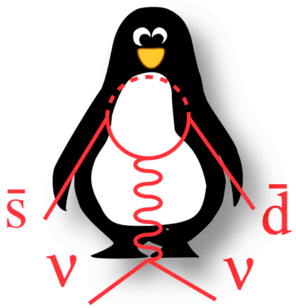
Lepton Universality tests with Leptonic Kaon decays



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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)

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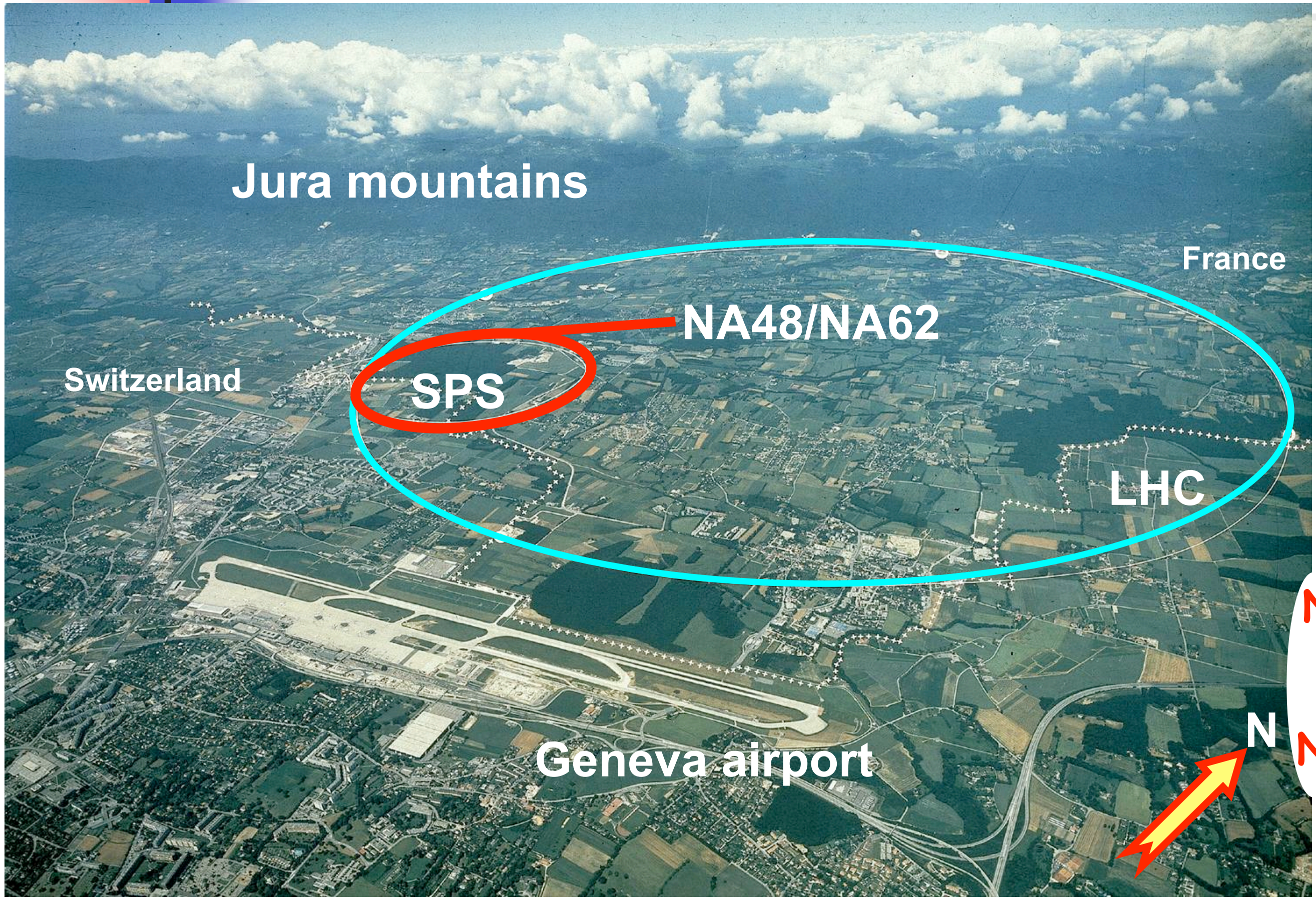
CERN NA48/NA62



Primary SPS protons (400 GeV/c): 1.8×10^{12}/SPS spill
Unseparated secondary positive beam: $p=(74.0\pm1.6)$ GeV/c
Composition: $K^+(\pi^+) = 5\%(63\%)$.
K^+ decaying in vacuum tank: 18%.

NA48 discovery of direct CPV
- **1997: ε'/ε: 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**

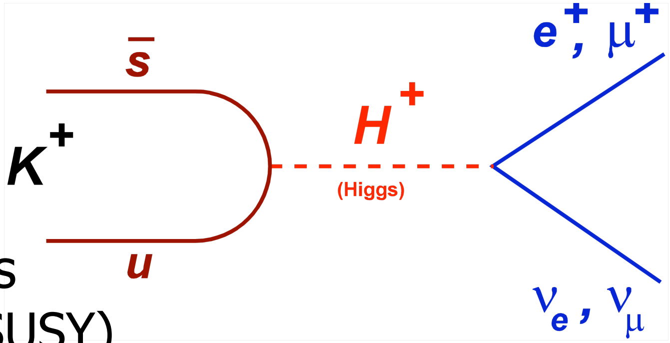
NA48/1
- **2002: K_S/hyperons**

NA48/2
- **2003: K^+/K^-**
- **2004: K^+/K^-**

NA62 (phase I)
- **2007: $K^\pm_{e2}/K^\pm_{\mu2}$**
- **2008: $K^\pm_{e2}/K^\pm_{\mu2}$**

NA62 (phase II)
- **2007–2011: design & construction**
- **2012–2015: $K^+\rightarrow\pi^+\nu\bar{\nu}$ data taking**

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/c², $\tan\beta = 40$)

$\pi^+ \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_\pi/m_H)^2\, m_d/(m_u+m_d)\, \tan^2\beta \approx 2\times10^{-4}$
$K^+ \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_K/m_H)^2 \tan^2\beta \approx 0.3\%$
$D^+_s \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_D/m_H)^2\, (m_s/m_c) \tan^2\beta \approx 0.4\%$
$B^+ \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_B/m_H)^2 \tan^2\beta \approx 30\%$

$R=Br(K\to\mu\nu)/Br(K_{e3})$:
$(\delta R/R)_{exp}=1.0\%$,
challenging
by not hopeless

PRL100 (2008) 241802

$f_{Ds}^{(QCD)}=(241\pm3)$MeV
$f_{Ds}^{(exp)}=(277\pm9)$MeV

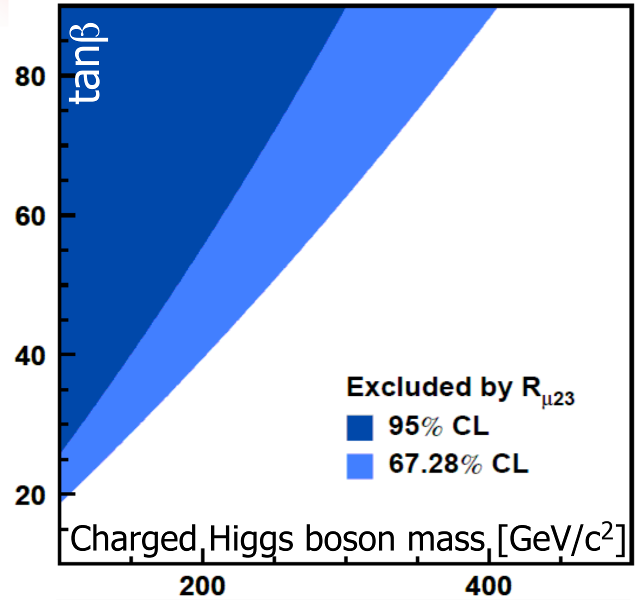
~4σ discrepancy + new data:
PRD79 (2009) 052001

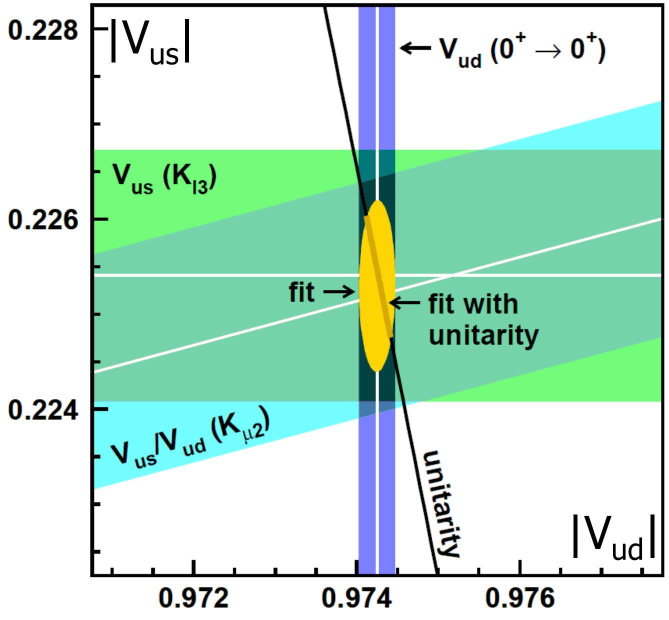
BaBar, Belle: $Br_{exp}(B\to\tau\nu)=(1.42\pm0.43)\times10^{-4}$
Standard Model: $Br_{SM}(B\to\tau\nu)=(1.33\pm0.23)\times10^{-4}$

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

Challenged by hadronic uncertainties

H± exchange in $K^+\to\mu^+\nu$





Comparison of $|V_{us}|$ determined from helicity suppressed $K^+\to\mu^+\nu$ decays vs helicity allowed $K^+\to\pi^0\mu^+\nu$ decays

To reduce the uncertainties of hadronic and EM corrections:

$$R_{\mu23} = \underbrace{\left(\frac{f_K/f_\pi}{f_+(0)}\right)^{-1}}_{\text{Lattice QCD input}} \underbrace{\left(\left|\frac{V_{us}}{V_{ud}}\right|\frac{f_K}{f_\pi}\right)_{\mu2}}_{\text{Measured with } K_{\mu2}/\pi_{\mu2}} \underbrace{\frac{\overbrace{|V_{ud}|_{0^+\to0^+}}^{\text{average from nuclear } \beta \text{ decays, PRC79 (2009) 055502}}}{[|V_{us}|f_+(0)]_{\ell3}}}_{\text{Measured with } K\to\pi\mu\nu}$$

Charged Higgs mediated contribution:

$$R_{\mu23} \approx \left|1 - \frac{m_{K^+}^2}{m_{H^+}^2}\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|$$

Experiment: $R_{\mu23} = 0.999(7)$,
$|V_{us}|^2+|V_{ud}|^2-1 = -0.0001(6)$.
Precision limited by lattice ICQ input.
(Flavianet Kaon WG, arXiv:1005.2323)

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

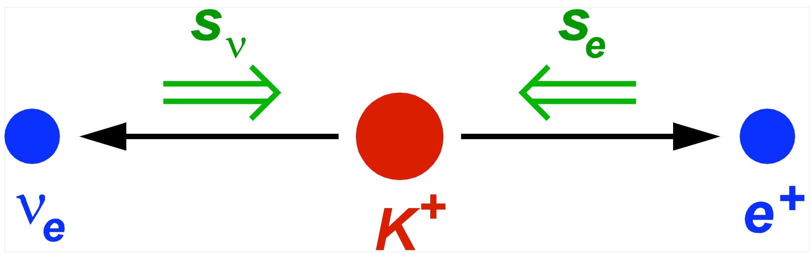
Observable sensitive to lepton flavour violation and its SM expectation:

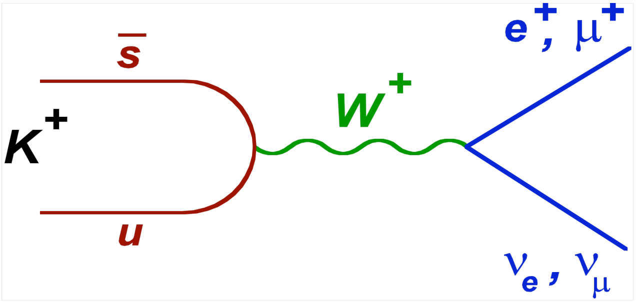
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{(1 + \delta R_K^{\mathrm{rad.corr.}})}$$

(similarly, R_π in the pion sector)

Radiative correction (few %) due to $K^+ \to e^+ \nu\gamma$ (IB) process, by definition included into R_K

Helicity suppression: $f \sim 10^{-5}$





- SM prediction: excellent sub-permille accuracy due to cancellation of hadronic uncertainties.
- Measurements of R_K and R_π 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

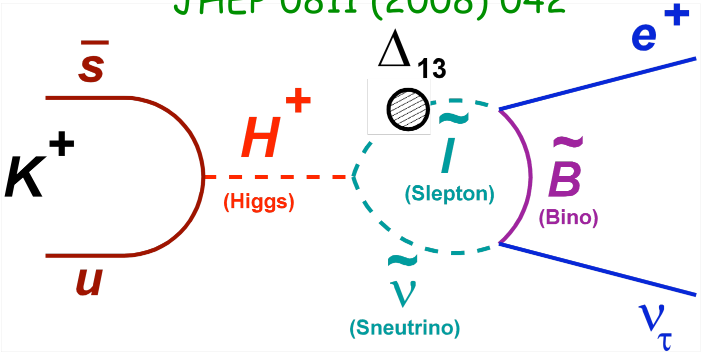
2HDM – tree level

(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 ΔR_K: $H^\pm$ mediated LFV (rather than LFC) with emission of ν_τ

→ R_K enhancement can be experimentally accessible

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

Up to ~1% effect :

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

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)

Large effects in B decays
due to $(M_B/M_K)^4\sim10^4$:

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

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

Out of reach: $Br^{SM}(B_{e\nu})\approx10^{-11}$

R_K: experimental status

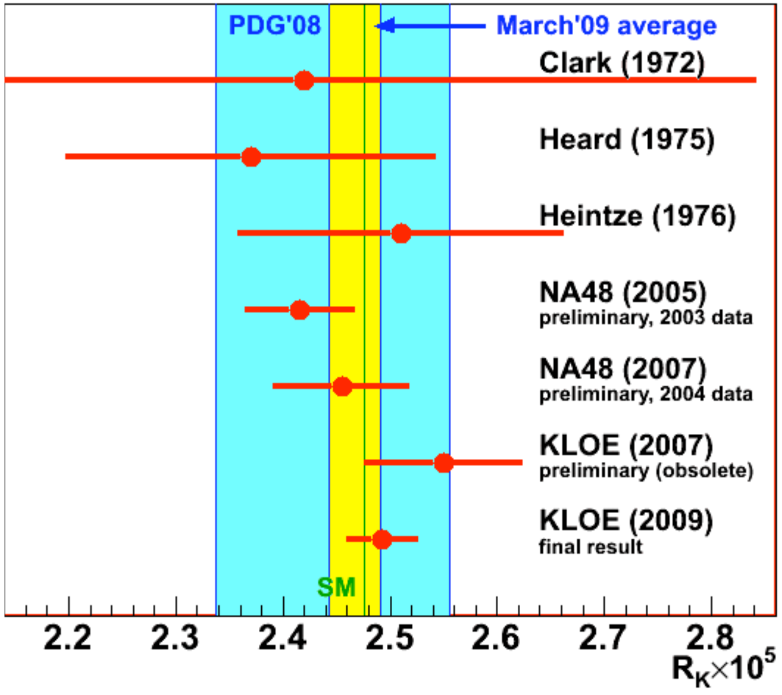
Kaon experiments:

→ 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)



NA62 (phase I)
- **2007: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$**
- **2008: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$**

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

Data taking:

- Four months in 2007:
  ~400K SPS spills, 300TB of raw data
- Two weeks in 2008:
  special data sets allowing reduction of the systematic uncertainties.

Measurement strategy

(1) $K_{e2}/K_{\mu 2}$ candidates are collected concurrently:

- analysis 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)

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

$N(K_{e2})$, $N(K_{\mu 2})$:	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_μ:	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;
$D=150$:	downscaling factor of the $K_{\mu 2}$ trigger.

(3) MC simulations used to a limited extent:

- Geometrical part of the acceptance correction comes from simulation;
- PID, trigger, readout efficiencies are measured directly.

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: 13GeV/c<p<65GeV/c.

Kinematic separation

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

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

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

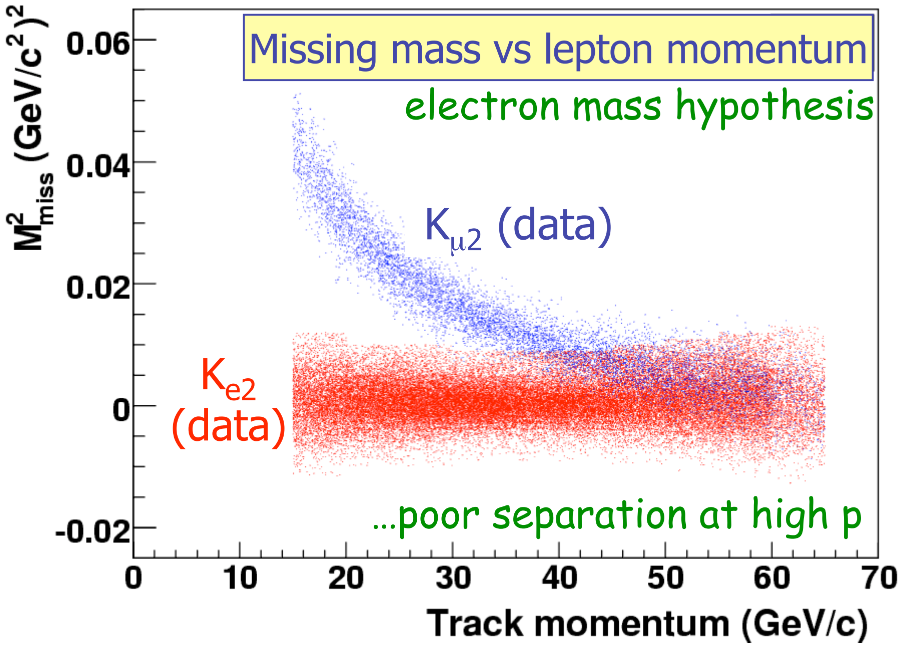
Separation by particle ID

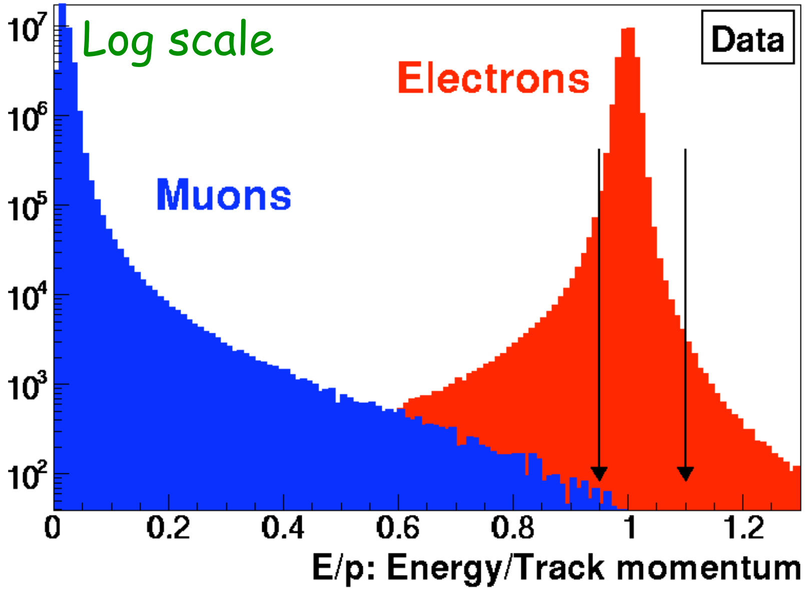
E/p = (LKr energy deposit/track momentum).

(0.9 to 0.95)<E/p<1.10 for electrons,

E/p<0.85 for muons.

→ Powerful $\mu^\pm$ suppression in $e^\pm$ sample: ~10^6





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

Main background source

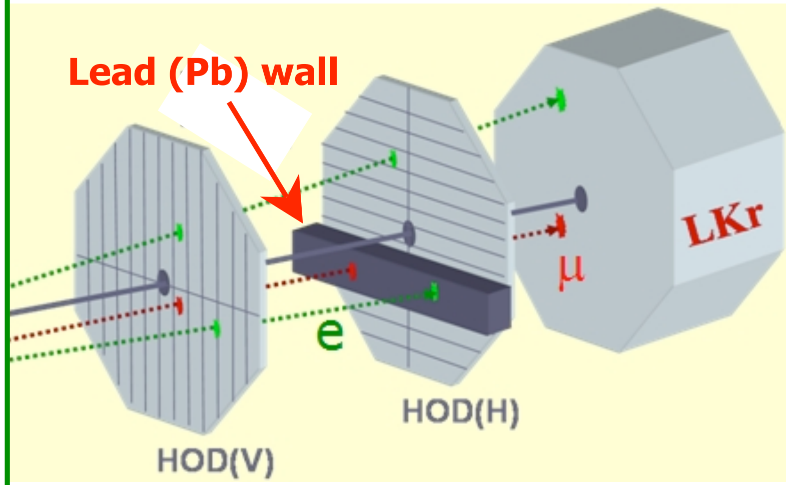
Muon "catastrophic" energy loss in LKr by emission of energetic bremsstrahlung photons. $P_{\mu e} \sim 3\times10^{-6}$ (and momentum-dependent).

$P_{\mu e} / R_K \sim 10\%$:
$K_{\mu 2}$ decays represent a major background

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.

$K_{\mu 2}$ candidates, track traversing Pb, $p>30$GeV/c, $E/p>0.95$: positron contamination $<10^{-8}$.



