Measurement of V_{us} at KLOE

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for the KLOE collaboration

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Overview

- Introduction
- DAΦNE and KLOE – experimental setup
- K_S, K_L, $K^{\pm}$ decay parameters at KLOE
- V_{us}, unitarity and universality

Interest in V_{us} measurement with kaons

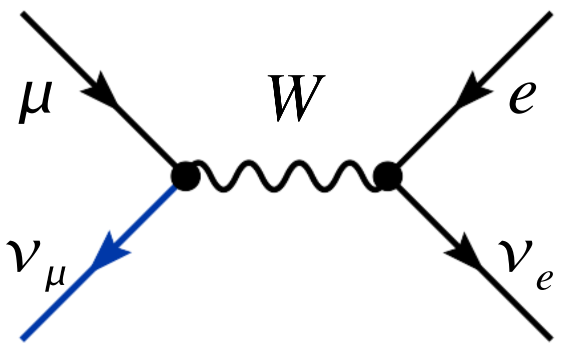
SM interaction with W:

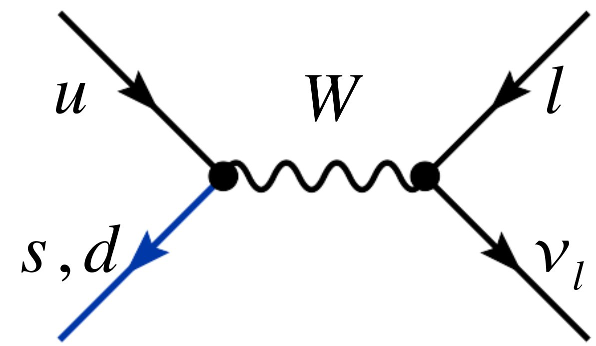
$$\frac{g}{\sqrt{2}} W_{\alpha}^{+} \left(\bar{U}_L V_{CKM} \gamma^{\alpha} D_L + \bar{e}_L \gamma^{\alpha} \nu_{eL} + \bar{\mu}_L \gamma^{\alpha} \nu_{\mu L} + \bar{\tau}_L \gamma^{\alpha} \nu_{\tau L} \right)$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

~10^{-5}

The most precise unitarity test of V_{CKM} from 1st row



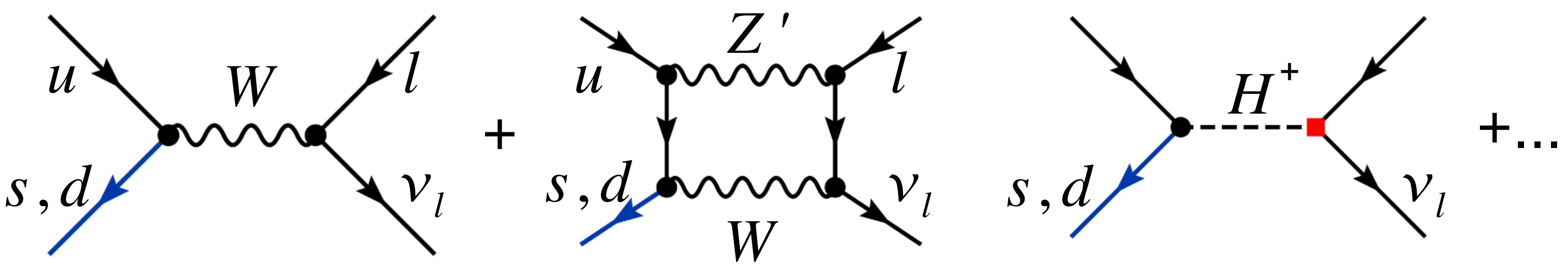


$$\frac{(g_{\mu} g_e)^2}{M_W^4} = G_F^2$$

$$\frac{(g_q g_l)^2}{M_W^4} \left(|V_{ud}|^2 + |V_{us}|^2 \right) = G_{CKM}^2$$

Interest in V_{us} measurement with kaons

New Physics extensions of the SM can break gauge universality



$$\mathrm{SM + NP} \;\propto\; G_F^2 |V_{uq}|^2 \left(1 + a\left(M_W / M_X\right)^2\right)^2, \text{ naively } a_{\mathrm{tree}} \sim 1,\; a_{\mathrm{loop}} \sim g^2$$

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

τ decay: $G_F = 1.1678(26)$

ew precision test: $G_F = 1.1655(12)$

V_{us} at 0.5%: G_F = 1.16xx(4) $\Rightarrow$ M_{tree}~5 TeV, M_{loop}~1 TeV

Extraction of V_{us} from K_{l3} decays

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_{K,l}(\lambda) \left(1 + \delta_K^{SU(2)} + \delta_{K,l}^{EM}\right)^2$$

where $K = K^+, K^0$; $l = e, \mu$ and $C_K^2 = 1/2$ for K^+, 1 for K^0

From experiment:

From experiment:	$\Gamma(K_{l3(\gamma)})$	Branching ratios and lifetimes
	$I_{K,l}(\lambda)$	Phase space from form factor parametrization
From theory:	$f_+(0)$	Hadronic matrix element at zero momentum
	S_{EW}	Short distance radiative correction factor
	$\delta_K^{SU(2)}$	Strong SU(2) breaking correction
	$\delta_{K,l}^{EM}$	Long distance electromagnetic correction

Extraction of V_{us}/V_{ud} from $K_{\mu 2}$ decays

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

From experiment: $\Gamma(K_{\mu 2(\gamma)})$ KLOE branching ratio and lifetime

$\Gamma(\pi_{\mu 2(\gamma)})$ PDG value

From theory: $f_K/f_\pi=1.189(7)$ from HPQCD/UKQCD

$1+\alpha(C_K-C_\pi)=0.9930(35)$ radiative corrections

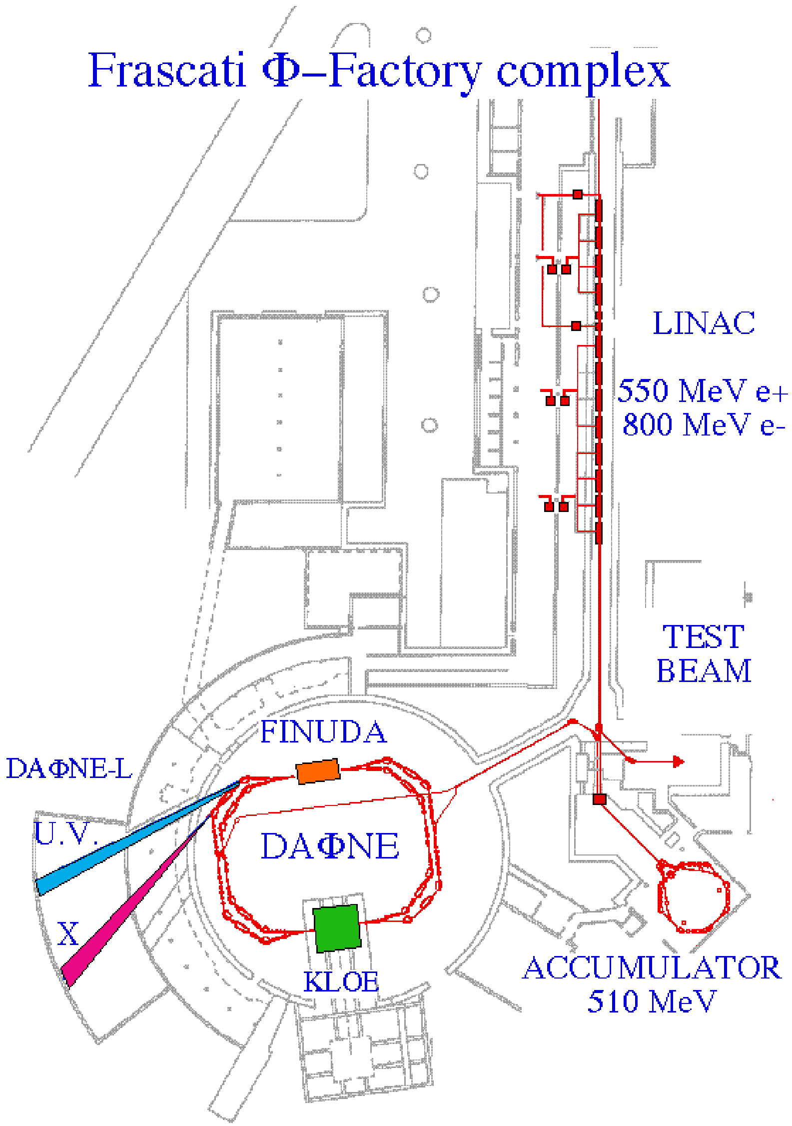
[Finkemeir, Marciano-Sirlin]

Kaon parameters measured by KLOE

K_{Se3}	PLB 636(2006) 173	K_S BRs
$K_S \to \pi\pi$	EPJC 48(2006) 767	
K_L decay distribution(τ)	PLB 626(2005) 15	
K_L decays and lifetime	PLB 632(2006) 43	K_L BRs
$K_L \to \pi^+\pi^-$	PLB 638(2006) 140	
$K_L \to \gamma\gamma$	PLB 566(2003) 61	lifetime
K^0 mass	JHEP 12(2007) 073	FFs
$K_{Le3\gamma}$	EPJC 55(2008) 539	
ff K_{Le3}	PLB 636(2006) 166	
ff $K_{L\mu3}$	JHEP 12(2007) 105	
$K^+_{\mu2}$	PLB 632(2006) 76	
K^+ lifetime	JHEP 01(2008) 073	$K^\pm$ BRs
K^+_{l3}	JHEP 02(2008) 098	lifetime
$K^+_{\tau'}$	PLB 597(2004) 139	
$K^+_{\pi2}$	PLB 666(2008) 305	

KLOE V_{us} JHEP 04(2008) 059

DAΦNE e^+e^- collider at LNF



Fixed energy $\sqrt{s} \sim m_\phi = 1019.46\,\mathrm{MeV}$

$\sigma_\phi(\sqrt{s} \sim m_\phi) \sim 3.1\ \mu\mathrm{b}$

Crossing angle ~ 12.5 mrad

Peak luminosity $\mathcal{L}_{\mathrm{peak}} \sim 1.5 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Kaon physics at KLOE

The φ-meson decays at the rest frame provides **pure** and **monochromatic** kaon beams.

