ORKA at Fermilab: Seeking New Physics with Measurements of the "Golden Kaon" Decay $K^+ \to \pi^+ \nu \bar{\nu}$

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April 25, 2013 Argonne Intensity Frontier Workshop

Precision Flavor Physics in the LHC Era

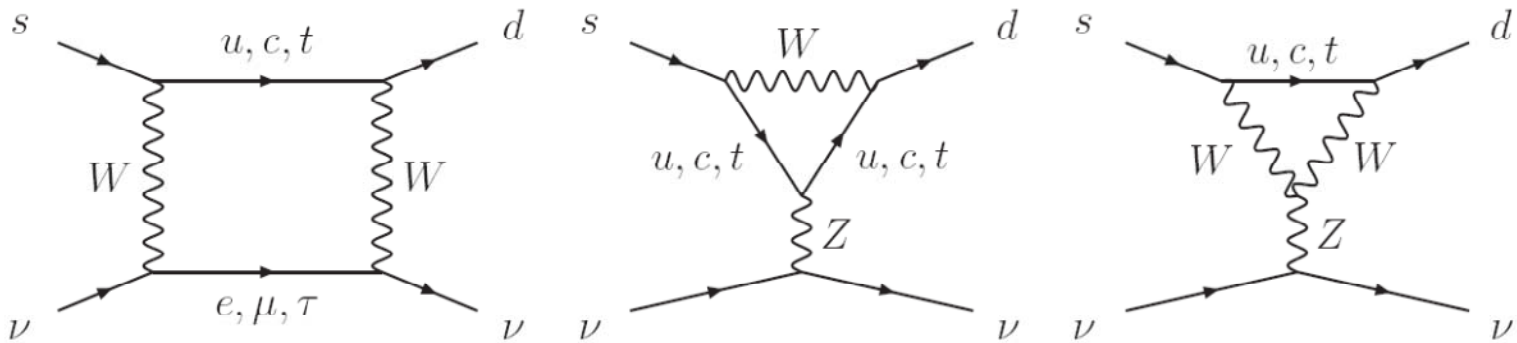
A small set of crucial rare particle decays extremely sensitive to new physics at high mass scales

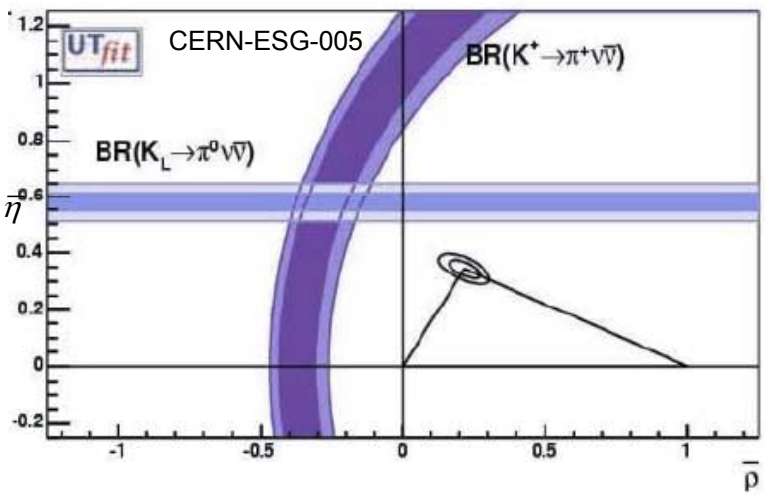
Q(L) Flavor	Processes to Study NP
1(2)	μ-e Conversion, $\mu \to e\gamma, \mu \to eee$
	$\pi(K)^+ \to e^+\nu$
2	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L^0 \to \pi^0\nu\bar{\nu}$
3(3)	$b \to s\gamma$, $\mathrm{B} \to \mu\mu$, $\tau \to \mu\gamma$...

Discoveries of new physics at the LHC and elsewhere will require a range of precision flavor physics experiments to home in on the new interpretation.

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

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





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

Remain clean in most New Physics models

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

$$B_{SM}(K_L^0 \to \pi^0 \nu\bar{\nu}) = (2.43 \pm 0.39) \text{ x } 10^{-11}$$

Expect total SM theory error ≤6%.

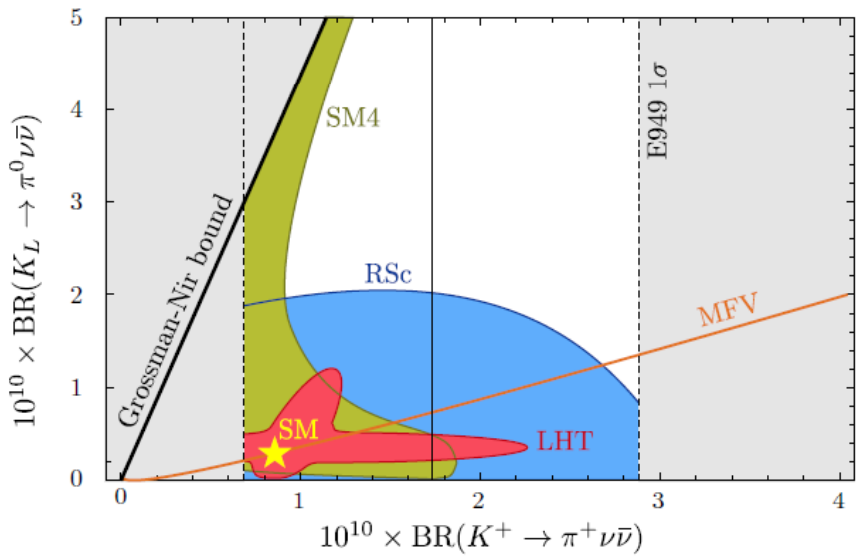
30% deviation from the SM would be a 5σ signal of NP

J. Brod, M. Gorbahn, E. Stamou PRD83,034030(2011)

$K \to \pi\nu\bar{\nu}$: High Sensitivity to New Physics

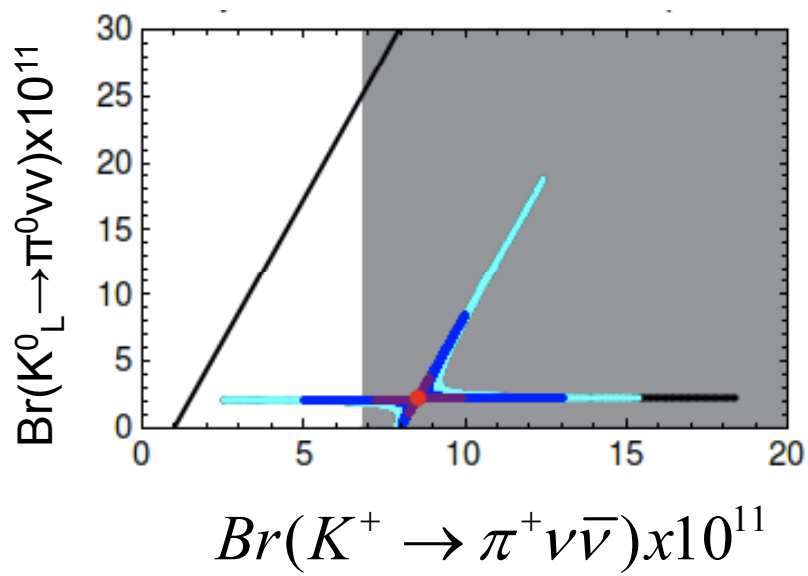
High mass scale effects, Warped Extra Dimensions as a Theory of Flavor, Z', …??

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



D. M. Straub, arXiv:1012.3893

$Z'\ (m_{Z'} = 5 - 30\,TeV)$



Buras, De Fazio, Girrbach
arXiv:1211.1896

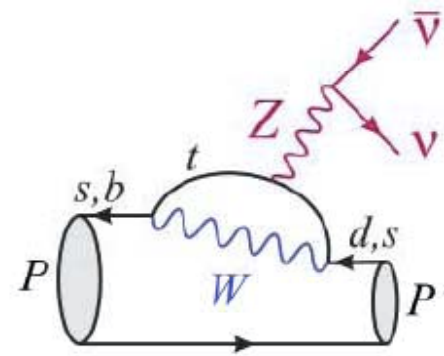
Kamenik and Smith (2012)

"FCNC portals to the dark sector"

Dark Sector Decays $K / B \to \pi^+ XX$ compete with SM Decays $K / B \to \pi \nu \bar{\nu}$

Operator Dimensional Analysis

$$\frac{m_I^{n-6}}{\Lambda^{n-4}} \approx \frac{g^2}{M_W^2} \frac{g^2}{16\pi^2} \left| V_{tI} V_{tJ} \right|$$



K *decays Highly sensitive for low* dimension operators

	$n=5$	$n=6$	$n=7$	$n=8$	$n=9$
$s \to d$	$3.3 \cdot 10^7$ TeV	130 TeV	2.0 TeV	0.25 TeV	0.07 TeV
$b \to d$	$1.3 \cdot 10^5$ TeV	26 TeV	1.5 TeV	0.37 TeV	0.16 TeV
$b \to s$	$2.7 \cdot 10^4$ TeV	12 TeV	0.9 TeV	0.25 TeV	0.11 TeV

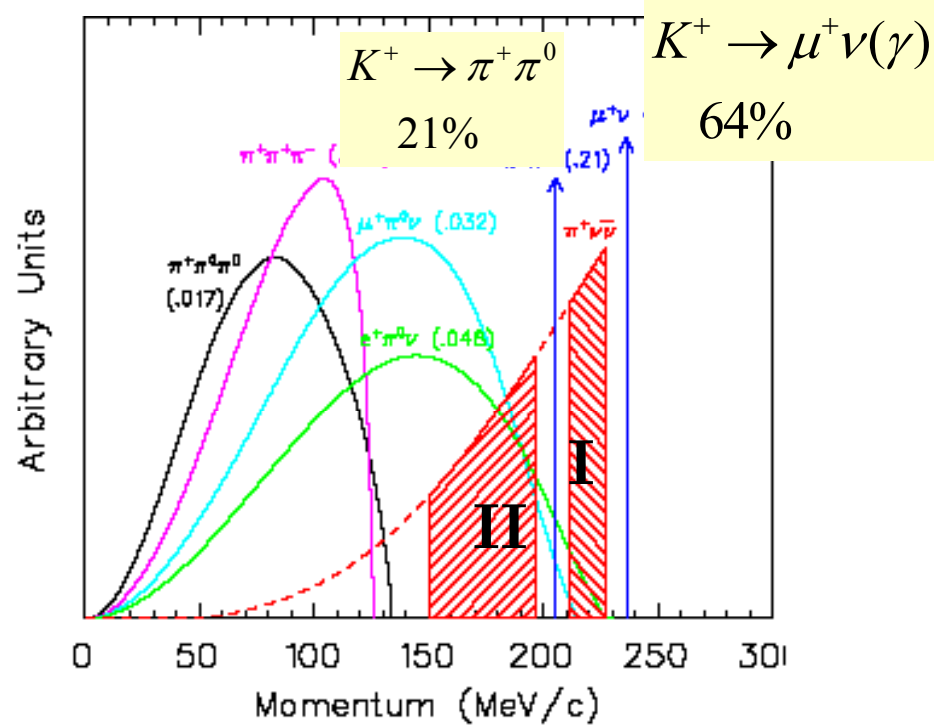
link.springer.com/content/pdf/10.1007/JHEP03(2012)090

