Future experiments on rare Kaon decays

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*member of the KLOE and NA62 collaborations

Kaon physics results in this conference

SM flavor test: V_{us}	$K_{S,L}$ lifetimes – KLOE	M. Dreucci
	$K_{\mu 3}$ form factors – NA48	M. Ita-Hochgesand
	V_{us} determination from Kaons	C. Bloise
SM flavor tests	Lattice inputs for V_{us}, V_{us}/V_{ud}	V. Lubicz
SM flavor test: LFV	$K_{e2}/K_{\mu 2}$ – KLOE	B. Sciascia
	$K_{e2}/K_{\mu 2}$ – NA62	A. Sergi
Rare K decays Chiral pert. theory	Rare decays from NA48 & KLOE	G. Anzivino
	Kaon radiative decays - NA48	M. Pepe
	ππ scattering from K_{e4} decays - NA48	C. Biino

Kaon physics – the landscape

Kaon is the lightest strange particle, studied since 60's to test fundamental properties of nature

SM @ E ~ M_K appears remarkably simple:

$L_{SM} = L_{QCD}(m_u{=}m_d, m_s) + L_{QED} + L_{IB}(m_u{-}m_d) + L_{ew}$

only 2 parameters in L_{QCD}: m_s and $m_d \sim m_u \sim (m_d+m_u)/2$

L_{QED} and L_{IB} isospin-breaking: often neglected, but add 3rd parameter

L_{ew} is the link to physics at electroweak scale

breaks many symmetries: P, CP, flavor

Kaons reach the highest sensitivities to CPT violation, QM tests

Competitive with B decays to test new physics in LFV or CPV transitions

CPV from K decay: still a stringent NP test

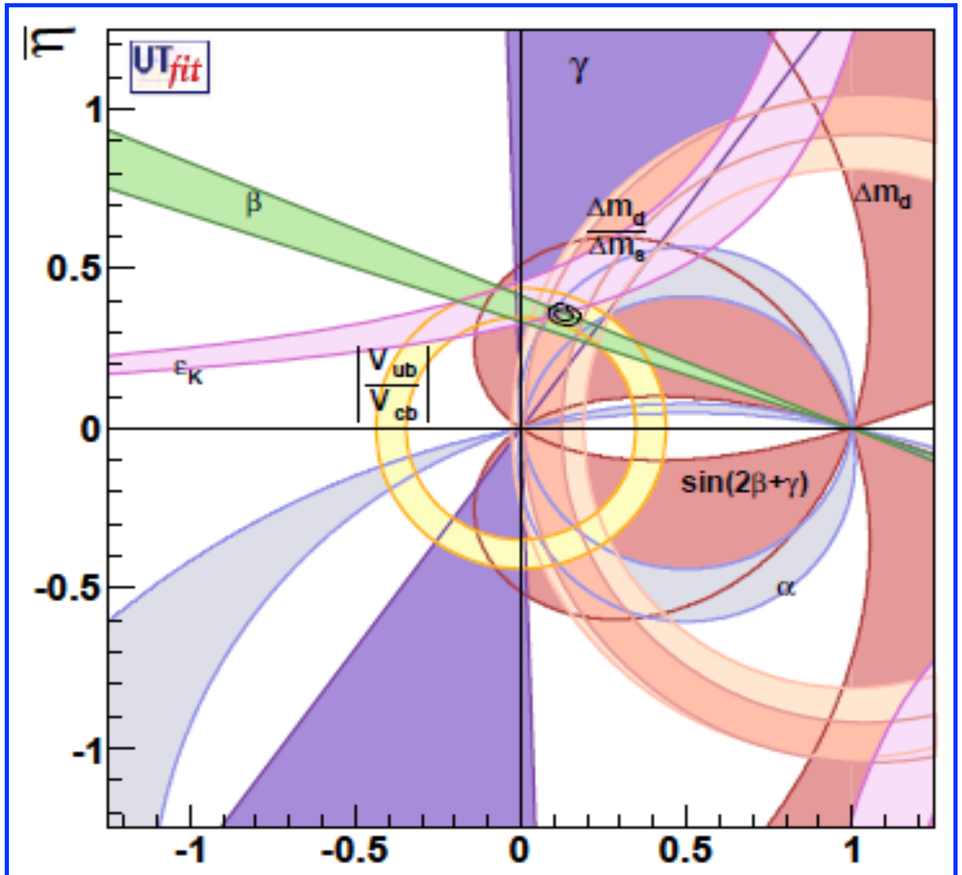
After 20 years of precision physics:

Indirect CPV, $|\varepsilon| = (2.223 \pm 0.010) \times 10^{-3}$

Direct CPV, $R(\varepsilon'/\varepsilon) = (16.8 \pm 1.4)10^{-4}$

$Re(\varepsilon'/\varepsilon) \propto Im(V_{td}V_{ts}^*)$, but for a NP test need to precisely evaluate K--ππ ΔS=1 hadronic elements, a future task for lattice calculations

After guadagnoli et al., $R(\varepsilon'/\varepsilon)$ used for evaluation of expected value of $|\varepsilon|$



From C. Tarantini talk

See M. Gorbahn talk

Dramatic recent improvements in lattice input to theoretical expectation of |ε|

Exp ~ 2σ away wrt expectation…but better discuss unanbiguous NP signals

LFV: search for NP signals from K decays

Try to isolate LFV transitions, forbidden/ultra rare in SM

Sensitivity ~ up by × 10^2 per decade

Limits determined by statistics

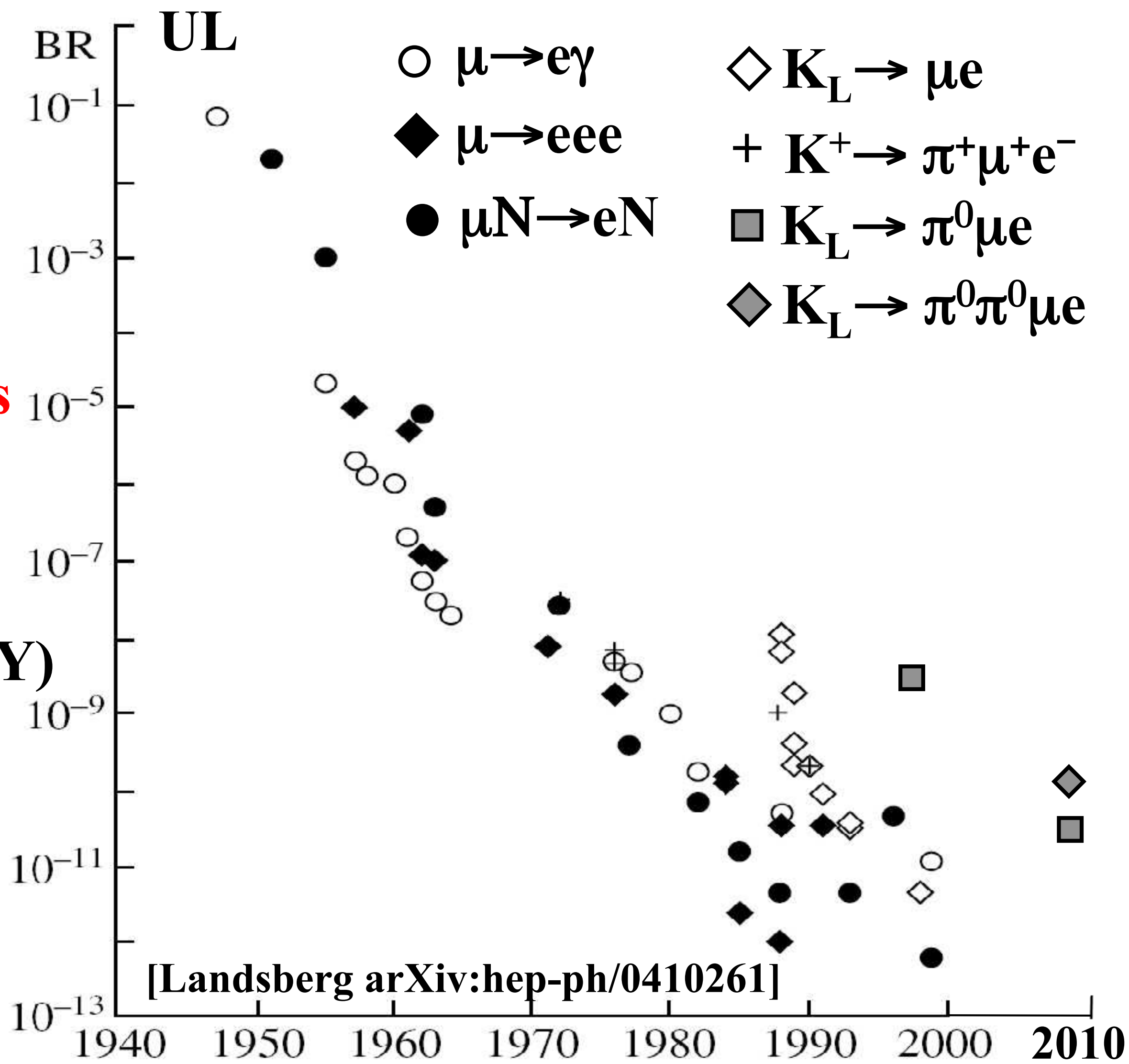
NP with < ~100 TeV mediator masses ruled out (some model dependence: Technicolor, SUSY)

Cfr. also:

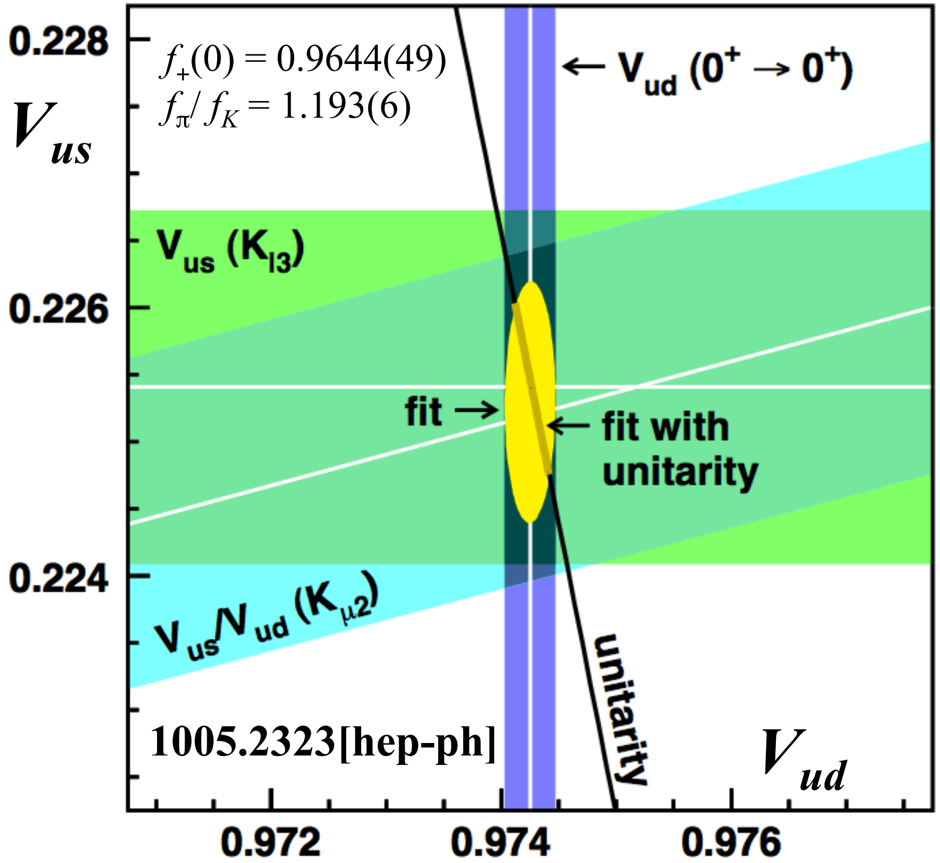
μ→eγ @ MEG → Y. Uchiyama

μN→eN future expts → S. Mihara

τ→ e/μ γ, lh, ll^+l^- @ B factories → A. Lusiani



Universality of ew couplings: a precise NP test



Fit (no CKM unitarity constraint):

$V_{ud} = 0.97425(22)$

$V_{us} = 0.2253(9)$

$\chi^2/\text{ndf} = 0.14/1\ (91\%)$

$1 - V_{ud}^2 - V_{us}^2 = -0.0001(6)$

Tests universality of lepton/quark couplings:

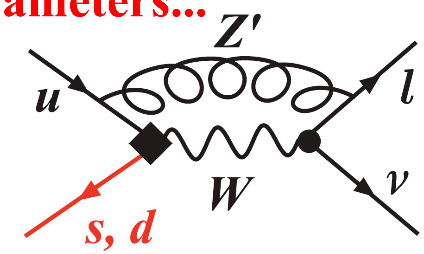
$$G_\mu = 1.166371(6)\times 10^{-5}\ \text{GeV}^{-2}$$

$$G_{CKM} \equiv G_\mu [V_{ud}^2 + V_{us}^2 + V_{ub}^2]^{1/2} = 1.16633(35)\times 10^{-5}\ \text{GeV}^{-2}$$

Next most precise value for G_F - better than τ decays, EW parameters...