BR($\varphi \to K^+K^-$) = 49.1 %; p*= 127 MeV/c; $\lambda_\pm$=95 cm

BR($\varphi \to K_SK_L$) = 34.1 %; p*= 110 MeV/c; λ_S=6 mm; λ_L=3.4 m

Tagging: observation of $K_{S,L}$ indicates $K_{L,S}$ on opposite side; same for $K^\pm$

KLOE is unique:

- measure at the same time the absolute BR's of $K_{S,L}$ and $K^\pm$

  only KTeV provides an independent set of K_L BRs
- measure lifetimes for K_L and $K^\pm$
- Form factor slopes with precise knowledge of momentum transfer
- K_S beam
- Kaon momentum is monochromatic with 1 MeV resolution

PDG 04: old K_{l3} data give 2σ unitarity violation

From 2003 to 2008: substantial experimental effort to clarify the picture: BNL865, KTeV, KLOE, ISTRA+, NA48 measure BRs and *ff:*

- Much higher statistics
- Radiative corrections carefully taken into account
- Proper reporting of correlations between measurements

The KLOE detector

Magnet with SC coil, B = 0.6 T

EM Calorimeter: Pb-scint fiber
4880 PMs, 2440 cells

$\sigma_E / E = 5.7\% / \sqrt{E(\text{GeV})}$

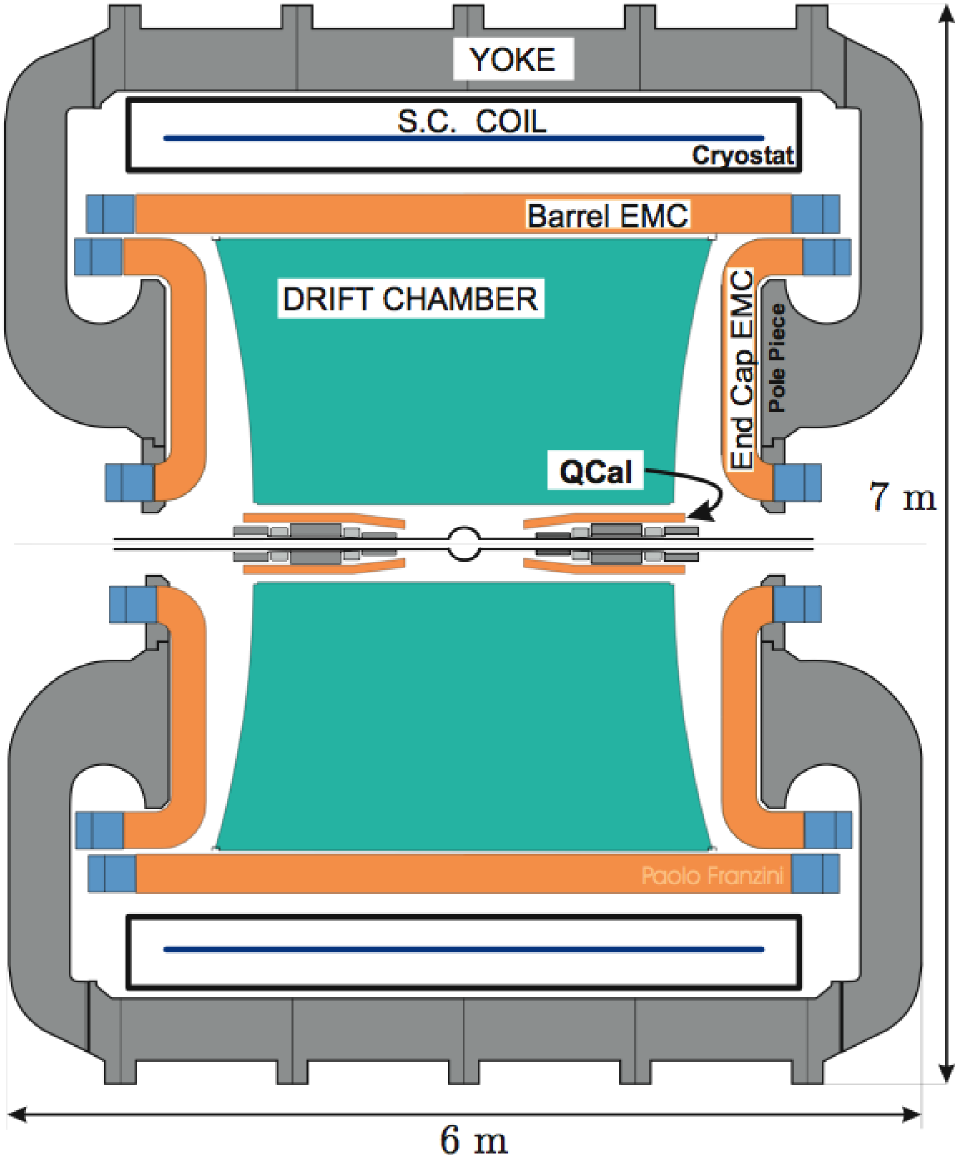
$\sigma_t = 57 / \sqrt{E(\text{GeV})} \oplus 140\,\text{ps}$

