Low energy parameters

and new physics

or

What you might need from low energy physics if and when you find new physics

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Frascati, 16 May 2008

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4. K_L, K_S, $K^{\pm}$ decays
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6. $|V_{us}|^2/|V_{ud}|^2$
7. Unitarity and universality

History

1947: Rochester and Butler, $K^0 \to \pi^+\pi^-$, $K^+ \to \pi^+\pi^0$

. . . 60 Years of hard work. . .

2008: KLOE first round, $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9996 \pm 0.0007$

Standard Model

$$\frac{g}{\sqrt{2}} W^+_\alpha (\bar{\mathbf{U}}_L \, \mathbf{V}_{\text{CKM}} \gamma^\alpha \, \mathbf{D}_L + \bar{e}_L \gamma^\alpha \nu_{e\,L} + \bar{\mu}_L \gamma^\alpha \nu_{\mu\,L} + \bar{\tau}_L \gamma^\alpha \nu_{\tau\,L}) \ + \ \text{h.c.}$$

There is just one gauge coupling g, $G_F = g^2/(4\sqrt{2}\,M_W^2)$

The quarks are mixed by a unitary matrix **V**

Quarks and leptons have the same weak charge

At the opposite extreme:

$g_q, \ \ g_e, \ \ g_\mu, \ \ g_\tau$

V is not unitary

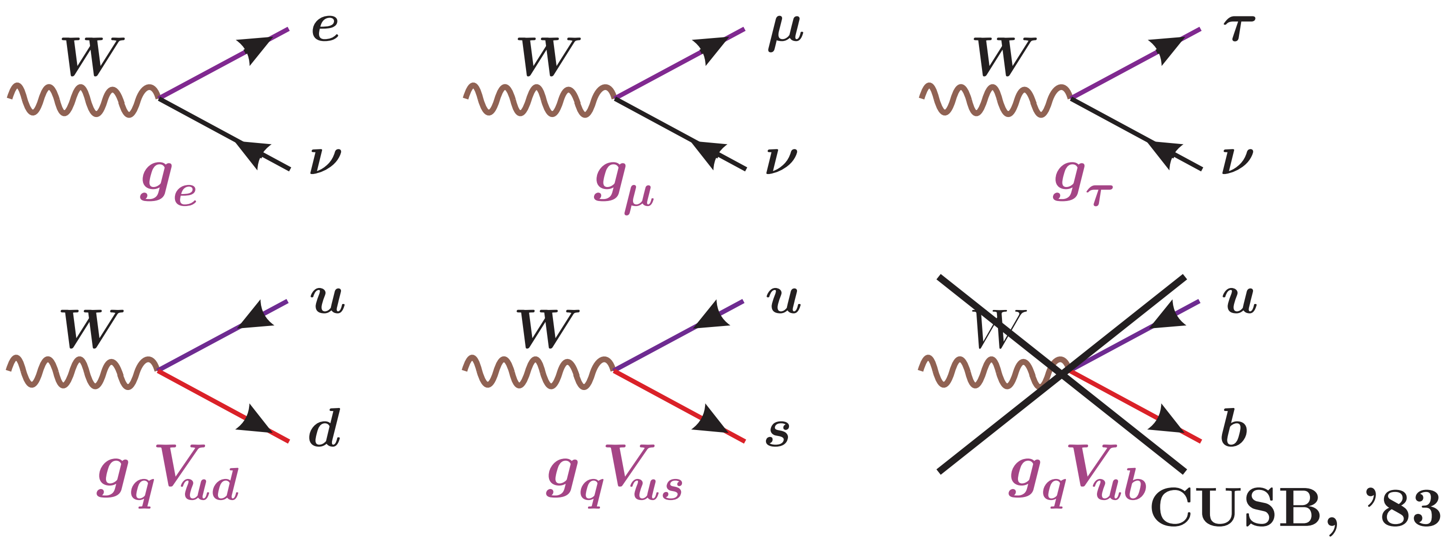
(But probabilities <u>are</u> conserved!)

$$\mathbf{U} = \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \ \mathbf{D} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{ud} & V_{us} & V_{ub} \\ V_{ud} & V_{us} & V_{ub} \end{pmatrix}$$

this is tex

We can measure



With kaons, pions, nuclear β-decay, and muons we can measure

g_e, g_μ, g_q, V_{ud} and V_{us}

and check whether $g_e = g_\mu = g_q$, $|V_{ud}|^2 + |V_{us}|^2 = 1$

Decay Width

From $\langle f|J_\alpha J^\alpha|i\rangle \Rightarrow$

$$\Gamma(|\Delta S|=1) = \boxed{|V_{us}|^2 \times G^2 \times F_1(\text{wi})} \times F_2(\text{emi}) \times F_3(\text{si}).$$

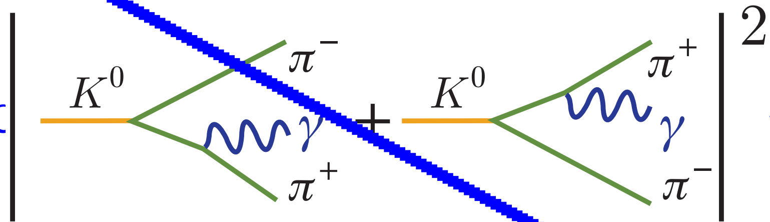
1. F_1: kinematics, spinor algebra, phase space, OK
2. F_2: Cannot turn off electromagnetism. Painfull but calculable. Few % correction, to .1% accuracy
3. F_3: Strong interactions are hardest to compute, can have large effects, choose best processes, lattice to the rescue!

F_2 – Radiation must be included

$m(\gamma) = 0 \Rightarrow$ charge particles radiate.

Take for example $K_S \to \pi^+\pi^-$. In the real world the em interaction

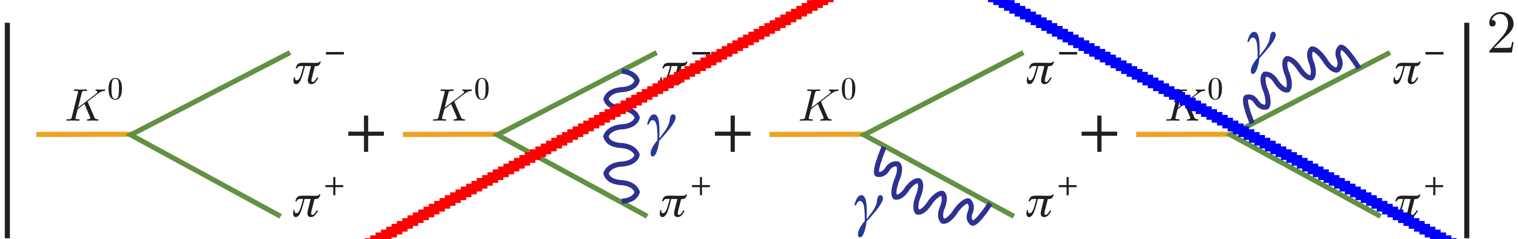
gives $\Gamma_1 \propto$



$\to \infty$ for $\omega \to 0$. .

The infinity is cancelled by an opposite sign contribution:

$\Gamma_2 \propto$



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$\Gamma_1 + \Gamma_2$ is finite but contains a correction of $\mathcal{O}\left(\frac{\alpha}{\pi} \times \log \frac{\omega_0}{m}\right)$.

ω_0 is finite and experimental acceptance dependent.

Radiation inclusive branching ratios

Inclusion (or exclusion) of photons does affect event acceptance. It is modern practice to give results fully inclusive of radiation up to the kinematic limit. This requires correct accounting of radiation in the Monte Carlo detector simulation program.

In the KLOE MC simulation, Geanfi, radiation is included at the event generation level, event by event. In the following, even if not explicitly stated, BRs are totally inclusive of radiation.

BR($K \to f(\gamma)$) stands for BR($K \to f,\ f+\gamma,\ 0 < \omega < \omega_{\text{max}}$)

I will also just use BR($K \to f$)

F_3 – SI – Hadrons vs Quarks

Nuclear β-decay. Look at $0^+ \to 0^+$ transitions. No axial current.

CVC helps with nuclear matrix elements.

$|\Delta S| = 1$ decays. Corrections to

$$\langle f|\bar{u}\gamma_\alpha s|i\rangle$$

appear only at 2[nd] order in $m_s - m_d$. A-G theorem.

Kaon semileptonic decays. $K \to \pi\ell\nu \;\Rightarrow 0^- \to 0^-$.