Probing mass scales: O[1TeV] loop level
O[10 TeV] tree level

Constrains models: Z' boson, SUSY, technicolor…



Marciano 2007

Kaon physics to test H^+ exchange: K_{l2}/π_{l2}

Test performed by measuring : $\left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})} \right|$ **= 0.999(7)**

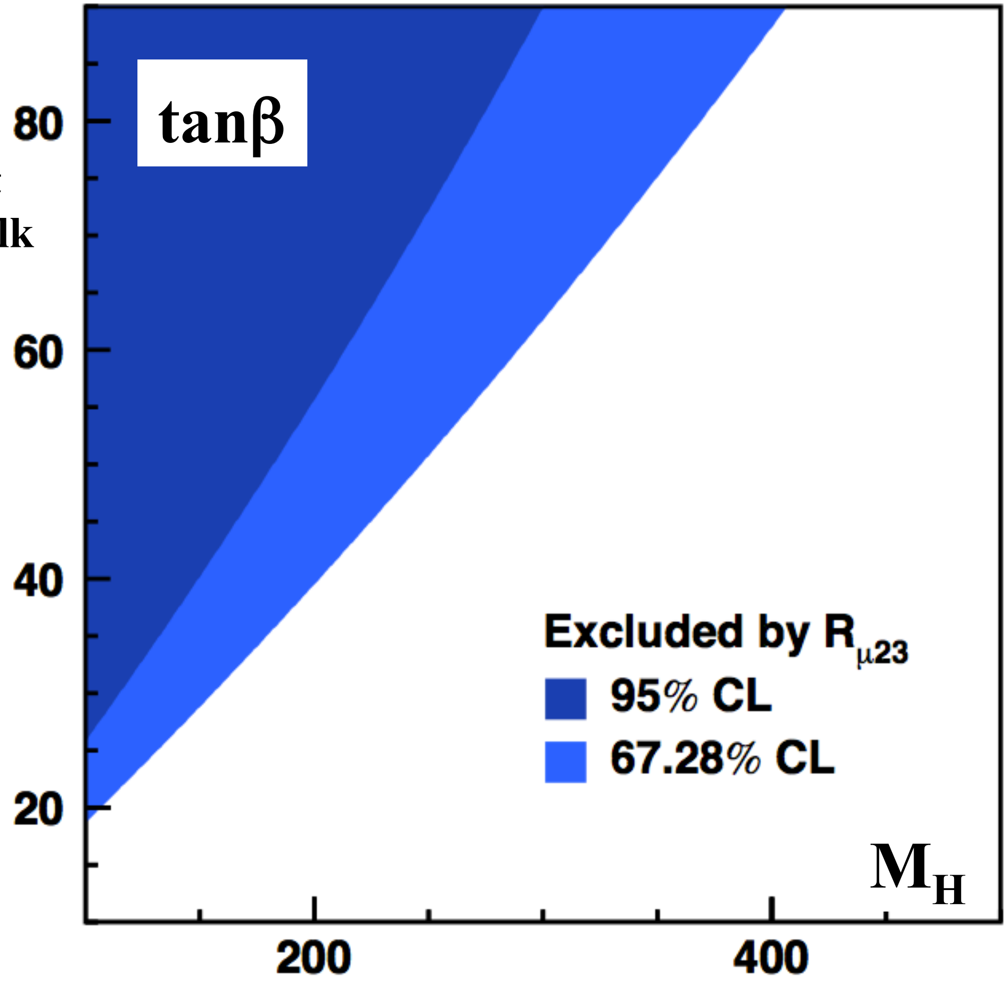
NP sensitivity from K→ μν ~ as that from BR(B → τν) = 1.64(34)×10^{-4}

For Belle and Babar updates and a combined fit in 2-Higgs doublet models, see D. Lindemann talk

Exclude the region @low M_H and high tanβ favored by B → τν

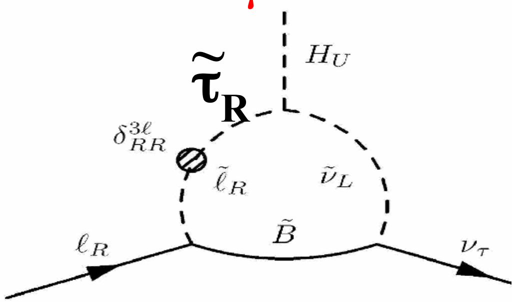
Error dominated by theoretical uncertainties in form factors

NP induced by weak right-handed currents can be also tested (there, complement lattice information with Callan-Treiman scalar ff constraint)
[FlaviaNet arXiv:0801.1817]

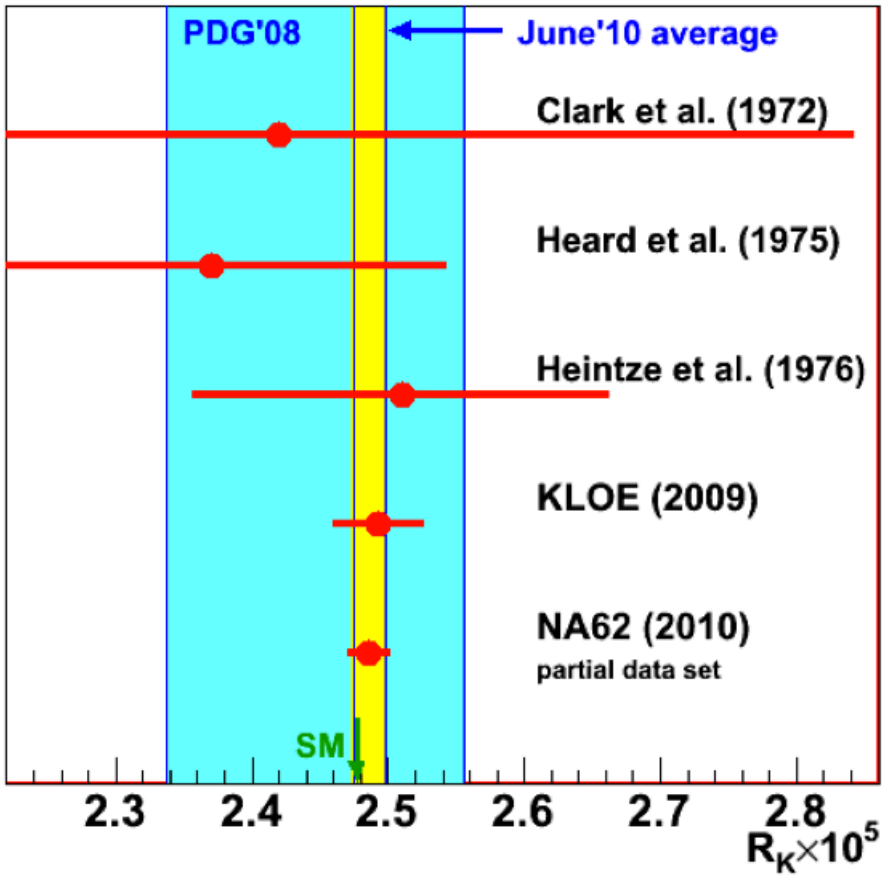


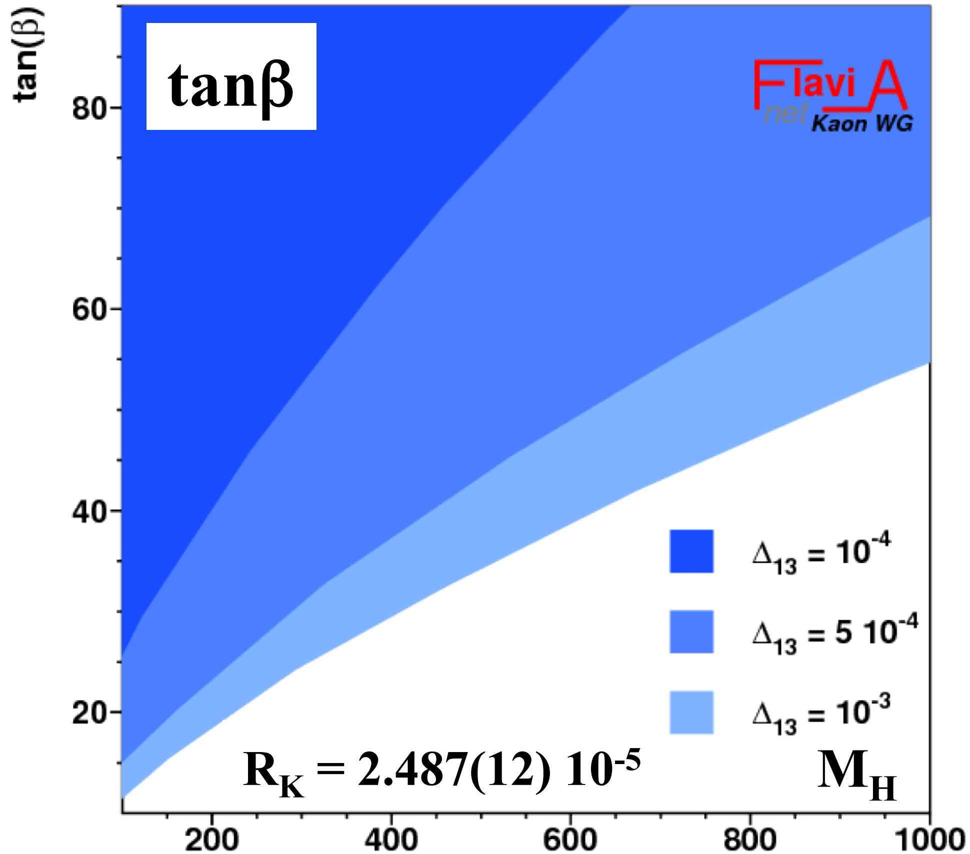
New-physics potential of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ *

Cpr. WA with: $R_K^{SM}\left[1+\left(\frac{m_K}{m_H}\right)^4\left(\frac{m_\tau}{m_e}\right)^2|\Delta_{13}|^2\tan^6\beta\right]$



***See dedicated talk by A. Sergi**



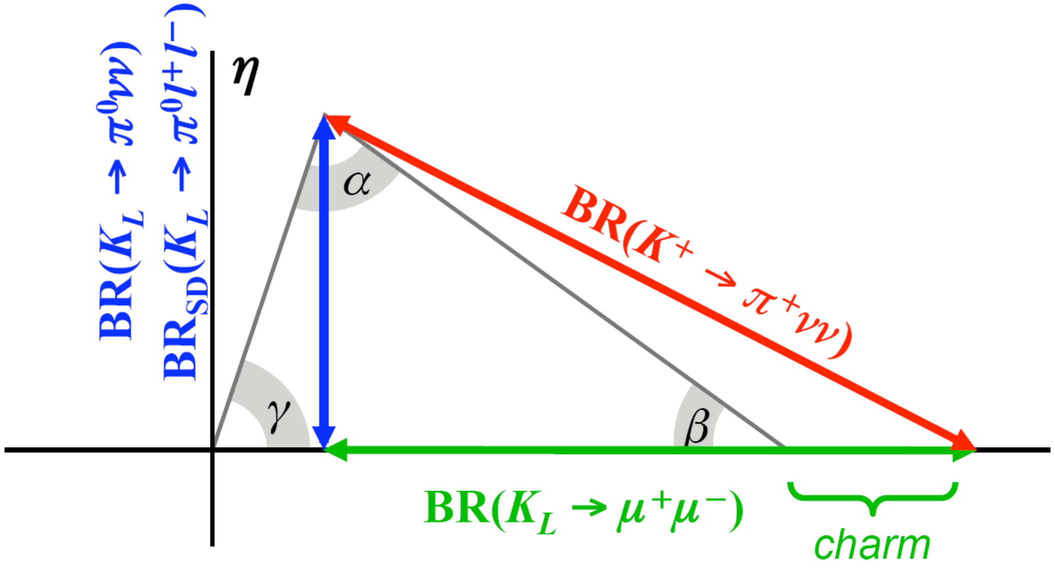


Golden K modes for new-physics search

FCNC processes dominated by Z penguin and box diagrams

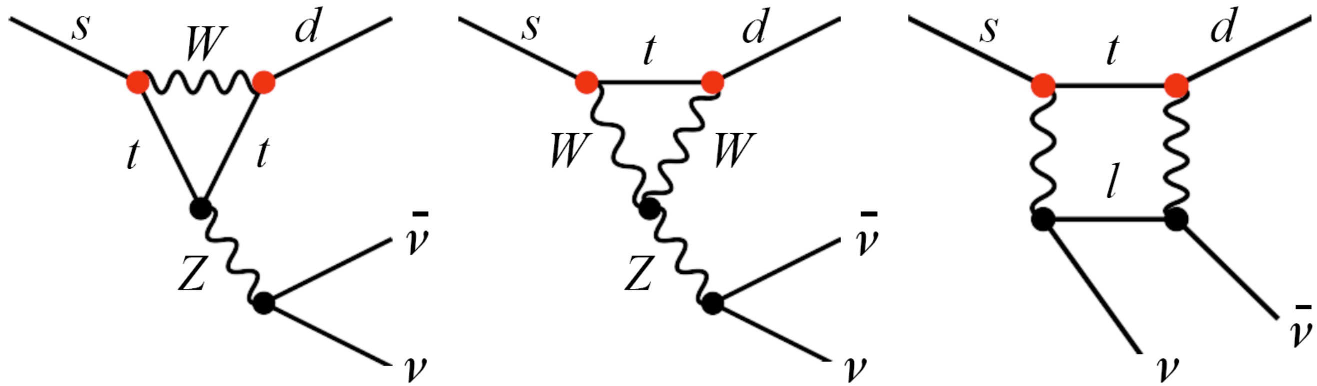
Can give direct information on CKM matrix elements:

- **No long distance contributions fron processes with intermediate γ's**
- **Hadronic matrix elements can be obtained from BR's of leading K decays**
- **$K_L \to \pi^0\nu\nu$ is nearly pure CPV**



	Γ_{SD}/Γ	Irreducible theory err. (amp)	SM BR
$K_L \to \pi^0\nu\nu$	>99%	1%	3×10^{-11}
$K^+ \to \pi^+\nu\nu$	88%	3%	8×10^{-11}
$K_L \to \pi^0 e^+ e^-$	38%	15%	3.5×10^{-11}
$K_L \to \pi^0 \mu^+ \mu^-$	28%	30%	1.5×10^{-11}

SM prediction for $K \to \pi\nu\nu$



SM prediction [Buras et al., Mescia and Smith, Brod and Gorbahn]

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right] = 8.5(7) \times 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 = 2.6(4)\times 10^{-11}$$

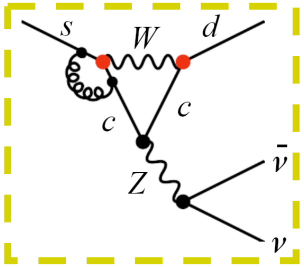
, where $x_q \equiv m_q^2/m_W^2$ **and**

$$\lambda = V_{us}, \quad \lambda_c = V_{cs}^* V_{cd}, \quad \lambda_t = V_{ts}^* V_{td}$$

Loops favor top contribution

Hadronic matrix elements from BR(Ke3) via isospin rotation:

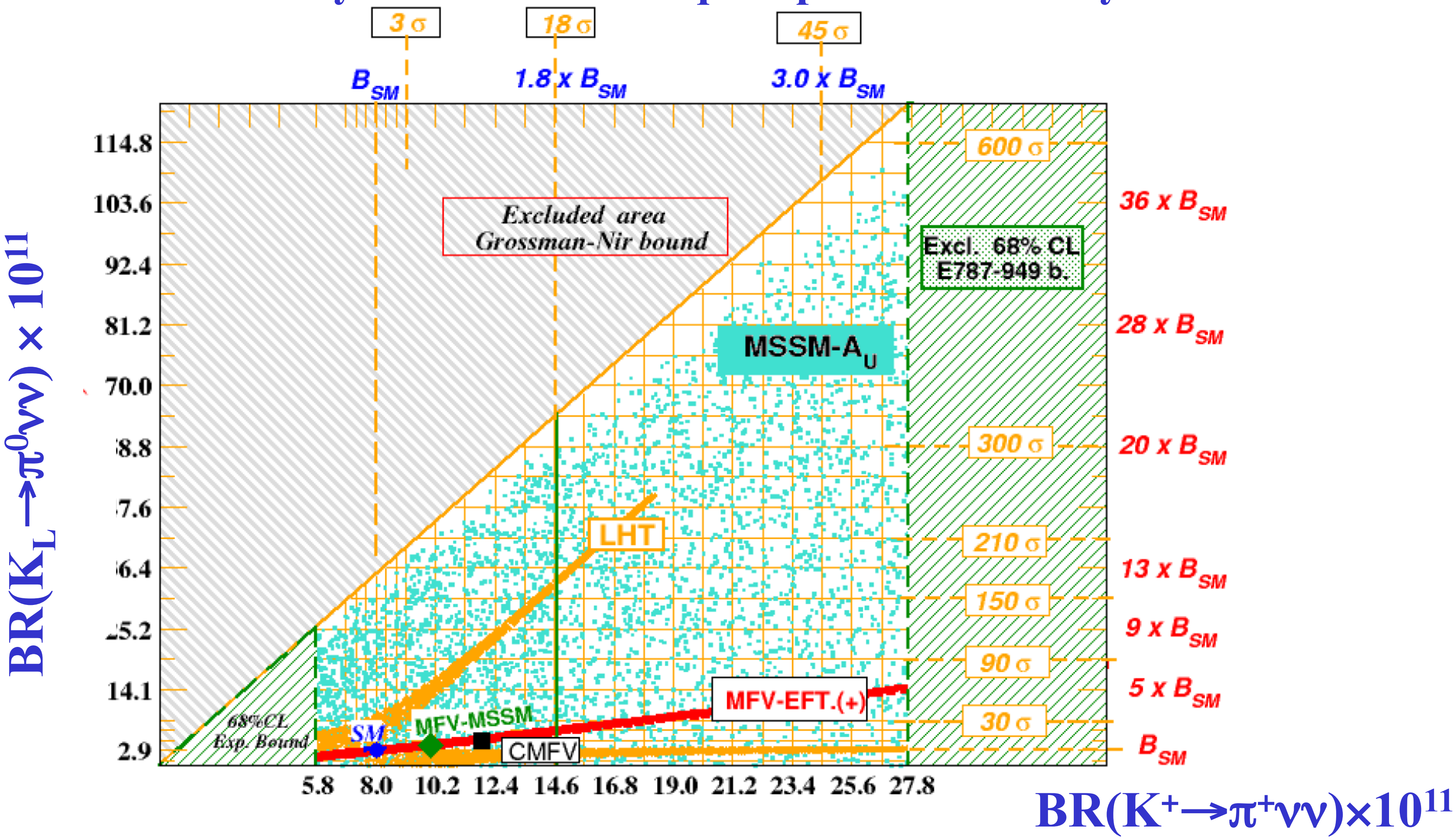
$$\kappa_+ = r_{K^+} \frac{3\alpha^2\, \mathrm{BR}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \lambda^8$$



Charm contribute to theory error: non-parametric error ~7% for K^+, 3% for K_L

SM and BSM prediction for $K \rightarrow \pi\nu\nu$

Deviations from SM by more than 10% quite possible in many NP models



General notes on $K_L \to \pi^0 \nu\nu$ searches

Essential signature: "2γ + nothing"

All other decays have 2 extra γ or 2 tracks

Exception: $K_L \to \gamma\gamma$, not a big problem since $p_\perp = 0$, $\phi_{12} = 180^\circ$

Main backgrounds:

$K_L \to \pi^0\pi^0$ with 2 lost γ ➡ Hermetic veto, including beam exit

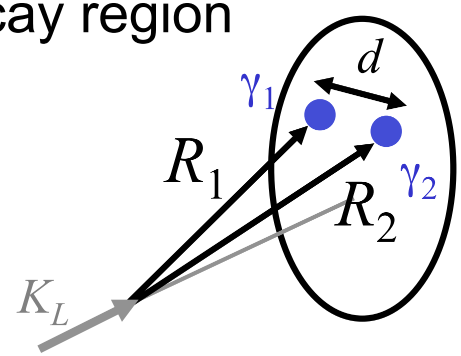
n + gas → $X\pi^0$, $X\eta$ ➡ High vacuum decay region

$M(\gamma\gamma) = m_{\pi 0}$ is the only sharp kinematic constraint

Generally used to reconstruct vertex position

Additional topological constraints advantageous:

- Small beam cross section
- Measurement of photon directions
- Microbunched beam for TOF constraints



$$m_{\pi^0}^2 = 2E_1E_2\,(1-\cos\theta)$$

$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1E_2}}{m_{\pi^0}}$$

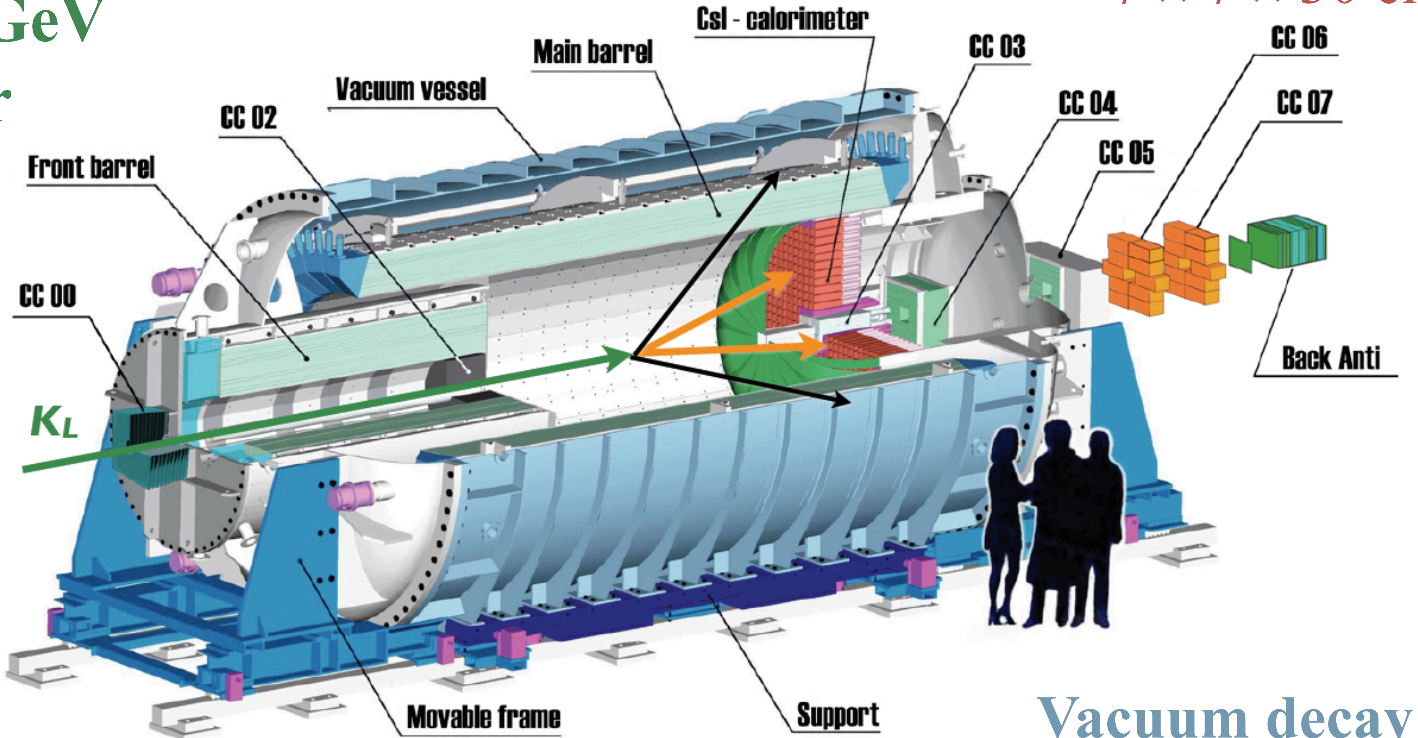
Veto system performance & experiment design are paramount

KEK 391a: 1st dedicated $K_L \to \pi^0 \nu\nu$ search

Neutral secondary beam from 12 GeV KEK PS
Pb and Be filters to screen γ, *n*

Forward photon veto
Pure CsI crystals
$7 \times 7 \times 30$ cm^3

p(K_L) ~ 2 GeV at detector



Vacuum decay volume
10^{-7} mbar

Collimated to "pencil beam"
Geometric constraint for π^0 vertexing
Halo suppressed to 10^{-4} at $r = 4$ cm

