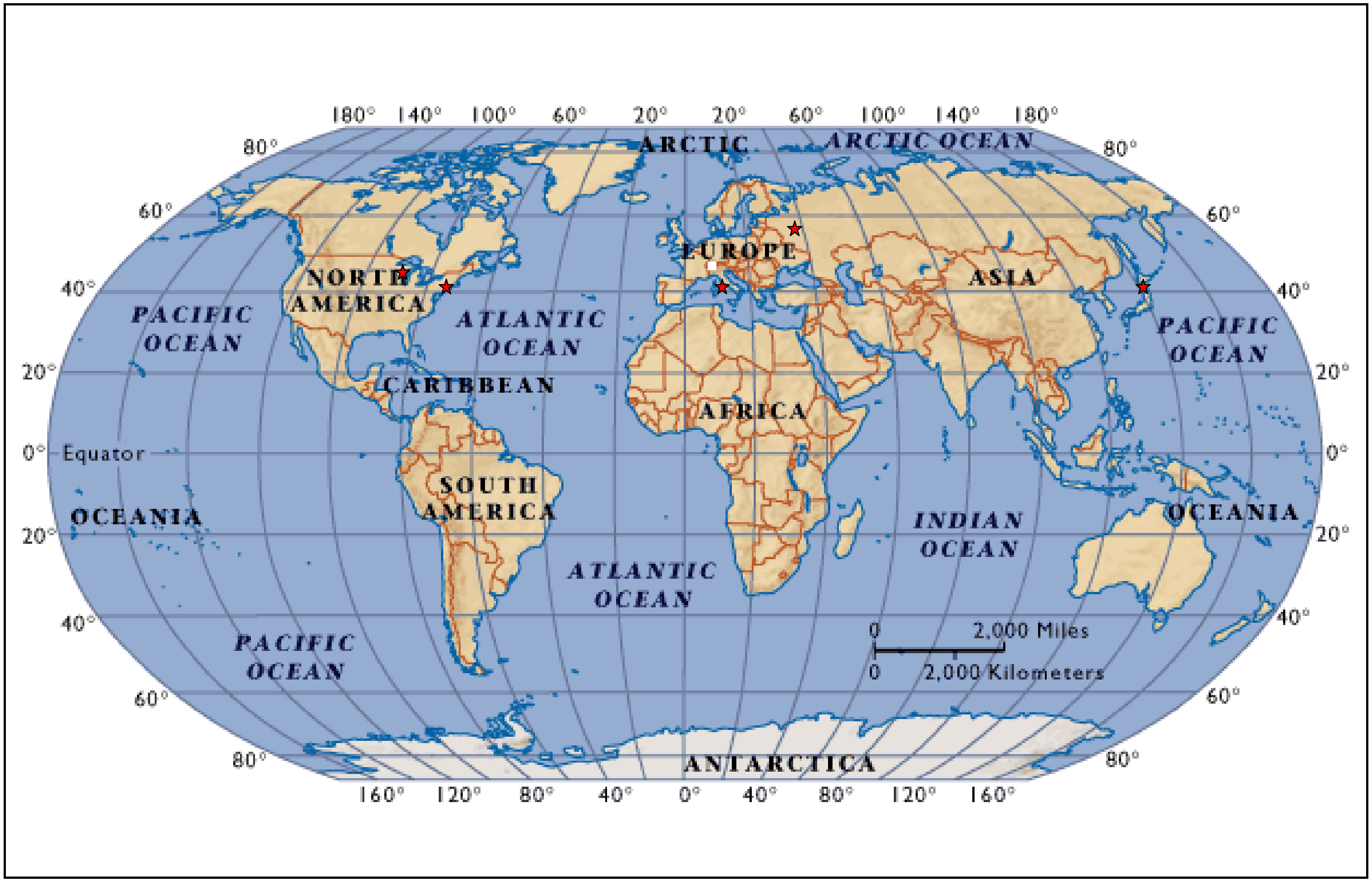
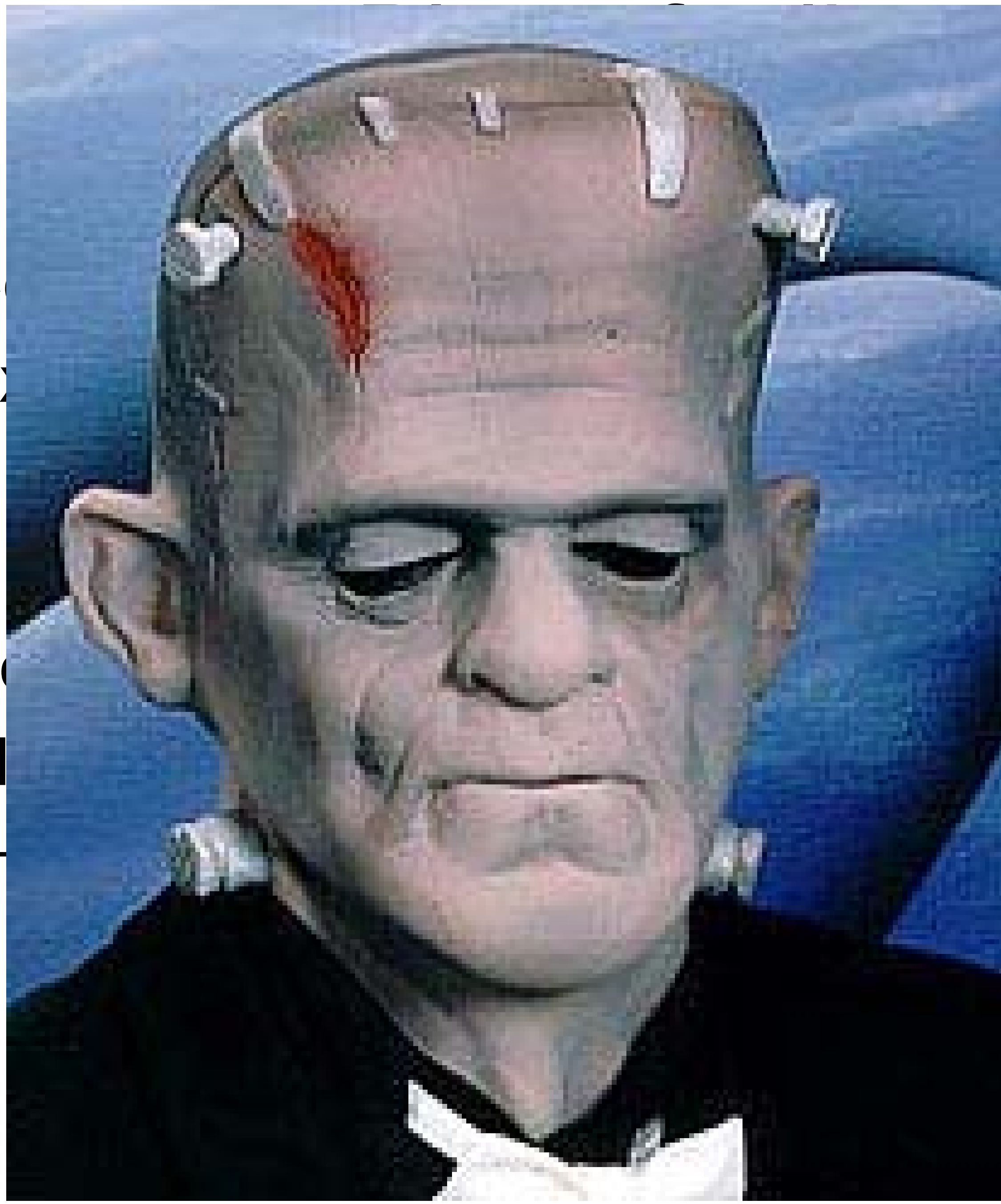
The kaon physics programme outside CERN

L. Littenberg - BNL



Villars sur Ollon 26 Sept 2004

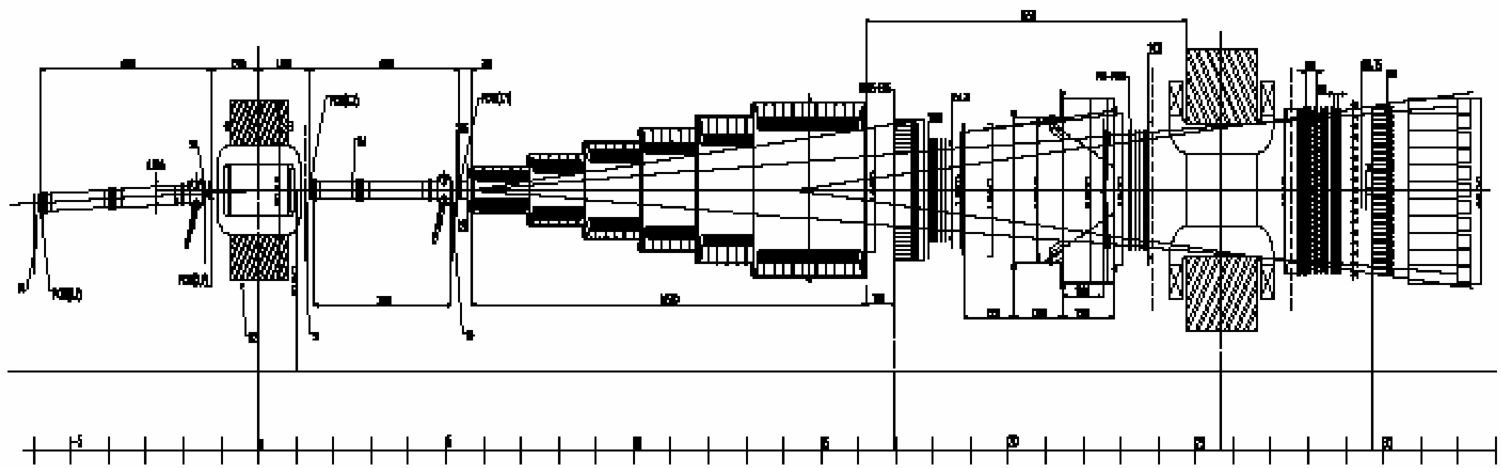
Closeup of excluded area

- C  am
- Ex ilities
- K
- A sses
- S s
- M
  –
- A

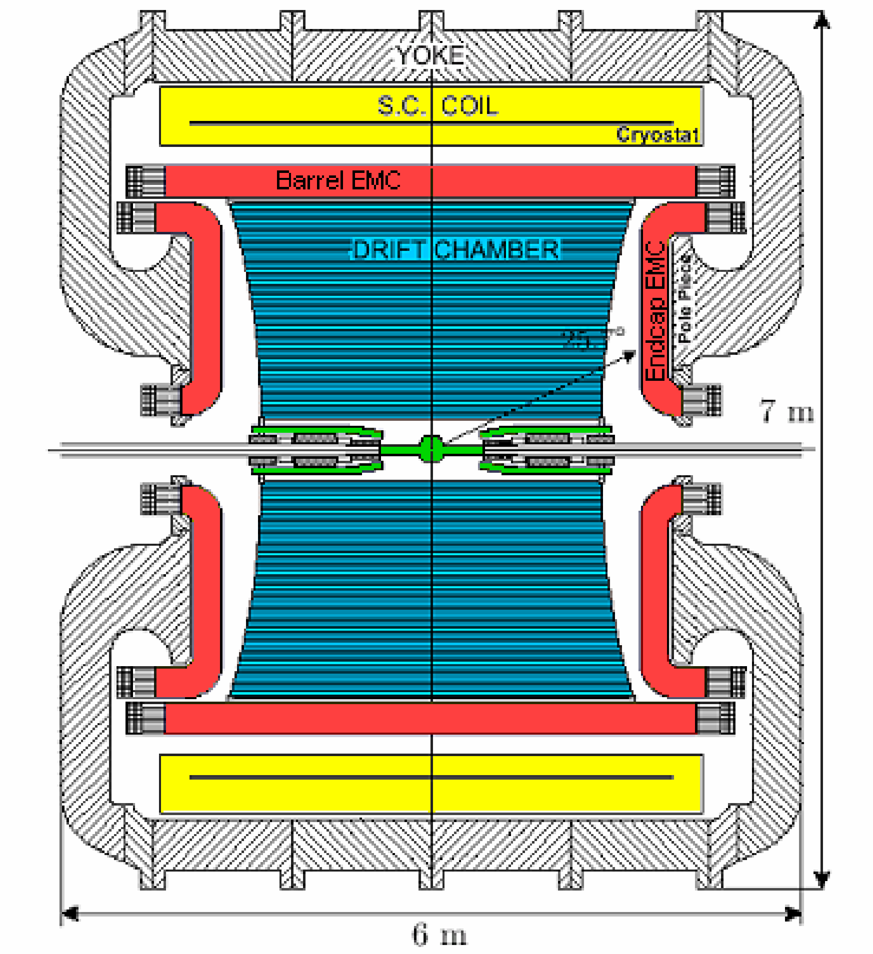
IHEP

- Present: a couple of experiments with unseparated K beams
  - precision studies of common modes + medium rare decays
- Future: OKA
  - separated beam 5×10^6 12-18 GeV/c K^+, 75% pure
  - spectrometer, partID, lead glass, μ-ID, etc.
  - few $\times\ 10^{-11}$/event sensitivity
  - high-precision studies of common to medium-rare decays

OKA setup at U-70 IHEP



The KLOE experiment at DAΦNE



Be beam pipe (0.5 mm thick)
Instr. permanent magnet quads

Drift chamber (4 m ∅ × 3.3 m)

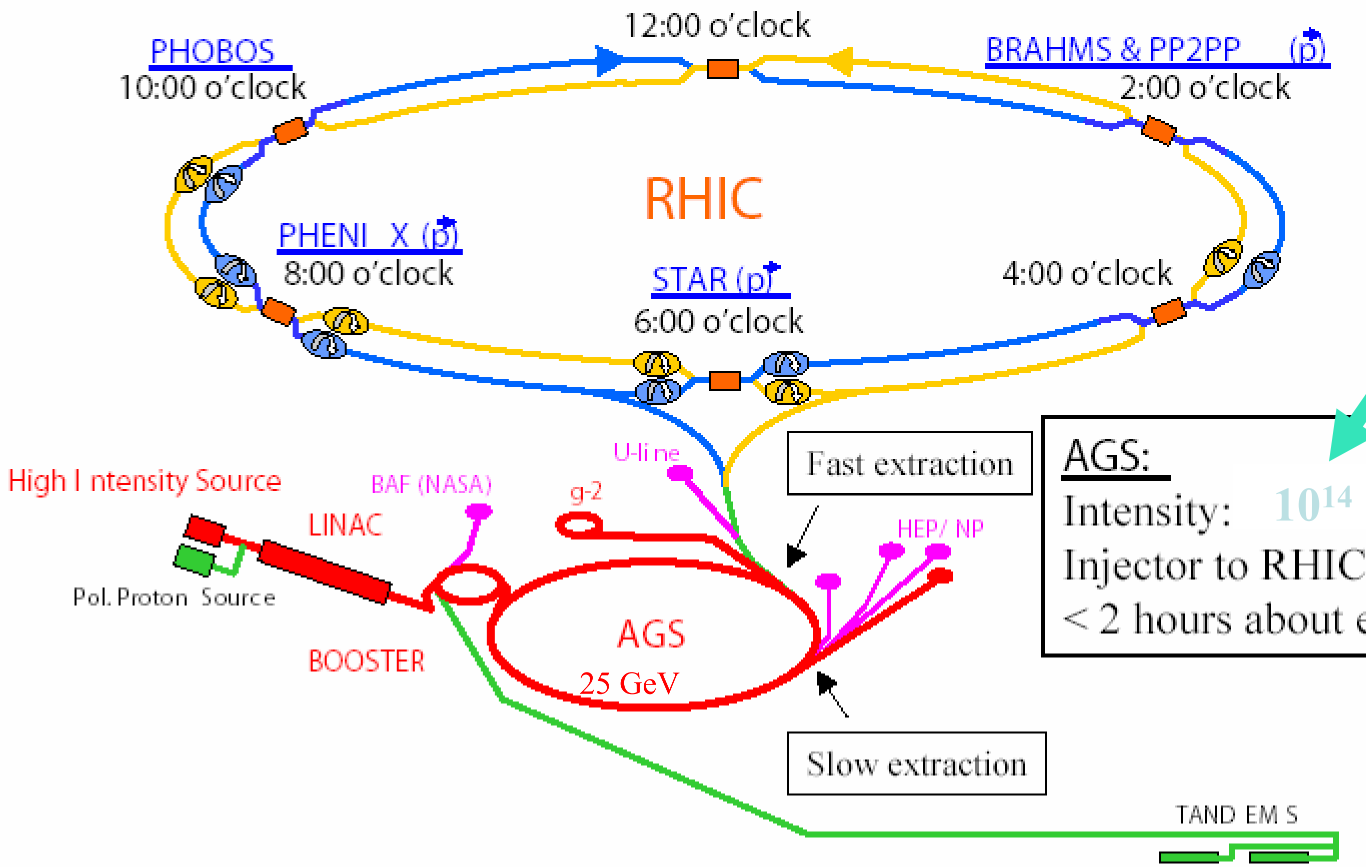
Scifi electromagnetic calorimeter

Superconducting coil (5 m bore)
$B = 0.52$ T (⇩ $B\,dl$ = 2 T·m)

Present: Precision studies of common modes; K_S, $K^{\pm}$ sensitivity @ 10^{-7} level

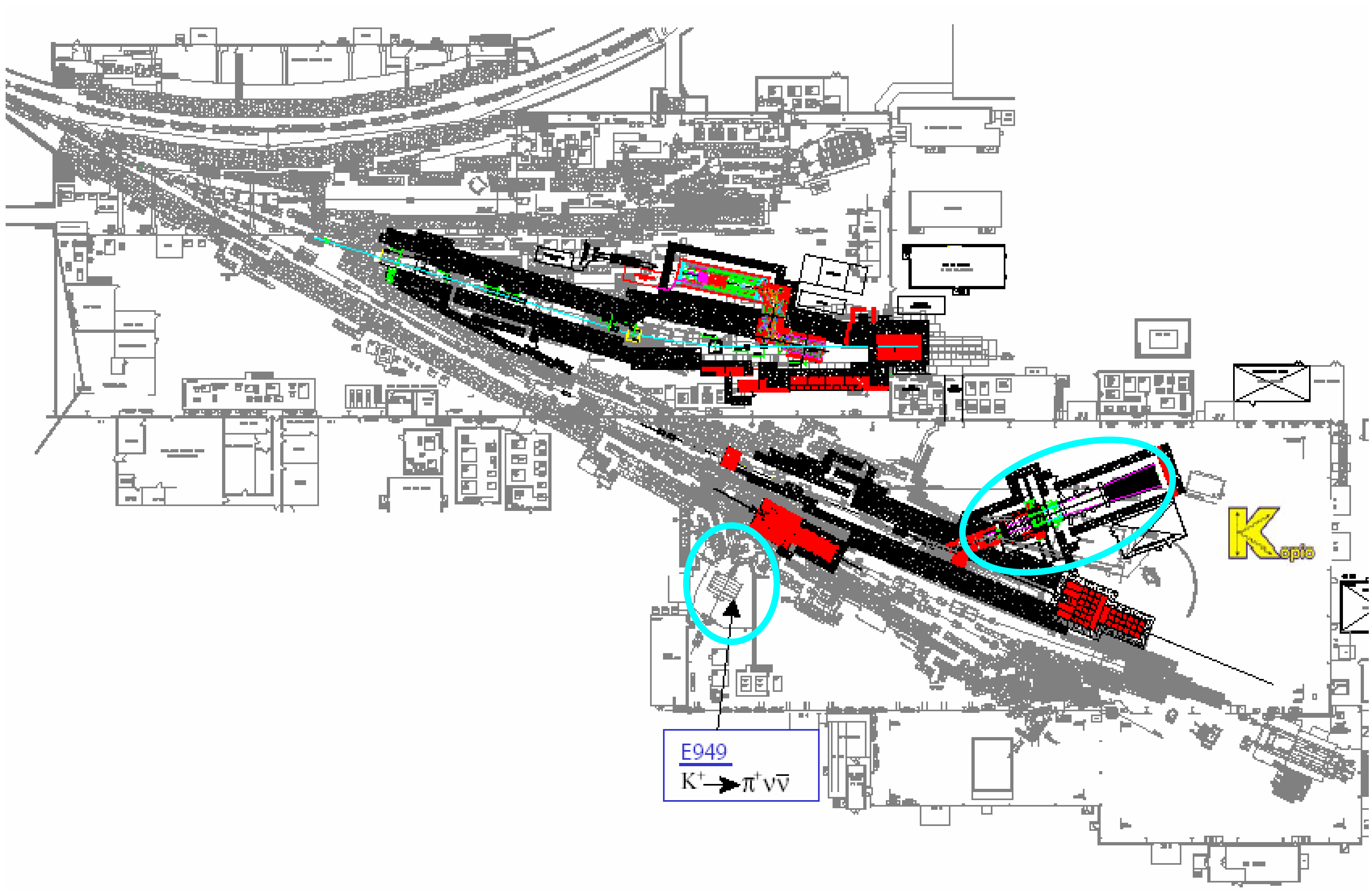
Future: 5 × more sensitivity by end 2005. Another factor 100 with DAΦNE upgrade (by 2011 or 12?)

