The Fermilab Kaon Physics Program

R. Tschirhart , Fermilab

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Villars

I. KTeV status in a nutshell.

II. The future Fermilab rare decay program.

III. Constrasts of the CERN and Fermilab future programs.

Relevant Topics on the KTeV Analysis Horizon.

- $K_L \rightarrow \pi^0 e^+ e^-$ backgrounds severe, but well understood.
- $K_L \rightarrow \pi^0 \mu^+ \mu^-$ backgrounds possibly better, analysis in progress.
- LFV modes **$K_L \rightarrow \pi\mu e$, $\pi\pi\mu e$**, and **$\pi \rightarrow \mu e$** near final results.
- Final KL charge asymmetry (δ_e) data set double that published, final analysis underway.
- Final Re(ε'/ε) data set double that published, final analysis underway.

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.*"

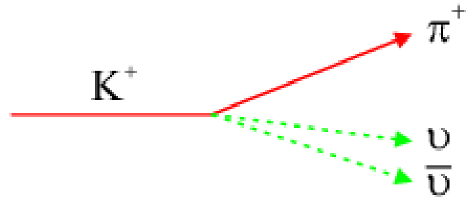
- Adapt to an unseparated ~45 GeV/c beam in KTeV hall - **P940**
  - Demonstration of μMegas in NA48 → tracking in 230MHz tractable
  - Detectors other than beam tracker remain identical.
  - Vetoing photons gets easier (E_{π^0} > 1 GeV → >7 GeV)
  - Accidental backgrounds?

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}, $K_{\mu 3}$, $K_{\mu 4}$, $K^+ \to \pi^+ e^+ e^-$, $K^+ \to \pi^+ \mu^+ \mu^-$
    - 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

Backgrounds a (the) Problem!

Signal



Tools

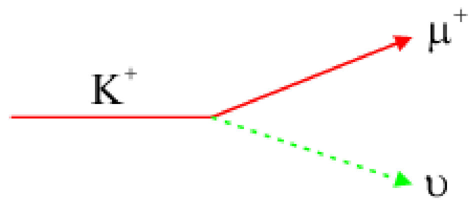
- momentum
- direction
- particle ID
- 3-body decay

For every 10 billion K+ decays we get:

1

$(BR = 1x10^{-10})$

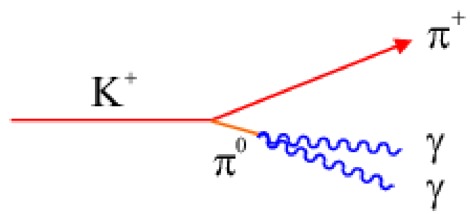
Backgrounds



- particle ID
- 2-body decay

6,350,000,000

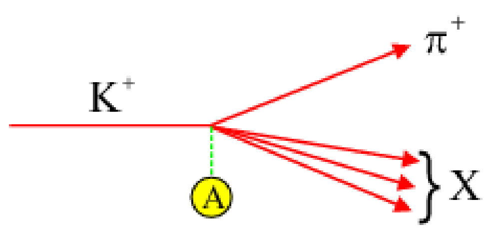
(BR = 0.635)



- particle ID
- 2-body decay

2,120,000,000

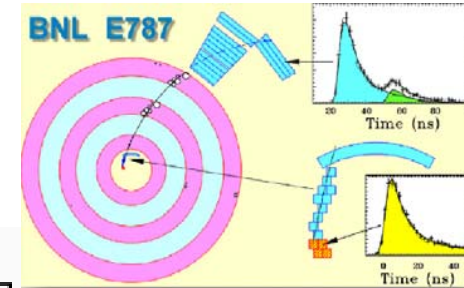
(BR = 0.212)

