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

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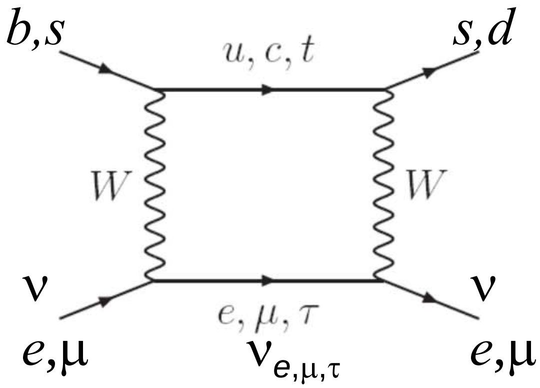
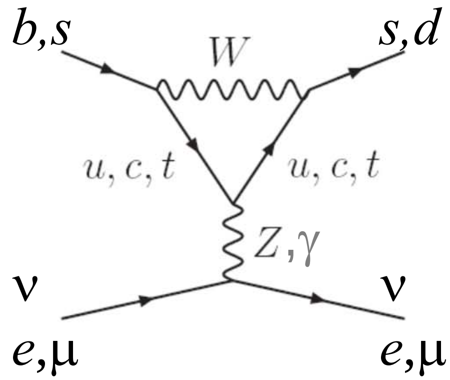
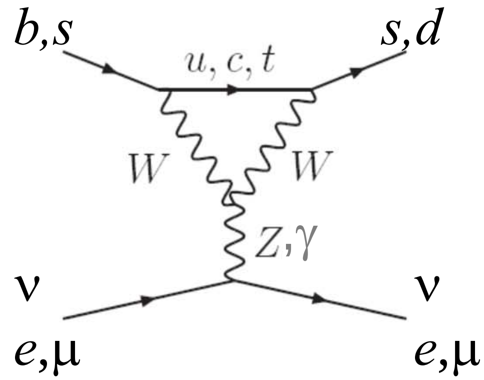
Outline

- Physics Motivation
- Experimental Background
  - BNL E787/E949
- The Opportunity at Fermilab
- Improvements for ORKA
- Status and Timeline
- Summary/Conclusions

Flavor Changing Neutral Currents







Responsible for rare decays in Standard Model

e.g.,

$B \to X_s \gamma$

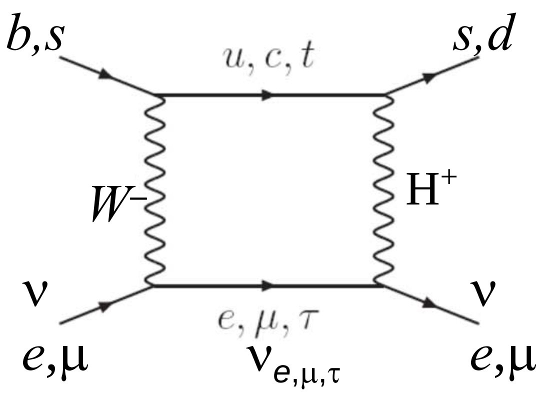
$B \to X_s \ell^+ \ell^- \ (\ell = e \text{ or } \mu)$

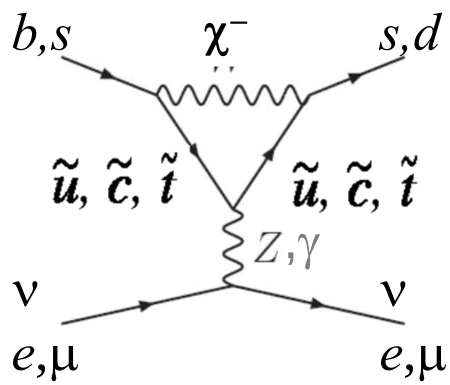
$B_s \to \mu^+ \mu^-$

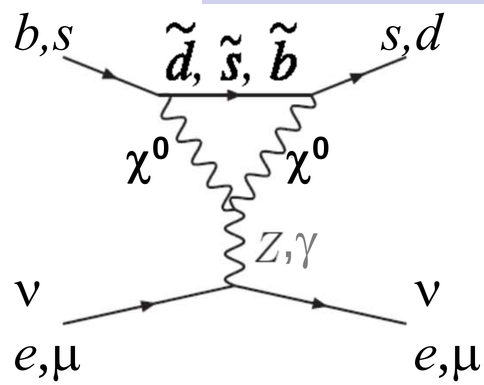
$K_L^0 \to \mu^+ \mu^-$

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

$K_L^0 \to \pi^0 \nu \bar{\nu}$



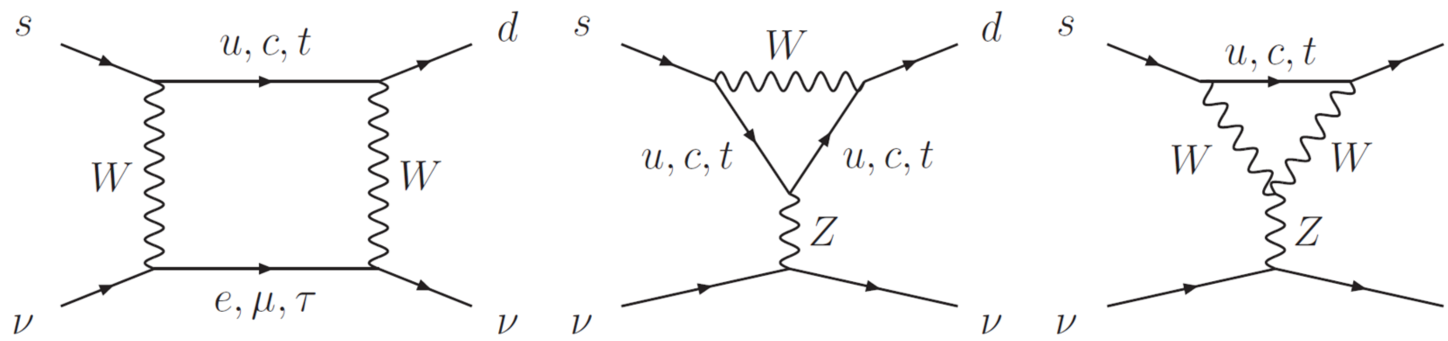


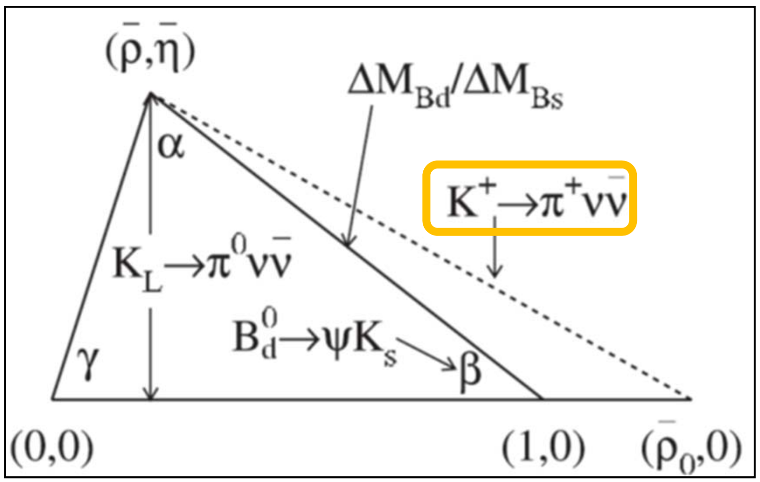


Sensitive to new (high-mass) particles in loops.

