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A precision test of lepton flavour universality in $K^+ \to l^+\nu$ decays by NA62

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for the NA62 collaboration

Birmingham, Bratislava, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati,
Liverpool, Louvain, Mainz, Merced, INR Moscow, Napoli, Perugia, Pisa, IHEP Protvino,
Roma I, Roma II, Saclay, San Luis Potosí, SLAC, Sofia, Torino, TRIUMF

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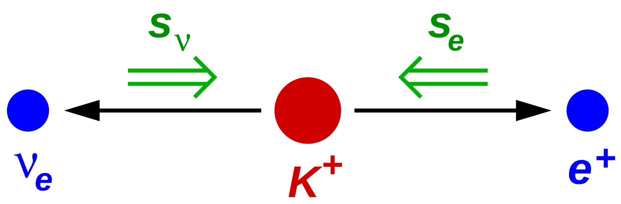
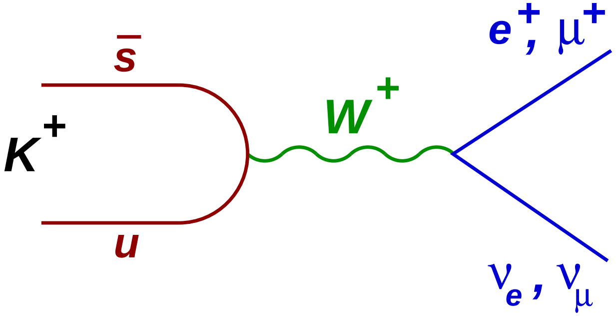
$\mathrm{R_K} = \Gamma(\mathrm{K} \to e\nu)/\Gamma(\mathrm{K} \to \mu\nu)$ in the SM

- **Precision tests** → search for deviations from the SM in rare or forbidden processes
- **Leptonic meson decays: $\mathbf{P^+ \to l^+\nu}$**
  Angular momentum conservation leads to helicity suppression of SM contribution
- Excellent sub-permille accuracy of SM prediction due to cancellation of hadronic uncertainties in the ratio $\mathrm{R_K = K_{e2}/K_{\mu 2}}$
  (similarly, $\mathrm{R_\pi}$ in the pion sector)





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

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

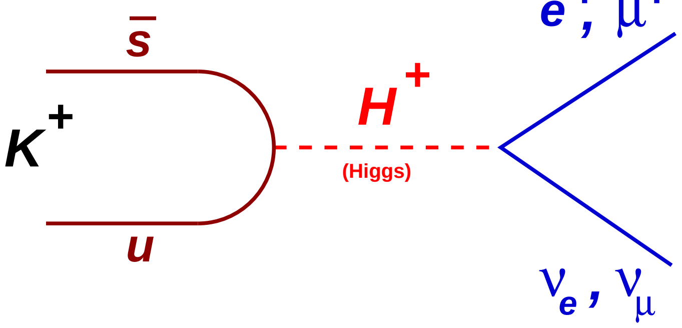
(V. Cirigliano, I. Rosell, JHEP 0710:005 (2007))

- Radiative corrections $\delta R_K^{\mathrm{rad.corr.}}$ (few $\%$) due to the IB part of the radiative $\mathrm{K} \to e\nu\gamma$ process (by definition included in $\mathrm{R_K}$)
- Measurements of $\mathrm{R_K}$ and $\mathrm{R_\pi}$ have long been considered as tests of lepton universality
- Strong helicity suppression of $\mathrm{R_P}$ enhances sensitivity to non-SM effects

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

2HDM (incl. SUSY) - tree level:

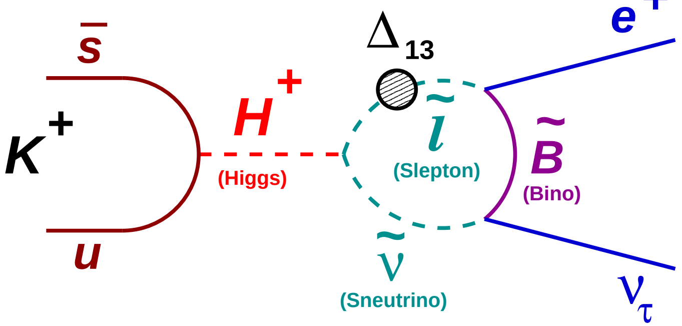
$K^+ \rightarrow l^+\nu$ can proceed via exchange of charged Higgs H^+ instead of W^+
→ ratio R_K remains unchanged



Possible scenario, one loop level:

(Masiero, Paradisi, Petronzio, PRD 74, 2006)

'Loop effects are predicted to lead to **lepton flavour violating (LFV) couplings** $lH^+\nu_\tau$ which give dominant contribution to ΔR_K'



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

Up to ~1 % effect possible in large (not extreme) $\tan\beta$ regime with relatively massive charged Higgs → experimentally accessible !

Example:

$\Delta_{13} = 5\times10^{-4}$, $M_H = 500\,\mathrm{GeV}$, $\tan\beta = 40$:
$R_K^{LFV} \approx R_K^{SM}(1+0.013)$

Analogous SUSY effects in pion decay are suppressed by factor $(m_\pi/M_K)^4 \approx 6\times10^{-3}$

However, large effects expected in B decays due to $(M_B/M_K)^4 \sim 10^4$

Experimental situation

PDG2008: $\mathrm{R_K} = (2.45 \pm 0.11) \times 10^{-5}$ based on three measurements from the 1970's ($4.5\,\%$ accuracy)

2009: KLOE (LNF) final result

$$\boxed{\mathrm{R_K} = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}}$$

$1.3\,\%$ accuracy; ~13800 $\mathrm{K_{e2}}$ candidates, $16\,\%$ background; data from 2001-2005

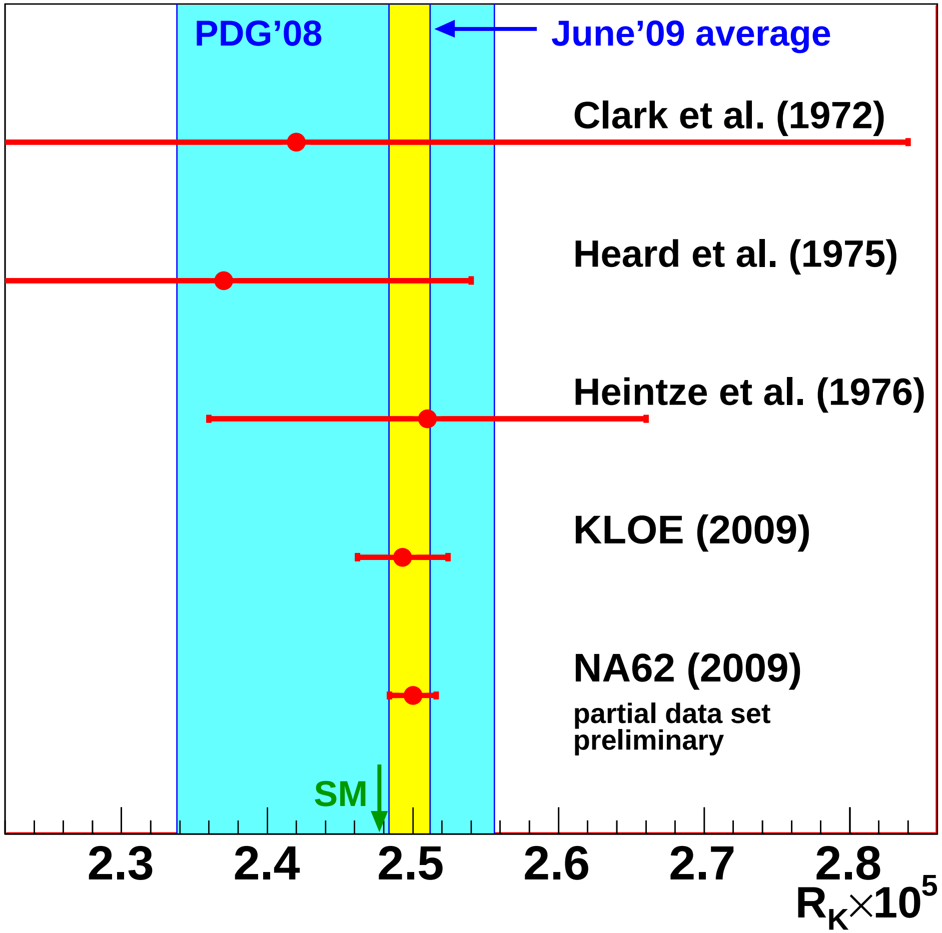
2009: NA62 (CERN)

preliminary result shown at KAON'09

$0.7\,\%$ accuracy; ~51100 $\mathrm{K_{e2}}$ candidates; based on part of 2007 data

Now: NA62 final result !

