Physics with kaons
status and perspectives

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There's beauty in Kaons

Outline:

- The Kaon legacy
- Kaons vs. CP
- Kaons vs. CPT
- Kaons vs. QM
- Kaons vs. CKM
- Kaons vs. LFV
- Kaons vs. ChPT
- Kaons vs. QCD
- Kaons vs. Time reversal
- Kaons vs. the unexpected
- **Kaons vs. New Physics**

The legacy of fixed-target high-energy hadron beams: KTeV and NA48

100 physicists
12 USA/Japan groups
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…)

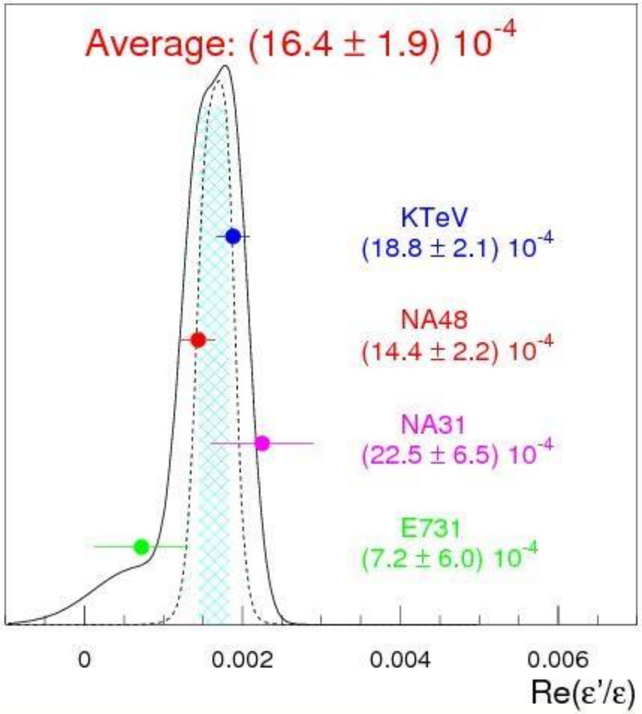
Innovative detection and analysis **techniques**

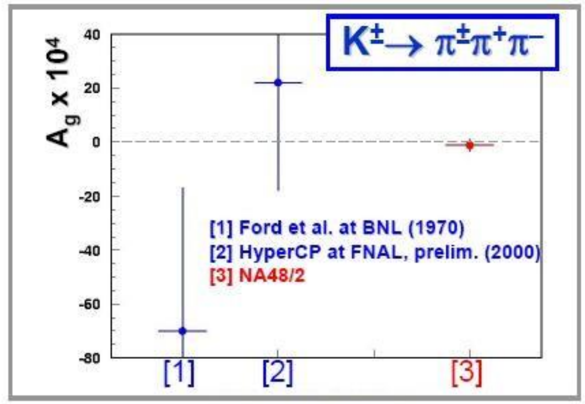
Two state-of-the-art EM **calorimeters**

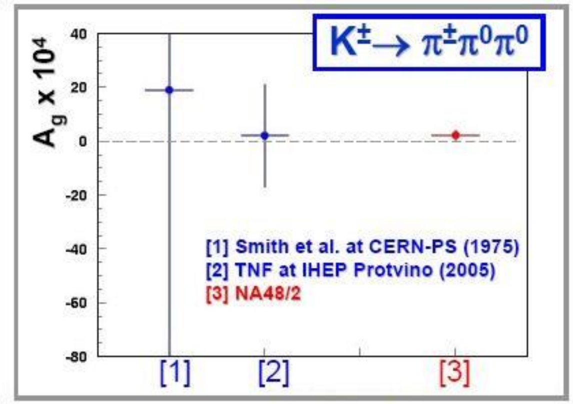
Much more physics:
50 papers each and counting…

130 physicists
16 European groups
1998-2003

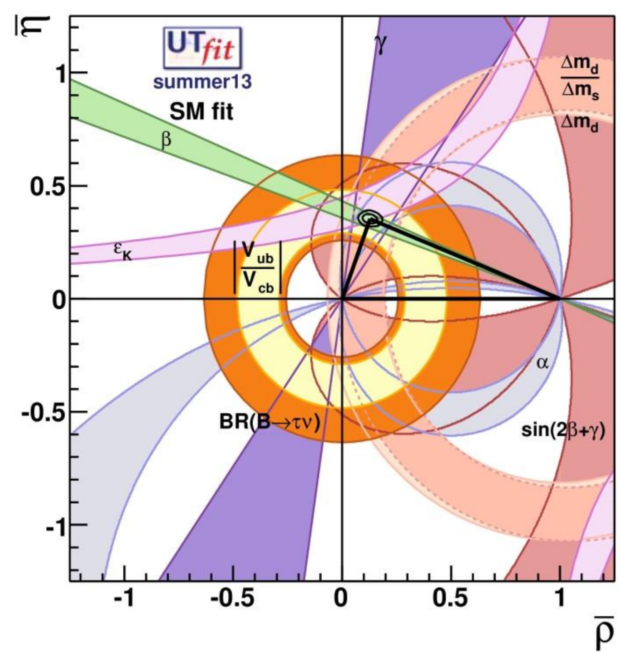
Kaons: the qualitative phase







Reasonably precise experimental data but…



Not an impressive impact on the Unitarity Triangles

Actually *training ground* for LQCD

Still waiting for Lattice improvements…

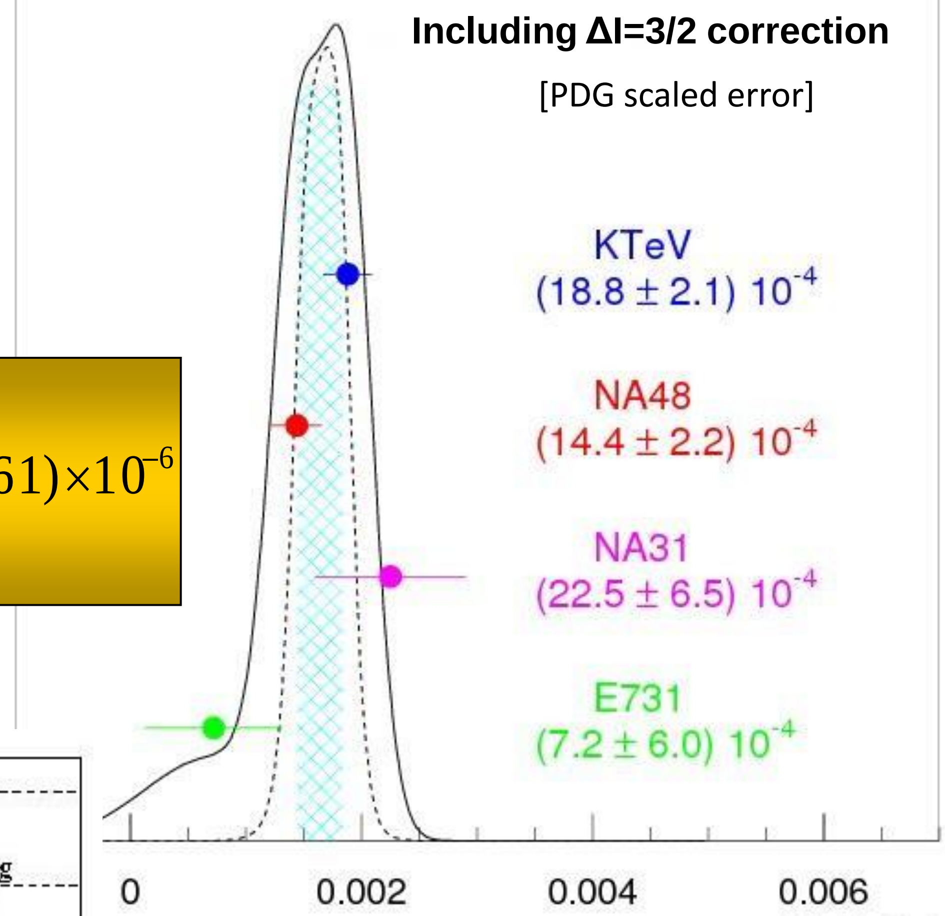
ε'/ε and direct CPV

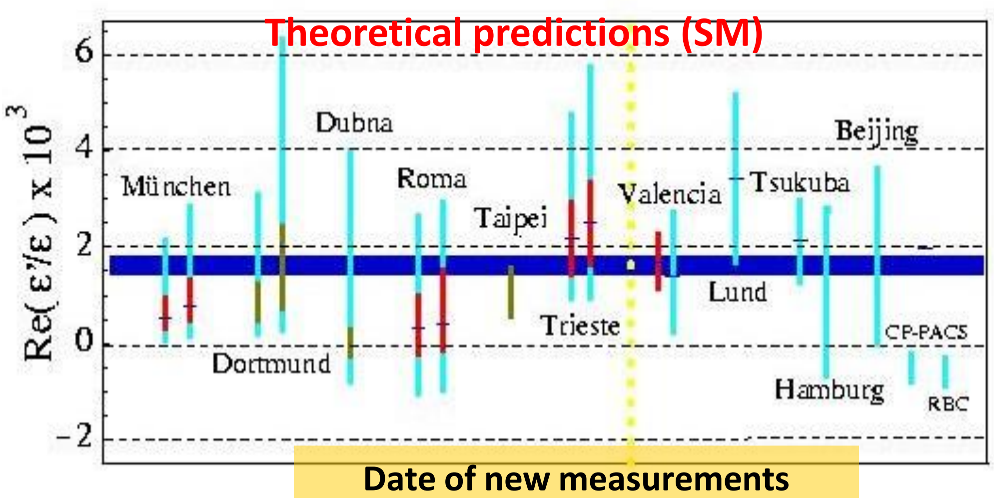
Direct CPV in K decays at ≈ 9 standard deviations

First confirmation of CKM paradigm

$$\frac{\Gamma(K^0\to\pi^+\pi^-)-\Gamma(\overline{K}^0\to\pi^+\pi^-)}{\Gamma(K^0\to\pi^+\pi^-)+\Gamma(\overline{K}^0\to\pi^+\pi^-)}=(5.18\pm0.61)\times10^{-6}$$

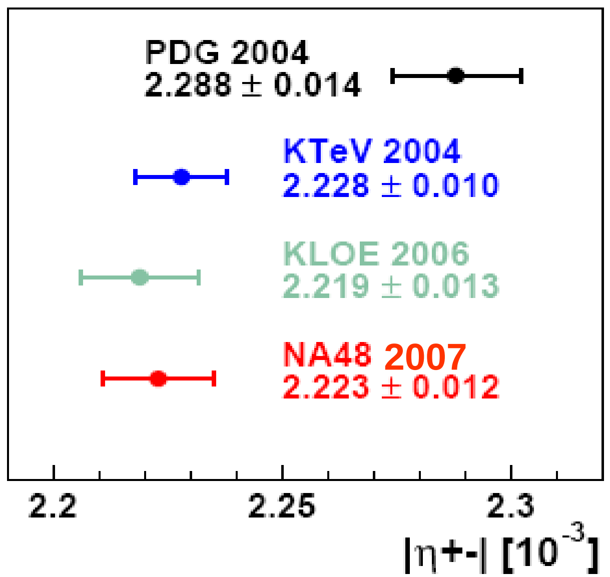
$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.4 \pm 1.9)\cdot 10^{-4}$





SM is *accidentally* quasi-superweak: hadronic nightmare with large cancellations.
Not appearing yet on UT
Theoreticians do not give up!

"Modern" ε_K



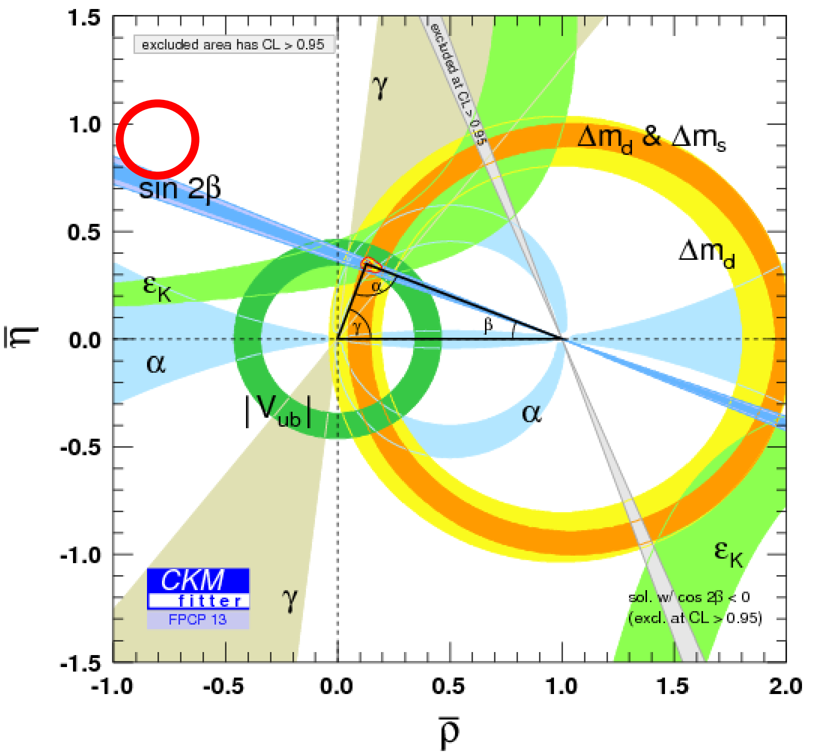
"Kaon BR revolution"
Proper treatment of radiative corrections and correlations
Several 10^4 evts/experiment

$$\varepsilon_K = (2.228 \pm 0.011) \cdot 10^{-3}$$

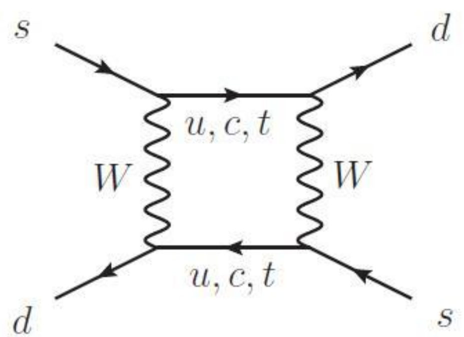
measured to 0.5%

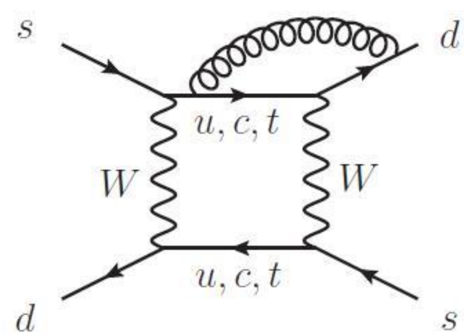
Semi-leptonic charge asymmetries with $2 \div 3 \cdot 10^8$ events (KTeV, NA48) give $\mathrm{Re}(\varepsilon_K)$, *e.g.*

$$\delta_L(e) = (3.34 \pm 0.07) \times 10^{-3}$$



Quantitative ε_K ?