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

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





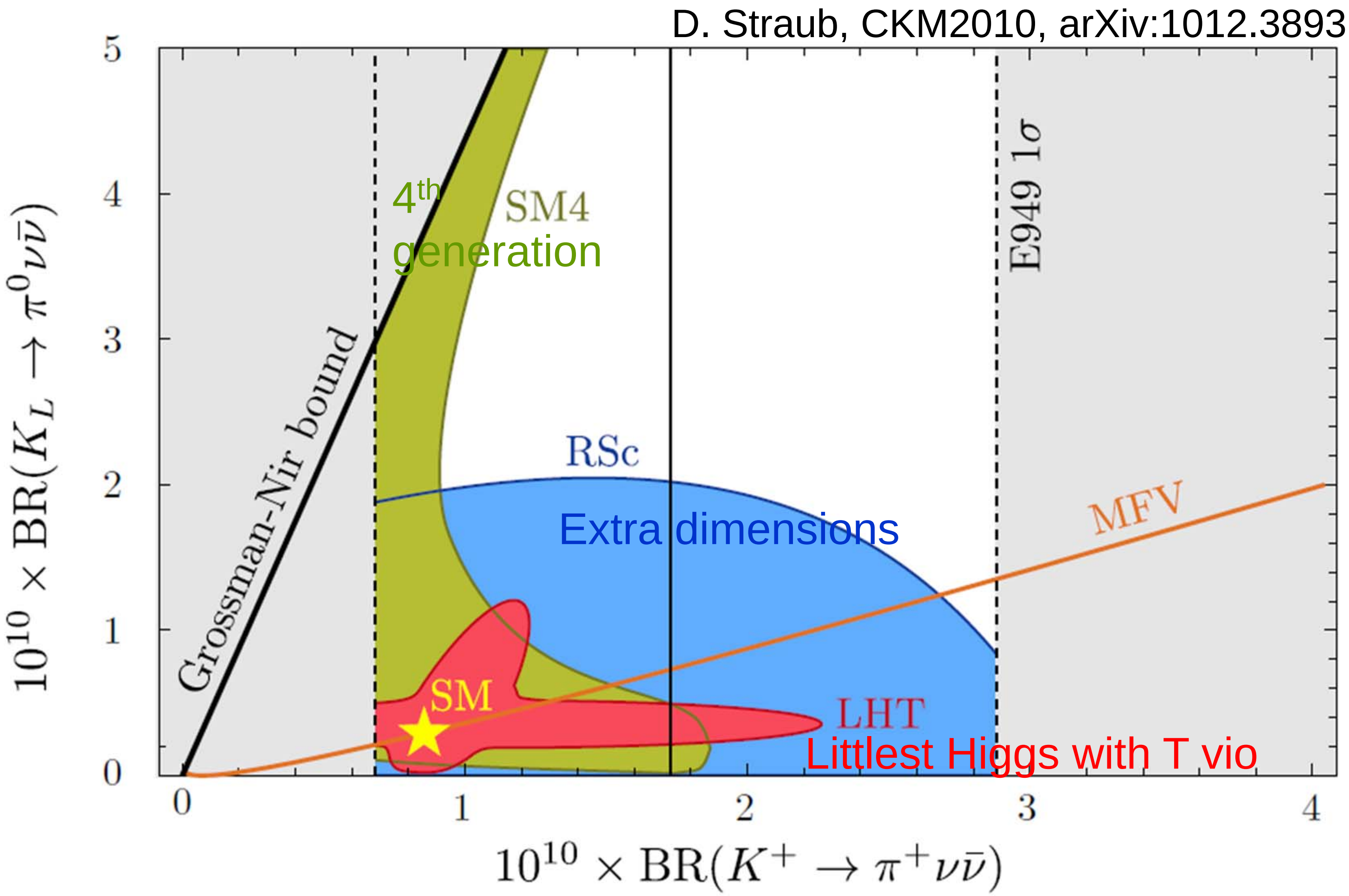
- A single effective operator $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with $K \to \pi e \nu$
- Largest uncertainty from CKM elements (which will improve)

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

Brod, Gorbahn, and Stamou, PR D **83**, 034030(2011)