Challenges for Measuring

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

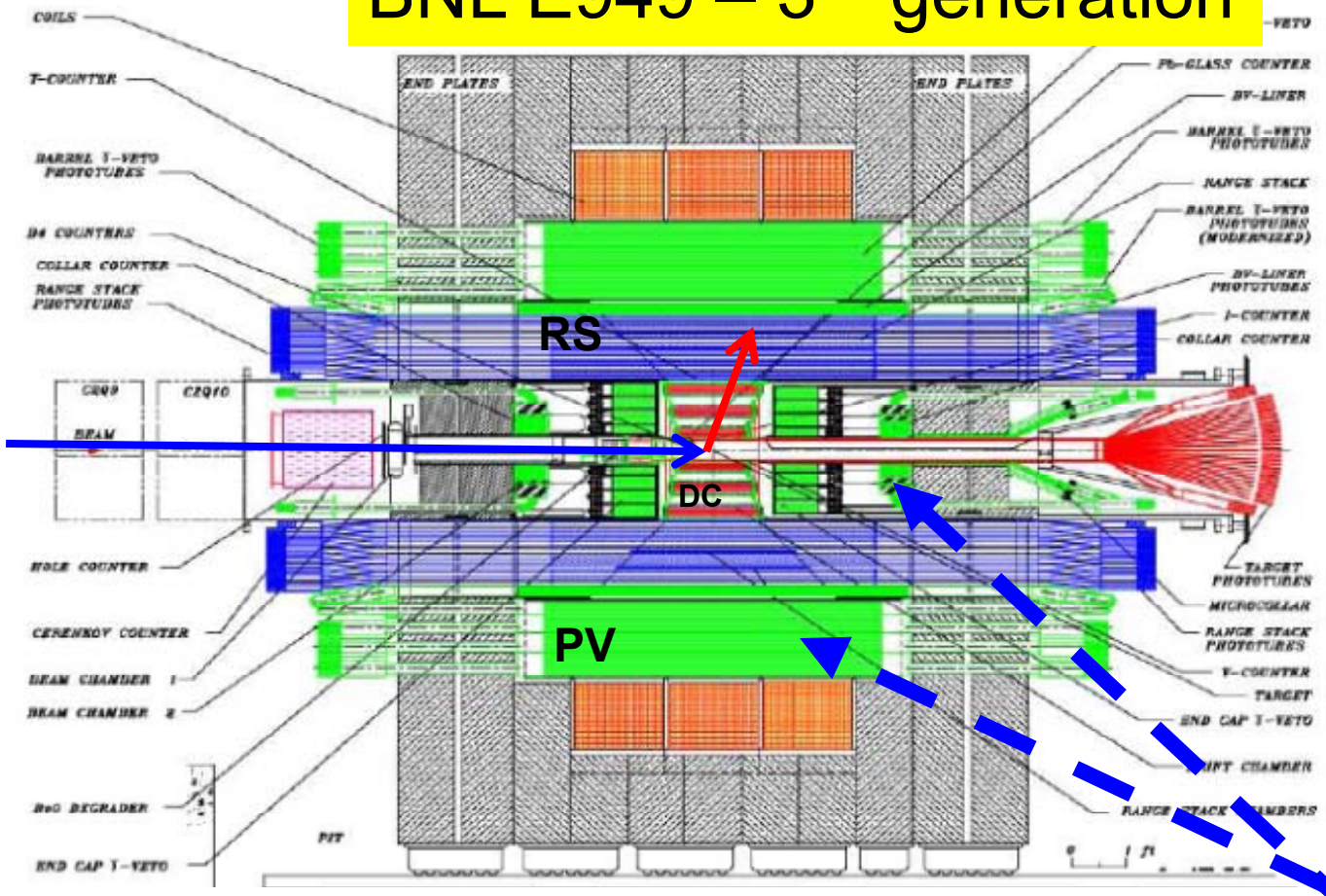
$B_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (7.8 \pm 0.8) \times 10^{-11}$

Experimentally weak signature: backgrounds exceed signals by $>10^{10}$



- Determine everything possible about the K and π
  - π^+/μ^+ particle ID better than 10^6 ($\pi^+ \to \mu^+ \to e^+$)
  - Work in the CM system (stopped K^+)
- 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

BNL E949 – 3nd generation



Stop 700 MeV/c K^+

Scintillating fiber tgt.

π^+ Momentum in DC

Energy, range in RS

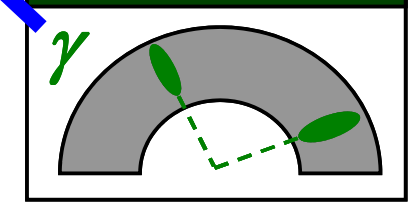
$\pi \rightarrow \mu \rightarrow e$

$>10^6$ μ suppression

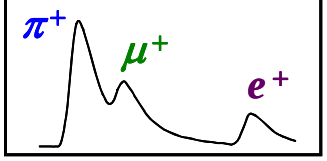
4π Photon Veto

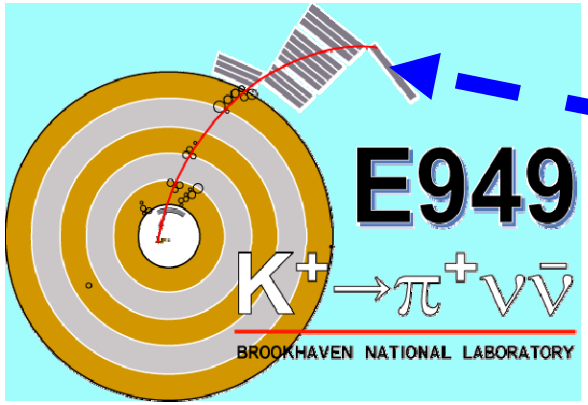
$>10^6 \pi^0$ suppression

4π Photon Veto



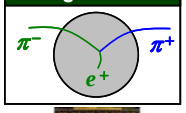
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ Decay Sequence





500 MHz digitizers

Veto Additional Charged Tracks

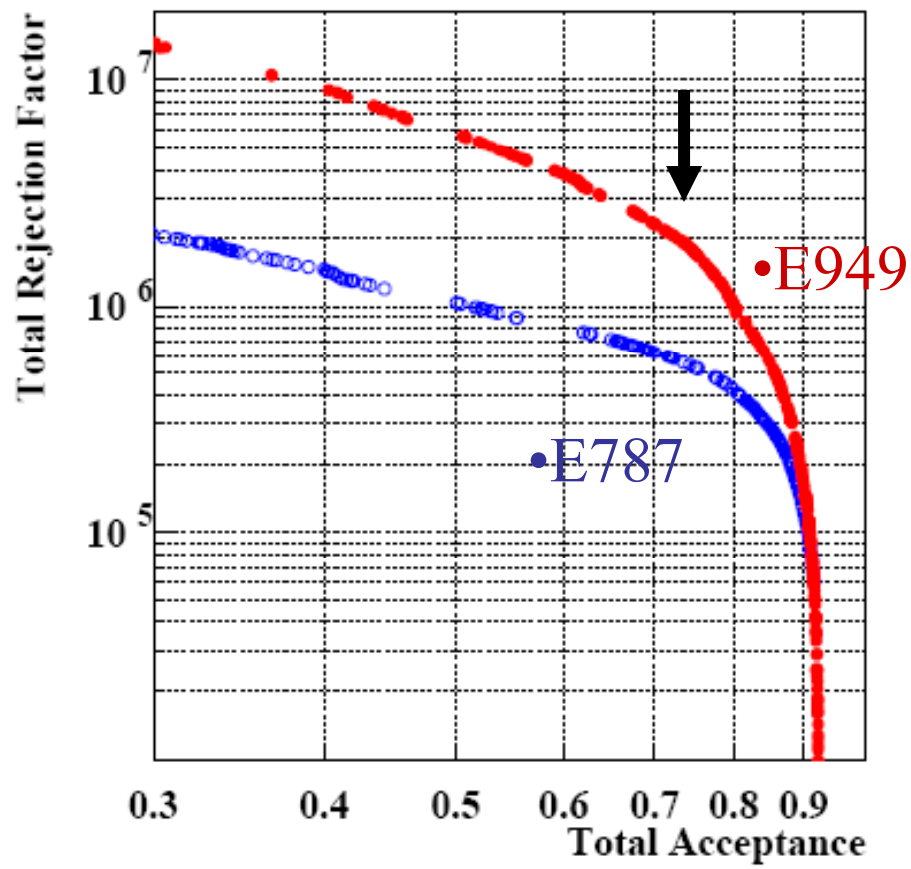


Background Suppression:
E949 Extreme Photon Detection Efficiency

π^0 Rejection: $>10^6 - 10^7$

Possibly the most efficient photon detector built so far.

Rejection vs. Acceptance

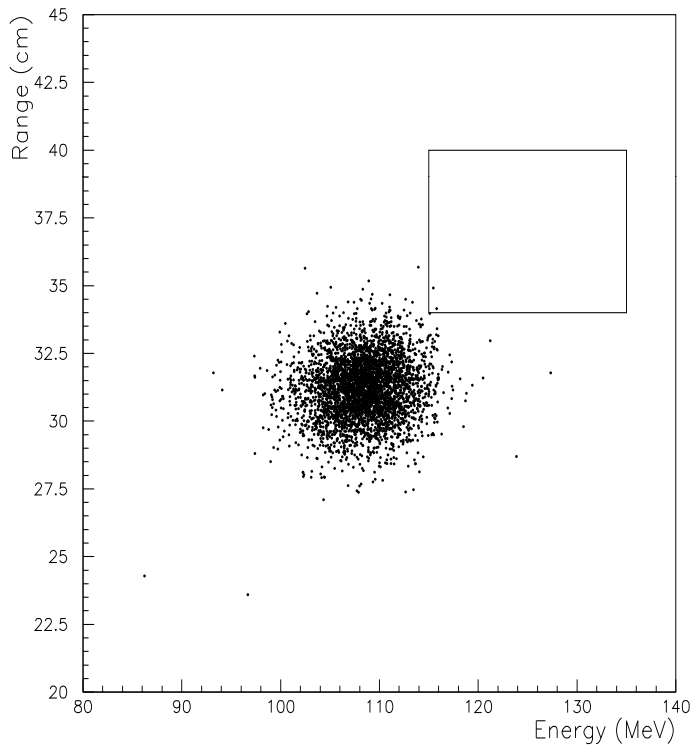


$K^+ \rightarrow \pi^+\pi^0$ Background Suppression: 21% $\rightarrow$ <10^{-11}

Dual cuts: γ Veto and Kinematics (P,R,E...)

