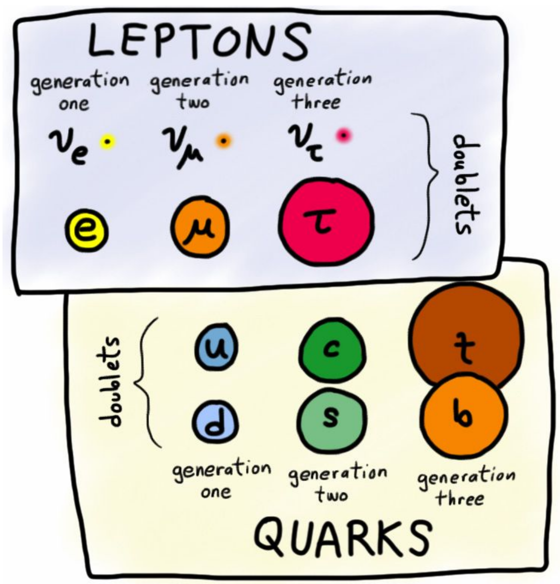
Low-energy constraints on New Physics

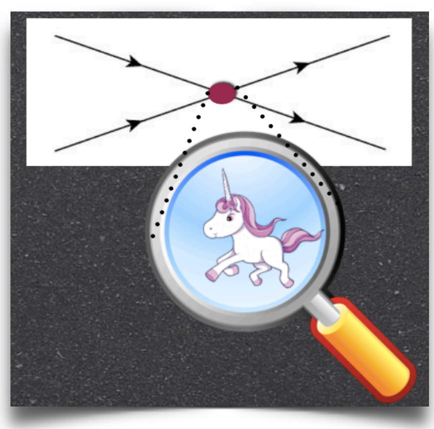
IFAE seminar June 2019



Martín González-Alonso
CERN-TH

Outline

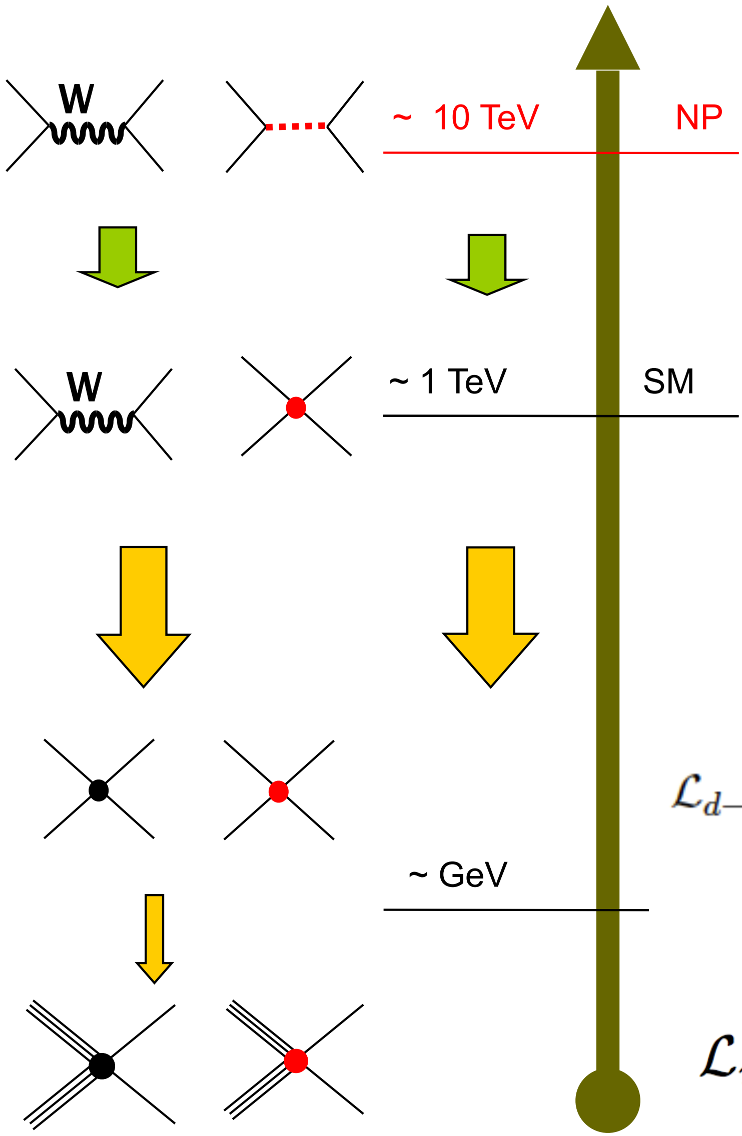
- Introduction
- SMEFT fit to Electroweak Precision Data
- Hadronic Tau Decays as a New Physics probe
- Neutrino oscillations as EFT constraints



Introduction

- I'll focus on precision measurements in non-forbidden processes:
  - Both exp & theory (lattice!) **precision** needed
  - Precision ~ 10^{-2} - 10^{-3} → Λ ~ O(1) TeV
  - Much higher scales if SM is suppressed ($\pi \rightarrow e\nu$, CPV, CKM, ...)
- Still a very wide subject:
  - Leptonic processes, flavor (kaons, B's, LFU, ...), ...
  - Nuclear decays, atomic PV, neutrino, ...
  - Z/W data (LEP & LHC), LEP2, top, Higgs, ... → low-energy?
- I'll assume "heavy NP" → Effective Field Theory

EFT 101



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

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

Standard Model EFT

[Buchmuller & Wyler'86,
Leung et al.'86,
Grzadkowksi et al., 10,
Jenkins et al'13, ...]

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

Low-energy EFT

[Cirigliano et al'09,
Aebischer al.'15,
Jenkins et al'18, ...]

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

EFT: motivation

Take your favorite precision experiment:

→ Implications for NP model M?

$$O_{i,exp} - O_{i,SM} = f_i\,(g', M')$$

Nontrivial:

- Atomic/nuclear/hadronic/PDF TH;
- Correlations;
- Cuts, SM assumed?
- Large logs resummation

$$O_{i,exp} - O_{i,SM} = \delta O\,(\alpha_1, \alpha_2, \ldots, \alpha_{80})$$ → $$\chi^2 = \chi^2\,(\alpha_i)$$ →

Specific NP model

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

EFT: motivation

Take your favori[...]

→ Implicatio[...]

$O_{i,exp}$ - O[...]

[...]ear/hadronic/PDF TH;

[...];

[...]umed?

[...]esummation

Useful especially if…

- ➡ **Global analysis**
- ➡ **Final likelihood public**
- ➡ **Avoid additional assumptions**

Valid also if NP is found!

Example: EFT for "B anomalies"
[Aebischer et al'19, Algueró et al'19, Ciuchini et al.'19, Arbey et al.'19, ...]

$$O_{i,exp} - O_{i,SM} = \delta O\,(\alpha_1, \alpha_2, \ldots, \alpha_{80})$$

→ $\chi^2 = \chi^2\,(\alpha_i)$

→ **Specific NP model**

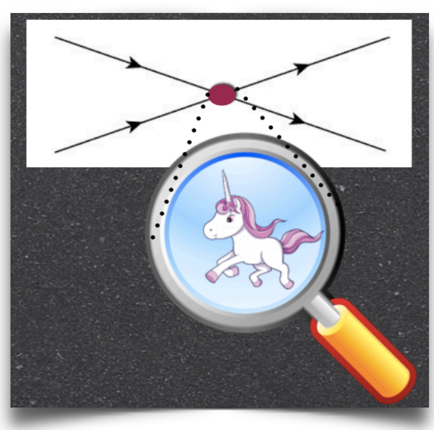
$$\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\,(g_{NP}, M_{NP})$$

Outline

- Introduction
- SMEFT fit to Electroweak Precision Data
- Hadronic Tau Decays as a New Physics prob
- Neutrino oscillations as EFT constraints

2005: global fit in the "flavor-universal" SMEFT
[Han-Skiba'05]

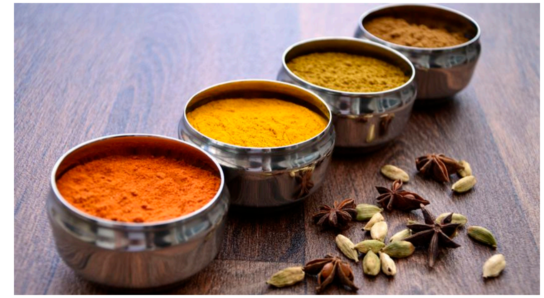
2015-2017: global fit in the flavor general SMEFT
[Efrati, Falkowski & Soreq'15;
Falkowski & Mimouni'15;
Falkowski, MGA & Mimouni'17]



EWPO fit in the flavorful SMEFT

[Falkowski, MGA & Mimouni, 2017]

- 258 experimental input
  - Z- & W-pole data
  - $e^+e^- \to l^+l^-$, qq
  - Low-energy processes:
    - Nuclear and hadron decays ($d \to ul\nu$)
    - Neutrino scattering
    - PV in atoms and in scattering
    - Leptonic tau decays



Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[47]	2.4950	$\sum_f \Gamma(Z \to ff)$
$\sigma_{\rm had}$ [nb]	41.541 ± 0.037	[47]	41.484	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\rm FB}^{0,e}$	0.0145 ± 0.0025	[47]	0.0163	$\frac{3}{4}A_e^2$
$A_{\rm FB}^{0,\mu}$	0.0169 ± 0.0013	[47]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{\rm FB}^{0,\tau}$	0.0188 ± 0.0017	[47]	0.0163	$\frac{3}{4}A_e A_\tau$
R_b	0.21629 ± 0.00066	[47]	0.21578	$\frac{\Gamma(Z\to bb)}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[47]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
$A_b^{\rm FB}$	0.0992 ± 0.0016	[47]	0.1032	$\frac{3}{4}A_e A_b$
$A_c^{\rm FB}$	0.0707 ± 0.0035	[47]	0.0738	$\frac{3}{4}A_e A_c$
A_e	0.1516 ± 0.0021	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to \mu_R^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	0.136 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_e	0.1498 ± 0.0049	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_τ	0.1439 ± 0.0043	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	0.923 ± 0.020	[47]	0.935	$\frac{\Gamma(Z\to b_L b_L)-\Gamma(Z\to b_R b_R)}{\Gamma(Z\to b\bar{b})}$
A_c	0.670 ± 0.027	[47]	0.668	$\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$
A_s	0.895 ± 0.091	[48]	0.935	$\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$
R_{uc}	0.166 ± 0.009	[45]	0.1724	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$

