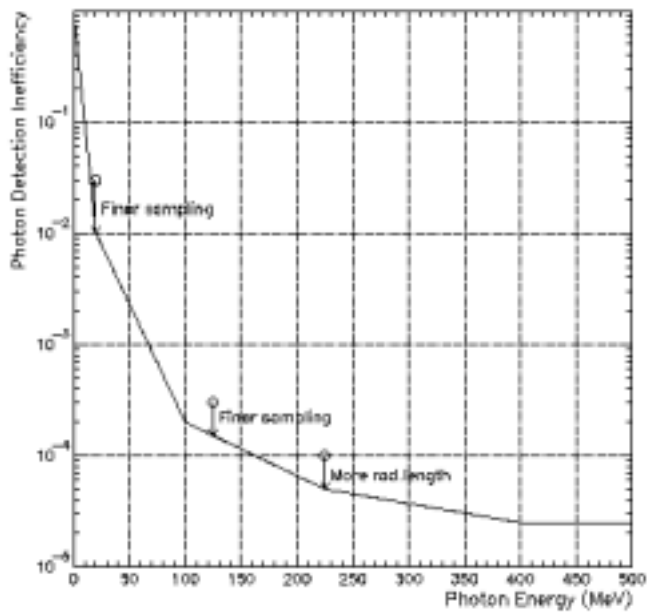


Note that **overall** σ_E depends strongly on preradiator

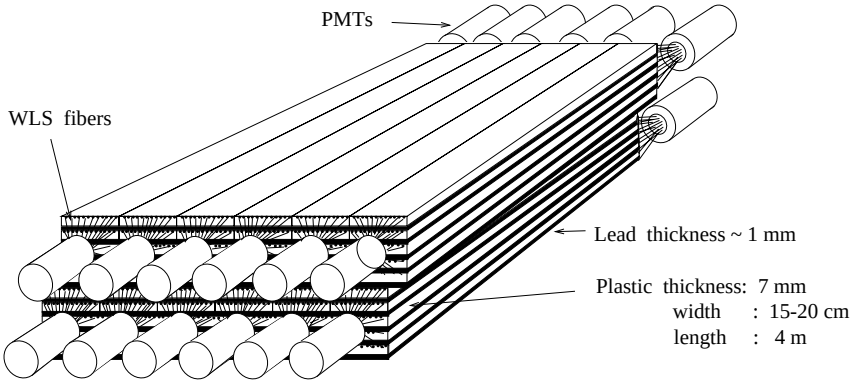
- MC of latest configuration indicates $\sigma_E/E \sim 0.027/\sqrt{E}$

KOPIO Photon Veto

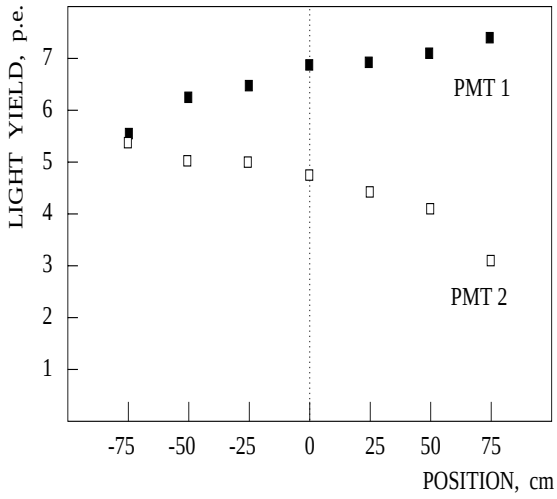
Require photon veto inefficiency only a little better than that already demonstrated in E787.

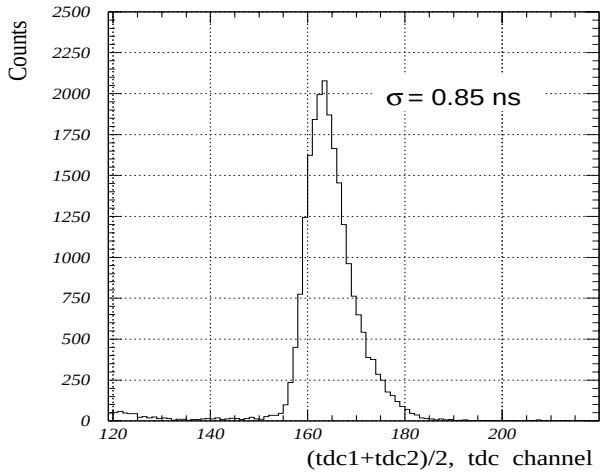


Technology similar, but wls readout gives better uniformity, brightness, and KOPIO will have more radiation lengths.