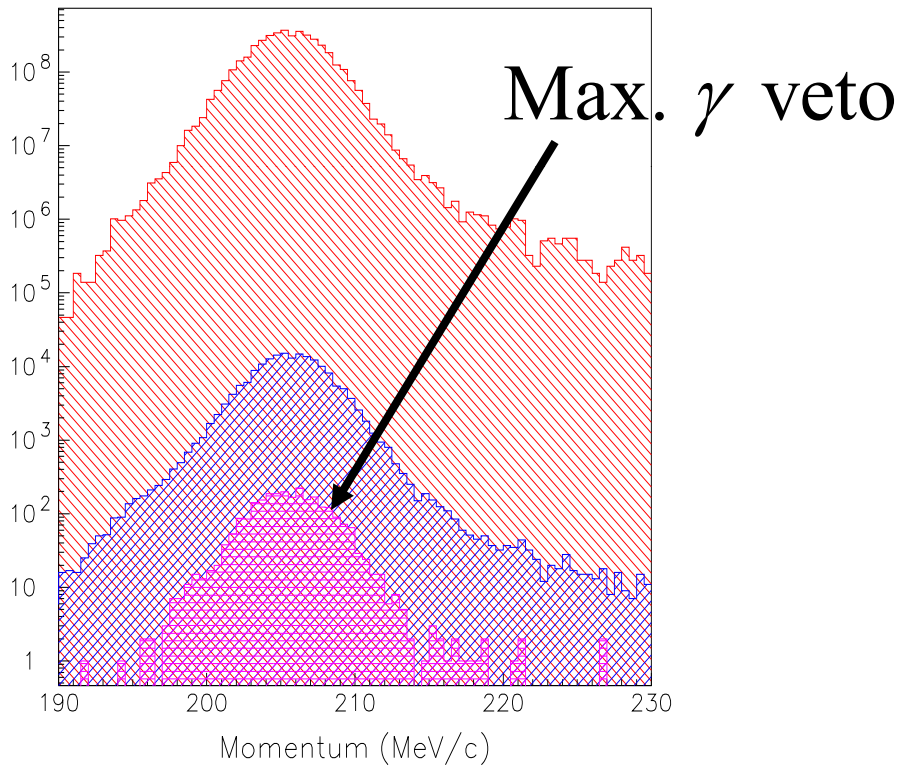
γ Veto Reversed

Range vs. Energy



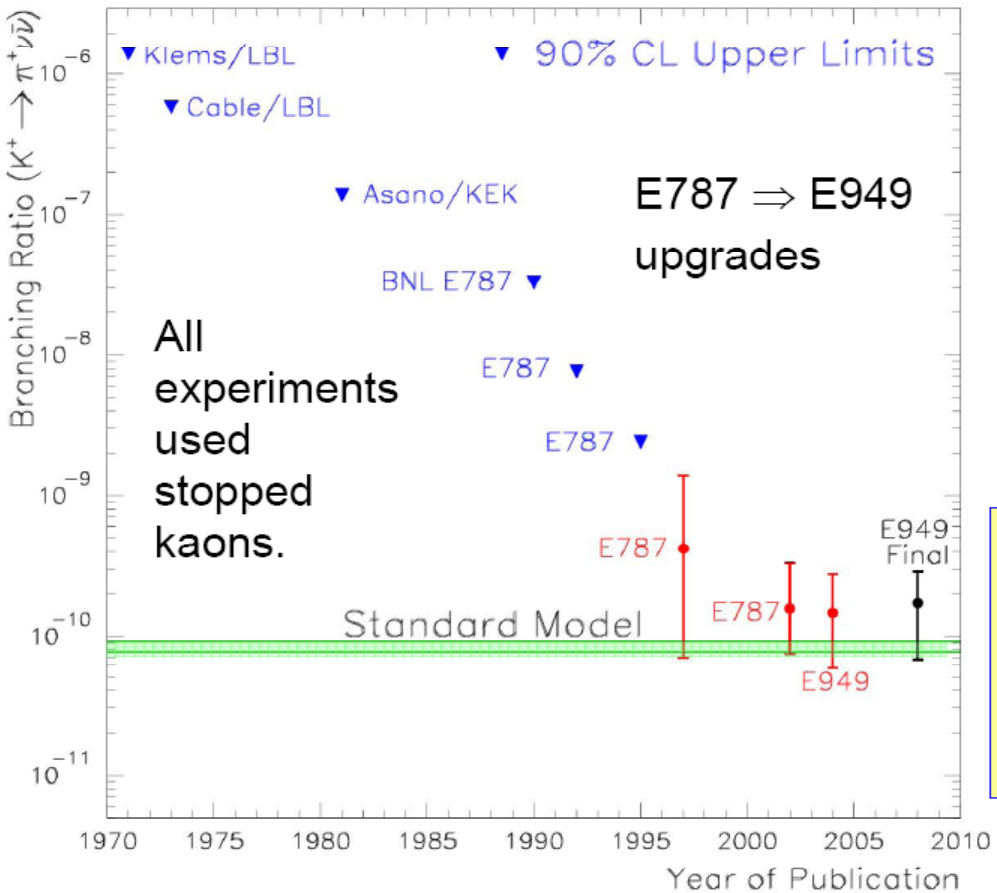
γ Veto Applied

Momentum

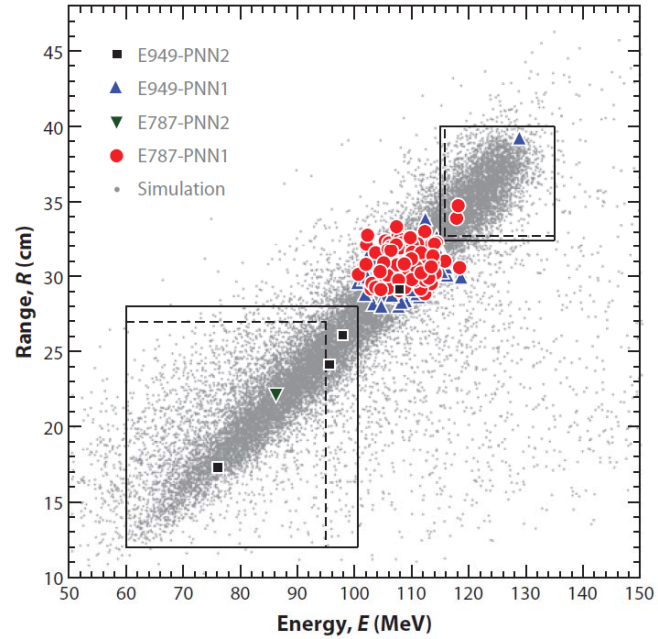


Check for correlations

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



Pion Range vs. Energy



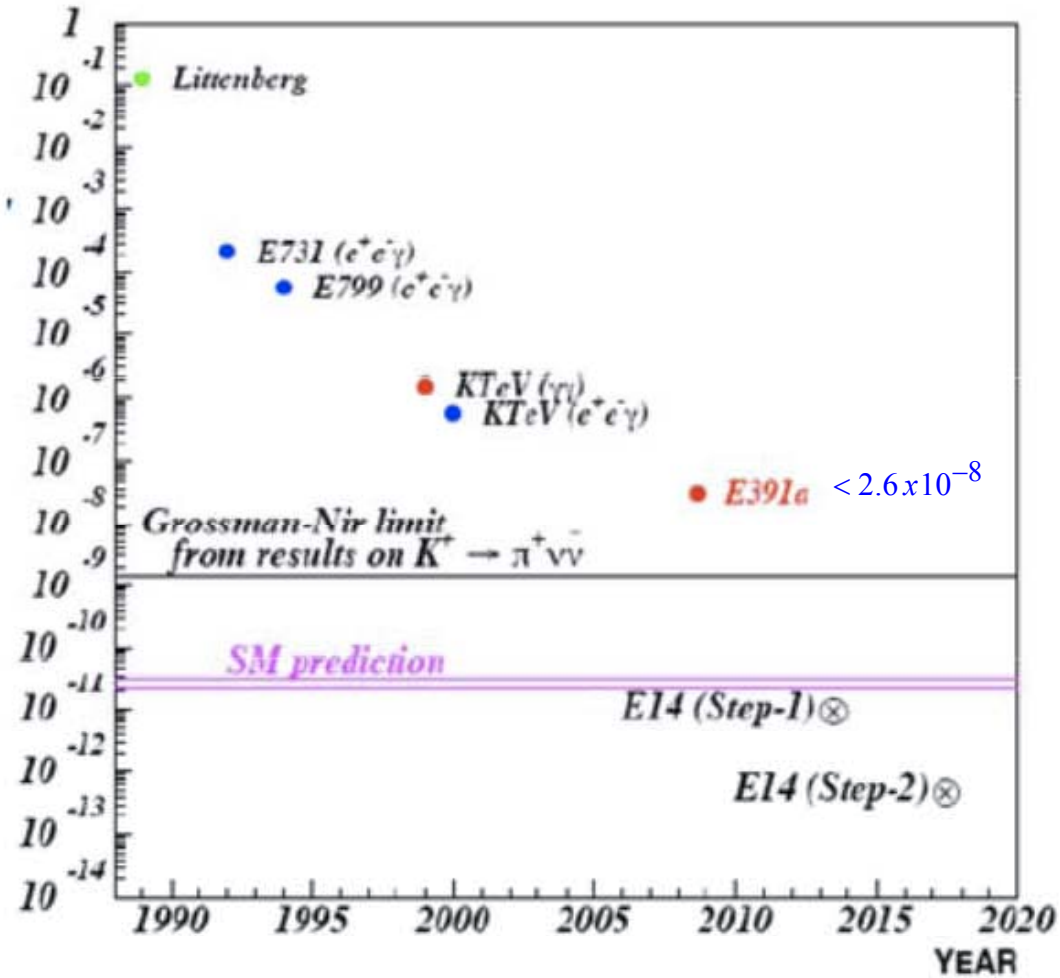
E787/E949 Final: 7 events observed

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

Standard Model:

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

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



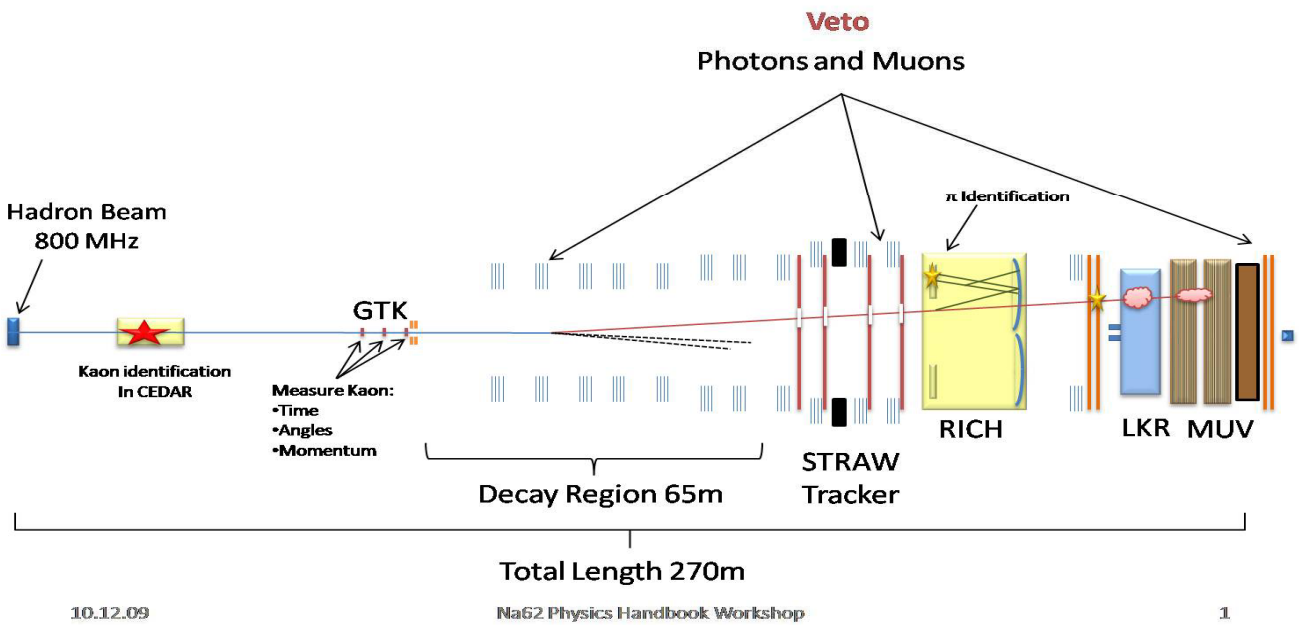
J. Ma 2011

Emerging $K \to \pi\nu\bar{\nu}$ Measurements

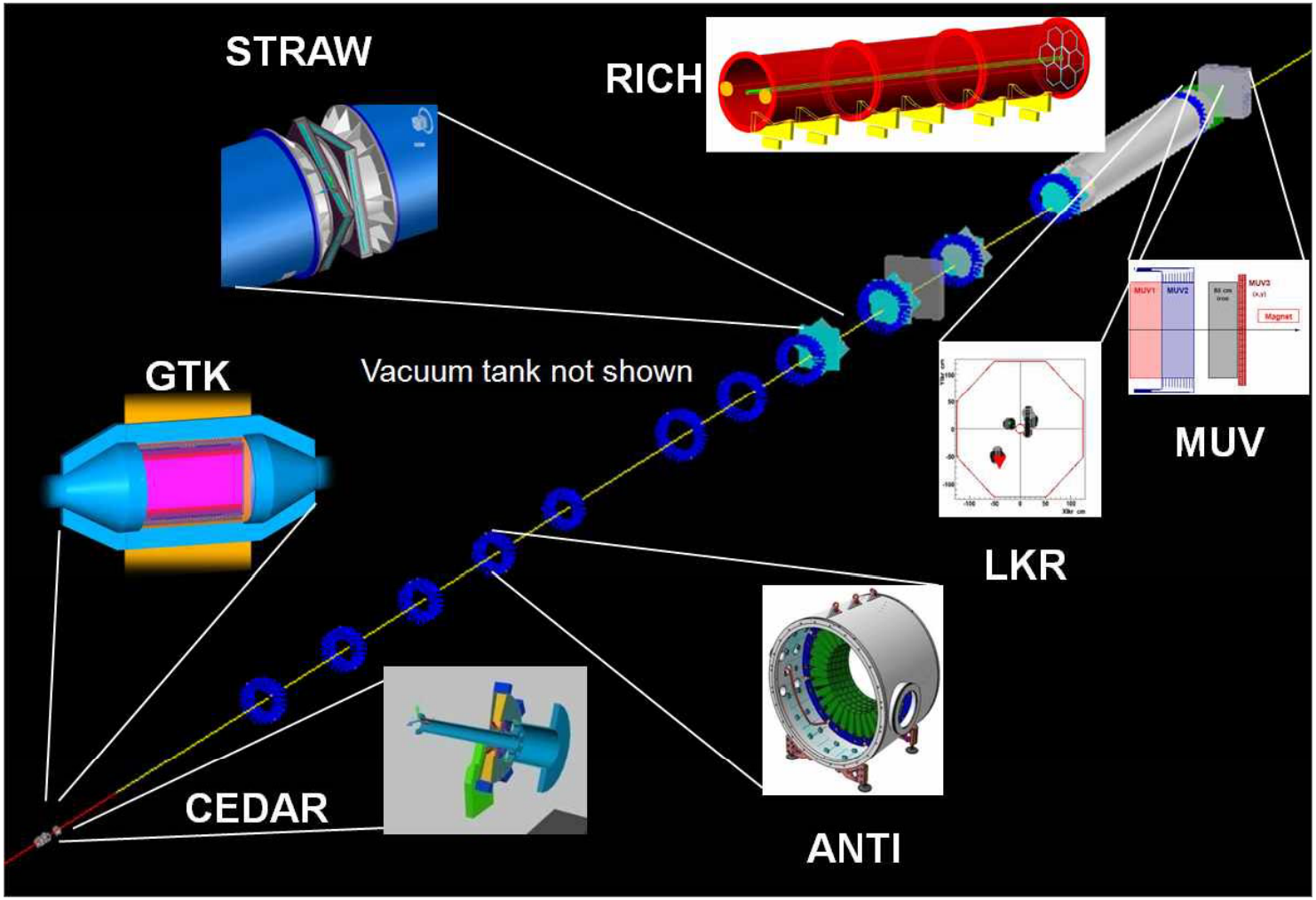
$K^+ \to \pi^+\nu\bar{\nu}$ at CERN

75 GeV Kaon Decays-in-flight

Proton beam from SPS



- Builds on NA-31/NA-48
- Un-separated GHz beam
- Aim: 40-50 events/yr at SM
- Under construction; start 2013



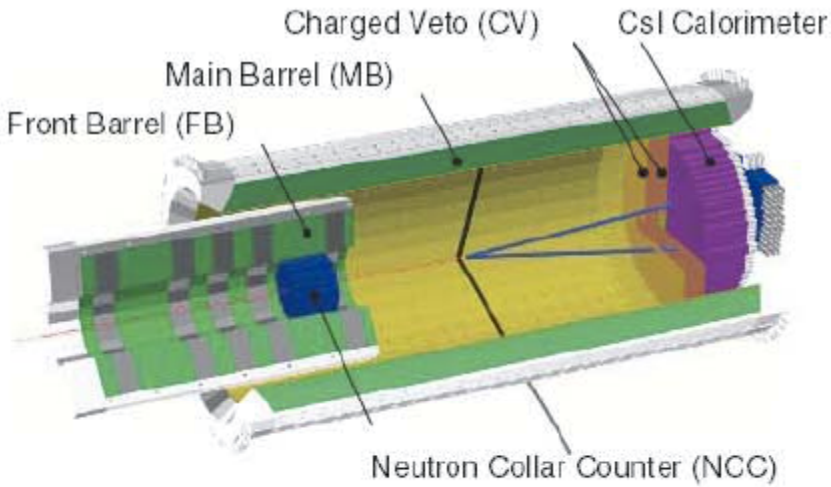
π^0 Rejection goal: 10^8 μ Rejection goal: 10^5

π / μ RICH separation up to 35 GeV/c

Beam tracking: 40 MHz/cm^2

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

Impoved setup based on KEK E391a ($< 2.6 x 10^{-8}$)

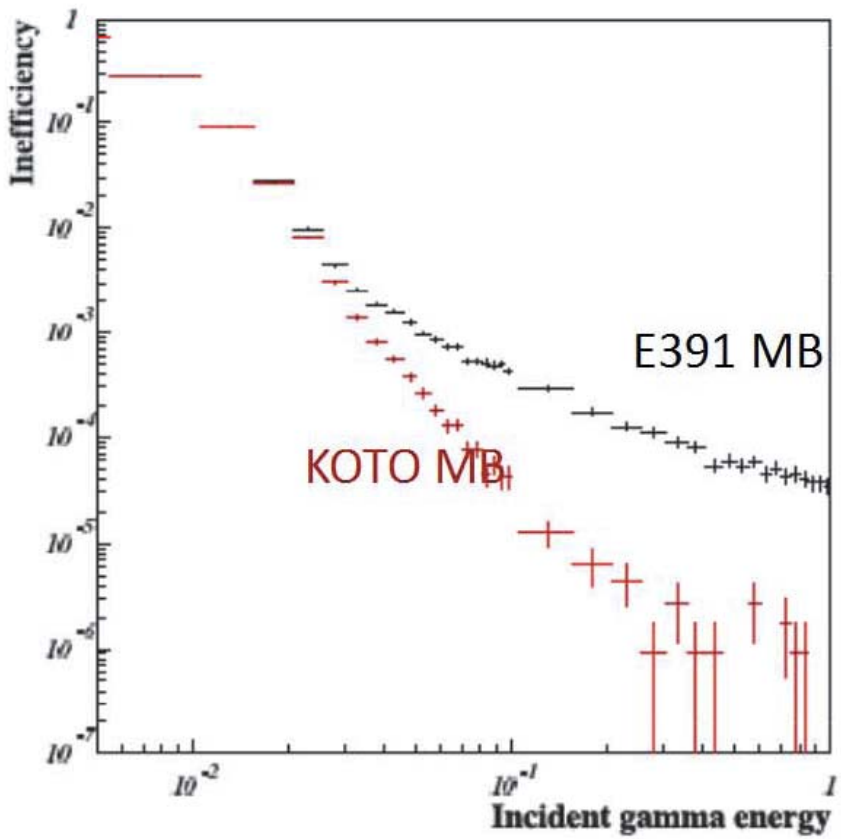


- Improved J-PARC Beam line
- Upgraded Detector
- 100 x proton intensity
- Aim: few events (S/B~1) at SM
- Under construction; start 2013

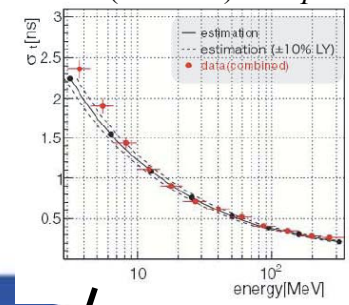
Background source	#evts
$K_L \to \pi^0\pi^0$	1.8
$K_L \to \pi^+\pi^-\pi^0$	0.46
n + residual gas	0.04
n + upstream veto	0.13
accidental coincidence	0.10
sum	2.5
$K_L \to \pi^0\nu\bar{\nu}$ signal	3.5