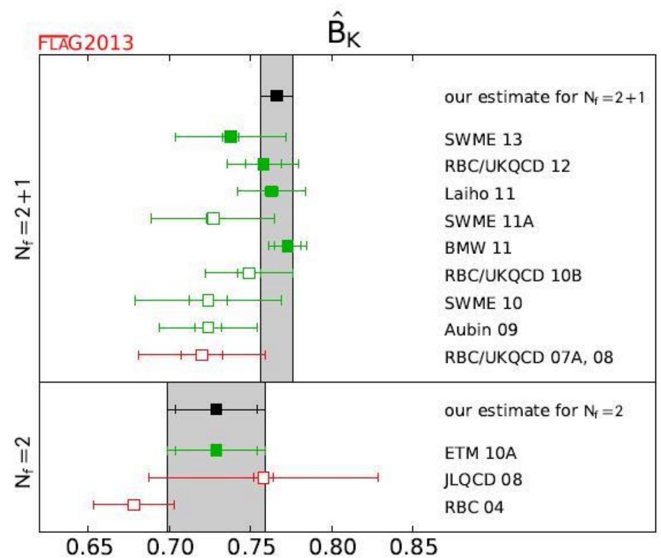


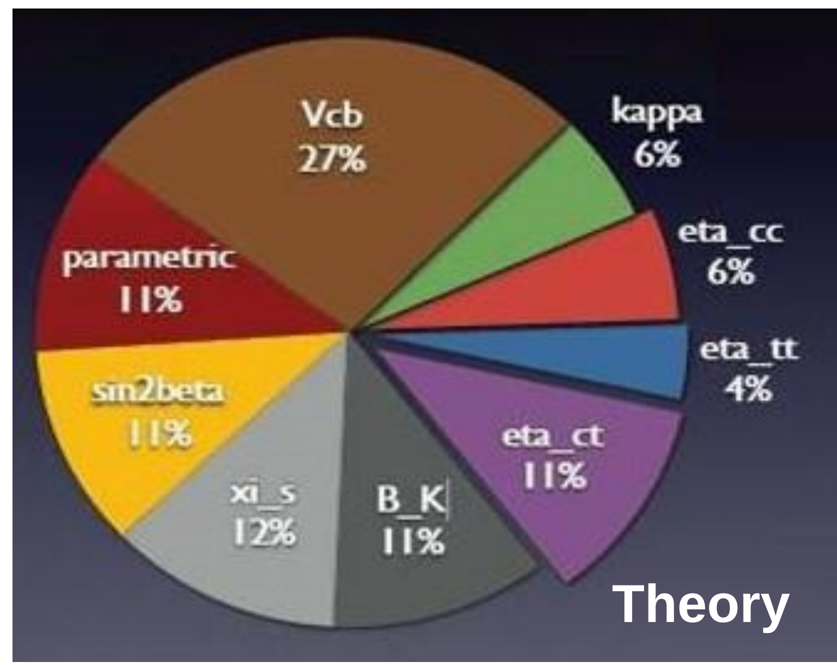
ε computed to ~ 7% theory error

B_K known from lattice to ~ 2% with NNLO RG corrections

Parametric error dominated by $|V_{cb}|$

Overall SM prediction to 14%





Progress in theory (not just lattice anymore) for ε_K to become also a *quantitative* test of SM (but sub-percent still a "long term perspective")

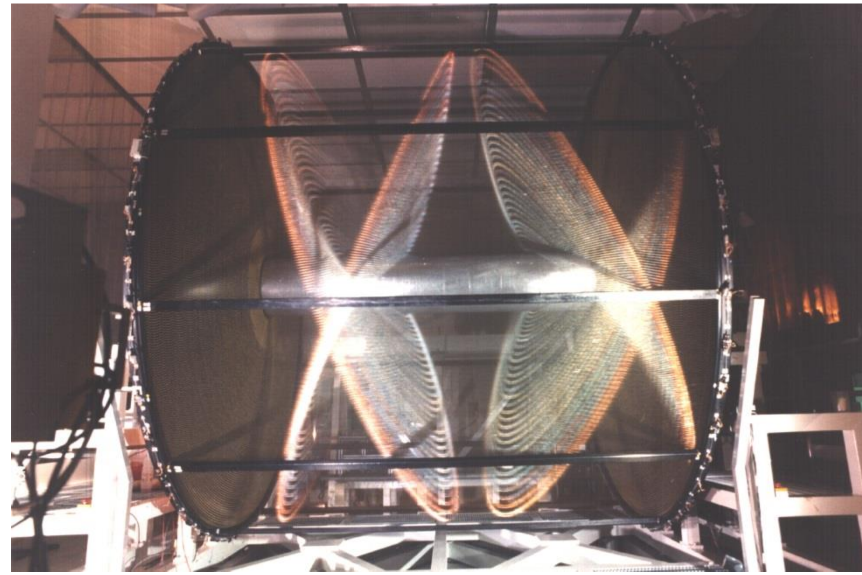
Φ-factory: KLOE

Integrated luminosity: **~ 2.5 fb^{-1}**
(~ 2.5 · 10^9 $K_S K_L$ events)

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

Not the original ε′/ε goal
but lots of physics:
BR and lifetimes measurements

BR($K^+ \to \pi^+ \pi^- \pi^0$)	1,7%	2004
BR($K^+ \to \mu^+ \nu$)	0,3%	2006
BR($K^+ \to \pi^+ \pi^0$)	0,5%	2008
BR($K^+ \to \pi^0 e^+ \nu$)	1,0%	2008
BR($K^+ \to \pi^0 \mu^+ \nu$)	1,2%	2008
$\tau(K^+)$	0,24%	2008
BR($K^+ \to \pi^+ \pi^- \pi^+$)	0,7%	2014



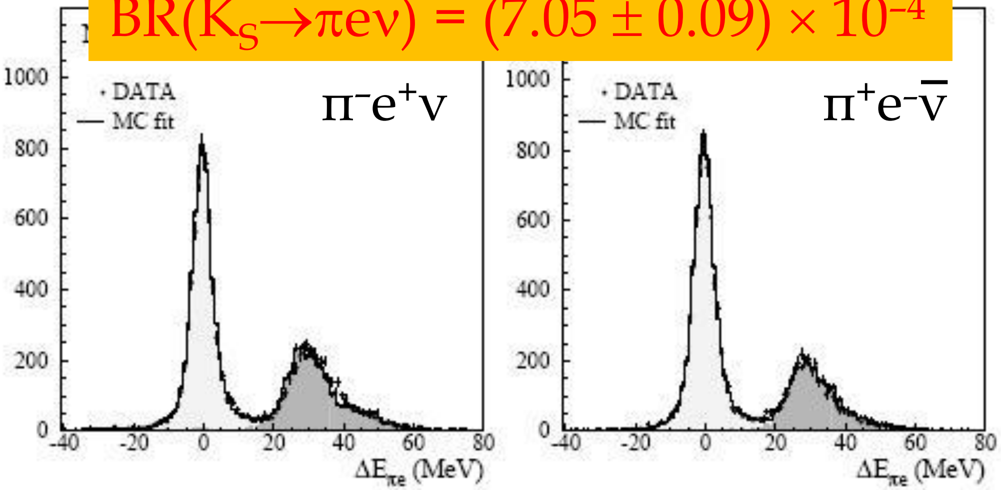
93 physicists - 15 institutions - 2000-2006

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

$$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{sys})\ 10^{-18}\ \text{GeV}$$
$$\Delta a_X = (0.9 \pm 1.5_{stat} \pm 0.6_{sys})\ 10^{-18}\ \text{GeV}$$
$$\Delta a_Y = (-2.0 \pm 1.5_{stat} \pm 0.5_{sys})\ 10^{-18}\ \text{GeV}$$
$$\Delta a_Z = (3.1 \pm 1.7_{stat} \pm 0.6_{sys})\ 10^{-18}\ \text{GeV}$$

KLOE and CPV

BR($K_S \to \pi e \nu$) = $(7.05 \pm 0.09) \times 10^{-4}$



2001-2002 data (410 pb^{-1}):
first observation, 13K events

(Indirect) CPV **charge asymmetry**:

$$\delta_S(e) = (1.5 \pm 9.6_{stat} \pm 2.9_{syst}) \cdot 10^{-3}$$

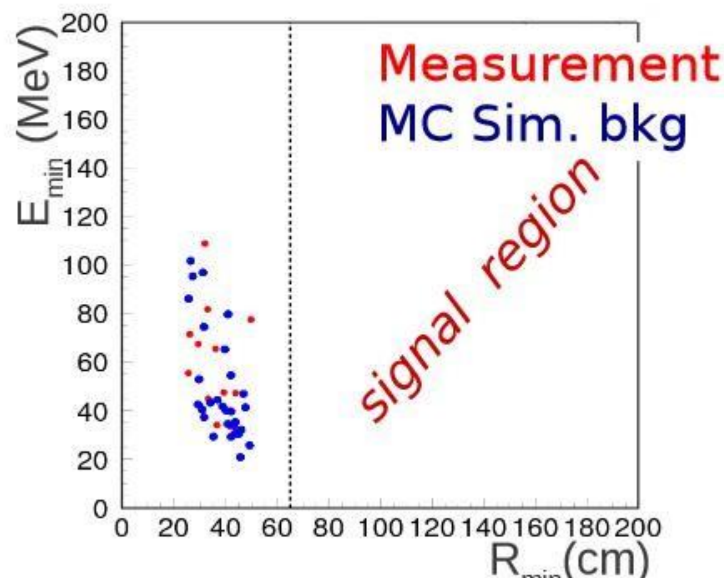
CPT test by comparison to $\delta_L(e)$
(still far from being significant)

(Indirect) CPV **$K_S \to 3\pi^0$**:

17 fb^{-1} full data set, 0 events

BR($K_S \to 3\pi^0$) < 2.6×10^{-8} (90% CL)

SM expectation: 2×10^{-9}



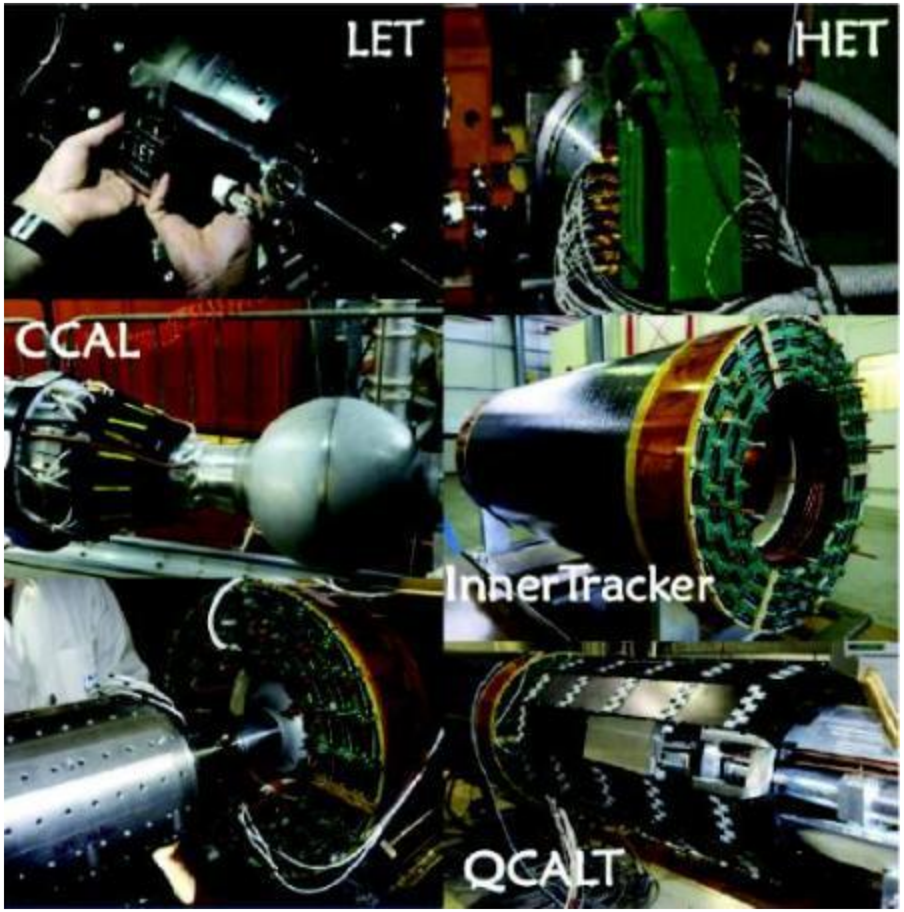
DAΦNE and KLOE-2: a new marriage in Frascati

New **collision scheme**: larger crossing angle, smaller beams, crab-waist configuration.

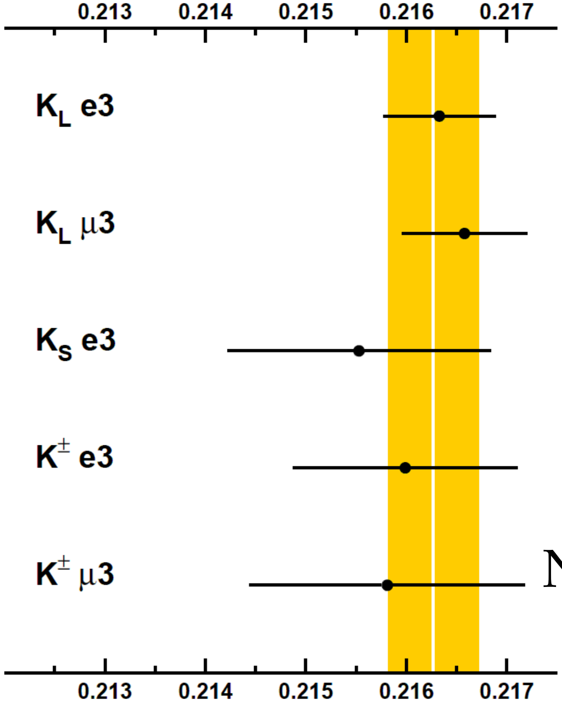
Detector upgrades: γγ taggers for e^+e^- detection, new inner tracker, new small calorimeters

Commissioning in progress.
Goal: **5 fb^{-1}** in 2-3 years

Physics program: light meson spectroscopy, study of $\sigma/f_0(600)$, tests of CPT and QM, test of CPT in K_S, letpon universality, ChPT, hadronic cross sections



Kaons confront CKM



FlaviaNet global fit:

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

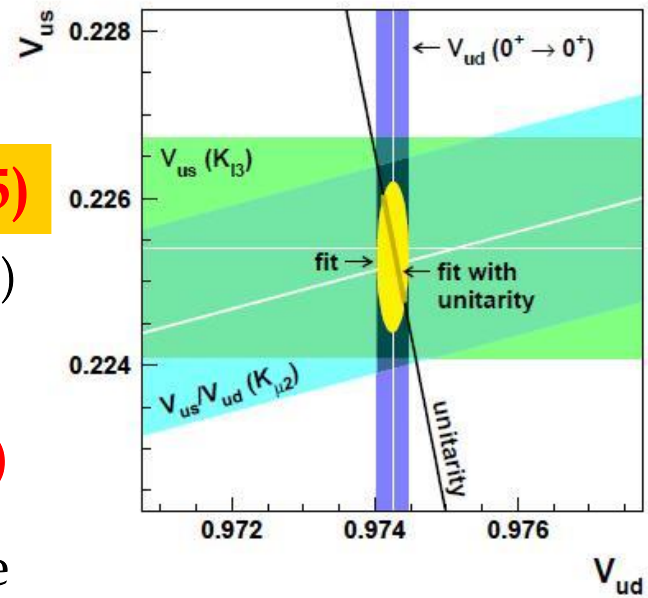
χ^2/ndf = 0.77/4 (P=94%)

0.23% measurement

$|V_{us}| = 0.2253(14)$

0.6% $f_+(0)$ from Lattice

No hint of **unitarity** violations

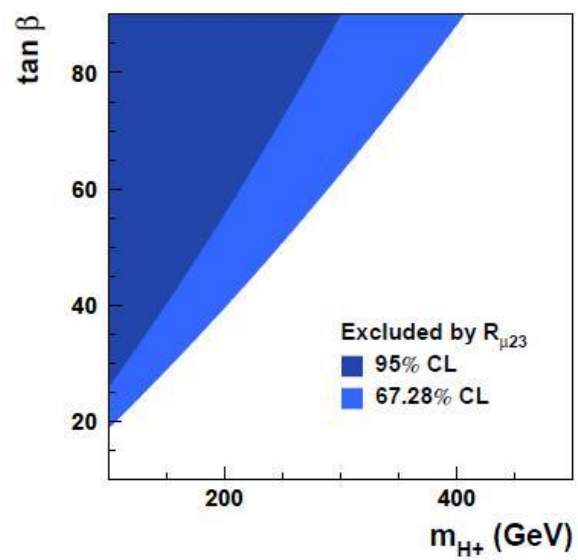


Lepton universality test:

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

Kμ3/Ke3 comparison

$U(3)^5$ symmetry test:
Deviation from V−A by
H^+ exchange
contribution in 2HDM:
Kμ2/Kℓ3 comparison
(helicity structure)

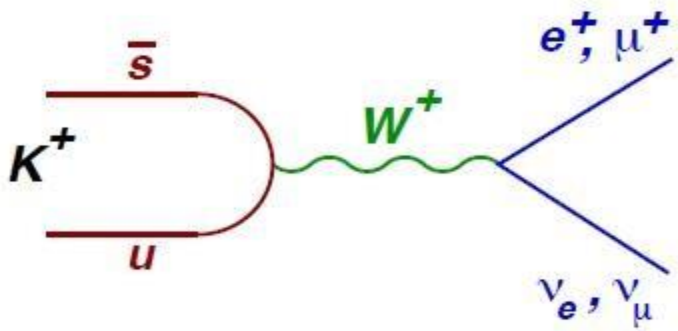


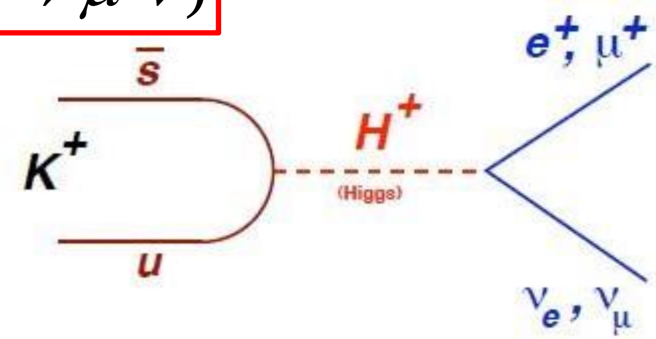
Leptonic K decays

Helicity-suppressed $K_{\ell 2}$ decays: $K^{\pm} \to e^{\pm}\upsilon$ $K^{\pm} \to \mu^{\pm}\upsilon$
Axial current in SM, hadronic physics in normalization f_K factorizes in ratio (ChPT and lattice matching).

