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

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**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) Preliminary results and prospects.

UNIVERSITY OF BIRMINGHAM

CERN

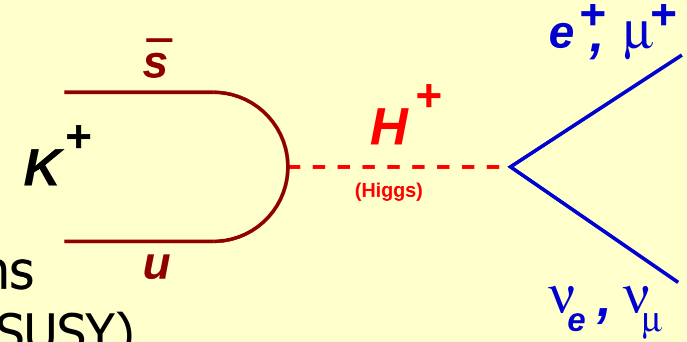
*Rencontres de Moriond (EW session)*

*La Thuile, Italy • 10 March 2010*

# 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/$c^2$, $\tan\beta$ = 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 by not hopeless

PRL100 (2008) 241802

$f_{Ds}^{(QCD)}$=(241±3)MeV
$f_{Ds}^{(exp)}$=(277±9)MeV

~4σ discrepancy + new data: PRD79 (2009) 052001

BaBar, Belle: $Br_{exp}(B\to\tau\nu)=(1.42\pm0.43)\times10^{-4}$
Standard Model: $Br_{SM}(B\to\tau\nu)=(1.33\pm0.23)\times10^{-4}$

(SM uncertainties: $\delta f_B/f_B$=10%, $\delta|V_{ub}|^2/|V_{ub}|^2$=13%)

⇒ $\Delta\Gamma/\Gamma_{SM}=1.07\pm0.37$

(JHEP 0811 (2008) 42)

Obstructed by hadronic uncertainties

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

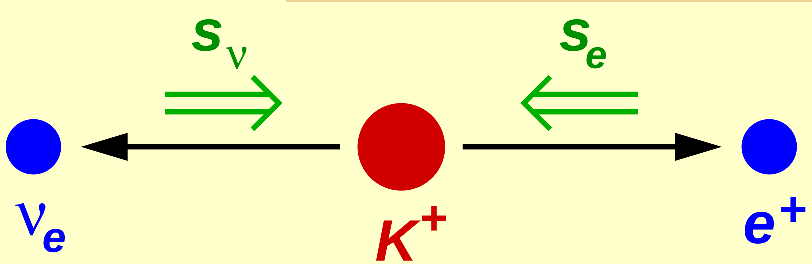
Observable sensitive to lepton flavour violation and its SM expectation:

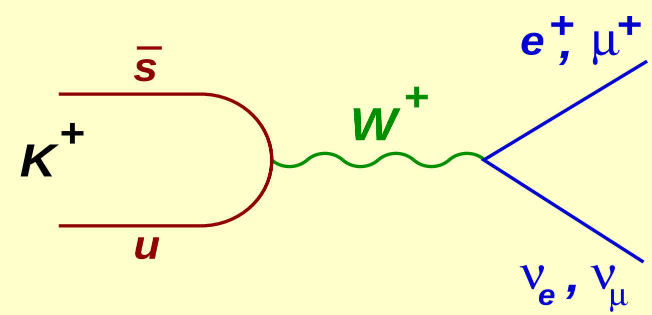
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$

(similarly, $R_\pi$ 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-permille accuracy due to cancellation of hadronic uncertainties.
- Measurements of $R_K$ and $R_\pi$ 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. Lett. 99 (2007) 231801

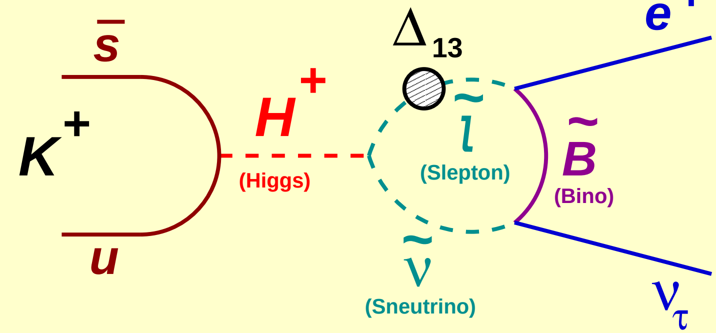
# $R_K = K_{e2}/K_{\mu 2}$ beyond the SM

**2HDM – tree level** (including SUSY)

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

→ Does not affect the ratio $R_K$

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




**2HDM – one-loop level**

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

→ $R_K$ enhancement can be experimentally accessible

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

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)

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

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

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

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

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

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

# $R_K$ & $R_\pi$: experimental status

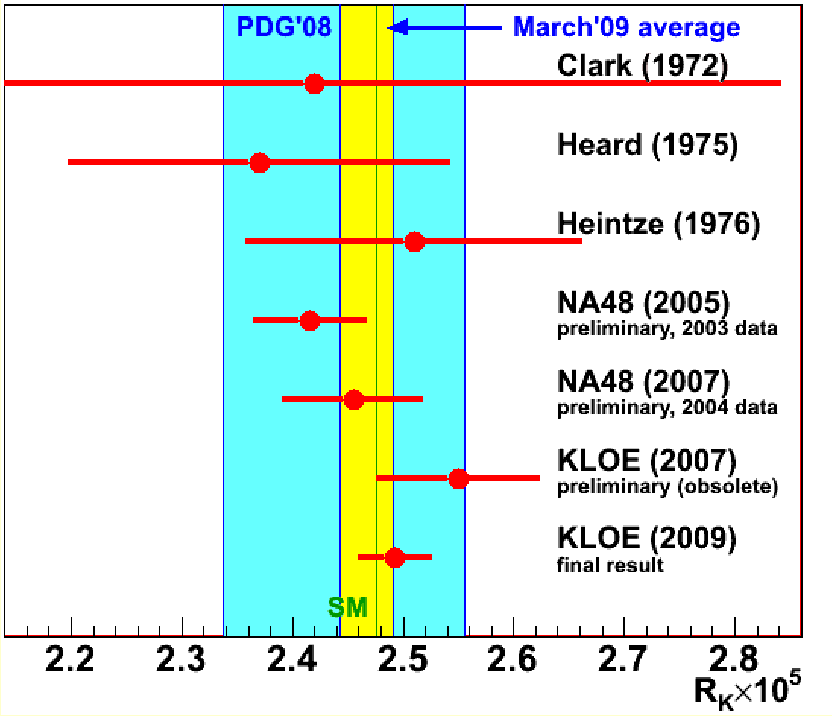
## Kaon experiments:

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

→ Recent improvement: KLOE (Frascati).
Data collected in 2001–2005,
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)

→ NA62 (phase I) goal:
dedicated data taking strategy,
~150K $K_{e2}$ candidates, <10% background,
$\delta R_K/R_K<0.5\%$ : a stringent SM test.

