Near-term Measurements of $K^+ \to \pi^+ \nu \bar{\nu}$

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Outline

- Motivation
- Prior Experiments
- Stopped K’s versus Decays-in-flight
- CERN NA-62
- Opportunity with the Fermilab complex
- P996
- Summary

Flavor Physics in the LHC Era

New Physics found at LHC
⇒ New particles with unknown favor- and CP-violating couplings

New Physics NOT found at LHC

Precision π, K, B, μ, and τ expts will be needed to help sort out the flavor- and CP-violating couplings of the NP.

Precision π, K, B, μ, and τ expts will be needed since they are sensitive to NP at mass scales beyond the LHC (through virtual effects).

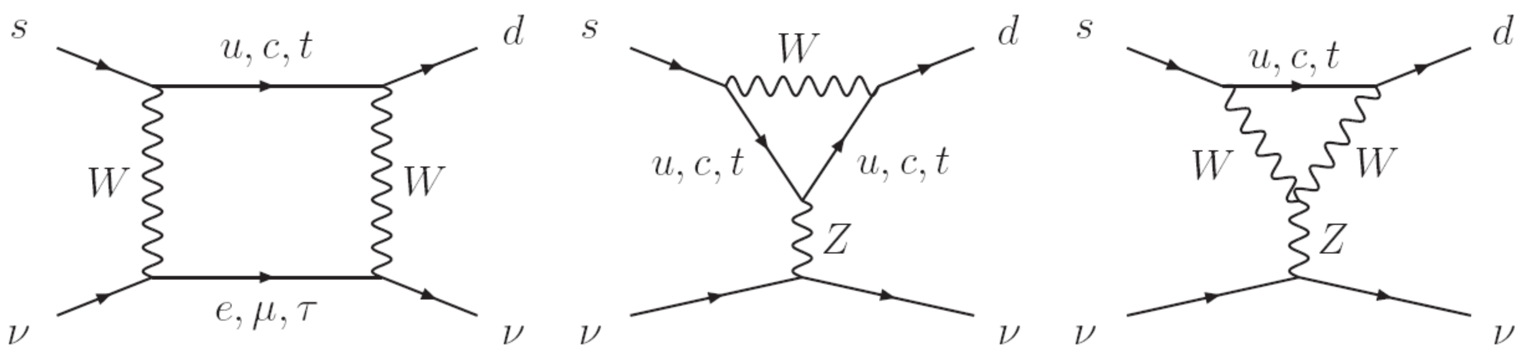
$K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$ have special status because of their small SM uncertainty and large NP reach.

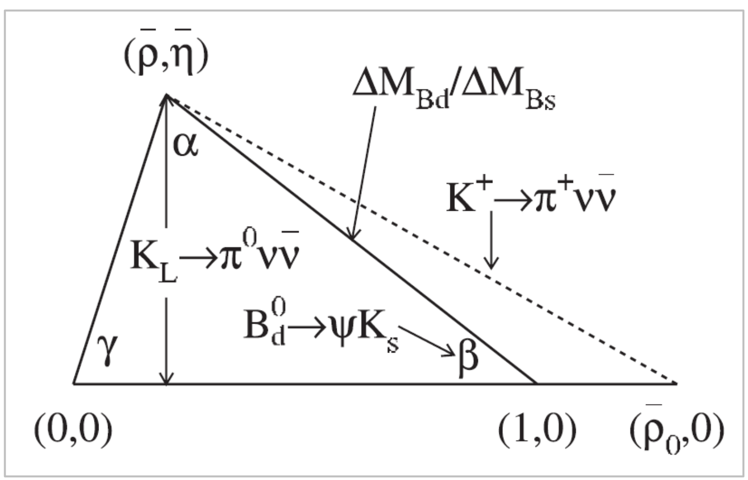
Precision measurement of $B(K^+ \to \pi^+ \nu \bar{\nu})$ is an immediate high priority.

- –It is experimentally more accessible than the neutral mode.
- –The outcome will guide the Project-X Intensity Frontier program.

$K^+ \to \pi^+ \nu \bar{\nu}$ in the Standard Model

The $K \to \pi \nu \bar{\nu}$ decays are remarkable because they are the most reliably and precisely calculated FCNC decays.





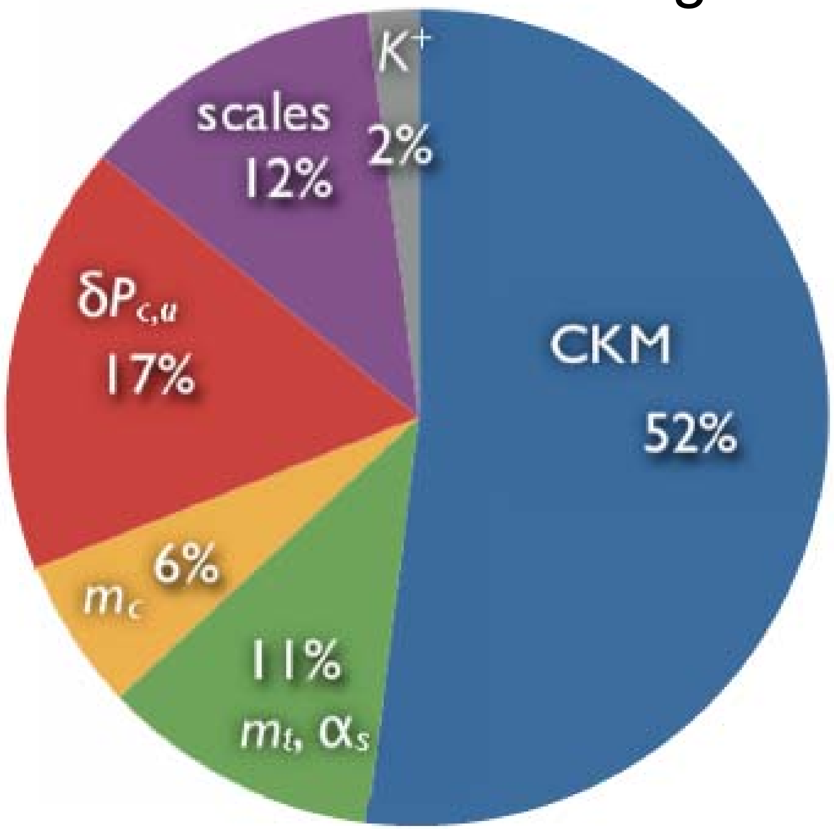
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with $K \to \pi e \nu$
- Largest uncertainty (≅7%) from CKM elements (which will improve)

$$B_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.5 \pm 0.7) \times 10^{-11}$$

Brod and Gorbahn, PRD 78, 034006(2008)

Summary of SM Theory Uncertainties

CKM parameter uncertainties dominate the error budget today.



Other parametric uncertainties are important (≈17%): m_c, m_t, α_s

With foreseeable improvements, it is reasonable to expect the total SM theory error ≤6%. Unmatched by any other FCNC process (K or B).

SM theory error for neutral ($K_L \to \pi^0 \nu \bar{\nu}$) mode is no longer smaller.

U. Haisch, arXiv:0707.3098

New Physics

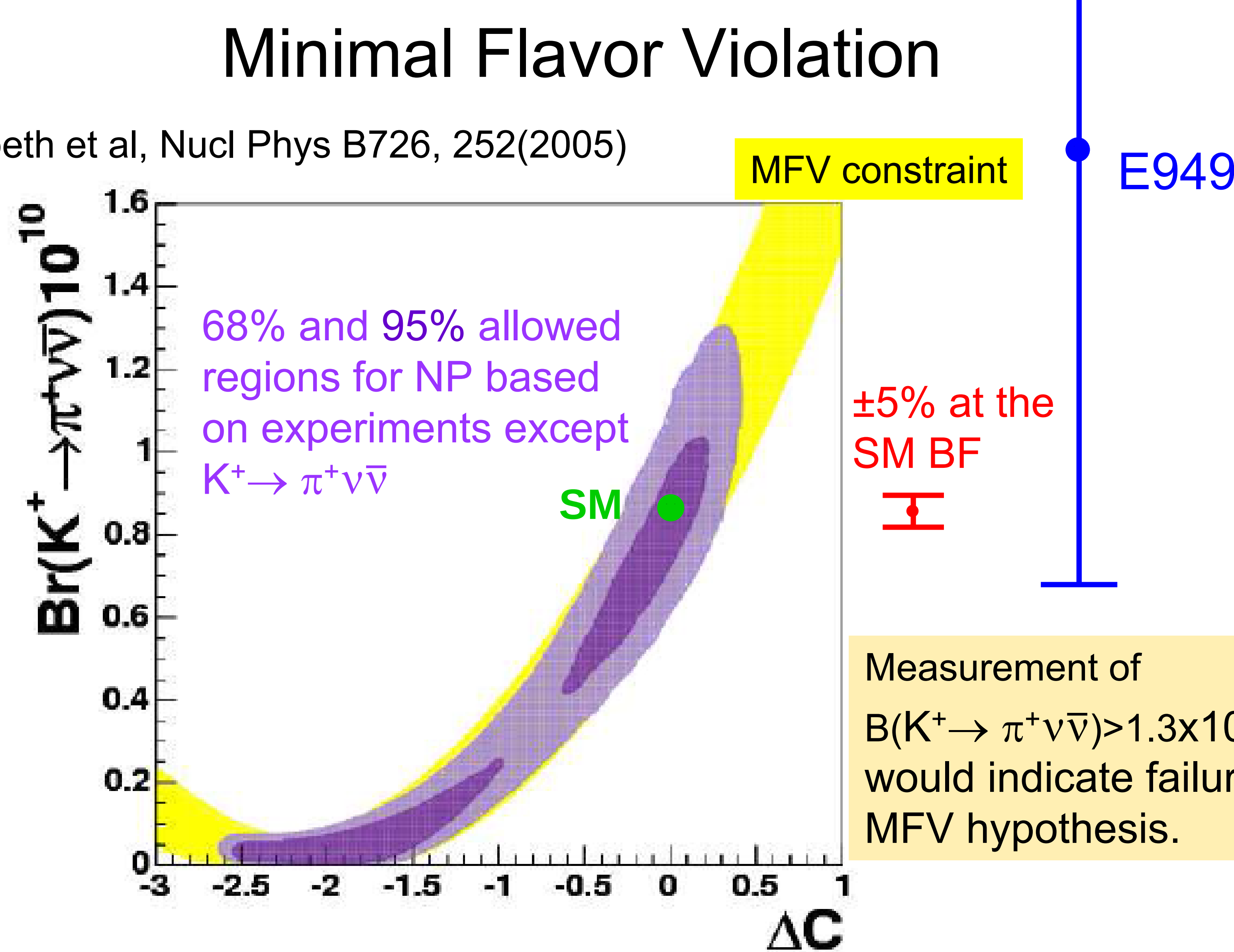
- $K \to \pi \nu \bar{\nu}$ remains clean in non-SM scenarios
  - A single effective operator due to $\nu \bar{\nu}$; Wilson coefficient calculable in perturbation theory, free of long-distance effects.