Sub per-mille precision on

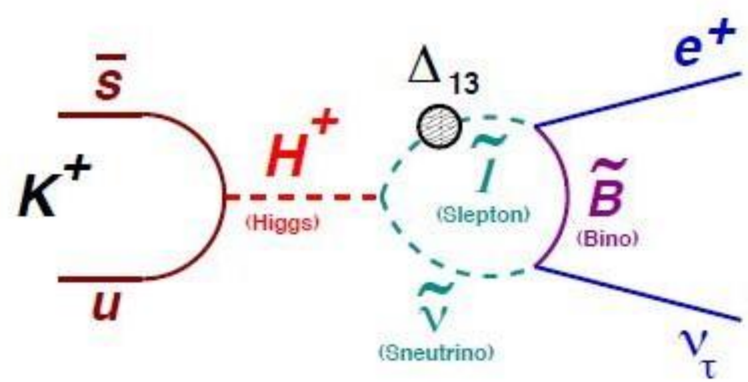
$$R_K = \frac{\Gamma(K^{\pm} \to e^{\pm}\nu)}{\Gamma(K^{\pm} \to \mu^{\pm}\nu)}$$





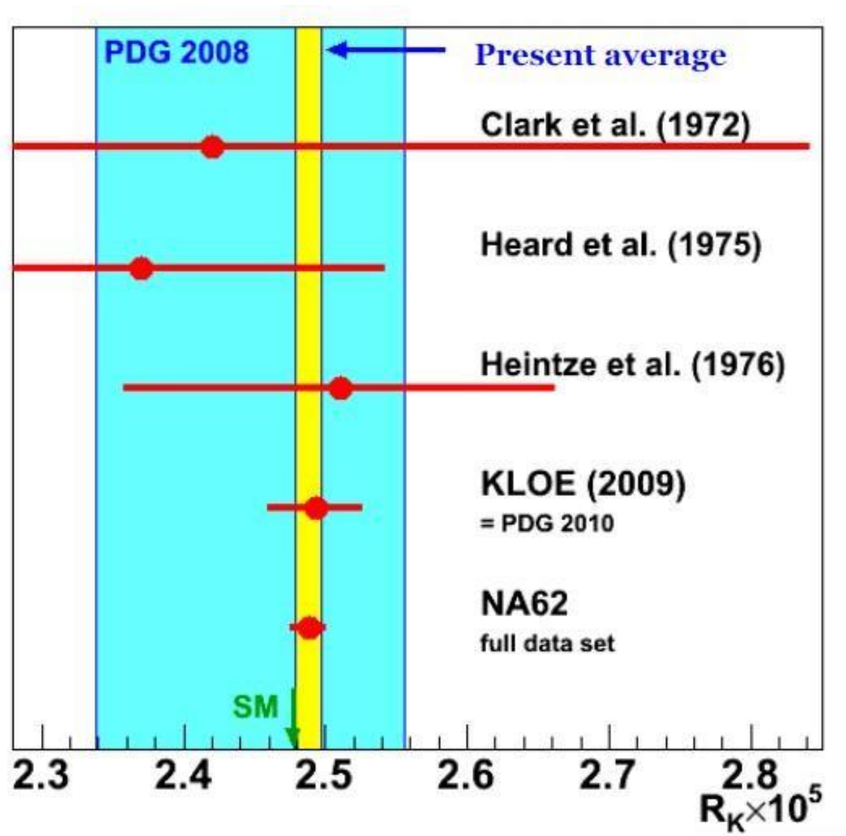
$$R_K(SM) = (2.477 \pm 0.001) \cdot 10^{-5}$$

BSM: scalar densities or RH currents
H^+ affects rates and possibly R_K
MSSM allows O(1%) effect



Leptonic K decays

Fully exploit kinematics and strong particle ID
Main background from Kμ2



KLOE (2009) 14K events, 16% bkg
NA62 (2013) 147K events, 11% bkg

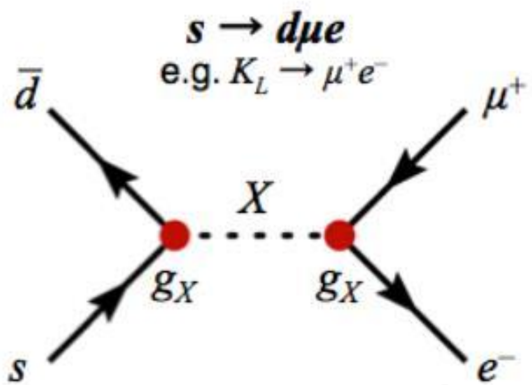
$$R_K = (2.488 \pm 0.009) \cdot 10^{-5}$$

x10 improvement , consistent with SM
0.4%, stat/syst dominated

NP potential still open (factor 10)
CERN NA62 prospects:
factor ~2: stat, more hermetic vetoing, better resolutions and PID
J-PARC TREK stopped K proposal:
2.5 per mille error

LFV in K decays

Unmeasurable rates within SM: good probe
K offer high statistics, clean signatures,
controllable backgrounds: sensitivity to very low BRs



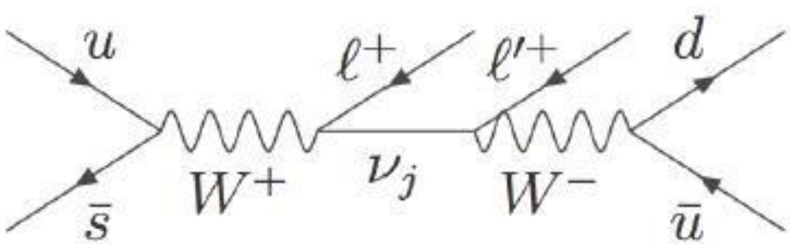
$$\frac{\Gamma(LFV)}{\Gamma(LFC)} \sim O\left(\frac{g_X}{g_W}\frac{m_W{}^2}{m_X{}^2}\right)$$

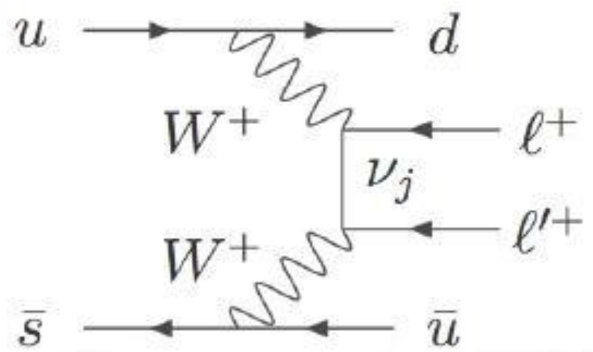
For $g_X \sim g_W$ a 10^{-12} BR probes $m_X \sim 100$ TeV

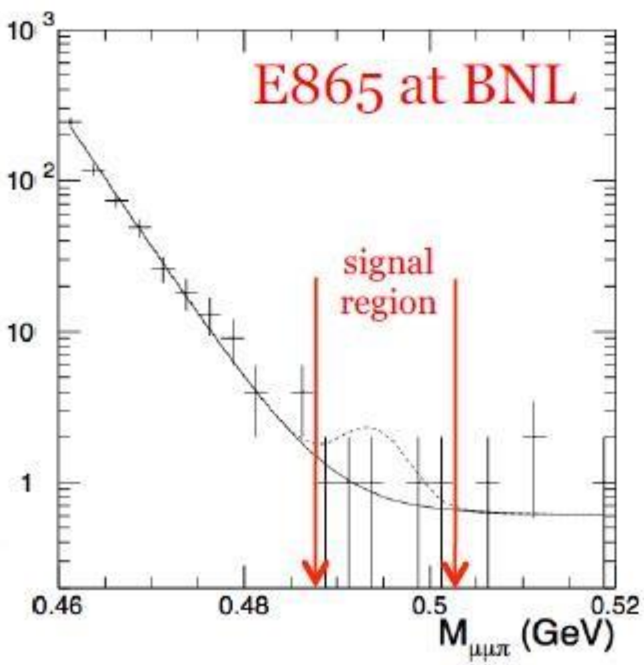
Decay mode	Physics Interest	UL at 90% CL (Experiment)
$K^+ \to \pi^+ \mu^+ e^-$	LFV	$< 1.3 \times 10^{-11}$ (BNL E777/E865)
$K^+ \to \pi^+ \mu^- e^+$	LFV	$< 5.2 \times 10^{-10}$ (BNL E865)
$K^+ \to \pi^- \mu^+ e^+$	LFNV: $\Delta L_\mu = \Delta L_e = -1$	$< 5.0 \times 10^{-10}$ (BNL E865)
$K^+ \to \pi^- e^+ e^+$	LNV: $\|\Delta L_e\| = 2$	$< 6.4 \times 10^{-10}$ (BNL E865)
$K^+ \to \pi^- \mu^+ \mu^+$	LNV: $\|\Delta L_\mu\| = 2$	$< 1.1 \times 10^{-9}$ (NA48/2)
$K^+ \to \mu^- \nu_\mu e^+ e^+$	LNV: $\|\Delta L_e\| = 2$ or LFV	$< 2.8 \times 10^{-8}$ (Geneva-Saclay)
$K^+ \to e^- \nu_e \mu^+ \mu^+$	LNV: $\|\Delta L_\mu\| = 2$ or LFV	No Data
$\pi^0 \to \mu \pm e^\mp$	LFV	$< 3.6 \times 10^{-10}$ (KTEV)

LFV: $K^+ \rightarrow \pi^- \ell^+ \ell^+$ decays

$|\Delta L|=2$ transitions mediated by Majorana neutrino exchange
Best probe for $|\Delta L_\mu|=2$







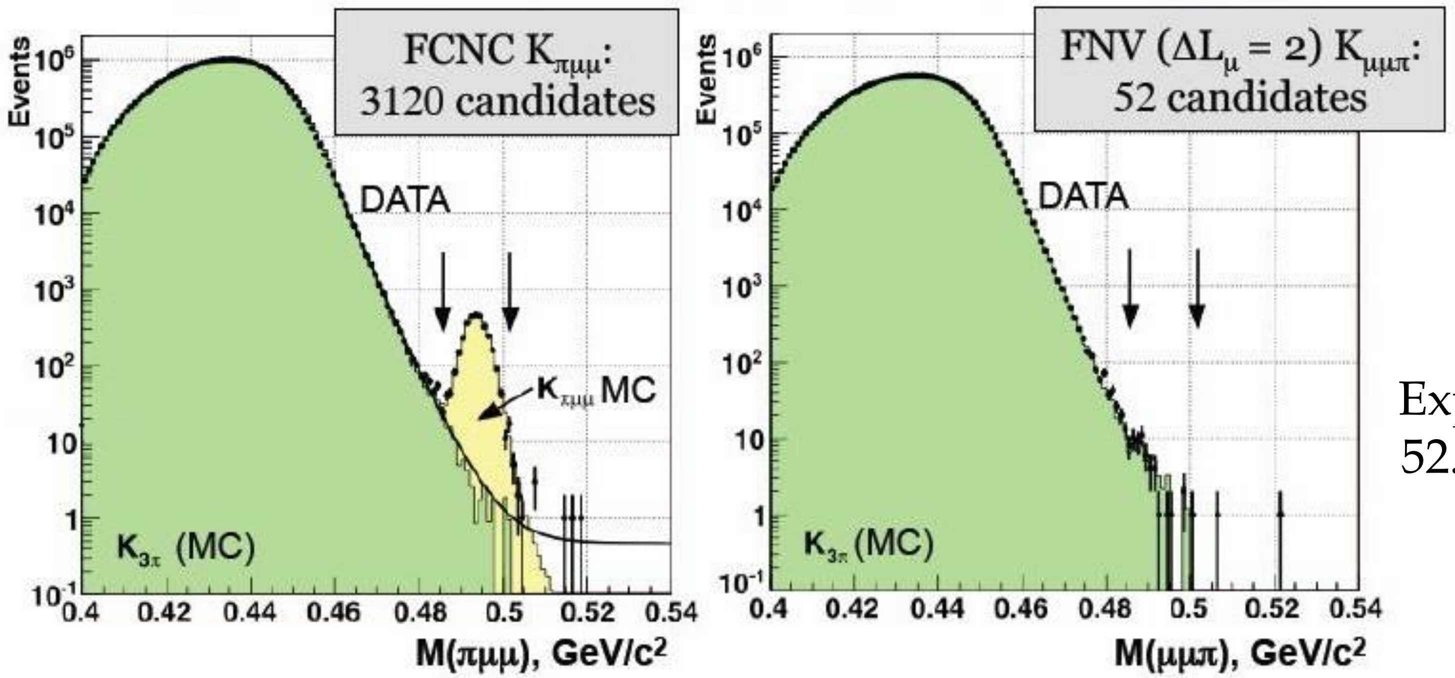
BNL E865 (2000): ~ 400 events

$$BR(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 3.0 \cdot 10^{-9} (90\%\ CL)$$

BRs close to limit allowed BSM

NA48/2: $K^+ \to \pi^- \ell^+ \ell^+$

Byproduct of 6-month (2003-04) running with simultaneous $K^\pm$ beams for search of direct CPV in $K \to 3\pi$ decays



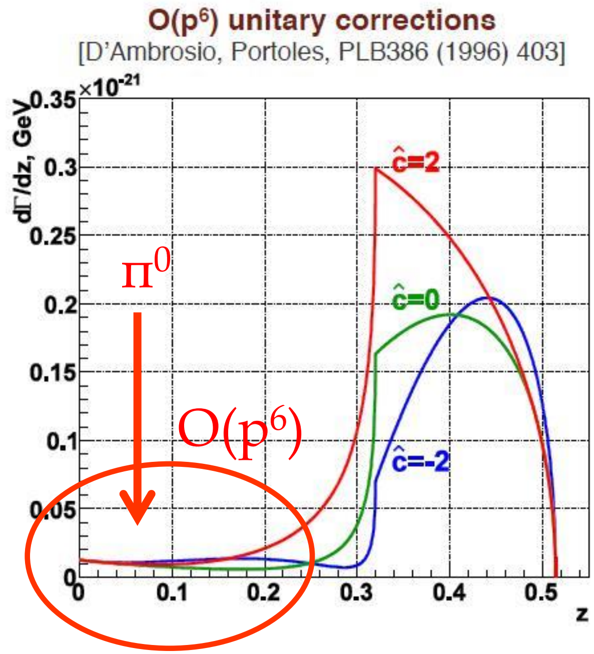
Expected bkg: 52.6±19.8 evts

NA48/2 (2011): 3.1K events

$$BR(K^+ \to \pi^- \mu^+ \mu^+) < 1.1 \cdot 10^{-9} \; (90\% \; CL)$$

NA62 potential: up to 1000 x

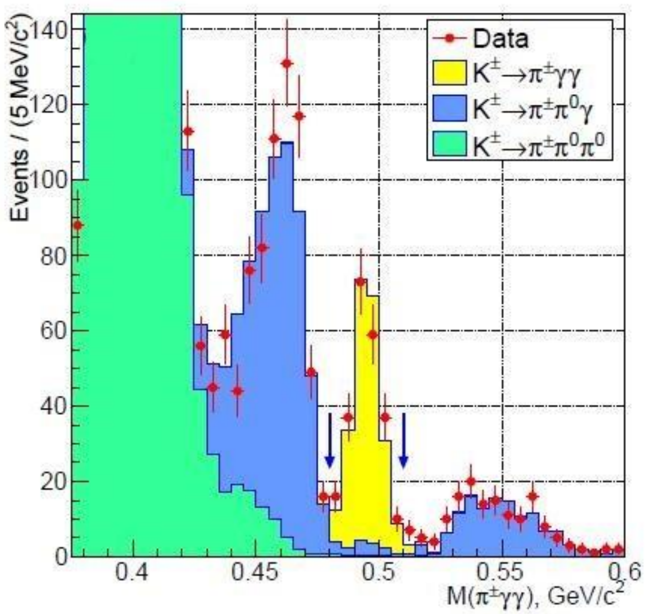
ChPT: $K^+ \to \pi^+\gamma\gamma$



Interesting decay in ChPT, computed to $O(p^6)$, depending on single parameter $\hat{c}$ (combination of LE ChPT constants). $z = (m_{\gamma\gamma}/m_K)^2$