Drift chamber
12582 sense wires
52140 total wires
Carbon fiber walls

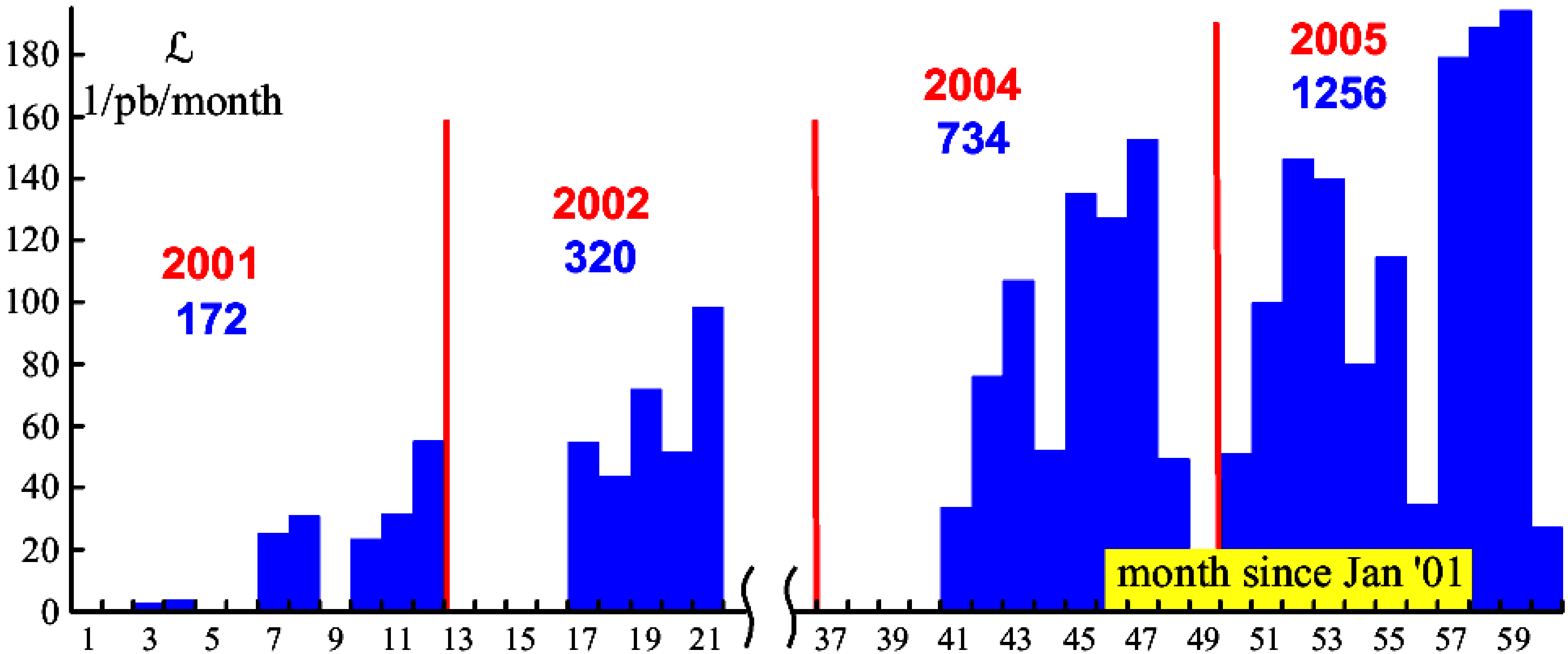
$\sigma_{p_\perp} / p_\perp = 0.4\%,$

$\sigma_{x,y} \sim 150\,\mu\text{m}, \;\; \sigma_z \sim 2\,\text{mm}$

Al-Be beam pipe
r = 10 cm, 0.5 mm thick



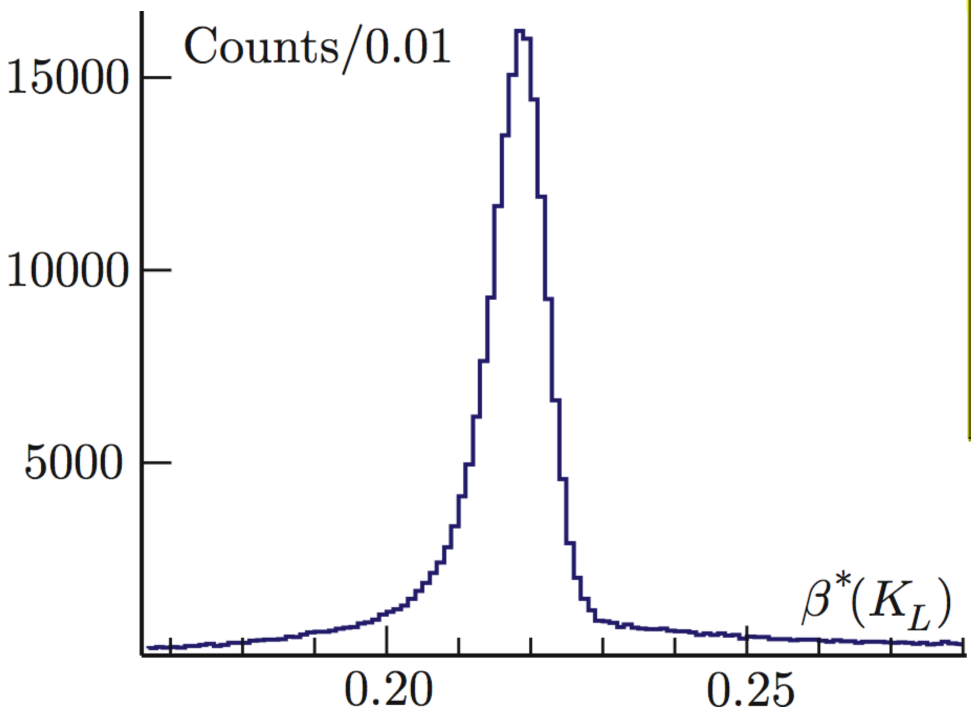
KLOE integrated luminosity

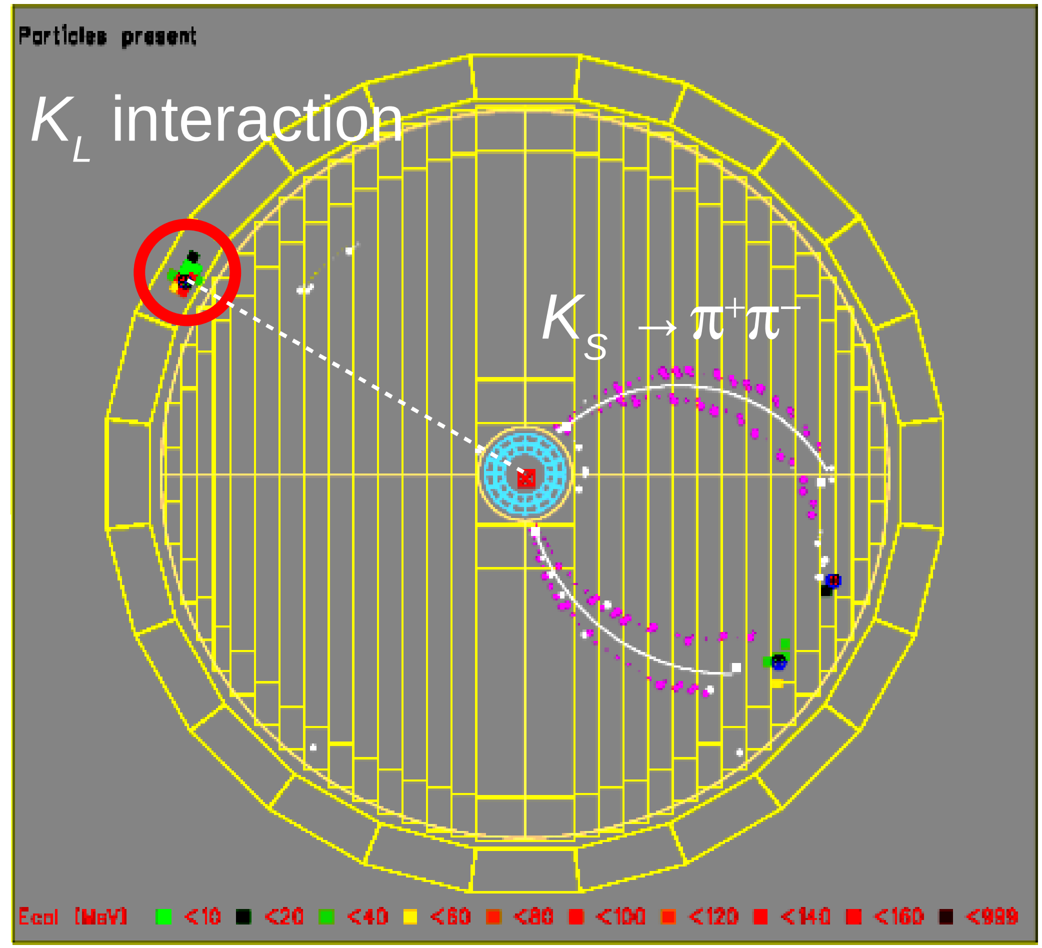


$$\int \mathcal{L} \sim 2.5\,\text{fb at}\ \phi\ \text{peak, gives} \approx 2\times 10^9\, K_S K_L\ \text{decays}$$

K_S beam

K_L velocity $\beta \sim 0.22$
K_S tagged by K_L interactions in calorimeter, identified by TOF





K_S momentum from $p_\varphi - p_{KL}$ with 1 MeV resolution

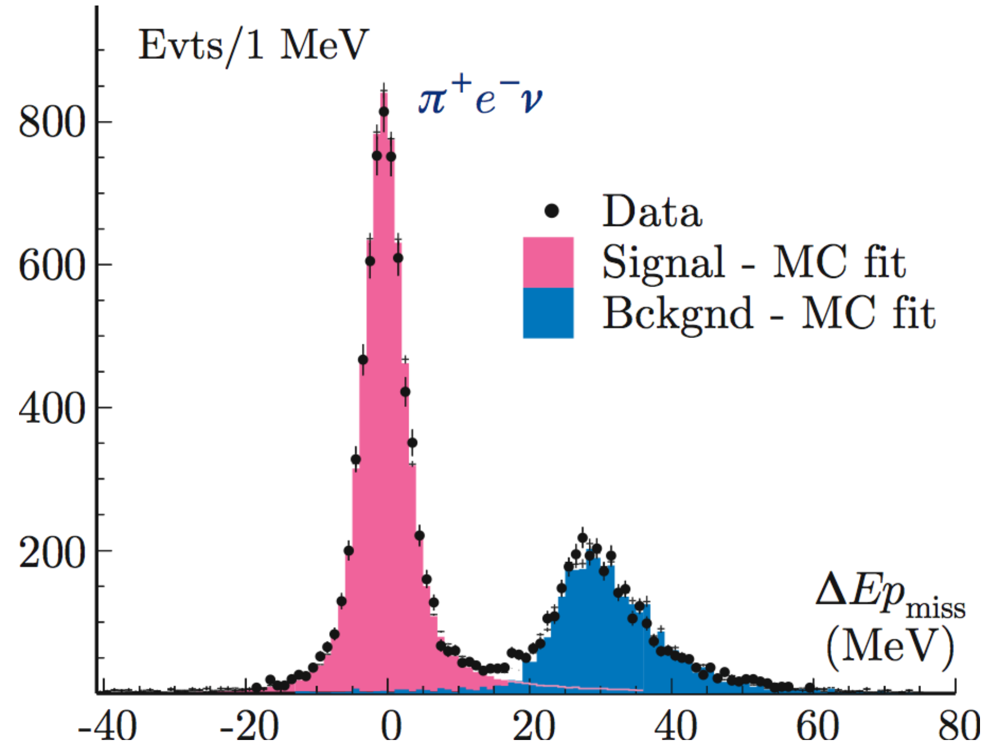
$K_S \to \pi e \nu$

Signal selection and π/e separation by TOF in calorimeter

$\Delta E p_{\mathrm{miss}} = E_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|$ variable is used to isolate signal events

13000 signal events

Normalize to $\pi^+\pi^-$ counts

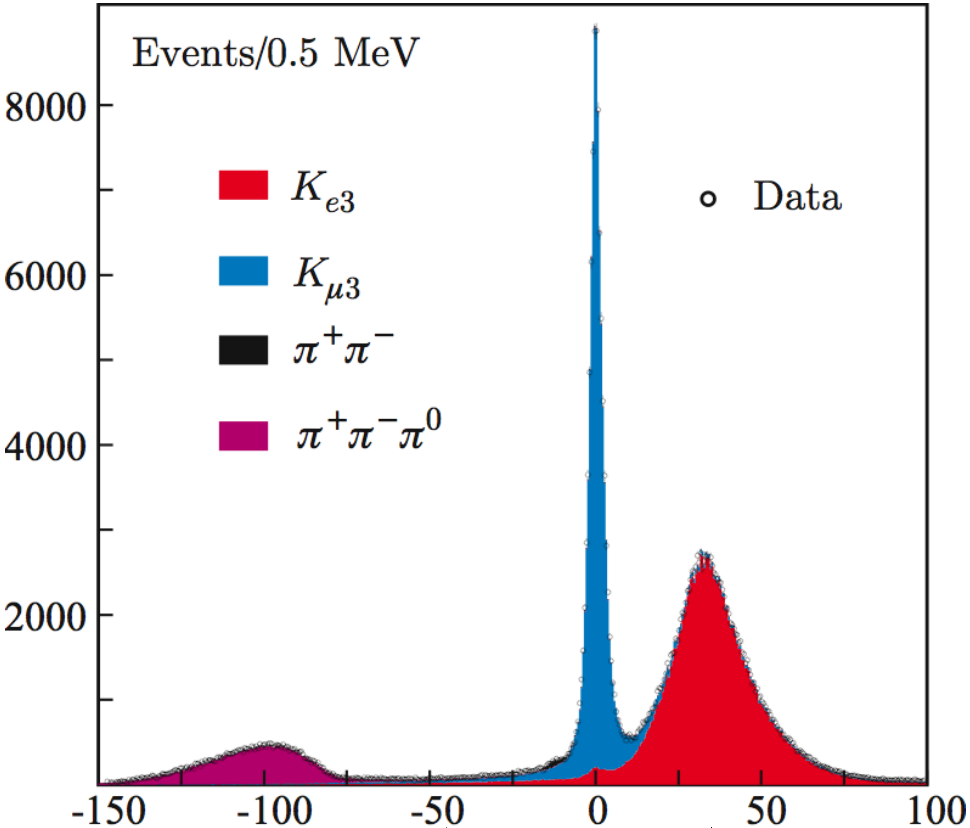


BR($K_S \to \pi e \nu$) = (7.046 ± 0.077 ± 0.049) ×10^{-4}

precision 1.3%, V_{us} at 0.7% (with τ_S from PDG)

