Rare Kaon decays

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Flavour and the 4th Generation
Durham, UK • *14-16 September 2011*

Outline

$K \rightarrow \pi\nu\nu$

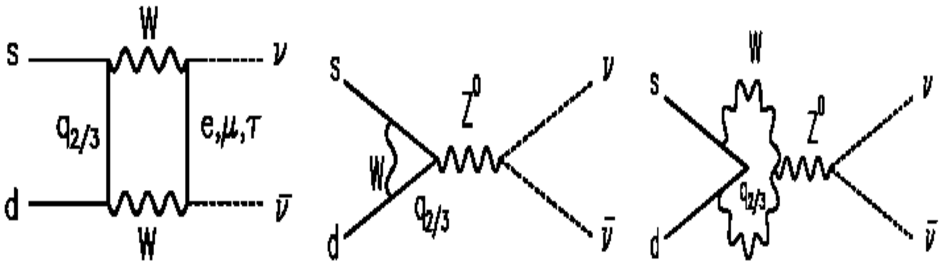
$R_K = K_{e2} / K\mu 2$

Search for ν_H

But no recent updates or
plans for $K_L \rightarrow \pi ll$

K→ πυυ : Standard Model

- **FCNC loop processes**
- **Short distance dynamics dominated**
- **One semileptonic operator**
- **Hadronic Matrix Element related to measured quantities in semileptonic K decay**



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

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \cdot \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

Charm contribution

$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) = \kappa_L \cdot \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

Top contribution

was the largest theoretical error now reduced by NNLO calc

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

The Hadronic Matrix Element is measured and isospin rotated

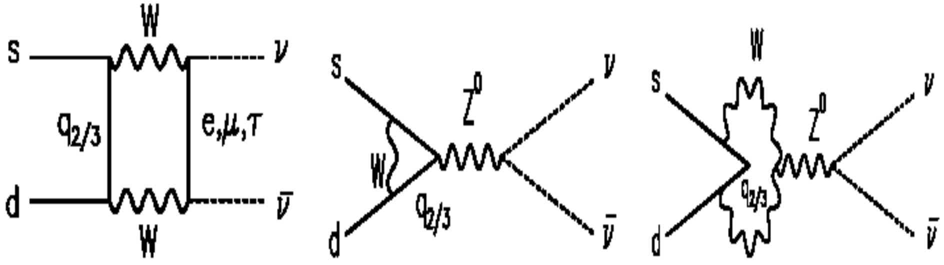
$K \to \pi \ell \ell$ decays

Quantitative tests of the SM

Tiny BRs can be

computed to very high

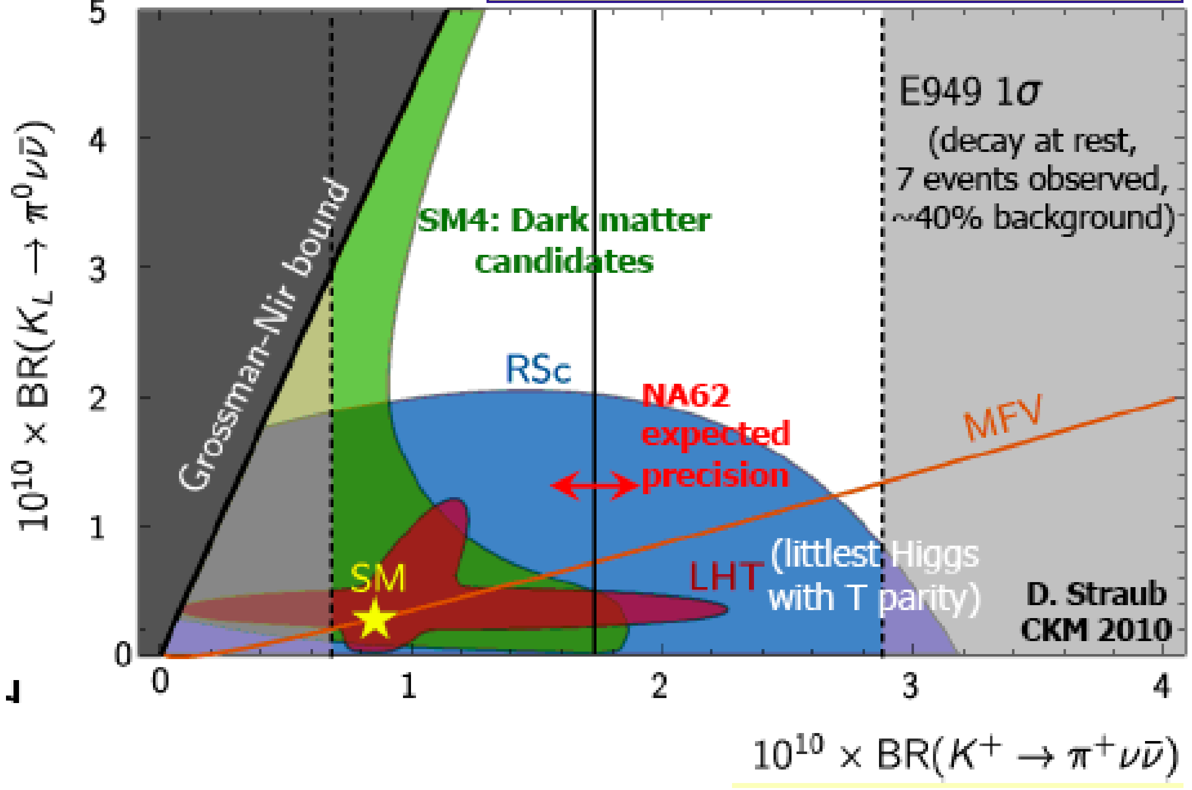
(few percent) precision



	SM prediction	Exp. Limit	Signal(Backg)
$K_L \to \pi^0 e^+ e^-$	$(3.54-1.56)\cdot 10^{-11}$ $(CPV_{dir}\ 3\cdot 10^{-12})$	$< 2.8 \cdot 10^{-10}$ (FNAL KTeV)	3 ev. (2.05 bkg)
$K_L \to \pi^0 \mu^+ \mu^-$	$(1.41-0.95)\cdot 10^{-11}$ $(CPV_{dir}\ 1\cdot 10^{-12})$	$< 3.8 \cdot 10^{-10}$ (FNAL KTeV)	2 ev. (0.87 bkg)
$K^+ \to \pi^+ \nu\nu$	$(8.5 \pm 0.7)\cdot 10^{-11}$	$1.73^{+1.15}_{-1.05} \cdot 10^{-10}$ (BNL E787+E949)	7 evt. (bkg. 1.38)
$K_L \to \pi^0 \nu\nu$	$(2.8 \pm 0.6)\cdot 10^{-11}$	$< 6.7 \cdot 10^{-8}$ (KEK E391a)	

K→πνν beyond SM

BR($K_L\to\pi\nu\nu$) vs BR($K^+\to\pi^+\nu\nu$)



(hep-ph/0906.5454, hep-ph/0812.3803,hep-ph/0604074)

SM4 : hep-ph/1002.2126

BR($K^+\to\pi^+\nu\nu$) ×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

Differences between SM4, RSc, LHT enhancements

SM4 predictions

Plots from:
Buras, Duling, Feldmann, Heidsieck, Promberger, Recksiegel:
1002.2126

Plot density is NOT a probability density; correlations represented by enveloping curves

For general input discussion see S.Nandi talk and references

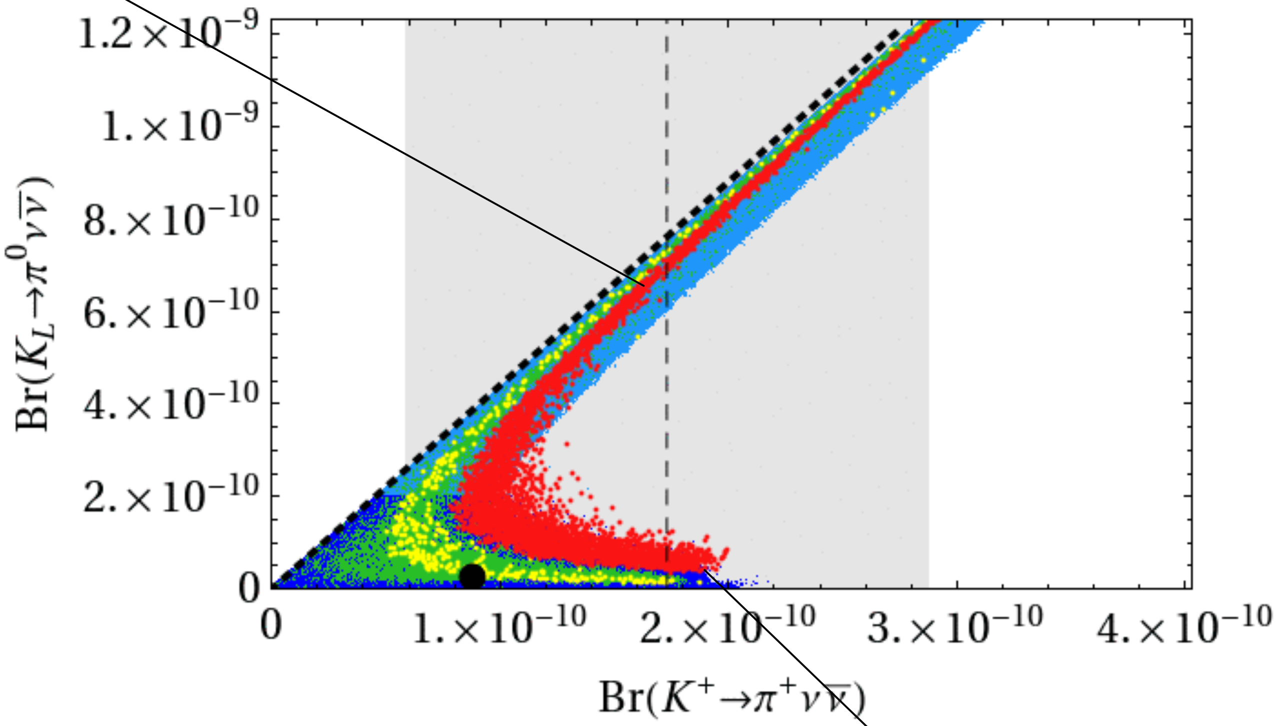
But mixing in lepton sector assumed to be $W_{l4} \sim O(\lambda)$ and so neglected here (in presence of substantial mixing with 4G leptons, charm contribution in $\pi\nu\nu$ will be affected)

Also recent SM4 1σ limit (Soni, Alok, Giri, Mohanta, Nandi 1002.0595):
$Br(K+ \to \pi+\nu\nu) = (4.0 \to 13.0)\ 10^{-11}$ $m_{t'}$ = 400-600 GeV
$Br(K_L \to \pi0\nu\nu) = (1.0 \to 6.2)\ 10^{-11}$ $m_{t'}$ = 400-600 GeV

SM4 $\pi\nu\nu$

$Br(K_L \to \mu\mu)_{SD} < 2.5\ 10^{-9}$
subdominant

Light blue:
$Br(K_L \to \pi 0 \nu\nu) > 2\ 10^{-10}$
Dark blue:
$Br(K_L \to \pi 0 \nu\nu) < 2\ 10^{-10}$

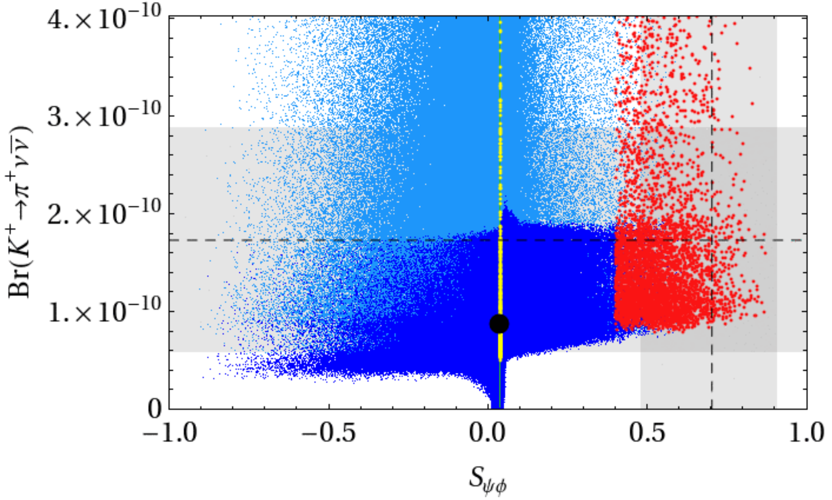


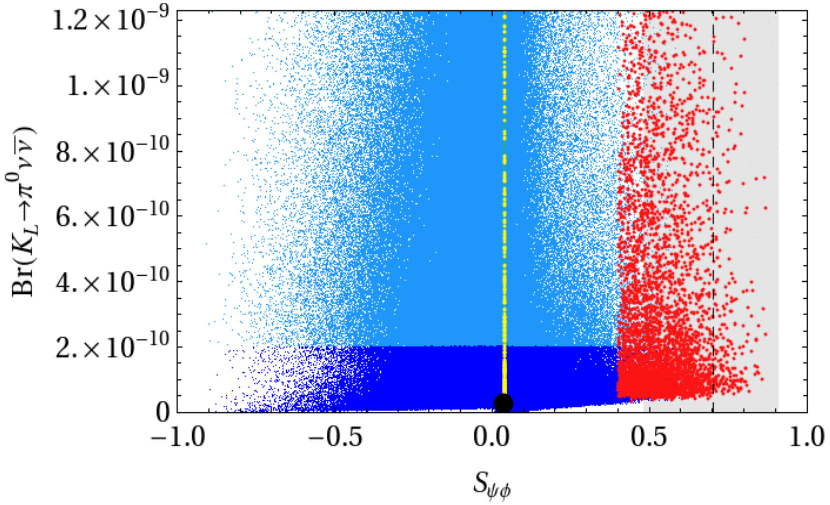
	BS1 (yellow)	BS2 (green)	BS3 (red)
$S_{\psi\phi}$	0.04 ± 0.01	0.04 ± 0.01	≥ 0.4
$Br(B_s \to \mu^+\mu^-)$	$(2 \pm 0.2) \cdot 10^{-9}$	$(3.2 \pm 0.2) \cdot 10^{-9}$	$\geq 6 \cdot 10^{-9}$

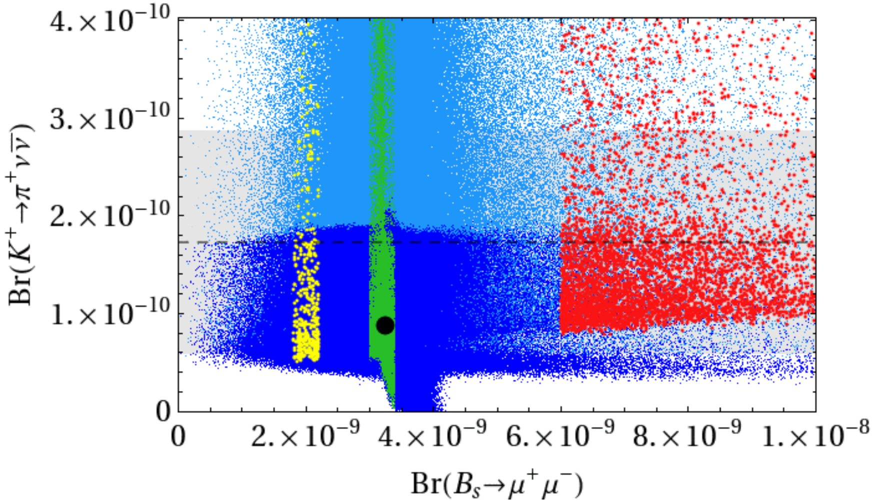
Effect of
$Br(K_L \to \mu\mu)_{SD} < 2.5\ 10^{-9}$