E787 (1997): 31 events, 5 bkg $\quad \hat{c} = 1.1 \pm 0.6$

NA48/2: 3-day run (2004): 149 events, 10% bkg
NA62-phase1: 3-month (downscaled) run (2007): 232 events, 8% bkg

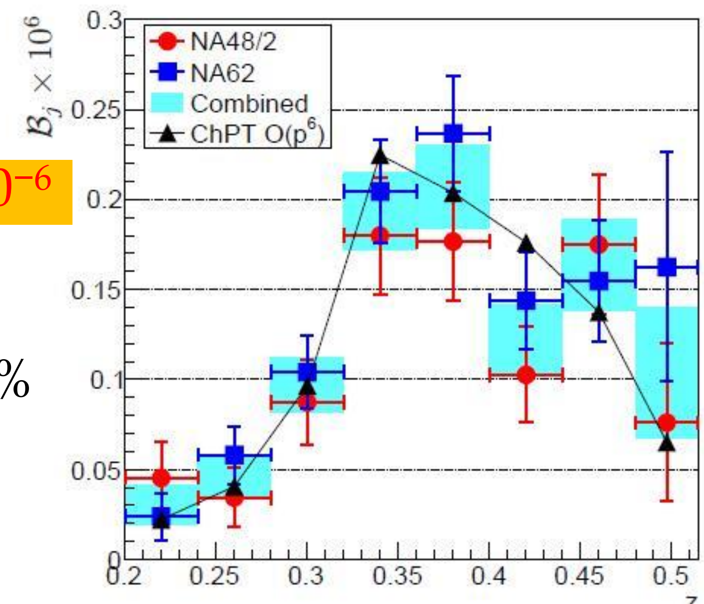


2014: BR in z bins
$BR(p^6)=(1.00\pm0.07)\cdot10^{-6}$
$K^\pm$ asym: -0.03 ± 0.06
Compatible $\hat{c}$ values for $O(p^4)$, $O(p^6)$ at 15%

$\hat{c}_4 = 1.72 \pm 0.21$

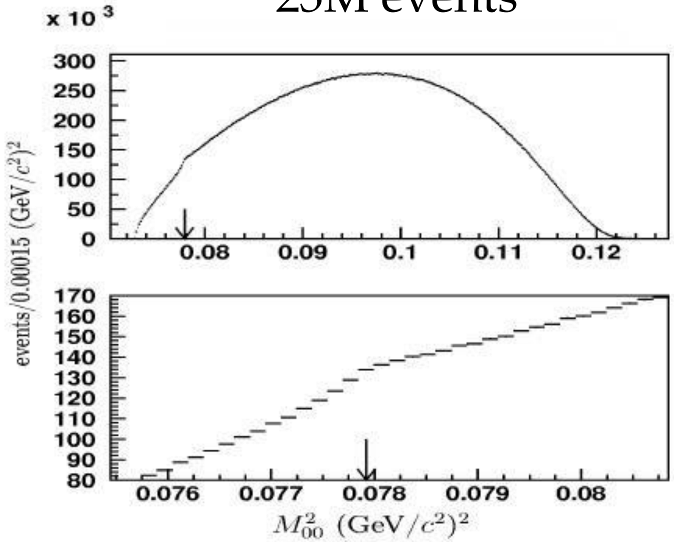
$\hat{c}_6 = 1.86 \pm 0.25$

Statistics dominated

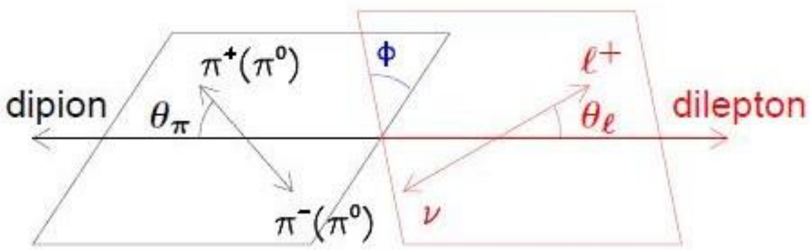


NA48/2: QCD

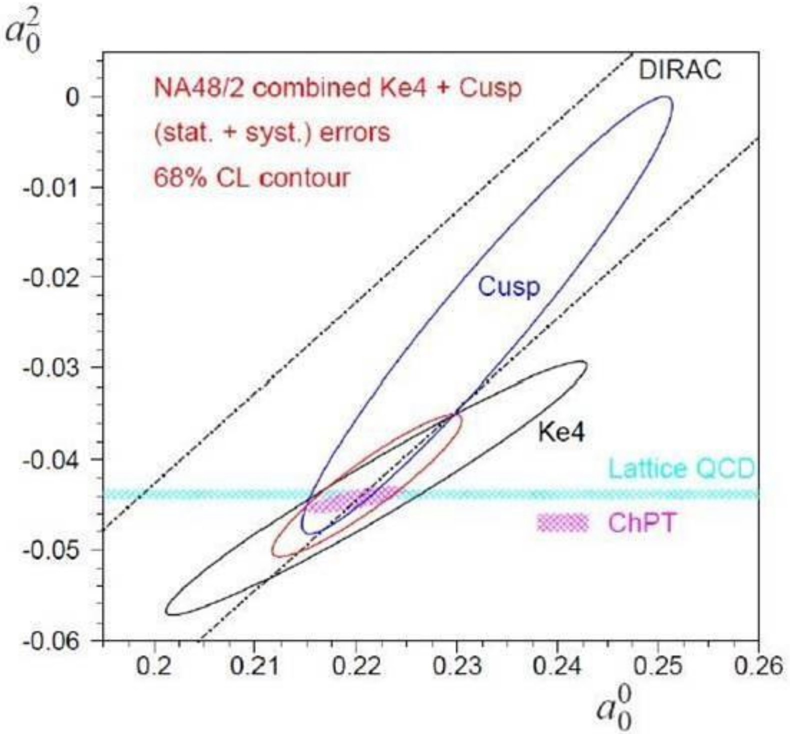
Threshold cusp
in $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ decays
23M events



Partial wave analysis of
$K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$ (Ke4) decays
1.1M events, 0.5% bkg



S-wave $\pi^+\pi^-$ scattering lengths:
fundamental QCD quantities
predicted at 2% using ChPT



$a_0^0 = 0.2210 \pm 0.0047 \pm 0.0040$
$a_0^2 = -0.0429 \pm 0.0044 \pm 0.0028$

NA48/2: K_{e4}^{00}

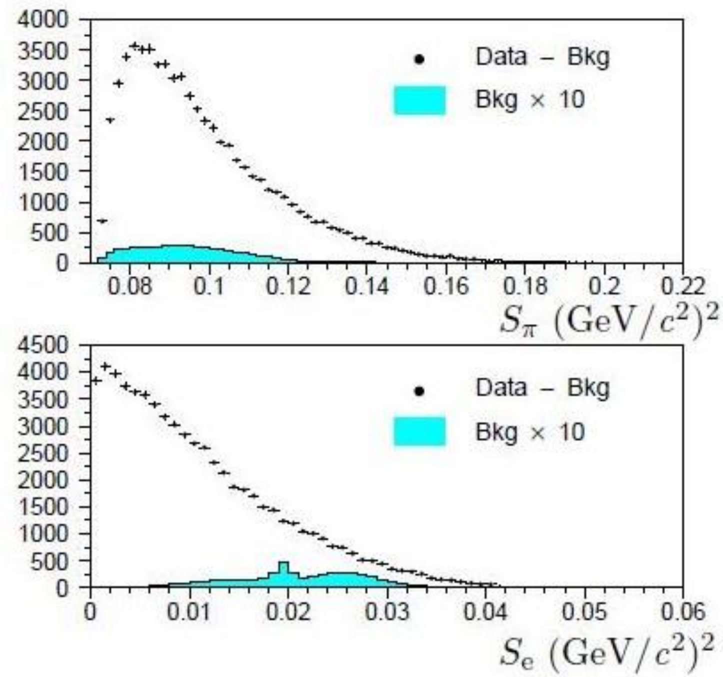
O(200) events world sample (KEK 2004)

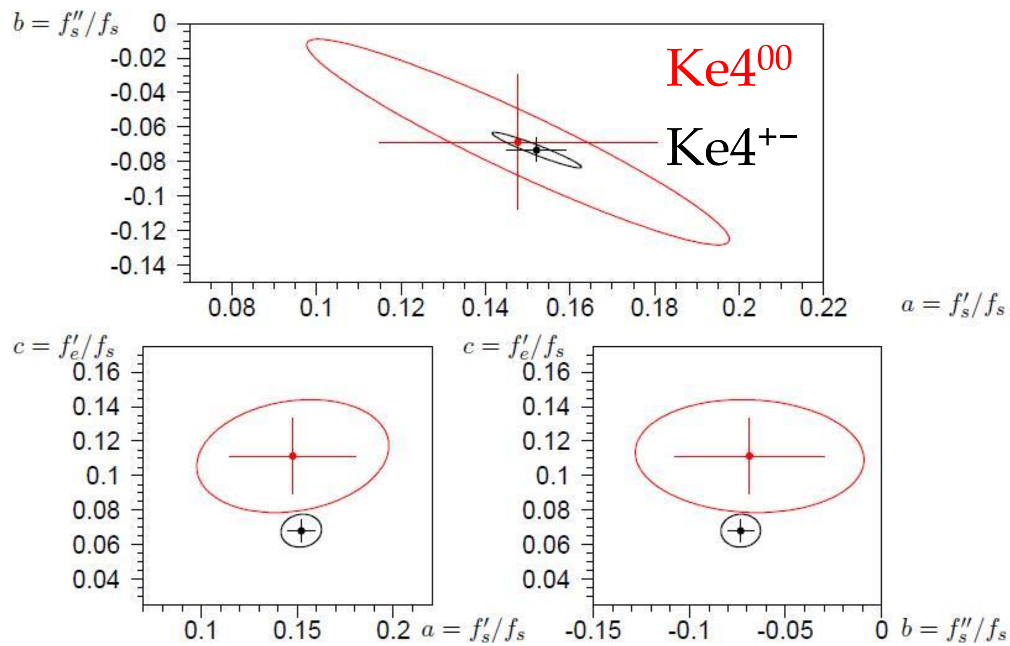
NA48/2: 65K $K^{\pm}\rightarrow\pi^0\pi^0 e^{\pm}\nu$ events
1% background

BR =$(2.552\pm0.010_{stat}\pm0.010_{syst}\pm0.032_{ext})\cdot10^{-5}$

x10 improvement
Dominant error by normalizatior
($K^{\pm}\rightarrow \pi^{\pm}\pi^0\pi^0$)

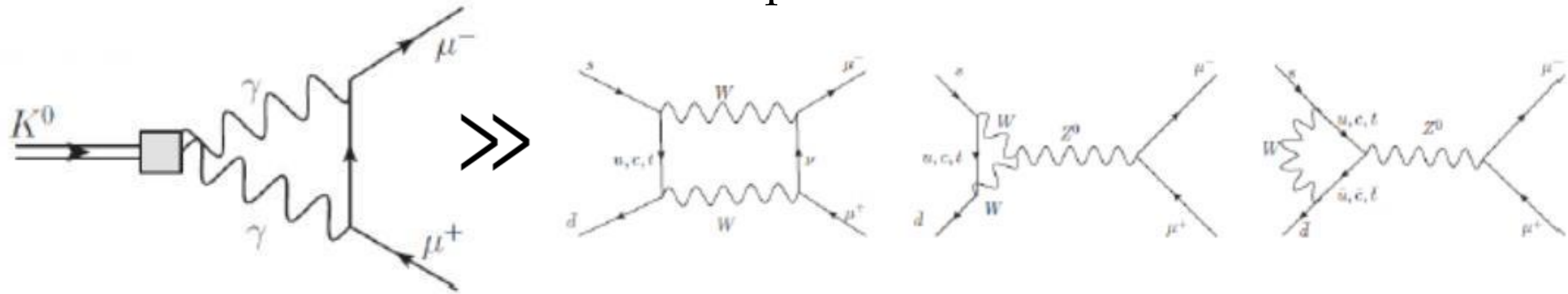
First measurement of hadronic form factors





$K_S \to \mu^+\mu^-$

Not quite like its heavier B cousins…

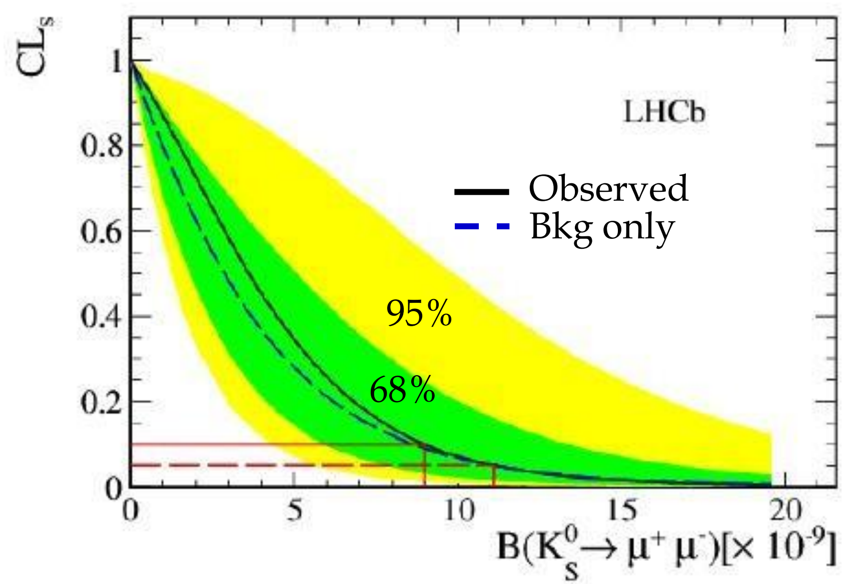


Long-distance (γγ) dominated, BR(SM) = $(5.0\pm1.5)\cdot10^{-12}$
Short-distance $O(10^{-13})$ constraints CPV in $s\to d\ell^+\ell^-$, (η^2) sensitive to NP
with room for enhancements up to $O(10^{-11})$ *e.g.* from new scalars,
independently from K_L decay which matches SM BR = $(6.84\pm0.11)\cdot10^{-9}$
But no SD/LD interference (as in K_L)
Exp: BR < $3.1\cdot10^{-7}$ (1973)

LHCb produces ~10^{13} K_S per fb^{-1}
~40% decaying in VELO
→ 4 MeV mass resolution

$BR(K_S\to\mu^+\mu^-) < 9\cdot10^{-9}$ (90% CL)

