The SMEFT/geoSMEFT- the modern EFT analysis of collider data

Prepared for: QUC summer school

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Lecture Two.

Outline for today

Second lecture

- Parameter counts and symmetry violation in SM, Lepton number violation and neutrino's mass

- Flavour symmetry violation in the SM and beyond, Dimension 6 operator parameter counts

- Need for global studies combining data sets in SMEFT, field redefinition invariance Leads to field space geometry.

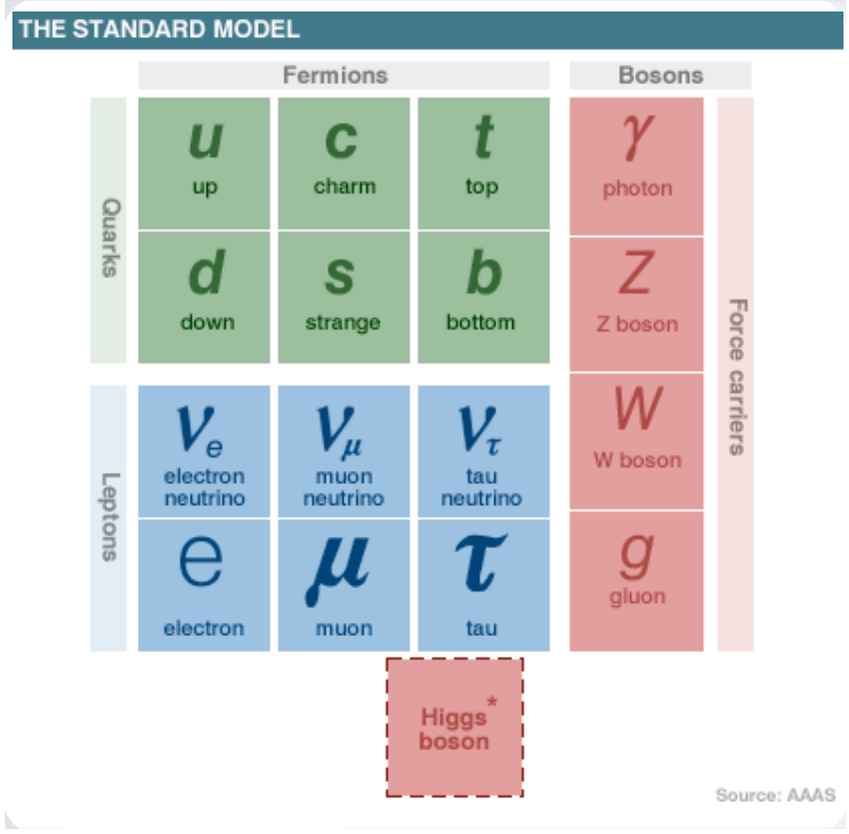
- The LEP example in SMEFT. The reparameterization invariance explanation of flat Directions. Another hint for the importance of field space geometry.

Counting Parameters in the SMEFT

Counting parameters in SM

- The SM, an SU(3) xSU(2)xU(1) linearly realized gauge theory :

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$
$$- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right],$$