(same partial data sample)



Goal of NA62 for a stringent test of lepton flavour universality

- Collect ~150000 $\mathrm{K_{e2}}$ decays with < $10\,\%$ background
- Measure $\mathrm{R_K}$ with accuracy better than 0.5% !

NA62 experimental setup and data taking

Beam setup and detector of NA48/2 experiment slightly optimized for precision measurement of R_K

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

Simultaneous K^+ and K^- beams with narrow momentum band p = (74 ± 1.6) GeV/c

$\sim$100 m long beam-defining section followed by 114 m long vacuum decay volume

Data taking:

Four months in 2007 (23/06 - 22/10):
$\sim$400k SPS spills, 300 TB of raw data (90 TB recorded), data preparation finished

Two weeks in 2008 (11/09 - 24/09):
Special data sets allowing reduction of systematic uncertainties

Kaon sign:

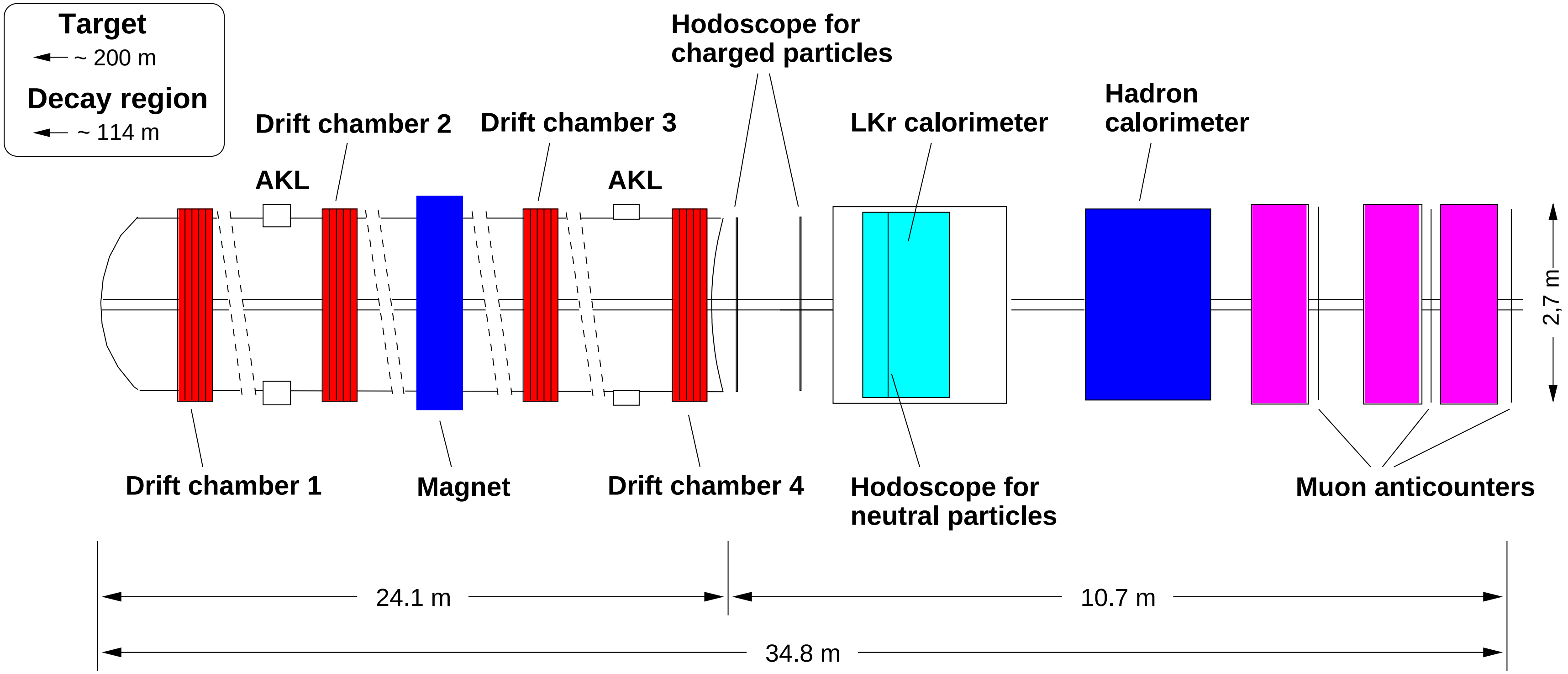
Beam halo background much higher for K^-_{e2} $(\sim 20\,\%)$ than for K^+_{e2} $(\sim 1\,\%)$

$\sim 90\,\%$ of data sample: K^+ only
$\sim 10\,\%$ of data sample: K^- only

$\rightarrow$ Collection of K^+ ONLY and K^- ONLY sets allow direct 'cross-measurements' of beam halo background with excellent precision

The following results presented in this talk are based on a partial data sample $(\sim 40\,\%)$ with pure K^+ beam!

The NA48 detector for NA62



Magnetic spectrometer

- 4 drift chambers with central dipole magnet, 4 views/chamber
- $\Delta p/p = 0.47\,\% + 0.020\,\% \times p$

Scintillator Hodoscope

- Fast trigger + good time resolution

Liquid Krypton EM calorimeter (LKr)

- Quasi homogeneous, $\sim 7\,\mathrm{m}^3$ liquid krypton as active medium (27 X_0 deep $\rightarrow$ fully contains γ's up to 100 GeV)
- Energy resolution $3.2\,\%/\sqrt{E(\mathrm{GeV})}$, spatial resolution $\sim 1\,\mathrm{mm}$ (at 20 GeV)

Measurement method

$\mathbf{K_{e2}}$ and $\mathbf{K_{\mu 2}}$ candidates collected simultaneously

- Measurement independent of kaon flux
- A number of systematic effects cancel at first order in the ratio $\mathrm{R_K}$ (e.g. reconstruction/trigger efficiencies, time-dependent effects).

MC simulation used only to limited extent

- Acceptance correction (only for geometry, not for particle ID or trigger efficiency)
- Dedicated simulation of muon bremsstrahlung

A counting experiment in 10 independent bins of lepton momentum

$$\mathbf{R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{A(K_{\mu 2}) \times f_\mu \times \epsilon(K_{\mu 2})}{A(K_{e2}) \times f_e \times \epsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}}$$

$\mathbf{N(K_{e2}), N(K_{\mu 2})}$: numbers of selected $\mathbf{K_{l2}}$ candidates

$\mathbf{N_B(K_{e2}), N_B(K_{\mu 2})}$: numbers of background events

$\mathbf{A(K_{e2}), A(K_{\mu 2})}$: geometric acceptances (from MC)

