Current and future kaon experiments

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and INFN

CKM 2010

Warwick

Nicola Cabibbo
(1935-2010)

Physicist
member of the NA48 and NA62
collaborations

Fixed-target high-energy hadron beams: KTeV and NA48

100 physicists
12 USA/Japan institutions
1997-1999

Physics with K in the 90s driven by ε'/ε experiments

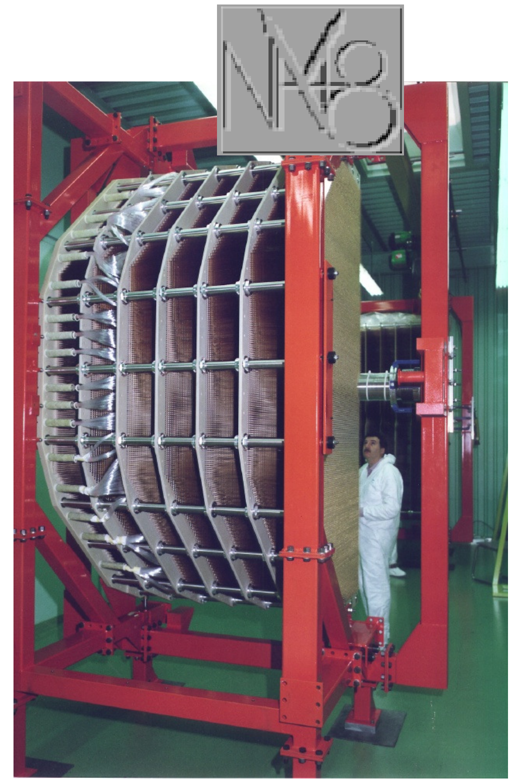
Their legacy:
The first confirmation of the CKM picture of CPV

A 12% **measurement** of ε'/ε (and much more: ε_K, CPT…)

Innovative detection and analysis **techniques**

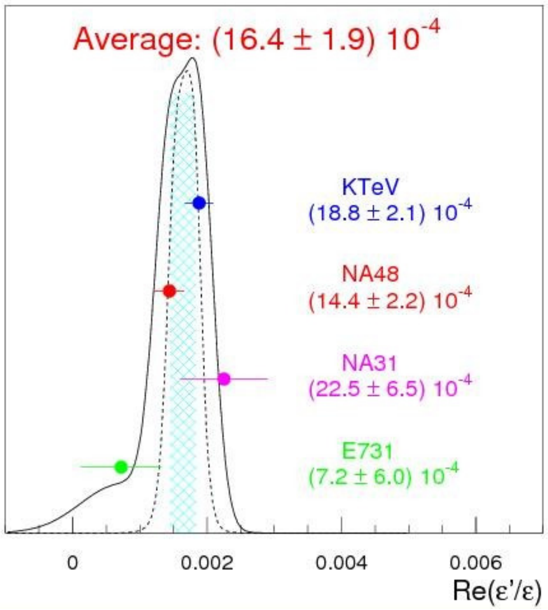
Two state-of-the-art EM **calorimeters**

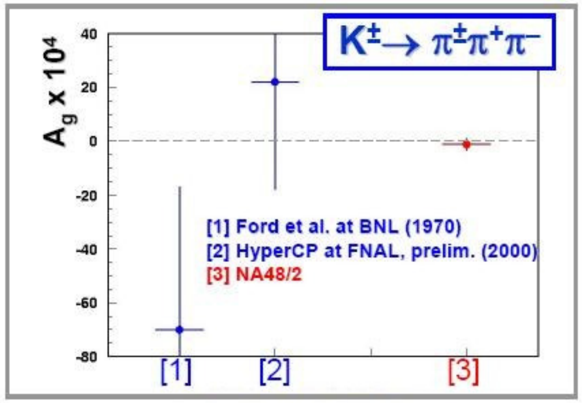
Much more physics: **50 papers each** and counting…

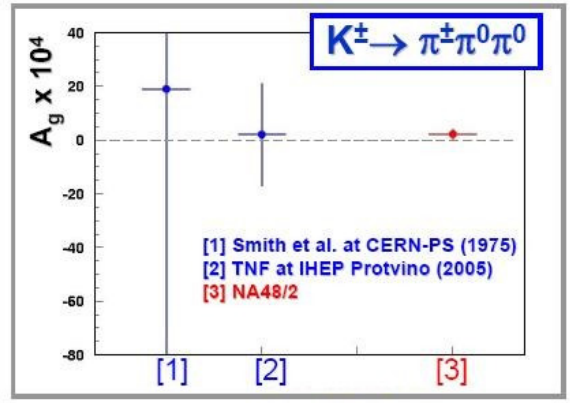


130 physicists
16 European institutions
1998-2003

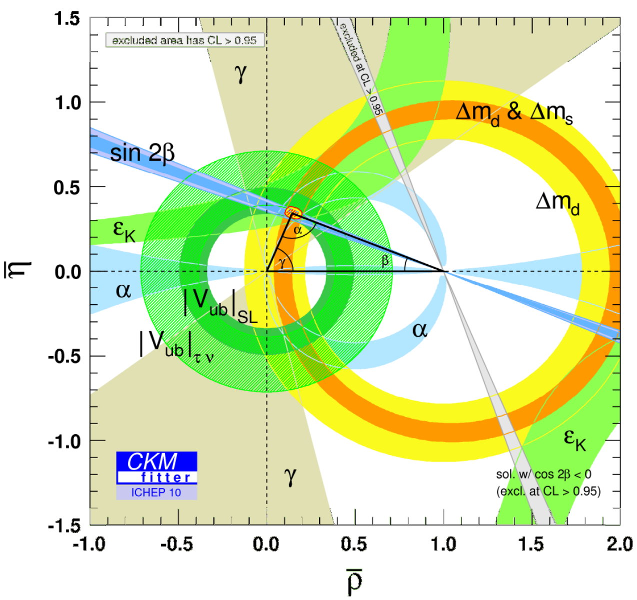
Kaons: the qualitative phase







Reasonably precise experimental data but…

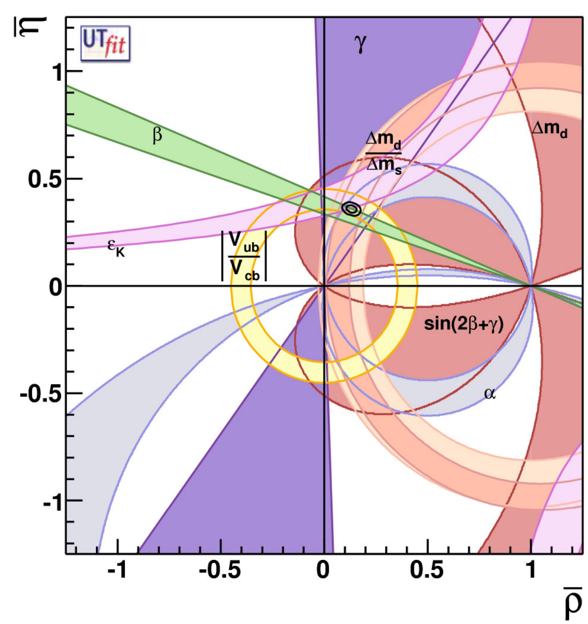


Not an impressive impact on the Unitarity Triangles

Actually *training ground* for LQCD

Waiting for Lattice breakthrough…

CKM10



Φ-factories: KLOE

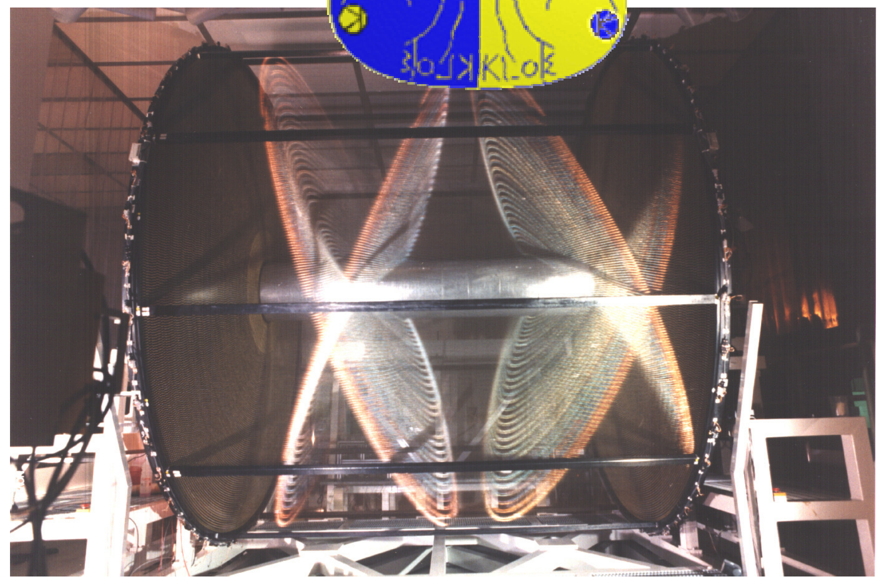
Not the original ε′/ε goal
but lots of physics:

Integrated luminosity: **~ 2.5 fb^{-1}**
(~ 2.5 · 10^{9} $K_S K_L$ events)
Peak: 1.6 ·10^{32} cm^{-2} s^{-1}

Approach with unique potential for **K_S physics**, absolute normalizations

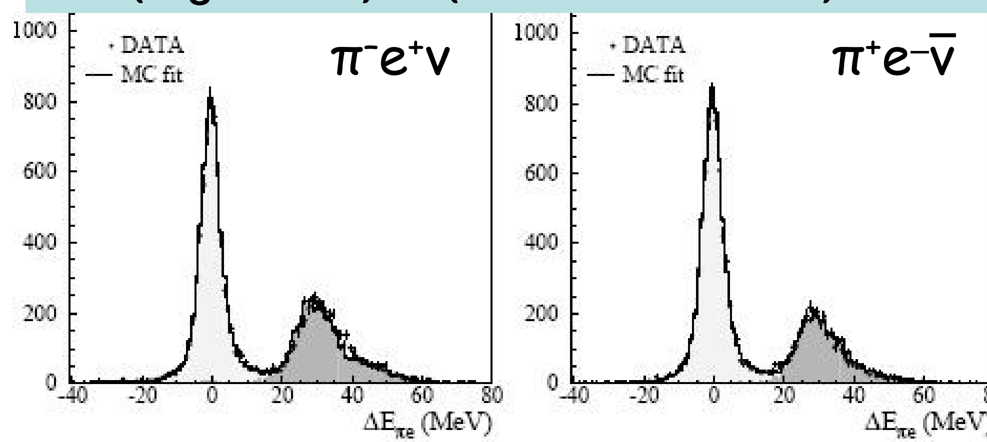
Campaign of **BR and lifetimes** measurements

Beginning of K **interferometry** physics,
CPT and QM tests



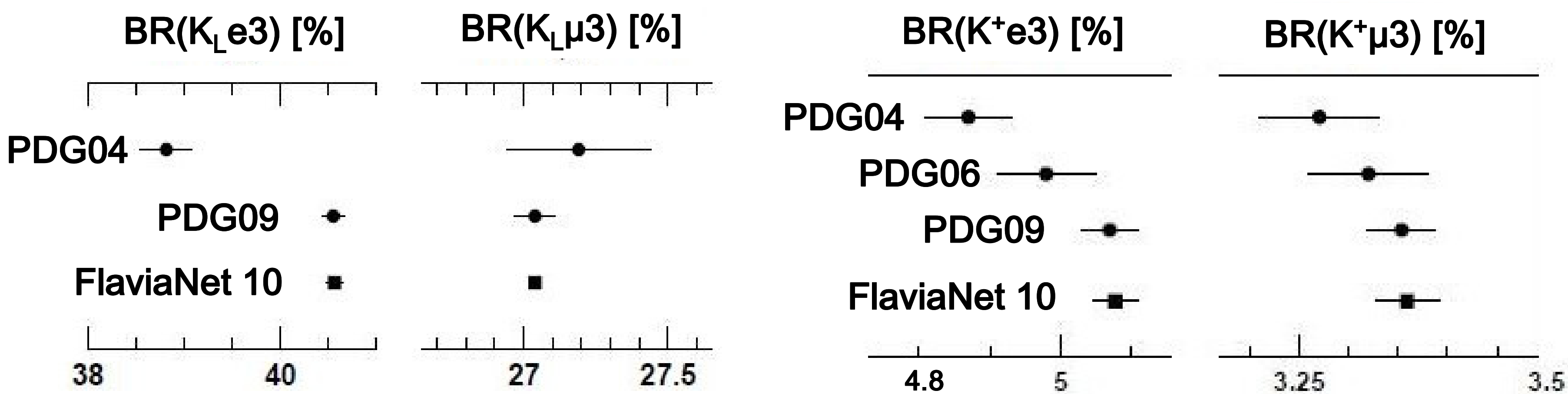
93 physicists - 15 institutions - 2000-2006

$BR(K_S \to \pi e \nu) = (7.028 \pm 0.092) \times 10^{-4}$



M.S. Sozzi

Kaons: the quantitative phase



The Kaon BR revolution (2003-2010):
large (several %, several σ) variations in world data
(higher statistics, radiative corrections)

10^5-10^7 events samples
~0.1% background
(for K^+, K_L)

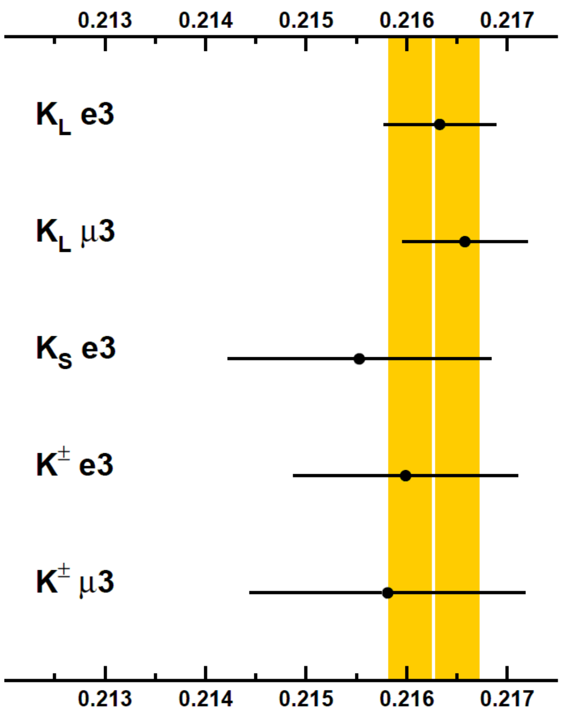
Cabibbo angle from Kℓ3 (K_L, K_S, K^+) and LQCD:

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} \left|V_{us}\right|^2 \left|f_+^{K^0\pi^-}(0)\right|^2 I_{Kl}(\lambda) \left(1+2\Delta_K^{SU(2)}+2\Delta_{Kl}^{EM}\right)$$

$$\frac{\Gamma_{K\ell 2}}{\Gamma_{\pi\ell 2}} = \frac{|V_{us}|^2}{|V_{ud}|^2}\frac{f_K^2}{f_\pi^2}\frac{m_K(1-m_\ell^2/m_K^2)^2}{m_\pi(1-m_\ell^2/m_\pi^2)^2}(1+\delta_{\rm EM})$$

|Vus|/|Vud| from (K/π)ℓ2 and LQCD

Kaons confront CKM

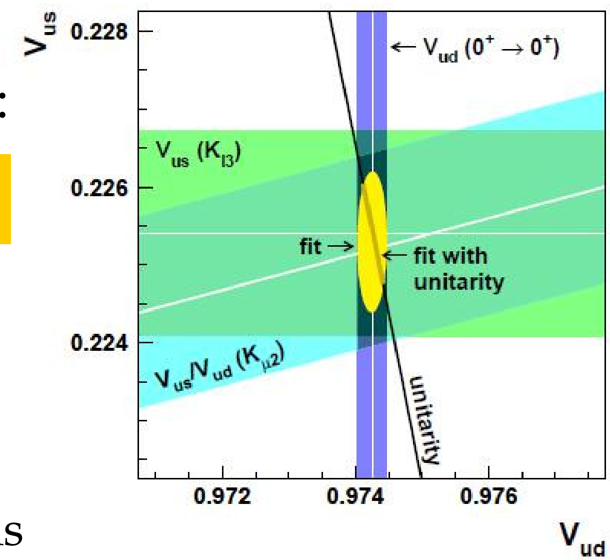


FlaviaNet 2010 global fit:

$|V_{us}|f_+(0) = 0.2163(5)$

$\chi^2/\mathrm{ndf} = 0.77/4$
(P=94%)

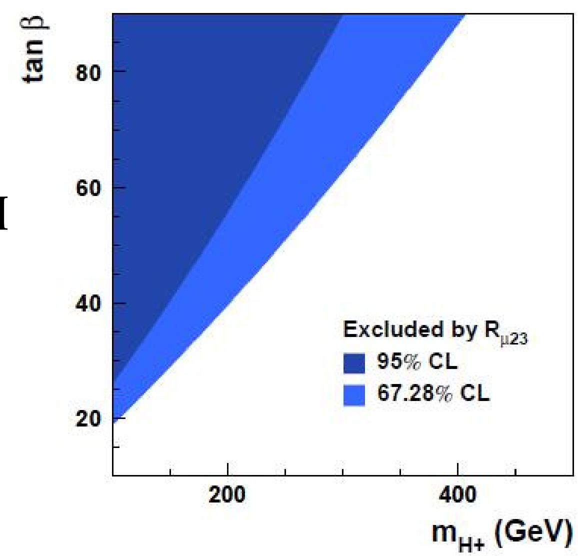
0.23% relative precision
No hint of unitarity violations



Lepton universality test:

$r_{\mu e} = 1.002(5)$

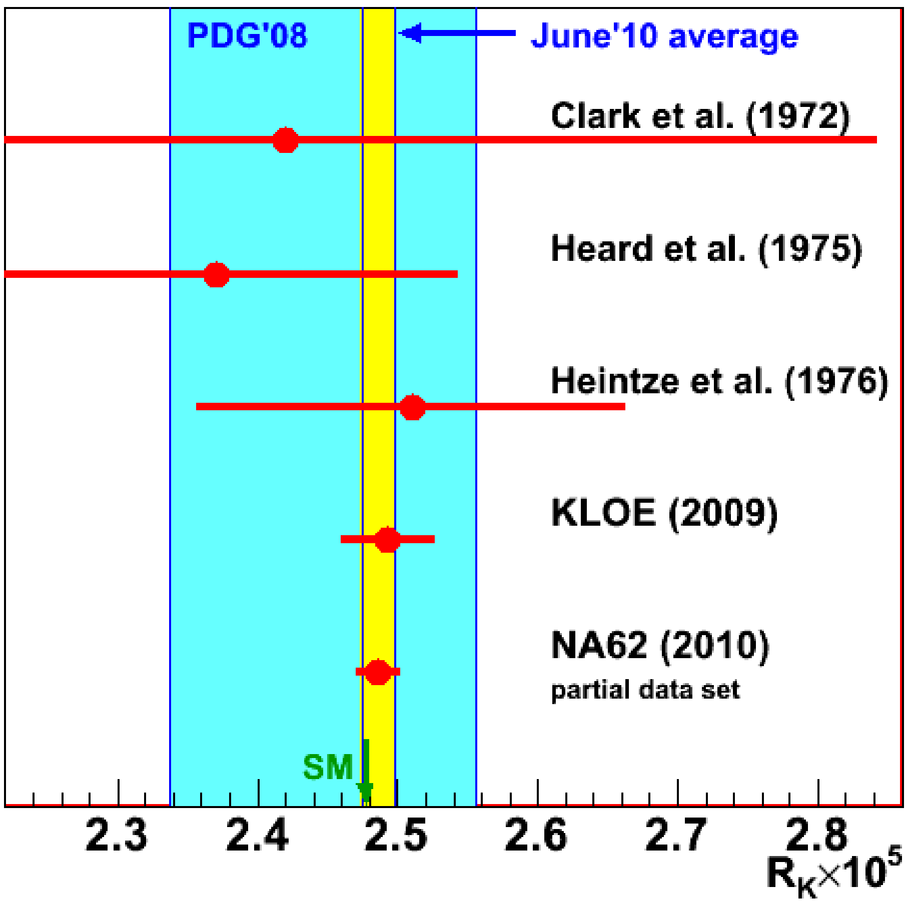
U(3)⁵ symmetry test:
Deviation from V-A by H exchange contribution in 2HDM:
Kμ2/Kℓ3 comparison



Leptonic K decays

Helicity-suppressed Kℓ2 decays: $K^{\pm}\rightarrow e^{\pm}\upsilon$ $K^{\pm}\rightarrow \mu^{\pm}\upsilon$
Axial current in SM, hadronic physics in normalization f_K (ChPT and lattice matching). Sub per-mille precision on

$$R_K = \frac{\Gamma(K^{\pm} \rightarrow e^{\pm}\nu)}{\Gamma(K^{\pm} \rightarrow \mu^{\pm}\nu)}$$



$$R_K(SM) = (2.477 \pm 0.001)\cdot 10^{-5}$$

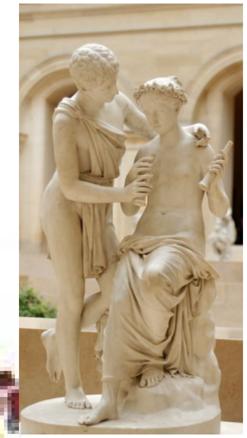
BSM: scalar densities or RH currents
H^+ affects rates and possibly RK !

NA62 (40% data set)
60K candidates, 9% background

KLOE (final)
14K candidates, 15% background

$$R_K = (2.487 \pm 0.012)\cdot 10^{-5}$$

DaΦne and KLOE: a new marriage



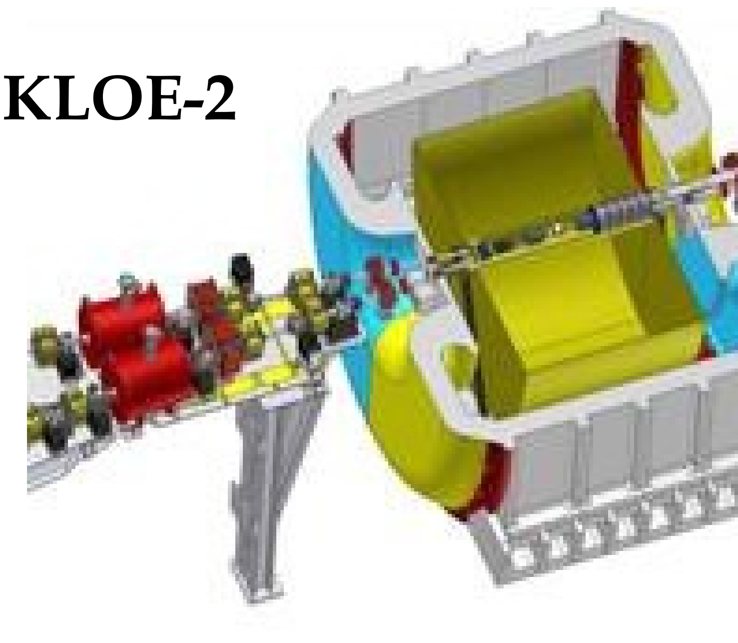
Starting 2008 new crab-waist interaction scheme reached **$4.5 \cdot 10^{32}$ cm^{-2} s^{-1}** luminosity

Step 0 (2010): collect **5fb^{-1}** running at 10^{33} luminosity, with 2 pairs of new e^+e^- taggers for γγ physics
Resonance physics, hadronic σ, precision CKM measurements:
$|V_{us}| f_+(0) \rightarrow$ **0.14%**

Step 1 (late 2011): collect **20 fb^{-1}** with
- Small-angle crystal calorimeters
- Tile calorimeters on beam quadrupoles
- GEM light tracker for improved vertex resolution

CPT and Lorentz violation tests
Dark matter searches
Marginal for $K_S \rightarrow \pi^0 \ell^+ \ell^-$

KLOE-2



Mode	$\delta\|V_{us}\| \times f_+(0)$ (%)	$\mathcal{B}$	τ	δ	$I_{K\ell}$
$K_L e3$	0.21	0.09	0.13	0.11	0.09
$K_L \mu3$	0.25	0.10	0.13	0.11	0.15
$K_S e3$	0.33	0.30	0.03	0.11	0.09
$K^\pm e3$	0.37	0.25	0.05	0.25	0.09
$K^\pm \mu3$	0.40	0.27	0.05	0.25	0.15

KLOE-2 Step0: **few 10^{-4}** CKM univ. test

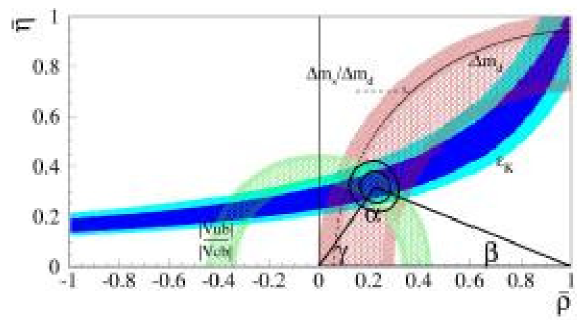
The role of Lattice

Roma, Italy
September 9-13, 2008

Lattice QCD and the Unitarity Triangle

Three of the five determinations of the UT parameters depend in a critical way from Lattice QCD results.

We would like measurements that are as far as possible independent from details of the hadron physics. The answer: $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$.



Measurement	$V_{CKM} \times$ other	Constraint
$b \to u / b \to c$	$\lvert V_{ub}/V_{cb}\rvert^2$	$\bar{\rho}^2 + \bar{\eta}^2$
Δm_d	$\lvert V_{td}\rvert^2 f_{B_d}^2 B_{B_d} f(m_t)$	$(1-\bar{\rho})^2 + \bar{\eta}^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\frac{\lvert V_{td}\rvert^2}{\lvert V_{ts}\rvert^2} \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}}$	$(1-\bar{\rho})^2 + \bar{\eta}^2$
ε_K	$f(A, \bar{\eta}, \bar{\rho}, B_K)$	$\propto \bar{\eta}(1-\bar{\rho})$

A. Stocchi, from analysis by M. Ciuchini et al.

Why ultra-rare K decays?

Let's face it:

the flavour structure of "TeV scale" BSM physics is not too weird

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The easy (SM) stuff has been done

"When the going gets tough,
the tough get going"

Why ultra-rare K decays?

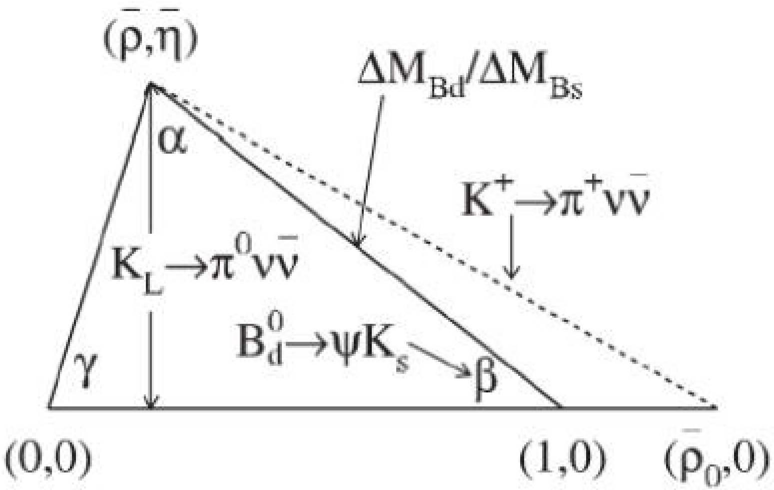
Let's face it:
the flavour structure of "TeV scale" BSM physics is not too weird

The easy (SM) stuff has been done

**"When the going gets tough,
the tough get going"**

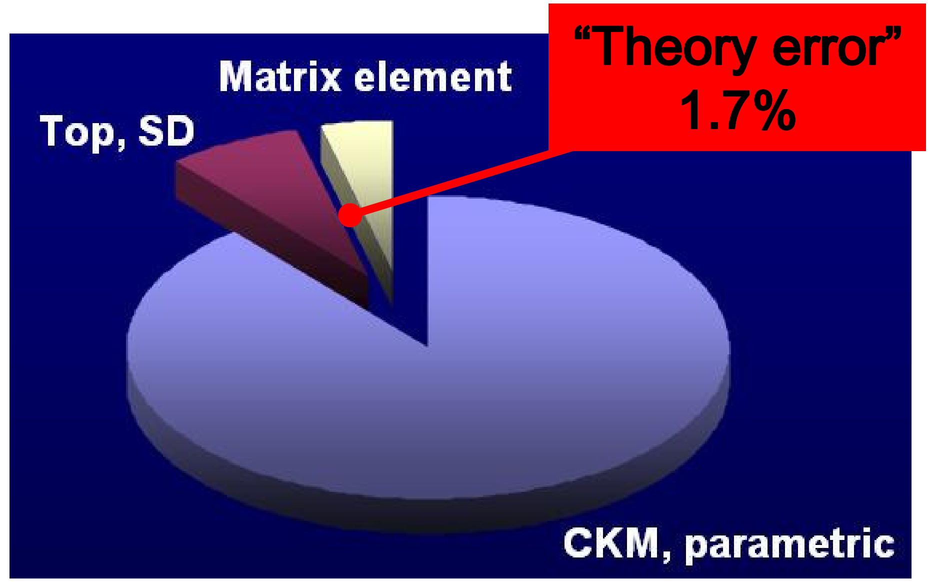
K **theoretical cleanliness** unmatched, simple system, few decay channels
Extreme **hard-GIM SM-suppressed** FCNC decays: room for NP up to 10x SM

Unique sensitivity to **flavour couplings** of BSM physics about to be produced at LHC…
… or sensitivity to **extremely high NP scales** in the unfortunate case that…
(10% measurement of $K \to \pi\nu\nu$ BR can probe **1000 TeV** NP scale)



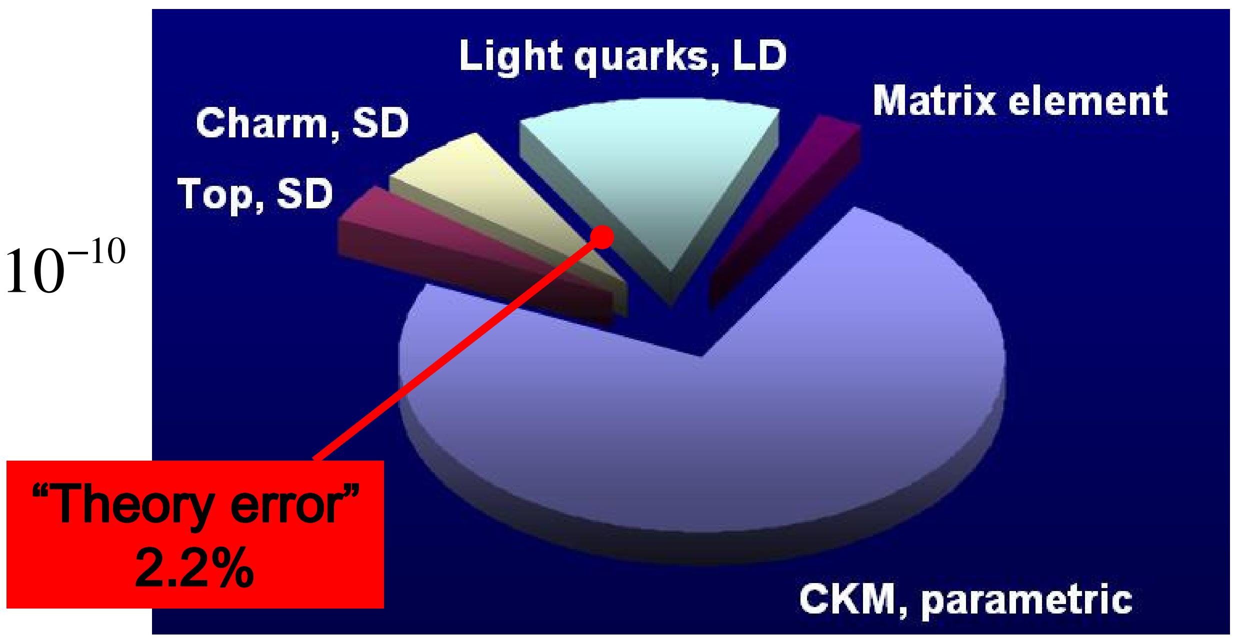
$K\rightarrow\pi\upsilon\upsilon$ BR predictions

