Future Kaon Physics Program at Fermilab and CERN.

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I. Recent history.

II. Physics goals and current status.

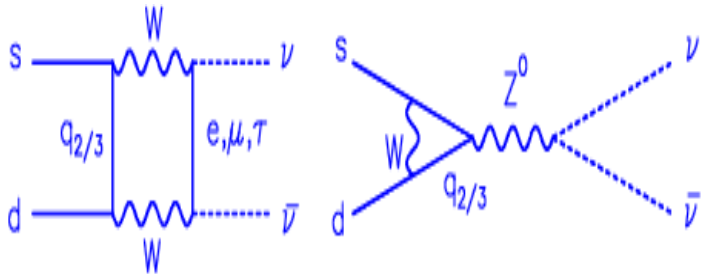
III. The In-Flight technique and its challenges

IV. Future Kaon Program at CERN & Fermilab.

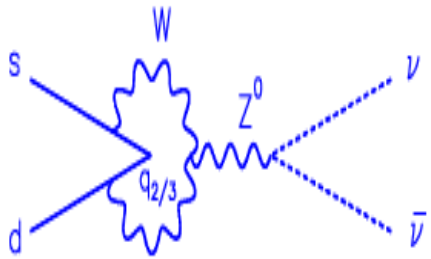
Thanks for material from Giuseppe Ruggiero (Firenze) & Augusto Ceccucci (CERN)

Primary Physics Goal: Precision Measurement of Br[$K^+ \to \pi^+ \nu \bar{\nu}$]

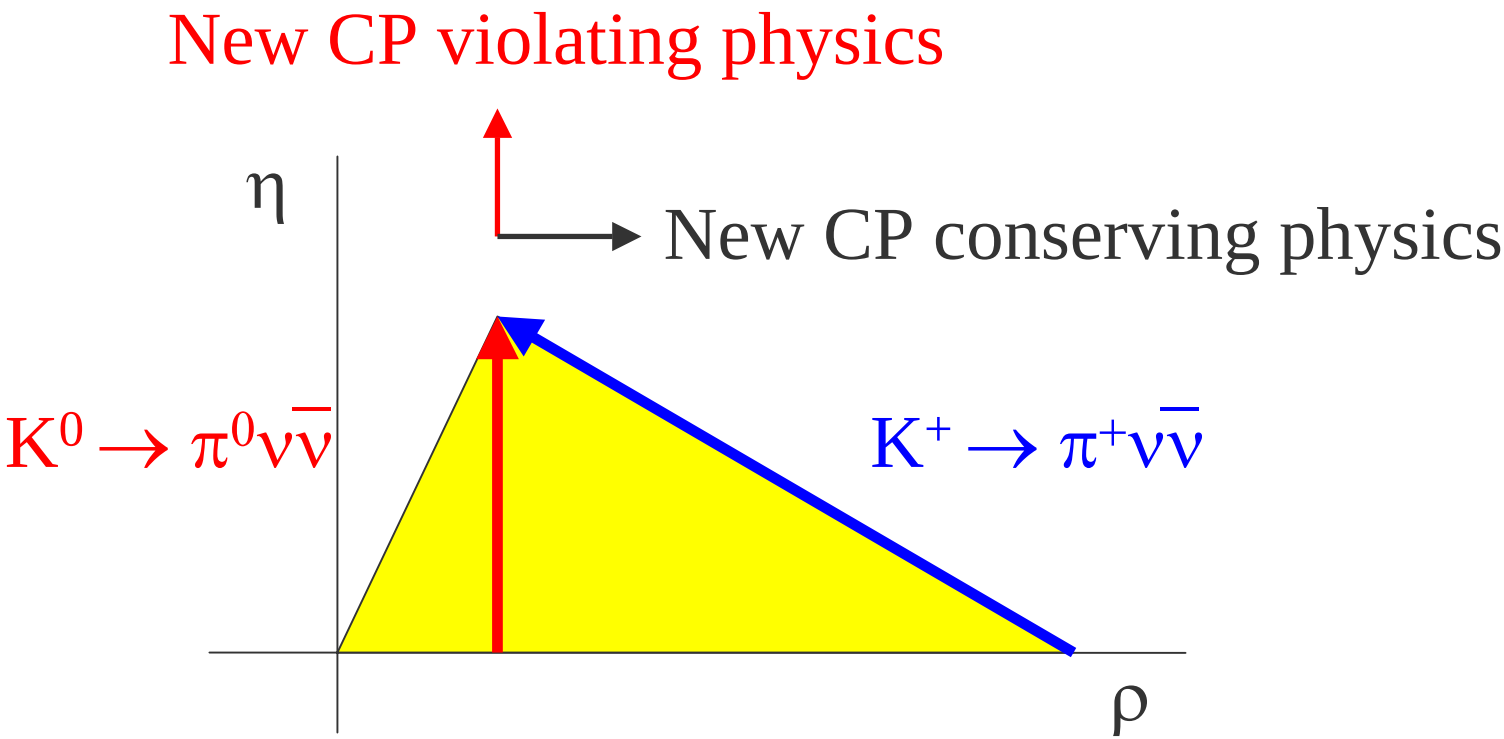
This decay is determined by loop processes to high order in the SM, and hence has a reach for *new physics at the EW scale and beyond*.



The SM rate can be reliably calculated; hence any deviation in the measured rate is a signal for new physics.



New Physics sensitivity in $K^+ \to \pi^+ \nu\bar{\nu}$



$K^+ \to \pi^+ \nu\bar{\nu}$ Sensitive to all new physics in $s \to d$ transitions

$K^0 \to \pi^0 \nu\bar{\nu}$ Sensitive to only CP violating $s \to d$ new physics

CKM Status and how to proceed

- CKM(E921) at Fermilab is an approved experiment to measure Br[$K^+ \rightarrow \pi^+ \nu \bar{\nu}$] with 100 signal / <10 background in a high flux separated kaon beam at 22 GeV/c
- **P5** stops **CKM** - Oct 2003

  P5 judged *"CKM to be an elegant world class experiment* which *based on present budgetary models should not proceed."*
- Adapt to an unseparated ~45 GeV/c beam in KTeV hall - **P940**
  - Demonstration of μMegas in NA48 → tracking in 230MHz tractable
  - Other 3 trackers unchanged (2 RICHes + Straws in vacuum)
  - Vetoing photons gets easier (E_{π^0} > 1 GeV → >7 GeV)
  - Accidental backgrounds?

Measuring $|V_{td}|$ with $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is the best way to measure $|V_{td}|$ in the Standard Model
  - Structure of K^+ controlled by measurement, NO final state interactions.
  - Theoretical uncertainties are small (m_{charm}) and robustly estimated. (~8%)
  - Need 100 signal events with <10 background (6%) to match theory error.
- Experimental Challenge
  - Br[$K^+ \rightarrow \pi^+ \nu \bar{\nu}$] = $(8 \pm 1) \times 10^{-11}$ (Standard Model)
  - 3 clean events seen in BNL787 /949 (Br = $15^{+13}_{-9} \times 10^{-11}$)
- The tyranny of tiny decay rates
  - 100 events / 10^{-10} (Br) / 1% (acc) = 10^{14} K decays must be studied
  - 10^7 sec/year $\rightarrow$ 10^7 K decay /sec to see 100 in 1 year
  - Need to control background to 10^{-11} of all K^+ decays

Other Physics Measurements

- π^+ decay physics
  - $\Gamma[\pi^+\to e^+\nu(\gamma)]/\Gamma[\pi^+\to\mu^+\nu(\gamma)]$ is calculated to 0.05% in the SM
  - Helicity suppresses the dominant V-A and IB amplitudes
  - $\pi^+\to e^+\nu\gamma$ Dalitz plot – access to non V-A terms in hadronic weak current
  - An excellent place to search for models like leptoquarks, multiple Higg, etc.
- Other K^+ decay physics
  - All the other K decays studies from the CKM proposal remain
    - K_{e3}, K_{e4}, $K_{\mu3}$, $K_{\mu4}$, $K^+\to\pi^+e^+e^-$, $K^+\to\pi^+\mu^+\mu^-$
    - Lepton flavor violation - $K^+\to\pi^-\mu^+\mu^+$, etc.
    - T odd correlations in $K^+\to\pi^+l^+\nu\gamma$
  - $\Gamma[K^+\to e^+\nu(\gamma)]/\Gamma[K^+\to\mu^+\nu(\gamma)]$, $K^+\to e^+\nu\gamma$ in parallel with pion decays

Changes in the physics situation

What's changed since the CKM approval in 2001?

- Another $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ event from BNL E949.
- B_s mixing isn't going to be measured at the SM level (17 ps^{-1}) soon.
- Some unusual CP & Flavor results are emerging at Belle and Fermilab:
  - e.g. $B^0 \rightarrow \phi K_S^0$ asymmetries disagrees with ψK_S^0. Two lifetimes found in B_S : $B_S^{(heavy)}$ & $B_S^{(light)}$…..disagreement with theory?
- 1st row unitarity restored? New measurements of V_{us} are topical
- There is experimental evidence for non V-A terms in the pion hadronic weak current in $\pi^+ \rightarrow e^+ \nu \gamma$
  - 5σ claim by PiBeta for tensor form-factor $F_T/F_V = -0.061 \pm 0.011$

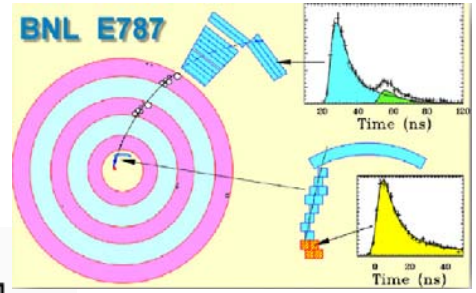
    hep-ex/0311013, hep-ex/0312029
  - ISTRA at IHEP also reported a non-zero tensor form-factor.