Only vector part of current contributes to

$$\langle\pi|\bar{u}_{\mathsf{L}}\gamma_\alpha s_{\mathsf{L}}|K\rangle$$

$$\langle\pi|\bar{u}\gamma_\alpha s|K\rangle = f_+(t)(P+p)_\alpha + f_-(t)(P-p)_\alpha$$

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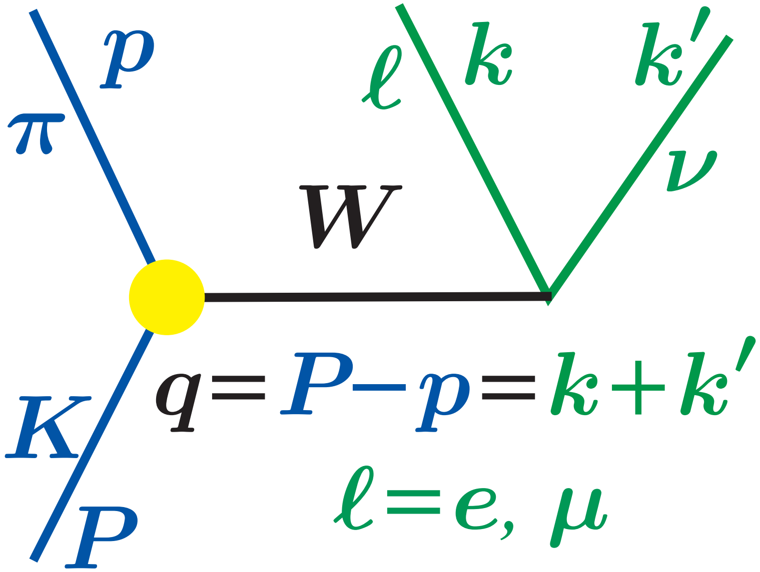
is
tex

Vector Current is protected



$$\langle\pi|J_\alpha|K\rangle = \boxed{f_+(0)} \times \left((P+p)_\alpha\,\tilde f_+(t) + (P-p)_\alpha\left(\tilde f_0(t) - \tilde f_+(t)\right)\frac{\Delta}{t}\right)$$

$$\Delta = M^2 - m^2$$

Form factor because K, π are not point like

Scalar and vector FFs equal at $t{=}0$ (by construction)

Factor out $f_+(0)$. $f_+(0) < 1$ because $K \neq \pi$

$\boxed{f_+(0)} - 1 \ll 1$ (0.04) – small SU(3) breaking

$\tilde f_+(0) = \tilde f_0(0) = 1$

Decay Width

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{768\,\pi^3} S_{\rm EW} \boxed{|V_{us}|^2 f_+(0)^2} I_{K\ell}$$

192

128

$$\times \left(1 + \delta_K^{\rm SU(2)} + \delta_{K\ell}^{\rm EM}\right)$$

$C_K^2 = 1(1/2)$ for $K^0(K^\pm)$; $S_{\rm EW} = 1.0232(3)$, EW corr, Sirlin

$I_{K\ell}$ phase space integral

Define

$f_+(0)$ as

$f_+^{K^0\to\pi^\pm}(0)$

	$\delta_K^{SU(2)}(\%)$	$\delta_{K\ell}^{\rm EM}(\%)$
K_{e3}^0	0	+0.57(15)
K_{e3}^+	2.36(22)	+0.08(15)
$K_{\mu3}^0$	0	+0.80(15)
$K_{\mu3}^+$	2.36(22)	+0.05(15)

Phase space integral, K_{e3}

$$\rho(E_e,\ E_\nu) \propto \sum_{\text{spins}} |\mathfrak{M}|^2 \propto G^2\, C_K^2\, M^4 \left[\frac{E_e}{M}\,\frac{E_\nu}{M} + \frac{\vec{k}\cdot\vec{k}'}{M^2}\right]$$

$$I_{K\ell} \propto \iint \rho(E_e\, E_\nu)\, \mathrm{d}E_e\, \mathrm{d}E_\nu$$

$$\Gamma = \frac{G^2\, C_K^2\, M_K^5}{768\,\pi^3} \underbrace{\int_{zm}^{zM} \mathrm{d}z\, f(t)^2 \int_{xm(z)}^{xM(z)} 24\,((z+x-1)(1-x)-\alpha)\,\mathrm{d}x}_{I_{K\ell}}$$

With 768 in the denominator, $f(t)=1$, all final state masses zero:

$$I_{K\ell} = 1.0$$

768 corresponds to 192 in muon decay rate. $I_{K\ell}$ is dimensionless.

$$x = \frac{2E_e}{M},\ \ y = \frac{2E_\nu}{M},\ \ z = \frac{2E_\pi}{M},\ \ \alpha = \frac{m}{M}$$

End of introduction

this is tex

DAΦNE

An e^+e^- collider operated (mostly) at $W = M_\phi$

$$e^+e^- \to \phi \to \begin{cases} K_S + K_L & 34.0\% \quad \text{tagged } K_S, K_L \text{beams} \\ K^+ + K^- & 49.3\% \quad \text{tagged } K_S, K_L \text{beams} \end{cases}$$

⇒ Tagged, monochromatic, pure K_S, K_L, K^+, K^- beams

$$\text{BR}(K_S \to \pi\ell\nu) = (7.04 + 4.69) \times 10^{-4} \quad \text{"difficult"}$$

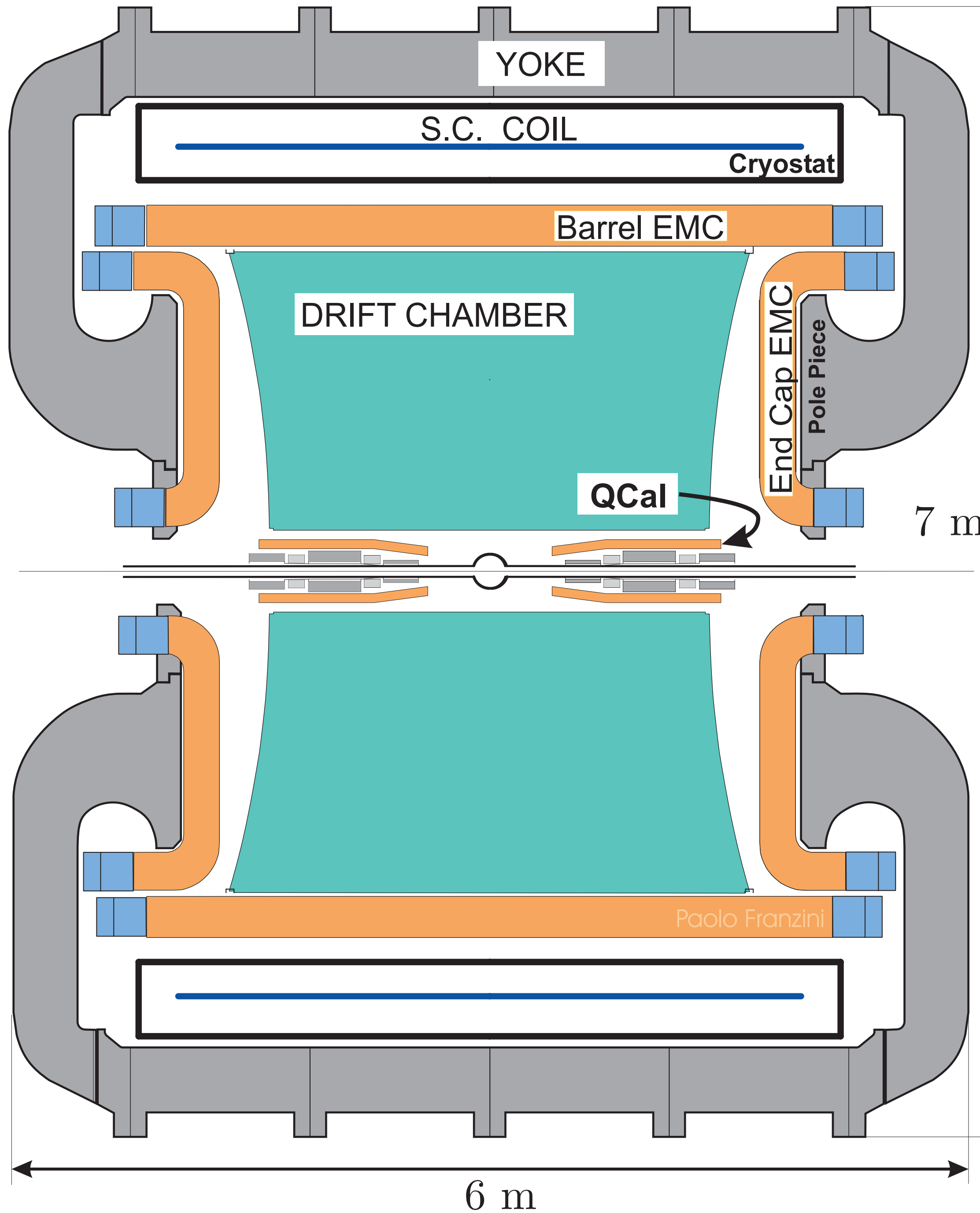
$$\text{BR}(K^\pm \to \pi\ell\nu) = (4.98 + 3.32) \times 10^{-2} \quad \text{"so so"}$$

$$\text{BR}(K_L \to \pi\ell\nu) = (\underset{e}{4.06} + \underset{\mu}{2.71}) \times 10^{-1} \quad \text{"best"}$$