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

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

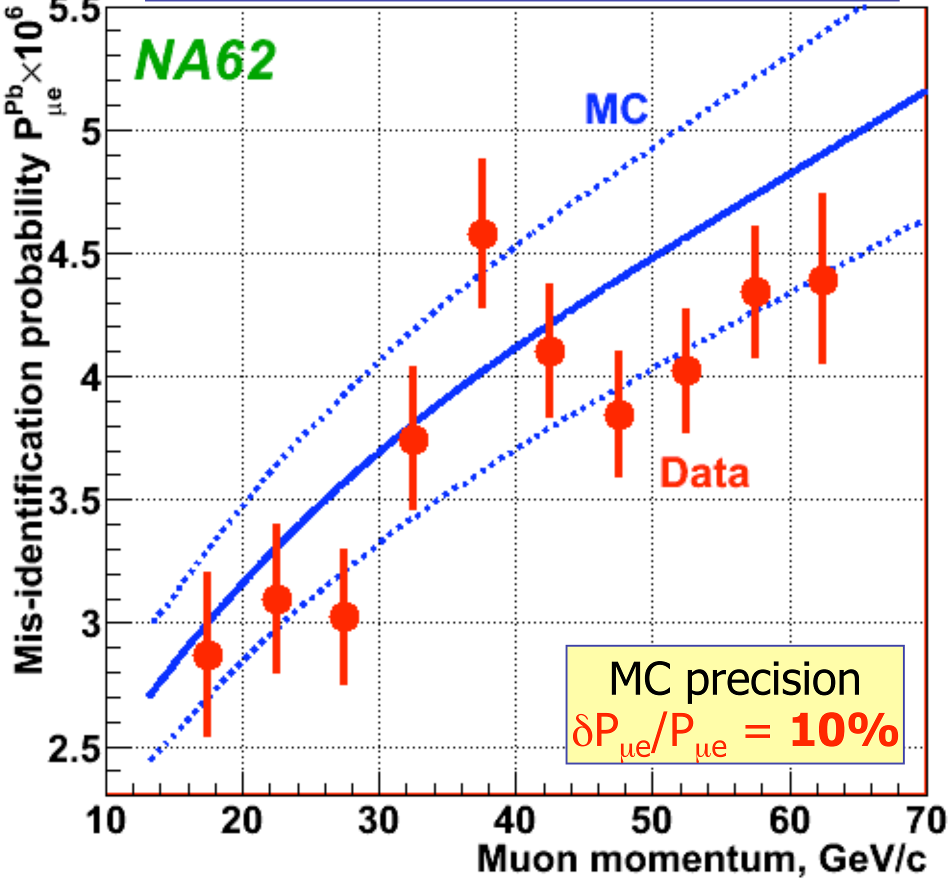
⇨

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]

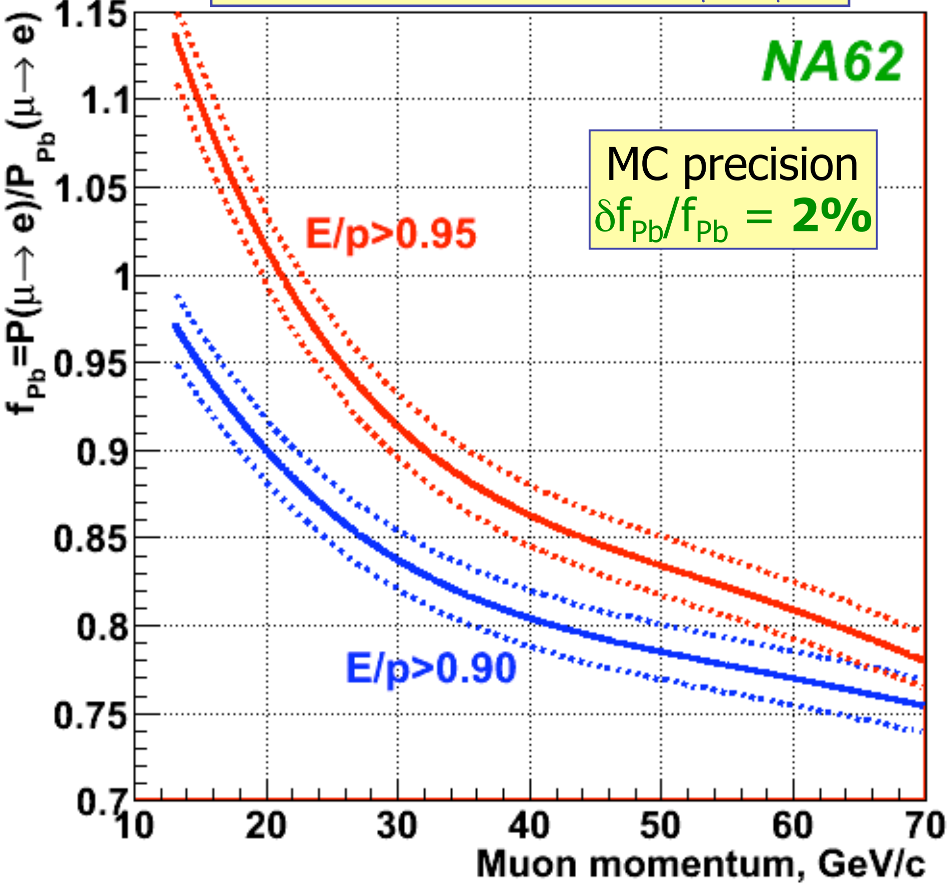
Muon mis-identification

$P_{\mu e}$ vs momentum (Pb wall installed)



MC precision
$\delta P_{\mu e}/P_{\mu e}$ = **10%**

Correction for Pb: $f_{Pb}=P_{\mu e}/P_{\mu e}^{Pb}$



MC precision
$\delta f_{Pb}/f_{Pb}$ = **2%**

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

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

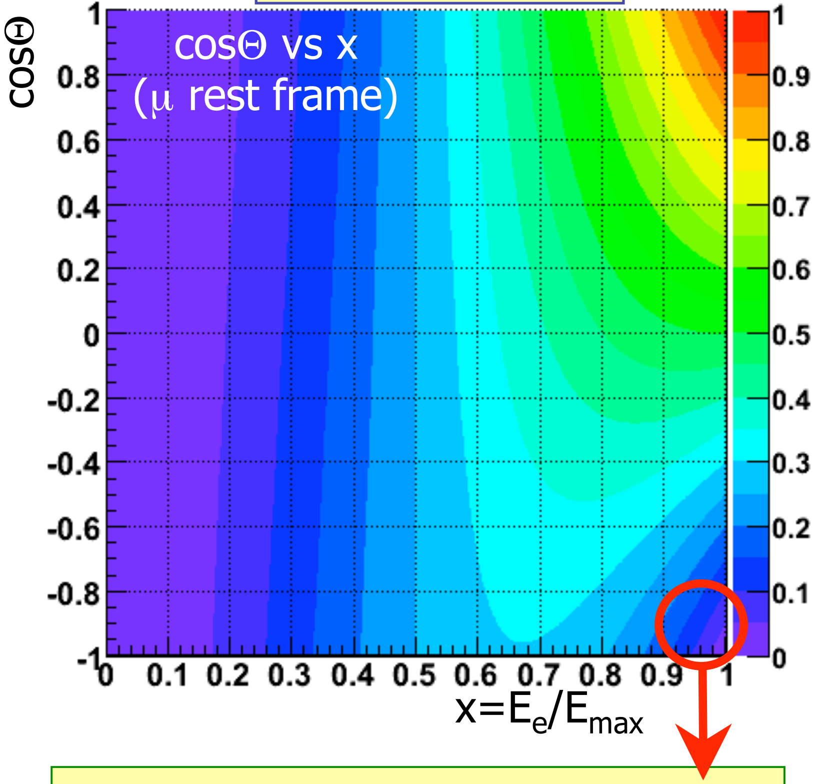
$$d^2\Gamma/dx\,d(\cos\Theta) \sim x^2[(3-2x) - \cos\Theta(1-2x)]$$

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

Michel distribution



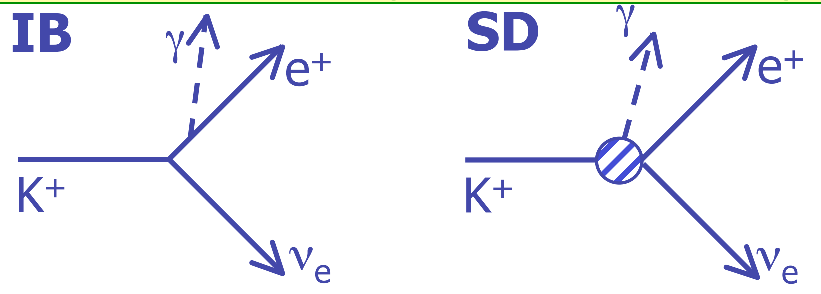
Only energetic forward positrons are selected as K_{e2} candidates

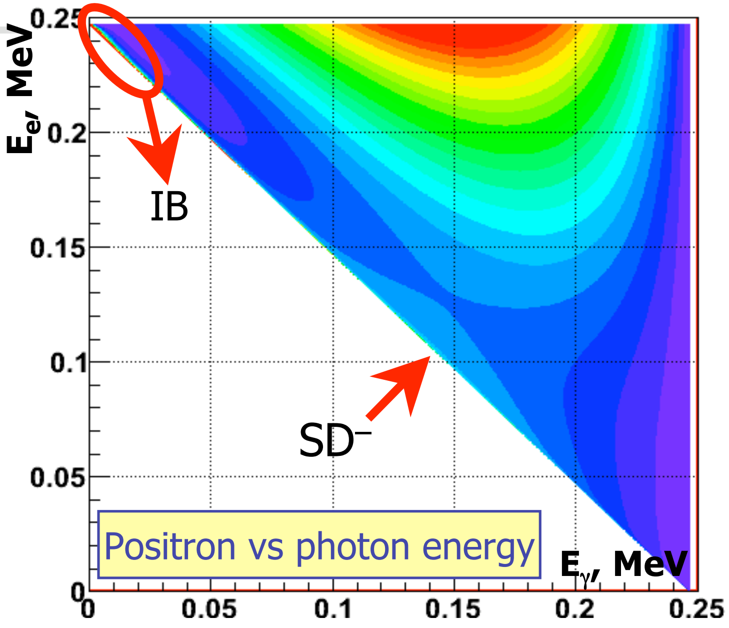
They are naturally suppressed by the muon polarisation

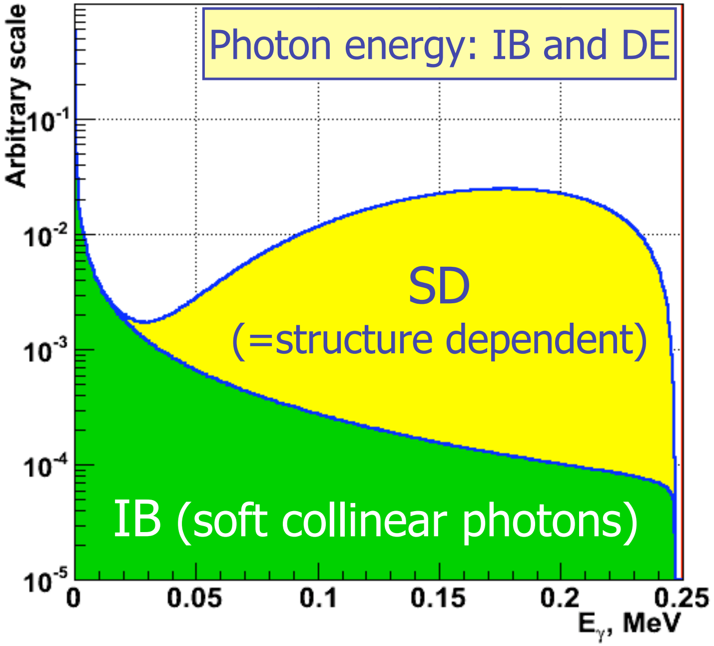
(radiative corrections provide another ~10% suppression)