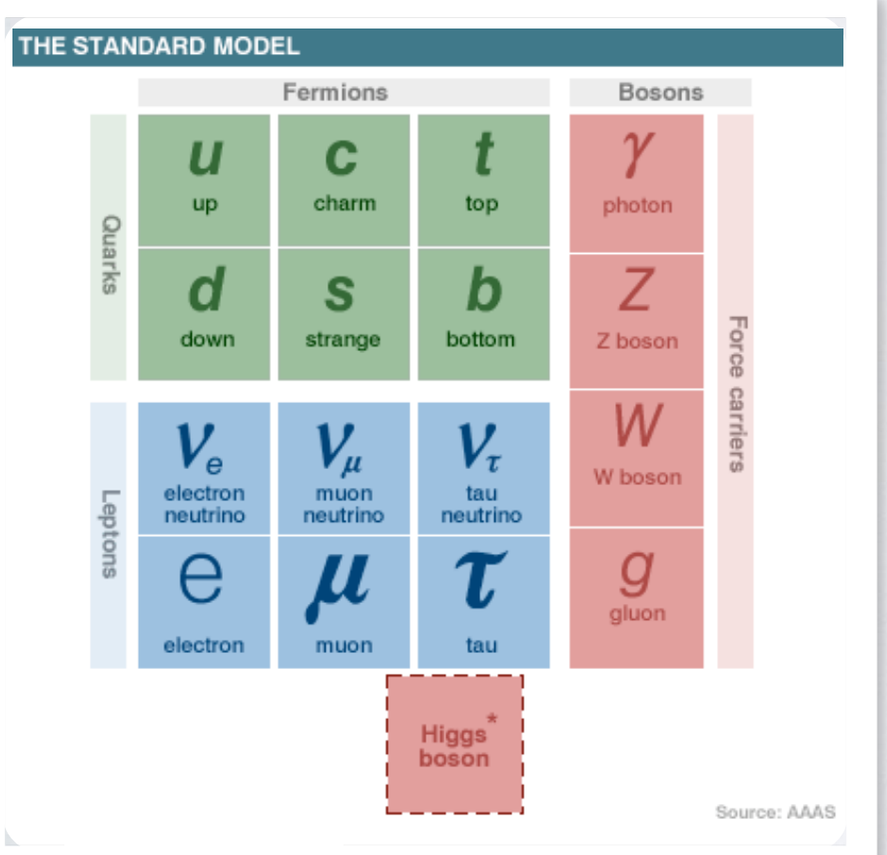
- We can count the number of parameters present in the theory.

m_e, m_μ, m_τ, m_u, m_d, m_c, m_s, m_t, m_b : 9 masses

The Standard model ...

- The SM, an SU(3) xSU(2)xU(1) gauge theory:

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$
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- We can count the number of parameters present in the theory.

$m_e,\, m_\mu,\, m_\tau, m_u,\, m_d,\, m_c,\, m_s,\, m_t,\, m_b$: 9 masses

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

N^2 real parameters in NxN

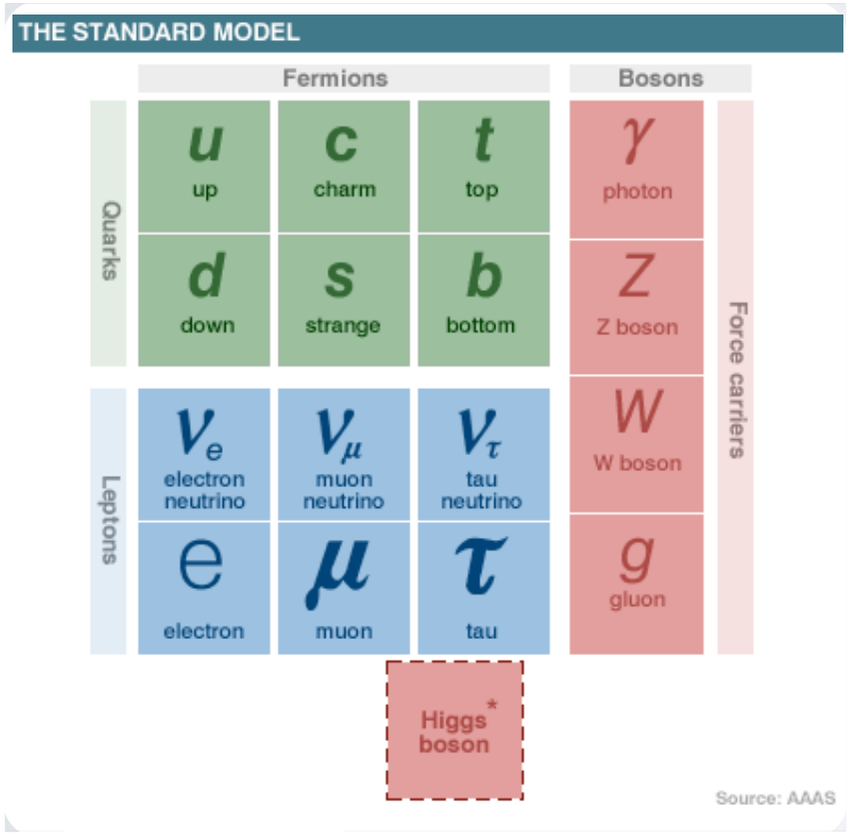
$2N-1$ relative phases

$(N-1)^2$ physical parameters

The Standard model ...

