Lepton Universality tests with Leptonic Kaon decays in NA62

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for the NA62 collaboration

(Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, IHEP Protvino, INR Moscow, Liverpool, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, Sofia, TRIUMF, Turin)

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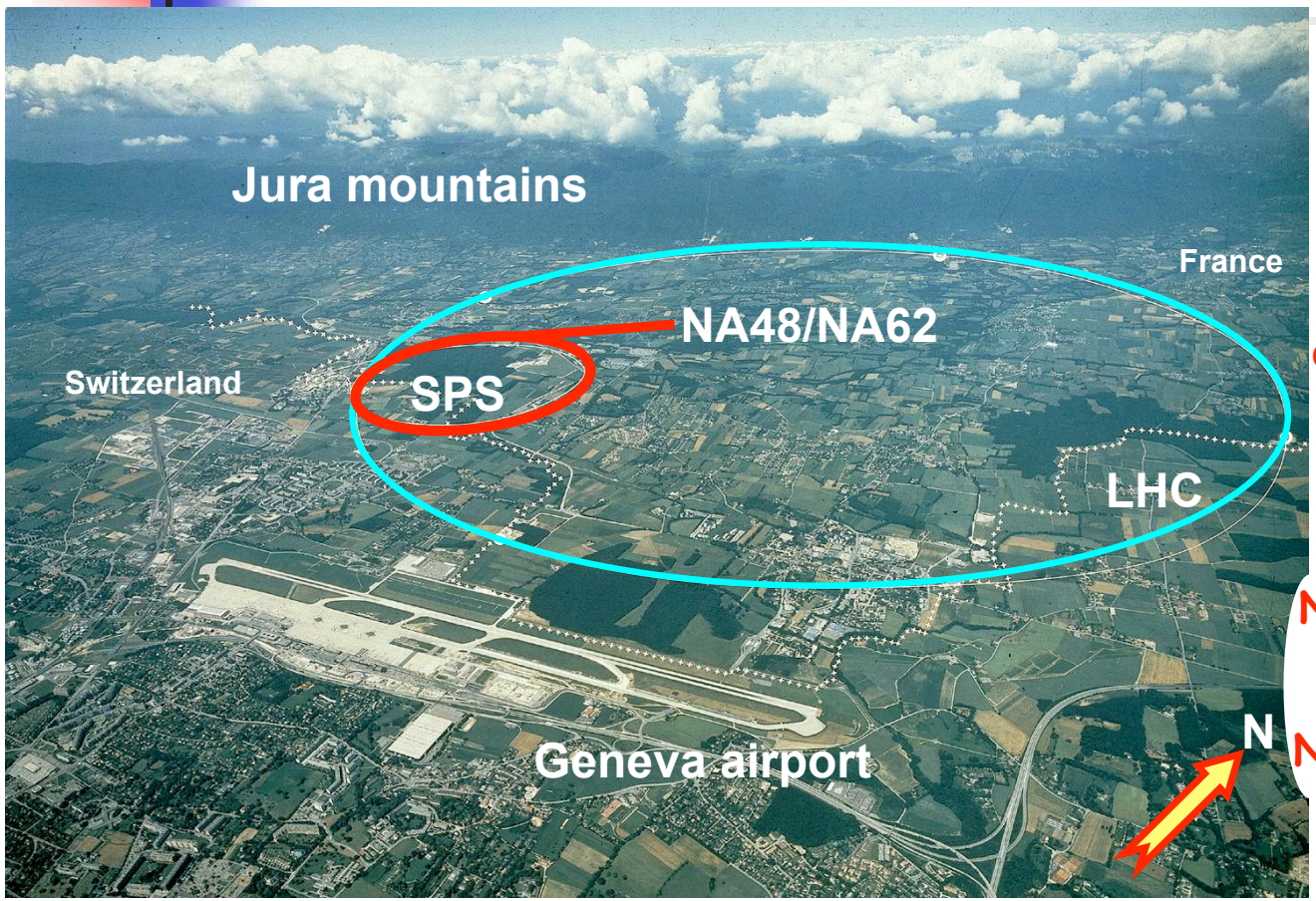
CERN NA48/NA62



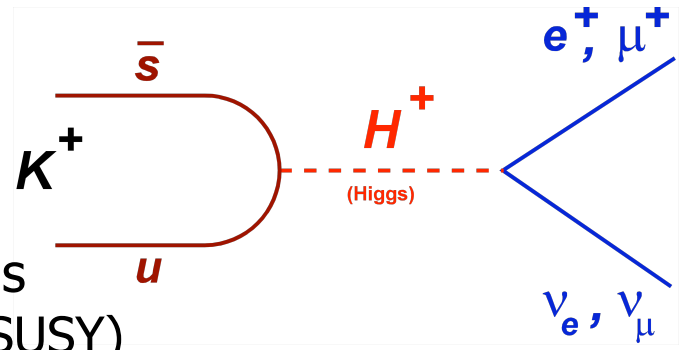
NA48 discovery of direct CPV	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 (R_K)	2007: $K^\pm_{e2}/K^\pm_{\mu 2}$	
	2008: $K^\pm_{e2}/K^\pm_{\mu 2}$	
NA62	2007–2013: design & construction 2012: first data taking	

Primary SPS protons (400 GeV/c): 1.8×10^{12}/SPS spill
Unseparated secondary positive beam: p=(74.0±1.6) GeV/c
Composition: $K^+(\pi^+)$ = 5%(63%).
K^+ decaying in vacuum tank: 18%.

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, tanβ = 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 but not hopeless

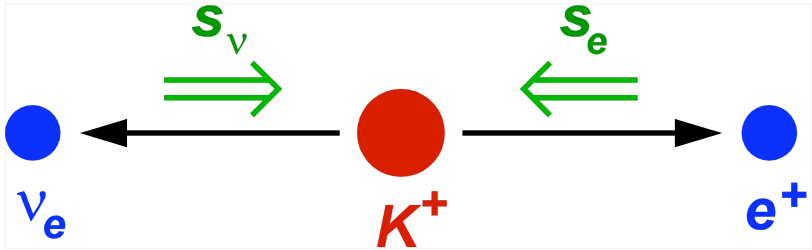
Subject to hadronic uncertainties

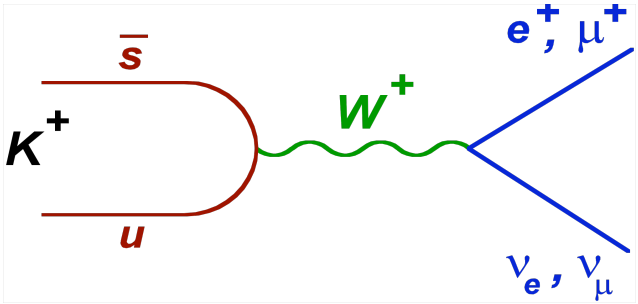
$R_K = K_{e2}/K_{\mu 2}$ in the SM

Observable sensitive to lepton flavour and its SM expectation:

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}}_{\text{Helicity suppression: } f\sim 10^{-5}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{(1 + \delta R_K^{\text{rad.corr.}})}_{\text{Radiative correction (few \%) due to } K^+\to e^+\nu\gamma \text{ (IB) process, by definition included into } R_K}$$

(similarly, R_π in the pion sector)





- SM prediction: excellent sub-per mille 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. Rev. Lett. 99 (2007) 231801

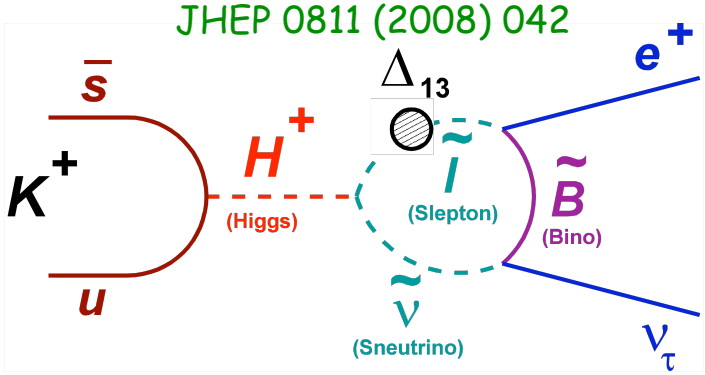
$R_K = K_{e2}/K_{\mu 2}$ beyond the SM

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

2HDM – tree level (including SUSY)

K_{l2} can proceed via exchange of charged Higgs $H^{\pm}$ (in place of $W^{\pm}$)

→ Does not affect the ratio R_K



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

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

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 :

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

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, measured 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;

$D=50\text{-}150$ downscaling factor of the $K_{\mu 2}$ trigger.

