Future Prospects for K Decay Experiments

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BNL

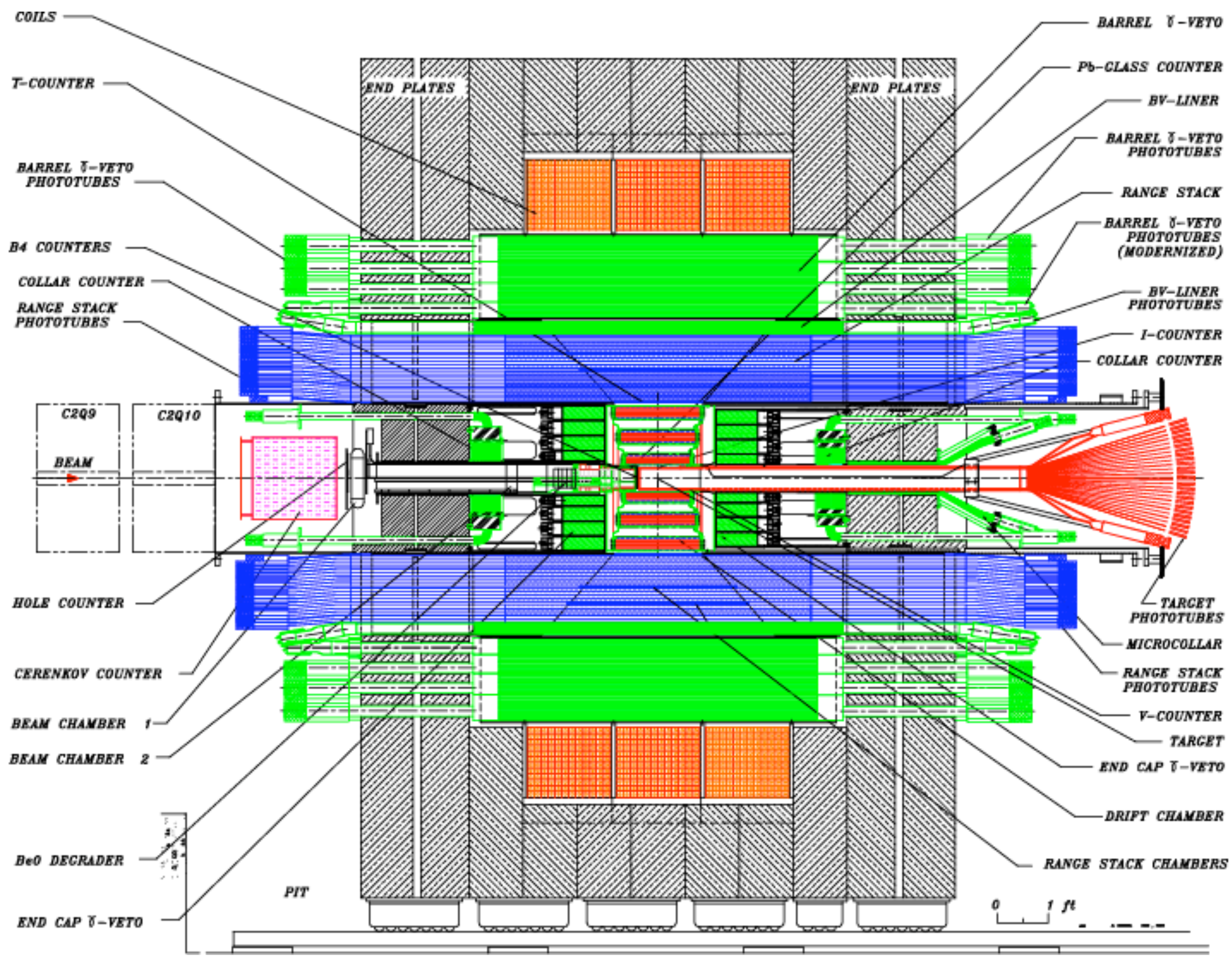
Outline

- What should we be doing?
- Is (American) history any guide?
- The leading opportunities
  - $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
  - $K_L \rightarrow \pi^0 \nu\bar{\nu}$
  - $K_L \rightarrow \pi^0 \ell^+ \ell^-$
- Conclusions

What should we be doing?

- $K_L \to \pi^0 \nu\bar{\nu}$ & $K^+ \to \pi^+ \nu\bar{\nu}$
  – NP governed by a single effective operator
  – Determine the IP & modulus of any NP contribution
  – Can be calculated in almost any model
  – Sensitive to high mass scales
- $K_L \to \pi^0 e^+ e^-$ & $K_L \to \pi^0 \mu^+ \mu^-$
  – In SM, same information as $K_L \to \pi^0 \nu\bar{\nu}$
  – NP can contribute to >1 operator: richer but harder to interpret
  – Recent developments show these more accessible!
- LFV processes, T-violation, medium rare
- Some pion decays

BNL AGS E949 $K^+ \to \pi^+ \nu\bar{\nu}$



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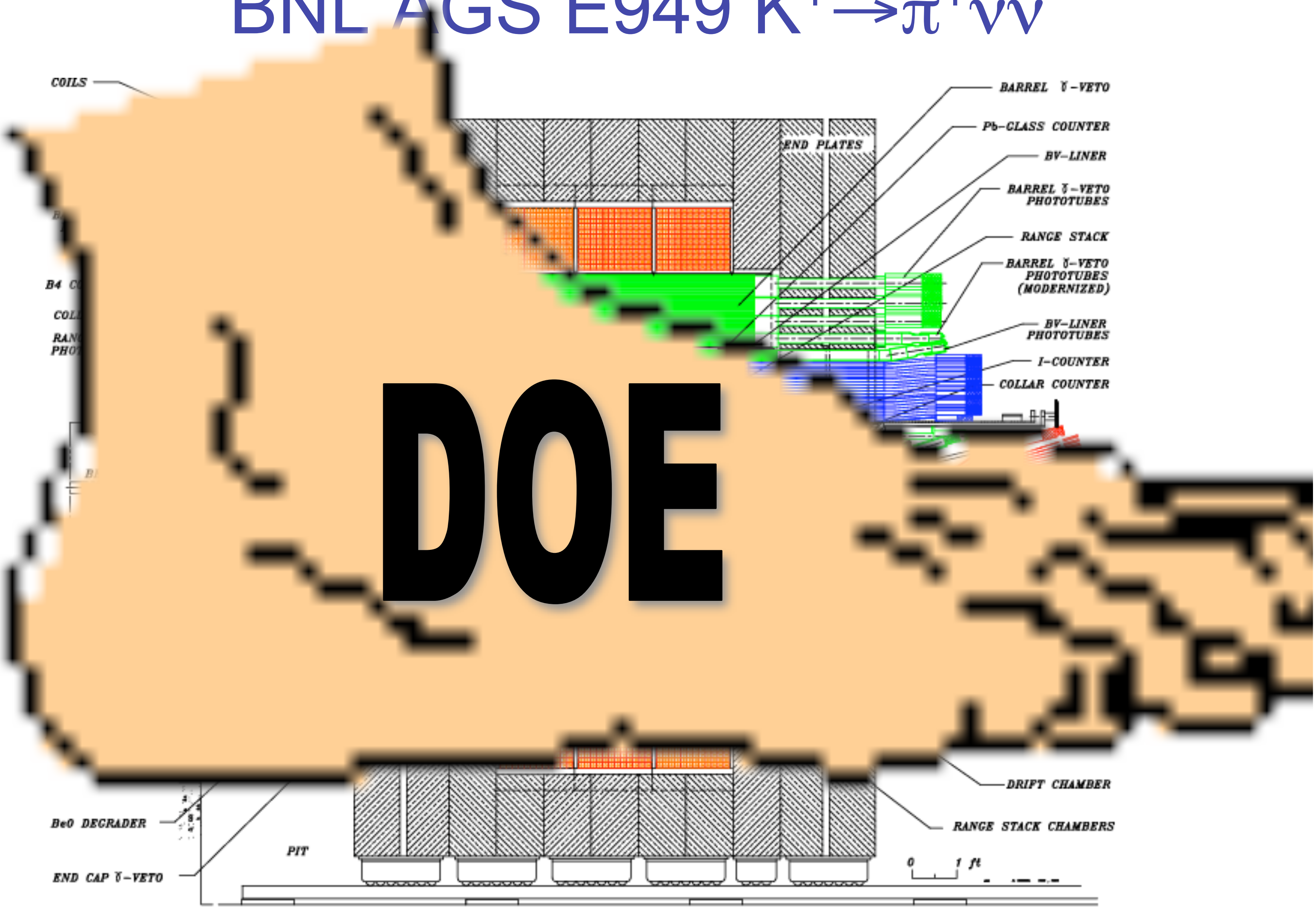
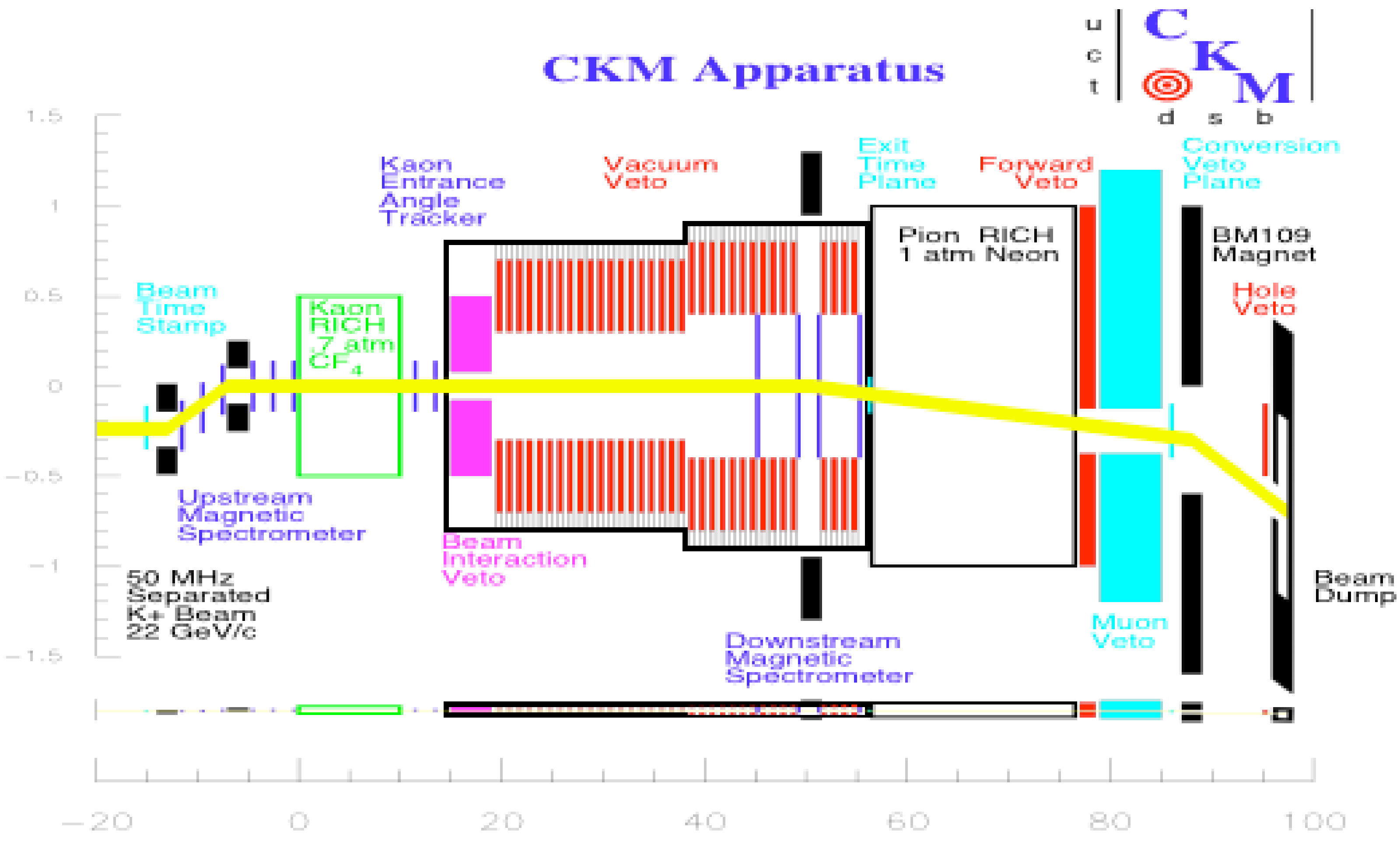
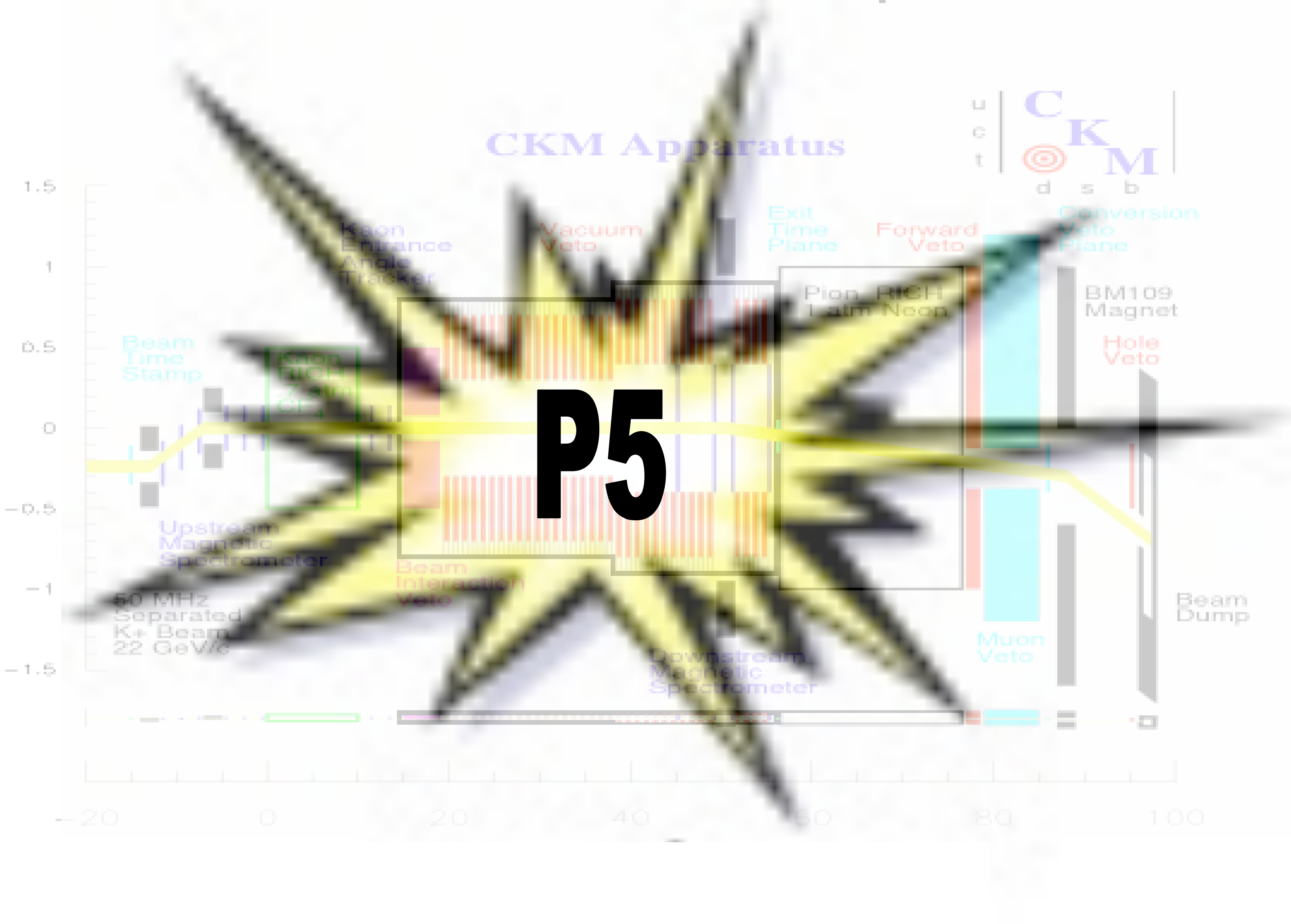


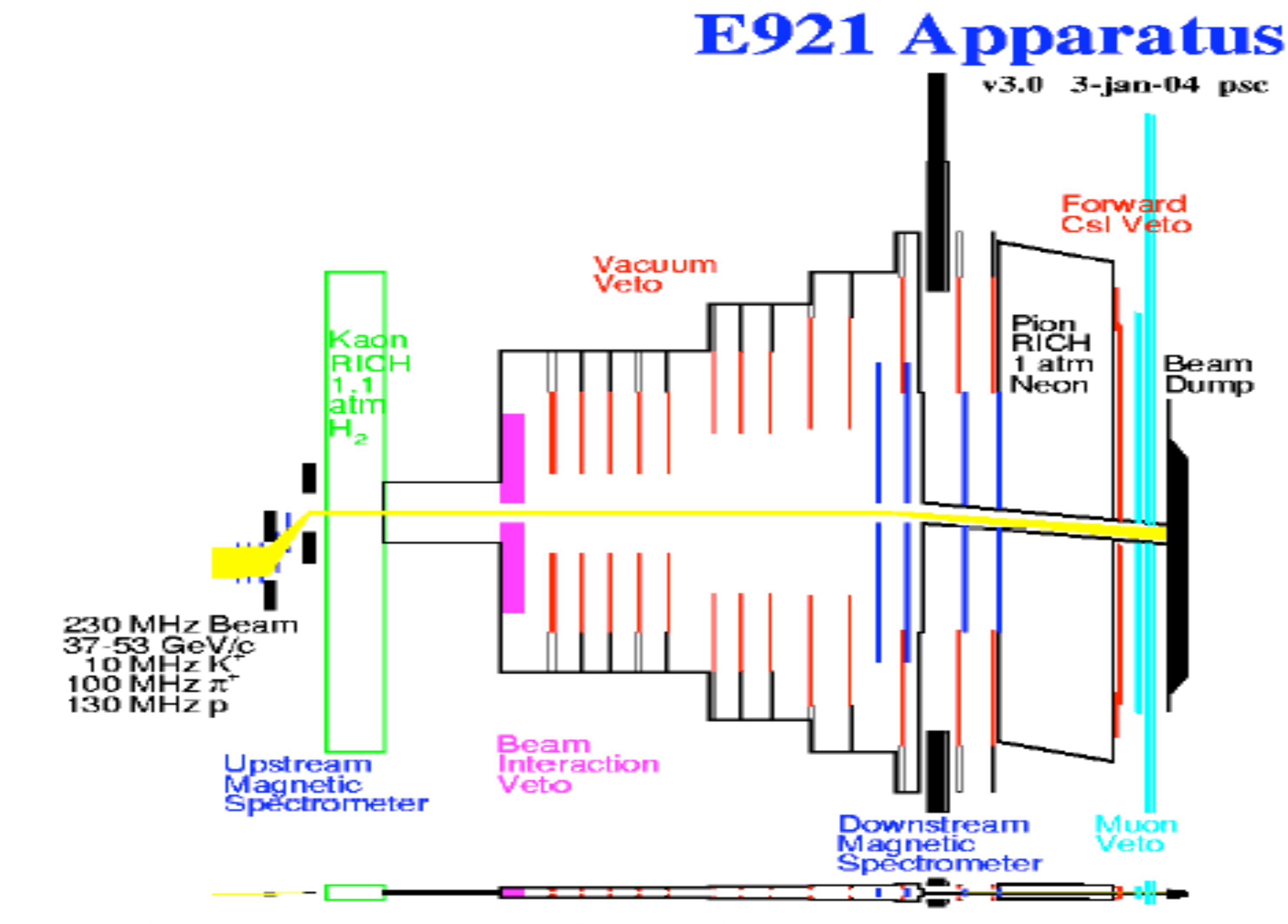
FNAL CKM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Experiment



