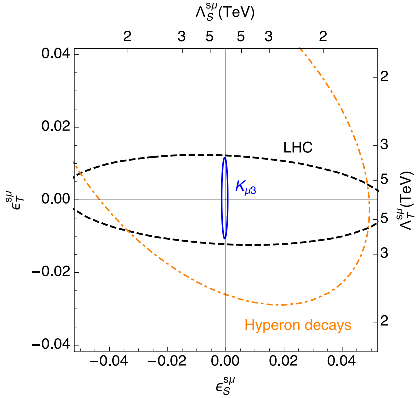
Model-independent BSM searches: interplay between flavor and the LHC

HC2NP Sept 2016



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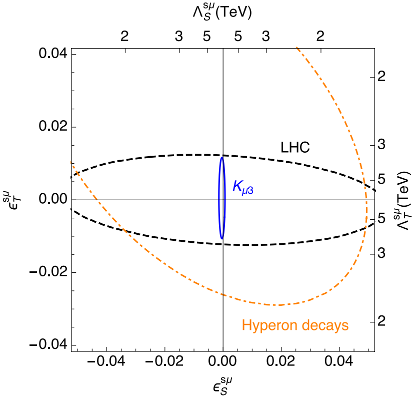
Model-independent BSM searches: interplay between flavor and the LHC

$d \to u l \nu$
$s \to u l \nu$

HC2NP — Sept 2016



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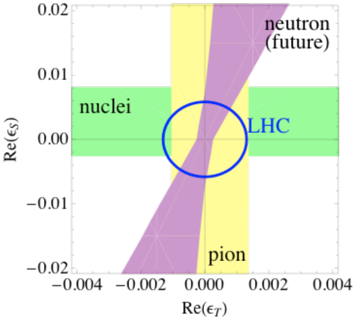
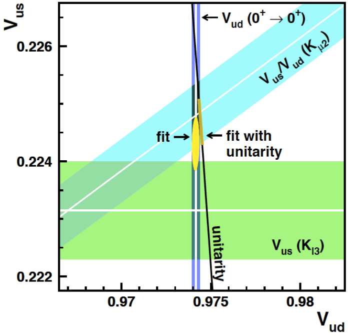
Outline

- EFT: Intro & motivation;
- Global analysis of *d→ulν, s→ulν*;
  - Beta decays & $g_{S,T}$;
- Comparison with LHC;
- Summary;



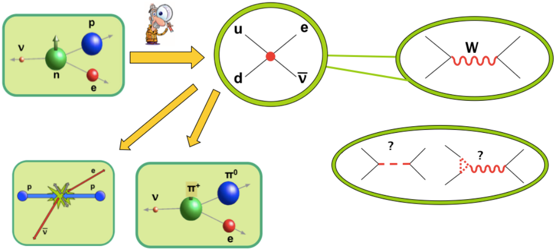
[*Cirigliano, MGA & Jenkins*, NPB830 (2010)
Bhattacharya et al., PRD85 (2012)
Cirigliano, MGA & Graesser, JHEP1302 (2013)
MGA & Naviliat-Cuncic, Ann. Phys. 525 (2013)
MGA & Martin Camalich, PRL112 (2014)
Chang, MGA & Martin Camalich, PRL114 (2015)
Courtoy, Baessler, MGA & Liuti, PRL115 (2015)
MGA & Martin Camalich, 1605.07114]

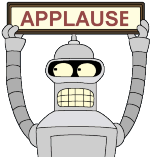
EFT: intro & motivation



OK, amazing precision, but...

- what are we really probing here?
- is it competitive (vs LEP & LHC)?



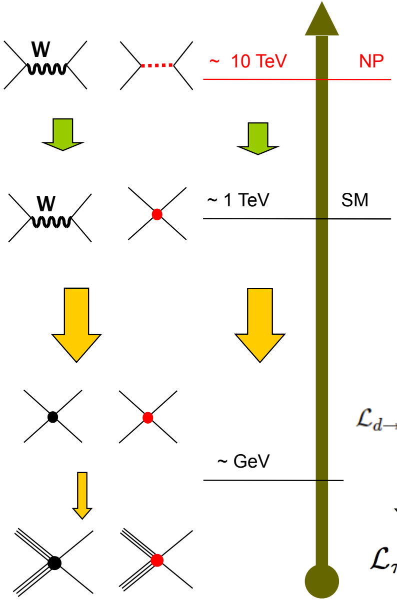


- if I am interested in a model... how can I use this analysis?

→ An EFT analysis can help!

EFT: intro & motivation

EFT = Fields + Symmetries



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

[Buchmüller-Wyler'1986, Leung et al.'1986, Grzadkowski et al'2010]

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i \mathcal{O}_i$$

[Cirigliano, MGA, Jenkins'2010, Cirigliano, MGA, Graesser'2012]

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L + \sum_{\rho\delta\Gamma}\epsilon^\Gamma_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

$$\mathcal{L}_{\pi,N,\ldots} = \ldots$$

$$\varepsilon_i = f(\alpha_j)$$

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

EFT: intro & motivation

Data

↓ **QCD input!!!**

(Correlated) bounds on the EFT Wilson Coefficients ϵ

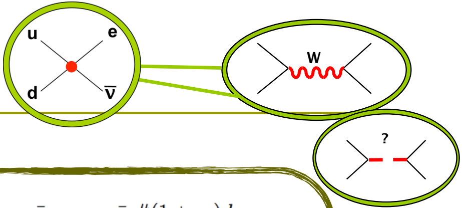
↓ **RGE!**

Matching with a specific model (or a HEP EFT)

$$\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\left(g_{NP}, M_{NP}\right)$$

- **Efficiency**:
  The analysis (bkg, PDFs, FF, simulations, …) is done once and for all!
- Useful especially if…
  - Global analysis;
  - Avoid additional assumptions.
- Valid also if NP is found.
- Analyzing (semi)leptonic hadron decays within a model-indep. EFT setup allows us to…
  - identify the (combinations of) WC probed by each measurement;
  - assess the interplay with other processes;
    (e.g. hyperon vs kaons, flavor vs LHC, …)
  - obtain results that can be applied to any given model later;

Low-E EFT



- All we can have: V_{ij} + 5 Wilson Coefficients / transitions;

$$\mathcal{L}_{d\to u e^- \bar{\nu}_e} = -\sqrt{2} G_F V_{ud} \Big[(1+\epsilon_L)\, \bar{e}_L \gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu (1-\gamma_5) d + \epsilon_R\, \bar{e}_L \gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu (1+\gamma_5) d$$

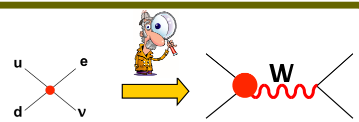
$$+ \ \epsilon_S\ \bar{e}_R \nu_L \cdot \bar{u} d - \ \epsilon_P\ \bar{e}_R \nu_L \cdot \bar{u}\gamma_5 d + 2\ \epsilon_T\ \bar{e}_R \sigma_{\mu\nu} \nu_L \cdot \bar{u}\sigma^{\mu\nu} d_L \Big]$$

$$= -\sqrt{2} G_F V_{ud} \left(1 + \epsilon_L + \epsilon_R\right) \Big[\bar{e}_L \gamma_\mu \nu_L \cdot \bar{u} \left(\gamma^\mu - (1 - 2\epsilon_R)\gamma^\mu \gamma_5\right) d$$

$$\tilde{V}^e_{ud} \qquad + \ \epsilon_S\ \bar{e}_R \nu_L \cdot \bar{u} d - \ \epsilon_P\ \bar{e}_R \nu_L \cdot \bar{u}\gamma_5 d + 2\ \epsilon_T\ \bar{e}_R \sigma_{\mu\nu} \nu_L \cdot \bar{u}\sigma^{\mu\nu} d_L \Big]$$

- Matching with the HEP EFT: ε_R is lepton independent; *[Cirigliano, MGA & Jenkins, 2010]*
  - → Very different in b → s e e, where some structures are forbidden! *[Alonso, Grinstein & Martin Camalich'2014]*
  - → Not true in the non-linear EFT! (Flavor probing the Higgs sector!) *[Cata & Jung'2015]*
- Global fit of *d→ulν* & *s→ulν* transitions;

  [MGA & Martin Camalich, 1605.07114]



$\bar{e}_L \gamma_\mu \nu_L \cdot \bar{u}_R \gamma^\mu d_R$ $\qquad$ $i(\varphi^T \epsilon D_\mu \varphi)(\bar{u}\gamma^\mu d)$

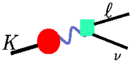
EFT fit of d(s)→ulν

[MGA & Martin Camalich, 1605.07114]

- CP-cons observables;
- Each process deserves a whole talk:

Exp + **Theory (SM)** + **NP implications**

- K→eν, μν
  π→eν, μν



Convenient ratios:

- K→eν / K→μν
- π→eν / π→μν
- π→μν / K→μν
- + K→μν

$$\Gamma_{P_{\ell 2(\gamma)}} = \frac{G_F^2 |\tilde{V}_{uD}^{\ell}|^2 f_{P^\pm}^2}{8\pi} m_{P^\pm} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{P^\pm}^2}\right)^2$$

