Measurement of BR($K \to e\nu$)/BR($K \to \mu\nu$) in the NA62 experiment @ CERN

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on behalf of 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)

DISCRETE 2010
Roma – Università la Sapienza
06-11 December 2010

Outline

- Theory for R_K (SM and beyond SM)
- NA62 phase I : detector (NA48) and data taking periods
- Analysis details and new preliminary result
- World average and conclusions

The ratio R_K

R_K accurately predicted within the SM:

$$R_K = \frac{\Gamma\left(K^\pm \to e^\pm \nu_e\right)}{\Gamma\left(K^\pm \to \mu^\pm \nu_\mu\right)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1 + \delta R_{QED}\right) = \left(2.477 \pm 0.001\right) \cdot 10^{-5}$$

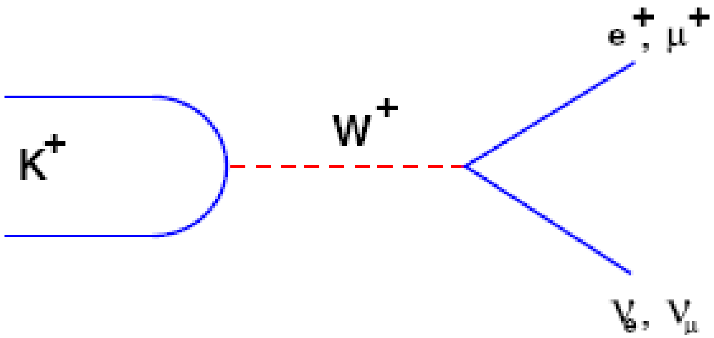
[V. Cirigliano and I Rosell, JHEP 0710:005 (2007)]

ChPT, $O(e^2p^4)$

Helicity suppression

Radiative corrections

Adronic contributions cancel in the ratio



→ Excellent sub-permille accuracy for SM prediction

Recently understood: Helicity suppression of R_K might enhance sensitivity to non-SM effects to an experimentally accessible level.

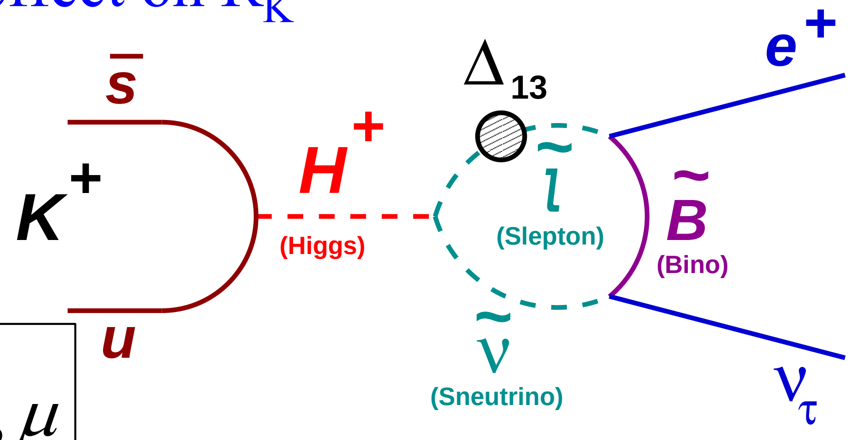
A precise measurement of R_K (R_π) probes μ–e universality and provides a stringent test of the SM.

R_K beyond the SM

SUSY effects (MSSM framework) can modify R_K wrt SM up to 3%

(PRD74 (2006) 011701, JHEP 0811 (2008) 042)

R-parity is the source of new physics effect on R_K



2HDM – tree level

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

→ Does not affect the ratio R_K

$$lH^\pm\nu_\tau \rightarrow \frac{g_2}{\sqrt{2}}\frac{m_\tau}{M_W}\Delta_R^{31}\tan^2\beta \qquad l = e, \mu$$

Δ^{31} is the LFV term connected to helicity suppression in Ke2

2HDM – one-loop level

Dominant contribution to ΔR_K: $H^\pm$ mediated LFV $O(\tan\beta^6)$ with emission of ν_τ

→ R_K enhancement can be experimentally accessible

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

R_K in SUSY

The measurement of R_k produces limits to the value of $\Delta_{31}=\Delta_{31}(m_{H\pm},\tan\beta)$

$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{m_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_{31}|^2\tan^6\beta\right]$$

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

For large tanβ values (still not experimentally excluded) LFV contributions dominate producing sizable (~1%) effects on R_K

Example:

$\Delta_{13}=5\times10^{-4}$, $\tan\beta=40$ and $M_H=500$ GeV/c^2

$$R_K^{LFV} = R_K^{SM}(1 + 0.013)$$

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

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

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

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

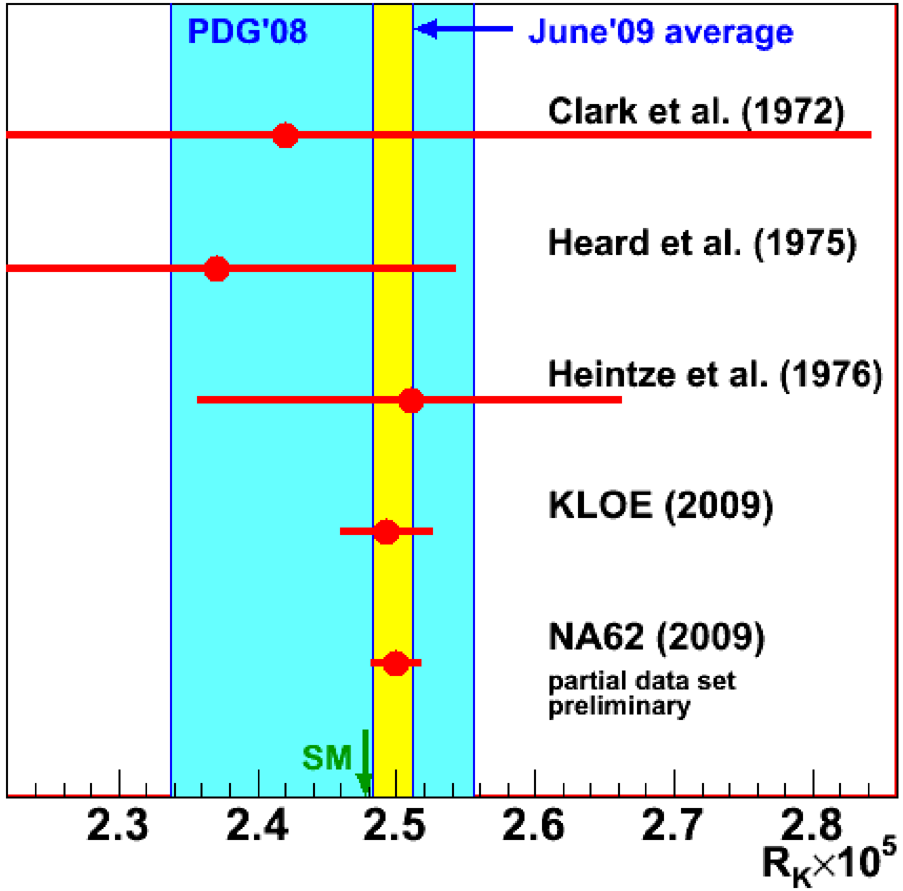
Experimental status

→ PDG'08 average (1970s measurements):
$R_K=(2.45\pm0.11)\times10^{-5}$ $(\delta R_K/R_K=4.5\%)$

New measurements:

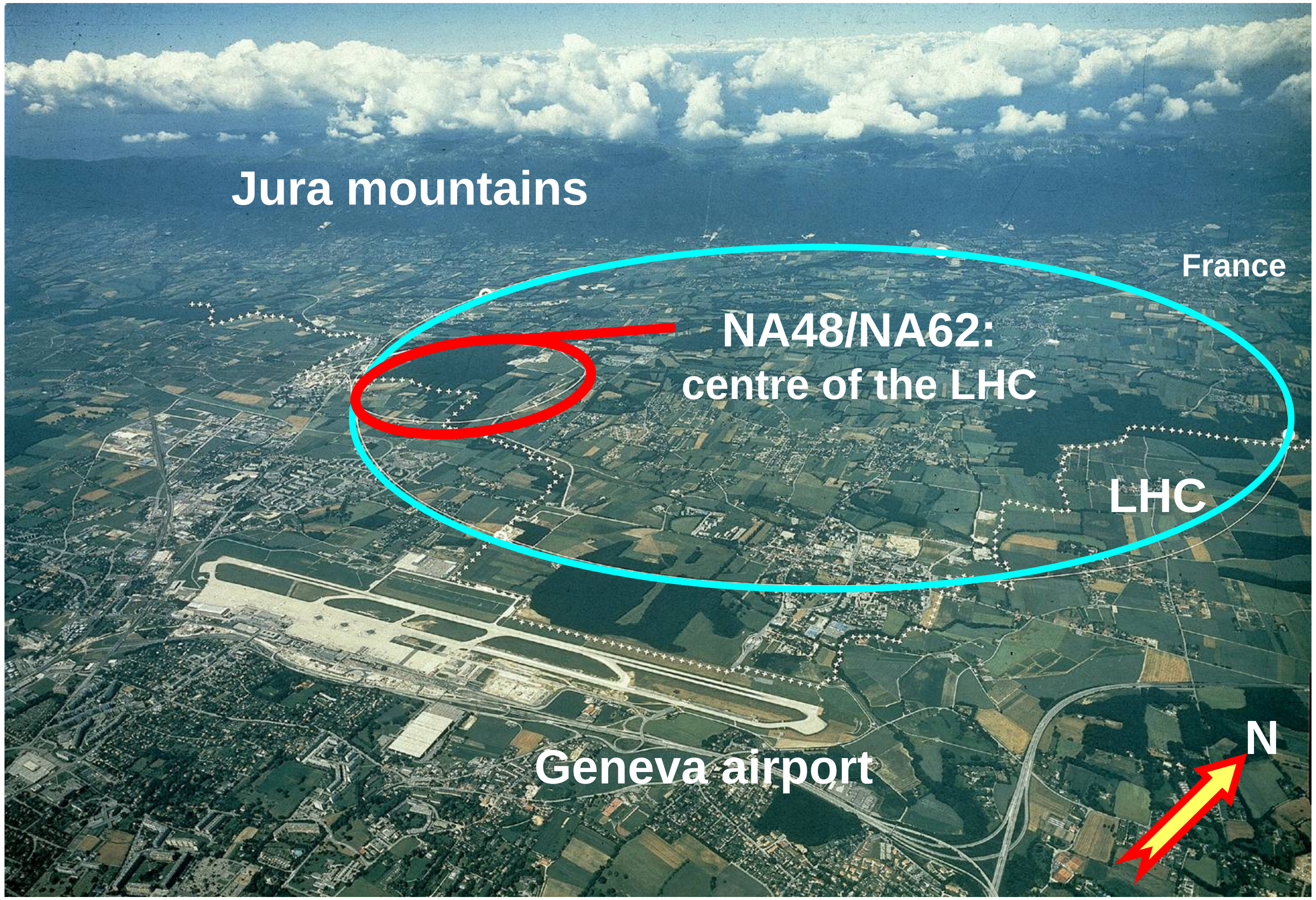
→ 2009: KLOE (LNF), 2001–2005 data.
13.8K K_{e2} candidates, 16% background.
$R_K=(2.493\pm0.031)\times10^{-5}$ $(\delta R_K/R_K=1.3\%)$
(EPJ C64 (2009) 627)

