

# Lepton Universality Test with $K^+ \rightarrow l^+ \nu$ Decays at CERN NA62



Evgueni Goudzovski  
(University of Birmingham)



for the NA62 collaboration

(Bern ITP, Birmingham, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, IHEP Protvino, INR Moscow, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin)

## Outline:

- 1) Motivation & experimental status;
- 2) Beam, detector and data taking;
- 3) Backgrounds & systematic effects;
- 4) Result and prospects.

*Kaon 2009 • Tsukuba, Japan*  
*June 10, 2009*



# $K_{l2}$ and $\pi_{l2}$ decays in the SM

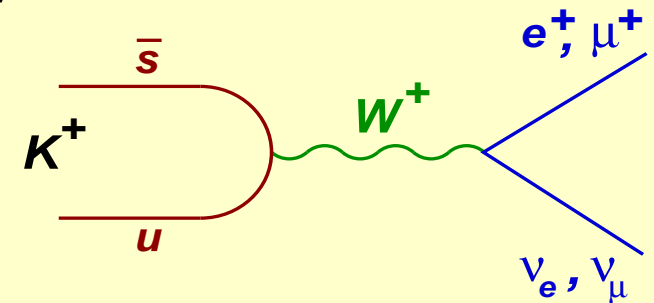
$$R_K = \frac{\Gamma(K^\pm \rightarrow e^\pm \nu)}{\Gamma(K^\pm \rightarrow \mu^\pm \nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}} \cdot \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot \underbrace{(1 + \delta R_K^{\text{rad. corr.}})}$$

**Helicity suppression (V–A couplings):**  
enhances sensitivity to non-SM effects

Radiative correction (few %) due to the IB part of the radiative  $K \rightarrow e \nu \gamma$  process, by definition included into  $R_K$

## Standard Model:

- excellent sub-permille accuracy of  $R_P$  ( $P=K, \pi$ ) due to cancellation of hadronic uncertainties in the ratio;
- strong helicity suppression of the electronic channel enhances sensitivity to non-SM effects.



SM uncertainties well below  $10^{-3}$

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

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

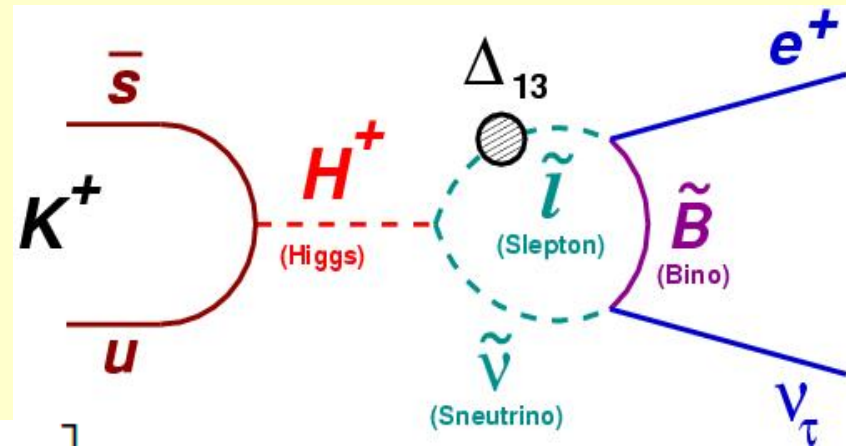
V. Cirigliano and I. Rosell,  
Phys. Lett. 99 (2007) 231801

# $K_{12}$ decays beyond the SM

## Possible scenario in MSSM:

charged Higgs mediated SUSY LVF contribution with emission of  $\tau$  neutrino can be strongly enhanced.

A. Masiero, P. Paradisi and R. Petronzio,  
PRD74 (2006) 011701 and JHEP 0811 (2008) 042



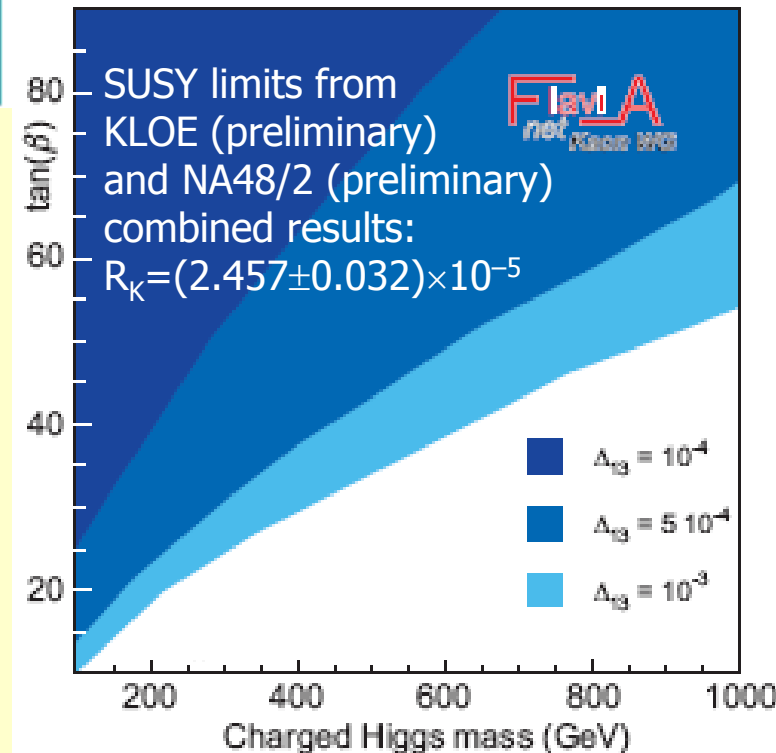
$$R_K^{LFV} \approx R_K^{SM} \left[ 1 + \left( \frac{m_K^4}{M_{H^\pm}^4} \right) \left( \frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

A **few percent** effect in large (not extreme)  $\tan\beta$  regime with massive charged Higgs.

Example:

( $\Delta_{13}=5 \times 10^{-4}$ ,  $\tan\beta=40$ ,  $M_H=500 \text{ GeV}/c^2$ )  
lead to  $R_K^{LFV} = R_K^{SM}(1+0.013)$ .

NB: analogous SUSY effect in pion decay is suppressed by a factor  $(m_\pi/M_K)^4 \approx 6 \times 10^{-3}$



# $K_{l2}$ & $\pi_{l2}$ : experimental status

## Kaon decay:

→ PDG'08 average (1970s measurements):

$$R_K = (2.45 \pm 0.11) \times 10^{-5} \quad (\delta R_K / R_K = 4.5\%)$$

→ NA48/2: two preliminary results based on 2003 and 2004 data sets

$$R_K = (2.416 \pm 0.049) \times 10^{-5} \quad (\delta R_K / R_K = 2.0\%)$$

$$R_K = (2.455 \pm 0.061) \times 10^{-5} \quad (\delta R_K / R_K = 2.5\%)$$

L. Fiorini, PoS (HEP2005) 288,  
V. Kozhuharov, PoS (KAON) 049

→ Recent improvement: **final** KLOE result

$$R_K = (2.493 \pm 0.031) \times 10^{-5} \quad (\delta R_K / R_K = 1.3\%)$$

Mario Antonelli, La Thuile '09

## Pion decay:

→ PDG'08 average (1980s, 90s data):

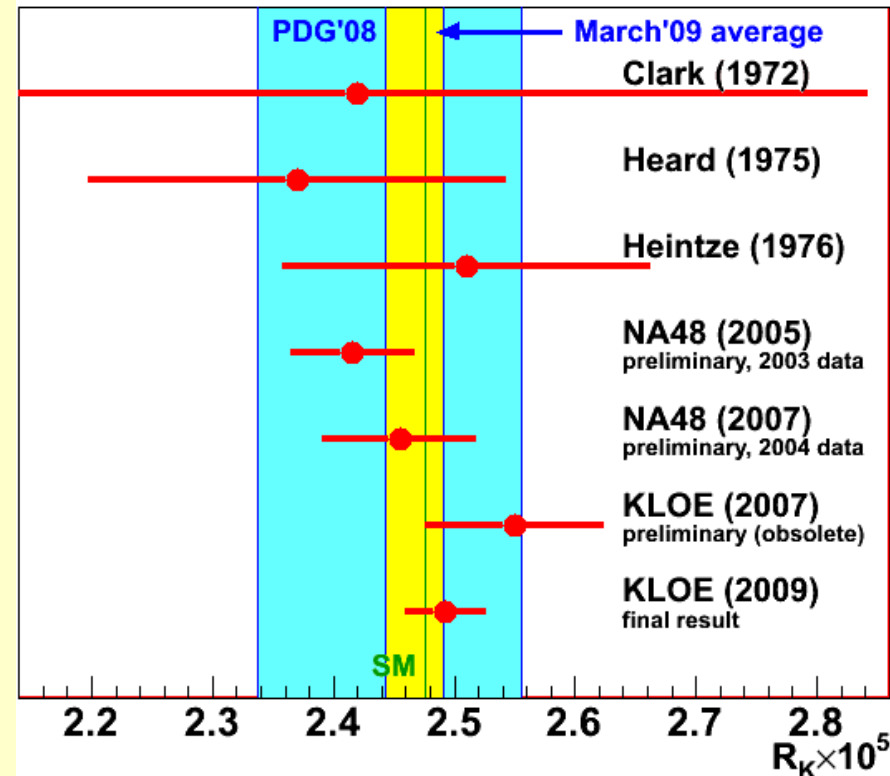
$$R_\pi = (12.30 \pm 0.04) \times 10^{-5} \quad (\delta R_\pi / R_\pi = 0.3\%)$$