AGS/RHIC Accelerator Complex

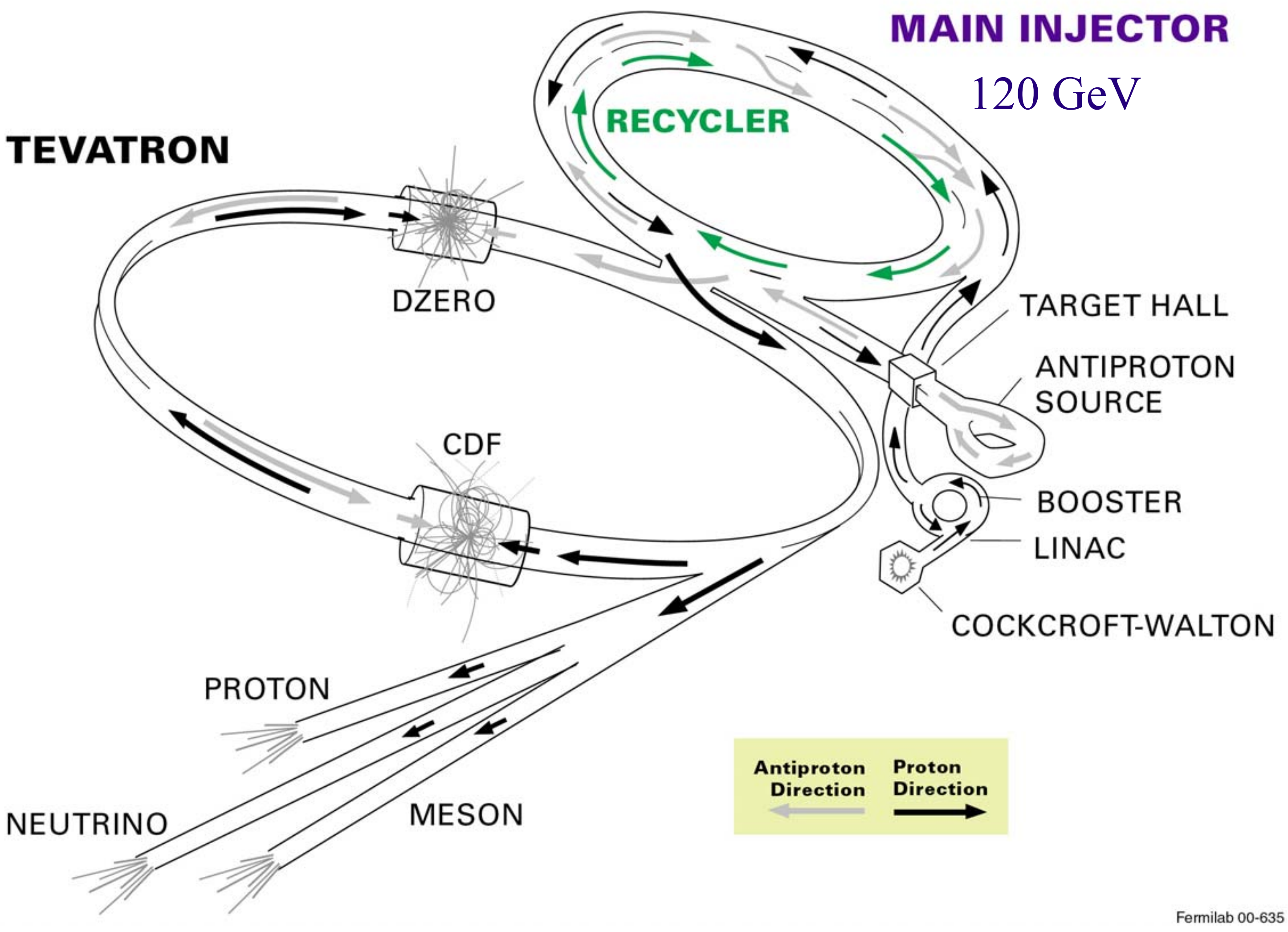


AGS:
Intensity: 10^{14} protons/pulse
Injector to RHIC:
< 2 hours about every 10 hours

AGS Experimental Hall



Fermilab Accelerator Complex

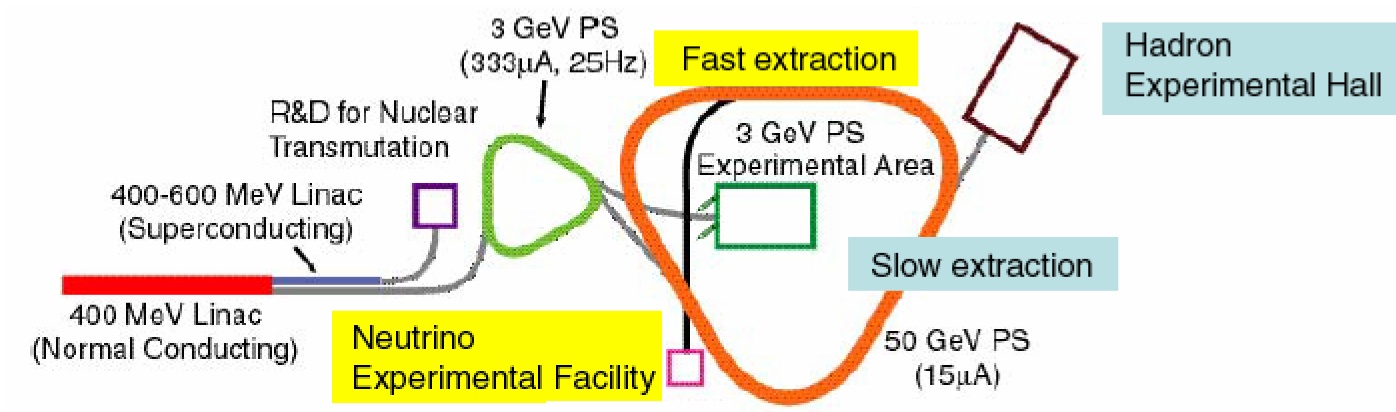


FNAL Fixed Target Experimental Halls

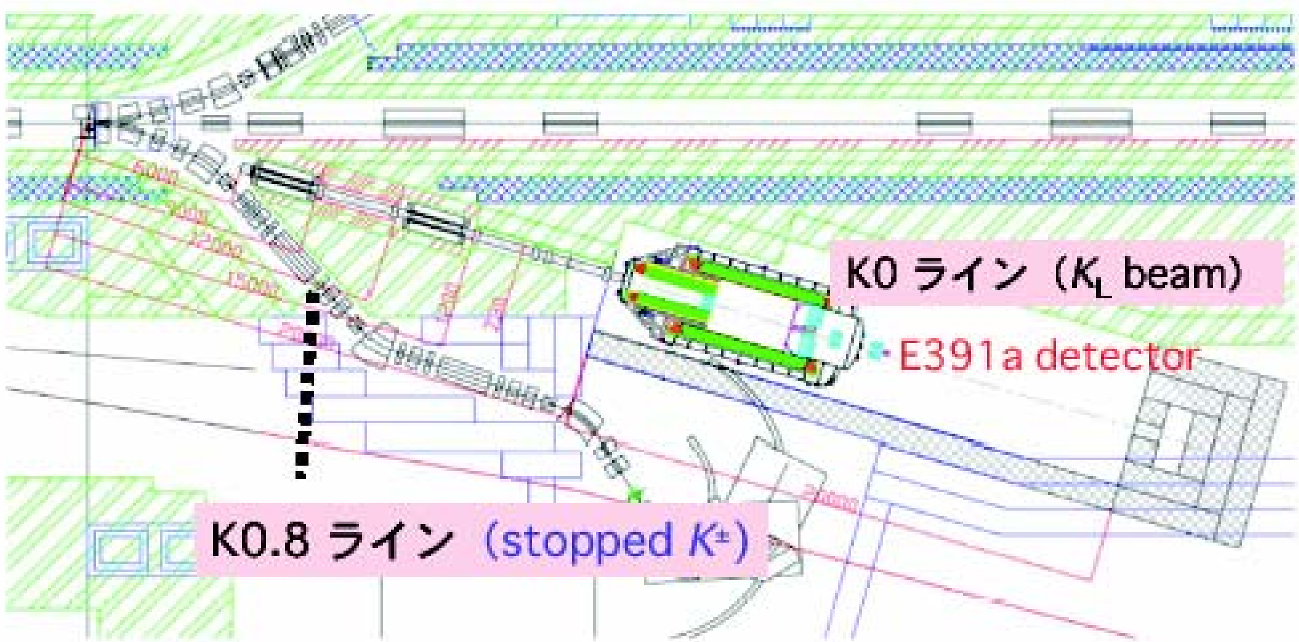
J-PARC


原子核素粒子実験室
Nuclear and Particle Physics Experimental Hall
物質・生命科学実験施設
Materials and Life Science Facility
3 GeVシンクロトロン
3GeV Synchrotron
ニュートリノ実験施設
Neutrino Facility
50 GeVシンクロトロン
50GeV Synchrotron
リニアック
Linac
核変換実験施設
Accelerator-Driven Transmutation Experimental Facility

J-PARC Hadron Hall



Phase 1
Hall



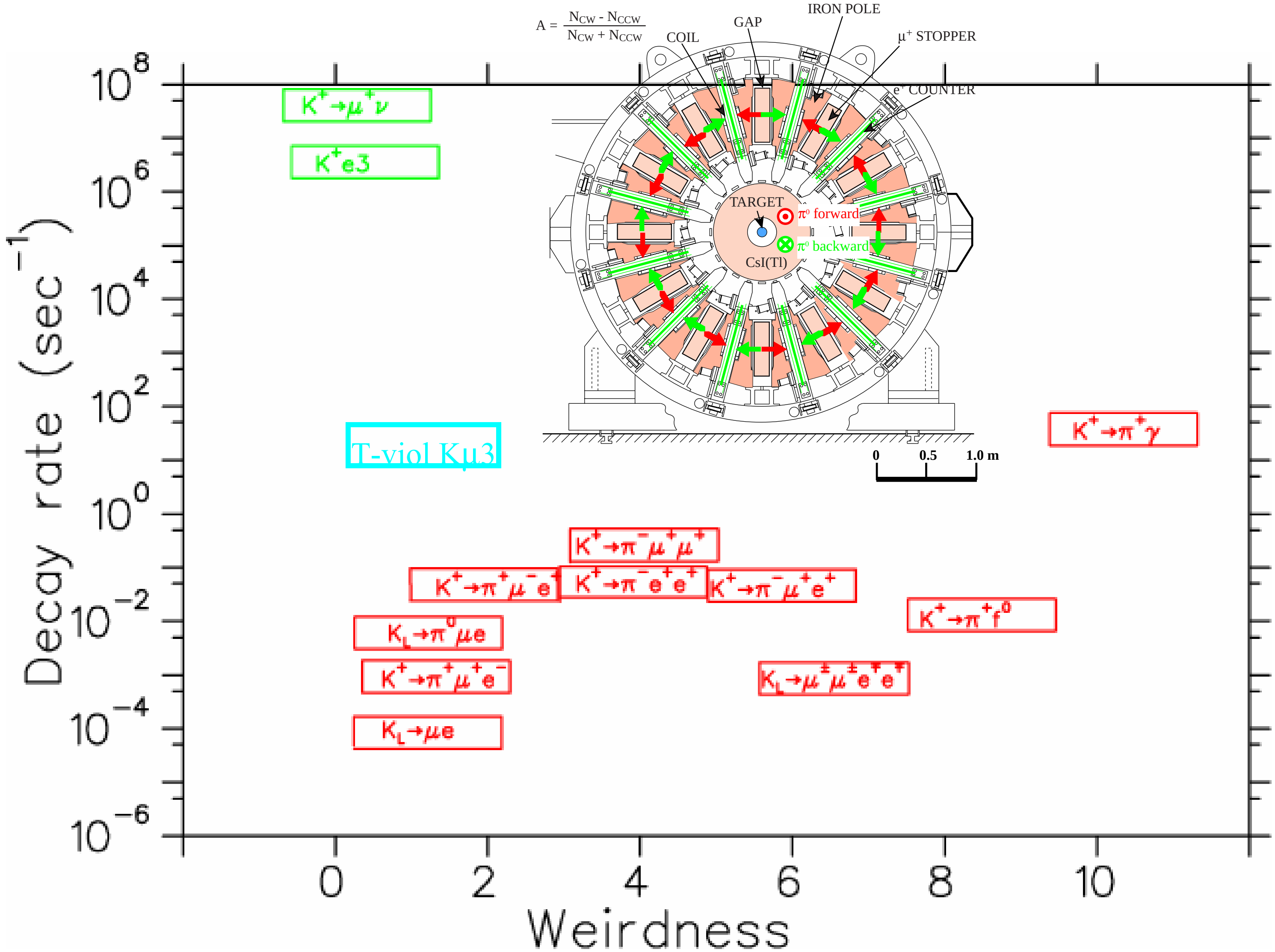
Comparison of Facilities

Facility	**AGS**	**KEK**	**J-PARC**	**FNAL MI**
$\mathbf{P_{proton}}$	2--28	12	30-50	90-120
p/cycle (TP)	65--100	2	100--200	30
cycle time (s)	3-10	4	3.4-5.6	2.9-4
spill length (s)	1-7	2	0.75-3	1-2
duty factor	up to ~0.70	0.50	.22-.53	.33-.50
K utilization factor	0.8/0.4	0.3	0.3	0.40
Share with	RHIC/MECO	ν	ν	collider,ν

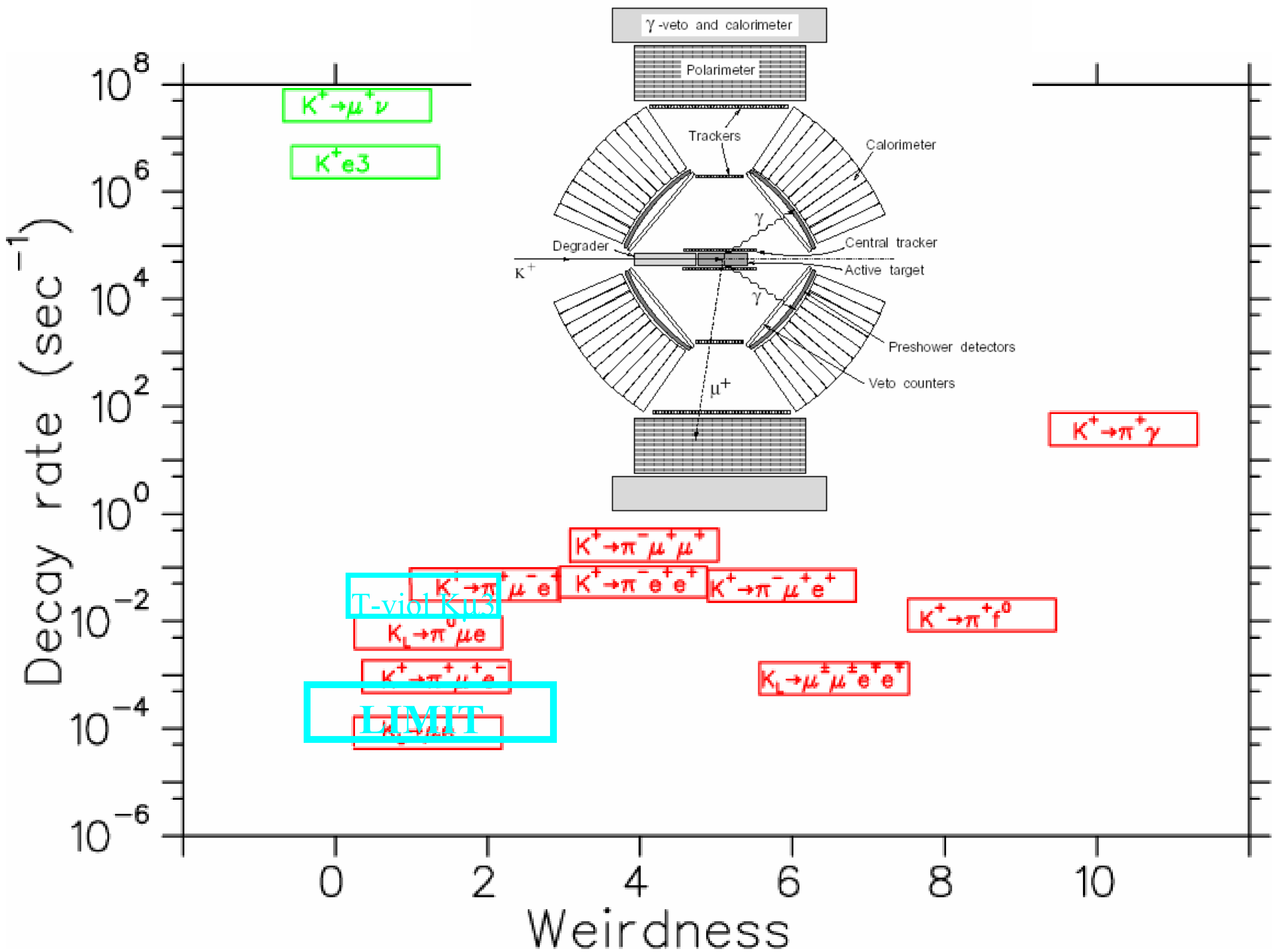
Beyond the Standard Model

- A number of dedicated BSM experiments (mainly LFV) ran for a decade starting in the late 1980's
- BSM limits also produced by other experiments of the period
- Very impressive limits set (BRs as low as 4.7×10^{-12})
- But theoretical impetus ran dry
- Now a few results still trickling out, but almost no new initiatives on the horizon (one exception)
- Results were at or near background limit
- Should new experiments be considered?
  - Some theorists think it interesting
  - Advances in beams/detectors could make possible further progress.