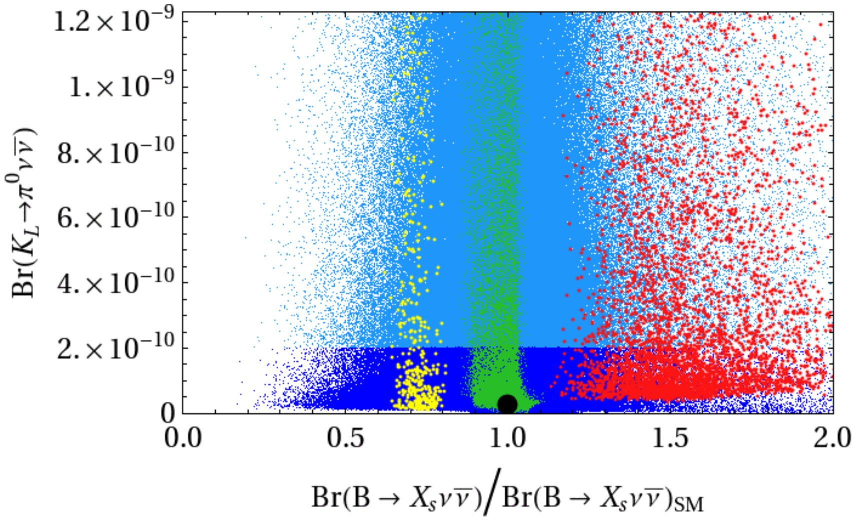
For red points (BS3) now disfavoured by LHC result;
Also disfavoured if ε′/ε taken into account

SM4 correlations







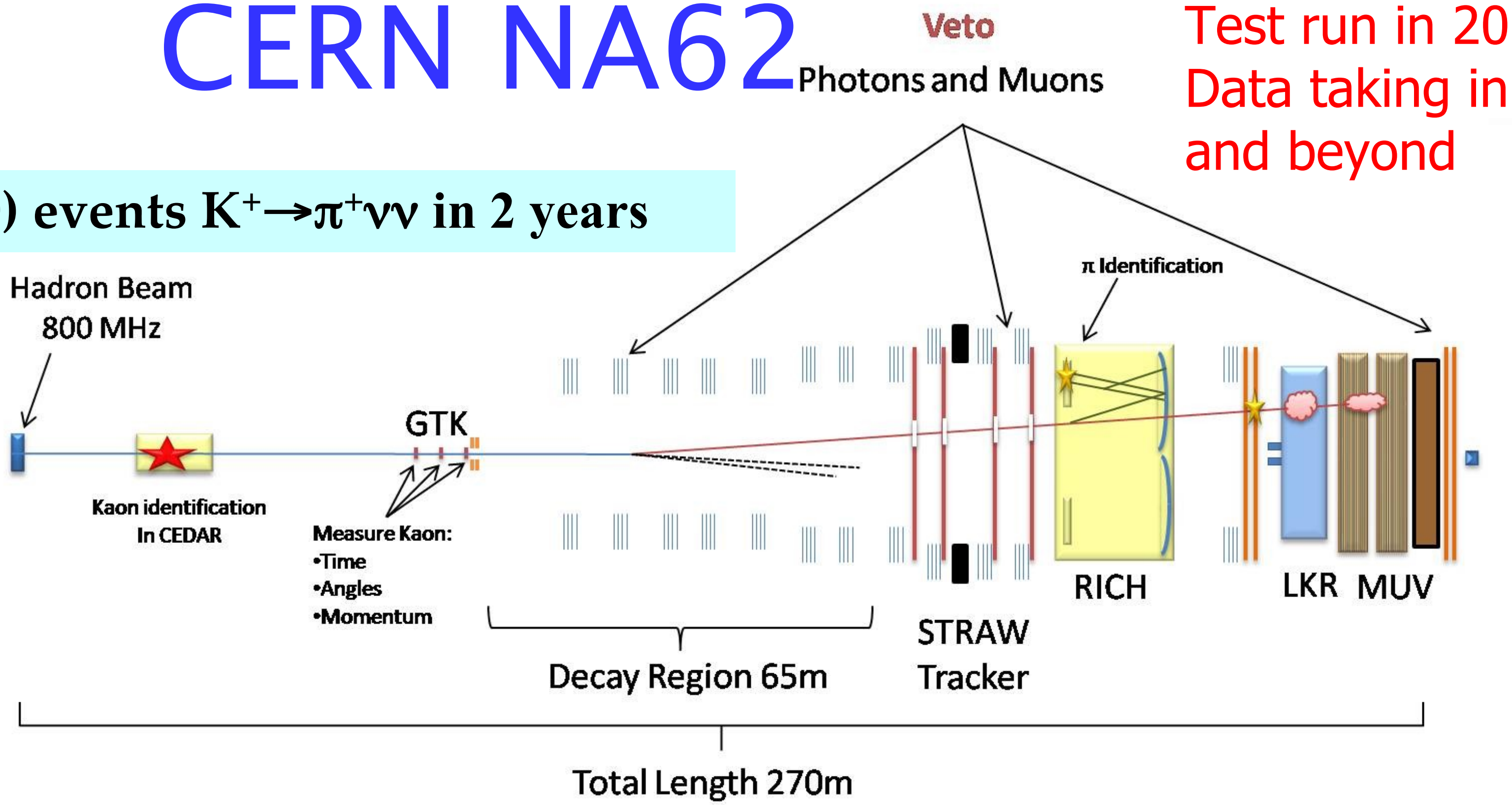


Red points now disfavoured by LHC
Even for small effects in B->μμ and Sφφ, large effects possible in K

CERN NA62

$\mathcal{O}(100)$ events $K^+\to\pi^+\nu\nu$ in 2 years

Test run in 2012;
Data taking in 2014
and beyond



Measurement of $K^+\to\pi^+\upsilon\upsilon$ with new decay in-flight technique
Intense un-separated (6% K^+) 75 GeV/*c* hadron beam: $5\cdot10^{12}$ ppp
High-energy: high yield, large decay volume, more powerful vetoing
Track incoming K^+ in 800MHz beam, particle ID, photon vetoing

$5\cdot10^{12}$ K^+ decays/year
55 SM events/(<Snowmass) year

Expected precision: 10%

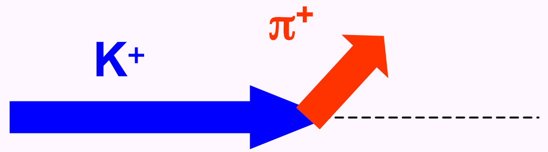
NA62 : principle of experiment

Decay-in-flight very different from stopped kaon technique

BR(SM) = 8×10^{-11}
~ 10^{12} K^+ decays
Acceptance= 10%

- K decays in flight
- Intense beam of protons from SPS
- High energy K (P_K = 75 GeV/c)
- Cherenkov K ID: CEDAR

Kinematic rejection



$m^2_{miss} = (P_K - P_\pi)^2$

Signature:
•Incoming **high** momentum K^+
•Outgoing **low** momentum π^+

- **Kaon: beam tracking**
- **Pion: spectrometer**
- **Excellent timing for K−π association**

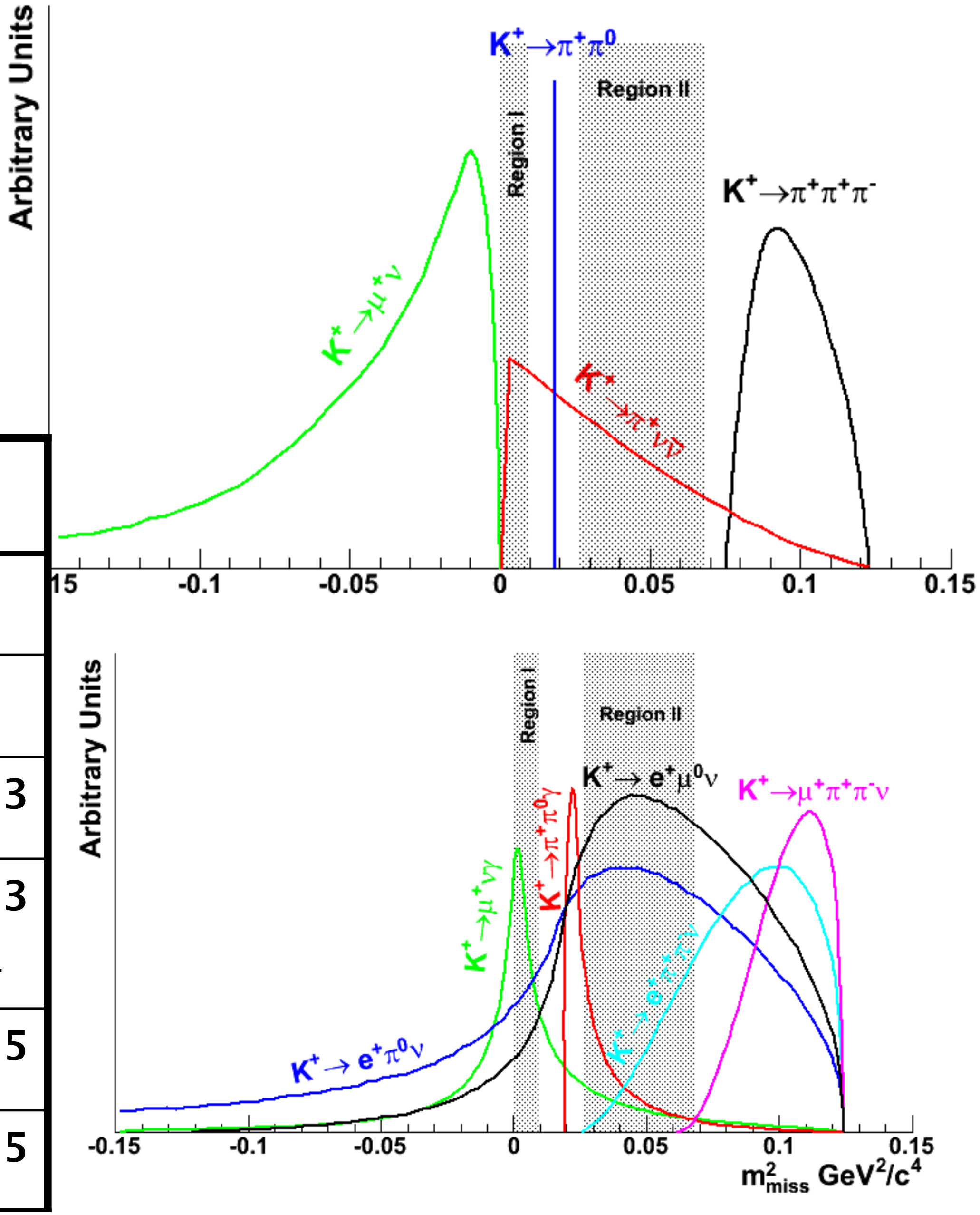
Veto and PID

- **γ/μ : calorimeter**
- **Charge Veto : spectrometer**
- **π/μ separation : RICH**

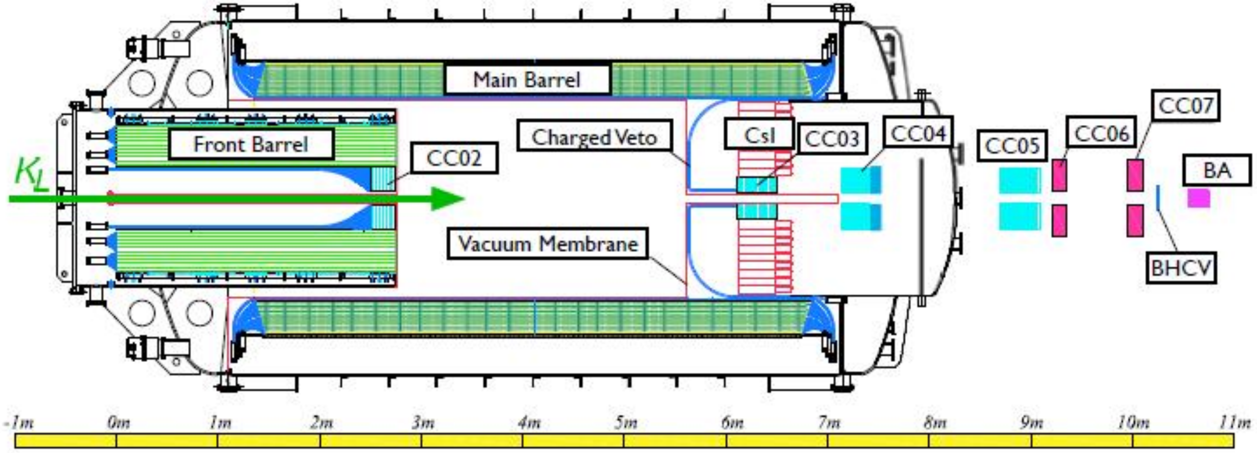
Backgrounds

Decay	BR
$K^+ \to \mu^+\nu$ ($K_{\mu2}$)	0.634
$K^+ \to \pi^+\pi^0$ ($K_{\pi2}$)	0.209
$K^+ \to \pi^+\pi^+\pi^-$ $K^+ \to \pi^+\pi^0\pi^0$	0.073

Decay	BR
$K^+ \to \pi^0 e^+\nu$ (K_{e3})	0.049
$K^+ \to \pi^0\mu^+\nu$ ($K_{\mu3}$)	0.033
$K^+ \to \mu^+\nu\,\gamma$ ($K_{\mu2\gamma}$)	6.2×10^{-3}
$K^+ \to \pi^+\pi^0\gamma$	1.5×10^{-3} (2.75×10^{-4}
$K^+ \to \pi^+\pi^- e^+\nu$ (K_{e4})	4.1×10^{-5}
$K^+ \to \pi^+\pi^-\mu^+\nu$ ($K_{\mu4}$)	1.4×10^{-5}



