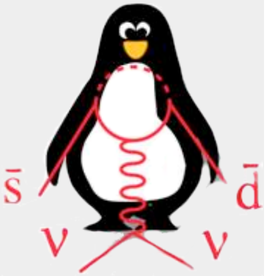
Test of Lepton Flavour Universality in Kaon Decays at CERN NA62 experiment



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for the NA62 collaboration

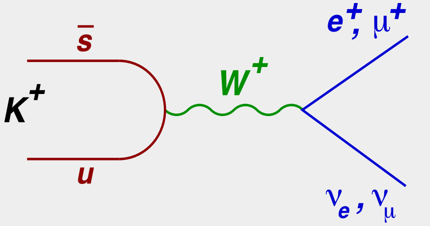
(Bern ITP, Birmingham, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, IHEP Protvino, INR Moscow, Liverpool, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin)

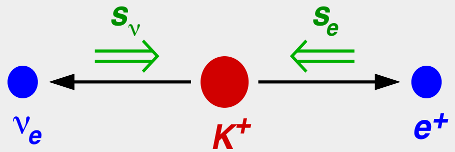
IFAE 2011

Perugia (Italy), 27th – 29th April 2011

R_K in the SM

- Ideal test of SM
- Hadronic uncertainties cancel in the ratio $R_K = K_{e2}/K_{\mu 2}$
- Helicity suppression: ~ 10^{-5}





RK SM expectation:

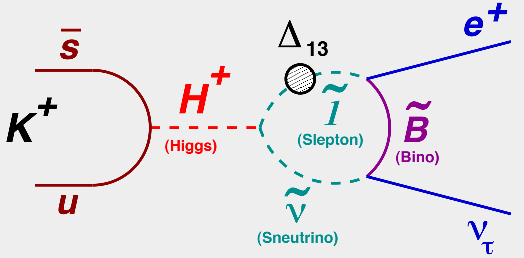
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)}$$

$$R_K = \underbrace{\frac{m_e^2}{m_\mu^2}}_{\text{Helicity suppression}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{(1 + \delta R_K^{rad.corr.})}_{\text{Radiative correction (few\%)}}$$

[V.Cirigliano, I.Rosell JHEP 0710:005 (2007)]

R_K beyond SM

- Indirect search of NP
- MSSM scenario: LFV terms (charged Higgs coupling) introduces extra contributions to the SM amplitude
- Up to 1% variation



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

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

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

Phys. Lett. 99 (2007) 231801

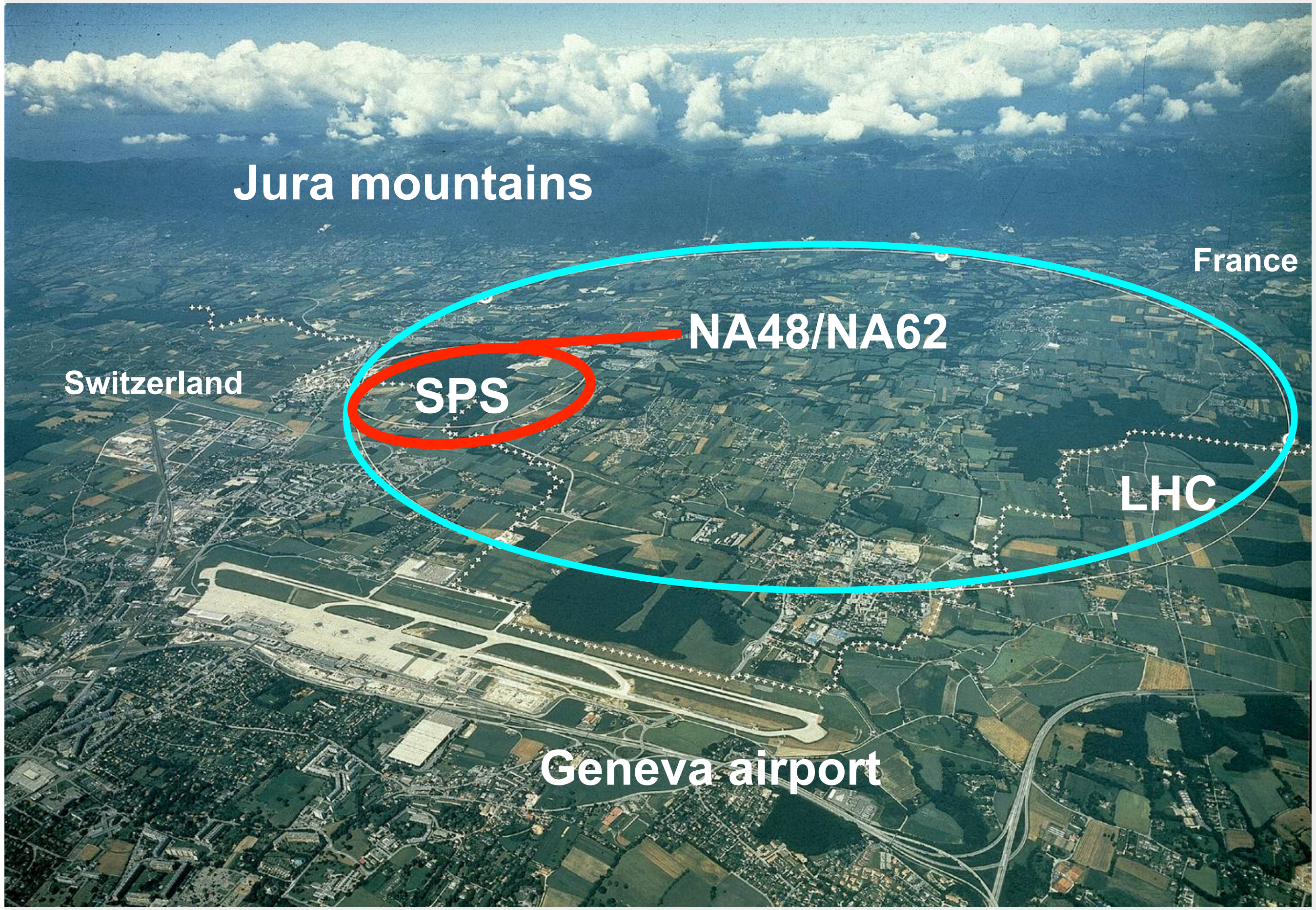
Experimental status:

- PDG'08 average (1970s measurements): -> $R_K = (2.45 \pm 0.11) \times 10^{-5}$ ($\delta R_K/R_K = 4.5\%$)
- Recent improvement KLOE (Frascati): -> $R_K = (2.493 \pm 0.031) \times 10^{-5}$ ($\delta R_K/R_K = 1.3\%$)

(EPJ C64 (2009) 627)

NA62 (phase I) goal: measurement of R_K with accuracy level below 1% (~0.5%)

CERN NA48/NA62



Experiment	Year	Data	
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)	2007–2013	design & construction	
	2014–2016	$K^+\rightarrow\pi^+\nu\bar{\nu}$ 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
K^+ decaying in vacuum tank: 18%

Data Taking and Detector

- Four months in 2007:

  ~ 400K SPS spills, 300TB of raw data
- Two weeks in 2008:

  special data sets allowing reduction of the systematic uncertainties.
- Beam composition: $K^+(\pi^+) = 5\%(63\%)$

Principal subdetectors for R_K:

- Magnetic spectrometer (4 DCHs):

  4 views/DCH ⇒ high efficiency;

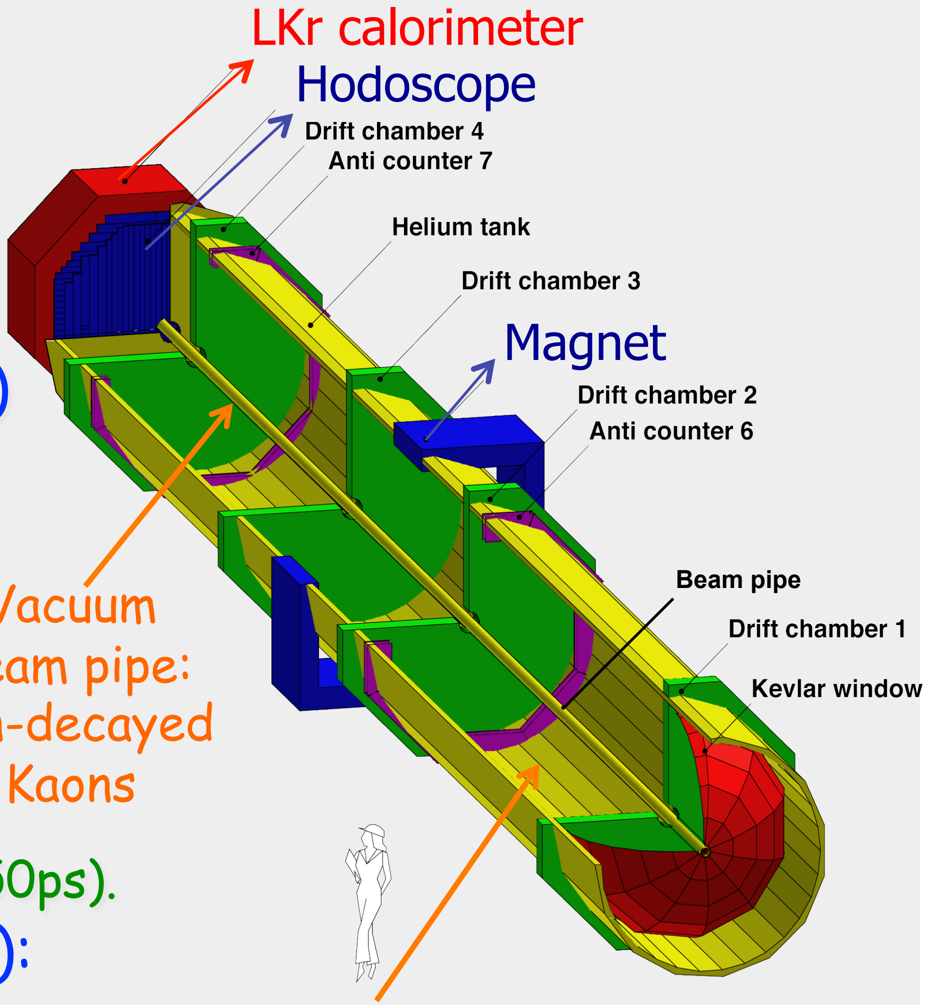
  $\sigma_p/p = 0.47\% + 0.020\% \cdot p$ [GeV/c]
- Hodoscope:

  fast trigger, precise time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr):

  High granularity, quasi-homogeneous;

  $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]

  $\sigma_x=\sigma_y=0.42/E^{1/2} + 0.6$mm (1.5mm@10GeV).



