Kaon physics: recent experimental results

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Outline

CP violation

CPT invariance & tests on QM

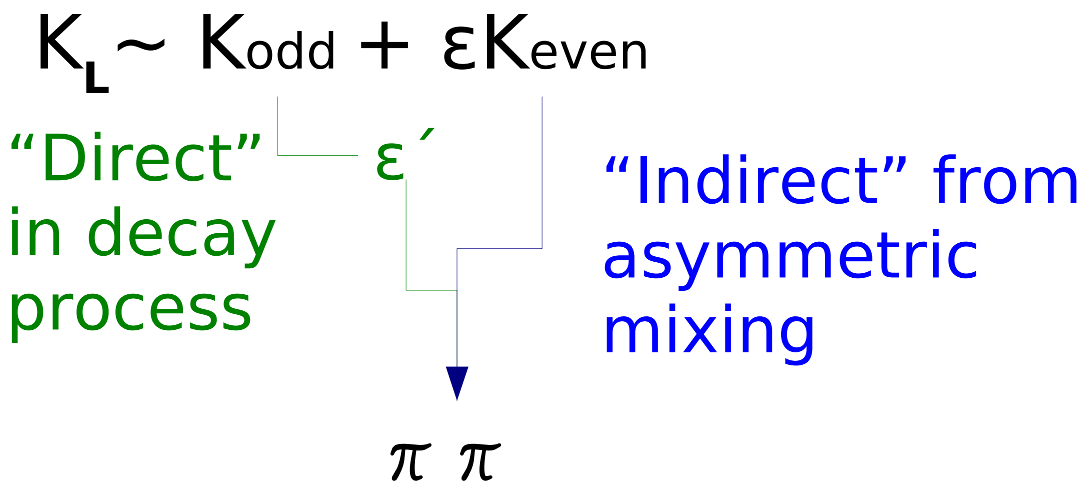
helicity suppressed modes

radiative decays

rare semileptonic decays

CP violation

ε´/ε : Indirect vs. Direct $\cancel{CP}$



$K_L \sim K_{odd} + \varepsilon K_{even}$

"Direct" in decay process

ε´

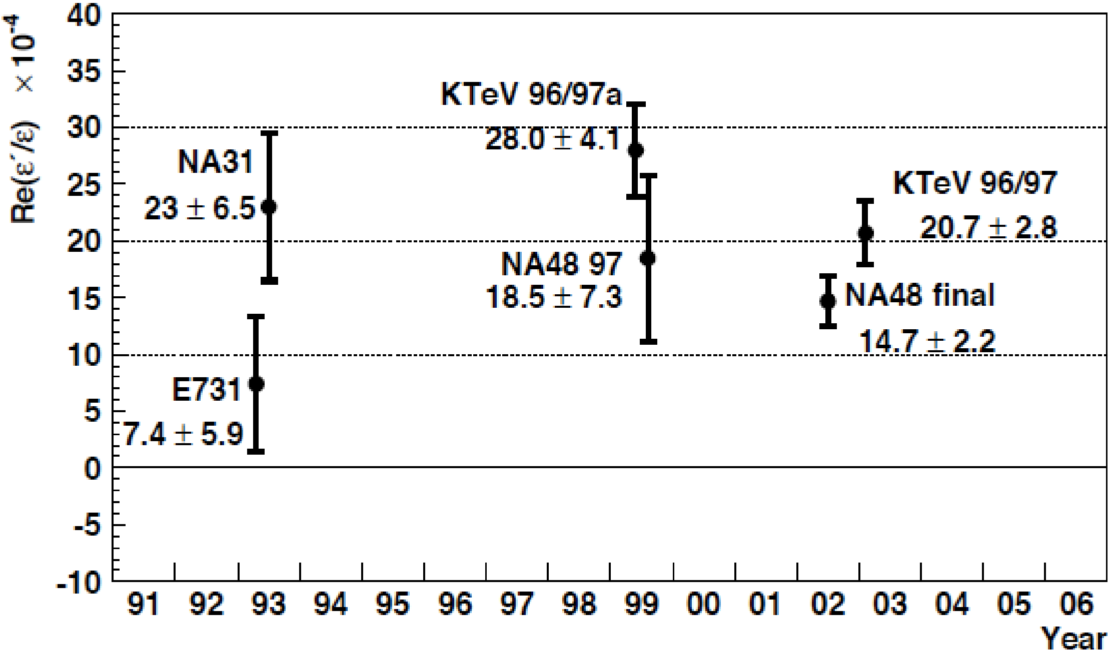
"Indirect" from asymmetric mixing

$\pi\ \pi$

To distinguish between direct and indirect CP violation, compare $K_{L,S} \to \pi^+\pi^-,\ \pi^0\pi^0$:

$$6\,\mathrm{Re}(\varepsilon\,'/\varepsilon) \approx \frac{\Gamma(K_L \to \pi^+\pi\quad)\ /\ \Gamma(K_s \to \pi^+\pi\quad)}{\Gamma(K_L \to \pi^0\pi^0)\ /\ \Gamma(K_s \to \pi^0\pi^0)} - 1$$

Measurements of Re(ε´/ε) @2008



Final result by NA48

partial data sample for KTeV

Final KTeV result

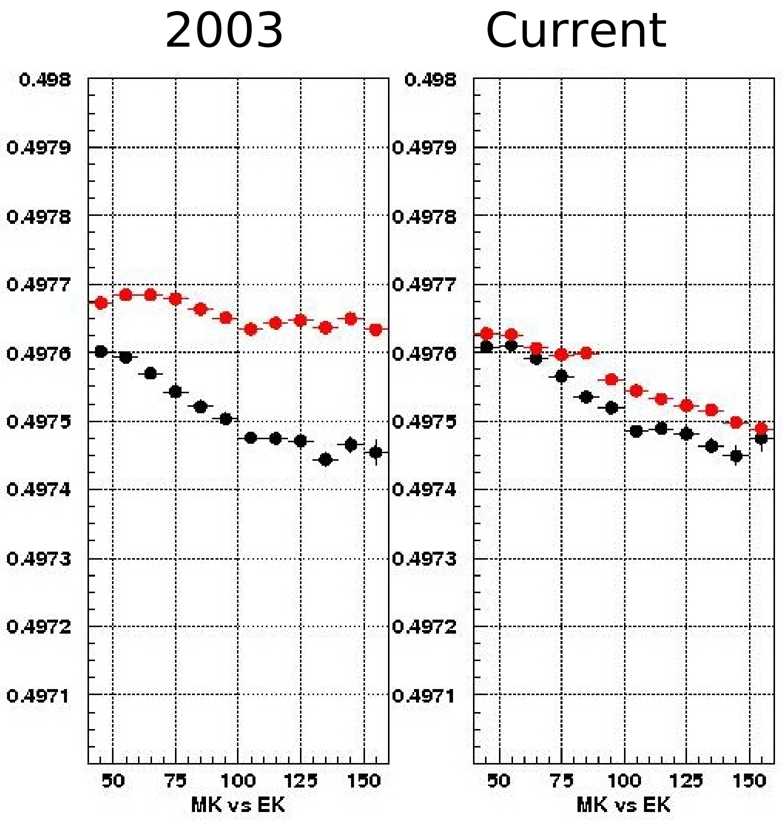
x2 statistics

Improved syts.(½) due to calorimeter energy scale knowledge:

- Calorimeter calibrated with momentum-analyzed electrons from K→π eν

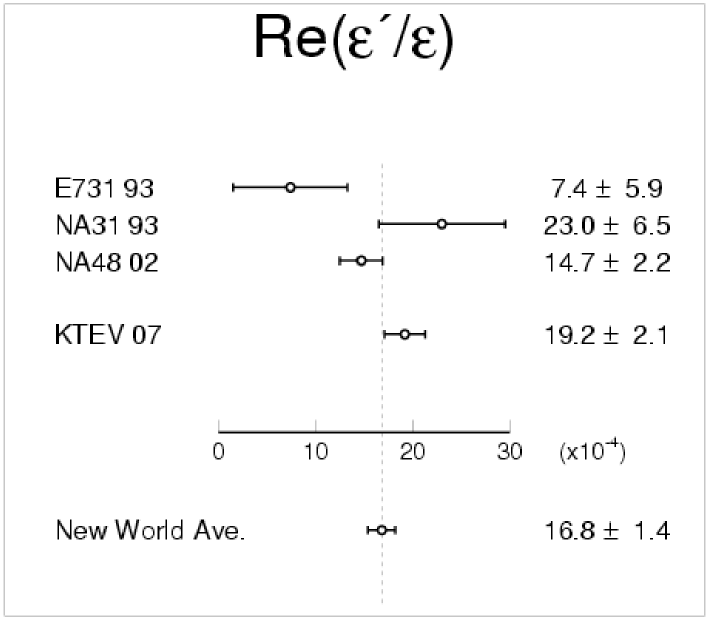
- Final energy scale adjustment based on $K^0 \rightarrow \pi^0 \pi^0$ at regenerator edge

Mass vs. Energy



KTeV Result:

$\mathrm{Re}(\varepsilon'/\varepsilon) = [19.2 \pm 1.1(\mathrm{stat}) \pm 1.8(\mathrm{syst})] \times 10^{-4}$



World average:

$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4}$

(confidence level = 13%)

(KTeV 2003: $\mathrm{Re}(\varepsilon'/\varepsilon) = [20.7 \pm 1.5(\mathrm{stat}) \pm 2.4(\mathrm{syst})] \times 10^{-4}$)

CP violation in K vs B decays

Recent lattice results for B_K and previously neglected contributions lead to 15% smaller ε_K, in conflict with $\sin 2\beta$

Assuming SM, use $\sin 2\beta$, $|V_{cb}|$, λ, $\Delta M_s/\Delta M_d$, ξ, $B_K=0.720(39)$ RBC-UKQCD

$|\varepsilon_K|^{SM}=(1.78\pm0.25)10^{-3}$ vs $|\varepsilon_K|^{exp}=(2.221\pm0.006)10^{-3}$

'04 value $|\varepsilon_K|^{exp}=(2.284\pm0.014)10^{-3}$ replaced with new measurements

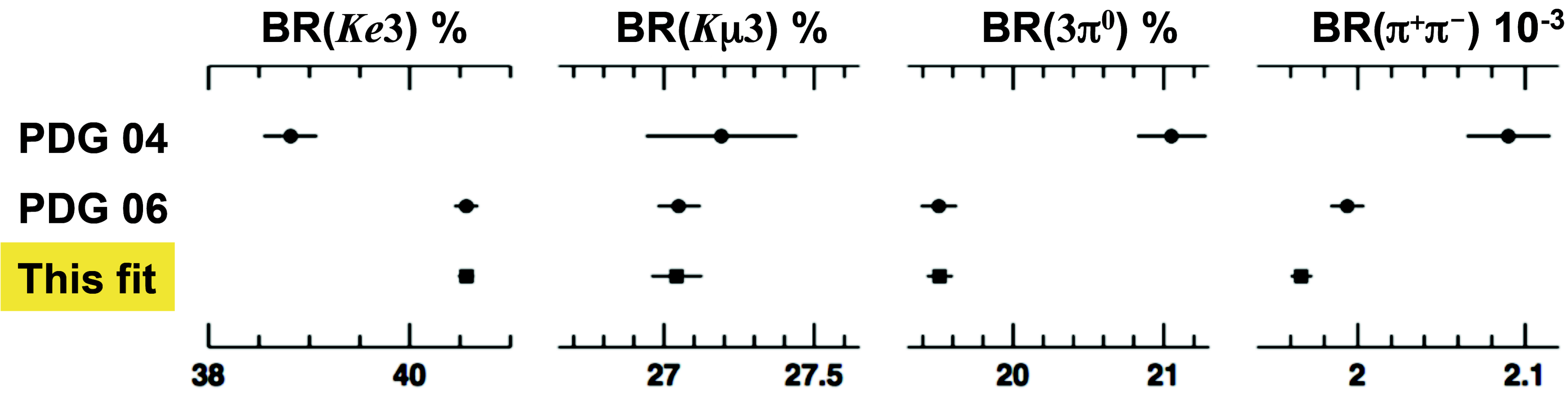
1.8-2.1σ depending on assigned errors Buras,Guadagnoli,Lunghi Soni

Easy to find new physics explanations, even in CMFV

better agreement using $|V_{cx}|$ from exclusive:

- $d|\varepsilon_K|^{SM}$ dominated by $d|V_{cb}|$ (inclusive-exclusive ~ 2.5σ)
- inclusive-exclusive ~ 2-1.5σ for V_{ub} determination

RBC-UKQCD B_K determination confirmed by Aubin et al '09 and ETMC



Differences between FlaviaNet and PDG are minor

Since PDG '04:

- Proper radiative corrections, especially for $Ke3$
- Exclusion of old measurements

from K_L BRs:	**PDG '04**	**This fit**	
$K_{\mu3}/K_{e3}$	**0.701(9)**	**0.6666(29)**	ok with lepton universality
$\lvert\eta_{+-}\rvert\times10^3$	**2.284(14)**	**2.223(6)**	$>3\sigma$ difference

CPT invariance

Time evolution of the neutral kaons

$$i\frac{d}{dt}\begin{pmatrix}K^0\\ \overline{K}^0\end{pmatrix} = \left(M - i\,\Gamma/2\right)\begin{pmatrix}K^0\\ \overline{K}^0\end{pmatrix}$$

CPT invariance

$$M_{11} = M_{22} \quad \Gamma_{11} = \Gamma_{22}$$

Diagonalization

$$K_{S,L} = N\left(\left(1+\varepsilon_{S,L}\right) K^0 \pm \left(1-\varepsilon_{S,L}\right)\overline{K}^0\right)$$

$$\varepsilon_{S,L} = \varepsilon \pm \delta$$

$$\boxed{\delta = \frac{i\,(m_K - m_{\overline{K}}) + (\Gamma_K - \Gamma_{\overline{K}})/2}{\Gamma_S - \Gamma_L}\cos\phi_{SW}\, e^{i\phi_{SW}}}$$

$\Downarrow$ $\Delta\Gamma = 0$

$$\phi_{SW} = \tan^{-1}\frac{2\left(m_L - m_S\right)}{\Gamma_S - \Gamma_L} = 43.5°$$

$$\left|\frac{m_K - m_{\overline{K}}}{m_K}\right| \cong 3\times 10^{-14}\,|\mathrm{Im}\delta|$$

Unitarity and Bell Steinberger relation

Even if CPT is violated, we can assume that **unitarity** is preserved (**= conservation of probability**)

$$\Gamma_{11} = \Sigma_f\, A^*(K^0 \to f\,)\, A(K^0 \to f\,)$$

$$\Gamma_{12} = \Sigma_f\, A^*(\bar{K}^0 \to f\,)\, A(K^0 \to f\,)$$

Expressing the decay amplitudes in the K_S K_L basis and using the definitions of ε and δ

$$\left(\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L} + i\tan\phi_{SW}\right)\left(\frac{\mathrm{Re}\,\varepsilon}{1+|\varepsilon|^2} - i\,\mathrm{Im}\,\delta\right) = \frac{1}{\Gamma_S-\Gamma_L}\,\Sigma_f\, A^*(K_S \to f\,)\, A(K_L \to f\,)$$

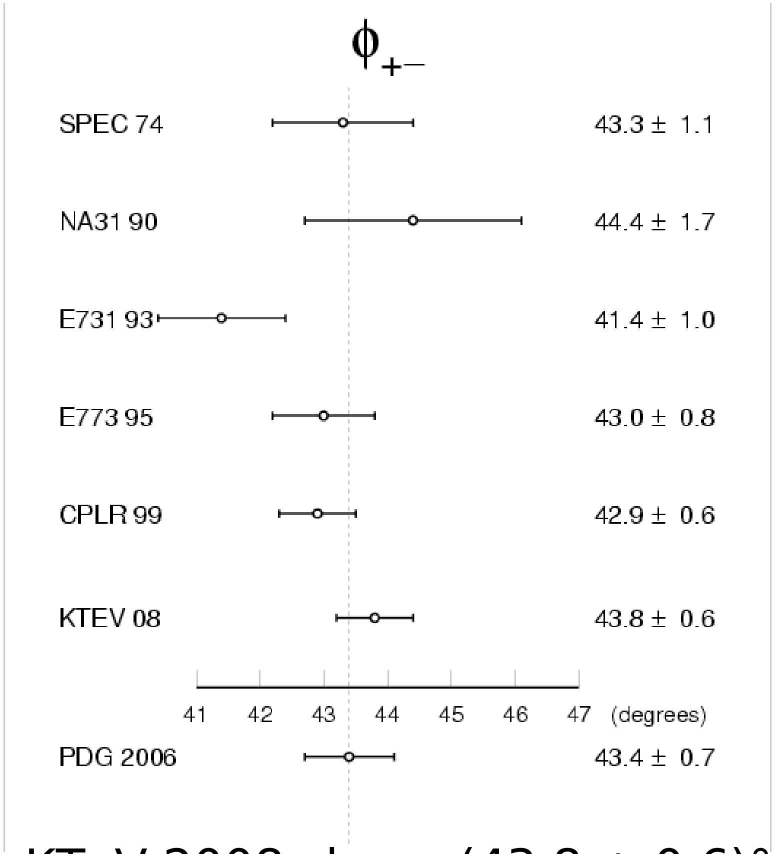
Exp. inputs

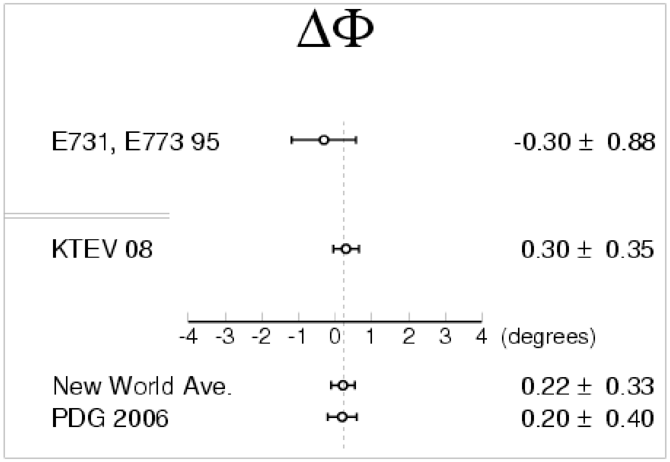
Two outputs

Exp. Inputs: only ππ, 3π and π*l*ν give appreciable contribution, **≥ 10^{-7}**

Im δ ≠ 0 could only be due to: violation of CPT, violation of unitarity, new exotic invisible final states

New measurement of ϕ_{+-} and $\Delta\phi$ from KTeV





KTeV 2008: ϕ_{+-} = (43.8 ± 0.6)°
(KTeV 2003: ϕ_{+-} = (44.1 ± 1.4)°)

better treatment of reg. transmission, screening

KTeV 2008: $\Delta\phi$ = (0.30 ± 0.35)°
(KTeV 2003: $\Delta\phi$ = (0.39 ± 0.50)°)

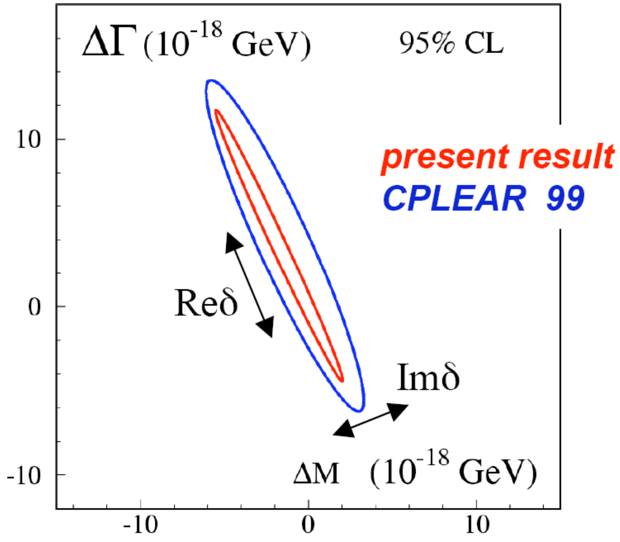
Improvement: neutral energy scale

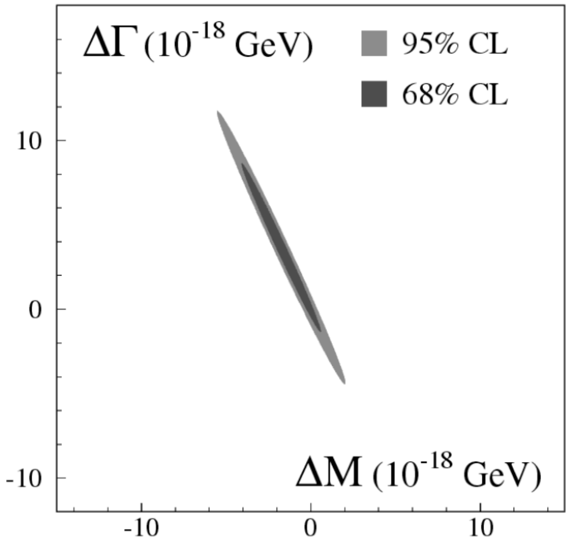
	CPLEAR99	KLOE06	PDG08	**Present result**
Analysis strategy	**fit to BSR and $\pi l\nu$ asymm.**	**Evaluation of α's**		
Im δ ($\times 10^5$)	2.4 ± 5.0	0.4 ± 2.1	-0.6 ± 1.9	-0.1 ± 1.4
σ(Im δ)	$4.5 \oplus 2.1$ 3π $\pi\pi$ $\pi l\nu$	$1.8 \oplus 1.2$ $\pi\pi$ $\pi l\nu$	$1.8 \oplus 0.6$ $\pi\pi$ $\pi l\nu$	$1.3 \oplus 0.6$ $\pi\pi$ $\pi l\nu$
Comments	**$\pi l\nu$ vs time**	**new $K_L \to \pi\pi$, $K_s \to 3\pi^0$, A_S and A_L**		
			better treatment of CPLEAR data	***new $\phi_{\pi\pi}$***
Re ε ($\times 10^5$)	164.9 ± 2.5	159.6 ± 1.3	161.2 ± 0.6	161.2 ± 0.6

CPT test: $m(K)-m(\overline{K})$

$$\delta = \frac{1}{2}\,\frac{M_{11}-M_{22}-i(\Gamma_{11}-\Gamma_{22})/2}{m_S-m_L-i(\Gamma_S-\Gamma_L)/2} \Rightarrow \begin{cases} \Delta M \propto -\sin\phi_{SW}\,\mathrm{Re}\,\delta + \cos\phi_{SW}\,\mathrm{Im}\,\delta \\ \Delta\Gamma \propto \cos\phi_{SW}\,\mathrm{Re}\,\delta + \sin\phi_{SW}\,\mathrm{Im}\,\delta \end{cases}$$

$\mathrm{Im}\delta = (-0.1 \pm 1.4)\times 10^{-5}$ from BSR; $\mathrm{Re}\delta = (2.5 \pm 2.3)\times 10^{-4}$ *essentially* from CPLEAR





Assuming CPT violation *only* in the mass matrix:

	CPLEAR99	**KLOE06**	**PDG08**	**Present result**
ΔM at $\Delta\Gamma=0$ (10^{-19} GeV)	**3.3 ± 7.0**	**0.5 ± 3.0**	**-0.9 ± 2.6**	**-0.1 ± 2.0**

Test of QM

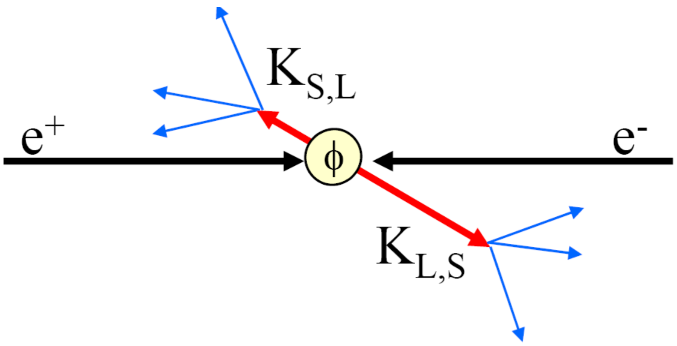
Neutral kaons at a φ-factory

Production of the vector meson φ in e^+e^- annihilations:

- $e^+e^- \to \phi$ $\sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ MeV
- $BR(\phi \to K^0\bar{K}^0) \sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:

$p_K = 110$ MeV/c

$\lambda_S = 6$ mm $\lambda_L = 3.5$ m



$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$

$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)}\Big/\left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

The detection of a kaon at large (small) times tags a K_S (K_L)
⇒ possibility to select a pure K_S beam (**unique** at a φ-factory, not possible at fixed target experiments)

$\varphi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of QM coherence

- Analysed data:
  L=1.5 fb^{-1} (2004-05 data)
- Fit including Δt resolution and efficiency effects + regeneration
- Γ_S, Γ_L, Δm fixed from PDG

KLOE FINAL:

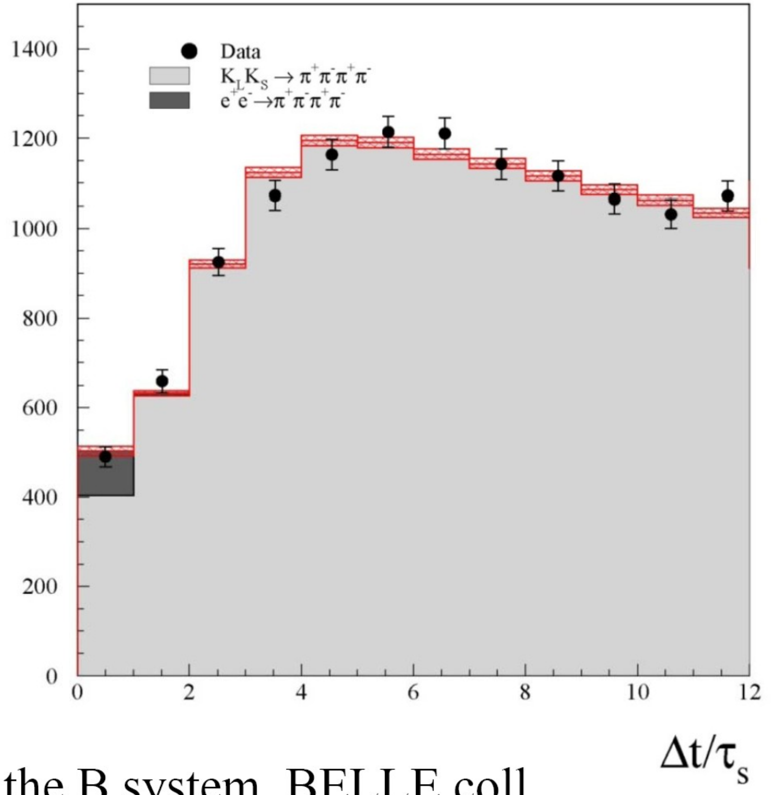
$$\boxed{\zeta_{0\bar{0}} = (1.4 \pm 9.5_{\mathrm{STAT}} \pm 3.8_{\mathrm{SYST}}) \times 10^{-7}}$$

as CP viol. $O(|\eta_{+-}|^2) \sim 10^{-6}$
=> high sensitivity to $\zeta_{0\bar{0}}$

- Improvement x 2 wrt published KLOE measurement (PLB 642(2006) 315)

- From CPLEAR data $(p\bar{p})_{REST} \to K^0\overline{K}^0$
Bertlmann et al. obtain (PR D60 (1999) 114032):

$$\zeta_{0\bar{0}} = 0.4 \pm 0.7$$



- In the B system, BELLE coll. (PRL 99 (2007) 131802) obtains:

$$\zeta^B_{0\bar{0}} = 0.029 \pm 0.057$$

- Comparison with quantum optics tests: precision O(10^{-3})

$\varphi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\ \pi^+\pi^-$: CPTV by QG

Study of time evolution of **single kaons** decaying in $\pi^+\pi^-$ and semileptonic final state

CPLEAR **PLB 364, 239 (1999)**

$$\boxed{\begin{aligned}\alpha &= (-0.5 \pm 2.8)\times 10^{-17}\ \text{GeV}\\ \beta &= (2.5 \pm 2.3)\times 10^{-19}\ \text{GeV}\\ \gamma &= (1.1 \pm 2.5)\times 10^{-21}\ \text{GeV}\end{aligned}}$$

Complete positivity guarantees the positivity of the eigenvalues of density matrices describing states of correlated kaons.

