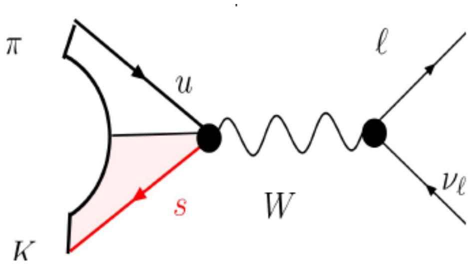
E. De Lucia (LNF-INFN)
for the KLOE Collaboration

# Vus and lepton universality with kaons at KLOE

# Kaon Physics




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

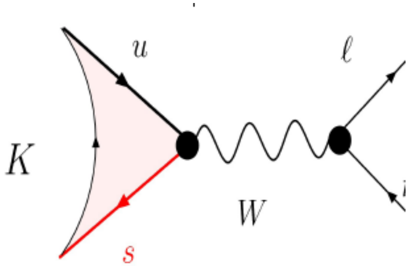
Vector transition: only 2nd order SU(3) breaking [Ademollo-Gatto]

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

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

- Lepton-Quark universality of weak int.

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




$\mathbf{K}_{\ell 2}$: $K \rightarrow \ell \nu$

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* $\mathbf{BR}(\mu^+ \to e^+ \bar{\nu}_e \nu_\mu)$ *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 $\Lambda_{NP}$ 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

$\Delta_{Kl}^{EM}$ 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: $\lambda$s parameterize form factor dependence on $t$ :

*$K_{e3}$ : only $\lambda_+$ (or $\lambda_+'$ $\lambda_+''$)*

*$K_{\mu3}$ : need $\lambda_+$ and $\lambda_0$*

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%**
**$BR(K_{\mu3}) = 0.2699(14)$** **0.52%**

Based on $13\times10^6$ $K_L$ decays tagged by $K_S\to\pi^+\pi^-$

**PLB 626 (2005)**

**$\tau_L = 50.92(30)$ ns** **0.58%**

Fit the time dependence over $0.4\tau_L$ of $8.5\times10^6$ $K_L\to\pi^0\pi^0\pi^0$ 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 $1.2\times10^8$ events

**PLB 636 (2006)**

| $\lambda'_+\times10^3$ | $\lambda''_+\times10^3$ |
|---|---|
| $25.5\pm1.8$ | $1.4\pm0.8$ |

Based on $2\times10^6$ $K_Le3$ 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 $1.8\times10^6$ $K_L\mu3$ 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 $4.2\times10^6$ $\phi\to K^+K^-$ tagged by $K^-_{\mu2}$ decays

**JHEP 01 (2008)**

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

From $15\times10^6$ $\phi\to K^+K^-$ 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%**

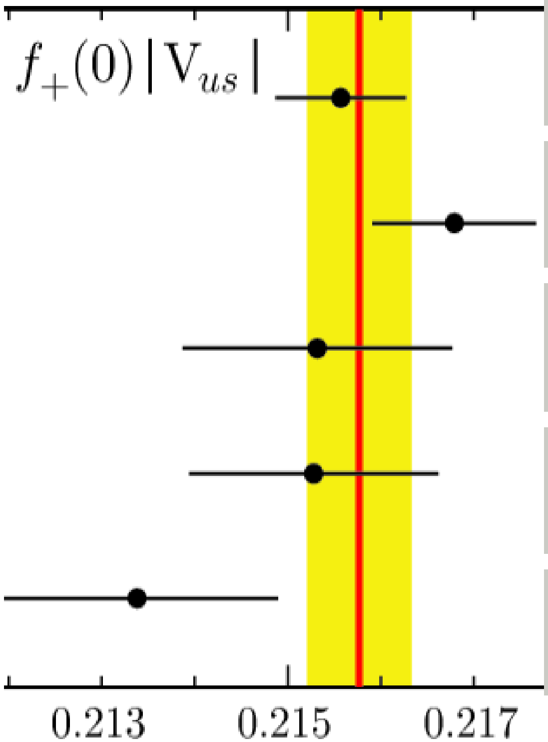
From $6\times10^7$ $\phi\to K^+K^-$ decays tagged by both $K_{\mu2}$ and $K_{\pi2}$ decays