(3) MC simulations use minimised:

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

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

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

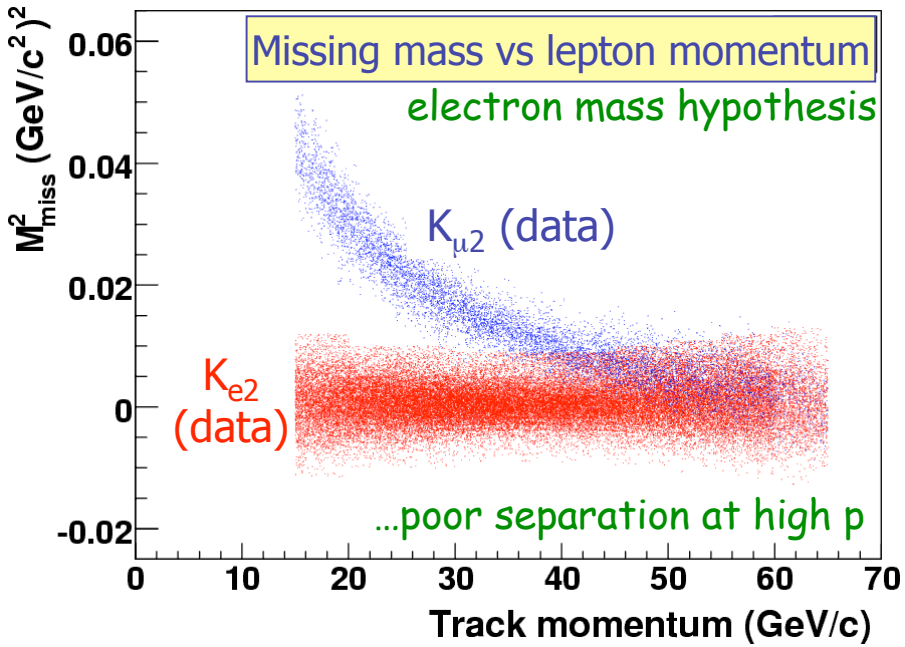
Separation by particle ID

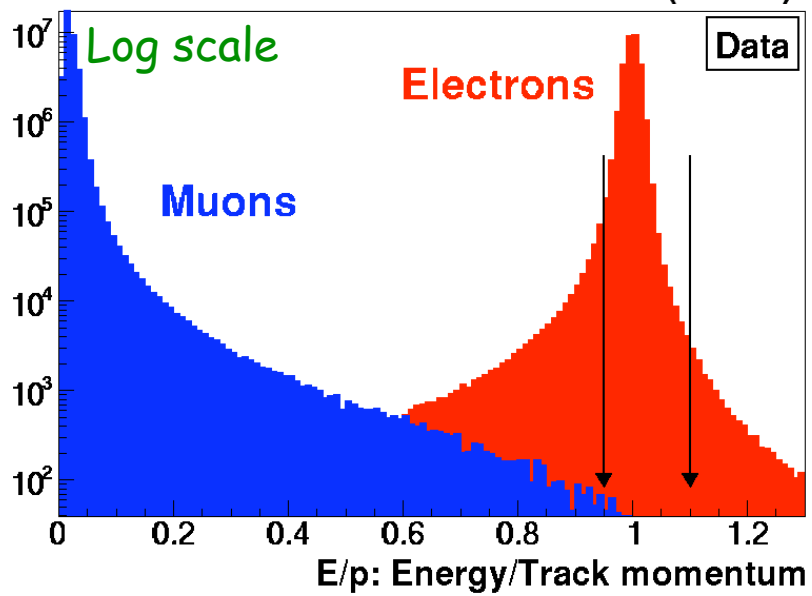
E/p = (LKr energy deposit/track momentum).

(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

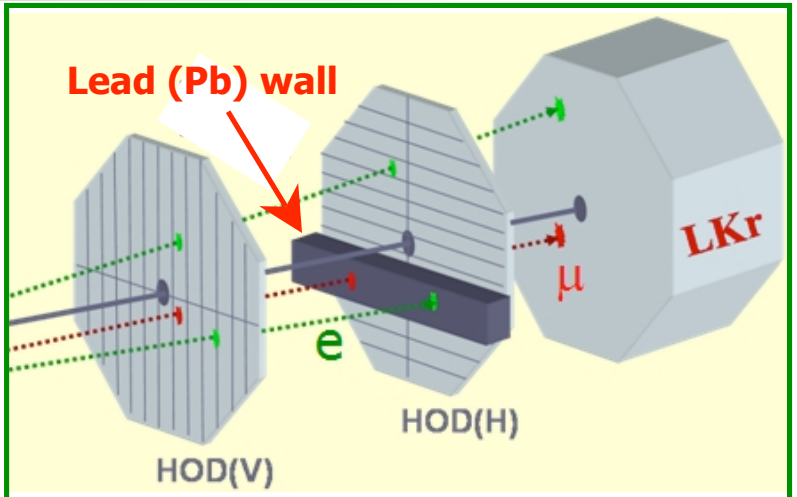
Muon "catastrophic" energy loss in LKr by emission of energetic bremsstrahlung photons. $P_{\mu e} \sim 3\times10^{-6}$ (and momentum-dependent).

$P_{\mu e} / R_K \sim 10\%$:
$K_{\mu 2}$ 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:	$\sim9.2X_0$ (Pb+Fe)
Width:	240cm (=HOD size)
Height:	18cm (=3 counters)
Area:	~20% of HOD area
Duration:	~50% of R_K runs + special muon runs

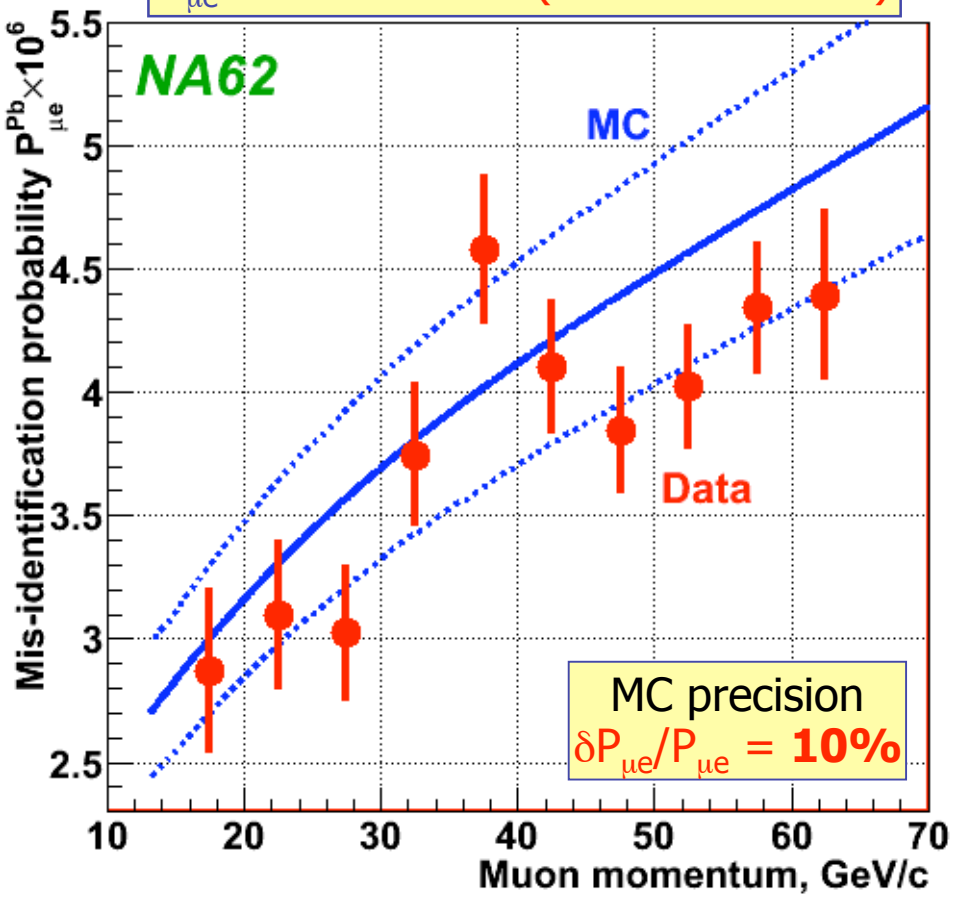
$P_{\mu e}$ is modified by the Pb wall:
→ ionization losses in Pb (low p);
→ bremsstrahlung in Pb (high p).

