ORKA, The Golden Kaon Experiment: Precision Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ and other ultra-rare processes

(Orcinus orca), Life ofSea blogspot

The ORKA Collaboration

"…[US HEP] must provide opportunities for achieving transformational or paradigm changing scientific advances."*

Excerpt from Persis Drell's remarks to the
Intensity Frontier Workshop
December 2011

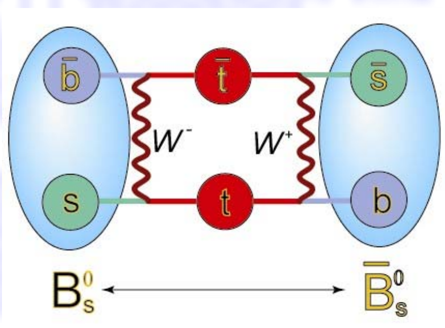
*Source Website: https://news.slac.stanford.edu/features/director-why-healthyparticle-physics-program-important-nation

Precision Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ can deeply challenge the Flavor Problem:

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

Some Favorites

- Accurately measure sides + angles of Unit. Tr. (obvious)
- CPV in $B_s - \bar{B}_s$ (SM "accidentally" small)
- $K \rightarrow \pi \nu \nu$ (miniscule in SM + incredibly clean theoretically)
- $\mu \rightarrow e$, $\tau \rightarrow e, \mu$ (suggested by big ν angles)



Flavor Physics: Pushing Beyond the LHC.
Intensity Frontier Workshop
Nima Arkani-Hamed
(Princeton, IAS)

Rare Decays in the LHC Era

New Physics found at LHC
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

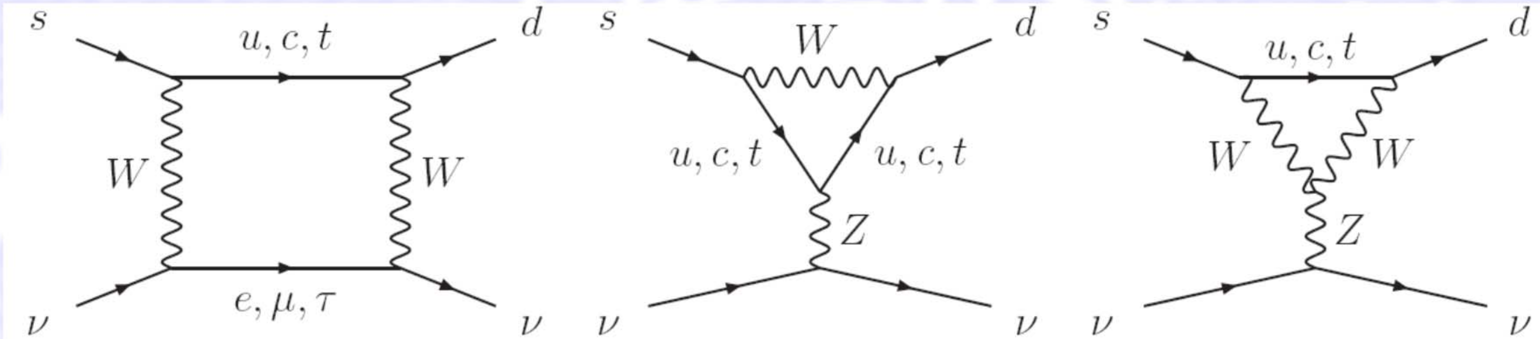
Precision flavor-physics experiments needed -> sensitive to NP at mass scales beyond the reach of the LHC (through virtual effects).

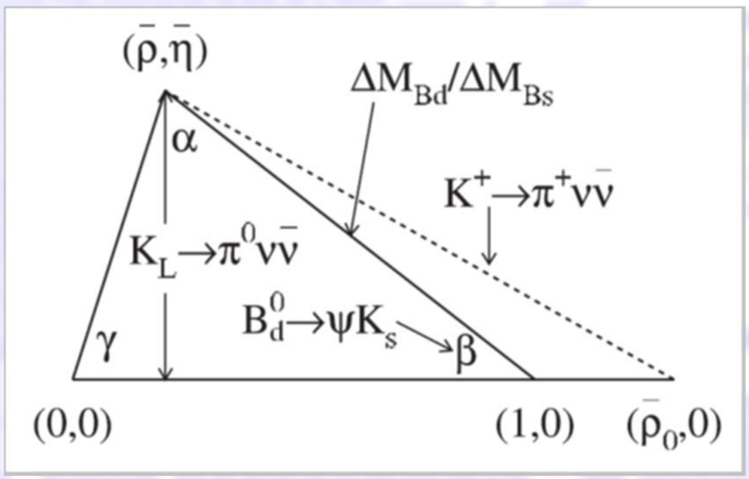
Q(L) Flavor	Processes to Study NP
1(2)	μ-e Conversion, $\pi^+ \to e^+\nu$
(2)	$\mu \to e\gamma$
2	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L^0 \to \pi^0\nu\bar{\nu}$
2(2)	$K^+ \to e^+\nu$
3(3)	$b \to s\gamma$, $B \to \mu\mu$, $\tau \to \mu\gamma$...

These reactions have special status because of their small SM uncertainties and large NP reach.

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

The $K^+\to\pi^+\nu\bar{\nu}$ *decays are the most precisely predicted FCNC decays with quarks*





$(\bar{s}_L\gamma^\mu d_L)(\bar{\nu}_L\gamma_\mu\nu_L)$

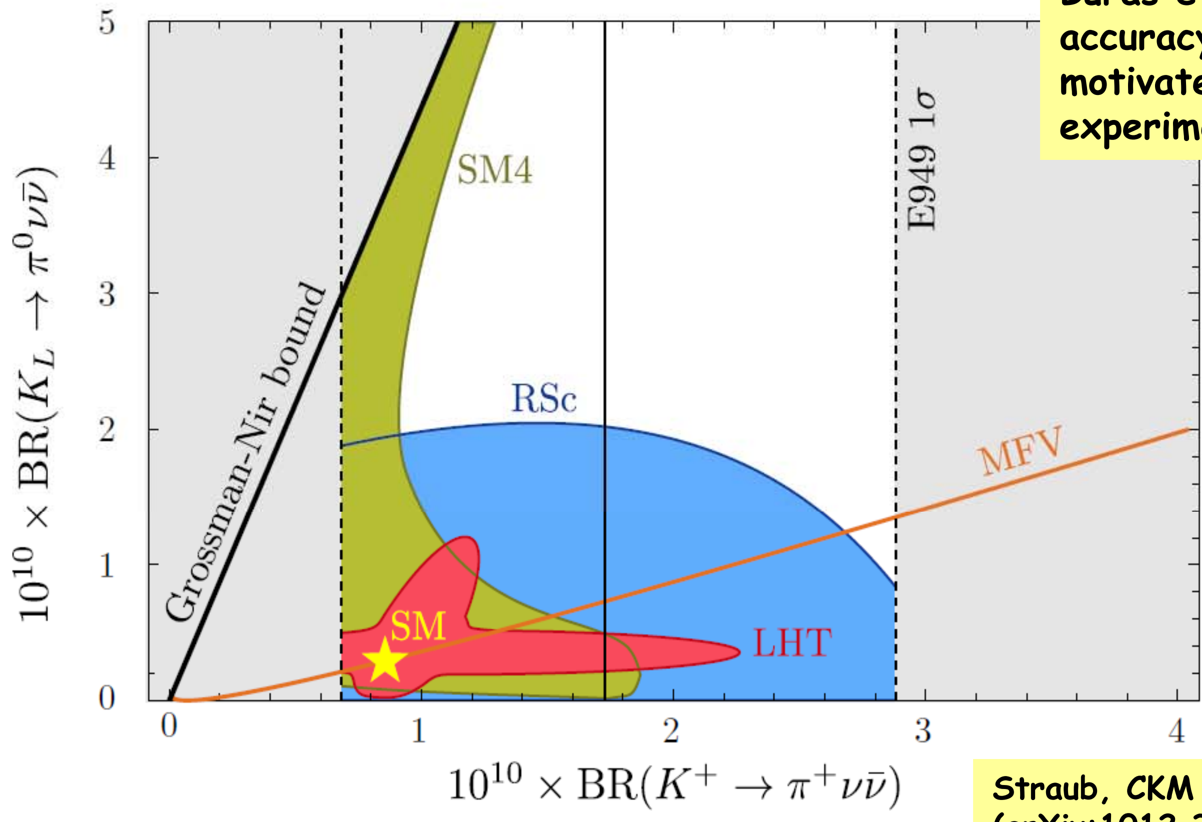
- A single effective operator
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with Ke3
- Uncertainty from CKM elements (*will improve*)
- **Remains clean in most New Physics models**

  (unlike many other observables)

Brod, Gorbahn, Stamou PR **D83**, 034030 (2011)

$$B_{SM}(K^+\to\pi^+\nu\bar{\nu}) = (7.8 \pm 0.8) \text{ x } 10^{-11}$$

Rare processes sensitive to new physics… e.g. Warped Extra Dimensions as a Theory of Flavor??



Buras et al. SM accuracy of <5%, motivates 1000-event experiments

Straub, CKM 2010 workshop (arXiv:1012.3893v2)

Figure 1: Correlation between the branching ratios of $K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model-independently by the GN bound. The SM point is marked by a star.

Comments from the Fermilab PAC December 2011

The Committee feels that even in a constrained budget, the Laboratory should direct resources to this activity over the next several years in order to (1) assess the impact that ORKA might have on the current physics program (NOvA, Mu2e, g-2, etc.) and the planned LBNE effort, and (2) determine in more detail the resources that are needed from the Laboratory to make this a successful experiment. In particular, the ORKA collaboration brought up several matters in its presentation that may need immediate attention, including for example:

- The options for siting the experiment in the CDF hall at B0 or elsewhere at the Laboratory need to be resolved.
- Slow extraction from the Main Injector appears to be a solvable problem, but this needs to be verified.

Support from the Laboratory should be directed to fleshing out solutions to these issues. The ORKA collaboration presented a rather aggressive schedule to the Committee. This appears to be manageable given that the experimental technique is proven and is relatively low-risk. The collaboration appears to be strong presently, but may need to be strengthened, as it proposed already.

The Committee is eager to learn at the June meeting about the following issues:

- Attraction of substantive resources/in-kind contributions from other nations/laboratories/institutions.
- Progress on the dogleg design described in the ORKA presentation.
- Progress in more precisely determining the contingencies.

Excerpt from Pier Oddone's letter granting Stage-1 approval for ORKA

As you see, the PAC recommended Stage I approval, and I accept that recommendation. Nevertheless, as also noted by the PAC, we need to understand better the possible site of the experiment, technical issues associated with use of the Main Injector as proposed, and how we might fit the cost of ORKA into anticipated budgets of the Laboratory. All of these issues will be necessary before Stage II approval might be given.

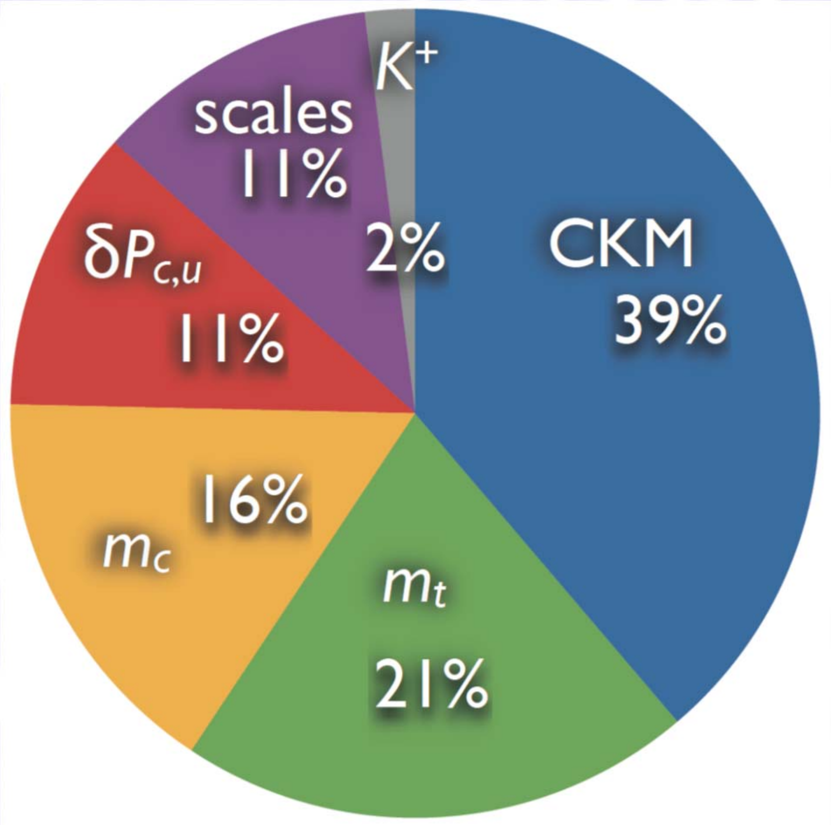
We look forward to working with you to resolve these issues, recognizing that even working on them now will be difficult, given our severely constrained resources. At the same time, the Stage I approval I am granting now should help in finding additional collaborators, outside resources, and help within the Laboratory.

Sincerely,

Piermaria Oddone

Summary of SM Theory Uncertainties

CKM parameter uncertainties dominate the error budget today.



With foreseeable improvements, expect total SM theory error ≤6%.

(ORKA proposal)

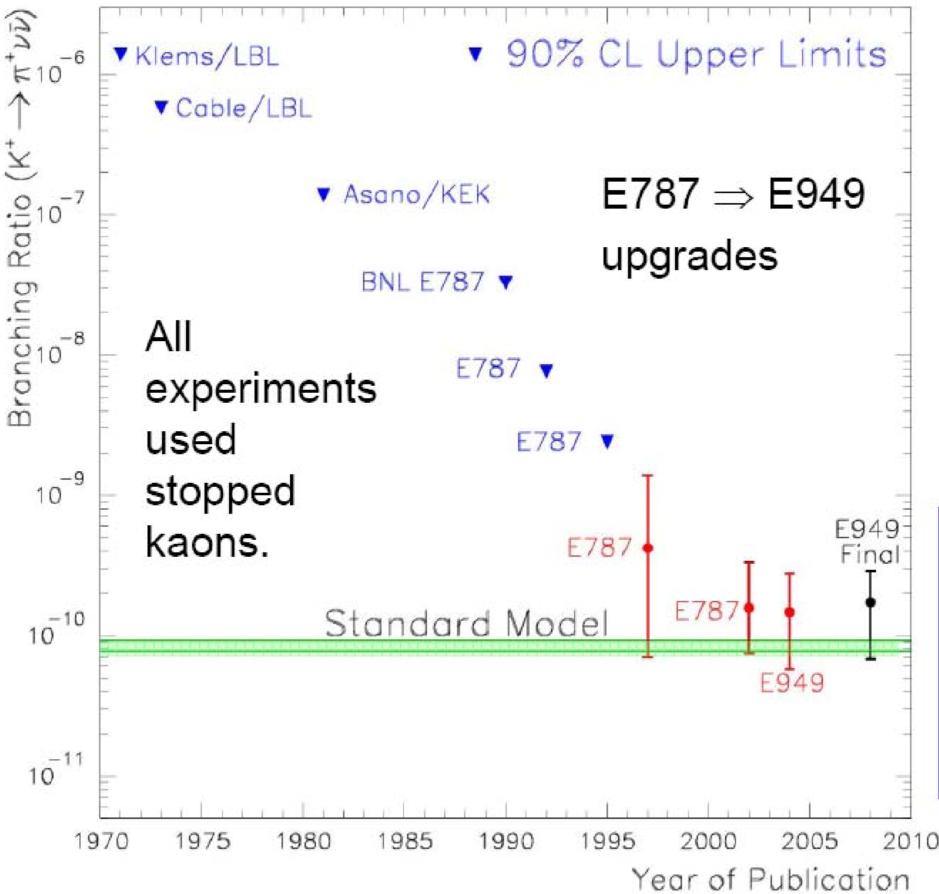
Unmatched by any other FCNC process (K or B).

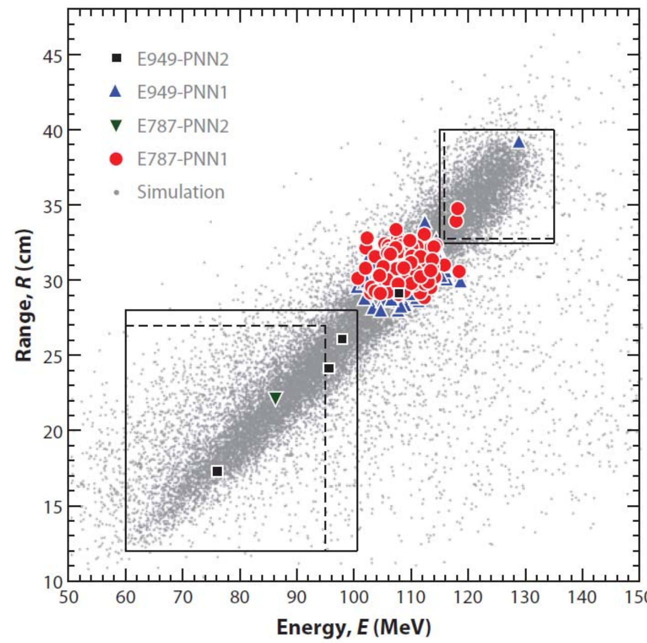
30% deviation from the SM would be a 5σ signal of NP

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

J. Brod, M. Gorbahn, and E. Stamou, Phys. Rev. D83, 034030 (2011) [arXiv:1009.0947 [hep- ph]].

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





E787/E949 Final: 7 events observed

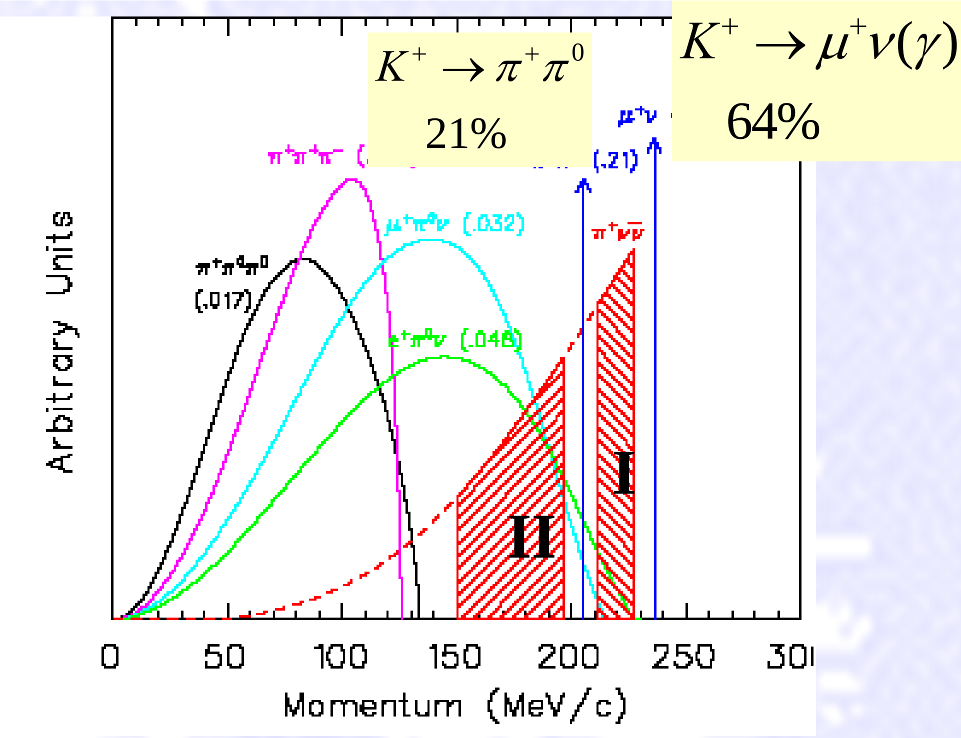
$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$

Standard Model:

$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ = (0.78+-0.08) $x10^{-10}$

Special Features of Measuring

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



Experimentally weak signature with background processes exceeding signal by $>10^{10}$

Determine everything possible about the K^+ and π^+

* π^+ / μ^+ particle ID better than 10^6 (π^+ - μ^+- e^+)

Eliminate events with extra charged particles or ***photons***

* π^0 inefficiency $< 10^{-6}$

Suppress backgrounds well below the expected signal (S/N~10)

* Predict backgrounds *from data*: dual independent cuts
* Use "Blind analysis" techniques
* Test predictions with outside-the-signal-region measurements