→ Future plans: TRIUMF proposal S1072

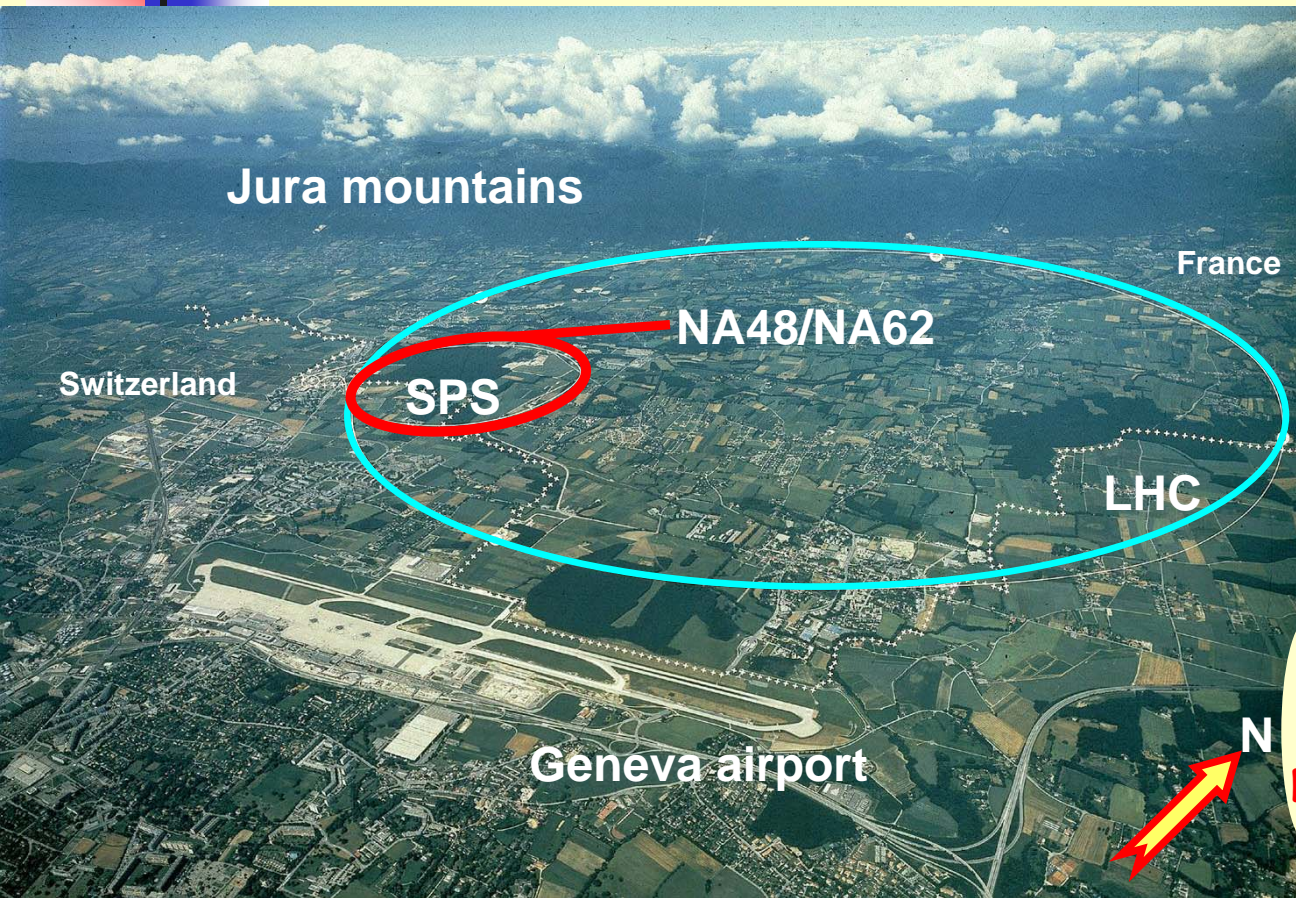
$\delta R_\pi / R_\pi = 0.06\%$  precision foreseen

Toshio Numao, PANIC '08

NA48: valuable for development of the NA62 method, however analyses are not completed. No plans to finish the measurements.



# NA48/NA62: kaons at CERN



Dedicated to  $K_{e2}$  (aiming to collect 150K events),  $\Rightarrow$   
 40% partial data set presented here

Talk by Giuseppe Ruggiero  $\Rightarrow$

NA48	1997: $\varepsilon'/\varepsilon$ run $K_L+K_S$
	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	2007: $K_{e2}^+/K_{\mu2}^+$ tests
	2008: $K_{e2}^+/K_{\mu2}^+$ tests
	2006–2010: design & construction 2011: start of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ run

NA62 (phase I)

NA62 (phase II)

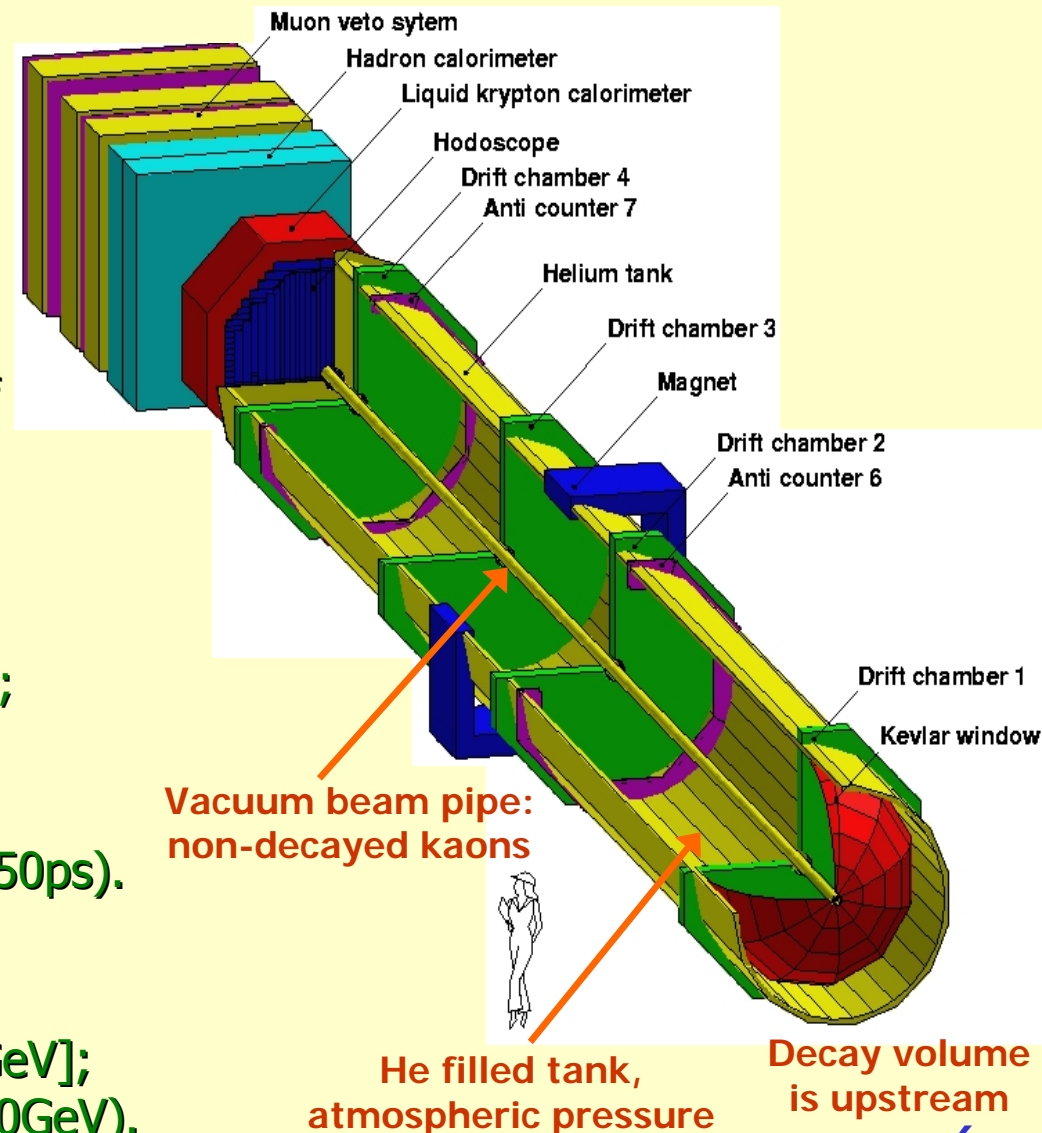
# NA62 data taking: 2007/08

## Data taking:

- Four months in 2007 (23/06–22/10):  
~400K SPS spills, 300TB of raw data (90TB recorded); reprocessing & data preparation finished.
- Two weeks in 2008 (11/09–24/09):  
special data sets allowing reduction of the systematic uncertainties.