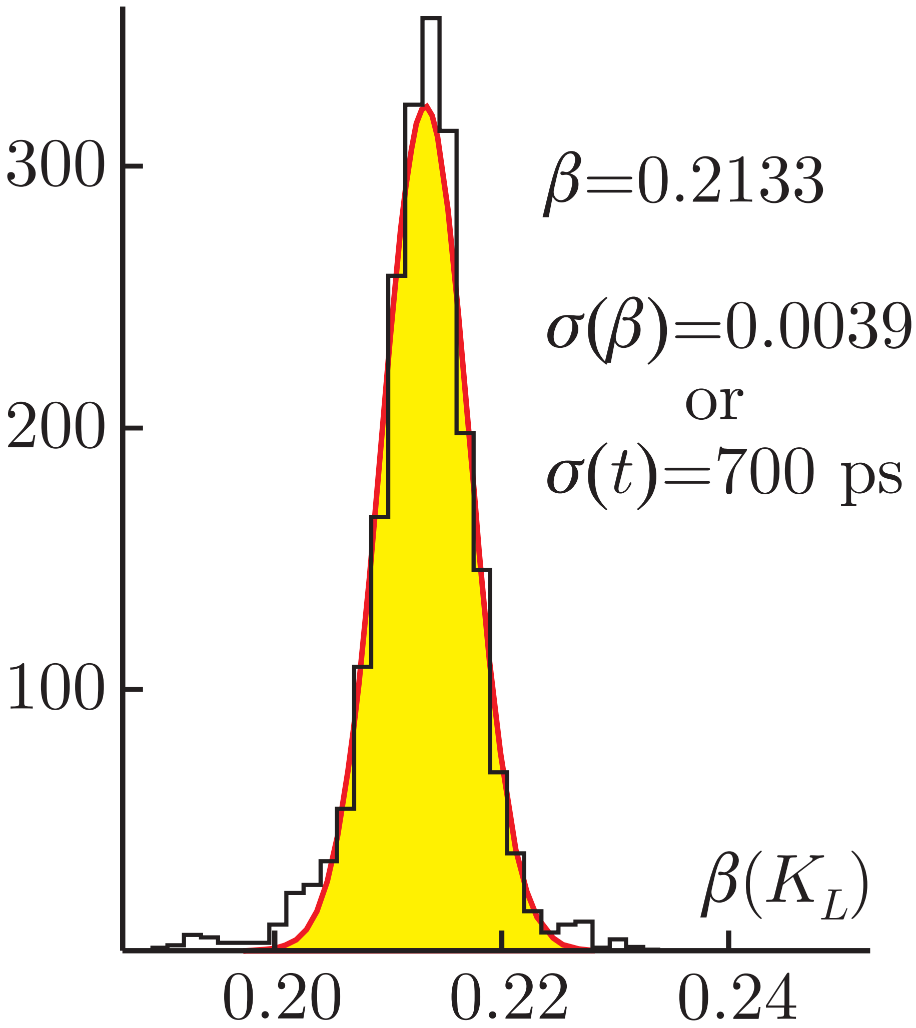
KLOE: measure all BR, lifetimes,

FF parameters ⇛ $\Gamma(K_i \to f)$

KLOE


YOKE
S.C. COIL
Cryostat
Barrel EMC
DRIFT CHAMBER
End Cap EMC
Pole Piece
QCal
7 m
Paolo Franzini
6 m

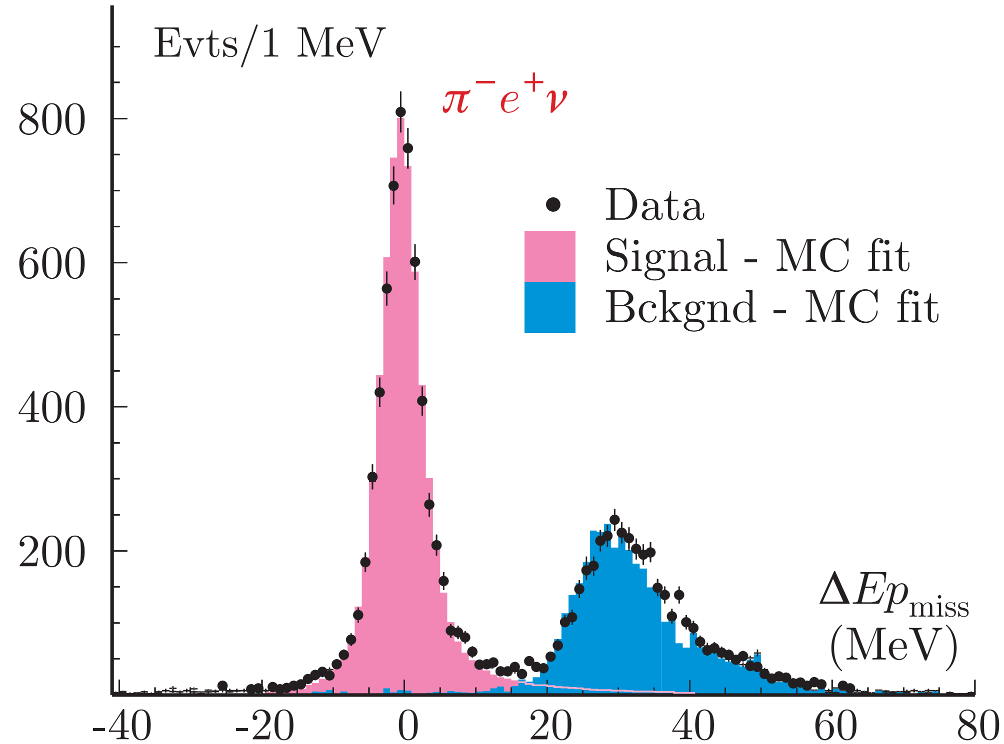
The K_S beam

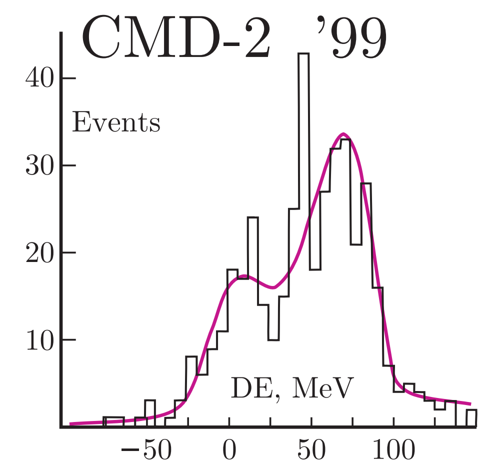


δW(DAΦNE)=1 MeV
gives $\delta\beta$=0.004

∼50% of the K_L-mesons reach the calorimeter where most interact. Since $\beta(K^0)\sim0.2$, we identify kaon interactions by TOF.

$K_S \to \pi e \nu$, 2005





$\sim$13,000 signal events

BR($K_S \to \pi e \nu$)=$(7.046 \pm 0.091) \times 10^{-4}$

$|V_{us}|$ to 0.7%

K_L decays

$$\mathrm{BR}(K_{e3}) + \mathrm{BR}(K_{\mu 3}) + \mathrm{BR}(K \to 3\pi^0) + \mathrm{BR}(K \to \pi^{+-0}) = 1 - \Delta$$

$$\text{Solve for :} \begin{cases} \text{4 BRs} \\ K_L \text{ lifetime} \end{cases}$$

$$\mathrm{BR}(K_{Le3}) = 0.4009 \pm 0.0015$$

$$\mathrm{BR}(K_{L\mu 3}) = 0.2699 \pm 0.0014$$

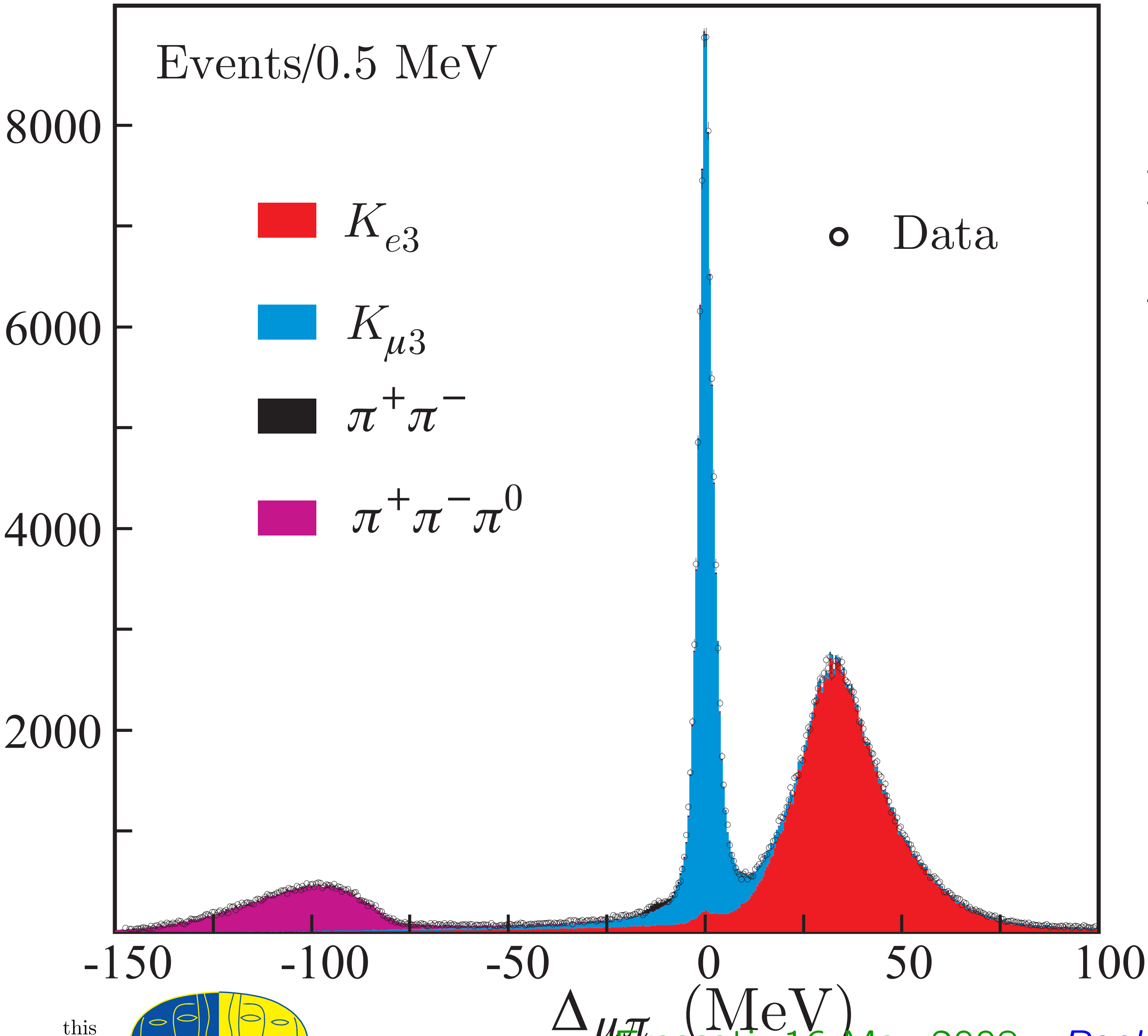
$$\mathrm{BR}(K_L \to 3\pi^0) = 0.1996 \pm 0.0020$$

$$\mathrm{BR}(K_L \to {}^{+-0}) = 0.1261 \pm 0.0011$$

$$\tau(K_L) = 50.72 \pm 0.37 \text{ ns}$$

There are of course correlations...