Vacuum beam pipe: non-decayed Kaons

Helium filled tank

Decay volume is upstream

Measurement strategy

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

- analysis does not rely on kaon flux measurement;
- several systematic effects cancel in the ratio (at first order);

(2) MC simulations used to a limited extent:

- Geometrical part of the acceptance correction;
- Correction for bkg from catastrophic energy loss of muons in the LKr;

(3) PID, trigger, readout efficiencies are measured directly from data.

Analysis in 10 bins of reconstructed lepton momentum:

(owing to strong momentum dependence of backgrounds and event topology)

Signal events · *Particle ID eff* · *Trigger efficiency*

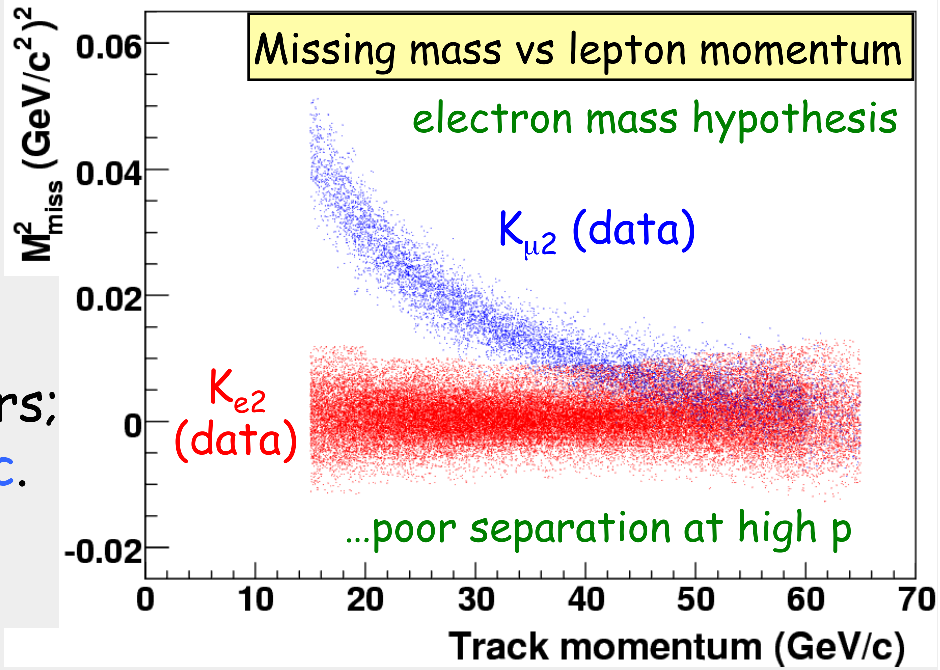
$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \cdot \frac{f_\mu \cdot A(K_{\mu2}) \cdot \varepsilon(K_{\mu2})}{f_e \cdot A(K_{e2}) \cdot \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKR}}$$

$K_{\mu2}$ downscaling · *Background events* · *Geometrical acceptance* · *Global LKr readout eff*

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

<u>**Large common part**</u> (topological similarity)

- one reconstructed track;
- geometrical acceptance cuts;
- K decay vertex: closest distance of approach between track & kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: 13GeV/c < p < 65GeV/c.



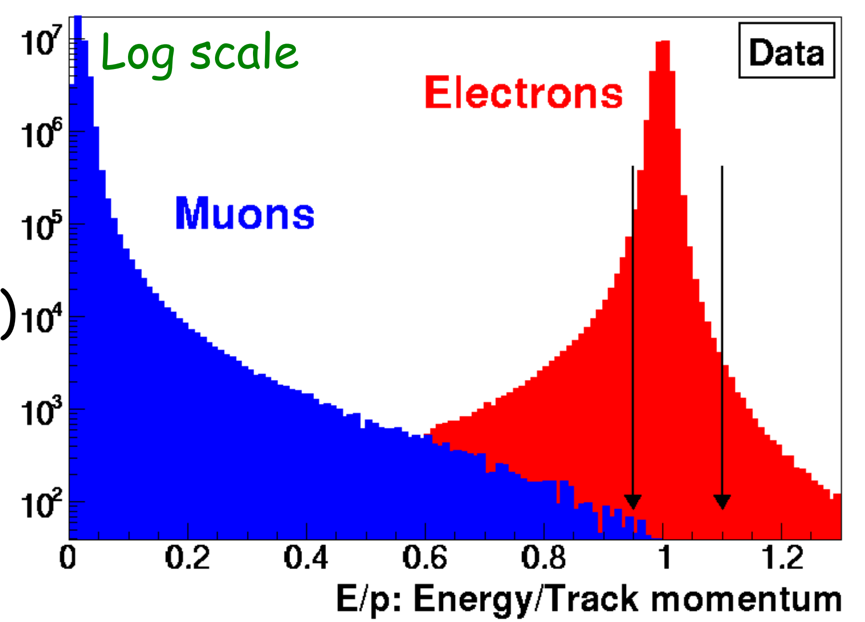
Kinematic identification

- 2 body decay $M^2_{miss} = (P_K - P_l)^2$
(kaon momentum measured with $K_{3\pi}$ decays)
- sufficient $K_{e2}/K_{\mu 2}$ separation up to 25GeV/c

Particle Identification

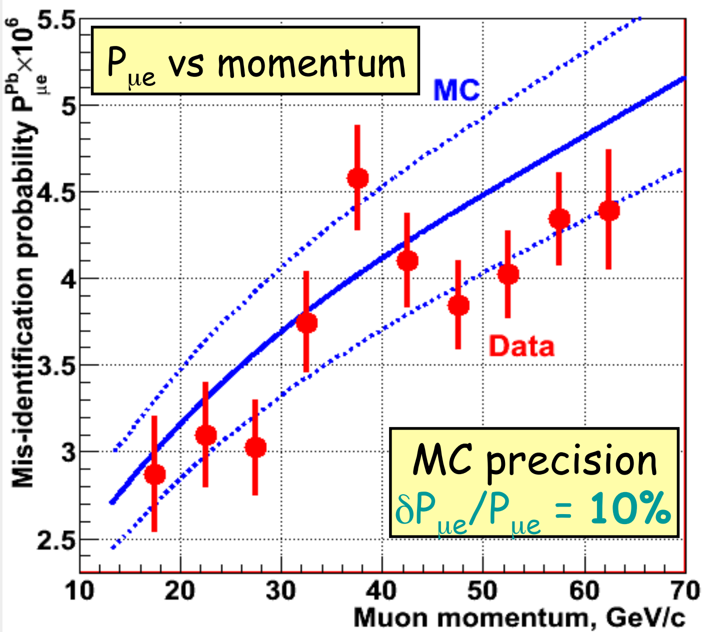
- E/p = (LKr energy deposit/track momentum)
- (0.9 to 0.95) < E/p < 1.10 for electrons
- E/p < 0.85 for muons

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



$K_{\mu2}$ background in K_{e2} sample

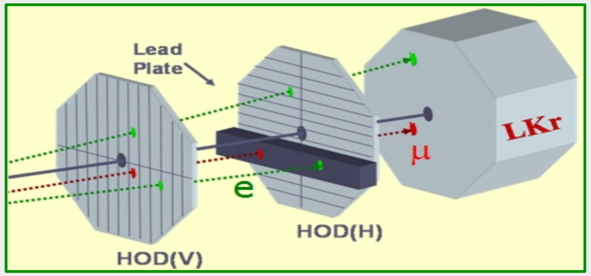
- **The main background in the K_{e2} sample** is due to catastrophic energy loss of muons in the LKr ($E_{LKr}/p_{DCH} > 0.95$ -> misID events as K_{e2})



- **To measure directly P(μ->e)** a "lead wall" (~9.2 X_0) has been installed on ~18% LKr surface for ~50% of the run time:

$P(\mu\text{->}e) \sim (3\div5)\cdot10^{-6}$

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

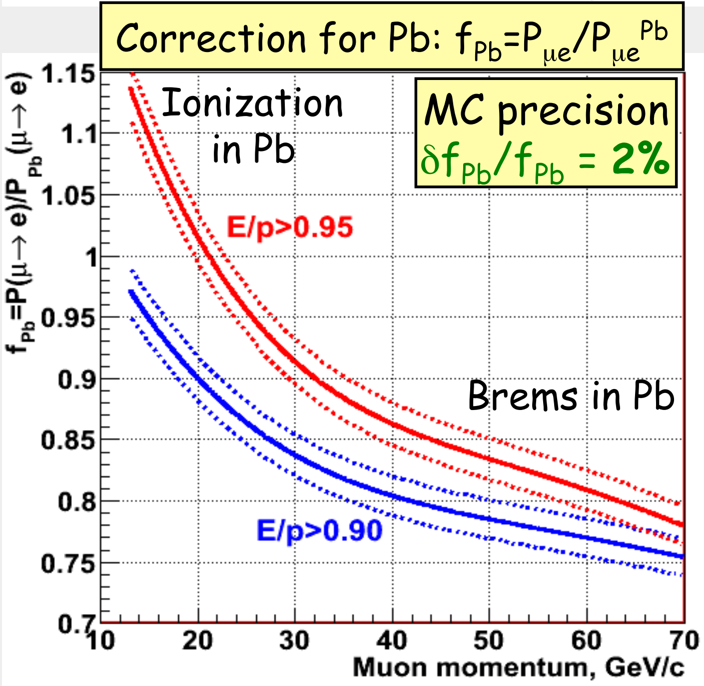


- $K_{\mu2}$ candidates, track traversing Pb, p>30GeV/c, E/p>0.95: electron contamination $<10^{-8}$.
- The result agrees with Geant4 simulation. (p dependence)
- P(μ->e) is modified by the Pb wall: the correction f_{Pb} is evaluated with a dedicated Geant4-based simulatio

