

Precision vs. energy in the (*flavorful*) Standard Model EFT

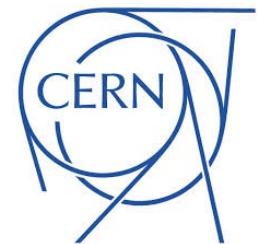
53rd Rencontres de Moriond - EW

March 2018



Martín González-Alonso

CERN - TH



Motivation

- The SM is in very good shape...
[cf. Kogler's talk]



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[cf. Fuentes-Martin's talk]



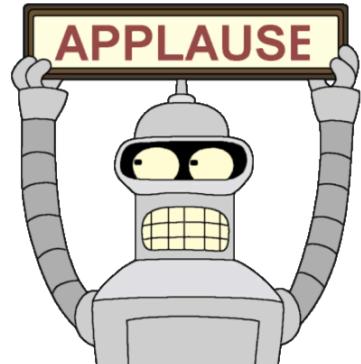
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[cf. Kogler's talk]

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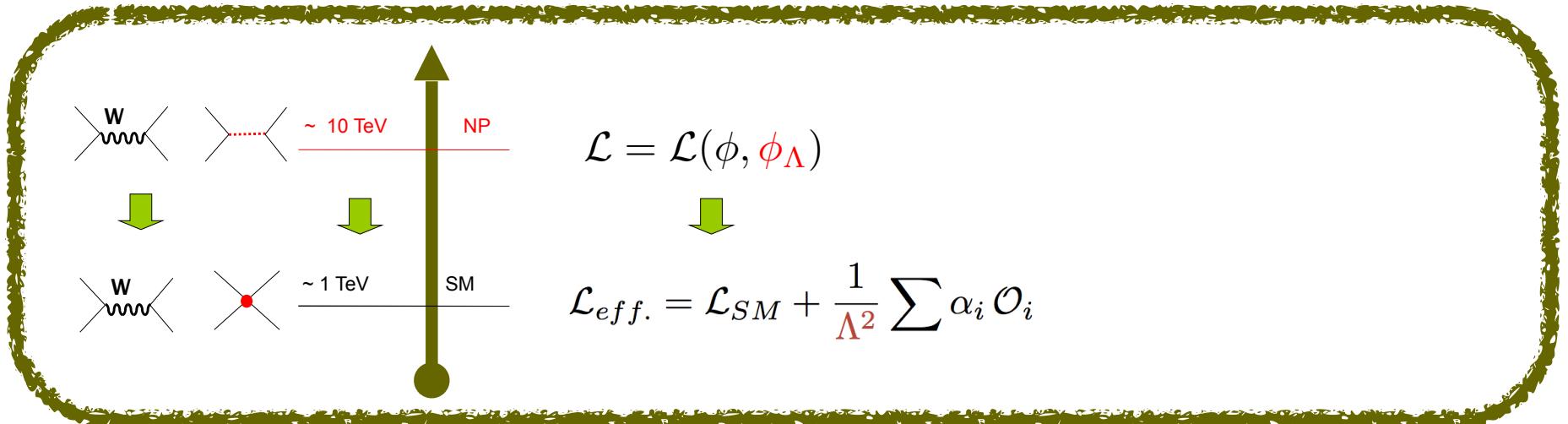


- Different extractions of (e.g.) the weak angle in good agreement;
→ Impressive, but what's the UV meaning?



After quite some work, one can answer this question for a specific model

Standard Model EFT

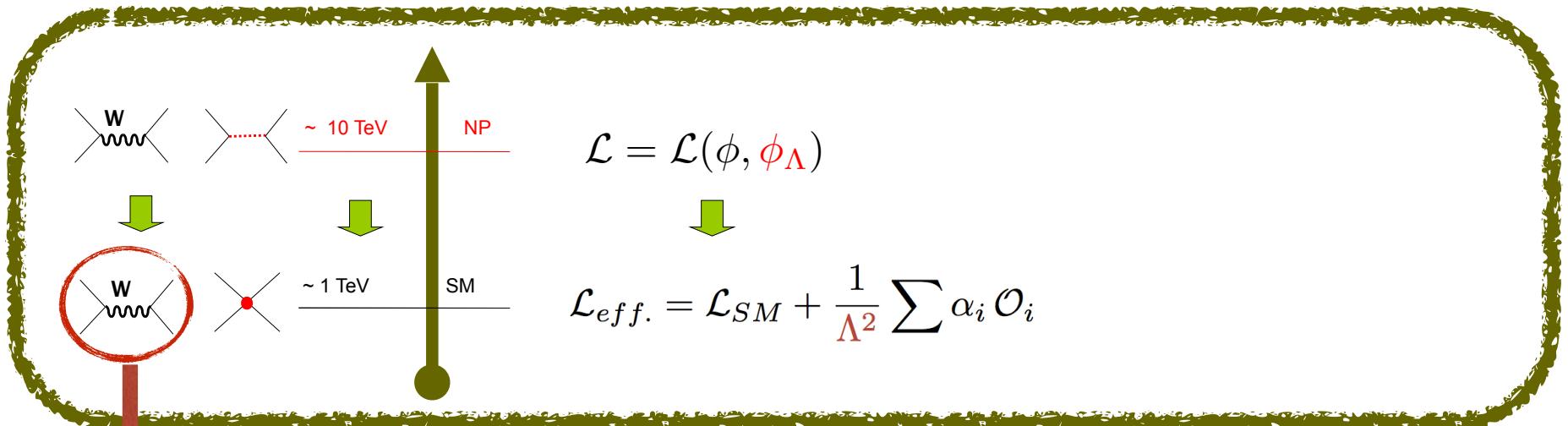


α : Wilson coefficients (UV physics)

59 dim-6 operators

[Buchmuller & Wyler'1986, Leung et al.'1986,
Grzadkowski et al., 2010]

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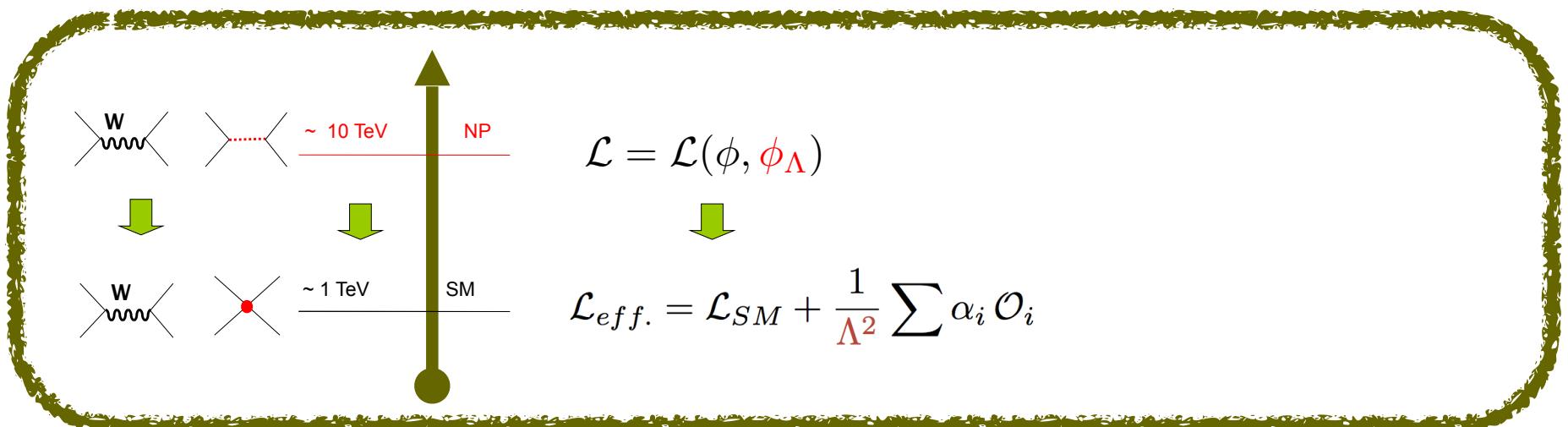
$$-\frac{4G_F}{\sqrt{2}} \bar{e}\gamma_\mu(1 - \gamma_5)\nu_e \cdot \bar{\nu}_\mu\gamma^\mu(1 - \gamma_5)\mu$$



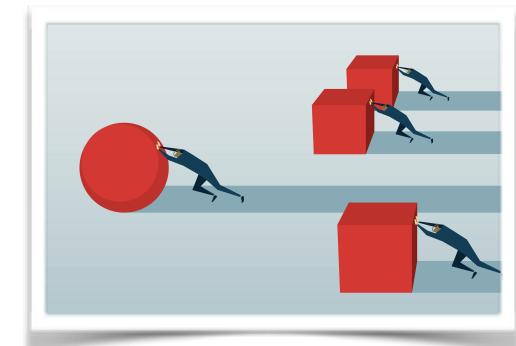
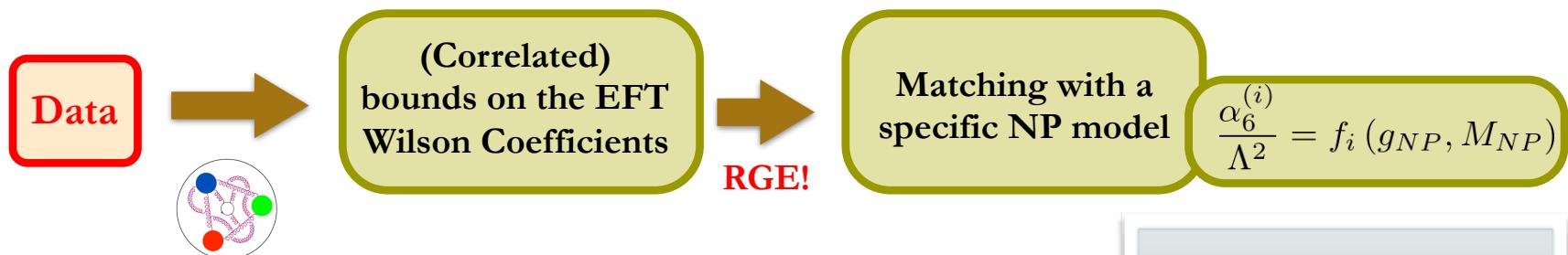
$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient

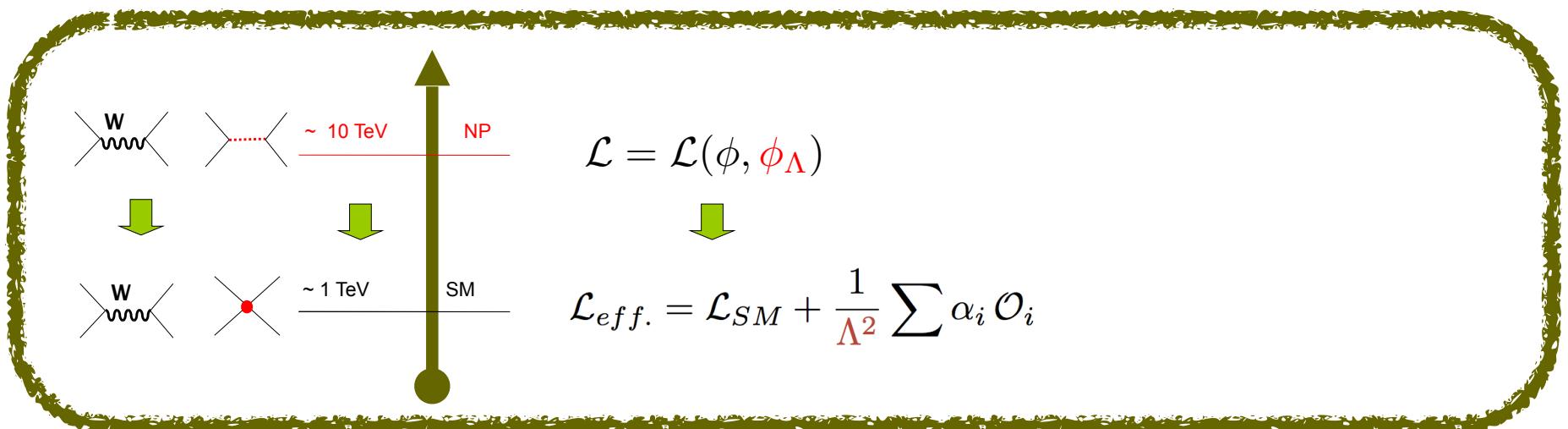
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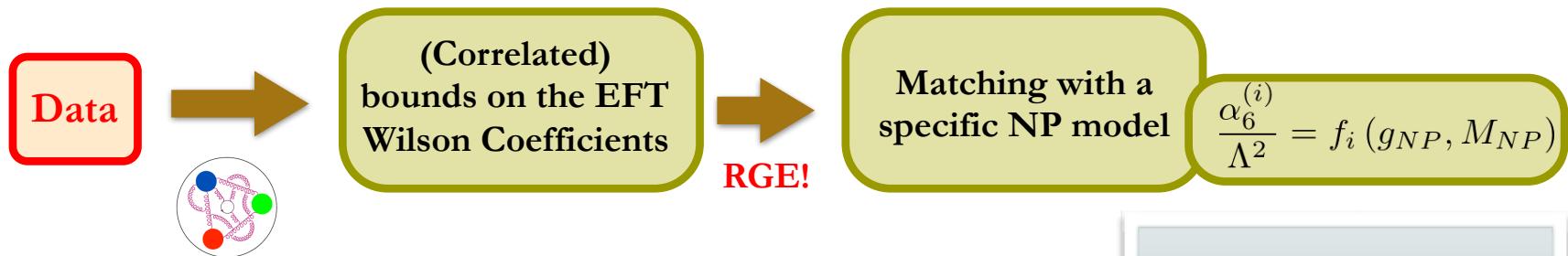
- Efficiency: Analysis (bkg, PDFs, FF, simulations, ...) done once and for all!



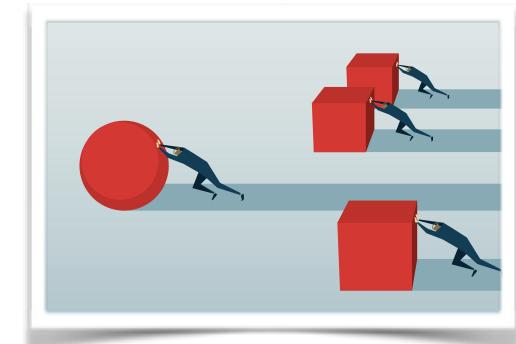
Standard Model EFT



- Efficiency: Analysis (bkg, PDFs, FF, simulations, ...) done once and for all!



- Useful especially if...
 - Global analysis
 - Final likelihood public
 - Avoid additional assumptions



EW precision observables (EWPO) in the SMEFT

- ◆ Precedent: flavor universal [Han-Skiba'05], non global [de Blas-Chala-Santiago'13], ...
- ◆ New: Flavor-general case! [*Efrati, Falkowski & Soreq'15*;
Falkowski & Mimouni'15;
Falkowski, MGA & Mimouni'17]

Flavorful SMEFT



B anomalies!

EWPO fit in the flavorful SMEFT

[Falkowski, MGA & Mimouni, 2017]

- ◆ Precedent: flavor universal [Han-Skiba'05], or non global [de Blas-Chala-Santiago'13];
- ◆ 264 experimental input
 - ◆ Z- & W-pole data
 - ◆ $[e^+e^- \rightarrow l^+l^-]$, qq
 - ◆ Low-energy processes:
 - ◆ Nuclear and hadron decays ($d \rightarrow ulv$)
 - ◆ Neutrino scattering
 - ◆ PV in atoms and in scattering
 - ◆ Leptonic tau decays

Class	Observable	Exp. value
$\nu_e\nu_{eqq}$	$R_{\nu_e\nu_e}$	0.41(14)
	$(g_L^{\nu_\mu})^2$	0.3005(28)
	$(g_R^{\nu_\mu})^2$	0.0329(30)
	$\theta_L^{\nu_\mu}$	2.500(35)
$\nu_\mu\nu_{\mu qq}$	$\theta_R^{\nu_\mu}$	$4.56^{+0.42}_{-0.27}$
	$g_{AV}^{eu} + 2g_{AV}^{ed}$	0.489(5)
	$2g_{AV}^{eu} - g_{AV}^{ed}$	-0.708(16)
	$2g_{VA}^{eu} - g_{VA}^{ed}$	-0.144(68)
PV low-E $eeqq$	$g_{VA}^{eu} - g_{VA}^{ed}$	-0.042(57)
	$g_{VA}^{eu} - g_{VA}^{ed}$	-0.120(74)
	$b_{SPS}(\lambda = 0.81)$	$-1.47(42) \cdot 10^{-4}$
	$b_{SPS}(\lambda = 0.66)$	$-1.74(81) \cdot 10^{-4}$
$d(s) \rightarrow ul\nu$	$\epsilon_i^{d_J \ell}$	eq. (3.17)
$e^+e^- \rightarrow q\bar{q}$	$\sigma(q\bar{q})$	
	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)
$e^-e^- \rightarrow e^-e^-$	g_{AV}^{ee}	0.0190(27)
$\nu_\mu\gamma^* \rightarrow \nu_\mu\mu^+\mu^-$	$\frac{\sigma}{\sigma_{SM}}$	1.58(57) 0.82(28)
$\tau \rightarrow \ell\nu\nu$	$G_{\tau e}^2/G_F^2$	1.0029(46)
	$G_{\tau\mu}^2/G_F^2$	0.981(18)
$e^+e^- \rightarrow \ell^+\ell^-$	$\frac{d\sigma(ee)}{d\cos\theta}$	
	$\sigma_\mu, \sigma_\tau, \mathcal{P}_\tau$	$f(\sqrt{s})$
	A_{FB}^μ, A_{FB}^τ	

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

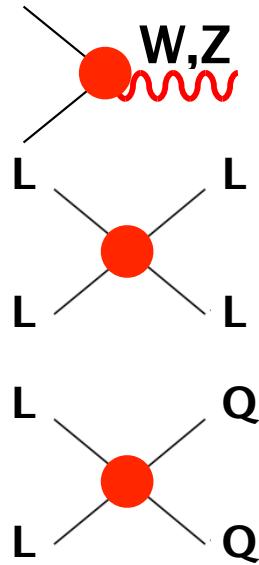
Observable	Experimental value	Ref.	SM prediction	Definition
m_W [GeV]	80.385 ± 0.015	[50]	80.364	$\frac{g_L^W}{2} (1 + \delta m)$
Γ_W [GeV]	2.085 ± 0.042	[45]	2.091	$\sum_f \Gamma(W \rightarrow ff')$
$Br(W \rightarrow e\nu)$	0.1071 ± 0.0016	[51]	0.1083	$\frac{\Gamma(W \rightarrow e\nu)}{\sum_f \Gamma(W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

EWPO fit in the flavorful SMEFT

[Falkowski, MGA & Mimouni, 2017]

- ◆ Precedent: flavor universal [Han-Skiba'05], or non global [de Blas-Chala-Santiago'13];
- ◆ 264 experimental input
- ◆ They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]

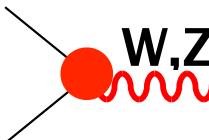
$$\mathbf{O} = \mathbf{O}_{\text{SM}} + \mathbf{O} (c_1, c_2, \dots, c_{80}) \rightarrow \chi^2 = \chi^2 (c_i)$$



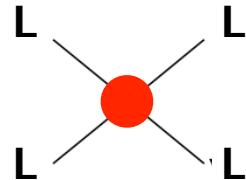
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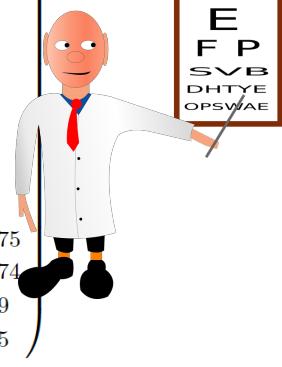
 δg_L^{We} $\delta g_L^{W\mu}$ $\delta g_L^{W\tau}$ δg_L^{Ze} $\delta g_L^{Z\mu}$ $\delta g_L^{Z\tau}$ δg_R^{Ze} $\delta g_R^{Z\mu}$ $\delta g_R^{Z\tau}$ δg_L^{Zu} δg_L^{Zc} δg_L^{Zt} δg_R^{Zu} δg_R^{Zc} δg_R^{Zd} δg_L^{Zs} δg_L^{Zb} δg_R^{Zd} δg_R^{Zs} δg_R^{Zb} $\delta g_R^{Wq_1}$

$$= \begin{pmatrix} -1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \\ -0.023 \pm 0.028 \\ 0.01 \pm 0.12 \\ 0.018 \pm 0.059 \\ -0.033 \pm 0.027 \\ 0.00 \pm 0.14 \\ 0.042 \pm 0.062 \\ -0.8 \pm 3.1 \\ -0.15 \pm 0.36 \\ -0.3 \pm 3.8 \\ 1.4 \pm 5.1 \\ -0.35 \pm 0.53 \\ -0.9 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.17 \\ 3 \pm 16 \\ 3.4 \pm 4.9 \\ 2.30 \pm 0.88 \\ -1.3 \pm 1.7 \end{pmatrix} \times 10^{-2}.$$



$$= \begin{pmatrix} [c_{\ell\ell}]_{1111} & 1.01 \pm 0.38 \\ [c_{\ell e}]_{1111} & -0.22 \pm 0.22 \\ [c_{ee}]_{1111} & 0.20 \pm 0.38 \\ [c_{\ell\ell}]_{1221} & -4.8 \pm 1.6 \\ [c_{\ell e}]_{1122} & 1.5 \pm 2.1 \\ [c_{\ell e}]_{1222} & 1.5 \pm 2.2 \\ [c_{ee}]_{1122} & -1.4 \pm 2.2 \\ [c_{\ell\ell}]_{2211} & 3.4 \pm 2.6 \\ [c_{\ell e}]_{2211} & 1.5 \pm 1.3 \\ [c_{ee}]_{1331} & 0 \pm 11 \\ [c_{\ell\ell}]_{1133} & -2.3 \pm 7.2 \\ [c_{\ell e}]_{1133} & 1.7 \pm 7.2 \\ [c_{ee}]_{1133} & -1 \pm 12 \\ [\hat{c}_{\ell\ell}]_{2222} & -2 \pm 21 \\ [\hat{c}_{\ell\ell}]_{2332} & 3.0 \pm 2.3 \end{pmatrix} \times 10^{-2}.$$