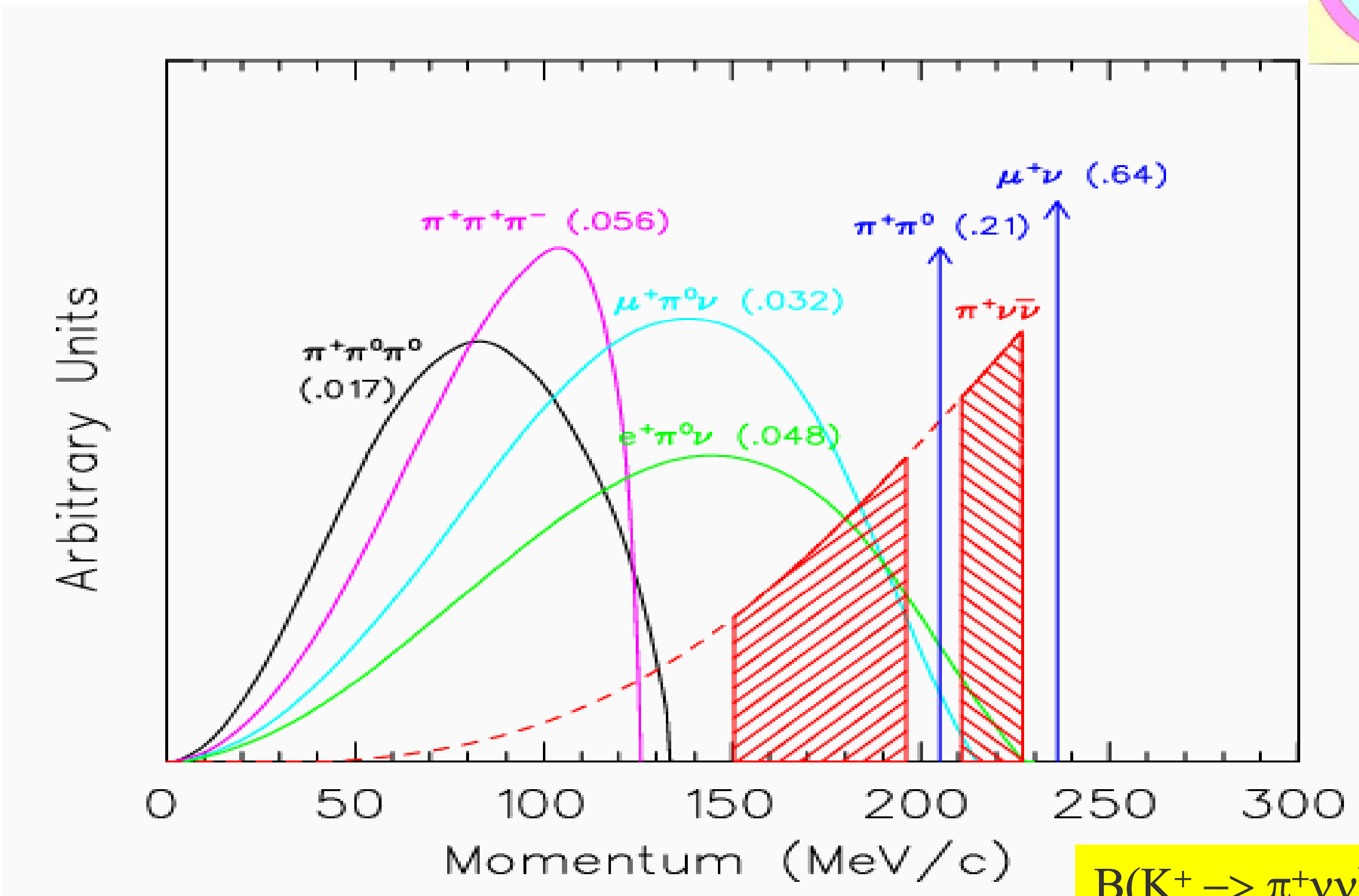


- γ-veto
- charged veto
- low material

lots!

Stopped (COM) K^+ Kinematics





$B(K^+ \rightarrow \pi^+\nu\nu) = 15^{+13}_{-9} \times 10^{-11}$

3 events seen.

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

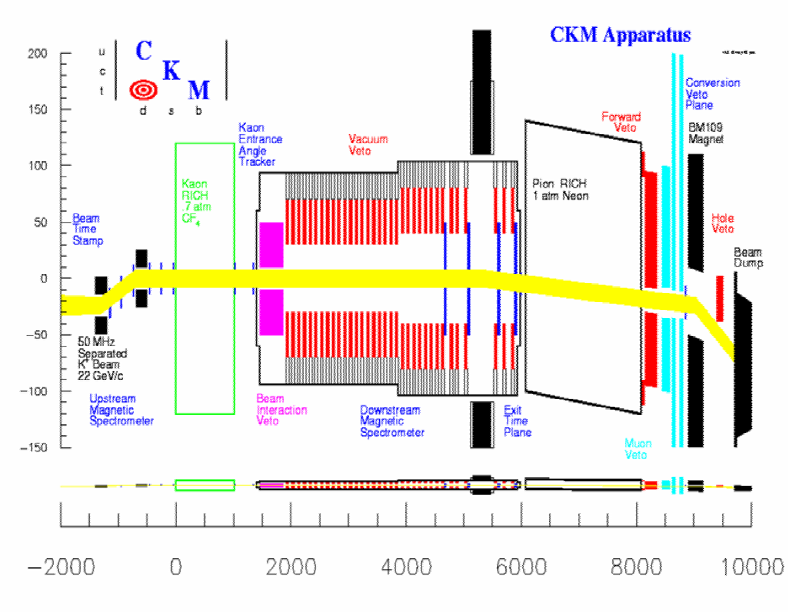
- Must measure K^+ momentum to effectively recover rest-frame Kinematics.
- Relatively large decay volume.
- Not possible to follow the π–μ–e decay chain.
- Decay occurs in vacuum, no low-energy K^+A interactions, no complex energy loss mechanisms.
- Kinematics ***and backgrounds*** of Region-I and Region-II are similar, leads to potentially higher total acceptance.
- High energy muons and photons from $K\mu 2$ and $K\pi 2$ are in principle easier to veto.
- Existing high performance Experiments: KTeV & NA48.

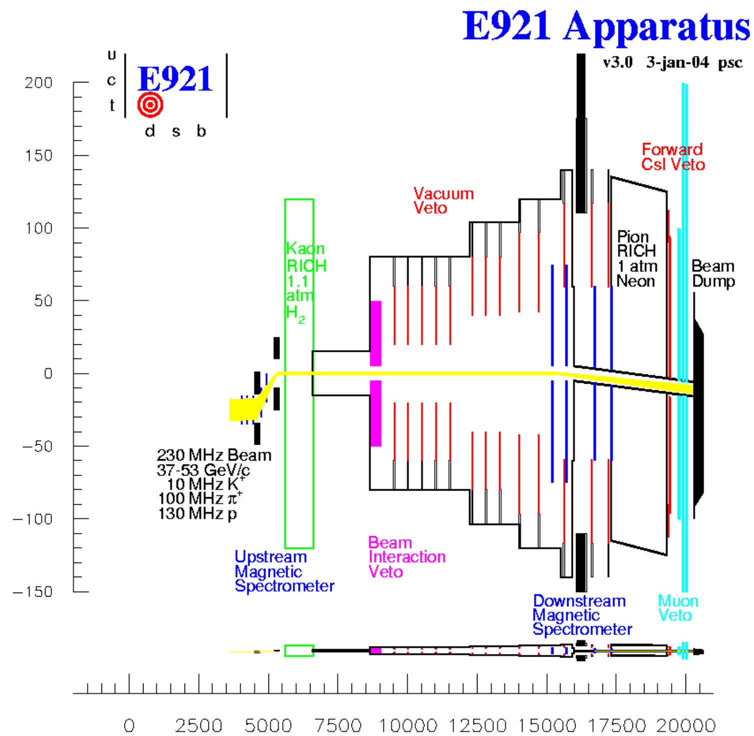
Fermilab Technique

- 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 the $K^+ \rightarrow \pi^+\pi^0$ background peak.