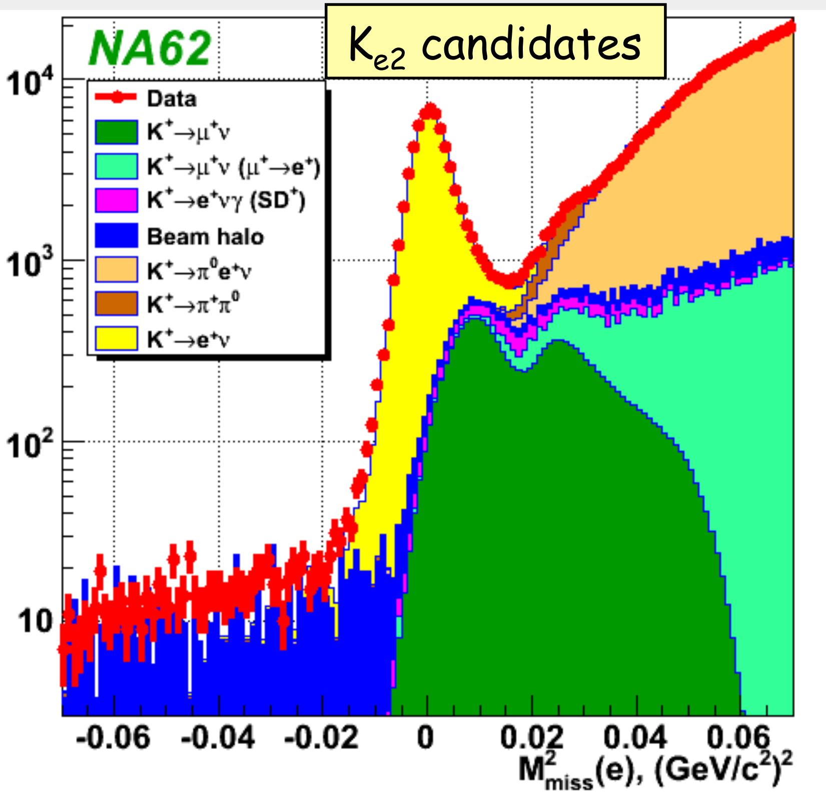
Result: B/(S+B) = (6.11±0.22)%

Uncertainty ~3 times smaller than using only simulation

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



Partial (40%) data set



K_{e2} candidates

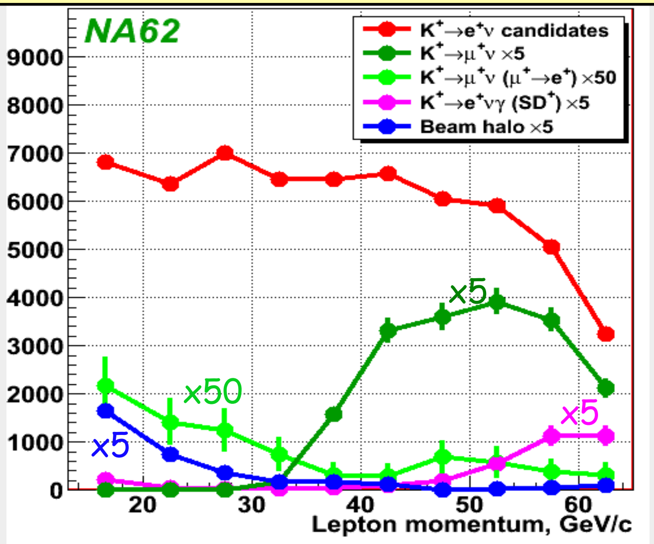
59,813 $K^+ \to e^+\nu$ candidates.
Positron ID efficiency: (99.27±0.05)%.
$B/(S+B) = (8.71\pm0.24)\%$.

NA62 estimated total K_{e2} sample:
~146k candidates (11% bkg)

K_{e2} background sources:

- $K_{\mu2}$ (CB) (6.11±0.22)%
- $K_{\mu2}$ (m->e) (0.27±0.04)%
  - measured with MC
- Beam halo (1.16±0.06)%
  - directly measured on data (special runs)
- $K_{e2\gamma}$ (DE$^+$) (1.07±0.05)%
  - limited by the error on the measured BR (Ongoing NA62 measurement -> 2% precision)
- $K_{2\pi D}$ (0.05±0.03)%
- K_{e3D} (0.05±0.03)%

K_{e2} candidates and backgrounds in momentum bins

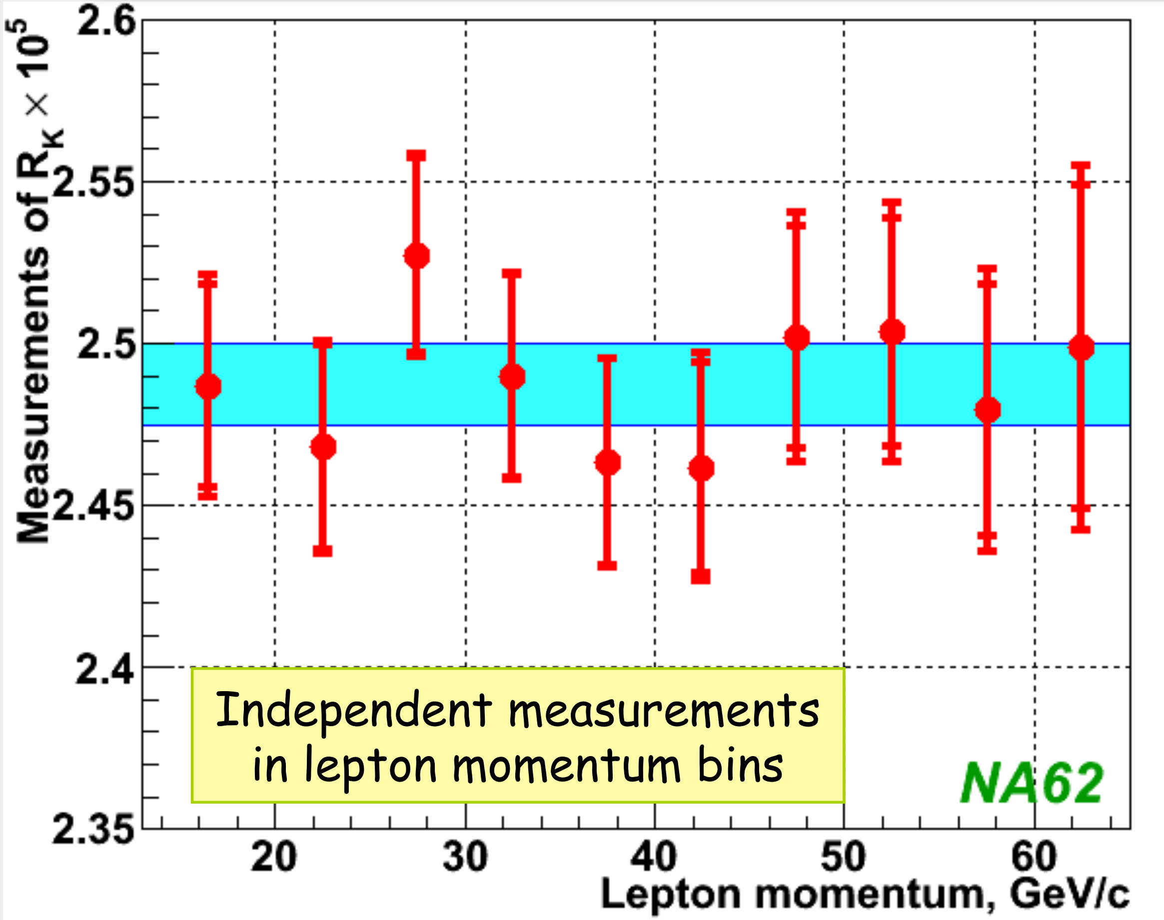


(selection criteria specifically tuned in each bin)

NA62 Result (40% data set)

$$R_K = (2.487 \pm 0.011_{stat} \pm 0.007_{syst}) \times 10^{-5}$$
$$= (2.487 \pm 0.013) \times 10^{-5}$$

Recently published:
PLB B698 (2011) 105



Independent measurements in lepton momentum bins

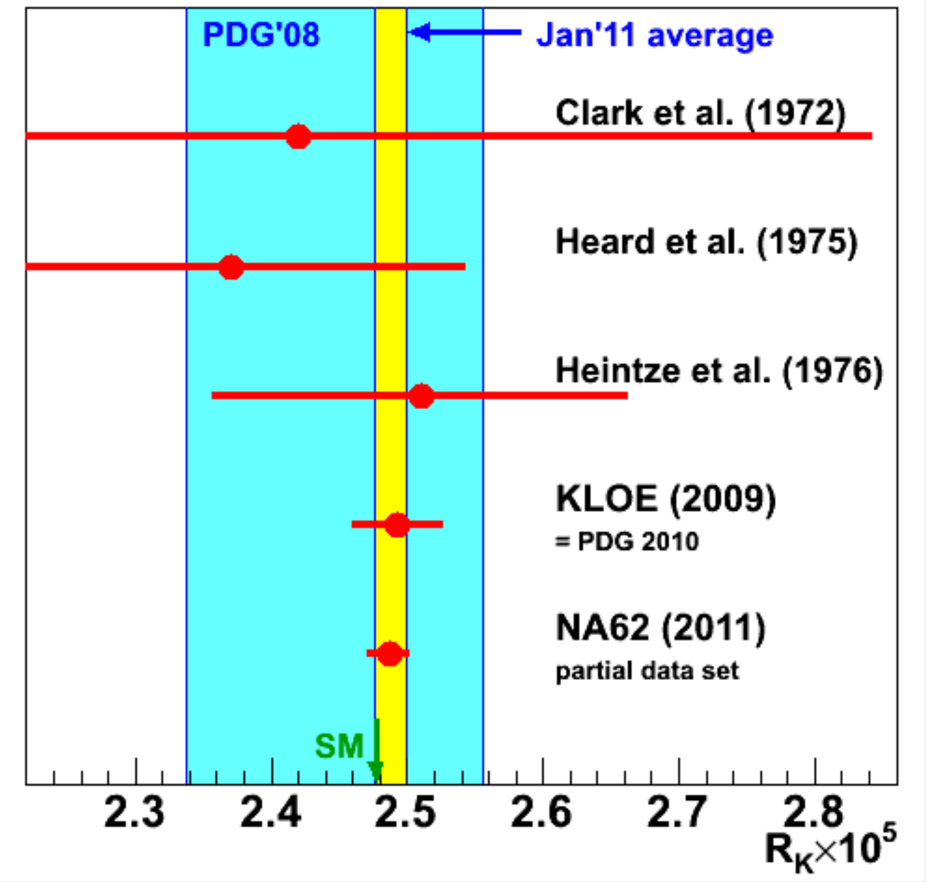
(systematic errors included, partially correlated)

