CKM unitarity and lepton universality tests with kaons

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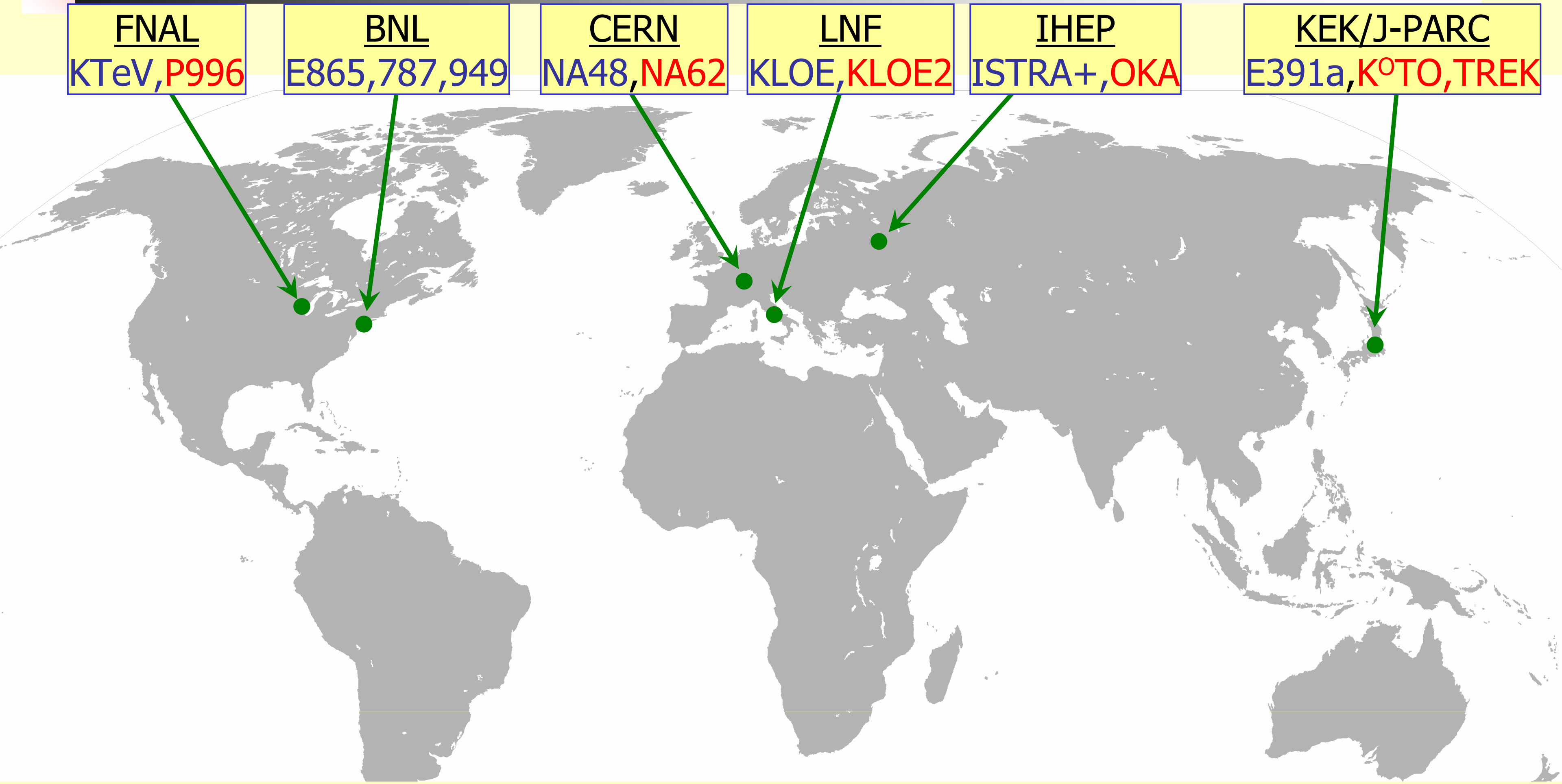
Outline:

1) Semileptonic K decays and CKM unitarity;
2) Leptonic K decays and lepton universality tests;
3) The future: ultra-rare decays $K\to\pi\nu\nu$.

Lattice meets Phenomenology • IPPP, Durham
17 September 2010

Major recent & future K experiments



FNAL
KTeV, P996

BNL
E865,787,949

CERN
NA48, NA62

LNF
KLOE, KLOE2

IHEP
ISTRA+, OKA

KEK/J-PARC
E391a, K^OTO, TREK

Variety of experimental techniques used:
decay-in-flight, decay-at-rest, ϕ factory (tagged decays).

Semileptonic kaon decays (K→πlν)

→ Precise CKM unitarity test by measurement of $|V_{us}|$

$|V_{us}|$ with K_{l3} decays

$K\to\pi l\nu$ (K_{l3}) decays: ideal channels for $|V_{us}|$ determination

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

(with $K=K_S, K_L, K^+$; $l=e,\mu$; $C_K^2 = ½$ for K^+, $C_K^2 = 1$ for K^0)

Inputs from experiment

$\Gamma(K_{l3(\gamma)})$:
radiation-inclusive decay rates;
in practice, branching ratios & lifetimes.

$I_{Kl}(\lambda)$:
phase space integrals;
λs parameterize form factor dependence on momentum transfer $t=(P_K-P_\pi)^2$.
E.g. Taylor expansion parameterization:
$(\lambda_+', \lambda_+'')$ for K_{e3}, $(\lambda_+', \lambda_+'', \lambda_0')$ for $K_{\mu3}$.

Inputs from theory

S_{EW}=1.0232(3):
short-distance EW correction

$f_+(0)$:
P.A.Boyle et al., arXiv:1004.0886
vector form factor at zero momentum transfer ($t=0$)

$\Delta^{SU(2)}$ and Δ^{EM}:
channel-dependent isospin breaking and long-distance EM corrections

$|V_{us}|$ from K_{l3}: recent history

2002: $|V_{ud}|^2 + |V_{us}|^2 - 1 = -0.0035(15)$.
(PDG 2004) A 2.3σ hint for CKM unitarity violation.

2003: BNL E865 measured a higher $BR(K^+_{e3})=0.0513(10)$. ← 1.9 %
Start of the $|V_{us}|$ revolution:
first modern measurement, consistent with unitarity.

2004-present: Many new measurements (ISTRA+, KLOE, KTeV, NA48)

- BRs, lifetimes, form factor shapes;
- Much higher statistical precision than early measurements;
- Adequate treatment of radiative corrections;
- Correlations between measurements properly reported.

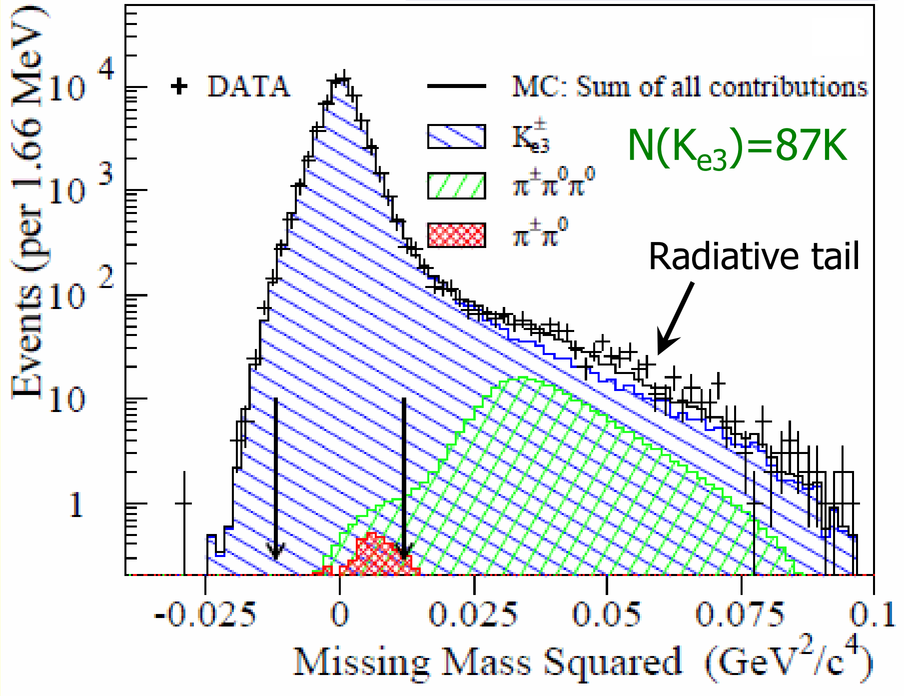
2008-beyond: Value of $|V_{us}|$ used for precision tests of the SM

FlaviaNet Kaon WG [www.lnf.infn.it/wg/vus]
arXiv:0801.1817 + update arXiv:1005.2323

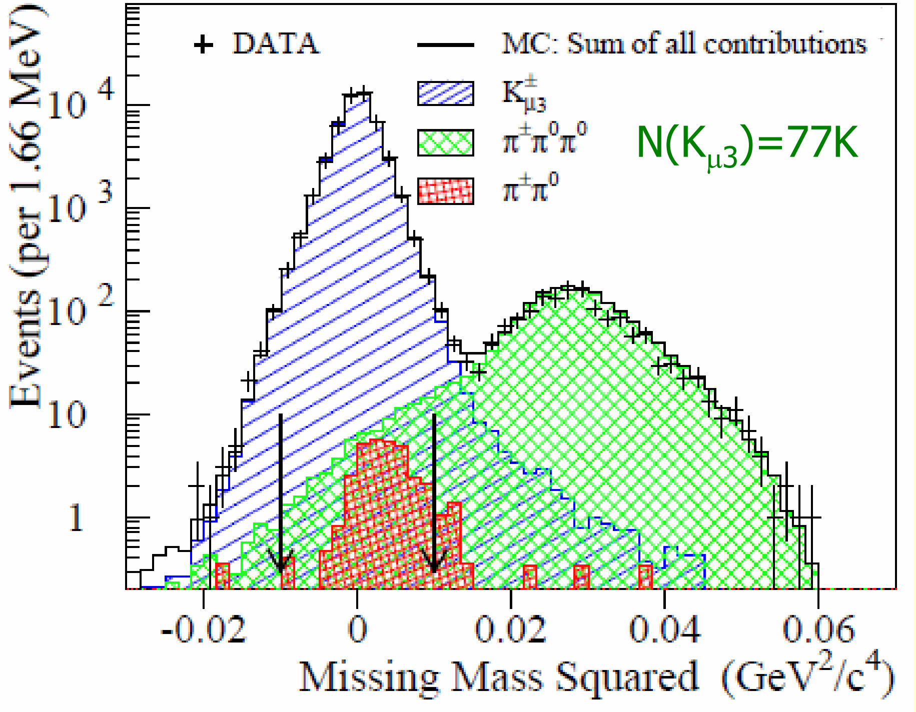
Example: K± from CERN NA48/2

Short special run in 2003: EPJ C50 (2007) 329

$K^\pm \to \pi^0 e^\pm \nu$ candidates



$K^\pm \to \pi^0 \mu^\pm \nu$ candidates



K_{l3} are major decay modes of K_L, K±:
not limited by statistics, low backgrounds.
Typical K_L, $K^\pm \to \pi l \nu$ samples analyzed by modern experiments
are 10^5 to 10^7 events with ~0.1% background.

K_S measurements are limited by signal statistics.

BR & τ measurements: K_L

FlaviaNet'10 fit: 21 input measurements (published final results, mostly 2003-06)

KLOE: 4 absolute BRs, $BR(\pi^+\pi^-)/BR(K_{l3})$, $BR(\gamma\gamma)/BR(3\pi^0)$,

$\tau_{KL}=50.92(30)$ns [2001/02 $K_L \to 3\pi^0$ sample]

$\tau_{KL}=50.56(25)$ns [2004/05 preliminary/not used]

KTeV: 5 ratios of BRs, $BR(\pi^+\pi^-\gamma)/BR(\pi^+\pi^-)$
2 meas. of $BR(\pi^+\pi^-\gamma_{DE})/BR(\pi^+\pi^-)$

NA48: $BR(K_{e3})/BR(2\text{-track})$,
$BR(\pi^+\pi^-)/BR(K_{l3})$, $BR(\gamma\gamma)/BR(3\pi^0)$

PDG: $BR(\pi^0\pi^0)/BR(\pi^+\pi^-)$

E731: $BR(\pi^+\pi^-\gamma_{DE})/BR(\pi^+\pi^-)$

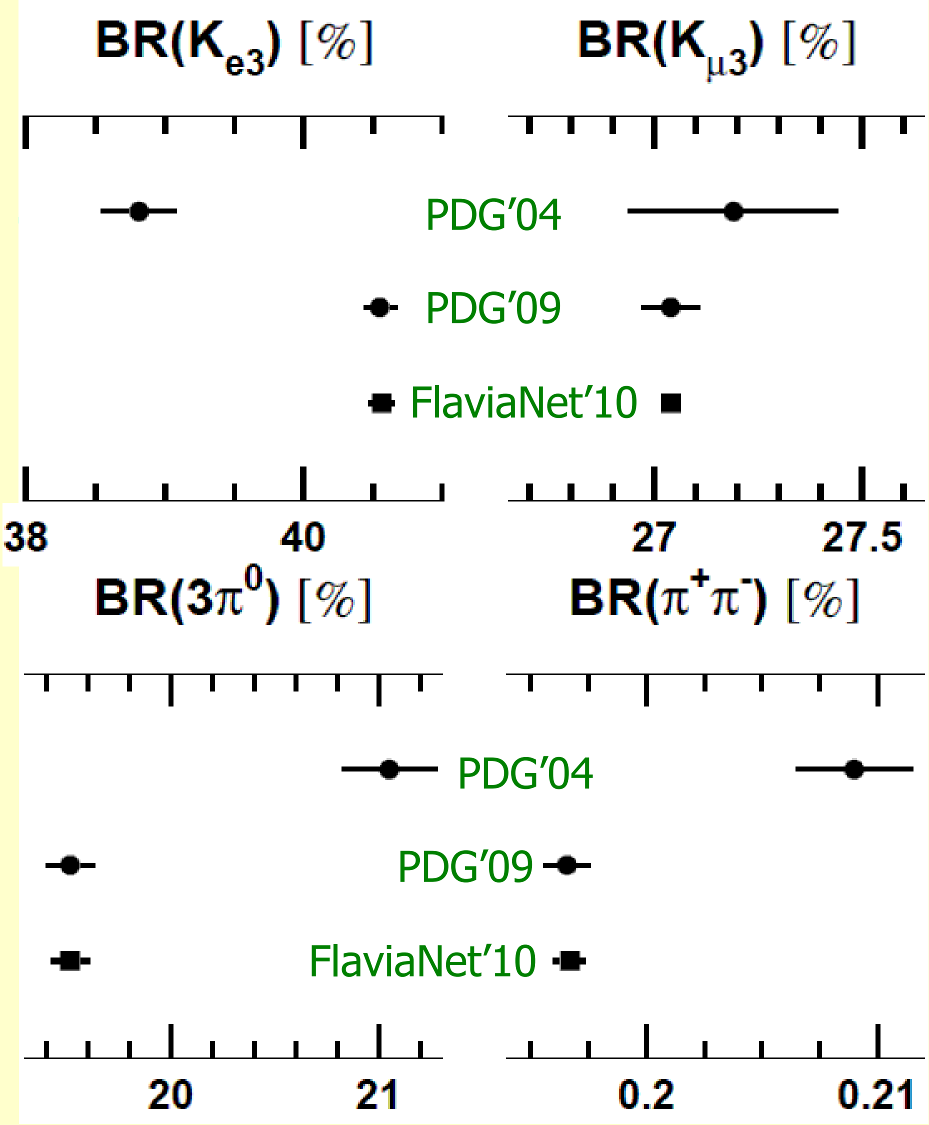
Vosburgh (1972): τ_{KL}

Free parameters: 9 main BRs, lifetime τ_{KL}.
Constraint: $\Sigma BR_i = 1$.

Fit quality: χ^2/ndf=19.8/12 (P=7.1%).
Cf. PDG'09: χ^2/ndf=35.7/17 (P=0.5%).

~5σ shifts wrt PDG'04: many new results, elimination of old results with no radiative corrections or not reporting correlations.

Evolution of main K_L BRs



BR & τ measurements: $K^\pm$

FlaviaNet'10 fit: 17 input measurements
(mostly 2000s, but also earlier results)

KLOE: 5 absolute BRs, τ_K with $K^\pm \to \mu^\pm \nu$
[$K^\pm \to 3\pi^\pm$ missing: analysis in progress]

NA48/2: BR(K_{e3})/BR($\pi^\pm\pi^0$), BR($K_{\mu3}$)/BR($\pi^\pm\pi^0$)

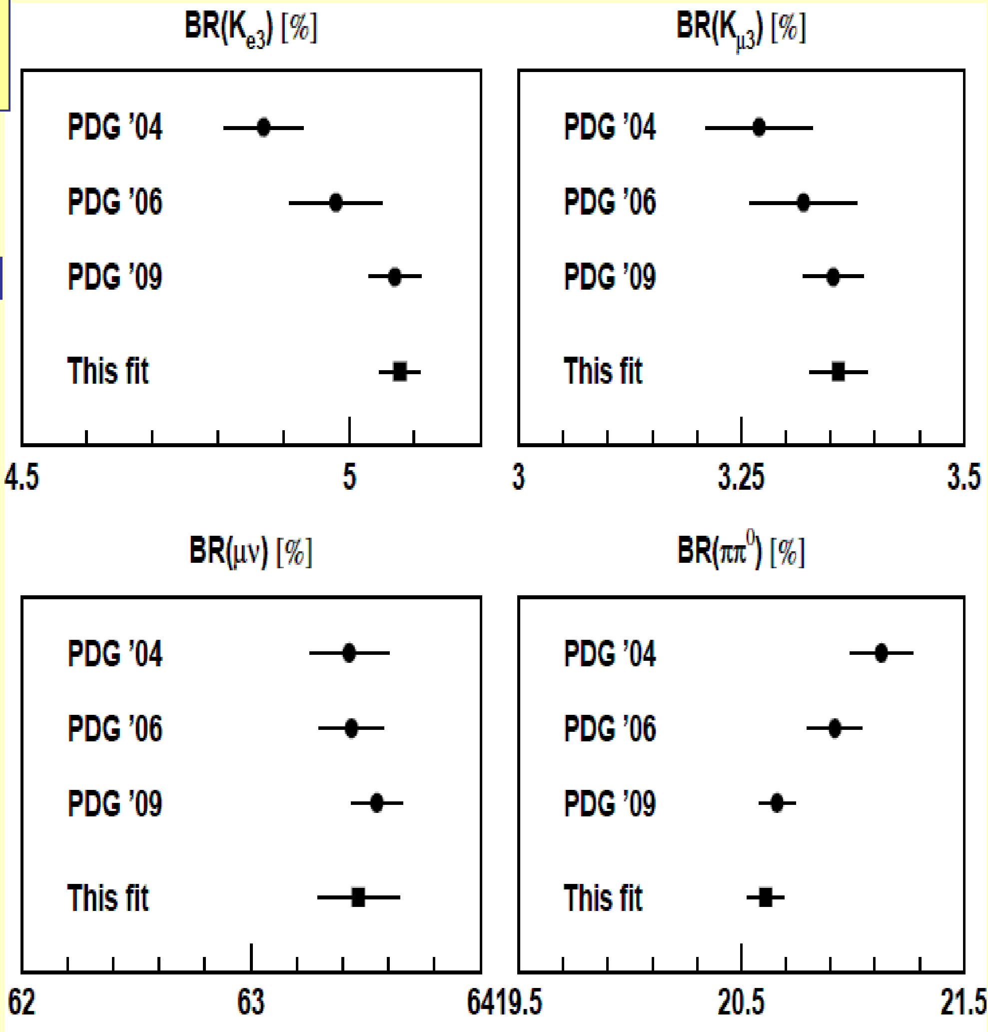
E865: BR(K_{e3})/BR($\pi^\pm\pi^0$+$K_{\mu3}$+$K_{3\pi}$, π^0 Dalitz)

KEK246: BR(K_{e3})/BR($K_{\mu3}$)

Earlier: BR($K_{3\pi}$), 3 meas. of τ_K,
3 meas. of BR($K \to \mu\nu$)/BR($\pi^\pm\pi^0$)

Free parameters: 6 main BRs, lifetime τ_K.
Constraint: $\Sigma BR_i = 1$.
Fit quality: χ^2/ndf=25.8/11 (P=0.7%).
Cf. PDG'09: χ^2/ndf=52/24 (P=0.1%).

