Rare Decays & Project-X: Now and Then

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Fermilab

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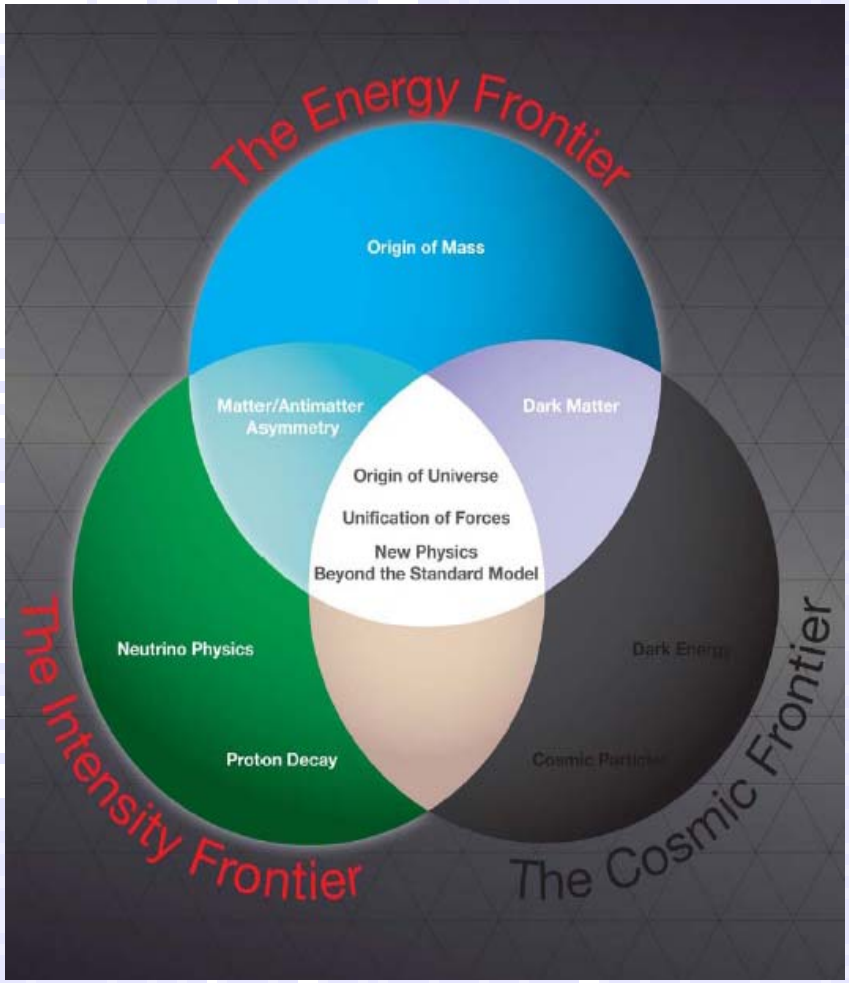
The Promise of the Intensity Frontier

High Intensity Proton Sources that drive next generation experiments in rare processes and long-base neutrino physics can explore:

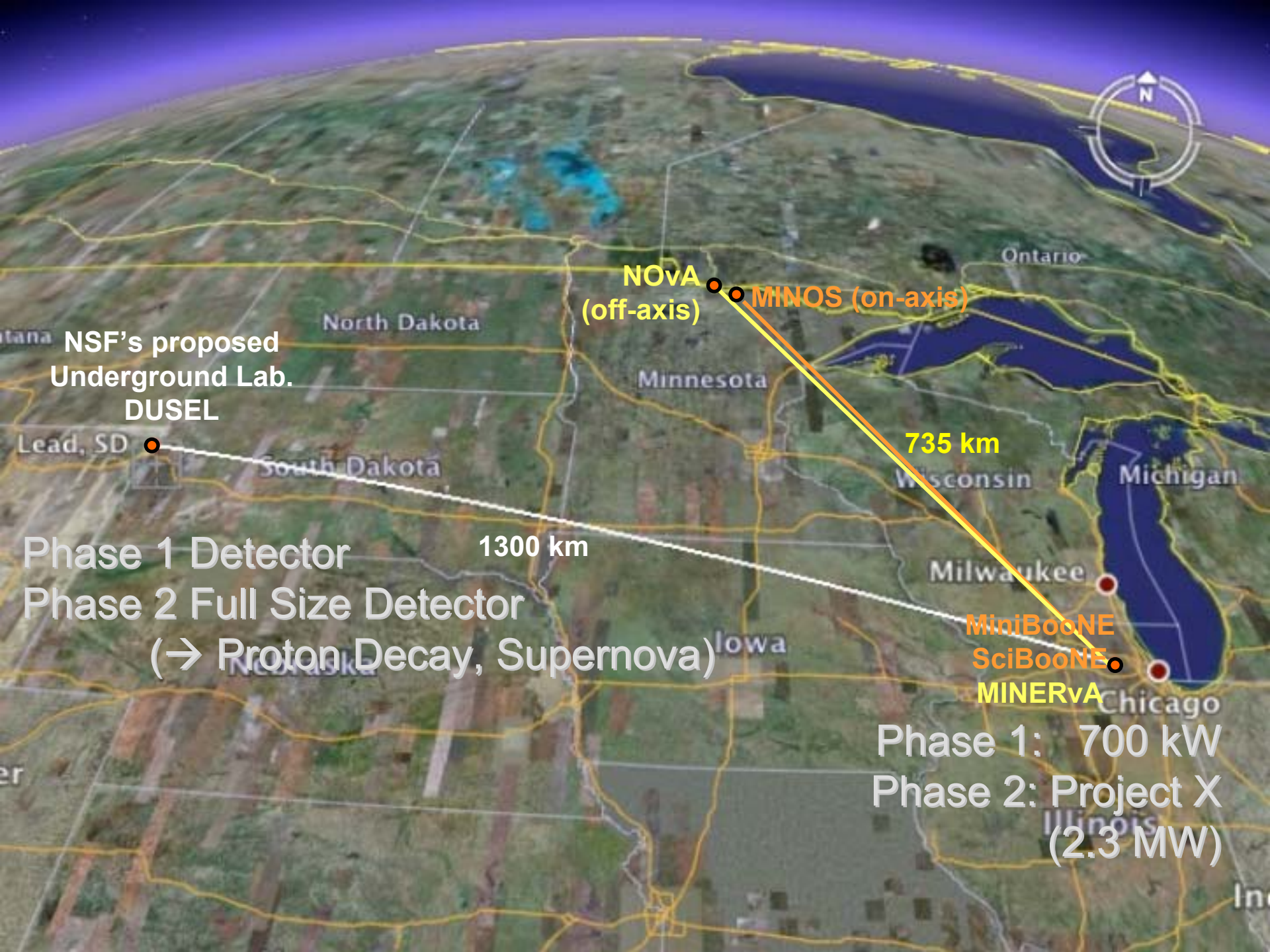
- ***The origin of the universe***
- ***Unification of Forces***
- ***New Physics Beyond the Standard Model.***



The Intensity Frontier Research Program with Proton Sources

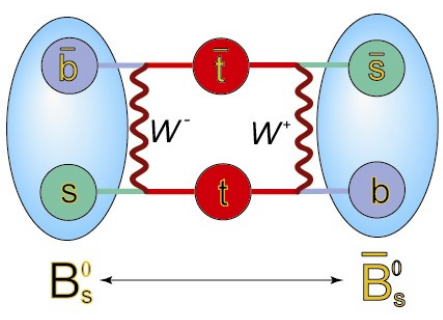
- ***A neutrino beam for long baseline neutrino oscillation experiments.*** A high-power proton source with proton energies between 50 and 120 GeV that would produce intense neutrino beams, directed toward the Deep Underground Science and Engineering Laboratory (DUSEL).

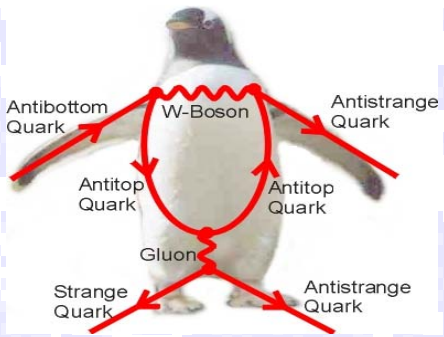
- ***Kaon, muon, nuclei & neutron precision experiments driven by high intensity proton beams running simultaneously with the neutrino program.*** These could include world leading experiments searching for muon-to-electron conversion, precision measurement of $(g\text{-}2)_\mu$, nuclear and neutron electron dipole moments (edms), world-leading precision measurements of ultra-rare kaon decays, and many other experiments.


NOvA
(off-axis)
MINOS (on-axis)
Ontario
North Dakota
NSF's proposed
Underground Lab.
DUSEL
Minnesota
Lead, SD
South Dakota
735 km
Wisconsin
Michigan
1300 km
Phase 1 Detector
Phase 2 Full Size Detector
(→ Proton Decay, Supernova)
Milwaukee
MiniBooNE
SciBooNE
MINERvA
Iowa
Chicago
Phase 1: 700 kW
Phase 2: Project X
(2.3 MW)

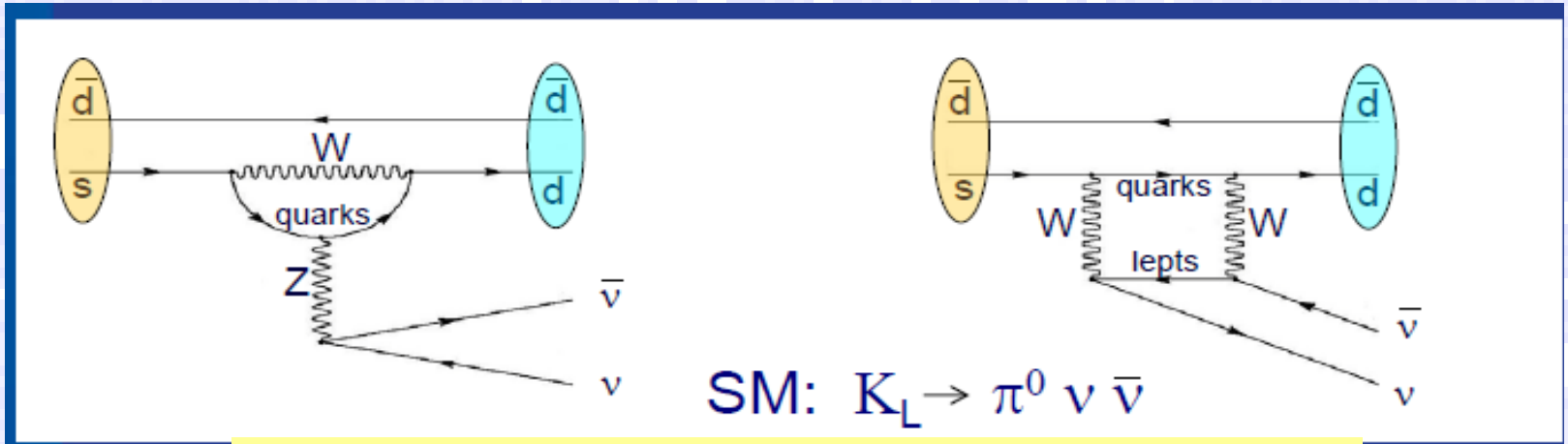
Kaon, Muon and EDM Experiments Deeply Attack The Flavor Problem

Why don't we see the *Terascale Physics we expect* affecting the flavor physics we study today??

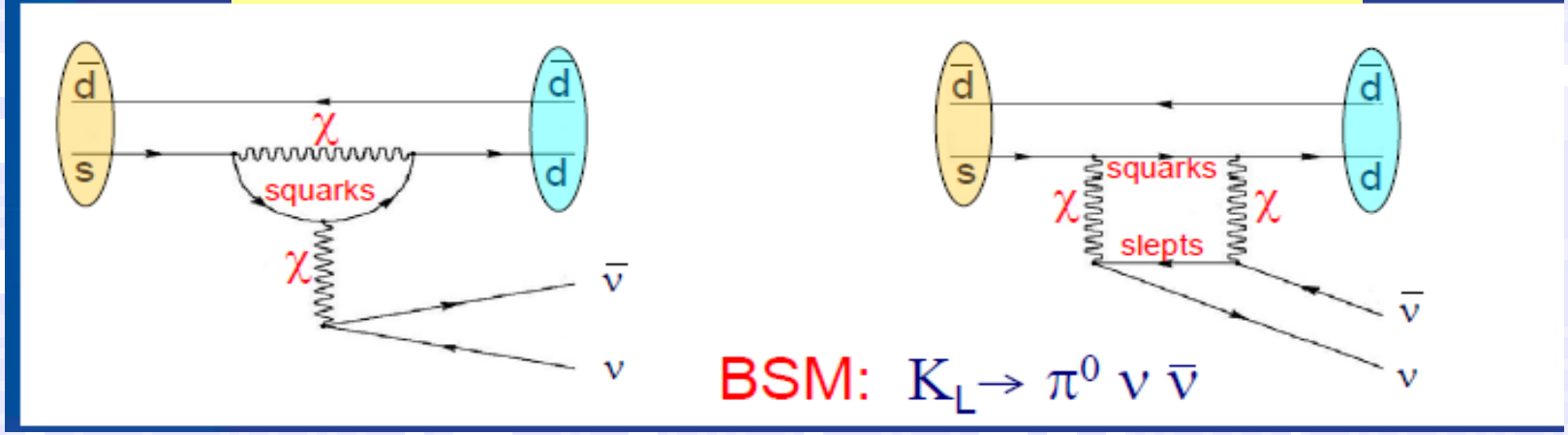




Ultra-rare Kaon Decays Deeply Probe the Flavor Problem in the Quark Sector



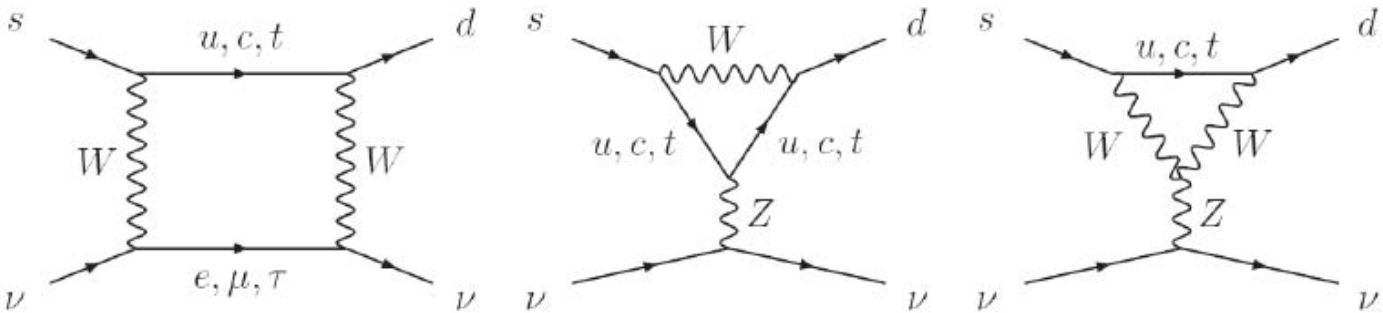
Standard Model rate of 30 parts per trillion!

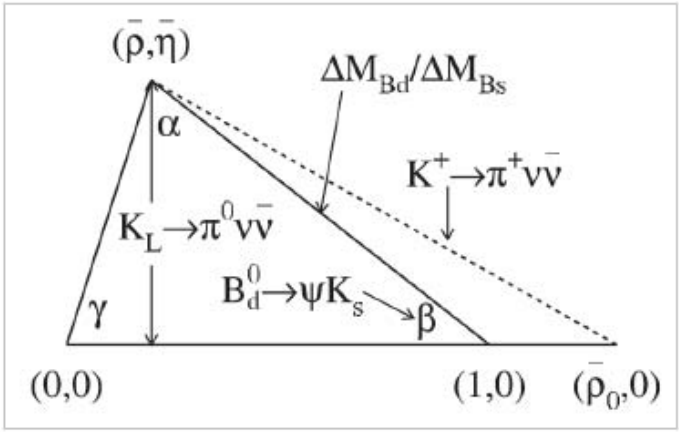


BSM particles within loops can increase the rate up to x10 with respect to SM.

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

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





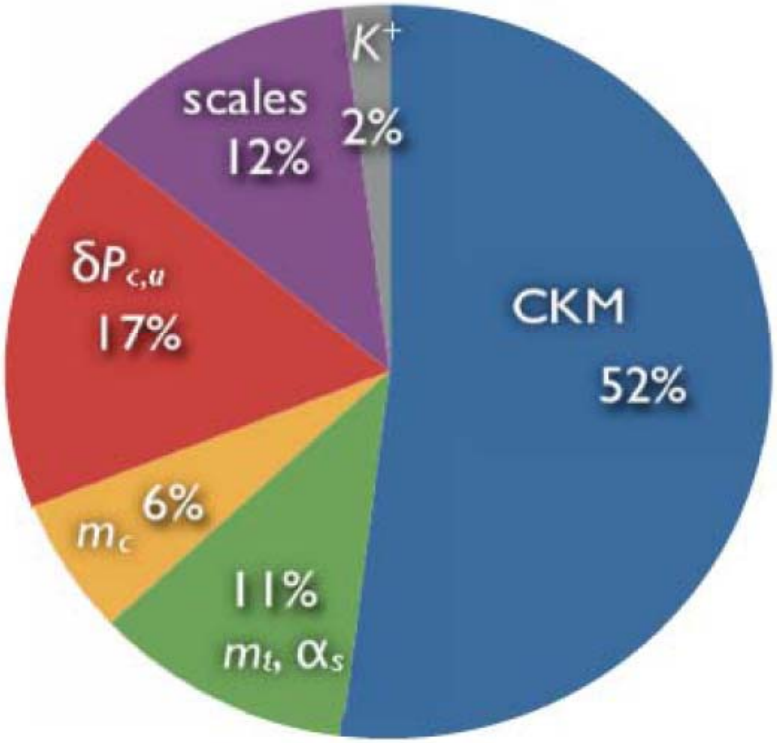
- A single effective operator $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with Ke3
- uncertainty from CKM elements (*will improve*)
- **Remains clean in New Physics models** *(unlike many other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