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

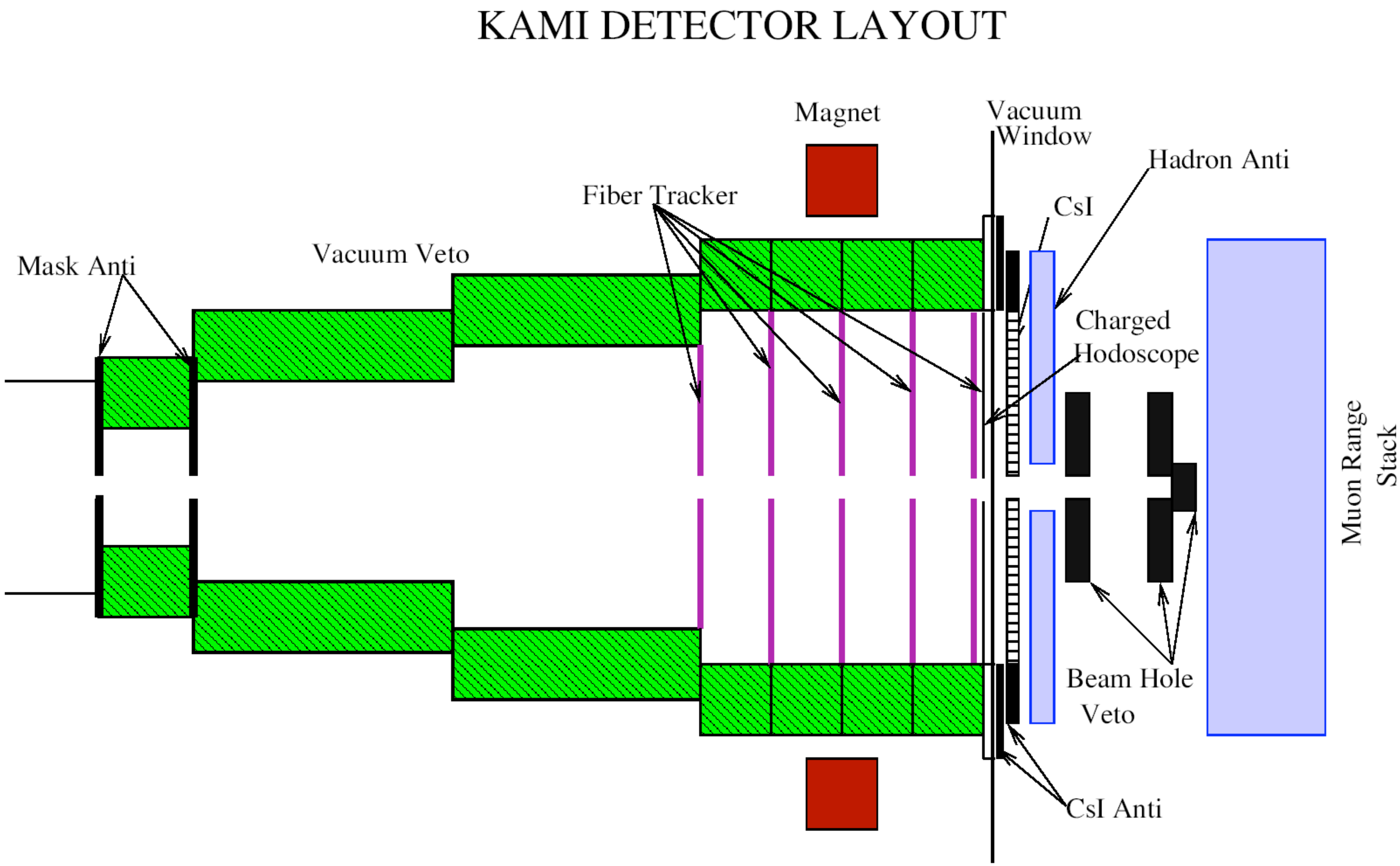


FNAL P940 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

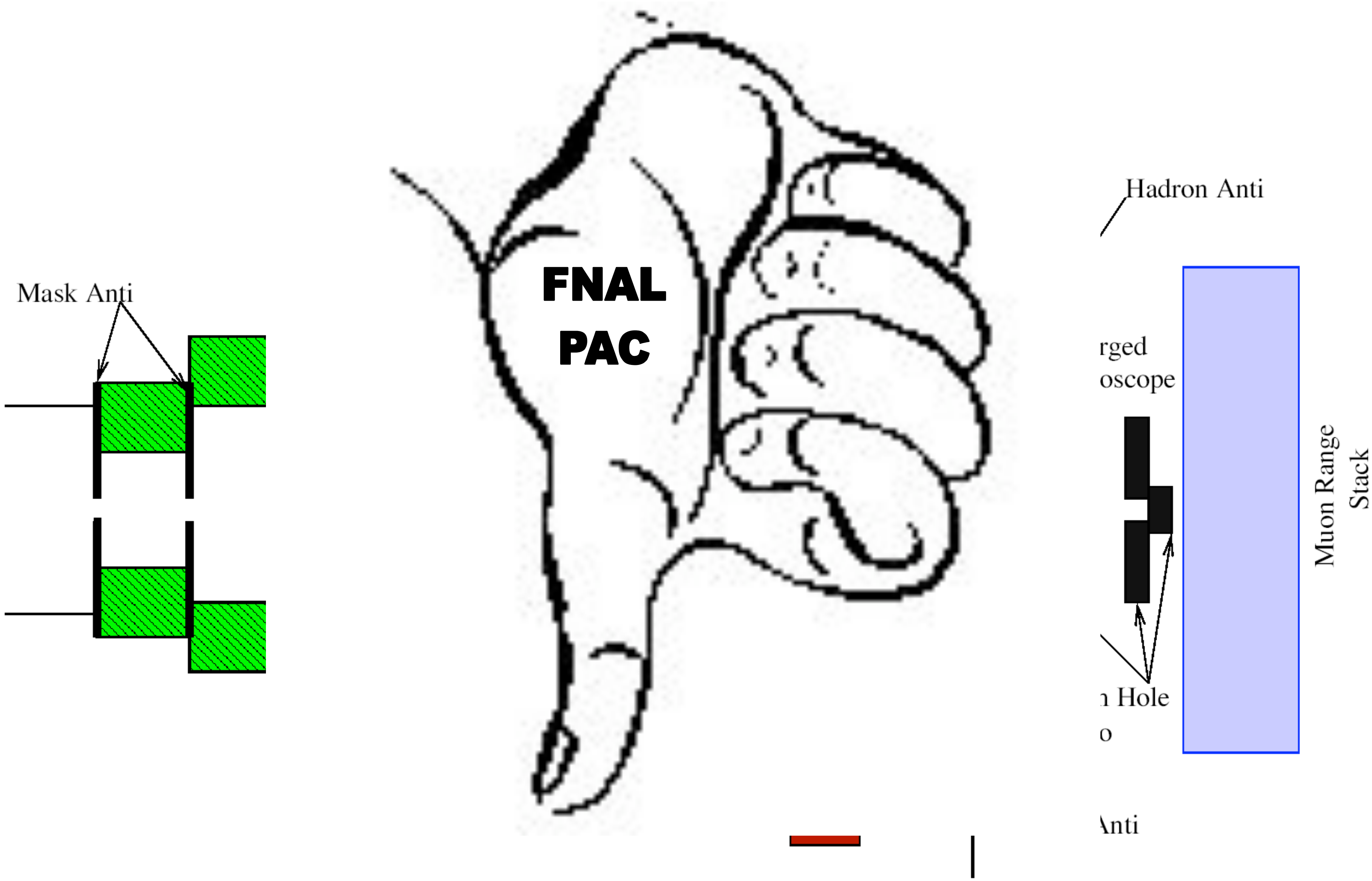


FNAL P940 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

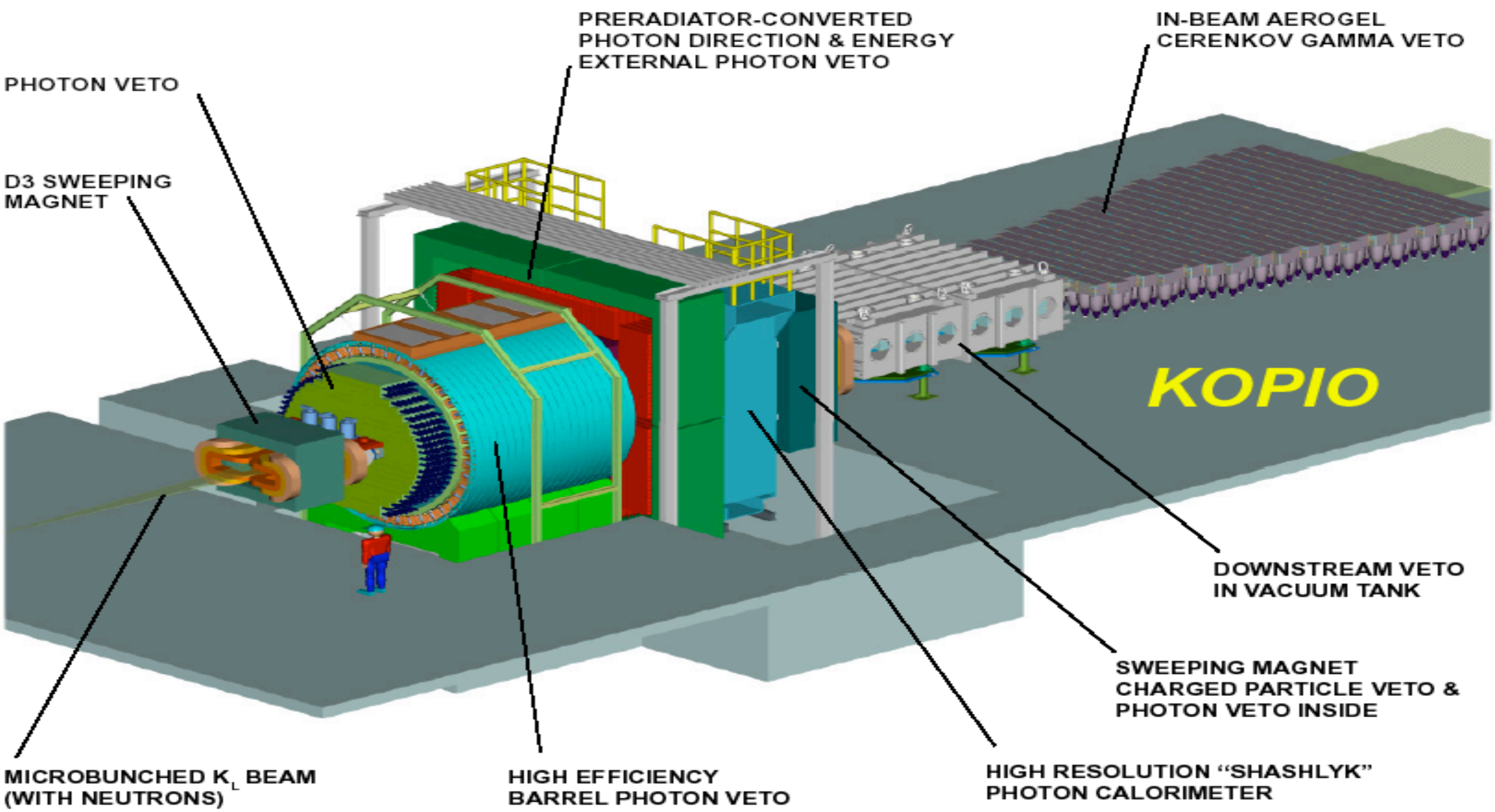
KAMI $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at FNAL



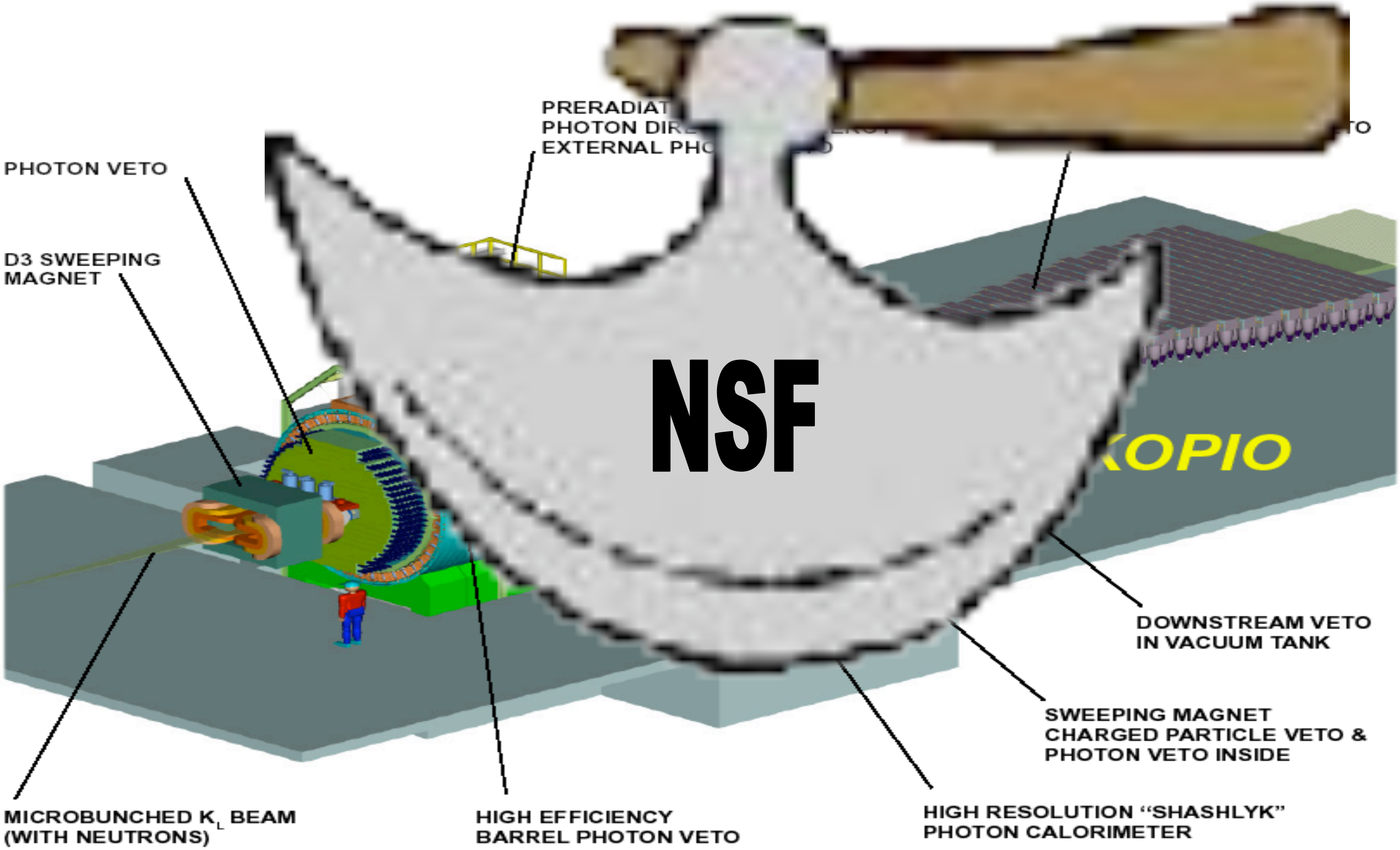
KAMI $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at FNAL



KOPIO $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at BNL

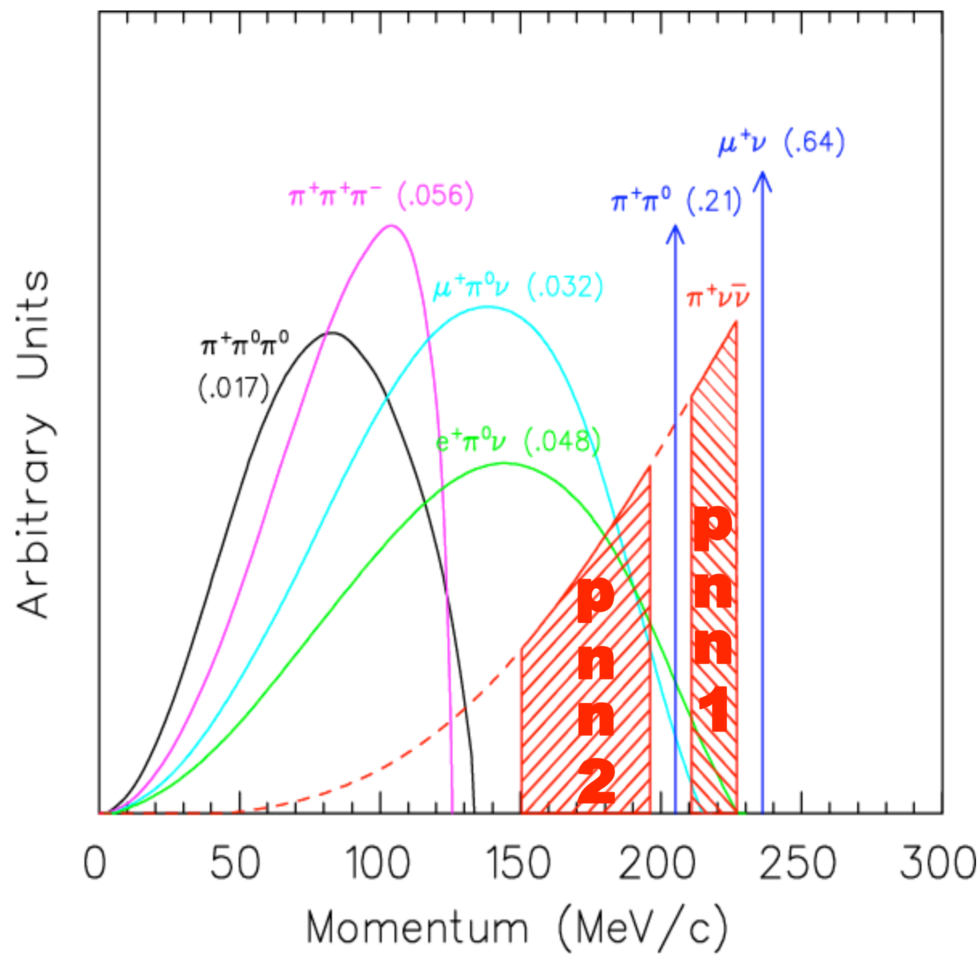


KOPIO $K_L \to \pi^0 \nu \bar{\nu}$ at BNL



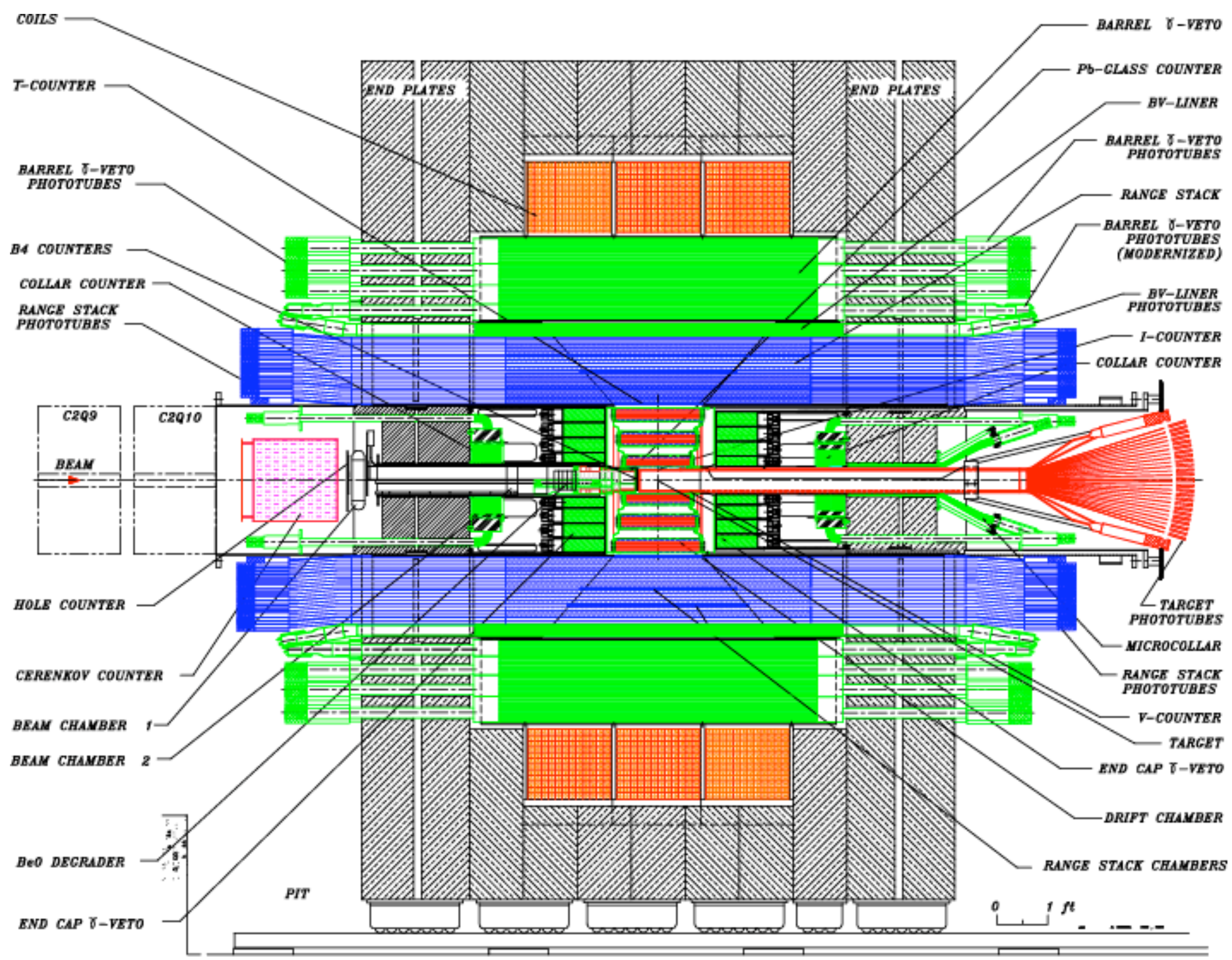
Experimental considerations for $K^+ \to \pi^+ \nu \bar{\nu}$

- BR ~ 8×10^{-11}
- 3-body decay, only 1 visible
- π^+ common K decay product
- Backgrounds:
  - $K^+ \to \mu^+ \nu(\gamma)$
  - $K^+ \to \pi^+ \pi^0$
  - $K^+ n \to K^0 p$; $K_L \to \pi^+ \ell^- \nu$, ℓ^- missed
  - Ke4
  - Beam (stopped-K configuration)
    - Beam π^+ mis-ID as K^+, then fakes K decay at rest
    - K^+ decay in flight
    - 2 beam particles
  - Beam (in-flight)
    - Beam π^+ mis-ID as K^+, then interacts
    - 2 beam particles