$K_L \to$two track events



For $K_L \to \pi^{\pm}\ell^{\mp}\nu$:

$E_{\rm miss} \neq 0$

$\mathbf{p}_{\rm miss} \neq 0$

$m_\nu = 0 \to$

$\Delta = E_{\rm miss} - |\mathbf{p}_{\rm miss}| = 0$

$\Delta_{\mu\pi}$=smallest of

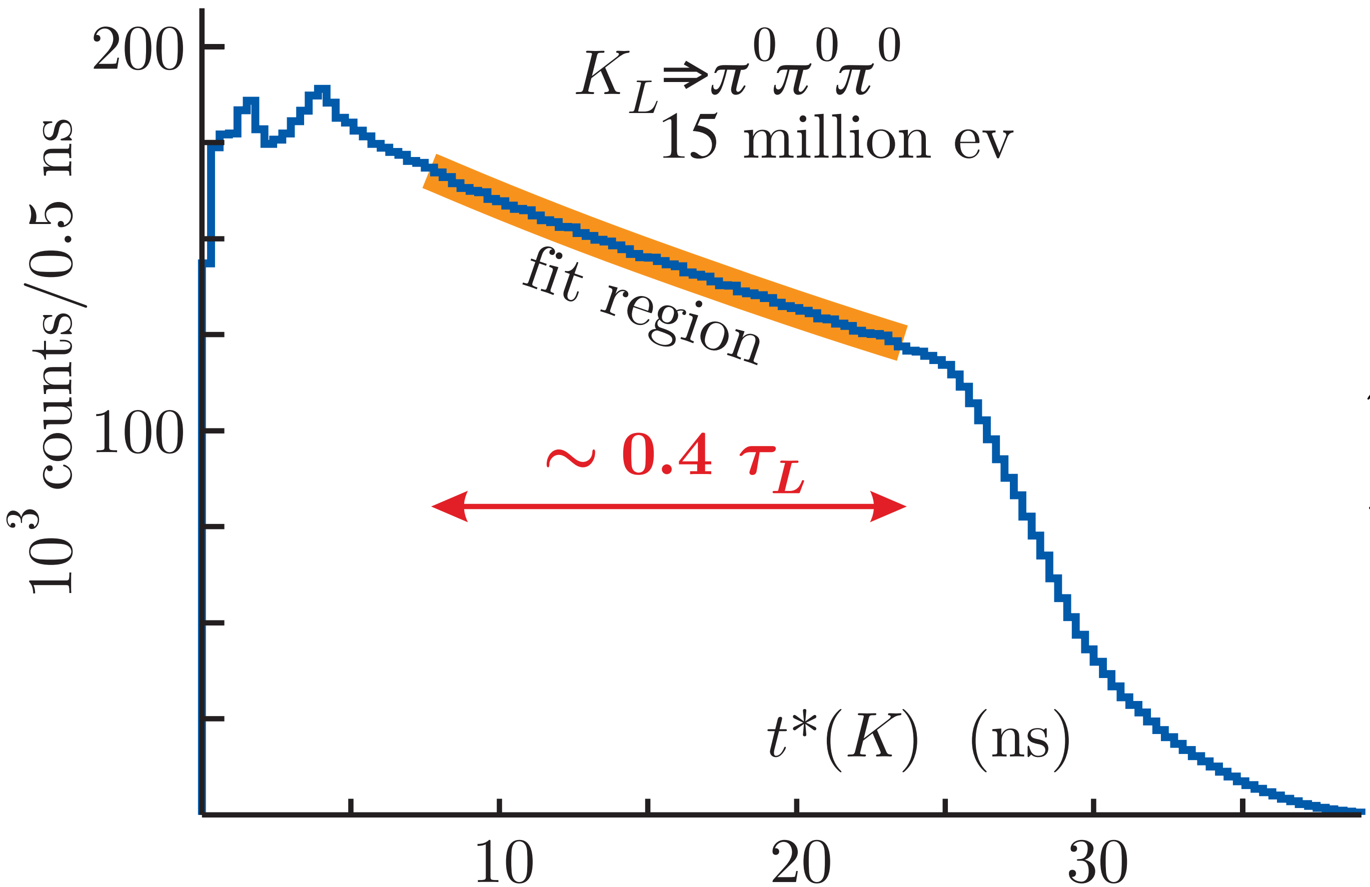
$\Delta_{\mu^+\pi^-}$, $\Delta_{\pi^+\mu^-}$

Fit to MC shapes

Count, BRs

14 sub-samples

Time dependence of $K_L \to \pi^0\pi^0\pi^0$



$\tau(K_L) =$

50.92 ± 0.30 ns

All KLOE K_L results

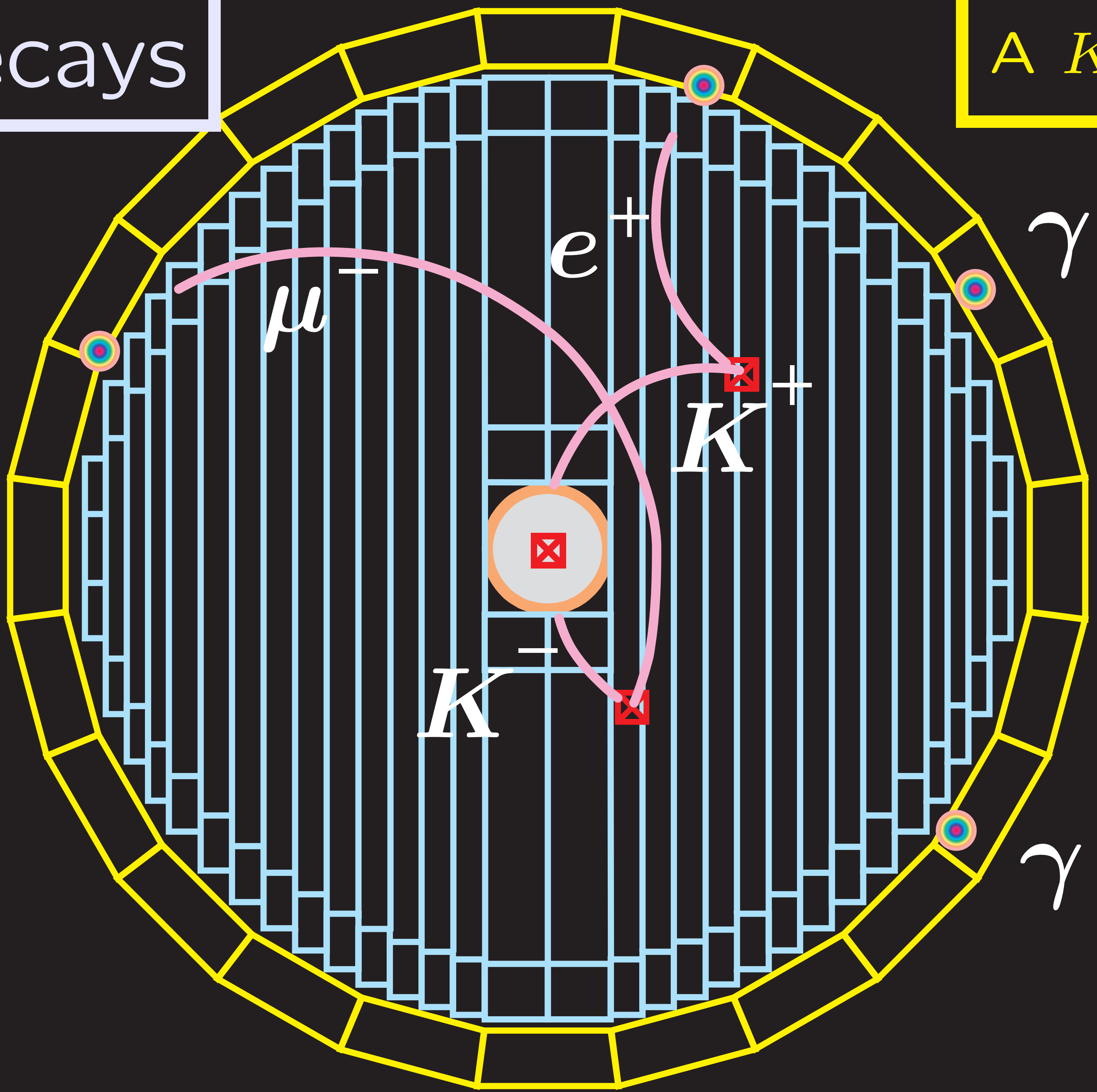
Param.	Value	Correlation coefficients						
BR(K_{Le3})	0.4008(15)							
BR($K_{L\mu3}$)	0.2699(14)	-0.31						
BR($3\pi^0$)	0.1996(20)	-0.55	-0.41					
BR($^{+-0}$)	0.1261(11)	-0.01	-0.14	-0.47				
BR($\pi^+\pi^-$)	$1.96(2) \times 10^{-3}$	-0.15	0.50	-0.21	-0.07			
BR($\pi^0\pi^0$)	$8.49(9) \times 10^{-4}$	-0.15	0.48	-0.20	-0.07	0.97		
BR($\gamma\gamma$)	$5.57(8) \times 10^{-4}$	-0.37	-0.28	0.68	-0.32	-0.14	-0.13	
τ_L	50.84(23) ns	0.16	0.22	-0.14	-0.26	0.11	0.11	-0.09

We can do it!