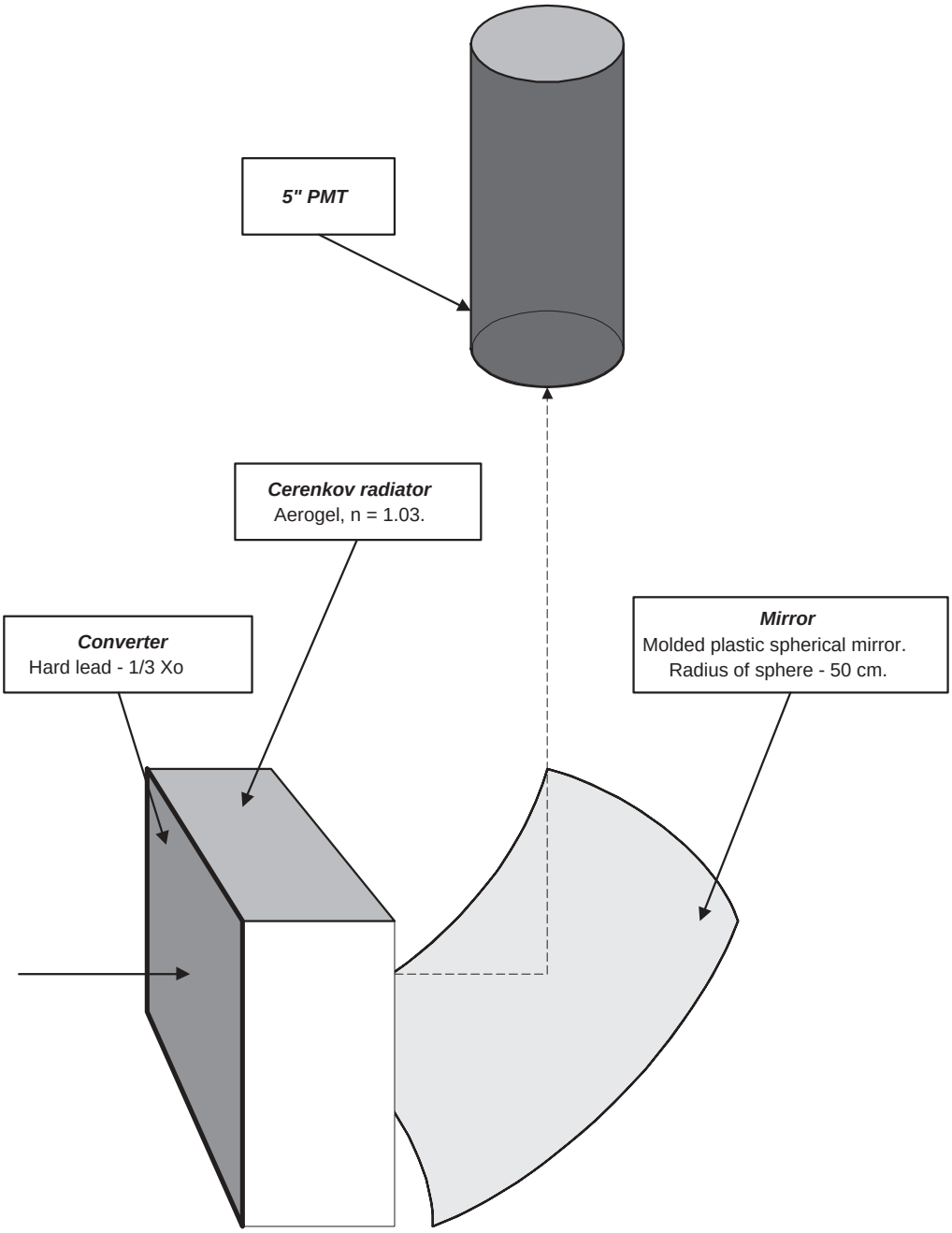


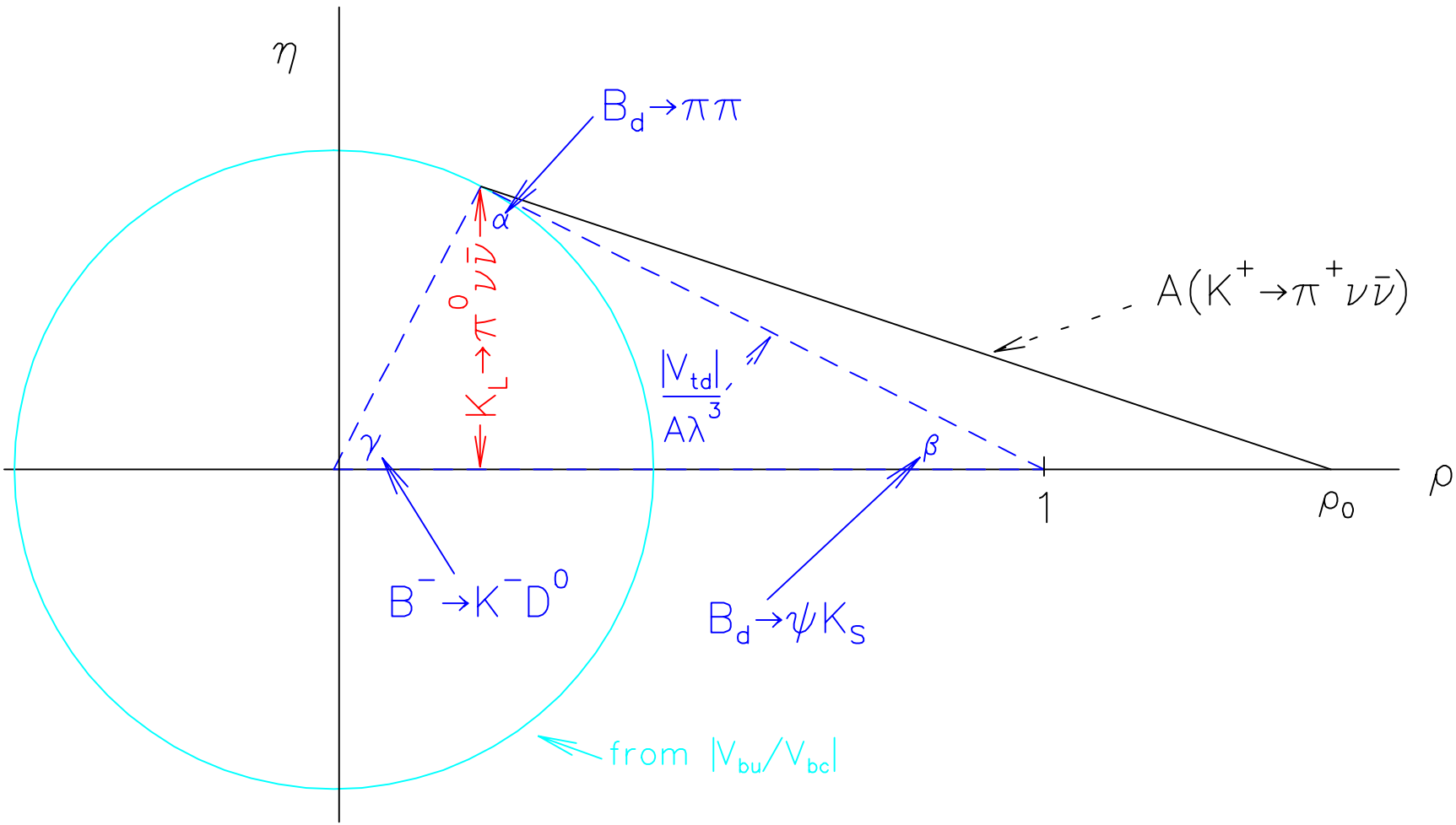
Prototype scintillators show required brightness, uniformity and time resolution:

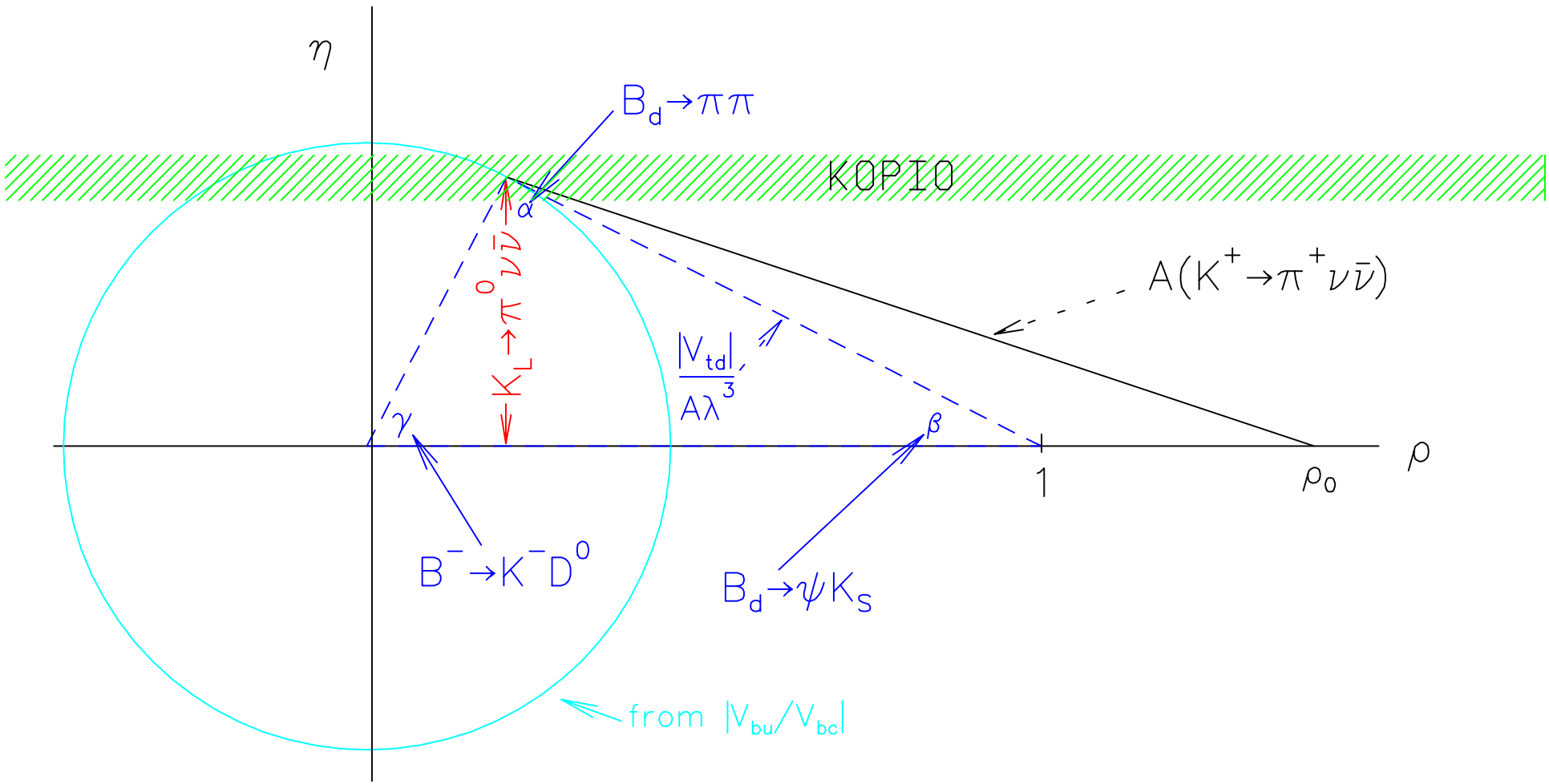


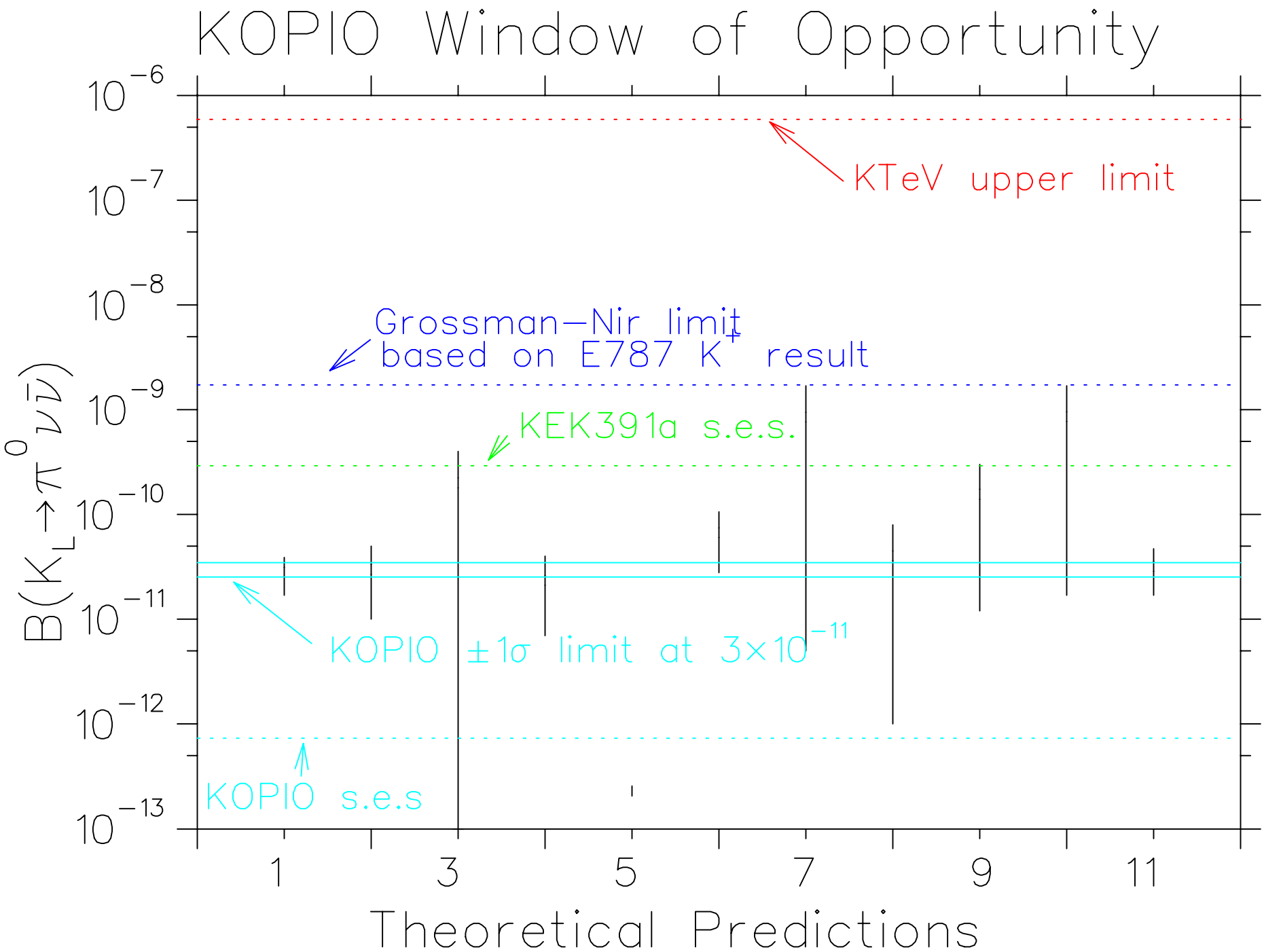


KOPIO Beam Catcher Module




η
ρ
$B_d \to \pi\pi$
α
$A(K^+ \to \pi^+ \nu\bar{\nu})$
$K_L \to \pi^0 \nu\bar{\nu}$
$\frac{|V_{td}|}{A\lambda^3}$
γ
β
1
ρ_0
$B^- \to K^- D^0$
$B_d \to \psi K_S$
from $|V_{bu}/V_{bc}|$


η
B_d→ππ
KOPIO
α
A(K⁺→π⁺νν̄)
K_L→π⁰νν̄
|V_td|/Aλ³
γ
β
ρ
1
ρ₀
B⁻→K⁻D⁰
B_d→ψK_S
from |V_bu/V_bc|


KOPIO Window of Opportunity
KTeV upper limit
Grossman–Nir limit
based on E787 K+ result
KEK391a s.e.s.
KOPIO ±1σ limit at 3×10−11
KOPIO s.e.s
B(K_L→π^0 νν̄)
Theoretical Predictions

A New Challenge: $K \to \pi\pi\nu\bar{\nu}$

Another interesting short-distance dominated decay

Related to $Ke4$ the way $K^+ \to \pi^+\nu\bar{\nu}$ is related to $Ke3$

Calc. by C. Geng, I Hsu, & Y. Lin, also by G. Valencia & LL
Latter obtain:

$$B\left(K_L \to \pi^+\pi^-\nu\bar{\nu}\right) \approx \left[1.8\,(1.4-\rho)^2 + 0.3\eta^2\right] \times 10^{-13}$$
$$B\left(K_L \to \pi^0\pi^0\nu\bar{\nu}\right) \approx 1.0 \times 10^{-13}\,(1.4-\rho)^2$$
$$B\left(K^+ \to \pi^+\pi^0\nu\bar{\nu}\right) \approx 7.0 \times 10^{-15}\left[(1.4-\rho)^2 + \eta^2\right]$$

Very interesting angular distributions in charged case
- ρ & η terms correspond to different $\ell_{\pi\pi}$ states
- therefore can in principle extract ρ and η separately

In practice ρ term dominates almost completely

$K_L \to \pi^+\pi^-\nu\bar{\nu}$ major experimental challenge:
- must reject $K_L \to \pi^+\pi^-\pi^0$ by $> 10^{-12}$!
- $K\mu3$ by a similar factor
- $K_L \to \pi^+\pi^-\gamma$ by $> 10^{-8}$
- best to get into K_L c.m. (only at low momenta)
- γ veto & particle ID usually best at high momenta

$K_L \to \pi^0\pi^0\nu\bar{\nu}$ seems harder, but has certain advantages:
- detector can focus on photon detection and vetoing
- $K_L \to \pi^0\pi^0\gamma$ very suppressed

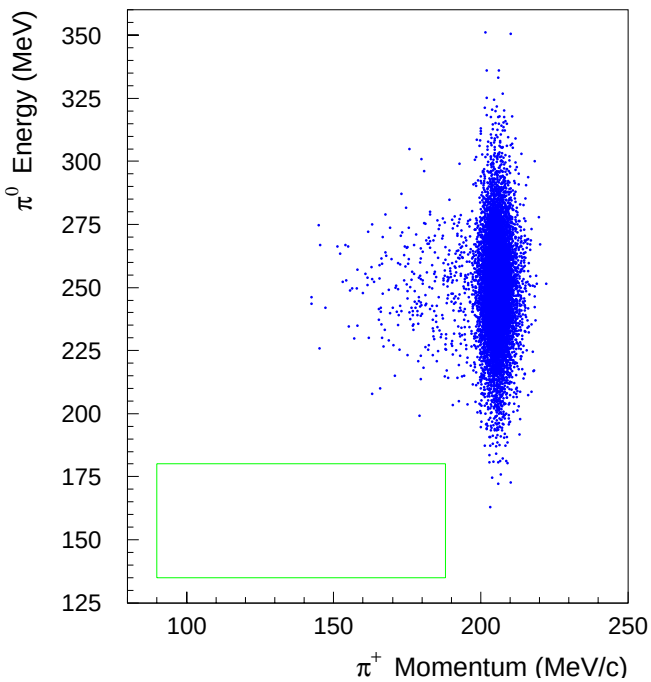
Experiments seeking $K_L \to \pi^0\nu\bar{\nu}$ can add this to their menu

So far only $K^+ \to \pi^+\pi^0\nu\bar{\nu}$ has been probed

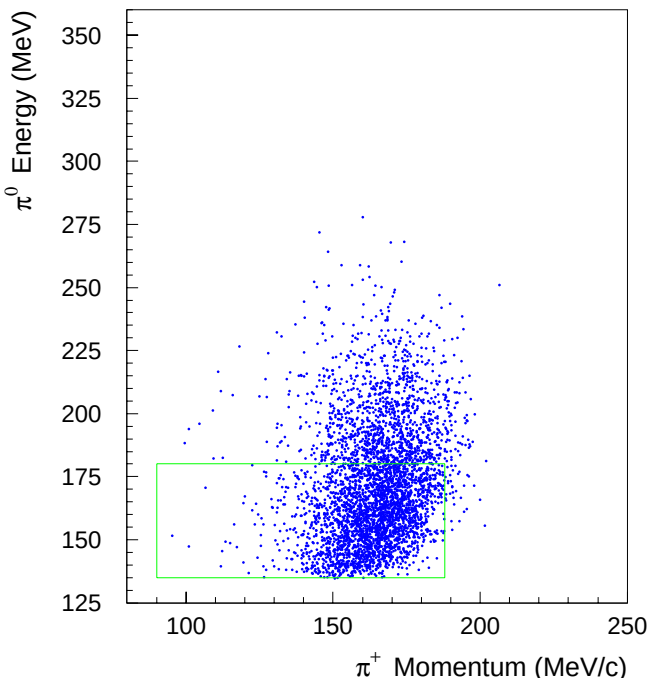
E787 Search for $K^+ \to \pi^+\pi^0\nu\bar{\nu}$