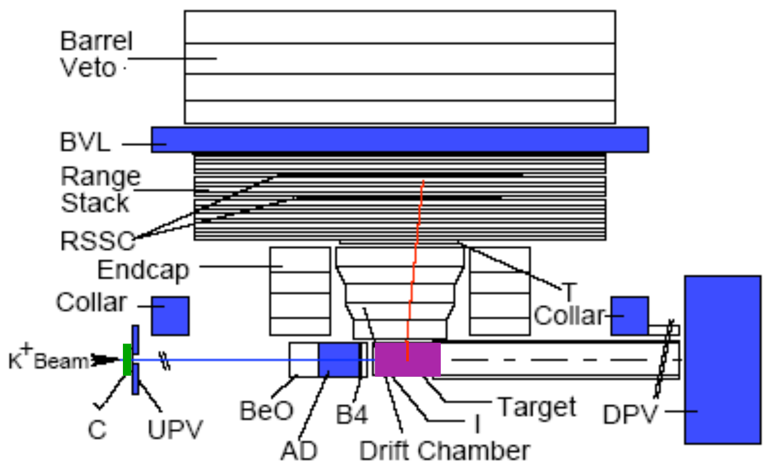


E787/949

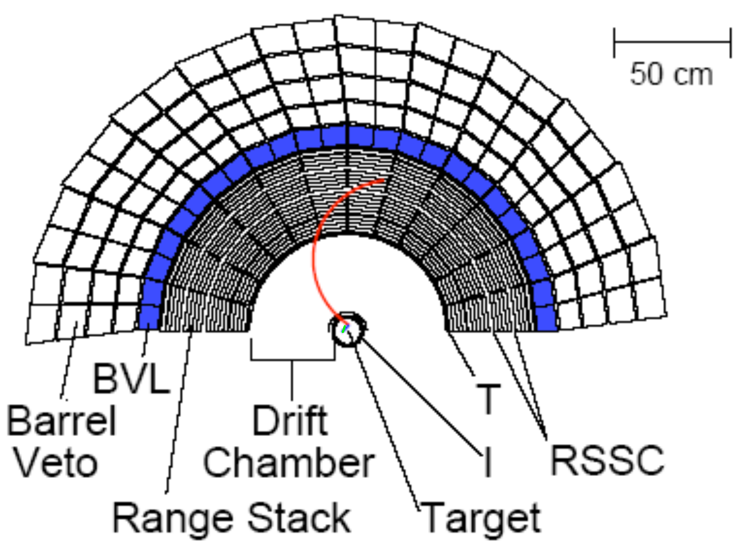
Solenoidal detector at the end of a stopped K^+ beam



E787/949 Technique



- Incoming 700MeV/c beam K^+: identified by Č, WC, scintillator hodoscope (B4). Slowed down by BeO



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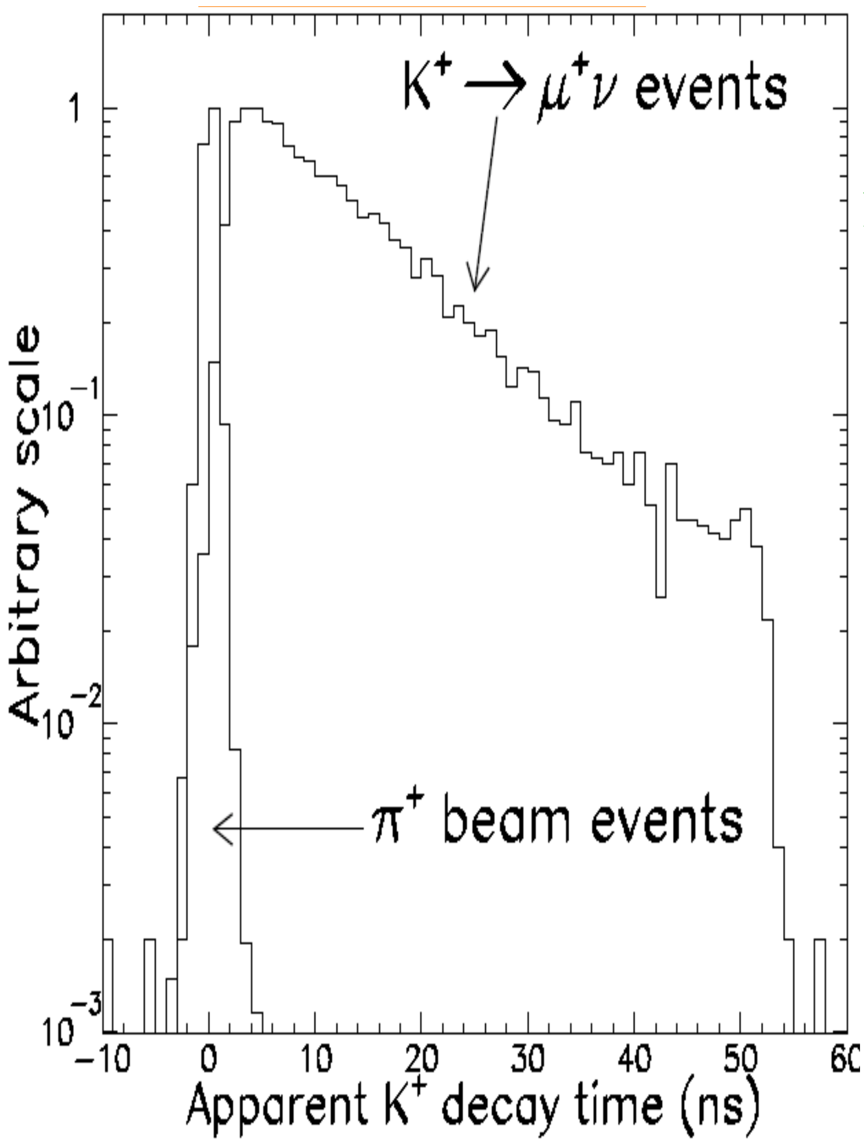

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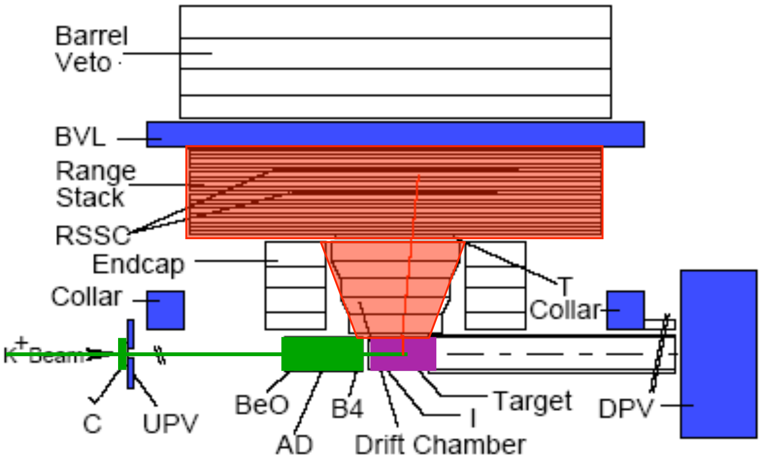
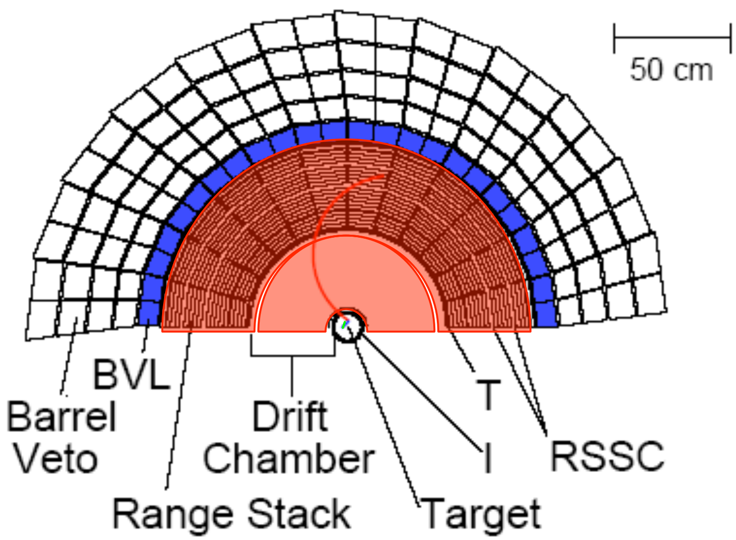
- K^+ stops & decays at rest in scintillating fiber target – measure delay (2ns)

E787/949 Technique





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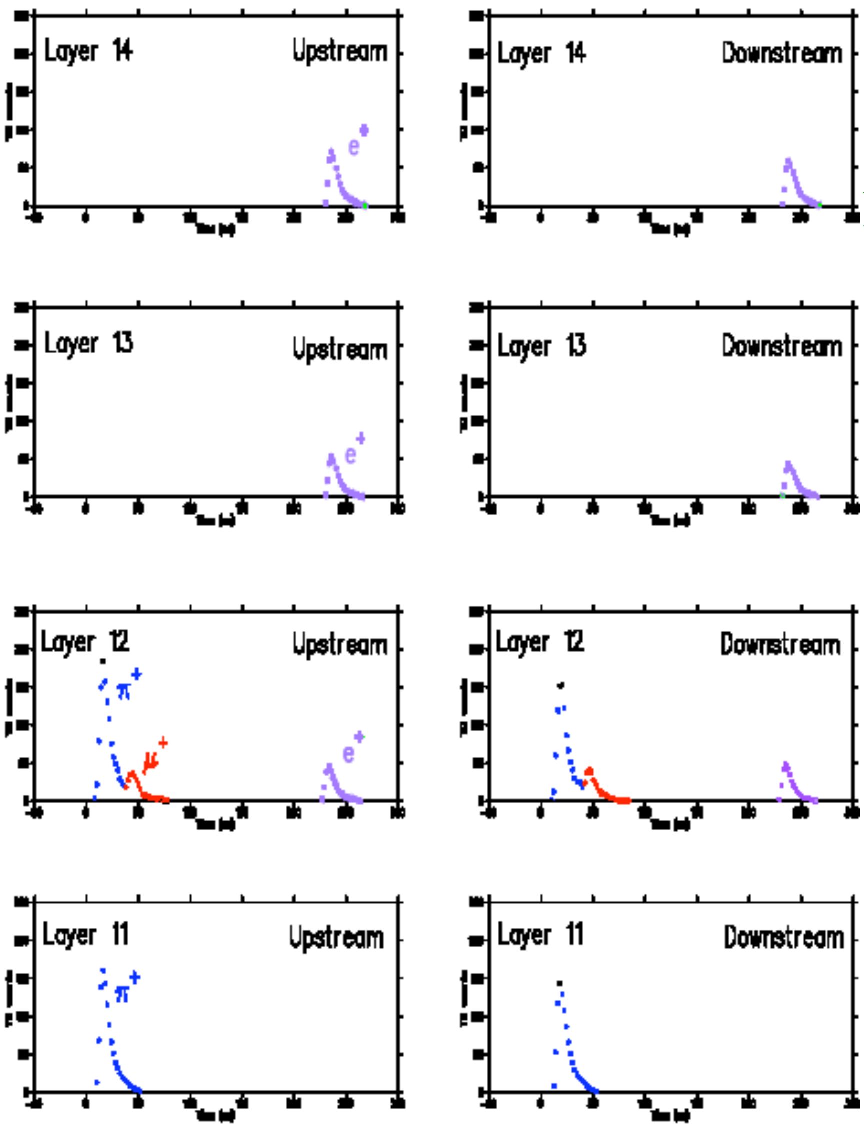
- K^+ stops & decays at rest in scintillating fiber target – measure delay (2ns)
- Outgoing π^+: verified by IC, VC, T counter. Momentum measured in UTC, energy & range in RS and target

(1T magnetic field parallel to beam)

E787/949 Technique



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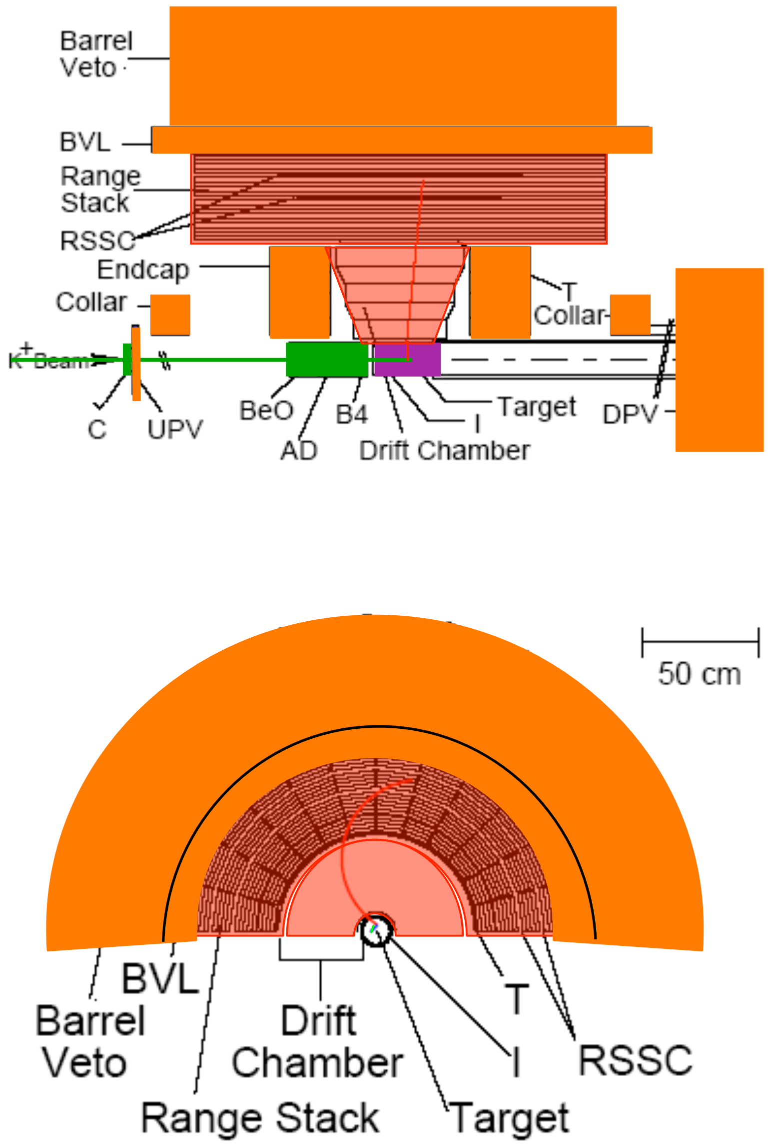
- π^+ stops & decays in RS – detect $\pi^+ \to \mu^+ \to e^+$ chain

E787/949 Technique



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(1T magnetic field parallel to beam)
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- Photons vetoed hermetically in BV-BVL, RS, EC, CO, USPV, DSPV

E787/949 Analysis Strategy

Signal region "the BOX"

PNN1: $p_\pi > p(K^+ \to \pi^+\pi^0) = 205$MeV/c

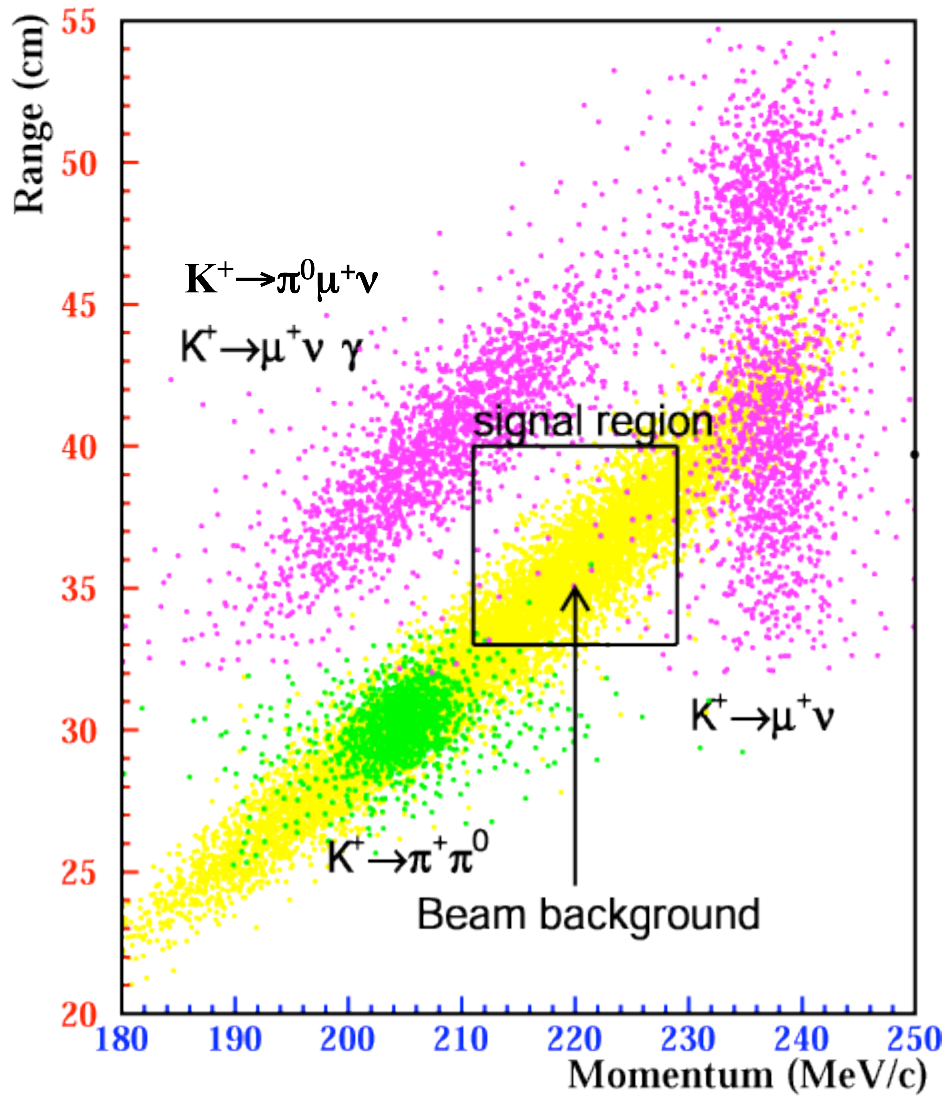
Background sources

Identify *a priori.* at least 2 independent cuts to target each background:

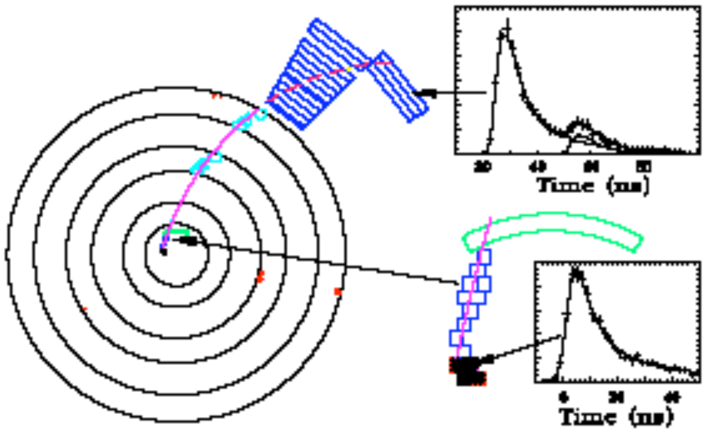
- $K^+ \to \pi^+\pi^0$
- muon background ($K^+ \to \mu+\nu(\gamma)$,…)
- Beam background
- etc.

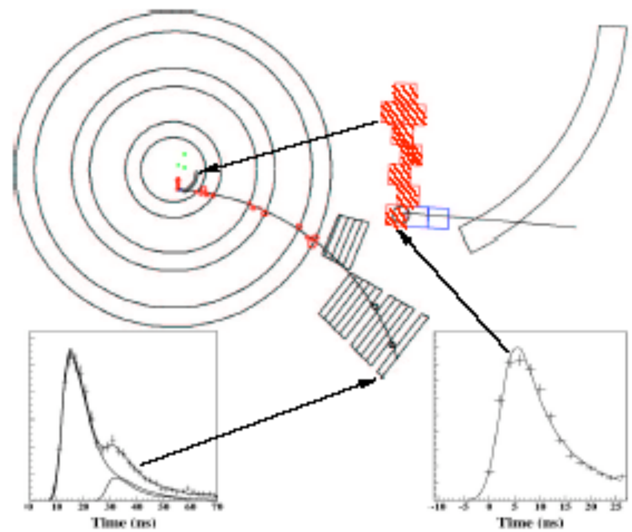
Analysis Strategy

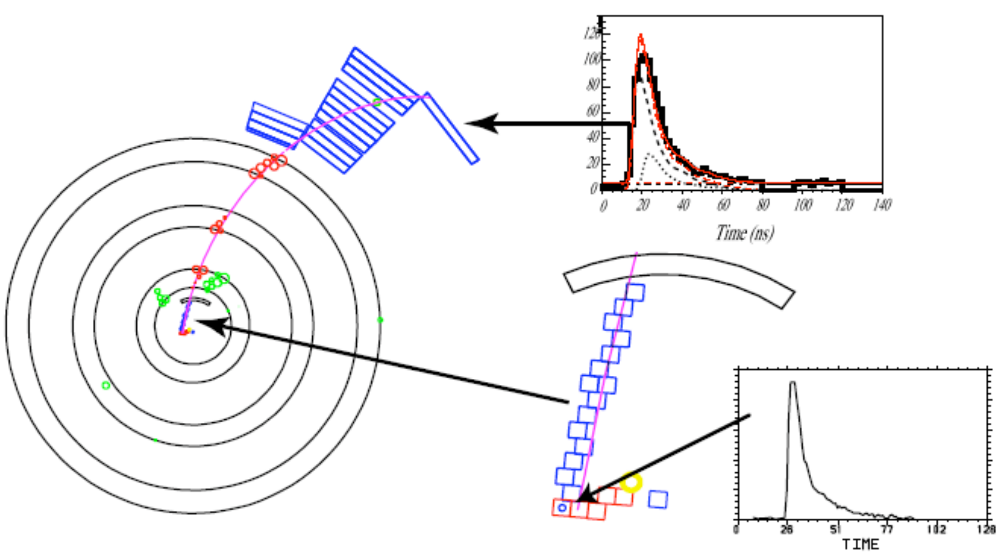
- Blind Analysis
- Measure background level with real data
- To avoid bias,
- 1/3 of data ⇒ cut development
- 2/3 of data ⇒ background measurement
- Characterize backgrounds using background functions
- Likelihood Analysis