**$R_K$ world average (March 2009)**

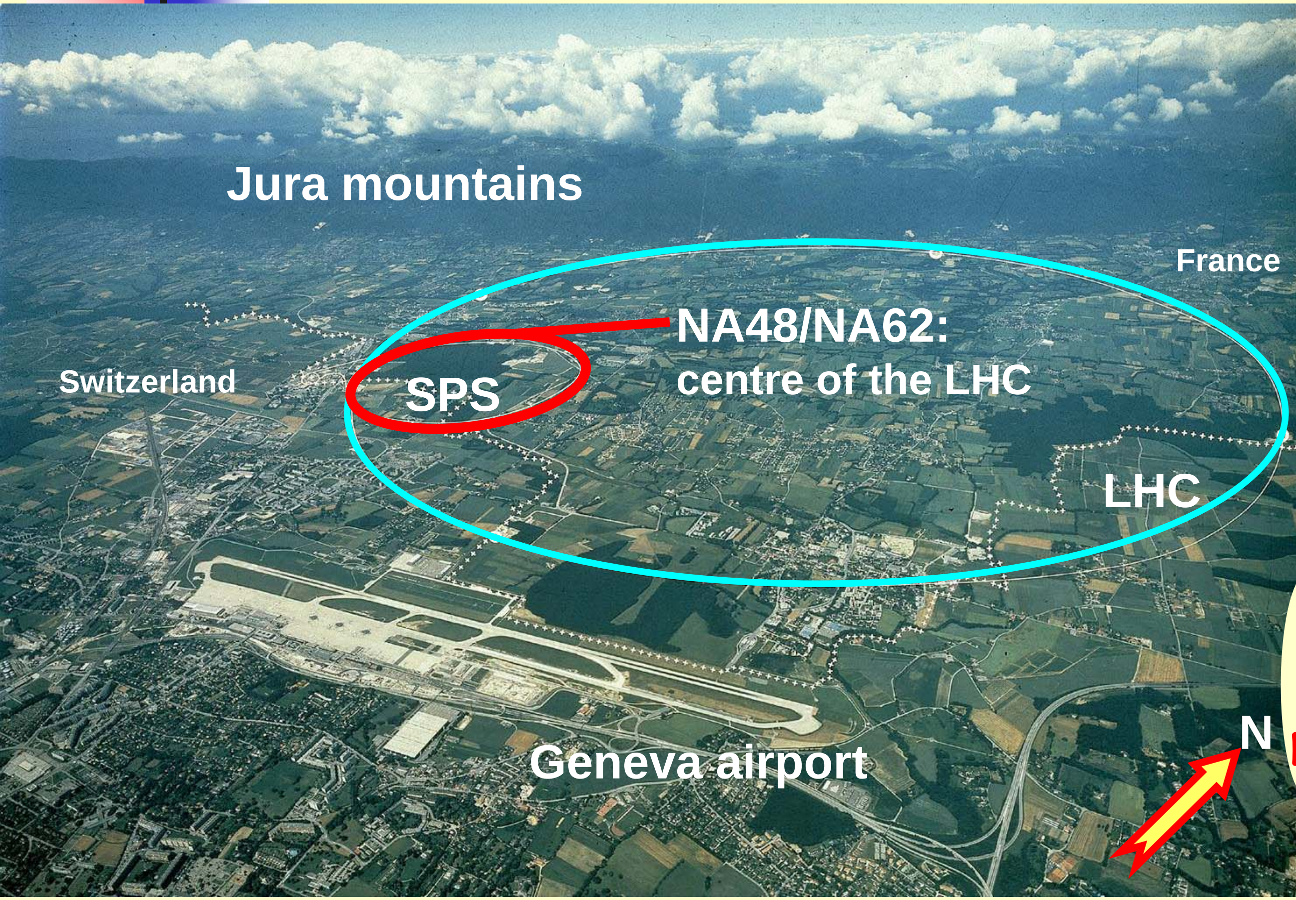



## Pion experiments:

→ PDG'08 average (1980s, 90s measurements):
$R_\pi=(12.30\pm0.04)\times10^{-5}$ ($\delta R_\pi/R_\pi=0.3\%$)

→ Current projects: PEN@PSI (stopped $\pi$) running (arXiv:0909.4358)
PIENU@TRIUMF (in-flight) proposed (T. Numao, PANIC'08 proceedings, p.874)
$\delta R_\pi/R_\pi\sim0.05\%$ foreseen (similar to SM precision)

# CERN NA48/NA62




**NA48** discovery of direct CPV
- 1997: $\varepsilon'/\varepsilon$: $K_L + K_S$
- 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 (phase I)**
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