In the complete positivity hypothesis

$\alpha = \gamma$, $\beta = 0$

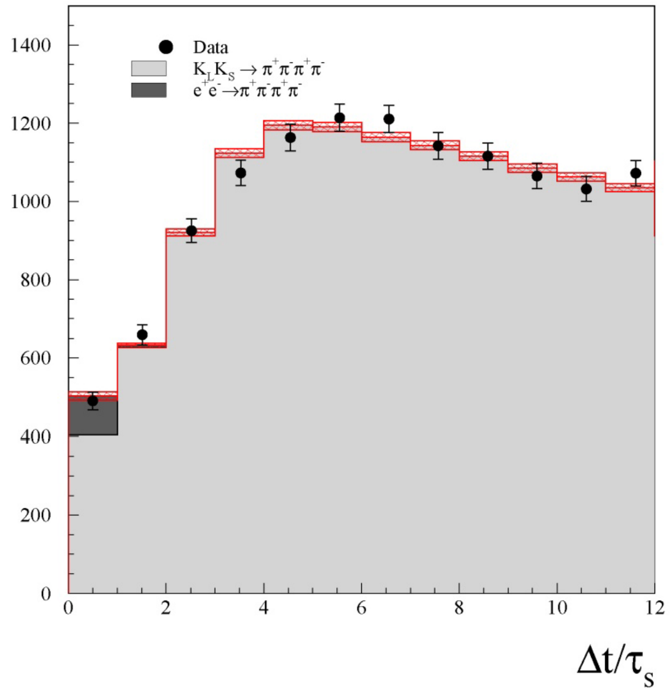
=> only one independent parameter: γ

The fit with $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\gamma)$ gives:

KLOE FINAL L=1.5 fb^{-1}

$$\boxed{\gamma = (0.7 \pm 1.2_{STAT} \pm 0.3_{SYST})\times 10^{-21}\ \text{GeV}}$$

- Improvement x 2 wrt published KLOE



$\varphi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: CPTV in K-K states

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator “ill-defined”) the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state [Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180]:

$$|i\rangle \propto \left(K^0\overline{K}^0 - K^0\overline{K}^0\right) + \boxed{\omega}\left(K^0\overline{K}^0 + K^0\overline{K}^0\right)$$

|ω| could be at most: $\boxed{|\omega|^2 = O\left(\frac{E^2 / M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}}$

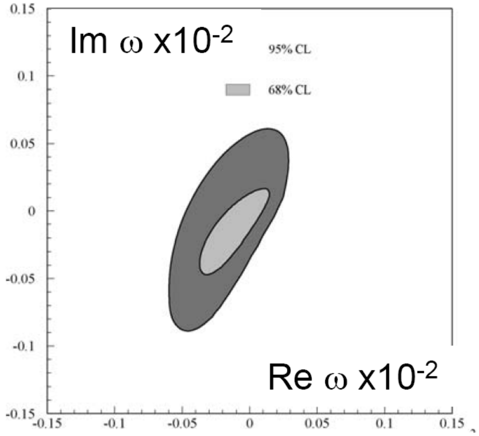
Fit of $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\omega)$:

L=1.5 fb^{-1}

KLOE FINAL :

$$\boxed{\begin{aligned} \Re\omega &= \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4} \\ \Im\omega &= \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4} \\ |\omega| &< 1.0\times 10^{-3} \quad \text{at } 95\%\ \text{C.L.} \end{aligned}}$$

-Improvement x 2 wrt published KLOE



- In the B system [Alvarez, Bernabeu, Nebot JHEP 0611, 087]

$$-0.0084 \le \Re\omega \le 0.0100 \quad \text{at } 95\%\ \text{C.L.}$$

KLOE-2 at upgraded DAΦNE

Upgrade of DAΦNE in luminosity:

Crabbed waist scheme at DAΦNE (proposal by P. Raimondi)

- increase L by a factor *O*(5)
- requires minor modifications
- relatively low cost

- Successful experimental test at DAΦNE

KLOE-2 Plan:

- phase 0: KLOE restart taking data end 2009 with a minimal upgrade (L~5 fb^{-1})
- phase 1: full KLOE upgrade (KLOE-2) > 2011 (L>20 fb^{-1})

Physics issues:

- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, muon anomaly

Detector upgrade issues:

- Inner tracker R&D
- $\gamma\gamma$ tagging system
- Calorimeter, increase of granularity
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)

Helicity suppressed

$P_{\ell 2}$ decays

$$\Gamma(P_{\ell 2(\gamma)}) = \frac{G_F^2\,|V_{uq}|^2}{8\pi}\; f_P^2\;\; m_\ell M_P (1-m_\ell^2/M_P^2)^2\;\; (1+C_{P\ell})$$

Inputs from theory:

f_P	decay constants
$C_{P\ell}$	Radiative inclusive electroweak corrections

Inputs from experiment:

$\Gamma(P_{\ell 2(\gamma)})$ Rates with well-determined treatment of radiative decays:

- Branching ratios
- lifetimes

Used to determine pseudoscalar decay constants

Small uncertainties for ratios:

$\Gamma(K_{\mu 2(\gamma)})/\Gamma(\pi_{\mu 2(\gamma)})$ **f_K/f_π from lattice → determine V_{us}/V_{ud}**

[Mariciano]

$R_P=\Gamma(P_{e2(\gamma)})/\,\Gamma(P_{\mu 2(\gamma)})$ **no f_P → test lepton universality**

[Cirigliano, Rosell]

Decay constants & f(0)

In the Standard Model f_P can be determined from the measurement of Γ $(P_{\ell 2(\gamma)})$ and the value of the relevant CKM matrix element.

f_K = 156.1(8) MeV

f_π=130.4(2) MeV

V_{us} = 0.2247(12) from Kl3

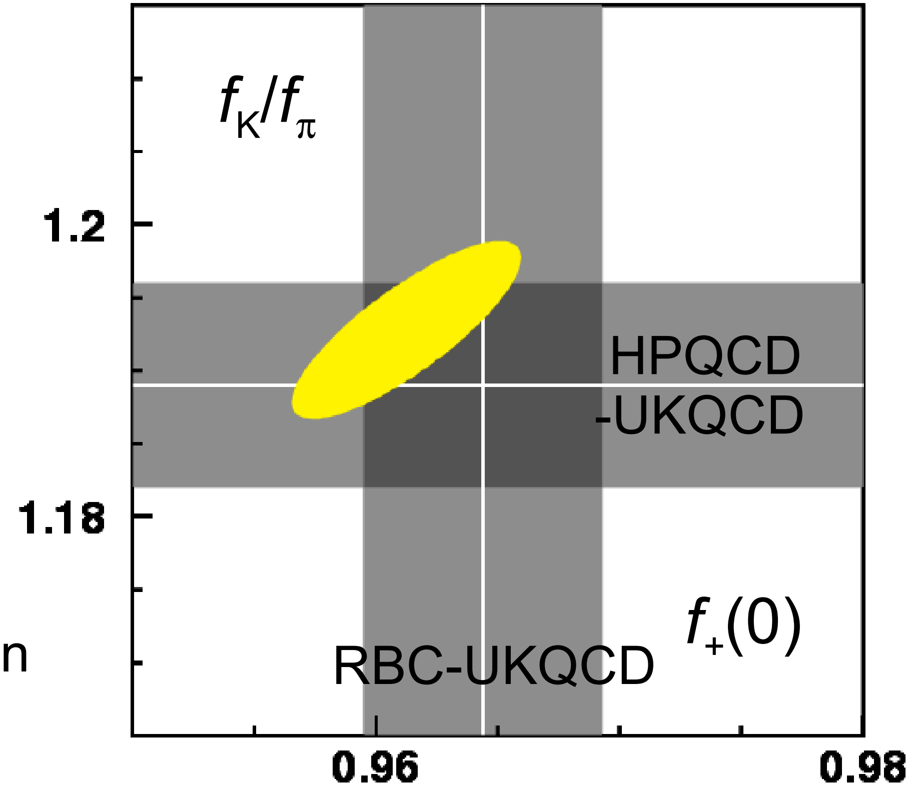
V_{ud}=0.97425(23) from β decays

unitarity + V_{ud} , $f_0 V_{us}$,Γ $(P_{\ell 2(\gamma)})$

f_K/f_π = 1.1928(61)

$f_+(0)$ = 0.9612(47)

0.8 correlation



sensitivity to NP: charged Higgs

JHEP
0804:059

Pseudoscalar currents, e.g. due to H±, affect the K width:

$$\frac{\Gamma(M\to\ell\nu)}{\Gamma_{SM}(M\to\ell\nu)} = \left[1-\tan^2\beta\left(\frac{m_{s,d}}{m_u+m_{s,d}}\right)\frac{m_M^2}{m_H^2}\right]^2$$

for M = K, π

Hou, Isidori-Paradisi

The observable

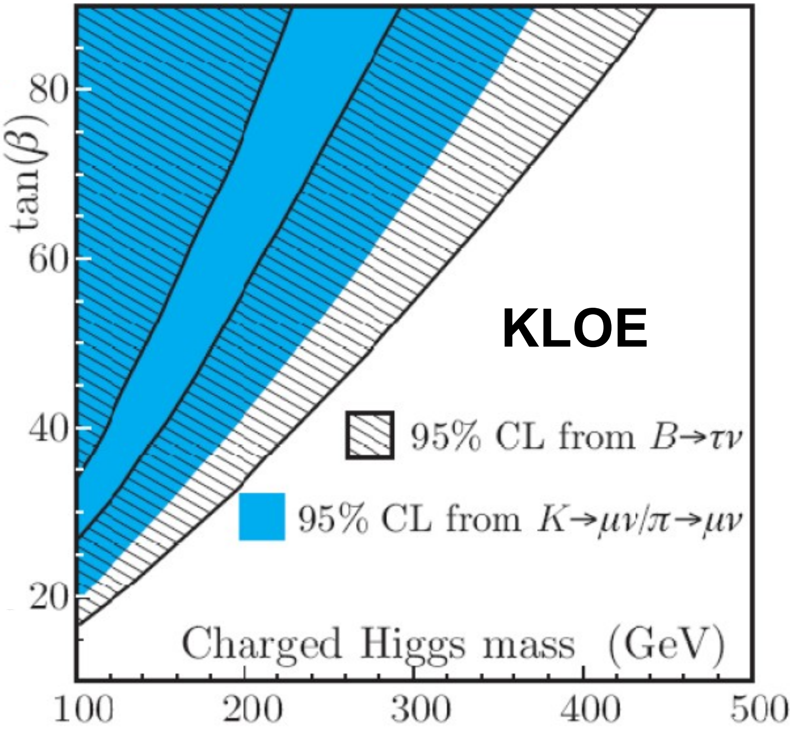
$$R_{\ell 23} = \left|\frac{V_{us}(K_{\mu 2})}{V_{us}(K_{\ell 3})}\times\frac{V_{ud}(0^+\to 0^+)}{V_{ud}(\pi_{\mu 2})}\right|$$

KLOE: **R_{l23} = 1.008(8)**

(unitarity for K_{l3} and β-decays is used)

R_{l23} sensitivity to H± exchange

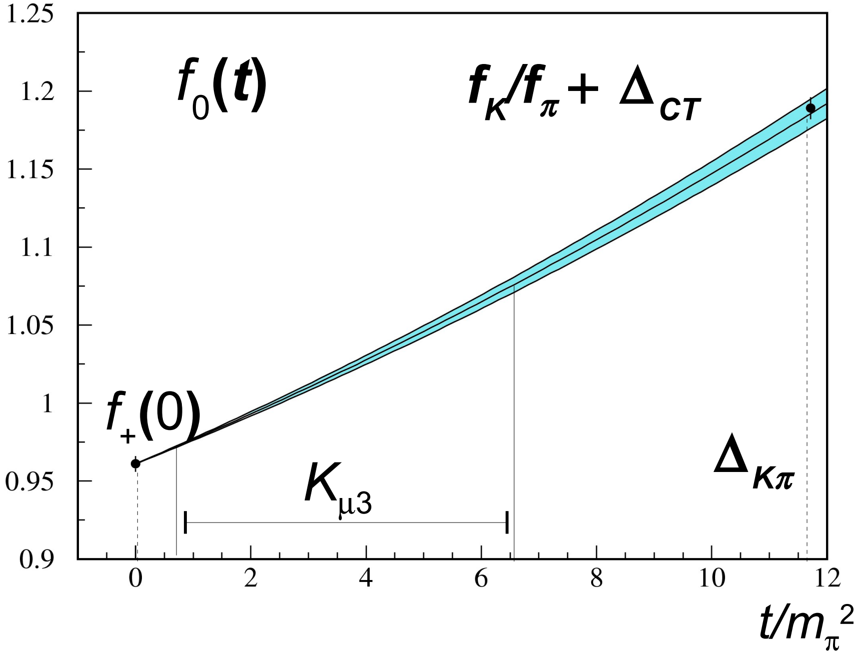
$$R_{\ell 23} = \left|1-\frac{m_{K^+}^2}{m_{H^+}^2}\left(1-\frac{m_{\pi^+}^2}{m_{K^+}^2}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|$$

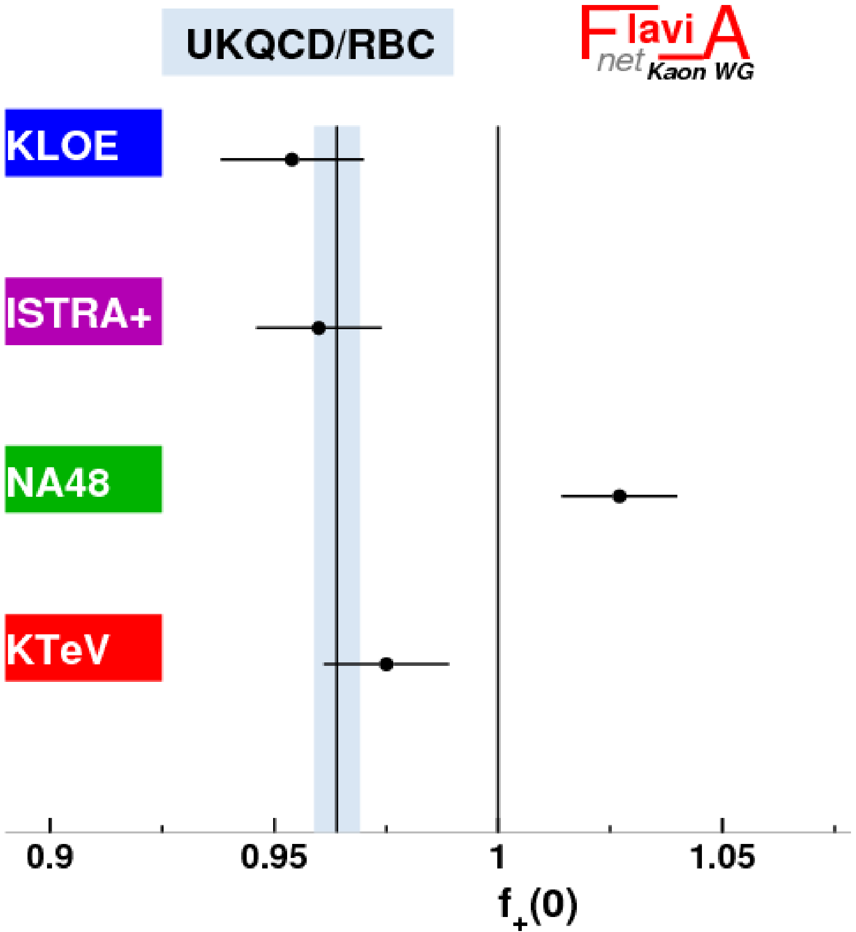


Same effect for scalar ff

Callan-Treiman relation

Check from measurement of scalar ff slopes in Kμ3 and use of dispersive parametrization [Stern et al] [Pich et al] (further info from τ)





$$f_+(0) = (f_K/f_\pi + \Delta_{CT})/C$$

$f_K/f_\pi = 1.189(7)$ from HPQCD-UKQCD

$$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$$

The special role of $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$

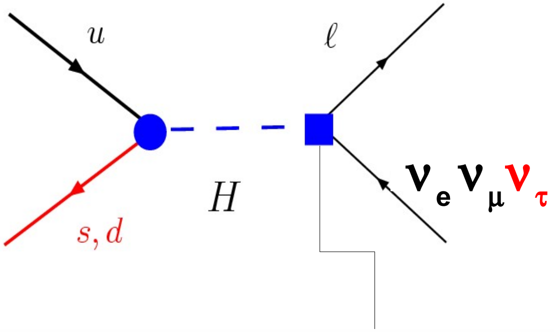
SM: very well known no hadronic uncertainties (no f_K)

In MSSM, LFV can give up to % deviations

[Masiero, Paradisi, Petronzio]

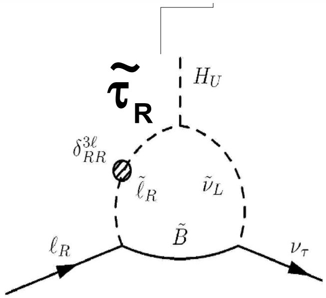
NP dominated by contribution of $e\nu_\tau$ final state:

$$R_K \approx \frac{\Gamma(K \rightarrow e\nu_e) + \Gamma(K \rightarrow e\nu_\tau)}{\Gamma(K \rightarrow \mu\nu_\mu)}$$



$$R_K \approx R_K^{SM}[\,1 + \frac{m_K^4}{m_H^4}\,\frac{m_\tau^2}{m_e^2}\,|\Delta_R^{31}|^2 \tan^6\beta]$$

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



1% effect (Δ^R_{31} ~5x10^{-4}, tanβ~40, m_H~500GeV) not unnatural

Present accuracy on R_K @ 6% Need for precise measurements

$K_{e2}/K_{\mu 2}$: SM prediction

SM prediction made in terms of IB process only (unobservable)

$R_K = 2.477(1) \times 10^{-5}$

[Cirigliano, Rosell]

Radiative corrections: IB + DE amplitudes in MC generator

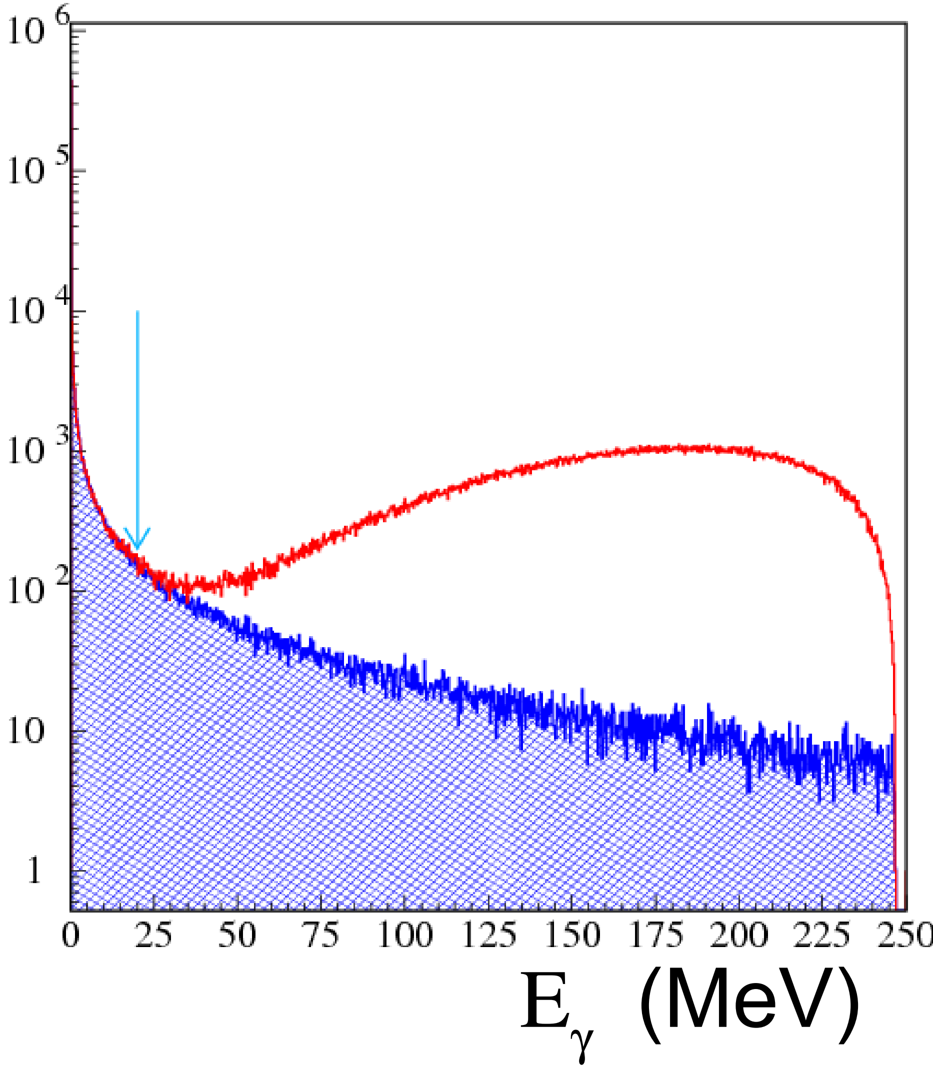
KLOE define Signal:

$K \to e\nu(\gamma)$, $E_\gamma < 10$ MeV

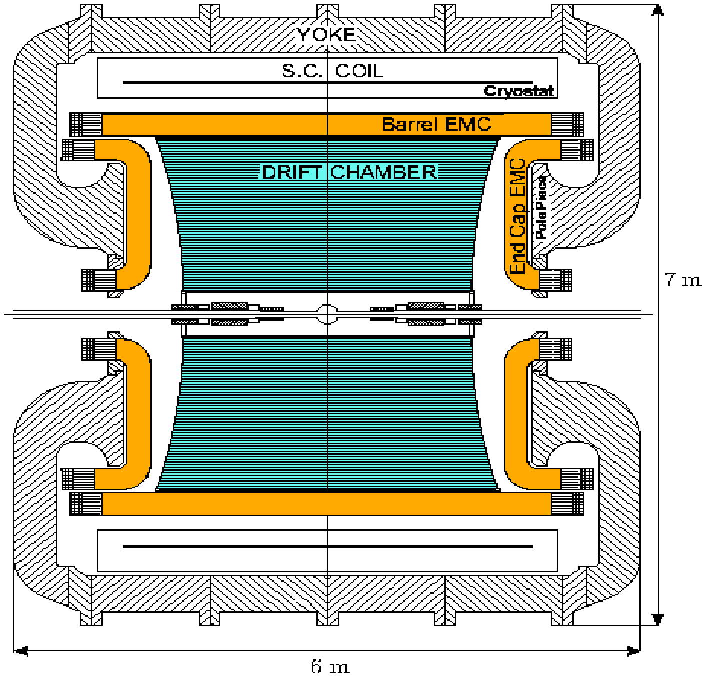
DE is negligible in this range

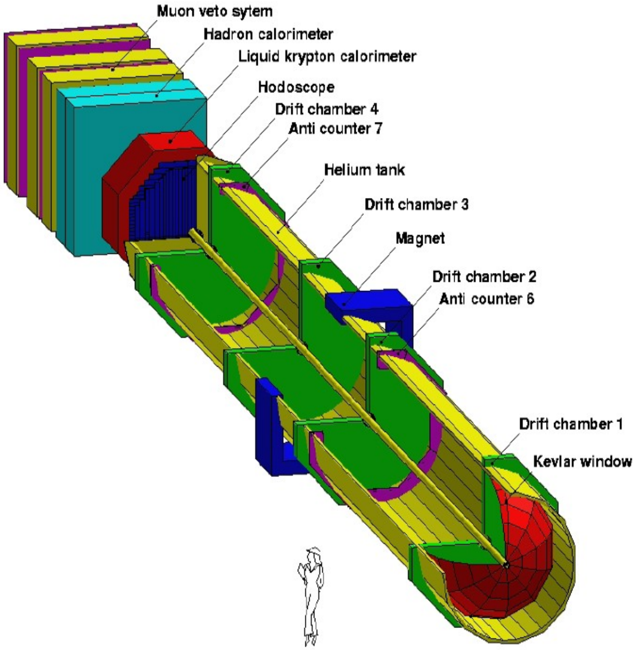
NA62 suppress DE with γ veto

determine ε with IB only



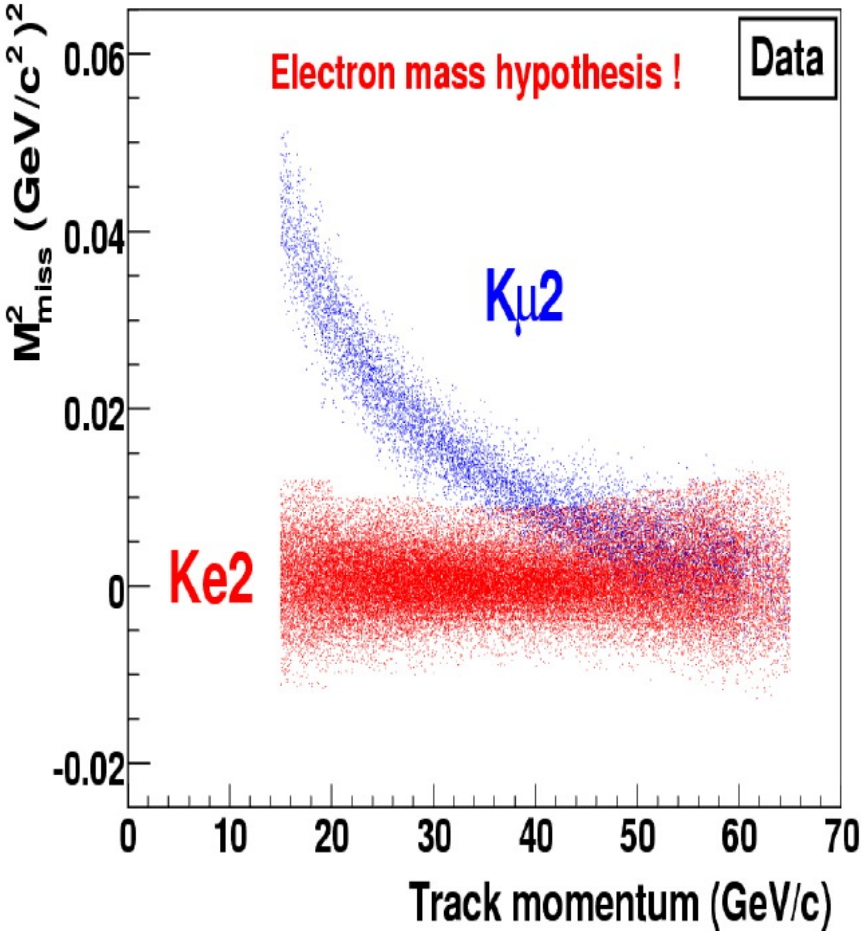
R_K: KLOE vs NA62

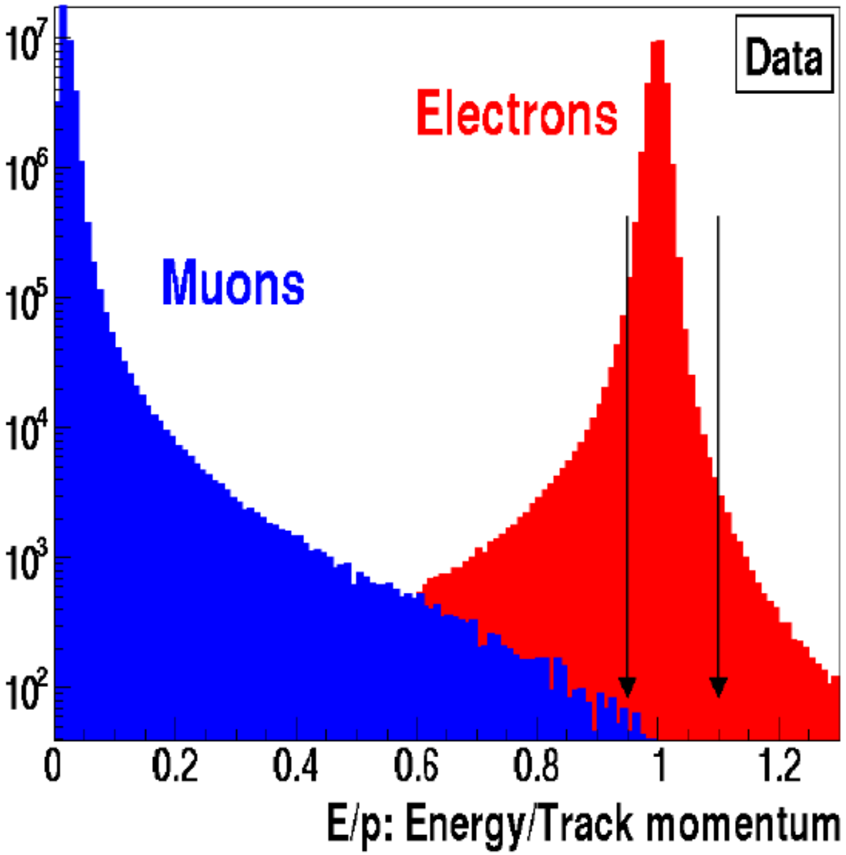




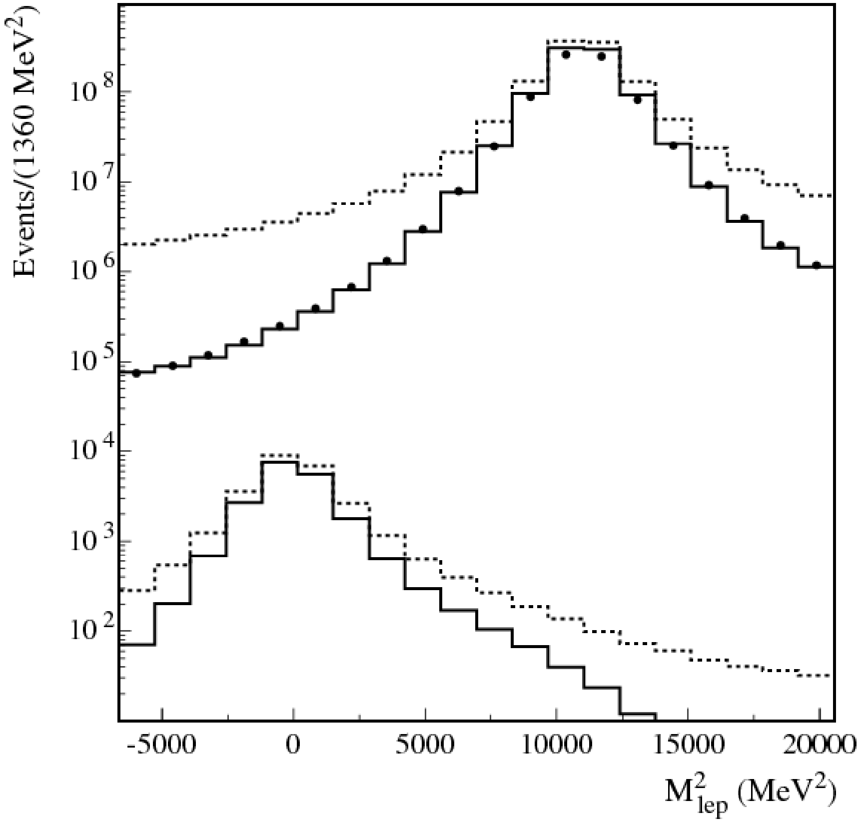
K_{e2} On tape	~ 30,000	~ 100,000
kine rejection	$\sim 10^3$ @ $\varepsilon_{l2}\sim 60\%$	$\sim 10^3 - 1$ p_l (20-60GeV)
EMC e/μ rejection	$\sim 10^3$	$\sim 10^6$

