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) Result and prospects.

Kaon 2009 • Tsukuba, Japan
June 10, 2009

K_{l2} and π_{l2} decays in the SM

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

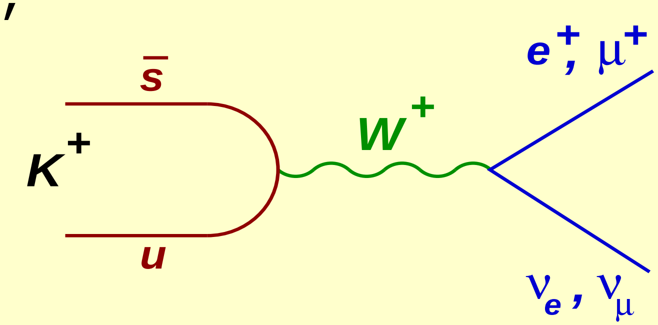
Helicity suppression (V–A couplings):
enhances sensitivity to non-SM effects

Radiative correction (few %) due to the IB part of the radiative $K\to e\nu\gamma$ 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}

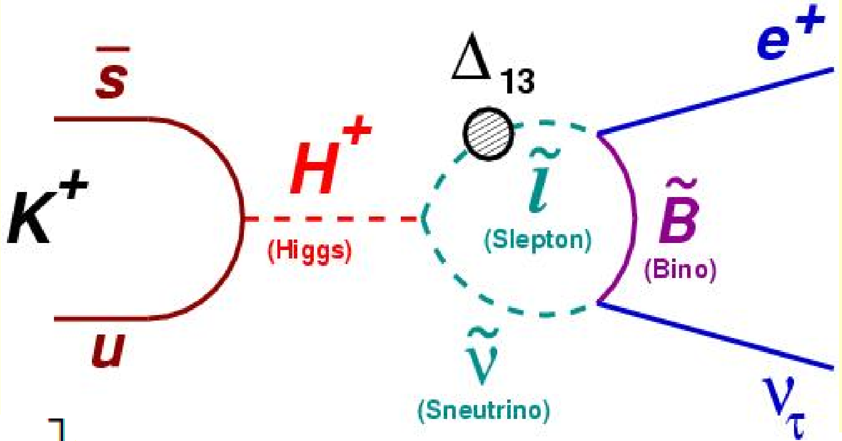
$R_K^{SM} = (2.477\pm0.001)\times10^{-5}$
$R_\pi^{SM} = (12.352\pm0.001)\times10^{-5}$

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

K_{l2} decays beyond the SM

Possible scenario in MSSM:
charged Higgs mediated SUSY LVF contribution with emission of τ neutrino can be strongly enhanced.

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

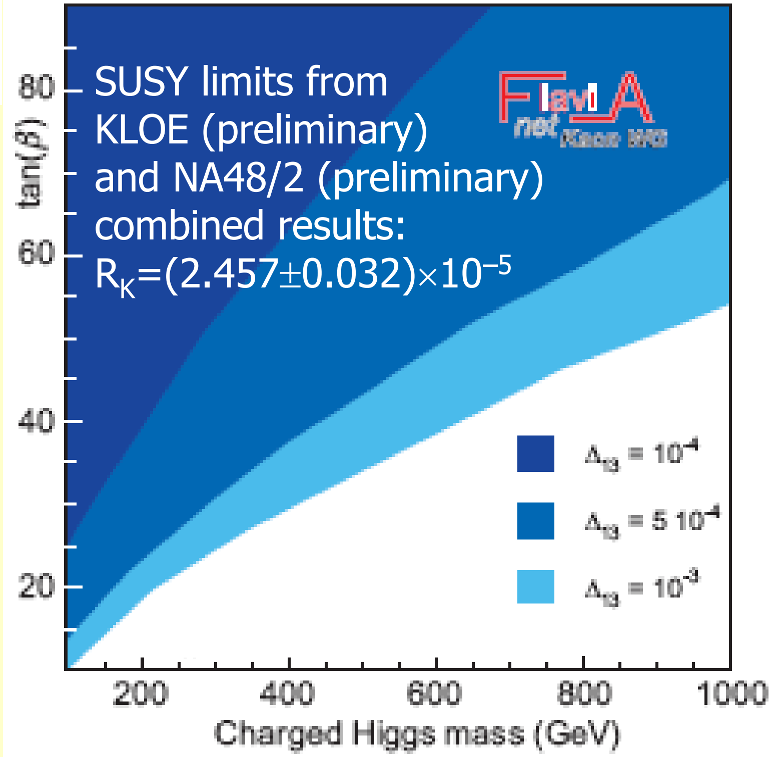


$$R_K^{LFV} \approx R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_{H\pm}^4} \right) \left(\frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

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

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

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



K_{l2} & π_{l2}: experimental status

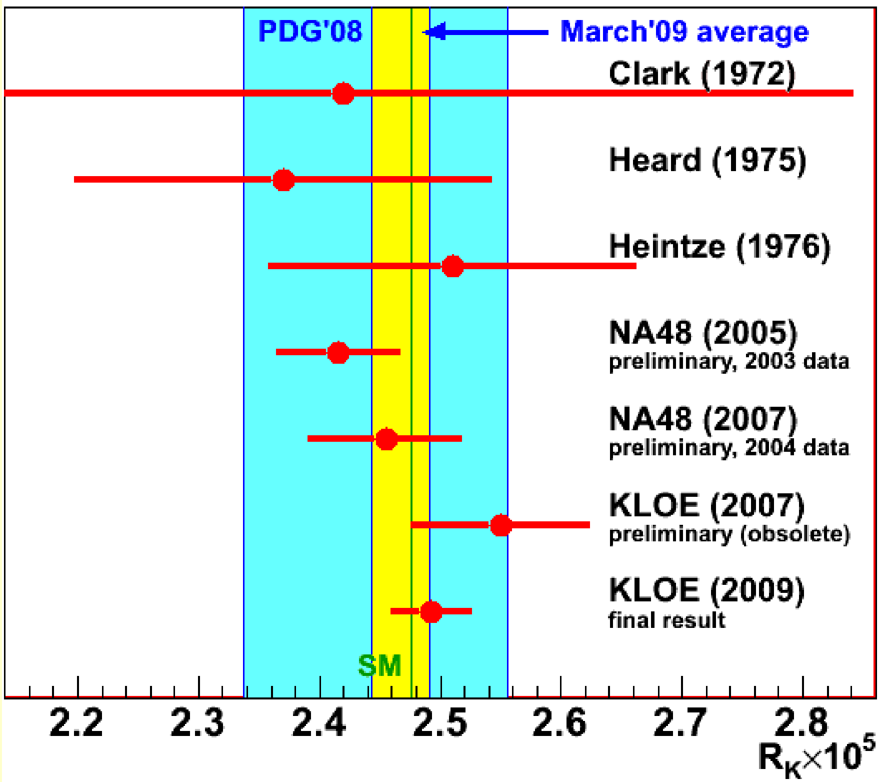
Kaon decay:

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

→ NA48/2: two preliminary results based on 2003 and 2004 data sets
$R_K=(2.416\pm0.049)\times10^{-5}$ ($\delta R_K/R_K=2.0\%$)
$R_K=(2.455\pm0.061)\times10^{-5}$ ($\delta R_K/R_K=2.5\%$)
L. Fiorini, PoS (HEP2005) 288,
V. Kozhuharov, PoS (KAON) 049

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

→ Recent improvement: final KLOE result
$R_K=(2.493\pm0.031)\times10^{-5}$ ($\delta R_K/R_K=1.3\%$)
Mario Antonelli, La Thuile '09