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

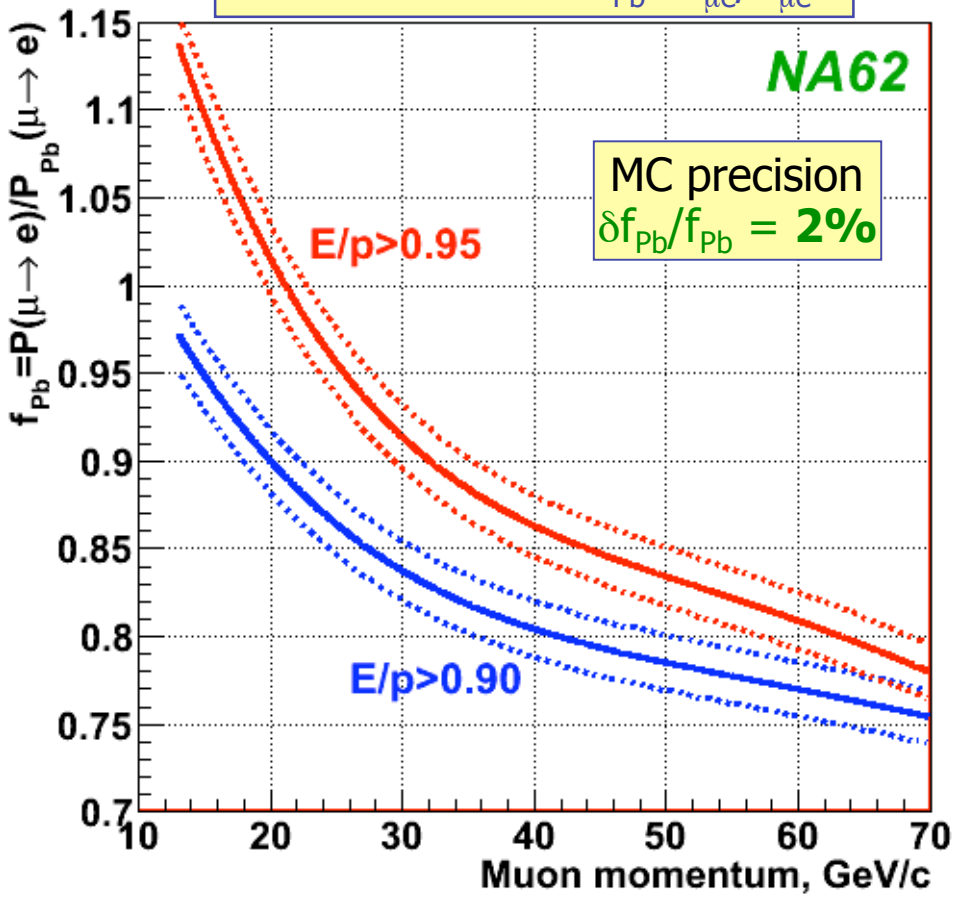
[Muon bremsttranlung: Phys. Atom. Nucl. 60 (1997) 576]

Muon mis-identification

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



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



Result: B/(S+B) = (5.64±0.20)%

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

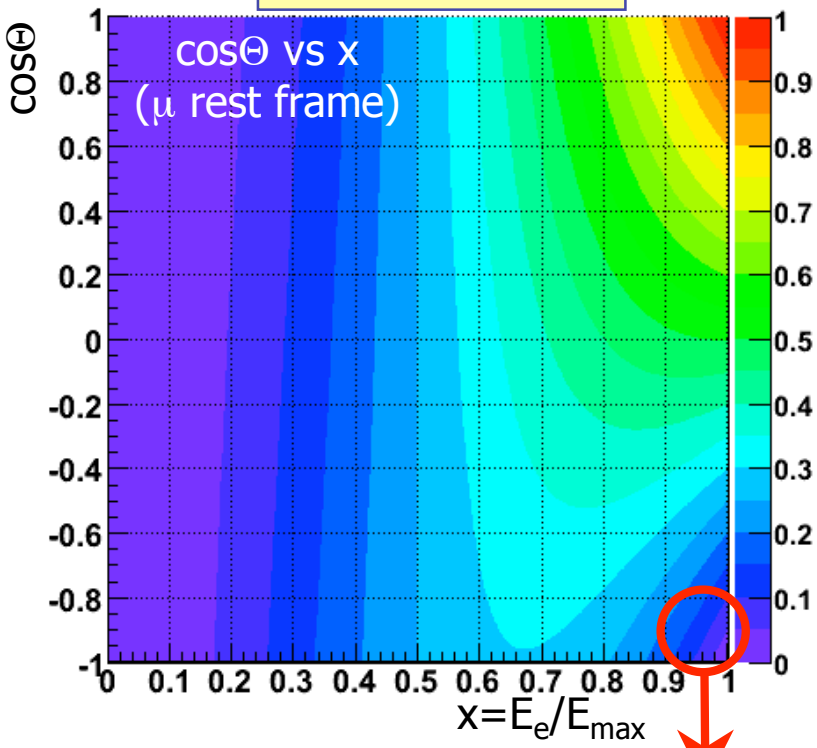
$$d^2\Gamma/dxd(\cos\Theta) \sim x^2[(3-2x) - \cos\Theta(1-2x)]$$

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

Result: $B/(S+B) = (0.26 \pm 0.03)\%$

Important but not dominant background

Michel distribution



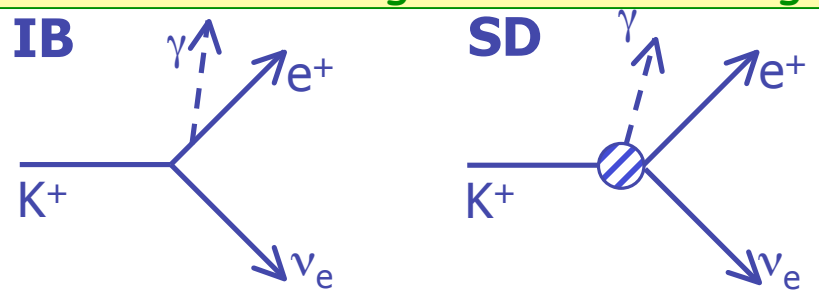
Only energetic forward positrons are selected as K_{e2} candidates

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.



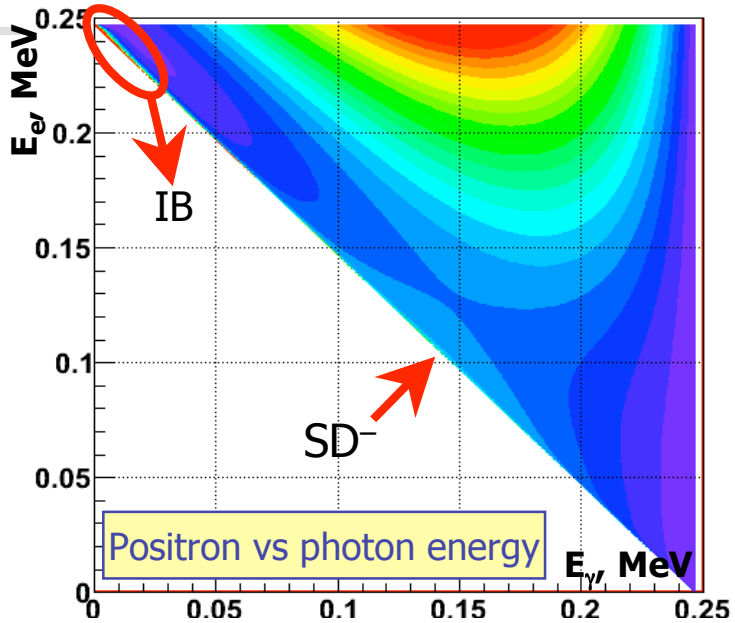
SD radiation is not helicity suppressed.
KLOE measurement of the form factor leads to
BR(SD^+, full phase space) = $(1.37 \pm 0.06) \times 10^{-5}$.
(EPJC64 (2009) 627)