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

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







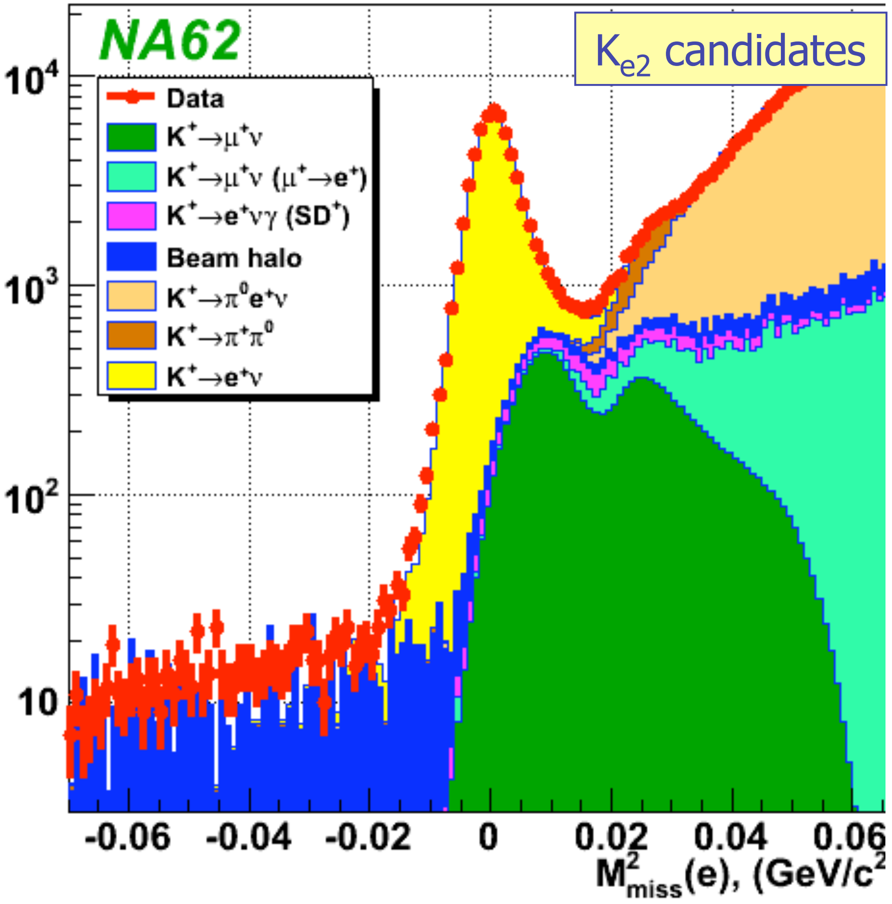
SD radiation is not helicity suppressed.
KLOE measurement of the form factor leads to
BR(SD$^+$, full phase space) = $(1.37 \pm 0.06) \times 10^{-5}$.
(EPJC64 (2009) 627)

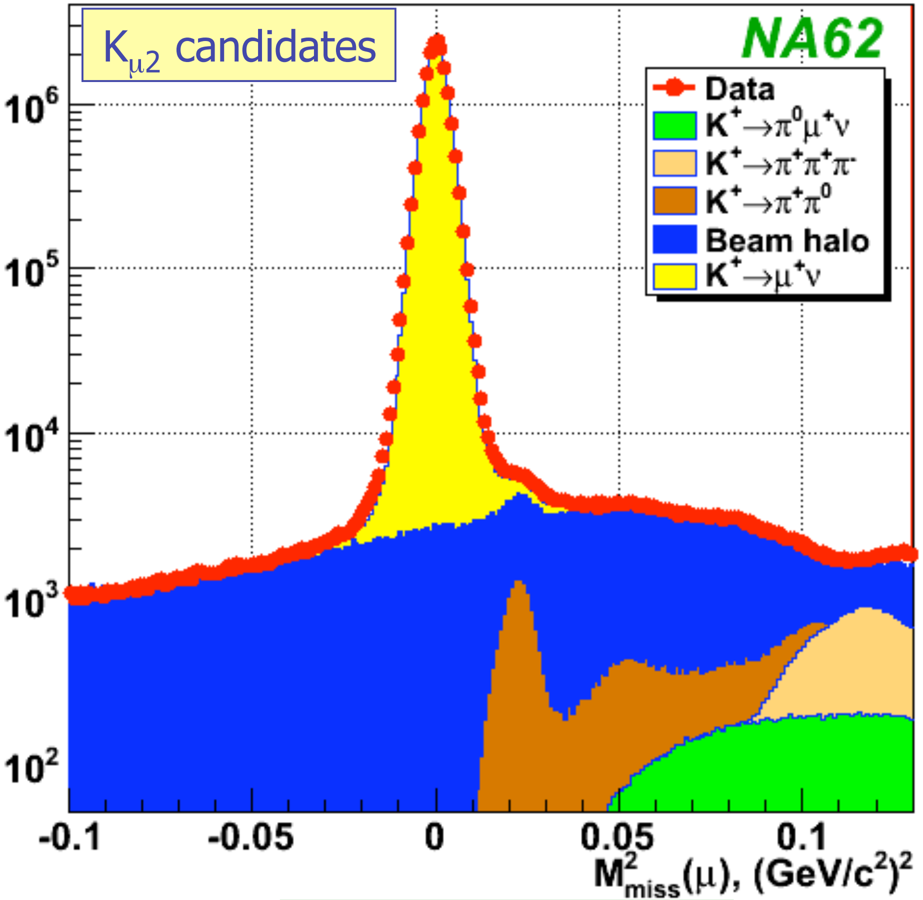
SD background contamination
B/(S+B) = (1.15±0.17)%

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.

Partial (40%) data set





59,963 $K^+\to e^+\nu$ candidates.
Positron ID efficiency: (99.27±0.05)%.
B/(S+B) = (8.8±0.3)%.

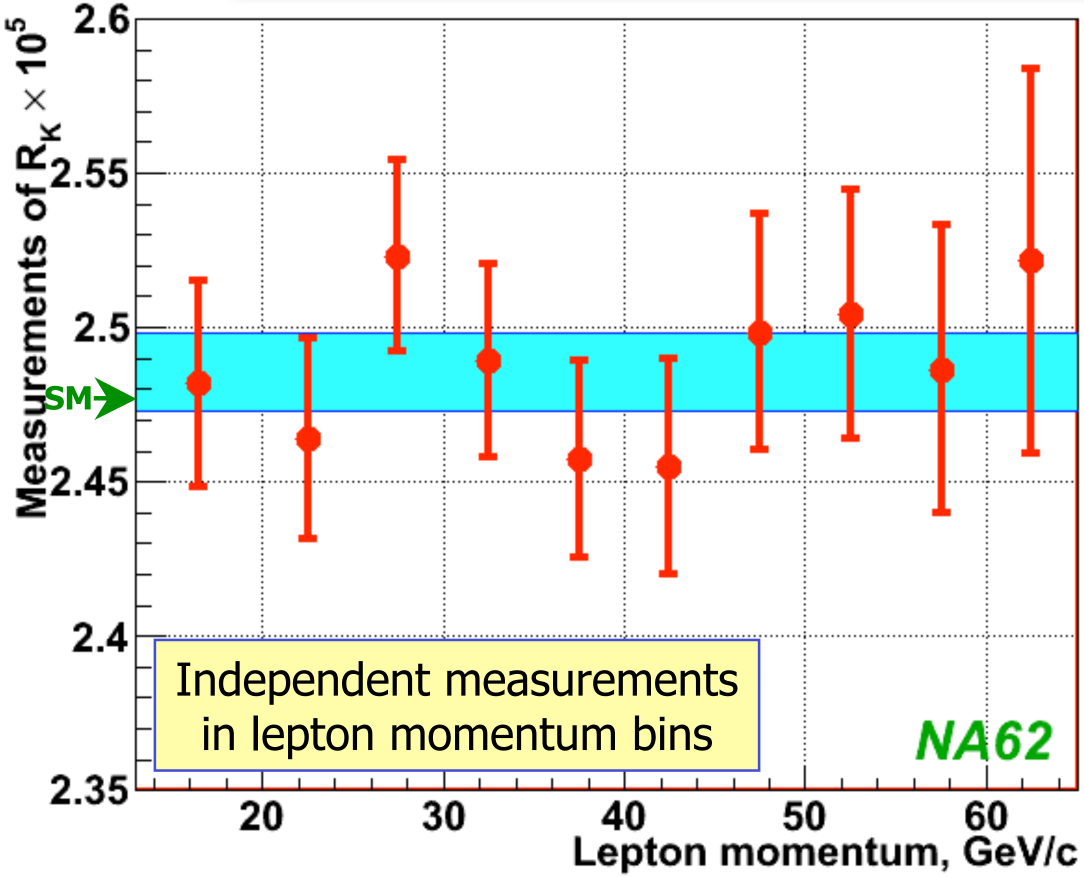
18.030 M candidates
with low background
B/(S+B) = 0.38%

NA62 estimated total K_{e2} sample:
~130K K^+ & ~20K K^- candidates

NA62 final result (40% data set)

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

(new: June 2010)



Independent measurements in lepton momentum bins

(systematic errors included, partially correlated)

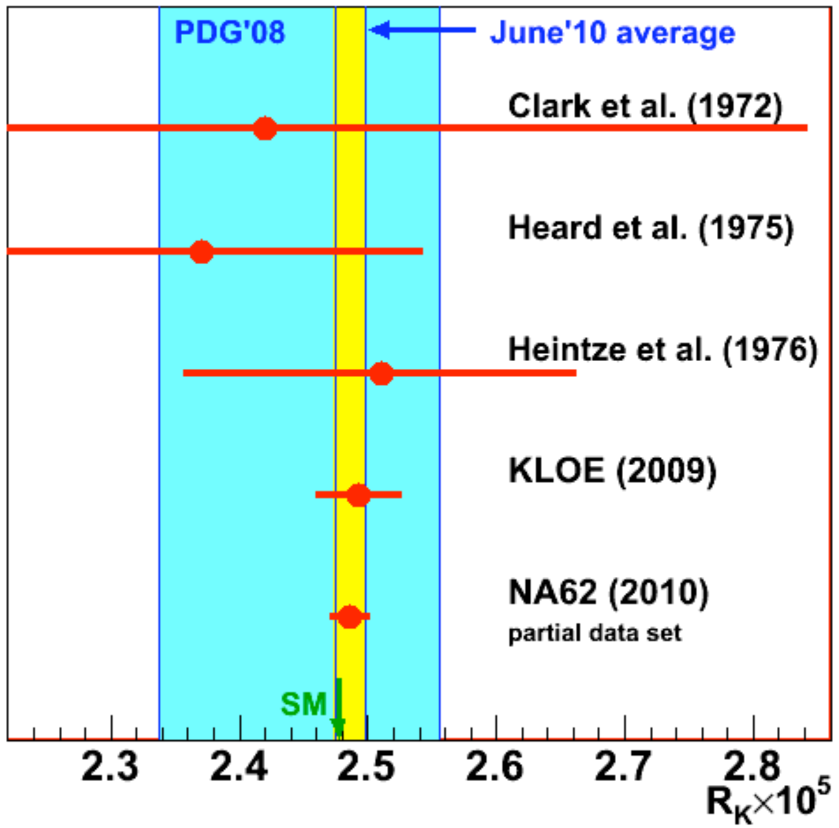
Uncertainties

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	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.