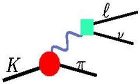
$$\mathbf{x} \left(1 + \delta_{\text{em}}^{P\ell}\right)$$ *[Marciano-Sirlin'93, Cirigliano-Rosell'07, ...]*

$$\mathbf{x} \left(-4\epsilon_R^D - \frac{2m_{P^\pm}^2}{m_\ell (m_D + m_u)} \epsilon_P^{D\ell}\right)$$

EFT fit of d(s)→ulν

[MGA & Martin Camalich, 1605.07114]

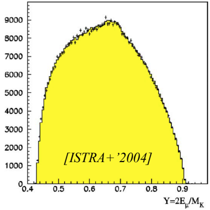
K_{l3} (K_L, K_S, K^+→πeν, πμν)



- SM analysis nicely done by Flavianet; *[Antonelli et al'2010]*
- Kinematic distr:
  - BSM ($\varepsilon_{S,T}$) and QCD (FF slopes);
  - Interference ~m_l/E ==> K_{e3} effects ~ $|\varepsilon_{S,T}|^2$
  - μ channel: ε_S accessible via Callan-Treiman theorem:

$$\bar{f}_0(q^2_{\rm CT})_{exp} = \bar{f}_0(q^2_{\rm CT})_{QCD}\left(1+\epsilon_S^{s\mu}\frac{m_K^2-m_\pi^2}{m_\mu(m_s-m_u)}\right)$$
$$\frac{f_K}{f_\pi}\frac{1}{f_+(0)}+\Delta_{\rm CT}$$

[Bernard et al.'06, '09; FLAG'13; Gasser & Leutwyler'84; Bijnens & Ghorbani'07;]



- Total rates:

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3}\, C\, S_{\rm EW}\, |\tilde{V}^\ell_{us}|^2 f_+(0)^2\, \overbrace{I_K^\ell(\lambda_{+,0},\,\epsilon_S^{s\ell},\,\epsilon_T^{s\ell})}^{\text{Phase-space Int.}}\left(1+\delta^c+\delta^{c\ell}_{\rm em}\right)^2$$

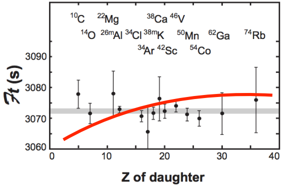
$$\to \{\tilde{V}^e_{us}\,,\ \tilde{V}^\mu_{us}\} \to \{\tilde{V}^e_{us}\,,\ \epsilon_L^{s\mu}-\epsilon_L^{se}\}$$

Mode	$V_{us}\, f_+(0)$
$K_{L\,e3}$	0.2163(6)
$K_{L\,\mu 3}$	0.2166(6)
$K_{S\,e3}$	0.2155(13)
$K^\pm_{e3}$	0.2172(8)
$K^\pm_{\mu 3}$	0.2170(11)

EFT fit of d(s)→ulν

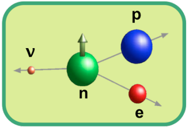
[MGA & Martin Camalich, 1605.07114]

- Nuclear / baryon decays:



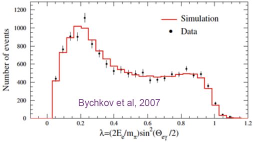
- Superallowed nuclear β decays
  - SM → V_{ud};
  - BSM → $\tilde{V}^{e}_{ud}$, $b_F \sim g_S\, \varepsilon_S$

- Neutron decay → $g_A^{\text{expt}} = (1 - 2\epsilon_R^d)\, g_A$ ➡ $\langle p(p_p)|\, \bar{u}\gamma_\mu\gamma_5 d\, |n(p_n)\rangle$
- Hyperon decays → $g_1^{\text{expt}} = (1 - 2\epsilon_R^s)\, g_1$



- Radiative pion decay → $F_{T\pi}\, \varepsilon_T$

  $\pi \to e\nu\gamma$



EFT fit of d(s)→ulν

[MGA & Martin Camalich, 1605.07114]

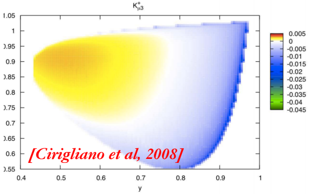
- Theory:
  - Radiative & isospin-breaking corrections;
    E.g. $R_\pi^{\rm SM} = 1.2352(1)\times 10^{-4}$

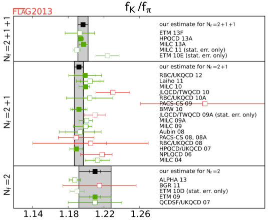
    $R_K^{\rm SM} = 2.477(1)\times 10^{-5}$

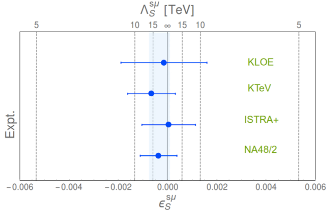
    [Cirigliano & Rosell, 2007]
  - Form factors:
    - $f_+(0)$, f_K/f_π, f_K
    - g_A, g_1
    - B_T, g_S, $F_{T\pi}$
  - Callan-Treiman theorem:

$$\bar f_0(q^2 = m_K^2 - m_\pi^2) = \frac{f_K}{f_\pi}\frac{1}{f_+(0)} + \Delta_{\rm CT}$$

$$\langle\pi|\bar s\gamma^\mu u|K\rangle$$
$$\langle\pi|\bar s u|K\rangle$$
$$\langle\pi|\bar s\sigma^{\mu\nu}u|K\rangle$$
$$\langle 0|\bar s\gamma^\mu u|K\rangle$$
$$\langle p|\bar u\gamma^\mu\gamma^5 d|n\rangle$$
$$\langle p|\bar u d|n\rangle$$







EFT fit of d(s)→ulν

[MGA & Martin Camalich, 1605.07114]

$$
\begin{pmatrix}
\tilde{V}^e_{ud} \\
\tilde{V}^e_{us} \\
\epsilon_L^{s\mu} - \epsilon_L^{se} \\
\epsilon_L^{de} - \epsilon_L^{d\mu} + 24\,\epsilon_P^{d\mu} \\
\epsilon_P^{de} \\
\epsilon_R^{d} \\
\epsilon_P^{se} \\
\epsilon_P^{s\mu} \\
\epsilon_R^{s} \\
\epsilon_S^{s\mu} \\
\epsilon_T^{s\mu} \\
\epsilon_S^{de}
\end{pmatrix}
=
\begin{pmatrix}
0.97451 \pm 0.00038 \\
0.22408 \pm 0.00087 \\
1.0 \pm 2.5 \\
1.9 \pm 3.8 \\
4.0 \pm 7.8 \\
-1.3 \pm 1.7 \\
-0.4 \pm 2.1 \\
-0.7 \pm 4.3 \\
0.1 \pm 5.0 \\
-3.9 \pm 4.9 \\
0.5 \pm 5.2 \\
1.4 \pm 1.3
\end{pmatrix}
\times 10\wedge
\begin{pmatrix}
0 \\ 0 \\ -3 \\ -2 \\ -6 \\ -2 \\ -5 \\ -3 \\ -2 \\ -4 \\ -3 \\ -3
\end{pmatrix}
$$

$$
\begin{aligned}
\Delta_{\text{CKM}} &= 1 - |\tilde{V}^e_{ud}|^2 - |\tilde{V}^e_{us}|^2 - |\tilde{V}^e_{ub}|^2 \\
&= 1.9\,(\epsilon_L^{de} + \epsilon_R^{d}) + 0.1\,(\epsilon_L^{se} + \epsilon_R^{s}) - 2\frac{\delta G_F}{G_F} \\
&= -(1.2 \pm 8.4)\cdot 10^{-4}
\end{aligned}
$$

$$\epsilon_T^{de} = (0.1 \pm 0.8) \times 10^{-3},$$

$$\epsilon_S^{se} = (-1.6 \pm 3.3) \times 10^{-3},$$

$$\epsilon_T^{se} = (0.9 \pm 1.8) \times 10^{-2},$$

[at μ=2 GeV, MS-bar scheme]

(+ QCD quantities!)

$$
\rho = \begin{pmatrix}
1. & 0. & 0. & 0.01 & 0.01 & 0. & 0. & 0. & 0. & 0. & 0. & 0.82 \\
- & 1. & -0.12 & 0. & 0. & 0. & 0.04 & 0.04 & 0. & -0.26 & 0. & 0. \\
- & - & 1. & 0. & 0. & 0. & 0. & 0.03 & 0. & 0. & 0.72 & 0. \\
- & - & - & 1. & 0.9995 & -0.87 & 0.09 & 0.09 & 0. & 0.04 & 0. & 0.01 \\
- & - & - & - & 1. & -0.87 & 0.09 & 0.09 & 0. & 0.04 & 0. & 0.01 \\
- & - & - & - & - & 1. & 0. & 0. & 0. & 0. & 0. & 0. \\
- & - & - & - & - & - & 1. & 0.9993 & -0.98 & -0.01 & 0. & 0. \\
- & - & - & - & - & - & - & 1. & -0.98 & -0.01 & 0.02 & 0. \\
- & - & - & - & - & - & - & - & 1. & 0. & 0. & 0. \\
- & - & - & - & - & - & - & - & - & 1. & 0. & 0. \\
- & - & - & - & - & - & - & - & - & - & 1. & 0. \\
- & - & - & - & - & - & - & - & - & - & - & 1.
\end{pmatrix}
$$

$$\tilde{V}^\ell_{uD} = \left(1 + \epsilon_L^{D\ell} + \epsilon_R^{D} - \frac{\delta G_F}{G_F}\right) V_{uD}$$