Uncertainties

Source	$\delta R_K \times 10^5$
Statistical	0.011
$K_{\mu2}$	0.005
$BR(K_{e2\gamma}\ SD^+)$	0.001
Helium purity	0.003
Beam halo	0.001
Acceptance	0.002
DCH alignment	0.001
Positron ID	0.001
Lkr readout inef	0.001
1-track trigger	0.002
Total	0.013

(0.5% precision)

R_K: world average

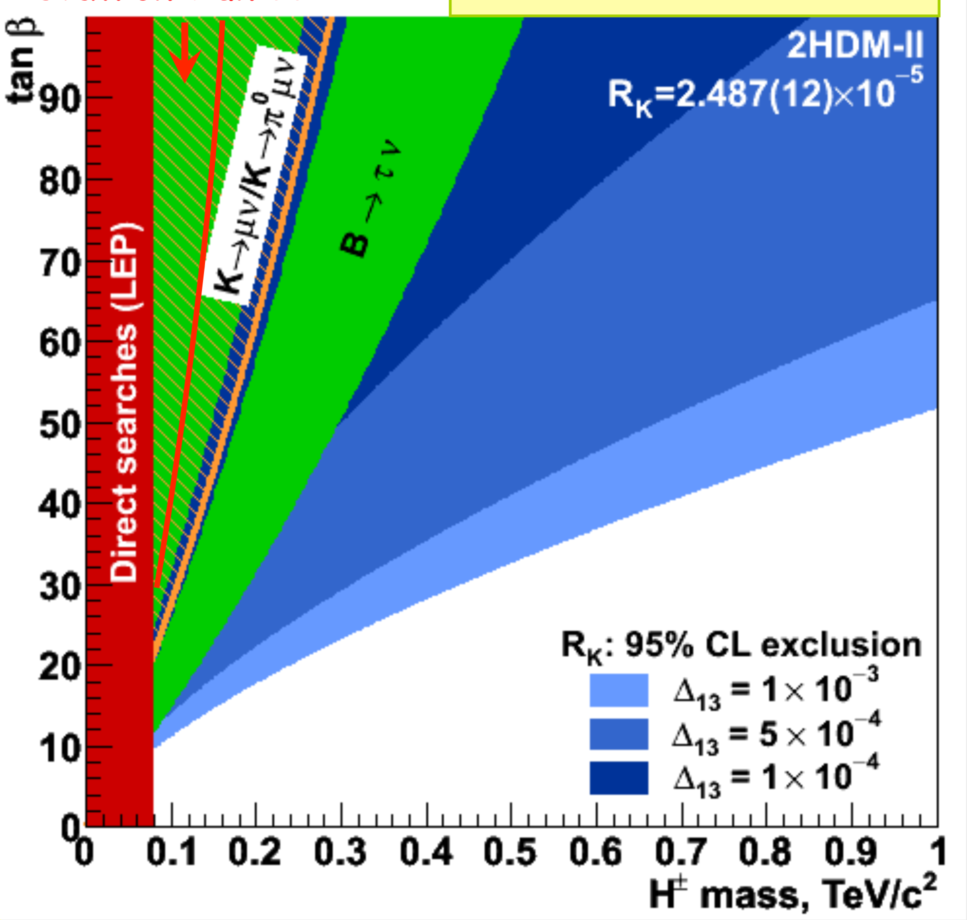


World average	$\delta R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
January 2011	2.487±0.012	0.48%

R_K measurements are currently in agreement with the SM expectation at ~1σ.

(M_H, tanβ)
95% exclusion limits

Tevatron Run II



Any significant enhancement with respect to the SM would be evidence of new physics.

Conclusions & Future Prospects

- 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.

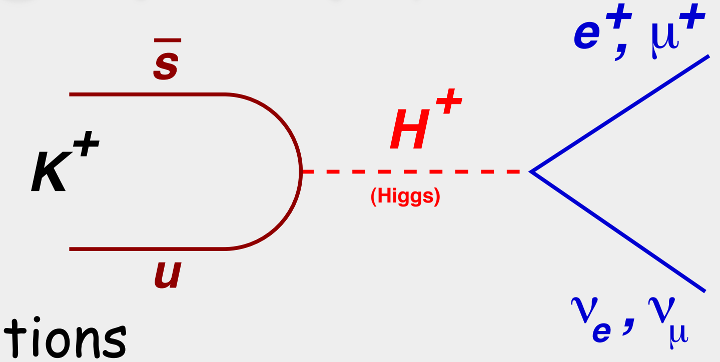
- Preliminary result based on ~40% of the NA62 K_{e2} sample: $R_K = (2.487 \pm 0.013)\times10^{-5}$, reaching a new level of accuracy of ~0.5%.

- With the full 2007/2008 NA62 data sample, the precision is expected to improve to a level $\delta R_K/R_K=0.4\%$.

- One of the NA62 (phase-II, see V.Palladino's talk) goals will be to improve the precision on the R_K measurement by a factor of ~2.

Spares

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. Barlow, CKM 2010, arXiv:1102.1267)

BaBar, Belle:	$Br_{exp}(B\to\tau\nu)=(1.64\pm0.34)\times10^{-4}$
Standard Model:	$Br_{SM}(B\to\tau\nu)=(1.20\pm0.25)\times10^{-4}$

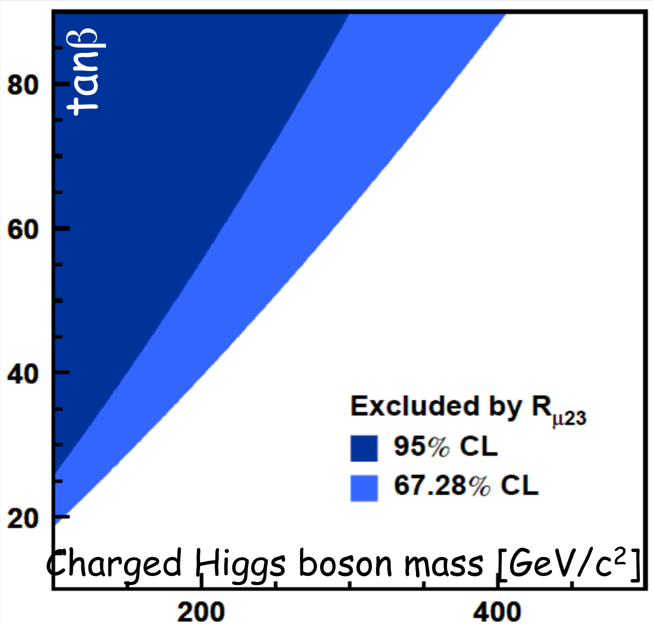
(SM uncertainties: $\delta f_B/f_B$=10%, $\delta|V_{ub}|^2/|V_{ub}|^2$=13%)

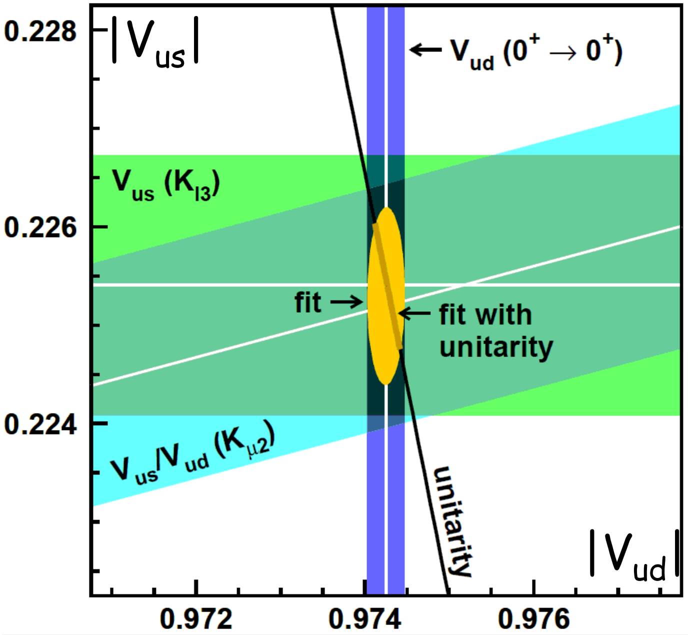
~3σ discrepancy between Bτν measurement and expectation froma global CKM fit

[UTfit, CKMfitter, ICHEP2010]

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:

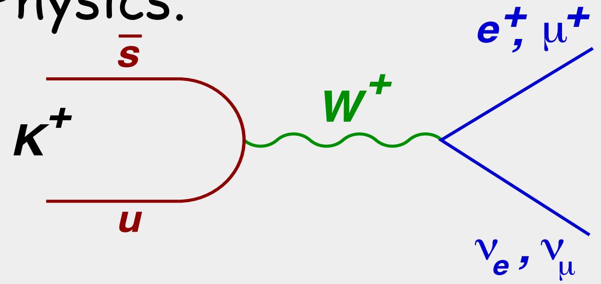
$$R_{\mu23} \approx \left| 1 - \frac{m^2_{K^+}}{m^2_{H^+}} \frac{\tan^2\beta}{1+\epsilon_0\tan\beta} \right|$$

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

(Flavianet Kaon WG, arXiv:1005.2323)

R_K in the SM

A precise measurement of the ratio of $K \to l\nu_l$ leptonic decays provides an ideal test of SM and indirect search for New Physics.

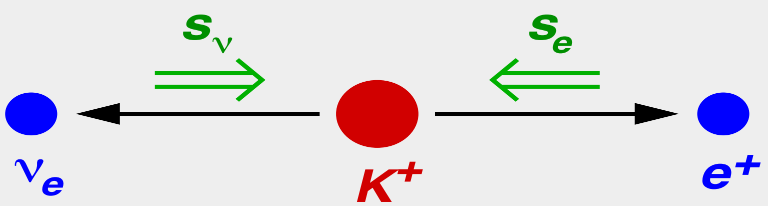


- Hadronic uncertainties cancel in the ratio $K_{e2}/K_{\mu2}$
- SM prediction: excellent sub-permille accuracy

R_K is sensitive to lepton flavour violation and its SM expectation:

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

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



Radiative correction (few %) due to $K^+ \to e^+\nu\gamma$ (IB) process, by definition included into R_K
[V.Cirigliano, I.Rosell JHEP 0710:005 (2007)]

Recently understood: helicity suppression of R_K might enhance sensitivity to non-SM effects to an experimentally accessible level.