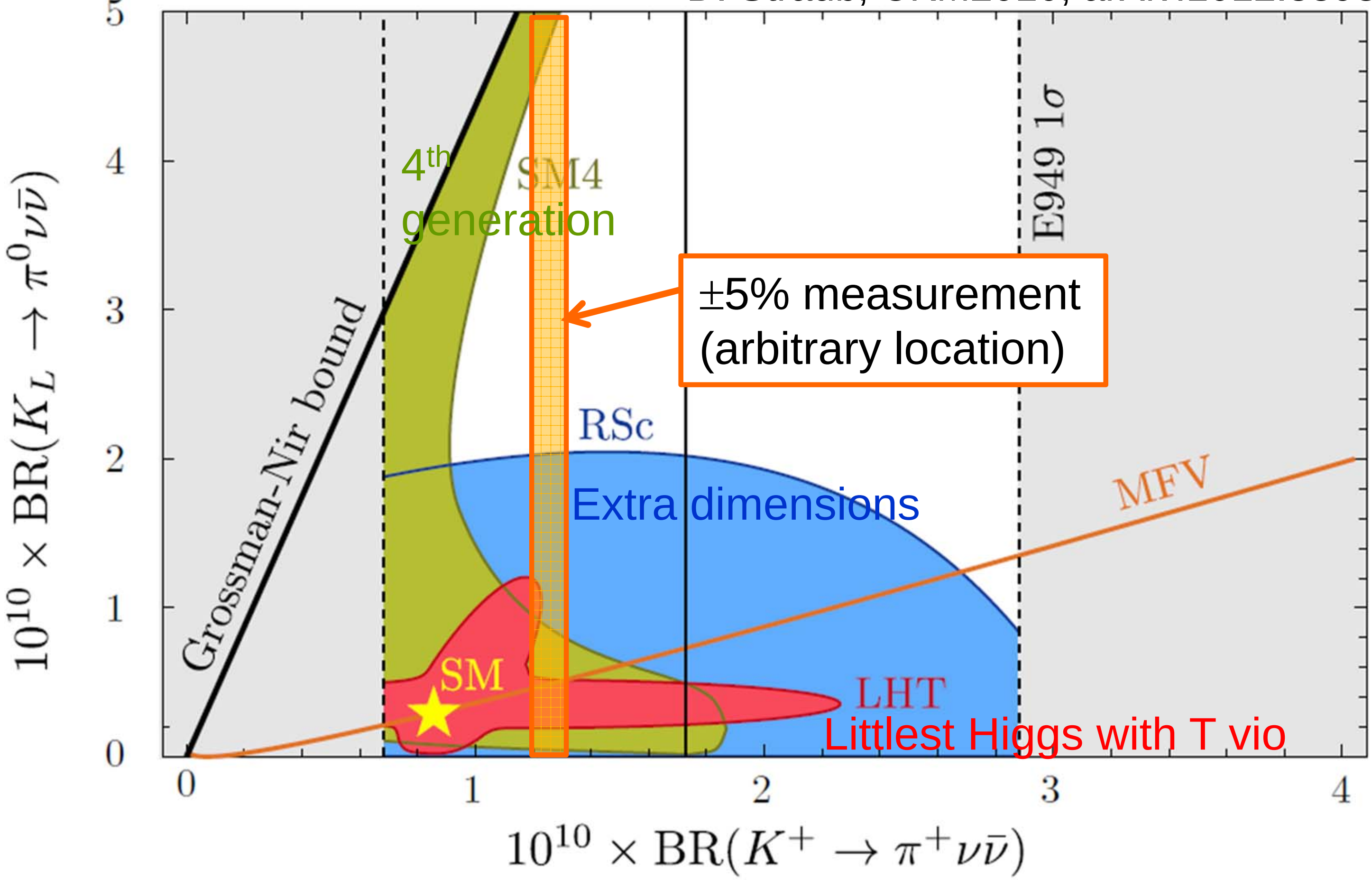
- Remains clean in New Physics models

Sensitive to New Physics

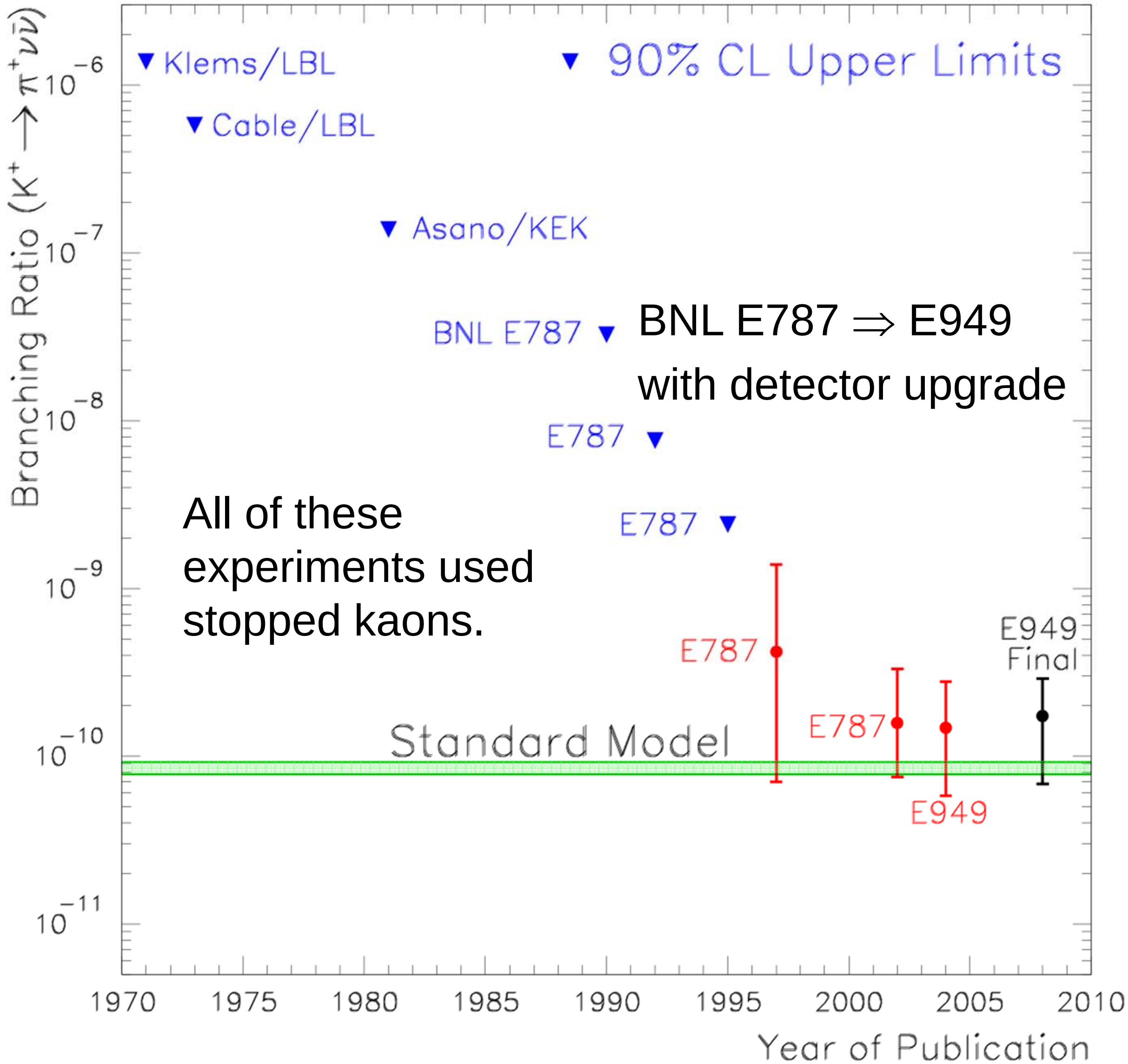


Sensitive to New Physics

D. Straub, CKM2010, arXiv:1012.3893



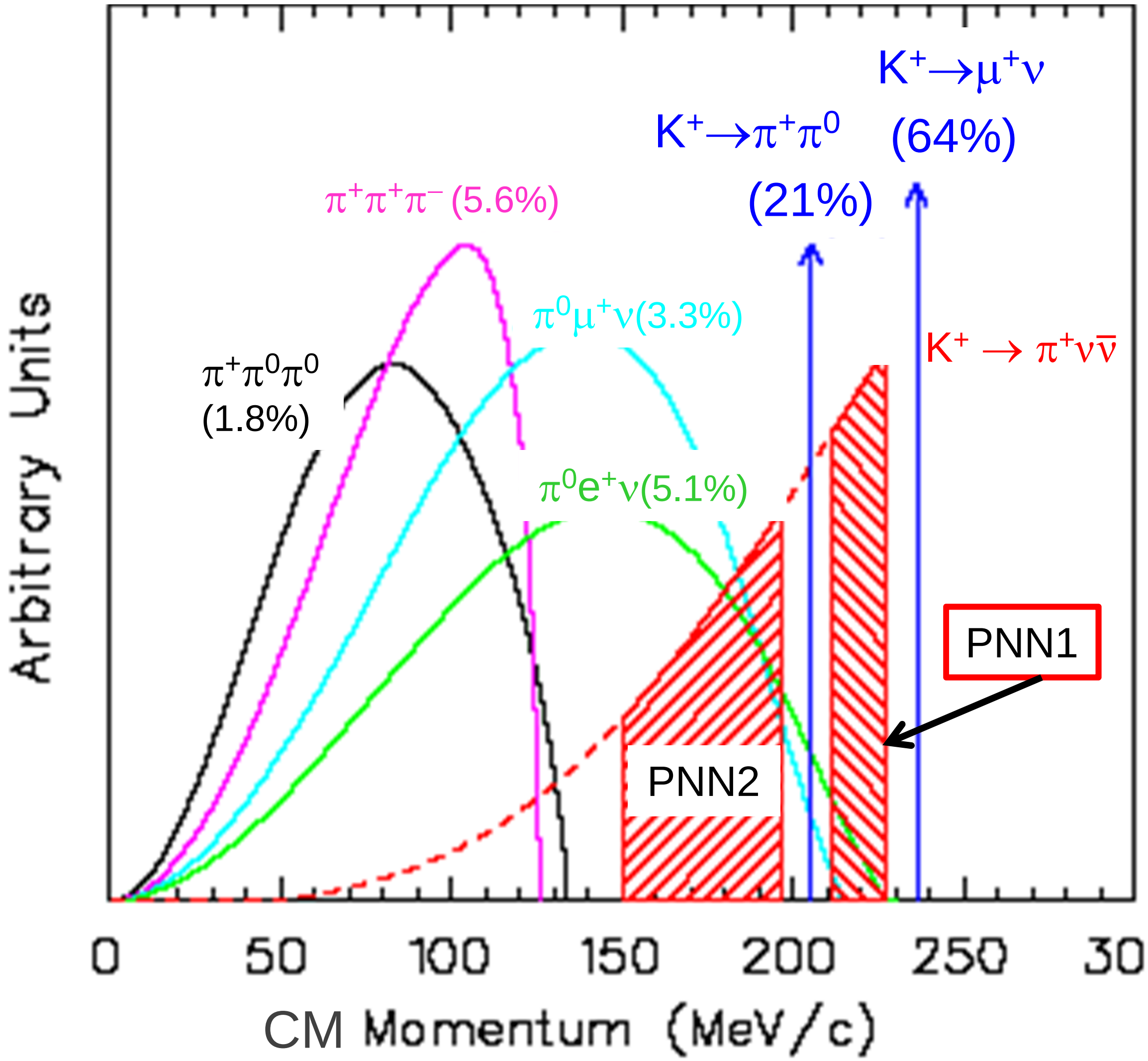
$K^+ \to \pi^+ \nu\bar{\nu}$ History



BNL E787 ⇒ E949 with detector upgrade

All of these experiments used stopped kaons.

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



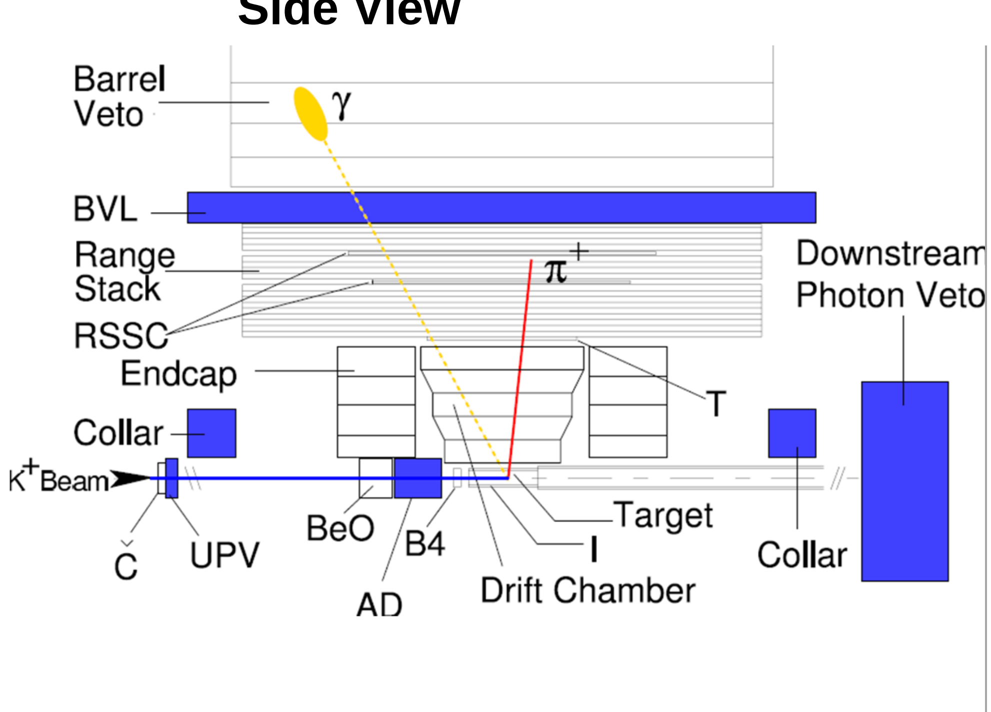
Rejection from:

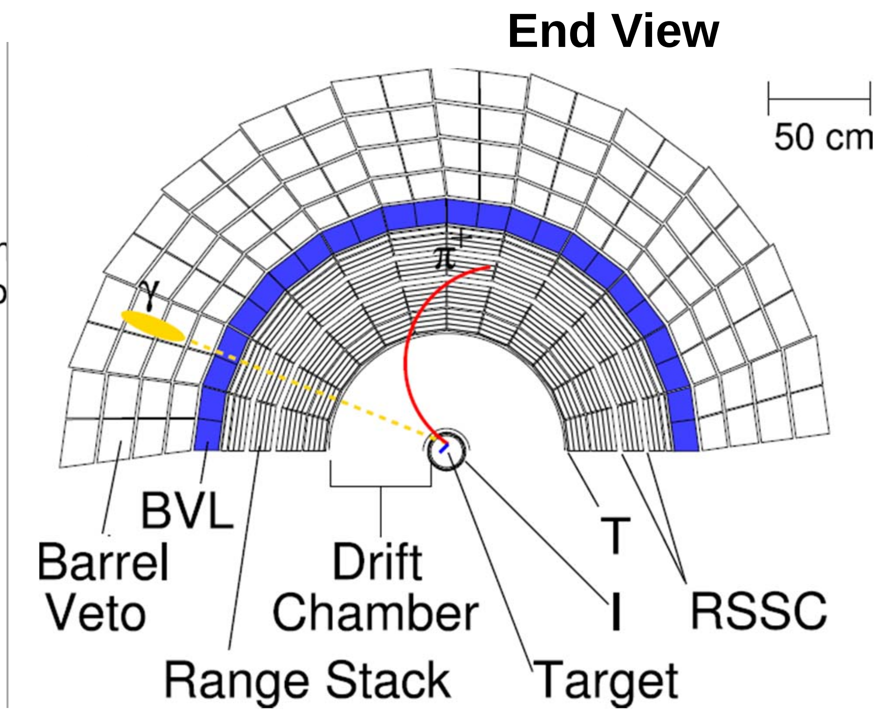
- Kinematics (tracking) to reject 2-body decays
- Particle ID to select π (reject μ)
- Photon veto (rejection of π^0)

For stopped K's, p = 0.

It is not key that the CM is at rest, but that the K's momentum is known when it decays.

BNL E787/E949

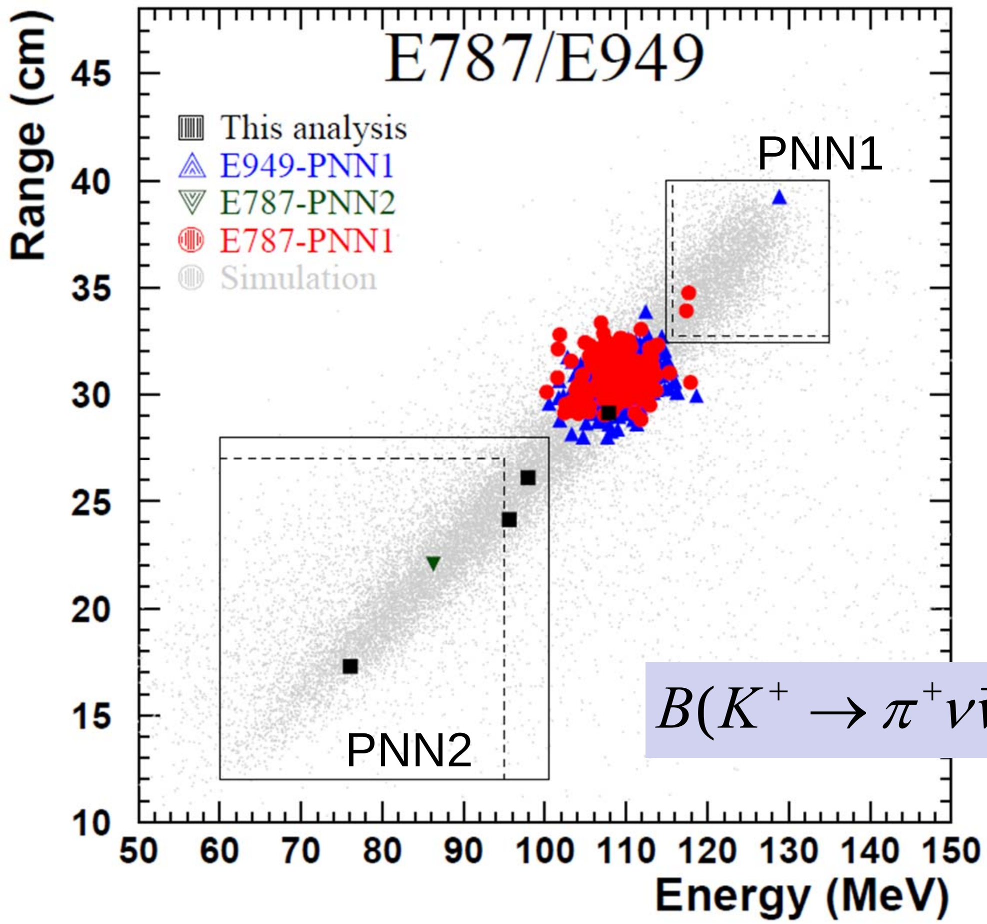




The E949 detector provided

- Measurement of the K-decay vertex in an active (sci-fi) stopping target
- Redundant measurements of pion energy, momentum, and range
- Strong pion identification based on observing the full decay chain $\pi \rightarrow \mu \rightarrow e$
  - Decay history from 500 MHz (8-bit) waveform digitizers on range stack counters
- Nearly 4π detection of photons with energy down to a few MeV

E787/E949 Results



	PNN1	PNN2
E787	2	1
E949	1	3

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

$$B_{\mathrm{SM}}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (0.78 \pm 0.08) \times 10^{-10}$$

What is ORKA?

- ORKA will apply the method and techniques that were demonstrated in BNL E878/E949.
  - ORKA does not assume (or require) better background rejection than E949 achieved.
- ORKA will use existing facilities at Fermilab.
  - Main Injector slow extracted beam to produce kaons.
  - Existing infrastructure (e.g., B0 hall).
  - Existing superconducting magnet (from CDF).
- ORKA will be a modern detector based on the E949 concept.
  - E787 was built in the mid-1980's; E949 was an upgrade in late 1990's.
- ORKA will observe about 1000 $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events in a few years of running (~200 events/yr at SM BF).

ORKA vs E949 detector

ORKA will improve the performance of all detector systems.