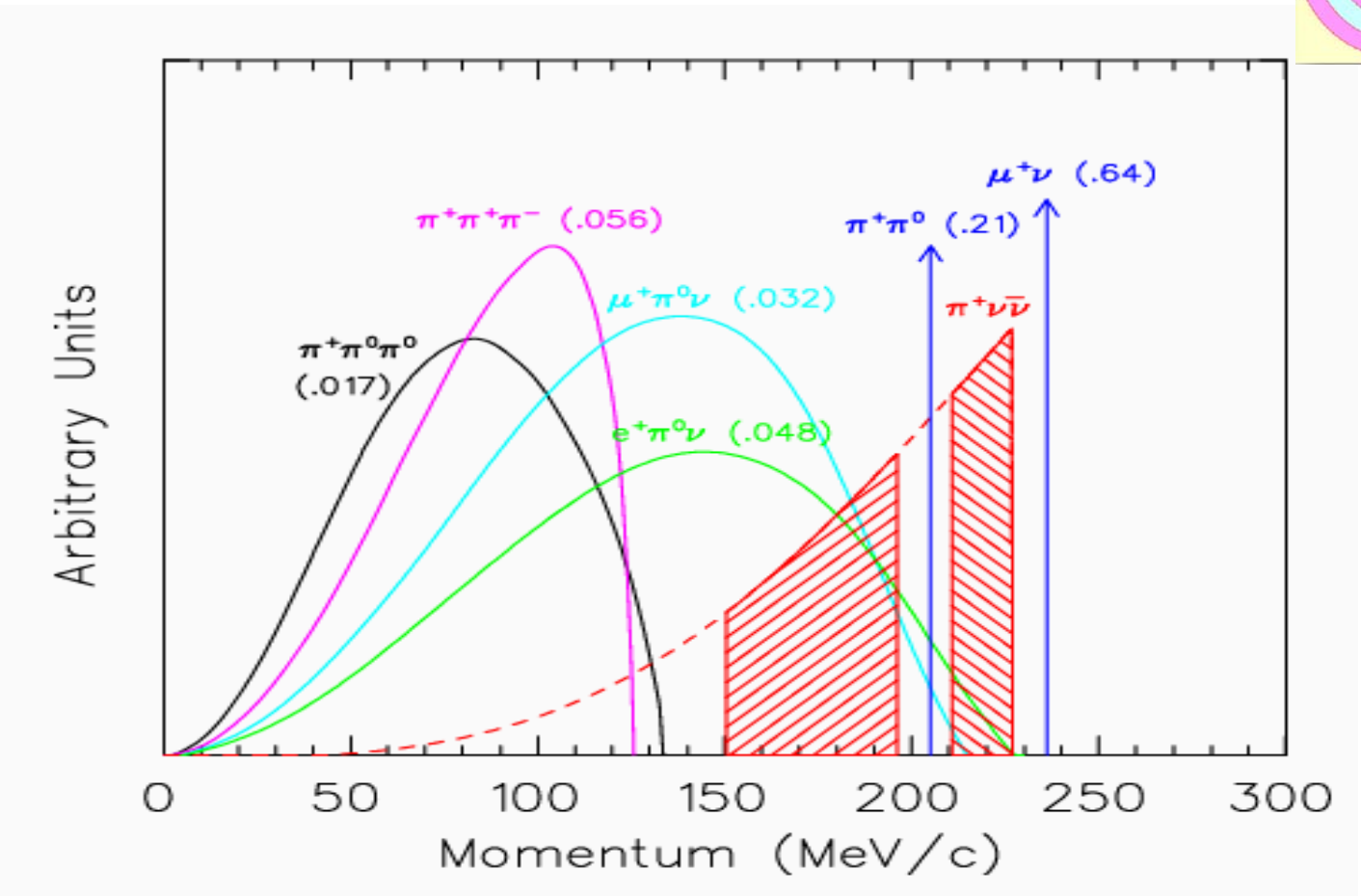
    Phys.Lett.**B243** (1990)308, hep-ph/0307166

In-Flight Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$

- Must measure K^+ momentum to recover rest-frame Kinematics.
- Relatively large decay volume.
- Not possible to follow the π–μ–e decay chain.
- Decay occurs in vacuum, no low-energy K^+A interactions, no complex energy loss mechanisms.
- Kinematics ***and backgrounds*** of Region-I and Region-II are similar, leads to potentially higher total acceptance.
- High energy muons and photons from $K\mu2$ and $K\pi2$ are in principle easier to veto.
- Existing high performance Experiments: KTeV & NA48.