Target of opportunity in monitoring data of for $K^+ \to \pi^+\nu\bar{\nu}$

Data

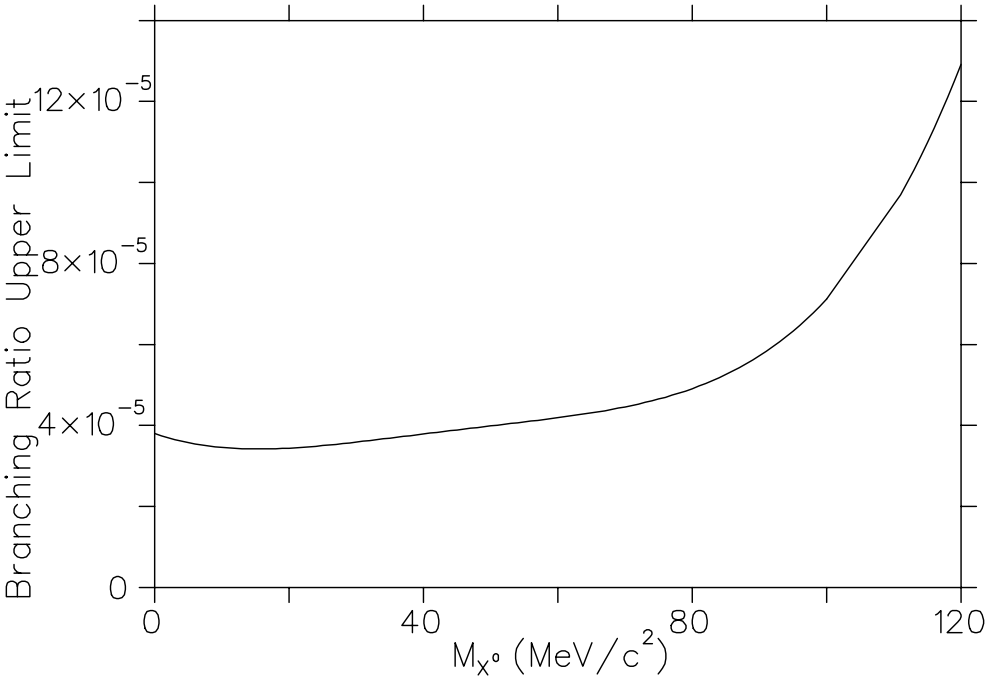


Monte Carlo signal



No events observed & 90% CL limit established:
$B(K^+ \to \pi^+\pi^0\nu\bar{\nu}) < 4.3 \times 10^{-5}$, *far* short of SM expectation!
But comparable to level of 1st order process $K^+ \to \pi^+\pi^-e^+\nu_e$

Can also get limits on non-SM process $K^+ \to \pi^+\pi^0X^0$:



$K_L \to \pi^0 \ell^+ \ell^-$

These decays also sensitive to $ImV_{ts}^* V_{td}$

"Direct" BR $\approx \frac{1}{6} B\left(K_L \to \pi^0 \nu\bar{\nu}\right)$ but nonetheless at first sight much more tractible than $K_L \to \pi^0 \nu\bar{\nu}$

But they suffer from a number of problems, both experimental and theoretical

In addition to $B\left(K_L \to \pi^0 \ell^+ \ell^-\right)_{dir}$ there are 3 problematical contributions:

1. Background from $K_L \to \gamma\gamma\ell^+\ell^-$
   $\sim 10^{-5}\times$ larger than $K_L \to \pi^0 \ell^+ \ell^-$
   Even with very good resolution very hard to fight,
   already seems to be appearing in signal boxes

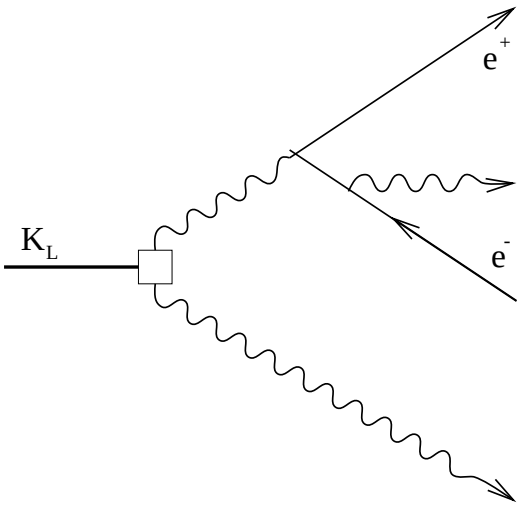
2. CP-conserving 2γ-mediated state
   Roughly comparable in size to CP-violating piece
   Information on $K_L \to \pi^0 \gamma\gamma$ relevant
   New data from NA48
   But not so easy to make the connection
   F. Gabbiani & G. Valencia hep-ph/01005006
   absorptive contribution model dependent
   + large uncertainty in dispersive contribution

3. State-mixing CP-violating contribution $\propto |\epsilon|^2 B\left(K_S \to \pi^0 \ell^+ \ell^-\right)$
   Best knowledge is of $B\left(K_S \to \pi^0 e^+ e^-\right)$, $< 1.4 \times 10^{-7}$ (NA48)
   This yields $B\left(K_L \to \pi^0 e^+ e^-\right)_{indir} < 4.8 \times 10^{-10}$
   Still probably $100\times$ larger than actual effect
   To make life even more interesting, there's interference

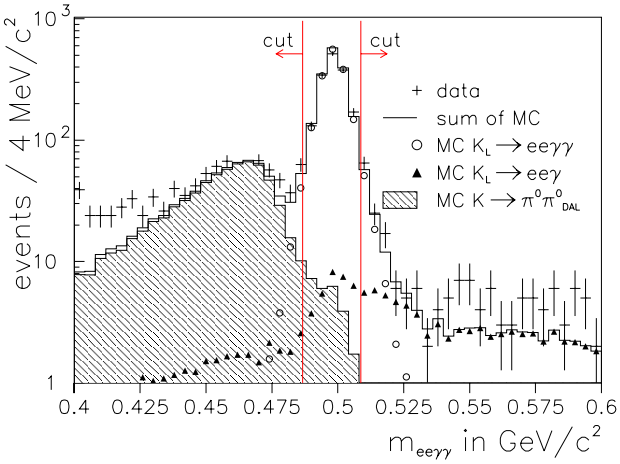
Is there a way out of this morass?

$K_L \to e^+e^-\gamma\gamma$

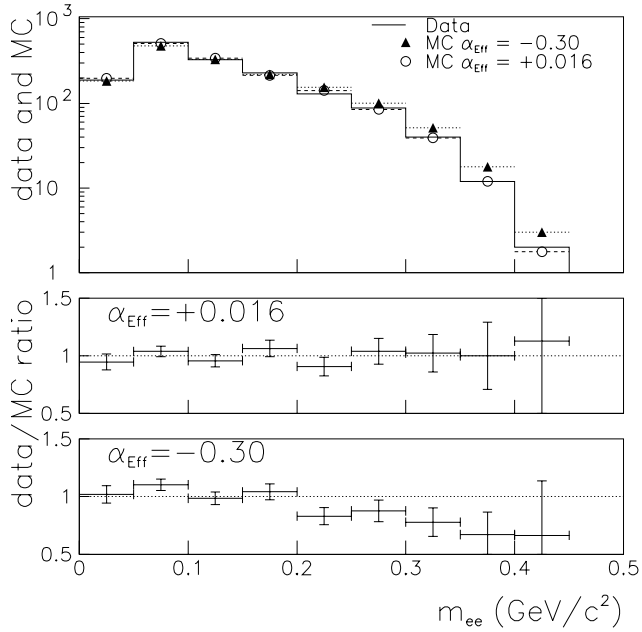
Discovered by AGS E845
as bkgnd to $K_L \to e^+e^-\pi^0$
Radiative corr. to $K_L \to e^+e^-\gamma$
Turned out to be a big problem



Now large samples available
(This from KTeV ⇒)