Evaluate candidate events with S/N function

The BNL E787/E949 stopped kaon technique

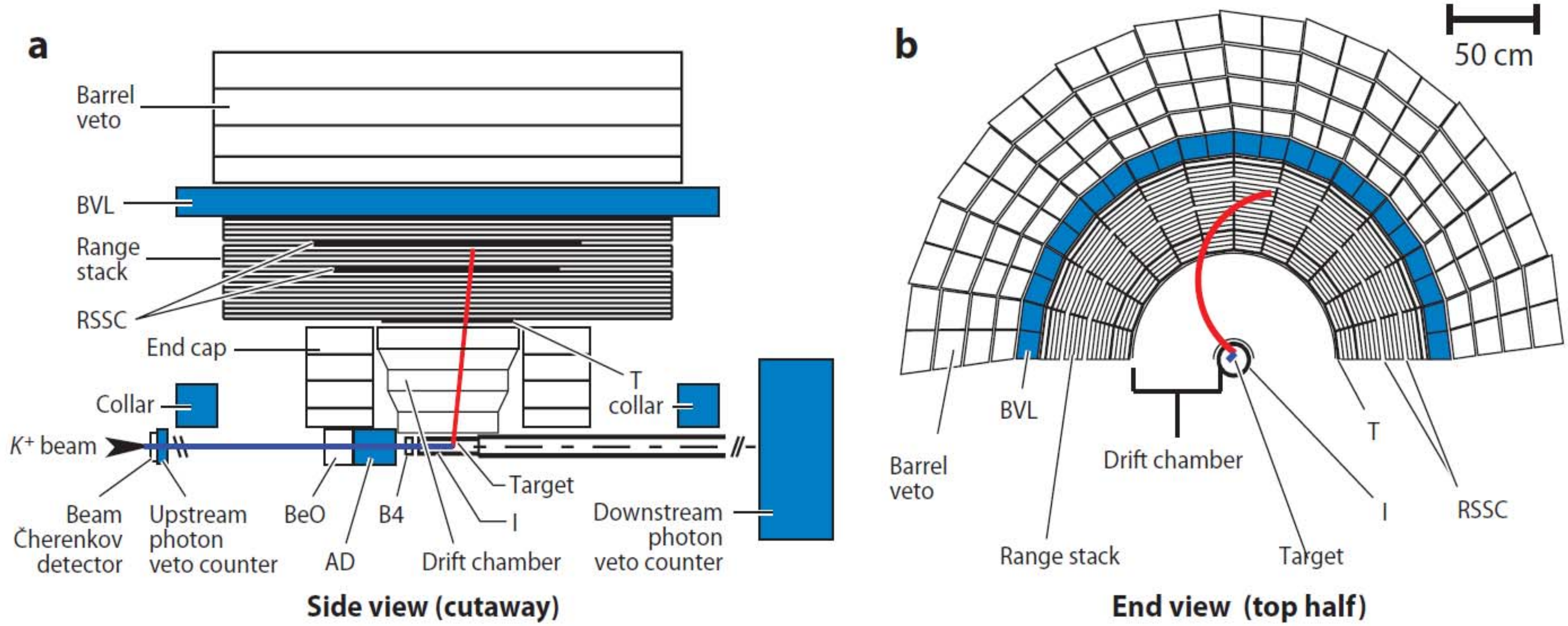
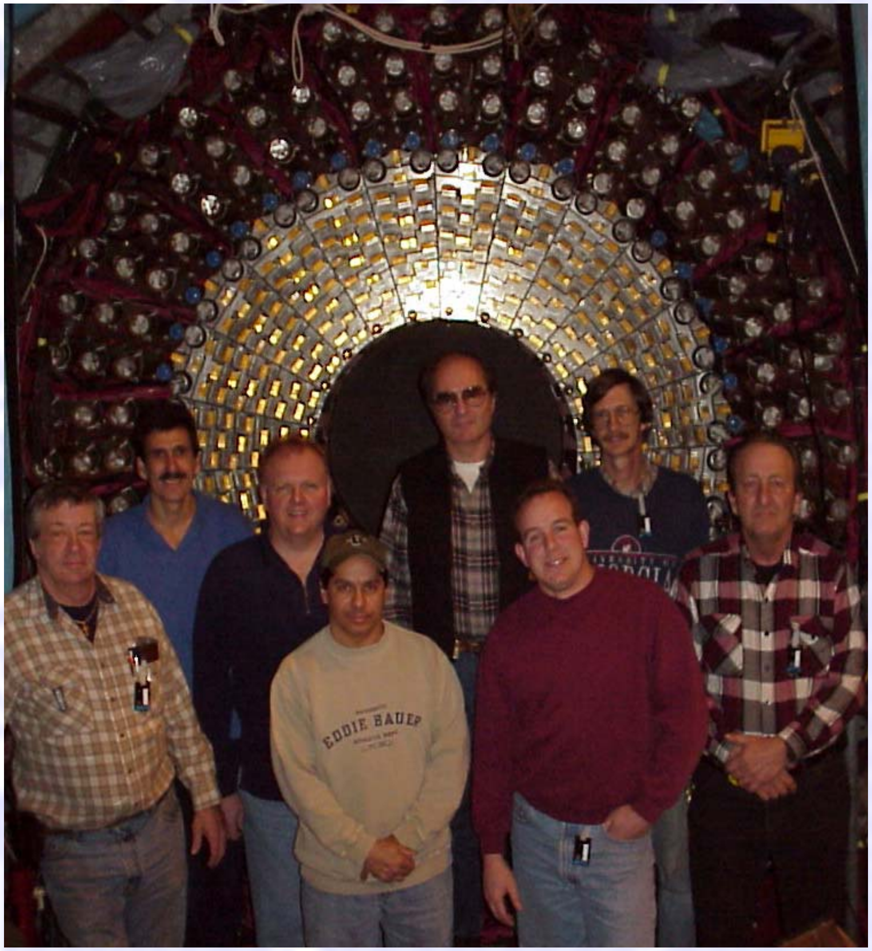


Figure 1

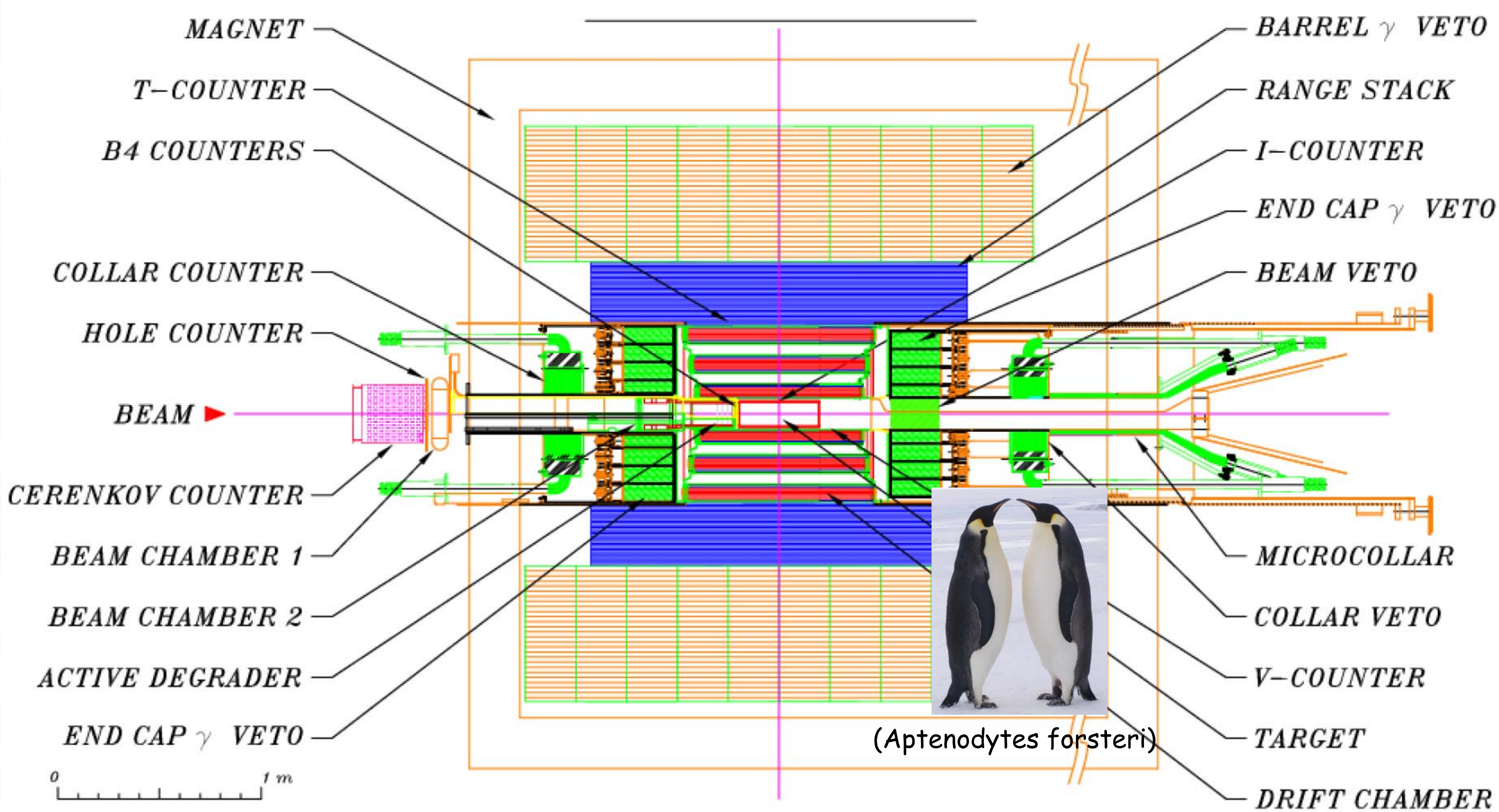
Elevation side view and end view schematic of the BNL E787 and E949 technique. (*a*) The 700-MeV/*c* K^+ beam enters from the left. (*b*) The stopped K^+ decays in the stopping target, and the subsequent decay π^+ track is momentum-analyzed by the tracker. The decay π^+ then stops in the range stack, where its range and energy are measured. The range stack STRAW chamber (RSSC) measures the position of the putative charged pion with the range stack. The barrel veto liner (BVL) is an upgrade of photon veto performance in E949 and E787. Abbreviations: AD, active degrader; DPV, UPV.

D. Bryman, W. Marciano, R. Tschirhart, and T. Yamanaka, Ann. Rev. Nucl. Part. Sci. 61, 331(2011).

The Range Stack measures the π^+ energy, range, and progeny. BNL implementation based on 1980's technology…Ripe for upgrade.



ORKA is a 4th Generation Detector - x100 sensitivity - x10 from kaon flux, x10 from detector



(Aptenodytes forsteri)

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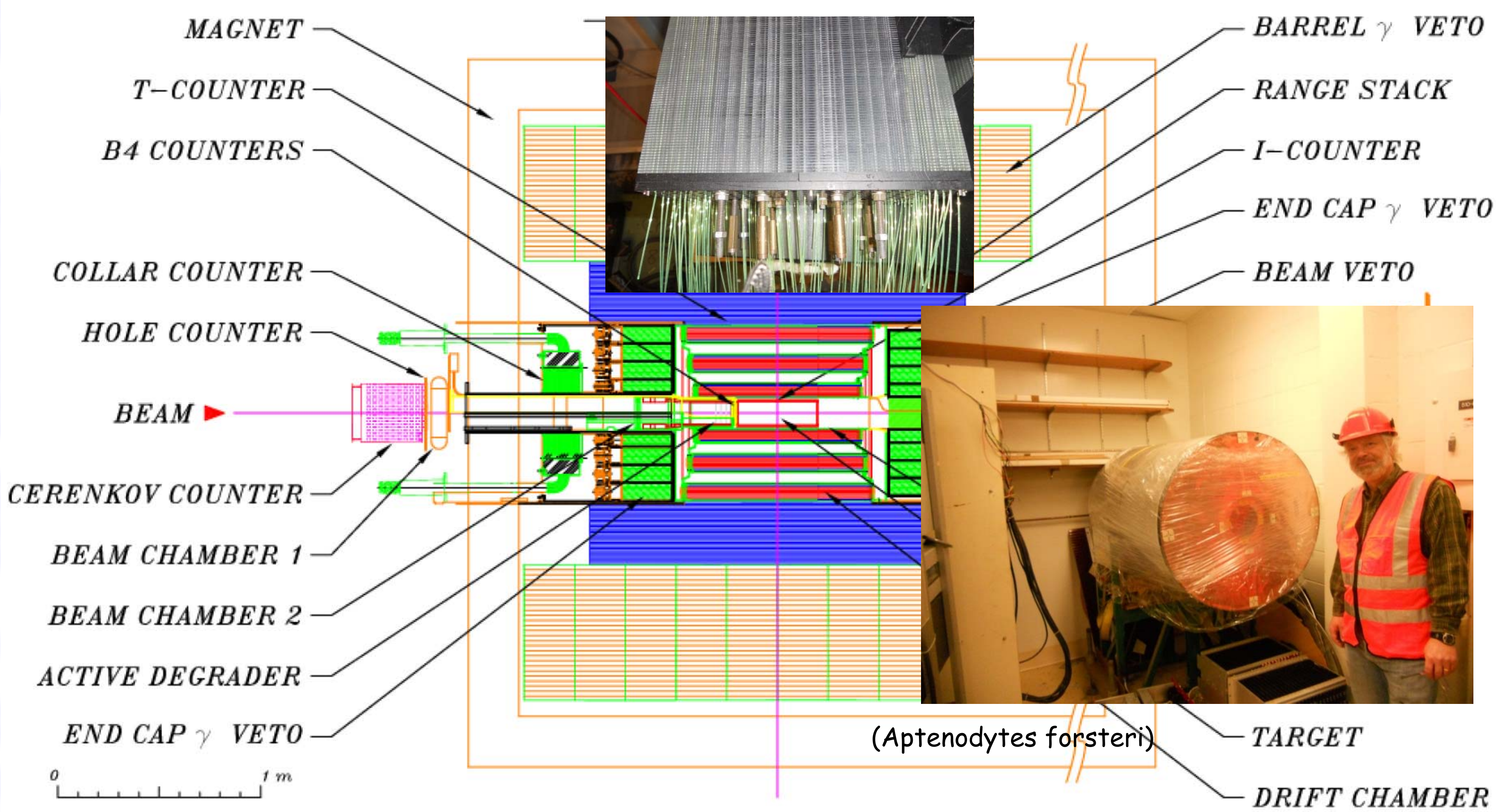


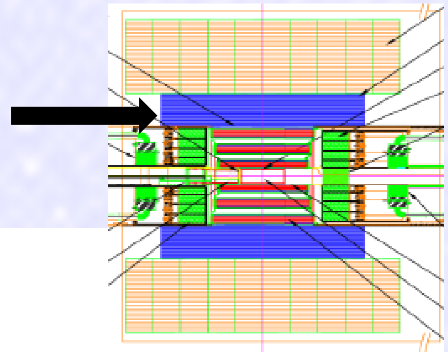
(Aptenodytes forsteri)

ORKA Detector Improvements

Incremental increases in signal acceptance based largely on E787/E949 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 ($R_{\rm acc}$)	$11.28^{+3.25}_{-2.22}$

Additional acceptance gains expected from trigger improvements.



$\pi \to \mu \to e$ Acceptance Factors

1. Identify range stack counter where π^+ stops
2. Detect $\pi \to \mu$ decay in stopping counter
3. Detect $\mu \to e$ in stopping counter and neighboring counters

Quantity	Acceptance	Range
π decay	0.8734	(3,105) ns
μ decay	0.9450	(0.1,10) μs
μ escape	0.98	
e^+ detection	0.97 ± 0.03	
Product	0.78 ± 0.02	
E949 acceptance	0.35	
Improvement factor	2.24 ± 0.07	

Detector Improvements and $\pi \rightarrow \mu \rightarrow e$ Acceptance

1. Eliminate 4x multiplexing of range stack (RS) waveform digitizers used in E949.
   - Reduced loss due to accidentals
2. E949 RS: 19 layers (1.9cm thick), 24 azimuthal sectors.
   ORKA RS: 30 layers (0.95cm thick), 48 sectors.
   - Reduced accidental veto loss (μ^+ and e^+)
   - Improved discrimination of π and μ
3. Increased RS scintillator light yield by higher QE photodetectors and/or better optical coupling.
   - Improved μ identification
4. Deadtime-less DAQ and trigger: $\pi \rightarrow \mu \rightarrow e$ acceptance improvements; rudimentary $\pi \rightarrow \mu$ identification was an essential component of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ trigger in E787/E949.

Livetime and Delayed-Coincidence Acceptance

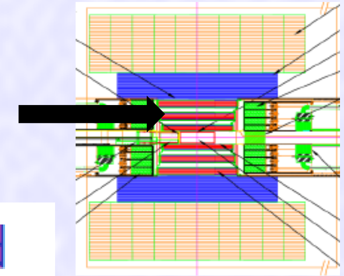
Livetime	
E949 livetime	0.74
ORKA estimate	1.00
Acceptance increase	1.35

Macro-efficiency	
E949 average	0.76
E949 best week	0.84
MiniBooNE (FY08)	0.85
ORKA estimate	0.85 ± 0.05
Acceptance increase	1.11 ± 0.07

E949 required a delayed coincidence of 2 ns between the stopped kaon and the outgoing pion to suppress prompt backgrounds.

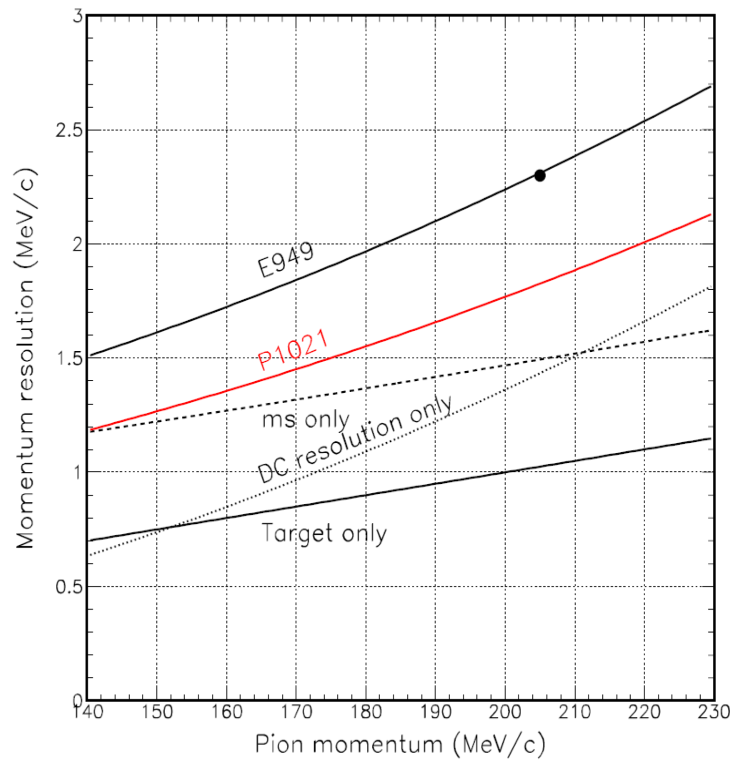
Delayed coincidence	
E949 acceptance	0.763
ORKA estimate	0.851 ± 0.035
Acceptance increase	1.11 ± 0.05

Improved Momentum and Range Resolution and Increased Solid Angle

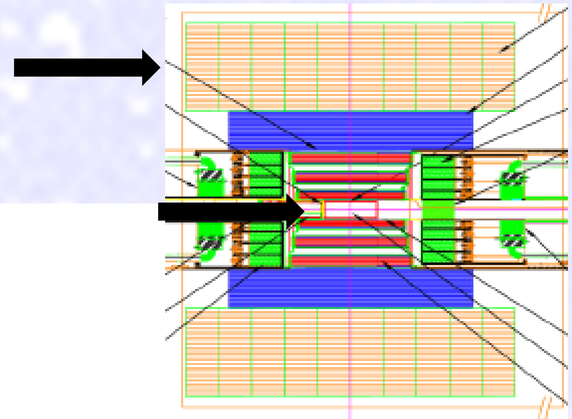


ORKA/E949 momentum resolution	0.90
Acceptance increase	1.12 ± 0.05
ORKA/E949 range resolution	0.87 ± 0.05
Acceptance increase	1.12 ± 0.06
E949/E787 energy resolution	0.93
Acceptance increase	1.12

	Solid angle increase	
	Drift chamber	Range Stack
E949	50.8	180
ORKA	84.7	250
Acceptance increase	1.38	



Photon Veto and Target Improvements



Photon veto	
E949	17.3 radiation lengths
ORKA	23.0 radiation lengths
Acceptance increase	$1.65^{+0.39}_{-0.18}$