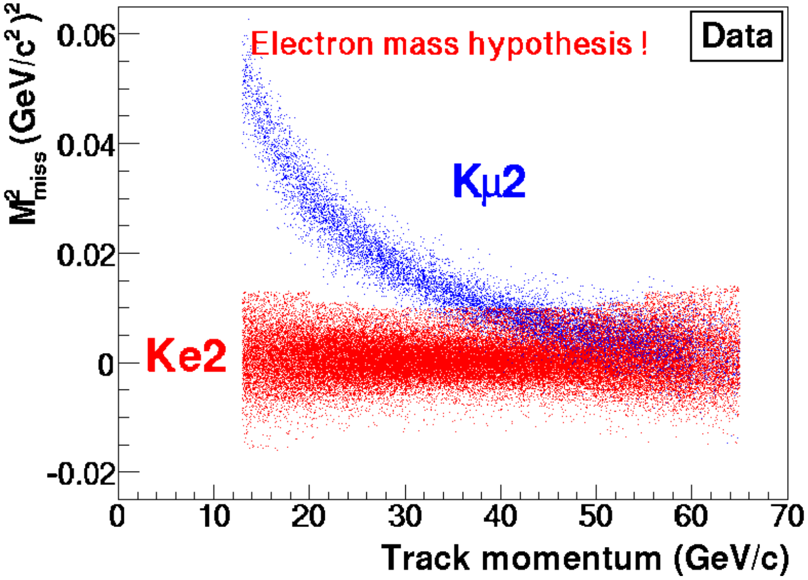
$\mathbf{f_e, f_\mu}$: measured particle ID efficiencies (from data)

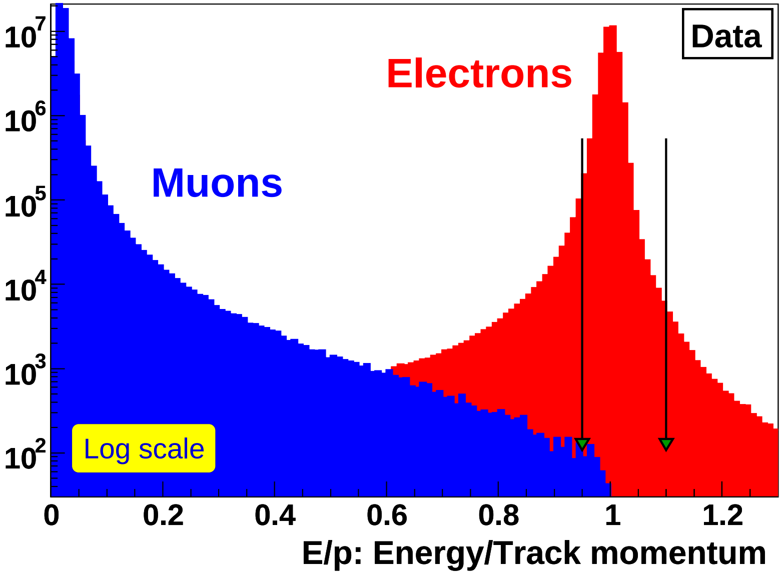
$\mathbf{\epsilon(K_{e2})/\epsilon(K_{\mu 2}) > 99.9\,\%}$: $\mathbf{E_{LKr}}$ trigger efficiency

$\mathbf{f_{LKr} = 0.9980\,(3)}$: global LKr readout efficiency

$\mathbf{D = 150}$: downscaling factor of the $\mathbf{K_{\mu 2}}$ trigger

$\mathrm{K_{e2}}$ and $\mathrm{K_{\mu 2}}$ selection





Large common part (topological similarity)

- One reconstructed track
- Geometrical acceptance cuts
- Decay vertex defined as closest approach of track + nominal kaon axis
- Veto extra LKr energy deposition clusters
- Track momentum 13 - 65 GeV/c

Kinematic separation

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

$\mathbf{P_K}$ average measured with $\mathbf{K^\pm \to 3\pi}$ decays

$\Rightarrow$ No $\mathbf{K_{\mu 2}}$ background in $\mathbf{K_{e2}}$ only for momenta < 25 GeV/c ($\sim \mathbf{15}$ % of data)

Particle identification

$\boxed{\text{E/p}}$ LKr energy deposit / track momentum

< 0.85 for muons, electrons: (0.90-0.95) <E/p <1.10

$\longrightarrow$ powerful $\mu^\pm$ suppression in $\mathrm{e}^\pm$ sample ($\sim \mathbf{10^6}$)

$K_{\mu 2}$ background in K_{e2} sample

Problem:

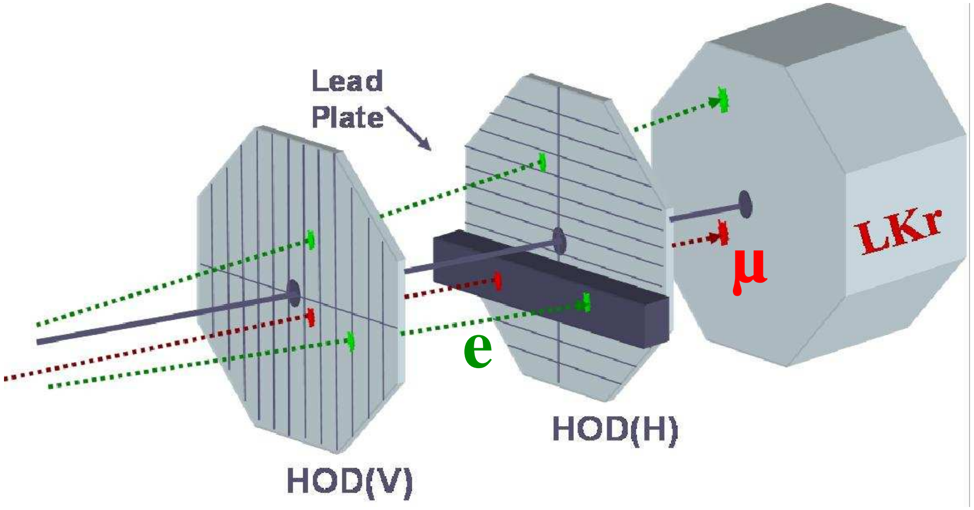
'Catastrophic' energy loss of muons in LKr $\Rightarrow$ Muons with E/p > 0.95 identified as electrons ($P_{\mu e} \sim 3 \times 10^{-6}$ and momentum-dependent)

$P_{\mu e} \,/\, R_K \sim 10\,\%$ $\Rightarrow$ $K_{\mu 2}$ decays represent the major background

Solution: **direct measurement of $P_{\mu e}$**

$\Rightarrow$ Lead wall ($9.2\, X_0$) in front of LKr (between the hodoscope planes)

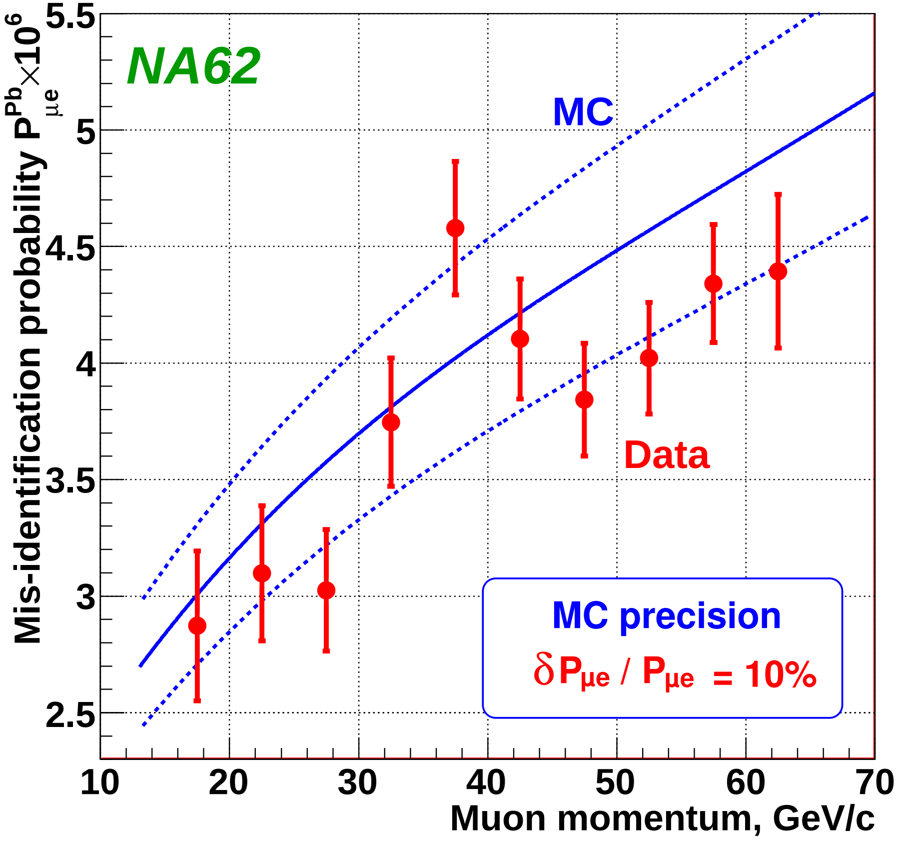
$\Rightarrow$ Tracks traversing the Pb wall with E/p > 0.95 provide pure muon samples with catastrophic bremsstrahlung (positron contamination $< 10^{-8}$)