Evolution of main $K^\pm$ BRs



BR & τ measurements: K_S

The most recent development: $|V_{us}|$ from K_S decays

KLOE (2006): PLB636 (2006) 173, EPJC48 (2006) 767

$BR(K_S\to\pi e\nu) / BR(K_S\to\pi^+\pi^-) = 10.19(13) \times 10^{-4}$ ← **1.3%**

$BR(K_S\to\pi^+\pi^-) / BR(K_S\to\pi^0\pi^0) = 2.2459(54)$

Rare decay!
13K candidates.
Error dominated
by statistics.

NA48 (2007): PLB653 (2007) 145

$BR(K_S\to\pi e\nu)/BR(K_L\to\pi e\nu) = 0.993(34)$

Lifetime from $K_S\to\pi^+\pi^-$ decays

KTeV: PRD67 (2003) 012005 $\tau_{KS} = 89.580(130)$ ps

NA48: PLB537 (2008) 28 $\tau_{KS} = 89.598(\ 70)$ ps

} ← **0.07%**

KLOE M.Antonelli, BEACH2010 $\tau_{KS} = 89.562(\ 52)$ ps ← new! not used

Additional constraint:
assuming lepton universality
and using the measured form factors,
$BR(K_{e3})/BR(K_{\mu3}) = 0.6655(15)$.

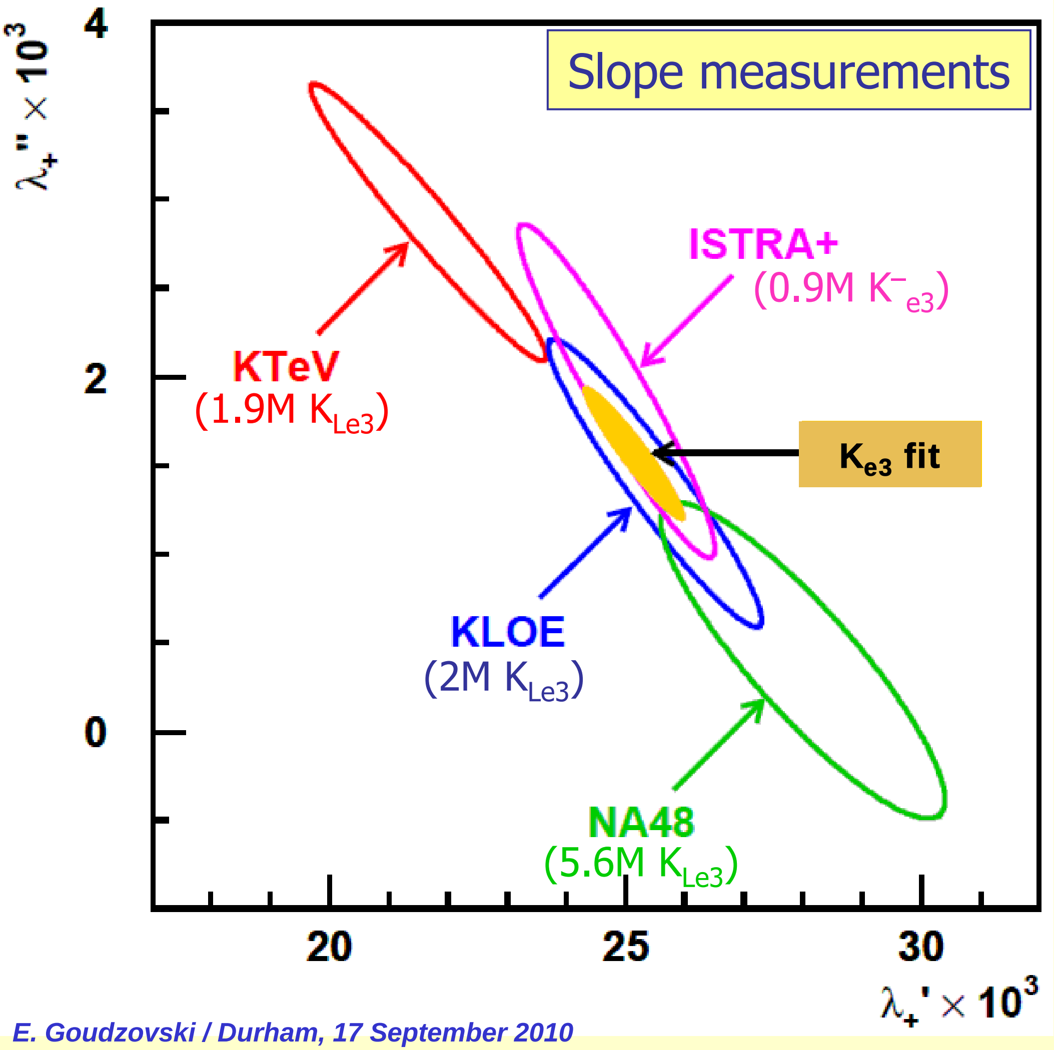
FlaviaNet'10 fit: 5 inputs.
Free parameters:
4 BRs ($\pi^+\pi^-$,$\pi^0\pi^0$,K_{e3},$K_{\mu3}$) + lifetime.
Constraint: $\Sigma BR_i = 1$.
$\chi^2/ndf = 0.015/1$ (P=90%)

Fit result: $BR(K_{e3}) = 7.05(8) \times 10^{-4}$ ← **1.1%**

Form factors with K_{e3}: (λ'_+,λ''_+)

Polynomial parameterization:

$$f_+(t)/f_+(0) = 1 + \lambda'(t/m_\pi^2) + ½\lambda''(t/m_\pi^2)^2 + \ldots$$



Slope parameters $\times 10^3$

λ' = 25.1±0.9
λ'' = 1.6±0.4
$\rho(\lambda',\lambda'')$ = –0.94
χ^2/ndf = 3.5/6 (P=51%)

Phase Space Integrals:

$I(K^0_{e3})$ = 0.15463(21)
$I(K^\pm_{e3})$ = 0.15900(22)

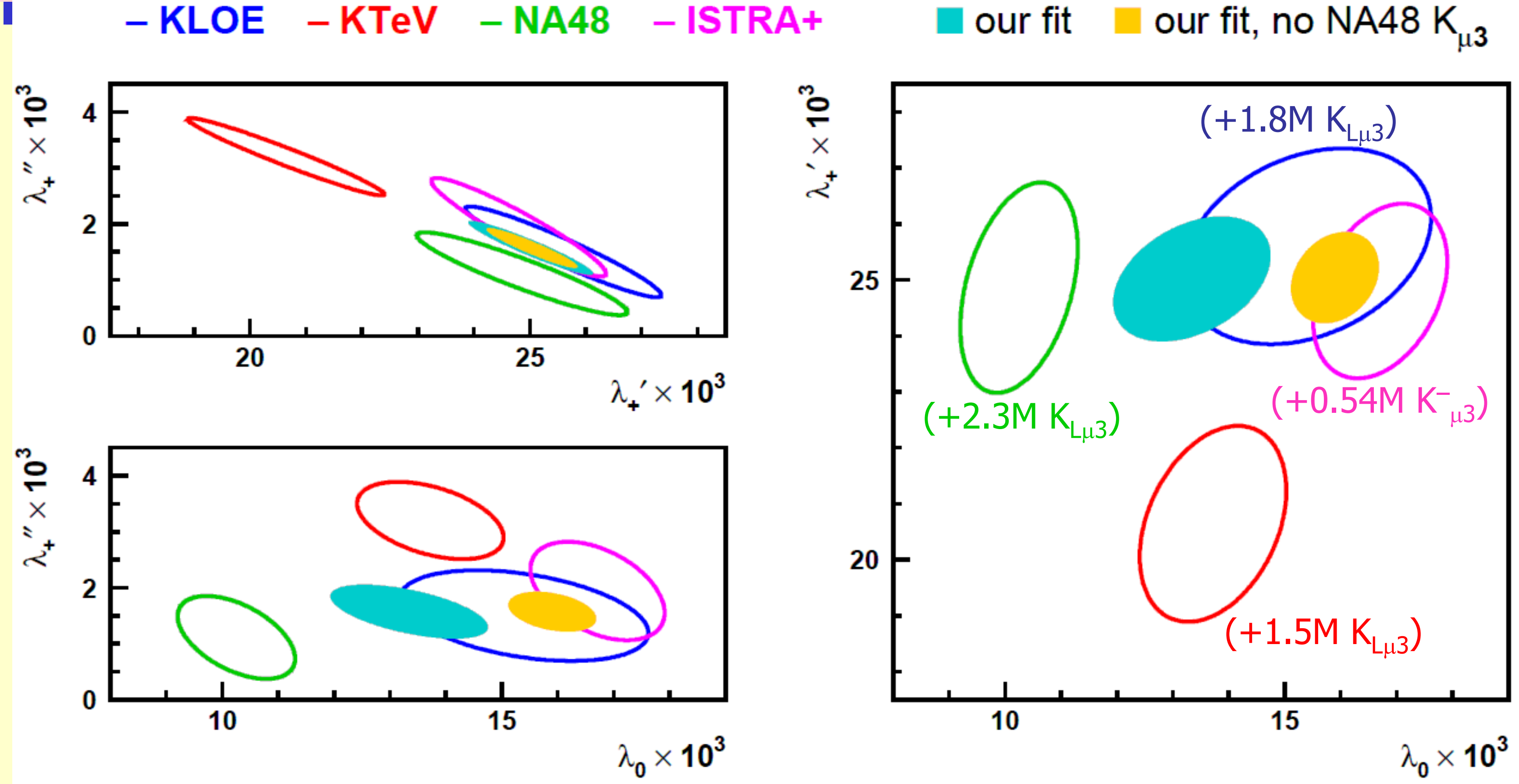
← 0.14%

Significance of λ'' slope: 4σ

Fits to pole and dispersive parameterizations lead to similar PSIs within 0.1%

Similar averaging is done for combined $K_{e3}+K_{\mu3}$

Form factors, K_{e3}+$K_{\mu3}$: $(\lambda'_+, \lambda''_+, \lambda_0)$



NA48 $K_{\mu3}$ measurement is inconsistent and has been excluded

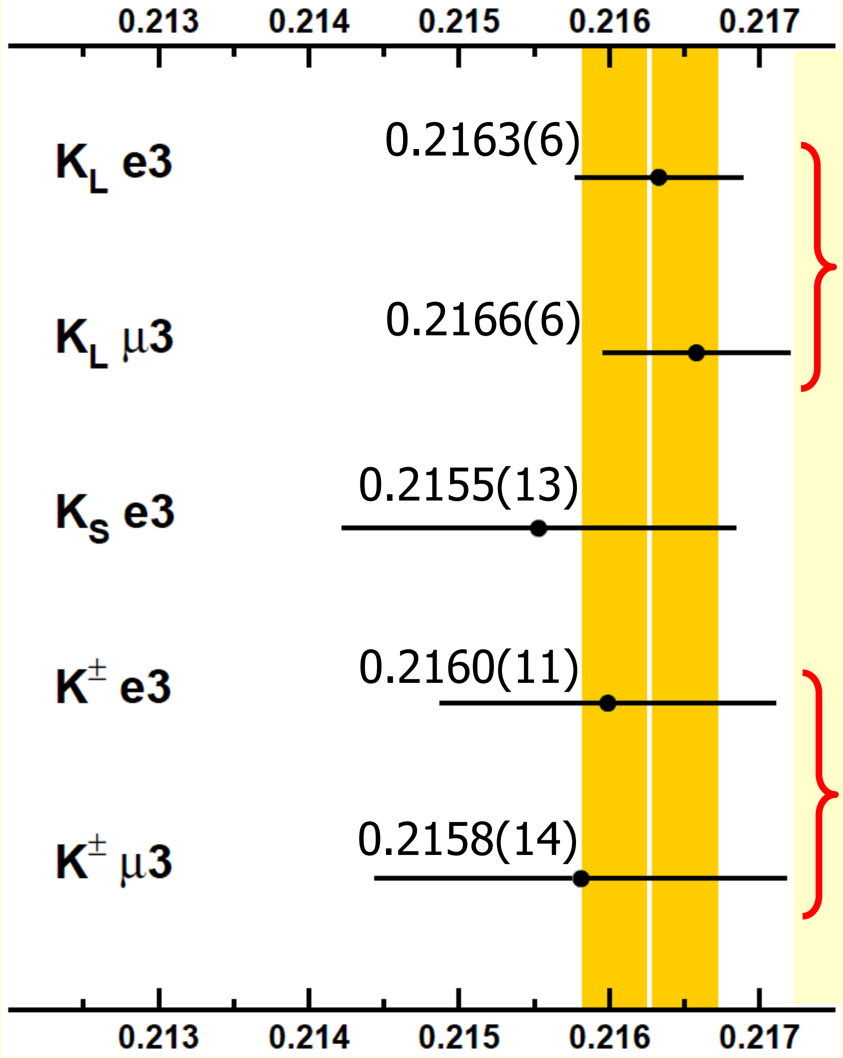
χ^2/ndf=5.6/5 (P=34%)

Phase Space Integrals:

$I(K^0_{e3})$ = 0.15457(20) $I(K^0_{\mu3})$ = 0.10266(20)
$I(K^\pm_{e3})$ = 0.15894(21) $I(K^\pm_{\mu3})$ = 0.12564(20)

+New NA48/2 $K^\pm_{\mu3}$ result: M.Veltri, CKM2010

$|V_{us}|f_+(0)$ measurements with K_{l3}



$|V_{us}|f_+(0)$ from various decay modes

Main error sources

K_L lifetime
will be
improved soon

BR
(statistics)

BRs,
isospin
breaking
corrections

Global fit result:

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

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

0.23% relative precision

Prospects:

KLOE-2/step-0 alone expect 0.14% precision on $|V_{us}|f_+(0)$ by improving on $BR(K_{Se3})$ and K_L, $K^\pm$ lifetimes. (arXiv:1003.3868)

NA48/NA62: improvements on K^+ BRs and FFs.

