Challenges for Rare Kaon Experiments

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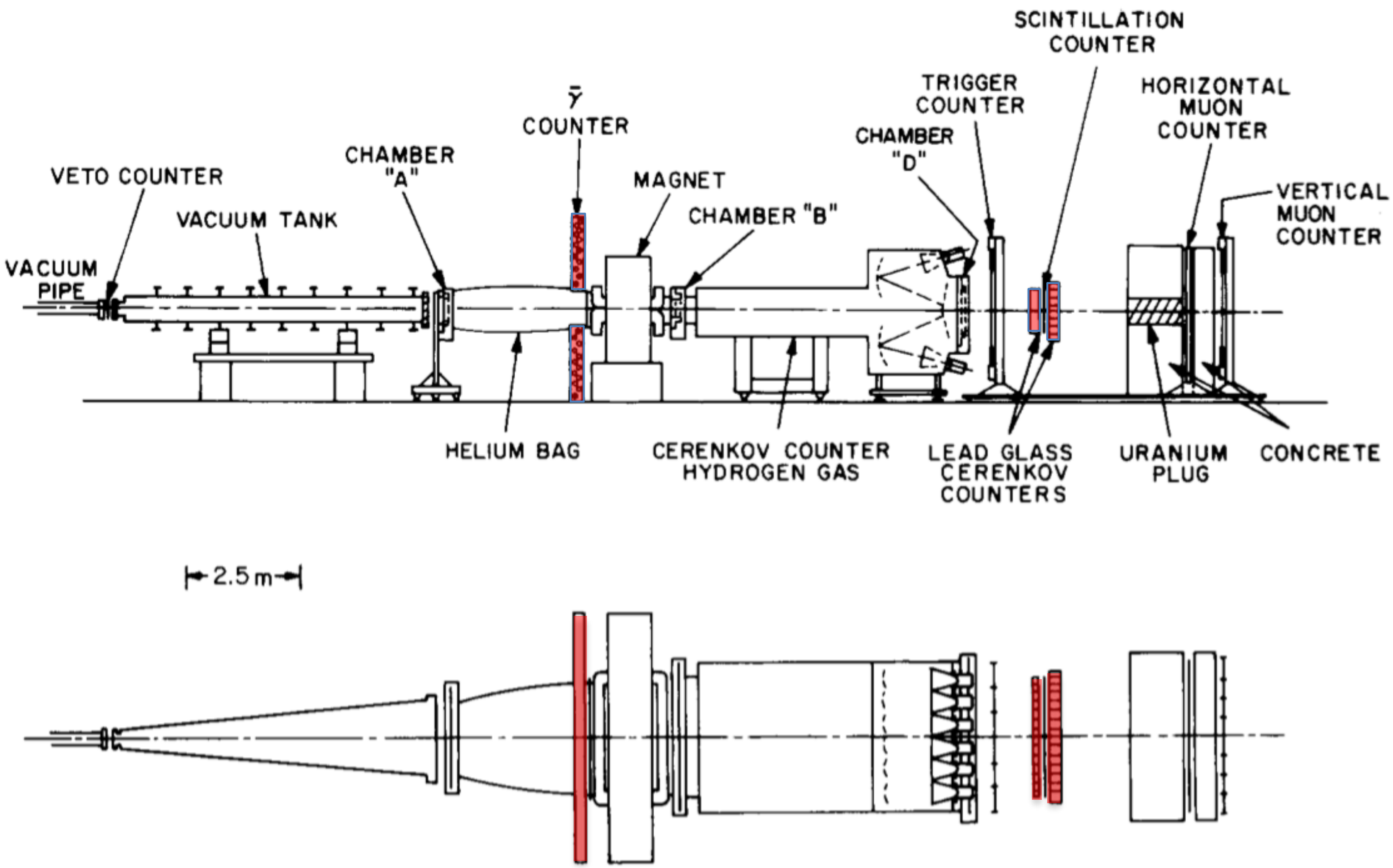
In spite of the instructions, a little history

- I came to Brookhaven 40 years ago to work on a study of $K_L \to \pi^+\pi^-\gamma$ & other radiative decays:



Most of the apparatus was recycled

- A famous experiment to hunt for $K_L \rightarrow \mu^+\mu^-$

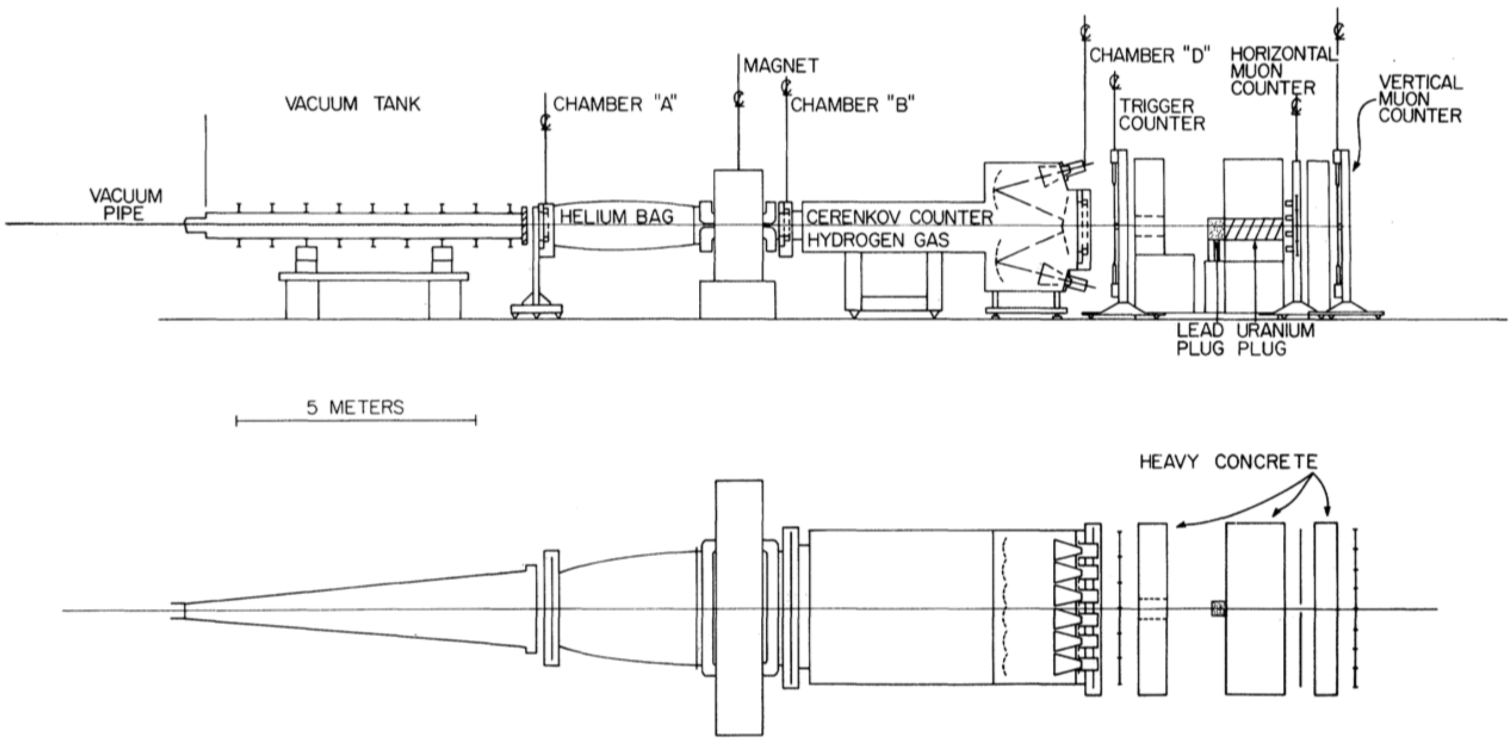
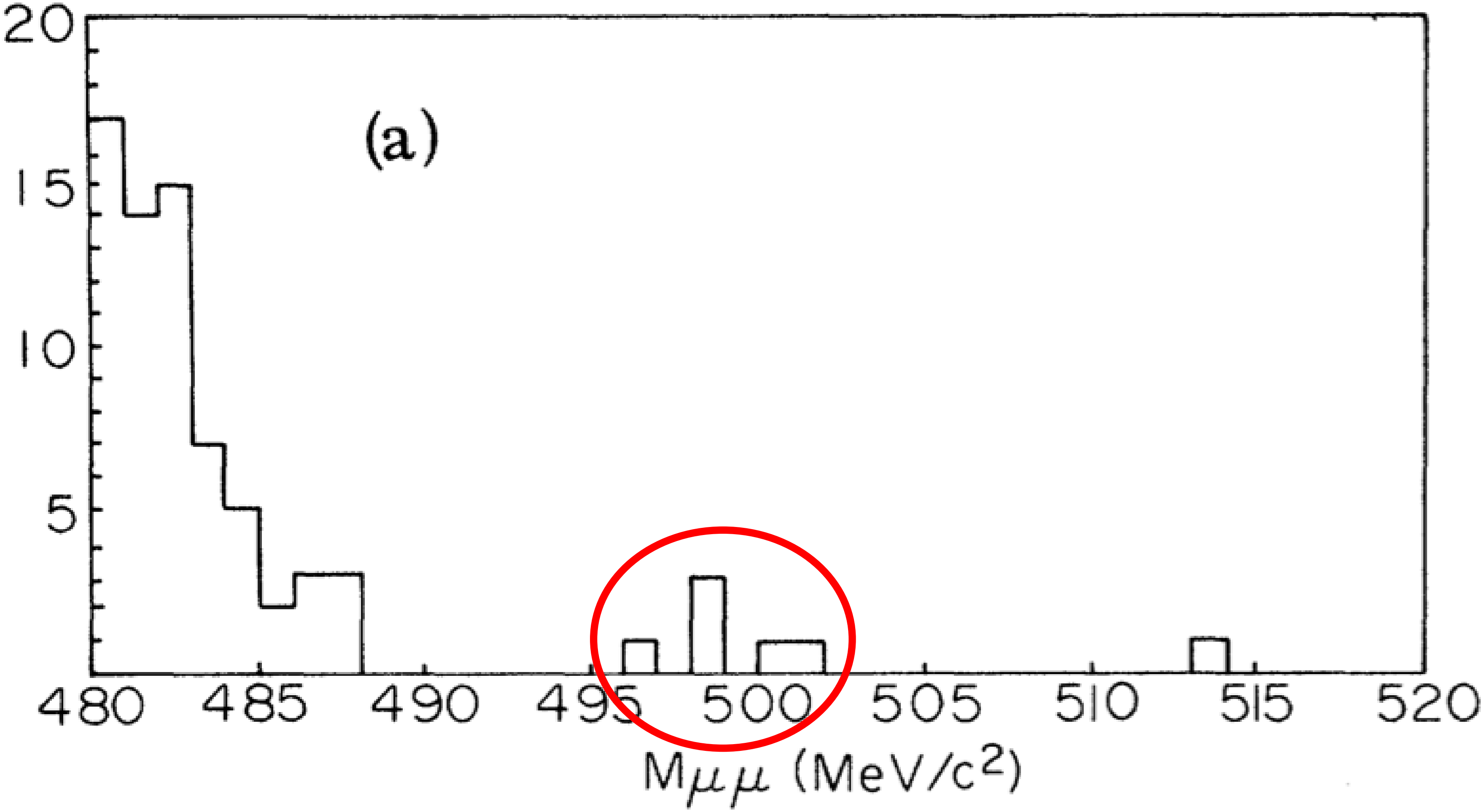


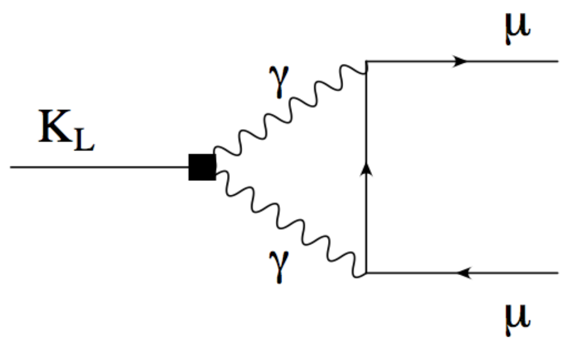
FIG. 1. Layout of the apparatus. MWPC's are chambers "*A*," "*B*," and "*D*."

And found it



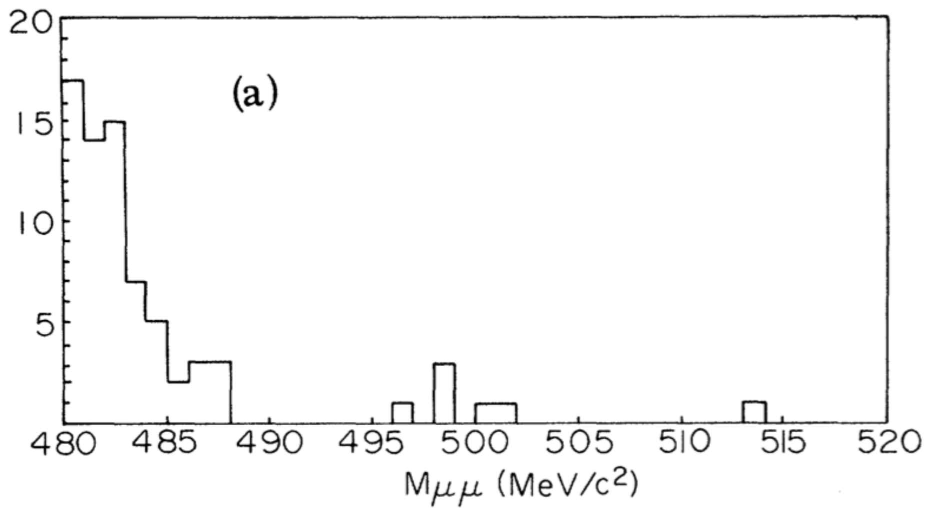
Why did anyone care?

