KAON '07, Frascati, May 21 2007

Precision tests of the Standard Model with Kl3 decays

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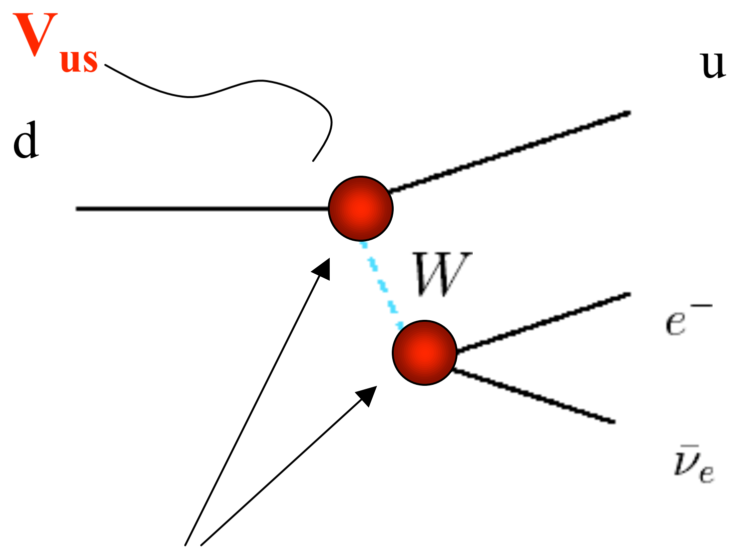
What are we after:



- Probe nature of weak vertices

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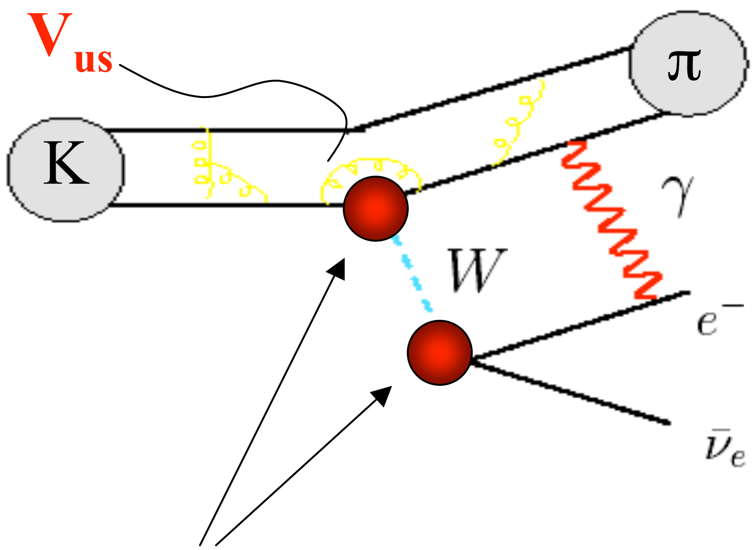

- Probe nature of weak vertices through (despite?) hadronic decay

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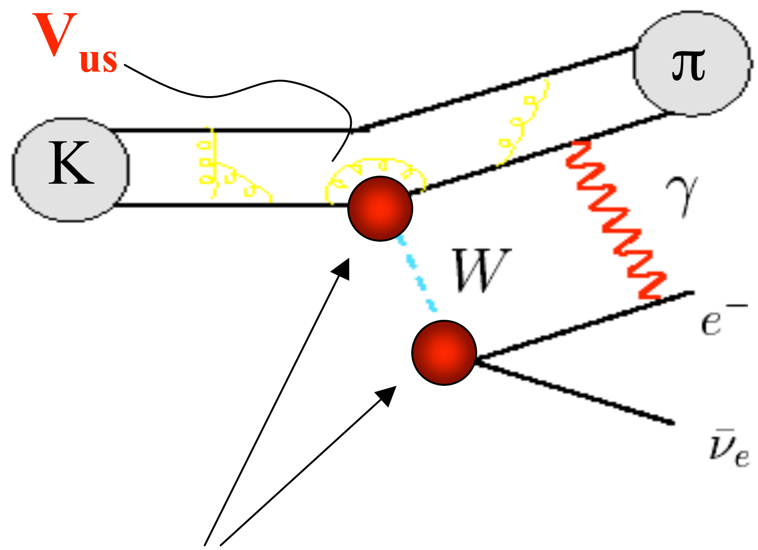

- Probe nature of weak vertices through (despite?) hadronic decay
- Th. tools: ChPT, matching techniques ($1/N_C$, …), Lattice QCD
- I will discuss Kl3 decays as probes of: (1) lepton universality; (2) V_{us} and CKM unitarity; (3) ratios of light quark masses.

Outline

- Kl3 master formula and overview of current status in ChPT

- Precision SM tests with Kl3 decays:

  - EM corr. $\xrightarrow{+\text{ EXPT}}$ lepton universality
  - (EM +) IB corr. $\rightarrow$ quark mass ratios
  - (EM + IB +) SU(3) corr. $\rightarrow$ V_{us} and CKM unitarity

- Conclusions

Kl3 master formula and overview of current status in ChPT

$K \to \pi \ell \nu$ master formula

$$K = \{K^+, K^0\} \quad \ell = \{e, \mu\}$$

$$\Gamma_{K_{\ell 3[\gamma]}} = C_K^2 \frac{G_\mu^2 S_{\mathrm{ew}} M_K^5}{192\pi^3} \cdot |V_{us}|^2 \, |f_+^{K^0\pi^-}(0)|^2 \cdot I^{K\ell}(\lambda_i) \cdot [1 + 2\,\Delta_{SU(2)}^K + 2\,\Delta_{\mathrm{EM}}^{K\ell}]$$

$K \to \pi \ell \nu$ master formula

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Short distance electroweak correction:

Long distance electromagnetic correction

$$S_{ew} = 1 + \frac{2\alpha}{\pi}\left(1 + \frac{\alpha_s}{4\pi}\right) \log \frac{M_Z}{M_\rho} + O\left(\frac{\alpha\alpha_s}{\pi^2}\right) = 1.0232$$

Sirlin '82

$K \to \pi\, \ell\, \nu$ master formula

$$K = \{K^+, K^0\} \quad \ell = \{e, \mu\}$$

$$\Gamma_{K_{\ell 3[\gamma]}} = C_K^2 \frac{G_\mu^2\, S_{\mathrm{ew}}\, M_K^5}{192\pi^3} \cdot |V_{us}|^2\, |f_+^{K^0\pi^-}(0)|^2 \cdot I^{K\ell}(\lambda_i) \cdot [1 + 2\,\Delta_{SU(2)}^{K} + 2\,\Delta_{\mathrm{EM}}^{K\ell}]$$

$$t = (p_K - p_\pi)^2$$

$$\langle \pi^-(p_\pi) | \bar{s}\gamma_\mu u | K^0(p_K) \rangle = f_+^{K^0\pi^-}(t)\,(p_K + p_\pi)_\mu + f_-^{K^0\pi^-}(t)\,(p_K - p_\pi)_\mu$$

K → π ℓ ν master formula

$$K = \{K^+, K^0\} \quad \ell = \{e, \mu\}$$

$$\Gamma_{K_{\ell 3[\gamma]}} = C_K^2 \frac{G_\mu^2 \, S_{\mathrm{ew}} \, M_K^5}{192\pi^3} \cdot |V_{us}|^2 \, |f_+^{K^0\pi^-}(0)|^2 \cdot I^{K\ell}(\lambda_i) \cdot [1 + 2\,\Delta_{SU(2)}^K + 2\,\Delta_{\mathrm{EM}}^{K\ell}]$$

$$t = (p_K - p_\pi)^2$$

$$f_{+,0}(t) = f_+(0) \left(1 + \lambda_{+,0} \frac{t}{M_\pi^2} + \lambda''_{+,0} \frac{t^2}{M_\pi^4} + \ldots \right)$$

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

$K \to \pi \ell \nu$ master formula

$$K = \{K^+, K^0\} \quad \ell = \{e, \mu\}$$

$$\Gamma_{K_{\ell 3[\gamma]}} = C_K^2 \frac{G_\mu^2 \, S_{\rm ew} \, M_K^5}{192\pi^3} \cdot |V_{us}|^2 \, |f_+^{K^0\pi^-}(0)|^2 \cdot I^{K\ell}(\lambda_i) \cdot [1 + 2\,\Delta_{SU(2)}^K + 2\,\Delta_{\rm EM}^{K\ell}]$$

$$t = (p_K - p_\pi)^2$$

$$\Delta_{SU(2)}^K \equiv \frac{f_+^{K^+\pi^0}(0)}{f_+^{K^0\pi^-}(0)} - 1$$

$K \rightarrow \pi \ell \nu$ master formula

$$K = \{K^+, K^0\} \quad \ell = \{e, \mu\}$$

$$\Gamma_{K_{\ell 3[\gamma]}} = C_K^2 \frac{G_\mu^2 \, S_{\rm ew} \, M_K^5}{192\pi^3} \cdot |V_{us}|^2 \, |f_+^{K^0\pi^-}(0)|^2 \cdot I^{K\ell}(\lambda_i) \cdot [1 + 2\,\Delta_{SU(2)}^K + 2\,\Delta_{\rm EM}^{K\ell}]$$