Class	Observable	Exp. value
$\nu_e\nu_e qq$	$R_{\nu_e\bar{\nu}_e}$	0.41(14)
$\nu_\mu\nu_\mu qq$	$(g_L^{\nu_\mu})^2$	0.3005(28)
	$(g_R^{\nu_\mu})^2$	0.0329(30)
	$\theta_L^{\nu_\mu}$	2.500(35)
	$\theta_R^{\nu_\mu}$	$4.56^{+0.42}_{-0.27}$
PV low-E $eeqq$	$g_{AV}^{eu} + 2g_{AV}^{ed}$	0.489(5)
	$2g_{AV}^{eu} - g_{AV}^{ed}$	−0.708(16)
	$2g_{VA}^{eu} - g_{VA}^{ed}$	−0.144(68)
	$g_{VA}^{eu} - g_{VA}^{ed}$	−0.042(57) −0.120(74)
PV low-E $\mu\mu qq$	$b_{\rm SPS}(\lambda = 0.81)$	$-1.47(42) \cdot 10^{-4}$
	$b_{\rm SPS}(\lambda = 0.66)$	$-1.74(81) \cdot 10^{-4}$
$d(s) \to u\ell\nu$	$\epsilon_i^{d_j\ell}$	eq. (3.17)
$e^+e^- \to q\bar{q}$	$\sigma(q\bar{q})$	$f(\sqrt{s})$
	σ_c, σ_b	
	A_{FB}^{cc}, A_{FB}^{bb}	

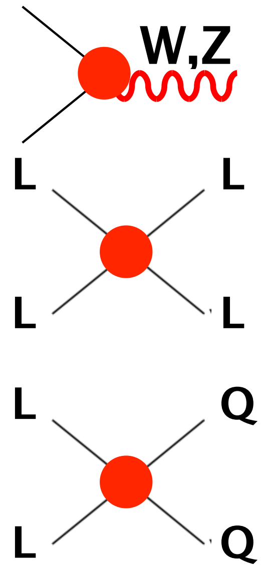
Class	Observable	Exp. value
$\nu_\mu\nu_\mu ee$	$g_{LV}^{\nu_\mu e}$	−0.040(15)
	$g_{LA}^{\nu_\mu e}$	−0.507(14)
$e^-e^- \to e^-e^-$	g_{AV}^{ee}	0.0190(27)
$\nu_\mu\gamma^* \to \nu_\mu\mu^+\mu^-$	$\frac{\sigma}{\sigma_{\rm SM}}$	1.58(57) 0.82(28)
$\tau \to \ell\nu\nu$	$G_{\tau e}^2/G_F^2$	1.0029(46)
	$G_{\tau\mu}^2/G_F^2$	0.981(18)
$e^+e^- \to \ell^+\ell^-$	$\frac{d\sigma(ee)}{d\cos\theta}$	$f(\sqrt{s})$
	$\sigma_\mu, \sigma_\tau, \mathcal{P}_\tau$	
	A_{FB}^μ, A_{FB}^τ	

Observable	Experimental value	Ref.	SM prediction	Definition
m_W [GeV]	80.385 ± 0.015	[50]	80.364	$\frac{g_L v}{2}(1+\delta m)$
Γ_W [GeV]	2.085 ± 0.042	[45]	2.091	$\sum_f \Gamma(W \to ff')$
${\rm Br}(W \to e\nu)$	0.1071 ± 0.0016	[51]	0.1083	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to ff')}$
${\rm Br}(W \to \mu\nu)$	0.1063 ± 0.0015	[51]	0.1083	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to ff')}$
${\rm Br}(W \to \tau\nu)$	0.1138 ± 0.0021	[51]	0.1083	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to ff')}$
R_{Wc}	0.49 ± 0.04	[45]	0.50	$\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$
R_σ	0.998 ± 0.041	[52]	1.000	$g_L^{Wq_3}/g_{L,{\rm SM}}^{Wq_3}$

EWPO fit in the flavorful SMEFT [Falkowski, MGA & Mimouni, 2017]

- 258 experimental input
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]

$$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{80}) \rightarrow \chi^2 = \chi^2\,(c_i)$$



Results given at the EW scale

(QEDxQCD running included in precise low-E observables)

[MGA, M. Camalich & Mimouni, PLB'17]

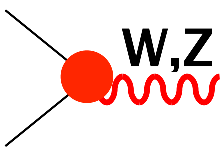
EWPO fit in the flavorful SMEFT [Falkowski, MGA & Mimouni, 2017]

- 258 experimental input
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]

$$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{80}) \rightarrow \chi^2$$

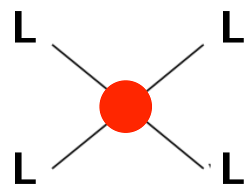
$$\bar{e}\gamma_\mu e \cdot \bar{q}\gamma^\mu q$$
$$\bar{\ell}\gamma_\mu \ell \cdot \bar{q}\gamma^\mu q$$

$$[\hat{c}_{eq}]_{1111} = [c_{eq}]_{1111} + [c_{\ell q}]_{1111}$$



δg_L^{We}	=	-1.00 ± 0.64
$\delta g_L^{W\mu}$		-1.36 ± 0.59
$\delta g_L^{W\tau}$		1.95 ± 0.79
δg_L^{Ze}		-0.023 ± 0.028
$\delta g_L^{Z\mu}$		0.01 ± 0.12
$\delta g_L^{Z\tau}$		0.018 ± 0.059
δg_R^{Ze}		-0.033 ± 0.027
$\delta g_R^{Z\mu}$		0.00 ± 0.14
$\delta g_R^{Z\tau}$		0.042 ± 0.062
δg_L^{Zu}		-0.8 ± 3.1
δg_L^{Zc}		-0.15 ± 0.36
δg_L^{Zt}		[illegible]
δg_R^{Zu}		[illegible]
δg_R^{Zc}		[illegible]
δg_L^{Zd}		[illegible]
δg_L^{Zs}		[illegible]
δg_L^{Zb}		[illegible]
δg_R^{Zd}		3 ± 16
δg_R^{Zs}		3.4 ± 4.9
δg_R^{Zb}		2.30 ± 0.88
$\delta g_R^{Wq_1}$		-1.3 ± 1.7

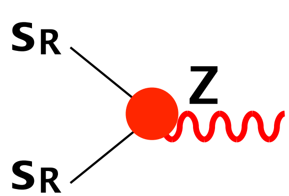
$\times 10^{-2}$.

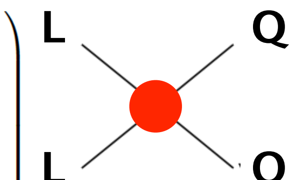


$[c_{\ell\ell}]_{1111}$	=	1.01 ± 0.38
$[c_{\ell e}]_{1111}$		-0.22 ± 0.22
$[c_{ee}]_{1111}$		0.20 ± 0.38
$[c_{\ell\ell}]_{1221}$		-4.8 ± 1.6
$[c_{\ell\ell}]_{1122}$		1.5 ± 2.1
[illegible]		[illegible]
$[c_{\ell\ell}]_{2332}$		3.0 ± 2.3

$\times 10^{-2}$.

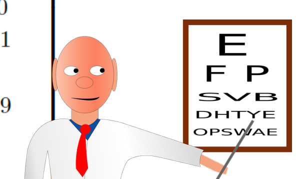
$$\delta g_R^{Zs} = (3.4 \pm 4.9) \times 10^{-2}$$





$[c_{\ell q}^{(3)}]_{1111}$	=	-2.2 ± 3.2
$[\hat{c}_{eq}]_{1111}$		100 ± 180
$[\hat{c}_{\ell u}]_{1111}$		-5 ± 11
$[\hat{c}_{\ell d}]_{1111}$		-5 ± 23
$[\hat{c}_{eu}]_{1111}$		-1 ± 12
$[\hat{c}_{ed}]_{1111}$		-4 ± 21
$[\hat{c}_{\ell q}^{(3)}]_{1122}$		-61 ± 32
$[c_{\ell u}]_{1122}$		2.4 ± 8.0
$[\hat{c}_{\ell d}]_{1122}$		-310 ± 130
$[c_{eq}]_{1122}$		-21 ± 28
$[c_{eu}]_{1122}$		-87 ± 46
$[\hat{c}_{ed}]_{1122}$		270 ± 140
$[\hat{c}_{\ell q}^{(3)}]_{1133}$		-8.6 ± 8.0
$[c_{\ell d}]_{1133}$		-1.4 ± 10
$[c_{eq}]_{1133}$		-3.2 ± 5.1
$[c_{ed}]_{1133}$		18 ± 20
$[c_{\ell q}^{(3)}]_{2211}$		-1.2 ± 3.9
$[c_{\ell q}]_{2211}$		1.3 ± 7.6
$[c_{\ell u}]_{2211}$		15 ± 12
$[c_{\ell d}]_{2211}$		[illegible]
$[\hat{c}_{eq}]_{22}$[illegible]		[illegible]
$[c_{\ell equ}]_{1}$[illegible]		[illegible]
$[c_{\ell edq}]_{1}$[illegible]		[illegible]
$[c_{\ell equ}^{(3)}]_{11}$[illegible]		[illegible]
$\epsilon_P^{d\mu}(2\text{ GeV})$		[illegible]

$\times 10^{-2}$.