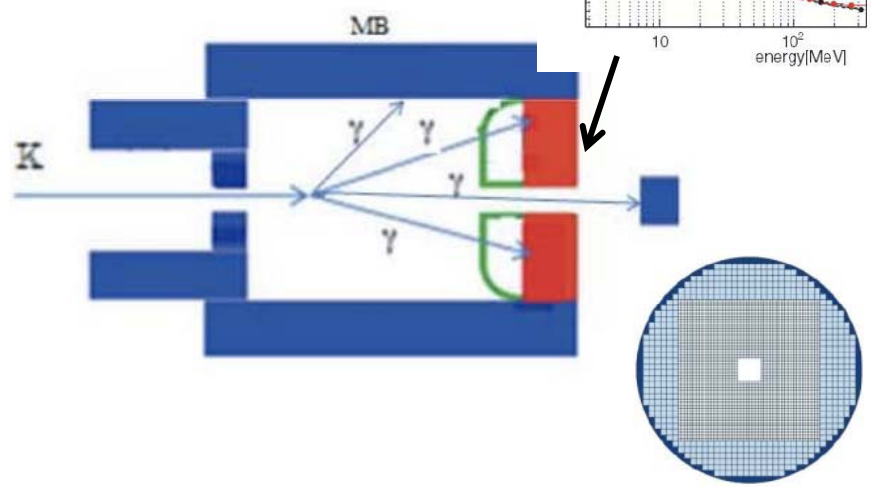
Expected Photon Veto Performance

Principal background: $K_L^0 \to \pi^0\pi^0$



CsI Calorimeter: Δt (50 MeV)~500 ps





	J-PARC KOTO	KEK-E391a	improvement
KL yield/spill	8.1×10^{6}	3.3×10^{5}	x30/sec
Run time	12 months	2 months	x6
Decay prob.	3.6%	2.1%	x2
Acceptance	4.7%	1%	x3.6
Sensitivity	0.8×10^{-11}	1.1×10^{-8}	x1300

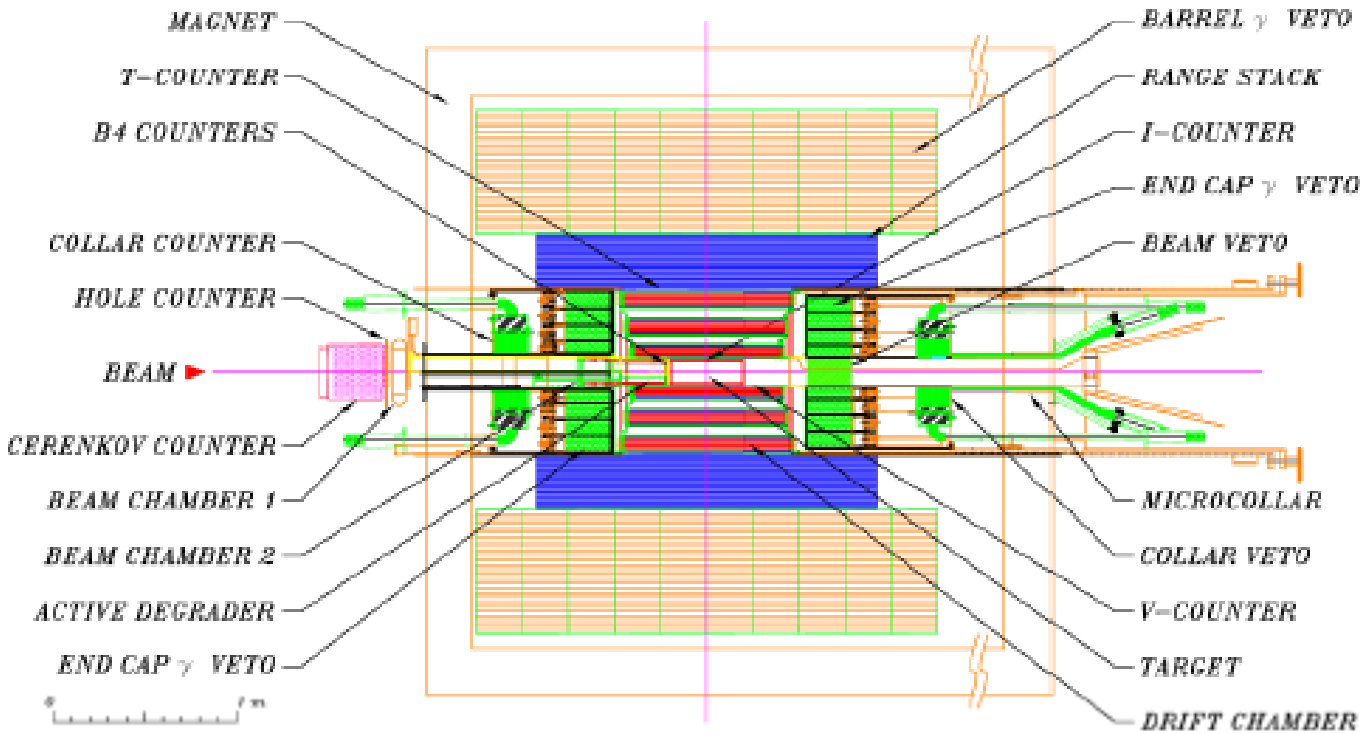
J. Ma 2011, T. Yamanaka 2012

ORKA at Fermilab

- 17 institutes in six countries: Canada, China, Italy, Mexico, Russia, USA
  - Six US universities
  - Two US National Laboratories
- Leadership from previous BNL and FNAL US rare kaon decay experiments

ORKA at the FNALMain Injector

4th Generation $K^+ \to \pi^+ \nu\bar{\nu}$ Experiment



Incremental Improvements

- 600 MeV/c
- K stopping rate **x5** with comparable instantaneous rate
- Larger solid angle
- Acceptance **x 10**
- Fine segmentation, improved resolutions

Reduced backgrounds: <5% precision

Overall, >**100 x** sensitivity

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

ORKA at Fermilab

Main Injector

Slow Spill 75 KW

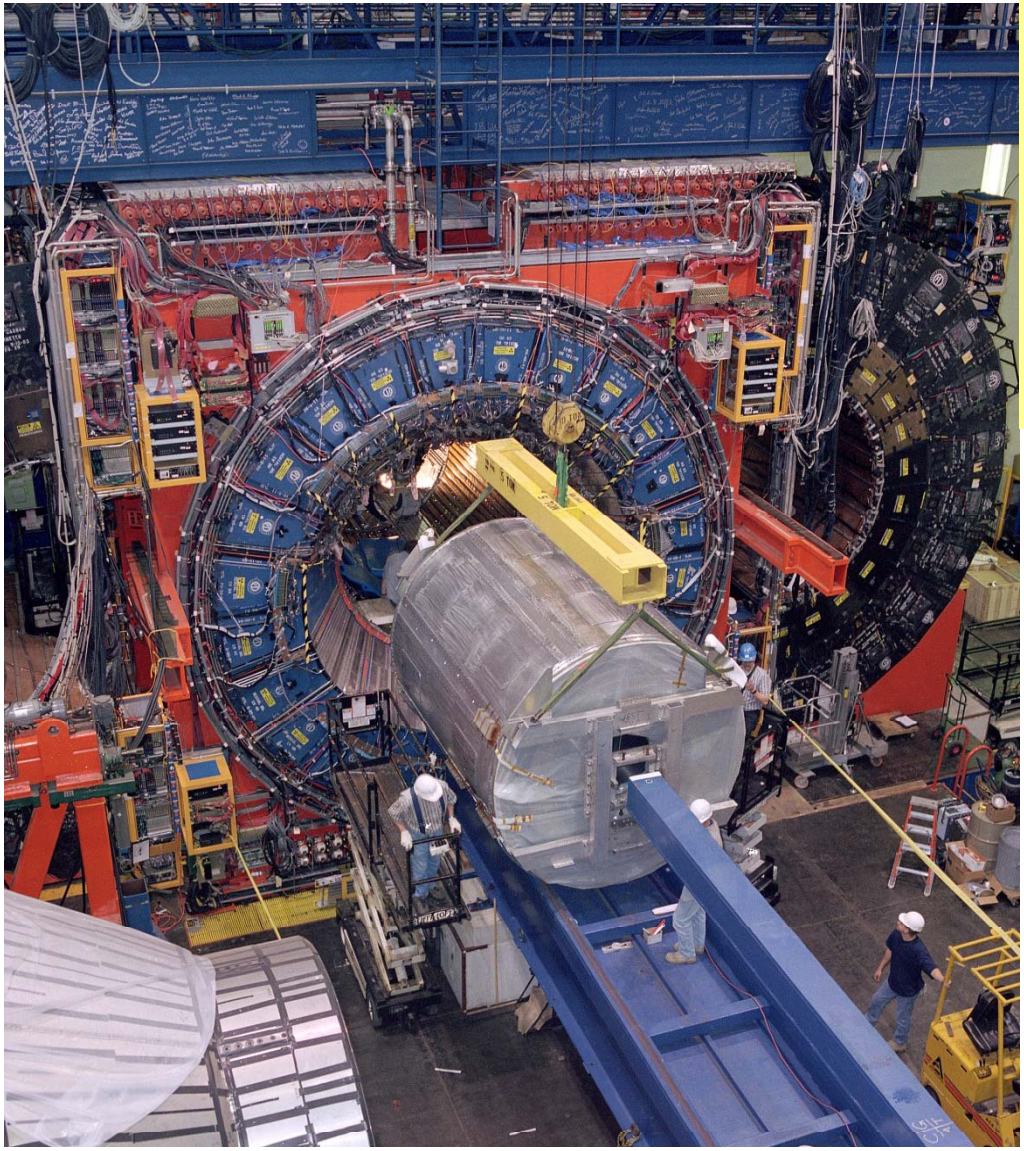
95 GeV/c

44% duty factor

(10 s cycle, 4.4 s spill)

CDF(B0) collision hall:

Existing tunnels and hall, Rad hard, adequate space, existing superconducting magnet, A0->B0 beamline needed; (required interplay with IARC)



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

E949 Central tracker (similar diameter to ORKA)