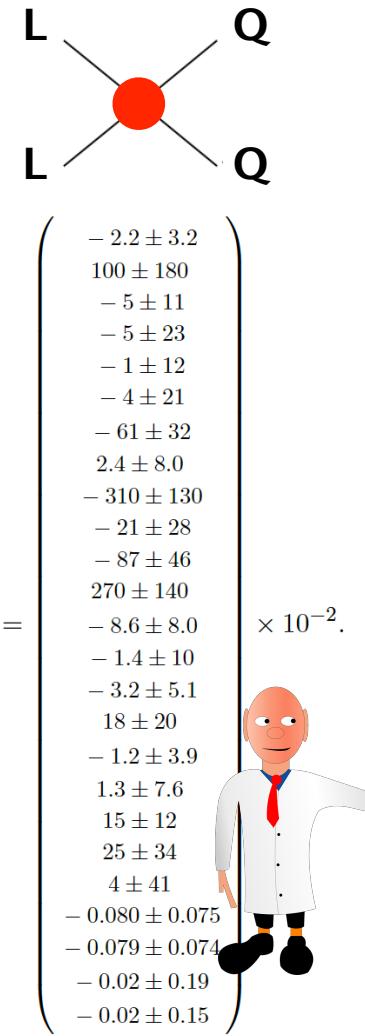
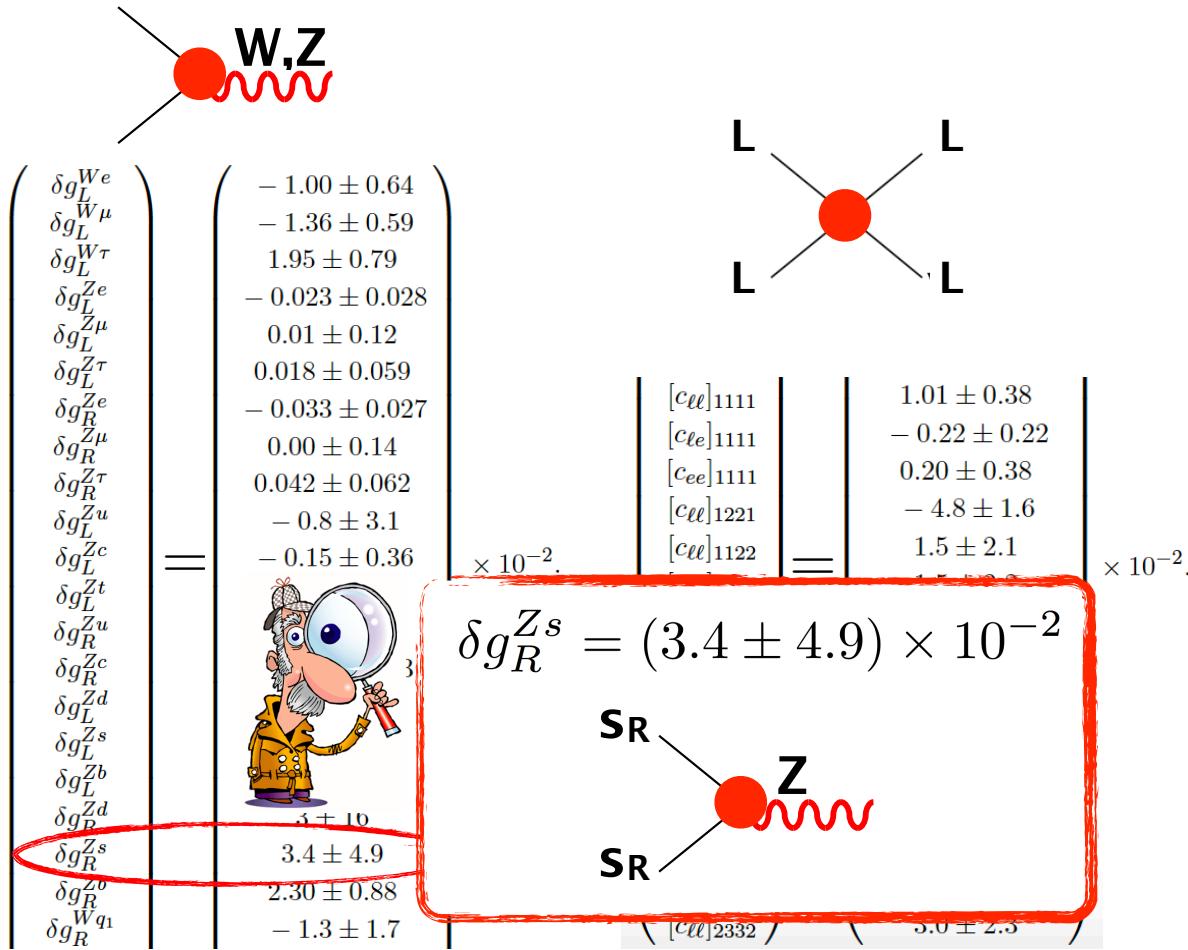
$$= \begin{pmatrix} [c_{\ell q}^{(3)}]_{1111} & -2.2 \pm 3.2 \\ [\hat{c}_{eq}]_{1111} & 100 \pm 180 \\ [\hat{c}_{\ell u}]_{1111} & -5 \pm 11 \\ [\hat{c}_{\ell d}]_{1111} & -5 \pm 23 \\ [\hat{c}_{eu}]_{1111} & -1 \pm 12 \\ [\hat{c}_{ed}]_{1111} & -4 \pm 21 \\ [\hat{c}_{\ell q}^{(3)}]_{1122} & -61 \pm 32 \\ [c_{\ell u}]_{1122} & 2.4 \pm 8.0 \\ [\hat{c}_{\ell d}]_{1122} & -310 \pm 130 \\ [c_{eq}]_{1122} & -21 \pm 28 \\ [c_{eu}]_{1122} & -87 \pm 46 \\ [\hat{c}_{ed}]_{1122} & 270 \pm 140 \\ [\hat{c}_{\ell q}^{(3)}]_{1133} & -8.6 \pm 8.0 \\ [c_{\ell d}]_{1133} & -1.4 \pm 10 \\ [c_{eq}]_{1133} & -3.2 \pm 5.1 \\ [c_{ed}]_{1133} & 18 \pm 20 \\ [c_{\ell q}^{(3)}]_{2211} & -1.2 \pm 3.9 \\ [\hat{c}_{\ell q}]_{2211} & 1.3 \pm 7.6 \\ [c_{\ell u}]_{2211} & 15 \pm 12 \\ [\hat{c}_{\ell d}]_{2211} & 25 \pm 34 \\ [\hat{c}_{eq}]_{2211} & 4 \pm 41 \\ [c_{lequ}]_{1111} & -0.080 \pm 0.075 \\ [\hat{c}_{ledq}]_{1111} & -0.079 \pm 0.074 \\ [\hat{c}_{equ}^{(3)}]_{1111} & -0.02 \pm 0.19 \\ \epsilon_P^{\mu}(2 \text{ GeV}) & -0.02 \pm 0.15 \end{pmatrix} \times 10^{-2}.$$



EWPO fit in the flavorful SMEFT

[Falkowski, MGA & Mimouni, 2017]