→ 2009: NA62 (CERN), part of 2007 data.
preliminary result presented at Kaon'09:
51.1K K_{e2} candidates,
$R_K=(2.500\pm0.016)\times10^{-5}$ $\delta R_K/R_K=0.7\%$.
(arXiv:0908.3858, 1005.1192)



→ Now: NA62 final result, same data set:
60.0K K_{e2} candidates, $\delta R_K/R_K=0.5\%$.

NA62 experiment



NA62 phase I

Dedicated 2007 run to measure:

$$R_K = \frac{\Gamma\left(K^{\pm} \to e^{\pm}\nu_e\right)}{\Gamma\left(K^{\pm} \to \mu^{\pm}\nu_\mu\right)}$$

NA62 phase II

measurement of the decay

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

(2009-2011 R&D
& construction
2012 start of data taking)

<u>NA62 phase I:</u> Bern ITP, Birmingham, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Mainz, Merced, Moscow INR, Napoli, Perugia, Pisa, IHEP Protvino Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, Torino, TRIUMF

The beam

Data taking conditions optimized for a precision $K_{e2}/K_{\mu 2}$ measurement: a low intensity run with a minimum bias trigger

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

Unseparated secondary positive beam: p=(74.0±1.6) GeV/c. Entrance to the 114m long vacuum decay volume: 2.5×10^{7} particles per SPS spill

View of the NA48/NA62 beamline (2003-2008)

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

K^+ decaying in vacuum tank: 18%

The NA62 phase I detector

Data taking:

Four months in 2007 (23/06–22/10):
~400K SPS spills, 300TB of raw data (90TB recorded); reprocessing finished.

Two weeks in 2008 (11/09–24/09):
special data sets allowing reduction of the systematic uncertainties.

Main detectors:

Magnet spectrometer (4 DCHs):

4 view: redundancy $\Rightarrow$ efficiency

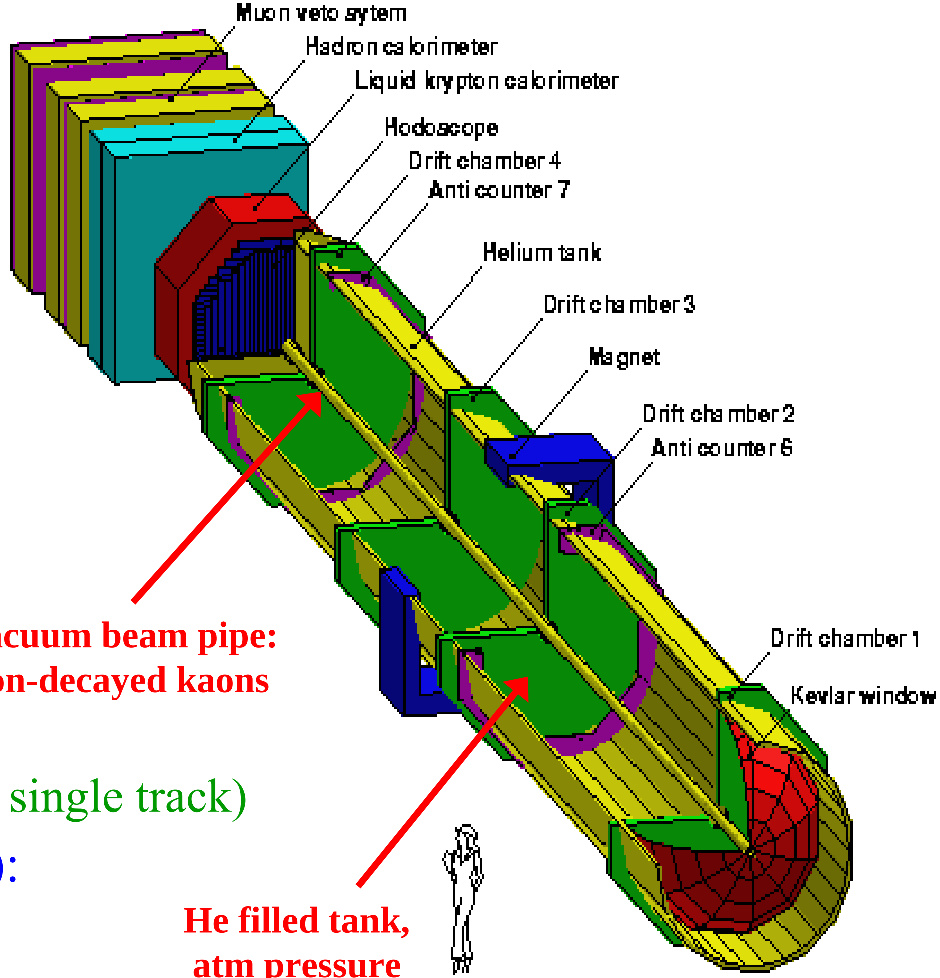
$\sigma(p)/p = 0.47\% + 0.020\%\ p\ [\mathrm{GeV}/c]$

Charged Hodoscope:

Fast trigger and good time resolution (~200ps on single track)

E.m. calorimeter with Liquid Krypton (LKr):
$10\ \mathrm{m}^3$ (~22 t), 1.25 m (27 X_0), 13212 cells
granularity:$2\mathrm{x}2\ \mathrm{cm}^2$, quasi-homogeneous

$\sigma(E)/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV] $\sigma_x = \sigma_y = (0.42/\sqrt{E} + 0.6)\mathrm{mm}$



Analysis strategy

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_{BG}(K_{e2})}{N(K_{\mu 2}) - N_{BG}(K_{\mu 2})} \cdot \frac{Acc(K_{\mu 2}) \cdot \varepsilon_{TR}(K_{\mu 2}) \cdot \varepsilon_{PID}(K_{\mu 2})}{Acc(K_{e2}) \cdot \varepsilon_{TR}(K_{e2}) \cdot \varepsilon_{PID}(K_{e2})} \cdot \frac{1}{f_{LKr}}$$

$N(K_{\ell 2})$ = number of candidates evts

$N_{BG}(K_{\ell 2})$ = number of background evts

$Acc(K_{\ell 2})$ = geometrical acceptance (MC)

$\varepsilon_{TR}(K_{\ell 2})$ = trigger efficiency

$\varepsilon_{PID}(K_{\ell 2})$= Measured PID efficiency (no MC!)