The experimental challenges stimulated a flurry of theoretical improvements



$K_L\rightarrow\pi^0\upsilon\upsilon$

$$BR_{SM} = (0.26 \pm 0.04)\cdot 10^{-10}$$

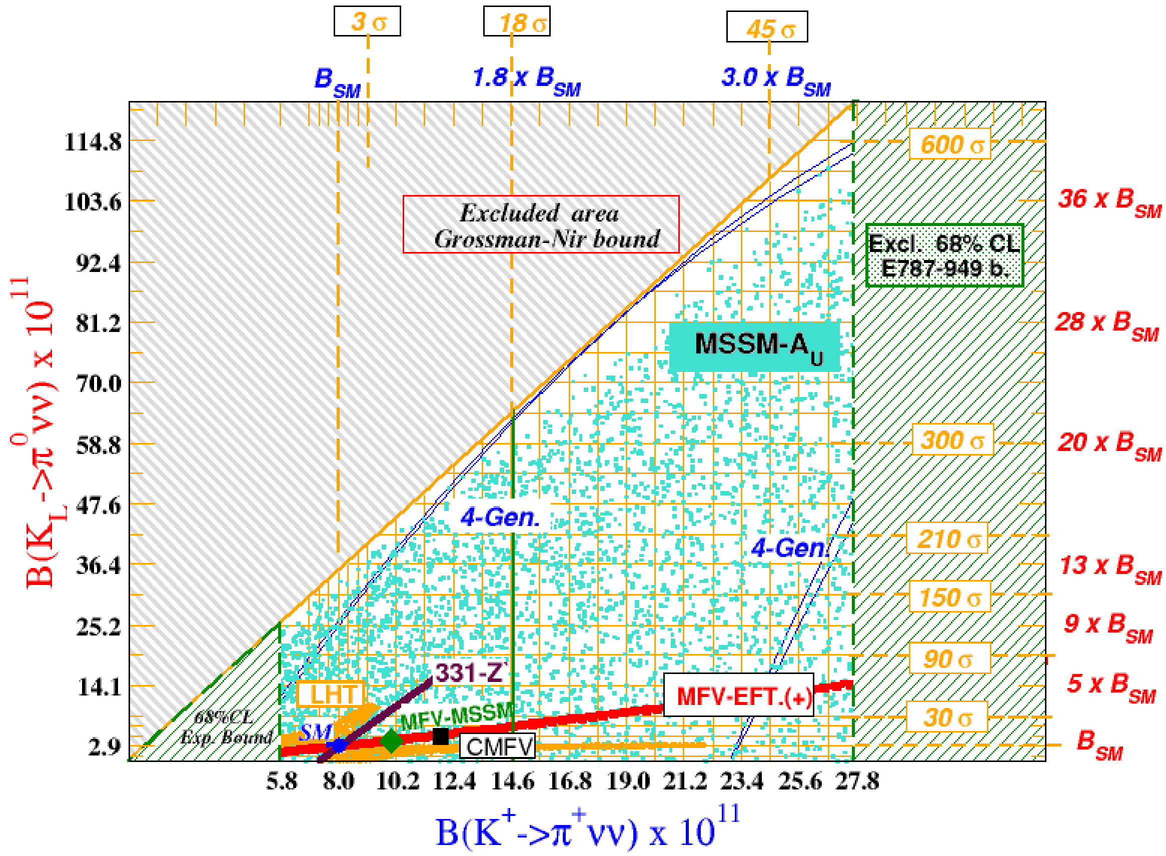


$K^+\rightarrow\pi^+\upsilon\upsilon$

$$BR_{SM} = (0.85 \pm 0.07)\cdot 10^{-10}$$

Comparable, unprecedented, *tiny* theoretical errors

$K \to \pi\nu\nu$ beyond SM

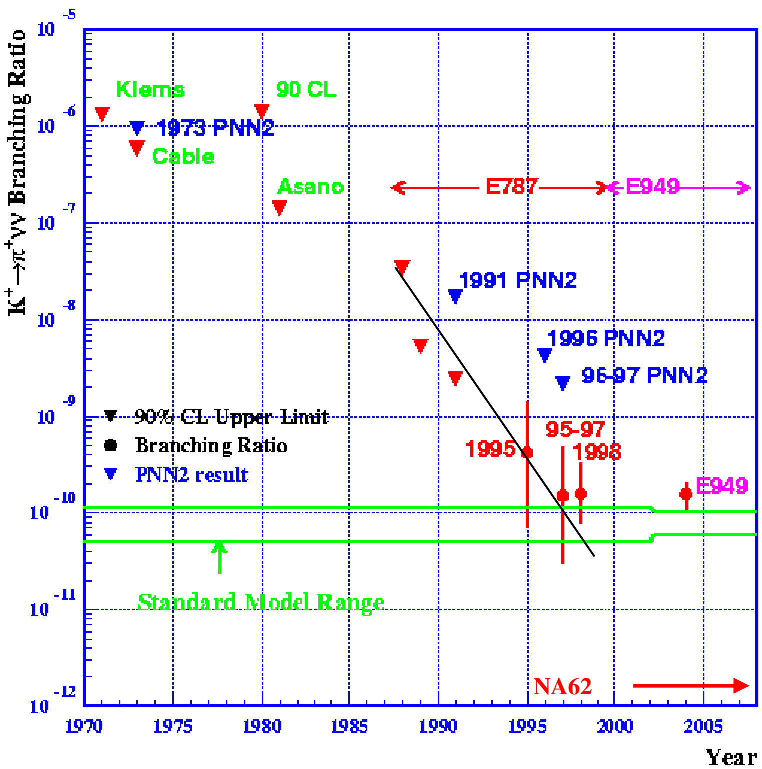


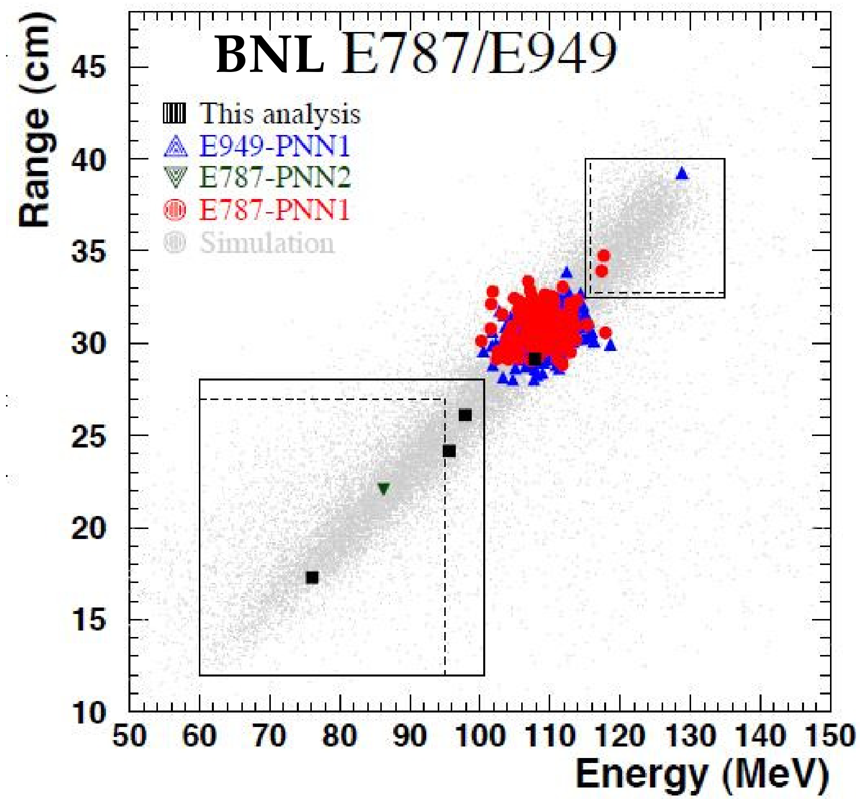
$BR(K^+ \to \pi^+\nu\nu) \times 10^{10}$: some examples	
SM	0.85±0.07
MFV (hep-ph/0310208)	1.91
EEWP (NPB697 (2004) 133, hep-ph/0402112)	0.75±0.21
EDSQ (PRD70 (2004) 093003, hep-ph/0407021)	up to 1.5
MSSM (NPB713 (2005) 103, hep-ph/0408142)	up to 4.0

$K \to \pi\nu\nu$ **remains clean** also beyond SM:
single effective $\nu\nu$ operator, calculable Wilson coeff., no long-distance effects

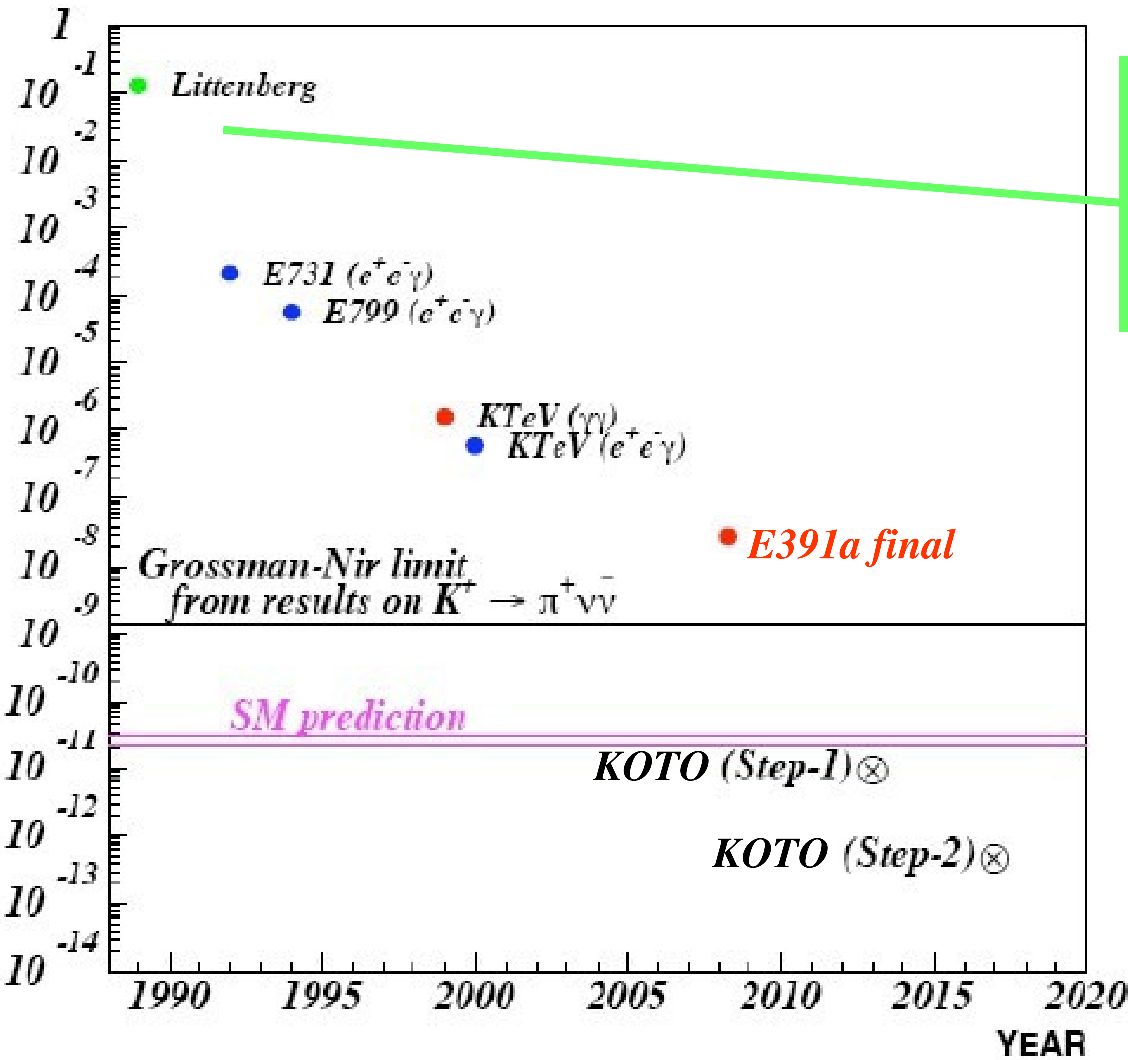
The long $K^+ \to \pi^+ \upsilon\upsilon$ march

First search: 1969 (10^{-4}) Observation: 1997 (10^{-10})