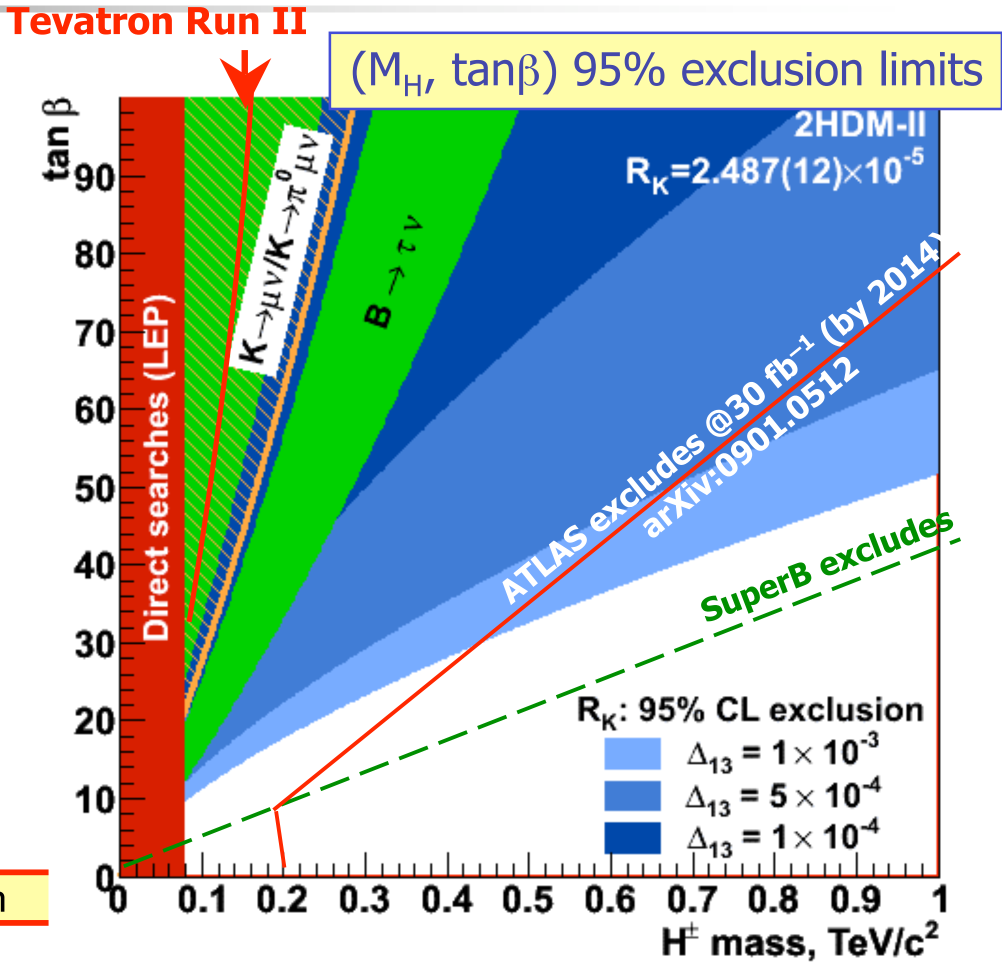
R_K: world average



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

R_K measurements are currently in agreement with the SM expectation at $\sim 1\sigma$.
Any significant enhancement with respect to the SM would be evidence of new physics.

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



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

Future prospects

- The whole NA62 2007 sample will allow statistical uncertainty ~0.3%, and total uncertainty of 0.4–0.5%.

In the future, new detector will be used (see talk in WG III).

- at present Kμ2/Ke2 can not be separated kinematically at high lepton momentum: particle identification is essential. But model-dependent MC correction required to evaluate the muon mis-ID probability.

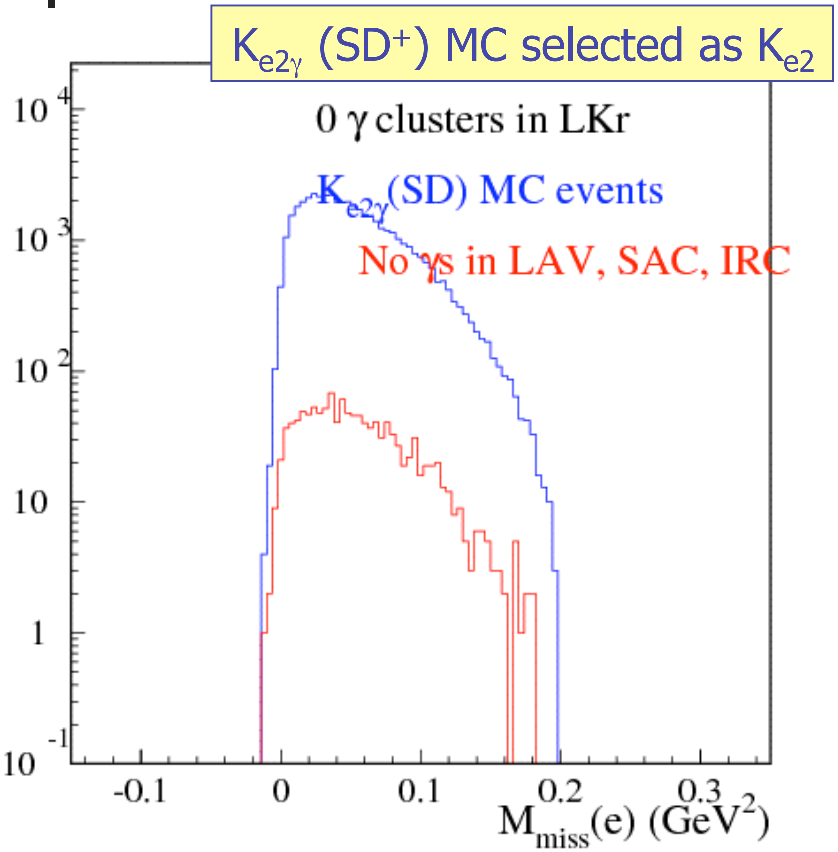
P($\mu \to e$) precision limited to ~3% relative → $\Delta R_K/R_K \sim 0.5\%$ for $p > 40$GeV/c.
~50% of K_{e2} sample not interesting when statistical precision reaches ~0.1%.

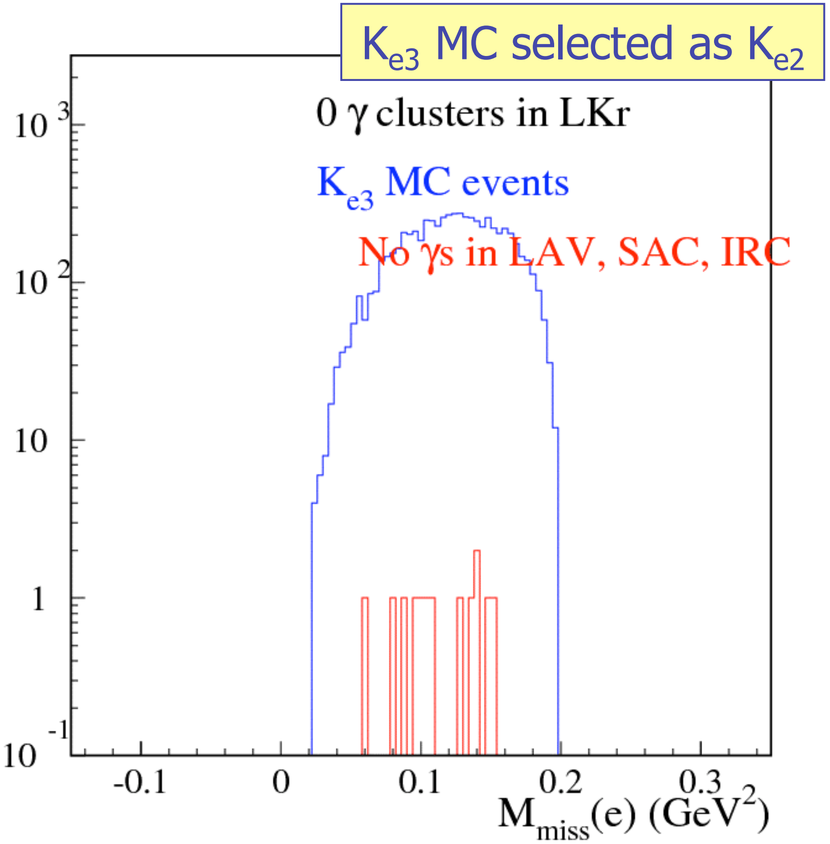
Besides, LKr efficiency was monitored vs time ⇒ A demanding task
Analysis without electron identification allows to avoid the uncertainty.
Possibility: future NA62 analysis at $p < 40$GeV/c without electron identification.

- For NA62 conditions (75 GeV/c beam, ~100 m decay volume):

P($K_{\mu 2}$, $\mu \to e$ decay)/R_K ~ 10 but they are naturally suppressed by the muon polarisation
Irreducible background: ~0.2% however known to excellent precision

$K_{e2\gamma}$ (SD), K_{e3} suppression





$K_{e2\gamma}$ (SD$^+$) sample reduced by a factor of 35

K_{e3} sample reduced by a factor of 500

Rejection provided by the new veto detectors is excellent for K_{e2} analysis

K_{e2} sample untouched by the veto requirement

Future prospects

- Ke2γ background:

KLOE measurement (arXiv:0907:3594): precision improved by a factor of 4;
NA62 (2007 data): analysis in progress; expect precision similar to KLOE;

future NA62 hermetic veto (large-angle and small-angle veto counters) will strongly decrease the background.
SD background will not be relevant for a future NA62 precision RK measurement

- beam halo: future beam spectrometer (beam tracker plus beam Cherenkov) will allow time correlation between incoming kaons and decay products
Expect background to be reduced to negligible level.

Summary (1)

- Due to the suppression of the K_{e2} decay in the SM, the measurement of R_K is well-suited for a stringent SM test.
- Preliminary result based on ~40% of the NA62 K_{e2} sample: $R_K = (2.486 \pm 0.013)\times10^{-5}$, reaching a record ~0.5% accuracy. With the full NA62 data sample of 2007/08, the precision is expected to be improved to better than $\delta R_K/R_K=0.4\text{-}0.5\%$.
- After recent precise R_K measurements, the R_K world average has a 0.5% precision

Summary (2)

Backgrounds in the future NA62 K_{e2} sample

- Only the $K_{\mu 2}$ ($\mu \to e$) expected to remain, at ~0.3% level but well known;
- $K_{\mu 2}$, $K_{e2\gamma}$ (SD), K_{e3}, $K_{2\pi}$ backgrounds not present at $p<40$GeV/c;
- There are alternative ways to suppress backgrounds by the veto counters.
- Beam halo background: suppressed by beam spectrometers & veto counters.

Other known systematic effects:

Geometric acceptance (incl. soft photons): up to 0.1%

Assuming an analysis at low lepton momentum and not using electron ID, measurement of R_K with 0.1-0.2% relative precision is feasible.

Required statistical uncertainty is ~0.05% → few million K_{e2} candidates.
Required kaon decay flux: $N_K \sim 10^{12}$
Expected NA62 flux: $N_K \sim 10^{13}$

K_{e2} trigger implemented during ~1 month of data taking, or downscaled by D=10, is sufficient for such R_K measurement.

Spares

K_{l3}: lepton universality test

Comparison of $|V_{us}|$ determined from
K_{e3} vs $K_{\mu3}$ decays

SM

$$r_{\mu e} = \frac{[|V_{us}|f_+(0)]^2_{\mu3,\,\mathrm{exp}}}{[|V_{us}|f_+(0)]^2_{e3,\,\mathrm{exp}}} = \frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}}\frac{I_{e3}\,(1+2\delta^{Ke}_{\mathrm{EM}})}{I_{\mu3}\,(1+2\delta^{K\mu}_{\mathrm{EM}})} = (g_\mu/g_e)^2 = 1$$

lepton coupling
at the W→lν vertex

Experimental results

$K^\pm$: $r_{\mu e} = 0.998(9)$

K^0: $r_{\mu e} = 1.003(5)$

→ $r_{\mu e} = 1.002(4)$

Non-kaon measurements:

$\pi \to l\nu$: $r_{\mu e} = 1.0042(33)$ (PRD 76 (2007) 095017)

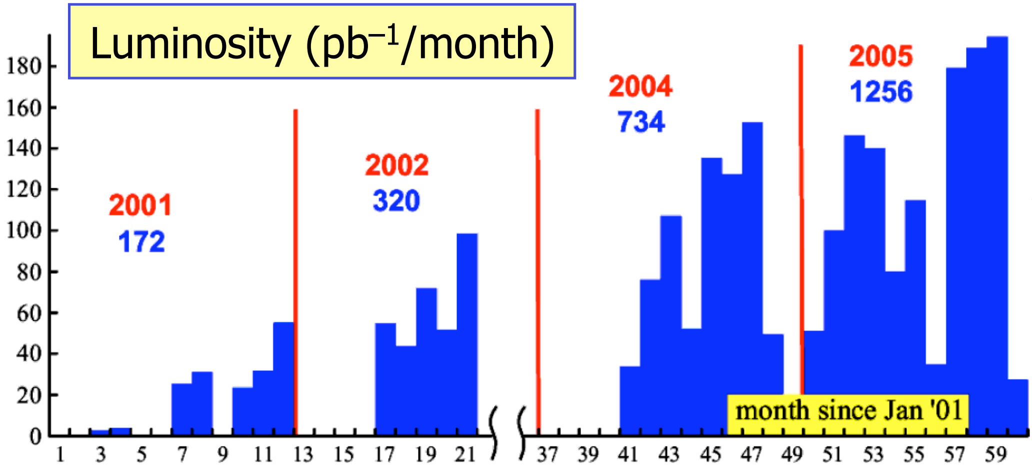
$\tau \to l\nu\nu$: $r_{\mu e} = 1.000(4)$ (Rev.Mod.Phys. 78 (2006) 1043)

The sensitivity in kaon sector approaches those obtained in the other fields.