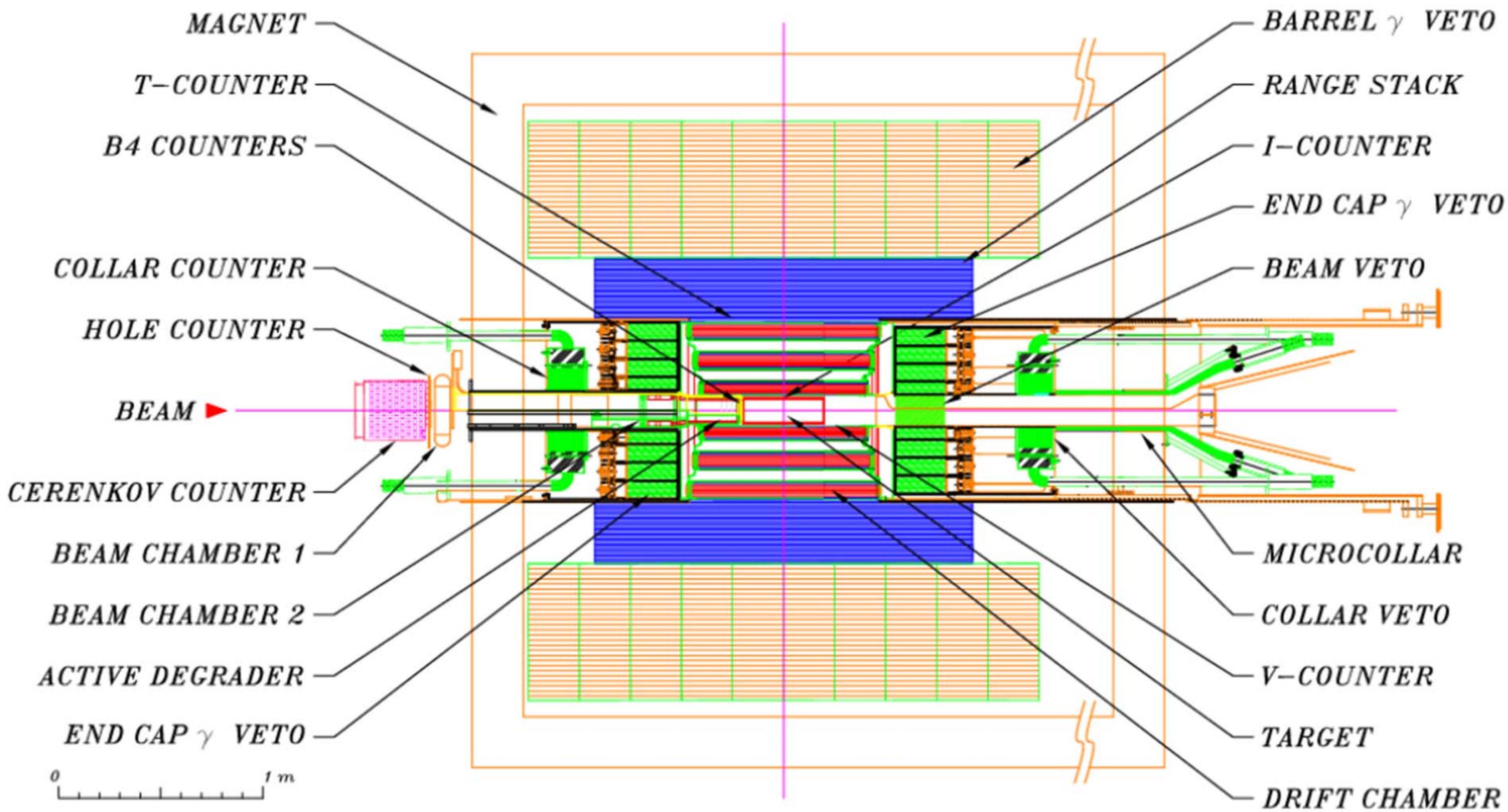
- Higher magnetic field (1.0 T $\rightarrow$ 1.25 T) with superconducting solenoid; better momentum resolution
- Longer drift chamber; larger geometrical acceptance
- Improved scintillating fiber stopping target; smaller fibers and better light collection; better beam K-π separation, better vertex position
- Finer segmentation of the range stack, higher QE photodetectors; better dE/dx resolution (better π-μ separation), reduce accidentals
- Better, thicker ($17X_0 \rightarrow 23X_0$) photon veto system; Shashlyk (or other); improved π^0 rejection
- Wave form digitizers (500 MHz, 10-bit) on all scintillators (no multiplexing); less sensitive to accidentals
- Modern “triggerless” DAQ system; eliminate deadtime

Detector Improvements

Estimates based on E949 experience.

Component	Acceptance factor
$\pi \rightarrow \mu \rightarrow e$	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})	$11.28^{+3.25}_{-2.22}$

ORKA Detector



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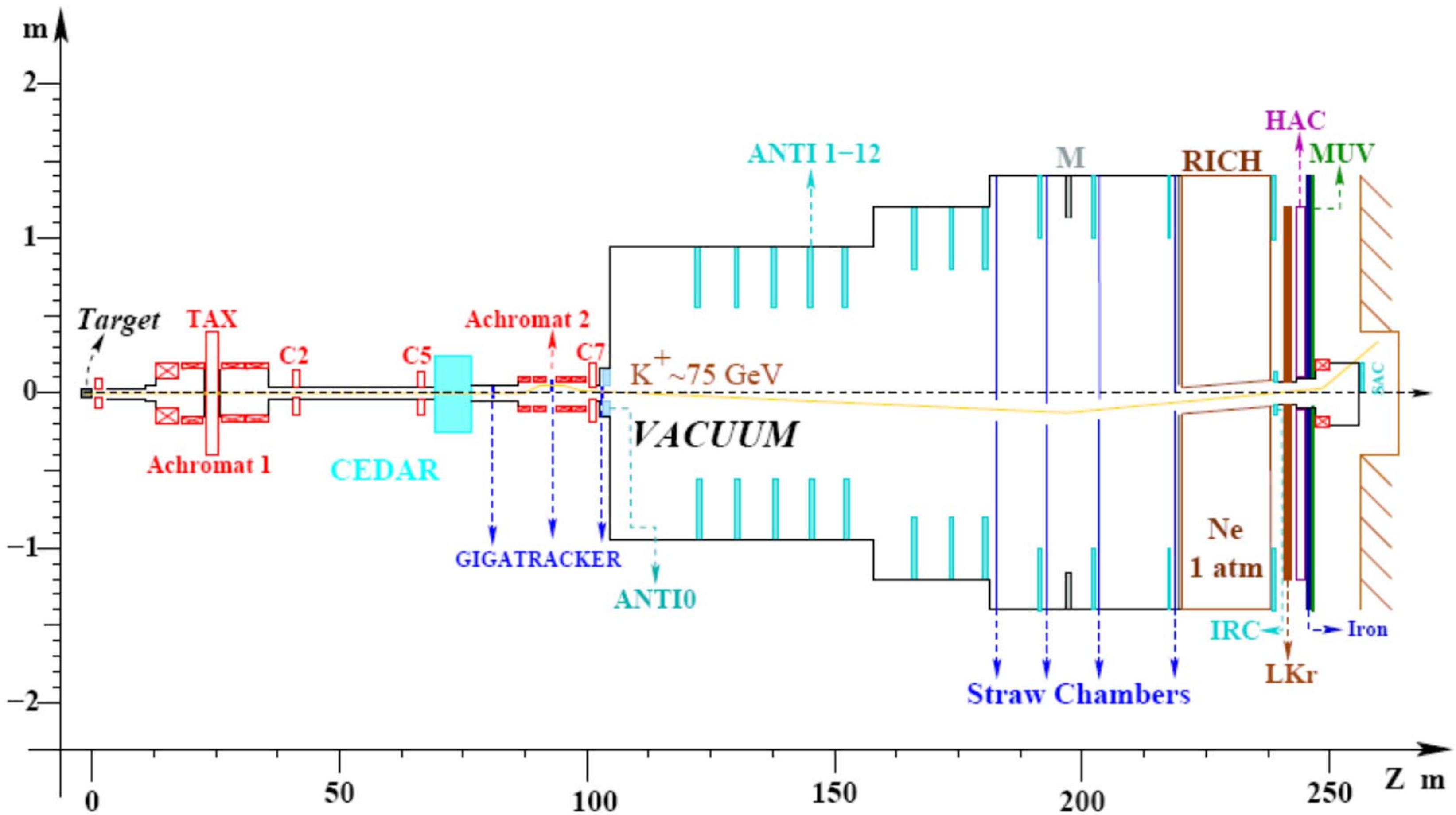
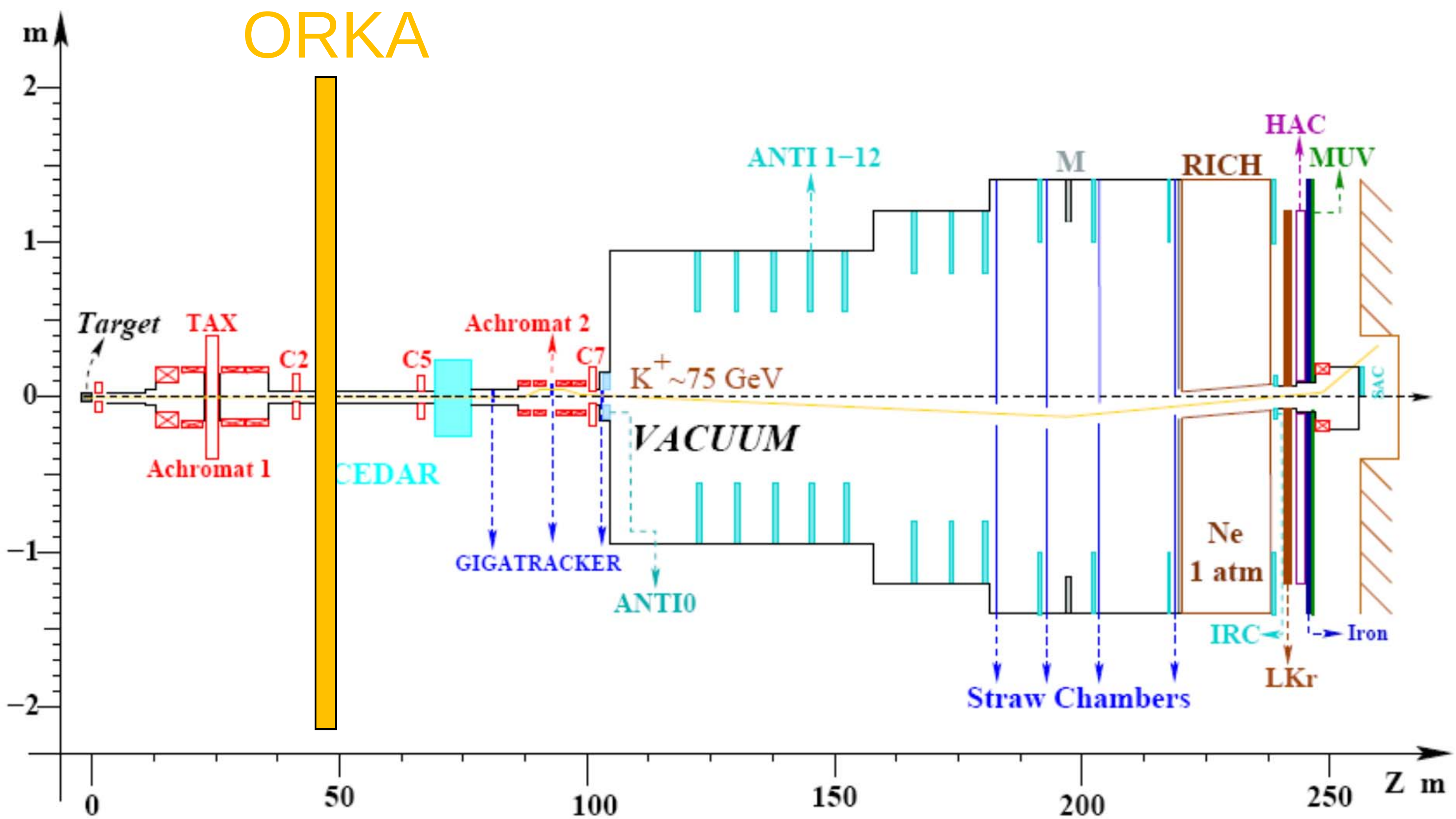