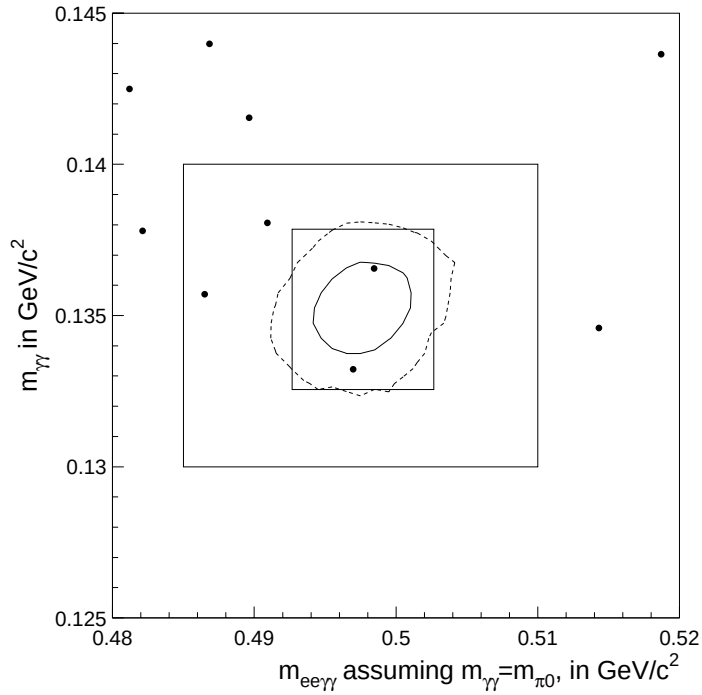
Even form factor
info. now available



KTeV $K_L \to \pi^0 \ell^+ \ell^-$

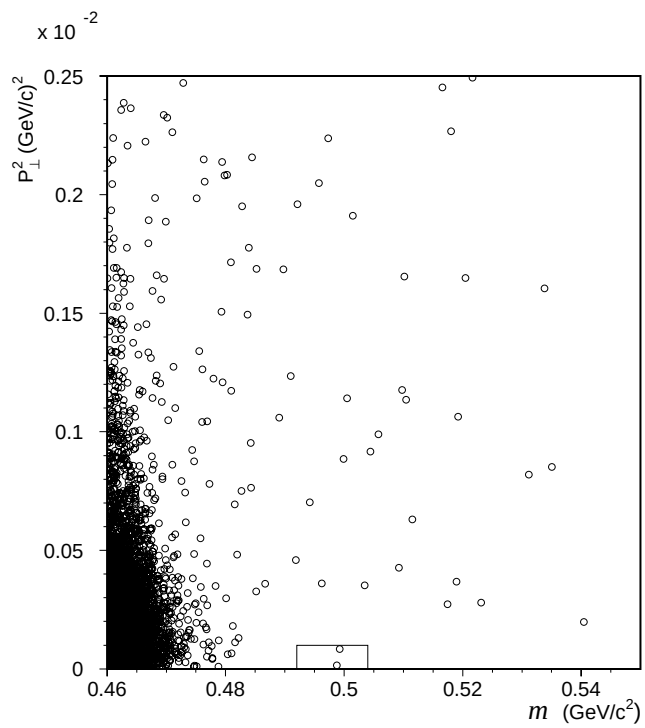
$B(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$

Main background:
$K_L \to \gamma\gamma e^+ e^-$



$B(K_L \to \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$

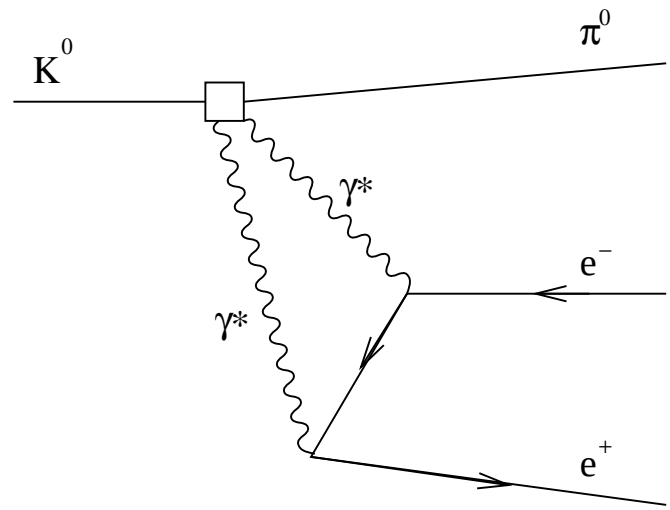
Main backgrounds:
$K_L \to \gamma\gamma\mu^+\mu^-$
$K_L \to \pi^0\pi^+\pi^-$
$K_L \to \pi^\pm\mu^\mp\nu$ + 2 accid γ



Near term prospect: $\sim 2.5\times$ more data
- but background already closing in.

CP-conserving contribution to $K_L \to \pi^0 e^+ e^-$

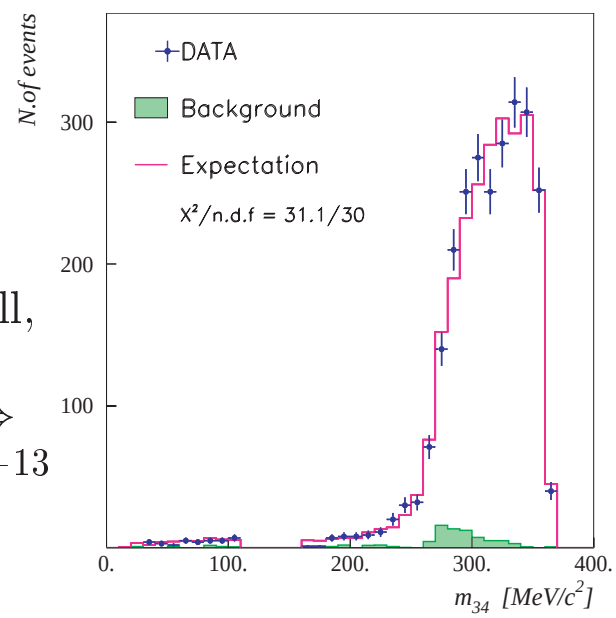
Mediated by $K_L \to \pi^0\gamma\gamma$.
Can get absorptive part
by measuring this process.



$$\mathcal{M}(K_L \to \pi^0\gamma\gamma) = \frac{G_8\alpha}{4\pi}\epsilon_\mu(q_1)\epsilon_\nu(q_2)[\mathbf{A}(q_2^\mu q_1^\nu - q_1\cdot q_2\, g^{\mu\nu})$$
$$+\mathbf{B}\frac{2}{m_K^2}(k\cdot q_1\, q_2^\mu p^\nu + p\cdot q_2\, q_1^\nu p^\mu - q_1\cdot q_2\, p^\mu p^\nu - g^{\mu\nu} p\cdot q_1\, p\cdot q_2)]$$

The **A** and **B** amplitudes refer to the $J_{\gamma\gamma} = 0$ and $J_{\gamma\gamma} = 2$ amplitudes respectively. The effect of the former on $K_L \to \pi^0 e^+ e^-$ is greatly suppressed by helicity conservation.

Large samples of $K_L \to \pi^0\gamma\gamma$ now available, e.g. from NA48 which contains > 2500 events.



NA48 data imply **B** rather small, (little action at low $m_{\gamma\gamma}$).
$a_V = -0.46 \pm 0.03_{stat} \pm 0.04_{syst} \Rightarrow$
$B(K_L \to \pi^0\gamma\gamma)^{CP}_{cons} = 4.7^{+2.2}_{-1.8} \times 10^{-13}$

But this absorptive only, & KTeV data disagrees with NA48!
Possible total contributions from $(0.25$ to $7.3) \times 10^{-12}$
C.f. direct contribution expected to be $\sim 5 \times 10^{-12}$ in SM

Mass-matrix contribution to $K_L \to \pi^0 e^+ e^-$

Arises from $\mathcal{O}(\epsilon)$ admixture of K_1 in K_L
Amplitude can be *measured* from $K_S \to \pi^0 e^+ e^-$
But this contribution interferes with vector part of direct:

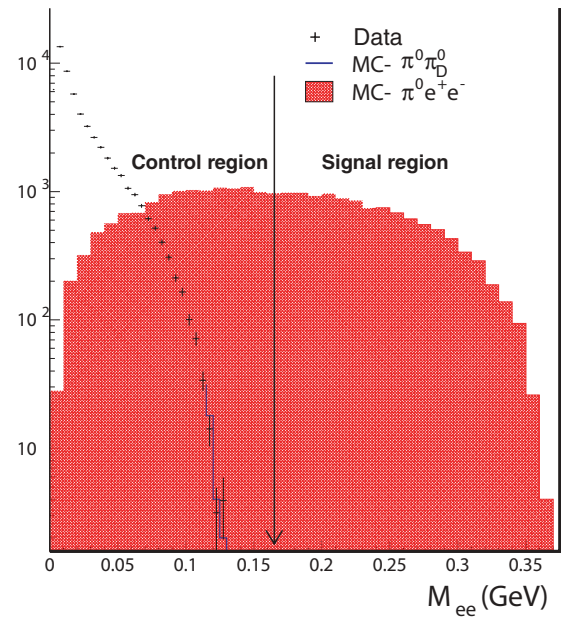
$$B(K_L \to \pi^0 ee)_{CPV} \approx \left(15.3 a_S^2 - 6.8 \frac{Im(\lambda_t)}{10^{-4}} + 2.8 (\frac{Im(\lambda_t)}{10^{-4}})^2\right) \cdot 10^{-12}$$

where $B(K_S \to \pi^0 e^+ e^-) = 5.2 \times 10^{-9} a_S^2$
and a_S is a parameter of order 1.