Bounds: 10^{-4} - O(1)

[c= $10^{-2} \longrightarrow \Lambda$=2.5 TeV]

EWPO fit in the flavorful SMEFT [Falkowski, MGA & Mimouni, 2017]

- 258 experimental input
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]

$$\mathbf{O = O_{SM} + O\,(c_1, c_2, \ldots, c_{80}) \rightarrow \chi^2 = \chi^2\,(c_i)}$$

Public!
www.dropbox.com/s/26nh71oebm4o12k/SMEFTlikelihood.nb?dl=0

"Flavor-universal" limit

$$\begin{pmatrix} \delta g_L^{We} \\ \delta g_L^{Ze} \\ \delta g_R^{Ze} \\ \delta g_L^{Zu} \\ \delta g_R^{Zu} \\ \delta g_L^{Zd} \\ \delta g_R^{Zd} \end{pmatrix} = \begin{pmatrix} -1.22 \pm 0.81 \\ -0.10 \pm 0.21 \\ -0.15 \pm 0.23 \\ -1.6 \pm 2.0 \\ -2.1 \pm 4.1 \\ 1.9 \pm 1.4 \\ 15 \pm 7 \end{pmatrix} \times 10^{-3}, \quad \begin{pmatrix} c_{\ell\ell}^{(3)} \\ c_{\ell\ell} \\ c_{\ell e} \\ c_{ee} \end{pmatrix} = \begin{pmatrix} -3.0 \pm 1.7 \\ 7.2 \pm 3.3 \\ 0.2 \pm 1.3 \\ -2.5 \pm 3.0 \end{pmatrix} \times 10^{-3}, \quad \begin{pmatrix} c_{\ell q}^{(3)} \\ c_{\ell q} \\ c_{eq} \\ c_{\ell u} \\ c_{\ell d} \\ c_{eu} \\ c_{ed} \end{pmatrix} = \begin{pmatrix} -4.8 \pm 2.3 \\ -15.4 \pm 9.1 \\ -14 \pm 23 \\ 4 \pm 24 \\ 6 \pm 42 \\ 4 \pm 11 \\ 26 \pm 18 \end{pmatrix} \times 10^{-3}.$$

EWPO fit in the flavorful SMEFT [Falkowski, MGA & Mimouni, 2017]

- 258 experimental input
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]

$$\mathbf{O = O_{SM} + O\,(c_1, c_2, \ldots, c_{80}) \rightarrow \chi^2 = \chi^2\,(c_i)}$$

Public!
www.dropbox.com/s/26nh71oebm4o12k/SMEFTlikelihood.nb?dl=0

Universal EFT
(oblique parameters)

$$\begin{pmatrix} S \\ T \\ Y \\ W \end{pmatrix} = \begin{pmatrix} -0.10 \pm 0.13 \\ 0.02 \pm 0.08 \\ -0.15 \pm 0.11 \\ -0.01 \pm 0.08 \end{pmatrix}, \qquad \rho = \begin{pmatrix} 1. & 0.86 & 0.70 & -0.12 \\ . & 1. & 0.39 & -0.06 \\ . & . & 1. & -0.49 \\ . & . & . & 1. \end{pmatrix}$$

EWPO fit in the flavorful SMEFT [Falkowski, MGA & Mimouni, 2017]

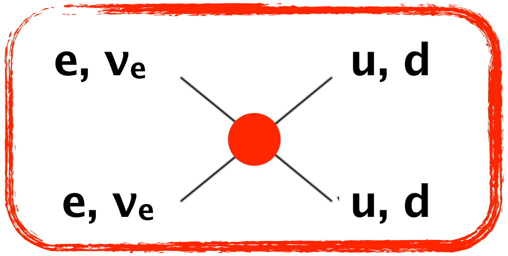
- 258 experimental input
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]

$$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{80}) \rightarrow \chi^2 = \chi^2\,(c_i)$$

Public!
www.dropbox.com/s/26nh71oebm4o12k/SMEFTlikelihood.nb?dl=0

One EFT operator at a time:
$$\chi^2 = \chi^2\,(c_{eeuu})$$

→ eeqq: best bounds come from APV or CKM-unitarity!
[competitive with LHC]



$$(\bar{\ell}_1 \gamma_\mu \ell_1)(\bar{q}_1 \gamma^\mu q_1)$$

PS: ττqq: no bound!

EWPO fit in the flavorful SMEFT [Falkowski, MGA & Mimouni, 2017]

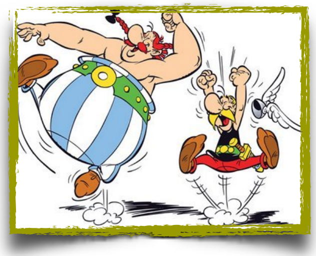
- 258 experimental input
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]

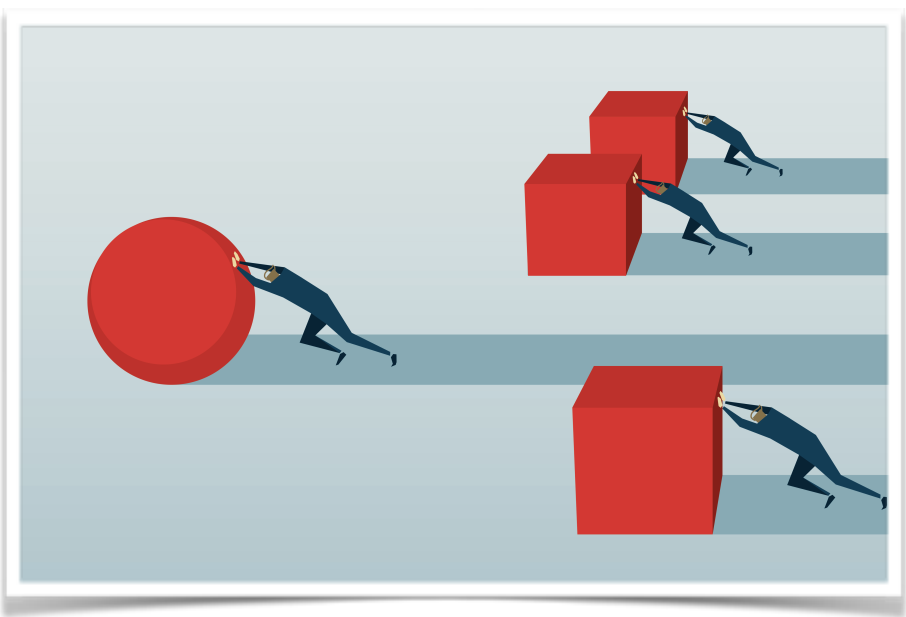
$$O = O_{SM} + O\,(c_1, c_2, \ldots, c_{80}) \rightarrow \chi^2 = \chi^2\,(c_i)$$

RGE!

Specific NP model

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





Z' flavor gauge bosons [Cline & Camalich, 1706.08510],
Minimal Z' models [Alioli et al., 1712.02347],
...

EWPO fit in the flavorful SMEFT [Falkowski, MGA & Mimouni, 2017]

- 258 experimental input
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]

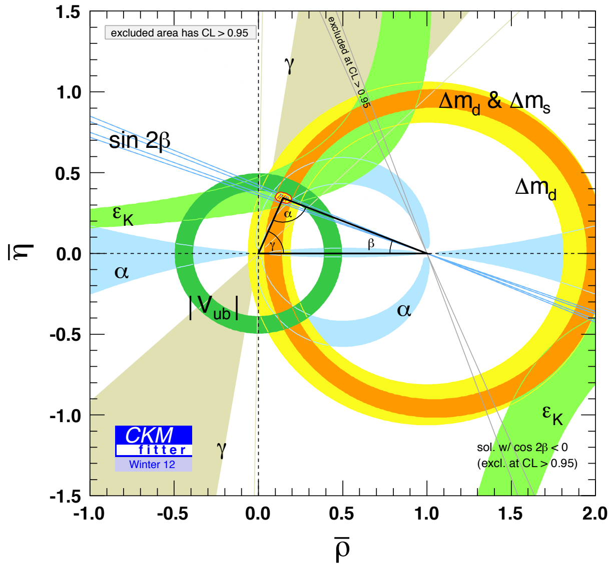
$$\mathbf{O = O_{SM} + O\,(c_1, c_2, \ldots, c_{80}) \rightarrow \chi^2 = \chi^2\,(c_i)}$$

Precision needed in any other observable to compete?

$$\chi^2 = \chi^2\,(c_i) \rightarrow \delta O(c_i) = \# \pm \#$$

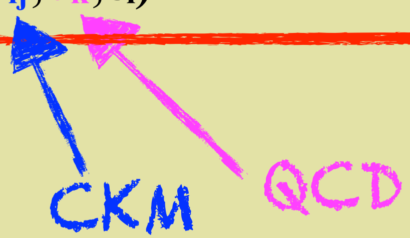
Cannot we do the same with flavor data?

- UV meaning of the famous CKM-triangle plot? Never done in the general SMEFT!
- Difficulties (flavor vs EWPO):
  - Nonperturbative QCD input;
  - CKM parameters (no hierarchy of observables)
    - Traditional approach: no NP in tree-level extraction of CKM from CC processes



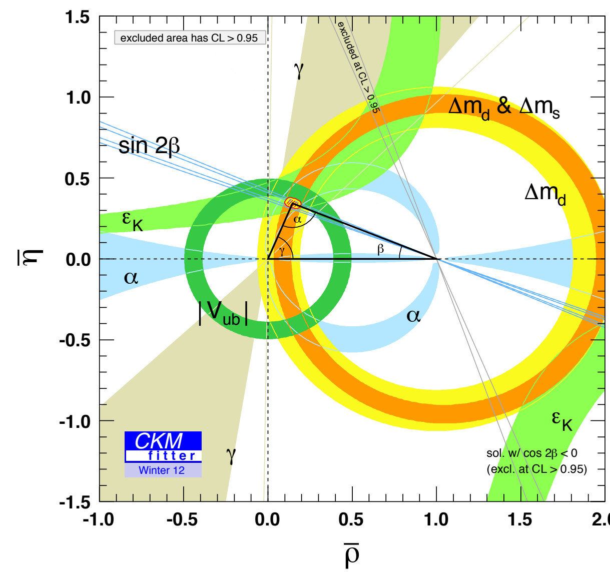
$$O = O_{SM}(V_{ij};\theta_k) + \delta O(V_{ij};\theta_k;\varepsilon_i)$$

$$\rightarrow \chi^2 = \chi^2(\tilde{V}_{ij};\theta_k;\varepsilon_i)$$



Cannot we do the same with flavor data?

- UV meaning of the famous CKM-triangle plot?
  Never done in the general SMEFT!



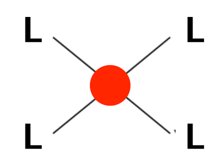
- Difficulties (flavor vs EWPO):
  - Nonperturbative QCD input;
  - CKM parameters (no hierarchy of observables)
    - Traditional approach: no NP in tree-level extraction of CKM from CC processes

- EW case:

NP affecting the extraction of EW parameters (g, g', v) taken into account

- Muon decay: v = 246.21965(6) GeV
- This observable fixes v-tilde
  and the rest is used to set NP bounds

$$G_F = \frac{1}{\sqrt{2}v^2}\left(1 + \frac{\delta G_F}{G_F}\right) \rightarrow \frac{1}{\sqrt{2}\tilde{v}^2}$$



$$O = O_{\rm SM}(v) + \delta O_{\rm NP}^{\rm direct} = O_{\rm SM}(\tilde{v}) + \delta O_{\rm NP}^{\rm indirect} + \delta O_{\rm NP}^{\rm direct}$$

Cannot we do the same with flavor data?