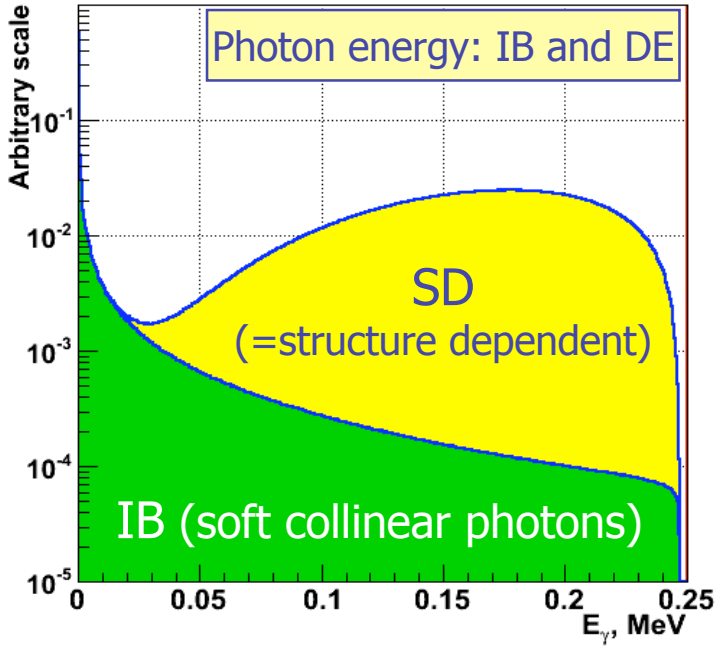
SD background contamination

B/(S+B) = (2.60±0.11)%

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

INT= interference; IB=inner bremsstrahlung





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

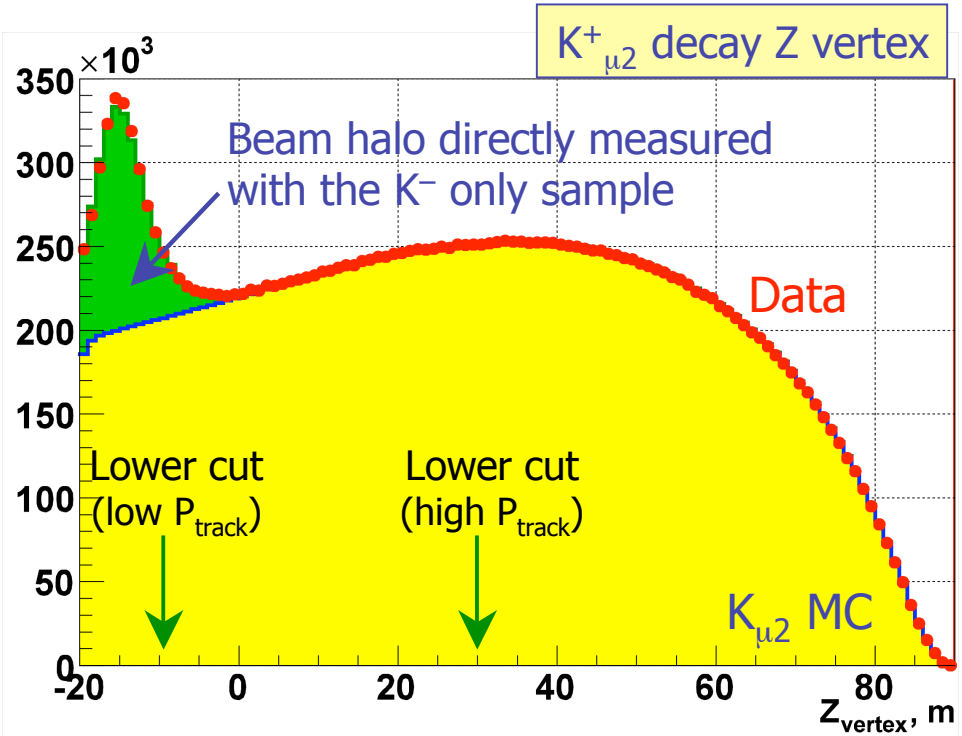
Background measurement:

- Halo background much higher for K_{e2}^- (~20%) than for K_{e2}^+ (~1%).
- Halo background in the $K_{\mu 2}$ sample is considerably lower.
- ~66% of the data sample is K^+ only, ~7% is K^- only, ~27% has both
- K^+ halo component is measured directly with the K^- sample and vice versa.

1-7% background in K^+/ K^- Pb/no Pb.
The background is measured 0.1-0.2% precision, and strongly depends on decay vertex position and track momentum.
The selection criteria (esp. Z_{vertex}) are optimized to minimize the halo background.

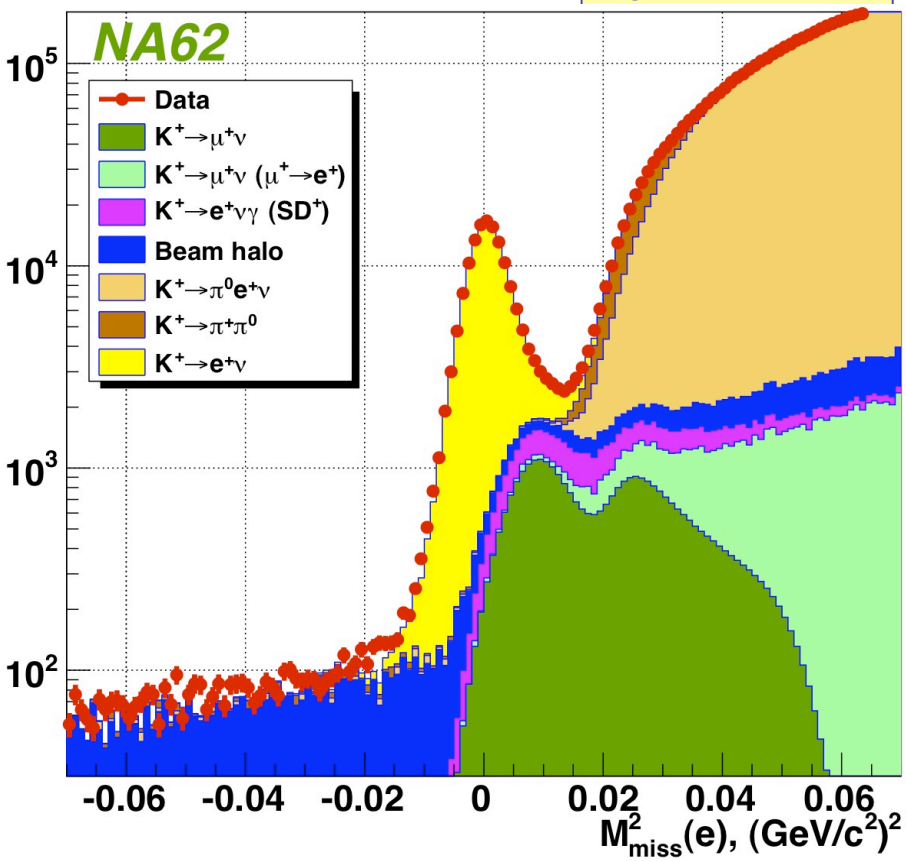
$B/(S+B) = (2.11 \pm 0.09)\%$

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

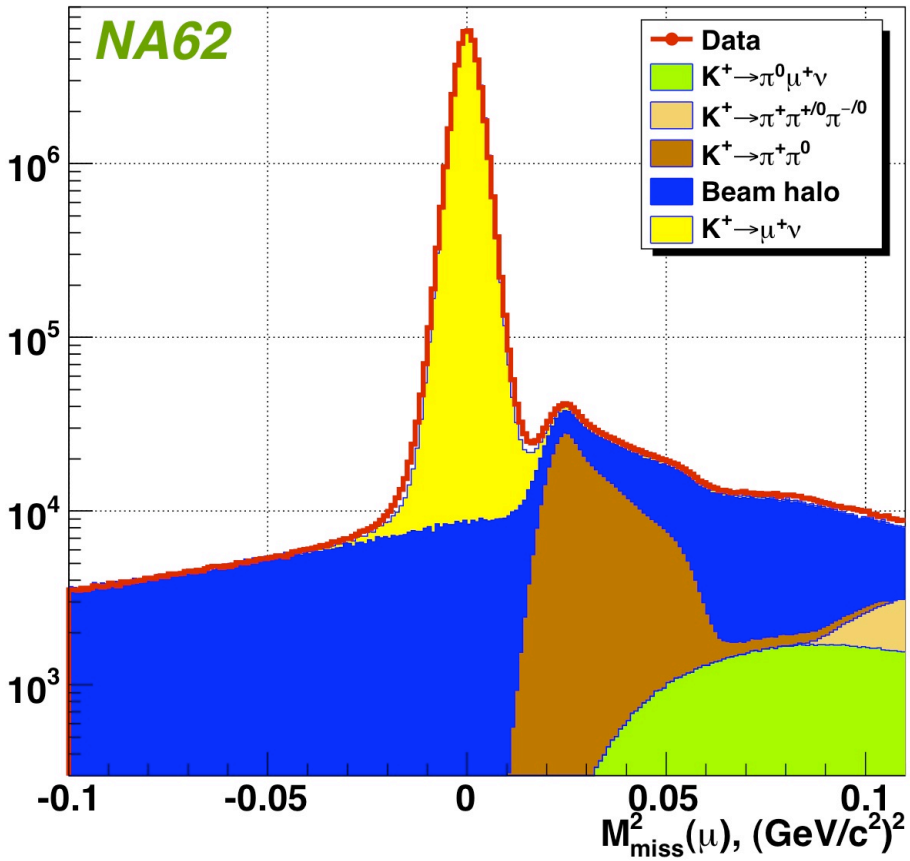


NA62 data set

K_{e2} candidates



$K_{\mu 2}$ candidates



145,958 $K^+ \to e^+\nu$ candidates.
Positron ID efficiency: (99.28±0.05)%.
B/(S+B) = (10.95±0.27)%.

42.817M candidates
with low background
B/(S+B) = (0.50±0.01)%

Backgrounds and Uncertainty

Backgrounds

Source	B/(S+B)
$K_{\mu 2}$	(5.64±0.20)%
$K_{\mu 2}$ ($\mu \to e$)	(0.26±0.03)%
$K_{e2\gamma}$ (SD^+)	(2.60±0.11)%
Beam halo	(2.11±0.09)%
$K_{e3(D)}$	(0.18±0.09)%
$K_{2\pi(D)}$	(0.12±0.06)%
Wrong sign K	(0.04±0.02)%
Total	(10.95±0.27)%