- Minimal Flavor Violating scenarios
  - The MFV hypothesis is that flavor- and CP-violating effects in New Physics are governed by the SM Yukawa couplings (CKM mixing and phase).
    - Invoked to explain how TeV-scale New Physics has not induced already-observable FCNC effects
  - Leads to constraints on and correlations between K and B observables.

- Non-MFV scenarios
  - Introduces new sources of flavor- and CP-violation
  - Large non-SM effects possible
  - K and B effects not always correlated

Minimal Flavor Violation

Bobeth et al, Nucl Phys B726, 252(2005)



Measurement of $B(K^+ \to \pi^+ \nu\bar{\nu}) > 1.3 \times 10^{-10}$ would indicate failure of MFV hypothesis.

C function characterizes the Z-penguin diagram; $\Delta C = C - C_{SM}$

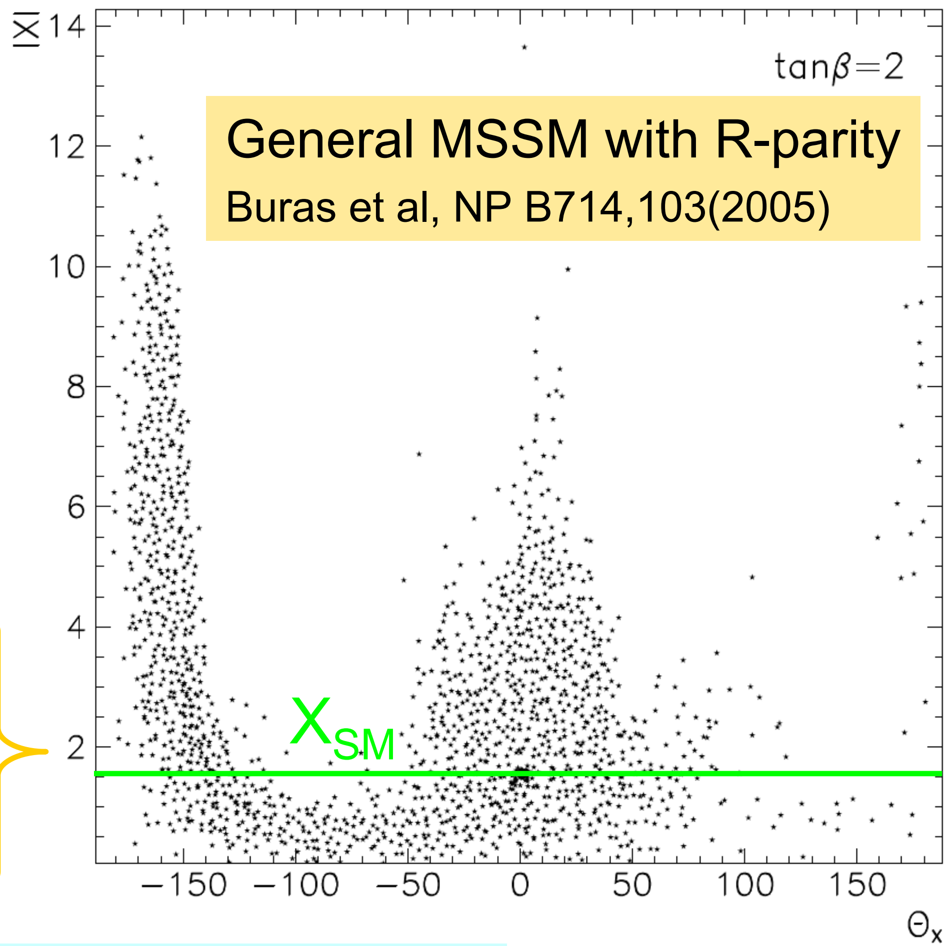
Sensitivity to non-MFV New Physics

New Physics can be parameterized by a function $X = |X|e^{i\theta_x}$, which is calculable in perturbation theory for given models.

Significant deviations from the SM are possible.

General MSSM with R-parity

Scan of parameters imposing experimental constraints except $B(K^+ \to \pi^+ \nu\bar{\nu})$

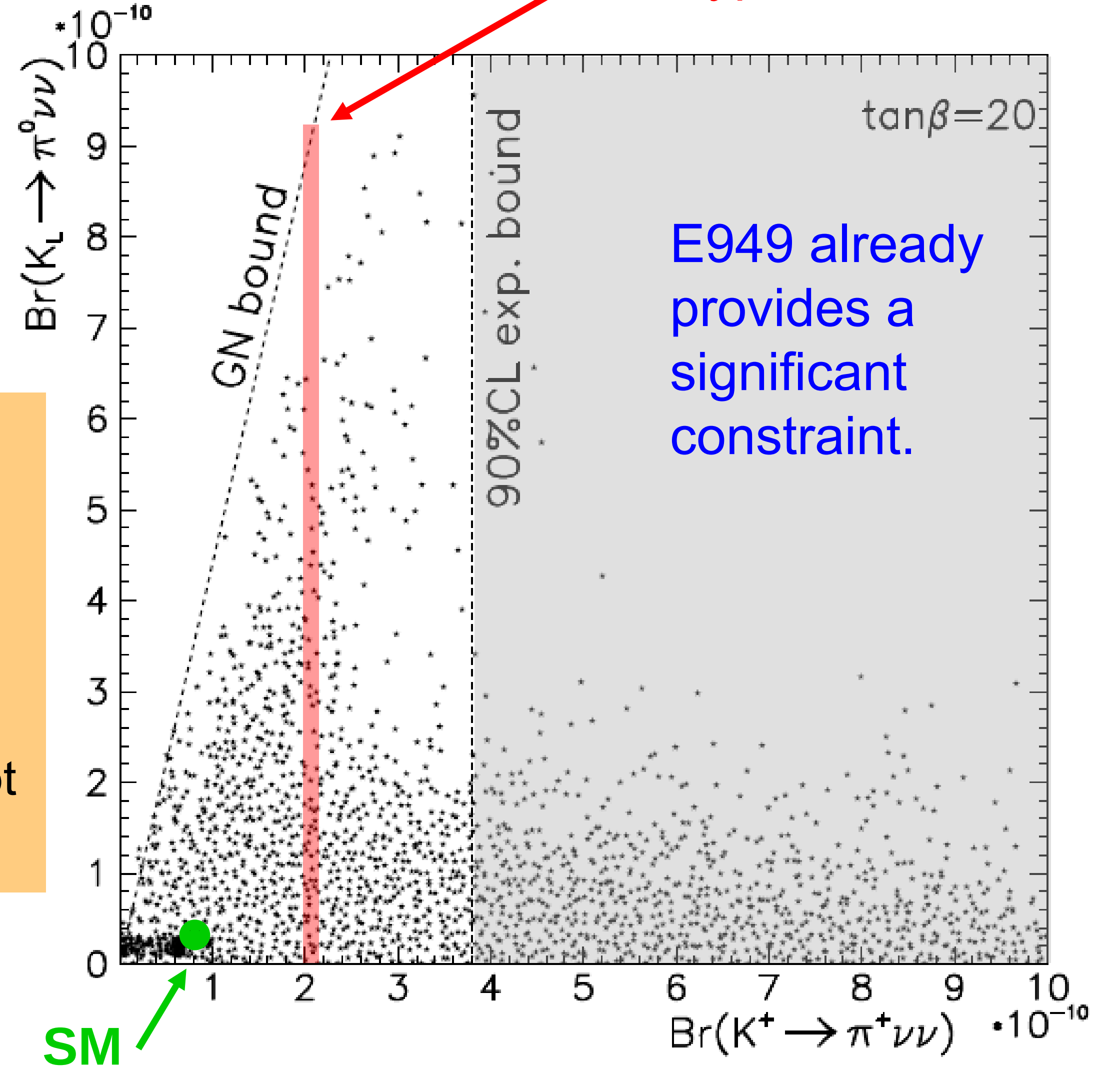


$$B(K^+ \to \pi^+ \nu\bar{\nu}) \propto (X_{SM} + |X|e^{i\theta_x})^2$$

General MSSM with R-parity

Buras et al, NP B714,103(2005)