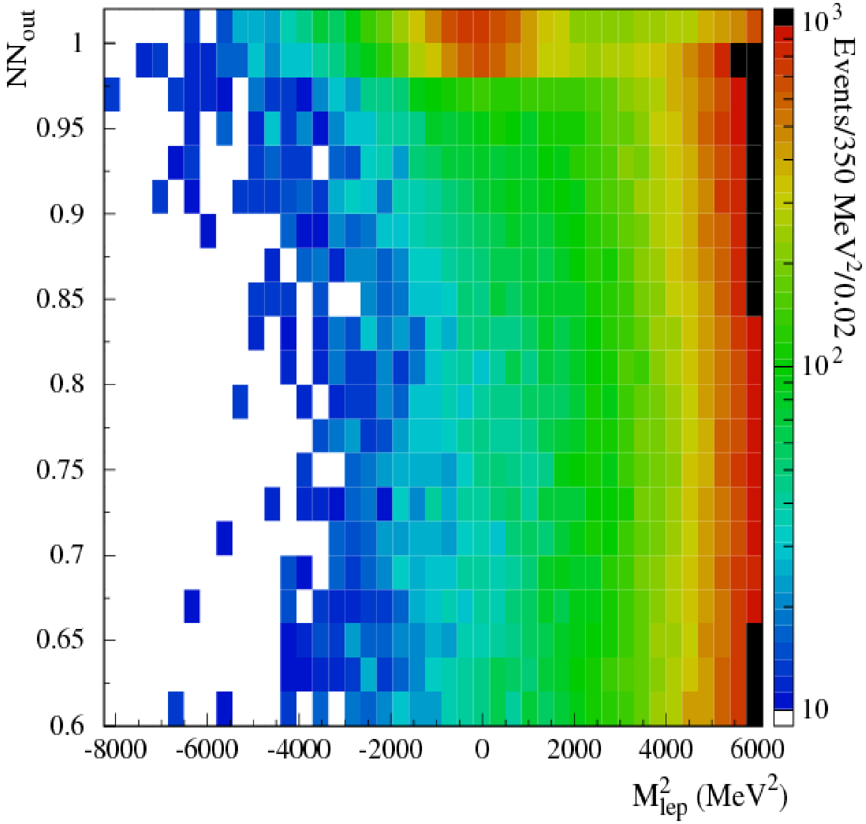
NA62: kinematics & e id





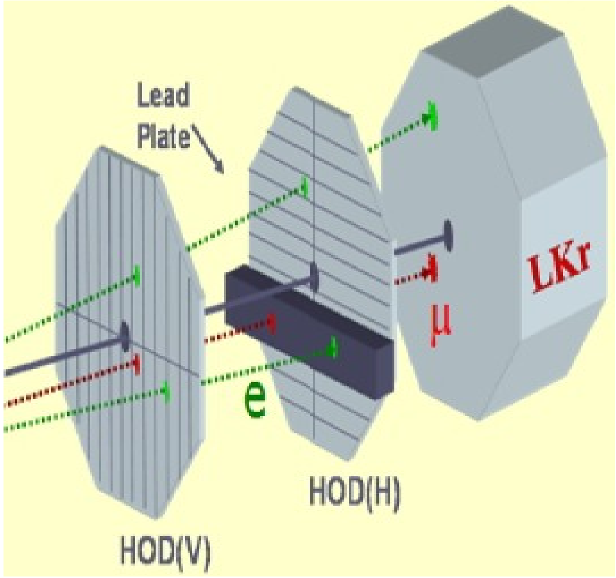
KLOE: kinematics & e id



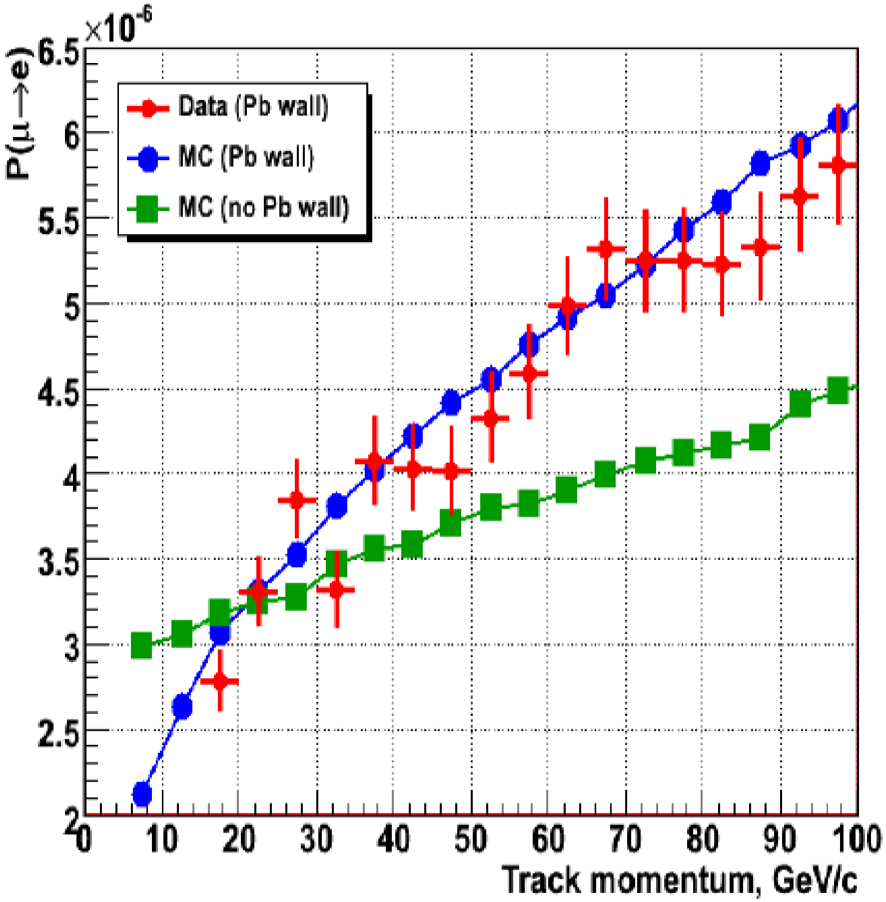


Experimental tricks: NA62

"Catastrophic" energy loss by muons in LKr.
Muons with E/p>0.95 are identified as electrons.
$P(\mu\rightarrow e) \sim 3\times10^{-6}$



Pb wall ($\sim 10X_0$) between the HOD planes: pure μ samples (electron contamination $<10^{-7}$)



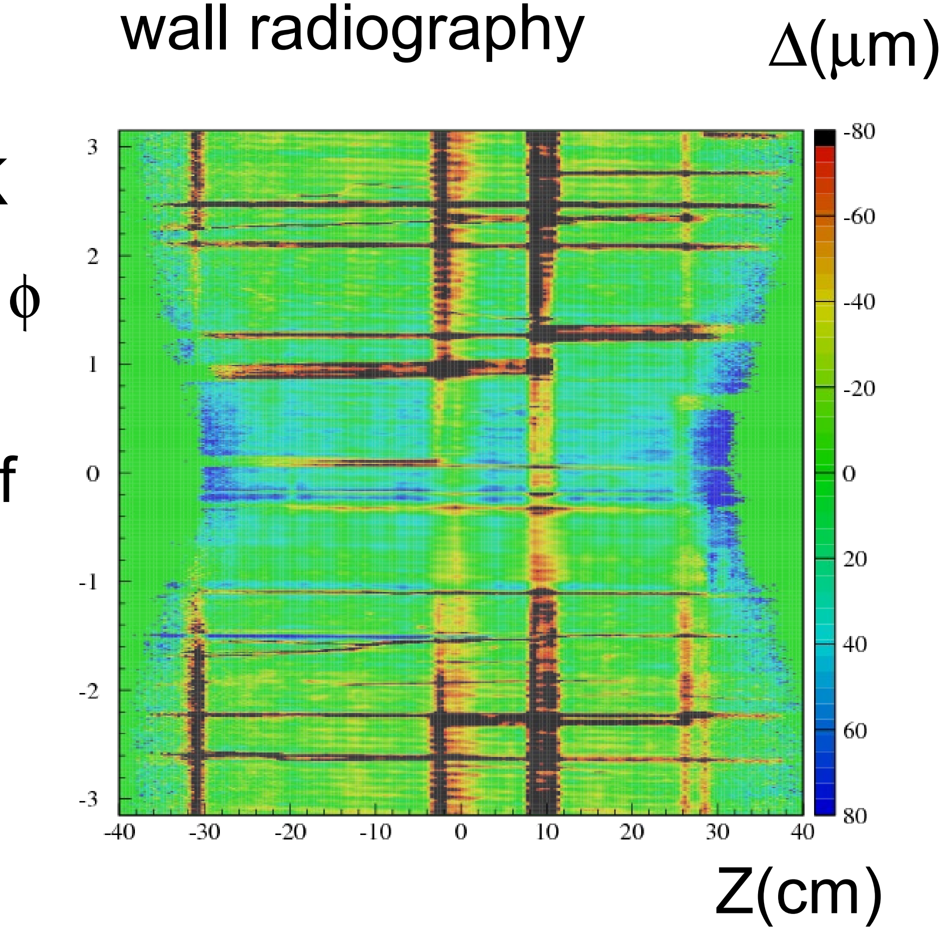
event frac. with E/p>0.95

Experimental tricks: KLOE

Use ϕ decay kinematics for a redundant determination of K momentum
but... $\beta_K \sim 0.2$

→ precise knowledge of material budget mandatory

Drift Chamber inner wall radiography

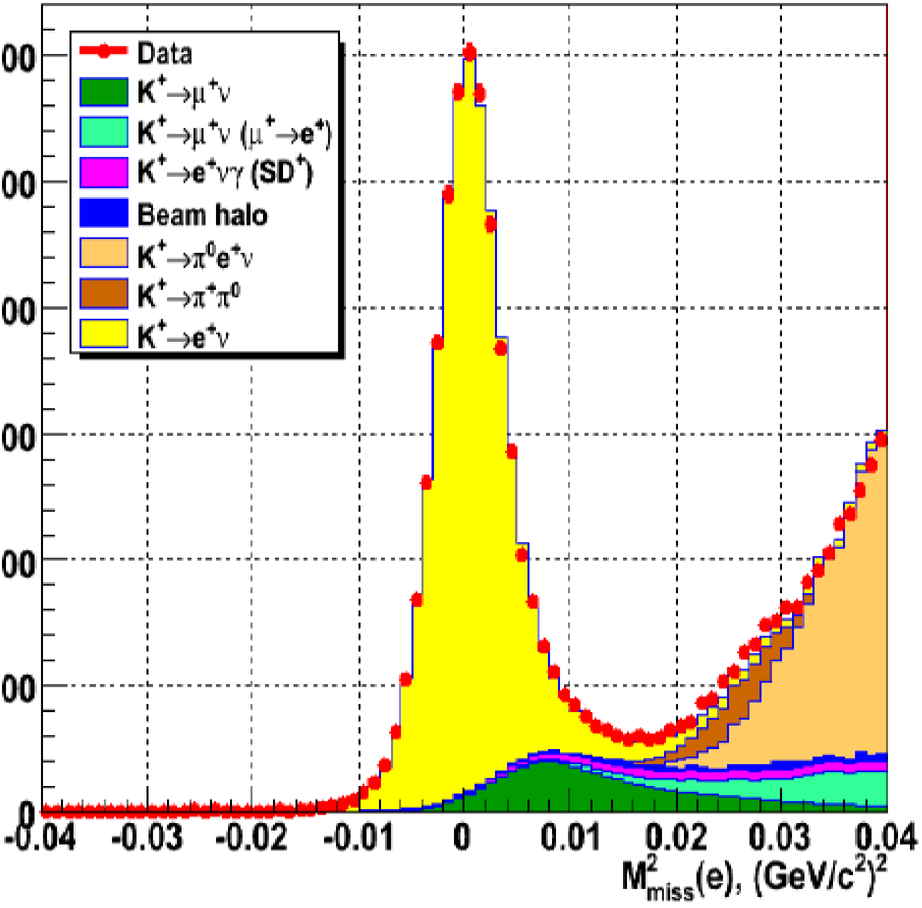


NA62: result

$R_K = (2.500 \pm 0.012_{\mathrm{stat}} \pm 0.011_{\mathrm{syst}}) \times 10^{-5}$

Preliminary result based on ~1/2 sample ~50,000 events

The whole sample will allow a statistical uncertainty ~0.3%, and total uncertainty of 0.4–0.5%.



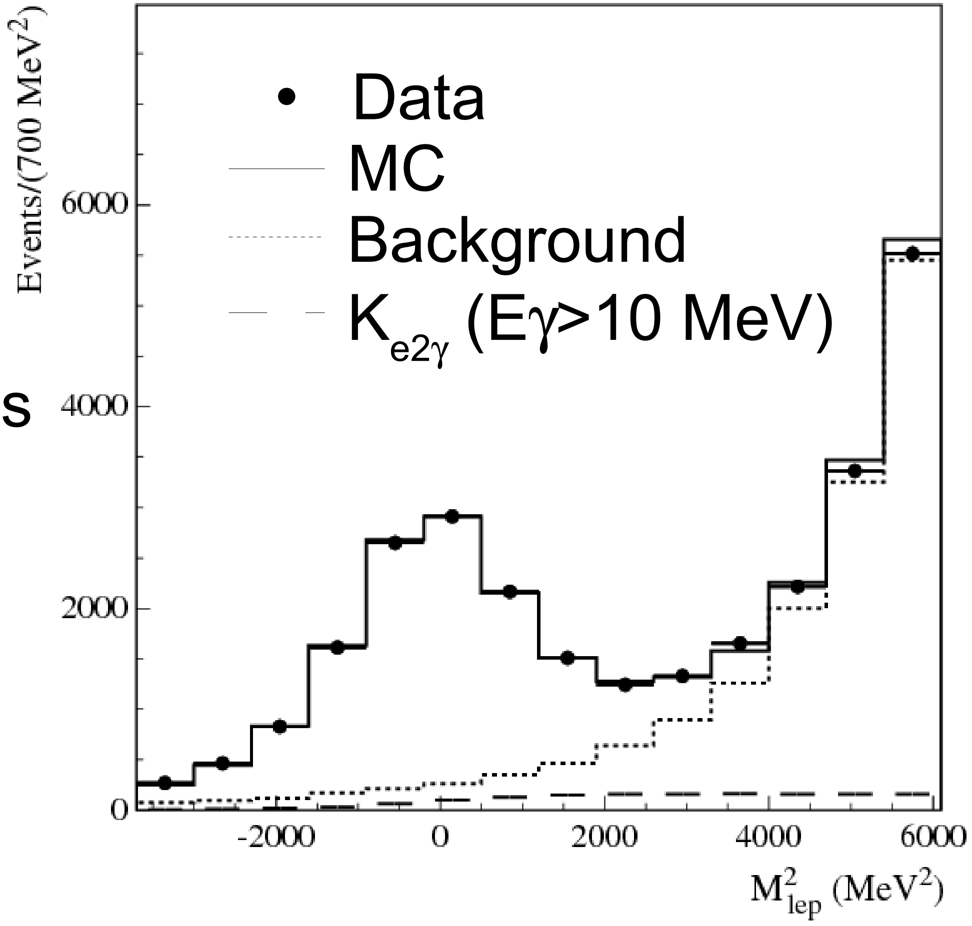
KLOE: result

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

About 14K events selected

~17% background

error dominated by statistics (Ke2 + C.S.)



KLOE: result

$R_K = (2.493 \pm 0.025_{stat} \pm 0.019_{syst})\ x10^{-5}$

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~17% background

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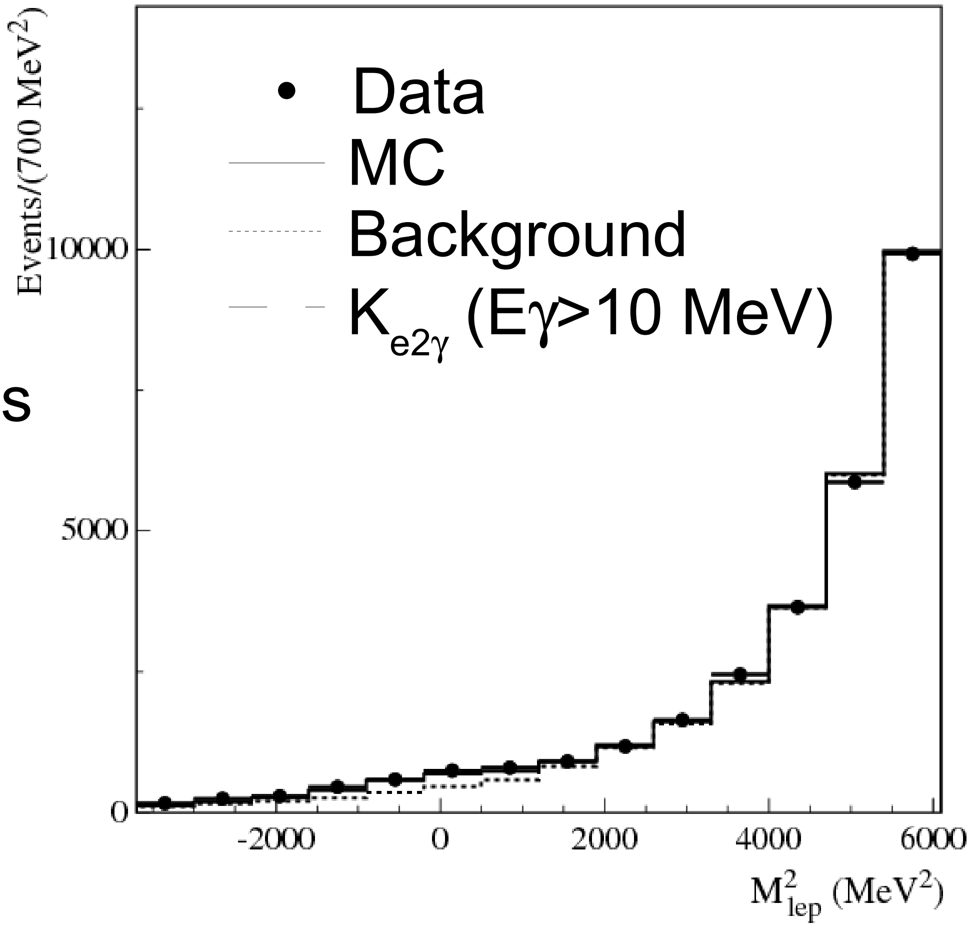
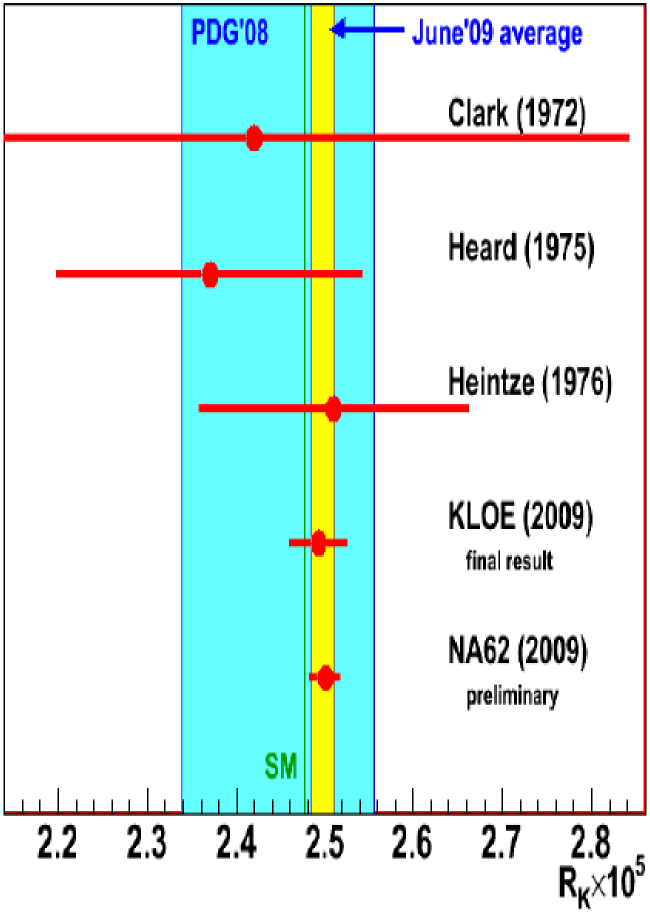
(Ke2 + C.S.)

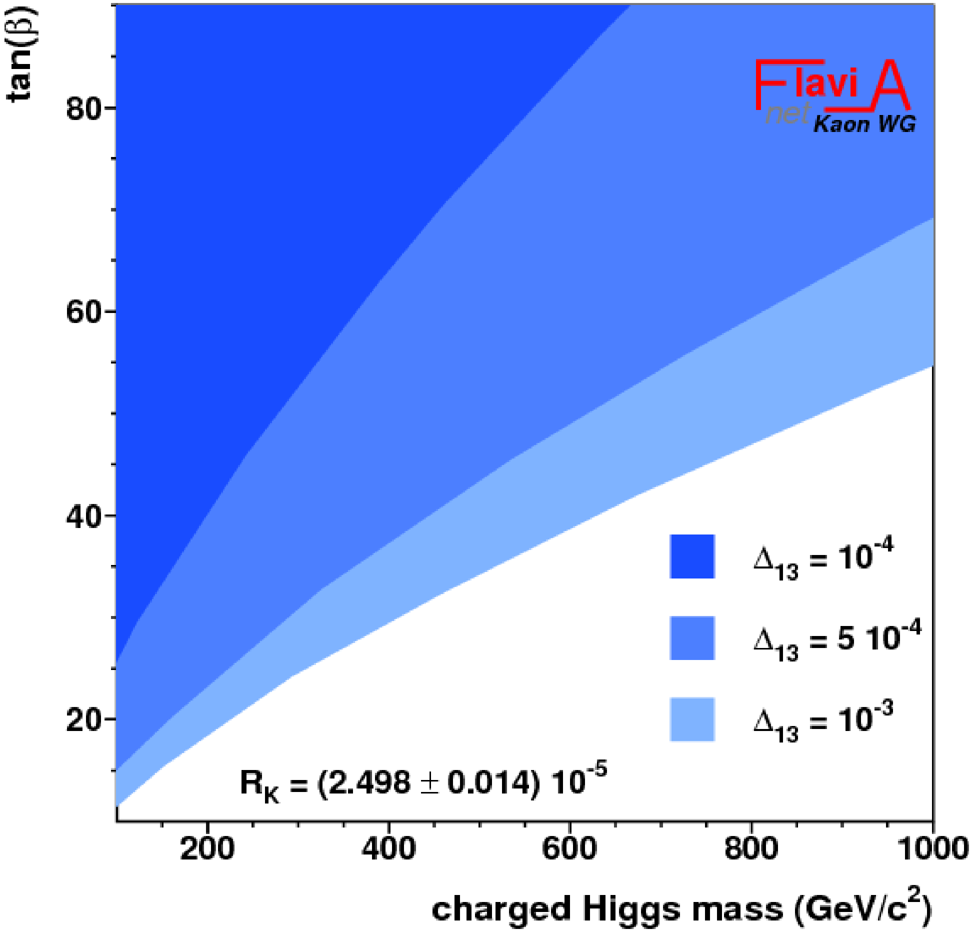


R_K: WA & constraints on NP

R_K= (2.493 ± 0.014) $\times 10^{-5}$ 0.56% accuracy



1.5 σ from SM



Radiative decays

K→eνγ: amplitudes

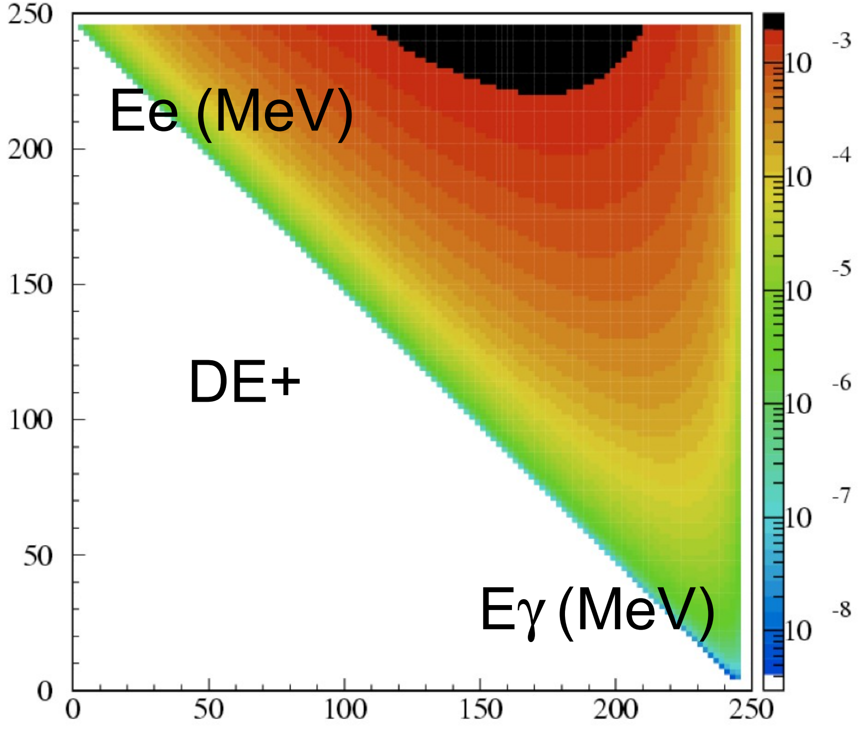
negligible

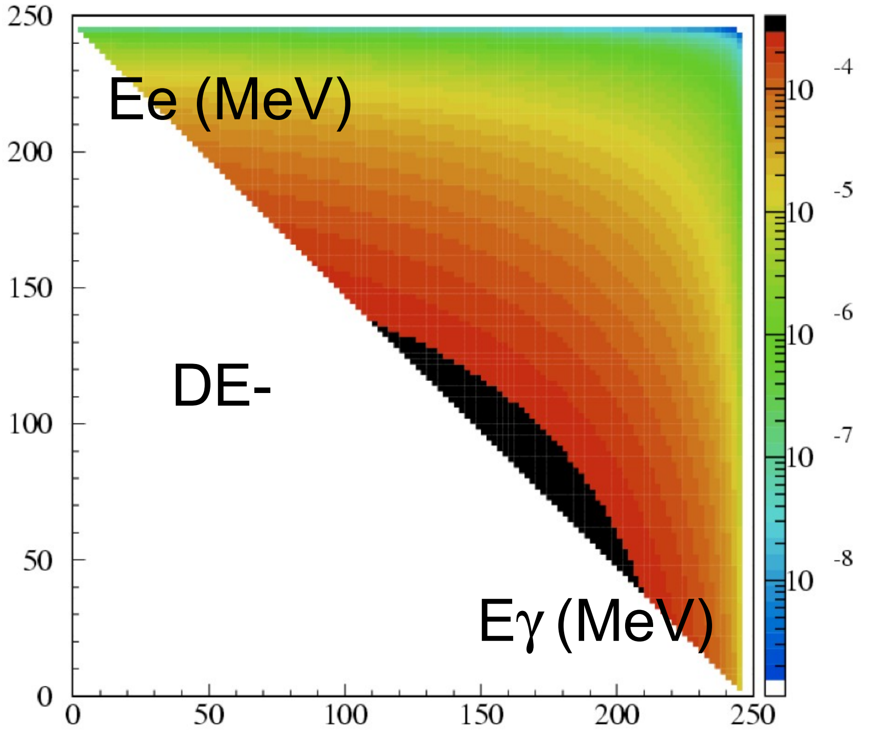
$$\frac{d\Gamma(K\rightarrow e\nu\gamma)}{dx\,dy}=\rho_{\mathrm{IB}}(x,y)+\rho_{\mathrm{SD}}(x,y)+\cancel{\rho_{\mathrm{INT}}(x,y)}$$

$$x=2E_{\gamma}^{*}/m_K$$
$$y=2E_{e}^{*}/m_K$$

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

V, A: effective vector and axial couplings





K→eνγ: KLOE measurement

No sensitivity for Ke2γ with
$p_e < 200$ MeV

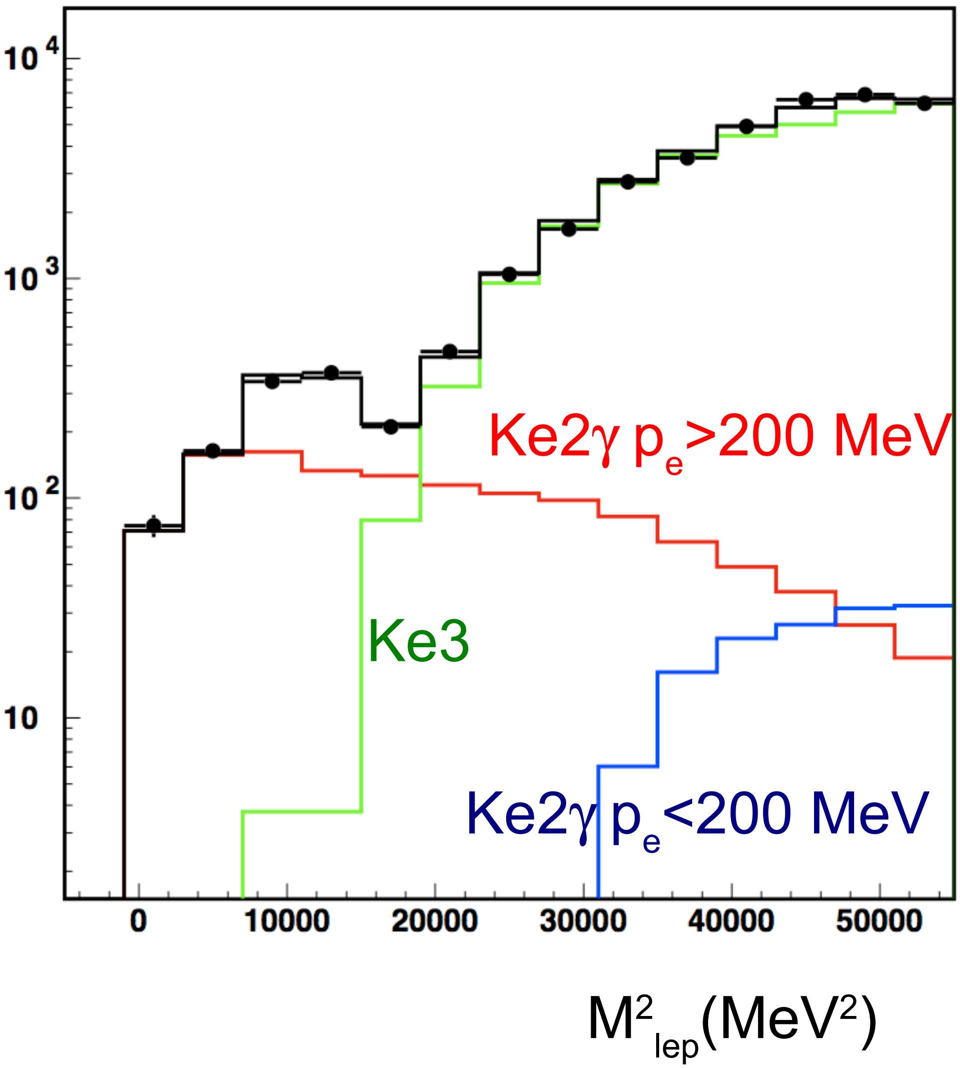
→

no sensitivity to DE- amplitude

We measure Ke2g with:

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

This selection has:
Acceptance for
- DE+ events ~90%
- DE- events ~2%



$K_{e2\gamma}$ spectrum vs O(p4) ChPT

We measure

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

where "SD+" means:

$E_\gamma^* > 10$ **MeV**

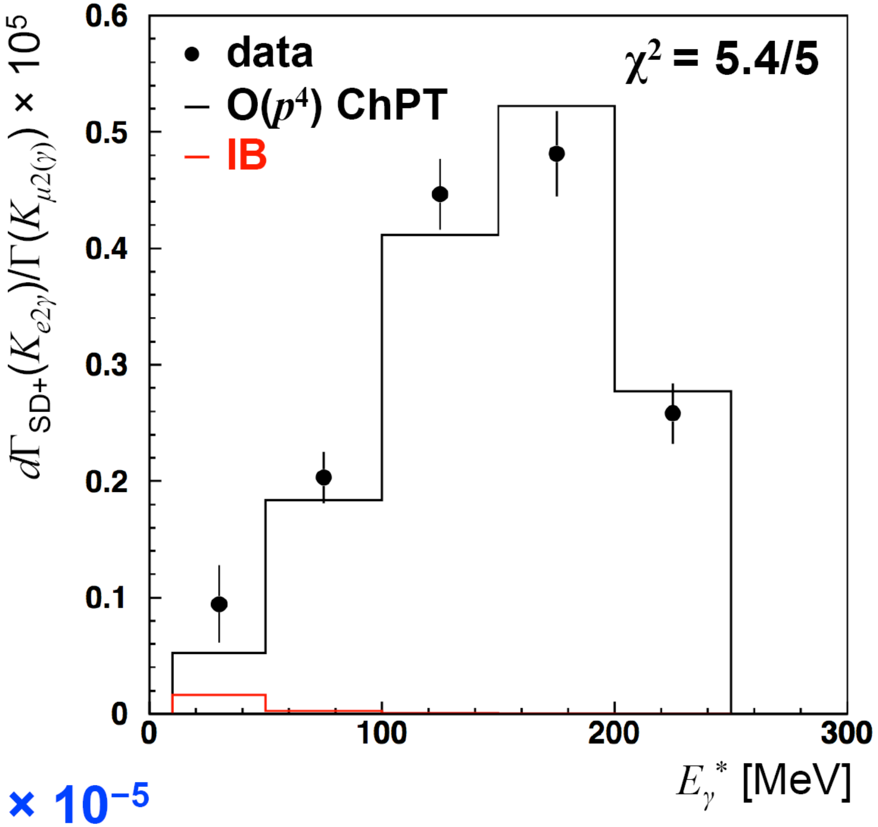
cos $\theta_{e\gamma}^* < 0.9$

$p_e^* > 200$ **MeV**

Summed over all bins in E_γ^*:

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

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



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%

$K_{e2\gamma}$ is there any slope ?