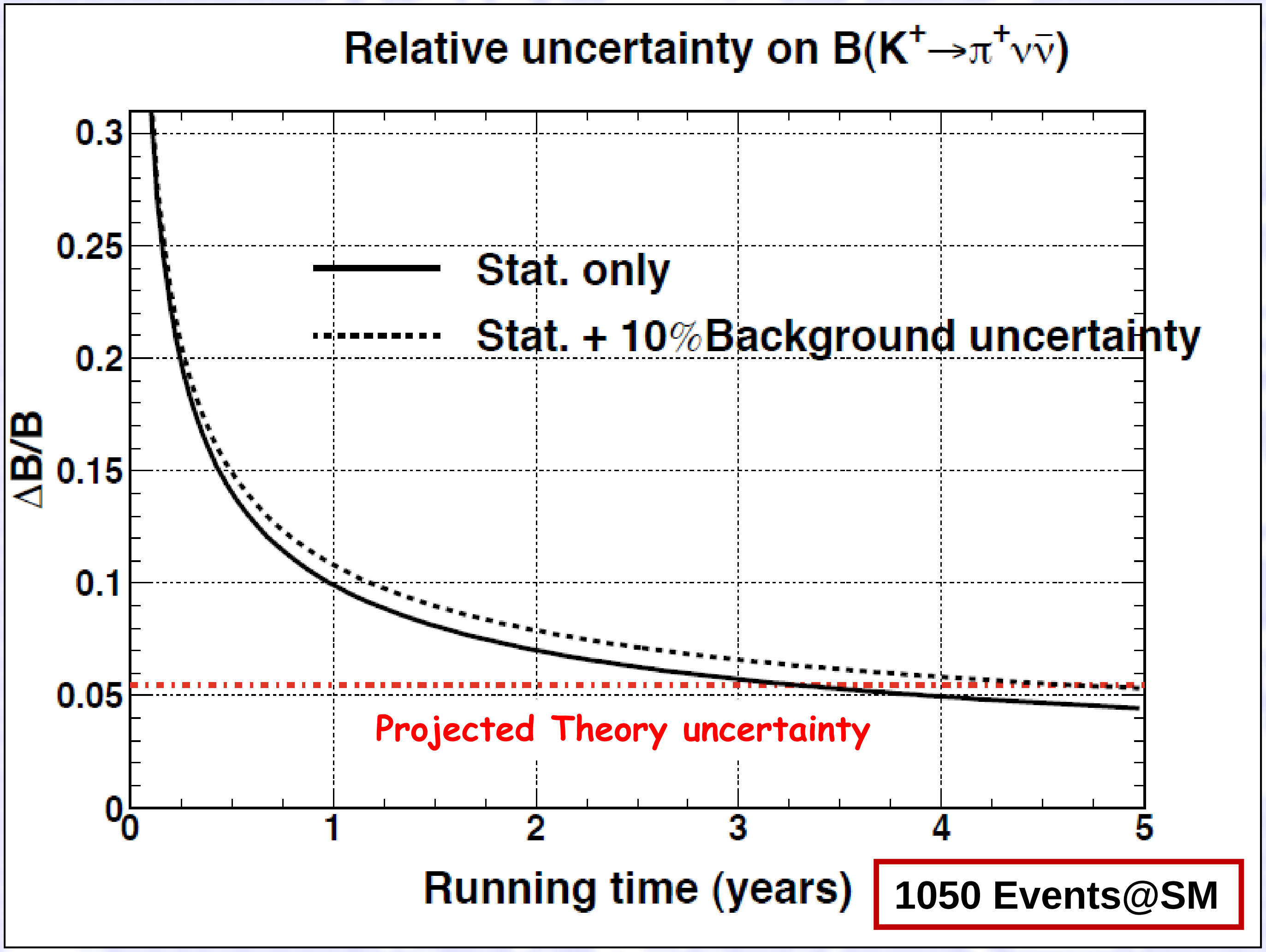
Estimated increase taken from simulated KOPIO PV performance.
KOPIO simulation was adjusted to agree with E949 PV efficiency.

Target	
E949	3.1 m long, single-end readout
ORKA	1.0 m long, double-end readout
Acceptance increase	1.06 ± 0.06

Comparison of ORKA and BNL E949

	E949	**ORKA**
P_p (GeV/c)	21.5	95
Duty Factor (%)	41	44
P_K (MeV/c)	710	600
Fraction of kaons that stop in target (%)	21	54
Average rate of stopping kaons/s (10^6)	0.69	4.78
Accidental loss (%)	23	28
Events/yr (SM)	**1.3**	**210**

ORKA Sensitivity *vs.* Time



$K \rightarrow \pi \nu \bar{\nu}$...
Past, Present, Future

Facility (Experiment)	Proton Power	Kaon Decay/stop rate	Kaon Properties	$K \rightarrow \pi \nu \bar{\nu}$ Sensitivity
BNL AGS (E787/E949):	50kW	1×10^6 K^+/sec	Pure stopped K^+ source	7 events
CERN (NA62):	20kW	10×10^6 K^+/sec	Un-separated 1- GHz $K^+/\pi^+/p^+$ beam	80 events
Fermilab: (ORKA):	**75kW**	**9×10^6 K^+/sec**	**Pure stopped K^+ source**	**1000 events**
Project-X $K^+ \rightarrow \pi \nu \bar{\nu}$	1500 kW	100×10^6 K^+/sec	Pure stopped K^+ source	>1000 events

How?

How Much??

Proton Source: Main Injector

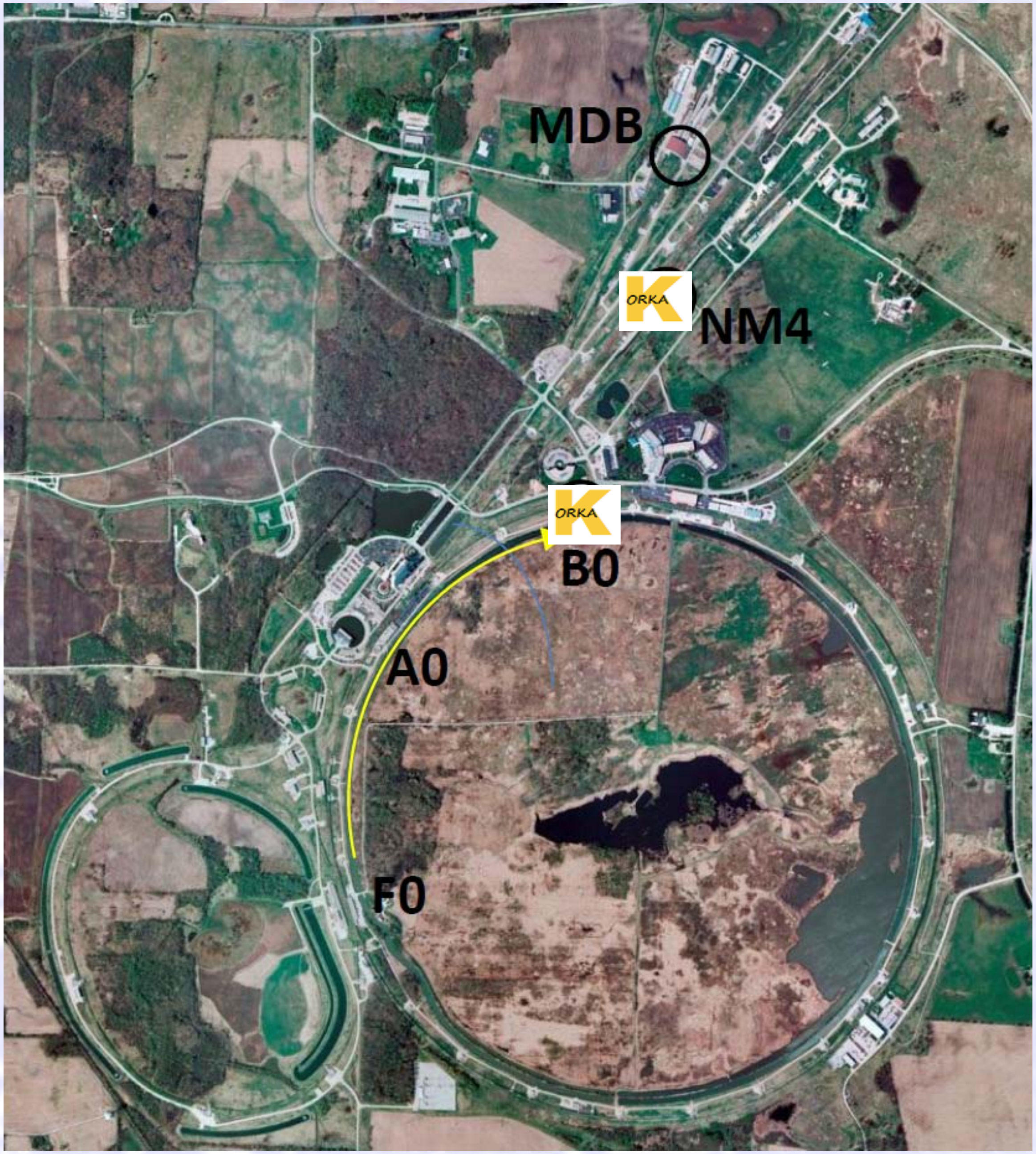
Possible* "Mixed Mode" Main Injector configurations with a slow spill cycle and a balance of NOvA cycles constrained to a total maximum magnet bus current of 4800 amps (rms).

E_{beam} [GeV]	T_{cycle} [s]	$t_{flattop}$	Duty Factor [%]	P_{ave} [kW]	P_{max} [kW]
120	15	2.5	16	62	377
120	20	3.3	16	46	283
120	25	4.1	16	38	232
120	30	4.9	16	31	189
100	10	3.5	35	77	222
100	15	5.0	33	52	154
100	20	6.5	33	39	118
100	25	8.1	32	31	96
95	**10**	**4.4**	**44**	**74**	**166**
95	15	6.3	42	49	116
95	20	8.3	41	37	89
95	25	10.1	40	29	73
90	10	5.9	59	70	118
90	15	8.3	56	46	83
90	20	10.8	54	33	61
90	25	13.3	53	28	52

*I. Kourbanis, personal communication

Sites considered:

- Sea-Quest/NM4:
  - -Existing beam transport, Adequate Shielding?
  - -Infrastructure at NM4 but no cryo.
- B0:
  - -Rad hard transport, requires A0 to B0 line.
  - -Resident magnet & cryo
  - -Infrastructure



B0 Assets for ORKA

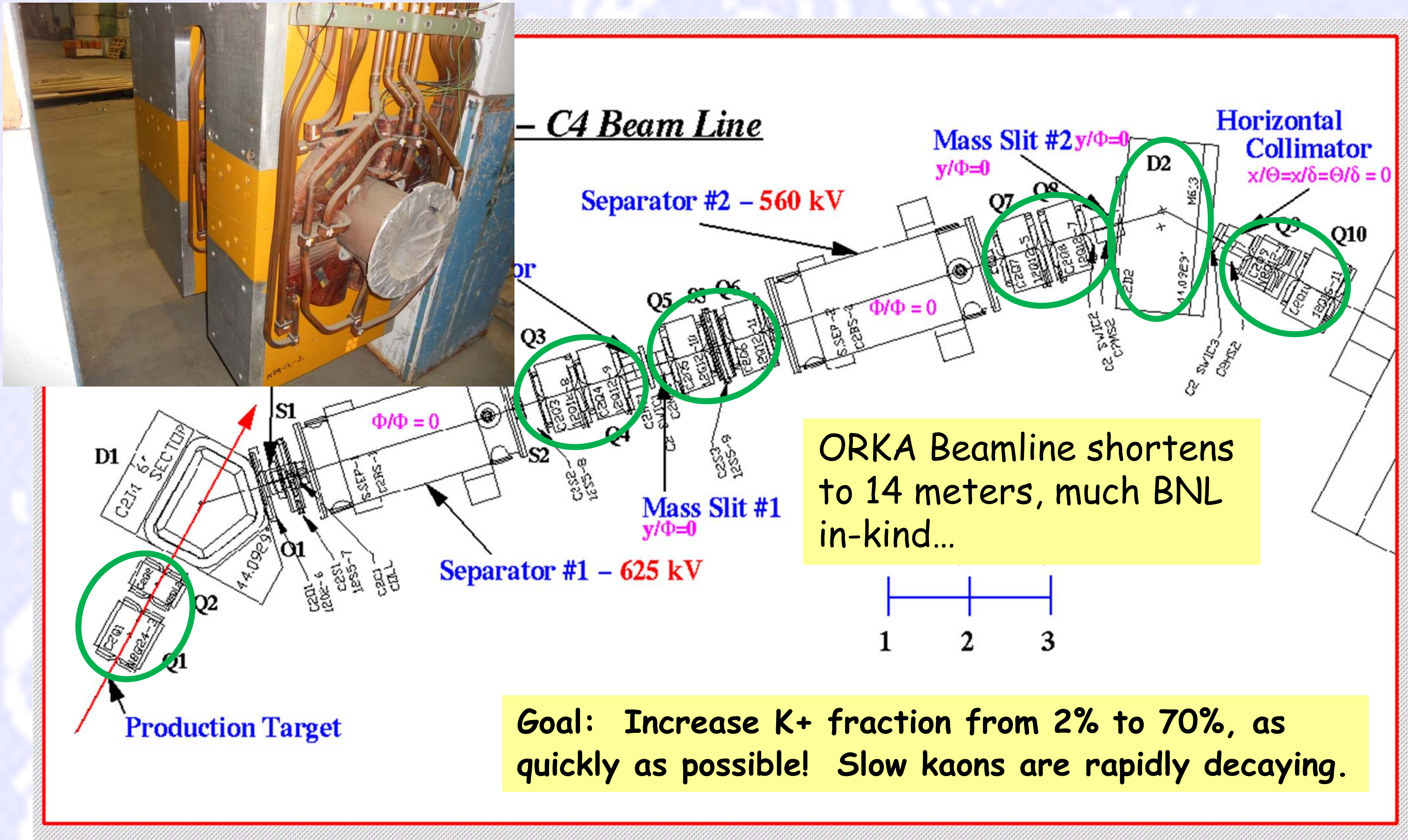
- No civil construction required. The existing Tevatron shielding can manifestly support loss of a maximum (4.8×10^{13} p) Main Injector pulse. Beam-Loss Monitors can halt multi-pulse losses.

- Re-use of existing solenoid magnet and return steel, cryogenics, and magnet control systems.

- Re-use of infrastructure for detector systems – power, cooling, etc.

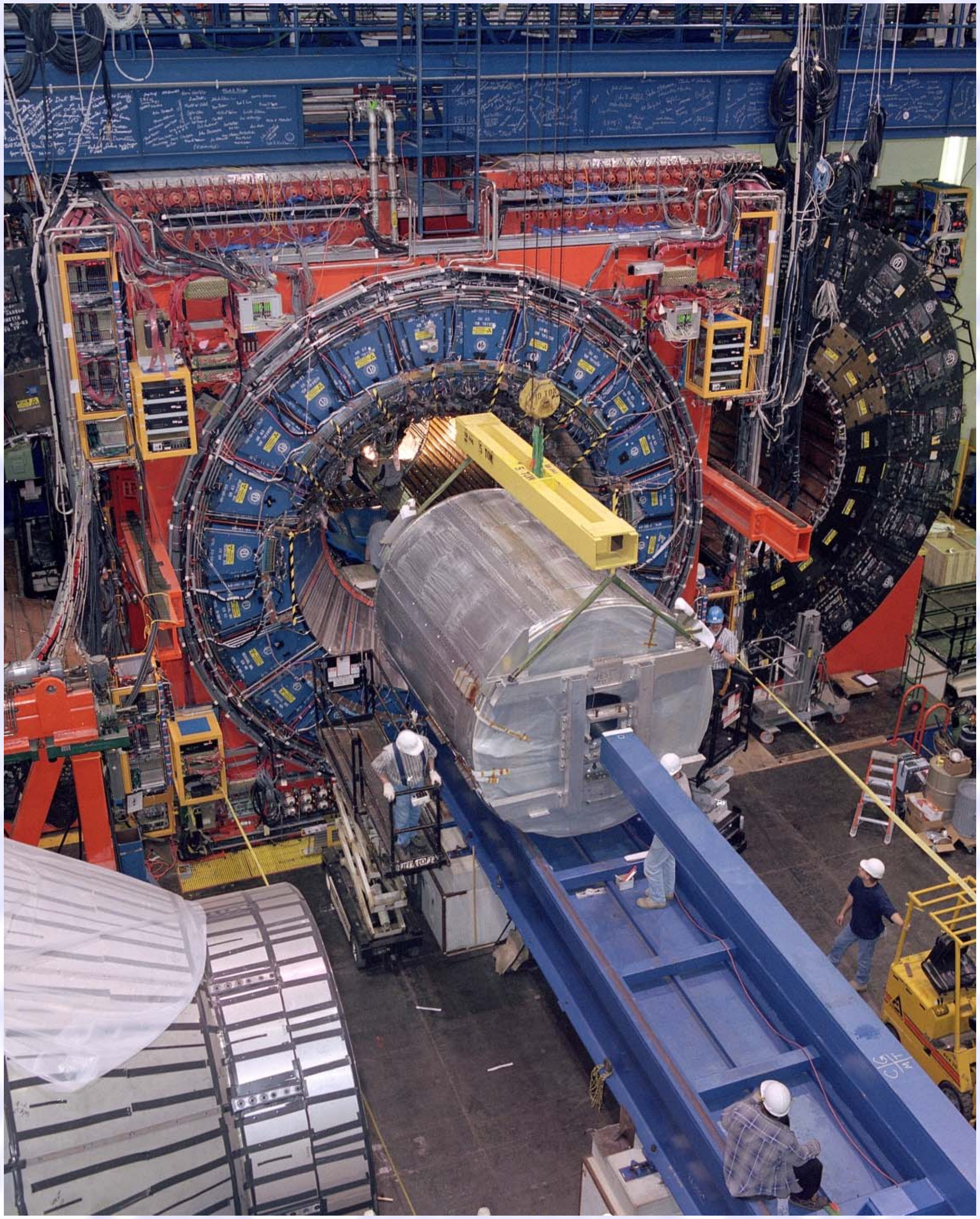
- Work can start in the near future through Accelerator Improvement Projects to prepare for ORKA while developing and maintaining the collider technology display for the next several years.

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

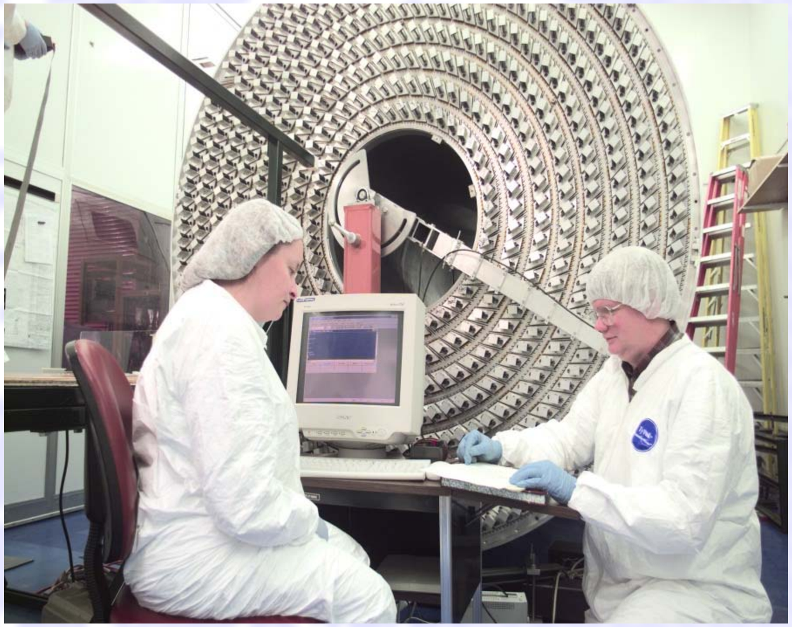


ORKA Beamline shortens to 14 meters, much BNL in-kind…

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



The ORKA new detector payload replaces the CDF tracker volume-ε.