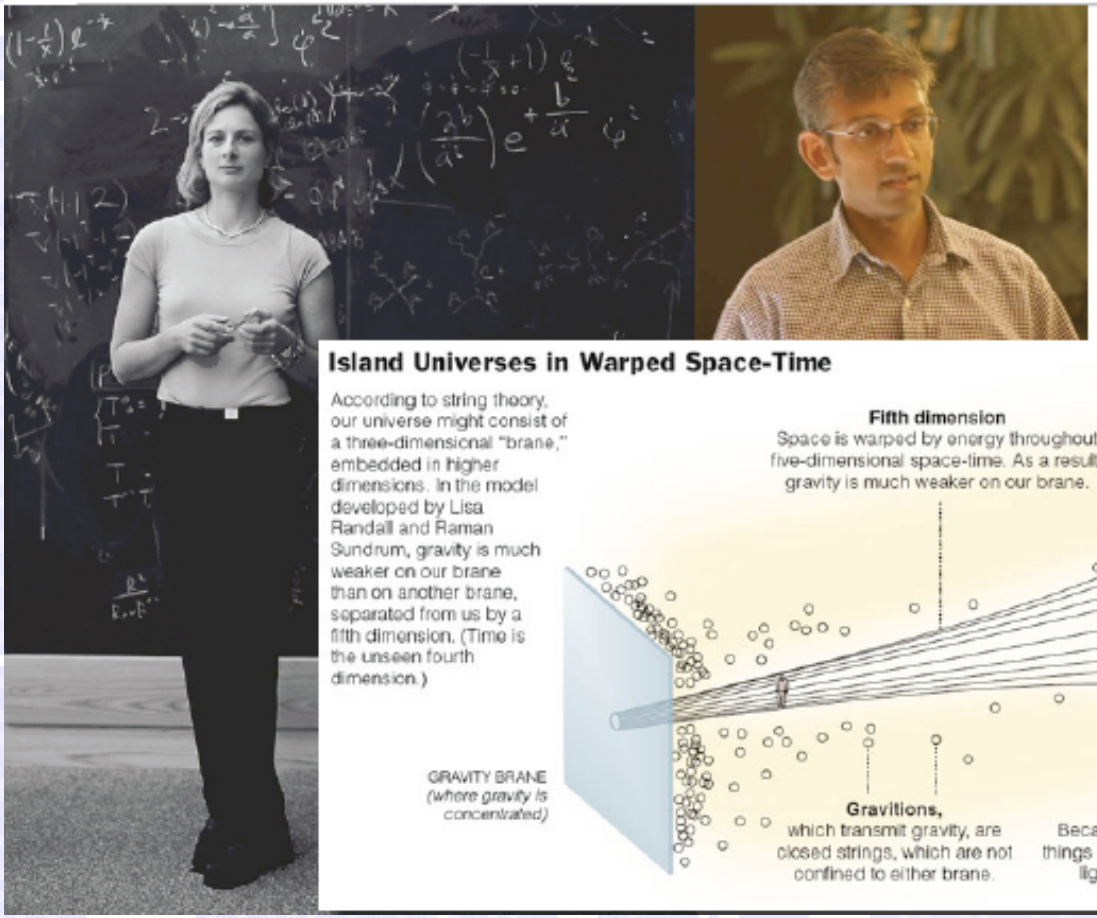
30% deviation from the SM would be a 5σ signal of NP

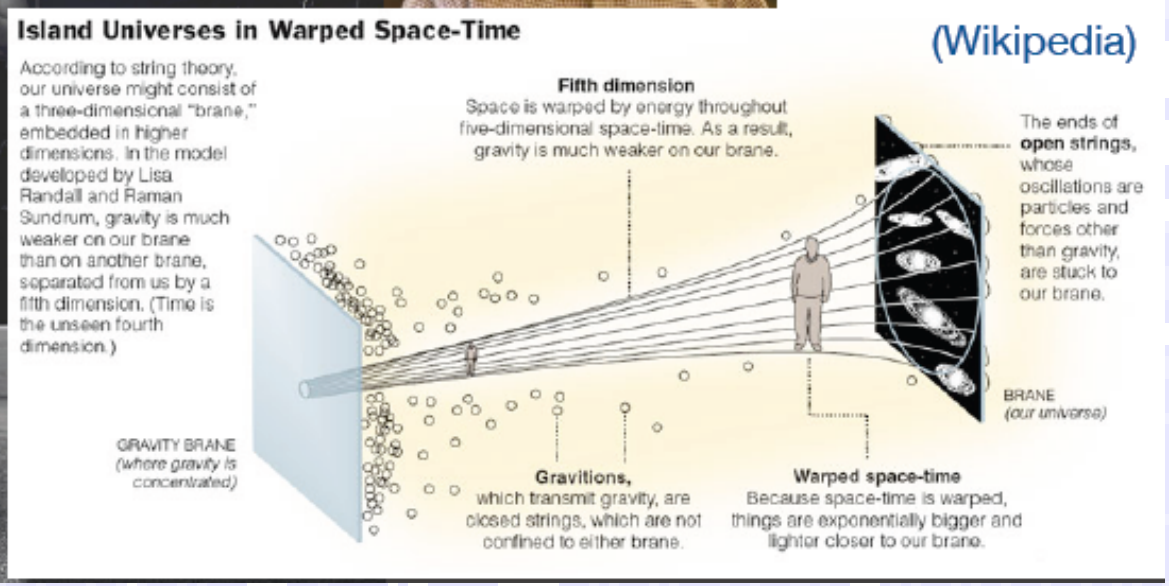
SM theory error for $K_L^0 \to \pi^0 \nu\bar{\nu}$ mode exceed that for $K^+ \to \pi^+ \nu\bar{\nu}$.

U. Haisch, arXiv:0707.3098

Rates sensitive to many BSMs: Warped Extra Dimensions as a Theory of Flavor??

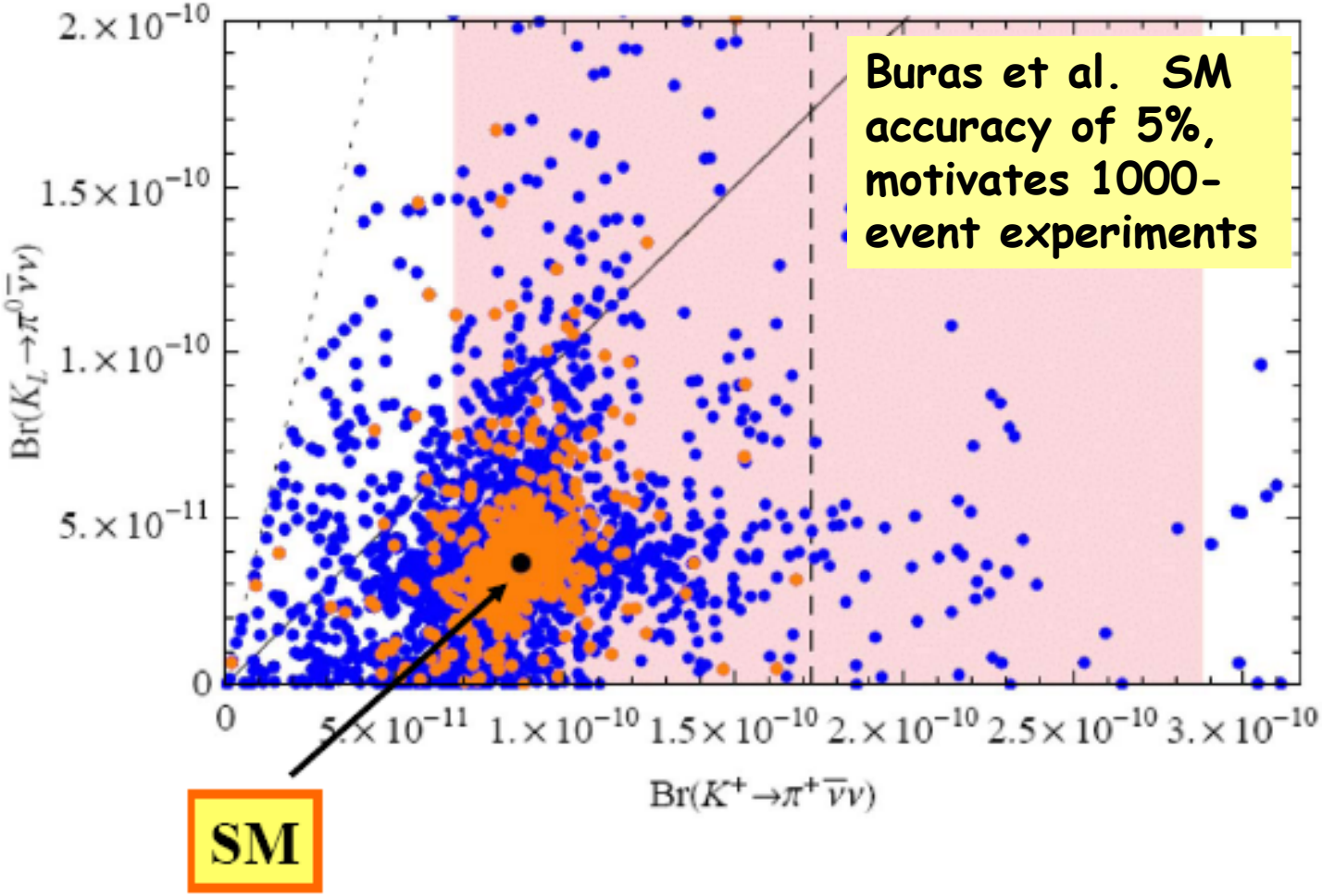
The Randall-Sundrum (RS) idea





$$K_L \to \pi^0 \nu\bar{\nu} \text{ vs. } K^+ \to \pi^+ \nu\bar{\nu}$$ (RS)

(Up to Factor 3 and 2 Enhancements)



Effect of Warped Extra Dimension Models on Branching Fractions

General MSSM with R-parity

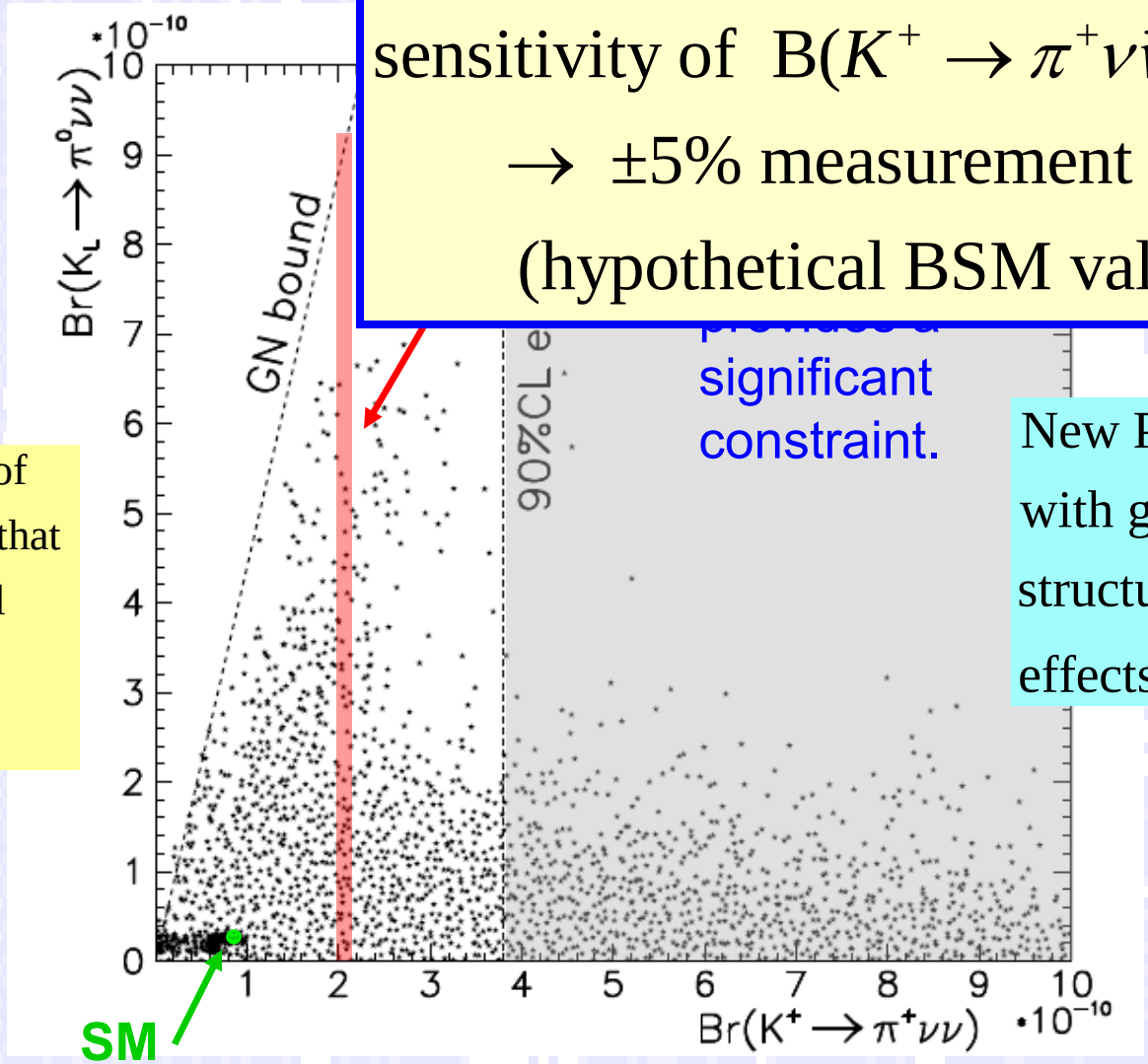
Fermilab P996 will improve the sensitivity of $B(K^+ \to \pi^+ \nu\bar{\nu})$ by >100 !

$\to$ ±5% measurement

(hypothetical BSM value)

Buras et al, NP B714,103(2005)

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



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.

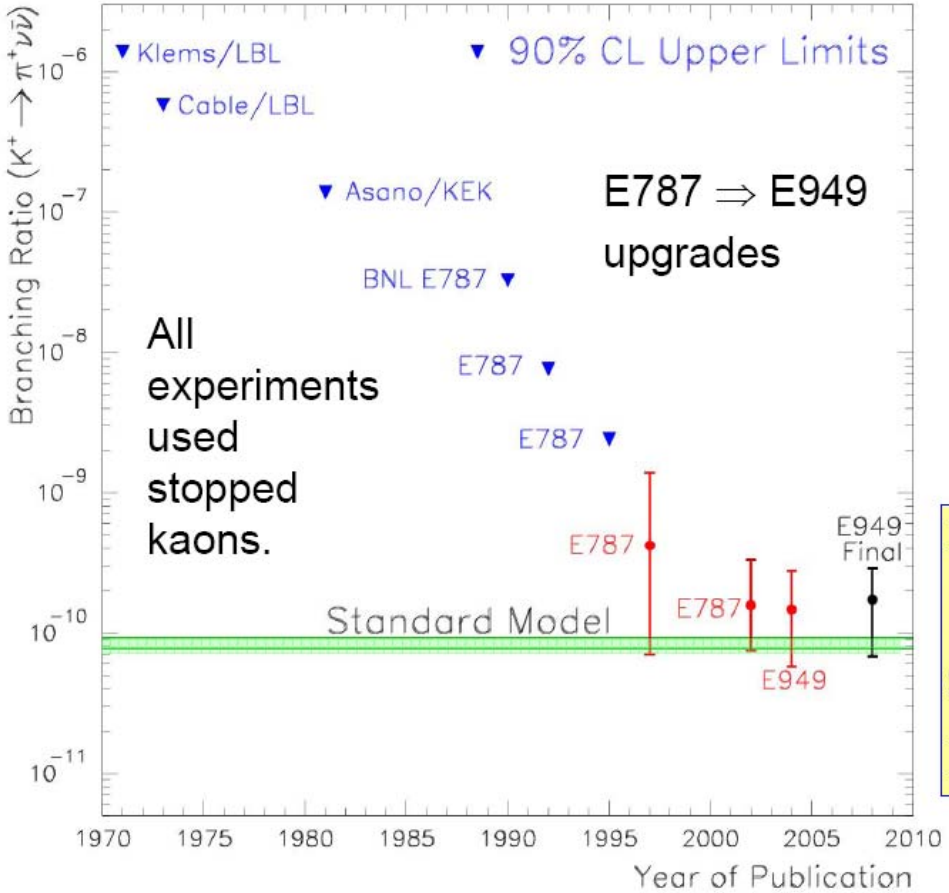
Sensitivity of Kaon Physics Today

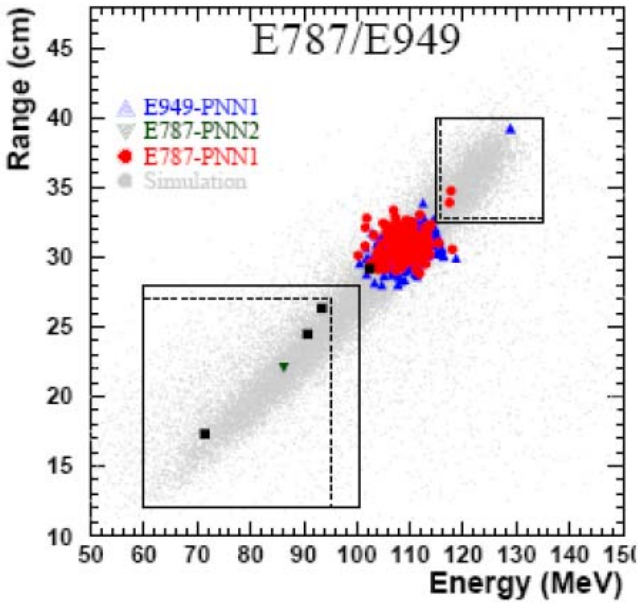
- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \to e^+ \nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \to \mu\mu ee$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \to \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20×10^{-12} measurement sensitivity of $K^+ \to \pi^+ \nu\bar{\nu}$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

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.**

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





E787/E949 Final: 7 events observed

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

Standard Model:

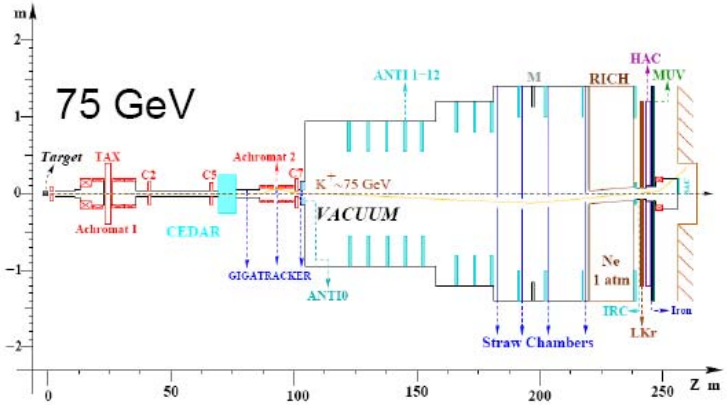
$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) x10^{-10}$$

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

- Measure $B(K^+ \to \pi^+ \nu \bar{\nu})$ 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.