Stopped K^+ Kinematics



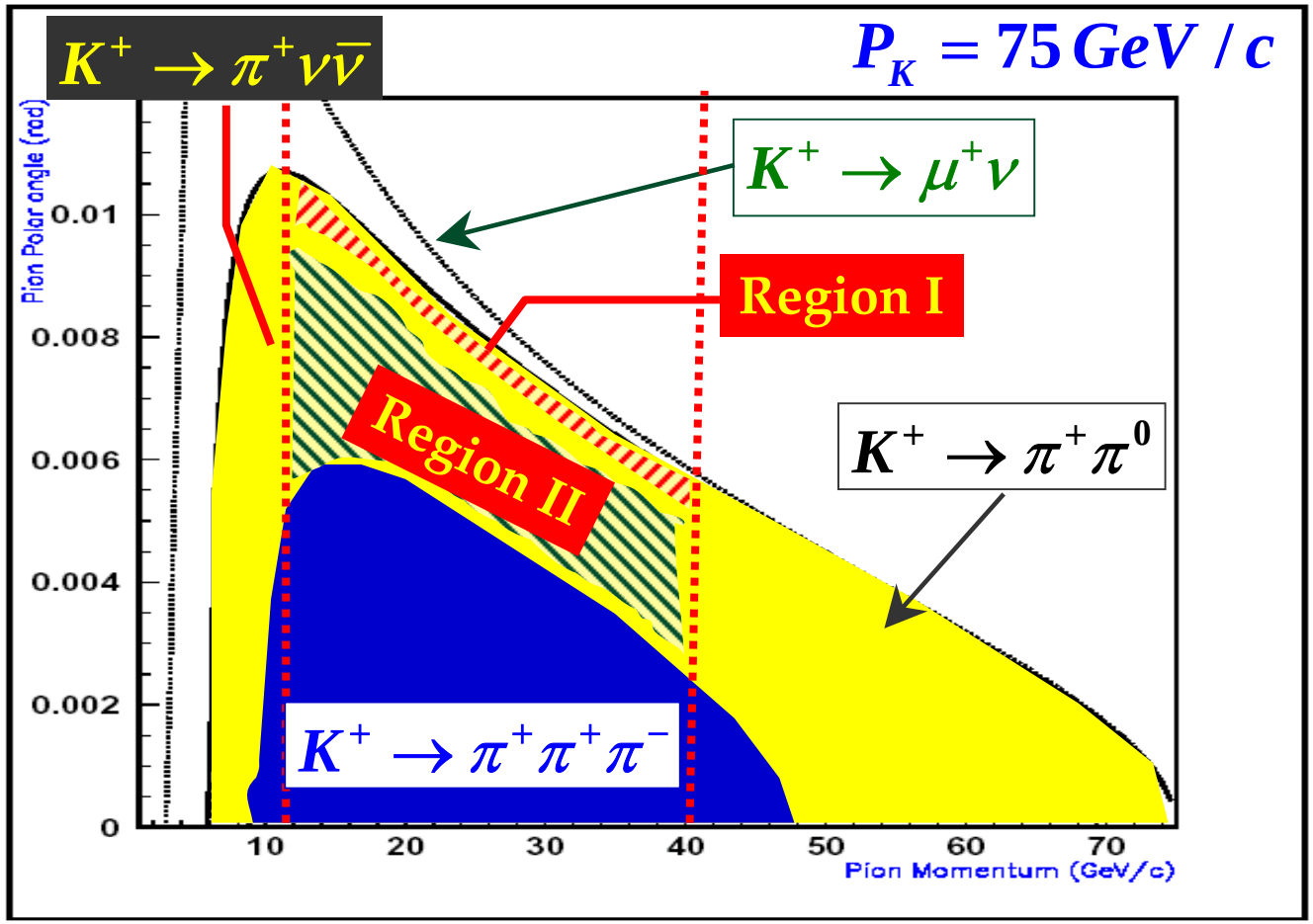


Kinematics of In-flight Decay

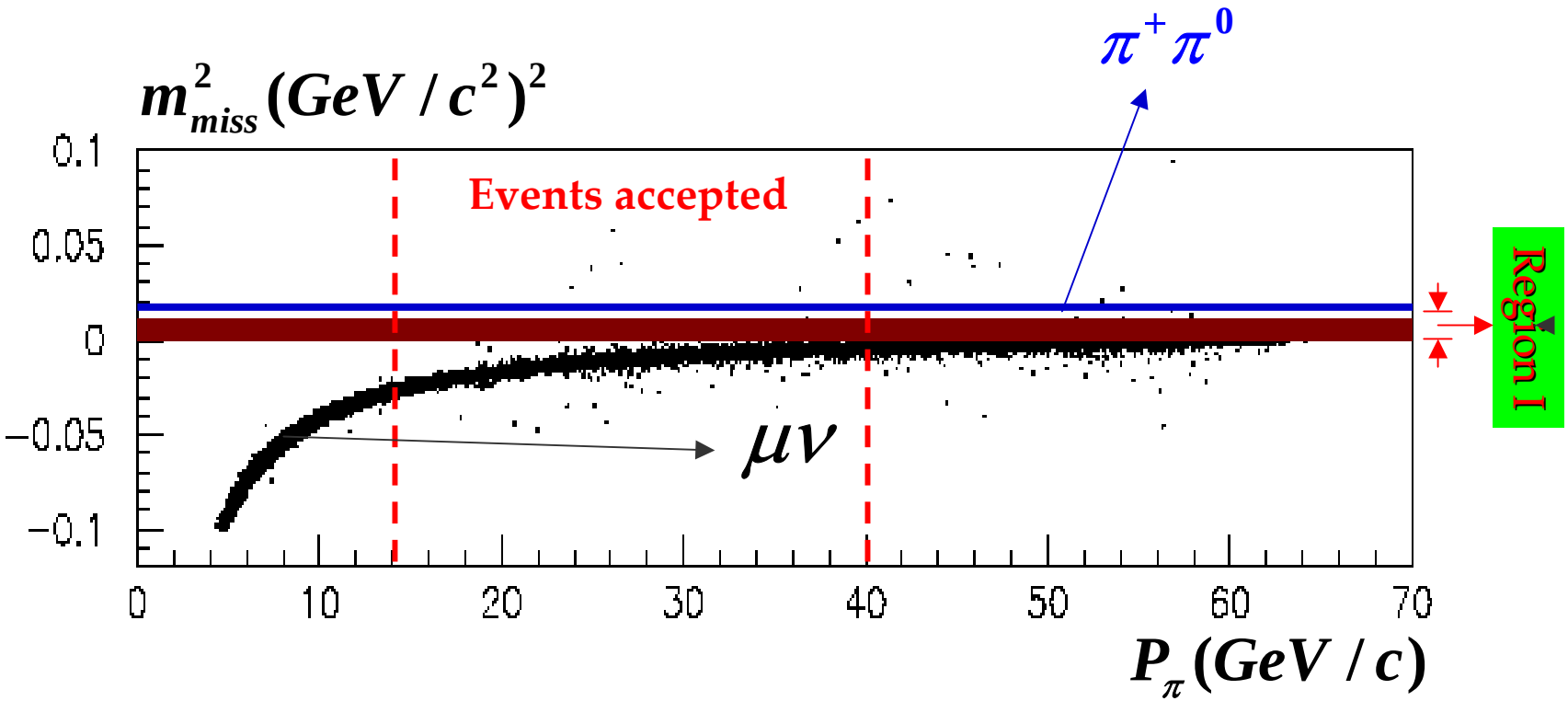
K^+ decay in flight
High energy K^+

Ultra-rare decay:
BR ~ 10^{-10}

- ✓ Kinematical cuts
- ✓ Veto systems
- ✓ Particle ID



Kinematical rejection



$$m^2_{miss} = m^2_K + m^2_\pi - 2(E_K E_\pi - p_K p_\pi \cos\theta_{K\pi})$$

Measured quantities

CERN Proposal (NA48/3)

CERN–SPSC–2004–010 / SPSC–EOI–002

- **NA48 detector upgrading to study $K^+ \to \pi^+ \nu \bar{\nu}$**

  - **High Physical potential**
    - **Aim to a 10 % measurement of $|V_{td}|$**

  - **Availability of experimental infrastructures (NA48/2):**
    - **Location for the experiment (ECN3 – high radiation area)**
    - **Beam line (*high intensity*, slowly extracted protons from SPS)**
    - **Subdetectors (e.g. LKr calorimeter)**
    - **2004 run (beam test)**

  - **Goal:**
    - ✓ ***About 50 Events with a S/B of 10:1 in 2 years of data taking***

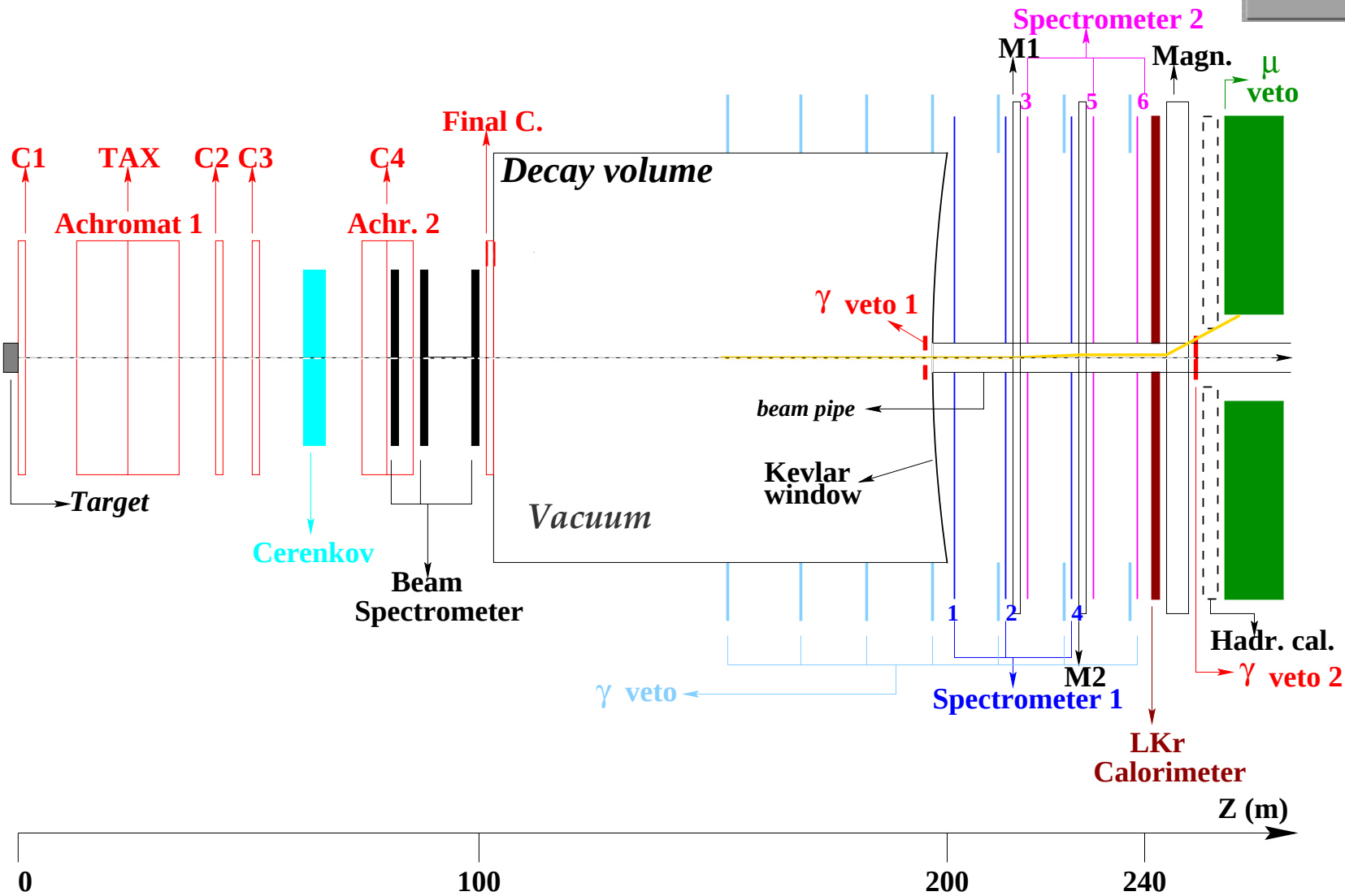
CERN Technique

- High Flux Un-separated 75 GeV/c Beam - 6% K^+ , $\delta p/p \sim 1\%$ (RMS)
  - Proton / π^+ : 160 / 480, **800 MHz total, ~40 MHz/cm^2 in beam tracker.** 5x5 cm^2 beam in decay volume.
  - 48 MHz K^+, 2.7 MHz decay in the accepted decay volume.
  - 3 x10^{12} 450 GeV proton /sec in slow spill from the SPS to produce the required K^+ beam.
  - Debunched proton beam required (SPS has ~10% 200 MHz ripple).
- Apparatus
  - Decay in-flight spectrometer with tagged incident K^+ and double magnetic spectrometer to measure the decay π^+ twice.
  - Significant requirements on photon vetoes, LKr ineff < 1x10^{-6} @ high energy.
  - Significant requirement on muon veto, ineff < 1x10^{-5} @ high energy.
  - **Redundancy** is critical to measure all backgrounds
  - Exploit signal regions on both sides of $K^+ \rightarrow \pi^+\pi^0$.