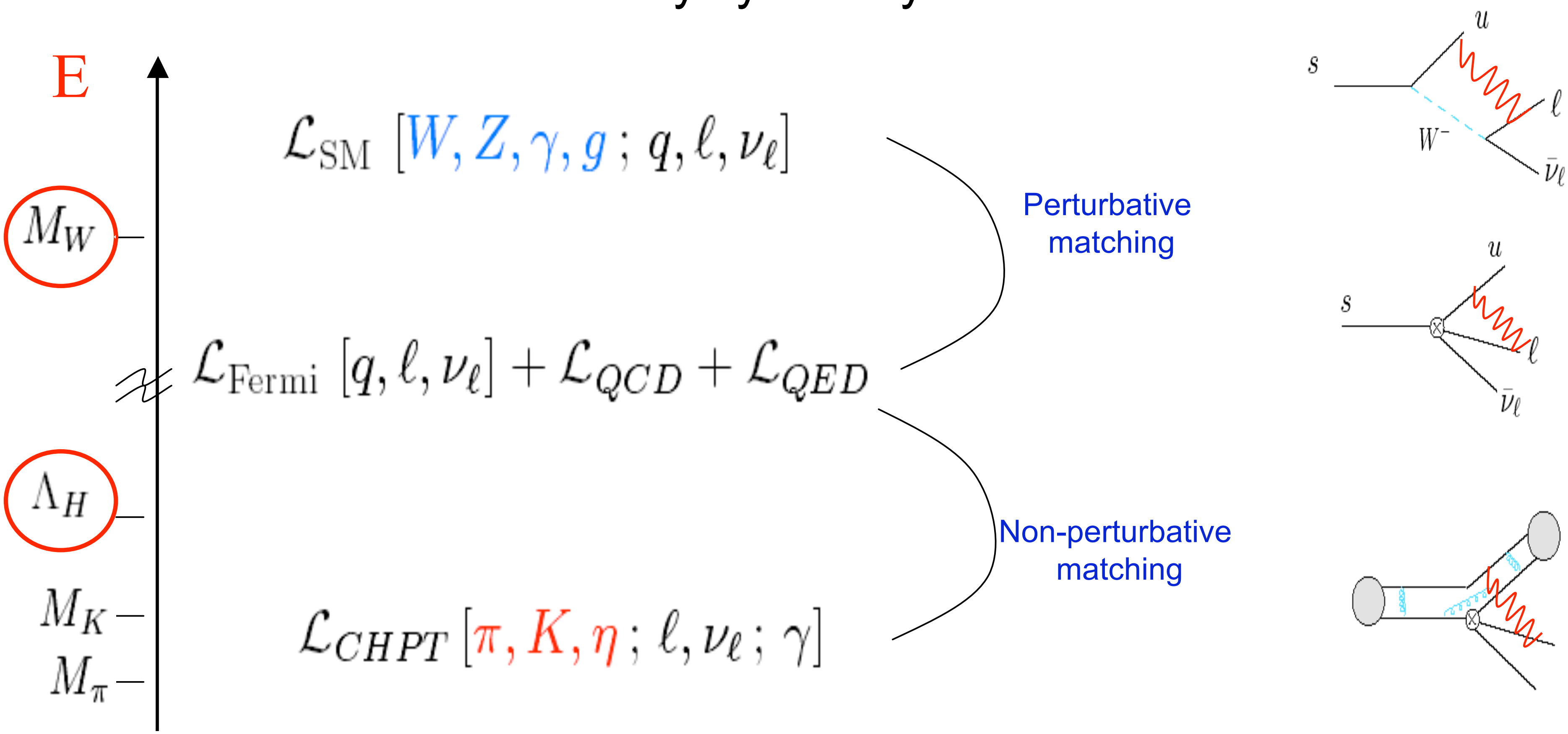
Γ_i & $I^{Kl}(\lambda_i)$ → Accessible by experiment

$S_{\rm ew}$ $\Delta_{SU(2)}^K$ $\Delta_{\rm EM}^{K\ell}$ $f_+^{K^0\pi^-}(0)$ → Accessible by theory

Chiral Perturbation Theory provides the framework to organize the theoretical analysis

Kaons and Chiral Perturbation Theory

- Special role of π,K,η: GB of SχSB → lightest hadrons
- Effective theory: integrate out heavy states → local interactions dictated by symmetry considerations



- In the chiral EFT the amplitudes are systematically expanded in:

momenta [GB nature] , m_{quark} + ew couplings

$$p^2 \sim \frac{p_{ext}^2}{\Lambda_H^2} \approx \frac{m_P^2}{\Lambda_H^2} \qquad m_q \sim m_P^2 \sim p^2 \qquad G_F\,,\quad e$$

$$\Lambda_H \sim 1\,GeV$$

- To a given order: - loops (leading IR singularities)
  - "contact" terms, LECs (UV div.+ finite part, reflecting short distance physics)

Status of $K \to \pi \ell \nu$ in ChPT

- Δ_{EM} to $O(e^2p^2)$
  - K^+_{e3} , K^0_{e3} — VC-Knecht-Neufeld Rupertsberger-Talavera' 01; VC-Neufeld-Pichl '04
  - $K^+_{\mu 3}$, $K^0_{\mu 3}$ — Neufeld, preliminary; Isidori-Morrocco, in progress
  - LECs X_i , K_i — Descotes-Moussallam 2005; Moussallam '97; Bijnens-Prades '97
- $\Delta_{SU(2)}$
  - $O(p^4)$ — Gasser-Leutwyler 1985
  - m_q — VC, explorations; Bijnens et al, in progress
  - $O(p^6)$
- $f_+(0)$
  - $O(p^4)$ — Gasser-Leutwyler 1985
  - $O(p^6)$ — Post-Schilcher 2002; Bijnens-Talavera 2003
  - LECs — VC-Ecker-Eidemuller-Kaiser-Pich-Portoles '05

EM corrections and lepton universality

Δ_{EM} to O(e²p²)

Virtual Photons

O(p²) vertices

X_n, K_n O(e² p²) vertices

- Formal matching in terms of quark currents correlators

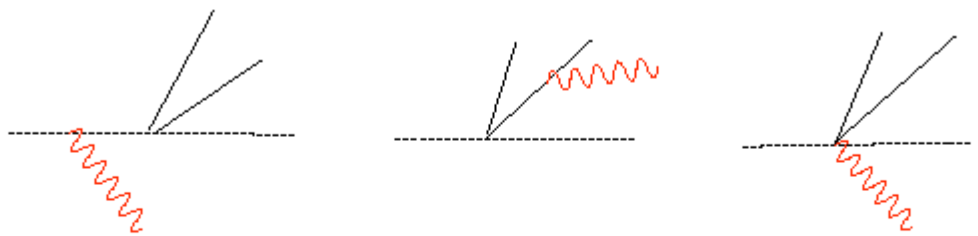
$$\tilde{X}_i = \int_0^\infty dQ^2\, W(Q^2)\, \Pi_{QCD}(Q^2)$$

Moussallam '97
Descotes and Moussallam '05

- Saturate Π_{QCD} (Q^2) with resonance interpolators (~ large N_C)
- Matching result consistent with naïve dimensional analysis:

$10^3\, X_1$: $0 \pm 6.7 \rightarrow -3.7$ $\qquad$ $10^3\, X_6^{phys}$: $16 \pm 8 \rightarrow 10.4$

Real Photons



$O(p^2)$ vertices

- Chiral power counting requires to use $O(p^2)$ amplitudes, equivalent to Low's theorem with constant form-factors
- According to experimental prescription, we quote results of the fully inclusive integration over 4-body phase space

- Results:

	$\Delta^{K\ell}_{\mathrm{EM}}(\%)$	
K^+_{e3}	$+0.08 \pm 0.15$	→ update (include X_i)
K^0_{e3}	$+0.57 \pm 0.15$	→ update (include X_i)
	$+0.65 \pm 0.15$	
$K^+_{\mu 3}$	-0.12 ± 0.15	→ Preliminary, H. Neufeld
$K^0_{\mu 3}$	$+0.80 \pm 0.15$	→ Preliminary, H. Neufeld
	$+0.95 \pm 0.15$	

RED: ChPT to $O(e^2 p^2)$
→ generous uncertainty to account for neglected higher order effects