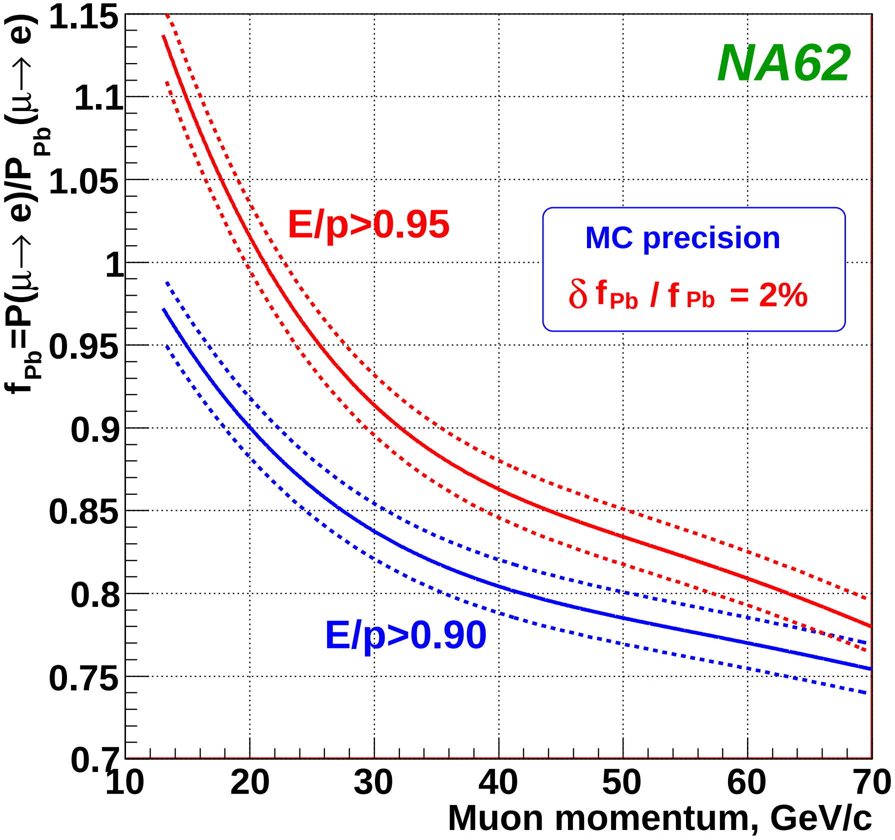
Thickness:	$\sim 10\, X_0$ (Pb + Fe)
Width:	240 cm (= HOD size)
Height:	18 cm (= 3 counters)
Area:	$\sim 20\,\%$ of HOD area
Duration:	$\sim 50\,\%$ of R_K data taking
	+ special muon runs

$\mathrm{K}_{\mu 2}$ background and muon mis-ID

$\mathrm{P}_{\mu e}$ vs momentum (with Pb wall)



Correction factors $f_{\mathrm{Pb}} = \mathrm{P}_{\mu e}/\mathrm{P}^{\mathrm{Pb}}_{\mu e}$ evaluated with a dedicated Geant4-based simulation



$\mathrm{P}_{\mu e}$ is modified by the Pb wall due to:

- muon ionization losses (low p)
- bremsstrahlung in Pb (high p)

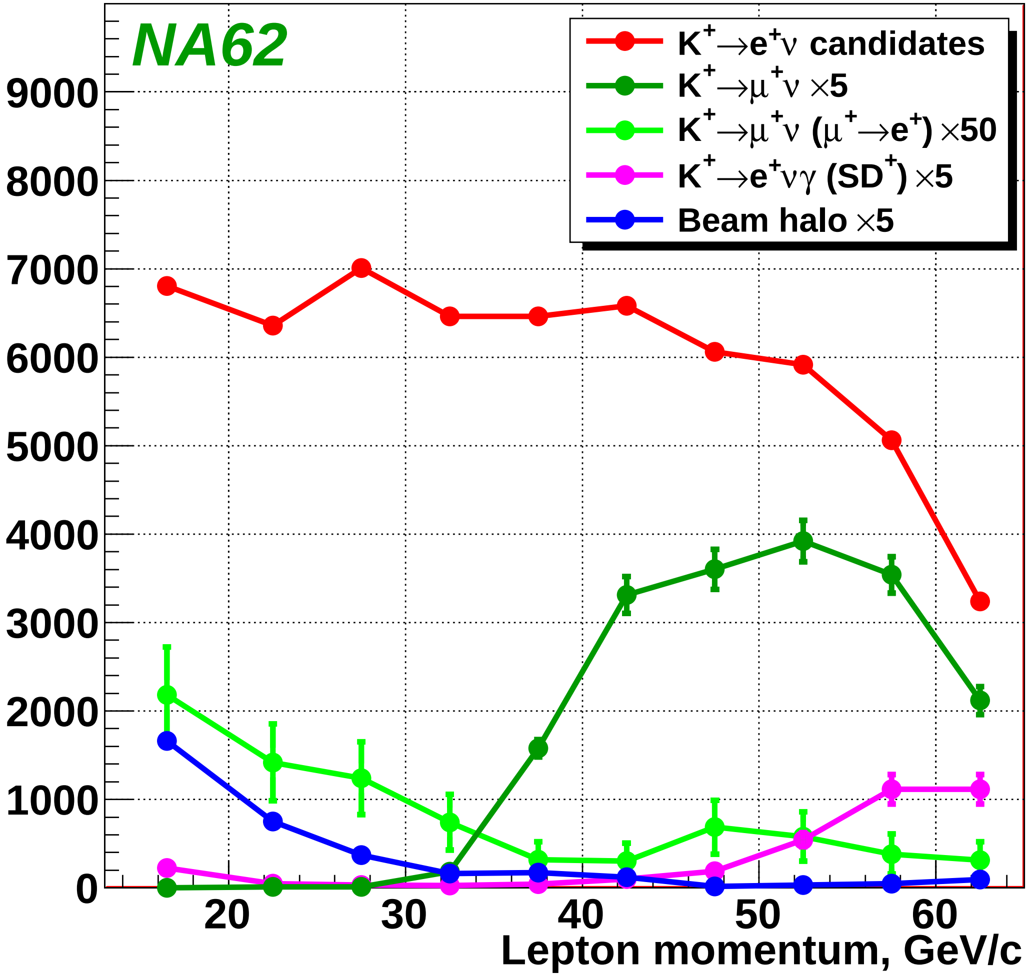
$\Rightarrow \mathrm{K}_{\mu 2}$ bkg: $\boxed{\mathrm{B/(S+B)} = (6.10 \pm 0.22)\,\%}$

