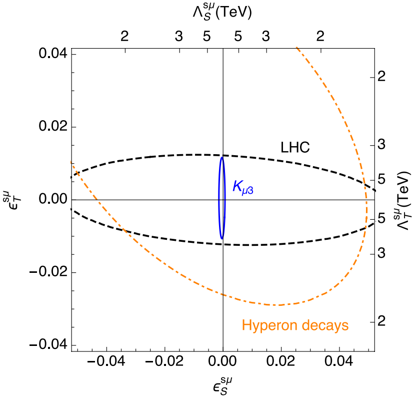
Global EFT analysis of (semi)leptonic kaon decays

KAON-2016

Sept 2016



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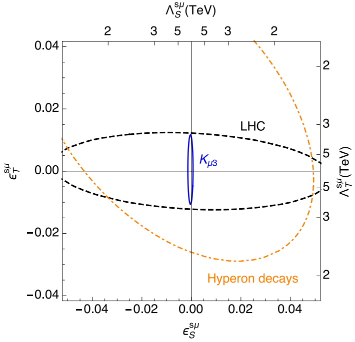
Outline

- Intro & motivation;
- EFT analysis of $d \to u l \nu$, $s \to u l \nu$;
  - BSM fit;
  - SM limit;
- Comparison with LHC;
- Summary;



[Talk mainly based on: MGA & Martin Camalich, 1605.07114]

but also… Cirigliano, MGA & Jenkins, NPB830 (2010)

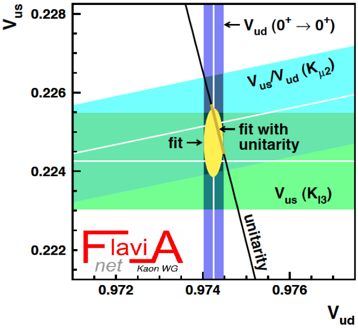
Bhattacharya et al., PRD85 (2012)

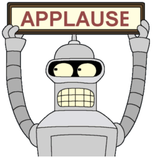
Cirigliano, MGA & Graesser, JHEP1302 (2013)

MGA & Martin Camalich, PRL112 (2014)

Chang, MGA & Martin Camalich, PRL114 (2015)

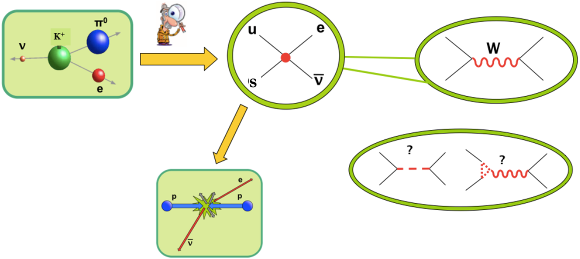
Intro & motivation





OK, SM looks great, but...

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

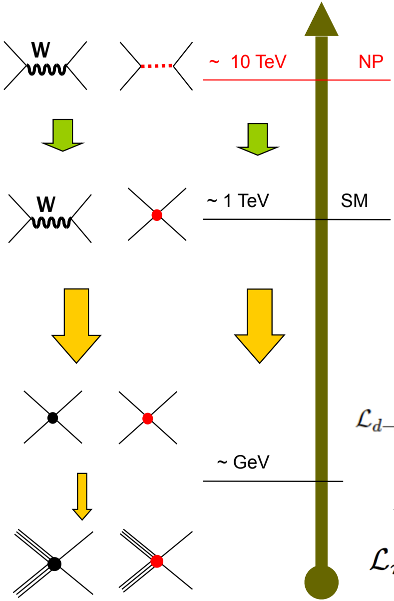


- if I am interested in a model...
  how can I use this analysis?

→ An EFT analysis can help!

The EFT framework

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]

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

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

$$\boxed{\varepsilon_i = f(\alpha_j)}$$

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

Intro & motivation

Goal:

to analyze (semi)leptonic K data within a model-indep. EFT setup so that…

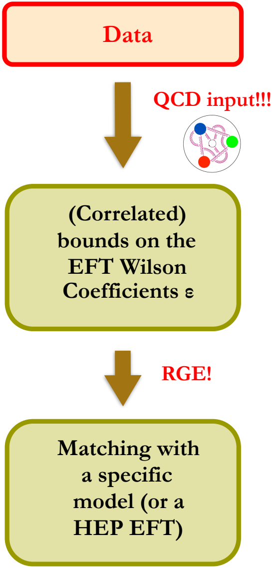
  - we can identify the (combinations of) WC probed by each measurement;
  - the interplay with other processes can be analyzed; (e.g. hyperon decays, LHC searches)
  - the results can be applied to any given model later:

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

- **Efficiency**: The analysis (bkg, PDFs, FF, simulations, …) is done once and for all!

- Useful especially if…
  - Global analysis (all operators present *simultaneously*);
  - Avoid additional assumptions (flavor symmetries, strong couplings, …).

