The Fermilab P996 Proposal: Precision Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$

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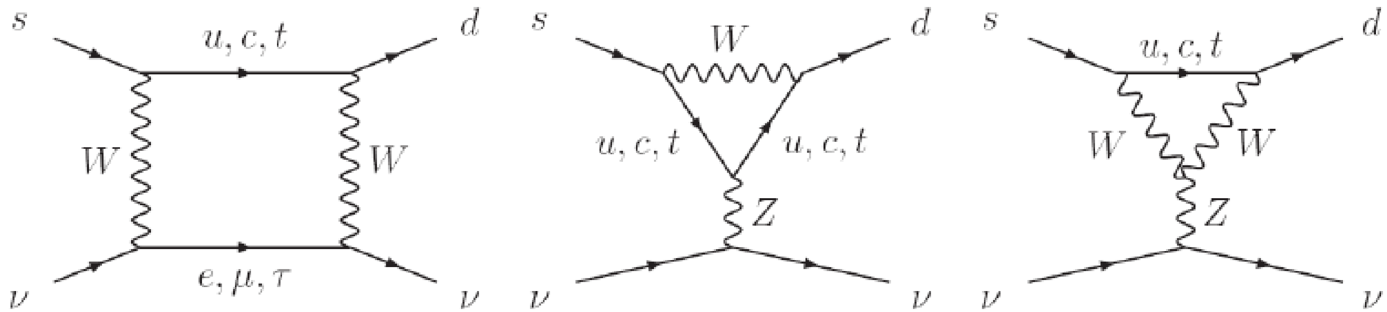
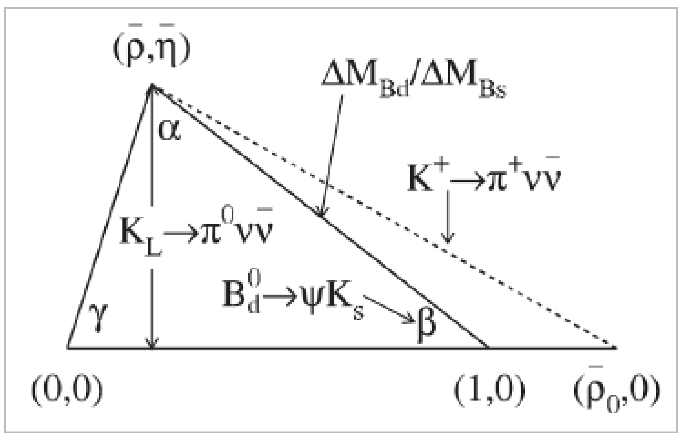
BEACH-2010
Perugia, June 2010

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

The $K \to \pi \nu \bar{\nu}$ decays are the most precisely calculated FCNC decays.





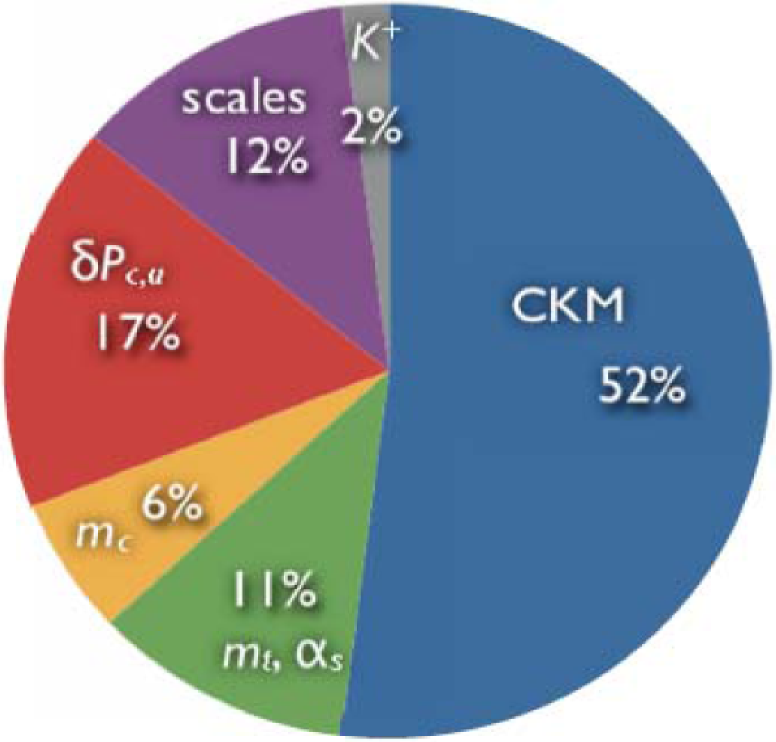
- A single effective operator $\boxed{(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)}$
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with Ke3
- uncertainty from CKM elements (*will improve*)
- **Remains clean in New Physics models** *(unlike many other observables)*

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

Brod and Gorbahn, PRD 78, 034006(2008)

Summary of SM Theory Uncertainties

CKM parameter uncertainties dominate the error budget today.



With foreseeable improvements, it is reasonable to expect the total SM theory error ≤6%.

A. Kronfeld

Unmatched by any other FCNC process (K or B).

30% deviation from the SM would be a 5σ signal of NP

SM theory error for $K_L^0 \to \pi^0 \nu \bar{\nu}$ mode exceed that for $K^+ \to \pi^+ \nu \bar{\nu}$.

U. Haisch, arXiv:0707.3098

General MSSM with R-parity

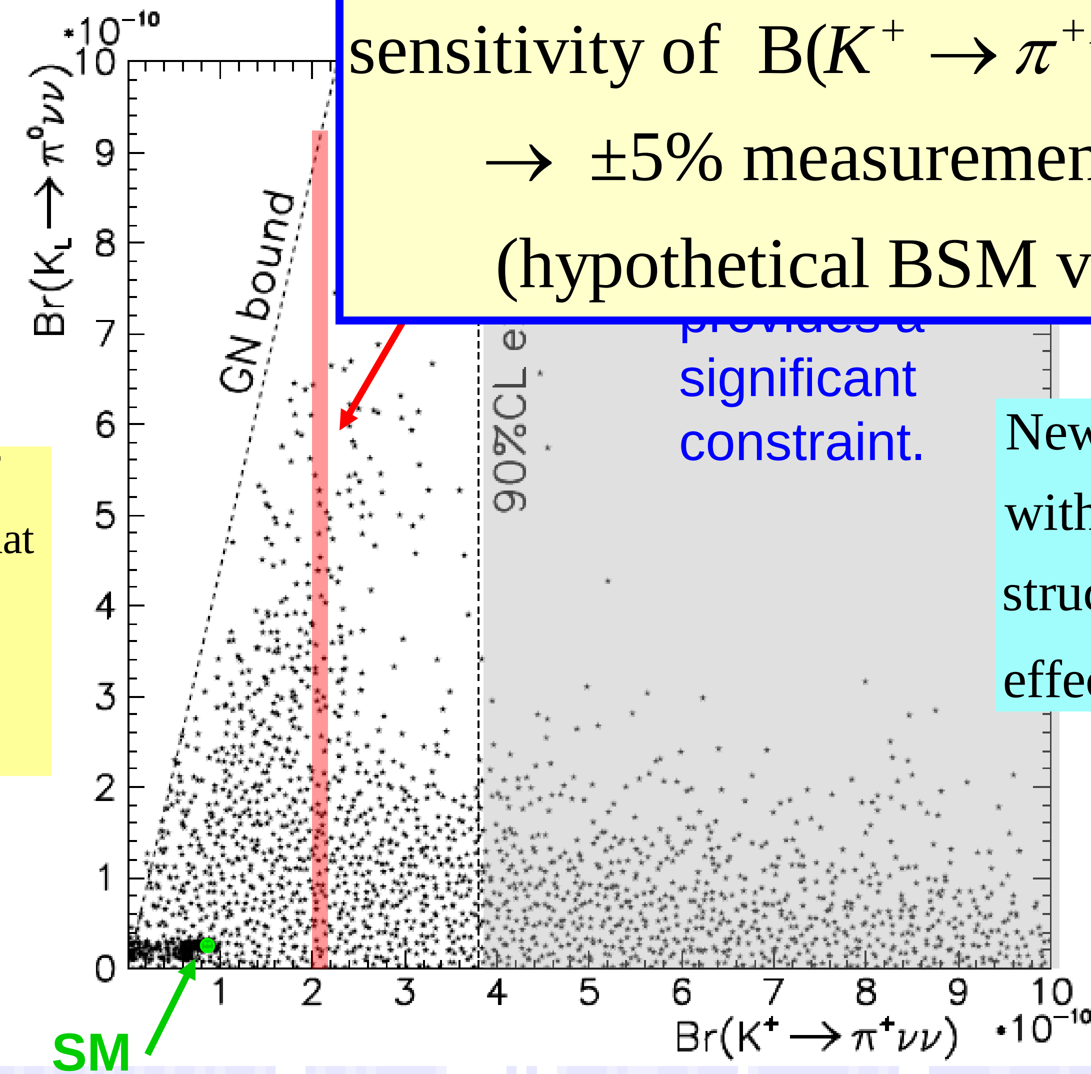
Fermilab P996 will improve the sensitivity of $B(K^+ \to \pi^+ \nu\bar{\nu})$ by >100 !

$\to$ ±5% measurement

(hypothetical BSM value)

Buras et al, NP B714,103(2005)

Points from a scan of MSSM parameters that satisfy experimental constraints except $B(K^+ \to \pi^+ \nu\bar{\nu})$



provides a significant constraint.

