Chiral Dynamics 2012, JLab, August 7 2012

Status of V_{us} and V_{ud} and implications for new physics

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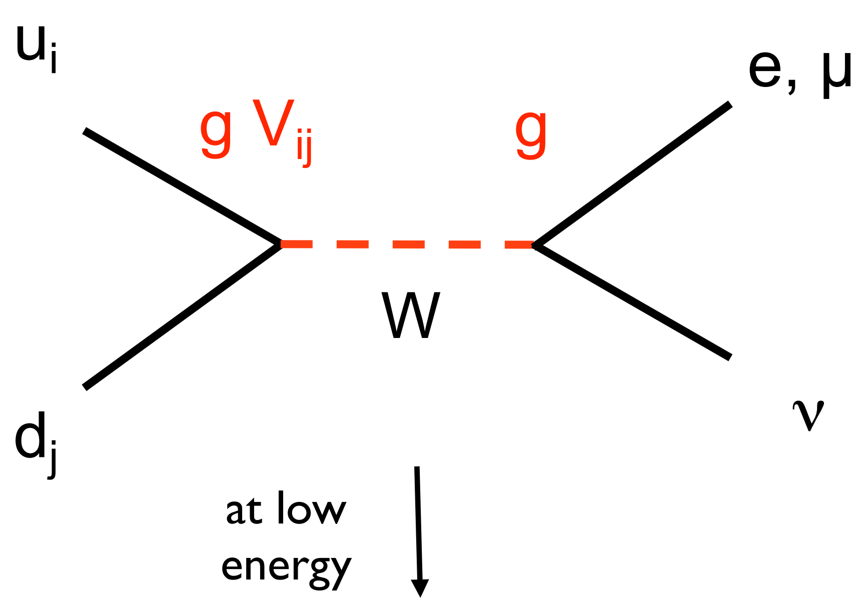
Outline

- Introduction: CC interactions and physics beyond the Standard Model
- V_{us} from K decays:
  - V_{us} from Kl3
  - V_{us}/V_{ud} from $K_{\mu 2}/\pi_{\mu 2}$
- Implications of Cabibbo universality tests for new physics
  - Model independent analysis
  - SUSY

CC interactions and BSM physics

- In the SM, W exchange ⇒ only V-A structure, universality relations



$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

Lepton universality

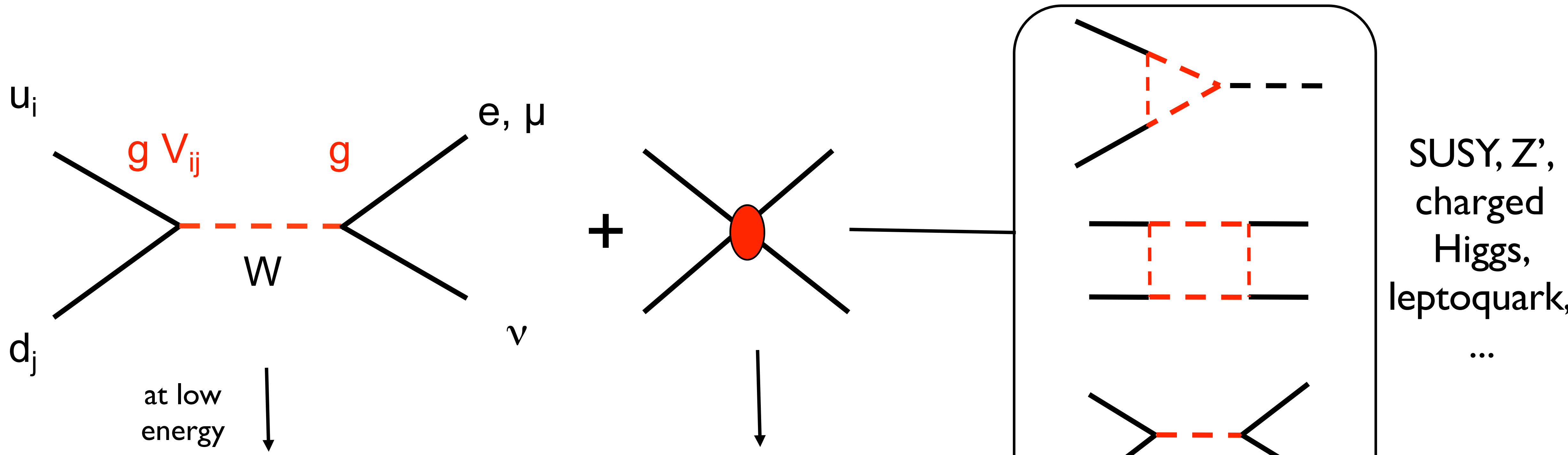
$$[G_F]_e/[G_F]_\mu = 1 + \Delta_{e/\mu}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{\mathrm{CKM}}$$

Cabibbo universality

CC interactions and BSM physics

- In the SM, W exchange ⇒ only V-A structure, universality relations



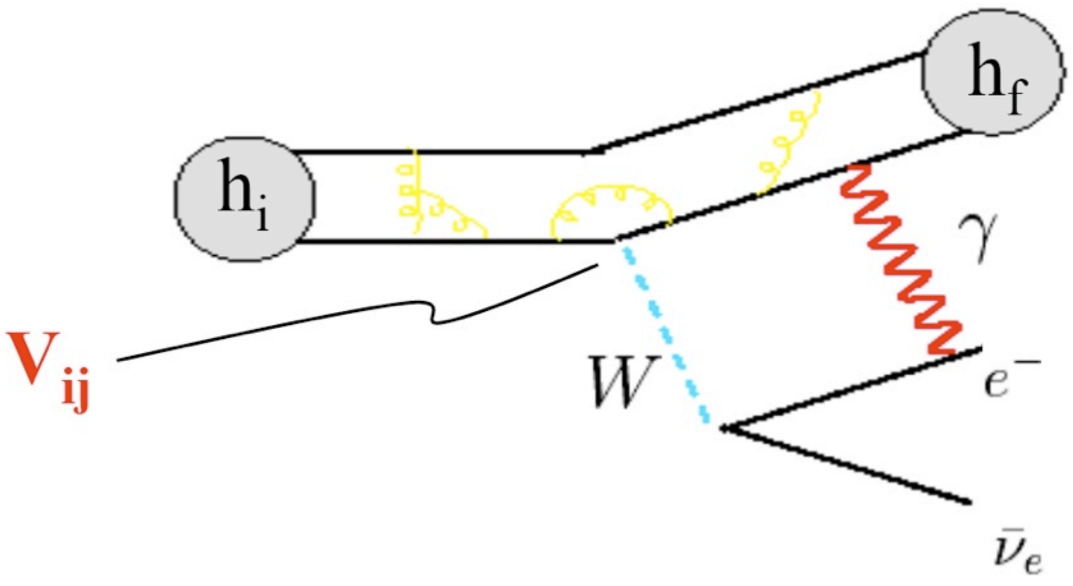
$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

$1/\Lambda^2$

- BSM: sensitive to tree-level and loop corrections from large class of models → "broad band" probe of new physics, with BSM effects scaling as $\Delta_{CKM} \sim (v/\Lambda)^2$

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e\nu)$	$n \to pe\bar{\nu}$	$\pi \to \mu\nu$	$\tau \to h_{NS}\,\nu_\tau$
V_{us}	$K \to \pi\ \ell\nu$	$\Lambda \to pe\bar{\nu},\ldots$	$K \to \mu\nu$	$\tau \to h_S\nu_\tau$ (inclusive)



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V_{us}	$K \to \pi\ \ell\nu$	$\Lambda \to pe\bar{\nu},\ldots$	$K \to \mu\nu$	$\tau \to h_S \nu_\tau$ (*inclusive*)

- Theory golden modes: only V current contributes $\langle A(p_A)|\bar{q}^i\gamma_\mu q^j|B(p_B)\rangle$
  - Normalization known in SU(2) [SU(3)] symmetry limit
  - Corrections start at 2nd order in SU(2) [SU(3)] breaking

Ademollo-Gatto
Berhends-Sirlin

- Currently, most precise determinations of V_{ud} (0.02%) and V_{us} (0.5%)

Paths to V_{ud} and V_{us}

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V_{us}	$K \to \pi \ \ell \nu$	$\Lambda \to p e \bar{\nu}, \ldots$	$K \to \mu \nu$	$\tau \to h_S \nu_\tau$ $(inclusive)$

- Both V and A currents contribute: need experimental input on <A> (e.g. β-asymmetry)
- Free of nuclear structure uncertainties
- Probe different combinations of BSM operators (compared to $0^+ \to 0^+$)

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e\nu)$	$n \to pe\bar{\nu}$	$\pi \to \mu\nu$	$\tau \to h_{NS}\,\nu_\tau$
V_{us}	$K \to \pi\ \ell\nu$	$\Lambda \to pe\bar{\nu},\ldots$	$K \to \mu\nu$	$\tau \to h_S \nu_\tau$ $(inclusive)$

- Purely A transition: <A> ↔ decay constants (from Lattice QCD)
- Input on F_K/F_π ⇒ information on ratio V_{ud}/V_{us}
- Probe different BSM operators than V-channels

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e\nu)$	$n \to pe\bar{\nu}$	$\pi \to \mu\nu$	$\tau \to h_{NS}\,\nu_\tau$
V_{us}	$K \to \pi\ \ell\nu$	$\Lambda \to pe\bar{\nu},\ldots$	$K \to \mu\nu$	$\tau \to h_S \nu_\tau$ (*inclusive*)

- Use OPE to calculate inclusive BRs
- Information from exclusive modes, too
- See talk by E. Passemar

V_{us} from $K \to \pi l \nu$ decays

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

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

--- EXP input
--- TH input

- Experimental input:
    - FLAVIANET paper [1005.2323, Eur.Phys.J. C69 (2010) 399]
    - Updates: M. Moulson's talk at CIPANP 2012

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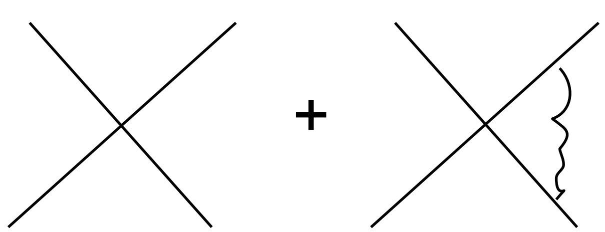
Short distance
electroweak correction:

Sirlin '82

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



+ … => $G_\mu V_{ij} \sqrt{S_{ew}}$

V_{us} from $K \rightarrow \pi l \nu$ decays

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

1 in $SU(3)_V$ limit ($m_u = m_d = m_s$)

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

- $f_+(0)$ is the key hadronic parameter
- Discuss effect of SU(3) breaking later on

V_{us} from $K \to \pi l \nu$ decays

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

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

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

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

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

- Various parameterizations of the form factors exist (polynomial, pole, dispersive)
- Phase space integrals consistent within uncertainty