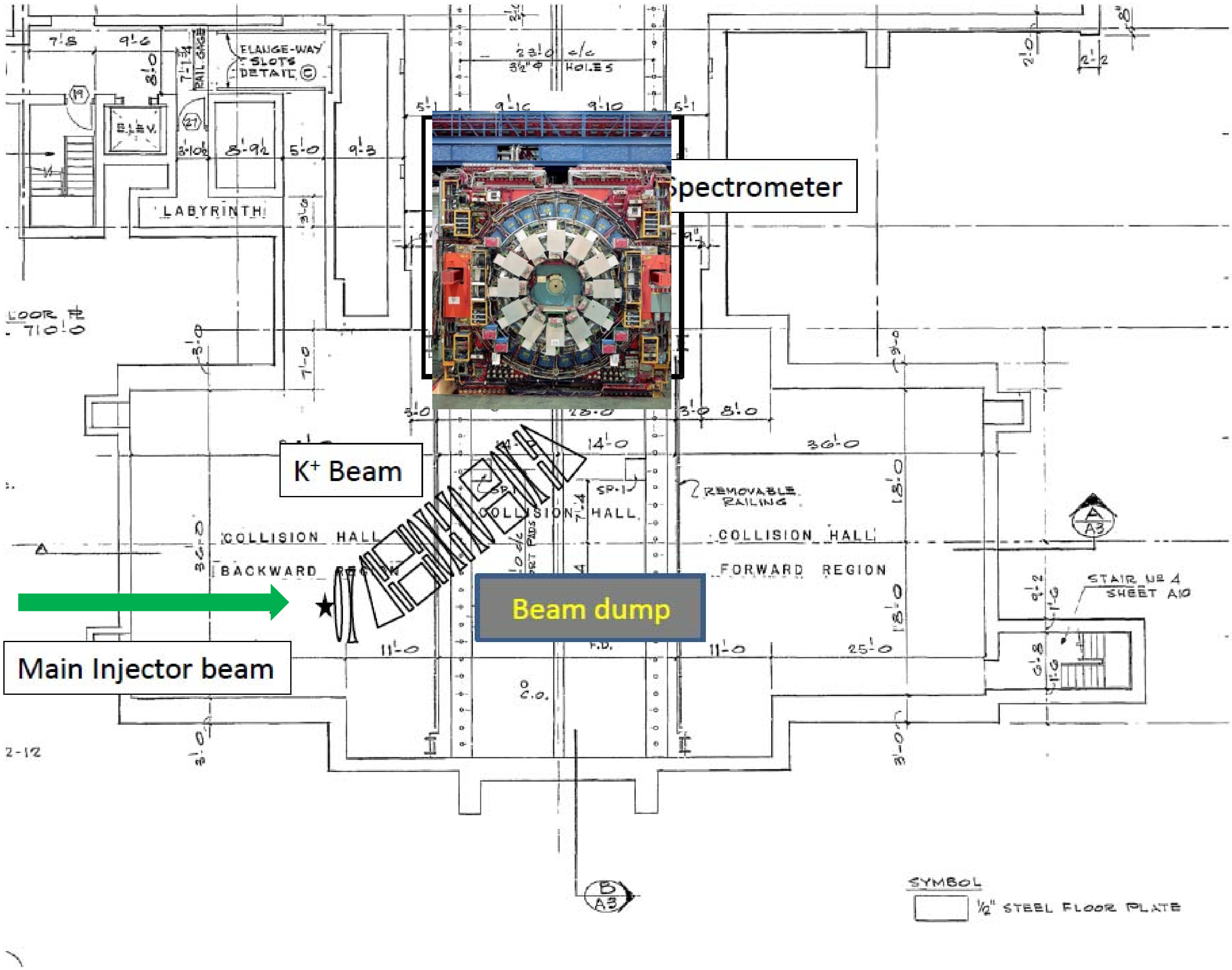
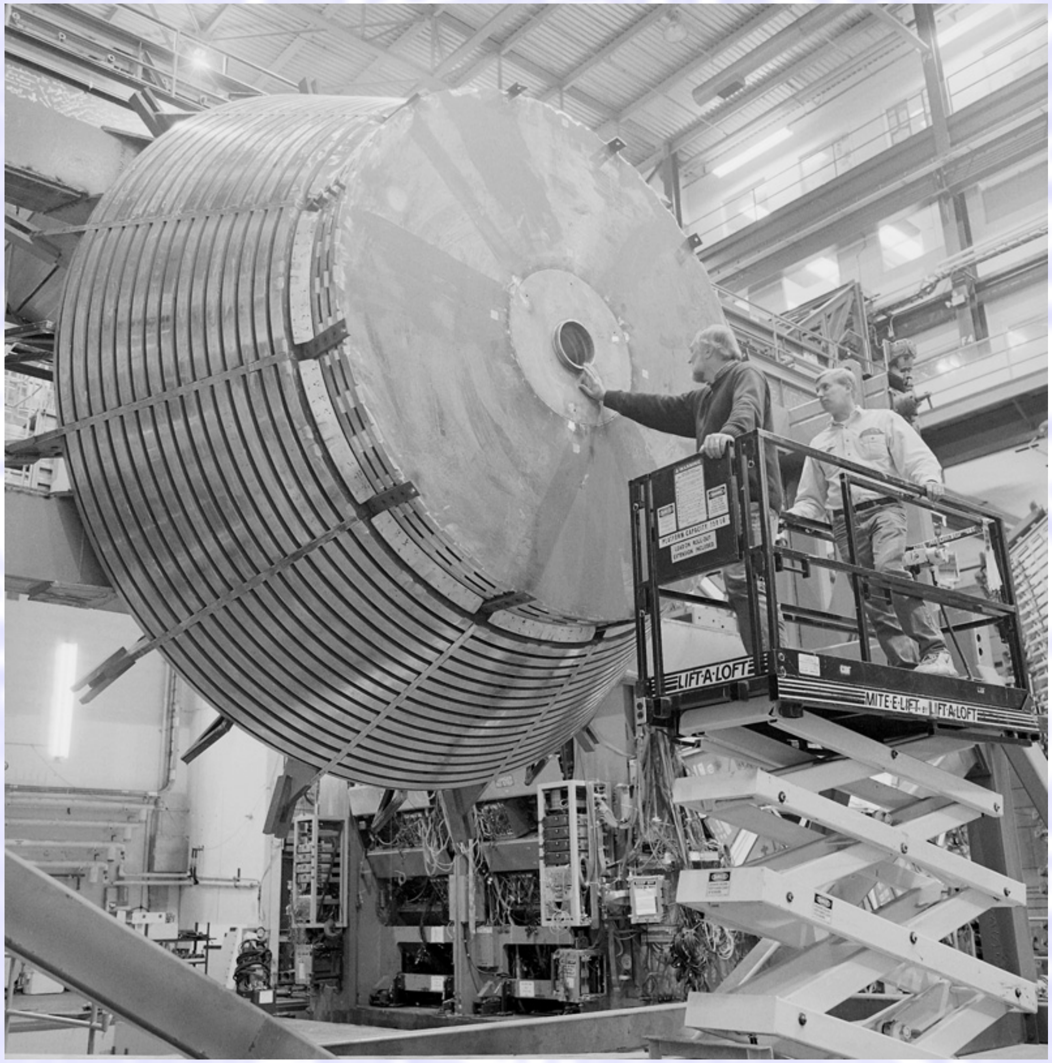


Figure 5.3: Illustration of the ORKA beam line and detector sited within the B0 collision hall.

One Plug Must be modified to Transport kaon beam to the center of the CDF solenoid

Some Plug plates will be retained to Carry Magnetic Flux



Estimated Cost

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**	**7,510**	**4,490**	**12,000**
	1.1.1	A0 to B0 transport*	2,200	1,300	3,500
	1.1.2	Target and Dump	940	560	1,500
	1.1.3	Kaon Beam	4,370	2,630	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	Commissioning	400	240	640

* Candidate for off-project Accelerator Improvement Project (AIP) funding.
† Included here although there is no uniform practice to do so.

Aggressive Schedule

Table 11.1: Our projected timescale for major milestones and activities. Dates refer to calendar year, not fiscal year.

Milestone/Activity	Time Period
Stage One Approval	Winter 2012
DOE Approval of Mission Need (CD-0)	Fall 2012
Beam/Detector Design	2012–2013
Approve Cost Range (CD-1)	early 2013
Baseline Review/CD-2	End of 2013
Start Construction (CD-3)	Spring 2014
Begin Installation	mid-2015
First Beam/Beam Tests	End of 2015
Complete Installation	Mid-2016
First Data (Start Operations/CD-4)	End of 2016

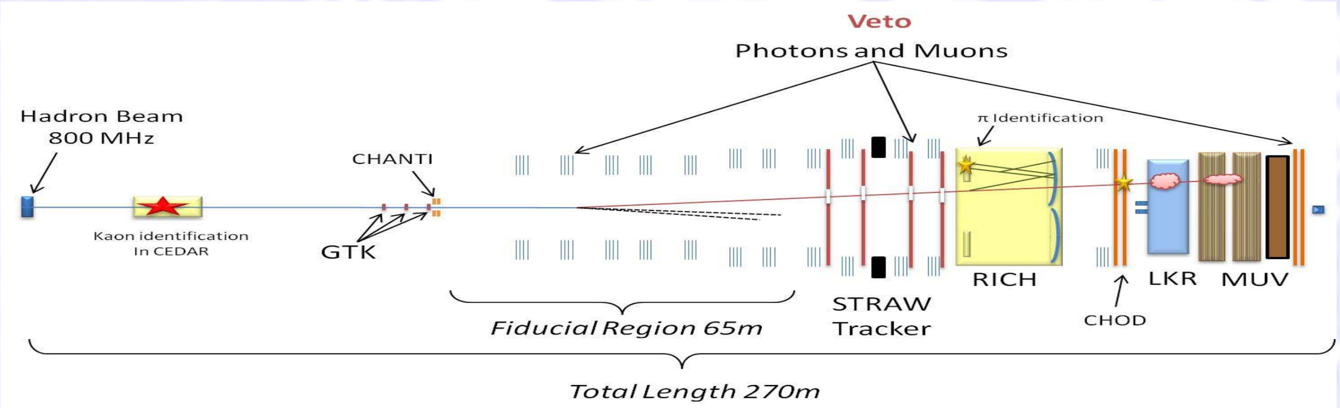
What about the Competition?

• **The CERN NA62 experiment:**

- Strong group, evolution of existing assets, new in-flight technique, complimentary to the established ORKA technique.

- Sensitivity goal: ~40 events/year.

- Development run in summer 2012 with SPS beam. First results in 2017. Running must be coincident with LHC ops, splits run-time with CNGS.



ORKA Roadmap in Particle Physics

- **2017**, first results from the NA62 CERN experiment:
  - **Evidence of new physics?:** ORKA will embark on confirming with a completely different method, provide definitive measurement.
  - **No evidence of new physics?:** ORKA will push the hunt for new physics to much higher sensitivity.
- **2020**, first results from the ORKA experiment:
  - Evidence of new physics or no evidence of new physics yet: ORKA will continue the hunt to "ultimate" sensitivity. Interplay with results from next generation flavor factories.

What is Needed to Launch ORKA

- Recommendation and generation of Stage-1 approval, initiation of Critical Decision timeline process within the DOE OHEP.
- Support for US Universities, other labs, and foreign institutions to participate.
- An integrated plan of support and development from "off-project" funding sources (e.g. AIP, DOE OHEP R&D) with Project support.

Near Term Issues and Opportunities for ORKA

- Evaluate critical issues for siting at B0:
  - Beam-line elements for transport from A0 to B0. Lattice, emphasize re-use of existing components.
  - Shielding analysis of the B0 siting solution.

- Develop an Accelerator Improvement Plan to transport beam from A0 to B0 and preparation of the collision hall.

- Work with funding agencies on identifying and supporting relevant detector R&D that can benefit ORKA in the near term.

ORKA

Detector R&D that can lower cost and increase performance and is important for Project-X

- **D:** Geiger Avalanche Mode (SiPMs, MPPCs) devices for scintillator readout of stopping target, range-stack, photo veto.
- **D:** Extruded scintillator for the stopping target and range stack.
- **D:** Fully streaming DAQ.
- **R:** High efficiency photon veto technology, synergy with Project X.

Additional key measurements & thesis topics

- $K^+ \to \pi^+ \nu\bar{\nu}(1)$ ^{T,P}
- $K^+ \to \pi^+ \nu\bar{\nu}(2)$ ^{T,P}
- $K^+ \to \pi^+ \nu\bar{\nu}\gamma$
- $K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$ ^{T,P}
- $K^+ \to \mu^+ \nu\gamma(\mathrm{SD})$ ^{T,P}
- $K^+ \to \pi^+ \pi^- \gamma(\mathrm{DE})$ ^{T,P}
- $K^+ \to \pi^+ X$ ^{P}
- $K^+ \to \pi^+ \tilde{\chi}_0 \tilde{\chi}_0(\mathrm{FF})$ ^{P}
- $K^+ \to \pi^+ \gamma$ ^{TP}
- $K^+ \to \pi^+ \gamma\gamma\gamma$
- $K^+ \to \mu^+ \nu_h$ (heavy neutrino) ^{T}
- $K^+ \to \mu^+ \nu M$ (M =majoran)
- $K^+ \to \pi^- \mu^+ \mu^+$ (LFV)
- $K^+ \pi^+ \mathrm{DP};\ \mathrm{DP} \to e^+ e-$ (DP = Dark Photon)
- $K^+ \to \mu^+ \nu\bar{\nu}\nu$
- $K^+ \to e^+ \nu\bar{\nu}\nu$
- $K^+ \to e^+ \nu \mu^+ \mu-$
- $\pi^0 \to \mathrm{nothing}$ ^{T,P}
- $\pi^0 \to \gamma \mathrm{DP};\ \mathrm{DP} \to e^+ e^-$
- $\pi^0 \to \gamma X$

^{T}E787/E949 Thesis ; ^{P}E787/E949 Publication

Summary

- The FNAL ORKA experiment is an exceptional opportunity to advance flavor physics in an era of constrained resources. ORKA reaches broadly across new physics models, and could lead to a paradigm shift in particle physics if realized in a timely fashion.

- The ORKA detector could be directly ported to the Project-X rare-decay campus, and the ORKA experience and detector development will be important for other future Project-X experiments such as $K_L \rightarrow \pi^0 \nu \bar{\nu}$.

- The ORKA detector is composed of many sub-systems, most of which within the reach of experienced research institutions. As such ORKA is a great opportunity for many US universities.

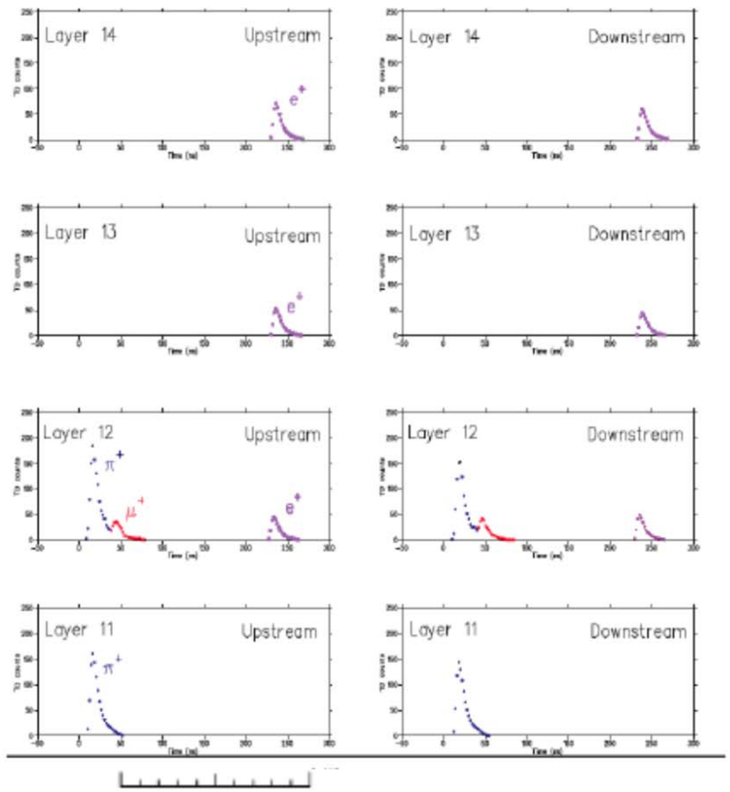
- The experiment scope is $50M (FY10,TPC) - relatively low-risk, requiring modest accelerator improvements, and no civil construction. Construction starting in 2014 is plausible, data taking by 2017, and first results in 2020.

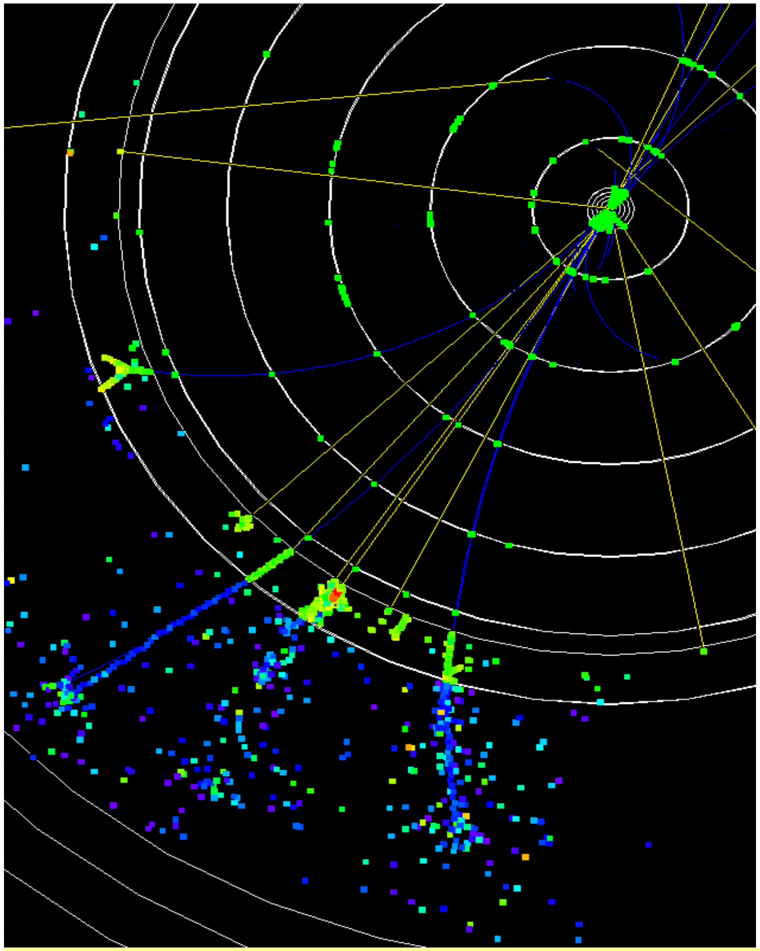
Spare Slides

ORKA Range Stack

Use existing (CDF or CLEO) solenoid

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



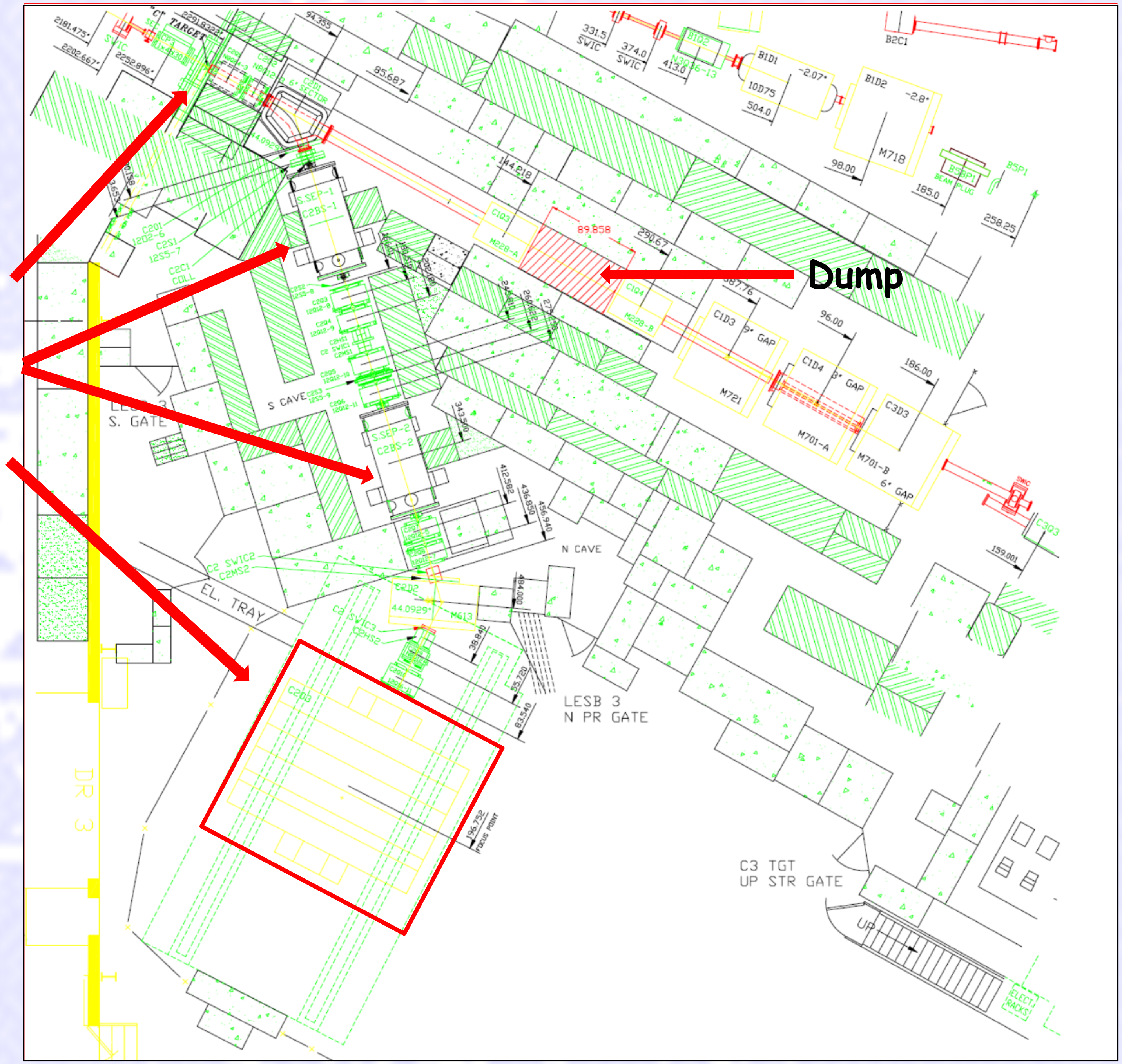


SiD fine grained calorimetery

Table 9.4: The E949 experiment "as run" is compared with the proposed experiment. N_K is the number of kaons entering the Cherenkov detector that defines the upstream end of the experiment. Instantaneous is abbreviated as "inst." and average as "ave." in the table. Descriptions can be found in the section indicated in the right hand column.