KEK E391a experiment

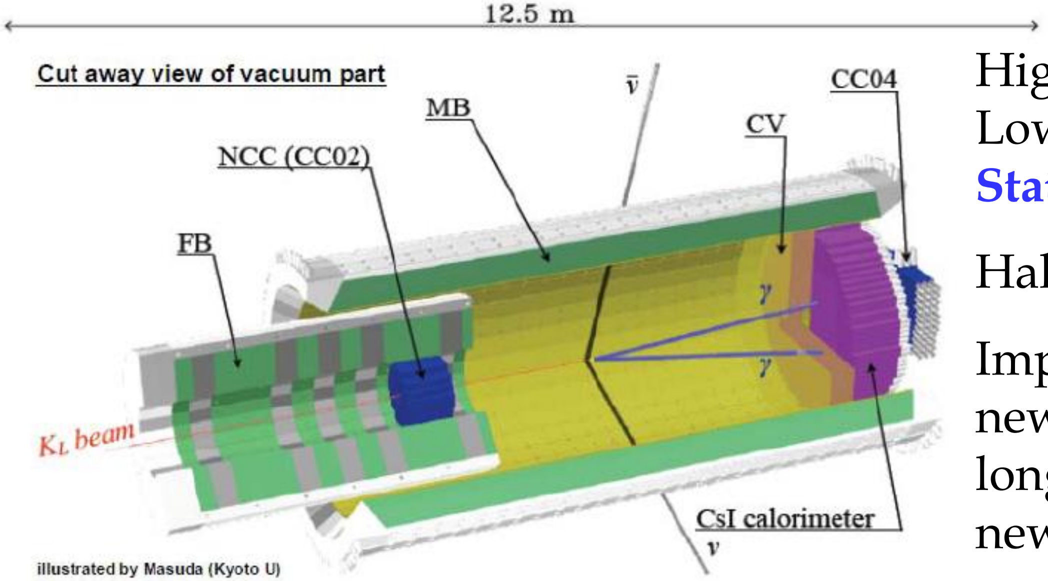


First dedicated pilot experiment to search for $K_L \rightarrow \pi^0 \nu\nu$ at the KEK-PS
Improve over KTeV (Dalitz) limit: BR < $5.9 \cdot 10^{-7}$

- 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 month total

BR($K_L \rightarrow \pi^0 \nu\nu$)<$6.7 \cdot 10^{-8}$ (90% CL)



illustrated by Masuda (Kyoto U)

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)

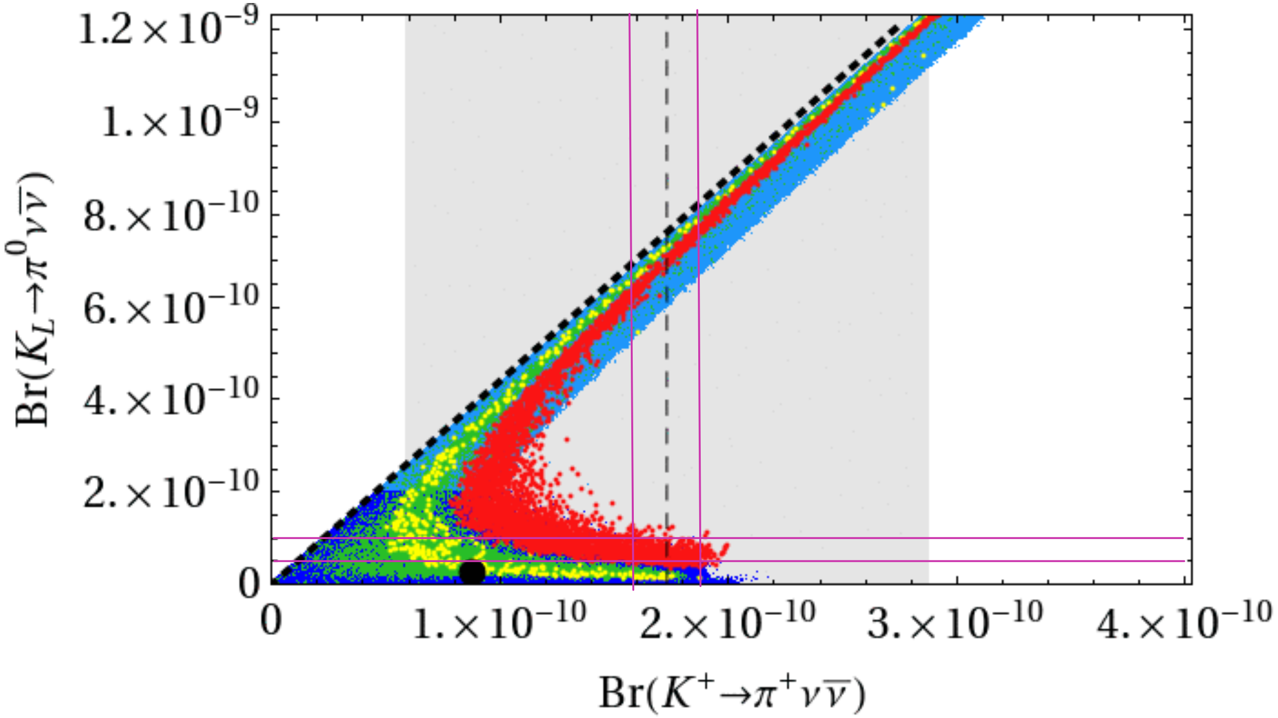
Step 1: SES = **2.7 SM events** (3 Snowmass years) with **2.2 background**

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

First physics run in 2013(?)

K→πυυ beyond SM



Purple bands: foreseen 10% precision

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

2HDM – tree level (including SUSY)

K_{l2} can proceed via exchange of charged Higgs $H^\pm$ (in place of $W^\pm$)

→ Does not affect the ratio R_K

2HDM – one-loop level

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

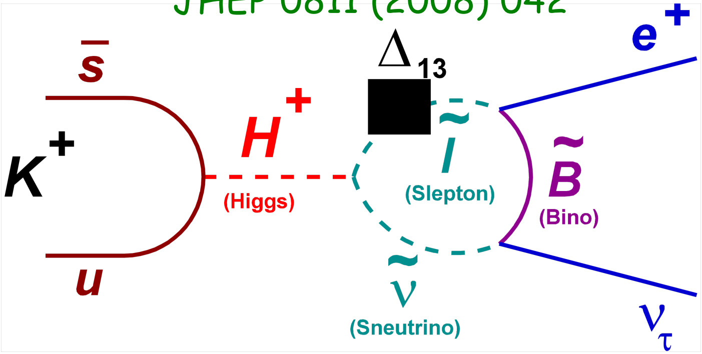
→ R_K enhancement can be experimentally accessible

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

Up to ~1% effect :

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

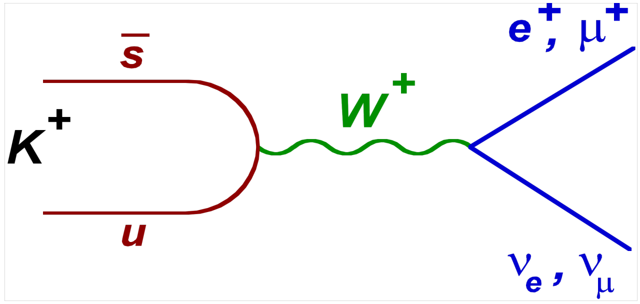
PRD 74 (2006) 011701,
JHEP 0811 (2008) 042



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)

$R_K^{SM} = (2.477\pm0.001)\times10^{-5}$



Backgrounds and Uncertainty

Backgrounds

Source	B/(S+B)
$K_{\mu 2}$	(5.64±0.20)%
$K_{\mu 2}$ ($\mu \to e$)	(0.26±0.03)%
$K_{e2\gamma}$ (SD^+)	(2.60±0.11)%
Beam halo	(2.11±0.09)%
$K_{e3(D)}$	(0.18±0.09)%
$K_{2\pi(D)}$	(0.12±0.06)%
Wrong sign K	(0.04±0.02)%
Total	(10.95±0.27)%

Lepton momentum bins are differently affected by backgrounds and thus the systematic uncertainties.

Uncertainties

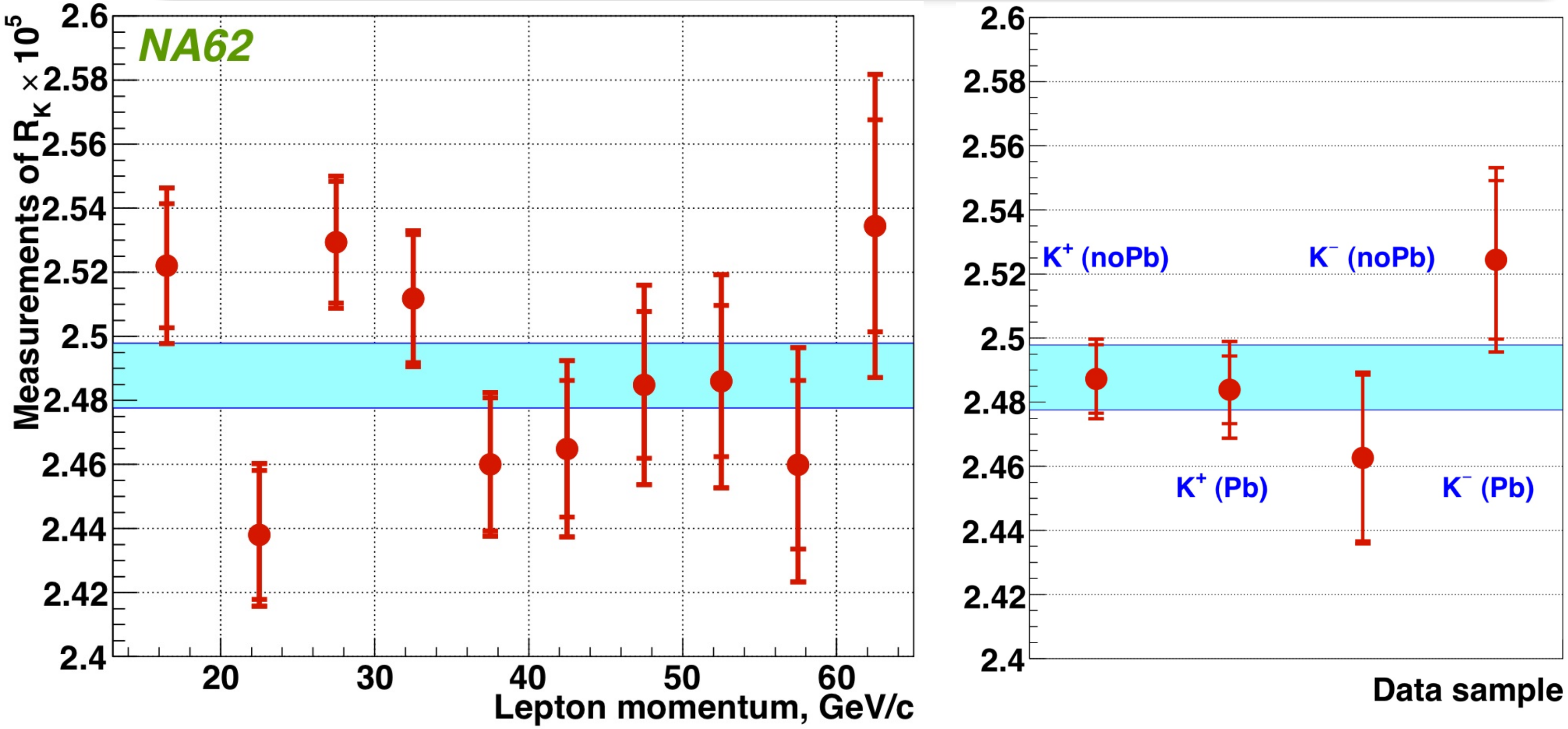
Source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$	0.004
BR($K_{e2\gamma}$ SD^+)	0.002
$K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$	0.003
Beam halo	0.002
Helium purity	0.003
Acceptance	0.002
DCH alignment	0.001
Positron ID	0.001
Lkr readout inef	0.001
1-track trigger	0.001
Total	0.010

(40% data set: PLB 698 (2011), 105)

NA62 result

$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$

$R_K = (2.488 \pm 0.010) \times 10^{-5}$

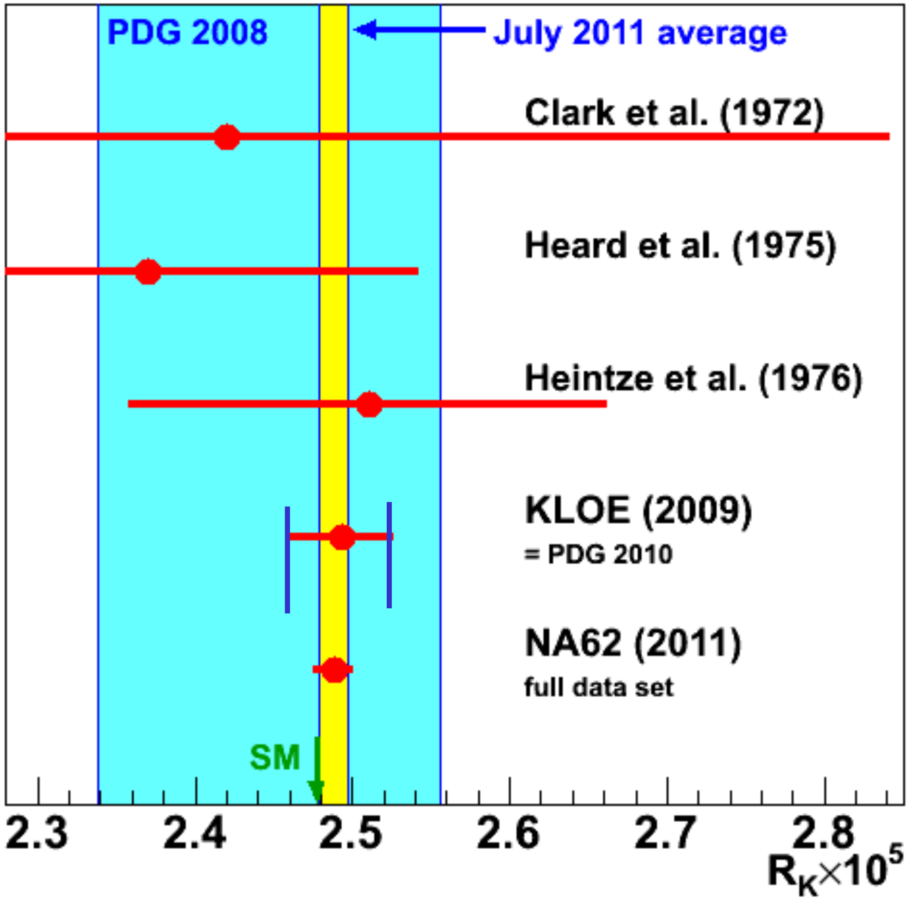


Independent measurements in lepton momentum bins

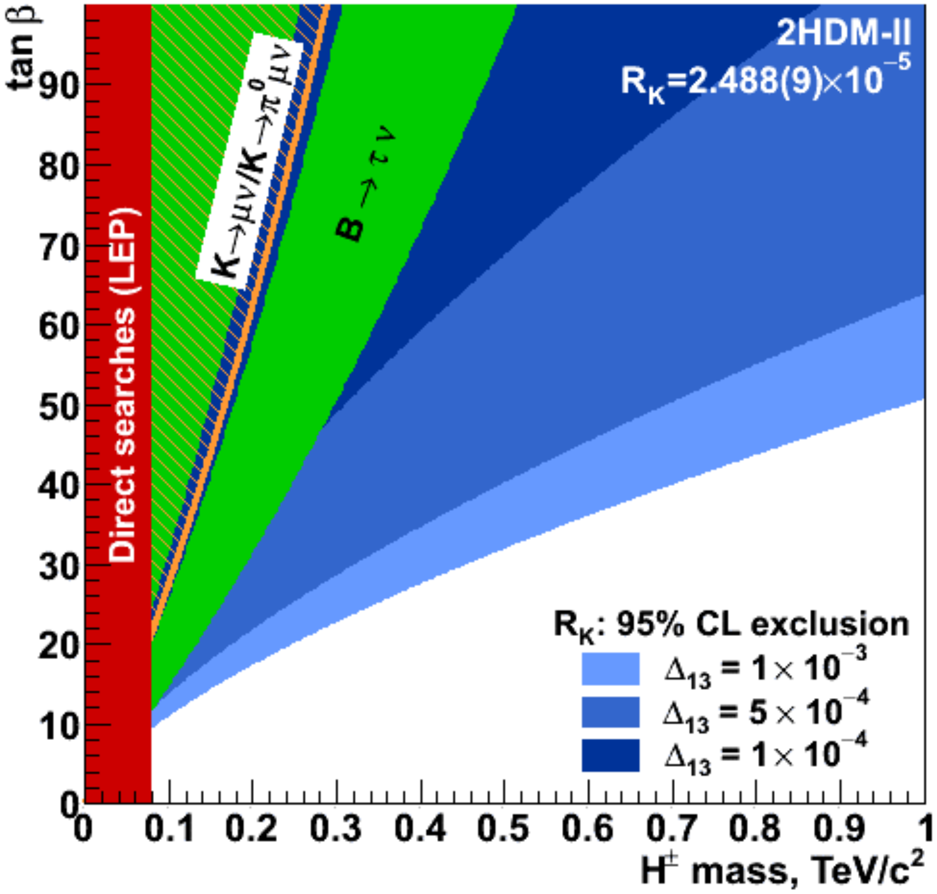
(systematic errors included, partially correlated)