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

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



- Builds on NA-31/NA-48
- Un-separated GHz beam
- Aim: 50 events/yr at SM
- Under construction; start >2012

$K_L^0 \to \pi^0 \nu \bar{\nu}$ at J-PARC

KOTO: 2nd try with ~same setup as KEK ($B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 2.6 x 10^{-8}$)

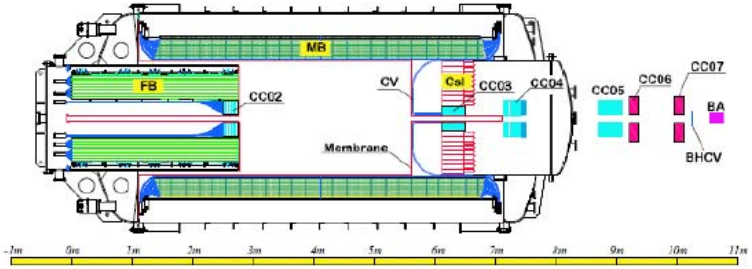
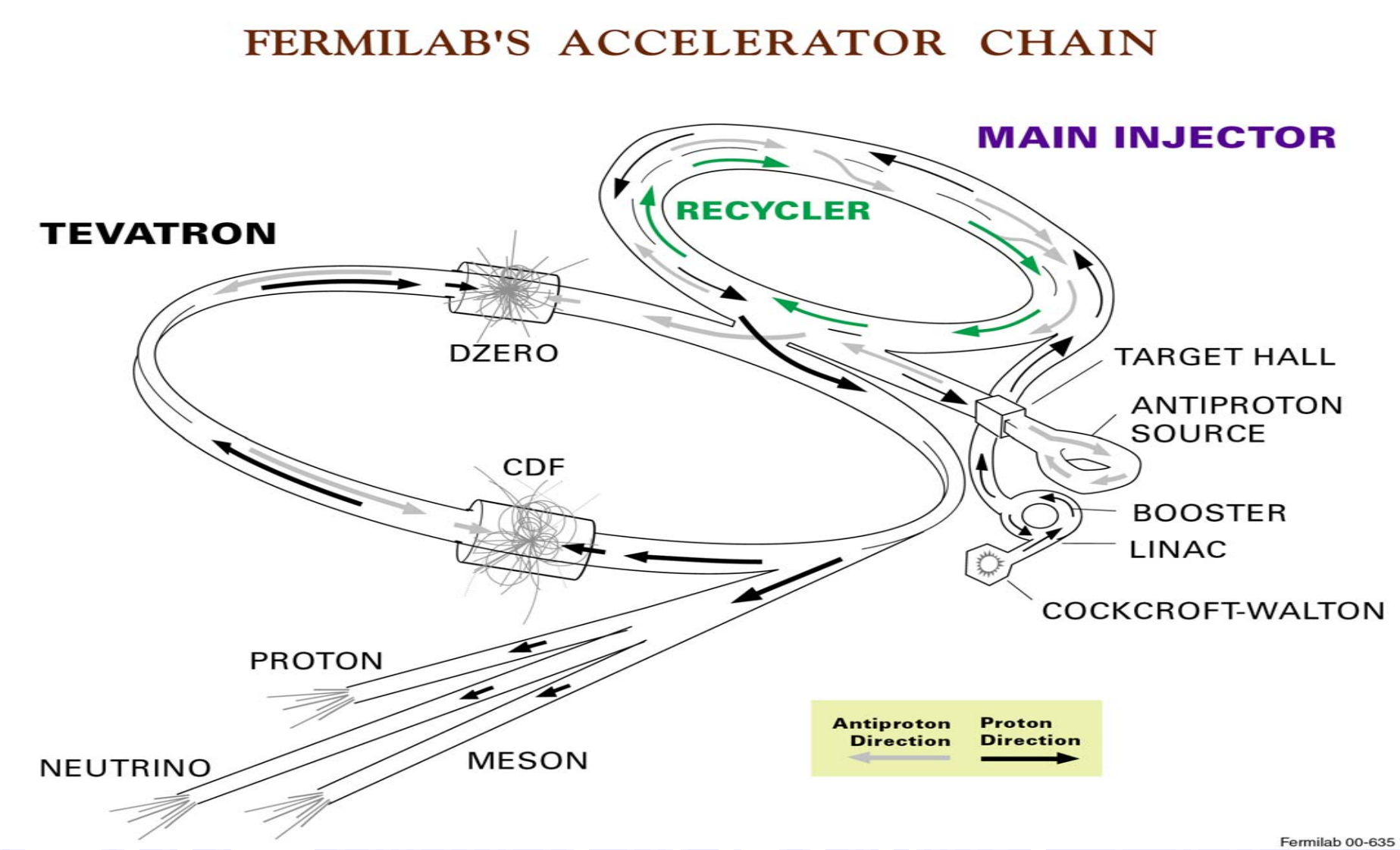


FIG. 1: Cross section of the E391a detector. K_L^0's enter from the left side.

- Improved J-PARC Beam line
- (Eventually) higher power
- Aim: 2.8 events (S/B~1) at SM
- Under construction; start >2011

Past experiments like these (at BNL, Fermilab, CERN, PSI, & TRIUMF) have taken several generations (spanning decades) to reach goals.

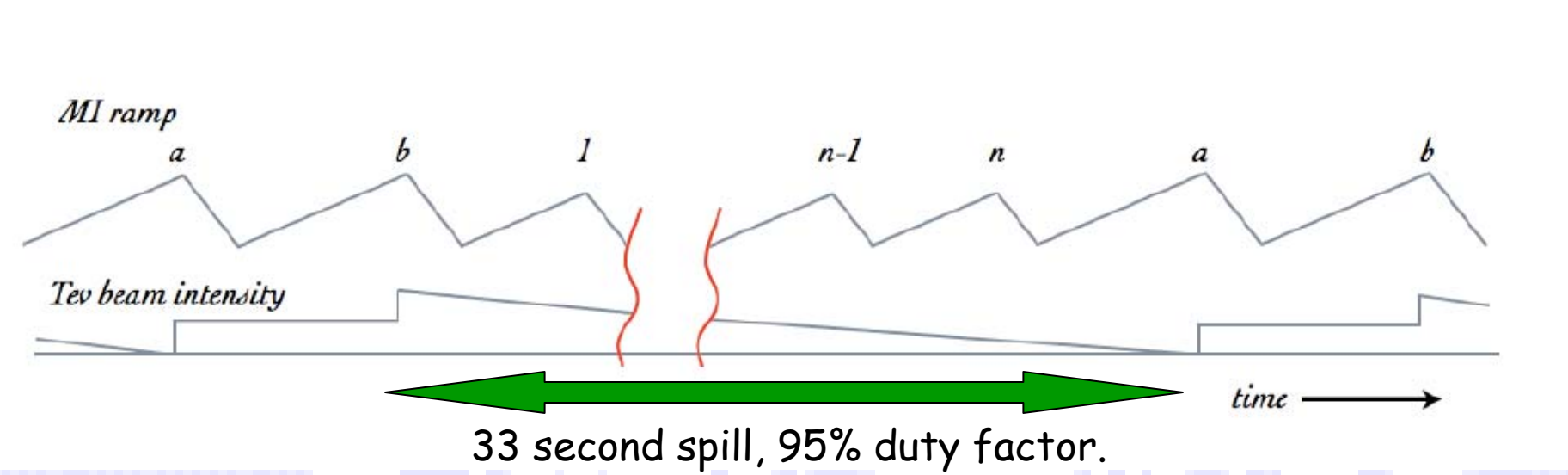
The Tevatron Stretcher Concept

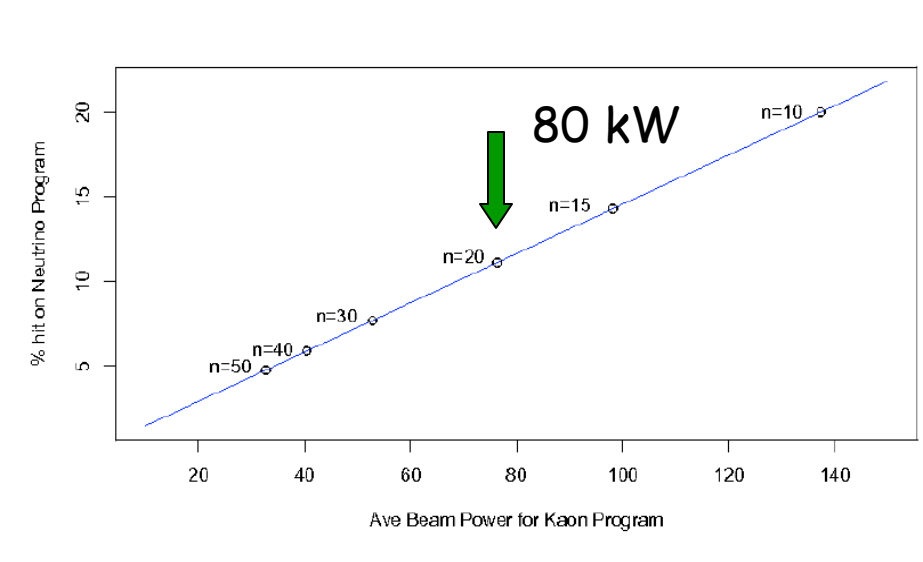


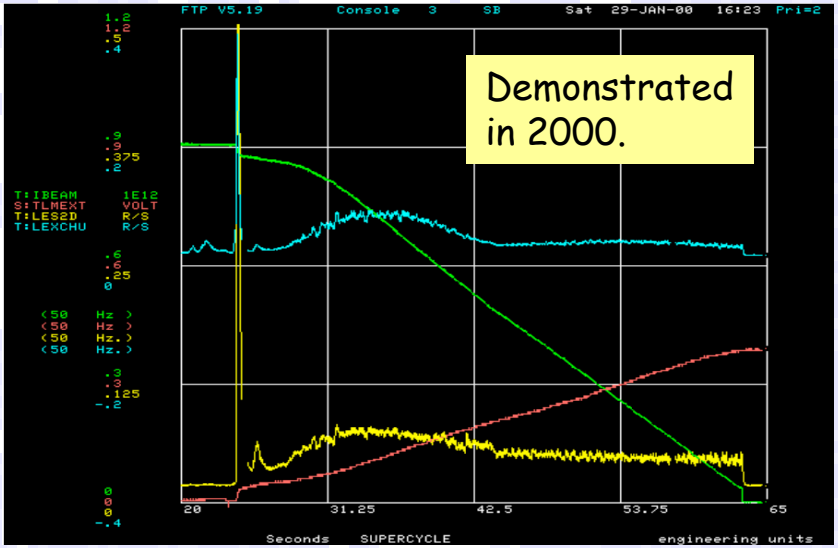
The Stretcher: A World-Leading Machine for the Field…

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 $\sim600\times10^{12}$

Continuous High Power Beam…





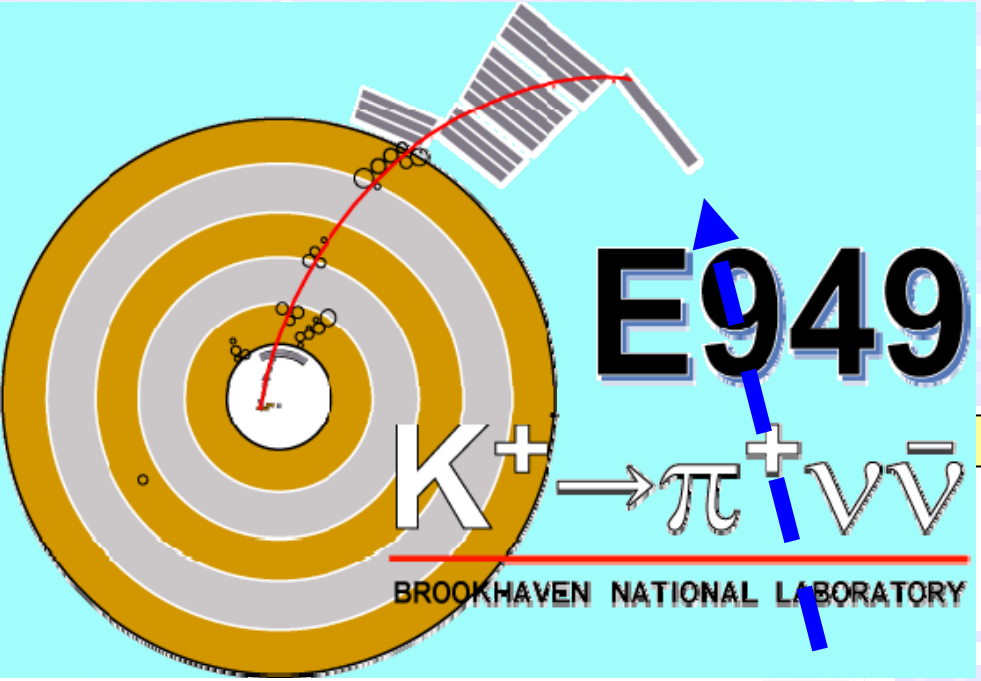


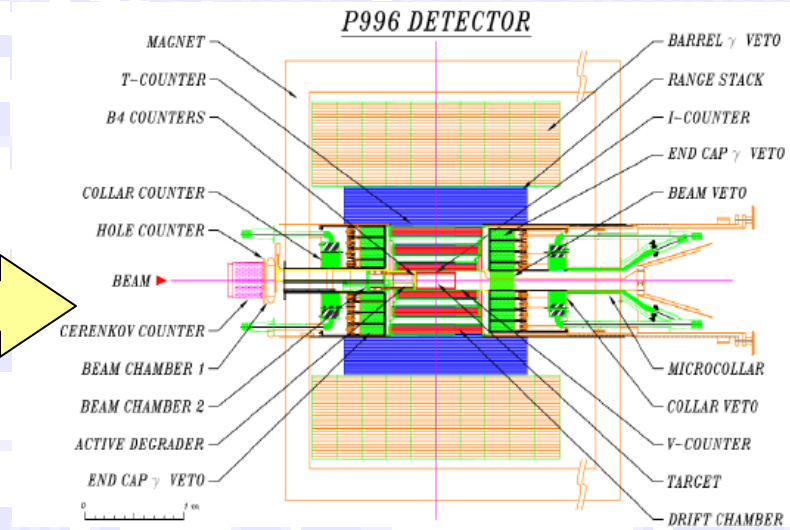
High Duty-Factor Proton Beams

Why is this important to Rare Decay Experiments?

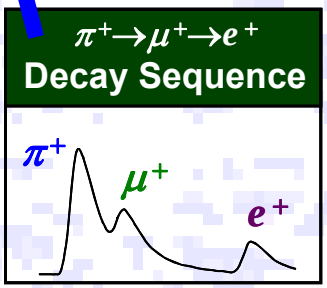
- Experiments that reconstruct an "event" to a particular time from sub-detector elements are intrinsically vulnerable to making mistakes at high instantaneous intensity (I). The probability of making a mistake is proportional to $I^2 x \delta t$, where δt is the event resolving time.
- Searching for rare processes requires high intensity.
- Controlling backgrounds means minimizing the instantaneous rate and maximizing the time resolution performance of the experiment.
- This is a common problem for Run-II, LHC, Mu2e, High-School class reunions, etc.

4th generation

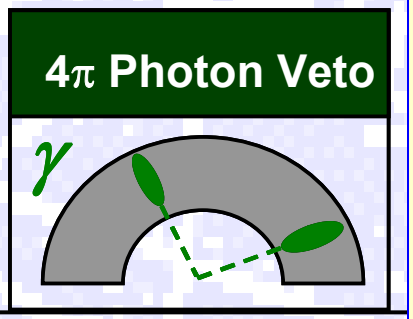




- **Measure everything possible**
- 710 MeV/c K^+ beam
- Stop K^+ in scintillating fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum in drift chamber
- Measure π^+ range and energy in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to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



500 MHz digitizers



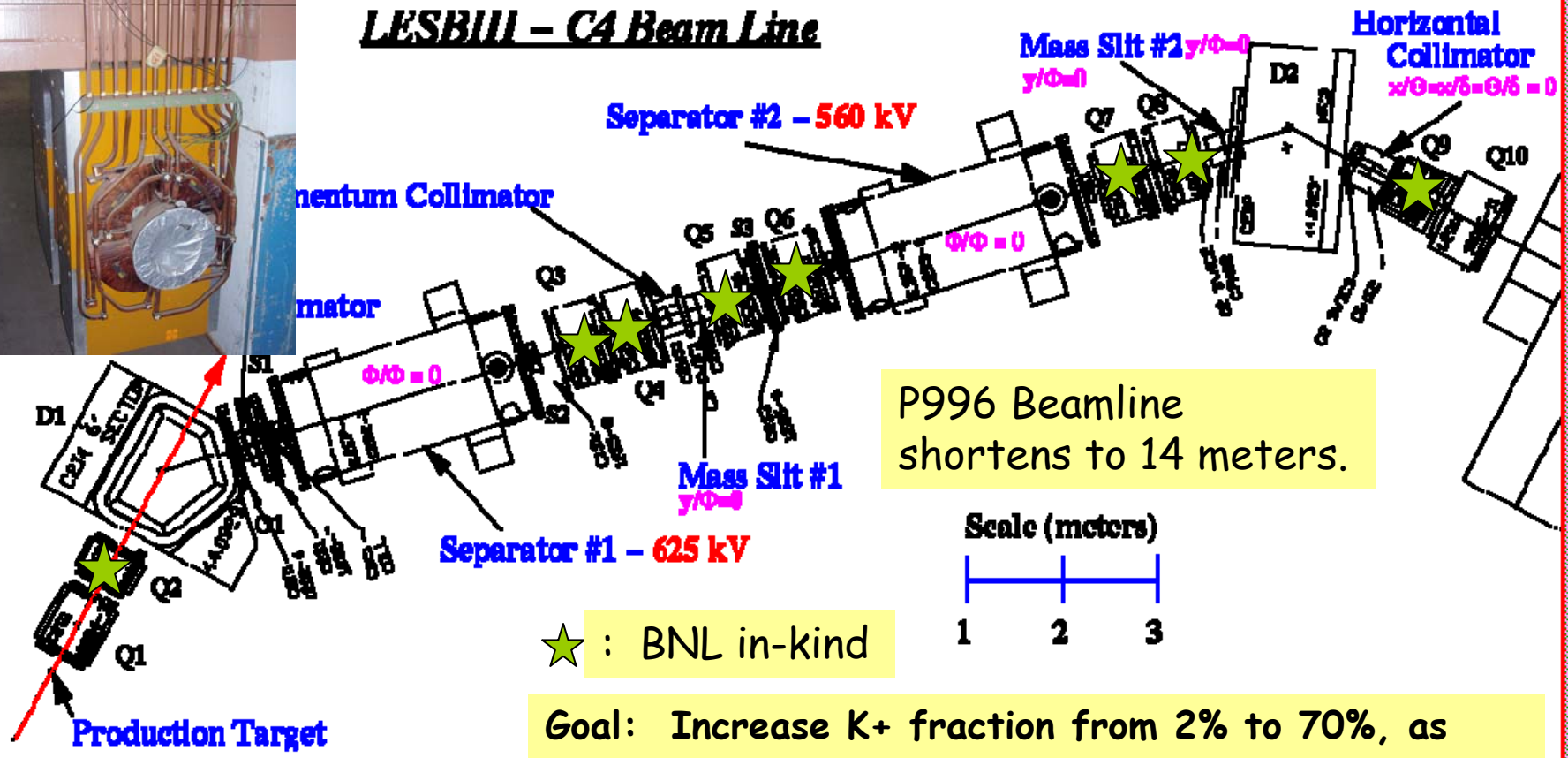
Incremental Improvements

- 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

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

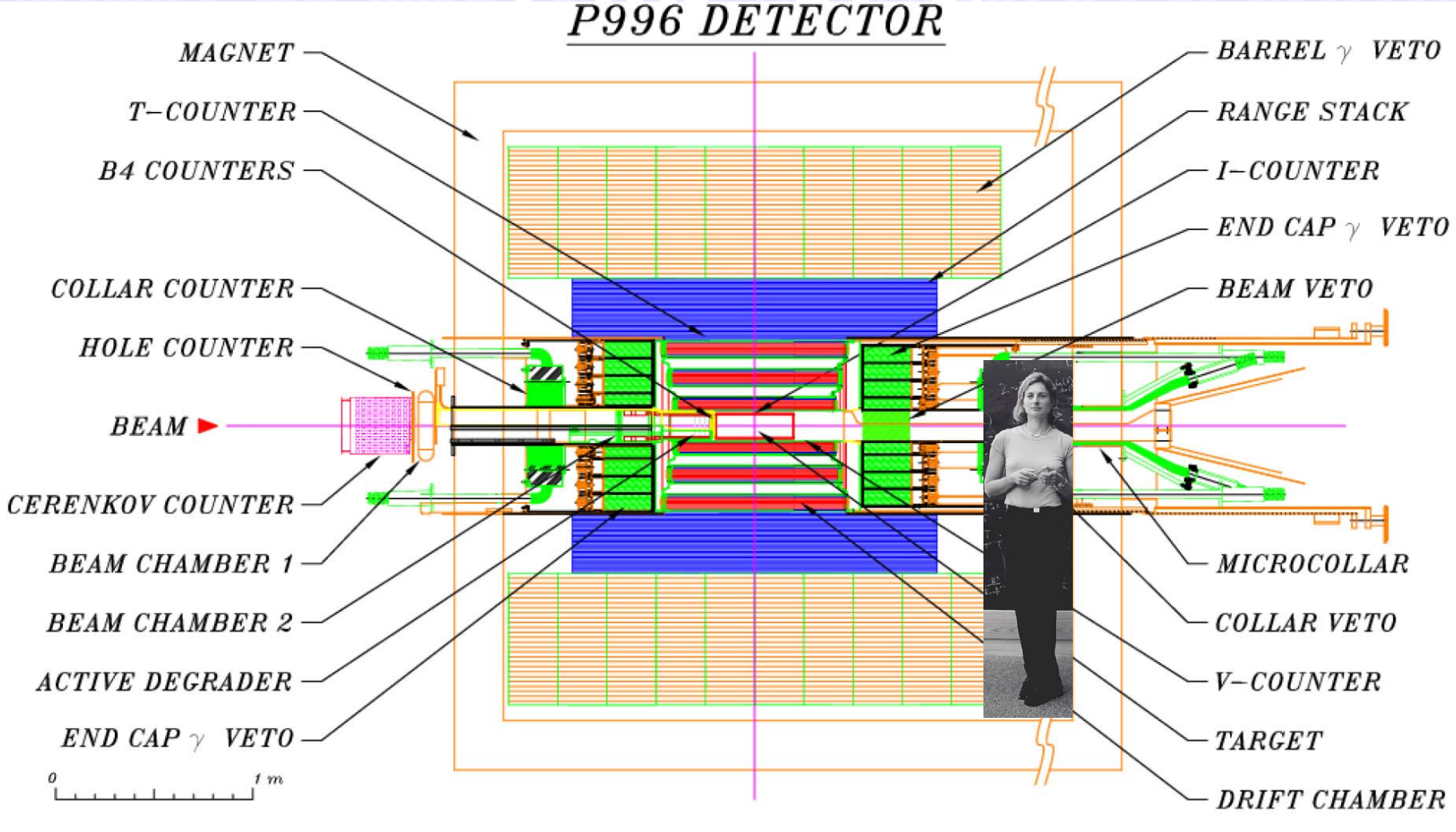


P996 Beamline shortens to 14 meters.