Fit data to extract $V + A$ for SD+

Get slope of vector form factor

$V = V_0\,[1 + \lambda(1 - x)]$

Not sensitive to SD− amplitude

Acceptance ~2%

Fix $V - A$ to O(p^6) prediction

Obtain:

$\mathbf{V_0 + A = 0.125 \pm 0.007}$

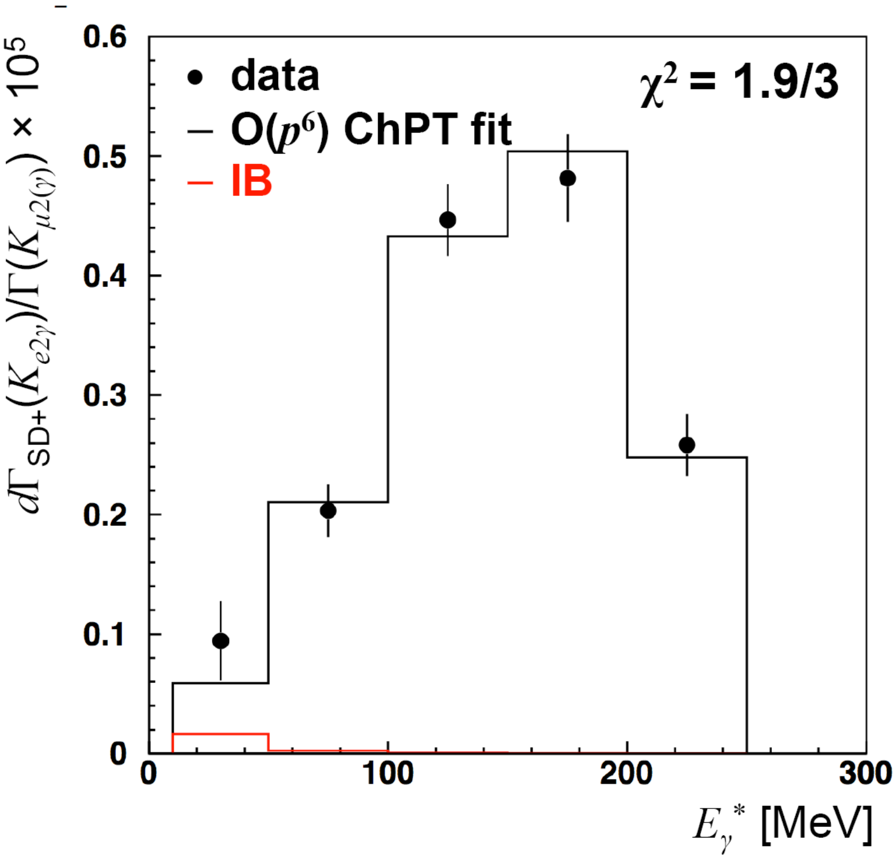
$\mathbf{\lambda = 0.38 \pm 0.21}$

Compare to ChPT O(p^6):

$\mathbf{V_0 + A \approx 0.116}$

$\mathbf{\lambda \approx 0.4}$

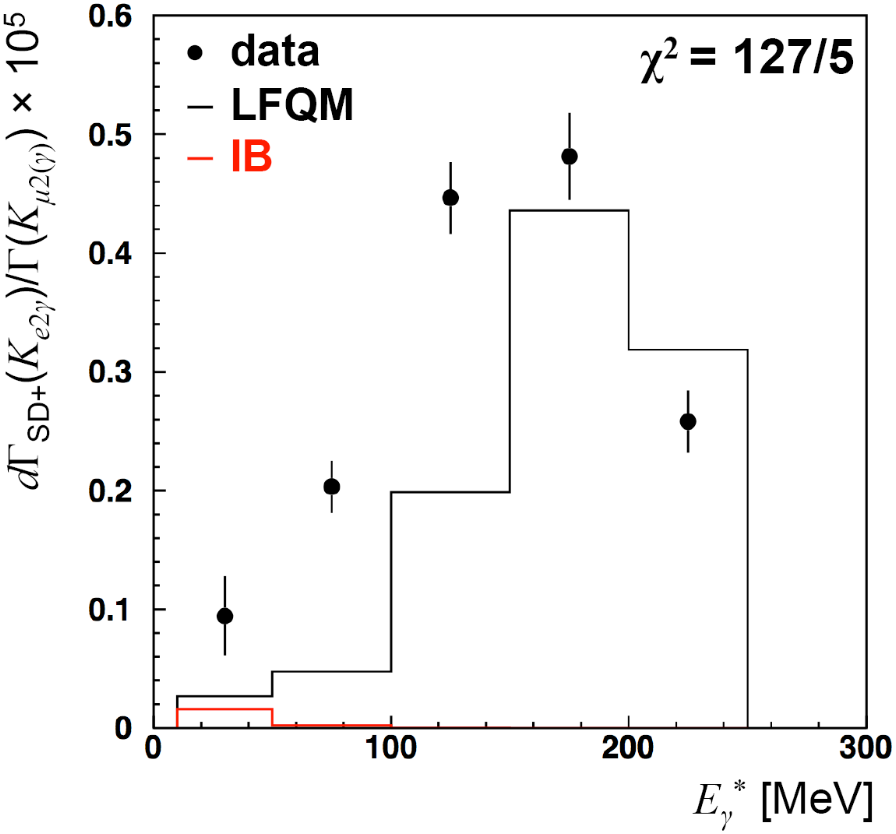
Chen, Geng, Lih ’08



$K_{e2\gamma}$ alternative models

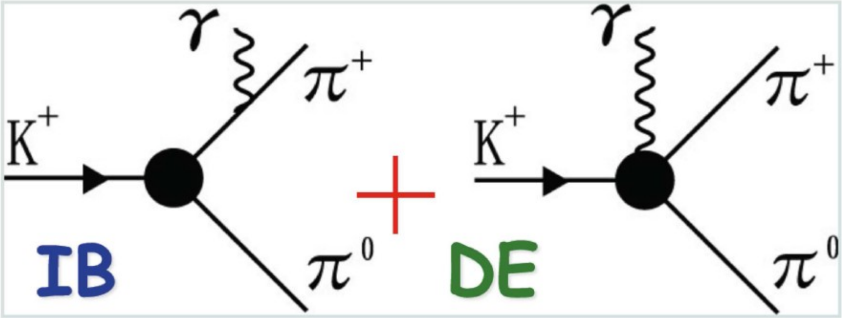
Light Front Quark Model with parameters as in Chen, Geng, Lih, '08

Excluded by our data
$\chi^2 = 127/5$



Chen, Geng, Lih '08

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



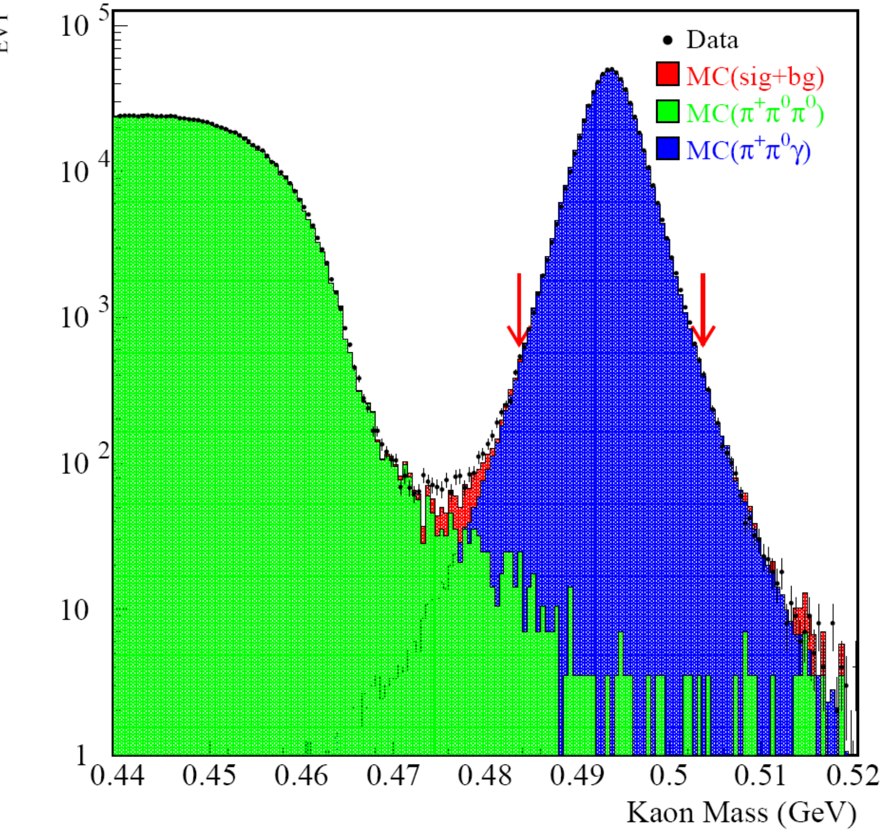
Kinematic variable:

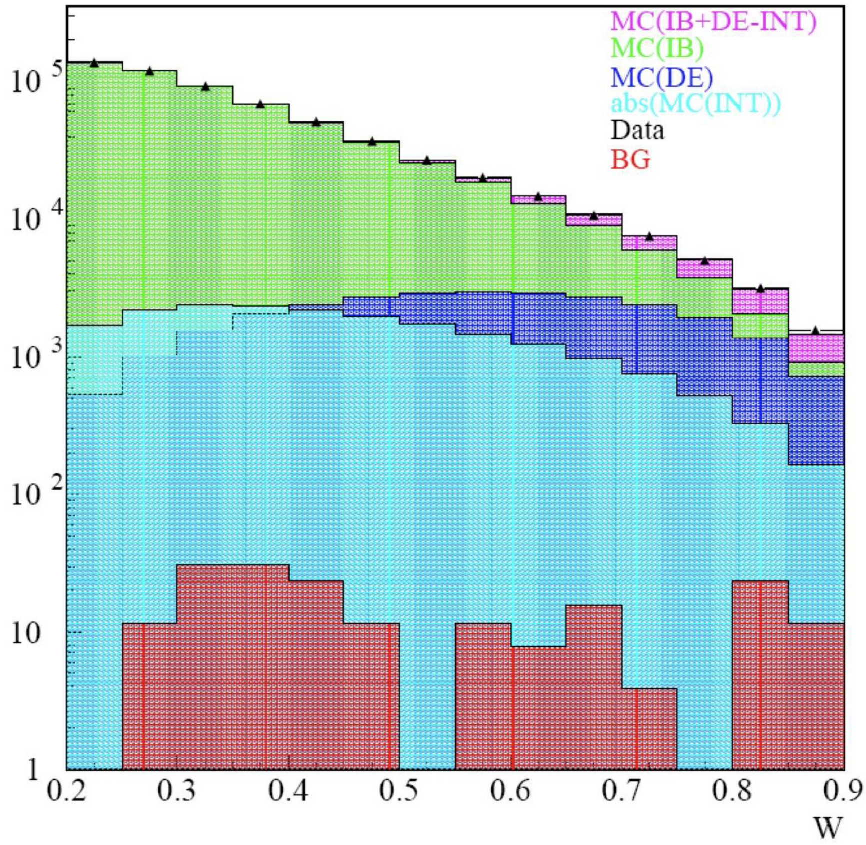
$$W^2 = \frac{(p_\pi \cdot p_\gamma)(p_K \cdot p_\gamma)}{m_K^2 m_\pi^2}$$

$$\frac{\partial\Gamma^{\pm}}{\partial W} = \underbrace{\frac{\partial\Gamma^{\pm}_{\text{IB}}}{\partial W}}_{\text{Inner Bremsstrahlung (IB)}} \Big[1 + \underbrace{2\cos\left(\pm\phi + \delta_1^1 - \delta_0^2\right)\,|X_E|\,W^2}_{\text{Interference (INT)}}$$

$$+ \underbrace{m_\pi^4 m_K^4 \left(|X_E|^2 + |X_M|^2\right) W^4}_{\text{Direct Emission (DE)}} \Big]$$

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





$$\text{Frac(DE)}_{0<T^\star_\pi<80\text{ MeV}} = (\ \ 3.32 \pm 0.15_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-2}$$

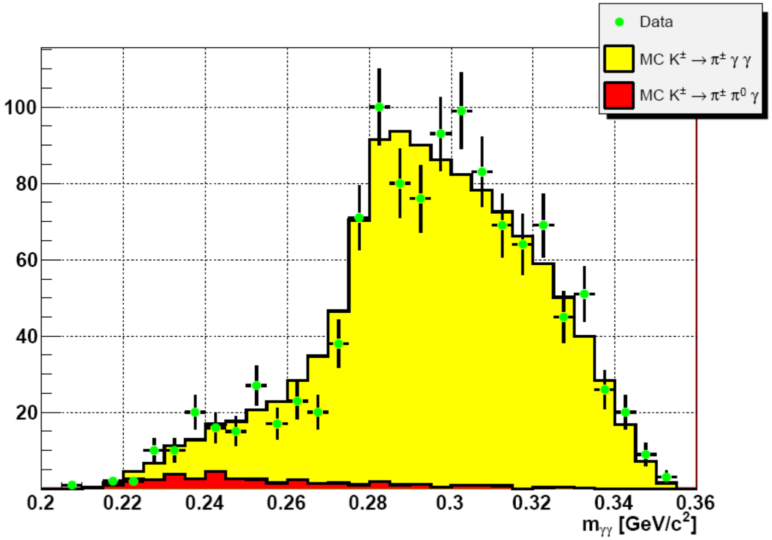
$$\text{Frac(INT)}_{0<T^\star_\pi<80\text{ MeV}} = (-2.35 \pm 0.35_{\text{stat}} \pm 0.39_{\text{syst}}) \times 10^{-2}$$

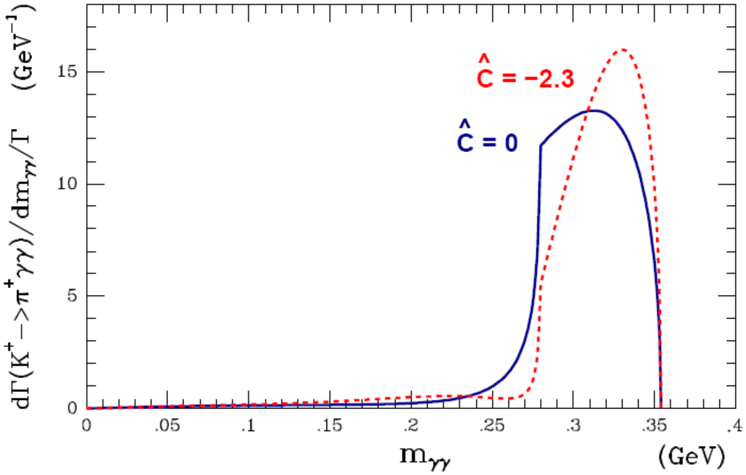
Correlation: $\rho = -0.93$

$K^\pm \rightarrow \pi^\pm\gamma\gamma$: NA48 measurement

1164 $K^\pm \rightarrow \pi^\pm\gamma\gamma$ candidates in 40% of NA48/2 data.

(About 40 times more than previous world sample!)





Assume ChPT $\mathcal{O}(p^6)$ and $\hat{c} = 2$:

(preliminary)

$$\boxed{\mathbf{Br}(K^\pm \rightarrow \pi^\pm\gamma\gamma)_{\hat{c}=2,\mathcal{O}(p^6)} = (1.07 \pm 0.04_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}}) \cdot 10^{-6}}$$

Model independent measurement and $\hat{c}$ extraction in preparation.

$K^{\pm} \rightarrow \pi^{\pm}\gamma e^{+}e^{-}$: NA48 measurement

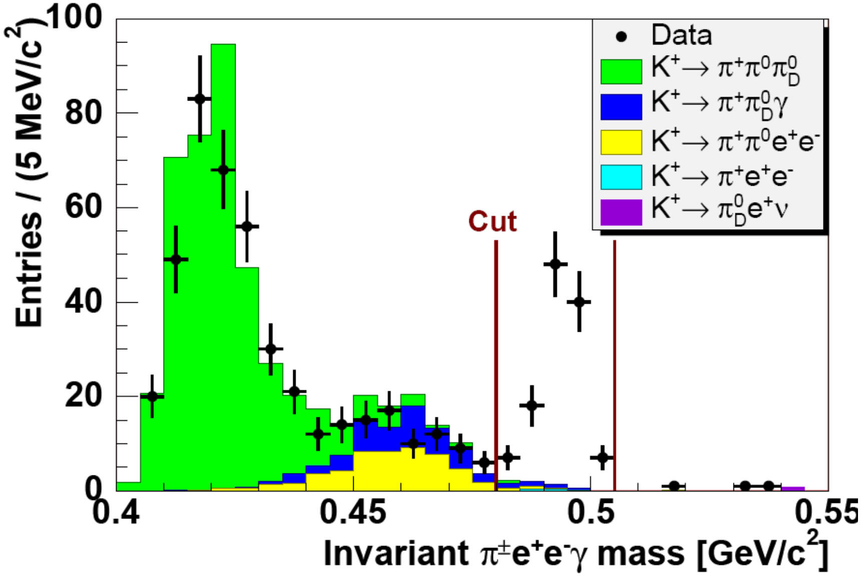
Same as $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$

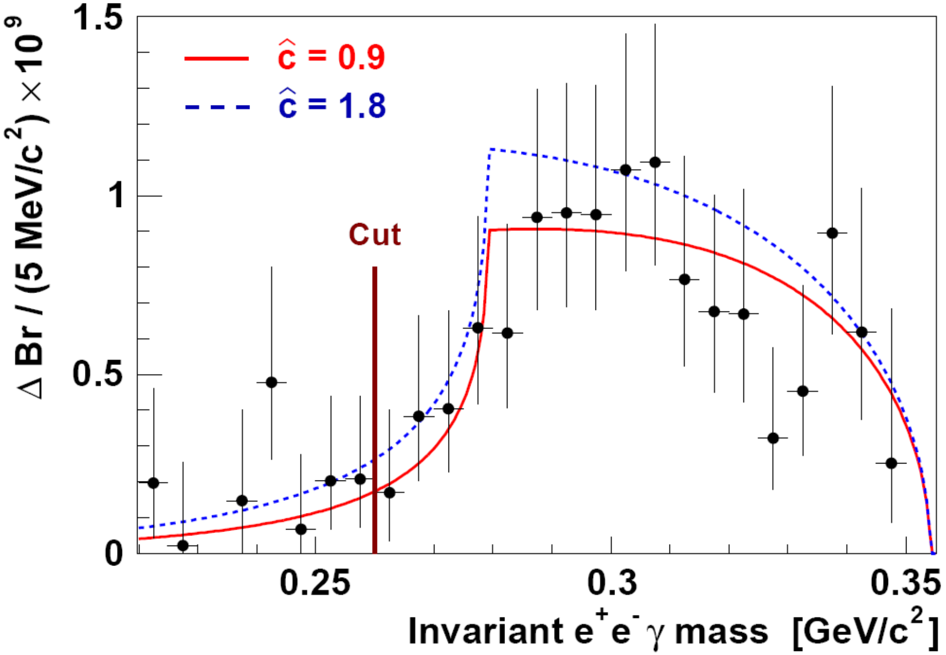
with an internal γ conversion.

Fit $m_{ee\gamma}$ distribution for $\hat{c}$ using $\mathcal{O}(p^6)$ ChPT:

$$\boxed{\hat{c} \;=\; 0.90 \pm 0.45}$$

$(\chi^2/N_{\text{dof}} = 8.1/17)$





$$\boxed{\mathbf{Br}(K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma)_{m_{ee\gamma}>260\,\text{MeV}} \;=\; (1.19 \pm 0.12_{\text{stat}} \pm 0.04_{\text{syst}}) \cdot 10^{-8}}$$

$K \longrightarrow \pi\nu\nu$

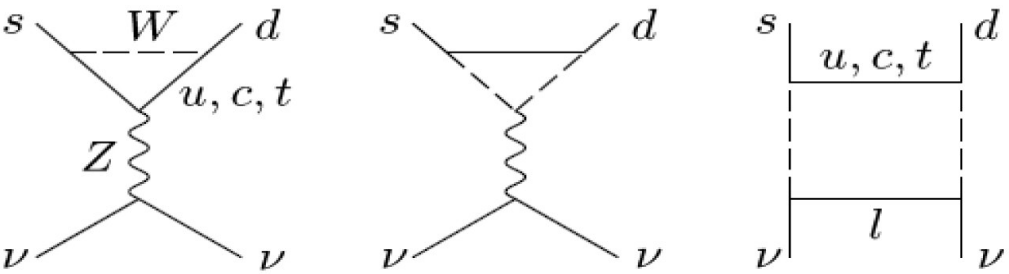
K→ πνν: introduction

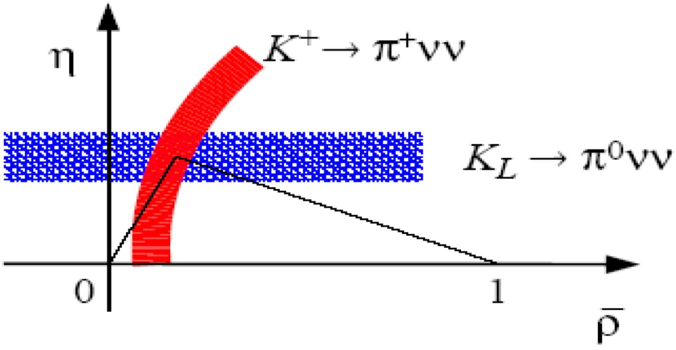
Standard Model *(Buras et al., Mescia and Smith, Brod and Gorbahn)*:

$$\mathrm{B}(K_L^0 \to \pi^0 \nu\bar{\nu}) = 1.8\,x10^{-10}\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2 = 2.76 \pm 0.40\,x10^{-11}$$

$$\mathrm{B}(K^+ \to \pi^+ \nu\bar{\nu}) \sim 1.0\,x10^{-10}\,A^4\left[\eta^2 + (\rho_0 - \rho)^2\right] = 8.5 \pm 0.7\,x10^{-1}$$

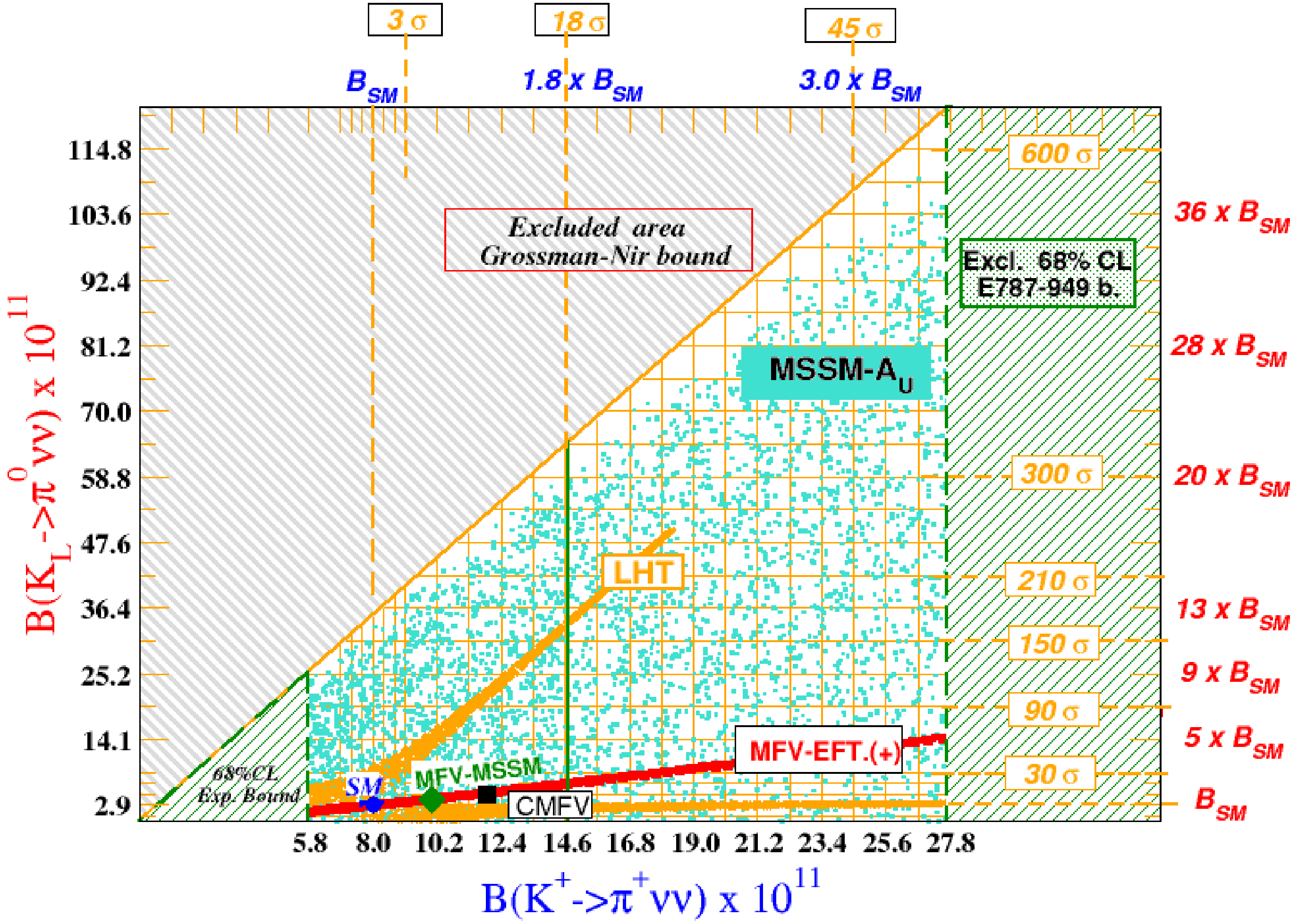
$\mathrm{Im}\,\lambda_t = \mathrm{Im} V_{ts}^* V_{td} = \eta A^2 \lambda^5$





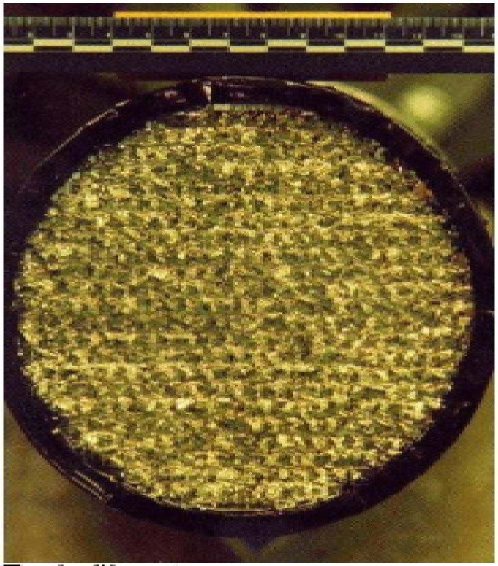
$K \to \pi\nu\nu$: NP sensitivity

deviations from SM >O(10%) even within MFV

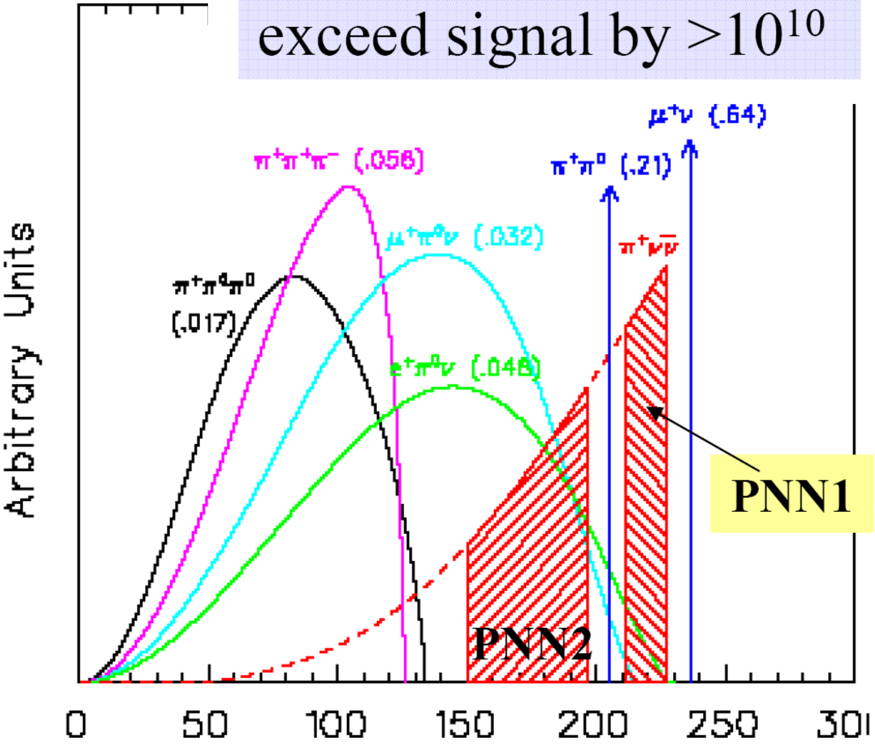


$K^\pm \rightarrow \pi^\pm \nu\nu$: BNL method

stop low energy
kaons in active degrader



Background processes exceed signal by $>10^{10}$



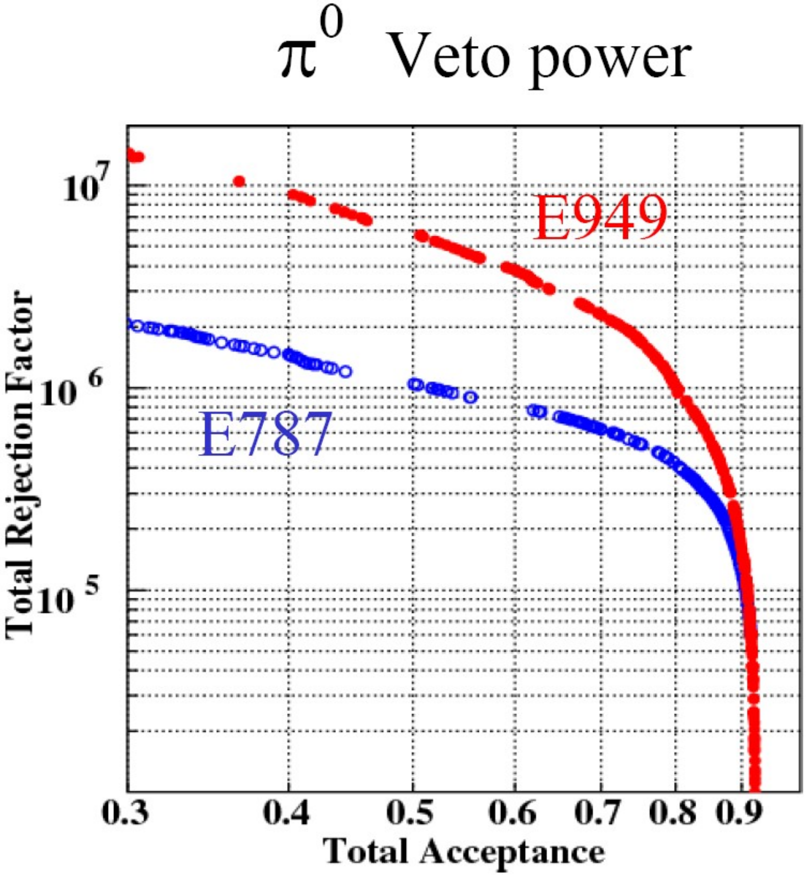
- Determine everything possible about the K^+ and π^+