Component	E949 "as run"	ORKA	Ratio	Section
Proton momentum (GeV/c)	21.5	95		9.2.1
Protons/spill	65×10^{12}	48×10^{12}	$R_{\text{proton}} = 0.738$	9.2.1
Spill length(s)	2.2	4.4		9.2.1
Interspill(s)	3.2	5.6		9.2.1
Duty factor	0.41	0.44		9.2.1
protons/sec(ave.)	12×10^{12}	4.8×10^{12}		9.2.1
protons/sec(inst.)	15.9×10^{12}	10.9×10^{12}		9.2.1
Kaon momentum (MeV/c)	710	600		9.2.2
K beamline length(m)	19.6	13.74		9.2.2
Effective beam length(m)	17.6	13.21		9.2.2
K survival factor	0.0372	0.0536	$R_{\text{surv}} = 1.4408$	9.2.2
Angular acceptance (msr)	12	20	$R_{\text{ang}} = 1.66$	9.2.2
$\Delta p/p(\%)$	4.0	6.0	$R_{\Delta p} = 1.5$	9.2.2
$K^+{:}\pi^+$ ratio	3	3.31 ± 0.41		9.2.2
Relative K/proton	—	—	$R_{K/p} = 6.5 \pm 0.8$	9.2.3
N_K/spill	12.8×10^6	$(88.5 \pm 10.9) \times 10^6$		9.2.5
N_K/sec(inst.)	6.3×10^6	$(20.1 \pm 2.5) \times 10^6$		9.2.5
$N_{K+\pi}$/sec(inst.)	8.4×10^6	26.2×10^6		9.2.5
N_K/sec(ave.)	2.6×10^6	$(8.85 \pm 1.09) \times 10^6$		9.2.5
Stopping fraction	0.21	0.54 ± 0.12		9.2.4
Kstop/s(ave.)	0.69×10^6	$(4.78 \pm 1.21) \times 10^6$		9.2.5
Running time(hr)	—	5000		9.2.5
Kstop/"year"	—	$(8.6 \pm 2.2) \times 10^{13}$		9.2.5
$\mathcal{S}'_{\text{loss}}$			0.77 ± 0.02	9.2.5

Siting of the E949 experiment at the BNL AGS operated at 50 kW



Estimate of ORKA accidental losses based on E949 (1)

- Relative loss due to accidentals is

$$\mathcal{S} = e^{\lambda(R_{\mathrm{ORKA}} - R_{\mathrm{E949}})}$$

  where R is the instantaneous rate of $K^+ + \pi^+$ into the experiment in MHz.
- λ was measured to be $-0.0345/\mathrm{MHz}$ for the photon veto (PV) acceptance in E949 at an average rate $R_{\mathrm{E949}} = 8.4$ MHz.
- The estimated rate of $K^+ + \pi^+$ in ORKA is $R_{\mathrm{ORKA}} = 26.2$ MHz. This would imply a relative loss of $\mathcal{S} = 0.54$ with respect to E949.
- We expect these losses to be mitigated by
  1. Increased light collection efficiency (next page)
  2. Higher K^+ stopping fraction in the target (ignored for now)

Estimate of ORKA accidental losses based on E949 (2)

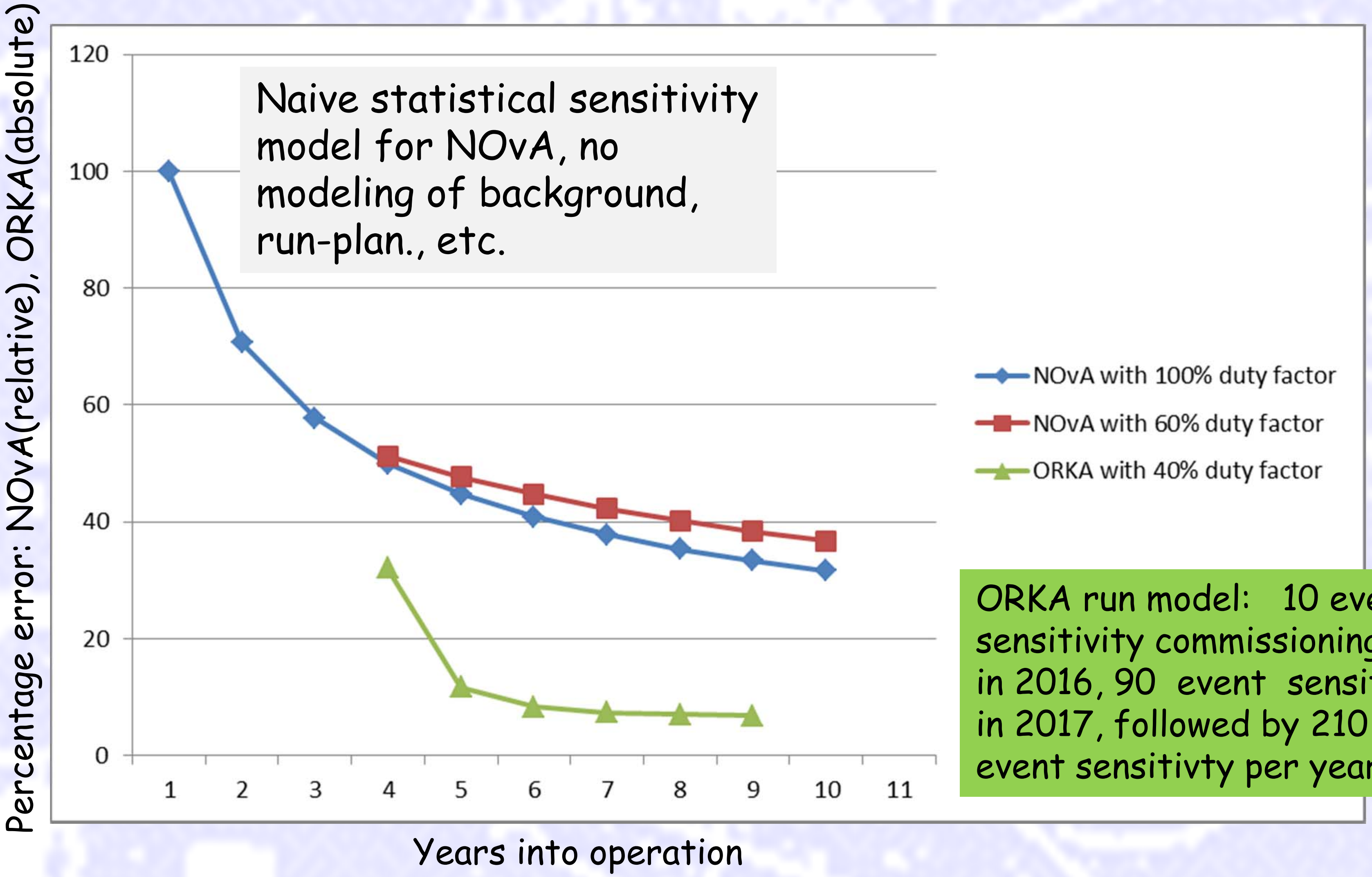
- The E949 PV threshold was set low enough to detect single photoelectrons(PEs), so the width in time of the PV was dominated by the decay time ($\tau \sim 2$ ns) of plastic scintillator.
- If light collection efficiency is doubled in ORKA, the same PV efficiency can be obtained with a 2 PE threshold or the width of the time window could be reduced by $\times 0.2$ with the same threshold.
- Assuming a width reduction by $\times 0.5$, The resulting relative loss in ORKA is then

$$\mathcal{S}' = 1 - \frac{1 - \mathcal{S}}{2} = 0.77 \pm 0.02$$

where the uncertainty is estimated from different measures of beam rates and λ in E949.

Details of estimate: projects-docdb:doc-1355

Consideration of NOvA and ORKA Joint Sensitivities



ORKA run model: 10 event sensitivity commissioning run in 2016, 90 event sensitivity in 2017, followed by 210 event sensitivty per year.

Buras et al "DNA"grades for Flavor models

	LHT	RSc	4G	2HDM	RHMFV
$D^0 - \bar{D}^0$ (CPV)	★★★	★★★	★★	★★	
ϵ_K	★★	★★★	★★	★★	★★
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	★★★
$S_{\phi K_S}$	★	★	★★		
$A_{\mathrm{CP}}\,(B \to X_s\gamma)$	★		★		
$A_{7,8}(K^*\mu^+\mu^-)$	★★	★	★★		
$B_s \to \mu^+\mu^-$	★	★	★★★	★★★	★★
$K^+ \to \pi^+\nu\bar{\nu}$	★★★	★★★	★★★		★★
$K_L \to \pi^0\nu\bar{\nu}$	★★★	★★★	★★★		★★
$\mu \to e\gamma$	★★★	★★★	★★★		
$\tau \to \mu\gamma$	★★★	★★★	★★★		
$\mu + N \to e + N$	★★★	★★★	★★★		
d_n	★	★★★	★	★★★	
d_e	★	★★★	★	★★★	
$(g-2)_\mu$	★	★★	★		

Table 3. "DNA" of flavour physics effects for the most interesting observables in a selection of non-SUSY models. ★★★ signals large NP effects, ★★ moderate to small NP effects and ★ implies that the given model does not predict visible NP effects in that observable. Empty spaces reflect my present ignorance about the given entry.

A. Buras, arXiv:1012.1447v2

The Relationship of ORKA to Project-X

- While the relevant accelerator R&D is adequately supported, the Project-X schedule is not clear.

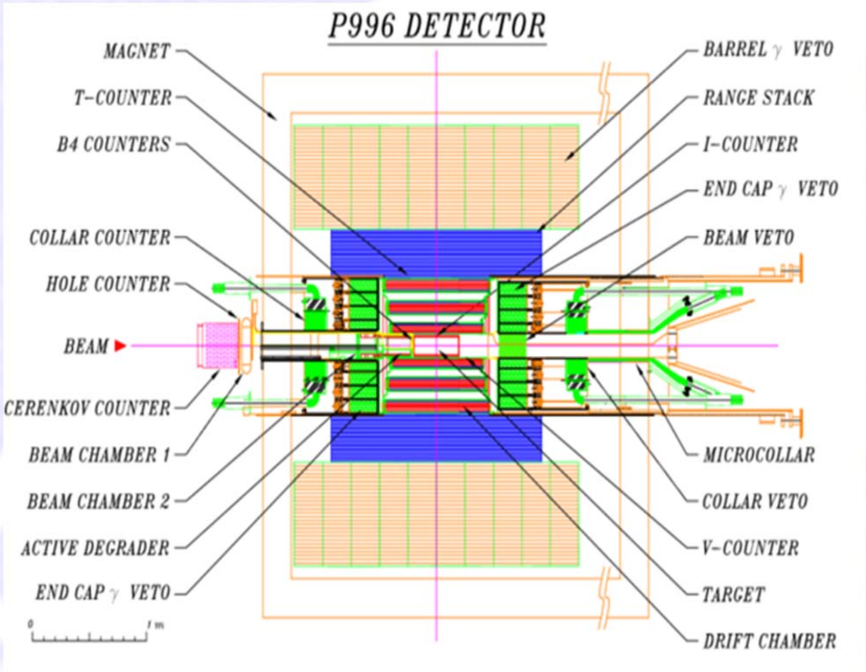
- The ORKA would come to full fruition with Project-X beam. The ORKA detector can be directly ported to the rare-decay campus as a candidate Day-1 experiment.

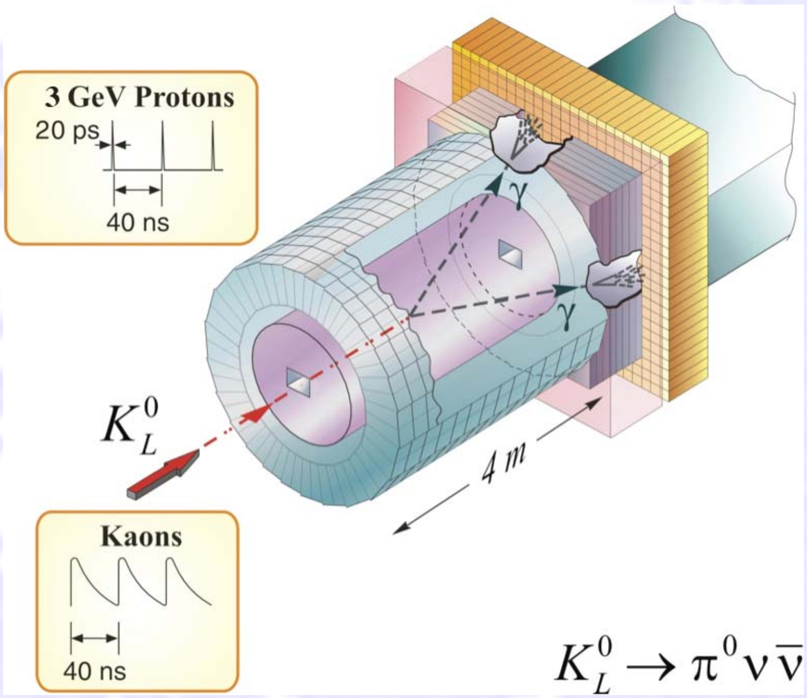
- The most important element of the Project-X research program is people. The promise of the ORKA research program has and will attract the best of the community. In parallel with ORKA, this community will develop the experimental techniques necessary to fully exploit the quark flavor physics potential of Project-X.

Project X Day-1 program goals: Definitive Measurement of $K \rightarrow \pi\nu\bar{\nu}$

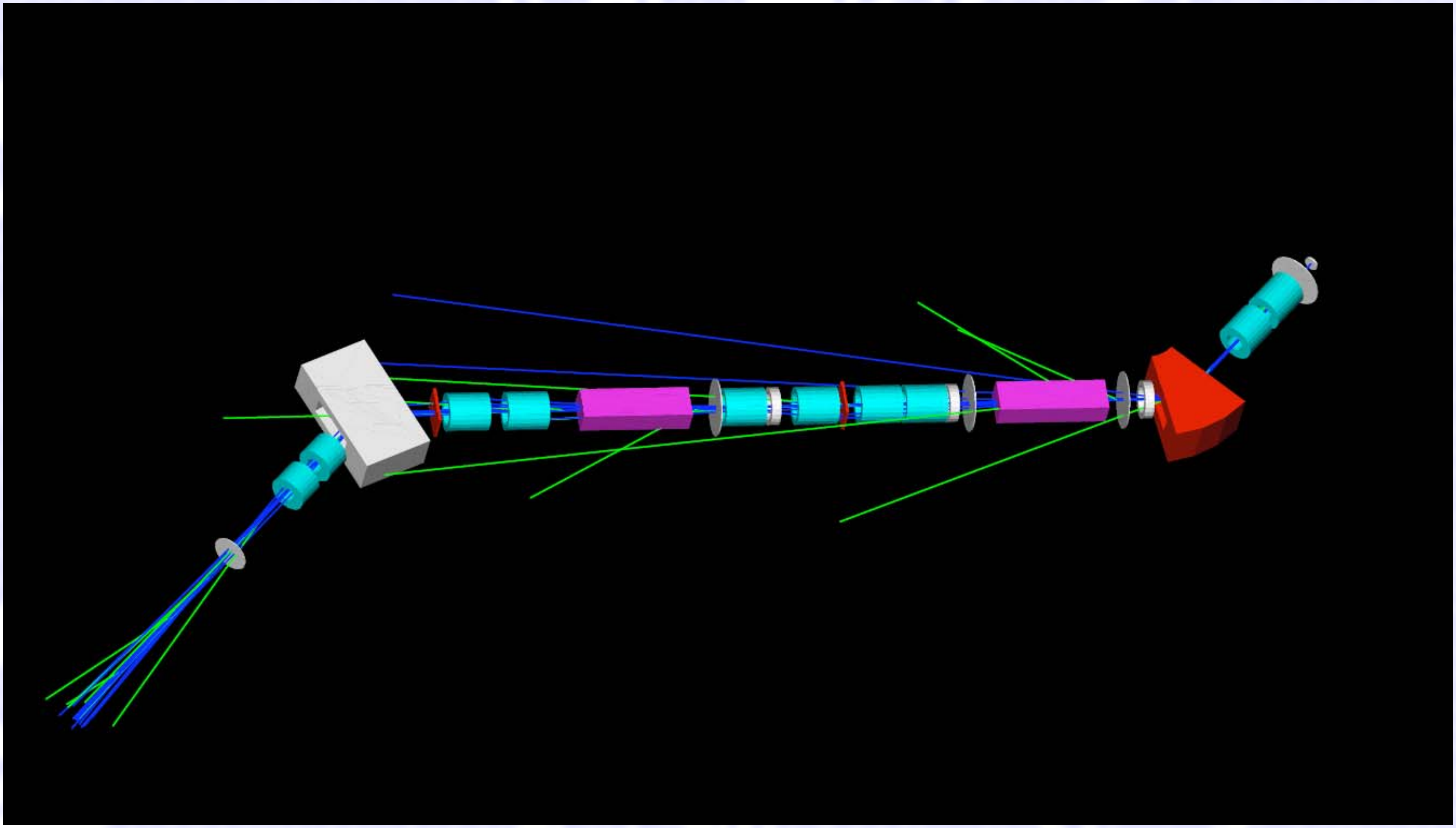
In the Project-X era the Fermilab ORKA experiment would precisely measure the rate and form-factor of $K^+ \rightarrow \pi\nu\bar{\nu}$.

The Project-X era presents an opportunity to measure the holy grail of kaon physics with precision: $K_L \rightarrow \pi\nu\bar{\nu}$.





G4Beamline dog-leg design underway to preserve CDF detector orientation.



Evolution of the CDF/B0 Infrastructure

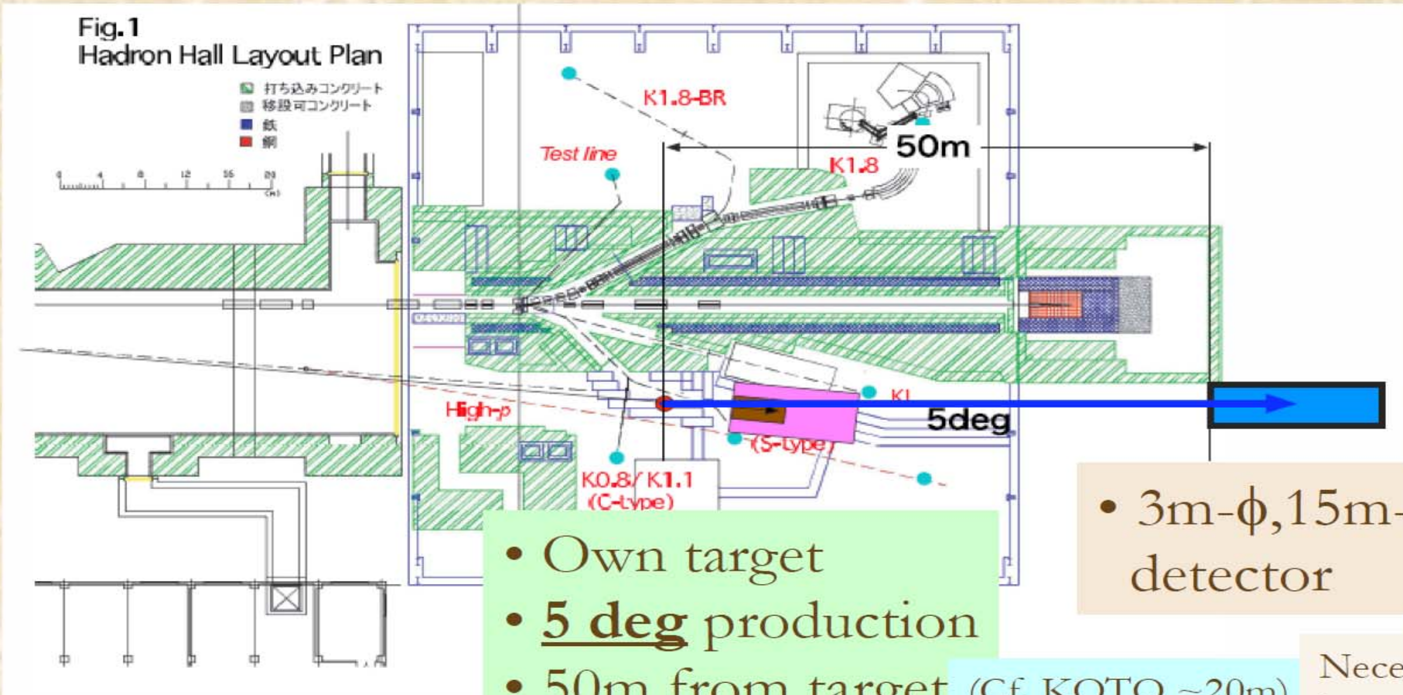
- 2012-2015: Stabilize ORKA infrastructure, collider-technology exhibit.
- Environment to communicate evolution from energy to intensity frontier to public, community, policy makers, investors.
- Project-X demonstrator experiment and proton-plasma wakefield experiment associated with IARC.