**NA62 (phase II)**
- 2007–2012: design & construction
- 2013–2015: $K^+ \to \pi^+ \nu\bar{\nu}$ data taking

NA62 phase I: 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

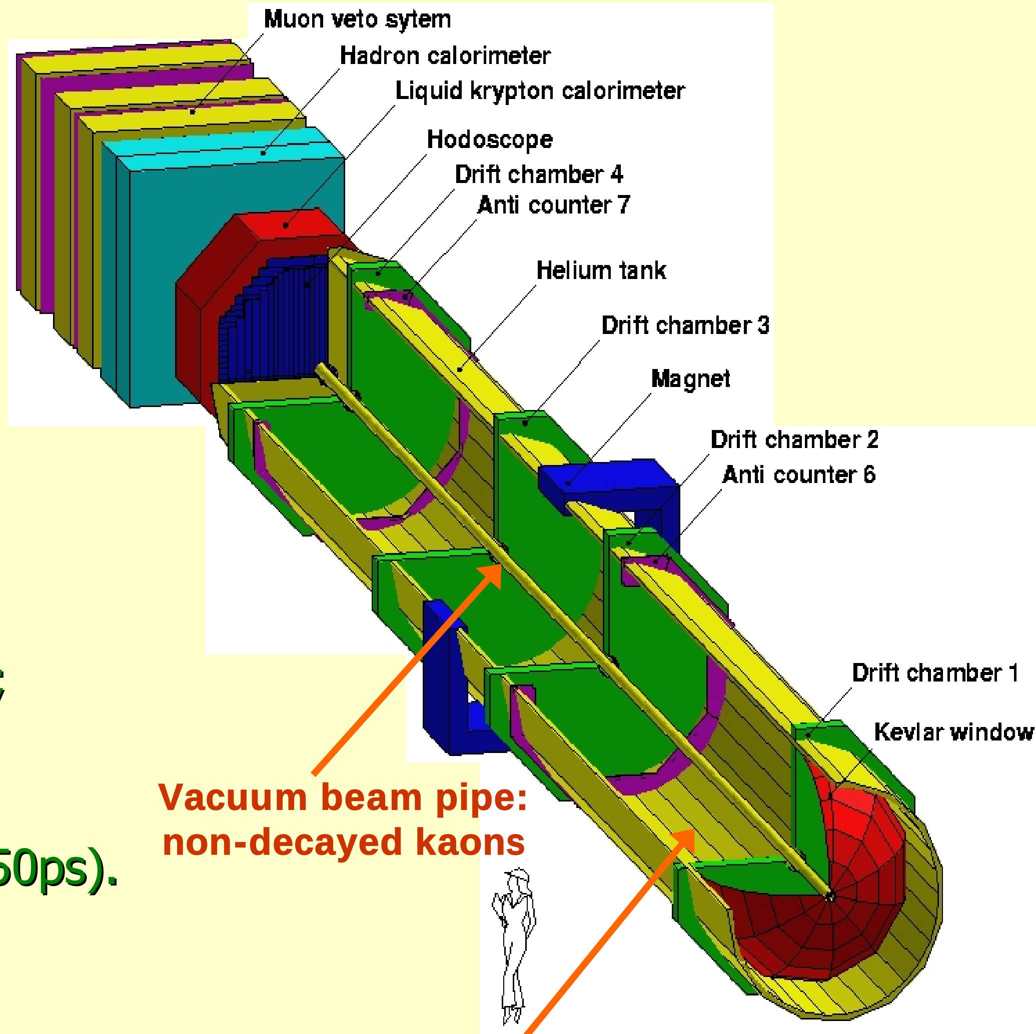
# NA62 data taking 2007/08

**Data taking:**

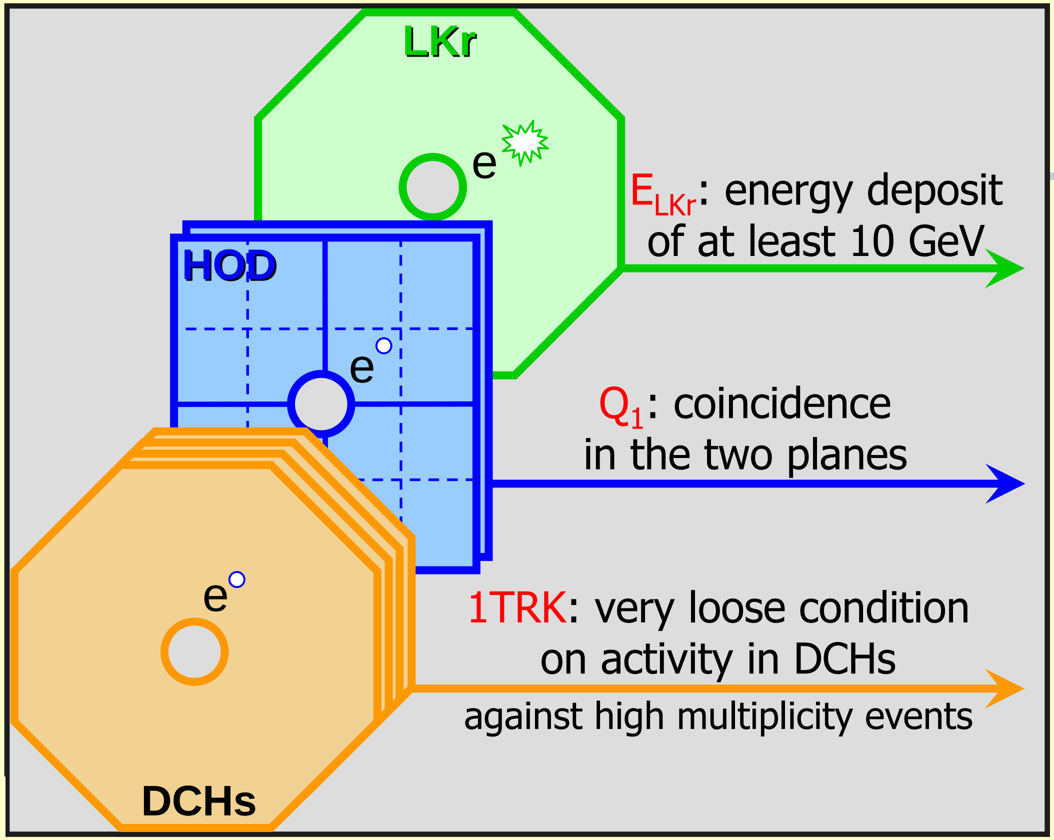
- Four months in 2007 (23/06–22/10):
  ~400K SPS spills, 300TB of raw data (90TB recorded); reprocessing & data preparation finished.
- Two weeks in 2008 (11/09–24/09):
  special data sets allowing reduction of the systematic uncertainties.

**Principal subdetectors for $R_K$:**

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



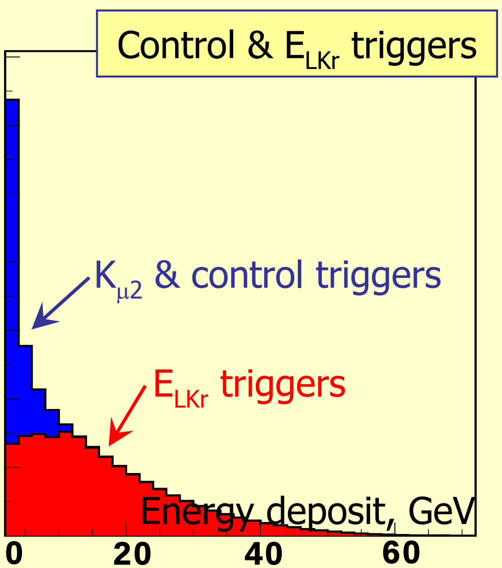
# Trigger logic

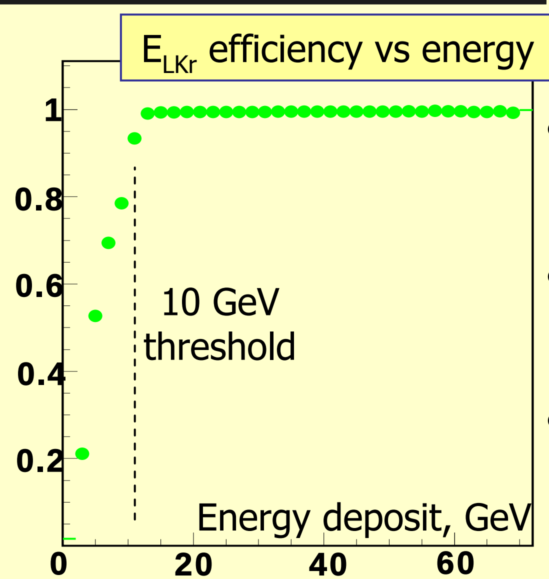



Minimum bias
(high efficiency, but low purity)
trigger configuration used

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

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




- Efficiency of $K_{e2}$ trigger: monitored with $K_{\mu 2}$ & other control triggers.
- $E_{LKr}$ inefficiency for electrons measured to be (0.05±0.01)% for $p_{track}$>15 GeV/c.
- Different trigger conditions for signal and normalization!

# Measurement strategy

(1) $K_{e2}/K_{\mu 2}$ candidates are 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) counting experiment, independently in 10 lepton momentum bins
(owing to strong momentum dependence of backgrounds and event topology)

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

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

$N_B(K_{e2})$, $N_B(K_{\mu 2})$: numbers of background events; → $N_B(K_{e2})$: main source of systematic errors

$A(K_{e2})$, $A(K_{\mu 2})$: MC geometric acceptances (no ID);

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

$\varepsilon(K_{e2})/\varepsilon(K_{\mu 2})>99.9\%$: $E_{LKr}$ trigger condition efficiency;

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

(3) MC simulations used to a limited extent only:

- Geometrical part of the acceptance correction (not for particle ID);
- simulation of “catastrophic” bremsstrahlung by muons.

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

**Large common part** (topological similarity)

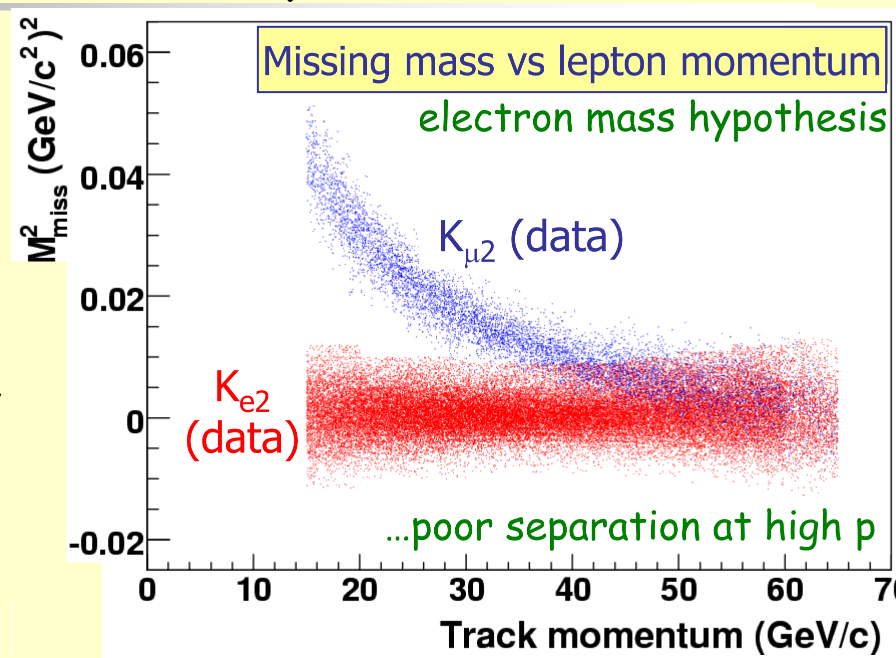
- one reconstructed track;
- geometrical acceptance cuts;
- K decay vertex: closest approach of track & nominal kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: 15GeV/c<p<65GeV/c.