$|V_{us}|/|V_{ud}|$ from $K^+/\pi^+\to\mu^+\nu$

SM ratio of radiation-inclusive leptonic decay widths:

$$\frac{\Gamma_{K\ell2}}{\Gamma_{\pi\ell2}} = \frac{|V_{us}|^2}{|V_{ud}|^2}\frac{f_K^2}{f_\pi^2}\frac{m_K(1-m_\ell^2/m_K^2)^2}{m_\pi(1-m_\ell^2/m_\pi^2)^2}(1+\delta_{\mathrm{EM}})$$

Extracted

Lattice QCD input:
average of BMW,MILC'09,HPQCD/UKQCD
f_K/f_π=1.193(6) ← **0.5%**

Experimental input

(1) from $K^\pm$ BR fit
$BR(K_{\mu2})$ = 0.6347(18) ← **0.28%**
$\tau(K^\pm)$ = 12.384(15) ns

(2) pion measurements (PDG 2009)
$\Gamma(\pi^\pm\to\mu^\pm\nu)$ = 38.408(7) μs^{-1}

Experimental result:

$|V_{us}/V_{ud}|\ f_K/f_\pi$ = 0.2758(5) ← **0.18%**

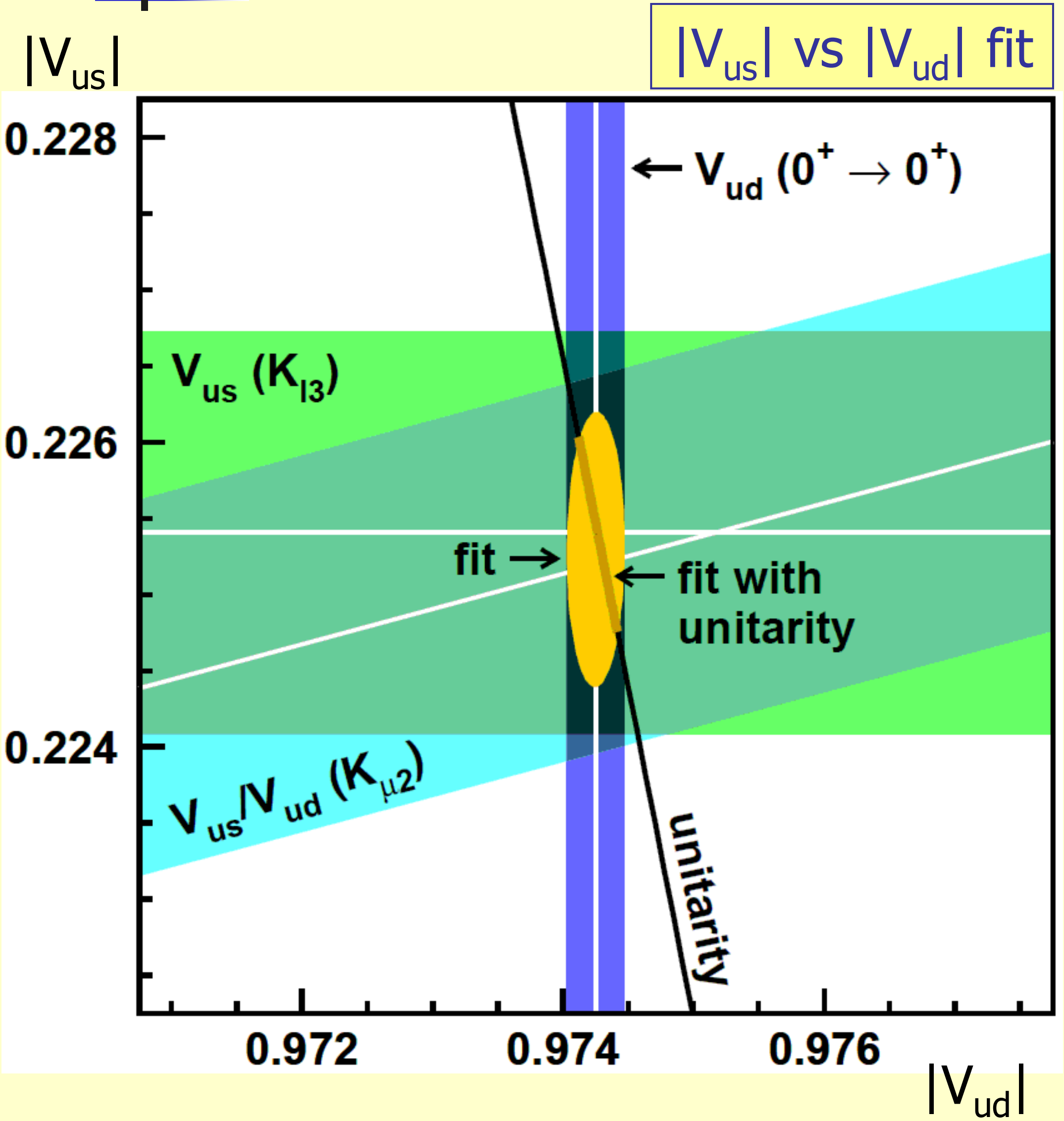
Long-distance EW correction

$$\delta_{\mathrm{EM}} = -0.0070(35)$$

Dominant short-distance radiative effects are universal and cancel out:
$2\alpha/\pi\ \ln(M_Z/M_\rho) \sim 2.4\%$.

(Marciano, PRL 93 (2004) 231803)

CKM unitarity test (1)



Experimental input: **~0.2%**

$|V_{us}|f_+(0)$ = 0.2163(5)
$|V_{us}/V_{ud}|\ f_K/f_\pi$ = 0.2758(5)
$|V_{ud}|$ = 0.97425(22)
(average from 20 nuclear beta decays, Hardy & Towner, PRC79 (2009) 055502)

Lattice input:

$f_+(0)$ = 0.959(6) **0.6%**
f_K/f_π = 1.193(6)

Fit result: **0.4%** error dominated by theory
$|V_{us}|$ = 0.2253(9)
Fit imposing unitarity:
$|V_{us}|$ = 0.2254(6)
CKM unitarity test:
$|V_{us}|^2+|V_{ud}|^2-1$ = −0.0001(6)

$|V_{us}|$ from τ decays
[BaBar, N.Gagliardi, BEACH2010]:
BR($\tau\to K\nu$)/BR($\tau\to\pi\nu$): $|V_{us}|$=0.2255(23).
Inclusive $\tau\to s$: $|V_{us}|$=0.2151(26),
3.7σ below the K+π result.

CKM unitarity test (2)

Another view on the unitarity test: comparison of weak couplings from K decay and muon decay.

From muon lifetime: $\tau_\mu \sim 1/G_F^2$.
MuLan collaboration,
PRL 99 (2007) 032001

G_μ = $1.166371(6)\times10^{-5}$ GeV^{-2}

G_{CKM} = $G_\mu\,(|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2)^{1/2}$ = $1.16633(35)\times10^{-5}$ GeV^{-2}

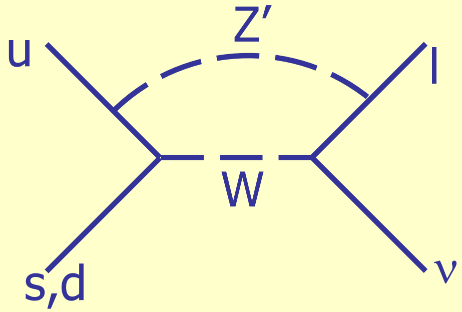
Example: additional Z′ gauge bosons

W. J. Marciano, A. Sirlin, PRD35 (1987) 1672

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 \approx 1 + 0.005\ \ln(M^2(Z')/(M^2(Z')-M^2(W)))$

→ M(Z′)>~400 GeV @ 90% CL

Other implications (exotic μ decays, heavy quarks and leptons) are discussed in arXiv:0907.5386



Model-independent constraint on the effective scale of NP operators:

Cirigliano, Jenkins, González-Alonso, NPB 830 (2010) 95

$\Delta_{CKM} = |V_{us}|^2 + |V_{ud}|^2 - 1 = -0.0001(6)$ → Λ>11TeV (90%CL)

K_{l3}: lepton universality test

Comparison of $|V_{us}|$ determined from
K_{e3} vs $K_{\mu3}$ decays

SM

$$r_{\mu e} = \frac{[|V_{us}|f_+(0)]^2_{\mu3,\,\mathrm{exp}}}{[|V_{us}|f_+(0)]^2_{e3,\,\mathrm{exp}}} = \frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}}\,\frac{I_{e3}\,(1+2\delta^{Ke}_{\mathrm{EM}})}{I_{\mu3}\,(1+2\delta^{K\mu}_{\mathrm{EM}})} = (g_\mu/g_e)^2 = 1$$

lepton coupling
at the W→lν vertex

Experimental results
$K^\pm$: $r_{\mu e} = 0.998(9)$
K^0: $r_{\mu e} = 1.003(5)$

→ $r_{\mu e} = 1.002(4)$

Cf. other measurements:
π→lν: $r_{\mu e} = 1.0042(33)$ (PRD 76 (2007) 095017)
τ→lνν: $r_{\mu e} = 1.000(4)$ (Rev.Mod.Phys. 78 (2006) 1043)

The sensitivity in kaon sector approaches those of the other measurements.

Leptonic kaon decays
($K^+ \rightarrow l^+ \nu$)

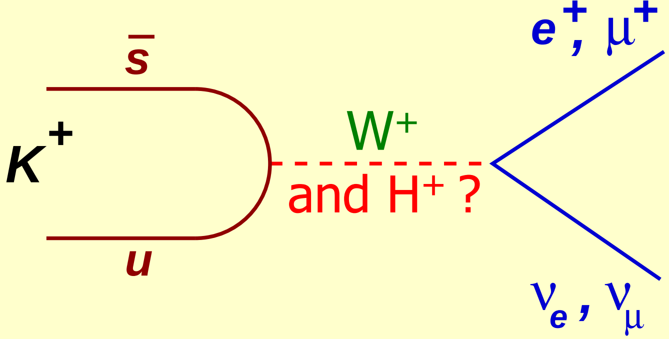
→ Test of SM with $\Gamma(K_{\mu 2})/\Gamma(\pi_{\mu 2})$:
NP contributions to charged weak currents;
charged Higgs boson exchange in SM extensions with 2 Higgs doublets.

→ Lepton flavour violation test in loop amplitude: $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$.

Leptonic meson decays: $P^+ \to l^+\nu$

Angular momentum conservation → SM contribution is suppressed

$$\Gamma(P^+ \to l^+\nu) = \frac{G_F^2 M_P M_l^2}{8\pi}\left(1-\frac{M_l^2}{M_P^2}\right)^2 f_P^2 |V_{qq'}|^2$$



Models with 2 Higgs doublets (2HDM-II including SUSY): sizeable charged Higgs ($H^\pm$) exchange contributions

PRD48 (1993) 2342; Prog.Theor.Phys. 111 (2004) 295

(numerical examples for M_H=500GeV/c^2, tanβ = 40)

$\pi^+\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_\pi/m_H)^2\, m_d/(m_u+m_d)\, \tan^2\beta \approx -2\times10^{-4}$

$K^+\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_K/m_H)^2 \tan^2\beta \approx -0.3\%$

$D^+_s\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_D/m_H)^2\, (m_s/m_c)\, \tan^2\beta \approx -0.4\%$

$B^+\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_B/m_H)^2 \tan^2\beta \approx -30\%$

$H^\pm$ exchange in $B^+\to\tau^+\nu$: (R.Barlow, CKM 2010)

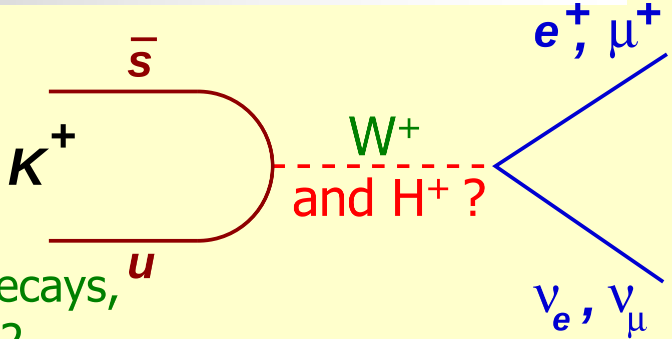
BaBar+Belle: $Br_{exp}(B\to\tau\nu) = (1.64\pm0.34)\times10^{-4}$
(HFAG)

Standard Model: $Br_{SM}(B\to\tau\nu) = (1.20\pm0.25)\times10^{-4}$
(f_B from HPQCD, $|V_{ub}|$ from HFAG)

$\Delta\Gamma/\Gamma_{SM}=0.37\pm0.35$

$K_{\mu2}$: sensitivity to new physics

Comparison of $|V_{us}|$ determined from helicity-suppressed $K_{\mu2}$ decays vs helicity allowed K_{l3} decays



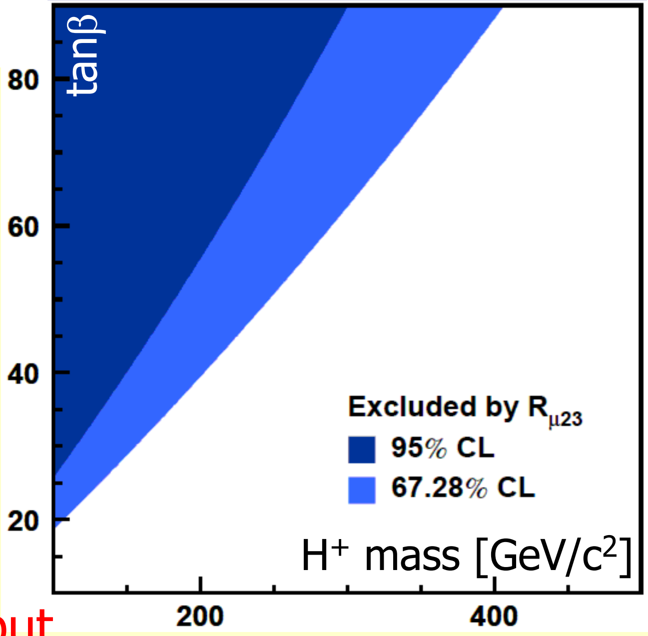
To reduce uncertainties of hadronic and EM corrections to $K_{\mu2}$:

$$R_{\mu23} = \underbrace{\left(\frac{f_K/f_\pi}{f_+(0)}\right)^{-1}}_{\substack{\text{Lattice QCD}\\ \text{input}}} \underbrace{\left(\left|\frac{V_{us}}{V_{ud}}\right|\frac{f_K}{f_\pi}\right)_{\mu2}}_{\substack{\text{Measured}\\ \text{with } K_{\mu2}/\pi_{\mu2}}} \underbrace{\frac{\overbrace{|V_{ud}|_{0^+\to0^+}}^{\substack{\text{average from nuclear } \beta \text{ decays,}\\ \text{PRC79 (2009) 055502}}}}{[|V_{us}|f_+(0)]_{\ell3}}}_{\substack{\text{Measured}\\ \text{with } K\to\pi\mu\nu}}$$

SM expectation: $R_{\mu23} = 1$.
Charged Higgs mediated currents lead to

$$R_{\mu23} \approx \left|1 - \frac{m^2_{K^+}}{m^2_{H^+}}\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|$$

tanβ vs H⁺ mass exclusion



Experiment: $R_{\mu23} = 0.999(7)$, limited by lattice QCD input.

(Flavianet Kaon WG, arXiv:1005.2323)

$R_K = K_{e2}/K_{\mu 2}$ in the SM

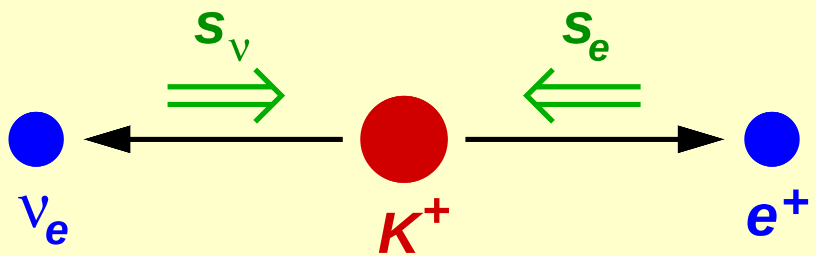
Observable sensitive to Lepton Flavour Violation and its SM expectation:

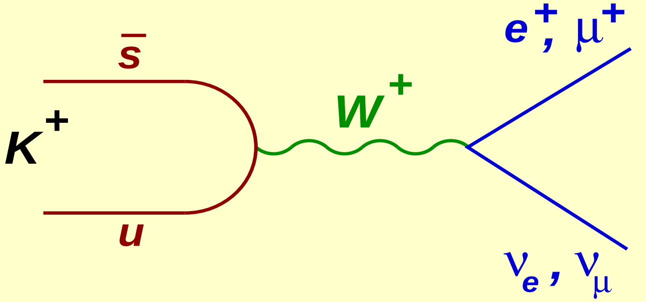
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{(1 + \delta R_K^{\mathrm{rad.corr.}})}$$

(similarly, R_π in the pion sector)

Radiative correction (few %) due to $K^+ \to e^+ \nu \gamma$ (IB) process, by definition included into R_K

Helicity suppression: $f \sim 10^{-5}$





- SM prediction: excellent sub-permille accuracy: not obstructed by hadronic uncertainties.
- Measurements of R_K and R_π have long been considered as tests of lepton universality.
- Understood recently: helicity suppression of R_K might enhance sensitivity to non-SM effects to an experimentally accessible level.

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

$R_\pi^{SM} = (12.352 \pm 0.001) \times 10^{-5}$

Phys. Lett. 99 (2007) 231801

$R_K=K_{e2}/K_{\mu2}$ beyond the SM

2HDM – tree level (including SUSY)

K_{l2} can proceed via exchange of charged Higgs $H^\pm$ instead of $W^\pm$

→ Does not affect the ratio R_K

2HDM – one-loop level

Dominant contribution to R_K: $H^\pm$ mediated LFV (rather than LFC) with emission of ν_τ

→ R_K enhancement can be experimentally accessible

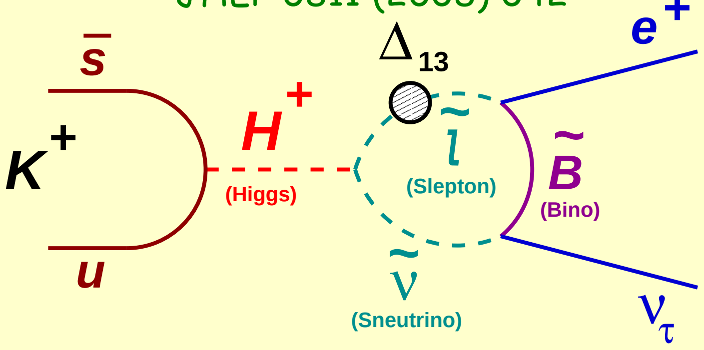
$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2\tan^6\beta\right]$$

Up to ~1% effect in large (but not extreme) $\tan\beta$ regime with a massive $H^\pm$

Example:

($\Delta_{13}=5\times10^{-4}$, $\tan\beta=40$, $M_H=500$ GeV/c^2)
lead to $R_K^{MSSM} = R_K^{SM}(1+0.013)$.

PRD 74 (2006) 011701,
JHEP 0811 (2008) 042



Analogous SUSY effect
in pion decay is suppressed
by a factor $(M_\pi/M_K)^4 \approx 6\times10^{-3}$

(see also PRD76 (007) 095017)

Large effects in B decays
due to $(M_B/M_K)^4 \sim 10^4$:

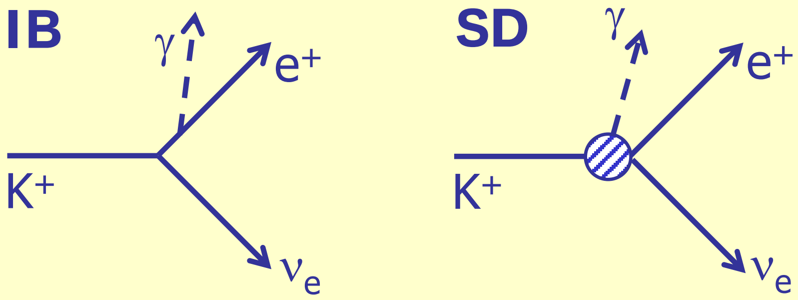
$B_{\mu\nu}/B_{\tau\nu}$ → ~50% enhancement;

$B_{e\nu}/B_{\tau\nu}$ → enhanced by
~one order of magnitude.