The ORKA Collaboration

Arizona State University USA, Brookhaven National Laboratory USA, Fermi National Accelerator Laboratory USA, Institute for Nuclear Research Russia, Joint Institute of Nuclear Research Dubna Russia, Istituto Nazionale di Fisica Nucleare Napoli Italy, 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, Universidad Nacional Autonoma de Mexico,Tsinghua University Beijing China

Long Term Vision* in Asia: KOTO

"Step 2" described in the E14 proposal (2006)



- Own target
- **5 deg** production
- 50m from target (Cf. KOTO ~20m)

- 3m-ϕ,15m-long detector

Necessary to consider hyperon BG in Step2

- intensity 3x10^{14} ppp (450kW !!!)
- 3 snowmass years run

➔133 SM events (S/N~5)

23 Octorber 2011 HUA WS on the future of the Hadron Hall, T. Nomura (KEK) 18

*Beyond current and approved experiments

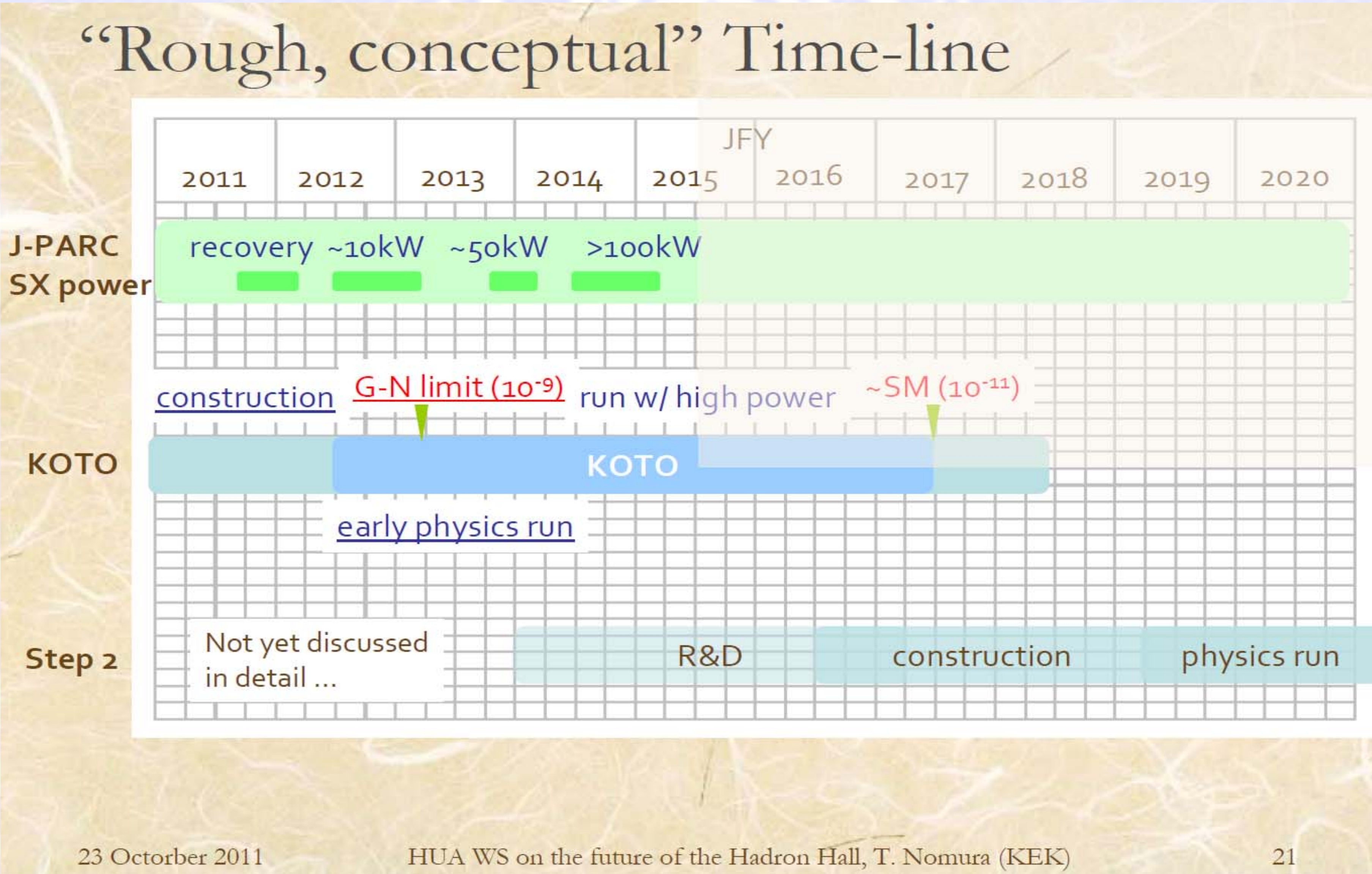
Slow Extracted Beam: The Standard Tool to Drive Ultra Rare Decay Experiments

- 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 beam: 64 kW of SEB in 1997
  BNL AGS 21 GeV beam: 65 kW of SEB in 2001

- JPARC Goal: >300 kW of SEB, 30 kW goal in near future.

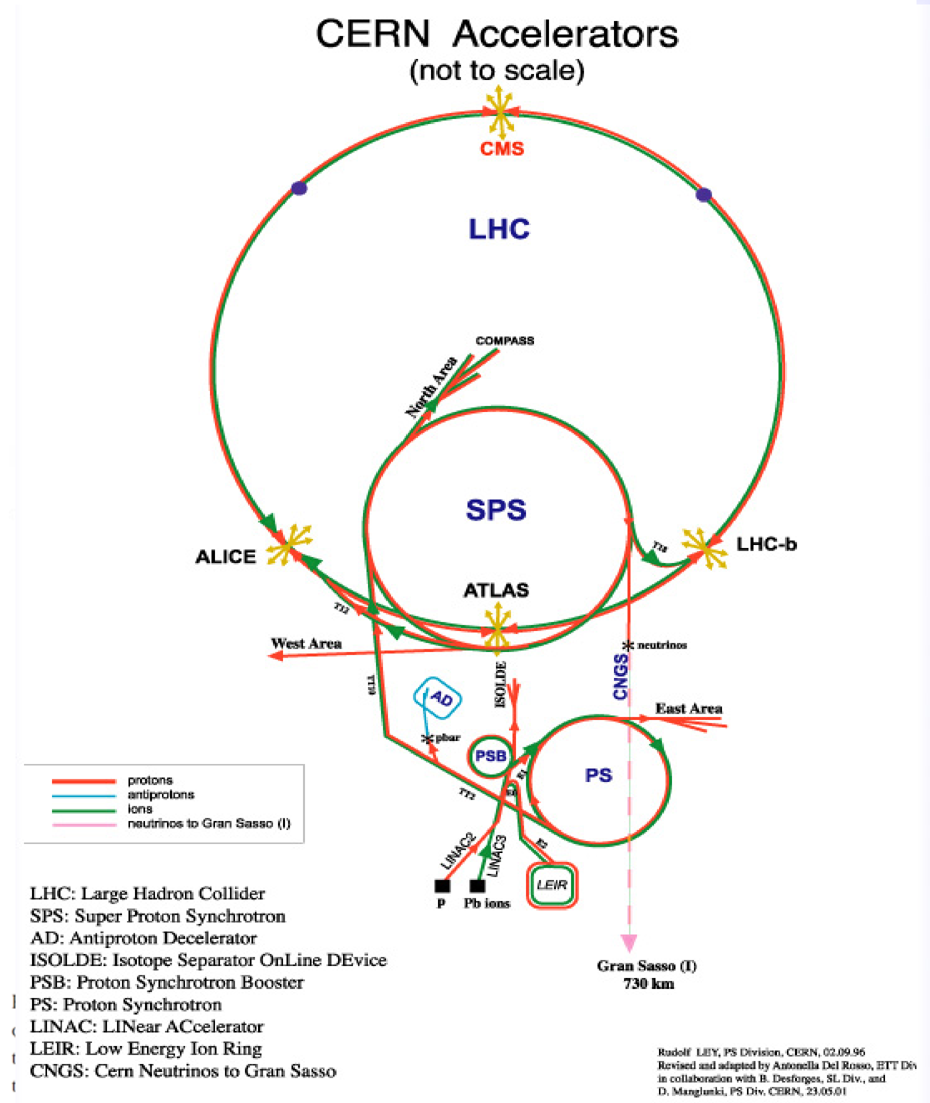
Long Term Vision* in Asia: KOTO



*Beyond current and approved experiments

Long Term Vision in Europe for High Sensitivity Experiments

- **2001:** CERN study outlined the evolution of higher power, high energy techniques, possibly implemented with the PS or SPS
- **2005-2007:** Landmark study: "Flavour in the LHC era"
- **2008-2009:** Recognition of SPS upgrades for the LHC program: Can benefit beam power & duty factor for the SPS SEB program.
- ESS & SPL duty factor too low for high rate experiments



The Project-X Research Program

- ***Neutrino oscillation experiments***
- A high-power proton source with proton energies between 8 and 120 GeV would produce intense neutrino beams directed toward near detectors on the Fermilab site and massive detectors at distant underground laboratories.

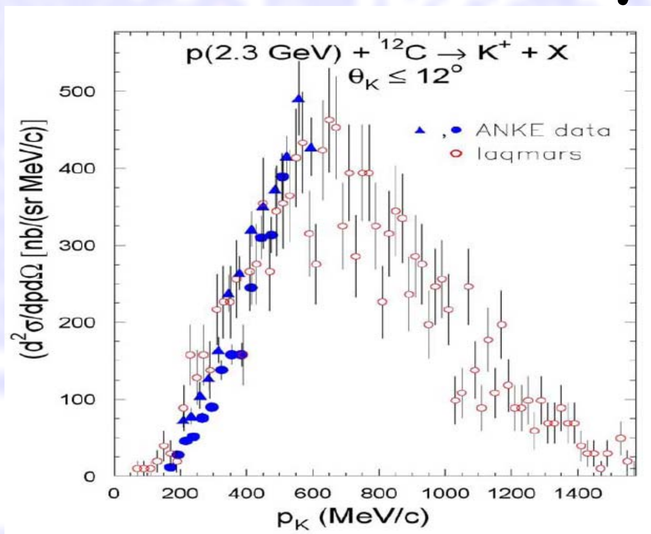
- ***Kaon, muon, nuclei & neutron precision experiments***
- These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), precision measurement of neutron properties and world-leading precision measurements of ultra-rare kaon decays.

- ***Platform for evolution to a Neutrino Factory and Muon Collider***
- Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.

- ***Nuclear Energy Applications***
- Accelerator, spallation, target and transmutation technology demonstration which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems.

Detailed Discussion: Project X website

BNL E949 and Project-X kaon momentum spectra and sensitivity comparisons



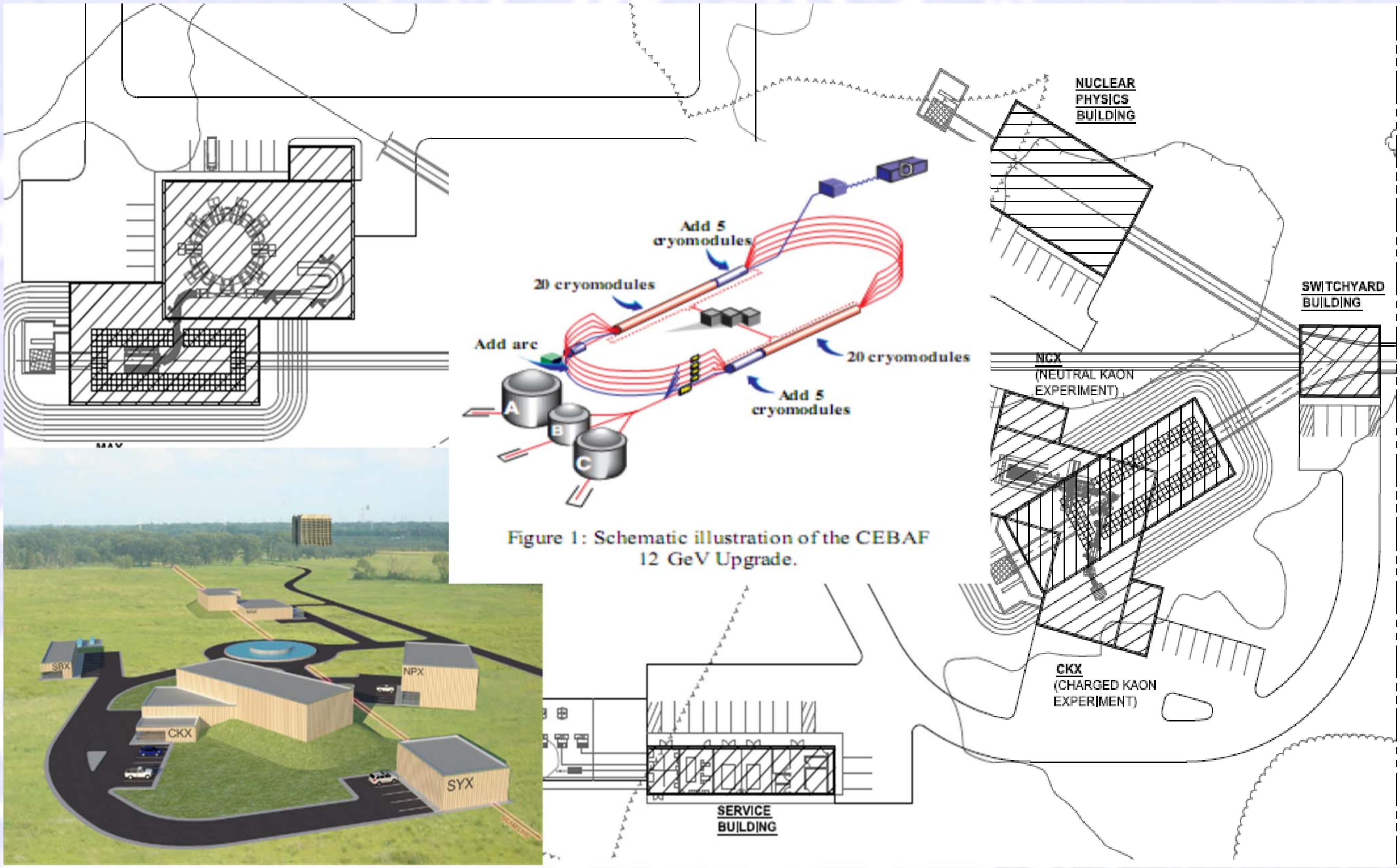
x140 average rate of stopping kaons with respect to BNL E949,
x11 the average stopping rate of ORKA.

	Beam Energy T_p	Protons/second (avg) on [target (λ_I)]	$p(K^+)$ (MeV/c)	Stopping K^+/second	K^+/π^+ Production Ratio
BNL AGS (E949)	21 GeV	12×10^{12} on [0.7 λ_I Pt.]	700-730	0.7×10^6 K^+/sec	1:24
Project-X/ K^+ expt	3.0 GeV	1/2 x 6000×10^{12} on [1.0 λ_I C]	450-570	98×10^6 K^+/sec	1:80

Table 1: Compares the measured rate of stopping K^+ in the BNL-E949 experiment with full LAQGSM/MARS thick-target simulations for Project-X charged kaon yield with ½ of the 1 ma 3.0 GeV proton beam.

Project-X kaon physics white paper

Project-X High-Intensity Campus



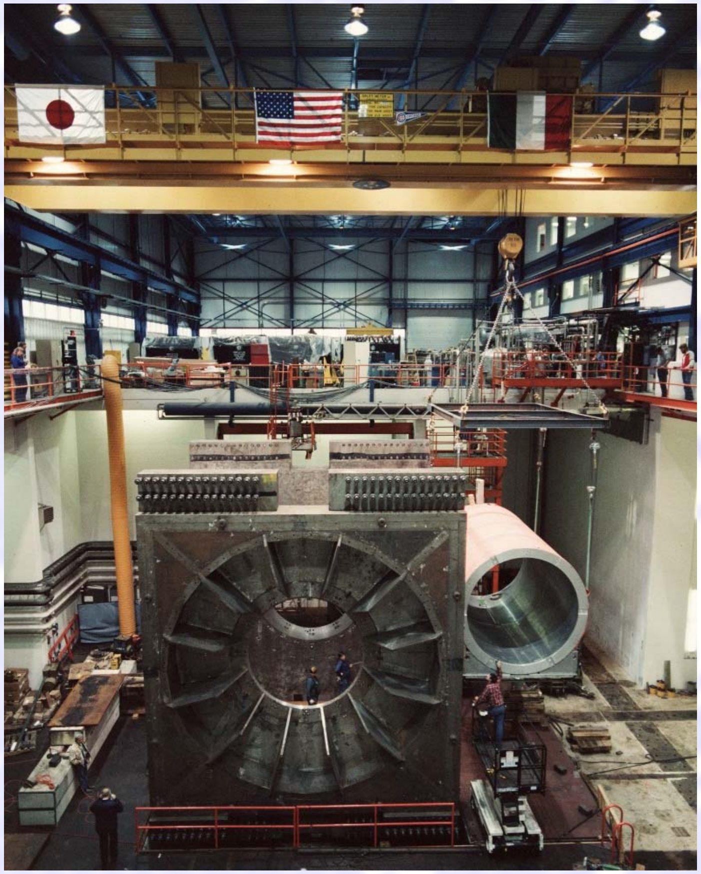
Footprint of charged and neutral detectors motivated by BNL-E949, KOPIO and JPARC

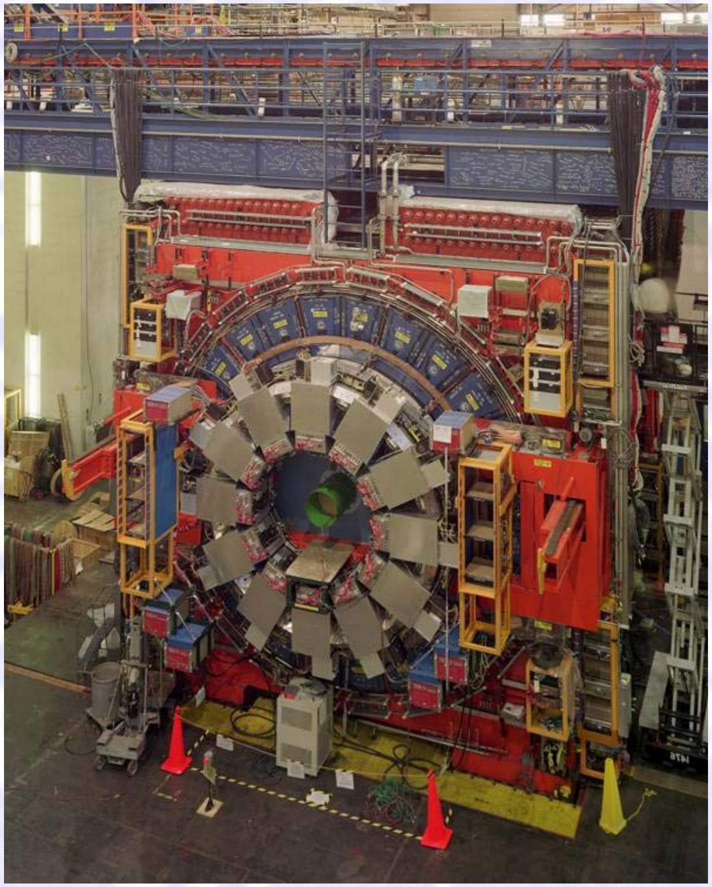
Project-X kaon physics white paper

Project-X R&D Challenges to the Community

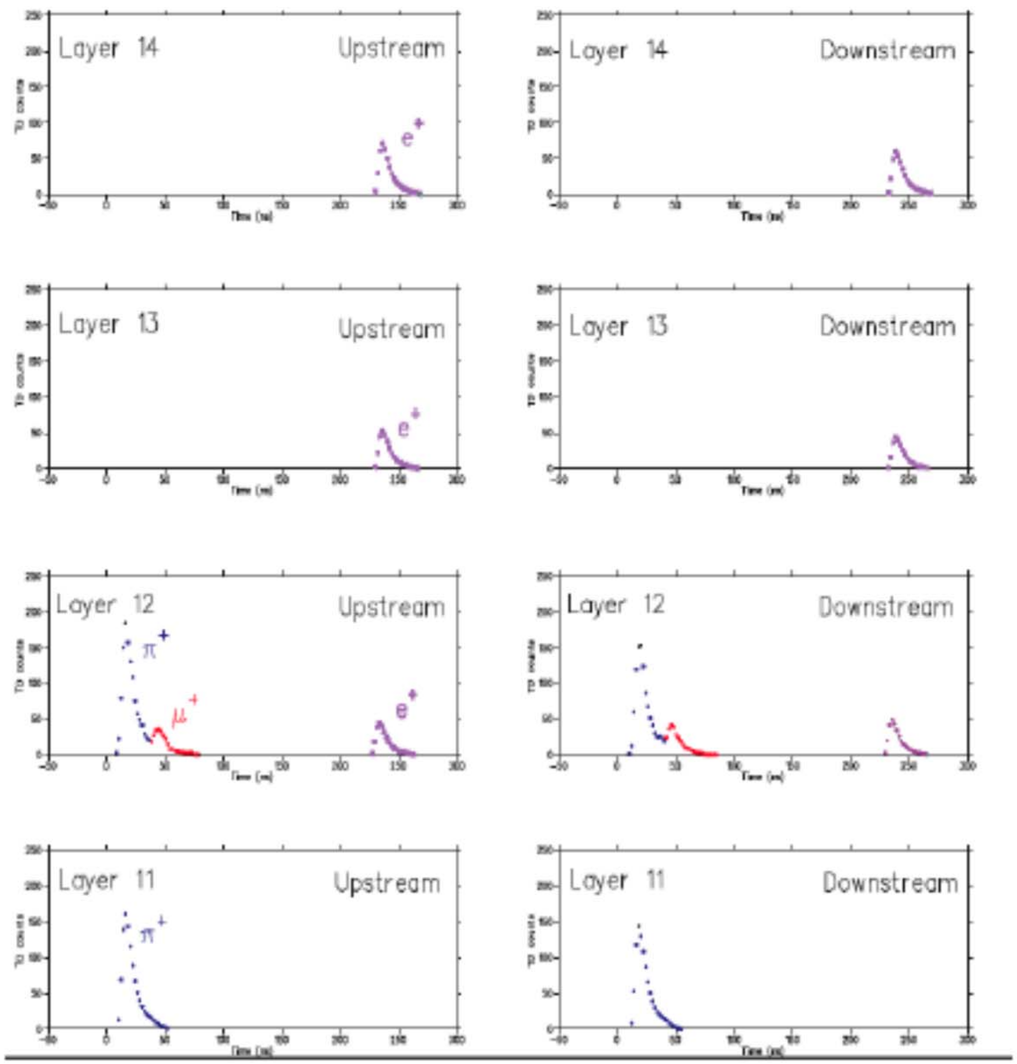
- High-rate, ultra-low-mass tracking
- Fine grained fast scintillator technology in high B-fields, in vacuum
- High-rate, ultra-high- efficiency photon tagging (10 MeV – 100 GeV)
- Breakthrough TOF *system* performance (<20psec)
- Design and build the perfect EM calorimeter:
  High rate, breakthrough -TOF, γ-pointing, fine grained particle-flow
- Fully streaming "triggerless" DAQ technologies:
  GHz front-ends to Peta-Byte data stores.