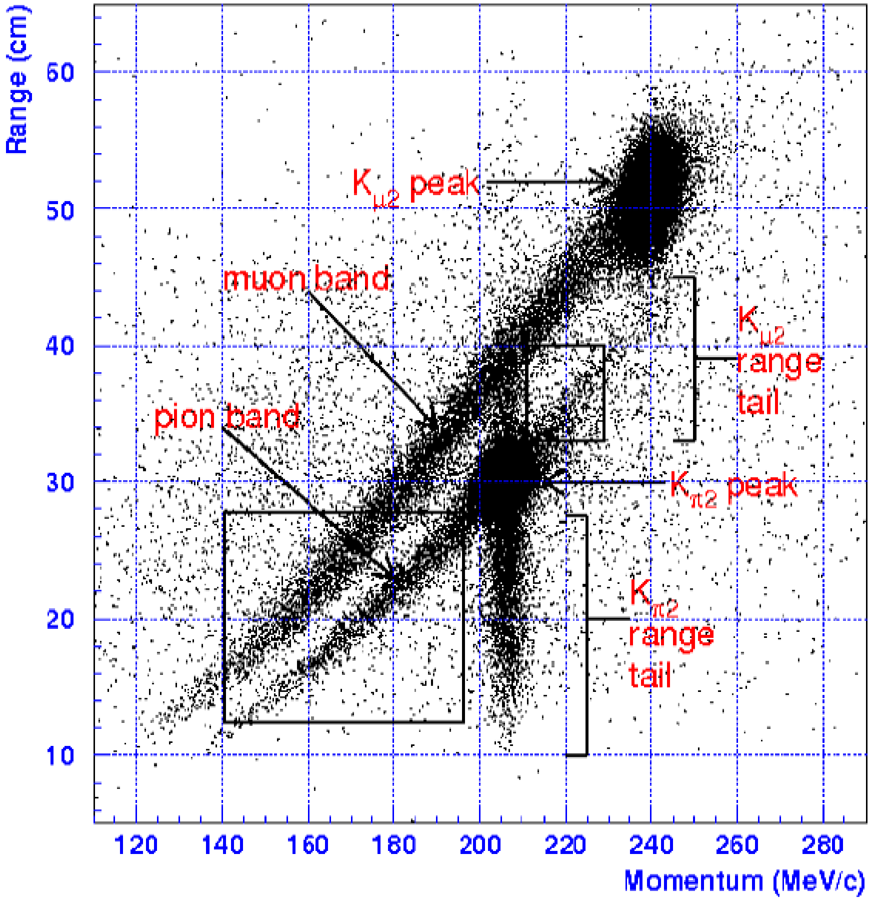
  * π^+/μ^+ particle ID better than 10^6 (π^+-μ^+-e^+)

- Eliminate events with extra charged particles or ***photons***

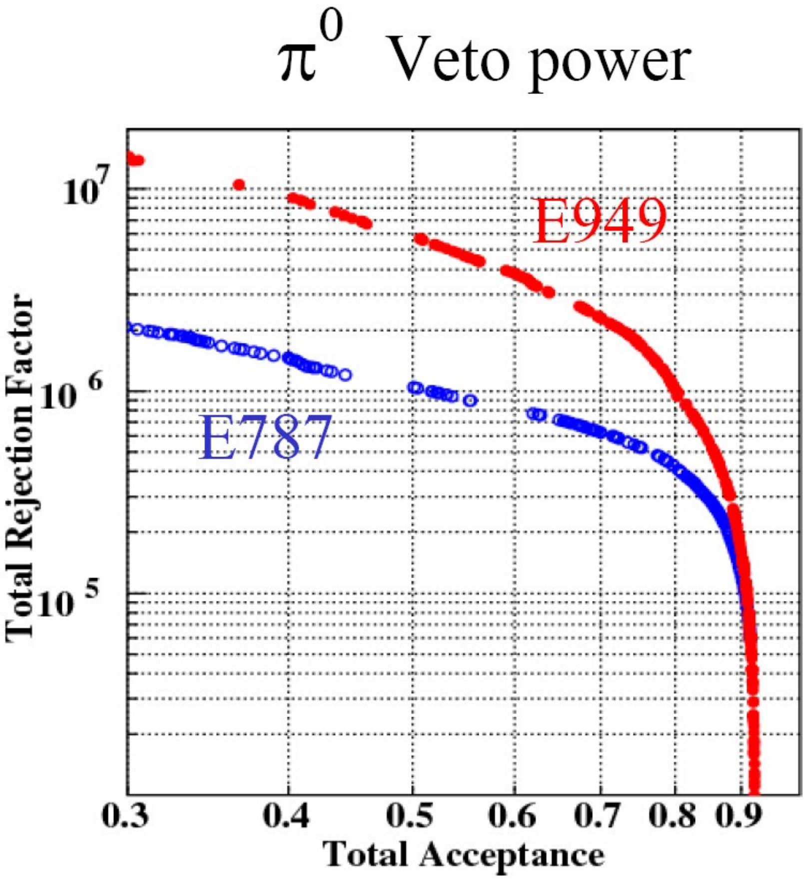
  * π^0 inefficiency $< 10^{-6}$

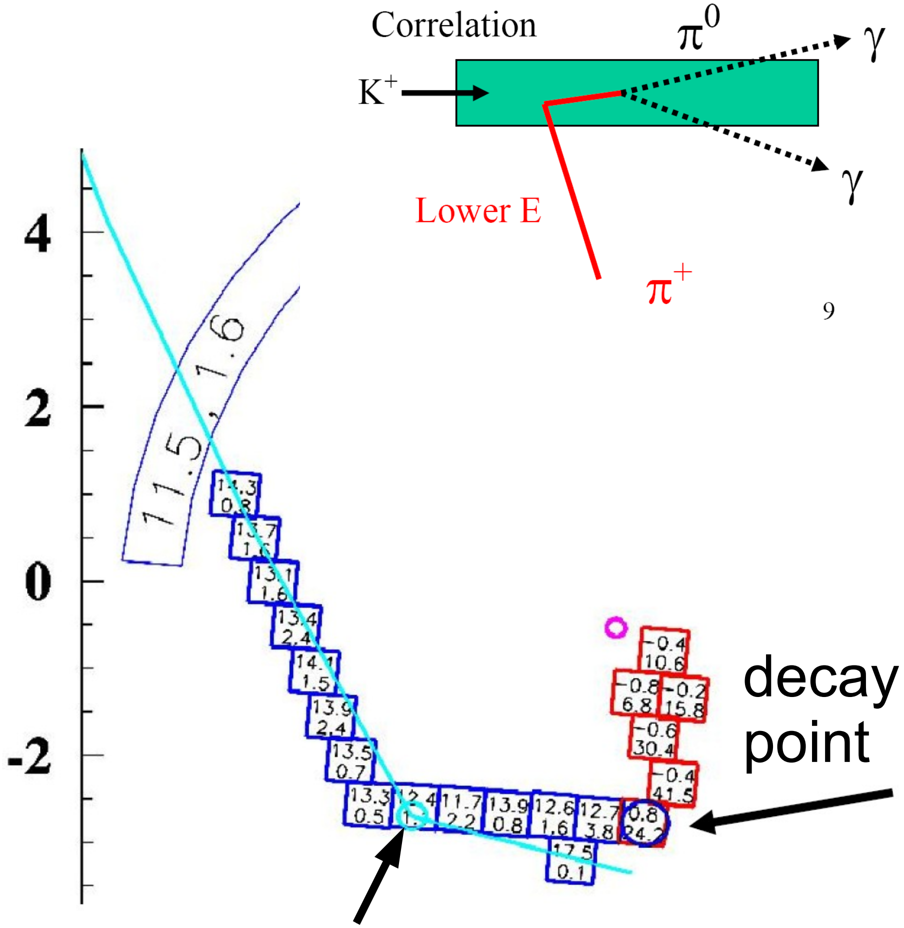
$K^{\pm} \rightarrow \pi^{\pm}\nu\nu$: E949 improvements





K± → π±νν: E949 improvements


π^0 Veto power

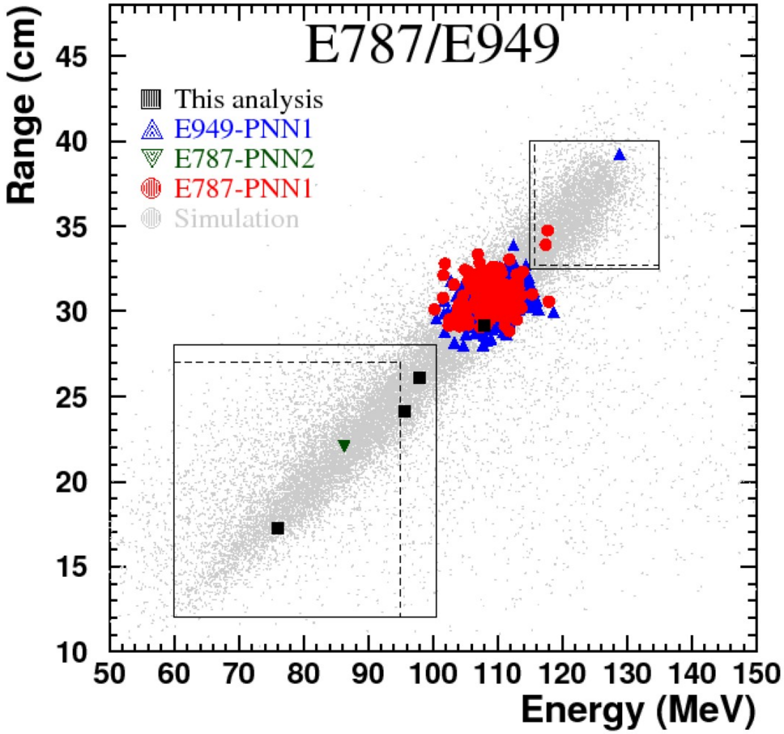


decay point

scattering point

Final results from E787/E949

7 events observed



$$B(K^+ \to \pi^+ \nu\overline{\nu}) = 1.73^{+1.15}_{-1.05} x 10^{-10}$$

Probability that All 7 events are due to background: 0.001

Prospects for continuing at JPARC or FNAL (Project X) ~ 1000 events

$K^{\pm} \rightarrow \pi^{\pm}\nu\nu$: NA62 method

Goals:

- $O(100)\, K^{+} \rightarrow \pi^{+} \nu \bar{\nu}$ events
- ~10% background

- BR(SM) ~ 8.5×10^{-11}
- Acceptance: 10%
- K decays: ~10^{13}

Principles:

- "High" momentum K^{+} beam: easier rejection of the π^{0} induced background
- Decay in-flight technique: beam-backgrounds suppressed wrt stopping kaon experiments

- Experimental techniques to exploit:

(1) Kinematic rejection: against 2-body and 3-body backgrounds

(2) Precise timing: matching of the outgoing π^{+} with the correct parent K^{+}

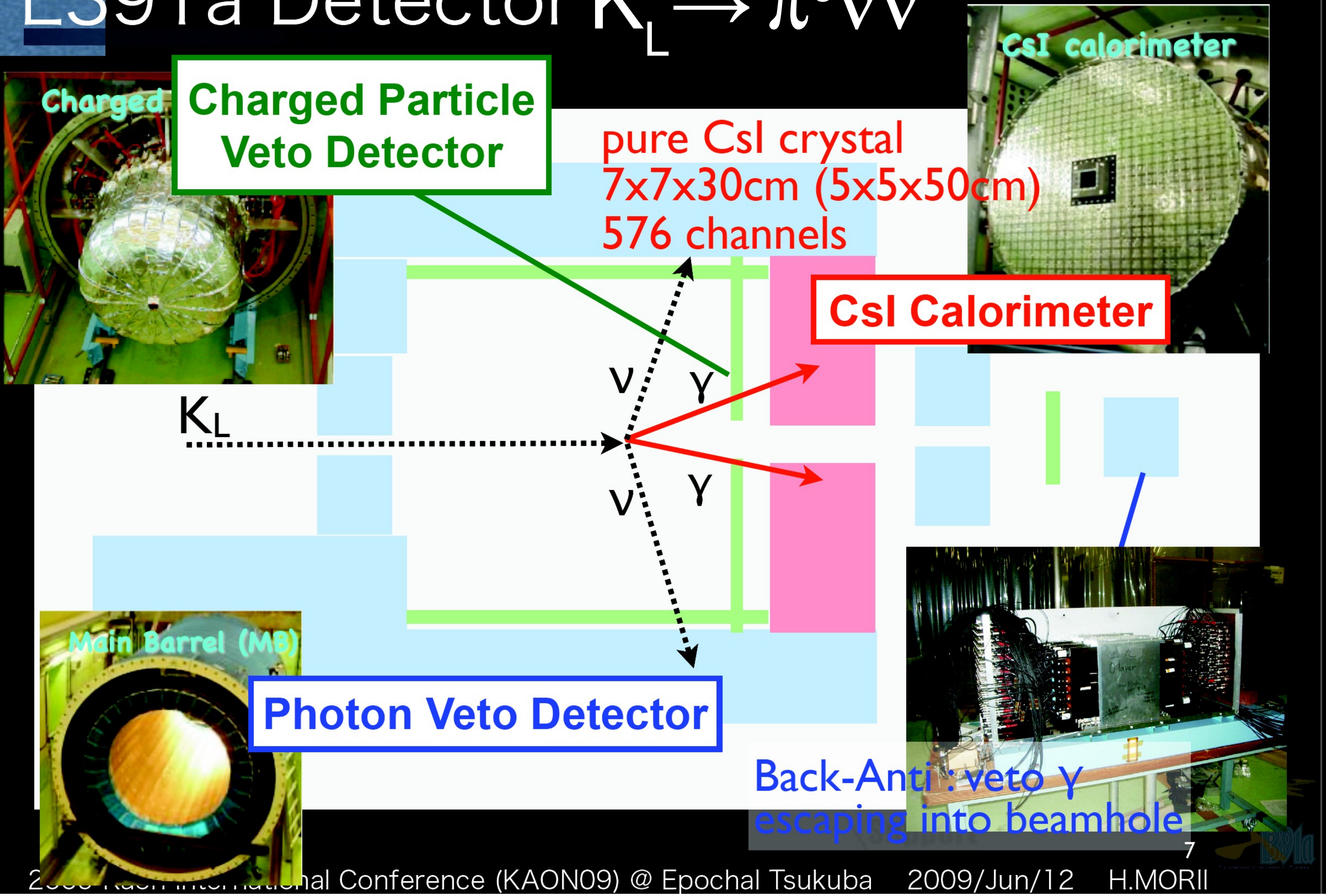
(3) Vetoes: rejection of events with γ and μ in final state

(4) Particle Identification: K/π (in the primary beam), π/μ (final state)

$K^{\pm} \rightarrow \pi^{\pm}\nu\nu$: NA62 sensitivity

Decay Mode	**Events**
Signal: $K^+ \rightarrow \pi^+\nu\nu$ *[flux = 4.8×10^{12} decay/year]*	**55** *evt/year*
$K^+ \rightarrow \pi^+\pi^0$ *[$\eta_{\pi 0} = 2\times10^{-8}$ (3.5×10^{-8})]*	**4.3% (7.5%)**
$K^+ \rightarrow \mu^+\nu$	**2.2%**
$K^+ \rightarrow e^+\pi^+\pi^-\nu$	**≤3%**
Other 3 – track decays	**≤1.5%**
$K^+ \rightarrow \pi^+\pi^0\gamma$	**~2%**
$K^+ \rightarrow \mu^+\nu\gamma$	**~0.7%**
$K^+ \rightarrow e^+(\mu^+)\ \pi^0\nu$, others	**negligible**
Expected background	**≤13.5% (≤17%)**

E391a Detector $K_L \to \pi^0 \nu\nu$



Charged Particle Veto Detector

pure CsI crystal
7x7x30cm (5x5x50cm)
576 channels

CsI Calorimeter

Photon Veto Detector

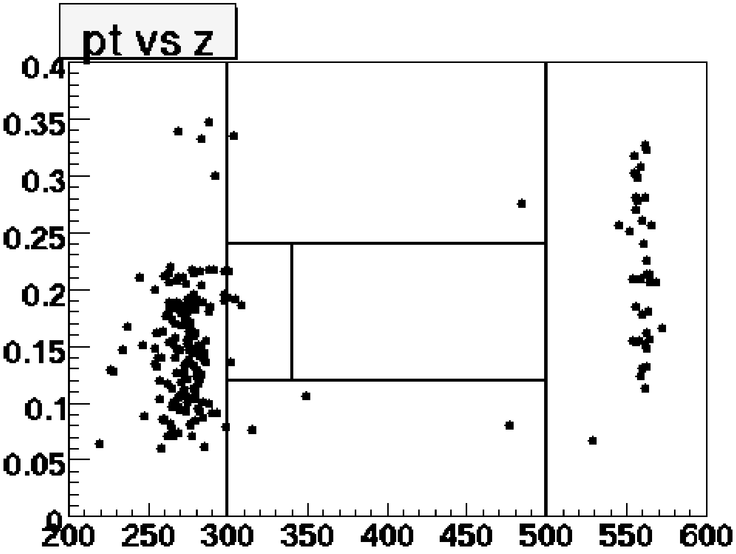
Back-Anti : veto γ escaping into beamhole

$K_L \rightarrow \pi^0 \nu\nu$: E391 new run result

Acceptance ~0.98% (cf previous run: 0.67%)

same single event sensitivity 2.95×10^{-8} with ~70% stat.

No event observed in data
(0.44 exp. background)



Preliminary result:
$BR(K_L \rightarrow \pi^0 \nu\nu) < 6.8 \times 10^{-8}$ (90% CL)

Previous run
$BR(K_L \rightarrow \pi^0 \nu\nu) < 6.7 \times 10^{-8}$ (90% CL)

Combination is ongoing

Prospects @ JPARC
S/beam bkg 1/240
upgrade detector KOTO

Conclusion

Very precise tests of SM with kaons:

CP violation

$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4}$

$\varepsilon_K = (2.221 \pm 0.006) \times 10^{-3}$

CPT invariance $M_K - M_{\bar{K}} = (-0.1 \pm 2.0) \times 10^{-19}$ GeV for $\Delta\Gamma = 0$

Tests with helicity suppressed

$R_{l23} = 1.008 \pm 0.008$

$R_K = (2.493 \pm 0.014) \times 10^{-5}$

Many new precise results on radiative decays

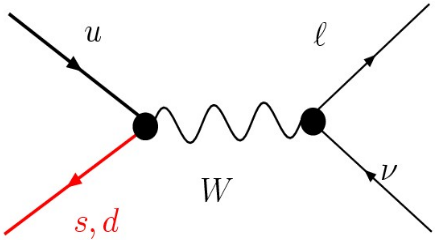
Start exploring $K \to \pi\nu\nu$

G_F universality violation

$|V_{ud}|^2 + |V_{us}|^2 + |\cancel{V_{ub}}|^2 \equiv 1$ →

Universality of Weak coupling- $G_F=(g_W/M_W)^2$

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



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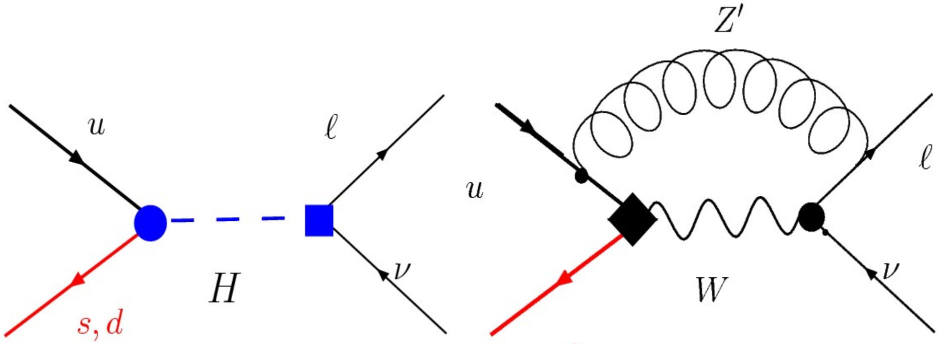
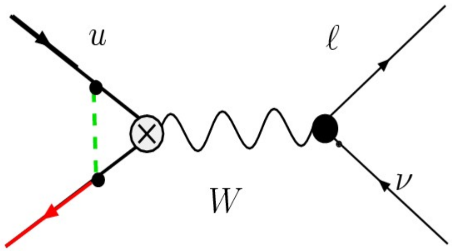




Sensitivity to new physics :
naively

$G_{CKM}=G_F\,[1+a(M_W/M_M)^2]$

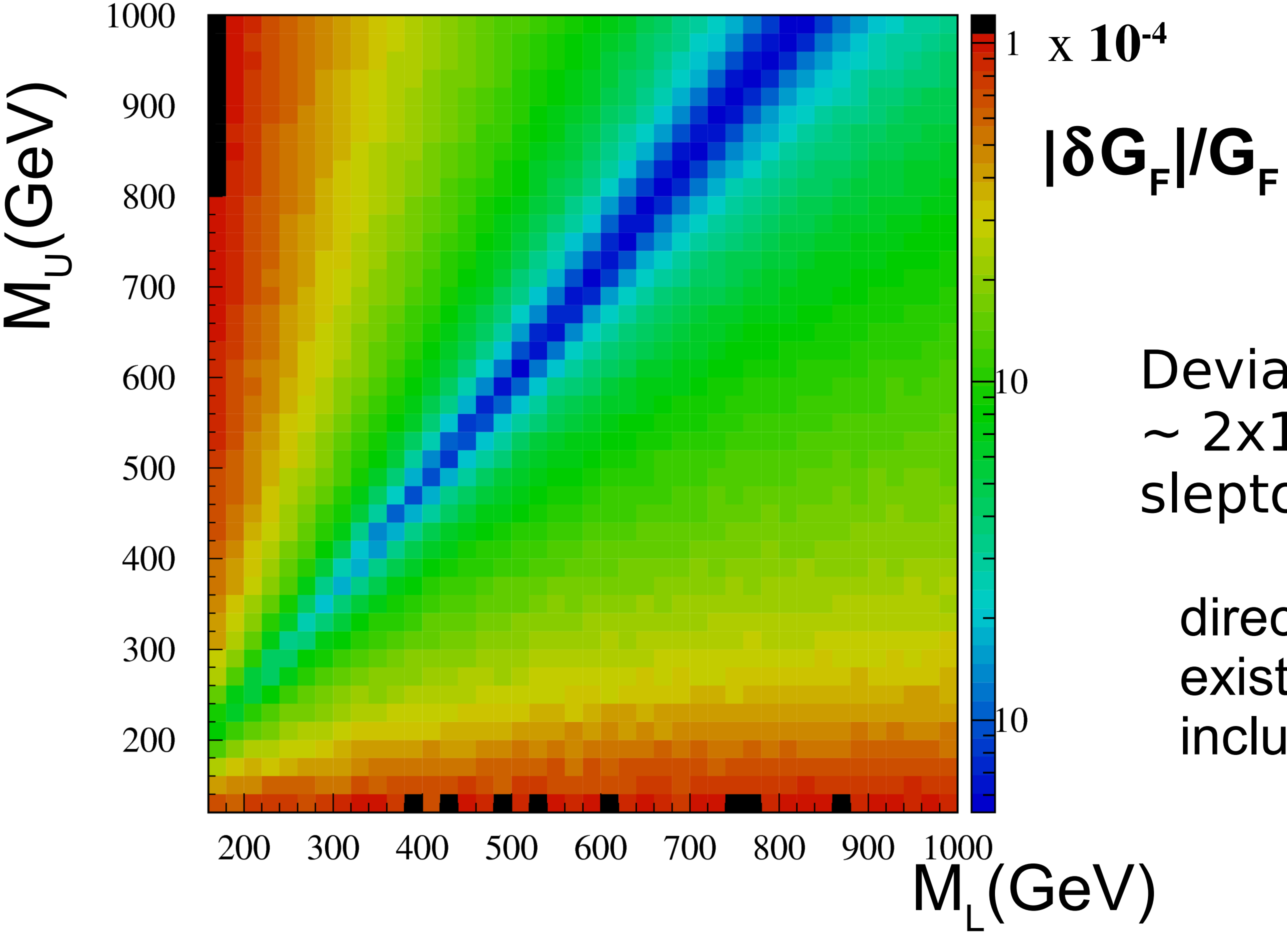
Tree level $a\sim1$ $M_M\sim10$ TeV

loops $a\sim g_W^2/(16\pi^2)$ $M_M\sim1$ TeV

sensitivity to NP: MSSM

sensitive to squark-slepton mass difference

[R. Barbieri '85,
K.Hagiwara et al
'95, A. Kurylov
et al '00]



Deviations up to
~ $2\text{x}10^{-4}$ for small
slepton mass

direct and indirect
existing limits
included

[© Mescia, Paradisi]

V_{us} *from* τ

check with kaons on exclusive modes(~70% of R_S):

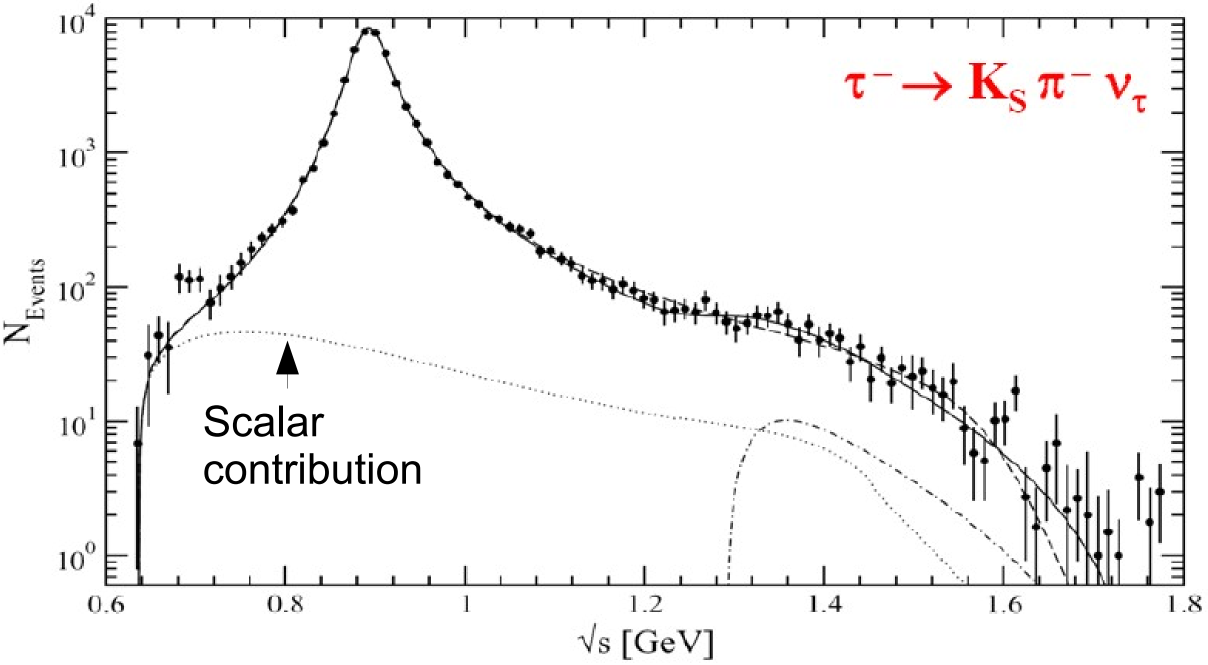
(46% of R_S) BR($K\pi\nu$) need precise form factor parameters

Prediction (no exp. Syst. included):

BR($K_S\pi^-\nu$) = 0.427(11)(21_{model})

In agreement with measured values but still limited accuracy (modeling)

Jamin-Pich-Portolés 08 fit to **BELLE** data

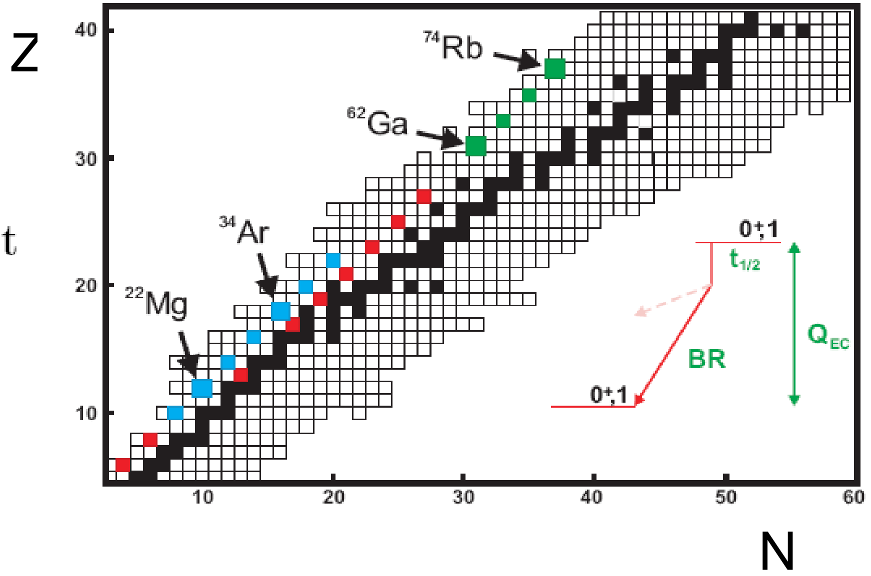


Many new results from Belle-BaBar expected

V_{ud} from Fermi transitions

$$V_{ud}^2 = \frac{K}{2G_F^2\overline{\mathcal{F}t}(1+\Delta_R)}$$

$$\mathcal{F}t = ft(1+\delta'_R)(1-(\delta_C-\delta_{NS})) = \text{constant}$$



Measured on 13 Nuclei:

$t = t_{1/2}$/BR = partial half life

f = statistical rate function $f(Z,Q_{ec})$*

Radiative and isospin breaking corrections:

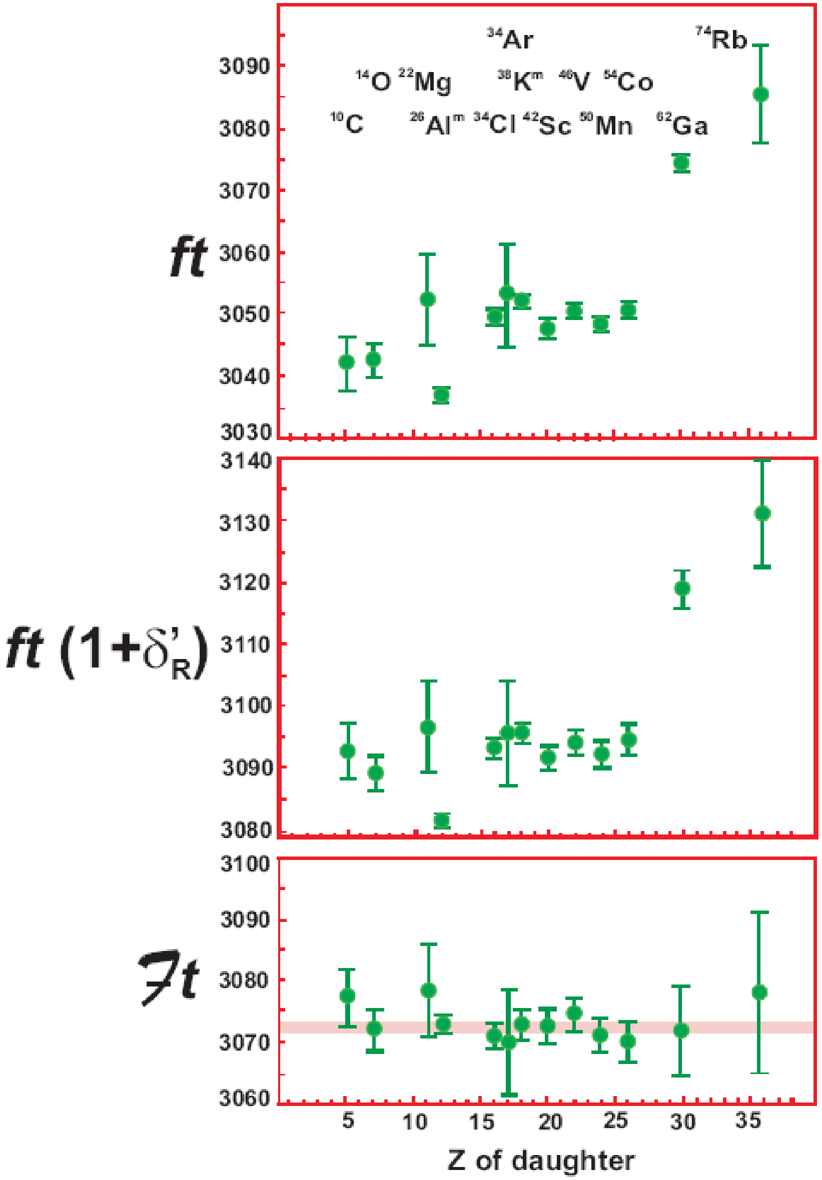
Δ_R=2.361(38)% Nucleus-independent [Marciano Sirlin]