40 measurements (4 data samples x 10 momentum bins) including correlations:
χ^2/ndf=47/39

R_K: world average



(M_H, tanβ) 95% exclusion limits



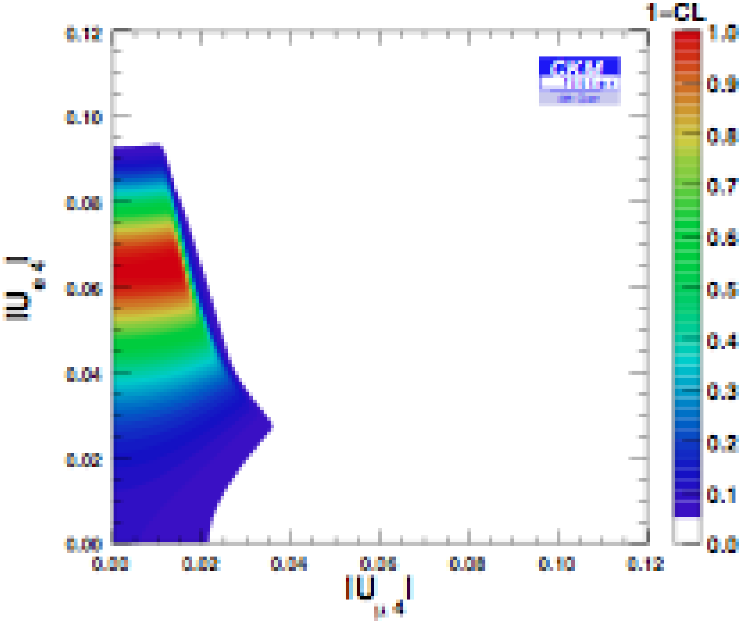
Other limits on 2HDM-II:
PRD 82 (2010) 073012.

SM with 4 generations:
JHEP 1007 (2010) 006.

4th generation constraints

Lacker, Menzel
arXiv:1003.4532v2

Radiative and leptonic μ,τ
Kl3, πl2 constraints



4th gen. PMNS matrix unitary:

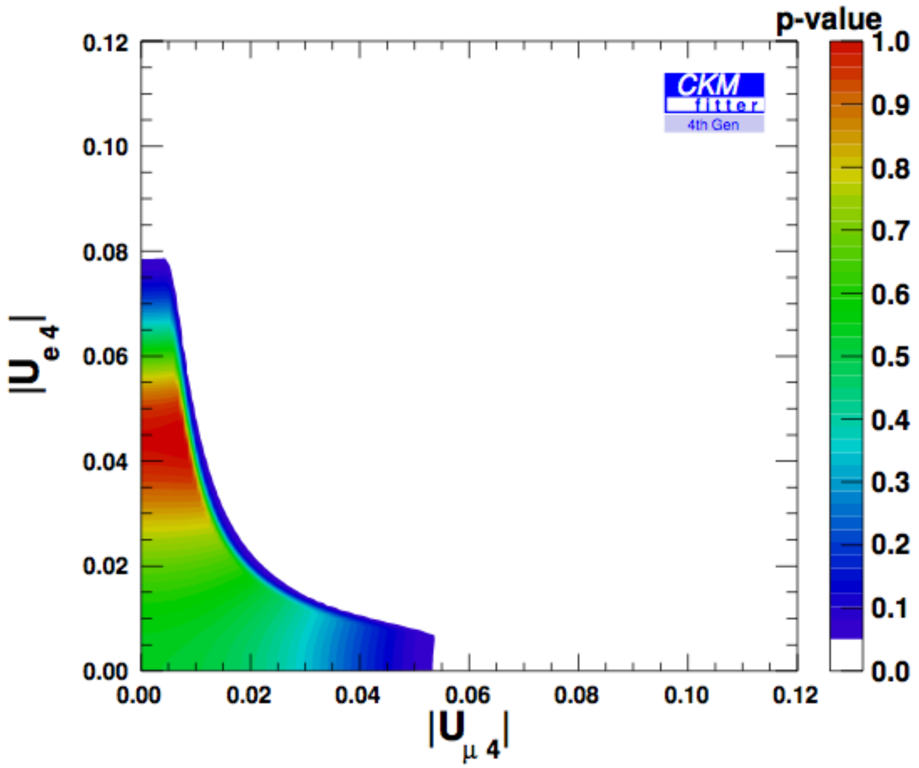
$$\sum_{j=1,2,3} |U_{\mu j}|^2 = 1 - |U_{\mu 4}|^2$$

$$\sum_{i=1,2,3} |U_{ei}|^2 = 1 - |U_{e4}|^2$$

$$R_K = (1 - |U_{e4}|^2)/(1 - |U_{\mu 4}|^2)$$

...cont.

New plot
from Lacker And Menzel



Radiative and leptonic μ,τ
Kl3, πl2 constraints and RK

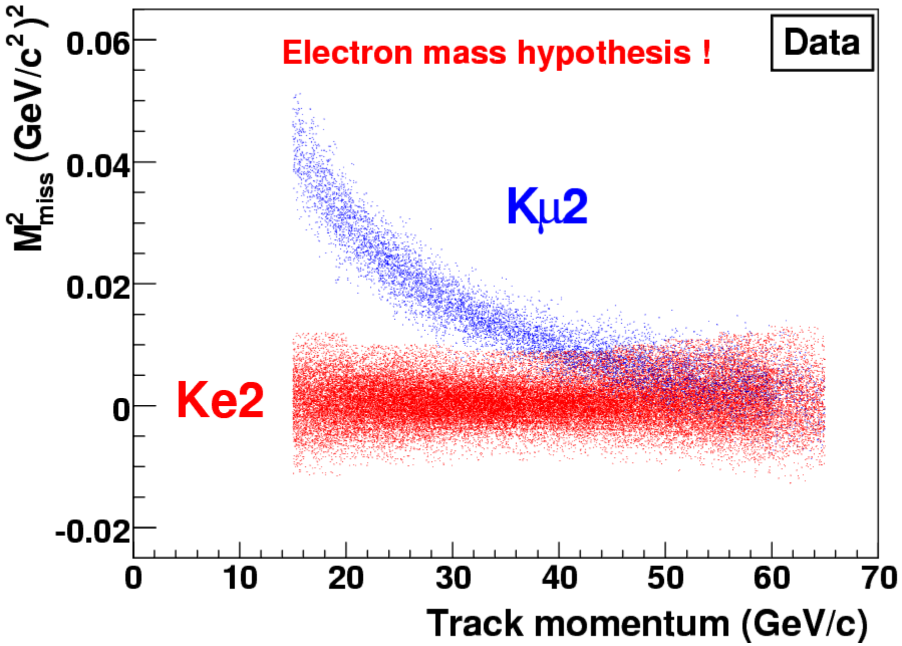
Old plot shows deviation of Ue4 from zero
Since then:

1) Kl3 results changed, lowering the effect
2) RK added, and pulls in opposite direction

Good agreement with Universality and improved Ue4 limit

Prospects with new NA62

- At present Kμ2/Ke2 can not be separated kinematically at high lepton momentum: particle identification is essential. Model-dependent MC correction required to evaluate the muon mis-ID probability.

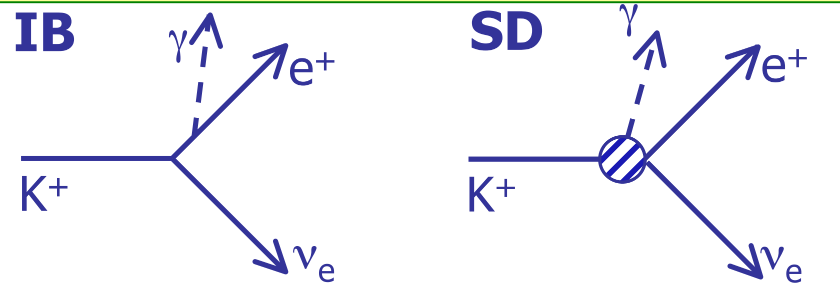


Analysis without electron identification allows to avoid the uncertainty.
Possibility: future NA62 analysis at p<40GeV/c without electron identification.

- For NA62 conditions (75 GeV/c beam, ~100 m decay volume):
$P(K_{\mu 2}, \mu \rightarrow e \text{ decay})/R_K \sim 10$ but they are naturally suppressed by the muon polarisation
Irreducible background: ~0.2% however known to excellent precision

…cont.

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



- Ke2γ background:

KLOE measurement (arXiv:0907:3594): precision improved by a factor of 4;
NA62 (2007 data): analysis in progress; expect precision similar to KLOE;
future NA62 hermetic veto (large-angle and small-angle veto counters) will strongly decrease the background.
SD background will not be relevant for a future NA62 precision RK measurement

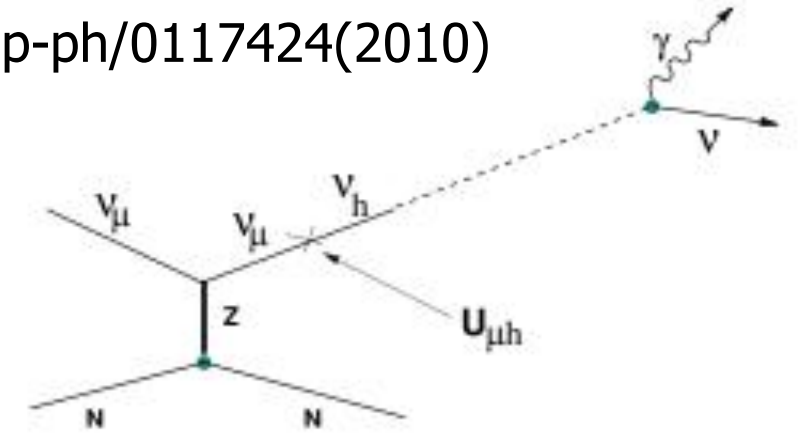
- beam halo: future beam spectrometer (beam tracker plus beam Cherenkov) will allow time correlation between incoming kaons and decay products
Expect background to be reduced to negligible level.

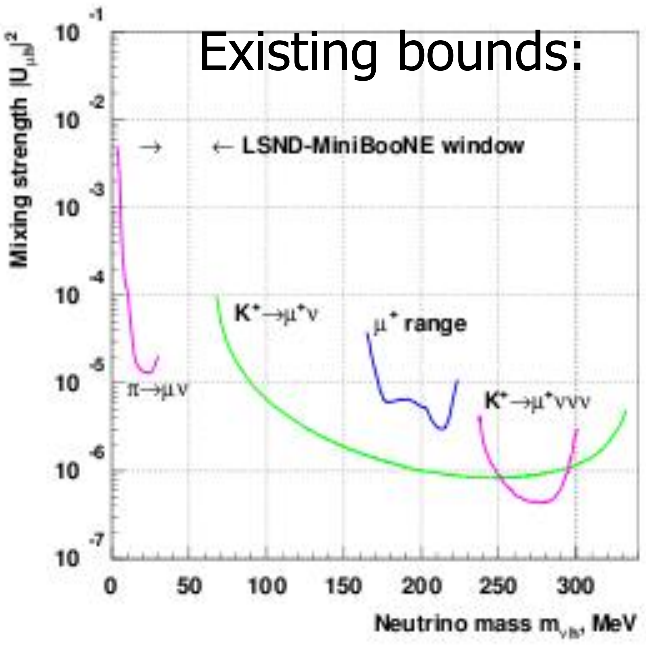
Larger statistics collectable in shorter time

To explain MiniBooNE results

- There is a 4th sterile neutrino, but it mixes with ν_μ and not with ν_e ;
- All LSND and MiniBooNE electron distributions can be explained assuming that this 4th neutrino is heavy (mass = 40 – 80 MeV) and decays to an ordinary neutrino + a photon: $\nu_H \to \nu + \gamma$ (LSND and MiniBooNE do not distinguish electrons from photons)

hep-ph/0117424(2010)




Existing bounds:

Gninenko's hypothesis requires $|U_{\mu H}|^2 = (2 – 8) \times 10^{-3}$; $\tau(\nu_H) \leq 10^{-9}$ s

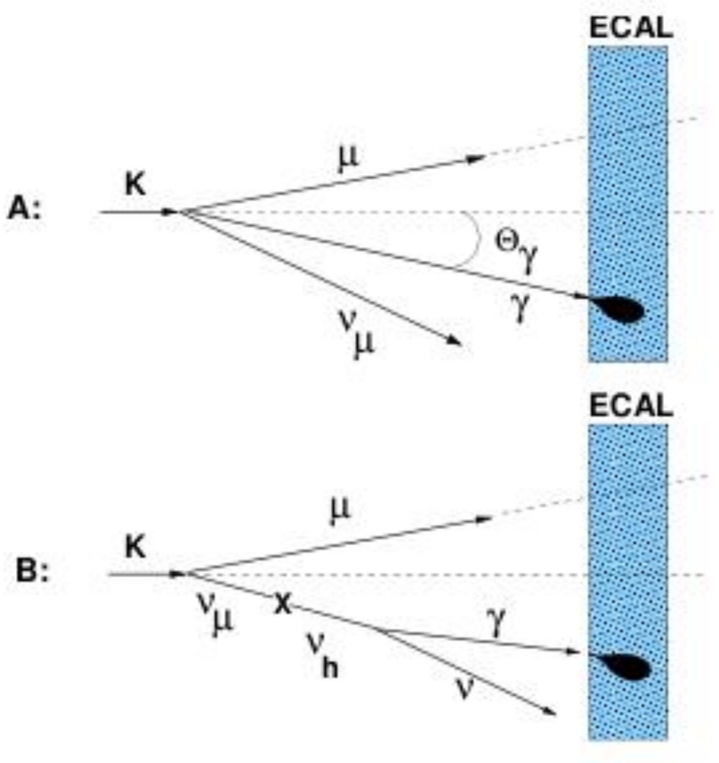
(in the rest frame)

$$\Gamma(K \to \mu\nu_H) = \Gamma(K \to \mu\nu_\mu)\left|U_{\mu H}\right|^2 \rho(m_{\nu_H}) \longrightarrow$$