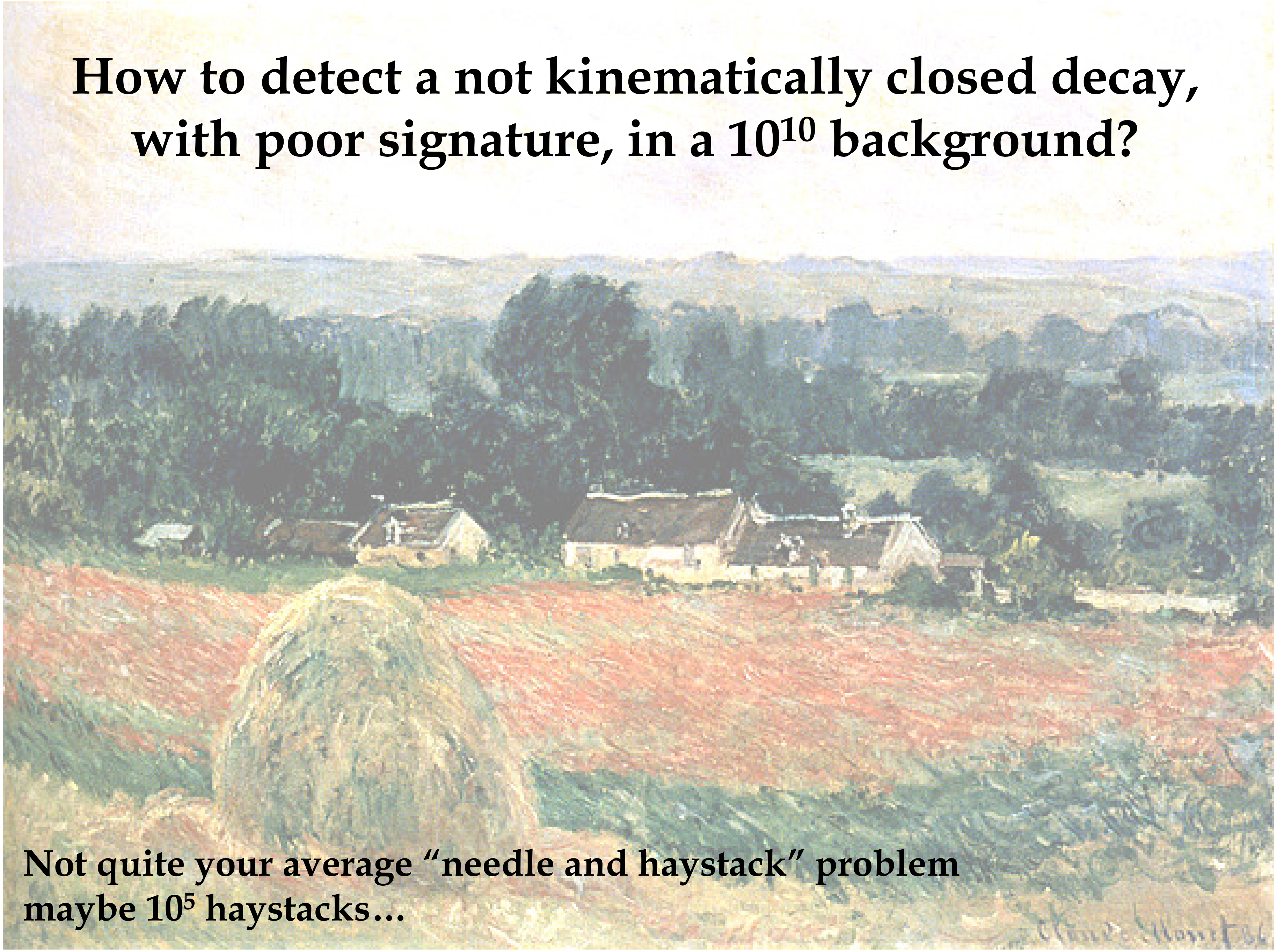


The new $K_L \to \pi^0 \nu\nu$ enterprise

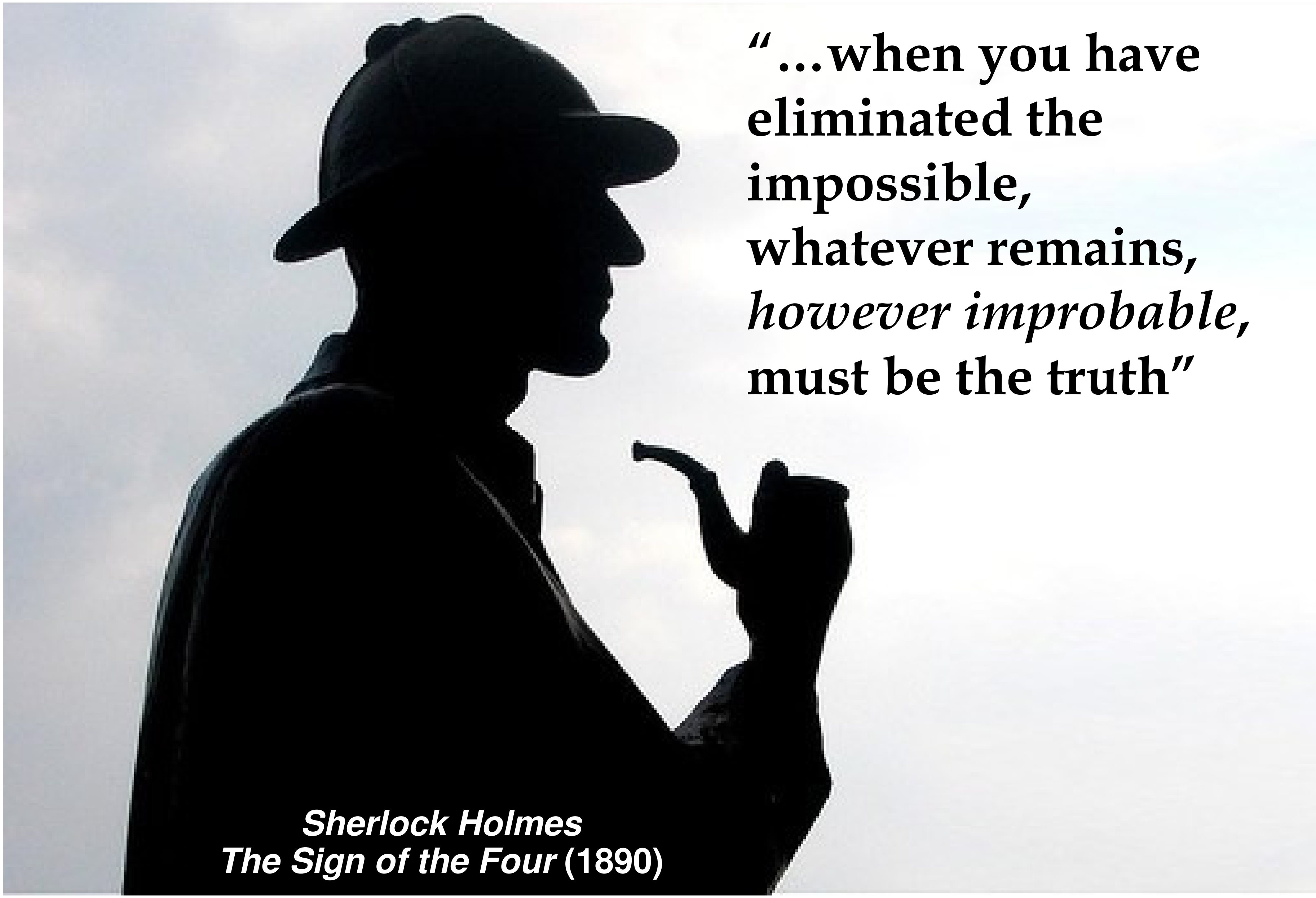


"The best it can be said is that so far nobody demonstrated conclusively that the measurement is impossible".

How to detect a not kinematically closed decay, with poor signature, in a 10^{10} background?

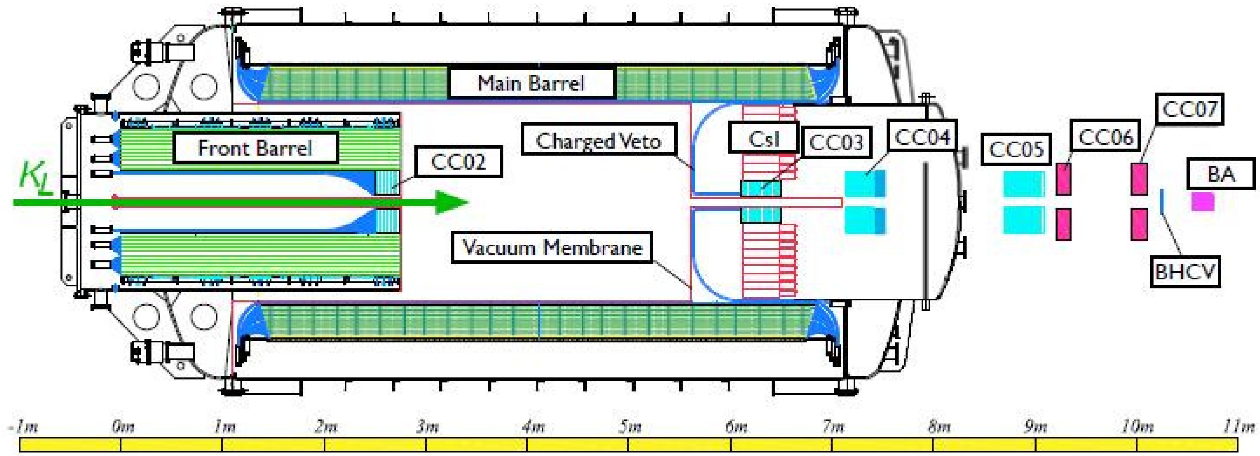


Not quite your average "needle and haystack" problem
maybe 10^5 haystacks…



Sherlock Holmes
The Sign of the Four **(1890)**

KEK E391a experiment



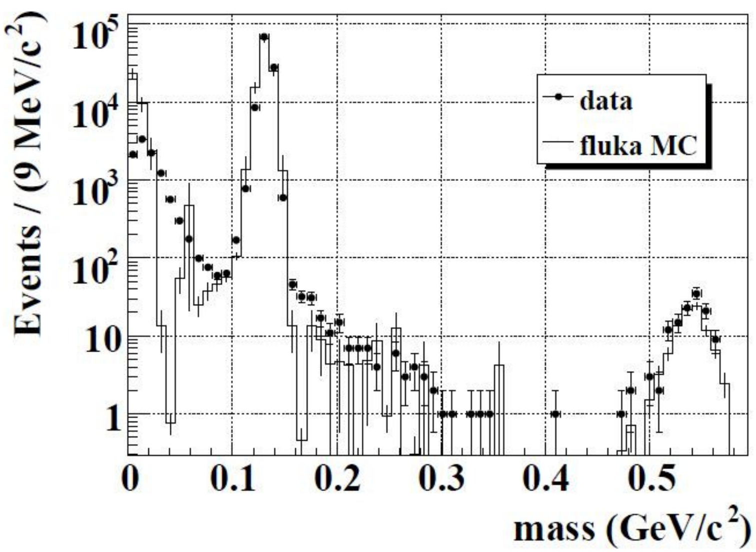
First dedicated pilot experiment to search for $K_L \rightarrow \pi^0 \nu\nu$ at the KEK-PS
Improve over KTeV (Dalitz) limit: BR < $5.9 \cdot 10^{-7}$

- High intensity: $2 \cdot 10^{12}$ ppp 12 GeV/*c* (50% DC)
- "Pencil" beam as transverse constraint: ~ 2 GeV/*c* KL at 4° and 11m
- Photon veto hermeticity down to 1-2 MeV: Pb/scint in high vacuum
- Good EM calorimetry: ~500 pure CsI 7x7 cm^2, with central hole

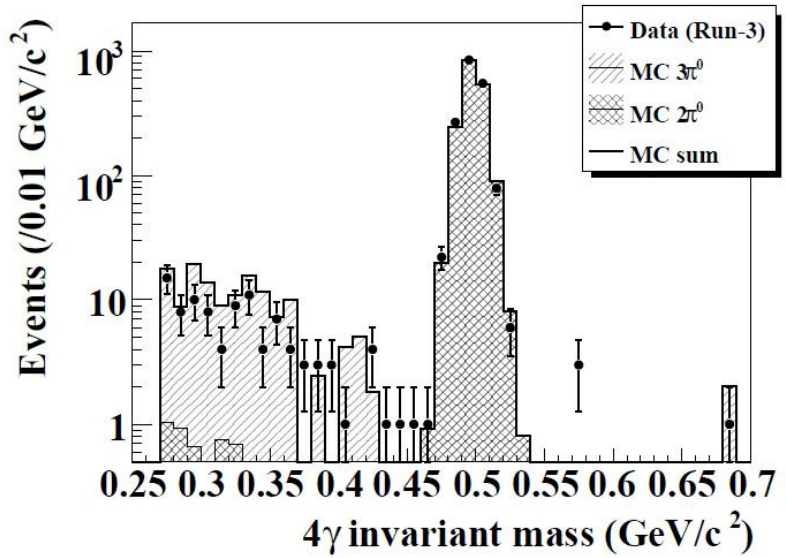
Three runs (2004-2005): 12 month total

GOAL…

KEK E391a results

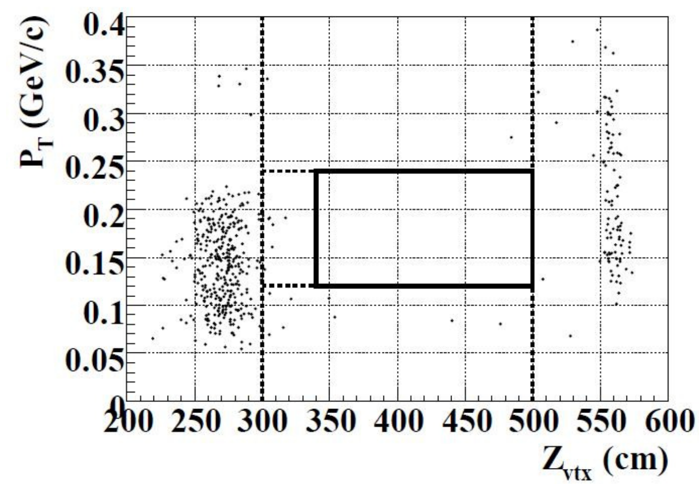


2γ mass with 5mm Al plate run



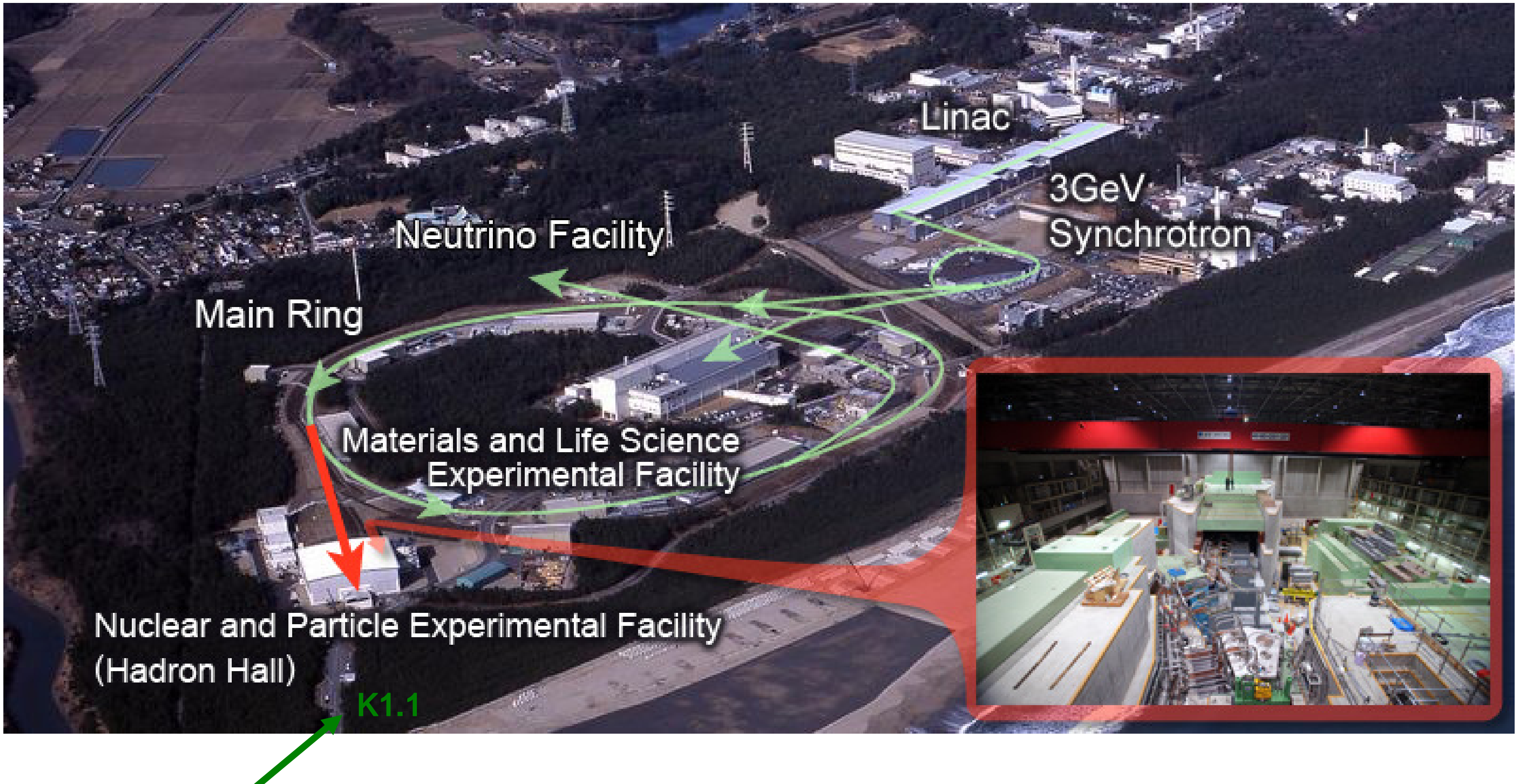
4γ mass in vacuum run

Detailed understanding of backgrounds
Bkg estimate: 0.87±0.41
3 flux normalizations
~1% total acceptance
SES $(1.11\pm0.02\pm0.10)\cdot10^{-8}$