V_{us} from $K \to \pi l \nu$ decays

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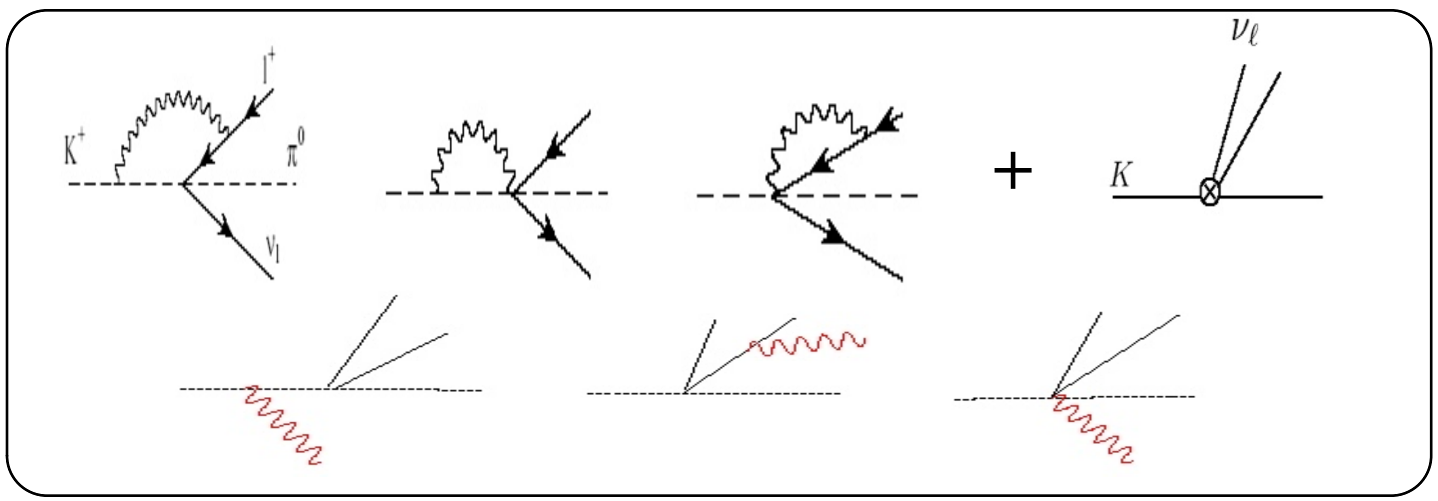
Long-distance EM corrections:



Δ^{EM}	
$K^0{}_{e3}$	+0.50(11)%
$K^+{}_{e3}$	+0.05(13)%
$K^0{}_{\mu 3}$	+0.70(11)%
$K^+{}_{\mu 3}$	+0.01(13)%

V. Cirigliano, M. Giannotti, H. Neufeld: JHEP 0811:006 (2008)

- ChPT to $O(e^2p^2)$
- Use fully inclusive prescription for real photons
- Uncertainty estimate: LECs (100%) + higher chiral orders

Anantharayan-Moussallam 2004,
Descotes-Jenon Moussallam 2005

V_{us} from $K \to \pi l \nu$ decays

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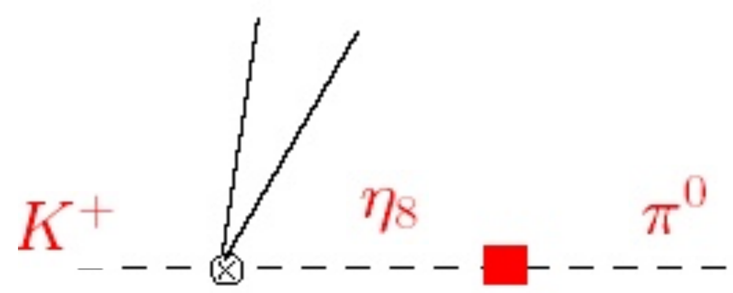
$$\Delta_{SU(2)}^K \equiv \frac{f_+^{K^+\pi^0}(0)}{f_+^{K^0\pi^-}(0)} - 1$$



+ IB in 1-loop graphs + CT

V_{us} from $K \to \pi l \nu$ decays

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

ChPT to $O(p^4)$ relates this to ratios of the light quark masses:

$$\Delta_{SU(2)}^K = \frac{3}{4}\frac{1}{Q^2}\left[\frac{m_K^2}{m_\pi^2} + \frac{\chi_{p^4}}{2}\left(1 + \frac{m_s}{\hat{m}}\right)\right]$$

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

0.219
(calculable chiral corr.)

$$\hat{m} = \frac{m_u + m_d}{2}$$

V_{us} from $K \to \pi l \nu$ decays

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- Predict $\Delta_{SU(2)}$ from quark mass ratios:

$m_s/\hat{m} = 24.7 \pm 1.1,$

$Q = 20.7 \pm 1.2$

$\Delta_{SU(2)} = (2.9 \pm 0.4)\ \%$

A. Kastner, H. Neufeld, 2008

$m_s/\hat{m} = 27.4 \pm 0.4$

$Q = 22.8 \pm 1.2$

$\Delta_{SU(2)} = (2.4 \pm 0.3)\ \%$

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V_{us} from $K \to \pi l \nu$ decays

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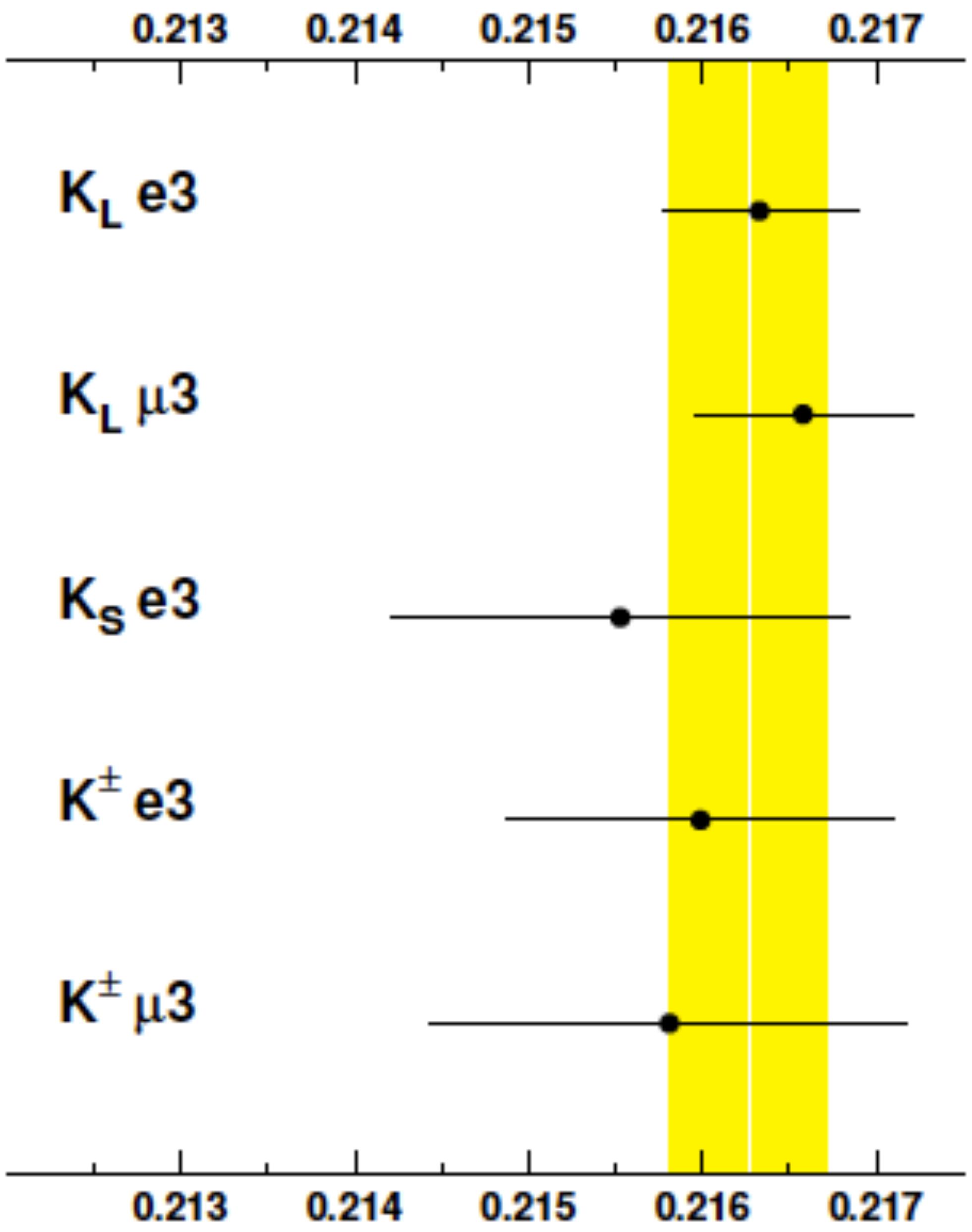
- Extract $\Delta_{SU(2)}$ from data + EM corr: constraint on quark masses

$$\Delta_{SU(2)}^K = \frac{\Gamma_{K_{\ell 3}^+}}{\Gamma_{K_{\ell 3}^0}} \cdot \frac{I^{K^0\ell}}{I^{K^+\ell}} \left(\frac{M_{K^0}}{M_{K^+}}\right)^5 - \frac{1}{2} - \left[\Delta_{\rm EM}^{K^+\ell} - \Delta_{\rm EM}^{K^0\ell}\right] \longrightarrow (2.7 \pm 0.4)\ \%$$

~ 0.15% from TH

V_{us} from $K \to \pi l \nu$ decays

- Experiment + rad. corr. (+ SU(2) corrections)



$$|V_{us}| f_+(0) = 0.2163 \pm 0.0005$$

0.25%

SU(3) breaking in $f_+(0)$

- CVC + Ademollo-Gatto theorem: $f_+^{K^0\pi^-}(0) - 1 = O\left((m_s - m_u)^2\right)$

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

chiral expansion

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

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

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

chiral expansion

f_{p^4}

- One-loop graphs in EFT

- 1st order in m_q, 2nd order in (m_s-m_u) $\Rightarrow$ $f_{p^4} \sim \frac{(m_s - m_u)^2}{m_s}$
- No local operators, UV finite, free of uncertainty

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

Gasser-Leutwyler'85

SU(3) breaking in $f_+(0)$

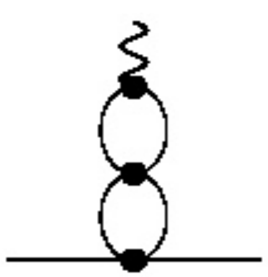
- CVC + Ademollo-Gatto theorem: $f_+^{K^0\pi^-}(0) - 1 = O\left((m_s - m_u)^2\right)$

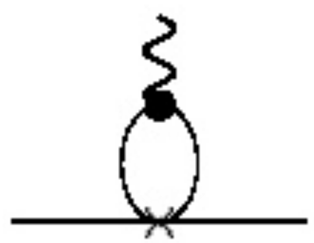
$$f_+^{K^0\pi^-}(0) = 1 \; + \; f_{p^4} \; + \; f_{p^6} \; + \ldots$$

chiral expansion

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

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





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

LECs not fixed by chiral symmetry:
rely on quark model, large-Nc estimates, LQCD

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

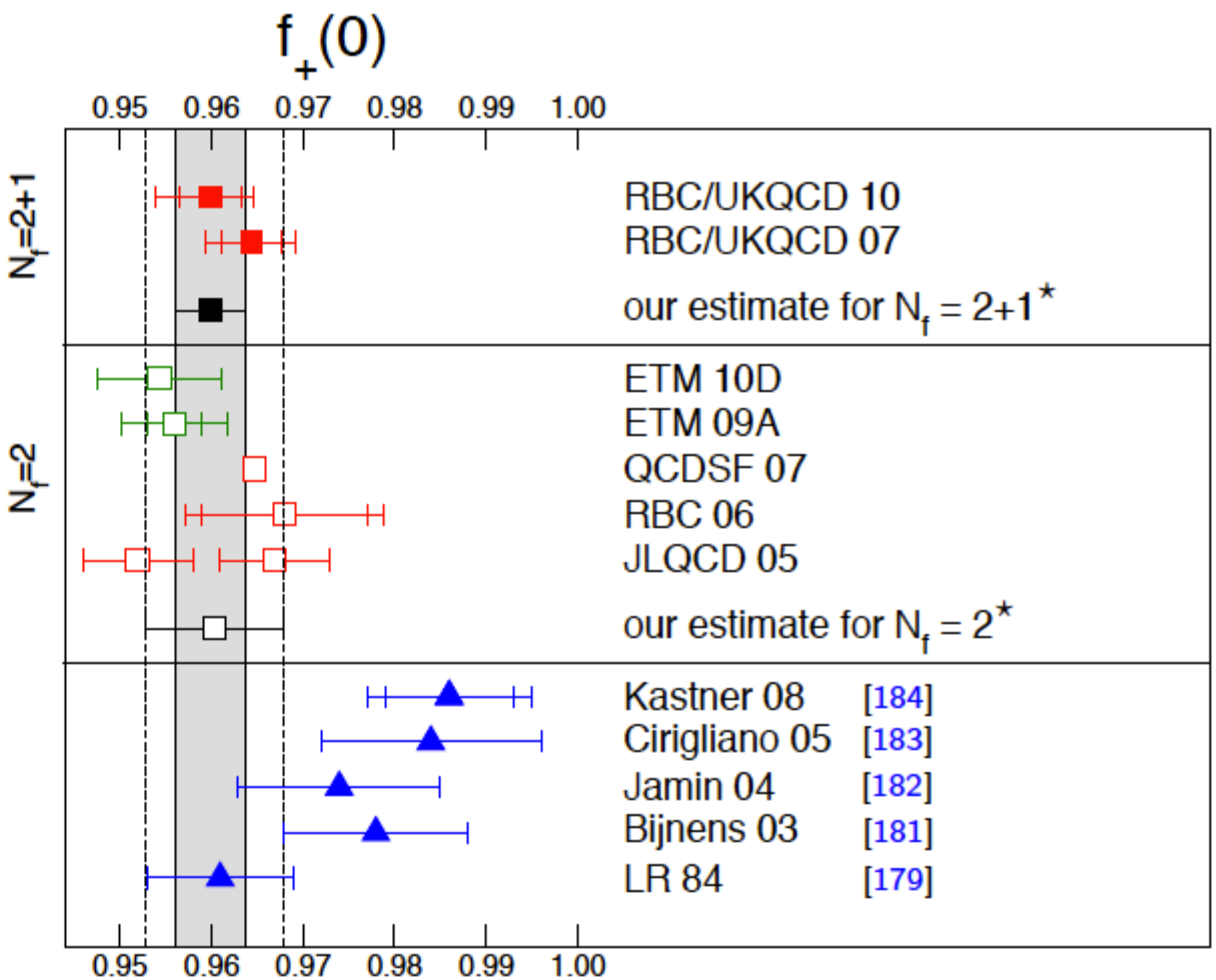
$$f_{p^6}^{2-\mathrm{loops}}(M_\rho) \; = \; 0.0113$$