**PLB 666 (2008)**

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

From $20\times10^6$ $\phi\to K^+K^-$ 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 |

**JHEP04(2008)059**

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

**Lepton universality**

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

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

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

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

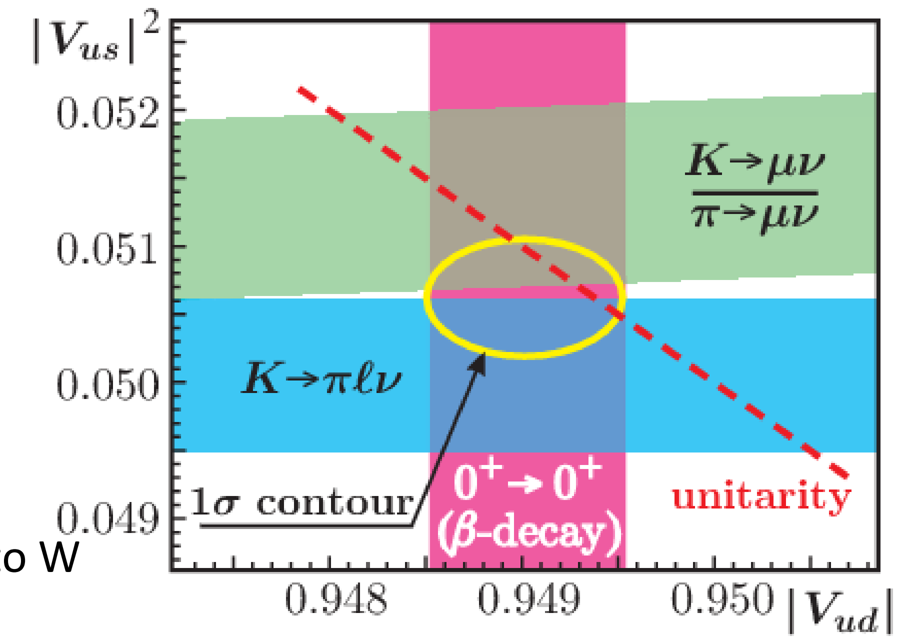
$|V_{us}| = 0.2237(13)$ from Kl3 decays

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

- 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

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

- Universality of lepton and quark weak coupling to W

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

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

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

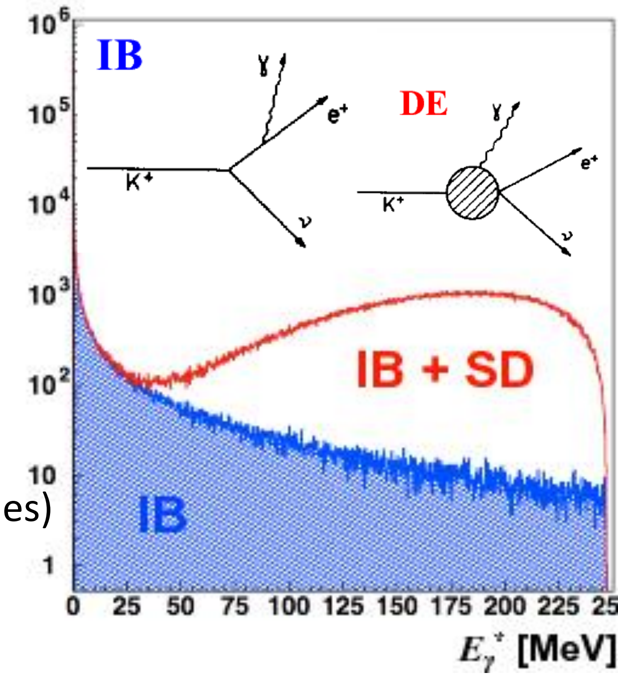
$$G_F^2 \equiv G_{CKM}^2 = (|V_{ud}|^2 + |V_{us}|^2)G_F^2$$

from ew precision tests

# Lepton Flavor Violation: $R_K = \Gamma(Ke2(\gamma_{IB}))/\Gamma(K\mu2(\gamma_{IB}))$

- $R_K = \Gamma(Ke2(\gamma_{IB}))/\Gamma(K\mu2(\gamma_{IB}))$ inclusive of IB only
- DE (or SD) ≈ IB presently known with 15% accuracy