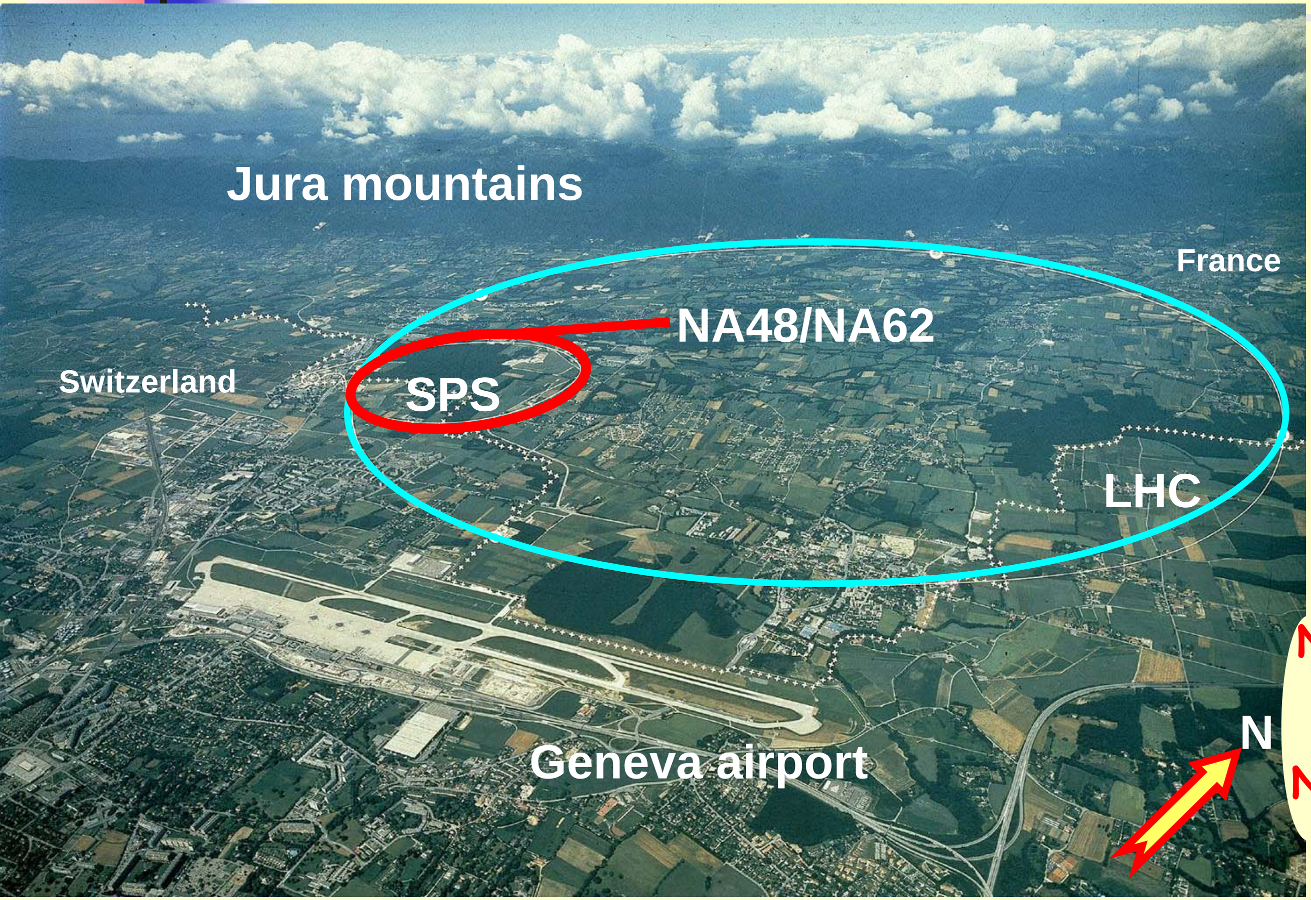


Pion decay:

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

→ Future plans: TRIUMF proposal S1072
$\delta R_\pi/R_\pi=0.06\%$ precision foreseen
Toshio Numao, PANIC '08

NA48/NA62: kaons at CERN



NA48
- 1997: ε'/ε 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 (phase I)
- 2007: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests
- 2008: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests

NA62 (phase II)
- 2006–2010: design & construction
- 2011: start of $K^+\to\pi^+\nu\bar{\nu}$ run

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

Talk by Giuseppe Ruggiero ⇒

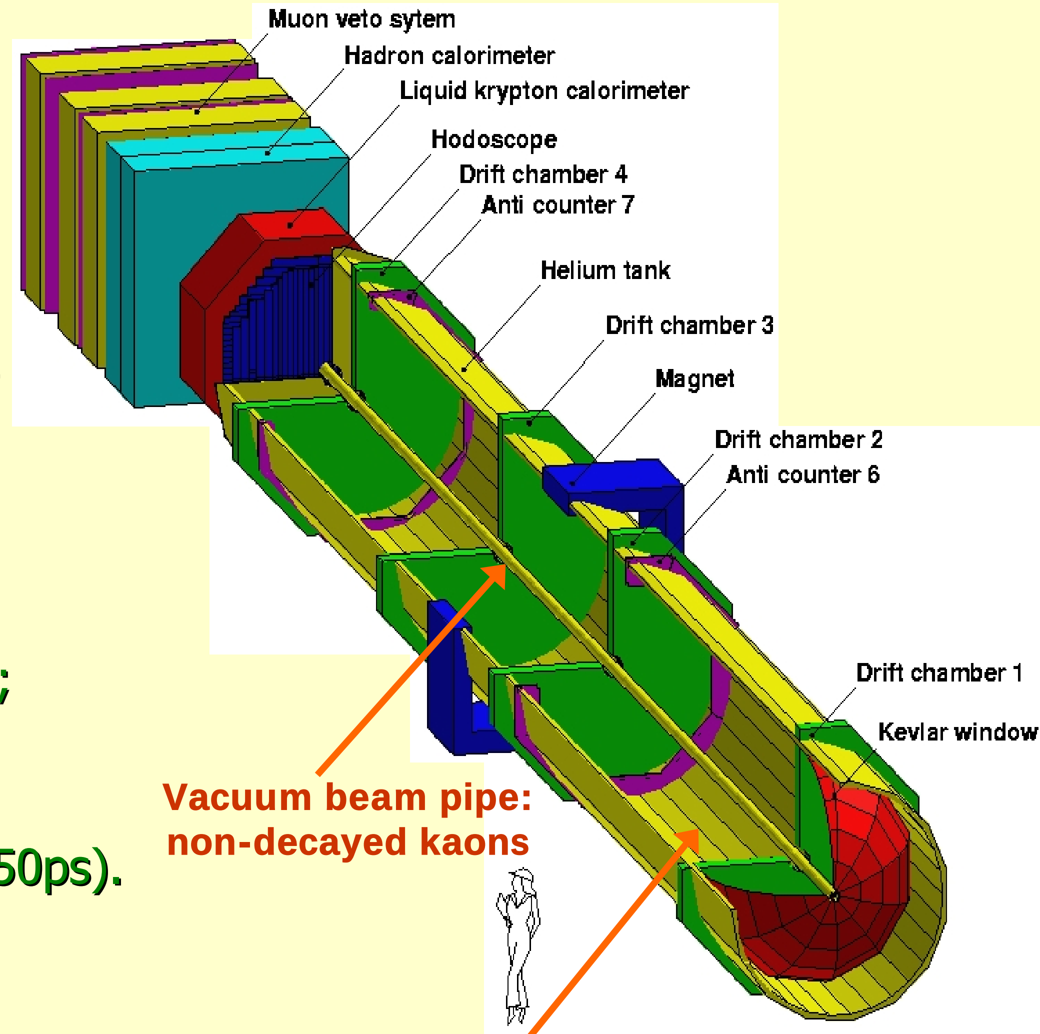
NA62 data taking: 2007/08

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-homogenious;
  $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=0.42/E^{1/2} + 0.6$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:

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

P_K not measured in every event (average used)

Improvement of $K_{e2}/K_{\mu 2}$ kinematic separation

⇩

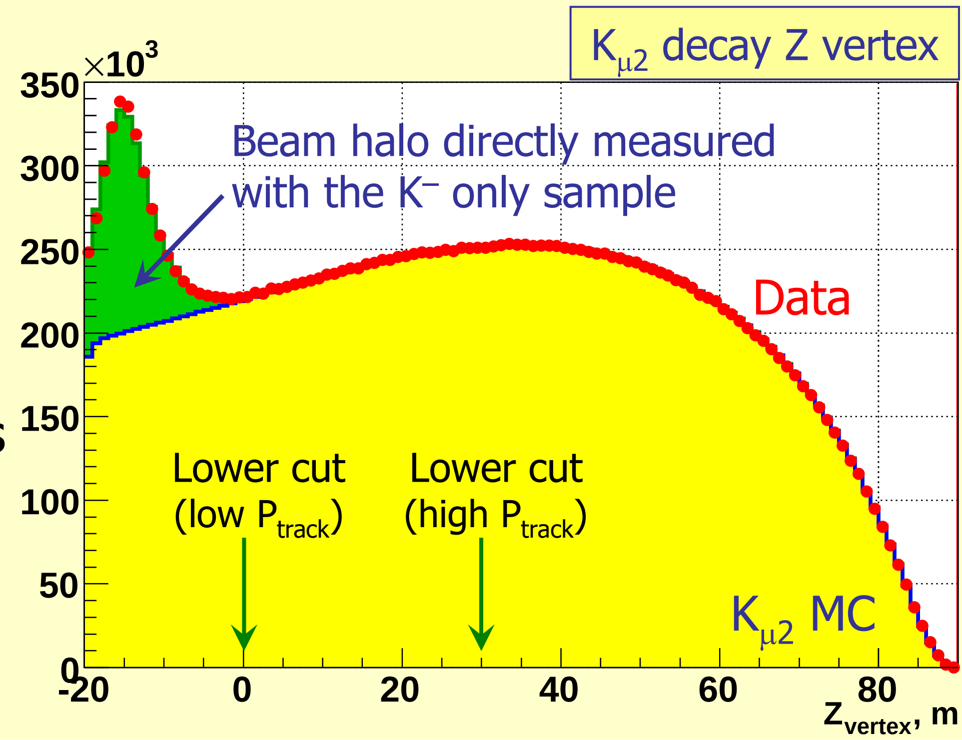
Optimization of M_{miss}^2 resolution:
narrow momentum band beams ($\Delta P_K^{RMS}/P_K$=2%)

Kaon sign

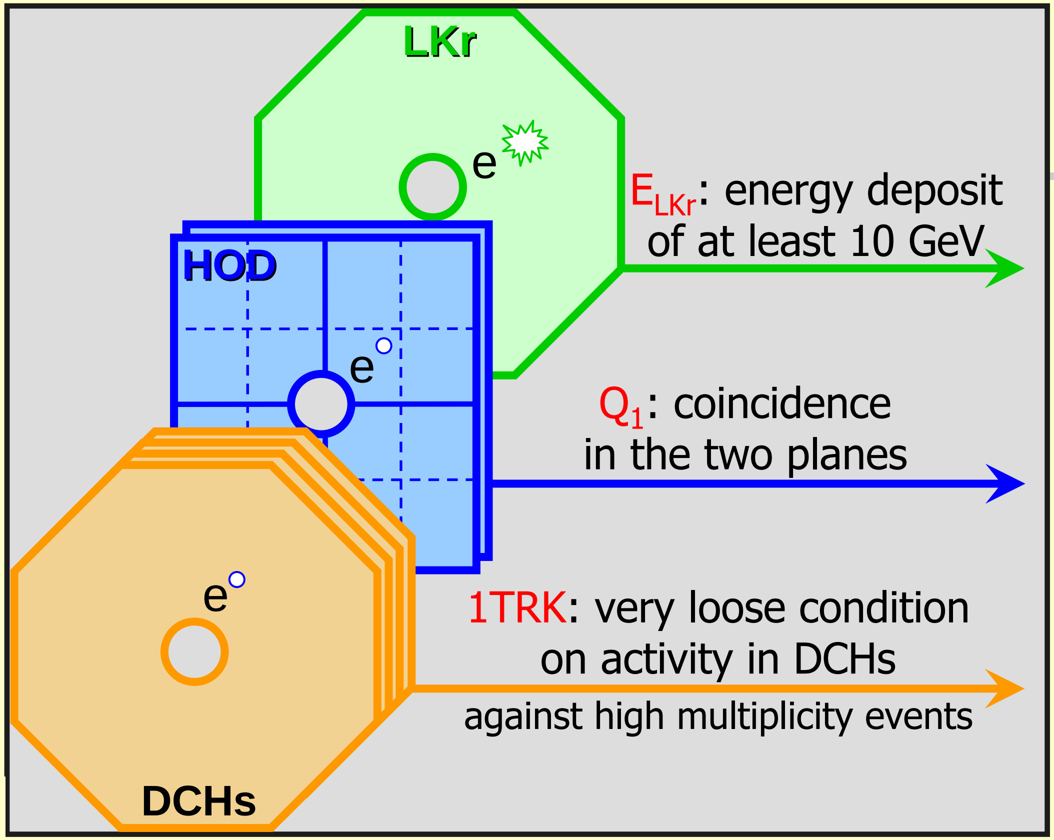
Beam halo background much higher for K_{e2}^- (~20%) than for K_{e2}^+ (~1%):

~90% of data sample: K^+ only.
~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.



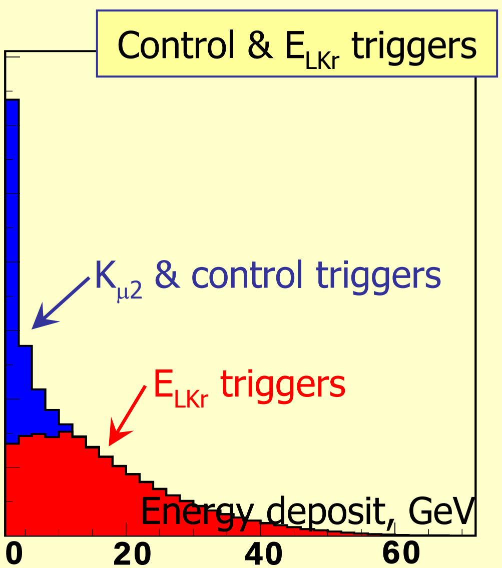
Trigger logic

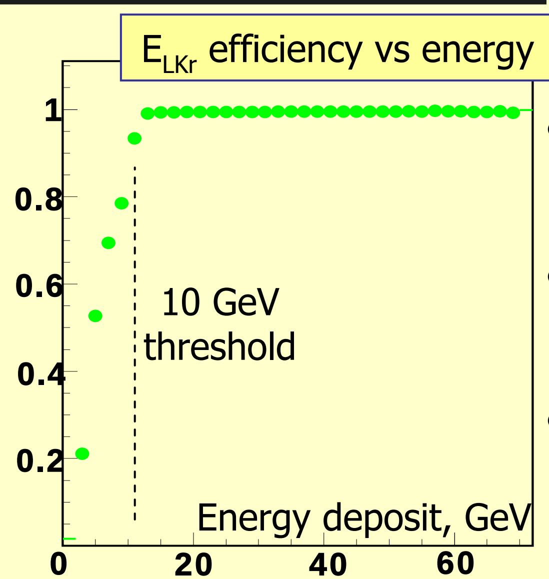


Minimum bias
(high efficiency, but low purity)
trigger configuration used

K_{e2} condition: $Q_1 \times E_{LKr} \times 1TRK$.
Purity ~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 $(0.05 \pm 0.01)\%$ for $p_{track} > 15$ GeV/c.
- Different trigger conditions for signal and normalization!