- People knew that $K_L \to \mu^+\mu^-$ was an important test of weak neutral currents, moreover it was experimentally tractable.
- There was a "unitarity" contribution from an intermediate $K_L \to \gamma\gamma$ decay which put a floor on how far down one could chase such effects



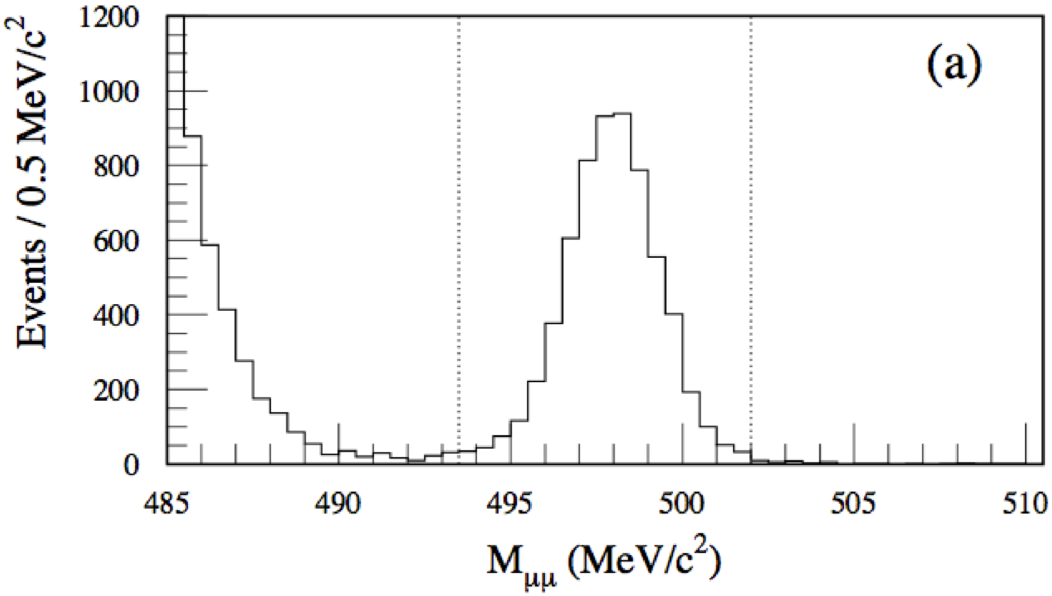
- So they were trying to measure the excess above this floor ($\sim 6 \times 10^{-9}$).
- But the first experiment with the sensitivity to see this claimed the BR was less than $\sim 2 \times 10^{-9}$. They couldn't see it at all!
- Got theorists quite excited.

So the 6 events brought everyone back to earth



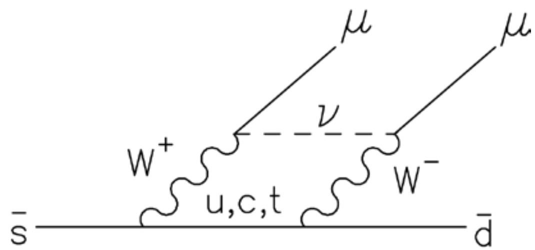
The BNL experiment of Dave and others found an answer about twice the unitarity limit but consistent with it

25 years later another BNL experiment produced 1000 times as many events!



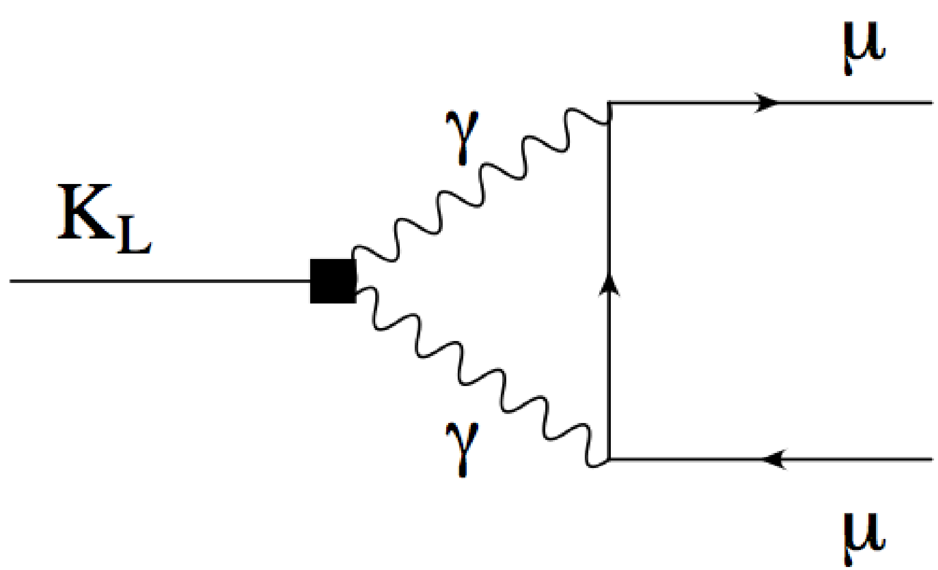
Why were people still doing this 25 years later?

- There was a very well-calculated electroweak SM contribution. It was sensitive to Re(λ_t).



- After B factory determinations of the CKM parameters, $K_L \to \mu^+\mu^-$ it remained quite useful for BSM hunts.
- Many possibilities were ruled out by the high precision measurement
- But the unitarity contribution limits what one can do with this result.

Murphy’s Law for Rare K Decay



The fundamental irony of rare kaon physics:
The very interactions that make the the process detectable, introduce obfuscating long-distance effects!

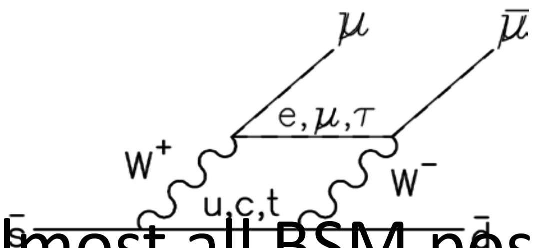
Aside from the previously mentioned absorptive part that is many times larger than the SM short-distance contribution there’s a hard-to-calculate dispersive component that can interfere with it.

A long distance to go

- We start off with the 6200 event experiment.
- The absorptive piece can be well-determined by measuring $K_L \to \gamma\gamma$
  - But it turns out to be ~95% as large as the total measured rate!
  - Subtracting it gives $B^{disp}(K_L \to \mu^+\mu^-) = (3.2 \pm 1.2) \times 10^{-10}$
  - A number ~20 times smaller than the absorptive part
  - And ~3 times smaller than SM fits to the short-distance part! This suggests the dispersive part has the opposite sign wrt the SM one-loop contribution
- This corresponds statistically to a 7 event experiment! Nature is a real killjoy.
- And this is before trying to untangle the dispersive interference.
  - Where there's agreement from all sectors of the theory world that this is very difficult!
- Further improvement in reach very slow with increasing statistics

This led in another direction

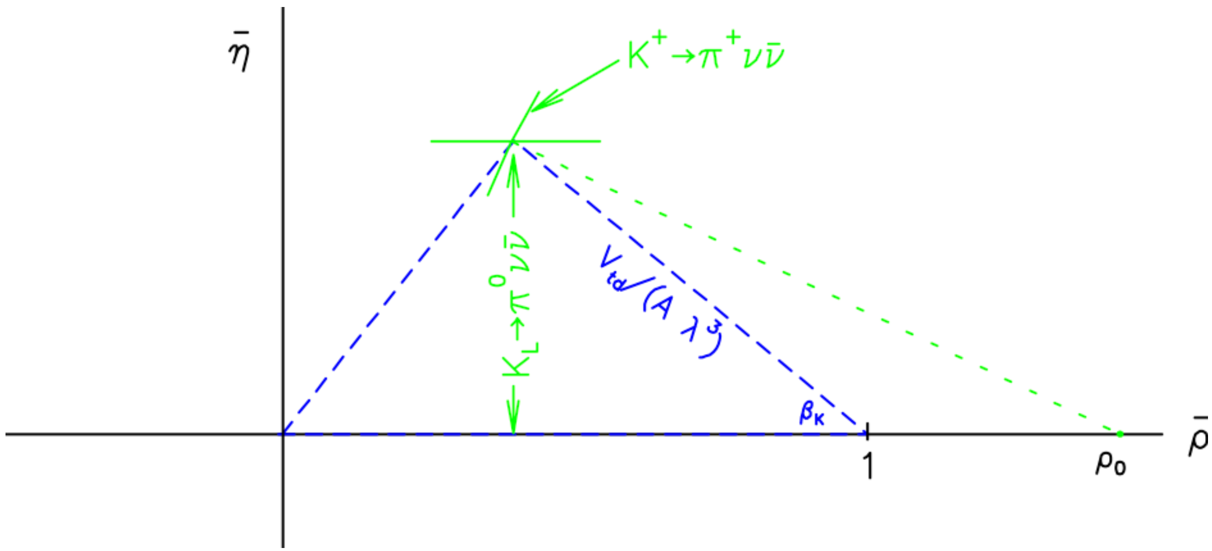
- Look at the one-loop diagrams.
- A simple rearrangement kills the long-distance pieces



- True for almost all BSM possibilities
- But you pay the devil’s bargain – you end up with three-body decays, two of which are undetectable.
- This presents the challenges of the title.

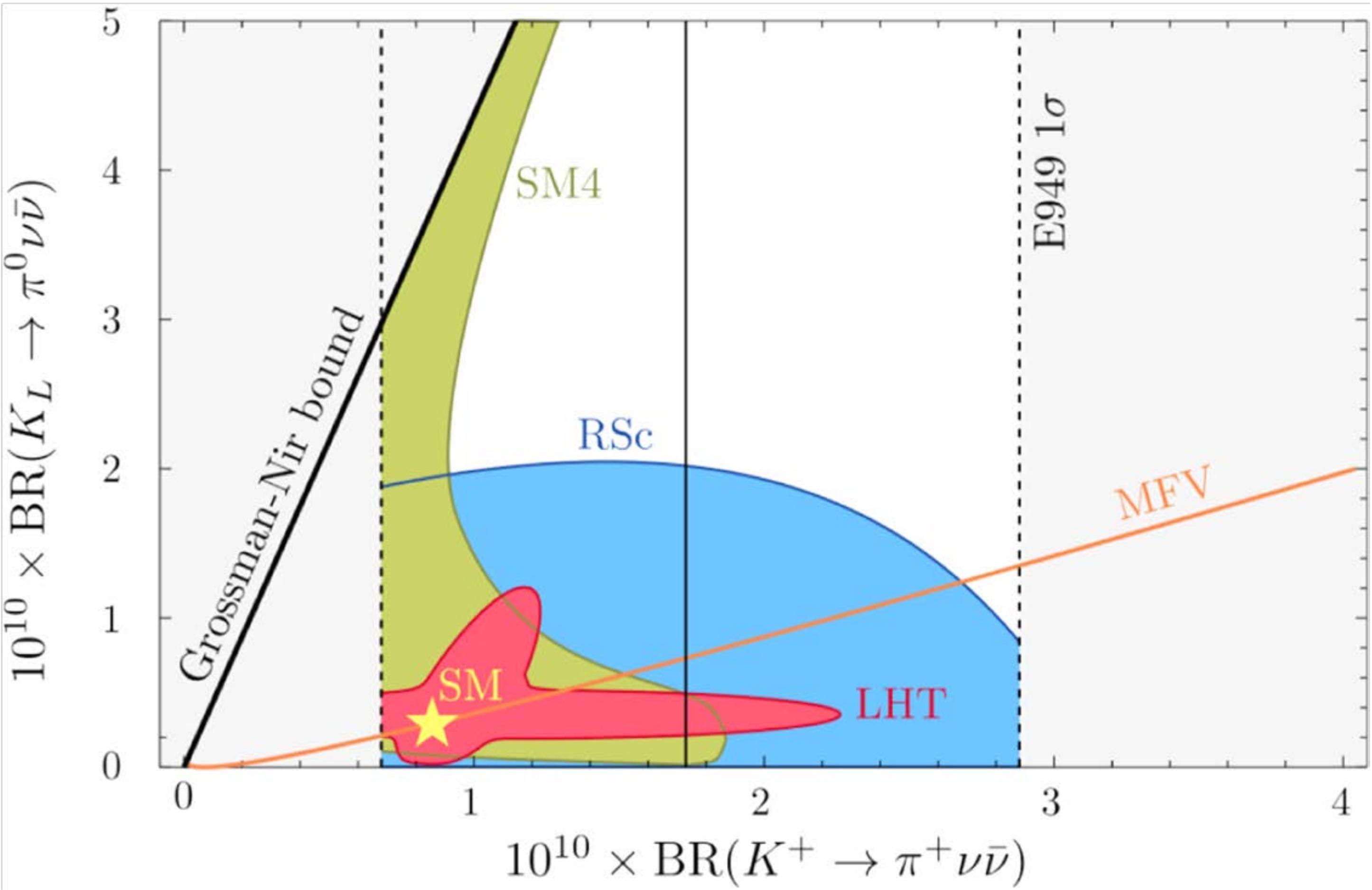
The "Golden" Channels

- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L \rightarrow \pi^o \nu\bar{\nu}$
- In the SM



- In virtually all BSM schemes, these are proportional to the modulus and imaginary part of the same amplitude.
- Recent candidates appear on the next slide.