D = 150 = Downscaling of $k_{\mu 2}$ trigger

f_{LKr}=0.9980(3)=Global LKr readout efficiency

- K_{e2} and $K_{\mu 2}$ collected concurrently

→ fluxes cancel in the ratio

several systematic effects cancel at first order

(e.g. reconstruction/trigger efficiencies, time-dependent effects)

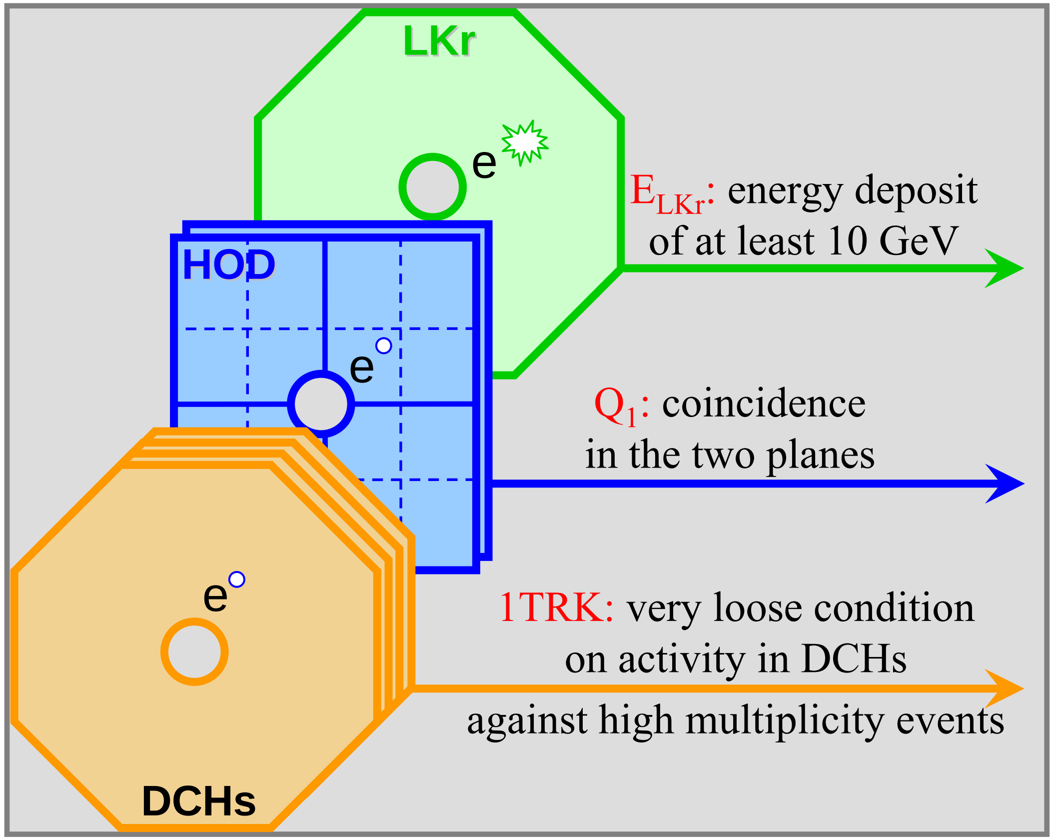
- Counting experiment, independently in 10 lepton momentum bins

(owing to strong momentum dependence of backgrounds and event topology)

The main contribution to systematic error comes from k_{e2} background subtraction

Trigger logic

NA62 trigger in 2007/08:



Minimum bias
(high efficiency, but low purity)
trigger configuration used

K_{e2} condition: $Q_1 \times E_{LKr} \times 1TRK$
Purity $\sim 10^{-5}$

$K_{\mu 2}$ condition: $Q_1 \times 1TRK/D$
downscaling D=150
Purity ~2%

Efficiency of K_{e2} trigger: monitored with $K_{\mu 2}$ & other control triggers.

Different trigger conditions for signal and normalization!

K_{e2} and $K_{\mu2}$ selections

Large common part:

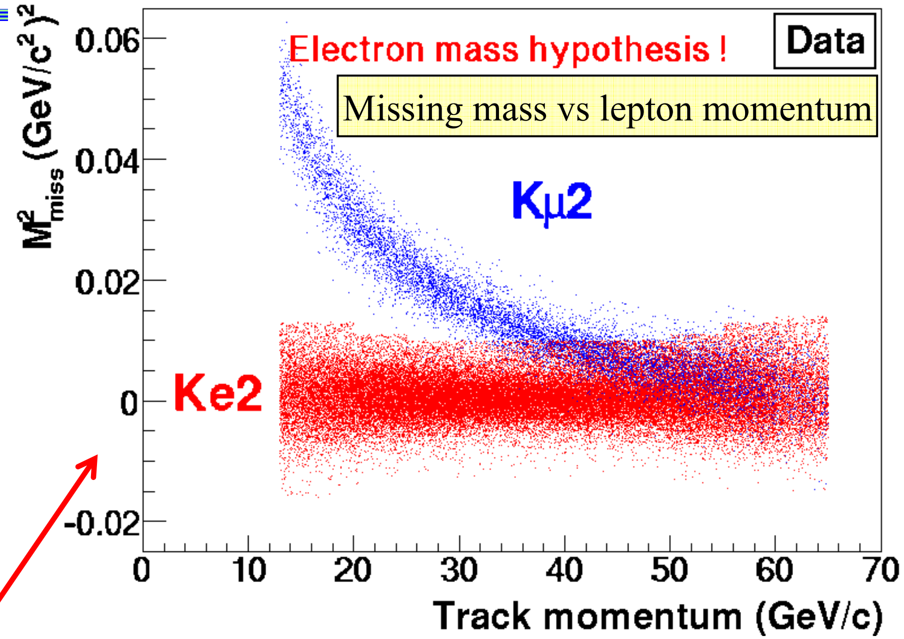
- one reconstructed track (lepton candidate);
- geometrical acceptance cuts;
- K decay vertex: closest approach between lepton track & nominal kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: 13GeV/c<p<65GeV/c.

Kinematic identification:

- Missing mass $M_{miss}^2 = (p_K - p_\ell)^2$

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

→ Sufficient $K_{e2}/K_{\mu2}$ separation at p_{track}<25GeV/c



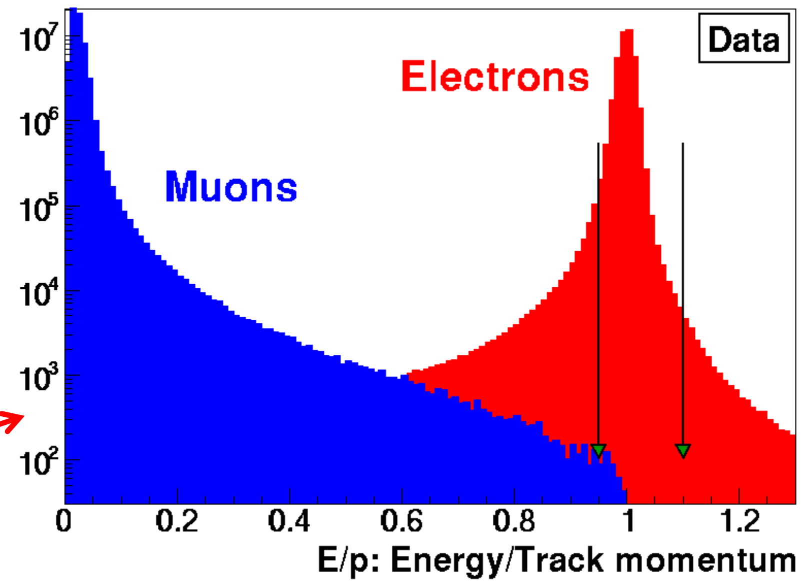
Particle ID (E/p):

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 ($\sim 10^6$)



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

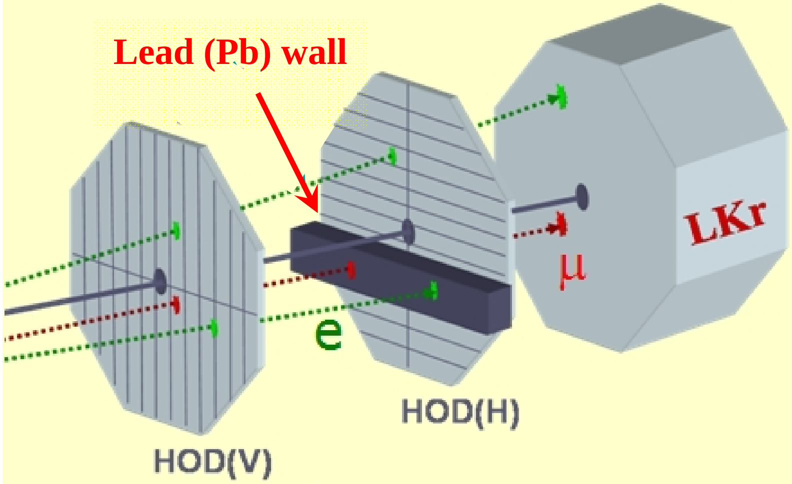
The main systematics come from background subtraction

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



Thickness:	$\sim10X_0$ (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.
$K_{\mu2}$ candidates, track traversing Pb, p>30GeV/c, E/p>0.95: positron contamination $<10^{-8}$.

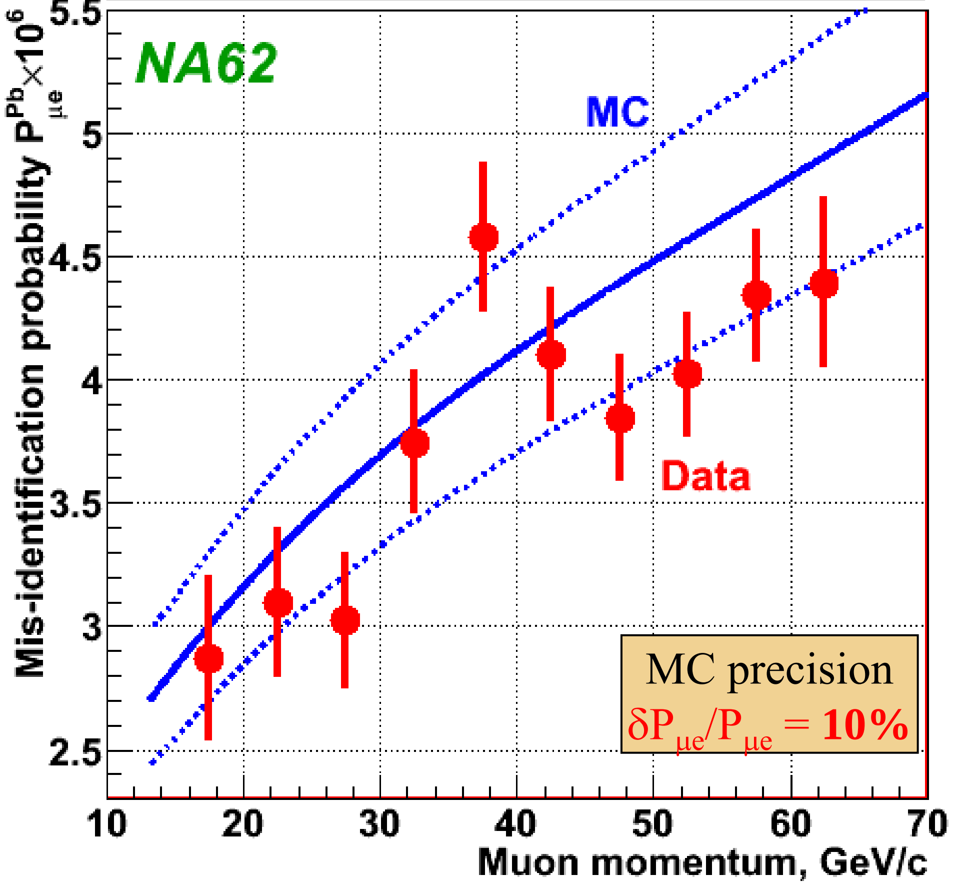
$P_{\mu e}$ is modified by the Pb wall:
→ ionization losses in Pb (low p)
→ bremsstrahlung in Pb (high p)