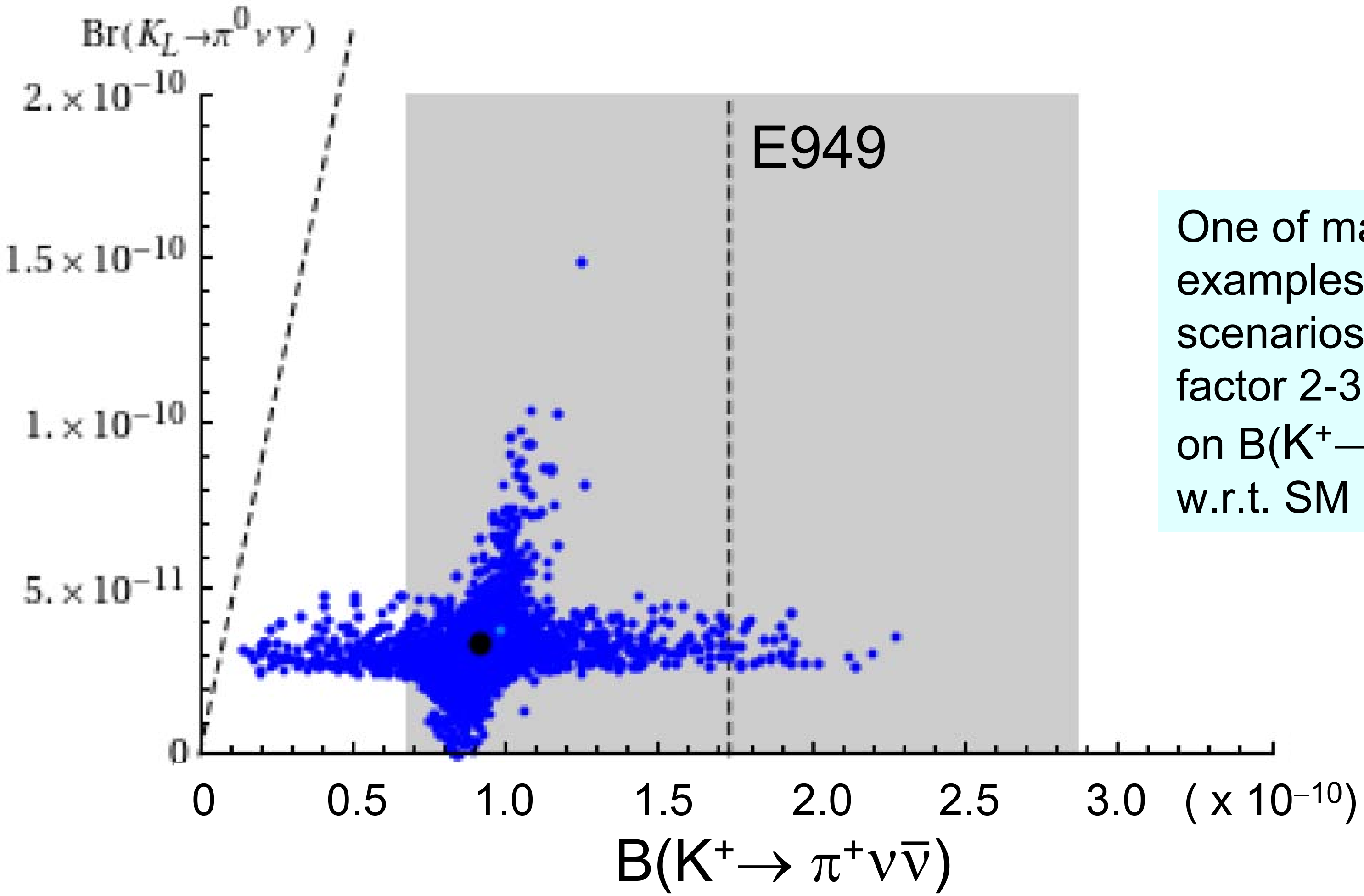
Effect of a ±5% measurement at a hypothetical non-SM BF



Each point is a combination of MSSM parameters that satisfies experimental constraints except $B(K^+ \to \pi^+ \nu \bar{\nu})$

Littlest Higgs model with T-parity

Blanke et al., arXiv:0906.5454



One of many examples of NP scenarios with factor 2-3 effects on B($K^+ \to \pi^+ \nu\bar{\nu}$) w.r.t. SM

$K^+ \to \pi^+ \nu \bar{\nu}$ Motivation

- No matter what happens at LHC, there are key flavor-physics measurements that will be needed.
  - $K^+ \to \pi^+ \nu \bar{\nu}$ is crucial.
- $K^+ \to \pi^+ \nu \bar{\nu}$ is a "golden mode" due to small SM theory errors.
  - Large deviations from the SM level appear in many plausible NP scenarios.
  - 30% deviation from the SM would be a 5σ signal of NP in P996
- Precision measurement of $K^+ \to \pi^+ \nu \bar{\nu}$, which is more accessible experimentally than $K_L \to \pi^0 \nu \bar{\nu}$, will provide guidance for Project -X.
  - A NP signal will imply high priority for the neutral mode AND the complimentary modes $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$

Backgrounds

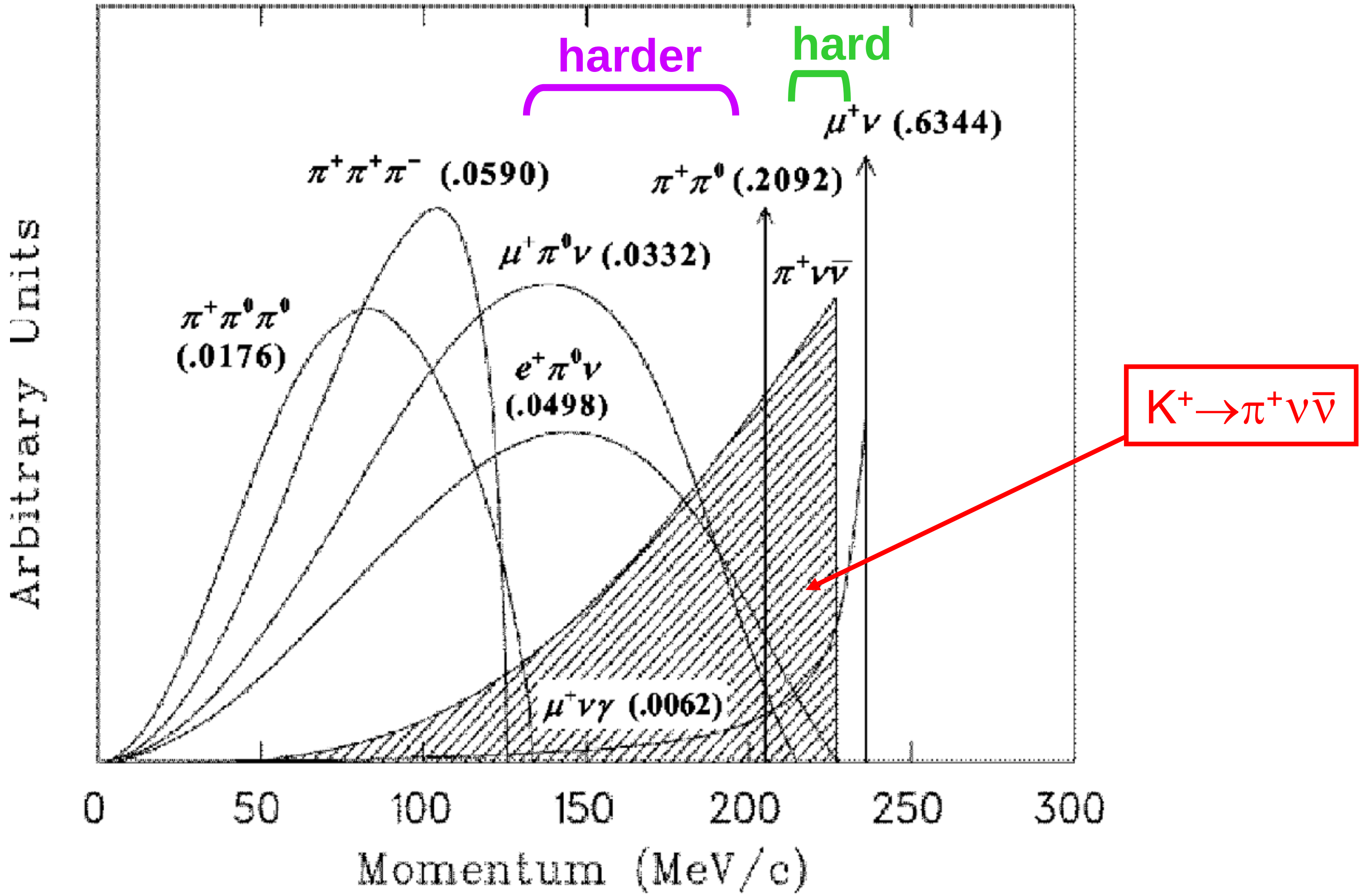
The signal BF is about 1×10^{-10}, so rejection $>10^{10}$ is needed for some modes, This is accomplished by a combination of:

- kinematic constraints
- strong particle identification
- vetos of extra particles, especially photons

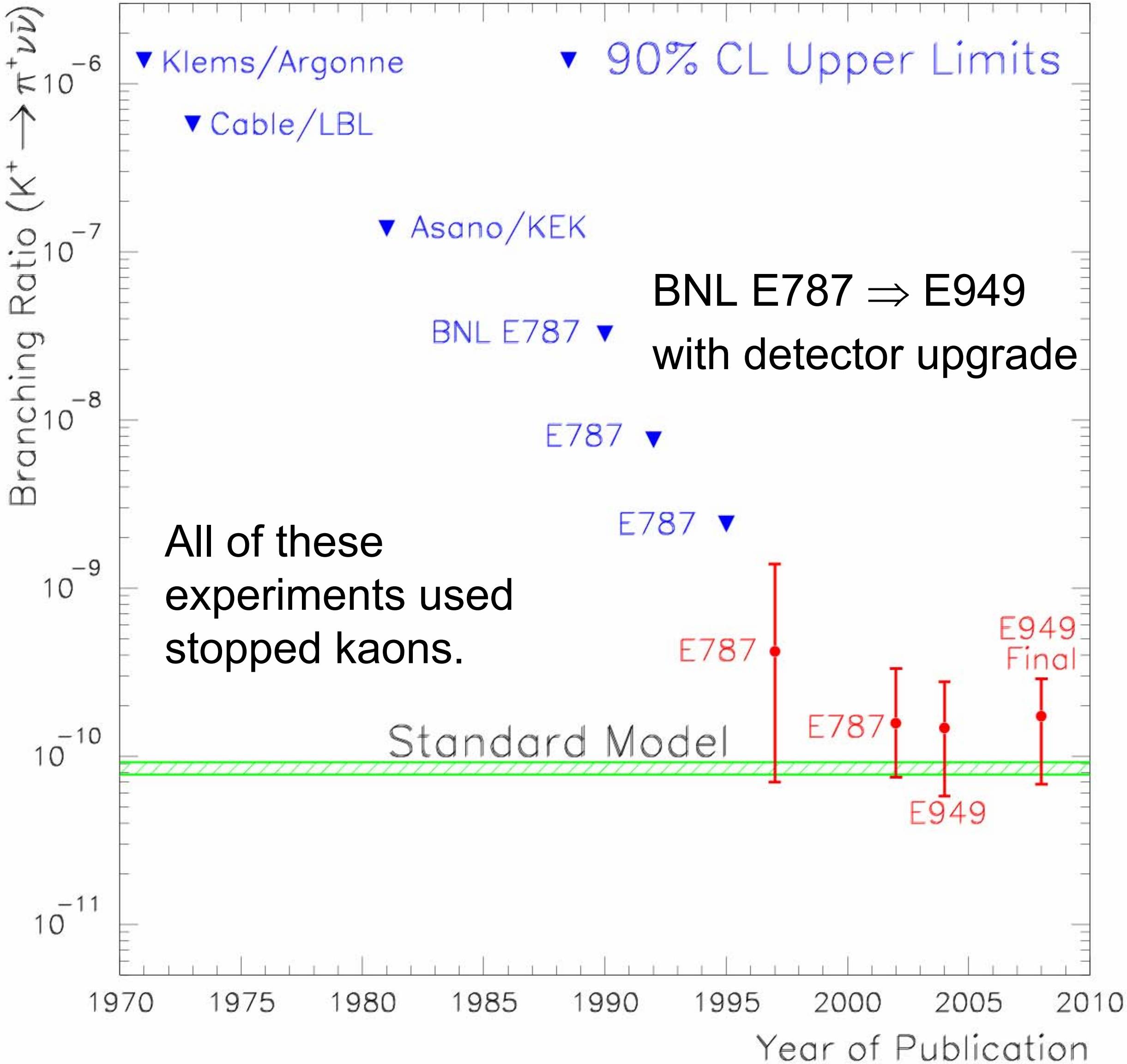
Even a low-level of mis-measurements is dangerous, so redundant measurements of key quantities are needed.

