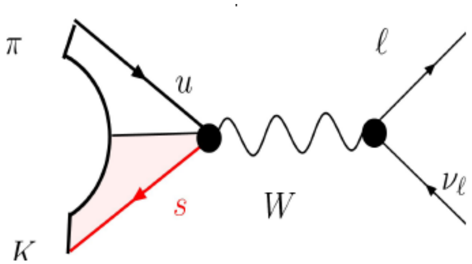
E. De Lucia (LNF-INFN)
for the KLOE Collaboration

Vus and lepton universality with kaons at KLOE

Kaon Physics



$\mathbf{K}_{\ell 3}$: $K \to \pi\, \ell\, \nu$

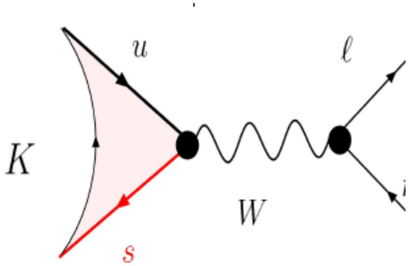
Vector transition: only 2nd order SU(3) breaking [Ademollo-Gatto]

- Precise determination of V_{us}
- Test of Lepton universality Ke3 vs Kμ3
- Most precise test of CKM unitarity

$$|V_{ud}|^2 + |V_{us}|^2 = 1 \qquad |V_{ub}|^2 \text{ negligible}$$

- Lepton-Quark universality of weak int.

$$G_F^2 \equiv G_{CKM}^2 = (|V_{ud}|^2 + |V_{us}|^2) G_F^2$$



$\mathbf{K}_{\ell 2}$: $K \to \ell\, \nu$

Helicity suppressed:
Sensitivity to NP enhanced

- Precise determination of V_{us}/V_{ud}
- Test of Physics beyond the SM
  - right-handed contributions to charged weak currents
  - charged Higgs exchange (2 Higgs doublet scenarios)

} $\Gamma(K_{\mu 2})/\Gamma(\pi_{\mu 2})$

- Lepton Flavor Violation test with $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$

Kaon physics (II)

❖ Set bounds on New Physics from Lepton-Quark Universality

New Physics extensions of the SM can break gauge universality in the form of tree or loop level contributions to muon decays and/or semileptonic processes.

i. *Exotic Muon Decays* would contribute to the muon lifetime

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1-\mathbf{BR(exotic\ muon\ decays)}$$

Provides best limit on $\mathbf{BR}(\mu^+\rightarrow e^+\bar{\nu}_e\nu_\mu)$ *better than direct search*

ii. *Additional Z' Gauge Bosons* contributing at loop level to muons and semileptonic decays differently (*Competitive with direct search*) [PRD 35 (1987)]

iii. SUSY particle loops affecting muon and semileptonic decays differently: constraints on *slepton-squark mass difference* (x*2-3 precision needed*) [PRL 75 (1995) , PRL 88 (2002)]

Present accuracy set bounds on the scale of New Physics Λ_{NP} at 1-2 TeV

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1+\varepsilon_{NP} \qquad \varepsilon_{NP}\approx M_W^2/\Lambda_{NP}^2$$

V_{us} from Kl3 rates

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \times I_{Kl}(\{\lambda\}_{Kl}) (1 + 2\Delta_K^{SU(2)} + 2\Delta_{Kl}^{EM})$$

with $K \in \{K^+, K^0\}$; $l \in \{e, \mu\}$, and:

C_K^2 1/2 for K^+, 1 for K^0

Inputs from theory:

- S_{EW} — Universal short distance EW correction (1.0232)
- $f_+^{K^0\pi^-}(0)$ — Hadronic matrix element at zero momentum transfer (t=0)
- $\Delta_K^{SU(2)}$ — Form factor correction for strong SU(2) breaking
- Δ_{Kl}^{EM} — Long distance EM effects

Inputs from experiment:

- $\Gamma(K_{l3(\gamma)})$ — **Branching ratios** with well determined treatment of radiative decays; **lifetimes**
- $I_{Kl}(\lambda)$ — Phase space integral: λs parameterize form factor dependence on t :
  - K_{e3} : only λ_+ (or λ_+' λ_+'')
  - $K_{\mu3}$: need λ_+ and λ_0

KLOE has measured all relevant inputs for charged and neutral kaons: BR's, lifetimes (K_L, K), form factors (FFs)

To extract V_{us} from neutral kaons

PLB 632 (2006)

$BR(K_{e3}) = 0.4008(15)$	**0.37%**	Based on 13×10^{6} K_L decays tagged by $K_S\to\pi^+\pi^-$
$BR(K_{\mu3}) = 0.2699(14)$	**0.52%**	

PLB 626 (2005)

$\tau_L = 50.92(30)$ ns — **0.58%**

Fit the time dependence over $0.4\tau_L$ of 8.5×10^{6} $K_L\to\pi^0\pi^0\pi^0$ decays tagged by $K_S\to\pi^+\pi^-$

(P. de Simone talk)

PLB 636 (2006)

$BR(K_S\to\pi e\nu) = 7.046(91)\times10^{-4}$ — **1.3%**

From tagged K_S beam 1.2×10^{8} events

PLB 636 (2006)