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

Uncertainties

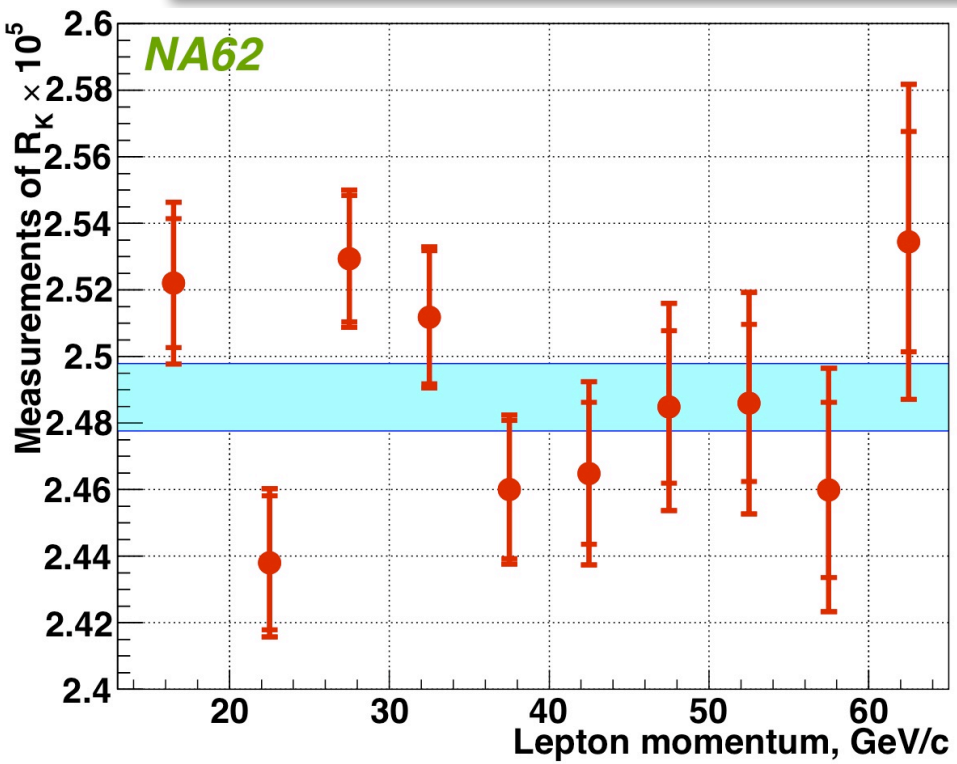
Source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$	0.004
BR($K_{e2\gamma}$ SD^+)	0.002
$K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$	0.003
Beam halo	0.002
Helium purity	0.003
Acceptance	0.002
DCH alignment	0.001
Positron ID	0.001
Lkr readout inef	0.001
1-track trigger	0.001
Total	0.010

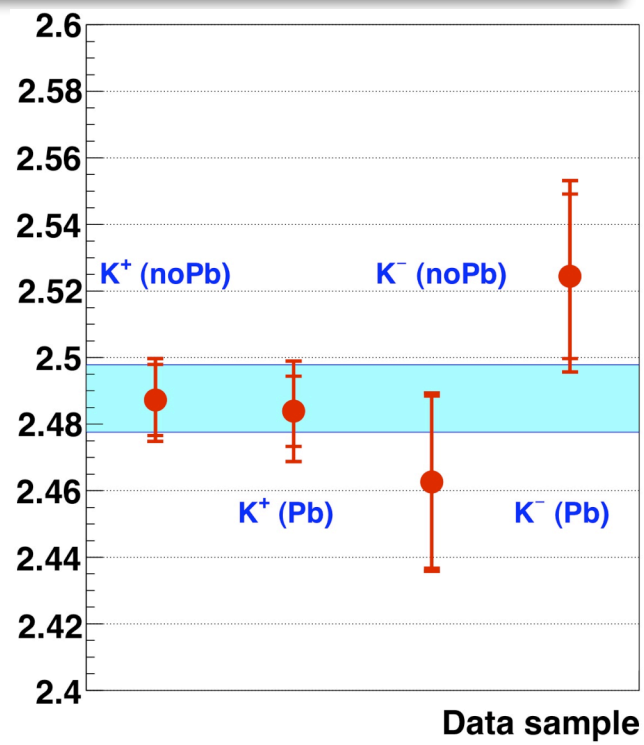
(40% data set: PLB 698 (2011), 105)

NA62 result

$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$

$R_K = (2.488 \pm 0.010) \times 10^{-5}$





Independent measurements in lepton momentum bins

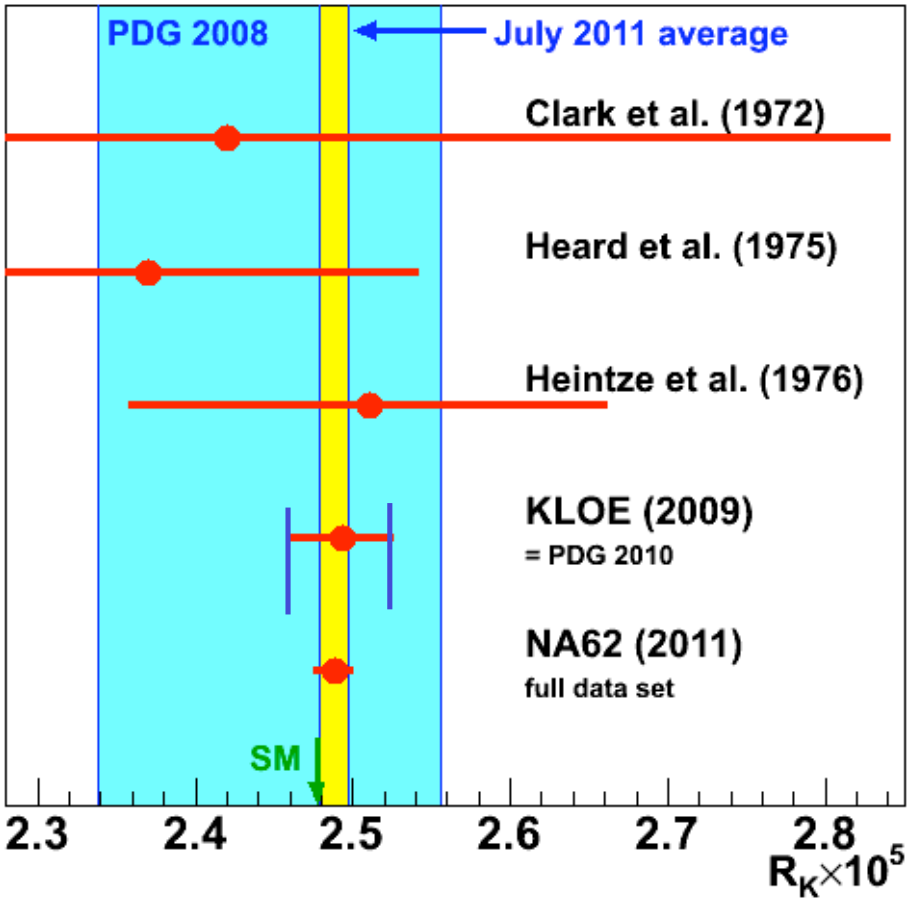
40 measurements (4 data samples x 10 momentum bins) including correlations:

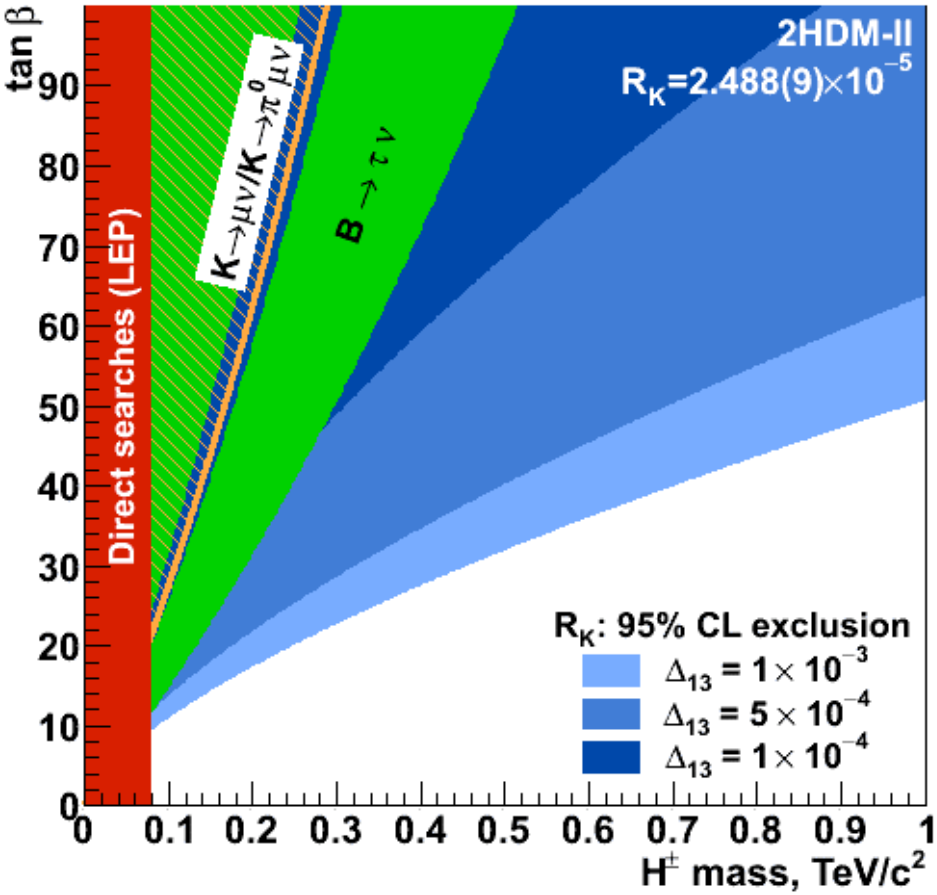
χ^2/ndf=47/39

(systematic errors included, partially correlated)

R_K: world average

(M_H, tanβ) 95% exclusion limits





Other limits on 2HDM-II:
PRD 82 (2010) 073012.
SM with 4 generations:
JHEP 1007 (2010) 006.