Not yet observed
Best 90% CL limit obtained
recently from NA48 $\Rightarrow$

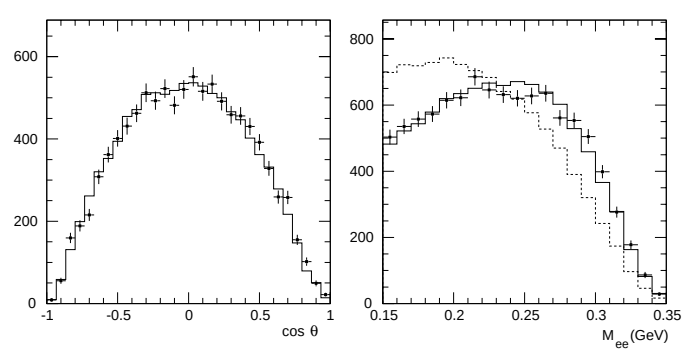
$B(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$

Expected BR 100× smaller!
Reachable by NA48/1?



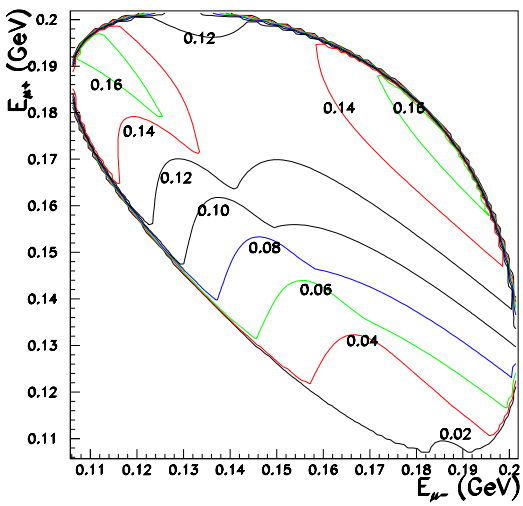
Guesstimates so far from measurements of $K^+ \to \pi^+ e^+ e^-$
which can be related via χPT + models to $K_S \to \pi^0 e^+ e^-$

Good data on $K^+ \to \pi^+ e^+ e^-$
10,000 events from AGS E865 $\Rightarrow$
But m_{ee} spectrum *disagrees*
with simple $\mathcal{O}(p^4)$ χPT
estimate on which guesses based!



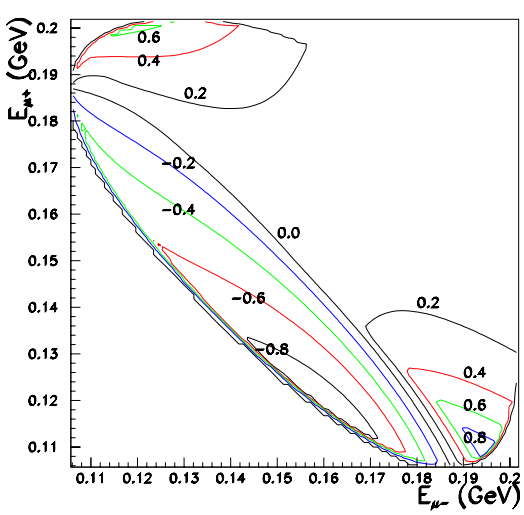
$\pi^0\mu^+\mu^-$ Summary

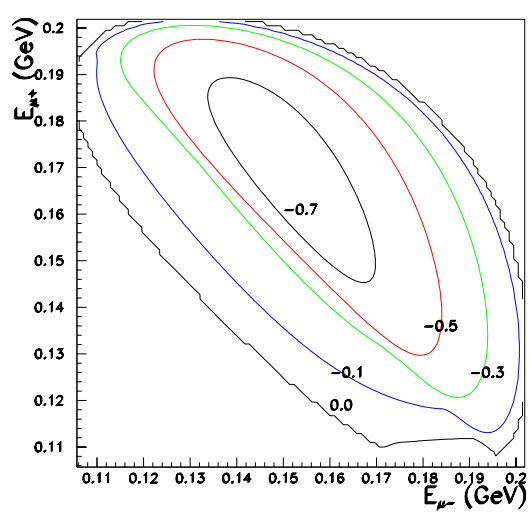
- The parity-odd observable P_L has the interesting property of being sensitive to Direct-CPV.
- Both out-of-plane polarization and the lepton energy asymmetry are sensitive to indirect CP.
- Could all three measurements and the branching ratio be used to obtain the direct component ?
- Still need to examine how well the decay is described in terms of a_s, α_V, and $Im(\lambda_t)$.



Decay distribution

Longitudinal and out-of-plane polarizations



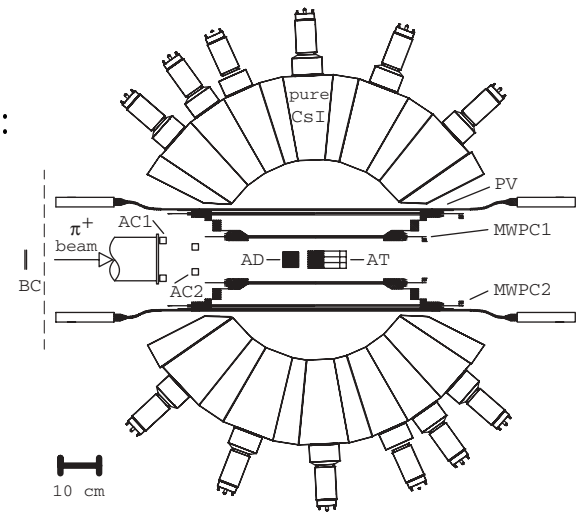


$\pi^+ \to \pi^0 e^+ \nu$

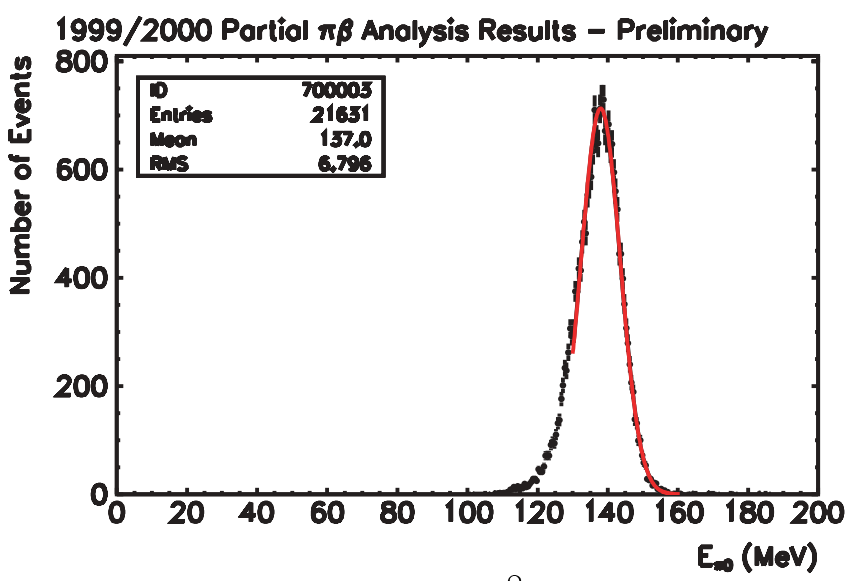
Suppressed by kinematics to the 10^{-8} level.
Main interest is potential for measuring $|V_{ud}|$
BR $\propto |V_{ud}|^2$, presently known to $\sim 4\%$

Want to check unitarity of the CKM matrix:
Should have $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
At present, best knowledge of $|V_{ud}|$ is from superallowed Fermi nuclear β decays
V_{us} known from K_{e3} decays, V_{ub} known to be tiny
One finds $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9962 \pm 0.0016$,
a 2.4σ discrepancy.