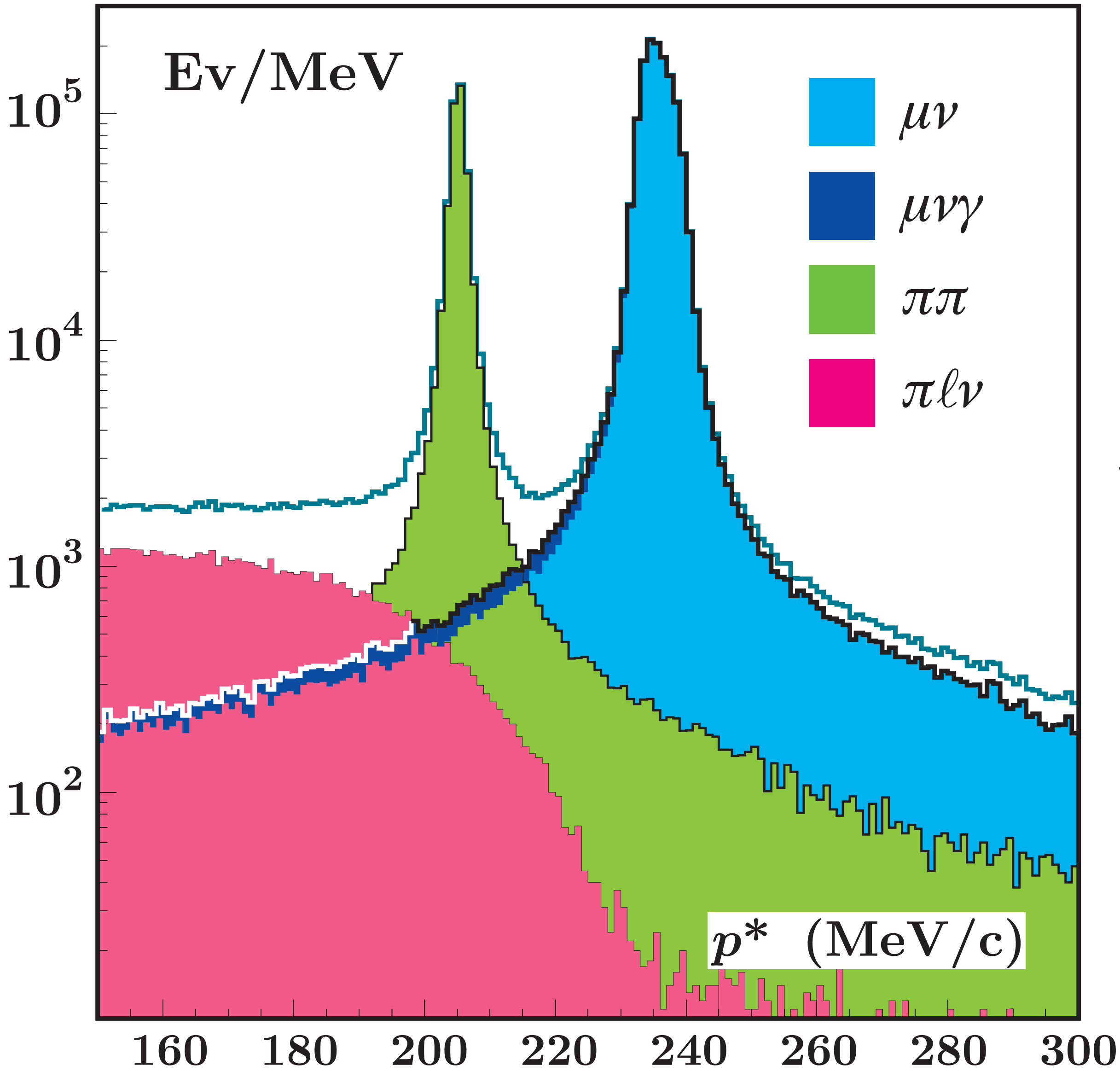
When PDG does it, combining inconsistent results from different experiments it can be a disaster!!!

$K^{\pm}$ decays

A $K^{\pm}_{e3}$ decay



Tagging decays and $K^{\pm} \to \mu\nu$ decays



Compute CM momentum using $m(\pi)$. The $\mu\nu$ decay peak is distorted but quite recognizable for tagging.

We also get

BR($K \to \mu\nu(\gamma)$) and

BR($K \to \pi\pi^0(\gamma)$)

Note the radiative tail!

BR($K^+ \to \mu^+\nu(\gamma)$) = 0.6366±0.0009±0.0015.

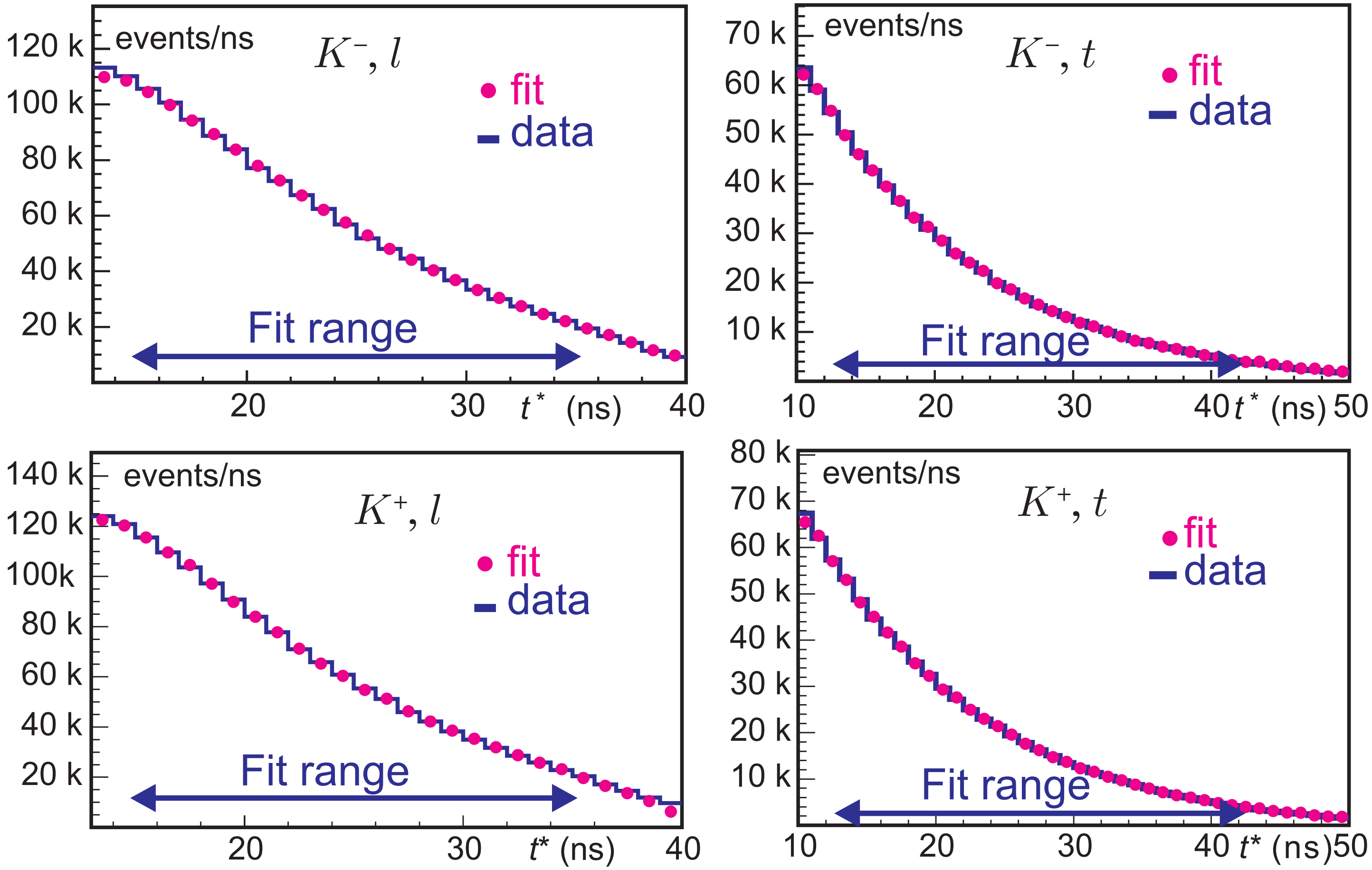
All KLOE $K^{\pm}$ results

Constrained fit:

$$\text{BR}(K^{\pm} \to \mu^{\pm}\nu) = 0.63766 \pm 0.0012$$
$$\text{BR}(K^{\pm} \to \pi^{\pm}\pi^{0}) = 0.2071 \pm 0.0009$$
$$\text{BR}(K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = 0.0553 \pm 0.0009 \text{ (input PDG '04)}$$
$$\text{BR}(K^{\pm} \to e^{\pm}\pi^{0}\nu) = 0.0498 \pm 0.0005$$
$$\text{BR}(K^{\pm} \to \mu^{\pm}\pi^{0}\nu) = 0.0324 \pm 0.0004$$
$$\text{BR}(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}) = 0.01765 \pm 0.00025$$
$$\tau \text{ (ns)} = 12.344 \pm 0.029$$