$\lambda'_+\times10^3$	$\lambda''_+\times10^3$
25.5 ± 1.8	1.4 ± 0.8

Based on 2×10^{6} K_Le3 decays tagged by $K_s\to\pi^+\pi^-$

JHEP12(2007)

$$\lambda_+' = (25.6\pm1.5_{stat}\pm0.9_{syst})\times10^{-3}$$
$$\lambda_+'' = (1.5\pm0.7_{stat}\pm0.4_{syst})\times10^{-3}$$
$$\lambda_0 = (15.4\pm1.8_{stat}\pm1.3_{yst})\times10^{-3}$$

Based on 1.8×10^{6} $K_L\,\mu3$ decays tagged by $K_s\to\pi^+\pi^-$ and from combined fit with K_Le3 data

To extract V_{us} from charged kaons

PLB 632 (2006)

$BR(K^+ \to \mu^+\nu) = 0.6366(17)$ **0.27%**

From 4.2×10^6 $\phi\to K^+K^-$ tagged by $K^-_{\mu2}$ decays

JHEP 01 (2008)

$\tau^{\pm} = 12.347(30)$ **0.24%**

From 15×10^6 $\phi\to K^+K^-$ tagged by $K_{\mu2}$ decays

JHEP 02 (2008)

$BR(K^{\pm} \to \pi^0 e^{\pm}\nu) = 0.04965(53)$ **1%**

$BR(K^{\pm} \to \pi^0 \mu^{\pm}\nu) = 0.03233(39)$ **1.2%**

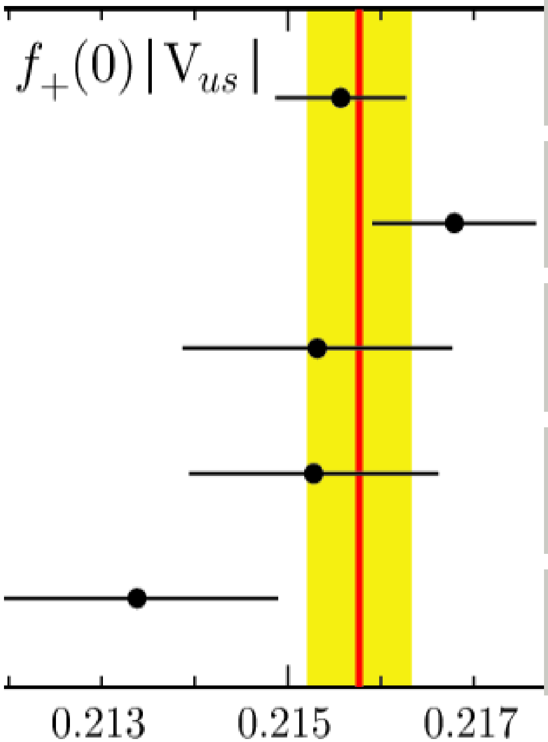
From 6×10^7 $\phi\to K^+K^-$ decays tagged by both $K_{\mu2}$ and $K_{\pi2}$ decays

PLB 666 (2008)

$BR(K^+ \to \pi^+ \pi^0 (\gamma))$ = **0.2065(9)** **0.43%**

From 20×10^6 $\phi\to K^+K^-$ decays tagged by both $K^-_{\mu2}$ and $K^-_{\pi2}$ decays

$|V_{us}| f_+(0)$ at KLOE



		err %
$K_L e3$	0.2155(7)	0.3
$K_L \mu 3$	0.2167(9)	0.4
$K_S e3$	0.2152(14)	0.7
$K^{\pm} e3$	0.2152(13)	0.6
$K^{\pm} \mu 3$	0.2132(15)	0.7

All KLOE exp. inputs
but K_S lifetime *(M. Dreucci talk)*

Lepton universality

$$r_{\mu e} \equiv \frac{|f_+(0)\, V_{us}|^2_{\mu 3,\ \exp}}{|f_+(0)\, V_{us}|^2_{e3,\ \exp}} = \frac{g_\mu^2}{g_e^2}$$

$r_{\mu e} = 1.000(8)$

τ decays: $(r_{\mu e})_\tau = 1.0005(41)$ (PDG06)
π decays: $(r_{\mu e})_\pi = 1.0042(33)$

JHEP04(2008)059

KLOE average $|V_{us}| f_+(0) = 0.2157(6)$ $\chi 2/ndf=7/4$ (13%)

World Average 0.2166(5)

$|V_{us}| = 0.2237(13)$
$1 - |V_{ud}|^2 - |V_{us}|^2 = 9(8) \times 10^{-4}$

$f_+(0) = 0.964(5)$ — **PRL 100 (2008)**
$|V_{ud}| = 0.97418(26)$ — **PRC 77 (2008)**

V_{us}, V_{ud} and V_{us}/V_{ud}

$|V_{us}/V_{ud}| = 0.2323(15)$

- $BR(K^{\pm} \to \mu^{\pm}\nu) = 0.6366(17)$
- $f_K/f_\pi = 1.189(7)$

PLB 632 (2006)

PRL 100 (2008)