New Physics models with generic flavor structure induce large effects in $K^+ \to \pi^+ \nu\bar{\nu}$.

R Parity: R = $(-1)^{2j+3B+L}$.

$K^+ \to \pi^+ \nu\bar{\nu}$ in the LHC Era

New Physics found at LHC

$\Rightarrow$ New particles with unknown flavor- and CP-violating couplings

Precision flavor-physics experiments needed to help sort out the flavor- and CP-violating couplings of the NP.

New Physics NOT found at LHC

Precision flavor-physics experiments needed -> sensitive to NP at mass scales beyond the reach of the LHC (through virtual effects).

Quark Gen.	Processes to Study NP
1	μ-e Conversion, $\pi \to e\nu$
2	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L^0 \to \pi^0\nu\bar{\nu}$
3	$b \to s\gamma$, other rare decays

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

* The result can guide the Project-X Intensity Frontier program.

From the Fermilab Physics Advisory Committee Aspen Retreat, June 2009

Mid-term Kaon Program

The Committee reiterates its view that a high-statistics, on the order of 1000 events, $K^+ \to \pi^+ \nu \bar{\nu}$ experiment represents very compelling science. While this was previously thought to be achievable only with the high power of Project X, the Committee was excited to hear about the prospects for such an experiment using the existing combination of the Main Injector and the Tevatron, operated as a stretcher ring, employing the well-studied techniques developed at Brookhaven National Laboratory where the initial observation of $K^+ \to \pi^+ \nu \bar{\nu}$ was made. Such a high-priority experiment would considerably strengthen Fermilab's intensity frontier program in advance of Project X.

The Committee strongly recommends that Fermilab evaluate the cost and feasibility of various options for making the Tevatron available for the $K^+ \to \pi^+ \nu \bar{\nu}$ and possibly other experiments. Should the Laboratory decide to proceed with this program, the Laboratory should ensure that the timeline is internationally competitive.

P-996 Collaboration Submitted a Proposal to Fermilab November 2009

Proposal:

- Arizona State University, USA.
- Brookhaven National Laboratory, USA.
- Fermilab, USA.
- Institute for Nuclear Research – Russia
- JINR (Dubna) - Russia
- Istituto Nazionale di Fisica Nucleare – Pisa, Italy.
- TRIUMF – Vancouver British Columbia, Canada
- University of British Columbia - Vancouver Canada.
- University of Texas at Austin, USA.
- University of Illinois, Urbana, USA.
- University of Northern British Columbia – Prince George – Canada.
- Universidad Autonoma de San Luis Potosi - Mexico.
- Tsinghua University, Beijing, China.

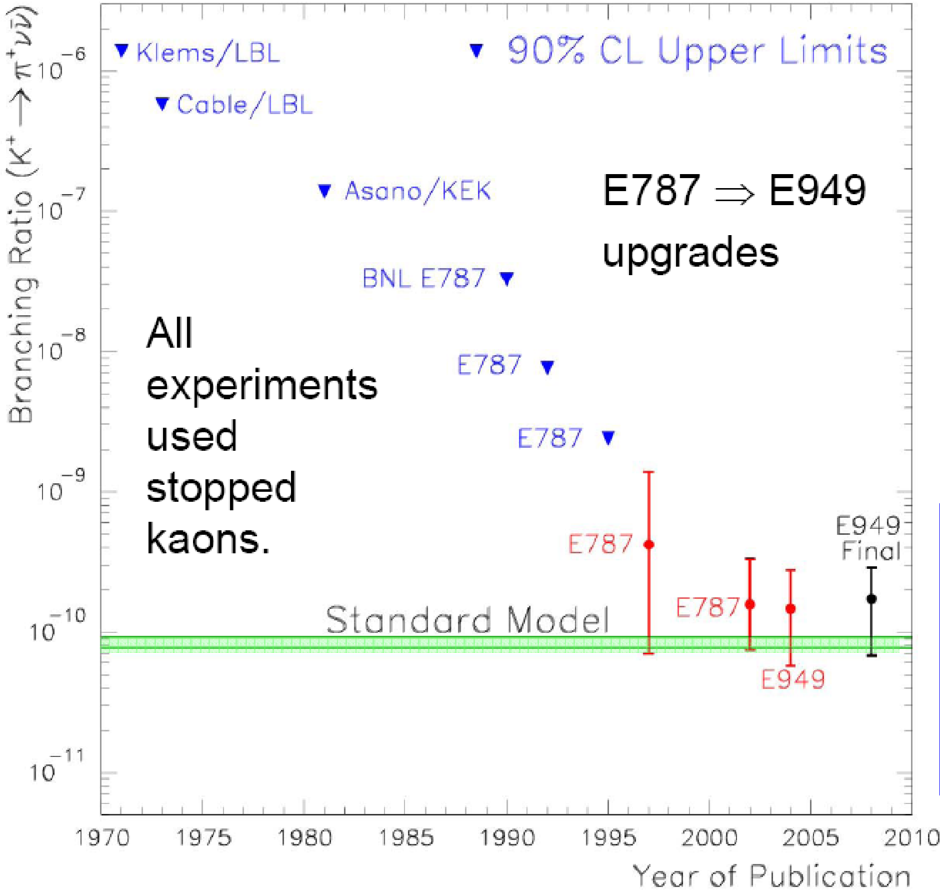
- **5 Countries, 13 institutes**
- **3 US universities, growing**
- **2 US National Laboratories**
- **Leadership from all US rare kaon decay experiments from the past 20 years.**

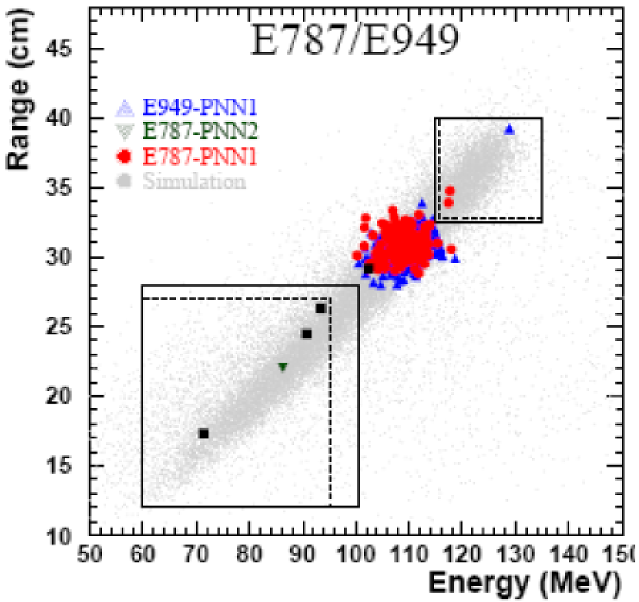
PAC:

"The Experiment [P996] meets the criteria of Stage-I Approval…."

...more later.

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





E787/E949 Final: 7 events observed

$$B(K^+ \to \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$$

Standard Model:

$$B(K^+ \to \pi^+ \nu \bar{\nu}) = (0.85 \pm 0.07) x10^{-10}$$

BNL AGS

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

- Measure $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ to ±5% using BNL E787/949 method
  - Build a modern **4th generation** detector based on the E949 concept.
  - Reliably estimate the sensitivity and backgrounds of the new experiment by extrapolating from E949 experience
  - Expect 200 events/year at SM branching fraction (100 x E949 sensitivity)

- 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, …

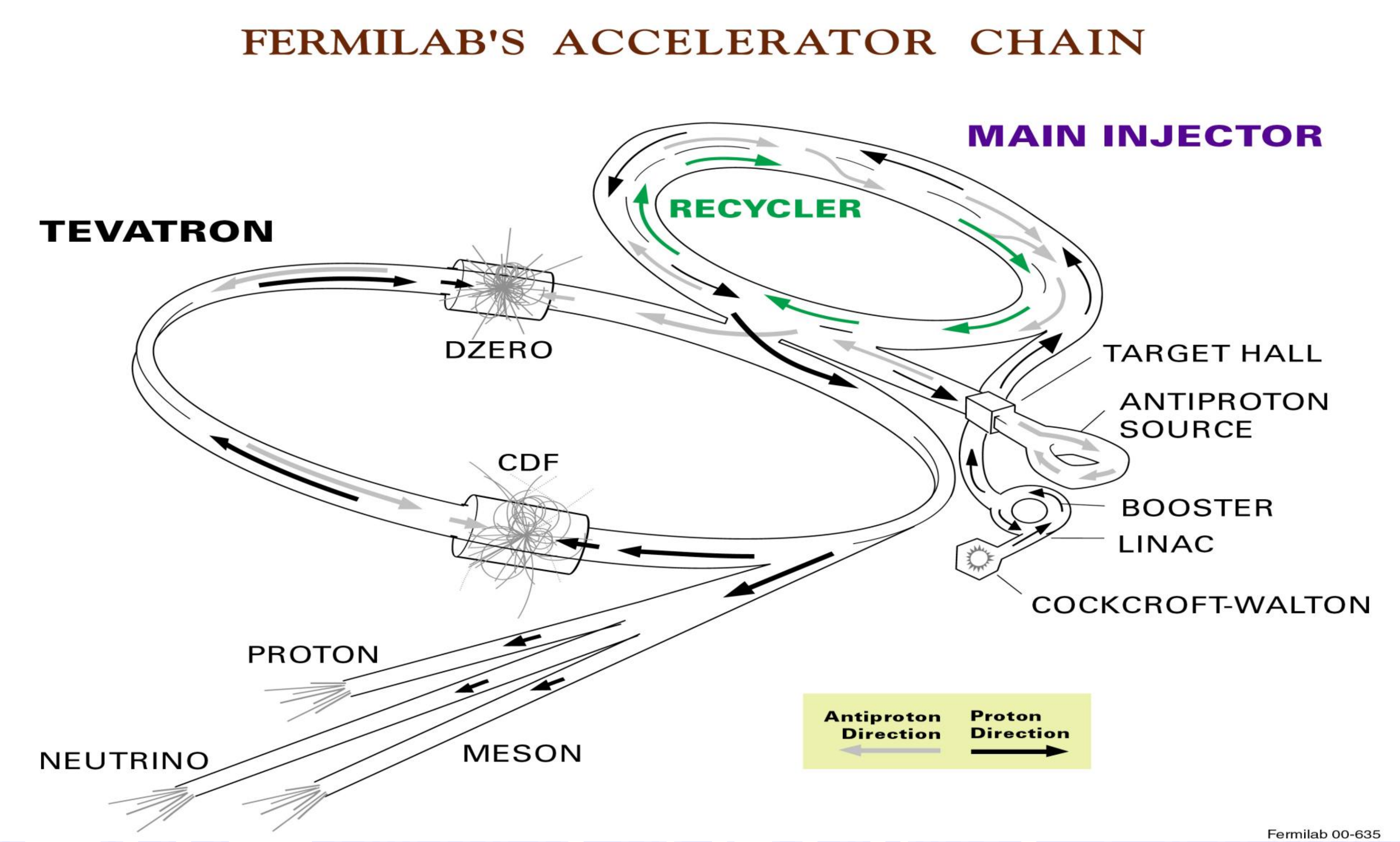
- Avoid civil construction by using an existing hall
  - Several possibilities have been identified