δ'_R, δ_{NS} Nucleus-dependent

δ_C Nucleus-dependent isospin breaking

* Z dependence account for e wave function

V_{ud} from Fermi transitions

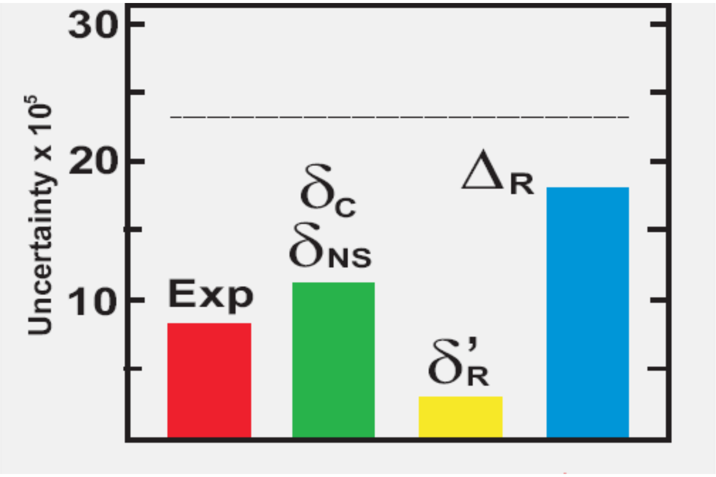


[Towner, Hardy 2008]

$$V_{ud}^2 = \frac{K}{2G_F^2 \overline{\mathcal{F}t}(1+\Delta_R)}$$

V_{ud} = 0.97425(23)

Error budget:



V_{us} and V_{us}/V_{ud} determination

$K_{\ell 3}$ decays

Vector transition protected against ~~SU~~(3) corrections: [Ademollo Gatto]

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

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

C_K^2	1/2 for K^+, 1 for K^0
S_{EW}	Universal SD EW correction (1.0232)

Inputs from theory:

$f_+^{K^0\pi^-}(0)$	Hadronic matrix element (form factor) at zero momentum transfer (t = 0)
$\Delta_K^{SU(2)}$	Form-factor correction for $SU(2)$ breaking
$\Delta_{K\ell}^{EM}$	Form-factor correction for long-distance EM effects

Inputs from experiment:

$\Gamma(K_{\ell 3(\gamma)})$	Rates with well-determined treatment of radiative decays: • Branching ratios • Kaon lifetimes
$I_{K\ell}(\{\lambda\}_{K\ell})$	Integral of dalitz density (includes ff) over phase space: • K_{e3}: Only λ_+ (or λ_+', λ_+'') • $K_{\mu 3}$: Need λ_+ and λ_0

$P_{\ell 2}$ decays

$$\Gamma(P_{\ell 2(\gamma)}) = \frac{G_F^2\,|V_{uq}|^2}{8\pi}\; f_P^2\;\; m_\ell M_P (1 - m_\ell^2/M_P^2)^2\;\;(1 + C_{P\ell})$$

Inputs from theory:

f_P	decay constants
$C_{P\ell}$	Radiative inclusive electroweak corrections

Inputs from experiment:

$\Gamma(P_{\ell 2(\gamma)})$ Rates with well-determined treatment of radiative decays:

- Branching ratios
- lifetimes

Used to determine pseudoscalar decay constants

Small uncertainties for ratios:

$\Gamma(K_{\mu 2(\gamma)})/\Gamma(\pi_{\mu 2(\gamma)})$ **f_K/f_π from lattice → determine V_{us}/V_{ud}**

[Mariciano]

$R_P = \Gamma(P_{e2(\gamma)})/\,\Gamma(P_{\mu 2(\gamma)})$ **no f_P → test lepton universality**

[Cirigliano, Rosell]

Results for K_L BRs, τ

18 input measurements

- **5 KTeV** ratios
- **NA48** BR(*Ke*3/2 track)
- **NA48** $\Gamma(3\pi^0)$ [prelim.]
- **4 KLOE** Brs
- **KLOE**, **NA48** BR($\pi^+\pi^-/Kl3$)
- **KLOE**, **NA48** BR($\gamma\gamma/3\pi^0$)
- **PDG** ETAFIT BR($2\pi^0/\pi^+\pi^-$)
- **KLOE** τ_L from $3\pi^0$
- **Vosburgh ’72** τ_L

1 **constraint: Σ BR = 1**

BR(*Ke*3)	**0.4056(7)**	**1.1**
BR(*K*μ3)	**0.2705(7)**	**1.1**
BR($3\pi^0$)	**0.1951(9)**	**1.2**
BR($\pi^+\pi^-\pi^0$)	**0.1254(6)**	**1.1**
BR($\pi^+\pi^-$)	**$1.997(7)\times10^{-3}$**	**1.1**
BR($2\pi^0$)	**$8.64(4)\times10^{-4}$**	**1.3**
BR($\gamma\gamma$)	**$5.47(4)\times10^{-4}$**	**1.1**
τ_L	**51.17(20) ns**	**1.1**

χ^2/ndf = 20.2/11 (4.3%)

	PDG ’04	This fit	
$\lvert\eta_{+-}\rvert$x10^3	**2.284(14)**	**2.223(6)**	~3.6 sigma change

Results for $K^{\pm}$ BRs, τ

25 input measurements:

- **5 older τ values in PDG**
- **KLOE τ**
- **KLOE BR $\mu\nu$, $\pi\pi^0$**
- **KLOE *Ke*3, *K*μ3 BRs**
  - with dependence on τ
- **ISTRA+ BR *Ke*3/$\pi\pi^0$**
- **NA48/2 BR *Ke*3/$\pi\pi^0$, *K*μ3/$\pi\pi^0$**
- **E865 BR *Ke*3/*K*Dal**
- **3 old BR $\pi\pi^0/\mu\nu$**
- **2 old BR *Ke*3/2 body**
- **3 *K*μ3/*Ke*3 (2 old)**
- **2 old + 1 KLOE results on 3π**

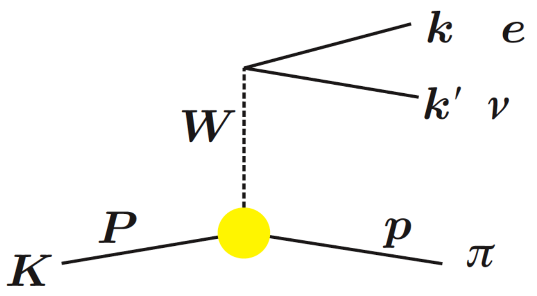
1 constraint: Σ BR = 1

BR($\mu\nu$)	**63.57(10)%**	**1.1**
BR($\pi\pi^0$)	**20.64(7)%**	**1.1**
BR($\pi\pi\pi$)	**5.593(32)%**	**1.1**
BR(*Ke*3)	**5.078(25)%**	**1.2**
BR(*K*μ3)	**3.365(26)%**	**1.7**
BR($\pi\pi^0\pi^0$)	**1.750(26)%**	**1.1**
$\tau_{\pm}$	**12.379(21) ns**	**1.7**

χ^2/ndf = 42.6/19 (0.15%)

Improves to χ^2/ndf = 24.8/15 (5.3%) with no changes to central values **(but τ)** or errors, if 5 older $\tau_{\pm}$ measurements replaced by PDG avg (with *S* = 2.1)

K_{l3} form-factor slopes



Hadronic matrix element:

$$\langle\pi|\,J_\alpha\,|K\rangle = f(0)\times[\tilde{f}_+(t)(P+p)_\alpha + \tilde{f}_-(t)(P-p)_\alpha]$$

$f_-(t)$ term only important for $K_{\mu3}$.

For $K_{\mu3}$, use $f_+(t)$ and $f_0(t) = f_+(t) + \dfrac{t}{m_K^2 - m_{\pi+}^2}\, f_-(t)$

For V_{us}, need integral over phase space of squared matrix element

Expand form factor:

Linear: $\tilde{f}_{+,0}(t) = 1 + \lambda_{+,0}\,[t/m_{\pi+}^2]$

Quadratic: $\tilde{f}_{+,0}(t) = 1 + \lambda'_{+,0}\,[t/m_{\pi+}^2] + 1/2\,\lambda''_{+,0}\,[t/m_{\pi+}^2]^2$

Pole: $\tilde{f}_{+,0}(t) = \dfrac{M_{V,S}^2}{M_{V,S}^2 - t}$

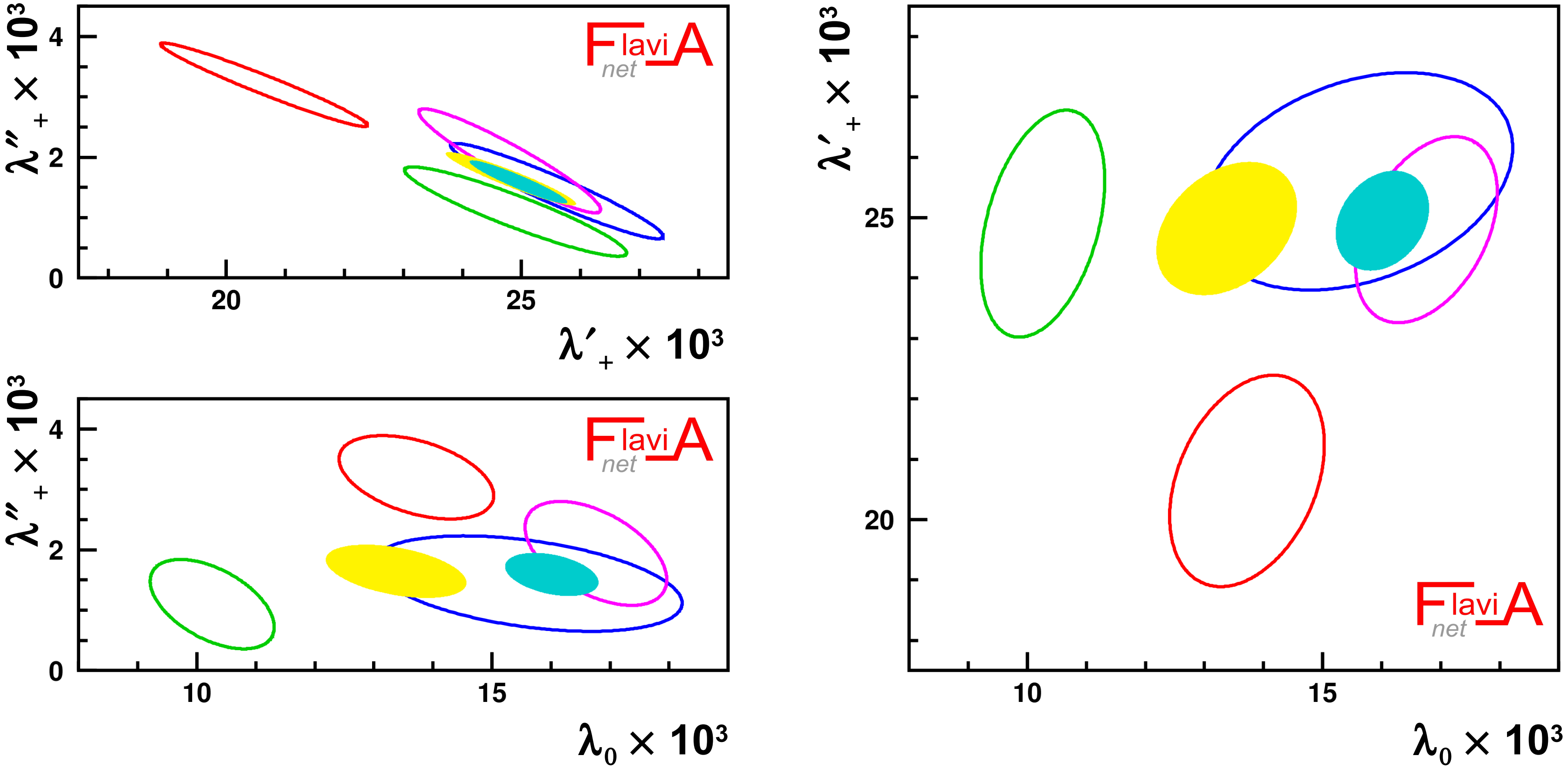
$\lambda' = (m_{\pi+}/M)^2$

$\boldsymbol{\lambda'' = 2\lambda'^2}$

poor sensitivity to quadratic terms

Fit to K_{l3} form-factor slopes

*e*3-μ3 averages from **KLOE** **KTeV** **ISTRA+** **NA48**

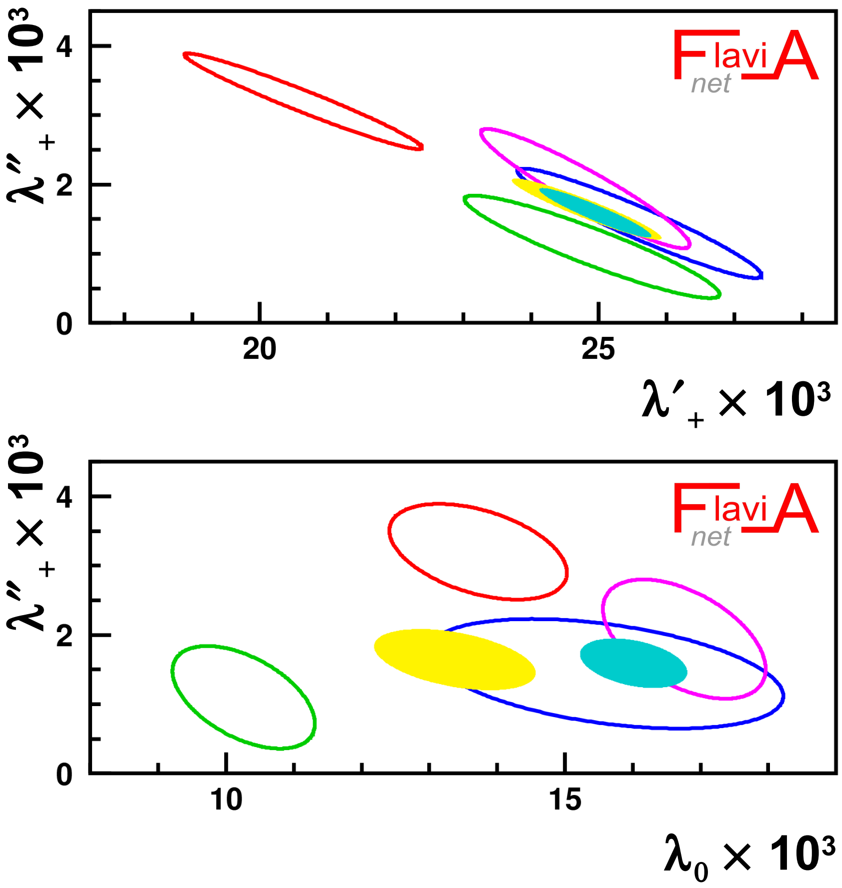


*Kl*3 fit, no NA48 *K*μ3: χ^2=12.6/10 (24.9%)

*Kl*3 fit, all data, χ^2=54/13 (10^{-6})

Fit to K_{l3} form-factor slopes

*e*3-μ3 averages from **KLOE** **KTeV** **ISTRA+** **NA48**



Measurements	16
χ^2/ndf	$54/13\ (7 \times 10^{-7})$
$\lambda'_+ \times 10^3$	$24.9 \pm 1.1\ (S = 1.4)$
$\lambda''_+ \times 10^3$	$1.6 \pm 0.5\ (S = 1.3)$
$\lambda_0 \times 10^3$	$13.4 \pm 1.2\ (S = 1.9)$
$\rho(\lambda'_+, \lambda''_+)$	-0.94
$\rho(\lambda'_+, \lambda_0)$	$+0.33$
$\rho(\lambda''_+, \lambda_0)$	-0.44
$I(K^0_{e3})$	0.15457(29)
$I(K^\pm_{e3})$	0.15892(30)
$I(K^0_{\mu3})$	0.10212(31)
$I(K^\pm_{\mu3})$	0.10507(32)
$\rho(I_{e3}, I_{\mu3})$	$+0.63$

*K*l3 fit, no NA48 *K*μ3: χ^2=12.6/10 (24.9%)

*K*l3 fit, all data, χ^2=54/13 (10^{-6})

SU(2) and *em* corrections

New values for $\delta^{K\ell}_{em}$ from ChPT $O(e^2p^2)$

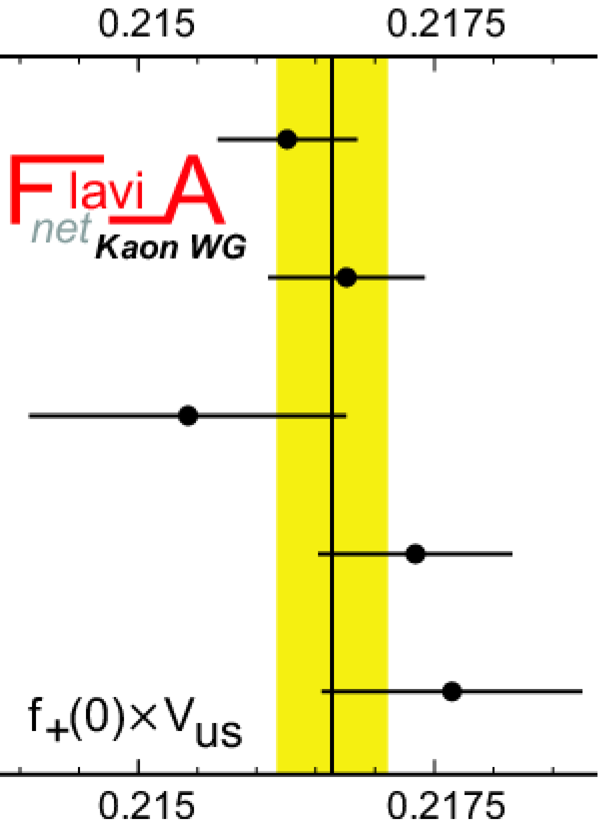
[Cirigliano, Giannotti, and Neufeld, 0807.4507]

error matrix available

	$\delta^{K}_{SU(2)}(\%)$	$\delta^{K\ell}_{em}(\%)$
K^0e3	**0**	**+0.50(11)**
$K^0\mu 3$	**0**	**+0.70(11)**
K^+e3	**+2.36(22)**	**+0.05(13)**
$K^+\mu 3$	**+2.36(22)**	**+0.01(12)**

	K^0e3	$K^0\mu 3$	K^+e3	$K^+\mu 3$
K^0e3	**1**	**0.69**	**0.08**	**–0.15**
$K^0\mu 3$		**1**	**–0.15**	**0.08**
K^+e3			**1**	**0.76**
$K^+\mu 3$				**1**

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



		% err	**Approx. contr. to % err from:** **BR**	**τ**	**δ**	**$I_{K\ell}$**
K_Le3	**0.2164(6)**	**0.26**	0.09	**0.19**	0.11	0.09
$K_L\mu 3$	**0.2170(6)**	**0.29**	0.10	**0.18**	0.11	0.15
K_Se3	**0.2156(13)**	**0.62**	**0.60**	0.03	0.11	0.09
$K^\pm e3$	**0.2174(8)**	**0.38**	**0.26**	0.13	**0.25**	0.09
$K^\pm \mu 3$	**0.2177(11)**	**0.51**	**0.40**	0.13	**0.25**	0.15

Average: $|V_{us}|\, f_+(0) = 0.2167(5)$ χ^2/ndf = 2.83/4 (59%)

SU(2) breaking correction comparing values from K_L and $K^\pm$: **2.81(38)%**.

χ_{PT} prediction **2.36(22)%** (Kastner and Neufeld: **2.9(4)%**).

$K_{\ell 2}$ decays

[Mariciano]

Small uncertainties in f_K/f_π from lattice → determine V_{us}/V_{ud}

Reduced uncertainty from e.m. Structure Dependence corrections

$$\frac{\Gamma(K_{\mu 2(\gamma)})}{\Gamma(\pi_{\mu 2(\gamma)})} = \frac{|V_{us}|^2}{|V_{ud}|^2} \times \frac{f_K^2}{f_\pi^2} \times \frac{M_K(1-m_\mu^2/M_K^2)^2}{m_\pi(1-m_\mu^2/m_\pi^2)^2} \times 0.9930(35)$$

WA dominated by KLOE

$\mathrm{BR}(K^+ \to \mu^+\nu(\gamma)) = 0.6366(17)$

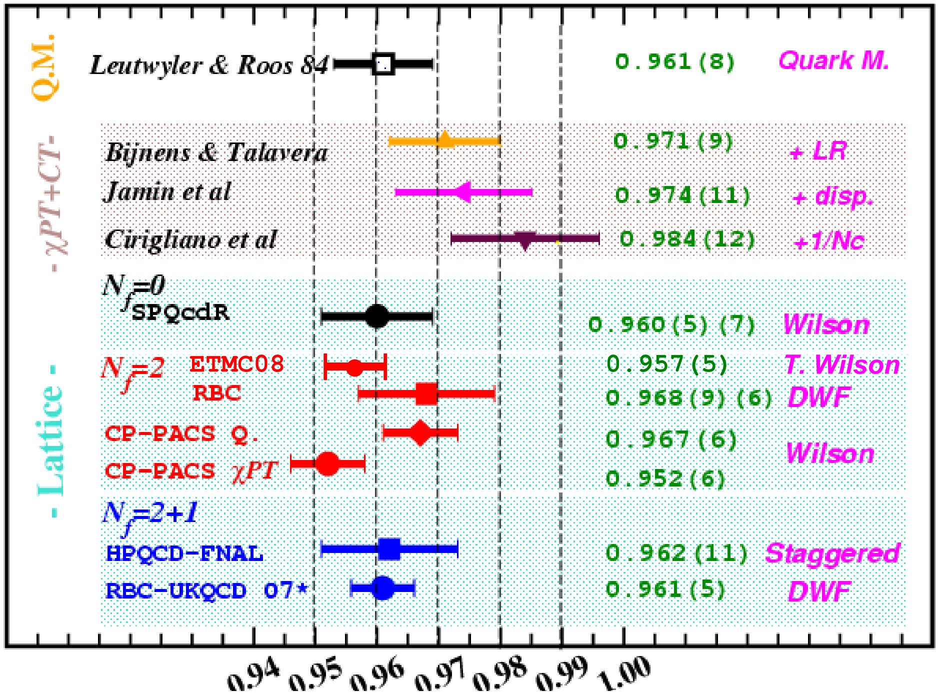
$|V_{us}|/|V_{ud}|\, f_K/f_\pi = 0.2760(6)$

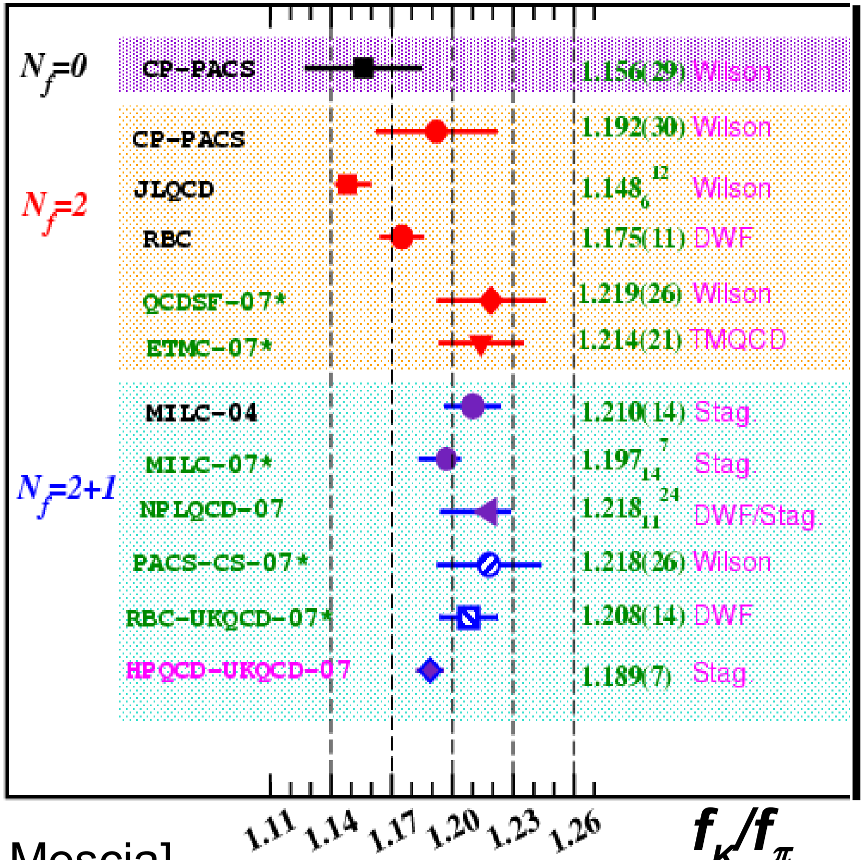
$f_K/f_\pi = 1.1890(7)$ HPQCD-UKQCD

$$\boldsymbol{V_{us}/V_{ud} = 0.2322(15)}$$

Evaluations of $f_+(0)$ and f_K/f_π

Lattice continuously improving





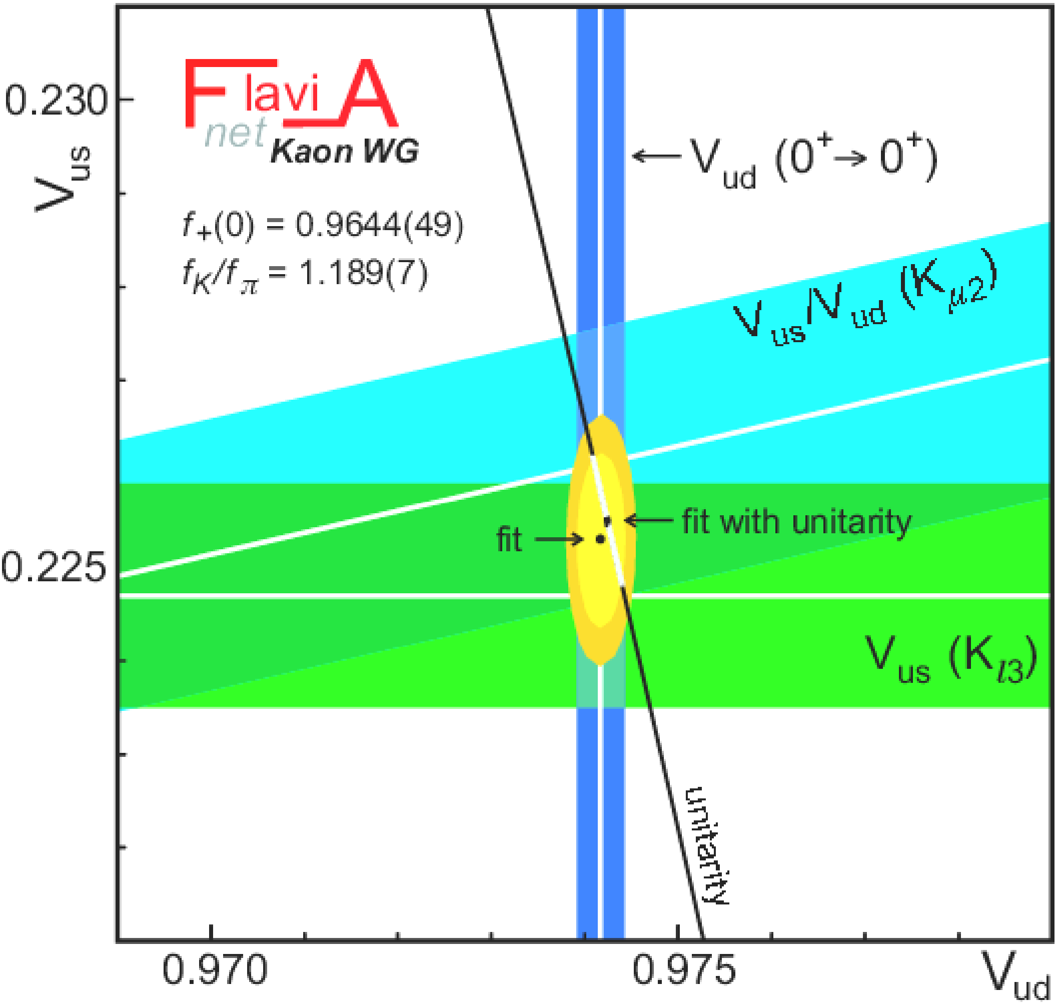
$f_+(0)$ [F. Mescia] **f_K/f_π**

Use:

$f_+(0)$ = 0.964(5) RBC-UKQCD

f_K/f_π = 1.1890(7) HPQCD-UKQCD

CKM unitarity



Fit results, no constraint:

$$V_{ud} = 0.97425(23)$$
$$V_{us} = 0.2254(9)$$
$$\chi^2/\text{ndf} = 0.6/1\ (44\%)$$

$$1-V_{us}^2-V_{us}^2 = 0.00003(60)$$

$$G_{CKM}=1.1662(4)\ \text{x}10^{-5}\ \text{GeV}^{-2}$$

Fit results, unitarity constraint:

$$V_{us} = \sin\theta_c = \lambda = 0.2254(7)$$
$$\chi^2/\text{ndf} = 0.6/2\ (74\%)$$

0.3 % accuracy!