- The SM, an SU(3) xSU(2)xU(1) gauge theory:

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m_e, m_μ, m_τ, m_u, m_d, m_c, m_s, m_t, m_b: 9 masses

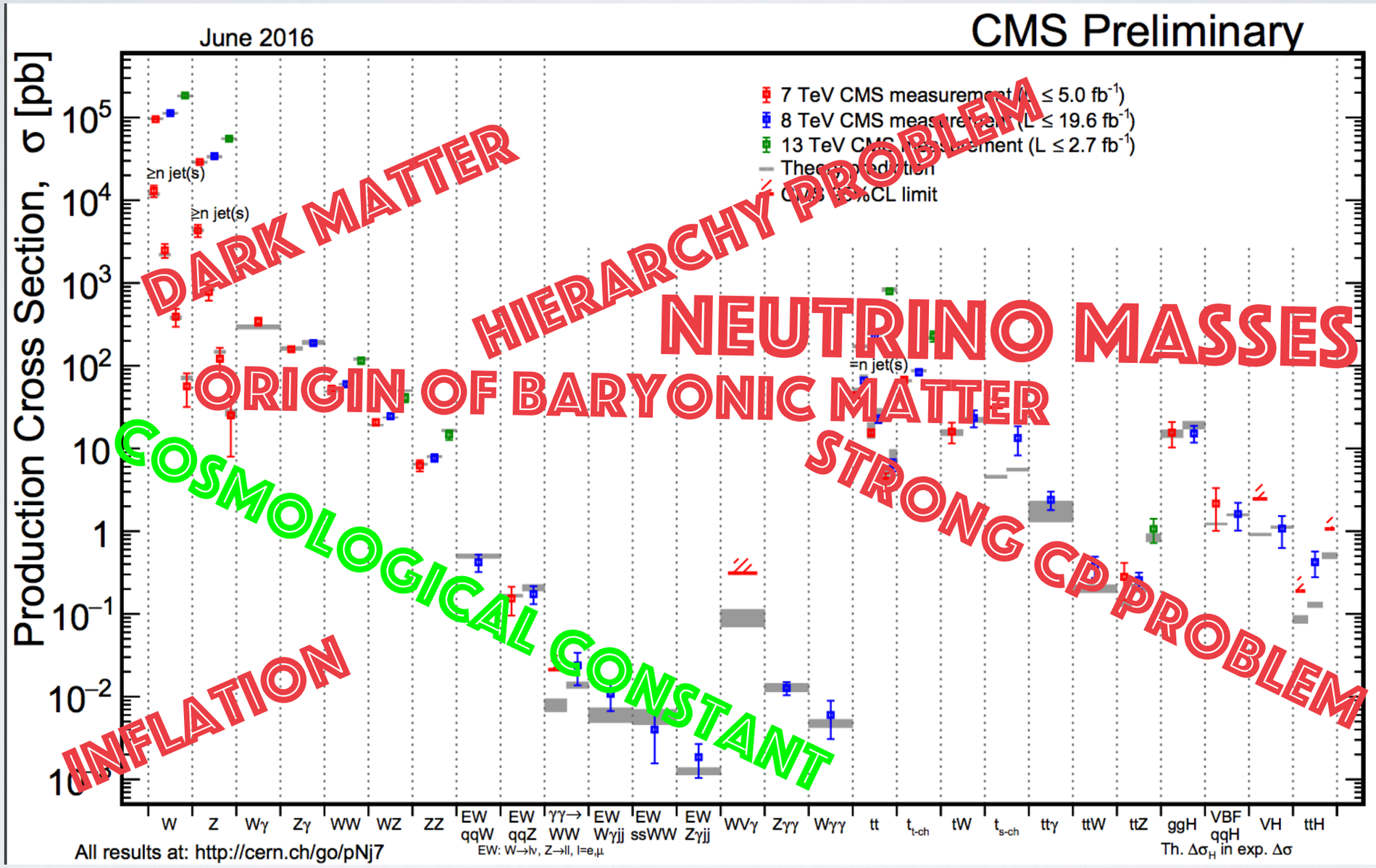
$\theta_{12}, \theta_{13}, \theta_{23}, \delta$: 4 quark mixing

g_1, g_2, g_3 : 3 gauge couplings

v, λ : 2 EW sector

This is the 18 parameters you hear about...

How the heck is this holding up at all??