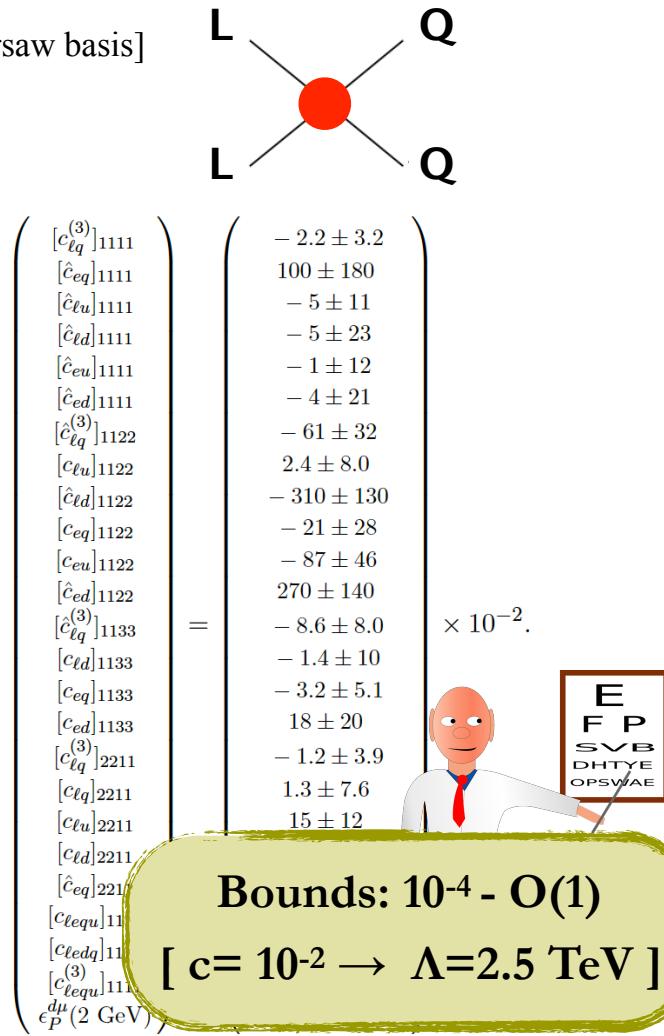
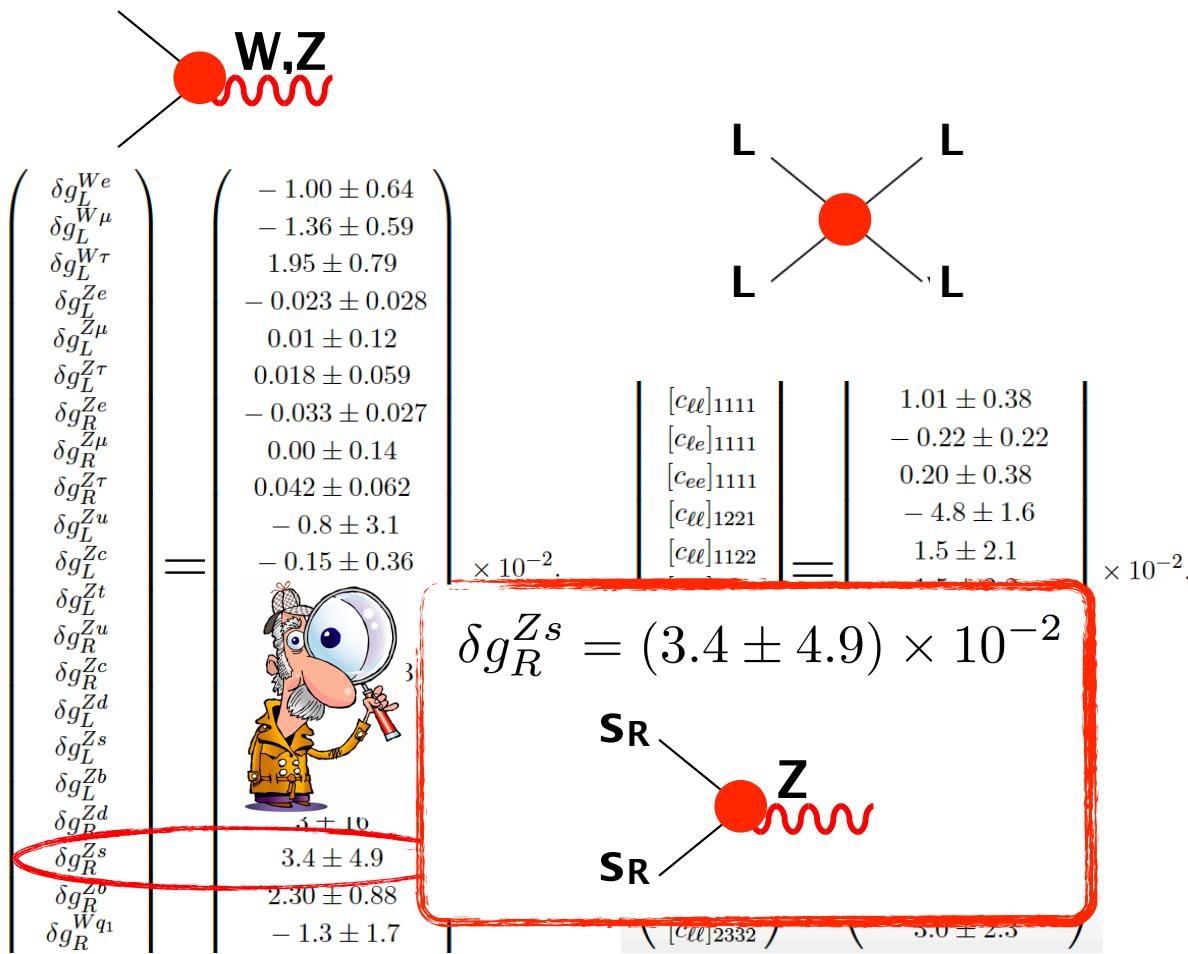
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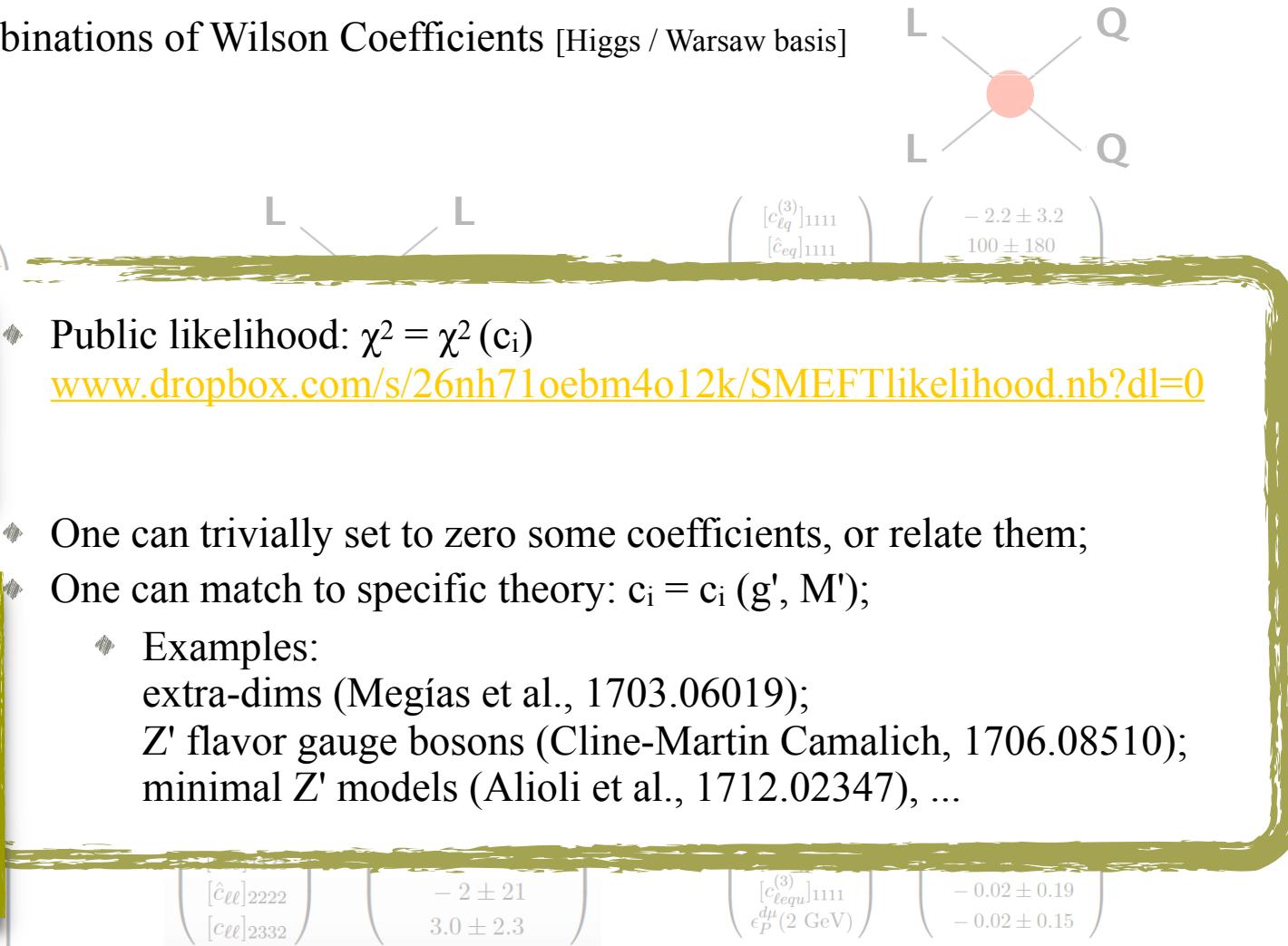
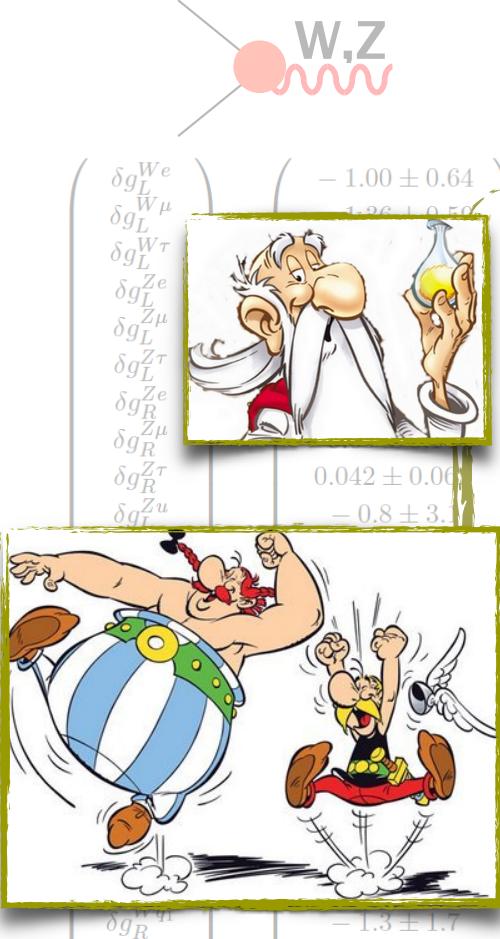
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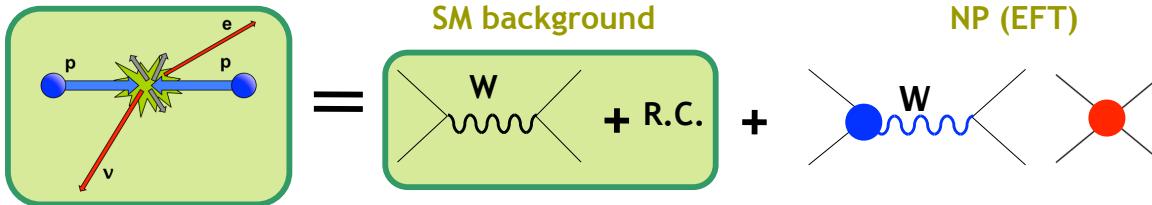
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What about high-p_T LHC data?

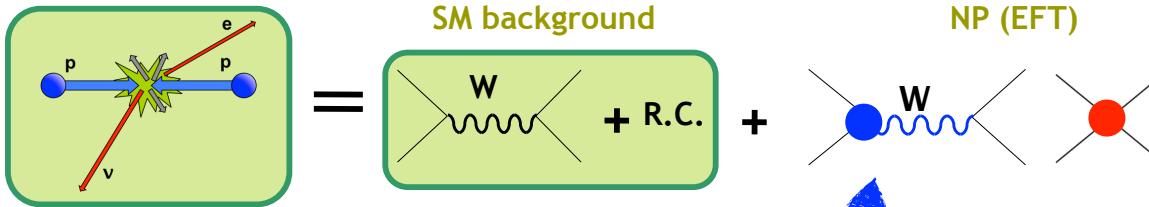


- ◆ Not so precise, but the energy might help:

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

$$x = (v, E) \ll \Lambda$$

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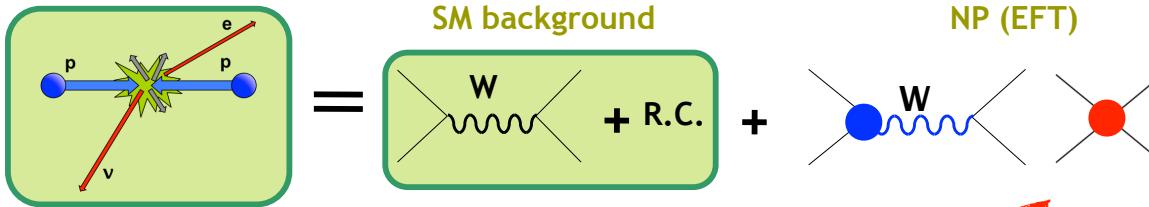
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*Vertex corrections
(SM-like amplitudes)*

**unless cancellations
happen between E-growing
SM amplitudes ($pp \rightarrow VV$)*

Precision is the key

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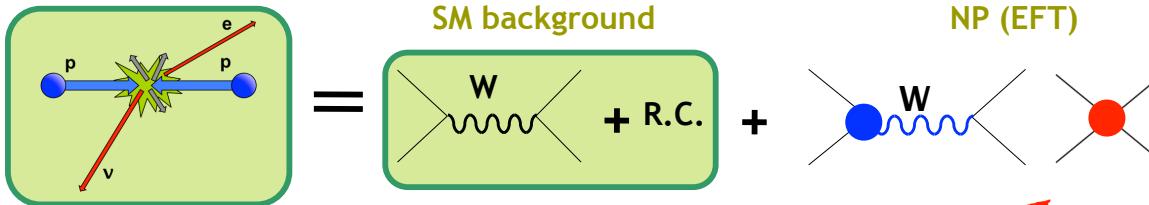
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Contact interactions
(propagator?)
 E^2/v^2 enhancement
wrt SM term

Bounds driven by
Precision + Energy

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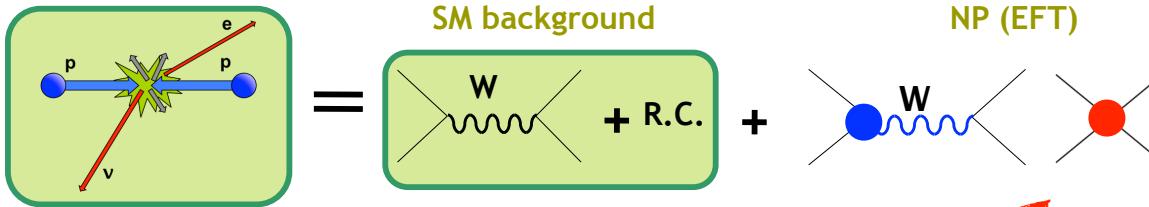
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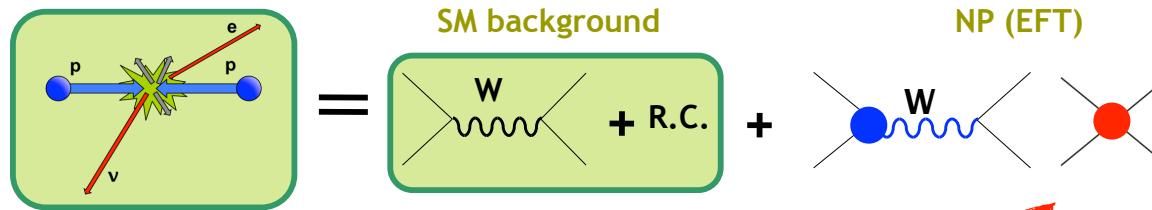
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- ◆ Recent analyses:
[Farina et al '16, Greljo & Marzocca '17, Falkowski, MGA & Mimouni '17, ...]