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

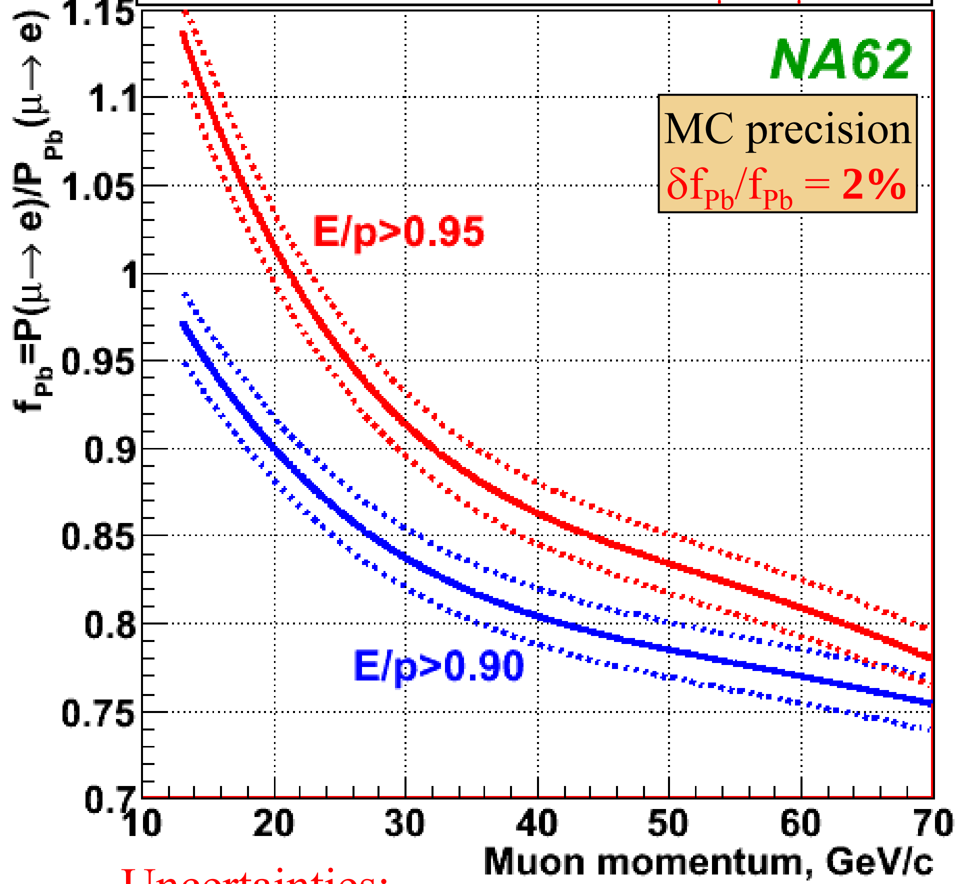
[Muon bremsttranlung: Phys. Atom. Nucl. 60 (1997) 576]

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) = (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%)

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

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

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

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

But muons from $K_{\mu 2}$ decay are fully polarized:

Michel electron distribution

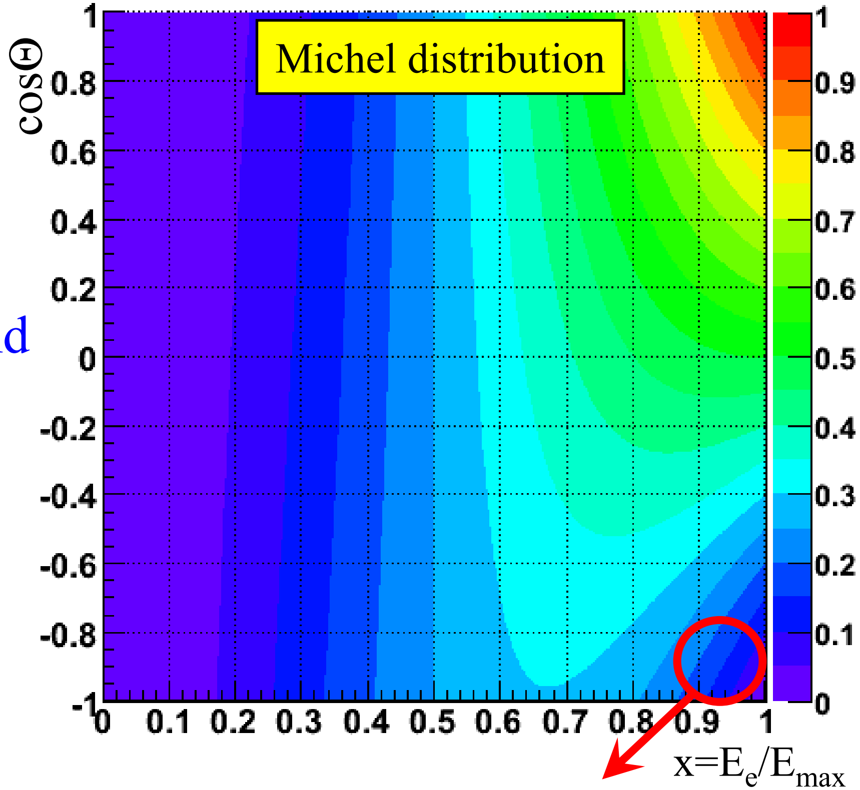
$$d^2\Gamma/dxd(\cos\Theta) \sim x^2[(3-2x) - \cos\Theta(1-2x)]$$

$$x = E_e/E_{max} \approx 2E_e/M_\mu$$

Θ is the angle between p_e and the muon spin
(all quantities are defined in muon rest frame)

Result: $B/(S+B) = (0.27 \pm 0.04)\%$

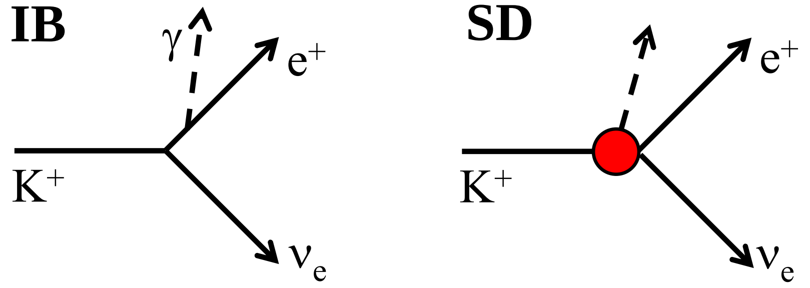
Important but not dominant background

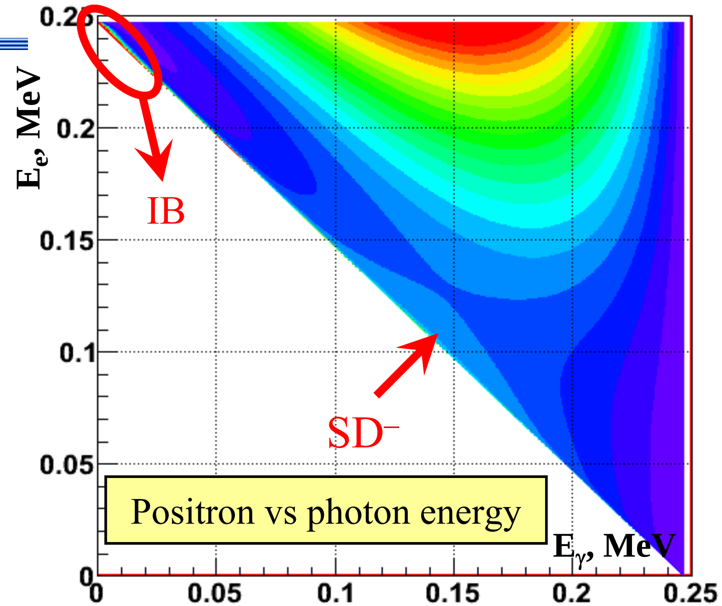


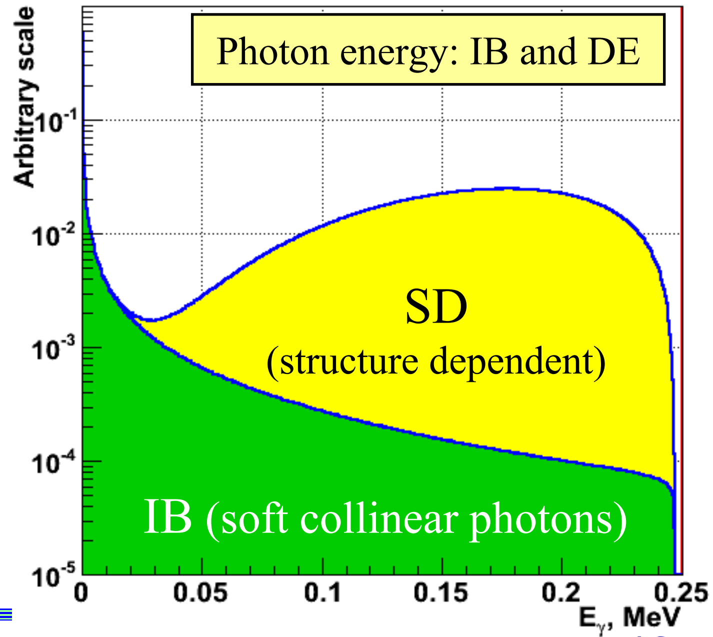
Only energetic forward positrons are selected as K_{e2} candidates
They are naturally suppressed by the muon polarisation
(radiative corrections provide another ~10% suppression)

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

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







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:

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

Conservative uncertainty ($3 \times \delta BR_{KLOE}$)
to accommodate the observed R_K variation
w.r.t the LKr veto selection condition.