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

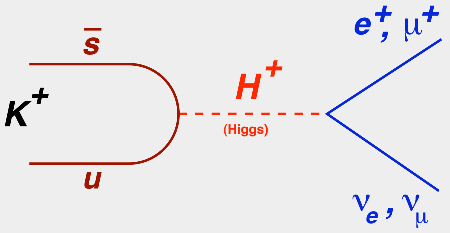
Phys. Lett. 99 (2007) 231801

R_K beyond the SM

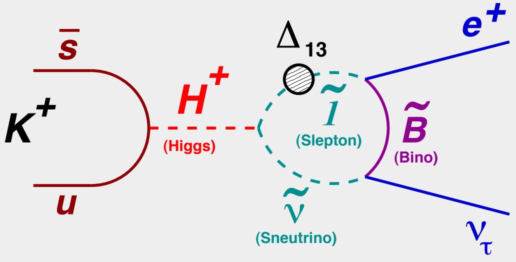
In the MSSM large tan β scenario, the presence of LFV terms (charged Higgs coupling) introduces extra contributions to the SM amplitude, enhancing the decay rate.

$$R_K^{LFV} = \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma_{LFV}(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$

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



Tree level



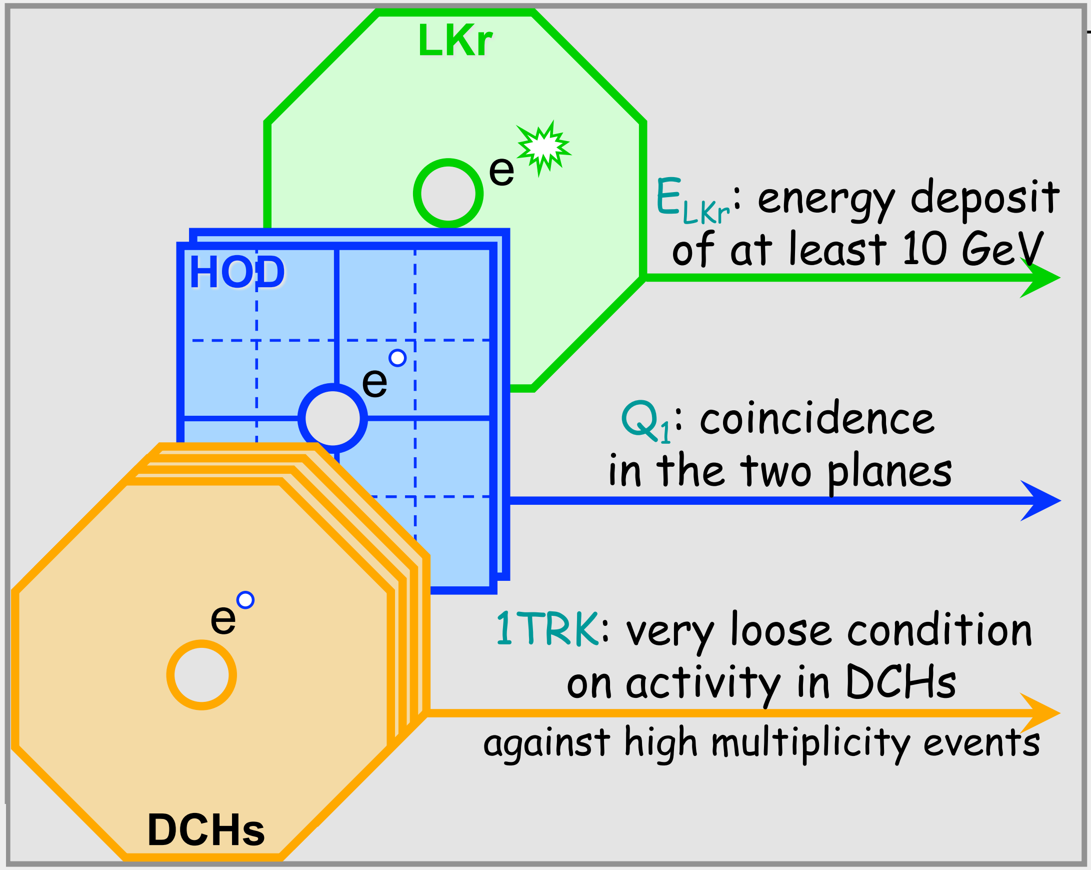
One-loop level

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

Up to 1% variation is predicted for reasonable SUSY parameters:

m_H = 500 GeV , $|\Delta_{13}| = 5\cdot10^{-4}$, tan β = 40 -> $R_K^{LVF} \cong R_K^{SM}(1 + 0.013)$

Trigger Logic



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

Q_1: coincidence in the two planes

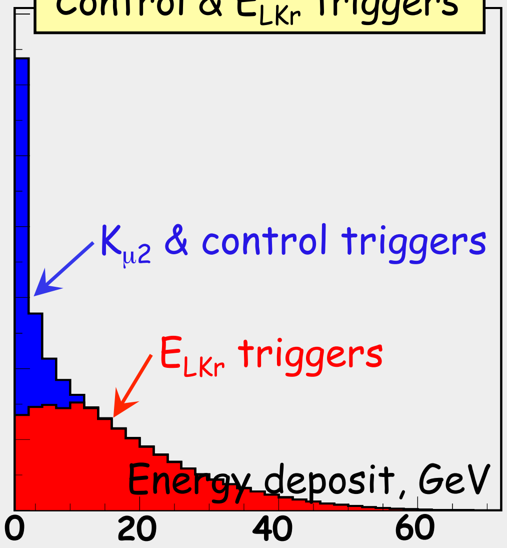
1TRK: very loose condition on activity in DCHs against high multiplicity events

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

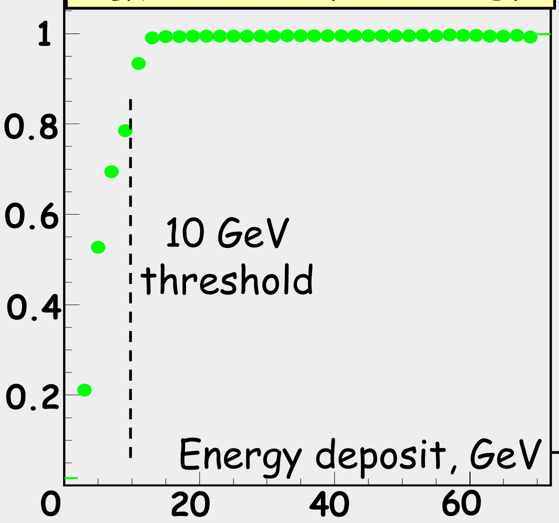
K_{e2} condition: $Q_1 \times E_{LKr} \times 1TRK$.
Purity $\sim 10^{-5}$.

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

Control & E_{LKr} triggers



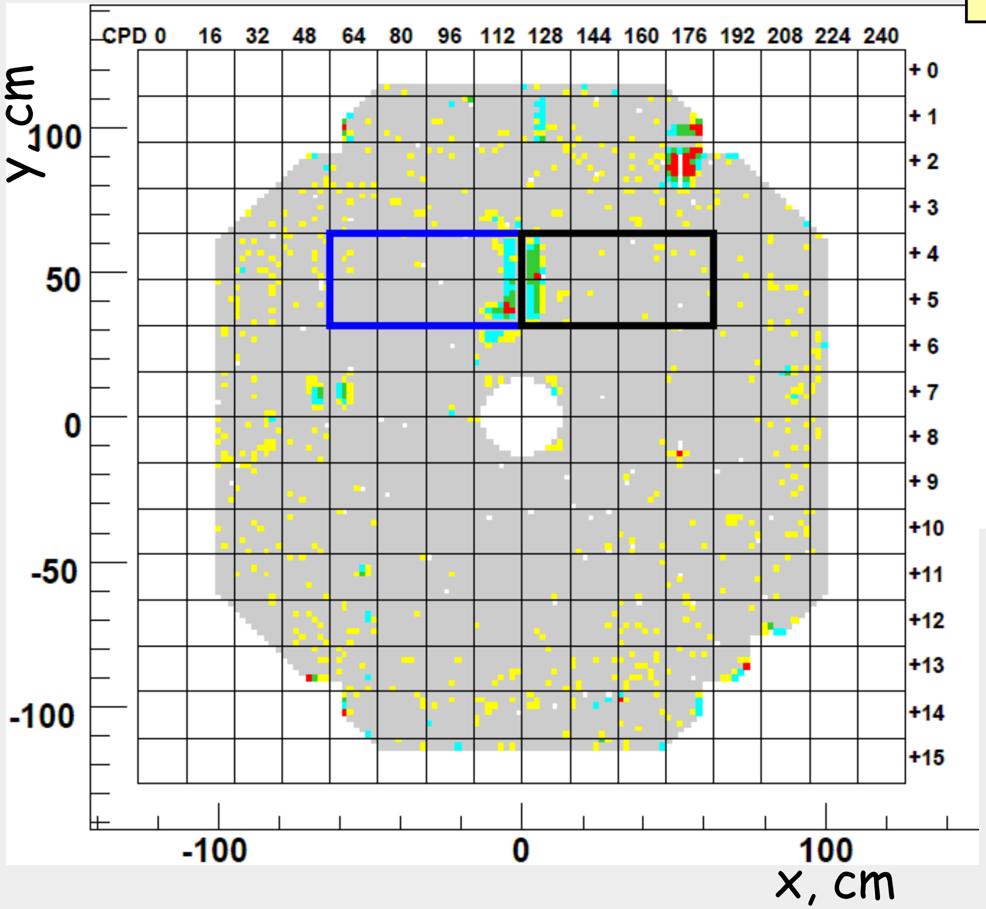
E_{LKr} efficiency vs energy



- 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!