- Use an existing superconducting solenoid.
  - CDF or CLEO is suitable

- Estimated TPC is **$38M** (FY2010 $); work in progress to reduce capital cost through reuse of existing equipment.

- Proposed schedule has a 3 year construction period.

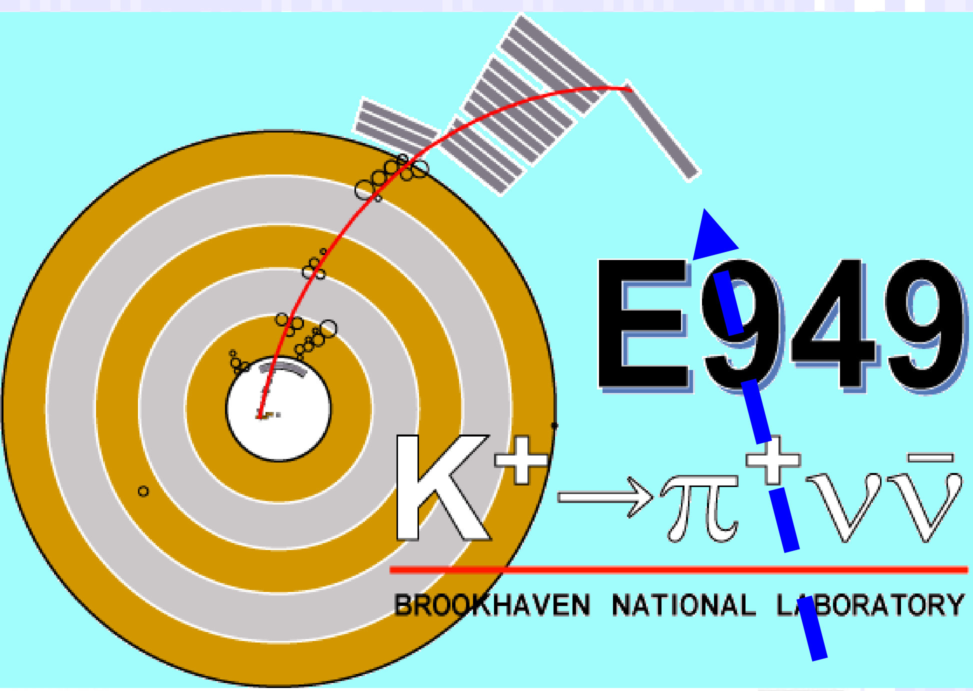
The Tevatron Stretcher Concept

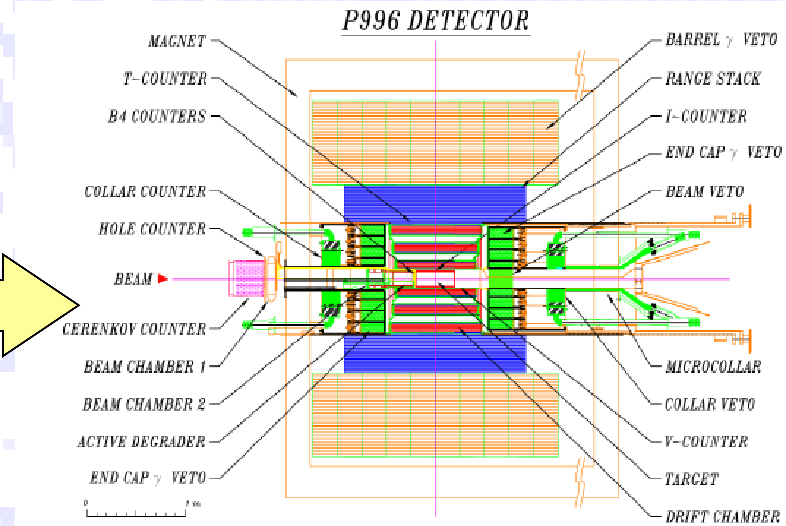


The Stretcher: A World-Leading Machine for the Field…

Slow-Spill proton facility	Beam Energy	Beam Power (average)	Duty Factor	Hours/year K+ decays/year
BNL AGS (E949)	22 GeV	40 kW	50%	1000 2×10^{12}
CERN SPS (NA62)	450 GeV	13 kW	30%	1400 5×10^{12}
JPARC MR	30 GeV	1 kW Plan: 50 kW Goal: +100 kW	20-30%	2000
FNAL Tevatron (97,99 FT runs)	800 GeV	65kW	30-50%	5000
FNAL Stretcher (P996)	**150 GeV**	Plan: **+80kW**	**95%**	**5000** **60×10^{12}**
Project-X	3 GeV	Goal: 1000kW	95%	5000 $\sim 600 \times 10^{12}$

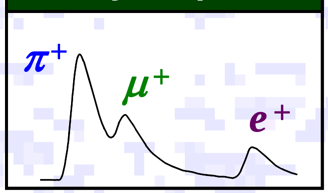
4th generation





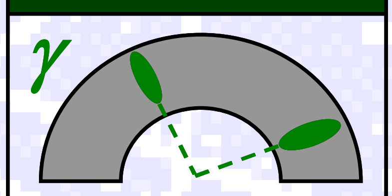
- Measure everything possible
- 710 MeV/c K^+ beam
- Stop K^+ in scintillating fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum in drift chamber
- Measure π^+ range and energy in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in range stack
- Veto photons, charged tracks

$\pi^+ \to \mu^+ \to e^+$ Decay Sequence



500 MHz digitizers

4π Photon Veto



Incremental Improvements

- 550 MeV/c K stopping rate **x5** with comparable instantaneous rate
- Larger solid angle – Acceptance **x 10**
- Finer segmentation, improved resolutions - **Reduced backgrounds**
- Overall **100 x** sensitivity

Rate of Stopped Kaons

For one year of running (5000 hours=18×10^6 s), the total number of stopped kaons in the experimental target is

$$\begin{aligned} N_{\mathrm{Kstop}}/\mathrm{year} &= N_K(\mathrm{P996})/\mathrm{spill}/(t_{spill} + t_{inter}) \times 5000 \text{ hours} \times f_{\mathrm{stop}} \\ &= (142 \pm 36) \times 10^6/27.33\mathrm{s} \times 18 \times 10^6 \times (0.60 \pm 0.13) \\ &= (5.6 \pm 1.9) \times 10^{13}. \end{aligned}$$

- $t_{spill} = 25.67$s spill,
- $t_{inter} = 1.67$s interspill with the stretcher,
- $f_{\mathrm{stop}} = 0.60 \pm 0.13$, K^+ stopping fraction estimated with FLUKA-based simulation. The same simulation estimated a 27% stopping fraction for E949 compared to the measured 21% stopping fraction.

	E949	P996	
Instantaneous Rate (K^+, π^+)	8.4	7.6	MHz

$K^+ \to \pi^+\nu\bar{\nu}$ Events per Year

The number of signal events per 5000-hour year is

$$
\begin{aligned}
N_{K^+\to\pi^+\nu\bar{\nu}} &= \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) \times N_{\mathrm{Kstop}} \times A_{\mathrm{E949}} \times R_{\mathrm{acc}} \\
&= (0.85 \pm 0.07) \times 10^{-10} \times (5.6 \pm 1.9) \times 10^{13} \\
&\quad \times (3.59 \pm 0.36) \times 10^{-3} \times (11.3^{+3.3}_{-2.3}) \\
&= 194^{+89}_{-79}
\end{aligned}
$$

where

- $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$
- $A_{\mathrm{E949}} = (2.22 \pm 0.17) \times 10^{-3} + (1.37 \pm 0.14) \times 10^{-3}$
  $= \mathrm{PNN1} + \mathrm{PNN2}$ acceptance
- $R_{\mathrm{acc}} = (11.3^{+3.3}_{-2.3})$, the product of acceptance factors gained over E949.