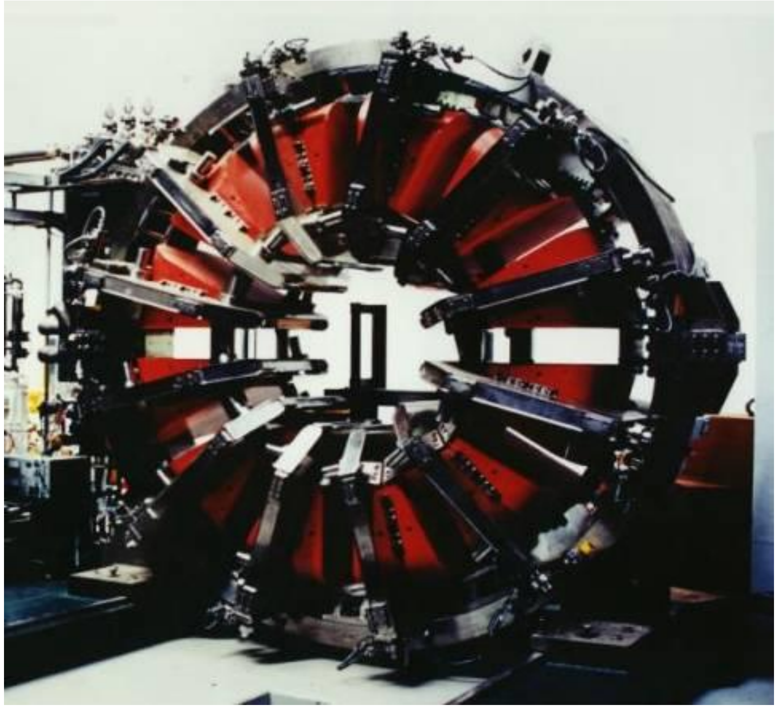
x30 improvement with 1 fb^{-1}



Time-Reversal Violation

Transverse μ^+ polarization in $K^+ \rightarrow \pi^0 \mu^+ \upsilon$ 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):

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

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

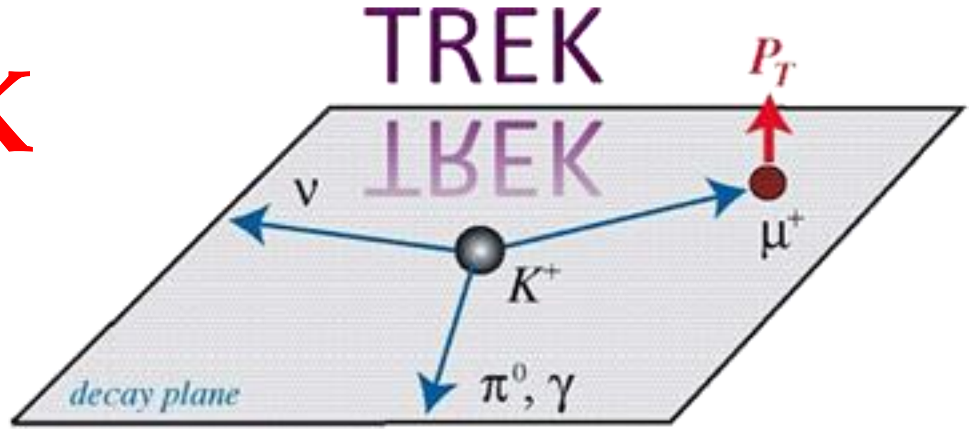
No sign of TRV
Statistically limited

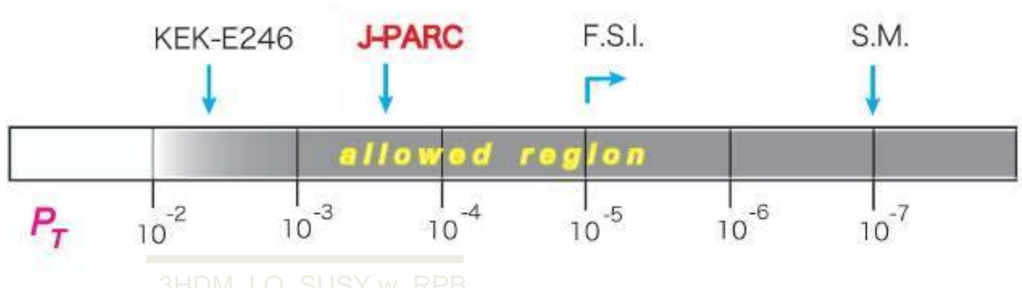
J-PARC TREK

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)

New muon polarimeter completed
No low-momentum K+ beam line after Ke2/Kμ2 experiment:
postponed waiting for new hadron hall and higher power

Ultra-rare K decays
or "The revenge of the Kaon"

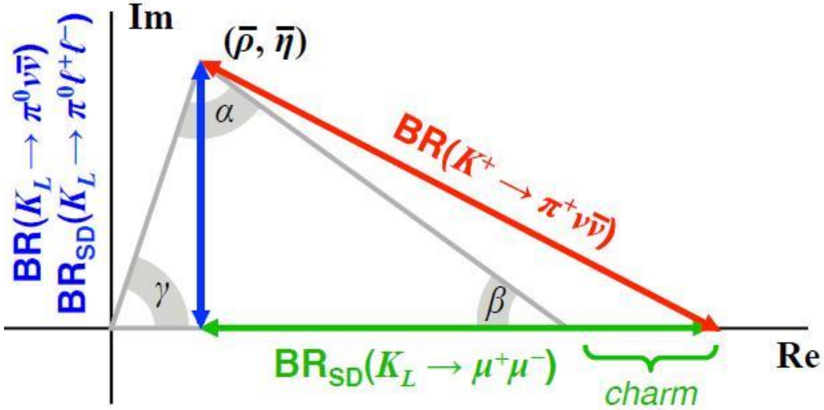
We learned that the flavour structure of any "TeV scale" BSM physics is <u>not too weird</u>

The easy (SM) stuff was done

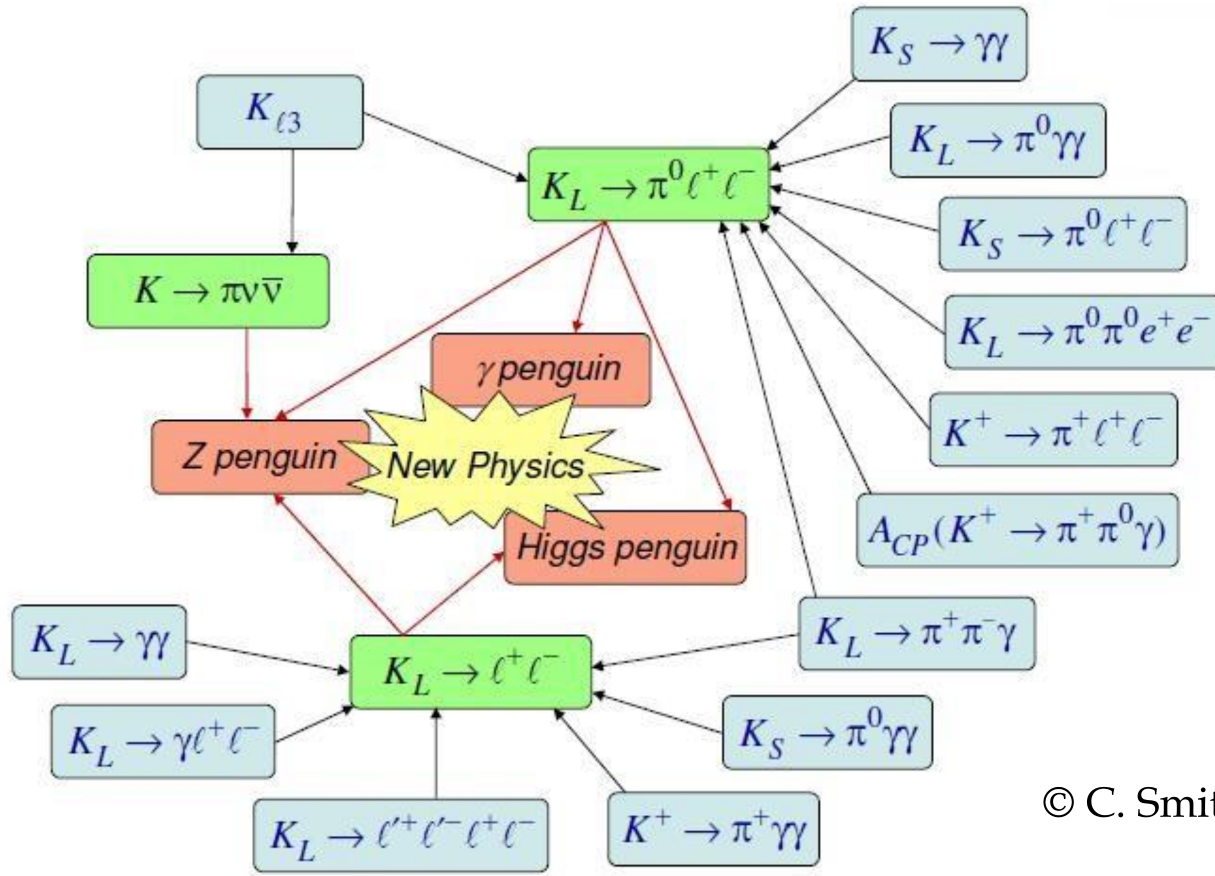
"When the going gets tough, the tough get going"

K **theoretical cleanliness** unmatched, simple system, few decay channels,
extreme **hard-GIM SM-suppressed**,
hadronic part known from Kℓ3 (+isospin)
FCNC decay: room for NP up to 10x SM

Unique probe for **flavour couplings** of BSM physics with sensitivity to **extremely high NP scales** (10% measurement of K→πυυ BR can probe **1000 TeV** scale)
Can determine UT **independently from B**



Precision K probes: the full picture



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Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{-11}	Exp. BR × 10^{-11}
$K_L \to \mu^+\mu^-$	40%	20%	681 ± 32	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	35 ± 10	< 28†
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	14 ± 3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	7.8 ± 0.8	17 ± 12
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.4 ± 0.4	<26000†

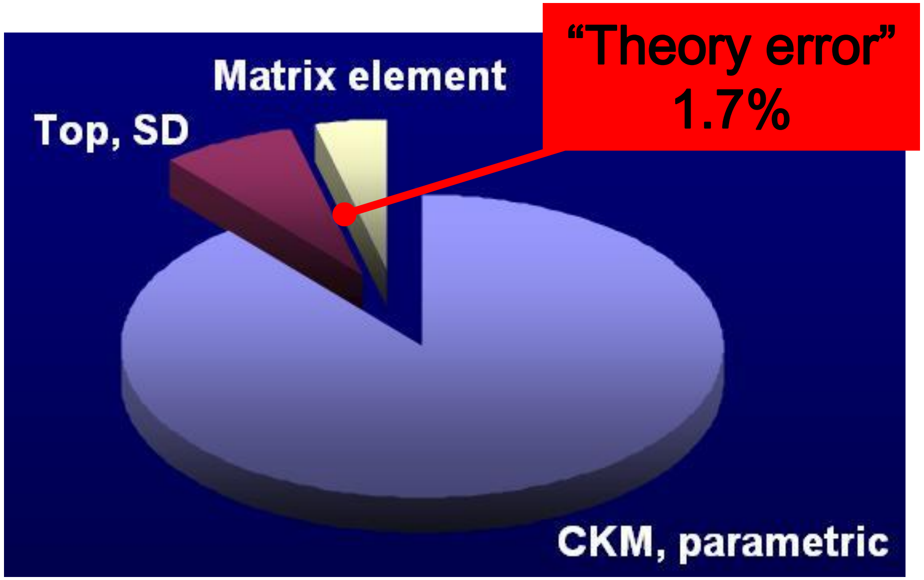
*Approx. error on LD-subtracted rate excluding parametric contributions †90% CL

K→ πνν BR (SM) predictions

Experimental challenges stimulated a flurry of theoretical refinements

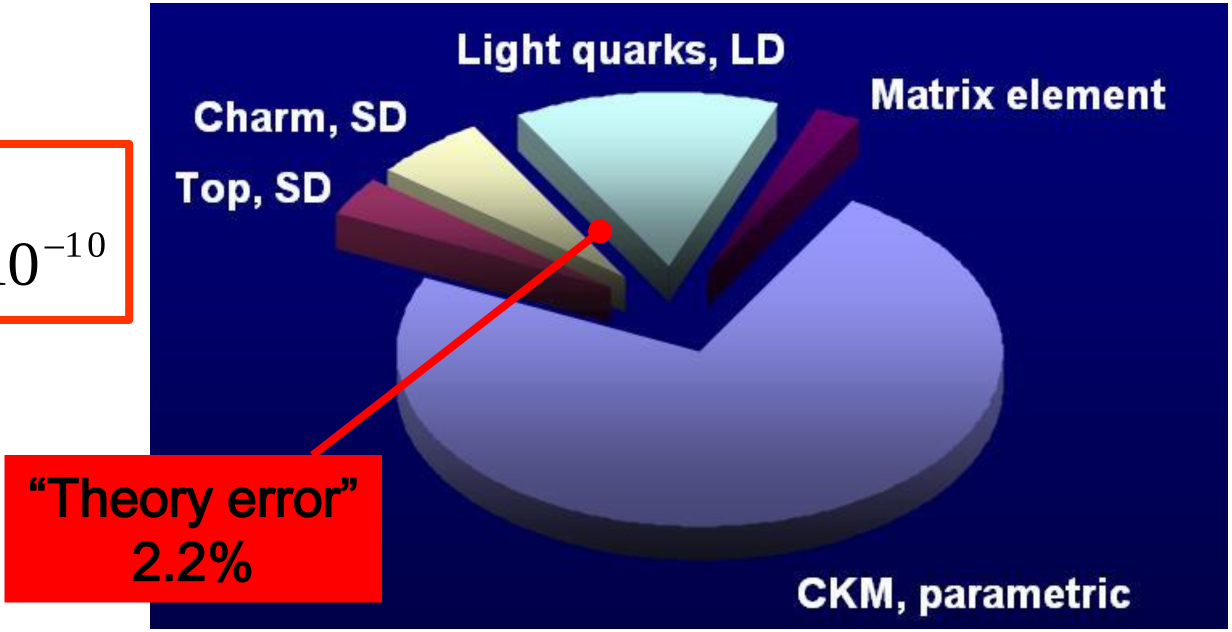
$K_L \to \pi^0 \nu\nu$

$$BR_{SM} = (0.24 \pm 0.04) \cdot 10^{-10}$$



$K^+ \to \pi^+ \nu\nu$

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



Comparable, unprecedented, *tiny* theoretical errors

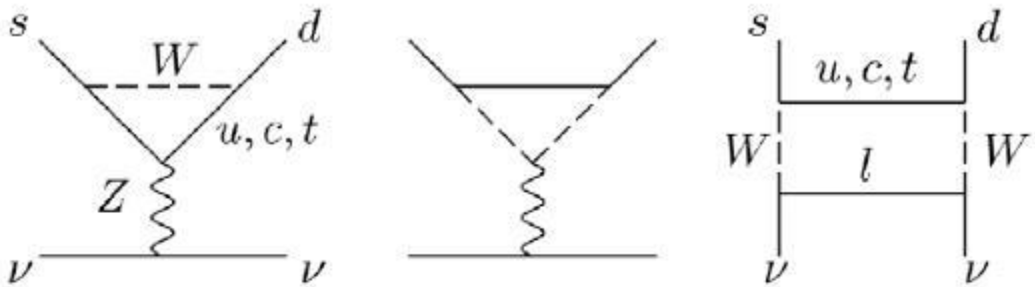
$K \to \pi\nu\bar{\nu}$: the "holy grail"

$$BR_{SM}(K \to \pi\bar{\nu}\nu) \propto r_{IB}\, BR(K^+ \to \pi^0 e^+ \nu) \frac{\alpha^2}{\sin^4\theta_W}$$

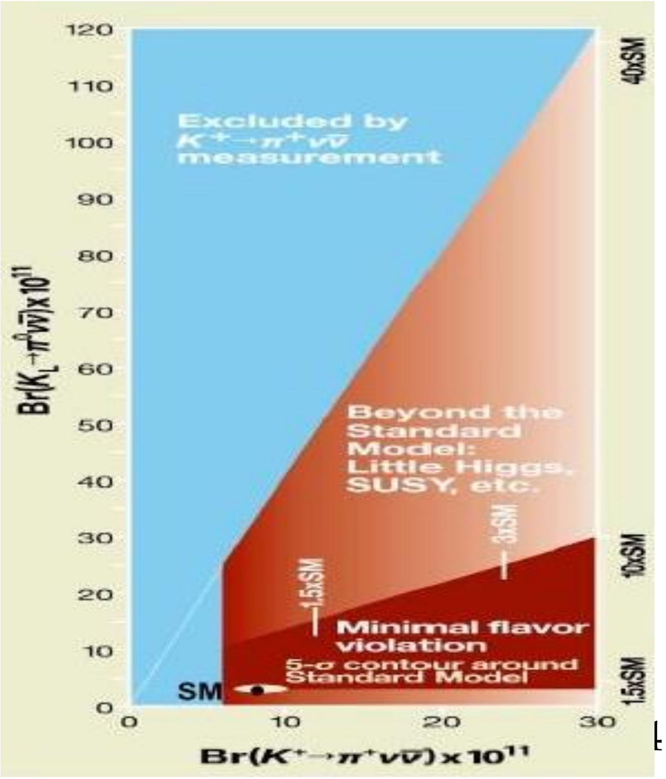
$$\sum_l \left[\frac{\mathrm{Im} V_{ts}^* V_{td}}{|V_{us}|} X(m_t, \alpha_S) + \frac{\mathrm{Im} V_{cs}^* V_{cd}}{|V_{us}|} X_{NL}(m_c, m_l, \alpha_S) \right]$$

c,u contribution
K^+ only (37%)