Large and positive chiral loop contributions
@ $\mu = M_\rho$

Bijnens Talavera 2003

SU(3) breaking in $f_+(0)$

- Lattice QCD calculations vs ChPT + models:



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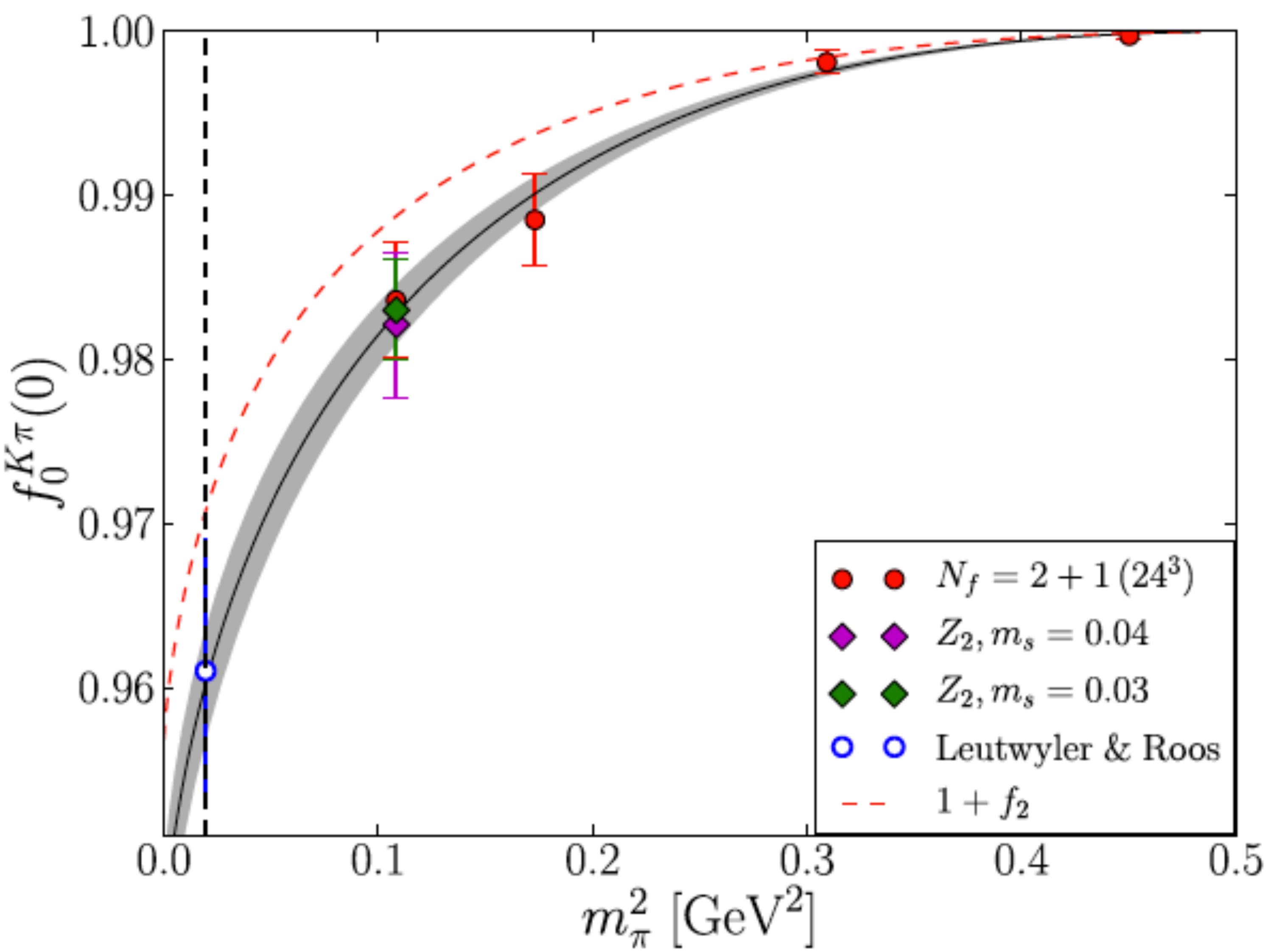
SU(3) breaking in $f_+(0)$

- N_f = 2+1 Lattice QCD: RBC- UKQCD



RBC-UKQCD 10

$f_+(0)$= 0.959(5) ⇒ V_{us} = 0.2255(13)   0.58%

V_{us}/V_{ud} from $K \to \mu\nu$ / $\pi \to \mu\nu$

Marciano '04 ,   VC + H. Neufeld 2011

$$\frac{\Gamma_{K_{\ell 2(\gamma)}}}{\Gamma_{\pi_{\ell 2(\gamma)}}} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{F_K^2}{F_\pi^2} \frac{M_{K^\pm} \left(1 - m_\ell^2/M_{K^\pm}^2\right)^2}{M_{\pi^\pm} \left(1 - m_\ell^2/M_{\pi^\pm}^2\right)^2} \left(1 + \delta_{\rm EM} + \delta_{\rm SU(2)}\right)$$

$$\frac{F_{K^\pm}^2}{F_{\pi^\pm}^2} = \frac{F_K^2}{F_\pi^2} \left(1 + \delta_{\rm SU(2)}\right)$$

V_{us}/V_{ud} from $K \to \mu\nu$ / $\pi \to \mu\nu$

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$$\frac{F_{K^\pm}^2}{F_{\pi^\pm}^2} = \frac{F_K^2}{F_\pi^2} \left(1 + \delta_{\rm SU(2)}\right)$$

- Extraction of V_{us}/V_{ud} requires:
  - F_K/F_π: lattice QCD in the isospin limit + isospin-breaking corrections (ChPT)
  - Long-distance radiative corrections: $\delta_{EM} = -0.0069(17)$
    - To $O(e^2p^2)$ in ChPT they are UV finite, no LECs. Uncertainty due to higher order corrections

Knecht et al '99 , VC- Neufeld 2011

SU(2) breaking in F_K/F_π

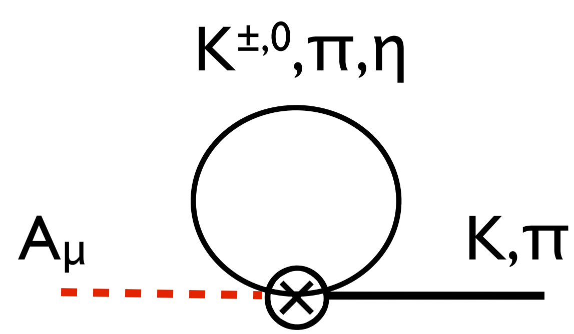
- SU(2) breaking to O(p[4]) in ChPT: $\frac{F^2_{K^\pm}}{F^2_{\pi^\pm}} = \frac{F^2_K}{F^2_\pi}\left(1+\delta_{SU(2)}\right)$

$$\delta_{SU(2)} = \sqrt{3}\,\varepsilon\left[-\frac{4}{3}\left(F_K/F_\pi - 1\right) + \frac{1}{3(4\pi)^2 F_0^2}\left(M_K^2 - M_\pi^2 - M_\pi^2 \ln\frac{M_K^2}{M_\pi^2}\right)\right]$$

Gasser-Leutwyler 1985 → VC- Neufeld 2011

Meson masses in the isospin limit

$$\varepsilon = \frac{\sqrt{3}}{4}\,\frac{m_d - m_u}{m_s - \hat{m}}$$



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Gasser-Leutwyler 1985 → VC- Neufeld 2011

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$$\varepsilon = \frac{\sqrt{3}}{4}\,\frac{m_d - m_u}{m_s - \hat{m}}$$

$$\varepsilon = \frac{\sqrt{3}}{4R} = 0.0116(13)\ , \quad F_K/F_\pi = 1.193(6)$$

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$\delta_{SU(2)} = -0.0043\ (5)_{\text{input}}\ (11)_{\text{higher order}}$

SU(2) breaking in F_K/F_π

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Gasser-Leutwyler 1985 → VC- Neufeld 2011

Meson masses in the isospin limit

$$\varepsilon = \frac{\sqrt{3}}{4}\,\frac{m_d - m_u}{m_s - \hat{m}} \qquad \varepsilon = \frac{\sqrt{3}}{4R} = 0.0116(13)\,, \quad F_K/F_\pi = 1.193(6)$$