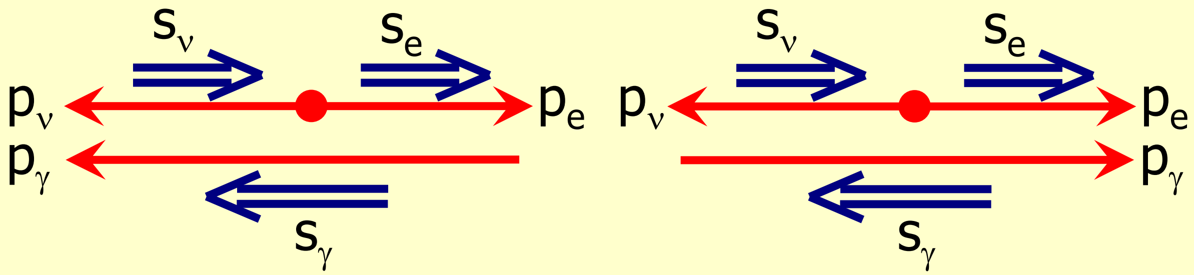
Out of reach: $Br^{SM}(B_{e\nu}) \approx 10^{-11}$

Radiative $K^+ \to e^+ \nu\gamma$ process

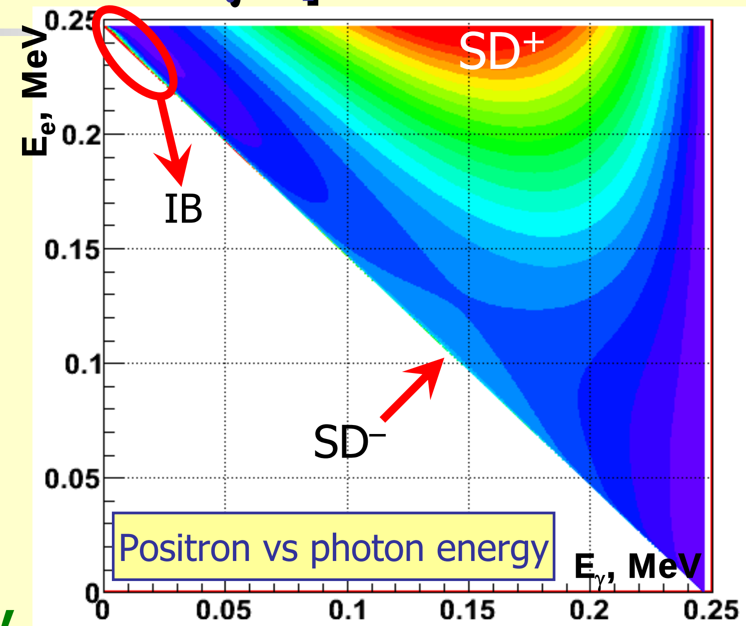
R_K is inclusive of IB radiation by definition.
SD radiation is a background. INT is negligible.

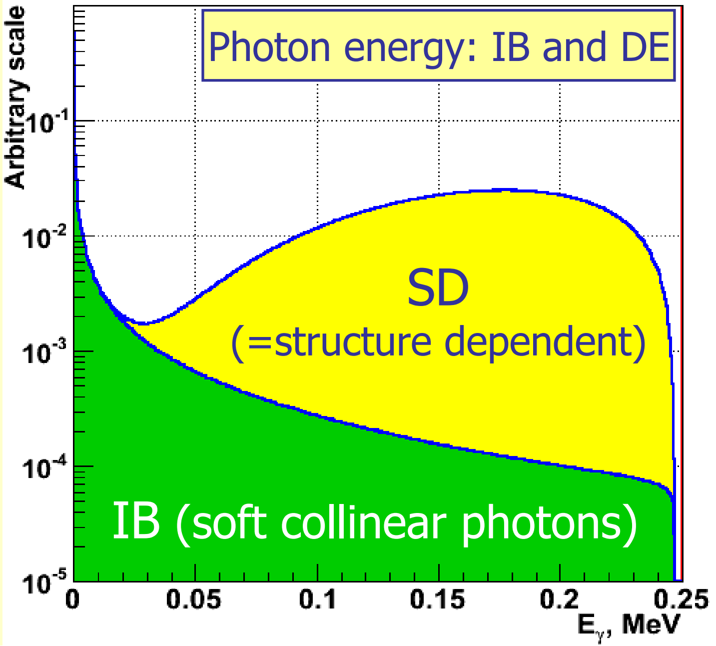


SD⁺: positive γ helicity **SD⁻: negative γ helicity**



SD radiation is not helicity suppressed.
KLOE measurement of the form factor leads to
BR(SD⁺, full phase space) = $(1.37 \pm 0.06) \times 10^{-5}$.
(EPJC64 (2009) 627)





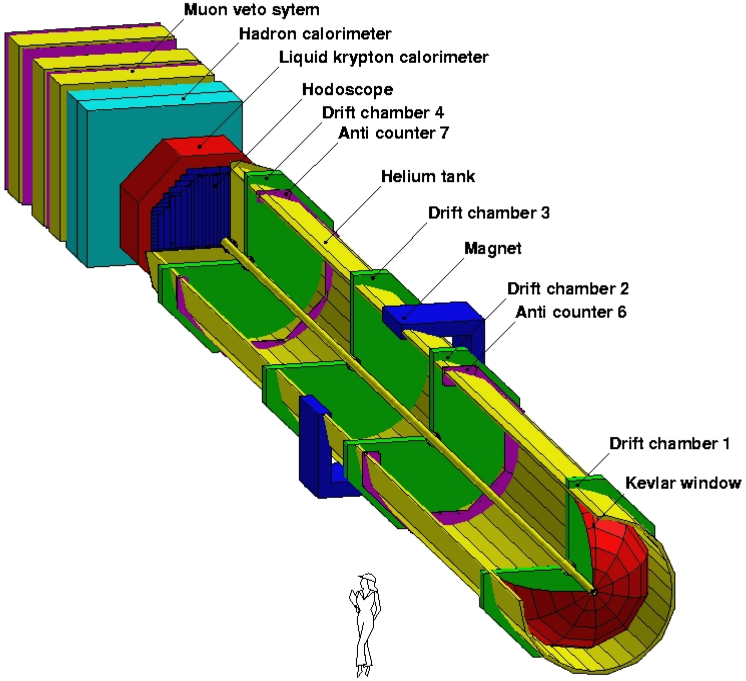
NA62: decay-in-flight technique

Narrow momentum band K^+ beam:
$P_K=(74.0\pm1.6)$ GeV/c

- Four months in 2007 (23/06–22/10):
  $\sim4\times10^5$ SPS spills,
  $\sim5\times10^{10}$ K^+ decays in 114m long vacuum tank

Principal subdetectors:

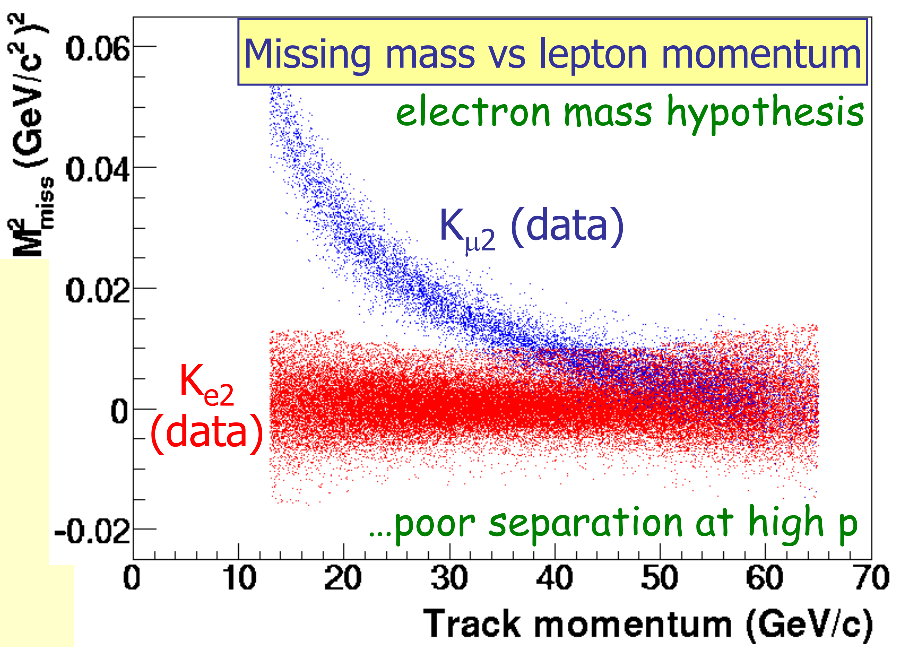
- Magnetic spectrometer (4 DCHs):
  4 views/DCH: redundancy $\Rightarrow$ efficiency;
  $\Delta p/p = 0.47\% + 0.020\% {*} p$ [GeV/c]
- Hodoscope
  fast trigger, precise time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=0.42/E^{1/2} + 0.6\text{mm}$ (1.5mm@10GeV).



NA62: K_{e2} vs $K_{\mu 2}$ selection

Large common part (topological similarity)

- one reconstructed track (lepton candidate);
- geometrical acceptance cuts;
- K decay vertex: closest approach of lepton track & nominal kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: $13\mathrm{GeV}/c<p<65\mathrm{GeV}/c$.



Kinematic identification

missing mass $\boxed{M^2_{miss}=(P_K-P_l)^2}$

P_K : average measured with $K_{3\pi}$ decays

→ Sufficient $K_{e2}/K_{\mu 2}$ separation at $p_{track}<25\mathrm{GeV}/c$

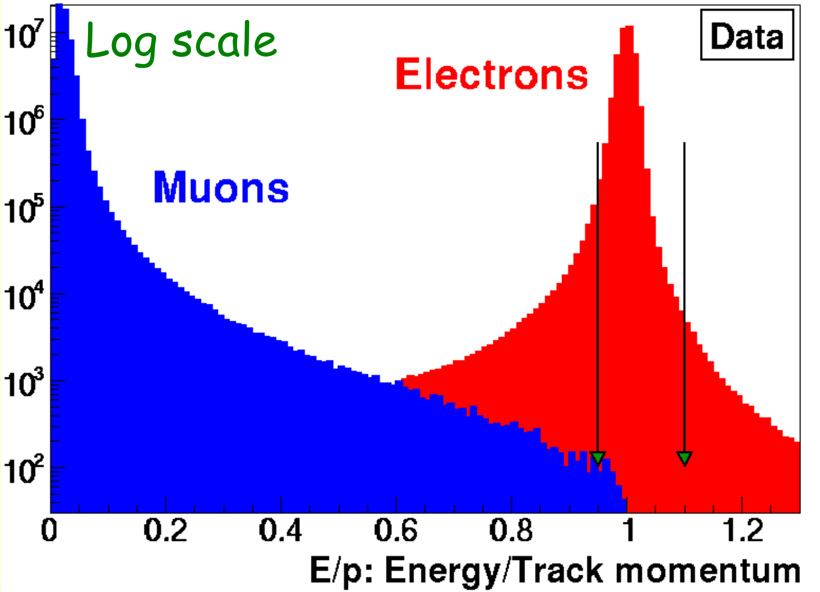
Lepton identification

E/p = (LKr energy deposit/track momentum).

(0.90 to 0.95)<E/p<1.10 for electrons,

E/p<0.85 for muons.

→ Powerful $\mu^\pm$ suppression in $e^\pm$ sample ($\sim 10^6$)

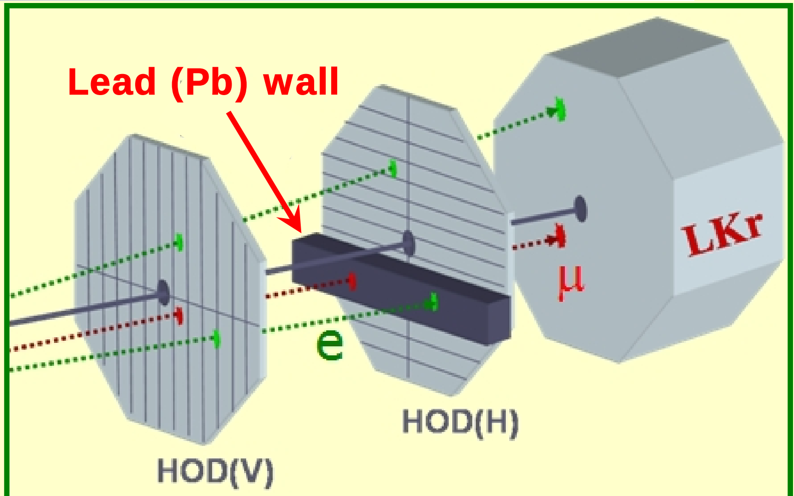


NA62: $K_{\mu 2}$ background

Main background source

Muon "catastrophic" energy loss in LKr by emission of energetic bremsstrahlung photons. $P_{\mu e} \sim 3\times10^{-6}$ (and momentum-dependent).

$P_{\mu e} / R_K \sim 10\%$:
$K_{\mu 2}$ decays represent a major background



Thickness:	~$10X_0$ (Pb+Fe)
Width:	240cm (=HOD size)
Height:	18cm (=3 counters)
Area:	~20% of HOD area
Duration:	~50% of R_K runs + special muon runs

Direct measurement of $P_{\mu e}$

Pb wall ($9.2X_0$) in front of LKr: suppression of $\sim10^{-4}$ positron contamination due to $\mu\to e$ decay.

$K_{\mu 2}$ candidates, track traversing Pb, $p>30$GeV/c, $E/p>0.95$: positron contamination $<10^{-8}$.

$P_{\mu e}$ is modified by the Pb wall:
→ ionization losses in Pb (low p);
→ bremsstrahlung in Pb (high p).

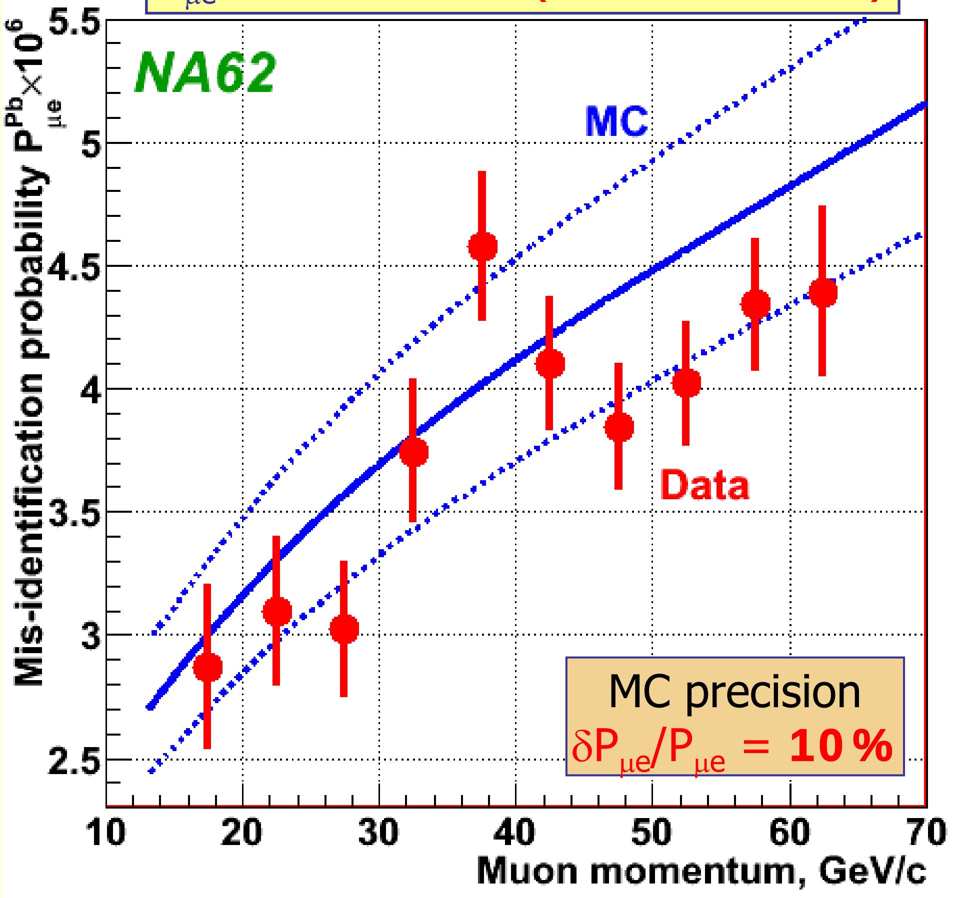
⇒

The correction $f_{Pb}=P_{\mu e}/P_{\mu e}^{Pb}$ is evaluated with a dedicated simulation

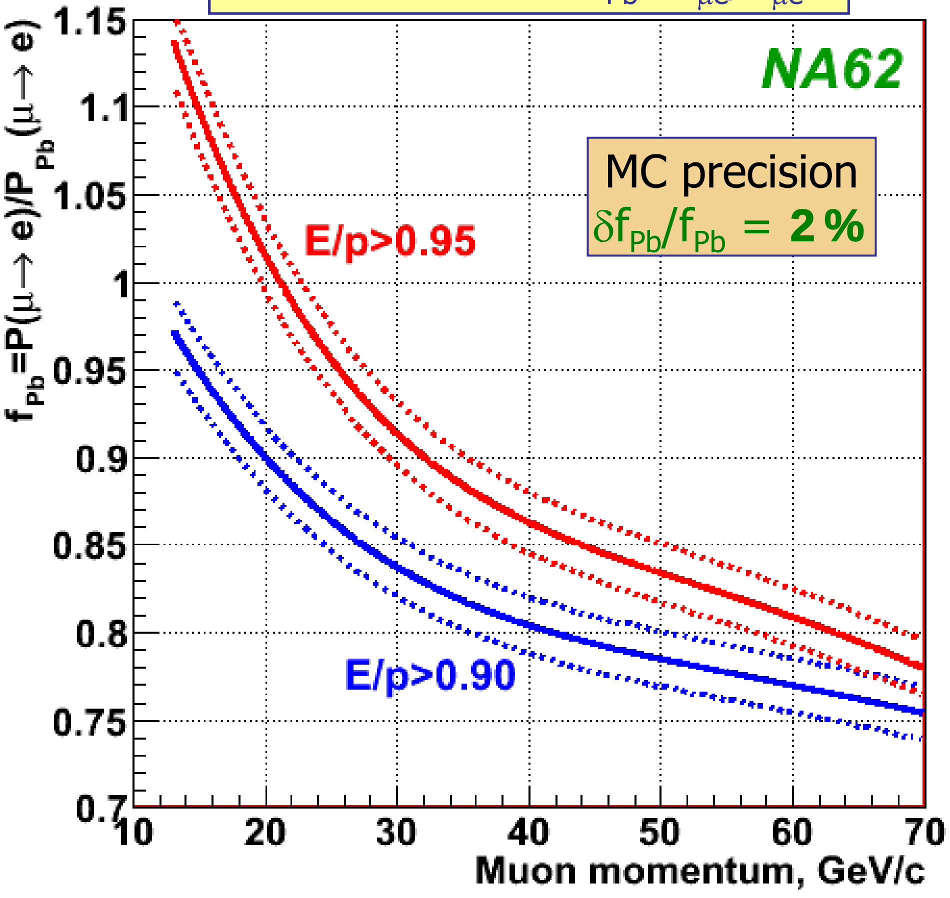
[Muon bremsttranlung:
Phys. Atom. Nucl. 60 (1997) 576]