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

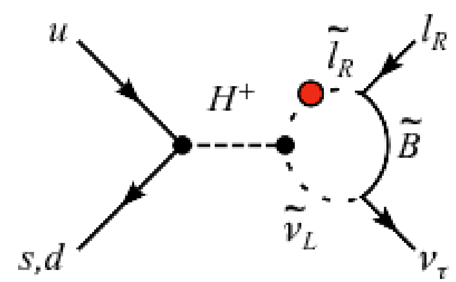



- In the SM $R_K$ calculated at 0.04% (no hadronic uncertainties)
  $R_K^{SM} = 2.477(1)\ 10^{-5}$ [Cirigliano, Rossell JHEP10(2007)005]

- 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 $e\nu_\tau$

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

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

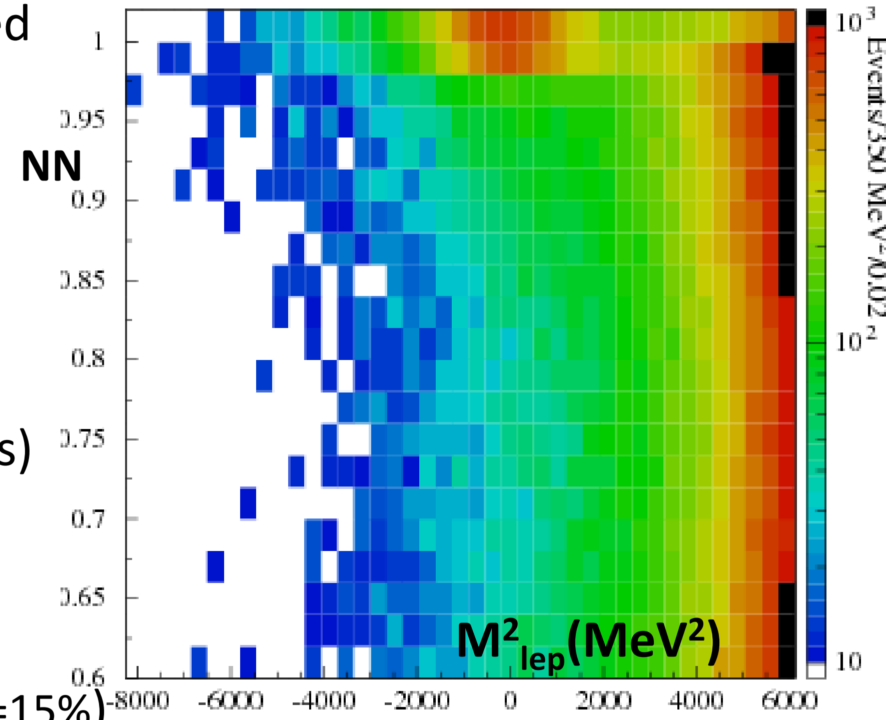


# $R_K$: analysis strategy

- 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 $E_\gamma$<10 MeV (no explicit photon detection)
- Exploit tracking of K and secondary: assuming $m_\nu$= 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 $E_\gamma$<10 MeV

(to O($\alpha_{em}$)) and resummation of leading logs)