FLAG 2010

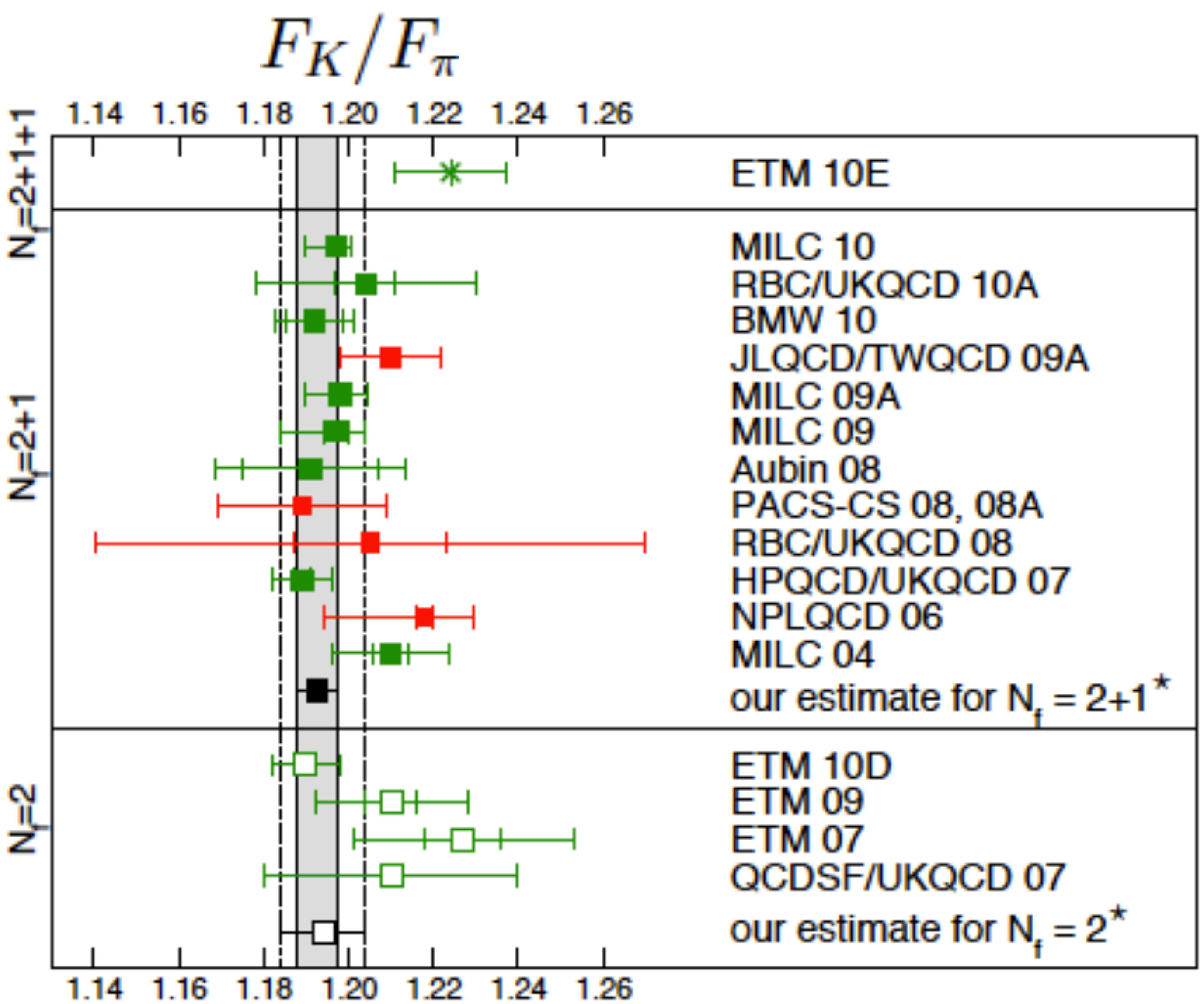
$\delta_{SU(2)}$ = -0.0043 (5)$_{\text{input}}$ (11)$_{\text{higher order}}$

- SU(2) breaking from N_f=2 (ETM) lattice QCD

RM123 collaboration 2011

$\delta_{SU(2)}$ = -0.0078 (6)$_{\text{lattice}}$ (4)$_{\text{Kaon EM mass splitting}}$

F_K/F_π from lattice QCD



$$F_K/F_\pi = 1.193 \pm 0.006$$

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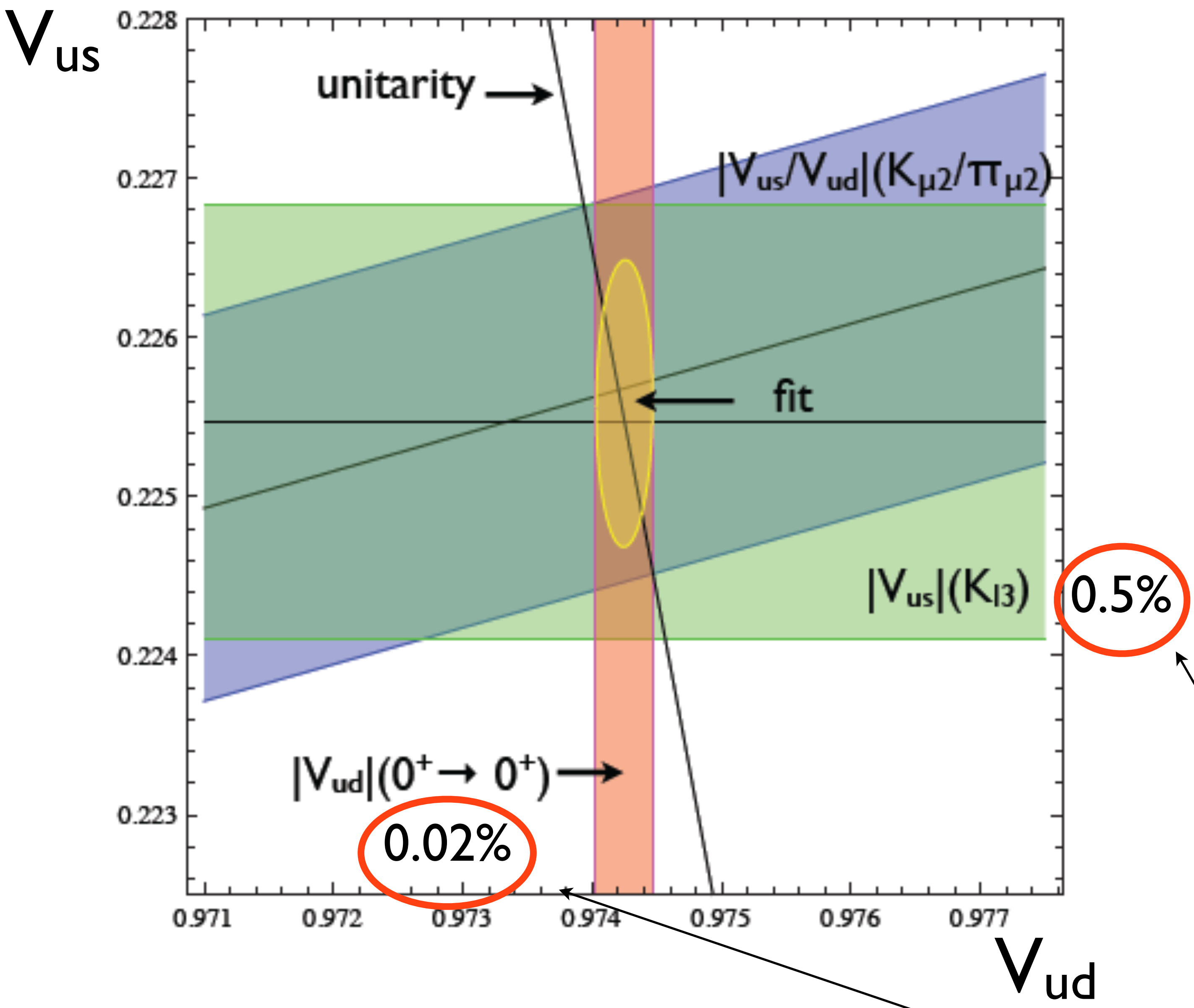
- Putting pieces together

$$V_{us}/V_{ud} = 0.2316(12) \longleftrightarrow 0.52\%$$

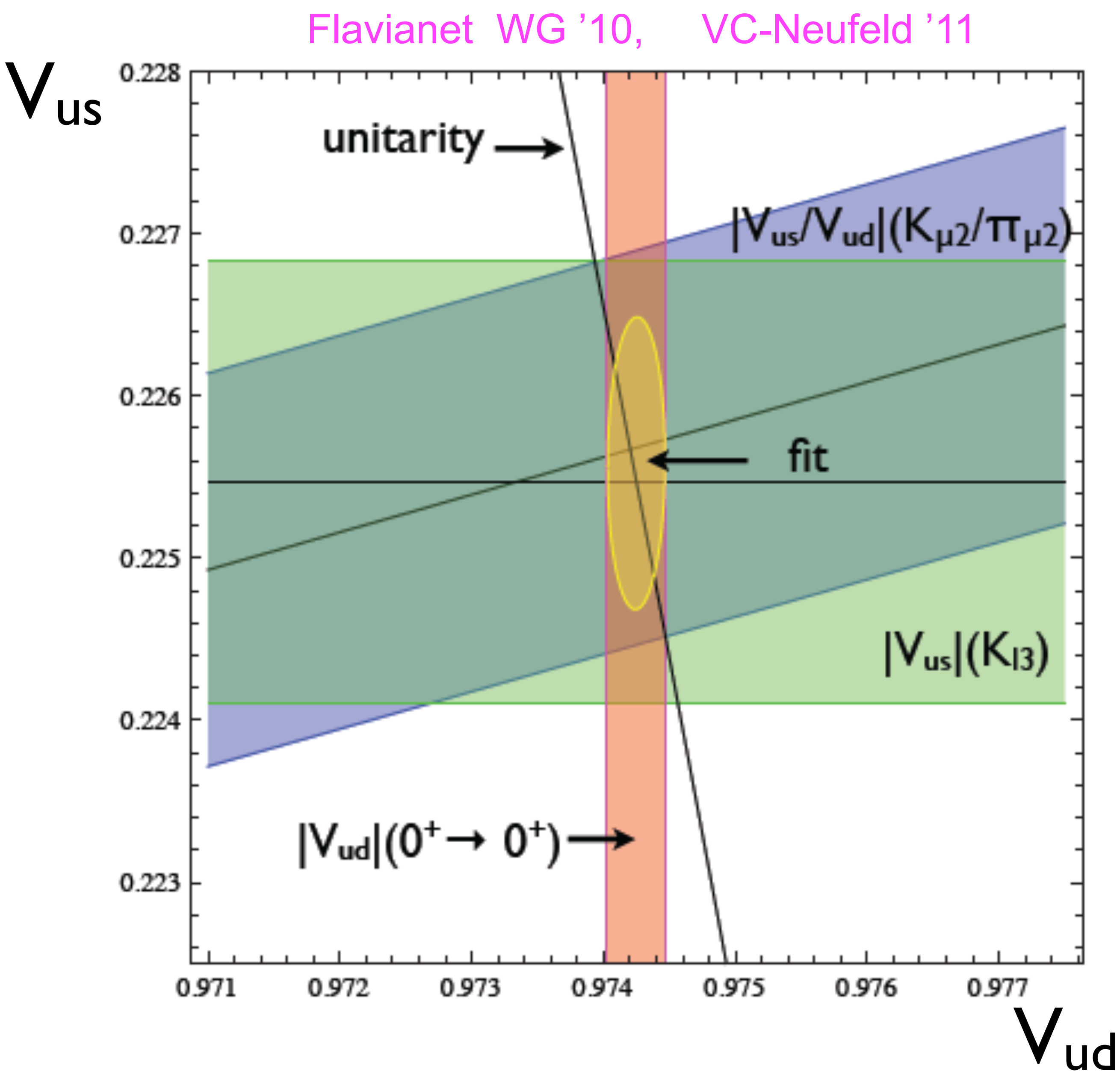
Summary on V_{ud} and V_{us}

Flavianet WG '10, VC-Neufeld '11



Theory dominated errors

Summary on V_{ud} and V_{us}



Fit result

$$V_{ud} = 0.97425\ (22)$$
$$V_{us} = 0.2256\ (9)$$

↓

$$\Delta_{CKM} = (1 \pm 6) * 10^{-4}$$

Error equally shared between V_{ud} and V_{us}

- Great success of the SM: confirms large EW radiative corrections, would naively fit $M_Z = (90 \pm 7)$ GeV !! [from S_{ew}] Marciano

Implications for BSM physics

$$\frac{1-|V_{uD}|^2}{1-|U_{\mu N}|^2}\cdot\frac{1}{1+BR^{\mu}_{\text{exotic}}}\cdot\frac{[G_F^{(\beta)}]^2}{[G_F^{(\mu)}]^2}=1+\Delta_{CKM}$$

Heavy fermion mixing

Exotic muon decays

Gauge universality violations

$|V_{uD}|\leq 0.03$

$|U_{\mu N}|\leq 0.03$

95% C.L.

$BR^{\mu}_{\text{exotic}}<0.001$

95% C.L.