BLUE: Andre'04 [KTeV]
→ non-constant form factors
→ hard UV cutoff in loops

- Larger effect in K^0 decay, as expected on account of Coulomb FSI

First application: lepton universality

$$\left(\frac{g_\mu}{g_e}\right)^2 = \frac{\Gamma_{K_{\mu 3}}}{\Gamma_{K_{e3}}} \cdot \frac{I^{Ke}}{I^{K\mu}} \left[1 + 2\,\Delta_{\rm EM}^{Ke} - 2\,\Delta_{\rm EM}^{K\mu}\right]$$

1 in the SM

Experimental input from FLAVIAnet
Kl3 working group fit (March 07)
M. Moulson, hep-ex/0703013

- From neutral K decays (more precise than charged modes):

$|g_\mu/g_e| = 1.0024 \pm 0.0027$ → ~ 0.0005 from theory

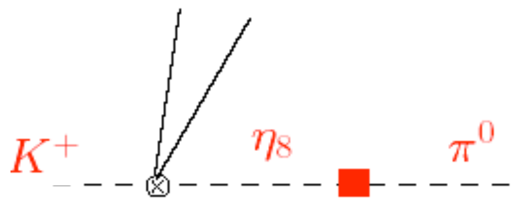
- Approaching the limit from $\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$:

$|g_\mu/g_e| = 1.0017 \pm 0.0015$

SU(2) breaking and ratios of light quark masses

SU(2) breaking in K_{l3} and quark masses

- ChPT to O(p^4) relates $\Delta_{SU(2)}$ to ratios of quark masses

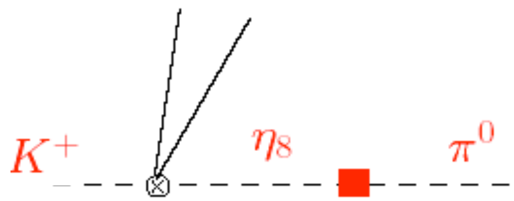


$$\Delta^K_{SU(2)} = \frac{3}{4}\frac{1}{R}$$

$$R = \frac{m_s - \hat{m}}{m_d - m_u} \qquad \hat{m} = \frac{m_u + m_d}{2}$$

SU(2) breaking in K_{l3} and quark masses

- ChPT to $O(p^4)$ relates $\Delta_{SU(2)}$ to ratios of quark masses



+ IB in 1-loop graphs + CT

$$\Delta^K_{SU(2)} = \frac{3}{4}\frac{1}{R}\left(1 + \chi_{p^4} + \frac{4}{3}\frac{M_K^2 - M_\pi^2}{M_\eta^2 - M_\pi^2}\Delta_M + O(m_q^2)\right)$$

$$R = \frac{m_s - \hat{m}}{m_d - m_u}$$

0.219
(calculable chiral corr.)

$$\frac{M_K^2}{M_\pi^2} = \frac{m_s + \hat{m}}{m_u + m_d}\left(1 + \Delta_M + O(m_q^2)\right)$$

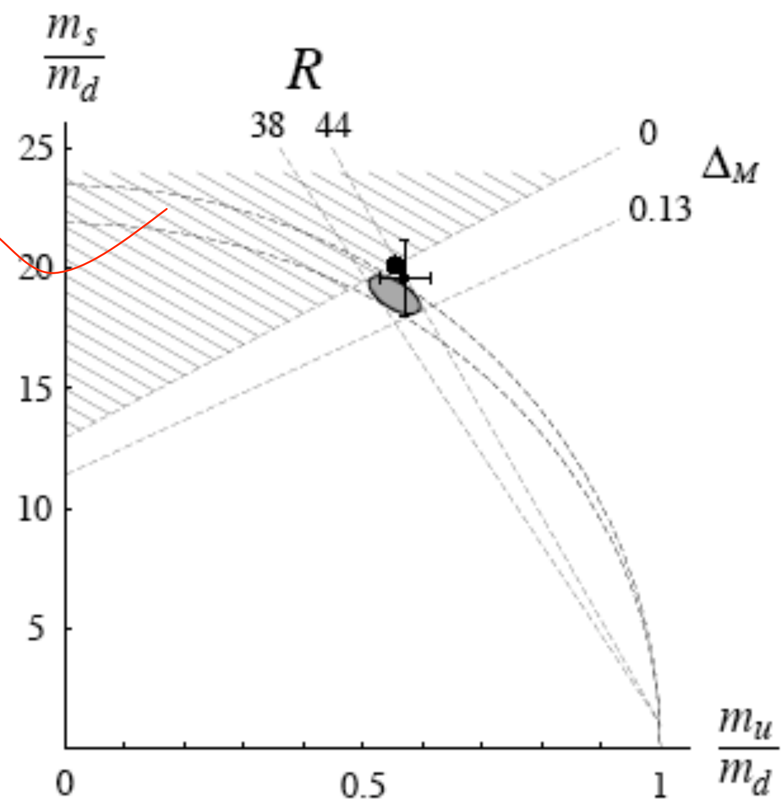
- Standard analysis: input from quark mass ratios → predict $\Delta_{SU(2)}$:

$$\left(\frac{m_u}{m_d}\right)^2 + \frac{1}{Q^2}\left(\frac{m_s}{m_d}\right)^2 = 1$$

$$Q^2 \equiv \frac{M_K^2}{M_\pi^2} \cdot \frac{M_K^2 - M_\pi^2}{M_{K^0}^2 - M_{K^+}^2}$$

or from

$\Gamma(\eta \to \pi^+ \pi^- \pi^0)$



Leutwyler '96

$Q = 22.7 \pm 0.8$

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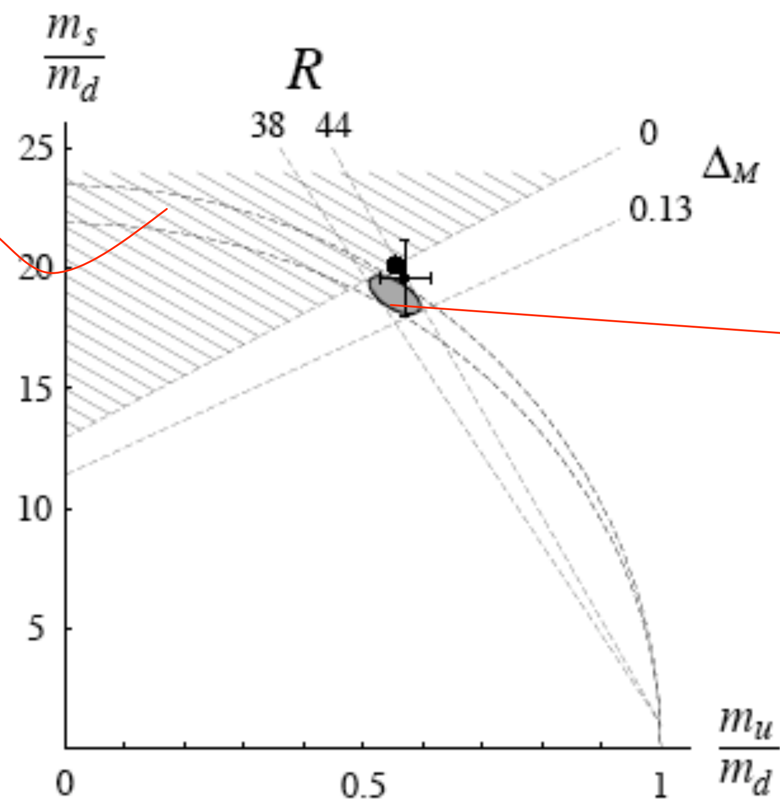


Leutwyler '96

Q = 22.7 ± 0.8
$\Delta_M > 0$
R < 44

↓

$$\Delta^K_{SU(2)} = (1.84 \pm 0.18(R) + 0.52 \pm 0.13(\Delta_M))\% = (2.36 \pm 0.22)\%$$

- On the other hand, data and EM corrections are becoming precise enough to allow for a phenomenological determination of $\Delta_{SU(2)}$
- Focus on K_{e3} modes:

$$\Delta^K_{SU(2)} = \frac{\Gamma_{K^+_{e3}}}{\Gamma_{K^0_{e3}}} \cdot \frac{I^{K^0 e}}{I^{K^+ e}} \left(\frac{M_{K^0}}{M_{K^+}}\right)^5 - \frac{1}{2} - \frac{1}{2} r^{(e)}_{EM}$$

$$r^{(e)}_{EM} = \Delta I^{K^+ e} - \Delta I^{K^0 e} - \frac{\alpha}{2\pi} \log \frac{M_K^2}{M_\pi^2} - 32\,\pi\,\alpha\,X_1 \;=\; -0.98\% \pm 0.15\%$$