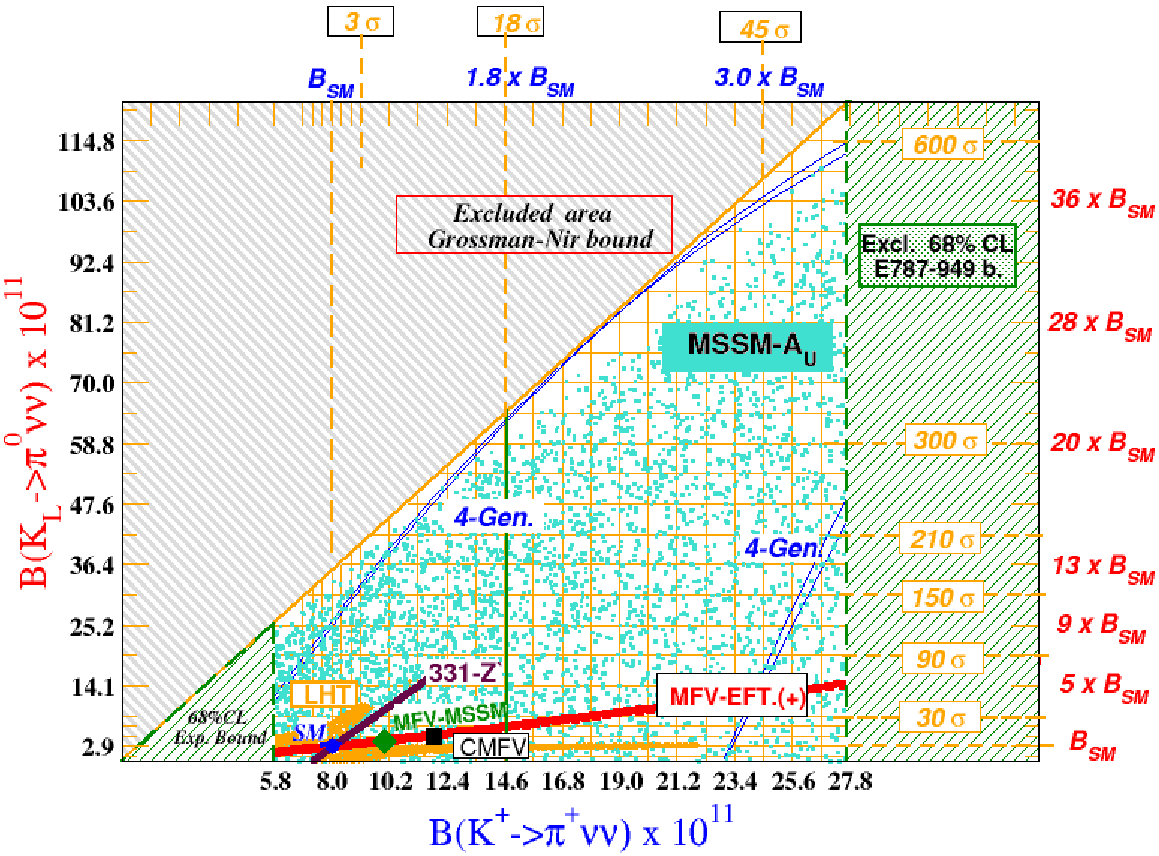
The best measurement of $|V_{td}|$?
Rather a highly-sensitive search for NP
Comparison of the two can discriminate
by itself the flavour structure of NP



Theoretically clean also BSM !



K→ πνν beyond SM



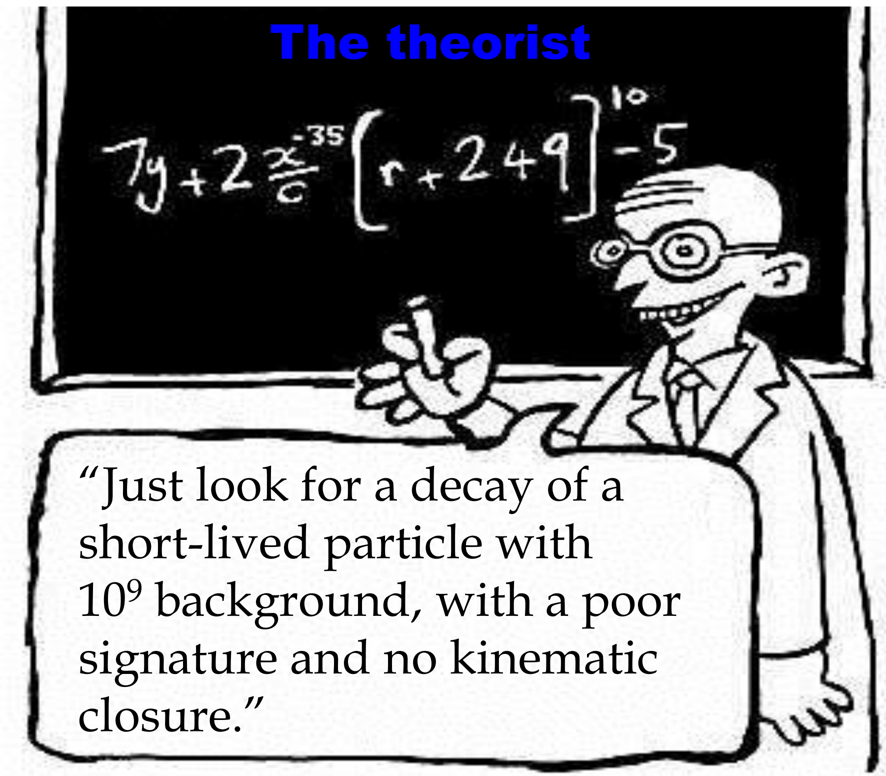
BR($K^+ \to \pi^+ \nu\nu$) $\times 10^{10}$: some examples	
SM	0.85±0.07
MFV (hep-ph/0310208)	1.91
EEWP (NPB697 (2004) 133, hep-ph/0402112)	0.75±0.21
EDSQ (PRD70 (2004) 093003, hep-ph/0407021)	up to 1.5
MSSM (NPB713 (2005) 103, hep-ph/0408142)	up to 4.0

K→πυυ **remains clean** also beyond SM:

single effective υυ operator, calculable Wilson coeff., no long-distance effects

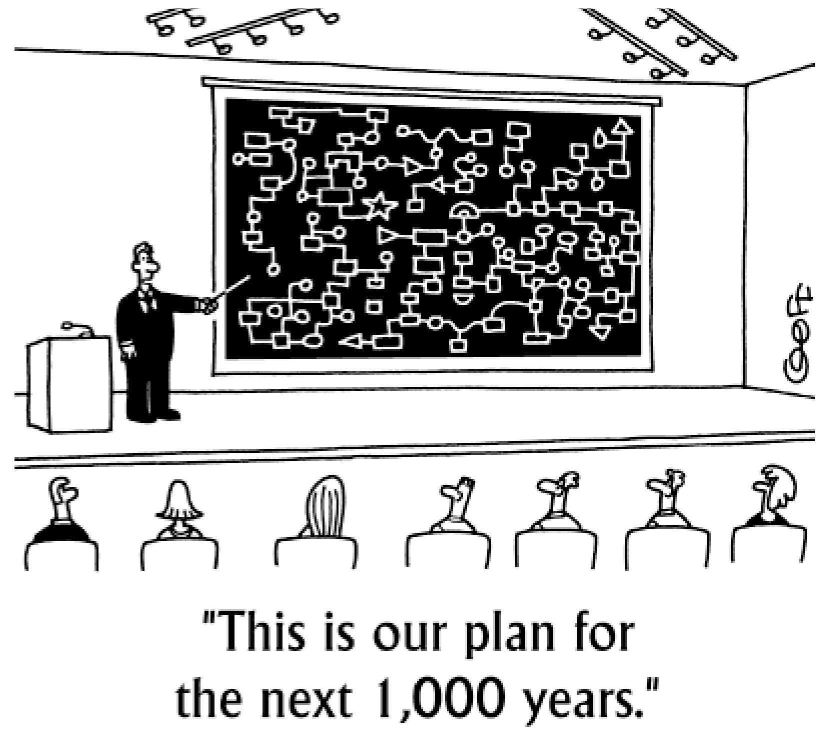
Pattern of correlation between the two modes discriminates among models

Searching for the holy grail



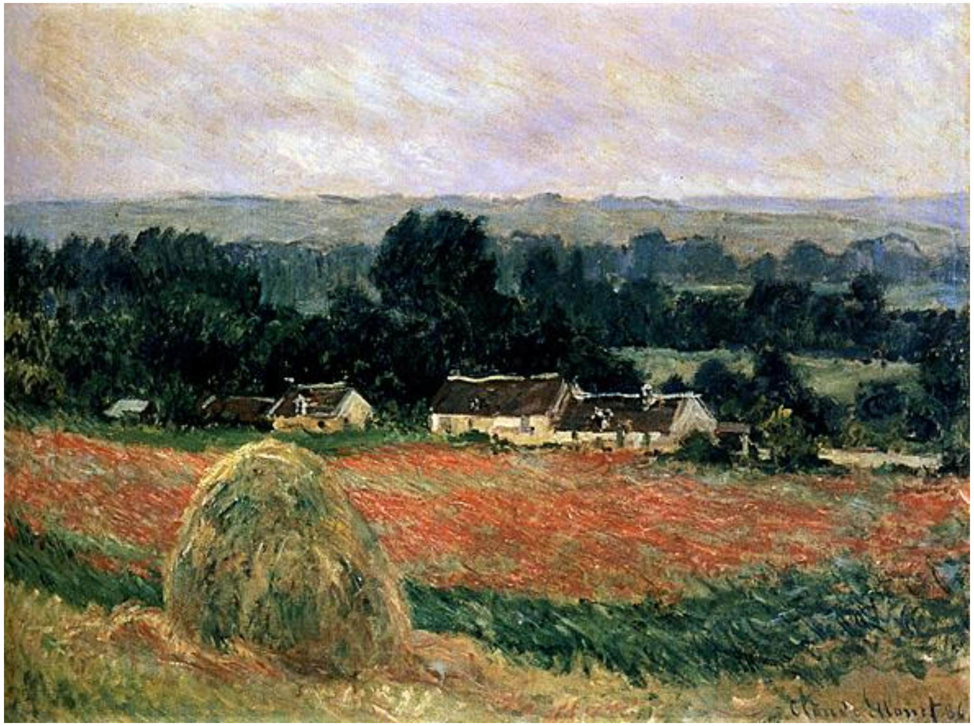
"Normal science: when the processes which can be easily handled by theorists are experimental nightmares (and vice versa)".
(Apologies to T. Kuhn)

The experimentalist

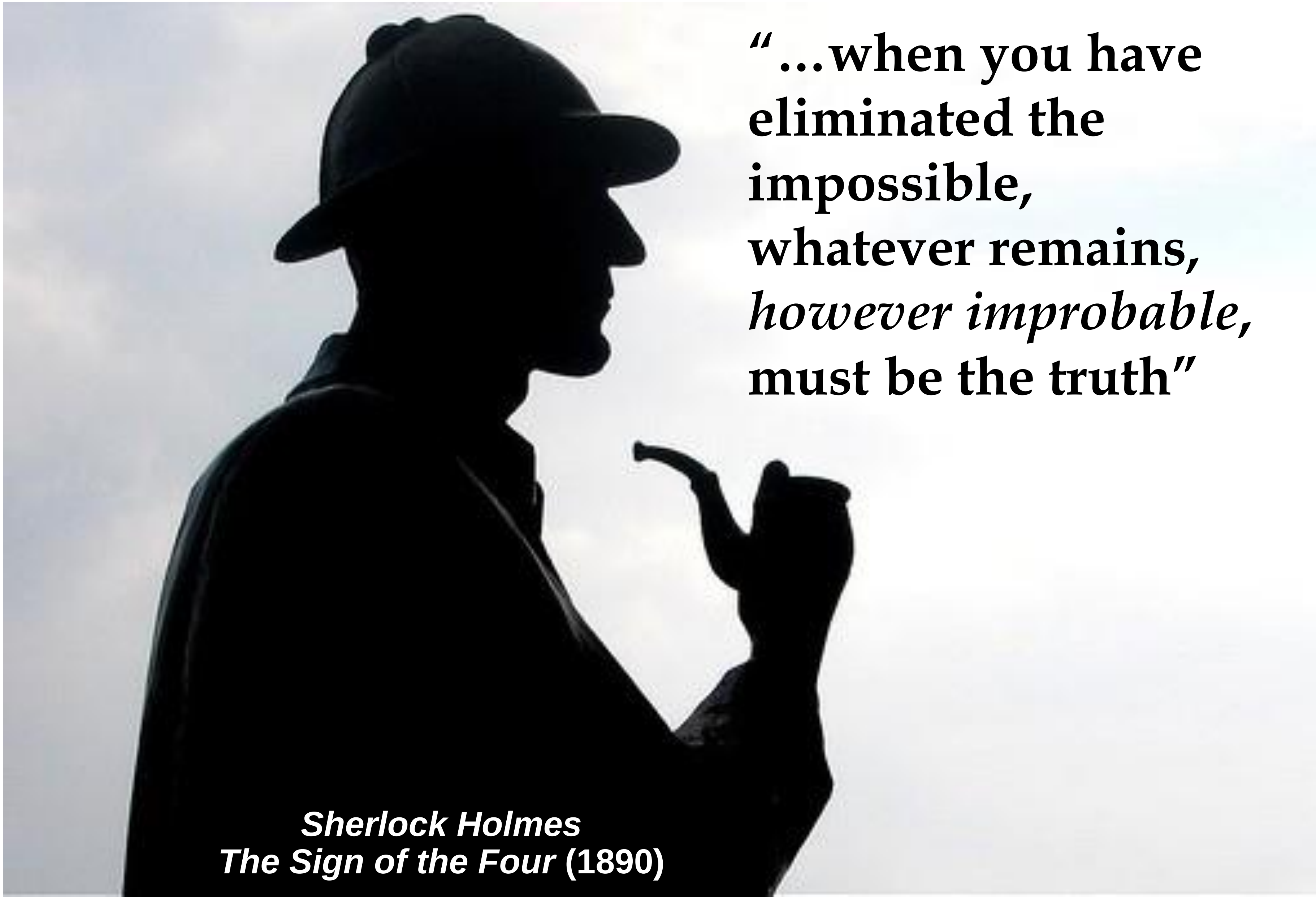


High fluxes, high vacuum, high ermeticity, excellent vetoing, excellent resolutions…
An interesting challenge

What do you mean by "precision physics"?



