# *Recent results in kaon physics*

Cristina Lazzeroni
(University of Birmingham)

# *Outline*

*Many new results from all the kaon experiments. A choice of topics:*

*- Vus and CKM unitary test*

*- RK and LFV tests*

*- pion-pion scattering lengths and ke4*

*- and $K^{\pm}\rightarrow\pi^{\pm}\nu\nu$ proposal*

# *Semileptonic decays and $V_{us}$*

# Semileptonic decays

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

with $K = K^+, K^0$; $l = e, \mu$ 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**

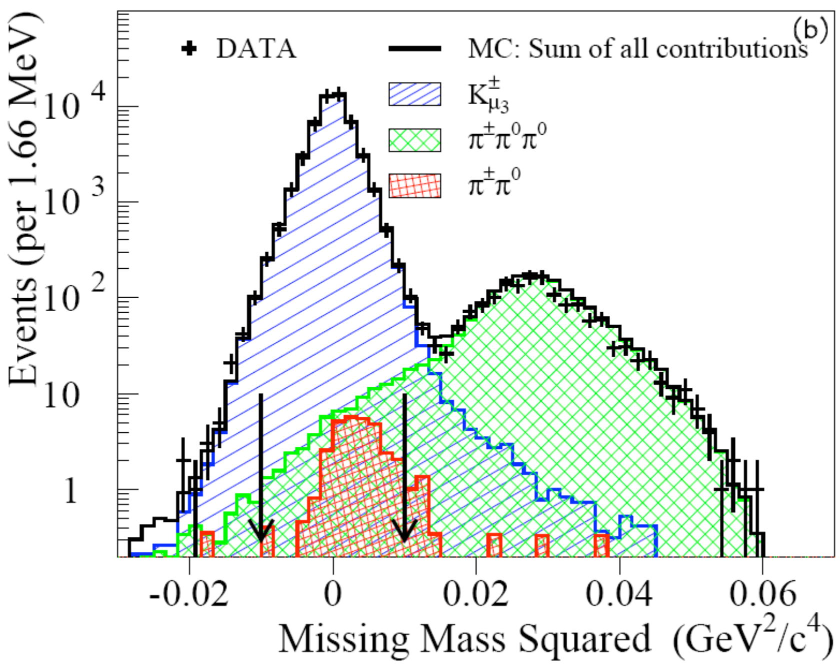
$I_{Kl}(\lambda)$ Phase space integral: λs parameterize form factor dependence on *t* :

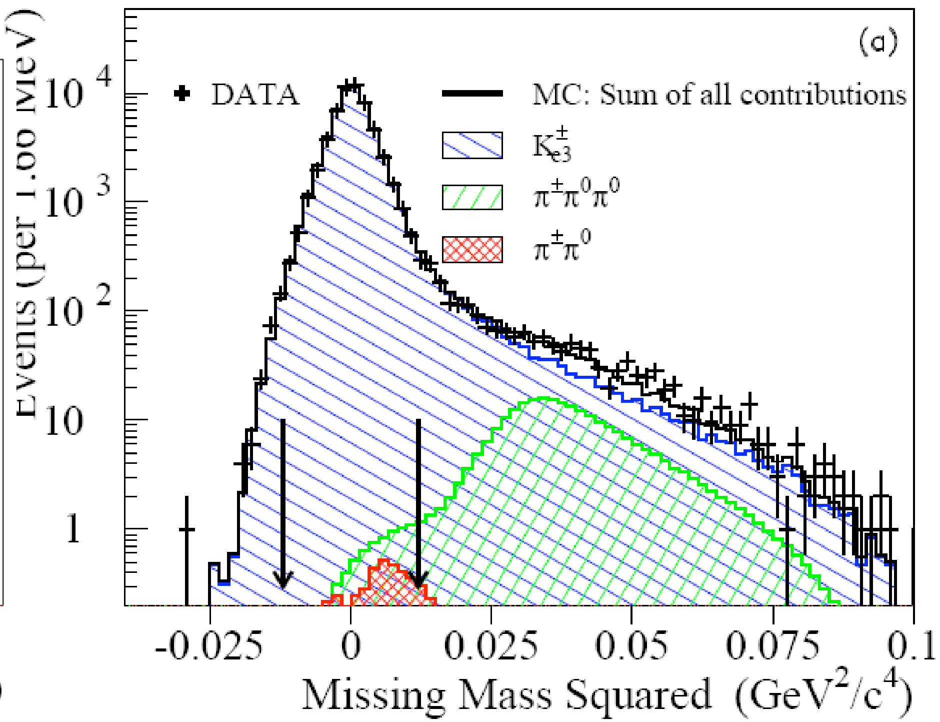
$K_{e3}$ *: only* $\lambda_+$ (or $\lambda_+'$ $\lambda_+''$)

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

# NA48: $K^{\pm} \rightarrow \pi^0 l^{\pm} \nu$

Arrows indicate signal region




**Total Number of events K+/(K-)**

| | |
|---|---|
| Ke3: | 56k (31k) |
| Kμ3: | 49k (28k) |
| $\pi^{\pm}\pi^0$ : | 462k(257k) |

**Acceptance * Particle ID K+(K-)**

| | | |
|---|---|---|
| Ke3: | 6.98 ± 0.01 | (6.94 ± 0.01)% |
| Kμ3: | 9.27 ± 0.01 | (9.25 ± 0.01)% |
| Pipi0: | 14.18 ± 0.01 | (14.12 ± 0.01)% |

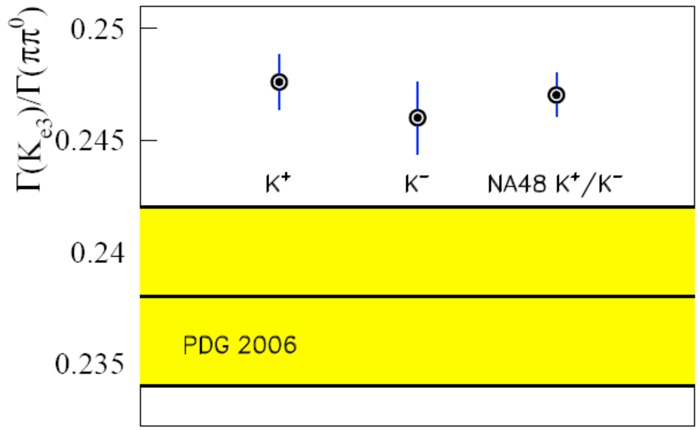
**Background < 1 %**

**Trigger efficiency > 99.8 %**

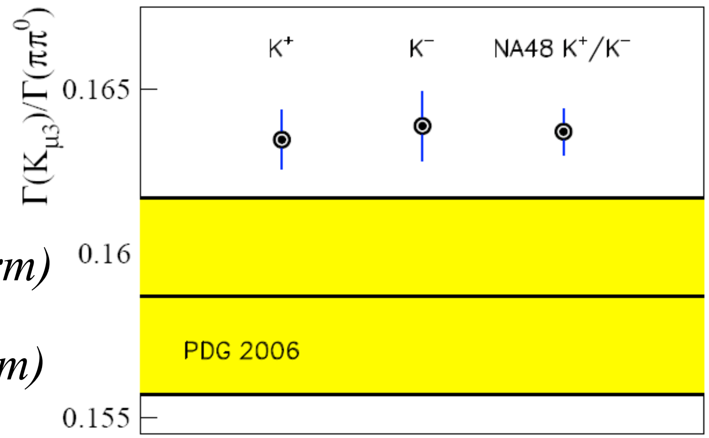
# NA48: Ratios of branching fractions

*R(Ke3/K2π)=0.2470±0.0009(stat)±0.0004(sys)*

*R(Kμ3/K2π)=0.1636±0.0006(stat)±0.0003(sys)*




*Systematics:*
*Detector acceptance with radiative effects*
*Particle ID efficiency*
*Trigger efficiency*
*Form Factors*




*Assuming Br(K2π) from PDG:*

*Br(Kμ3)=0.03425±0.00013(stat)±0.00006(sys)±0.00020(norm)*

*Br(Ke3)=0.05168±0.00019(stat)±0.00008(sys)±0.00030(norm)*

*Compatible with BNL-E865*

# NA48: Vus

Given Br(Ke3) and Br(Kmu3)

$$\frac{BR(K_{\ell 3})}{\tau_K} = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^\ell(\lambda_{+0})(1 + \delta_{SU(2)}^\ell + \delta_{EM}^\ell)$$

**External Input Used**

$M_{K^+}$ and $\tau_{K^+}$ from PDG

$G_F = (1.16637 \pm 0.00001) \times 10^{-5}$ GeV$^{-2}$

$S_{EW} = (1.0230 \pm 0.0003)$

$\delta_{SU2}^{e,\mu} = (2.31 \pm 0.22)\%$

$\delta_{EM}^{e} = (0.03 \pm 0.10)\%$

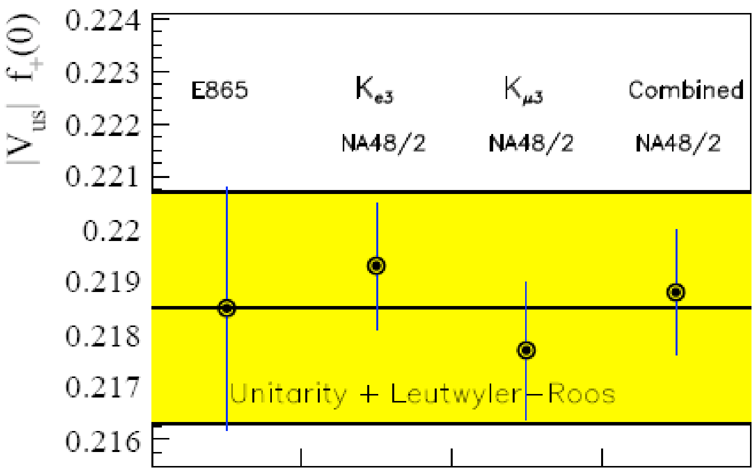
$\delta_{EM}^{\mu} = (0.20 \pm 0.20)\%$

$I_K^e = 0.1591 \pm 0.0012$

$I_K^\mu = 0.1066 \pm 0.0008$

$|V_{us}|f_+(0)=0.21928\pm0.00039(stat)\pm0.00017(sys)\pm0.00063(norm)\pm0.00096(ext)$ Ke3

$|V_{us}|f_+(0)=0.21774\pm0.00041(stat)\pm0.00019(sys)\pm0.00064(norm)\pm0.00103(ext)$ Kμ3




$|V_{us}|f_+(0)=0.2193\pm0.0012$ Ke3

$|V_{us}|f_+(0)=0.2177\pm0.0013$ Kμ3

$|V_{us}|f_+(0)=0.2188\pm0.0012$ Kl3

$|V_{us}|_{unitarity}f_+(0) = 0.2185\pm0.0022$

$|V_{ud}| = 0.9738\pm0.0003$ $|V_{ub}|=(3.60\pm0.7)x10^{-3}$

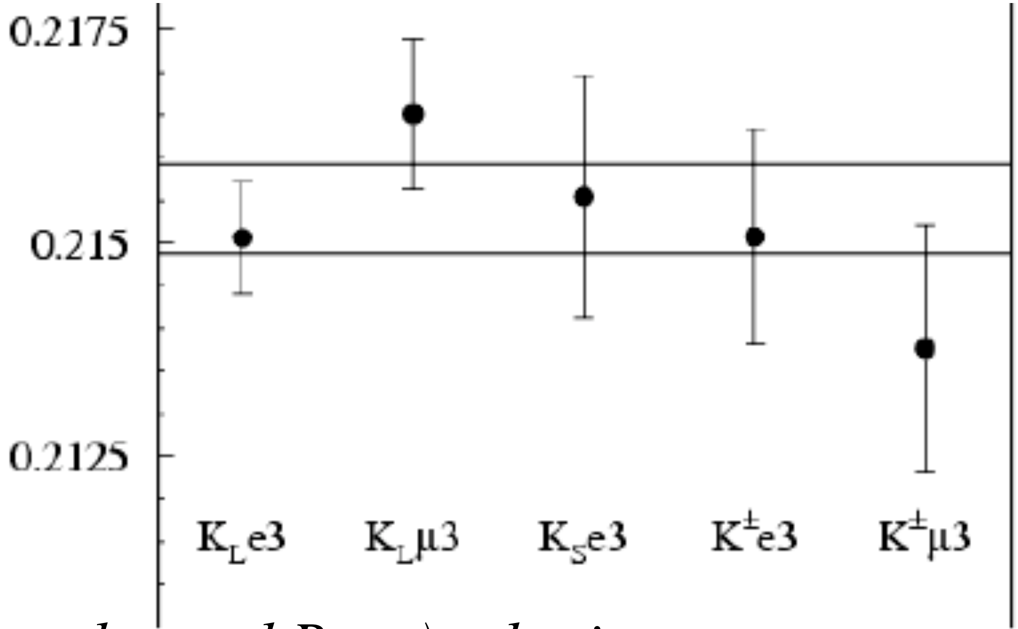
$f_+(0)=0.961(8)$

*In good agreement with CKM unitarity*

# *KLOE*

| $K_Le3$ | $K_L\mu3$ | $K_Se3$ | $K^{\pm}e3$ | $K^{\pm}\mu3$ |
|---|---|---|---|---|
| 0.4007(15) | 0.2698(15) | $7.046(91)\times10^{-4}$ | 0.04965(53) | 0.03233(39) |

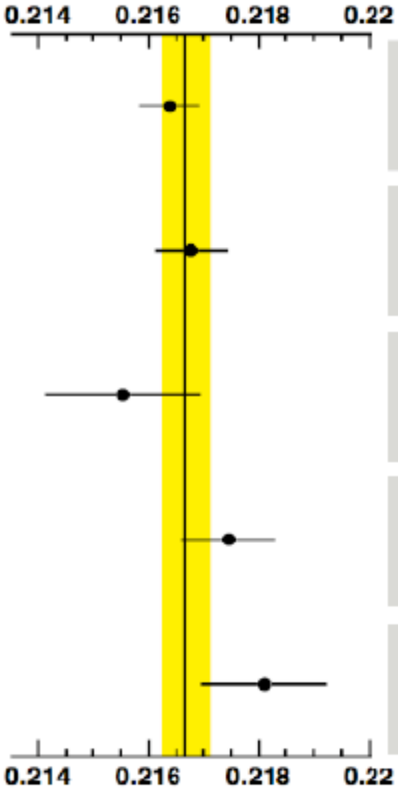
$V_{us} f_+(0) = 0.2154(5)$




*$\chi$/ndf =4.37/4*
*(36% probability)*

*Using $f_+(0)$=0.961(8) (Lautwyler and Roos), obtain*
***$V_{us}$ = 0.2241(19)***
*Using $V_{ud}$=0.97377(27), obtain* ***$V_{ud}^2 + V_{us}^2 -1 = -0.0015(10)$***
*compatible with unitarity at* ***-1.5σ***

# $|V_{us}| f_+(0)$ from $K_{l3}$ data




Approx. contrib. to % err from:

| | | % err | BR | $\tau$ | $\Delta$ | Int |
|---|---|---|---|---|---|---|
| $K_L e3$ | **0.21638(55)** | **0.25** | 0.09 | **0.19** | 0.10 | 0.10 |
| $K_L \mu 3$ | **0.21678(67)** | **0.31** | 0.10 | **0.18** | 0.15 | 0.15 |
| $K_S e3$ | **0.21554(142)** | **0.66** | **0.65** | 0.03 | 0.10 | 0.10 |
| $K^{\pm} e3$ | **0.21746(85)** | **0.39** | **0.29** | 0.09 | **0.24** | 0.09 |
| $K^{\pm} \mu 3$ | **0.21810(114)** | **0.52** | **0.42** | 0.09 | **0.26** | 0.15 |

**Average: $|V_{us}| f_+(0)$ = 0.21668(45)    $\chi^2$/ndf = 2.74/4 (60%)**

**$\Delta^{SU(2)}_{exp}$ = 2.86(38)%** → success of CHPT calculations    [$\Delta^{SU(2)}_{th}$ = 2.31(22)%]

**$K_{l3}$ average: $|V_{us}| f_+(0)$ = 0.21668(45)**

**-0.1% respect to CKM06 and PDG06**

Leutwyler & Roos '84

**$f_+(0)$ = 0.961(8)**

Conventional choice for value of $f_+(0)$ until a definitive evaluation becomes available

**$K_{l3}$ average: $|V_{us}|$ = 0.2255(19)**

Marciano & Sirlin '06

**$|V_{ud}|$ = 0.97377(27)**

Average from $0^+ \rightarrow 0^+$ $\beta$ decays with recent evaluation of EW radiative corrections

**$V_{ud}^2 + V_{us}^2 - 1$ = −0.0009(10)**

**Compatibility with unitarity −0.9$\sigma$**

For each state of kaon charge, we evaluate:

$$r_{\mu e} = \frac{(R_{\mu e})_{\rm obs}}{(R_{\mu e})_{\rm SM}} = \frac{\Gamma_{\mu 3}}{\Gamma_{e3}} \cdot \frac{I_{e3}\,(1+\delta_{e3})}{I_{\mu 3}\,(1+\delta_{\mu 3})} = \frac{[|V_{us}|\,f_+(0)]^2_{\mu 3,\,\rm obs}}{[|V_{us}|\,f_+(0)]^2_{e3,\,\rm obs}} = \frac{(G_F^\mu)^2}{(G_F^e)^2}$$

**$K^\pm$ modes**
**$r_{\mu e}$ = 1.0059(87)**

**$K_{L,S}$ modes**
**$r_{\mu e}$ = 1.0039(56)**

Using 2004 BRs*
$r_{\mu e}$ = 1.019(13)

Using 2004 BRs*
$r_{\mu e}$ = 1.054(15)

**Average**
(incl. $\rho$ = 0.12)
**$r_{\mu e}$ = 1.0045(50)**

Compare sensitivity from $\pi \to l\nu$ decays:

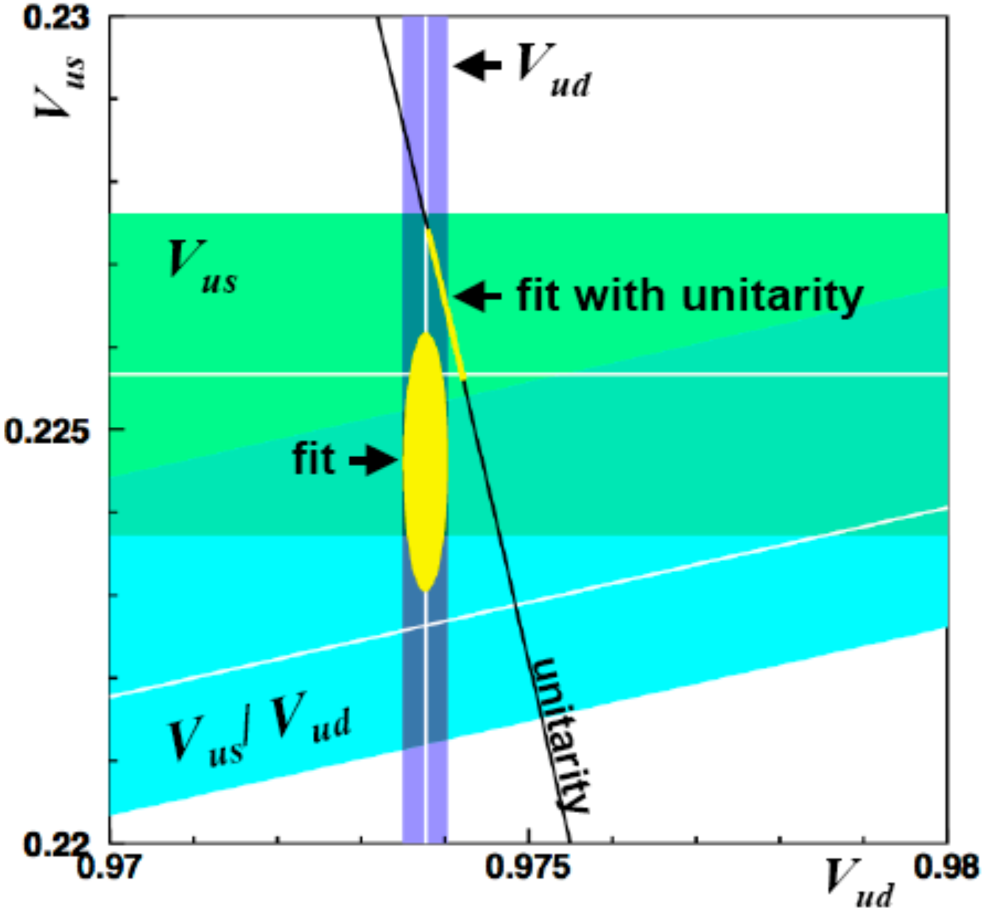
**$(r_{e\mu})_{\pi l2}$ = 0.9966(30)**
see Erler, Ramsey-Musolf '06