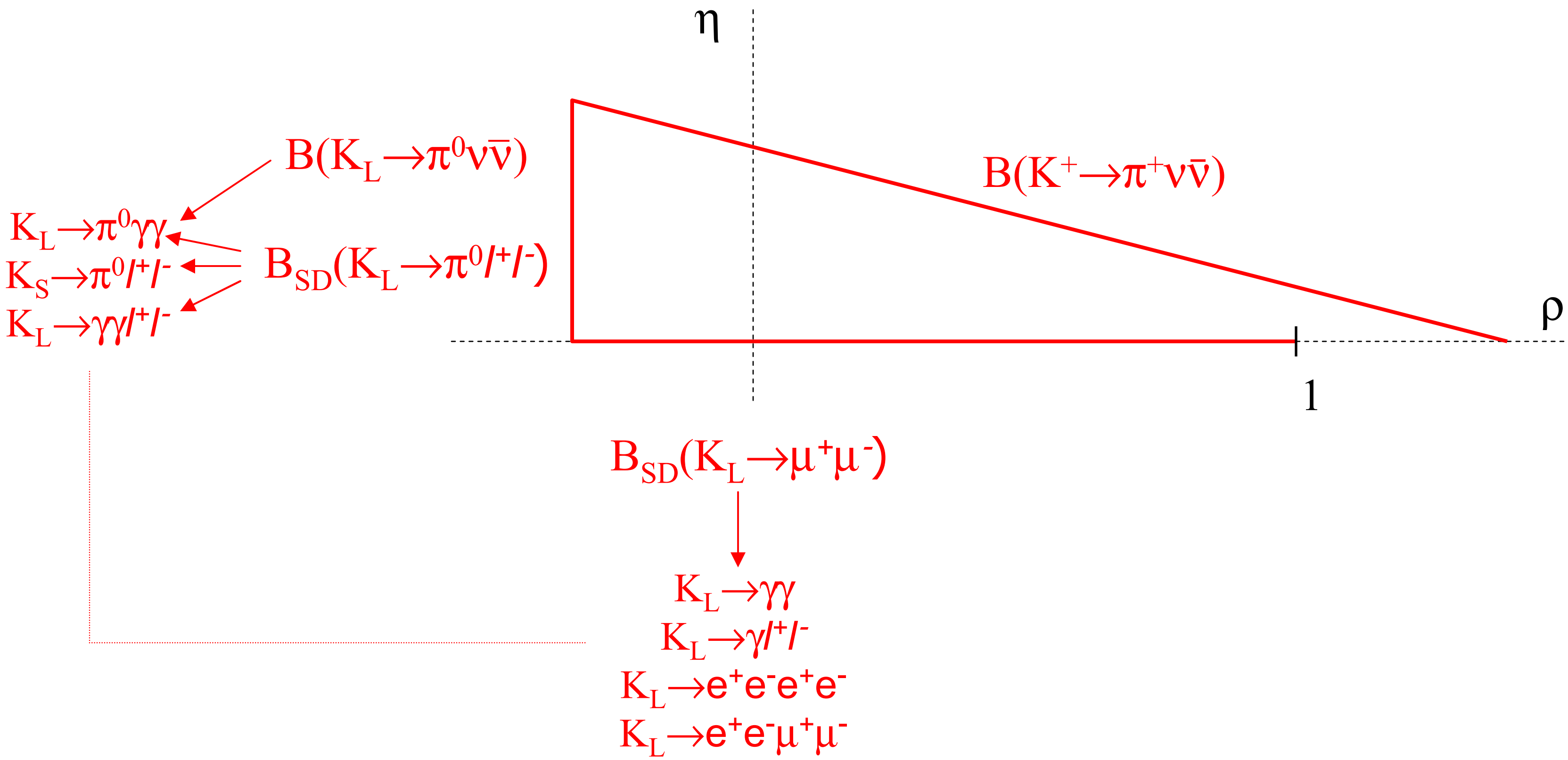
90% CL upper limits on non-SM Decays



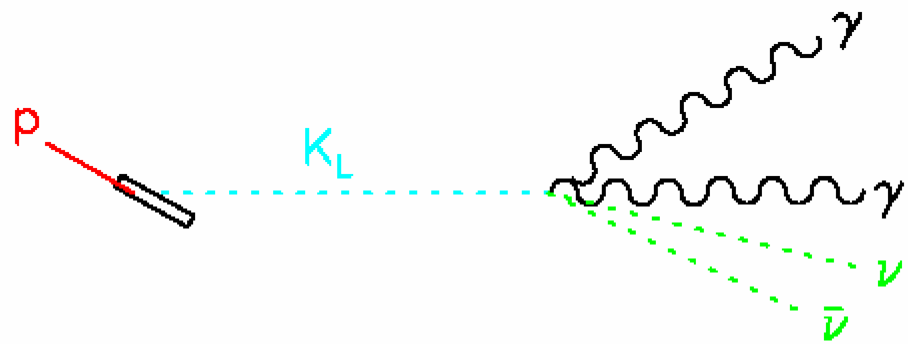
90% CL upper limits on non-SM Decays



Rare K decay & the Unitarity Triangle

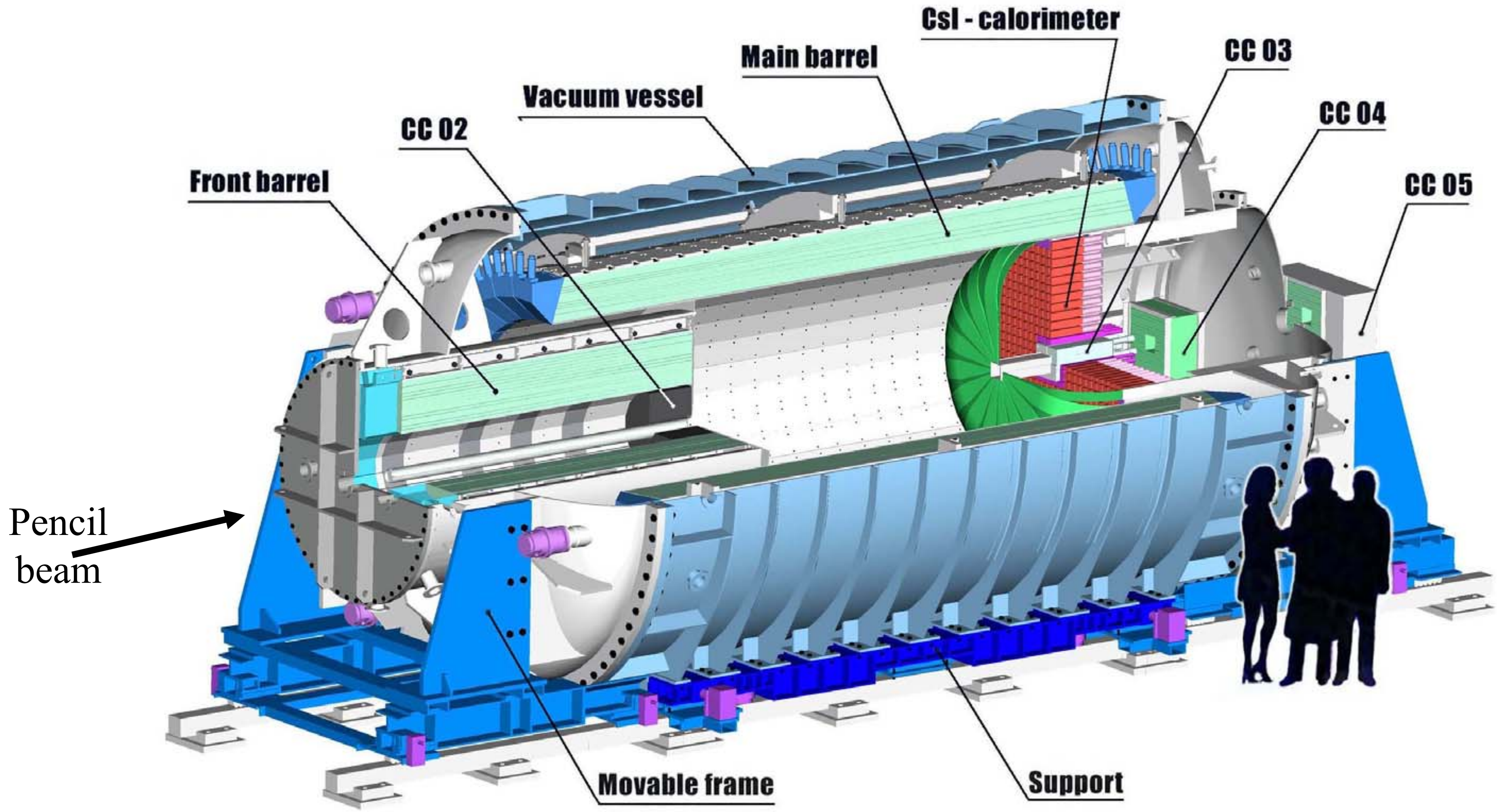


$K_L \rightarrow \pi^0 \nu \bar{\nu}$ Experimental Issues



- All-neutral initial & final state, γ's make π^0
- Expected BR ~ 3×10^{-11}
  - need high flux of K_L
- Largest background $K_L \rightarrow \pi^0 \pi^0$, BR ~ 10^{-3}
  - need excellent vetoes, other handles if possible
- Background from n-produced π^0's, η's
  - need 10^{-7} Torr vacuum
  - need a way to be sure decay vertex was in the beam

E391a detector system

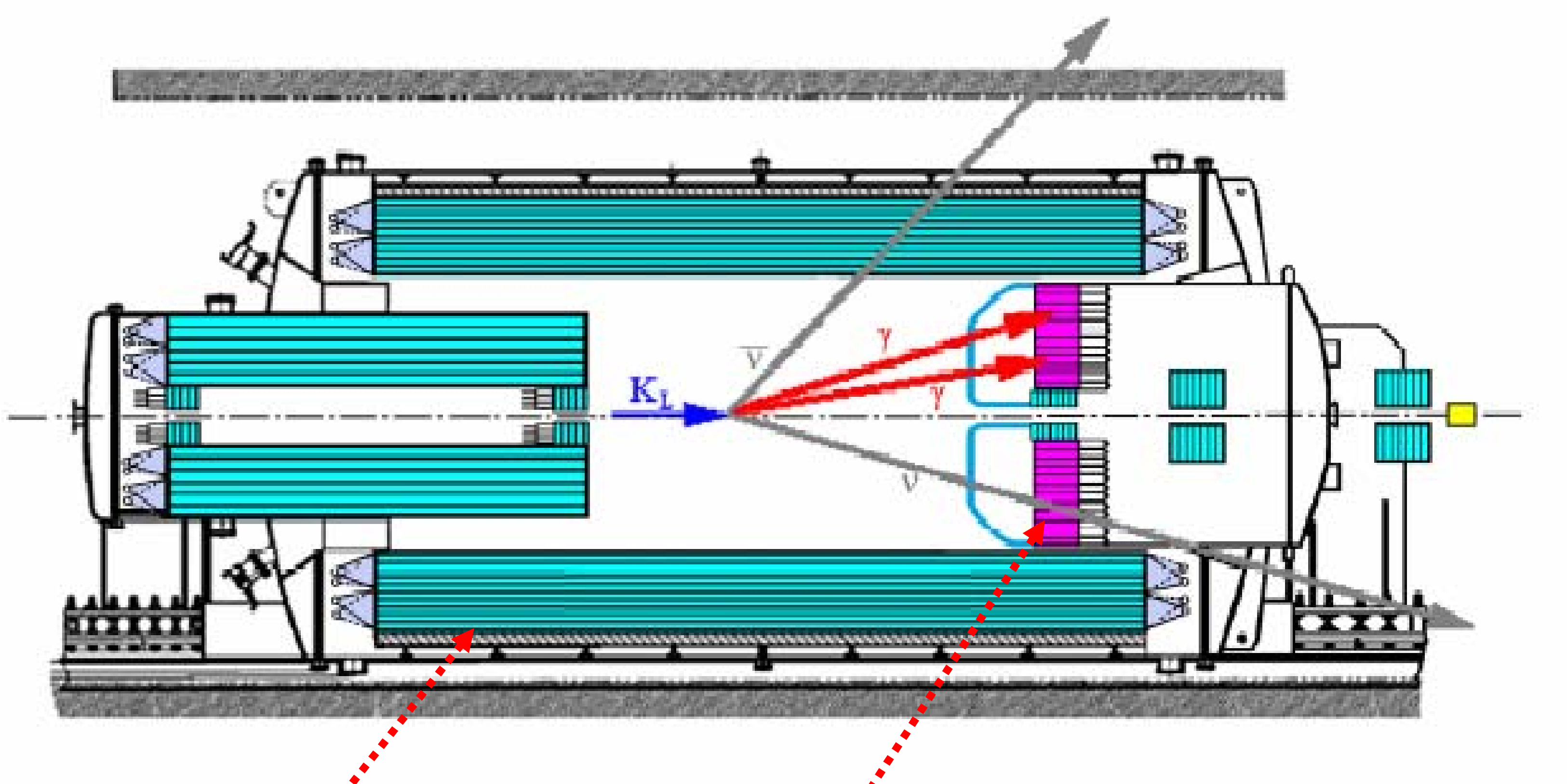


E391a status & prospects

- First physics run Feb-June this year
  - 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}
  - Analysis underway
  - first sight of the enemy
    - Halo neutrons, self-vetoing, etc.
- Second run proposed for next year