$BR(K_L\to\pi^0\nu\nu)<2.6\cdot10^{-8}$ (90% CL)

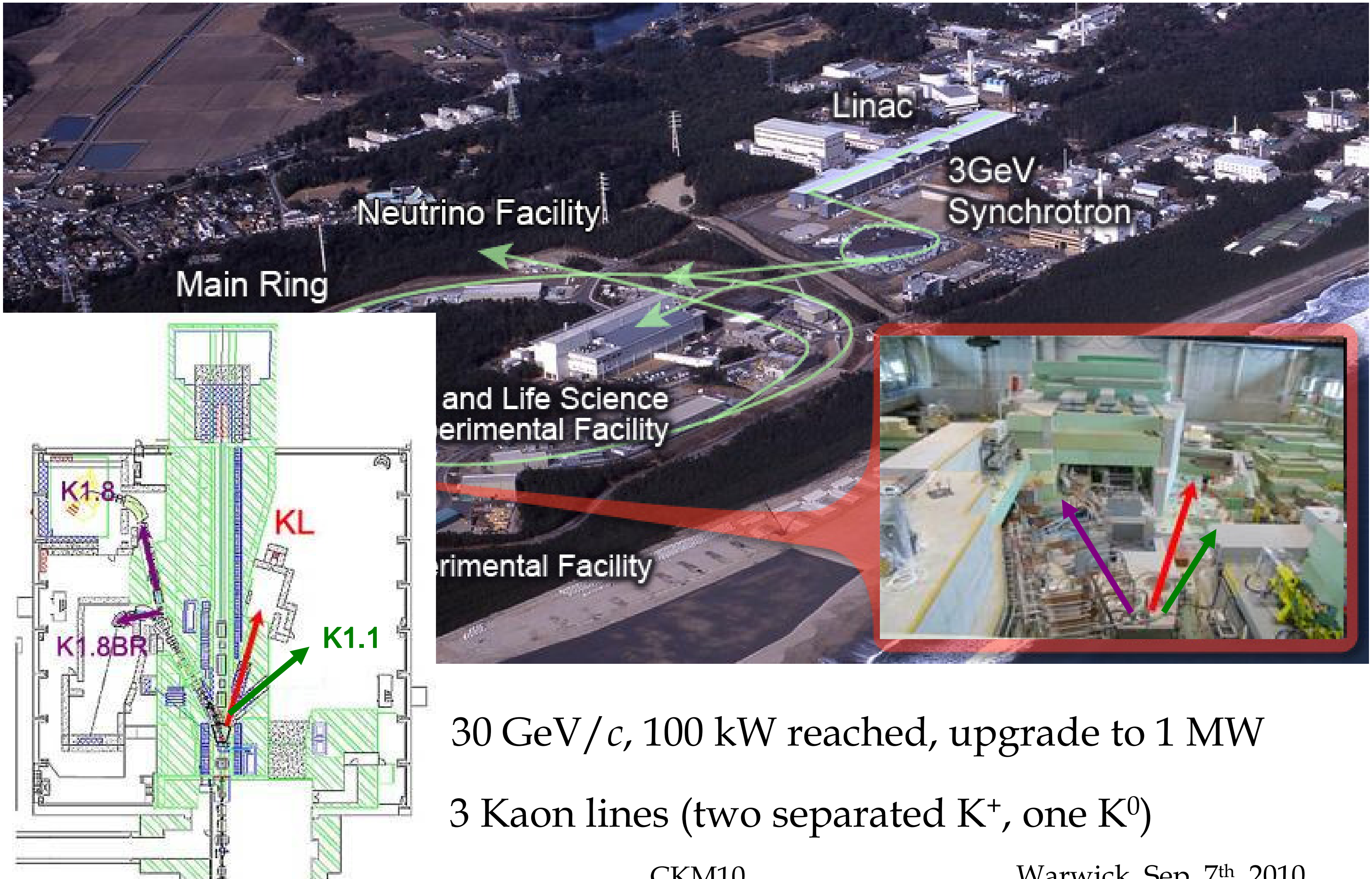
J-PARC



30 GeV/*c*, 100 kW reached, upgrade to 1 MW

3 Kaon lines (two separated K^+, one K^0)

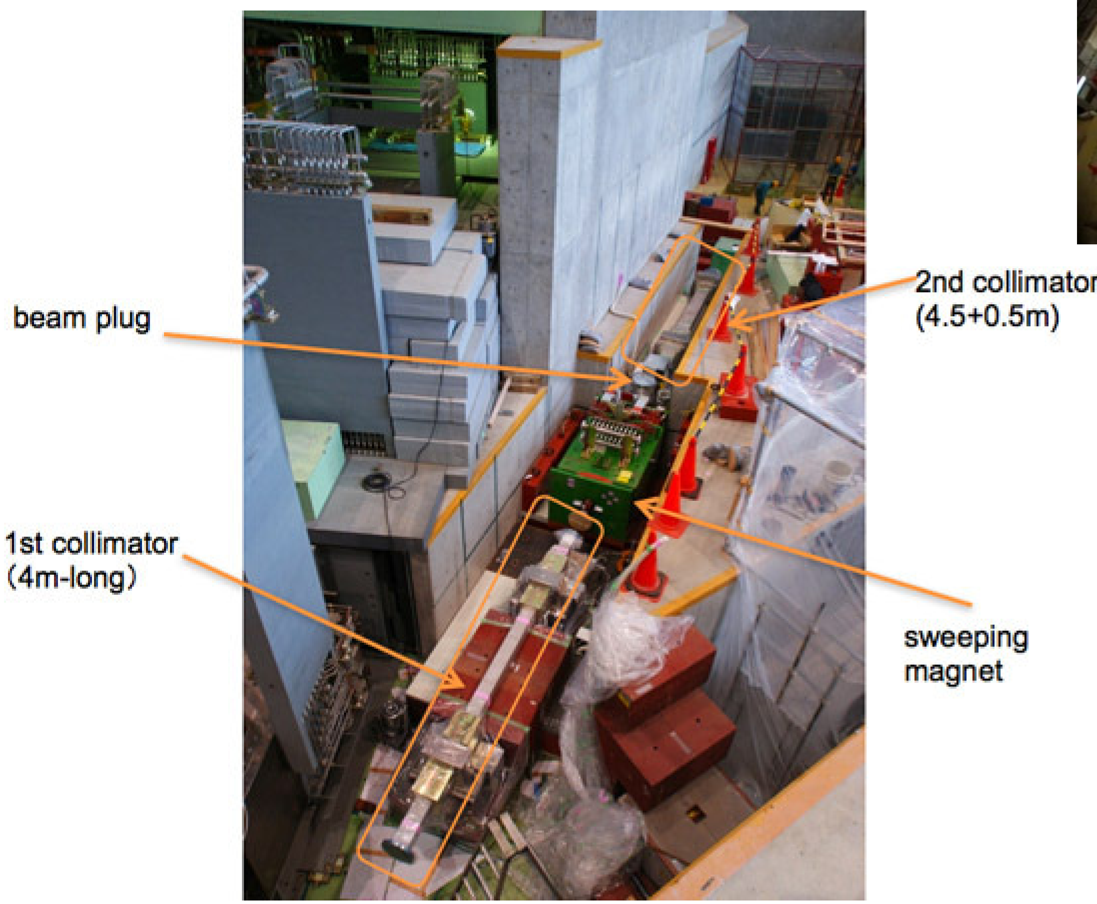
J-PARC



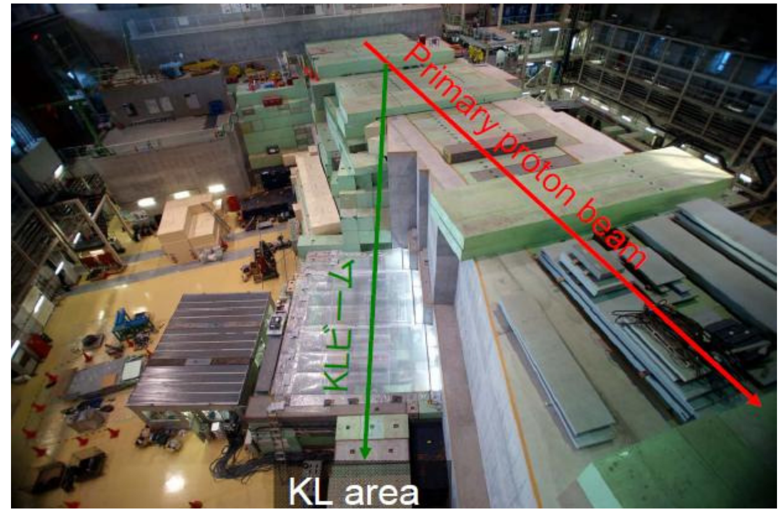
30 GeV/c, 100 kW reached, upgrade to 1 MW

3 Kaon lines (two separated K^{+}, one K^{0})

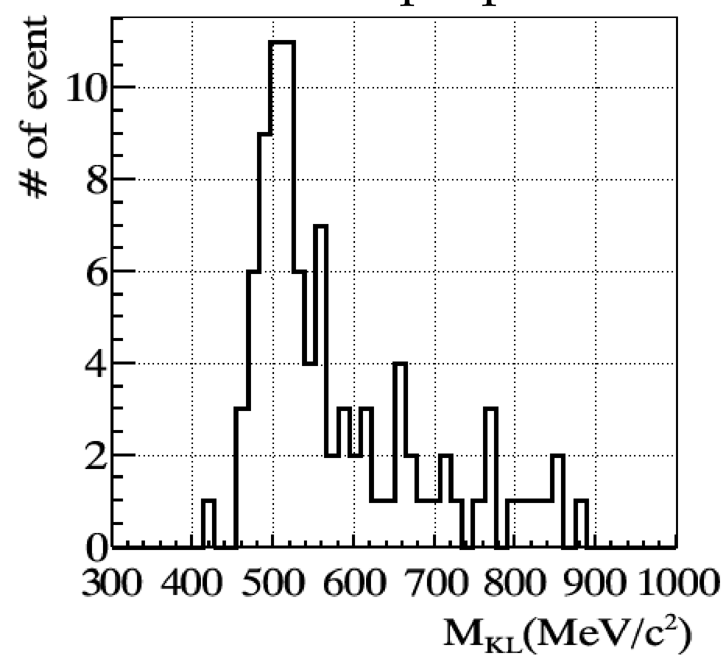
J-PARC K_L beam



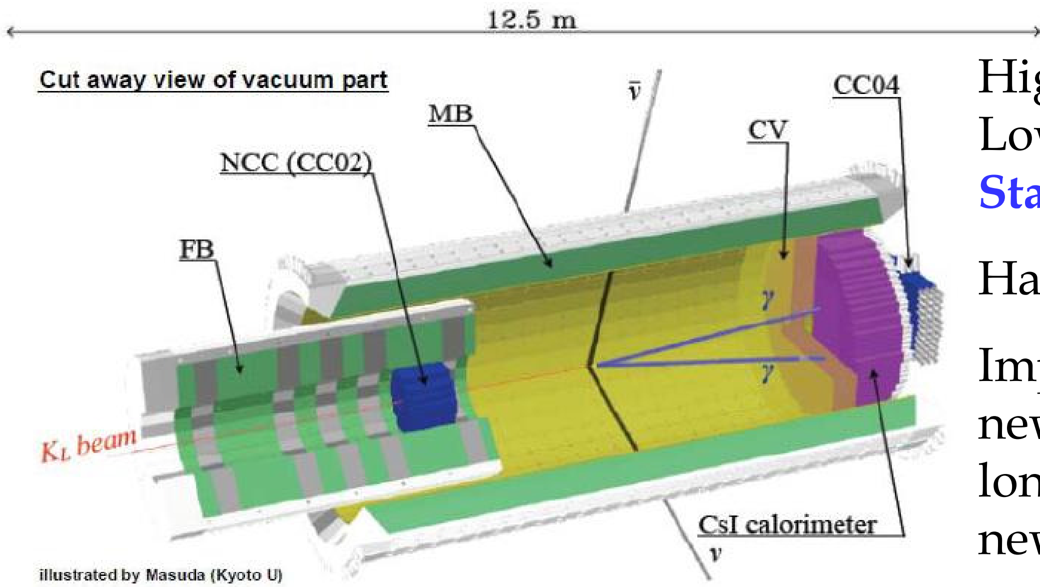
$0.2 \div 4$ GeV/c K_L



$K_L \to \pi^+\pi^-\pi^0$ detected
1-2 GeV/c
Yield: 2.3 x proposal



KOTO experiment



Higher beam intensity, acceptance
Lower DC, yield (angle):
Statistics: **3000 x E391a**

Halo **n/K**: **240x E391a:** new beam line

Improved **background** control:
new EM calorimeter (> granularity, longer), new backside charged veto, new beam-hole γ veto (25x Pb/aerogel)

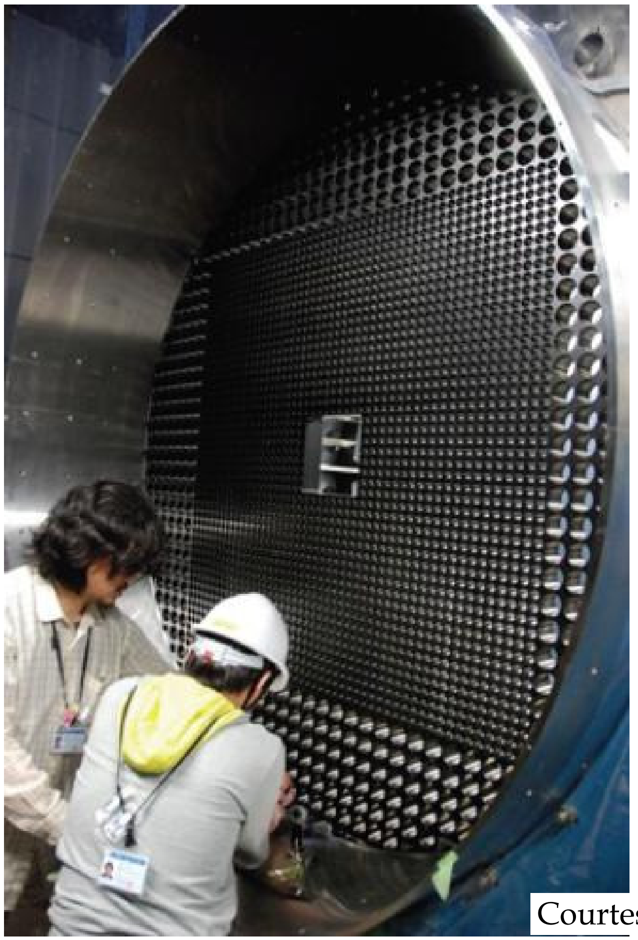
Step 1: SES = **2.7 SM events** (3 Snowmass years) with **2.2 background**

Step 2 upgrade**: 100 SM events**
(dedicated, smaller targeting angle beam line, larger detector)

66 people, 16 institutions (Japan, Korea, USA, Russia, Taiwan)
Stage 2 approval, beam line commissioned, in preparation

KOTO experiment

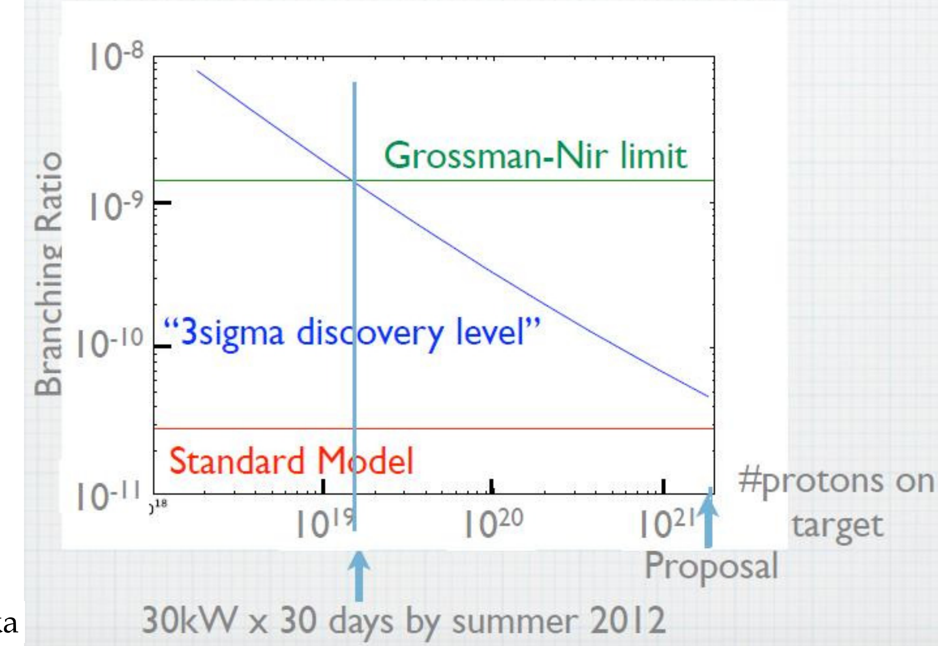
2700 CsI crystal EM calorimeter (KTeV) with new electronics, in vacuum. 144 ch. prototype tested OK, now stacking.