Golden Territory

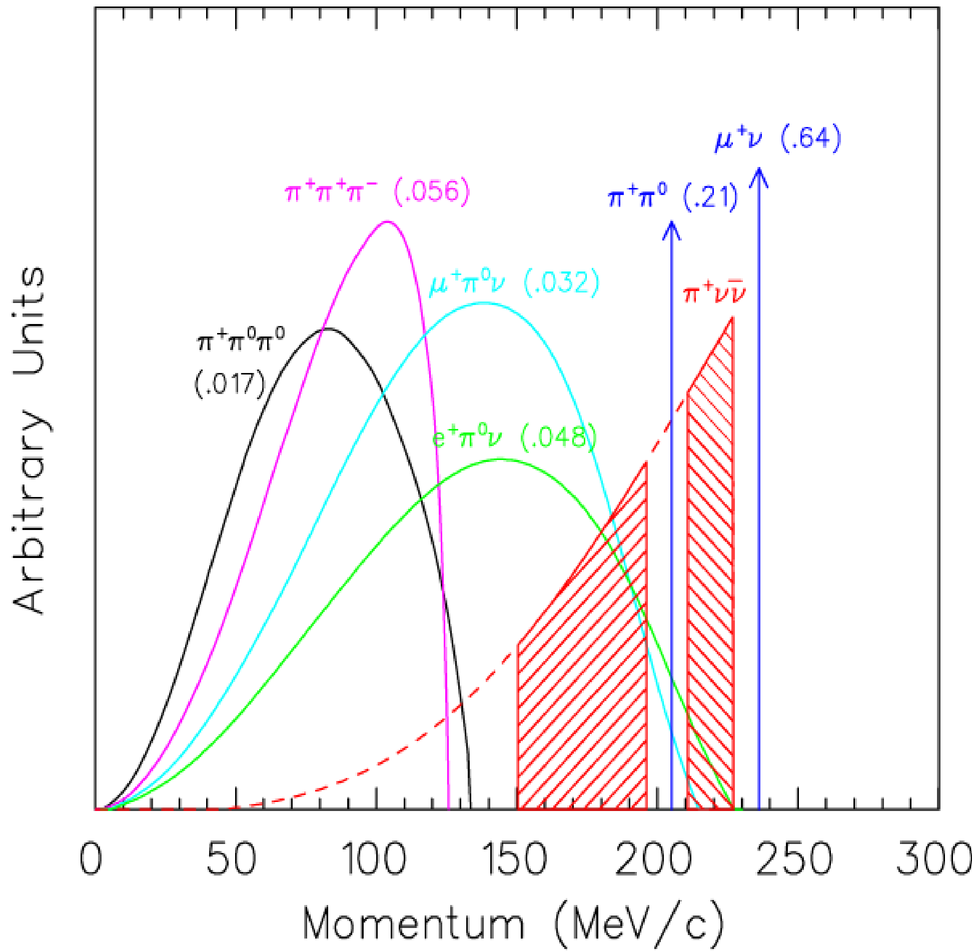


The Experimental Challenges

- The SM-predicted branching ratios are ~3×10^{-11} and 8×10^{-11} for the neutral and charged decays respectively. This means that high rate conditions will obtain.
- The kinematic signature is very poor - basically a range in CM energy for a single (of three) particles.
- The visible particle is a very common product of K decay.
- One is forced to prove a negative, *i.e*. that the decay was not something other than the signal. A great premium on vetoing (tends to be lossy at high rates).
- The only reason such experiments are possible is that the leading backgrounds are two-body decays with rather good signatures.

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:
  - $K^+ \to \mu^+ \nu(\gamma)$
  - $K^+ \to \pi^+ \pi^0$
  - $K^+ \to \pi^+ \gamma\gamma$ in pnn1 @ 10^{-6}
  - $K^+ n \to K^0 p$; $K_L \to \pi^+ \ell^- \nu$, lepton missed
  - Beam
    - Beam π^+ mis-ID as K^+, then fakes K decay at rest or at high energy scatters into the detector.
    - K^+ decay in flight
    - 2 beam particles



Just Say ‘No’

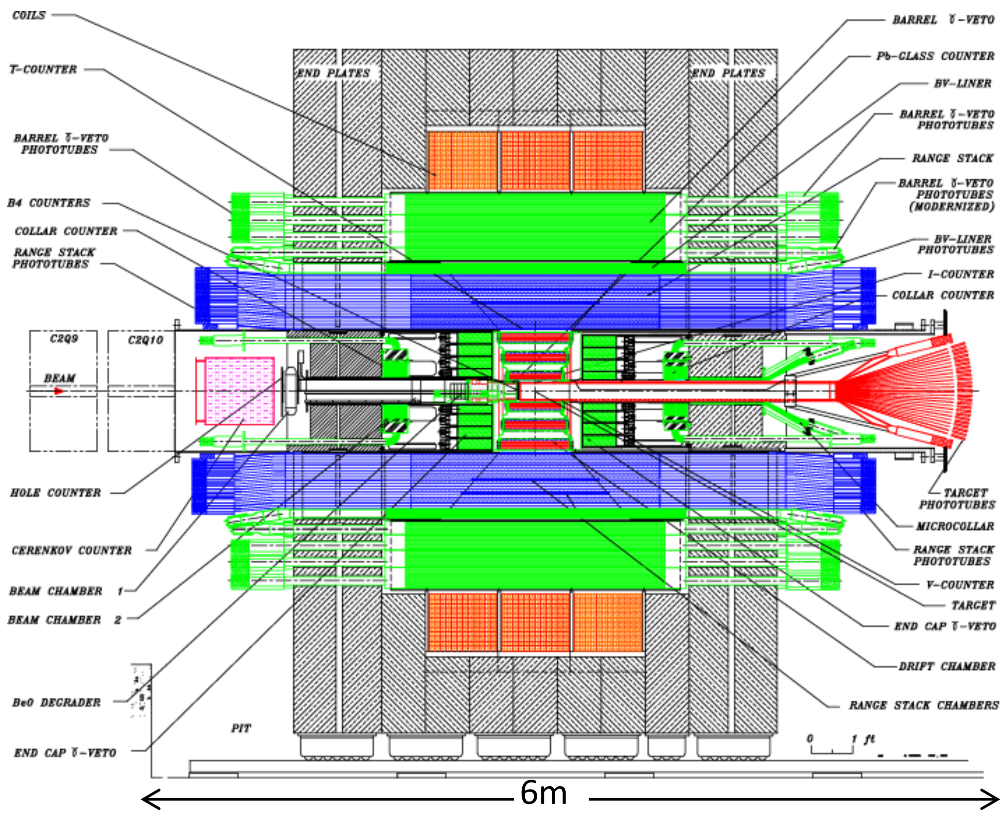
- Since negative information so important in dealing with these modes, vetoing extra decay products comes to the fore.
- This tends to be more important in rare-decay experiments than in say collider experiments.
  - Thus for example calorimeters used only for vetoing may be optimized differently from those used to measure particle characteristics, although in some experiments (*e.g.* neutral K) the calorimeter may serve both functions.
- Even charged particle vetoing can be difficult at the level required.
- Vetoing at high rates tends to be lossy.
  - The one series of experiments that actually observed any of these decays, E787/949, had acceptances in the 0.25% ball park.
  - Thus better time resolution could improve matters.
  - But sometimes even that runs into a brick wall – if the only visible indication of a photon is a neutron that wafts across the apparatus for 10ns, your hard-fought 1ns resolution is confounded.

What else can you do?

- You can reduce the rates
  - Use a separated charged K beam
  - Filter the neutral beam for the K_L case
- Other methods of rejecting the background
  - Particle ID – factors of $\varepsilon\,10^5$ can be required
  - Kinematic recognition – here's where resolution helps
- In both endeavors your enemy is tails – when you need one of these techniques to recognize 999,999 out of 1,000,000 cases, you run into non-gaussian phenomena.
- You must also nail the background size
  - Need to find non-correlated techniques of background rejection, e.g. vetoing of photons from $K^+ \rightarrow \pi^+\pi^0$, and kinematic ID of the π^+
  - Sometimes you have to settle for small, well-understood correlations.
  - Use Monte Carlo judiciously

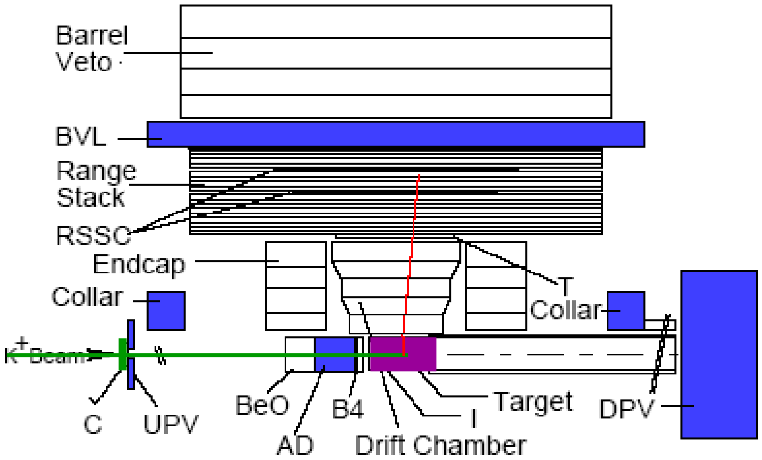
Approach #1 – Low Energy

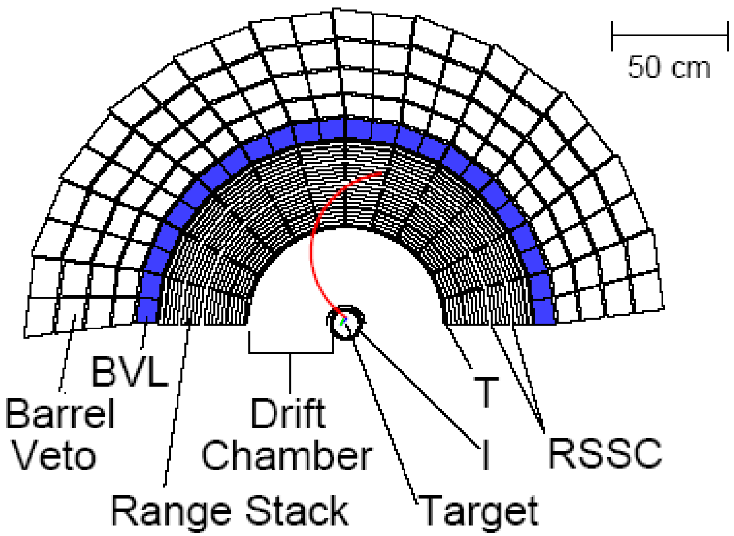
- Pure beam of K's, easier to approach hermeticity, certain kinematic gifts, some very effective particle ID techniques



- End up with something that looks like a collider detector – only 30 million times lower energy than at the LHC

E787/949 Technique

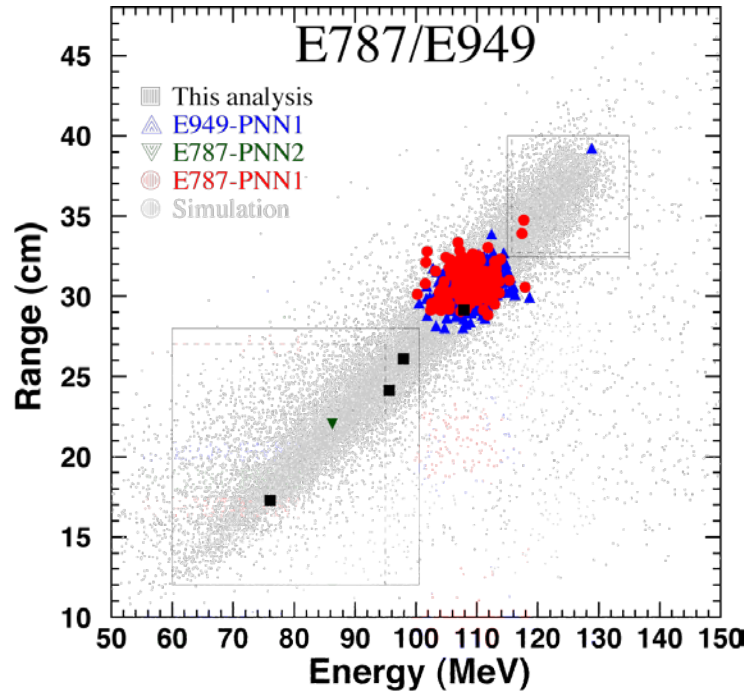


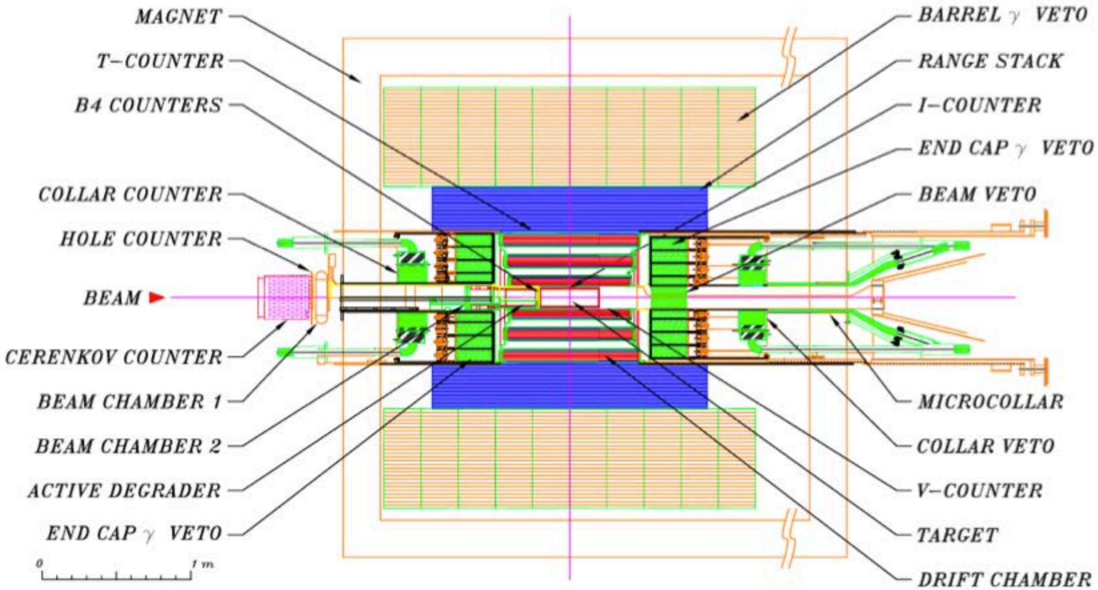


- Incoming 700MeV/c K^+: identified & tracked by beam instrumentation. Slowed by energy loss in a BeO "degrader"
- K^+ stops & decays at rest in scintillating fiber target – wait 2ns to make sure
- Outgoing π^+: verified by counters. Momentum measured in small drift chamber, energy & range in target & RS (1T magnetic field parallel to beam)
- π^+ stops & decays in RS – detect $\pi^+ \to \mu^+ \to e^+$ chain
- Photons registered by all systems so events can be eliminated