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

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:

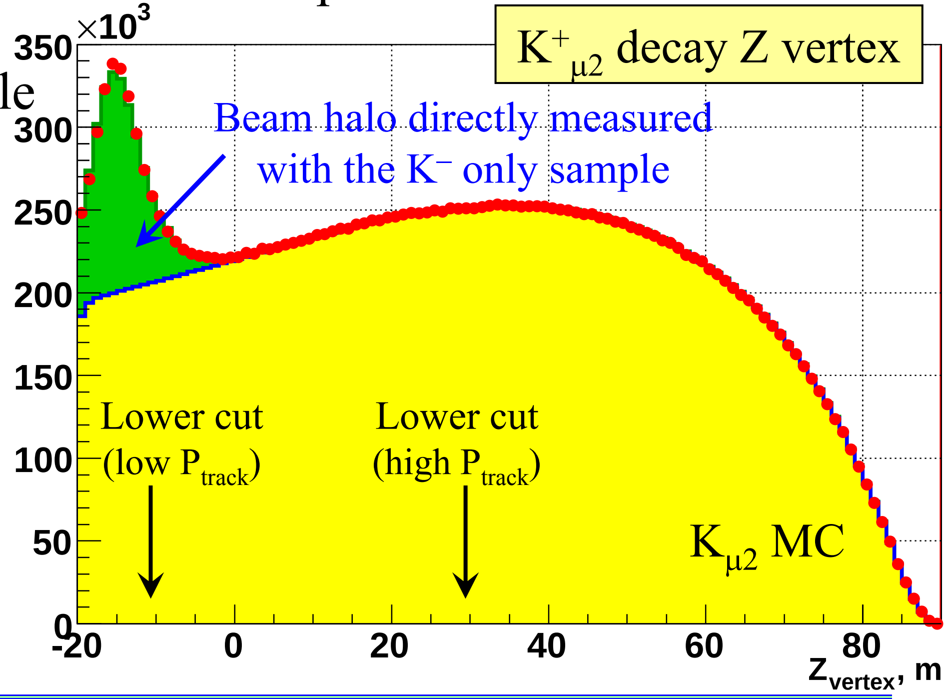
- Halo background much higher for K_{e2}^- (~20%) than for K_{e2}^+ (~1%).
- Halo background in the $K_{\mu 2}$ sample is considerably lower.
- ~90% of the data sample is K^+ only, ~10% is K^- only.
- K^+ halo component is measured directly with the K^- sample and vice versa.

The background is measured to sub-permille precision, and strongly depends on decay vertex position and track momentum.

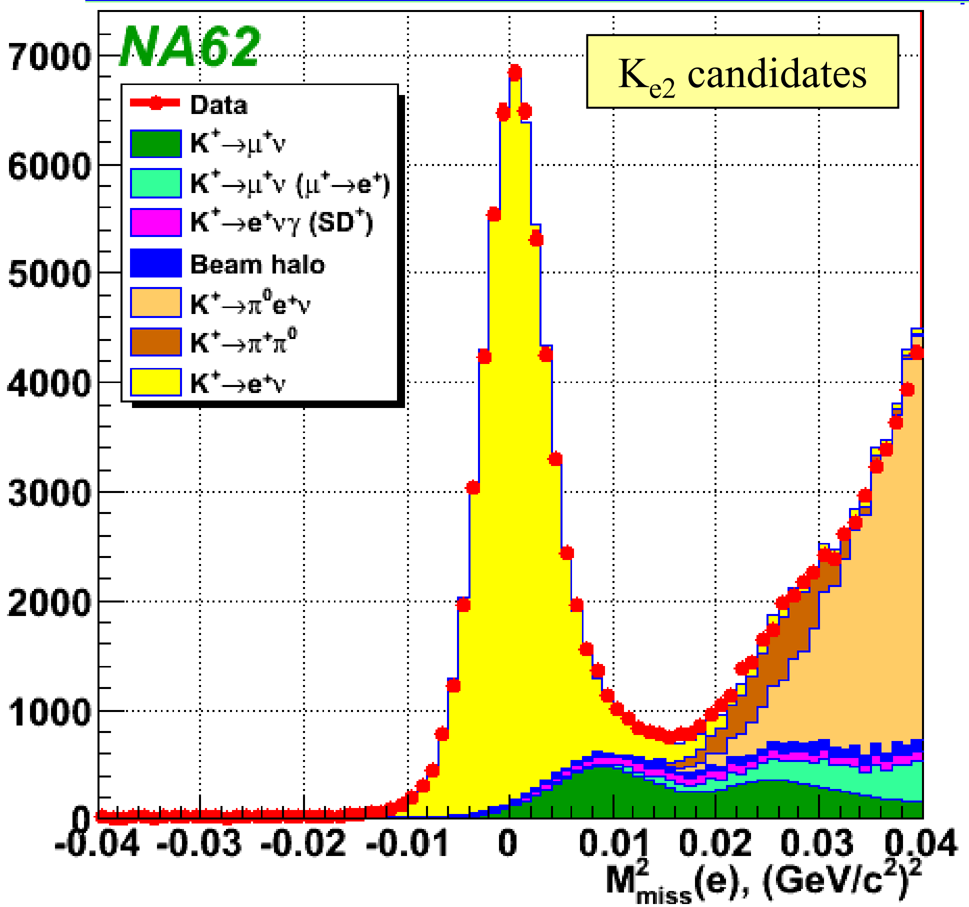
The selection criteria (Z_{vertex}) are optimized to minimize the halo background.