KEK-PS to J-PARC

100× more K_L

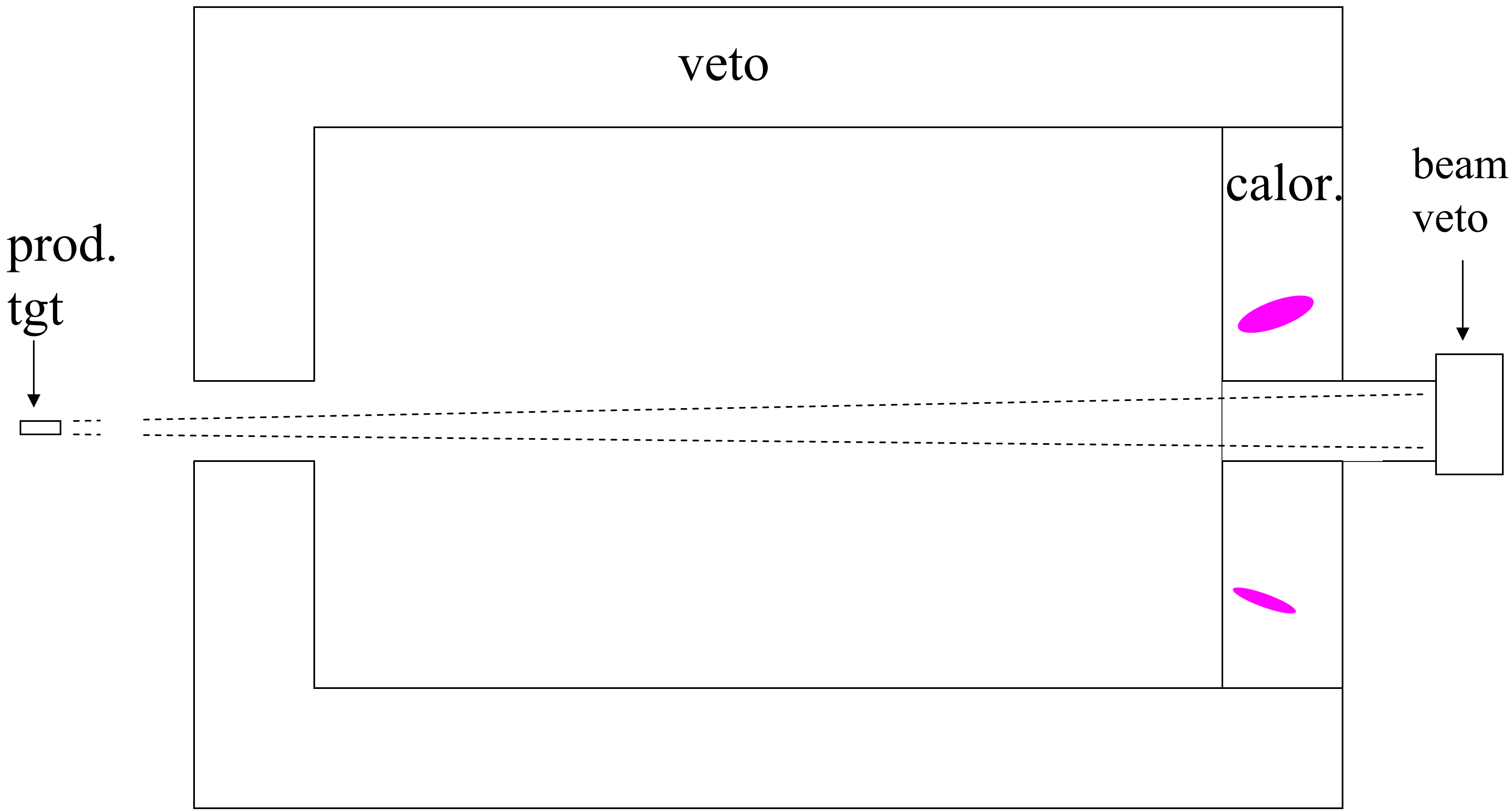


Thicker photon vetoes

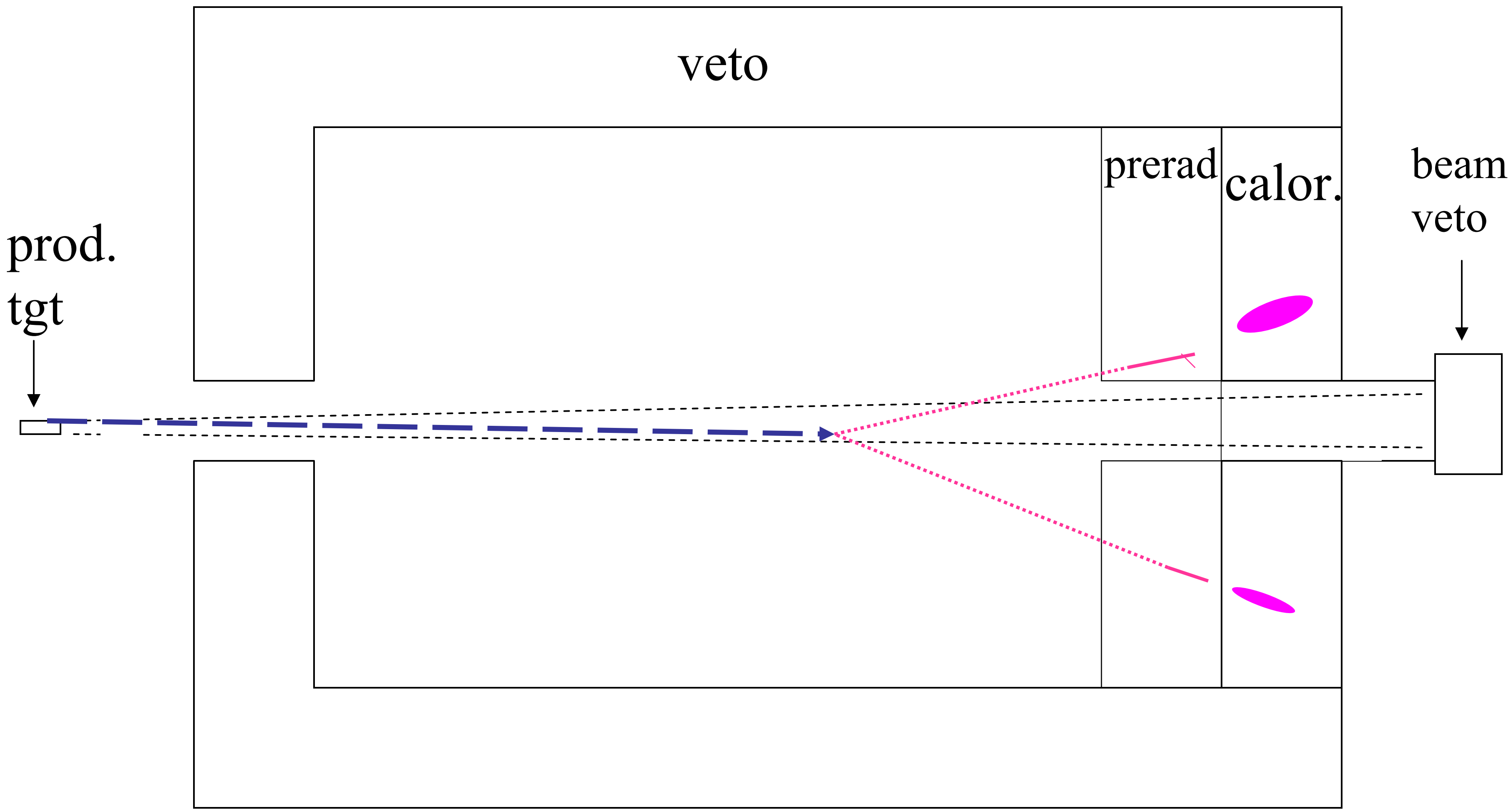
Deeper, more granular crystals

Faster electronics

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



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

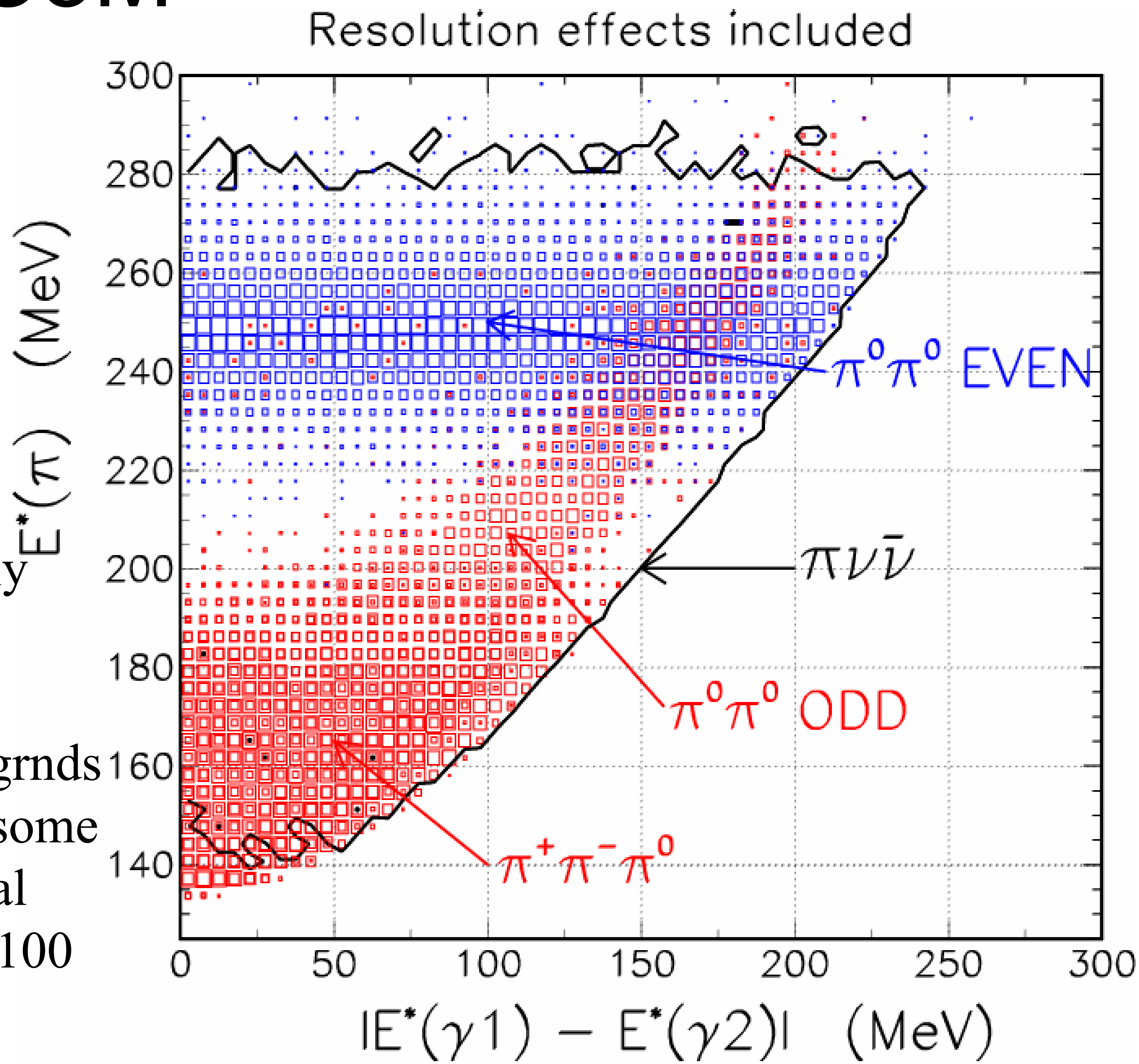


In the K_LCoM

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

- Kπ3 infests slightly different area

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



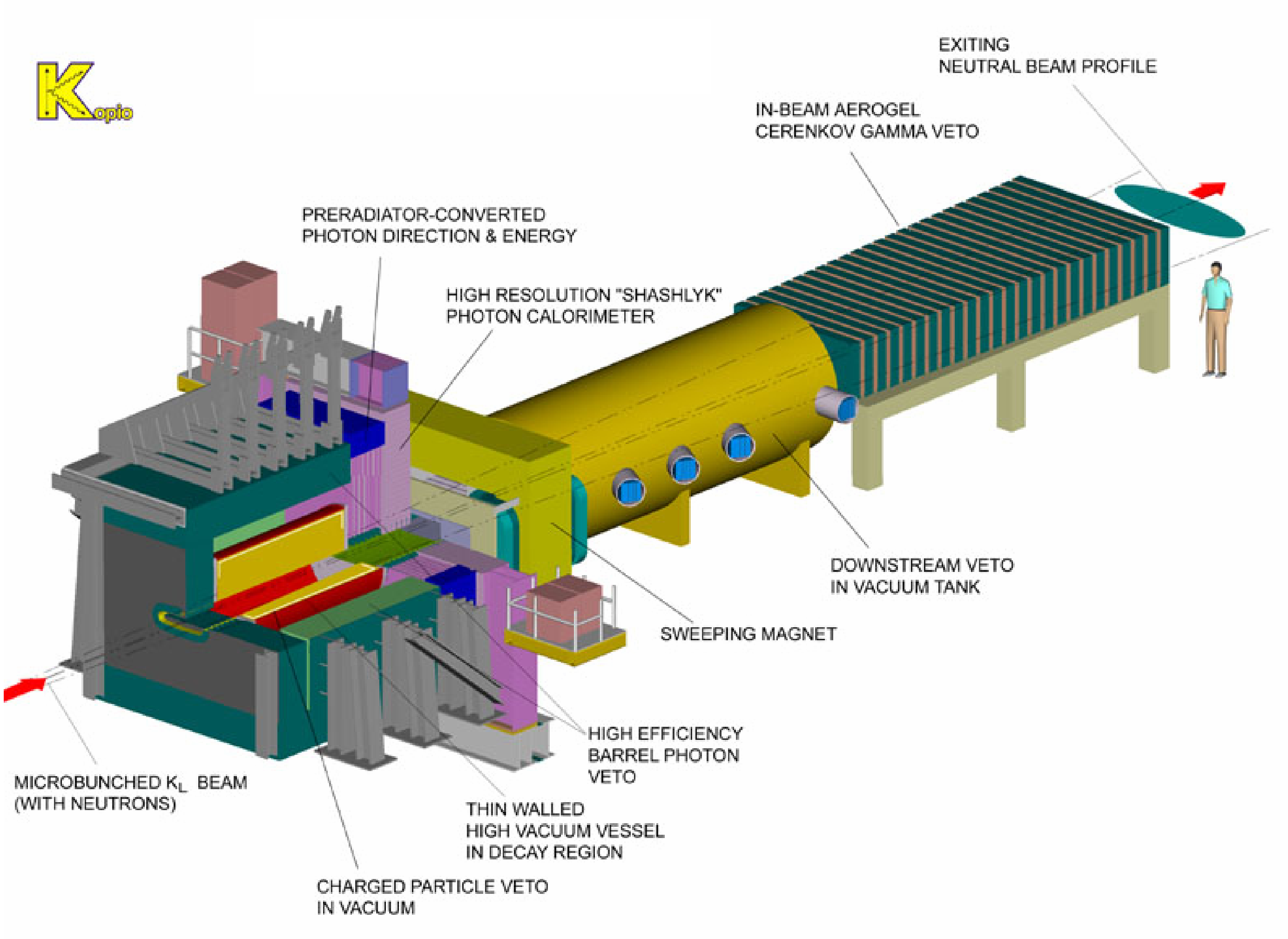
KOPIO $K_L \to \pi^0 \nu\bar{\nu}$ Experiment

BNL AGS experiment

Aim: to get >40 evts
with S:B ~2:1

Use the AGS between RHIC fills

Capitalize on the experience of previous AGS rare K decay experiments

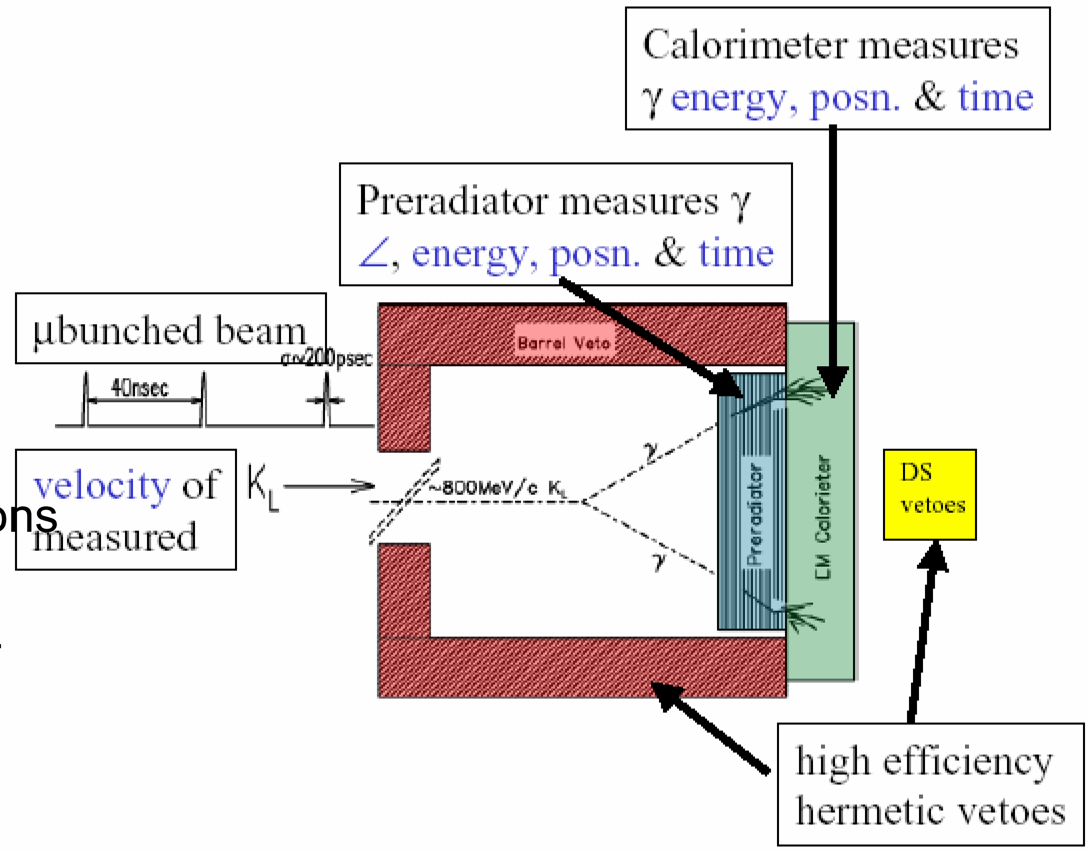


KOPIO Concept

- Detect π^0 and nothing
  - ↳ 2γ ↳ veto

Measure everything possible

- K_L TOF : to work in K_L CMS
  - µbunch AGS protons
  - Large angle (soft) beam
  - Asymmetric beam profile
  - 2 γ detection, timing of K_L
- Reconstruct π^0 decay from $\gamma\,\gamma$
  - Measure γ directions & positions in PR
  - Measure γ energy in PR+CAL
- Veto : cover 4 π solid angle
  - Photon veto
  - Charged particle veto

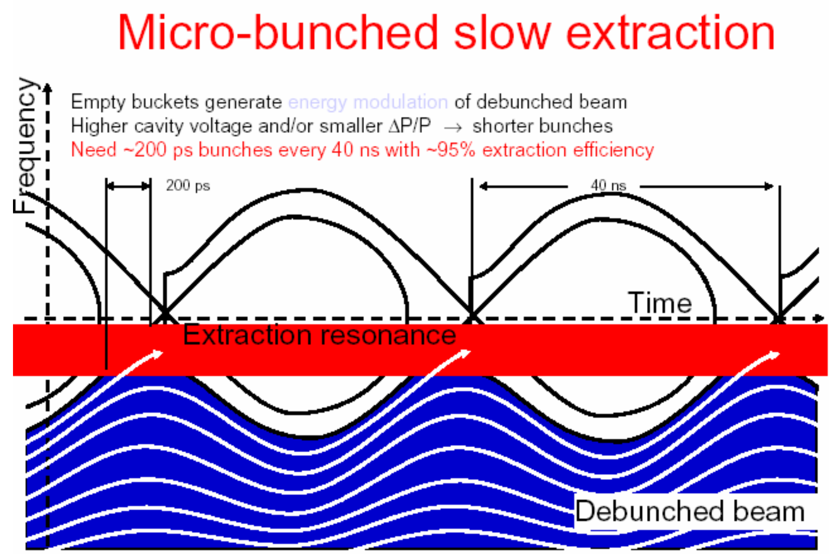


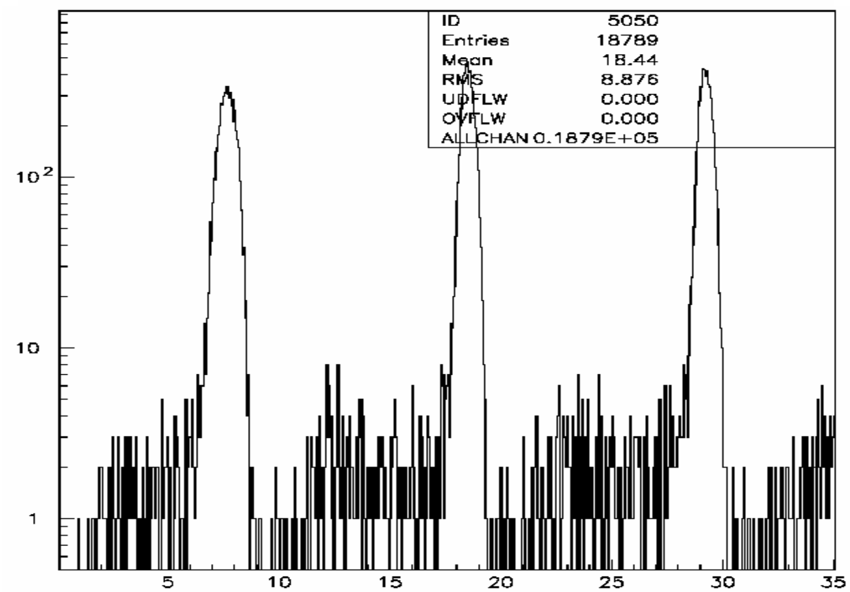
KOPIO Requirements

- 100 TP/AGS pulse (requires upgrade from 70TP)
- 250 ps μbunch width, every 40 ns, with $<10^{-3}$ between bunches
- Beamline at 42.5^{o}, 100 mr $\times$ 5mr, halo $\leq 10^{-4}$
  - Gives 3×10^{8} K_L/spill, (12% decay), but 100 $\times$ more n's)
- γ timing commensurate with bunching
- γ veto inefficiency of ~ 10^{-4}, ***~ 10^{-3} in beam***
- γ energy resolution of ~3%/$\sqrt{E}$
- γ angular resolution of ~ 30mr
- Charged particle inefficiencies $\leq 10^{-4}$