$-0.95\,\%$ (from $\Delta I^{K^+ e} - \Delta I^{K^0 e}$) ; $-0.30\,\%$ - (from the log term) ; $+0.27\,\%$ (from $-32\pi\alpha X_1$)

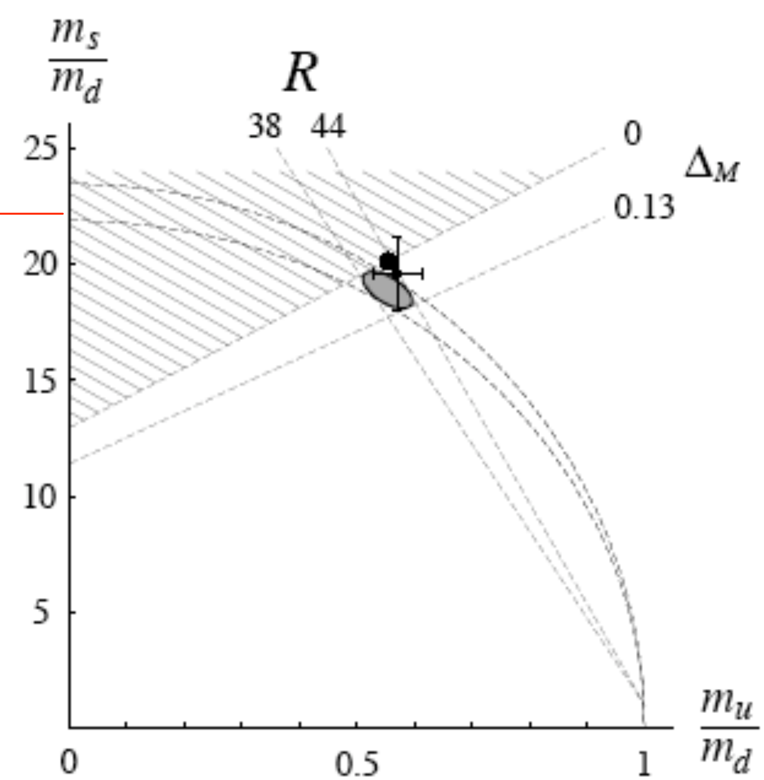
$$\Delta^K_{SU(2)}\Big|_{\rm pheno} = (3.24 \pm 0.43)\,\%$$

~ 2 σ disagreement with "standard" th. prediction

- What are the implications of $\Delta_{SU(2)} \approx 3.3\%$? [vs $\Delta_{SU(2)} \approx 2.4\%$]

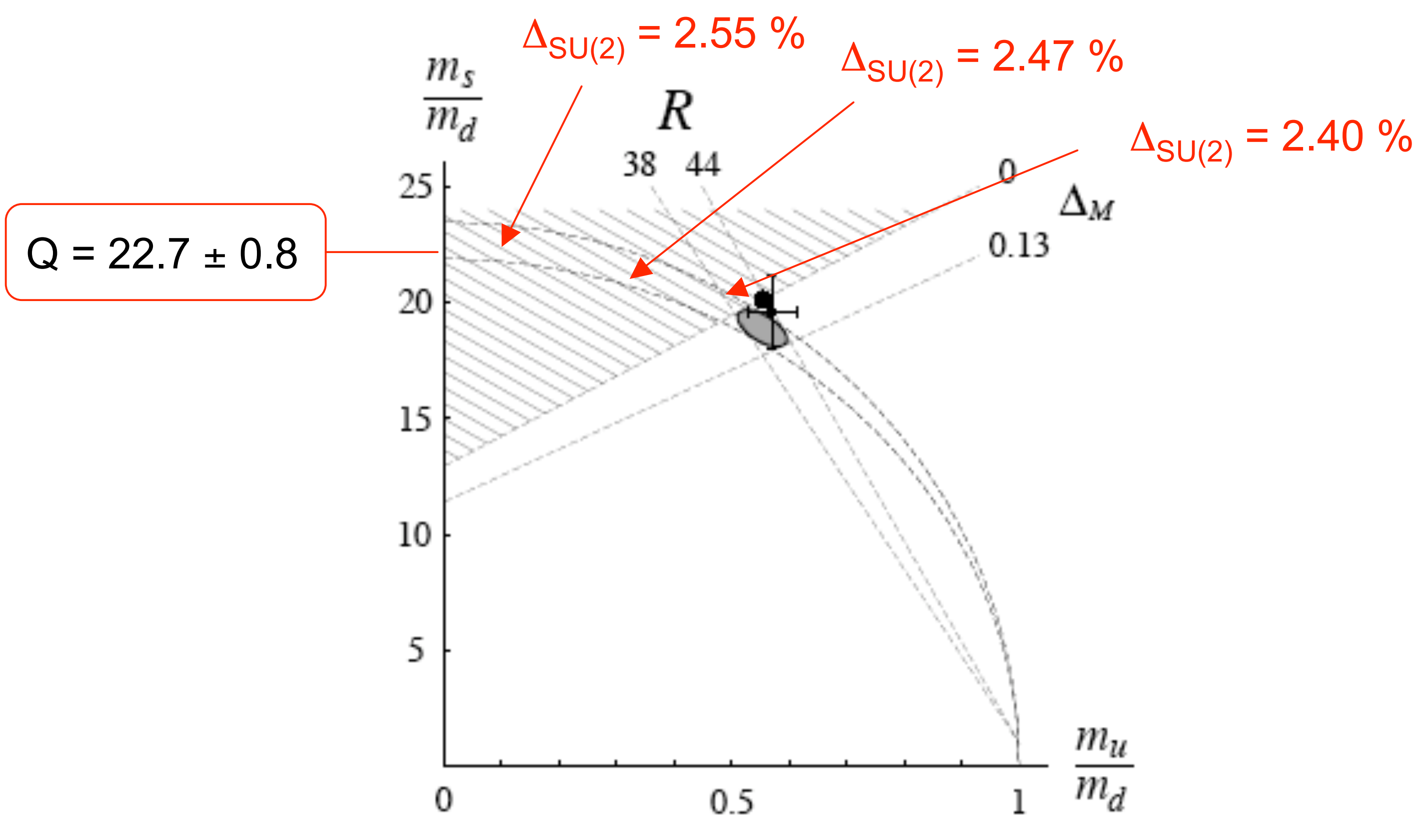
$$\Delta^{K}_{SU(2)} = \frac{3}{4}\frac{1}{R}\left(1 + \chi_{p^4} + \frac{4}{3}\frac{M_K^2 - M_\pi^2}{M_\eta^2 - M_\pi^2}\,\Delta_M + O(m_q^2)\right)$$