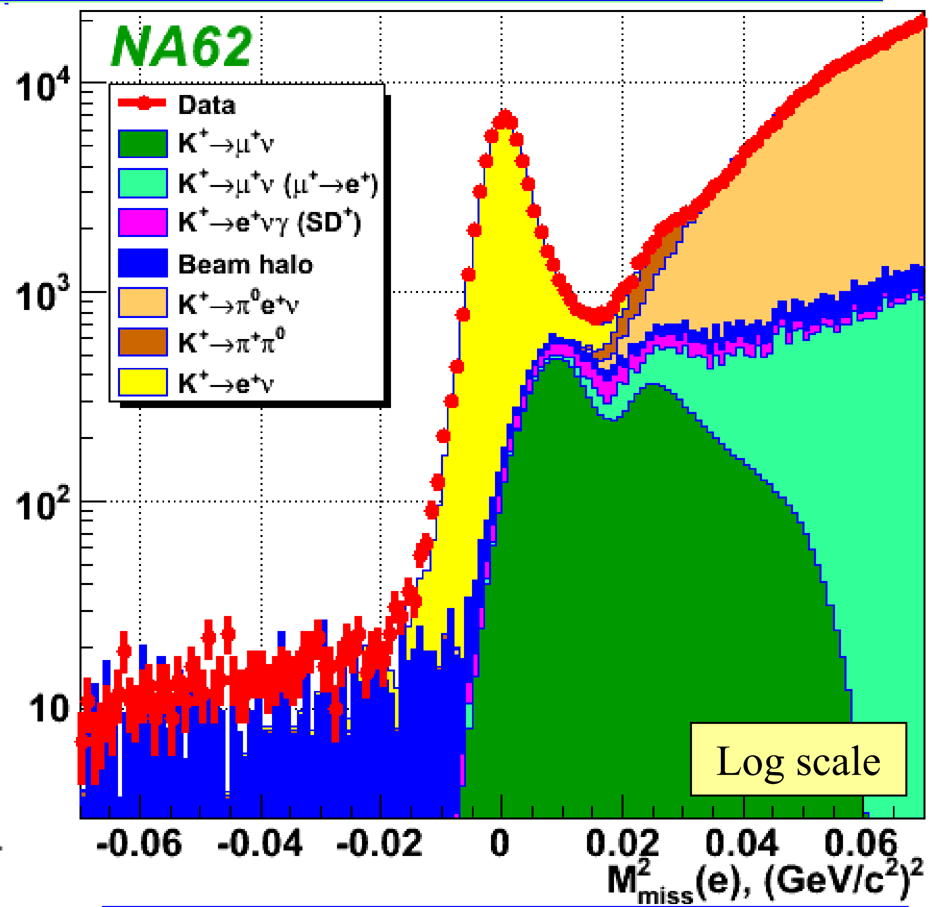
$$B/(S+B) = (1.14 \pm 0.06)\%$$

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



K_{e2}: partial (40%) data set



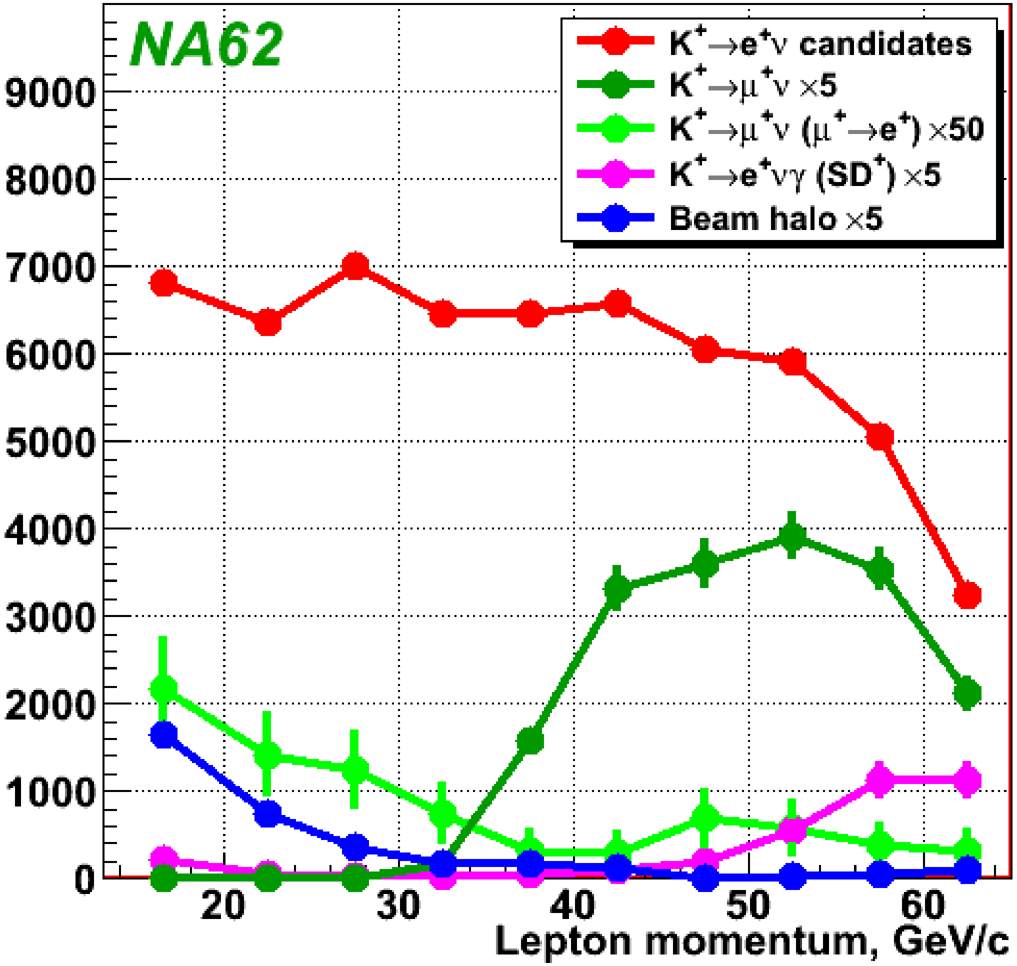


59,963 $K^+\to e^+\nu$ candidates
Positron ID efficiency: $(99.27\pm0.05)\%$
$B/(S+B) = (8.8\pm0.3)\%$

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

Backgrounds: summary

K_{e2} candidates and backgrounds in momentum bins



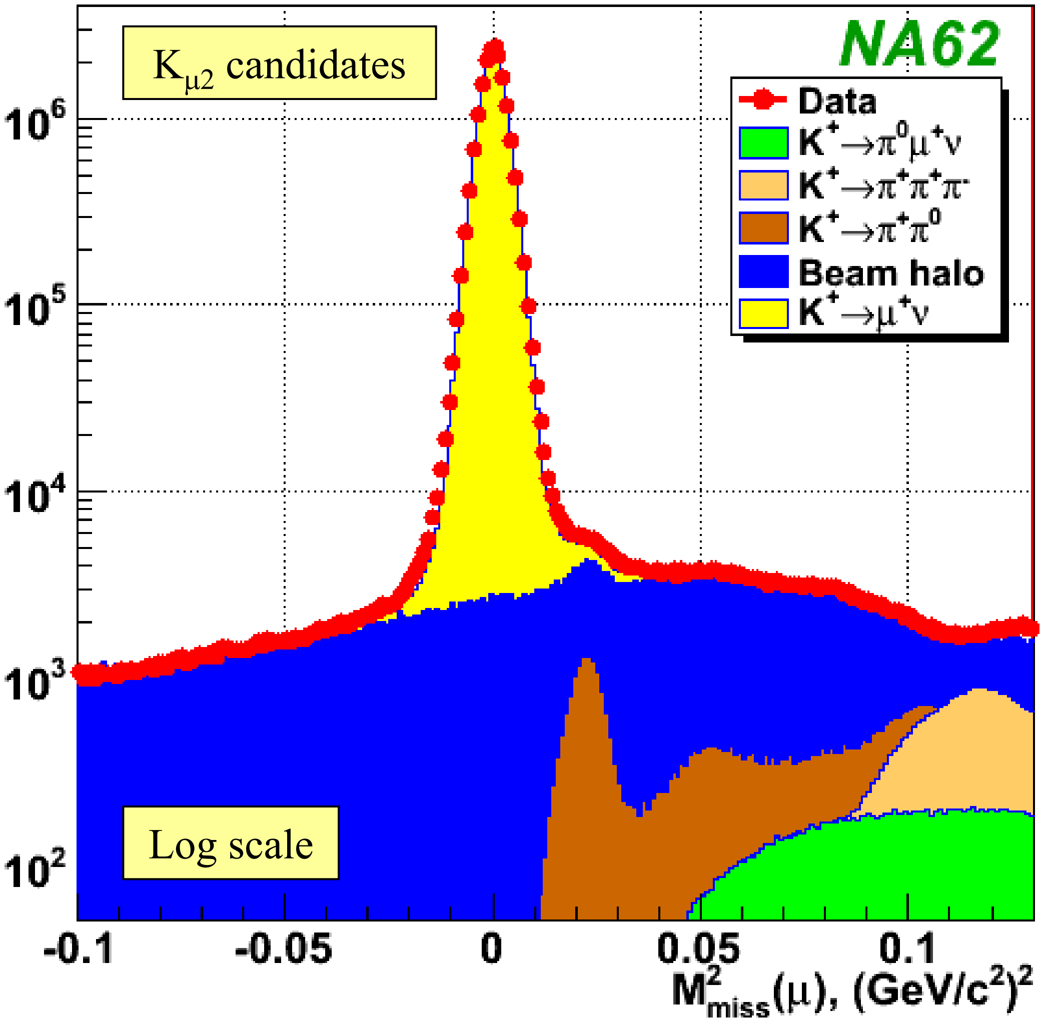
Backgrounds:

Source	B/(S+B)
$K_{\mu2}$	$(6.10\pm0.22)\%$
$K_{\mu2}$ $(\mu\to e)$	$(0.27\pm0.04)\%$
$K_{e2\gamma}$ (SD^+)	$(1.15\pm0.17)\%$
Beam halo	$(1.14\pm0.06)\%$
$K_{e3(D)}$	$(0.06\pm0.01)\%$
$K_{2\pi(D)}$	$(0.06\pm0.01)\%$
Total	$(8.78\pm0.29)\%$

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

selection criteria optimized individually in each P_{track} bin

$K_{\mu2}$: partial (40%) data set



Backgrounds:

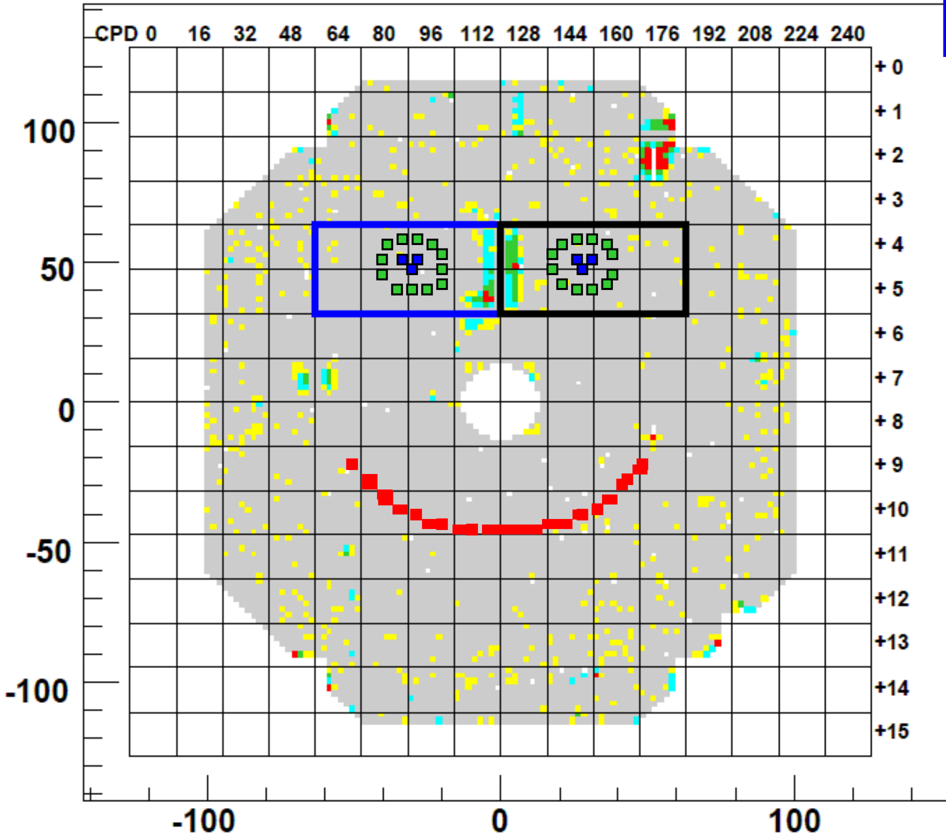
Source	B/(S+B)
Beam halo	(0.38±0.01)%
Total	(0.38±0.01)%