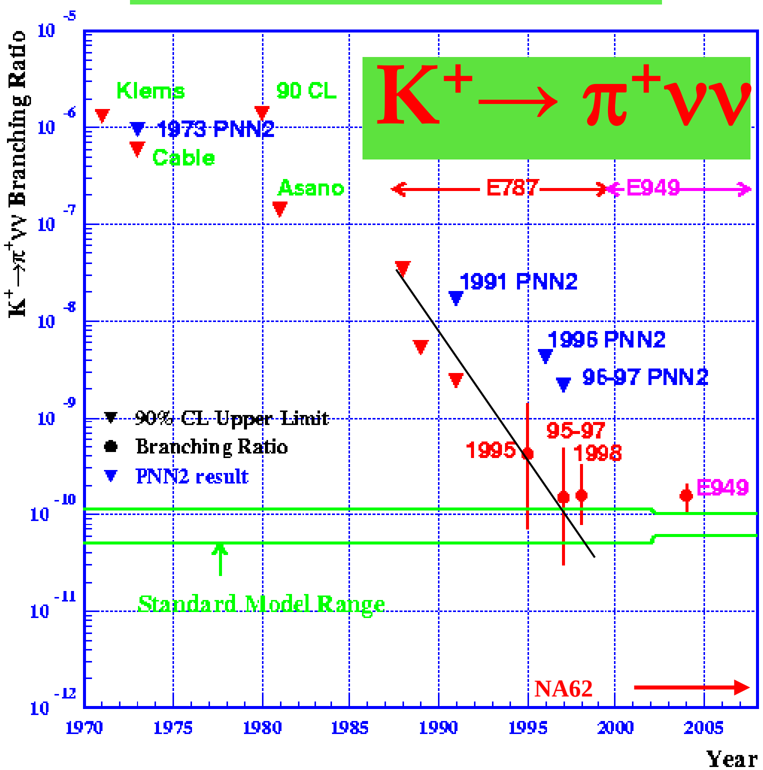
Your typical "needle in 10^5 haystacks" problem

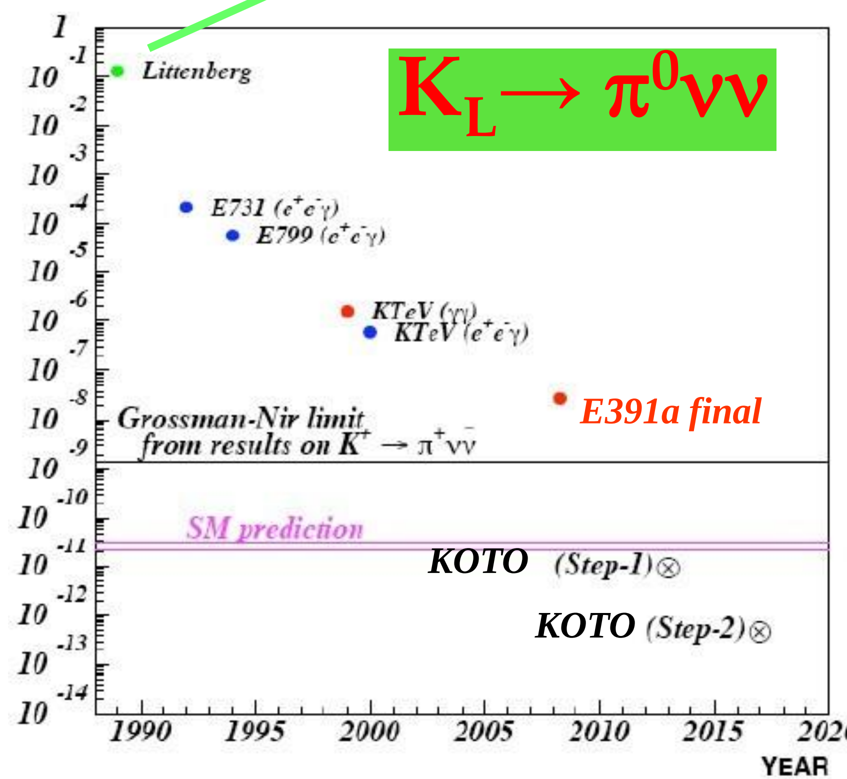

"…when you have eliminated the impossible, whatever remains, *however improbable*, must be the truth"
Sherlock Holmes
The Sign of the Four (1890)

The long $K \to \pi\nu\nu$ march

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

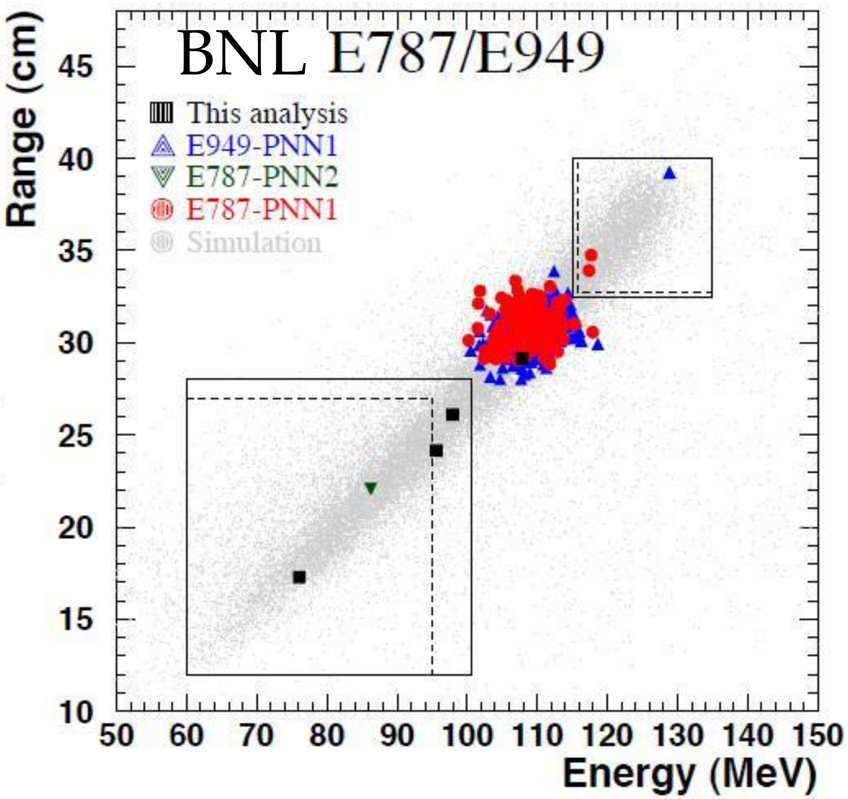
First search: 1969 (10^{-4})
Observation: 1997 (10^{-10})





The $K^+ \to \pi^+ \upsilon\upsilon$ enterprise

2 dedicated BNL experiments
stopped K^+ beam (0.7 GeV/c)
PID from full $\pi \to \mu \to e$ chain



7 candidates, 2.6 background

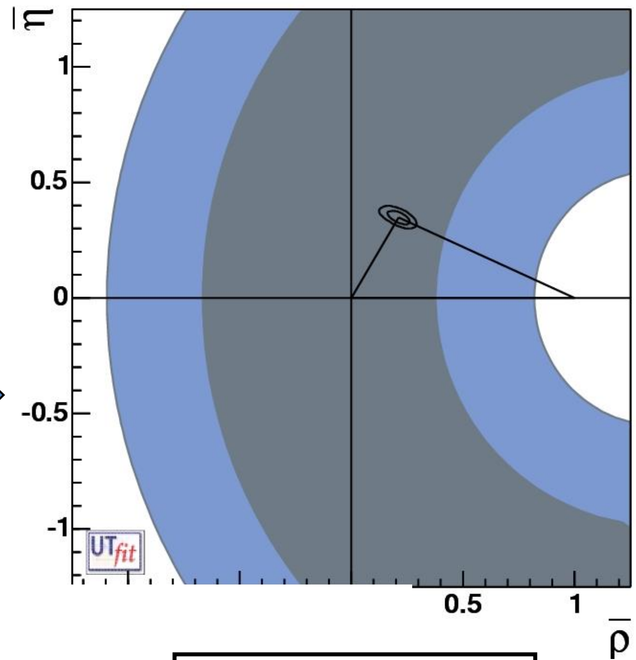
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \cdot 10^{-10}$$

(2009)

ORKA (project for moving E949 detector at FNAL MI) canceled by P5

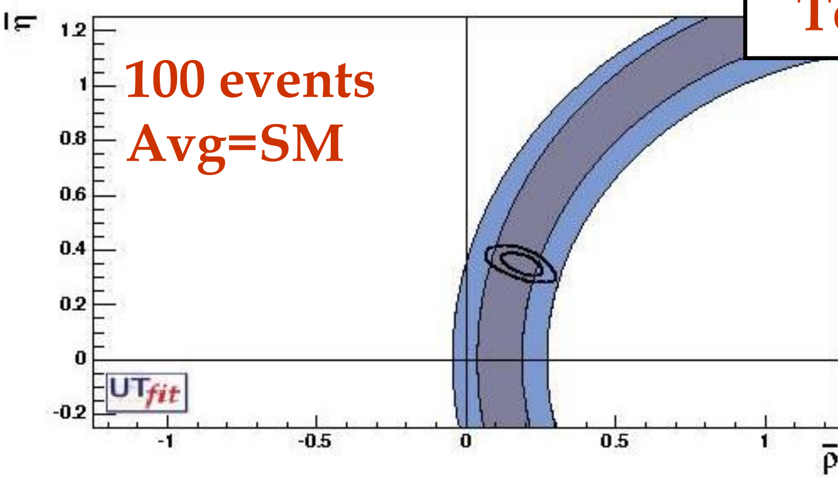
$K^+ \to \pi^+ \upsilon\upsilon$

Today

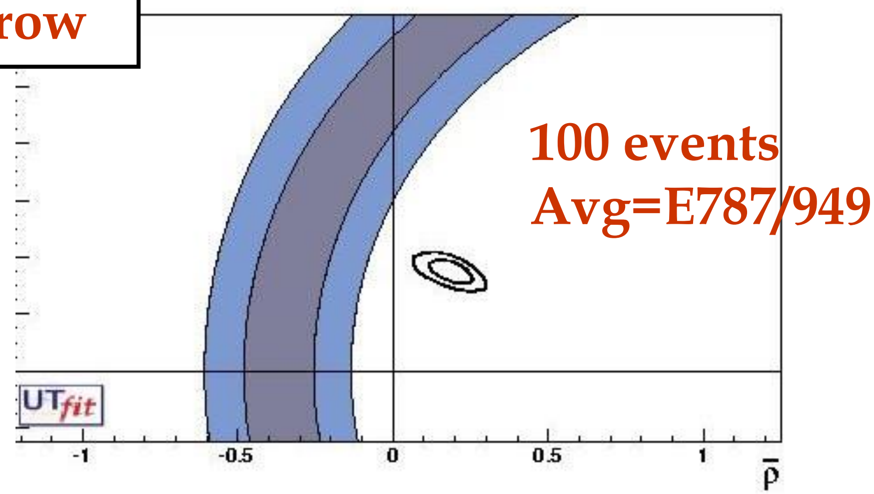


?

Tomorrow

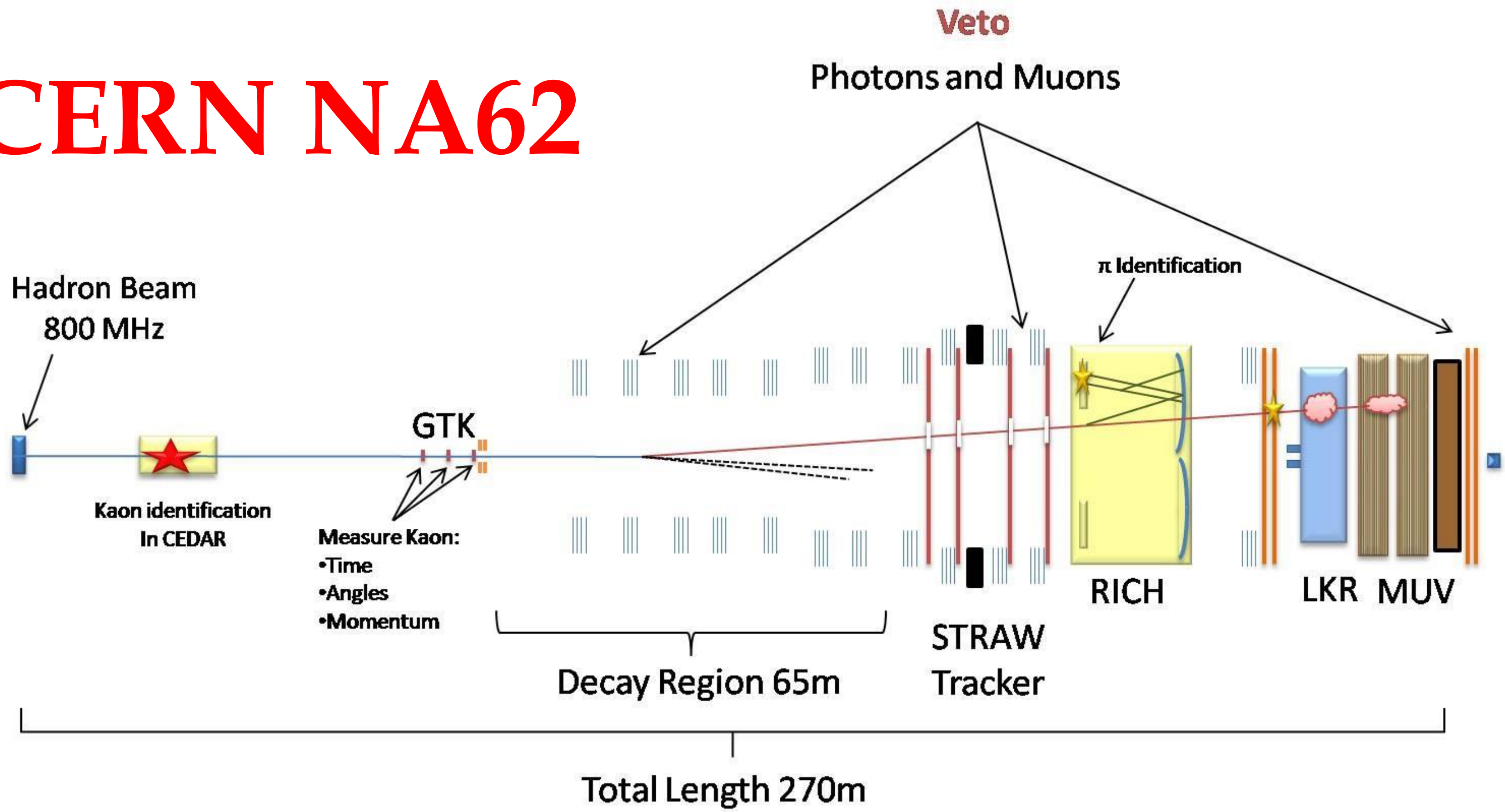


?



US: strong interest and (too) many casualties

CERN NA62

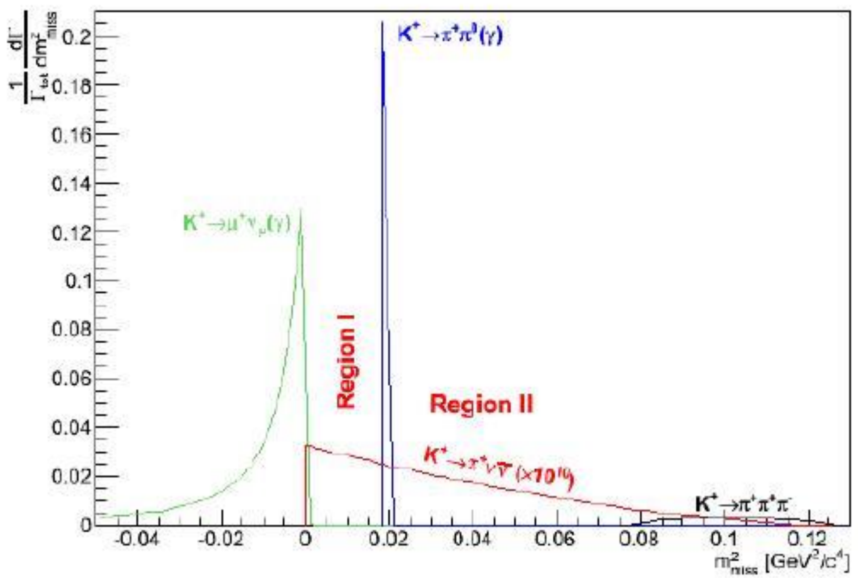


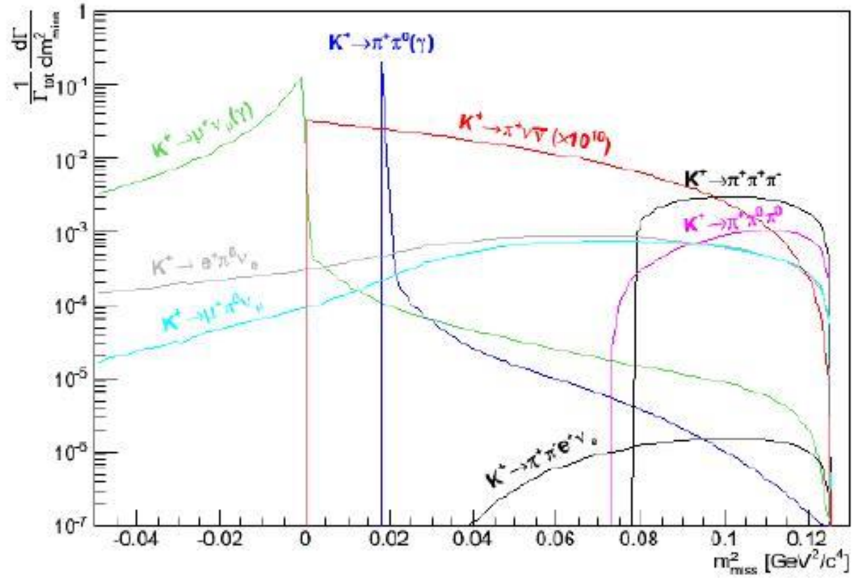
Measurement of $K^+ \rightarrow \pi^+ \upsilon\upsilon$ with new decay in-flight technique
Intense unseparated (6% K^+) 75 GeV/*c* hadron beam: $5 \cdot 10^{12}$ ppp
High-energy: high yield, large decay volume, more powerful vetoing
Track incoming K^+ in 800MHz beam, particle ID, photon vetoing