NA62: muon mis-identification

$P_{\mu e}$ vs momentum (Pb wall installed)



Correction for Pb: $f_{Pb}=P_{\mu e}/P_{\mu e}^{Pb}$



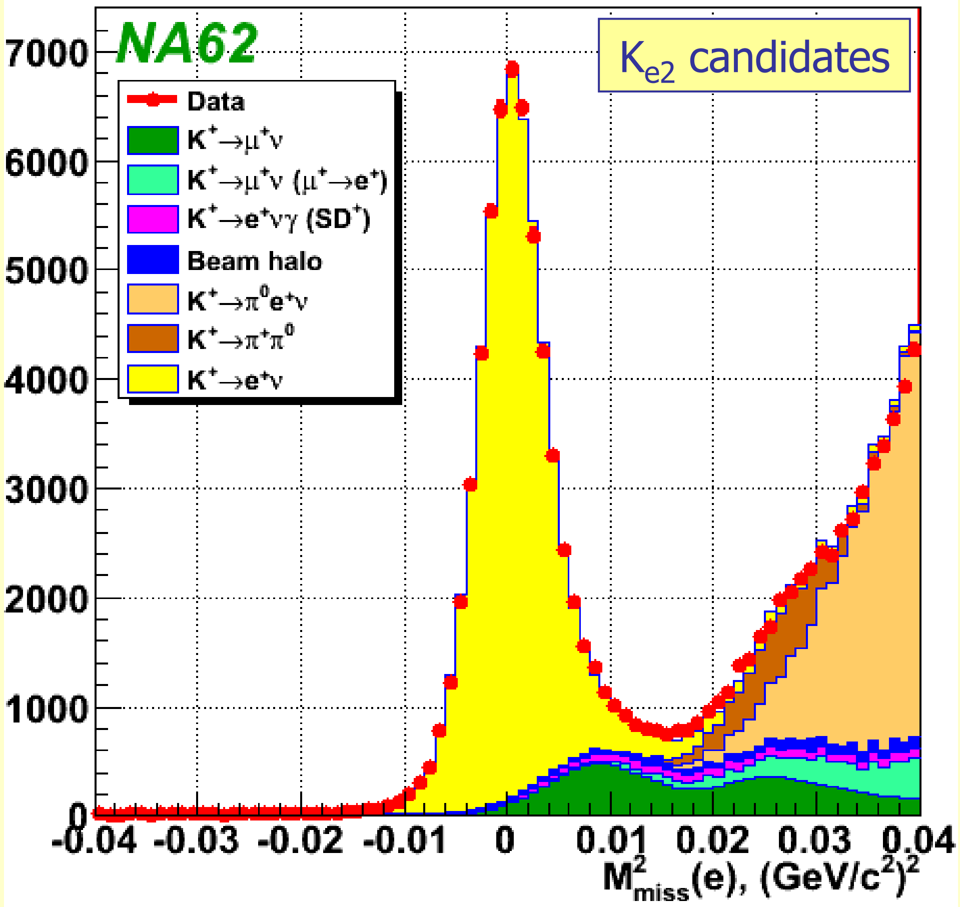
Result: B/(S+B) = (6.10±0.22)%

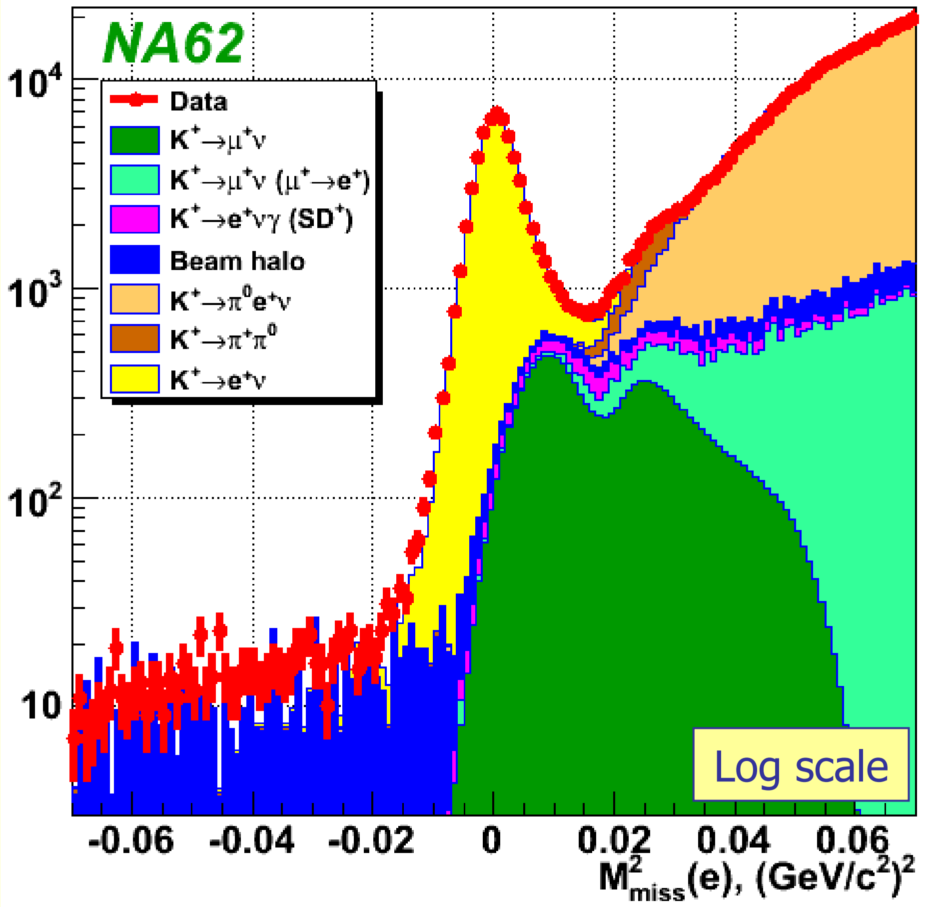
Uncertainty is ~3 times smaller than the one obtained solely from simulation

Uncertainties

Limited data sample (0.16%);
MC correction (0.12%);
M^2_{miss} vs P_{track} correlation (0.08%).

NA62: 40% data set





59,963 $K^+\to e^+\nu$ candidates.
Positron ID efficiency: (99.27±0.05)%.
B/(S+B) = (8.8±0.3)%.

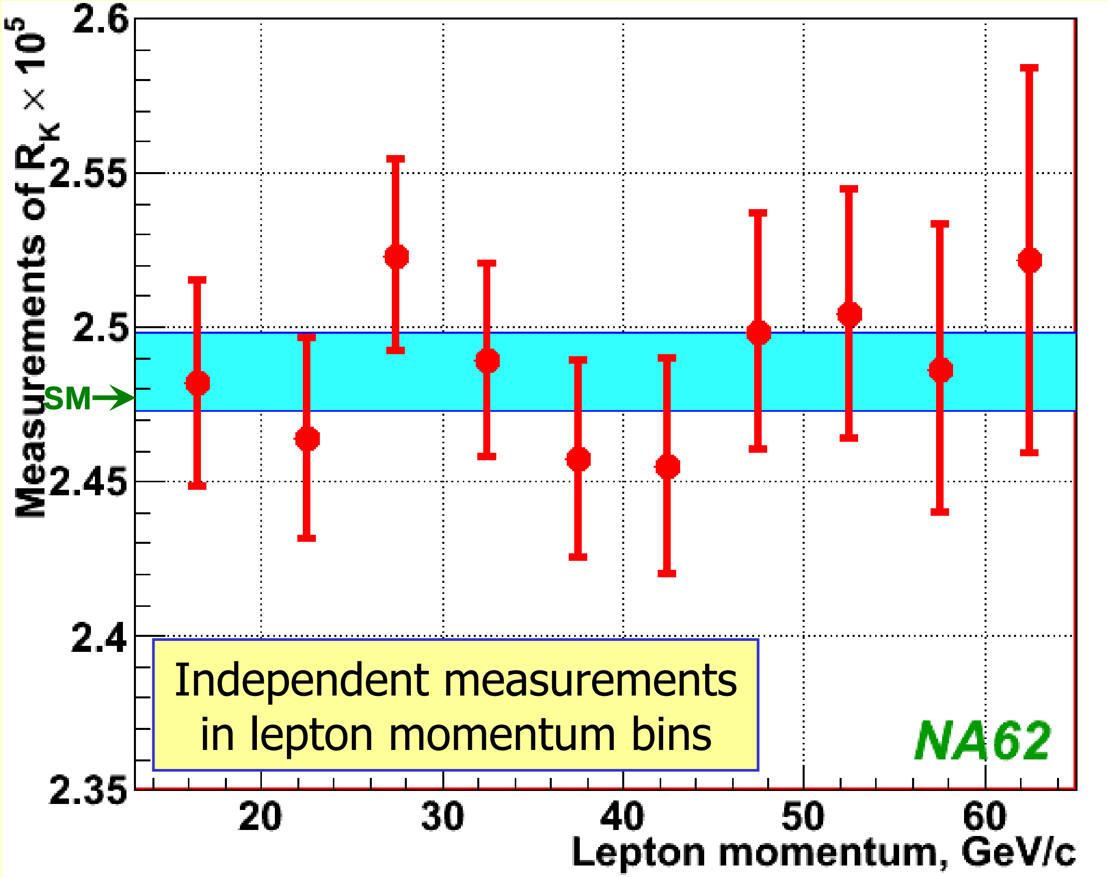
cf. KLOE: 13.8K candidates (K^+ and K^-),
~90% electron ID efficiency, 16% background

NA62 estimated total K_{e2} sample:
~130K K^+ & ~20K K^- candidates.
Proposal (CERN-SPSC-2006-033):
150K candidates

NA62 final result (40% data set)

(new: June 2010)

$$R_K = (2.486 \pm 0.011_{stat} \pm 0.007_{syst}) \times 10^{-5}$$
$$= (2.486 \pm 0.013) \times 10^{-5}$$



(systematic errors included, partially correlated)

Backgrounds

Source	B/(S+B)
$K_{\mu 2}$	(6.10±0.22)%
$K_{\mu 2}$ ($\mu \to e$)	(0.27±0.04)%
$K_{e2\gamma}$ (SD$^+$)	(1.15±0.17)%
Beam halo	(1.14±0.06)%
$K_{e3(D)}$	(0.06±0.01)%
$K_{2\pi(D)}$	(0.06±0.01)%
Total	(8.78±0.29)%

Uncertainties

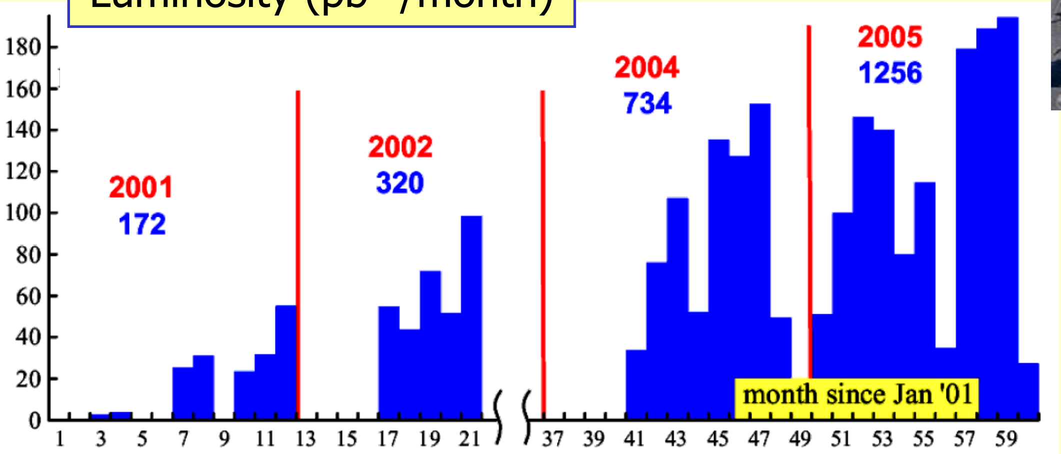
Source	$\delta R_K \times 10^5$
Statistical	0.011
$K_{\mu 2}$	0.005
BR($K_{e2\gamma}$ SD$^+$)	0.004
Beam halo	0.001
Acceptance corr.	0.002
DCH alignment	0.001
Positron ID	0.001
1-track trigger	0.002
Total	0.013

KLOE: ~110 MeV/c kaons

DAΦNE: e^+e^- collider at LNF Frascati

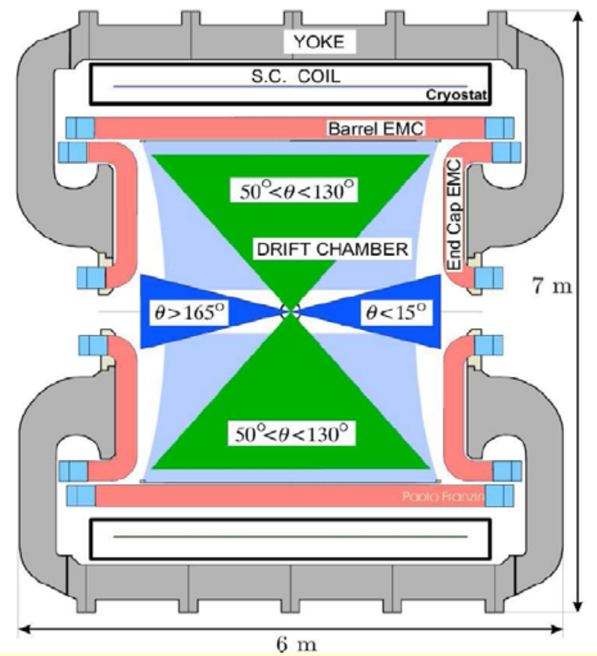
- CM energy ~ m_ϕ = 1.02 GeV;
- BR($\phi \to K^+K^-$) = 49.2%;
- ϕ production cross-section σ_ϕ=1.3μb;
- Residual momentum: p_ϕ~13MeV/c;
- Data sample (2001–05): 2.5 fb^{-1}.

Luminosity (pb^{-1}/month)



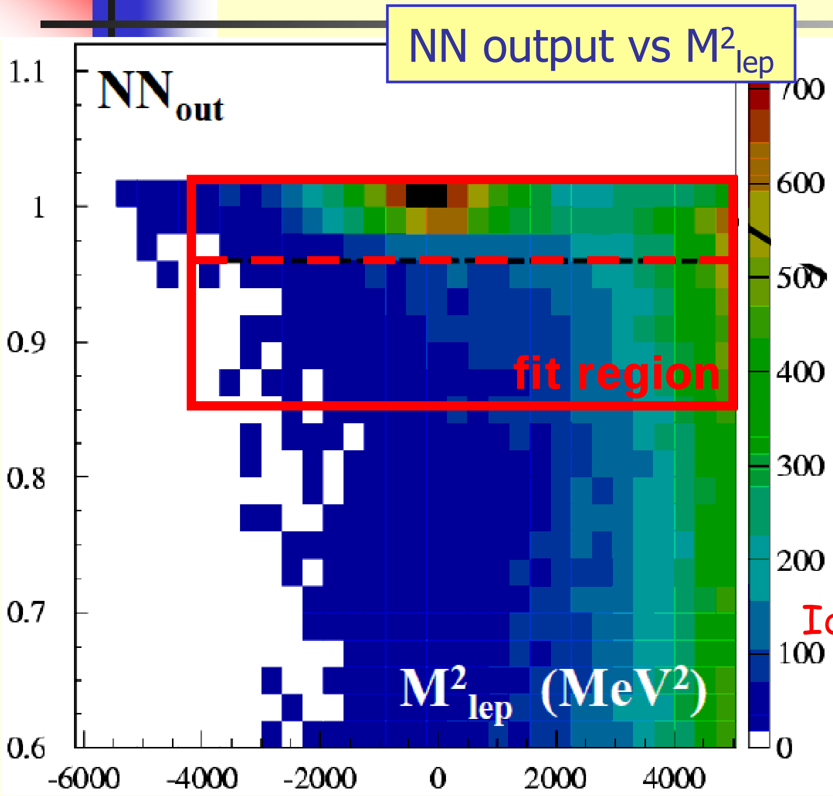
$K_{e2}/K_{\mu2}$ selection technique (vs NA62):

- Kinematics: by M^2_{lep} (equivalent to M_{miss}^2);
- PID: neural network with 12 input parameters (vs E/p for NA62).

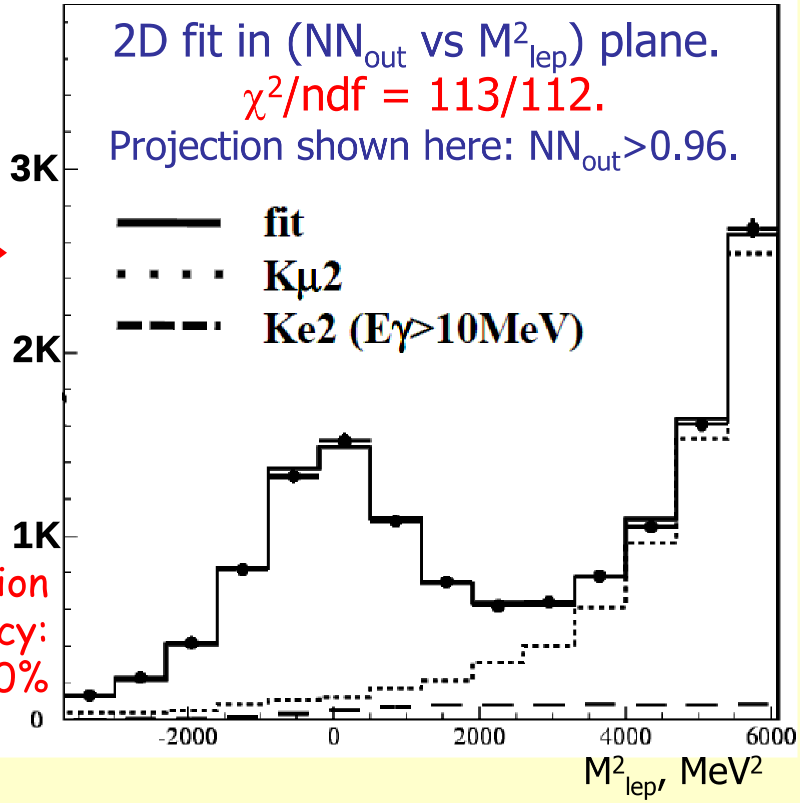


KLOE K_{e2} measurement

NN output vs M^2_{lep}



Identification efficiency: ~90%


2D fit in (NN_{out} vs M^2_{lep}) plane.
$\chi^2/ndf = 113/112$.
Projection shown here: $NN_{out}>0.96$.