- Valid also if NP is found.



Data

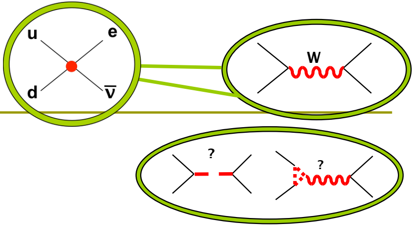
QCD input!!!

(Correlated) bounds on the EFT Wilson Coefficients ε

RGE!

Matching with a specific model (or a HEP EFT)

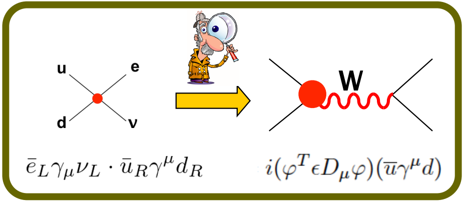
Low-E EFT



- All we can have:
  - V_{ud}, V_{us} + 5 Wilson Coefficients / channel;

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

- Matching with the HEP EFT removes 2 parameters: ε_R is lepton independent;
- This parametrizes *any* heavy NP!
  (W', LQ, 2HDM, SUSY, ..)
- Let's see what data tells us about them!



$\bar{e}_L\gamma_\mu\nu_L\cdot\bar{u}_R\gamma^\mu d_R$

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

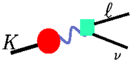
Our input

NA48, KTeV, KLOE, BNL-E865, ISTRA+, ...

- 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

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

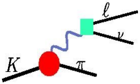
$$\mathbf{x} \left(1 + \delta^{P\ell}_{\mathrm{em}}\right)$$

[Marciano-Sirlin'93, Cirigliano-Rosell'07, ...]

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

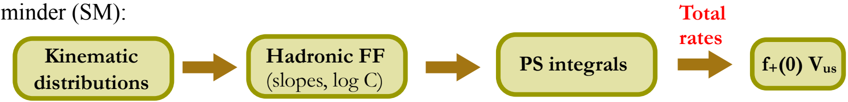
$$\tilde{V}^{\ell}_{uD} = \left(1 + \epsilon_L^{D\ell} + \epsilon_R^D - \frac{\delta G_F}{G_F}\right) V_{uD}$$

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



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

- Reminder (SM):



Kinematic distributions → **Hadronic FF** (slopes, log C) → **PS integrals** $\xrightarrow{\text{Total rates}}$ **$f_+(0)$ 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;

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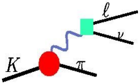

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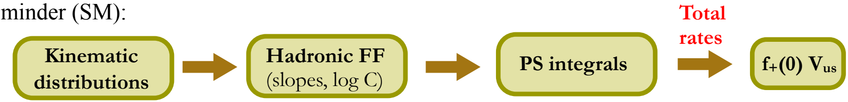

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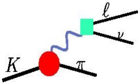
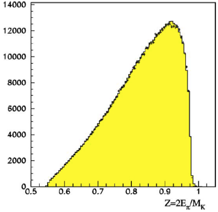
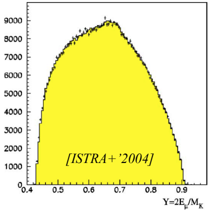


- $K_{\mu 3}$ kinematic distributions:

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

- Scalar interactions hidden in the SM scalar FF!





$$\begin{aligned}
\langle \pi^-(k)\,|\bar{s}\gamma^\mu u|K^0(p)\rangle &\sim \left(P^\mu - \frac{\Delta^2_{K\pi}}{q^2}q^\mu\right) f_+(q^2) + q^\mu f_0(q^2) \\
\langle \pi^-|\bar{s}u|K^0\rangle &\sim f_0(q^2), \\
\langle \pi^-|\bar{s}\sigma^{\mu\nu}u|K^0\rangle &= i\frac{p^\mu k^\nu - k^\mu p^\nu}{m_{K^0}} B_T(q^2)
\end{aligned}$$

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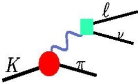


- $K_{\mu 3}$ kinematic distributions:

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

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

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

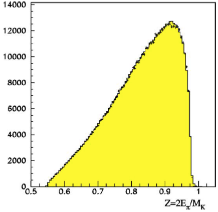
$\lambda_0^{\prime\, exp}$

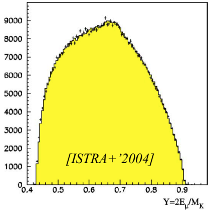
$$\left\{ \lambda'_+, \lambda'_0 \right\} \longrightarrow \left\{ \lambda'_+, \lambda'_0 \left(1 + \epsilon_S^{s\mu} \frac{m_\pi^2}{m_\mu (m_s - m_u)} \right), B_T(0)\, \epsilon_T^{s\mu} \right\}$$