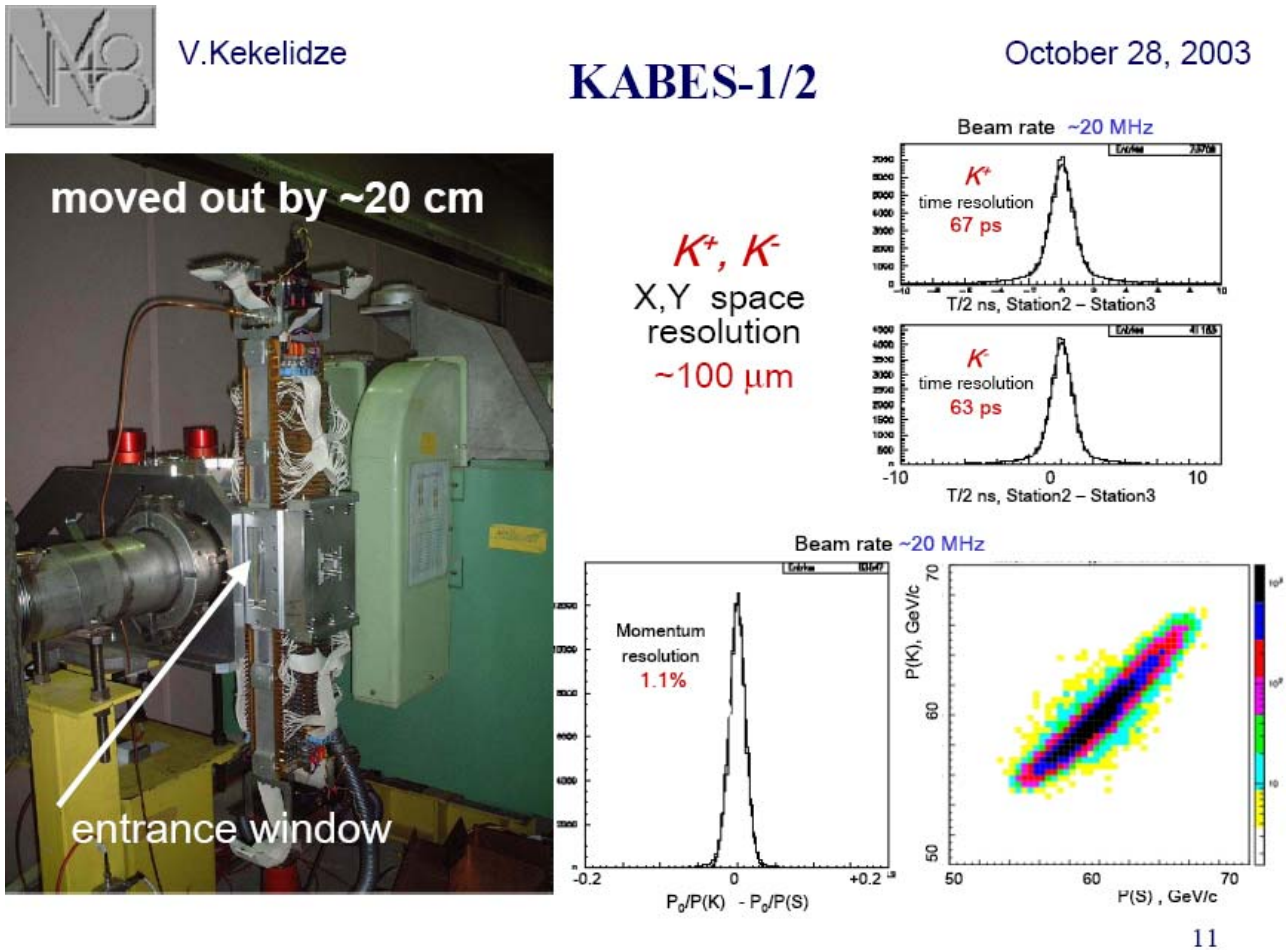
Detector Layout

- **Subdetectors downstream of the fiducial region:**
  - Double spectrometer
    - 6 drift chambers (4 chambers already employed in NA48)
    - 2 magnet (1 magnet already employed in NA48)
    - Momentum redundant measurements
  - Photon veto:
    - LKr calorimeter (already in NA48) + charged particle sweeping magnet
    - 2 small angle vetoes (CMS prototypes)
    - 8 rings as large angle vetoes (upgrade of AKL detectors in NA48)
  - Hadron calorimeter
  - Muon veto

CERN Experimental Layout



The NA48 Beam Tracker: A Breakthrough in Ultra-high Rate Tracking.



3 MHz/cm^2, 700 psec tag. No rate effects seen.

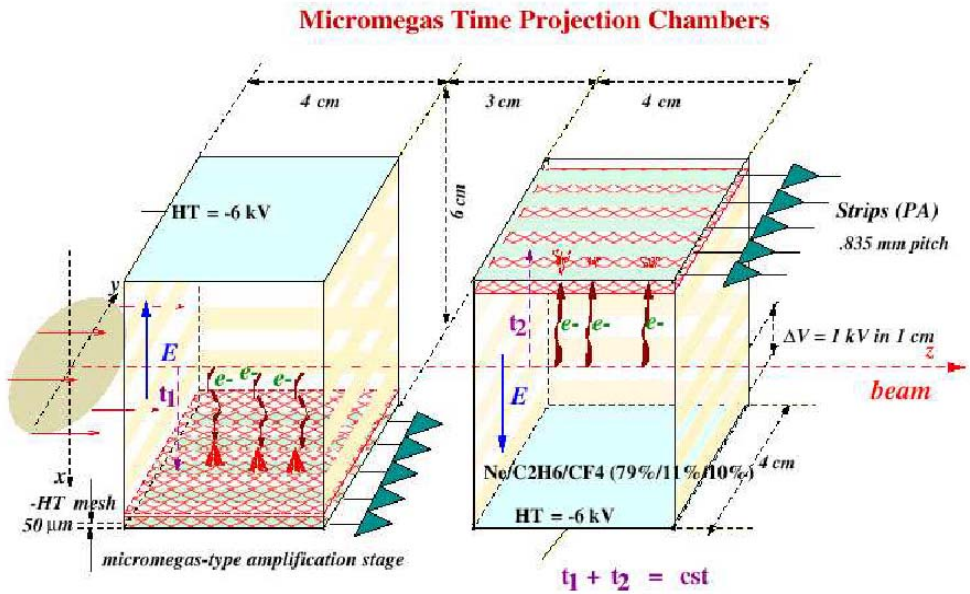
Kaon Spectrometer (KABES)

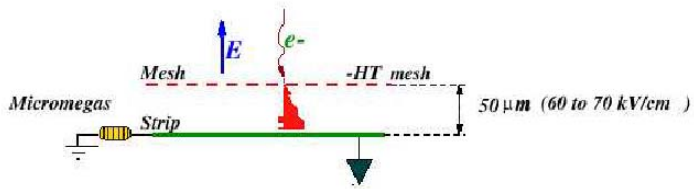
Currently used in NA48/2
@ 2 MHz/strip

- Resolution strips 80 μm
- Resolution drift 50 μm
- Time resolution 0.7 ns
- Dead time/strip 40 ns
- ΔP/P 0.5 %

Improvement for NA48/3
(expected 20 MHz/strip)

- New micro-mesh 25 μm
- New gas
- FADC → Old NA48 Tagger readout (1 GHz FADC)
- Smaller strip size
- Si micro-pixels (sub-ns time resol.)



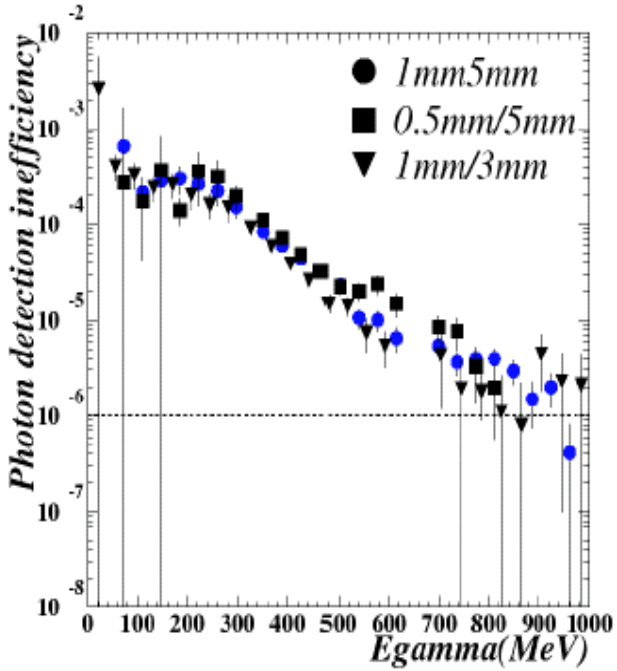


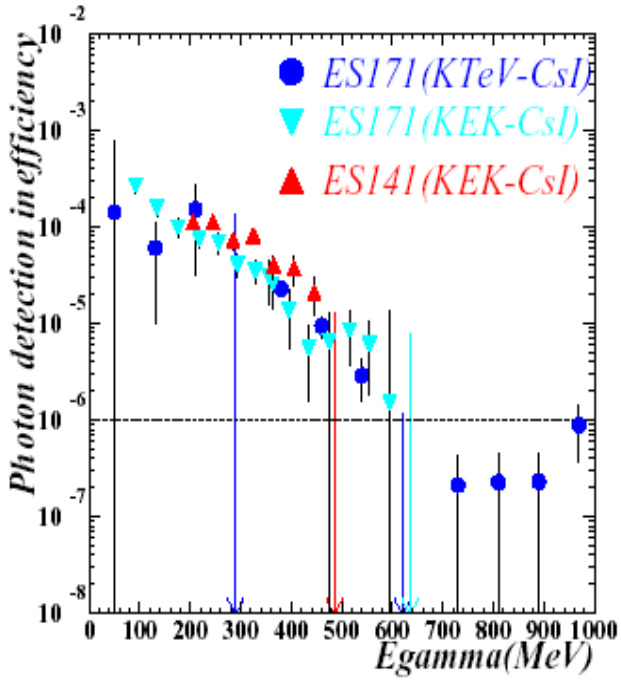
Test foreseen during 2004 run

Photon rejection

- Aim to reach 10^{-6} inefficiency
- For $P_\pi < 40$ GeV/c there are at least 35 GeV/c in the e.m. calorimeters