KLOE K_{e2} analysis: decays at rest

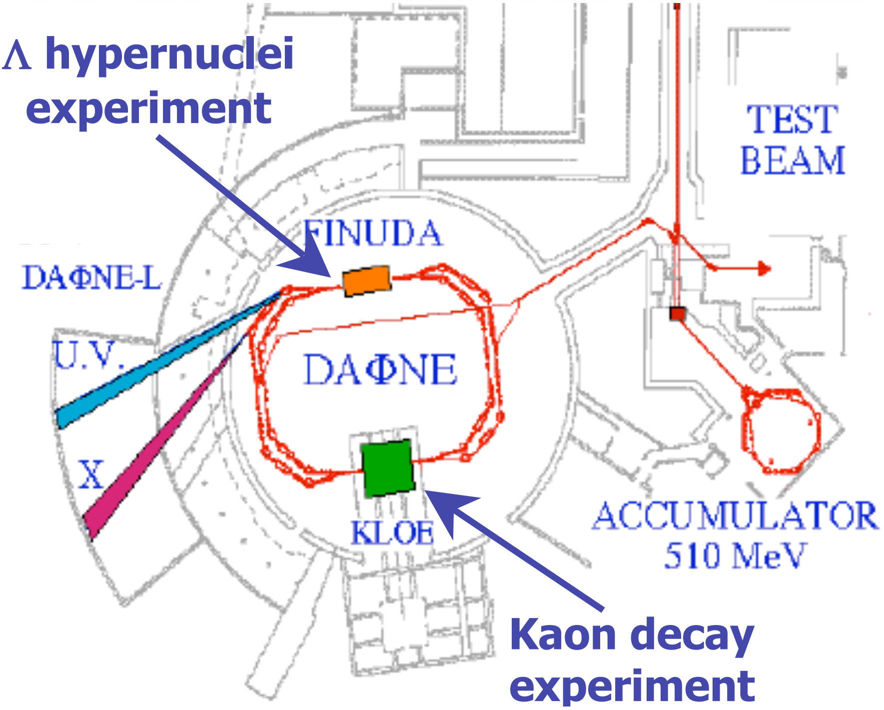
DAΦNE: an e^+e^- collider at LNF Frascati

- CM energy ~ m_ϕ = 1019.4 MeV;
- BR($\phi \to K^+K^-$) = 49.2%;
- ϕ production cross-section σ_ϕ=1.3μb;
- Data sample (2001–05): 2.5 fb^{-1}.



$K_{e2}/K_{\mu2}$ selection technique (vs NA62):

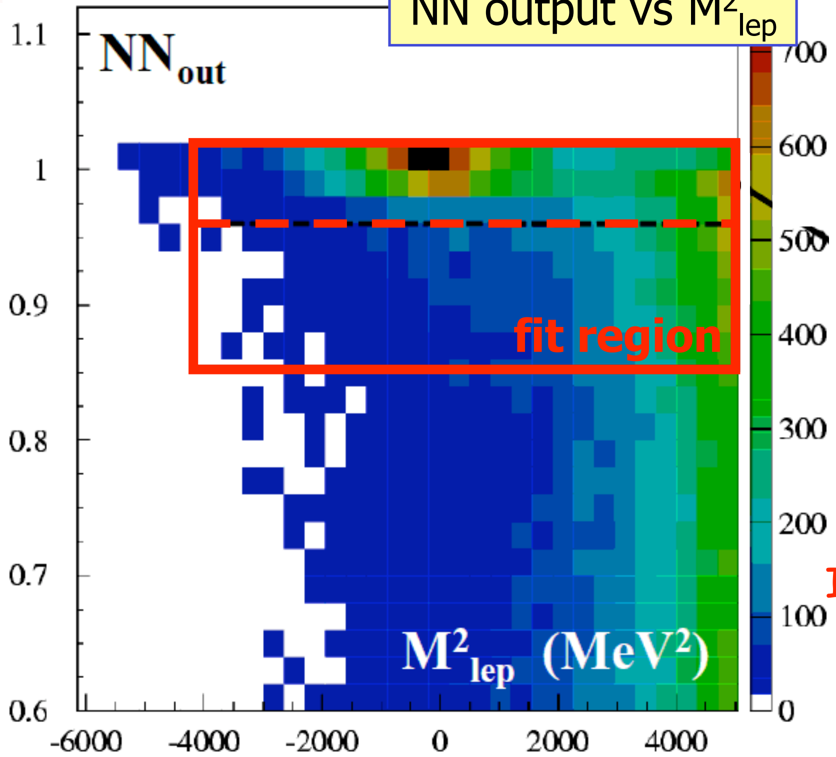
- Kinematics: by M^2_{lep} (equivalent to $M_{miss}{}^2$);
- PID: neural network with 12 input parameters (vs E/p for NA62).

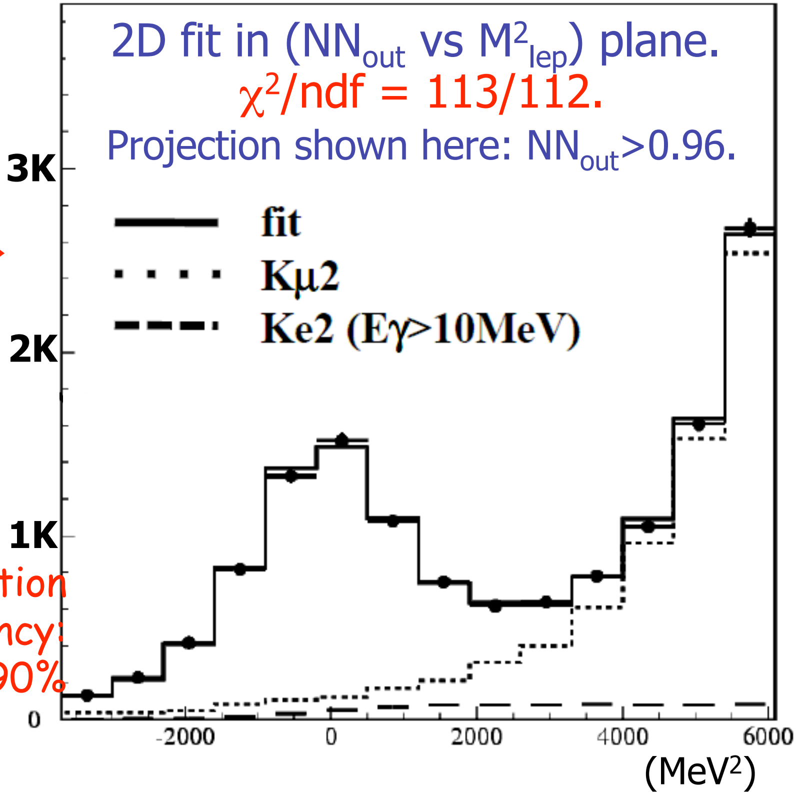

Λ hypernuclei experiment

Kaon decay experiment

KLOE K_{e2} sample

NN output vs M^2_{lep}





2D fit in (NN_{out} vs M^2_{lep}) plane.
$\chi^2/ndf = 113/112$.
Projection shown here: $NN_{out}>0.96$.

Identification efficiency: ~90%

Uncertainties	$\delta R_K/R_K$ (%)
Statistical	1.0
$K_{\mu 2}$ subtraction	0.3
$K_{e2\gamma}$ (SD^+)	0.2
Reconstruction efficiency	0.6
Trigger efficiency	0.4
Total	1.3

Full data sample analyzed
[EPJ C64 (2009) 627]

13.8K K_{e2} candidates, 16% background

KLOE-2: expect to start in 2010, $\delta R_K/R_K=0.4\%$.
[arXiv:1003.3862]

NA62 data taking 2007/08

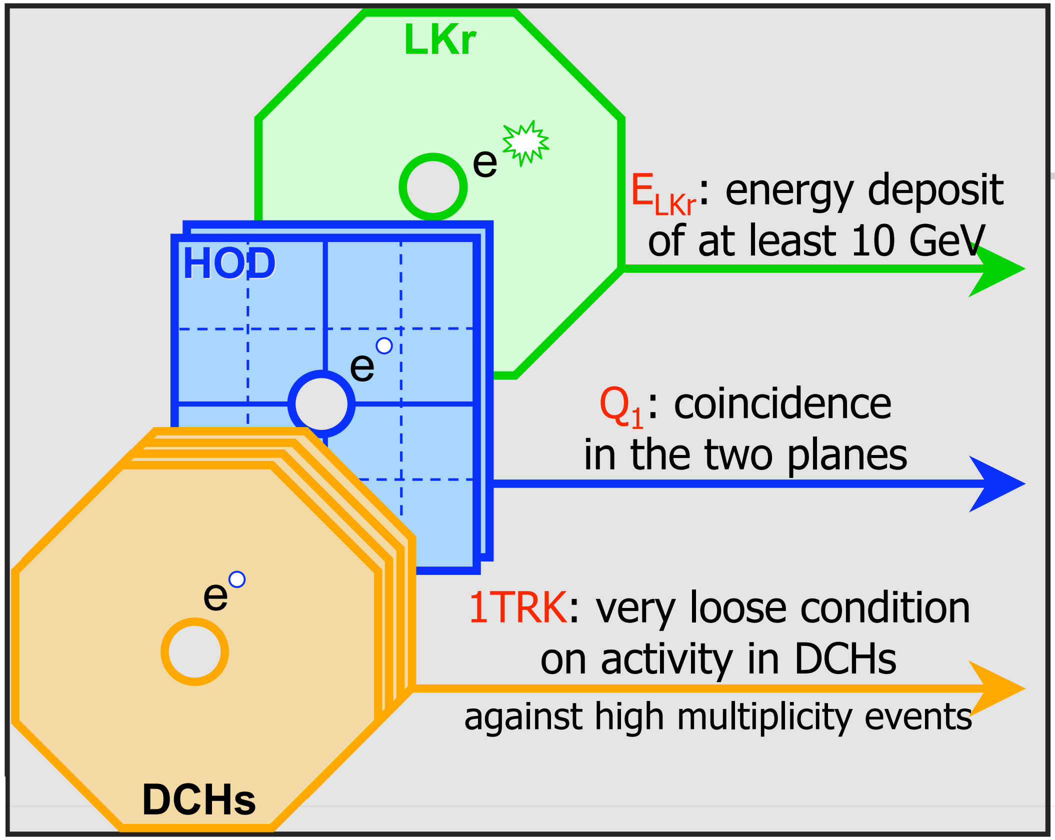
Data taking:

- 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;
  $\Delta p/p = 0.47\% + 0.020\% * p$ [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



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

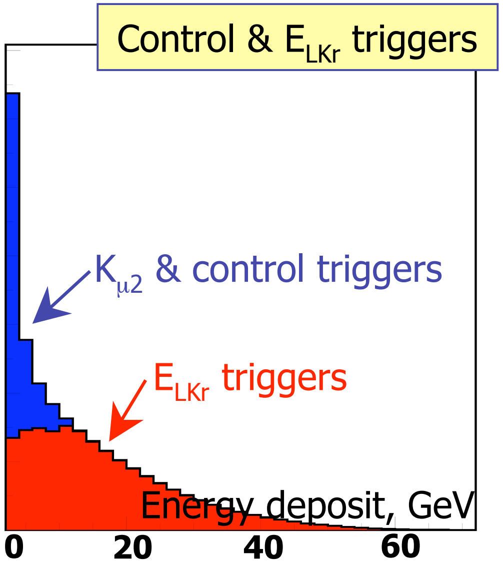
Q_1: coincidence in the two planes

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

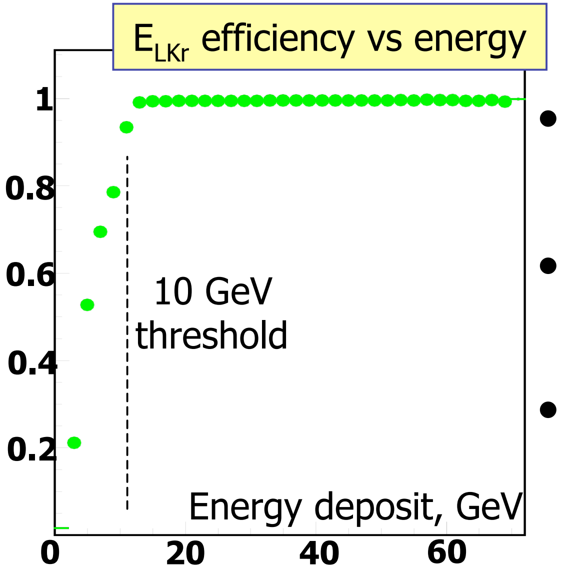
Minimum bias (high efficiency, but low purity) trigger configuration used

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%.