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;]





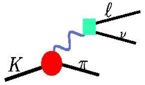
[ISTRA+'2004]

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

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

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

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



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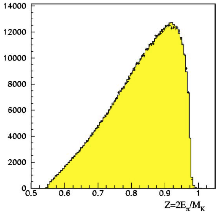

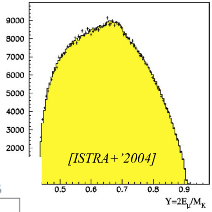

- Scalar interactions hidden in the SM scalar FF! Example:

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

$\lambda_0'^{\,exp}$

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

Callan-Treiman Th.
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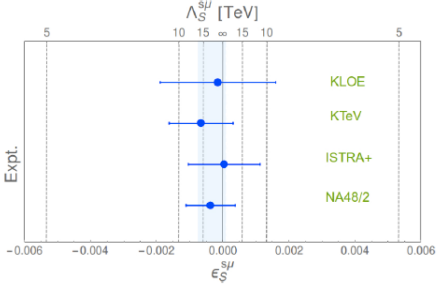
$f_+(0)$, f_K/f_π and χPT

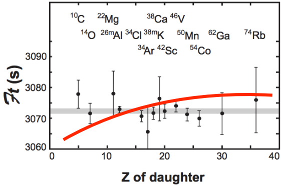
[Bernard et al.'06, '09; FLAG'13; Gasser & Leutwyler'84; Bijnens & Ghorbani'07;]



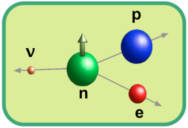
Our input

- Nuclear / baryon decays:

  - Superallowed nuclear β decays
    - SM → $V_{ud;}$
    - BSM → $\widetilde{V}^{e}_{ud}$, $b_F \sim g_s\, \varepsilon_s$

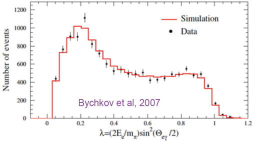


- Neutron decay → $g_A^{\rm expt} = (1 - 2\epsilon_R^d)\, g_A$ $\Longrightarrow$ $\langle p(p_p)|\, \bar{u}\gamma_\mu\gamma_5 d\,|\, n(p_n)\rangle$
- Hyperon decays → $g_1^{\rm expt} = (1 - 2\epsilon_R^s)\, g_1$



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

  $\pi \to e\nu\gamma$



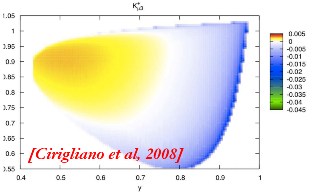
Bychkov et al, 2007

Our input

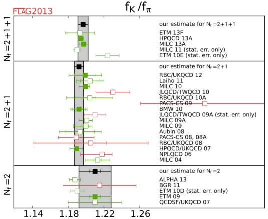
- Theory:
  - Radiative & isospin-breaking corrections;
    E.g. $R_\pi^{\rm SM} = 1.2352(1) \times 10^{-4}$
    $R_K^{\rm SM} = 2.477(1) \times 10^{-5}$
    [Cirigliano & Rosell, 2007]
  - Form factors:
    - $f_+(0)$, f_K/f_π, f_K
    - g_A, g_1
    - B_T, g_S, $F_{T\pi}$
  - Callan-Treiman theorem:

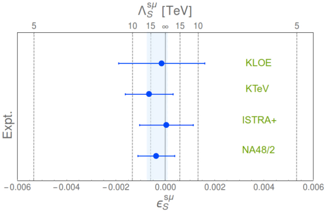
$$\bar{f}_0(q^2 = m_K^2 - m_\pi^2) = \frac{f_K}{f_\pi}\frac{1}{f_+(0)} + \Delta_{\rm CT}$$

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



[Cirigliano et al, 2008]





Our output

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

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

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

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

[at μ=2 GeV, MS-bar scheme]

(+ QCD quantities!)

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

$$\begin{aligned}\Delta_{\text{CKM}} &= 1 - |\tilde{V}^e_{ud}|^2 - |\tilde{V}^e_{us}|^2 - |\tilde{V}^e_{ub}|^2\\ &= -(1.2 \pm 8.4) \times 10^{-4}\end{aligned}$$

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

Our output

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

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

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

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

[at μ=2 GeV, MS-bar scheme]

(+ QCD quantities!)