## Principal subdetectors for $R_K$ :

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



# Kaon beams

NA48/2 beam line: capable of delivering simultaneous  $K^+/K^-$  beams (74 GeV/c in 2007)

Kinematic ID of the  $K_{l2}$  candidates:

$$M_{miss}^2 = (P_K - P_l)^2$$

$P_K$  not measured in every event (average used)

Improvement of  $K_{e2}/K_{\mu2}$  kinematic separation



Optimization of  $M_{miss}^2$  resolution:  
narrow momentum band  
beams ( $\Delta P_K^{RMS}/P_K=2\%$ )

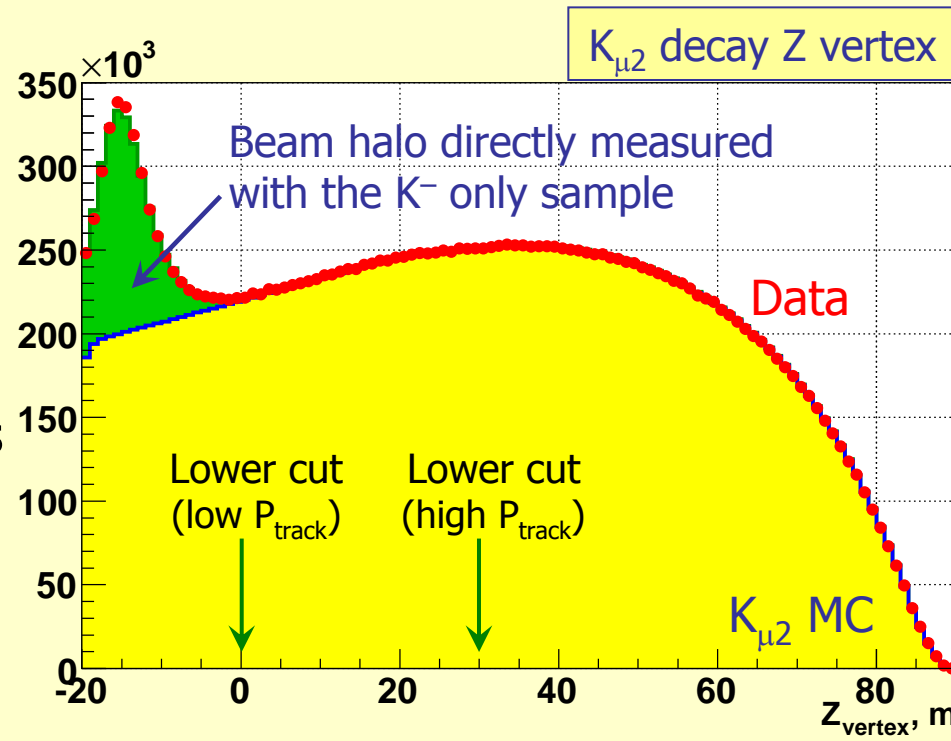
## Kaon sign

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.

Collection of  $K^+$  ONLY and  $K^-$  ONLY sets allows direct "cross-measurements" of beam halo background with excellent precision.

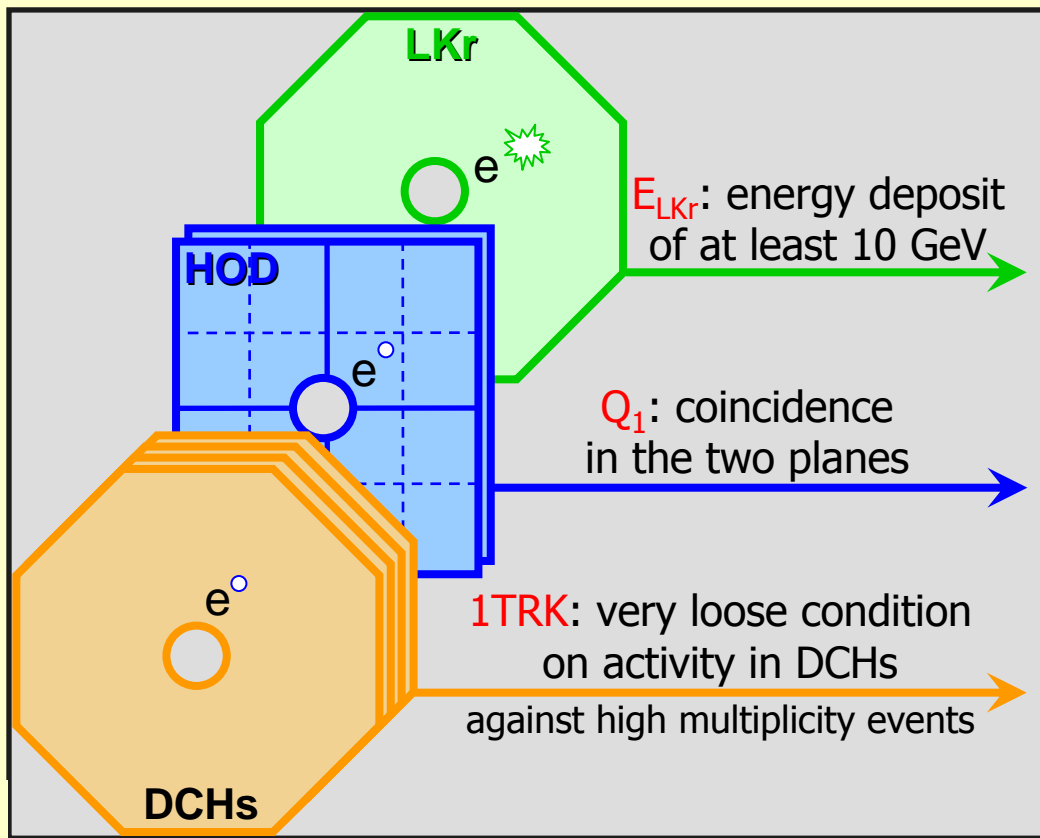


# Trigger logic

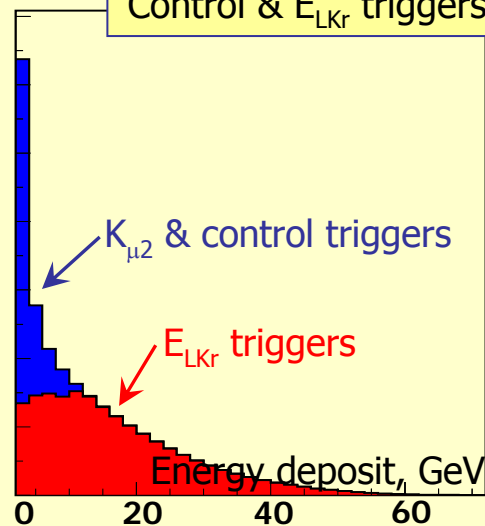
Minimum bias  
(high efficiency, but low purity)  
trigger configuration used

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

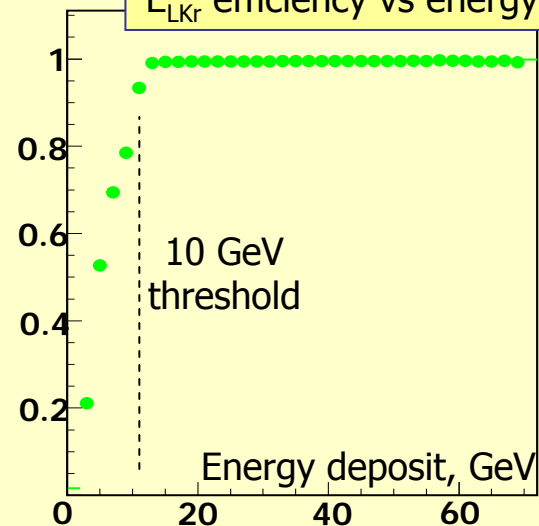
$K_{\mu2}$  condition:  $Q_1 \times 1TRK / D$ ,  
downscaling (D) 50 to 150.  
Purity  $\sim 2\%$ .



Control &  $E_{LKr}$  triggers



$E_{LKr}$  efficiency vs energy



- Efficiency of  $K_{e2}$  trigger: monitored with  $K_{\mu2}$  & other control triggers.
- $E_{LKr}$  inefficiency for electrons measured to be  $(0.05 \pm 0.01)\%$  for  $p_{track} > 15$  GeV/c.
- Different trigger conditions for signal and normalization!