Summary

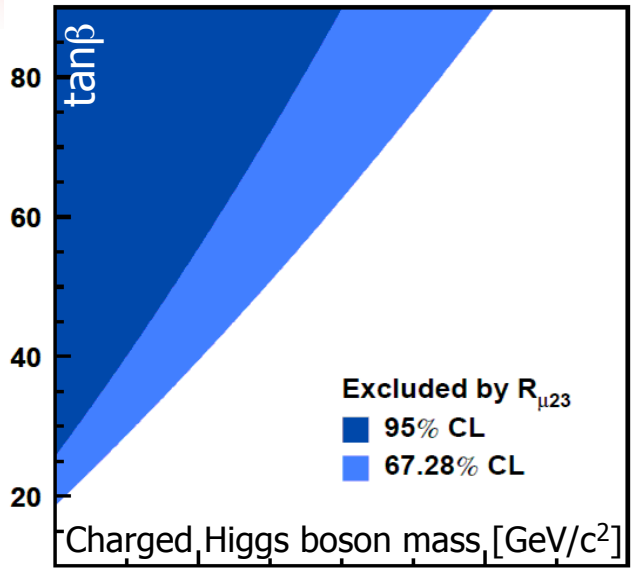
- Due to the suppression of the K_{e2} decay in the SM, the measurement of R_K is well-suited for a stringent SM test

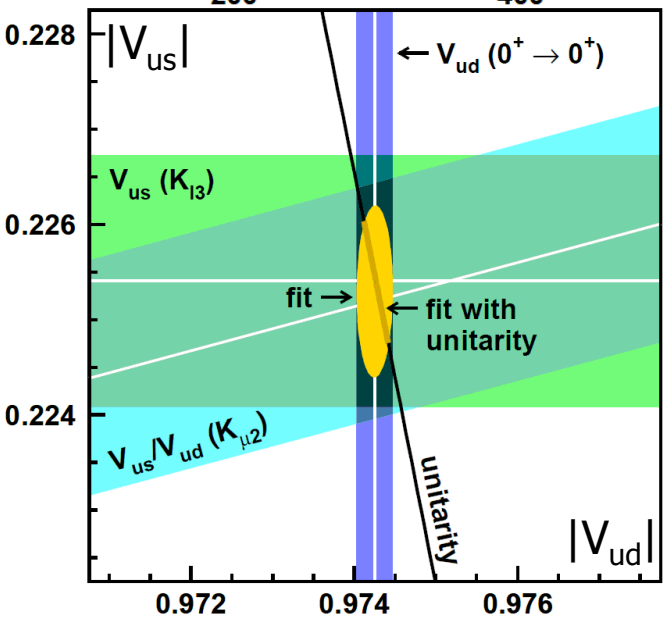
- Result based on total NA62 K_{e2} sample: $R_K = (2.488 \pm 0.010)\times10^{-5}$, reaching a record ~0.4% accuracy

- After recent precise R_K measurements, the R_K world average has a 0.4% precision

Spares

$H^{\pm}$ 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:

$$R_{\mu 23} = \underbrace{\left(\frac{f_K/f_\pi}{f_+(0)}\right)^{-1}}_{\text{Lattice QCD input}} \underbrace{\left(\left|\frac{V_{us}}{V_{ud}}\right| \frac{f_K}{f_\pi}\right)_{\mu 2}}_{\text{Measured with } K_{\mu 2}/\pi_{\mu 2}} \frac{\overbrace{|V_{ud}|_{0^+ \to 0^+}}^{\text{average from nuclear } \beta \text{ decays, PRC79 (2009) 055502}}}{\underbrace{[|V_{us}| f_+(0)]_{\ell 3}}_{\text{Measured with } K \to \pi \mu \nu}}$$

Charged Higgs mediated contribution:

$$R_{\mu 23} \approx \left| 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right|$$

Experiment: $R_{\mu 23} = 0.999(7)$,
$|V_{us}|^2 + |V_{ud}|^2 - 1 = -0.0001(6)$.

Precision limited by lattice ICQ input.

(Flavianet Kaon WG, arXiv:1005.2323)

K_{l3}: lepton universality test

Comparison of $|V_{us}|$ determined from K_{e3} vs $K_{\mu 3}$ decays

SM

$$r_{\mu e} = \frac{[|V_{us}| f_+(0)]^2_{\mu 3,\,\mathrm{exp}}}{[|V_{us}| f_+(0)]^2_{e3,\,\mathrm{exp}}} = \frac{\Gamma_{K\mu 3}}{\Gamma_{Ke3}} \frac{I_{e3}\,(1+2\delta^{Ke}_{\mathrm{EM}})}{I_{\mu 3}\,(1+2\delta^{K\mu}_{\mathrm{EM}})} = (g_\mu/g_e)^2 = 1$$

lepton coupling at the $W \to l\nu$ 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)

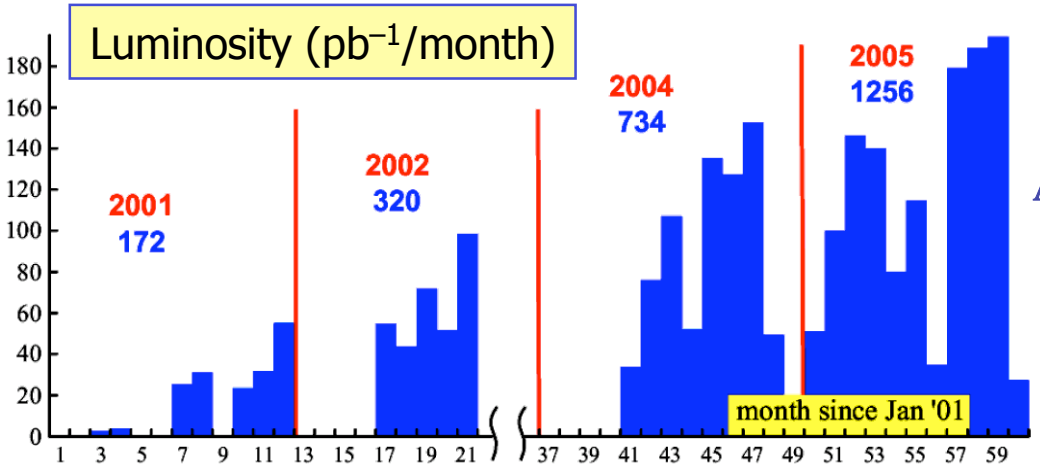
$\tau \to l\nu\nu$: $r_{\mu e} = 1.000(4)$ (Rev.Mod.Phys. 78 (2006) 1043)

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

KLOE K_{e2} analysis: decays at rest

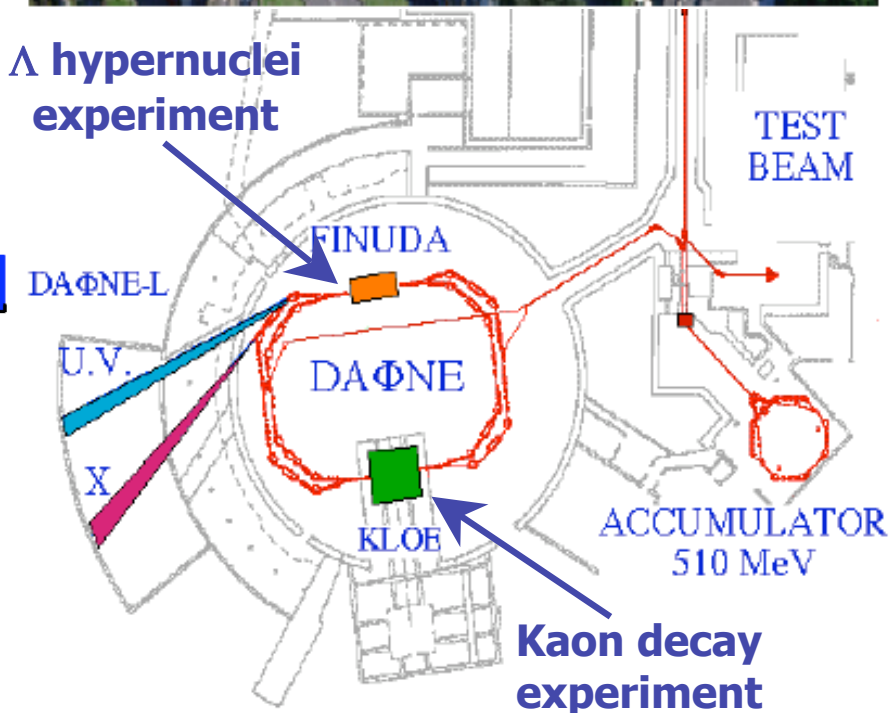
DAΦNE: an e^+e^- collider at LNF Frascati

- 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}.