Measurement strategy

(1) $K_{e2}/K_{\mu 2}$ 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:

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

$N(K_{e2})$, $N(K_{\mu 2})$:	numbers of selected K_{l2} candidates;
$N_B(K_{e2})$, $N_B(K_{\mu 2})$:	numbers of background events; ⇒ main source of systematic errors
$A(K_{e2})$, $A(K_{\mu 2})$:	MC geometric acceptances (no ID);
f_e, f_μ:	measured particle ID efficiencies;
$\varepsilon(K_{e2})/\varepsilon(K_{\mu 2})>99.9\%$:	E_{LKr} trigger condition efficiency;
$f_{LKR}=0.998$:	global LKr readout efficiency.

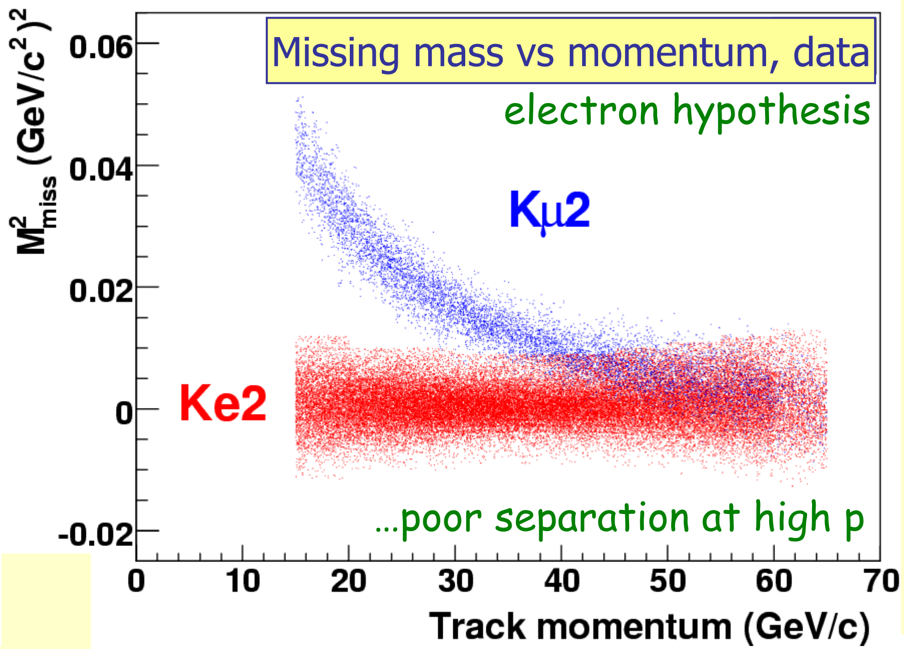
(3) MC simulations used to a limited extent:

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

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

Large common part
(due to topological similarity)

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



Kinematic separation

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

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

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

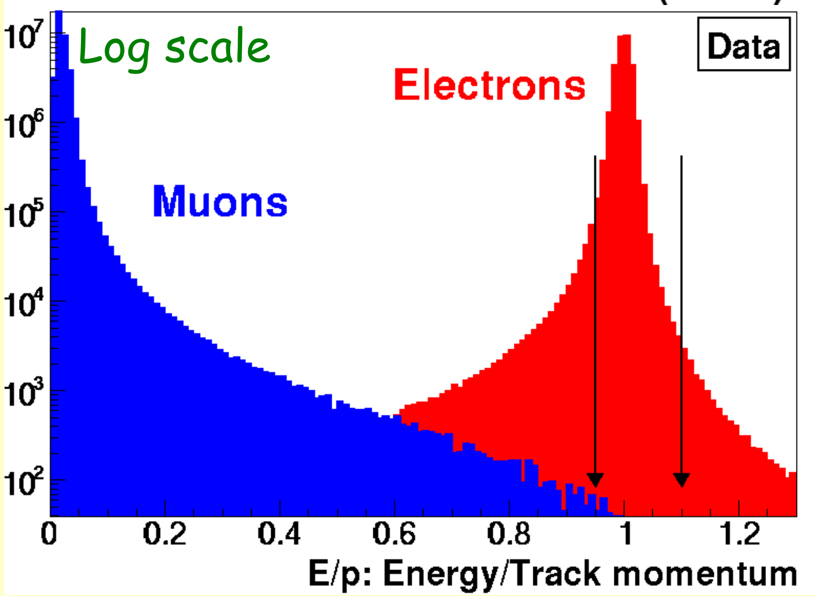
Separation by particle ID

E/p = (LKr energy deposit/track momentum

0.95<E/p<1.10 for electrons,

E/p<0.2 for muons.

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



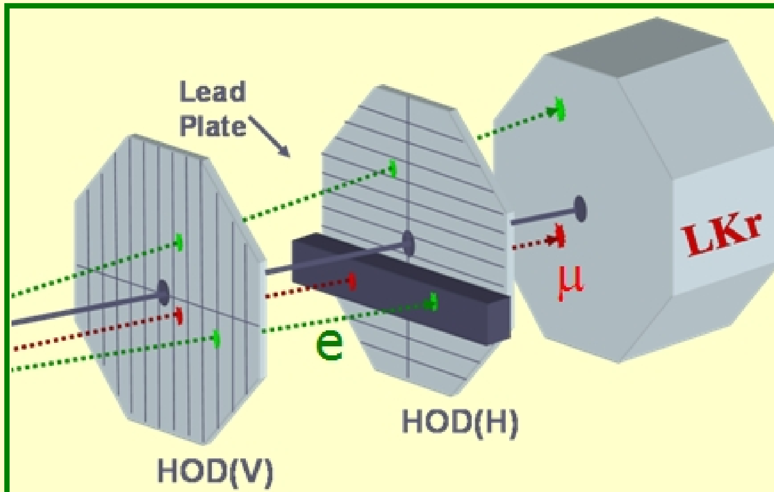
Muonic background in K_{e2} sample

Problem:
"Catastrophic" energy loss by muons in LKr.
Muons with $E/p>0.95$ are identified as electrons.
$P(\mu\to e) \sim 3\times10^{-6}$ (and momentum-dependent).