# Measurement strategy


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

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

(2) A counting experiment in track momentum bins:

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

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

$N_B(K_{e2}), N_B(K_{\mu2})$ : numbers of background events; 

main source of systematic errors

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

$f_e, f_{\mu}$ : measured particle ID efficiencies;

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

$f_{LKR} = 0.998$ : global LKr readout efficiency.

(3) MC simulations used to a limited extent:

- acceptance correction (only for geometry, not for particle ID);
- simulation of "catastrophic" bremsstrahlung by muon.

# $K_{e2}$ and $K_{\mu2}$ selection

## Large common part

(due to topological similarity)

- one reconstructed track;
- geometrical acceptance cuts;
- limit on LKr extra energy deposition;
- track momentum:  $15\text{GeV}/c < p < 65\text{GeV}/c$ ;
- decay vertex defined as closest approach of track & nominal kaon axis.

## Kinematic separation

missing mass

$$M_{miss}^2 = (P_K - P_l)^2$$

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

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

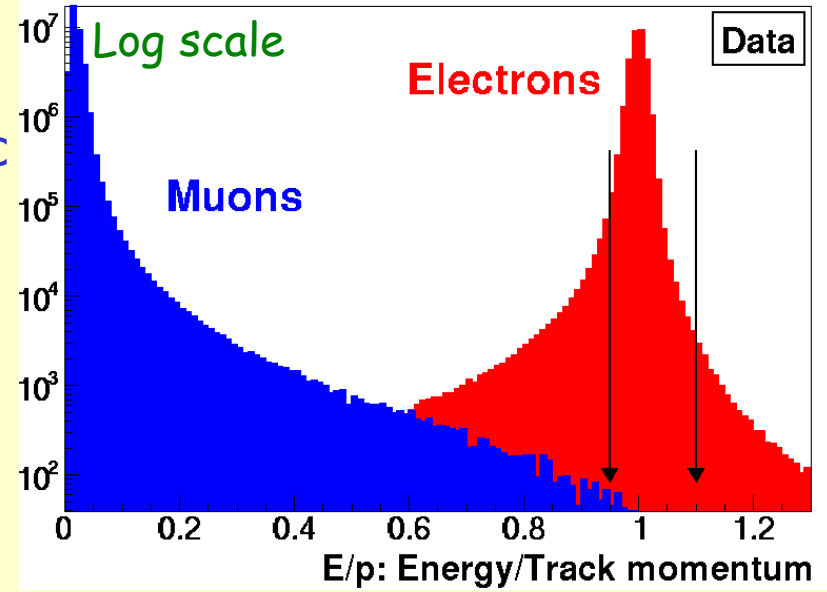
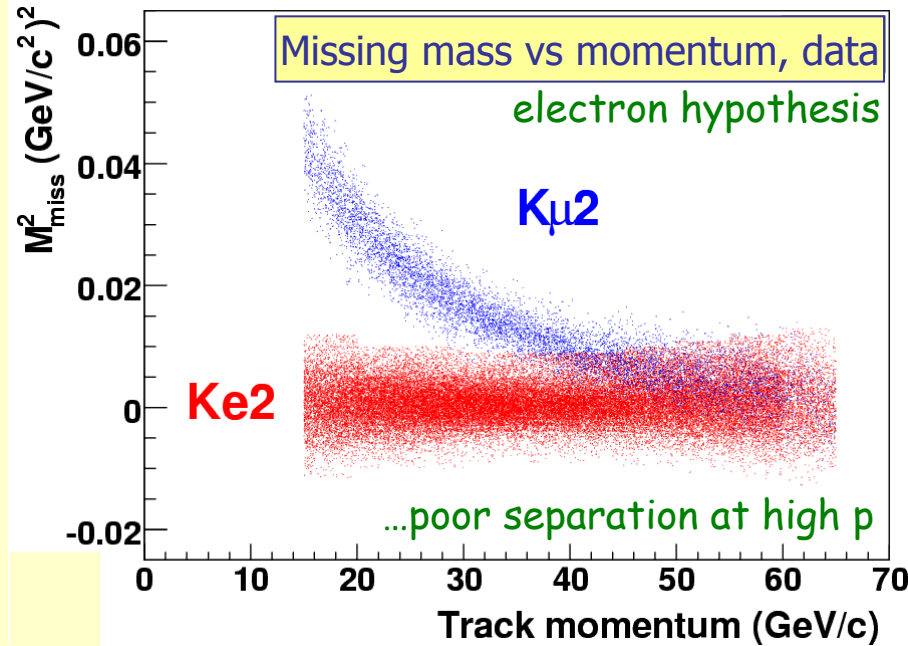
## Separation by particle ID

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

$0.95 < E/p < 1.10$  for electrons,

$E/p < 0.2$  for muons.

→ Powerful muon suppression by  $f \sim 10^6$



# Muonic background in $K_{e2}$ sample

## Problem:

“Catastrophic” energy loss by muons in LKr.  
Muons with  $E/p > 0.95$  are identified as electrons.  
 $P(\mu \rightarrow e) \sim 3 \times 10^{-6}$  (and momentum-dependent).

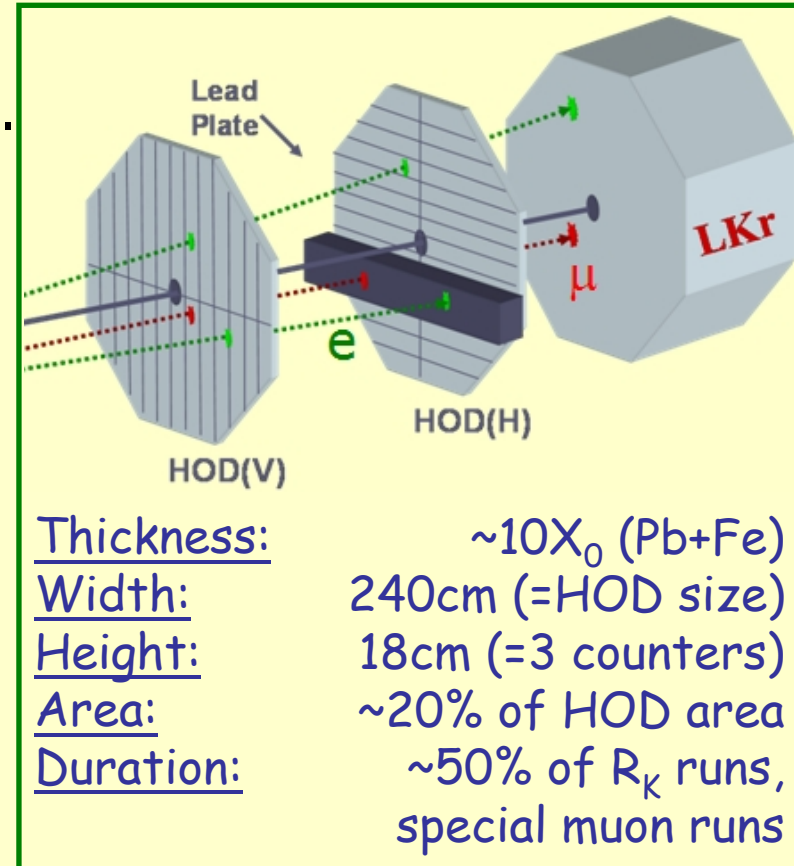
$$P(\mu \rightarrow e)/R_K \sim 10\%:$$

$K_{\mu 2}$  decays represent a major background

Need a direct measurement of  $P(\mu \rightarrow e)$   
with pure muon samples to validate  
theoretical bremsstrahlung cross-section  
in the very special high  $E_\gamma$  region.