Ratio of phase space

Search for $K \rightarrow \mu\nu_H$

Method to search for $K^+ \rightarrow \mu^+ + \nu_H$ followed by $\nu_H \rightarrow \nu + \gamma$



Radiative Kμ2

$K^+ \rightarrow \mu^+ + \nu_H$
followed by $\nu_H \rightarrow \nu + \gamma$

- The missing mass resolution of the NA62 detector in the 2007 configuration is not good enough to identify ν_H from the MM^2 distribution.
- In future, search for events containing a μ^+, one photon and NOTHING ELSE exploiting the full coverage of photon veto (LAV, LKr, IRC, SAC)

Summary/Discussion

- Kaon decays can give several constraints on 4th generation
- BR(K+,L→$\pi\nu\nu$) about to be measured
- RK reached record precision, and will improve in the future
- search for ν_H just started
- Possible to have strong effects in K and B at the same time
- Even for SM-like $S_{\varphi\phi}$ and Bs→$\mu\mu$, possible large effects and correlations in K

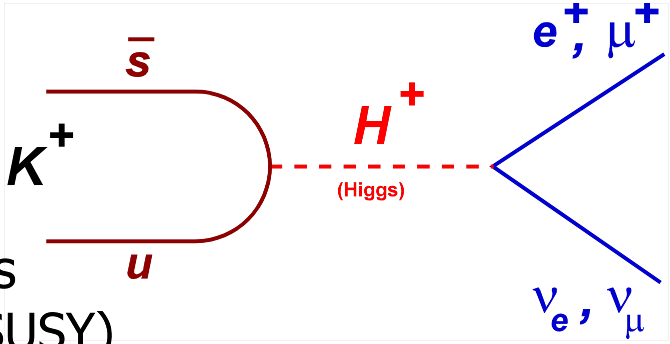
- Interplay between rare decays and RK when 4G lepton mixing is not negligible
- If 4G lepton mixing is large, but RM is SM (Ue4=Uμ4), how do rare decays change
- Nature, correlation and variation of inputs; theory errors
- How $\pi\nu\nu$ change for various 4G quark mixing matrix scenarios
- If $\pi\nu\nu$ deviates from SM, how important for SM4 is to measure πll

Spares

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

SM contribution is helicity suppressed:

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



Sizeable tree level charged Higgs ($H^\pm$) contributions in models with two Higgs doublets (2HDM including SUSY)

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

(numerical examples for M_H=500GeV/c², $\tan\beta = 40$)

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

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

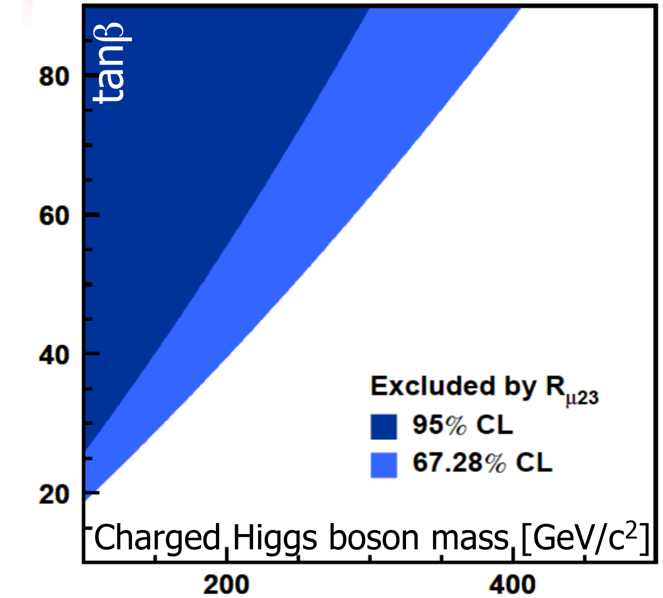
$D^+_s\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_D/m_H)^2\, (m_s/m_c)\, \tan^2\beta \approx 0.4\%$

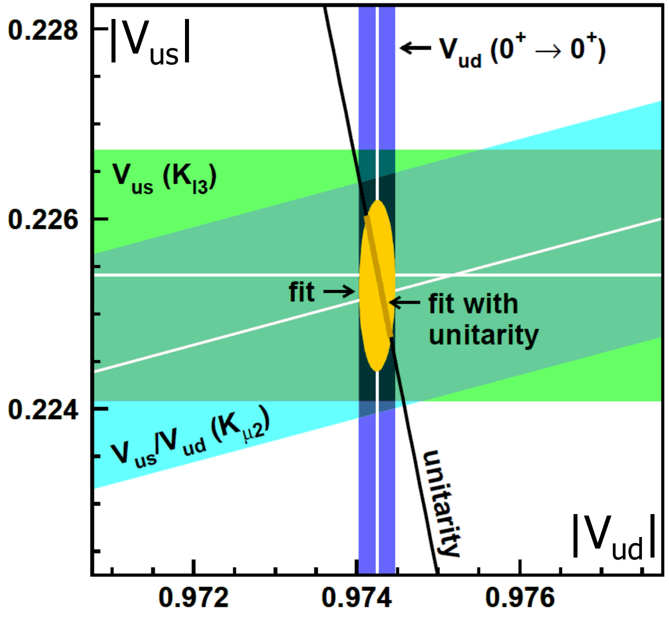
$B^+\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_B/m_H)^2 \tan^2\beta \approx 30\%$

$R=Br(K\to\mu\nu)/Br(K_{e3})$:
$(\delta R/R)_{exp}=1.0\%$,
challenging
but not hopeless

Subject to hadronic uncertainties

$H^\pm$ exchange in $K^+\to\mu^+\nu$





Comparison of $|V_{us}|$ determined from helicity suppressed $K^+\to\mu^+\nu$ decays vs helicity allowed $K^+\to\pi^0\mu^+\nu$ decays

To reduce the uncertainties of hadronic and EM corrections:

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

Charged Higgs mediated contribution:

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

Experiment: $R_{\mu23} = 0.999(7)$,
$|V_{us}|^2+|V_{ud}|^2-1 = -0.0001(6)$.
Precision limited by lattice input.
(Flavianet Kaon WG, arXiv:1005.2323)

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

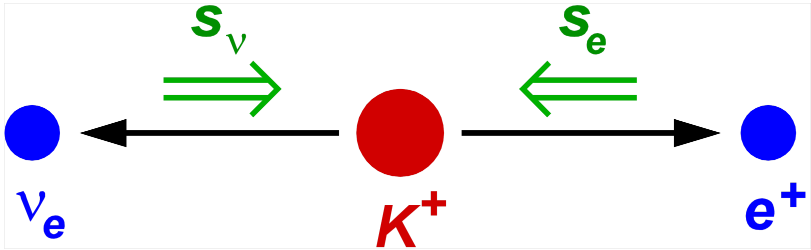
Observable sensitive to lepton flavour and its SM expectation:

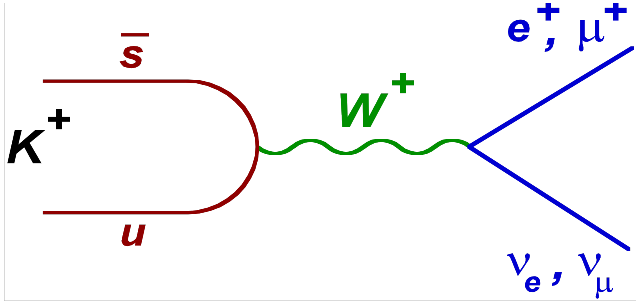
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{\left(1 + \delta R_K^{\mathrm{rad.corr.}}\right)}$$

(similarly, R_π in the pion sector)

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

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



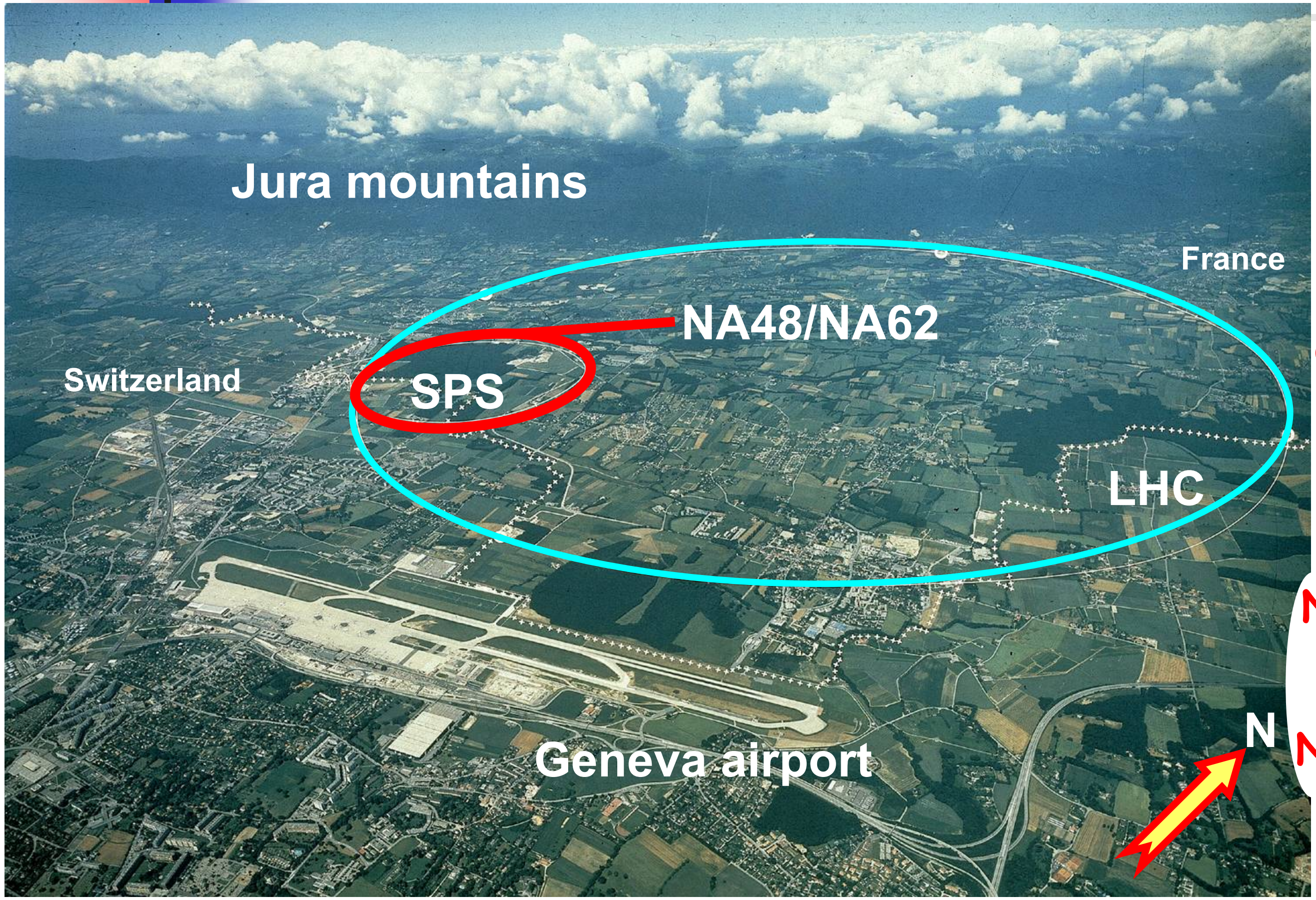


- SM prediction: excellent sub-per mille accuracy due to cancellation of hadronic uncertainties.
- Measurements of R_K and R_π have long been considered as tests of lepton universality.
- Recently understood: helicity suppression of R_K might enhance sensitivity to non-SM effects to an experimentally 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. Rev. Lett. 99 (2007) 231801

CERN NA48/NA62



NA48 discovery of direct CPV	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 (R_K)	2007: $K^\pm_{e2}/K^\pm_{\mu2}$	
	2008: $K^\pm_{e2}/K^\pm_{\mu2}$	
NA62	2007–2013: design & construction 2012: first data taking	

Primary SPS protons (400 GeV/c): 1.8×10^{12}/SPS spill

Unseparated secondary positive beam: $p=(74.0\pm1.6)$ GeV/c

Composition: $K^+(\pi^+) = 5\%(63\%)$.

K^+ decaying in vacuum tank: 18%.

Measurement strategy

(1) $K_{e2}/K_{\mu2}$ candidates are collected concurrently:

- analysis does not rely on kaon flux measurement;
- several systematic effects cancel at first order
  (e.g. reconstruction/trigger efficiencies, time-dependent effects).

(2) counting experiment, measured independently in 10 lepton momentum bins
(owing to strong momentum dependence of backgrounds and event topology)

$$R_K = \frac{1}{D}\cdot\frac{N(K_{e2})-N_B(K_{e2})}{N(K_{\mu2})-N_B(K_{\mu2})}\cdot\frac{A(K_{\mu2})\times f_\mu\times\varepsilon(K_{\mu2})}{A(K_{e2})\times f_e\times\varepsilon(K_{e2})}\cdot\frac{1}{f_{LKr}}$$

$N(K_{e2})$, $N(K_{\mu2})$: numbers of selected K_{l2} candidates;

$N_B(K_{e2})$, $N_B(K_{\mu2})$: numbers of background events; ⇒ $N_B(K_{e2})$: main source of systematic errors

$A(K_{e2})$, $A(K_{\mu2})$: MC geometric acceptances (no ID);

f_e, f_μ: directly measured particle ID efficiencies;

$\varepsilon(K_{e2})/\varepsilon(K_{\mu2})>99.9\%$: E_{LKr} trigger condition efficiency;

$f_{LKr}=0.9980(3)$: global LKr readout efficiency;

$D=50\text{-}150$ downscaling factor of the $K_{\mu2}$ trigger.

(3) MC simulations use minimised:

- Geometrical part of the acceptance correction comes from simulation;
- PID, trigger, readout efficiencies are measured directly.

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

Large common part (topological similarity)

- one reconstructed track;
- geometrical acceptance cuts;
- K decay vertex: closest approach of track & nominal kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: 13GeV/c<p<65GeV/c.