[Descotes-Genon, Falkowski, Fedele, MGA, & Virto, JHEP'19]

- Four "optimal" observables:

$$\Gamma(K \to \mu\nu_\mu)/\Gamma(\pi \to \mu\nu_\mu), \quad \Gamma(B \to \tau\nu_\tau), \quad \Delta M_d, \quad \Delta M_s.$$

→ Four tilde Wolfenstein parameters;

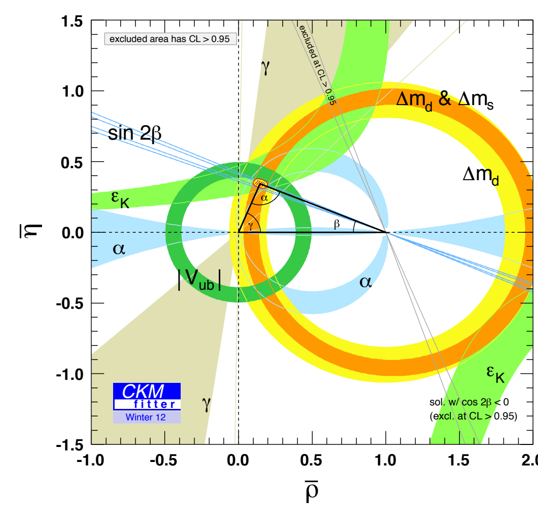
$$\begin{pmatrix} \tilde{\lambda} = \lambda + \delta\lambda \\ \tilde{A} = A + \delta A \\ \tilde{\rho} = \bar{\rho} + \delta\bar{\rho} \\ \tilde{\eta} = \bar{\eta} + \delta\bar{\eta} \end{pmatrix} = \begin{pmatrix} 0.22537 \pm 0.00046 \\ 0.828 \pm 0.021 \\ 0.194 \pm 0.024 \\ 0.391 \pm 0.048 \end{pmatrix}, \quad \rho = \begin{pmatrix} 1 & -0.16 & 0.05 & -0.03 \\ \cdot & 1 & -0.25 & -0.24 \\ \cdot & \cdot & 1 & 0.83 \\ \cdot & \cdot & \cdot & 1 \end{pmatrix}$$

→ NP effects in them calculated: $\delta\lambda = f(\varepsilon_i)$

- Any other flavor observable becomes a NP probe:

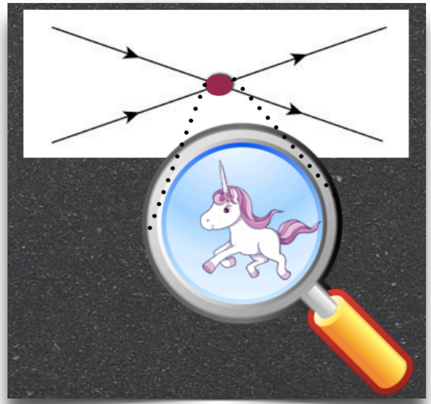
$$O_\alpha = O_{\alpha,\mathrm{SM}}(W_j) + \delta O^{\mathrm{direct}}_{\alpha,\mathrm{NP}} = O_{\alpha,\mathrm{SM}}(\widetilde{W}_j) + \delta O^{\mathrm{indirect}}_{\alpha,\mathrm{NP}} + \delta O^{\mathrm{direct}}_{\alpha,\mathrm{NP}}$$

W_i=(λ,A,ρ,η)

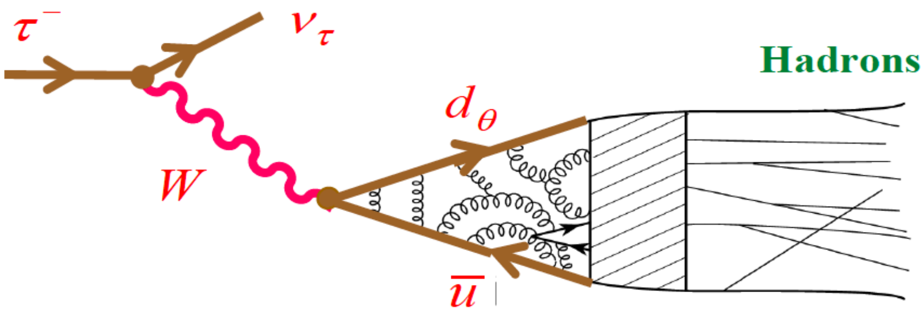


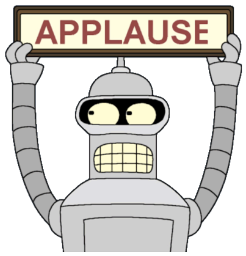
Outline

- Introduction
- SMEFT fit to Electroweak Precision Data
- Hadronic Tau Decays as a New Physics probe
- Neutrino oscillations as EFT constraints



Hadronic tau decays as NP probes





- Great EXP & TH precision in hadronic tau decays:
  α_s, V_{us}, m_s, ChPT LECs, QCD vacuum condensates, f_π, …

- UV meaning of their (dis)agreement with other determinations?
  What are they exactly probing?
  Are the competitive?
  → EFT!

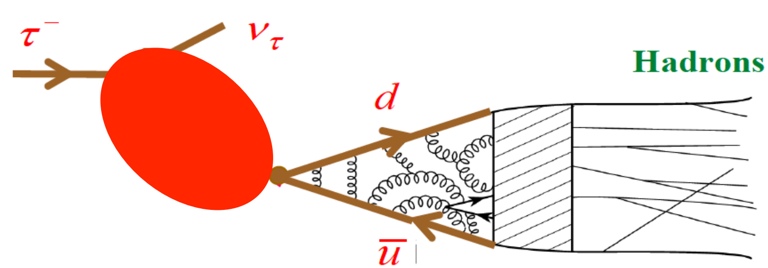
Low-energy EFT

ε^{de} couplings enter indirectly

$$
\begin{aligned}
\mathcal{L}_{\rm eff} \;=\; & -\frac{G_F V_{ud}}{\sqrt{2}}\Bigg[\left(1+\epsilon_L^{d\tau}\right)\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau\cdot\bar{u}\gamma^\mu(1-\gamma_5)d \\
& +\epsilon_R^{d\tau}\;\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau\;\bar{u}\gamma^\mu(1+\gamma_5)d \\
& +\bar{\tau}(1-\gamma_5)\nu_\tau\cdot\bar{u}\left[\epsilon_S^{d\tau}-\epsilon_P^{d\tau}\gamma_5\right]d \\
& +\epsilon_T^{d\tau}\;\bar{\tau}\sigma_{\mu\nu}(1-\gamma_5)\nu_\tau\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\Bigg]+\text{h.c.}
\end{aligned}
$$

Cirigliano et al. '10

We focus on non-strange decays!



[V. Cirigliano, A. Falkowski, MGA, & A. Rodríguez-Sánchez, PRL'19]

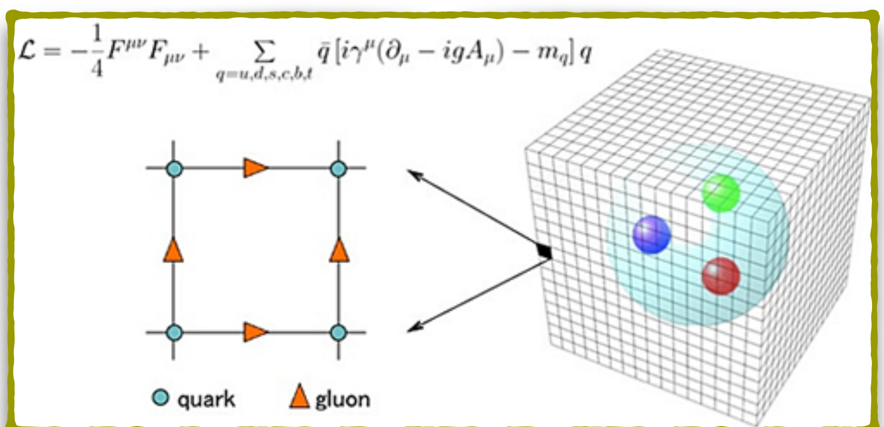
$\tau \longrightarrow \pi\nu$

- Only channel widely perceived as a NP probe

$$\Gamma = \frac{m_\tau^3 f_\pi^2 G_F^2 |V_{ud}|^2}{16\pi} \left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2 (1 + \delta_{RC}^{(\pi)})$$

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{m_\pi^2}{m_\tau(m_u + m_d)}\epsilon_P^\tau = -(1.5 \pm 6.7) \times 10^{-3}$$

Error dominated by f_π (2x exp. and 5x rad. corr)

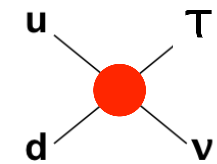


Source: http://lpc-clermont.in2p3.fr/IMG/theorie/LQCD2.jpg

$f_\pi = 130.2(8)$ MeV !