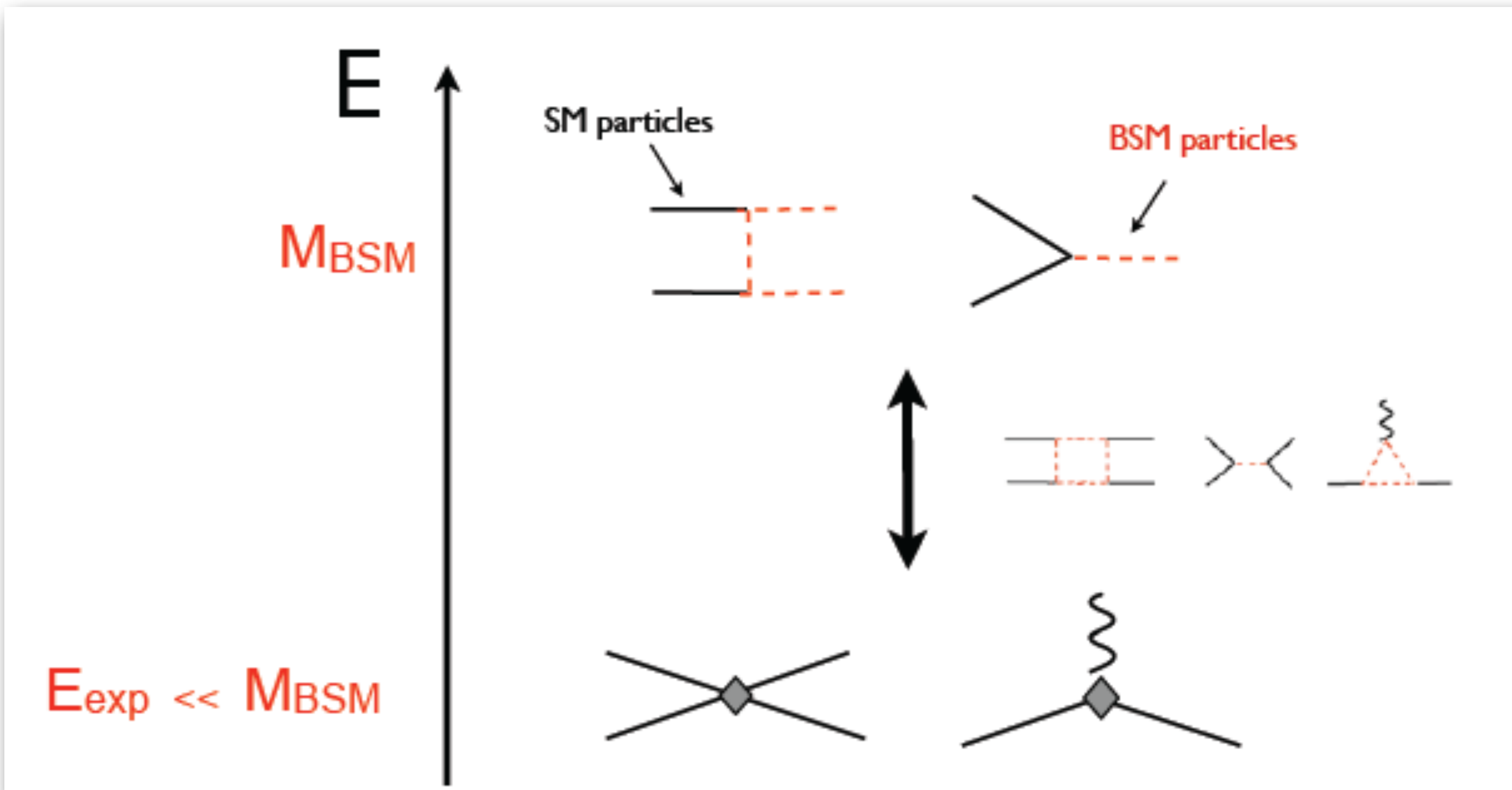
Stronger than direct limits

$BR(\mu^+\to e^+\bar{\nu}_e\nu_\mu)<0.012$

Constraints on TeV scale SM extensions

Model independent analysis

- Setup: integrate out heavy BSM degrees of freedom. Parameterize BSM interactions via SU(2)xU(1) gauge-invariant non-renormalizable operators built out of SM fields



Weinberg '79, Buchmuller-Wyler 1986, … … Han-Skiba 2004

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_X \frac{1}{\Lambda_X^2} O_X$$

stop at dim=6

V. Cirigliano, M. Gonzalez, J. Jenkins: arXiv: 0908.1754

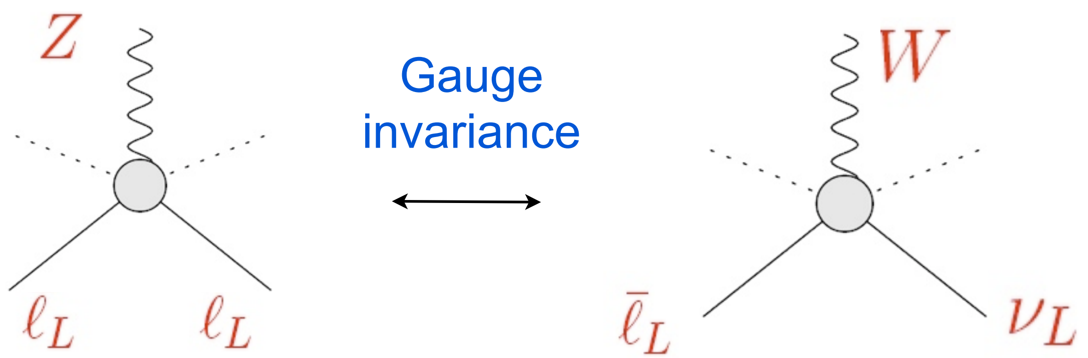
- Δ_{CKM} is sensitive to four operators**:

v~200 GeV

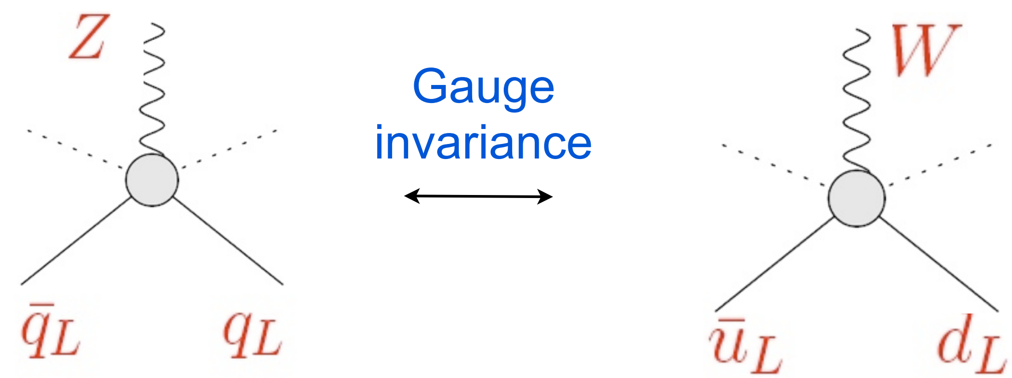
$$\Delta_{\mathrm{CKM}} = 4\left(\hat{\alpha}_{ll}^{(3)} - \hat{\alpha}_{lq}^{(3)} - \hat{\alpha}_{\varphi l}^{(3)} + \hat{\alpha}_{\varphi q}^{(3)}\right) \qquad \hat{\alpha}_X = \frac{v^2}{\Lambda_X^2}$$

Vertex corrections

$$O_{\varphi l}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi))(\bar{l}\gamma_\mu \sigma^a l)$$



$$O_{\varphi q}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{q}\gamma_\mu \sigma^a q)$$



$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \qquad \varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \qquad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$$

** Consider only U(3)^5-invariant operators ⇒ no problems with FCNC.

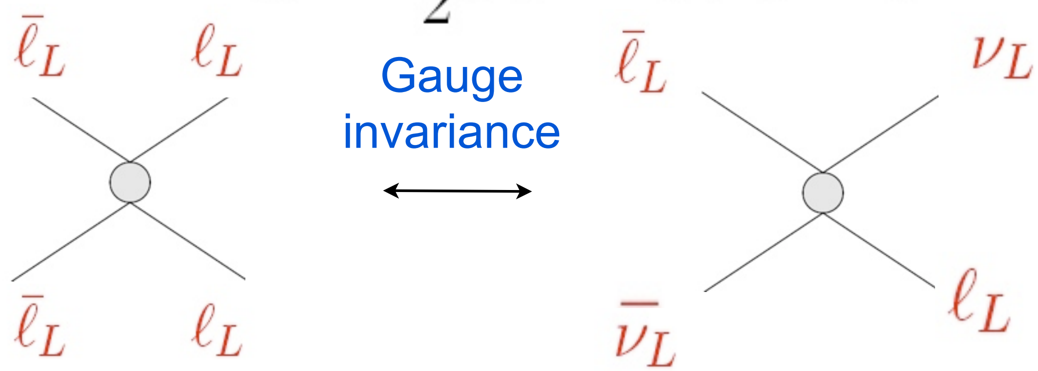
- Δ_{CKM} is sensitive to four operators:

$$\Delta_{\mathrm{CKM}} = 4\left(\hat{\alpha}_{ll}^{(3)} - \hat{\alpha}_{lq}^{(3)} - \hat{\alpha}_{\varphi l}^{(3)} + \hat{\alpha}_{\varphi q}^{(3)}\right) \qquad \hat{\alpha}_X = \frac{v^2}{\Lambda^2}$$

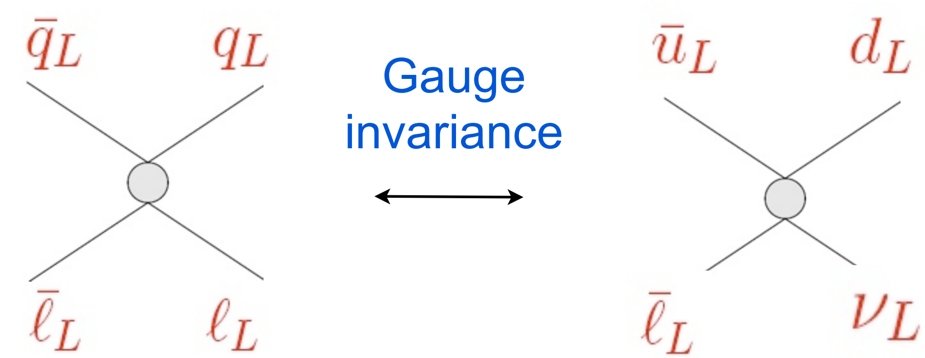
v~200 GeV

4-fermion operators

$$O_{ll}^{(3)} = \frac{1}{2}(\bar{l}\gamma^\mu\sigma^a l)(\bar{l}\gamma_\mu\sigma^a l)$$



$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$



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- Relevant operators affect other precision EW observables!

- In this framework, we can assess the significance of Δ_{CKM} constraint vs other EW precision observables in a model-independent way

1) What is the range of Δ_{CKM} allowed by precision EW tests?

$$-9.5 \times 10^{-3} \leq \Delta_{\rm CKM} \leq 0.1 \times 10^{-3}$$

90% C.L.