Fermilab Apparatus

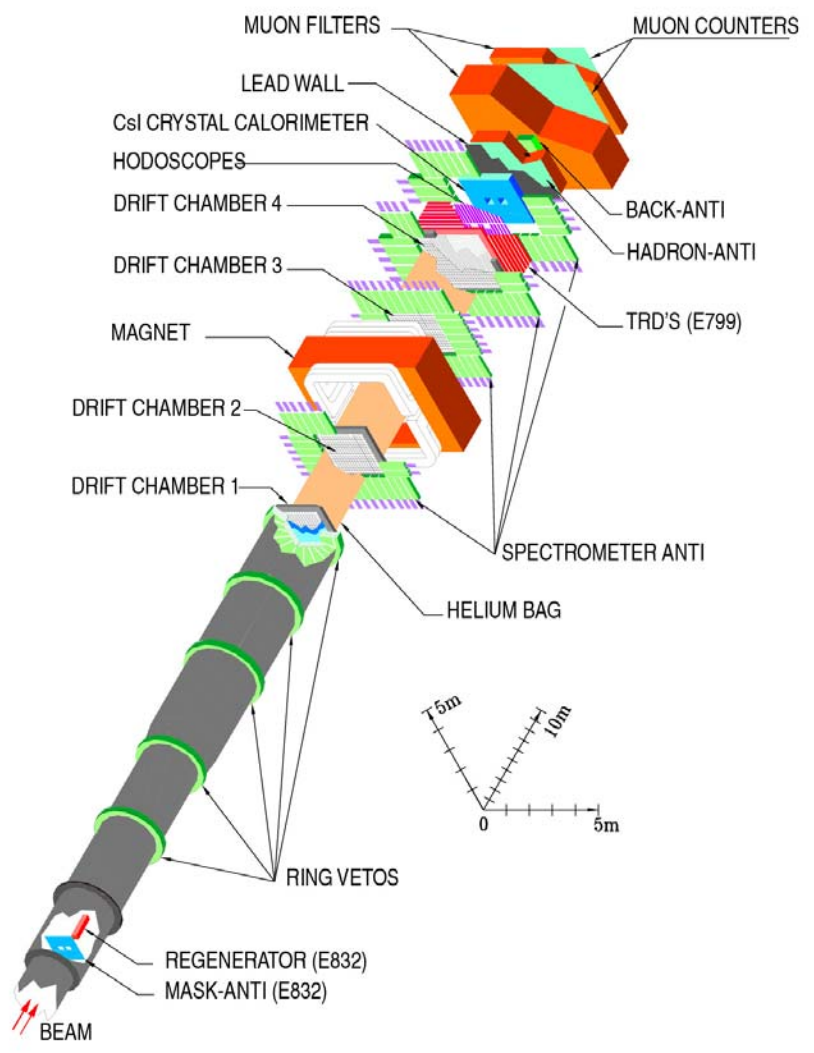
- Decay in flight
- Redundant high rate detectors and veto systems.
- separated K+ beam at 22 GeV/c. Un-separated + beam at 37-53 GeV





Exploiting the Legacy of the KTeV Detector.

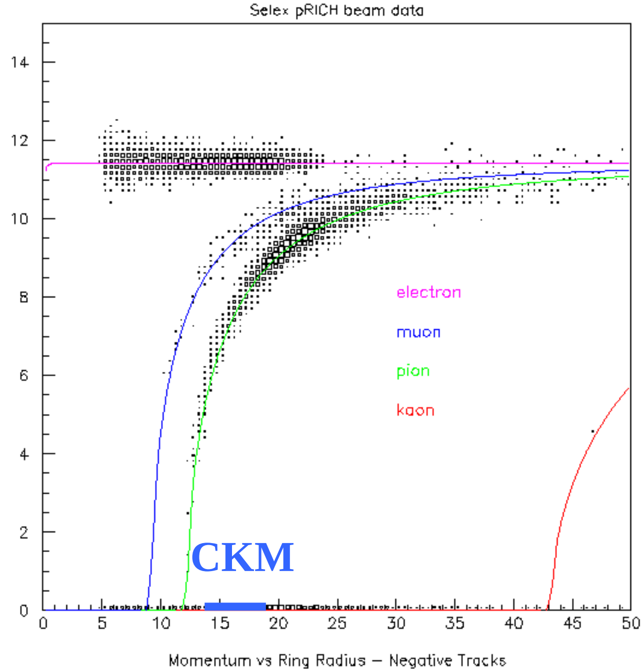
- **Pure CsI Calorimeter:**
(Energy resolution $<$ 1% at $<E_\gamma>$ = 10GeV; π/e rejection of $>$ 700)
- **Four drift chambers:**
resolutions: ~100μm
- **Transition radiation detectors:**
(π/e rejection of $>$ 200) [E799]
- **Intense beams: 5 x 10^{12} protons on target per spill → 5 x 10^9 kaons/spill**