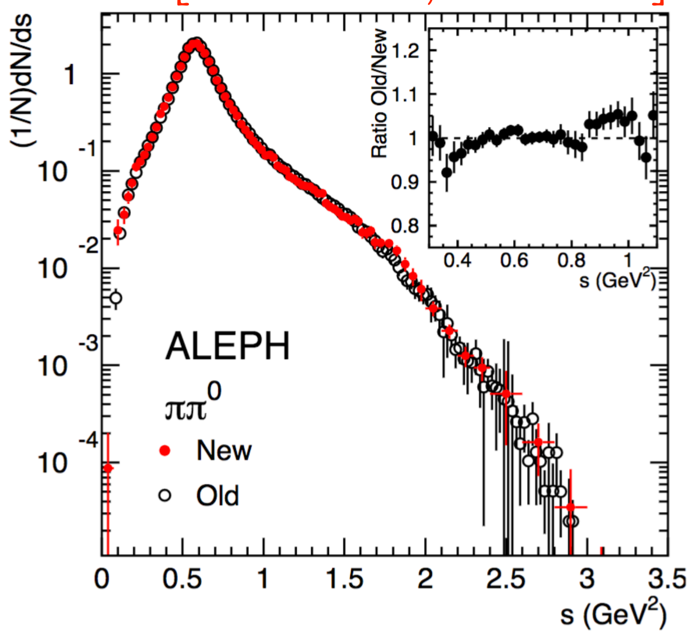
[FLAG'17, RBC / UKQCD'14]

$\tau \longrightarrow \pi\pi\nu$

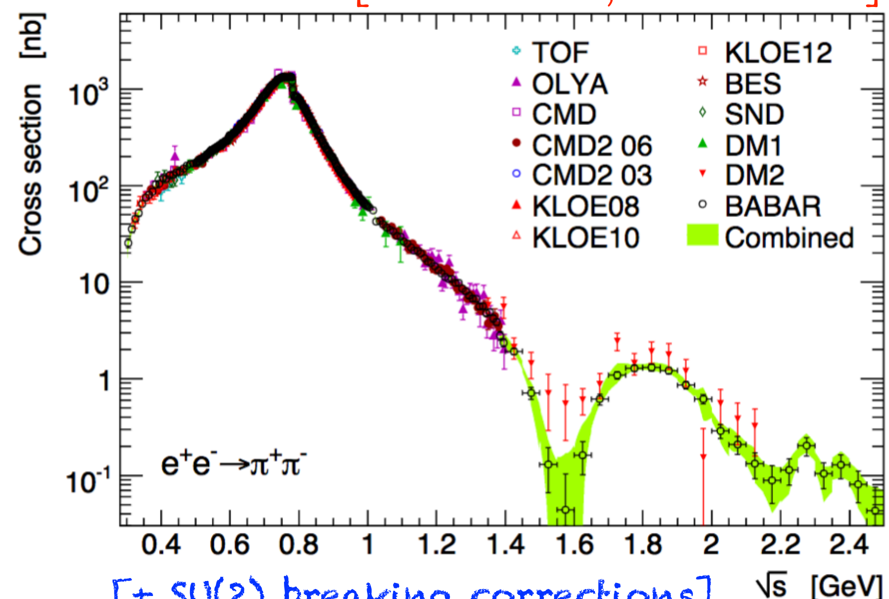


- Precise data;

[Davier et al., 1312.1501]



[Davier et al., 1706.09436]

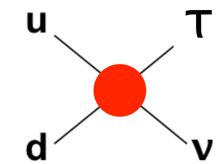


[+ SU(2) breaking corrections]

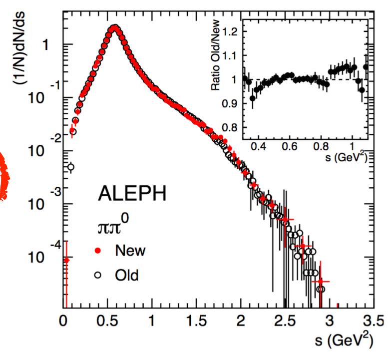
~~… But the QCD description is more involved~~
~~→ Hadronic physics probe;~~

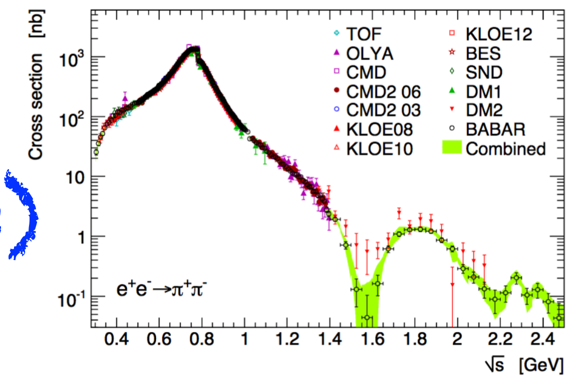
Way out:
To extract the SM value from $e^+e^- \to \pi\pi$
(which is free of heavy NP)!

$\tau \longrightarrow \pi\pi\nu$



- Precise data;

$\int$ K(s) 

ds vs. $\int$ K(s) 

ds

$a_\mu^{had,\,LO}[\pi\pi]_{\tau\text{-data}}$ $\qquad$ $a_\mu^{had,\,LO}[\pi\pi]_{e^+e^-\text{-data}}$

Using [Davier et al., 1706.09436]:

$$\frac{a_\mu^\tau - a_\mu^{ee}}{2\,a_\mu^{ee}} = \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e + 1.7\,\epsilon_T^\tau = (8.9 \pm 4.4)\cdot 10^{-3},$$

Main error: EXP !

- More data coming (& better agreement*);
- Lattice input too [M. Bruno et al., 1811.00508]
- Full spectrum available

* Using Keshavarzi et al.'18 one finds 3σ

$\tau \longrightarrow \eta\pi\nu$

- Suppressed in the SM → Enhanced sensitivity to scalar contributions:

$$\Gamma_{exp} \approx \Gamma_{SM} \left(1 + 700\, \epsilon_S^\tau + 1.6 \times 10^5\, \epsilon_S^\tau\right)$$

[Garcés, Hernández Villanueva, López Castro, P. Roig , 1708.07802]

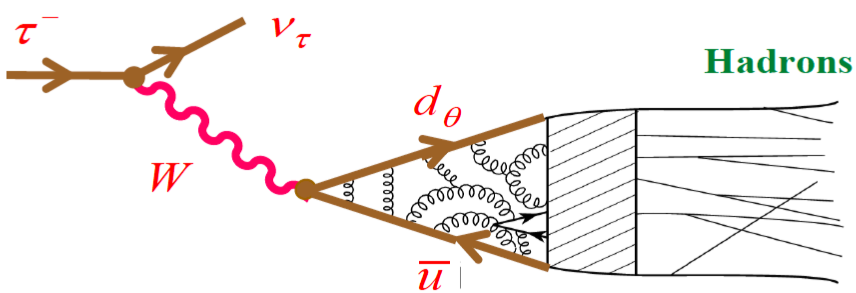
→ Nontrivial constraint on ε_S even though SM & NP contributions are hard to predict accurately.

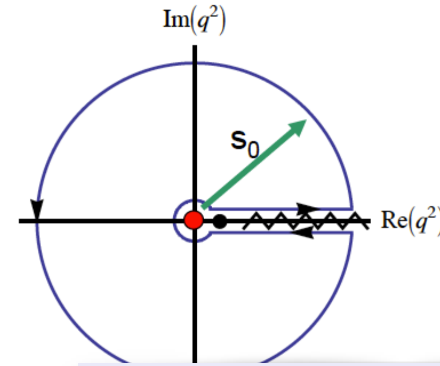
- Inputs:
  - Latest experimental results for the BR [BaBar'2010];
  - SM prediction (& uncertainty) [Escribano et al.'2016];
  - BSM prediction (& uncertainty) [Garcés et al., 2017];

$$\Rightarrow \quad \epsilon_S^\tau = (-6 \pm 15) \times 10^{-3}$$

Future?
It will improve if TH or EXP (Belle-II!) uncertainties can be reduced.

Inclusive tau decays





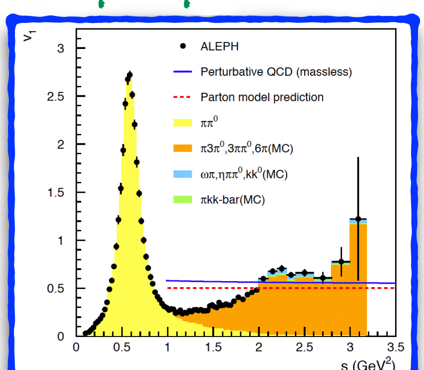
$$\Pi_{ij}(q) \sim \int ds\, e^{iqx} \langle 0|\, T(J_i(x)J_j(0))\, |0\rangle$$

$$\int_{4m_\pi^2}^{s_0} ds\,\omega(s)\,\rho_{\rm exp}(s) \sim \oint_{|s|=s_0} ds\,\omega(s)\Pi(s) = {\rm OPE}(\alpha_s, \mathcal{O}_d) + {\rm DV} + \#\epsilon_L + \#\epsilon_R + \#\epsilon_T$$

Exp. spectral functions

SM (QCD)

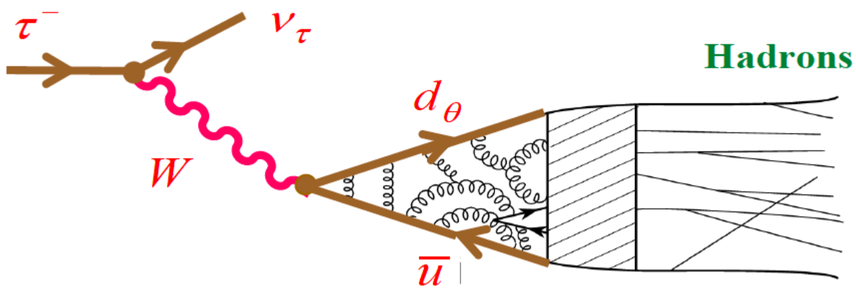
BSM

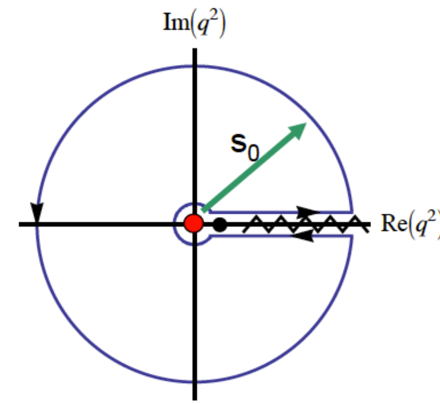


[ALEPH'05,
Davier et al. 1312.1501]

[Wilson'69, Shifman et al'79, Braaten et al'92, ...]