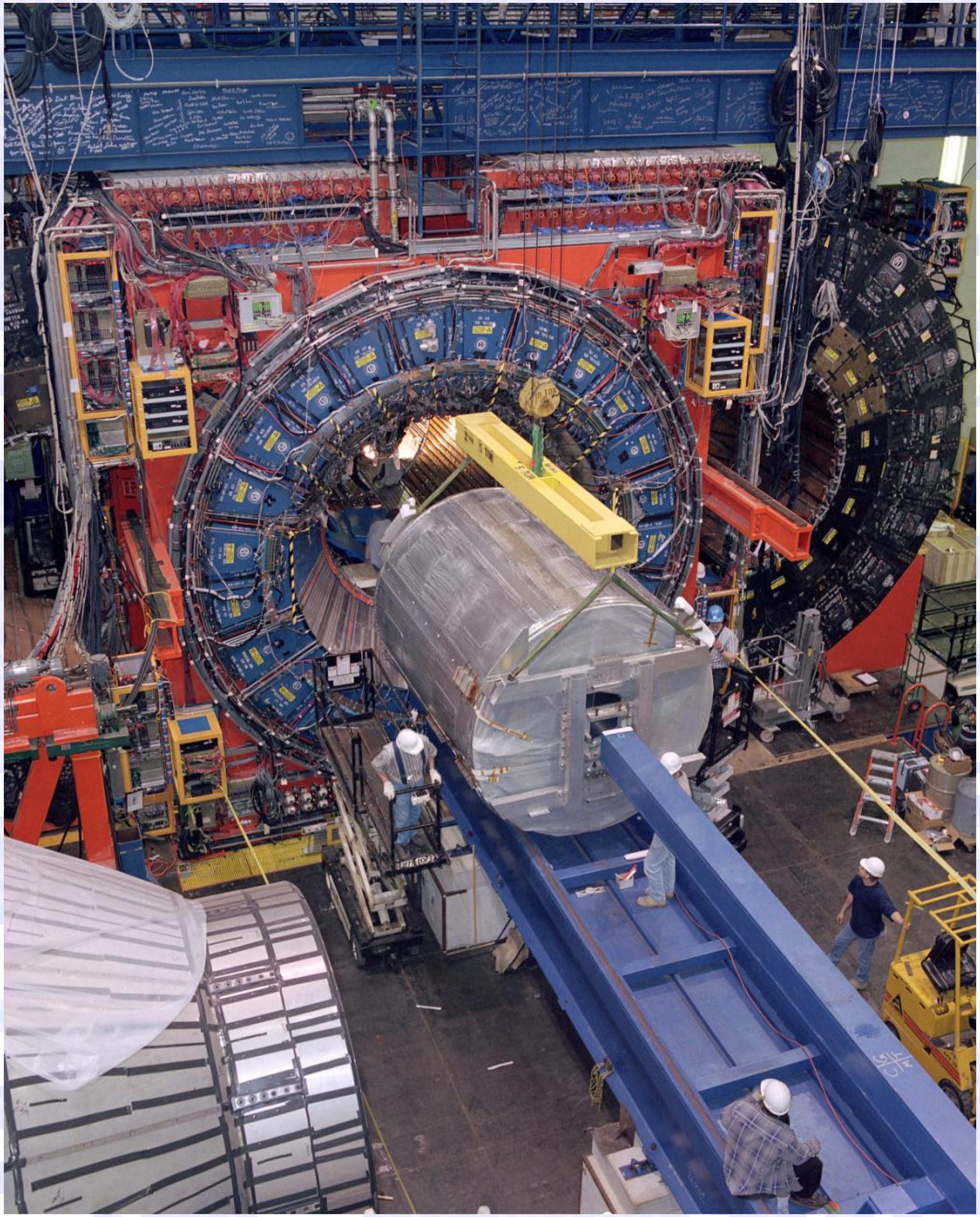
Summary of Improvement Factors

Ratio P996/E949	
$11.3^{+3.3}_{-2.3}$	Detector acceptance
6.3 ± 2.1	Stopped kaons per hour
5.3	Hours per year

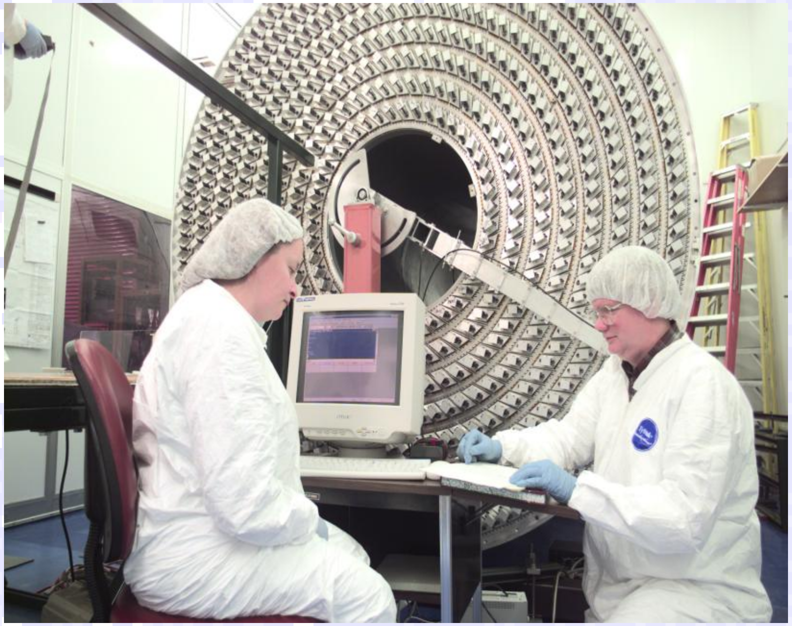
Stopped kaon yield $\equiv R_{\mathrm{prot}} \times R_{K/p} \times R_{\mathrm{surv}} \times R_{\mathrm{stop}}/R_{\mathrm{spill}}$
where

- R_{proton} is the ratio of protons per spill,
- $R_{K/p}$ is the relative production rate of K^+ into the P996 and E949 kaon beamline acceptance.
- R_{surv} is the relative K^+ survival rate in the kaon beamline,
- R_{stop} is the relative K^+ stopping fractions, and
- R_{spill} is the relative spill length.

Comparable K^+, π^+ instantaneous rate in E949 (8.4 MHz) and P996 (7.6 MHz).

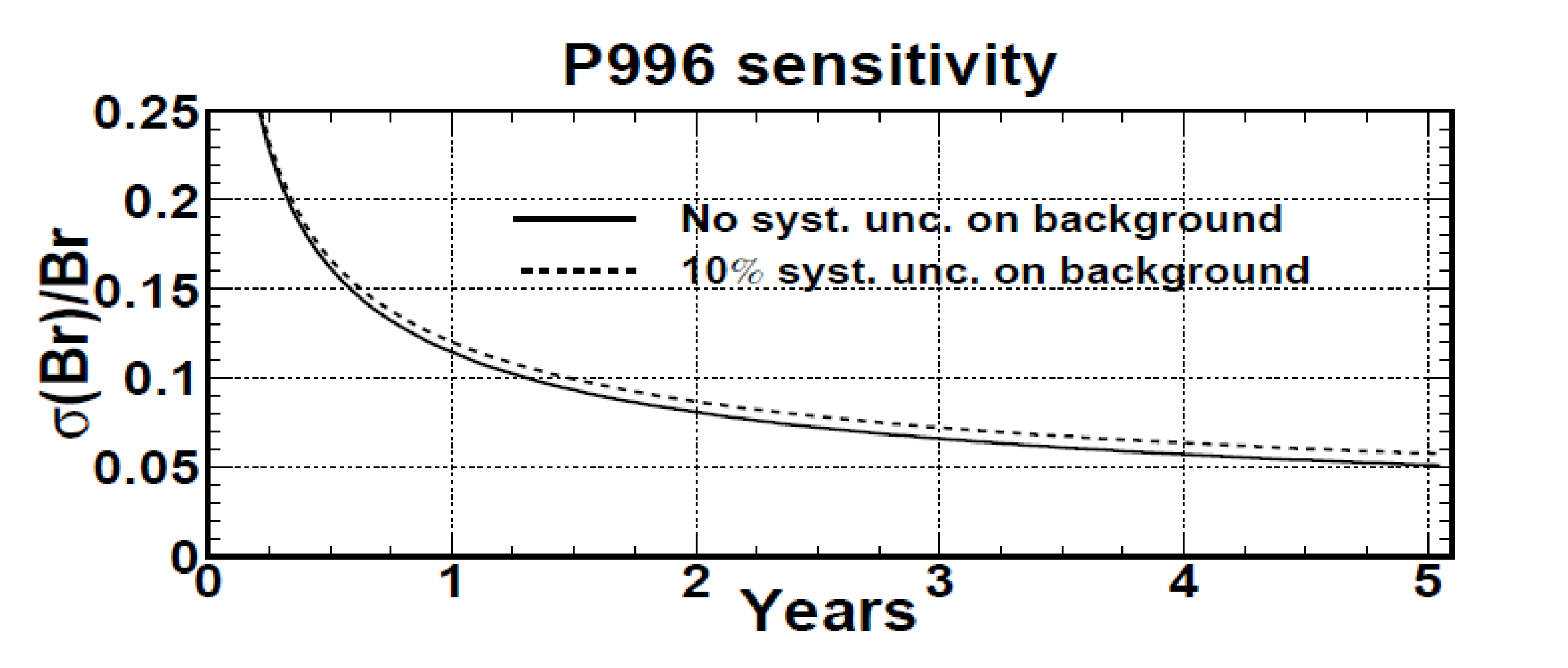


Proposed re-use of CDF infrastructure: The P996 detector payload replaces the CDF tracker volume.