For Fermilab P940 experiment $E_{\pi 0}$>7 GeV

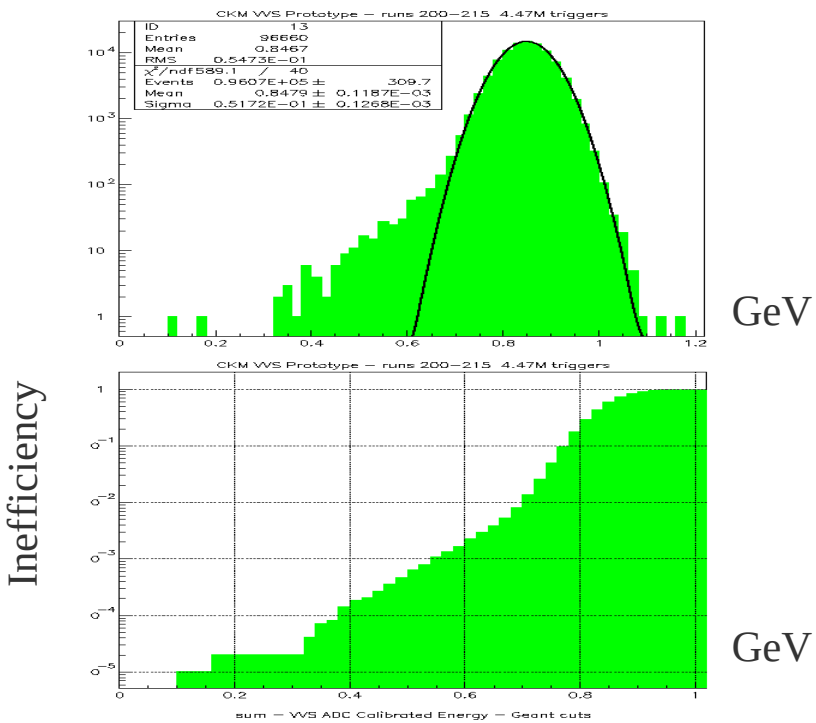


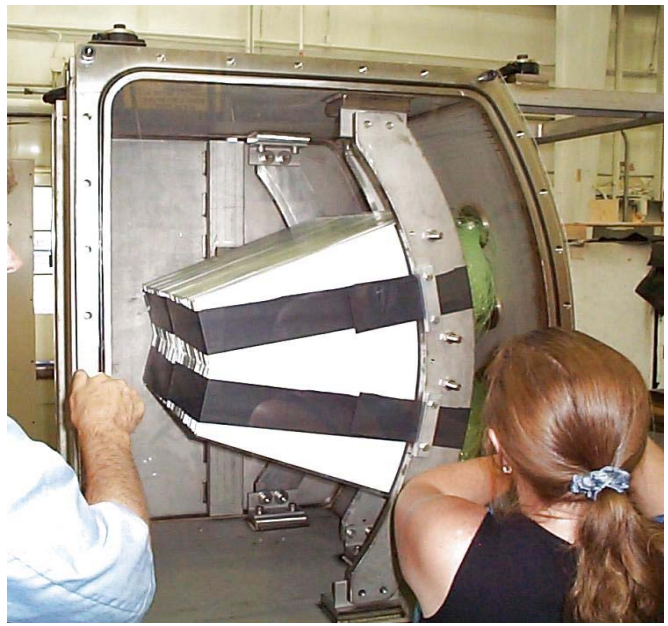


- Plans to study <u>our inefficiency</u> (LKr calorimeter + small angle veto) by collecting a large sample of $\pi^+\pi^0$ events in 2004 run

Photon Veto Inefficiency and Technology

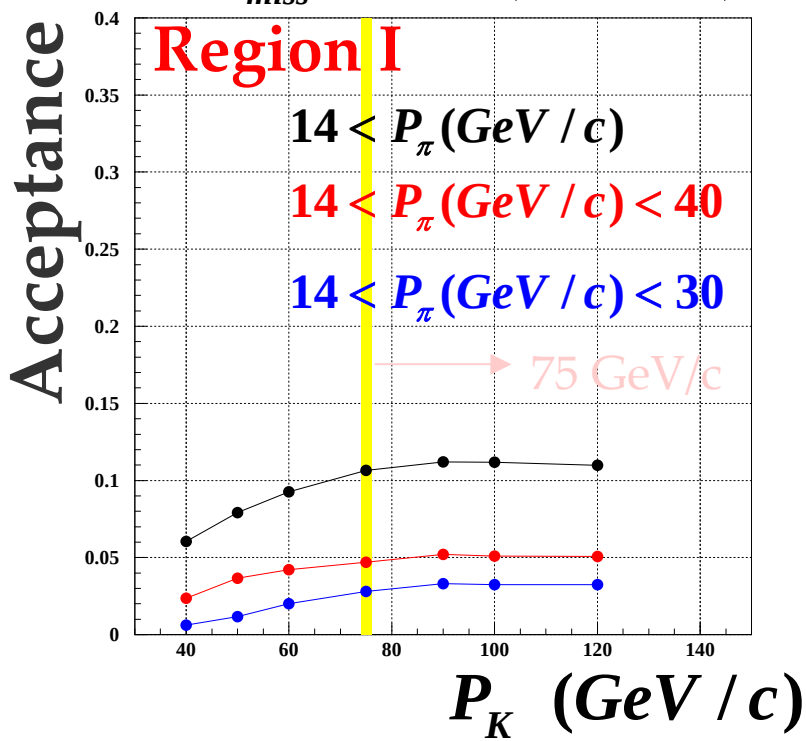
- 0.3% VVS Pb-Scintillator Prototype built
- Tested at JLAB in an e^- beam, published in NIM soon.
- Achieved <$1x10^{-5}$ ($3x10^{-6}$) veto inefficiency at 1 GeV (required $3x10^{-5}$)



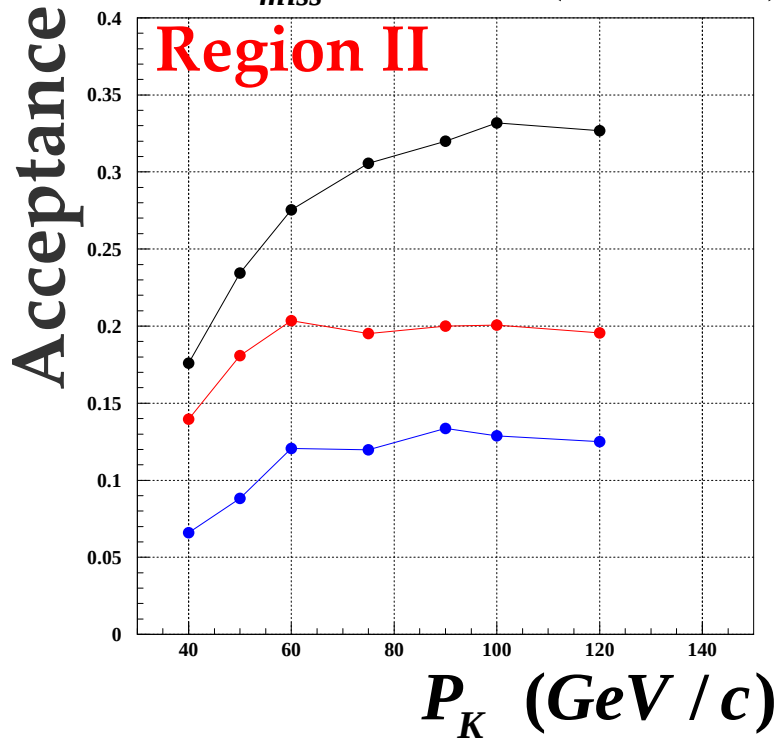


CERN Acceptance

$0 < m^2_{miss} < 0.01\ (GeV/c^2)^2$



$0.026 < m^2_{miss} < 0.068\ (GeV/c^2)^2$



$P_K = 75\,GeV/c \quad P_\pi < 40\,GeV/c$

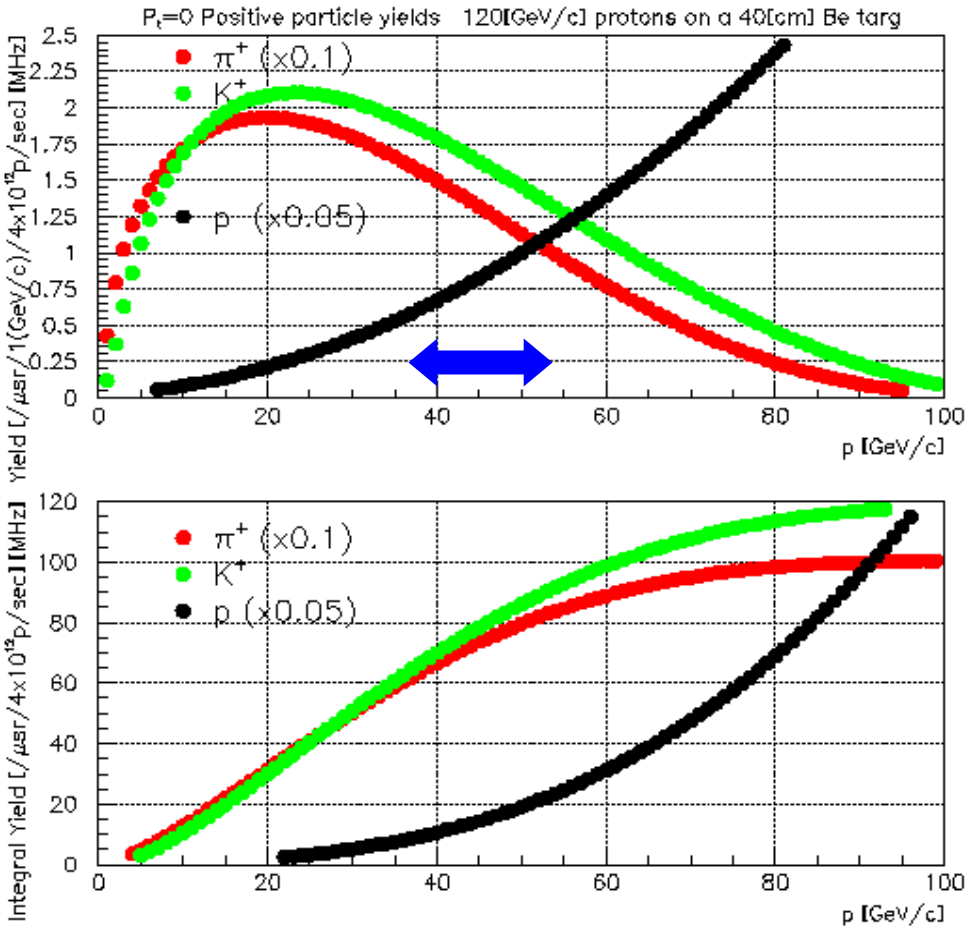
Acceptance (Region I) = □ 5%

20 events per year
@ BR = 10^{-10} (Region I)

Fermilab Technique

- High Flux Un-separated 37-53 GeV/c Beam - 4% K^+
  - Proton / π^+ : 120 / 100, **230 MHz total, ~30 MHz/cm^2 in beam tracker.** 1x1 cm^2 beam in decay volume.
  - 10 MHz K^+, 1.7 MHz decay in the accepted decay volume.
  - 5 x10^{12} 120 GeV proton /sec in slow spill from the Main Injector to produce the required K^+ beam (17% of design intensity)
  - Debunched proton beam required (~10% 53MHz ripple ok).
- Apparatus
  - Decay in flight spectrometer with both velocity (RICH) and momentum (magnetic) spectrometer both both K^+ and π^+.
  - Significant requirements on photon vetoes, CsI ineff < 1x10^{-6} @ high energy.
  - All detector technologies used are well established
  - **Redundancy** is critical to measure all backgrounds
  - Exploit signal regions on both sides of $K^+ \rightarrow \pi^+\pi^0$.