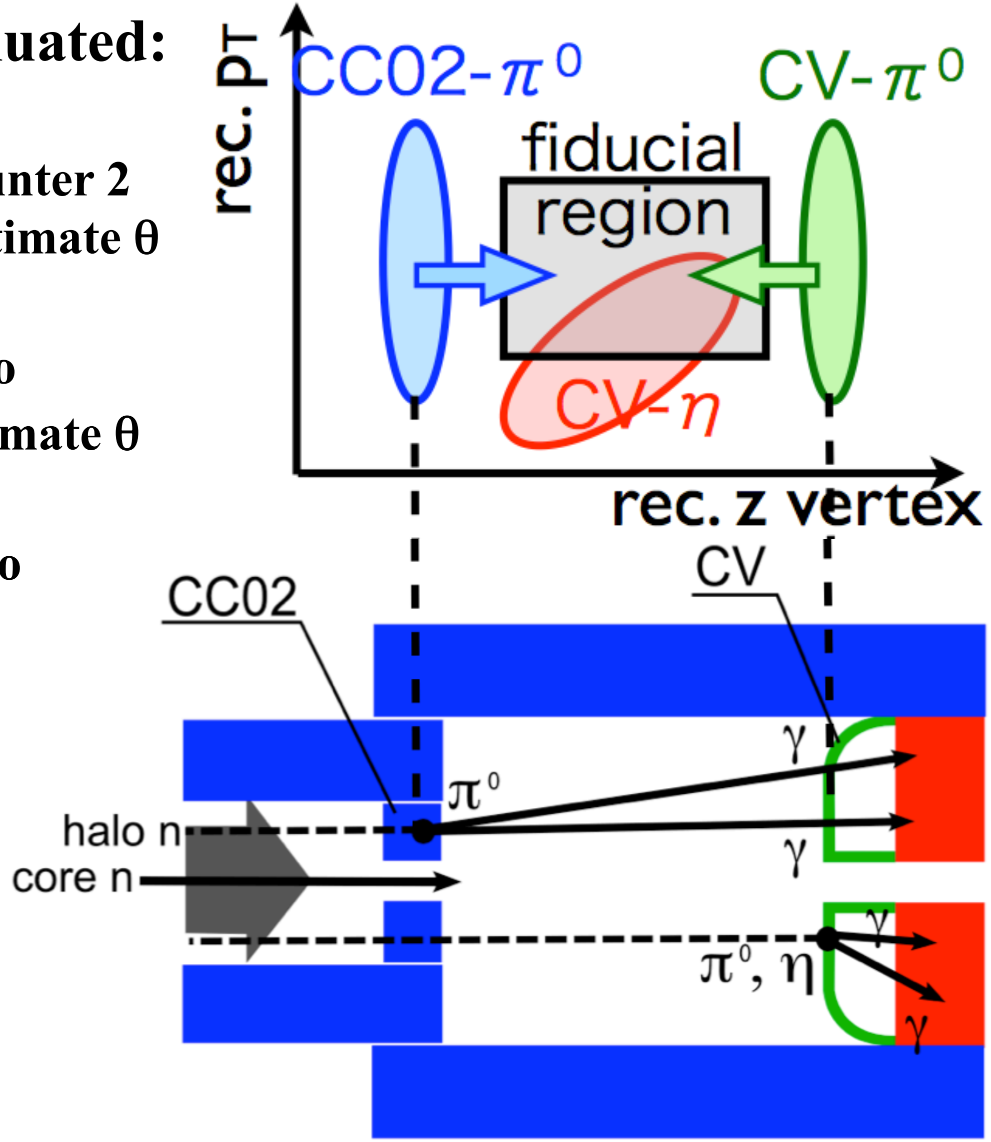
Background sources: neutrons in beam

Background sources carefully evaluated:

CC02: halo n's produce π^0's in Collar Counter 2 underestimate E_i (γ-N, leakage), so overestimate θ

CV-π^0: halo n's produce π^0's in Collar Veto overestimate E_i (γ-γ merging) so underestimate θ

CV-η^0: halo n's produce η^0's in Collar Veto wrong π^0 constraint, so underestimate θ

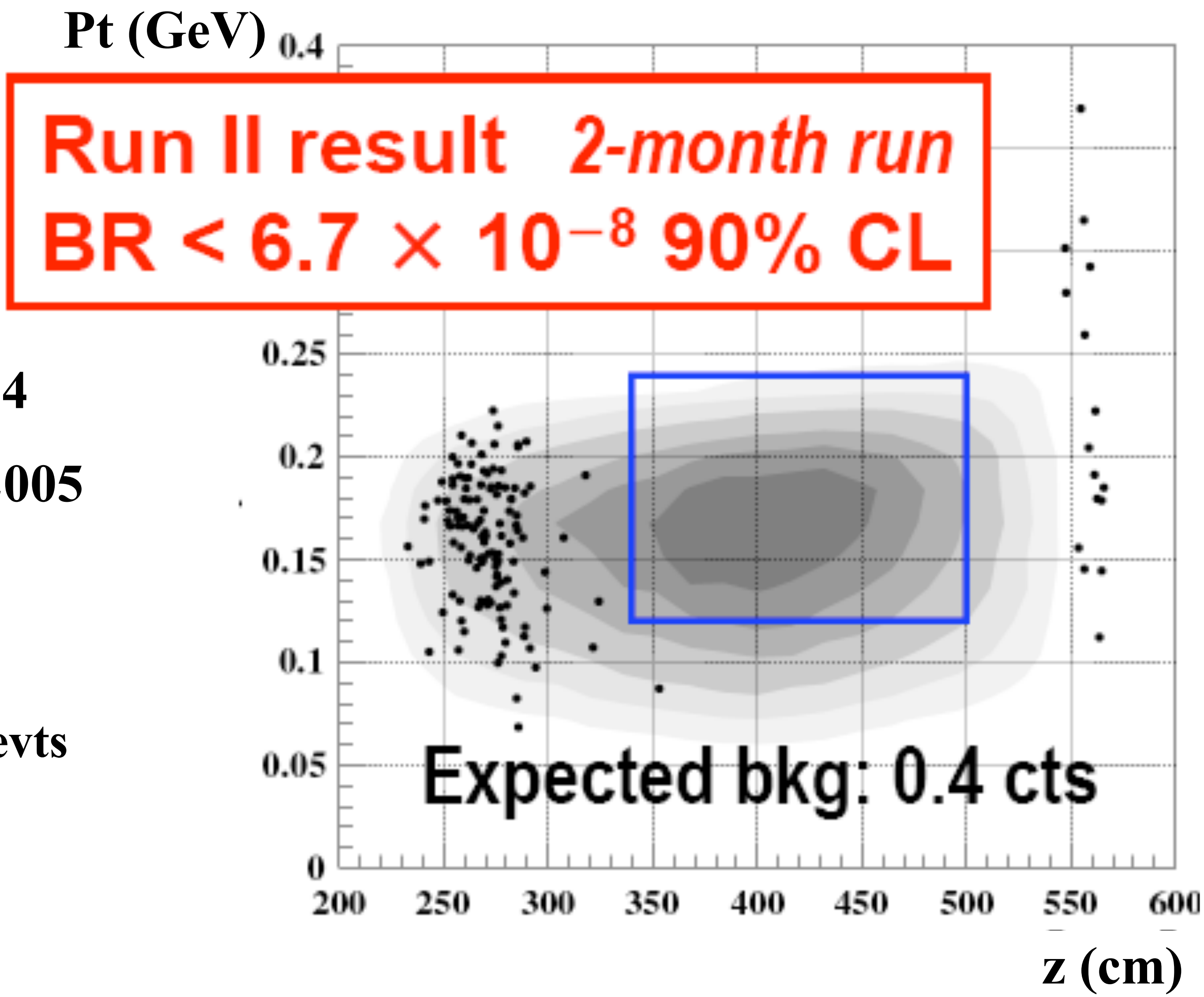


The road to sensitivity improvement: Run I-II

Run I: Feb - Jul 2004

Run II: Feb - April 2005

- 1.4×10^{18} POT
- K_L flux of 5×10^9
- Expected bkg: 0.4 evts



The road to sensitivity improvement: Run III

Run III: Nov - Dec 2005, K_L flux: 3.5 x 10^9 (0.7 of Run II: 5.0 x 10^9)

Improvements on RunII:

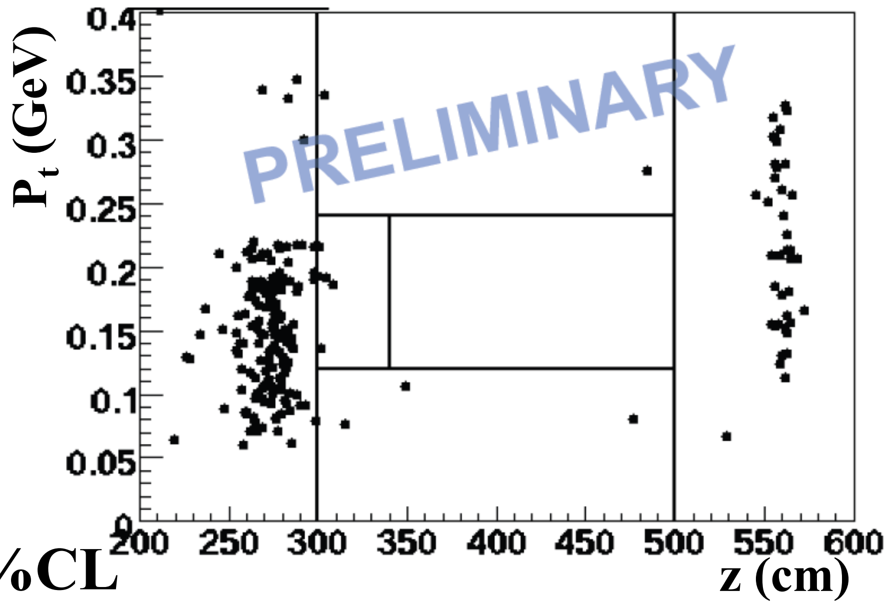
Special run with Al target, for MC tuning

Optimize event selection:

Acceptance 0.975(67)% (Run II: 0.670%)

Better background evaluation

source		estimated BG
K_L	$K_L \to 2\pi^0$	0.14 ± 0.05
	$K_L \to \pi^- e^+ \nu$	4.7(±0.7) x 10^{-3}
halo-n	CC02 π^0	0.15±0.05
	CV π^0	0.0 (<0.15)
	CV η	0.14 ± 0.07
total		0.44 ± 0.10



Run III SES (preliminary): 2.95 10^{-8}

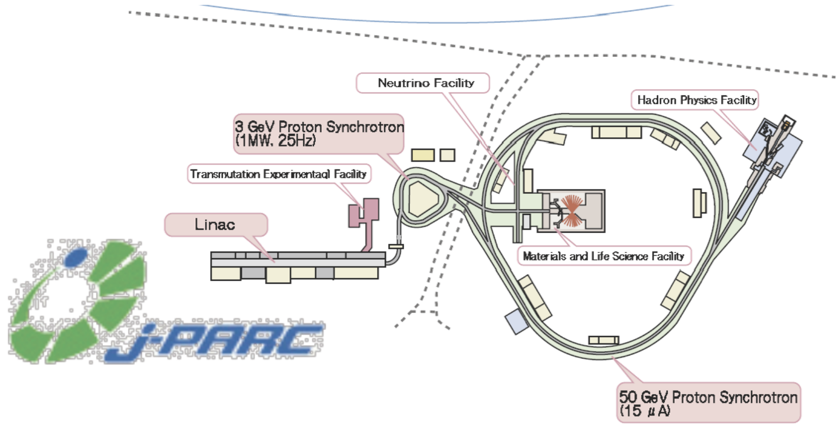
No events found in the signal box:

$B(K_L \to \pi^0 \nu\nu)$ < 6.8 10^{-8} @ 90% CL (prel. 2009)

Run II—III comb.: BR < 2.6 /10^{-8}, 90%CL

The future for $K^0 \to \pi^0 \nu\nu$, K^0TO (aka E14)

E391a as R&D for KOTO @ J-Parc



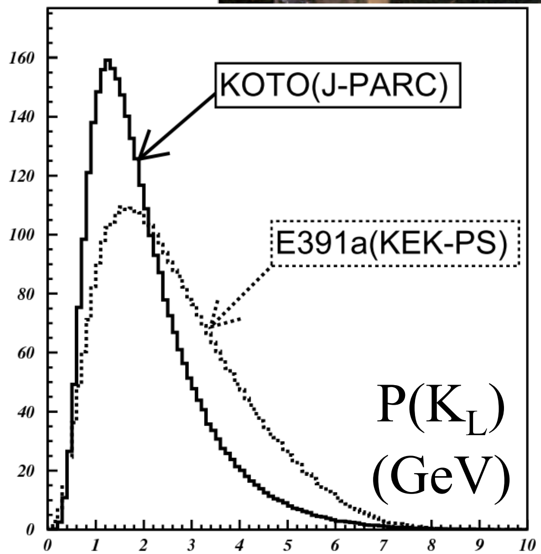
Wrt E391a: ×10 K_L beam, ×10 acceptance, ×10 running time