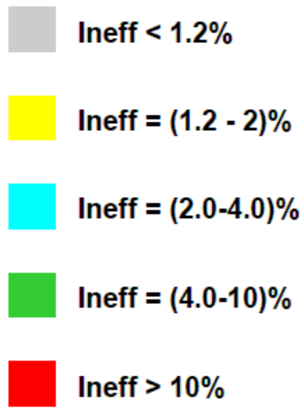
18.030 M candidates with low background B/(S+B) = 0.38%

The $K_{\mu2}$ trigger was pre-scaled by D=150

Systematic effect: positron ID

A typical inefficiency map

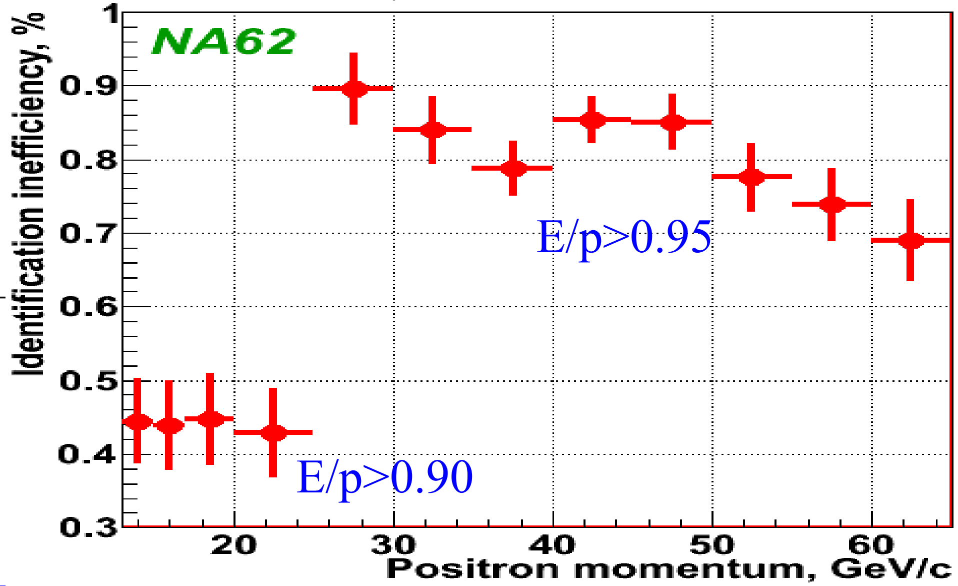




LKr energy response is calibrated for every 2×2cm^2 cell within acceptance

an effect of a loose cable is visible in this map

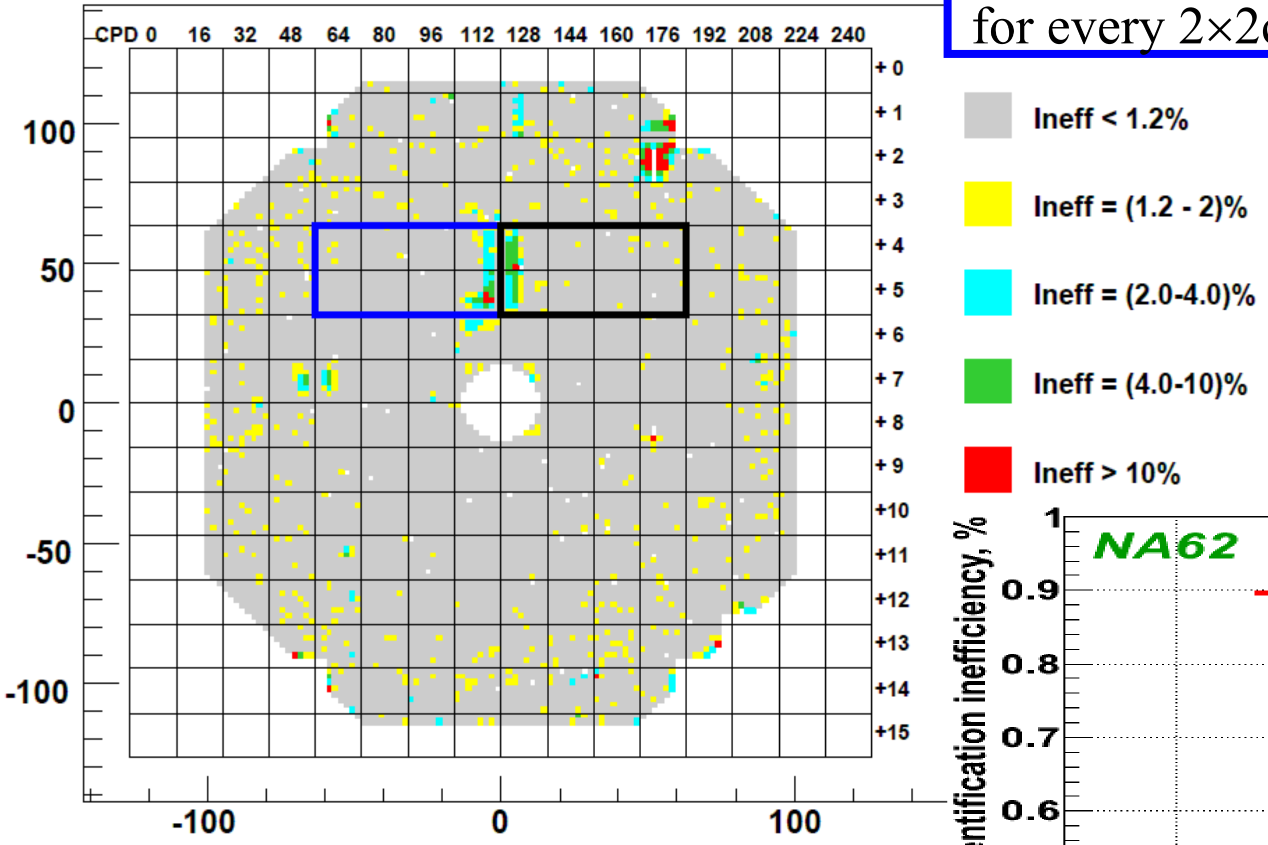
ID inefficiency vs momentum



Positron ID efficiency is measured with $K^+ \to \pi e \nu$ and $K_L \to \pi e \nu$ (s. runs) samples: integral $\varepsilon = (99.27 \pm 0.05)\%$

Systematic effect: positron ID

A typical inefficiency map



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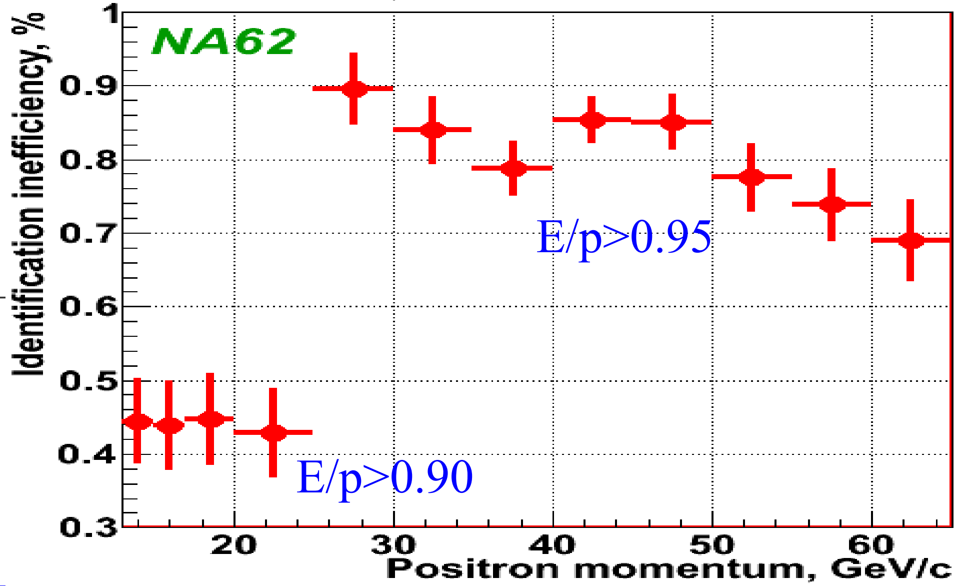