The Range Stack measures the π^+ decay chain, energy, range: Ripe for upgrade

5 Years or Running is not critical to reach new physics...



Investigating a scenario where experiment is tuned up with Main Injector beam (30% duty factor) followed by 2-year run with Stretcher. Running with Main Injector alone is a fall-back.

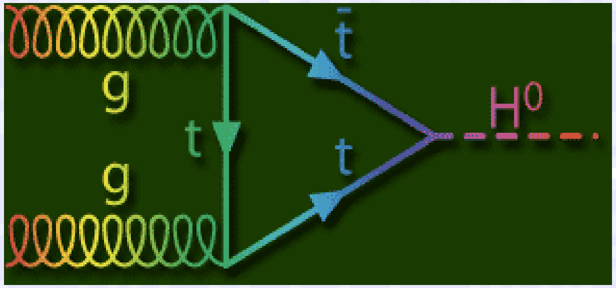
P996 Review Status

- Strong support from Fermilab PAC.

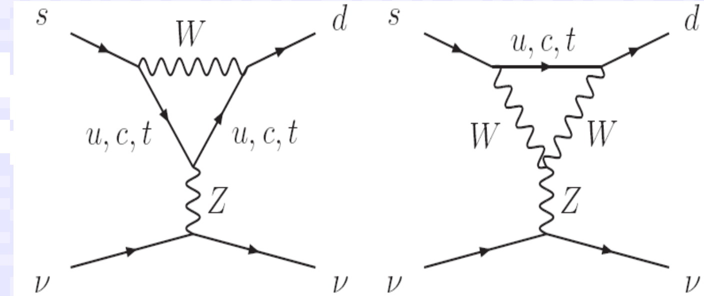
- P996 briefed the DOE office of HEP office in March.

- Good discussion—Tevatron Stretcher operating costs flagged.

- P996 is now investigating scenarios to mitigate operating costs.



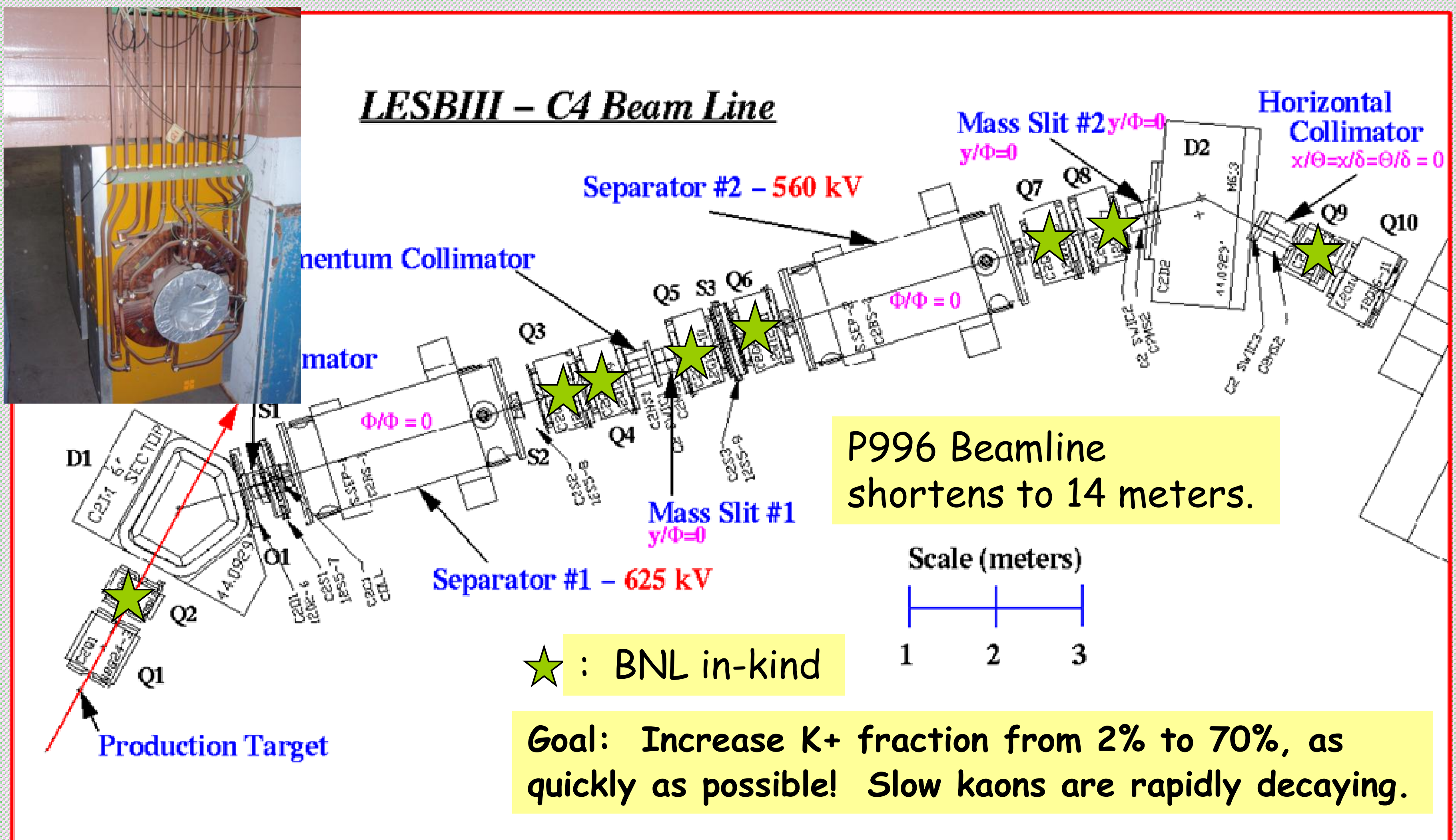
P996 Summary



- Fermilab Proposal P996 can deliver on the long sought after goal of precisely measuring $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. This goal can be achieved with modest resources.
- P996 is a "kaon experiment" in the same way that ATLAS, CMS, and LHCb are "proton experiments". We are using familiar hadrons as tools to explore and study the Terascale.
- P996 is a timely opportunity. It is a bridge to Project-X and the future discoveries there.

Spare Slides

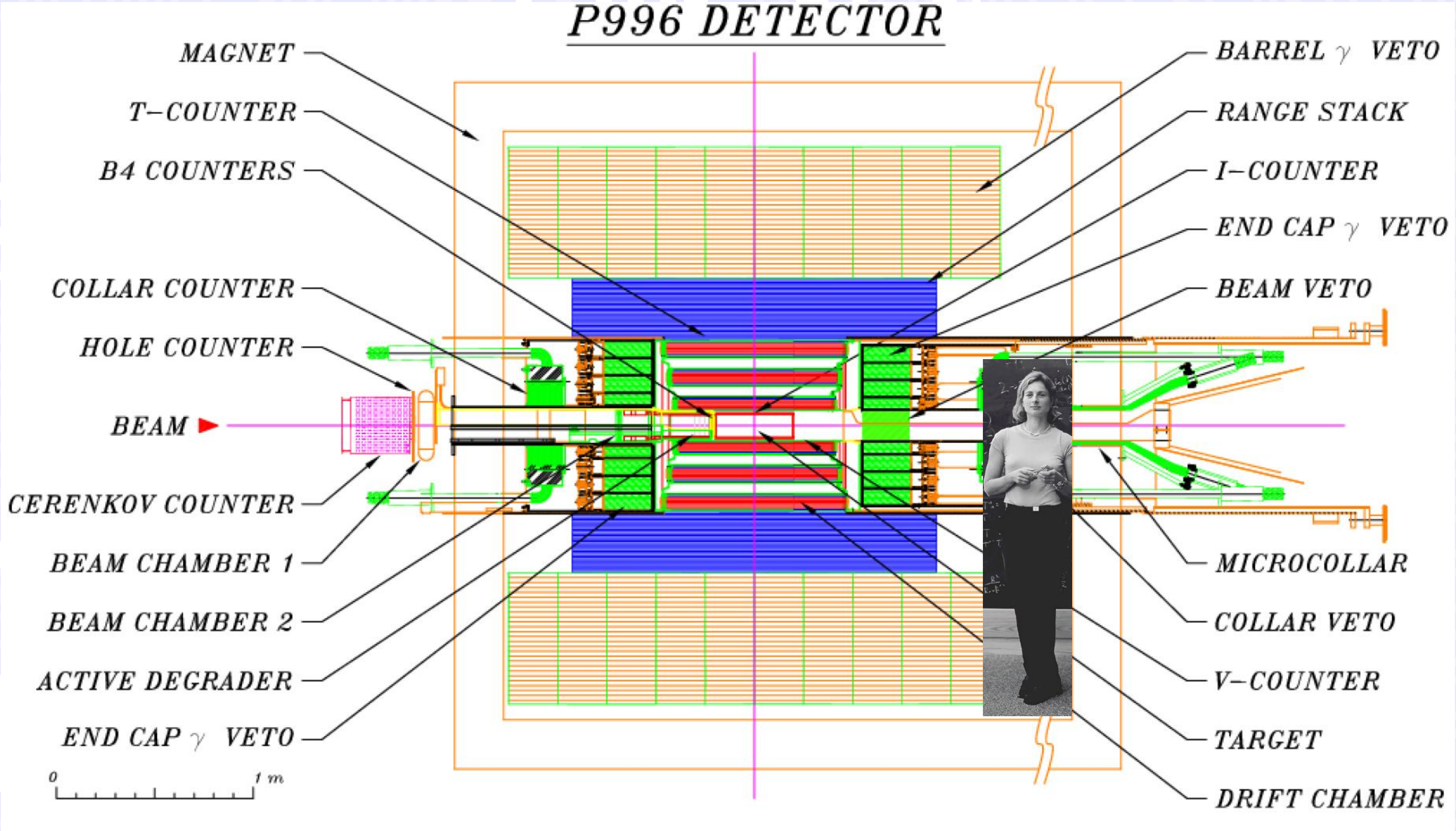
K⁺ Beamline: Focus a low energy separated charged beam on a stopping target. Measure kaon decays at Rest!