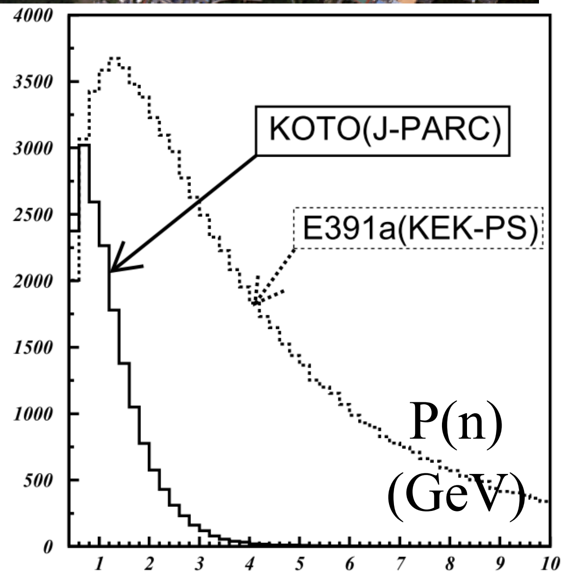
30 GeV primary beam

2 10^{14} ppp, 20-m K1.1 beam line

Core/halo, $10^{-4} \to 10^{-5}$

Neutron/K_L, 40 → 7

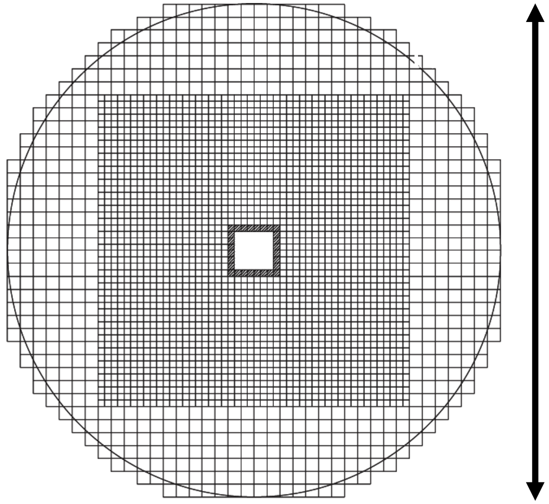




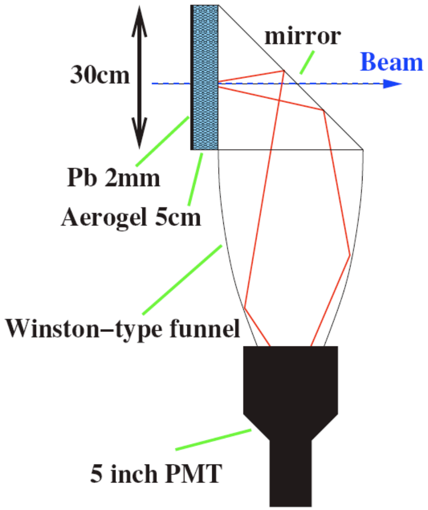
Detector upgrades for E14

Replace E391a CsI with KTeV CsI:

7×7×30 cm³ → **2.5×2.5×50 cm³**, **5×5×50 cm³**

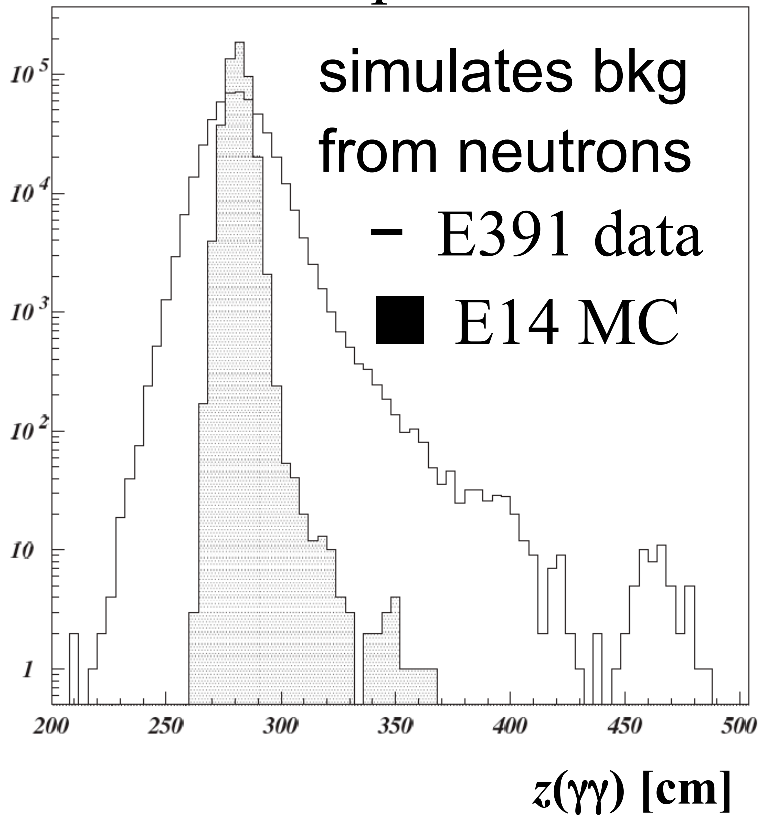


Better segmentation
Less γγ merging
Less punch-through
Less leakage



Pb/aerogel in-beam photon veto

π^0 from Al plate in beam



New veto counters around beam holes
High-rate electronics

Upgrade summary for E14 vs E391a

	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.	4%	2%	x2
Acceptance	3.6%	1%	x3.6
Sensitivity	0.8×10^{-11}	1.1×10^{-8}	x1300

Schedule:

2009, construction & survey of K_L beamline

2010, construction of CsI calorimeter & engineering run

2011, 1st physics run: 3-7 SM evts/ 3 years

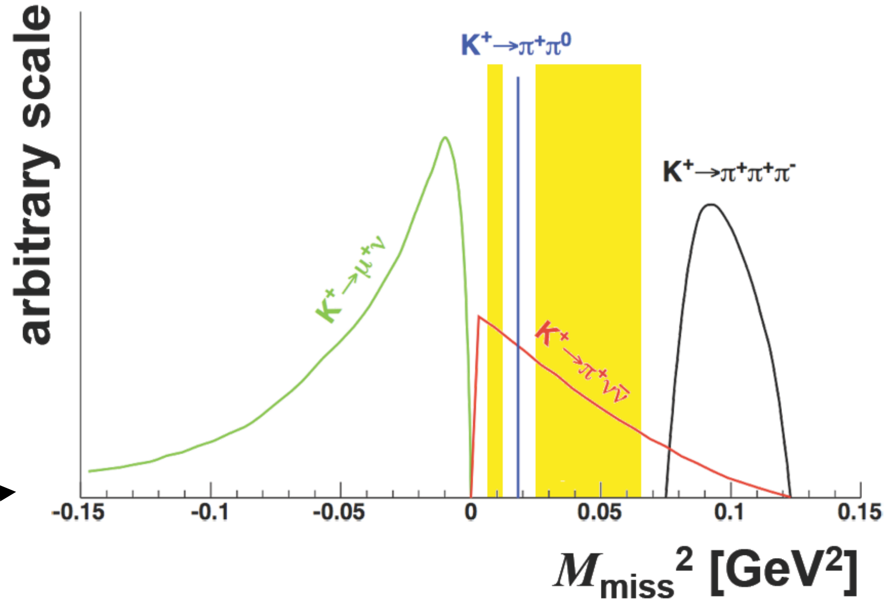
Possible upgrades: 100 SM evts/ 3 years

Experimental methods for $K^+ \rightarrow \pi\nu\nu$

Main backgrounds to $K^+ \rightarrow \pi^+\nu\nu$:

- **$K^+ \rightarrow \mu\nu$ with π ID for μ**
  need excellent PID, especially μ/π
- **$K^+ \rightarrow \pi\pi^0(\gamma)$ with γ's lost**
  need excellent γ vetoes

Kinematic rejection for 2 body →

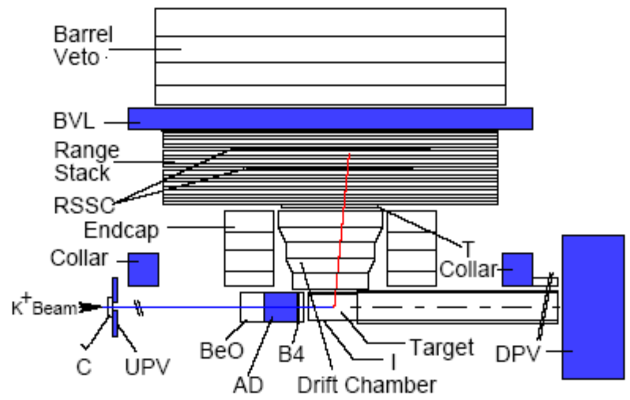


To reach 10^{-12}, PID & vetoes also reject unclosed bkg (K_{l3}, K_{l4}, …)

	Stopped K^+	Decay in flight
Kinematics	K^+ at rest	Must track K^+
Photon vetoes	Low-energy photons	High-energy photons
PID	Range π-μ-e decay chain	Advanced Cerenkov counters Muon detectors

Fixed target approach: E949 @ AGS

The entire AGS beam of 65 x 10^{12} (Tp/ spill) at a momentum of 21.5 GeV/c was delivered to the E949 K^+ production target



Duty Factor: 2.2 s / 5.4 s ~ 40%

1 interaction length Pt target

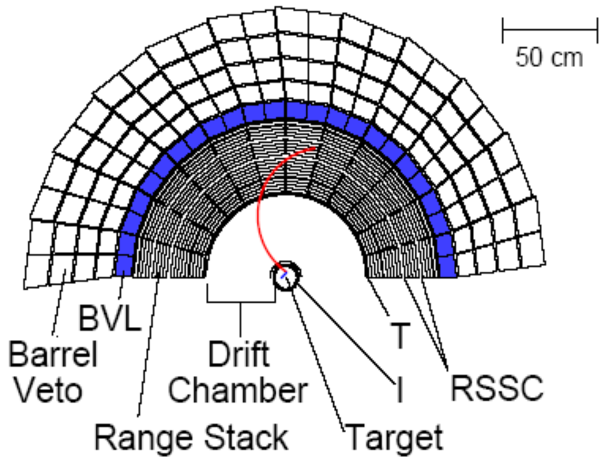
Before separators: 500 π : 500 p : 1 K

After separators: Purity K:π ~ 3--4 : 1

Incoming 710 MeV/c K^+ identified by Č and slowed down by BeO and Active Degrader

~27% K^+ stopped in the target (1.6 MHz)

Tracking in 1 T solenoid field

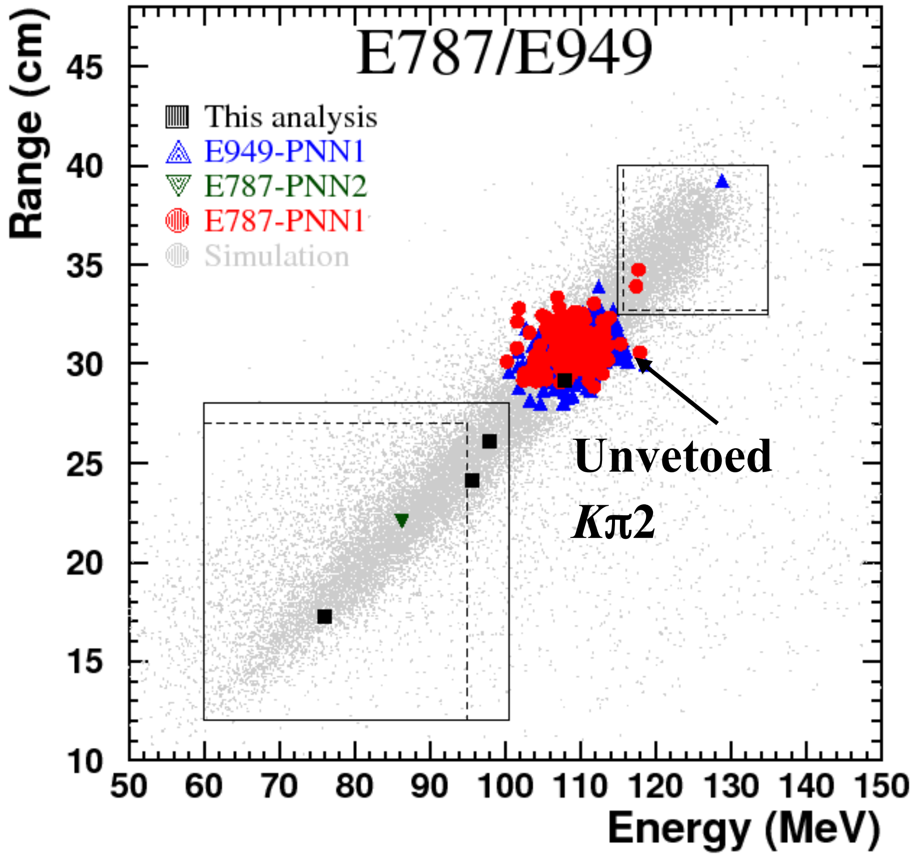


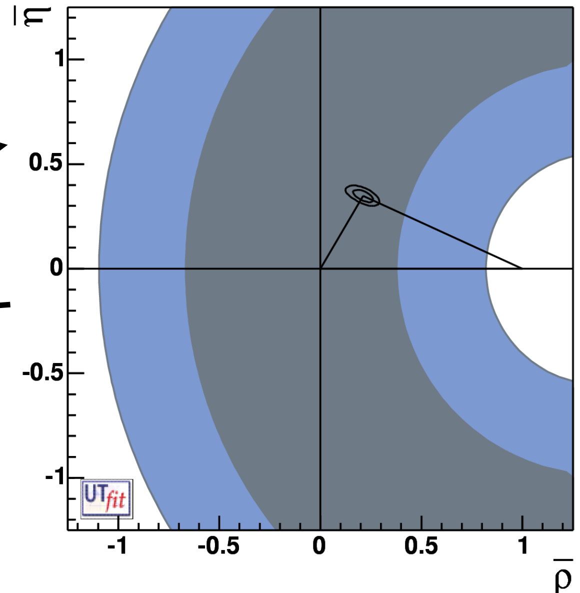
π^+ identification:
- **Delayed Coincidence**
- **Range**
- **Energy**
- **Momentum**
- **Detect entire $\pi^+ \to \mu^+ \to e^+$ chain**