Past & Future of Stopped K^+ Version

- E787/949 series of experiments over 15 years yielded 7 events PLUS very good understanding of technique





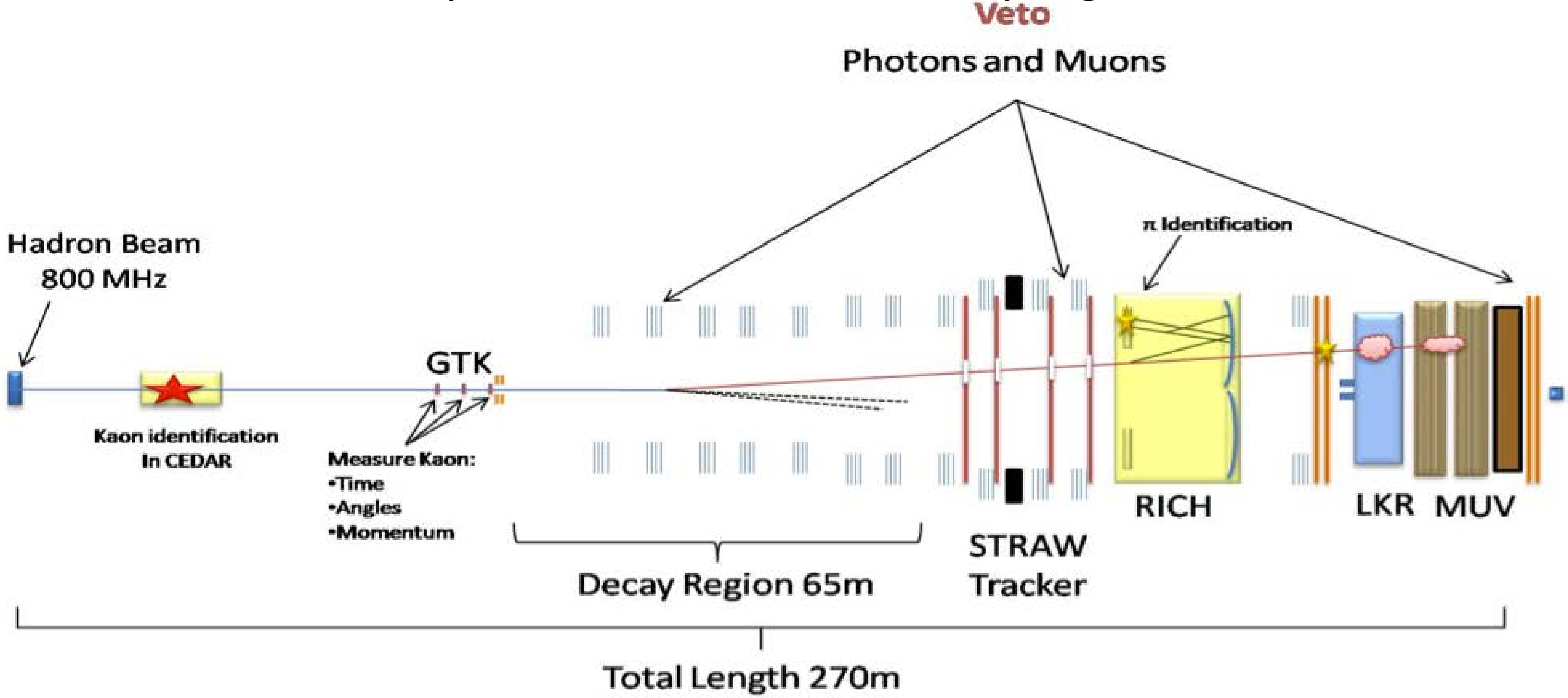
- Leads to the 1000-event ORKA proposal at Fermilab

What detector improvements could help?

- More efficient photon vetoes, especially at very low energy
- Better charged track timing – would allow another handle to separate π's from μ's.
- Better photon timing – would cut down on random veto losses
- Massless photodetectors – would allow 2-end readout of the stopping target
- Massless coating of target elements – coating would also need to reflect UV light.

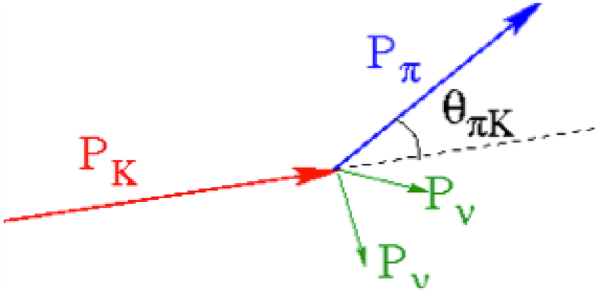
Approach #2 – High Energy (In-Flight)

- Most extra tracks easier to detect and thus veto. High energy particle ID techniques available. In the current example the beam is unseparated so rates are really high.



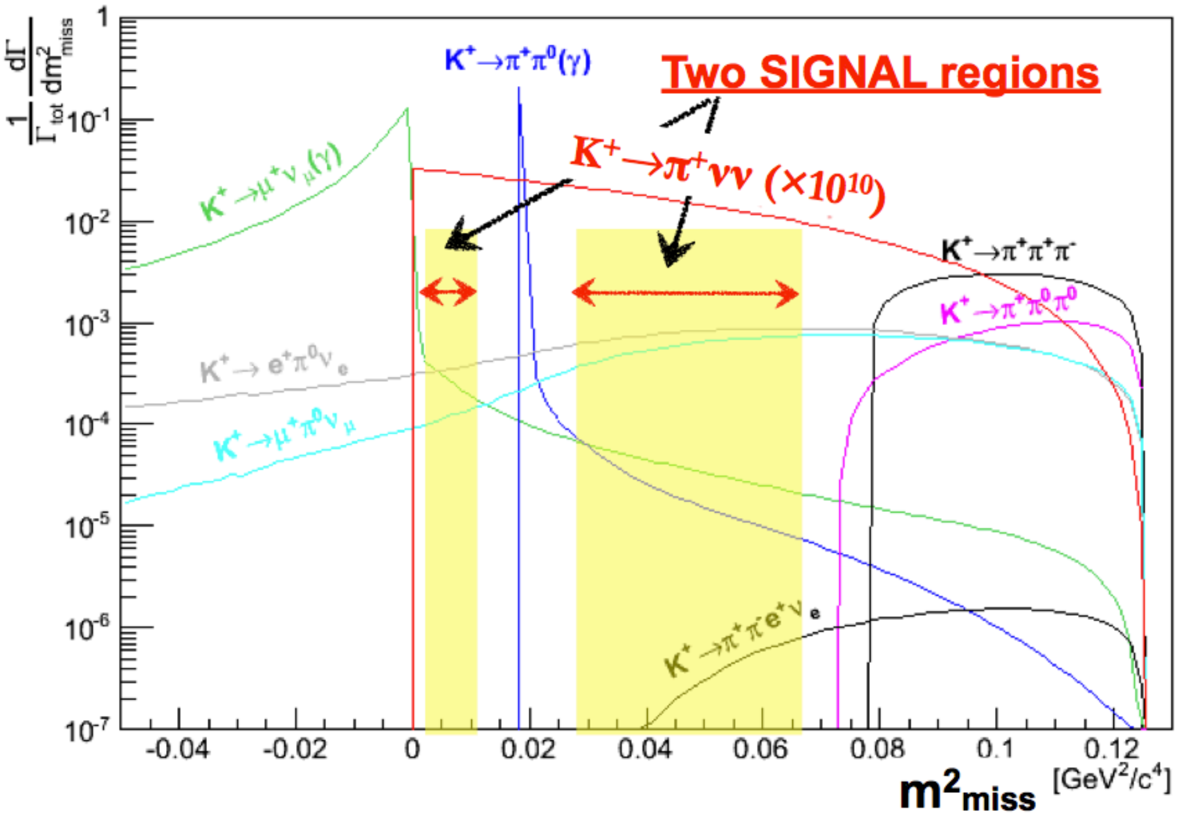
- CERN NA62 – 100 event experiment – physics data in 2015

NA62 Signal & Background



In-flight use $m^2_{miss} \equiv (P_K - P_\pi)^2$

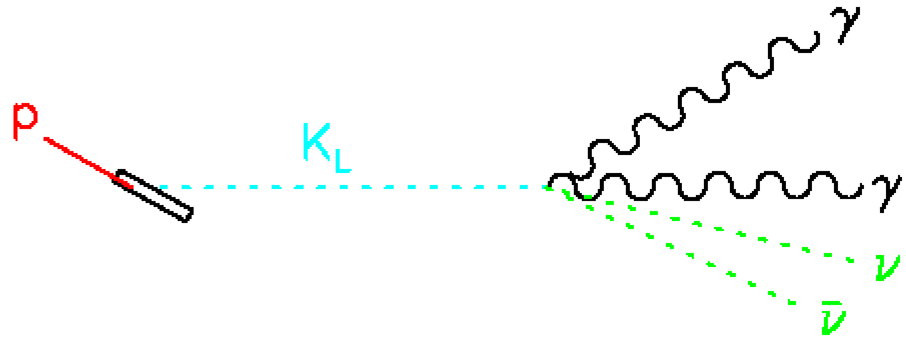
$K\pi_2$ comes at $m^2_{miss} = m_\pi^2$
$K\mu_2$ comes near $m^2_{miss} = 0$



What detector improvements could help?