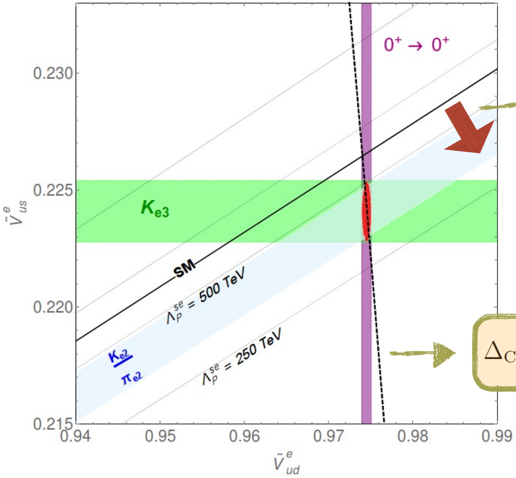
$$\begin{aligned} \tilde{V}^e_{uD} &= \left(1 + \epsilon^{De}_L + \epsilon^D_R - \tilde{v}_L\right) V_{uD} \\ \Delta_{\text{CKM}} &= 1.9(\epsilon^{de}_L + \epsilon^d_R) + 0.1(\epsilon^{se}_L + \epsilon^s_R) - 2\tilde{v}_L \\ \Delta^s_L &= \epsilon^{s\mu}_L - \epsilon^{se}_L \\ \Delta^d_{LP} &= \epsilon^{de}_L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

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

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

V_{ud} - V_{us} plot

- We can answer now the question of the first slide…



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

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

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

Our output

- Usual analysis

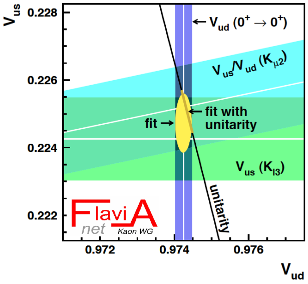
$$\begin{pmatrix} \tilde{V}_{ud} \\ \tilde{V}_{us} \end{pmatrix} = \begin{pmatrix} 0.97416(21) \\ 0.22484(64) \end{pmatrix} , \quad \rho = \begin{pmatrix} 1. & 0.03 \\ - & 1. \end{pmatrix}$$

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

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)			



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

$$\bar{f}_0(q^2 = m_K^2 - m_\pi^2) = \frac{f_K}{f_\pi} \frac{1}{f_+(0)} + \Delta_{\text{CT}}$$

Our output

- Usual analysis

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

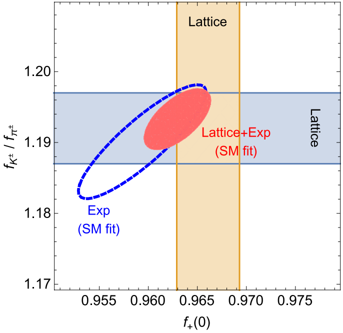
$$\Rightarrow \quad \Delta_{\text{CKM}} = -(4.6 \pm 5.2) \times 10^{-4}$$

- SM limit

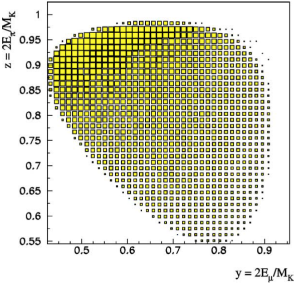
$$|V_{ud}| = 0.97432(12) \quad \text{or equivalently} \quad |V_{us}| = 0.2252(5).$$

(+ QCD quantities!)

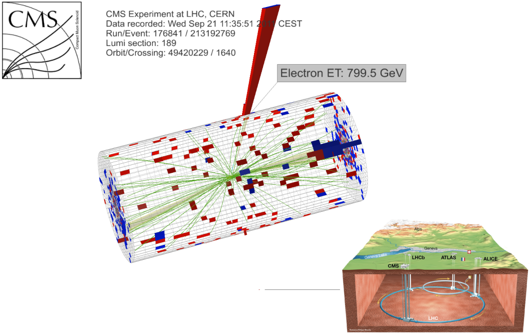
$$\begin{pmatrix} f_{K^\pm} \\ f_{K^\pm}/f_{\pi^\pm} \\ f_+(0) \end{pmatrix} = \begin{pmatrix} 155.62(44)\text{MeV} \\ 1.1936(30) \\ 0.9632(23) \end{pmatrix} , \quad \rho = \begin{pmatrix} 1. & 0.80 & 0.60 \\ - & 1. & 0.60 \\ - & - & 1. \end{pmatrix}$$



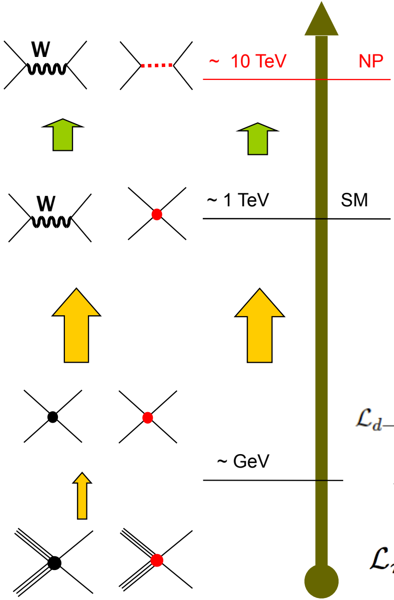
(Semi)leptonic hadron decays vs LHC: non-standard scalar & tensor searches