Microbunched Beam

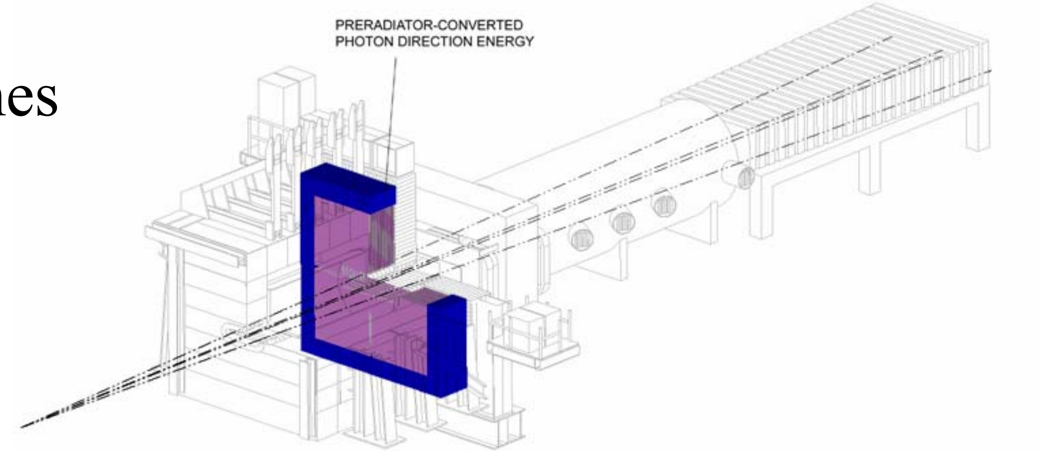
- Based on CERN technique
  - Used for smoothing beam
  - Cappi & Steinbach 1981
- Achieved 244ps µbunch rms with 93MHz cavity
- Recent tests with main AGS cavities showed extinction of ~ 10^{-5}
- 25 MHz cavity in design
  - based on RHIC 28 MHz

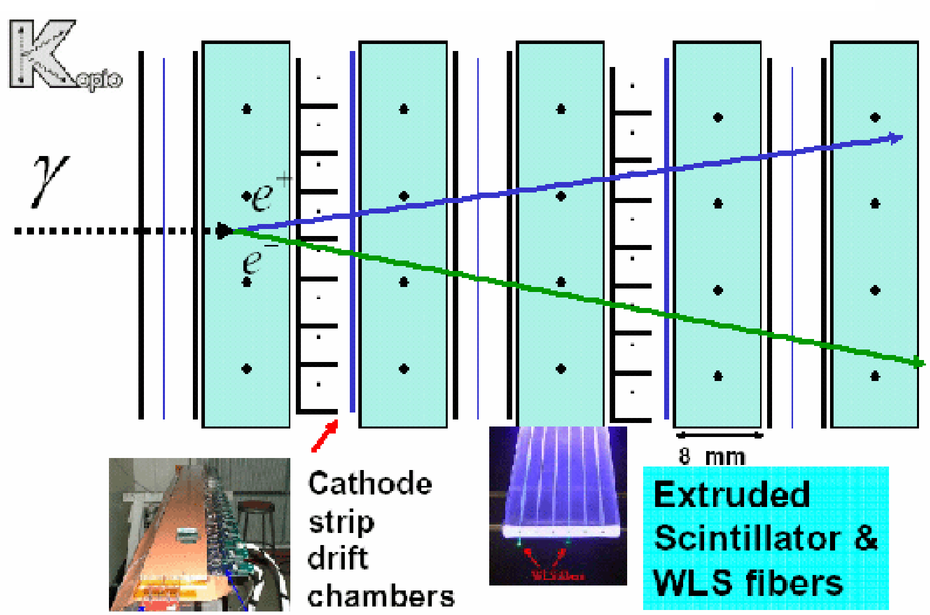




Preradiator

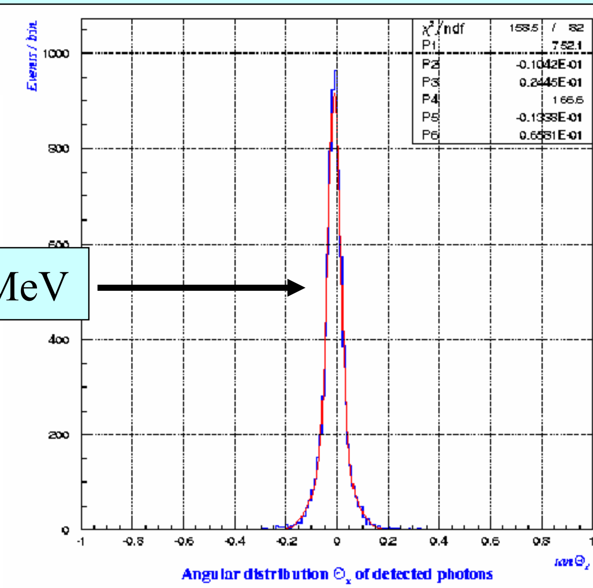
2 X_0 alternating DC & scint. planes
4m × 4m (four quadrants)
200,000 channels





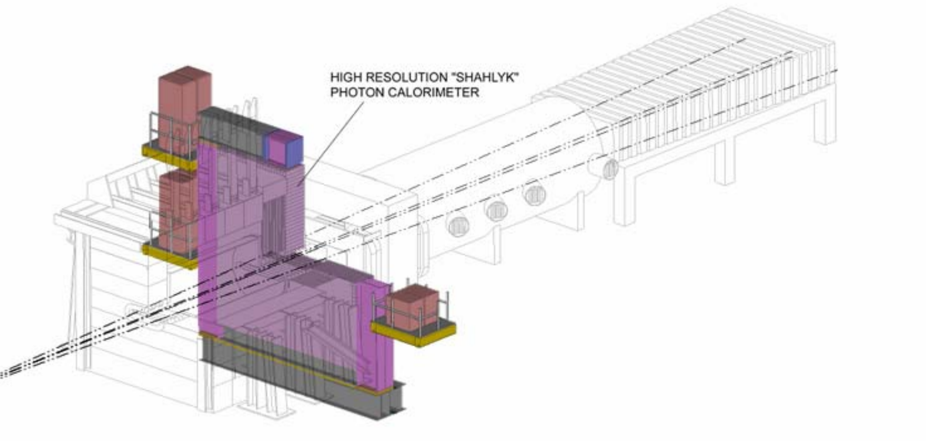
γ angular resolution measured at NSLS

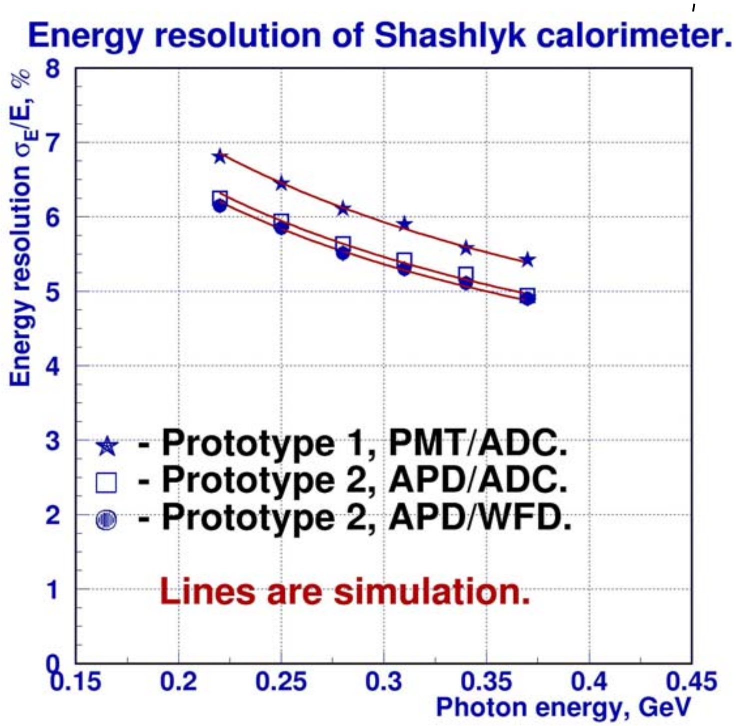
σ ~ 25 mr @ 250MeV



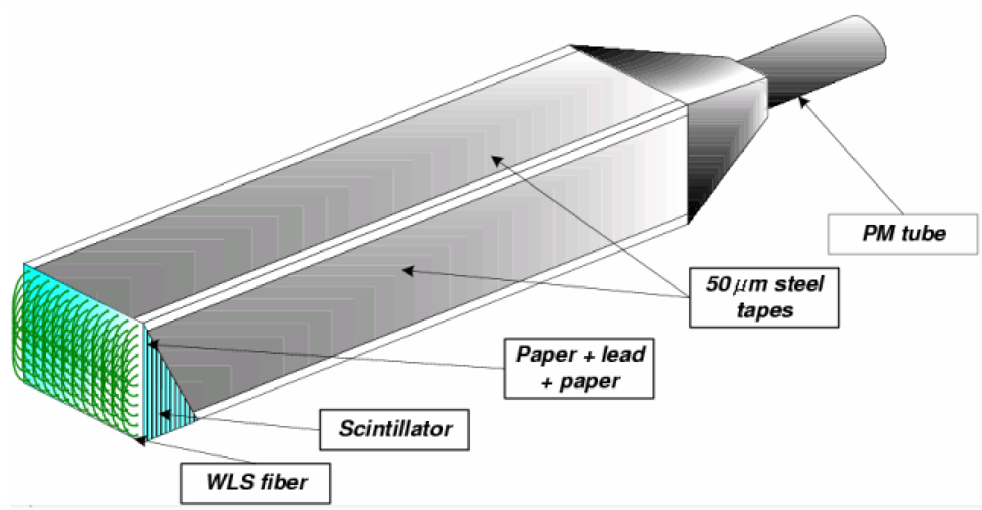
Shashlyk Calorimeter

- 2500 11cm^2 modules, 16 X_0 deep
- Pmt or APD readout
- Prototype tests have achieved
  - Energy resolution ~ 3%/ $\sqrt{E}$



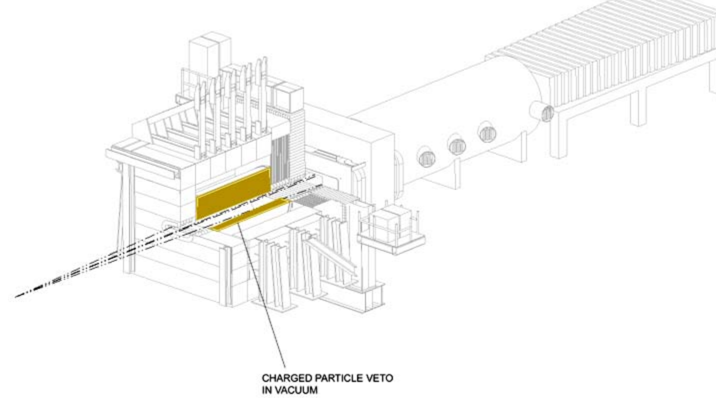


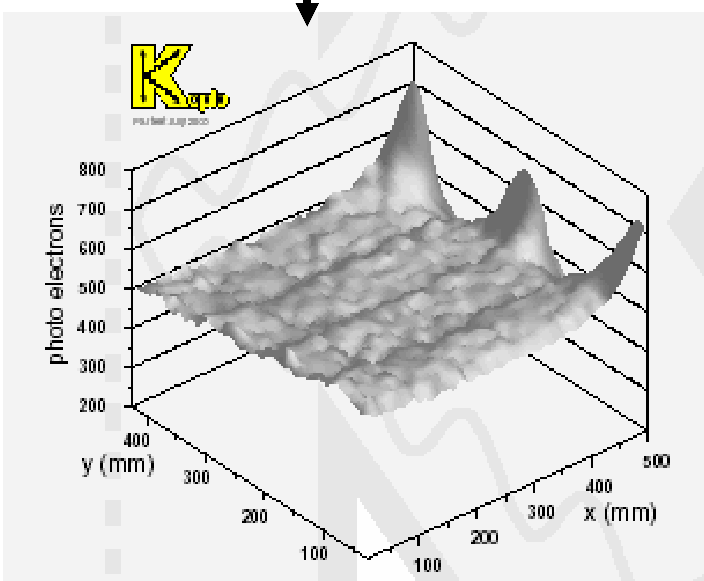
Shashlyk calorimeter

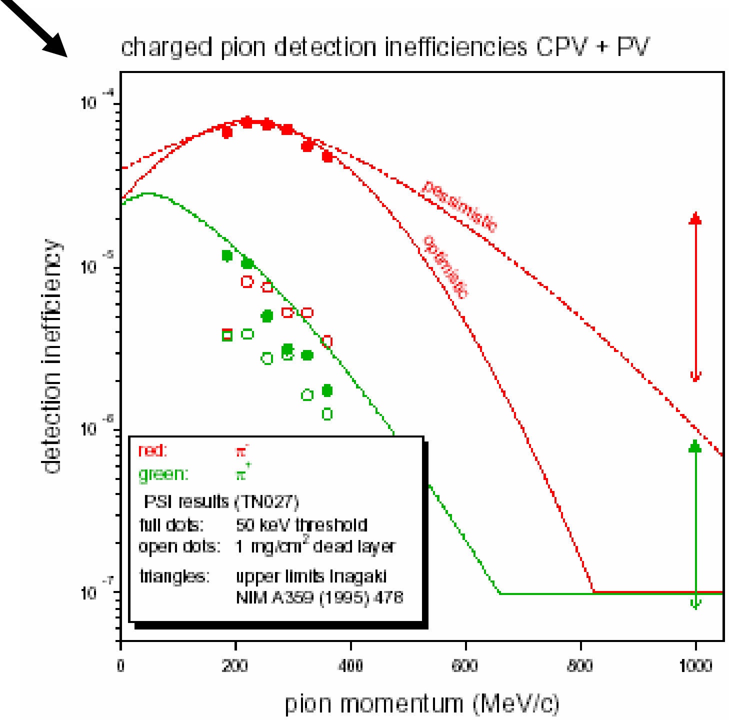


KOPIO Charged Particle Veto

- Thin scintillator directly read out by pmts in vacuum
- Tests of achievable inefficiency at PSI
  - Note γ vetoes back up CPV
- Prototype tests at PSI

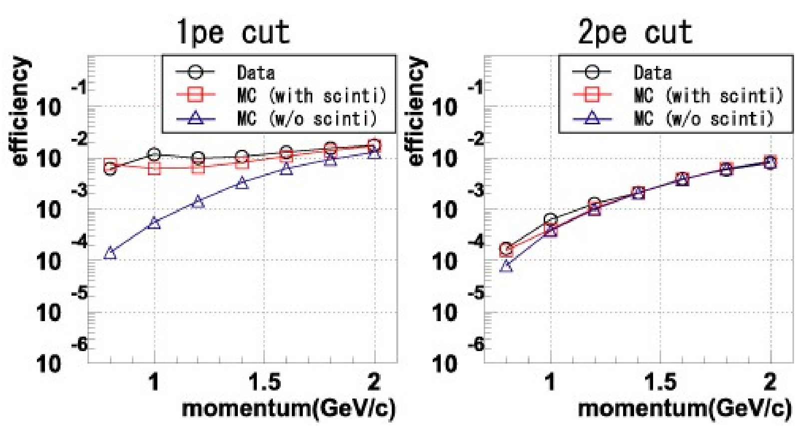


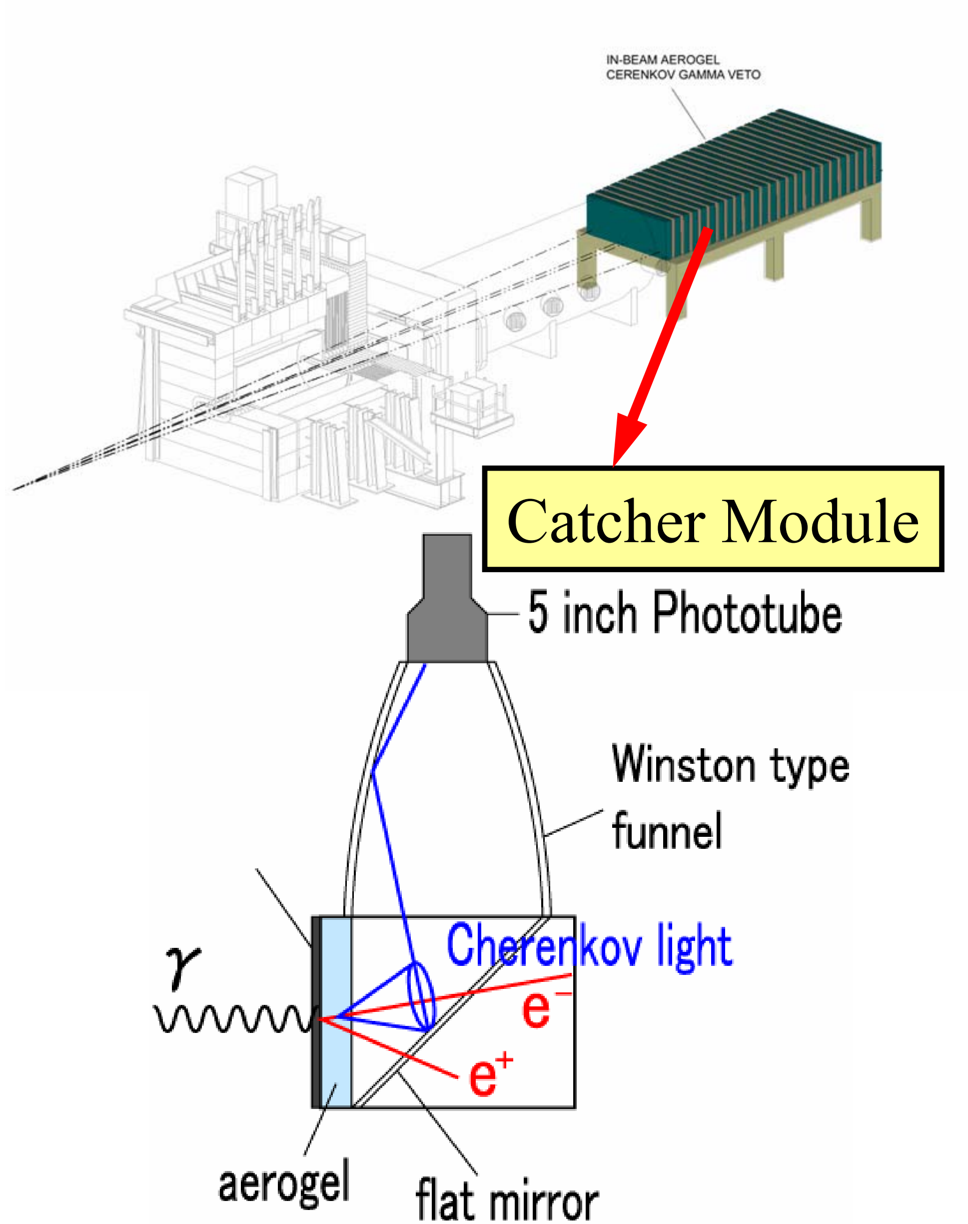




KOPIO Beam Catcher Veto

- Photon veto which covers beam core region
- in fierce□ neutron rate
- Needs to be…
  - efficient for γ rays
  - insensitive to neutrons
- Aerogel Cherenkov + distributed geometry
- Prototypes tested in γ□ & p beams:



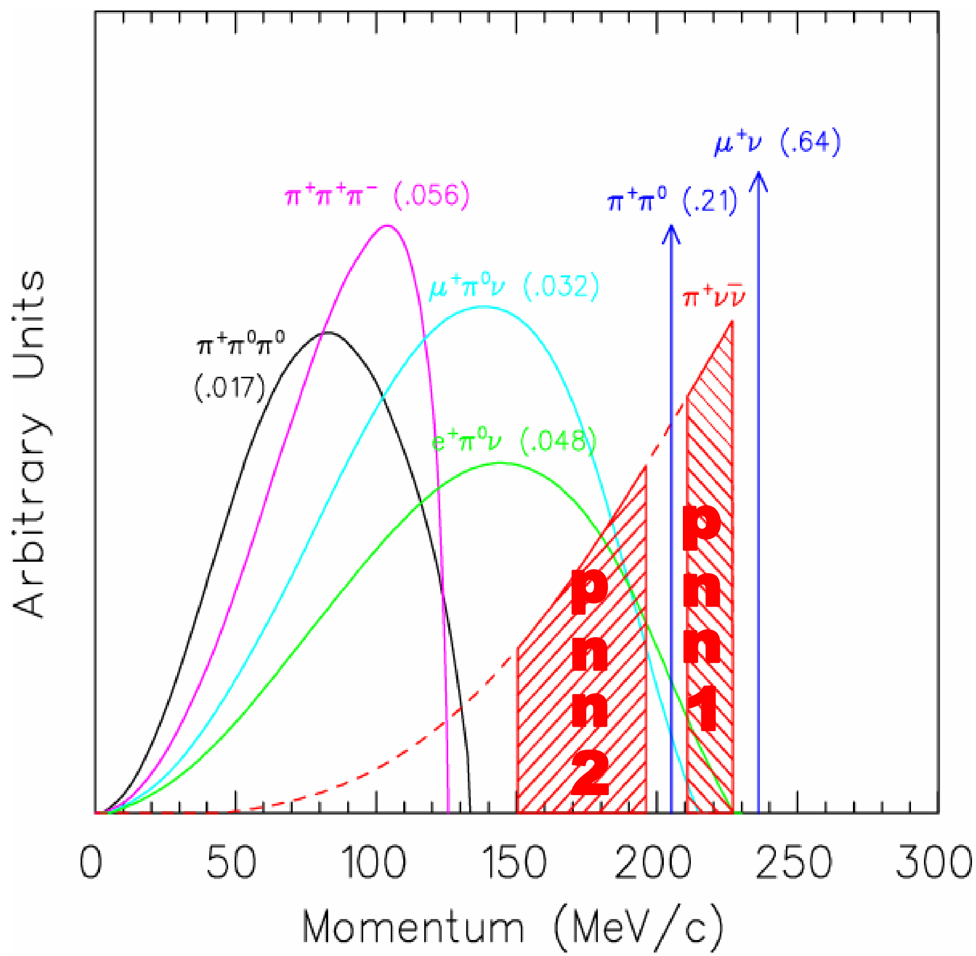


Status of KOPIO

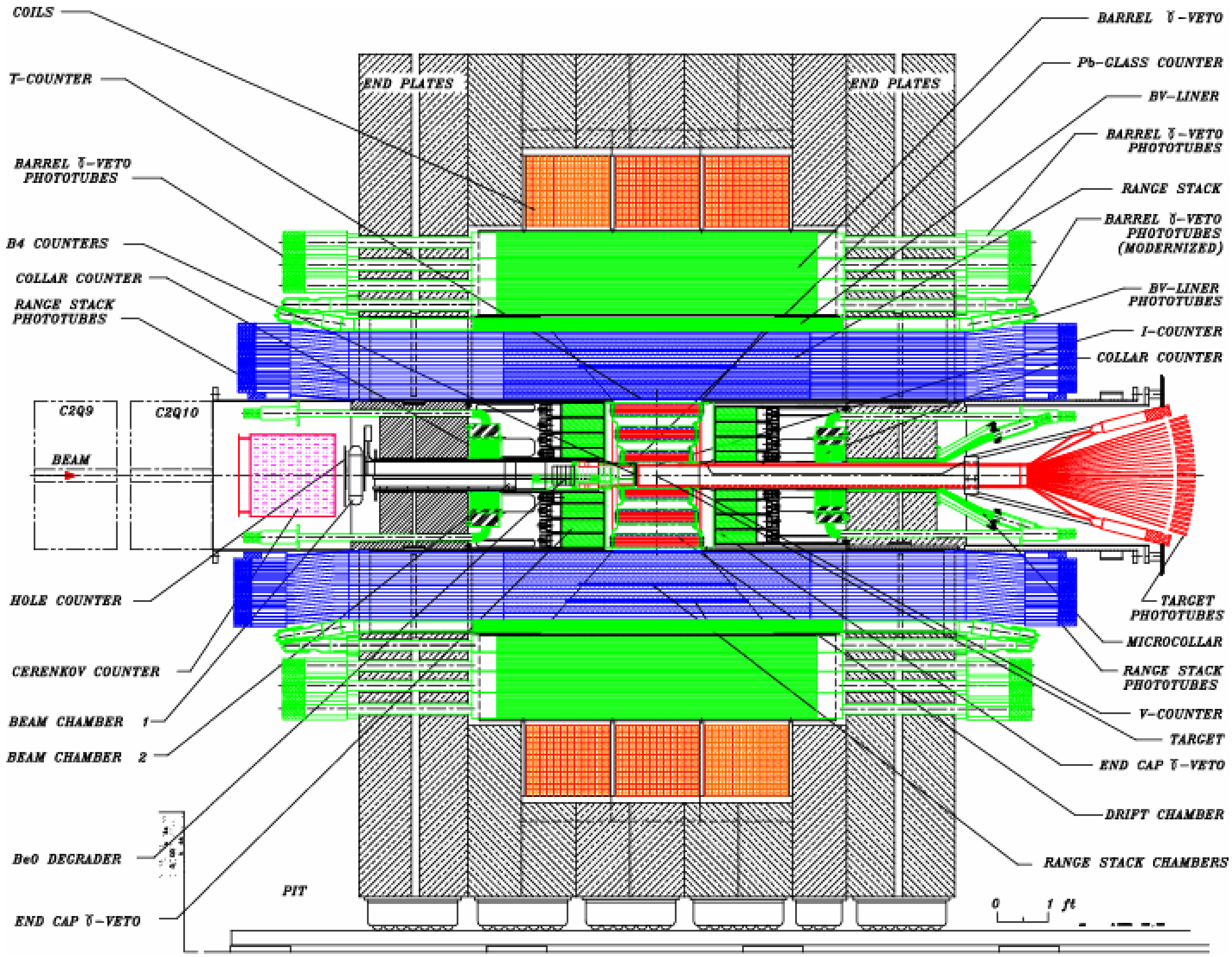
- RSVP approved all the way up the NSB
- Received $6M in R&D funds in FY04
- In the President’s FY05 budget for $30M
- In the House Appr. Sub-committee markup
- Waiting for Congress to complete its process
- All requirements shown to be met by prototype tests or performance of other experiments (e.g. E949).
- In late stage R&D, initial engineering
- **Still seeking collaborators!**

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

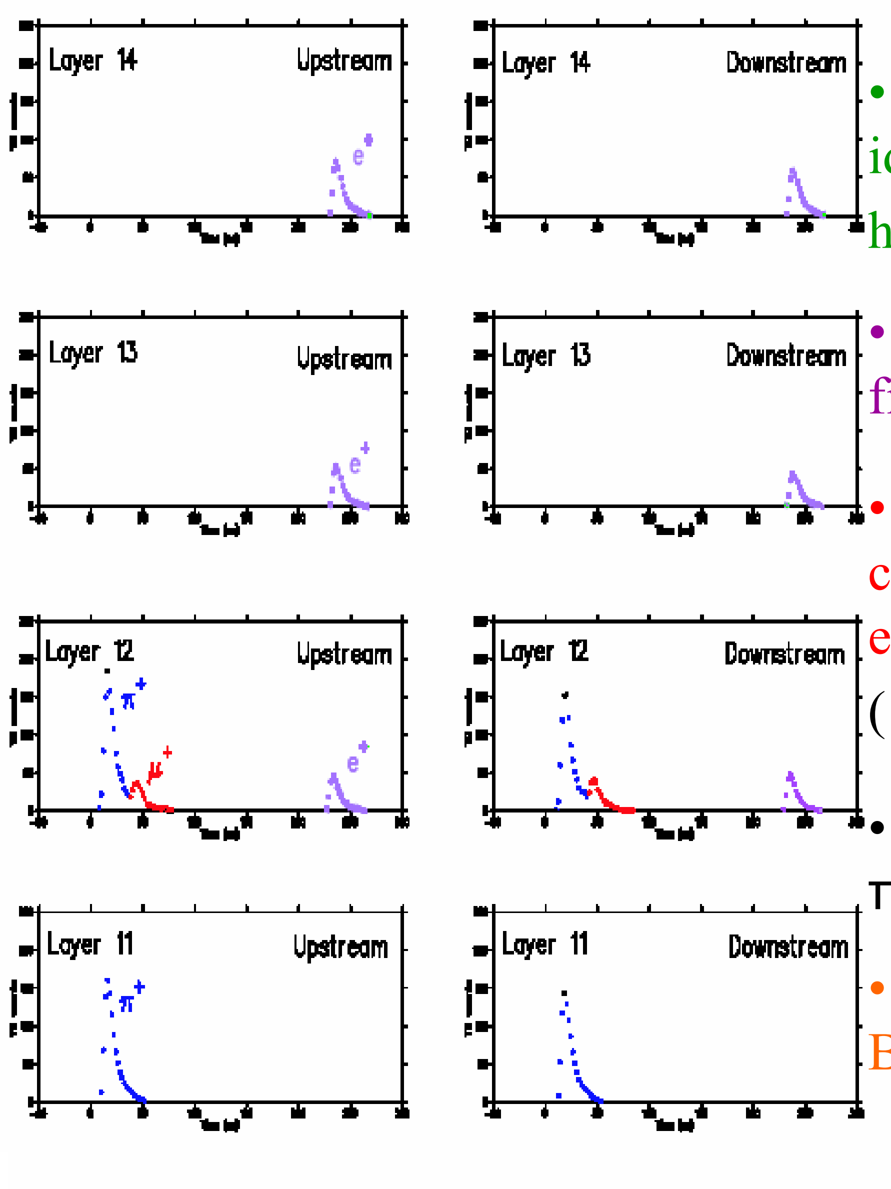
- 3-body decay, only 1 visible
- π^+ common K decay product
- BR ~ few × 10^{-11}
- Backgrounds:
  - $K^+ \to \mu^+ \nu(\gamma)$
  - $K^+ \to \pi^+ \pi^0$
  - Beam
    - Beam π^+ mis-ID as K^+, then fakes K decay at rest
    - K^+ decay in flight
    - 2 beam particles
  - $K^+ n \to K^0 p$; $K_L \to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



E787/949 Detector



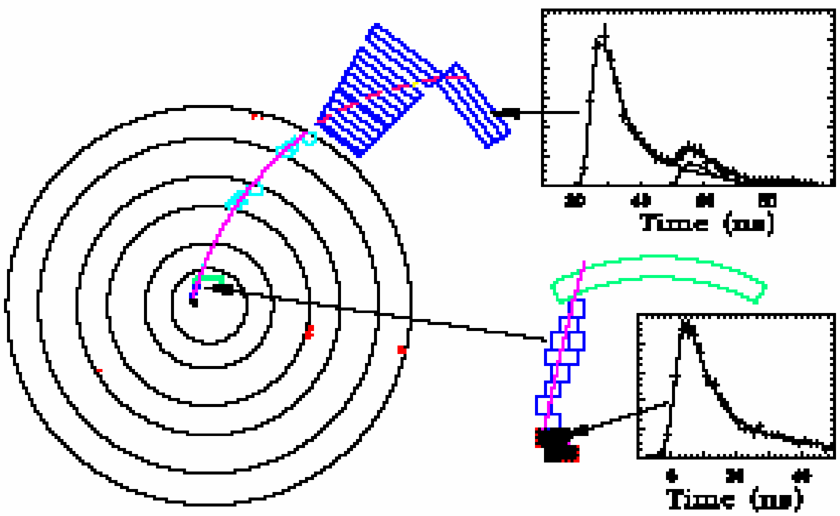
E787/949 Technique



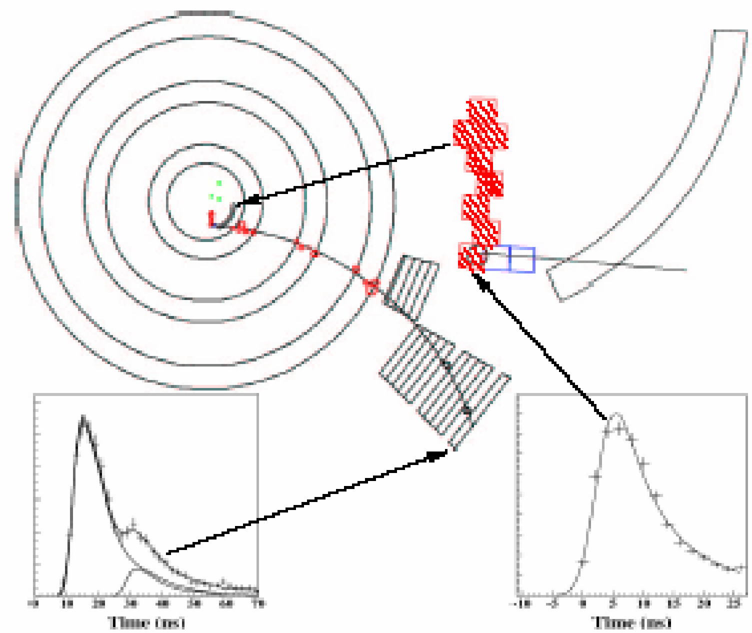
- Incoming 700MeV/c beam K^+: identified by Č, WC, scintillator hodoscope (B4). Slowed down by BeO
- K^+ stops & decays at rest in scintillating fiber target – measure delay (2ns)
- Outgoing π^+ : verified by IC, VC, T counter. Momentum measured in UTC, energy & range in RS and target (1T magnetic field parallel to beam)
- π^+ stops & decays in RS – detect $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ chain
- Photons vetoed hermetically in BV-BVL, RS, EC, CO, USPV, DSPV

E787 Events

Candidate E787A

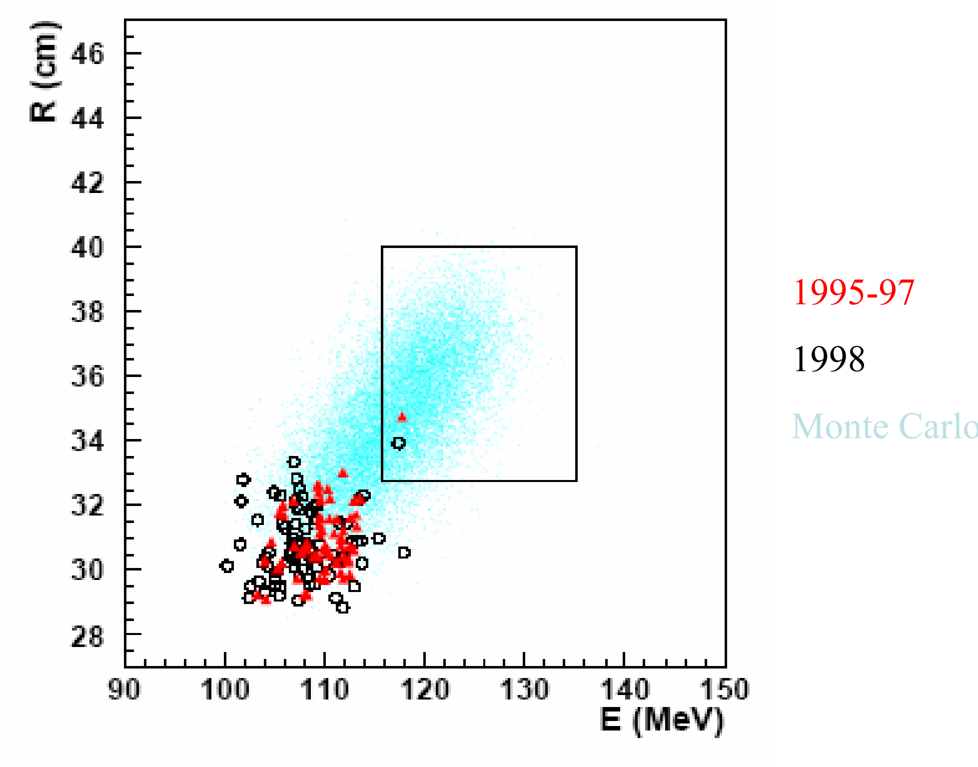


Candidate E787C

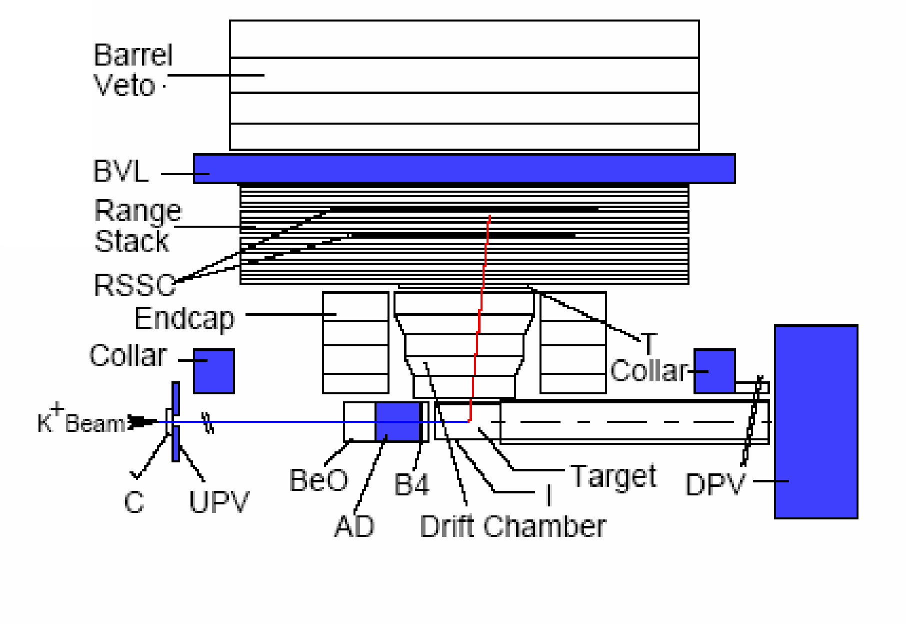


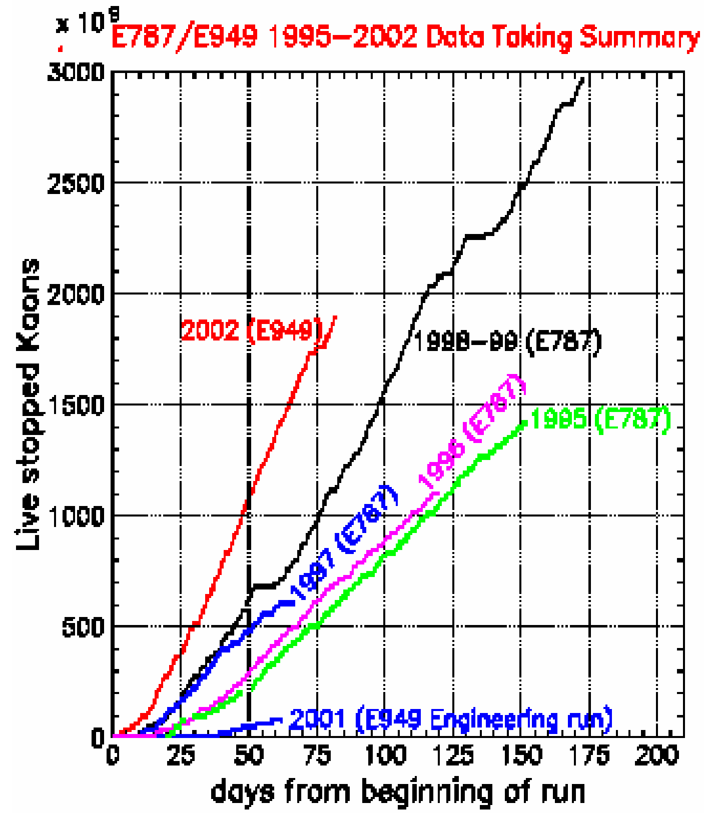
E787 Results

	PNN1	PNN2
P_π (MeV/c)	[211,229]	[140,195]
Years	1995-98	1996-97
Stopped K^+	5.9×10^{12}	1.7×10^{12}
Candidates	2	1
Background	0.15 ± 0.05	1.22 ± 0.24
BR($K^+\to\pi^+\nu\nu$)	$(1.57^{+1.75}_{-0.82})\times10^{-10}$	$< 22\times10^{-10}$ (90% CL)