P996 Beamline shortens to 14 meters.

Goal: Increase K+ fraction from 2% to 70%, as quickly as possible! Slow kaons are rapidly decaying.

P996: 1000 event measurement of $K^+ \rightarrow \pi^+ \nu\nu$



Lisa Randall with the experiment that discovers evidence for extra dimensions…

Rate of Incident Kaons

The expected rate of kaons incident on P996:

$$\begin{aligned} N_K(\mathrm{P996})/\mathrm{spill} &= N_K(\mathrm{E949})/\mathrm{spill} \times R_{\mathrm{surv}} \times R_{\mathrm{proton}} \times R_{K/p} \\ &= 12.8 \times 10^6 \times 1.1048 \times 1.48 \times (6.8 \pm 1.7) \\ &= (142 \pm 36) \times 10^6. \end{aligned}$$

- $R_{\mathrm{surv}} = 1.1048$, the relative rate of survival of 550 MeV/c kaons in the 13.74m P996 K^+ beamline compared to 710 MeV/c K^+ in the 19.6m E949 beamline,
- $R_{\mathrm{proton}} = (96 \times 10^{12})/(65 \times 10^{12})$ protons per spill,
- $R_{K/p} = 6.8 \pm 1.7$, the relative production rate of K^+ into the P996 and E949 kaon beamline acceptance as determined from MARS-LAQSGM simulation.

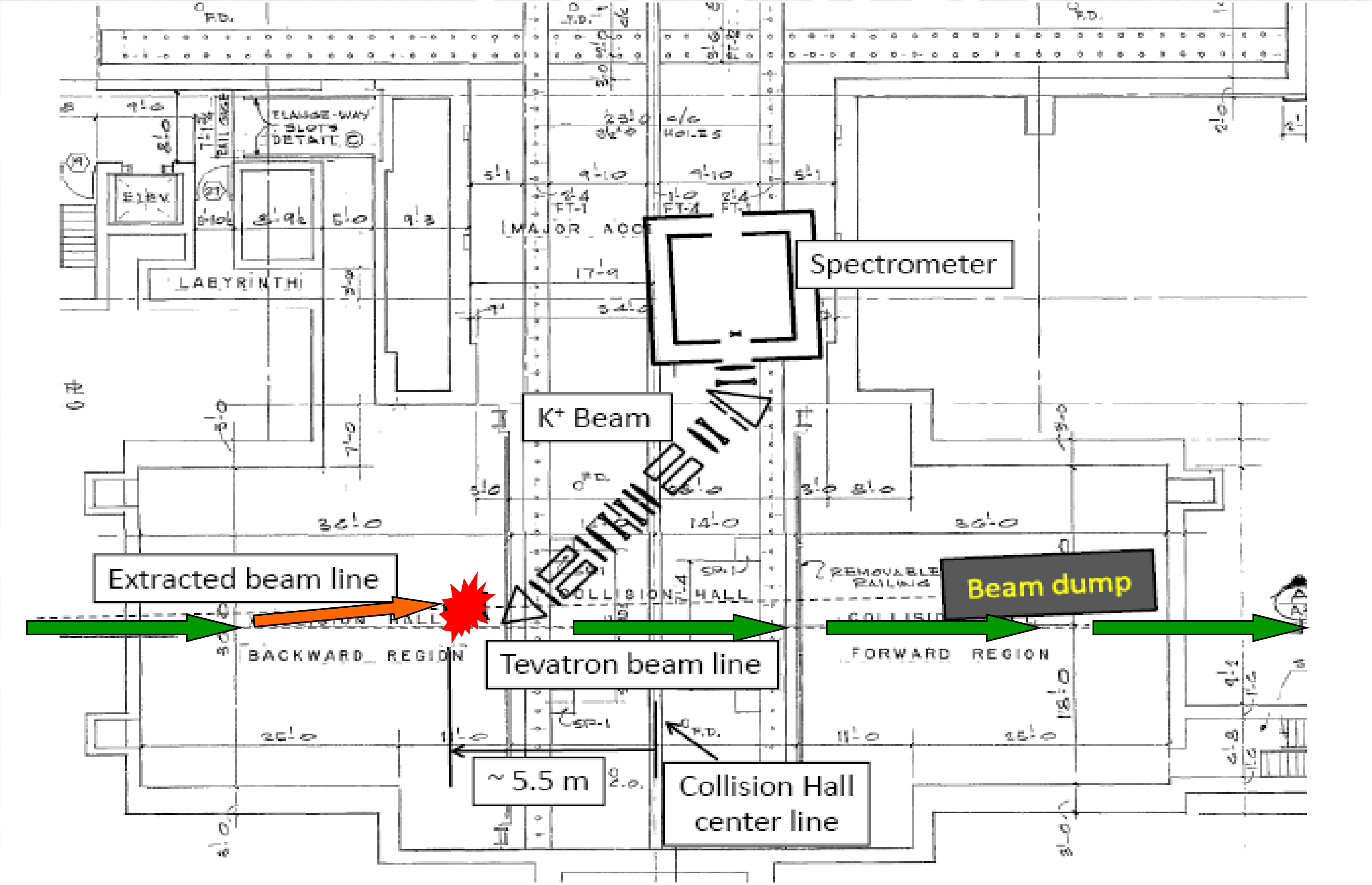
Detector Acceptance

P996 detector improvements will enable increases in signal acceptance. Expected increases are based largely on E949/E787 data and measurements.

Component	Acceptance factor
$\pi \to \mu \to e$	2.24 ± 0.07
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	1.12 ± 0.05
Range stack segmentation	1.12 ± 0.06
Photon veto	$1.65^{+0.39}_{-0.18}$
Improved target	1.06 ± 0.06
Macro-efficiency	1.11 ± 0.07
Delayed coincidence	1.11 ± 0.05
Product (R_{acc})	$11.28^{+3.25}_{-2.22}$

Additional acceptance gains expected from trigger improvements are not yet quantified.

P996 Beamline and Detector at CDF hall (B0)



Breadth of P996 program

- Similar to the recently completed KTeV program at Fermilab:

- 50 scientific publications, most in PRL.

- 35 PhDs produced.

- A high throughput open trigger system is important to breadth.

Other Possible P996 Measurements

$$K^+ \to \pi^+ \mu^+ \mu^-$$
$$K^+ \to \pi^+ \gamma\gamma$$
$$K^+ \to \mu^+ \nu\gamma$$
$$K^+ \to \pi^+ \pi^0 \gamma$$
$$K^+ \to \pi^+ X^0$$
$$K^+ \to \pi^+ \gamma\gamma$$
$$K^+ \to \pi^+ \gamma$$
$$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$$
$$K^+ \to \pi^+ H;\, H \to \mu^+ \mu^-$$
$$K^+ \to e^+ \nu \mu^+ \mu^-$$
$$\pi^0 \to \nu\bar{\nu}$$
$$\pi^0 \to \gamma + X^0$$

...and more.

Can the Booster or the Main-Injector Drive P996?

- Yes, but not as well.