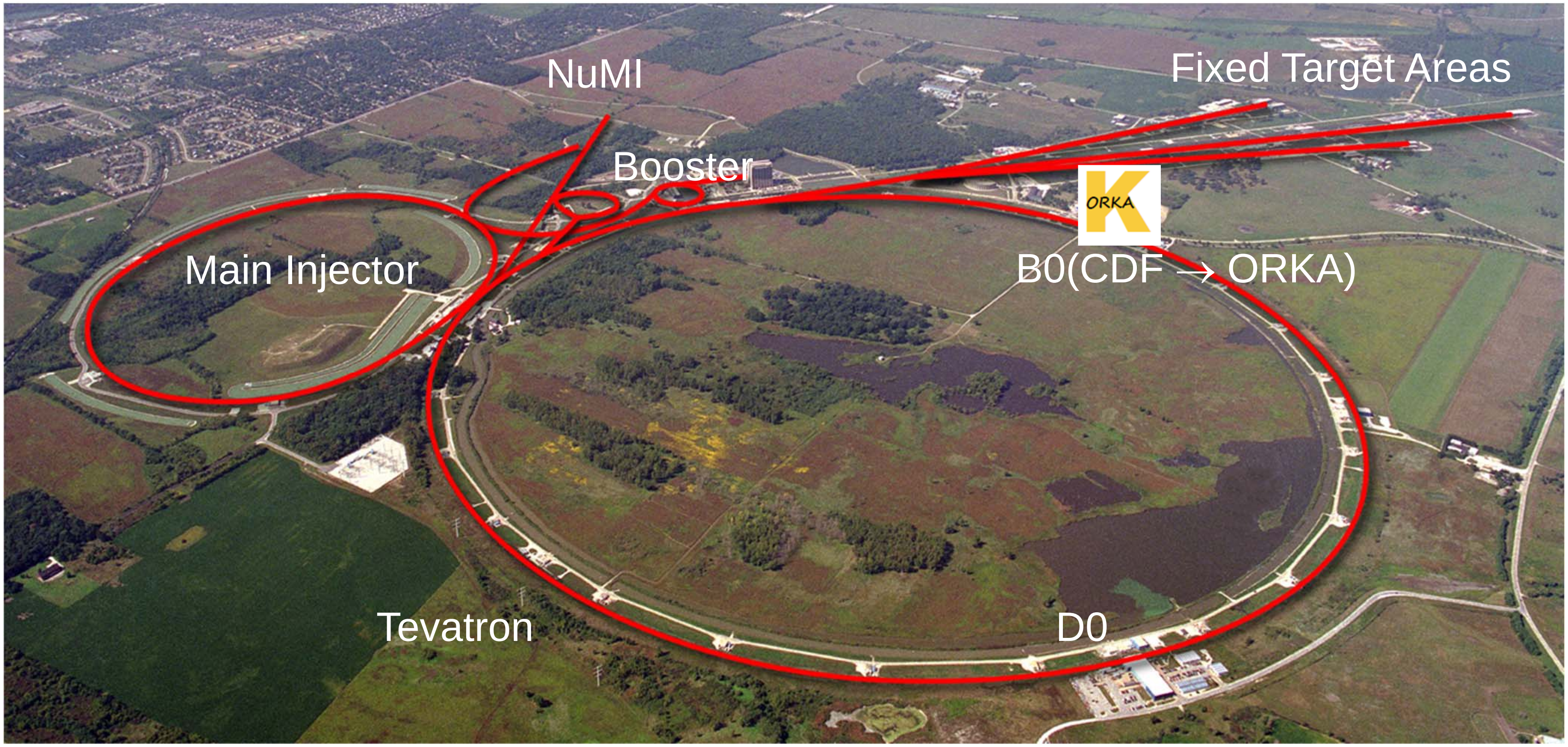
m
2
1
0
−1
−2
Target
TAX
C2
C5
Achromat 2
C7
K+~75 GeV
Achromat 1
CEDAR
GIGATRACKER
ANTI0
VACUUM
ANTI 1−12
M
RICH
HAC
MUV
SAC
Ne
1 atm
IRC
Iron
LKr
Straw Chambers
0
50
100
150
200
250
Z m

NA-62



ORKA
m
2
1
0
−1
−2
Target
TAX
C2
C5
Achromat 2
C7
Achromat 1
CEDAR
GIGATRACKER
ANTI0
ANTI 1−12
K^+~75 GeV
VACUUM
M
RICH
HAC
MUV
SAC
Ne
1 atm
IRC
Iron
LKr
Straw Chambers
0
50
100
150
200
250
Z m