E787/949 Events

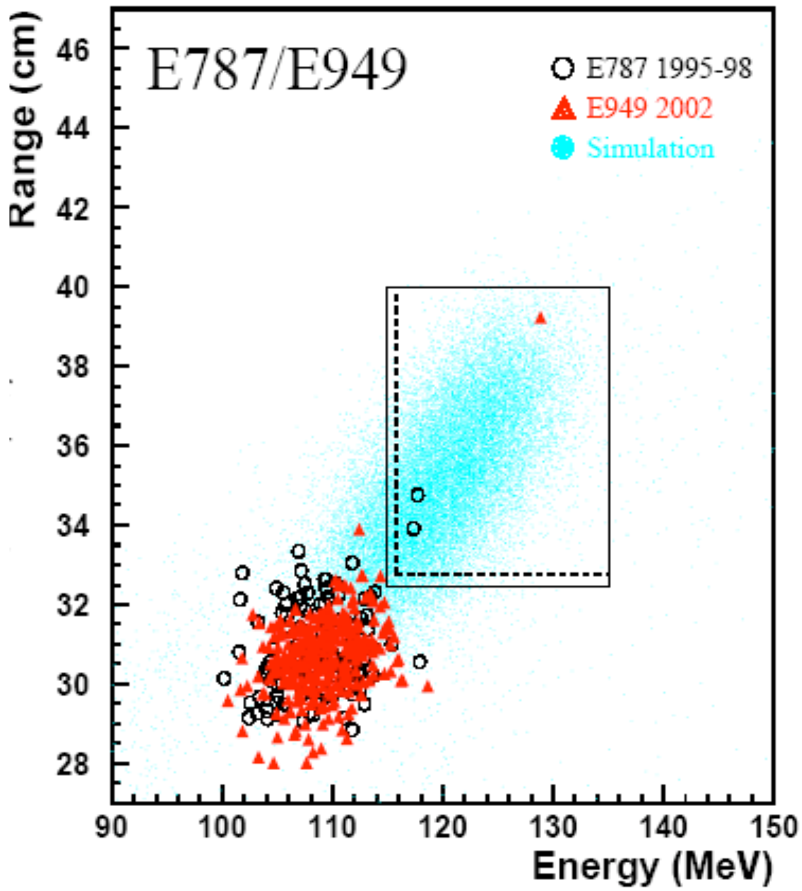






$$B(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$$

Combined E787/949 Result



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

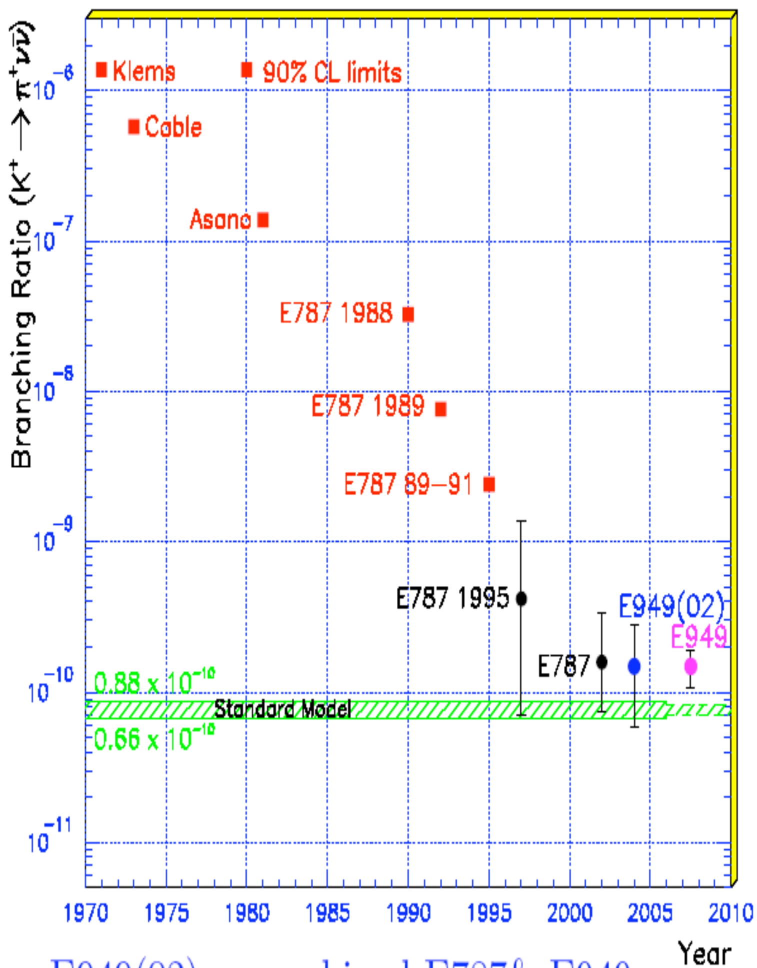
(68% CL interval)

E787 result:

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

	E787		E949
Stopped K^+ (N_K)	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
S.E.S.	0.8×10^{-10}		2.6×10^{-10}
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
$W_i \equiv \frac{S_i}{S_i+b_i}$	0.98	0.88	0.48

Status & prospects for E949



E949(02) = combined E787& E949.

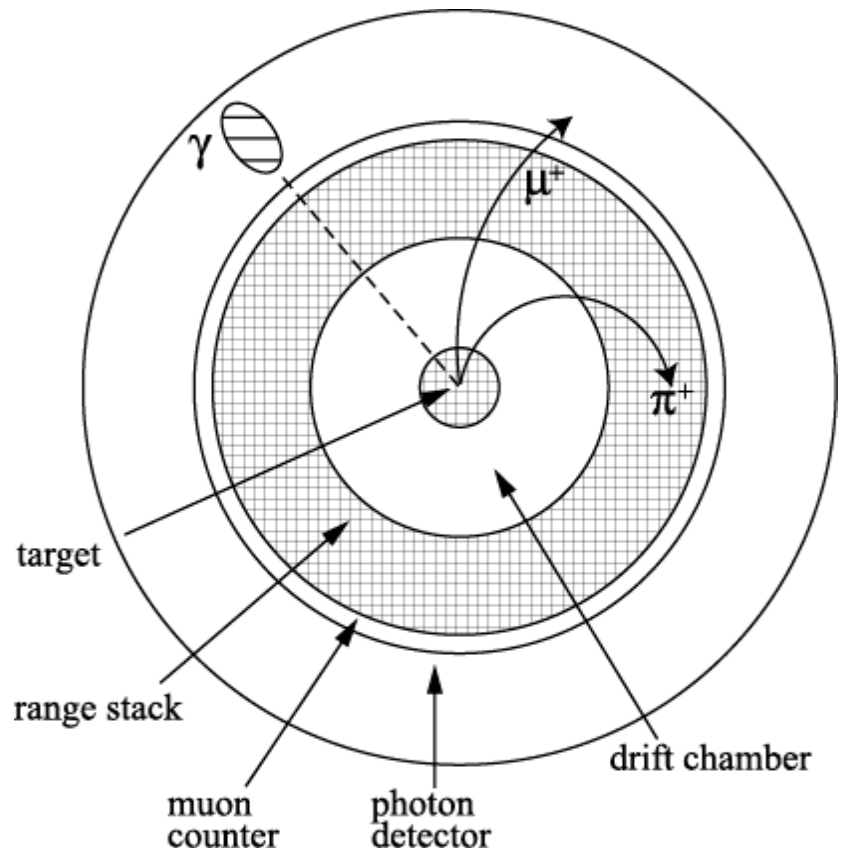
E949 projection with full running period.

- E949 detector worked well
- Obtained ~2/3 sensitivity of E787 in 12 weeks (1/3 pnn1+1/3 pnn2)
- Found one new pnn1 candidate
- pnn2 analysis currently in progress – looks promising
- AGS & beamline problems cost a factor ~2 in sensitivity/hour
- DOE cut off experiment after 12 of 60 promised weeks

J-PARC $K^+ \to \pi^+ \nu \bar{\nu}$ LOI

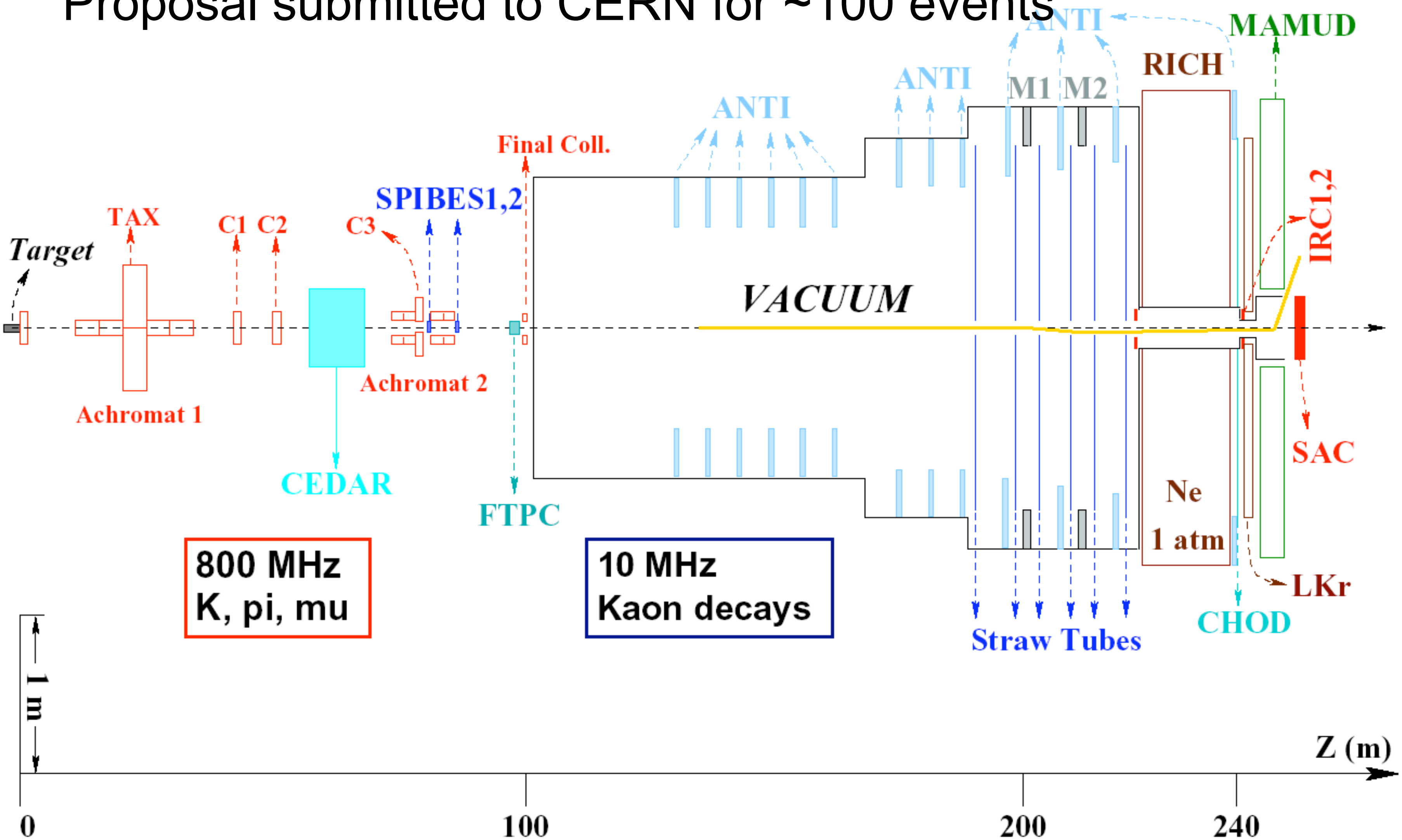
- Stopped K^+ experiment
- Builds on E787/949 experience
  - Lower energy separated beam
  - Higher B spectrometer
  - More compact apparatus
  - Better resolution
  - Finer segmentation
  - Improved γ veto (crystal barrel)
- Aims for 50 events

- Not an early experiment for J-PARC
  - Needs longer spill than planned
  - beamline
  - place on the floor
  - $ for detector



P326 (NA48/3) $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

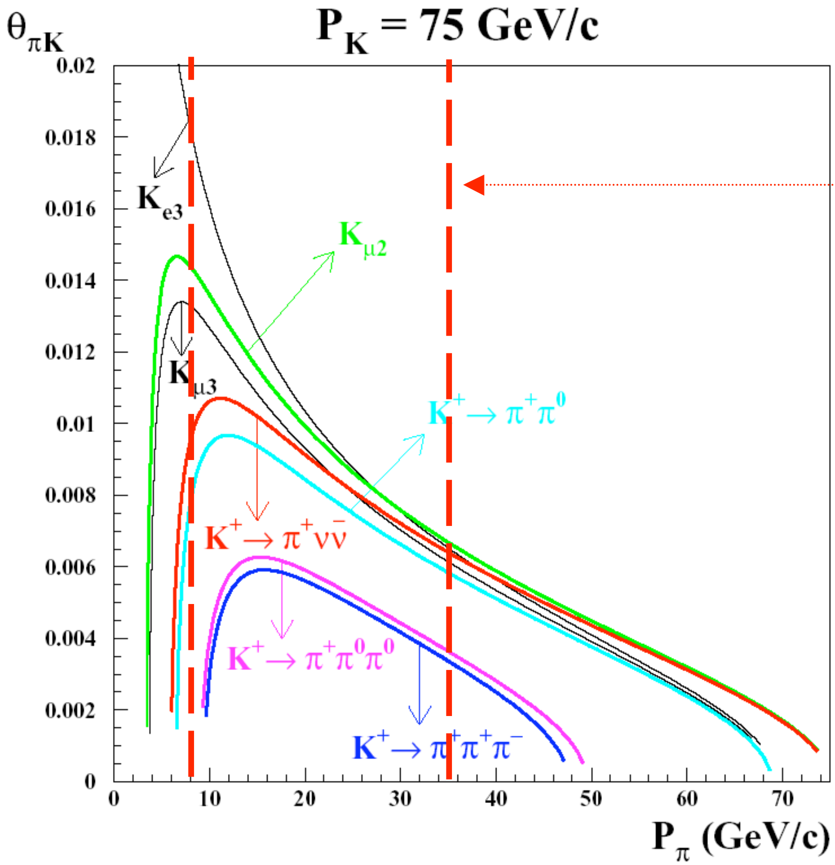
Proposal submitted to CERN for ~100 events



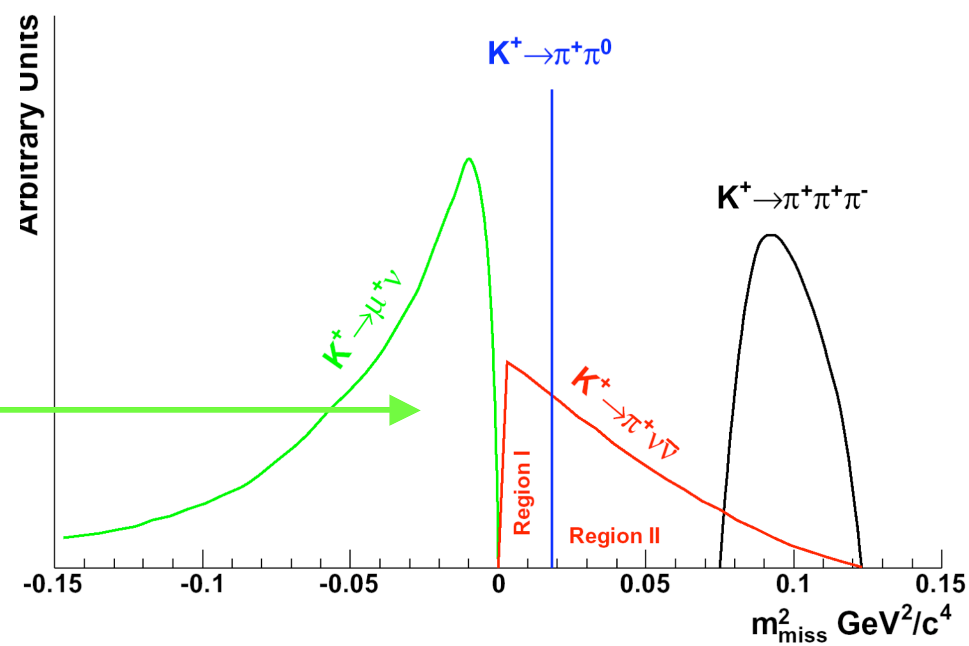
P326 Technique

- Detection in-flight
- High energy (75 GeV/c) unseparated beam (800 MHz!)
  - Careful design to keep halo to ~7MHz
  - Measure all beam tracks (“Gigatracker”)
  - Differential Cerenkov (“CEDAR”) for K ID
- Redundant measurement of pion momentum
  - Two-stage magnetic spectrometer (straws in vacuum)
  - Require large missing momentum
- Redundant pion I.D.
  - Magnetized hadron calorimeter (“MAMUD” + RICH)
- (Almost) hermetic photon veto system
  - NA48 liquid Krypton calorimeter
  - Small angle charged & neutral vetoes (beam bent out of the way)
  - Wide-angle frame anti’s

Kinematics



π^+ momentum cut requires a huge momentum mismeasurement to mistake a beam π^+ for a final state particle (75→35 GeV/c). Also guarantees large missing momentum, *e.g.* so that there's plenty of γ energy from $K^+ \rightarrow \pi^+\pi^0$



Assumption of pion mass spreads out $K^+ \rightarrow \mu^+\nu$ peak
0.3% resolution on p_K and 1% resolution on p_π allows >10% acceptance

Plan for P326

- 2005
  - Gigatracker R&D
  - Vacuum tests
  - Technical design & cost estimate
- 2006
  - Detector tests in present beam
- Construction & installation 2007-8
  - Construct new beamline
  - Construct & install detectors
- 2009-10
  - Data taking
- Expect ~80 events with S:B ~ 8:1

Stopped vs In-flight K^+

	E949 (prop.)	**P326**
beam/spill	25M	2500M
K^+/spill	30M	125M
purity	0.8	0.05
duty factor	4.1/6.4	4.8/16.8
inst. beam rate	7.2MHz	800MHz
'decay' factor	26%	10%
DKs/clock-sec	0.81M	0.74M
DAQ/veto livetime	1/1.7	1/1.7
eff. DK/clock-sec	0.48M	0.44M
acceptance	0.3%	17%
acc. DK/clock-sec	1400	74000

Stopped vs In-flight K^+

How far can stopped exp. be pushed?

	E949 (prop.)	**P326**	**J-PARC**
beam/spill	25M	2500M	41M
K^+/spill	30M	125M	31M
purity	0.8	0.05	0.75
duty factor	4.1s/6.4s	4.8s/16.8s	1.7s/4.4s
inst. beam rate	7.2MHz	800MHz	24MHz
'decay' factor	26%	10%	40%
DKs/clock-sec	0.81M	0.74M	2.8M
DAQ/veto livetime	1/1.7	1/1.7	1/1.9
eff. DK/clock-sec	0.48M	0.44M	1.5M
acceptance	0.3%	17%	0.6%
acc. DK/clock-sec	1400	74000	8800

How to pursue $K^+ \rightarrow \pi^+ \nu \bar{\nu}$?