Q = 22.7 ± 0.8

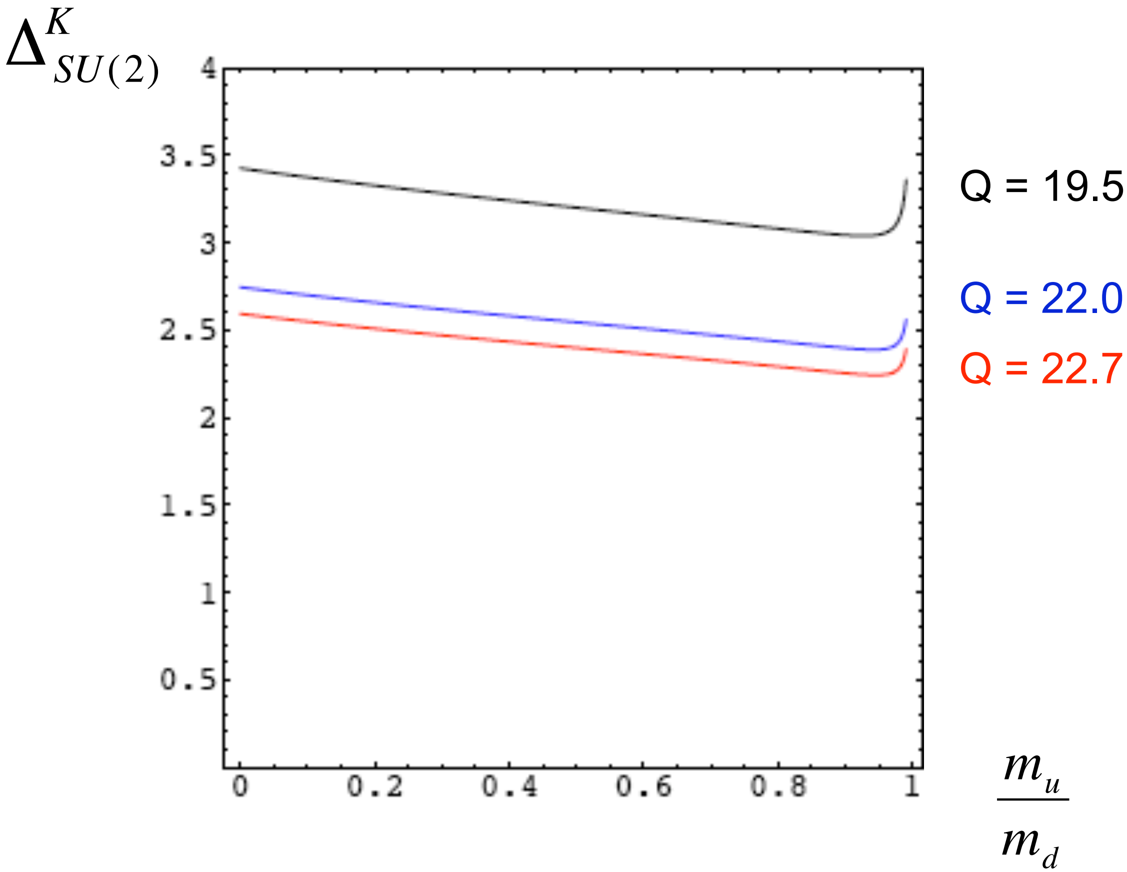


- What are the implications of $\Delta_{SU(2)} \approx 3.3\%$? [vs $\Delta_{SU(2)} \approx 2.4\%$]
- $\Delta_{SU(2)} \approx 3.3\%$ is not consistent with Q=22.7± 0.8
  ($\Leftarrow \Delta_{SU(2)}$ nearly constant along fixed-Q ellipses !!)

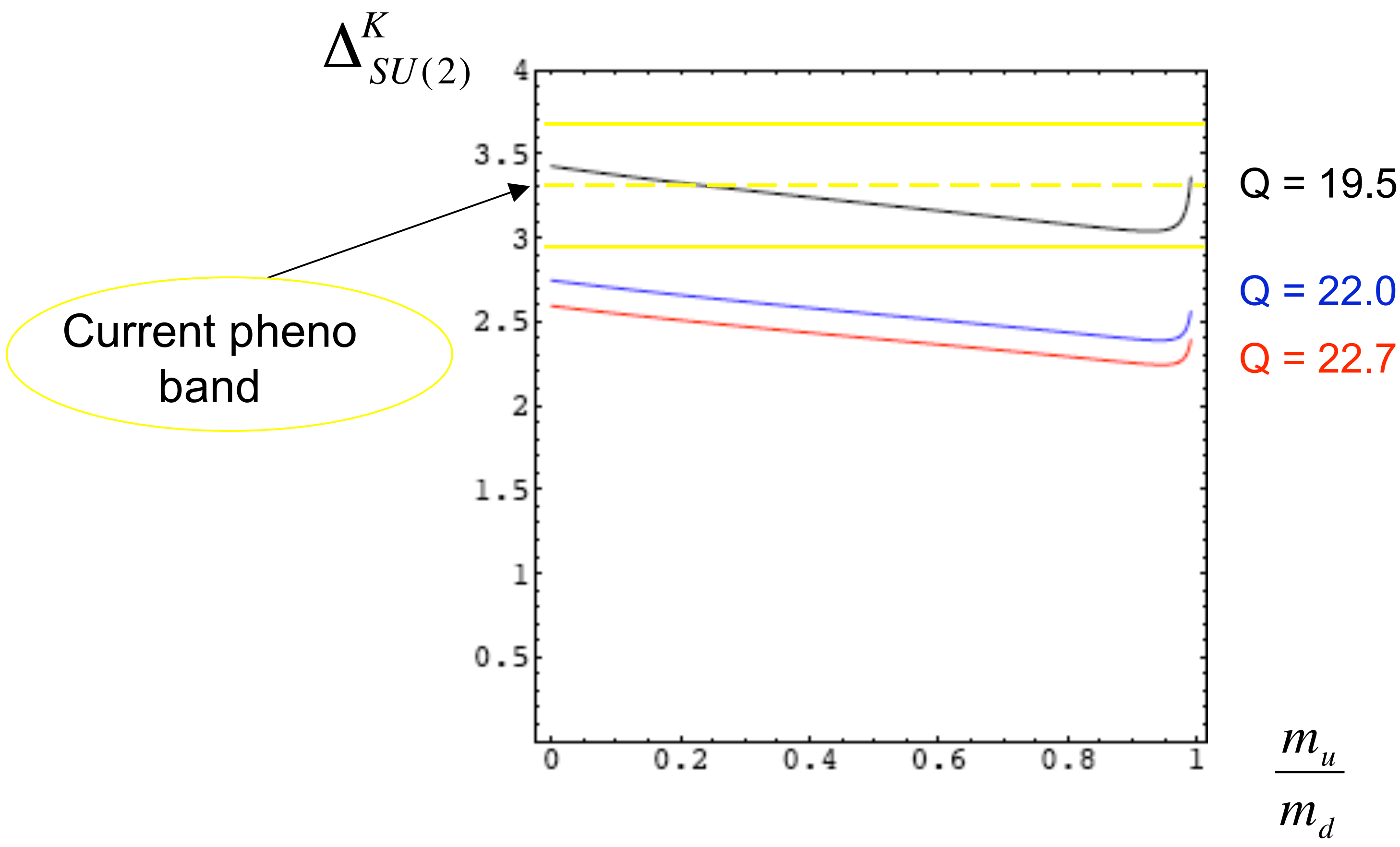
$$\Delta^{K}_{SU(2)} = \frac{3}{4}\frac{1}{R}\left(1 + \chi_{p^4} + \frac{4}{3}\frac{M_K^2 - M_\pi^2}{M_\eta^2 - M_\pi^2}\Delta_M + O(m_q^2)\right)$$



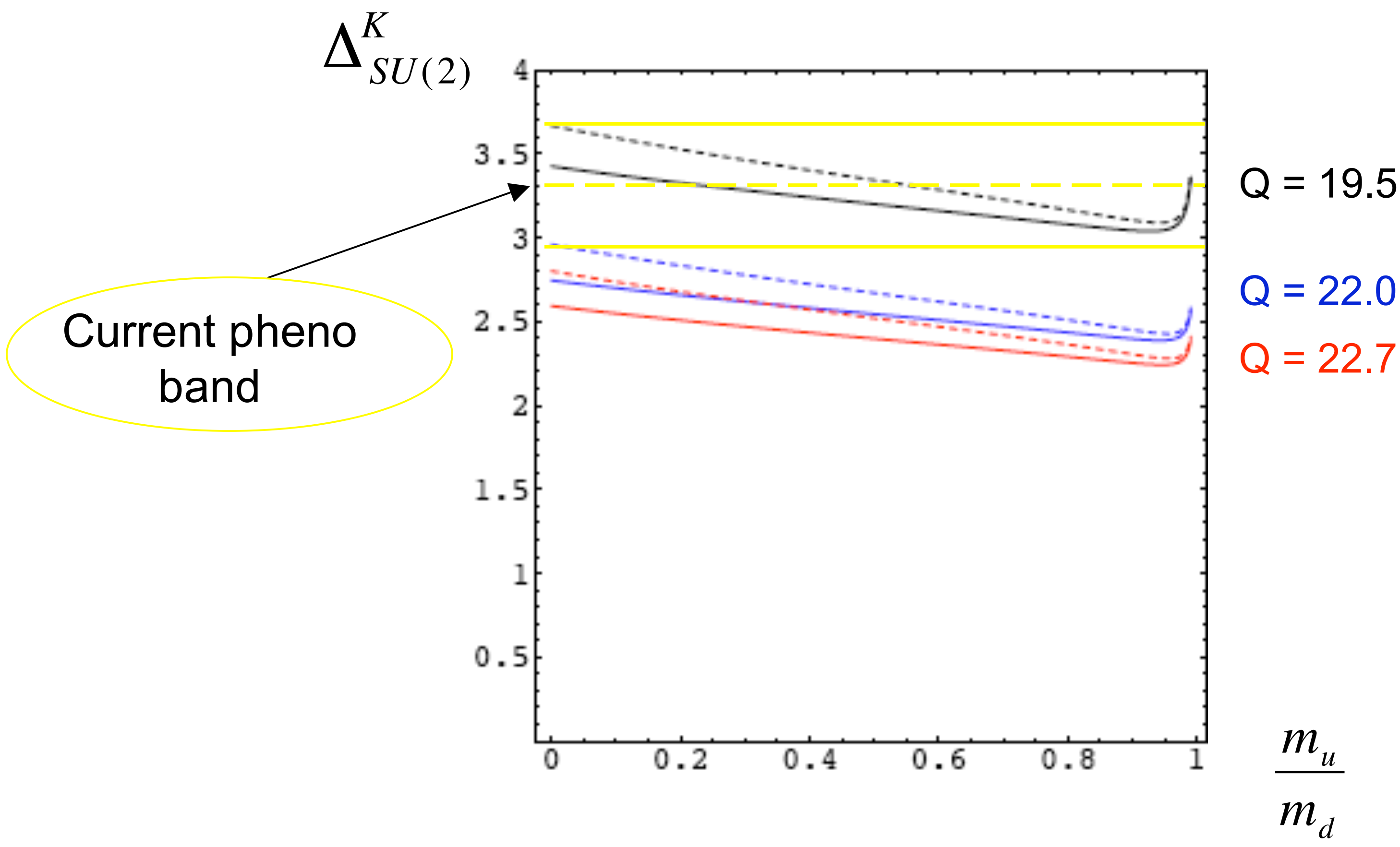
- $\Delta_{SU(2)} \approx 3.3\%$ suggests smaller values of Q