Thus the PIBETA experiment at PSI:



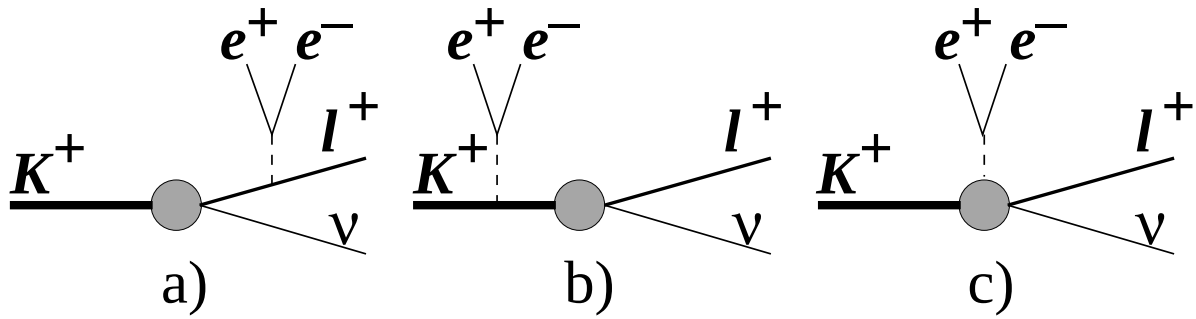
Partial data set
$> 21,000$ events



$B(\pi^+ \to \pi^0 e^+ \nu) = (1.044 \pm 0.007 \pm 0.015) \times 10^{-8}$, preliminary
c.f. unitarity prediction $(1.038 - 1.044) \times 10^{-8}$.
When full data set analyzed, precision will be $\pm 0.5\%$.
Other modes, *e.g.* $\pi^+ \to e^+ \nu$ will also be studied.

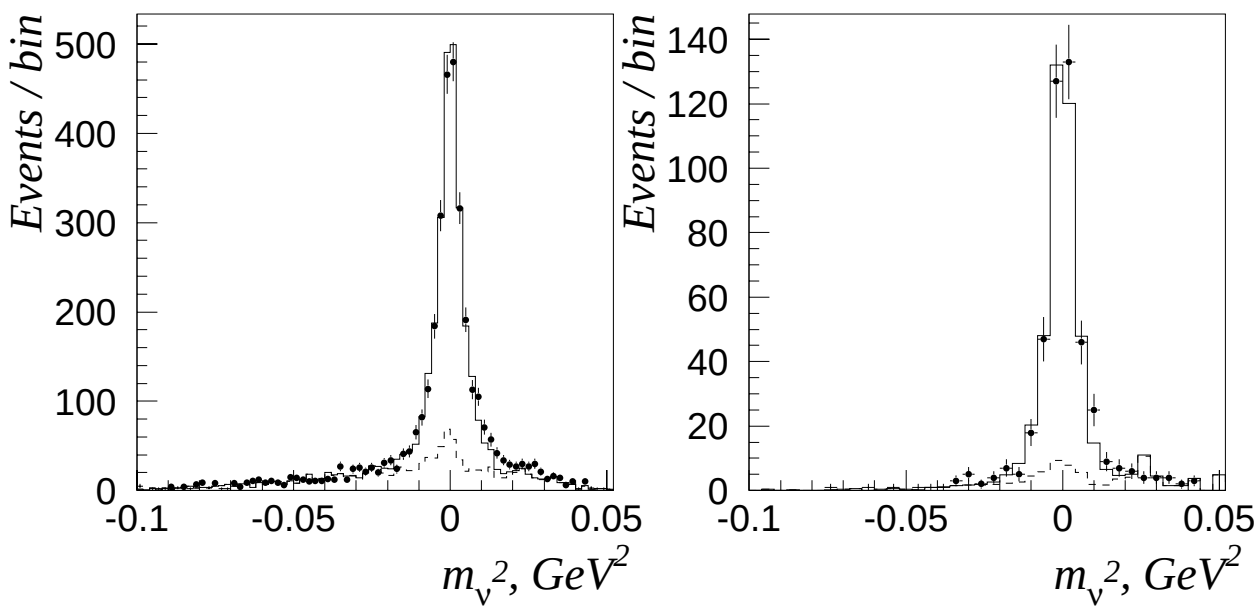
E865 study of $K^+ \to \mu^+\nu e^+e^-$ & $K^+ \to e^+\nu e^+e^-$

Exploration of kaon structure, check of χPT



2679 $K^+ \to \mu^+\nu e^+e^-$ evts of which 514 were background

410 $K^+ \to e^+\nu e^+e^-$ evts of which 40 were background



Form factor analysis:

ff	value $\pm$ stat,sys,model	"expected" value	π^+ value
F_V	$112 \pm 15 \pm 10 \pm 3$	96	60 ± 28
F_A	$35 \pm 14 \pm 13 \pm 3$	41 ± 6	41 ± 6
R	$227 \pm 13 \pm 10 \pm 9$	230 ± 34	209 ± 30
F_T	$-4 \pm 7 \pm 7 \pm 0.4$	0	-5.6 ± 1.7

New $\pi^+ \to e^+\nu\gamma$ data expected soon from PIBETA experiment.

Conclusions

LFV experiments have been pushed to remarkable sensitivities
- correspond to mass scale of well over 100 TeV

But success has killed most models predicting LFV in K decay
- future mainly as by-products of other studies

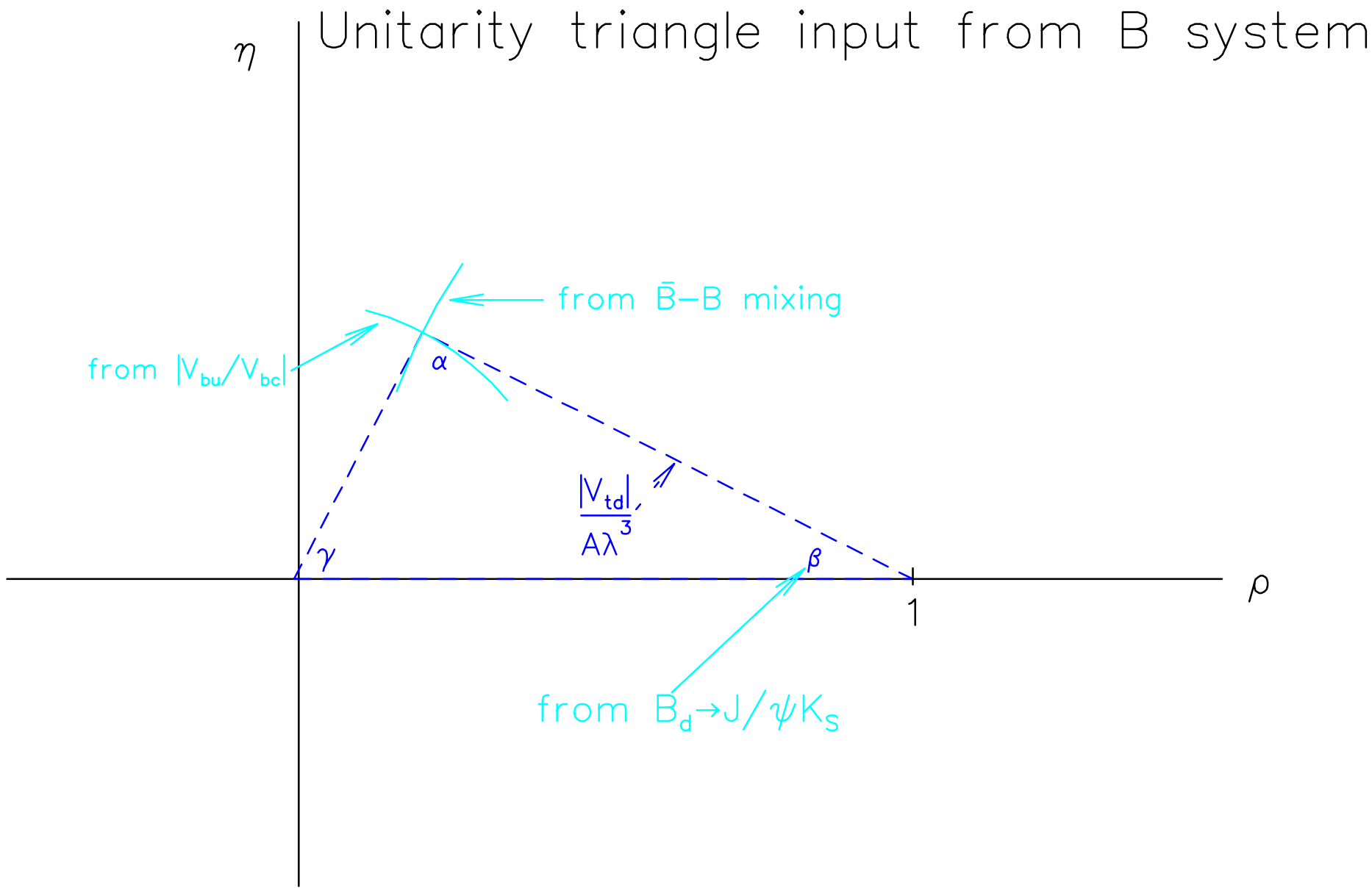
High precision measurement of $K_L \to \mu^+\mu^-$ available
- very useful if theoretical issues resolved
- auxilliary measurements to help this resolution in process
- but situation still unsettled