*Assuming current values for form-factor slopes and $\Delta^{\rm EM}$

*Compare also to :* $((g_\mu^2/g_e^2)_{\tau\to l\nu\bar\nu} = 0.9998(40))$

$f_+(0)$ from LR 84

$|V_{us}|$ = 0.2255(19) from $Kl3$




**Fit results, no constraint:**

**$V_{ud}$ = 0.97377(27)**
**$V_{us}$ = 0.2245(16)**
$\chi^2$/ndf = 0.75/1 (39%)

**Fit results, unitarity constraint:**

$V_{ud}$ = 0.97403(22)
$V_{us}$ = 0.2264(9)
**$\chi^2$/ndf = 3.13/2 (21%)**

**Agreement with unitarity at 1.3σ**

# *Form Factors*

*Kl3 matrix element:*

$$\mathcal{M} \propto \mathbf{f_+(q^2)(p_K + p_\pi)^\mu \bar{u}_l \gamma_\mu (1 + \gamma_5) u_v + f_-(q^2) m_l \bar{u}_l \gamma_\mu (1 + \gamma_5) u_v}$$

*Scalar form factor:*

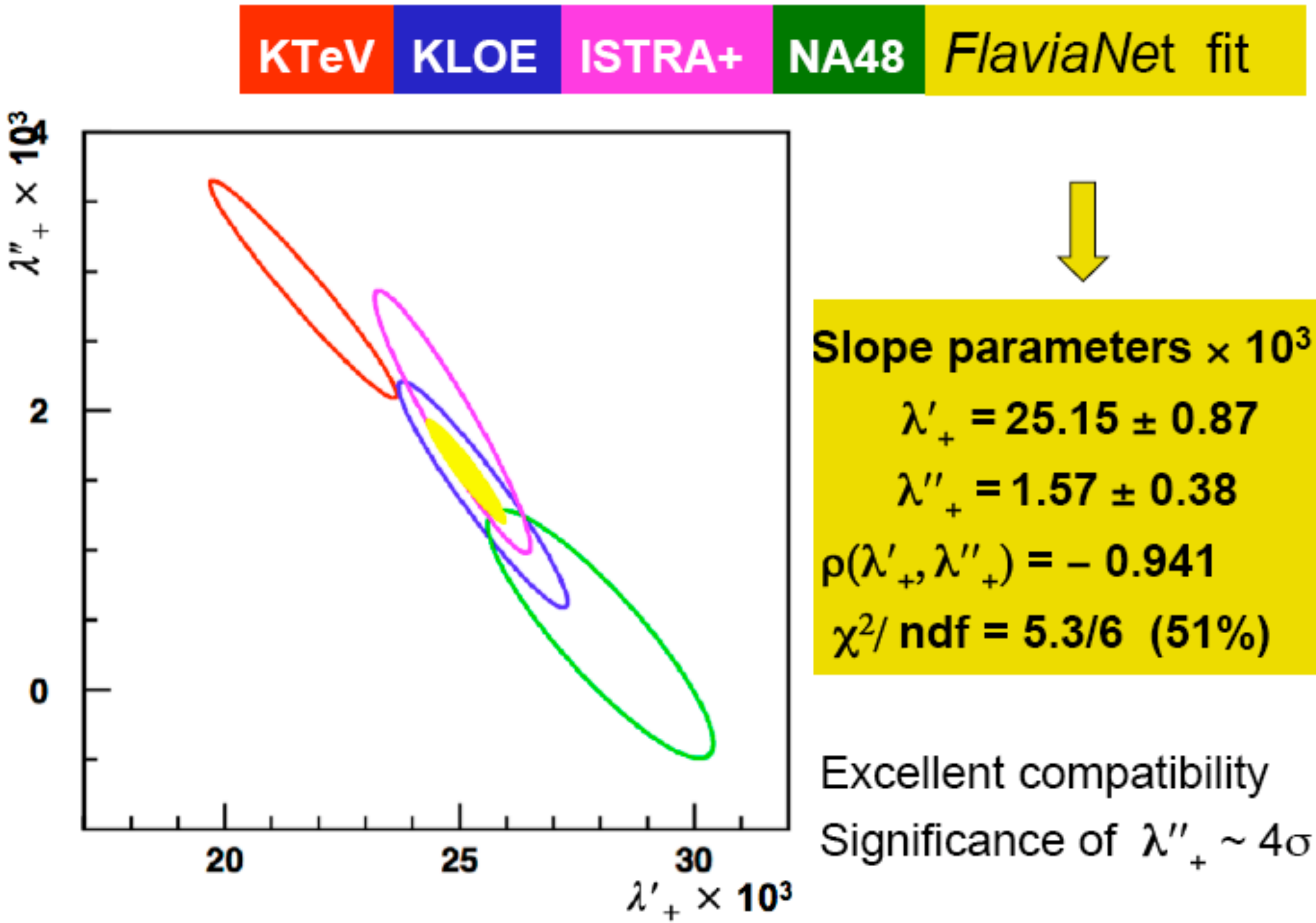
$$\mathbf{f_0(q^2) = f_+(q^2) + \frac{q^2}{m_K^2 - m_\pi^2} f_-(q^2)}$$

*Linear/Quadratic expansion:*

$$f_+(q^2) = f_+(0)\left(1 + \lambda'_+ \frac{q^2}{m_{\pi+}^2} + \frac{1}{2}\lambda''_+ \frac{q^4}{m_{\pi+}^4}\right)$$

$$f_0(q^2) = f_+(0)\left(1 + \lambda_0 \frac{q^2}{m_{\pi+}^2}\right)$$

*Slopes from Ke3*




**Slope parameters × $10^3$**

$\lambda'_+ = 25.15 \pm 0.87$

$\lambda''_+ = 1.57 \pm 0.38$

$\rho(\lambda'_+, \lambda''_+) = -0.941$

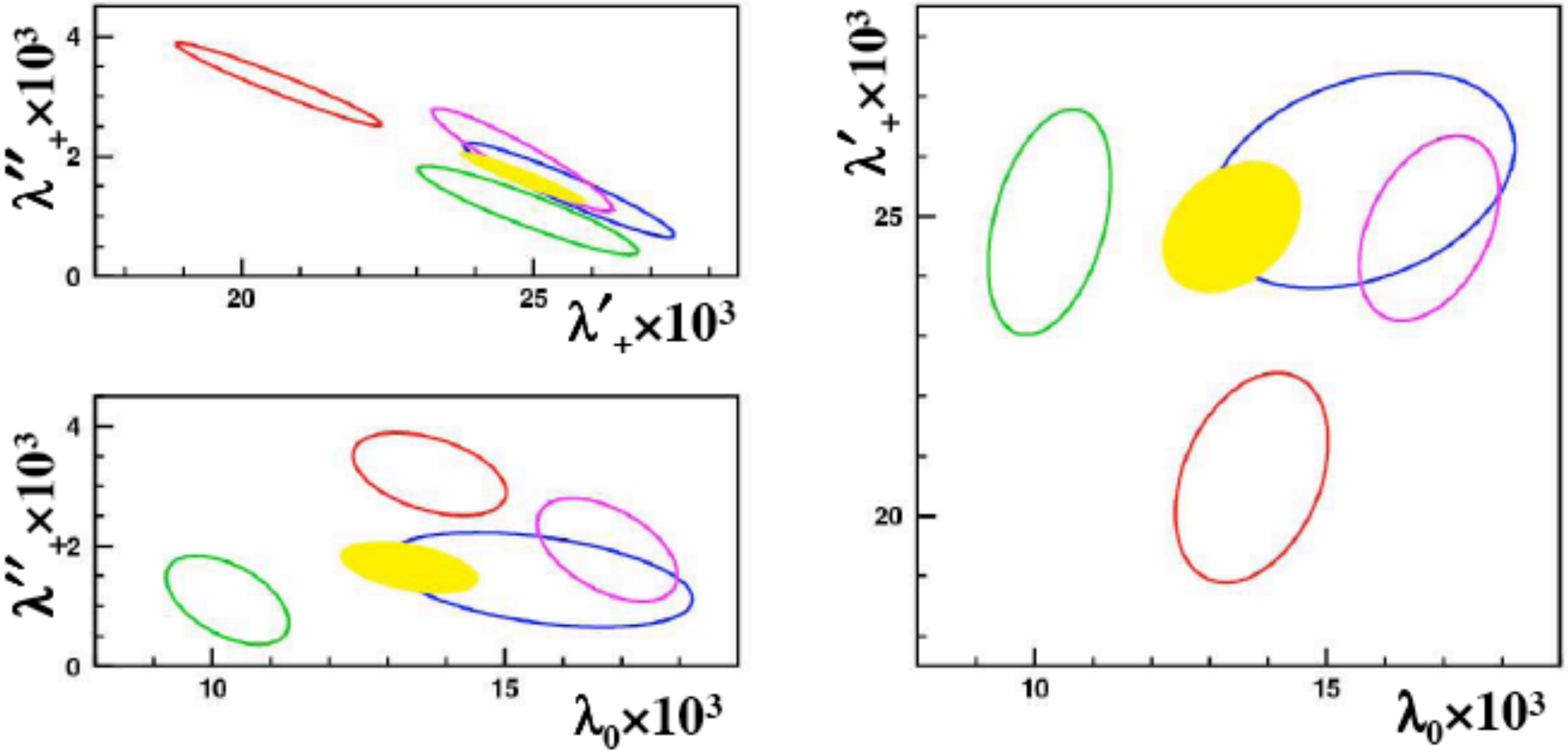
$\chi^2$/ ndf = 5.3/6 (51%)

Excellent compatibility

Significance of $\lambda''_+ \sim 4\sigma$

**KTeV** **KLOE** **NA48** **ISTRA+**

**Each ellipse is from the average of Ke3 and Kμ3**




$$\lambda'_+=(24.8\pm1.1)\times10^{-3} \quad \lambda''_+=(1.64\pm0.44)\times10^{-3} \quad \lambda_0=(13.4\pm1.2)\times10^{-3}$$

$$P(\chi^2) \sim 10^{-6}$$

# $R_K$ *and LFV*

# $R_K = \Gamma(K^+ \to e^+ \nu) / \Gamma(K^+ \to \mu^+ \nu)$

$$R_M := \frac{\Gamma(M \to e\nu_e(\gamma))}{\Gamma(M \to \mu\nu_\mu(\gamma))} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_M^2 - m_e^2}{m_M^2 - m_\mu^2}\right)^2 \left(1 + \delta R_M\right)$$

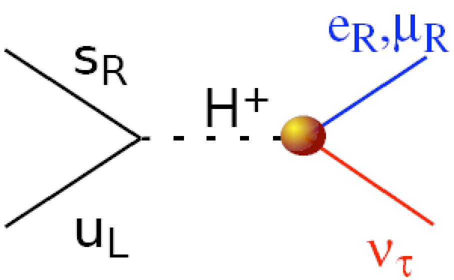
| | |
|---|---|
| PDG value | **2.45 ± 0.11** |
| SM prediction | **2.472 ± 0.001** |
| NA48/2 (2003) | **$2.416 \pm 0.043_{(stat)} \pm 0.024_{(syst)}$** |

*$\delta R_M$ from radiative corrections*

For $K^\pm$: $\delta R_K = -(3.78 \pm 0.04)\%$

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}\ , \quad i = e, \mu, \tau$$

**Masiero, Paradisi, Petronzio, hep-ph/0511289**




$$eH^\pm \nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi} \delta_{RR}^{31}$$

*out-of-diag slepton mixing matrix*

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \quad t_\beta = 40 \quad M_{H^\pm} = 500\,\mathrm{GeV}$$

$$\Downarrow$$

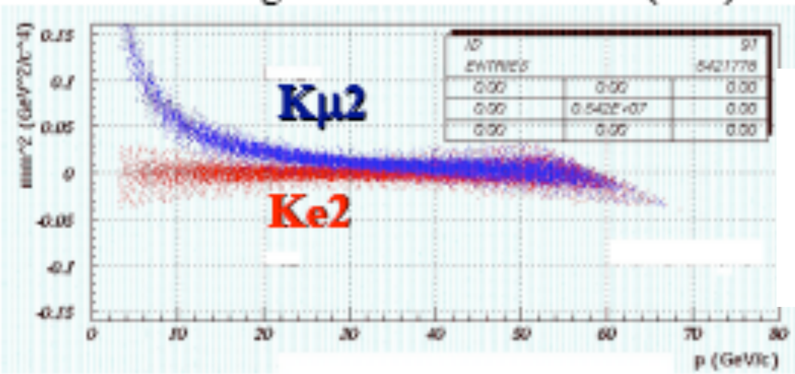
*LFV $\tau$ decay of $O(10^{-10})$*

$$\Delta r_{K\ SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

# *NA48: $R_K$*

*special run in 2004, simple trigger with 100% efficiency*

Missing mass vs momentum (MC)




- The dominant background is Kμ2
  - Measured from the data in momentum bins

The theory prediction for $R_K$ includes the IB term from Kl2γ decays

Radiative corrections applied according to the prescription of M. Finkemeier: (Phys.Lett.B387:391-394,1996) using the matrix elements from J. Bijnens et al (Nucl.Phys. B396 (1993) 81-118)

*proper treatment of radiative correction is important*

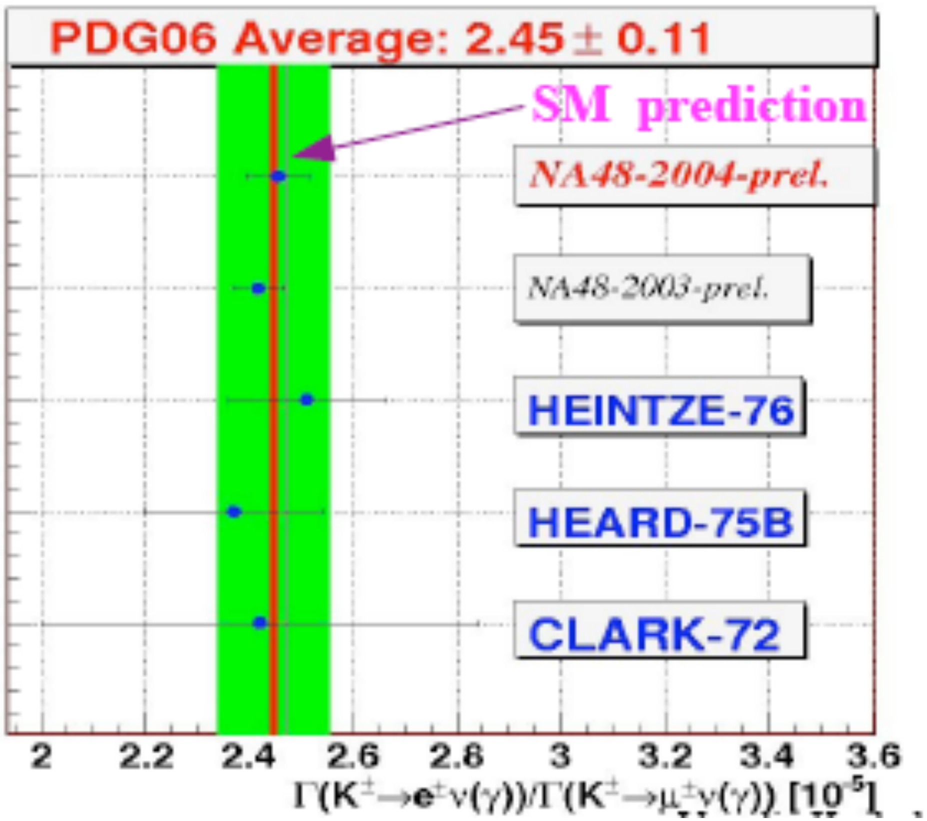
**Total Ke2 events: ( $3407 \pm 63_{stat} \pm 54_{syst}$ )**

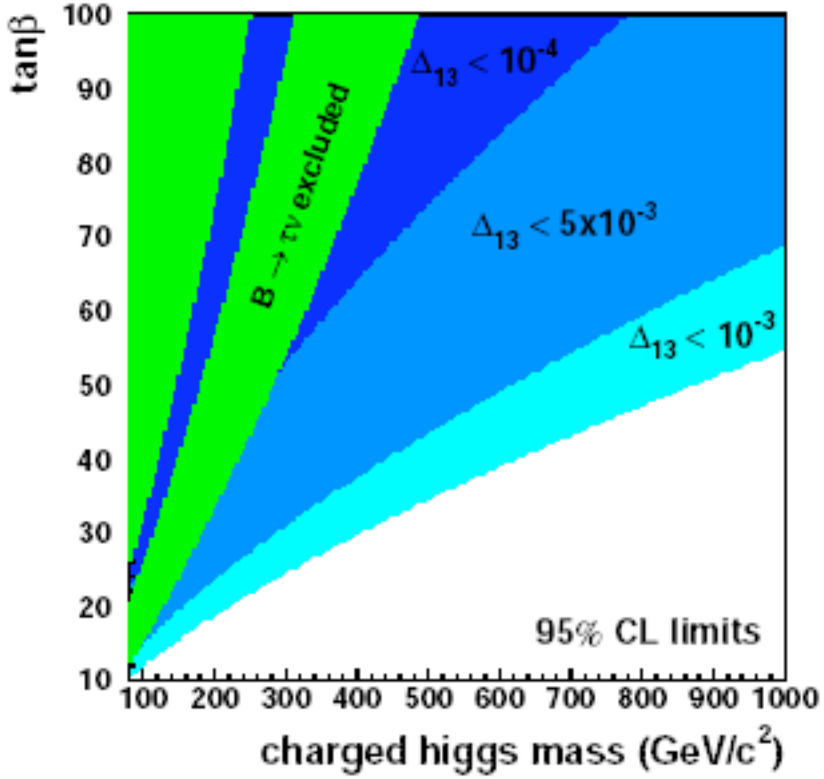
$$R_K = \frac{N_{Ke2raw} - N_{Ke2back}}{TrEff(Ke2) * Acc(Ke2) * C_e} * \frac{Acc(K\mu 2) * C_\mu}{D * (N_{K\mu 2raw} - N_{K\mu 2back})}$$

| | |
|---|---|
| $N_{kl2raw}$ | *Raw Kl2 events* |
| $N_{kl2back}$ | *Background in Kl2* |
| TrEff(Ke2) | *Ke2 trigger efficiency* |
| $C_l$ | *Losses due to E/p cut* |
| Acc(Kl2) | *Kl2 acceptance* |

**NB:** The dominant contribution to the systematics, the background subtraction error, scales with the statistics

| | |
|---|---|
| Standard Model | $(2.472 \pm 0.001) * 10^{-5}$ |
| PDG | $(2.45 \pm 0.11) * 10^{-5}$ |
| NA48: 2004 data | ***$(2.455 \pm 0.045 \pm 0.041) * 10^{-5}$*** |



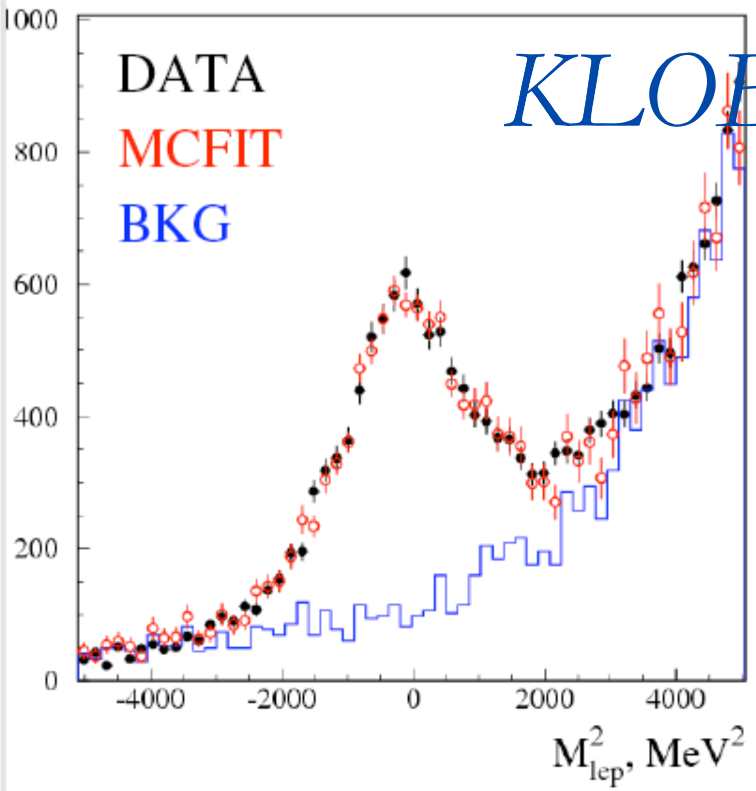

$$l H^{\pm} \nu_{\tau} \rightarrow \frac{g_2}{\sqrt{2}} \frac{m_{\tau}}{M_W} \Delta_{13} \tan^2 \beta$$