**Kinematic separation**

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

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

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



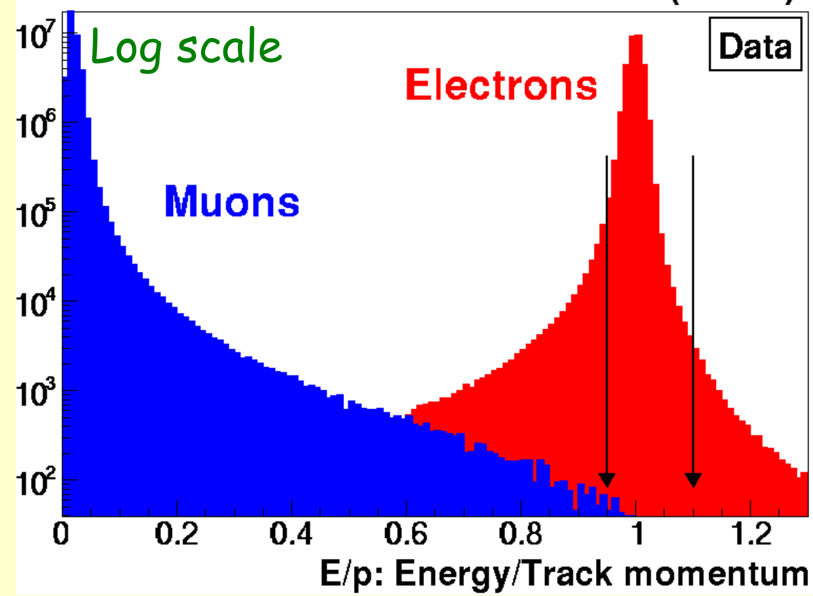

**Separation by particle ID**

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

0.95<E/p<1.10 for electrons,

E/p<0.85 for muons.

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



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

**Main background source**

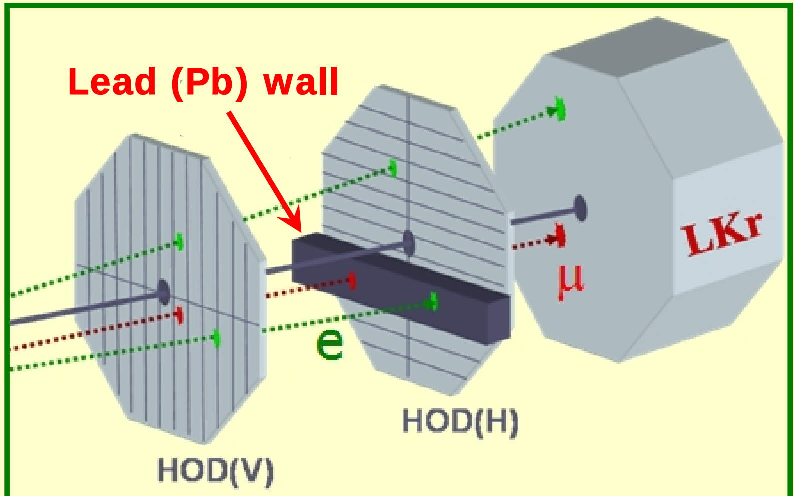
Muon "catastrophic" energy loss in LKr by emission of energetic bremsstrahlung photons.
$P(\mu\to e) \sim 3\times10^{-6}$ (and momentum-dependent).

$P(\mu\to e)/R_K \sim 10\%$:
$K_{\mu 2}$ decays represent a major background

Theoretical bremsstrahlung cross-section
[Phys. Atom. Nucl. 60 (1997) 576]
must be validated in the region $(E_\gamma/E_\mu)>0.9$
by a direct measurement of $P(\mu\to e)$
to $\sim10^{-2}$ relative precision.

**Obtaining pure muon samples**

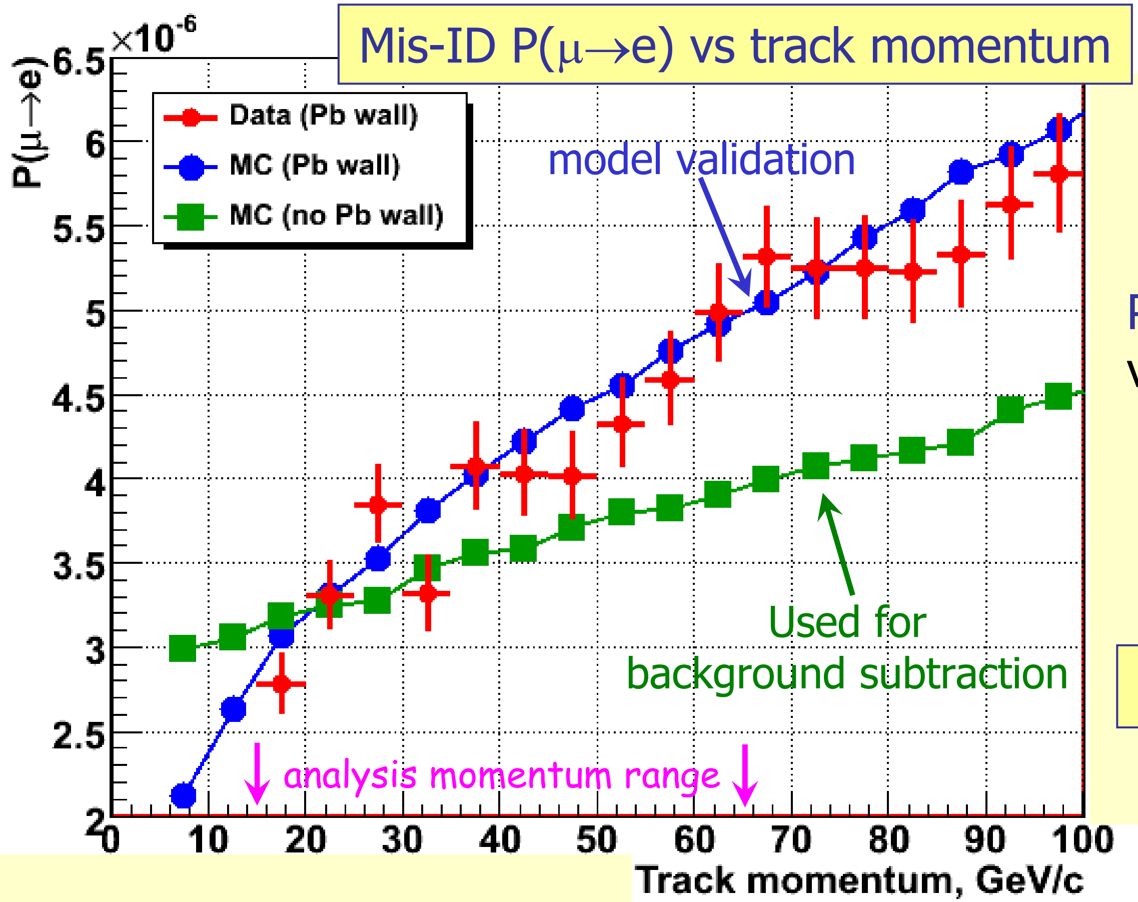
Electron contamination due to $\mu\to e$ decay: $\sim10^{-4}$.
Pb wall ($\sim10X_0$) placed between the HOD planes:
tracks traversing the wall and having $E/p>0.95$
are sufficiently pure muon samples (electron contamination $<10^{-7}$).




| | |
|---|---|
| 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 |

# $K_{\mu 2}$ background (2)

P(μ→e): measurement (2007 special muon run) vs Geant4-based simulation




[Cross-section model:
Phys. Atom. Nucl. 60 (1997) 576]

Good data/MC agreement
for the Pb wall installed

P(μ→e) is modified by the Pb wall
via two competing mechanisms:

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

→ a significant MC correction

Result: B/(S+B) = (6.28±0.17)%

(uncertainty is due to
the limited size of the data sample
used to validate
the cross-section model)

**Improvements:**

- Muons from regular $K_{\mu 2}$ decays from kaon runs with the Pb wall installed.