$\chi^2/\text{dof} = 0.59/1$, CL=44%

KLOE $\tau(K^{\pm})$



4 measurement of τ –

Consistent –

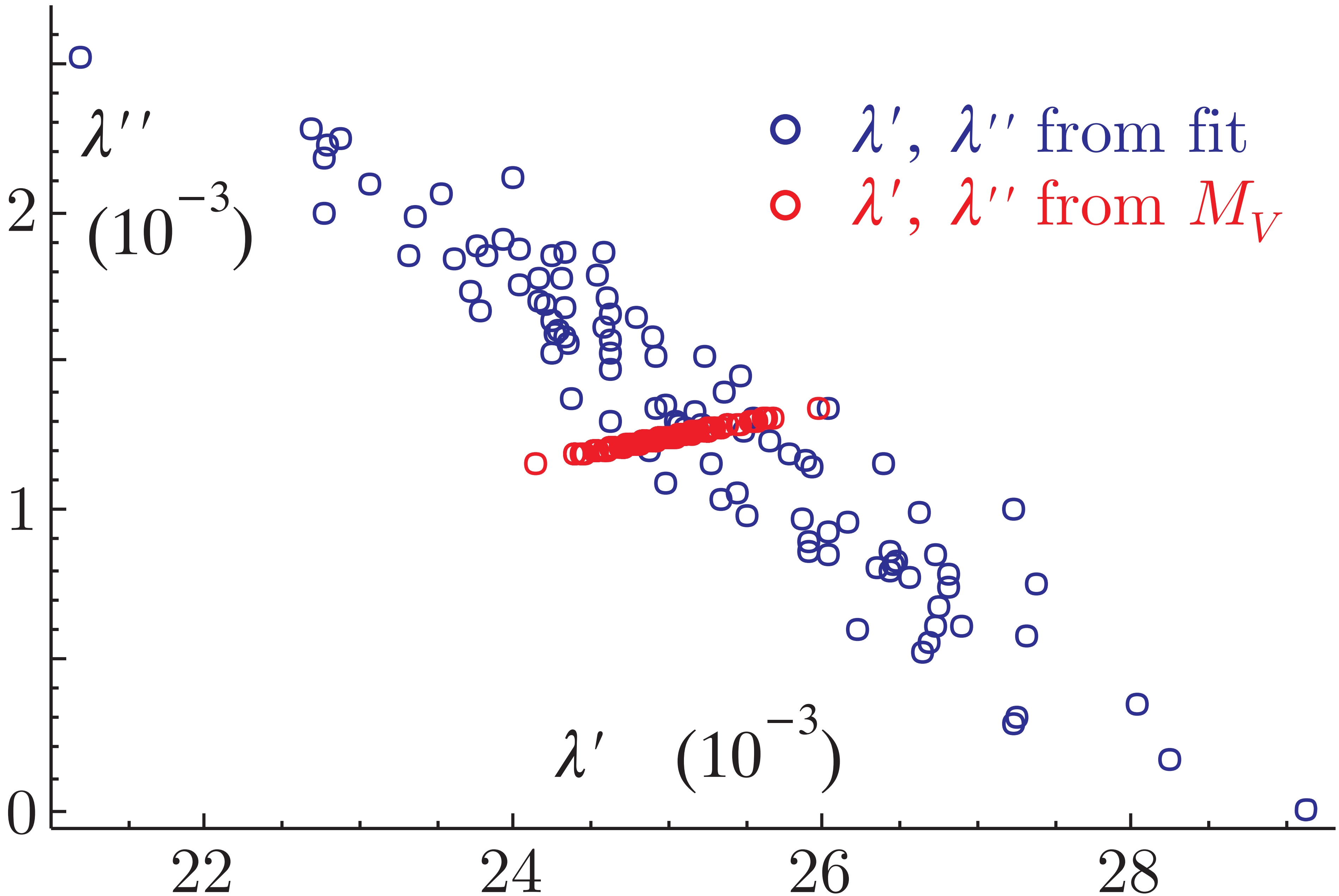
Can average

Use only our result

$$\tau(K^{\pm}) = 12.347 \pm 0.030, \quad 0.25\%$$

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

FF: quadratic, pole, disp.



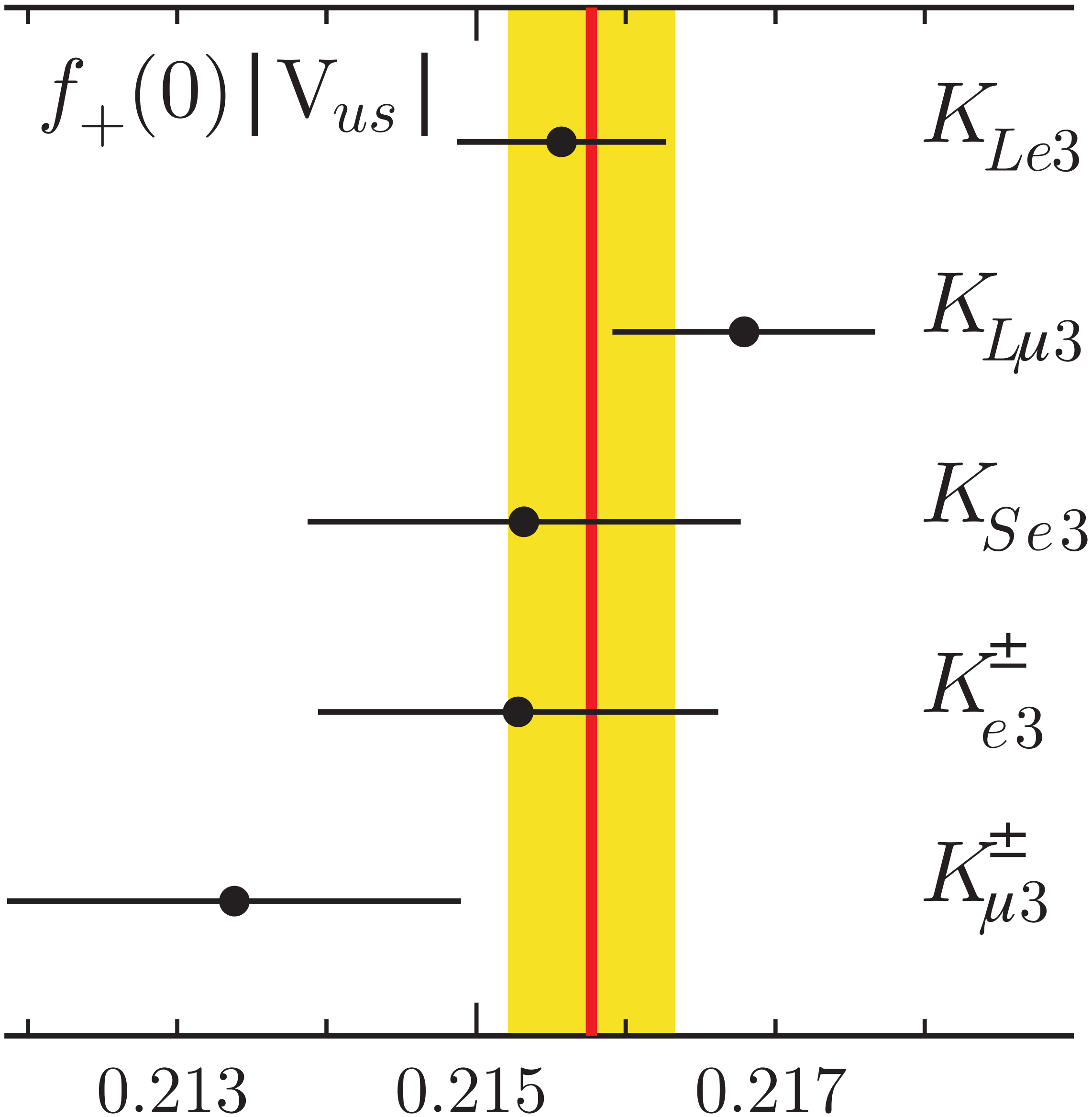
$f(0)|V_{us}|$

We are almost there. Let us begin with $f(0)|V_{us}|$. $f(0)$, by definition, belongs to $K^0 \to \pi^\pm$. If we know the I-spin corrections and the long distance EM corrections all decays must give the same value for $f(0)|V_{us}|$.

This is in fact a check of the $\delta\ldots$ estimates and of the experiment. We find

Channel	$f(0)\vert V_{us}\vert$	Correlation coefficients			
K_{Le3}	0.2155(7)				
$K_{L\mu 3}$	0.2167(9)	0.28			
K_{Se3}	0.2153(14)	0.16	0.08		
$K^\pm_{e3}$	0.2152(13)	0.07	0.01	0.04	
$K^\pm_{\mu 3}$	0.2132(15)	0.01	0.18	0.01	0.67

$f(0)|V_{us}|$



$\langle\rangle = -0.2157 \pm 0.0006$

χ^2/ndf =7.0/4
(CL=13%)

$SU(2)$ corrections are verified to 1.1 σ.