EFT fit of d(s)⟶ulν

[MGA & Martin Camalich, 1605.07114]

$$
\begin{pmatrix}
\tilde{V}^{e}_{ud} \\
\tilde{V}^{e}_{us} \\
\epsilon^{s\mu}_{L} - \epsilon^{se}_{L} \\
\epsilon^{de}_{L} - \epsilon^{d\mu}_{L} + 24\,\epsilon^{d\mu}_{P} \\
\epsilon^{de}_{P} \\
\epsilon^{d}_{R} \\
\epsilon^{se}_{P} \\
\epsilon^{s\mu}_{P} \\
\epsilon^{s}_{R} \\
\epsilon^{s\mu}_{S} \\
\epsilon^{s\mu}_{T} \\
\epsilon^{de}_{S}
\end{pmatrix}
=
\begin{pmatrix}
0.97451 \pm 0.00038 \\
0.22408 \pm 0.00087 \\
1.0 \pm 2.5 \\
1.9 \pm 3.8 \\
4.0 \pm 7.8 \\
-1.3 \pm 1.7 \\
-0.4 \pm 2.1 \\
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-3.9 \pm 4.9 \\
0.5 \pm 5.2 \\
1.4 \pm 1.3
\end{pmatrix}
\times 10^{\wedge}
\begin{pmatrix}
0 \\ 0 \\ -3 \\ -2 \\ -6 \\ -2 \\ -5 \\ -3 \\ -2 \\ -4 \\ -3 \\ -3
\end{pmatrix}
$$

$$\epsilon^{de}_{T} = (0.1 \pm 0.8) \times 10^{-3},$$

$$\epsilon^{se}_{S} = (-1.6 \pm 3.3) \times 10^{-3},$$

$$\epsilon^{se}_{T} = (0.9 \pm 1.8) \times 10^{-2},$$

[at μ=2 GeV, MS-bar scheme]

[Errors are the result of exp + helicity enhancements + + hadronic uncertainties (HC2NP)!]

$\langle p|\bar{u}\gamma^{\mu}\gamma^{5}d|n\rangle$ ***(g_A !)***

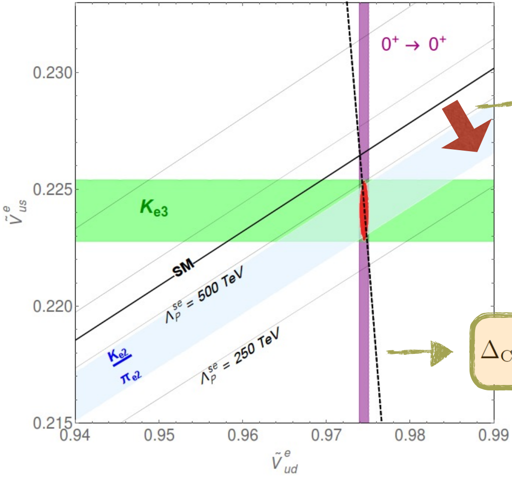
(+ QCD quantities!)

$$\tilde{V}^{\ell}_{uD} = \left(1 + \epsilon^{D\ell}_{L} + \epsilon^{D}_{R} - \frac{\delta G_F}{G_F}\right) V_{uD}$$

$$
\rho =
\begin{pmatrix}
1. & 0. & 0. & 0.01 & 0.01 & 0. & 0. & 0. & 0. & 0. & 0. & 0.82 \\
- & 1. & -0.12 & 0. & 0. & 0. & 0.04 & 0.04 & 0. & -0.26 & 0. & 0. \\
- & - & 1. & 0. & 0. & 0. & 0. & 0.03 & 0. & 0. & 0.72 & 0. \\
- & - & - & 1. & 0.9995 & -0.87 & 0.09 & 0.09 & 0. & 0.04 & 0. & 0.01 \\
- & - & - & - & 1. & -0.87 & 0.09 & 0.09 & 0. & 0.04 & 0. & 0.01 \\
- & - & - & - & - & 1. & 0. & 0. & 0. & 0. & 0. & 0. \\
- & - & - & - & - & - & 1. & 0.9993 & -0.98 & -0.01 & 0. & 0. \\
- & - & - & - & - & - & - & 1. & -0.98 & -0.01 & 0.02 & 0. \\
- & - & - & - & - & - & - & - & 1. & 0. & 0. & 0. \\
- & - & - & - & - & - & - & - & - & 1. & 0. & 0. \\
- & - & - & - & - & - & - & - & - & - & 1. & 0. \\
- & - & - & - & - & - & - & - & - & - & - & 1.
\end{pmatrix}
$$

EFT fit of d(s)→ulν

[MGA & Martin Camalich, 1605.07114]



$$-2(\epsilon_R^s - \epsilon_R^d) - \frac{B_0}{m_e}\left(\epsilon_P^{se} - \epsilon_P^{de}\right)$$

$$\Delta_{\rm CKM} = 2|V_{ud}^e|^2(\epsilon_L^{de} + \epsilon_R^d) + 2|V_{us}|^2(\epsilon_L^{se} + \epsilon_R^s) - 2\frac{\delta G_F}{G_F}$$

$$\tilde{V}_{uD}^\ell = \left(1 + \epsilon_L^{D\ell} + \epsilon_R^D - \frac{\delta G_F}{G_F}\right) V_{uD}$$

EFT fit of d(s)→ulν

[MGA & Martin Camalich, 1605.07114]

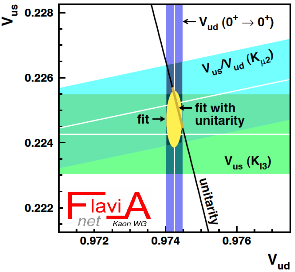
- Usual analysis*

$$\begin{pmatrix} \tilde{V}_{ud} \\ \tilde{V}_{us} \end{pmatrix} = \begin{pmatrix} 0.97416(21) \\ 0.22484(64) \end{pmatrix}, \quad \rho = \begin{pmatrix} 1. & 0.03 \\ - & 1. \end{pmatrix}$$

$$\Delta_{\rm CKM} = -(4.6 \pm 5.2) \times 10^{-4}$$

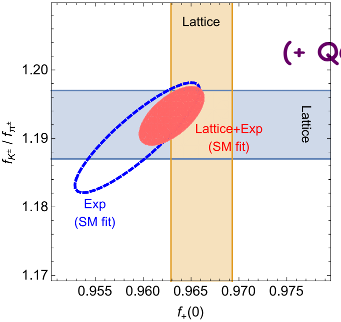
U(3)⁵ symmetry

$$\begin{pmatrix} l_e \\ l_\mu \\ l_\tau \end{pmatrix}, \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}, \begin{pmatrix} q_u \\ q_c \\ q_t \end{pmatrix}, \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- SM limit*

$$|V_{ud}| = 0.97432(12)$$
or equivalently
$$|V_{us}| = 0.2252(5)$$



(+ QCD quantities!)

$$\begin{pmatrix} f_{K^\pm} \\ f_{K^\pm}/f_{\pi^\pm} \\ f_+(0) \end{pmatrix} = \begin{pmatrix} 155.62(44)\text{MeV} \\ 1.1936(30) \\ 0.9632(23) \end{pmatrix}, \quad \rho = \begin{pmatrix} 1. & 0.80 & 0.60 \\ - & 1. & 0.60 \\ - & - & 1. \end{pmatrix}$$

* with some minor improvements:
$\Gamma(K_{\mu 2})$ & CT theorem implemented.

Future bounds from β decay

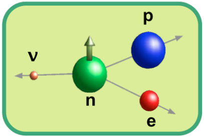
Neutron

LANSCE (Los Alamos), ILL (Grenoble), J-PARC (Tokai), PNPI (Gatchina), FRM-II (Munich), SNS (Oak Ridge), NIST (Gaithersburg), PSI (Villigen), ...

Nuclei

NSCL (^{6}He, ^{20}F), TRIUMF (^{38m}K, ^{37}K), CERN (^{32}Ar), GANIL (^{35}Ar, ^{6}He), PSI (^{8}Li), Louvain-la-Neuve (^{14}O/^{10}C, ^{114}In, ^{60}Co), Groningen (^{26m}Al/^{30}K), Oak Ridge (^{6}He), Seattle (^{6}He), Princeton (^{19}Ne), ...

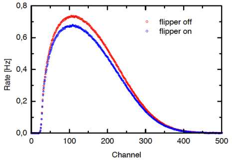
$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E)\left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + (B + b_B\frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$



$$\mathbf{b} = \#\, g_S\, \varepsilon_S + \#\, g_T\, \varepsilon_T$$

$\delta b_n \sim 0.001$

Clean powerful tree-level probes!



$$\langle p|\bar{u}d|n\rangle \Rightarrow g_S$$

$$\langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle \Rightarrow g_T$$

How well do we know them?

Future bounds from β decay

$b = \# \, g_S \, \varepsilon_S + \# \, g_T \, \varepsilon_T$

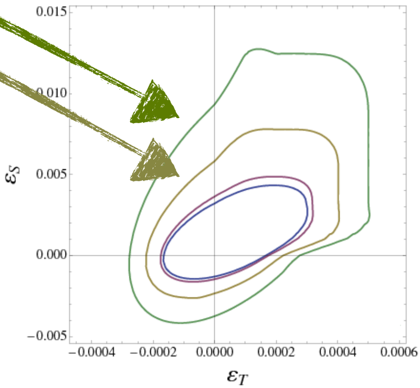
How well do we know g_S and g_T?