*Fixed parameter:*

$f_{DE}$= 10.2% (Ke2 contamination from

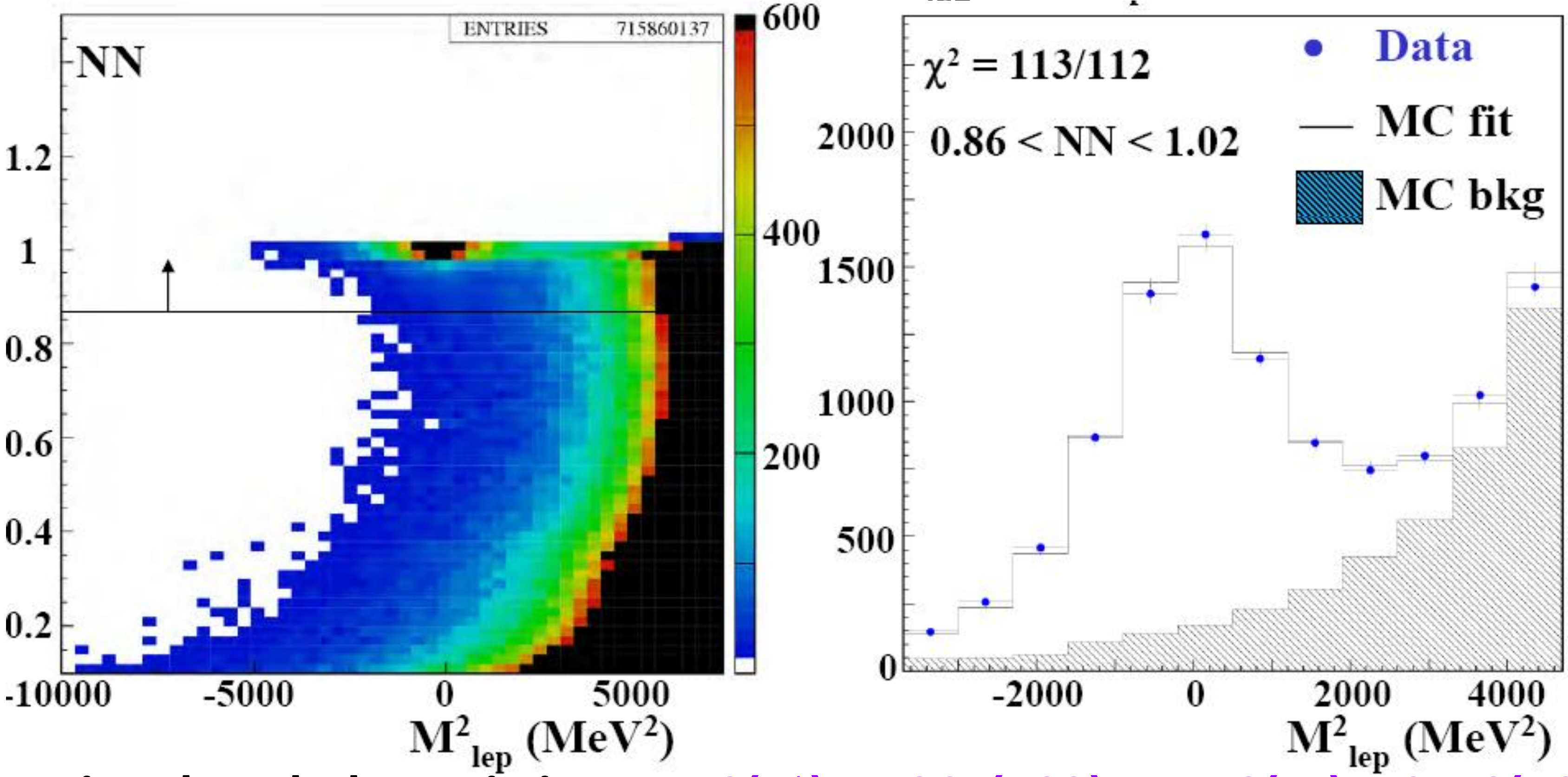
Ke2(γ) with $E_\gamma$>10 MeV )

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

⇒ **dedicated measurement of Ke2(γ) with $E_\gamma$>10 MeV**

# $R_K$ : fitting for $K_{e2}$ and $K_{\mu2}$ 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)**

- **K$\mu$2 counting from 1-dimensional fit of $M^2_{lep}$ distribution without PID**