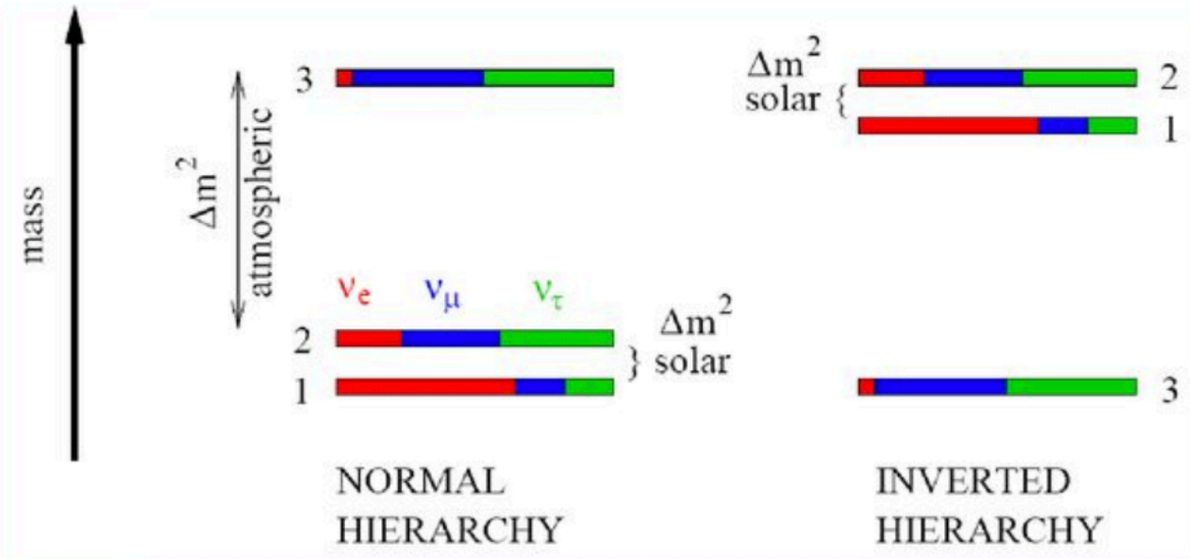
- Its (mostly) - decoupling.
  Which also leads to the unified data approach also advocated: SMEFT

It really isn't holding up, *in a controlled sense*, SM is incomplete

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$
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$$m_e ee + m_\mu \mu\mu + m_\tau \tau\tau$$

- But neutrinos are not massless.



Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	$6.93 - 7.96$
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	$2.45 - 2.69$ $(2.42 - 2.66)$
$\sin^2\theta_{12}$	0.297	$0.250 - 0.354$
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	$0.381 - 0.615$
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	$0.384 - 0.636$
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	$0.0190 - 0.0240$
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	$0.0190 - 0.0242$
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$
$$\text{NH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\text{IH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

Lepton Number

- Model independent minimal extension of the SM to accommodate neutrino mass and observed oscillations. Leading operator that can violate Lepton number of dim 5:

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$

$$- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right], + \left[\frac{C_{mn}}{\Lambda}\left(\overline{\ell^{c,m}}\tilde{H}^\star\right)\left(\tilde{H}^\dagger \ell^n\right) + h.c.\right]$$

- Charge conjugation defined as $\psi^c = C\overline{\psi}^T \text{ with } C = -i\gamma_2\,\gamma_0$

- Neutrino mass differences:

$$\delta M_\nu \sim 10^{-11} - 10^{-13}[\text{GeV}] \sim \frac{v^2 \delta C_{mn}}{\Lambda}$$

Sometimes people infer:
$\Lambda_{\Delta L} = 10^{16}\,\text{GeV}$

See Saw model

- Non zero Wilson coefficient for this operator is required.



Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2



Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald ***"for the discovery of neutrino oscillations, which shows that neutrinos have mass"***

- Introduce singlet right handed fields with majorana mass terms as

$$\overline{N^c_{R,p}}\, M_{pr}\, N_{R,r} + \overline{N_{R,p}}\, M^\star_{pr}\, N^c_{R,r}$$

Chiral projection and charge conjugation *do not commute*

ψ^c_L defined to be chiral projection that is subsequently charge conjugated

See Saw model

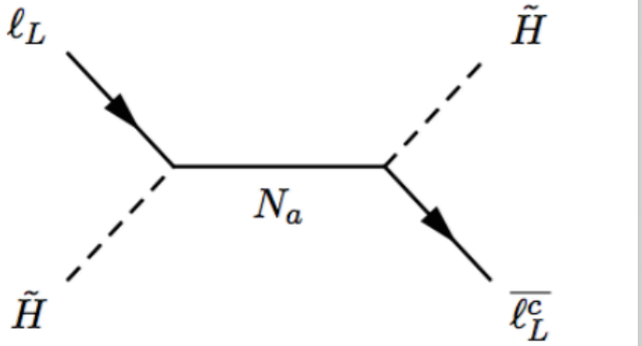
- Shift phases to couplings defining a field that is not a chiral eigenstate that satisfies Majorana condition (Broncano et al. hep-ph/0406019)

$$N_p = N_p^c \qquad N_p = e^{i\theta_p/2}\, N_{R,p} + e^{-i\theta_p/2}\, (N_{R,p})^c .$$

- Obtaining the Standard (type I) seesaw (Minkowski 77, Gell Mann et al 79, Yanagida 79,Mohapatra at al 79)

$$2\,\mathcal{L}_{N_p} = \overline{N_p}(i\partial\!\!\!/ - m_p)N_p - \overline{\ell_L^\beta}\,\tilde{H}\,\omega_\beta^{p,\dagger} N_p - \overline{\ell_L^{c\beta}}\,\tilde{H}^*\,\omega_\beta^{p,T} N_p - \overline{N_p}\,\omega_\beta^{p,*}\,\tilde{H}^T\,\ell_L^{c\beta} - \overline{N_p}\,\omega_\beta^p\,\tilde{H}^\dagger\,\ell_L^\beta .$$

- Integrating out the seesaw at tree level



$$(\not{s} + m_p)\frac{-1}{m_p^2}\left(\frac{1}{1 - s^2/m_p^2}\right) = -\frac{1}{m_p} - \frac{\not{s}}{m_p^2} - \frac{s^2}{m_p^3} + \cdots$$

Expand the propagator in the small momentum transfer - MATCH!

See Saw model

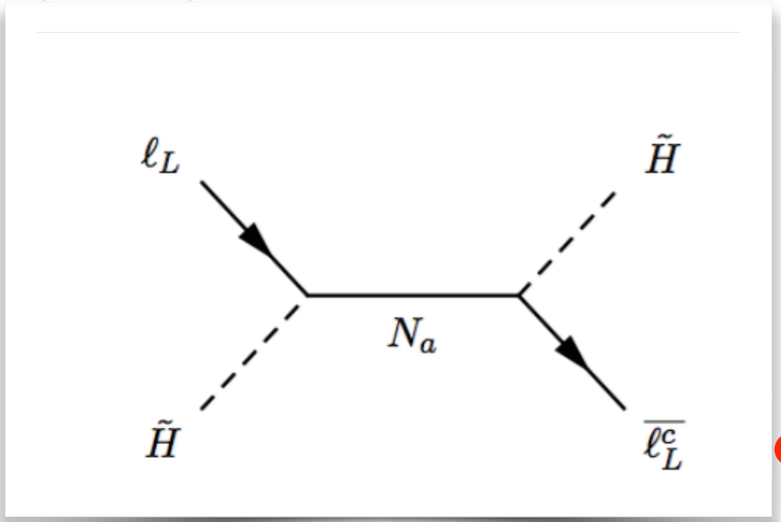
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- Integrating out the seesaw at tree level



- Extremely well known result

$$\mathcal{L}^{(5)} = \frac{c_{\beta\,\kappa}}{2}\,\mathcal{Q}_5^{\beta\,\kappa} + h.c. \qquad c_{\beta\,\kappa} = (\omega_\beta^p)^T\,\omega_\kappa^p/m_p$$

p summed over

- Standard neutrino mass obtained

$$m_\nu^p = \frac{v^2}{2}\,C_5^p$$

Lepton Number

- Model independent minimal extension of the SM to accommodate neutrino mass and observed oscillations. Leading operator that can violate Lepton number of dim 5:

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$$m_e ee + m_\mu \mu\mu + m_\tau \tau\tau$$

$$\mathcal{L}^{(5)} \supset -\frac{m_{\nu,k}}{2}\,\overline{\nu_L'^{c,k}}\,\nu_L'^{k} + \text{h.c.}, \qquad \text{where} \qquad m_{\nu,k} = -\frac{v^2}{2}(U^T)_{k\alpha}\, c_{5,\alpha\beta}\, U_{\beta k},$$

and $\nu_L'^k$ are the mass eigenstates of the light neutrinos $\nu_L^\alpha = U_{\alpha k}(\nu, L)\nu_L'^k$. The matrix $U(\nu, L)$ rotates the neutrinos from their weak eigenstates to their mass eigenstates.