Uncertainties	$\delta R_K/R_K$ (%)
Statistical	1.0
$K_{\mu2}$ subtraction	0.3
$K_{e2\gamma}$ (SD$^+$)	0.2
Reconstruction efficiency	0.6
Trigger efficiency	0.4
Total	1.3

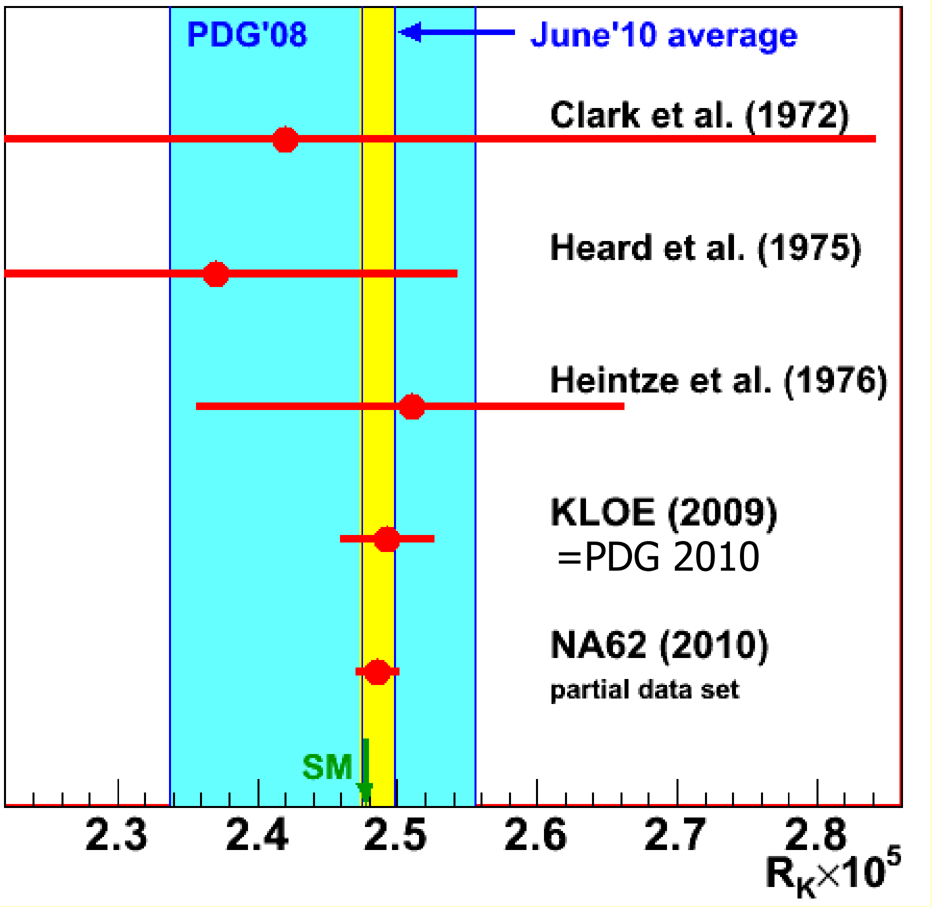
Final result [EPJ *C64* (2009) 627]

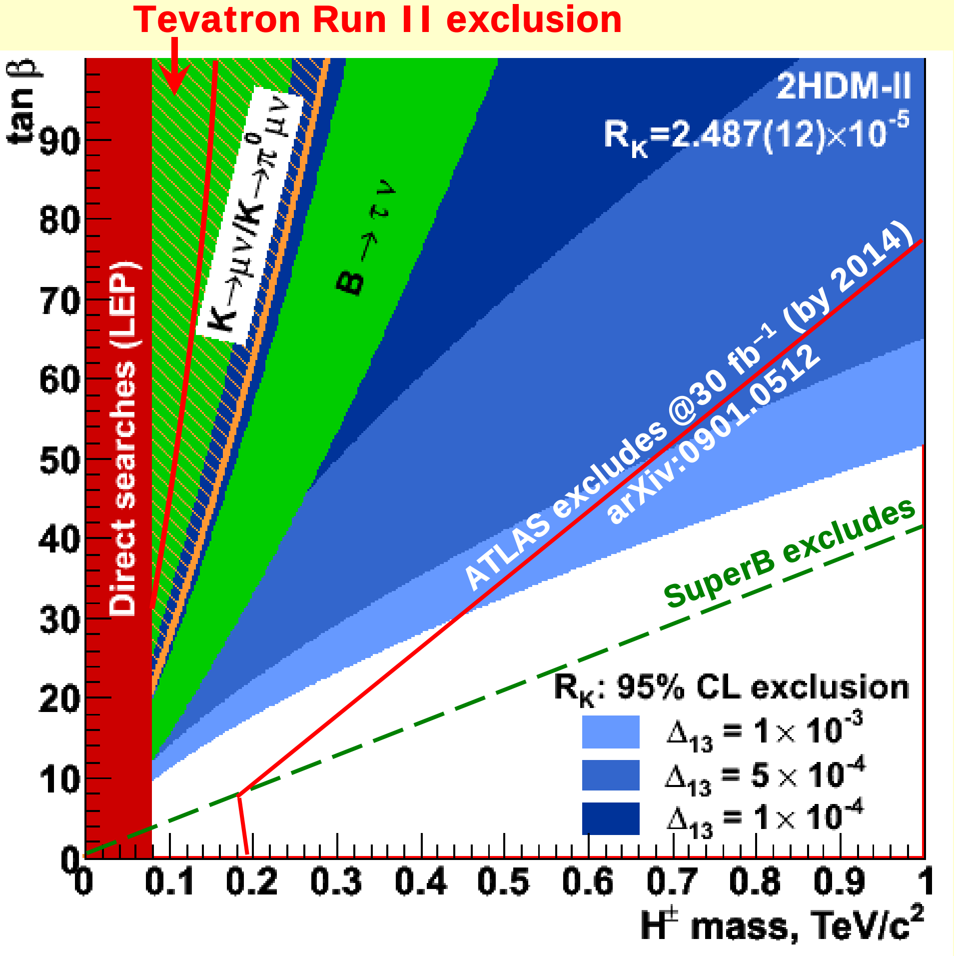
13.8K K_{e2} candidates, 16% background

$$R_K = (2.493 \pm 0.025_{stat} \pm 0.019_{syst}) \times 10^{-5}$$
$$= (2.493 \pm 0.031) \times 10^{-5}$$

KLOE-2: starting in 2010, expect $\delta R_K/R_K$=0.4%.
[arXiv:1003.3862]

R_K: world average





World average	$\delta R_K\times10^5$	Precision
March 2009	2.467±0.024	0.97%
June 2010	2.487±0.012	0.48%

For non-tiny values of the LFV slepton mixing Δ_{13}, sensitivity to $H^{\pm}$ in $R_K=K_{e2}/K_{\mu2}$ is better than in $B\to\tau\nu$

Ultra-rare kaon decays ($K\rightarrow\pi\nu\nu$)

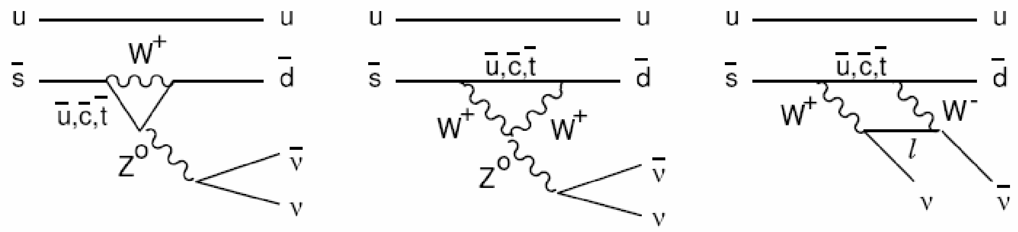
$K_{\pi\nu\nu}$: motivation

K→πνν: theoretically clean, sensitive to NP, almost unexplored

SM branching ratio $\times 10^{10}$

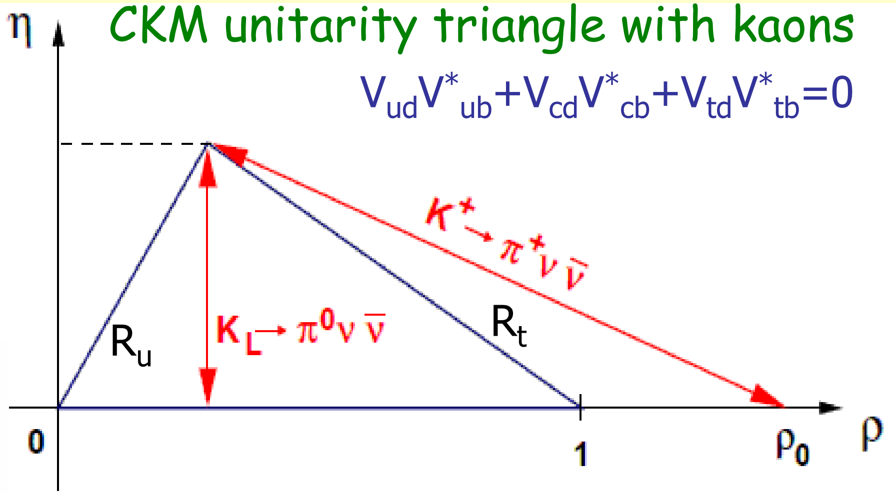
(FlaviaNet Kaon WG)

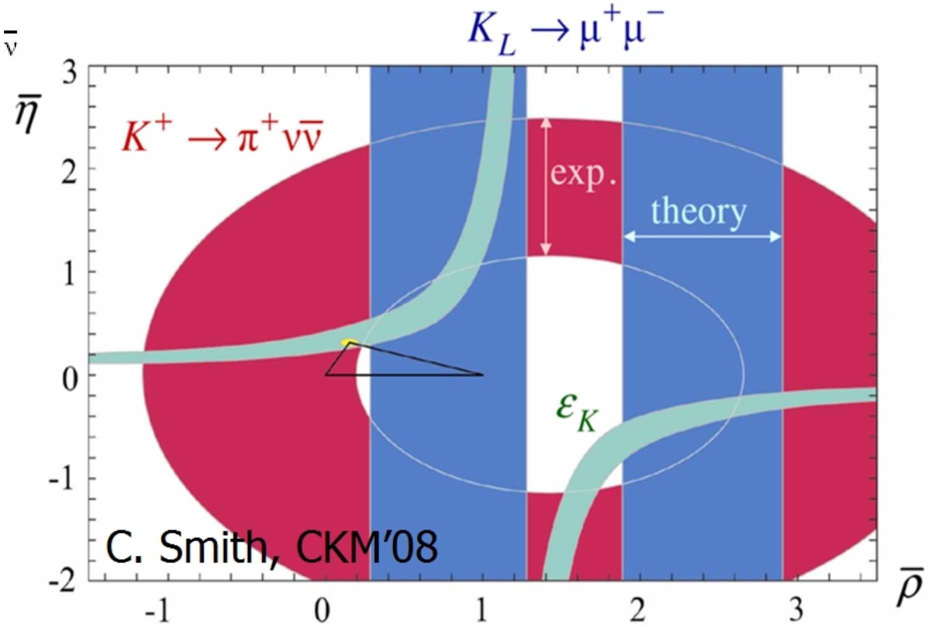
Mode	BR(SM)
$K^+ \to \pi^+ \nu\nu(\gamma)$	0.822 ± 0.084
$K_L \to \pi^0 \nu\nu$	0.276 ± 0.040



CKM unitarity triangle with kaons

$V_{ud}V^*_{ub}+V_{cd}V^*_{cb}+V_{td}V^*_{tb}=0$





C. Smith, CKM'08

- Ultra-rare FCNC processes, proceed via Z-penguin and W-box diagrams.
- Hadronic matrix element extracted from precise K→πeν measurements.
- Exceptional SM precision not matched by any other loop-induced meson decay.
- Main SM uncertainty: CKM parametric.

BNL E787/E949: $K^+ \to \pi^+ \nu\nu$

Technique: K^+ decay at rest.

Data taking: E787(1995–98), E949(2002).

Spill: 65×10^{12}pot × (2.2s/5.4s).

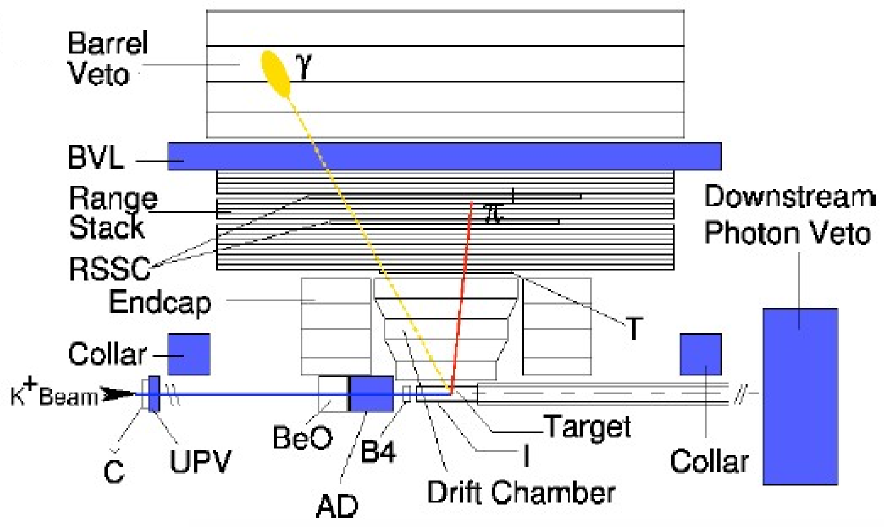
PID: range (entire $\pi/\mu/e$ decay chain).

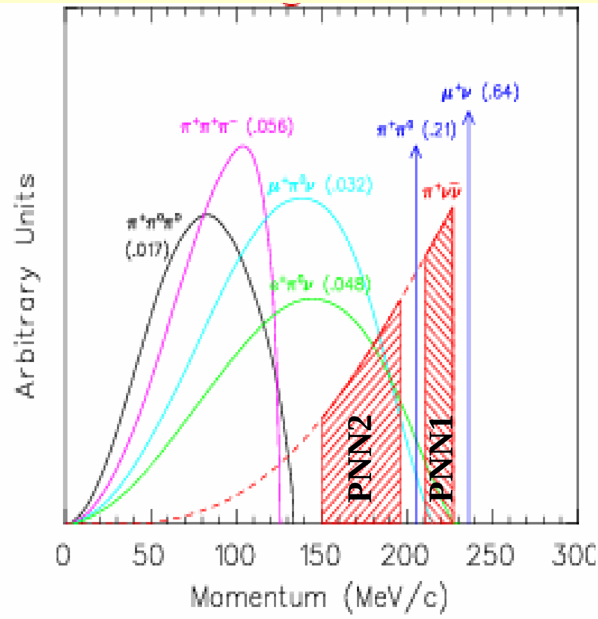
Observed events:	7
Expected background:	2.6
Final result:	$BR = (1.73 {}^{+1.15}_{-1.05}) \times 10^{-10}$

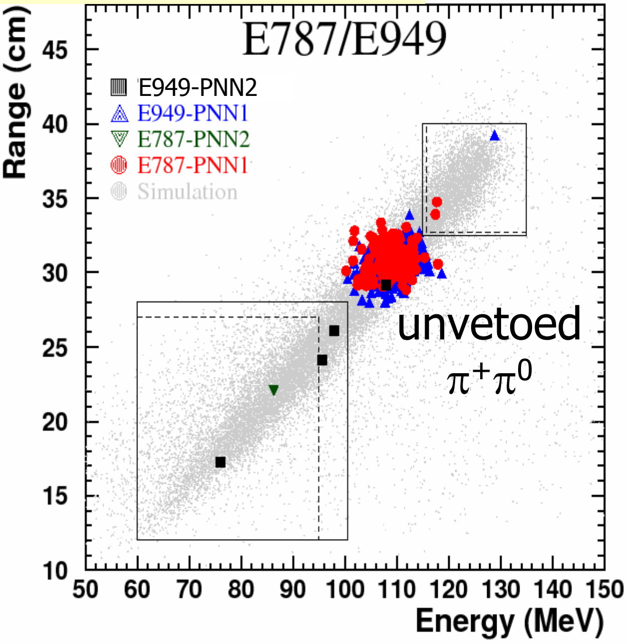
PRL 101 (2008) 191802, PRD 79 (2009) 092004

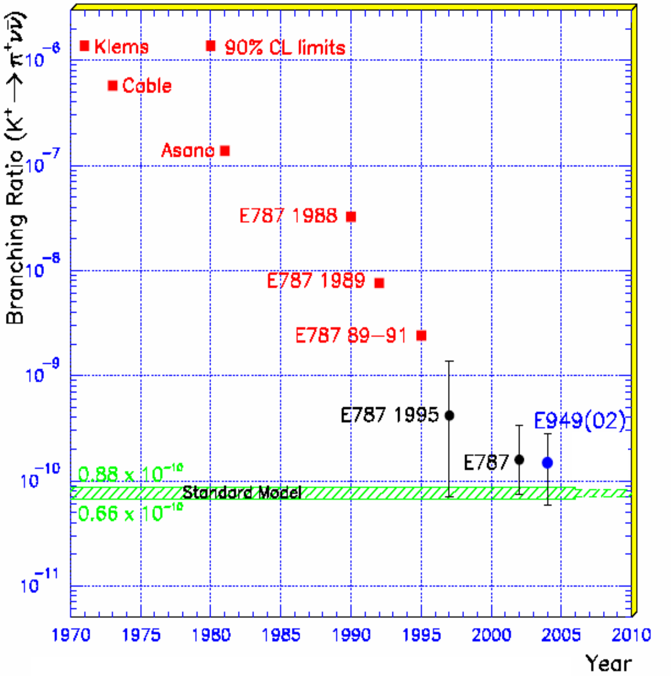
Future: ~10^3 SM events with stopped kaons @FNAL? (D.Bryman, Kaon'09)