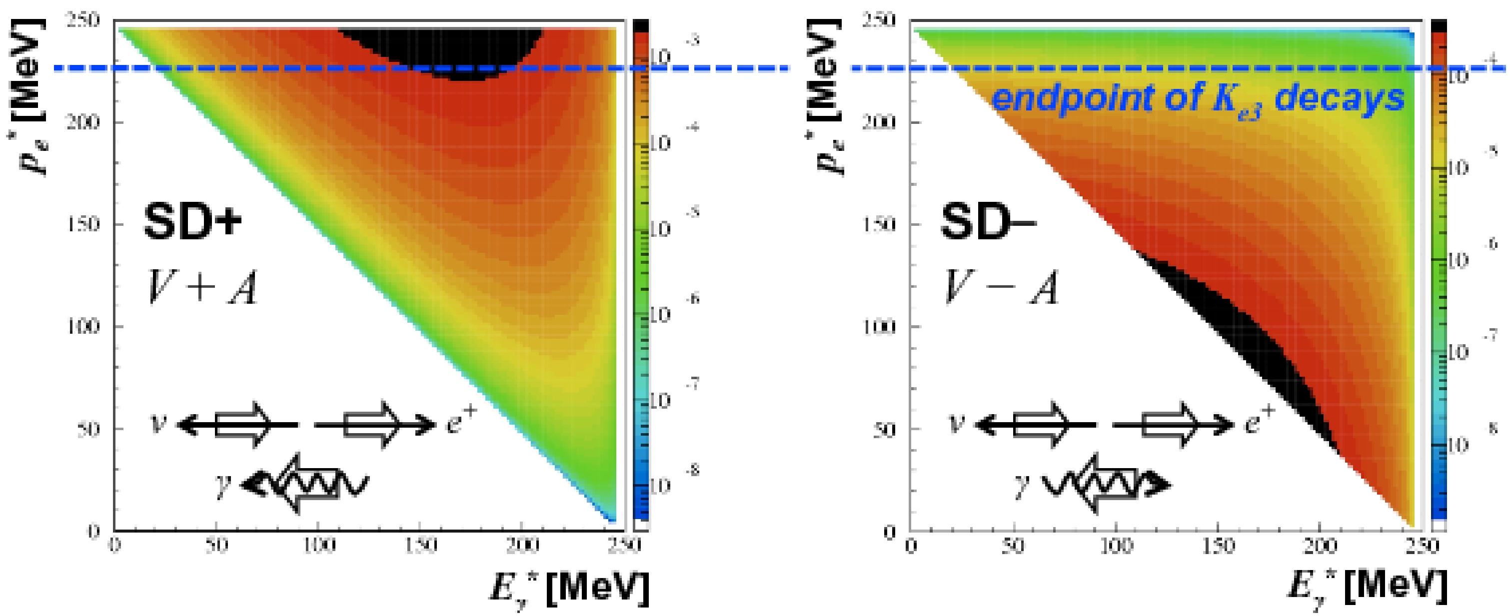
# Ke2γ amplitudes

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

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

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

$V$, $A$: effective vector and axial couplings

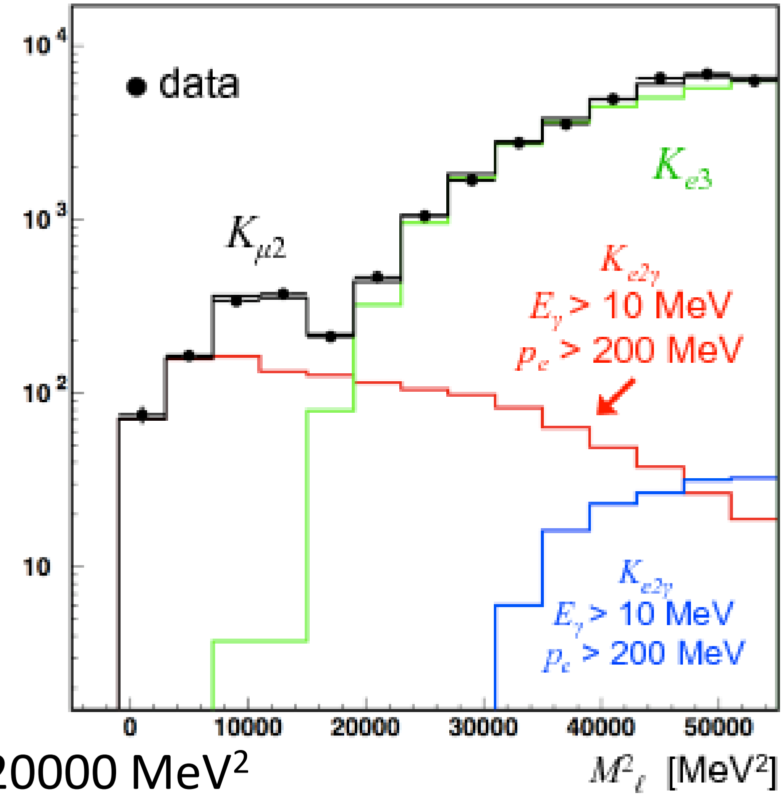


# $K_{e2\gamma}$: signal selection

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