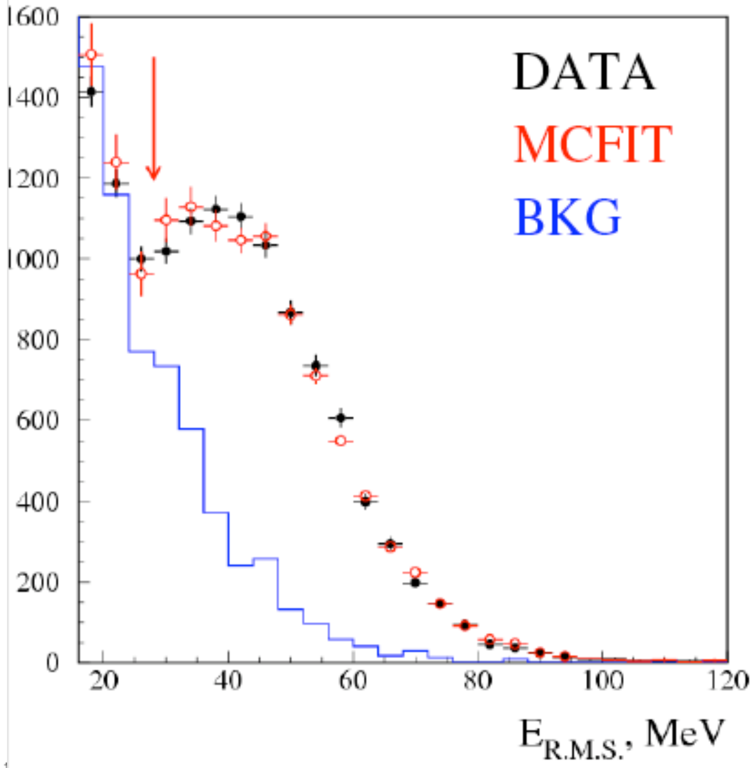
***2007 run to reach 0.3% precision***

$$\Delta_{3j} \sim \frac{\alpha_2}{4\pi} \delta_{3j}$$

slepton flavour mixing angle

# *KLOE: $R_K$*



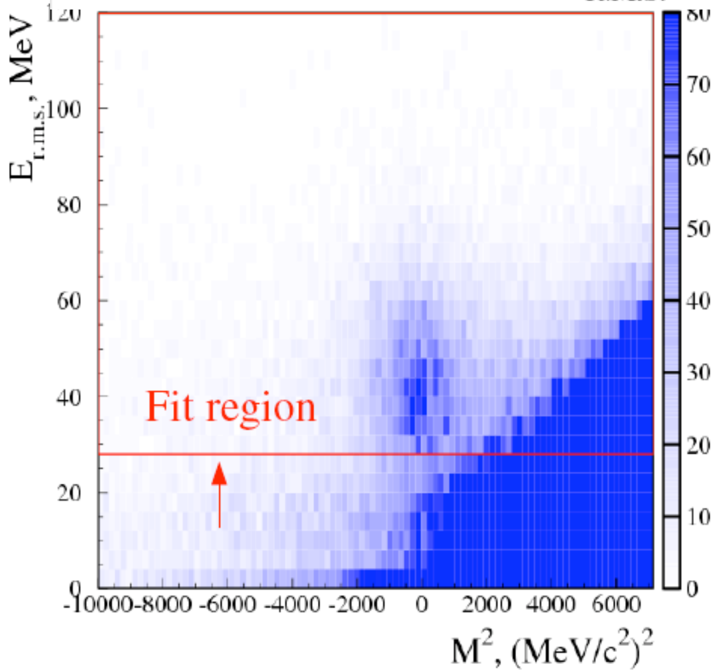




Fit data to the Monte Carlo $E_{rms}$ vs $M^2_{lep}$ distribution using log likelihood

Fit quality is 434/291 n.d.f

Count **8090(156)** events

IB/DE fixed in the fit to the actual PDG value



- Number of $K_{\mu 2}$ events
  - $N_{k\mu 2}$ = **499251584±35403**
- Number of $K_{e2}$
  - $N_{e2}$= **8090±156**

Systematics(fractional):

| | |
|---|---|
| – IB | 0.0005 |
| – IB/DE | 0.003 |
| – TRK+VTX | 0.009 |
| – PID | 0.009±0.015 |
| – TRG | 0.006±0.004 |

Present statistical accuracy 1.9%

Final statistics will be x1.3, counting >10k events

Present stat error dominated by background:

- Signal fluctuation 1.1%
- MC statistics (1.4%)⊕ background fluctuation (0.7%)

1 $fb^{-1}$ of additional MC statistics under production

Cuts still have to be tuned, PID can be improved

***R = (2.55±0.55±0.55)x10$^{-5}$***

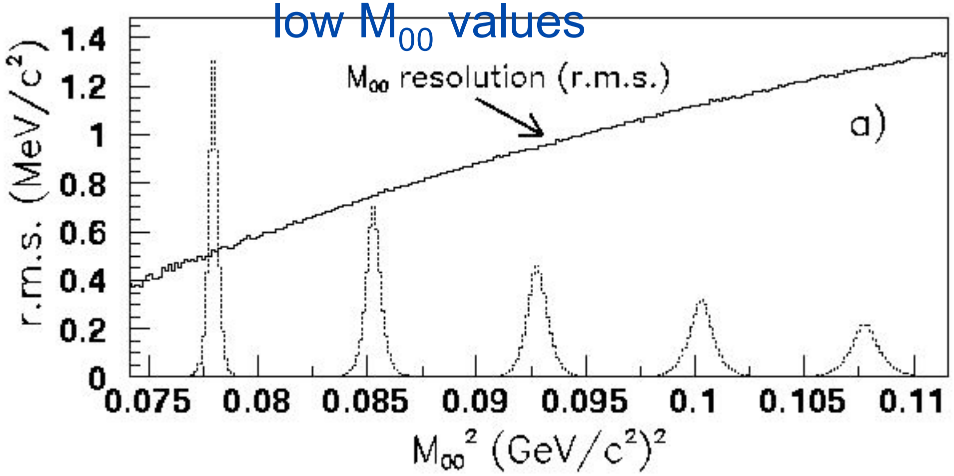
***SM R= (2.472±0.001)x10$^{-5}$***

# *Low-energy QCD*

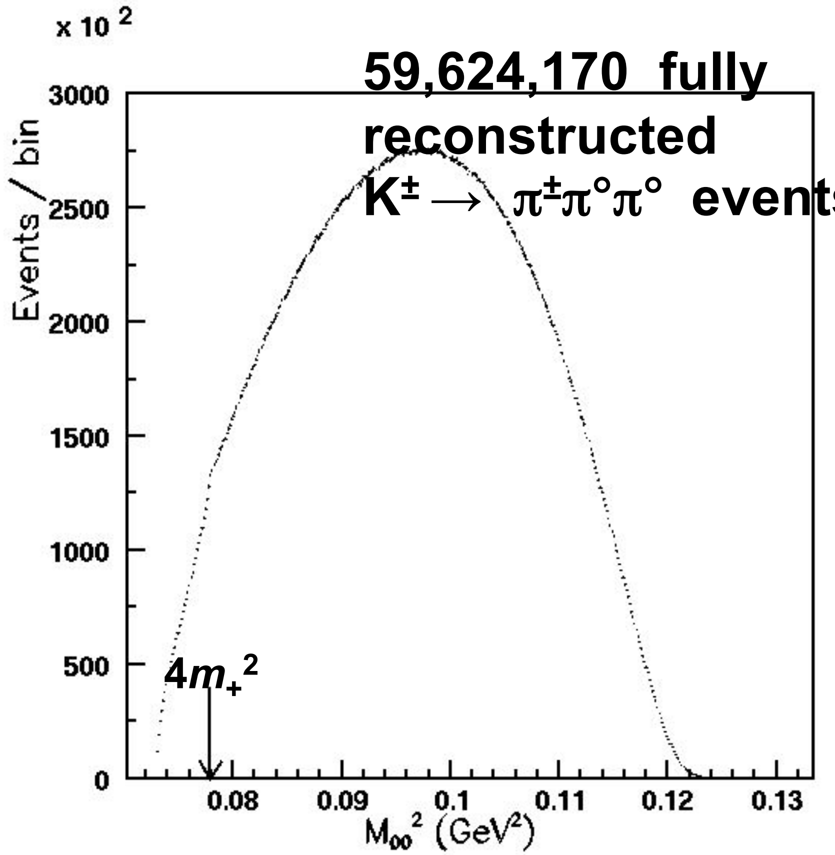
# *NA48: $\pi\pi$ scattering in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$*

**Observation of a cusp structure in the $\pi°\pi°$ invariant mass distribution at $M_{\pi°\pi°} = 2m_{\pi+}$ : an unexpected discovery from the NA48/2**

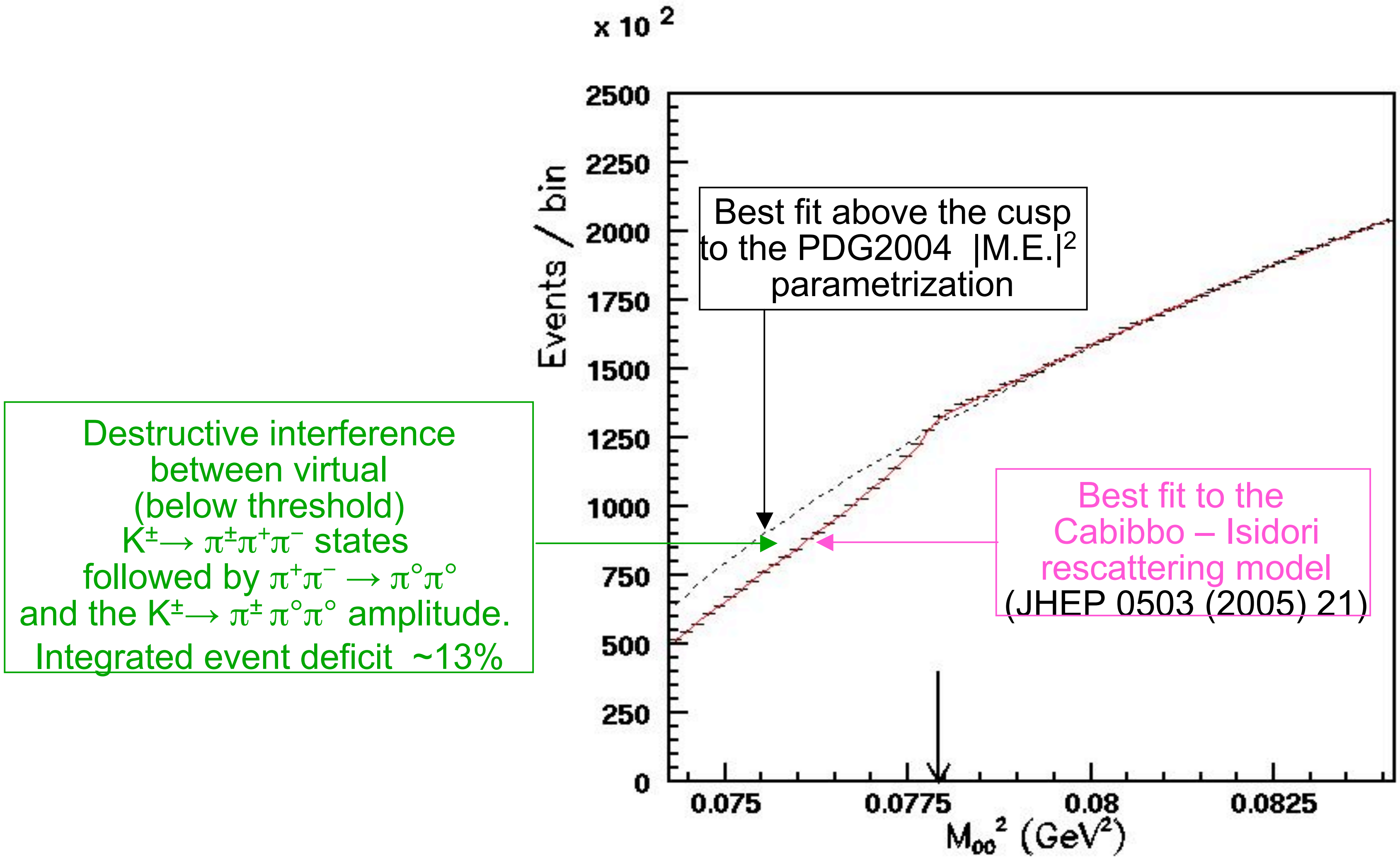
$M_{\pi°\pi°}$ ( ≡ $M_{00}$) resolution optimized for low $M_{00}$ values




**59,624,170 fully reconstructed $K^{\pm} \rightarrow \pi^{\pm}\pi°\pi°$ events**




**$M_{00}$ resolution $\sigma$ = 0.56 MeV at $M_{00} = 2m_+$**




*$\pi\pi$ charge exchange amplitude near threshold is proportional to the difference of scattering lengths a0 - a2 (Cabibbo PRL 93, 2004)*

**Fit results:**

$(a_0 - a_2)m_+ = 0.261 \pm 0.006 \pm 0.003 \pm 0.0013 \pm 0.013$

(stat.) (syst.) (ext.) (theor.)

$a_2 m_+ = -0.037 \pm 0.013 \pm 0.009 \pm 0.002$

**External uncertainty:**

from the uncertainty on the ratio of $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \pi^+\pi^\circ\pi^\circ$ decay widths

**Theoretical uncertainty on $(a_0 - a_2)m_+$:** ± 5%

(estimated effect from neglecting higher order diagrams and radiative corrections)

Fit with analiticity and chiral symmetry constraint between $a_0$ and $a_2$
(Colangelo, Gasser, Leutwyler, PRL 86 (2001) 5008)

$(a_0 - a_2)m_+ = 0.263 \pm 0.003 \pm 0.0014 \pm 0.0013 \pm 0.013$

(stat.) (syst.) (ext.) (theor.)

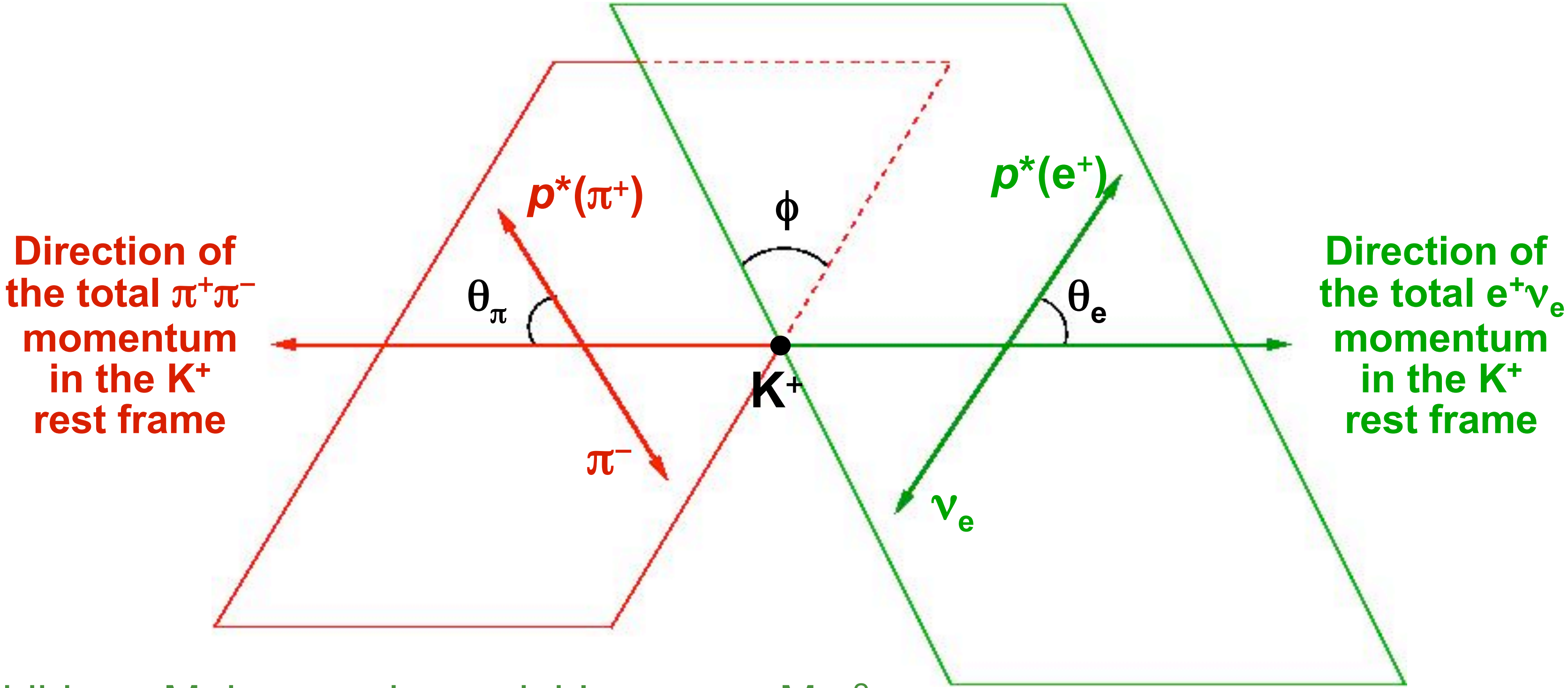
Pionium mean lifetime $\tau_{1s} = (2.91^{+0.24}_{-0.43}) \times 10^{-15}$ s

*DIRAC* $\Longrightarrow |a_0 - a_2| m_+ = 0.264^{+0.020}_{-0.011}$

*Good agreement*

# *NA48: ππ scattering in $K^{\pm}\rightarrow\pi^{+}\pi^{-}e^{\pm}\nu$*

A rare decay [ B.R. = (4.09 ± 0.09) x $10^{-5}$ ] described by five independent variables




Cabibbo – Maksymowicz variables : $s_{\pi} \equiv M_{\pi\pi}^{2}$
$s_{e} \equiv M_{e\nu}^{2}$
$\theta_{e}$
$\theta_{\pi}$
$\phi$

**For $K^{+} \Rightarrow K^{-}$**
**$\phi \Rightarrow \pi + \phi$**
**$\theta_{e} \Rightarrow \pi - \theta_{e}$**

partial wave expansion of the amplitude:

F, G = Axial Form Factors

$F = F_s e^{i\delta s} + F_p e^{i\delta p} \cos\theta_\pi + \text{d-wave term...}$