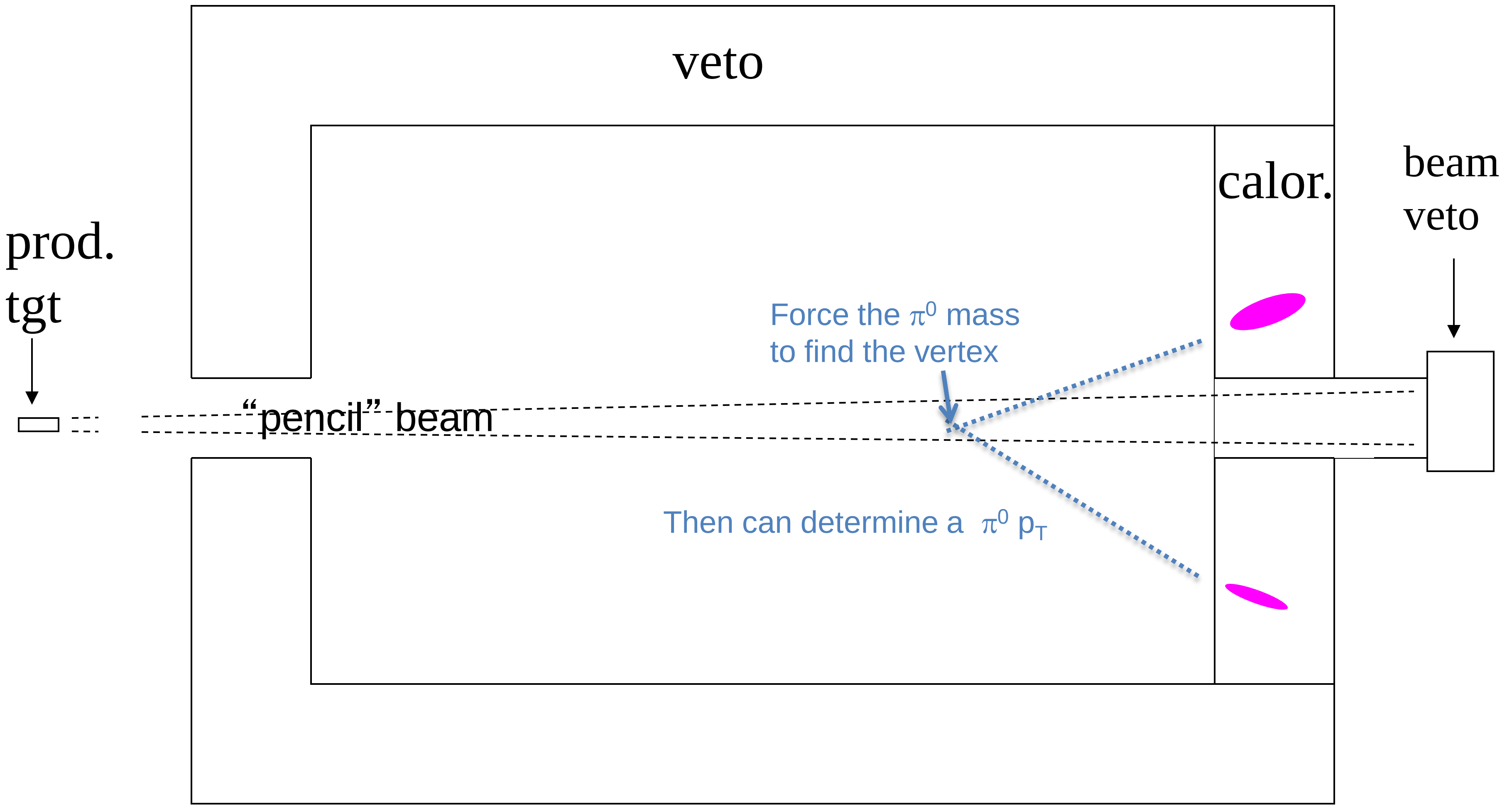
- A separated K^+ beam

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



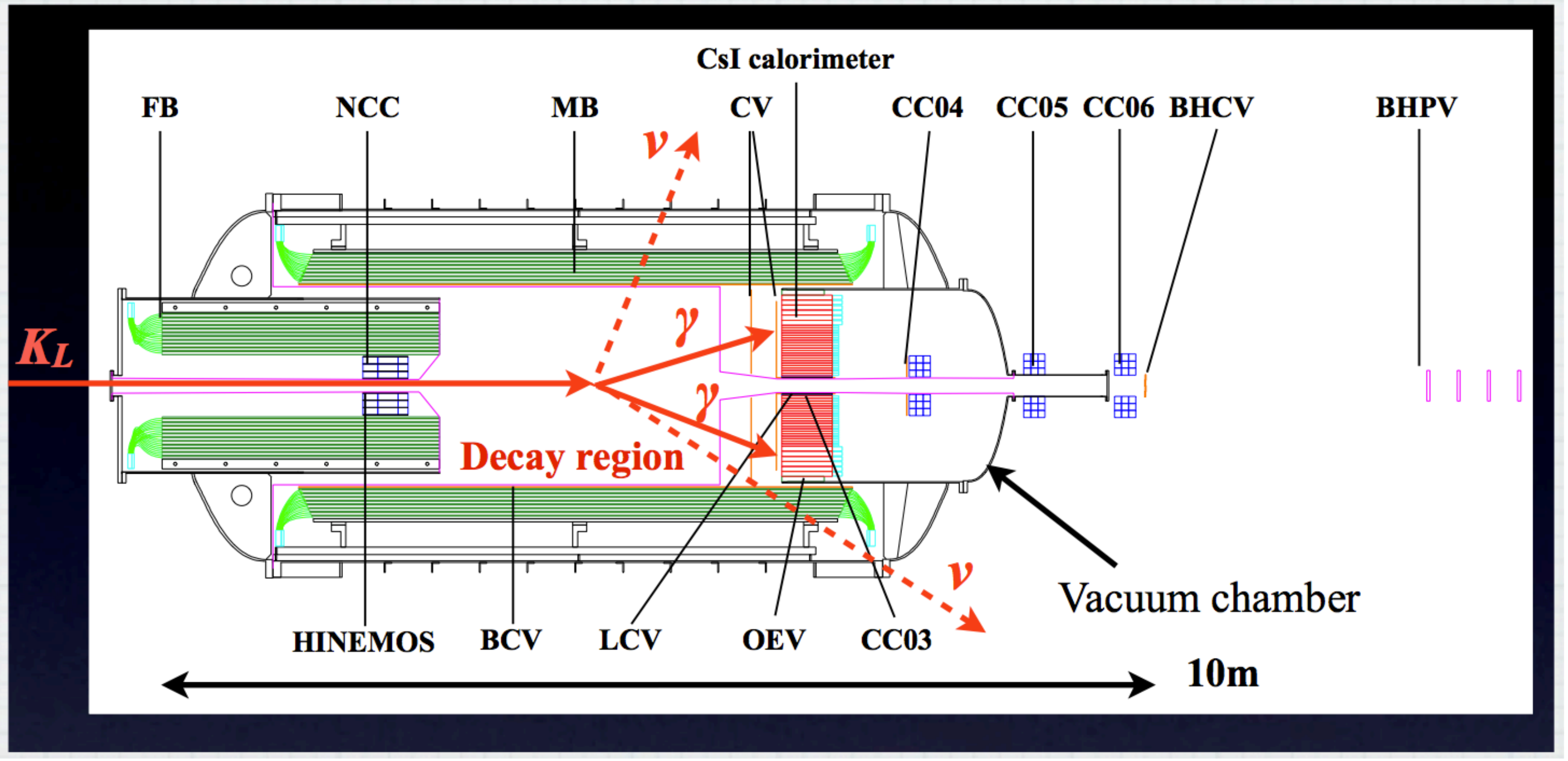
- All-neutral initial & final state, γ' s make π^0
- Expected BR ~ 3×10^{-11}
  - need high flux of K_L
- Largest background $K_L \to \pi^0 \pi^0$, BR ~ 10^{-3}
  - Can be "even" (miss 1 π^0) or "odd" (miss 1 γ from each π^0)
  - need excellent vetoes, other handles if possible
- Background from n-produced π^0s, ηs
  - need 10^{-7} Torr vacuum
  - A way to be sure decay vertex was in the beam very helpful

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



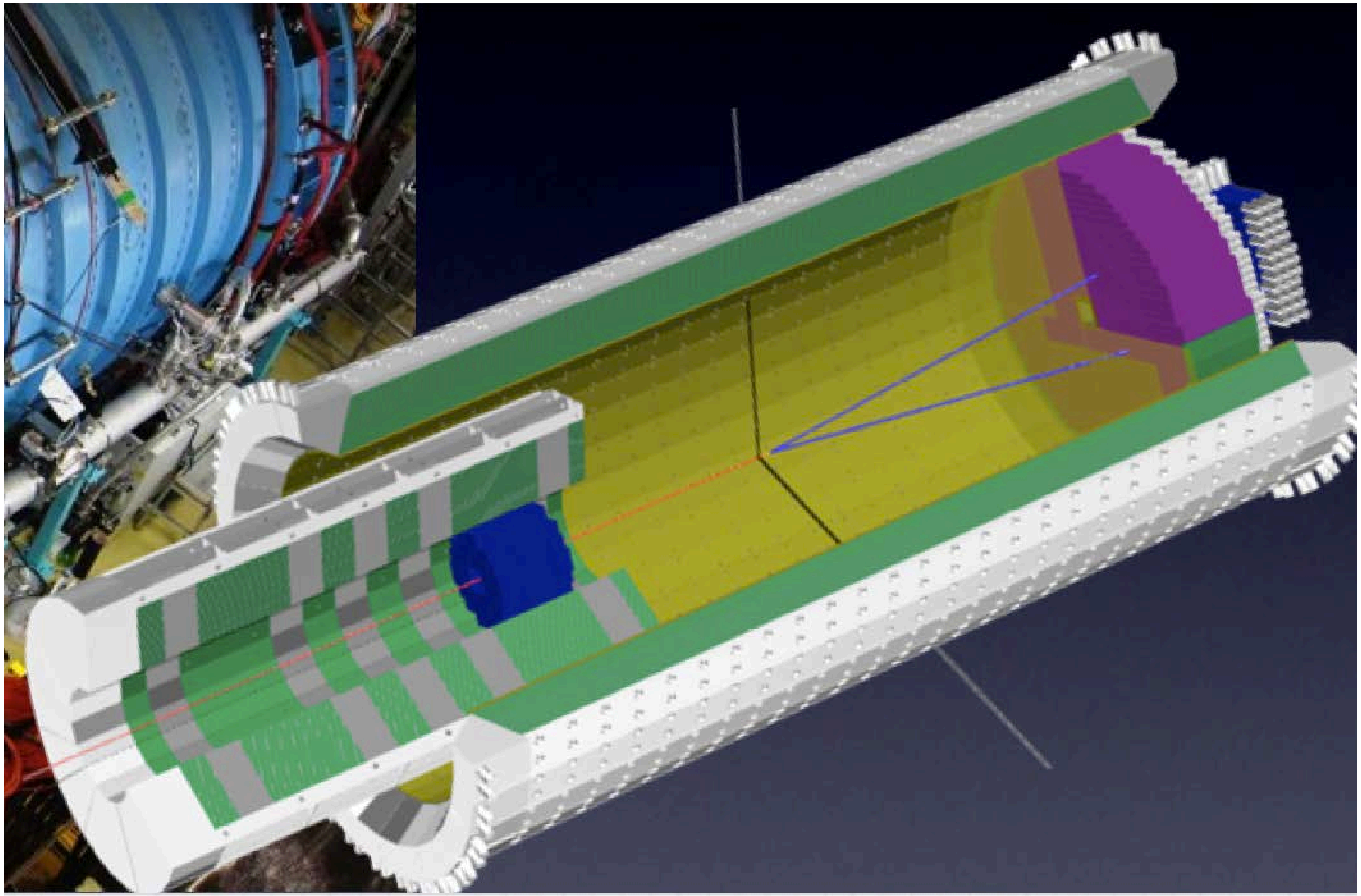
$K_L \rightarrow \pi^0 \nu \bar{\nu}$ "High" Energy

- Get the cleanest, thinnest beam possible, the best energy resolution & vacuum you can and veto like crazy – note the elaborate array of near & in-beam anti-counters
- Force the 2-γ vertex to make a π^0 emanating from the beam (a weakness!), then select on p_T – the signal persists to higher p_T than most backgrounds