Main uncertainties:

limited data sample + MC correction δf_{Pb}

Backgrounds: summary

Statistics in momentum bins



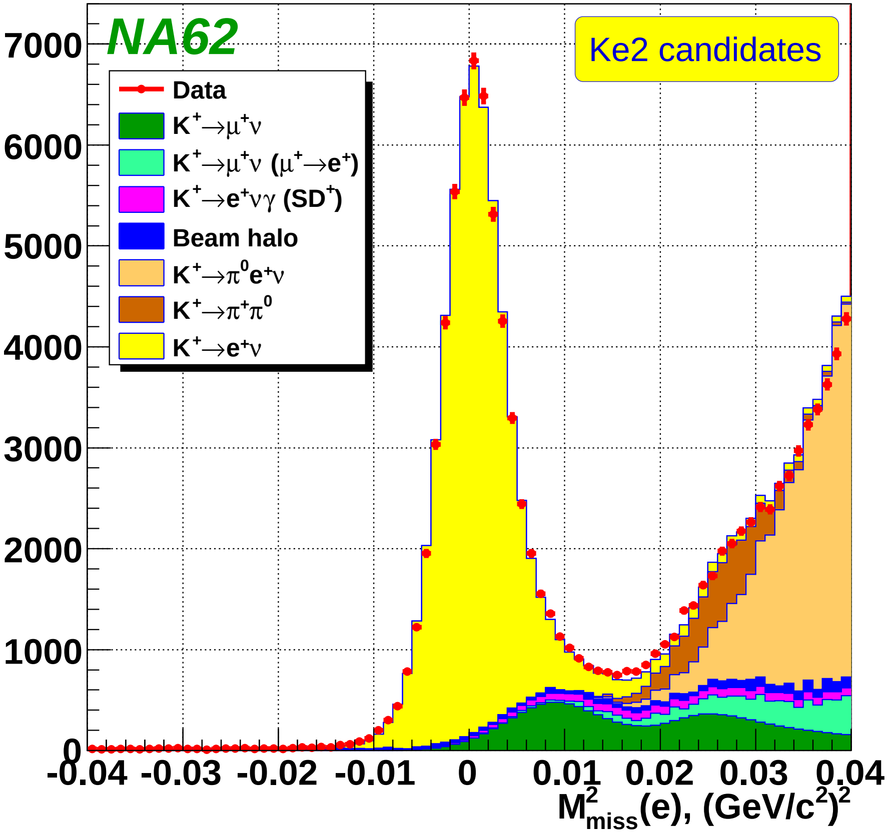
(selection criteria, e.g. for $\mathrm{Z_{vertex}}$ and $\mathrm{M^2_{miss}}$, are optimized individually in each $\mathrm{p_{track}}$ bin)

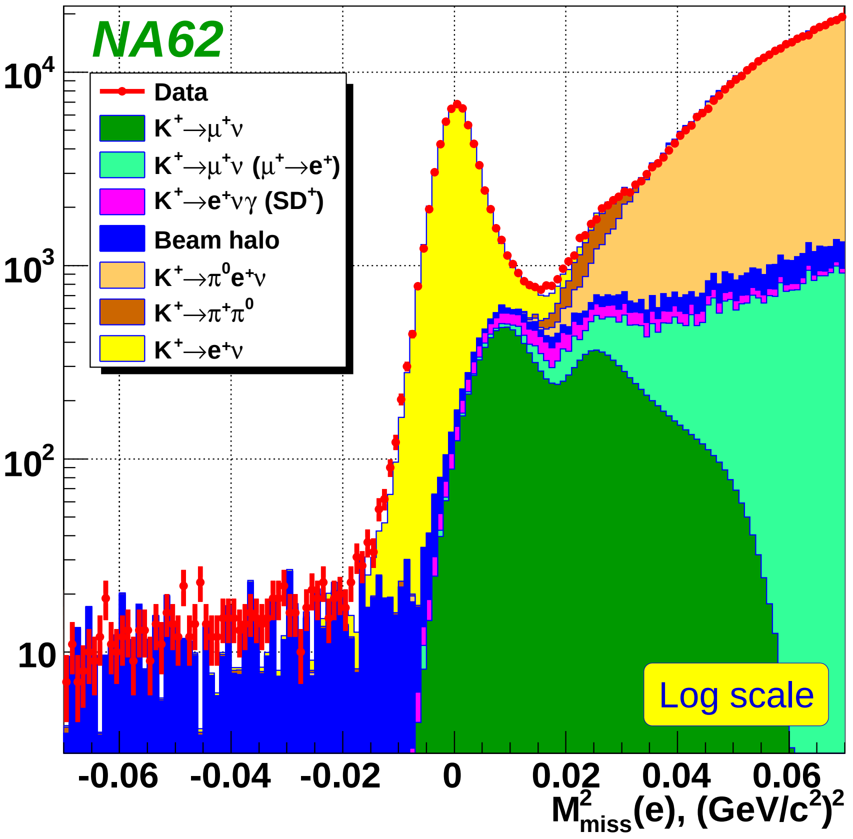
Background summary

Source	B/(S+B)
$\mathrm{K}_{\mu 2}$	$(6.10 \pm 0.22)\,\%$
$\mathrm{K}_{\mu 2}(\mu \to \mathrm{e})$	$(0.27 \pm 0.04)\,\%$
$\mathrm{K}_{\mathrm{e}2\gamma}(\mathrm{SD}^+)$	$(1.15 \pm 0.17)\,\%$
Beam halo	$(1.14 \pm 0.06)\,\%$
$\mathrm{K}_{\mathrm{e}3\,(D)}$	$(0.06 \pm 0.01)\,\%$
$\mathrm{K}_{2\pi\,(D)}$	$(0.06 \pm 0.01)\,\%$
Total	$(8.78 \pm 0.29)\,\%$

Record $\mathrm{K_{e2}}$ sample:
59963 candidates
with low background
B/(S+B) $= (8.8 \pm 0.3)\,\%$

$\mathrm{K_{e2}}$ candidates: $40\,\%$ of data set





59963 $\mathrm{K^+ \to e^+\nu}$ candidates

$(99.27 \pm 0.05)\,\%$ electron ID efficiency

B/(S+B) $= (8.8 \pm 0.3)\,\%$

cf. KLOE: 13.8k candidates (both $\mathrm{K^+}$ and$\mathrm{K^-}$),

$\sim 90\,\%$ electron ID efficiency, $16\,\%$ bkg.

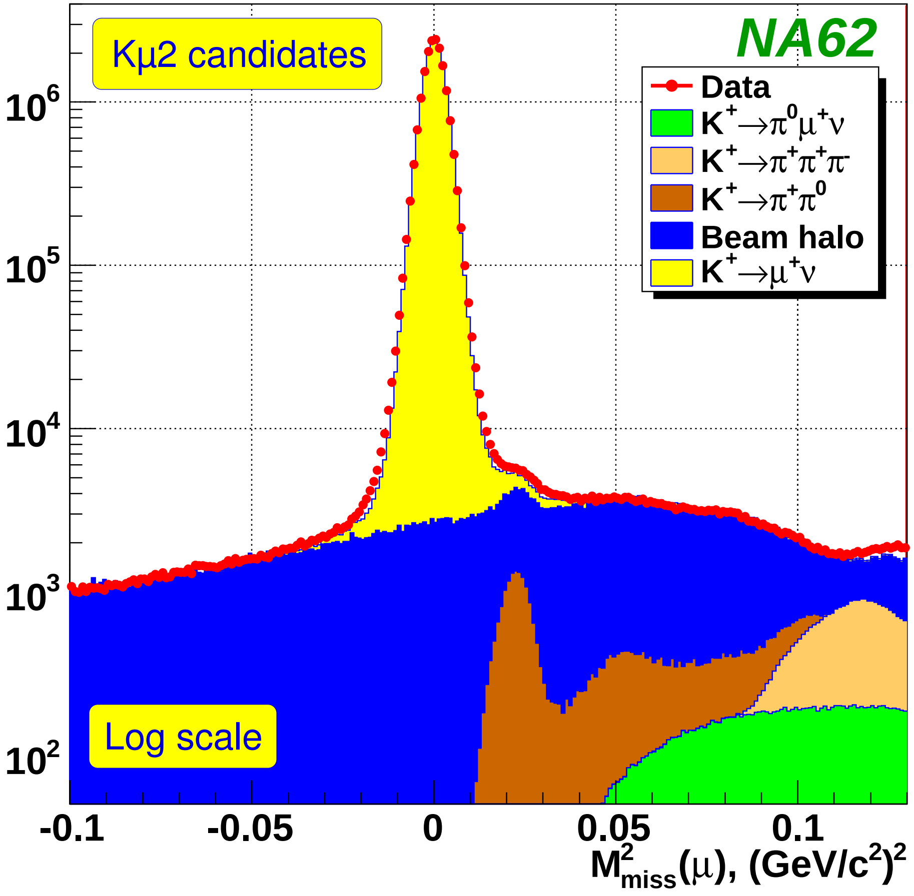
NA62 estimated total $\mathrm{K_{e2}}$ sample:

$\sim$130k $\mathrm{K^+}$ and 20k $\mathrm{K^-}$ candidates

Proposal (CERN-SPSC-2006-033):

150k candidates

$K_{\mu 2}$ candidates: $40\ \%$ of data set

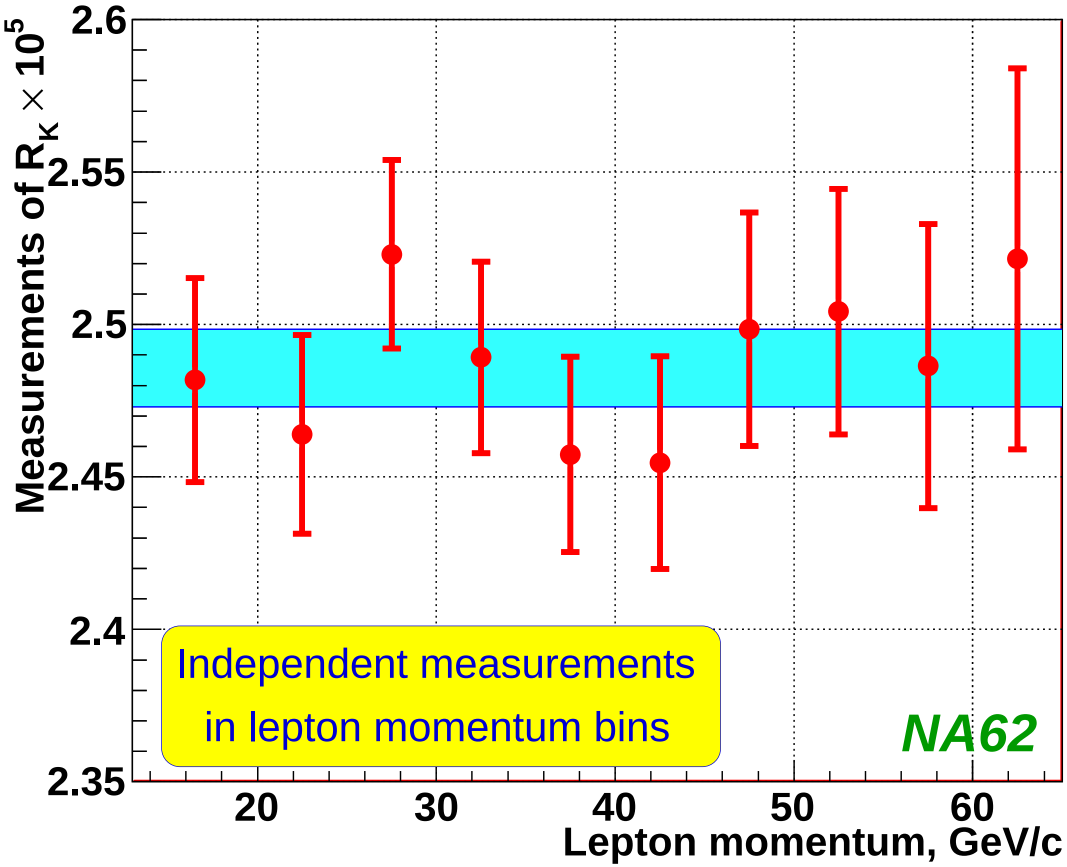


The only significant background source is the beam halo.

18.03M $K^+ \to \mu^+\nu$ candidates with very low background B/(S+B) $= (0.38 \pm 0.01)\ \%$

($K_{\mu 2}$ trigger was pre-scaled by D = 150)

NA62 final result ($40\,\%$ of data set)



Uncertainties summary

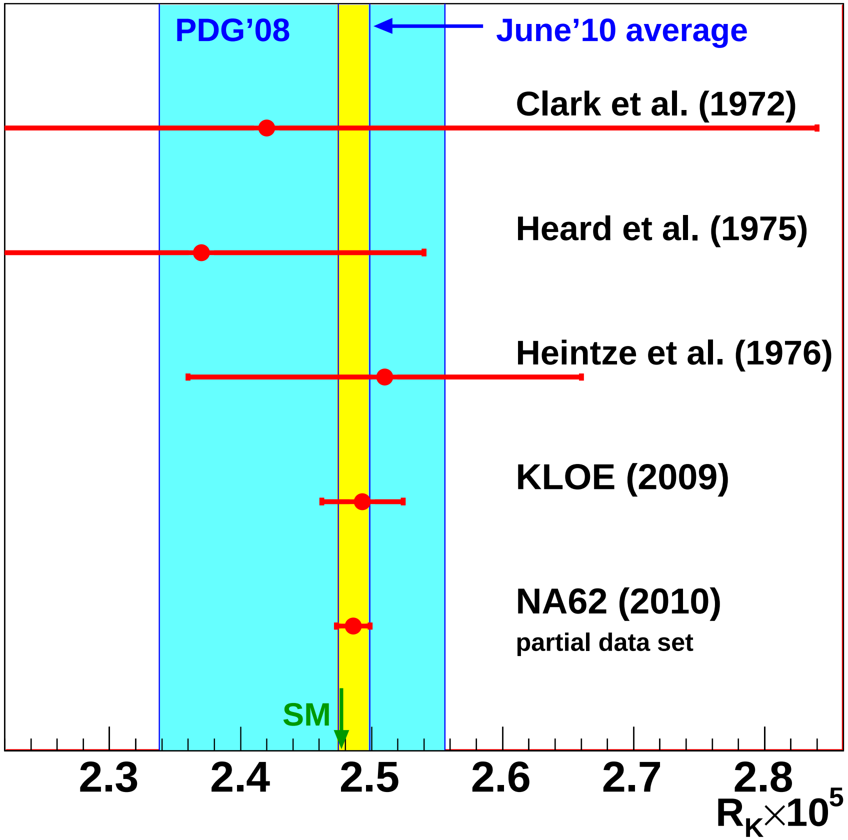
Source	$\delta R_K \times 10^5$
Statistical	0.011
$K_{\mu 2}$	0.005
$K_{e2\gamma}(SD^+)$	0.004
Beam halo	0.001
Positron ID	0.001
Acceptance	0.002
DCH calibration	0.001
1TRK trigger	0.002
Total	0.013