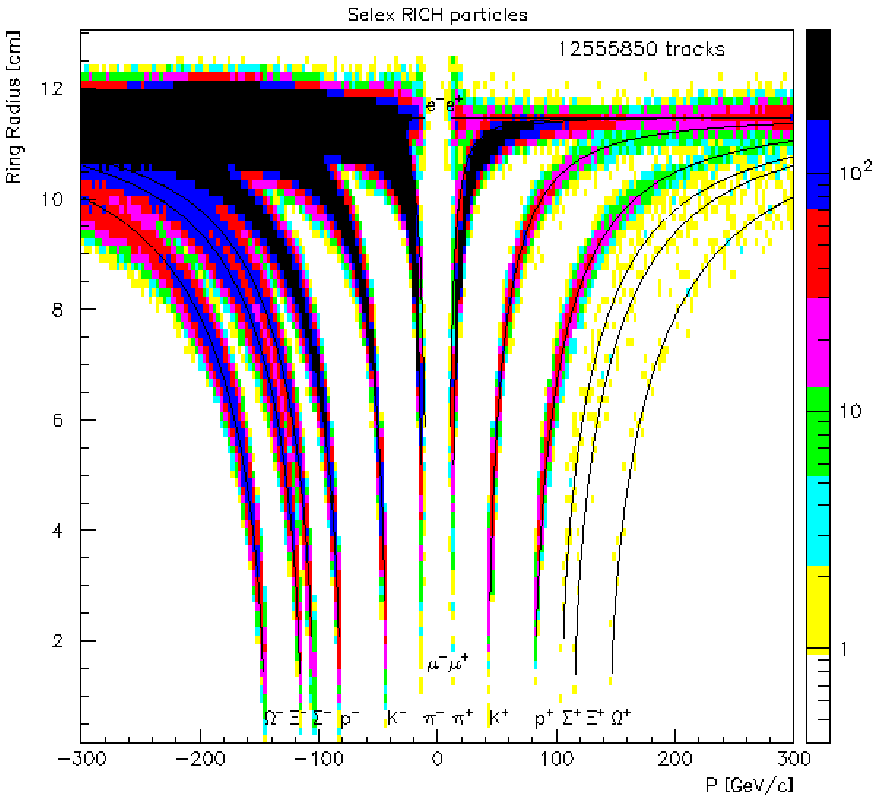


- **For E_K ~ 70 GeV: K_S: $\gamma\beta c\tau$ ~ 3.5m**
K_L: $\gamma\beta c\tau$ ~ 2.2 km