K-decay Backgrounds	Branching Ratio	Rejection Methods
$K^+ \to \mu^+\nu$	0.635	2-body kinematics, μ-veto
$K^+ \to \pi^+\pi^0$	0.212	2-body kinematics, γ-veto
$K^+ \to \mu^+\nu\gamma$	5.5×10^{-3}	μ-veto, γ-veto
$K^+ \to \pi^+\pi^0$	0.212	2-body kinematics, γ-veto
$K^+ \to \pi^0 e^+\nu$	0.048	e-veto, γ-veto
$K^+ \to \pi^0\mu^+\nu$	0.032	μ-veto, γ-veto
$K^+ \to \pi^+\pi^0\pi^0$	0.017	γ-veto
$K^+ \to \mu^+\nu\gamma$	5.5×10^{-3}	μ-veto, γ-veto
$K^+ \to \pi^+\pi^0\gamma$	2.8×10^{-4}	γ-veto

Pion momentum in the CM frame of K decay.



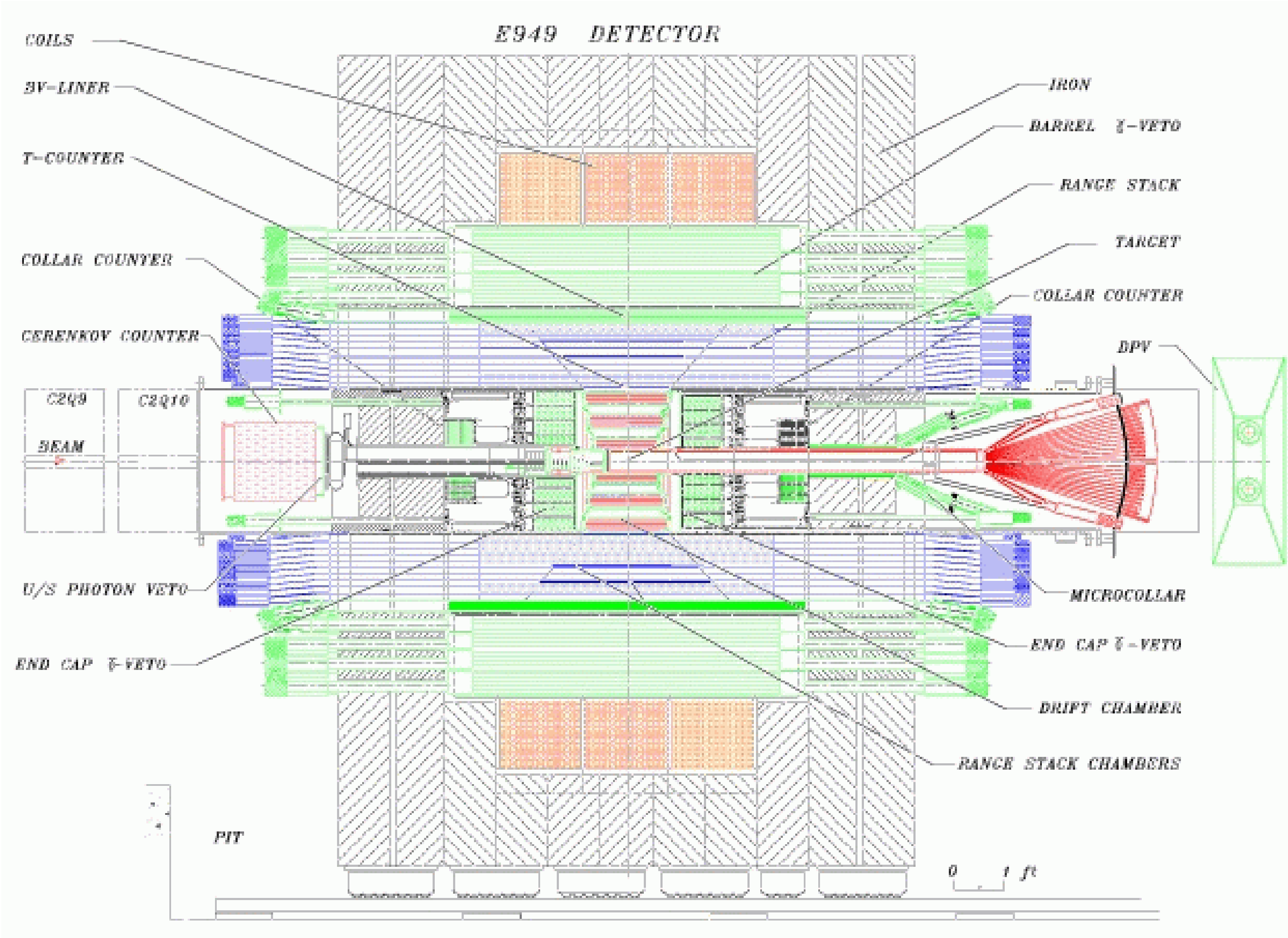
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ History



BNL E787 ⇒ E949 with detector upgrade

All of these experiments used stopped kaons.

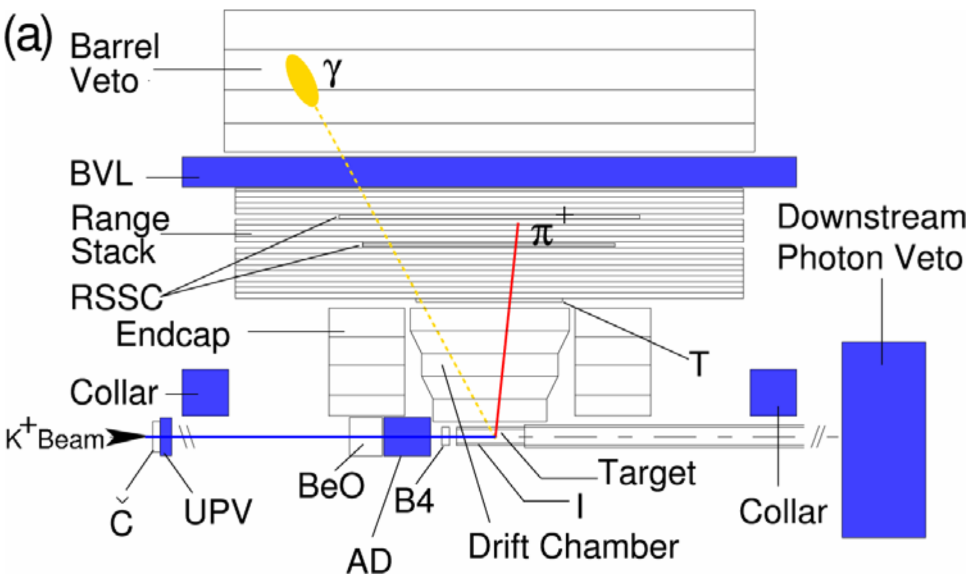
E949 Detector



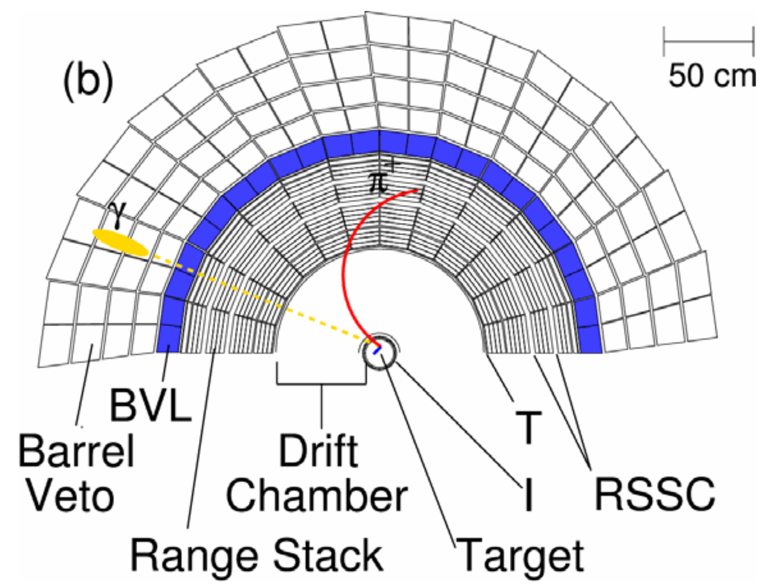
Elevation view of the E949 detector.