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

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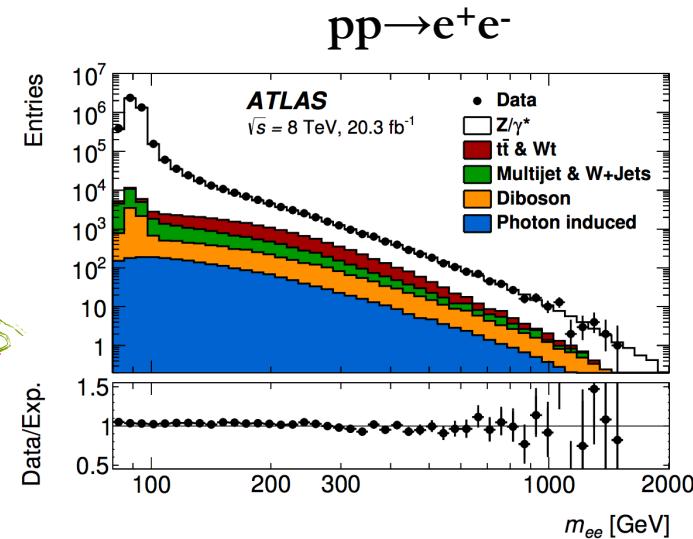
**Contact interactions
(propagator?)**
 **E^2/v^2 enhancement
wrt SM term**

*Bounds driven by
Precision + Energy*

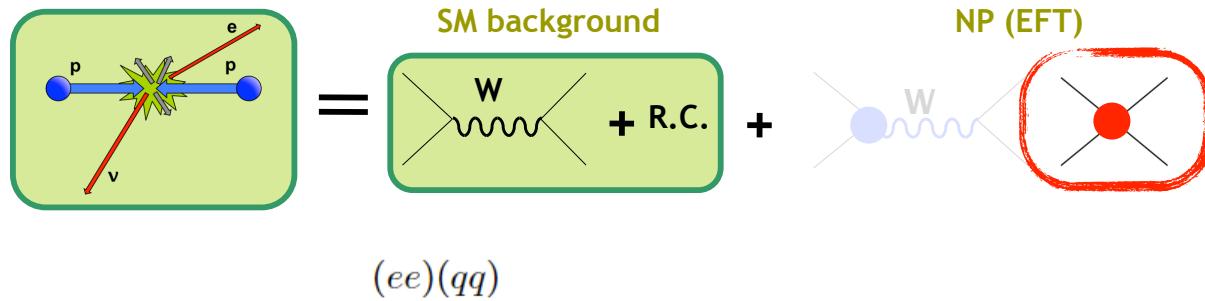
- ◆ LHC ($pp \rightarrow e^+e^-$, ev) is a sensitive probe of LLQQ interactions
[Cirigliano, MGA & Graesser '12]

- ◆ LHC ($pp \rightarrow e^+e^-$) bounds competitive with EWPO
[de Blas, Chala & Santiago '13]

- ◆ Recent analyses:
[Farina et al '16, Greljo & Marzocca '17, Falkowski, MGA & Mimouni '17]



What about high-pT LHC data?



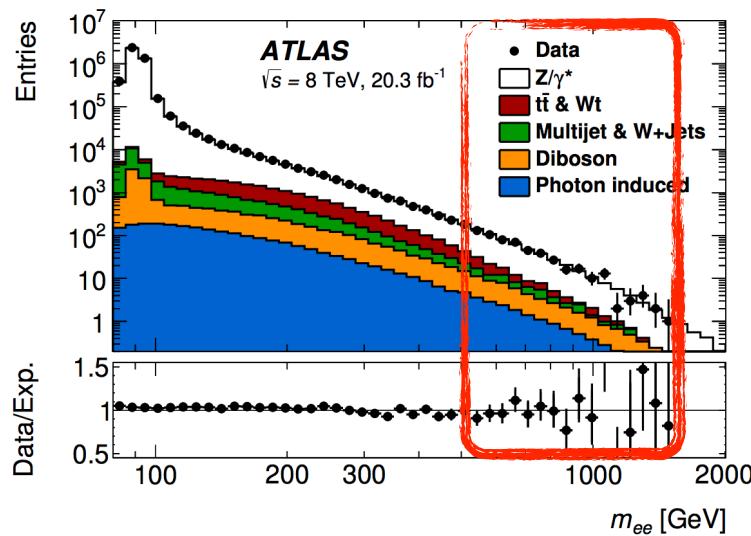
$(ee)(qq)$

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LHC _{1.5}	$-0.70^{+0.66}_{-0.74}$	$2.5^{+1.9}_{-2.5}$	$2.9^{+2.4}_{-2.9}$	$-1.6^{+3.4}_{-3.0}$	$1.6^{+1.8}_{-2.2}$	$1.6^{+2.5}_{-1.5}$	$-3.1^{+3.6}_{-3.0}$
LHC ₁₀	$-0.84^{+0.85}_{-0.92}$	$3.6^{+3.6}_{-3.7}$	$4.4^{+4.4}_{-4.7}$	$-2.4^{+4.8}_{-4.7}$	$2.4^{+3.0}_{-3.2}$	$1.9^{+2.5}_{-1.9}$	$-4.6^{+5.4}_{-4.1}$
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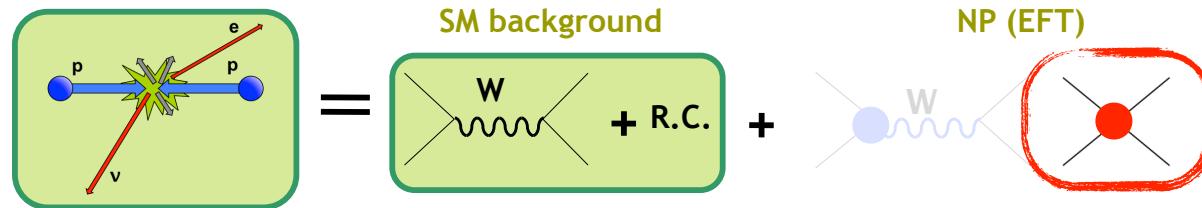
[Falkowski, MGA & Mimouni, 2017]

$\times 10^{-3}$

$0.5 \text{ TeV} < m_{ee} < 1.5 \text{ TeV}$



What about high-p_T LHC data?

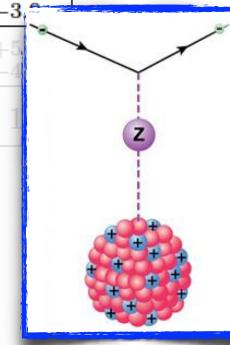


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[Falkowski, MGA & Mimouni, 2017]

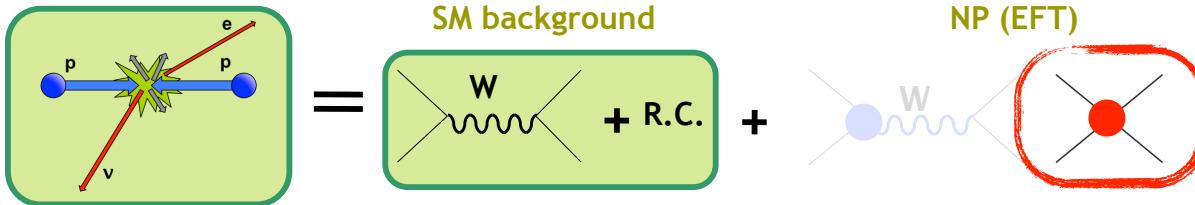
$\times 10^{-3}$



$$Q_W^{\text{Cs}} = -72.62 \pm 0.43$$

[Wood et al., Science '97]

What about high-p_T LHC data?

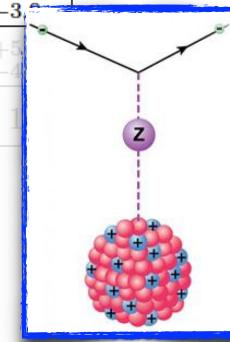


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[Falkowski, MGA & Mimouni, 2017]

$\times 10^{-3}$



$$\Delta_{\text{CKM}} \equiv |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 - 1$$

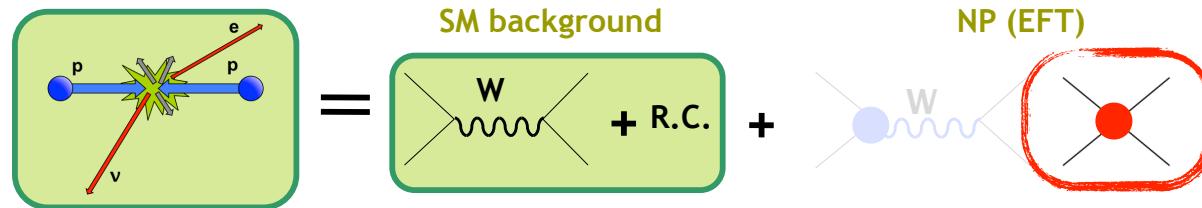
$$= -(4.6 \pm 5.2) \times 10^{-4}$$

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[Wood et al., Science '97]

[Hardy & Towner'14,
Flavianet'16,
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MGA, Naviliat-Cuncic & Severijns, 1803.XXXX]

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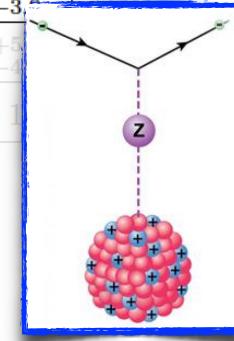


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[Falkowski, MGA & Mimouni, 2017]

$\times 10^{-3}$



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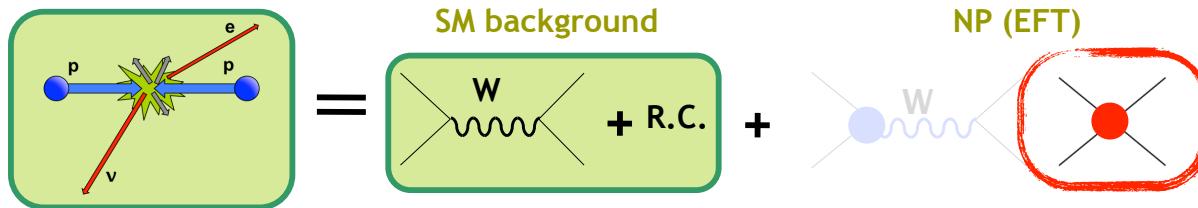
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LHC run 2 & HL-LHC
 $\rightarrow \sim 10^{-4}$ level bounds
[Greljo-Marzocca, 2017]

What about high-pT LHC data?