# $K_{\mu 2}$ 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

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

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

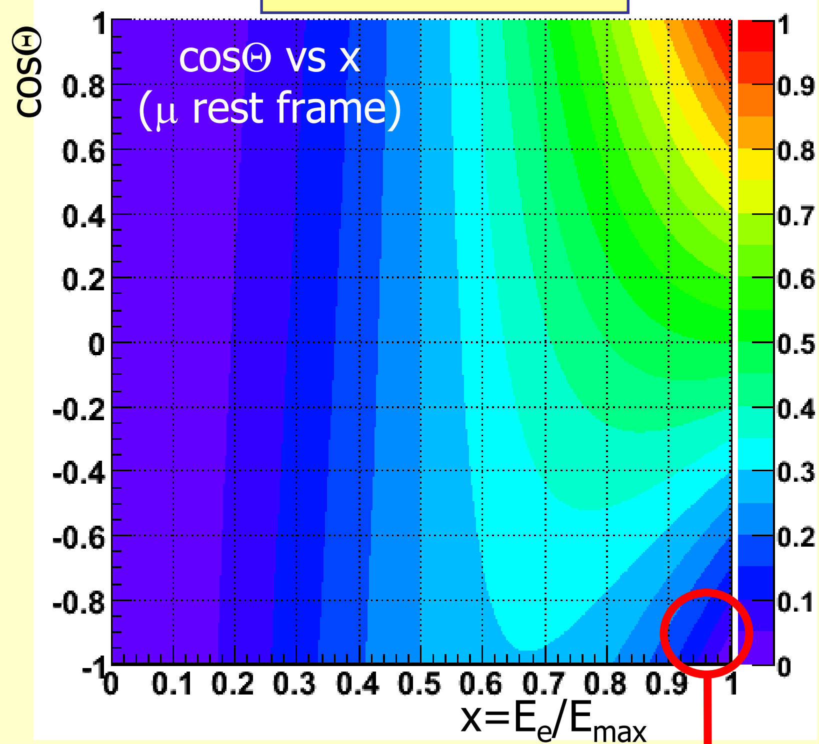
$x = E_e/E_{max} \approx 2E_e/M_\mu$,

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

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

Important but not dominant background

Michel distribution



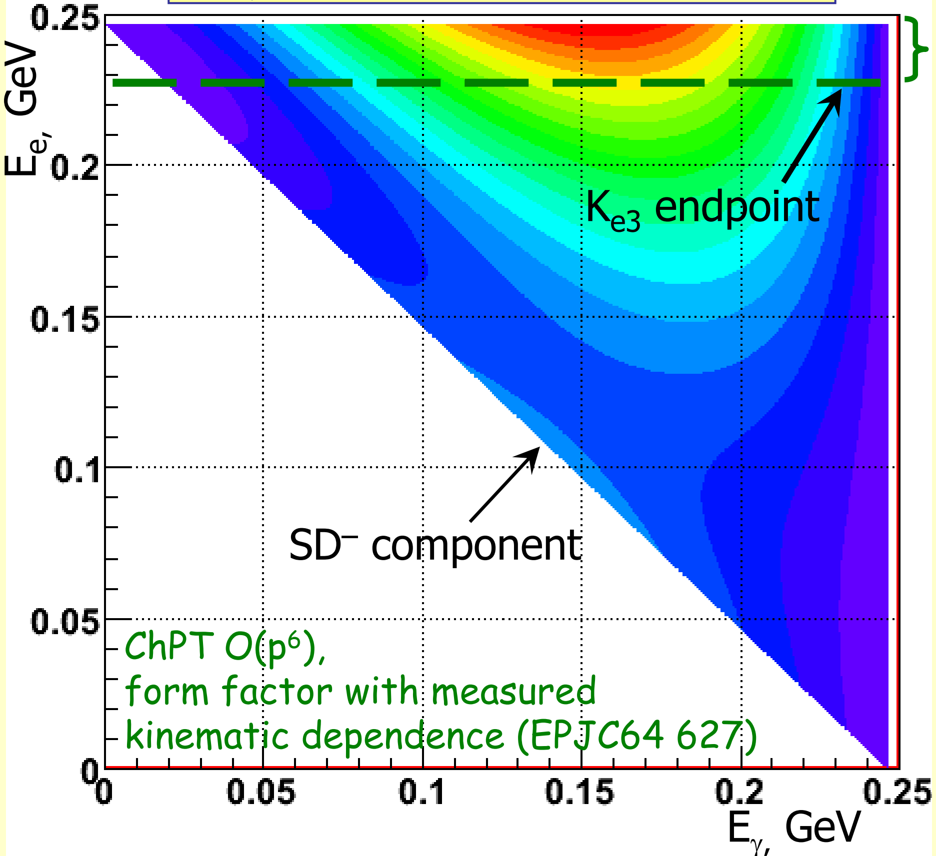

Only energetic forward electrons
(passing $M_{miss}$, E/p, vertex CDA cuts)
are selected as $K_{e2}$ candidates:
(high x, low cos$\Theta$).

They are naturally suppressed
by the muon polarisation

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

- Background by definition of $R_K$, no helicity suppression.
- Rate similar to that of $K_{e2}$, limited precision: $BR=(1.52\pm0.23)\times10^{-5}$.

$K_{e2\gamma}$ (SD) Dalitz plot distribution




$K_{e2\gamma}$ (SD⁻) background is negligible, peaking at $E_e = E_{max}/2 \approx 123$ MeV

Only energetic electrons ($E_e^*$>230MeV) are compatible to $K_{e2}$ kinematic ID and contribute to the background

⇩

This region of phase space is accessible for direct BR and form-factor measurement (being above the $E_e^*$=227 MeV endpoint of the $K_{e3}$ spectrum).

SD background contamination

$B/(S+B) = (1.02\pm0.15)\%$

(uncertainty due to PDG BR, will be improved using a recent KLOE measurement, EPJC64 627)

# 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.

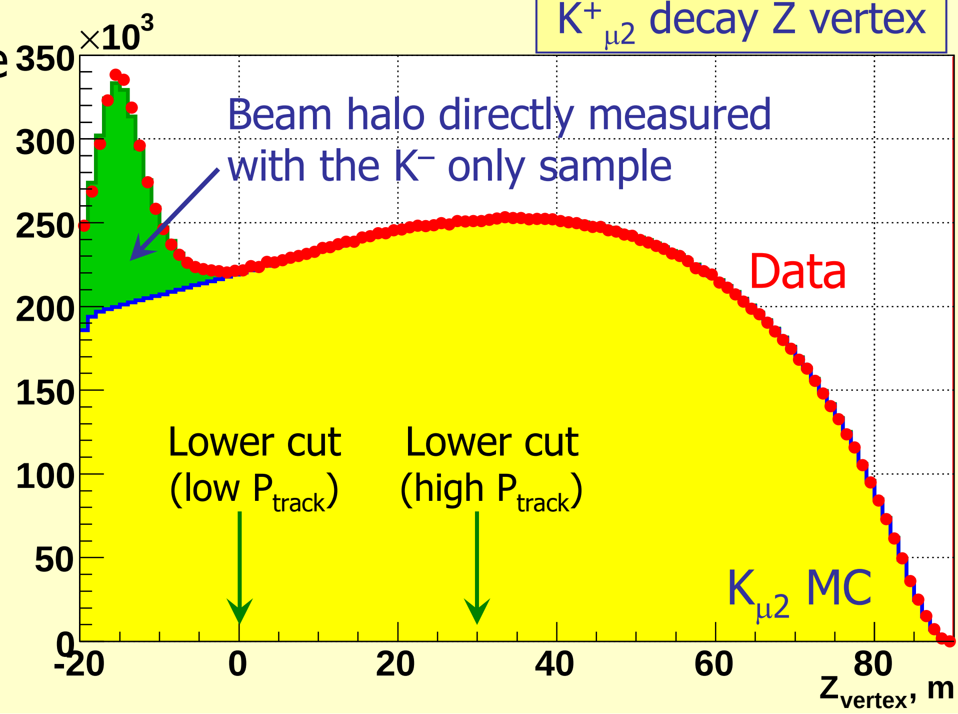
The background is measured to sub-permille precision, and strongly depends on decay vertex position and track momentum.