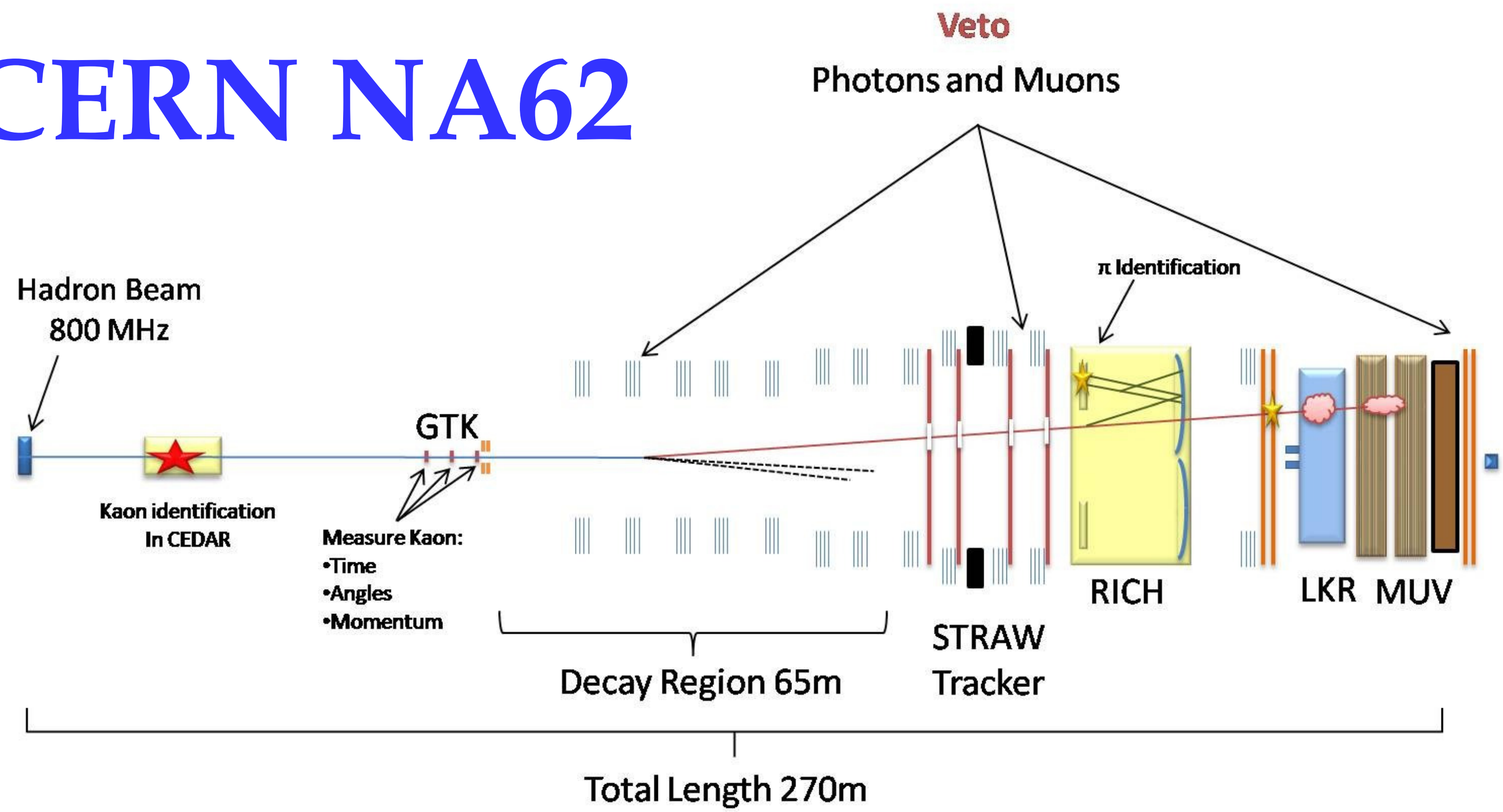
Courtesy T. Yamanaka

Beam in October to test calorimeter
Engineering run & first physics run fall 2011

Goal: reach GN limit before summer 2012 shutdown with 1 month 30 kW beam



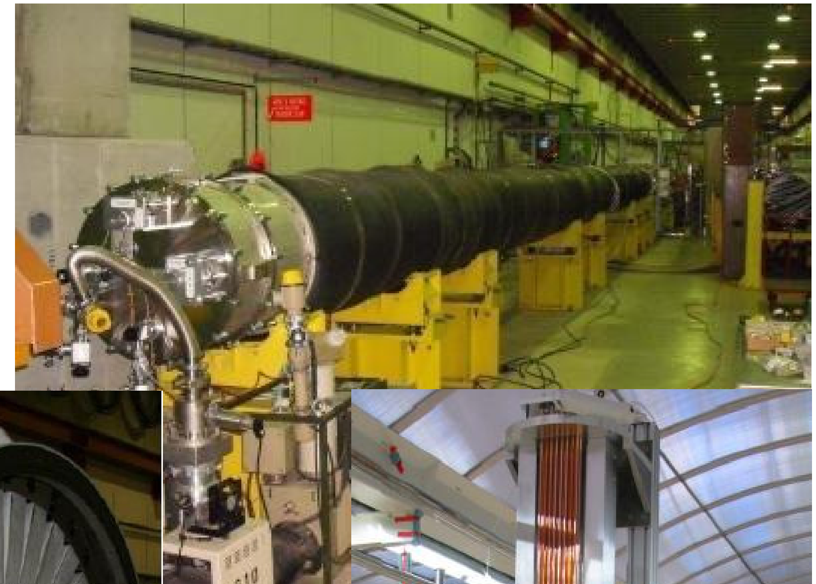
CERN NA62

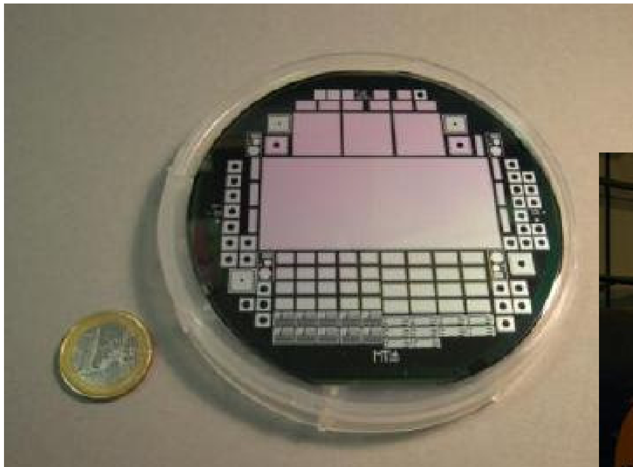


Measurement of $K^+ \to \pi^+ \upsilon\upsilon$ with new decay in-flight technique
Intense unseparated (6% K+) 75 GeV/*c* hadron beam: $5 \cdot 10^{12}$ ppp
High-energy: high yield, large decay volume, more powerful vetoing
Track incoming K^+ in 800MHz beam, particle ID, photon vetoing

$5 \cdot 10^{12}$ K^+ decays/year
55 SM events/(<Snowmass) year, $S/B \approx 5$

CERN NA62





Completing R&D
Starting construction

Partial engineering test 2011
First physics run 2013

US: strong interest and many casualties

FNAL P996 proposal

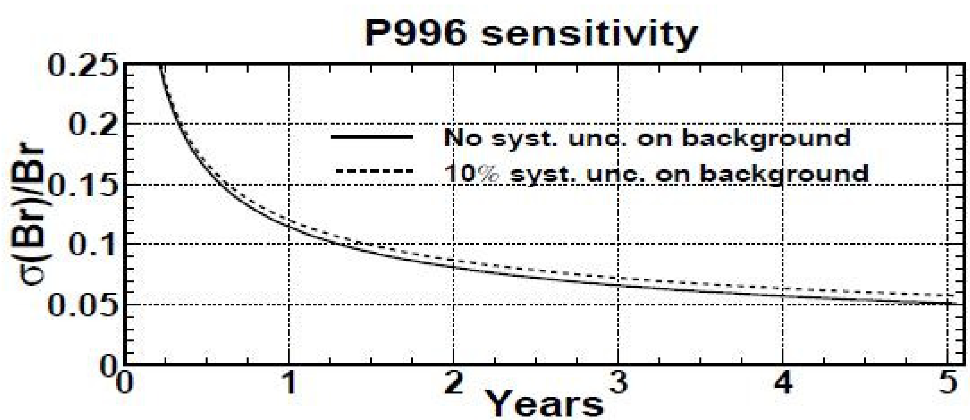
5% measurement of $BR(K^+ \to \pi^+ \nu\nu)$ with (proven) **stopped beam** technique, improving **x100** over BNL E949 by using:

- 10% of MI protons: $9.6 \cdot 10^{13}$ 150 GeV/c p (kaon yield x7)
- TeVatron as a stretcher ring (**95% DC**), same detector rates ($\approx$ 8 MHz)
- Separated 550 MeV/c K+ beam ($K/\pi \approx 2.5$, 13.5 m long, K^+ stops x4.5)

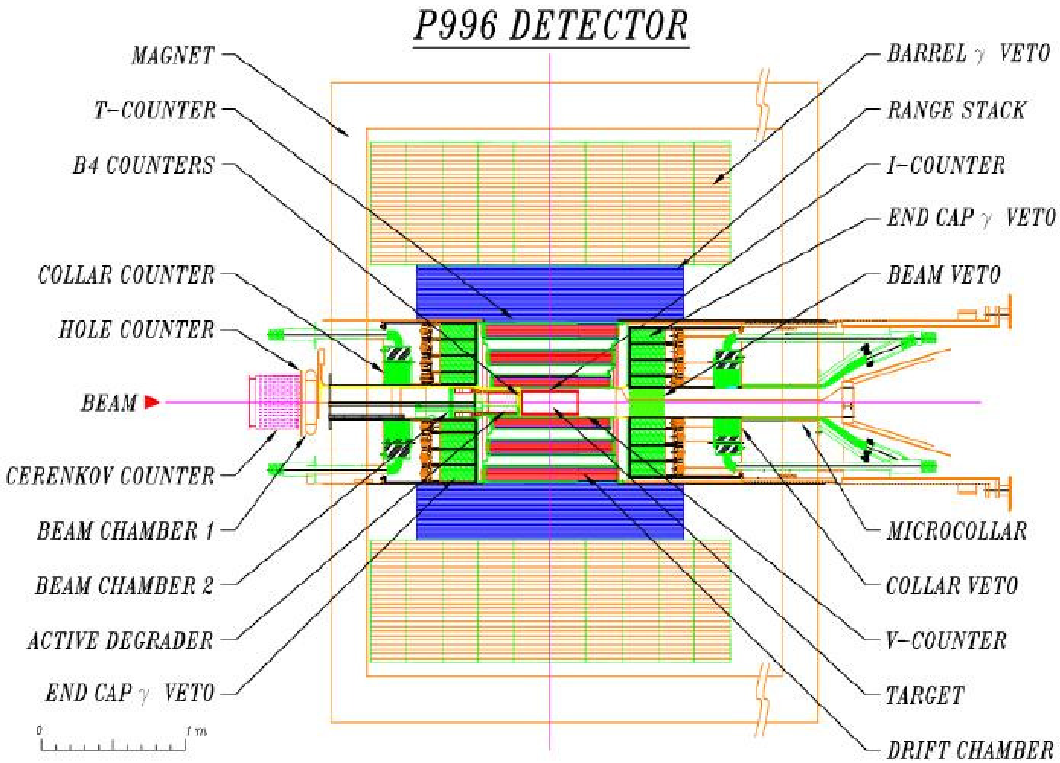
Goal: 194^{+89}_{-79} events/year

(1 year = 1.8 Snowmass years)
with $S/N \approx 4$

Ratio P996/E949	
$11.3^{+3.3}_{-2.3}$	Detector acceptance
6.3 ± 2.1	Stopped kaons per hour
5.3	Hours per year



FNAL P996 proposal



New detector in CDF hall based on E949 concept, CDF/CLEO solenoid

Acceptance x11:
many 10-50% improvements

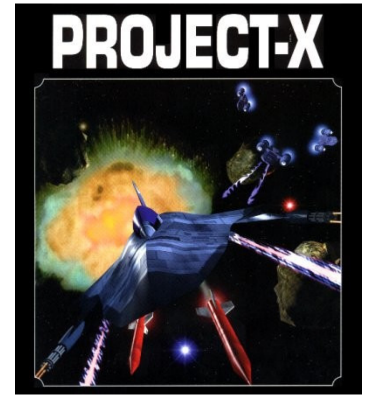
Component	Acceptance factor
$\pi \to \mu \to e$	2.24 ± 0.07
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	1.12 ± 0.05
Range stack segmentation	1.12 ± 0.06
Photon veto	$1.65^{+0.39}_{-0.18}$
Improved target	1.06 ± 0.06
Macro-efficiency	1.11 ± 0.07
Delayed coincidence	1.11 ± 0.05
Product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

13 institutes, PAC endorsement
Cost: 33.3 MUSD+contingengy
(cost for TeVatron running…)