$P(\mu\to e)/R_K \sim 10\%$:
$K_{\mu2}$ decays represent a major background

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

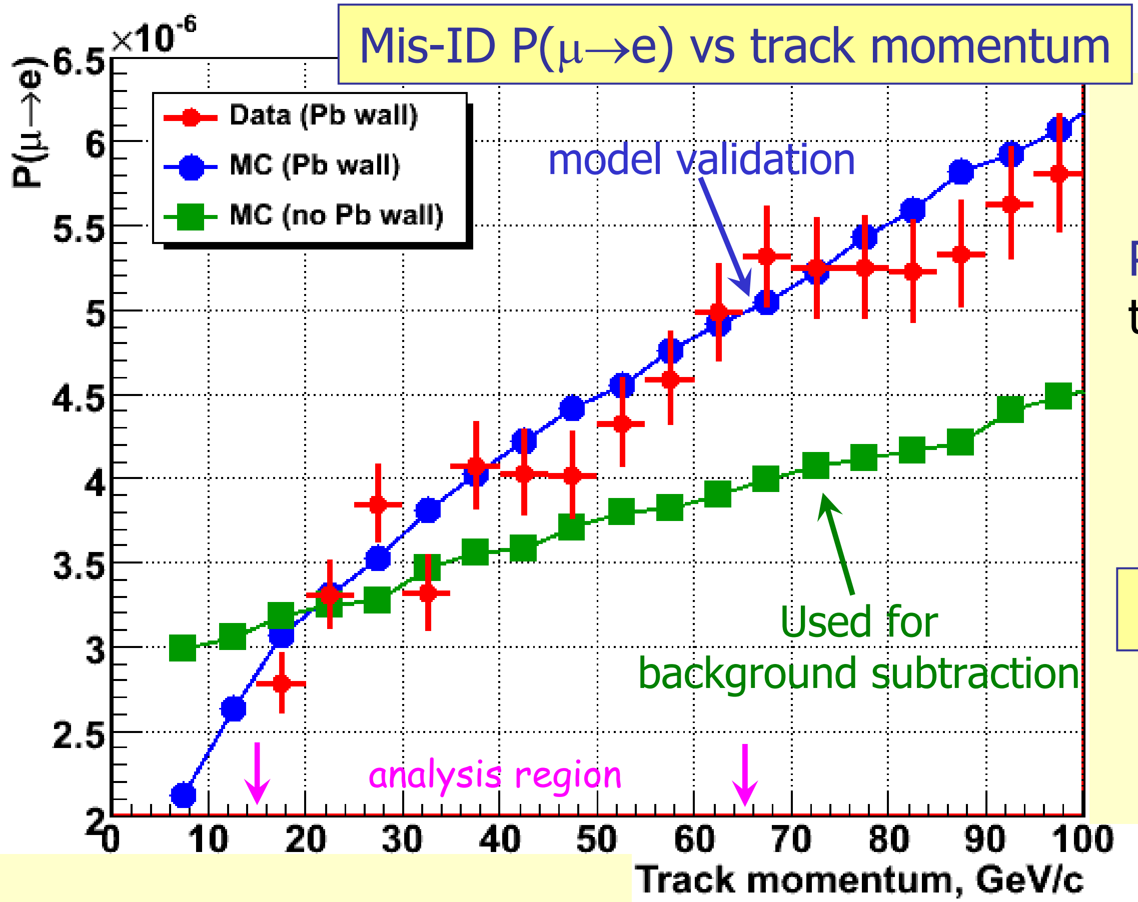
Solution:
Pb wall ($\sim10X_0$) between the HOD planes.
Tracks traversing the wall & with $E/p>0.95$
are pure muon samples (electron contamination $<10^{-7}$),
with the $\mu\to e$ decay component (initially $\sim10^{-4}$) suppressed.



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

Muonic background (2)

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



Excellent data/MC agreement for the Pb wall case!

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

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

Result: $B/(S+B) = (6.28\pm0.17)\%$

(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 $K_{\mu2}$ decays in good $K_{e2}/K_{\mu2}$ separation region (p<25GeV/c).

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

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

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

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

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

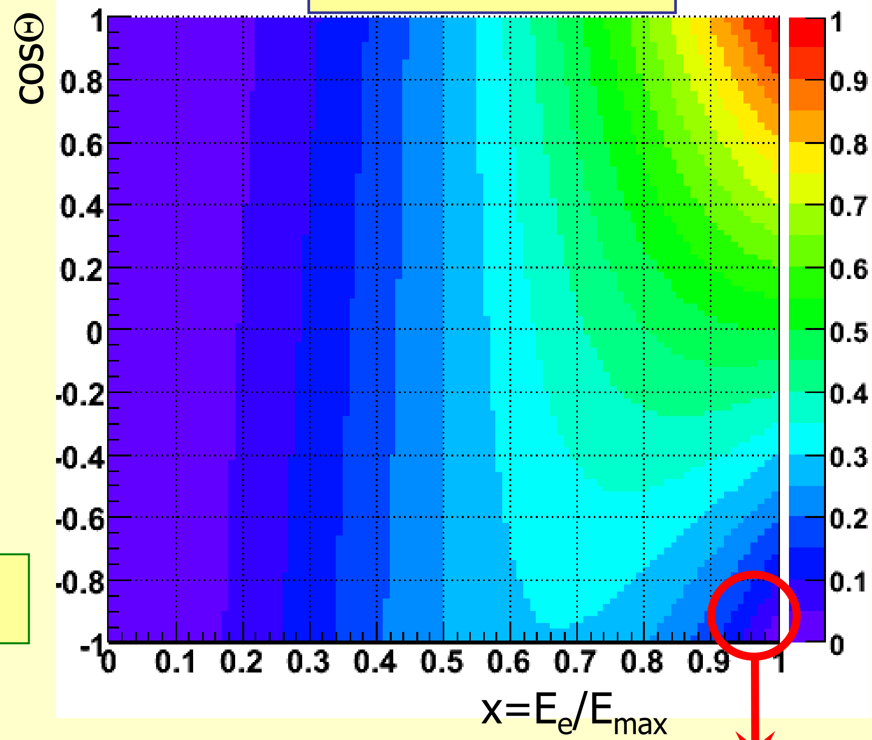
$$d^2\Gamma/dxd(\cos\Theta) \sim x^2[(3-2x) - \cos\Theta(1-2x)]$$

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

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

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 $\cos\Theta$),

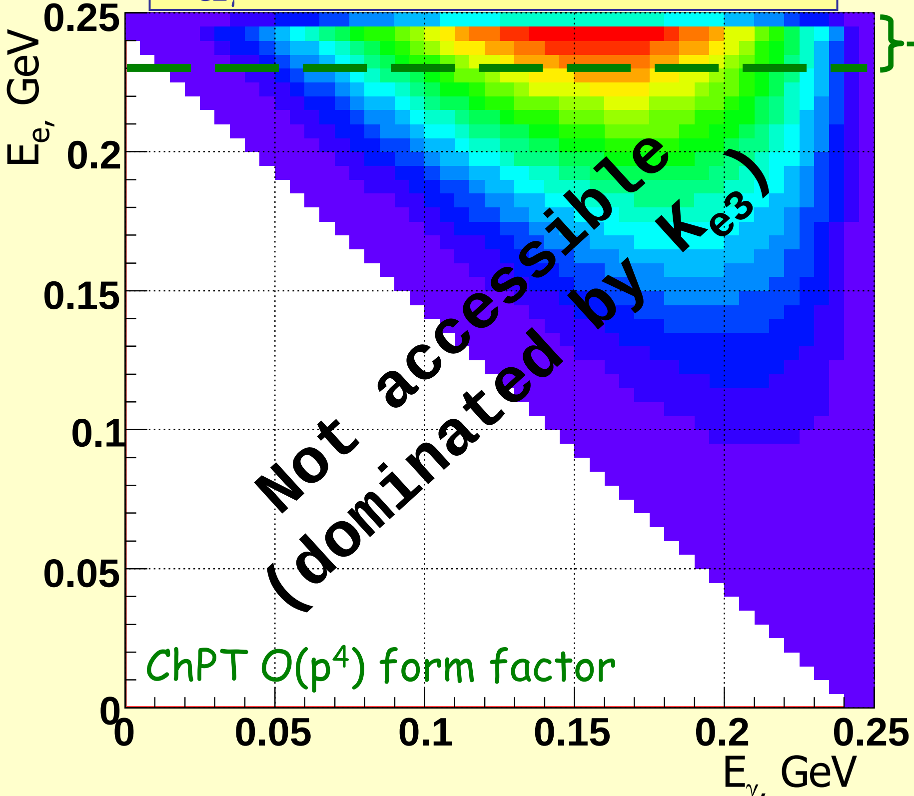
configuration highly suppressed according to the Michel distribution.

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

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

- Theory: BR=(1.12–1.34)×10^{-5}
  [model-dependent form factor]
- Experiment: BR=(1.52±0.23)×10^{-5}
  [1970s measurements]

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



Only energetic electrons (E_e^*>230MeV) 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 MeV populated by the K_{e3} background).