Inclusive tau decays





$$\epsilon_{V/A} \equiv \epsilon^{\tau}_{L\pm R} - \epsilon^{e}_{L+R}$$

$$\int_{4m_\pi^2}^{s_0} \frac{ds}{s_0}\omega\left(\frac{s}{s_0}\right) \rho^{\exp}_{V\pm A}(s) \approx (1+2\epsilon_V)\, X_{VV} \pm (1+2\epsilon_A)\left(X_{AA} - \frac{f_\pi^2}{s_0}\omega\left(\frac{m_\pi^2}{s_0}\right)\right) + \epsilon_T^\tau\, X_{VT} + \text{DV}$$

$$X_{VV/AA} = \frac{i}{2\pi}\oint_{|s|=s_0} \frac{ds}{s_0}\omega\left(\frac{s}{s_0}\right) \Pi^{(1+0)}_{VV/AA}(s) = \frac{i}{2\pi}\oint_{|s|=s_0} \frac{ds}{s_0}\omega\left(\frac{s}{s_0}\right)\left[f^{(pert.)}(\alpha_s; z) + \sum \mathcal{O}_{2d}/(-z)^d\right]$$

$$X_{VT} = -48\delta_{n,0}\frac{\langle \bar{q}q\rangle}{s_0\, m_\tau} \qquad [\text{for } \omega(x) = x^n]$$

[Balitsky et al'85, Cata & Mateu'08, Jamin & Mateu'08]

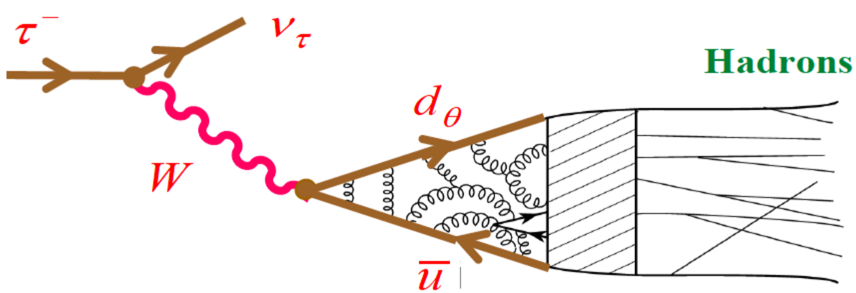
$$\alpha_s(M_z) = 0.1182(12)$$

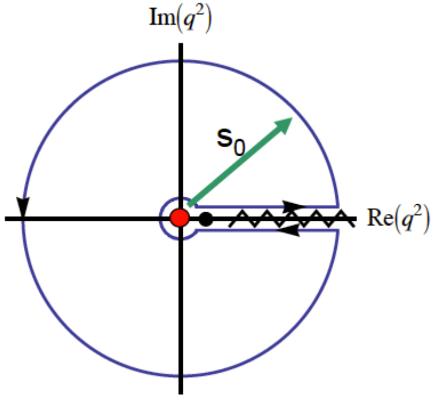
[FLAG'17]

$$|\mathcal{O}_{2d}^{V+A}| \lesssim (0.4\,\text{GeV})^{2\text{d}}(\text{d}-1)!$$
$$\mathcal{O}_6^{V-A} = -0.0042(13)\,\text{GeV}^6$$

[K→ππ, RBC/UKQCD coll.'12, Rodriguez-Sanchez & Pich'18]

Inclusive tau decays





$$\int_{4m_\pi^2}^{s_0} \frac{ds}{s_0}\omega\left(\frac{s}{s_0}\right)\rho^{\rm exp}_{V\pm A}(s) \approx (1+2\epsilon_V)\,X_{VV} \pm (1+2\epsilon_A)\left(X_{AA} - \frac{f_\pi^2}{s_0}\omega\left(\frac{m_\pi^2}{s_0}\right)\right) + \epsilon_T^\tau X_{VT} + \text{DV}$$

V+A channel

$$w(x) = (1-x)^2(1+2x) \quad\Rightarrow\quad \epsilon^\tau_{L+R} - \epsilon^e_{L+R} - 0.78\epsilon^\tau_R + 1.71\epsilon^\tau_T = (4\pm16)\cdot 10^{-3} \quad O_6,\ O_8$$

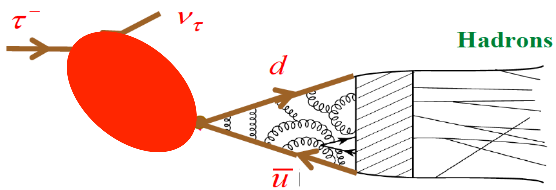
$$w(x) = 1 \quad\Rightarrow\quad \epsilon^\tau_{L+R} - \epsilon^e_{L+R} - 0.89\epsilon^\tau_R + 0.90\epsilon^\tau_T = (8.5\pm8.5)\cdot 10^{-3} \quad \text{Exp, DV}$$

V-A channel

$$w(x) = 1-x \quad\Rightarrow\quad \epsilon^\tau_{L+R} - \epsilon^e_{L+R} + 3.1\epsilon^\tau_R + 8.1\epsilon^\tau_T = (5.0\pm50)\cdot 10^{-3} \quad \text{DV}$$

$$w(x) = (1-x)^2 \quad\Rightarrow\quad \epsilon^\tau_{L+R} - \epsilon^e_{L+R} + 1.9\epsilon^\tau_R + 8.0\epsilon^\tau_T = (10\pm10)\cdot 10^{-3} \quad \text{Exp, } f_\pi$$

Recap: NP bounds from Hadronic Tau decays

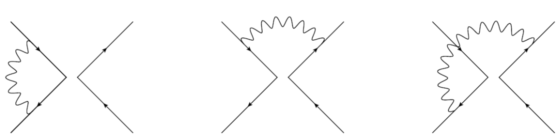


$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau \\ \epsilon_S^\tau \\ \epsilon_P^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 1.0 \pm 1.1 \\ 0.2 \pm 1.3 \\ -0.6 \pm 1.5 \\ 0.5 \pm 1.2 \\ -0.04 \pm 0.46 \end{pmatrix} \cdot 10^{-2}$$

$$\rho = \begin{pmatrix} 1 & 0.88 & 0 & -0.57 & -0.94 \\ & 1 & 0 & -0.86 & -0.94 \\ & & 1 & 0 & 0 \\ & & & 1 & 0.66 \\ & & & & 1 \end{pmatrix}$$

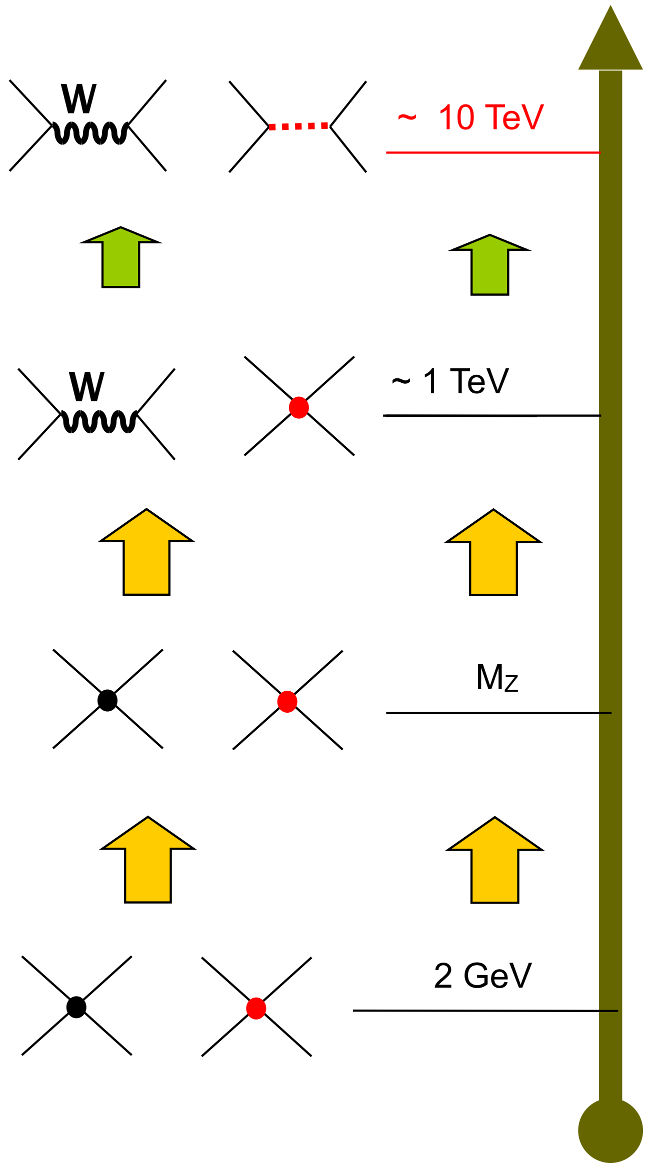
[MS-bar at μ = 2 GeV]

Running to higher energies:
(QCD x QED & QCD x EW)
[MGA, Martin Camalich & Mimouni'17]



$$\begin{pmatrix} \epsilon_L \\ \epsilon_R \\ \epsilon_S \\ \epsilon_P \\ \epsilon_T \end{pmatrix}_{(\mu = 2\text{ GeV})} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1.0046 & 0 & 0 & 0 \\ 0 & 0 & 1.72 & 2.46 \times 10^{-6} & -0.0242 \\ 0 & 0 & 2.46 \times 10^{-6} & 1.72 & -0.0242 \\ 0 & 0 & -2.17 \times 10^{-4} & -2.17 \times 10^{-4} & 0.825 \end{pmatrix} \begin{pmatrix} \epsilon_L \\ \epsilon_R \\ \epsilon_S \\ \epsilon_P \\ \epsilon_T \end{pmatrix}_{(\mu = Z)}$$

EFT matching, EWPO & LHC



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

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

RGE (EW x QCD) [Alonso et al.'14, MGA, Camalich & Mimouni'17]

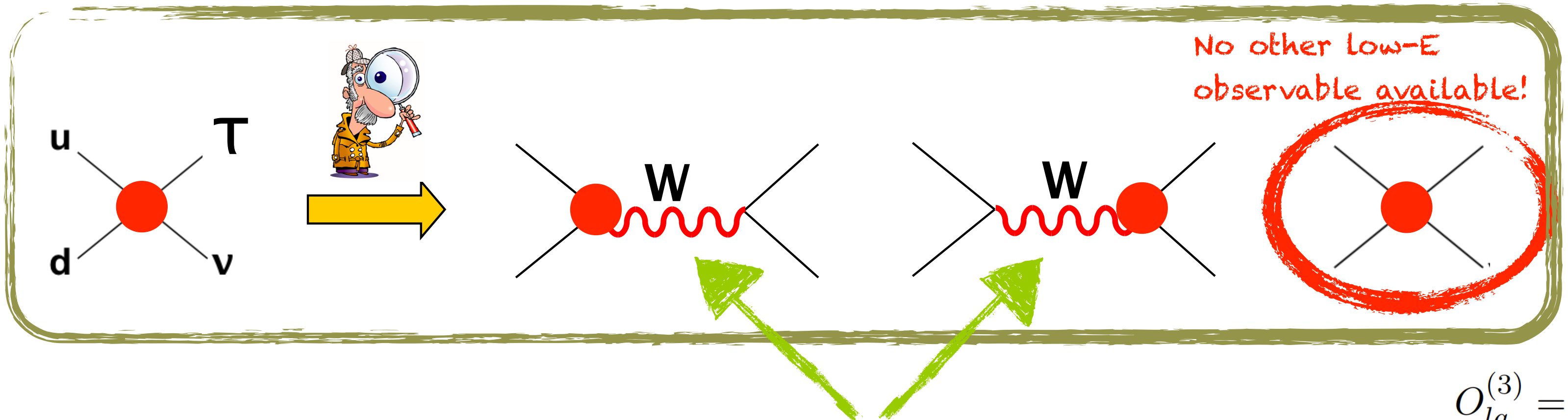
$$\varepsilon_i = f(\alpha_j)$$

MATCHING [Cirigliano, MGA & Jenkins '10]

RGE (QED x QCD) [MGA, Camalich & Mimouni'17]

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

EFT matching, EWPO & LHC



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

SMEFT Matching:

$$\epsilon_L^{\tau} - \epsilon_L^{e} = \delta g_L^{W\tau} - \delta g_L^{We} - [c_{\ell q}^{(3)}]_{\tau\tau 11} + [c_{\ell q}^{(3)}]_{ee11}$$

$$\epsilon_R^{\tau} = \delta g_R^{Wq_1},$$

→ ϵ_R is lepton independent!