K_L decays

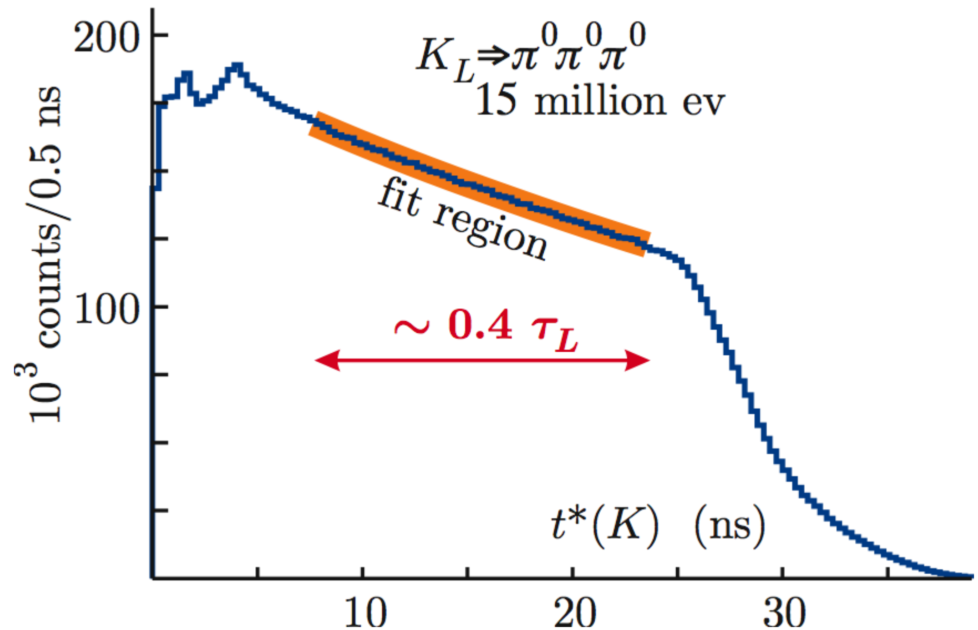
Detection of $K_S \to \pi^+\pi^-$, indicates presence of K_L on opposite side



$\min(\Delta_{\mu^+e^-}, \Delta_{\mu^-e^+})$ MeV

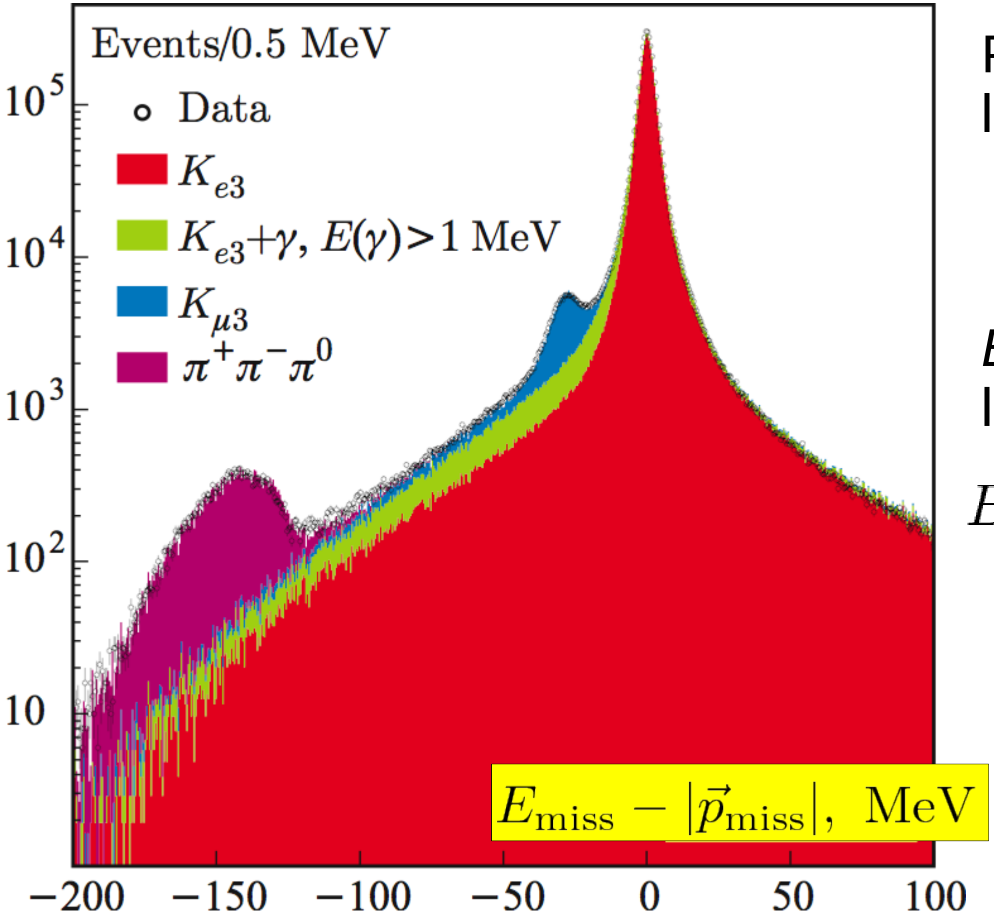
$\Delta = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$, in $K_L \to \pi\,\mu\,\nu$ hypothesis

$\tau_L = 50.92 \pm 0.30$ ns



Count tagged K_L with 3γ, 4γ, 5γ, 6γ: efficiency ≈ 100%, bckg ≈ 0.1%

Radiative correction



Photon radiation at event generator level is included to MC simulation

BR is included radiation within kinematic limits:

$$BR(K_L \to f(\gamma)) =$$
$$BR(K_L \to f, f+\gamma, 0 \le E_\gamma \le E_{\rm max})$$

Radiation effects do change acceptance and signal shapes at % level

KLOE K_L results

Count events in *FV*, correct for *FV* acceptance (≈30%) and efficiencies

Absolute *BR*: $$BR(K_L \to f) = \frac{N_f}{N_{\rm tag}\varepsilon_{FV}\varepsilon_{{\rm rec},f}} \times \frac{\langle\varepsilon_{\rm tag}\rangle}{\varepsilon_{{\rm tag},f}}$$

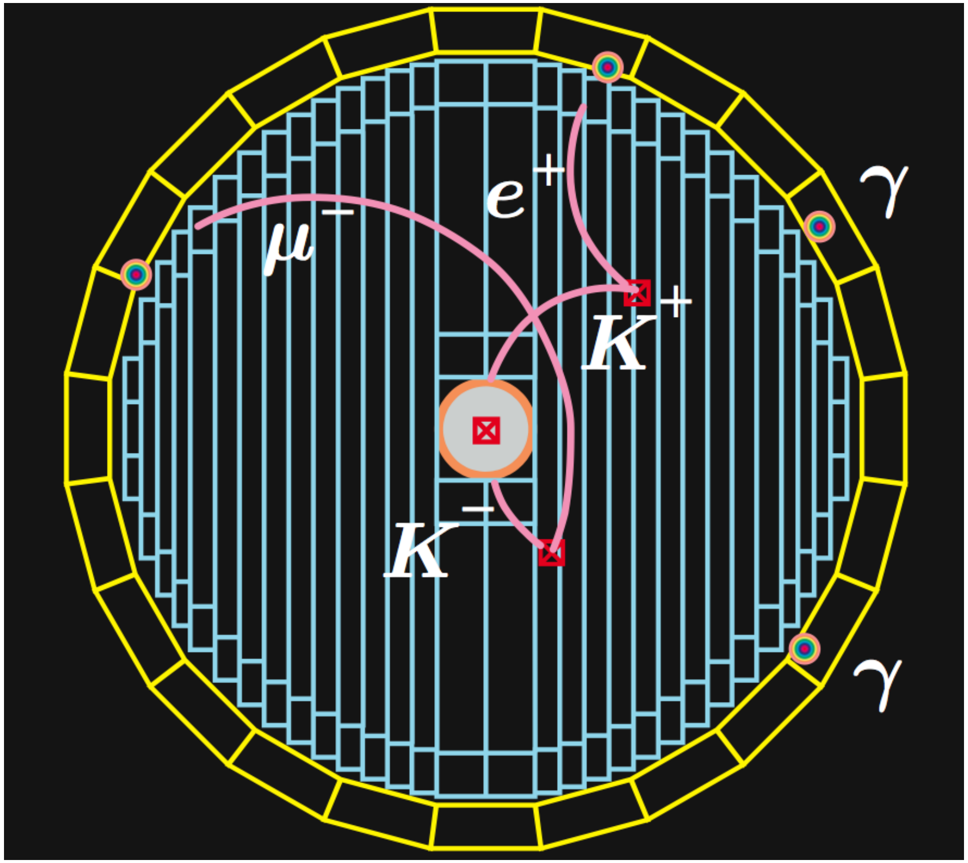
FV acceptance depends on K_L lifetime: $\varepsilon_{FV} = \varepsilon_{FV}^0 (1 + 0.0128\,\text{ns}^{-1}(\tau^0 - \tau))$

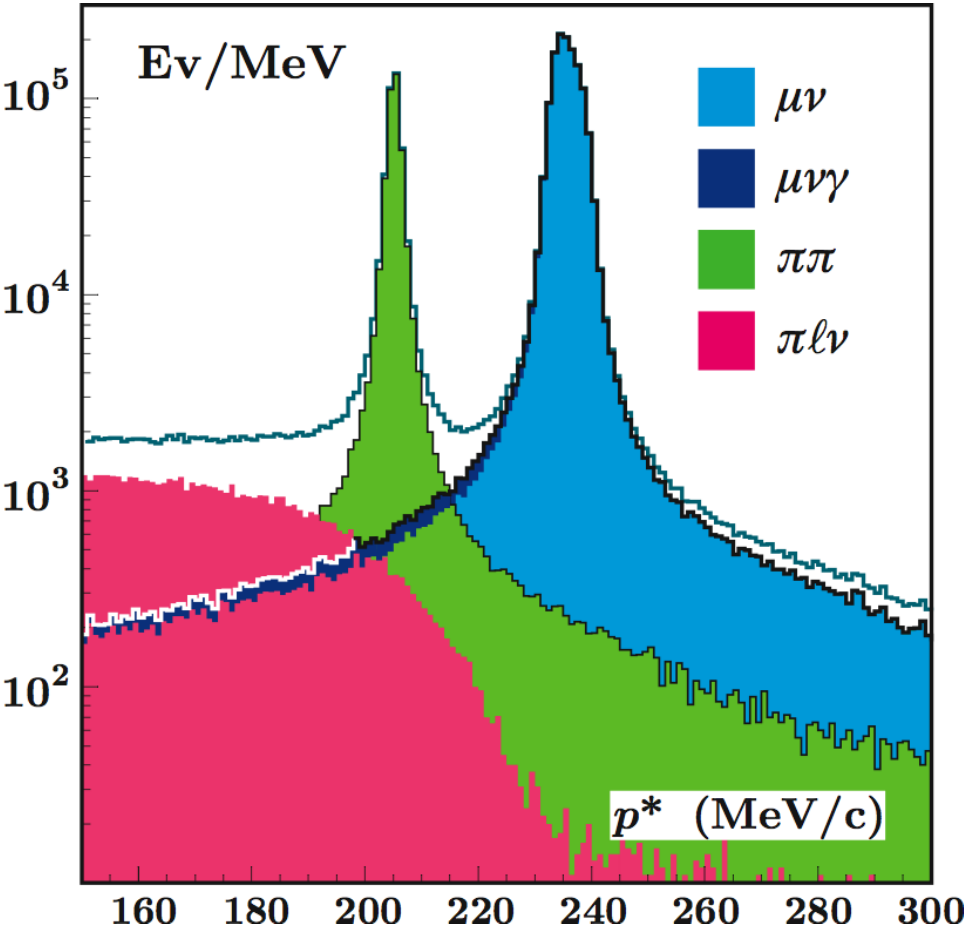
Constrained fit: $\Sigma BR_i = 1$, accounting for *BR* vs τ dependence