$G = G_p e^{i\delta g} + \text{d-wave term...}$

H = Vector Form Factor

$H = H_p e^{i\delta h} + \text{d-wave term...}$

expansion in powers of $q^2$ , $Se/4m\pi^2$

$(q^2 = (S_\pi/4m_\pi^2 - 1))$

$$F_s = f_s + f_s' q^2 + f_s'' q^4 + f_e\left(S_e/4m_\pi^2\right) + ..$$

$$F_p = f_p + f_p' q^2 + ..$$

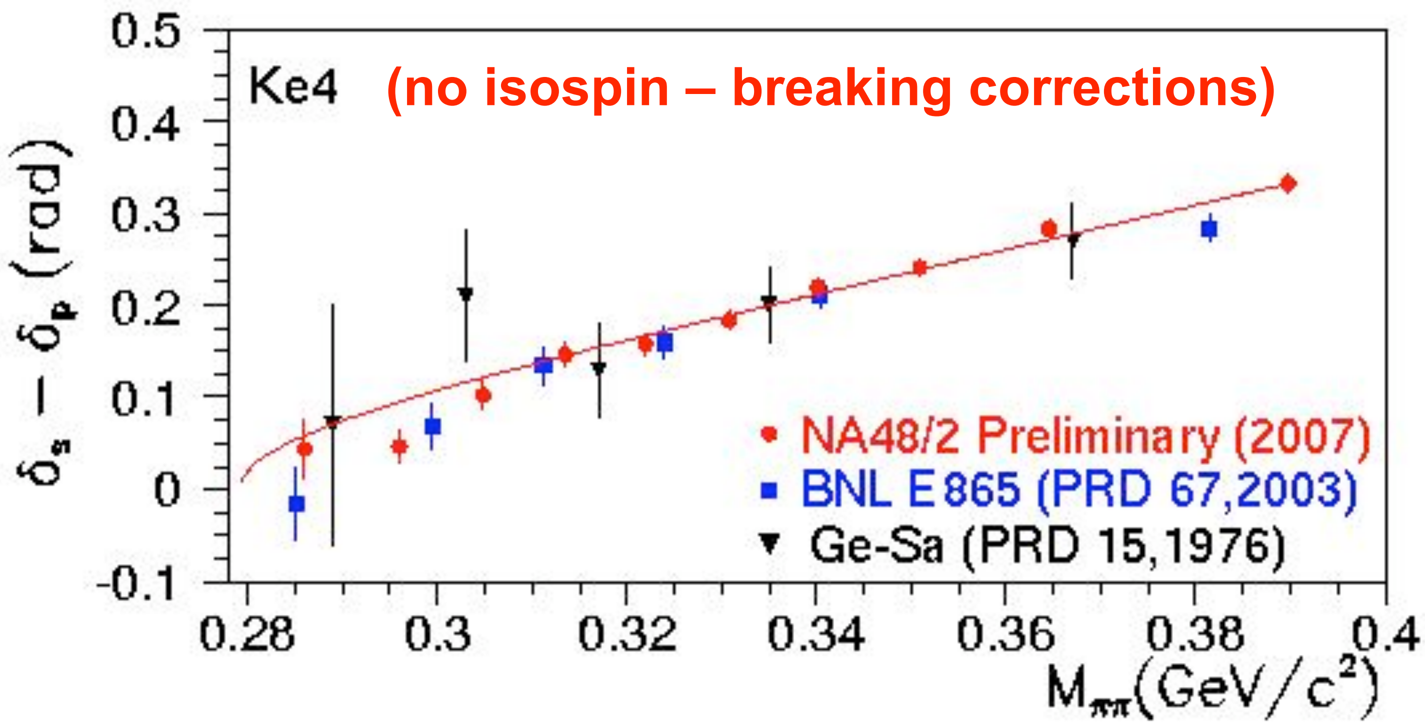
$$G_p = g_p + g_p' q^2 + ..$$

$$H_p = h_p + h_p' q^2 + ..$$

*Fit parameters:* $F_s$ $F_p$ $G_p$ $H_p$ and $\delta = \delta_s - \delta_p$

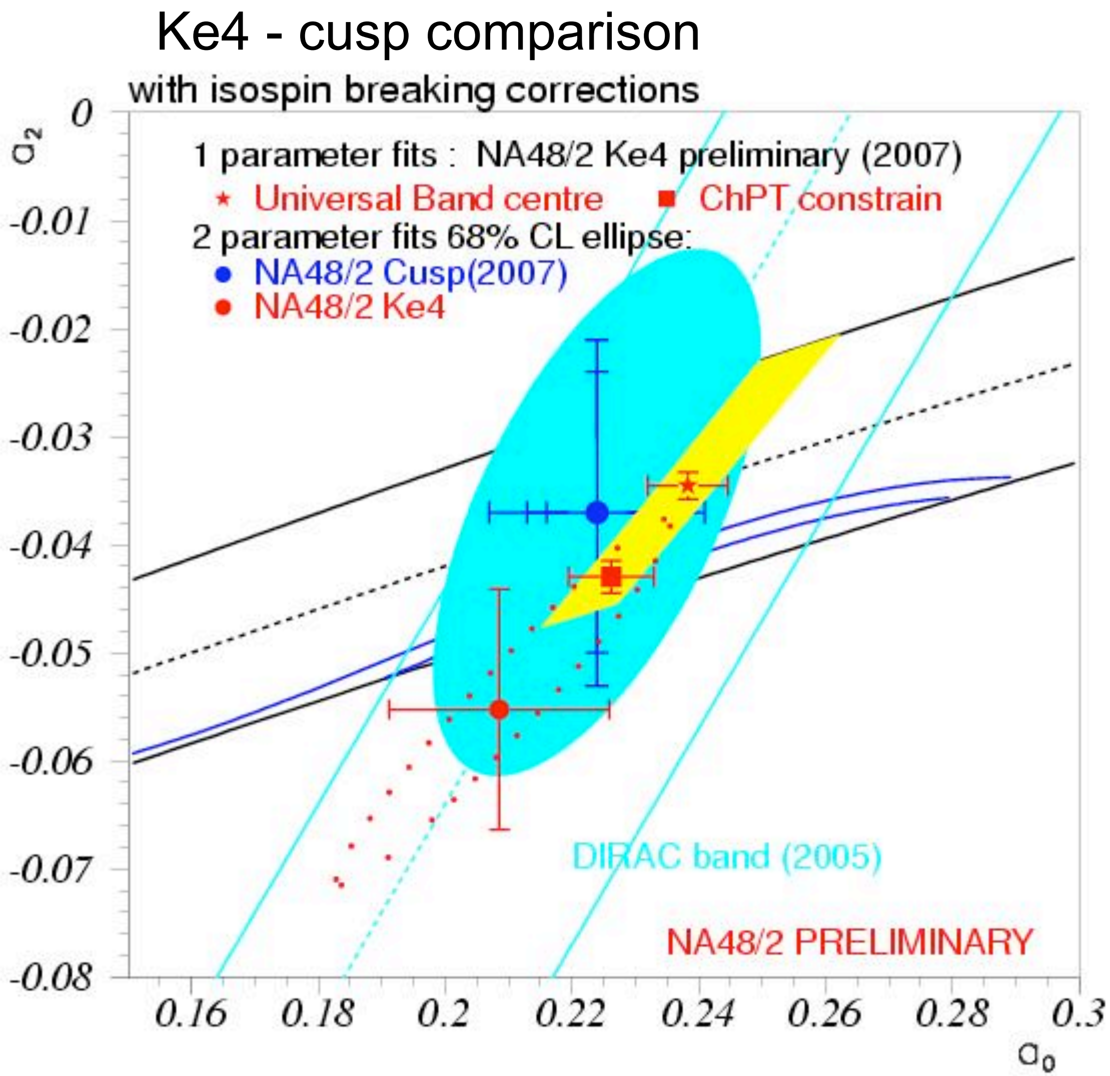
*Ten independent fits, one in each $M_{\pi\pi}$ bin.*
*This allow a model independent analysis*
*Without the overall normalization, one can quote relative form factors and their variation with $q^2$*
*Fs is obtained from relative bin to bin normalization data/MC after fit*

*To relate scattering lengths to δ, external data and theoretical work needed*
*An example is numerical solution of Roy equations (DFGS EPJ C24, 2002)*
*The centre line parameterization corresponds to a 1-param fit with fixed relation* $a_0^2 = f(a_0^0)$

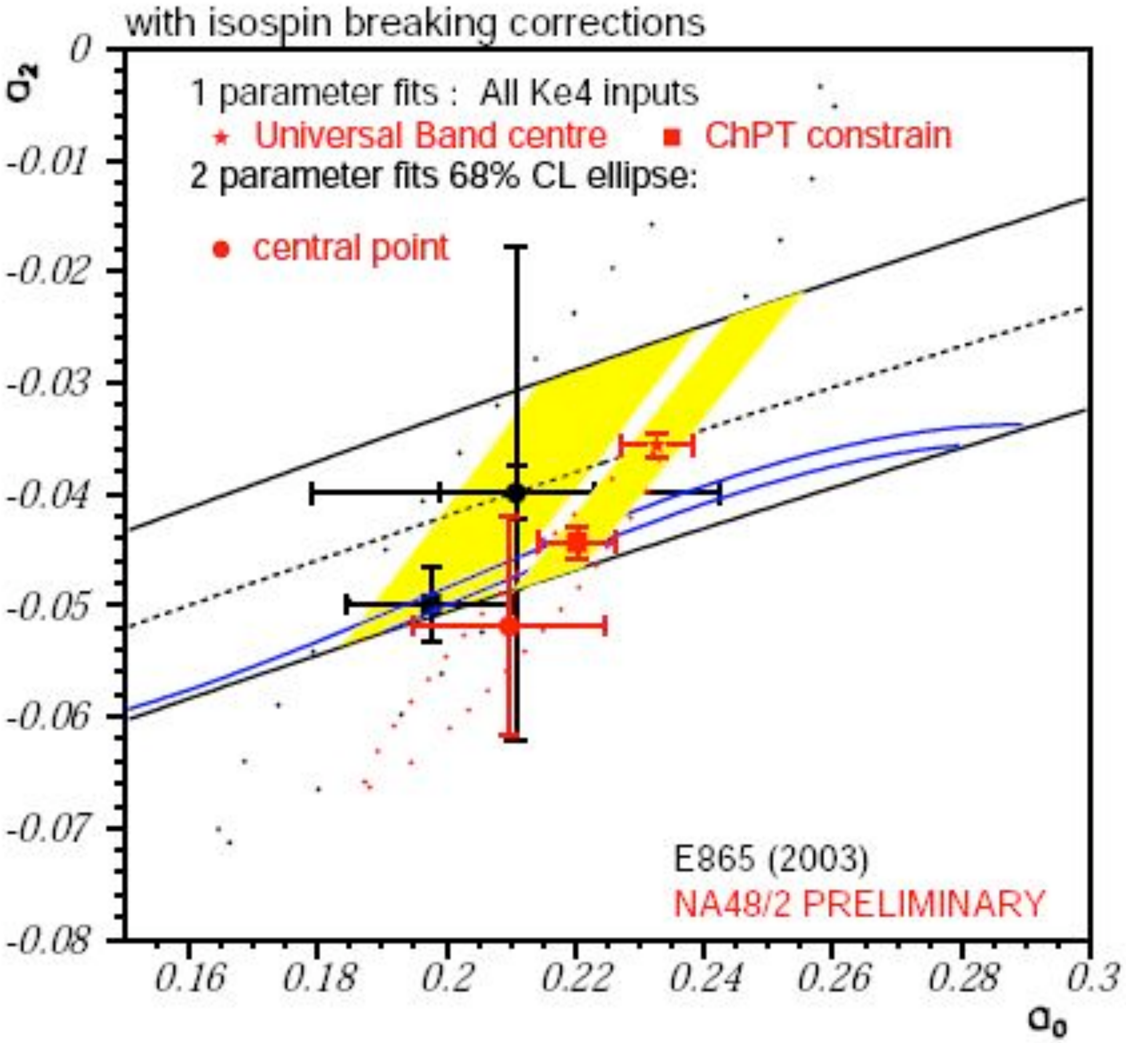



Geneva – Saclay : ~ 30,000 events , $p_{K^+}$ = 2.8 GeV/c
BNL E865 : 406,103 events (with ~ 4.4% background), $p_{K^+}$ = 6 GeV/c
NA48/2 : 677,510 events (with ~0.5% background), $p_{K^\pm}$ = 60 GeV/c
(the isospin – breaking corrections reduce δ by 0.01 – 0.012)

*One can correct measured Ke4 for isospin symmetry breaking before extracting $a_0^0$ (Gasser, 2007)*



*One can correct measured Ke4 for isospin symmetry breaking before extracting $a_0^0$ (Gasser, 2007)*




Ke4:
NA48/2 – BNL E865
comparison

## *Future experiments:* $K^{\pm} \rightarrow \pi^{\pm} \nu\nu$

*Given the great phenomenological success of the SM up to LEP energies and the limitations/unsatisfactory aspects of the model above the e.w. scale*
*$\Rightarrow$ natural to consider the SM as an effective theory*
*or the low-energy limit of a more fundamental theory with new degrees of freedom appearing above some energy threshold $\Lambda$*

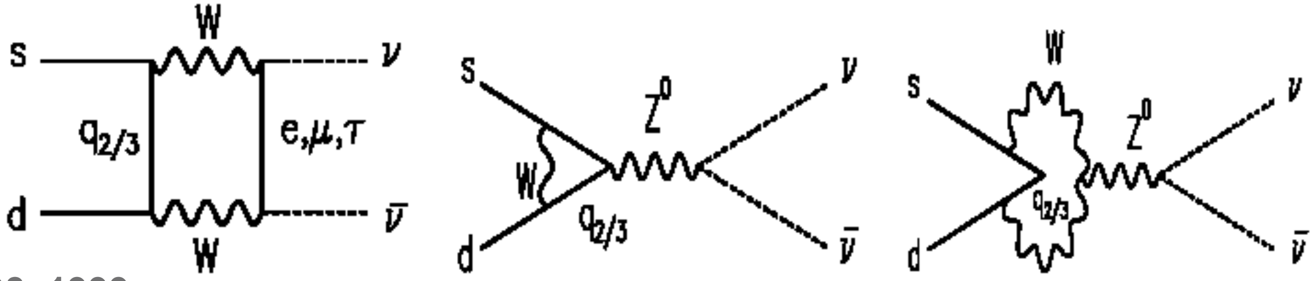
*High-energy experiments are the key tool to determine the energy scale of the new d.o.f. via their direct production*

*Low-energy experiments are a fundamental ingredient to determine the symmetry properties of the new d.o.f. via indirect effects in precisions observables*

*Precision measurements in the flavour sector allow us to study the flavour symmetries of physics beyond the SM*

*Rare FCNC decays and $\Delta F=2$ processes are the oservable more sensitive to new flavour-breaking couplings*

# $K\to\pi\,\nu\nu$ : SM Theoretical Prediction




NLO Calculation:
Buchalla & Buras: 1993, 1999
Misiak, Urban: 1999

$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$

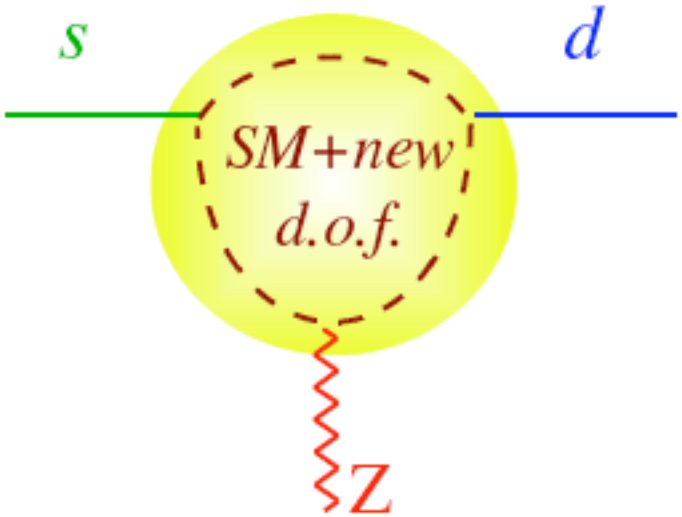
$$B(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \cdot \left[ \left( \frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left( \frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

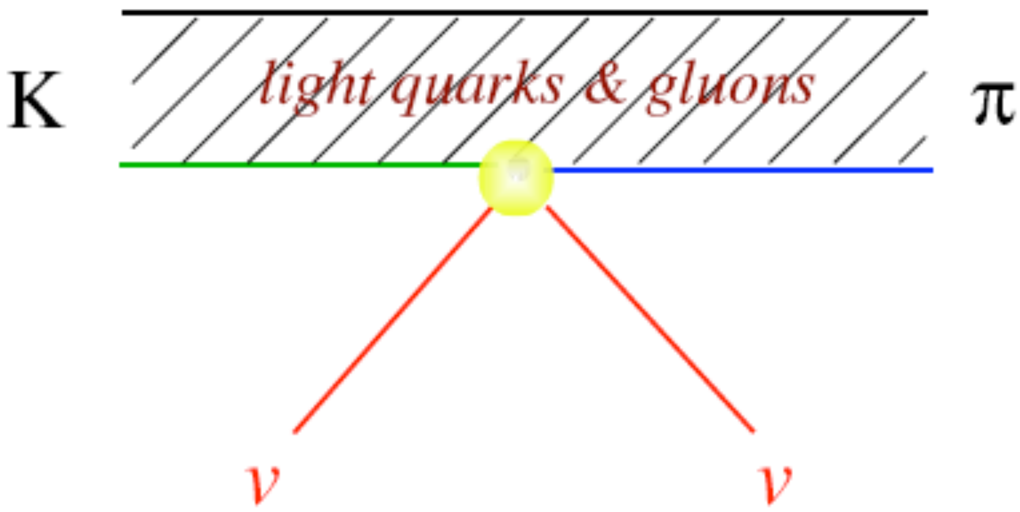
$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) = \kappa_L \cdot \left( \frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

charm contribution
NNLO
Buras, Gorbahn,
Haisch, Nierste

top
contributions

$$\kappa_+ = r_{K^+} \cdot \frac{3\alpha^2 Br(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W} \cdot \lambda^8$$




- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Predicted with high precision within the SM at the short-distance level

*Rare sensitivity and cleanness, even in B system*

*88% of total rate*
*irred. theo. error = 3%*

$$A(K \to \pi\nu\nu) = f\left(c_{SM}\frac{y_t^2\, V_{ts}^*V_{td}}{16\,\pi^2\, M_W^2} + c_{new}\frac{\Delta_{sd}}{\Lambda^2}\;;\;\delta_{long}\right)$$

*hadronic matrix element from BR($K^+ \to \pi^0 e^+ \nu$)*

*energy scale of new d.o.f*

## Two basic scenarios: *according to G.Isidori*

**Minimal Flavour Violation**

flavour symmetry broken only by the (SM) Yukawa couplings

↓

- Small deviations (10-20%) from SM
- Stringent correlations among the two $K \to \pi\nu\nu$ modes and a few rare B decays [$B\to K\nu\nu$, $B_{s,d} \to l^+l^-$ ]

A precise exp. info on one of the two $K\to \pi\ \nu\nu$ modes is a key ingredient to verify or disproof the MFV hypothesis

**New sources of Flavour Symmetry breaking around the TeV scale**

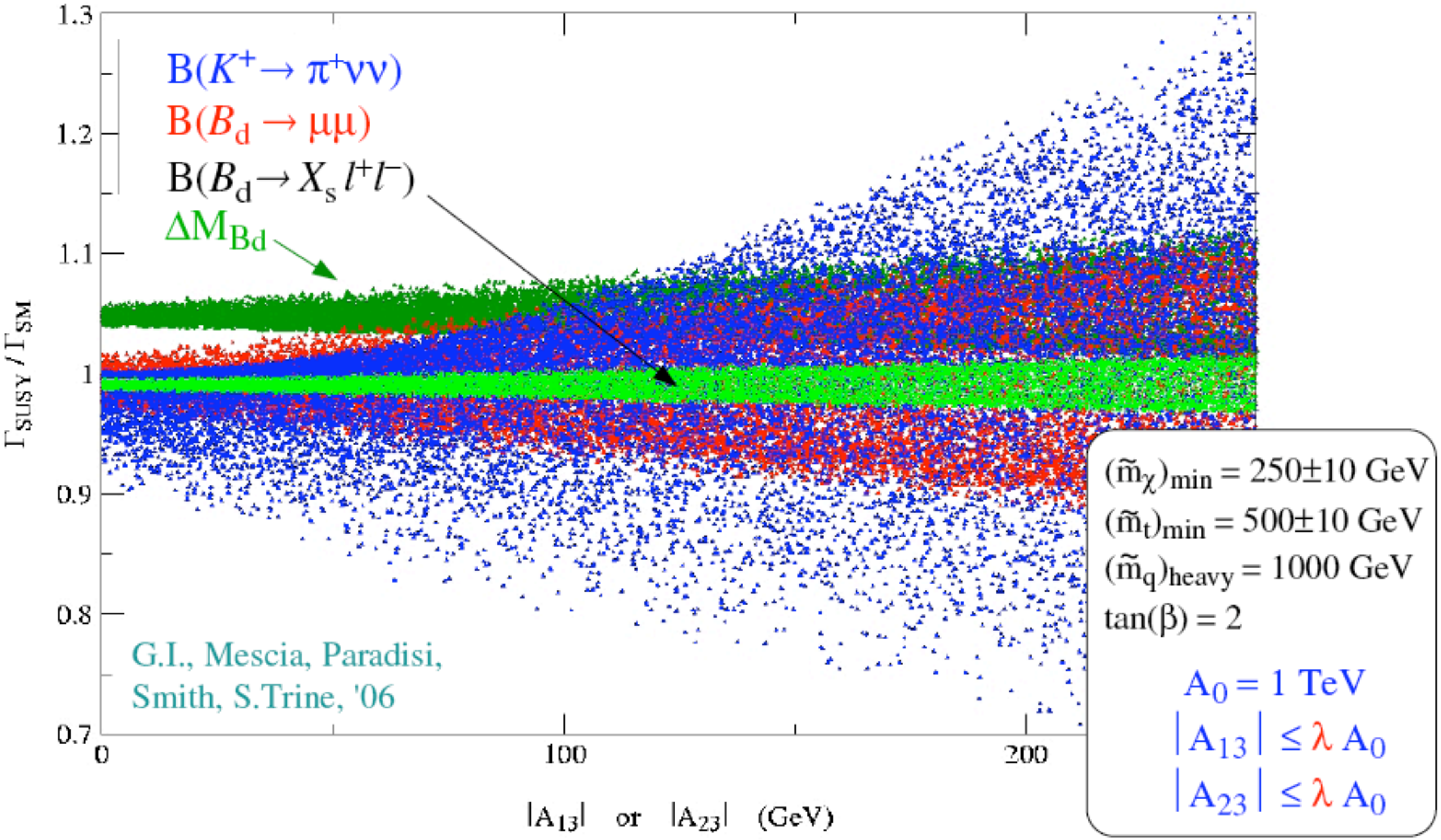
↓

- Potentially large effects, especially in the three CPV $K_L$ decays (no $\lambda^5$ suppression)
- Correlations with observables in B physics not obvious

In presence of sizable non-MFV couplings mandatory to explore also the $K_L \to \pi\ ll$ modes

- Non-standard effects induced by chargino-squarks amplitudes largely dominant in $K \to \pi\nu\nu$ with respect to similar effects in B physics
- The A terms are still largely unconstrained

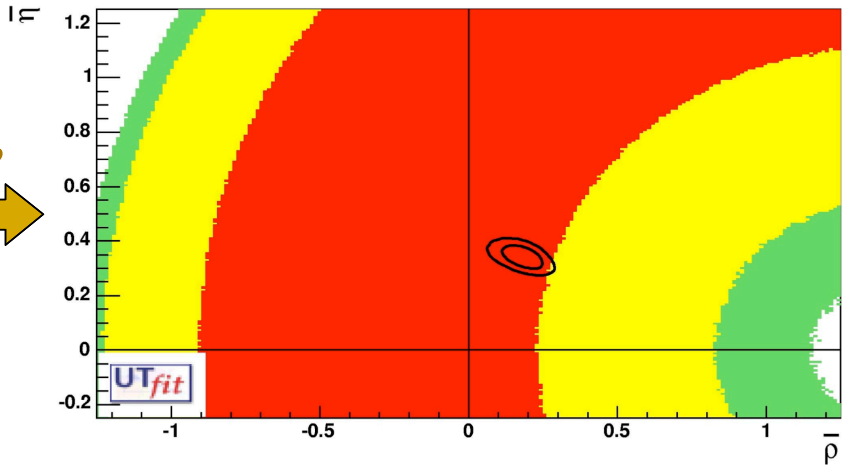
*squark-sector trilinear terms*



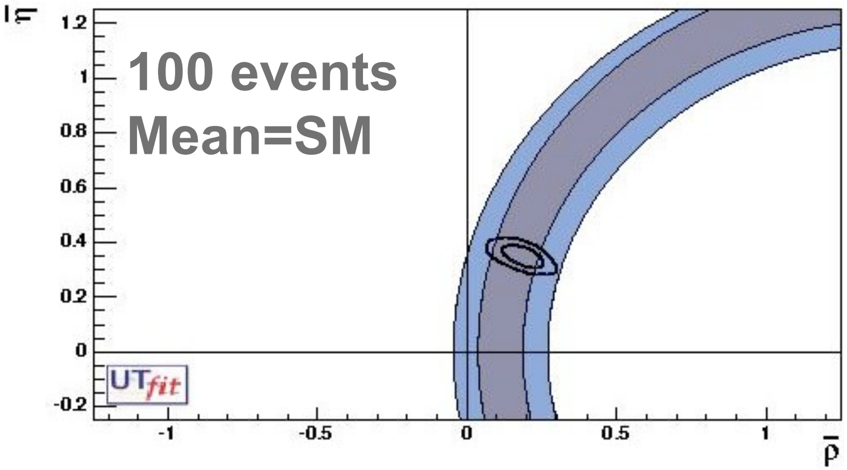
*SM expectation = (8.0±1.1) x $10^{-11}$ dominated by CKM uncertainty*