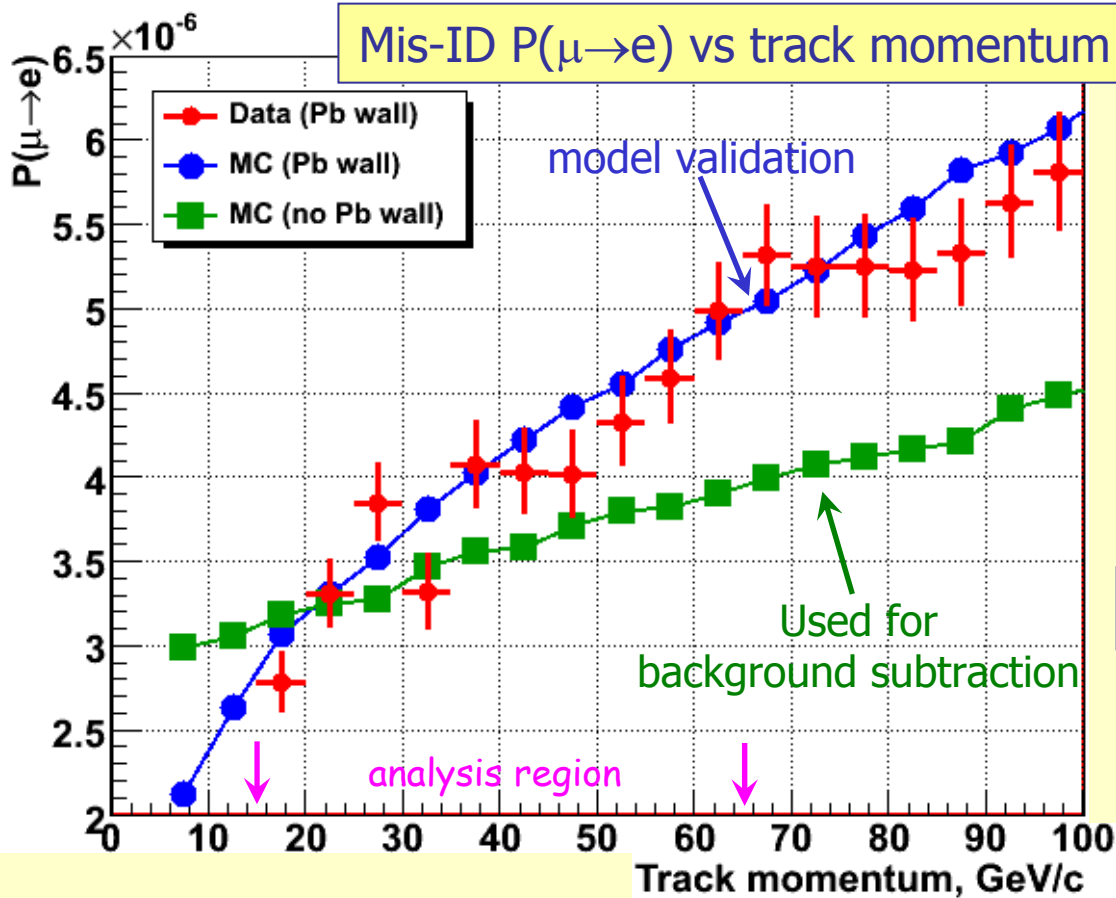
## Solution:

Pb wall ( $\sim 10X_0$ ) between the HOD planes.  
Tracks traversing the wall & with  $E/p > 0.95$   
are pure muon samples (electron contamination  $< 10^{-7}$ ),  
with the  $\mu \rightarrow e$  decay component (initially  $\sim 10^{-4}$ ) suppressed.



# Muonic background (2)

$P(\mu \rightarrow e)$ : measurement (2007 special muon run) vs Geant4-based simulation



Excellent data/MC agreement for the Pb wall case!

$P(\mu \rightarrow e)$  modified by the Pb wall via two main competing mechanisms:

- 1) ionization losses in Pb (low p);
- 2) bremsstrahlung in Pb (high p).

Result:  $B/(S+B) = (6.28 \pm 0.17)\%$

(uncertainty is due to the limited size of the data sample used to validate the simulation)

## Prospects:

- The 2008 special muon sample is twice as large as the 2007 one;
- Use muons from  $K_{\mu 2}$  decays in good  $K_{e2}/K_{\mu 2}$  separation region ( $p < 25 \text{ GeV}/c$ ).

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

For NA62 conditions  
(74 GeV/c beam,  $\sim 100$  m decay volume),

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

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

Muons from  $K^\pm$  decay are fully polarized:  
Michel electron spectrum

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

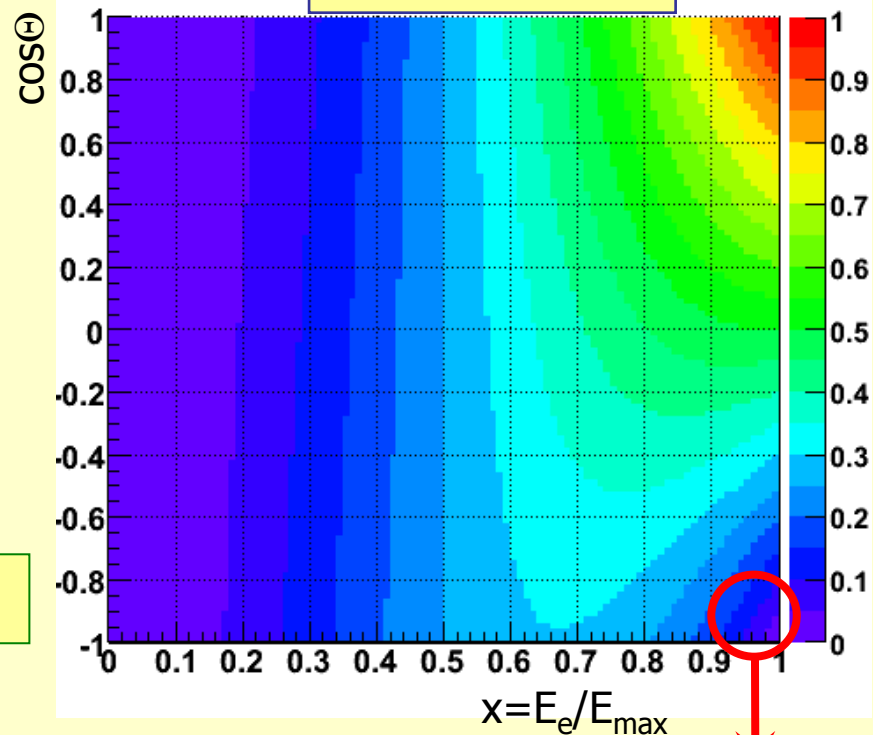
$$x = E_e/E_{\max} \approx 2E_e/M_{\mu'}$$

$\Theta$  is the angle between  $p_e$  and the muon spin,  
(all quantities are defined in muon rest frame).

$$\text{Result: } B/(S+B) = (0.23 \pm 0.01)\%$$

Important but not dominant background

Michel distribution



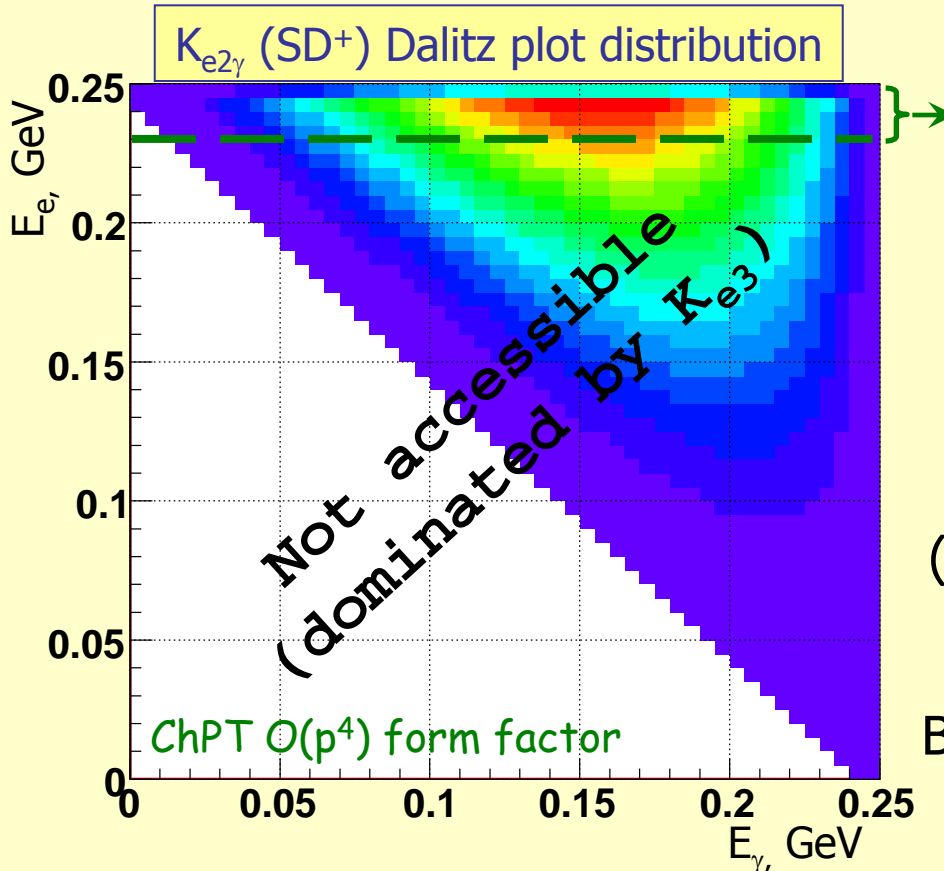
Only energetic forward electrons  
(passing  $M_{\text{miss}}$ ,  $E/p$ , vertex CDA cuts)  
are selected as  $K_{e2}$  candidates:  
(high  $x$ , low  $\cos\Theta$ ),

configuration **highly suppressed**  
according to the Michel distribution.

# $K^+ \rightarrow e^+ \nu \gamma$ ( $SD^+$ ) background

- Background by definition of  $R_K$
- Rate similar to that of  $K_{e2}$
- Known with poor precision of  $\sim 15\%$

- Theory:  $BR = (1.12 - 1.34) \times 10^{-5}$   
[model-dependent form factor]
- Experiment:  $BR = (1.52 \pm 0.23) \times 10^{-5}$   
[1970s measurements]



Only energetic electrons ( $E_e^* > 230 \text{ MeV}$ ) are compatible to  $K_{e2}$  kinematic ID



This region of phase space is accessible for direct BR and form-factor measurement (being outside the region  $E_e^* < 227 \text{ MeV}$  populated by the  $K_{e3}$  background).