- $\Delta_{SU(2)} \approx$ 3.3% suggests smaller values of Q

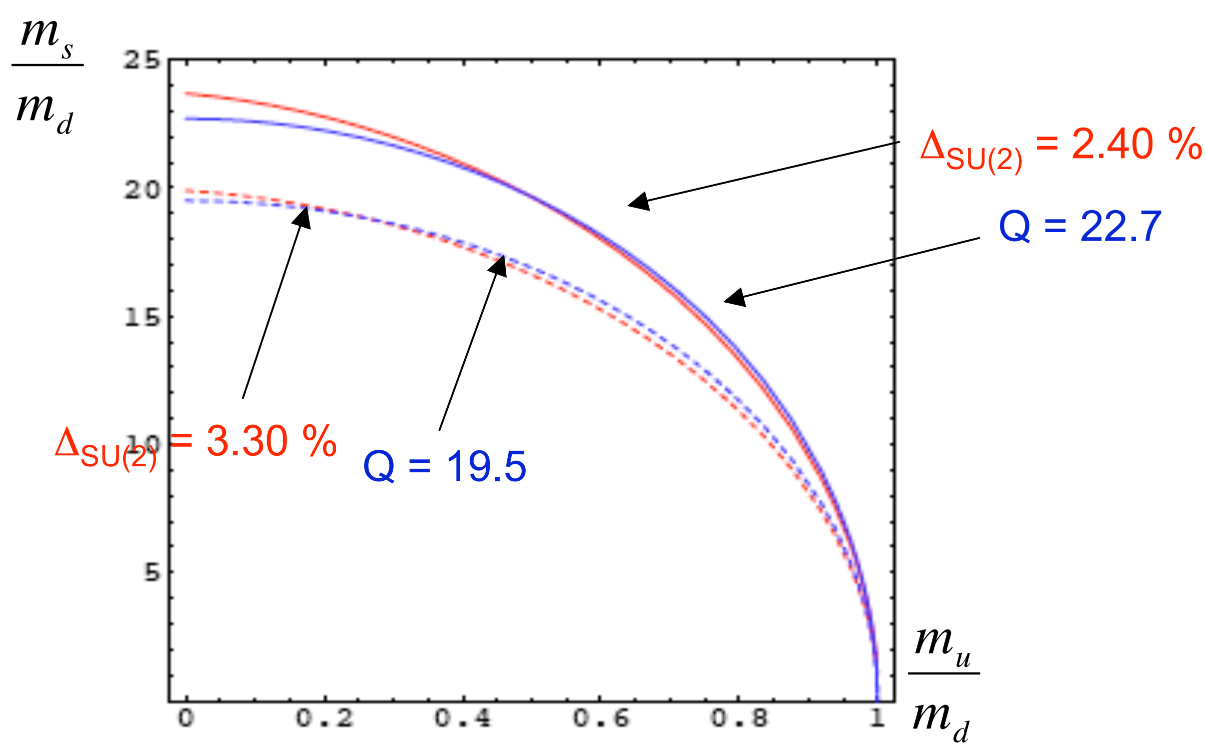


- $\Delta_{SU(2)} \approx 3.3\%$ suggests smaller values of Q
- This remains true even allowing for χ-corrections $O(m^2) \sim 0.3\, O(m)$



- Another way to look at this: ellipses parameterized by $\Delta_{SU(2)}$

$$\Delta^{K}_{SU(2)} = \frac{3}{4}\frac{1}{R}\left(1 + \chi_{p^4} + \frac{4}{3}\frac{M_K^2 - M_\pi^2}{M_\eta^2 - M_\pi^2}\,\Delta_M + O(m_q^2)\right)$$



- "$\Delta_{SU(2)}$" constraint is almost degenerate with "Q" constraint → hard to use it to pin down precisely the quark mass ratios (!)

- In summary, assuming that EM corrections are OK (all large logs identified and included), the current tension points to:

1) If Q ~ 22 is robust and chiral corrections are of "normal" size ⇒

inconsistency in the Kl3 data

2) If Q ~ 22 is robust and data is OK ⇒

anomalously large chiral corrections

3) If data is OK and chiral corrections are of "normal" size ⇒

lower values of Q (< 20)

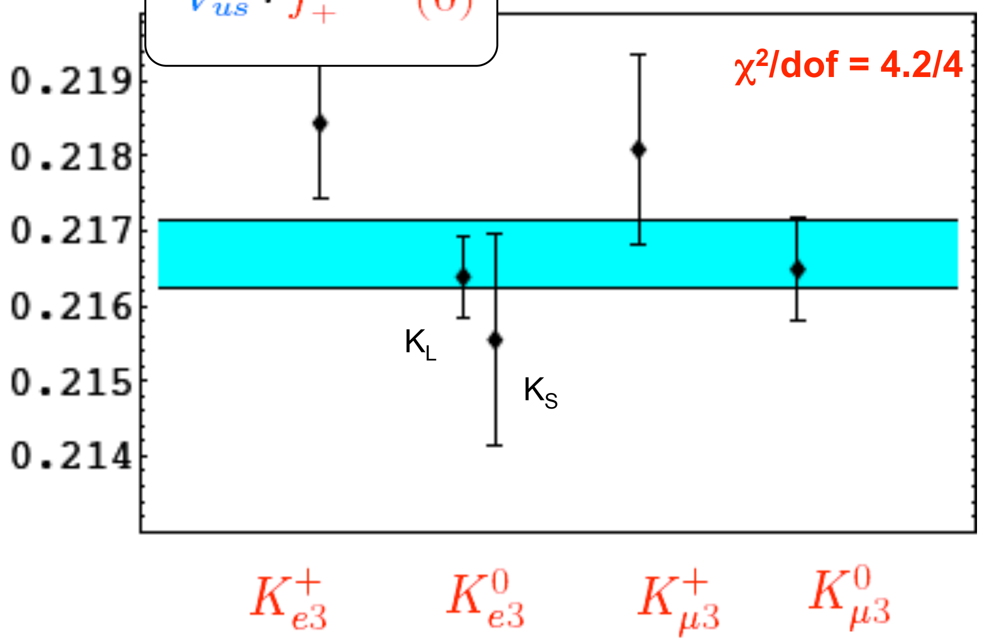
Work on chiral corrections and new data analyses is underway:
we will soon be able to discriminate these possibilities

SU(3) breaking and V_{us}

$\Delta_{EM} + \Delta_{SU(2)}$ + exp. data $\rightarrow$ $f_+(0)\, V_{us}$

$$V_{us} = \frac{C_K^{-1}}{f_+^{K^0\pi^-}(0)} \left[\frac{192\pi^3 \cdot \Gamma_{K_{\ell 3[\gamma]}}}{G_\mu^2 S_{\rm ew} M_K^5 \cdot I^{K\ell}} \right]^{1/2} \cdot \frac{1}{1 + \Delta_{SU(2)}^K + \Delta_{\rm EM}^{K\ell}}$$