Kinematic separation

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}<25GeV/c

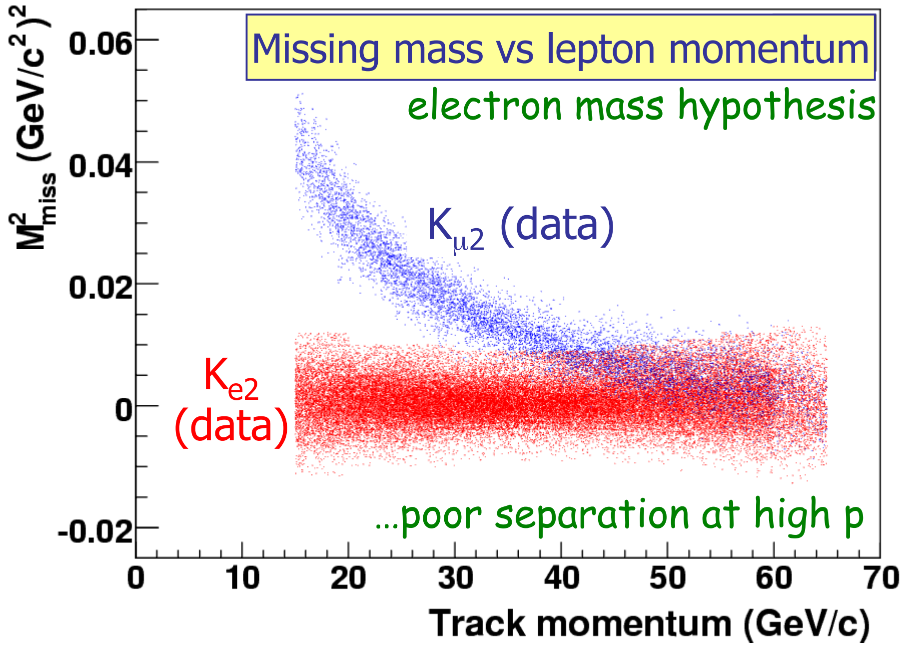
Separation by particle ID

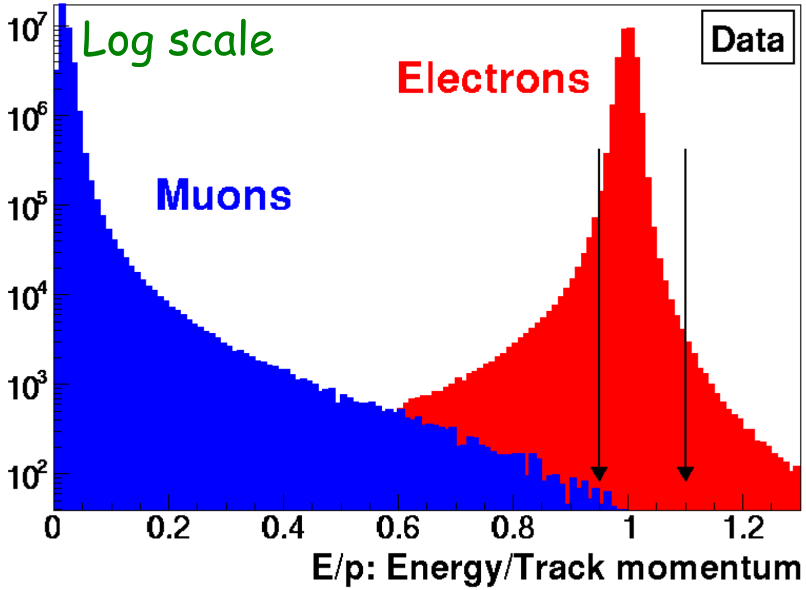
E/p = (LKr energy deposit/track momentum).

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

E/p<0.85 for muons.

→ Powerful $\mu^{\pm}$ suppression in $e^{\pm}$ sample: ~10^6





$K_{\mu2}$ background in K_{e2} sample

Main background source

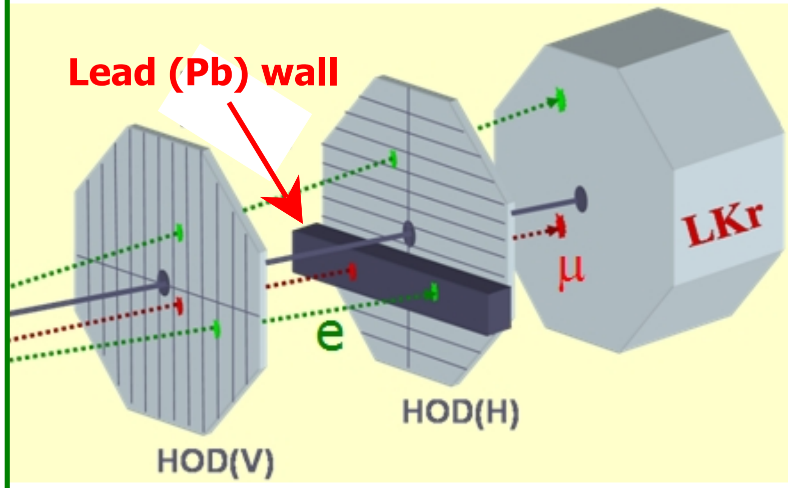
Muon “catastrophic” energy loss in LKr by emission of energetic bremsstrahlung photons. $P_{\mu e} \sim 3\times10^{-6}$ (and momentum-dependent).

$P_{\mu e} / R_K \sim 10\%$:
$K_{\mu2}$ decays represent a major background

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.

$K_{\mu2}$ candidates, track traversing Pb, $p>30$GeV/c, $E/p>0.95$: positron contamination $<10^{-8}$.



Thickness:	$\sim9.2X_0$ (Pb+Fe
Width:	240cm (=HOD size
Height:	18cm (=3 counters
Area:	~20% of HOD are
Duration:	~50% of R_K runs
	+ special muon runs

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

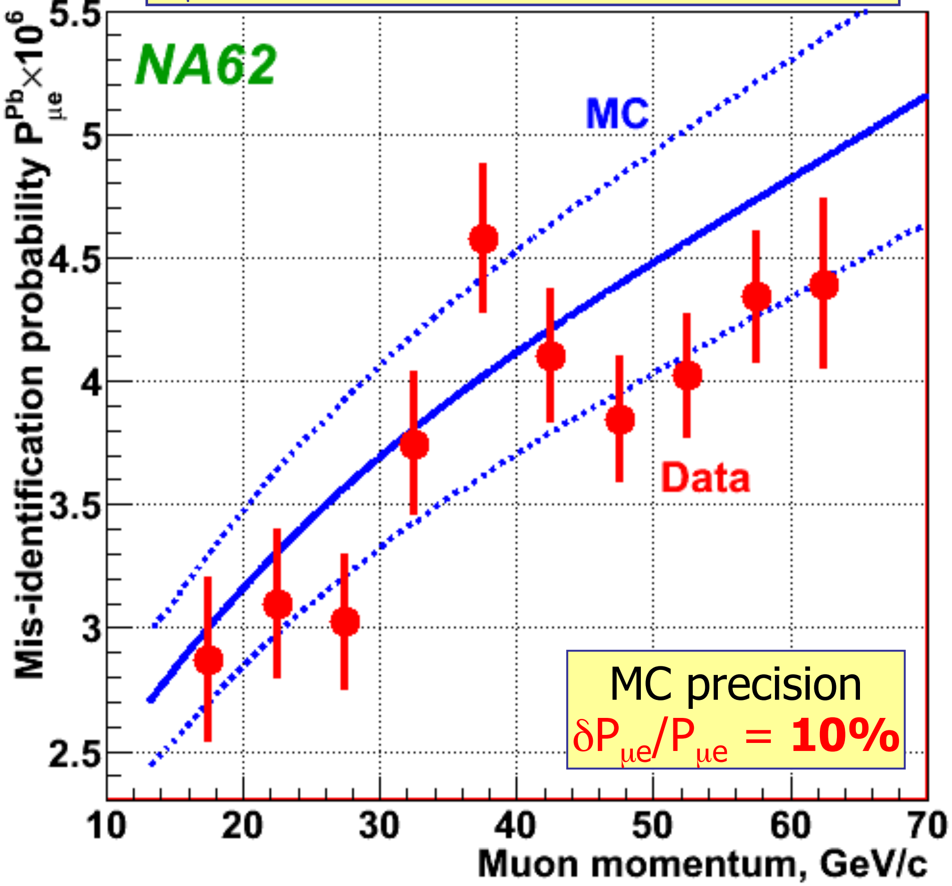
⇒

The correction $f_{Pb}=P_{\mu e}/P_{\mu e}^{Pb}$ is evaluated with a dedicated Geant4-based simulation

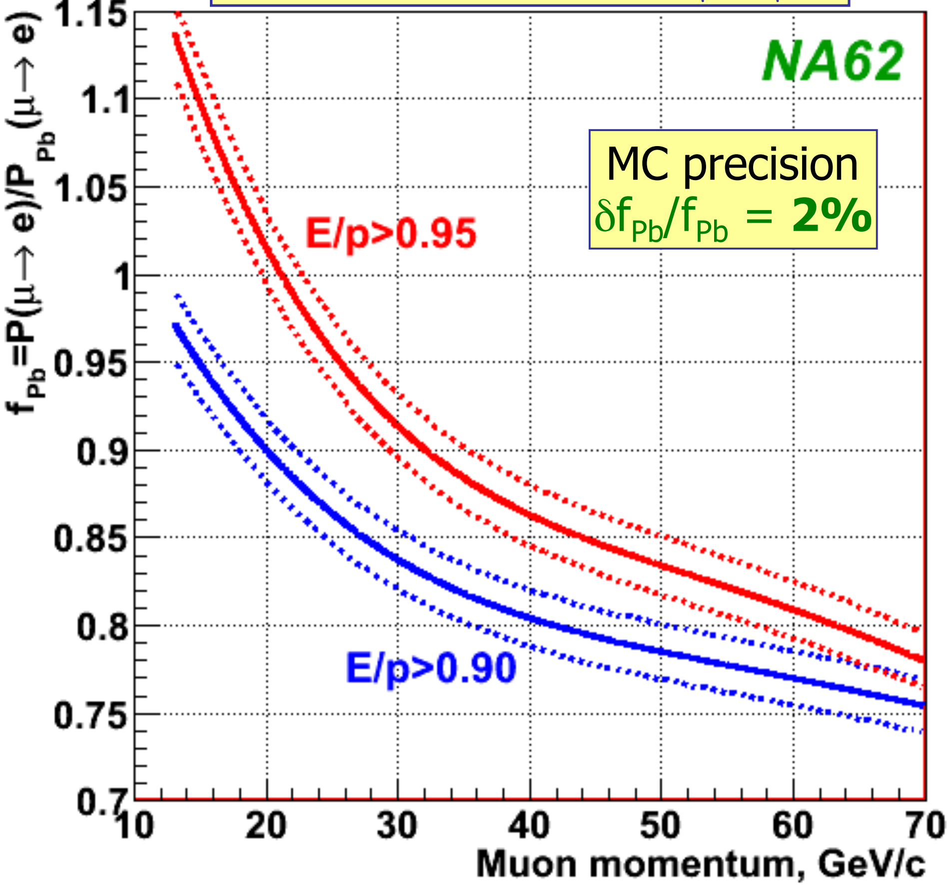
[Muon bremsttranlung:
Phys. Atom. Nucl. 60 (1997) 576]

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) = (5.64±0.20)%

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%).

$K_{\mu 2}$ with $\mu \rightarrow e$ decay in flight

For NA62 conditions
(74 GeV/c beam, ~100 m decay volume),

$N(K_{\mu 2}, \mu \rightarrow e \text{ decay})/N(K_{e2}) \sim 10$

$K_{\mu 2}$ ($\mu \rightarrow e$) naïvely seems a huge background

Muons from $K_{\mu 2}$ decay are fully polarized:
Michel electron distribution

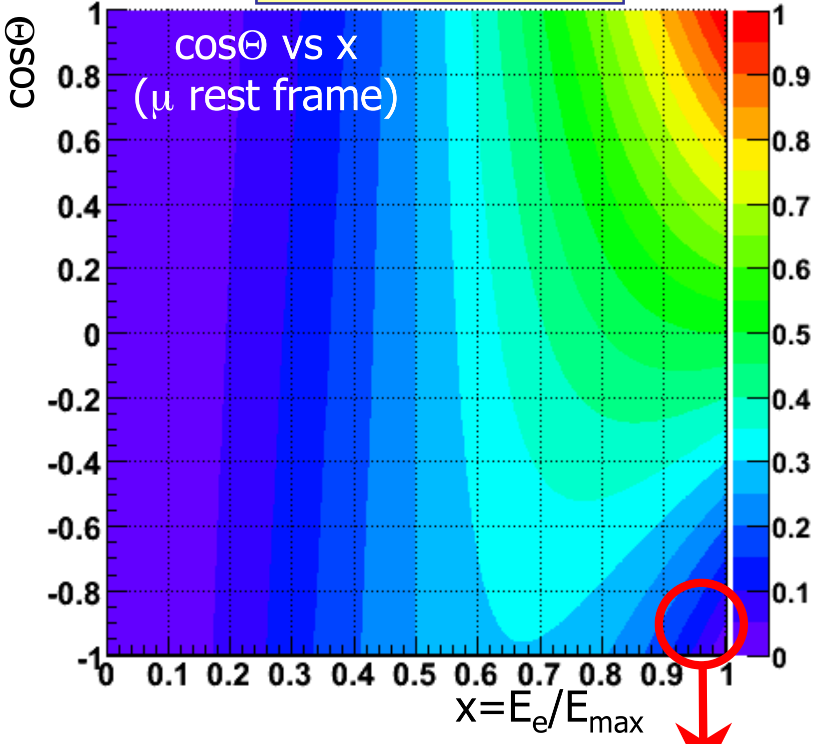
$$d^2\Gamma/dx\,d(\cos\Theta) \sim x^2[(3-2x) - \cos\Theta(1-2x)]$$

$x = E_e/E_{max} \approx 2E_e/M_\mu$,
Θ is the angle between p_e and the muon spin
(all quantities are defined in muon rest frame).