O(100) SM events in 3 years, with S/B ≈ 10

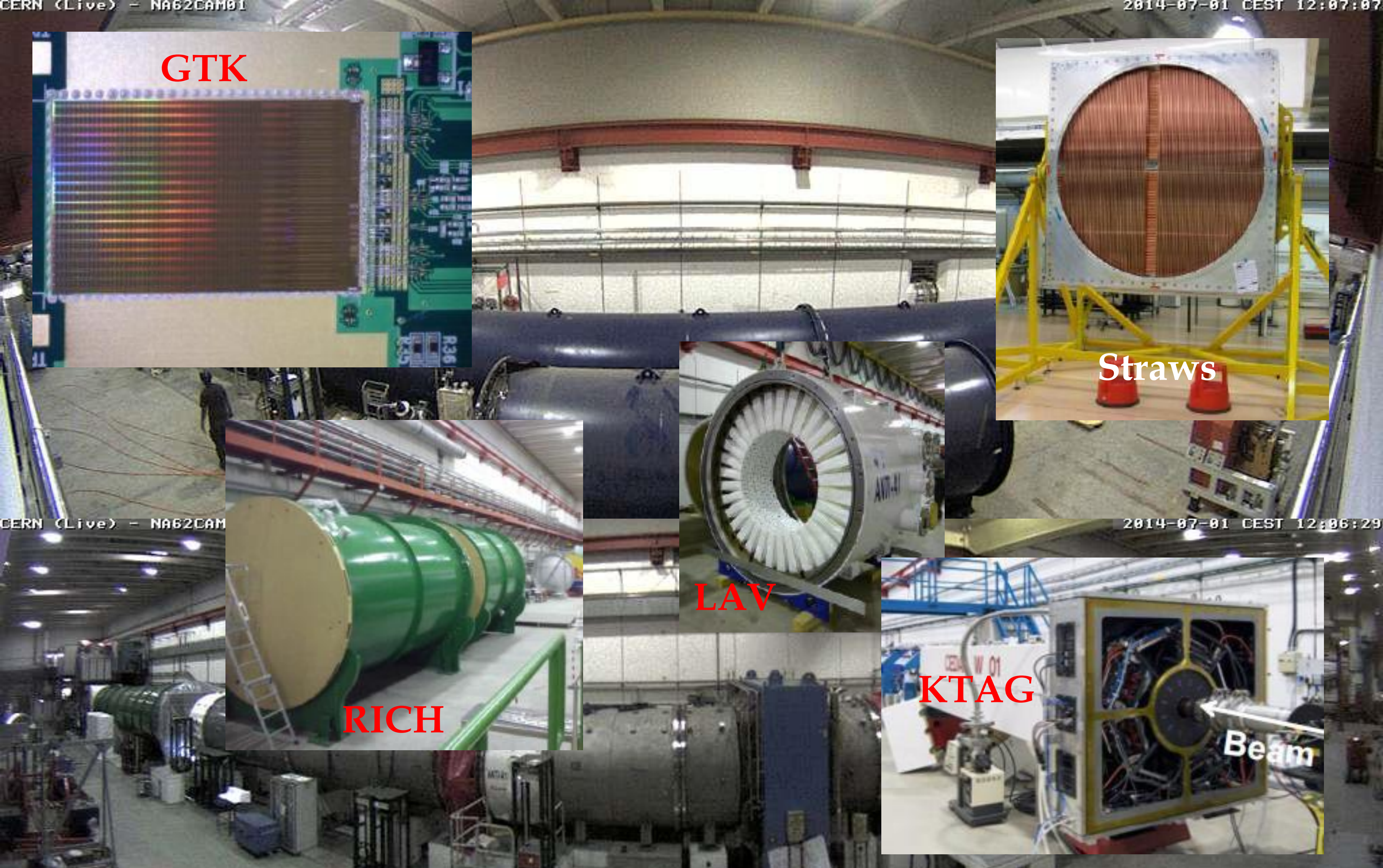
180 people, 27 institutions (Belgium, Bulgaria, CERN, Czech R., Germany, Italy, Mexico, Romania, Russia, Slovakia, UK, USA)

CERN NA62





$3 \cdot 10^{12}$ SPS protons/pulse (together with LHC)
Acceptance O(10%), π^+ backward in CM
Background reduction by: kinematics + PID + strong vetoing
Redundant measurements
Momentum, direction and PID on both K+ and π+ with O(100ps) timing
Full-digital 1MHz readout



First commissioning run Oct 2014 (reduced intensity)
Full run starting 2015

CERN NA62 additional reach

Decays in FV in 2 years of data: 1×10^{13} K^+ decays; 2×10^{12} π^0 decays

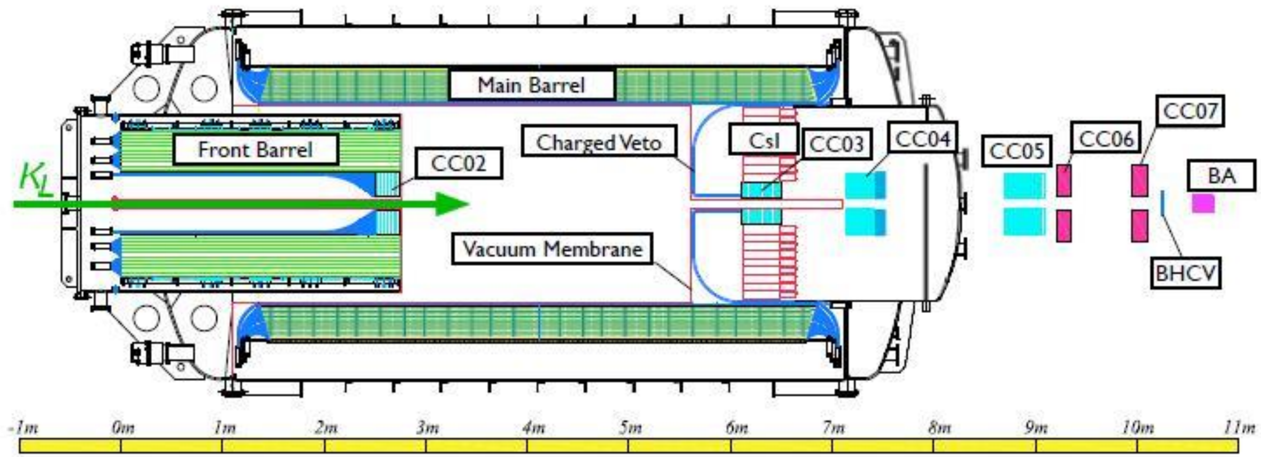
Single-event sensitivity 1/(decays × acceptance)

Mode	UL at 90% CL	Experiment	NA62 acceptance*
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL 777/865	~10%
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL 865	
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL 865	~10%
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL 865	~5%
$K^+ \to \pi^-\mu^+\mu^+$	1.1×10^{-9}	NA48/2	~20%
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva Saclay	~2%
$K^+ \to e^-\nu\mu^+\mu^+$	no data		~10%
$\pi^0 \to \mu^+e^-$	3.6×10^{-10}	KTeV	~2%
$\pi^0 \to \mu^-e^+$			

* From fast Monte Carlo simulation with flat phase-space distribution. Includes trigger efficiency.

NA62 single-event sensitivities: ~10^{-12} for K^+ decays; ~10^{-11} for π^0 decays

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 < $5.9 \cdot 10^{-7}$

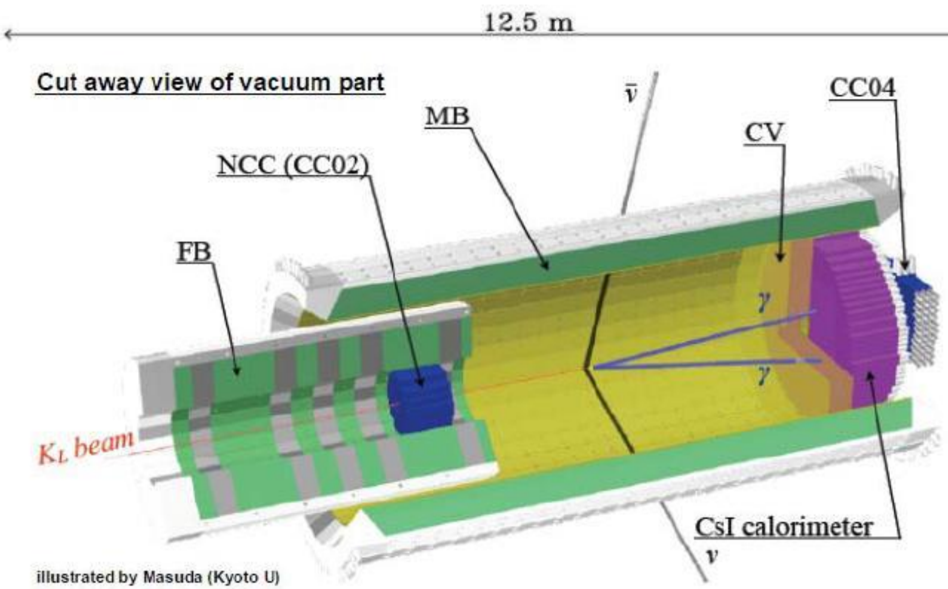
- High intensity: $2 \cdot 10^{12}$ ppp 12 GeV/c (50% DC)
- "Pencil" beam as transverse constraint: ~ 2 GeV/c K_L at 4° and 11m
- Photon veto hermeticity down to 1-2 MeV: Pb/scint in high vacuum
- Good EM calorimetry: ~ 500 pure CsI 7x7 cm^2, with central hole

Three runs (2004-2005): 12 months total
~1% total acceptance, Bkg estimate: 0.87±0.41

BR($K_L \rightarrow \pi^0 \nu\nu$) < $2.6 \cdot 10^{-8}$ (90% CL)

J-PARC KOTO

Dedicated $K_L \to \pi^0 \nu\nu$ measurement



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**

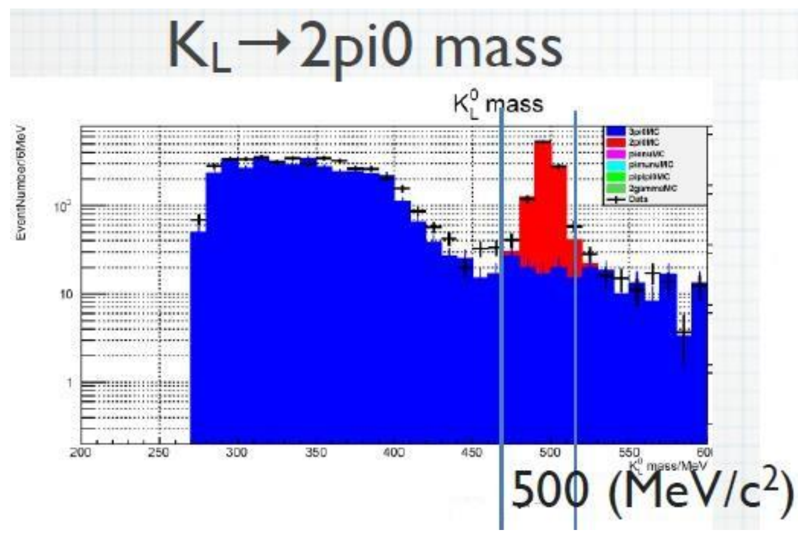
Step 2 upgrade**: 100 SM events**
(dedicated, smaller targeting angle beam line, larger detector)

66 people, 16 institutions (Japan, Korea, USA, Russia, Taiwan)

J-PARC KOTO

125 MHz waveform digitization (500 MHz in beam)
2700 CsI crystal EM calorimeter (KTeV)
with new electronics, in vacuum.

Engineering runs in 2013
Data-taking (20kW) 2013 (100h before stop)
Analyzing: results late summer 2014



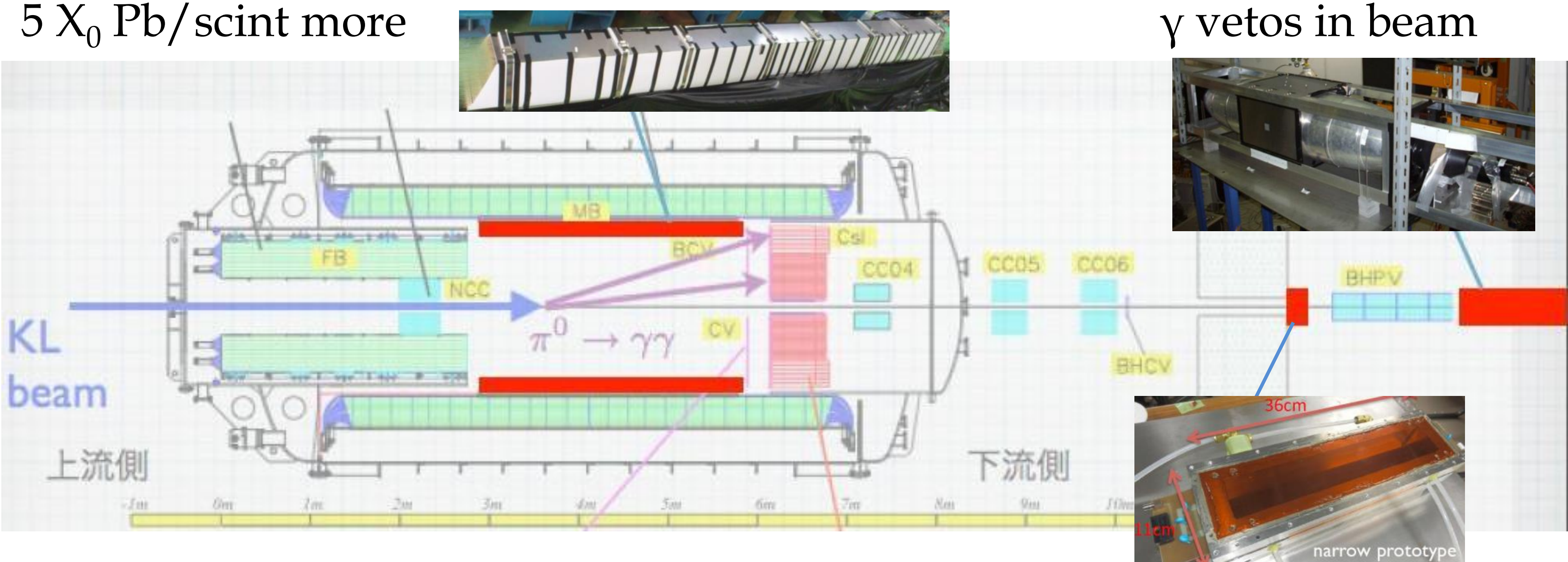
Expect data-taking start Jan 2015 (2-3m)
Goal: reach 0.5 x Grossman-Nir limit

J-PARC KOTO

Required improvements for measurement (2015):

Additional inner barrel γ veto
5 X_0 Pb/scint more

More aerogel
γ vetos in beam



New charged veto
Chamber

Kaons?

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

New Physics might already be there: ε_K? ε'/ε ?
More progress on theory required…

Powerful constraints on LFV, leptonic decays…

Low-energy QCD not always a bad thing (scattering lengths)…

From discovery tool to **quantitative probe**
Moving from **10s of kW** to **100s of kW** now

(and improvement on $|V_{cb}|$ would help)

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

Still the powerful "minimal flavour lab"

Thank-you