RICH Based Velocity Spectrometer

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

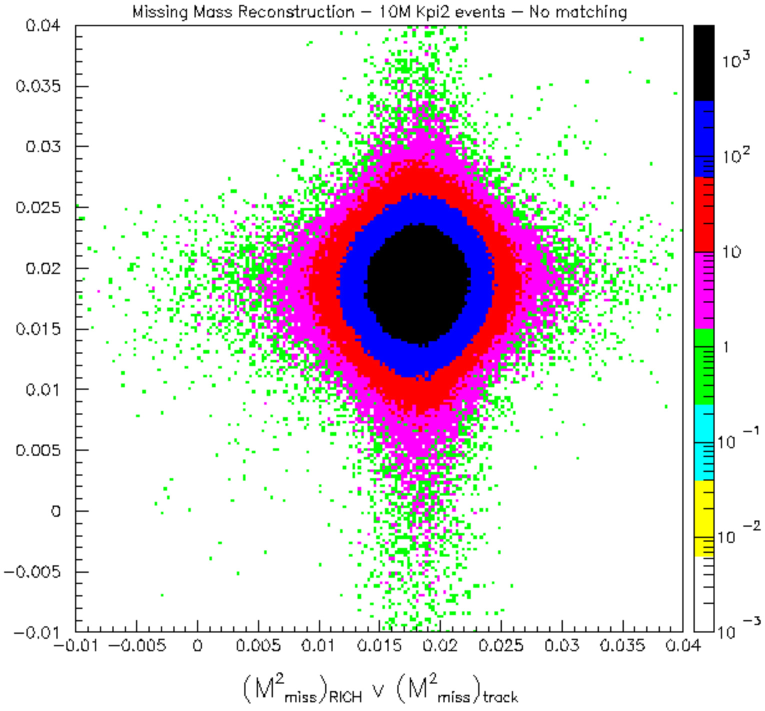




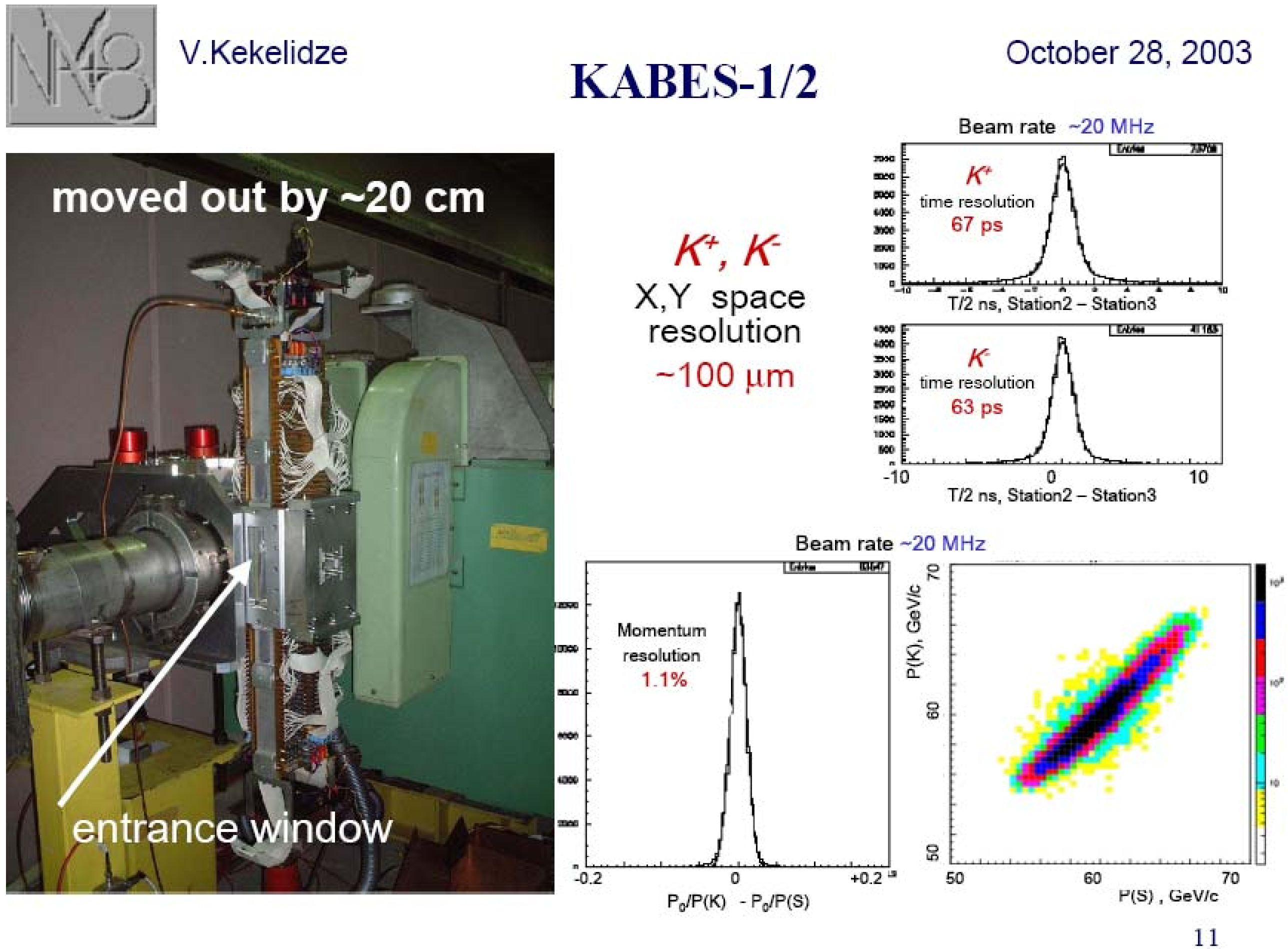
Simulated Fermilab Spectrometer Performance

- 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



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



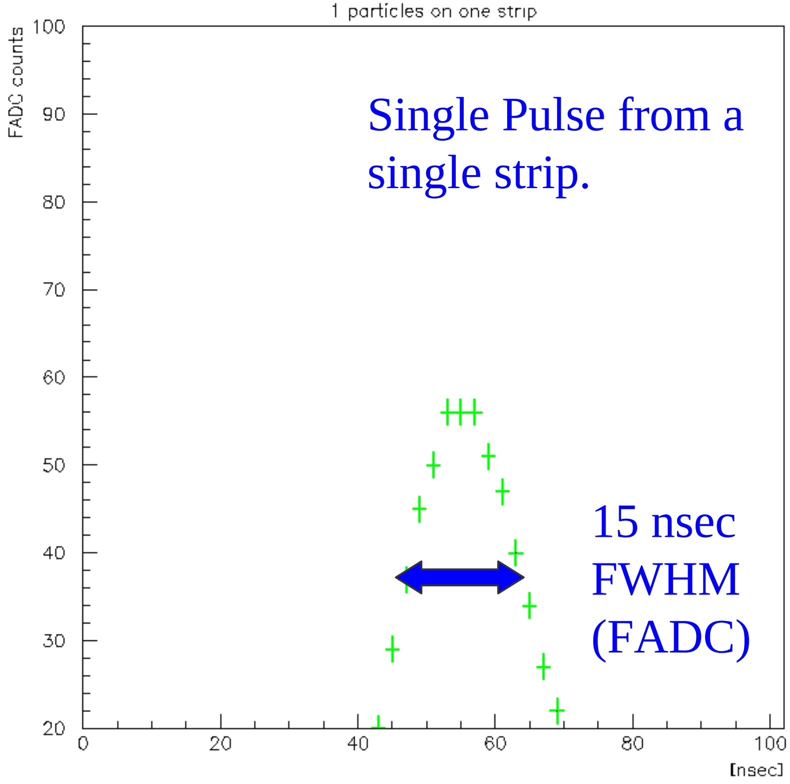
3 MHz/cm^2, 700 psec tag. No rate effects seen.