- KOTO Experiment at J-PARC – mean K momentum ~1.5 GeV/c

KOTO @ J-PARC

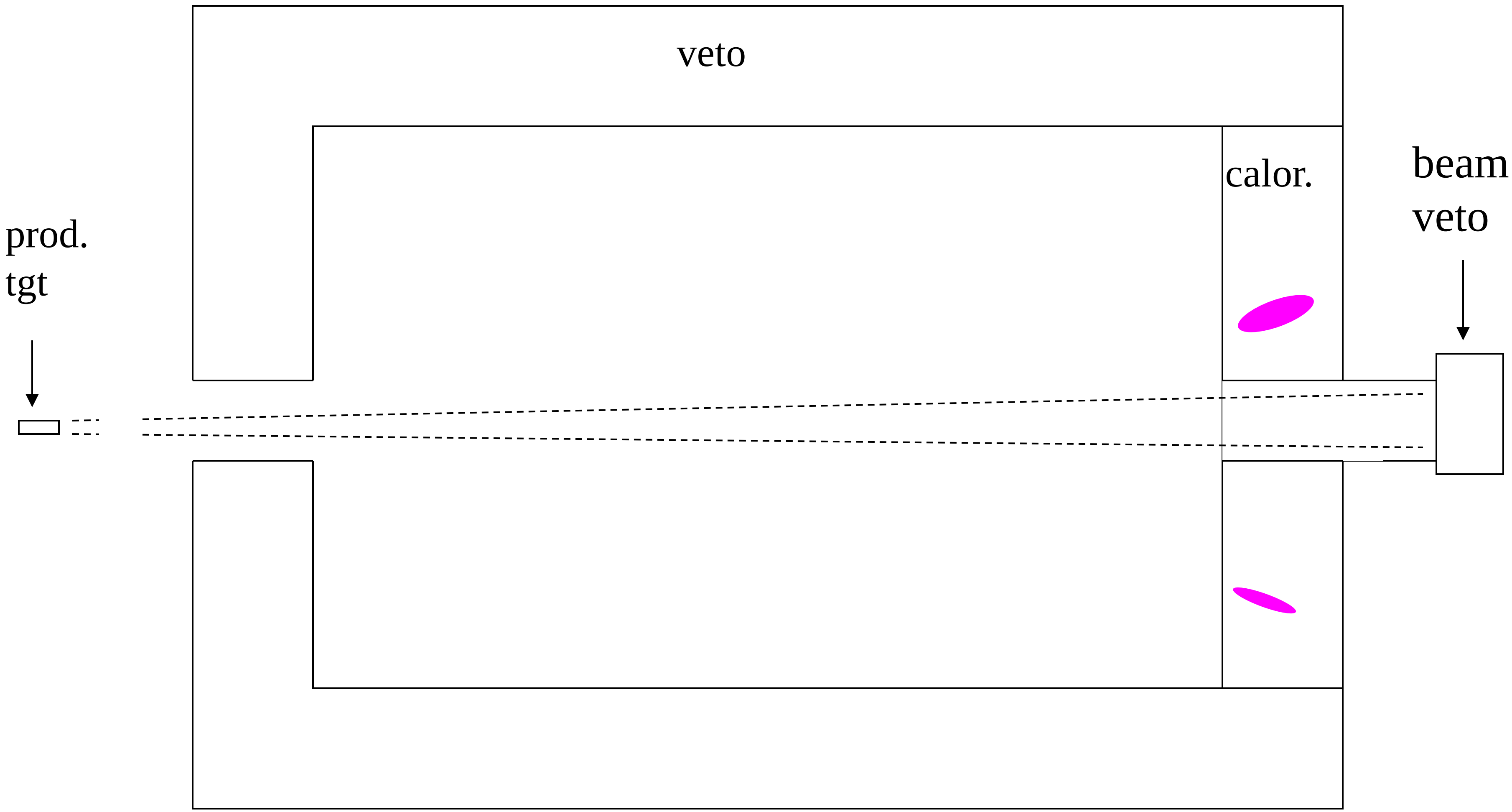


Follows on from E391a at KEK – a program rather than a project is needed

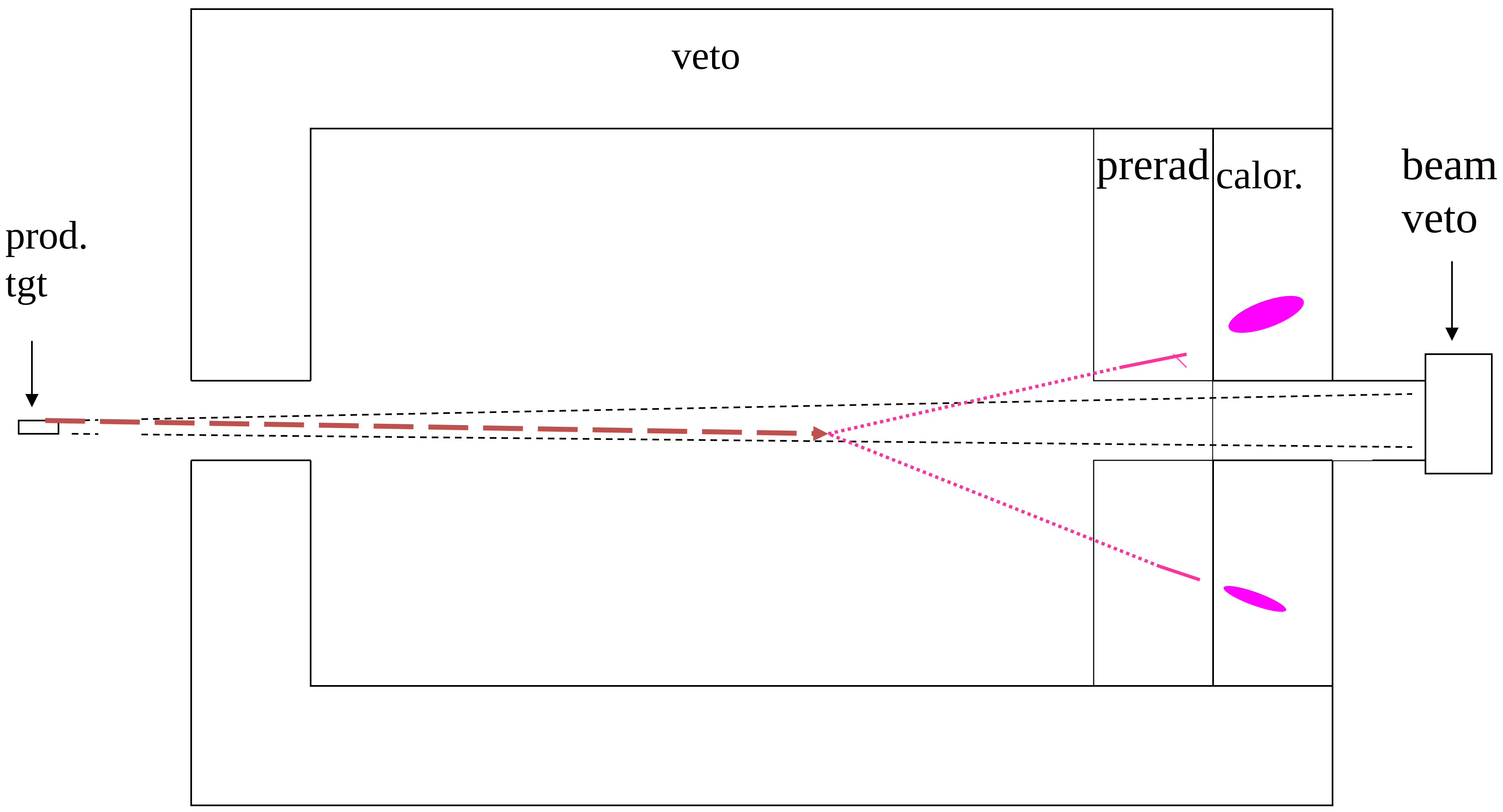
What detector improvements could help?

- More efficient photon vetoes
- Photon veto that works in a neutron beam
- Better photon timing – would cut down on random veto losses
- Better energy resolution
- Better separation of adjacent photons
- Method of directionalizing photons without degrading energy resolution

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



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

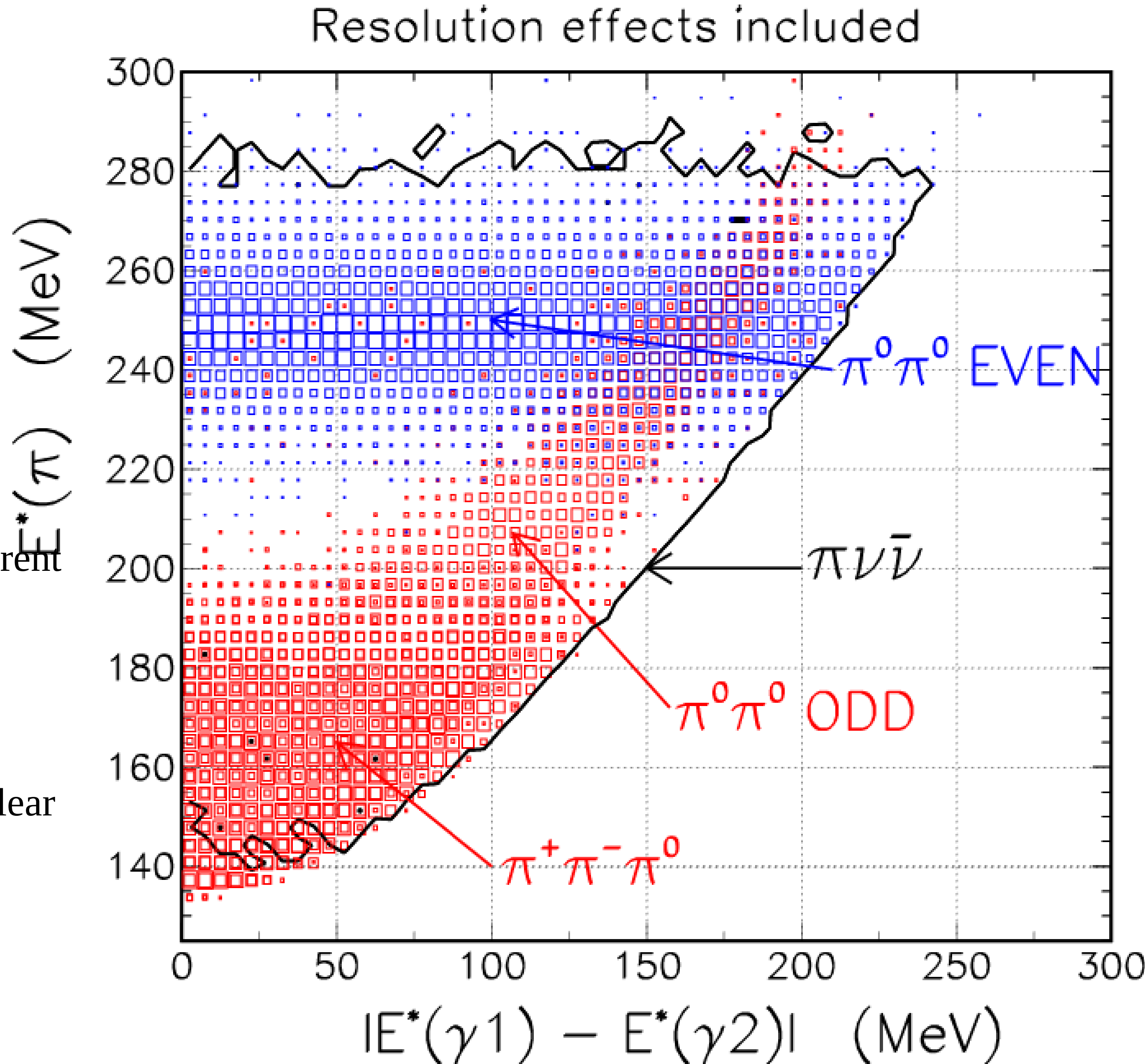


In the K_L CoM

• 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



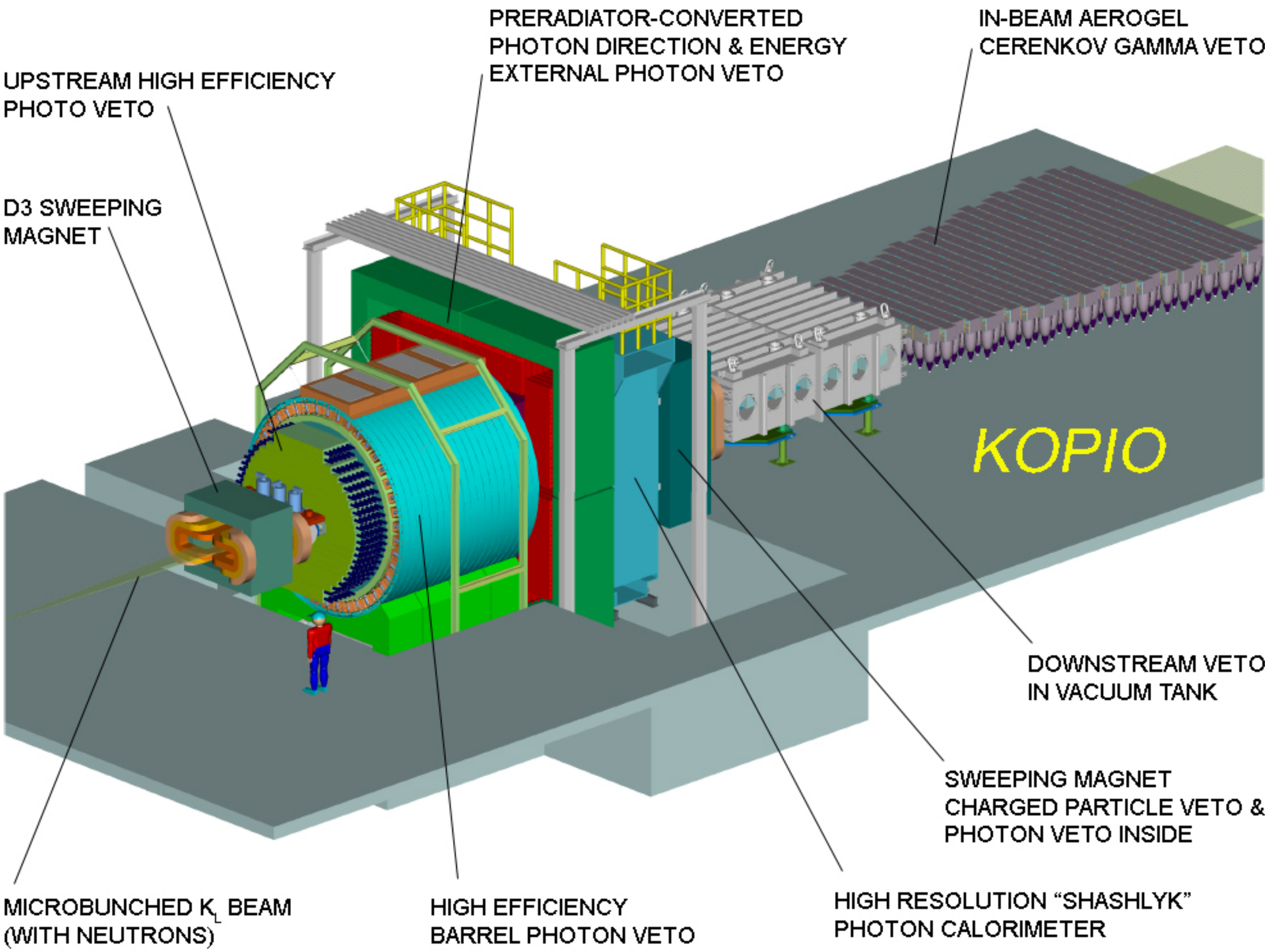
KOPIO $K_L \to \pi^0 \nu \bar{\nu}$ Experiment

BNL AGS experiment

Aim: “100” events

Use the AGS between RHIC fills

Capitalize on the experience of previous AGS rare K decay experiments

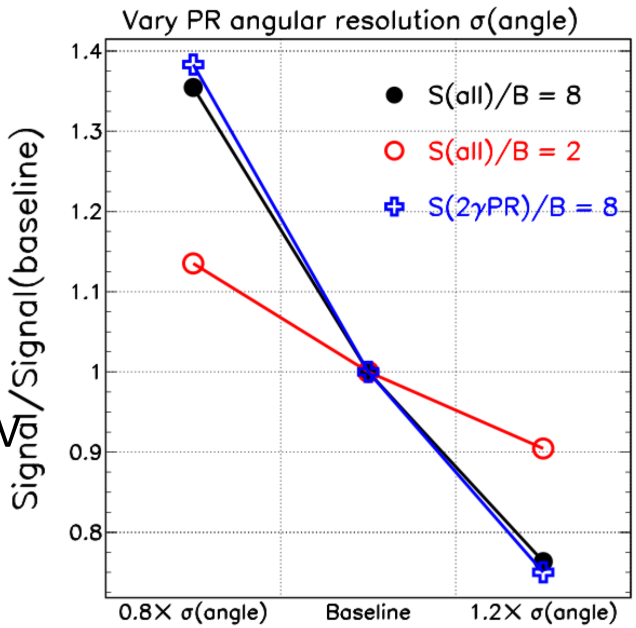


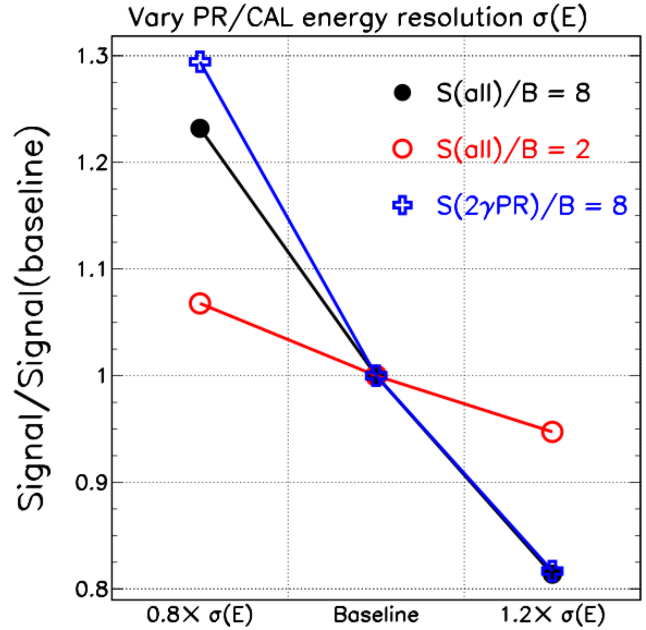
What detector improvements could help?