Main Injector (120 GeV proton) particle production yields.



5x10^{12} protons/pulse from the Main Injector (120 GeV) produces in 37-53GeV/c band:

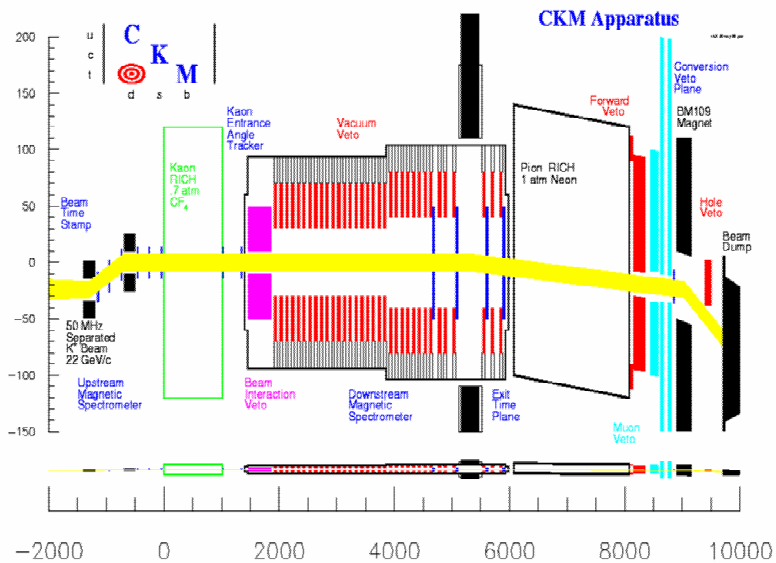
10 MHz K^+

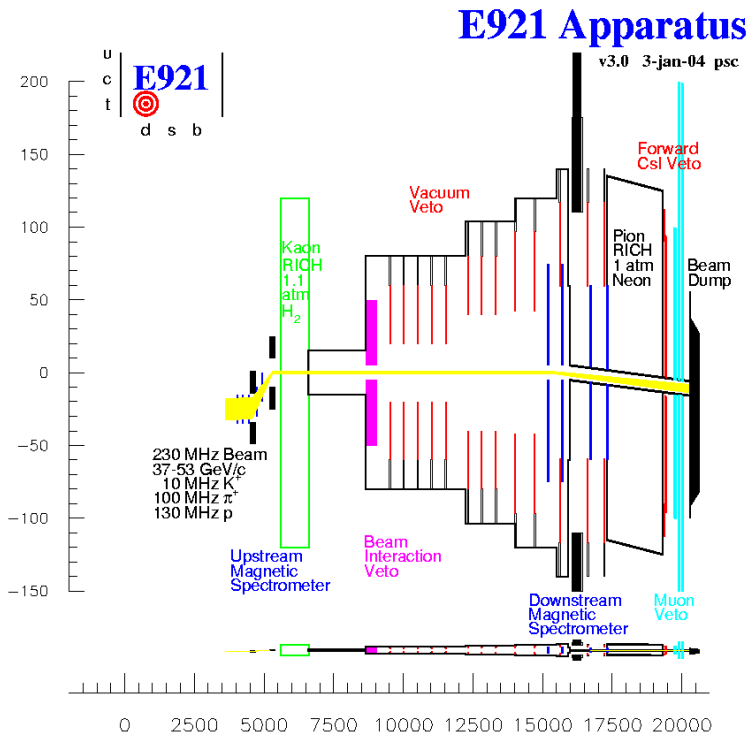
100 MHz π^+

120 MHz protons

Fermilab Apparatus

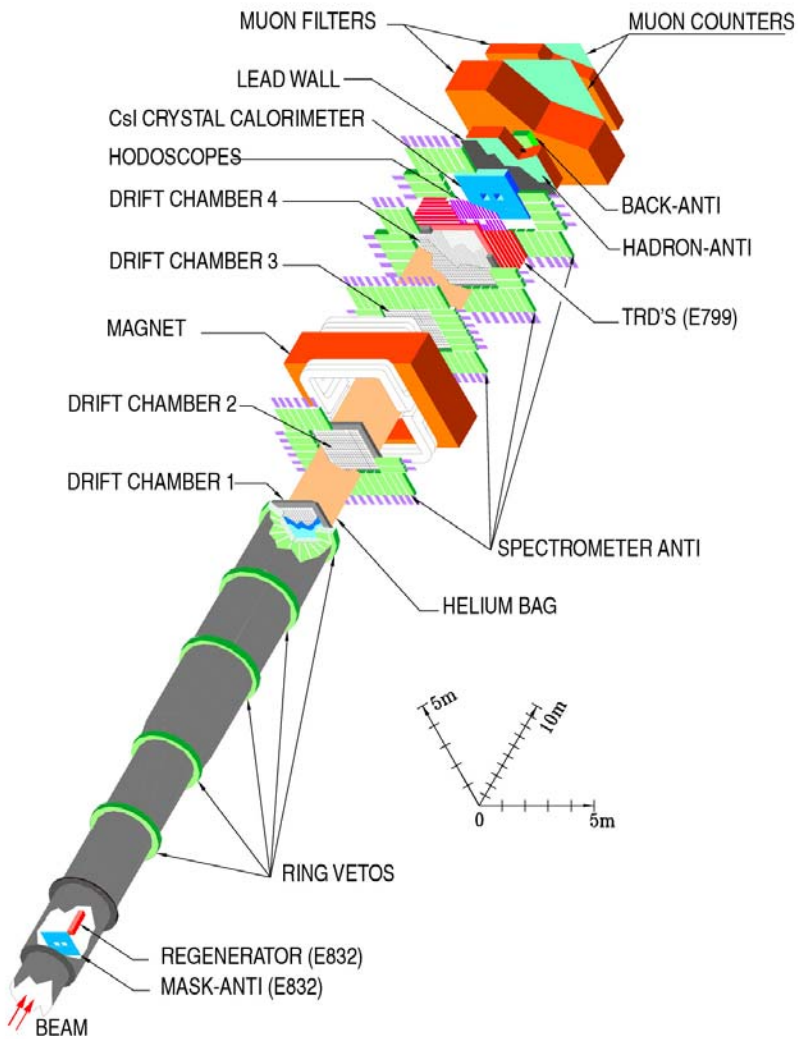
- Decay in flight
- Redundant high rate detectors and veto systems.
- separated K+ beam at 22 GeV/c. Un-separated + beam at 37-53 GeV





Exploiting the Legacy of the KTeV Detector.

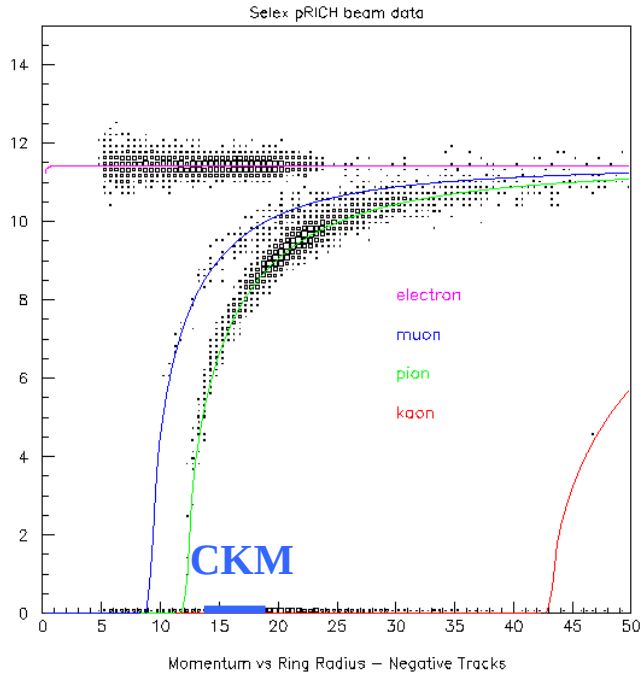
- **Pure CsI Calorimeter: (Energy resolution < 1% at $\langle E_\gamma \rangle$ = 10GeV; π/e rejection of > 700)**
- **Four drift chambers: resolutions: ~100μm**
- **Transition radiation detectors: (π/e rejection of > 200) [E799]**
- **Intense beams: 5 x 10^{12} protons on target per spill → 5 x 10^9 kaons/spill**