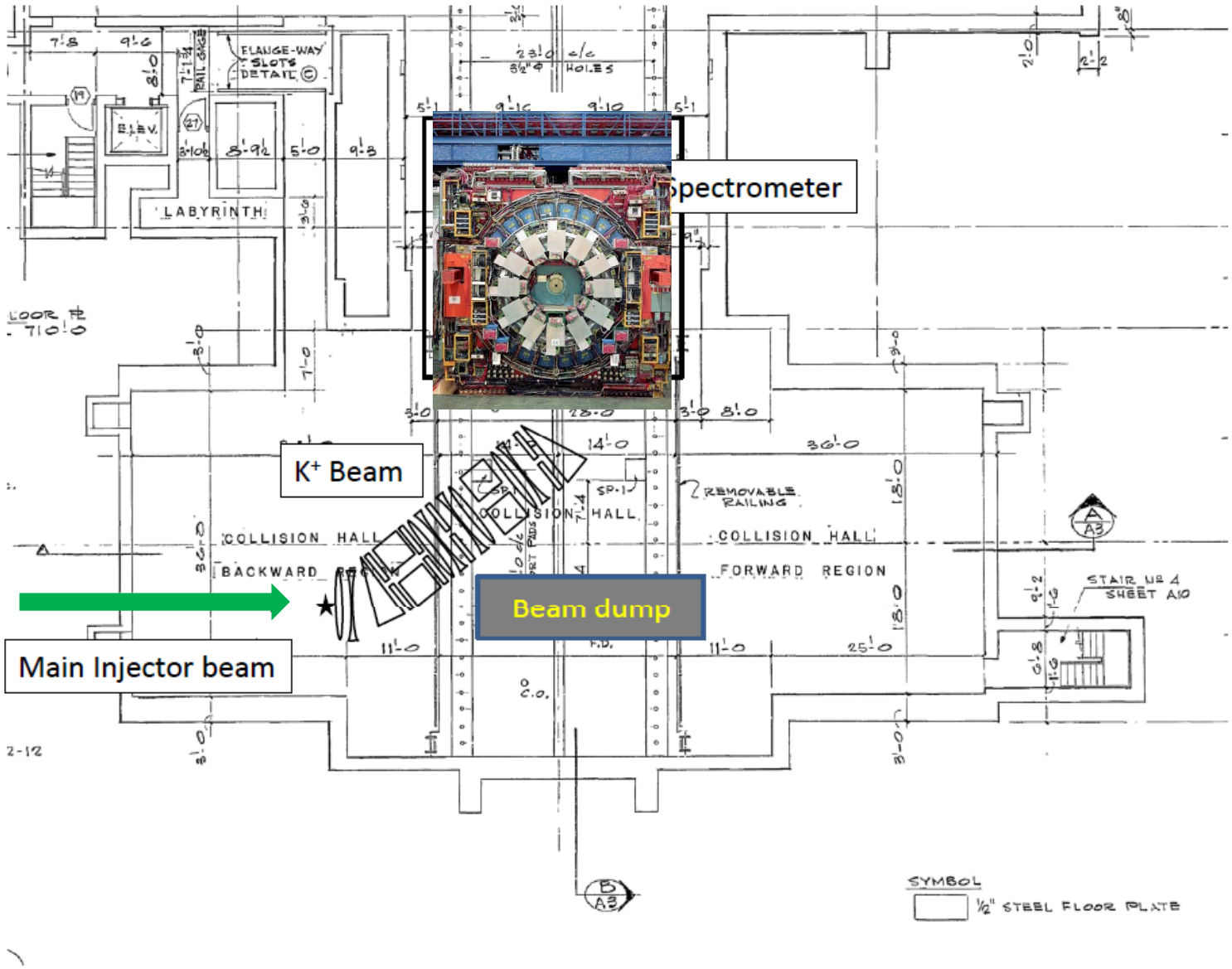
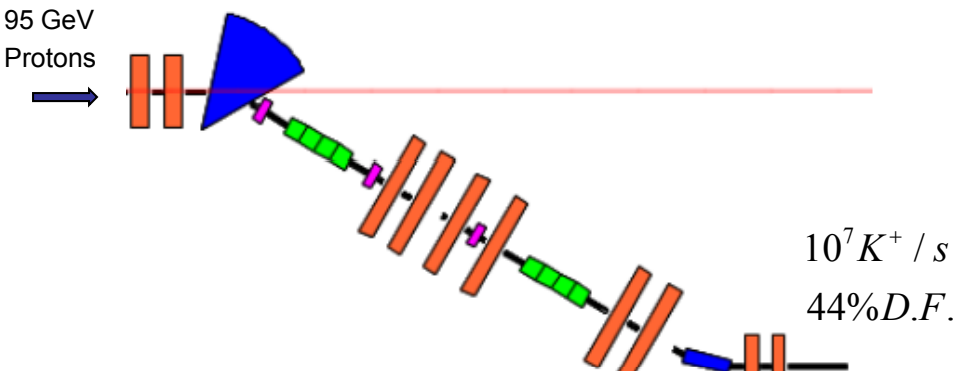


Figure 5.3: Illustration of the ORKA beam line and detector sited within the B0 collision hall.

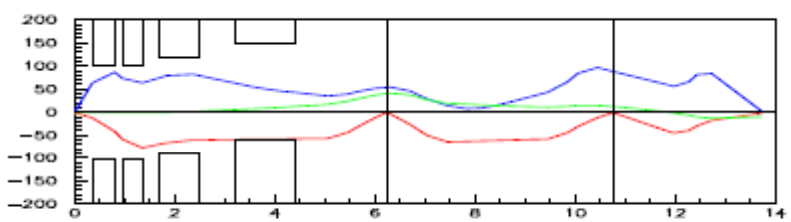
Kaon Beamline Design

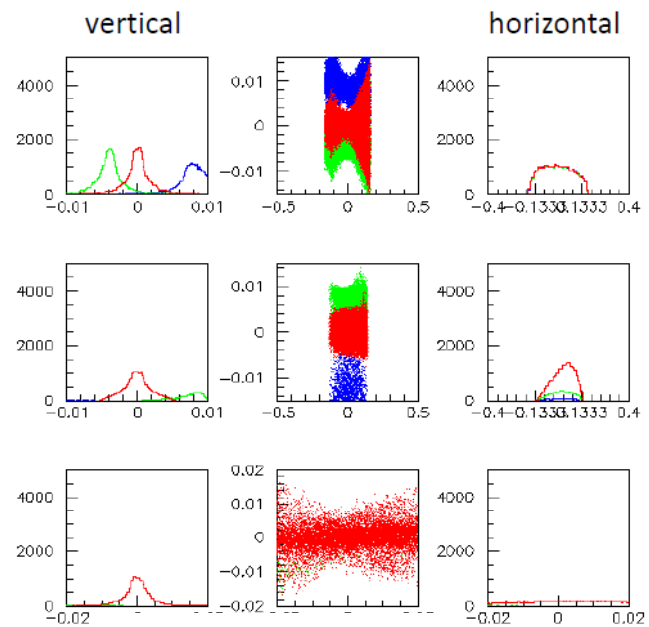
600 MeV/c separated K beam (**K/π~4**)
Measure kaon decays at rest.



$10^7 K^+ / s$

$44\% D.F.$



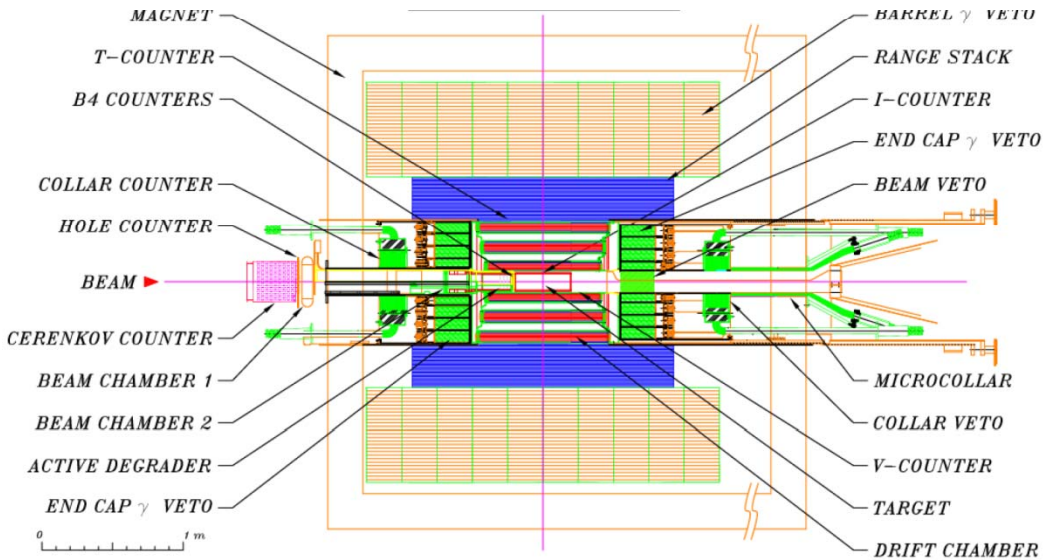


+/- 5% dp/p.
100,000 initial rays.

15% transmission.
0.5% contamination.