Fermilab



NuMI
Fixed Target Areas
Booster
ORKA
Main Injector
B0(CDF → ORKA)
Tevatron
D0

Headline News

Physicists raid Tevatron for parts

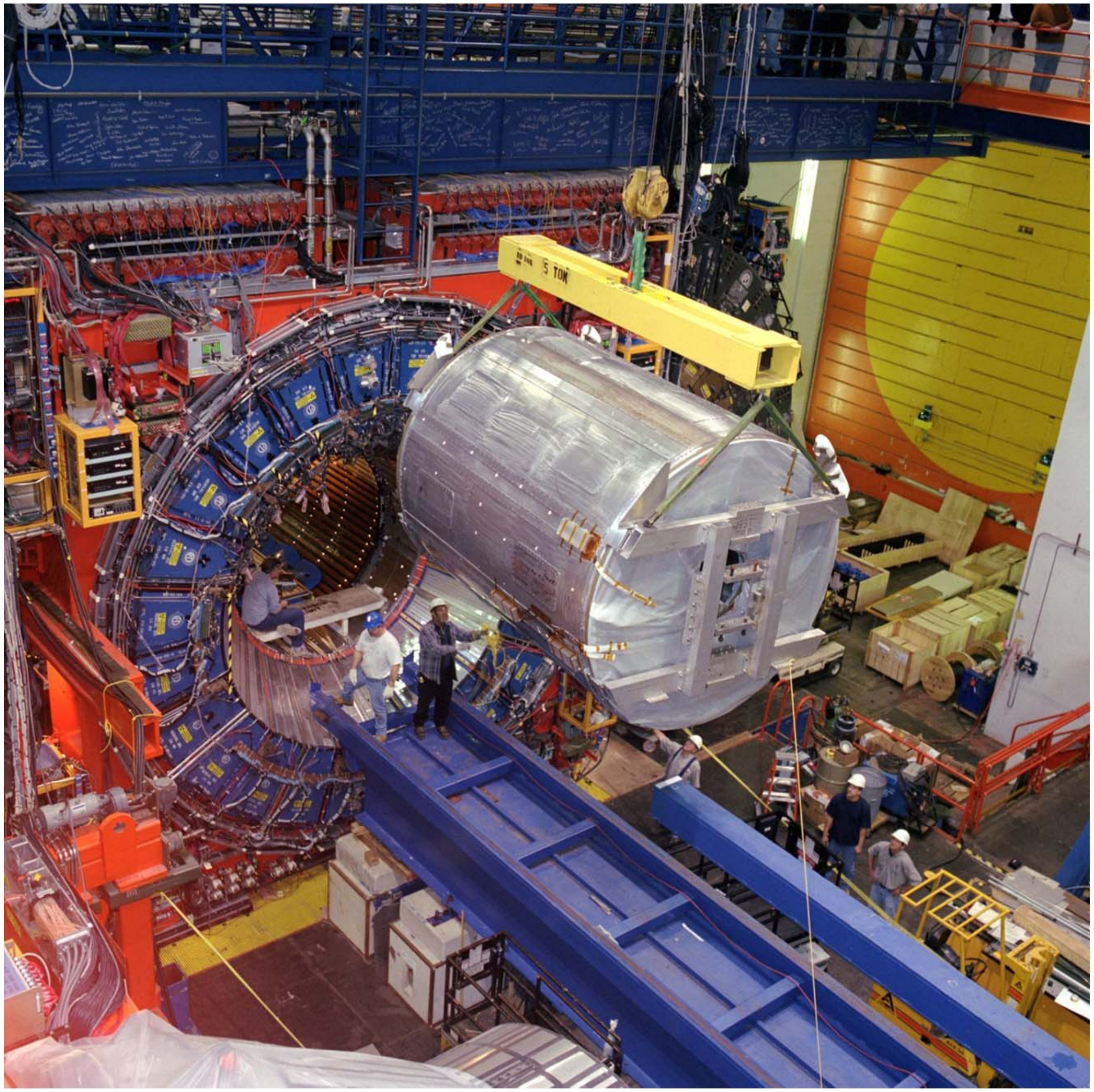
Fermilab icon plundered amid tight budgets and shifting scientific aims.

“ … During 26 years of operation at the Fermi National Accelerator Laboratory in Batavia, Illinois, this behemoth, the Collider Detector at Fermilab (CDF), helped to find the top quark and chased the Higgs boson. But since the lab's flagship particle collider, the Tevatron, was switched off in September 2011, the detector has been surplus stock — and it is now slowly being cannibalized for parts.

“ … the most ambitious recycling request so far would see it gutted. A proposed experiment called ORKA … needs a massive solenoid magnet like the one at the CDF's heart.

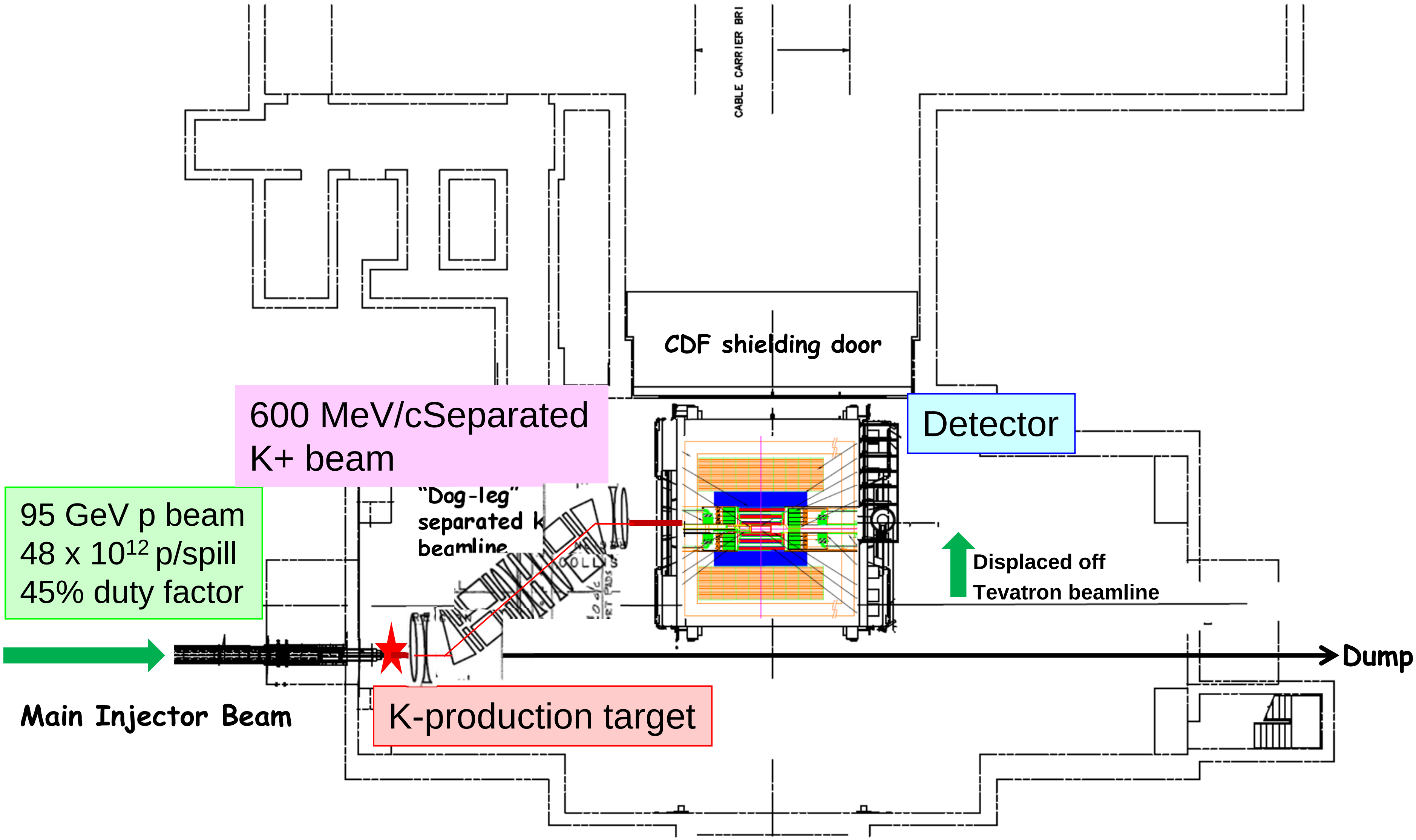
“Lab management will make a decision about whether ORKA can eviscerate the CDF in about 6 months' time.”

Nature 482, 453 (23 February 2012)



The entire ORKA detector will fit within the CDF tracking volume.

Possible ORKA layout in BO Hall



ORKA Beam

Component	E949 "as run"	ORKA
Proton momentum (GeV/c)	21.5	95
Protons/spill	65×10^{12}	48×10^{12}
Spill length(s)	2.2	4.4
Interspill(s)	3.2	5.6
Duty factor	0.41	0.44
protons/sec(ave.)	12×10^{12}	4.8×10^{12}
protons/sec(inst.)	15.9×10^{12}	10.9×10^{12}
Kaon momentum (MeV/c)	710	600
K beamline length(m)	19.6	13.74
Effective beam length(m)	17.6	13.21
K survival factor	0.0372	0.0536
Angular acceptance (msr)	12	20
$\Delta p/p(\%)$	4.0	6.0
$K^+{:}\pi^+$ ratio	3	3.31 ± 0.41
N_K/spill	12.8×10^6	$(88.5 \pm 10.9) \times 10^6$
N_K/sec(inst.)	6.3×10^6	$(20.1 \pm 2.5) \times 10^6$
$N_{K+\pi}$/sec(inst.)	8.4×10^6	26.2×10^6
N_K/sec(ave.)	2.6×10^6	$(8.85 \pm 1.09) \times 10^6$
Stopping fraction	0.21	0.54 ± 0.12
Kstop/s(ave.)	0.69×10^6	$(4.78 \pm 1.21) \times 10^6$

Main Injector

Seperated K^+ beam

Reaching detector

75 kW beam power from Main Injector to ORKA target (versus about 40 kW at BNL)

Lower p improves stopping efficiency; shorter beamline improves K^+ survival; larger acceptance improves flux