CDF detector, then and now…

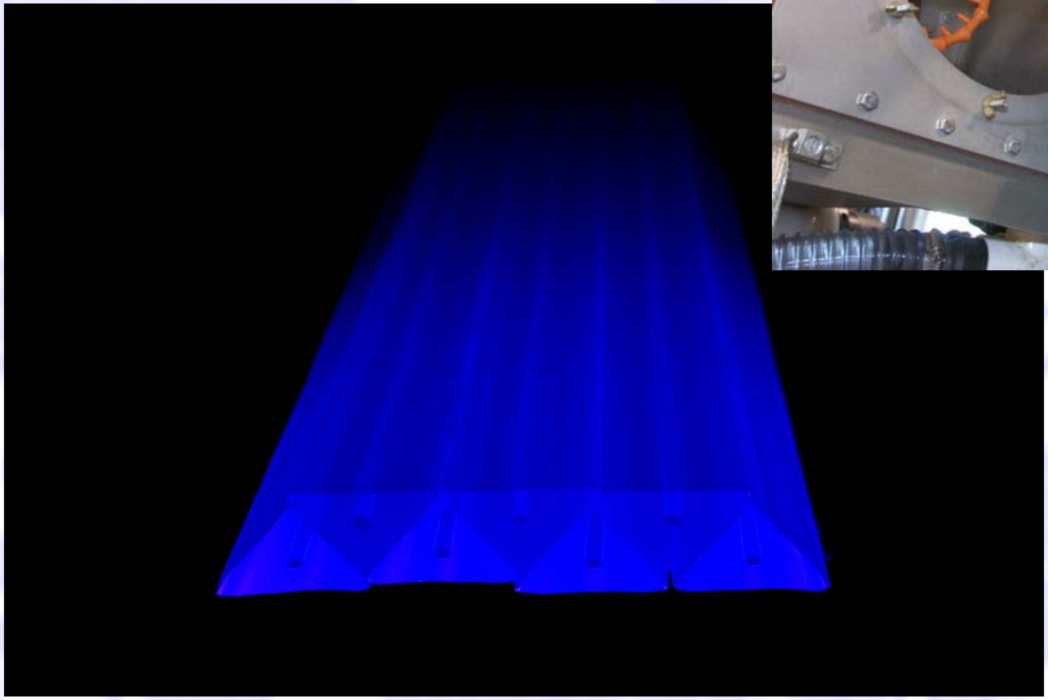


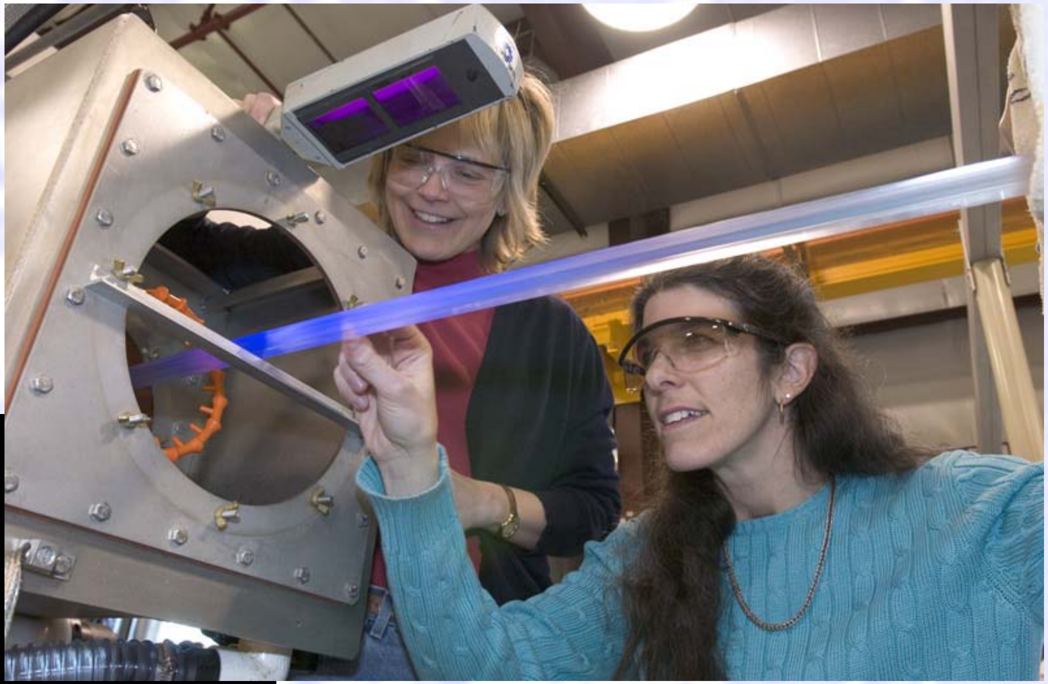


$\pi \rightarrow \mu \rightarrow e$ detection in E949



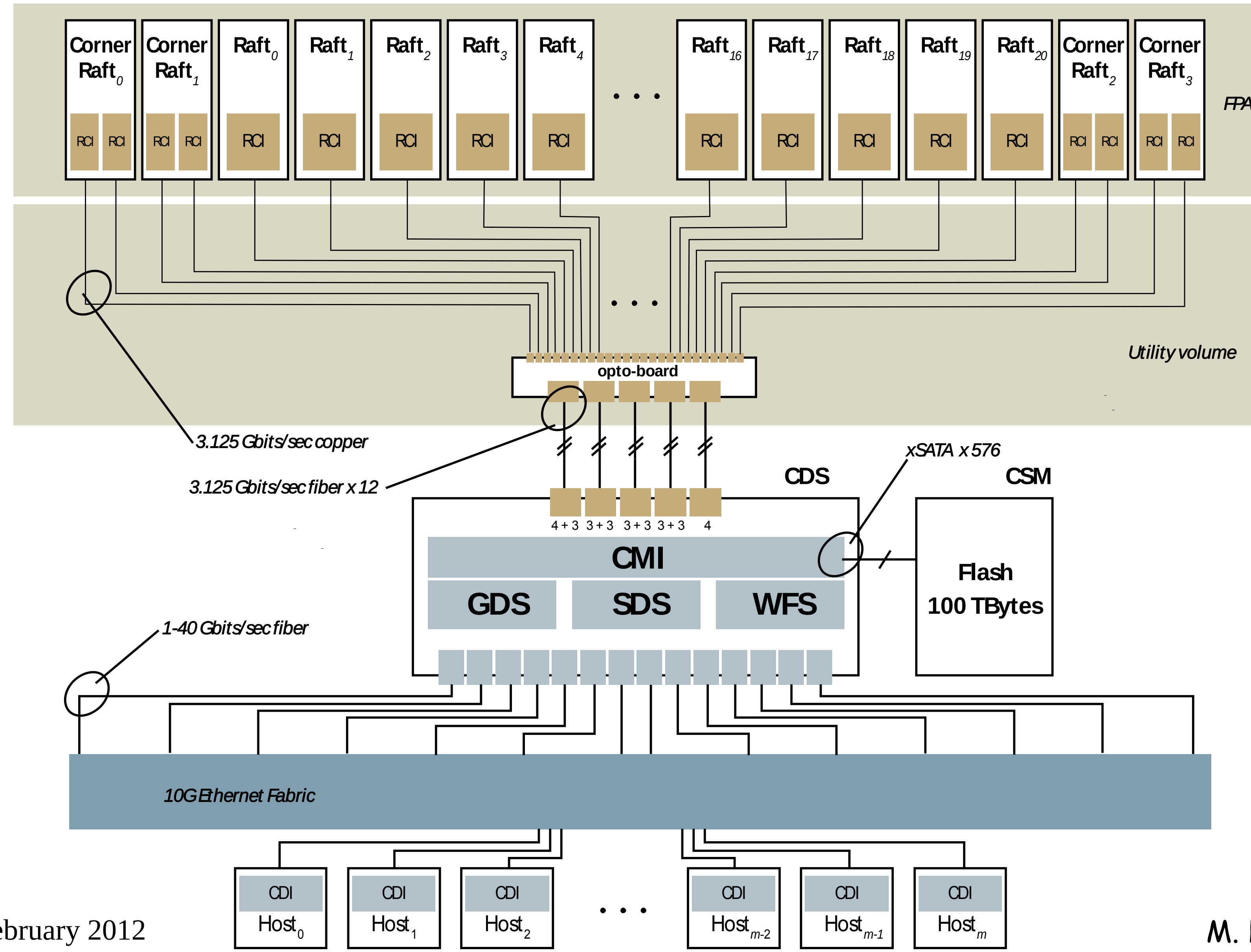
Extruded Scintillator technologies can lower costs…





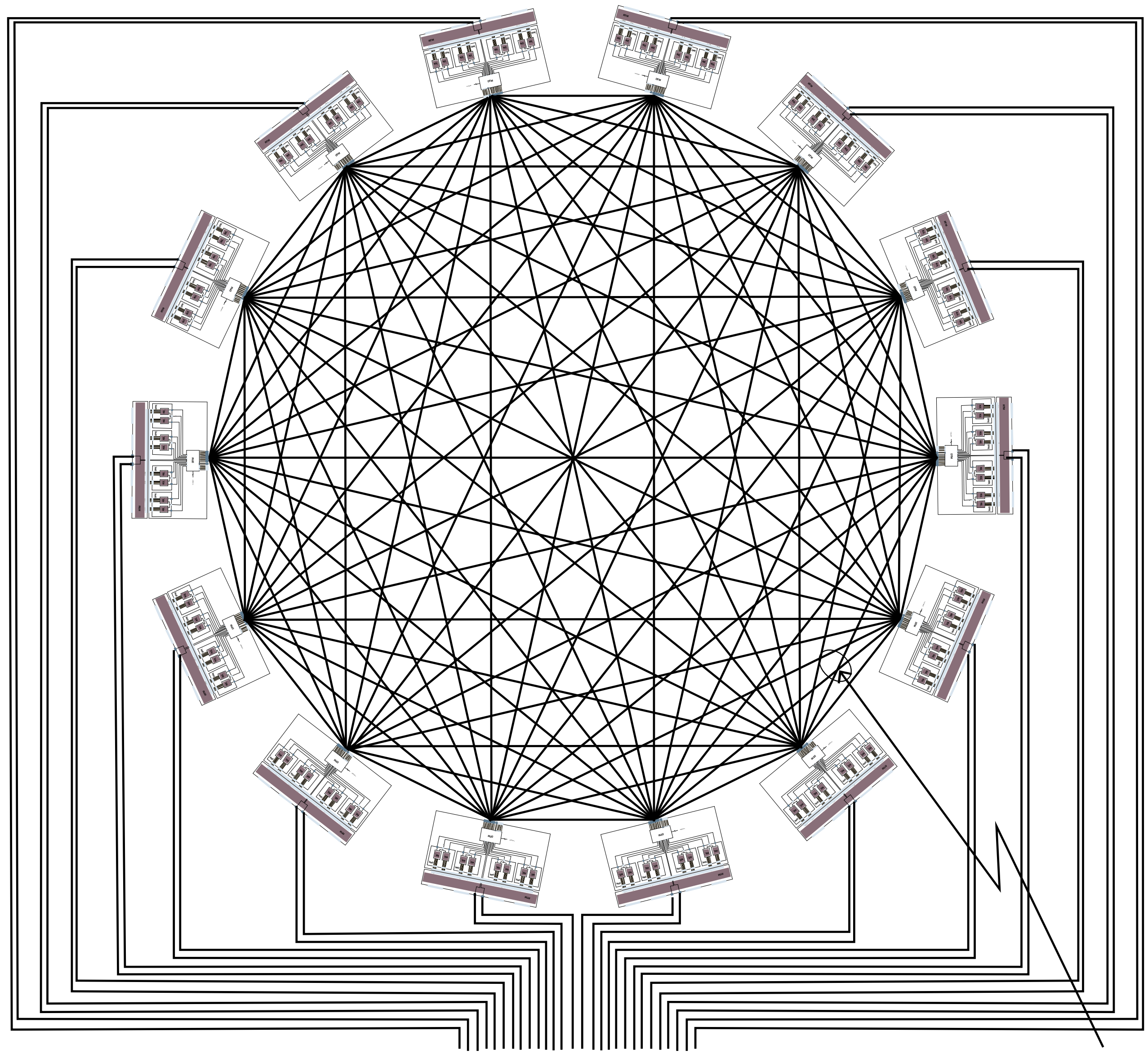
Minerva Scintillator

Block Diagram of the LSST DAQ System



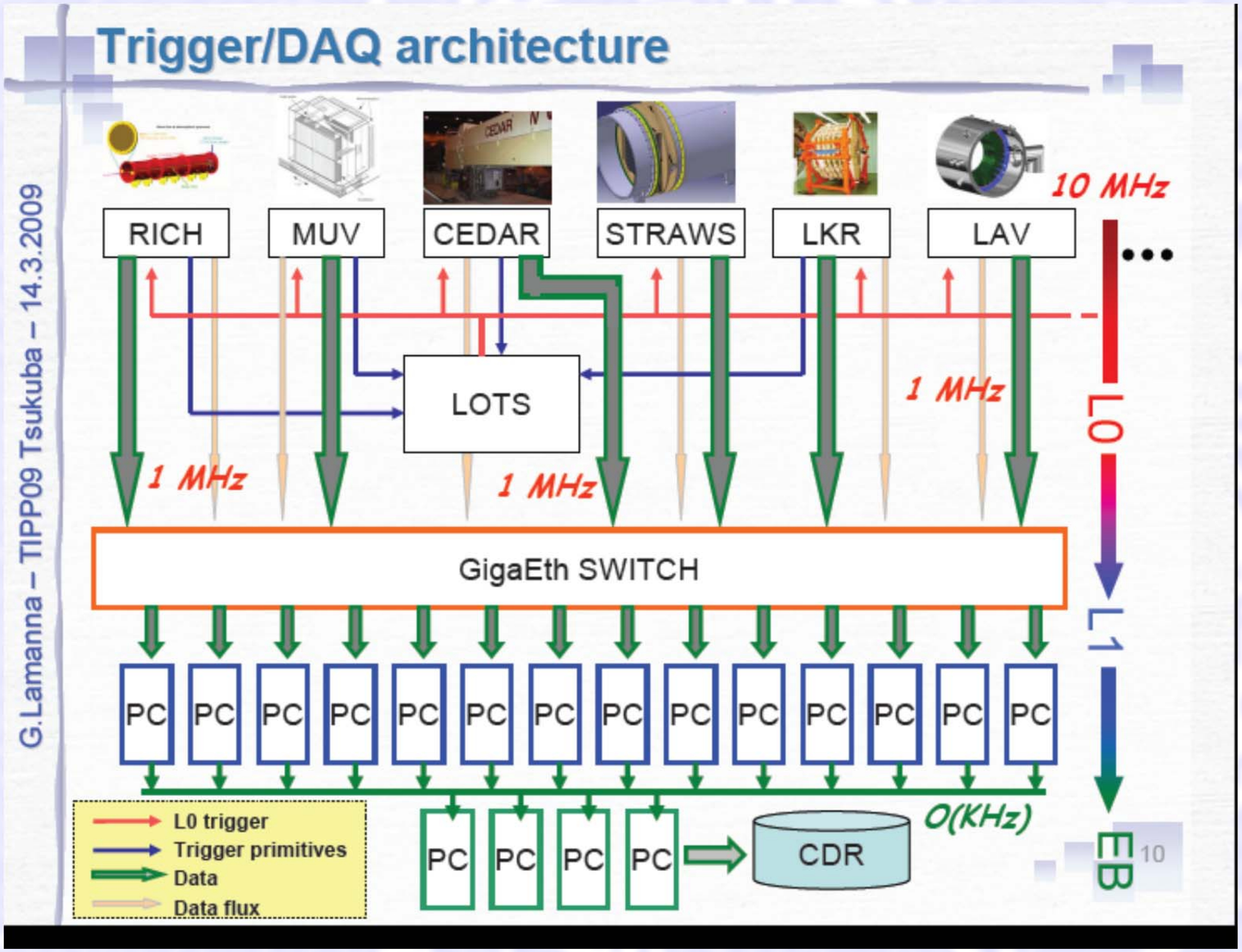
M. Huffer

Ethernet topology in a 14-slot shelf…

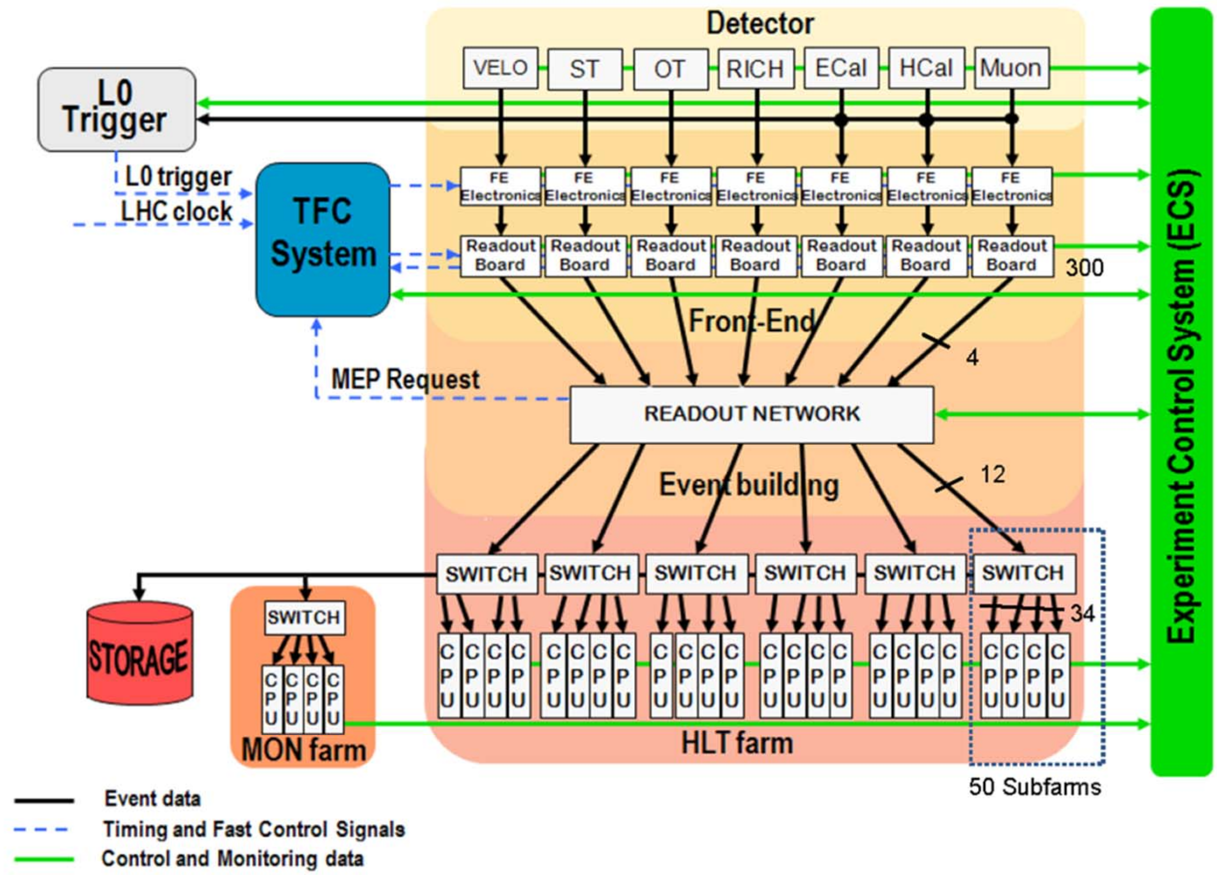


M. Huffer

NA62 near-Streaming DAQ



LHCb Streaming DAQ upgrade



Mu2e Streaming DAQ

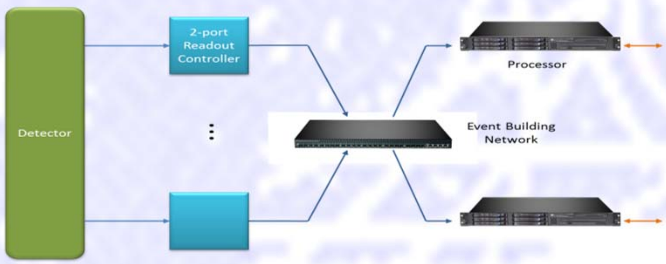


Figure 2a

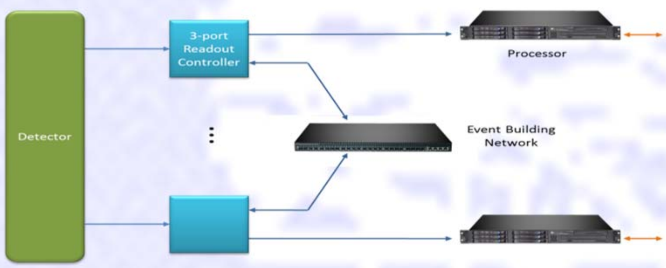


Figure 2b

In a switch based DAQ, the Readout Controller (ROC) collects data from the front-end systems and sends it through the Event Building (EVB) network to a Processor Farm. The typical ROC is a two-port device. Dataflow through the network is mostly unidirectional (Figure 2a) and final event assembly is done in the processors. Mu2e will use a three-port ROC. In this architecture the event building is done entirely in the ROCs and full events are then forwarded to the processors (Figure 2b). This has two advantages;