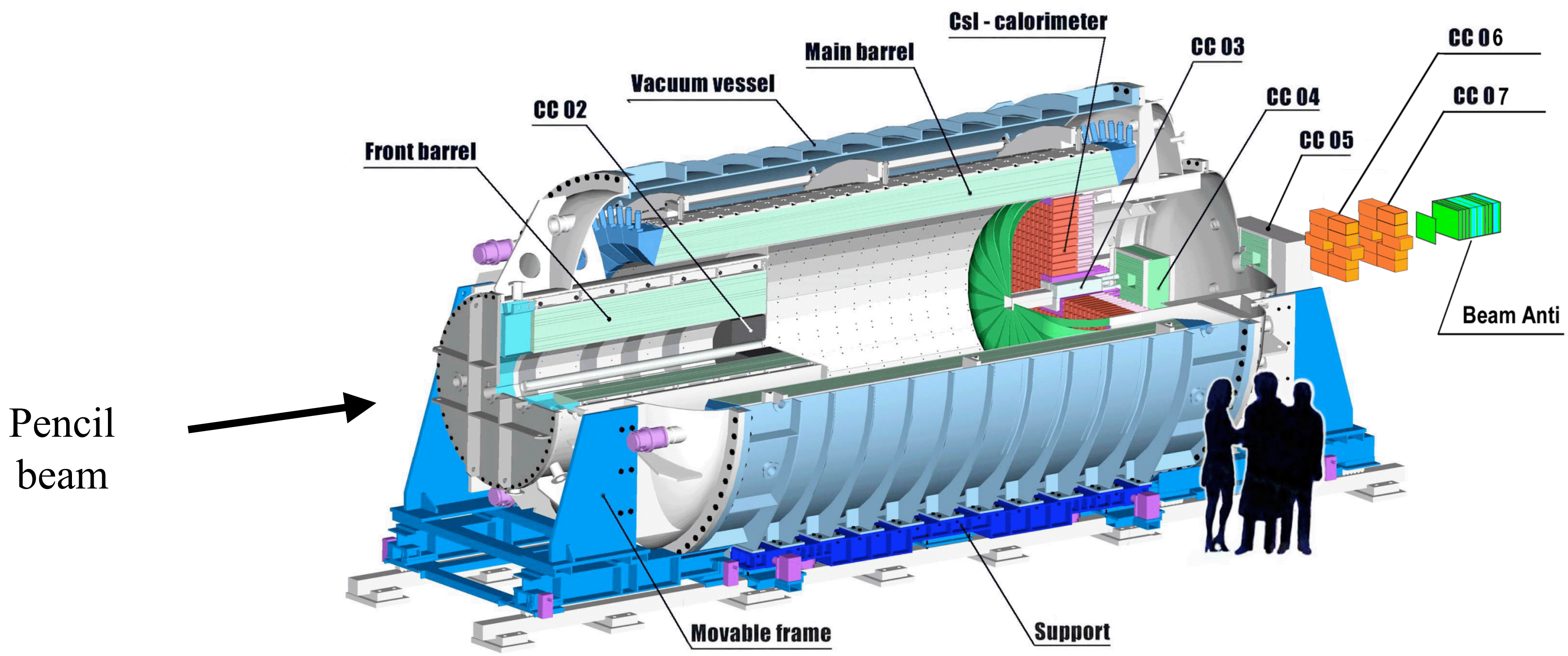
- In-flight has the "appeal of the new"
  - The only way to get >100 events
  - But requires 11 O.M. leap!
    - Watch out for tails, acceptance losses, the unexpected
- Stopping experiment very well understood
  - Technique shown to have sufficient S/B
  - Any further improvements can increase acceptance
    - Note acceptance of 787/949 is ~0.002-0.003
    - Plenty of room for improvement!
    - Trick is to increase the beam rate w/o losing acceptance
  - Could ***really know*** if 50-100 events possible
    - But so far very little support for such an experiment

The Challenge of $K_L \to \pi^0 \nu \bar{\nu}$

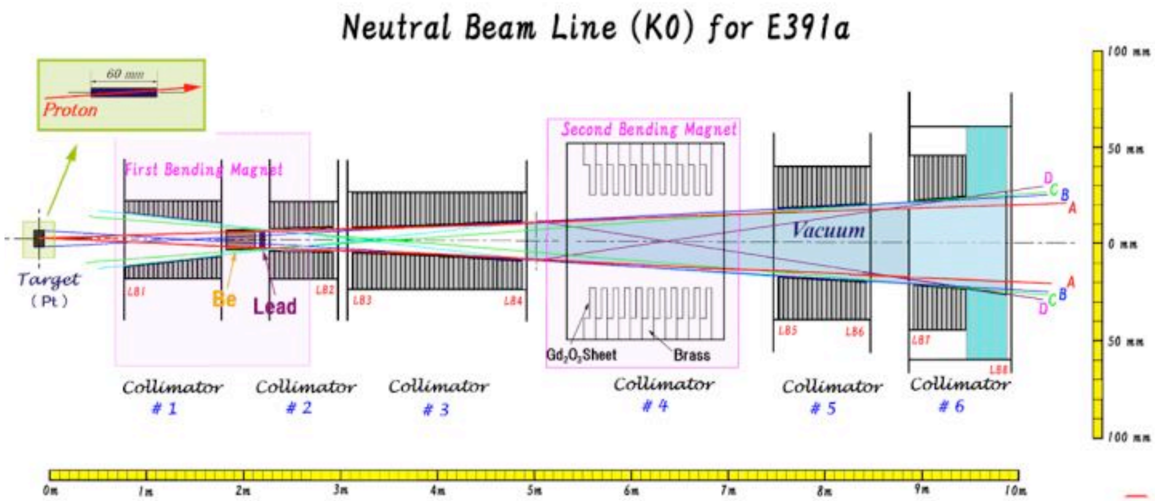
- $B(K_L \to \pi^0 \nu \bar{\nu}) \sim 3 \times 10^{-11}$, need intense flux of K's
  - rates inevitably rather high
  - hard to minimize both random vetoing & veto-blindness
- Kinematic signature weak (2 particles undetectable)
- Backgrounds with π^0 up to 10^{10} times larger than signal
- Veto inefficiency on extra particles, both charged particles and photons, must be $\leq 10^{-4}$
- Self-vetoing is a problem
  - shower spreading makes it hard to maximize both signal efficiency and veto power
- Huge flux of neutrons in beam
  - can make π^0 off residual gas – requires high vacuum
  - halo must be tiny
  - hermeticity requires photon veto in this beam
- Need convincing measurement of background

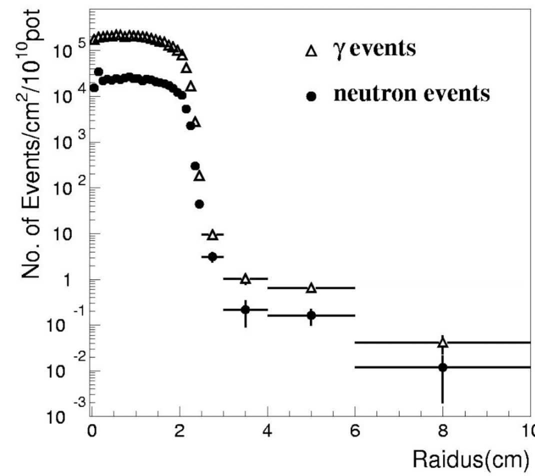
1st dedicated $K_L \to \pi^0 \nu\bar{\nu}$ experiment - E391a

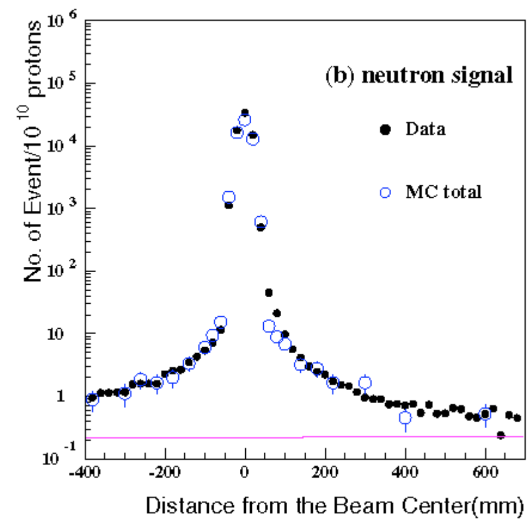
- KEK 12 GeV PS
- 4° "pencil" beam
- $\langle p_K \rangle \sim 2$ GeV/c
- CsI calorimeter



Pencil Beam







5 stages of collimators made of heavy metal (tungsten)

2 stages of sweeping magnets

Thermal neutron absorber

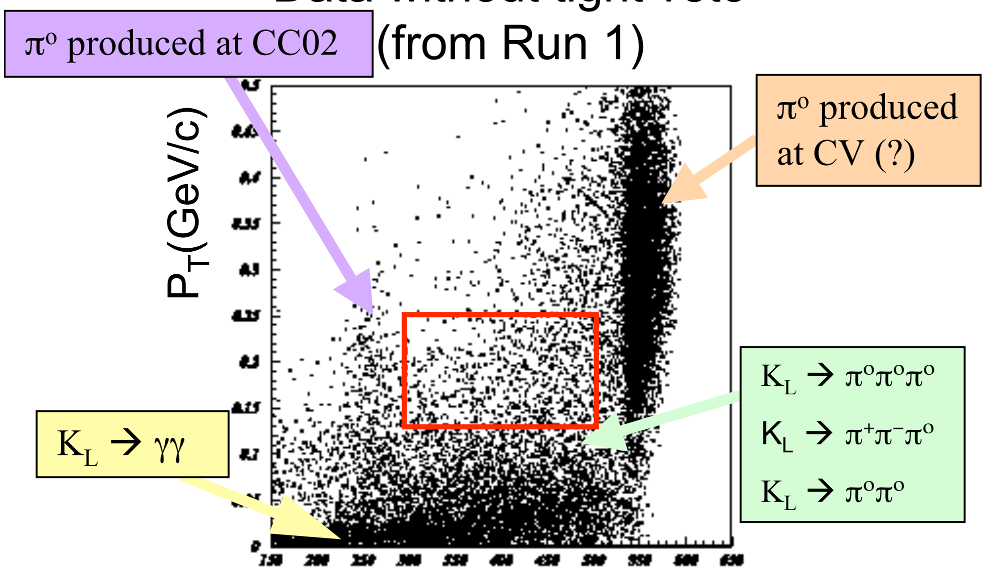
Pb/Be plug for control of γ/neutron flux

Fine alignment using telescope

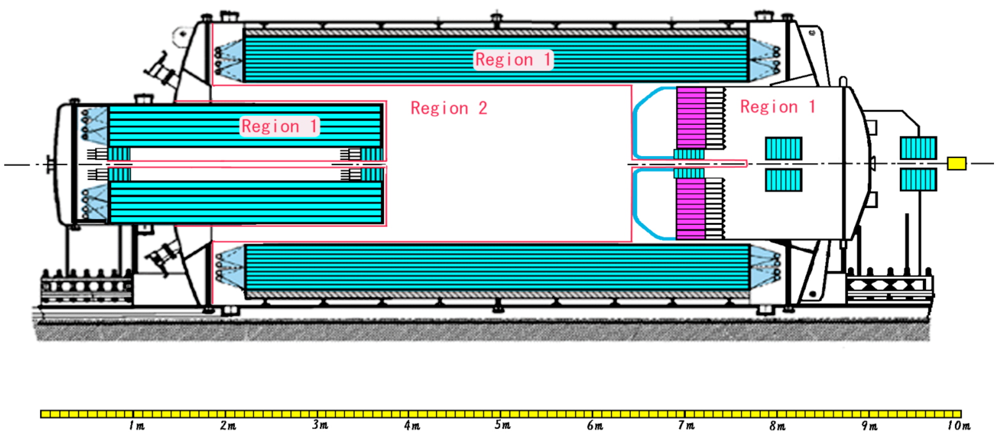
GEANT3 M.C. agrees well with the measurements

2γ analysis

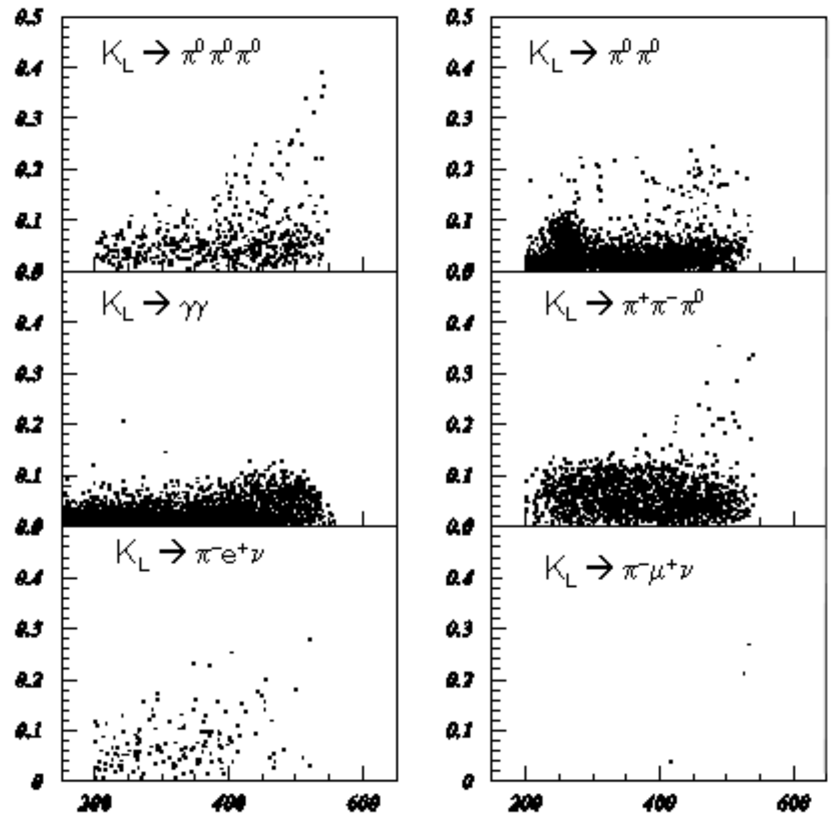
Data without tight veto (from Run 1)



Reconstructed vertex (cm)



M.C. for K_L decays (Without Normalization)

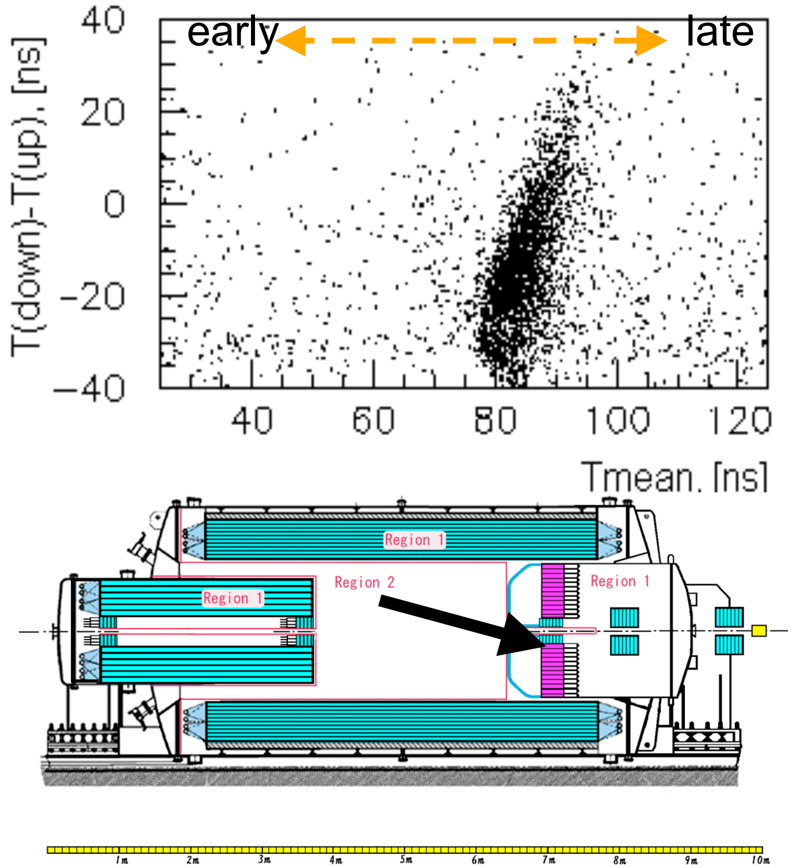


Veto Optimization

~Main-barrel timing (low E sample)~

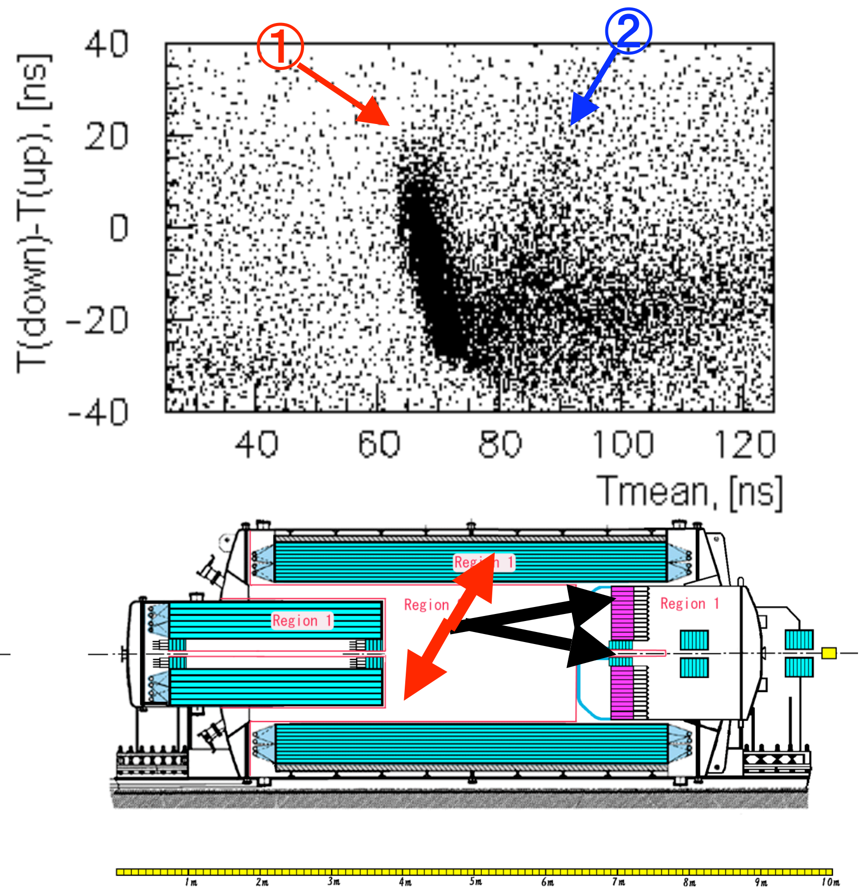
upstream

$K_L \rightarrow \gamma\gamma$ pure sample



Backsplash → should NOT veto!

$\gamma\gamma$ B.G.sample

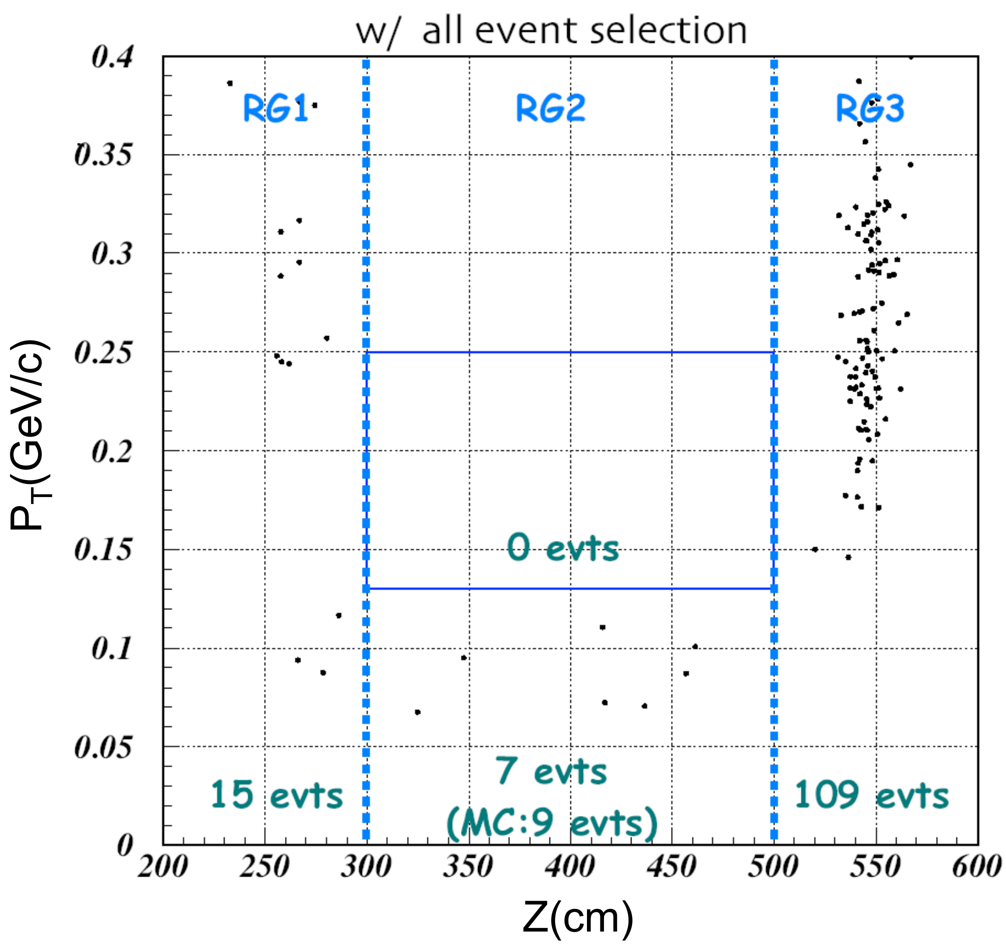


① Real photon hit → should veto.

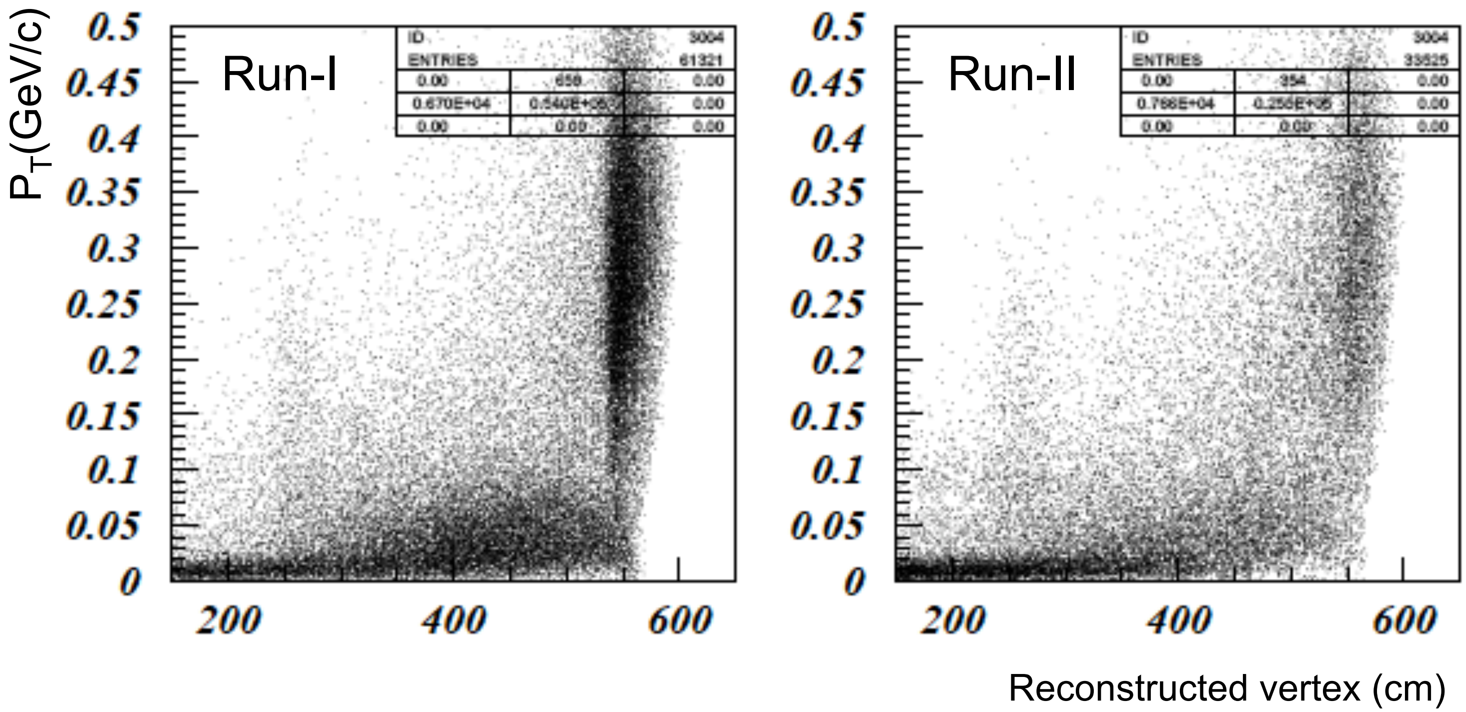
② Backsplash → should NOT veto.