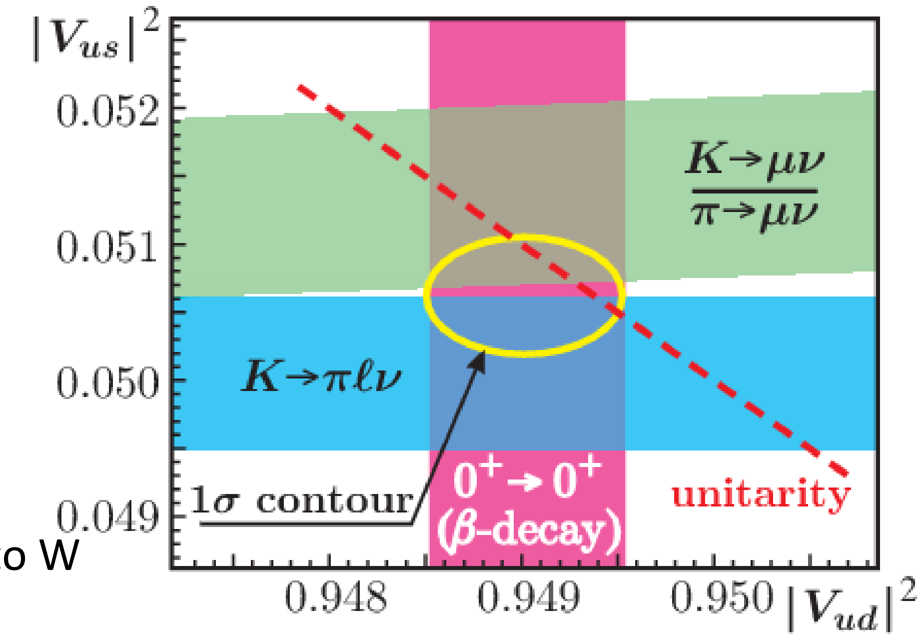
$|V_{us}| = 0.2237(13)$ from Kl3 decays

$|V_{ud}| = 0.97418(26)$

- Fit to $|V_{ud}|^2$, $|V_{us}|^2$ and $|V_{us}/V_{ud}|^2$

JHEP 04 (2008)

$|V_{ud}|^2 = 0.9490(5)$
$|V_{us}|^2 = 0.0506(4)$
$\chi^2 = 2.3/1$ (13%)



- Agreement with unitarity

$1-V_{ud}^2-V_{us}^2 = 4(7)\times10^{-4}$ @0.6σ

- Universality of lepton and quark weak coupling to W

$G_F = 1.166371(6)\times10^{-5}\ GeV^{-2}$

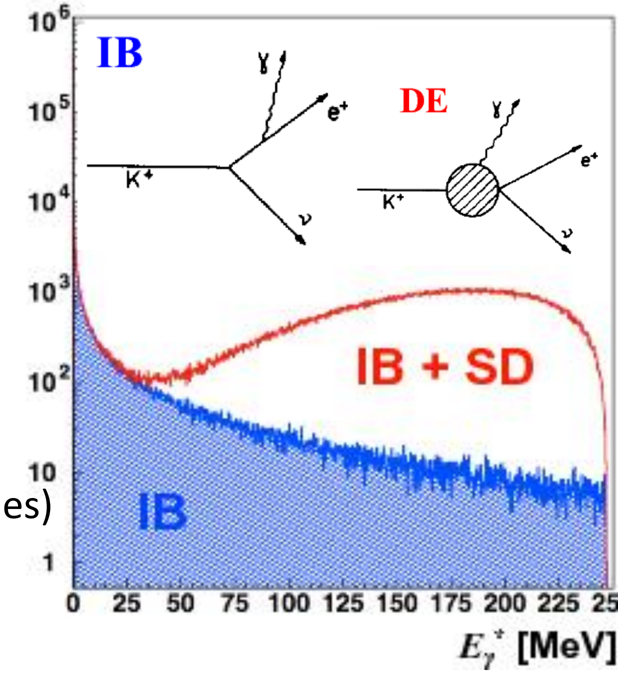
$G_{CKM} = 1.16604(40)\times10^{-5}\ GeV^{-2}$

$G_{ew} = 1.1655(12)\times10^{-5}\ GeV^{-2}$

$G_F^2 \equiv G_{CKM}^2 = (|V_{ud}|^2 + |V_{us}|^2)G_F^2$

from ew precision tests

Lepton Flavor Violation: $R_K = \Gamma(Ke2(\gamma_{IB}))/\Gamma(K\mu 2(\gamma_{IB}))$



- $R_K = \Gamma(Ke2(\gamma_{IB}))/\Gamma(K\mu 2(\gamma_{IB}))$ inclusive of IB only
- DE (or SD) ≈ IB presently known with 15% accuracy

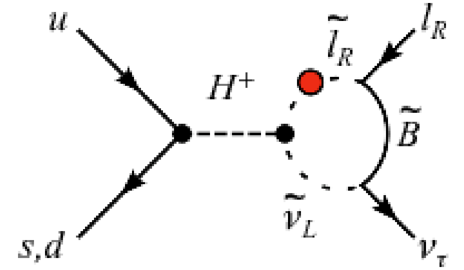
To achieve ~1% accuracy on R_K improve knowledge of DE

- In the SM R_K calculated at 0.04% (no hadronic uncertainties)
  $R_K^{SM} = 2.477(1)\ 10^{-5}$ [Cirigliano, Rossell JHEP10(2007)005]

- Lepton Flavor Violation in the MSSM would enhance R_K up to 1%
  LFV appears at 1-loop level via an effective $H^+\ell\nu_\tau$ Yukawa interaction dominated by $e\nu_\tau$

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

[Masiero-Paradisi-Petronzio PRD74 (2006) 011701]