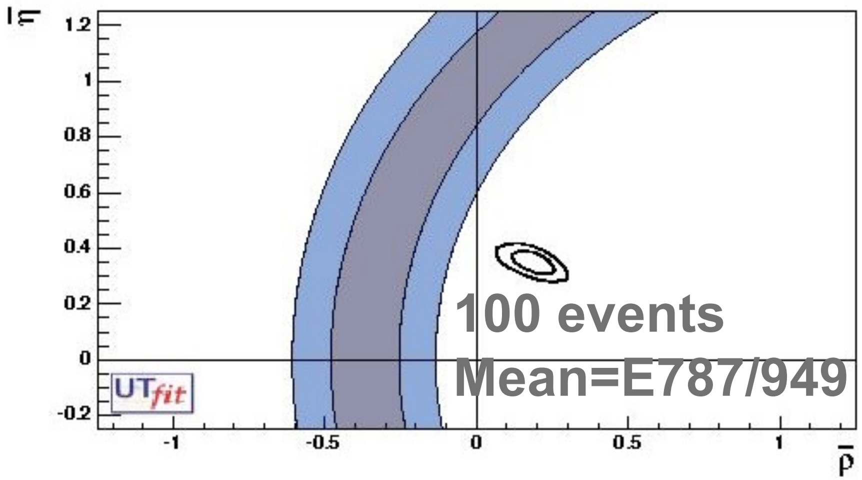
*3 events* **E787/E949: $BR(K^+ \to \pi^+ \nu\nu) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$**

**Current constraint on ρ, η plane**

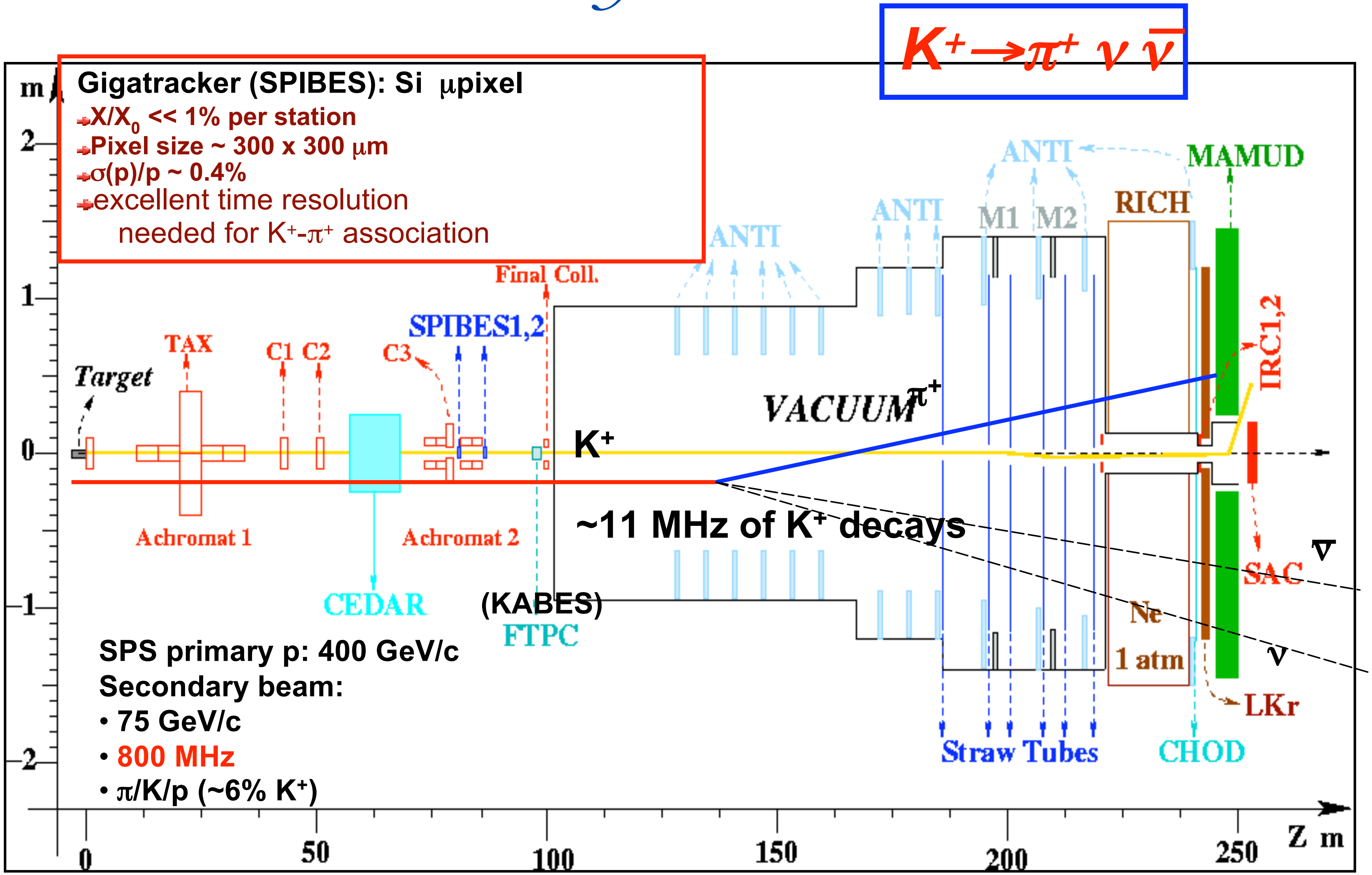



?

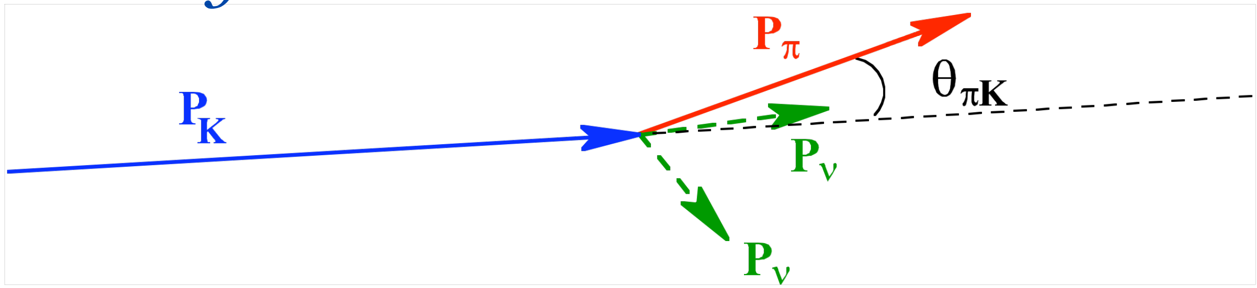


# NA62 Detector Layout

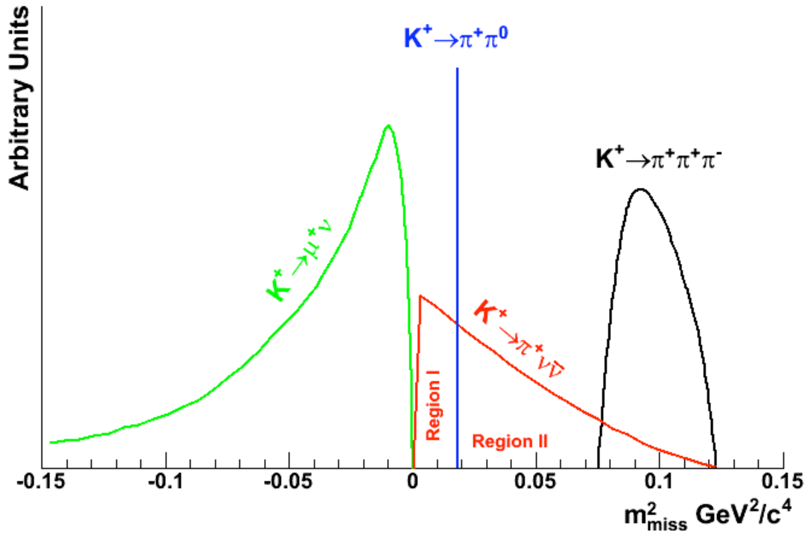


# Background rejection




1) Kinematical Rejection

$$m^2_{miss} \approx m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta^2_{\pi K}$$



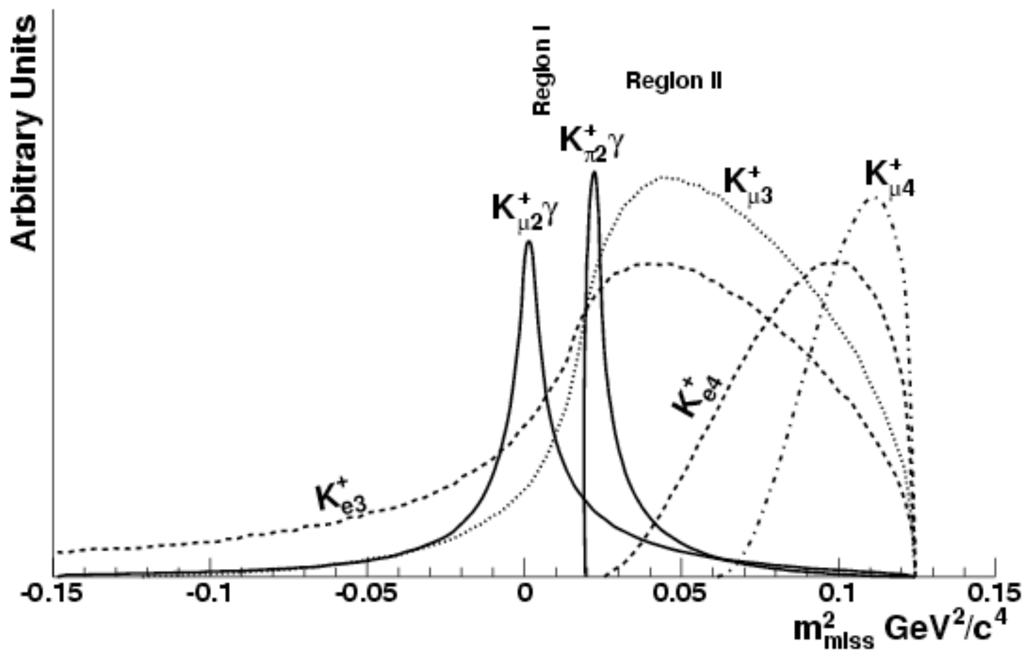

*I: 0<m<0.01*
*II: 0.026<m<0.068*

2) Photon vetoes to reject $K^+\to\pi^+\pi^0$ :

P($K^+$) = 75 GeV/c
Requiring P($\pi^+$) < 35 GeV/c
P($\pi^0$) > 40 GeV/c ➡ It can be hardly missed in the calorimeters!!

3) PID (RICH) for $K^+\to\mu^+\nu$ rejection

# Non kinematically constrained backgrounds




*Veto rejection and particle identification are essential*

# Conclusions

*Many new results from all the kaon experiments:*
*- Vus and CKM unitary test : compatibility with unitary at -0.9 $\sigma$*
*- RK and LFV tests: sensitivity of 2% reached but more data to come, so far no sign of LFV*
*- pion-pion scattering lengths from cusp and ke4 agree, limited by theoretical uncertainty*

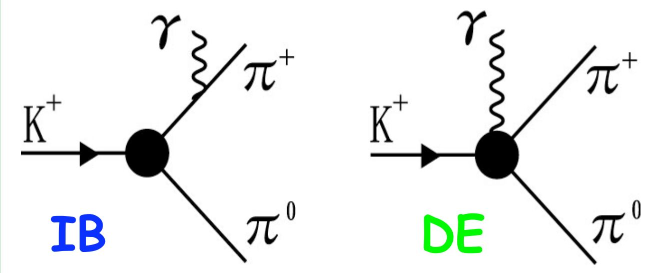
*I didn't have time to show results on radiative decays and test of $\chi$PT and CPV:*
*$K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$ : first evidence for interference between IB and DE contributions*
*BR($K_L\to\pi^{0}\gamma\gamma$) : KTeV and NA48 agree, also with $\chi$PT*
*BR($K_S\to\gamma\gamma$) : KLOE and NA48 disagree*
*CPV charge kaon asymmetry reach a sensitivity of $10^{-4}$, and new measurement of $\eta_{+-}$*

*Future Kaon experiments to measure rare decays*
*$K^{0}\to\pi^{0}\nu\nu$ (JPARC) and $K^{\pm}\to\pi^{\pm}\nu\nu$ (CERN)*
*Kaon physics is still very much alive !*

# *Spares:*

# *Spares: Radiative decays*

# $NA48: K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$

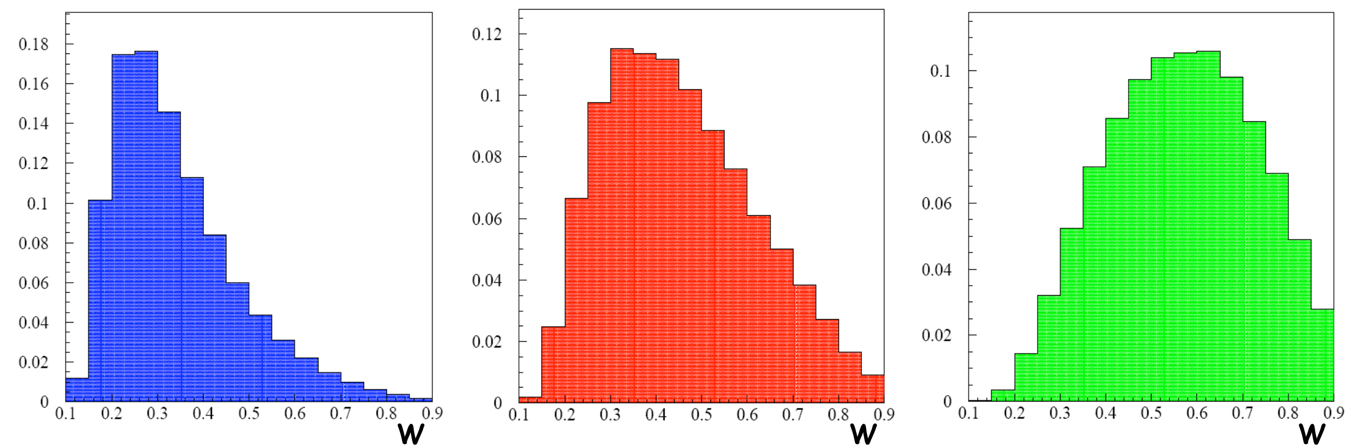



$$\frac{d\Gamma^{\pm}}{dW} \simeq \left(\frac{d\Gamma^{\pm}}{dW}\right)_{IB} \left[1 + 2\left(\frac{m_\pi}{m_K}\right)^2 W^2 |E| cos((\delta_1 - \delta_0) \pm \phi) + \left(\frac{m_\pi}{m_K}\right)^4 W^4 (|E|^2 + |M|^2)\right]$$

**IB**
from $K^{\pm} \to \pi^{\pm}\pi^{0}$

**INT**
sensitive to electric dipole

**DE**
sensitive to electric & magnetic dipole



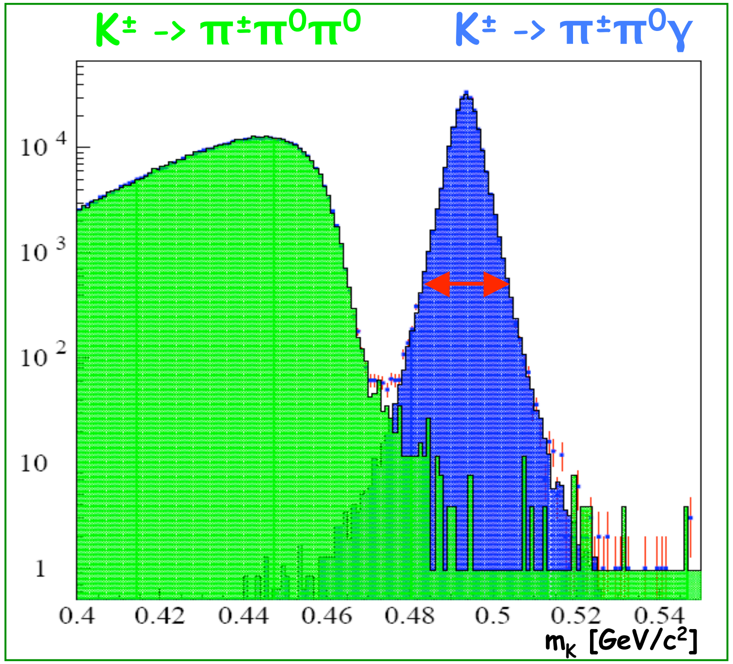

$$W^2 = \frac{(P_K^* \cdot P_\gamma^*)(P_\pi^* \cdot P_\gamma^*)}{(m_k m_\pi)^2}$$

| | | |
|---|---|---|
| **PDG** (55 MeV < $T^*_\pi$ < 90 MeV) | IB: | $(2.75 \pm 0.15)\cdot 10^{-4}$ |
| | DE: | $(4.4 \pm 0.8)\cdot 10^{-6}$ |
| | INT: | not yet measured |

$P^*_K$ = 4 momentum of the $K^{\pm}$
$P^*_\pi$ = 4 momentum of the $\pi^{\pm}$
$P^*_\gamma$ = 4 momentum of the radiative $\gamma$

## What's new in NA48/2 measurement?

- Simultaneous $K^+$ and $K^-$ beams -> check for CP-Violation
- Enlarged $T^*_\pi$ region in the low energy part (0÷80 MeV)
- Negligible background contribution (<1% of the DE component)
- γ miss-tagging probability ~ ‰ for IB, DE and INT



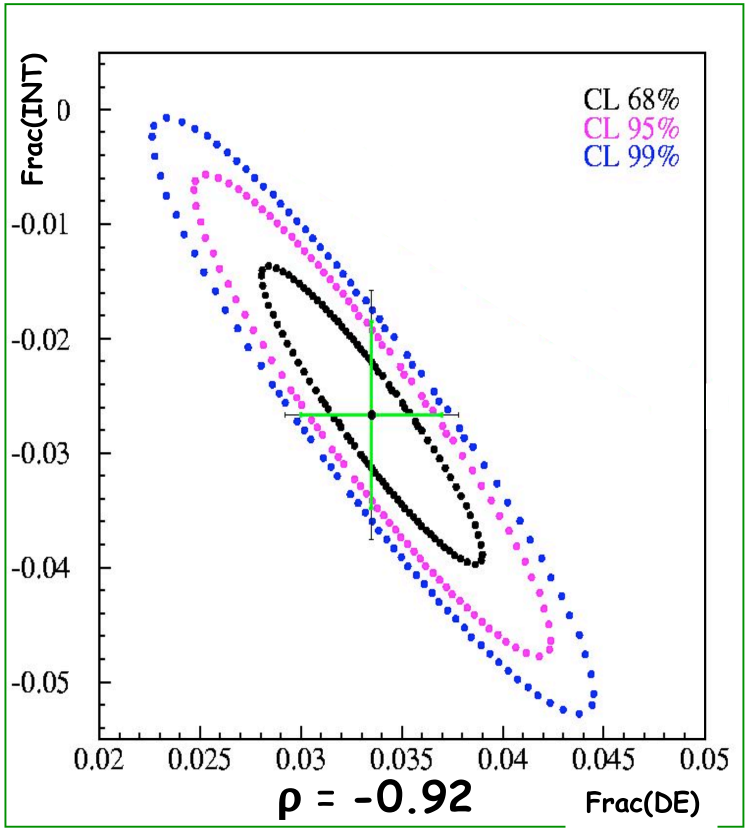

**After all cuts the background estimation is <1% of DE and can be explained in terms of $K^\pm \to \pi^\pm\pi^0\pi^0$**

Use extended Maximum Likelihood for $0.2 < W < 0.9$ to fit in the region 0 MeV < $T^*_\pi$ < 80 MeV (based on $124 \cdot 10^3$ events)

Fit performed with free INT term

Systematics dominated by trigger efficiency

-> First evidence of Interference between Inner Bremsstrahlung and Direct Emission amplitudes




$\text{Frac(DE)} = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\ \%$
$\text{Frac(INT)} = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\ \%$

*Preliminary*

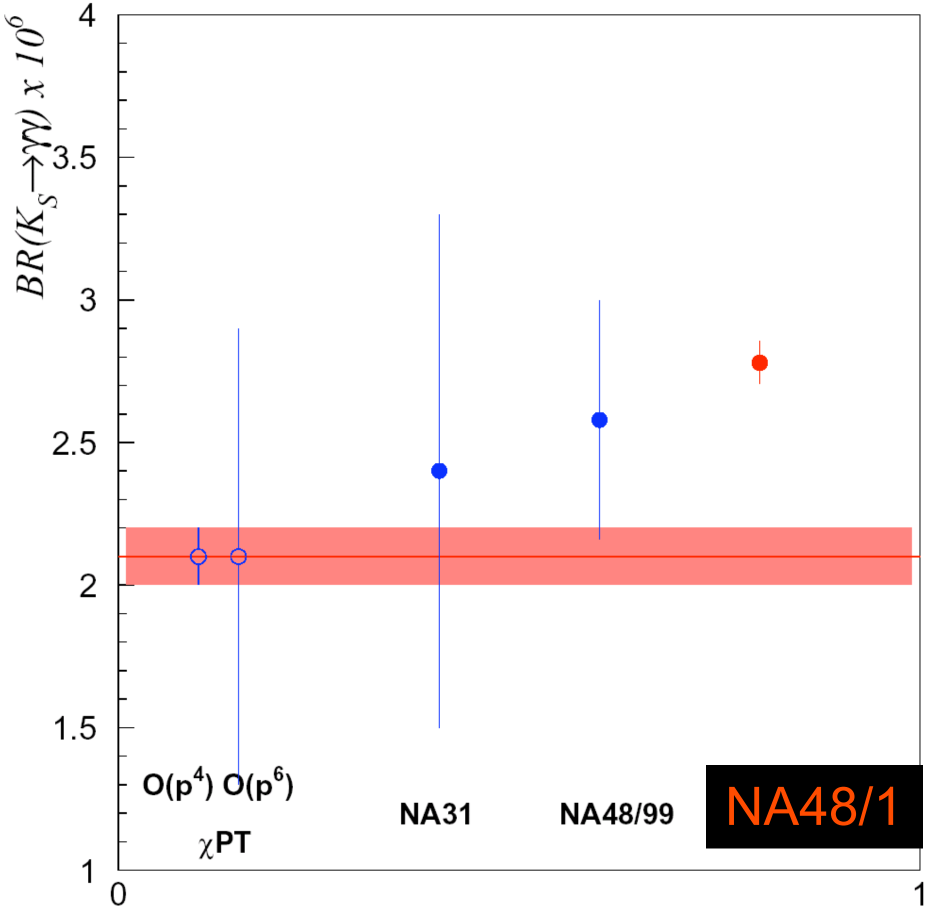
# KLOE: $K_S \to \gamma\gamma$

- It is a good test for ChPT
  (PRD 49 (1994) 2346)
- Experimental value of the BR changed along the years
- From 2003 it is known with a small error (3%) :

**$BR(K_S \to \gamma\gamma) = (2.71 \pm 0.06 \pm 0.04) \times 10^{-6}$**

due to a measurement of NA48/1 collaboration

- Differs from ChPT $O(p^4)$ by 30% (possible large $O(p^6)$ contribution).