[Yushchenko et al'2003 ($K_{\mu3}$)]



Connection with HEP



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

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

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

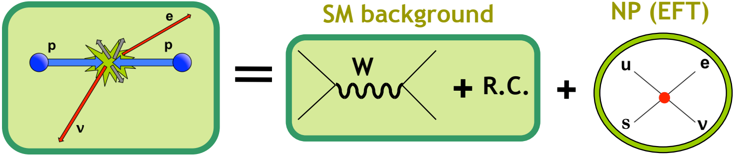
$$\boxed{\varepsilon_i = f(\alpha_j)}$$

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

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

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

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)

Reminder: EFT counting…

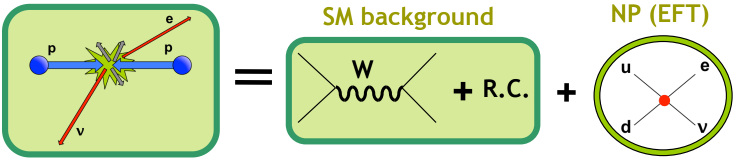
$$\mathcal{A} \sim \mathcal{A}_{SM}\left(1 + \alpha_6\frac{x}{\Lambda^2} + \alpha_8\frac{x^2}{\Lambda^4} + \ldots\right)$$

$$\mathcal{O} \sim \mathcal{O}_{SM}\left(1 + \alpha_6\frac{x}{\Lambda^2} + (\alpha_6^2 + \alpha_8)\frac{x^2}{\Lambda^4} + \ldots\right)$$

$x = (v, E)$

Validity of the EFT:
$E << \Lambda$

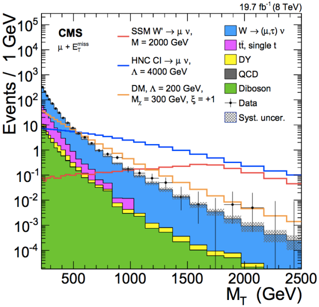
LHC limits on $\varepsilon_{S,T}$

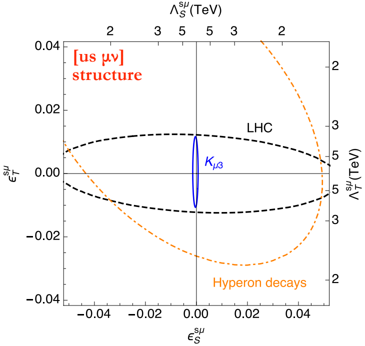


- ★ To suppress the bkg, we look for $(e{+}\nu)$-events with high m_T:

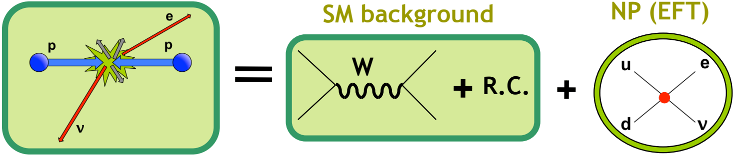
[Bhattacharya et al'2012, Cirigliano, MGA, Graesser'2012]

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





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



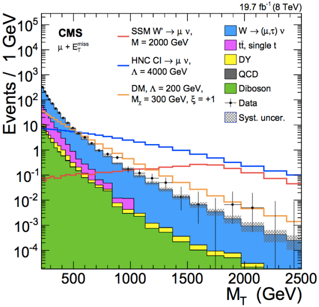
- ★ To suppress the bkg, we look for $(e+\nu)$-events with high m

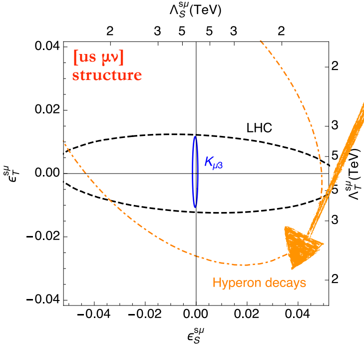
$$N_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times \mathrm{L} \times \sigma_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times$$

Old data!