- More efficient photon vetoes, particularly at low energy
- Photon veto that works in a neutron beam
- Better photon timing – would cut down on random veto losses, and improve CM kinematics
- Better energy resolution
- Better angular resolution
- Better charged track rejection, particularly in the beam direction
- Entire apparatus that could work in a vacuum

Parameter Variations

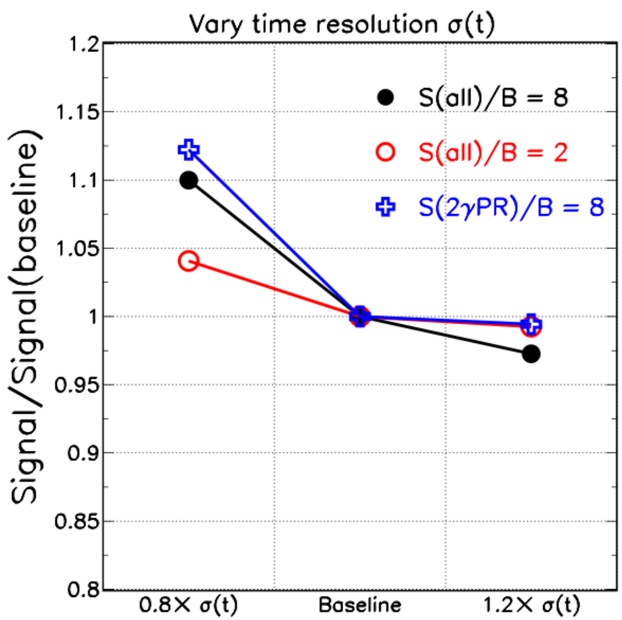
25mr@ 250MeV

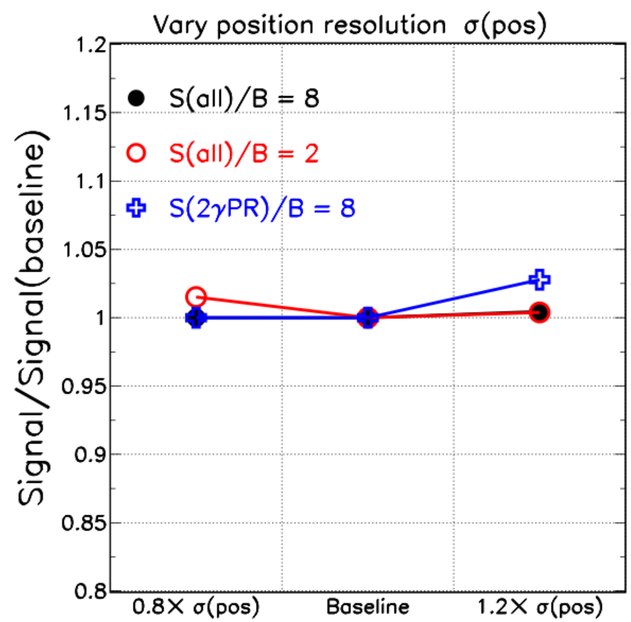




3%/√E

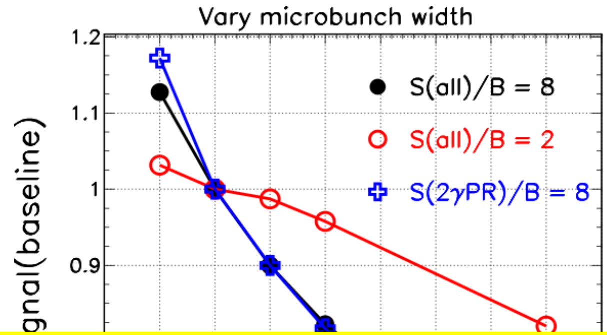
90ps/√E



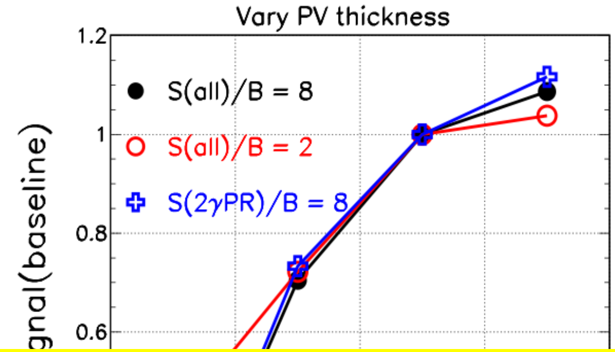


250μm

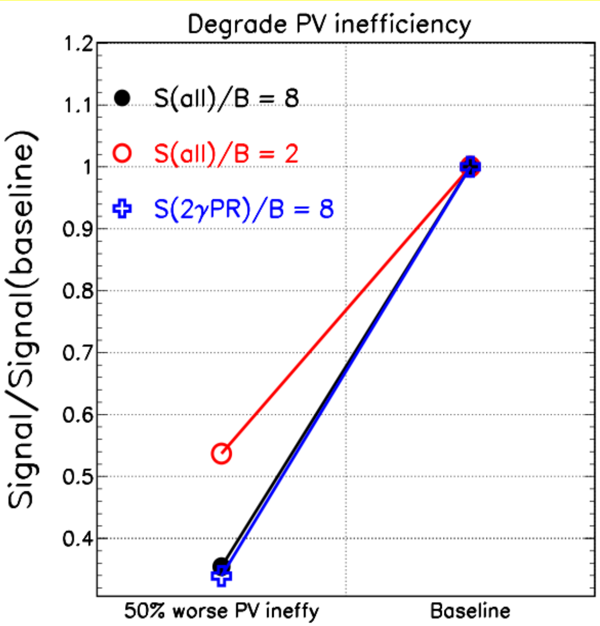
Parameter Variations-2



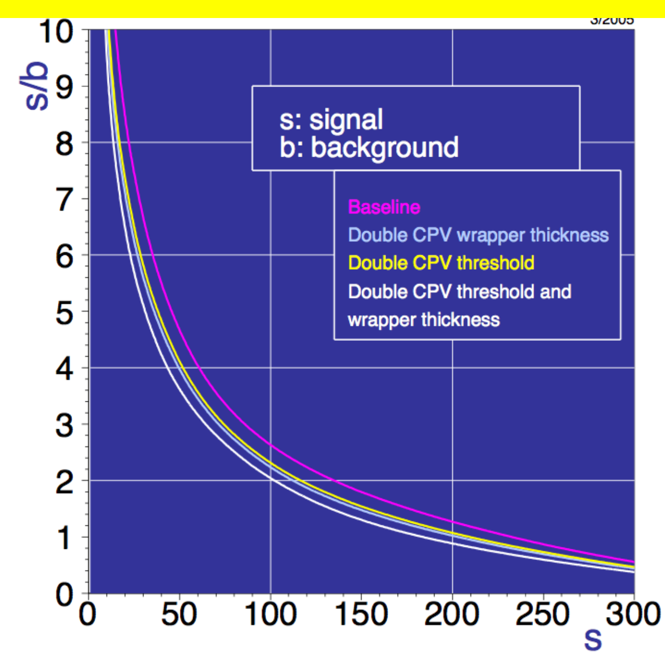
200ns



A 2008 study concluded it might be possible to get a factor 4 more highest quality events and a factor 2 for the majority of the events.



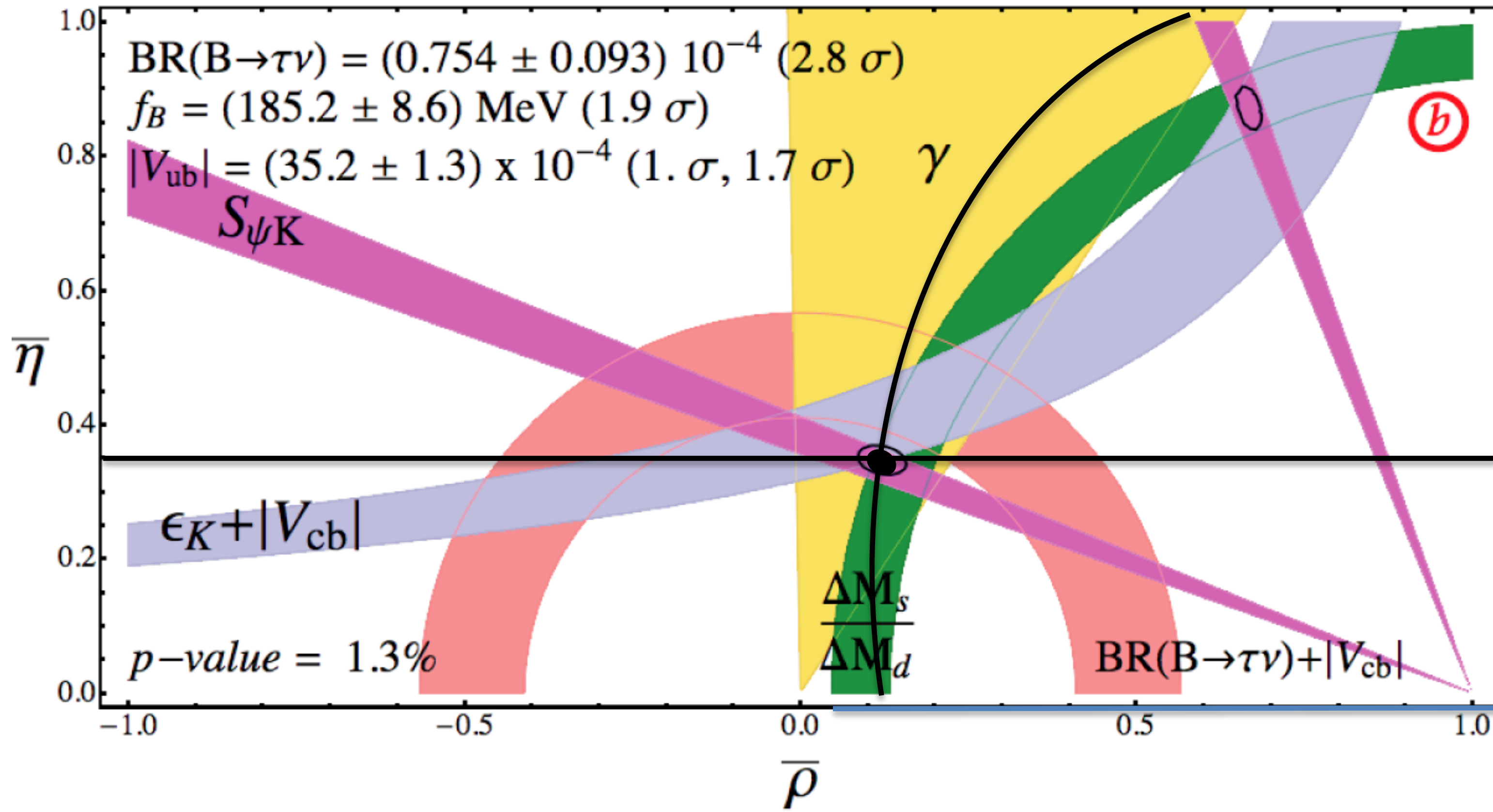
~$10^{-4}/\gamma$



50 keV
55mg/cm^2

Final Thoughts on $K \rightarrow \pi\nu\bar{\nu}$

- To achieve the sensitivities one would really like requires a factor of 100 in the charged mode and a factor 30,000 for the neutral
- Rare kaon decays present somewhat different detector challenges to those arising in collider experiments, largely because veto inefficiency must be extremely low:
  - The detectors have to be hermetic to a high degree.
  - It's necessary to veto rather low energy particles
  - There's a constraint that any substantial element of the apparatus be active (no "dead" material).
- Interesting sensitivities are so low that important phenomena are very difficult to simulate, either because they require too much computer time or because not enough is known about them.
- There are tradeoffs between detectors and beam/accelerator improvements
  - E.g. more intense low energy K_L beam would greatly reduce the need for improved beam photon vetoes
- Note - 1000 event K experiments would determine the CKM ρ and η better than all current world data.