Is this precision OK?
How well do we need to know them?
(assuming $b_n < 0.001$)

$\delta g_{S,T}/g_{S,T} \sim$ 15-20%

	g_S	g_T
Adler et al. '1975 (quark model)	0.60(40)	1.45(85)
PNDME 2011	0.80(40)	1.05(35) *[average]*
÷2.5	*20%*	*13%*
÷5.0	*10%*	*7%*

!!



[Bhattacharya, Cirigliano, Cohen, Filipuzzi, MGA, Graesser, Gupta, Lin, PRD85 (2012)]

Future bounds from β decay

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LHPC 2012	1.08(32)	1.04(02)
RQCD 2014	1.02(35)	1.01(02)
PNDME 2013/15	0.72(32)	1.02(08)
ETMC 2015	1.21(42)	1.03(06)

"We quantify all syst. errors, including for the 1st time a simultaneous extrapolation in a, V & m_q"

PS: gT pheno det are also possible. Active field, with more data in the near future…

$$g_T = \int \left(h_1^u(x) - h_1^d(x)\right) dx$$

[Gao et al., EPJ Plus 126 (2011), Goldstein et al, arXiv:1401.0438, Courtoy, Baessler, MGA, Liuti, PRL 115 (2015)]

Future bounds from β decay

How well do we know g_S and g_T?

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CVC	1.02(11)	

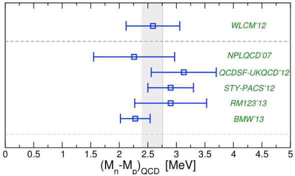
PNDME'2016 [1606.07049]

$g_S = 0.97(13)$
$g_T = 0.987(55)$

Is this precision OK?
How well do we need to know them?
(assuming b_n < 0.001)

$\delta g_{S,T}/g_{S,T} \sim$ 15-20%

Not trivial!
Not the case in rad. pion decays, SL hyperon decays, …



$$\partial_\mu (\bar{u}\gamma^\mu d) = -i(m_d - m_u)\bar{u}d$$

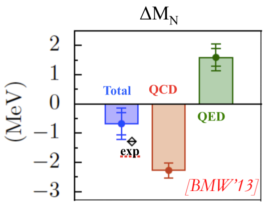
$$g_S = \frac{(M_n - M_p)_{QCD}}{m_d - m_u} g_V$$

Useful connection between two different Lattice efforts!

[MGA & Martin Camalich, Phys. Rev. Lett. 112 (2014)]

Future bounds from β decay

- *CVC used routinely to relate V & S FF in many other processes (e.g. meson decays, EDMs, …), but overlooked here;*
- *It's taking too long to be "digested" by the lattice community:*
  - *Lattice coll. working on m_n-m_p have not use it yet (?)*
  - *(Some) lattice coll. calculating g_s do not even quote g_S^{CVC}(?!)*
  - *Used for the first time in [PNDME, 1606.07049]!*



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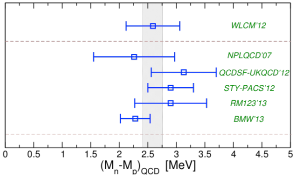

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Useful connection between two different Lattice efforts!

PNDME'2016 [1606.07049]

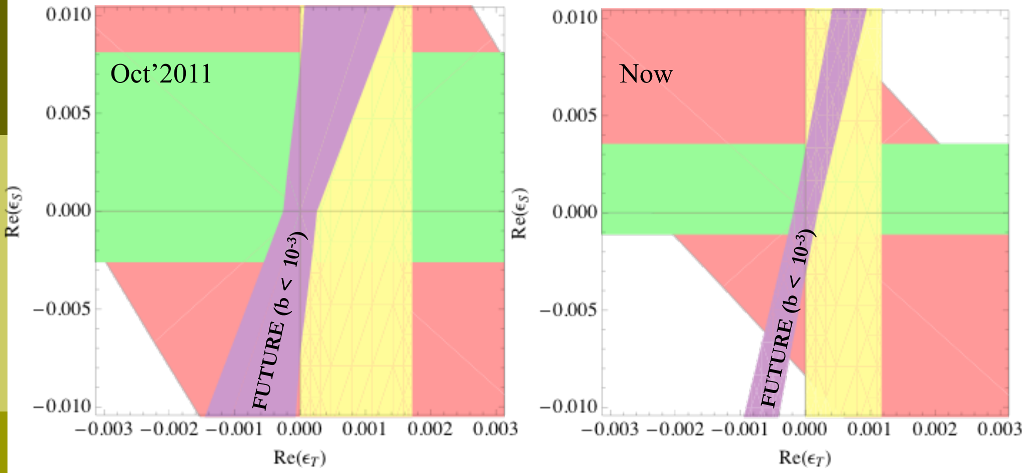
g_S = 0.97(13)
g_T = 0.987(55)

→ *ΔM_N = 2.28(27) MeV*
(2nd best det. ever)

[MGA & Martin Camalich, Phys. Rev. Lett. 112 (2014)]

Future bounds from β decay

!!



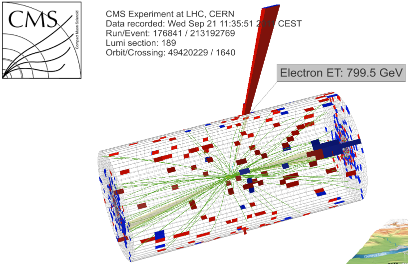
- We are benefiting here from the advance in the FF determinations!
- Conclusion: S,T are at least ~1000x weaker than the V-A Fermi interaction.

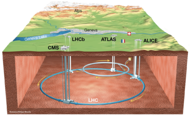
$$\varepsilon_i \sim \frac{M_W^2}{M_{NP}^2} \rightarrow M_{NP} \sim 2 \text{ TeV}$$

Connection with High Energy Physics:

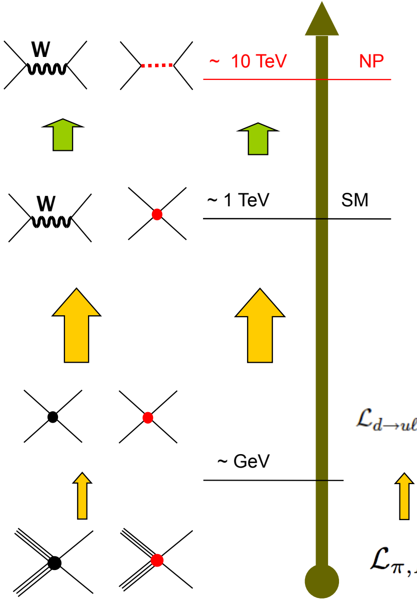
$$
\begin{pmatrix} \tilde{V}^e_{ud} \\ \tilde{V}^e_{us} \\ \Delta^s_L \\ \Delta^d_{LP} \\ \epsilon^{de}_P \\ \epsilon^d_R \\ \epsilon^{se}_P \\ \epsilon^{s\mu}_P \\ \epsilon^s_R \\ \epsilon^{s\mu}_S \\ \epsilon^{s\mu}_T \\ \epsilon^{de}_S \end{pmatrix} = \begin{pmatrix} 0.97451 \pm 0.00038 \\ 0.22408 \pm 0.00087 \\ 1.1 \pm 3.2 \\ 1.9 \pm 3.8 \\ 4.0 \pm 7.8 \\ -1.3 \pm 1.7 \\ -0.4 \pm 2.1 \\ -0.7 \pm 4.3 \\ 0.1 \pm 5.0 \\ -3.9 \pm 4.9 \\ 0.5 \pm 5.2 \\ 1.4 \pm 1.3 \end{pmatrix} \times 10\hat{} \begin{pmatrix} 0 \\ 0 \\ -3 \\ -2 \\ -6 \\ -2 \\ -5 \\ -3 \\ -2 \\ -4 \\ -3 \\ -3 \end{pmatrix}
$$

[at μ=2 GeV,
MS-bar scheme]





Connection with HEP



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

[Buchmüller-Wyler'1986, Leung et al.'1986, Grzadkowski et al'2010]

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i\,\mathcal{O}_i$$

$$\varepsilon_i = f(\alpha_j)$$

[Cirigliano, MGA, Jenkins'2010, Cirigliano, MGA, Graesser'2012]