Background estimate (ChPT phase space)

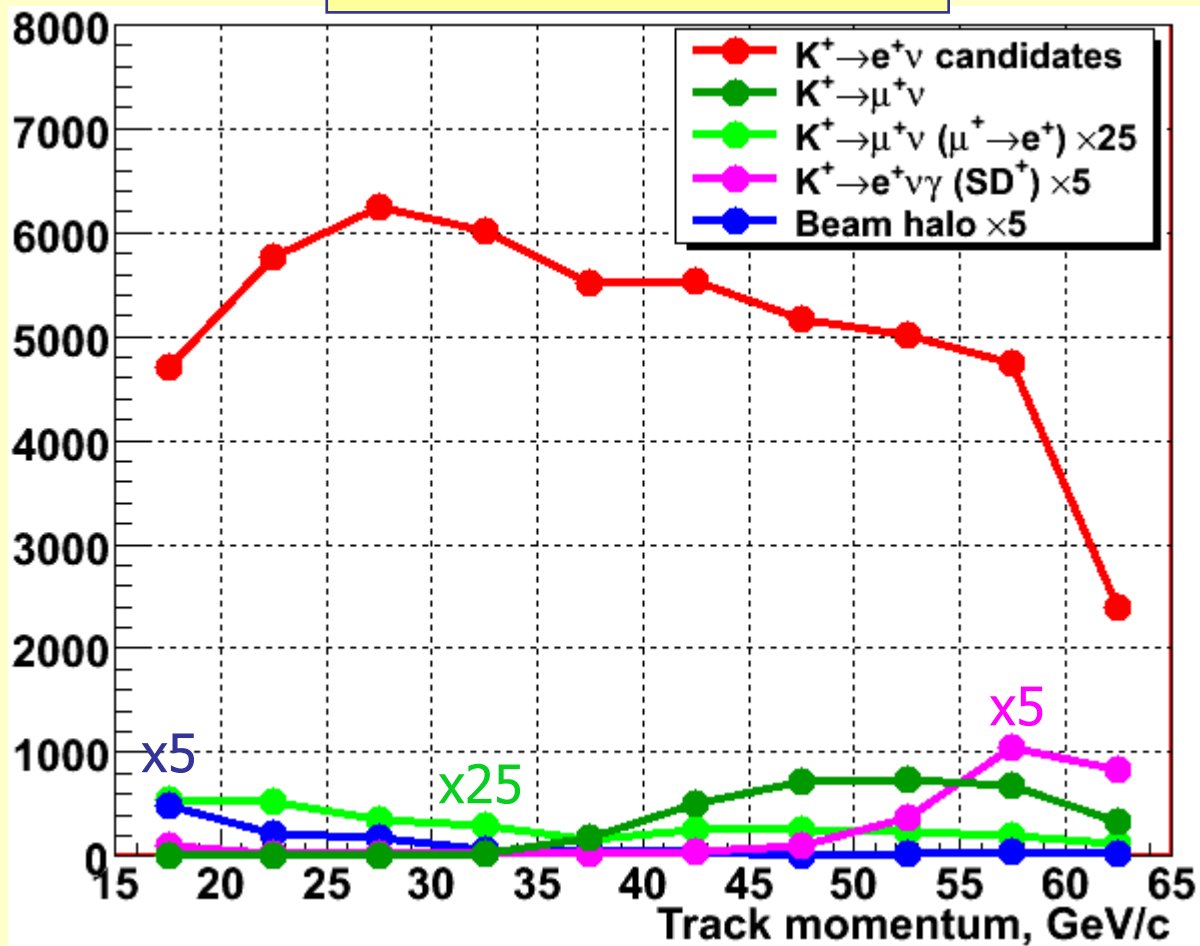
$$B/(S+B) = (1.02 \pm 0.15)\%$$

(uncertainty from PDG BR, to be improved by NA62&KLOE)

$K_{e2\gamma}$  ( $SD^-$ ) background is negligible, as this decay is suppressed at high  $E_e$

# Backgrounds: summary

Statistics in momentum bins



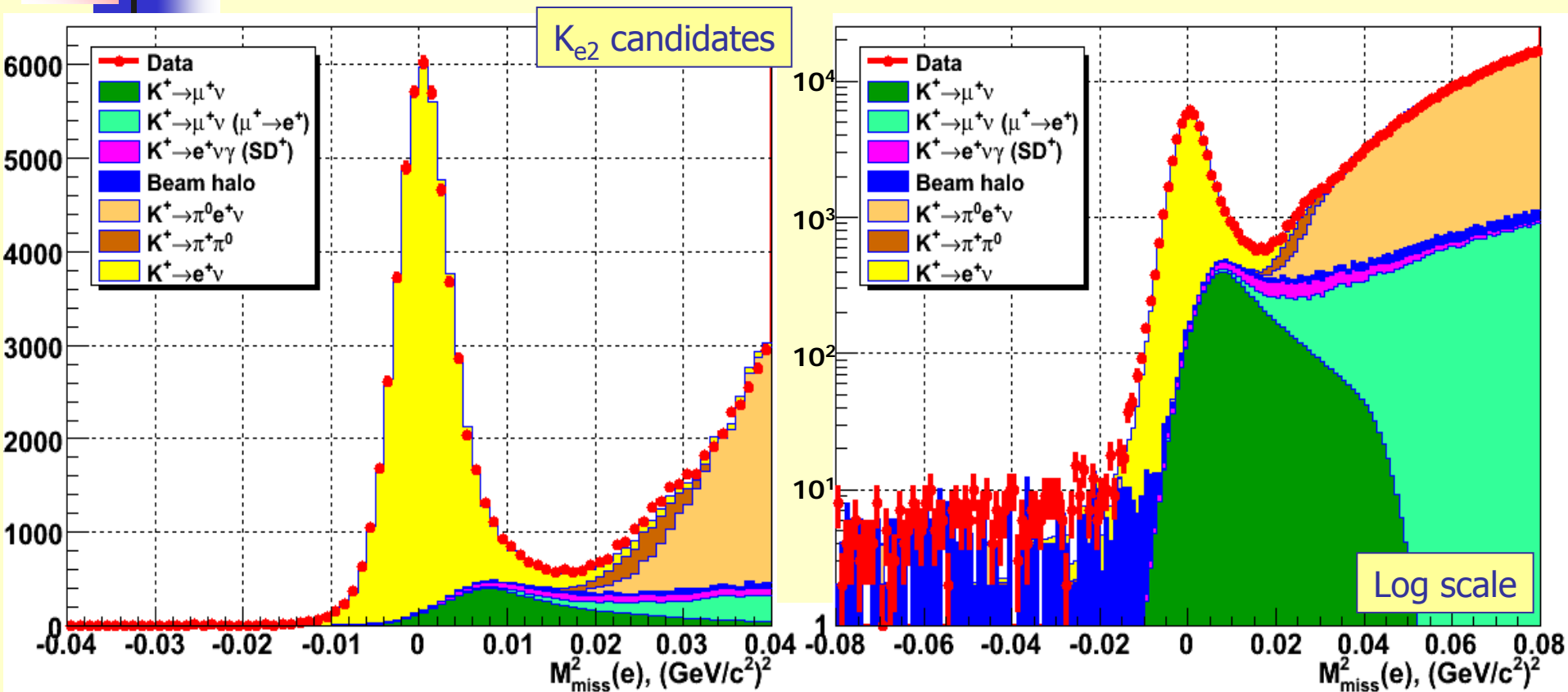
## Background summary

Source	B/(S+B)
$K_{\mu 2}$	$(6.28 \pm 0.17)\%$
$K_{\mu 2} (\mu \rightarrow e)$	$(0.23 \pm 0.01)\%$
$K_{e 2 \gamma} (SD^+)$	$(1.02 \pm 0.15)\%$
Beam halo	$(0.45 \pm 0.04)\%$
$K_{e 3}$	0.03%
$K_{2 \pi}$	0.03%
<b>Total</b>	<b><math>(8.03 \pm 0.23)\%</math></b>

Record  $K_{e 2}$  sample:  
51,089 candidates  
with low background  
 $B/(S+B) = (8.0 \pm 0.2)\%$

(selection criteria, e.g. for  $Z_{\text{vertex}}$  and  $M_{\text{miss}}^2$ ,  
are optimised individually in each  $P_{\text{track}}$  bin)