The Recent KABES Test Beam

Fermilab and NA48/3 recently collaborated in the study of ultra-high rate tracking in a high energy un-separated beam

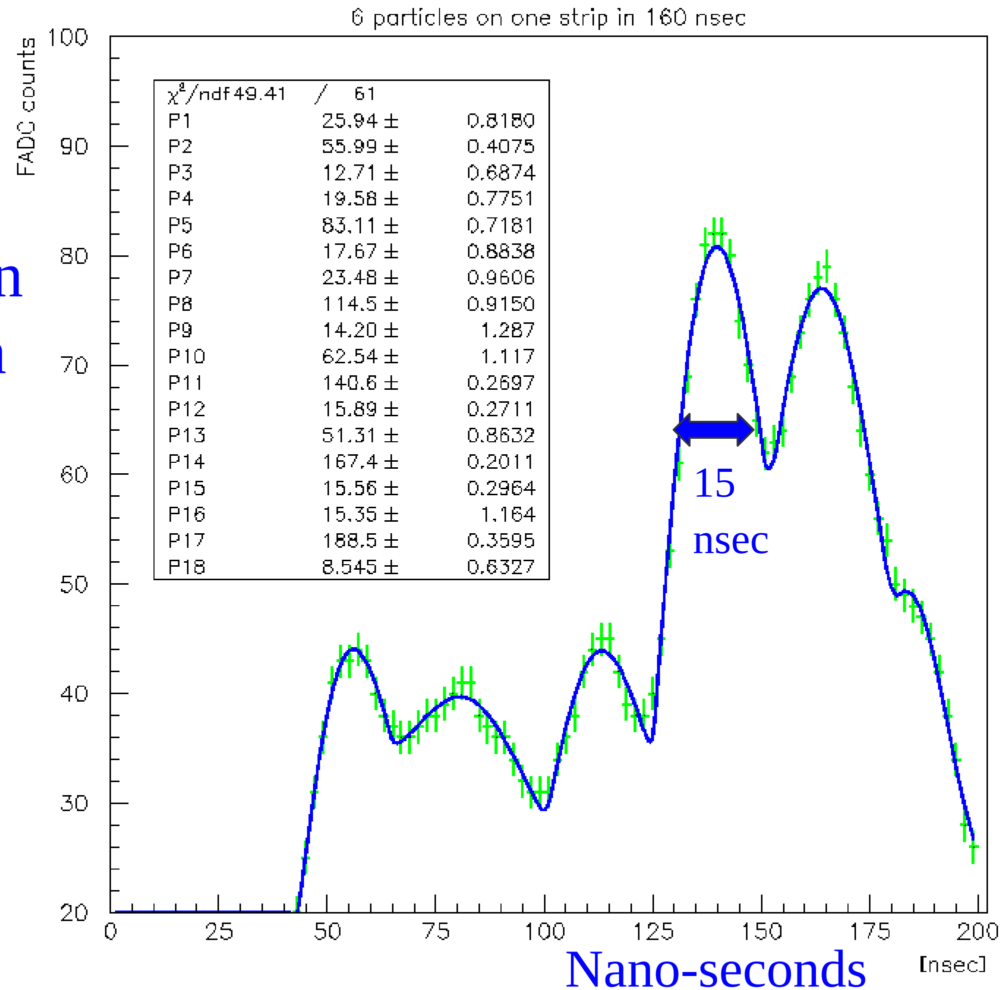
Reduced gap (25 μm) KABES chambers instrumented with Flash ADCs and TDCs were studied with the high performance NA48 detector and beamline.

The new chambers functioned well at rates **x4 higher** than the Fermilab requirement of 230 MHz.



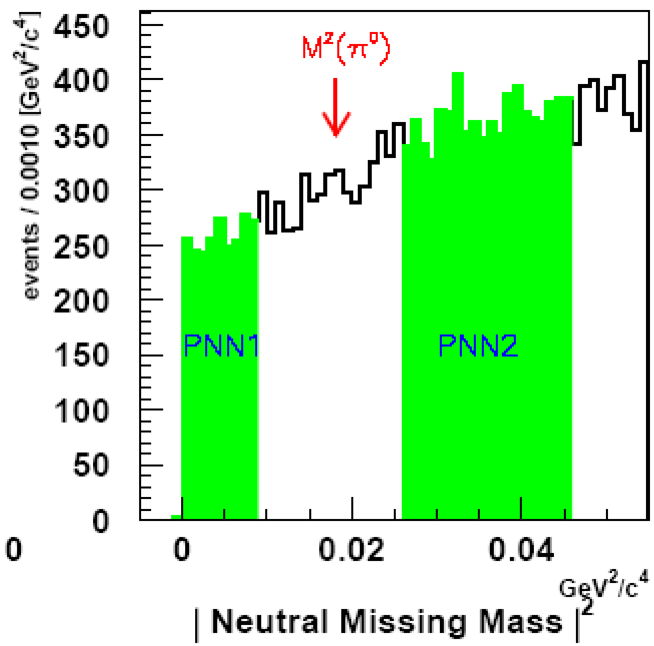
Robust Rate Performance:

Six similar pulses fit in a train of pulses corresponding to an instantaneous rate of 1- GHz per strip! (800 μm strips).



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
$K^+ \to \mu^+ \nu_\mu$	< 0.04	-
$K^+ \to \pi^+ \pi^0$	3.7	~5
$K^+ \to \mu^+ \nu_\mu \gamma$	< 0.09	-
$K^+ A \to X K^0_L \to \pi^+ e^- \nu$	< 0.14	TBD
$K^+ A \to \pi^+ X$ (trackers)	< 4.0	TBD
$K^+ A \to \pi^+ X$ (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
  - Return to Fermilab and the PAC with a vetted re-design
  - Time scale of a few months yet.

Contrasting the Fermilab and CERN Approaches.

- Fundamentally similar approaches.
- Fermilab requires lower total beam rate, but comparable rates/strip.
- Fermilab design currently has higher suppression of Kμ2 background.
- NA48 has an existing high-rate K^+ beam and excellent operational spectrometer that can evolve into NA48/3.

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 of the high-energy in-flight technique.
- There may be a future for rare decays at Fermilab and/or CERN after all!