E787 → E949



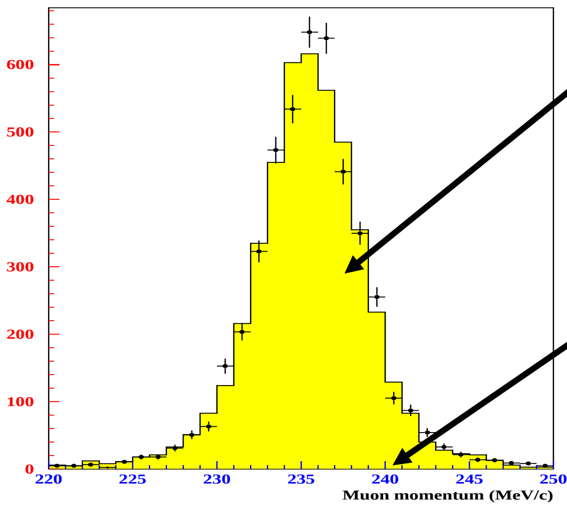


- Enhanced γ veto, beam instrumentation
- Much higher proton flux (65 TP)
- Improved tracking and energy resolution
- Higher rate capability due to DAQ, electronics and trigger improvements

- Lower beam duty factor (Siemans → Westinghouse)
- Lower proton energy (by 10%, cost 10% in flux)
- Problematic separators, worse K/π ratio (4 →3), fewer K/proton (factor ~1.5)
- **Total cost, factor 2**

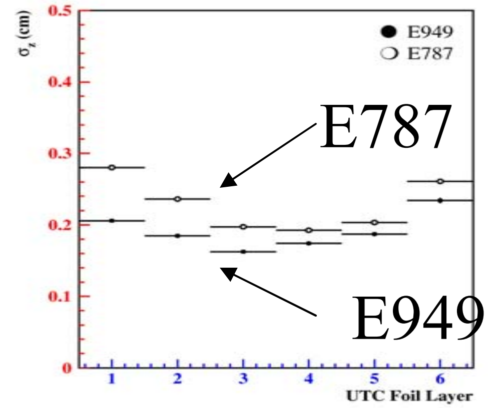
Upgrades in E949

μ^+ Momentum from $K^+ \to \mu^+ \nu$

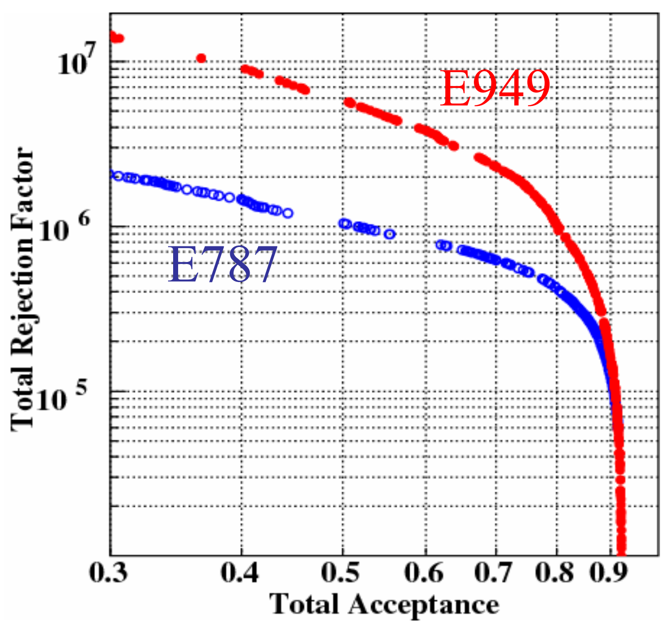


E949 at 2x inst. rate of E787

Improved UTC σ_Z

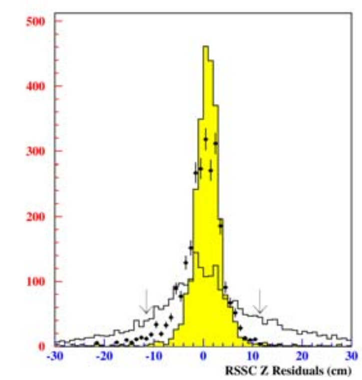


Range Stack Straw Chamber tracking Improved by 5 x

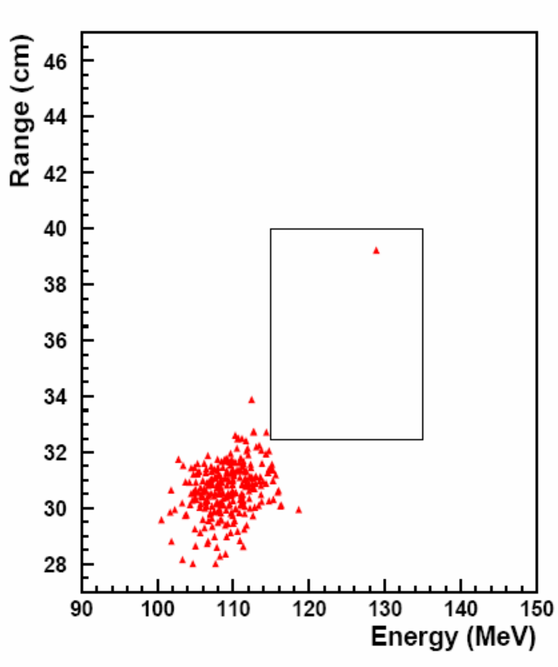


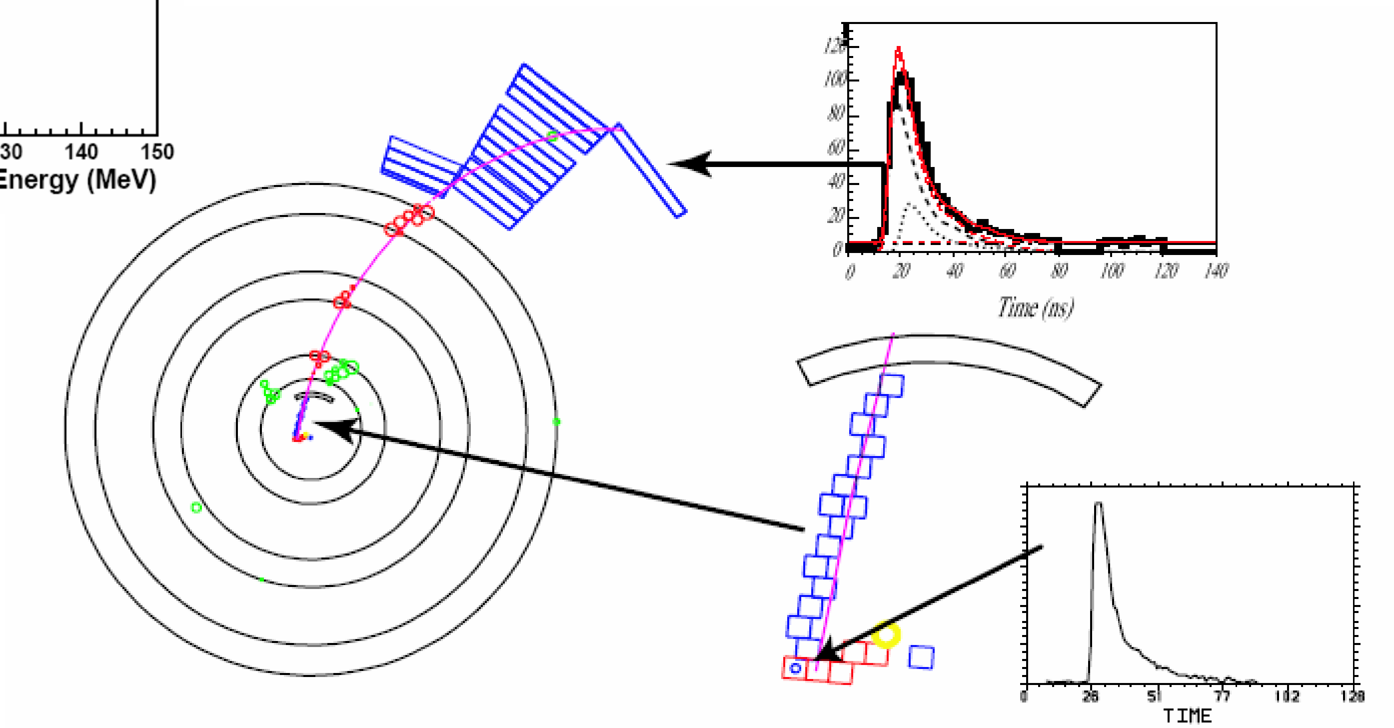
×2-10 better

π^0 efficiency

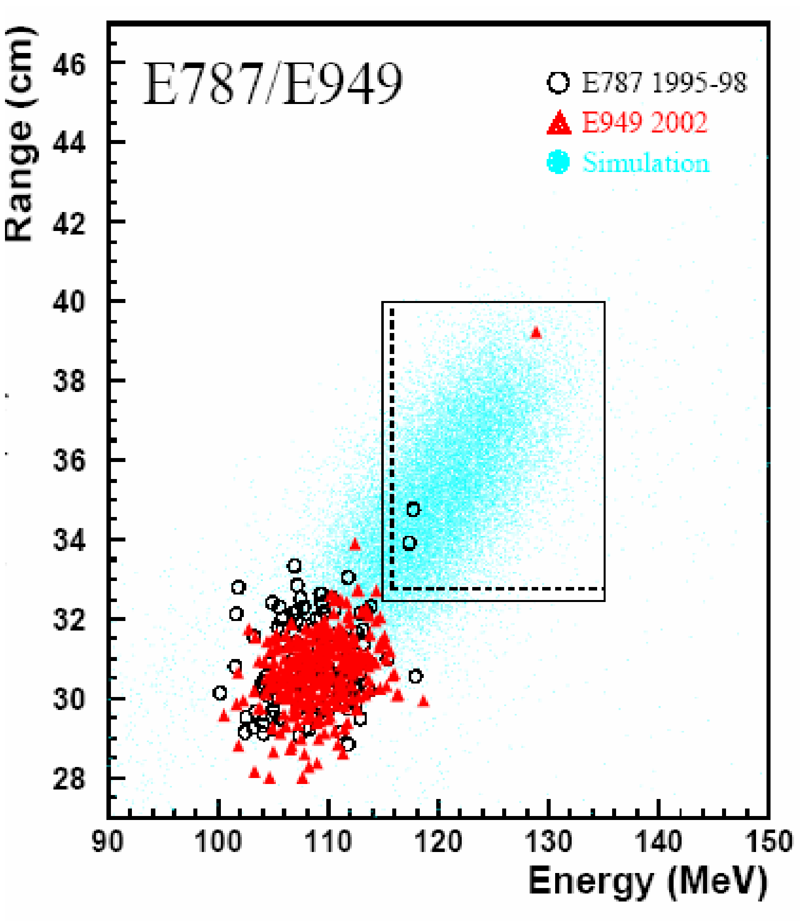


E949 Event


Range (cm)
46
44
42
40
38
36
34
32
30
28
90
100
110
120
130
140
150
Energy (MeV)


0
20
40
60
80
100
120
140
Time (ns)
0
26
51
77
102
128
TIME

Combined E787/949 Result



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

(68% CL interval)

E787 result:

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

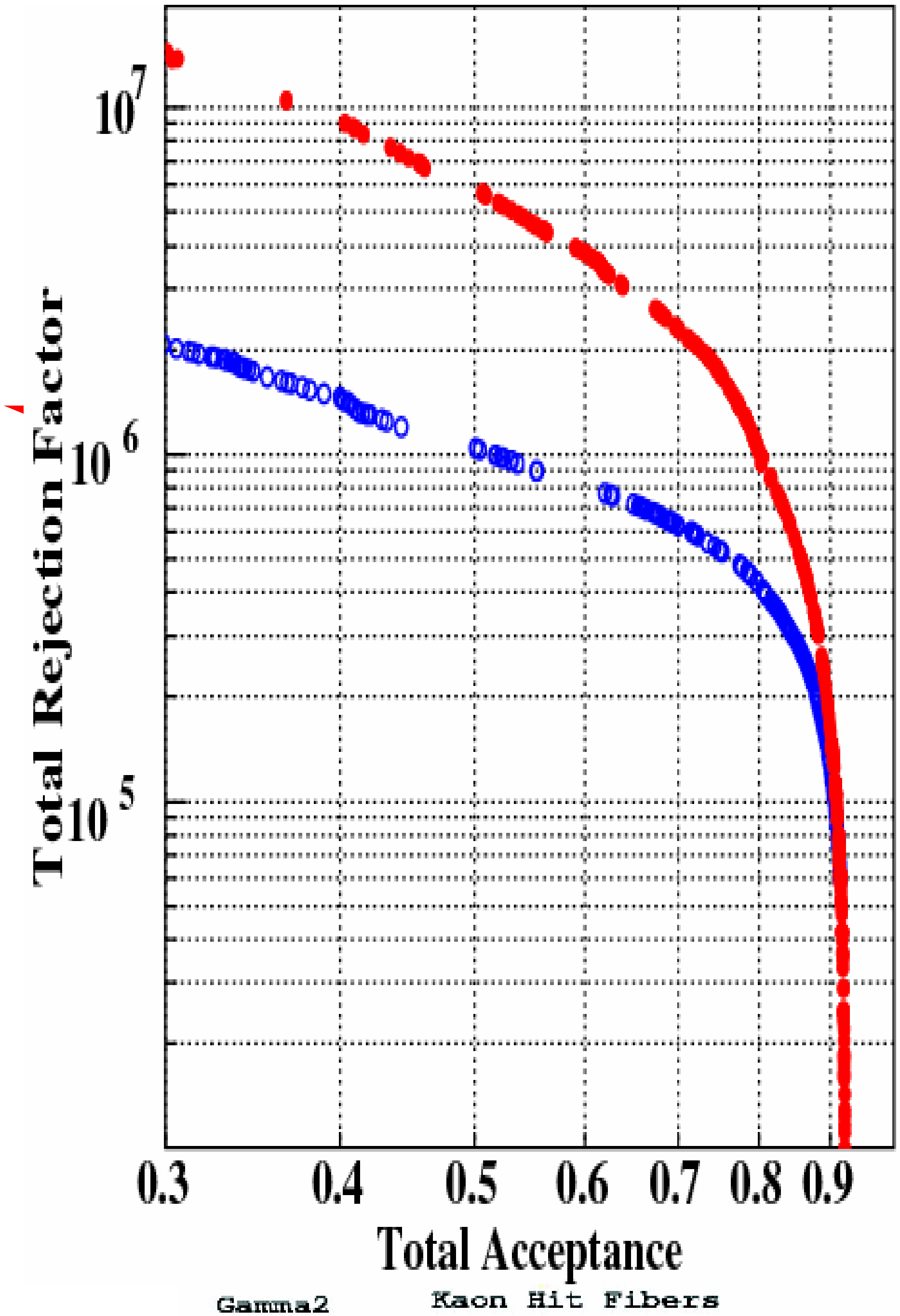
	E787		E949
Stopped K$^+$ (N_K)	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
S.E.S.	0.8×10^{-10}		2.6×10^{-10}
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
$W_i \equiv \frac{S_i}{S_i+b_i}$	0.98	0.88	0.48

pnn2

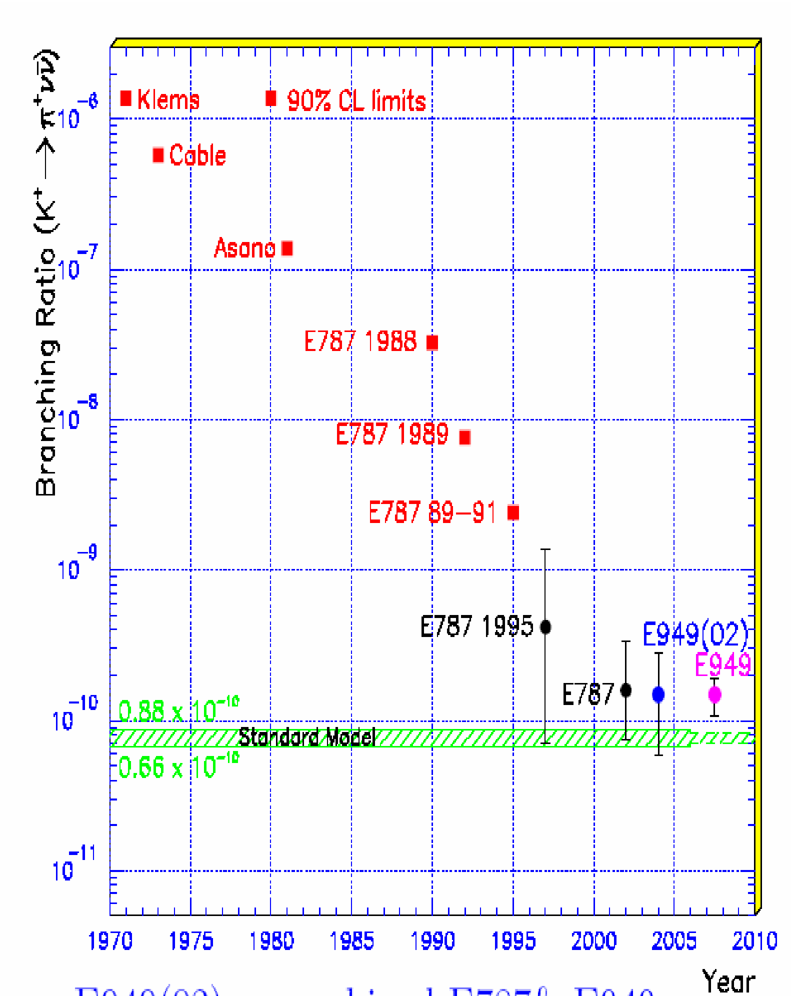
- Acceptance larger than for pnn1 (in principle)
- E787 bkgnd-limited at $\sim 10^{-9}$, another factor 10 needed to get to S:B ~ 1

- Main background from Kπ2 w/nasty correlation

- Improved photon vetoing in E949 very encouraging.
- Answer expected in a few months.