★ : BNL in-kind

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

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



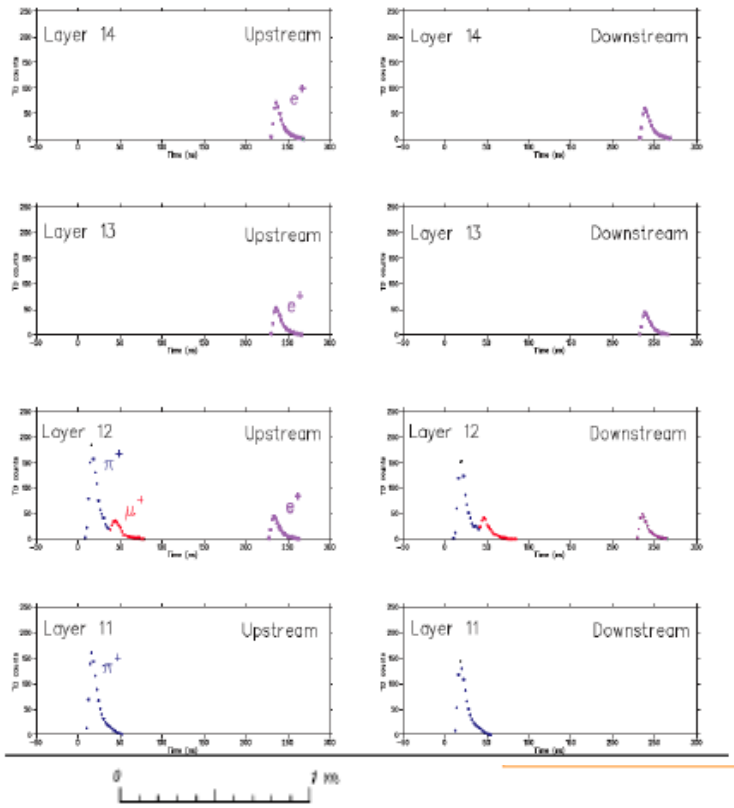
Lisa Randall with the experiment that discovers evidence for extra dimensions…

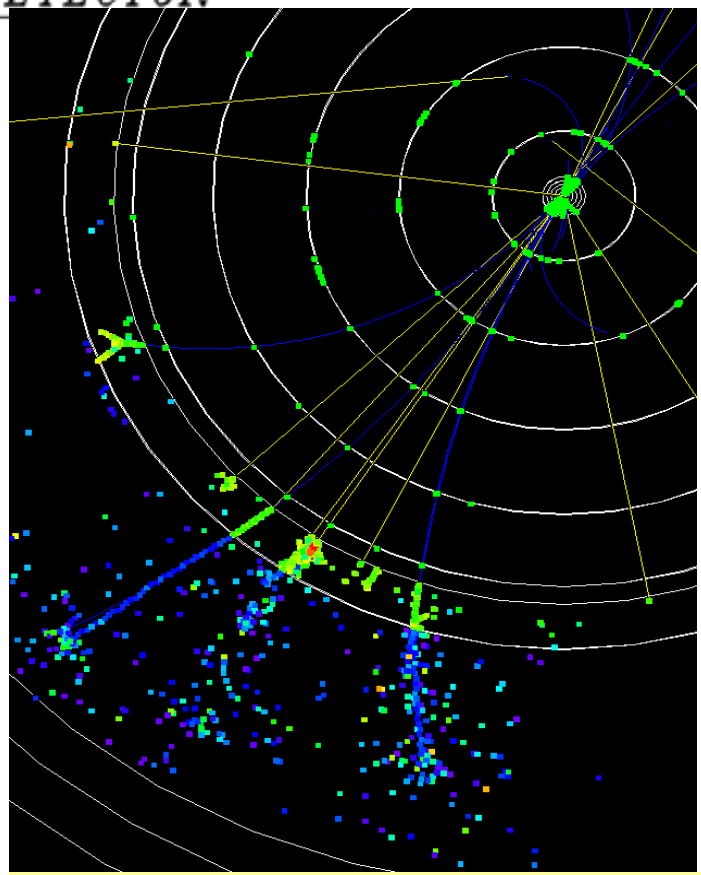
P996 Detector

Use existing (CDF or CLEO) solenoid

P996 DETECTOR

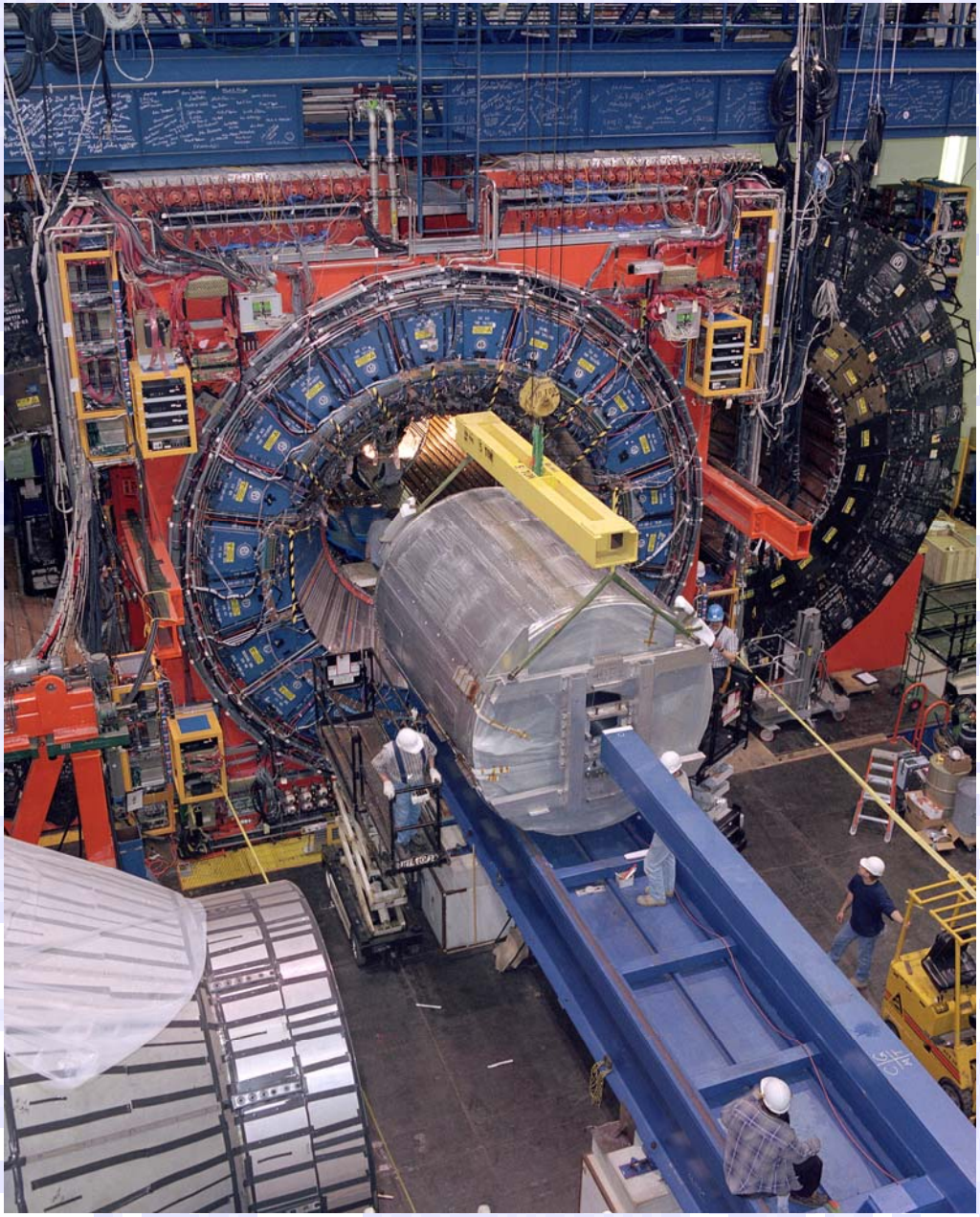
$\pi \rightarrow \mu \rightarrow e$ detection in E949





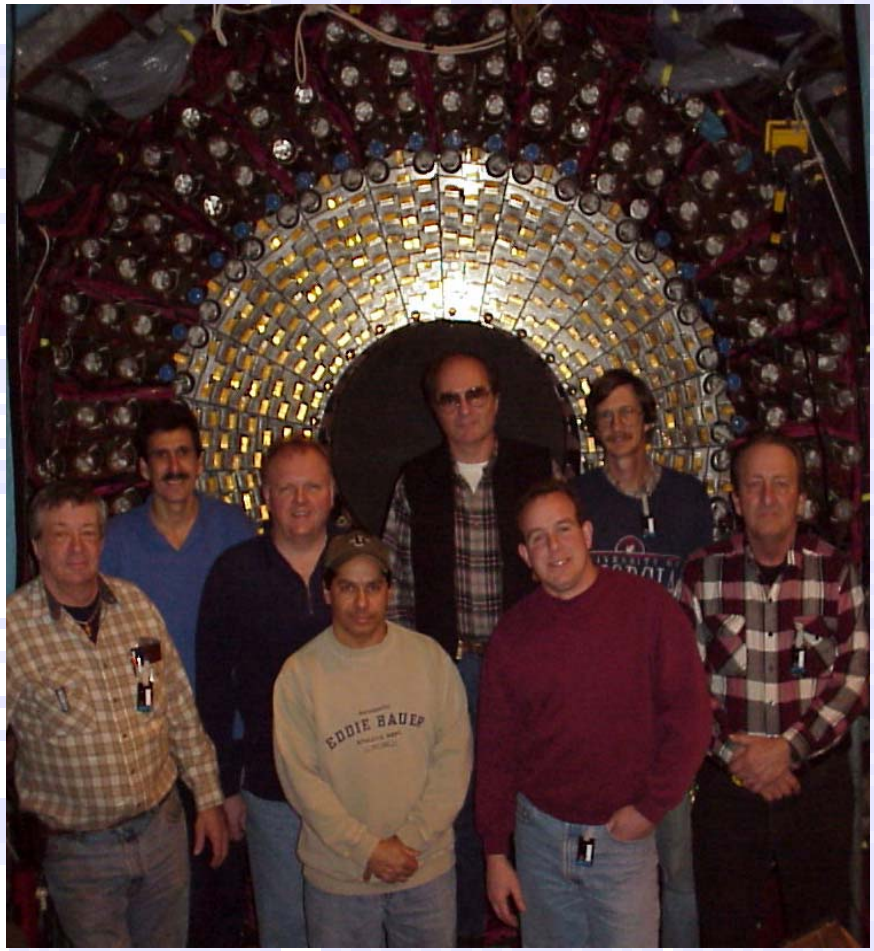
SiD fine grained calorimetery

P996 Experiment Site Options

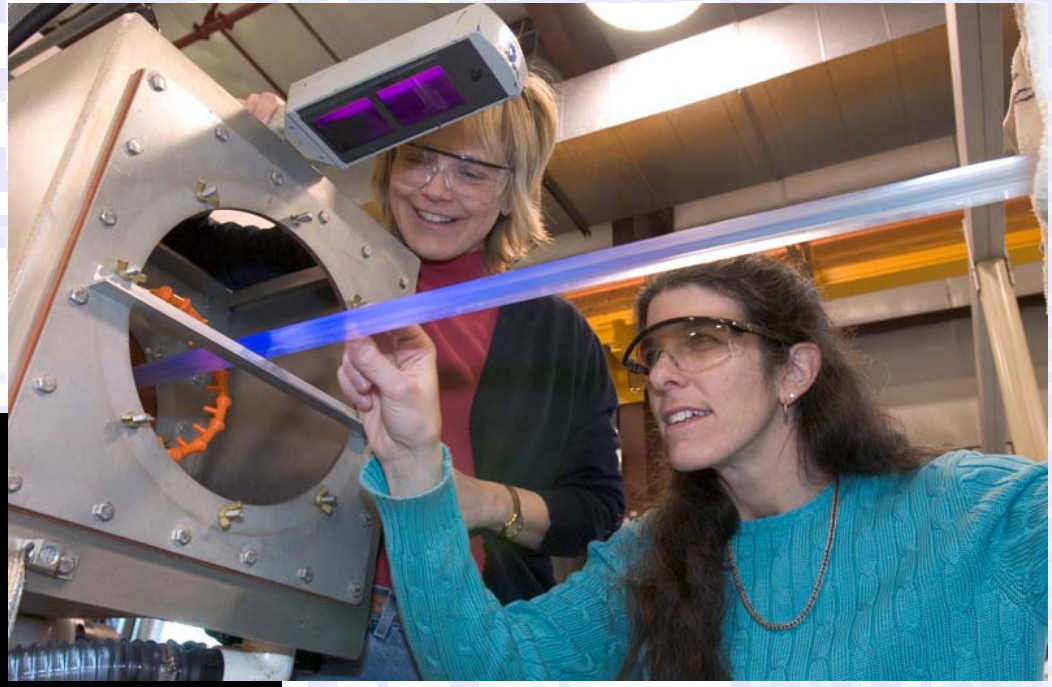


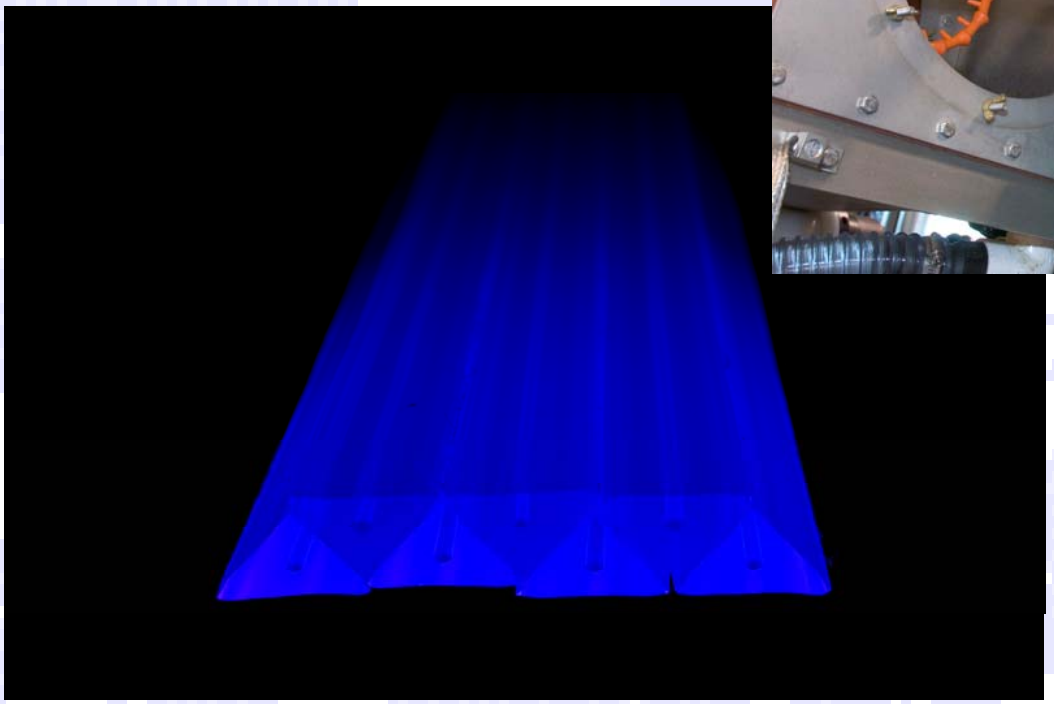
The P996 new detector payload replaces the CDF tracker volume.