Result: $B/(S+B) = (0.26\pm0.03)\%$

Important but not dominant background

Michel distribution



Only energetic forward positrons are selected as K_{e2} candidates

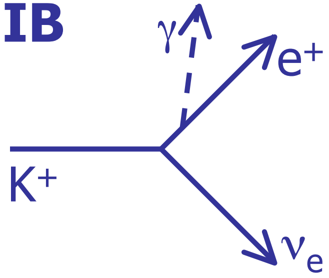
They are naturally suppressed by the muon polarisation

(radiative corrections provide another ~10% suppression)

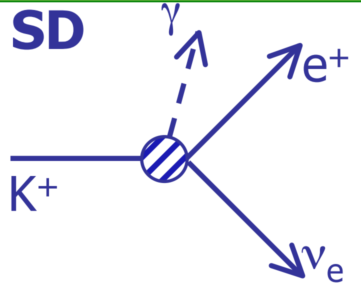
Radiative $K^+ \to e^+\nu\gamma$ process

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

IB



SD



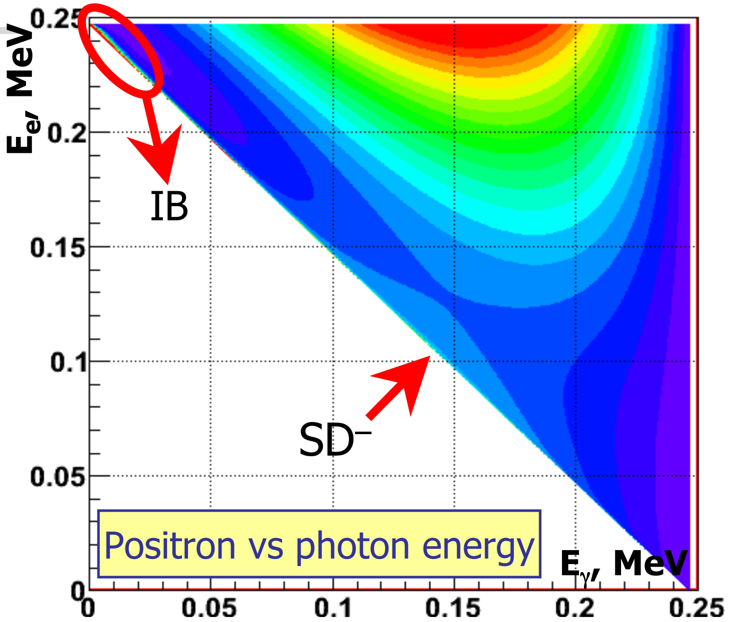
SD radiation is not helicity suppressed.
KLOE measurement of the form factor leads to
BR(SD$^+$, full phase space) = $(1.37 \pm 0.06) \times 10^{-5}$.
(EPJC64 (2009) 627)

SD background contamination

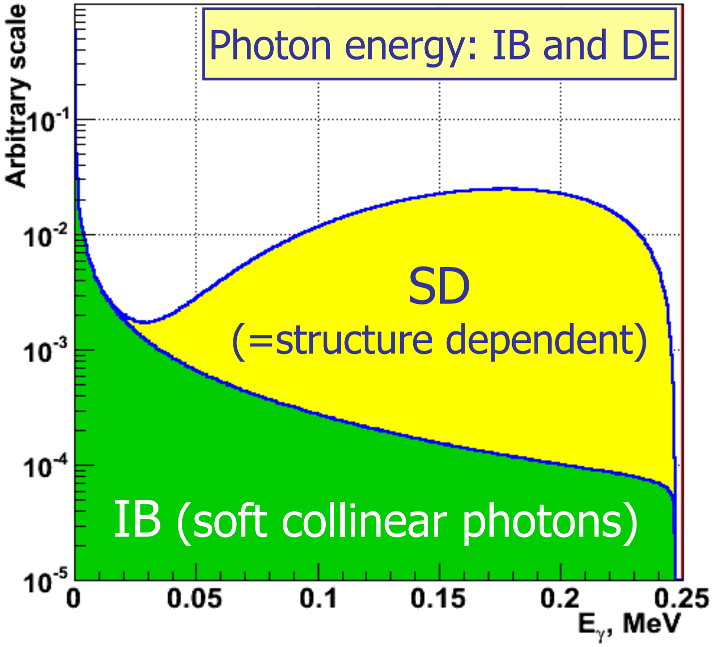
$B/(S+B) = (2.60 \pm 0.11)\%$

A new $K_{e2\gamma}$ (SD$^+$) measurement is being performed by NA62.

INT= interference; IB=inner bremsstrahlung



Positron vs photon energy



Photon energy: IB and DE

Beam halo background

Electrons produced by beam halo muons via $\mu\to e$ decay can be kinematically and geometrically compatible to genuine K_{e2} decays

Background measurement:

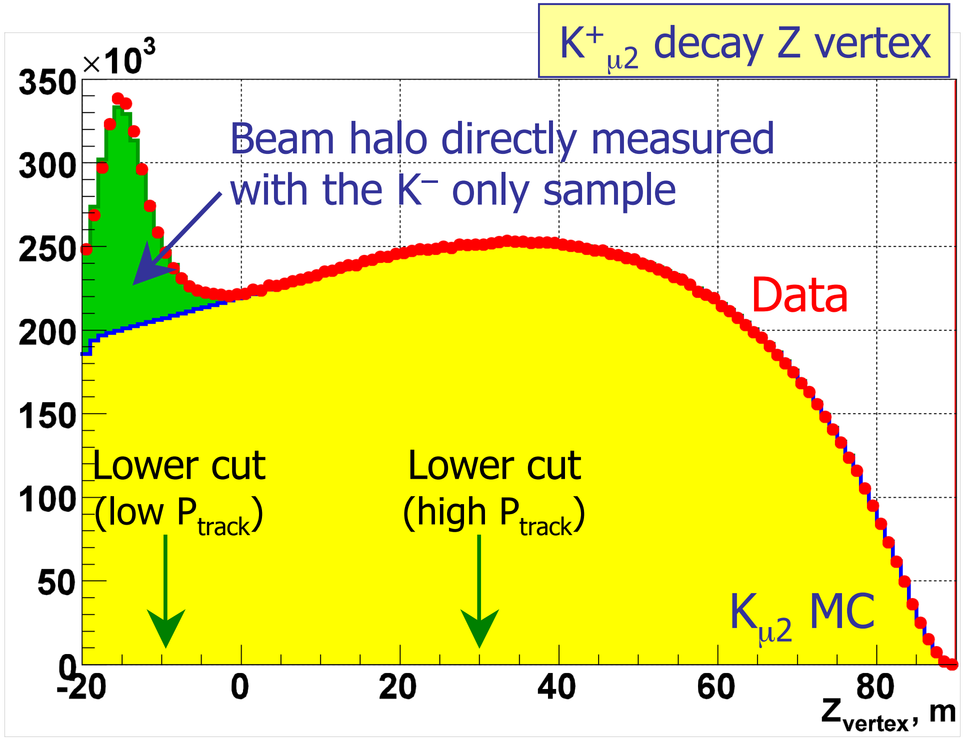
- Halo background much higher for K_{e2}^- (~20%) than for K_{e2}^+ (~1%).
- Halo background in the $K_{\mu2}$ sample is considerably lower.
- ~66% of the data sample is K^+ only, ~7% is K^- only, ~27% has both
- K^+ halo component is measured directly with the K^- sample and vice versa.

1-7% background in K^+/ K^- Pb/no Pb.
The background is measured 0.1-0.2% precision, and strongly depends on decay vertex position and track momentum.
The selection criteria (esp. Z_{vertex}) are optimized to minimize the halo background.

$B/(S+B) = (2.11\pm0.09)\%$

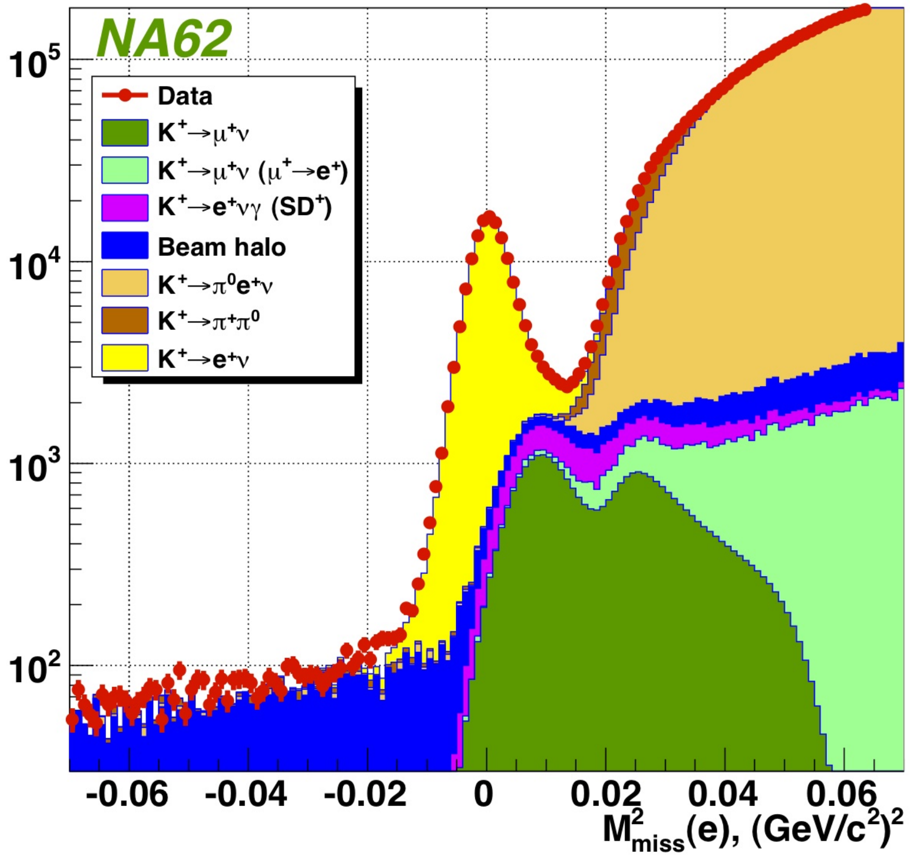
Uncertainty:
1) limited size of control sample;
2) π, K decays upstream vacuum tank.

$K^+_{\mu2}$ decay Z vertex



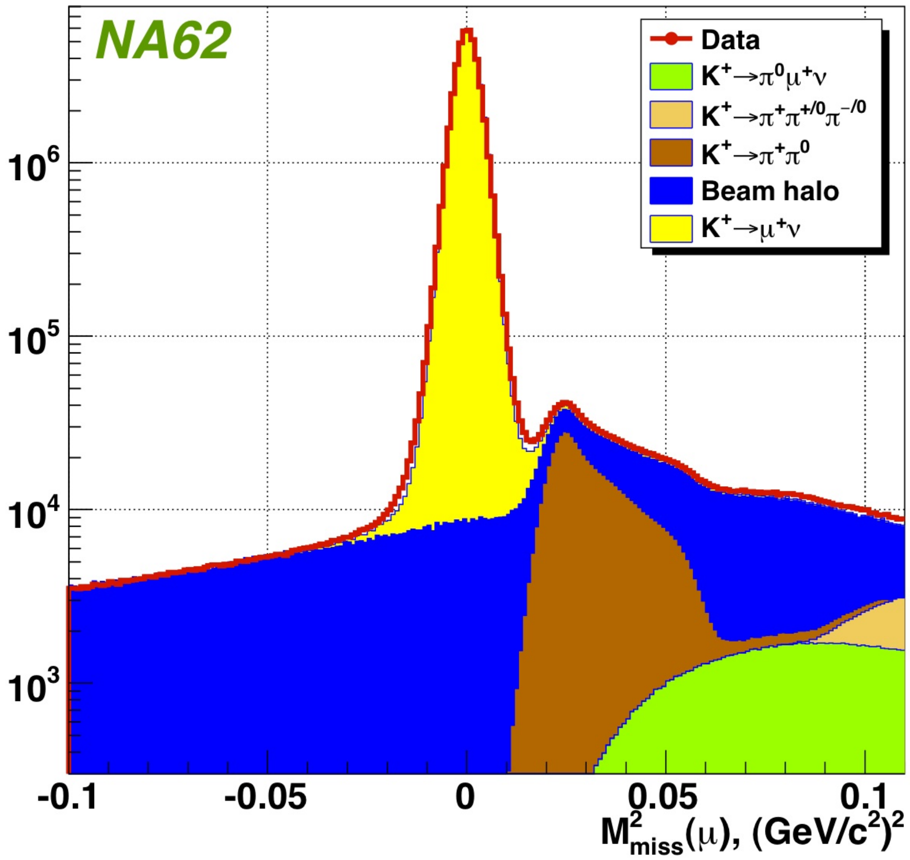
NA62 data set

K_{e2} candidates



145,958 $K^+\to e^+\nu$ candidates.
Positron ID efficiency: (99.28±0.05)%.
B/(S+B) = (10.95±0.27)%.

$K_{\mu2}$ candidates



42.817M candidates
with low background
B/(S+B) = (0.50±0.01)%

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: $r_{\mu e} = 1.003(5)$

→ $r_{\mu e} = 1.002(4)$

Non-kaon measurements:

$\pi\to l\nu$: $r_{\mu e} = 1.0042(33)$ (PRD 76 (2007) 095017)

$\tau\to l\nu\nu$: $r_{\mu e} = 1.000(4)$ (Rev.Mod.Phys. 78 (2006) 1043)

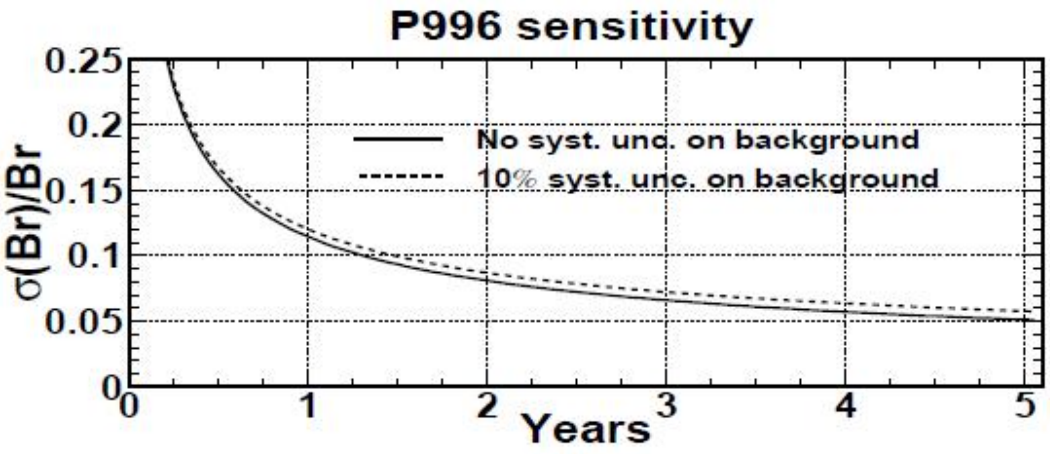
The sensitivity in kaon sector approaches those obtained in the other fields.

FNAL P996 proposal

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

- $9.6 \cdot 10^{13}$ 150 GeV/c p (kaon yield x7)
- TeVatron as a stretcher ring (95% DC), same detector rates (≈ 8 MHz)
- Separated 550 MeV/c K+ beam (K/π ≈ 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 ≈ 4



New detector based on E949 concept, many 10-50% improvements

Competition with NA62 ?