Decay constants & f(0)

In the Standard Model f_P can be determined from the measurement of Γ ($\mathbf{P}_{\ell 2(\gamma)}$) and the value of the relevant CKM matrix element.

f_K = 156.1(8) MeV

f_π=130.4(2) MeV

$\mathbf{V_{us}}$ **= 0.2247(12)** from Kl3

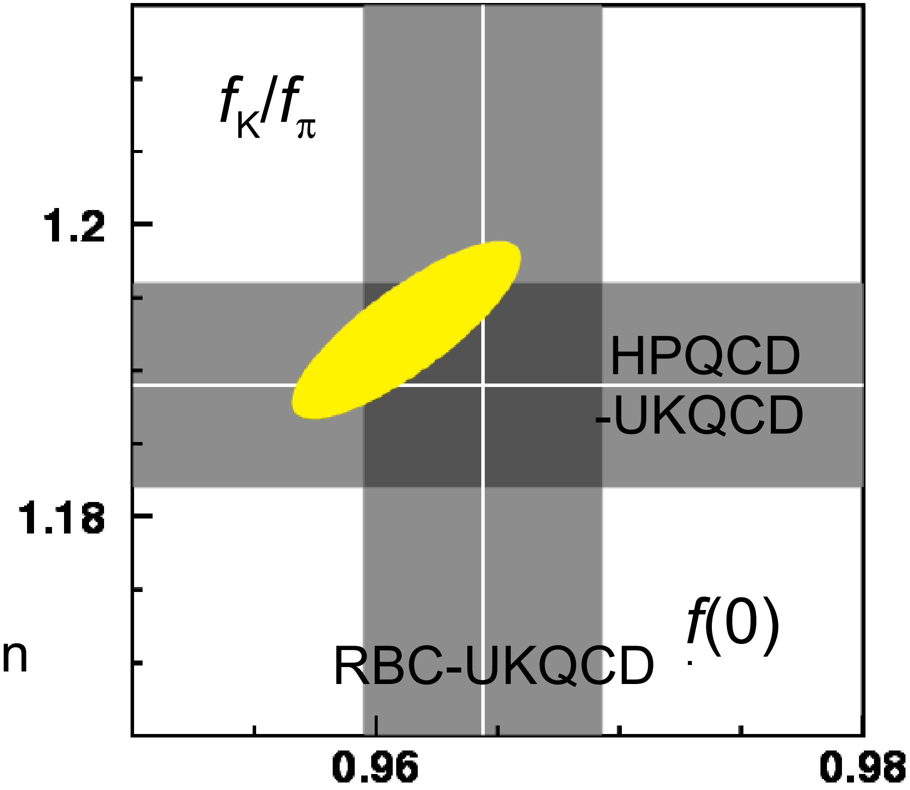
$\mathbf{V_{ud}}$**=0.97425(23)** from β decays

unitarity + V_{ud} , $f_0 V_{us}$,Γ ($\mathbf{P}_{\ell 2(\gamma)}$)

f_K/f_π = 1.1928(61)

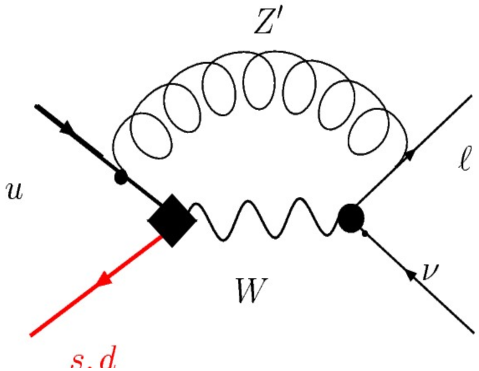
$f(0)$ = 0.9612(47)

0.8 correlation



sensitivity to NP: Z'oology

1)



$$G_F = G_{CKM}\left[1 - 0.007\,Q_{eL}(Q_{\mu L} - Q_{dL})\,\frac{2\ln(m_{Z'}/m_W)}{(m_{Z'}^2/m_W^2 - 1)}\right]$$

[Marciano]

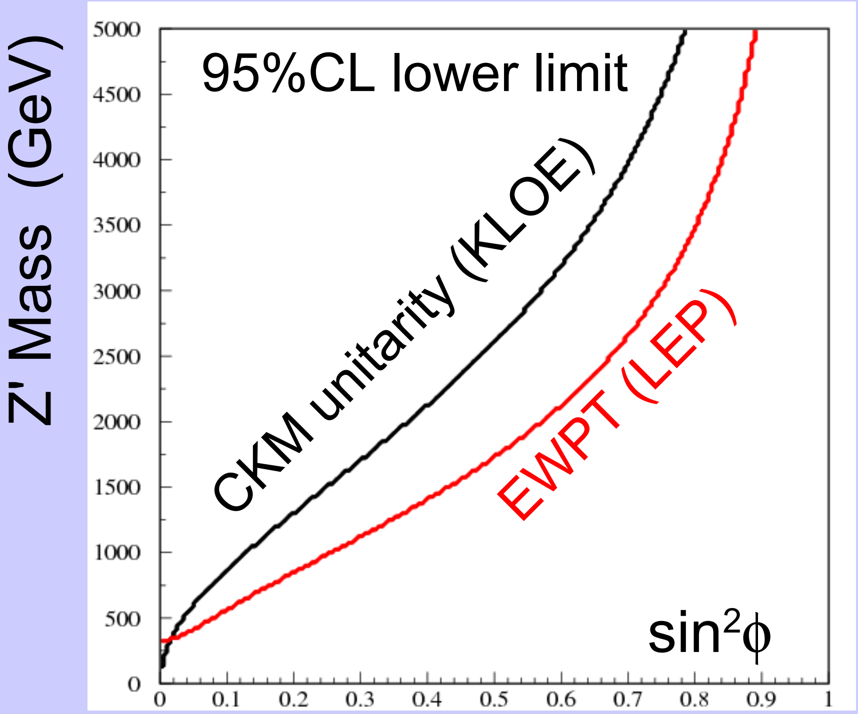
SO(10) Zχ Boson: $Q_{eL} = Q_{\mu L} = -3Q_{dL} = 1$

$m_{Z\chi} > 750$ GeV 95%CL

2)

[K.Y. Lee]

Tree level breaking of unitarity in models with non-universal gauge interaction



sensitivity to NP: charged Higgs

JHEP
0804:059

Pseudoscalar currents, e.g. due to H±, affect the K width:

$$\frac{\Gamma(M\to\ell\nu)}{\Gamma_{SM}(M\to\ell\nu)}=\left[1-\tan^2\beta\left(\frac{m_{s,d}}{m_u+m_{s,d}}\right)\frac{m_M^2}{m_H^2}\right]^2$$ for M = K, π

Hou, Isidori-Paradisi

The observable

$$R_{\ell 23}=\left|\frac{V_{us}(K_{\mu 2})}{V_{us}(K_{\ell 3})}\times\frac{V_{ud}(0^+\to 0^+)}{V_{ud}(\pi_{\mu 2})}\right|$$

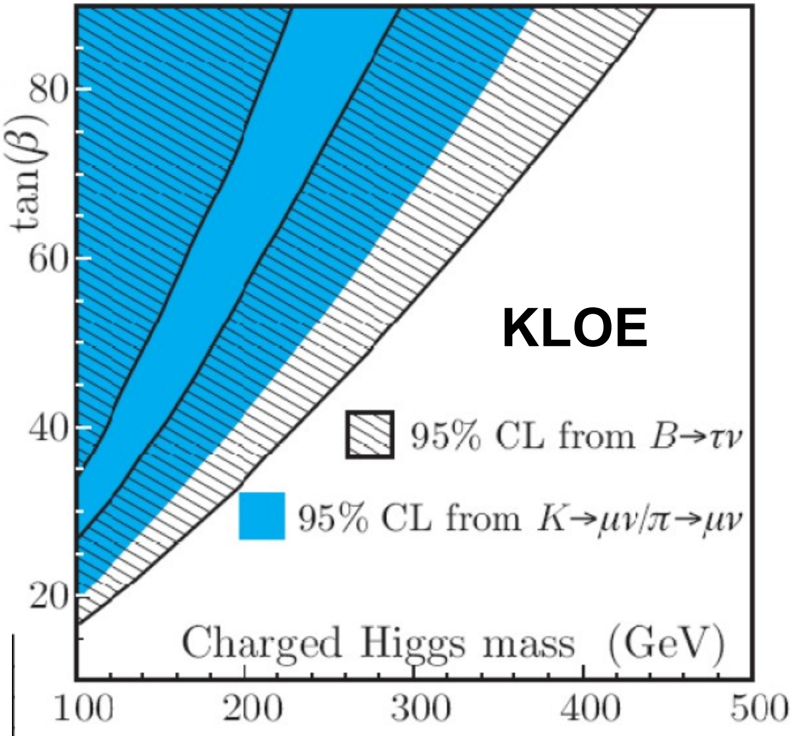
KLOE:

- **R_{l23} = 1.008(8)**

(unitarity for K_{l3} and β-decays is used)

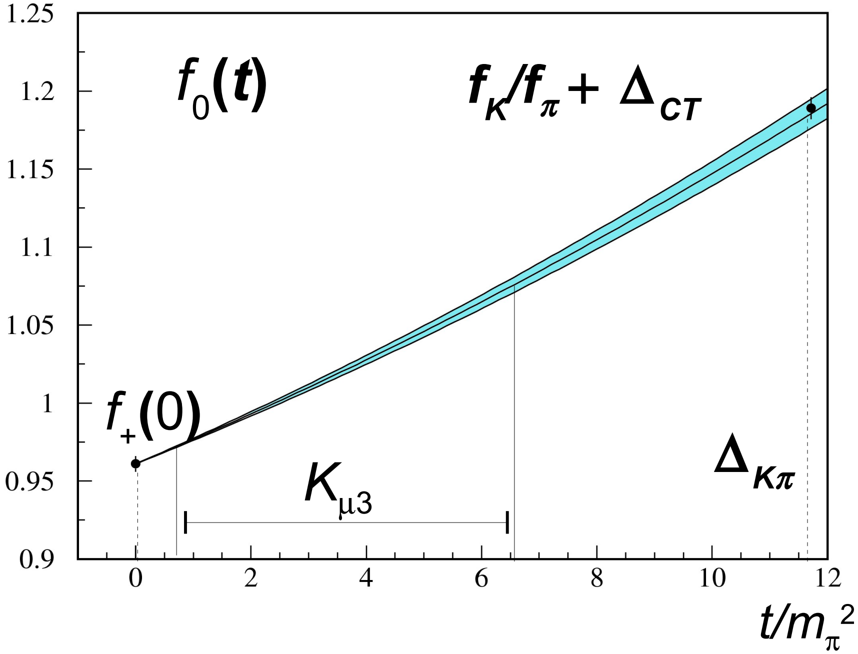
R_{l23} sensitivity to H± exchange

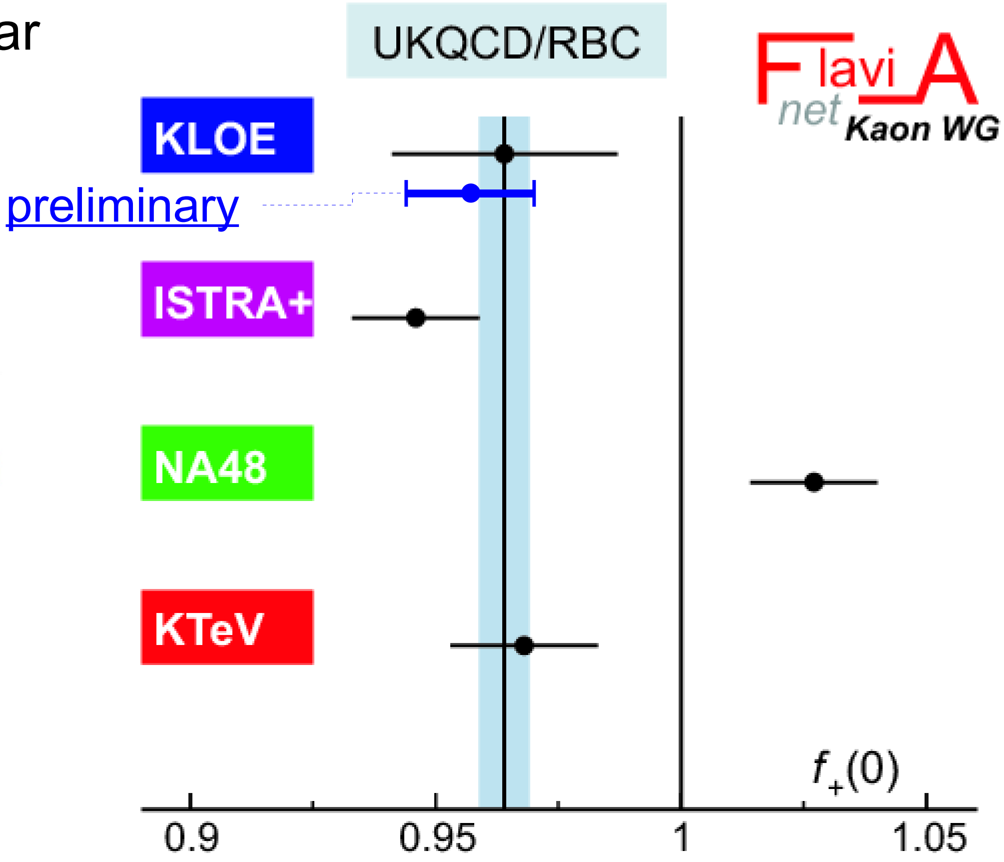
$$R_{\ell 23}=\left|1-\frac{m_{K^+}^2}{m_{H^+}^2}\left(1-\frac{m_{\pi^+}^2}{m_{K^+}^2}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|$$



Callan-Treiman relation

Check from measurement of scalar ff slopes in Kμ3 and use of dispersive parametrization [Stern et al] [Pich et al] (further info from τ)





$f_+(0) = (f_K/f_\pi + \Delta_{CT})/C$

$f_K/f_\pi = 1.189(7)$ from HPQCD-UKQCD

V_{us} from τ

V_{us} from inclusive $\tau \to \nu X_{us}$ involves PQCD

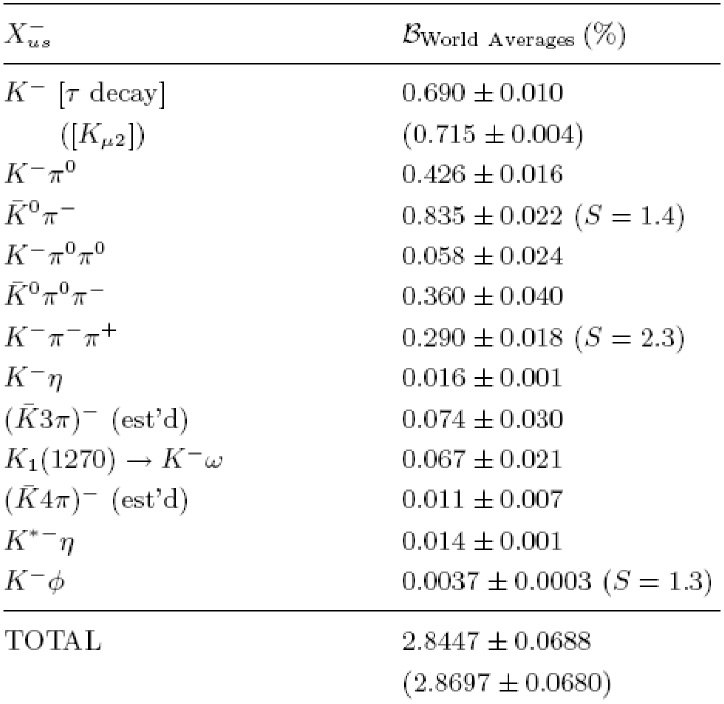
$$|V_{us}|^2 = \frac{R^{00}_{\tau,S}}{\dfrac{R^{00}_{\tau,V+A}}{|V_{ud}|^2} - \delta R^{00}_{\tau,\mathrm{th}}}$$

Gámiz-Jamin-Pich-Prades-Schwab

V_{us} = 0.2159 (30_{exp})(5_{th})

~3 σ lower wrt kaons (same fitting m_s, V_{us})
Theory? Exp.?

S. Banerjee arXiv:0811.1429



X^-_{us}	$\mathcal{B}_{\text{World Averages}}$ (%)
K^- [τ decay]	0.690 ± 0.010
([$K_{\mu 2}$])	(0.715 ± 0.004)
$K^-\pi^0$	0.426 ± 0.016
$\bar{K}^0\pi^-$	0.835 ± 0.022 ($S = 1.4$)
$K^-\pi^0\pi^0$	0.058 ± 0.024
$\bar{K}^0\pi^0\pi^-$	0.360 ± 0.040
$K^-\pi^-\pi^+$	0.290 ± 0.018 ($S = 2.3$)
$K^-\eta$	0.016 ± 0.001
$(\bar{K}3\pi)^-$ (est'd)	0.074 ± 0.030
$K_1(1270) \to K^-\omega$	0.067 ± 0.021
$(\bar{K}4\pi)^-$ (est'd)	0.011 ± 0.007
$K^{*-}\eta$	0.014 ± 0.001
$K^-\phi$	0.0037 ± 0.0003 ($S = 1.3$)
TOTAL	2.8447 ± 0.0688 (2.8697 ± 0.0680)

check with kaons on exclusive modes(~70% of R_S):

(24% of R_S) BR(Kν) = 0.69(1) vs 0.715(4) from Kμ2

but BR(Kν)/BR(πν) ok

V_{us} from τ

check with kaons on exclusive modes(~70% of R_S):

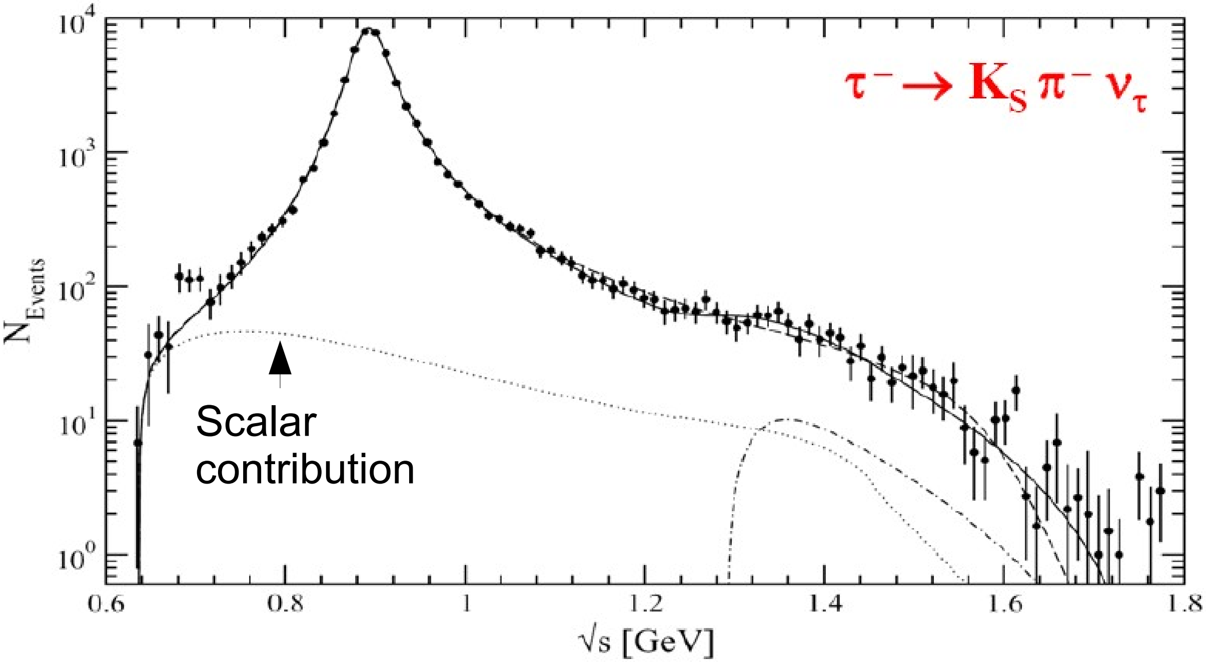
(46% of R_S)   BR($K\pi\nu$)   need precise form factor parameters

Prediction (no exp. Syst. included):

BR($K_S\pi^-\nu$) = $0.427(11)(21_{\text{model}})$

In agreement with measured values but still limited accuracy (modeling)

Jamin-Pich-Portolés 08 fit to **BELLE** data



Many new results from Belle-BaBar expected

lepton universality

For each state of kaon charge, we evaluate:

$$r_{\mu e} = \frac{(R_{\mu e})_{\rm obs}}{(R_{\mu e})_{\rm SM}} = \frac{\Gamma_{\mu 3}}{\Gamma_{e3}} \cdot \frac{I_{e3}\,(1+\delta_{e3})}{I_{\mu 3}\,(1+\delta_{\mu 3})} = \frac{g_\mu^2}{g_e^2}$$

$r_{\mu e}$ = 1.0050(44) from Kl3

$\tau \rightarrow l\nu\nu$ decays:

$(r_{\mu e})_\tau$ = 1.0005(41) [PDG08]

$(r_{\mu e})_{\pi l2}$ = 1.0030(32) Bryman @ Seattle '08

$r_{\mu e}$ = 1.0028(22) K, τ, π average

$$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$$

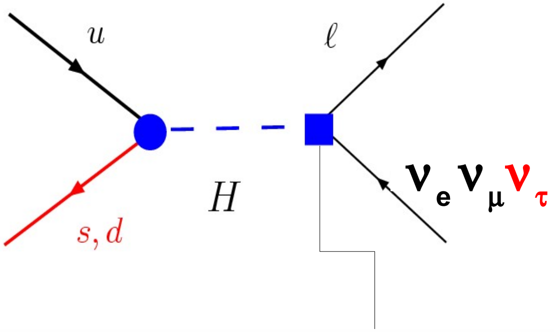
The special role of $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$

SM: very well known no hadronic uncertainties (no f_K)

In MSSM, LFV can give up to % deviations

[Masiero, Paradisi, Petronzio]

NP dominated by contribution of $e\nu_\tau$ final state:

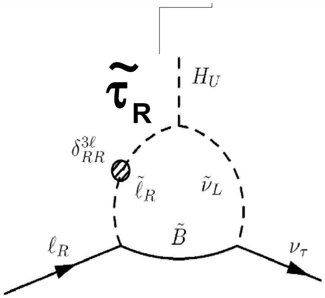


$$R_K \approx \frac{\Gamma(K\rightarrow e\nu_e) + \Gamma(K\rightarrow e\nu_\tau)}{\Gamma(K\rightarrow \mu\nu_\mu)}$$

$$R_K \approx R_K^{SM}\left[\, 1 + \frac{m_K^4}{m_H^4}\,\frac{m_\tau^2}{m_e^2}\,|\Delta_R^{31}|^2 \tan^6\beta\right]$$

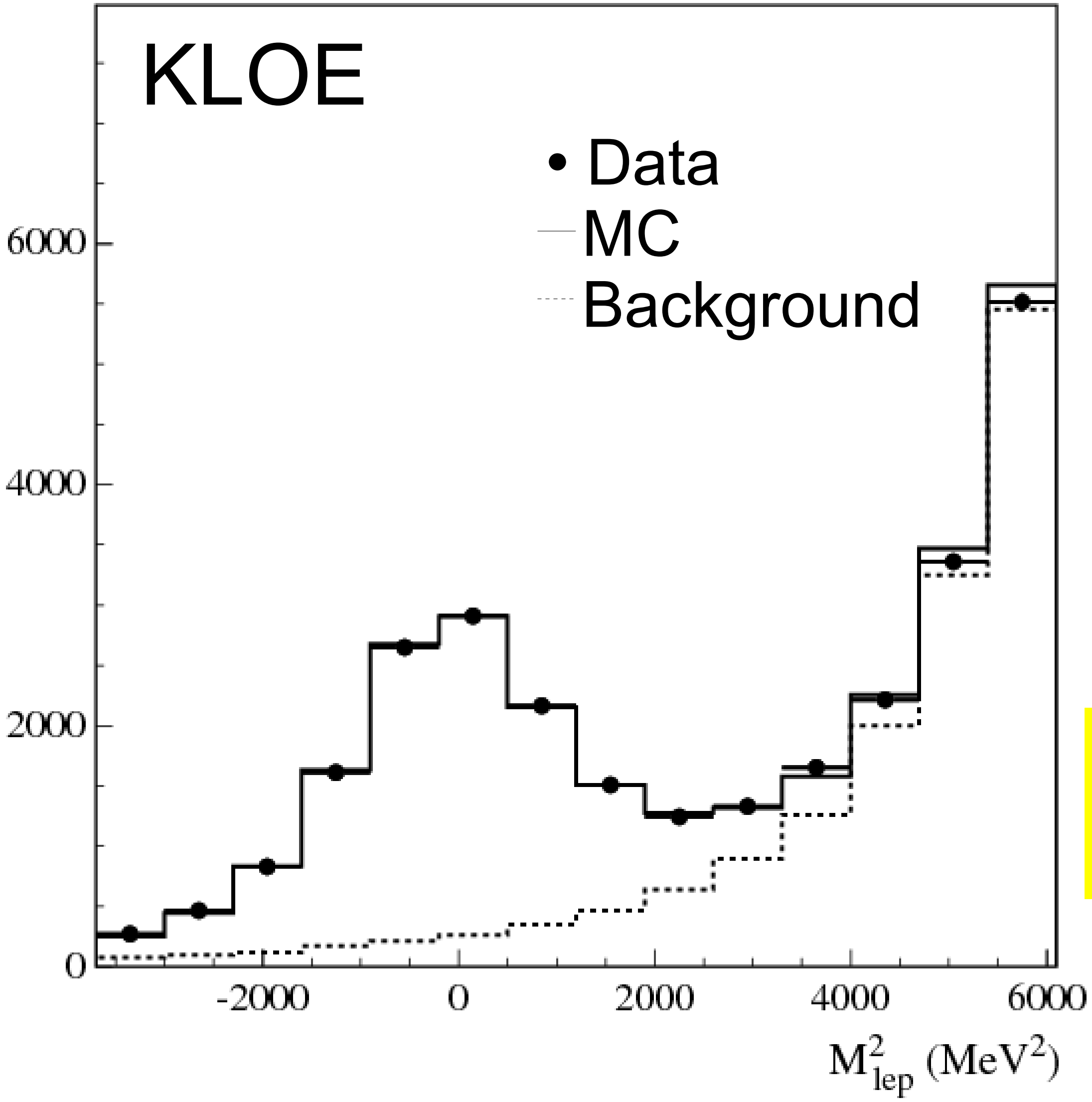
$$eH^{\pm}\nu_\tau \rightarrow \frac{g_2}{\sqrt{2}}\frac{m_\tau}{M_W}\Delta_R^{31}\tan^2\beta$$

1% effect (Δ^R_{31} ~5x10^{-4}, tanβ~40, m$_H$~500GeV) not unnatural



Present accuracy on R_K @ 6% Need for precise measurements

New KLOE measurement



About 14K events selected

~17% background

error dominated by statistics

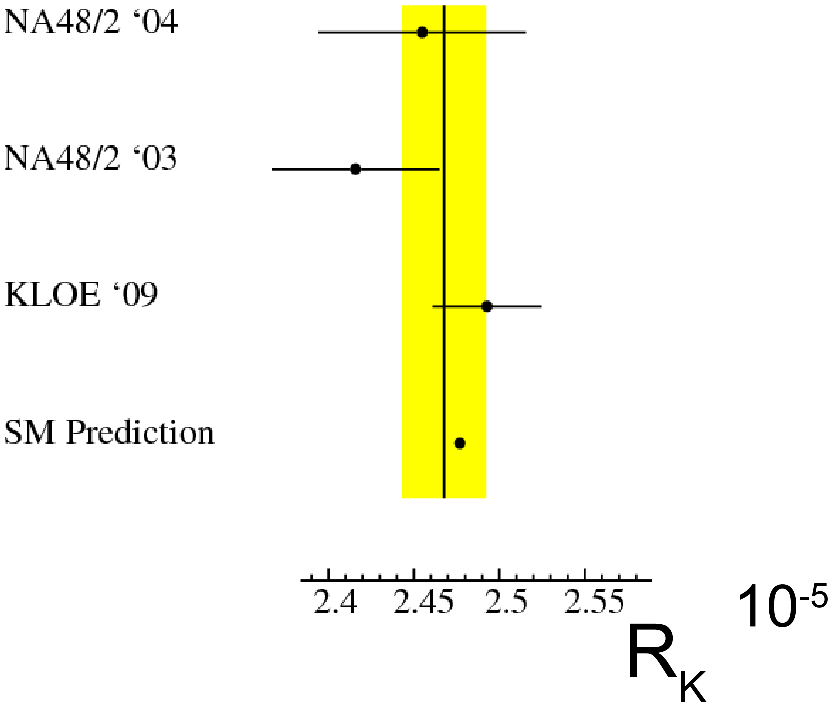
(Ke2 + C.S.)