Barrel detector: 1T solenoid field

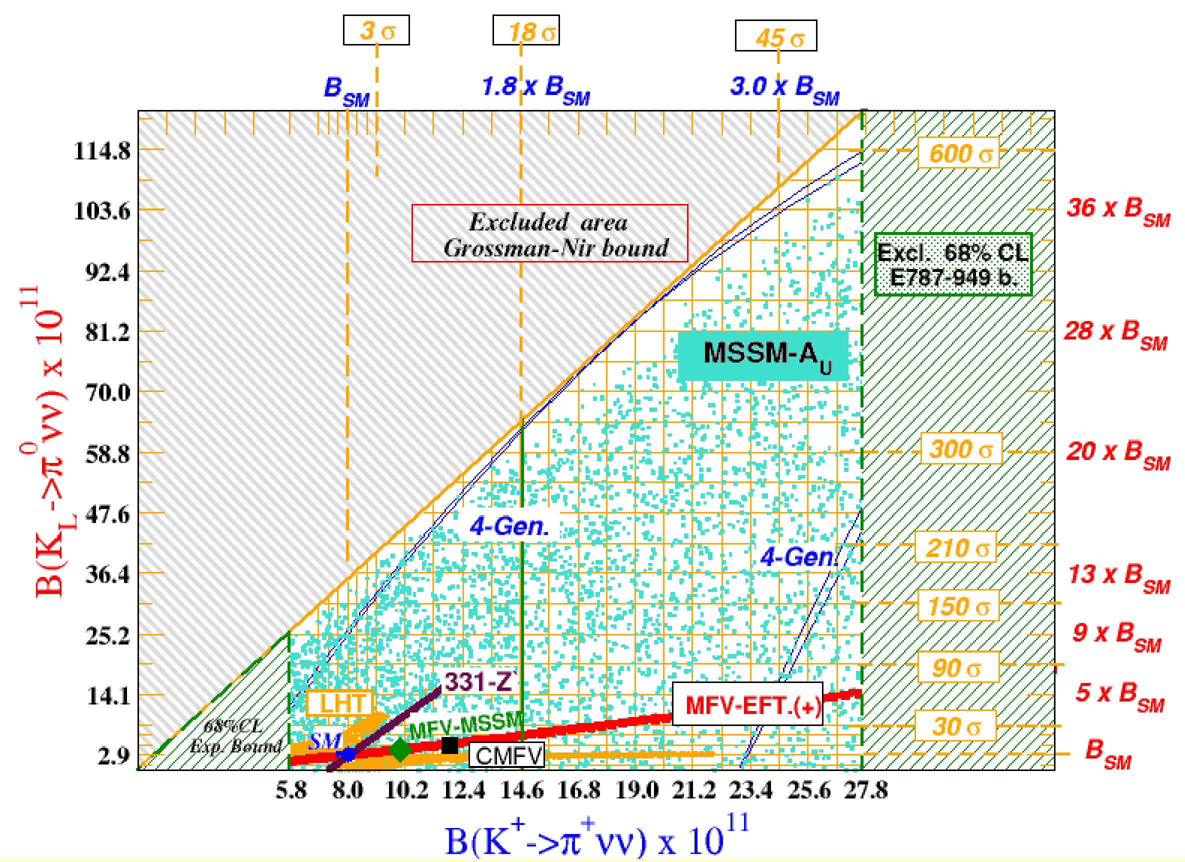








$K_{\pi\nu\nu}$: situation after E949



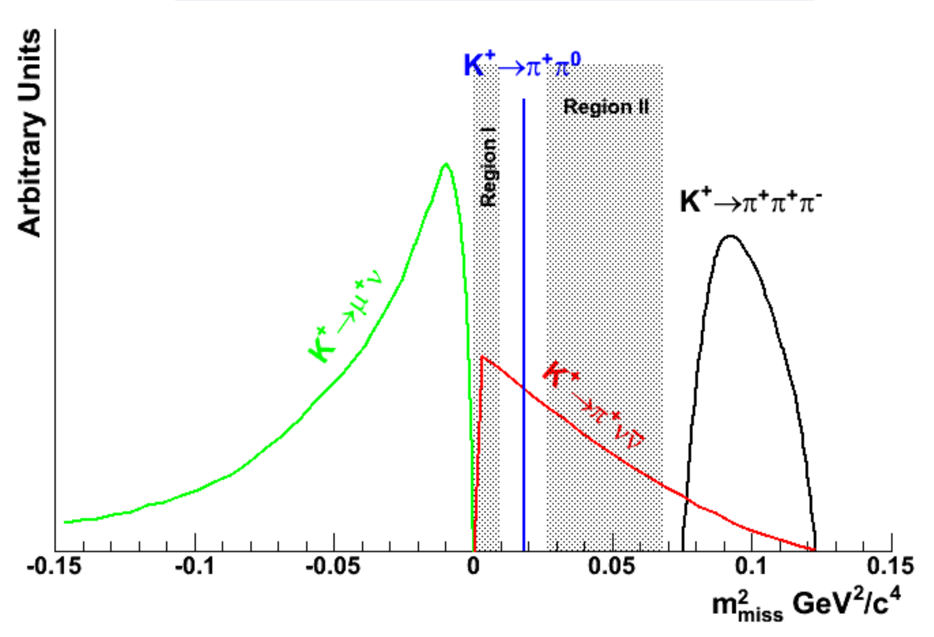
$BR(K^+ \to \pi^+ \nu\nu) \times 10^{10}$: selected models	
SM	0.82 ± 0.08
MFV (hep-ph/0310208)	1.91
EEWP (NPB697 (2004) 133, hep-ph/0402112)	0.75 ± 0.21
EDSQ (PRD70 (2004) 093003, hep-ph/0407021)	up to 1.5
MSSM (NPB713 (2005) 103, hep-ph/0408142)	up to 4.0

- Large variations in predictions for new physics.
- A 10% precision measurement will provide a stringent SM test.

The NA62 collaboration at CERN aims to measure O(100) $K^+ \to \pi^+ \nu\nu$ candidates with ~10% background in 2-3 years of data taking

CERN NA62: signal region

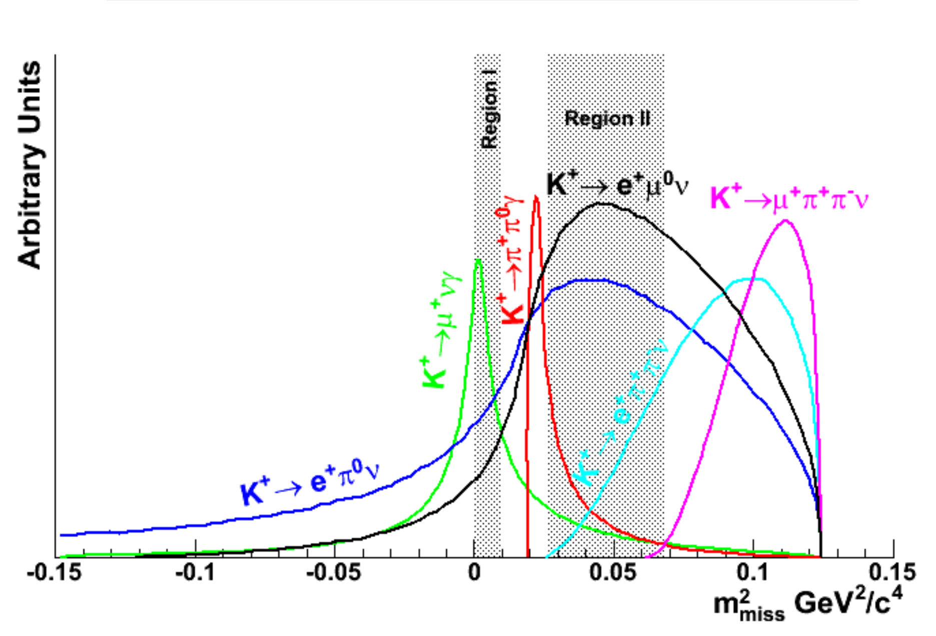
Kinematically constrained



92% of total background

- **Definition of the signal region**
- **$K^+ \to \pi^+\pi^0$ forces us to split it into two parts (Region I and Region II)**

NOT kinematically constrained



8% of total background

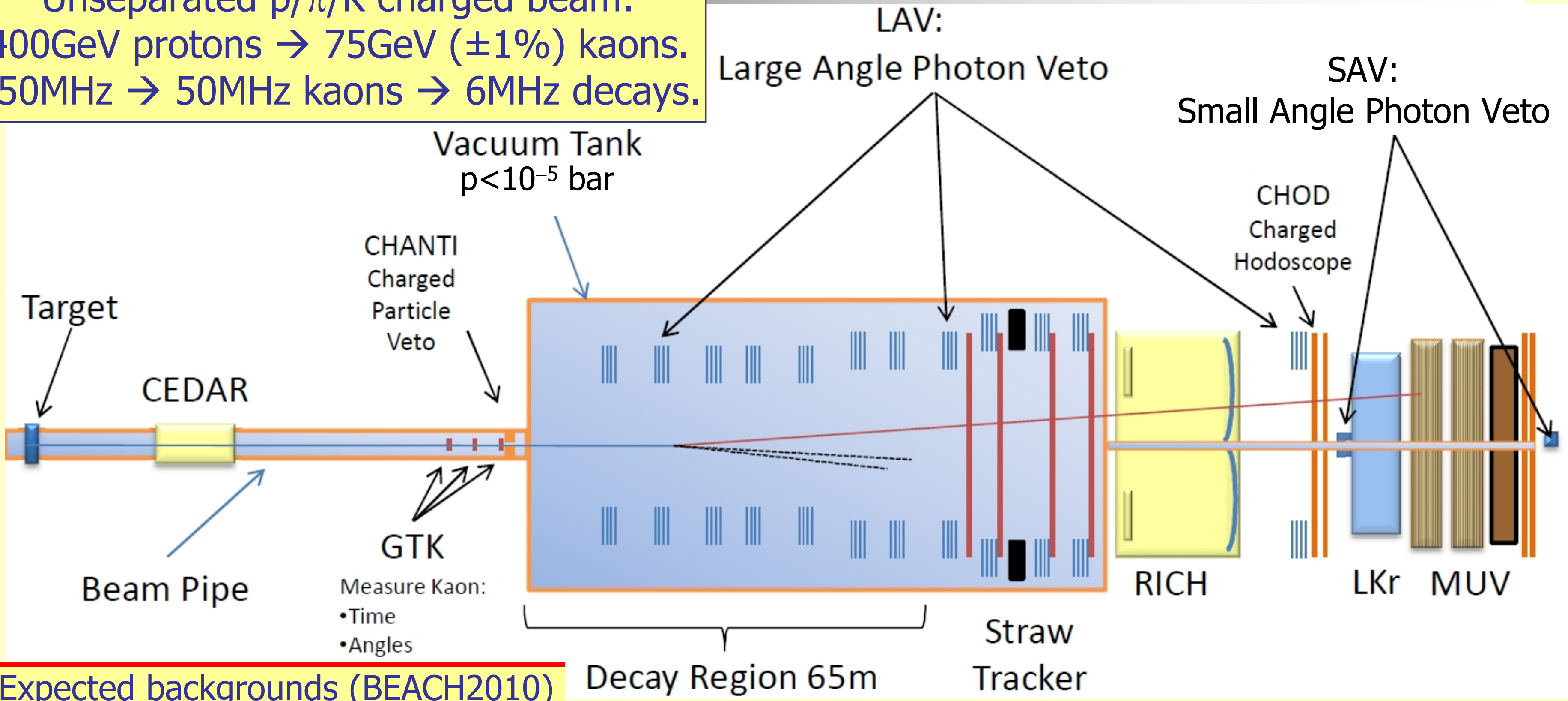
- **Span across the signal region**
- **Rejection relies on vetoes/PID**

Kinematic rejection power: 10^4 ($K^+ \to \pi^+\pi^0$), 10^5 ($K^+ \to \mu^+\nu$)

Sources of inefficiency: non-Gaussian MS tails; K/π mismatch.

CERN NA62: sensitivity

Unseparated p/π/K charged beam:
400GeV protons → 75GeV (±1%) kaons.
750MHz → 50MHz kaons → 6MHz decays.

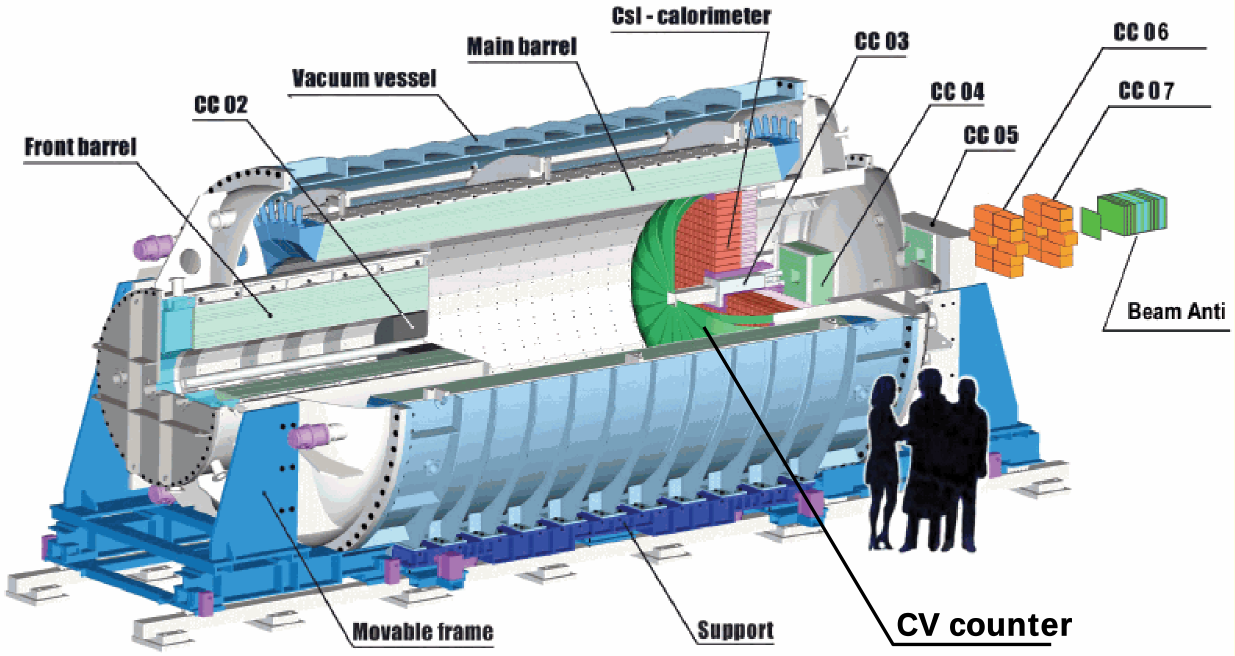


Expected backgrounds (BEACH2010)

Signal	45 evt/year
$K^+\to\pi^+\pi^0$	4.3%
$K^+\to\mu^+\nu$	2.2%
$K^+\to$ 3 charged tracks	<4.5%
$K^+\to\pi^+\pi^0\gamma$	~2%
$K^+\to\mu^+\nu\gamma$	~0.7%
Total background	<13.5%

- 4.8×10^{12} K^+ decays/year → record SES of $\sim10^{-12}$;
- Hermetic veto & redundant kinematics measurements;
- R&D finishing, detector construction has started;
- Physics runs are to start in 2013.

KEK E391a: $K_L\to\pi^0\nu\nu$



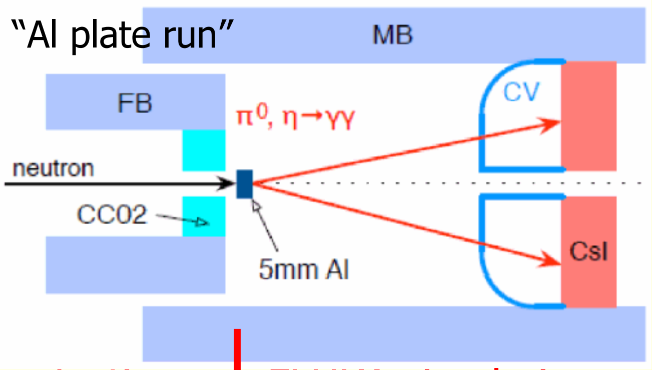
Good physics runs (Runs2,3):
Feb-Dec 2005

Pencil K_L beam, 2.5×10^{18} PoT.