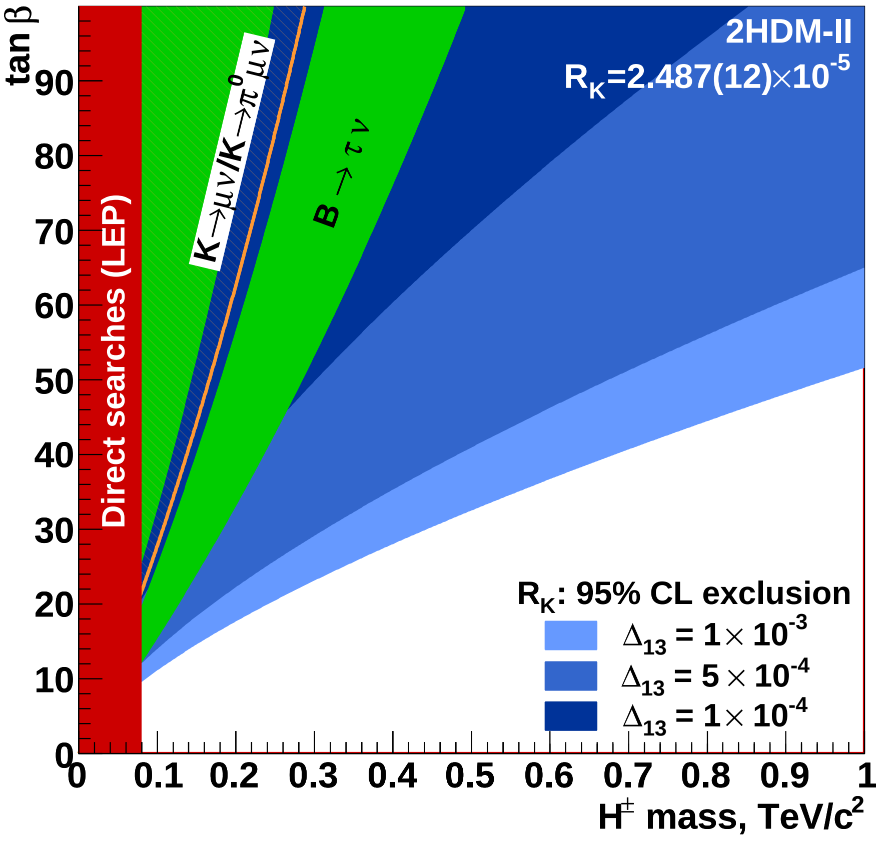
$$
\begin{aligned}
R_K &= (2.486 \pm 0.011_{stat} \pm 0.007_{syst}) \times 10^{-5} \\
&= (2.486 \pm 0.013) \times 10^{-5}
\end{aligned}
$$

$\Rightarrow$ **$0.52\,\%$ precision !**

The whole sample will allow statistical uncertainty $\sim$0.3 % total uncertainty of $\sim \mathbf{0.4}\,\%$

R_K: world average and New Physics limits





World average	$R_K \times 10^5$	Precision
March 2009	2.467 ± 0.024	$0.97\,\%$
June 2010	2.487 ± 0.012	$0.48\,\%$

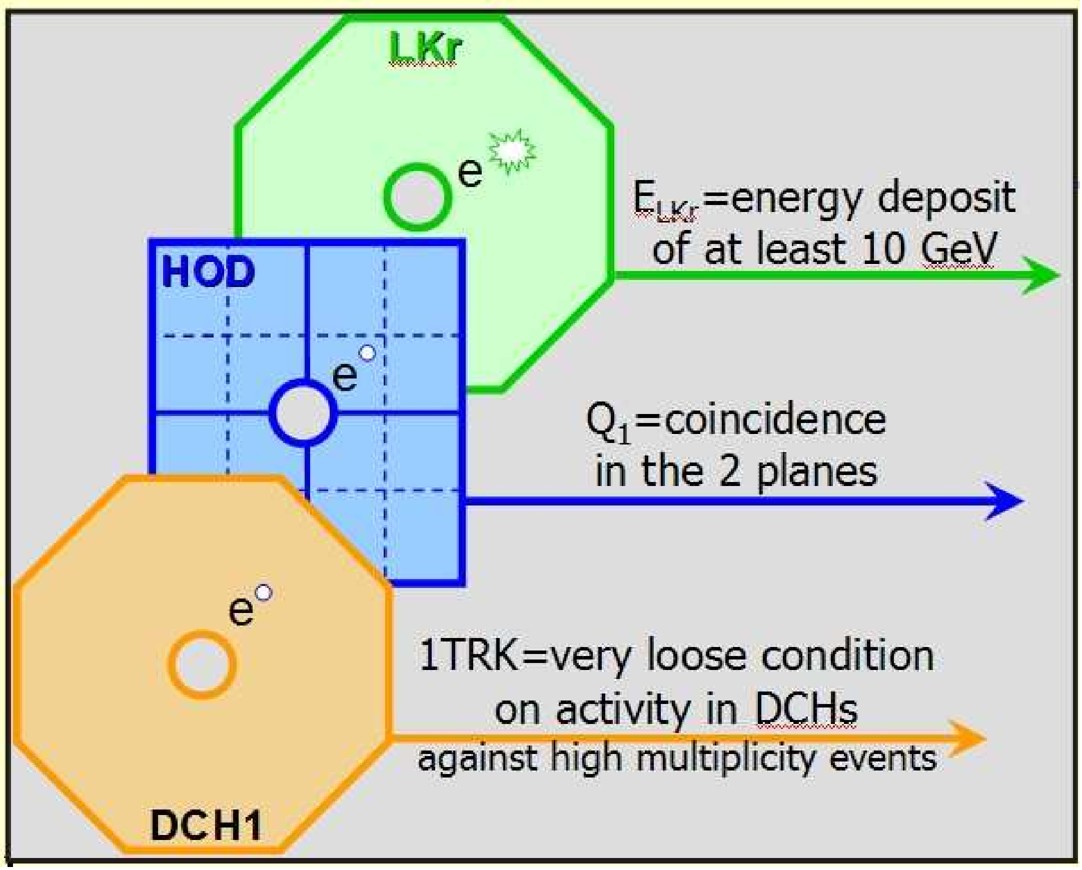
For non-tiny values of the LFV slepton mixing parameter Δ_{13}: Sensitivity to $H^{\pm}$ in $R_K = K_{e2}/K_{\mu2}$ is better than in $B \to \tau\nu$.

Conclusions

- Due to the helicity suppression of $\mathrm{K_{e2}}$, the measurement of $\mathrm{R_K} = \Gamma_{\mathrm{K_{e2}}}/\Gamma_{\mathrm{K_{\mu 2}}}$ is well-suited for a stringent test of lepton universality.
- The NA62 2007 run has increased the world $\mathrm{K_{e2}}$ sample by more than an order of magnitude. Data taking had been optimized for this measurement.
- Final result based on ($\sim 40\,\%$) of the NA62 $\mathrm{K_{e2}}$ sample: $\mathrm{R_K} = (2.486 \pm 0.013) \times 10^{-5}$ with a record accuracy of $\sim 0.5\,\%$, being compatible with the SM prediction.
- With full data sample, overall uncertainty of 0.4 $\%$, as declared in the proposal, is within reach.
- Future experiments for further improvement: NA62 phase II (2013-2015) and KLOE-2 (> 2010) aim at $\sim$0.2 $\%$ and $\sim$0.4 $\%$ precision.

Spare Slides

Trigger logic



E_{LKr}=energy deposit of at least 10 GeV

Q_1=coincidence in the 2 planes

1TRK=very loose condition on activity in DCHs against high multiplicity events

Minimum bias trigger used

(high efficiency, but low purity)

$\mathbf{K_{e2}}$ **condition:**

$\mathbf{Q_1 \times E_{LKR} \times 1TRK}$

Purity $\sim 10^{-5}$

$\mathbf{K_{\mu 2}}$ **condition:**

$\mathbf{Q_1 \times 1TRK/D}$

Downscaling (D) 50 to 150

Purity $\sim 2\,\%$

- Efficiency of $\mathrm{K_{e2}}$ trigger: monitored with $\mathrm{K_{\mu 2}}$ and other control triggers.
- Different trigger conditions for signal and normalization !