ORKA will have x7 more Kstop/s

ORKA Sensitivity

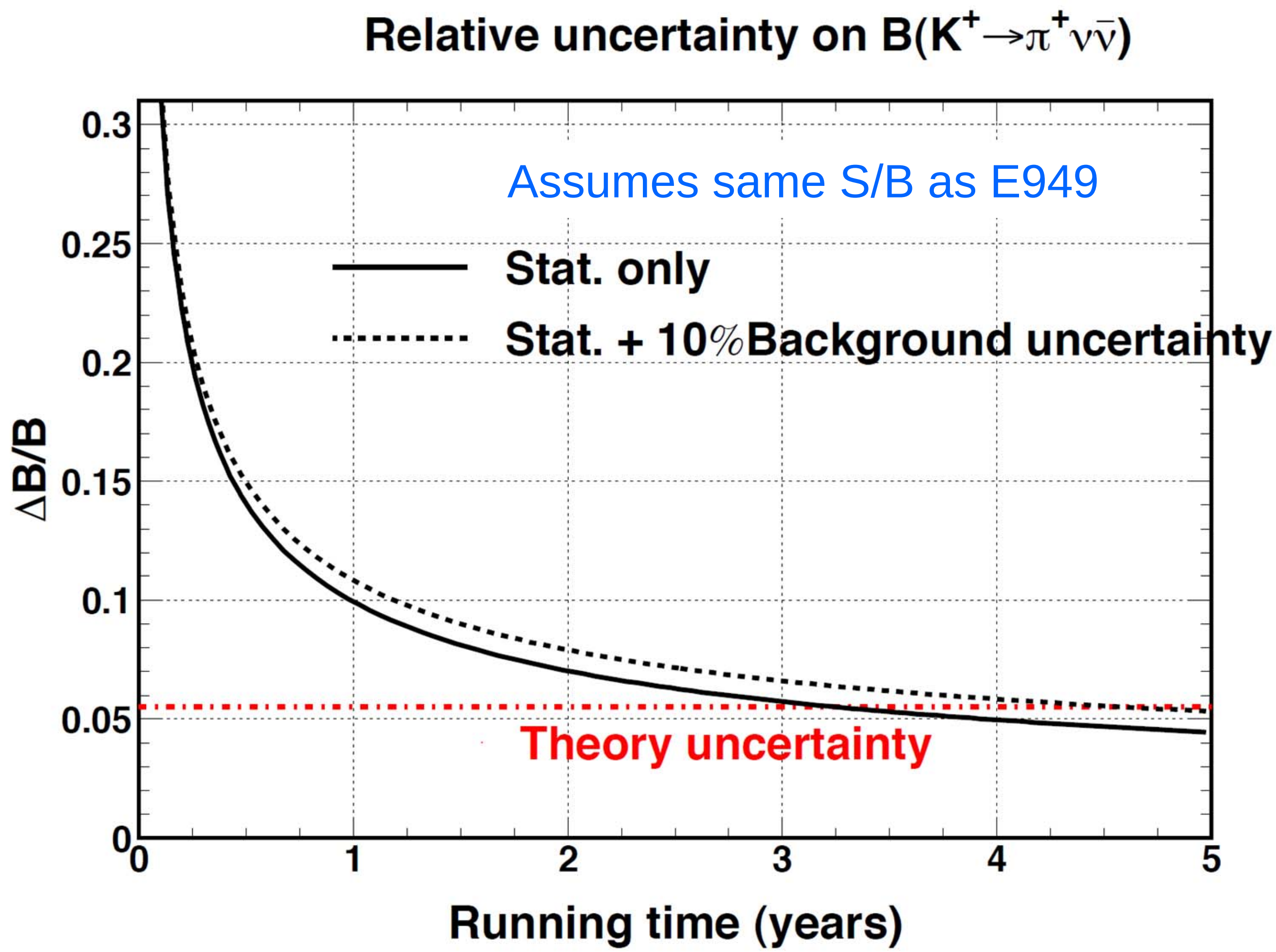
ORKA projection: 213 events/year at SM BF for 5000 hours/year running

Where does the improvement come from?

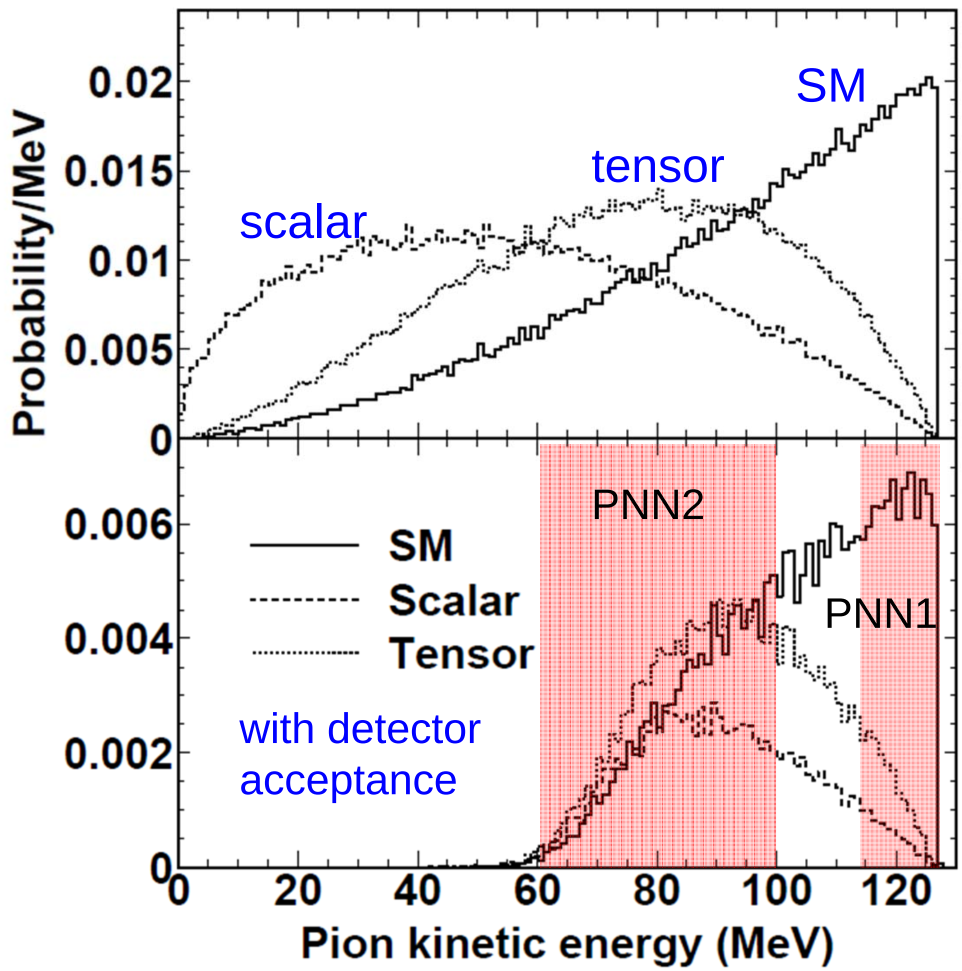
ORKA versus E949

Net detection efficiency per K-stop	detector	11.3 (+3.3/-2.3)
K-stops per hour	beam	6.9 ± 1.8
5000 hours(per yr)/E949 as run (940 hours)	running	5.3

ORKA Projected Precision



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



ORKA will have some sensitivity for scalar or tensor interactions.

A precise spectrum measurement will require Project-X type statistics.

ORKA will make several measurements.

Process	Current	ORKA
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$
$K^+ \to \pi^+ \gamma\gamma$	293 events	200,000 events
$\Gamma(Ke2)/\Gamma(K\mu2)$	$\pm 0.5\%$	$\pm 0.1\%$
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$

Status and Timeline

- ORKA (P-1021) received Stage 1 approval from Fermilab in December 2011.
- DOE is cogitating on the issue of "Mission Need" (aka CD-0).

Milestone/Activity	Time Period
Stage One Approval	Winter 2012
DOE Approval of Mission Need (CD-0)	Fall 2012
Beam/Detector Design Approve Cost Range (CD-1)	2012–2013 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

- ORKA could have data in 2017.

ORKA Collaboration

The collaboration is growing.

Summary/Conclusions

- $K^+ \to \pi^+ \nu\bar{\nu}$ is one of the theoretically cleanest FCNC processes.
  - A deviation from the SM branching fraction would be a clear signature for New Physics
- A precision measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching fraction is a high-priority experiment.
  - Important enough to do twice
- ORKA can exploit existing facilities at Fermilab to make a decisive (~1000 event) measurement by applying the proven BNL E949 method.
  - Can reduce experimental error to the size of the theory error
  - Low risk due to the demonstrated technique