R_K= 2.493(25)(19) x10^{-5}

R_K world average

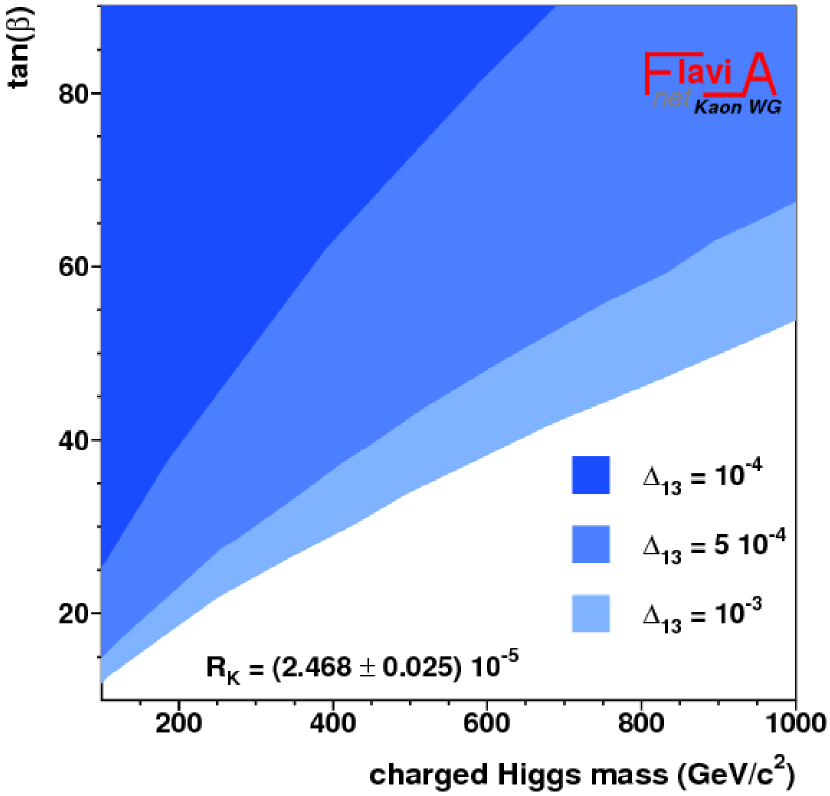
Uncertainty @ 1%

$R_K = (2.468 \pm 0.025) \times 10^{-5}$



95%-CL excluded regions in the tanβ - M_H plane, for

$\Delta_{13} = 10^{-3}$, 0.5×10^{-3}, 10^{-4}



CONCLUSION

V_{ud} = 0.97425(23)

V_{us} = 0.2247(12)

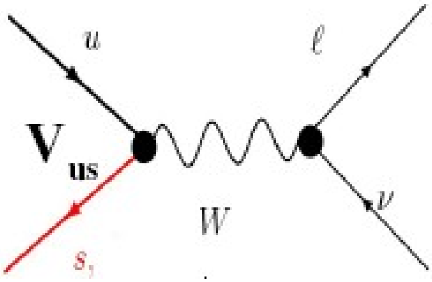
$V_{us}/V_{ud} = 0.2322(15)$

agreement with unitarity:

$1-V_{ud}^2-V_{us}^2 = 4(6)\times 10^{-4}$

Important constraints for physics BSM

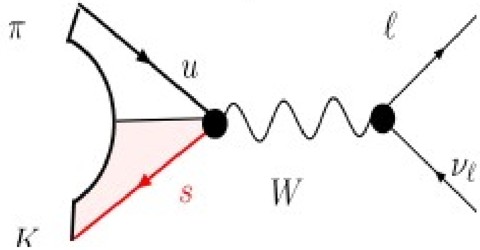
Kaon high precision observables



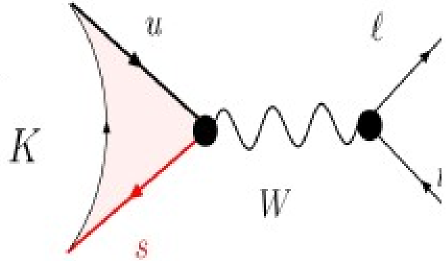
Short distance
physics

$K_{\ell 3}$: K→ π ℓ ν

$K_{\ell 2}$: K→ ℓ ν



Experimental
processes



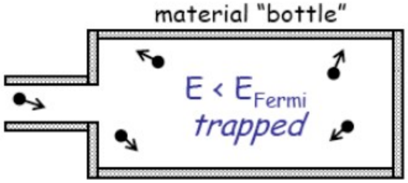
Vector transition protected against SU(3) corrections

Small uncertainties in f_K/f_π from lattice

Other V_{ud} determinations

neutron β decay *not pure vector, needs g_A/g_V but no nuclear structure. δV_{ud}~0.002, will be improved through asymmetry measuremnts at PERKEO, Heidelberg and UCNA, LANL. 2005 measurement of n lifetime (6σ away) serious problem!*

$$V_{ud} = 0.9746(4)_{\tau_n}(18)_{g_A}(2)_{\rm RC}$$



Ultracold neutrons

Long interaction times in apparatus

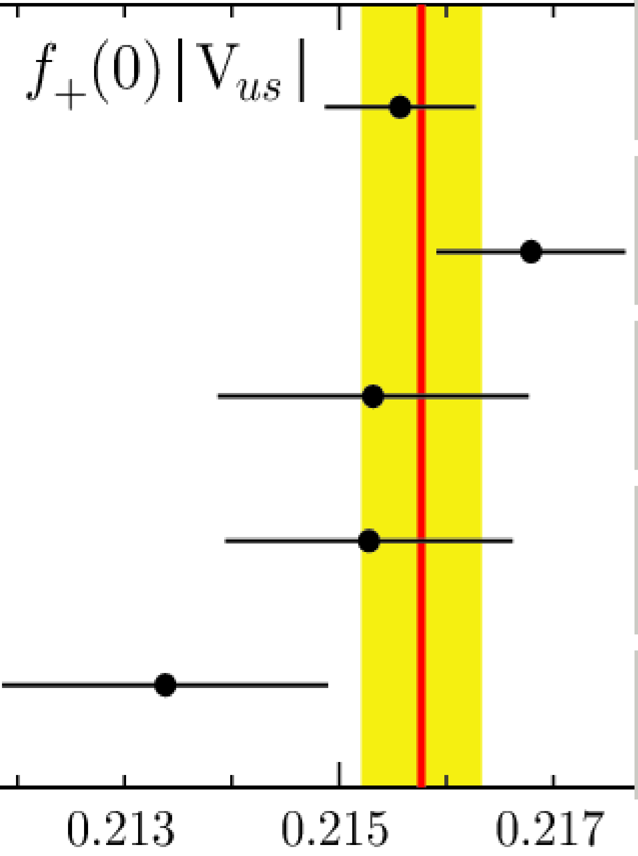
↓

Need relatively small number of neutrons

π^+ decay to $\pi^0 e\nu$ *th cleanest, promising in long term but BR~10^{-8} PIBETA at PSI has δV_{ud}~0.003*

$$V_{ud} = 0.9749(26)\left[\frac{BR(\pi^+ \to e^+\nu_e(\gamma))}{1.2352\times 10^{-4}}\right]^{\frac{1}{2}}$$

V_{us} from KLOE K_{l3} data



		% 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

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

KLOE Avg:
0.2157(6)
$\chi^2/\text{ndf} = 7/4$ (13%)

World Avg:
0.2166(5)

$f_+(0)=0.964(5)$

$V_{ud} = 0.97418(26)$

RBC/UKQCD

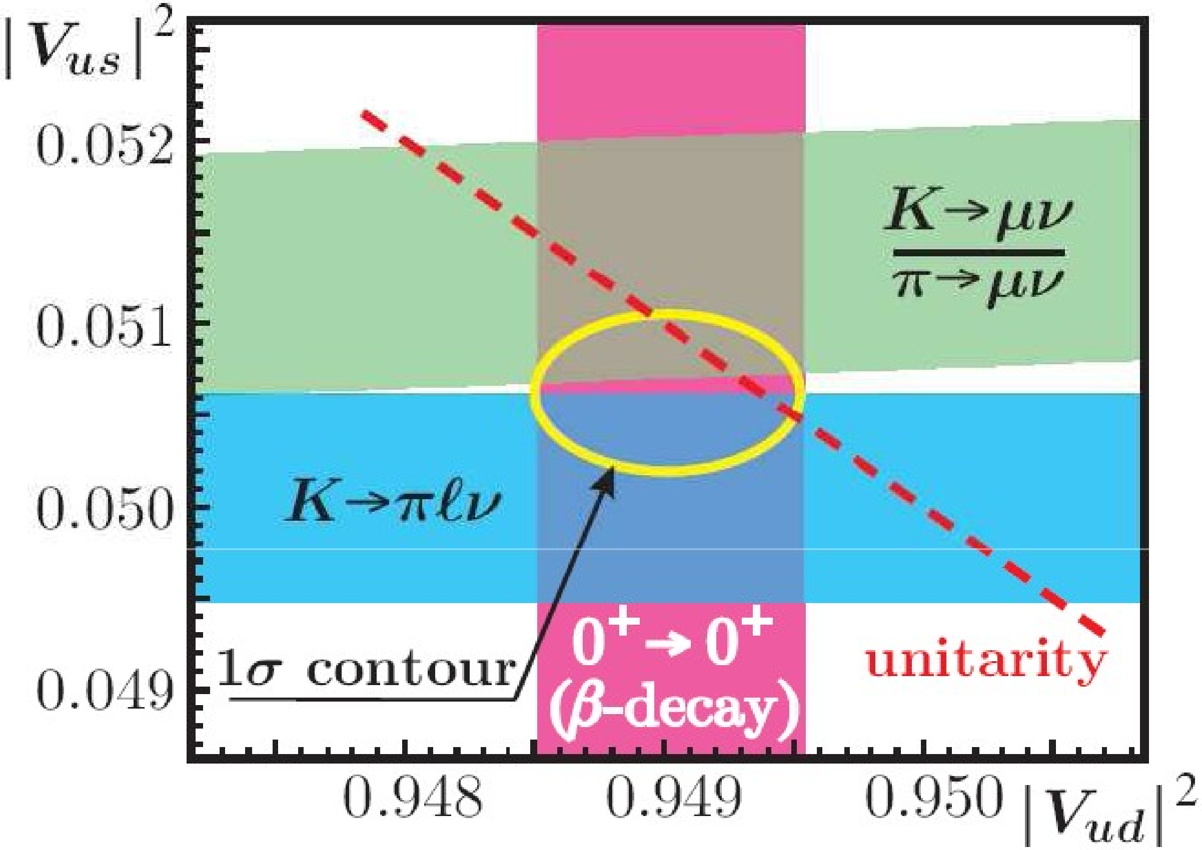
arXiv:0710.3181

$\Rightarrow V_{us} = 0.2237(13)$

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

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

JHEP 0804:059



no constraint:

$V_{ud}^2 = 0.9490(5)$

$V_{us}^2 = 0.0506(4)$

$\chi^2/\mathrm{ndf} = 2.3/1$ (13%)

agreement with unitarity:

$1 - V_{ud}^2 - V_{us}^2 = 4(7) \times 10^{-4}$

@ 0.6 σ

$|V_{ud}| = 0.97418(26)$ [Towner & Hardy arXiv:0710.3181]

$f_+(0) = 0.964(5)$ UKQCD/RBC NF=2+1, DWF

$f_K/f_\pi = 1.189(7)$ HPQCD-UKQCD(MILC) NF=2+1, Stag

RESULTS FROM $0^+ \rightarrow 0^+$ DECAY IN 2008

1) G_V constant $\boxed{\mathcal{F}t = \frac{K}{2G_V^2(1+\Delta_R)}}$ ✓ verified to ± 0.013%

2) Scalar current zero ✓ limit, $C_S/C_V = 0.0011\ (14)$

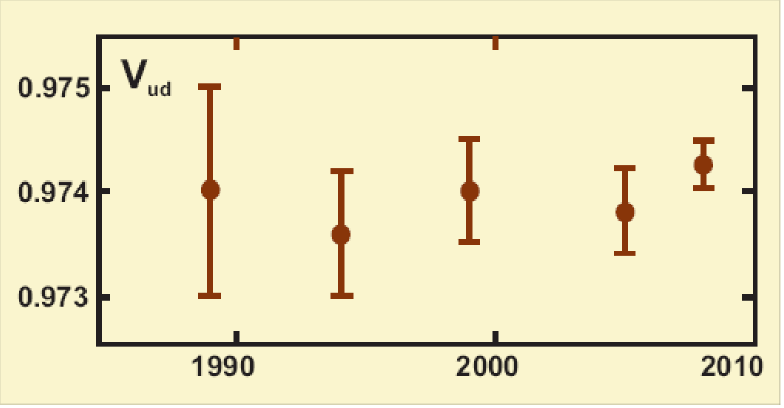
3) Precise value determined for V_{ud} $\boxed{V_{ud} = G_V/G_\mu}$

$$\boxed{V_{ud} = 0.97425 \pm 0.00023}$$

Compare:

neutron $V_{ud} = 0.9746 \pm 0.0019$

pion $V_{ud} = 0.9749 \pm 0.0026$



I. S. Towner
@ CKM08

Dominant K_L branching ratios

Absolute BR mmts to 0.5-1% using K_L beam tagged by $K_S \to \pi^+\pi^-$

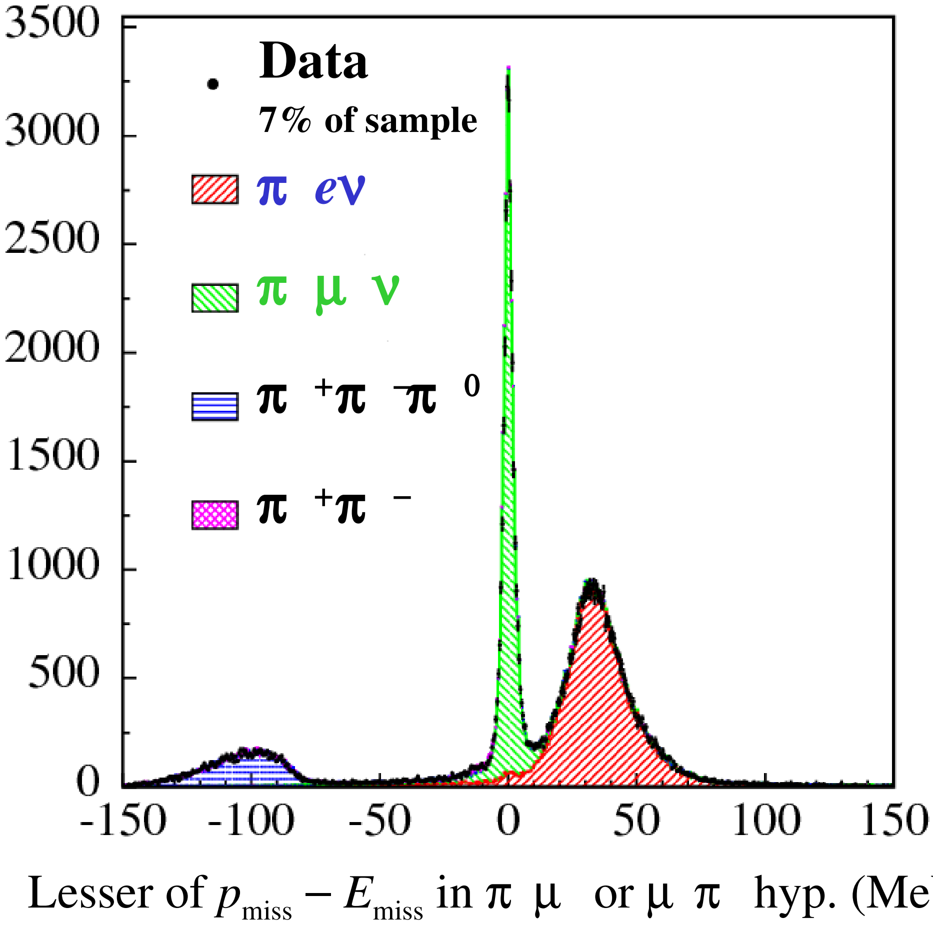
328 pb^{-1} ’01 + ’02 data

13×10^6 K_L’s for counting (25%)

75% used to evaluate efficiencies

BR’s to $\pi e\nu$, $\pi\mu\nu$, and $\pi^+\pi^-\pi^0$:

- K_L vertex reconstructed in DC
- PID using decay kinematics
- Fit with MC spectra including radiative processes and optimized EmC response to $\mu/\pi/K_L$



Lesser of $p_{\mathrm{miss}} - E_{\mathrm{miss}}$ in $\pi\mu$ or $\mu\pi$ hyp. (Me

BR to $\pi^0\pi^0\pi^0$:

- vertex by EmC TOF (≥ 3 clusters)
- $\varepsilon_{\mathrm{rec}}$ = 99%, background < 1%

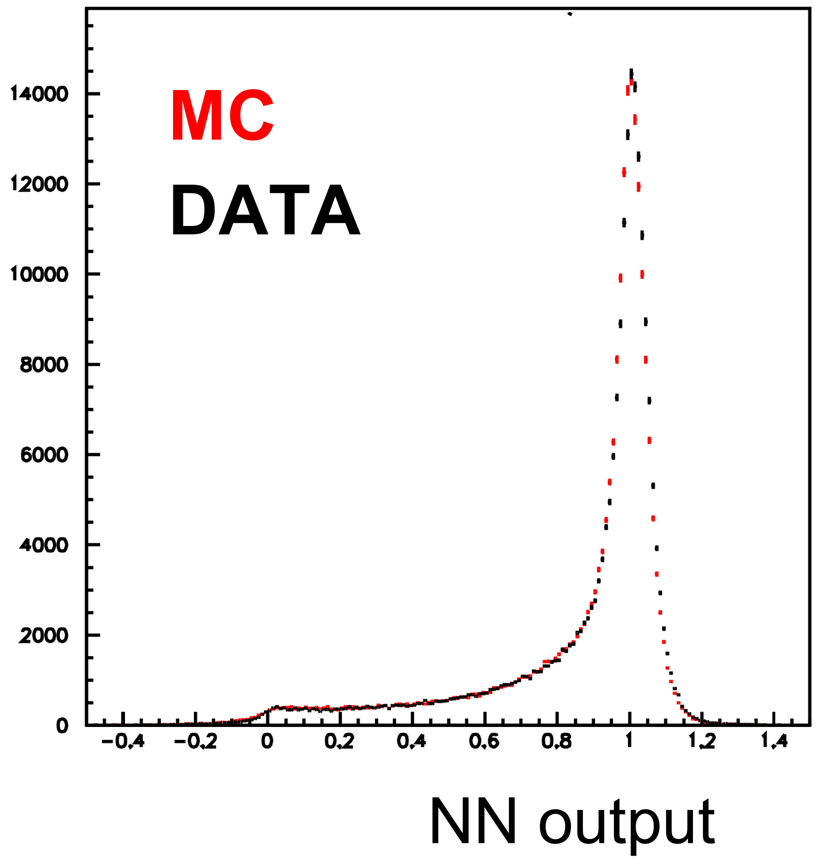
Particle Identification

particle ID exploits EmC granularity: energy deposits into 5 layers in depth

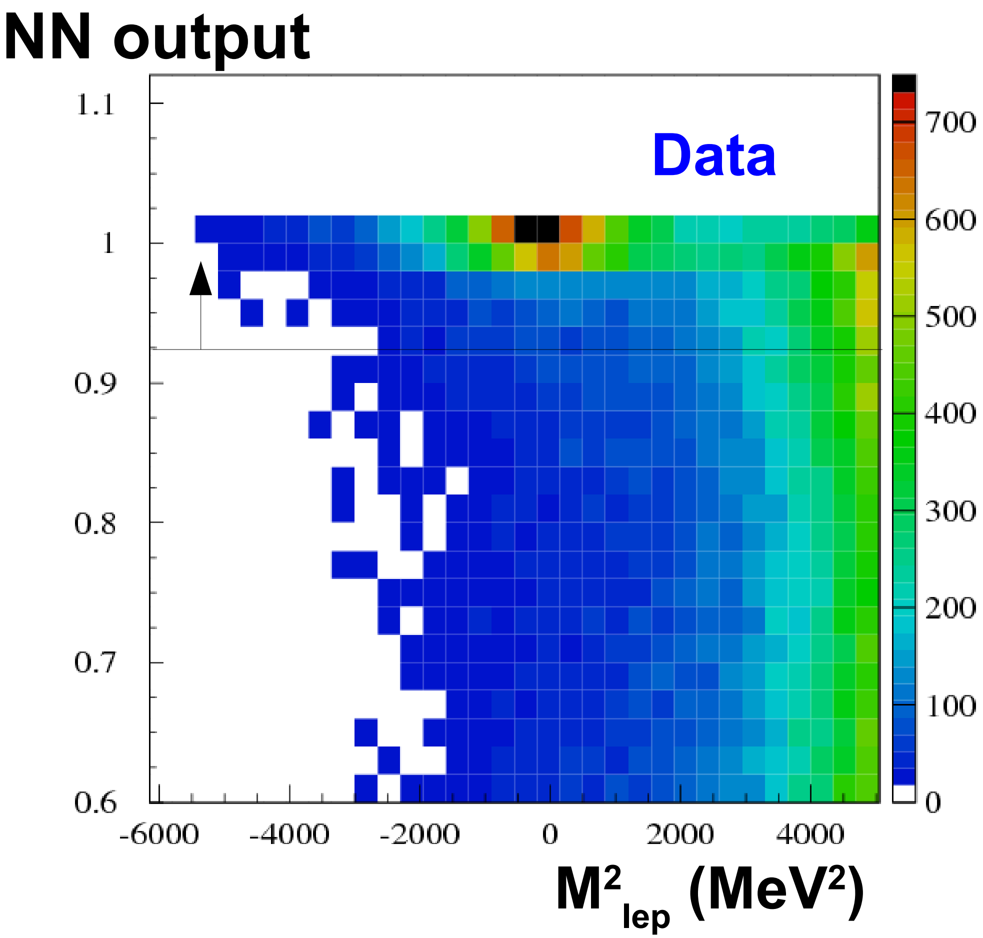
Combine infos with a neural network

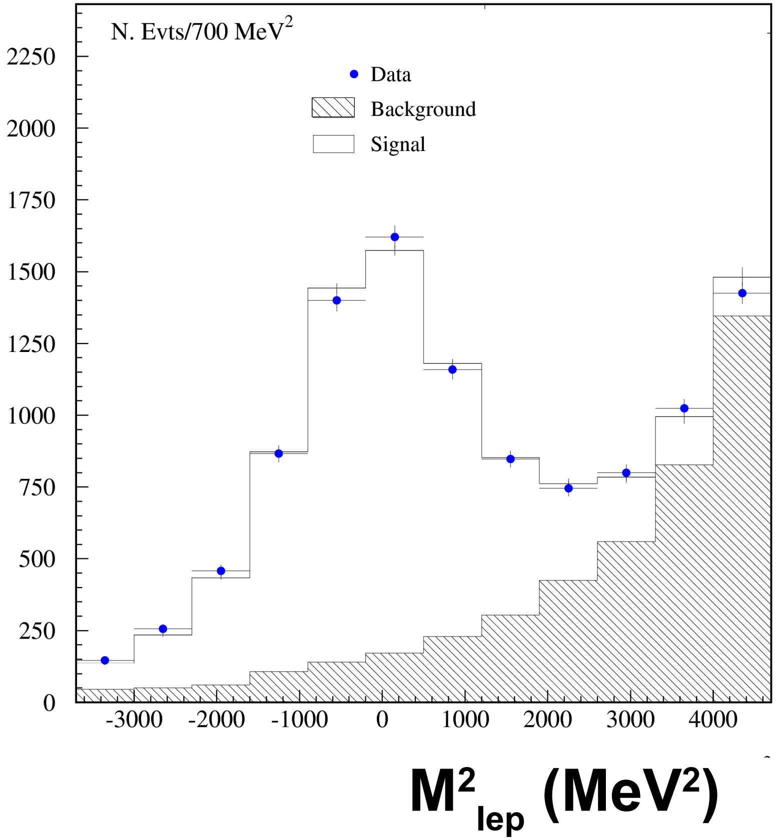
use pure sample of $K_L e3$ to correct cell response in MC and for NN training

$K_L e3$ control sample



Counting K_{e2} events



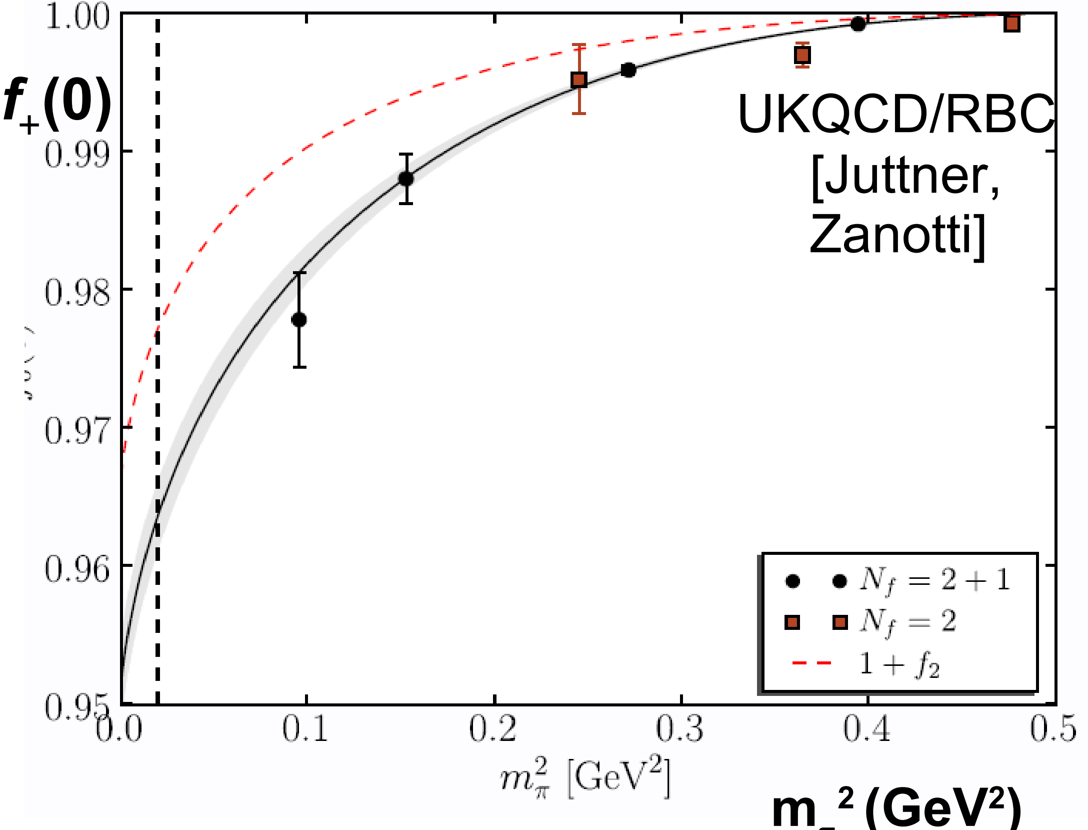


Two-dimensional binned likelihood fit in the plane

NN output - M^2_{lep} count 7060 + 6750 Ke2 events

Evaluations of $f_+(0)$

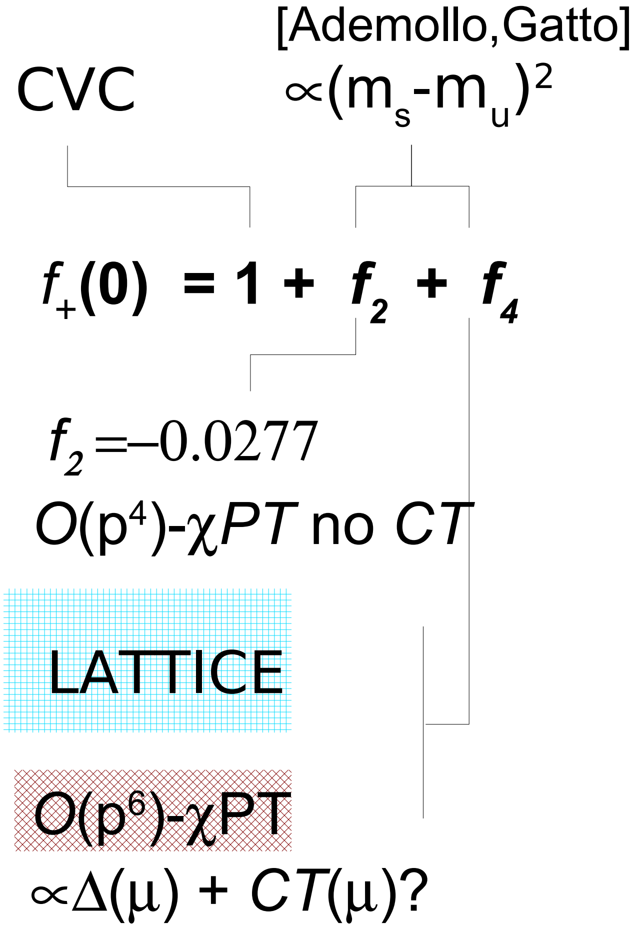
Chiral extrapolation seen for the first time



$f_+(0)$

UKQCD/RBC
[Juttner,
Zanotti]

m_π^2 (GeV^2)



CVC

[Ademollo,Gatto]
$\propto (m_s - m_u)^2$

$$f_+(0) = 1 + f_2 + f_4$$

$f_2 = -0.0277$

$O(p^4)$-χPT no CT

LATTICE

$O(p^6)$-χPT

$\propto \Delta(\mu) + CT(\mu)$?

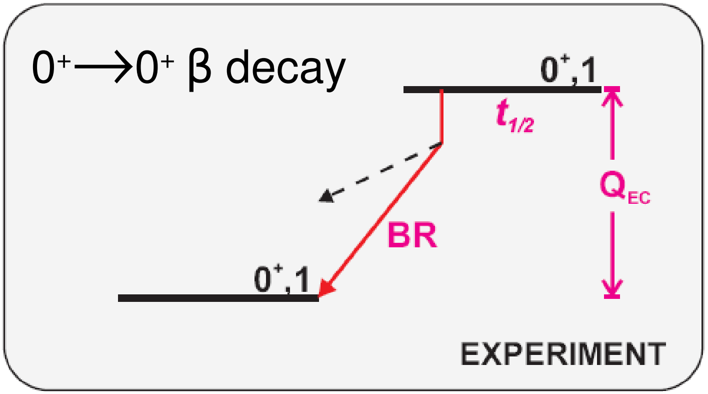
encouraging results from UKQCD/RBC NF=2+1, DWF, m_π>=300MeV:

$f_+(0) = 0.964(5)$

Vud from Fermi transitions

$$G_F^2|V_{ud}|^2 = \frac{K}{M_K(1-m_\mu^2/M_K^2)^2}$$

CVC



$$\frac{\Gamma(K_{\mu2(\gamma)})}{\Gamma(\pi_{\mu2(\gamma)})} = \frac{|V_{us}|^2}{|V_{ud}|^2} \times \frac{f_K^2}{f_\pi^2} \times \frac{M_K(1-m_\mu^2/M_K^2)^2}{m_\pi(1-m_\mu^2/m_\pi^2)^2} \times 1+\alpha(C_K-C_\pi)$$

[Marciano Sirlin]

$K_{\mu 3}$ form-factor slopes

- Knowledge of $\tilde{f}_0(t)$ important to test [Callan-Treiman] QCD parameters: $f_0(\Delta_{K\pi}=m_K^2-m_\pi^2) = f_K/f_\pi$
- Linear parametrization not a good physics approximation: hints for λ''_0 ?
- Fractional partial width difference by varying slopes values :

$\Delta(1/\Gamma\, d\Gamma/dt)$ **[λ''_0=0.4, 0]**

$\Delta(1/\Gamma\, d\Gamma/dt)$ **[λ'_0=14.7, 16]**

$\lambda \mathrm{x} 10^3$

- Almost exact cancellation

$\Delta(1/\Gamma\, d\Gamma/dt)$ **[λ'_0=14.7, 16: λ''_0=0.4, 0]**

- Correlation matrix from Ideal t-spectrum experiment:

λ'_0	1	-0.9996	-0.97	0.91
λ''_0		1	0.98	-0.92
λ'_+			1	-0.98
λ''_+				1

[Franzini]

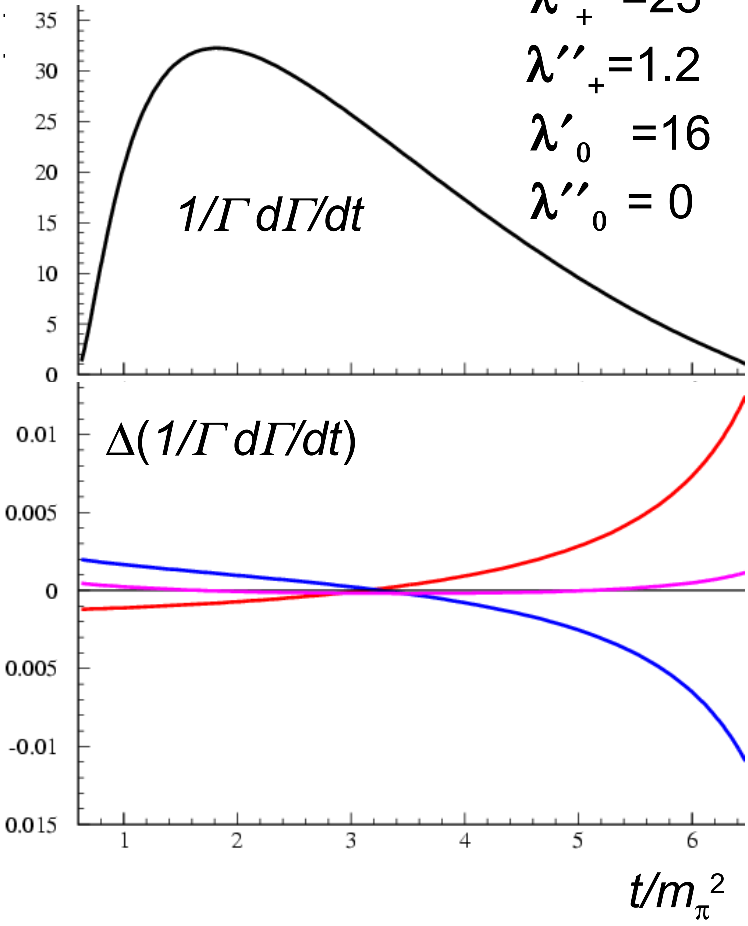
$\lambda \mathrm{x} 10^3$

λ'_+ =25

λ''_+=1.2

λ'_0 =16

λ''_0 = 0



Simultaneous λ'_0 , λ''_0 measurement not possible