Beam halo background

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

Reminder:

- Beam halo background much higher for $\mathrm{K}^-_{\mathrm{e2}}$ ($\sim 20\,\%$) than for $\mathrm{K}^+_{\mathrm{e2}}$ ($\sim 1\,\%$)
- $\sim 90\,\%$ of data sample: K^+ Only; $\sim 10\,\%$ of data sample: K^- Only

→ K^+ component Directly measured with K^- Only sample (and vice versa)

Method:

- We always produce simultaneous K^+ and K^- beams
- K^- Only beam means, we block the K^+ beam (but not its muon halo !)
- Selecting a $\mathrm{K}^+ \to \mathrm{e}^+\nu$ candidate in the K^- Only sample by definition selects a K^+ beam halo event

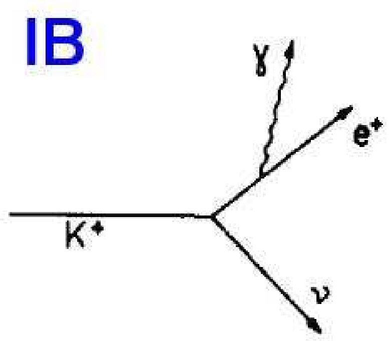
Result: B/(S+B) $= (1.14 \pm 0.06)\,\%$

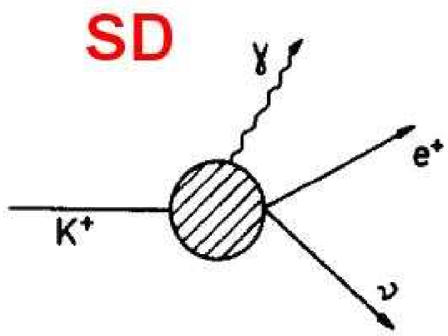
→ Uncertainty due to limited size of control data sample

→ 2008 K^- sample will improve precision (double statistics)

Radiative $\mathrm{K}_{e2\gamma}$ process

By definition, SM prediction for R_{K} includes only IB part of the radiative $\mathrm{K}_{e2\gamma}$ process



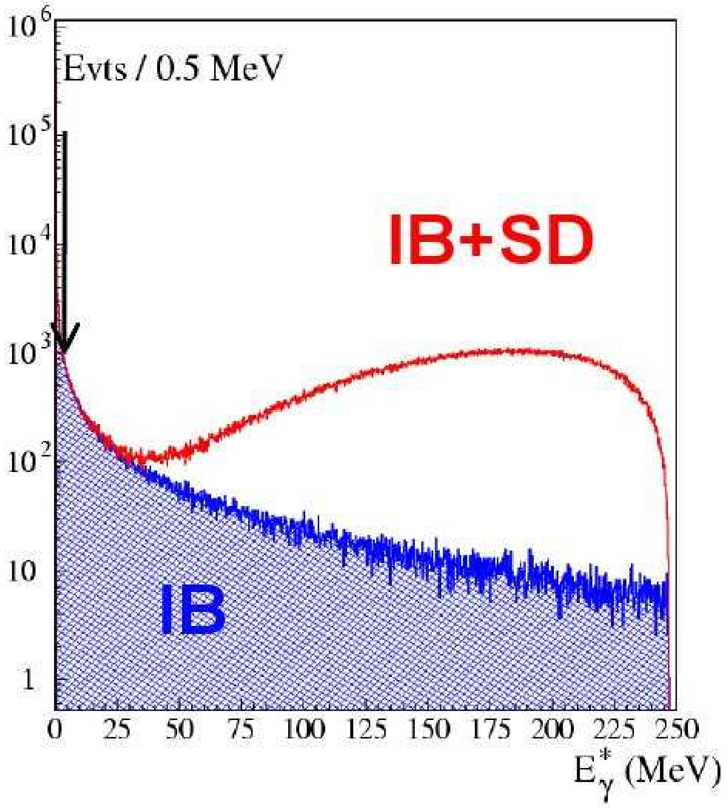


→ Regard SD part as background

→ Rate is similar to that of K_{e2}

→ Known with poor precision of $\sim 15\,\%$

PDG 2008: $\mathrm{BR} = (1.52 \pm 0.23) \times 10^{-5}$
(Measurements from 1970's)



Background estimate

B/(S+B) $= (1.15 \pm 0.17)\,\%$

We use differential decay rate from new KLOE measurement ($\mathrm{BR} = (1.34 \pm 0.06) \times 10^{-5}$), but scale error by factor of 3 (as suggested by stability checks)
Precision will be significantly improved by dedicated NA62 analysis !

Electron ID efficiency fe

To measure fe, select samples of pure electrons !

$\mathrm{K}^{\pm} \rightarrow \pi^0 \mathrm{e}^{\pm} \nu$ decays (charged K_{e3})

- Collected during main $\mathrm{R_K}$ data taking, perfectly reflecting the conditions for K_{e2}.
- Huge statistics ($\sim$40 million K_{e3} decays), allowing to measure efficiency even for single cells of the LKr calorimeter.
- Limited momentum range $p < 50\,\mathrm{GeV}/c$.

$\mathrm{K_L} \rightarrow \pi^{\pm} e^{\mp} \nu$ decays (neutral K_{e3})

- Collected in a special 15h $\mathrm{K_L}$ run.
- Ten times less statistics compared to charged mode.
- Covers whole track momentum range due to broad $\mathrm{K_L}$ momentum spectrum.

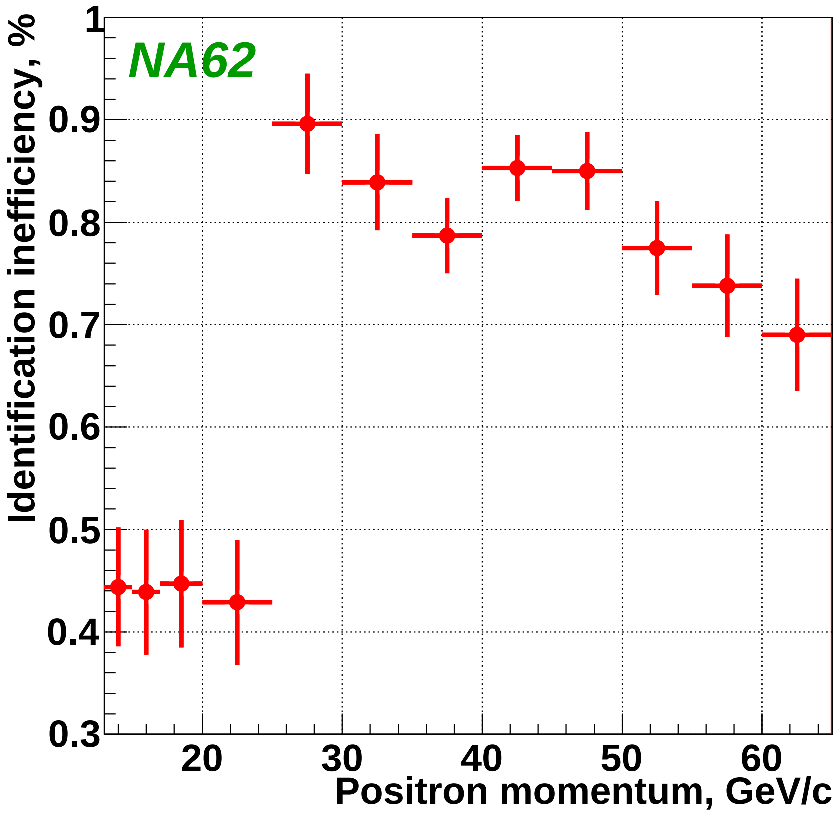
Measure fe as function of track momentum !

$\rightarrow$ Combine results from both measurements for momenta up to $50\,\mathrm{GeV}/c$.

$\rightarrow$ Use neutral K_{e3} for high track momenta.

$\rightarrow$ **Important for both modes:** Selections must reflect K_{e2} conditions as well as possible !

Electron ID efficiency fe



Average inefficiency

1 - fe = $(0.73 \pm 0.05)\,\%$

Measurements in bins of 5 GeV/c track momentum (exception: finer binning up to 20 GeV/c for better resolution of local inefficiencies, which peak at lowest momenta)

Good agreement between neutral and charged measurement!

Separate corrections for regions with increased inefficiency

Statistical error negligible, uncertainty due to small differences between charged and neutral ke3 results