$BR(K_{Le3})$	0.4008(15)	0.4%
$BR(K_{L\mu3})$	0.2699(14)	0.5%
$BR(3\pi^0)$	0.1996(20)	1.0%
$BR(\pi^+\pi^-\pi^0)$	0.1261(11)	0.9%
$BR(\pi^+\pi^-)$	$1.92(2)\times10^{-3}$	1.0%
$BR(\pi^0\pi^0)$	$849(9)\times10^{-4}$	input PDG'06(η_{00}/η_{+-})
$BR(\gamma\gamma)$	$5.57(8)\times10^{-4}$	1.4%
τ_L	50.84(23) ns	0.5%

χ^2/d.o.f. = 0.19/1, CL = 66%

Charged kaon decays





Tags

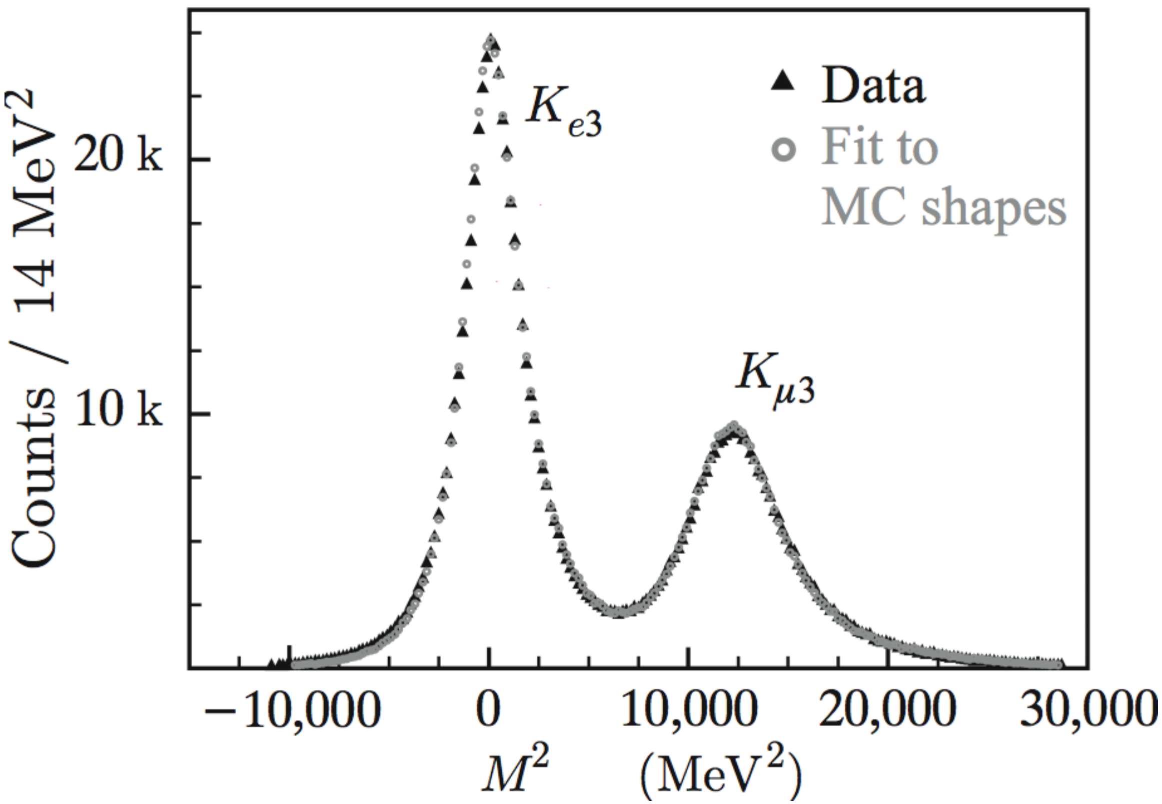
$K^+ \to \mu^+ \nu$ $\quad$ $K^- \to \mu^- \nu$

$K^+ \to \pi^+ \pi^0$ $\quad$ $K^- \to \pi^- \pi^0$

$BR(K^+ \to \mu^+ \nu(\gamma)) = 0.6366 \pm 0.0009_{stat} \pm 0.0015_{syst}$

$BR(K^+ \to \pi^+ \pi^0(\gamma)) = 0.2065 \pm 0.0005_{stat} \pm 0.0008_{syst}$

$K^{\pm} \to \pi^0 l^{\pm} \nu$ decays



verify by $\pi^0 \to \gamma\gamma$

lepton mass from *p* and TOF

$$t_K = t_{\text{lept}} - \frac{L_{\text{lept}}}{\beta c} = t_\gamma - \frac{L_\gamma}{c}$$

$$M^2 = p^2 \left(\frac{1}{\beta^2} - 1 \right)$$

	$K^+_{\mu 2}$−tagged	$K^+_{\pi 2}$−tagged	$K^-_{\mu 2}$−tagged	$K^-_{\pi 2}$−tagged
$BR(K_{e3})$	0.0495(7)	0.0493(10)	0.0497(8)	0.0502(10)
$BR(K_{\mu 3})$	0.0322(6)	0.0322(9)	0.0323(5)	0.0327(9)

Very good consistency!

Charged kaon lifetime

Poor consistency between old measurement, need confirmation

Kaon decay length

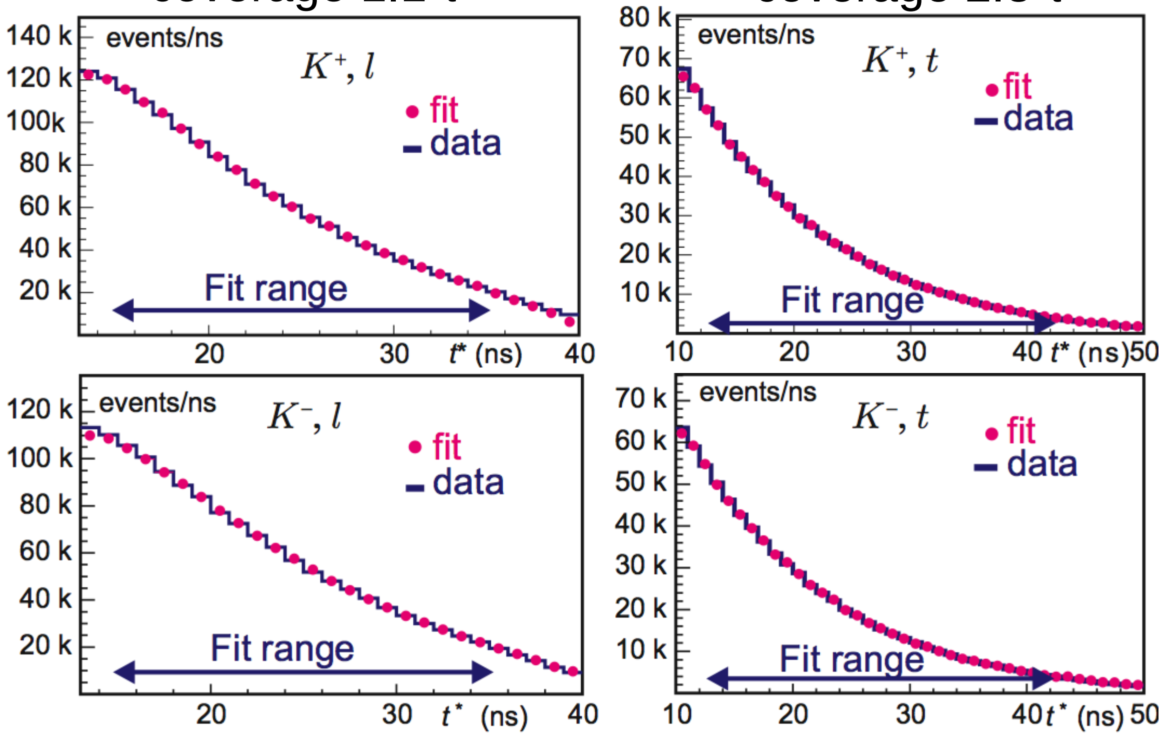
$$\tau_K = \int \frac{dl}{\beta \gamma c}$$