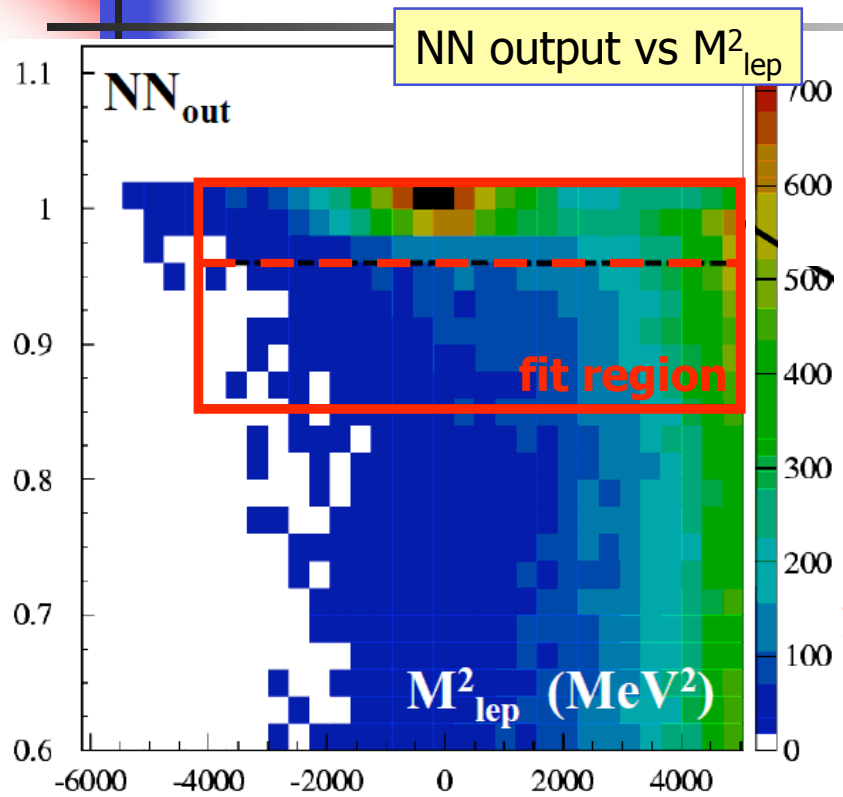


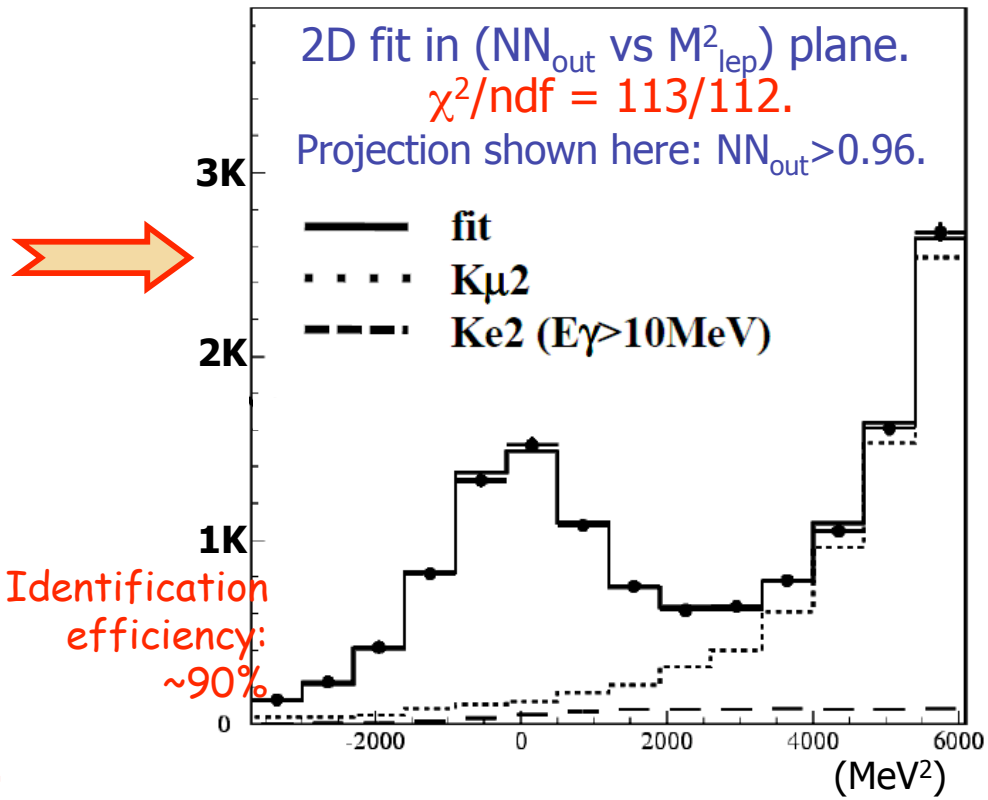
$K_{e2}/K_{\mu 2}$ selection technique (vs NA62):

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



KLOE K_{e2} sample





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

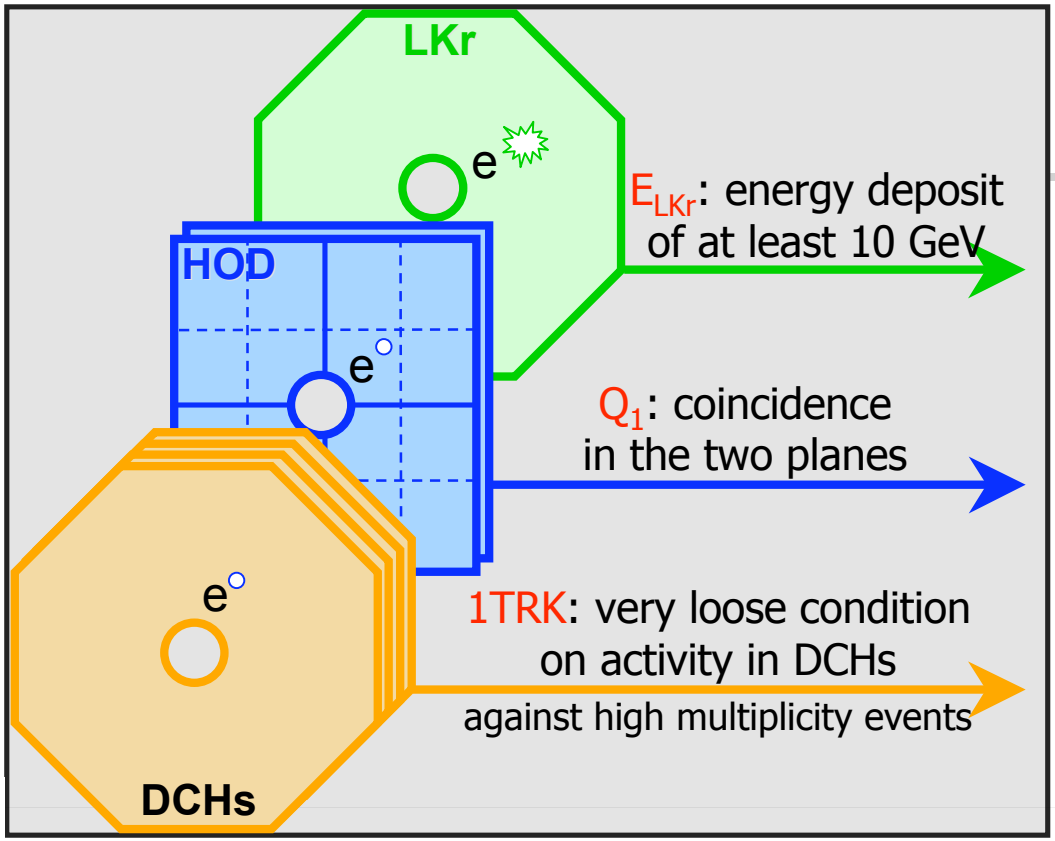
Data taking:

- 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 ⇒ 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];
  $\sigma_x=\sigma_y=4.2\text{mm}/E^{1/2} + 0.6\text{mm}$ (1.5mm@10GeV).

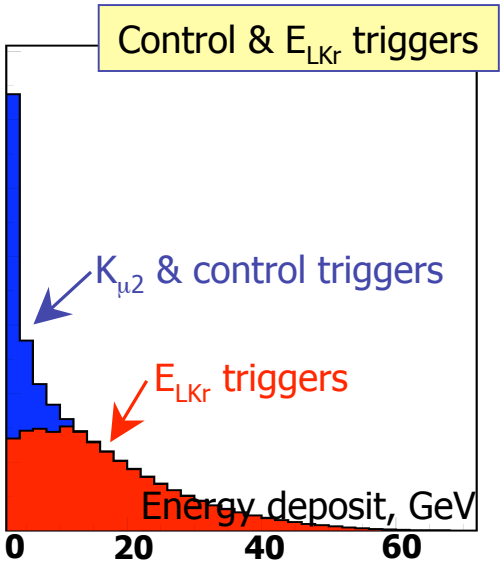
Trigger logic

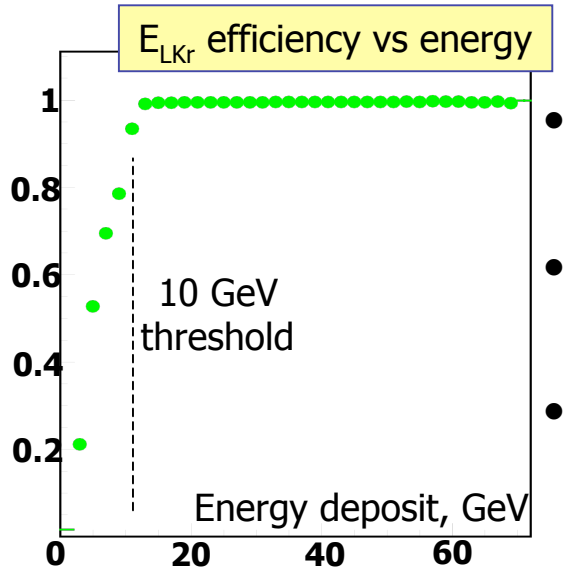


Minimum bias
(high efficiency, but low purity)
trigger configuration used

K_{e2} condition: $Q_1 \times E_{LKr} \times 1TRK$.
Purity ~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.
- 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!