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L + \sum_{\rho\delta\Gamma}\epsilon^{\Gamma}_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

$$\mathcal{L}_{\pi,N,\ldots} = \ldots$$

Connection with HEP

- Running + Matching with HEP Model/EFT:

$$\frac{d\,\vec{\epsilon}(\mu)}{d\log\mu} = \left(\frac{\alpha(\mu)}{2\pi}\gamma_{\rm ew} + \frac{\alpha_s(\mu)}{2\pi}\gamma_s\right)\vec{\epsilon}(\mu),$$

$$\frac{\delta G_F}{G_F} = 2\,[\hat{\alpha}^{(3)}_{\varphi l}]_{11+22} - [\hat{\alpha}^{(1)}_{ll}]_{1221} - 2[\hat{\alpha}^{(3)}_{ll}]_{1122-\frac{1}{2}(1221)}\,,$$

$$V_{1j}\cdot\epsilon_L^{j\ell} = 2\,V_{1j}\left[\hat{\alpha}^{(3)}_{\varphi l}\right]_{\ell\ell} + 2\left[V\hat{\alpha}^{(3)}_{\varphi q}\right]_{1j} - 2\left[V\hat{\alpha}^{(3)}_{lq}\right]_{\ell\ell 1j},$$

$$V_{1j}\cdot\epsilon_R^{j} = -[\hat{\alpha}_{\varphi\varphi}]_{1j}\,,$$

$$V_{1j}\cdot\epsilon_{s_L}^{j\ell} = -[\hat{\alpha}_{lq}]^*_{\ell\ell j1}\,,$$

$$V_{1j}\cdot\epsilon_{s_R}^{j\ell} = -\left[V\hat{\alpha}^{\dagger}_{qde}\right]_{\ell\ell 1j},$$

$$V_{1j}\cdot\epsilon_T^{j\ell} = -[\hat{\alpha}^t_{lq}]^*_{\ell\ell j1}\,,$$

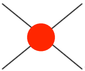
$$\hat{\alpha} = \alpha\frac{v^2}{\Lambda^2}$$

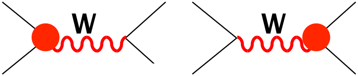
$$O_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{u}\gamma^\mu d) + \text{h.c.}$$

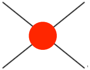
$$O^{(3)}_{\varphi q} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{q}\gamma_\mu\sigma^a q) + \text{h.c.}$$

$$O^{(3)}_{\varphi l} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{l}\gamma_\mu\sigma^a l) + \text{h.c.}$$

$$O'_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{\nu}\gamma^\mu e) + \text{h.c.}$$







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

$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$

$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$

$$O^t_{lq} = (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.}$$

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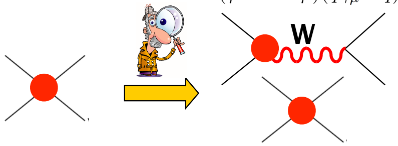
$i(\varphi^\dagger D^\mu\sigma^a\varphi)(\bar q\gamma_\mu\sigma^a q)$

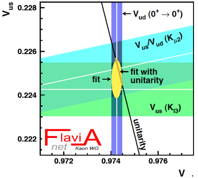


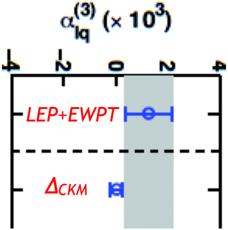
(V-A) x (V-A)

$(\bar l\gamma^\mu\sigma^a l)(\bar q\gamma_\mu\sigma^a q)$

Interferes with SM cross-sections at LEP1 & LEP2

Cirigliano, MGA & Jenkins, NPB830 (2010):
U(3)^5 symmetry: CKM unitarity test vs LEP





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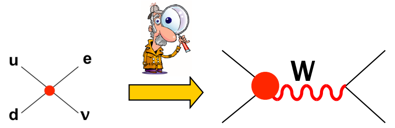
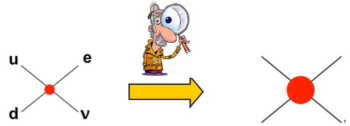


(V-A) x (V+A)

$$i(\varphi^T \epsilon D_\mu \varphi)(\overline{u}\gamma^\mu d)$$



S, P, T

$$(\bar{l}e)(\bar{d}q)$$

Their interference with the SM goes like m/E…

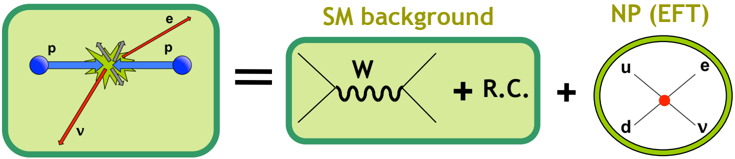
$$\sigma \sim \sigma_{SM}\left(1 + \frac{m}{\sqrt{s}}\,\hat{\alpha}_6\,\frac{\{v^2, s\}}{v^2} + \hat{\alpha}_6^2\,\frac{\{v^4, s^2\}}{v^4}\right)$$

O(1) for LEP, but large for the LHC.

EFT analyses of LHC data requires 2 extra assumptions:
- (D=8) << (D=6)^2
- NP scale is larger than LHC scales;

$$\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \frac{1}{\Lambda^4}\mathcal{L}_8(x) + \ldots$$

LHC limits on $\varepsilon_{S,T}$

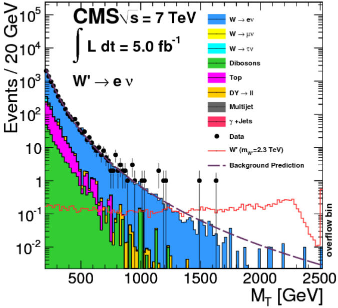


★ To suppress the bkg, we look for **(*e+ν*)**-events with high m_T:

[Bhattacharya et al'2012, Cirigliano, MGA, Graesser'2012]

$$N_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times \mathrm{L} \times \sigma_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times \mathrm{L} \times \left(\sigma_W + \sigma_S\ \varepsilon_S^2 + \sigma_T\ \varepsilon_T^2\right)$$

(Interference w/ SM ~ m/E)



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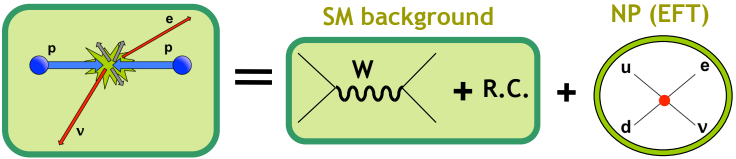

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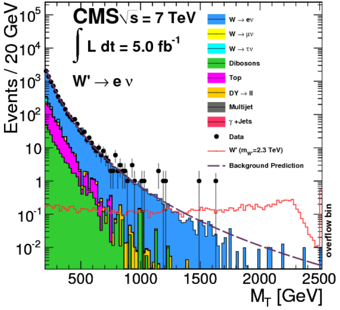
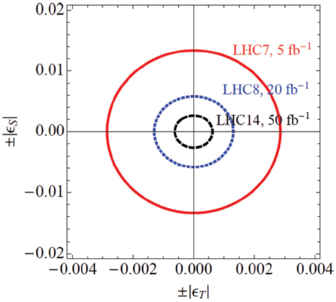


[MGA & Naviliat-Cuncic, 2013]



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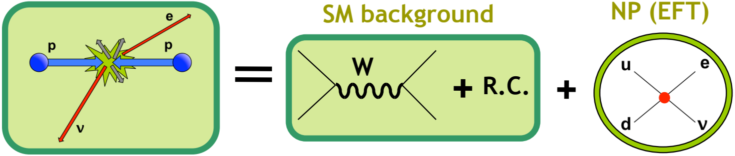

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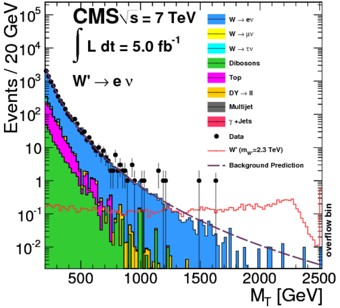
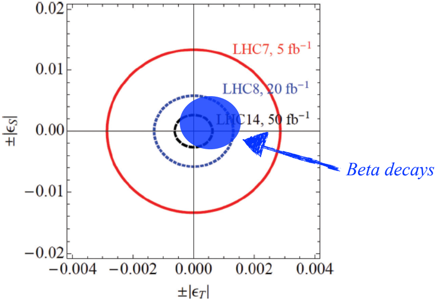
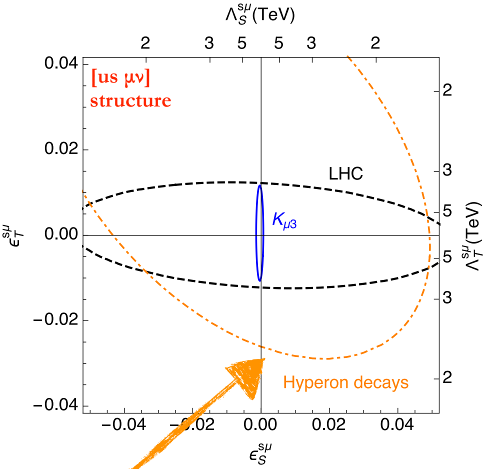


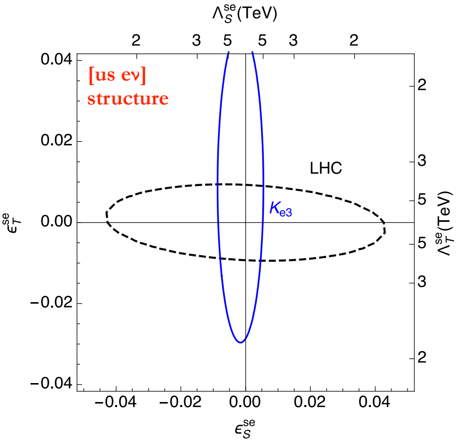
[MGA & Naviliat-Cuncic, 2013]



LHC limits on $\varepsilon_{S,T}$

Of course, the interplay is more interesting once we see a NP signal…





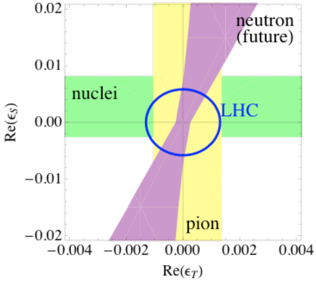
Old data!