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

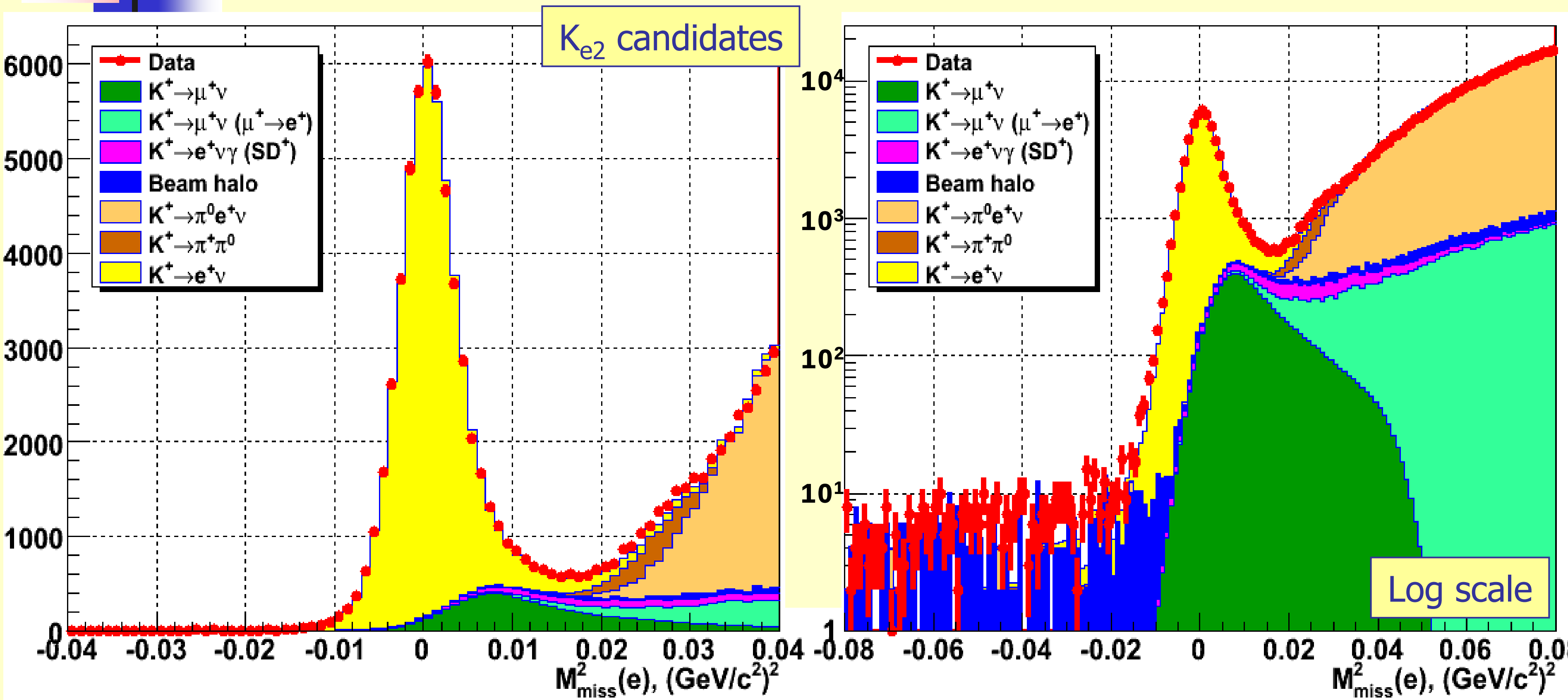
$$B/(S+B) = (0.45\pm0.04)\%$$

Uncertainty is due to the limited size of the control sample.

$K^+_{\mu 2}$ decay Z vertex



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



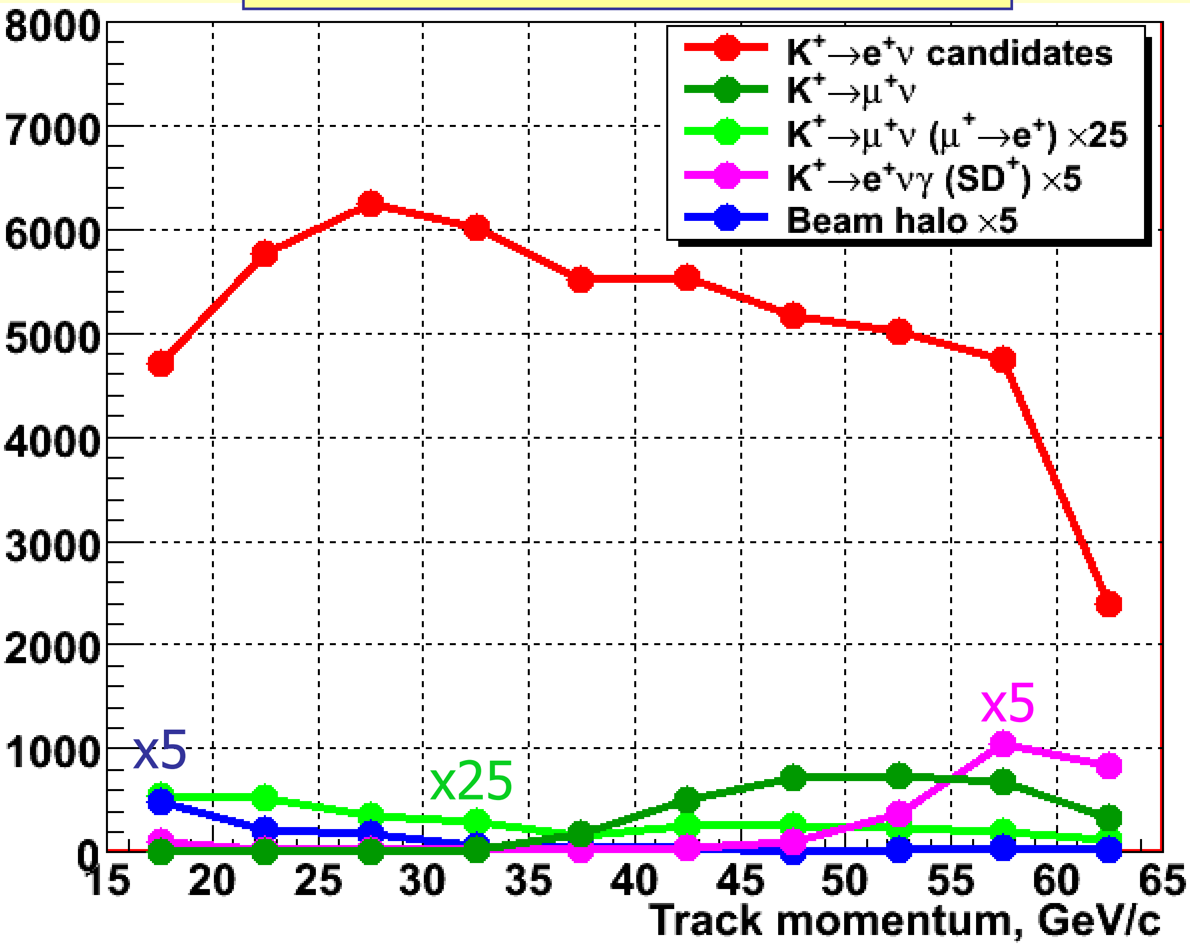

51,089 $K^+ \to e^+\nu$ candidates,
99.2% electron ID efficiency,
B/(S+B) = (8.0±0.2)%