Final results from E787/E949 (2008)

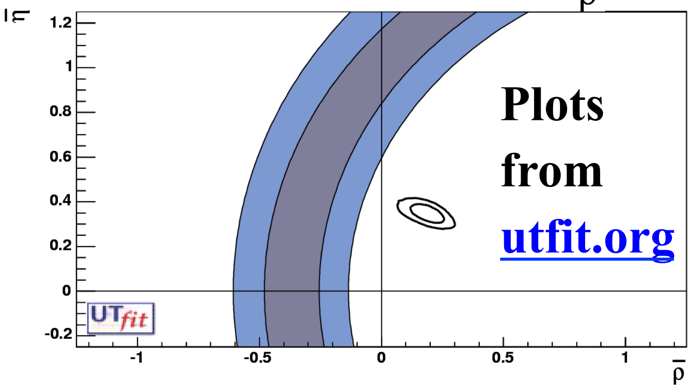
Combined results, from E787 (1995-8 runs) & E949 (12-weeks run in 2001)

$BR(K^+ \to \pi^+ \nu\nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$





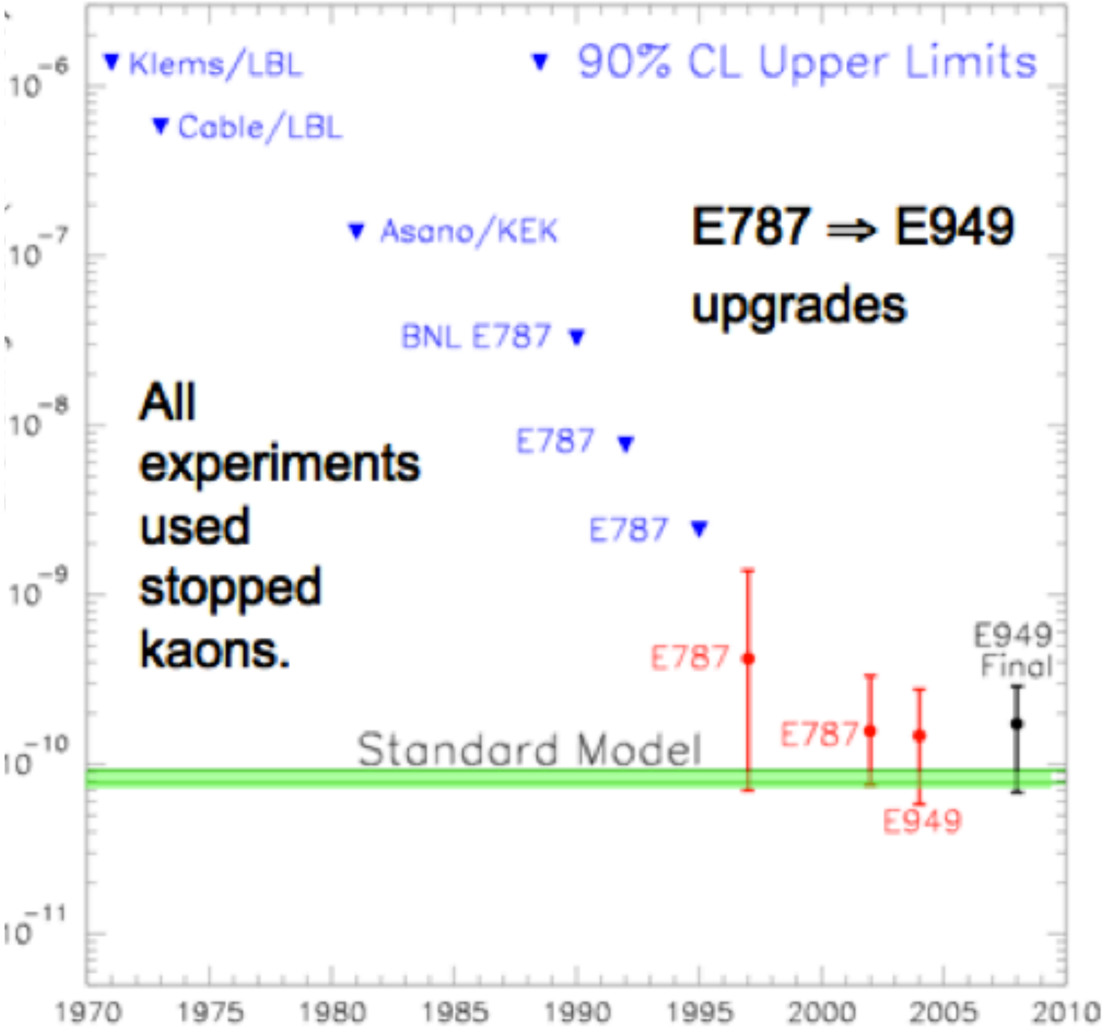
Same central value, 100 evts



Prob. all 7 obs. evts are bkg is $\sim 10^{-3}$

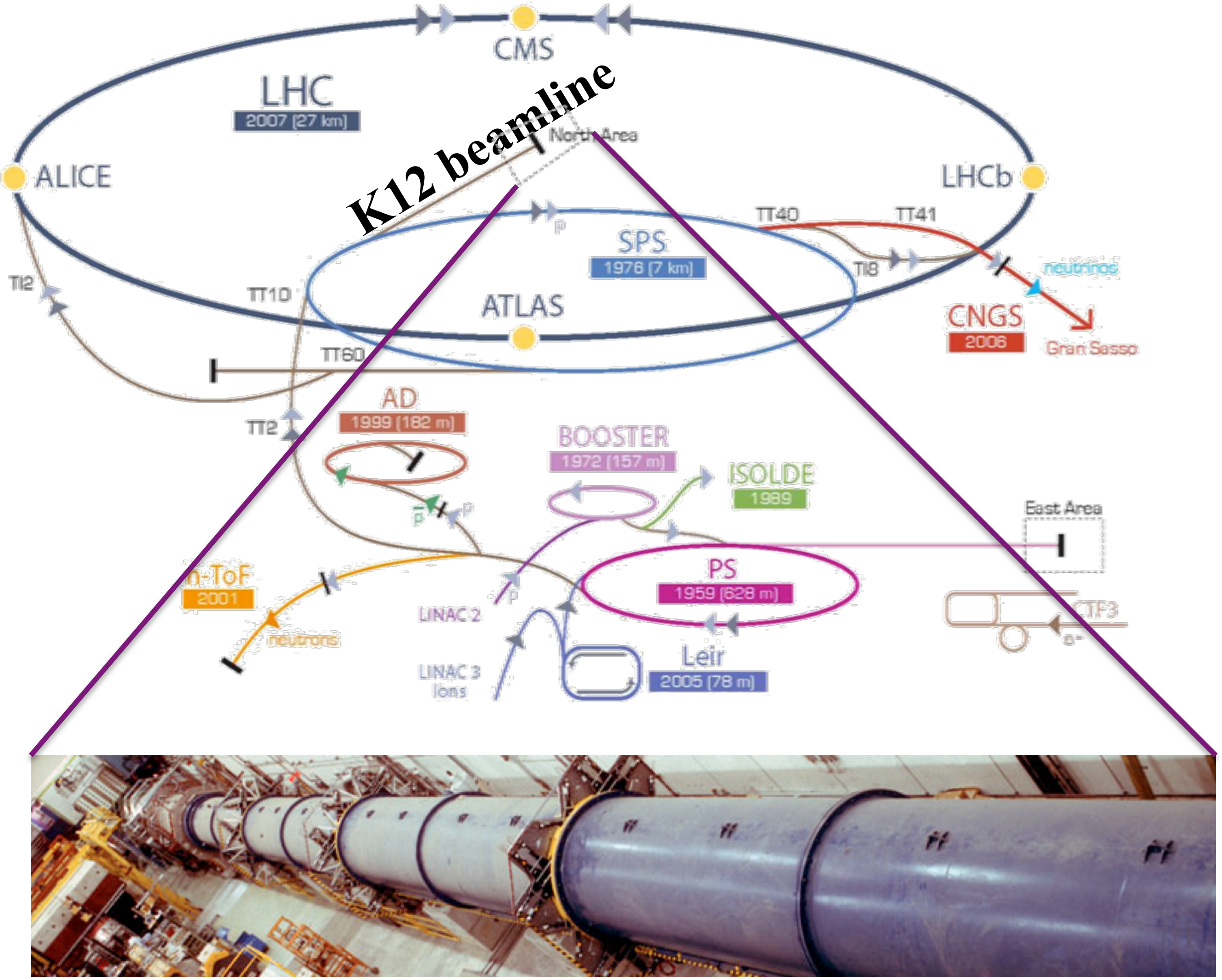
Hopefully not the end of a long story…

BR($K^+ \to \pi^+ \nu\nu$)×10[11]



Year of publication

...The in-flight approach: NA62 @ CERN*



Improve intensity of existing NA48 beamline by ×50

400 GeV SPS primary proton beam, producing unseparated 75-GeV K^+ beam:

- ~800 MHz beam
- 6% are K^+, i.e., ~ 50 MHz
- ~ 5 MHz decay in a 60-m fiducial volume

*See dedicated talk by G. Ruggiero

NA62 guiding principles

Support a high-rate environment

- **high-resolution timing**

Kinematic rejection by cutting on missing mass at decay

- **fast tracking to measure incoming K momentum**
- **high resolution tracking to measure daughter particle momenta**

Rejection of $K_{\mu 2,3,4}$, $K_{e2,3,4}$, … background, PID for all charged particles

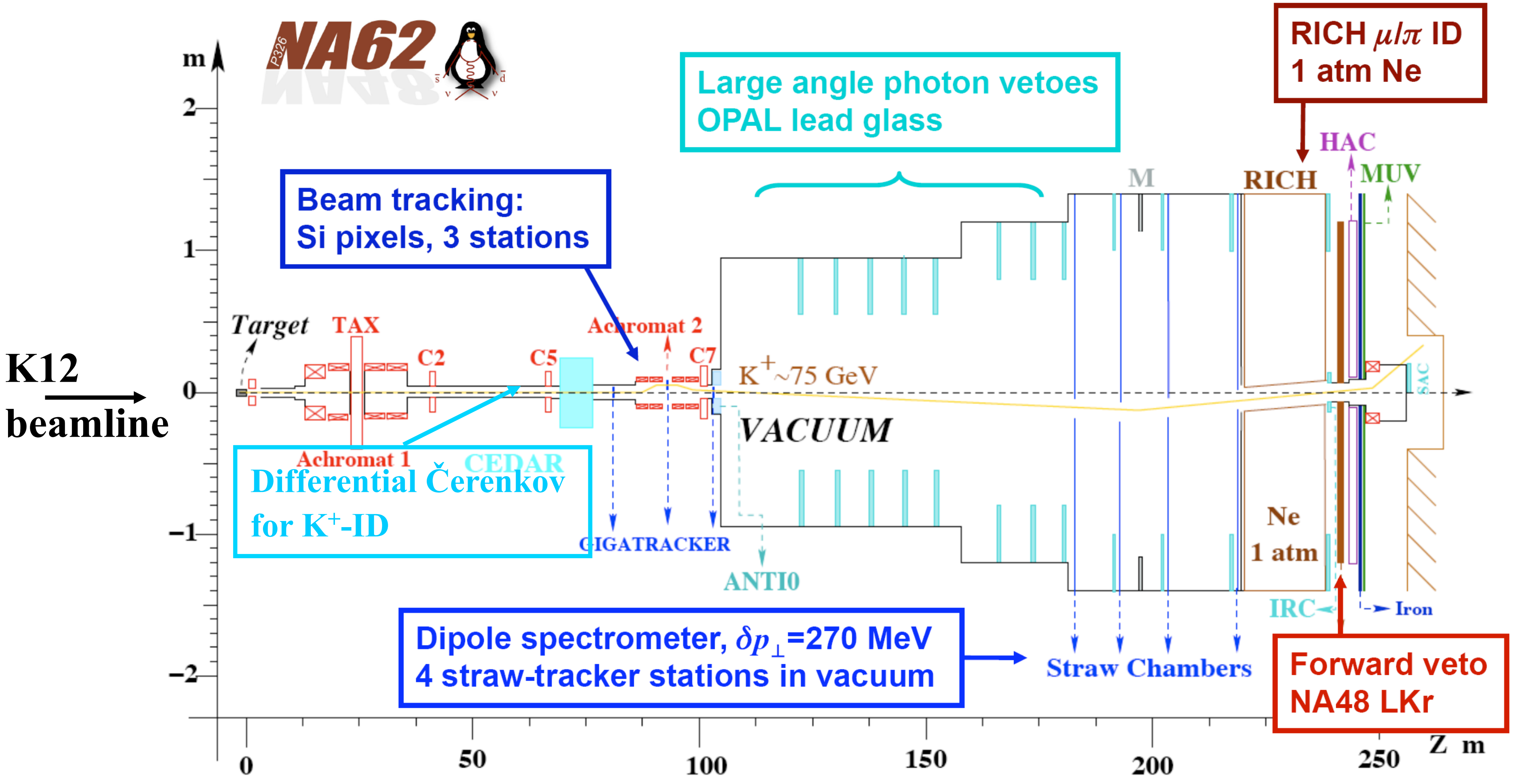
- **positive, non-destructive ID for incoming kaon**
- **ID for outgoing daughter pions, muons, electrons**
- **ID for outgoing muons**