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

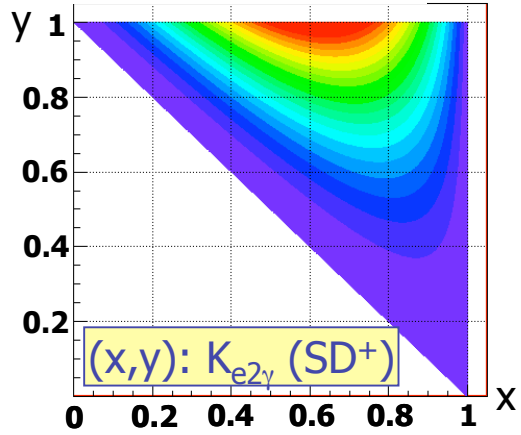
Decay density: $$\frac{d\Gamma(K\to e\nu\gamma)}{dxdy} = \underbrace{\rho_{IB}(x,y)}_{\text{helicity suppressed}} + \rho_{SD}(x,y) + \underbrace{\rho_{INT}(x,y)}_{\text{negligible}}$$

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

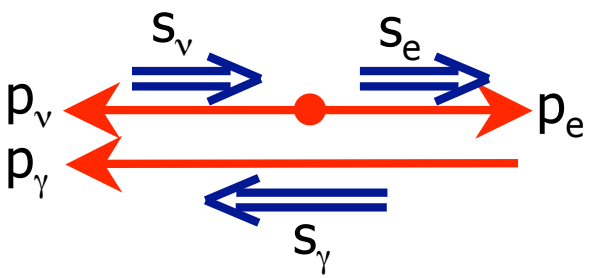
$$\rho_{SD}(x,y) = \frac{G_F^2|V_{us}|^2\alpha}{64\pi^2} M_K^5 \left((f_V+f_A)^2 f_{SD+}(x,y) + (f_V-f_A)^2 f_{SD-}(x,y)\right)$$

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

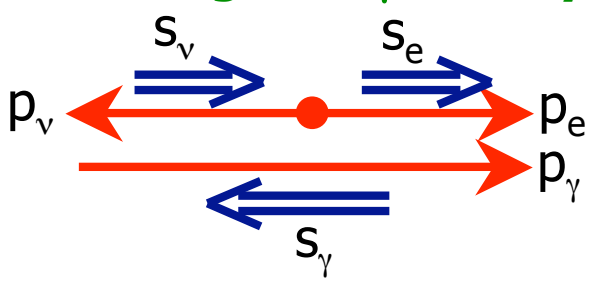
$f_V(x)$, $f_A(x)$: model-dependent effective vector and axial couplings

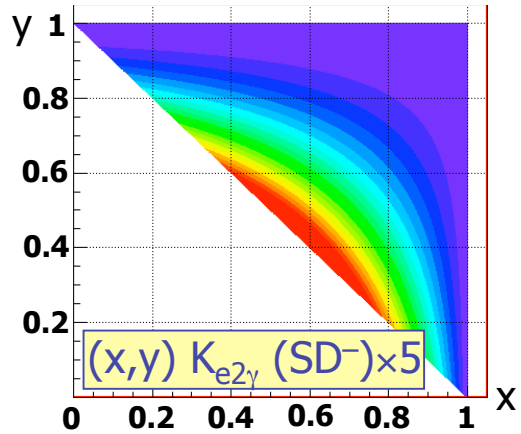


SD^+: positive γ helicity



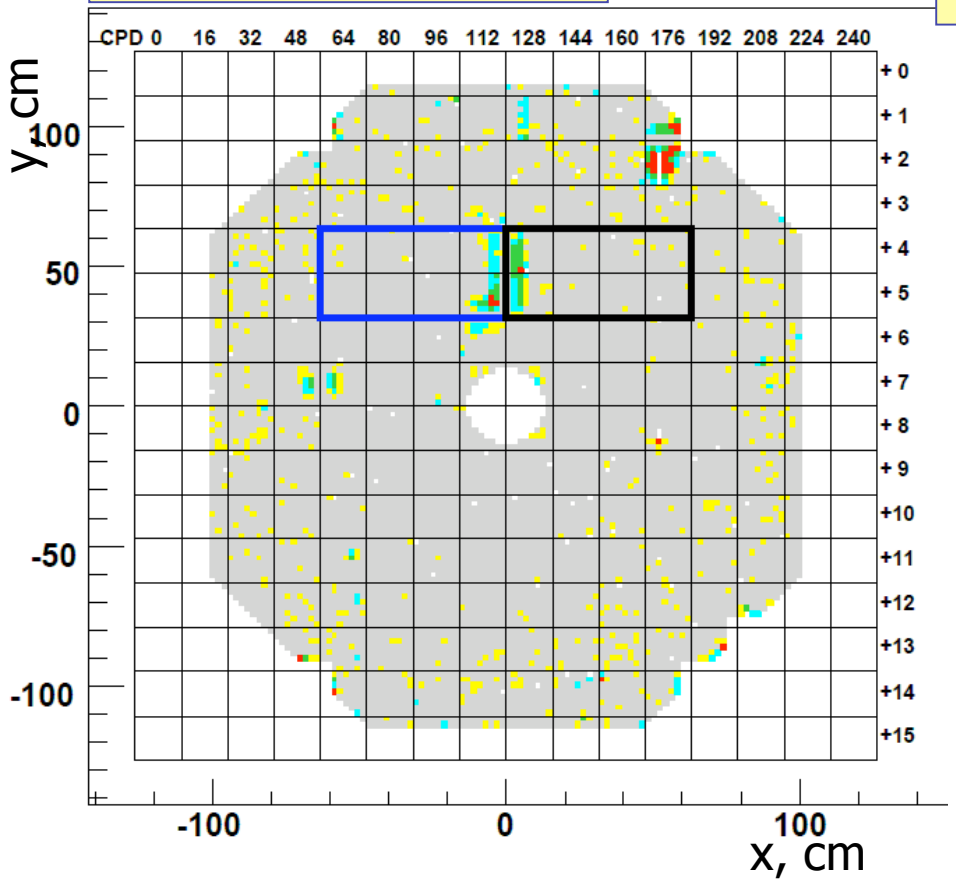
SD^-: negative γ helicity





Systematic effect: positron ID

A typical inefficiency map



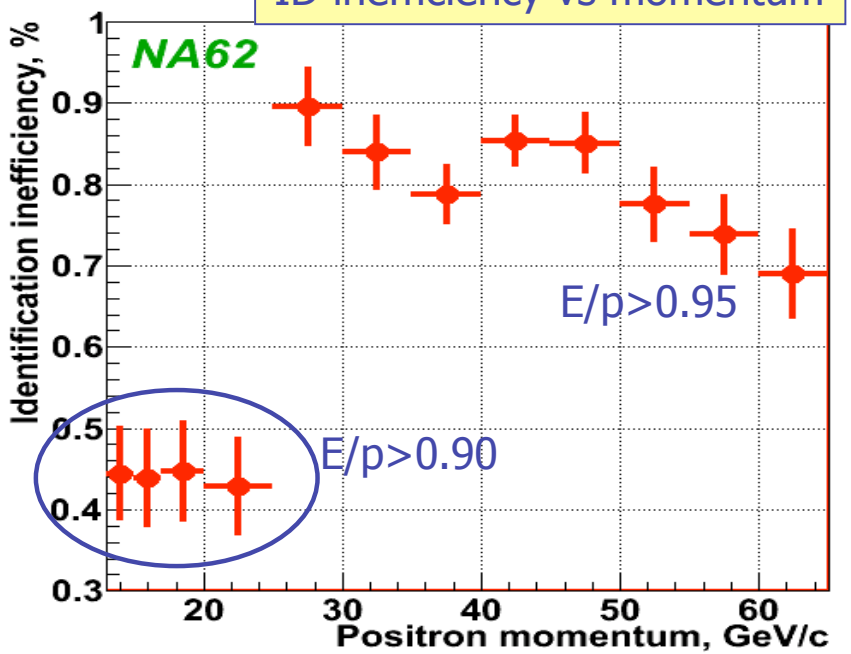
LKr energy response is calibrated for every 2×2cm² cell within acceptance

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 = (99.28±0.05)%

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 (R_K) goal:
dedicated data taking strategy,
51.1K K_{e2} candidates, <9% background,
$\delta R_K/R_K<0.7\%$ (preliminary)

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.