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- Number of parameters augmented to...

$m_e,\, m_\mu,\, m_\tau, m_u,\, m_d,\, m_c,\, m_s,\, m_t,\, m_b$: 9 masses

$\theta_{12}, \theta_{13}, \theta_{23}, \delta$: 4 quark mixing

$g_1,\, g_2,\, g_3$: 3 gauge couplings

v, λ : 2 EW sector

$s_{12},\, s_{13},\, s_{23},\, \delta_\nu, m_{\nu_e}, m_{\nu_\mu}, m_{\nu_\tau}$: 7 neutrino parameters

+2 majorana phases

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- What just happened here? New parameters were required as an (accidental SM) symmetry was violated.

New parameters that break symmetries are treated differently than those that preserve symmetries already present.

Neutrino massive =The SM is ruled out.

SMEFT a viable and natural replacement

SMEFT beyond SU(2)xU(1) Symmetry summary.

QCD SU(3)

Higgs Phase

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$

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Custodial sym

Flavour symmetry breaking "MFV"

Lepton Number breaking
Neutrino masses

Just do not mess with Baryon number.

$$\phi_q \to e^{i\,\phi_q}\,\phi_q$$

Flavour symmetry breaking as a guide for parameters in SMEFT

Flavour Symmetry

- The global flavour symmetry of the SM is

$$\mathrm{G_F} = \mathrm{U}(3)^5 = \mathrm{S_Q} \otimes \mathrm{S_L} \otimes \mathrm{U}(1)^5$$

$$q \to U_q q, \qquad l \to U_l l, \qquad u \to U_u u, \qquad d \to U_d d, \qquad e \to U_e e.$$

here $S_Q = \mathrm{SU}(3)_{\mathrm{Q_L}} \otimes \mathrm{SU}(3)_{\mathrm{U_R}} \otimes \mathrm{SU}(3)_{\mathrm{D_R}}$ $\quad S_L = \mathrm{SU}(3)_{\mathrm{L_L}} \otimes \mathrm{SU}(3)_{\mathrm{E_R}}$

- In the SM a well defined sense in which this flavour symmetry is restored:

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{G_F} + \Big[H^{\dagger j} \overline{d} \underbrace{Y_d}_{0} q_j + \widetilde{H}^{\dagger j} \overline{u} \underbrace{Y_u}_{0} q_j + H^{\dagger j} \overline{e} \underbrace{Y_e}_{0} l_j + \mathrm{h.c.} \Big]$$

Technically you can think of the Yukawas as symmetry breaking spurions

$$Y_u \sim (3, 1, \bar{3}), Y_d \sim (1, 3, \bar{3})$$

Flavour Symmetry

- Can make separate rotations on the left and right handed fermion fields. Leaves kinetic terms in the Lagrangian invariant:

$$\mathcal{L}_{kin} = \bar{Q}_L^i \, i \not{\partial} \, Q_L + \bar{L}_L^i \, i \not{\partial} \, L_L + \bar{u}_R \, i \not{\partial} \, u_R + \bar{d}_R \, i \not{\partial} \, d_R$$

- When Yukawa's turned on the inability to simultaneously diagonalise the yukawas and charged current interactions leads to flavour violation.

$$\sum_{\psi=q,u,d,l,e} \bar{\psi} i \not{D} \psi$$ Different eigenbases $$\left[H^{\dagger j} \bar{d} \, Y_d \, q_j + \tilde{H}^{\dagger j} \bar{u} \, Y_u \, q_j + H^{\dagger j} \bar{e} \, Y_e \, l_j + \text{h.c.} \right]$$

- Diagonalize the fermion masses and different components of the doublets rotated

$$\begin{pmatrix} U_L \\ D_L \end{pmatrix} = \mathcal{U}(U,L) \begin{pmatrix} U'_L \\ \mathcal{U}(U,L)^\dagger \mathcal{U}(D,L) D'_L \end{pmatrix}$$

V_{CKM}

Flavour Symmetry

- Structure of the breaking of G_F is what is important.