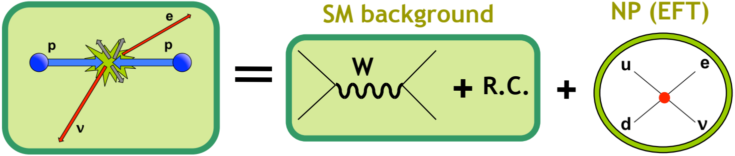
$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2\, \mu^- \, \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2\, e^- \, \bar{\nu}_e)}$$

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





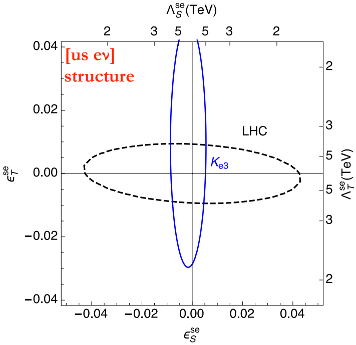
LHC limits on $\varepsilon_{S,T}$

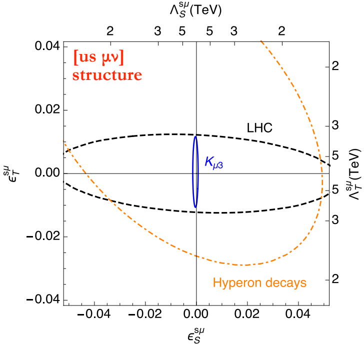


- ★ To suppress the bkg, we look for ***(e+ν)***-events with high m_T:

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

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

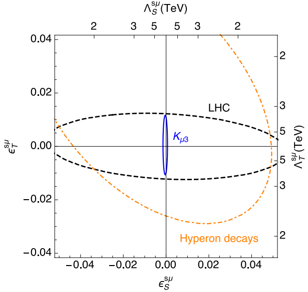




Summary

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

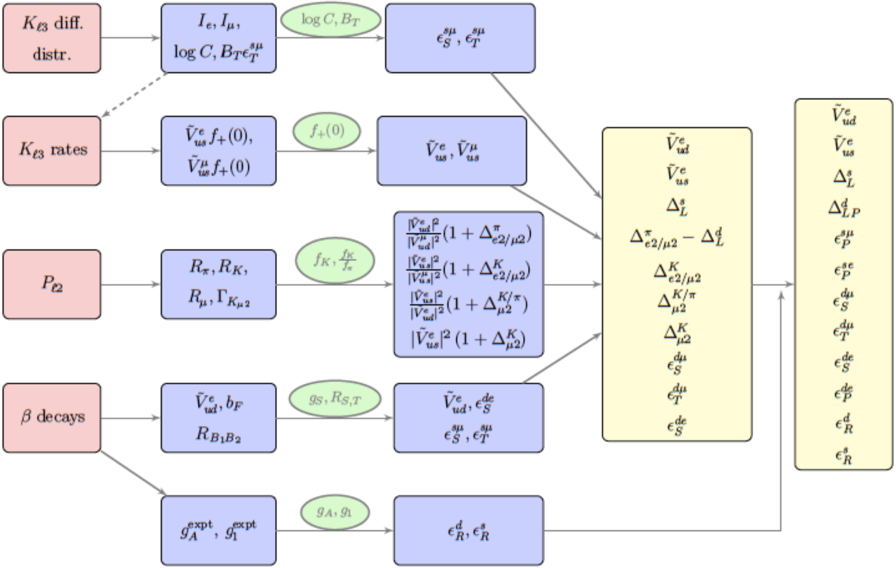
- EFT as a useful tool (analysis done once and for all);
- Systematic analysis of d→ulν & s→ulν transitions. Competitive (1-500) TeV probes.
- Flavianet-like fit?
- Results given at different scales, in the low-E & high-E EFT, easy to use.
- It contains the SM analysis as a particular case;



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

Backup slides

Our input



$K_{\ell 3}$ diff. distr.

$I_e, I_\mu,$ $\log C, B_T\epsilon_T^{s\mu}$

$\log C, B_T$

$\epsilon_S^{s\mu}, \epsilon_T^{s\mu}$

$K_{\ell 3}$ rates

$\tilde{V}_{us}^e f_+(0),$ $\tilde{V}_{us}^\mu f_+(0)$

$f_+(0)$

$\tilde{V}_{us}^e, \tilde{V}_{us}^\mu$

$P_{\ell 2}$

$R_\pi, R_K,$ $R_\mu, \Gamma_{K_{\mu 2}}$

$f_K, \frac{f_K}{f_\pi}$

$\frac{|\tilde{V}_{ud}^e|^2}{|\tilde{V}_{ud}^\mu|^2}(1+\Delta_{e2/\mu 2}^\pi)$

$\frac{|\tilde{V}_{us}^e|^2}{|\tilde{V}_{us}^\mu|^2}(1+\Delta_{e2/\mu 2}^K)$

$\frac{|\tilde{V}_{us}^e|^2}{|\tilde{V}_{ud}^e|^2}(1+\Delta_{\mu 2}^{K/\pi})$

$|\tilde{V}_{us}^e|^2\,(1+\Delta_{\mu 2}^K)$

β decays

$\tilde{V}_{ud}^e, b_F$ $R_{B_1 B_2}$

$g_S, R_{S,T}$

$\tilde{V}_{ud}^e, \epsilon_S^{de}$ $\epsilon_S^{s\mu}, \epsilon_T^{s\mu}$

$g_A^{\mathrm{expt}}, g_1^{\mathrm{expt}}$

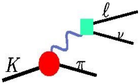
g_A, g_1

$\epsilon_R^d, \epsilon_R^s$

$\tilde{V}_{ud}^e$
$\tilde{V}_{us}^e$
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} ($K_L, K_S, K^+ \to \pi e\nu, \pi\mu\nu$)