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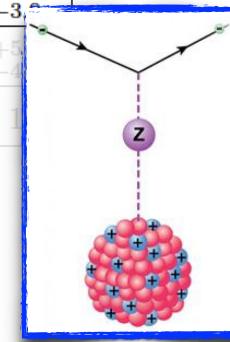
Daughter

$\times 10^{-3}$

[Falkowski, MGA & Mimouni, 2017]

$$\Delta_{CKM} \equiv |\tilde{V}_{ud}|^2 + |V_{us}|^2 + |V_{cd}|^2 = -(4.6 \pm 1.1)$$

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee



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[Wood et al., Science '97]

[Hardy & Towner'
Flavianet'16,
MGA & Martin Ca
MGA, Naviliat-Cu

Laser Cooling of Ra ions for Atomic Parity Violation

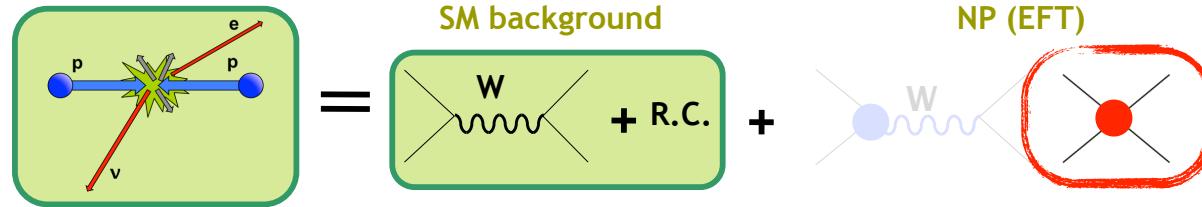
May 31, 2017

L. Willmann¹, K. Jungmann¹, N. Severijns², K. Wendt³

"The ion Ra+ renders the possibility for a 5x improvement in the accuracy of $\sin 2 \theta_W$ within 1 week of measurement time"

LHC run 2 & HL-LHC
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[Greljo-Marzocca, 2017]

What about high-p_T LHC data?



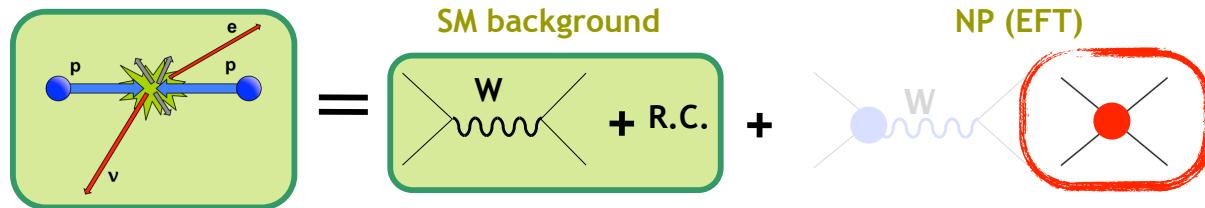
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[Falkowski, MGA & Mimouni, 2017]

$\times 10^{-3}$

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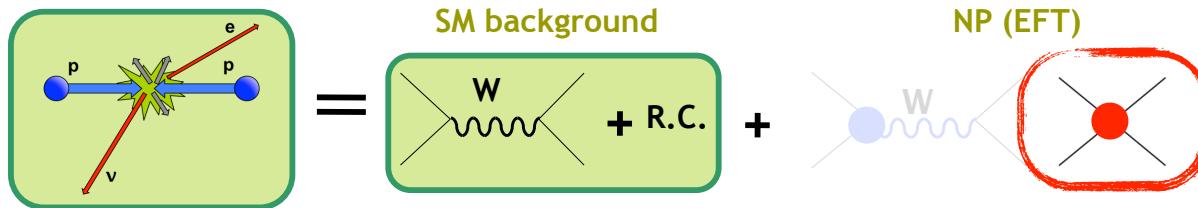
$\times 10^{-3}$

$(\mu\mu)(qq)$

	$[c_{\ell q}^{(3)}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
Low-energy	-0.2 ± 1.2	4 ± 21	18 ± 19	-20 ± 37	40 ± 390	-20 ± 190	40 ± 390
LHC _{1.5}	$-1.22^{+0.62}_{-0.70}$	1.8 ± 1.3	2.0 ± 1.6	-1.1 ± 2.0	1.1 ± 1.2	$2.5^{+1.8}_{-1.4}$	-2.2 ± 2.0
LHC _{1.0}	$-0.72^{+0.81}_{-0.87}$	$3.2^{+4.0}_{-3.5}$	$3.9^{+4.8}_{-4.4}$	$-2.3^{+4.9}_{-4.7}$	$2.3^{+3.1}_{-3.2}$	$1.6^{+2.3}_{-1.8}$	-4.4 ± 5.3
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$\times 10^{-3}$

What about high-p_T LHC data?



$(ee)(qq)$

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[Falkowski, MGA & Mimouni, 2017]

$\times 10^{-3}$

$(\mu\mu)(qq)$

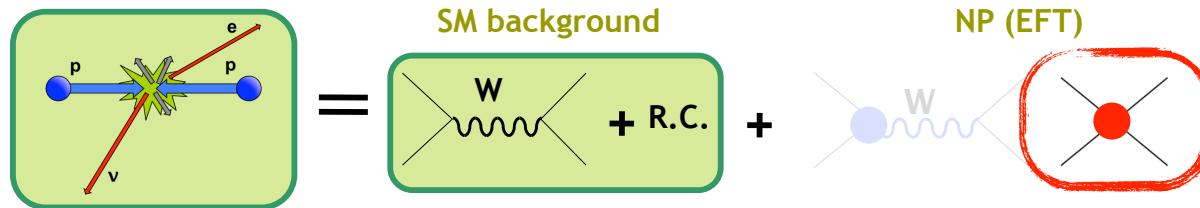
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[e.g. strongly coupled theories]

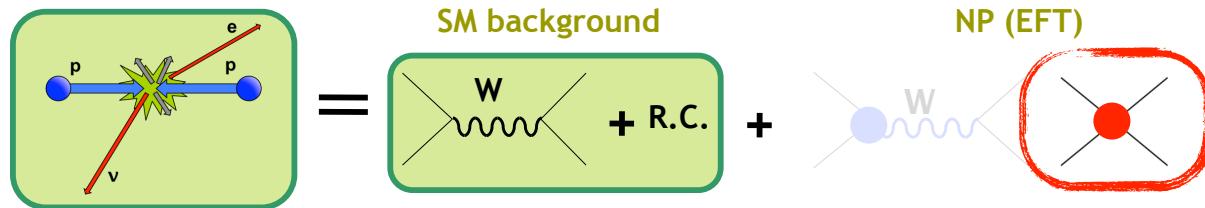


$x = (v, E)$

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

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

What about high-p_T LHC data?



$(ee)(qq)$

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$\times 10^{-3}$

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$(\mu\mu)(qq)$

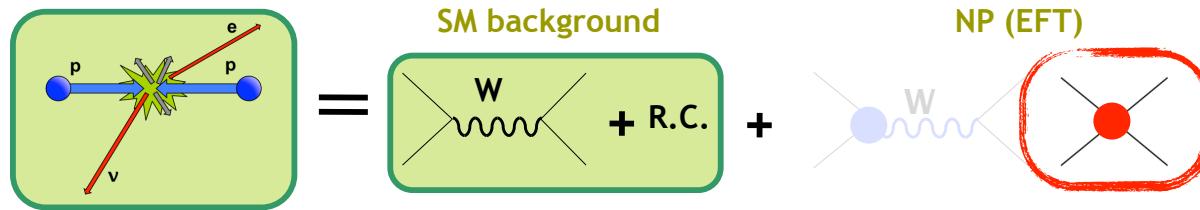
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[e.g. strongly coupled theories]
- Are there new particles within the LHC reach? Cuts on m_{ee} [Contino et al, 2016]



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$(ee)(qq)$

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LHC _{1.5}	$-0.70^{+0.66}_{-0.74}$	$2.5^{+1.9}_{-2.5}$	$2.9^{+2.4}_{-2.9}$	$-1.6^{+3.4}_{-3.0}$	$1.6^{+1.8}_{-2.2}$	$1.6^{+2.5}_{-1.5}$	$-3.1^{+3.6}_{-3.0}$
LHC _{1.0}	$-0.84^{+0.85}_{-0.92}$	$3.6^{+3.6}_{-3.7}$	$4.4^{+4.4}_{-4.7}$	$-2.4^{+4.8}_{-4.7}$	$2.4^{+3.0}_{-3.2}$	$1.9^{+2.5}_{-1.9}$	$-4.6^{+5.4}_{-4.1}$
LHC _{0.7}	$-1.0^{+1.4}_{-1.5}$	5.9 ± 7.2	7.4 ± 9.0	-3.6 ± 8.7	3.8 ± 5.9	$2.1^{+3.8}_{-2.9}$	-8 ± 10

[Falkowski, MGA & Mimouni, 2017]

$\times 10^{-3}$

$(\mu\mu)(qq)$

	$[c_{\ell q}^{(3)}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
Low-energy	-0.2 ± 1.2	4 ± 21	18 ± 19	-20 ± 37	40 ± 390	-20 ± 190	40 ± 390
LHC _{1.5}	$-1.22^{+0.62}_{-0.70}$	1.8 ± 1.3	2.0 ± 1.6	-1.1 ± 2.0	1.1 ± 1.2	$2.5^{+1.8}_{-1.4}$	-2.2 ± 2.0
LHC _{1.0}	$-0.72^{+0.81}_{-0.87}$	$3.2^{+4.0}_{-3.5}$	$3.9^{+4.8}_{-4.4}$	$-2.3^{+4.9}_{-4.7}$	$2.3^{+3.1}_{-3.2}$	$1.6^{+2.3}_{-1.8}$	-4.4 ± 5.3
LHC _{0.7}	$-0.7^{+1.3}_{-1.4}$	$3.2^{+10.3}_{-4.8}$	$4.3^{+12.5}_{-6.4}$	-3.6 ± 9.0	3.8 ± 6.2	$1.6^{+3.4}_{-2.7}$	-8 ± 11

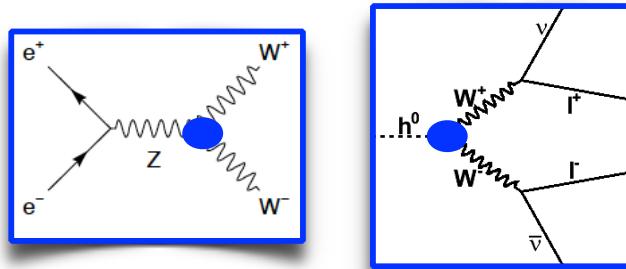
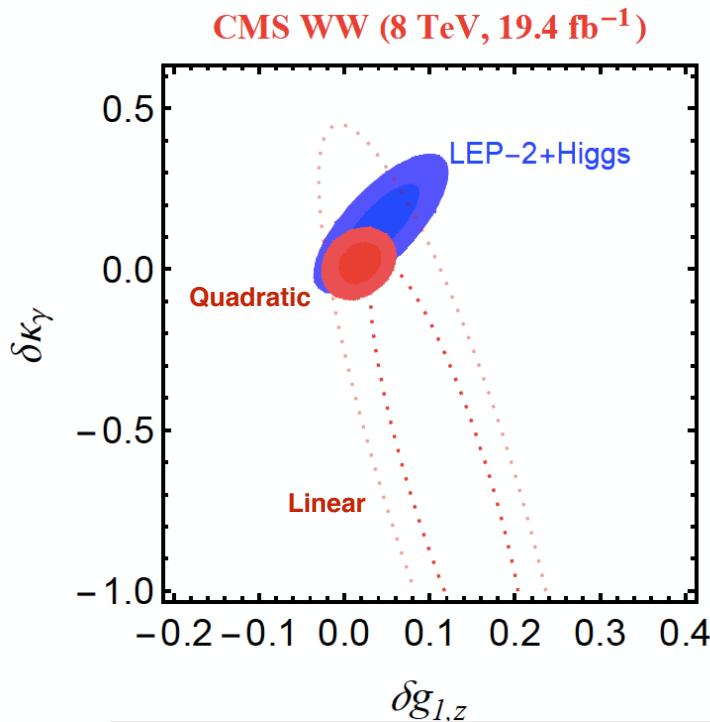
$\times 10^{-3}$