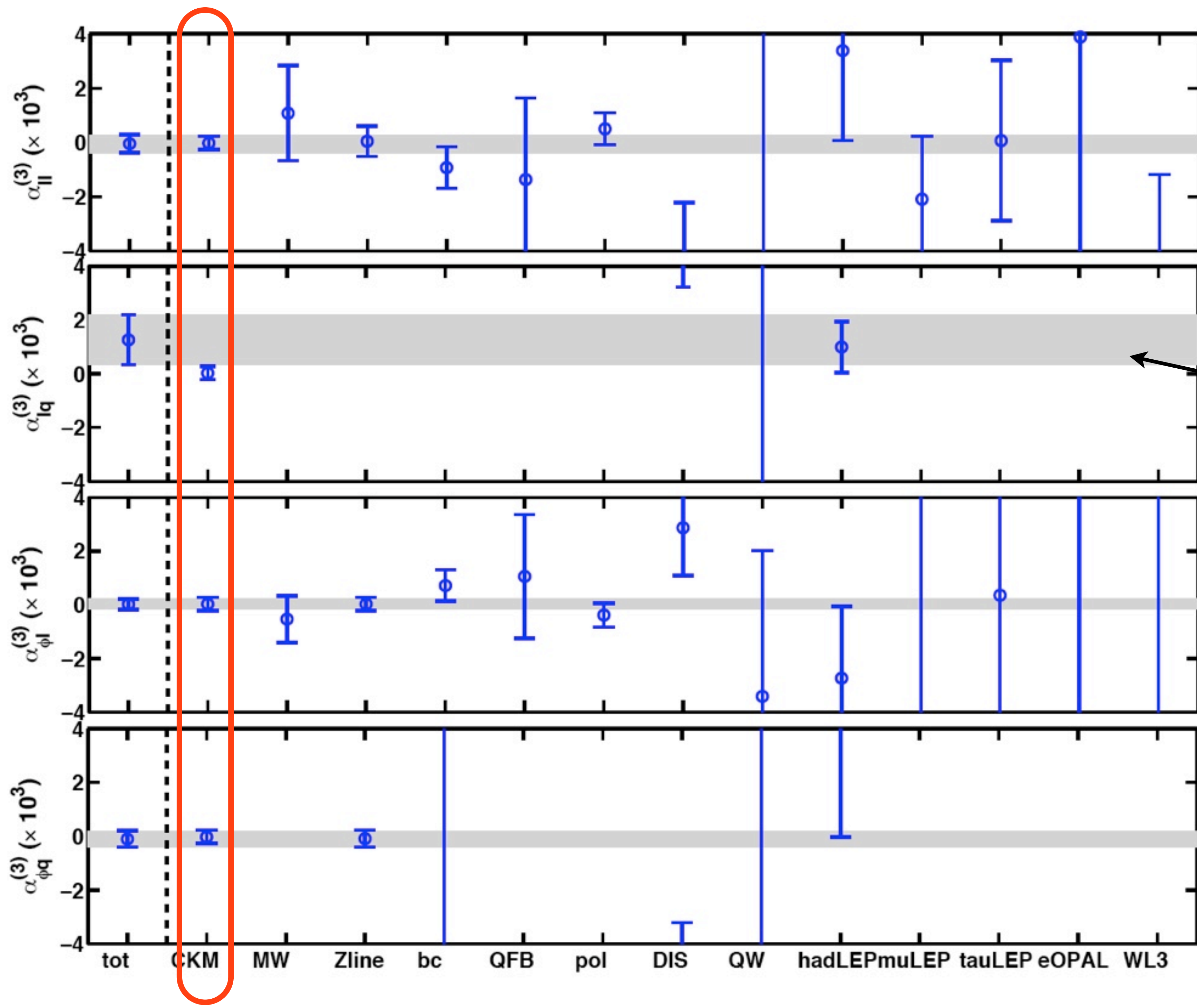
EW precision data alone would leave room for large Δ_{CKM}!

Direct constraint implies $|\Delta_{CKM}| \leq 1. \times 10^{-3}$ @ 90% CL

- In this framework, we can assess the significance of Δ_{CKM} constraint vs other EW precision observables in a model-independent way

2) What is the strength of Δ_{CKM} constraint? Same level or better than Z-pole observables (effective scale Λ > 11 TeV @ 90% CL)

$$\hat{\alpha}_X = \frac{v^2}{\Lambda_X^2}$$



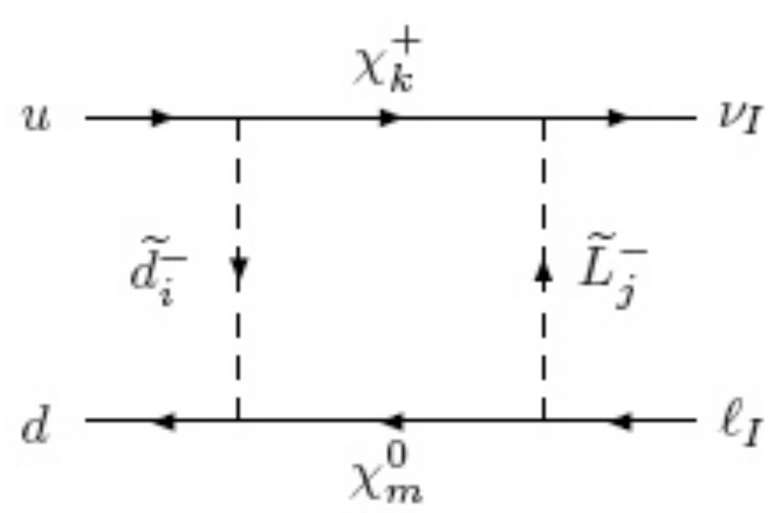
$O_{lq}^{(3)}$

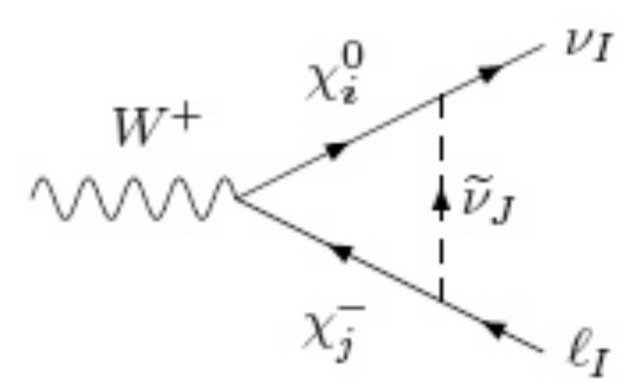
Dramatic improvement over LEP2 and APV

Deviations as large as Δ_{CKM} ~0.01 could be blamed on this operator

Universality and SUSY

- MSSM: box and vertex corrections induce non-universal corrections to the V-A CC operators
- S,P,T operators suppressed by insertions of Yukawa couplings

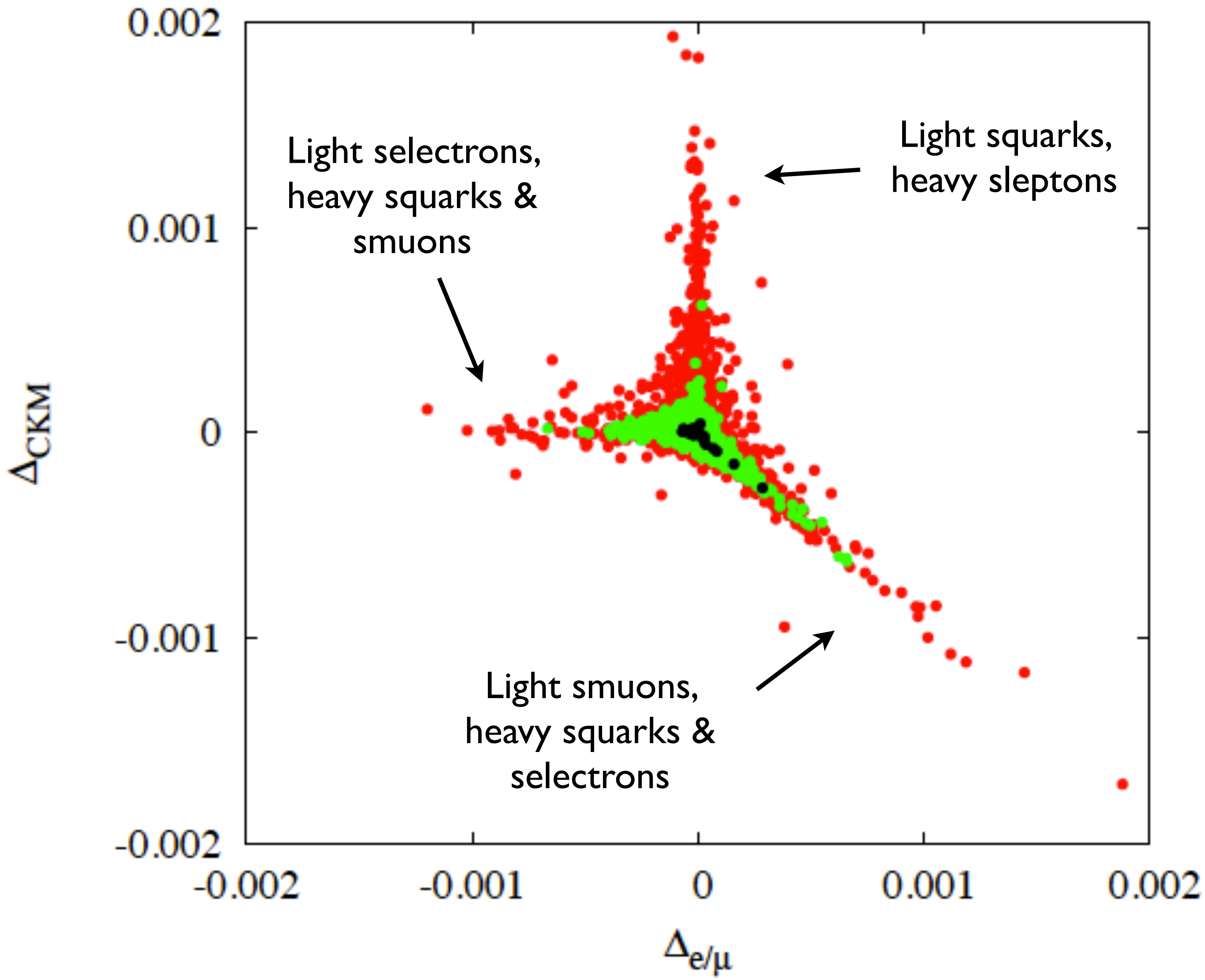




Barbieri et al '85
Hagiwara-Matsumoto-Yamada '95
Ramsey-Musolf Kurylov '01
Bauman, Erler, Ramsey-Musolf 2012

Universality and SUSY

Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035

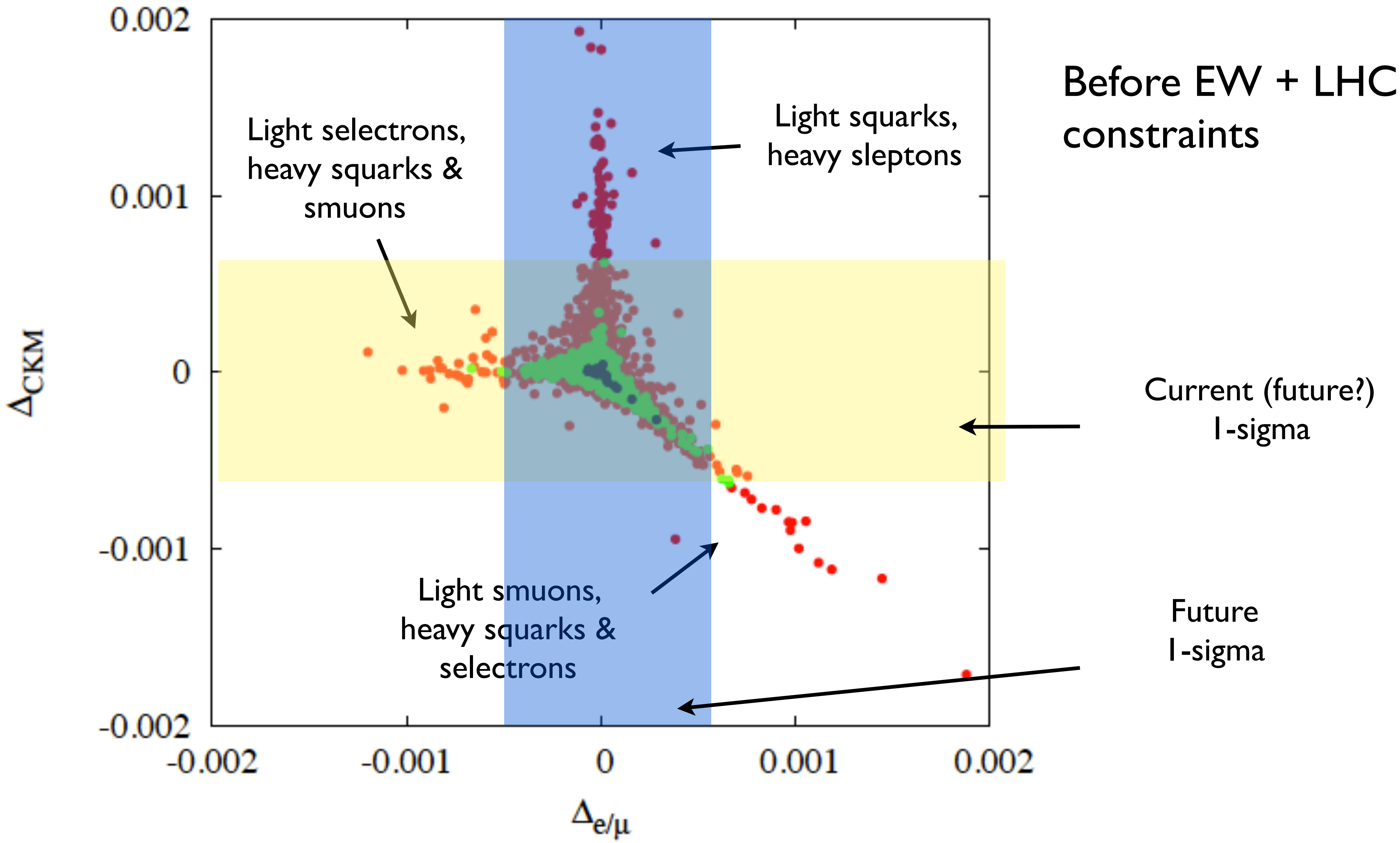


Before EW + LHC constraints

- Interesting correlation between Cabibbo universality and lepton universality: information on sfermion spectrum
- Essentially squark-slepton and selectron-smuon universality

Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035

Universality and SUSY



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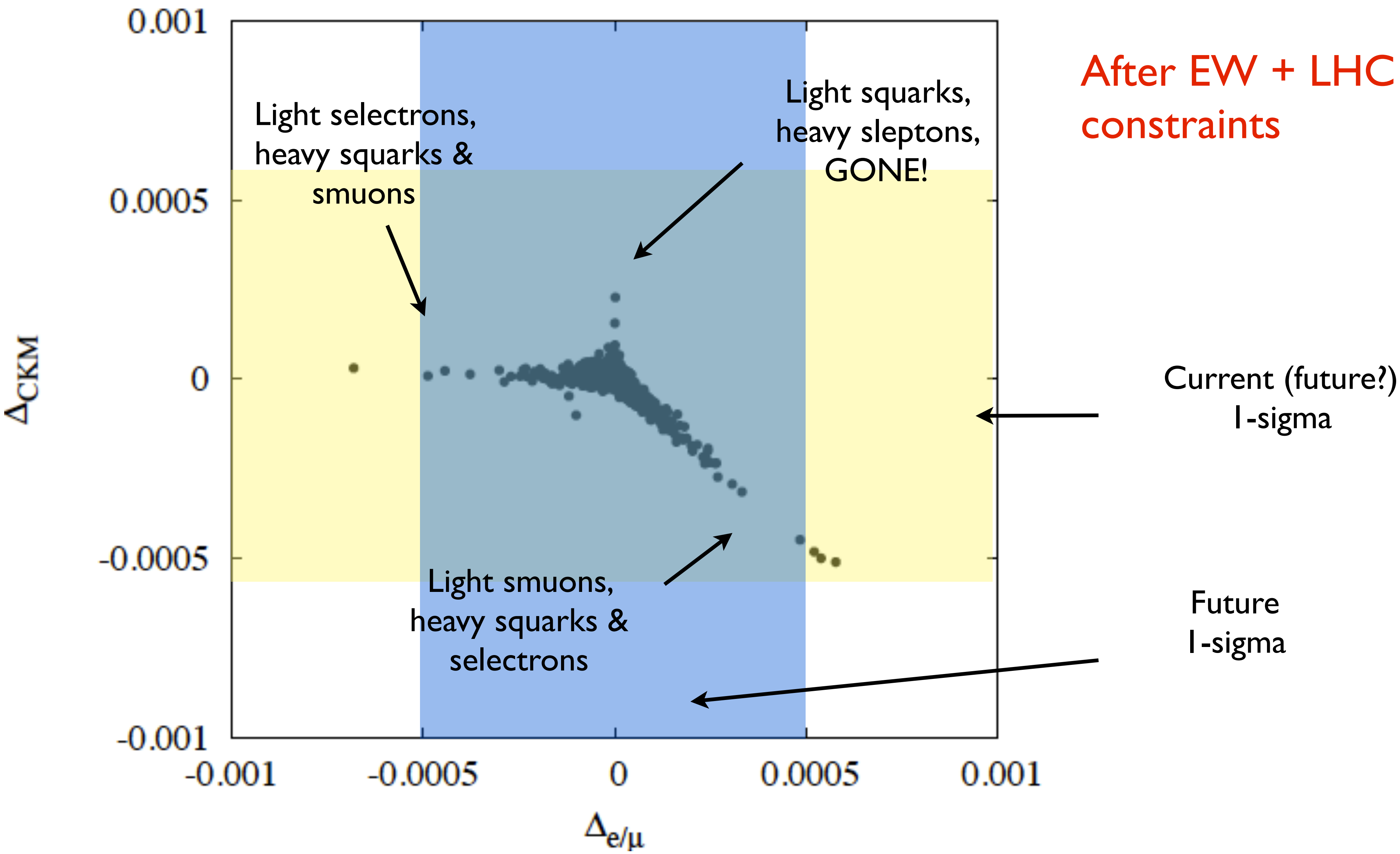
Universality and SUSY



- Effects in the MSSM are small.
- Probing MSSM parameter space requires improved precision

Summary

- CC universality tests are a "broad band" probe of new physics
- Th. developments in extraction of V_{us} since Chiral 2009
  - Kl3: new lattice calculation of $f_+(0)$ [RBC-UKQCD]
  - Kl2: isospin breaking in F_K/F_π
- BSM physics reach: $\Delta_{CKM} = (1 \pm 6) * 10^{-4}$
  - Model independent EFT analysis: Cabibbo universality probes effective scale $\Lambda \sim 11$ TeV
  - SUSY: probe squark, slepton spectrum. Effects of few 10^{-4}

Extra Slides

V_{ud} from $0^+ \rightarrow 0^+$ nuclear β decays

$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q) \, (1 + RC) \longrightarrow f\,t\,(1 + RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$

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$$(1 + RC) = (1 - \delta_C)\ (1 + \delta_R)\ (1 + \Delta_C)$$

$$\langle f | \tau_+ | i \rangle = \sqrt{2}\,(1 - \delta_C/2)$$

Coulomb distortion of wave-functions

$$\delta_C \sim 0.5\%$$

Towner-Hardy
Ormand-Brown

Nucleus-dependent rad. corr.
(Z, E^{max} ,nuclear structure)

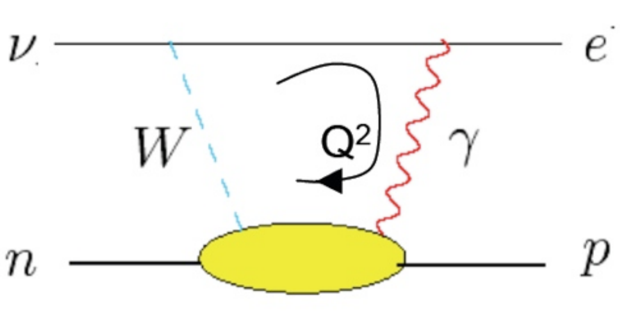
$$\delta_R \sim 1.5\%$$

Sirlin-Zucchini '86
Jaus-Rasche '87

Nucleus-independent short distance rad. corr.

$$\Delta_R \sim 2.4\%$$

Marciano-Sirlin '06



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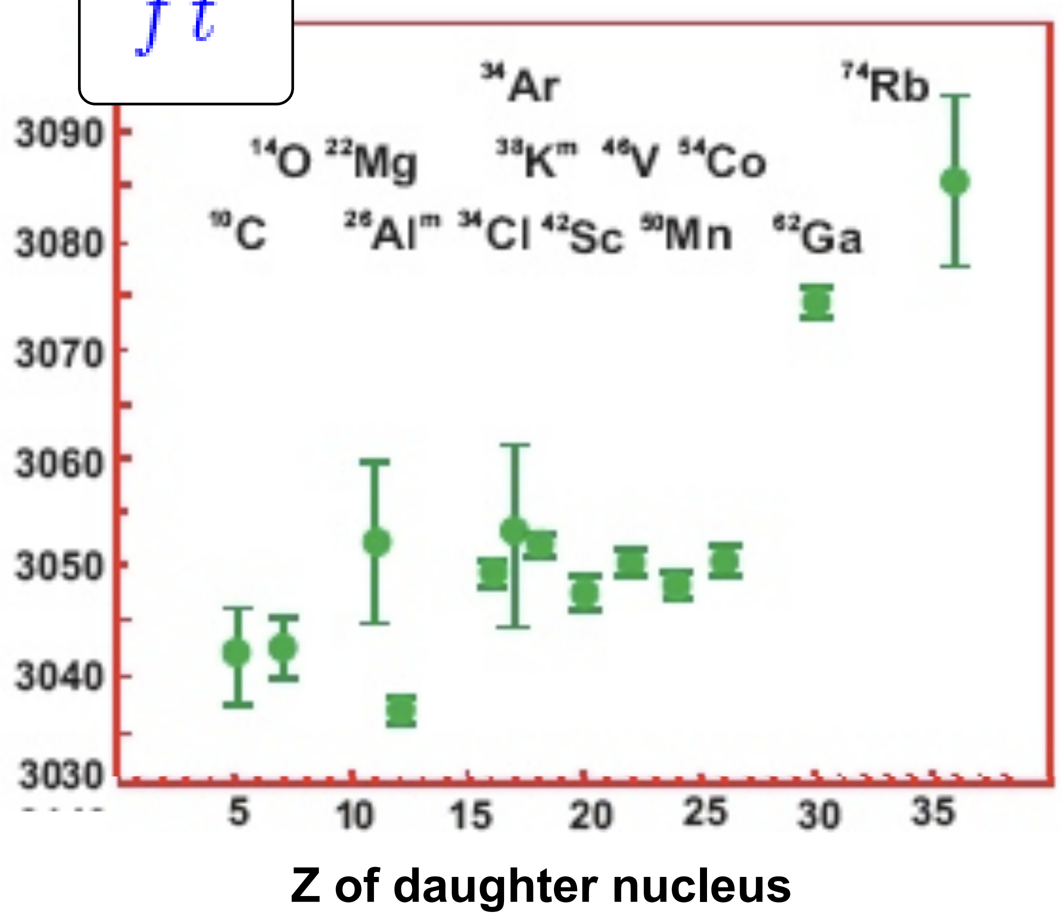
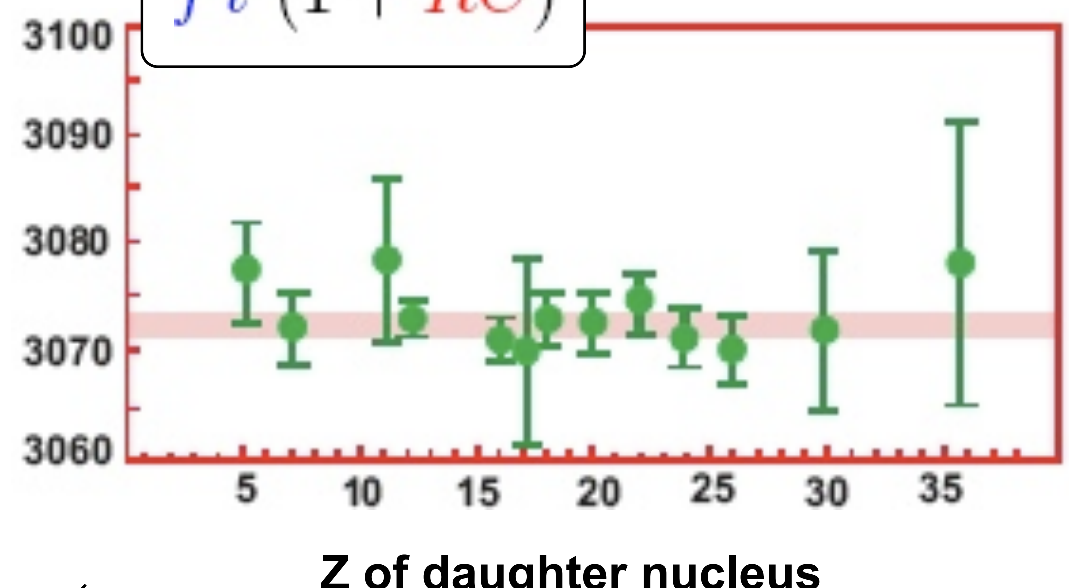
Towner-Hardy, Sirlin-Zucchini, Marciano-Sirlin