Status & prospects for 949



E949(02) = combined E787& E949.

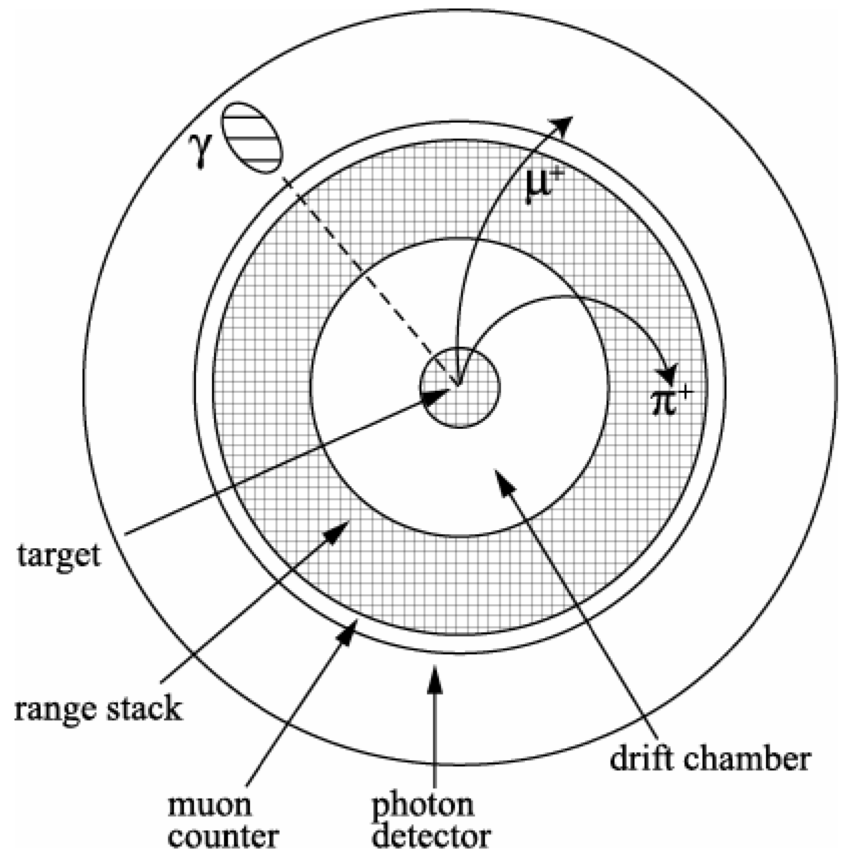
E949 projection with full running period.

- 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
- Currently seeking NSF support

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 beamline
  - place on the floor
  - $ for detector



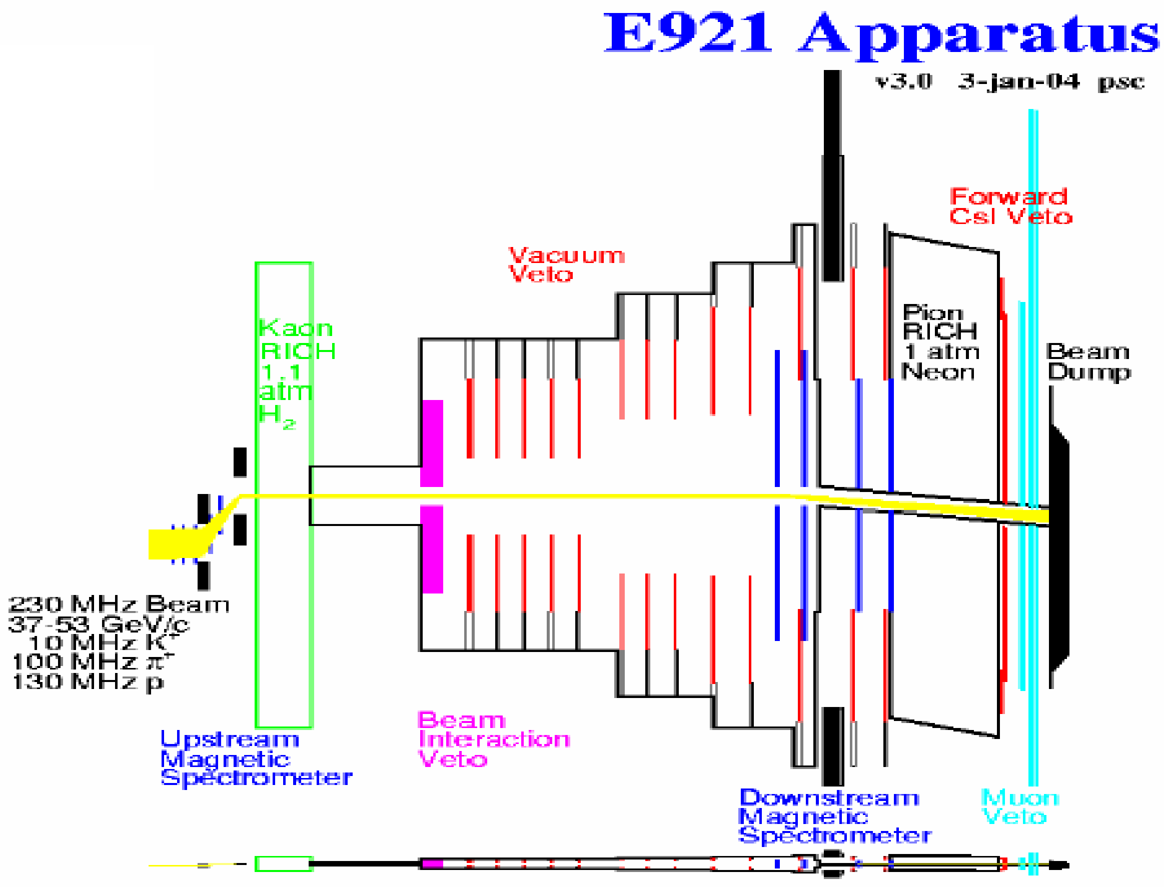
Pros & cons of stopped-K technique

- PROs
  - Long history
    - The enemies are known
    - Well-honed methods
    - S/B good enough!
  - Effective particle ID
  - Easy to be hermetic
  - Very pure beam
  - In CM right away
  - Clean separation of kinematics/part-ID

- CONs
  - Decay in matter
    - Nuclear effects
  - Require π's to stop
  - ID sensitive to rates
  - 3 timescales (up to μs)
  - Need low veto thresholds
  - Limited K flux
    - Most K's interact (typ 4/5)
  - Correlation of detector geometry w/CM system

Fermilab in-flight initiative

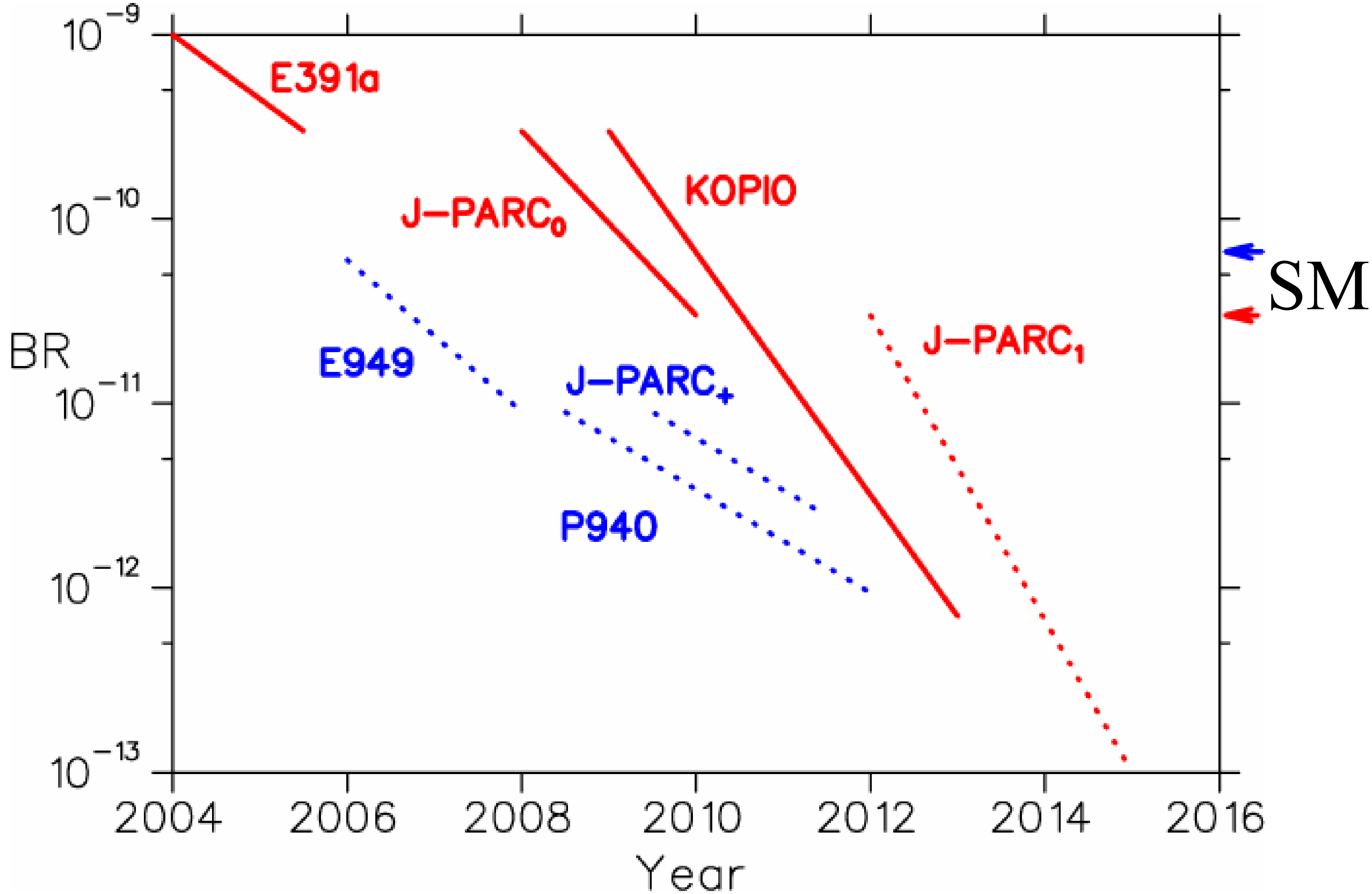
- Unseparated beam
  - 10MHz K^+/230MHz
  - 1cm $\times$ 1cm
  - 37-53 GeV/c
  - 17% decay
- K & π spectrometers
- RICH particle ID
- μ & γ vetoes
  - $10^{-6}/\gamma$
- pnn1 & pnn2
- 100 evts/2 years/10^{-10}
- Hope to run by 2009



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

- 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
    - Plenty of room for improvement!
  - Could ***really know*** if 50-100 events possible

World enough & time for K→πνν



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

In *SM*, gives the same info as $K_L \to \pi^0 \nu \bar{\nu}$

KTeV obtains 90% CL upper limits

$B(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$

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

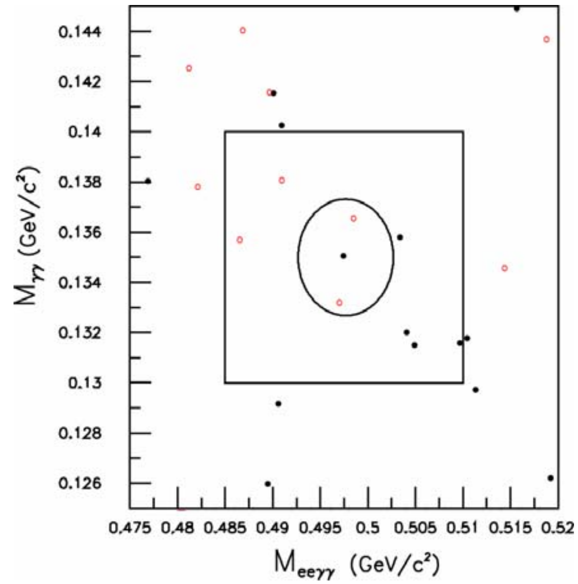
- already see background from $K_L \to \gamma\gamma\ell^+\ell^-$ at level 10× SM

This, + complicated interplay of CP-conserving & state-mixing contributions tends to discourage people.

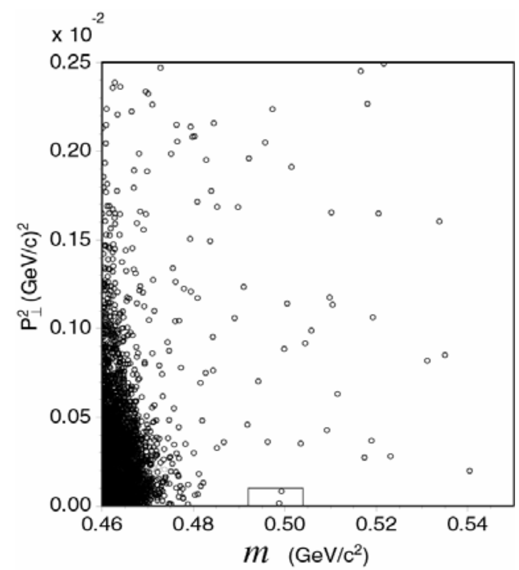
But recent experimental and theoretical progress here.

New mindset may be justified!

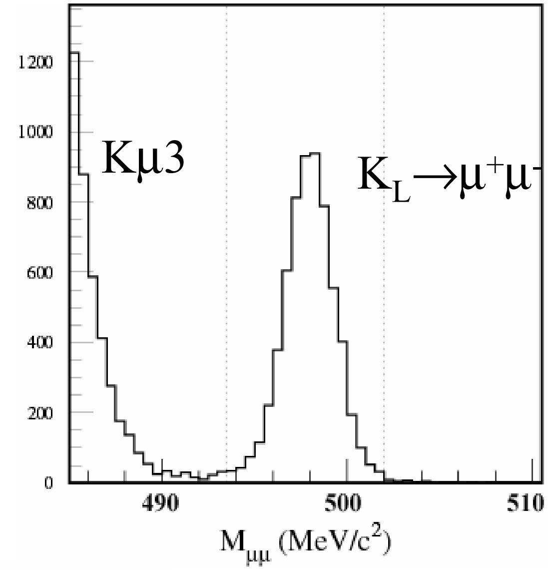
$K_L \to \pi^0 e^+ e^-$
'97+'99



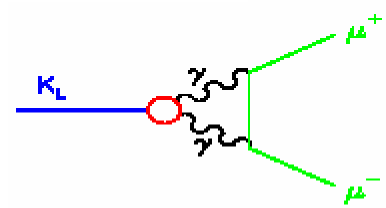
$K_L \to \pi^0 \mu^+ \mu^-$
'97



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



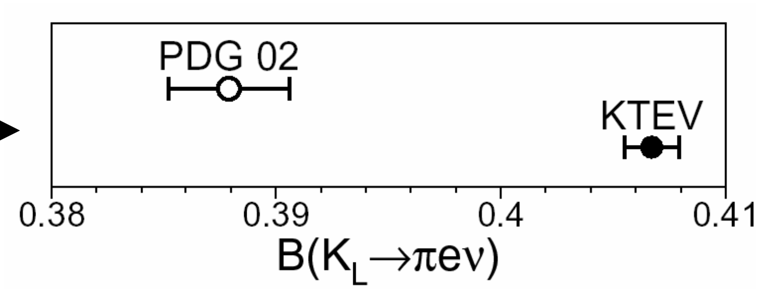
- $B_{SD}(K_L \to \mu^+\mu^-) \propto (\bar{\rho}^0 - \bar{\rho})^2$
- Potentially good source of info on $\bar{\rho}$
- Also possible BSM contributions
- Clean experimental result with 6000 evts



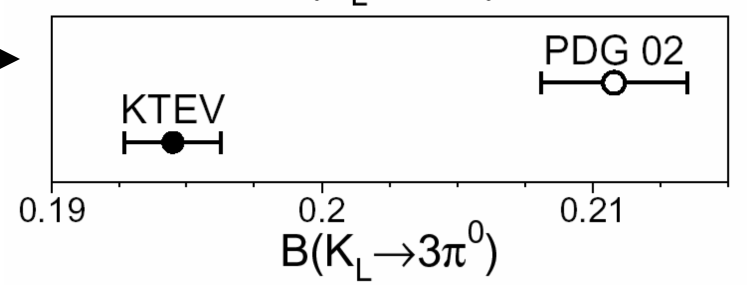
- **But** BR dominated by abs contrib:
  - >5× larger than SD
  - can be measured from $K_L \to \gamma\gamma$
  - uncertainty > that on $K_L \to \mu^+\mu^-$) meas.
- Subtraction can be addressed by other BR meas.
- **But** LD dispersive contribution of similar size to SD
  - interferes with SD
  - can get information from $K_L \to \ell^-\ell^+\gamma$, etc.
  - good progress, **but** would need 1000 × KTeV to go further
  - in the hands of theorists
- Better precision would be hard to get.

Do we need multiple experiments?

- If we can't get a 4×10^{-1} BR right to 5%



- & we can't get a 2×10^{-1} BR right to 8%



- Are we really going to get a **few × 10^{-11}** BR right to 10% the first time?

Conclusions

- $K^+ \to \pi^+ \nu\bar{\nu}$ seen, BR 2ce SM, but consistent with it
  - Could go at least 10× further with same technique
  - Initiative to go 100× further with in-flight technique
- $K_L \to \pi^0 \nu\bar{\nu}$ experiment aiming to w/i factor 10 of SM level, w/i some BSM predictions
  - Two initiatives to go >100× further
- Situation rife with uncertainty!
  - J-PARC accelerator will be there, but experiments?
  - Is FNAL really in the game?
  - BNL $K^+ \to \pi^+ \nu\bar{\nu}$ experiment stalled by DOE, future unclear
  - BNL $K_L \to \pi^0 \nu\bar{\nu}$ experiment probably has best prospects but not guaranteed (US Senate not helpful)

Gratuitous Advice

- Don’t worry too much about what others will or won’t do.
- If you are going to do it, don’t scrimp!
- Allow enough running time (years) for development, mid-course corrections, upgrades, and learning as you go.