$V_{us} \cdot f_+^{K^0\pi^-}(0)$



New results from KTeV, KLOE, NA48, ISTRA as of March 2007

I use FLAVIAnet fit (M. Moulson) hep-ex/0703013

$$V_{us} \cdot f_+^{K^0\pi^-}(0) = 0.2167 \pm 0.0005$$

Dominated by K^0 modes

SU(3) breaking in $f_+^{K\pi}(0)$

Ademollo-Gatto:

$$f_+^{K^0\pi^-}(0) = 1 + O(m_s - m_d)^2$$

$SU(3)_V$

Chiral Expansion:

$$f_+^{K^0\pi^-}(0) = 1 + f_{p^4} + f_{p^6} + \dots$$

f_{p^4}: $O(m_q)$ $\quad$ f_{p^6}: $O(m_q^2)$

$SU(3)_L \times SU(3)_R$

SU(3) breaking in $f_+^{K\pi}(0)$

Ademollo-Gatto: $$f_+^{K^0\pi^-}(0) = 1 + O(m_s - m_d)^2$$ $SU(3)_V$

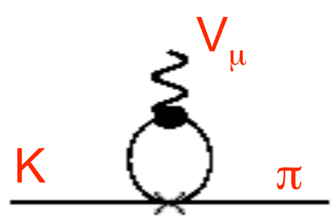
Chiral Expansion: $$f_+^{K^0\pi^-}(0) = 1 + f_{p^4} + f_{p^6} + \dots$$ $SU(3)_L \times SU(3)_R$

f_{p^4}: $O(m_q)$, f_{p^6}: $O(m_q^2)$

Gasser-Leutwyler'85

$$f_{p^4} \sim \frac{(m_s - m_u)^2}{m_s}$$

UV finite one loop diagrams in EFT:



$$f_{p^4} = -0.0227$$

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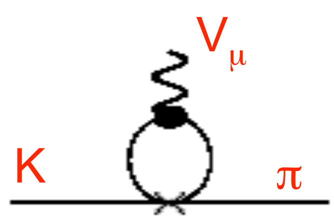


$$f_{p^4} = -0.0227$$

Up to two-loop graphs in EFT:

"local" terms and chiral logs

Estimated by Leutwyler-Roos'84 within quark model

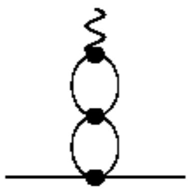
$$f_{p^6}^{LR} = -0.016 \pm 0.008$$

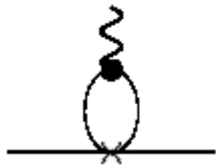
$$f_+^{K^0\pi^-}(0) = 0.961 \pm 0.008$$

Analytic calculation of $f_+(0)$ to $O(p^6)$

Post-Schilcher '02, Bijnens-Talavera '03

$$f_{p^6} = f_{p^6}^{2-\text{loops}}(\mu) + f_{p^6}^{L_i \times \text{loop}}(\mu) + f_{p^6}^{\text{tree}}(\mu)$$





$$f_{p^6}^{L_i \times \text{loop}}(M_\rho) = -0.0020$$

$$f_{p^6}^{2-\text{loops}}(M_\rho) = 0.0113$$

$$8\frac{(M_K^2 - M_\pi^2)^2}{F_\pi^2}\left[\frac{(L_5^r(M_\rho))^2}{F_\pi^2} - C_{12}^r(M_\rho) - C_{34}^r(M_\rho)\right]$$

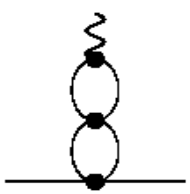
Effective couplings not fixed by Chiral Symmetry

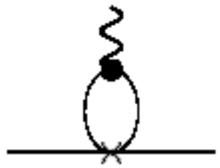
Large and positive chiral loop contributions @ $\mu = M_\rho$ (mildly scale dependent)

Analytic calculation of $f_+(0)$ to $O(p^6)$

Post-Schilcher '02, Bijnens-Talavera '03

$$f_{p^6} = f_{p^6}^{2-\text{loops}}(\mu) + f_{p^6}^{L_i\times\text{loop}}(\mu) + f_{p^6}^{\text{tree}}(\mu)$$





$$8\frac{(M_K^2 - M_\pi^2)^2}{F_\pi^2}\left[\frac{(L_5^r(M_\rho))^2}{F_\pi^2} - C_{12}^r(M_\rho) - C_{34}^r(M_\rho)\right]$$

$$f_{p^6}^{L_i\times\text{loop}}(M_\rho) \;=\; -0.0020$$

$$f_{p^6}^{2-\text{loops}}(M_\rho) \;=\; 0.0113$$

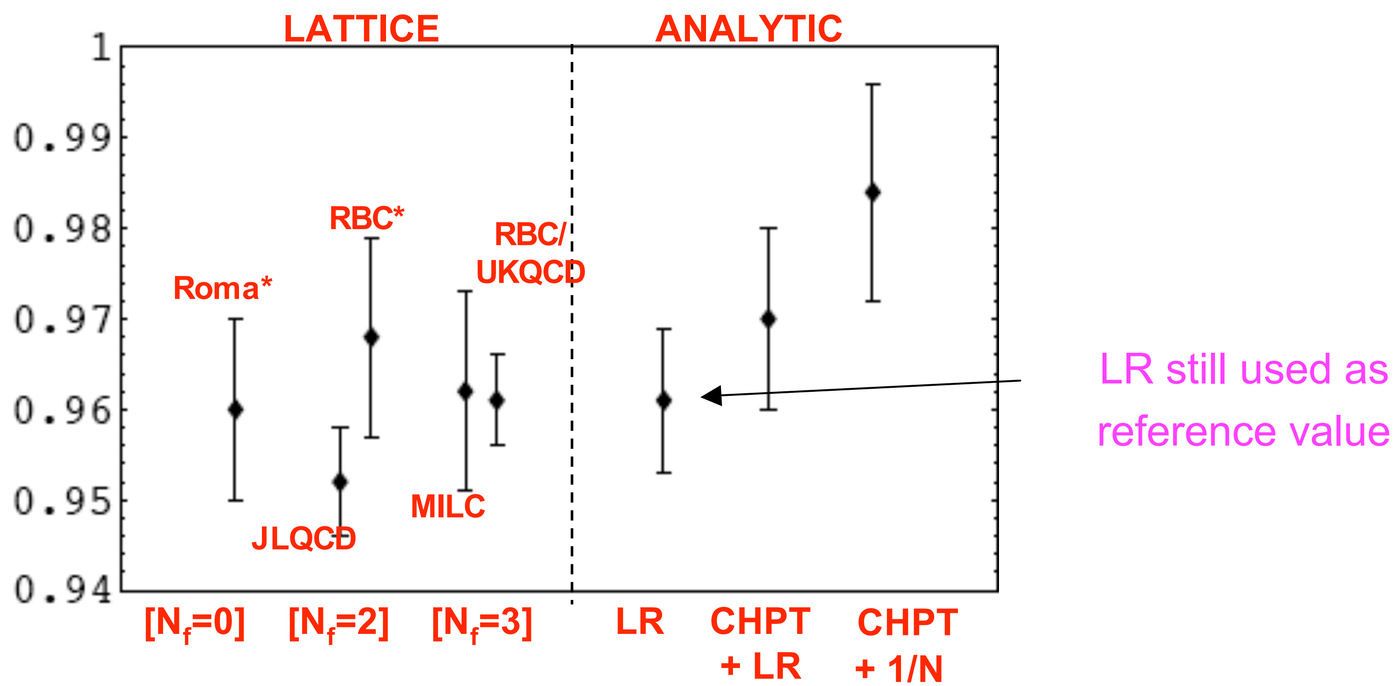
Large and positive
chiral loop contributions
@ $\mu = M_\rho$
(mildly scale dependent)

Effective couplings not fixed by
Chiral Symmetry

- Identify this with result by Leutwyler-Roos
- Obtain LECs from <SPP> in truncated $1/N_C$ (VC et al 05)
- Nothing new since Kaon 05

Summary on form factor

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

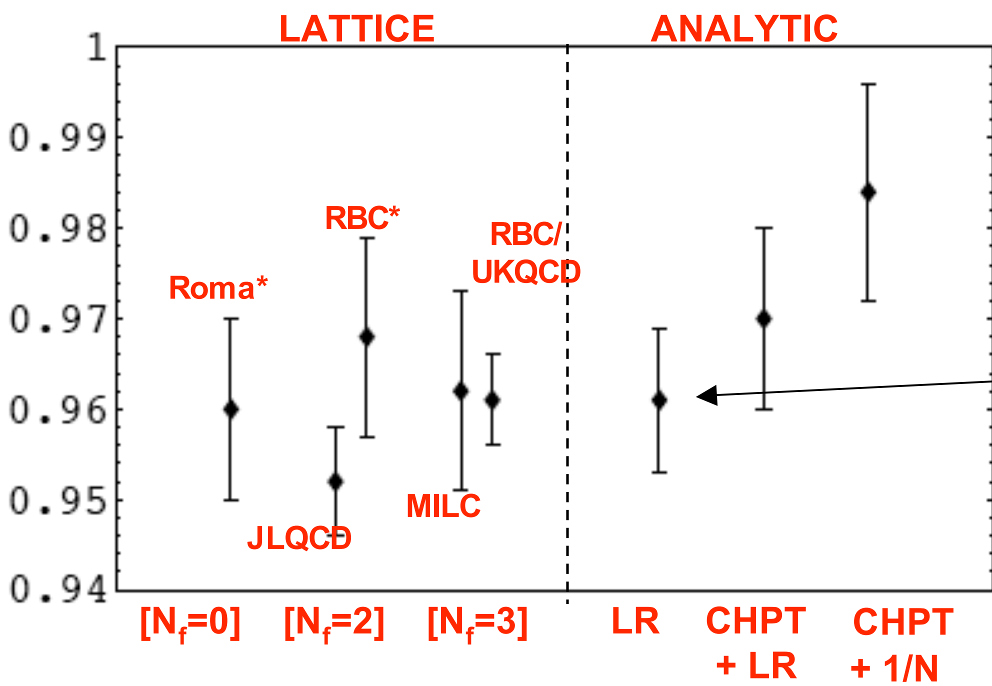


The dust hasn't settled yet… [see lattice talks]