Lepton Universality

From:

$$R_{\mu e} \equiv \frac{[f(0)V_{us}]^2_{\mu 3}}{[f(0)V_{us}]^2_{e3}} = \frac{\Gamma_{\mu 3}}{\Gamma_{e3}} \frac{I_{e3}\,(1+\delta_e)^2}{I_{\mu 3}\,(1+\delta_\mu)^2}$$

$\Rrightarrow$

$$R_{\mu e} = \frac{g_e^2}{g_\mu^2} = 1.000 \pm 0.008$$

Competitive with pure leptonic processes, τ decays

$(R_{\mu e})_\tau = 1.000 \pm 0.004$

Also with $\pi \to \ell\nu$ results

$(R_{\mu e})_\pi = 1.0042 \pm 0.0033$

$f(0)$ and $|V_{us}|$

The accepted value was $f(0) = 0.961 \pm 0.008$, Roos & Leutwyler, 1984. Recently Lattice results have become convincing. We take $f(0) = 0.9644 \pm 0.0049$, RBC and UKQCD, 2007. Then

$$|V_{us}| = 0.2237 \pm 0.0013$$

$$|V_{us}|^2 = 0.05002 \pm 0.00057$$

$0^+ \rightarrow 0^+$ and $|V_{ud}|^2$

$$|V_{ud}|^2 = 0.9490 \pm 0.0005$$

$$1 - |V_{us}|^2 - |V_{ud}|^2 = 0.0009 \pm 0.0008 \quad (\sim 1.1\sigma)$$

But we can do better

$K \to \mu\nu/\pi \to \mu\nu$

$$\frac{\Gamma(K_{\mu 2(\gamma)})}{\Gamma(\pi_{\mu 2(\gamma)})} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K \left(1 - m_\mu^2/m_K^2\right)^2}{m_\pi \left(1 - m_\mu^2/m_\pi^2\right)^2} \times (0.9930 \pm 0.0035)$$

Cancellations in f_K^2/f_π^2. From lattice

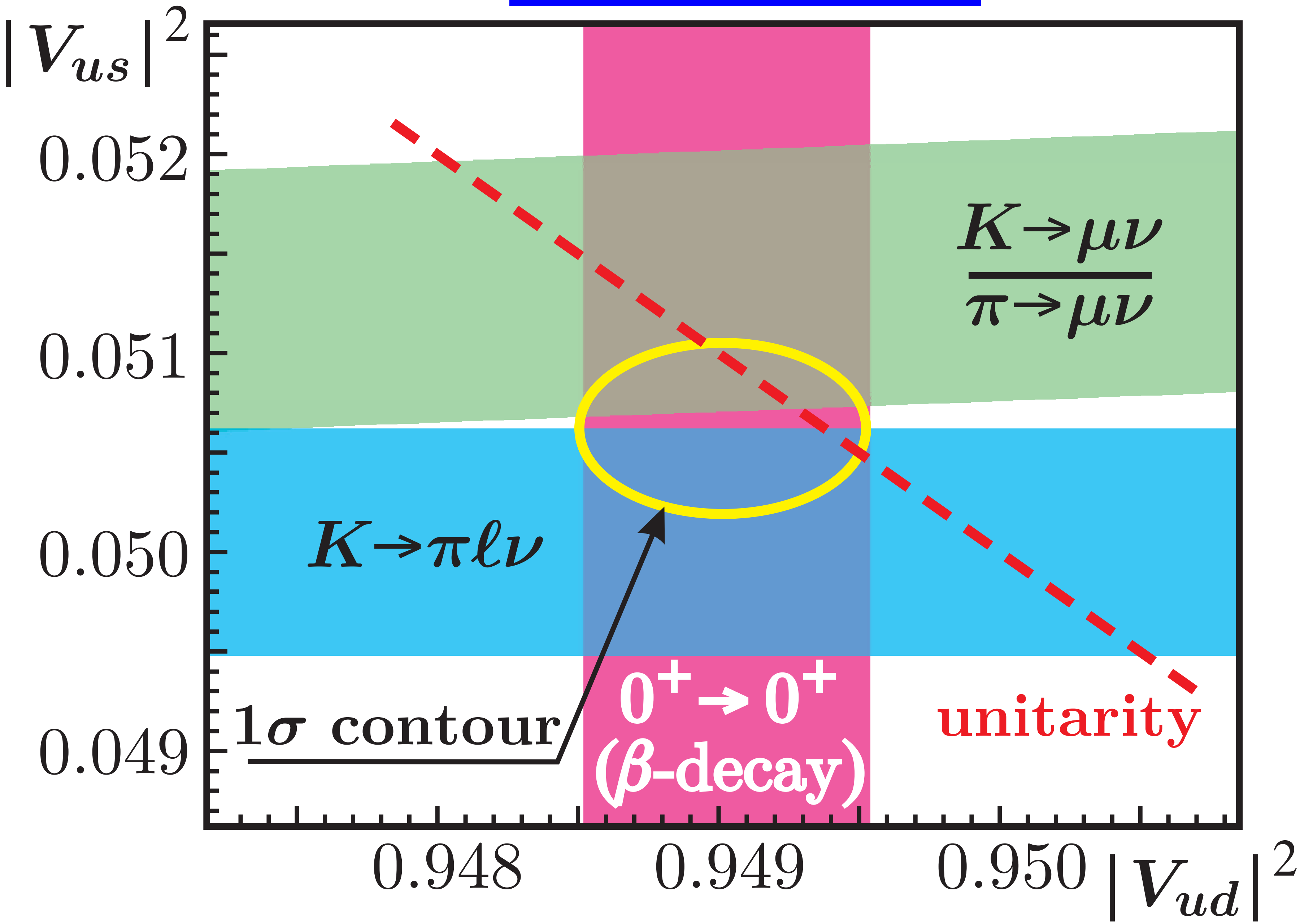
Cancellations in rad. cor. From Marciano.

KLOE $\Rrightarrow$ $|V_{us}/V_{ud} \times f_K/f_\pi|^2 = 0.0765 \pm 0.0005$

HPQCD/UKQCD $\Rrightarrow$ f_K/f_π=1.189±0.007

$$|V_{us}/V_{ud}|^2 = 0.0541 \pm 0.0007$$

CKM Unitarity



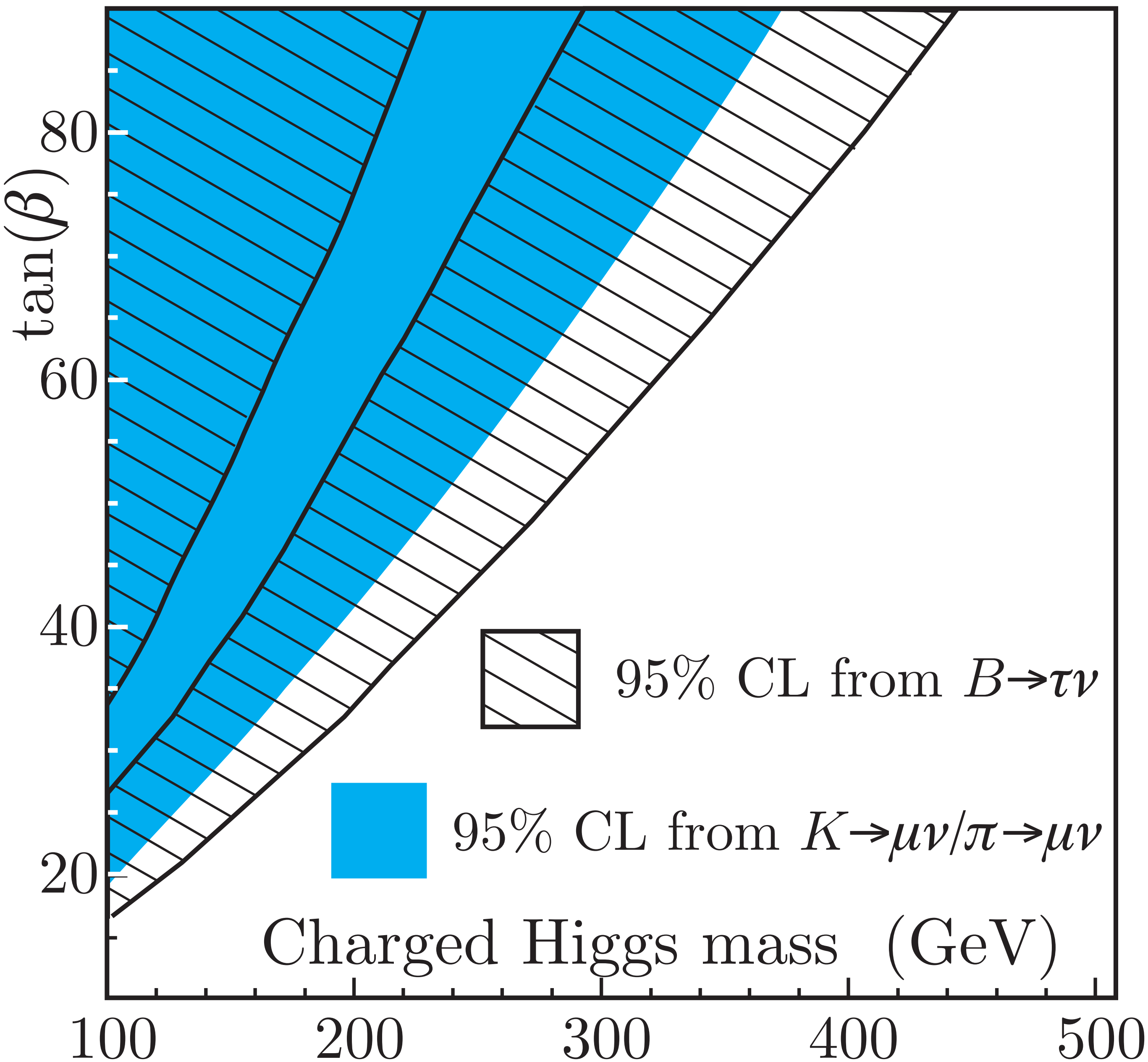
From the fit

$$1 - |V_{us}|^2 - |V_{ud}|^2 = 0.0004 \pm 0.0007 \quad (\sim 0.6\sigma)$$
$$|V_{us}| = 0.2249 \pm 0.0010$$
$$|V_{ud}| = 0.97417 \pm 0.00026$$