Schedule: want to compete with NA62
TeVatron run II end ?…

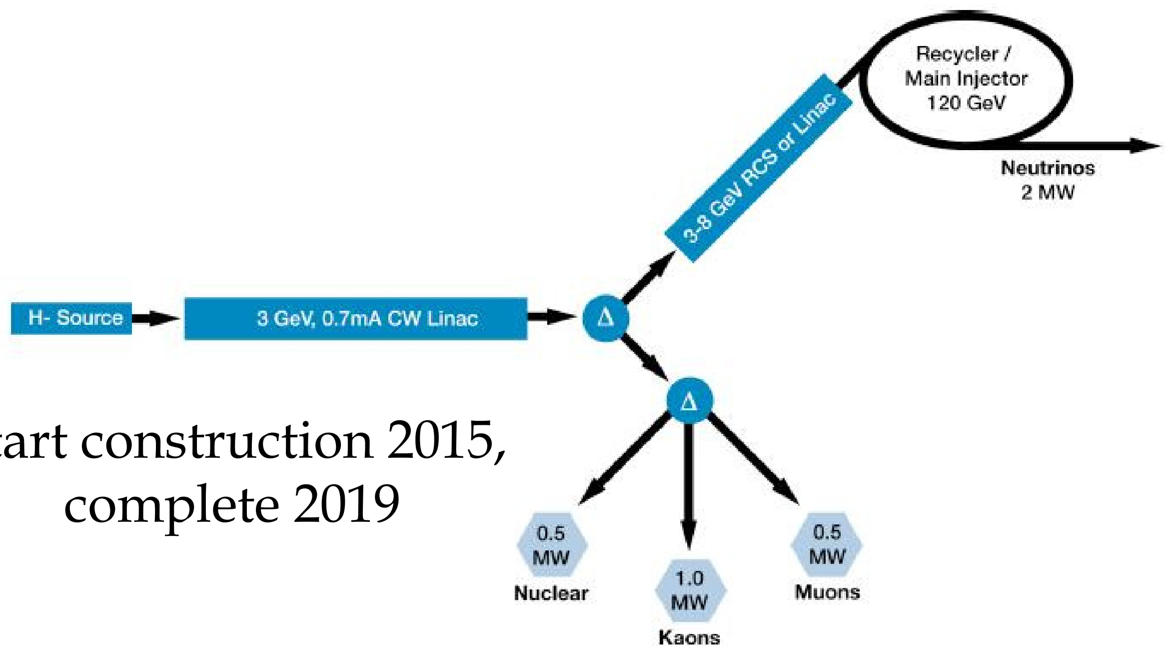
FNAL Project-X

(megatron, intensitron,…)



Ultimate proton driver for the next decade
50-120 GeV for υ, K, μ, n(EDM)

Slow extraction limited from circular machines (10s of kW):
Continuous-Wave LINAC (p or H^-), **2 MW** at 2 GeV, $2\cdot10^{15}$ p/s
10x AGS K yield (1/30 K/p, 300x flux)



Start construction 2015, complete 2019

Kaons at Project-X

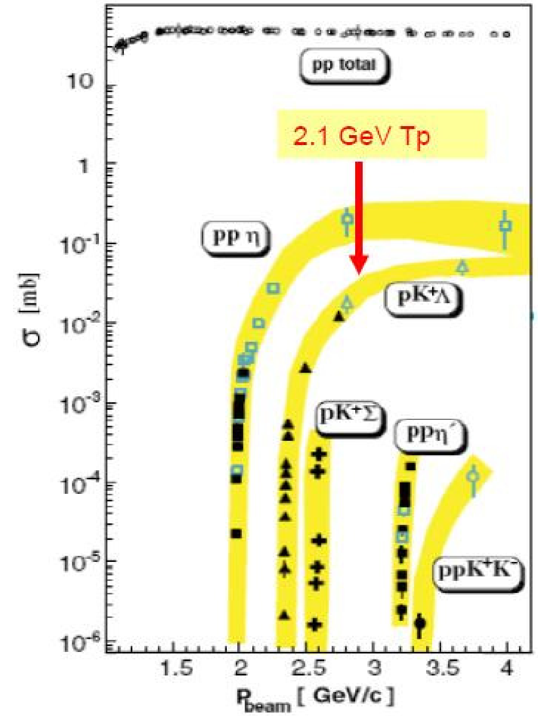
Flux potential for **ultimate** ultra-rare K decay measurements

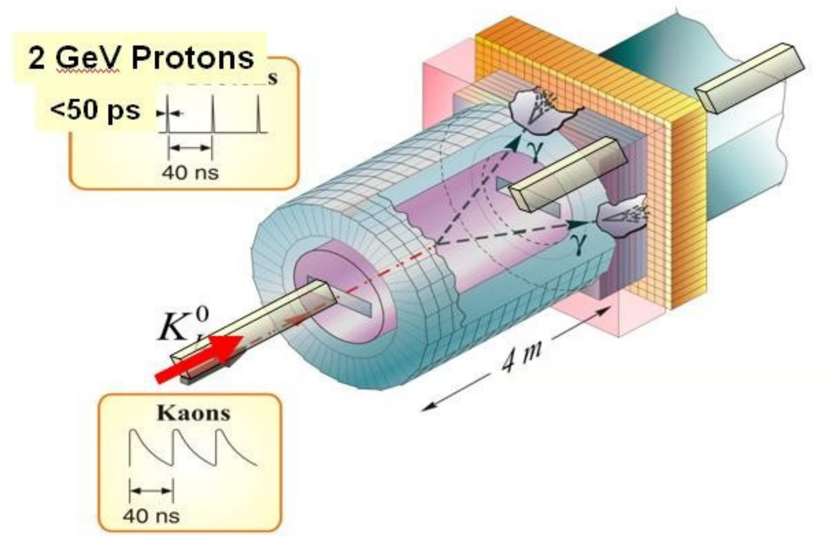
~500 $K^+ \to \pi^+ \nu\nu$ events/year (S/B ~ 4)

$K_L \to \pi^0 \nu\nu$ experiment: the best of both worlds
- Intrinsic high-precision timing:
TOF approach (KOPIO)
beam microbunching 50ps/40ns)
- Round and small beam
(acceptance and bkg rejection)

~200 $K_L \to \pi^0 \nu\nu$ evts/year (S/B ~ 5-10)

Ultimate CPT test at **Planck scale**:
interference from pure K^0 beam





Time-Reversal Violation

Transverse μ^+ polarization in $K^+ \to \pi^0 \mu^+ \upsilon$ decay
CPV not suppressed by $\Delta I=1/2$ (can be 20x $\varepsilon'/\varepsilon \approx 10^{-4}$)
Tiny SM contribution ($\approx 10^{-7}$), small FSI ($\approx 10^{-5}$):
good window for New Physics search
Relative phase of scalar coupling FF

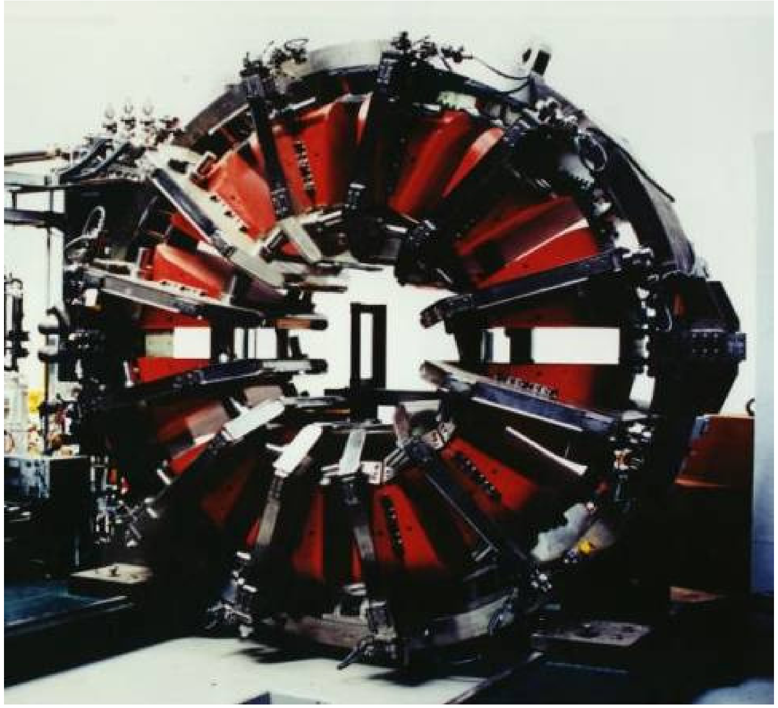
40 years of experimental history

KEK E246 experiment (final 2006):

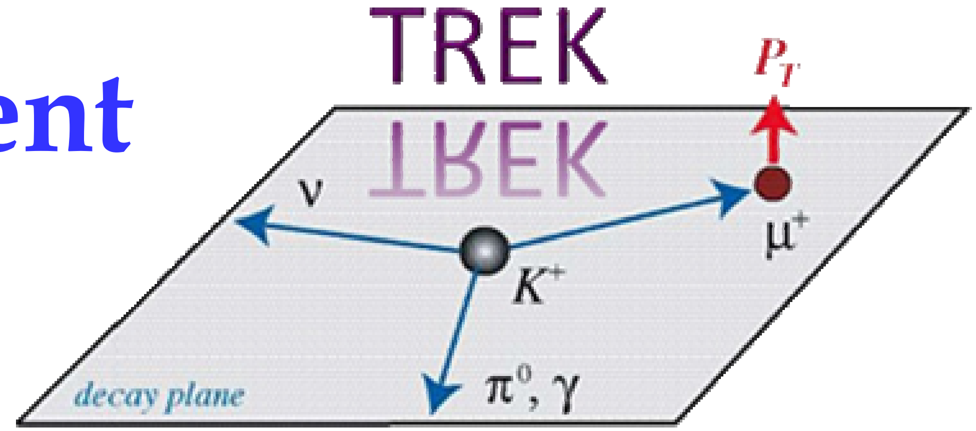
$$P_T = -0.0017 \pm 0.0023 \pm 0.0011$$

$$P_T < 5 \cdot 10^{-3} \quad (90\% \, CL)$$

No sign of TRV
Statistically limited



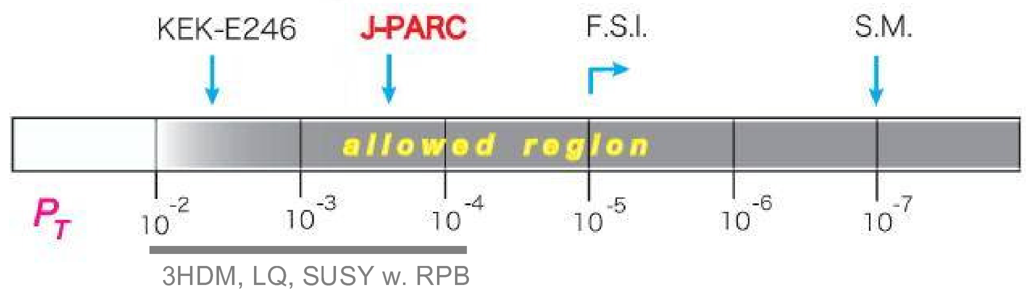
TREK experiment



J-PARC experiment
Goal:

$$\sigma(P_T) \approx 10^{-4}$$

in 1 year



Factor **20** over E246:
0.8 GeV/*c* separated K+ branch line (K/π ≈ 2)
Higher beam **intensity** (2 MHz K^+), 1 year (300 kW beam)
Active polarimeter (lower systematics, higher acceptance)
New tracking (w. thinner target and He bags: higher background rejection)

45 people, 20 institutions (Japan, Russia, USA, Canada, Vietnam, Thailand)
Stage 1 approval, R&D, beam line commissioned, 1 polarimeter sector in 2009

Kaons?

K experiments **complementary** to proton experiments (LHC)
after all Higgs (or his lookalike) is the source of flavour effects…

Measured BRs and sensitivities in the **10^{-12}** BR range

New Physics might already be there: ε_K? ε'/ε ?
Only Lattice knows… (at least LQCD *can* be done…)

From discovery tool to **quantitative probe** (CKM) field…

… working even beyond the SM: ultra-rare K decays are the holy grail

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… working even beyond the SM: ultra-rare K decays are the holy grail

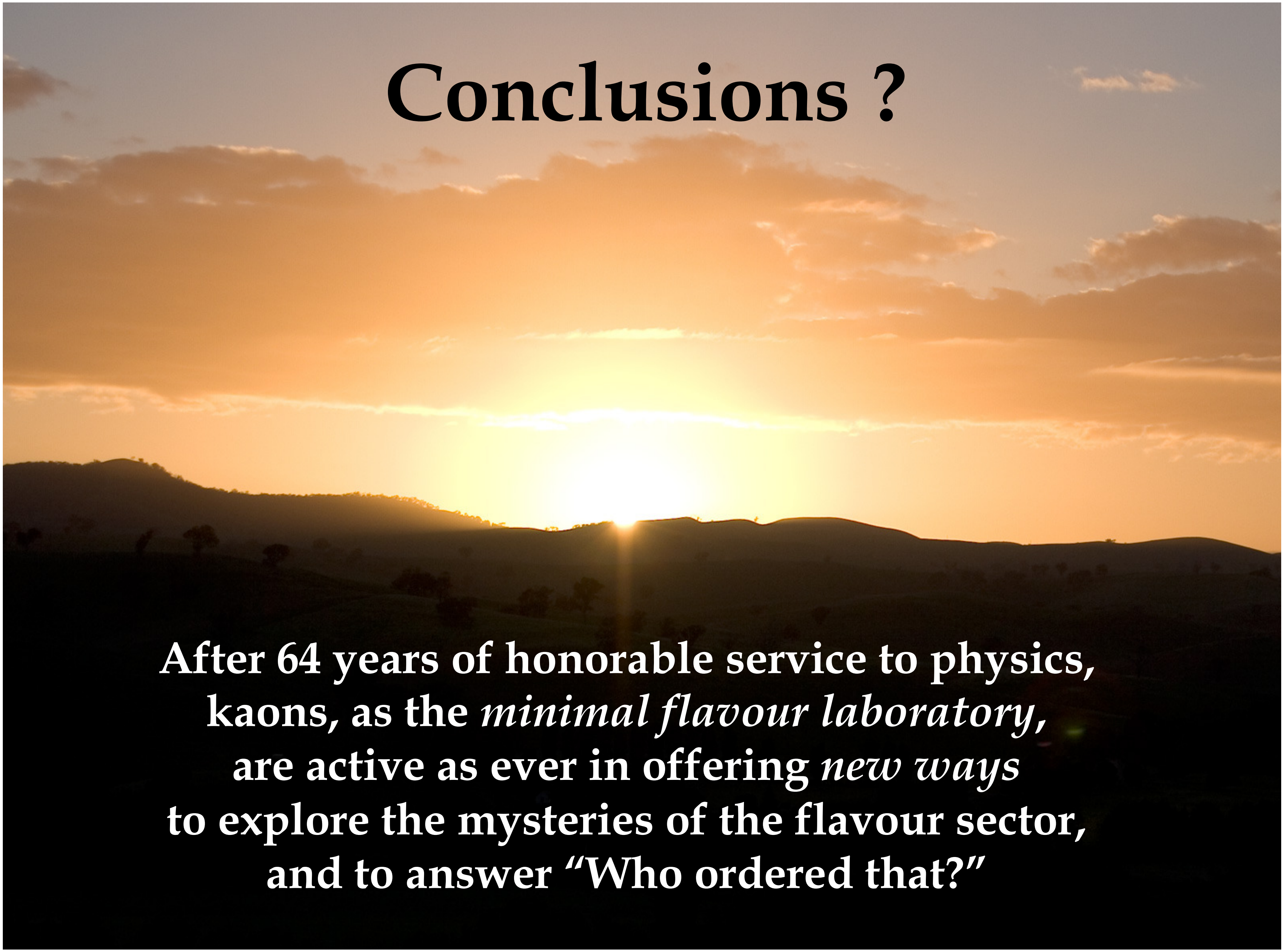
Effects seen with **10s of kW**, need **100s of kW** now

(and improved $|V_{cb}|$, $|V_{ub}|$ would help)

A flourishing of **challenging computations**
and **ultra-challenging experimental enterprises**

Kaons!

Conclusions ?