Calorimeter:

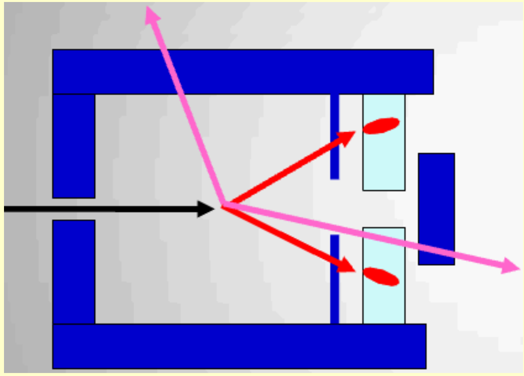
496 $(7\times7\times30)\text{cm}^3$ CsI crystals

Veto: Pb+scintillator+WLS fibers

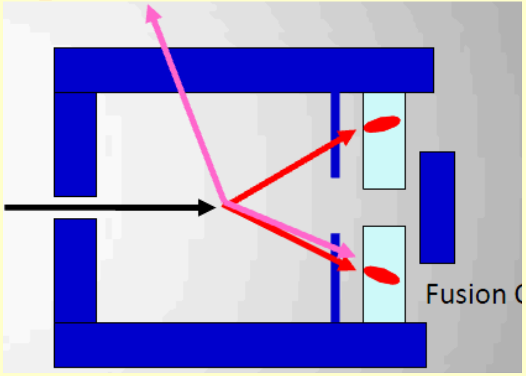


Principal backgrounds:

$K_L\to\pi^0\pi^0$ (2 lost photons)

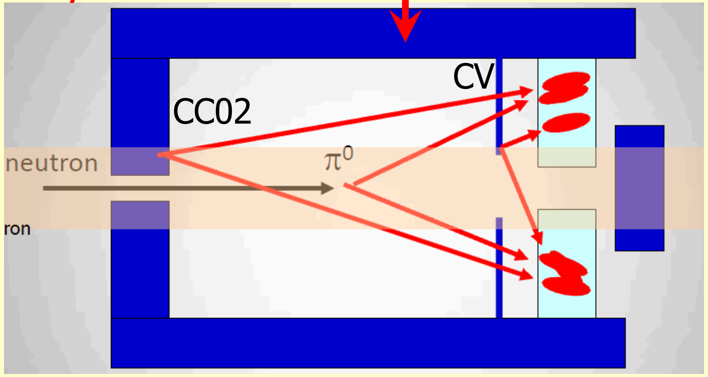


$K_L\to\pi^0\pi^0$ (merged clusters)



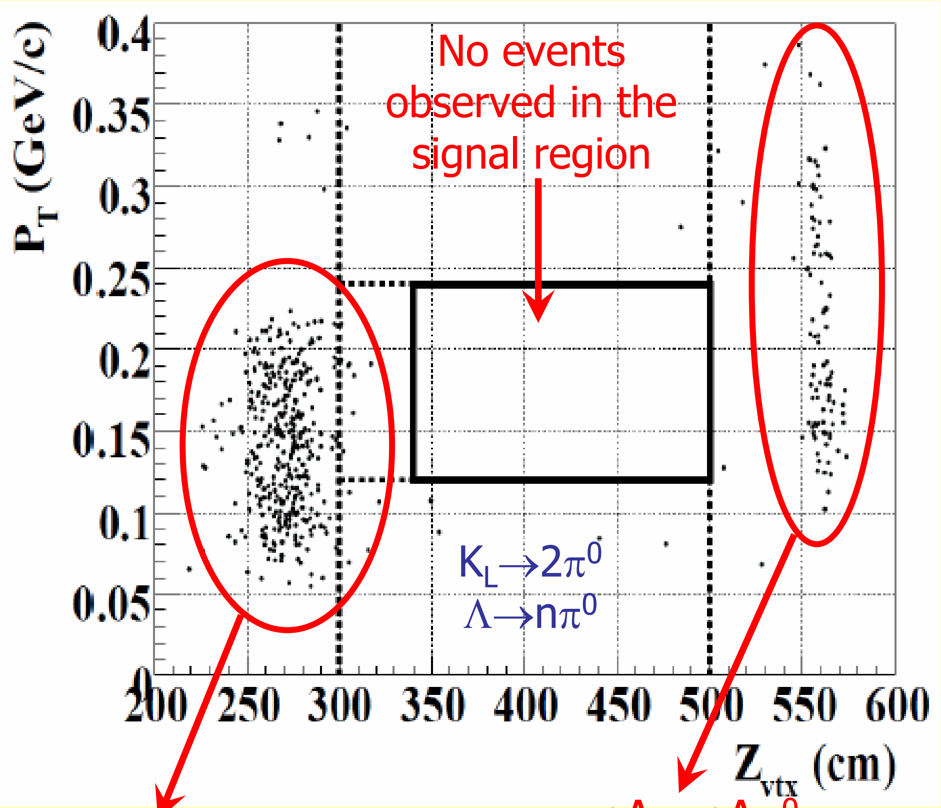
π^0/η production by halo neutrons

FLUKA simulation validated with data



KEK E391a: final result

Signature: a high-p_T π^0 + nothing
Blind analysis technique employed.

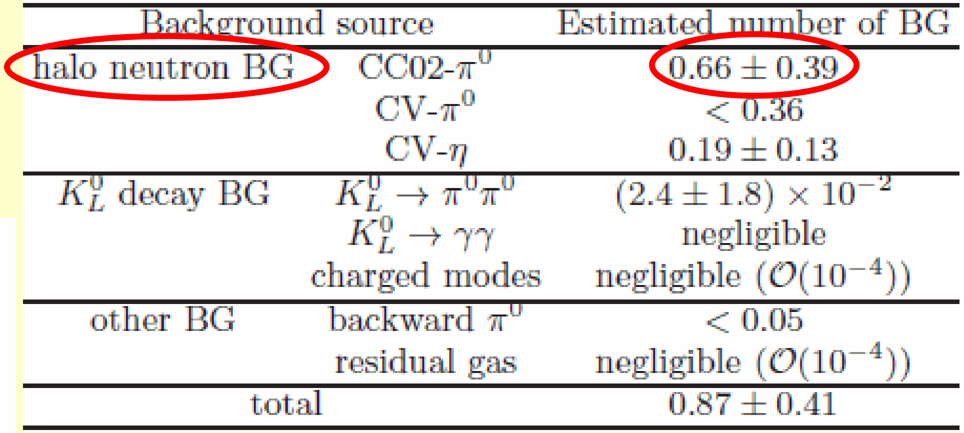


No events observed in the signal region

$K_L \to 2\pi^0$
$\Lambda \to n\pi^0$

$nA \to nA\pi^0$ at CC02

$nA \to nA\pi^0$, $nA \to nA\eta$ at CV



Background source		Estimated number of BG
halo neutron BG	CC02-π^0	0.66 ± 0.39
	CV-π^0	< 0.36
	CV-η	0.19 ± 0.13
K_L^0 decay BG	$K_L^0 \to \pi^0\pi^0$	$(2.4 \pm 1.8) \times 10^{-2}$
	$K_L^0 \to \gamma\gamma$	negligible
	charged modes	negligible ($\mathcal{O}(10^{-4})$)
other BG	backward π^0	< 0.05
	residual gas	negligible ($\mathcal{O}(10^{-4})$)
total		0.87 ± 0.41

Background is dominated by beam interactions

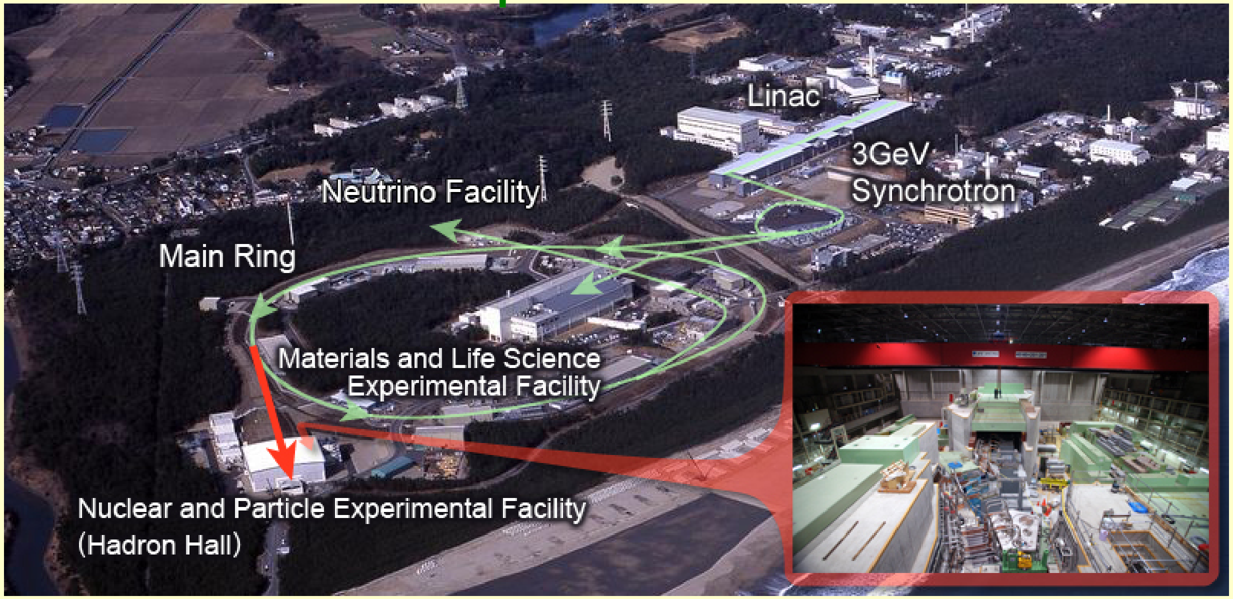
Number of K_L decays:
$N=(8.70\pm0.17_{stat}\pm0.59_{syst})\times10^9$
Signal acceptance: ~1%
SES: $(1.11\pm0.02_{stat}\pm0.10_{syst})\times10^{-8}$

Final result:
$BR(K_L\to\pi^0\nu\nu)<2.6\times10^{-8}$ @90% CL
PRD81 (2010) 072004

Order of magnitude above the GN limit; seen as preparation for JPARC E14

Next step: JPARC E14 (K^{O}TO)

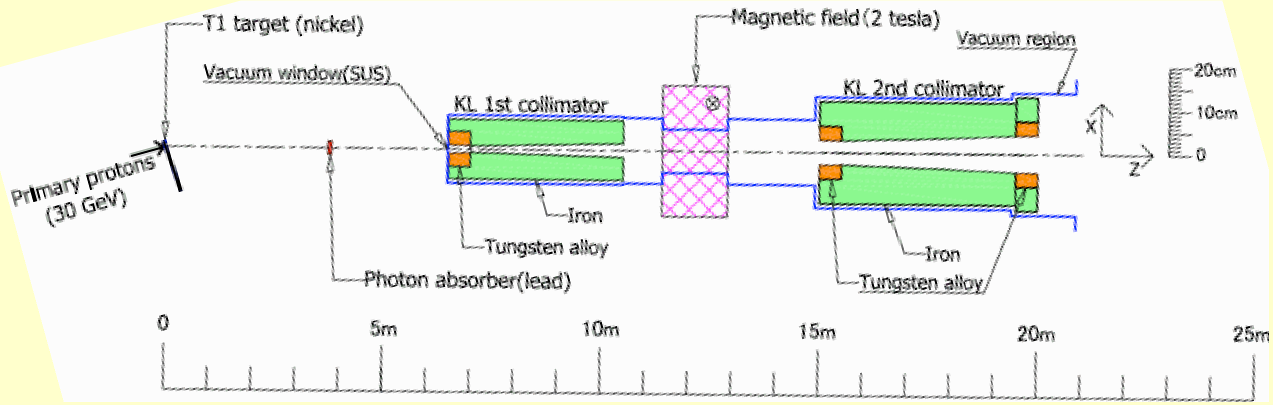
J-PARC accelerator complex

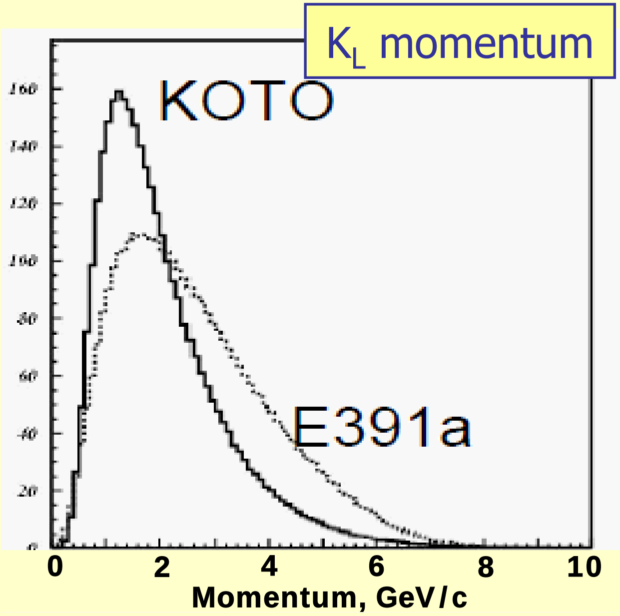


- Proton energy: 30 GeV
- Intensity: 2×10^{14} PoT/spill
- Spill duration: 0.7s/3.3s
- Solid angle: 9μStr
- K_L/spill: 7.8×10^{6}
- Decay probability: 4%

Physics runs planned: 2011-2013
(12 months in total)

K_L beam: suppression of halo neutrons to ~$10^{-3}/K_L$.
Flux * RunTime * Acc = 3000×E391a (=discovery of SM decay).

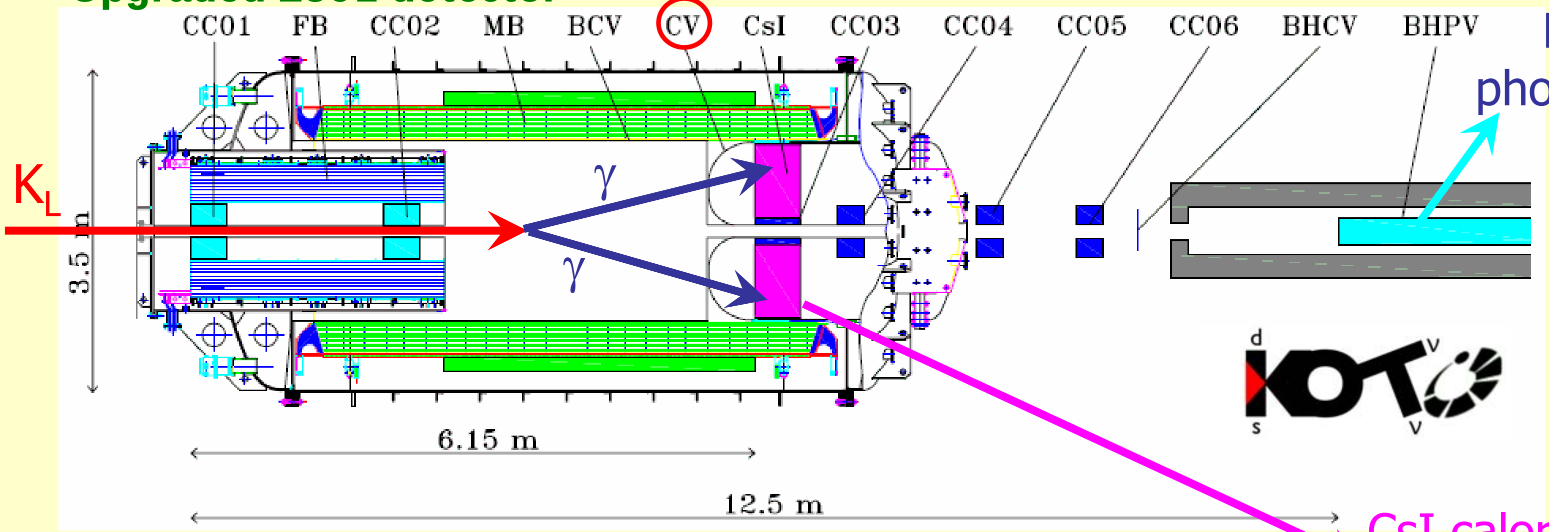




JPARC E14 (K^{O}TO): sensitivity

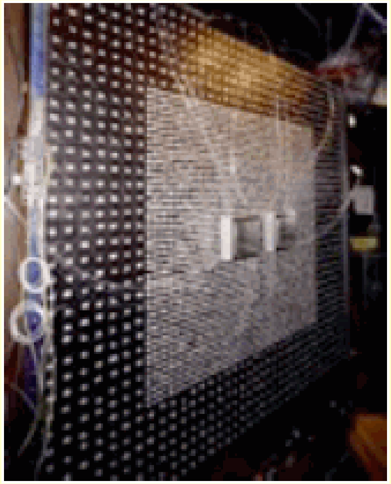
Upgraded E391 detector

Charged track veto counters



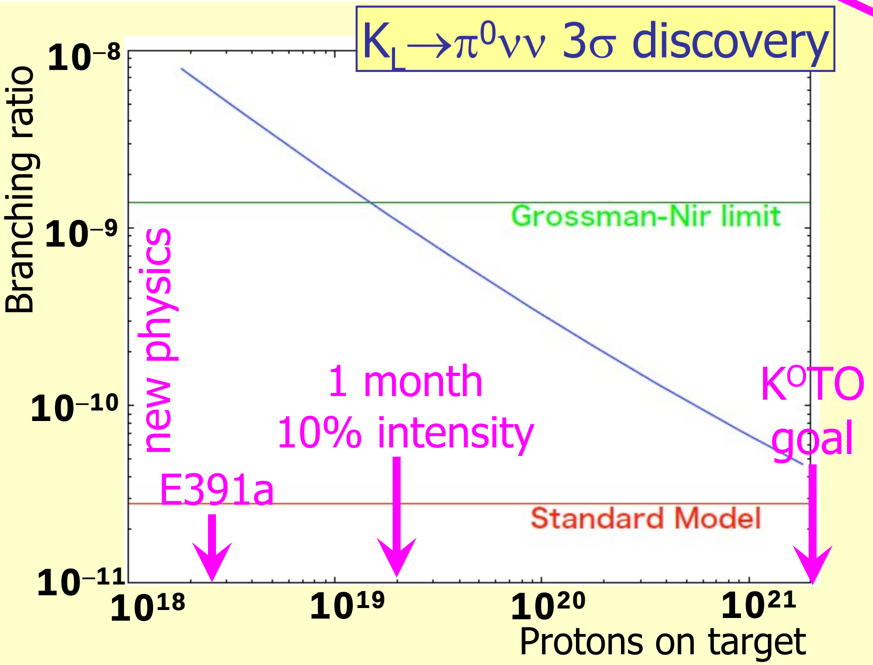
Beam photon veto

CsI calorimeter (KTeV crystals)



Signal & background (3 years) PoS(KAON09)047	
Signal	2.7
$K_L \to \pi^0\pi^0$	1.7
Halo neutron: CC02	0.01
Halo neutron: CV-π^0	0.08
Halo neutron: CV-η	0.3
Total background	2.1

Possible K^{O}TO upgrade aims at collecting ~100 SM events



Summary

- Tremendous progress in measurements and interpretation of semileptonic kaon decays: $|V_{us}|f_+(0)$ measured to 0.23% precision, $|V_{us}|$ extracted with 0.4% precision.

- CKM unitarity with $|V_{ud}|^2+|V_{us}|^2$ tested at 0.06% precision:
  → O(10 TeV) lower bound on the scale of new physics.

- Precision measurements of leptonic decays $K\to l\nu$ place non-trivial bounds on the 2HDM parameters.

- Most future K experiments aim at $K\to\pi\nu\nu$; still significant experimental improvements in both K_{l3} and K_{l2} are expected in the medium-term (KLOE, NA48/NA62).

Data interpretation (except $K_{e2}/K_{\mu2}$) is limited by lattice QCD input