# $K_{e2}$ : 40% of data set



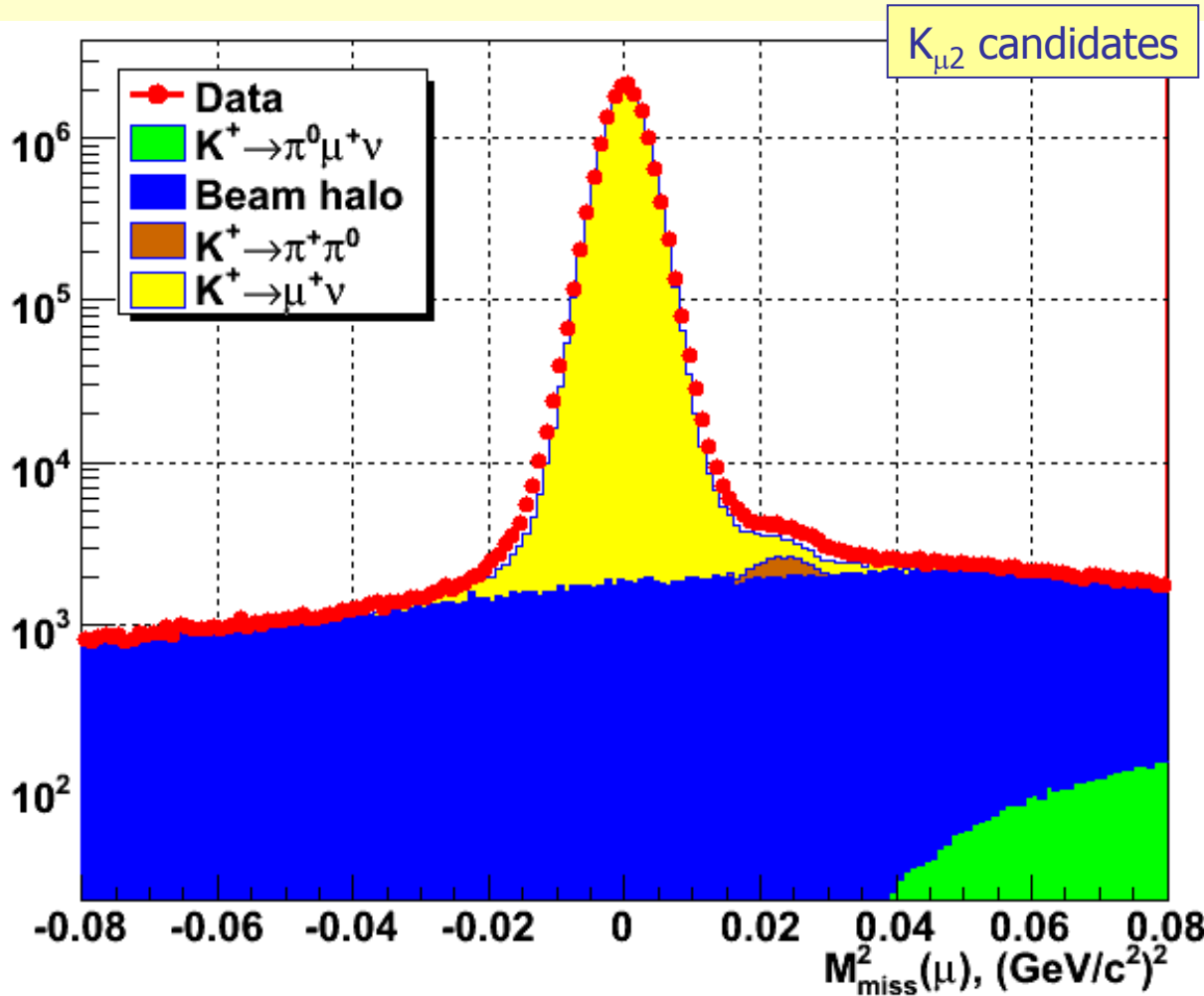
51,089  $K^+ \rightarrow e^+ \nu$  candidates,  
 99.2% electron ID efficiency,  
 $B/(S+B) = (8.0 \pm 0.2)\%$

NA62 estimated total  $K_{e2}$  sample:  
 ~120K  $K^+$  & ~15K  $K^-$  candidates.  
 Proposal (CERN-SPSC-2006-033):  
 150K candidates

*cf.* KLOE: 13.8K candidates (both  $K^+$  and  $K^-$ )  
 ~50% electron ID efficiency, 16% background



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



15.56M candidates  
with low background  
 $B/(S+B) = 0.25\%$

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

The only significant  
background source  
is the beam halo.

# Other systematic effects

## Electron ID efficiency $f_e$ (99.2%)

measured with samples of pure electrons

- $K^\pm \rightarrow \pi^0 e^\pm \nu$  from **main K data taking** (limited momentum range  $p < 50 \text{ GeV}/c$ );
- $K_L \rightarrow \pi^\pm e^\pm \nu$  from a **special 15h  $K_L$  run** (wider track momentum range, due to broad  $K_L$  momentum spectrum).

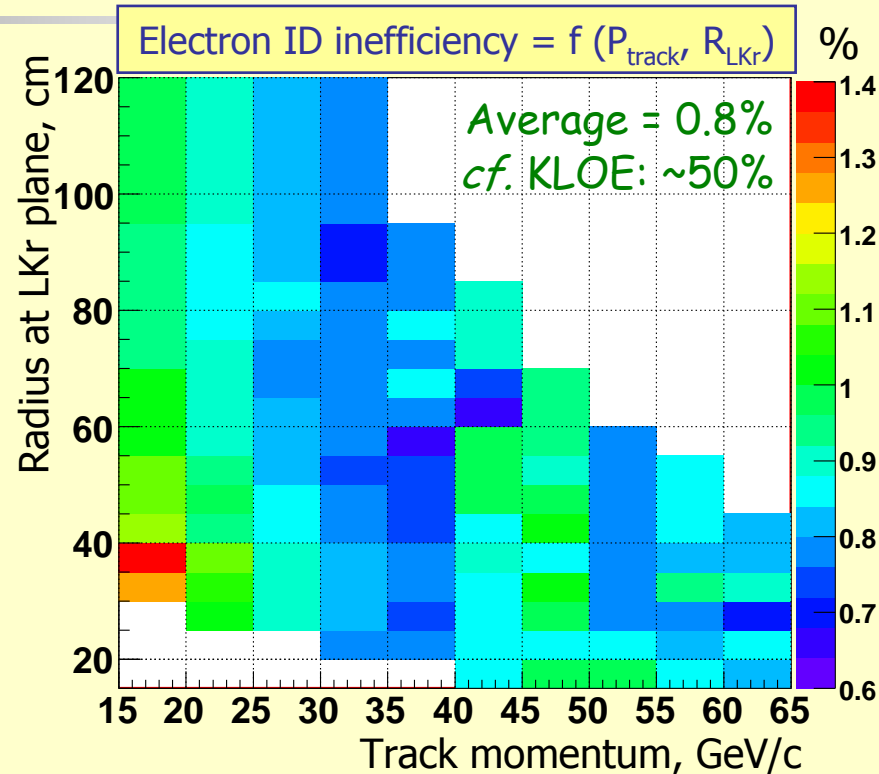
*Good agreement between the two measurements, precision better than 0.1%.*

## Acceptance correction

- $p_{\text{track}}$ -dependent,  $A(K_{\mu 2})/A(K_{e 2}) \sim 1.3$ ;
- strongly affected by the radiative (IB) corrections to  $K_{e 2}$ ;

*IB process simulated according to  
V. Cirigliano and I. Rosell,  
Phys. Lett. 99 (2007) 231801*

- conservative systematic uncertainty for prelim. result:  $\delta R_K/R_K = 0.3\%$ , due to approximations used in IB simulation.