(Pseudo)scalar & tensor couplings: LHC can't compete with low-E [backup slide]

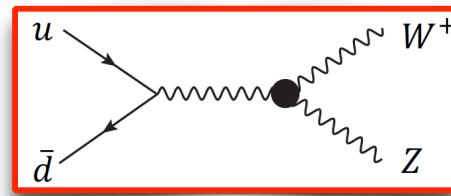
→ RGE running & mixing very important

$$|\mathcal{A}(P \rightarrow \ell\nu)|^2 \sim m_\ell^2 \left(1 + \frac{M_{QCD}}{m_\ell} \epsilon_P\right)^2$$

Same game: triple gauge couplings

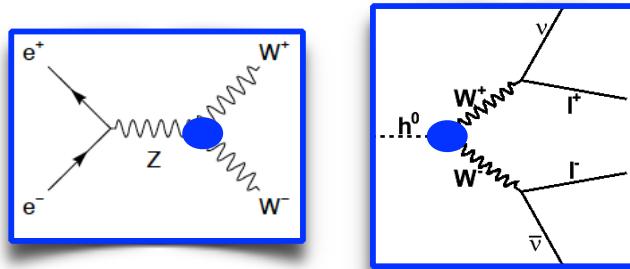
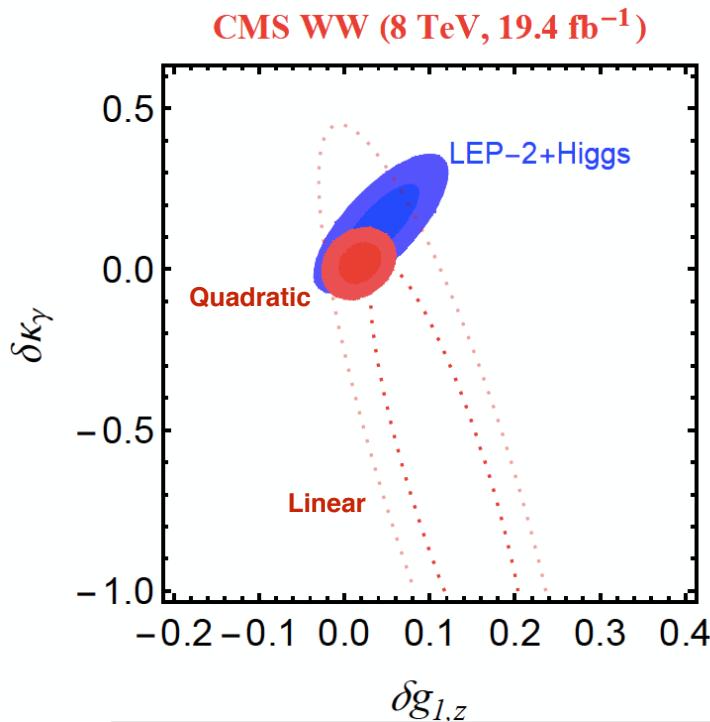


[Falkowski, MGA, Greljo & Marzocca, PRL (2016)]

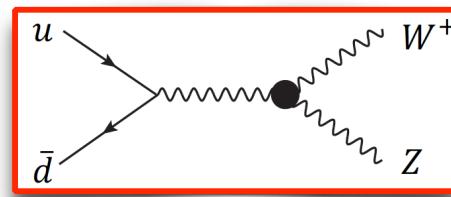


[Falkowski et al., JHEP (2017)]
[Butter et al., JHEP (2016)]

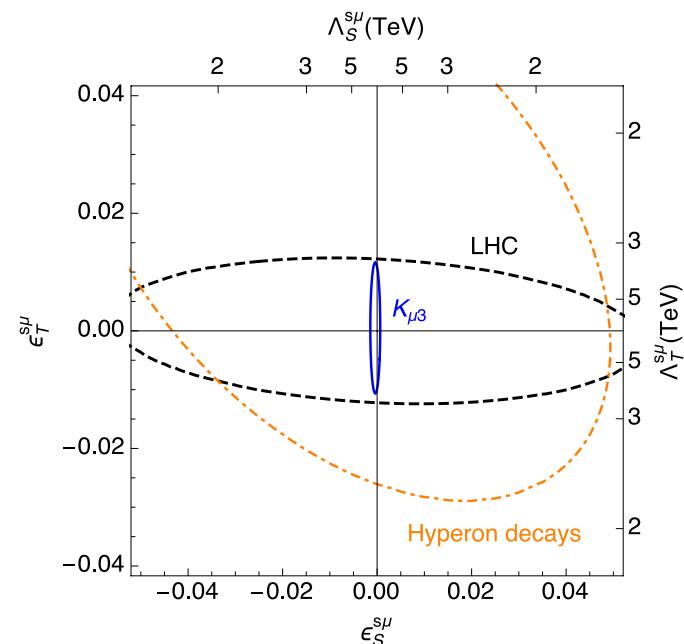
Same game: triple gauge couplings



[Falkowski, MGA, Greljo & Marzocca, PRL (2016)]



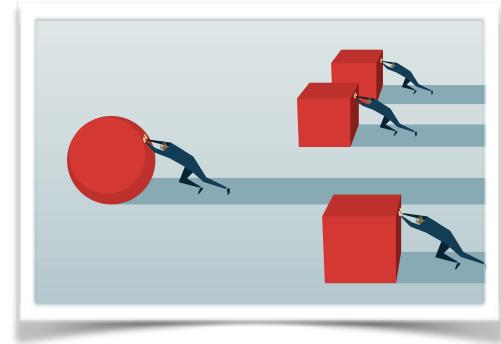
[Falkowski et al., JHEP (2017)]
[Butter et al., JHEP (2016)]



- ◆ Likewise: flavor ($d_j \rightarrow u_i l v$) vs. LHC ($pp \rightarrow ll$)
*[Chang, MGA & Martin Camalich, PRL 114 (2015),
MGA & Martin Camalich, JHEP 1612 (2016) 052
Greljo & Marzocca, EPJC77 (2017) 8, 548]*

Summary

- ◆ SMEFT as an efficient framework / tool



- ◆ 1st flavor-general EFT fit to EW precision observables (& publicly available!)



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



- ◆ LHC bounds (on some interactions!) are very strong, but they come with a series of caveats.



Backup slides

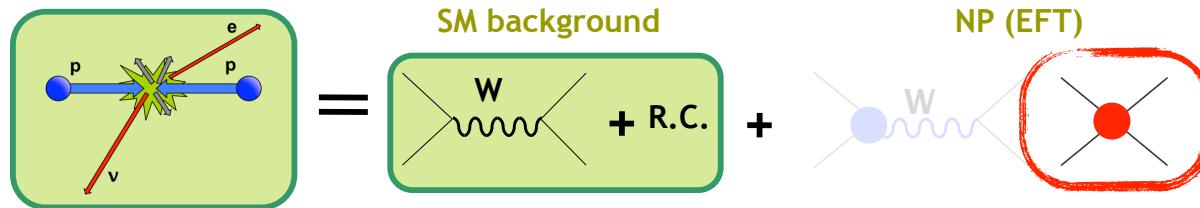
SMEFT: (our) Higgs basis

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{\text{kin}} = & -\frac{1}{2}W_{\mu\nu}^+W_{\mu\nu}^- - \frac{1}{4}Z_{\mu\nu}Z_{\mu\nu} - \frac{1}{4}A_{\mu\nu}A_{\mu\nu} + \frac{g_L^2 v^2}{4}(1+\delta m)^2 W_\mu^+W_\mu^- + \frac{(g_L^2 + g_Y^2)v^2}{8}Z_\mu Z_\mu \\ & + i\bar{e}_I \bar{\sigma}_\mu \partial_\mu e_I + i\bar{\nu}_I \bar{\sigma}_\mu \partial_\mu \nu_I + ie_I^c \sigma_\mu \partial_\mu \bar{e}_I^c.\end{aligned}$$

$$\begin{aligned}\mathcal{L} \supset & e A^\mu \sum_{f=u,d,e} Q_f (\bar{f}_I \bar{\sigma}_\mu f_I + f_I^c \sigma_\mu \bar{f}_I^c) \\ & + \frac{g_L}{\sqrt{2}} \left[W^{\mu+} \bar{\nu}_I \bar{\sigma}_\mu (\delta_{IJ} + [\delta g_L^{We}]_{IJ}) e_J + W^{\mu+} \bar{u}_I \bar{\sigma}_\mu \left(V_{IJ} + [\delta g_L^{Wq}]_{IJ} \right) d_J + \text{h.c.} \right] \\ & + \frac{g_L}{\sqrt{2}} \left[W^{\mu+} u_I^c \sigma_\mu [\delta g_R^{Wq}]_{IJ} \bar{d}_J^c + \text{h.c.} \right] \\ & + \sqrt{g_L^2 + g_Y^2} Z^\mu \sum_{f=u,d,e,\nu} \bar{f}_I \bar{\sigma}_\mu \left((T_3^f - s_\theta^2 Q_f) \delta_{IJ} + [\delta g_L^{Zf}]_{IJ} \right) f_J \\ & + \sqrt{g_L^2 + g_Y^2} Z^\mu \sum_{f=u,d,e} f_I^c \sigma_\mu \left(-s_\theta^2 Q_f \delta_{IJ} + [\delta g_R^{Zf}]_{IJ} \right) \bar{f}_J^c.\end{aligned}\tag{2.2}$$

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{c_{4f}}{v^2} \mathcal{O}_{4f} \quad \left[c_{4f} = \alpha_{4f} \frac{v^2}{\Lambda^2} \right]$$

What about high-p_T LHC data?