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



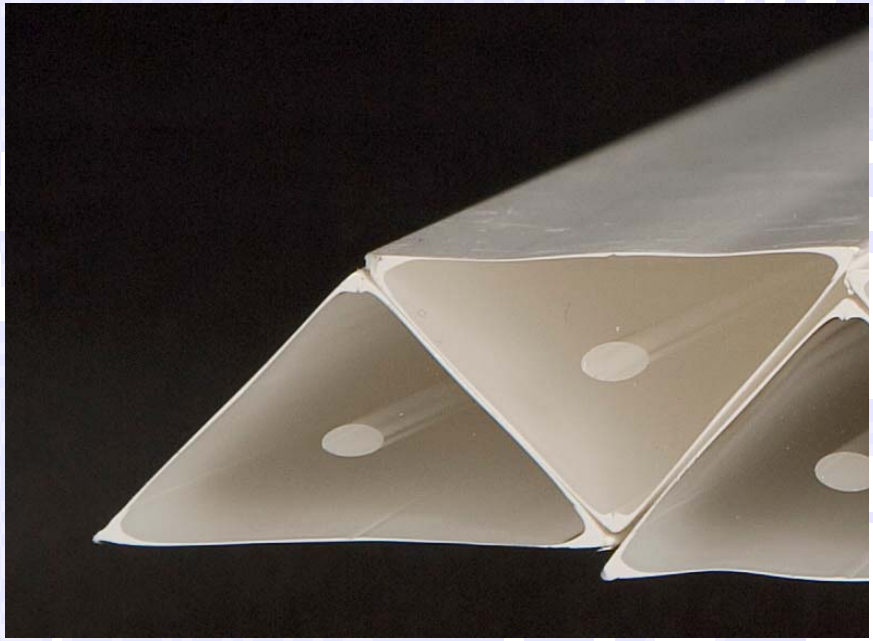
Extruded Scintillator technologies can lower costs…

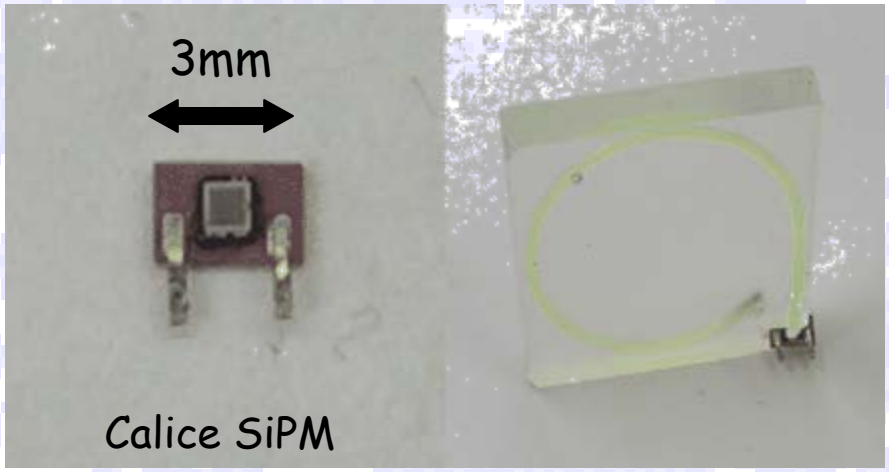


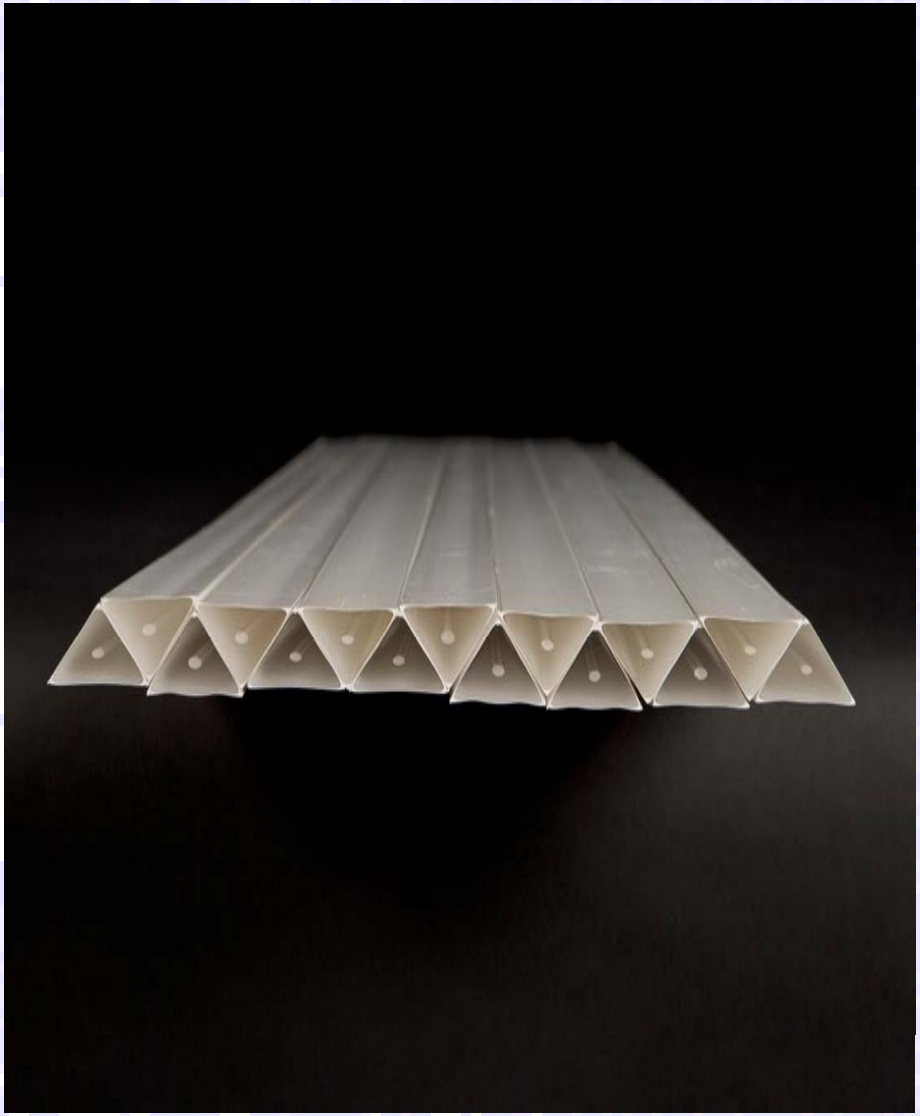


Minerva Scintillator

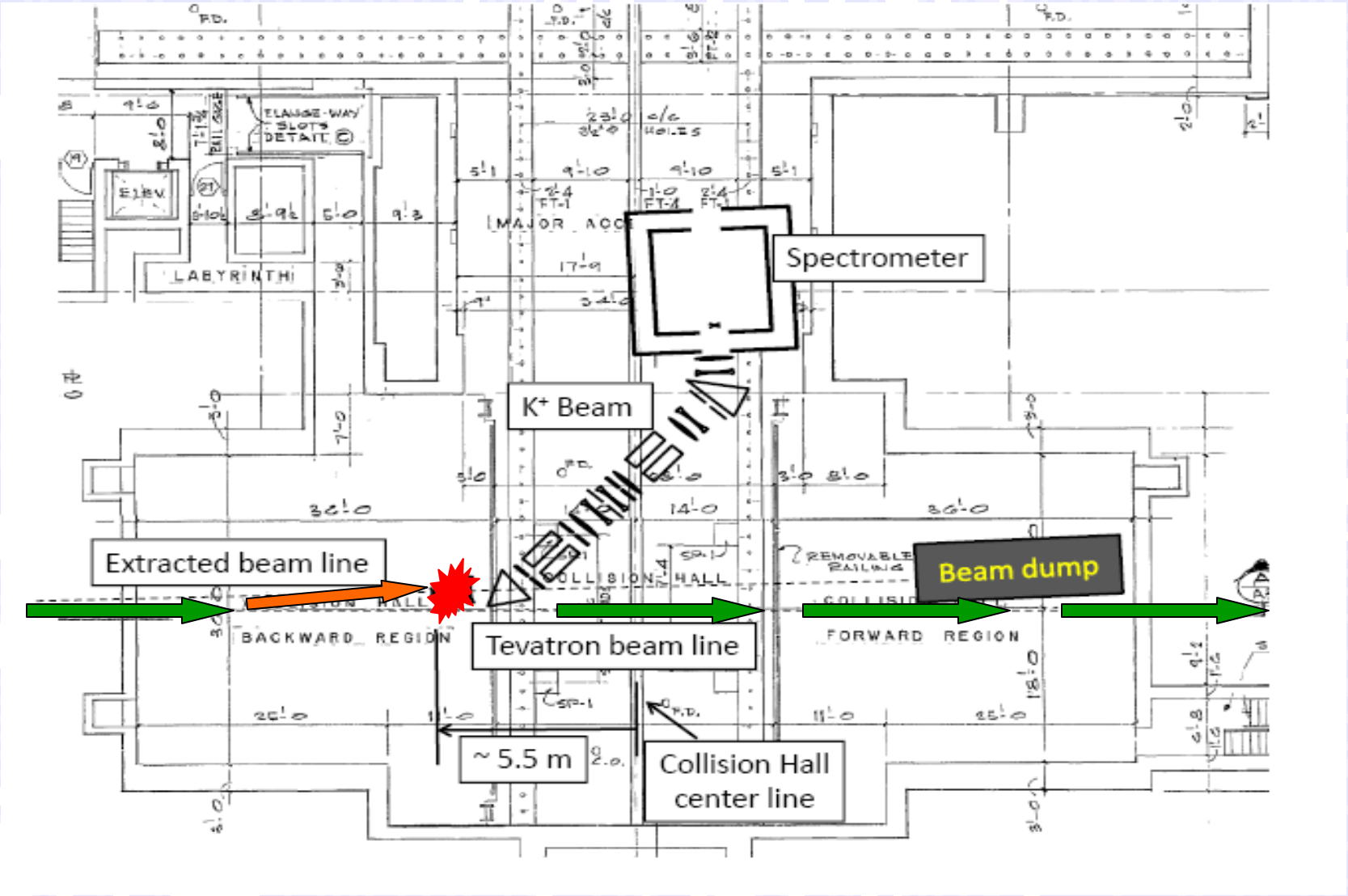
Development required for more precise extrusion and compact photon readout…







P996 Beamline and Detector at CDF hall (B0)



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.

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

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

- $t_{spill} = 25.67$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

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.

$K^+ \to \pi^+ \nu\bar{\nu}$ 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).

Table 10.2: Estimated project cost. All costs in FY10 $k.

WBS element		Description	Total Cost	60% conting.	Total w/cont.
1.0		**TPC**	**$33M**	**$20M**	**$53M**
1.1		**Accelerator and Beams**	**7,500**	**4,500**	**12,000**
	1.1.1	Tevatron Modifications	940	560	1,500
	1.1.2	Extraction and Lines	1,250	750	2,000
	1.1.3	Target and Dump	940	560	1,500
	1.1.4	Kaon Beam	4,370	2630	7,000
1.2		**Detector**	**22,390**	**13,430**	**35,820**
	1.2.1	Spectrometer Magnet	500	300	800
	1.2.2	Beam and Target	600	360	960
	1.2.3	Drift Chamber	1,900	1,140	3,040
	1.2.4	Range Stack	2,500	1,500	4,000
	1.2.5	Photon Veto	3,000	1,800	4,800
	1.2.6	Electronics	4,000	2,400	6,400
	1.2.7	Trigger and DAQ	2,000	1,200	3,200
	1.2.8	Software and Computing	2,000	1,200	3,200
	1.2.9	Installation and Integration	5,890	3,530	9,420
1.3		**Project Management**	**2,740**	**1,640**	**4,380**
1.4		**OPC**	**700**	**420**	**1,120**
	1.4.1	R&D	300	180	480
	1.4.2	Comissioning	400	240	640

From P996 Proposal

Progress on Reducing the Experiment TPC

- Direct savings on CDF decommissioning and infrastructure:

- Save $6-9M in CDF decommissioning (retaining central detector and coil)
- Save $2-3M on electronics (Racks, power, crates, cooling, monitoring, etc)
- Save $0.4M on Drift Chamber front-end electronics (ASDQ)
- Save $0.5M on power and cooling infrastructure for trigger/DAQ farm

- CDF re-use reduces TPC estimate by: $9-13M
- BNL in-kind reduces TPC estimate by: $3M
- S&C off project reduces TPC by: $3.2M

- TPC after CDF reductions, BNL in-kind, and removing S&C:

$53M – $(15-18)M = $(35-38)M

Proposed Schedule..

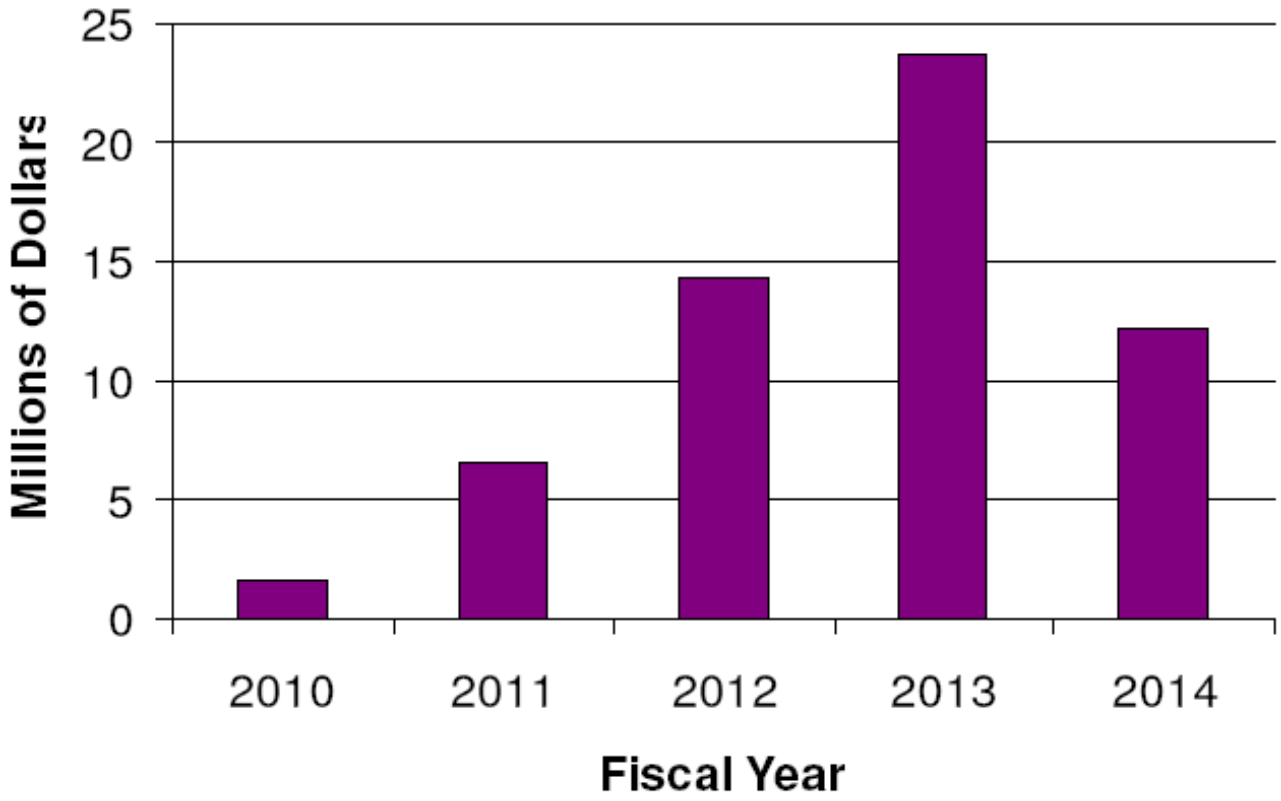


Figure 11.1: A funding profile that assumes our estimated TPC of $58M in then-year dollars. While based on general considerations rather than detailed plans, a funding profile close to this will be necessary to meet our proposed schedule.

From P996 Proposal

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.

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

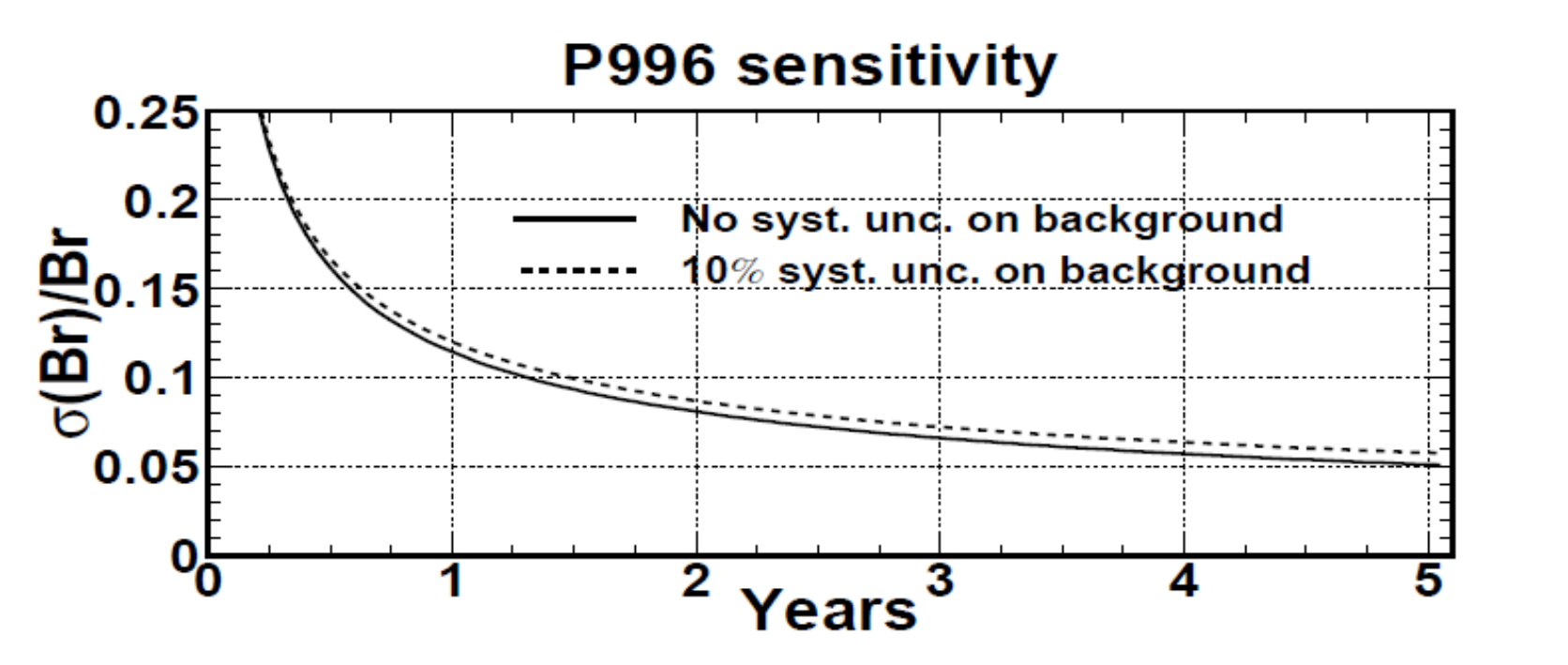
$$K^+ \to \pi^+\mu^+\mu^-$$
$$K^+ \to \pi^+\gamma\gamma$$
$$K^+ \to \mu^+\nu\gamma$$
$$K^+ \to \pi^+\pi^0\gamma$$
$$K^+ \to \pi^+X^0$$
$$K^+ \to \pi^+\gamma\gamma$$
$$K^+ \to \pi^+\gamma$$
$$K^+ \to \pi^+\pi^0\nu\bar{\nu}$$
$$K^+ \to \pi^+H;\ H \to \mu^+\mu^-$$
$$K^+ \to e^+\nu\mu^+\mu^-$$
$$\pi^0 \to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

...and more.