E391a Result from 10% of Run I

- No events observed/expected background of 0.03±0.01 events (mainly $K\pi 2$)
- 1.14×10^{9} K_L decay, 0.0073 acceptance $\Rightarrow$ s.e.s of 1.17×10^{-7}
- $B(K_L\rightarrow\pi^0\nu\bar{\nu})<2.86\times10^{-7}$ @ 90% CL (c.f. 5.9×10^{-7} from KTeV)



Better quality of data *(online plots)*

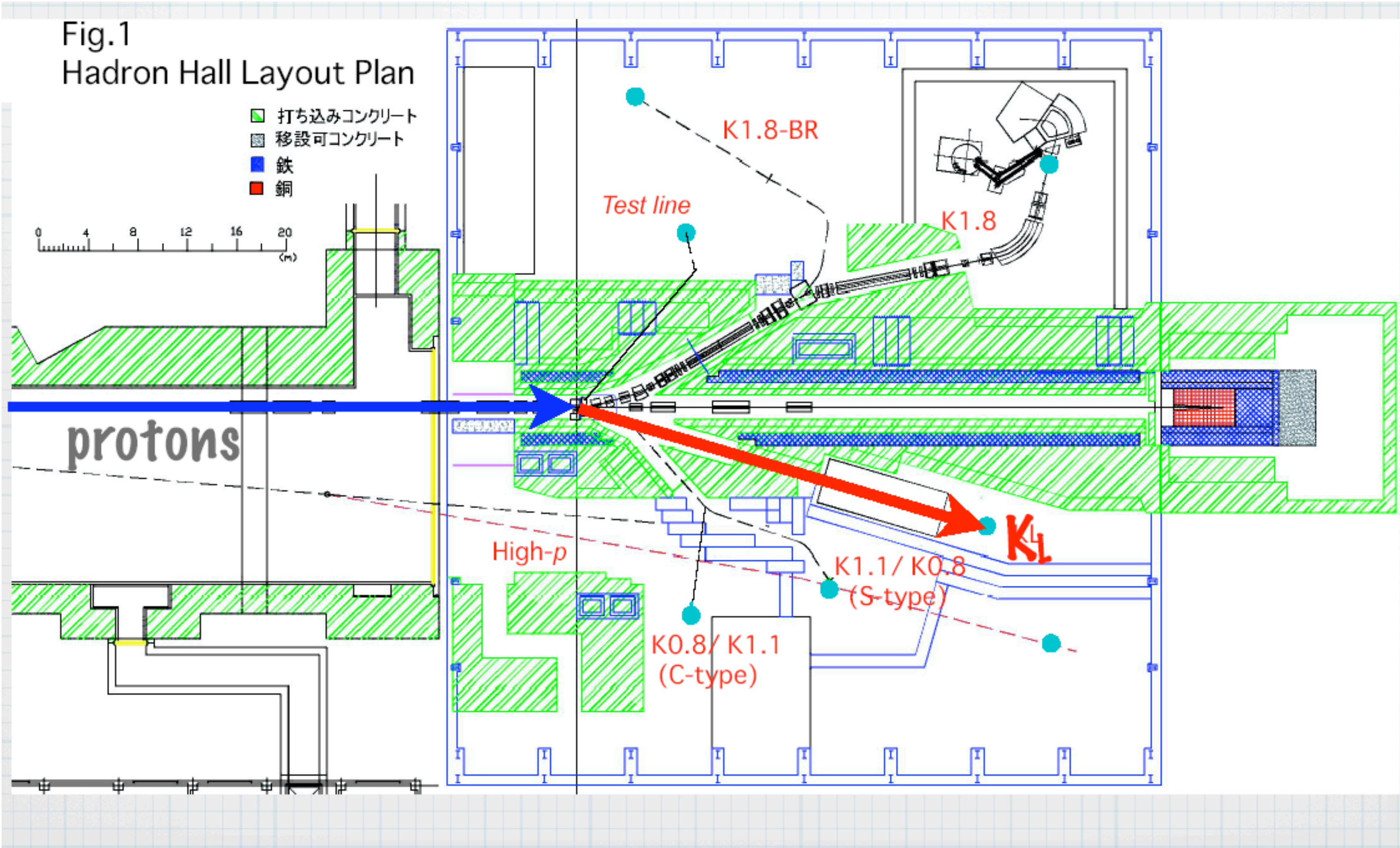


Run-II analysis → Run-III (starting now)

E391a status & prospects

- First physics run Feb-June 2004
  - 2.2×10^{12} 12 GeV POT, 50% duty factor
  - 5×10^{5} K_L/pulse
  - Detector worked well
  - Nominal s.e.s. 4×10^{-10}
    - But acceptance ~ 15× lower than in proposal (0.0073)
  - first sight of the enemy
    - Halo neutrons, self-vetoing, etc.
  - Analysis of 10% of data $\Rightarrow B(K_L\rightarrow\pi^0\nu\bar{\nu})<2.86\times10^{-7}$
- Run II, Feb-March 2005
  - Many problems fixed, 60% of Run 1
- Run III, Nov-Dec 2005, starting now

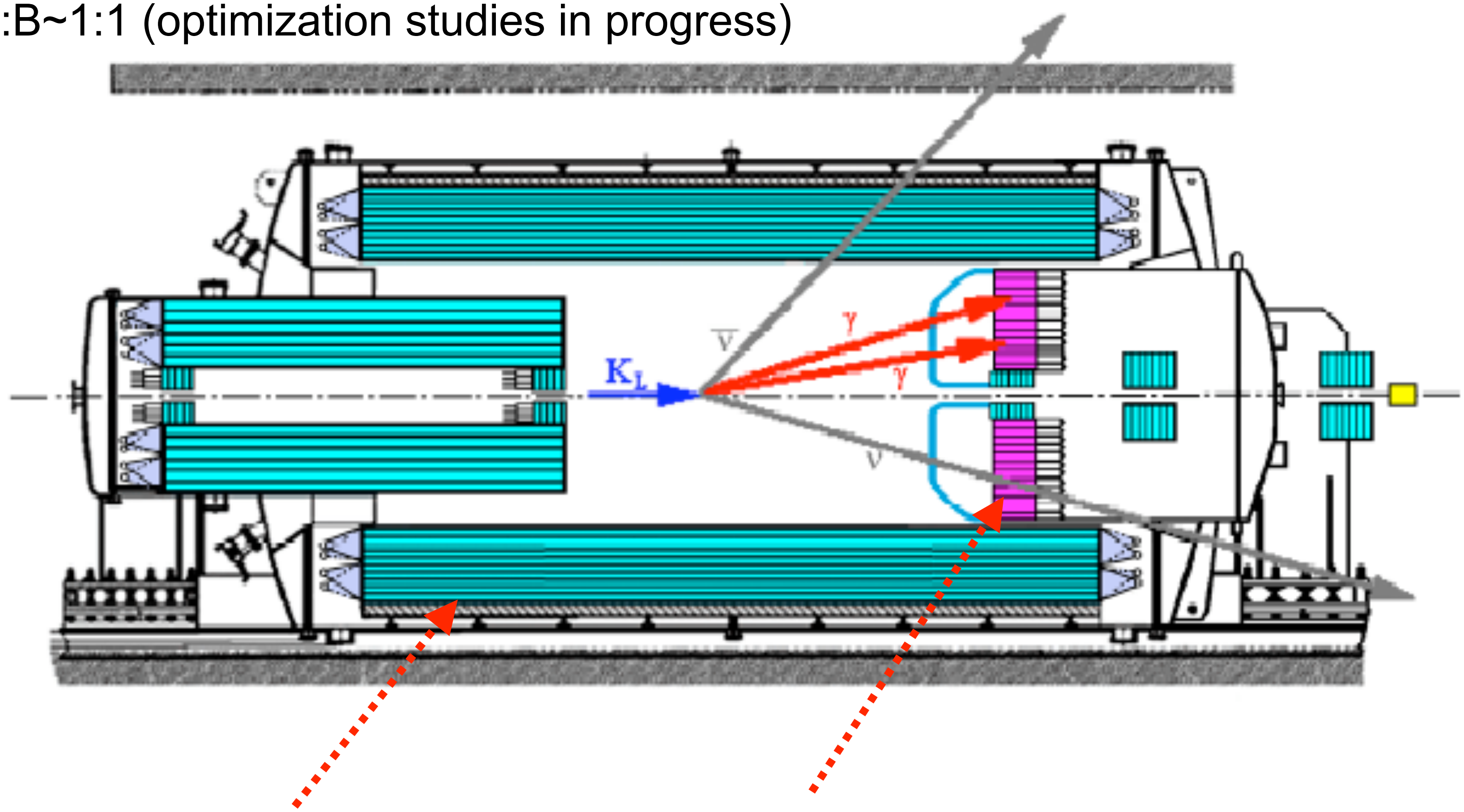
JPARC Phase I Beamlines



KEK-PS to J-PARC

- 10^{14} interacting 30 GeV protons/cycle, 5μsr beamline @ 16°
- 22MHz K_L @ 20m, $\langle p_K \rangle$ = 2.1 GeV/c, 9%/5m decay
- 4% acceptance
- 23 events in 3 Snowmass years (competition from ν)
- S:B~1:1 (optimization studies in progress)

100× more K_L



Thicker photon vetoes

Deeper, more granular crystals

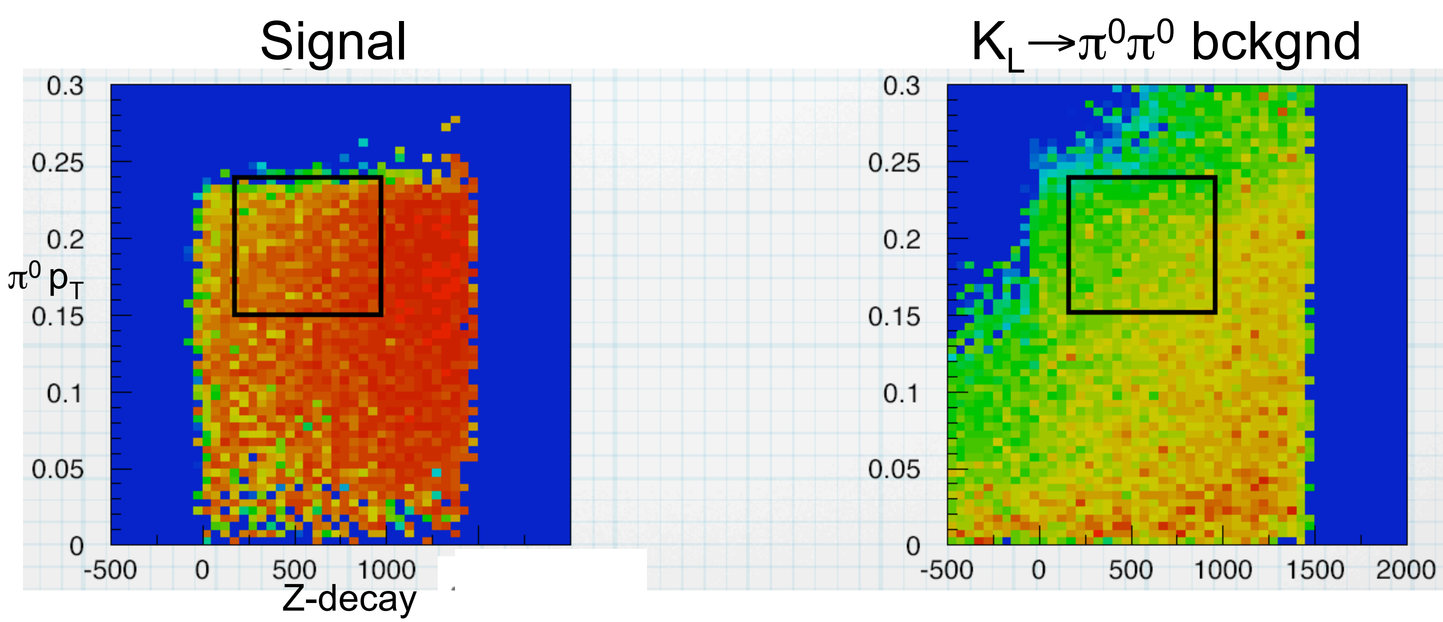
Faster electronics

Step by step at JPARC

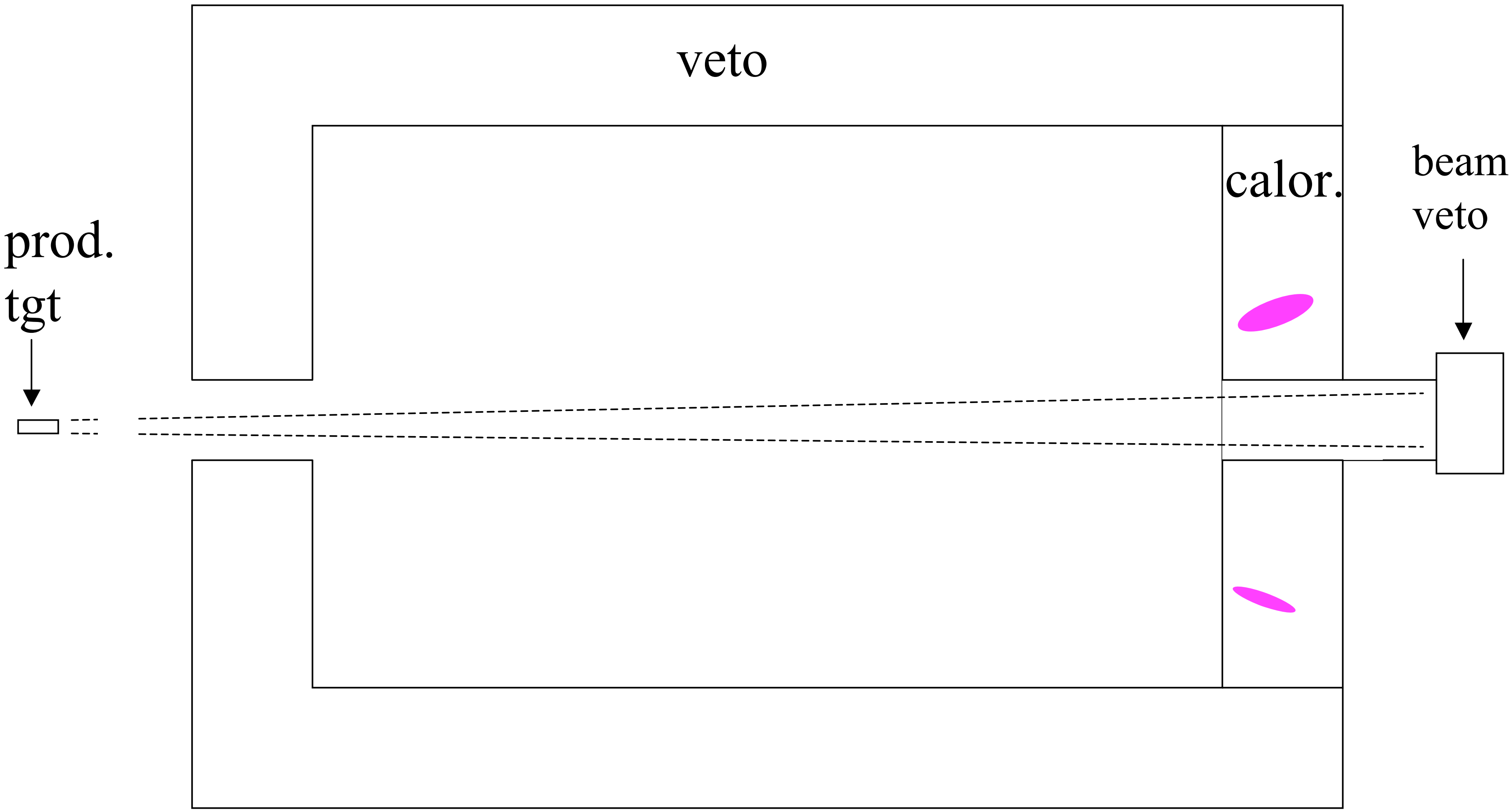
- "Step by step" approach, learning as they go
- Different beam angles, lengths
- Larger detector
- Eventual goal – few 100 evts

Tgt ∠ z-det	Beam size	K_L flux (MHz)	Decay prob	Decay rate
16° 20m	10cm	27MHz	25%	6.8MHz
5° 50m	10cm	63MHz	11%	6.9MHz
8° 70m	15cm	28MHz	14%	3.9MHz

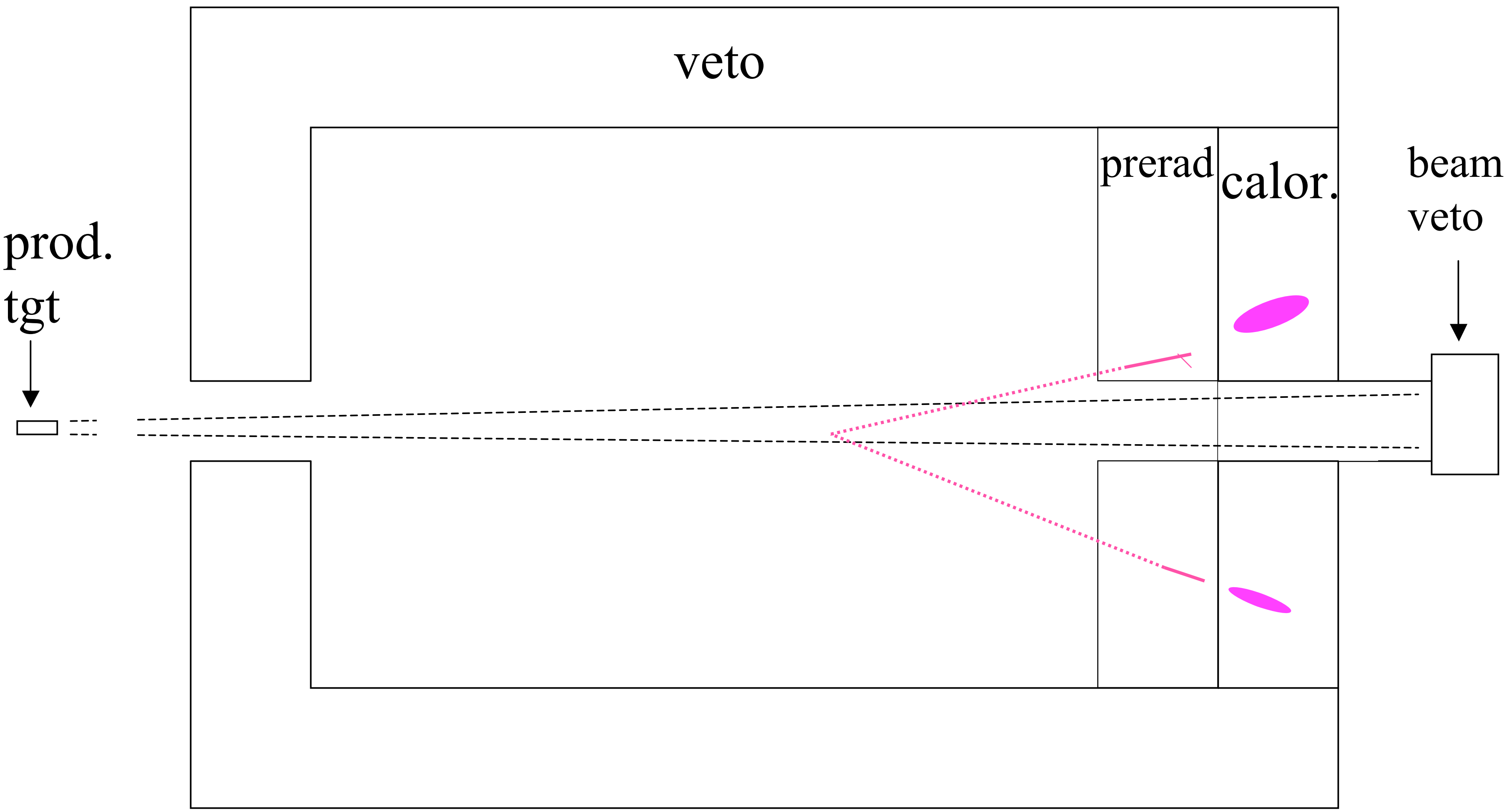
16° case



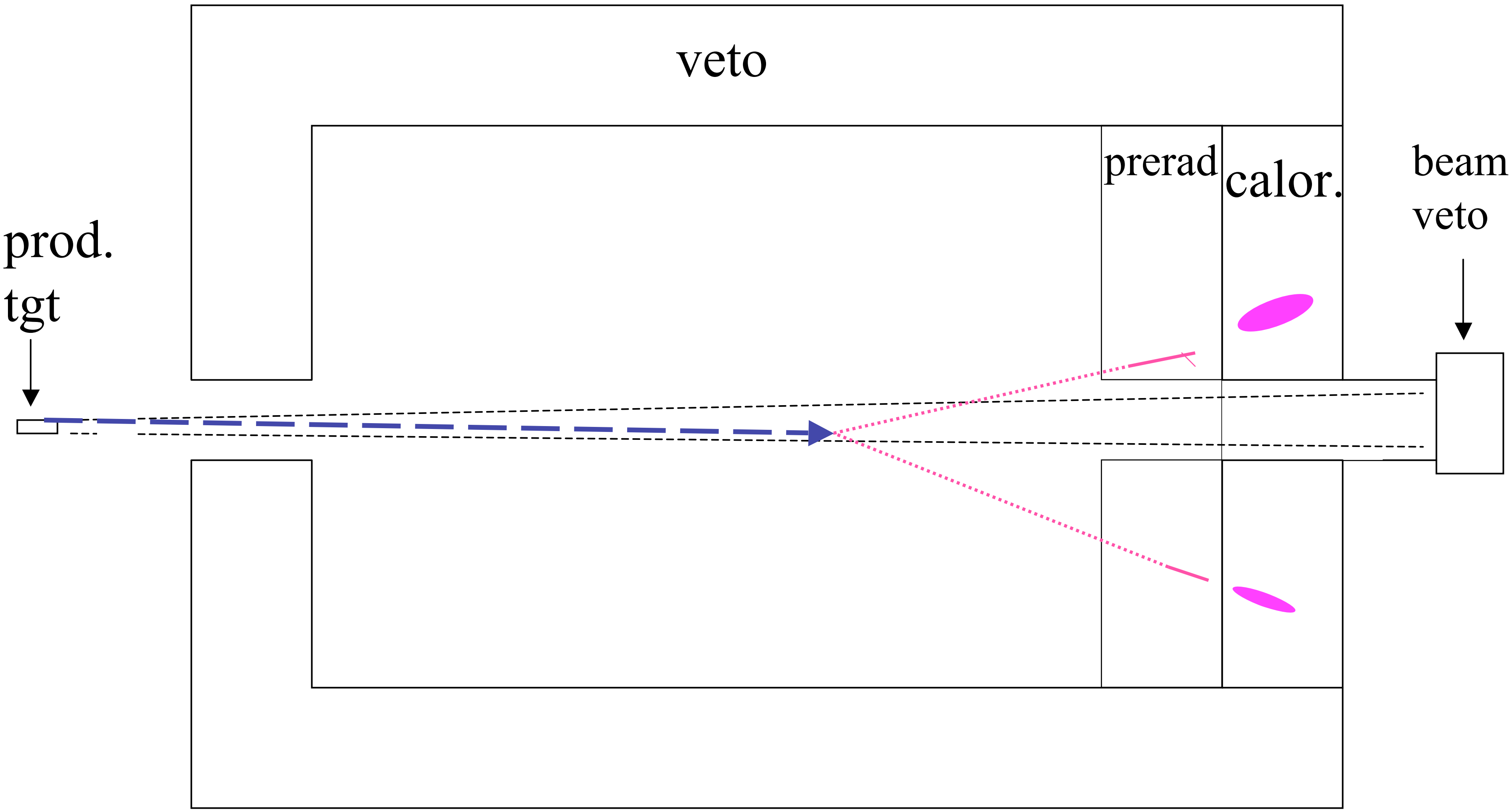
$K_L \to \pi^0 \nu \bar{\nu}$ Experiment