Chirality-violating operators ($\mu = 1 \text{ TeV}$)

	$[c_{\ell equ}]_{1111}$	$[c_{\ell edq}]_{1111}$	$[c_{\ell equ}^{(3)}]_{1111}$	$[c_{\ell equ}]_{2211}$	$[c_{\ell edq}]_{2211}$	$[c_{\ell equ}^{(3)}]_{2211}$
Low-energy	$(-0.6 \pm 2.4)10^{-4}$	$(0.6 \pm 2.4)10^{-4}$	$(0.4 \pm 1.4)10^{-3}$	$0.014(49)$	$-0.014(49)$	$-0.09(29)$
LHC _{1.5}	0 ± 2.0	0 ± 2.6	0 ± 0.91	0 ± 1.2	0 ± 1.6	0 ± 0.56

[Falkowski, MGA & Mimouni, 2017]

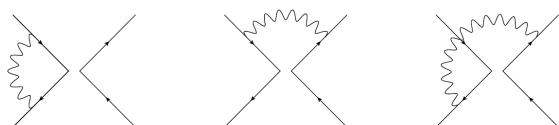
$\times 10^{-3}$

PS: interference w
the SM $\sim m/E$.

$$|\mathcal{A}(P \rightarrow \ell\nu)|^2 \sim m_\ell^2 \left(1 + \frac{M_{QCD}}{m_\ell} \epsilon_P \right)^2$$

Running
(QCD x QED
& QCD x EW)

[Alonso et al.'13, Aebischer et al.'17,
MGA, Martin Camalich & Mimouni'17]

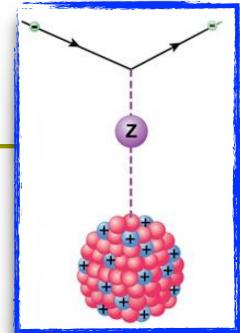


$$\begin{pmatrix} \epsilon_L \\ \epsilon_R \\ \epsilon_S \\ \epsilon_P \\ \epsilon_T \end{pmatrix}_{(\mu = 2 \text{ GeV})} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1.0046 & 0 & 0 & 0 \\ 0 & 0 & 1.72 & 2.46 \times 10^{-6} & -0.0242 \\ 0 & 0 & 2.46 \times 10^{-6} & 1.72 & -0.0242 \\ 0 & 0 & -2.17 \times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

$$\begin{pmatrix} w_{ledq} \\ w_{\ell equ} \\ w_{\ell equ}^{(3)} \end{pmatrix}_{(\mu = m_Z)} = \begin{pmatrix} 1.19 & 0. & 0. \\ 0. & 1.20 & -0.185 \\ 0. & -0.00381 & 0.959 \end{pmatrix} \begin{pmatrix} w_{ledq} \\ w_{\ell equ} \\ w_{\ell equ}^{(3)} \end{pmatrix}_{(\mu = 1 \text{ TeV})}$$

EWPO

[Falkowski, MGA & Mimouni, 2017]



$$Q_W^{\text{Cs}} = -72.62 \pm 0.43$$

[Wood et al.,
Science, 1997]

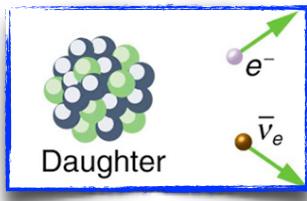
$\times 10^{-3}$

	$[c_{\ell q}^{(3)}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
CHARM	-80 ± 180	700 ± 1800	370 ± 880	-700 ± 1800	x	x	x
APV	27 ± 19	1.6 ± 1.1	3.4 ± 2.3	3.0 ± 2.0	-1.6 ± 1.1	-3.4 ± 2.3	-3.0 ± 2.0
QWEAK	7.0 ± 12	-2.3 ± 4.0	-3.5 ± 6.0	-7 ± 12	2.3 ± 4.0	3.5 ± 6.0	7 ± 12
PVDIS	-8 ± 12	24 ± 35	38 ± 48	-77 ± 96	-77 ± 96	-12 ± 17	24 ± 35
SAMPLE	-8 ± 45	x	-17 ± 90	17 ± 90	x	-17 ± 90	17 ± 90
$d_j \rightarrow u\ell\nu$	0.38 ± 0.28	x	x	x	x	x	x
LEP-2	3.5 ± 2.2	-42 ± 28	-21 ± 14	42 ± 28	-18 ± 11	-9.0 ± 5.7	18 ± 11

$(\mu\mu)(qq)$

	$[c_{\ell q}^{(3)}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
PDG ν_μ	20 ± 15	4 ± 21	18 ± 19	-20 ± 37	x	x	x
SPS	0 ± 1000	0 ± 3000	0 ± 1500	0 ± 3000	40 ± 390	-20 ± 190	40 ± 390
$d_j \rightarrow u\ell\nu$	-0.4 ± 1.2	x	x	x	x	x	x

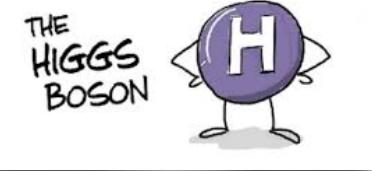
$\times 10^{-3}$



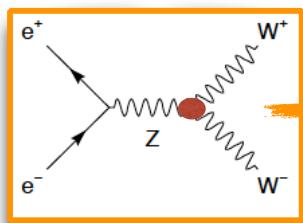
$$\Delta_{\text{CKM}} = -(4.6 \pm 5.2) \times 10^{-4}$$

[Hardy & Towner'14,
Flavianet'16,
MGA & Martin Camalich'16]

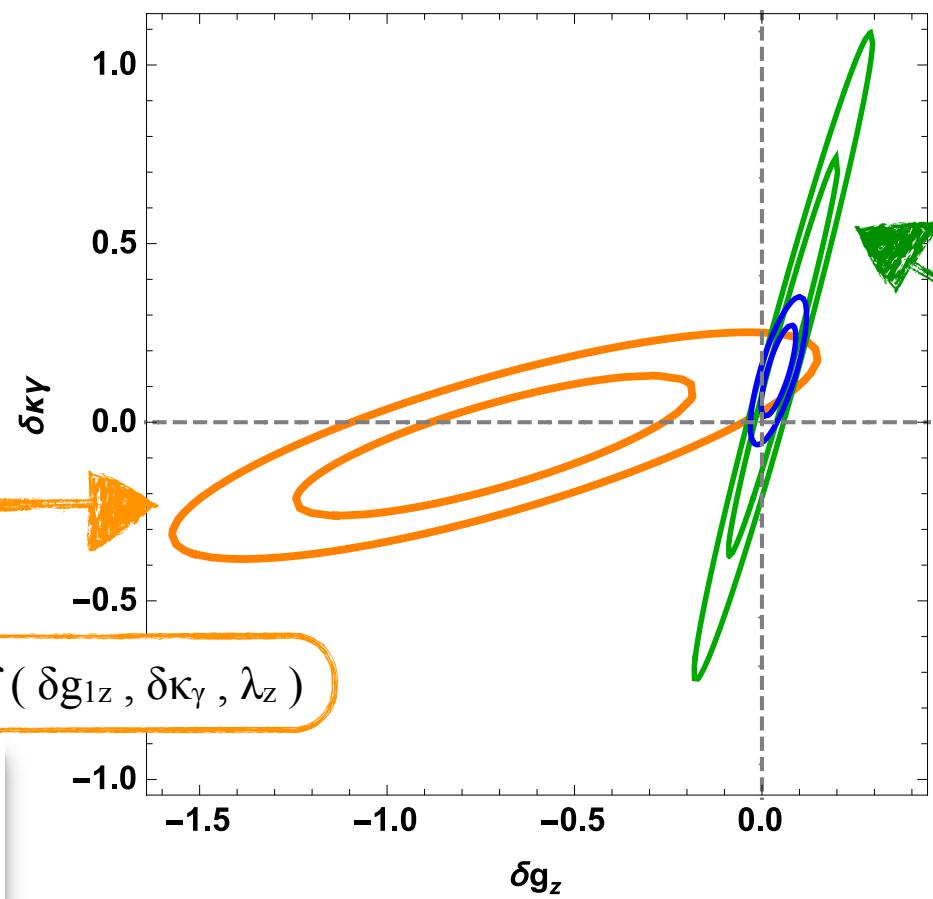
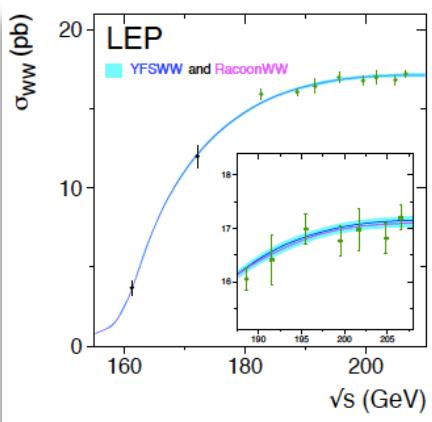
LEP2 vs Higgs



LEP2
($e^+e^- \rightarrow WW$)



$$\sigma_{WW}, d\sigma_{WW} \approx \text{SM} + f(\delta g_{1z}, \delta \kappa_\gamma, \lambda_z)$$



$$\mu_i \approx \text{SM} + f(c_1, c_2, \dots, c_9)$$

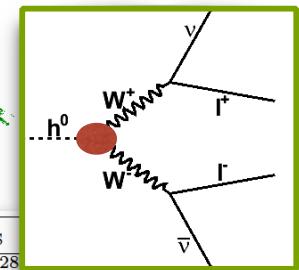
Symmetries relate TGC & anomalous Higgs couplings:

$$\delta g_{1z} = f(c_1, c_2, \dots, c_9)$$

$$\delta \kappa_\gamma = g(c_1, c_2, \dots, c_9)$$

λ_z = unconstrained

Higgs



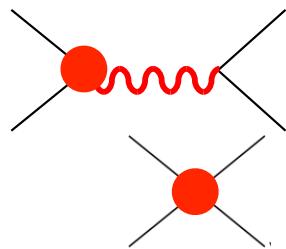
Channel	μ_{ATLAS}		
$\gamma\gamma$	$1.17^{+0.28}_{-0.26}$	$1.1^{+0.22}_{-0.22}$	total
$Z\gamma$	$2.7^{+4.6}_{-4.5}$	$-0.2^{+4.9}_{-4.9}$	
ZZ^*	$1.46^{+0.40}_{-0.34}$	$1.00^{+0.29}_{-0.29}$	2D
WW^*	$1.18^{+0.24}_{-0.21}$	$0.83^{+0.21}_{-0.21}$	2D
	$2.1^{+1.9}_{-1.6}$	-	Wh
	$5.1^{+4.3}_{-3.1}$	-	Zh
	-	$0.80^{+1.09}_{-0.93}$	Vh
$\tau\tau$	$1.44^{+0.42}_{-0.37}$	$0.91^{+0.28}_{-0.28}$	2D
	-	$0.87^{+1.00}_{-0.88}$	Vh
bb	$1.11^{+0.65}_{-0.61}$	-	Wh
	$0.05^{+0.52}_{-0.49}$	-	Zh
	-	$0.89^{+0.47}_{-0.44}$	Vh
	-	$2.8^{+1.6}_{-1.4}$	VBF
	$1.5^{+1.1}_{-1.1}$	$1.2^{+1.6}_{-1.5}$	tth
$\mu\mu$	$-0.7^{+3.7}_{-3.7}$	$0.8^{+3.5}_{-3.4}$	total
multi- ℓ	$2.1^{+1.4}_{-1.2}$	$3.8^{+1.4}_{-1.4}$	tth

CKM unitarity test

$$\begin{pmatrix} \tilde{V}_{ud} \\ \tilde{V}_{us} \end{pmatrix} = \begin{pmatrix} 0.97416(21) \\ 0.22484(64) \end{pmatrix} \rightarrow \Delta_{\text{CKM}} \equiv |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 - 1 = -(4.6 \pm 5.2) \times 10^{-4}$$

$$\rightarrow \Delta_{\text{CKM}} \equiv |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 - 1 = 2 \left(-\delta g_L^{W\ell} + \delta g_L^{Zu} - \delta g_L^{Zd} - c_{\ell q}^{(3)} + c_{\ell\ell}^{(3)} \right)$$

[From Falkowski, MGA & Mimouni, 2017]



$\delta g_L^{W\ell}$	0.15 ± 0.18	0.23 ± 0.26
δg_L^{Zu}	0.48 ± 0.45	-0.23 ± 0.26
δg_L^{Zd}	-0.05 ± 0.27	0.23 ± 0.26
$c_{\ell\ell}^{(3)}$	-0.40 ± 0.37	0.23 ± 0.26
$c_{\ell q}^{(3)}$	-1.11 ± 0.89	-0.23 ± 0.26

$\times 10^3 =$

LEP/EWPO vs. Δ_{CKM}

LHC can't compete here

$\text{pp} \rightarrow e^+e^-$
LHC reaching this level...
HL-LHC x10



[Falkowski, MGA & Mimouni'17,
Greljo & Marzocca'17]