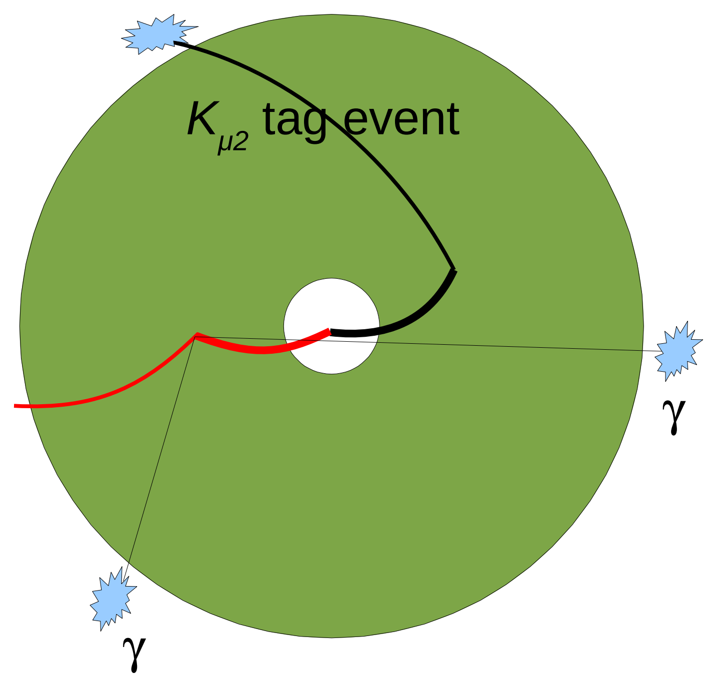
coverage 1.1 τ

Kaon decay time

$$\tau_K = (t_\gamma - R_\gamma / c) / \gamma_K$$

coverage 2.3 τ





$\tau(K^{\pm}) = 12.347 \pm 0.030$ ns

$\tau(K^{+})/\tau(K^{-}) = 1.004 \pm 0.004$

precision 0.25%

KLOE charged kaon results

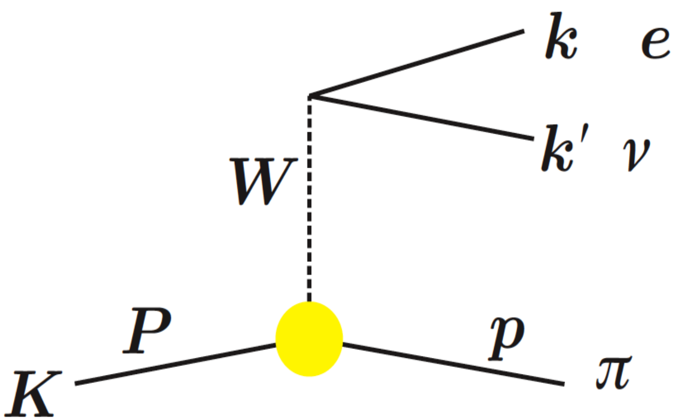
FV acceptance depends on K_L lifetime: $\varepsilon_{FV} = \varepsilon^0_{FV}(1 + 0.0395\,\text{ns}^{-1}(\tau^0 - \tau))$

Constrained fit: *ΣBRi = 1*, accounting for *BR* vs *τ* dependence

$BR(K^+ \rightarrow \mu^+\nu)$	0.6376(12)	0.2%
$BR(K^+ \rightarrow \pi^+\pi^0)$	0.2071(9)	0.4%
$BR(K^\pm \rightarrow \pi^\pm\pi^+\pi^-)$	0.0553(9)	input PDG ‘04 KLOE has an ongoing analysis
$BR(K^\pm \rightarrow \pi^0 e^\pm\nu)$	0.0499(5)	1.0%
$BR(K^\pm \rightarrow \pi^0\mu^\pm\nu)$	0.0325(4)	1.2%
$BR(K^\pm \rightarrow \pi^\pm\pi^0\pi^0)$	0.0177(3)	1.7%
$\tau(K^\pm)$	12.344(30) ns	0.24%

χ^2/d.o.f. = 0.60/1, CL = 44%

K_{l3} form factors



$t=(P-p)^2$

$$\langle\pi|J^V_\alpha|K\rangle = f_+(0)\cdot\left((P+p)_\alpha \tilde{f}_+(t) + (P-p)_\alpha \times \times(\tilde{f}_0(t)-\tilde{f}_+(t))\frac{\Delta_{K\pi}}{t}\right)$$

$f_+(0)$ – Lattice calculation

$\tilde{f}_+(t)$ – K_{e3} and $K_{\mu 3}$ vector form factor

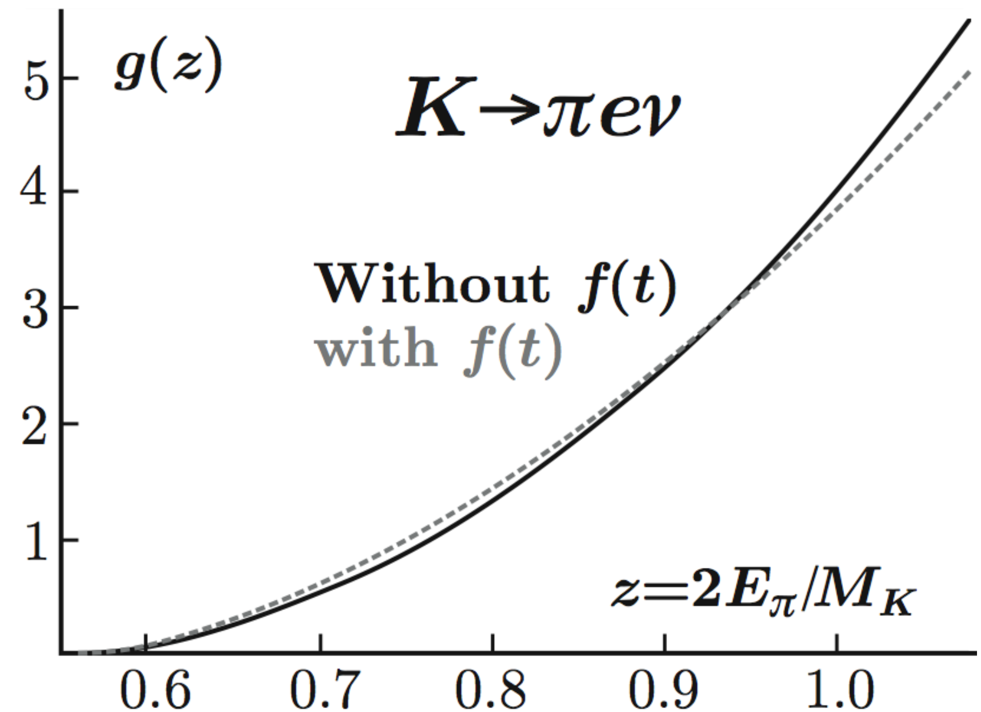
$\tilde{f}_0(t)$ – $K_{\mu 3}$ scalar form factor

To evaluate $I_{K,l}(\lambda)$ we need to measure form factor dependence on *t*

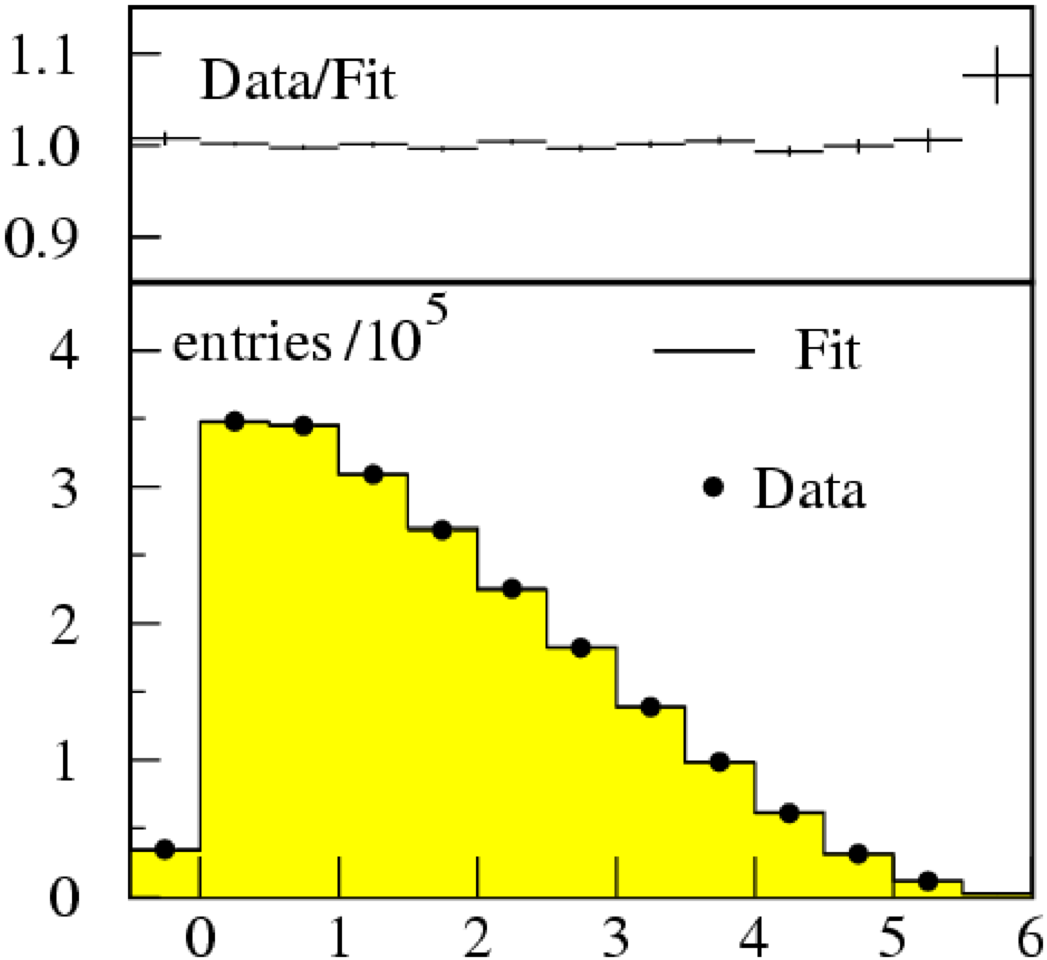
$$\tilde{f}_{+,0} = 1 + \lambda'_{+,0}\frac{t}{m^2} + \frac{1}{2}\lambda''_{+,0}\left(\frac{t}{m^2}\right)^2$$

$\rho(\lambda'_+, \lambda''_+) = -0.95$ larger errors

$\rho(\lambda'_0, \lambda''_0) = -0.9996 \Rightarrow$ only linear parametrization



Vector form factor



We can select high purity sample of K_{Le3} decays by kinematics and make *e/μ* separation by TOF