Kaons at Project-X

High-Intensity frontier
path for Fermilab

Expect CD-3: 2014
Start construction: 2015
Complete: 2019

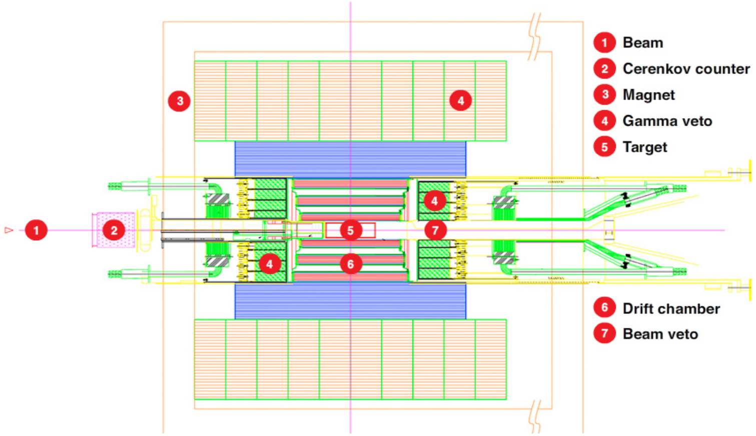
Flux potential for **ultimate** ultra-rare K decay measurements

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

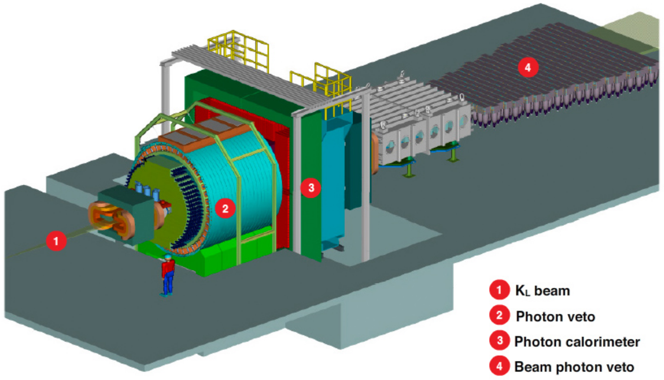
$K_L \to \pi^0 \nu\nu$ experiment:
- Intrinsic high-precision timing:
TOF approach (KOPIO)
beam microbunching (50ps/40ns)
- Round and small beam
(acceptance and bkg rejection)

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

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



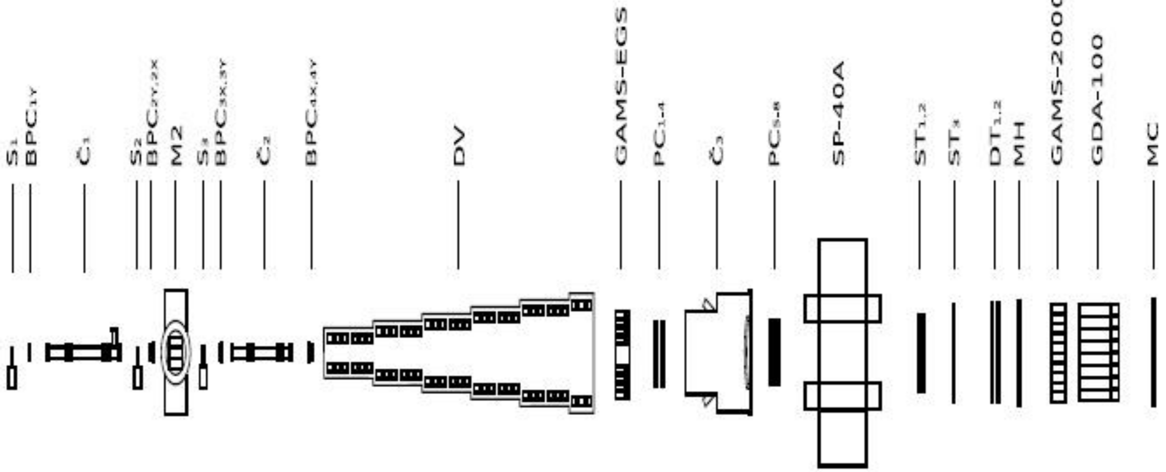
$K_L \to \pi^0 \nu\bar{\nu}$ Experiment



C.Lazzeroni

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

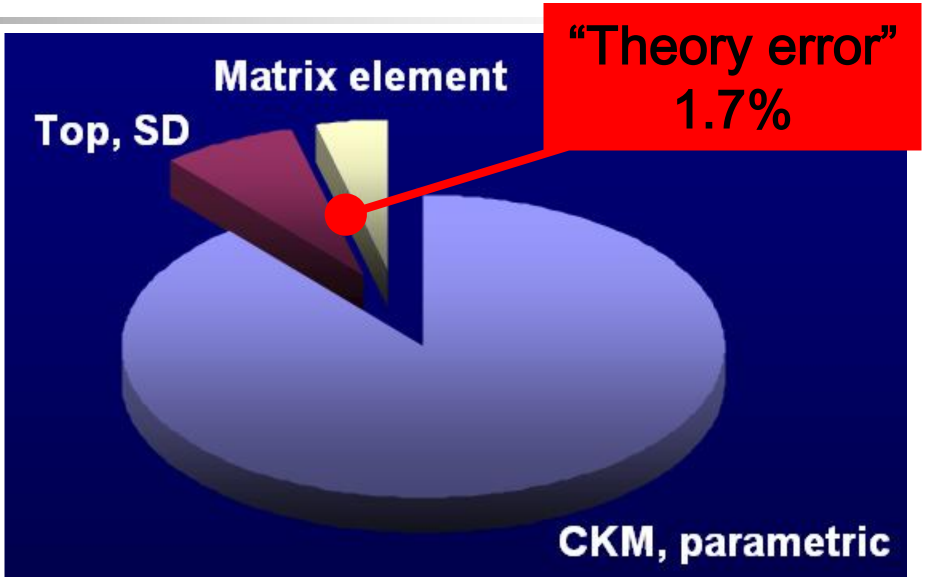


Ongoing R&D for a $K_L \to \pi^0 \nu\nu$ experiment **KLOD**
Neutral pencil beam extracted @ 35 mrad, 10 GeV/c K^0
300 MHz n background: dual-readout spaghetti calorimeter
Aim at **1 SM event** ($S/B \approx 3$) with 10 days of beam

K→πυυ BR predictions

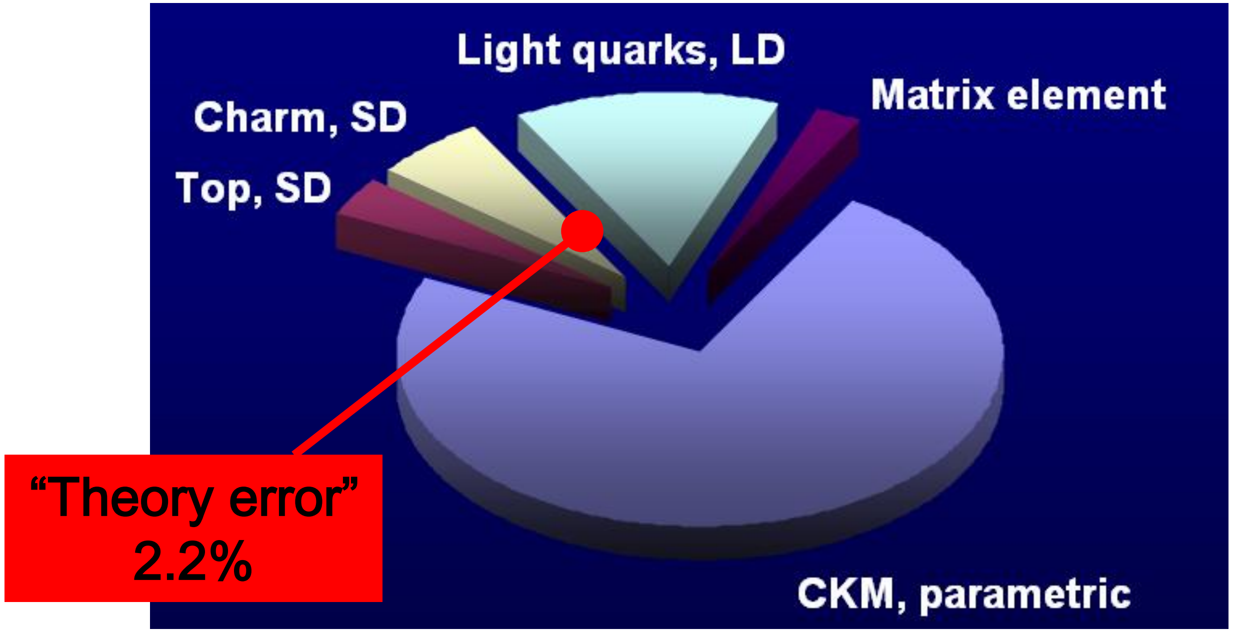
Theoretical improvements make the errors small

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



"Theory error"
1.7%

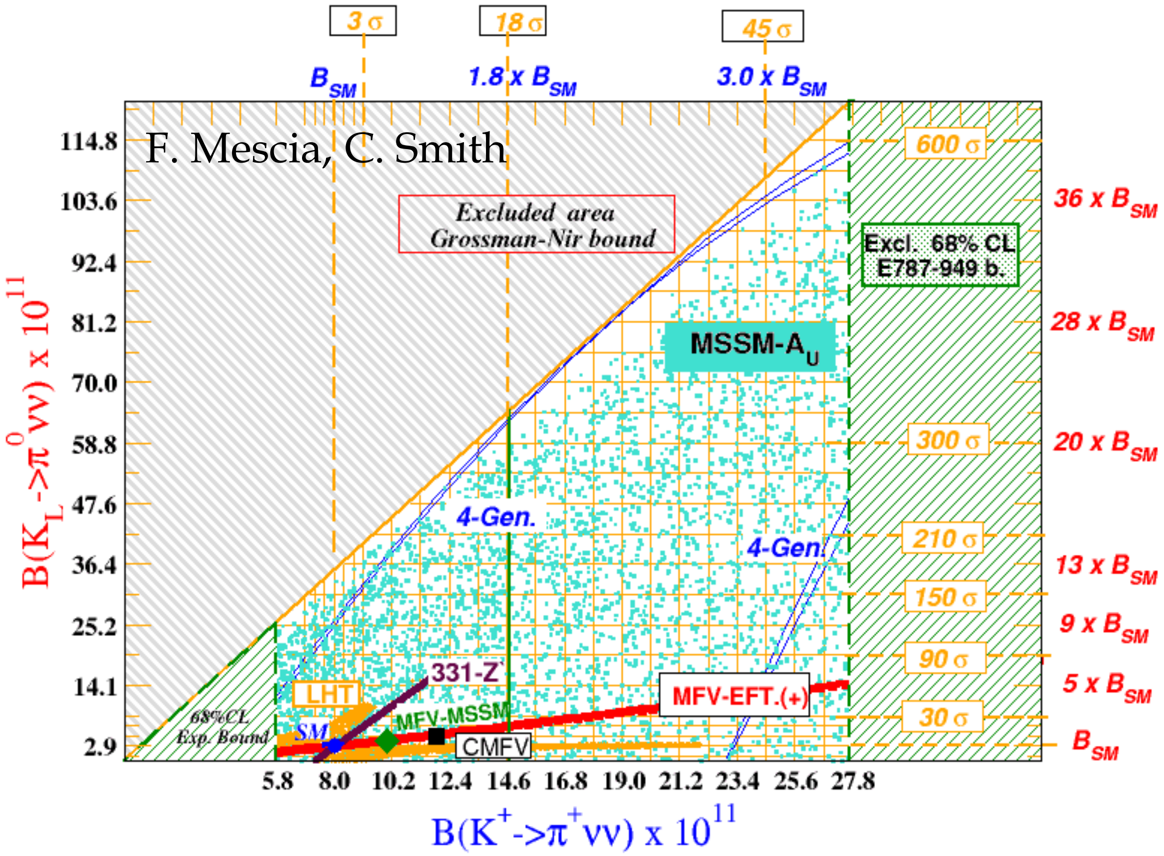
$K^+ \rightarrow \pi^+ \upsilon\upsilon$



"Theory error"
2.2%

Comparable,
unprecedented,
***tiny* theoretical errors**

K→πυυ 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

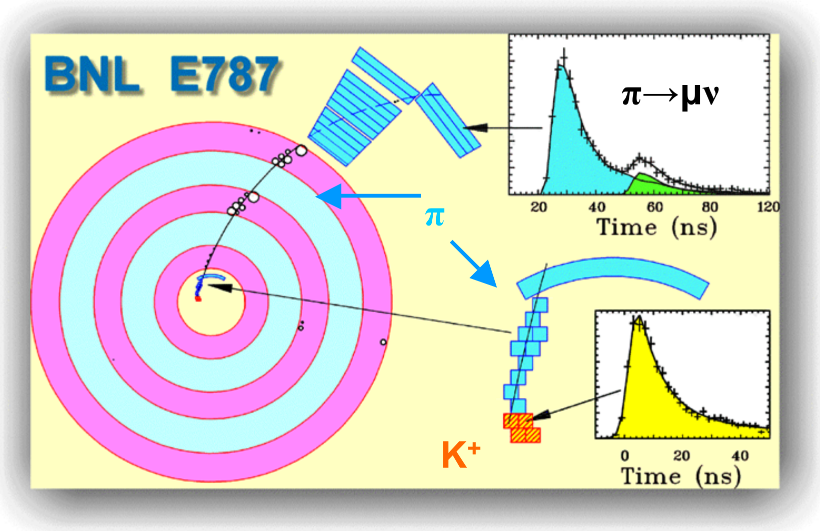
K→πυυ **remains clean** also beyond SM:
single effective υυ operator, calculable Wilson coeff., no long-distance effects

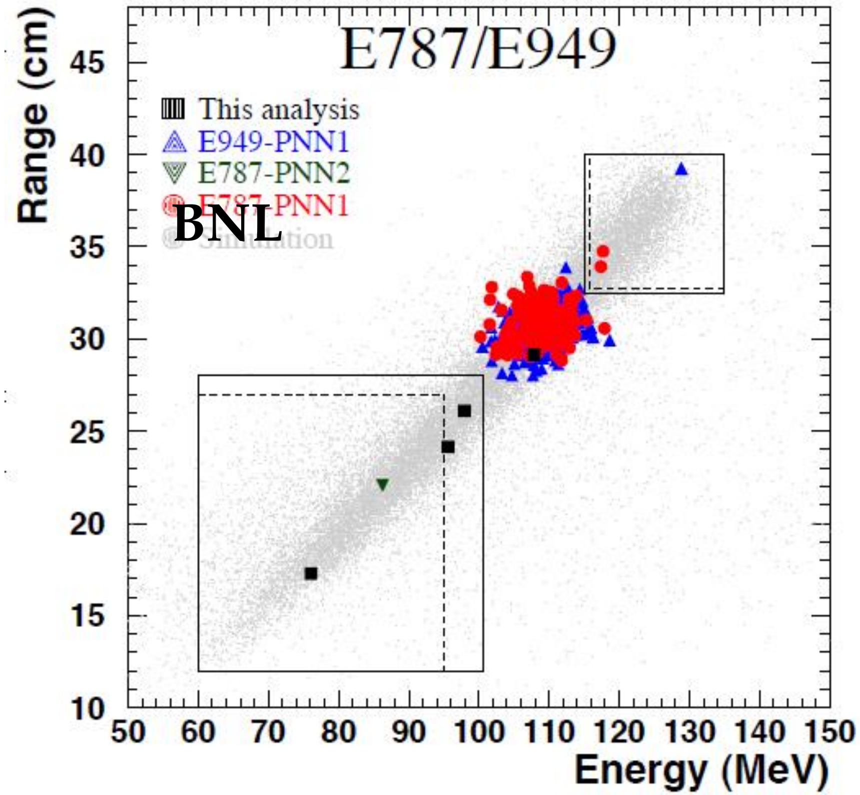
The long quest for $K^+ \to \pi^+ \upsilon\upsilon$

$1.8 \cdot 10^{12}$ Stopped K^+

($211 < P_\pi < 229$ MeV/c)

~ 0.1 % signal acceptance





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