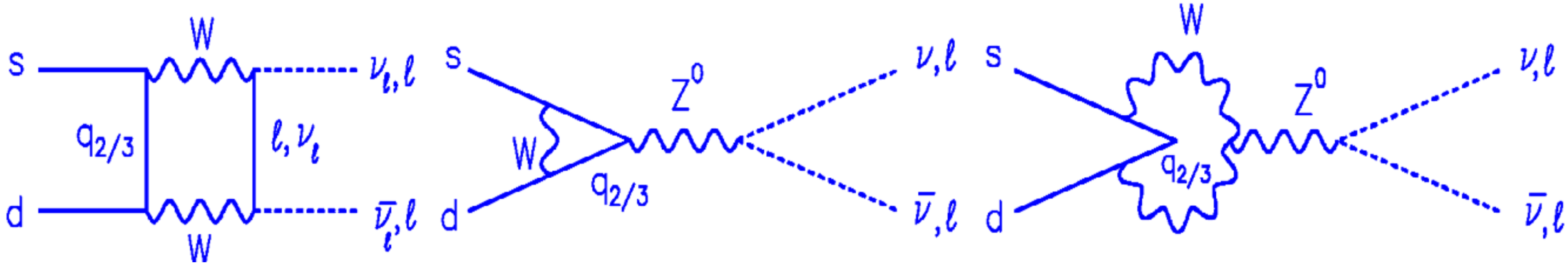


BR(B→τν) = (0.754 ± 0.093) 10^−4 (2.8 σ)
f_B = (185.2 ± 8.6) MeV (1.9 σ)
|V_ub| = (35.2 ± 1.3) x 10^−4 (1. σ, 1.7 σ)
γ
S_ψK
ε_K+|V_cb|
ΔM_s / ΔM_d
BR(B→τν)+|V_cb|
p−value = 1.3%
b
η̄
ρ̄
1.0
0.8
0.6
0.4
0.2
0.0
−1.0
−0.5
0.0
0.5
1.0

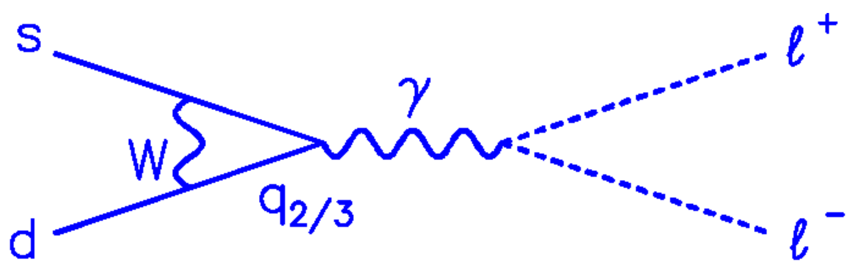
BACKUP

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 K decays such as $K^+ \to \pi^0 e^+ \nu$. These one-loop contributions can be cleanly calculated in terms of $\sin\theta_C$, m_t, m_c, and the product of CKM elements $V_{ts}{}^* V_{td} \equiv \lambda_t$.



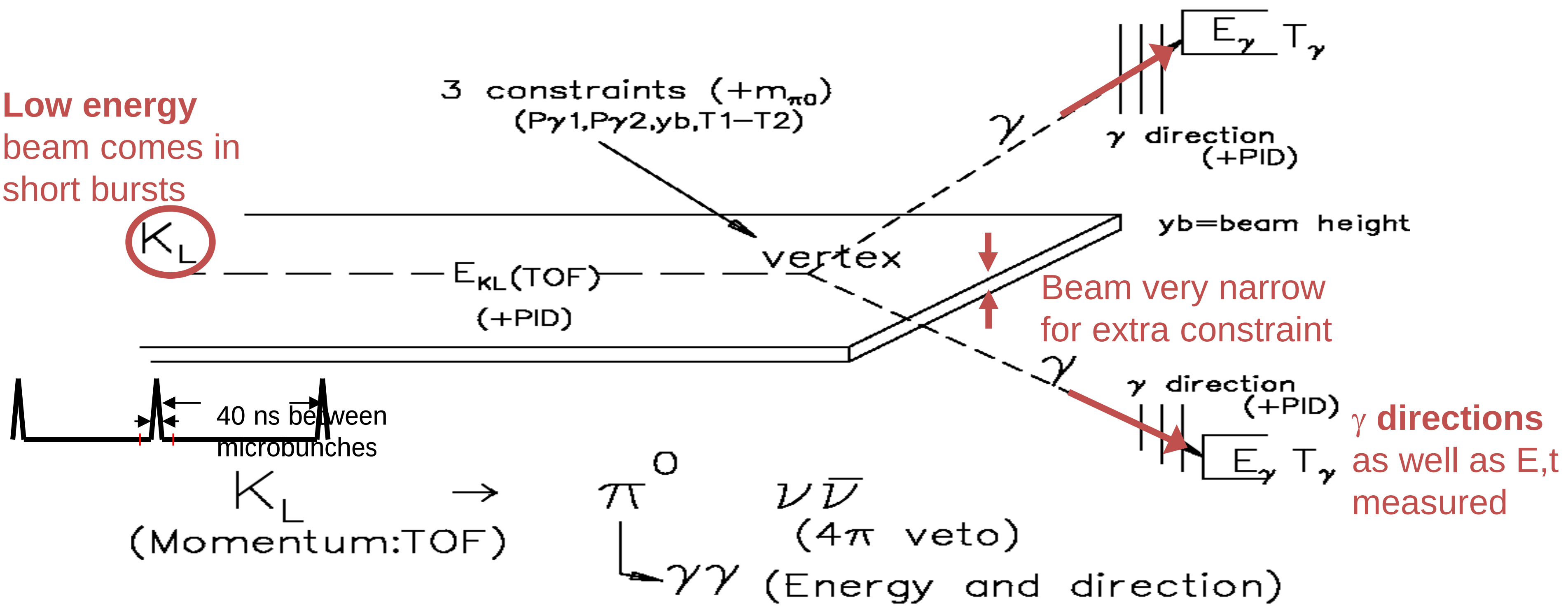
But there’s a Murphy’s Law to these processes. The same interactions that allow final state leptons to be detected mediate long-distance contributions. E.g.:



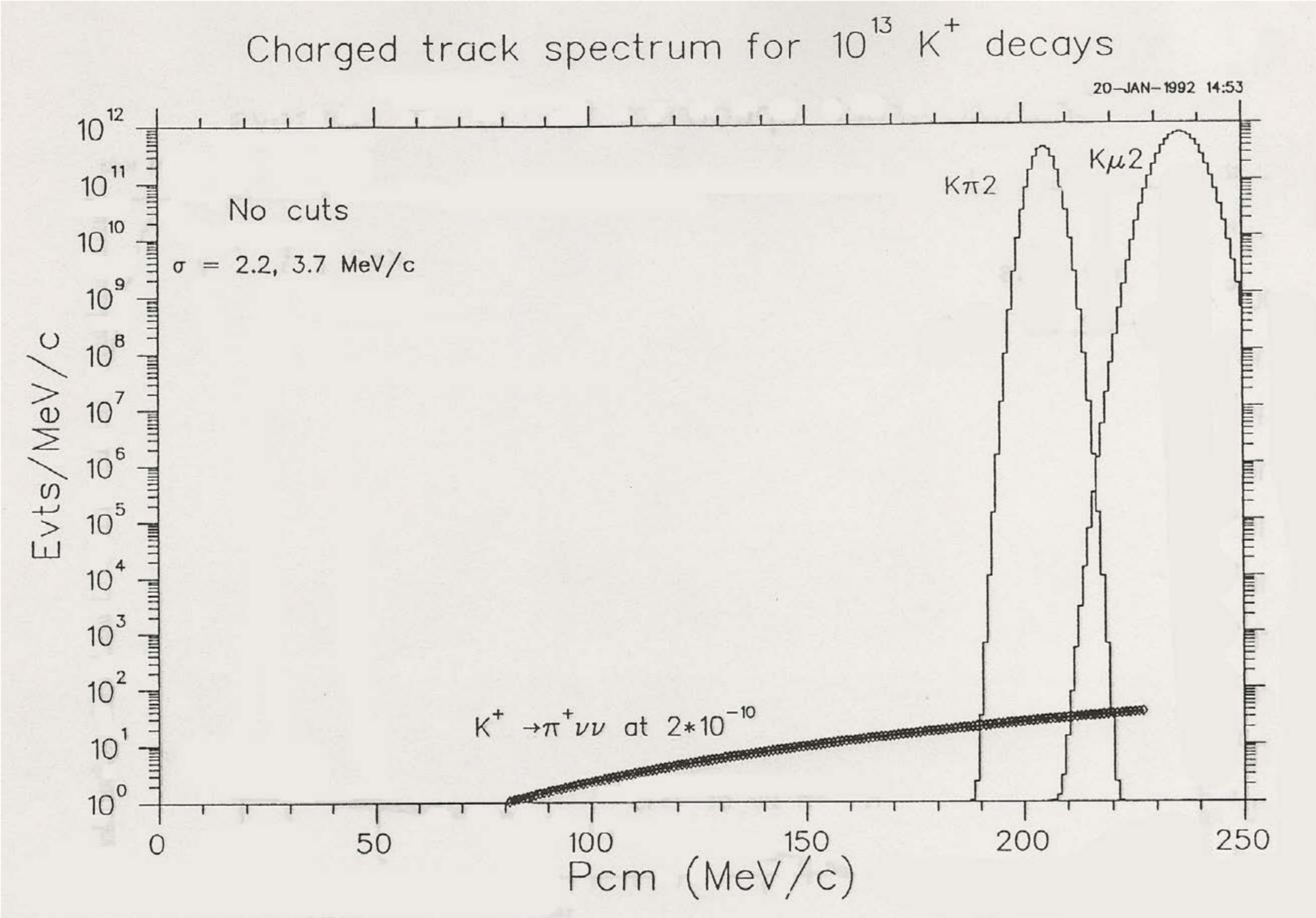
To avoid this one must exploit decays containing a final state $\nu\bar{\nu}$ pair.

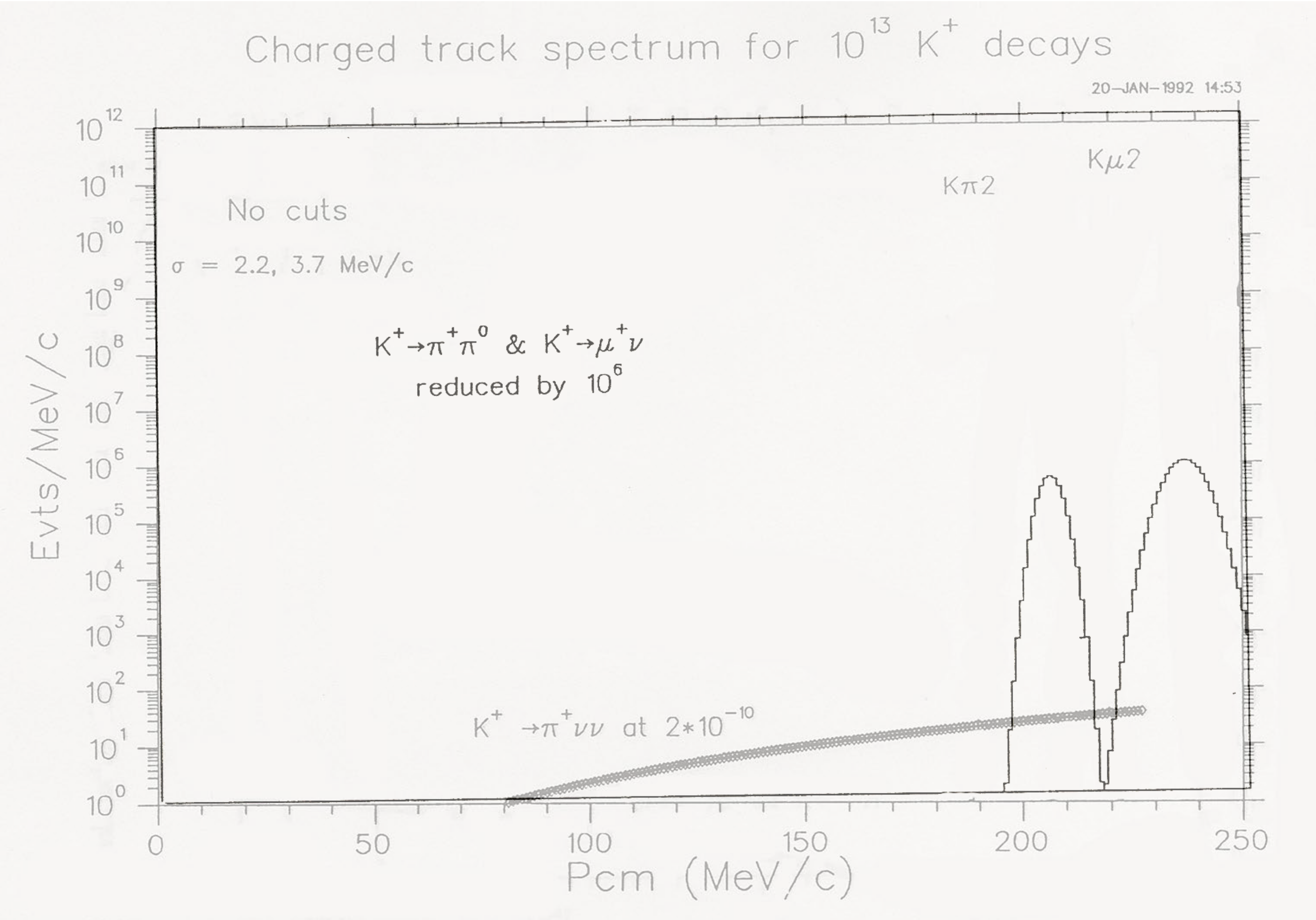
KOPIO Technique

- High intensity micro-bunched beam to measure K velocity
- Measure everything! (energy, position, ***direction***, time)
- Eliminate extra charged particles or *photons* by $>10^4$



Reality


Charged track spectrum for 10^13 K^+ decays
20-JAN-1992 14:53
No cuts
σ = 2.2, 3.7 MeV/c
Kπ2
Kμ2
K^+ →π^+νν at 2*10^-10
Evts/MeV/c
Pcm (MeV/c)
0
50
100
150
200
250
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12


Charged track spectrum for 10^13 K+ decays
20-JAN-1992 14:53
No cuts
σ = 2.2, 3.7 MeV/c
K+→π+π0 & K+→μ+ν
reduced by 10^6
Kπ2
Kμ2
K+ →π+νν at 2*10^-10
Evts/MeV/c
Pcm (MeV/c)
0
50
100
150
200
250
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12