Fit with unitarity as constraint

$$|V_{us}| = 0.2253 \pm 0.0007$$
$$|V_{ud}| = \sqrt{1 - |V_{us}|^2} = 0.97429 \pm 0.00017.$$
$$\theta_C = 13.02^\circ \pm 0.06^\circ$$

$\tan\beta - M(\text{Higgs}^{\pm})$



$$R_{\ell 23} = \left| \frac{V_{us}(K_{\mu 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\mu 2})} \right| = 1$$

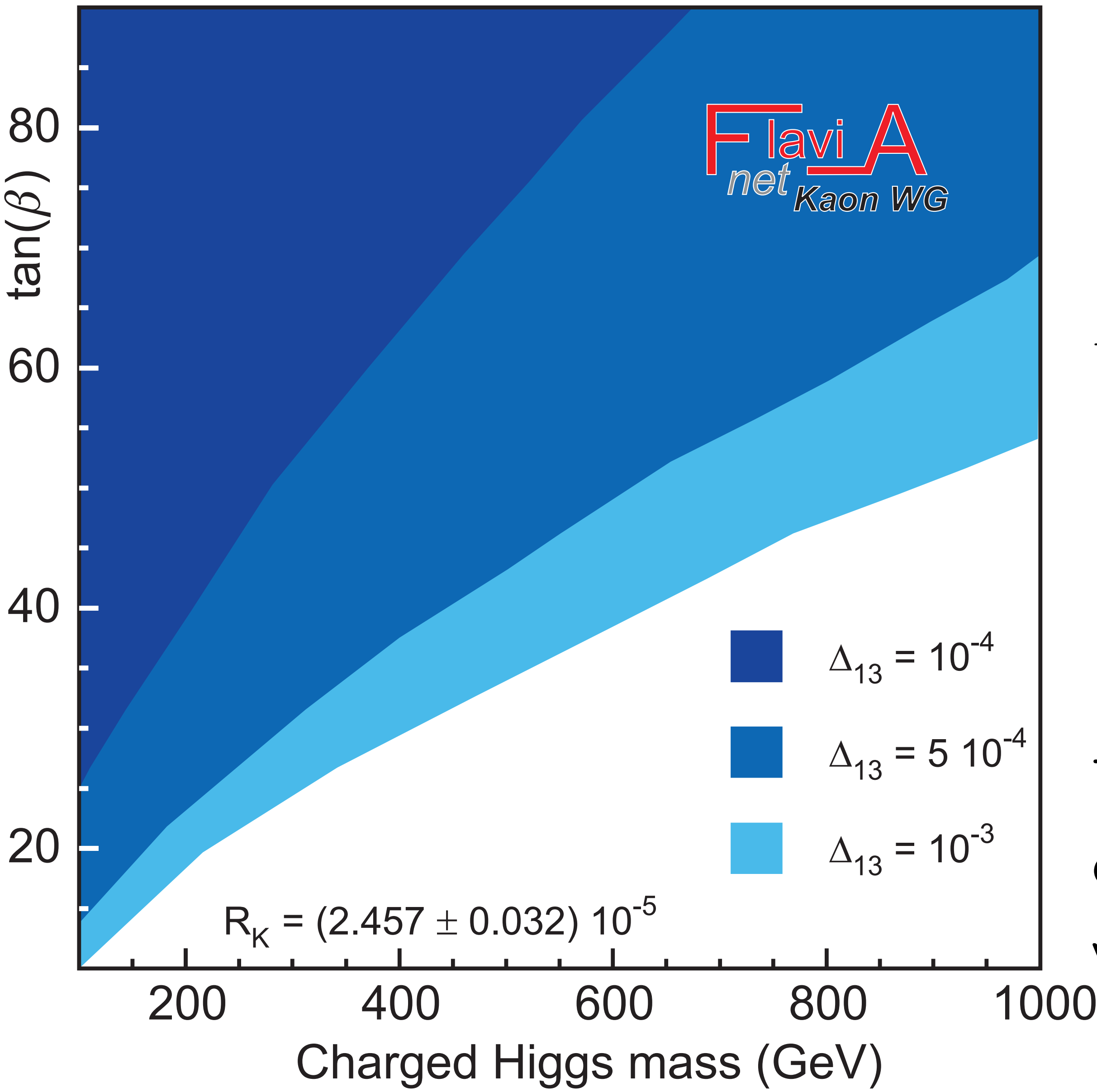
in the SM. With charged Higgs exchange $R_{\ell 23}=$

$$\left| 1 - \frac{m^2_{K^+}}{m^2_{H^+}} \left(1 - \frac{m^2_{\pi^+}}{m^2_{K^+}} \right) \times \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta} \right|$$

$$\epsilon_0 \approx 1/(16\pi^2)$$

this is tex

$K^{\pm} \to e^{\pm}\nu$



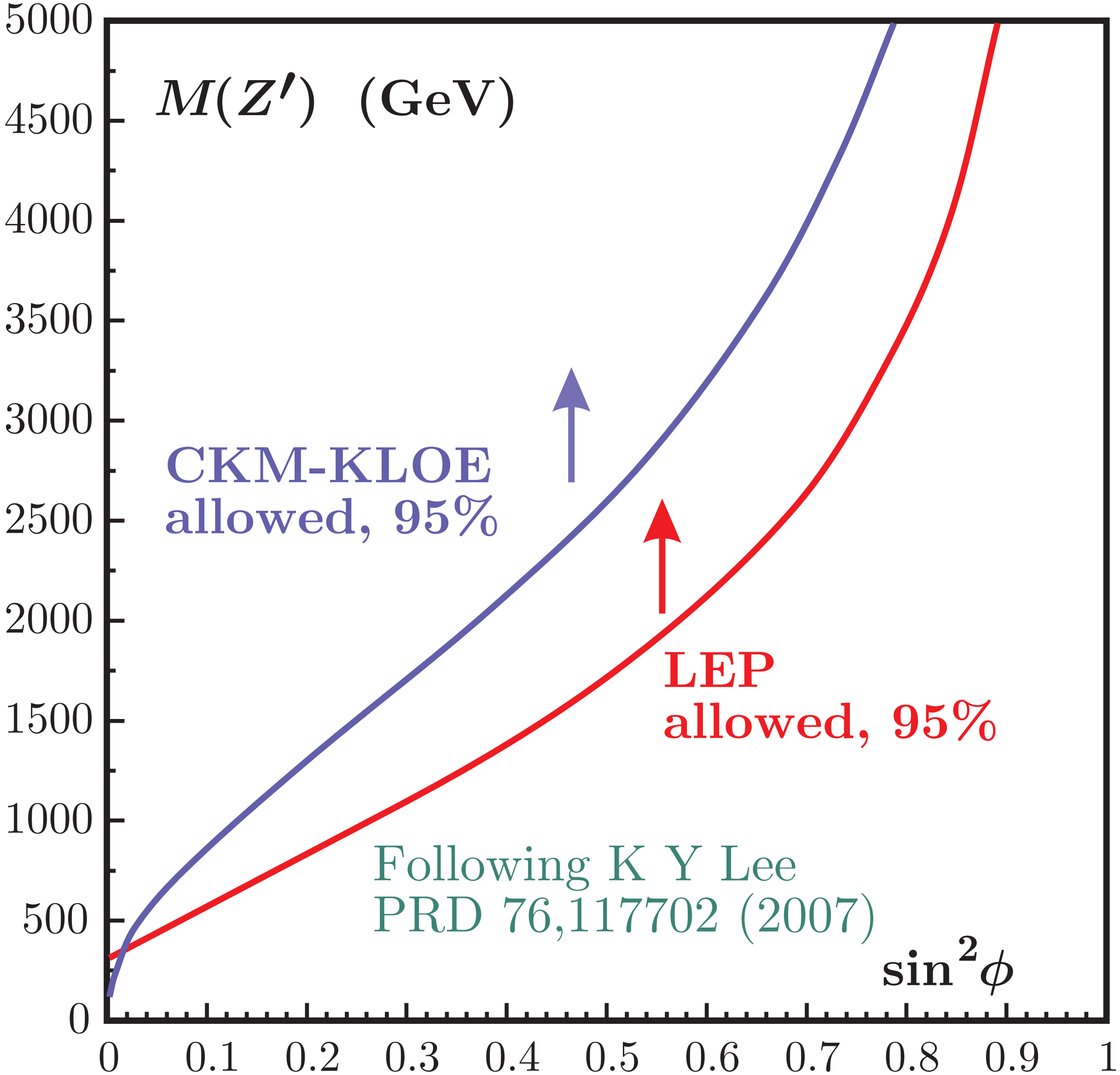
$$R_K = \frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)}$$

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

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

The lepton flavor violating coupling Δ_{13} could reach values of $\mathcal{O}(10^{-3})$

Z'



Gauge group is
$SU(2)_L \times SU(2)_L \times U(1)_Y$.
$SU(2)_L$ for light quarks
(u, d, c, s)
$SU(2)_H$ for heavy (t, b)
2 Z bosons
2 mixing angle

Conclusions

Unitarity is verified at the 0.1% level

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

Muons, electrons and quarks

carry the same weak charge to better than 0.5%

Kaon properties limit the parameter space

for some new physics models