•T. Kobilarcik, D. Jensen (FNAL), et al.
G4Beamline studies

Evolution to 4th Generation Detector

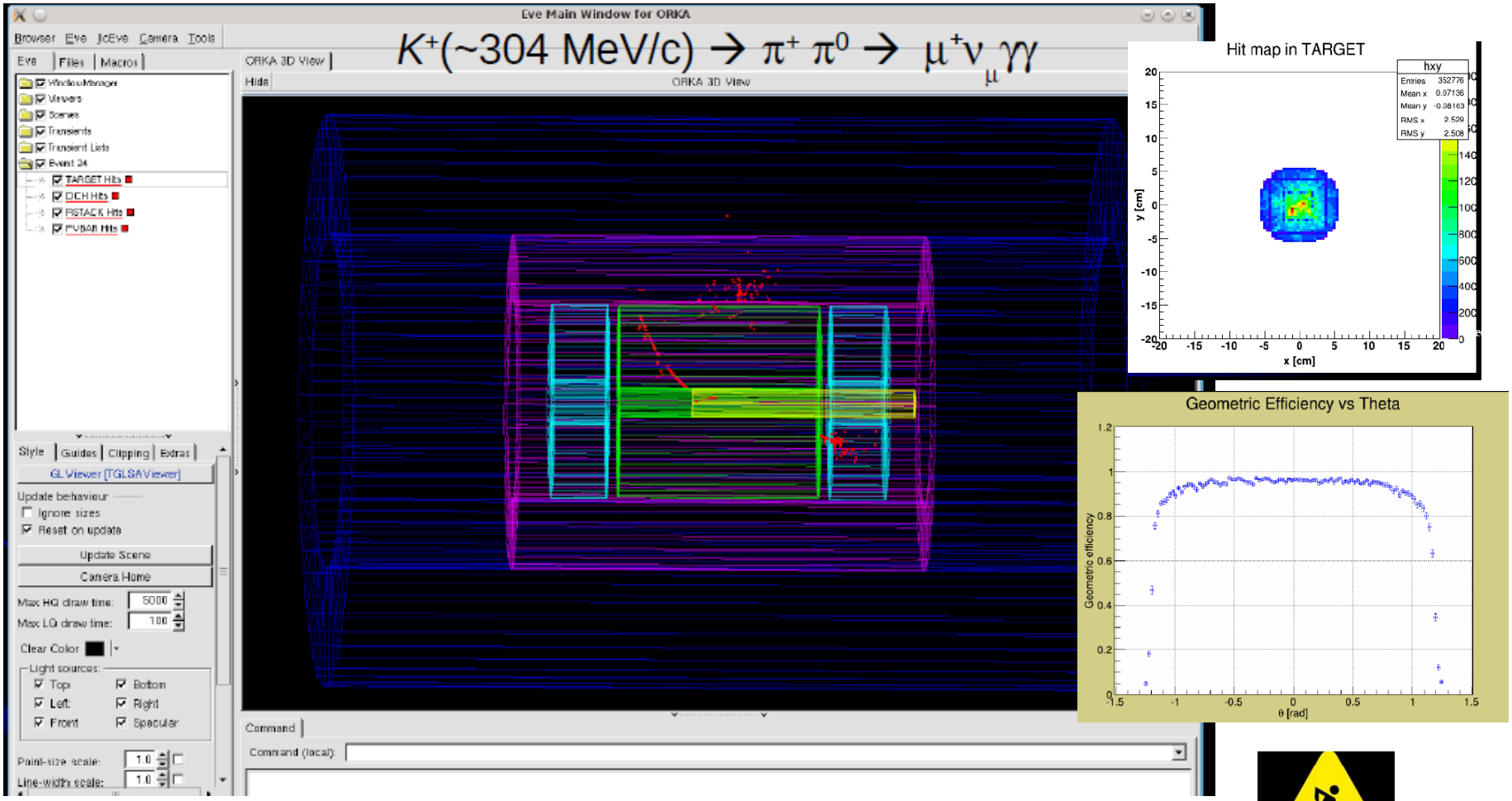


- *R & D* underway on detector refinements
  - Efficient photon detectors
    - Adriano (INFN), Shashlyik
  - Solid state photo-sensors -- SiPMs
  - Range stack tracking -- GEM
  - Low mass drift chamber design

- Simulations studies
  - ILCroot framework established
  - Range stack segmentation and readout
  - Photon veto geometry and function
  - Target segmentation and readout
  - Drift chamber parameters
  - Kaon beam line: G4Beamline

- Preliminary engineering concepts
  - Detector support in CDF magnet
  - Installation issues
  - Power, cooling and cabling issues

ILCroot Simulations



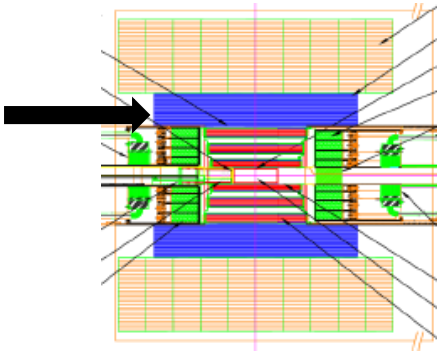
BNL/FNAL/INFN/TRIUMF-UBC

ORKA Detector improvements

Incremental increases in signal acceptance based largely on E787/E949 measurements.

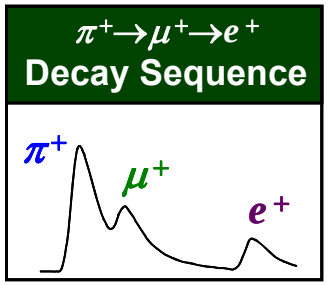
Component	Acceptance factor
$\pi \to \mu \to e$	2.24 ± 0.07
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	1.12 ± 0.05
Range stack segmentation	1.12 ± 0.06
Photon veto	$1.65^{+0.39}_{-0.18}$
Improved target	1.06 ± 0.06
Macro-efficiency	1.11 ± 0.07
Delayed coincidence	1.11 ± 0.05
Product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

Additional acceptance gains expected from trigger improvements.



$\pi \rightarrow \mu \rightarrow e$ Acceptance Factors

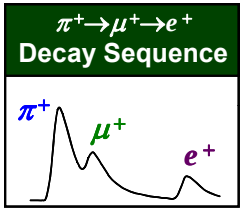
1. Identify range stack counter where π^+ stops
2. Detect $\pi \rightarrow \mu$ decay in stopping counter
3. Detect $\mu \rightarrow e$ in stopping counter and neighboring counters



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 $\pi \to \mu \to e$ 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: $\pi \to \mu \to e$ acceptance improvements; rudimentary $\pi \to \mu$ identification was an essential component of the $K^+ \to \pi^+ \nu \bar{\nu}$ trigger in E787/E949.

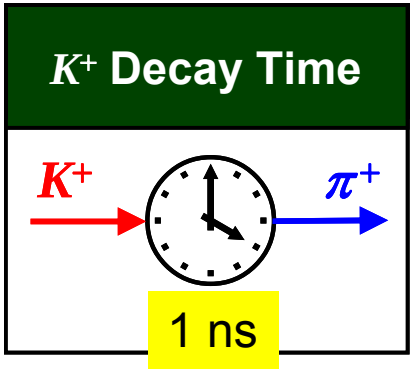
Livetime and Delayed-Coincidence Acceptance

Livetime	
E949 livetime	0.74
ORKA estimate	1.00
Acceptance increase	1.35

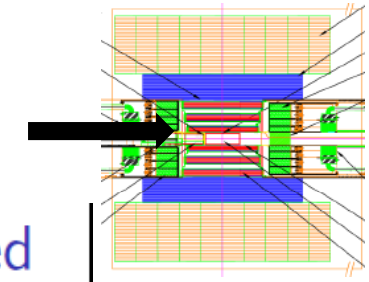
Macro-efficiency	
E949 average	0.76
E949 best week	0.84
MiniBooNE (FY08)	0.85
ORKA estimate	0.85 ± 0.05
Acceptance increase	1.11 ± 0.07

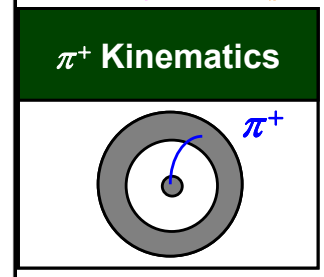
E949 required a delayed coincidence of 2 ns between the stopped kaon and the outgoing pion to suppress prompt backgrounds.

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

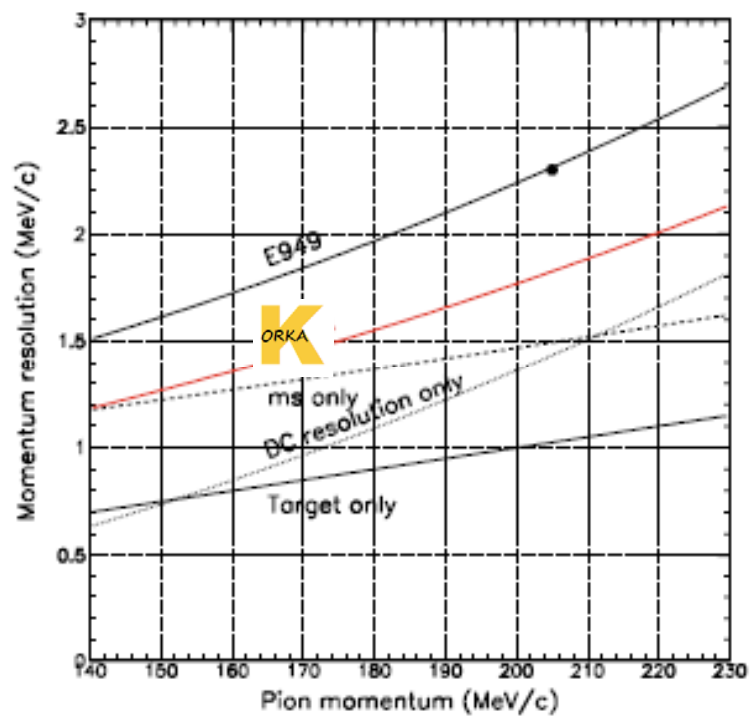


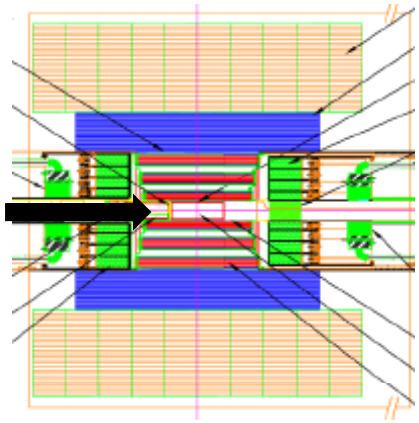


ORKA /E949 momentum resolution	0.90	Increase B from 1 T
Acceptance increase	1.12 ± 0.05	to 1.25 T
ORKA /E949 range resolution	0.87	
Acceptance increase	1.12	
E949/E787 energy resolution	0.	
Acceptance increase	1.	

Solid angle incr

	Drift chamber	Ran
E949	50.8	
ORKA	84.7	
Acceptance increase	1.38	



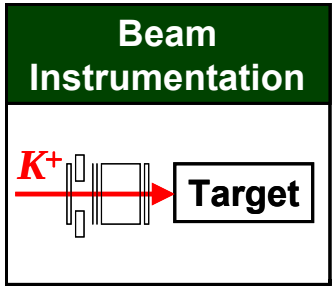


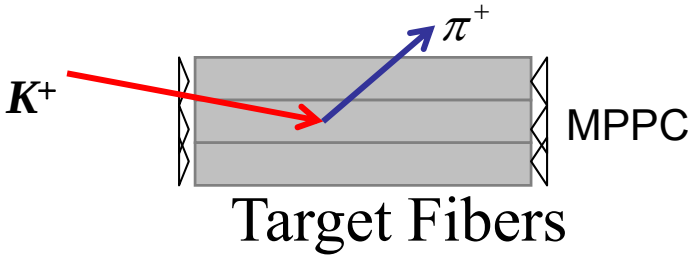
Scintillating Fiber Target

E949 3.1 m long, single ended readout

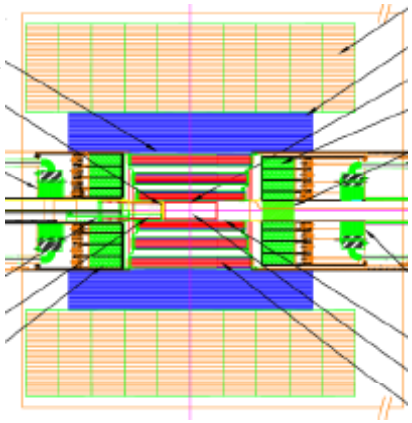
ORKA 1 m long, double ended readout, SiPMs