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2\, \mu^- \,\bar{\nu}_\mu)}{\Gamma(B_1 \to B_2\, e^- \,\bar{\nu}_e)}$$

[Chang, MGA & Martin Camalich,
Phys. Rev. Lett. 114 (2015)*]*

Summary

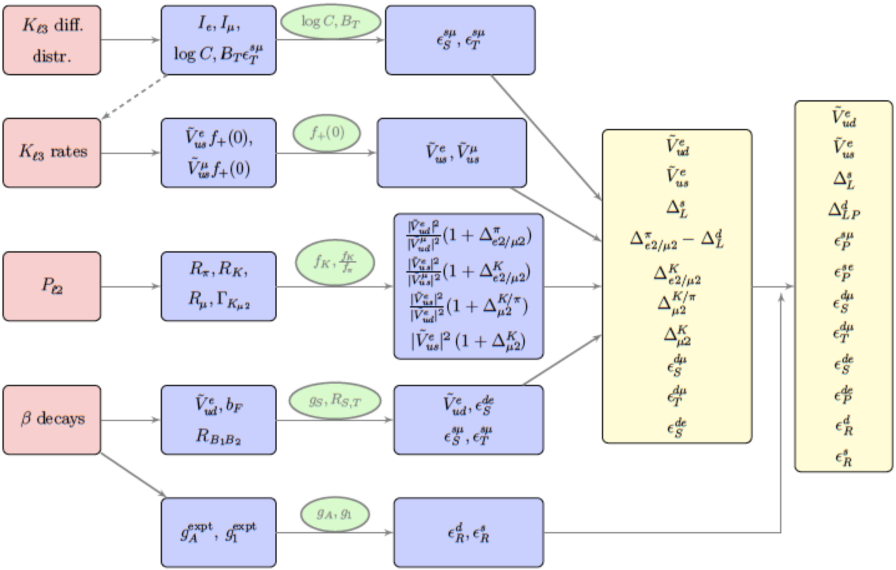
- EFT as a useful tool (analysis done once and for all);
- Systematic analysis of d→ulν & s→ulν transitions.
  - (1-500) TeV probes;
  - Thanks to great control of HC2NP (but not always!)
- Interplay with LHC searches (with heavy mediators);
- Much more interesting once a NP signal is found.



$$\begin{pmatrix} \tilde{V}_{ud}^{e} \\ \tilde{V}_{us}^{e} \\ \Delta_L^s \\ \Delta_{LP}^d \\ \epsilon_P^{de} \\ \epsilon_R^d \\ \epsilon_P^{se} \\ \epsilon_P^{s\mu} \\ \epsilon_R^s \\ \epsilon_S^{s\mu} \\ \epsilon_T^{s\mu} \\ \epsilon_S^{de} \end{pmatrix} = \begin{pmatrix} 0.97451 \pm 0.00038 \\ 0.22408 \pm 0.00087 \\ 1.1 \pm 3.2 \\ 1.9 \pm 3.8 \\ 4.0 \pm 7.8 \\ -1.3 \pm 1.7 \\ -0.4 \pm 2.1 \\ -0.7 \pm 4.3 \\ 0.1 \pm 5.0 \\ -3.9 \pm 4.9 \\ 0.5 \pm 5.2 \\ 1.4 \pm 1.3 \end{pmatrix} \times 10\hat{} \begin{pmatrix} 0 \\ 0 \\ -3 \\ -2 \\ -6 \\ -2 \\ -5 \\ -3 \\ -2 \\ -4 \\ -3 \\ -3 \end{pmatrix}$$

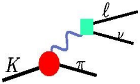
Backup slides

Our input



$K_{\ell 3}$ diff. distr.
I_e, I_μ, $\log C, B_T\epsilon_T^{s\mu}$
$\log C, B_T$
$\epsilon_S^{s\mu}, \epsilon_T^{s\mu}$
$K_{\ell 3}$ rates
$\tilde V_{us}^e f_+(0)$, $\tilde V_{us}^\mu f_+(0)$
$f_+(0)$
$\tilde V_{us}^e, \tilde V_{us}^\mu$
$P_{\ell 2}$
R_π, R_K, $R_\mu, \Gamma_{K_{\mu 2}}$
$f_K, \frac{f_K}{f_\pi}$
$\frac{|\tilde V_{ud}^e|^2}{|\tilde V_{ud}^\mu|^2}(1+\Delta_{e2/\mu 2}^\pi)$
$\frac{|\tilde V_{us}^e|^2}{|\tilde V_{us}^\mu|^2}(1+\Delta_{e2/\mu 2}^K)$
$\frac{|\tilde V_{us}^e|^2}{|\tilde V_{ud}^e|^2}(1+\Delta_{\mu 2}^{K/\pi})$
$|\tilde V_{us}^e|^2(1+\Delta_{\mu 2}^K)$
β decays
$\tilde V_{ud}^e, b_F$, $R_{B_1 B_2}$
$g_S, R_{S,T}$
$\tilde V_{ud}^e, \epsilon_S^{de}$, $\epsilon_S^{s\mu}, \epsilon_T^{s\mu}$
$g_A^{\text{expt}}, g_1^{\text{expt}}$
g_A, g_1
$\epsilon_R^d, \epsilon_R^s$
$\tilde V_{ud}^e$ $\tilde V_{us}^e$ Δ_L^s $\Delta_{e2/\mu 2}^\pi - \Delta_L^d$ $\Delta_{e2/\mu 2}^K$ $\Delta_{\mu 2}^{K/\pi}$ $\Delta_{\mu 2}^K$ $\epsilon_S^{d\mu}$ $\epsilon_T^{d\mu}$ ϵ_S^{de}
$\tilde V_{ud}^e$ $\tilde V_{us}^e$ Δ_L^s Δ_{LP}^d $\epsilon_P^{s\mu}$ ϵ_P^{se} $\epsilon_S^{d\mu}$ $\epsilon_T^{d\mu}$ ϵ_S^{de} ϵ_P^{de} ϵ_R^d ϵ_R^s

Our input: K_{l3} ($K_L, K_S, K^+ \to \pi e \nu$, $\pi \mu \nu$)



$$\Gamma(K_{\ell 3(\gamma)}) = \underbrace{\frac{G_F^2 m_K^5}{192\pi^3}}_{\text{Measured in } \mu \text{ decay}} C\, S_{\rm EW}\, \underbrace{|\tilde{V}_{us}^{\ell}|^2}_{\left(1+\epsilon_L^{s\ell}+\epsilon_R^{s}-\tilde{v}_L\right) V_{us}^{\rm SM}} f_+(0)^2\, \overbrace{I_K^{\ell}(\lambda_{+,0},\, \epsilon_S^{s\ell},\, \epsilon_T^{s\ell})}^{\text{Phase-space Int.}} \underbrace{\left(1+\delta^c+\delta_{\rm em}^{c\ell}\right)^2}_{\text{Rad. and isosp. corr.}}$$

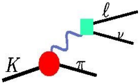
- Reminder (SM):

Kinematic distributions → **Hadronic FF** (slopes, log C) → **PS integrals** —**Total rates**→ **$f_+(0)\, V_{us}$**

- Correlations! (between channels & between slopes) Nicely done by Flavianet (Antonelli et al.'2010);

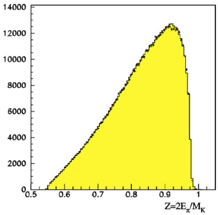
- In a general BSM setup:
  - S & T from kinematic distributions (QCD slopes too!) ←
  - Interference goes ~m_l/E ==> K_{e3} effects ~ $|\varepsilon_{S,T}|^2$
  - Total rates $\to \{\tilde{V}_{us}^{e},\ \tilde{V}_{us}^{\mu}\} \to \{\tilde{V}_{us}^{e},\ \epsilon_L^{s\mu}-\epsilon_L^{se}\}$
  - General BSM fit not done by the collaborations;

Our input: K_{l3} ($K_L, K_S, K^+ \to \pi e\nu$, $\pi\mu\nu$)



- $K_{\mu 3}$ kinematic distributions:

$$\left\{ f_+(q^2), f_0(q^2) \right\} \rightarrow \left\{ f_+(q^2), f_0(q^2)\left(1 + \epsilon_S^{s\mu}\frac{q^2}{m_\mu(m_s - m_u)}\right), B_T(q^2)\,\epsilon_T^{s\mu} \right\}$$



- Scalar interactions hidden in the SM scalar FF! Example:

$$f_{+,0}(q^2) = f_+(0)\left(1 + \lambda'_{+,0}\frac{q^2}{m_\pi^2} + \frac{1}{2}\lambda''_{+,0}\left(\frac{q^2}{m_\pi^2}\right)^2 + \dots\right)$$

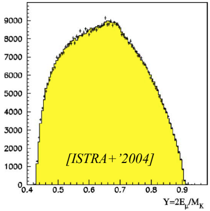
$\lambda_0'^{\,exp}$

$$\left\{ \lambda'_+, \lambda'_0 \right\} \rightarrow \left\{ \lambda'_+, \lambda'_0\left(1 + \epsilon_S^{s\mu}\frac{m_\pi^2}{m_\mu(m_s - m_u)}\right), B_T(0)\,\epsilon_T^{s\mu} \right\}$$

Callan-Treiman Th.
gives us its QCD value!