P996 Review Status

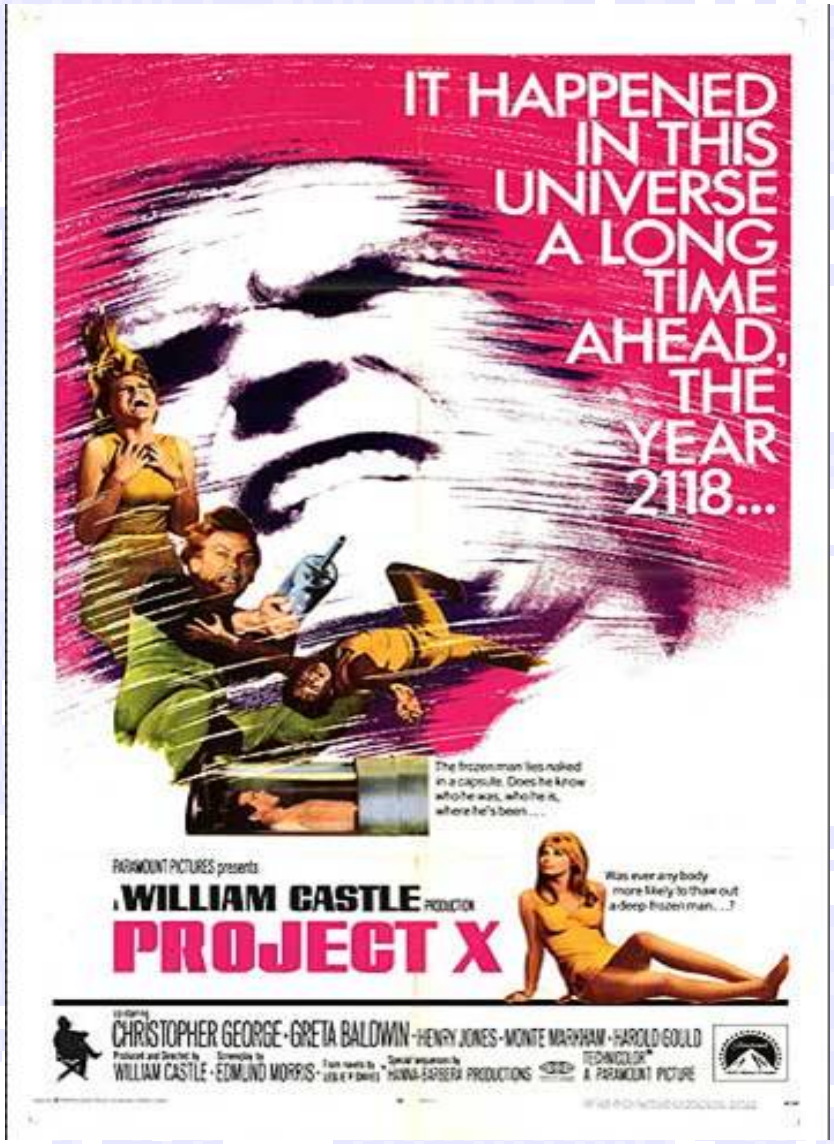
- Strong support from Fermilab PAC.
- P996 briefed Dennis Kovar's OHEP office in March.
- Good discussion—Tevatron Stretcher operating costs flagged.
- P996 is now investigating scenarios to mitigate operating costs.
- P996 will be reviewed in a national context this summer.

Stretcher Ops Mitigation



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.

Turning to Project-X, What it's not…

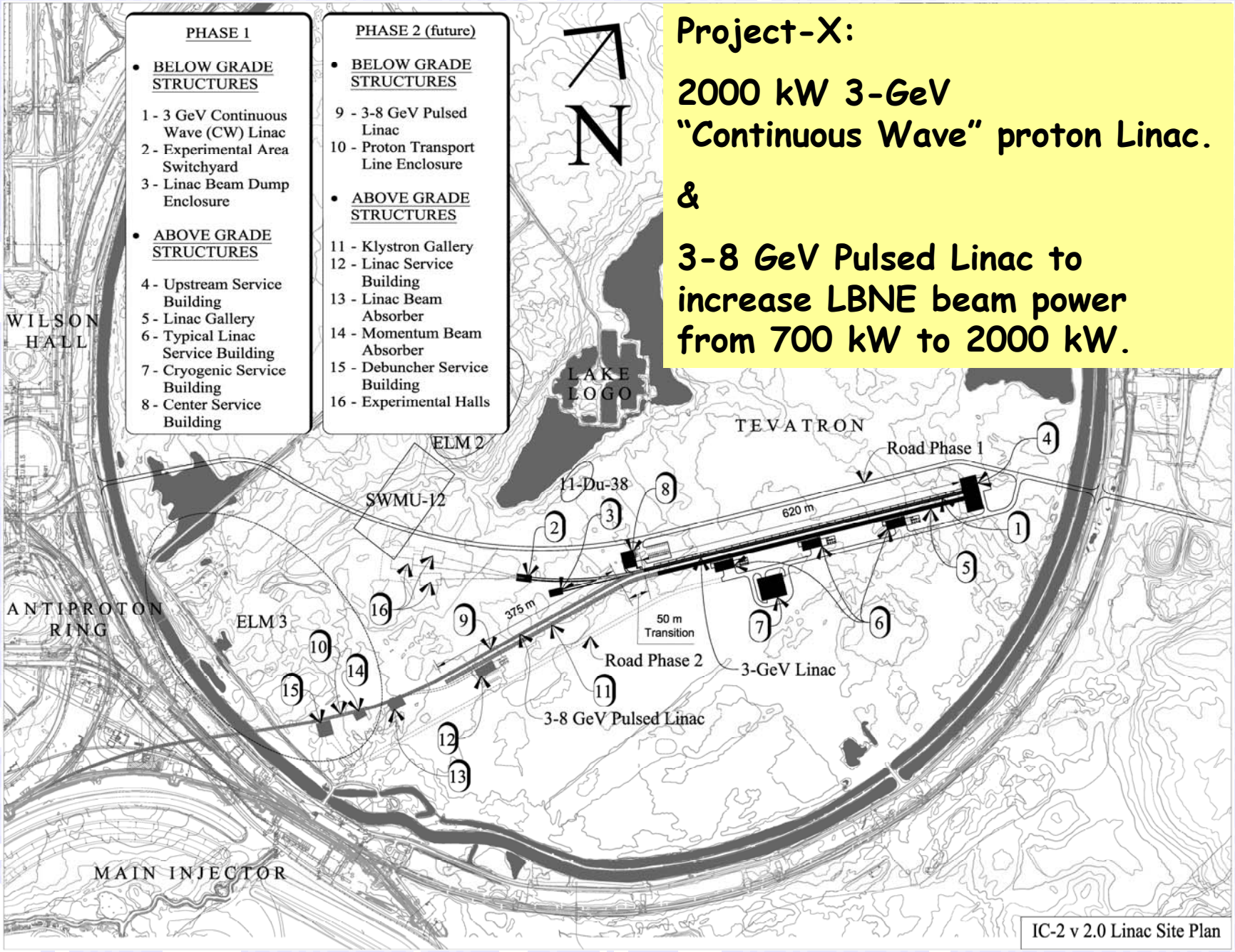


Project-X:

2000 kW 3-GeV "Continuous Wave" proton Linac.

&

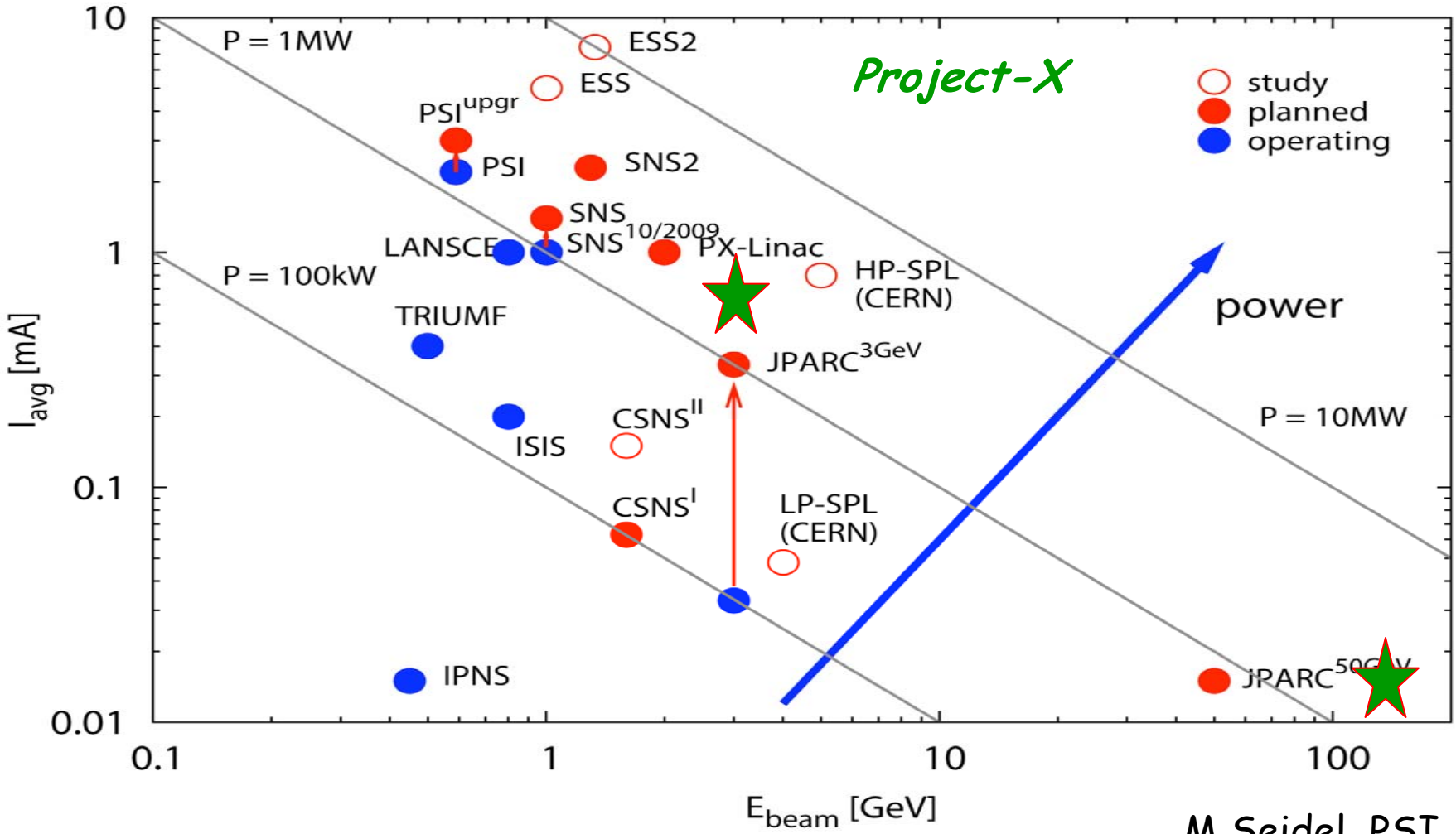
3-8 GeV Pulsed Linac to increase LBNE beam power from 700 kW to 2000 kW.



What is good about a CW Linac

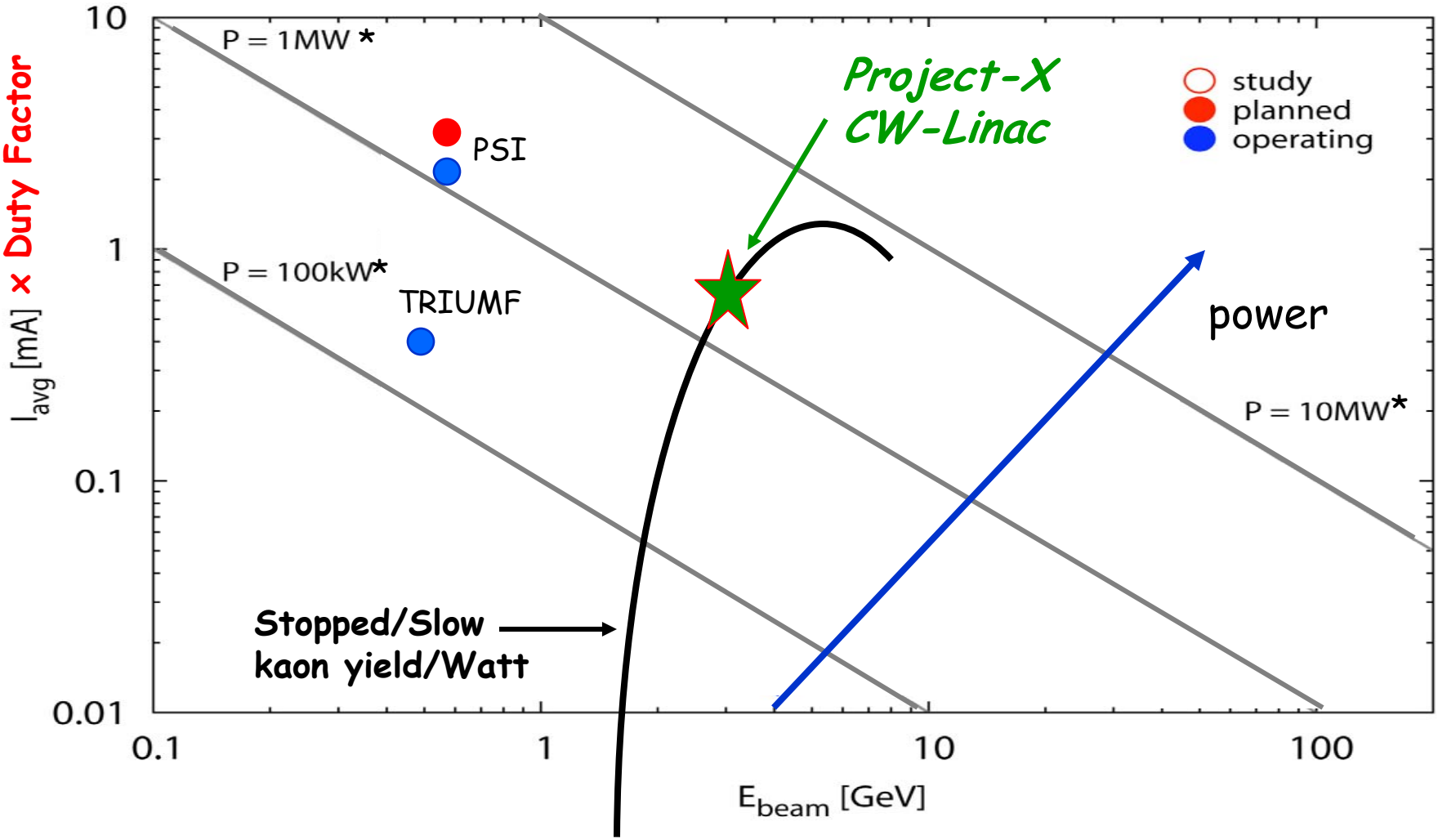
- Beam extraction challenge is finessed.
- Duty factor is very high. [Continuous train of pulses 8 nsec apart]
- The high frequency bandwidth intrinsic to a Linac can be exploited to generate excellent time resolution (*small* δt) crucial to survival in a high intensity environment.
- JLAB has demonstrated that beam can be cleanly multiplexed between many targets with minimal losses. These "touchless" RF beam multiplexers are enabled by the high linac bandwidth.
- The intrinsic properties of this SCRF CW Linac enables the phyiscs rather than fighting with it. Excellent beam power scaling for rare process experiments.

This Science has attracted Competition: The Proton Source Landscape This Decade...



M Seidel, PSI

The High Duty Factor Proton Source Landscape This Decade...



* Beam power x Duty Factor

An Incomplete Menu of World Class Research Targets Enabled by Project-X

Neutrino Physics:

- Mass Hierarchy
- CP violation
- Precision measurement of the θ_{23} (atmospheric mixing). Maximal??
- Anomalous interactions, e.g. $\nu_\mu \rightarrow \nu_\tau$ probed with target emulsions (Madrid Neutrino NSI Workshop, Dec 2009)
- Next generation precision cross section measurements

An Incomplete Menu of World Class Research Targets Enabled by Project-X. continued…

Muon Physics:

- Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.
- Next generation $(g\text{-}2)_\mu$ if motivated by next round, theory, LHC. New techniques proposed to JPARC that are beam-power hungry…
- μ edm
- $\mu \rightarrow 3e$
- $\mu^+e^- \rightarrow \mu^-e^+$
- $\mu^- A \rightarrow \mu^+ A'$; $\mu^- A \rightarrow e^+ A'$; $\mu^- e^-(A) \rightarrow e^- e^-(A)$
- Systematic study of radiative muon capture on nuclei.

An Incomplete Menu of World Class Research Targets Enabled by Project-X. continued…

Kaon Physics:

- $K^+ \rightarrow \pi^+\nu\nu$: >1000 events, Precision rate and form factor.
- $K^+ \rightarrow \pi^0\mu^+\nu$: Measurement of T-violating muon polarization.
- $K^+ \rightarrow (\pi,\mu)^+\nu_x$: Search for anomalous heavy neutrinos.
- $K_L \rightarrow \pi^0\nu\nu$: 1000 events, enabled by high flux & precision TOF.
- $K_2 \rightarrow \pi^0 e^+e^-$: <10% measurement of CP violating amplitude.
- $K_L \rightarrow \pi^0\mu^+\mu^-$: <10% measurement of CP violating amplitude.
- $K^0 \rightarrow X$: Precision study of a pure K^0 interferometer: Reaching out to the Plank scale ($\Delta m_K/m_K \sim 1/m_P$)
- $K^0, K^+ \rightarrow$LFV: Next generation Lepton Flavor Violation experiments

…and more

An Incomplete Menu of World Class Research Targets Enabled by Project-X. continued…

Baryons:

- $pp \rightarrow \Sigma^+ K^0 p^+$; $\Sigma^+ \rightarrow p^+ \mu^+ \mu^-$ (HyperCP anomaly, and other rare Σ^+ decays)
- $pp \rightarrow \underline{K^+} \Lambda^0 p^+$; Λ^0 ultra rare decays
- $\Lambda^0 \leftrightarrow \overline{\Lambda^0}$ oscillations (Project-X operates below anti-baryon threshold)
- neutron EDM

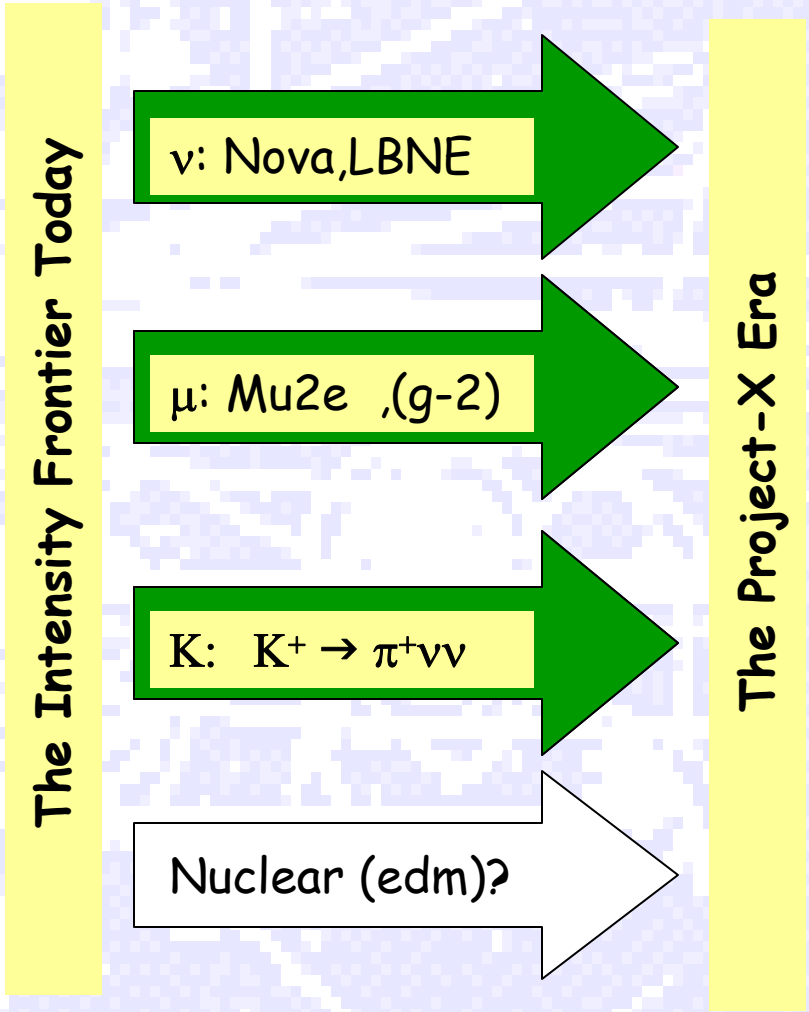
Nuclei:

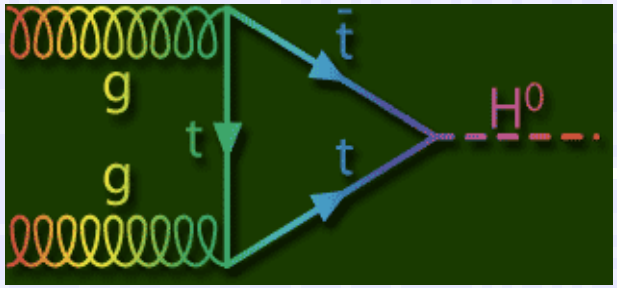
- Production of Ra, Rd, Fr isotopes for nuclear edm experiments that are uniquely sensitive to Quark-Chromo and electron EDM's.