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



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

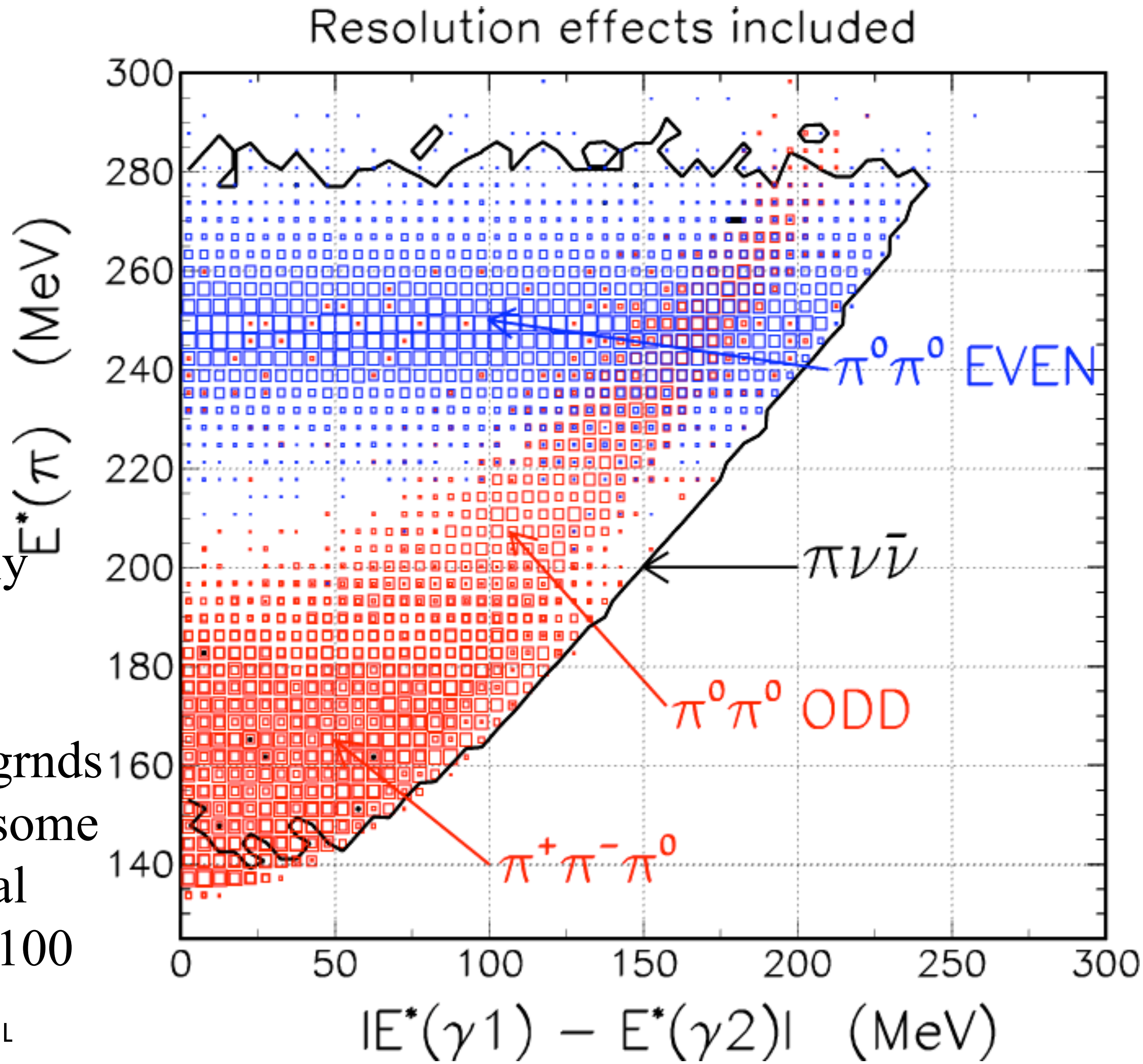


In the K_LCoM

- Bckgnd mainly in discrete areas
- Obvious for $K_L \rightarrow \pi^0\pi^0$ "even"
- But even "odd" case not ubiquitous

- $K\pi3$ infests slightly different area

- Even after all bckgrnds accounted for, still some clear space for signal
- Can get factor 50-100



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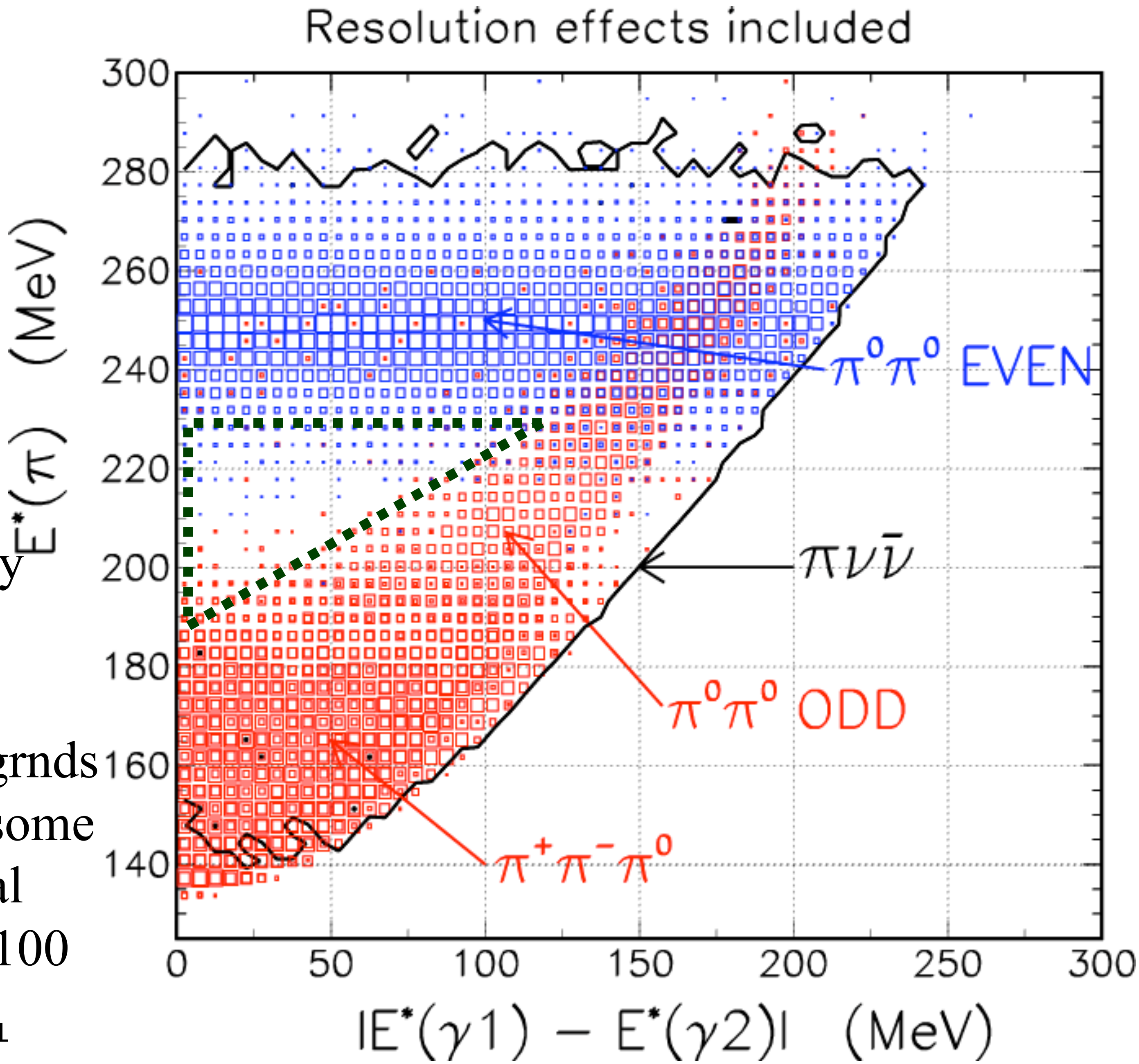
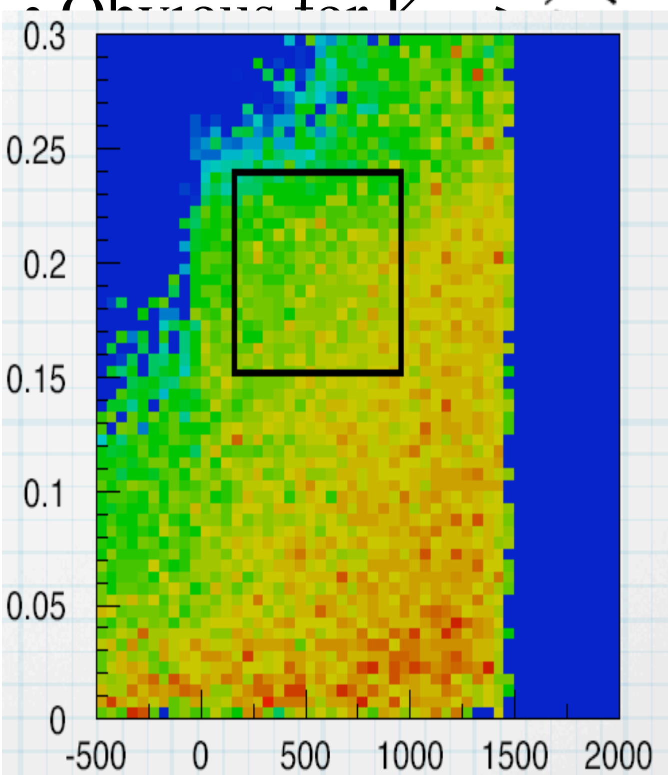


In the K_L CoM

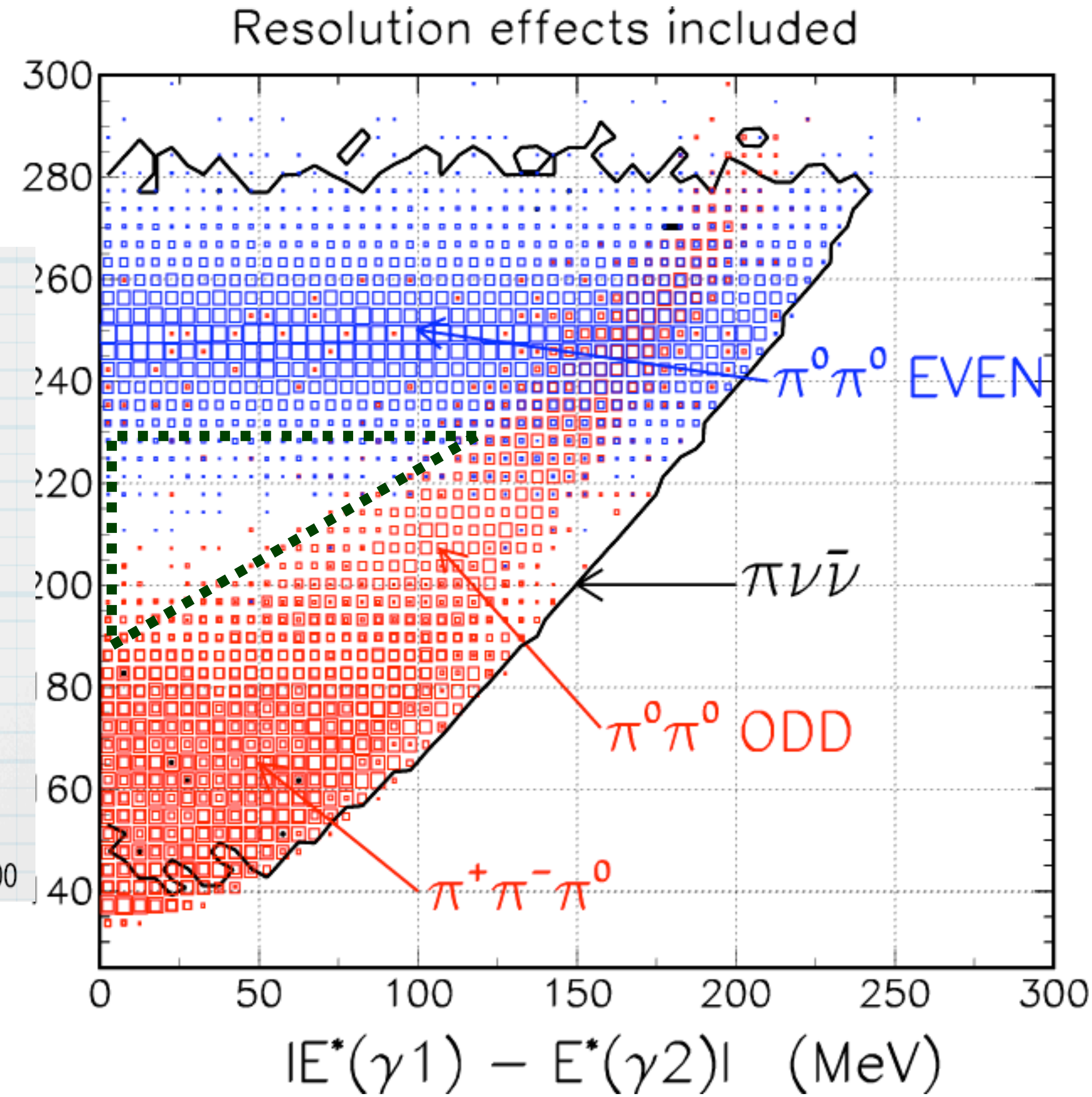
• Bckgnd mainly in discrete areas

• Obvious for K

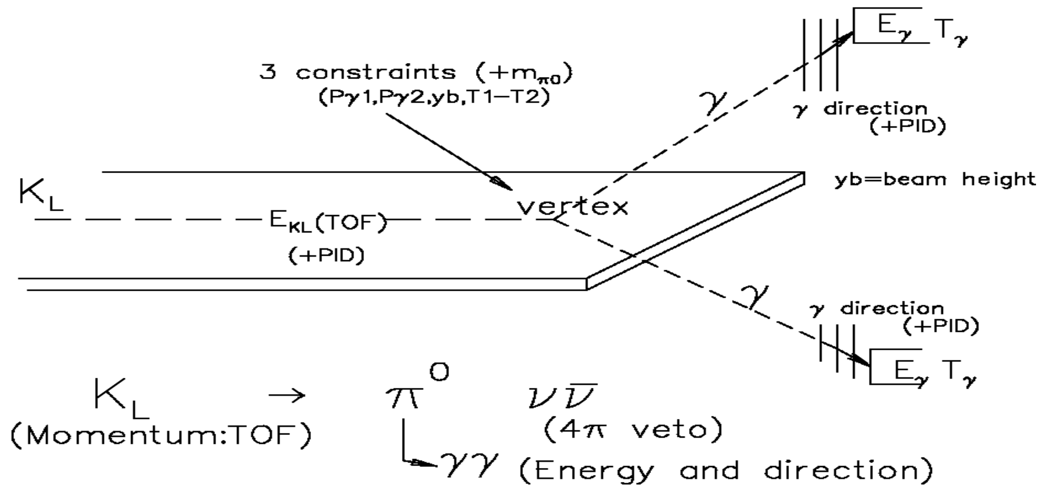


clear space for signal

• Can get factor 50-100

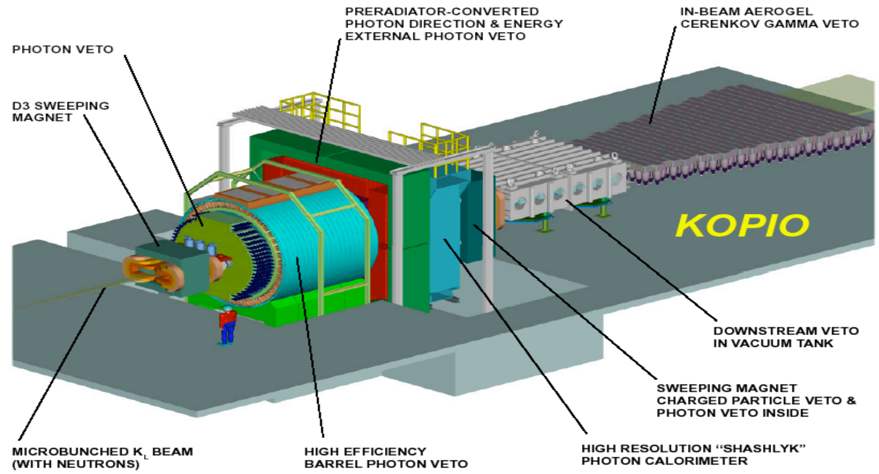


KOPIO Technique



- High intensity micro-bunched beam from the AGS
- Measure everything! (energy, position, angle, time)
- Eliminate extra charged particles or *photons*
  - KOPIO: π^0 inefficiency < 10^{-8}
- Suppress backgrounds
  - Predict backgrounds *from data*:dual cuts
  - Use “blind” analysis techniques
  - Test predictions “outside the box”
- Weight candidate events with S/N likelihood function

Is KOPIO completely dead?

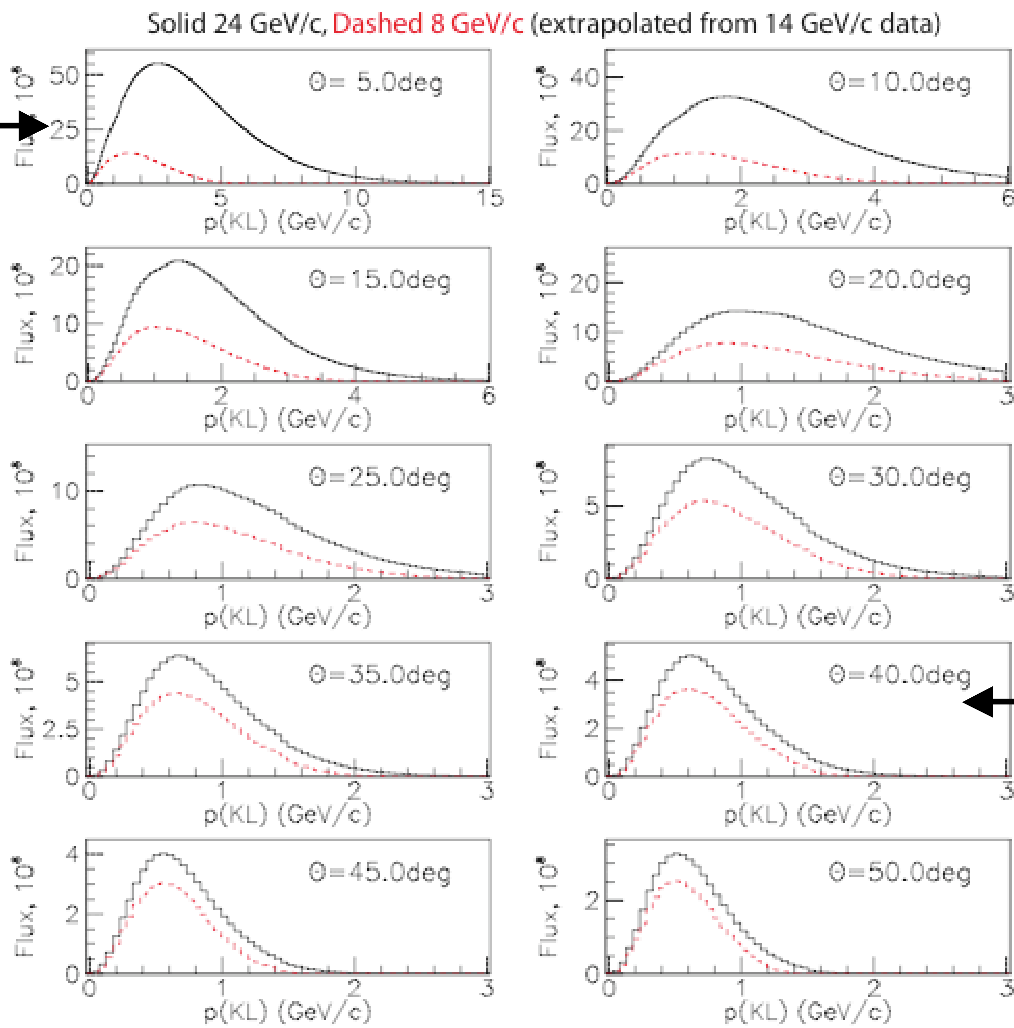


- AGS E926 is certainly completely dead
- But we asked whether Fermilab might be interested
  - Would use 8 GeV proton beam from Booster
  - Answer - not immediately, but maybe later
  - Agreed to have accelerator physicists help
  - Some studies were done ….