E949 Detector

Side view

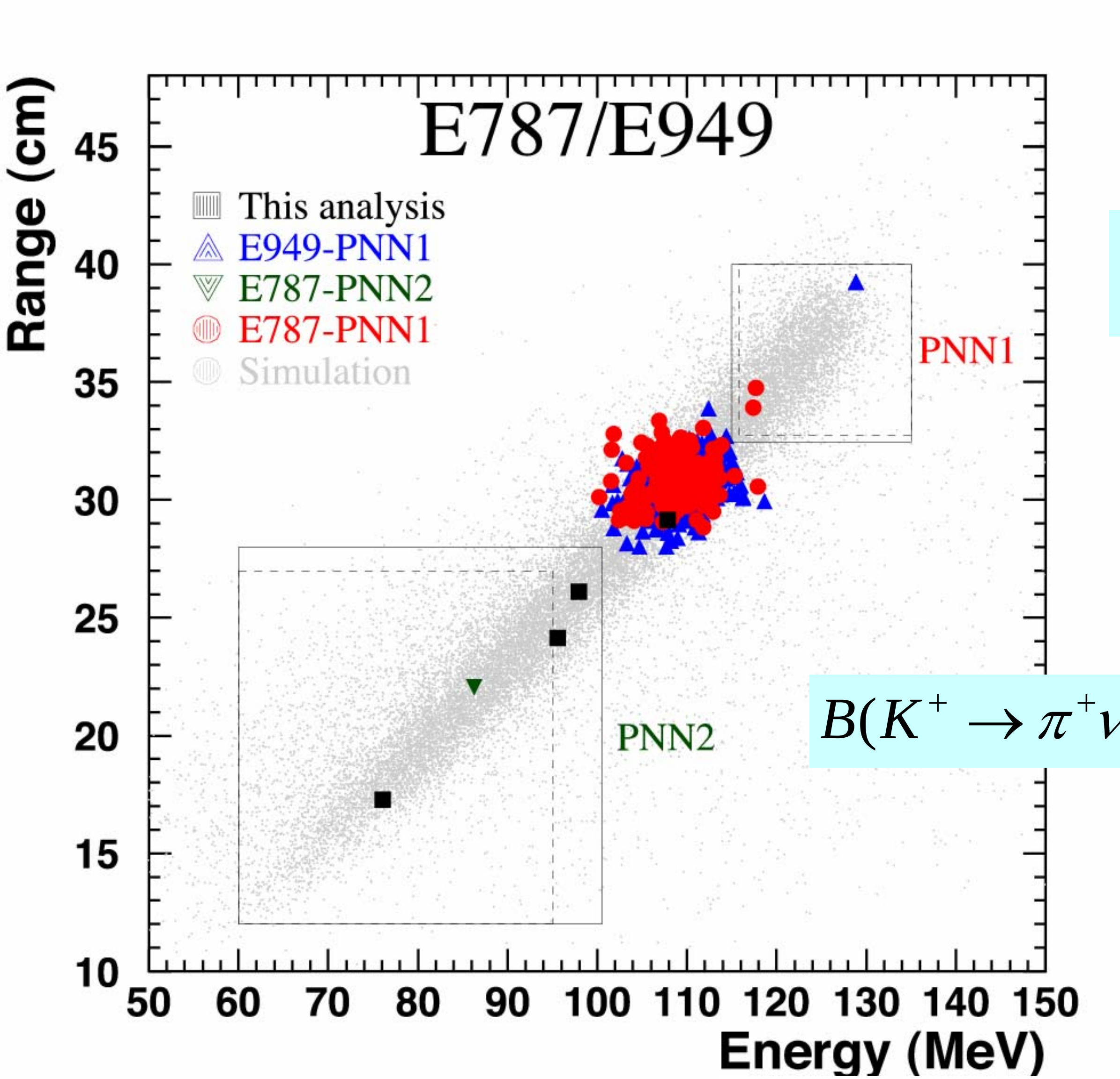


End view



Ran with 710 MeV separated K^+ beam at the BNL AGS

E787/949 Final Results



E787/949 observed a total of 7 signal events.

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Two approaches

Stopped K

- Stop K's (p_K=0) in active target
- Measure π^+ energy, momentum, and range
- Pion ID from decay chain $\pi \rightarrow \mu \rightarrow e$
- Photon veto system

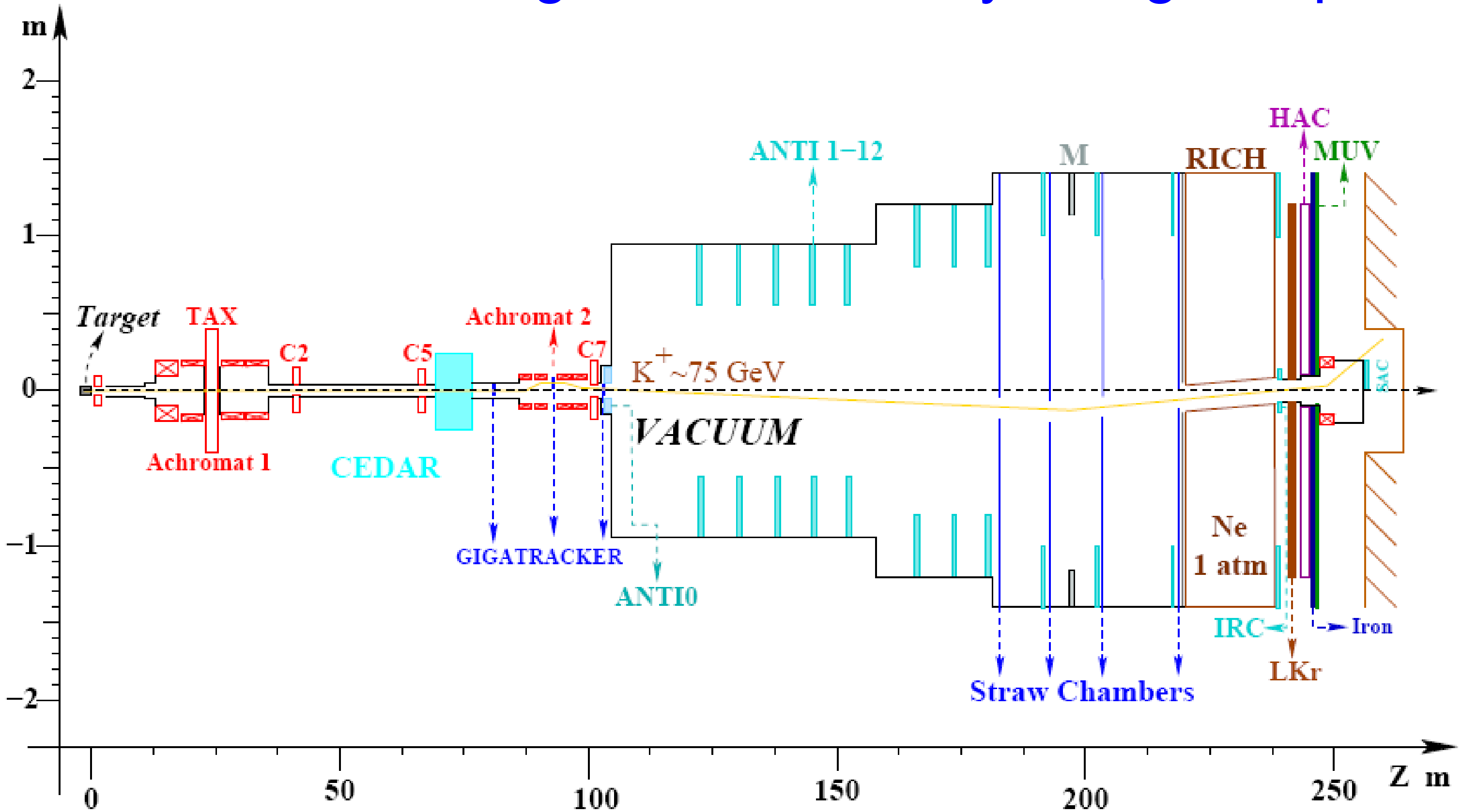
K decays in flight

- Measure beam p with tracking spectrometer
- Measure π^+ momentum, velocity, and range
- Pion ID from RICH and instrumented range stack
- Photon veto system

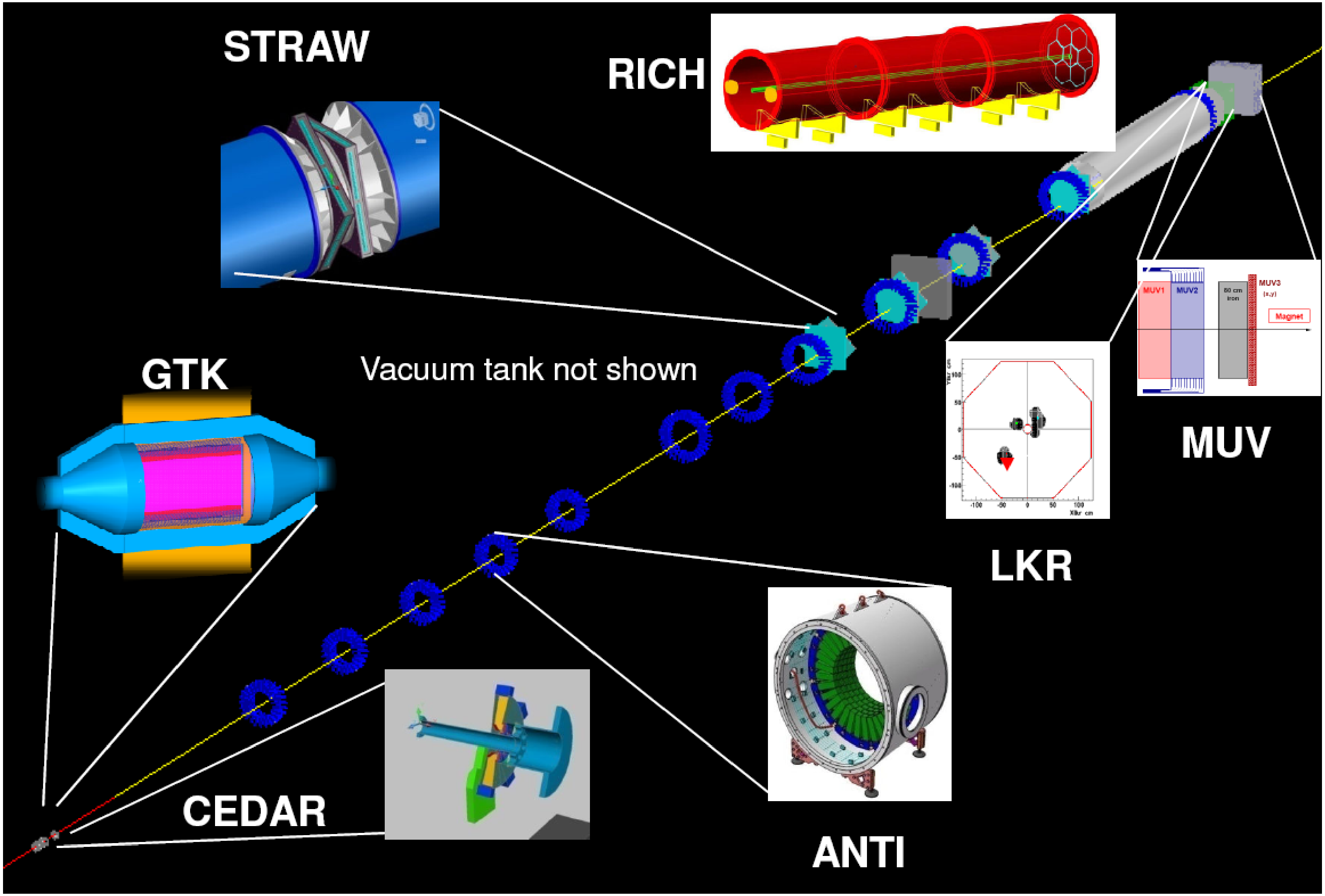
All experiments so far have used stopped K's. Advent of RICH counters has given impetus to the decay-in-flight approach.