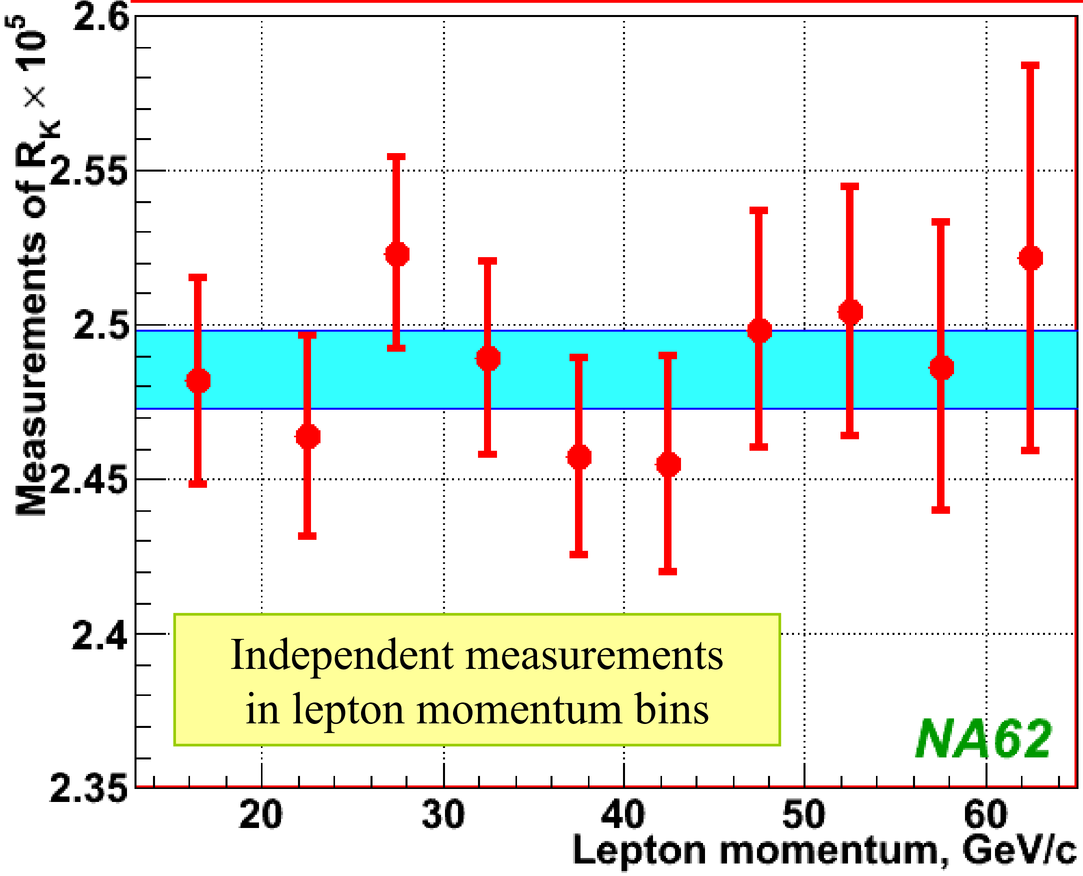
Positron ID efficiency is measured with $K^+ \to \pi e \nu$ and $K_L \to \pi e \nu$ (s. runs) samples: integral $\varepsilon = (99.27 \pm 0.05)\%$

NA62 final result (40% data set)

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

$$R_K = (2.486 \pm 0.013) \times 10^{-5}$$

(June 2010)



(systematic errors included, partially correlated)

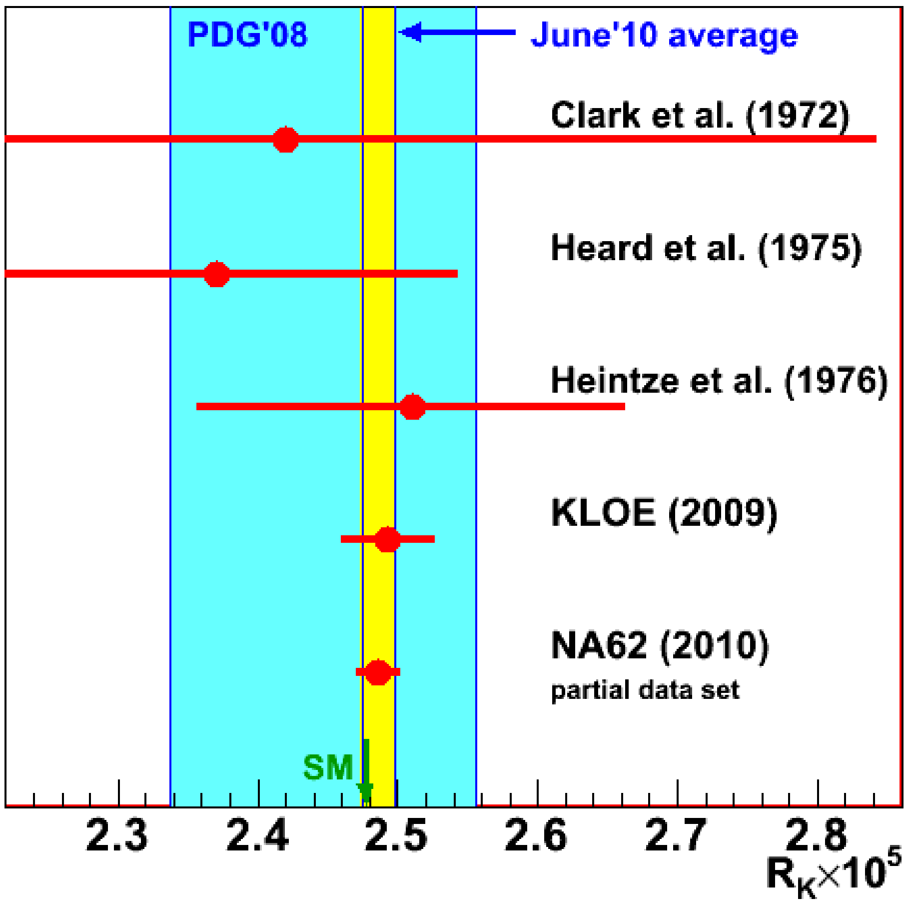
Uncertainties:

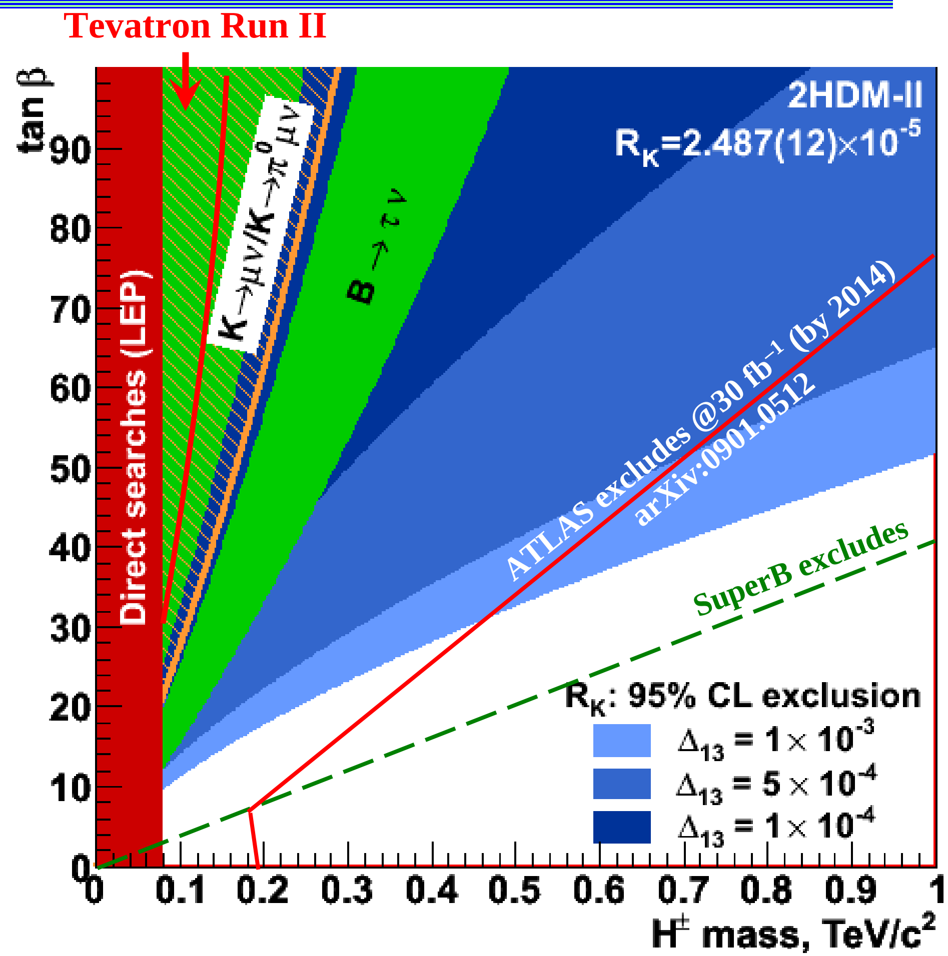
Source	$\delta R_K \times 10^5$
Statistical	0.011
$K_{\mu 2}$	0.005
BR($K_{e2\gamma}$ SD$^+$)	0.004
Beam halo	0.001
Acceptance corr.	0.002
DCH alignment	0.001
Positron ID	0.001
1-track trigger	0.002
Total	0.013

(0.52% precision)

Preliminary result: R_K=2.500(16)$\times 10^{-5}$
Shift due to multi-photon corrections
to the $K_{e2\gamma}$ (IB) decay.

R_K: new 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 $B\to\tau\nu$

Conclusions

$R_K = K_{e2}/K_{\mu 2}$ is sensitive to lepton flavour violation in multi-Higgs models

- NA62 data taking in 2007/08 was optimised for R_K measurement. NA62 K_{e2} sample is ~10 times the world sample, with excellent $K_{e2}/K_{\mu 2}$ separation (99.3% electron ID efficiency, 6% $K_{\mu 2}$ background).
- Final result based on ~40% of the NA62 K_{e2} sample $R_K = (2.486 \pm 0.013) \times 10^{-5}$ (0.5% accuracy reached).
- Future improvements on R_K:
  1) the full NA62 phase I data sample of 2007/08: $\delta R_K / R_K < 0.4\%$
  2) NA62 phase II (2012–2015) aims at ~0.2% precision.