First Surprise

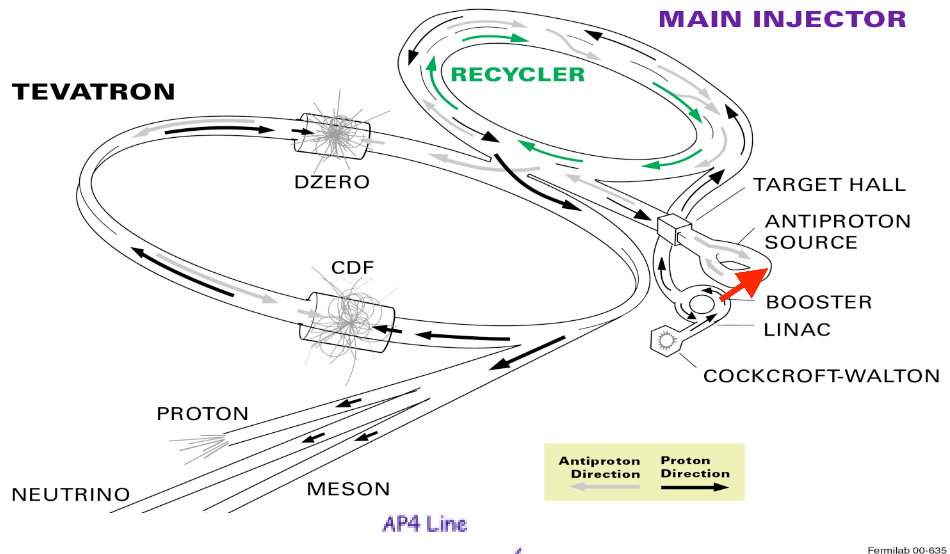
- Useful K flux not much impacted!

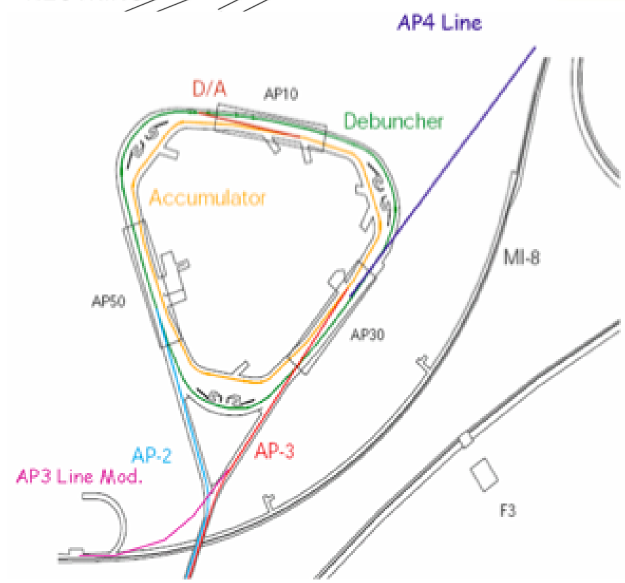
Large loss in forward dirn.



Small loss at KOPIO-type ∠

How to get the protons





Send 8 GeV protons from the Booster to the Accumlator (need new line)

Momentum stack Booster batches in Accumulator and debunch. Then microbunch at 26MHz on extraction (need slow extraction system, beam-line, etc.)

Dave McGinnis' Scenarios

- NUMI and 4/23 batches to KOPIO
  - Accelerator cost not including slow extraction ~10-12 M$
  - Constraints
    - Cycle time – 1.5 Seconds
    - C.O.D 6 mm
    - Loss 550W
    - Booster Notching - 3 / 84 bunches
      - Improvement comes because notching is not needed for momentum stacking KOPIO beam
  - NUMI – 12 batches @ 4.8e12 protons/batch
  - KOPIO – 4.6e16protons/hr
- NUMI and 8/23 batches to KOPIO
  - Constraints
    - Cycle time – 1.5 Seconds
    - C.O.D 6 mm
    - Loss 600 W
    - Booster Notching - 2.4 / 84 bunches
      - Improvement comes because notching is not needed for momentum stacking KOPIO beam
  - NUMI – 12 batches @ 4.8e12 protons/batch
  - KOPIO – 9.2e16protons/hr

Second Surprise

From Mc Ginnis' Summary:

- To run NUMI and KOPIO at 4.6e16 protons/hour:
  - Decrease the closed orbit distortion by 40% from present
  - Decrease the notching loss by 43% from present
  - Increase the permitted loss in the Booster tunnel by 20% from present
  - KOPIO spill length 82% of cycle

KOPIO is VERY sensitive to duty factor (67% @ AGS)

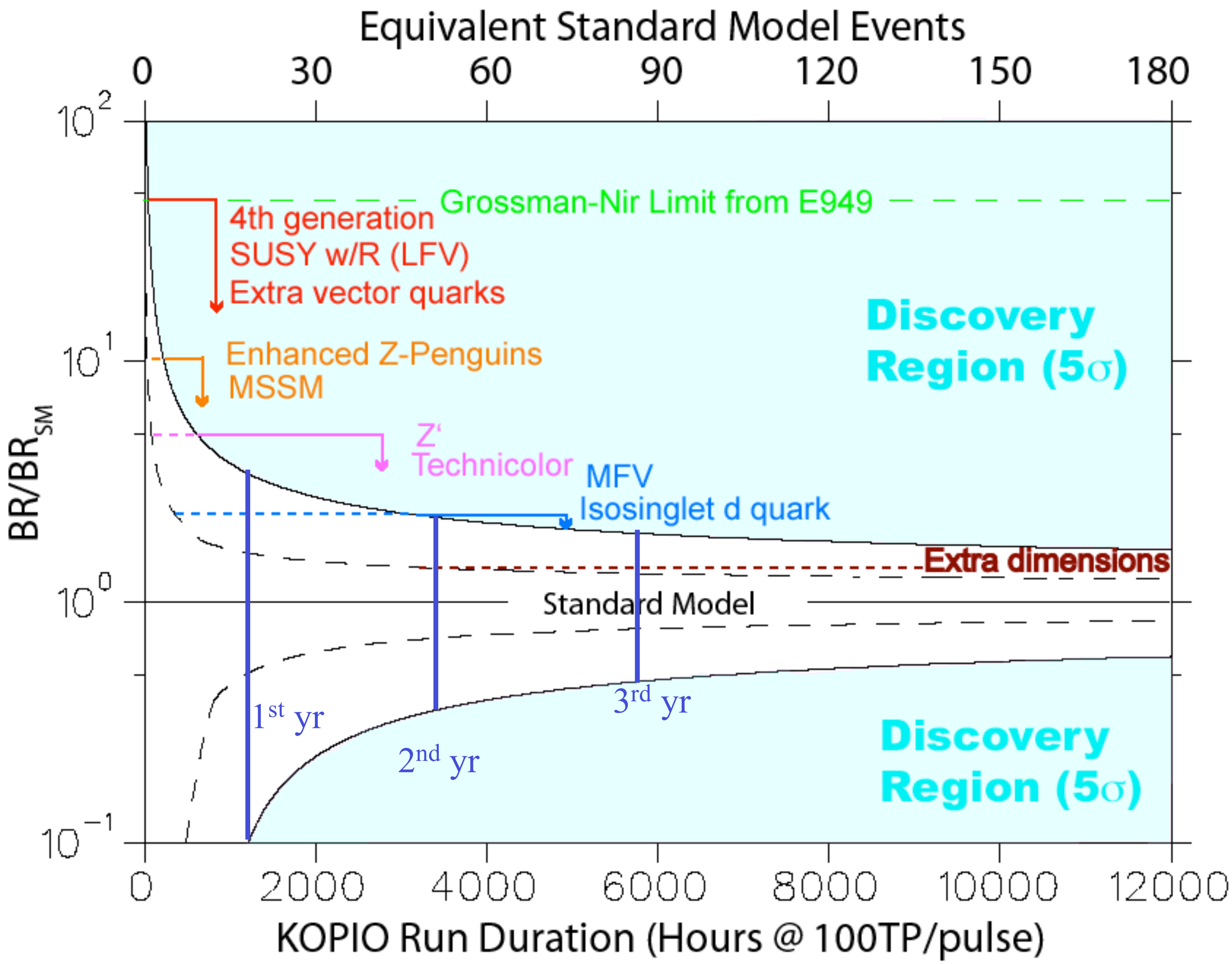
Inst. K rate a little lower than at AGS

Bottom line - Sensitivity/hour = 93% of AGS

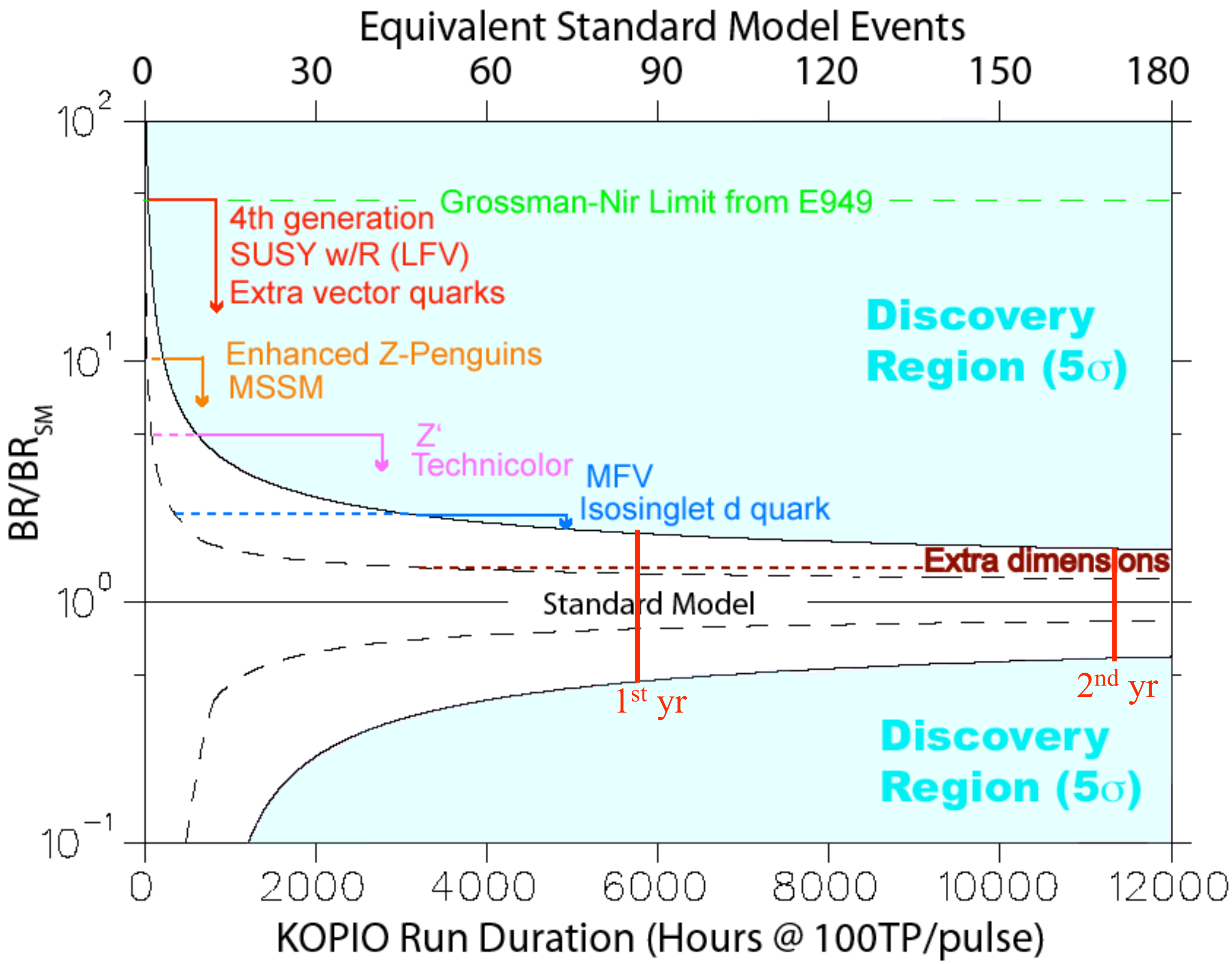
Third Surprise

- When E926 (KOPIO) proposed, asked for 3000 hours per year for three years.
  - That was thought aggressive but possible in the "AGS-2000" era
- When RSVP plan finally set, we were given 6240 hours over three years
  - But not all at 100 TP, equivalent was 5684 hours
- Fermilab seems to assume ~6000 hours/year

Discovering/Constraining New Physics



Discovering/Constraining New Physics at FNAL



How many K's needed to see $K_L \to \pi^0 \mu^+ \mu^-$?

From thesis of
M. Sadamoto
Osaka, 1999
(KTeV)

The number of K_L necessary to see $K_L \to \pi^0 \mu^+ \mu$

In order to discover the $K_L \to \pi^0 \mu^+ \mu^-$ decay, the number of the signal events must be significant by more than 3σ above the background. In this section, we will assume that the all the background sources are well understood and that the number of the background events is large enough so that the fluctuation can be treated as a Gaussian. This assumption leads to the following relation:

$$N_S > 3\sqrt{N_S + N_{BG}} \qquad (7.2)$$
$$N_S = \#K_L \times Br(K_L \to \pi^0 \mu^+ \mu^-) \times \epsilon_{\pi^0 \mu^+ \mu^-} \qquad (7.3)$$
$$N_{BG} = \#K_L \times Prob_{bg}, \qquad (7.4)$$

where N_S is the number of observed $K_L \to \pi^0 \mu^+ \mu^-$, $\#K_L$ is the number of K_L decays, N_{bg} is the number of observed background events, $\epsilon_{\pi^0 \mu^+ \mu^-}$ is the detector acceptance for $K_L \to \pi^0 \mu^+ \mu^-$, and $Prob_{bg}$ is the probability of a K_L to generate a background event, respectively. (If we use the same condition as in KTeV experiment, we can assume $\epsilon_{\pi^0 \mu^+ \mu} = 0.05$, $Prob_{bg} = 3.3 \times 10^{-12}$.)

Let us assume the following predicted numbers as described in Chapter 1,

$$Br(K_L \to \pi^0 \mu^+ \mu^-)_{CP\_conserve} = 4.4 \times 10^{-12} \qquad (7.5)$$
$$Br(K_L \to \pi^0 \mu^+ \mu\ )_{indirect} = 2.0 \times 10^{-13}.$$

To be conservative, the contribution of the direct CP violation is neglected at this time. By using Equation 7.2, we need more than 6.0×10^{14} K_L decays to discover the $K_L \to \pi^0 \mu^+ \mu$ decay. This corresponds to about 2200 times the K_L decays in KTeV experiment. If the effective cuts to reject $K_L \to \mu^+ \mu^- \gamma\gamma$ with a high statistics study, it will decrease the minimum number of K_L decays to find $K_L \to \pi^0 \mu^+ \mu^-$.

How many K's needed?

If we regard the indirect CP violating and CP conserving contributions as background, we can calculate the number of K_L decays required to detect the direct CP violation. At this time, we can assume $Prob_{bg} = 7.9 \times 10^{-12}$. For confirming the direct CP violating $K_L \to \pi^0 \mu^+ \mu$ with the branching ratio of 1.0×10^{-12}, we need more than 1.4×10^{15} K_L decays.

Fermilab is planning KAMI experiment which is the next generation of KTeV experiment. KAMI plans to observe 5.6×10^{13} kaon decays for searching the direct CP violating phenomena. However, it is still a factor of 10 lower than the sensitibity to detect $K_L \to \pi^0 \mu^+ \mu^-$.

- In 1999, thought it would require two further generations of experiments to see $K_L \to \pi^0 \mu^+ \mu^-$ at 3σ ($K_L \to \pi^0 e^+ e^-$ similar)
- Also, most people thought in terms of measuring SM η, so high precision needed
- **Situation today is completely different**

New Situation for $K_L \to \pi^0 \ell^+ \ell^-$

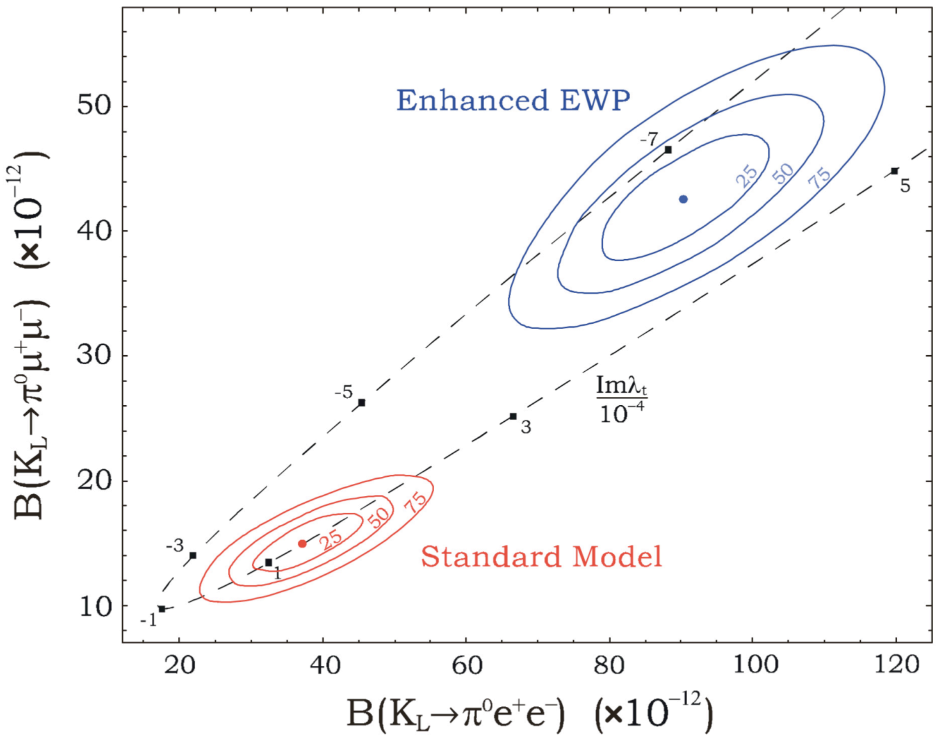
- Now that NA48 observed $K_S \to \pi^0 \ell^+ \ell^-$ at higher end of expectation
- & arguments for constructive interference between mixing & direct CP-violating components strong as ever
- SM expectation for $K_L \to \pi^0 \ell^+ \ell^-$ rather large:
  - $B(K_L \to \pi^0 e^+ e^-) = (4 \pm 1) \times 10^{-11}$
  - $B(K_L \to \pi^0 \mu^+ \mu^-) = (1.5 \pm 0.3) \times 10^{-11}$
- Compare with $K_L \to \gamma\gamma\ell^+ \ell^-$ background (worst one):

	$K_L \to \pi^0 e^+ e^-$ ('99)	$K_L \to \pi^0 \mu^+ \mu^-$ ('97)
KTeV s.e.s..	10.4×10^{-11}	7.5×10^{-11}
$K_L \to \gamma\gamma\ell^+ \ell^-$ evts	0.99	0.37
$B(K_L \to \gamma\gamma\ell^+ \ell^-)_{effective}$	10.3×10^{-11}	2.8×10^{-11}
S:B	1:2.5	1:1.9

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

Add to this, now we are interested in bigger game than $\mathrm{Im}\lambda_t$.

E.g., from Isidori, *et al.*, hep-ph/0404127 $\Longrightarrow$



- Take KaMI as example of a next-generation experiment with sensitivity to $K_L \to \pi^0 \mu^+ \mu^-$. In 3 years, KaMI would have reached a s.e.s of 4×10^{-13}.

- In the example above, would collect 110±13 signal events (with 70 events of background) compared with a SM expectation of 37 events.

- Similar sensitivity experiment possible for $K_L \to \pi^0 e^+ e^-$

Conclusions

- K experiments extinct in US
  - State of the art in 4 of the 5 most interesting decays
  - Some data analysis continuing
  - Experiments could be mounted at FNAL (KOPIO?)
  - But K experiments seem low on DOE priority list
- Continuing $K \rightarrow \pi \nu \bar{\nu}$ program in Japan
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ proposal at CERN
- Could use a KOPIO-type $K_L \rightarrow \pi^0 \nu \bar{\nu}$ experiment
  - or at least one with photon pointing.
- $K_L \rightarrow \pi^0 \ell^+ \ell^-$ experiment(s) now seem very worthwhile
  - Could be done!
  - But no proposals yet