$K^+ \to \pi^+ \nu \bar{\nu}$ at CERN

CERN NA-62 is a first-generation decay-in-flight experiment.



- Builds on the experience of NA-31/NA-48 collaboration
- Many features in common with the FNAL CKM proposal
  - but uses an un-separated charged beam (75 GeV)

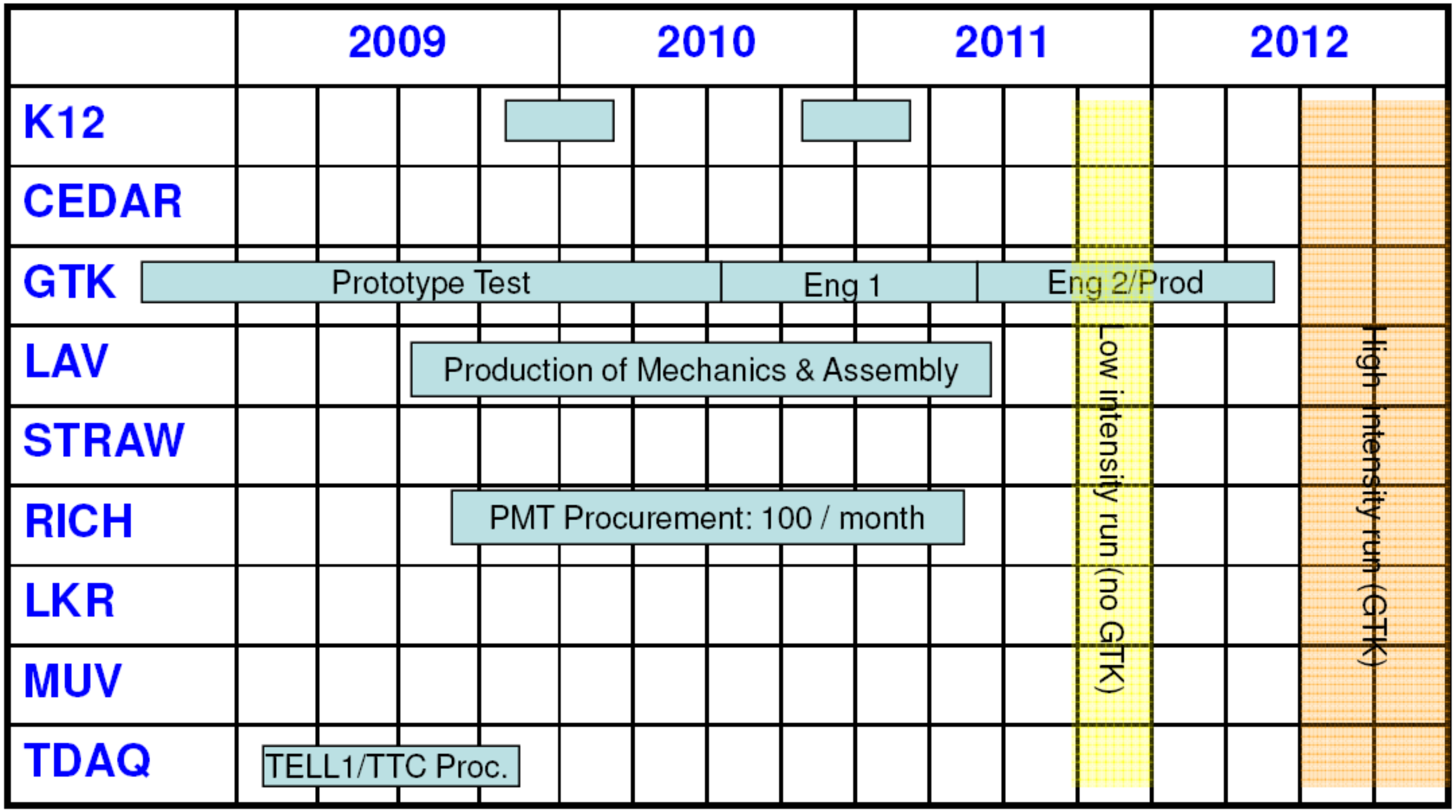

STRAW
RICH
GTK
Vacuum tank not shown
MUV
LKR
CEDAR
ANTI

NA-62

Decay Mode	Events
Signal: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ *[flux = 4.8×10^{12} decay/year]*	55 *evt/year*
$K^+ \rightarrow \pi^+\pi^0$ $[\eta_{\pi 0} = 2\times10^{-8}$ (3.5×10^{-8})]	4.3% (7.5%)
$K^+ \rightarrow \mu^+\nu$	2.2%
$K^+ \rightarrow e^+\pi^+\pi^-\nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \rightarrow \pi^+\pi^0\gamma$	~2%
$K^+ \rightarrow \mu^+\nu\gamma$	~0.7%
$K^+ \rightarrow e^+(\mu^+)\ \pi^0\nu$, others	negligible
Expected background	≤13.5% (≤17%)

Source: Augusto Ceccucci, August 2009 (Extreme Beam)

NA-62 Schedule



Source: Augusto Ceccucci, August 2009 (Extreme Beam)

Fermilab Proposal P996

October 14, 2009

Measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ Decay at Fermilab

A new measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ is being proposed for Fermilab.

PAC consideration later this week.

Fermilab Proposal P996

October 14, 2009

Measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ Decay at Fermilab

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Why here, why now?

- Existing Fermilab facilities (MI and Tevatron) provide an opportunity to make a ±5% measurement.
  - Either New Physics will manifest, or severe constraints result.
- This measurement will provide critical input to planning the Project-X Intensity Frontier program.
- This experiment will be a nucleation site for rebuilding the U.S. K-physics community, which is needed for Project-X.
- To be timely, this must compete head-to-head with CERN's NA-62 experiment.
- The measurement relies on Tevatron stretcher operation which is only viable if done soon after collider running ends.

Stopped K's versus Decays in Flight

- A decay-in-flight experiment (CKM) was proposed at Fermilab in 1998 (by some of us).

- Whatever the hypothetical advantages, the decay-in-flight method has not yet been proven for $K^+ \to \pi^+ \nu \bar{\nu}$.

- The deciding factors - here and now - are **opportunity** and **cost**:
  - The E949 method has been demonstrated at a level sufficient to accomplish the goals of P996. This is the opportunity.
  - The cost of a low-energy (550 MeV) electromagnetostatic separated K^+ beam is significantly less than a high-energy SCRF-separated beam.
    - Unseparated beam results in enormous rates in some detector elements; this is the Achilles heel of NA62.
  - The cost of the compact (low-energy) detector is much less.

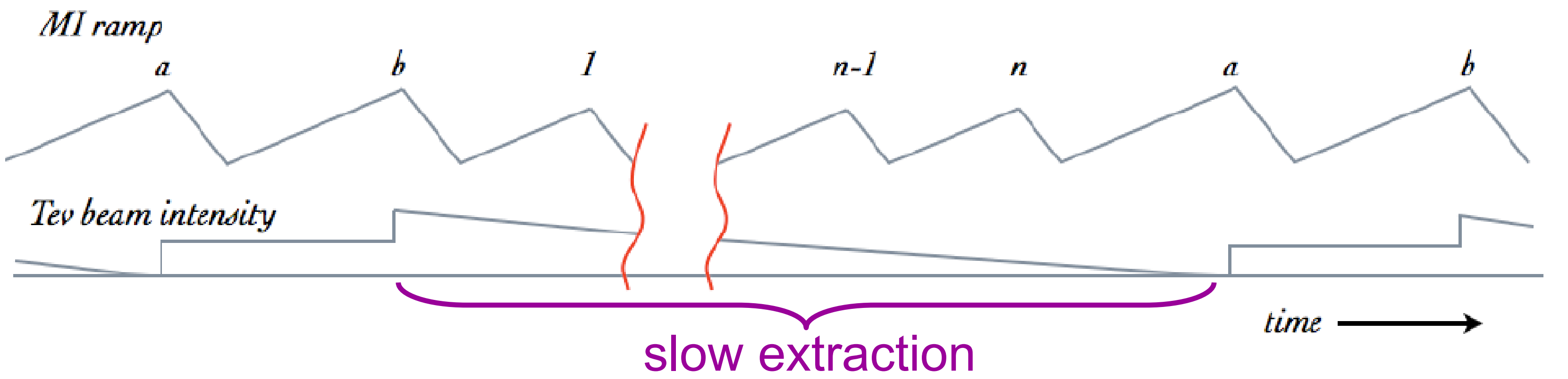
Overview of $K^+ \to \pi^+ \nu \bar{\nu}$ at Fermilab

- Measure $B(K^+ \to \pi^+ \nu \bar{\nu})$ to ±5% using the method developed in BNL E787/949.
  - Build a modern detector based on the E949 concept.
  - Estimate the sensitivity and backgrounds of the new experiment by extrapolating from E949 experience.
  - Expect 194^{+89}_{-79} events/year at SM branching fraction
- Use the Tevatron as a Stretcher, filled by the Main Injector, to get high duty factor (≈95%).
  - 10% hit on protons to NOvA; no effect on microBooNE, mu2e, g-2, …
- Avoid civil construction by using an existing hall.
  - Several possibilities have been identified.
- Contain cost by using an existing superconducting solenoid (preferred is CDF).
- Estimated TPC is $53M (FY2010 $), $58M (then-year $).
- Proposed schedule has first physics running in 2014.