Extra Slides

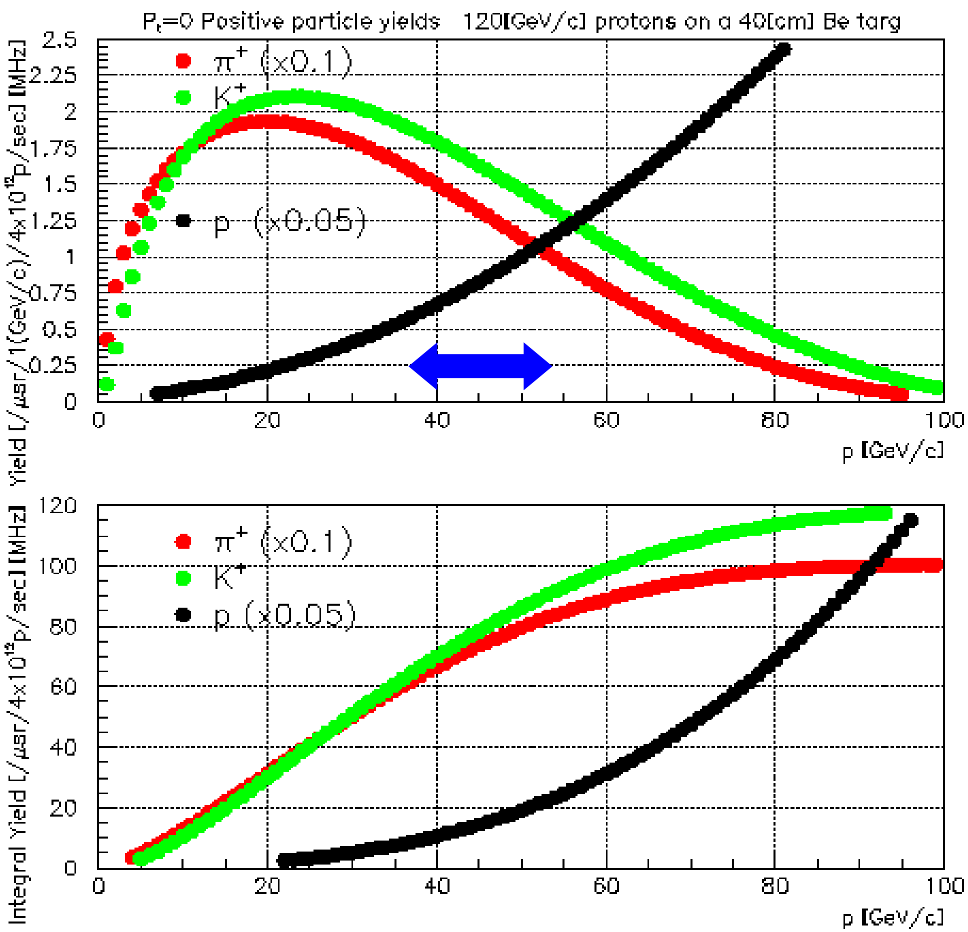
P5

- 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 (120 GeV proton) particle production yields.



5×10^{12} protons/pulse from the Main Injector (120 GeV) produces in 37-53GeV/c band:

10 MHz K^+

100 MHz π^+

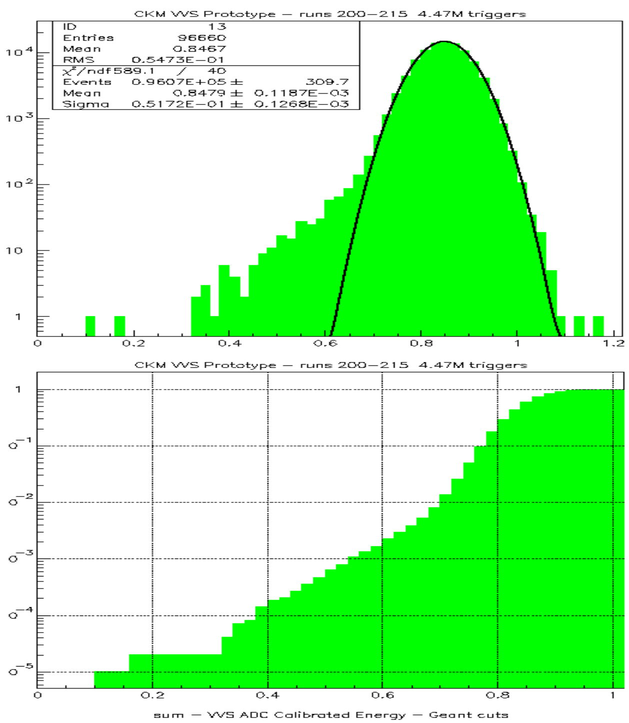
120 MHz protons

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.

Photon Veto Inefficiency and Technology

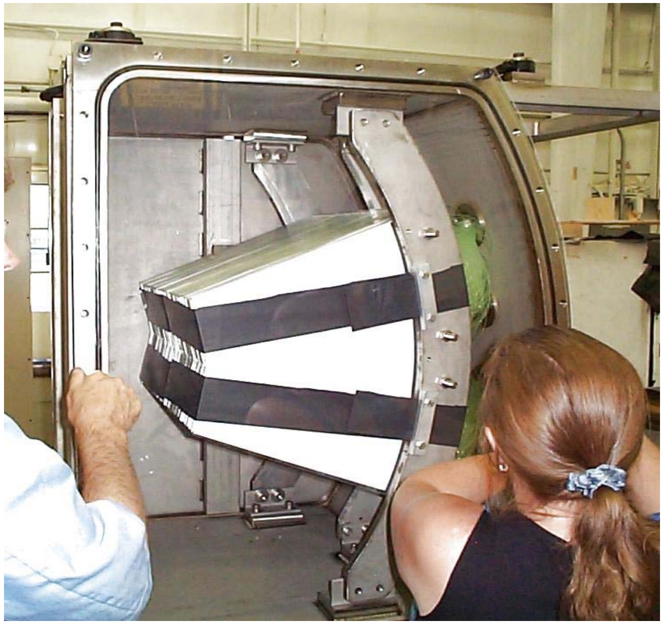
- 0.3% VVS Pb-Scintillator Prototype built
- Tested at JLAB in an e⁻ beam, published in NIM soon.
- Achieved <1x10^{-5} (3x10^{-6}) veto inefficiency at 1 GeV (required 3x10^{-5})