Background estimate (ChPT phase space)

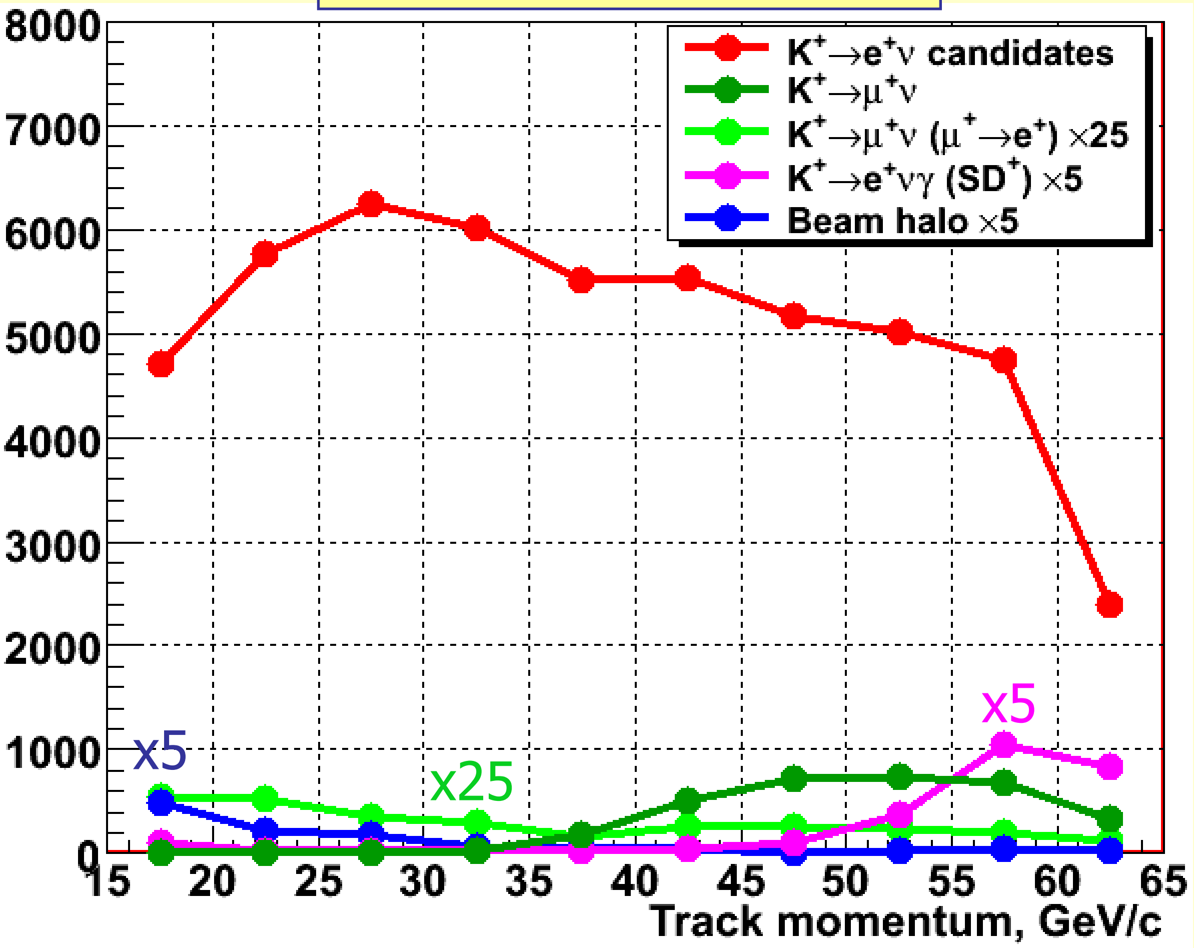
B/(S+B) = (1.02±0.15)%

(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



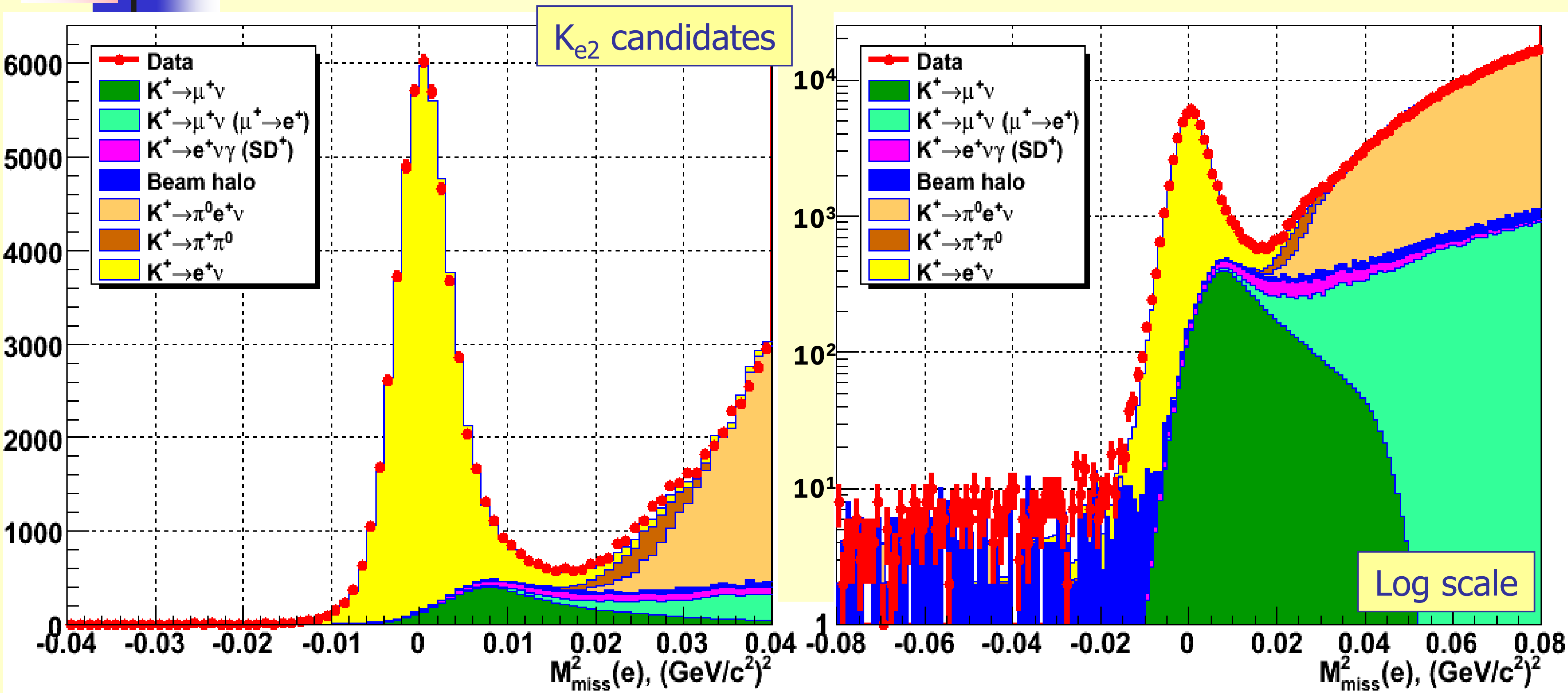
(selection criteria, e.g. for Z_{vertex} and M_{miss}^2, are optimised individually in each P_{track} bin)