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

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

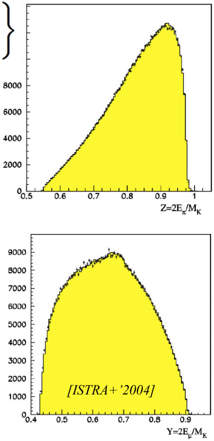
- Scalar interactions hidden in the SM scalar FF!
  Examples:

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

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

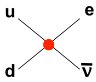
The $K_{\mu 3}$ fits

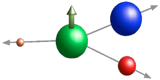
λ_+, λ_0	λ'_+, λ'_0	$f_T/f_+(0)$, $f_S/f_+(0)$
0.0277 ± 0.0013	0.	0.
0.0183 ± 0.0011	0.	0.
0.0215 ± 0.0060	0.0010 ± 0.0010	0.
0.0160 ± 0.0021	0.	0.
0.0216 ± 0.0013	0.001063	0.
0.0163 ± 0.0011	0.	0.
0.0276 ± 0.0014	0.	0.
0.0170 ± 0.0059	0.0002 ± 0.0008	0.
0.0276 ± 0.0014	0.	-0.0007 ± 0.0071
0.0183 ± 0.0011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



[ISTRA+'2004]

Neutron β decay bSM





Lifetime shift ➔ CKM unitarity

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2-1=(0.1\pm0.6)\cdot 10^{-3}$$

$$\tilde{g}_A \approx g_A(1-2\epsilon_R)$$

$$g_A = \langle p|\bar{u}\gamma_\mu\gamma_5 d|n\rangle$$

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

Our output

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

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

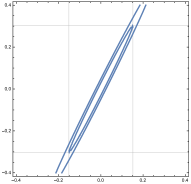
$$\epsilon^{se}_S = (-1.6 \pm 3.3) \times 10^{-3},$$

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

[at μ=2 GeV, MS-bar scheme]

(+ QCD quantities!)

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



$$\epsilon^{de}_P = (0.7 \pm 2.5) \times 10^{-7}$$

$$\epsilon^{se}_P = -(4.5 \pm 3.7) \times 10^{-7}$$

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

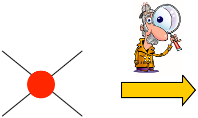
Connection with HEP

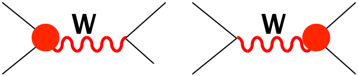
- Running + Matching with HEP Model/EFT:

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

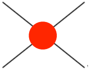
$$\begin{aligned}
\tilde{v}_L &= 2\,[\hat{\alpha}^{(3)}_{\varphi l}]_{11+22} - [\hat{\alpha}^{(1)}_{ll}]_{1221}\;, \\
V_{1j}\cdot\epsilon_L^{j\ell} &= 2\,V_{1j}\left[\hat{\alpha}^{(3)}_{\varphi l}\right]_{\ell\ell} + 2\,[V\hat{\alpha}^{(3)}_{\varphi q}]_{1j} - 2\left[V\hat{\alpha}^{(3)}_{lq}\right]_{\ell\ell 1j}, \\
V_{1j}\cdot\epsilon_R^{j} &= -\,[\hat{\alpha}_{\varphi\varphi}]_{1j}\,, \\
V_{1j}\cdot\epsilon_{s_L}^{j\ell} &= -\,[\hat{\alpha}_{lq}]^*_{\ell\ell j1}\,, \\
V_{1j}\cdot\epsilon_{s_R}^{j\ell} &= -\left[V\hat{\alpha}^\dagger_{qde}\right]_{\ell\ell 1j}, \\
V_{1j}\cdot\epsilon_T^{j\ell} &= -\,[\hat{\alpha}^t_{lq}]^*_{\ell\ell j1}\;,
\end{aligned}$$

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



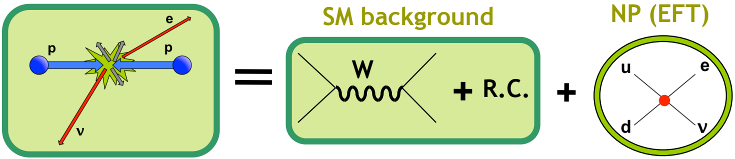


$$\begin{aligned}
O_{\varphi\varphi} &= i(\varphi^T\epsilon D_\mu\varphi)(\overline{u}\gamma^\mu d) + \text{h.c.} \\
O^{(3)}_{\varphi q} &= i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{q}\gamma_\mu\sigma^a q) + \text{h.c.} \\
O^{(3)}_{\varphi l} &= i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{l}\gamma_\mu\sigma^a l) + \text{h.c.} \\
O'_{\varphi\varphi} &= i(\varphi^T\epsilon D_\mu\varphi)(\overline{\nu}\gamma^\mu e) + \text{h.c.}
\end{aligned}$$



$$\begin{aligned}
O^{(3)}_{lq} &= (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q) \\
O_{qde} &= (\bar{l}e)(\bar{d}q) + \text{h.c.} \\
O_{lq} &= (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.} \\
O^t_{lq} &= (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.}
\end{aligned}$$