Control & E_{LKr} triggers

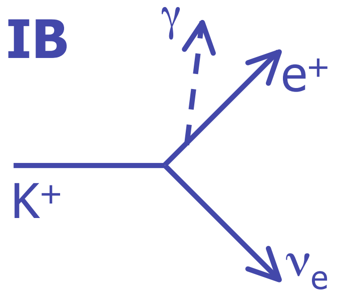


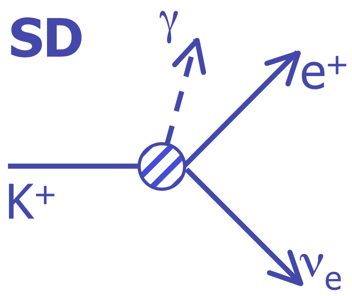
E_{LKr} efficiency vs energy

- 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!

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

By definition, R_K is inclusive of the IB part of the radiative $K_{e2\gamma}$ process



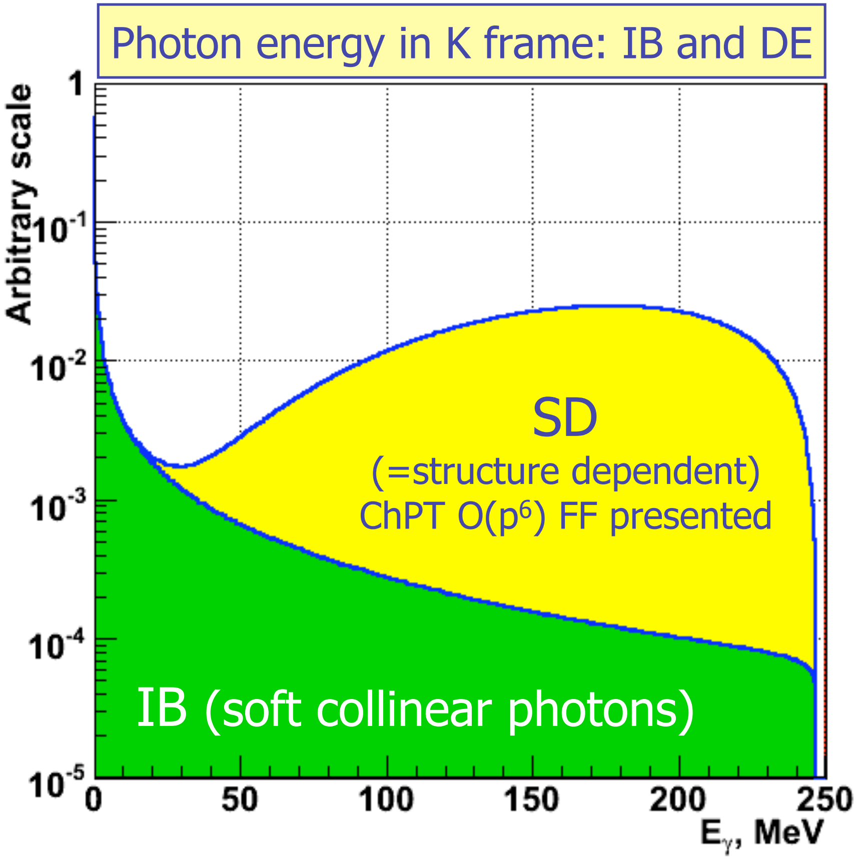


- The $K_{e2\gamma}$ (SD) process is a background.
- SD is not helicity suppressed, and its rate is similar to that of K_{e2}.
- Known to a limited precision of ~15%.

(NB: a recent 4% precision measurement, EPJC64 (2009) 627, not used in present analysis)

<u>Experiment:</u> BR=$(1.52\pm0.23)\times10^{-5}$
(average of 1970s measurements)

<u>Theory:</u> BR=$(1.38–1.53)\times10^{-5}$ [PRD77 (2008) 014004]
(uncertainty due to a model-dependent form factor)


Photon energy in K frame: IB and DE

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

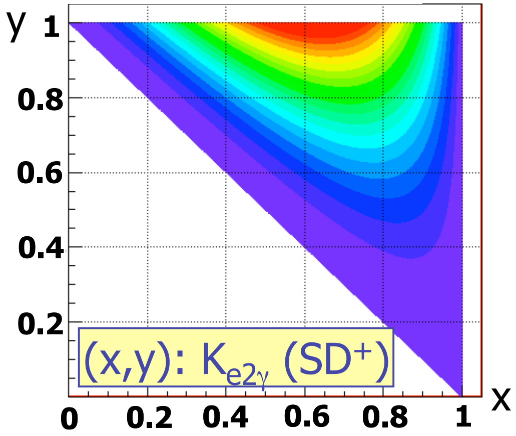
Decay density: $$\frac{d\Gamma(K\to e\nu\gamma)}{dxdy} = \underbrace{\rho_{IB}(x,y)}_{\text{helicity suppressed}} + \rho_{SD}(x,y) + \underbrace{\rho_{INT}(x,y)}_{\text{negligible}}$$

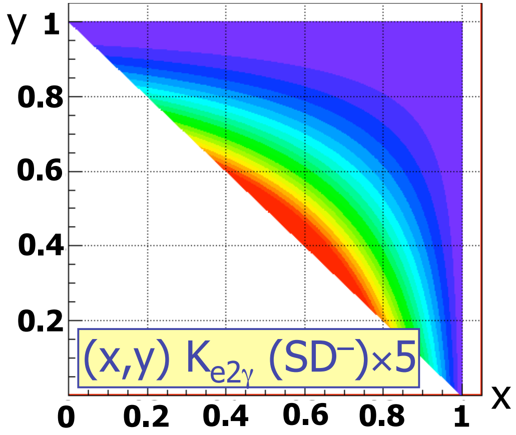
Kinematic variables (kaon frame): $$x = 2E_\gamma/M_K, \quad y = 2E_e/M_K$$

$$\rho_{SD}(x,y) = \frac{G_F^2|V_{us}|^2\alpha}{64\pi^2}M_K^5\left((f_V+f_A)^2 f_{SD+}(x,y) + (f_V-f_A)^2 f_{SD-}(x,y)\right)$$

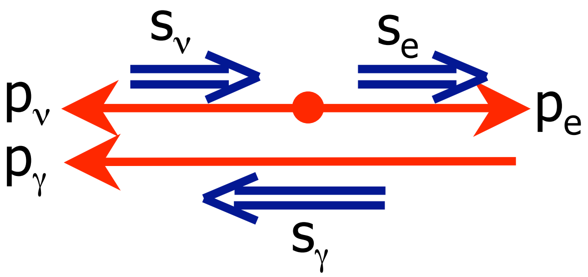
Two non-interfering contributions SD⁺ and SD⁻: emission of photons with positive and negative helicity

$f_V(x)$, $f_A(x)$: model-dependent effective vector and axial couplings

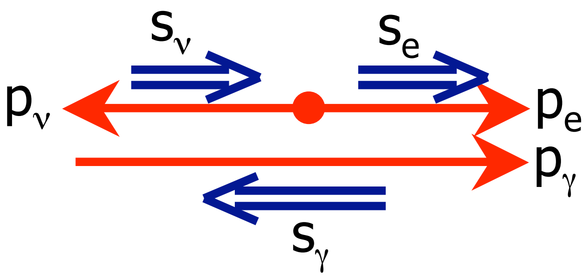




SD⁺: positive γ helicity

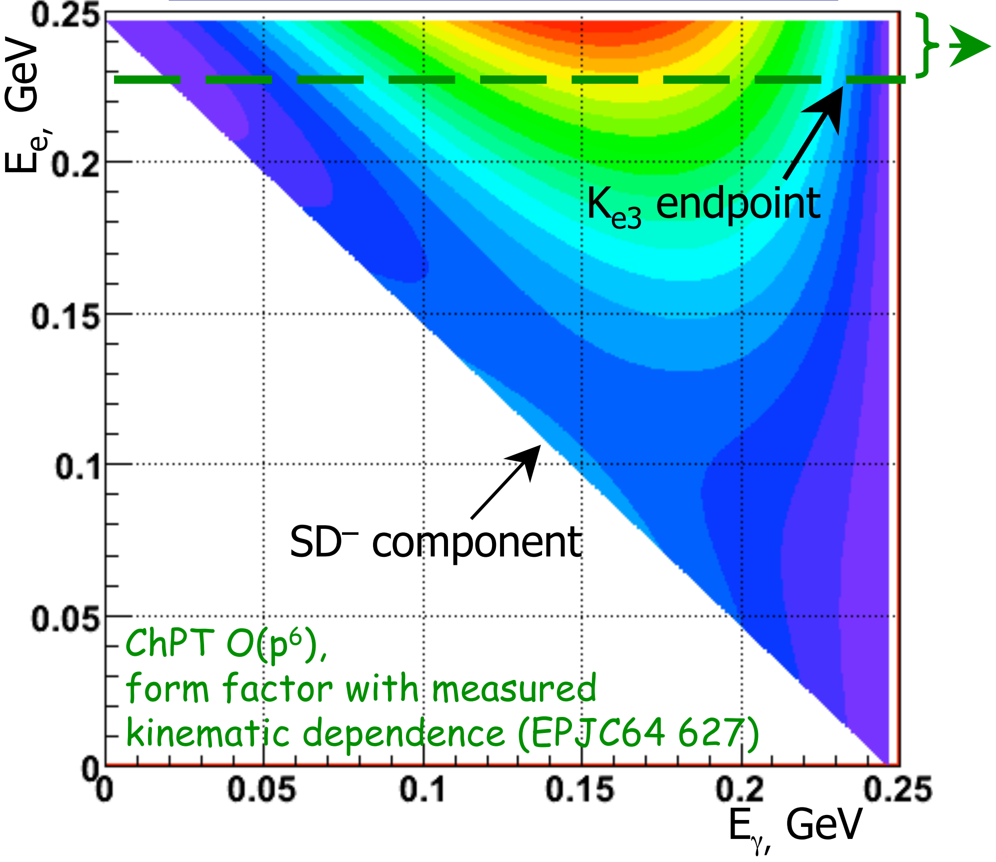


SD⁻: negative γ helicity



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

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



ChPT $O(p^6)$,
form factor with measured
kinematic dependence (EPJC64 627)

Only energetic electrons ($E_e^* > 230$MeV) 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).