Relationship of P996 to Project-X

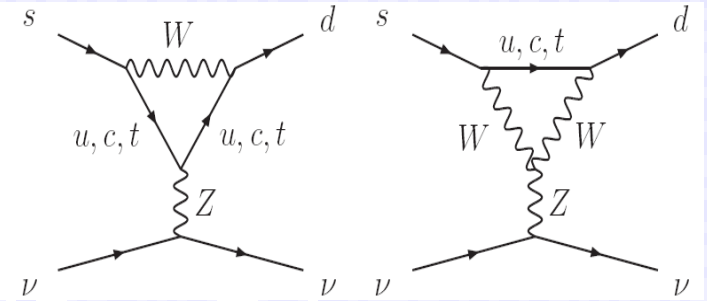
- Physics from P996 will energize the flavor physics community this decade.
- The P996 detector can be driven with Project-X beam in Stage-II.
- Project-X era experiments are challenging:

  The P996 experiment and community will be well positioned to exploit the revolutionary beam power of Project-X.





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 CMS and ATLAS 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

Can the Booster or the Main-Injector Drive P996?

- Yes, but not as well.

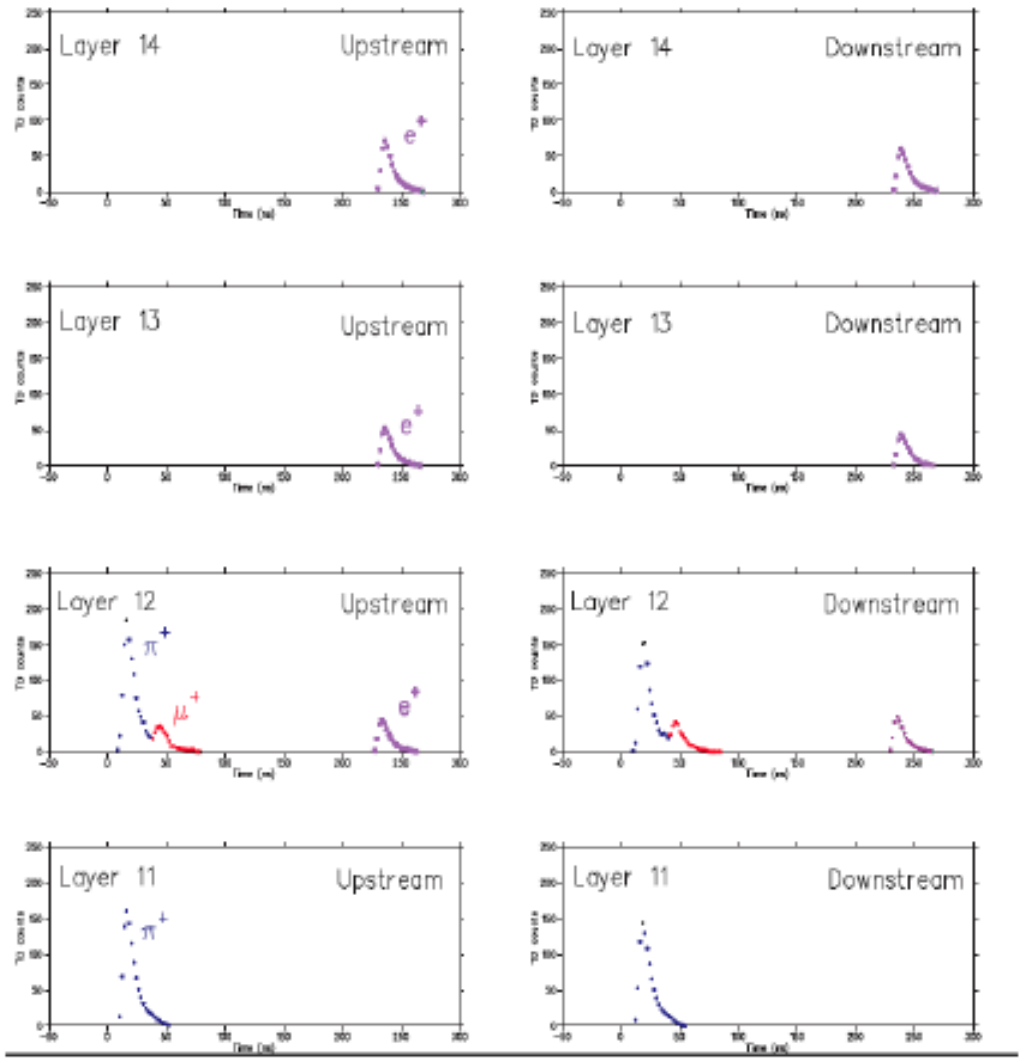
- Booster:

  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.

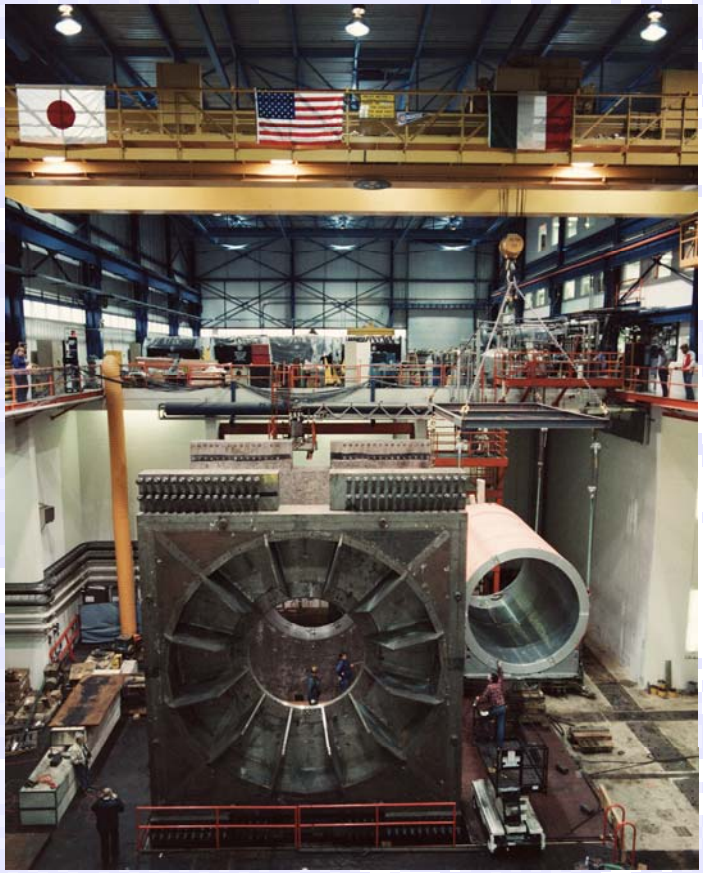
- Main Injector:

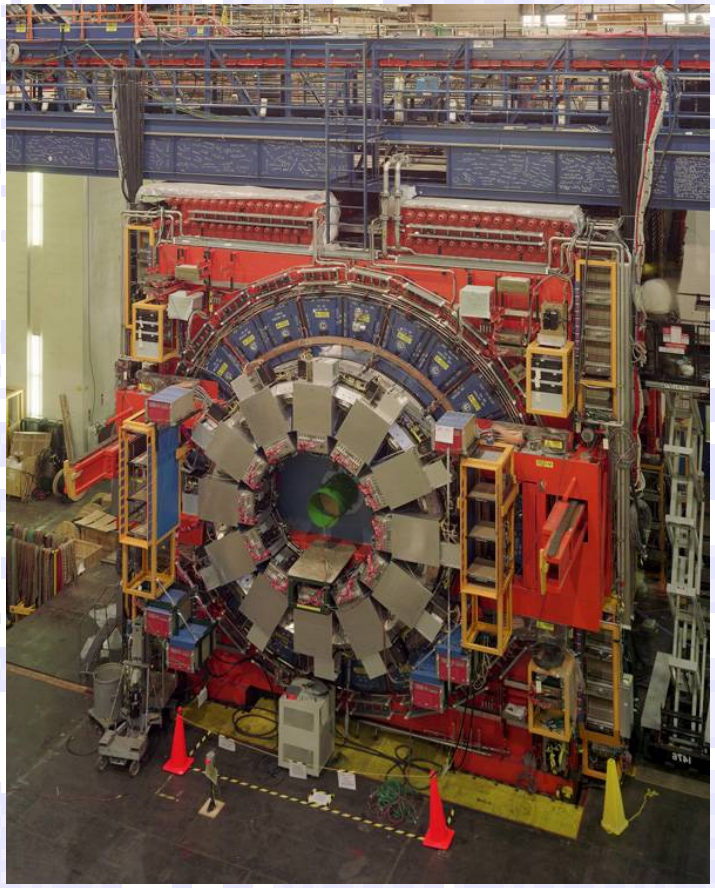
  Slow-extraction Flat-top is limited to 30% from magnet heating (not a SC machine). Maintaining the same instantaneous rates as BNL E949 corresponds to a ~1/3 sensitivity/year wrt P996. This would also increase the hit on the Nova program from 10% to 30% .

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



CDF detector, then and now…



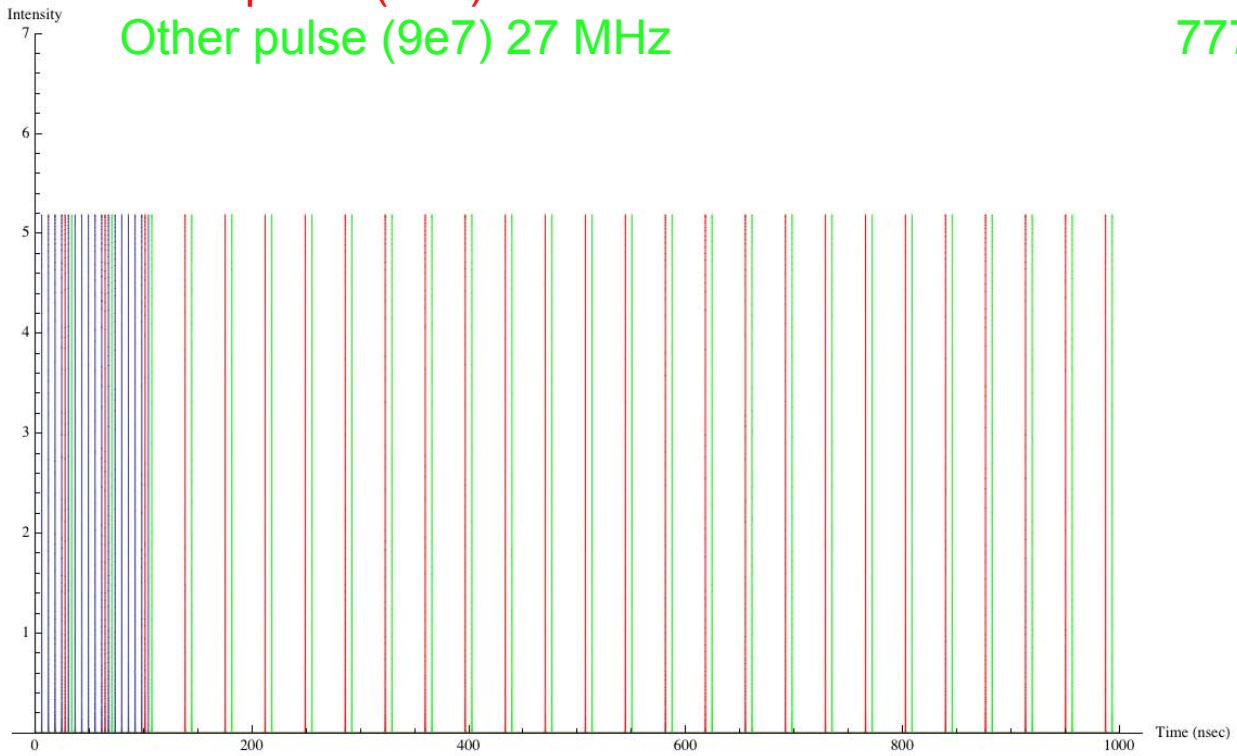


Example of a High Duty-Factor IC2 Operating Scenario

1 μsec period at 2 GeV

mu2e pulse (9e7) 162.5 MHz, 100 nsec	518 kW
Kaon pulse (9e7) 27 MHz	777 kW
Other pulse (9e7) 27 MHz	777 kW

Out[156]=



Extreme BEAM, June 11, 2009 - S. Holmes

Slow Extracted Beam: The Standard Tool to Drive Ultra Rare Decay Experiments

- Techniques developed in the late 1960's to "slow spill" beam from a synchrotron.

- Technique operates at the edge of stability---Betatron oscillations are induced which interact with material in the beam (wire septum) to eject particles from the storage ring beam phase space.

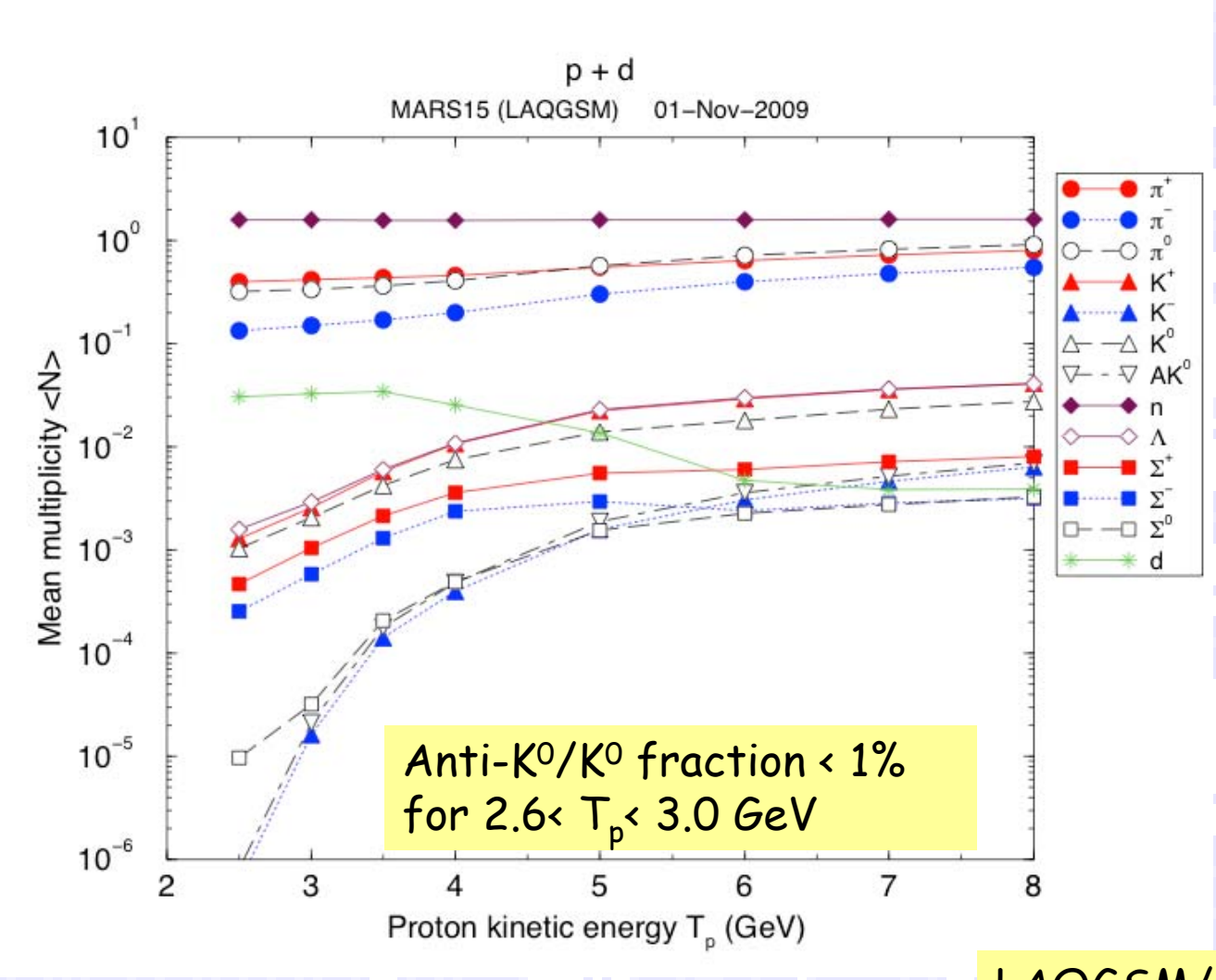
- Technique limited by septum heating & damage, beam losses, and space charge induced instabilities. Works better at higher energies where the beam-power/charge ratio is more favorable.

- Performance milestones:

  Tevatron 800 GeV FT: 64 kW of SEB in 1997.
  BNL AGS 24 GeV beam, 50-70 kW of SEB.

- JPARC Goal: 300 kW of SEB someday, a few kW within reach now.

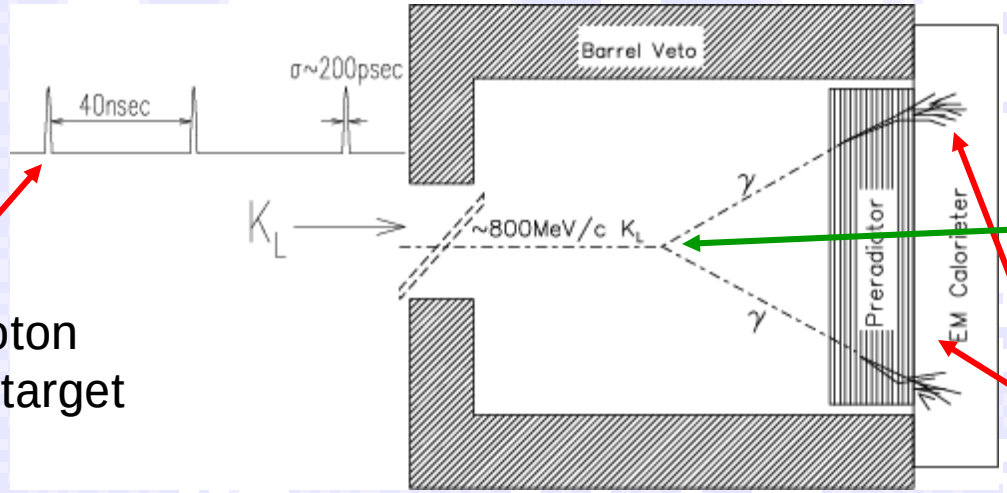
IC2 is high power, but what about kaon yields??