Tevatron in Stretcher Mode

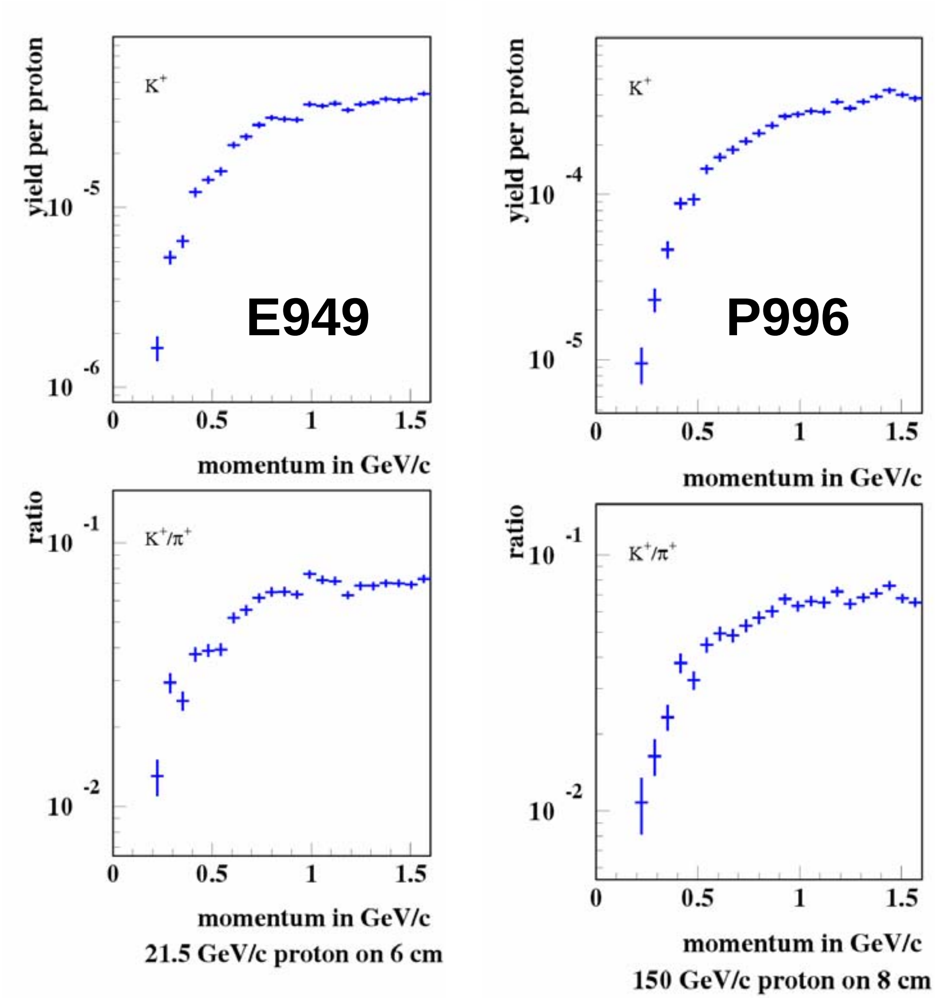
Stretcher operating scenario

- With NOvA, n pulses to NuMI beam (1.33 s ramp to 120 GeV) + 2 pulses to Tevatron (1.67 s ramp to 150 GeV); n ≈ 18
  10% reduction in protons to NOvA; no effect on mu2e, g-2



- 96 Tp (1 TP = 10^{12} p) with 27.3 s cycle;
  duty factor = 94% (high duty factor is key to P996)
- Extraction hardware exists; 150 GeV is the normal Tevatron injection energy; 150 GeV extraction has been done before.
- If NOvA is off, higher intensity to P996 is possible.

K^+ Yield



Calculation of K flux into the detector is based on:

- LAQGSM-MARS model for ratio (150 GeV vs 21.5 GeV) accounting for target lengths, solid angles, momentum bites
- A complete secondary beam design
- Ray-tracing simulations from production target to stopping target
- FLUKA simulations of stopping target to estimate stopping fraction.
  ~60% of K^+ stop in active target

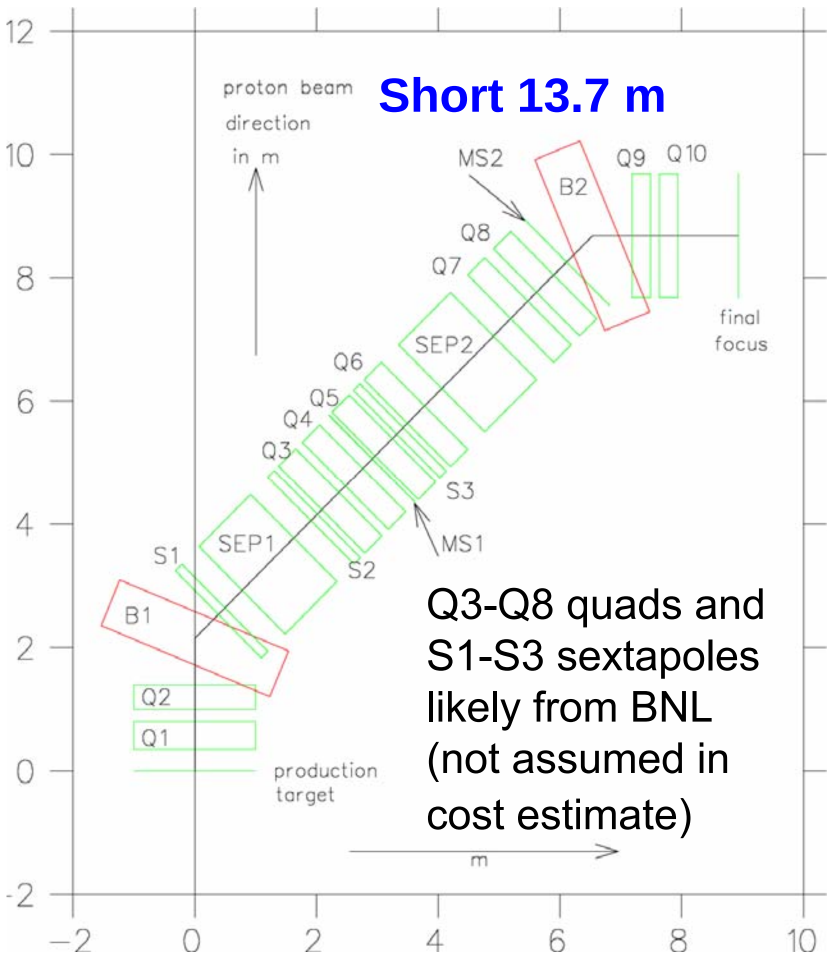
Factor 4.5 more K-stop/sec with less total beam (π+K) into detector

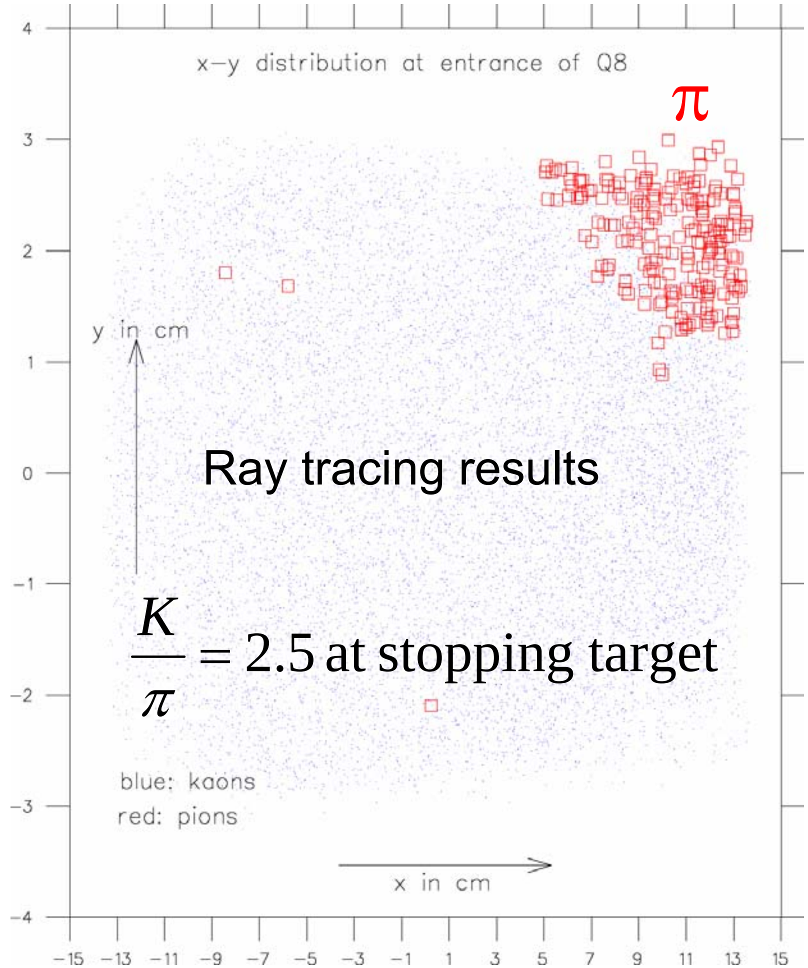
Relative P996/E949 K^+ production from multiple models consistent.