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)%**

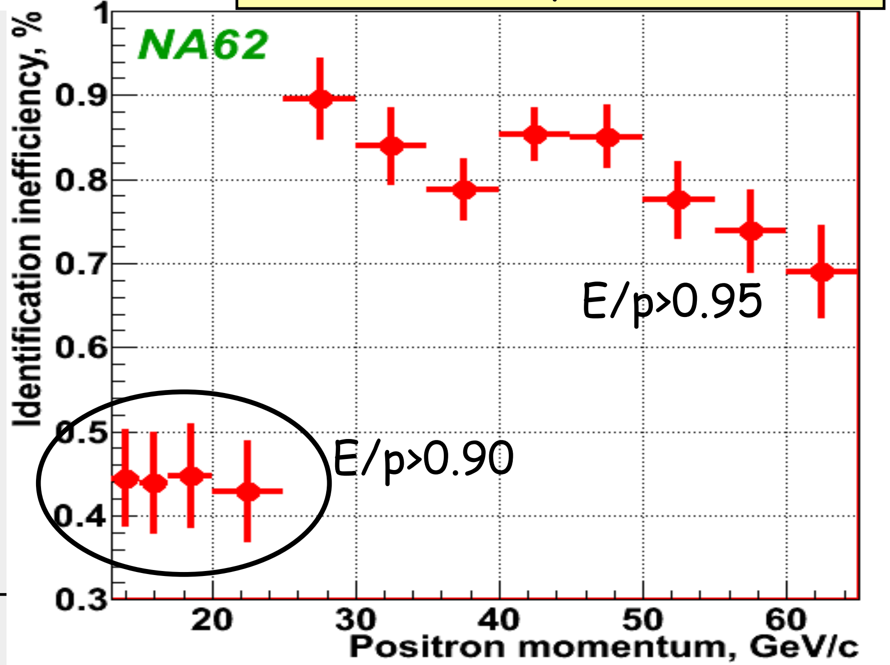
🟦 **Ineff = (2.0-4.0)%**

🟩 **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)%

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

Decay density:

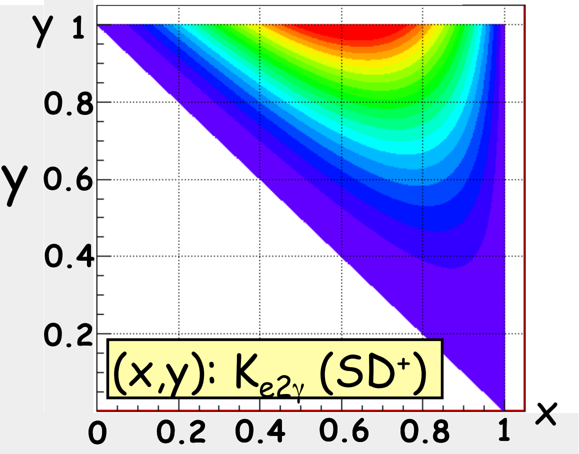
$$\frac{d\Gamma(K\to e\nu\gamma)}{dxdy} = \underbrace{\rho_{IB}(x,y)}_{\text{helicity suppressed}} + \rho_{SD}(x,y) + \underbrace{\rho_{INT}(x,y)}_{\text{negligible}}$$

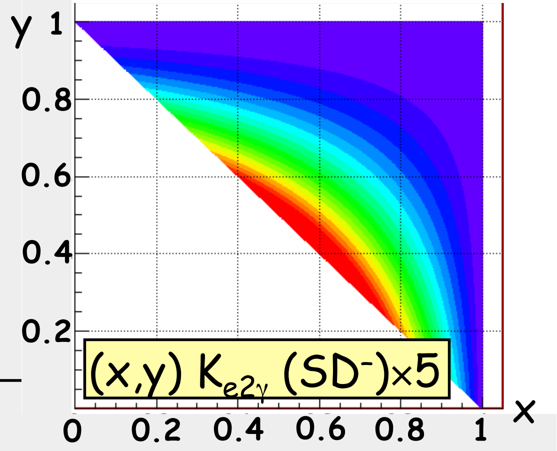
Kinematic variables (kaon frame): $x = 2E_\gamma/M_K, \quad y = 2E_e/M_K$

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

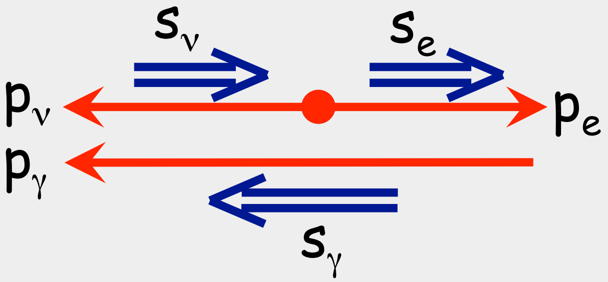
Two non-interfering contributions SD^+ and SD^-: emission of photons with positive and negative helicity

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

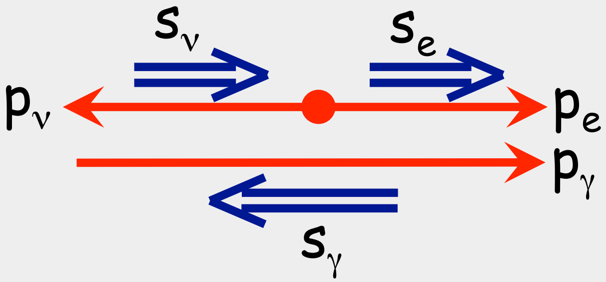




SD⁺: positive γ helicity

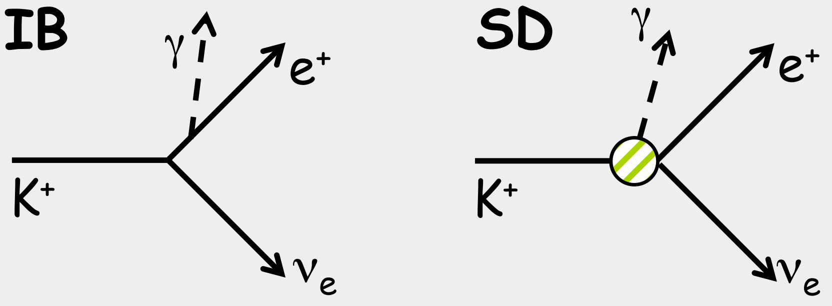


SD⁻: negative γ helicity



Radiative $K^+ \rightarrow e^+ \nu \gamma$ background in K_{e2} sample

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

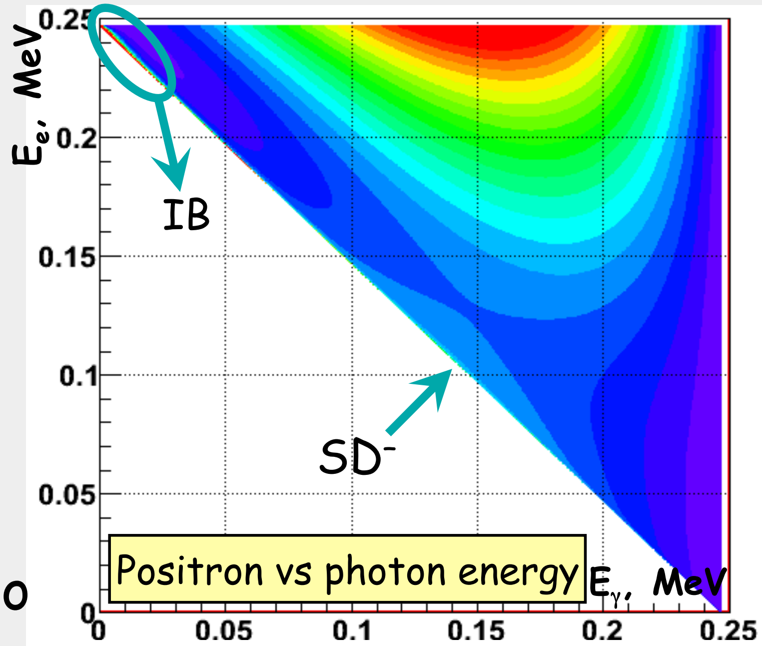


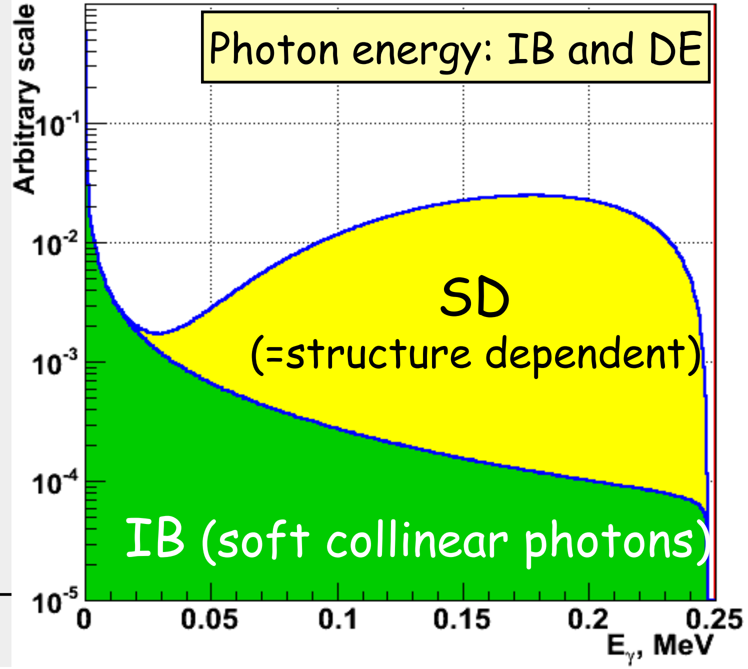
SD radiation is not helicity suppressed.
KLOE measurement of the form factor leads to
BR(SD^+, full phase space) = $(1.37 \pm 0.06) \times 10^{-5}$.
(EPJC64 (2009) 627)