LAQGSM/MARS-15

Horsepower to seriously mount a TOF-based $K_L \rightarrow X$ experiment..

Fully reconstruct the neutral Kaon in $K_L \rightarrow \pi^0 \nu \bar{\nu}$ measuring the Kaon momentum by time-of-flight.



Start when proton beam hits the target

End at the decay time and decay point reconstructed from the two photons.

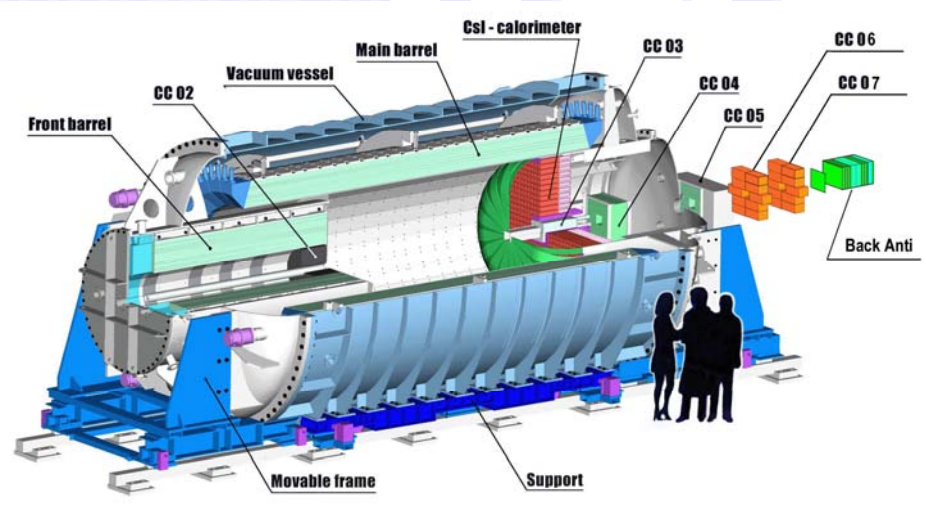
Timing uncertainty due to microbunch width should not dominate the measurement of the kaon momentum; requires RMS width < 200ps. CW linac pulse timing of less than 50ps is intrinsic.

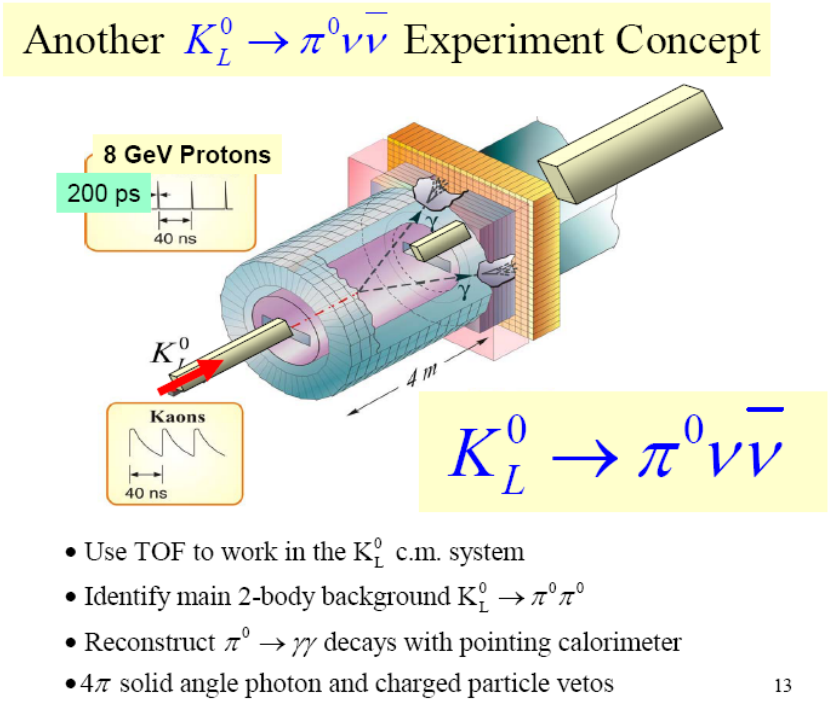
$K_L \to \pi^0 \nu\nu$ Experimental Challenge: "Nothing-in nothing out"

•KEK/JPARC approach emphasizes high acceptance for the two decay photons while vetoing everything else:

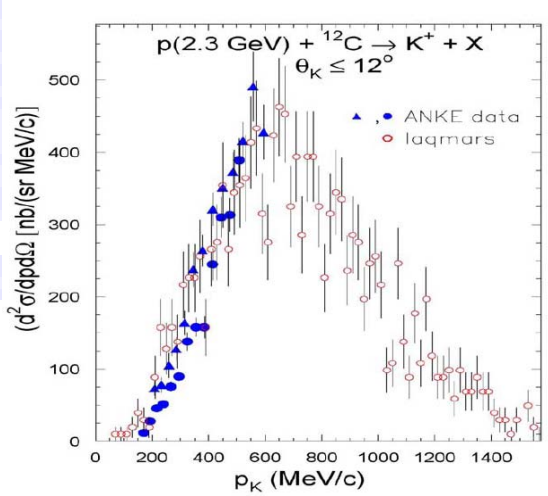
A hermetic "bottle" approach.

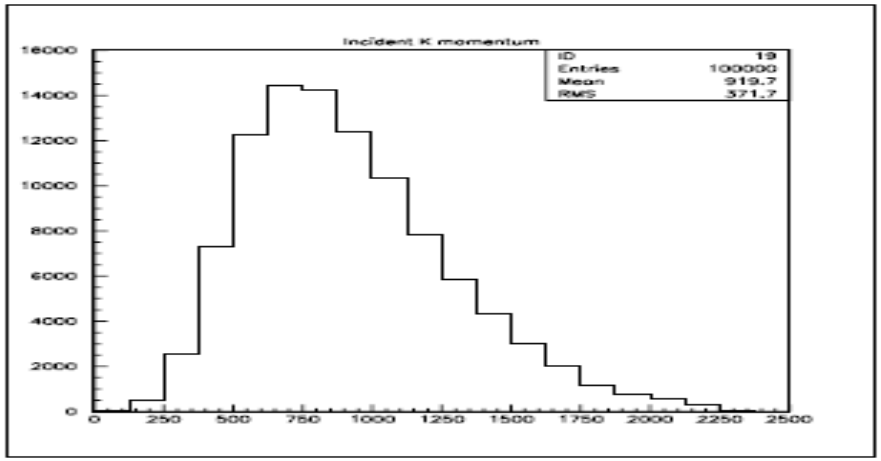
•The original KOPIO concept measures the kaon momentum and photon direction…Good! But costs detector acceptance and requires a large beam to compensate. Project-X Flux can get back to small kaon beam!





KOPIO and IC2 kaon momentum spectra comparison





KOPIO Proposal

Figure 13: K_L^0 spectrum incident on KOPIO decay volume.

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 $\Sigma^+ \rightarrow p\mu^+\mu^-$ signal or Σ^+ EDM search using bent crystals (Wah, Chicago).
- A $K_L \rightarrow \pi^0 \nu\nu$ experiment if the accelerator pulse timing resolution can be improved (requires R&D).
- $K^+ \rightarrow \pi^0 \mu^+ \nu$ 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.

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

$$B_{\rm SM}(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{\tau_{K^+} M_{K^+}^5}{32\pi^3}(1+\Delta_{\rm EM}) \left|f_+^{K^+\pi^+}(0)\right|^2 \mathcal{I}_\nu^+ \left|\frac{G_F \alpha(M_Z)}{2\pi\sqrt{2}\sin^2\theta_W} Y\right|^2$$

Radiative correction ≅ –0.003

Form factor from Ke3

$$Y = V_{td}^* V_{ts} X(x_t) + V_{cd}^* V_{cs}\left[X(x_c) + |V_{us}|^4 \delta P_{c,u}\right]$$

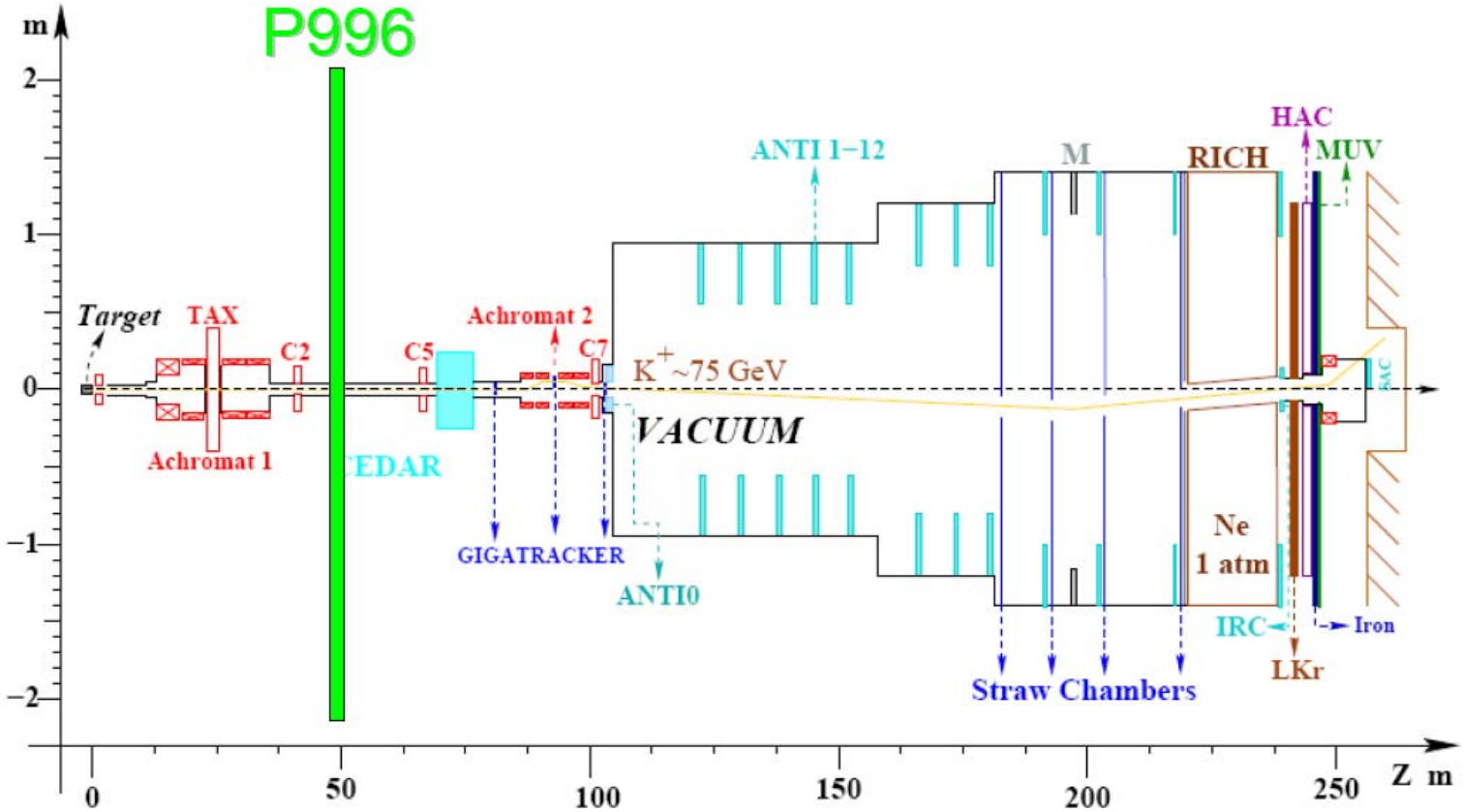
Top loop ≈70% of BF; NLO in perturbation theory, good to 2%

Charm loop ≈30% of BF; recent calculations reduce error to 2.3%; remaining parametric uncertainty from charm quark mass

Higher dimn charm loop, long-dist u-quark effects; (0.04±0.02)

Bottom line - BSM($K^+ \to \pi^+ \nu\bar{\nu}$) = (8.5 ± 0.7) x 10^{-10} (9% err)

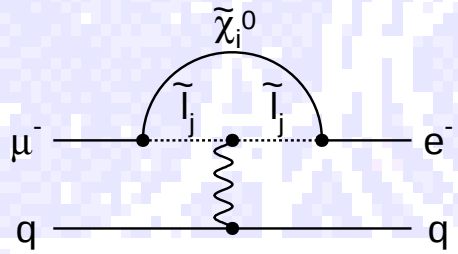
NA-62 Detector Layout

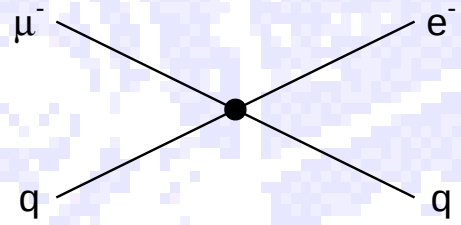


$\mu^- N \rightarrow e^- N'$ is a particulary Deep Probe...

Supersymmetry

Predictions at 10^{-15}



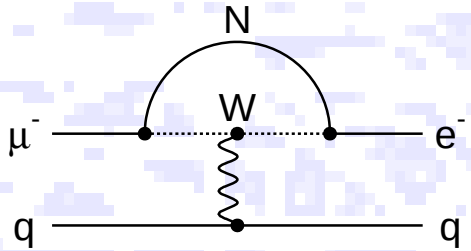


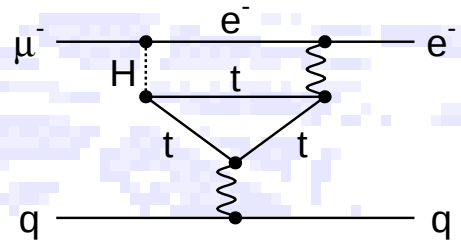
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2 = 8 \times 10^{-13}$



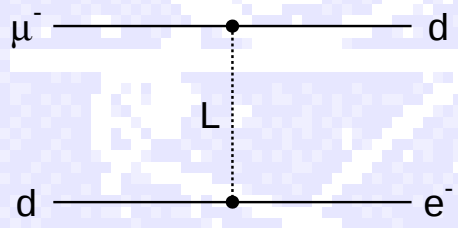


Second Higgs doublet

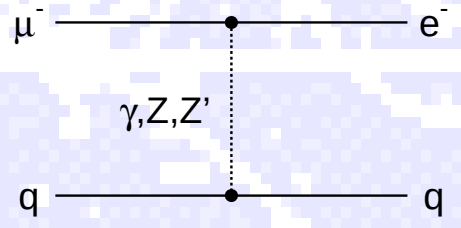
$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L = 3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/c^2



After W. Marciano



Heavy Z', Anomalous Z coupling

$M_{Z'} = 3000$ TeV/c^2

$B(Z \rightarrow \mu e) < 10^{-17}$

Why now? Why Fermilab?

LHC discoveries would demand the results from $K^+ \to \pi^+ \nu\bar{\nu}$ and other flavor experiments.

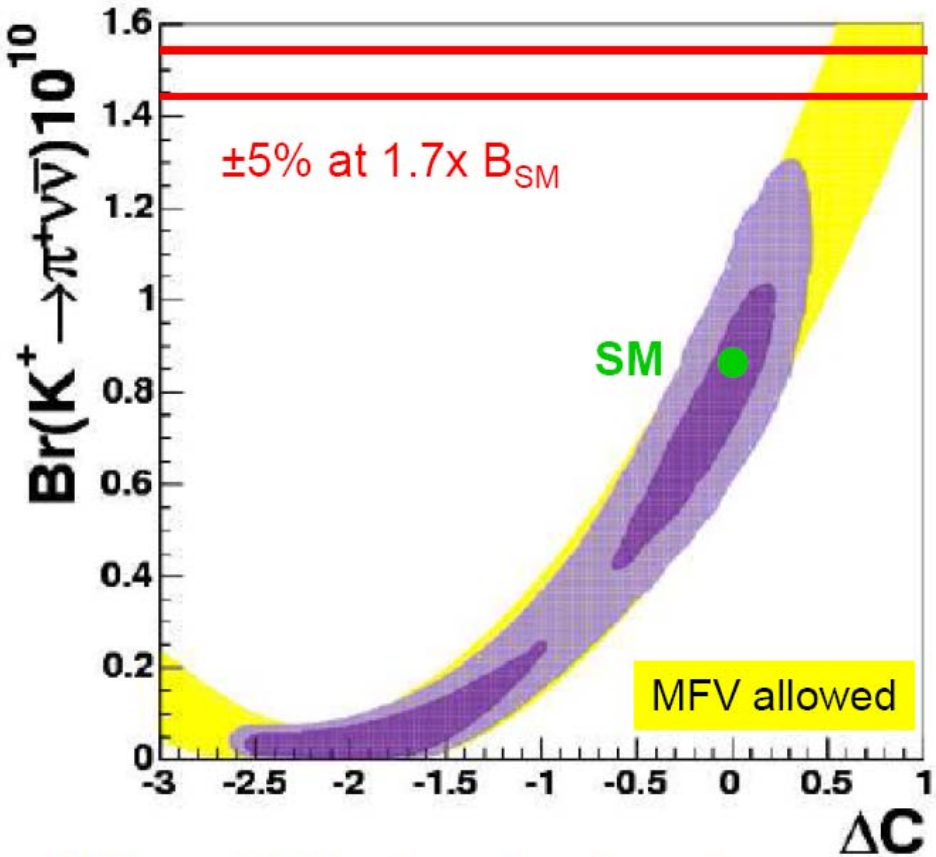
Either New Physics from $K^+ \to \pi^+ \nu\bar{\nu}$ will appear or severe constraints will result.

To be timely, P996 should compete head-to-head with CERN's NA-62 and J-PARC's KOTO "flagship" experiments. P996 is the only comparable effort "guaranteed" to succeed.

- Existing Fermilab facilities (MI and Tevatron) provide an opportunity to make the decisive measurement – no other lab comes close
- Tevatron stretcher operation is viable (if done soon after collider running ends).
- The experiment provides important input for planning the Project-X Intensity Frontier program.
- This experiment will foster rebuilding the U.S. kaon-physics community, essential for the success of Project-X.

Minimal Flavor Violation (*a highly pessimistic hypothesis*)

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



68% and 95% allowed regions for NP, based on $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$

The MFV hypothesis assumes that all flavor- and CP-violating effects in New Physics are governed by the SM Yukawa couplings (CKM mixing and phase).

±5% measurement of $B(K^+ \to \pi^+\nu\bar{\nu})$ will provide strong constraints on New Physics within MFV, or demonstrate failure of the MFV hypothesis.

$\Delta C = C - C_{SM}$,
where C characterizes the Z-penguin in b→s