Rejection of modes with π^0's and/or (possibly radiative) photons

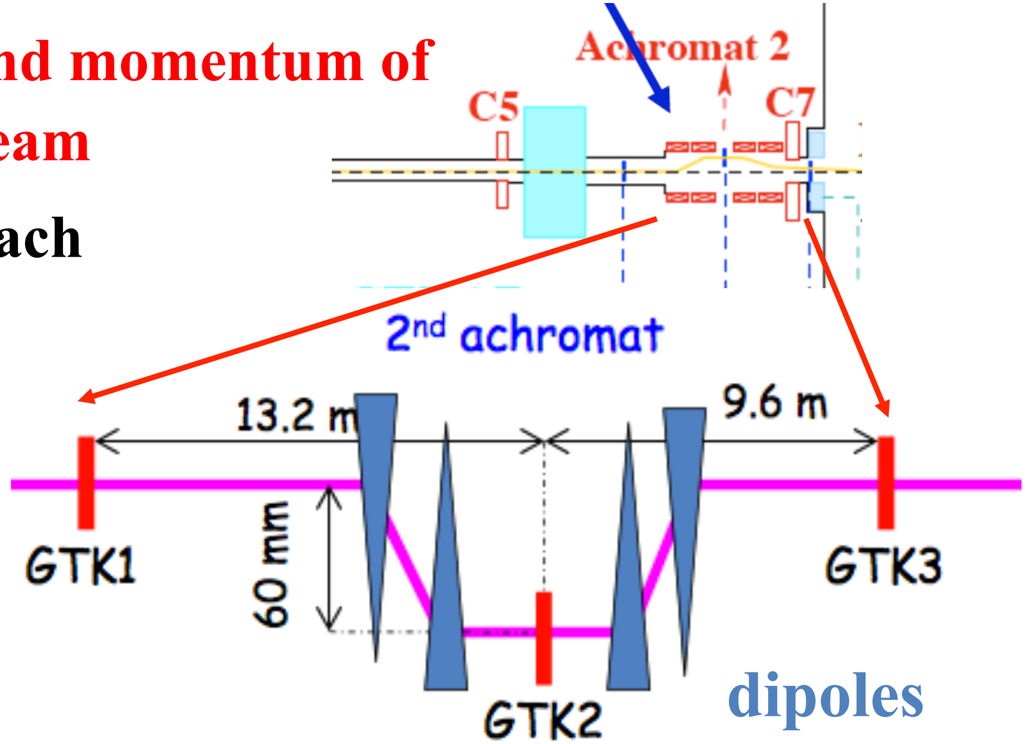
- **Hermetic, high-efficiency γ vetoing from 0 out to 50 mrad angles**

Redundancy of information

The in-flight approach: NA62 @ CERN



Fast tracking before decay volume – GTK



Aim to measure time, coordinates, and momentum of individual particles in a 800 MHz beam

3 silicon μ-pixel stations, <0.5% X_0 each

Other demanding constraints:

- **100 μm space resolution**
- **δp/p ~ 0.2%, i.e., δp ~ 150 MeV**
- **δα/α ~ 12 μrad**

Structure:

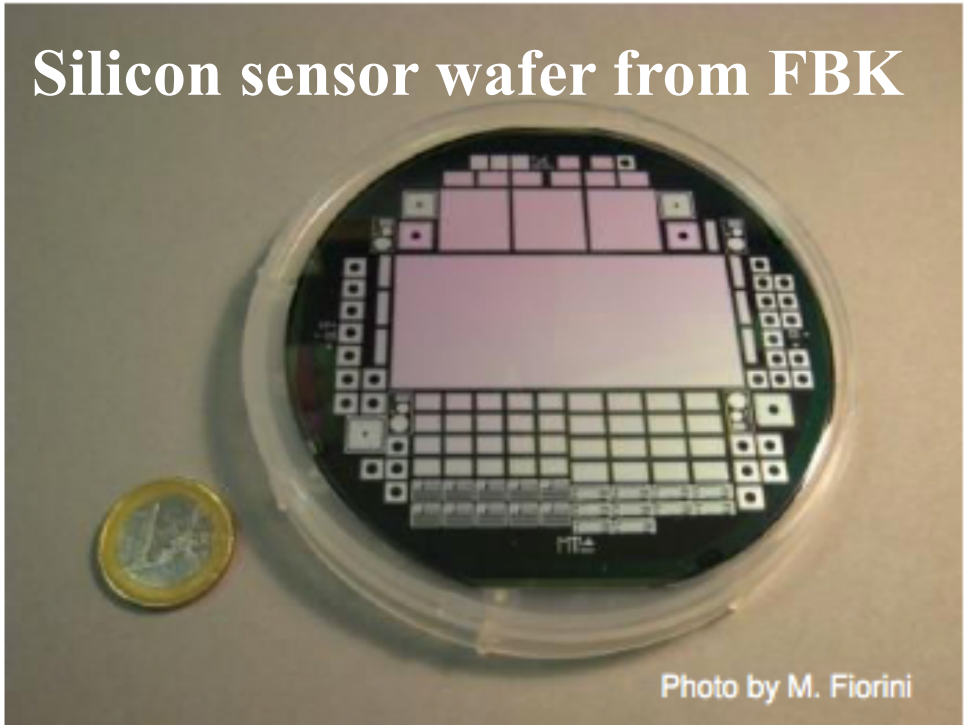
- **18000 300×300 μm² pixels, sensitive area of 60×27 mm²**

Technological challenge:

- **<1% hit mismatch @ 800 MHz → 200 ps time resolution**
- **read out able to sustain rates up to 150 KHz/pixel**

GTK technology and read out

Have to read out with dead time <100 ns, with a charge/pixel varying between 0.8 fC (5000 e-) to 10 fC (60000 e-)



- **have to correct for slewing effects**
- **maintain noise < 200 e-**
- **operate with reasonable power consumption, < 2 W/cm^2**

R&D almost completed

- **2 read out prototypes developed & compared, both with FE circuits in 130-nm IBM CMOS technology**

For details, see Report by J. Kaplon et al., IEEE NSS conference, Orlando, FA, USA

Photon vetoing in NA62

Have to reject $K^+ \rightarrow \pi^+\pi^0$ @ the level of 10^{-12}

Need π^0 rejection of $O(10^{-8})$ for γ's from K decay in fiducial volume (~60 m)

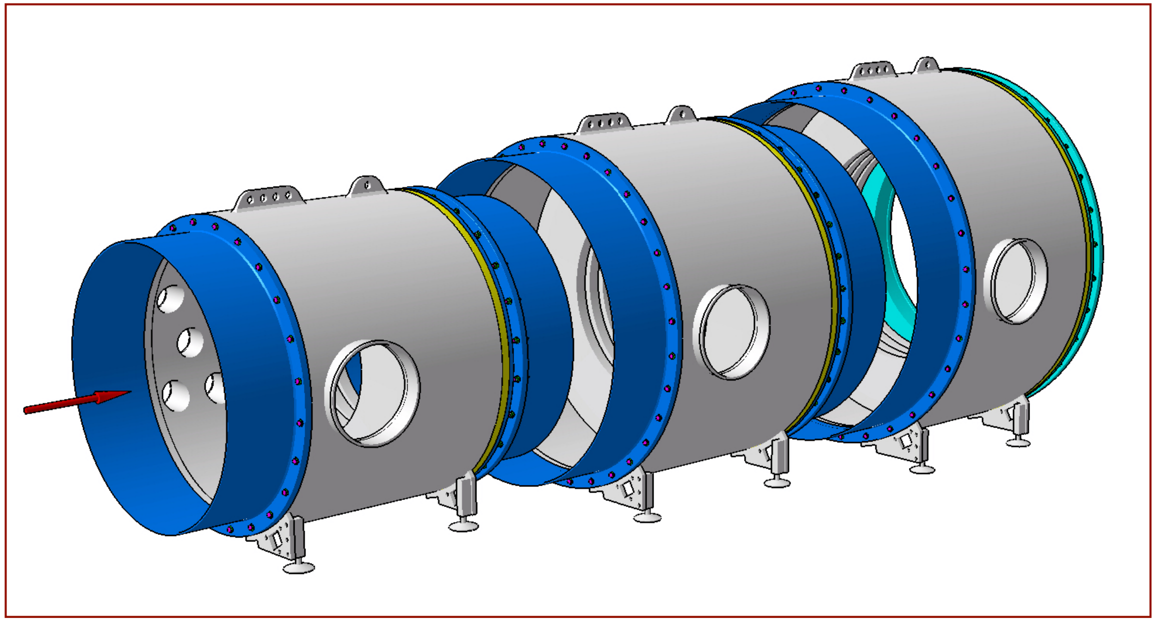
A composite system:

- **Very small angle, below 2 mrad**
  - **A new compact calorimeter**
  - **Inefficiency required $<10^{-6}$ for γ's above 6 GeV**
- **Small angle, 1 to ~8 mrad:**
  - **Re-use NA48 LKr calorimeter, $\sigma_E/E = 0.032/\sqrt{E[GeV]} + 0.09/E[GeV] + 0.0042$**
  - **Inefficiency measured $<10^{-5}$, for γ's above 6 GeV**
- **Large angle, ~8 to 50 mrad:**
  - **A new veto system (LAV system)**
  - **Inefficiency required $< \sim 10^{-4}$ for 100 MeV $< E_\gamma <$ 25 GeV**
  - **Able to operate in a vacuum of 10^{-6} mbar**

Large angle veto layout and geometry

Rearrange SF4 lead crystals from OPAL in staggered layers (rings)
Install rings inside existing vacuum vessel (so called "blue tube")

- **12 stations of increasing diameter to cover hermetically the range θ = 7–50 mrad**
- **3 different sizes of vacuum vessels (last downstream station operated in air)**
- **4 to 5 layers/station for a total depth of 29 to 37 X_0, particles traverse > 20 X_0**
- **32 to 48 crystals/layer**
- **A total of ~ 2500 blocks**



NA62 expected sensitivity

Decay Mode	Events
Signal: $K^+ \to \pi^+\nu\nu$ *[flux = 4.8×10^{12} decay/year]*	*55 evt/year*
$K^+ \to \pi^+\pi^0$ *[$\eta_{\pi0}$ = 2×10^{-8} (3.5×10^{-8})]*	4.3% (7.5%)
$K^+ \to \mu^+\nu$	2.2%
$K^+ \to e^+\pi^+\pi^-\nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \to \pi^+\pi^0\gamma$	~2%
$K^+ \to \mu^+\nu\gamma$	~0.7%
$K^+ \to e^+(\mu^+)\ \pi^0\nu$, others	negligible
Expected background	≤13.5% (≤17%)

Aim to obtain O(~10%) signal acceptance with <10% background

year & running efficiency from NA48 story: ~100 days/year, 60% data taking efficiency

NA62 past and future

In 2007-2008, NA62 "phase 1":

- **Runs with original NA48/2 detector, beam carefully tuned for the measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ at few per mil (see T. Sergi talk)**
- **Data acquired useful for high-statistics studies of Kl3 form factor slopes, needed for Vus extraction (see M. Ita-Hochgesand Talk)**
- **In parallel, R&D studies for new sub-detectors started**
- **December 2008, approval by CERN research board**

In 2009-2010, NA62 "phase 2":

- **Collaboration consolidated: at present 191 participants from 25 institutes**
- **Main beam tests for advanced prototypes (RICH, GTK) or parts of single sub-detectors (LAV)**

In 2011-2012, construction and commissioning

In 2013, first physics run

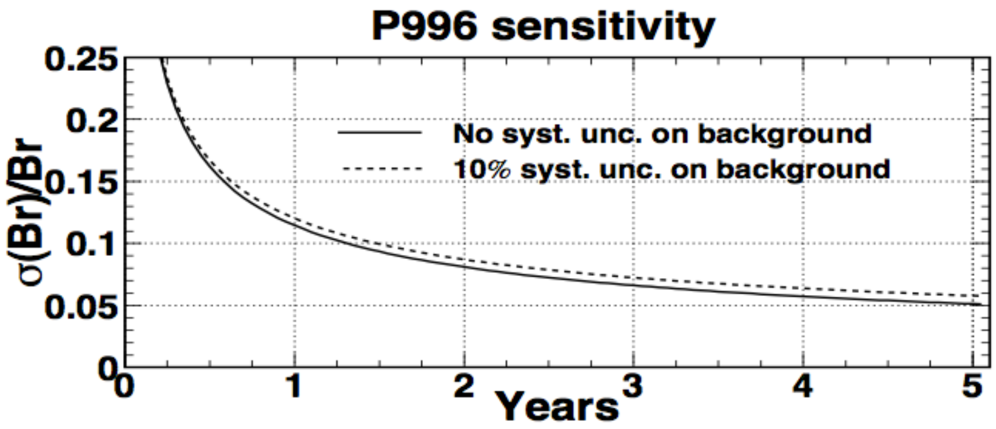
Another player in the game? P996 @ Fermilab