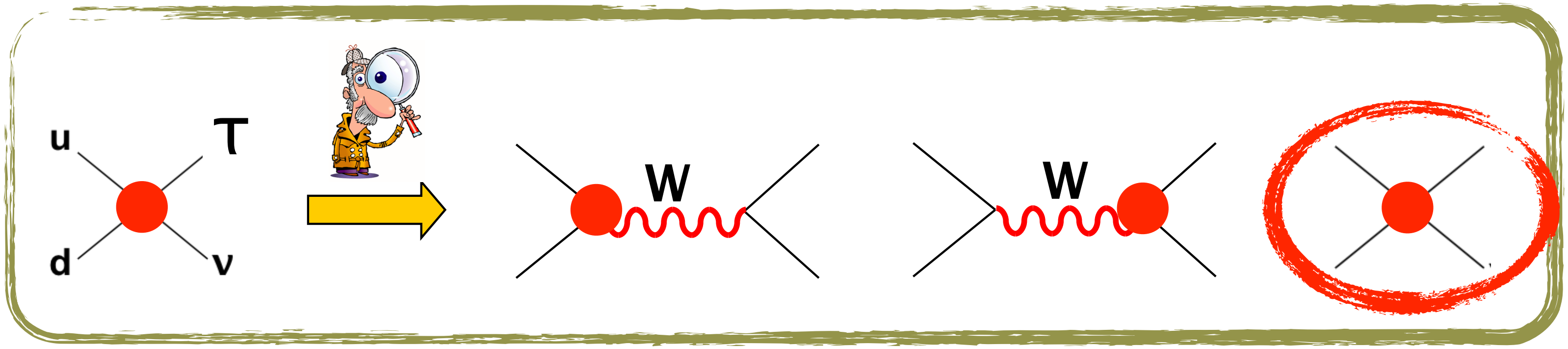
$$\epsilon_{S,P}^{\tau} = -\frac{1}{2}[c_{lequ} \pm c_{ledq}]^{*}_{\tau\tau 11} \,,$$

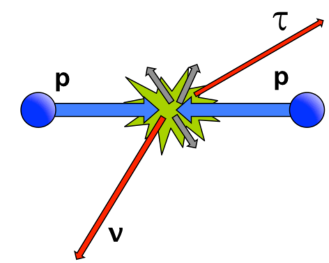
$$\epsilon_T^{\tau} = -\frac{1}{2}[c_{lequ}^{(3)}]^{*}_{\tau\tau 11} \,.$$

EWPO
[Falkowski, MGA & Mimouni, 2017]

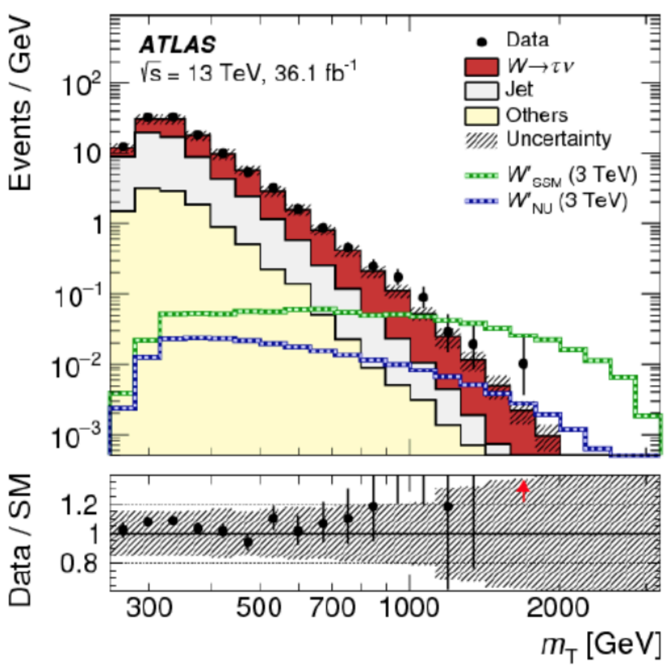
$$\begin{bmatrix} c_{lq}^{(3)} \\ c_{lequ} \\ c_{ledq} \\ c_{lequ}^{(3)} \end{bmatrix}_{\tau\tau 11} = \begin{pmatrix} 1.2 \pm 2.9 \\ -0.2 \pm 1.1 \\ 0.9 \pm 1.1 \\ -0.36 \pm 0.93 \end{pmatrix} \times 10^{-2}$$

EFT matching, EWPO & LHC





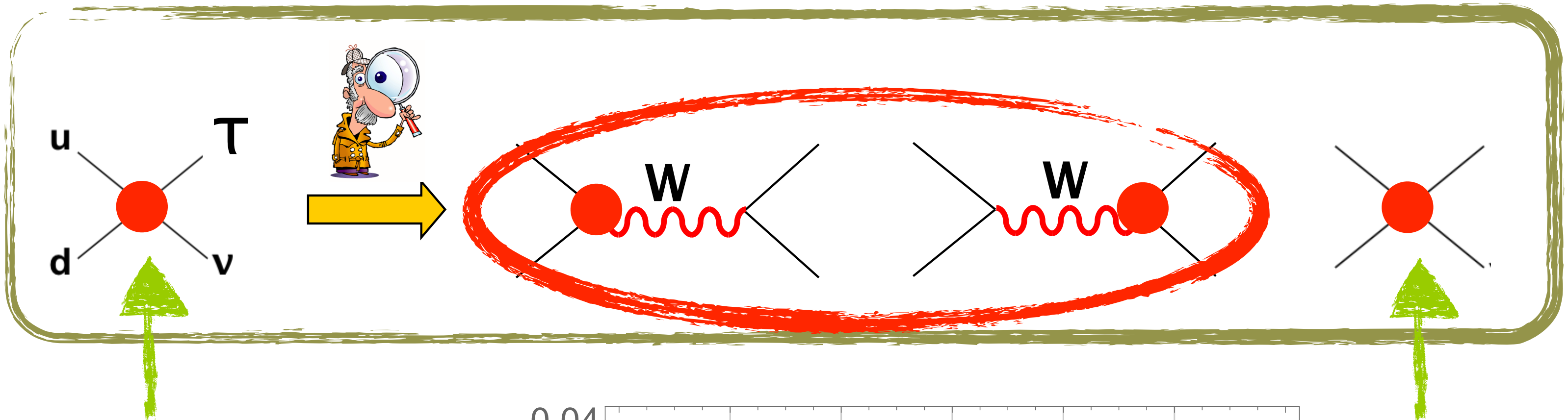
Less precision compensated by higher E:
$A_{4f} \sim s/\Lambda^2$



Coefficient	ATLAS $\tau\nu$	τ and π decays
$[c_{\ell q}^{(3)}]_{\tau\tau 11}$	$[0.0, 1.6]$	$[-7.6, 2.1]$
$[c_{\ell equ}]_{\tau\tau 11}$	$[-5.6, 5.6]$	$[-5.6, 2.3]$
$[c_{\ell edq}]_{\tau\tau 11}$	$[-5.6, 5.6]$	$[-2.1, 5.8]$
$[c_{\ell equ}^{(3)}]_{\tau\tau 11}$	$[-3.3, 3.3]$	$[-8.6, 0.7]$

95% CL intervals (in 10^{-3} units) at $\mu = 1$ TeV

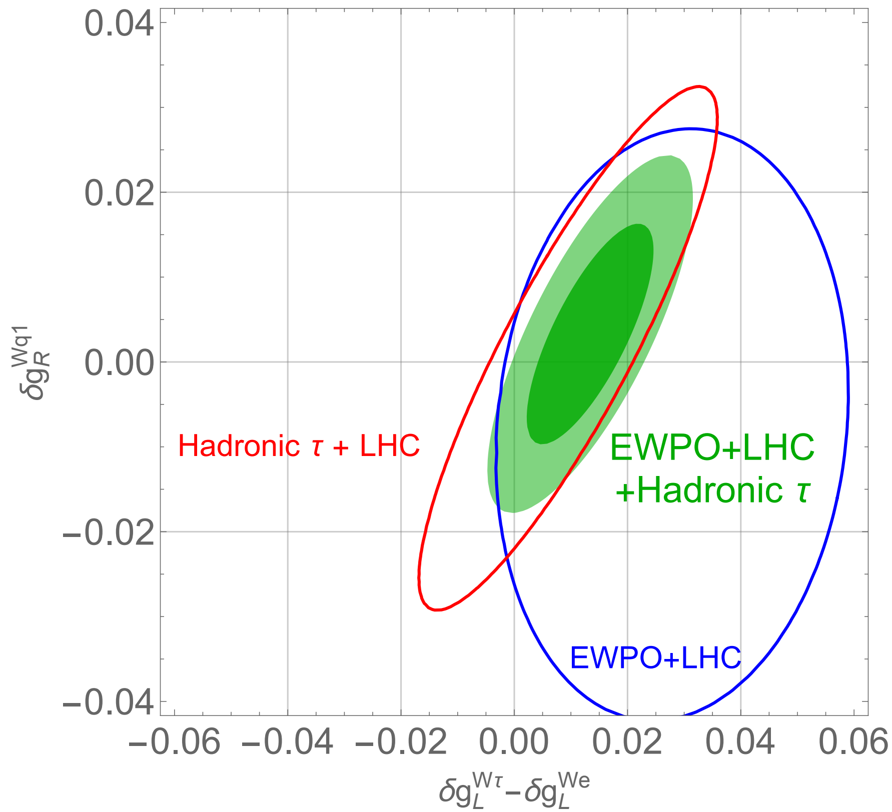
EFT matching, EWPO & LHC



Hadronic Tau Decays

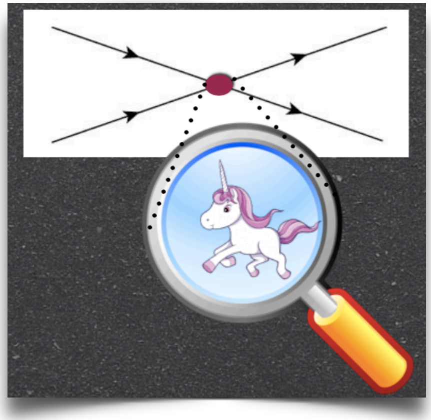
LHC

A new %-level probe of LFU of vertex correction!