- Inclusion of chiral logs increases analytic estimates over LR
- Key issue: understand role of (χ-logs)^2 both in chiral extrapolation of lattice data and in analytic estimates

Summary on form factor and V_{us}

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



LR still used as reference value

$$V_{us}^{K_{\ell 3}} = 0.2255\,(4)_{\rm exp}(19)_{\rm th} \cdot \frac{0.961}{f_+^{K^0\pi^-}(0)}$$

Summary

- Kl3 decays allow us to test different aspects of the SM
- Theoretical input: EM, SU(2), SU(3) corrections

lepton universality

Approaching sensitivity of $\pi \to \ell\nu$ (factor of two worse)

Burden is on experiment

quark mass ratios

Interesting new constraint on m_u/m_d - m_s/m_d plane points to smaller value of Q

More work required on both theory and experiment

V_{us} and CKM unitarity

V_{us} best determined by K^0 modes.

Theory not yet at the 1% level

Several lattice talks on this!

Additional slides

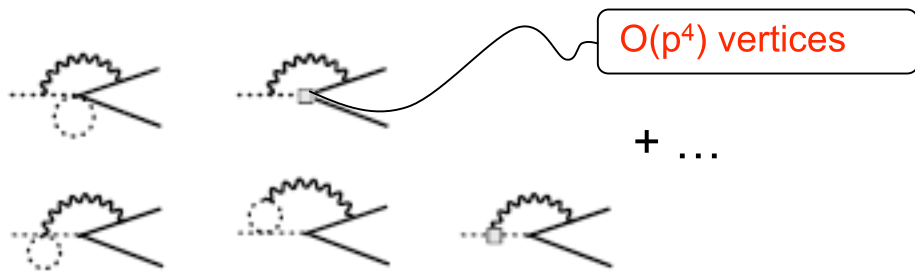
VC & I. Rosell, in progress

$R_{e/\mu} = \Gamma(P \to e\nu)/\Gamma(P \to \mu\nu)$ to $O(e^2p^4)$ in ChPT

$$P = \pi, K$$

$$R_{e/\mu}^{(P)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2}\right)^2 \times \left[1 + \Delta_{e^2p^2}^{(P)} + \Delta_{e^2p^4}^{(P)} + \dots\right]$$

- Up to two loop graphs with virtual photons, one loop with real photons



⟷ Model-independent double logs + finite parts

- LEC determined by matching with meromorphic approximations for Π ~ <0|VA|π>, <0|VV|π> (~ large N_C)

$$\int d^dq\, K(q)\, \Pi_{\rm QCD}(q) = \int d^dq\, K(q)\, \Pi_{\rm ChPT}(q) + T_{\rm LEC}$$

ChPT + truncated large N_C

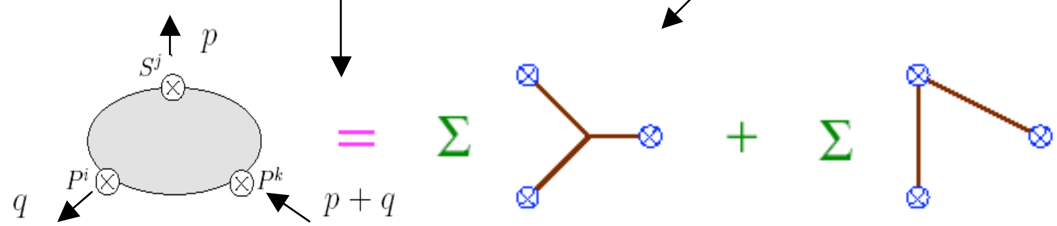
(Cirigliano-Ecker-Eidemuller-Kaiser-Pich-Portoles 2005)

- Obtain effective couplings by large-N inspired matching procedure:

Matching = impose correct QCD asymptotic behavior

Finite number of narrow resonances

$$P^a(x) = \bar{q}(x) i\gamma_5 \lambda^a q(x)$$
$$S^a(x) = \bar{q}(x) \lambda^a q(x)$$

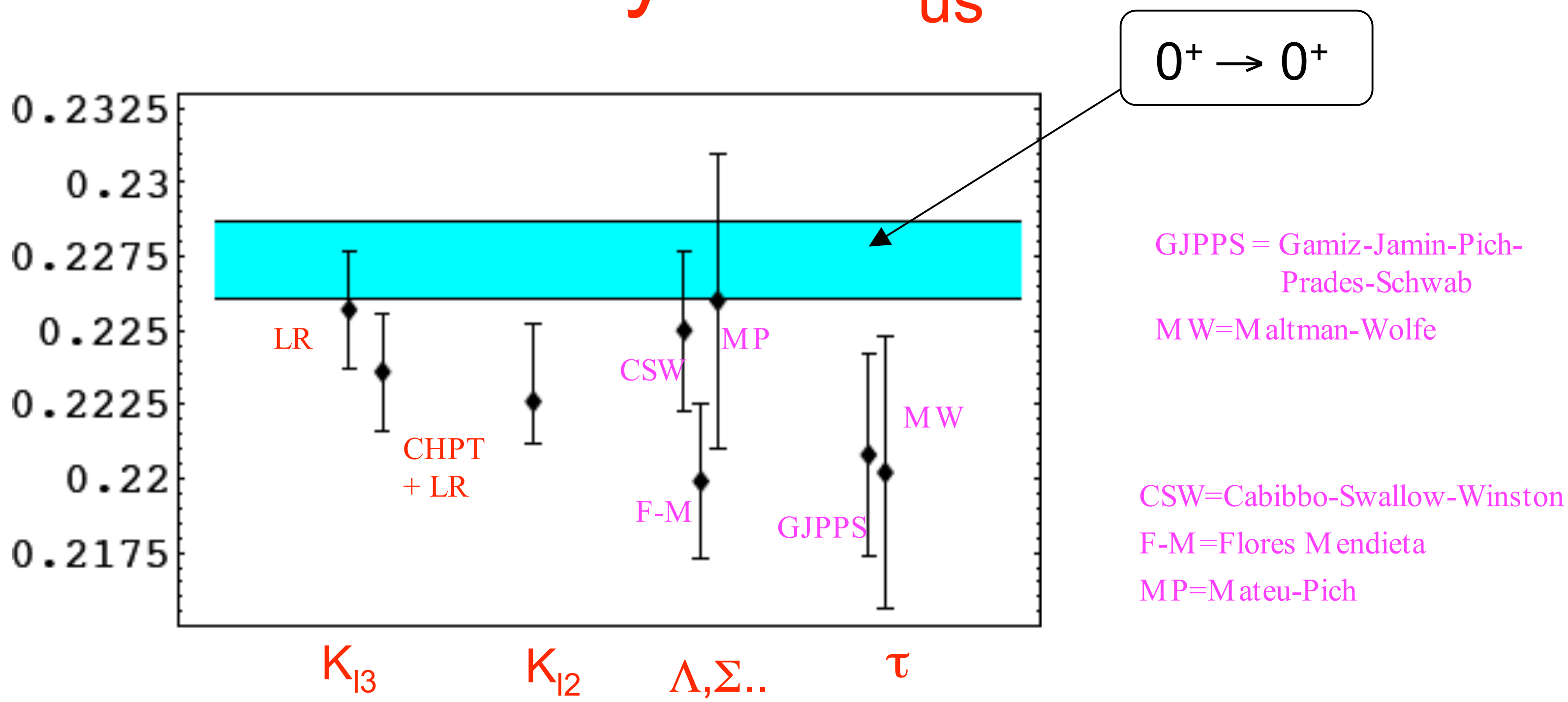


$$f_+^{K^0\pi^-}(0) = 0.984 \pm 0.012$$

- Scale ambiguity (0.008)
- Resonance parameters

- Cross-checks: F_K/F_π and slope of scalar ff λ_0

Summary on V_{us}



- At the moment K decays provide best determination of V_{us}
- Meaningful unitarity test will need to await for final value of $f_+(0)$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -(1.0 \pm 0.6_{V_{ud}} \pm 0.9_{V_{us}}) \cdot 10^{-3}$$