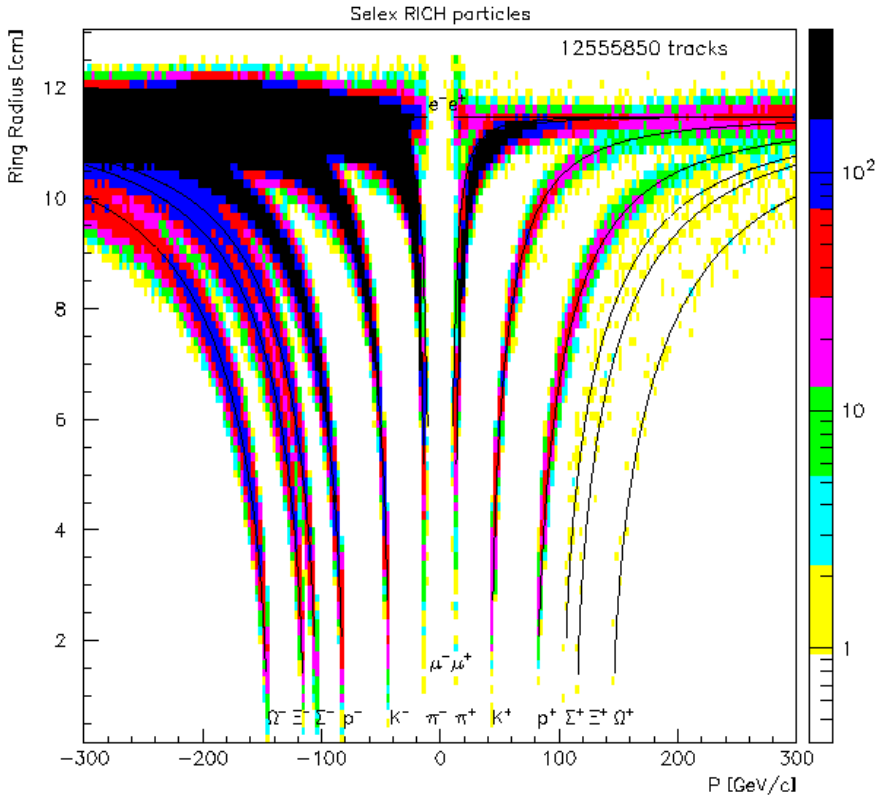


- **For E_K ~ 70 GeV: K_S: $\gamma\beta c\tau$ ~ 3.5m**
  K_L: $\gamma\beta c\tau$ ~ 2.2 km

RICH Based Velocity Spectrometer

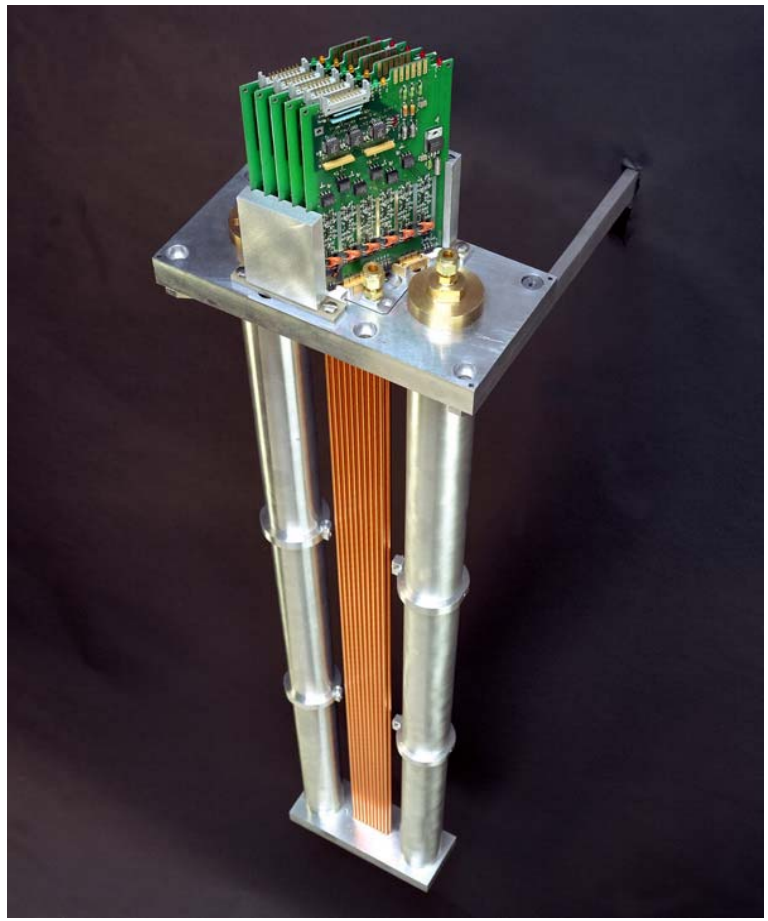
- High rate high resolution
- Matched to momentum resolution
- Based on successful Selex RICH
- Photo-detectors are individual PMTs





Straws in Vacuum: Old Wine, New Bottle.

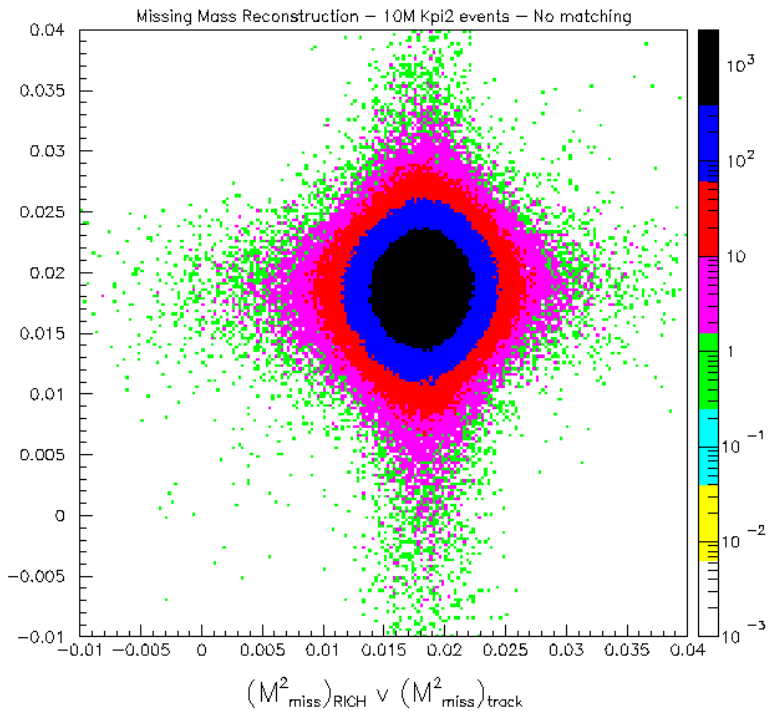
- Mechanical properties extensively studied. (Fermi-Pub 02-241-E)
- Prototype operating in vacuum.
- Proven Principle. Now ready for detailed engineering.



Simulated Fermilab Spectrometer Performance

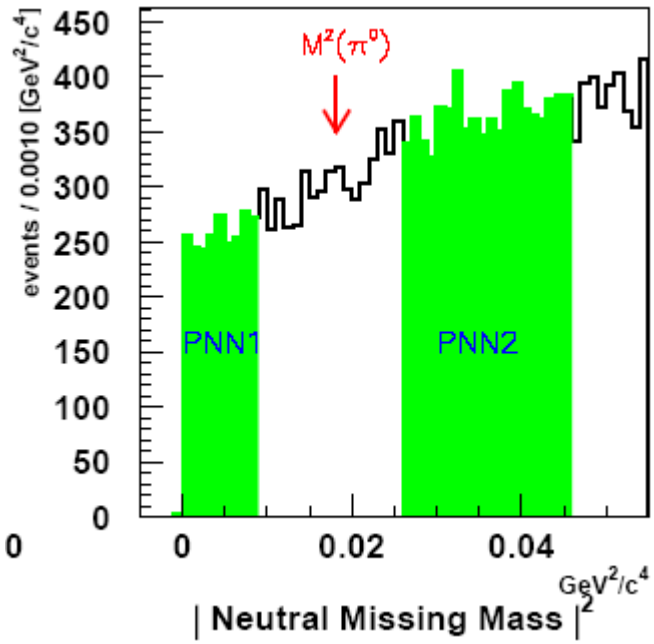
- Missing mass resolution for $M^2_{\pi^0}$ from $K^+ \rightarrow \pi^+ \pi^0$:
- Matched resolution from momentum and velocity spectrometers
- Low non-Gaussian tails
- Uncorrelated measurements

  Backgrounds from Mis-measurements to be studied and quantified from the data
- Study needs to be redone for P940



Fermilab Acceptance

- Acceptance was re-evaluated for P940. Decay fraction increased 13% → 16.5%
- PNN2 acceptance limited to 1.4x PNN1 pending more serious background studies
- Nearly identical sensitivity as CKM for same 120 GeV beam incident.



parameter	CKM	E921
$K^+ flux[MHz]$	30	10
beam-sec/year	0.75×10^7	0.75×10^7
years of data	2	2
sensitive K decays	5.8×10^{13}	2.5×10^{13}
nominal Branching ratio	1×10^{-10}	1×10^{-10}
taxes (other losses)	-15%	-15%
PNN1 (s+b)	$95+ \leq 10$	$44+ \leq 4$
PNN2	$(130+ \leq 40)$	$62+ \leq 20$
total	$95+ \leq 10$	$106+ \leq 24$
Br precision	$< 11\%$	$< 12\%$

Fermilab Backgrounds Studies

Background Source	Effective BR ($\times 10^{-12}$) CKM	P940
• $K^+ \rightarrow \mu^+ \nu_\mu$	< 0.04	-
• $K^+ \rightarrow \pi^+ \pi^0$	3.7	~5
• $K^+ \rightarrow \mu^+ \nu_\mu \gamma$	< 0.09	-
• $K^+ A \rightarrow X K^0_L \rightarrow \pi^+ e^- \nu$	< 0.14	TBD
• $K^+ A \rightarrow \pi^+ X$ (trackers)	< 4.0	TBD
• $K^+ A \rightarrow \pi^+ X$ (gas)	< 2.1	TBD
• Accidentals (K^+ + beam track)	-	TBD
• Accidentals (2 K^+)	0.51	0.17
• TOTAL	<10.6	TBD

Fermilab Near-term Plan

- In the middle of this redesign now – goals:
  - Complete the unseparated beamline design for KTeV hall.
  - Assess KABES feasibility in a 230 MHz beam
  - Re-evaluate backgrounds from Kaon interaction in detectors
  - Estimate backgrounds from non-kaon interaction accidentals
  - Evaluate PNN2 cuts, acceptance and backgrounds
  - Re-assess losses from deadtime, reconstruction, …
- The Plan
  - Complete the list above
  - Have external technical review of the redesign (a-la CKM)
  - Return to Fermilab and the PAC with a vetted re-design
  - Time scale of a few months yet.