Quadratic parametrization:

$$\lambda'_+ = (22.5 \pm 1.5_{\rm stat} \pm 1.0_{\rm syst}) \times 10^{-3}$$

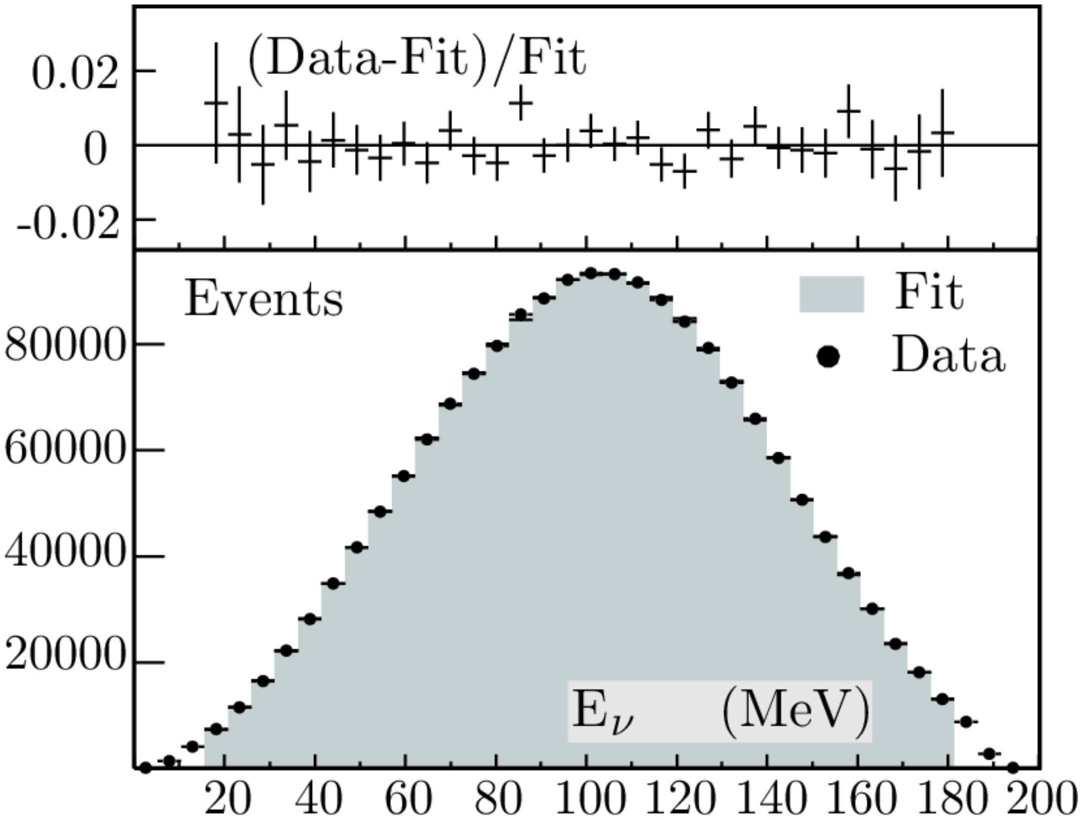
$$\lambda''_+ = (1.4 \pm 0.7_{\rm stat} \pm 0.4_{\rm syst}) \times 10^{-3}$$

Pole parametrization:

$$M_V = 870 \pm 6_{\rm stat} \pm 7_{\rm syst} \text{ MeV}$$

Phase space stable at 0.2%, w.r.t. parametrization

Scalar form factor



We can select high purity sample of $K_{L\mu3}$ decays by kinematics.

Low energies
→difficulties in π/μ separation
→fit E_ν spectrum (2-3 times less statistical sensitive)
→fit together with K_{Le3} data

Due to large correlation fit only linear coefficient:

$$\lambda_0 = (15.4 \pm 2.2) \times 10^{-3}$$

Phase space stable at 0.4%, w.r.t. parametrization

Dispersive approach

New parametrization based on dispersive relations (twice-subtracted) and $K\pi$ scattering data: f_+ and f_0 depend only on parameters λ_+ and λ_0

[Passemar-Stern,Jamin-Pich]

$\lambda_+ = (25.7 \pm 0.4_{stat} \pm 0.4_{syst} \pm 0.2_{param})\times10^{-3}$

$\lambda_0 = (14.0 \pm 1.6_{stat} \pm 1.3_{syst} \pm 0.2_{param})\times10^{-3}$

χ^2/ndf=2.6/3 ρ = -0.26

Parameters	$I(K^0_{e3})$	$I(K^0_{\mu3})$	$I(K^+_{e3})$	$I(K^+_{\mu3})$
$\lambda'_+, \lambda''_+, \lambda'_0$	0.15483(40)	0.10271(52)	0.15919(41)	0.10568(54)
λ_+, λ_0	0.15477(35)	0.10262(47)	0.15913(36)	0.10559(48)
Δ (%)	0.04	0.09	0.04	0.09

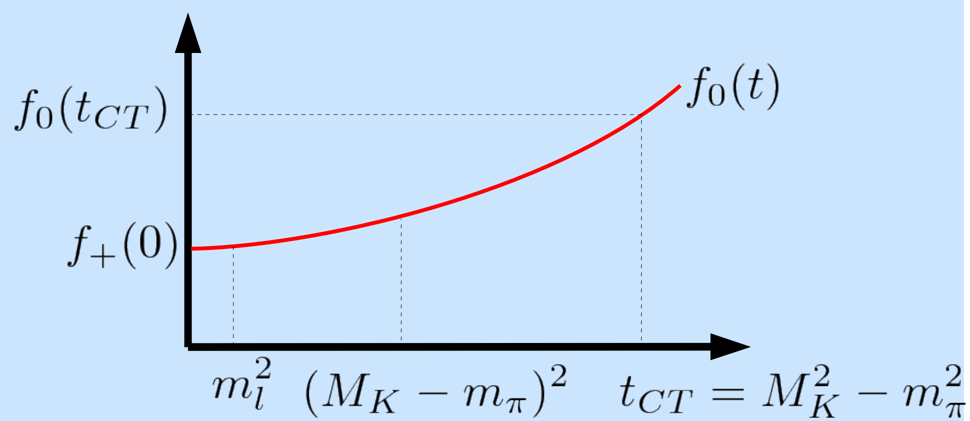
Test of lattice QCD with Callan-Treiman relation

$$f_0(t_{CT}) = f_K/f_\pi + \Delta_{CT}$$

$f_K/f_\pi = 1.189 \pm 0.007$ (HPQCD/UKQCD)

$f_+(0) = 0.967 \pm 0.025$ which agrees with

$f_+(0) = 0.9644 \pm 0.0049$ (RBC/UKQCD)



SU(2) and EM corrections

$$\delta_K^{SU(2)} = +2.36(22) \text{ for } K_{l3}^{+} \text{ and } = 0 \text{ for } K_{l3}^{0}$$

χPT, depends on quark mass ratios (Leutwyler 96, Cirigliano 2007)

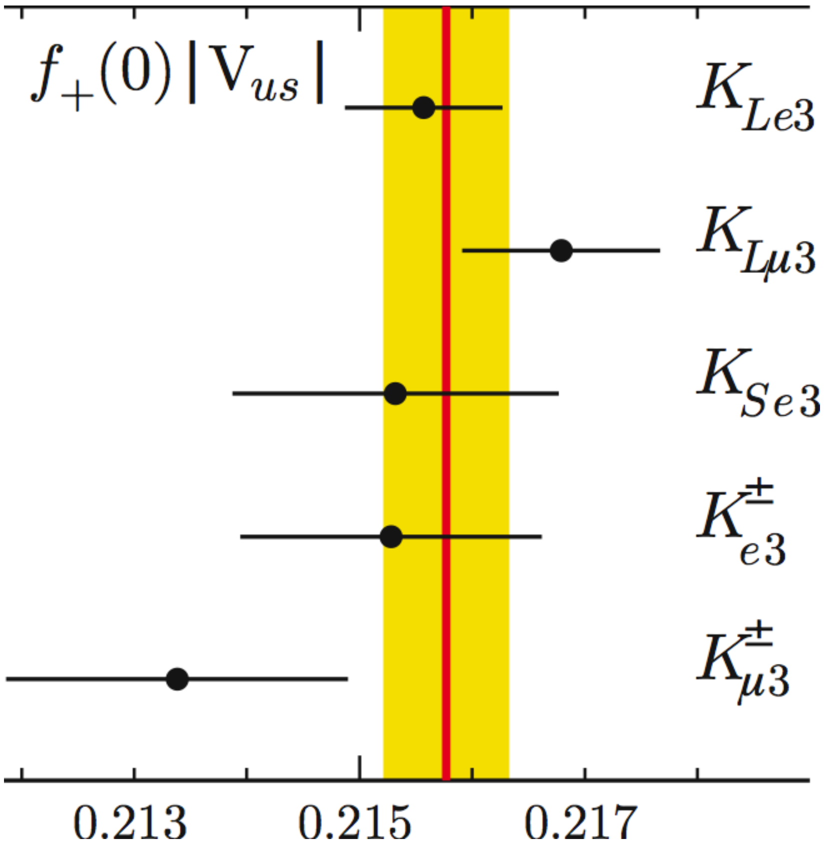
$\delta_{K,l}^{EM}$ for full phase space-all measurements assumed fully inclusive

$\delta_{K,l}^{EM}$	**Cirigliano** χPT	**Neufeld** χPT	**Andre** Had. model
K^0_{e3}	+0.52(10)%	+0.57(15)%	+0.65(15)%
K^+_{e3}	+0.03(10)%	+0.08(15)%	
$K^0_{\mu3}$		+0.80(15)%	+0.95(15)%
$K^+_{\mu3}$		- 0.12(15)%	

New corrections available

Correlations included, e.g.: $\rho(K^0_{e3},K^0_{\mu3}) = +0.78$, $\rho(K^0_{e3},K^+_{e3}) = +0.11$

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



K_{Le3}	0.2155(7)	0.3%
$K_{L\mu3}$	0.2167(9)	0.4%
K_{Se3}	0.2153(14)	0.7%
$K^{\pm}_{e3}$	0.2152(13)	0.6%
$K^{\pm}_{\mu3}$	0.2132(15)	0.7%

KLOE avg: 0.2157(6)

χ^2/dof = 7.0/4 (14%)

Precision 0.3% using only KLOE results but K_S lifetime

World avg: 0.2166(5)

Precision 0.23%

K^0 vs $K^{\pm}$ agree within 1.1σ

alternatively, $K^0 - K^{\pm}$ gives $\delta^{SU(2)}_{\text{exp}} = 1.7(6)\% \Leftrightarrow \delta^{SU(2)}_{\text{theory}} = 2.36(22)\%$

Lepton universality

$$R_{\mu e} = \frac{|f_+(0)V_{us}|^2_{\mu 3}}{|f_+(0)V_{us}|^2_{e3}} = \frac{\Gamma_{\mu 3}}{\Gamma_{e3}} \frac{I_{e3}(1+\delta_K^{SU(2)}+\delta_e^{EM})^2}{I_{\mu 3}(1+\delta_K^{SU(2)}+\delta_\mu^{EM})^2} = \frac{g_\mu^2}{g_e^2}$$