SD background contamination

$$\boxed{B/(S+B) = (1.07 \pm 0.05)\%}$$

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





$K_{\mu2}$ with $\mu \to e$ decay in flight

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

$N(K_{\mu2}, \mu \to e \text{ decay})/N(K_{e2}) \sim 10$

$K_{\mu2}$ ($\mu \to e$) naïvely seems a huge background

Muons from $K_{\mu2}$ decay are fully polarized:
Michel electron distribution

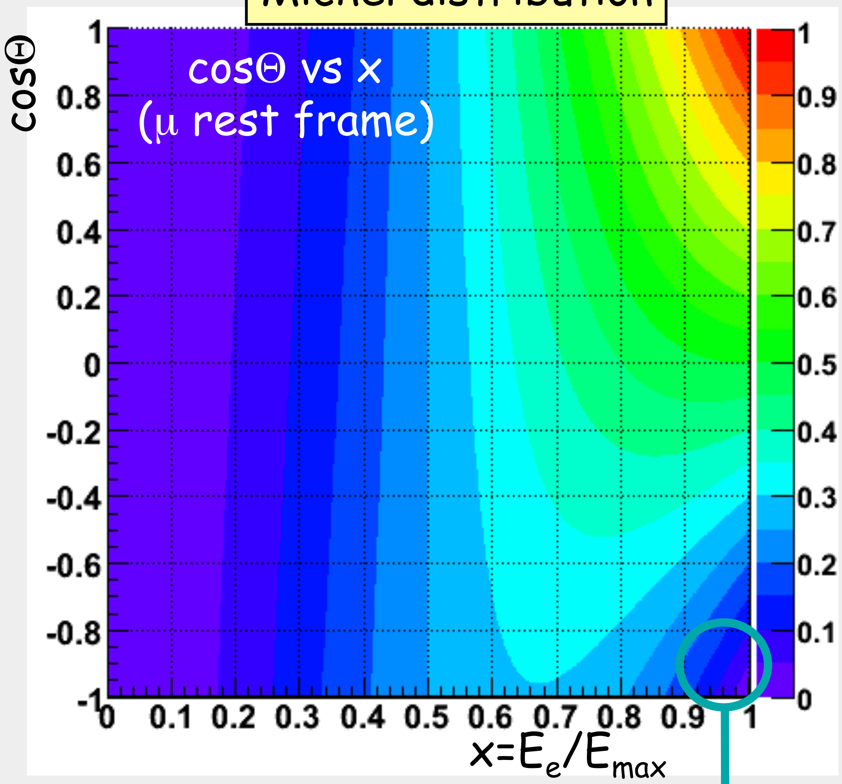
$$d^2\Gamma/dx\,d(\cos\Theta) \sim x^2[(3-2x) - \cos\Theta(1-2x)]$$

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

Beam halo background

Electrons produced by beam halo muons via μ→e decay can be kinematically and geometrically compatible to genuine K_{e2} decays

Background measurement:

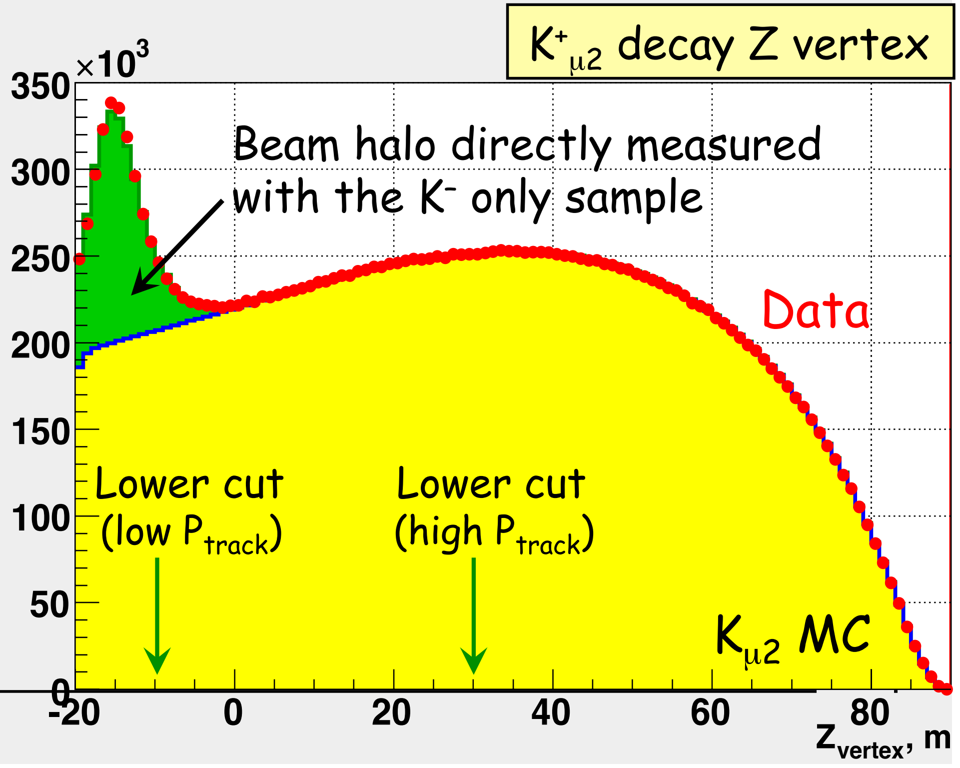
- Halo background much higher for K_{e2}^- (~20%) than for K_{e2}^+ (~1%).
- Halo background in the $K_{\mu2}$ sample is considerably lower.
- ~80% of the data sample is K^+ only, ~20% is K^- only.
- K^+ halo component is measured directly with the K^- sample and vice versa.

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

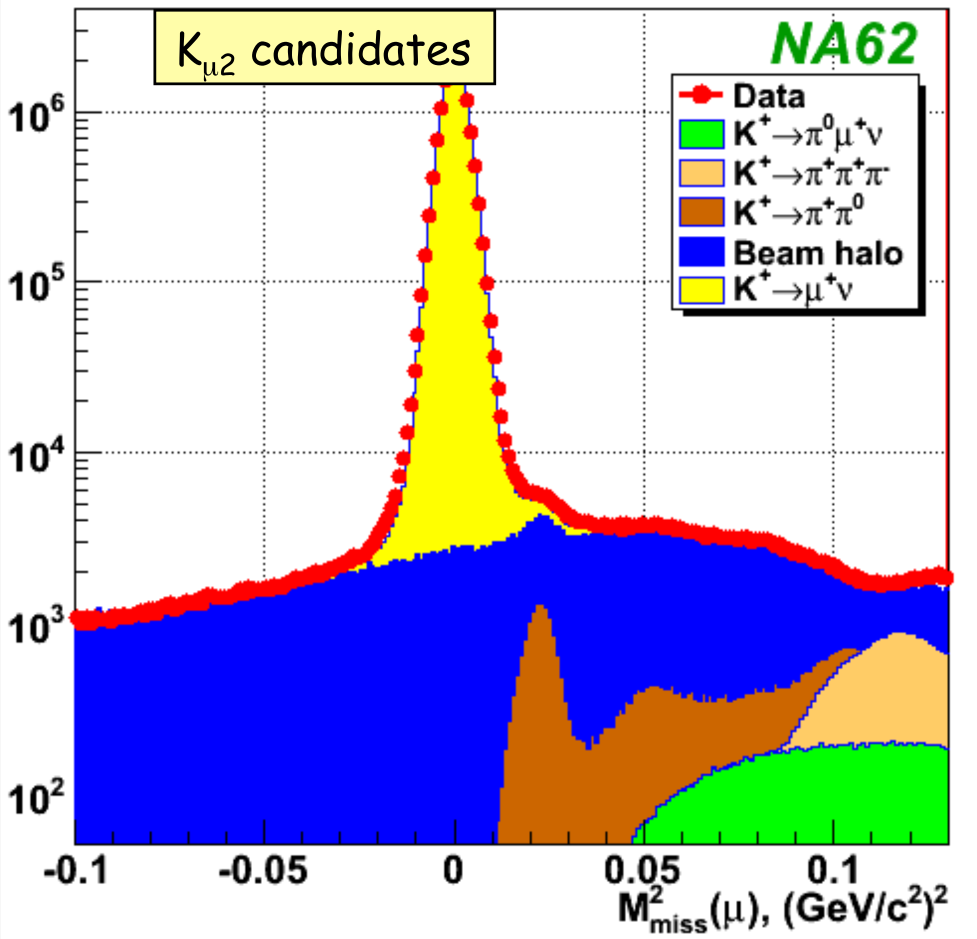
The selection criteria (esp. Z_{vertex}) are optimized to minimize the halo background.

$B/(S+B) = (1.16\pm0.06)\%$

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



Partial (40%) data set



18.03 M candidates
with low background
B/(S+B) = (0.38±0.01)%

$K_{\mu 2}$ background source:

- Beam halo (0.38±0.01)%

Future prospects-II

Future NA62 (phase II - data taking in 2013–2015):
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 spectrometer (beam tracker plus beam Cherenkov) will allow time correlation between incoming kaons and decay products (improved PID).
Expect beam halo background to be reduced to negligible level.

Only the $K_{\mu 2}$ ($\mu \rightarrow e$) background will remain: well known ~0.3% contamination.
Expected total uncertainty <0.2%.

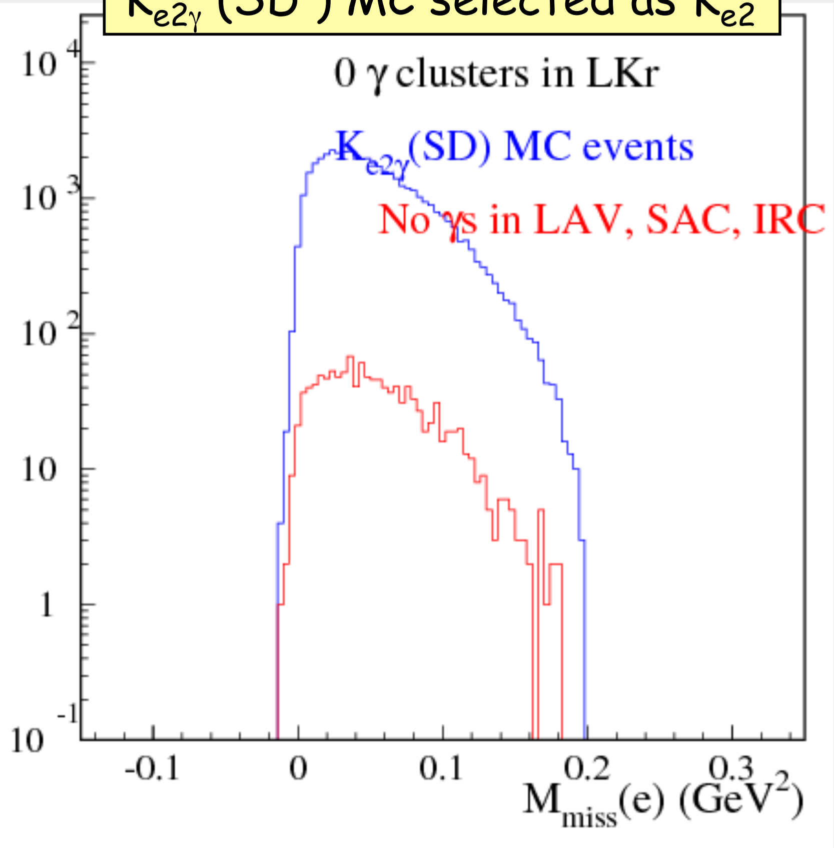
Assuming an analysis at low lepton momentum and not using electron ID, measurement of R_K with 0.1-0.2% relative precision is feasible.