$K_L \to \pi^0\ell^+\ell^-$ experiments have been pushed by an O.M.
- Experiments on auxillary processes have made similar progress
- But background is starting to be seen
- and progress in untangling the components slow
- Maybe new idea will help

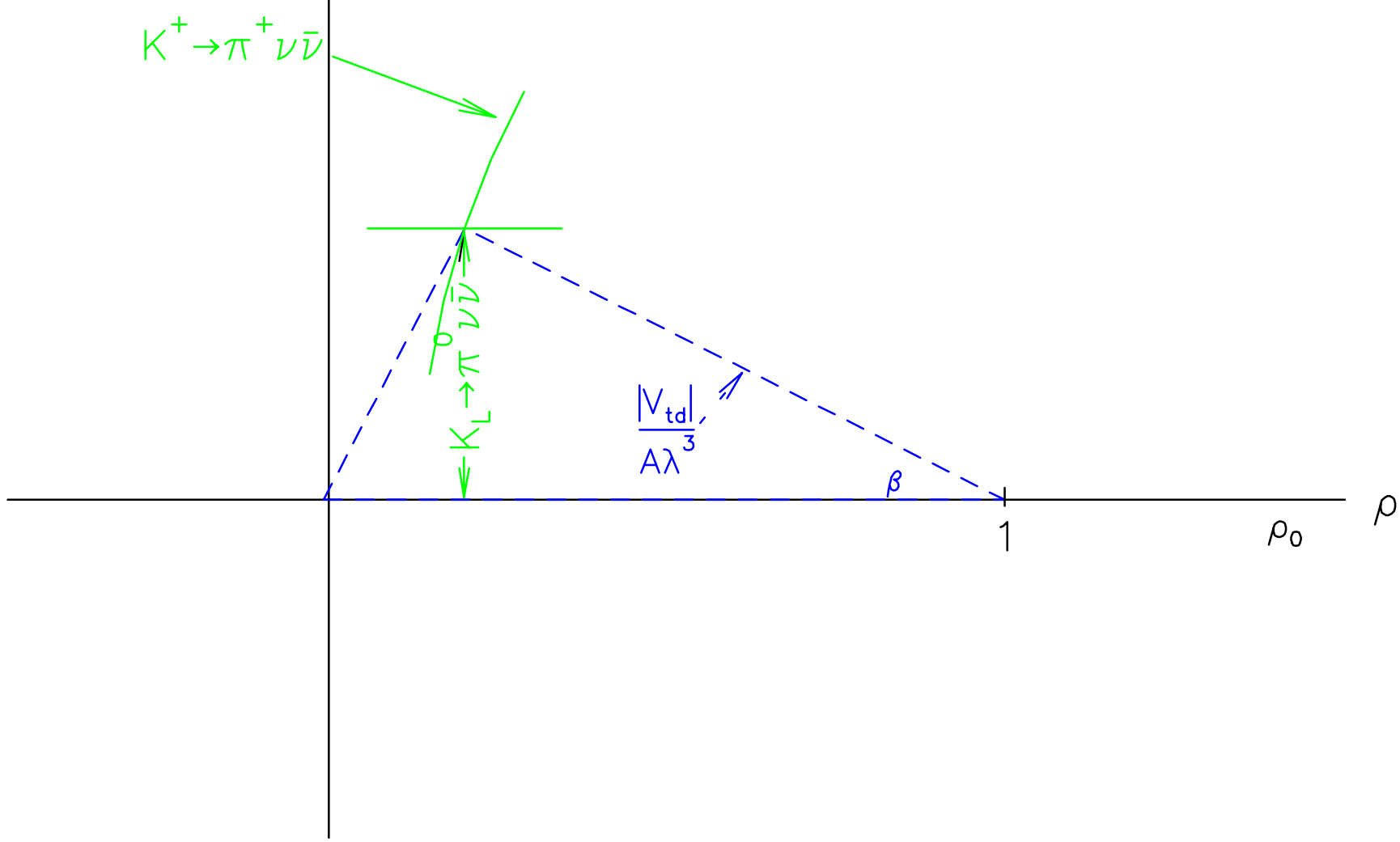
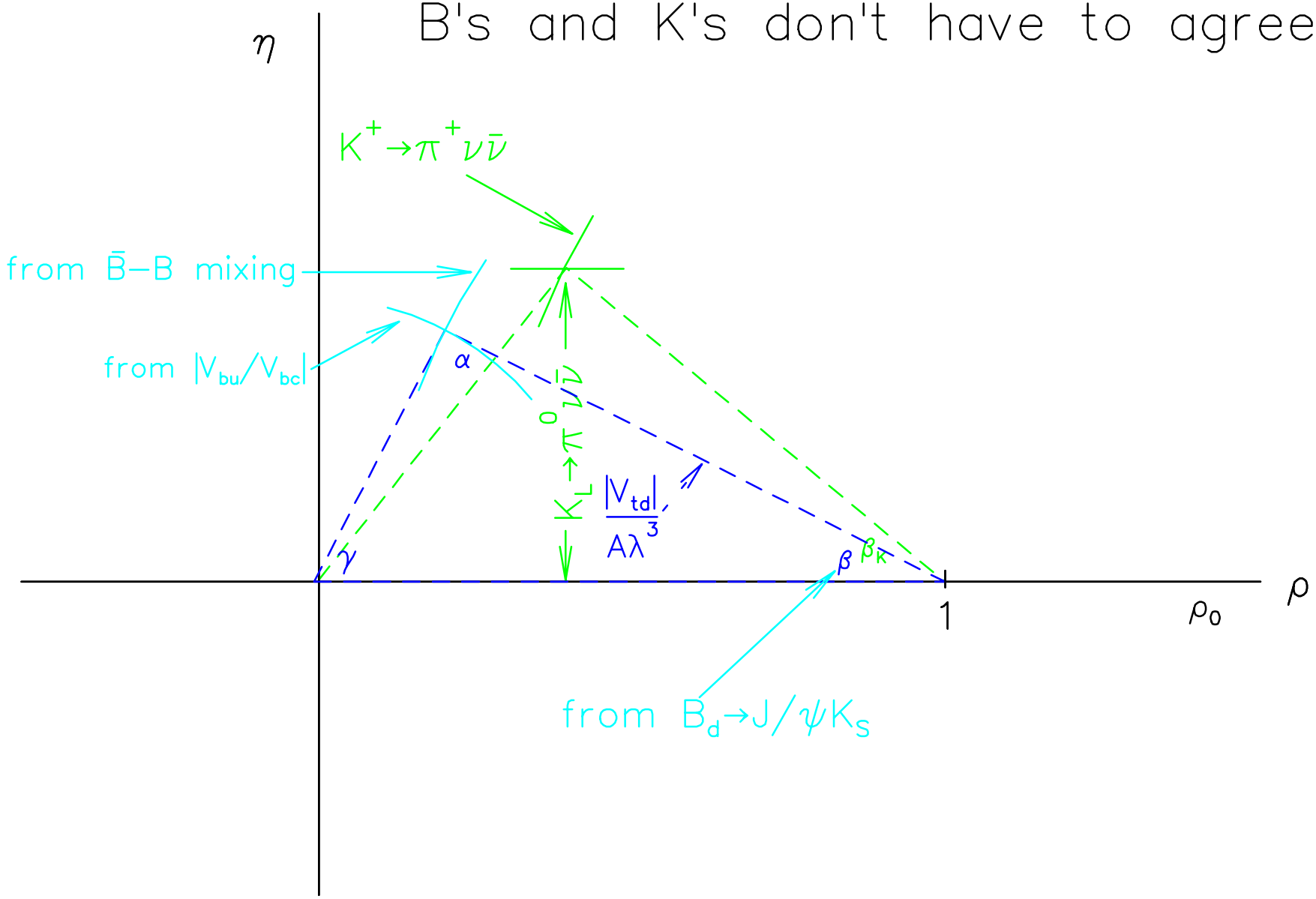
$K^+ \to \pi^+\nu\bar{\nu}$ has been seen,
- clear that it can be exploited
- two initiatives to pursue it further
  - 10^{-11}/evt level experiment in testing stage
  - 10^{-12}/evt level experiment in R&D phase

First dedicated experiment to seek $K_L \to \pi^0\nu\bar{\nu}$ proceeding
Initiative to go all the way in progress
- trying for $\sim 10\%$ measurement of η

Goal is future high precision determinations of λ_t from K's
to be compared to B information to critically test SM


Unitarity triangle input from B system
η
ρ
1
from B̄–B mixing
from |V_bu/V_bc|
α
|V_td|/Aλ^3
γ
β
from B_d→J/ψK_S

$K \to \pi \nu \bar{\nu}$ and the Unitarity Triangle



B's and K's don't have to agree!