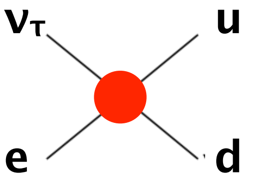


Outline

- Introduction
- SMEFT fit to Electroweak Precision Data
- Hadronic Tau Decays as a New Physics probe
- Neutrino oscillations as EFT constraints



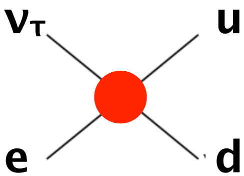
NP bounds from Neutrino Oscillation data



[A. Falkowski, MGA, & Z. Tabrizi, JHEP'19]

- Similar to flavor physics: $O = O\,(\theta_i, \Delta m^2)$
- NP constrained by the observed consistency: $O = O\,(\theta_i, \Delta m^2, \varepsilon_j)$
  - Linear sensitivity (EFT counting) to non-diagonal flavor structures
  - (Of course processes with charged leptons are expected to be way more powerful...)

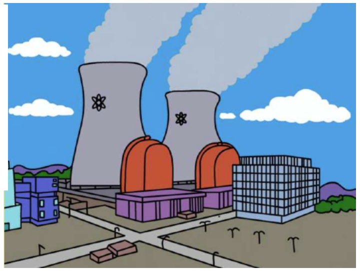
NP bounds from Neutrino Oscillation data



[A. Falkowski, MGA, & Z. Tabrizi, JHEP'19]

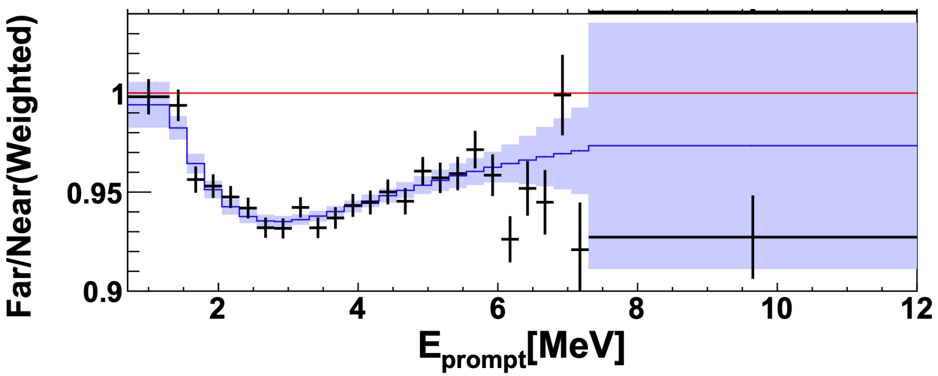
- Similar to flavor physics: $O = O\,(\theta_i, \Delta m^2)$
- NP constrained by the observed consistency: $O = O\,(\theta_i, \Delta m^2, \varepsilon_j)$
- Concrete example:
  short-baseline reactor neutrino experiments

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu) \;=\; 1 - \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)\sin^2\left(2\theta_{13}\right)$$

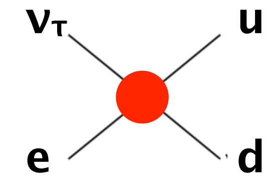


[PS: no anomaly in far/near ratios]

  - Precision: $\theta_{13} = 0.0856(29)$
    [DayaBay'18, ~4M neutrino events!]



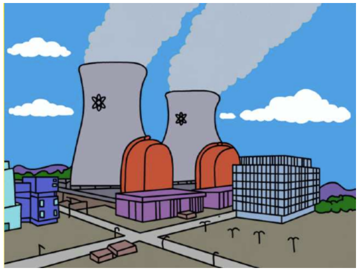
NP bounds from Neutrino Oscillation data



[A. Falkowski, MGA, & Z. Tabrizi, JHEP'19]

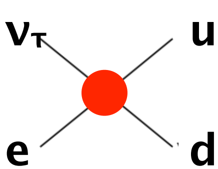
- Similar to flavor physics: $O = O(\theta_i, \Delta m^2)$
- NP constrained by the observed consistency: $O = O(\theta_i, \Delta m^2, \epsilon_j)$
- Concrete example:
  short-baseline reactor neutrino experiments

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu) = 1 - \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \sin^2\left(2\theta_{13}\right)$$

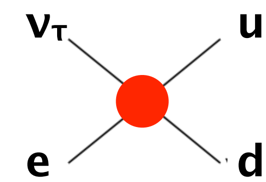


  - Precision: $\theta_{13} = 0.0856(29)$
    [DayaBay'18, ~4M neutrino events!]

  - Again: UV-meaning of the good agreement with the SM?
    - No access to NC NSI (negligible matter effects): ννqq
    - Non-standard V-A ($e_L \gamma_\mu \nu_\tau \; u_L \gamma^\mu d_L$) gets hidden: $\theta_{13} \to \theta'_{13}$ [Ohlsson-Zhang'09]
    - S, T and Im(V+A) can be probed



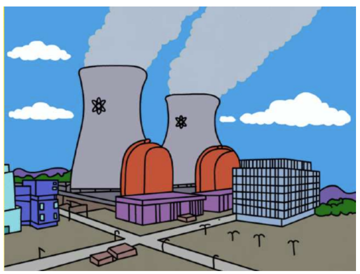
NP bounds from Neutrino Oscillation data

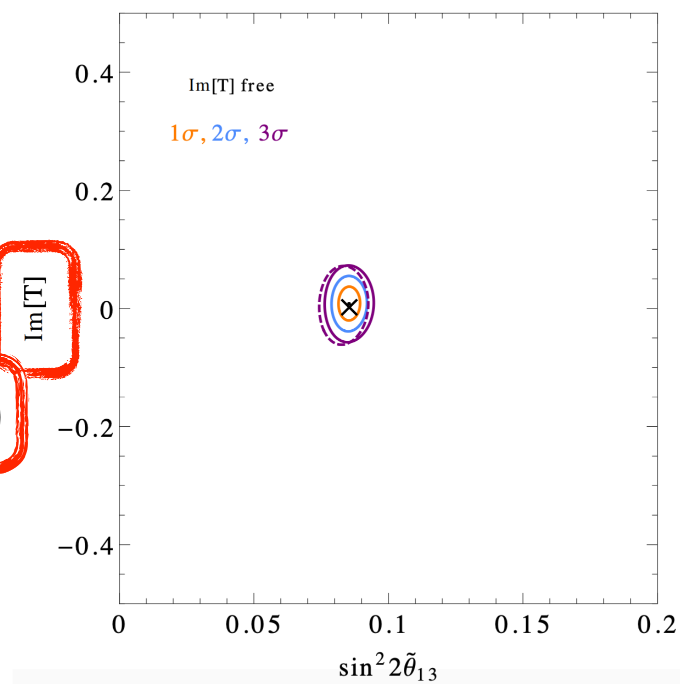


[A. Falkowski, MGA, & Z. Tabrizi, JHEP'19]

- Similar to flavor physics: $O = O\,(\theta_i, \Delta m^2)$
- NP constrained by the observed consistency: $O = O\,(\theta_i, \Delta m^2, \epsilon_j)$
- Concrete example:
  short-baseline reactor neutrino experiments

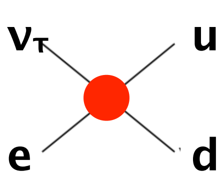
$$\begin{aligned} P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu) &= 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)\sin^2\left(2\theta_{13} - \alpha_D \frac{m_e}{E_\nu - \Delta} - \alpha_P \frac{m_e}{f_T(E_\nu)}\right) \\ &+ \sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\theta_{13})\left(\beta_D \frac{m_e}{E_\nu - \Delta} - \beta_P \frac{m_e}{f_T(E_\nu)}\right) + \mathcal{O}(\epsilon_X^2) \end{aligned}$$



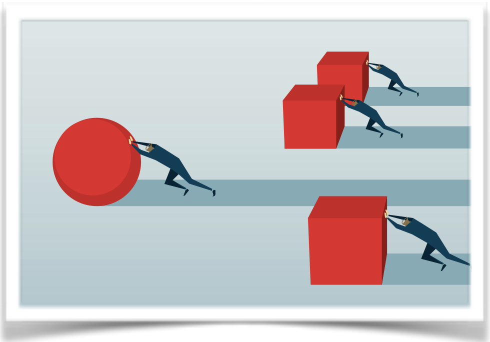


% level bounds (TeV scale)

$$[Q^{(3)}_{\ell equ}]_{\alpha 111} = (\bar{\ell}^m_\alpha \sigma_{\mu\nu} e_1)\epsilon_{mn}(\bar{q}^n_1 \sigma^{\mu\nu} u_1)$$



Summary



- The (SM)EFT is an ***efficient*** framework to combine / compare / interpret precision low-E experiments

- Intense activity in recent years:
  EFT basis, RGEs, **global fits**, BSM matching, ...
  - Flavor-general SMEFT fit to EWPO (publicly!) available
    [Falkowski, MGA & Mimouni, JHEP'17]

$$\chi^2 = \chi^2 (c_i)$$

- The UV information of many precision measurements has not been explored:
  - Hadronic Tau Decays
    [V. Cirigliano, A. Falkowski, MGA, & A. Rodríguez-Sánchez, PRL'19]
  - Reactor neutrinos
    [A. Falkowski, MGA, & Z. Tabrizi, JHEP'19]