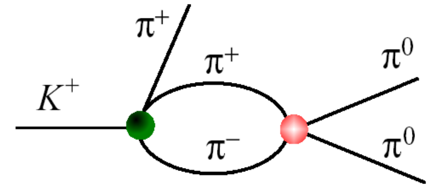


**After 64 years of honorable service to physics,
kaons, as the *minimal flavour laboratory*,
are active as ever in offering *new ways*
to explore the mysteries of the flavour sector,
and to answer “Who ordered that?”**

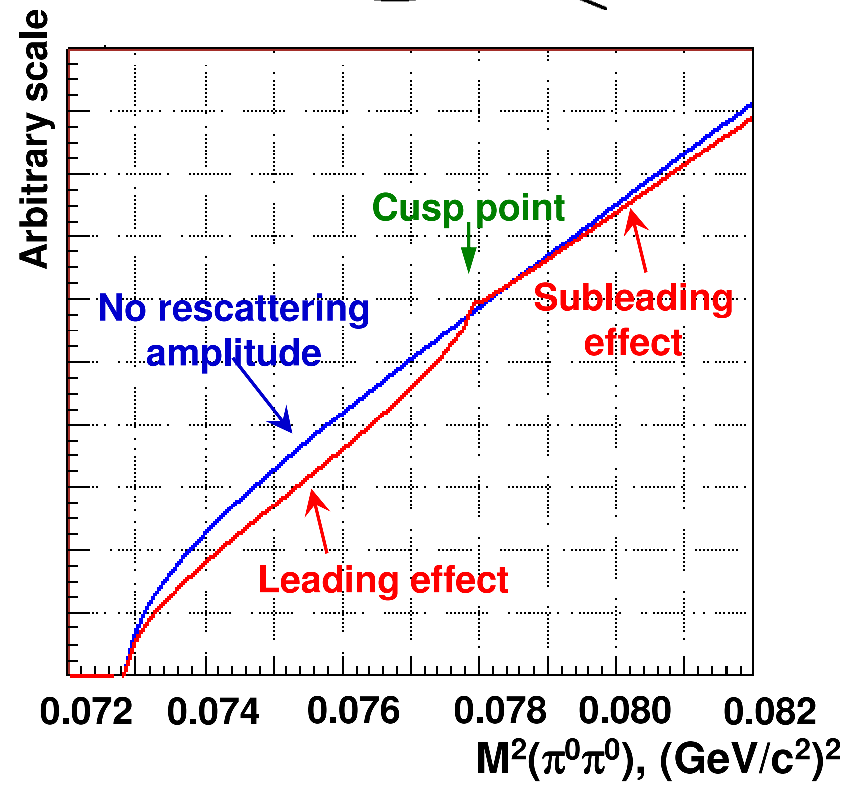
Thank-you

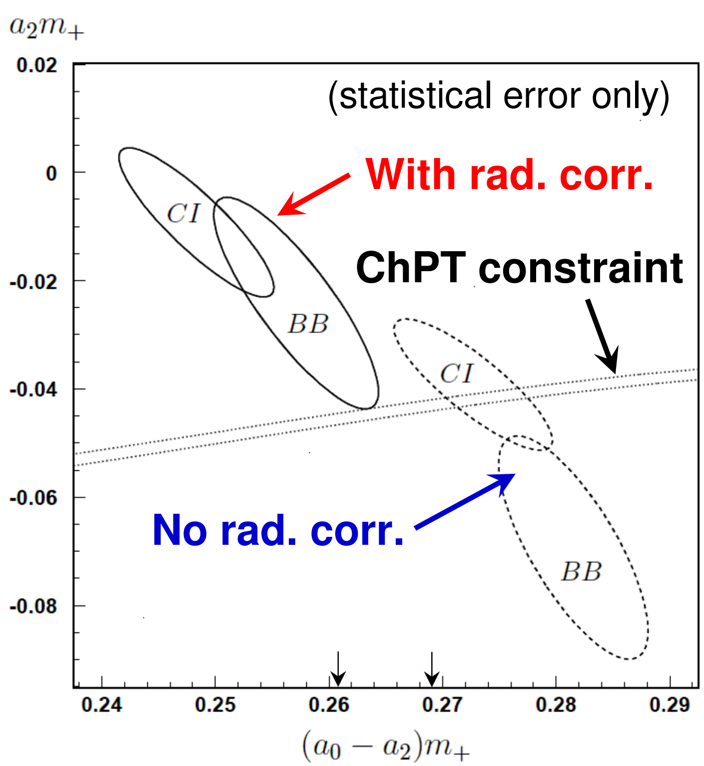
Spares

QCD from K: new way



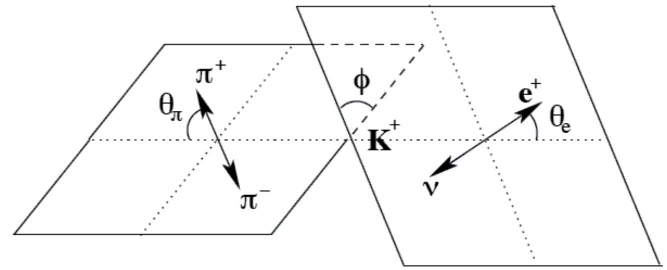
$\pi^+\pi^-\to\pi^0\pi^0$ rescattering sensitive to S-wave pion scattering lengths
(Budini, Fonda 1961 – Cabibbo 2004,
Improvements: Isidori *et al.*, Colangelo *et al.*, Bissinger *et al.*

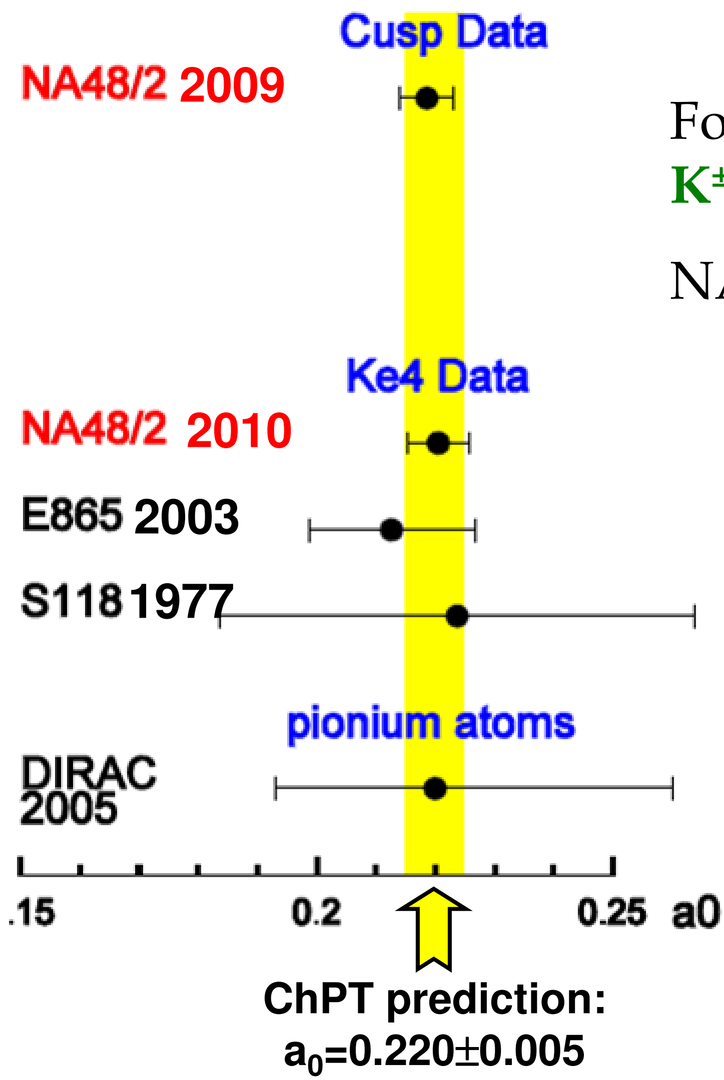




NA48/2 huge statistics

QCD from K: old way



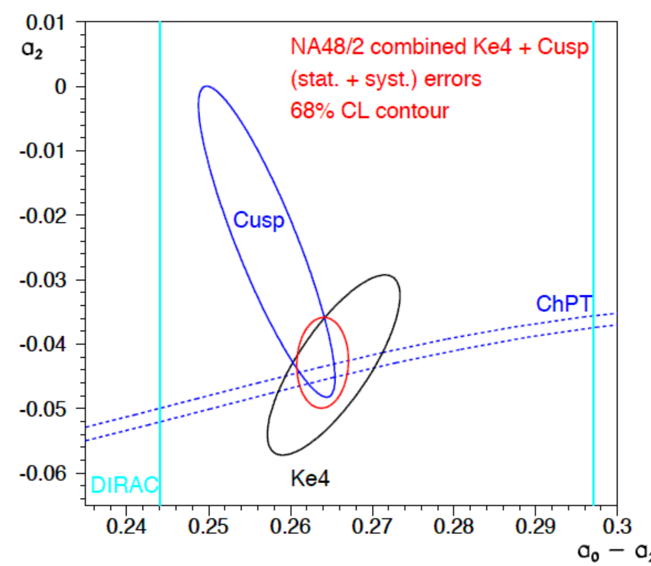


Form factor analysis of
$K^{\pm}\to\pi^{+}\pi^{-}e^{\pm}\nu$ **(Ke4)** decays

NA48/2 largest world statistics: **$1.13\cdot10^{6}$** events

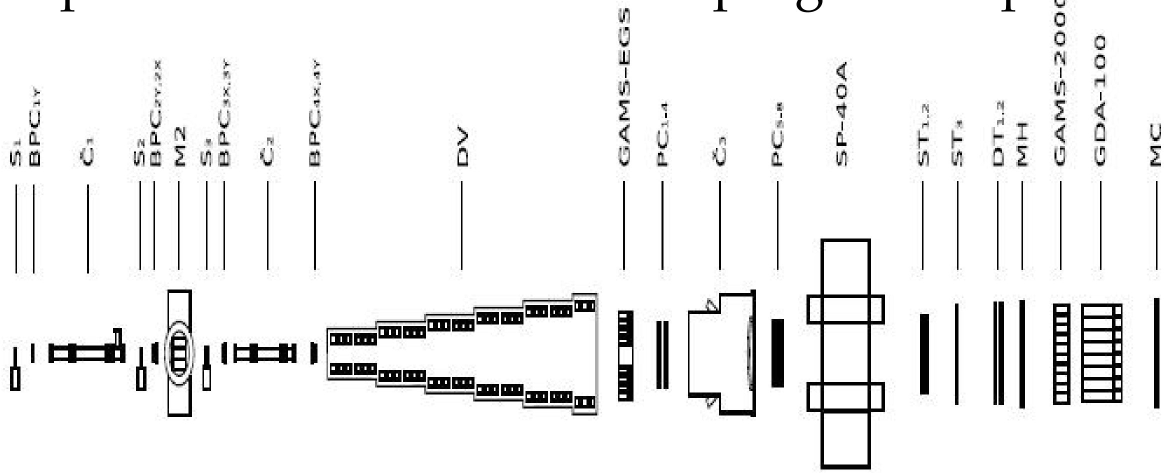
$$a_0 = 0.2210 \pm 0.0047_{stat} \pm 0.0040_{syst}$$
$$a_2 = -0.0429 \pm 0.0044_{stat} \pm 0.0028_{syst}$$
$$a_0 - a_2 = 0.2639 \pm 0.0020_{stat} \pm 0.0015_{syst}$$

Combined NA48/2 results: Striking test of QCD



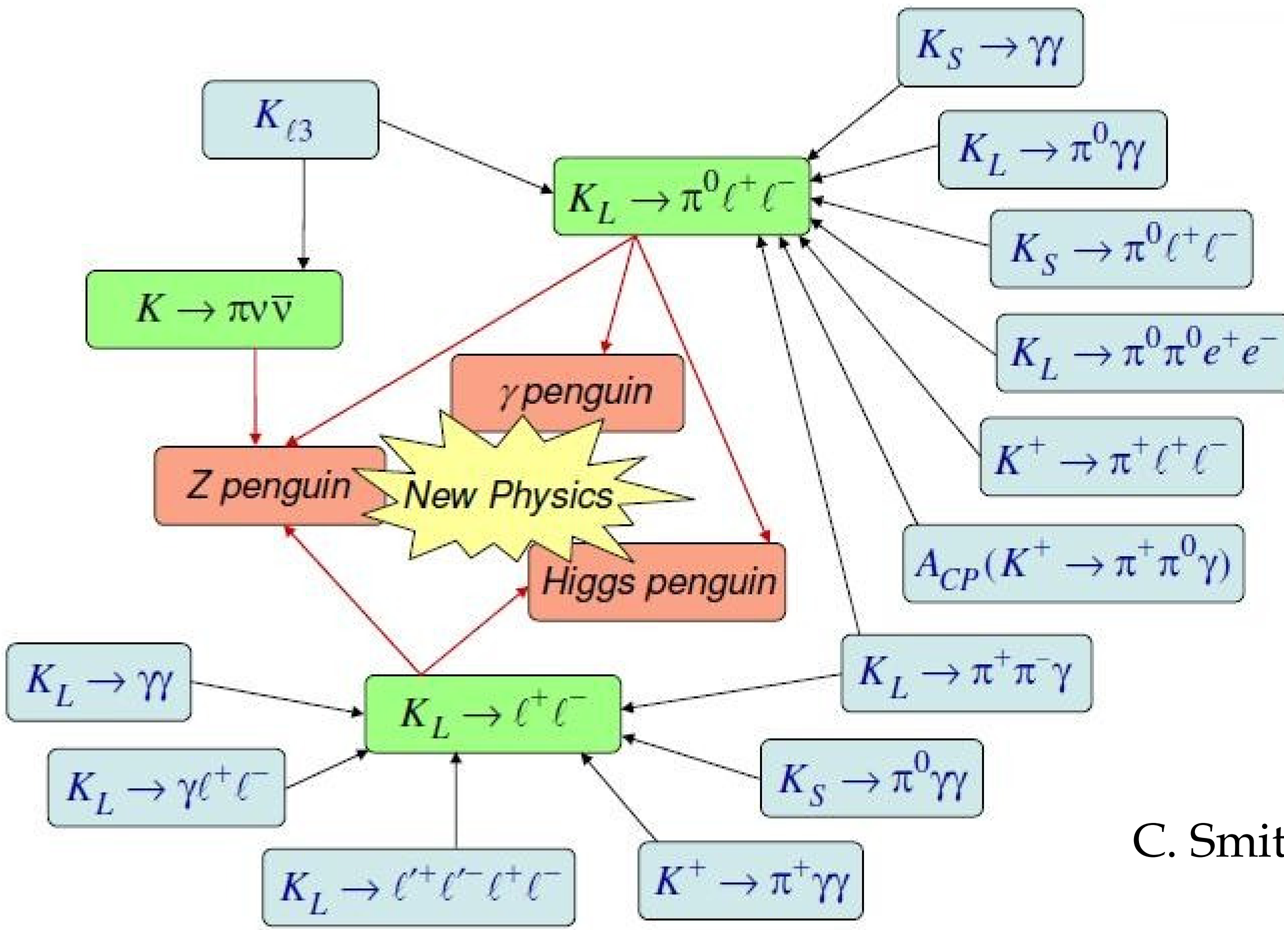
Two Protvino projects

SPHINX+GAMS+ISTRA → **OKA** at Protvino:
65-70 GeV 10^{13} ppp at U-70 (38% DC)
12.5 GeV RF-separated K^+ beam **5 $\cdot 10^6$ Kpp** ($K/\pi \approx 4$)
Commissioning beam and detector with runs started 2009
10-100x improvement on ISTRA Kaon program + spectroscopy



Ongoing R&D for a $K_L \rightarrow \pi^0 \nu\nu$ experiment **KLOD**
Neutral pencil beam extracted @ 35 mrad, 10 GeV/c K^0
300 MHz n background: dual-readout spaghetti calorimeter
Aim at **1 SM event** ($S/B \approx 3$) with 10 days of beam

Rare K decays: the full picture



C. Smith