Average of charged and neutral modes

$$\mathbf{R_{\mu e} = 1.000 \pm 0.008}$$

World avg: 0.999(4)

was 1.023(7) for K_L in PDG 04

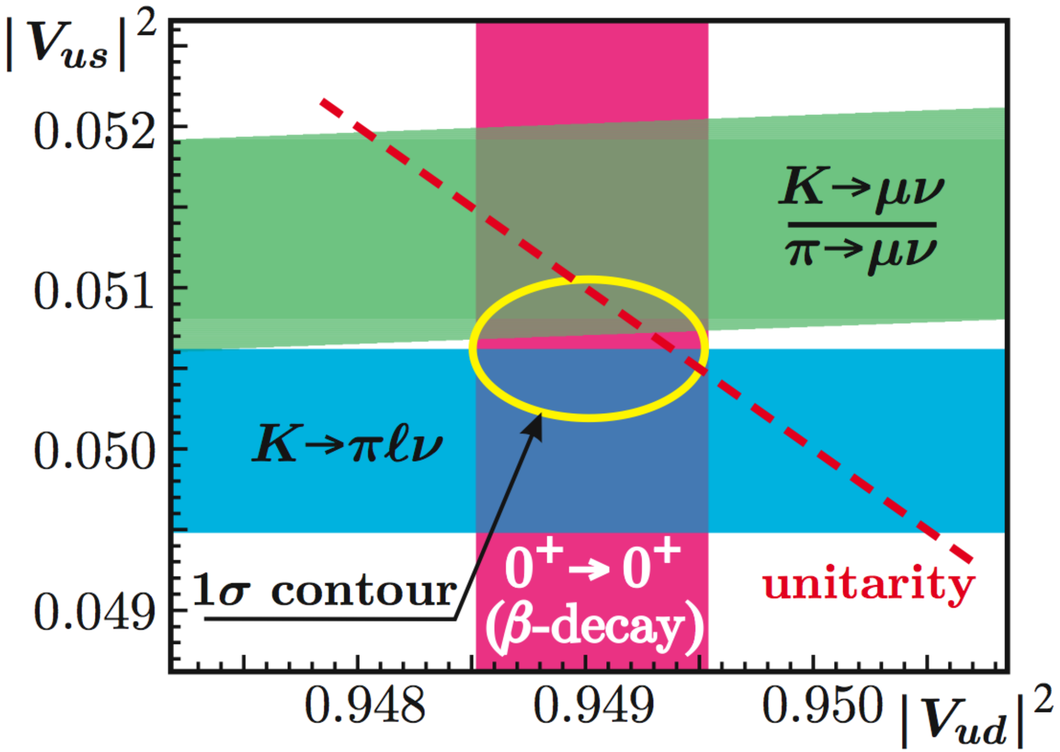
$$\text{From } \pi \to l\nu \text{ decays} : R^{\pi}_{\mu e} = 1.0042 \pm 0.0033$$

[Ramsey-Musolf, Su, Turlin 07]

$$\text{From } \tau \to l\nu \text{ decays} : R^{\tau}_{\mu e} = 1.000 \pm 0.004$$

[Davier, Hocker, Zhang 06]

CKM unitarity



V_{us}	K_{l3}
V_{us}/V_{ud}	$K_{\mu 2}/\pi_{\mu 2}$
V_{ud}	$0^+ \to 0^+$ β decay (HardyTowner07)

New value available

$|V_{us}| = 0.2249 \pm 0.0010$
$|V_{ud}| = 0.97418 \pm 0.00026$

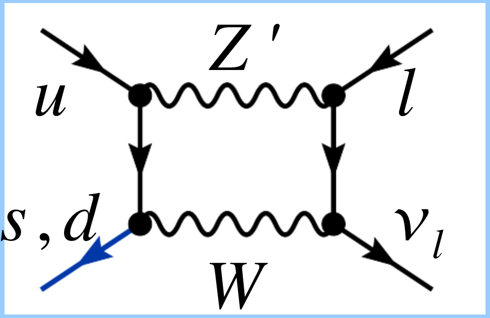
$1 - |V_{us}|^2 - |V_{ud}|^2 = 0.0004 \pm 0.0007$

Was 0.0031 ± 0.0015 in PDG04

Constraints on new physics from unitarity

G_F = 1.166371(6)×10^{-5} GeV^{-2}

G_{CKM} = 1.16614(40)×10^{-5} GeV^{-2}



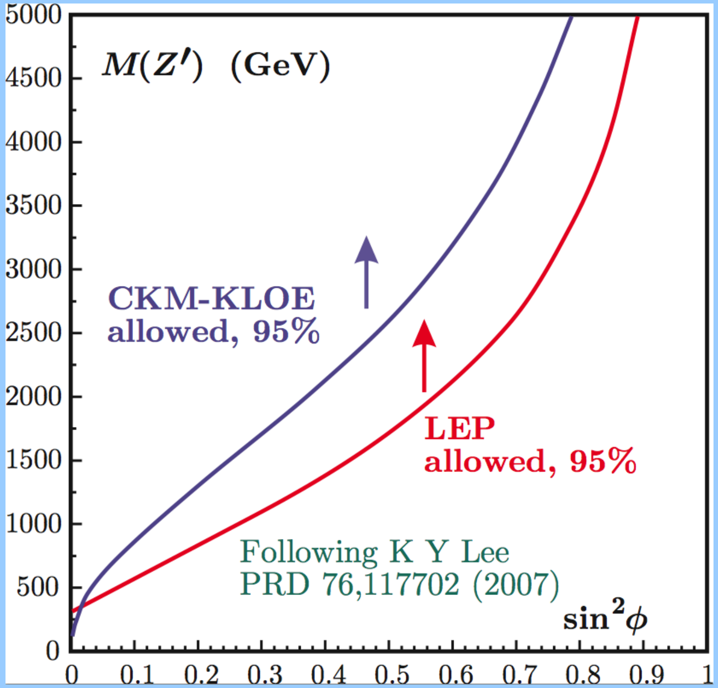
$$G_F = G_{CKM}\left(1 - 0.007 Q_{eL}(Q_{\mu L} - Q_{dL})\frac{2\ln\frac{m_{Z'}}{m_W}}{\frac{m^2_{Z'}}{m^2_W} - 1}\right)$$

SO(10) Z_χ boson:

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

[Marciano]

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



$K_{\mu 2}$: sensitivity to new physics

Scalar currents, e.g. due to Higgs exchange, affect $K \to \mu\nu$ width

$$R_{l23} = \left| \frac{V_{us}(K_{\mu 2})}{V_{us}(K_{l3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\mu 2})} \right|$$

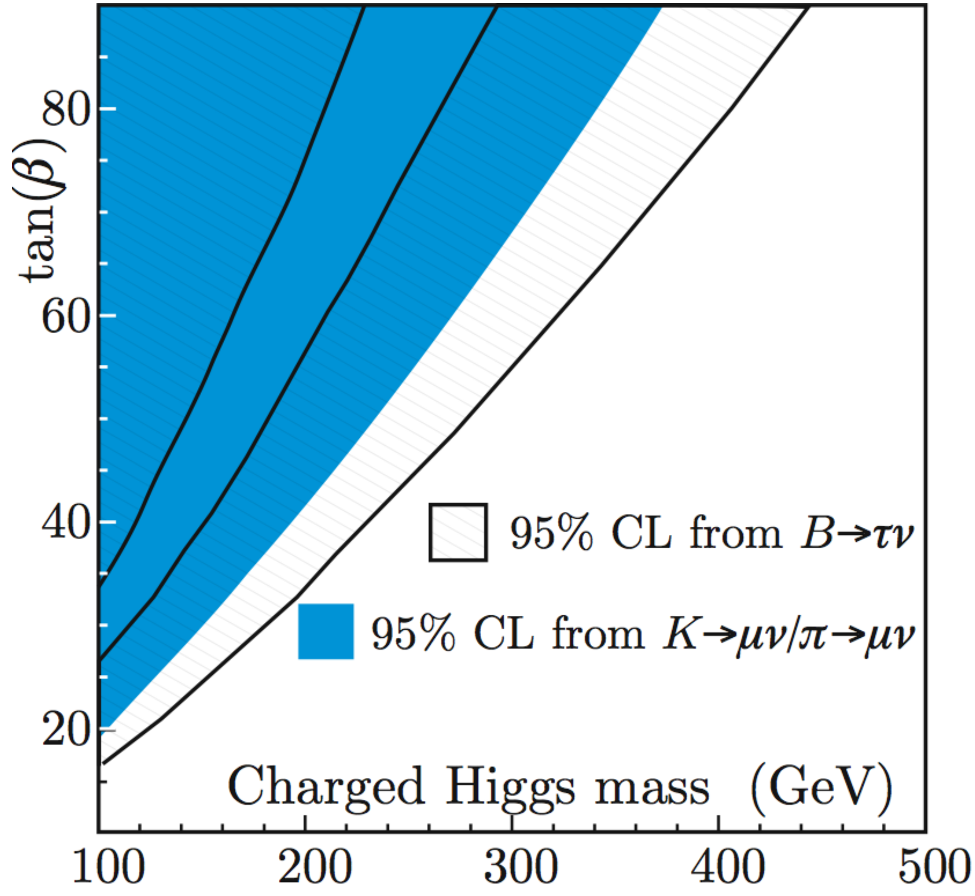
$$= \left| 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \left(1 - \frac{m_{\pi^+}^2}{m_{K^+}^2} \right) \frac{\tan\beta^2}{1 - \varepsilon_0 \tan\beta} \right|$$

[Hou, Isidori-Paradisi]

$$\mathbf{R_{l23}^{SM} = 1}$$

$$\mathbf{R_{l23} = 1.008 \pm 0.008}$$

Main uncertainty from $f_+(0)/(f_K/f_\pi)$



Kaon physics gives complementary information to B physics

Conclusion

- KLOE experiment has precisely measured the kaon decay parameters needed to probe SM prediction
- Using β decay data and recent lattice calculation together with KLOE data the precision test can be performed for the first row of CKM matrix.

CKM unitarity is checked at level better than 0.1%:

$$1 - |V_{us}|^2 - |V_{ud}|^2 = 0.0004 \pm 0.0007$$

- A competitive test of the universality of lepton and quark weak couplings can be performed with kaon physics
- New physics parameters were constrained by kaon decay parameters

Evaluation $f_+(0)$

CVC implies $f_+(0)=1$; SU(3) breaking is small (Ademollo-Gatto theorem)

Analytic
large uncertainties

Lattice
is improving