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

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

# Backgrounds: summary

Statistics in lepton momentum bins




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

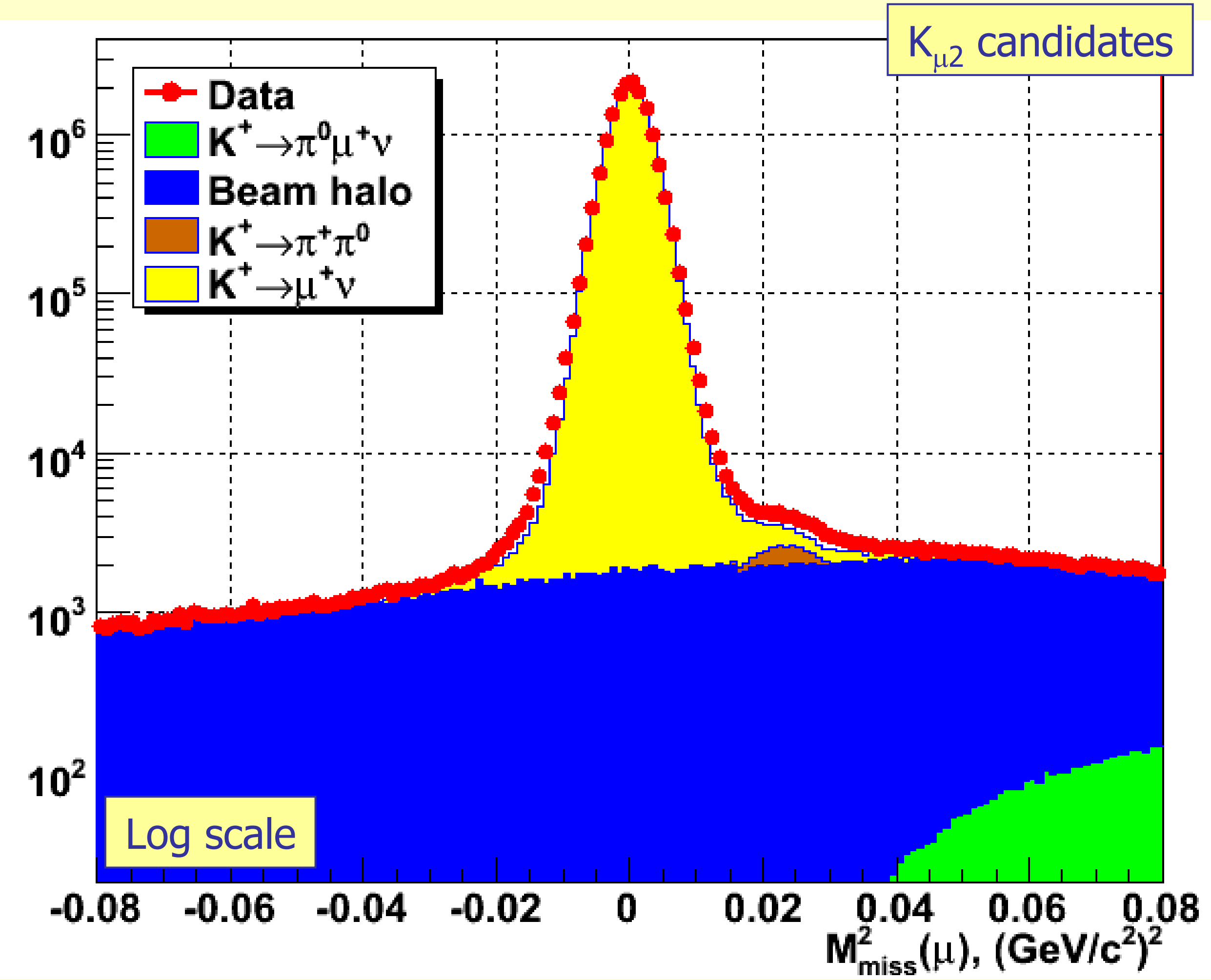
## Backgrounds

| Source | B/(S+B) |
|---|---|
| $K_{\mu 2}$ | (6.28±0.17)% |
| $K_{\mu 2}$ ($\mu \to e$) | (0.23±0.01)% |
| $K_{e2\gamma}$ ($SD^+$) | (1.02±0.15)% |
| Beam halo | (0.45±0.04)% |
| $K_{e3}$ | 0.03% |
| $K_{2\pi}$ | 0.03% |
| Total | (8.03±0.23)% |

Record $K_{e2}$ sample:
51,089 candidates
with low background
B/(S+B) = (8.0±0.2)%

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

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




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

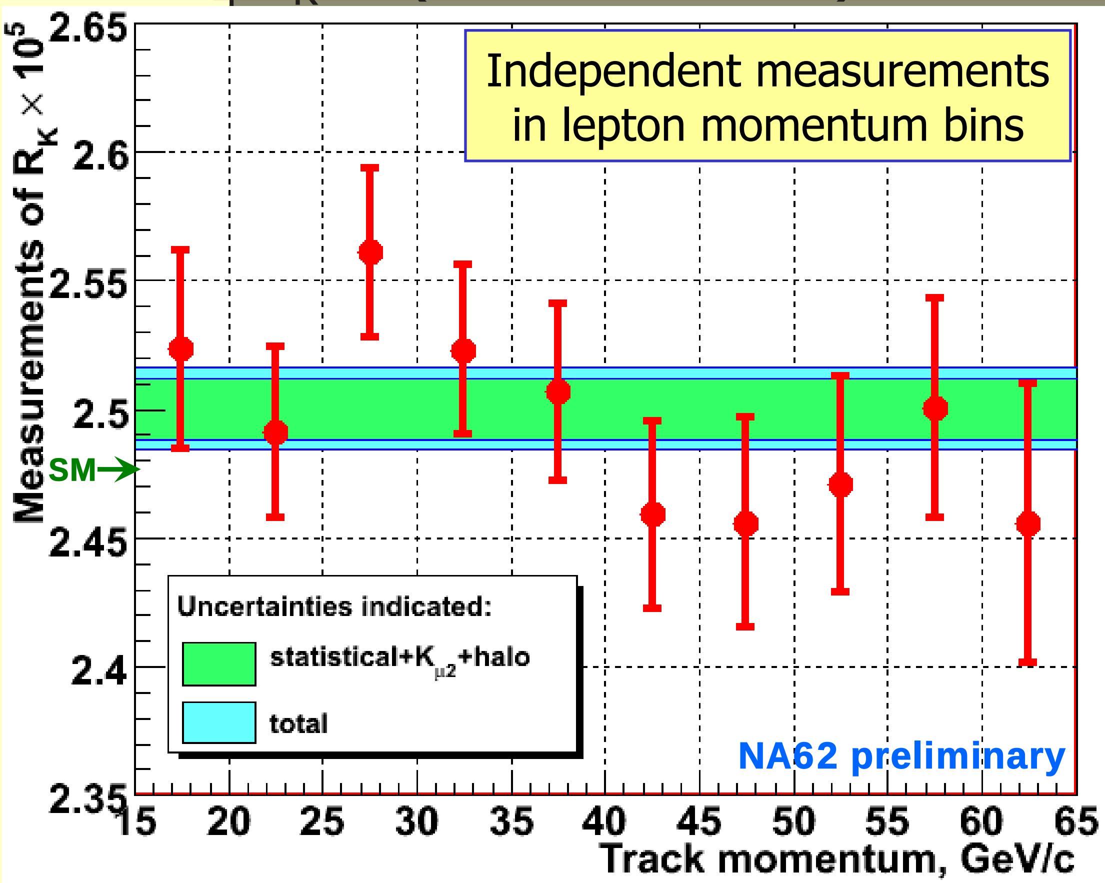
($K_{\mu 2}$ trigger was pre-scaled by D=150)

The only significant background source is the beam halo.

# Preliminary result (40% data set)

$$R_K = (2.500 \pm 0.012_{stat} \pm 0.011_{syst}) \times 10^{-5}$$
$$= (2.500 \pm 0.016) \times 10^{-5}$$

(arXiv:0908.3858)