Background summary

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)%

K_{e2}: 40% of data set

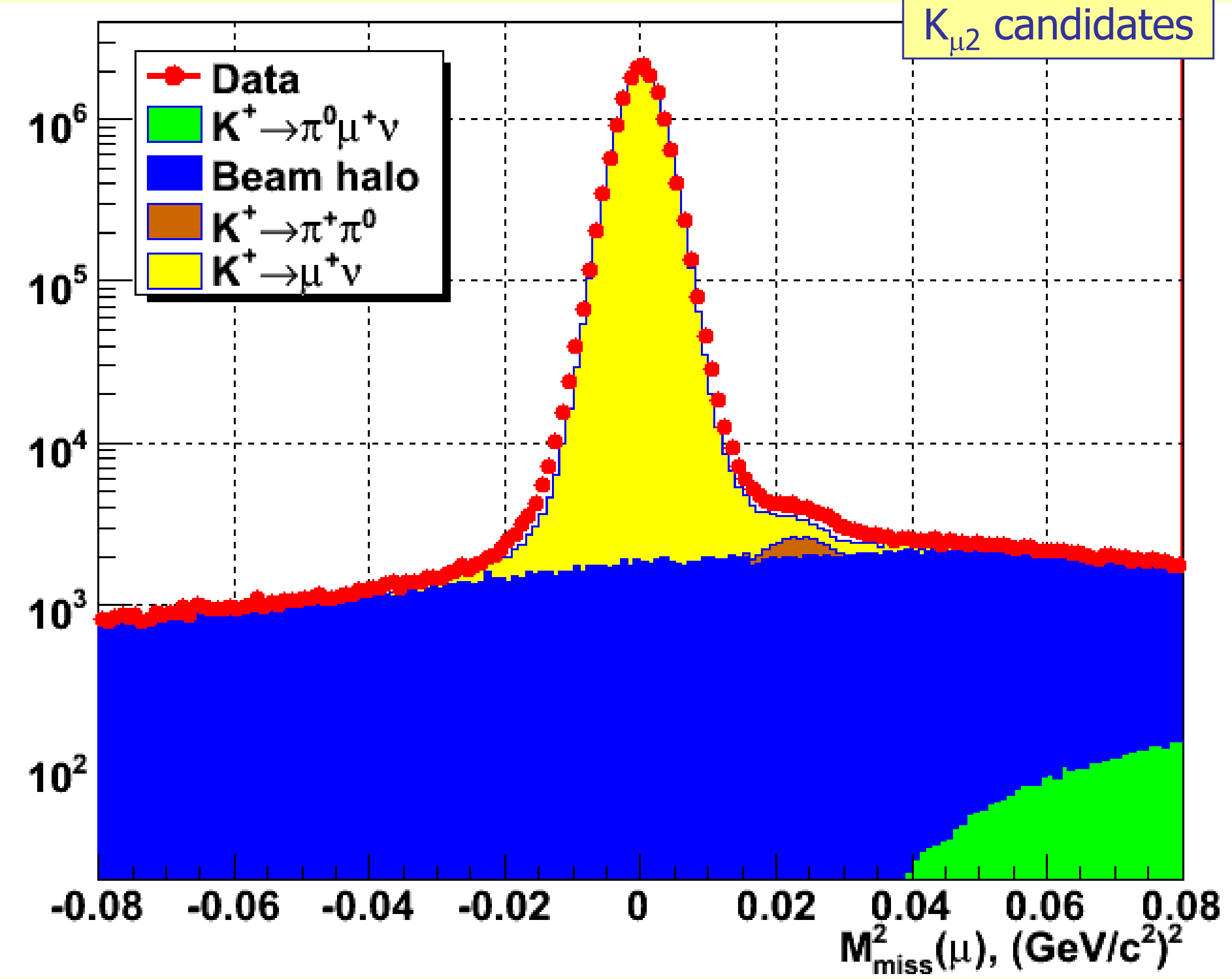


51,089 $K^+\to e^+\nu$ candidates,
99.2% electron ID efficiency,
$B/(S+B) = (8.0\pm0.2)\%$

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

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

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



$K_{\mu 2}$ candidates

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

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

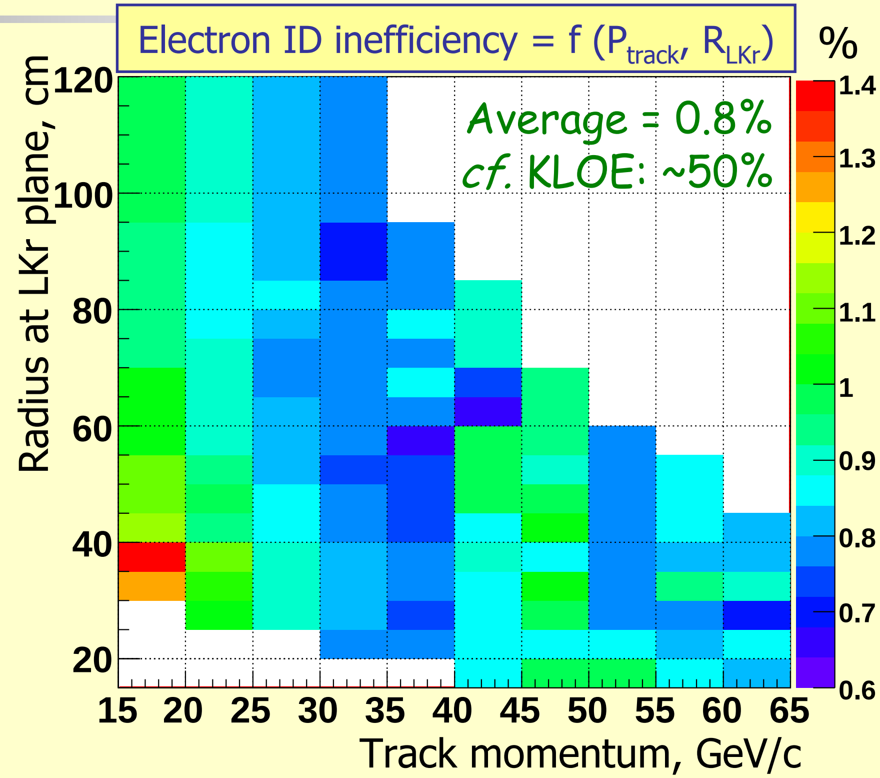
The only significant background source is the beam halo.

Other systematic effects

Electron ID efficiency f_e (99.2%)
measured with samples of pure electrons

- $K^\pm \to \pi^0 e^\pm \nu$ from main K data taking (limited momentum range $p<50$GeV/c);
- $K_L \to \pi^\pm e^\pm \nu$ 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_{track}-dependent, $A(K_{\mu 2})/A(K_{e2})\sim 1.3$;
- strongly affected by the radiative (IB) corrections to K_{e2};