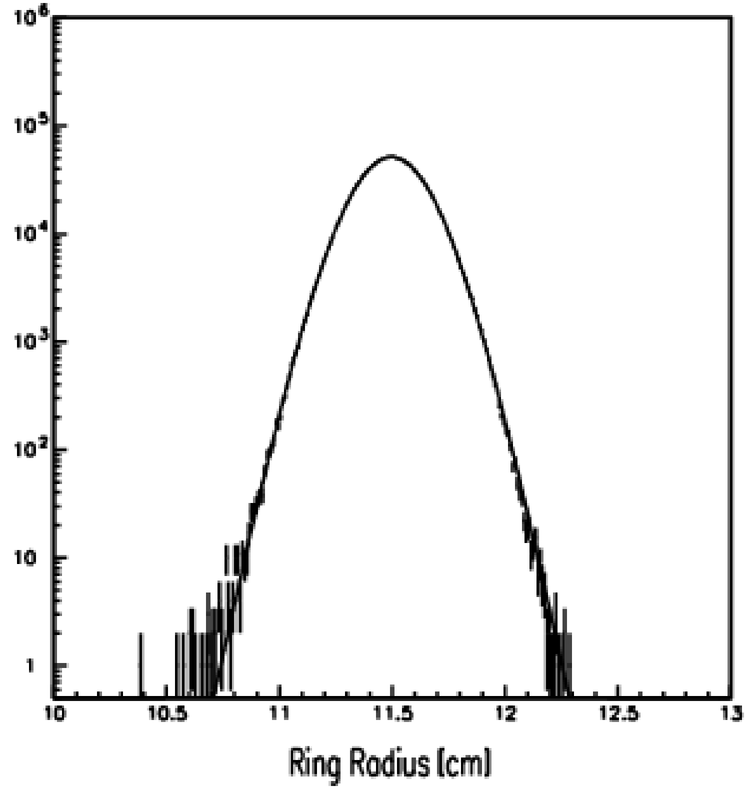
Inefficiency

GeV

GeV



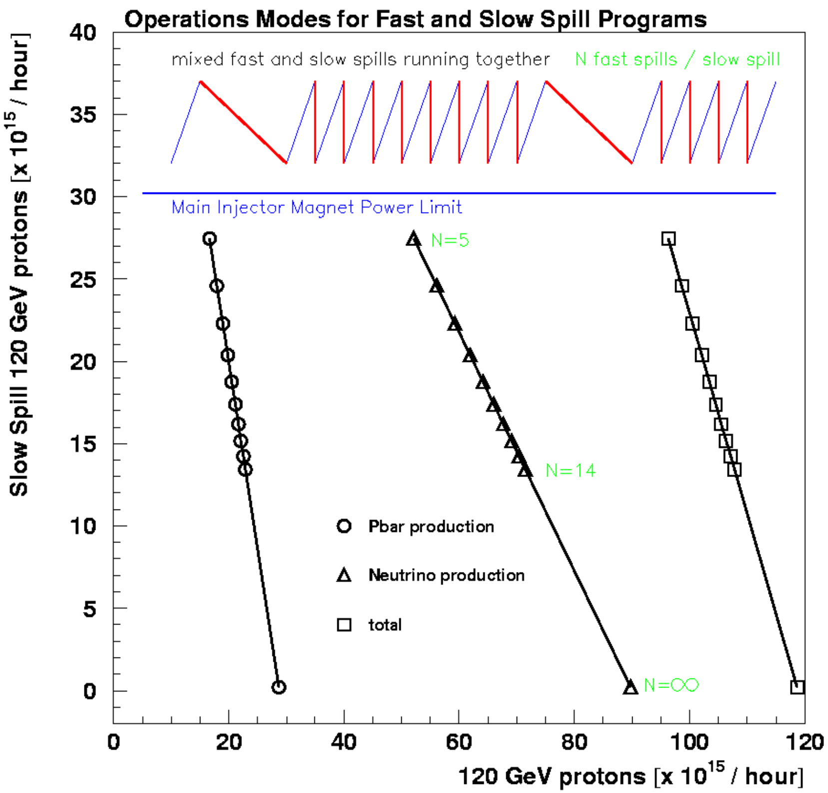
SELEX RICH Rings Gaussian over Five Orders of Magnitiude



β=1 Rings

Main Injector Proton Economics

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



Fermilab Changes from CKM Design

- 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
- Kaon RICH $10 \rightarrow 12$m, radiator gas to H_2 at 1.1 atm – only sees beam Kaons
- DMS same strawtube in vacuum design as CKM, hole for 10cm beampipe
- Pion RICH
  - Same basic design as CKM (1atm Ne, 3000 1/2in PMTs)
  - Optics modified to accommodate beampipe down the middle.
- Photon Vetoes
  - 90% of photons now hit CsI $1\text{-}\varepsilon \sim 3\text{x}10^{-6}$ 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.
- Muon Vetoes combined KTeV MVS + descoped CKM design
- UMS replace CKM MWPC's with μMegas of KABES design