**Uncertainties**

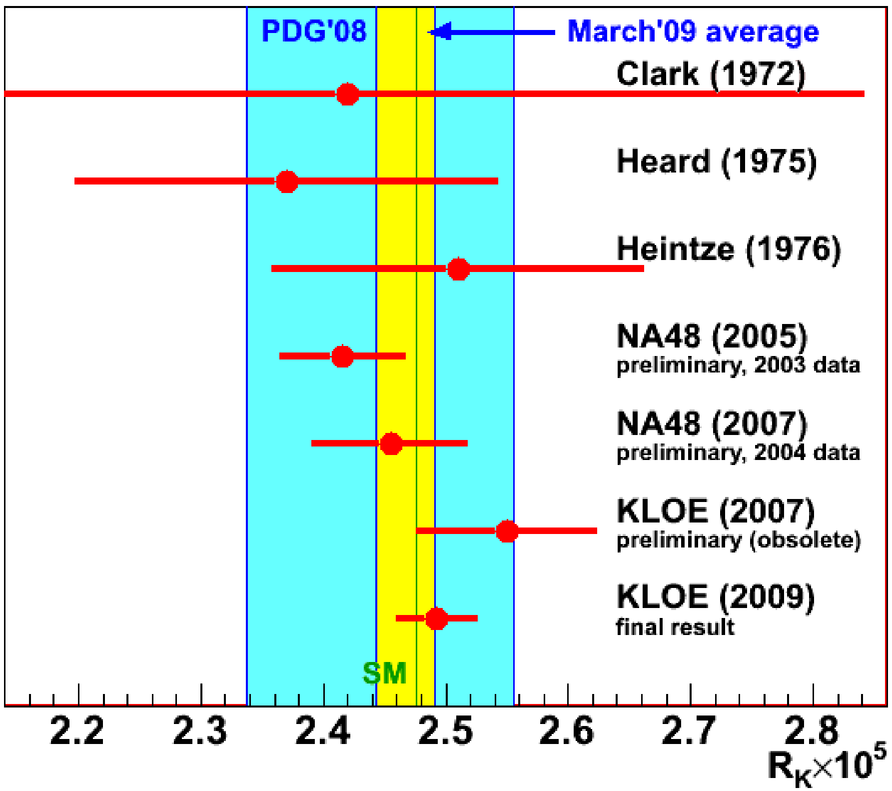
| Source | $\delta R_K \times 10^5$ |
|---|---|
| Statistical | 0.012 |
| $K_{\mu 2}$ | 0.004 |
| Beam halo | 0.001 |
| $K_{e2\gamma}$ (SD+) | 0.004 |
| Electron ID | 0.001 |
| IB simulation | 0.007 |
| Acceptance | 0.002 |
| Trigger timing | 0.007 |
| Total | 0.016 |

(0.64% precision)

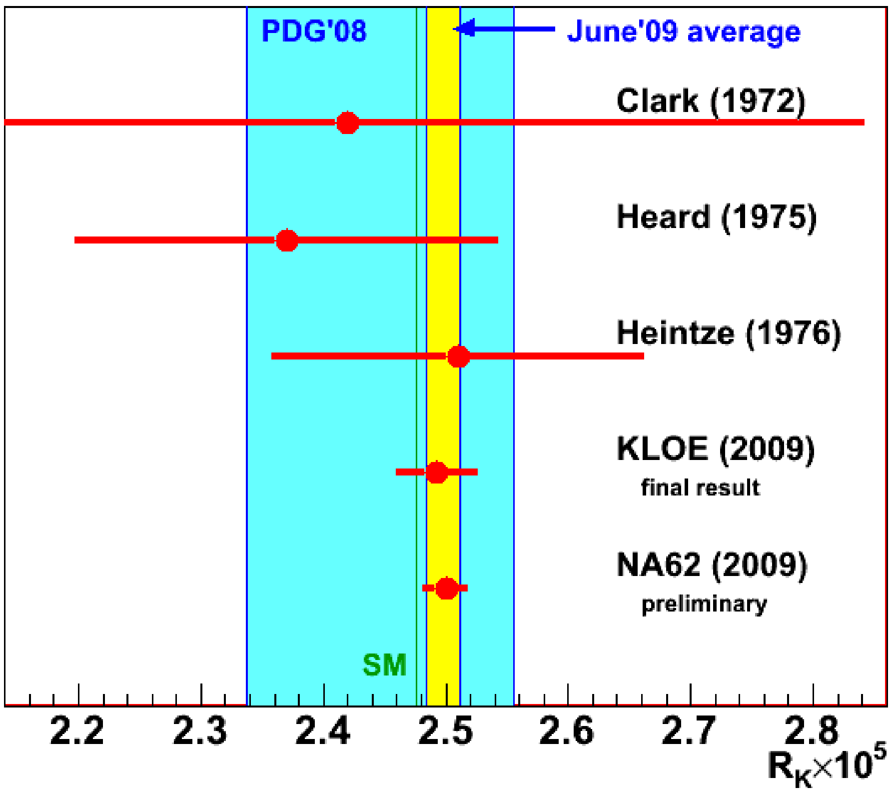
The whole 2007 sample will allow statistical uncertainty ~0.3%, total uncertainty of 0.4–0.5%.

# Comparison to world data

**March 2009**




**Now**




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

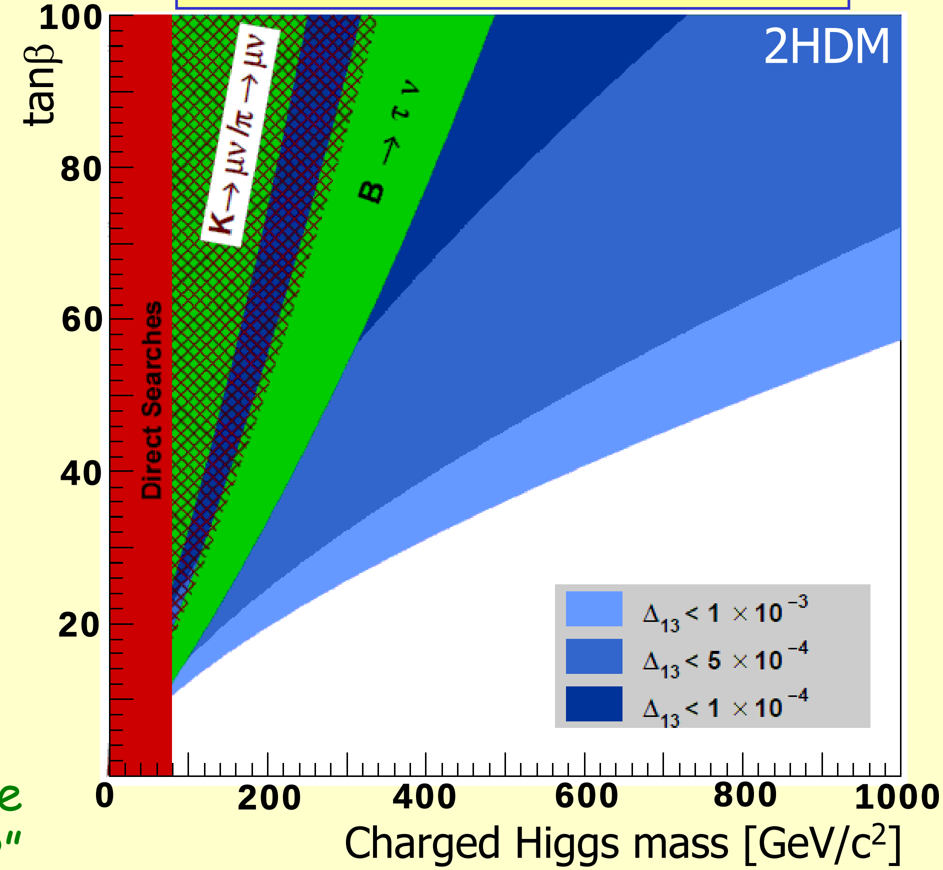
(NA48/2 preliminary results excluded from the new average: they are superseded by NA62)

# $R_K$: sensitivity to new physics

$R_K$ measurements are currently in agreement with the SM expectation at $\sim 1.5\sigma$.
Any significant enhancement with respect to the SM value would be an evidence of new physics.

For non-tiny values of the LFV slepton mixing $\Delta_{13}$, sensitivity to $H^{\pm}$ in $R_K = K_{e2}/K_{\mu 2}$ is better than in $B \to \tau\nu$

($M_H$, $\tan\beta$) 95% exclusion limits




*"Maybe NA62 will find the first evidence for a charged Higgs exchange?"*
*-- John Ellis (arXiv:0901.1120)*

# Conclusions & prospects

- 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 ~10 times the world sample. Powerful $K_{e2}/K_{\mu2}$ separation (>99% electron ID efficiency and $\sim10^6$ muon suppression) leads to a low 8% background.
- Preliminary result based on ~40% of the NA62 $K_{e2}$ sample: $R_K = (2.500\pm0.016)\times10^{-5}$, 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 $\delta R_K/R_K=0.5\%$.
- $R_K$ measurement with ~0.1% precision has been proposed in the framework of the NA62 (phase II) experiment.