$f_+(0)$, f_K/f_π and χPT

[Bernard et al.'06, '09; FLAG'13; Gasser & Leutwyler'84; Bijnens & Ghorbani'07;]

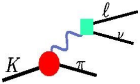


$$\langle \pi^-(k)|\bar{s}\gamma^\mu u|K^0(p)\rangle \sim \left(P^\mu - \frac{\Delta^2_{K\pi}}{q^2}q^\mu\right) f_+(q^2) + q^\mu f_0(q^2)$$

$$\langle \pi^-|\bar{s}u|K^0\rangle \sim f_0(q^2),$$

$$\langle \pi^-|\bar{s}\sigma^{\mu\nu}u|K^0\rangle = i\frac{p^\mu k^\nu - k^\mu p^\nu}{m_{K^0}} B_T(q^2)$$

Our input: K_{l3} ($K_L, K_S, K^+ \to \pi e \nu, \pi \mu \nu$)



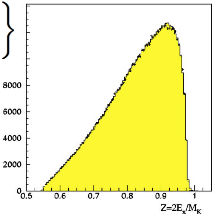
- $K_{\mu 3}$ kinematic distributions:

$$\left\{ f_+(q^2), f_0(q^2) \right\} \Rightarrow \left\{ f_+(q^2), f_0(q^2) \left(1 + \epsilon_S^{s\mu} \frac{q^2}{m_\mu (m_s - m_u)}\right), B_T(q^2)\, \epsilon_T^{s\mu} \right\}$$

- Scalar interactions hidden in the SM scalar FF!
  Examples:

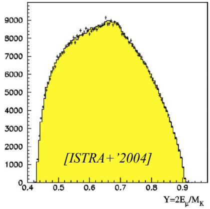
$$\left\{ \lambda_+, \lambda'_+, \log C \right\} \Rightarrow \left\{ \lambda_+, \lambda'_+, \log C + \epsilon_S^{s\mu} \frac{m_K^2 - m_\pi^2}{m_\mu (m_s - m_u)}, B_T(0)\, \epsilon_T^{s\mu} \right\}$$

$$C_{\rm QCD} = \frac{f_K}{f_\pi} \frac{1}{f_+(0)} + \Delta_{\rm CT}$$



The $K_{\mu 3}$ fits

λ_+, λ_0	λ'_+, λ'_0	$f_T/f_+(0), f_S/f_+(0)$
0.0277 ± 0.0013	0.	0.
0.0183 ± 0.0011	0.	0.
0.0215 ± 0.0060	0.0010 ± 0.0010	0.
0.0160 ± 0.0021	0.	0.
0.0216 ± 0.0013	0.001063	0.
0.0163 ± 0.0011	0.	0.
0.0276 ± 0.0014	0.	0.
0.0170 ± 0.0059	0.0002 ± 0.0008	0.
0.0276 ± 0.0014	0.	-0.0007 ± 0.0071
0.0183 ± 0.0011	0.	0.
0.0277 ± 0.0013	0.	0.
0.017	0.	0.0017 ± 0.0014



EFT fit of d(s)⟶ulν

[MGA & Martin Camalich, 1605.07114]

$$\begin{pmatrix} \tilde{V}^e_{ud} \\ \tilde{V}^e_{us} \\ \Delta^s_L \\ \Delta^d_{LP} \\ \epsilon^{de}_P \\ \epsilon^d_R \\ \epsilon^{se}_P \\ \epsilon^{s\mu}_P \\ \epsilon^s_R \\ \epsilon^{s\mu}_S \\ \epsilon^{s\mu}_T \\ \epsilon^{de}_S \end{pmatrix} = \begin{pmatrix} 0.97451 \pm 0.00038 \\ 0.22408 \pm 0.00087 \\ 1.1 \pm 3.2 \\ 1.9 \pm 3.8 \\ 4.0 \pm 7.8 \\ -1.3 \pm 1.7 \\ -0.4 \pm 2.1 \\ -0.7 \pm 4.3 \\ 0.1 \pm 5.0 \\ -3.9 \pm 4.9 \\ 0.5 \pm 5.2 \\ 1.4 \pm 1.3 \end{pmatrix} \times 10\wedge \begin{pmatrix} 0 \\ 0 \\ -3 \\ -2 \\ -6 \\ -2 \\ -5 \\ -3 \\ -2 \\ -4 \\ -3 \\ -3 \end{pmatrix}$$

$$\epsilon^{de}_T = (0.1 \pm 0.8) \times 10^{-3},$$

$$\epsilon^{se}_S = (-1.6 \pm 3.3) \times 10^{-3},$$

$$\epsilon^{se}_T = (0.9 \pm 1.8) \times 10^{-2},$$

[at μ=2 GeV, MS-bar scheme]

$$\begin{aligned} \tilde{V}^e_{uD} &= \left(1 + \epsilon^{De}_L + \epsilon^D_R - \tilde{v}_L\right) V_{uD} \\ \Delta_{\rm CKM} &= 1.9(\epsilon^{de}_L + \epsilon^d_R) + 0.1(\epsilon^{se}_L + \epsilon^s_R) - 2\tilde{v}_L \\ \Delta^s_L &= \epsilon^{s\mu}_L - \epsilon^{se}_L \\ \Delta^d_{LP} &= \epsilon^{de}_L - \epsilon^{d\mu}_L + 24\epsilon^{d\mu}_P \end{aligned}$$

$$\begin{aligned} \mathcal{A}(P \to \ell\nu) &\sim m_\ell\, u\gamma_\mu\gamma_5 v + M_{QCD}\, u\gamma_5 v\, \epsilon_P \\ |\mathcal{A}(P \to \ell\nu)|^2 &\sim m_\ell^2 \left(1 + \frac{M_{QCD}}{m_\ell}\epsilon_P\right)^2 \end{aligned}$$

$$\rho = \begin{pmatrix} 1. & 0. & 0. & 0.01 & 0.01 & 0. & 0. & 0. & 0. & 0. & 0. & 0.82 \\ - & 1. & -0.12 & 0. & 0. & 0. & 0.04 & 0.04 & 0. & -0.26 & 0. & 0. \\ - & - & 1. & 0. & 0. & 0. & 0. & 0.03 & 0. & 0. & 0.72 & 0. \\ - & - & - & 1. & 0.9995 & -0.87 & 0.09 & 0.09 & 0. & 0.04 & 0. & 0.01 \\ - & - & - & - & 1. & -0.87 & 0.09 & 0.09 & 0. & 0.04 & 0. & 0.01 \\ - & - & - & - & - & 1. & 0. & 0. & 0. & 0. & 0. & 0. \\ - & - & - & - & - & - & 1. & 0.9993 & -0.98 & -0.01 & 0. & 0. \\ - & - & - & - & - & - & - & 1. & -0.98 & -0.01 & 0.02 & 0. \\ - & - & - & - & - & - & - & - & 1. & 0. & 0. & 0. \\ - & - & - & - & - & - & - & - & - & 1. & 0. & 0. \\ - & - & - & - & - & - & - & - & - & - & 1. & 0. \\ - & - & - & - & - & - & - & - & - & - & - & 1. \end{pmatrix}$$

(+ QCD quantities!)

EFT fit of d(s)→ulν

[MGA & Martin Camalich, 1605.07114]

- Usual analysis

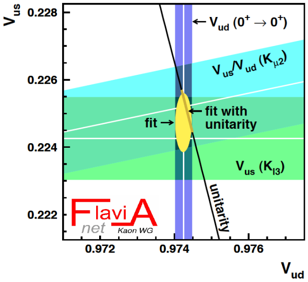
$$\begin{pmatrix}\tilde V_{ud}\\ \tilde V_{us}\end{pmatrix} = \begin{pmatrix}0.97416(21)\\ 0.22484(64)\end{pmatrix},\quad \rho = \begin{pmatrix}1. & 0.03\\ - & 1.\end{pmatrix}$$

$$\Rightarrow \Delta_{\rm CKM} = -(4.6 \pm 5.2)\times 10^{-4}$$

U(3)^5 symmetry

$$\begin{pmatrix}l_e\\ l_\mu\\ l_\tau\end{pmatrix},\begin{pmatrix}e\\ \mu\\ \tau\end{pmatrix},\begin{pmatrix}q_u\\ q_c\\ q_t\end{pmatrix},\begin{pmatrix}u\\ c\\ t\end{pmatrix},\begin{pmatrix}d\\ s\\ b\end{pmatrix}$$

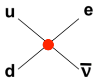
Analysis	V_{us}	Data	Form Factors	$K_{\mu 2(\gamma)}$ and CTT
This work	0.22484(64)	2014 [43]	2013 [5]	yes
Moulson'2014 [43]	0.2248(7)	2014 [43]	2013 [5]	no
(our code)	0.2248(7)			
FLAG'2013 [5]	0.2247(7)	2010 [2]	2013 [5]	no
(our code)	0.2245(7)			
Flavianet'2010 [2]	0.2253(9)	2010 [2]	2010 [2]	no
(our code)	0.2254(9)			