In **NA48**, the $K_L \to \gamma\gamma$ background is a relevant component of the fit.

In **KLOE**, the background from $K_L$ is reduced to 0 (tagging).

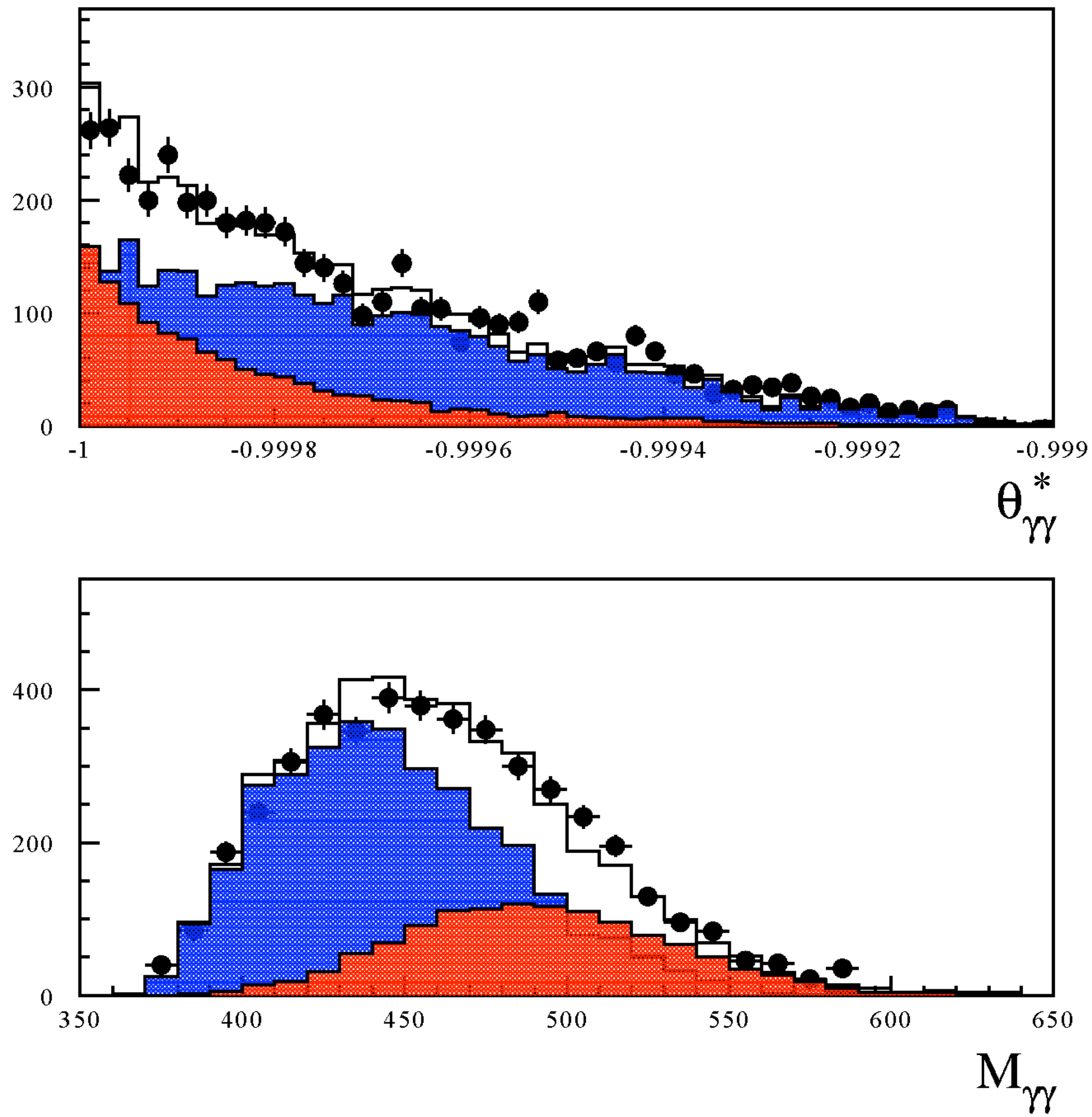
**First measurement of this decay with a pure $K_S$ beam.**

***From 1.6 fb$^{-1}$***

To extract the number of signal, the 2D-plot in data is fit using signal and background shapes from MC

**$N_{sig}$ = 600.3 ± 34.8**
**(5.8% stat. error)**

- •• DATA
- -- MC all
- Signal
- Background




***Background dominated by $K_s \rightarrow 2\pi^0$***

$$BR(K_S \to \gamma\gamma) = N_{\gamma\gamma} \times \frac{\varepsilon_{2\pi^0}(tot \mid K_L - crash)}{\varepsilon_{SIG}(tot \mid K_L - crash)} \times \frac{BR(K_S \to 2\pi^0)}{N_{2\pi^0}}$$

- Where for the signal:

**$\varepsilon_{SIG}$ (tot| $K_L$-crash) = ε(presel) x ε(veto) x ε($\chi^2$) =**

**= (50.8 ± 0.6)%**

- For the normalization sample, we count events with 4 prompt photons:

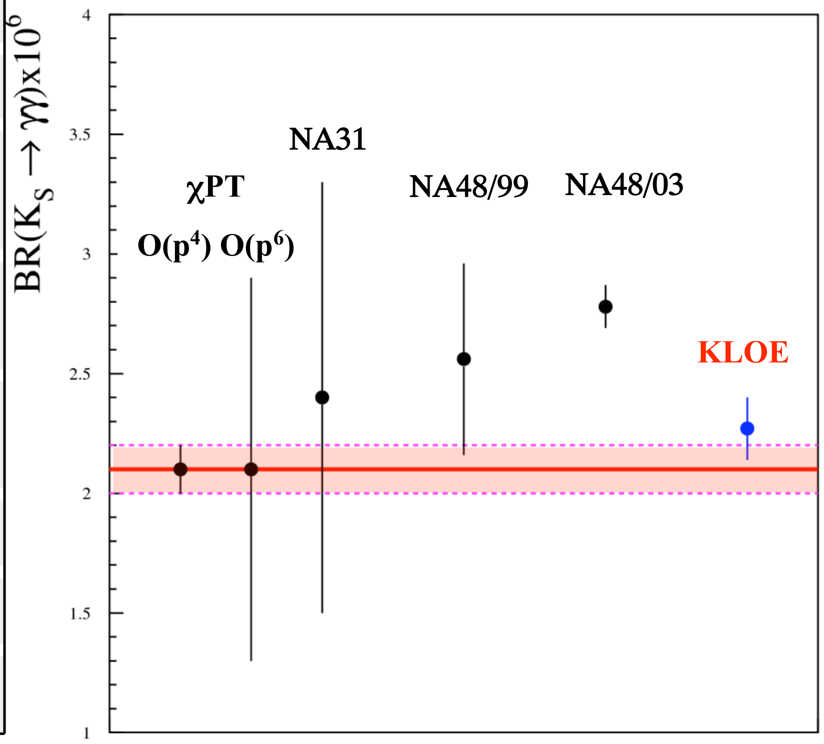
**$\varepsilon_{2\pi 0}$ (tot | $K_L$-crash) = $(65.0 \pm 0.2_{stat} \pm 0.1_{sys})\%$**

**$N_{2\pi 0}$ = 159.8 Mevts**

Systematics mainly due to application of data-MC correction curve for cluster efficiency.
Cross checked with counting (3-5) prompt photons (159.5 Mevts)

$$BR(K_S \to \gamma\gamma) = \left(2.27 \pm 0.13_{stat} \; {}^{+0.03}_{-0.04}\right) \times 10^{-6}$$

| Source | +Syst (%) | -Syst (%) |
|---|---|---|
| Signal acceptance | 0.12 | 0.12 |
| QCAL | 0.88 | 0.51 |
| $\chi2$ cut | 0.44 | 0.44 |
| $\chi2$, $\theta_{\gamma\gamma}$ scale from signal | --- | 0.55 |
| Fit procedure | 0.88 | 0.44 |
| Energy scale | --- | 1.32 |
| Norm sample | 0.15 | 0.15 |
| **Total** | **+1.33** | **-1.65** |



# *KLOE: Ke3γ*

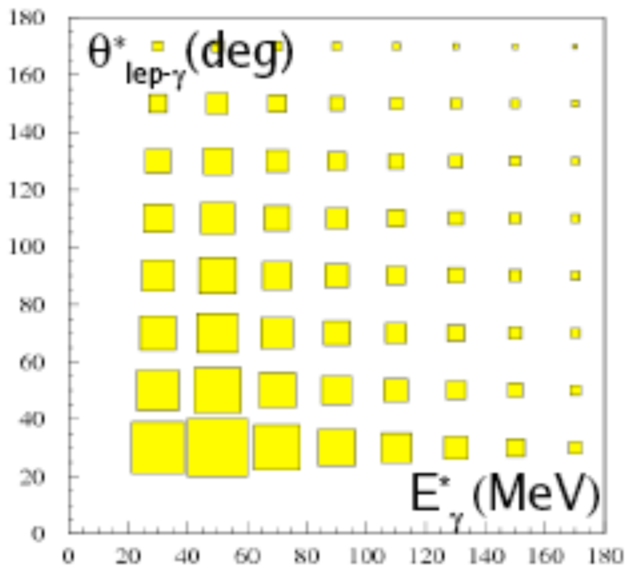
We measure R = **BR**(Ke3γ ; $E^*_\gamma$>30 MeV, $\theta^*_{lep\text{-}\gamma}$>20°) / **BR**( Ke3(γ)),

using a 328 $pb^{-1}$ 2001-2002 data sample ;

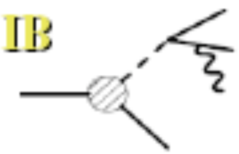
Both IB and DE emission contribute to R;

Separation between IB and DE never measured(*); for the first time the DE contribution is measured ;

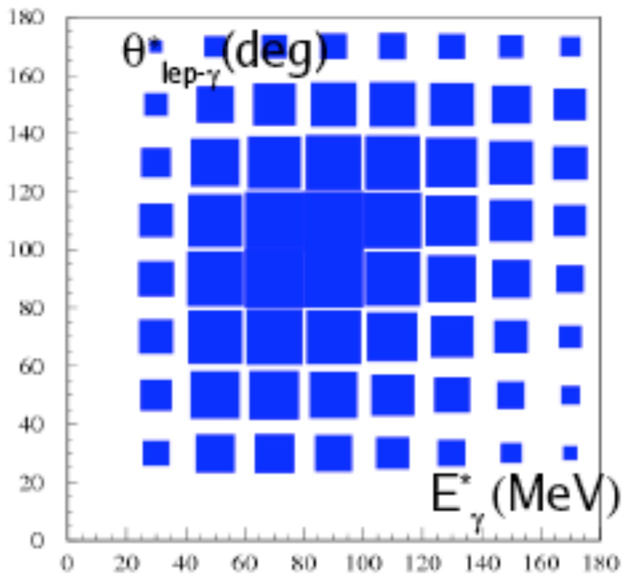
What needs : $E^*_\gamma$-$\theta^*_{ele\text{-}\gamma}$ analysis + low BKG




IB



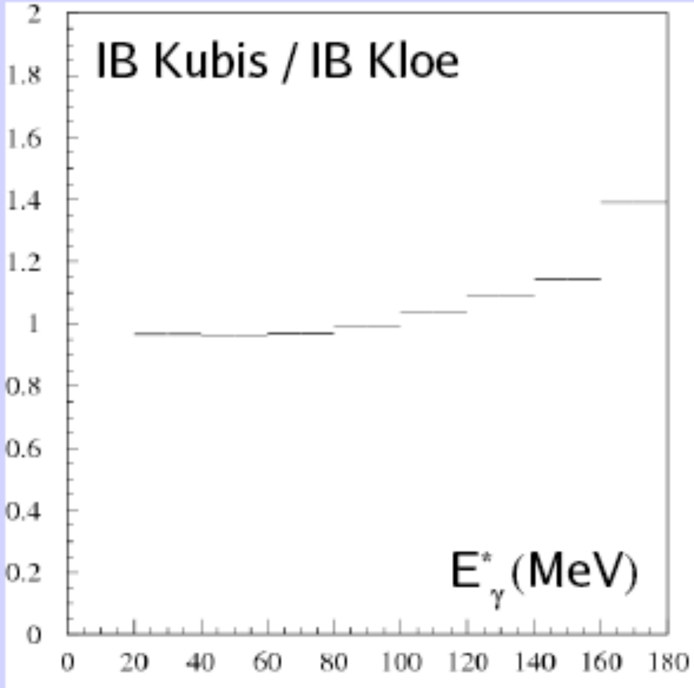
DE

# Monte Carlo Reliability

- *BR*($K_{e3\gamma}$) is largely dominated by the IB, as the DE contribution via IB–DE interference is ~1% level (pure DE is negligibly). DE e ects becomes more significant at high energy, but the number of events is severely reduced.

- KLOE MC [(1)], $\mathcal{O}(p^2)$ accuracy ~ few % for $K_{e3\gamma}$ after integration, but DE contribution ~1% IB -> δ(DE)~100%
- We use a stand alone MC production for IB and DE , $\mathcal{O}(p^6)$ [(2)]




KUBIS-MC~14 mill, KLOE-MC~270000

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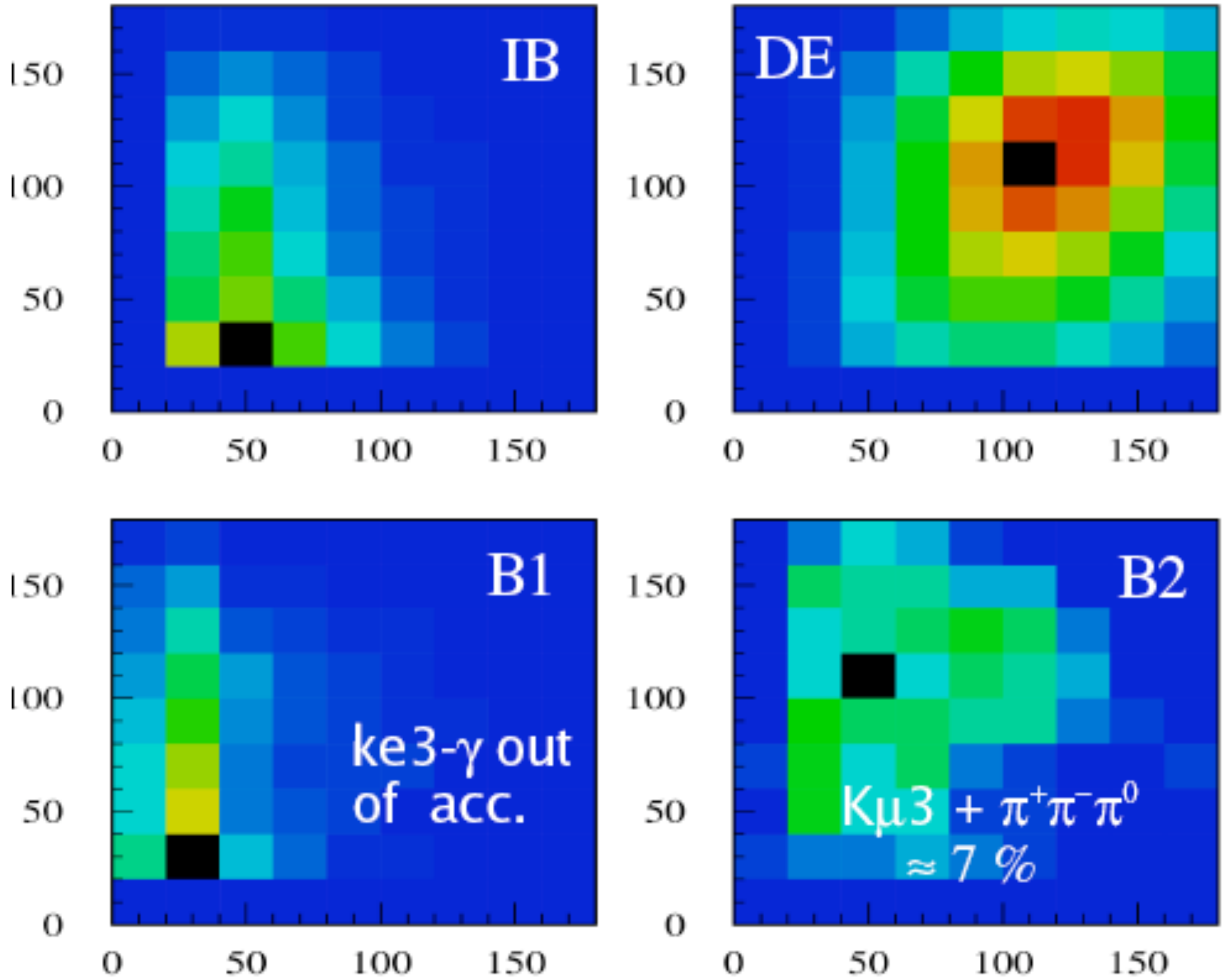
(1) C.Gatti, "*Monte Carlo Simulation for radiative kaon decay*" Eur.Phys. J C45 (2006) 417

(2) *J. Gasser, B. Kubis, N. Paver, M. Verbeni* Eur.Phys. J C40 (2005) 205




Inputs => 4 MC shapes

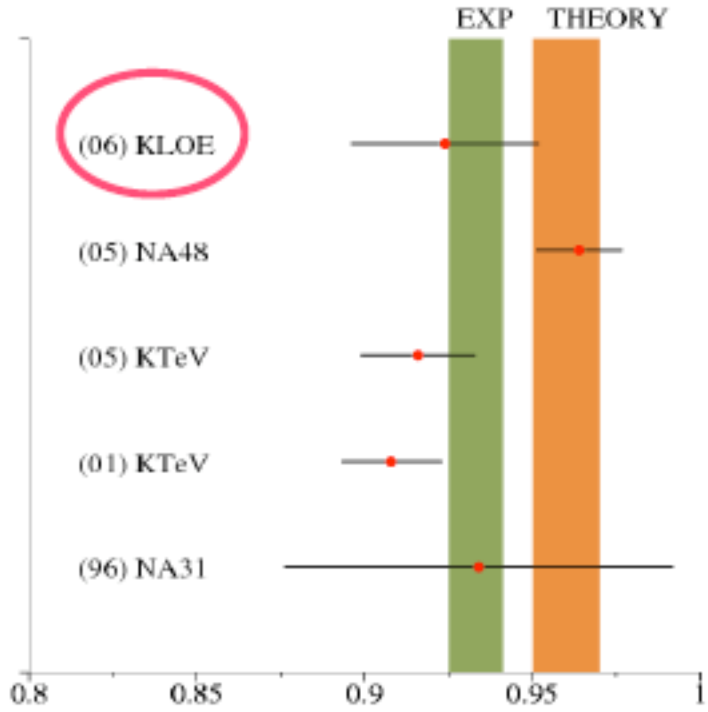
**free parameters = IB + B1 + DE normalization**