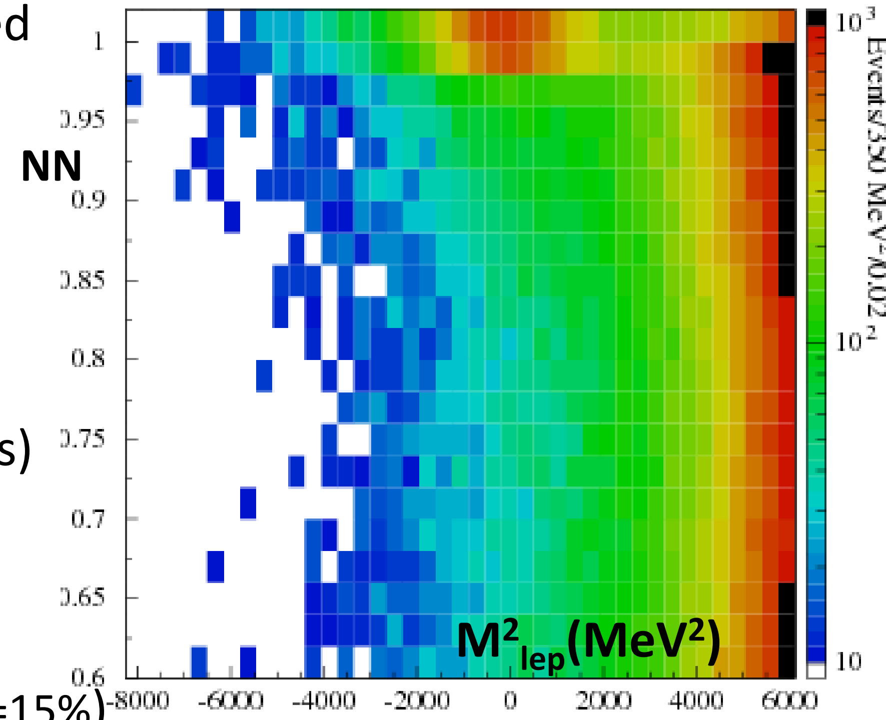


R_K: analysis strategy

- Perform Direct search for K_{e2} and $K_{\mu 2}$, no tag: gain ×4 of statistics
- Select 1-prong kinks in DC, K track from IP & secondary P > 180 MeV

  Signal events with E_γ<10 MeV (no explicit photon detection)
- Exploit tracking of K and secondary: assuming m_ν= 0 get M^2_{lep} (S/B~1/10)
- Particle Identification by Neural Network based

  on EMC information (training with KLe3)



Signal count from fit in NN- M^2_{lep}

Free parameters:

normalization factors for Kμ2 and

Ke2(γ) including only IB with E_γ <10 MeV

(to O(α_{em}) and resummation of leading logs)

Fixed parameter:

f_{DE}= 10.2% (Ke2 contamination from

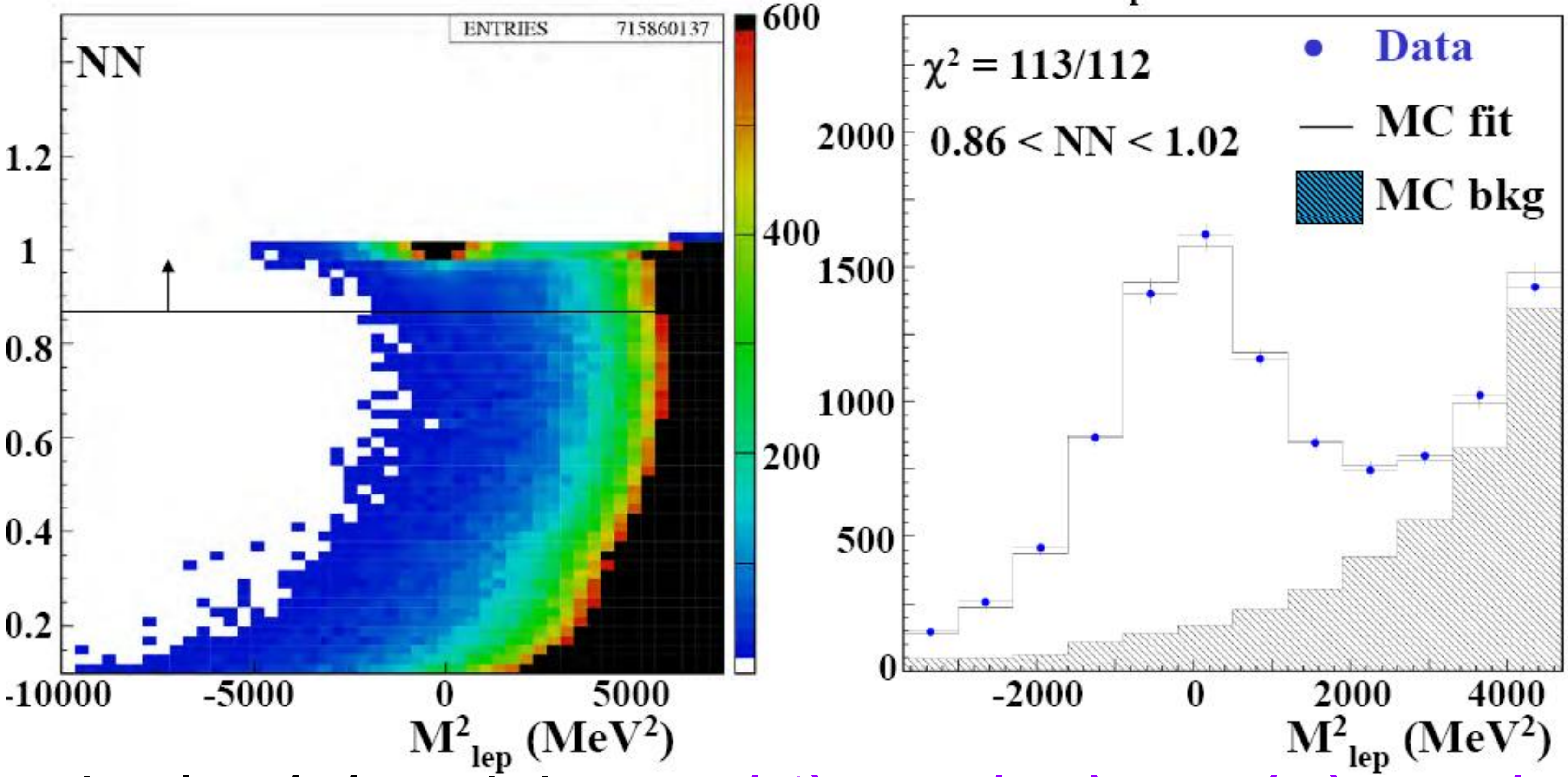
Ke2(γ) with E_γ >10 MeV)