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

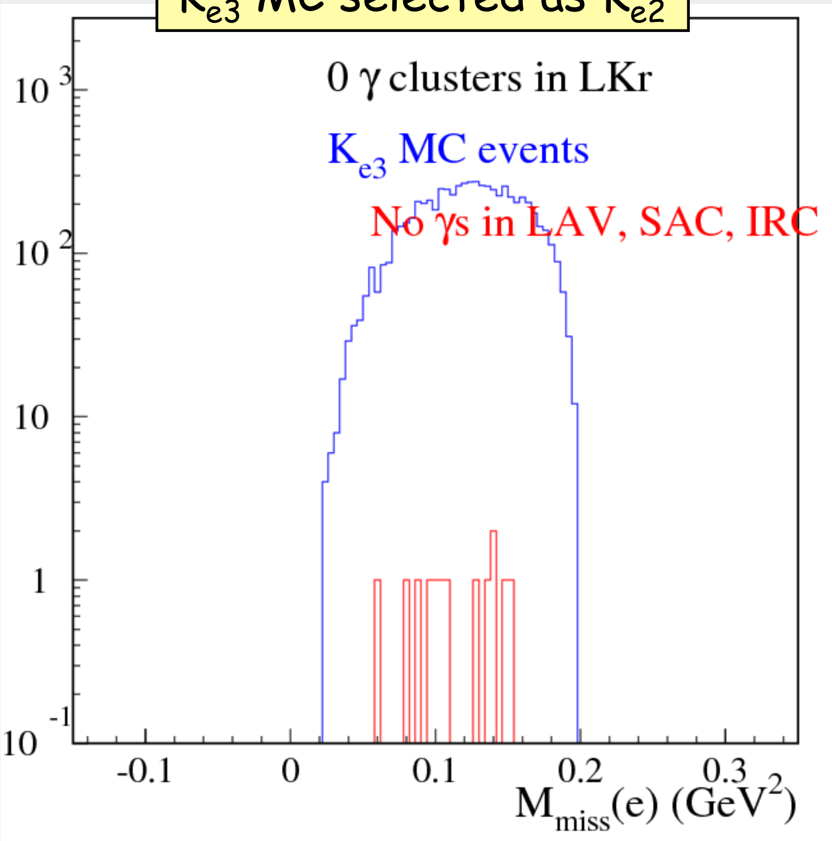
K_{e2} trigger ~1 month of data taking sufficient for such R_K measurement.

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

$K_{e2\gamma}$ (SD$^+$) MC selected as K_{e2}



K_{e3} MC selected as K_{e2}



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

K_{e3} sample reduced by a factor of 500

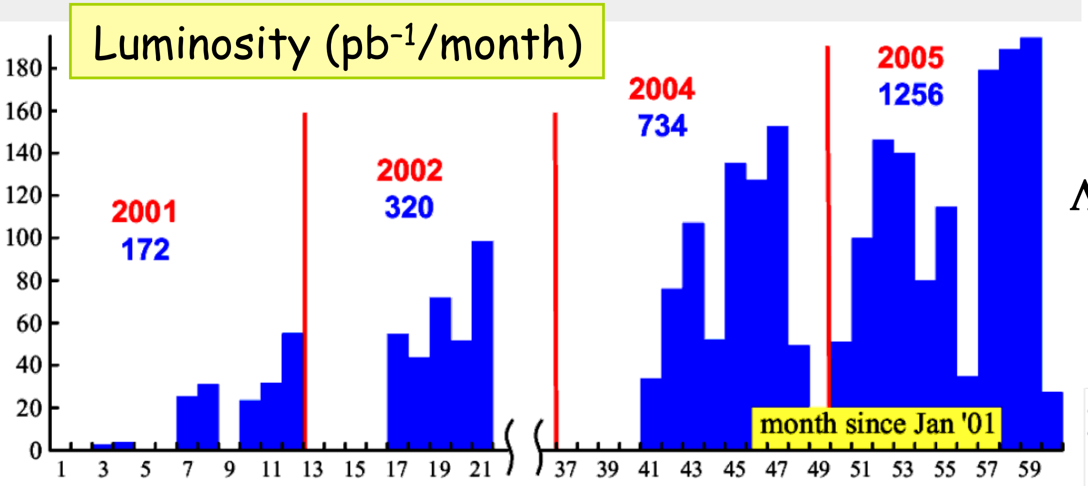
Rejection provided by the new veto detectors is excellent for K_{e2} analysis

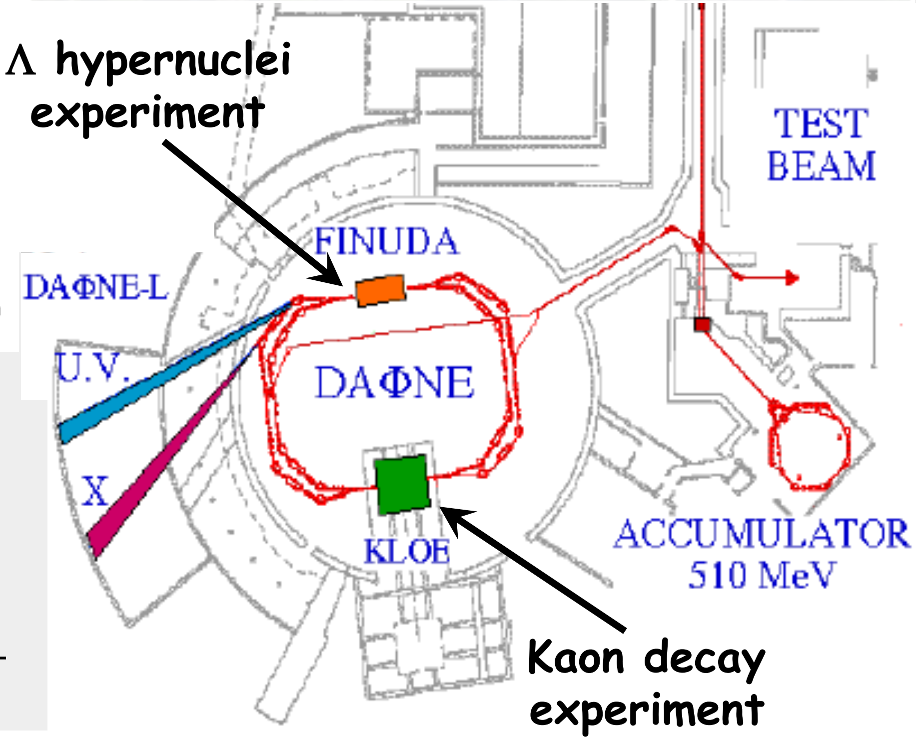
K_{e2} sample untouched by the veto requirement

KLOE K_{e2} analysis: decays at rest

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

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





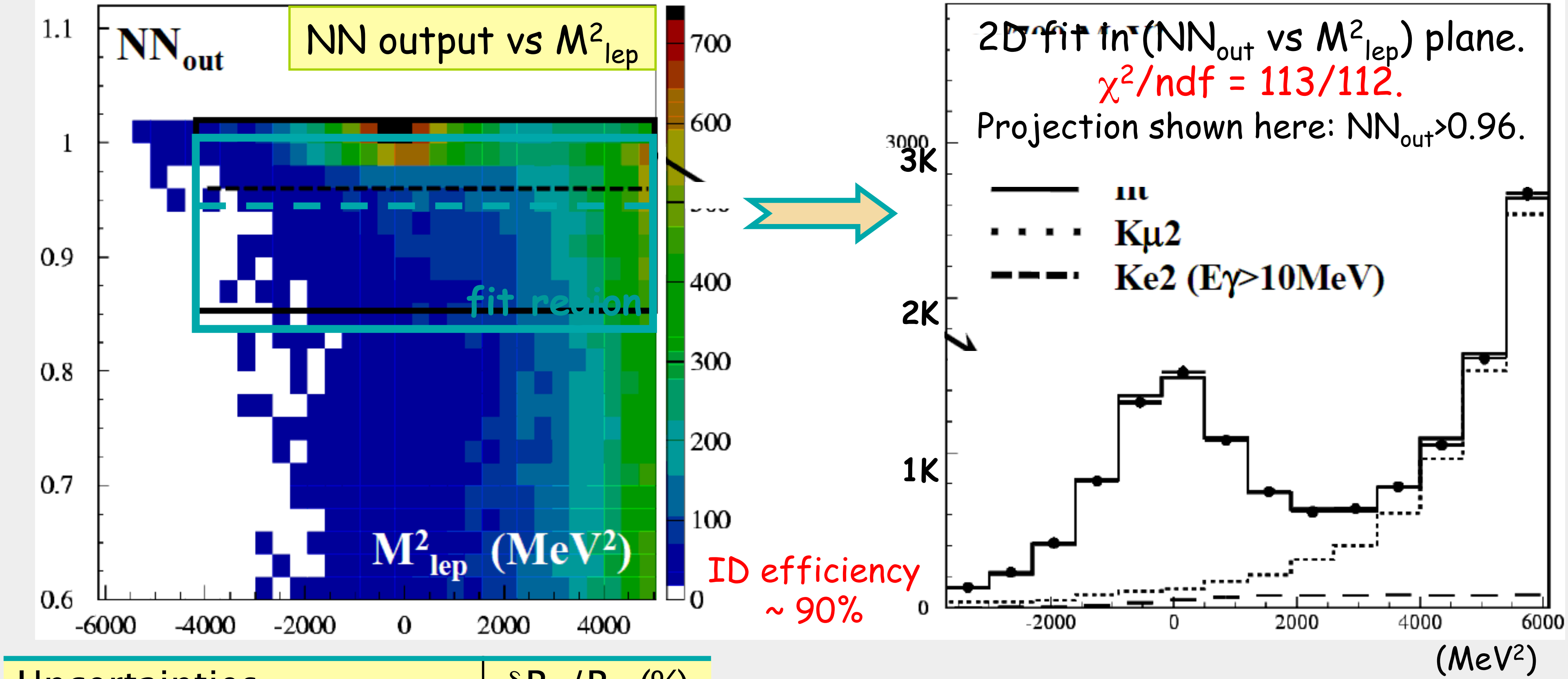
Λ hypernuclei experiment

Kaon decay experiment

$K_{e2}/K_{\mu2}$ 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).

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]