Rare π^+ Decays: What's New? What's Left??

2003 PDG.

π^+ DECAY MODES

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the appropriate Search setions (Massive Neutrino Peak Search Test, A^0 (axion), and Other Light Boson (X^0) Searches, etc.).

	Mode			Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\mu^+\nu_\mu$		[a]	(99.98770 ± 0.00004) %	
Γ_2	$\mu^+\nu_\mu\gamma$		[b]	$(2.00 \pm 0.25) \times 10^{-4}$	
Γ_3	$e^+\nu_e$		[a]	$(1.230 \pm 0.004) \times 10^{-4}$	
Γ_4	$e^+\nu_e\gamma$		[b]	$(1.61 \pm 0.23) \times 10^{-7}$	
Γ_5	$e^+\nu_e\pi^0$			$(1.025 \pm 0.034) \times 10^{-8}$	
Γ_6	$e^+\nu_e e^+ e^-$			$(3.2 \pm 0.5) \times 10^{-9}$	
Γ_7	$e^+\nu_e\nu\overline{\nu}$			$< 5 \times 10^{-6}$	90%
	Lepton Family number (*LF*) or Lepton number (*L*) violating modes				
Γ_8	$\mu^+\overline{\nu}_e$	*L*	[c]	$< 1.5 \times 10^{-3}$	90%
Γ_9	$\mu^+\nu_e$	*LF*	[c]	$< 8.0 \times 10^{-3}$	90%
Γ_{10}	$\mu^- e^+ e^+\nu$	*LF*		$< 1.6 \times 10^{-6}$	90%

Physics of $\pi e2(\gamma)$ decays.

- Helicity suppression constrains the branching fraction allowing new physics to peak out.
- The prediction of $R = \Gamma(\pi e2(\gamma))/\Gamma(\pi\mu2(\gamma))$ is remarkably well understood.

$$R_{\mathbf{theory}} = 1.2352(5) \times 10^{-4} \quad \text{(PRL V71, 1993)}$$
$$R_{\mathbf{expt}} = 1.2300(40) \times 10^{-4} \quad \text{(PSI,Triumf)}$$

Window of x8 remains to search for new physics.

Measuring this BR and $\pi e2\gamma$ Form-Factor Probes:

- Multiple Higgs multiplets, $M_{\mathbf{H}} > M_{\mathbf{Z}}$.
- Lepto-quarks, mass range > 200 GeV/c^2
- Quark compositeness > 1 TeV/c^2.
- Tev-scale Brane worlds.
- Some Marjorna neutrino mixing models.

Consider a toy pion configuration…

- Narrow band (2% bite) at 20 GeV π/non-π ratio of about x4.
- Ultra-low mass: Run without Kabes tracker, reduce beam H_2 RICH pressure by x2 to achieve a threshold of about 18 GeV. Trigger requires RICH, beam sees ~1×10^{-4} X_0
- Set beam rate to 100 MHz, requires about 2e12 protons/pulse, corresponds to about 6 MHz of pion decays in the P940 decay volume.

6 MHz of 20 GeV pion decays:

- Guess 10% acceptance for $\pi e2$ decays, leads to 120 hours of clock time with 30% beam duty factor, 3-second cycle to get to 10 million accepted events.
- Guess 5% acceptance for $\pi e2(\gamma)$ decays, leads to about 500 hours of clock time with 30% beam duty factor, 3-second cycle for 100K events (5.5×10^{-7} branch).

Sounds Good, But: Systematic issues?

- Background from $\pi\mu 2$ followed by muon decay. Effective raw branching ratio is about 2%.
- Crucial issues are: Demonstrating acceptance understanding at the sub-per-mil level! What are the tricks? Where are the cancellations? Likewise background control at the sub-per-mil level.

Are there intrinsic advantages to In-flight?

- Minimal material. High energy reduces the effect of residual material.
- Excellent electron and photon ID and energy resolution. (CsI or LKr).
- Excellent tag of primary pion.
- Need an acceptance control argument.

Summary & Outlook

- The existing KTeV and NA48 experiments and their proton drivers are both strong foundations for new high sensitivity K^+ and π^+ rare decay experiments.
- The recent breakthrough performance of the micro-megas "KABES" technology allows consideration of an unseparated beam experiment to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.
- The high efficiency of tagging high-energy muons and photons together with comparable Region-I and Region-II acceptance are large potential advantages.
- There may be a future for rare decays at Fermilab and CERN after all!

Extra Slides

P5

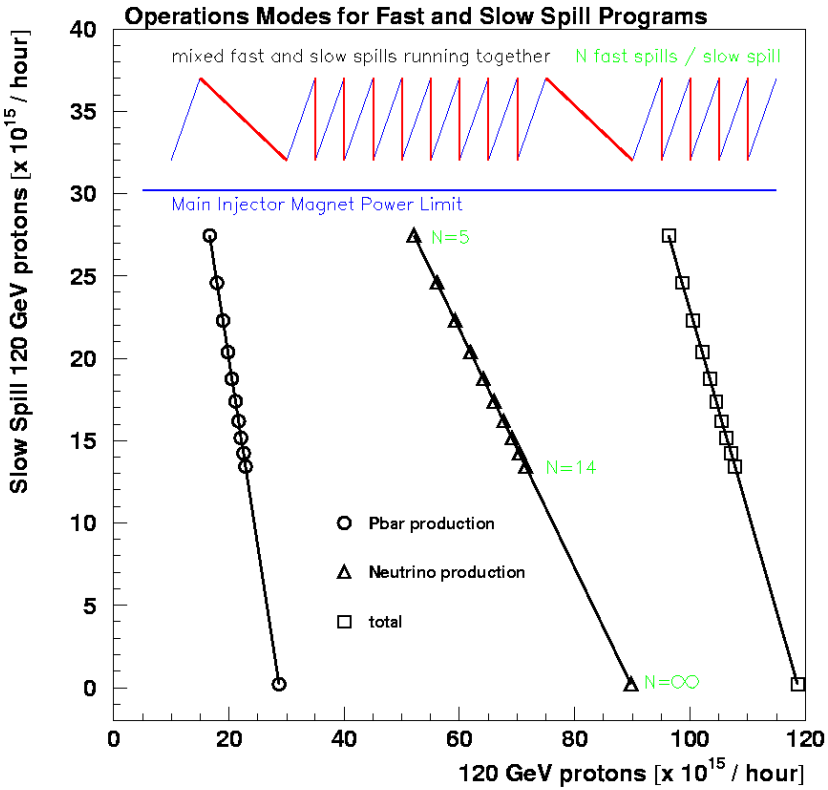
- The Particle Physics Project Prioritization Panel (P5) reviewed BTeV, CKM and the Tevatron detector upgrades; concluding for CKM:

Evaluation – The subpanel was impressed with the excellent work of the proponents on the design of the experiment and their successful prototyping results. CKM is an elegant world-class experiment, which would be able to produce important physics results. However, the committee assigns it a lower priority than the BTeV experiment. The main reason is that BTeV has a much broader physics program at a comparable cost.

Suggestions Based on Prioritization – The present Fermilab plan calls for a similar funding profile and time-line for BTeV and CKM construction, with both starting to take data around 2009. The P5 Subpanel believes that this plan is likely to be too ambitious given the need to optimize the physics from the Tevatron Collider, as well as the desire to have BTeV completed promptly. *Based on current budgetary models, P5 does not recommend proceeding with CKM.*

Main Injector Proton Economics

- o We require debunched protons from the Main Injector (10% 53MHz ripple is OK).
- o Separate fast (neutrino+Pbar) and slow spill Main Injector cycles make these different modes of operation independent by timesharing
- o N=8 fast cycles / slow cycle gives both fast and slow spill 2/3 of the maximum available to either.
- o Setting N in this model is a program planning decision.



Fermilab Changes from CKM Design

- o Beamline — existing NM2 beamline and NM3-4 detector hall (KTeV)
  - 120 GeV proton transport estimated at 250K$+50% (C. Brown)
  - Target station can be modified – designed for required intensity
- o Kaon RICH — 10 $\rightarrow$ 12m, radiator gas to H_2 at 1.1 atm – only sees beam Kaons
- o DMS — same strawtube in vacuum design as CKM, hole for 10cm beampipe
- o Pion RICH
  - Same basic design as CKM (1atm Ne, 3000 1/2in PMTs)
  - Optics modified to accommodate beampipe down the middle.
- o Photon Vetoes
  - 90% of photons now hit CsI $1-\varepsilon \sim 3\times10^{-6}$ for E>1 GeV
  - VVS - 5 existing Pb-scint rings from KTeV + 9 new ones of CKM design
  - Photon energy threshold can be >1.5 MIP everywhere.
- o Muon Vetoes — combined KTeV MVS + descoped CKM design
- o UMS — replace CKM MWPC's with μMegas of KABES design