**fixed** = B2, from MC normalized to Data

**Goodness of fit** => $\chi^2$/dof = 60/69

$$R = (924 \pm 23_{stat} \pm 16_{syst}) \times 10^{-5}$$

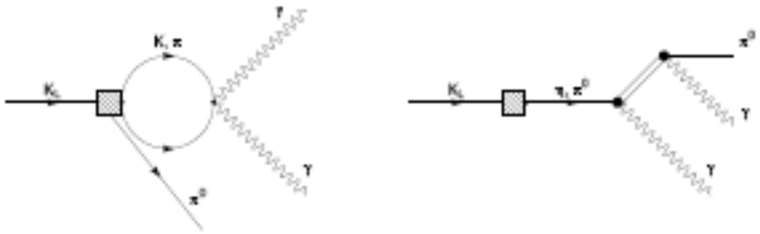
Gasser J. et al, Eur.Phys. J C40 (2005) 205




- **DE:** first measurement of DE contribution; it is in agreement with $\chi PT@O(p^6)$ prediction ;
- **R**: our accuracy on R is not sufficient to solve experimental disagreement ;

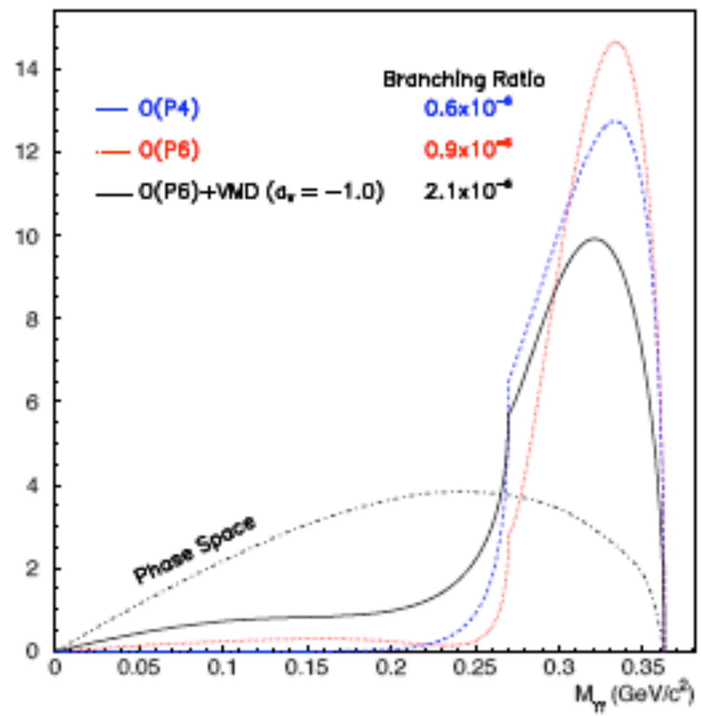
- KTeV measurement refers to a phenomenological model for DE , the FFS model [1], based on four parameters. No enough sensitivity to measure all parameters -> *soft kaon approximation* ;

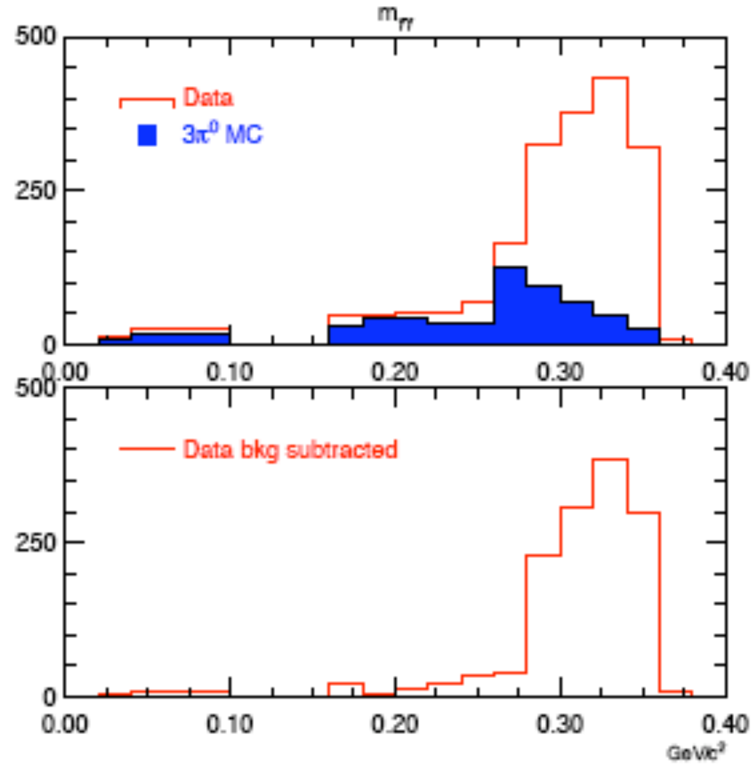
# KTeV: $K_L \rightarrow \pi^0\gamma\gamma$



- $\mathcal{O}(p^4)$ chiral perturbation calculations
  - No free parameters $\rightarrow$ BR$(K_L \rightarrow \pi^0\gamma\gamma) = 0.6 \times 10^{-6}$
  - Prediction low by factor of 2-3.
  - $\mathcal{O}(p^6)$ calculations increase rate.
  - Addition of VMD terms further increases rate ($a_V$).
    - Major background comes from $3\pi^0$ decays with 4 clusters in the calorimeter.
      - With missing $\gamma$, event reconstructs downstream.
      - Photon vetoes help reduce this background.

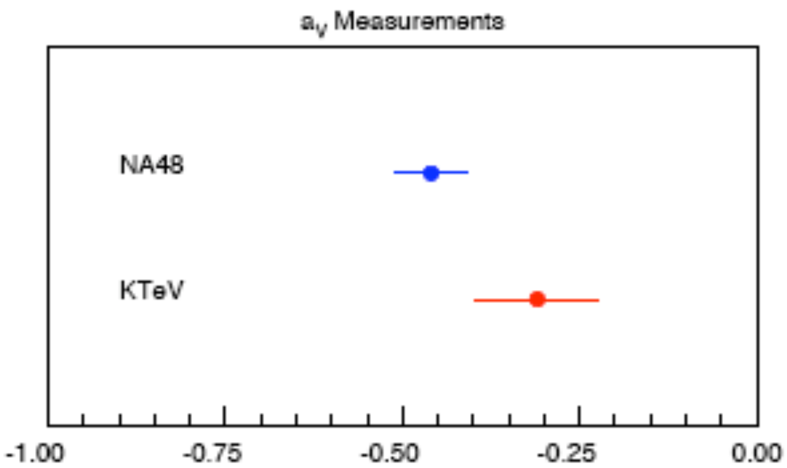
## ***Full data set***

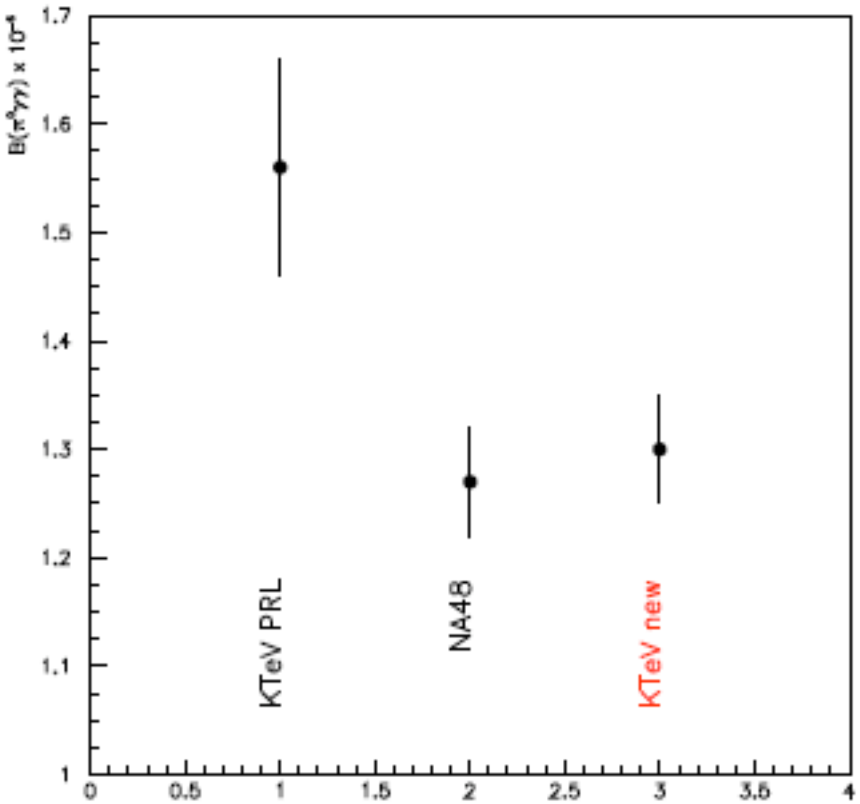



Candidates: 1982, Background: 601, $K_L \to 2\pi^0$ events: 919,322

- Underestimate of background led to higher value in previous KTeV result.
  - New results consistent with published NA48 result.
- Result supercedes previous KTeV result.
- All BR adjusted to new $K_L \to \pi^0\pi^0$ BR.



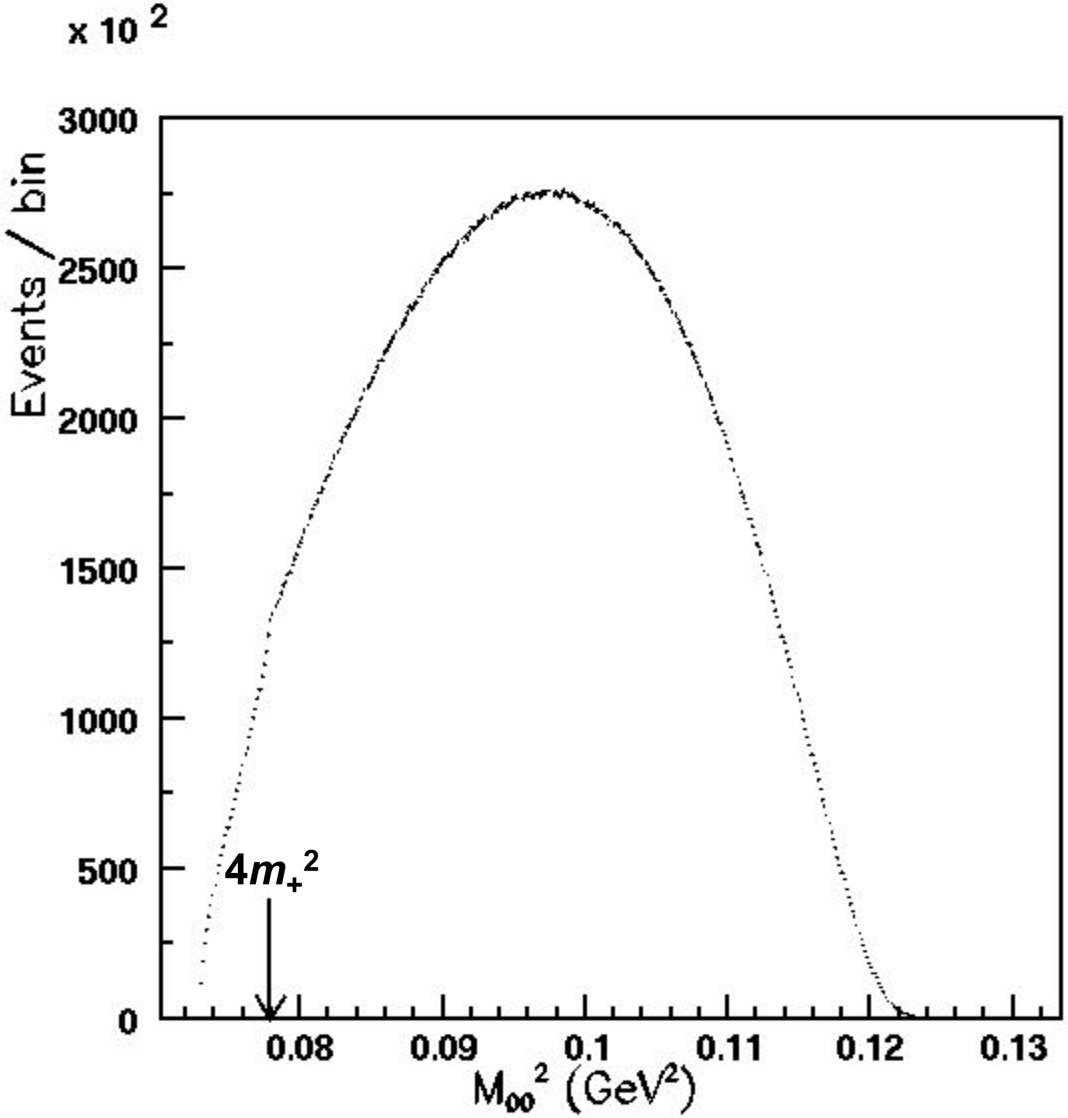

$$\mathrm{BR} = (1.30 \pm 0.03 \pm 0.04) \times 10^{-6}$$

$$a_V = -0.31 \pm 0.05 \pm 0.07$$

# *Spares : Cusp*

# NA48/2 (PRELIMINARY)

**59,624,170 fully reconstructed $K^{\pm} \rightarrow \pi^{\pm}\pi^{\circ}\pi^{\circ}$ events**




$m_+ \equiv m(\pi^+)$

## Fit results:

$(a_0 - a_2)m_+ = 0.261 \pm 0.006 \pm 0.003 \pm 0.0013 \pm 0.013$

(stat.) (syst.) (ext.) (theor.)

$a_2 m_+ = -0.037 \pm 0.013 \pm 0.009 \pm 0.002$

(the sensitivity to $a_2$ comes from higher-order terms)

**External uncertainty:**

from the uncertainty on the ratio of $K^+ \rightarrow \pi^+\pi^+\pi^-$ and $K^+ \rightarrow \pi^+\pi^\circ\pi^\circ$ decay widths:

$$\frac{\Gamma(K^+ \rightarrow \pi^+\pi^+\pi^-)}{\Gamma(K^+ \rightarrow \pi^+\pi^0\pi^0)} = 3.182 \pm 0.047$$

**(PDG 2006)**

giving $$\frac{A(K^+ \rightarrow \pi^+\pi^+\pi^-)}{A(K^+ \rightarrow \pi^+\pi^0\pi^0)} = 1.975 \pm 0.015$$ at the Dalitz plot centres ($u = v = 0$)

(exact isospin symmetry predicts 2)

**Theoretical uncertainty on $(a_0 - a_2)m_+$:** ± 5%

(estimated effect from neglecting higher order diagrams and radiative corrections)

**Fit with analiticity and chiral symmetry constraint**
**between $a_0$ and $a_2$** (Colangelo, Gasser, Leutwyler, PRL 86 (2001) 5008)

$(a_0 - a_2)m_+ = 0.263 \pm 0.003 \pm 0.0014 \pm 0.0013 \pm 0.013$

(stat.) (syst.) (ext.) (theor.)

Pionium mean lifetime $\tau_{1s} = (2.91^{+0.24}_{-0.43}) \times 10^{-15}$ s

*DIRAC* $\Longrightarrow$ $|a_0 - a_2| m_+ = 0.264^{+0.020}_{-0.011}$

**NA48/2 :** $(a_0 - a_2)m_+ = 0.261 \pm 0.006 \pm 0.003 \pm 0.0013 \pm 0.013$

stat. syst. ext. theor.

Very little theoretical uncertainty in the prediction of the pionium lifetime because the interaction responsible for $\pi^+\pi^- \longrightarrow \pi^\circ\pi^\circ$ is made effectively "weak" by the large pionium radius:

$$R_{pionium} \approx R_\infty \frac{2m_e}{m_+} \approx 3.9 \times 10^{-11}\, cm$$

($R_\infty$ : Bohr radius for $M_{nucleus} = \infty$ )

$R_{pionium}$ >> strong interaction radius ( $\sim 10^{-13}$ $cm$)

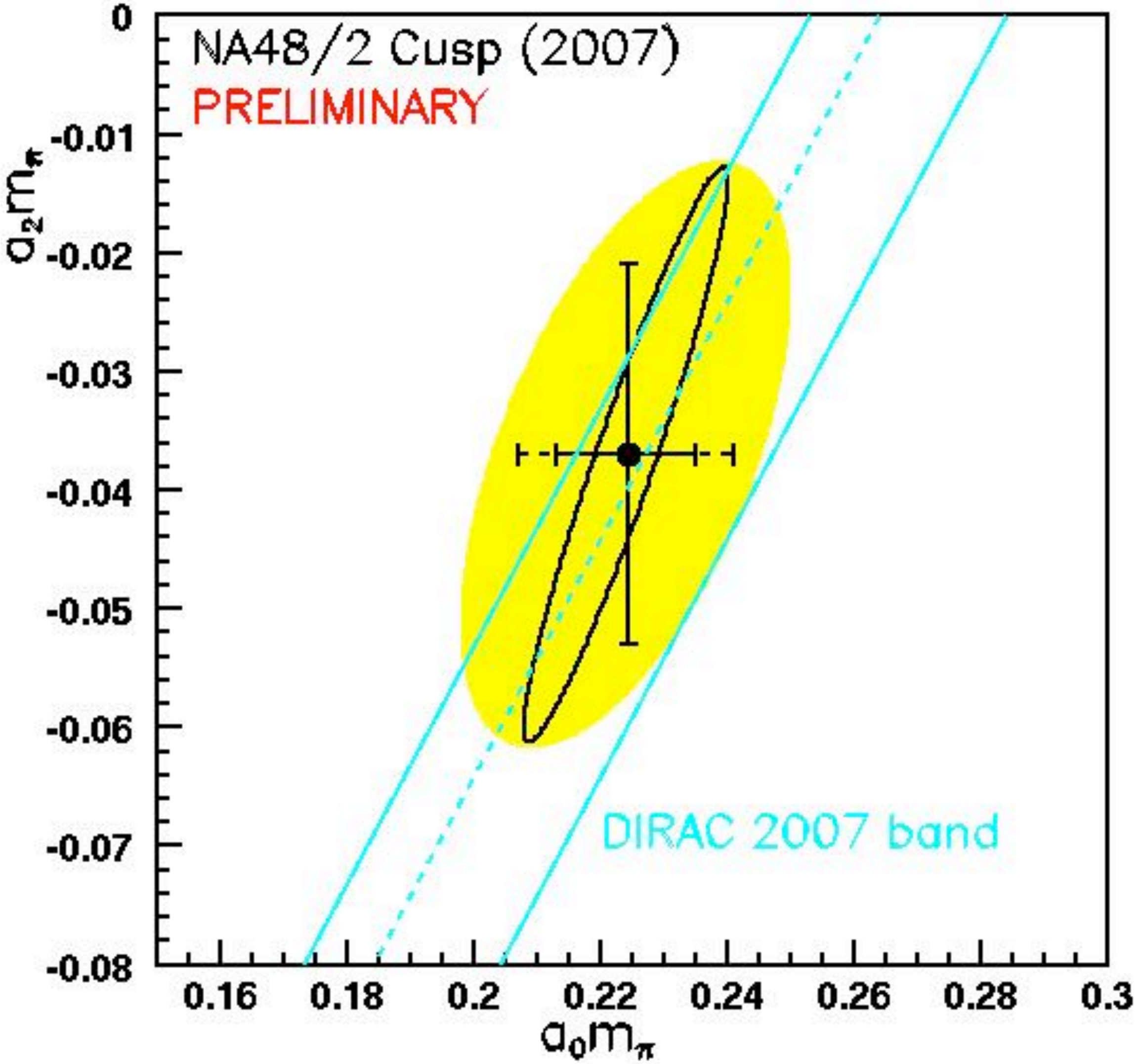
$\Rightarrow$ very little overlap of the $\pi^+\pi^-$ atomic wave function with the strong interaction volume

## NA48/2 (PRELIMINARY): from (a0 – a2) and a2 extract a0

(must take into account the statistical error correlation coefficient ≈ –0.92)

$a_0 m_+ = 0.224 \pm 0.008 \pm 0.006 \pm 0.003 \pm 0.013$

stat. svst. ext. theor.