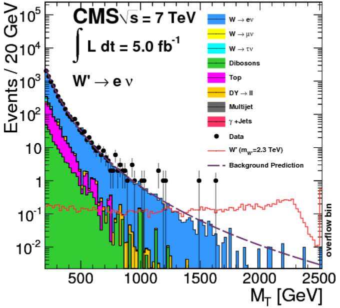
LHC limits on $\varepsilon_{S,T}$



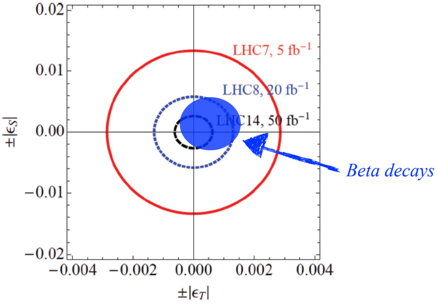
- ★ To suppress the bkg, we look for ***(e+ν)***-events with high m_T:

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

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

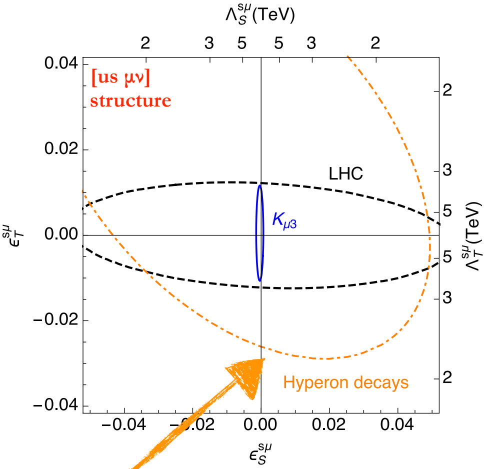


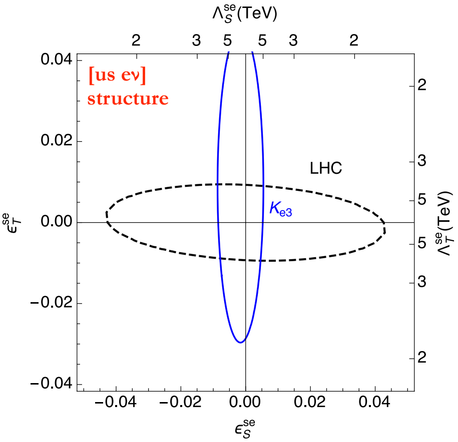
[MGA & Naviliat-Cuncic, 2013]



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

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





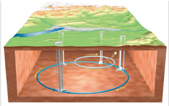
Old data!

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

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

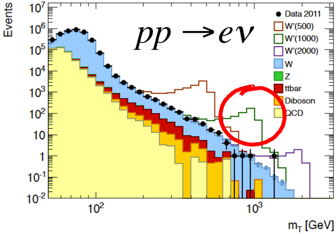
$$\mathcal{O} \quad \sim \quad \mathcal{O}_{SM}\left(1 + \frac{m}{\sqrt{s}}\,\epsilon_i\,\frac{\{v^2, s\}}{v^2} + \epsilon_i^2\,\frac{\{v^4, s^2\}}{v^4}\right)$$

Scalar resonance



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

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



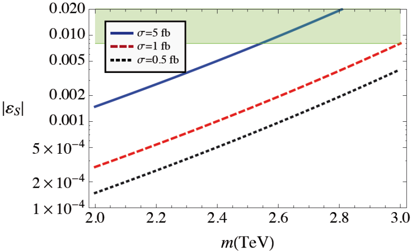
- Then we have a lower-limit value for ε_S:

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

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

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

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



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

[T. Battacharya et al., 2012]

CKM tests vs. LEP

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

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

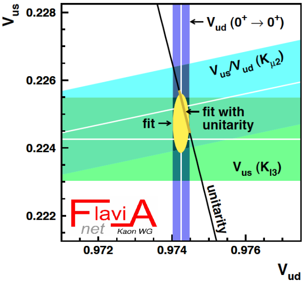
Simple limit: $U(3)^5$ sym

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)]

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

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

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

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

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

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

(Han & Skiba, PRD71, 2005)

LHC not competitive either

[Cirigliano, MGA, Graesser'2012]