**With this selction we measure Ke2γ with:**

**$E_\gamma^*$>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 MeV$^2$ and Ke3 for $M^2_{lep}$ > 20000 MeV$^2$

- 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 $E_\gamma^*$**

# Ke2γ spectrum vs O(p⁴) ChPT

We measure

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

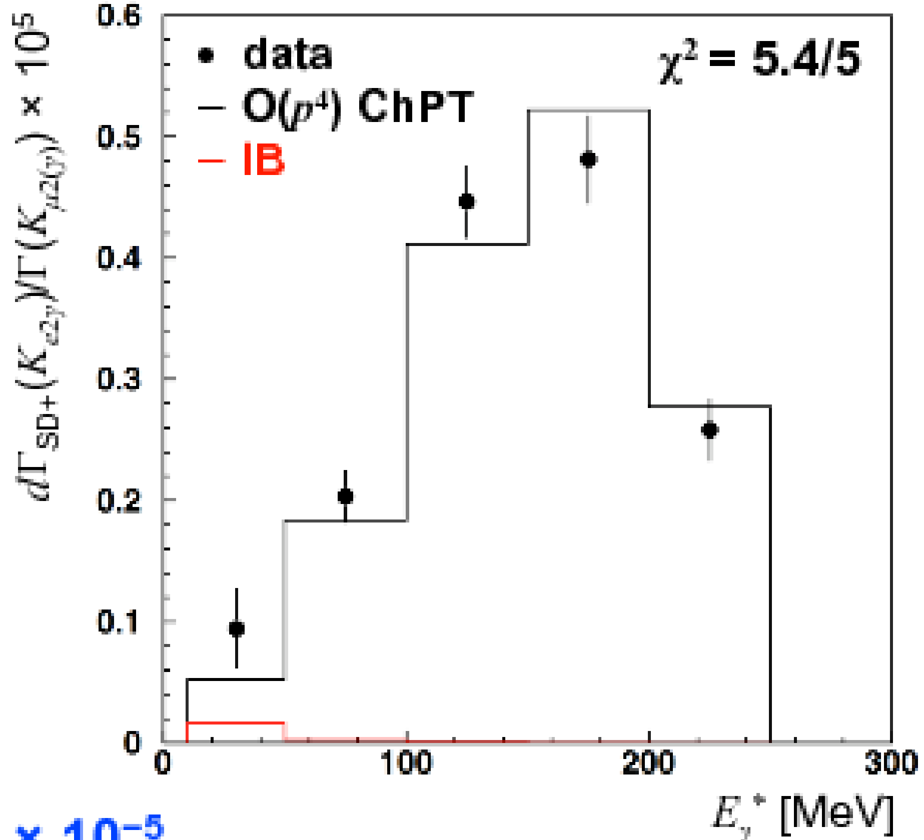
where "SD+" means:

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

Summed over all bins in $E_\gamma^*$:

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

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




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*

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

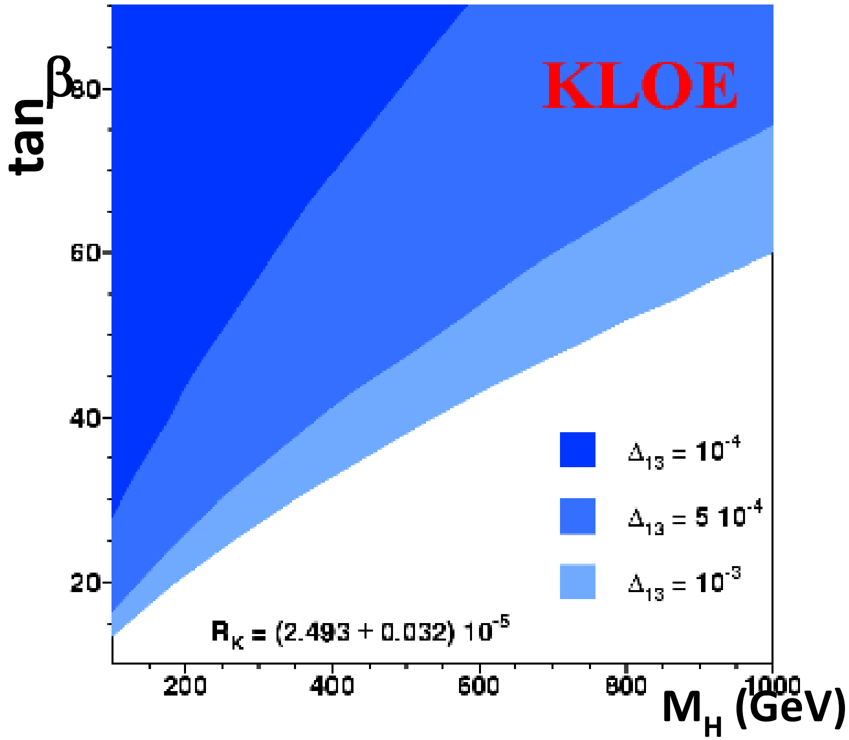
1.0% 0.8%

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

| 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, $\Delta_{13}$ = $10^{-3}$, $0.5\times10^{-3}$, $10^{-4}$**