The yellow area represents theoretical uncertainty (assumed Gaussian)

The dashed bars represent the theoretical uncertainty

# *Spares : Vus*

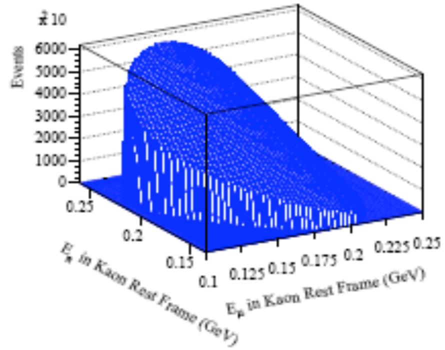
# *Form factors*

Events generated according to the Dalitz plot density distribution

$$\rho^0(E_l^*, E_\pi^*) = \frac{dN^2(E_l^*, E_\pi^*)}{dE_l^*\ dE_\pi^*} \propto Af_+^2(t) + Bf_+(t)f_-(t) + Cf_-^2(t)$$

A, B and C are kinematic terms, and t is the transferred 4-momentum to the lepton pair ($q^2$)

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)}\ f_-(t)$$



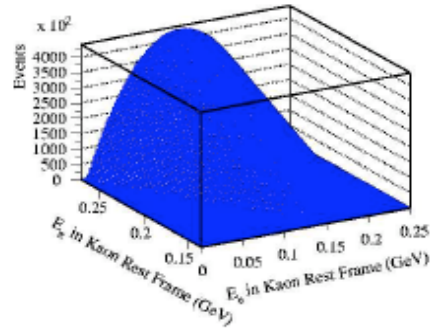

Use PDG 2006 form factors for Charge Kaon decays

Quadratic $\quad f_+(t) = f_+(0)\left(1 + \lambda'_+ \frac{t}{m_{\pi^\pm}^2} + \frac{1}{2}\lambda''_+ \frac{t^2}{m_{\pi^\pm}^4}\right)$

$$\lambda'_+ = 0.02485 \pm 0.00163 \pm 0.00034$$
$$\lambda''_+ = 0.00192 \pm 0.00062 \pm 0.0071$$

Linear $\quad f_0(t) = f_+(0)\left(1 + \lambda_0 \frac{t}{m_{\pi^\pm}^2}\right)$

$$\lambda_0 = 0.0196 \pm 0.0012$$



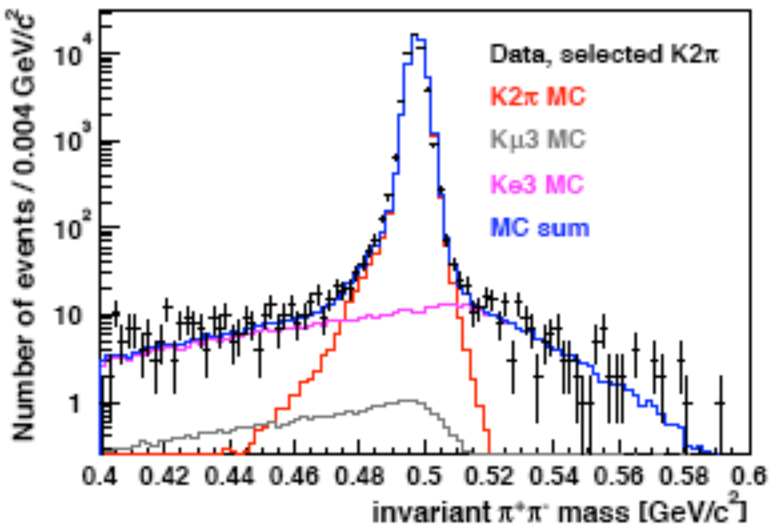

Other models considered - Pole $\quad f_{+,0}(t) = f_+(0)\left(\frac{m_{V,S}^2}{m_{V,S}^2 - t}\right)$

# *CP violation*

# NA48: $\eta_{+-}$

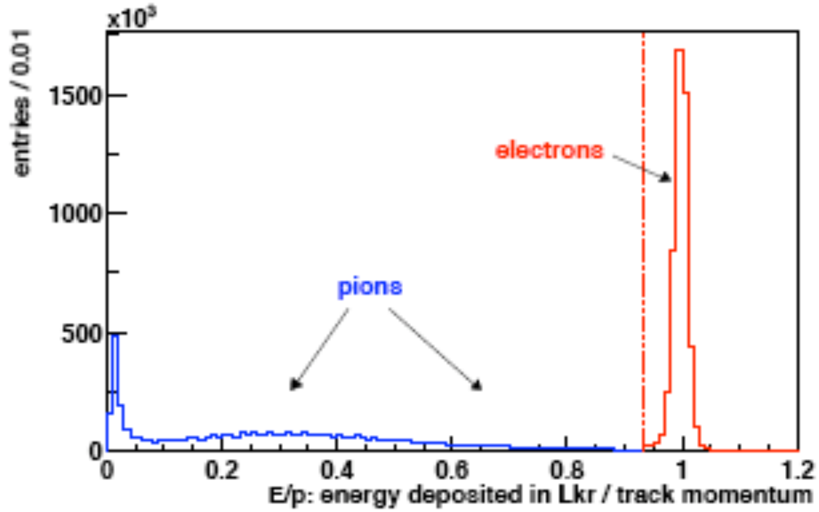
## $K_L \to \pi^+\pi^-$

- Need to suppress main decay channels by 4-5 orders of magnitude
- Only small background of $\sim 0.5\,\%$
- Data are well described by MC
- About 47000 selected $\pi^+\pi^-$ events




## $K_L \to \pi^\pm e^\mp \nu$

- Selection of $K_{e3}$ decays via ratio E/p (energy in electromagnetic calorimeter over track momentum)
  $\rightarrow$ E/p $\sim$ 1 for electrons
- About 5 million $K_{e3}$ events selected with small background of $\sim 0.5\,\%$



# NA48: $\eta_{+-}$

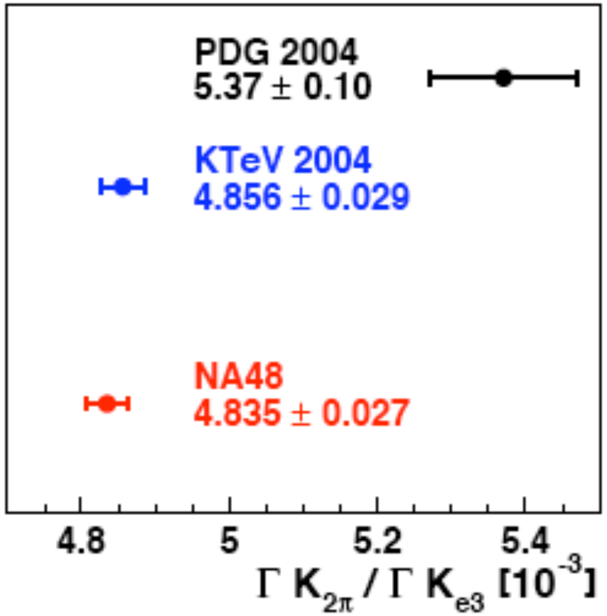
Parameter $\eta_{+-}$ = fundamental observable of CP violation, defined as the CP-violating ratio of the neutral kaon decaying into two charged pions

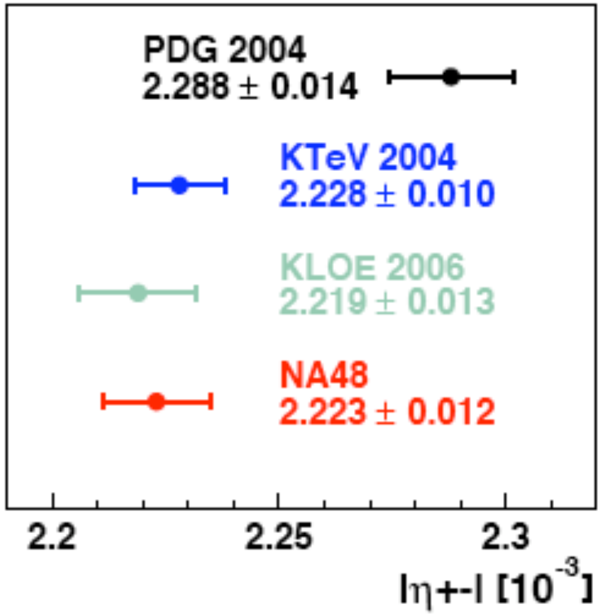
$$\eta_{+-} := \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \qquad\qquad \eta_{+-} = \epsilon + \epsilon'$$

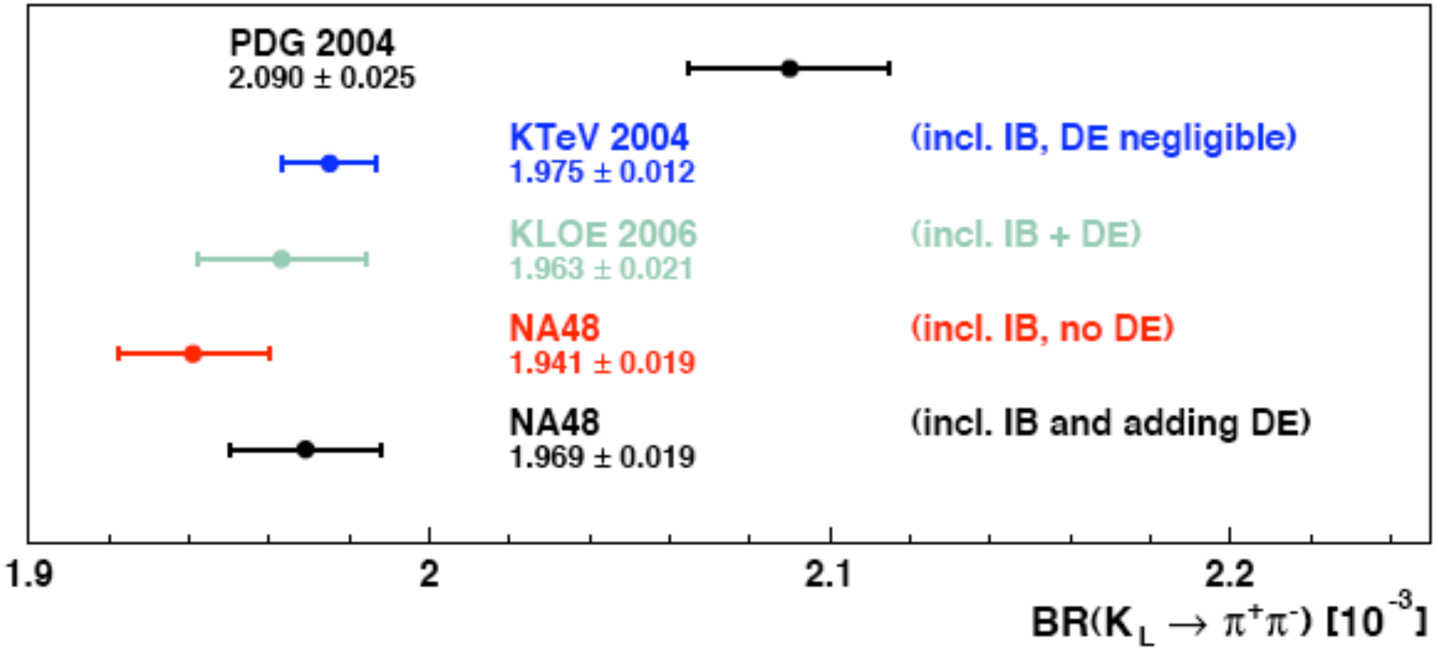
$$\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e^\mp \nu)} = (4.835 \pm 0.022_{stat.} \pm 0.016_{syst.}) \times 10^{-3}$$
$$= (4.835 \pm 0.027) \times 10^{-3}$$

$$BR(K_L \to \pi^+\pi^-) = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi e \nu)} \cdot BR(K_L \to \pi e \nu)$$
$$= (1,941 \pm 0.019) \times 10^{-3}$$

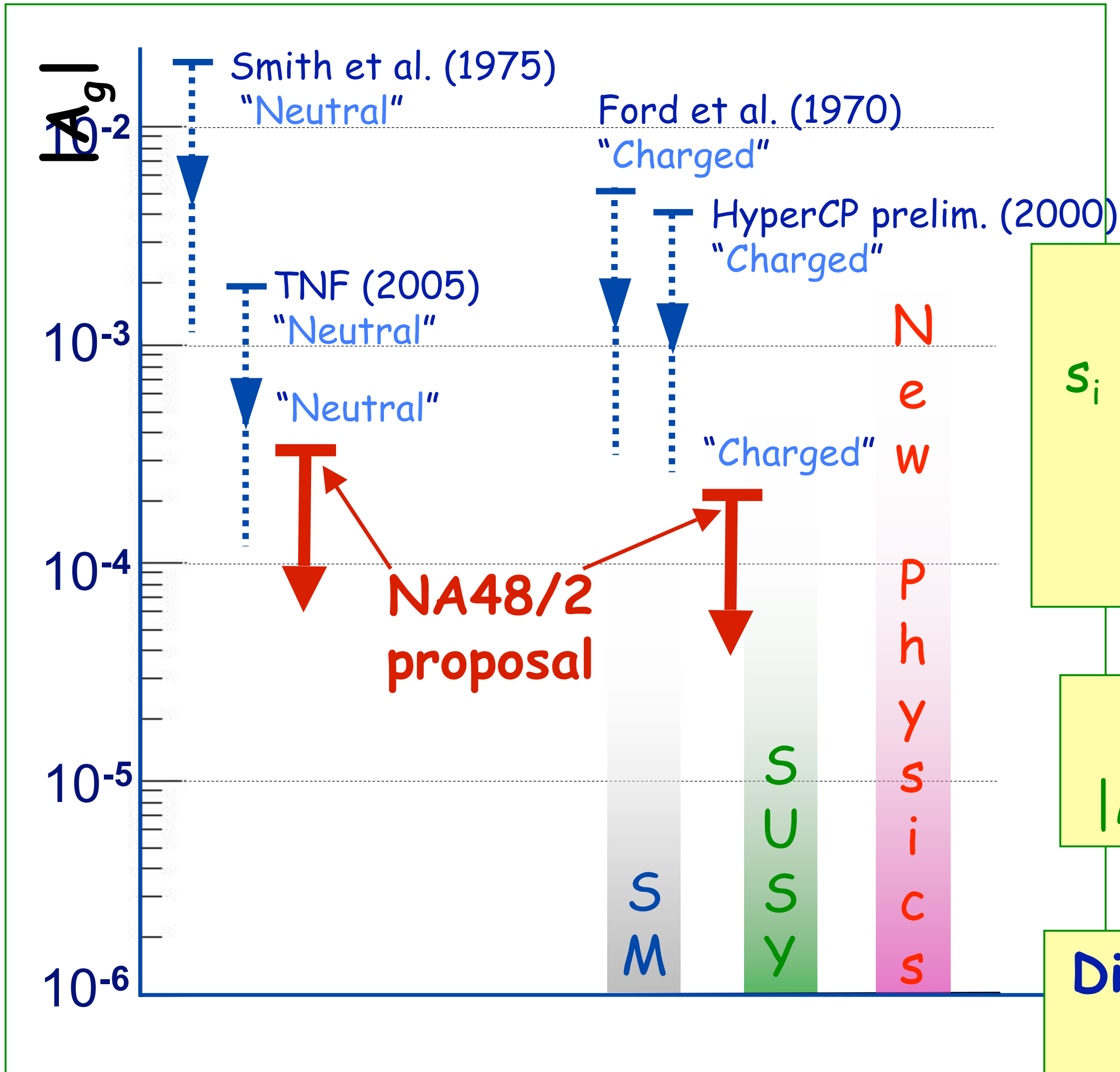
$$|\eta_{+-}| = \sqrt{\frac{\tau_{KS}}{\tau_{KL}} \cdot \frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)}} = (2.223 \pm 0.012) \times 10^{-3}$$


PDG 2004
5.37 ± 0.10
KTeV 2004
4.856 ± 0.029
NA48
4.835 ± 0.027
4.8
5
5.2
5.4
$\Gamma K_{2\pi} / \Gamma K_{e3}$ [$10^{-3}$]


PDG 2004
2.288 ± 0.014
KTeV 2004
2.228 ± 0.010
KLOE 2006
2.219 ± 0.013
NA48
2.223 ± 0.012
2.2
2.25
2.3
$|\eta_{+-}|$ [$10^{-3}$]


PDG 2004
2.090 ± 0.025
KTeV 2004
1.975 ± 0.012
(incl. IB, DE negligible)
KLOE 2006
1.963 ± 0.021
(incl. IB + DE)
NA48
1.941 ± 0.019
(incl. IB, no DE)
NA48
1.969 ± 0.019
(incl. IB and adding DE)
1.9
2
2.1
2.2
BR($K_L \to \pi^+\pi^-$) [$10^{-3}$]

# NA48: $A_g$




$$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$$

$$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$$

**Kinematics:**

$s_i = (P_K - P_{\pi i})^2$, $i = 1,2,3$ ($3 = \pi_{odd}$)

$s_0 = (s_1 + s_2 + s_3) / 3$

$u = (s_3 - s_0) / m_\pi^2$

$v = (s_2 - s_1) / m_\pi^2$

**Matrix element:**

$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$

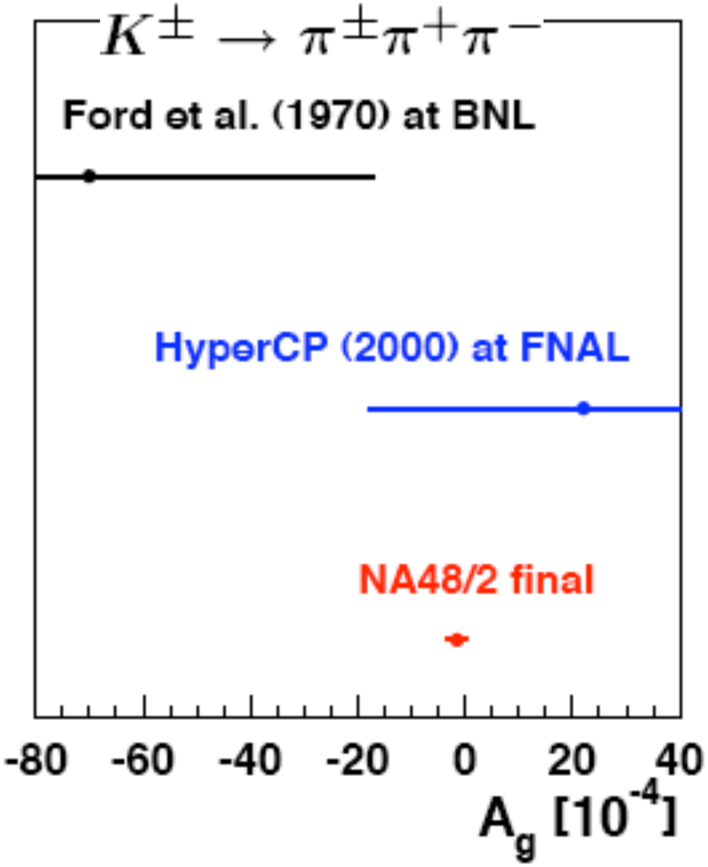
**Direct CP violating quantity: slope asymmetry**

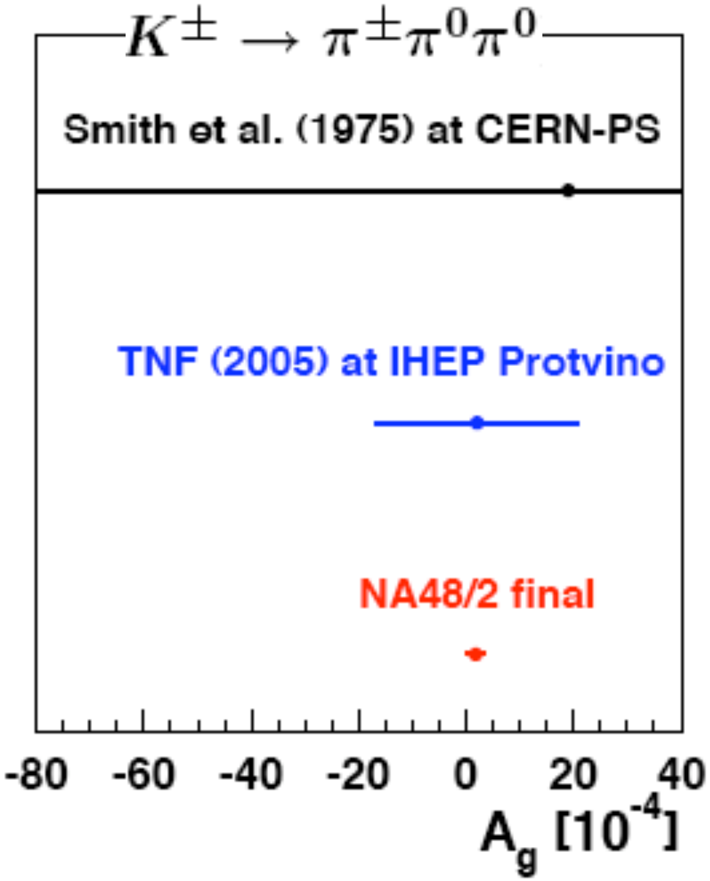
$A_g = (g^+ - g^-) / (g^+ + g^-) \neq 0$

$$R(u) = \frac{N^+(u)}{N^-(u)} \sim 1 + \frac{\Delta g\, u}{1 + gu + hu^2}$$

$$A_g = \frac{g^+ - g^-}{g^+ + g^-} \approx \frac{\Delta g}{2g}$$

$A_g = (1.8 \pm 1.7_{stat} \pm 0.9_{syst}) \cdot 10^{-4}$
$A_g = (1.8 \pm 1.9) \cdot 10^{-4}$




$A_g = (-1.5 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.1_{syst}) \cdot 10^{-4}$
$A_g = (-1.5 \pm 2.1) \cdot 10^{-4}$