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

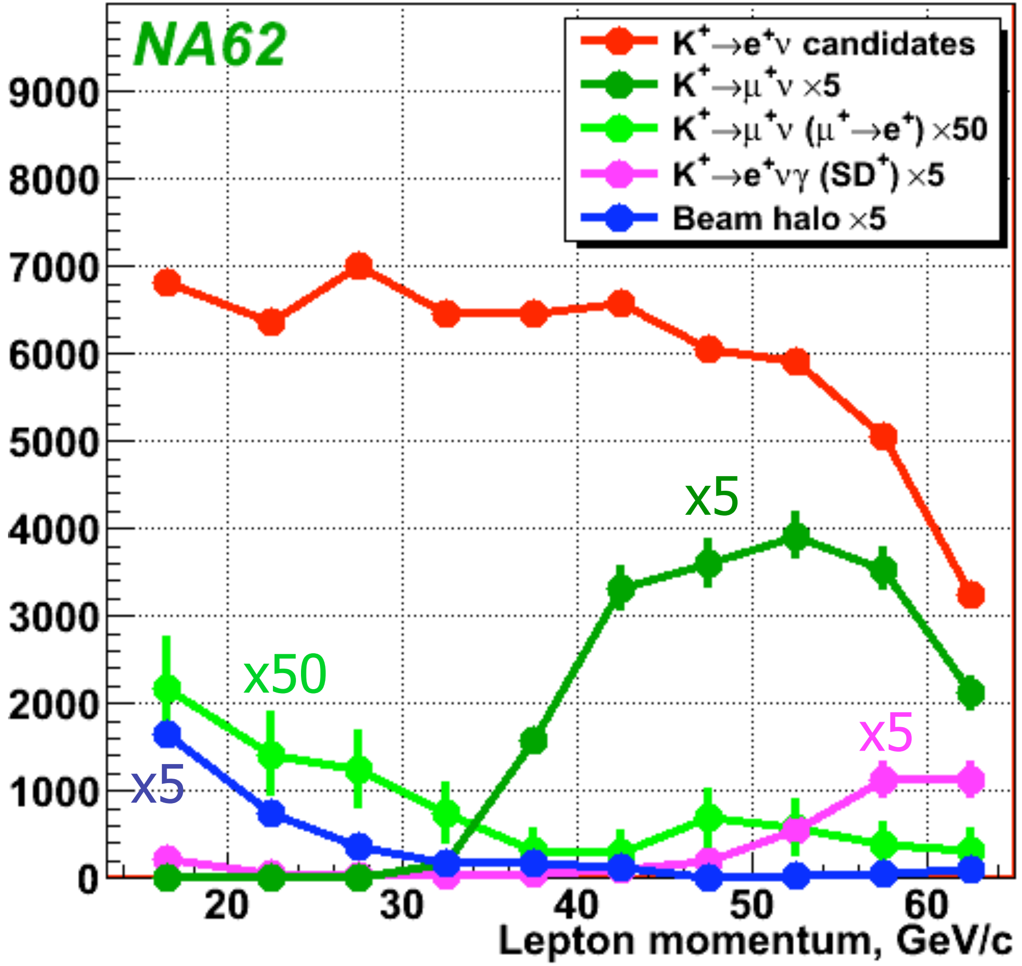
SD background contamination

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

(uncertainty due to PDG BR, to be improved by new BR measurements)

Backgrounds: summary

K_{e2} candidates and backgrounds in momentum bins



(selection criteria optimized individually in each P_{track} bin)

Backgrounds

Source	B/(S+B)
$K_{\mu2}$	(6.10±0.22)%
$K_{\mu2}$ ($\mu \to e$)	(0.27±0.04)%
$K_{e2\gamma}$ (SD^+)	(1.15±0.17)%
Beam halo	(1.14±0.06)%
$K_{e3(D)}$	(0.06±0.01)%
$K_{2\pi(D)}$	(0.06±0.01)%
Total	(8.78±0.29)%

Record K_{e2} sample:
59,963 candidates
with low background
B/(S+B) = (8.8±0.3)%

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

Beam halo background

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

Background measurement:

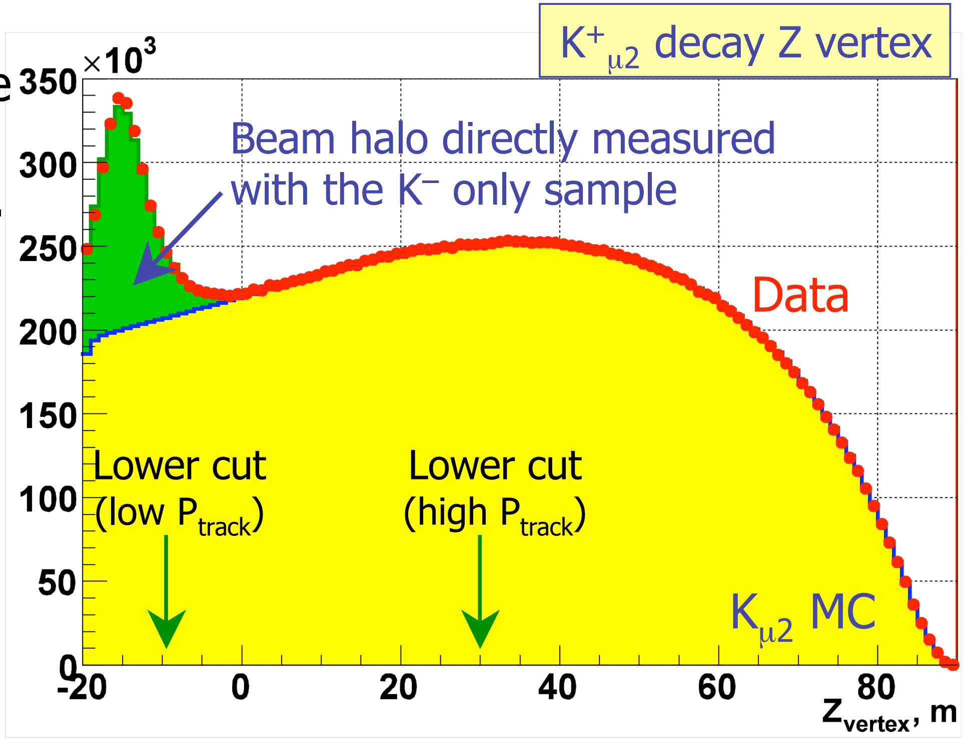
- Halo background much higher for K_{e2}^{-} (~20%) than for K_{e2}^{+} (~1%).
- Halo background in the $K_{\mu 2}$ sample is considerably lower.
- ~90% of the data sample is K^{+} only, ~10% is K^{-} only.
- K^{+} halo component is measured directly with the K^{-} sample and vice versa.

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.

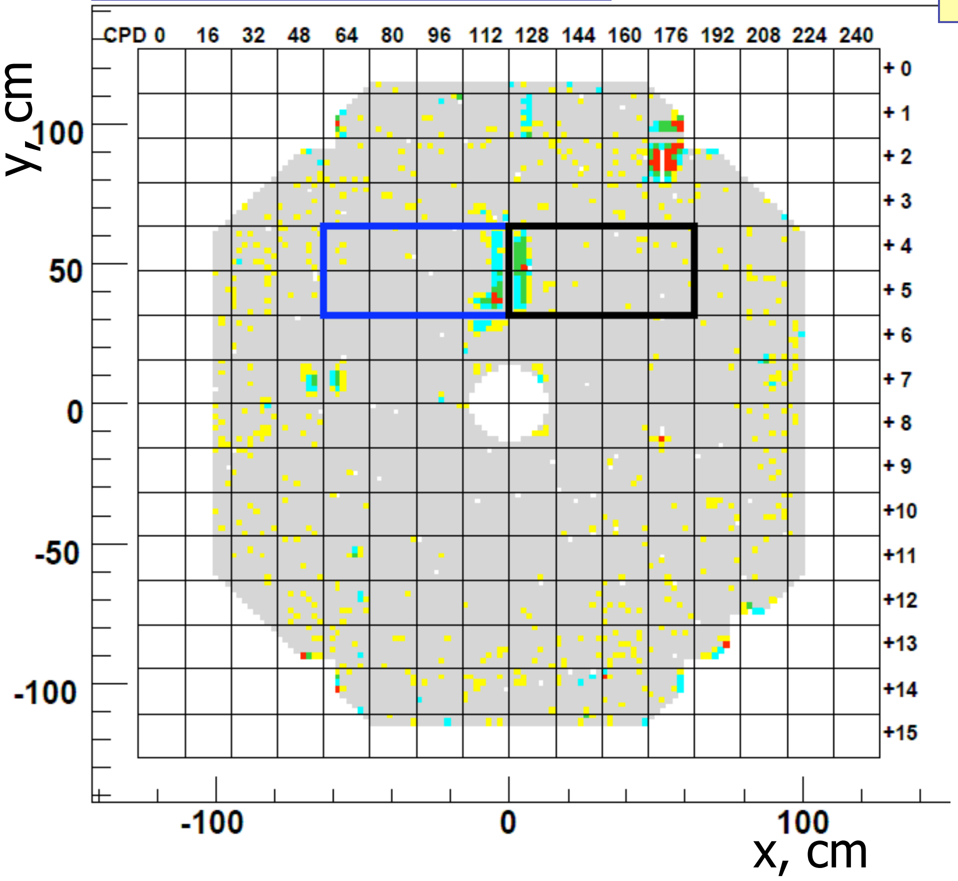
$B/(S+B) = (1.14 \pm 0.06)\%$

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



Systematic effect: positron ID

A typical inefficiency map



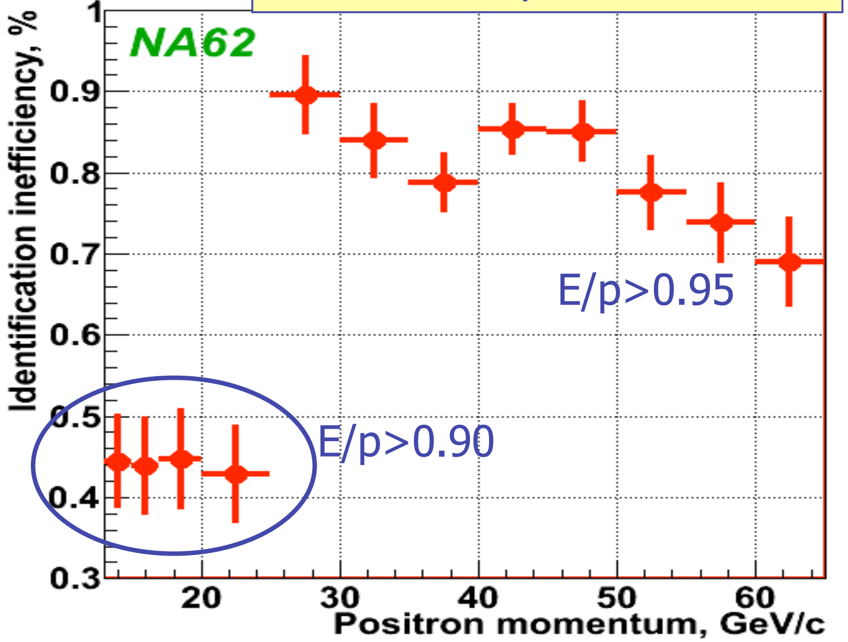
LKr energy response is calibrated for every 2×2cm² cell within acceptance

Colour code

- ⬜ Ineff < 1.2%
- 🟨 Ineff = (1.2 - 2)%
- 🟦 Ineff = (2.0-4.0)%
- 🟩 Ineff = (4.0-10)%
- 🟥 Ineff > 10%

(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 special $K_L \to \pi e \nu$ samples: integral ε = (99.27±0.05)%