But 0.5% systematics on R_K from f_{DE} (δ(DE)/DE=15%)

⇒ **dedicated measurement of Ke2(γ) with E_γ >10 MeV**

R_K : fitting for K_{e2} and $K_{\mu 2}$ counting

- Ke2 counts from two-dimensional binned likelihood **fit in the NN- M^2_{lep} plane** with 0.86 < NN < 1.02 and -3700 < M^2_{lep} < 6100



Using the whole statistics: **NKe2(e^+) = 7064(102) , NKe2(e^-) = 6750(101)**

- Kμ2 counting from 1-dimensional **fit of M^2_{lep} distribution** without PID

Ke2γ amplitudes

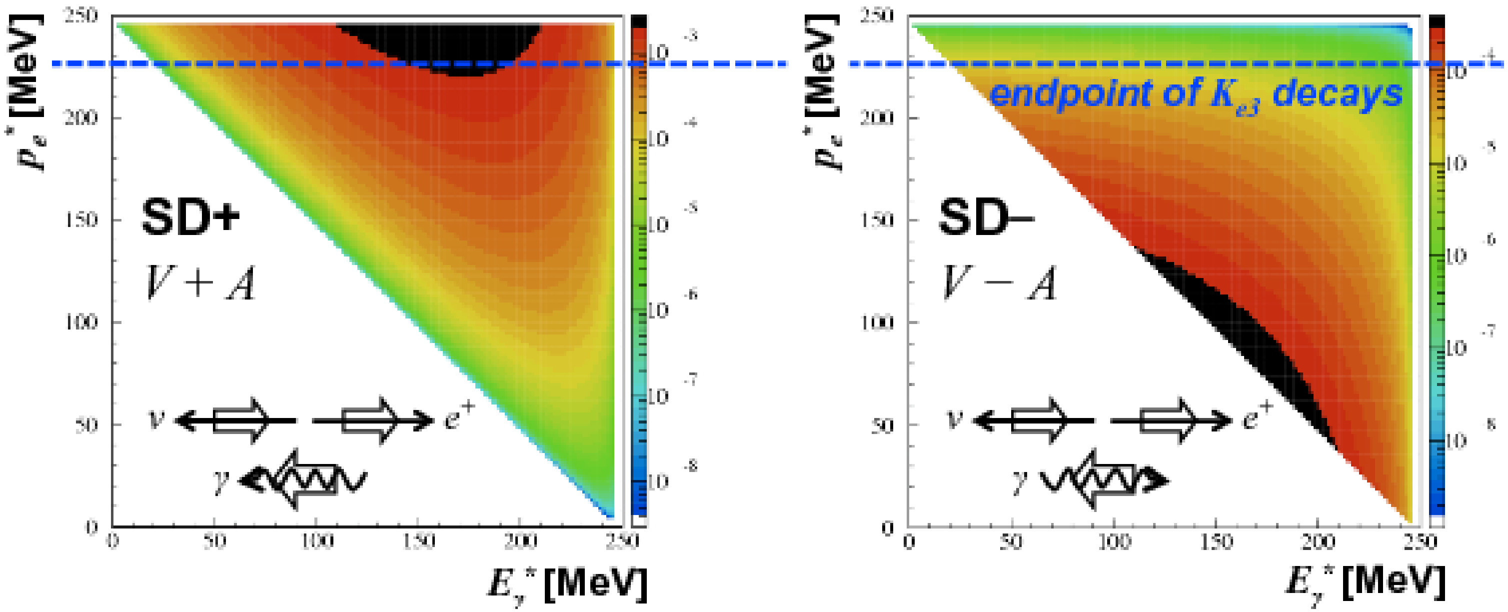
$$\frac{d\Gamma(K \to e\nu\gamma)}{dx\,dy} = \rho_{IB}(x,y) + \rho_{SD}(x,y) + \rho_{INT}(x,y)$$

negligible

$$x = 2E^*_\gamma / m_K$$
$$y = 2E^*_e / m_K$$

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

V, A: effective vector and axial couplings



Ke2γ: signal selection

- 1-prong selection -- NN > 0.98 -- 1 photon cluster with E_γ>20 MeV in time with K
- Cluster times for photon and electron must be compatible

With this selction we measure Ke2γ with:

E_γ^*>10 MeV

$\cos\theta_{e\gamma}^*$>0.9

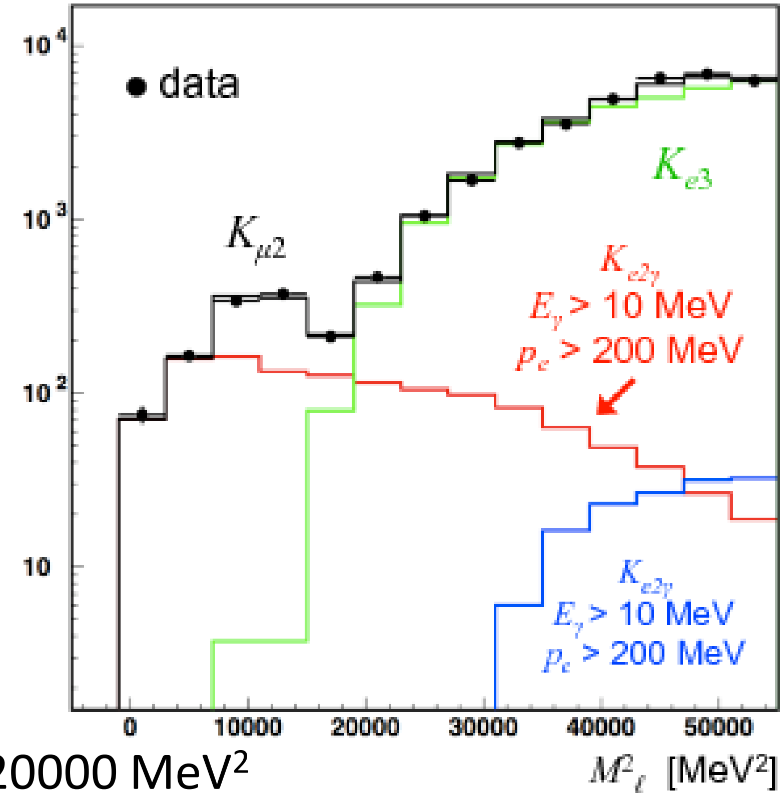
p_e^*>200 MeV

No sensitivity for Ke2γ with p_e<200 MeV (SD-)

Acceptance for SD+ events ~90%

SD- events ~2%

Residual IB events ~1%



Dominant backgrounds:

Kμ2 for M^2_{lep}< 20000 MeV² and Ke3 for M^2_{lep} > 20000 MeV²

- Further reject Ke3 decays with $\Delta E_\gamma = E_\gamma^{LAB} - E_\gamma^{CAL}$ ($\sigma_E^{LAB} \approx$ 12 MeV $\sigma_E^{CAL} \approx$ 30 MeV)

Signal count from 2-dimensional binned likelihood fit in M^2_{lep}, $\Delta E_\gamma/\sigma$ in 5 bins of E_γ^*

Ke2γ spectrum vs O(p⁴) ChPT

We measure

$$\frac{1}{\Gamma(K_{\mu 2(\gamma)})}\frac{d\Gamma_{\mathrm{SD+}}(K_{e2\gamma})}{dE_\gamma}$$

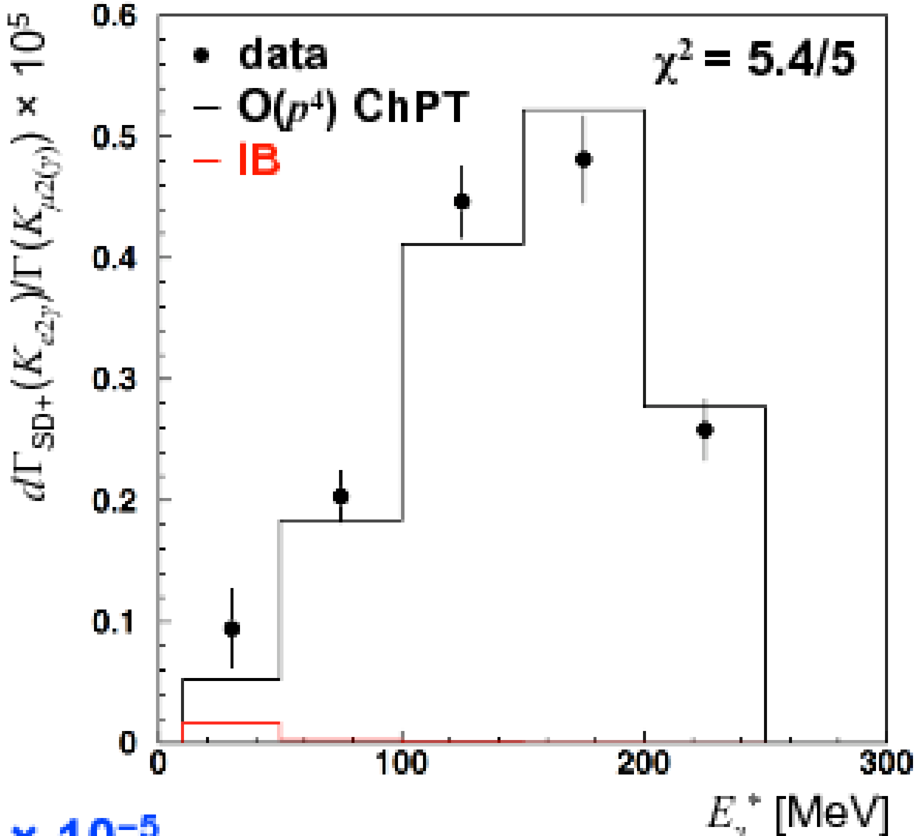
where "SD+" means:

$E_\gamma^* > 10$ MeV
$\cos\theta_{e\gamma}^* < 0.9$
$p_e^* > 200$ MeV

Summed over all bins in E_γ^*:

$N_{\mathrm{SD+}}(K_{e2\gamma}) = 1378 \pm 63$

$$\frac{\Gamma_{\mathrm{SD+}}(K_{e2\gamma})}{\Gamma(K_{\mu 2(\gamma)})} = 1.484(66)_{st}(16)_{sy} \times 10^{-5}$$



in agreement with ChPT $O(p^4)$ prediction, **1.447×10^{-5}** [Bijnens, Ecker, Gasser '93]

KLOE MC implements $O(p^4)$ ChPT for SD – used in analysis of R_K

Validated to within 4.6% - systematic error on R_K from SD = 0.2%

R_K: the final result

Using the complete KLOE data set (2.2 fb^{-1}) we obtain: *Draft paper under Collaboration's revision*

$$R_K = (2.493 \pm 0.025_{stat} \pm 0.019_{syst}) \times 10^{-5}$$

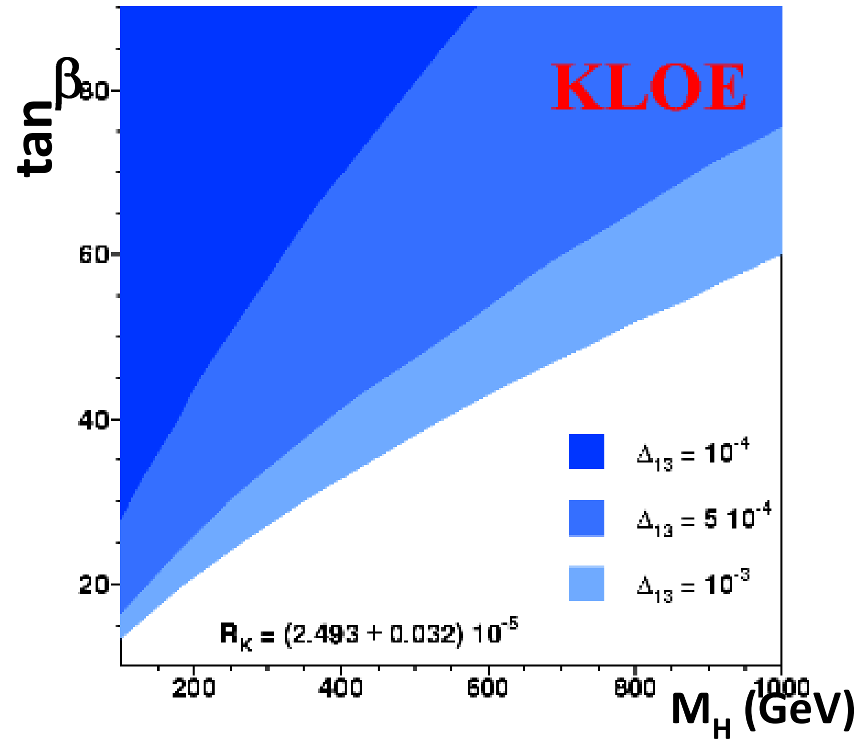
1.0% 0.8%

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

Systematic errors %	stat	syst
Reconstruction	0.4	0.4
Trigger efficiency	0.4	-
Background sub	-	0.3
Ke2(DE) comp.	0.2	-
Clustering	0.2	
Total	0.6	0.5

- Main contribution to systematic uncertainty from control-sample statistics (0.6%)

Sensitivity shown as 95%-CL excluded regions in the tanβ - M_H plane, for fixed values of the 1-3 slepton-mass matrix element, Δ_{13} = 10^{-3}, 0.5×10^{-3}, 10^{-4}