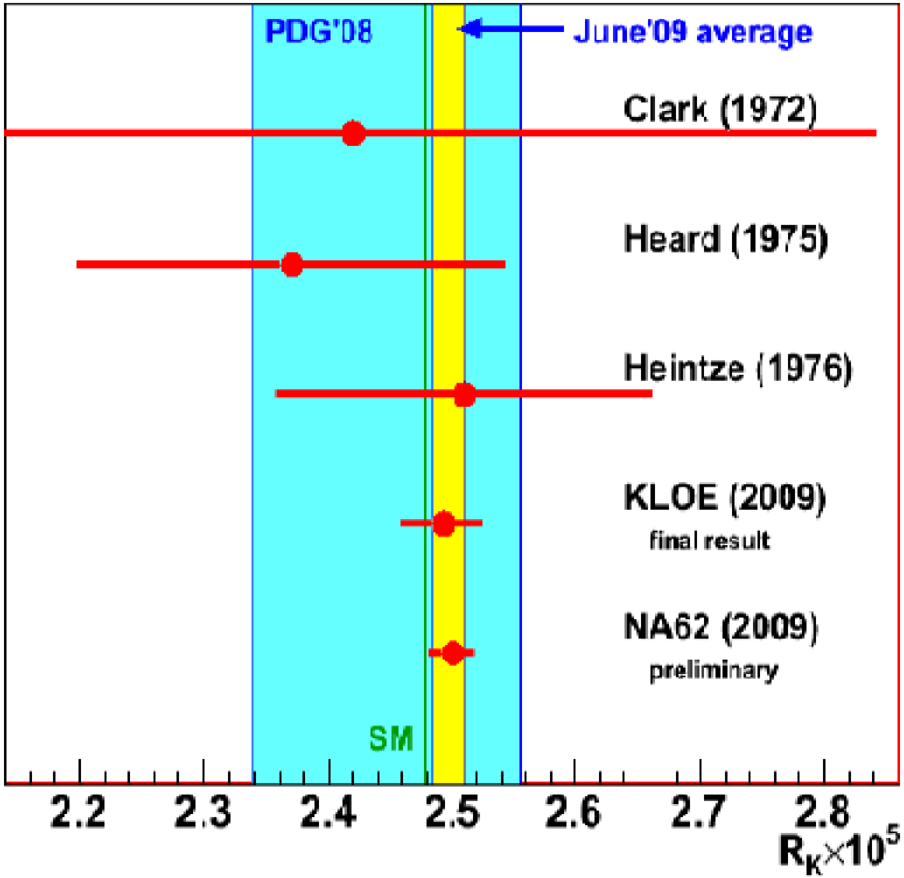


# $R_K$: World Average

**World average: $R_K$= 2.498(14)×10$^{-5}$ (0.56%)**

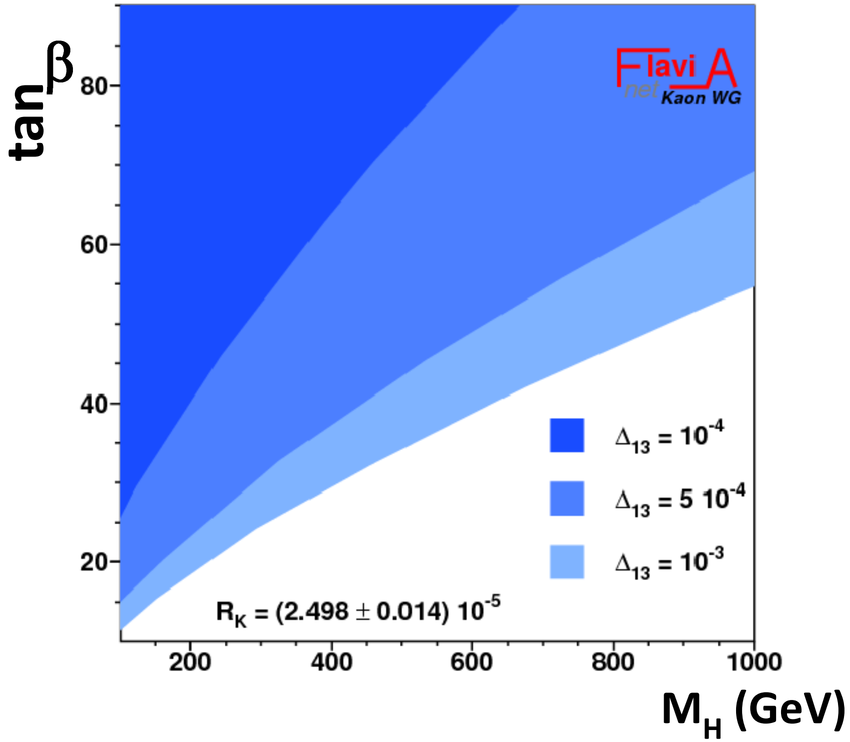
Includes NA62 preliminary (40% data set):

$R_K$= 2.500(16)×10$^{-5}$ (0.64%)




**$R_K^{SM}$ = (2.477 ± 0.001) 10$^{-5}$**

**Sensitivity shown as 95%-CL excluded regions in the tanβ - $M_H$ plane, for fixed values of the 1-3 slepton-mass matrix element, $\Delta_{13}$ = 10$^{-3}$,0.5×10$^{-3}$,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 $1.4\times10^4$ 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

$$\sigma(1-V_{ud}^2-V_{us}^2) = 6 \times 10^{-4} \quad \begin{cases} V_{us} \text{ @ 0.4\% from fit} \\ V_{ud} \text{ @ 0.026\%} \end{cases}$$

- $f_+(0)$ @ 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%** |

- $f_K / f_\pi$ @ 0.1% within few years and $|V_{us}/V_{ud}|$ @ 0.28% from $\Gamma(K_{\mu 2})/\Gamma(\pi_{\mu 2})$

- 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

$$\sigma(1-V_{ud}^2-V_{us}^2) = (3 \div 4) \times 10^{-4}$$

*Improve constraints on New Physics and interplay with other sectors*