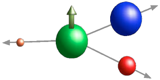


$$\Gamma(K_{\mu 2}) \sim V_{us}^2 f_K^2$$

$$\bar f_0(q^2 = m_K^2 - m_\pi^2) = \frac{f_K}{f_\pi}\frac{1}{f_+(0)} + \Delta_{\rm CT}$$

Neutron β decay bSM





Lifetime shift ➔ CKM unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (0.1 \pm 0.6)\cdot 10^{-3}$$

$$\tilde{g}_A \approx g_A(1 - 2\epsilon_R)$$
$$g_A = \langle p|\bar{u}\gamma_\mu\gamma_5 d|n\rangle$$

After hadronization and at O(ε) …

$$\mathcal{L}_{n\to pe^-\bar{\nu}_e} = -\sqrt{2}G_F V_{ud}\Big(1 + \mathrm{Re}\,(\epsilon_L + \epsilon_R)\Big)\Big[\bar{e}_L\gamma_\mu\nu_L\cdot\bar{p}\Big(\gamma^\mu - \tilde{g}_A\gamma^\mu\gamma_5\Big)n + g_S\,\epsilon_S\,\bar{e}_R\nu_L\cdot\bar{p}n + 2g_T\,\epsilon_T\,\bar{e}_R\sigma_{\mu\nu}\nu_L\cdot\bar{p}\sigma^{\mu\nu}n_L\Big]$$

S and T affect the angular distributions and the spectrum
SM analysis not valid;
New Form factors;

PS:
SM prediction very clean (*backup slide*),
thanks to SU(2) + q/M <<1

Form factors in β decay (SM)

Weinberg'58:

Related to $\mu_p - \mu_n$ (up to isospin breaking corr.)

$$\langle p(p_p)|\,\bar{u}\gamma_\mu d\,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_V(q^2)\gamma_\mu + \frac{\tilde{g}_{T(V)}(q^2)}{2M_N}\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_S(q^2)}{2M_N}q_\mu\right]u_n(p_n)$$

$g_V(0)=1$ (Ademollo-Gatto'64)

$$\langle p(p_p)|\,\bar{u}\gamma_\mu\gamma_5 d\,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_A(q^2)\gamma_\mu + \frac{\tilde{g}_{T(A)}(q^2)}{2M_N}\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_P(q^2)}{2M_N}q_\mu\right]\gamma_5 u_n(p_n)$$

$g_A(0)$???

Key feature: $\frac{q}{M} \sim \frac{\Delta M}{M} \sim 10^{-3}$ ⇒ One can safely neglect $O(q^2/M^2)$ & quadratic corrections to the isospin limit

+ R.C. $\frac{\alpha}{2\pi} \sim 10^{-3}$

[Marciano & Sirlin, 1986]
[Czarnecki et al., 2004]
[Ando et al., 2004]
[Marciano & Sirlin, 2006]

$$O_{th} = O_{th}(G_F V_{ud}, g_A)$$

$$\delta O_{th} \sim 10^{-4} - 10^{-5}\,!!!!$$

g_S & the nucleon splitting

[MGA & Martin Camalich, Phys. Rev. Lett. 112 (2014)]

$$\partial_\mu (\bar{u}\gamma^\mu d) = -i(m_d - m_u)\bar{u}d$$

$$g_S = \frac{(M_n - M_p)_{QCD}}{m_d - m_u} g_V$$

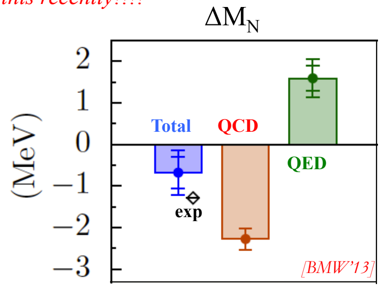
1

Isospin splitting in the nucleon

$$(M_n - M_p)_{exp} = 1.2933322(4)\ \text{MeV}$$

$$M_n - M_p = (M_n - M_p)_{QCD} + (M_n - M_p)_{QED}$$

It turns out lattice-QCD is being calculating this recently!!!!



Useful connection between two different Lattice efforts!

Well known, used in many other processes, e.g. EDMs or K→πeν…

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

[e.g. Anselm et al'1985, Ellis et al'2008, Engel et al'2013, …]

Resuscitating the pseudoscalar interaction

Likewise...

[MGA & Martin Camalich, Phys. Rev. Lett. 112 (2014)]

$$\partial_\mu \left(\bar{u}\gamma^\mu\gamma_5 d\right) = i(m_d + m_u)\bar{u}\gamma_5 d \quad \Rightarrow \quad g_P = \frac{M_n + M_p}{m_d + m_u} g_A = 348(11)$$

Implications? It almost compensates the bilinear suppression!

- ***P bilinear ~ q/M ~10^{-3};***

$$\langle p(p_p)|\bar{u}\gamma_5 d|n(p_n)\rangle = g_P(q^2)\bar{u}_p(p_p)\gamma_5 u_n(p_n)$$

"since the nucleons are treated nonrelativistically, the pseudoscalar couplings are omitted"

[Jackson, Treiman & Wyld, 1957]

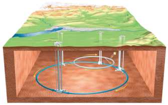
Message:

the same β decay experiments that set bounds on S & T, are almost as sensitive to P!

But… the bounds on ε_P from pion decays are much stronger!!!

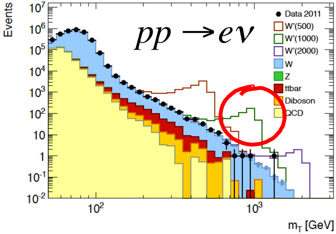
$$R_\pi \equiv \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \approx R_\pi^{SM}\left(1 - \frac{B_0}{m_e}\varepsilon_P\right)$$

Scalar resonance



- What if we see a bump? EFT breaks down…
  TOY model: scalar resonance:

$$\mathcal{L} \;=\; \lambda_S V_{ud}\,\phi^+\,\overline{u}d + \lambda_l\,\phi^-\,\overline{e}P_L\nu_e$$



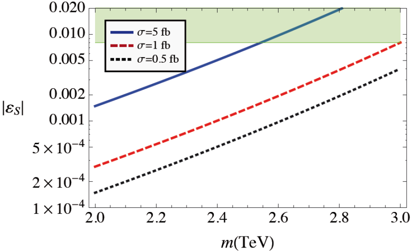
- Then we have a lower-limit value for ε_S:

$$\sigma \cdot \mathrm{BR} \;\le\; \frac{|V_{ud}|}{12v^2}\,\frac{\pi}{\sqrt{2N_c}}\,|\epsilon_S|\,\tau L(\tau)$$

$$L(\tau) = \int_\tau^1 dx\, f_q(x) f_q'(\tau/x)/x$$

$$\tau = m^2/s$$

$$\epsilon_S \;=\; 2\lambda_S\lambda_l\frac{v^2}{m^2}$$



Nice interplay of two experiments separated for so many orders of magnitudes!!!!

[T. Battacharya et al., 2012]

CKM tests vs. LEP

$$\begin{pmatrix} l_e \\ l_\mu \\ l_\tau \end{pmatrix}, \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}, \begin{pmatrix} q_u \\ q_c \\ q_t \end{pmatrix}, \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$U(3)_l \times U(3)_e \times U(3)_q \times U(3)_u \times U(3)_d$

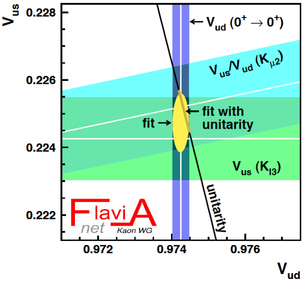
Simple limit: $U(3)^5$ sym

All NP effects vanish except one…

$$\begin{aligned} \Delta_{\rm CKM} &= 1 - |\tilde{V}^e_{ud}|^2 - |\tilde{V}^e_{us}|^2 - |\tilde{V}^e_{ub}|^2 \\ &= 2\epsilon_L - 2\tilde{v}_L \\ &= 2\left(-\alpha^{(3)}_{\varphi l} + \alpha^{(3)}_{\varphi q} - \alpha^{(3)}_{\ell q} + \alpha^{(3)}_{ll}\right)\frac{v^2}{\Lambda^2} \end{aligned}$$

$$\Delta_{\rm CKM} = -(4.6 \pm 5.2) \times 10^{-4}$$

$$\Lambda_{NP} > 11 \text{ TeV}$$



How does it compare with LEP & LHC bounds?

[Cirigliano, MGA, Jenkins'2010]

[Cirigliano, MGA, Graesser'2012]

Flavor sym. considerations make CKM unitarity test special wrt the other NP searches in d→ueν.

CKM tests vs. LEP

[Cirigliano, MGA & Jenkins, Nucl. Phys B830 (2010)]

$$\Delta_{CKM} = 4\left(-\hat{\alpha}_{\varphi l}^{(3)} + \hat{\alpha}_{\varphi q}^{(3)} - \hat{\alpha}_{lq}^{(3)} + \hat{\alpha}_{ll}^{(3)}\right) = -(4.6 \pm 5.2) \times 10^{-4}$$

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

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

$$O_{\varphi l}^{(3)} = i(h^\dagger D^\mu\sigma^a\varphi)(\bar{l}\gamma_\mu\sigma^a l) + \text{h.c.},$$

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

What did we know about them from LEP and other EWPT?

(Han & Skiba, PRD71, 2005)

LHC not competitive either
[Cirigliano, MGA, Graesser'2012]