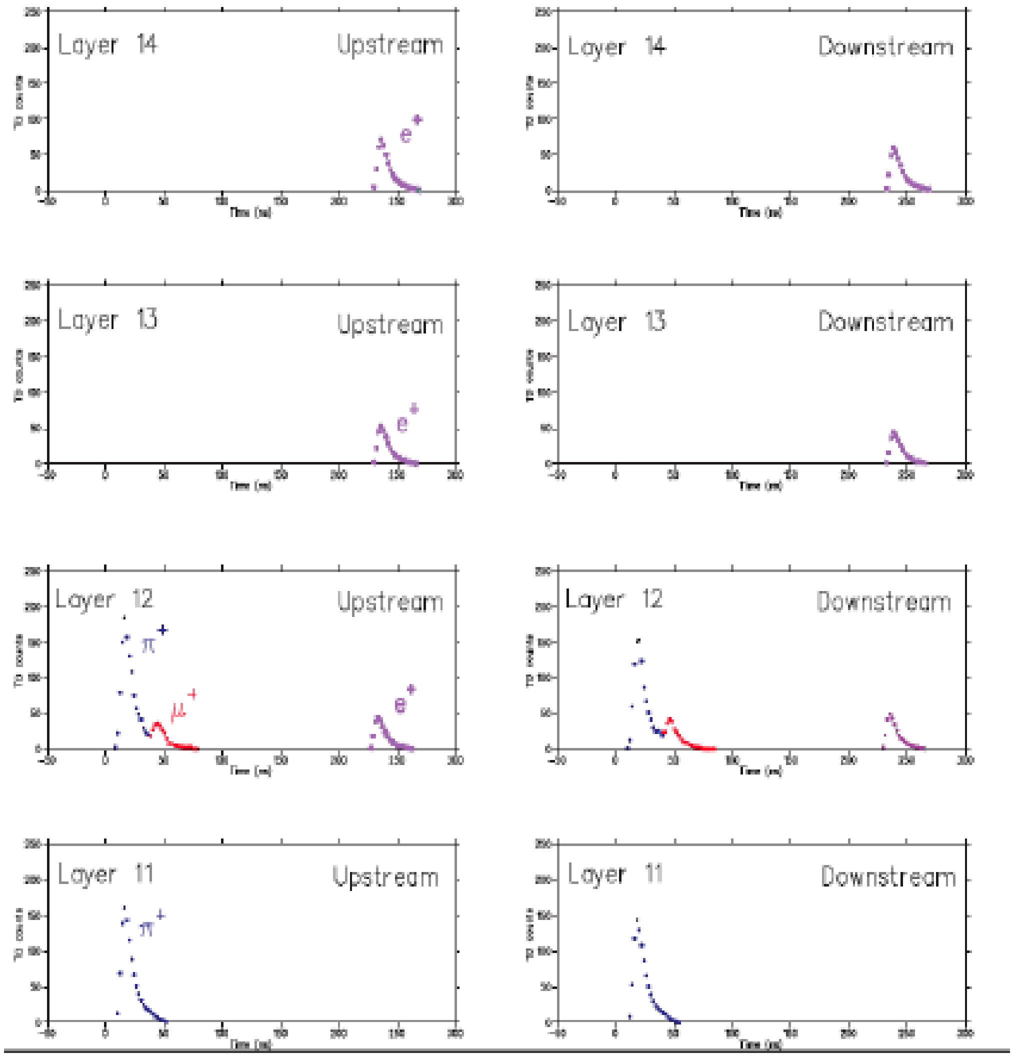
- Booster:

  Would have to time-share with micro/mini-BooNE, Mu2e, (g-2). Mu2e is based on 25 kW of extracted beam, and this is a challenge for the modified 8 GeV complex due to space-charge effects at extraction. The P996 sensitivity is based on 80kW of beam, means a dedicated Booster program would likely have ~1/3 sensitivity/year.

- Main Injector:

  Slow-extraction Flat-top is limited to 30% from magnet heating (not a SC machine). Maintaining the same instantaneous rates as BNL E949 corresponds to a ~1/3 sensitivity/year wrt P996. This would also increase the hit on the Nova program from 10% to 30% .

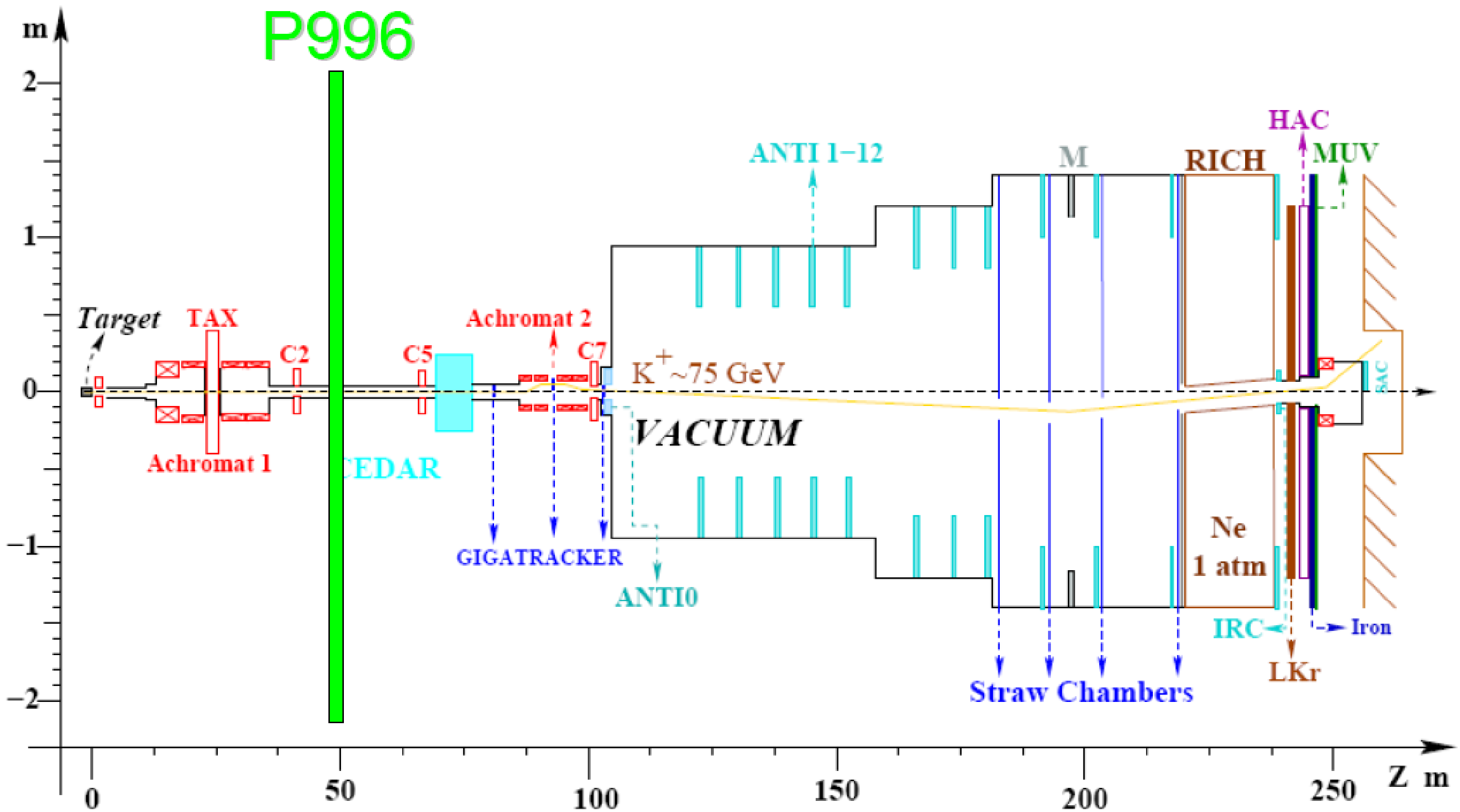
$\pi \rightarrow \mu \rightarrow e$ detection in E949



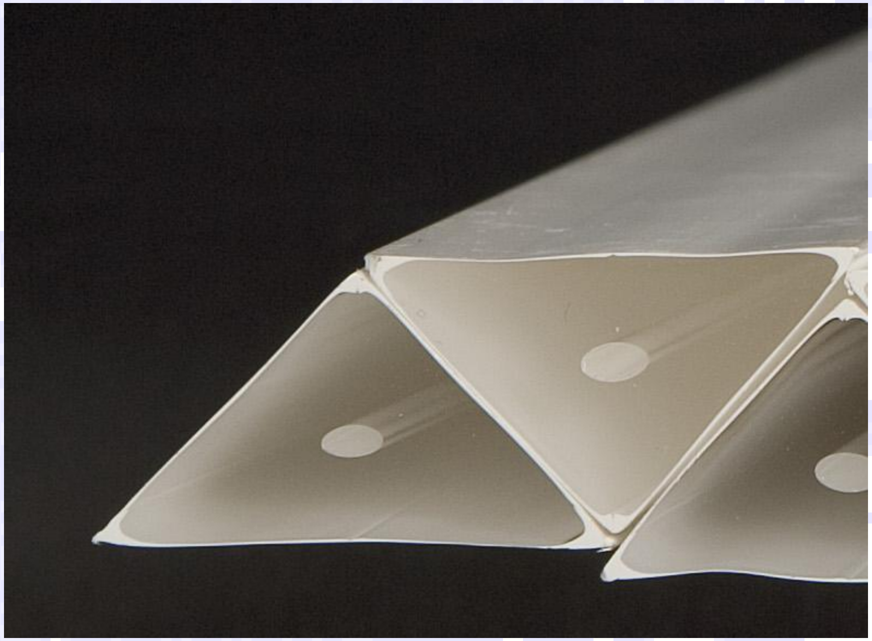
Other Possible Stretcher Experiments

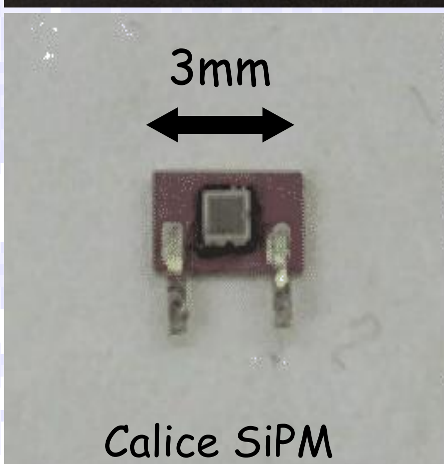
- Next generation Drell-Yan experiment (follow up of current E906)
- Next generation neutral kaon beam experiment tuned to the interference region to pursue CP and CPT studies in a variety of final states.
- Next generation hyperon experiments, such as a follow-up of the putative evidence for new physics in the $\Sigma^+ \to p\mu^+\mu^-$ signal or Σ^+ EDM search using bent crystals (Wah, Chicago).
- A $K_L \to \pi^0 \nu\nu$ experiment if the accelerator pulse timing resolution can be improved (requires R&D).
- $K^+ \to \pi^0 \mu^+ \nu$ Transverse μ^+ polarization: Stringent test of non-SM time reversal invariance.
- High duty factor test-beam program, which will reduce the cost to NOvA. As configured now the test-beam program will be a 5% hit on NOvA operations, and P996 would be 10%, raising the aggregate hit to 15%. Driving test beams in parallel with P996 will reduce the aggregate NOvA hit to 10% as well as providing better test beams.