Measure BR(K^+) at 5% using stopped K^+

- **Build a modern version of E949 detector**
- **Use Tevatron as a "stretcher", filled by the main injector:**
  - **achieve as high as 95% duty factor**
  - **increase the number of stopped K/hour and the running time**
  - **reduce 10% of protons for NOνA**

Expect increase factors on E949:

- **×11 Detector acceptance**
- **×6 Stopped K's/hour**
- **×5 Running hours/year**



Fermilab proposal P996 submitted October 2009

$K \rightarrow \pi\nu\nu$ sensitivity summary

Expt	Primary beam	Intensity (ppp)	SM evts/yr	Start date + run yrs	Total SM evts
NA62	**SPS 450 GeV**	3×10^{12}	**55**	**2012+2**	**110**
FNAL $K^{\pm}$	Booster 8 GeV	2×10^{13}	40	2015+2	80
FNAL $K^{\pm}$	Project X 8 GeV	2×10^{14}	250	2018+5	1250
P996	Tevatron up <150 GeV	1×10^{13}	120	2018+5	600
E14	**JPARC-I 30 GeV**	$\mathbf{2 \times 10^{14}}$	**1-2**	**2011+3**	**3-7**
E14	JPARC-II 30 GeV	3×10^{14}	30	2018+3	100
FNAL K_L	Booster 8 GeV	2×10^{13}	30	2016+2	60
FNAL K_L	Project X 8 GeV	2×10^{14}	300	2018+5	1500

All dates/estimates are speculative, some are more speculative than others

Summary and outlook: a brilliant future…

Much recent progress in kaon physics:

- Verification of first-row CKM unitarity and SM constraints
- Verification of lepton universality in kaon decays
- Improved knowledge of *CP*/*CPT* parameters in kaon physics

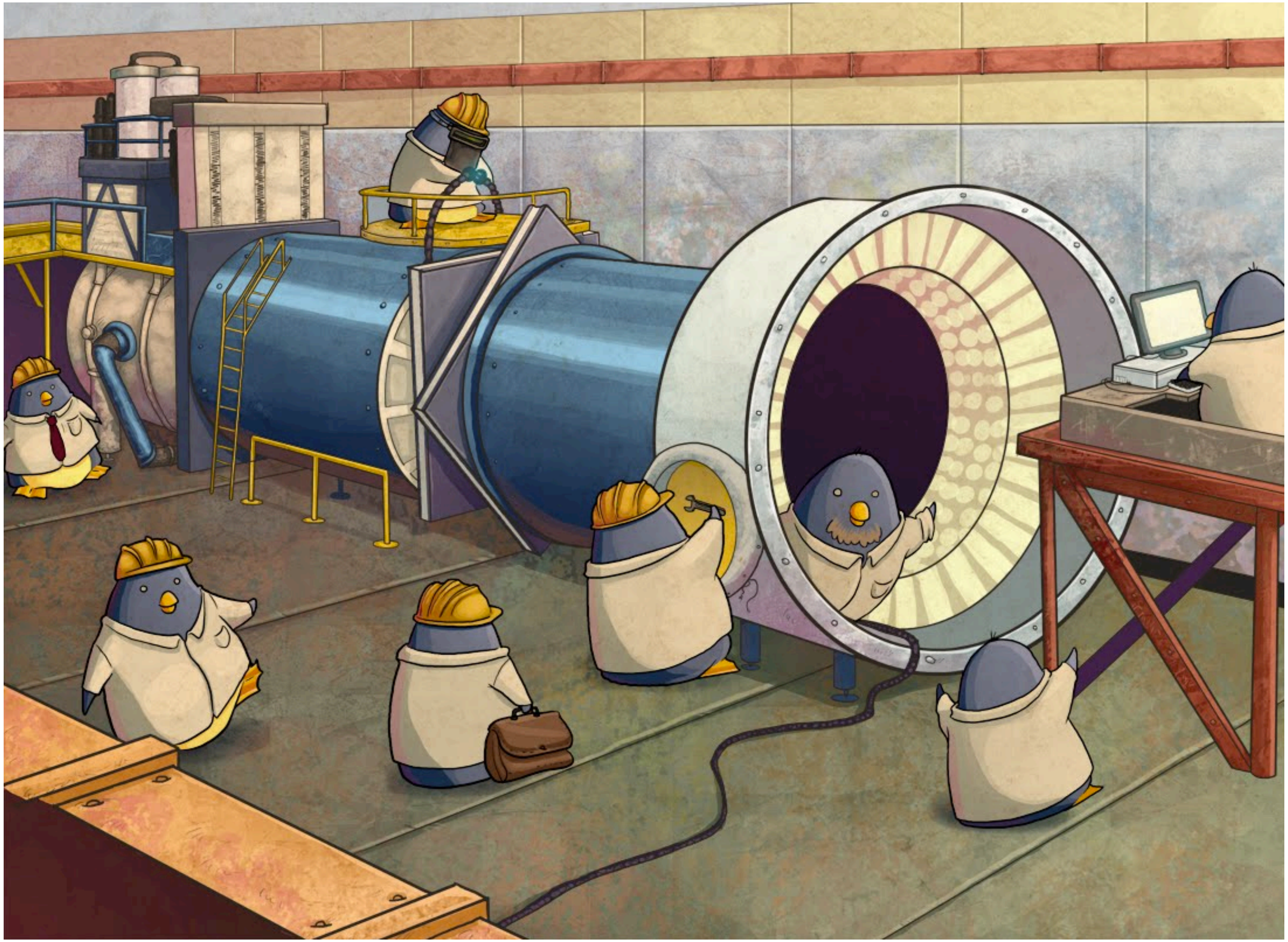
Still many more results to come:

- Remaining data from NA48, KLOE, others

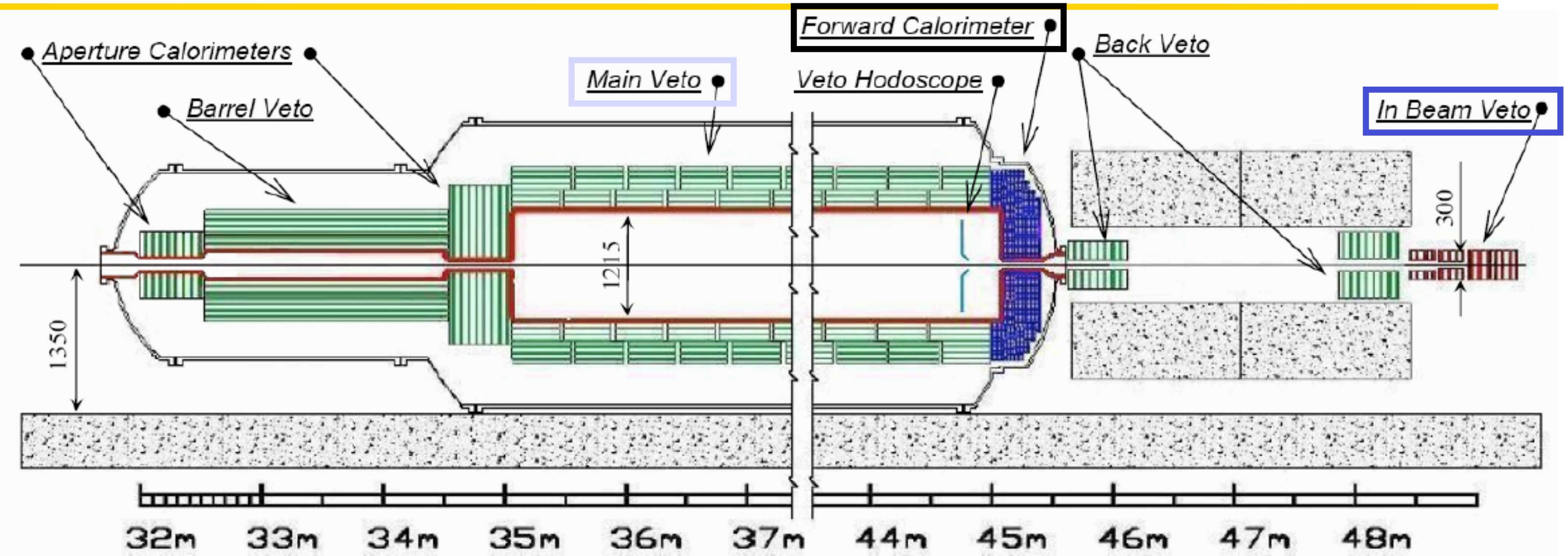
Longer-term future in kaon physics dominated by $K \rightarrow \pi\nu\nu$:

- Precise SM predictions - sensitive probes for BSM physics
- Good measurements can provide insight on BSM flavor structure
- Good chance to know K^+ BR with 10% precision within ~3 years
- Discussion started for 3% mmts, possibly within 10-15 years

… but (as usual) a lot of tough work on the way



$K_L \rightarrow \pi^0 \nu\nu$ at Protvino: KLOD



IHEP U-70 neutral beamline:

70 GeV primary beam

2-5×10^{13} ppp, RF microbunching?

Large extraction angle

10^8 K_L/pulse, $\langle p_K \rangle$ = 10 GeV

n/K_L ratio < 10

TDR complete

Forward veto: Pb/SciFi calorimeter

Similar to KLOE calorimeter

X, *U*, *V* fiber views for shower tracking

Main veto: Shashlyk modules

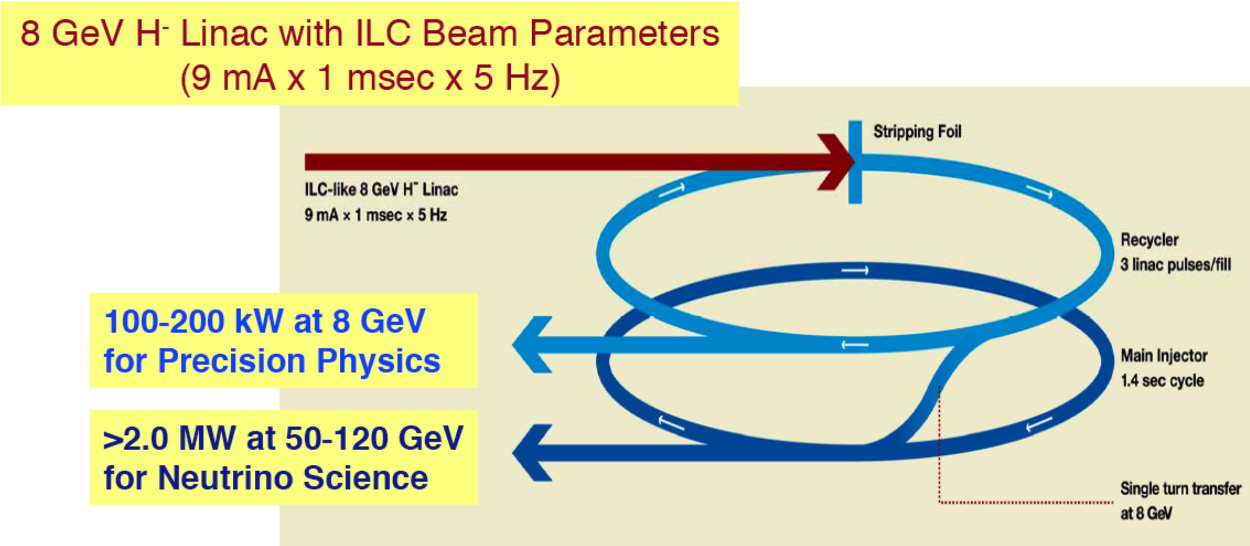
0.3 mm Pb/1 mm scintillator

In-beam veto: Fiber calorimeter

Dual readout: clear + scintillating fibers

e/h = 5: ID for neutral beam interactions

$K \rightarrow \pi\nu\nu$ and Fermilab Project X



Proposed in 2007 as an interim program while ILC delayed: ν, μ, *K* …

1000-SM evt measurements for both $K \rightarrow \pi\nu\nu$ channels

$K^+ \rightarrow \pi^+\nu\nu$

Compact, E949-like stopped K^+ setup

400 MeV K^+ beam

3T field (up from 1T in E949)

Finely segmented range stack

Homogenous LXe photon veto?

$K_L \rightarrow \pi^0\nu\nu$

KOPIO-like microbunched beam

- p_{beam} from TOF event by event

Pencil beam collimation like E391a

- Good geometrical constraints
- Increases acceptance
- Eases KOPIO design issues

Made possible by high Project-X intensity