Acceptance Increase: 1.06±0.06





Photon Veto Improvements

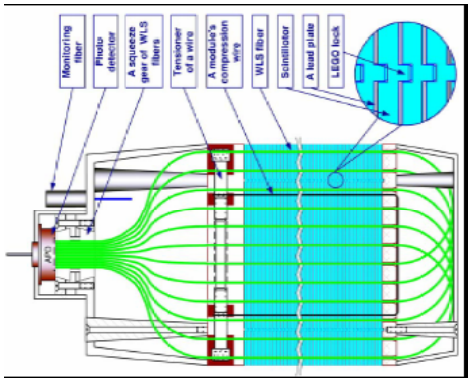


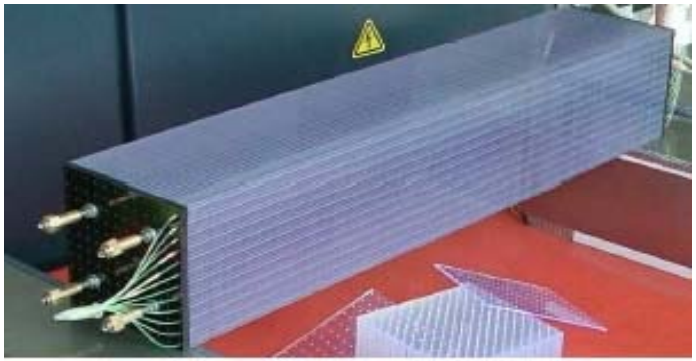
E949	17.3 Radiation Lengths
ORKA	23.0 Radiation Lengths

Acceptance Increase : $1.65^{+0.39}_{-0.18}$

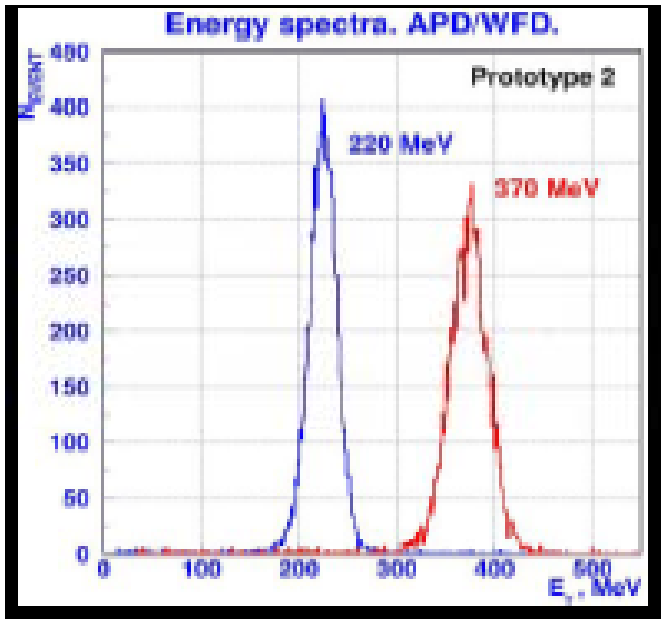
Estimate based on simulated KOPIO PV performance
Adjusted to agree with E949 PV efficiency.

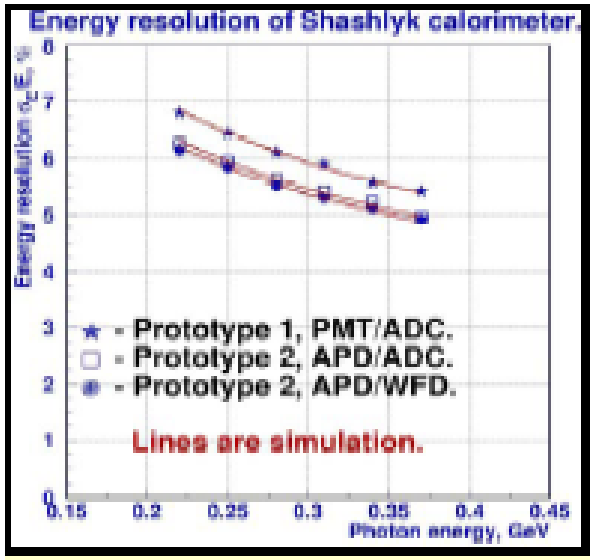
Shashlyk – Calorimeter Candidate for ORKA





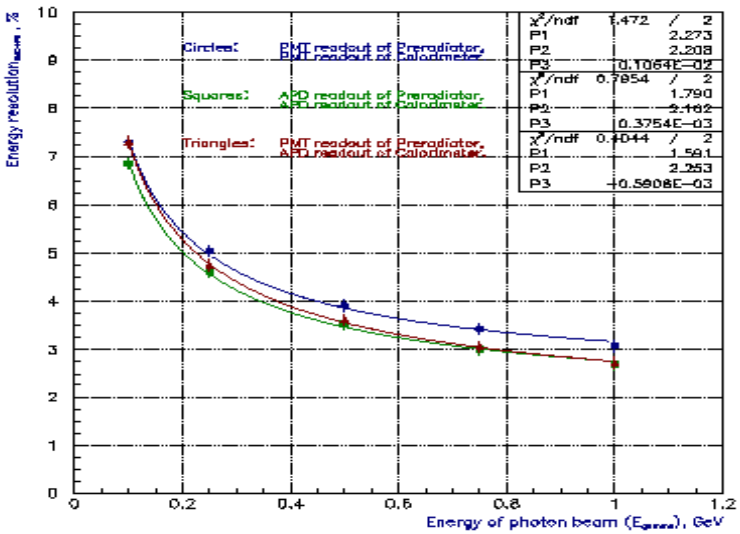
Shashlyk Beam Measurements





Simulation: Combined Energy Resolution

$$\sigma = \frac{2.7\%}{\sqrt{E(GeV)}}$$

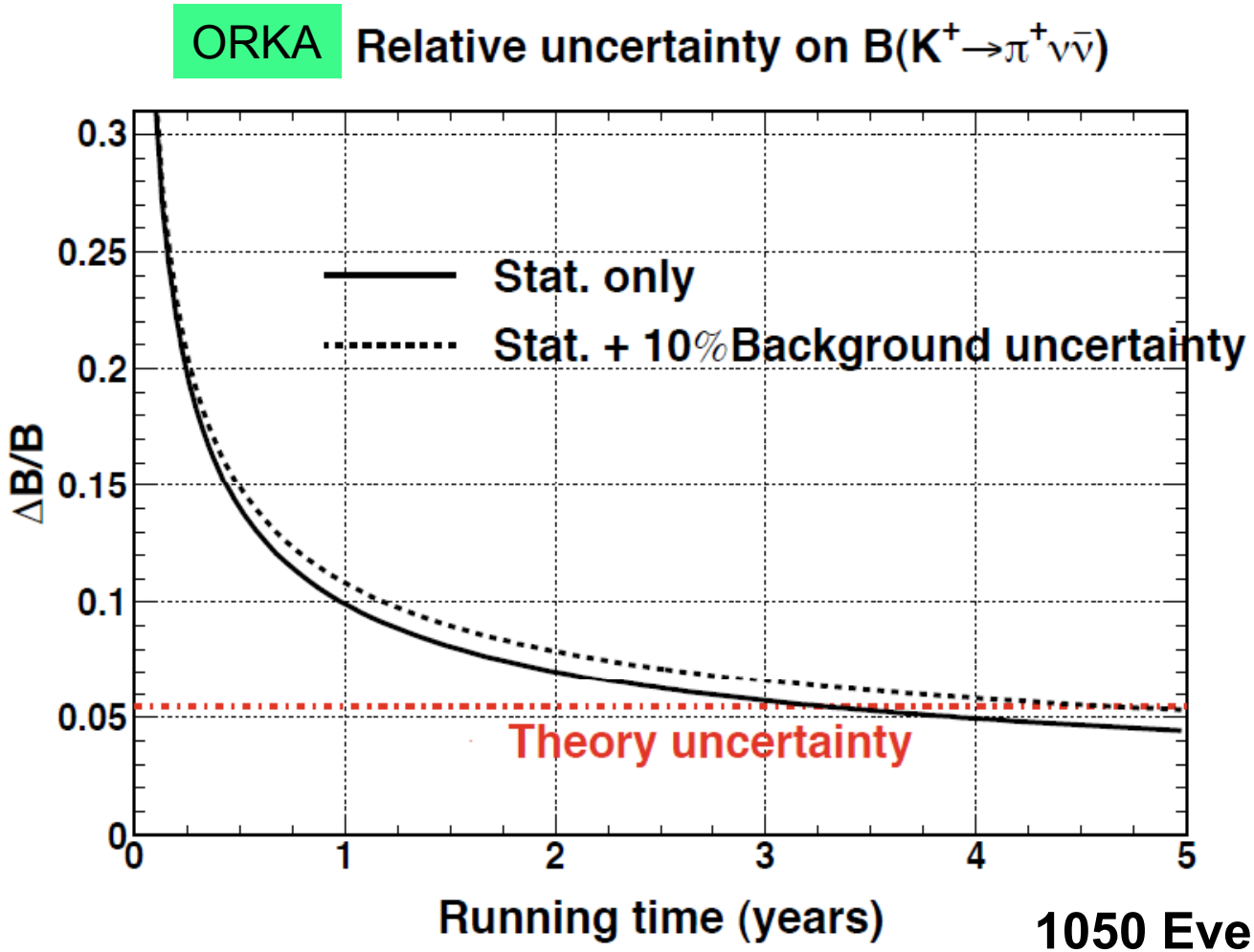


Comparison of ORKA and BNL E949

	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**

1050 Events at SM→<5% precision

ORKA Sensitivity *vs*. Time



1050 Events at SM

Selected ORKA Physics Opportunities

Processes that can be probed by ORKA.

Process	Current	ORKA	Comment
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events	
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$	$K^+ \to \pi^+ \nu\bar{\nu}$ is a background
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$	
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$	150 MeV $< m_\nu <$ 270 MeV
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$	
$K^+ \to \pi^+ \gamma\gamma$	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 $< 4 \times 10^{-9}$	depending on tech nique
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$	

E787/E949: 42 publications, 26 Theses

KTEV: 50 publications, 32 Theses

$K \to \pi\nu\bar{\nu}$ Prospects

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

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

(7 events)

Future: Sensitivity at SM $(0.78 \pm 0.08)x10^{-10}$

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

Now: $B(K_L^0 \to \pi^0\nu\bar{\nu}) < 2.6\,x10^{-8}$

Future: Sensitivity at SM $(2.5 \pm .4)\,x10^{-11}$

Goals	NA62 CERN	ORKA	Proj.X FNAL
Events/ yr	50	210	500
S/N	5	5	5
Precision	10%	5%	3%

>30% deviation→ >5σ signal of NP

Goals	KOTO* J-PARC	Proj.X FNAL
Events/yr	~1	"200"
S/N	~1	5-10
Precision		5%

* J-PARC plans a phase II to reach higher sensitivity.