K^+/p Ratio(P996/E949) = 6.8±1.7

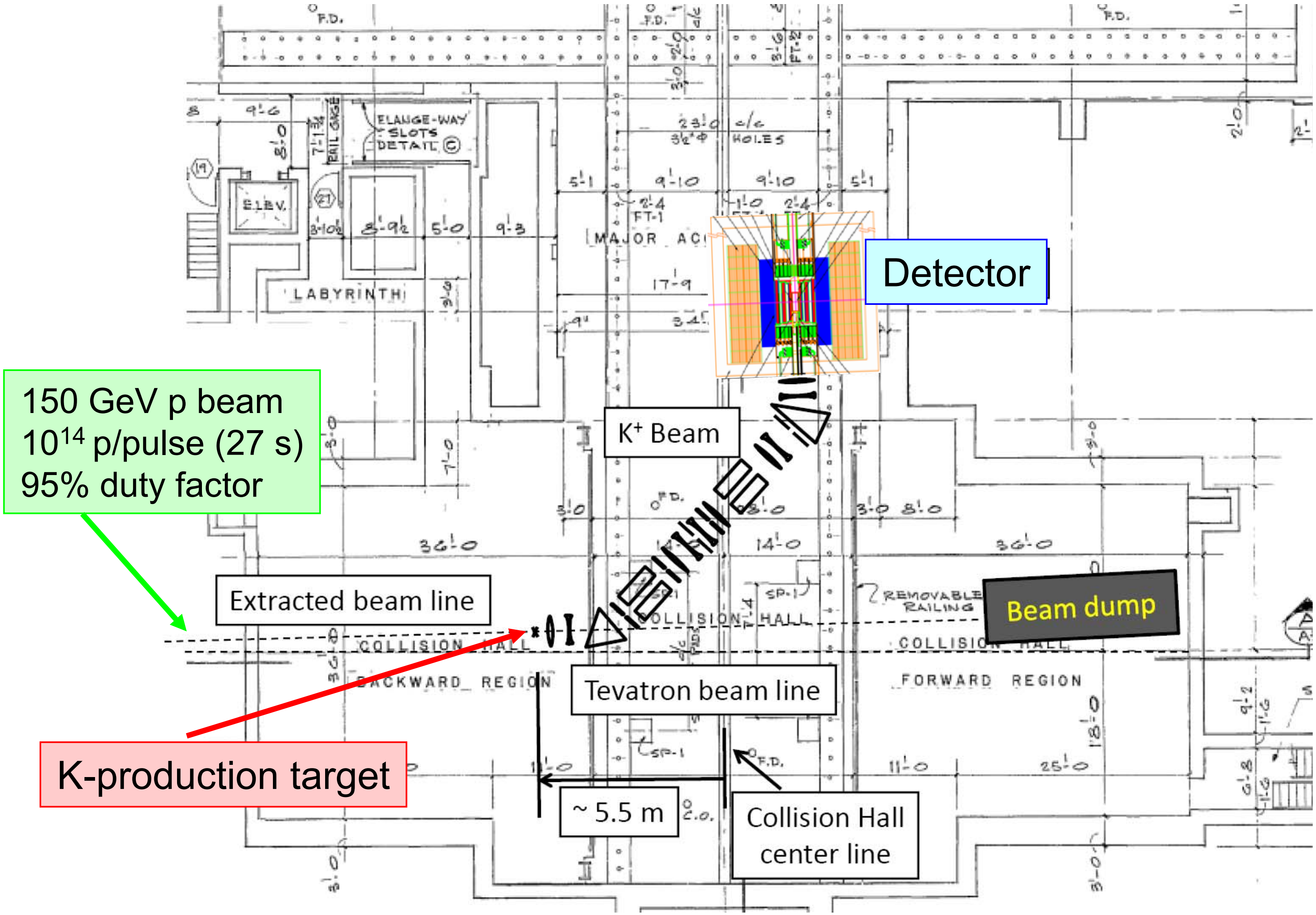
Separated 550 MeV K+ Beam

Design by Jaap Doornbos (designer of BNL LESB-III)

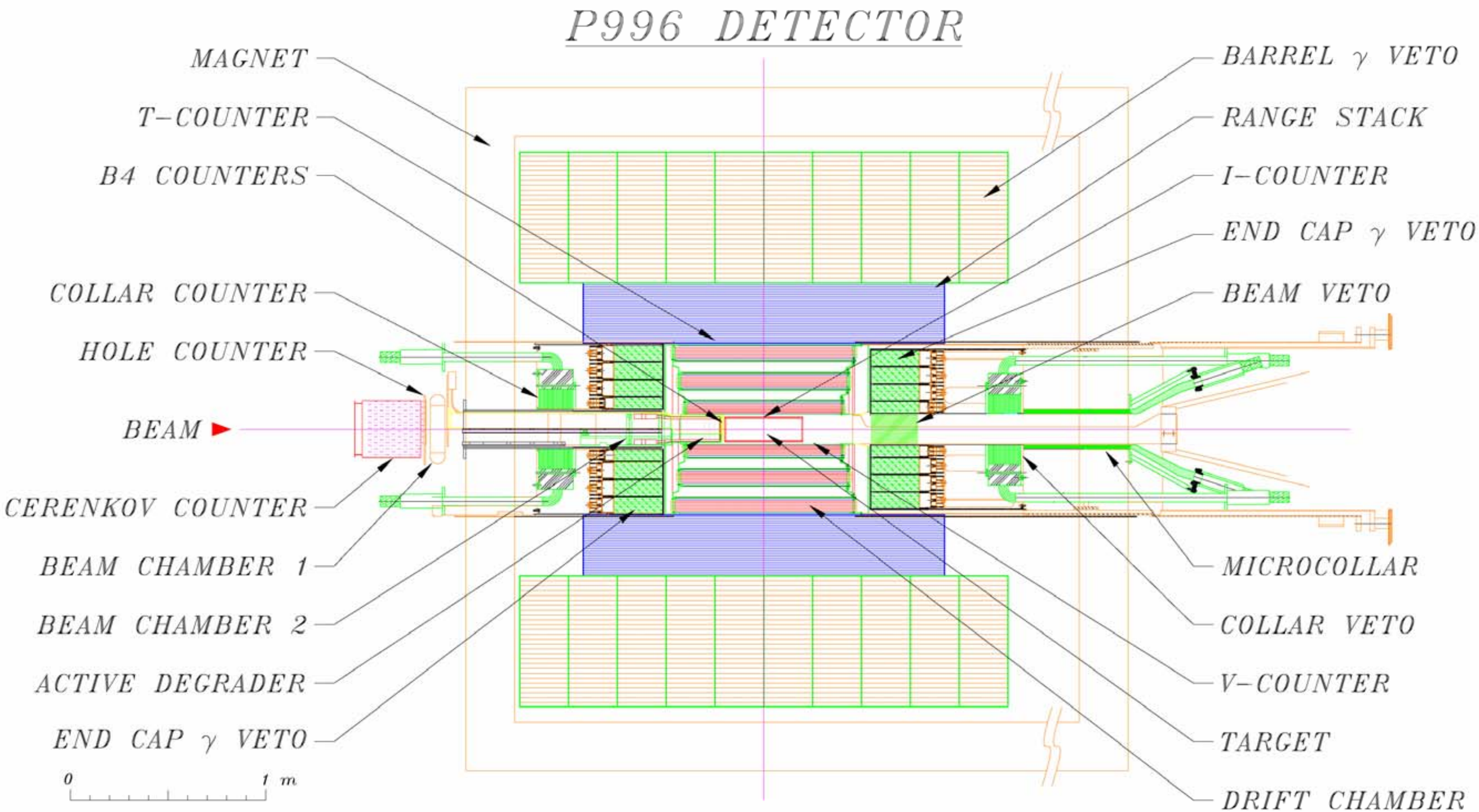




P996 will use an existing hall to avoid civil construction. Several possibilities identified.   Example: CDF B0 Hall



Component	E949 "as run"	P996	Ratio
Proton momentum (GeV/c)	21.5	150	
Protons/spill	65×10^{12}	96×10^{12}	$R_{\text{proton}} = 1.48$
Spill length(s)	2.2	25.67	
Interspill(s)	3.2	1.67	
Duty factor	0.41	0.94	
protons/sec(ave.)	12×10^{12}	3.6×10^{12}	
protons/sec(inst.)	15.9×10^{12}	3.8×10^{12}	
Kaon momentum (MeV/c)	710	550	
K beamline length(m)	19.6	13.74	
Effective beam length(m)	17.6	13.21	
K survival factor	0.0372	0.0411	$R_{\text{surv}} = 1.1048$
Angular acceptance (msr)	12	20	$R_{\text{ang}} = 1.66$
$\Delta p/p(\%)$	4.0	6.0	$R_{\Delta p} = 1.5$
K^+:π^+ ratio	3	2.63 ± 0.33	
Relative K/proton	—	—	$R_{K/p} = 6.8 \pm 1.7$
N_K/spill	12.8×10^6	$(142 \pm 36) \times 10^6$	
T_{eff}/spill (s)	2.0		
N_K/sec(inst.)	6.3×10^6	$(5.5 \pm 1.4) \times 10^6$	
$N_{K+\pi}$/sec(inst.)	8.4×10^6	7.6×10^6	
N_K/sec(ave.)	2.6×10^6	$(5.2 \pm 1.3) \times 10^6$	
Stopping fraction	0.21	0.60 ± 0.13	
Kstop/s(ave.)	0.69×10^6	$(3.1 \pm 1.0) \times 10^6$	
Running time(hr)	—	5000	
Kstop/5000 hr	—	$(5.6 \pm 1.9) \times 10^{13}$	


P996 DETECTOR
MAGNET
T-COUNTER
B4 COUNTERS
COLLAR COUNTER
HOLE COUNTER
BEAM
CERENKOV COUNTER
BEAM CHAMBER 1
BEAM CHAMBER 2
ACTIVE DEGRADER
END CAP γ VETO
0
1 m
BARREL γ VETO
RANGE STACK
I-COUNTER
END CAP γ VETO
BEAM VETO
MICROCOLLAR
COLLAR VETO
V-COUNTER
TARGET
DRIFT CHAMBER

P996 Improvements

- Larger B-field (1 T $\rightarrow$ 1.25 T), improves momentum resolution
- Longer detector, increases solid angle
- Finer range stack segmentation (reduces accidental losses)
- Thicker photon veto (17.3 $X_0 \rightarrow$ 23 X_0), more efficient photon veto
- Double-ended readout of active stopping target, proves z of decay
- Deadtimeless trigger and data-acquisition, reduces losses from various sources of deadtime in E949

These and other incremental improvements (e.g., running efficiency) provide an estimated factor of 11 improvement (per stopped-K).

Expect 194^{+89}_{-79} events per 5000 hr year at SM BF.

	Ratio(P996/E949)
Net detection efficiency per K-stop	11.3 (+3.3/-2.3)
K-stops per hour	6.1 ± 2.2
5000 hours/E949 as run (940 hours)	5.3

P996 Summary

- We have proposed a realistic, modest-scale experiment to use the Tevatron in stretcher mode to achieve a ±5% measurement of B($K^+ \to \pi^+ \nu \bar{\nu}$) over a few years of running.
- 30% deviation from the SM would be a 5σ signal of NP in P996.
- We are requesting Stage 1 approval from Fermilab (this week).
- We are proposing an aggressive schedule that competes head-to-head with CERN NA-62.
- New collaborators are welcome.

Conclusions

- The $K \to \pi \nu \bar{\nu}$ decays are the cleanest FCNC processes in the Standard Model and New Physics scenarios.
  - Measurements are crucial and should be high-priorities.
- The charged mode is more experimentally accessible, making precision measurement possible within the next decade.
  - This will provide guidance to planning the flavor physics program internationally and the Project-X program locally.
- The CERN NA-62 experiment will begin physics running in about 3 years.
  - First decay-in-flight experiment; a lot will be learned quickly.
- Fermilab should be in this business
  - P996 provides an(other) opportunity.