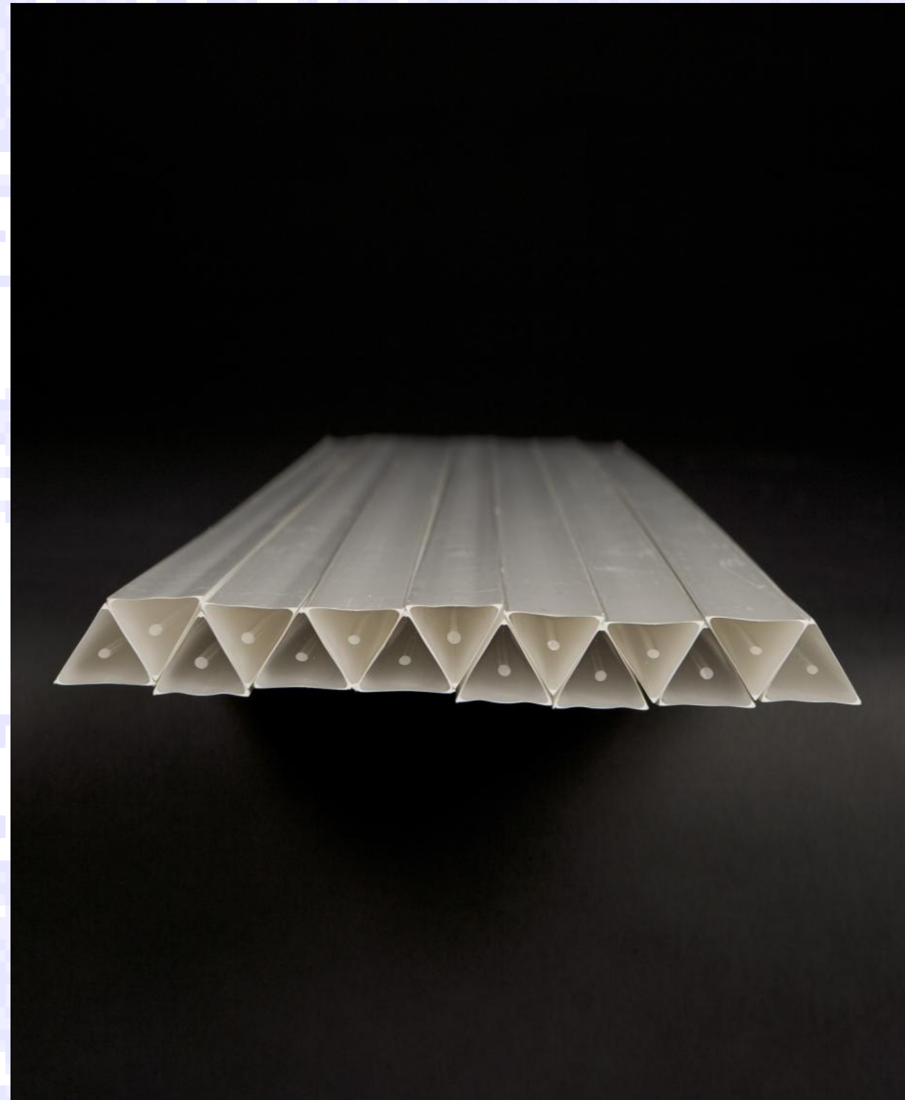
NA-62 Detector Layout



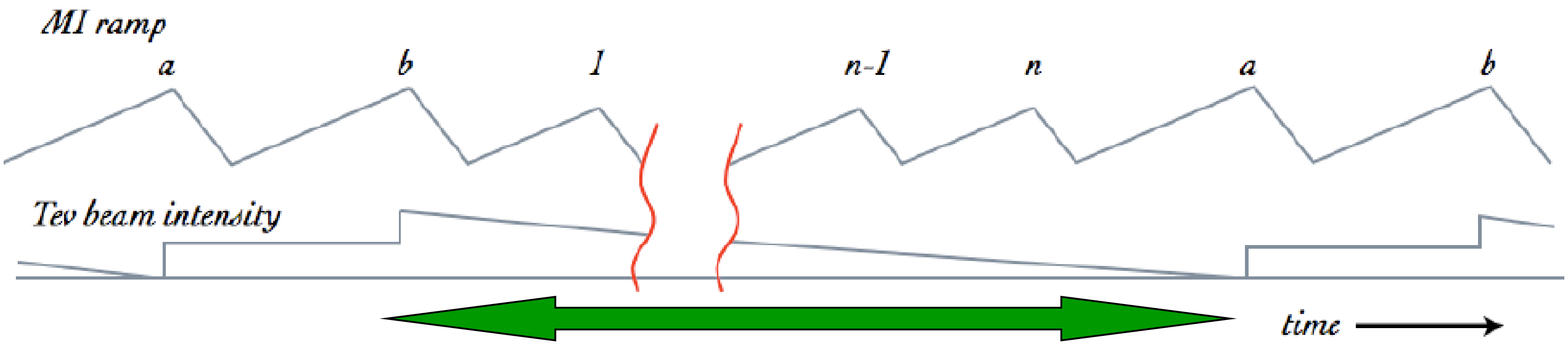
Development required for more precise extrusion and compact photon readout…



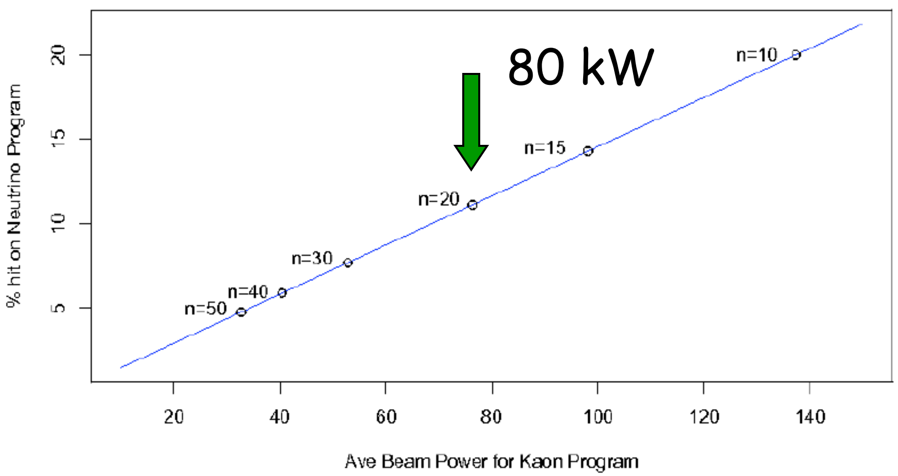


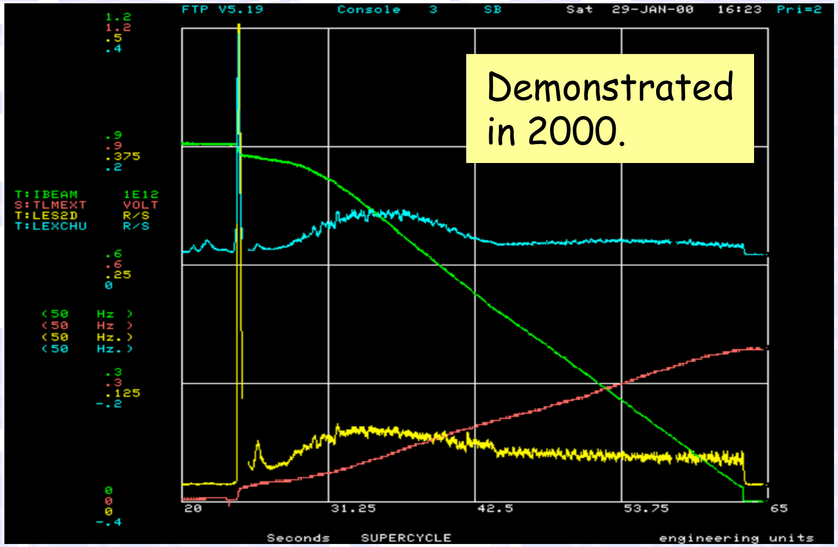


Continuous High Power Beam…



33 second spill, 95% duty factor.





Sensitivity of Kaon Physics Today

- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \rightarrow e^+\nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \rightarrow \mu\mu ee$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \rightarrow \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20×10^{-12} measurement sensitivity of $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- BNL E871: 1×10^{-12} measurement sensitivity of $K_L \rightarrow e^+e^-$
- BNL E871: 1×10^{-12} search sensitivity for $K_L \rightarrow \mu e$

Probing new physics above a 10 TeV scale with 20-50 kW of protons.

Next goal: 1000-event $\pi\nu\nu$ **experiments...10^{-14} sensitivty**.

Opportunities for Collaboration

- **Entire detector systems of moderate scope:**

➢ Fully active stopping target for incident kaons.
➢ Ultra-low mass drift chamber to measure pion momenta to $\delta p/p$ = 1% .
➢ Range-stack for stopping pions.
➢ Photon veto systems.

Enabling technologies:

➢ High performance wave-form digitizers on every detector channel.
➢ "Triggerless DAQ" architectures, fully streaming DAQ.
➢ Geiger-mode photo detectors (SiPMs, MPPCs) to instrument fibers.
➢ Extruded fast scintillator.