$f\,t$



→

$f\,t\ (1 + RC)$



$$V_{ud} = 0.97425\ (22)$$

Townwer-Hardy 2009

Isospin symmetry limit

- $m_u = m_d$, $e = 0$

- Choice for the values of isospin symmetric meson masses

$$M_\pi^2 = M_{\pi^0}^2$$

$$M_K^2 = \frac{1}{2}\left(M_{K^\pm}^2 + M_{K^0}^2 - M_{\pi^\pm}^2 + M_{\pi^0}^2\right)$$

Subtraction of higher order EM effects produces tiny changes in $\delta_{SU(2)}$

- To leading order:

$$M_\pi^2 = 2B_0\widehat{m}, \quad M_K^2 = B_0(m_s + \widehat{m}).$$

$$\widehat{m} = \frac{1}{2}(m_u + m_d)$$

F_K, F_π: one loop results

$$\begin{aligned} F_{\pi^\pm} &= F_0\Big\{1+\frac{4}{F_0{}^2}\left[L_4^r(\mu)(M_\pi^2+2M_K^2)+L_5^r(\mu)M_\pi^2\right] \\ &\quad -\frac{1}{2(4\pi)^2F_0{}^2}\left[2M_\pi^2\ln\frac{M_\pi^2}{\mu^2}+M_K^2\ln\frac{M_K^2}{\mu^2}\right]\Big\}, \\ F_{K^\pm} &= F_0\Big\{1+\frac{4}{F_0{}^2}\left[L_4^r(\mu)(M_\pi^2+2M_K^2)+L_5^r(\mu)M_K^2\right] \\ &\quad -\frac{1}{8(4\pi)^2F_0{}^2}\left[3M_\pi^2\ln\frac{M_\pi^2}{\mu^2}+6M_K^2\ln\frac{M_K^2}{\mu^2}+3M_\eta^2\ln\frac{M_\eta^2}{\mu^2}\right] \\ &\quad -\frac{8\sqrt{3}\,\varepsilon}{3F_0^2}L_5^r(\mu)(M_K^2-M_\pi^2) \\ &\quad -\frac{\sqrt{3}\,\varepsilon}{4(4\pi)^2F_0^2}\left[M_\pi^2\ln\frac{M_\pi^2}{\mu^2}-M_\eta^2\ln\frac{M_\eta^2}{\mu^2}-\frac{2}{3}(M_K^2-M_\pi^2)\left(\ln\frac{M_K^2}{\mu^2}+1\right)\right]\Big\}. \end{aligned}$$

$$\varepsilon=\frac{\sqrt{3}}{4}\,\frac{m_d-m_u}{m_s-\hat{m}}$$

↓

$$\frac{F_{K^\pm}^2}{F_{\pi^\pm}^2}=\frac{F_K^2}{F_\pi^2}\,(1+\delta_{\mathrm{SU}(2)})$$

$$\begin{aligned} \delta_{\mathrm{SU}(2)} &= -\frac{16\sqrt{3}\,\varepsilon}{3F_0^2}L_5^r(\mu)(M_K^2-M_\pi^2) \\ &\quad -\frac{\sqrt{3}\,\varepsilon}{2(4\pi)^2F_0^2}\left[M_\pi^2\ln\frac{M_\pi^2}{\mu^2}-M_\eta^2\ln\frac{M_\eta^2}{\mu^2}-\frac{2}{3}(M_K^2-M_\pi^2)\left(\ln\frac{M_K^2}{\mu^2}+1\right)\right] \end{aligned}$$

Neutron decay and V_{ud}

$$V_{ud} = \left[\frac{4908.7(1.9)\ s}{\tau_n (1 + 3 g_A^2)} \right]^{1/2}$$

Theory input (rad. corr.) under control
Czarnecki, Marciano, Sirlin 2004

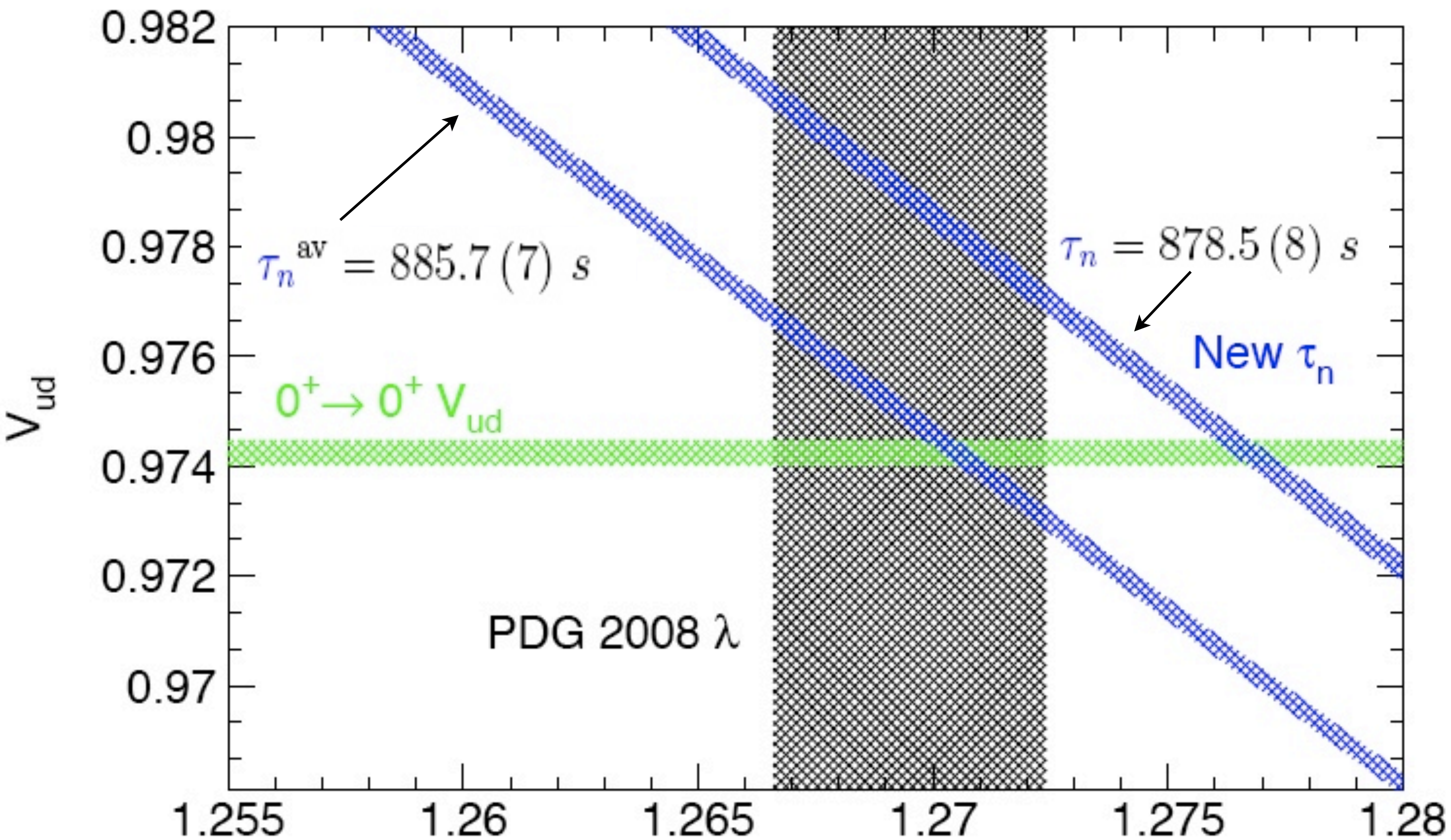
$(1-2\epsilon_R)*g_A$

- Experimental input not settled yet
- Competitive V_{ud} extraction requires:

$\delta g_A/g_A \sim 0.025\%$
$(\delta A/A \sim 0.1\%)$

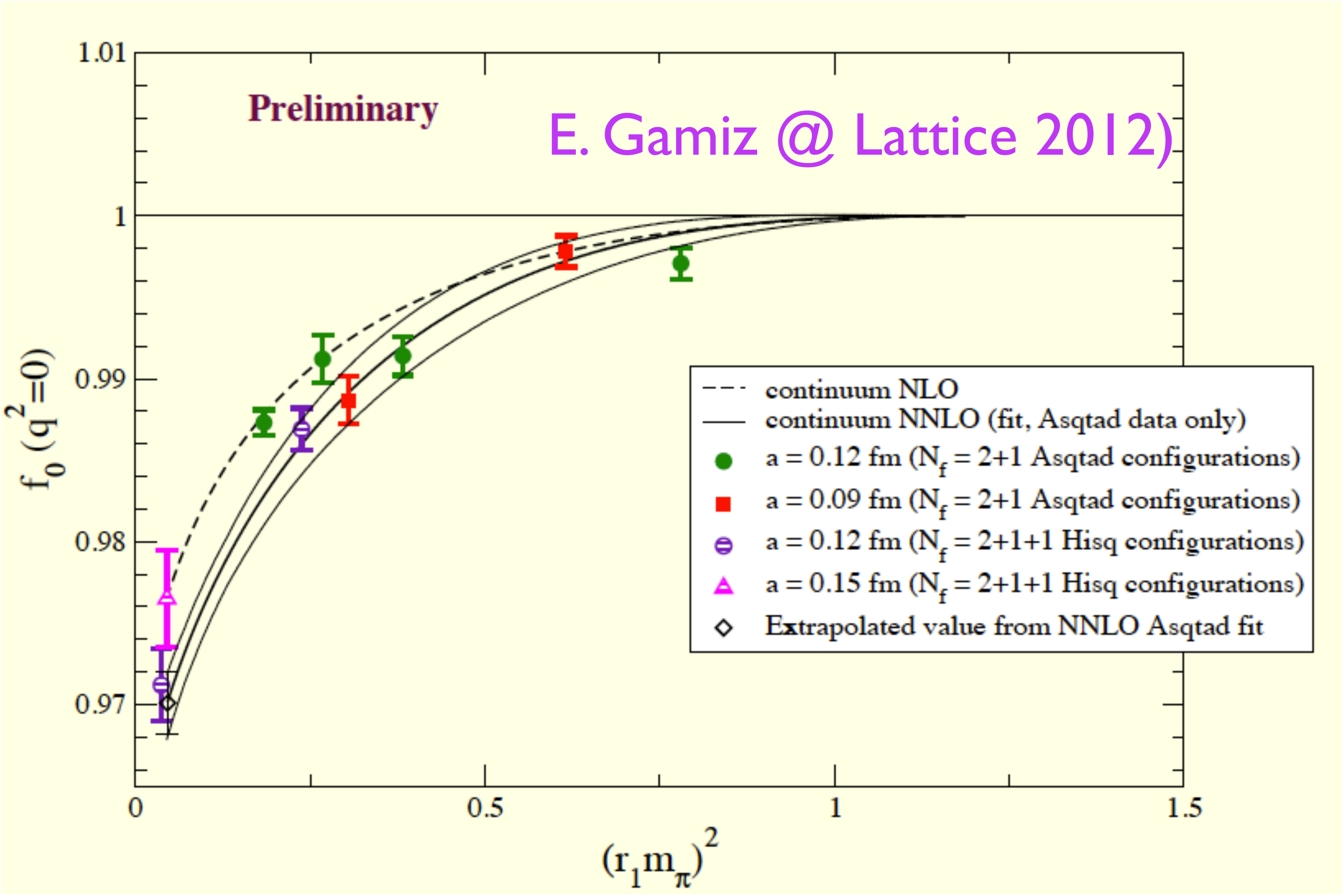
$\delta\tau_n \sim 0.35$ s
$\delta\tau_n/\tau_n \sim 0.04\ \%$

Brad Plaster, CKM 2008



$(1-2\epsilon_R)*g_A$

- N_f = 2+1 Lattice QCD: MILC preliminary



- Best fit central value $f_+(0)$ = 0.97, error estimate 0.35-0.5% [no volume extrapolation yet]