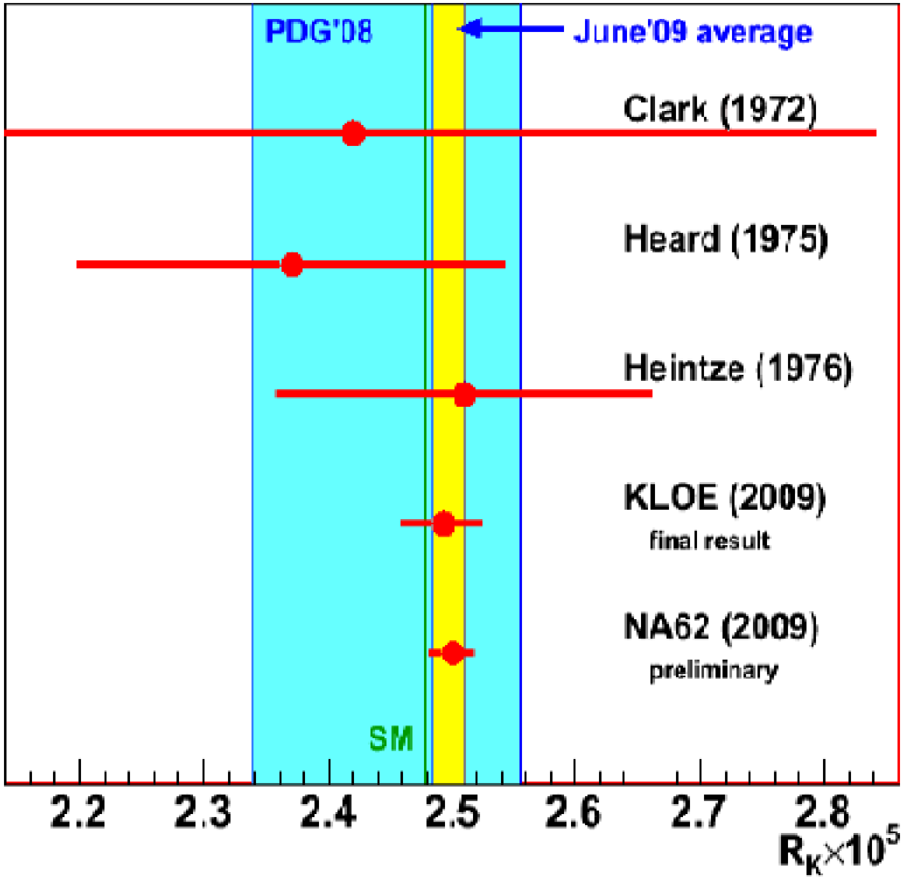


R_K: World Average

World average: $R_K = 2.498(14)\times10^{-5}$ (0.56%)

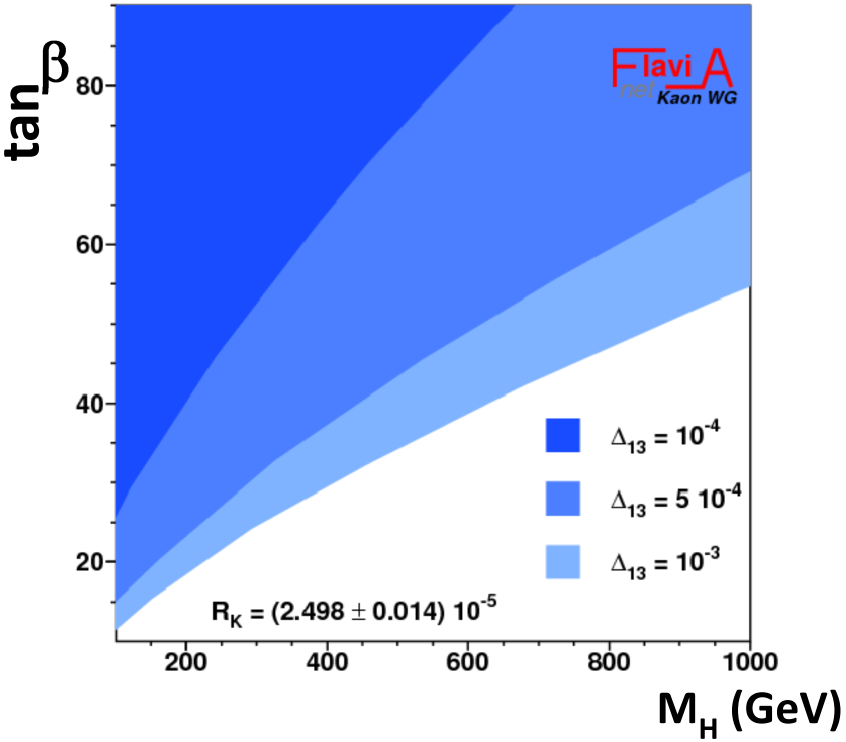
Includes NA62 preliminary (40% data set):

$R_K = 2.500(16)\times10^{-5}$ (0.64%)



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

Sensitivity shown as 95%-CL excluded regions in the $\tan\beta$ - M_H plane, for fixed values of the 1-3 slepton-mass matrix element, $\Delta_{13} = 10^{-3}, 0.5\times10^{-3}, 10^{-4}$



Summary & conclusions

Precision physics with Kaon decays to test the Standard Model

- Today $|V_{us}|f_+(0)$ @ 0.3% with KLOE (0.2% from World Average Fit)
- Lepton universality satisfied to better than 0.5%
- Unitarity of CKM matrix satisfied to better than 0.1% ($|V_{us}|$ at 0.4%)
- Universality of lepton and quark weak coupling from unitarity

and set constraints on New Physics models

- with Z' and $H^{\pm}$ boson, with Lepton Flavor Violation
- R_K at 1.3% from 1.4×10^4 Ke2 decays with 2.2 fb^{-1} data sample
- $\Gamma(Ke2\gamma; 10<E_\gamma<250$ MeV and $p_e>200$ MeV$)/\Gamma(K\mu2)$ at 4.6%

reduces from 0.5% to 0.2% the systematic uncertainty on R_K from DE which is also very important for NA62 R_K measurement

SPARE SLIDES

Outlook : Universality

- Today with $f_+(0)$ @ 0.5% the accuracy on the unitarity relation of the first row is

$$\sigma(1-V_{ud}^2-V_{us}^2) = 6\times10^{-4}$$

V_{us} @ 0.4% from fit
V_{ud} @ 0.026%

- $f_+(0)$ @ 0.1% accuracy from lattice within few years

	$f_+(0)V_{us}$	V_{us}
KLOE today *(World Average)*	0.28% (0.23%)	0.30% (0.25%)
KLOE + Step0 (5 fb^{-1}) + World Average	0.14%	0.17%

- f_K/f_π @ 0.1% within few years and $|V_{us}/V_{ud}|$ @ 0.28% from $\Gamma(K_{\mu2})/\Gamma(\pi_{\mu2})$

- With $|V_{ud}|$ @ 0.02% and $|V_{us}|$ @0.17% the accuracy on the unitarity relation of the first row would improve by a factor of ~2

$$\sigma(1-V_{ud}^2-V_{us}^2) = (3\div4)\times10^{-4}$$

Improve constraints on New Physics and interplay with other sectors