## Trigger efficiency correction

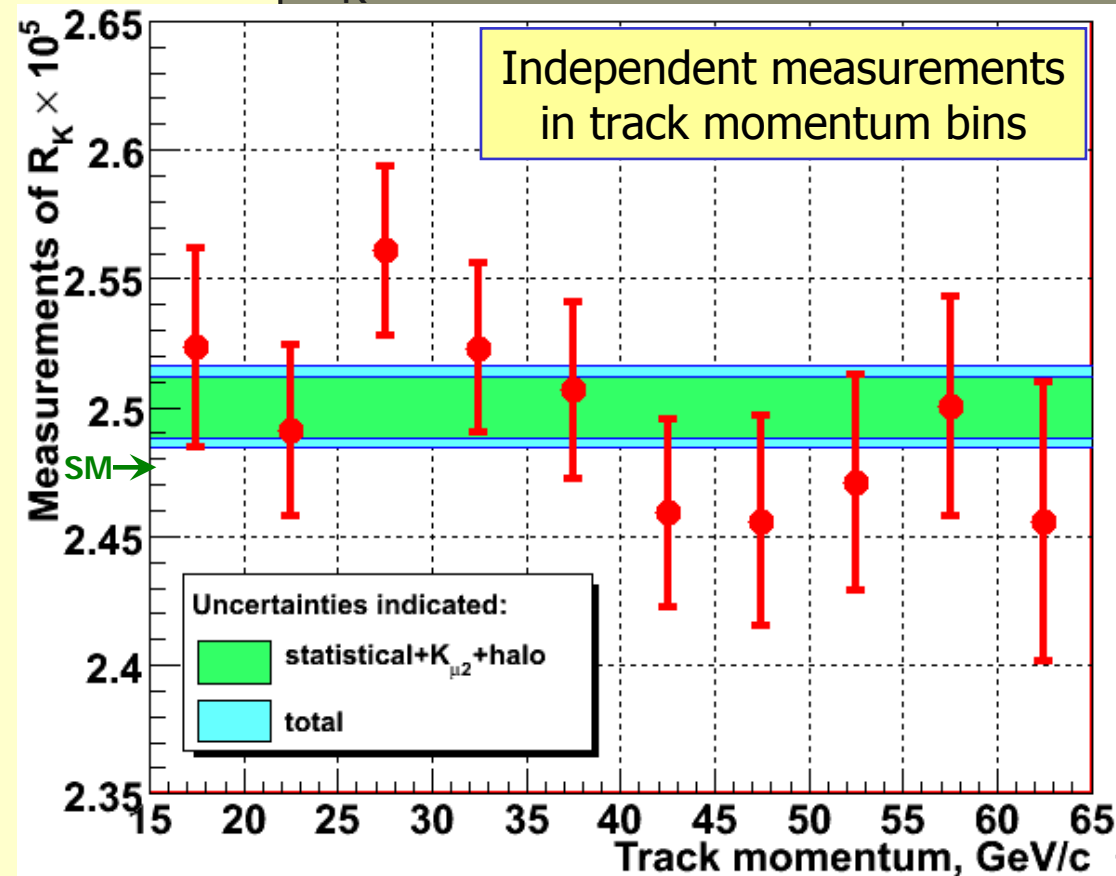
- $E_{\text{LKr}}$  efficiency directly affects  $R_K$ ;
- monitored with control trigger samples;
- conservative systematic uncertainty for preliminary result:  $\delta R_K/R_K = 0.3\%$  (dead time generated by accidentals).

# Preliminary result (40% data set)

$$R_K = (2.500 \pm 0.012_{\text{stat}} \pm 0.011_{\text{syst}}) \times 10^{-5}$$

$$= (2.500 \pm 0.016) \times 10^{-5}$$

(New, June 09)



## Uncertainties

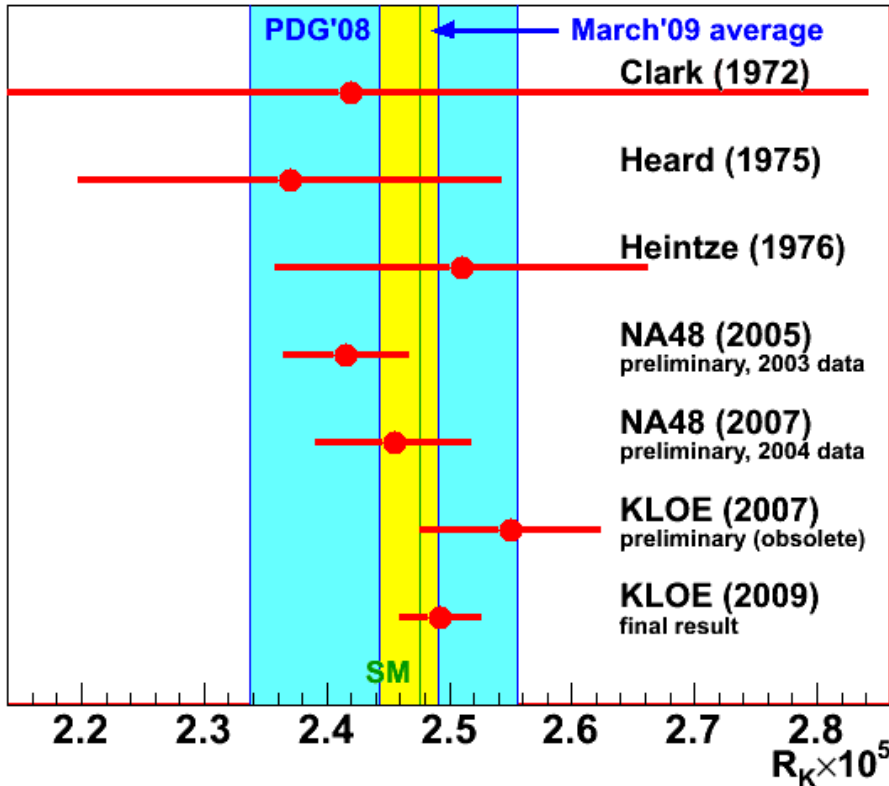
Source	$\delta R_K \times 10^5$
Statistical	0.012
$K_{\mu 2}$	0.004
Beam halo	0.001
$K_{e 2 \gamma}$ (SD <sup>+</sup> )	0.004
Electron ID	0.001
IB simulation	0.007
Acceptance	0.002
Trigger timing	0.007
<b>Total</b>	<b>0.016</b>

(0.64% precision)

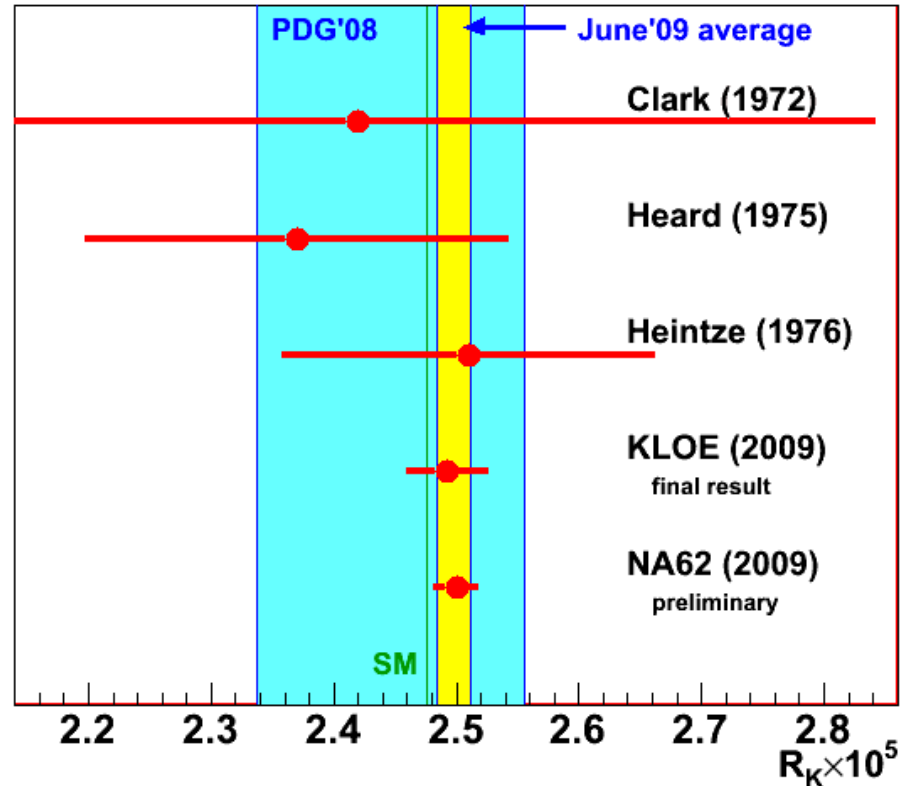
The whole sample will allow a statistical uncertainty  $\sim 0.3\%$ , and total uncertainty of 0.4–0.5%.

# Comparison to world data

March 2009

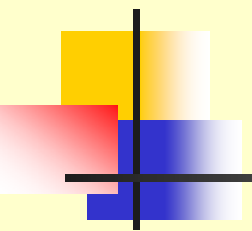


June 2009



World average	$\delta R_K \times 10^5$	Precision
March 2009	$2.467 \pm 0.024$	0.97%
June 2009	$2.498 \pm 0.014$	0.56%

(NA48/2 preliminary results excluded from the new average: they are superseded by NA62)



# Conclusions & prospects

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- Due to the helicity suppression of the  $K_{e2}$  decay, the measurement of  $R_K$  is well-suited for a **stringent test of the Standard Model**.
- NA62 data taking in 2007/08 was **optimised for  $R_K$  measurement**. The NA62  $K_{e2}$  sample is  $\sim 10$  times the world sample. Powerful  $K_{e2}/K_{\mu 2}$  separation ( $>99\%$  electron ID efficiency and  $\sim 10^6$  muon suppression) leads to a low  $8\%$  background.
- Preliminary result based on  $\sim 40\%$  of the NA62  $K_{e2}$  sample:  
 $R_K = (2.500 \pm 0.016) \times 10^{-5}$ , reaching **a record 0.7% accuracy** and compatible to the SM prediction. A timely result, as direct searches for New Physics at the **LHC** are approaching.
- With the full NA62 data sample of 2007/08, the precision is **expected to be improved** to better than  $\delta R_K/R_K = 0.5\%$ .