  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

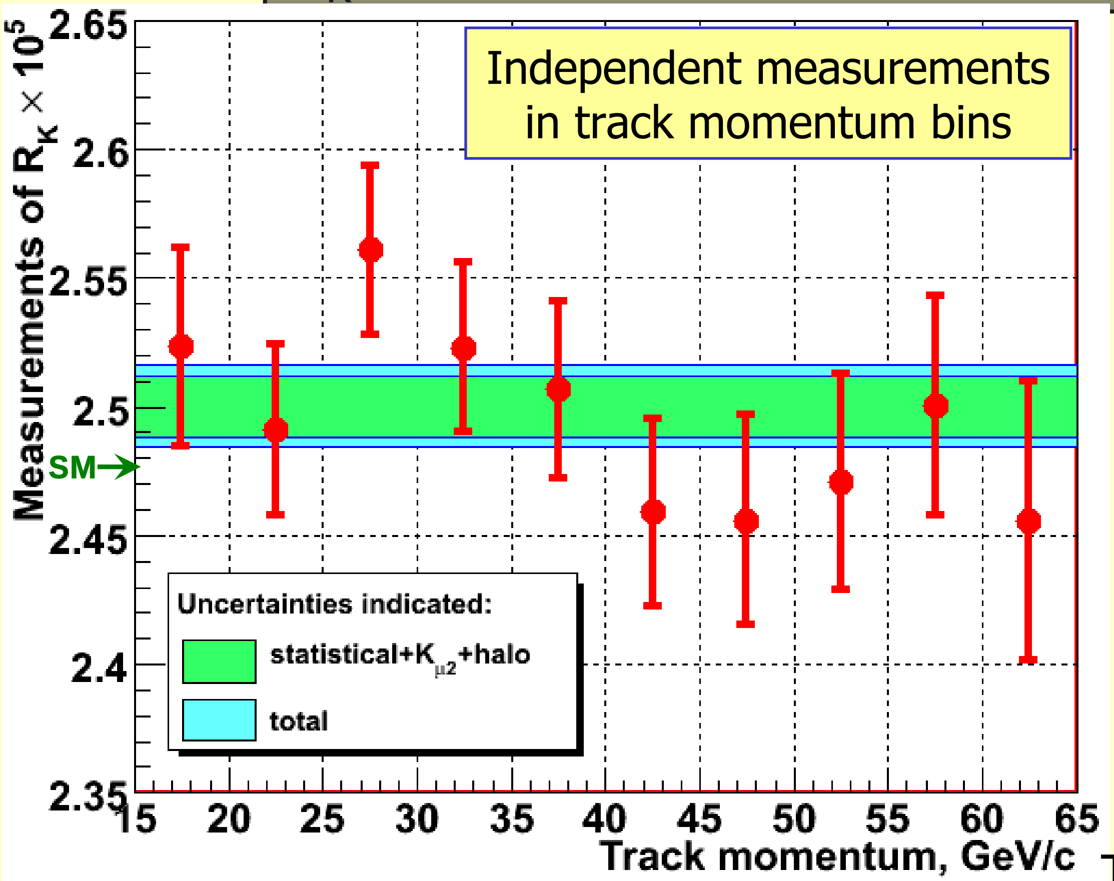
- E_{LKr} efficiency directly affects R_K;
- monitored with control trigger samples;
- conservative systematic uncertainty for preliminary result: $\delta R_K/R_K=0.3\%$ (dead time generated by accidentals).

Preliminary result (40% data set)

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

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

(New, June 09)



Uncertainties

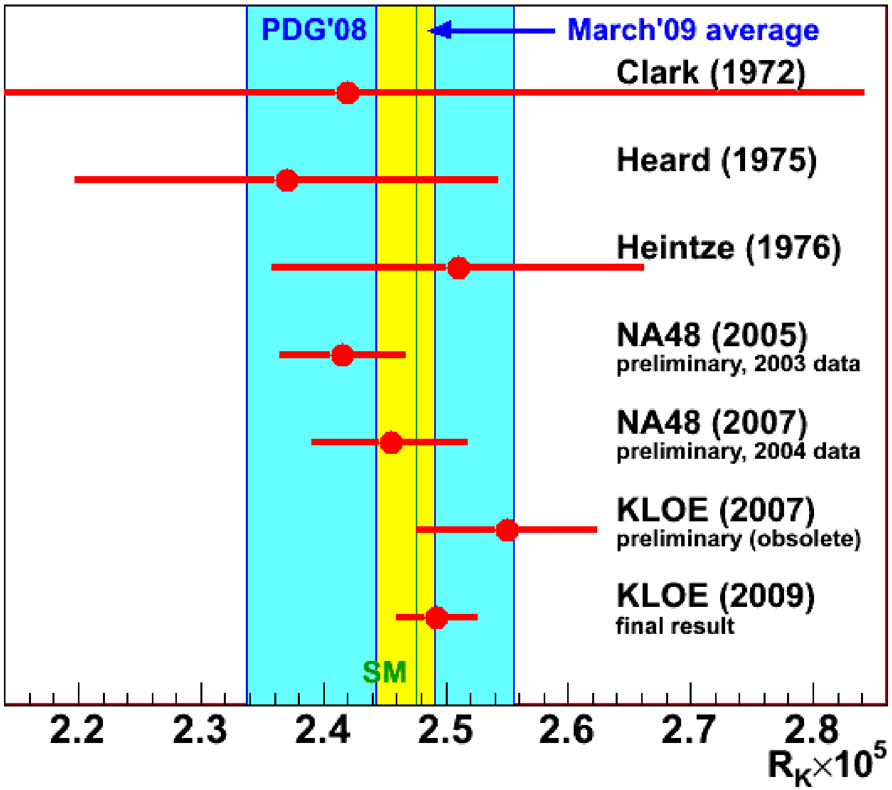
Source	$\delta R_K \times 10^5$
Statistical	0.012
$K_{\mu2}$	0.004
Beam halo	0.001
$K_{e2\gamma}$ (SD$^+$)	0.004
Electron ID	0.001
IB simulation	0.007
Acceptance	0.002
Trigger timing	0.007
Total	0.016

(0.64% precision)

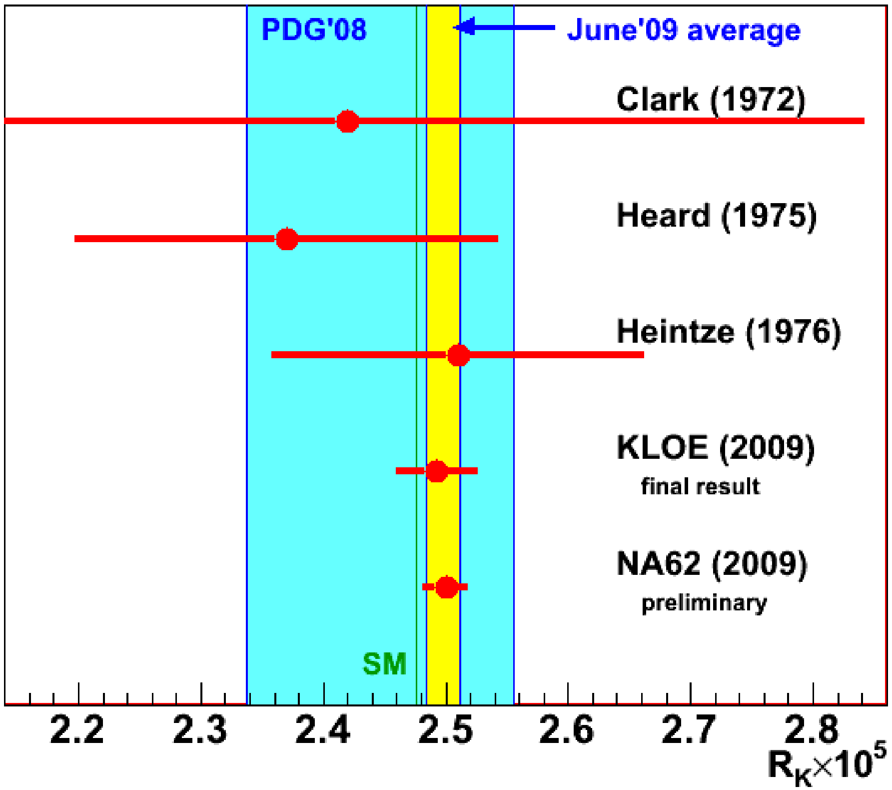
The whole sample will allow a statistical uncertainty ~0.3%, and total uncertainty of 0.4–0.5%.

Comparison to world data

March 2009



June 2009



World average	$\delta R_K \times 10^5$	Precision
March 2009	2.467 ± 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)

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 $K_{e2}/K_{\mu 2}$ separation (>99% electron ID efficiency and $\sim 10^6$ muon suppression) leads to a low 8% background.

- Preliminary result based on ~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 $\delta K_R/R_K = 0.5\%$.