1) the EVB network connections are handled by an FPGA and can run at a full 10 Gbps wire speed (not usually possible with a processor running a software IP stack). Bidirectional data flow reduces the number of switch ports required.
2) the FPGA in the ROC has access to the fully assembled events, and can serve as a trigger pre-processor in addition to its function as readout controller and event builder. This offloads the farm and provides several TeraOps of supplementary processing power.

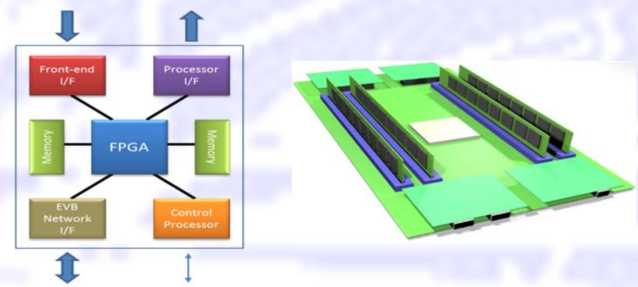


Figure 3

The Readout Controller I/O (Figure 3) is modular to support multiple applications. For Mu2e, the front-end interface is a 12-channel parallel optical receiver, and the EVB network interface is dual channel 10Gbps Ethernet (SFP+).

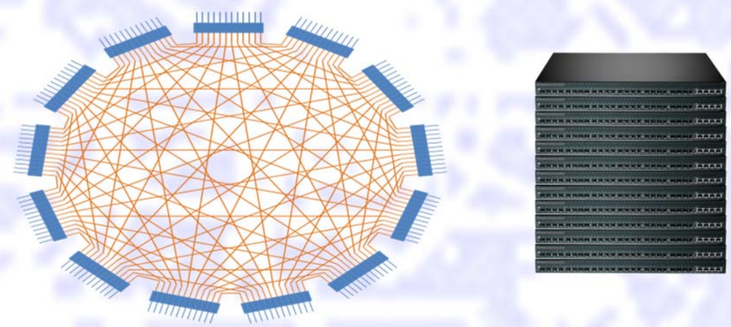


Figure 4

Figure 4 shows a 156 port EVB network using thirteen 24 port Ethernet switches. Each switch port is 10Gbps, for a total bandwidth capacity of 150 GBytes/sec. Interswitch connections are "direct attach" SFP+ copper cables. External connections are copper or optical depending on distance.

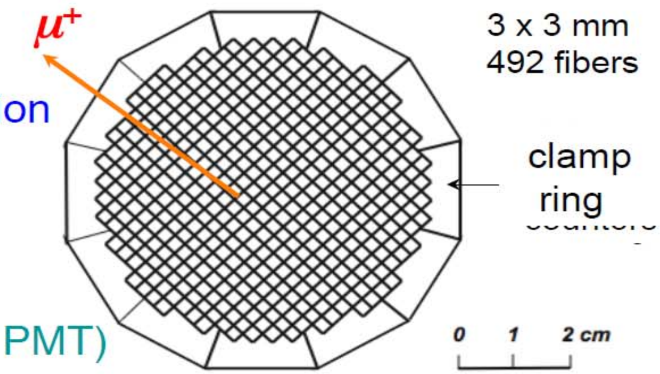
Active fiber target

1. Finer segmentation for
   - Higher μ^+ tracking resolution
   - Higher K^+ stop point resolution
   - Better $K\pi2$ background suppression

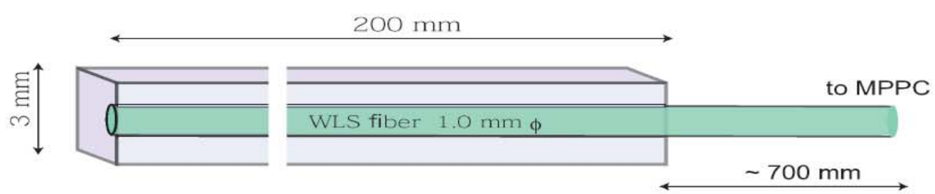
   (E246 : 256 fibers with 5 x5 mm^2)
2. Compact and light system
   - By using MPPCs

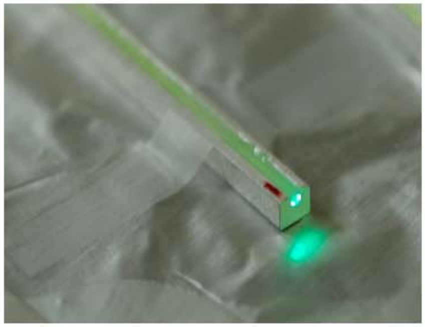
   (E246 : each fiber was read by a1/2" PMT)

Cross section



One element





- MPPC direct readout test at KEK (2008)
- Radiation damage test of MPPC with 130 MeV/c π^+ (2008)

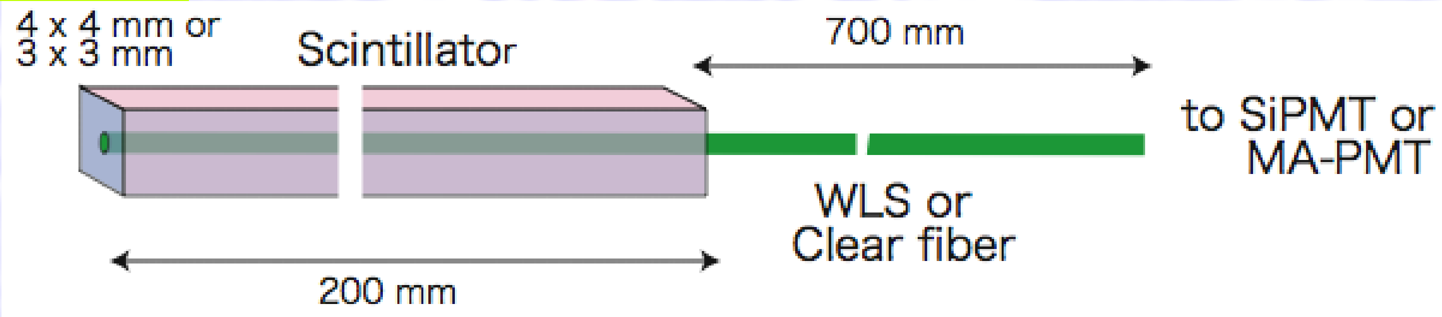
24

Detector preparation
(2) Active fiber target

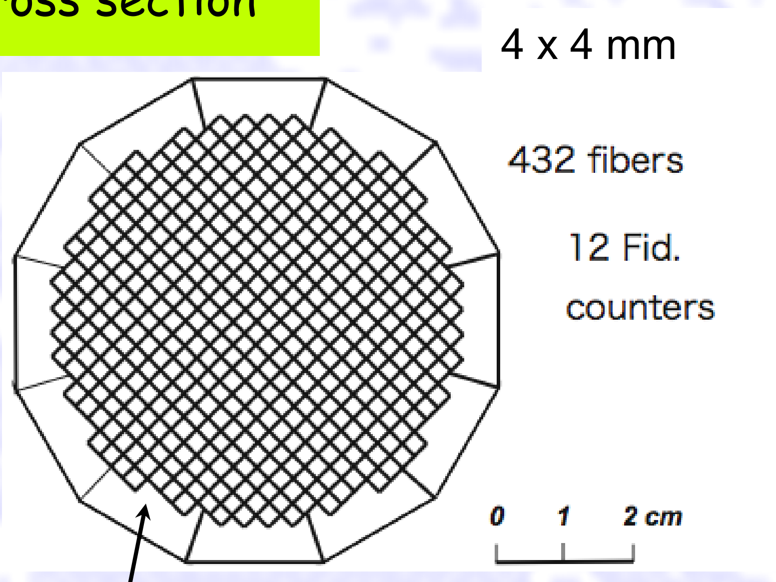
Current baseline design

c.f. E246 Ring counte
PSI FAST targe

One element



Cross section



Timing counters

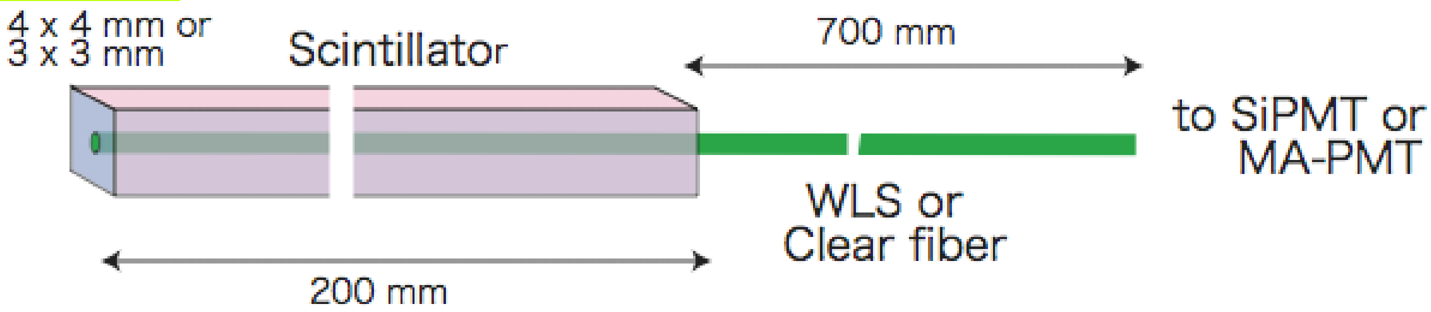
- Light guide :
  - Bicron 692 WLS or
  - Kuraray Y11 WLS or
  - Clear optical fiber
- Readout:
  - SiPMT (HPK MPPC) or
  - MA-PMT
- Beam test using 100 MeV/c pions at TRIUMF in this year

Detector preparation
(2) Active fiber target

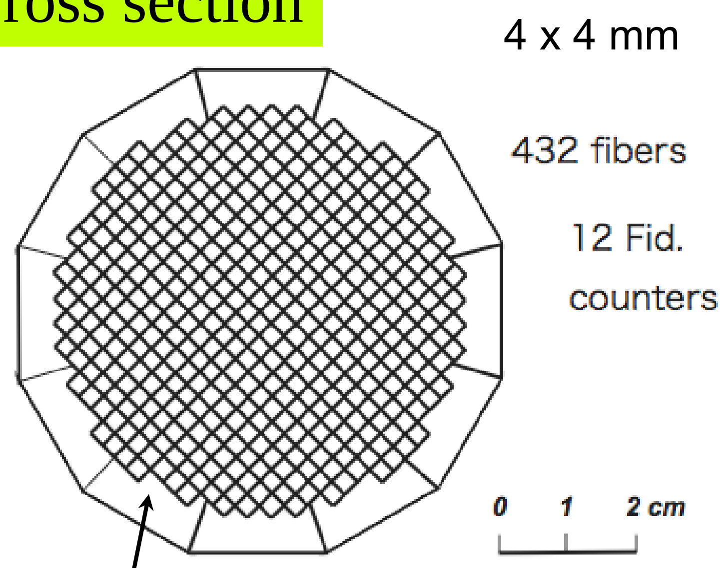
Current baseline design

c.f. E246 Ring counters
PSI FAST target

One element



Cross section



Timing counters

- Light guide :
  Bicron 692 WLS or
  Kuraray Y11 WLS or
  Clear optical fiber
- Readout:
  SiPMT (HPK MPPC) or
  MA-PMT
- Beam test using 100 MeV/*c* pions at TRIUMF in this year

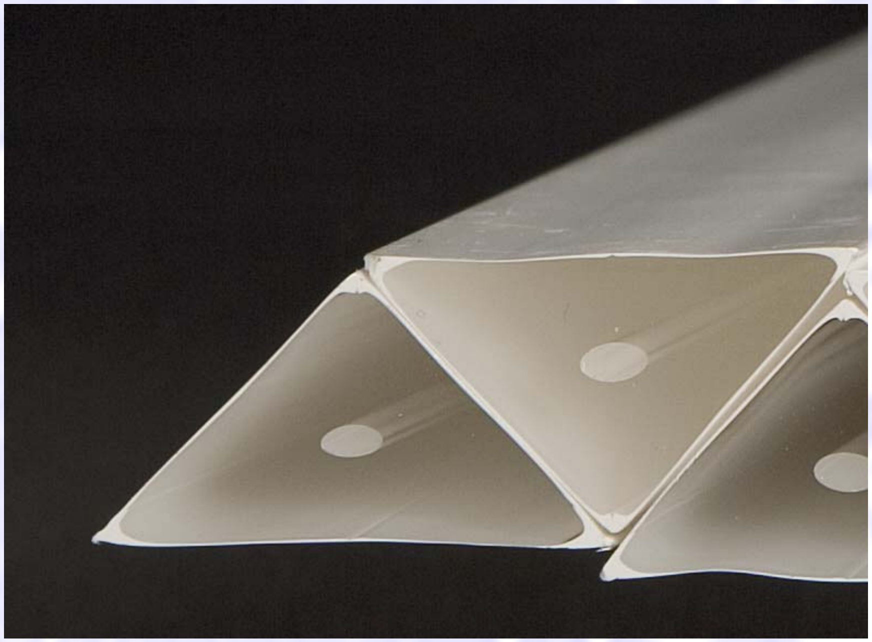
Sensitivity Frontier of Kaon Physics Today

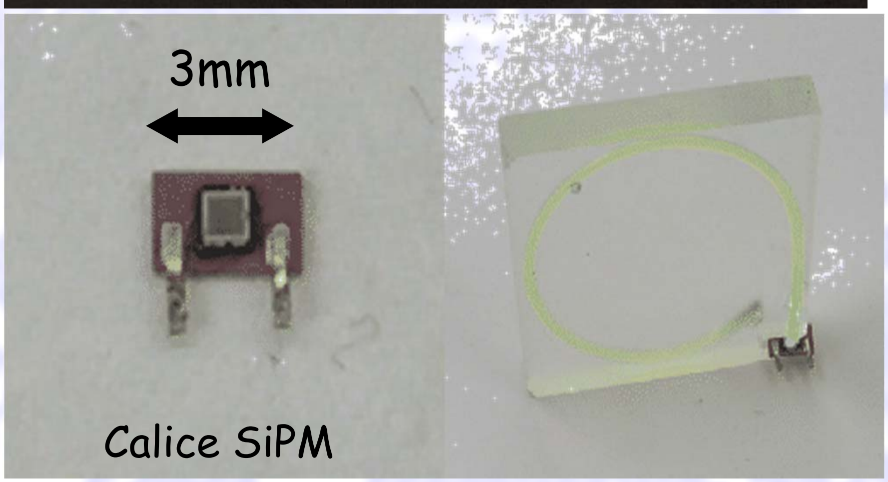
- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \rightarrow e^+\nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \rightarrow \mu\mu ee$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \rightarrow \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20×10^{-12} measurement sensitivity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

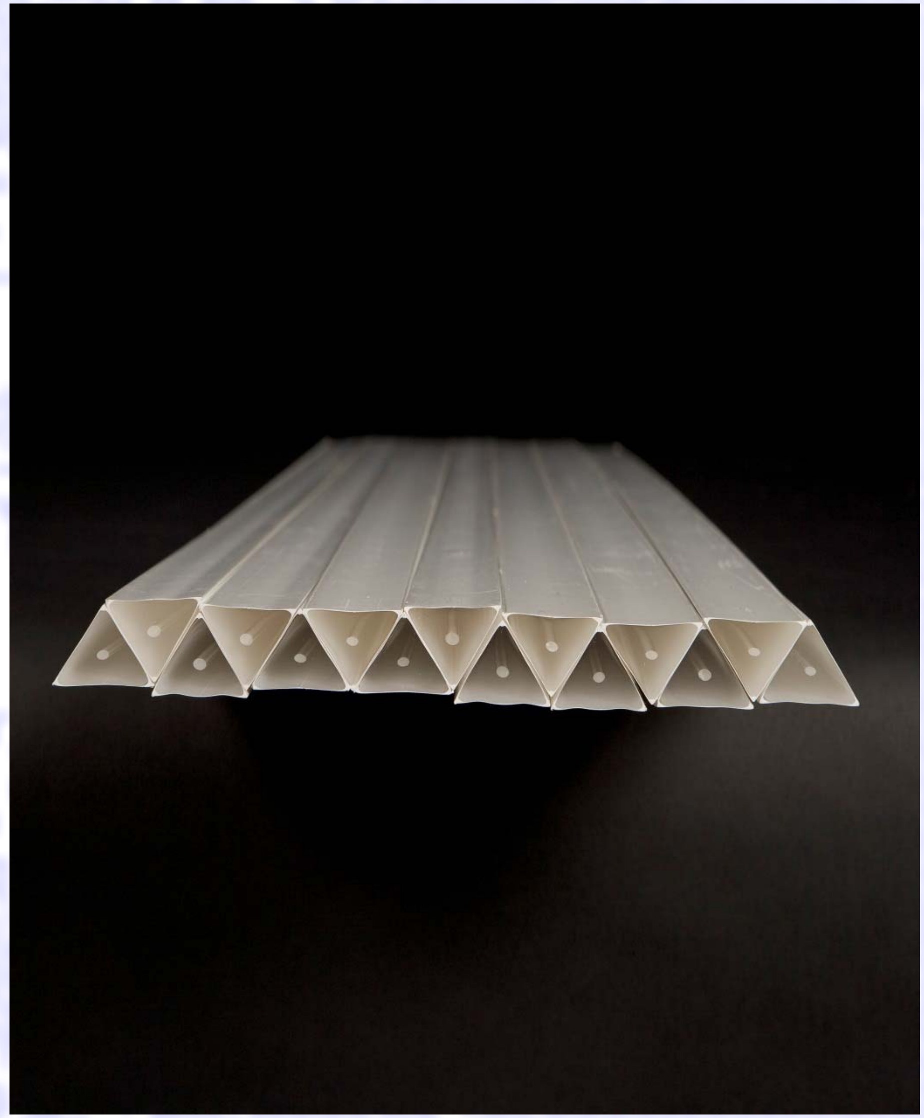
Probing new physics above a 10 TeV scale with 20-50 kW of protons.

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

Development required for more precise extrusion and compact photon readout…







ORKA, The Golden Kaon Experiment: Precision Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$: Receives Stage-I Approval