- Trivially

$$[U_{u,d,e}, \sigma_i] = 0, [U_{u,d,e}, Y] = 0$$

Left handed doublet fields couple to the generators of the neutral currents as

$$\mathbf{y_i}\psi_L = y_i \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \psi_L, \quad \tau^3\psi_L = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \psi_L.$$

These also commute with U_q, U_ℓ rotations between weak and mass eigen.

Therefore: NO flavour changing neutral currents at tree level in the SM.

Flavour Symmetry

- Structure of the breaking of G_F is what is important.

- NO flavour changing neutral currents at tree level in the SM.

  Flavour changing charged currents allowed and present.

$$\frac{g_2}{\sqrt{2}} W^+ \bar{u}_L \gamma^\mu d_L = \frac{g_2}{\sqrt{2}} W^+ \bar{u'}_L \gamma^\mu V_{CKM} d'_L$$

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

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$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3[1 - (\rho + i\eta)] & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

Here rephased the quark fields to go down to $(N-1)^2$ real parameters AND implemented an expansion (Wolfenstein parameterization)

CKM matrix should be unitary. This leads to a number of unitarity triangles:

$$V_{ud} V_{ub}^\star + V_{cd} V_{cb}^\star + V_{td} V_{tb}^\star = 0$$

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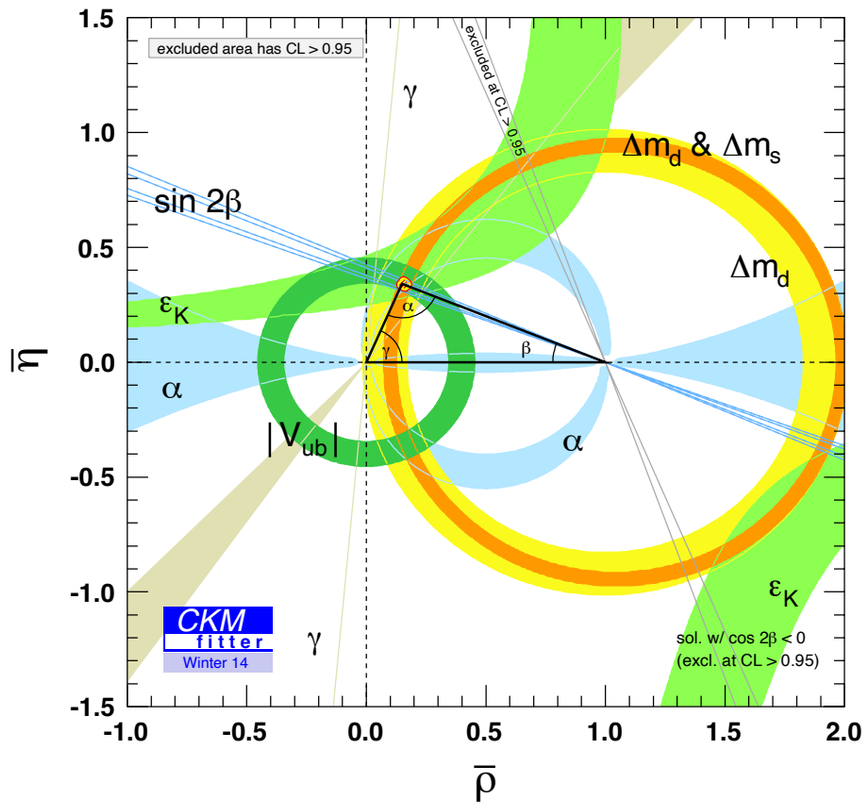
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CKM matrix should be unitary. This leads to a number of unitarity triangles:

$$A\lambda^3(\rho + i\eta) - A\lambda^3 + A\lambda^3(1 - \rho - i\eta) = 0$$

Flavour Symmetry



$$A\,\lambda^3(\rho+i\eta) - A\lambda^3 + A\lambda^3(1-\rho-i\eta) = 0$$

One of many equivalent “CKM triangles”
(any column times row gives a relation)

For CP violation better to think in invariants

$$J_{CP} = \pm \mathrm{Im}\left(V_{ik}\,V_{jl}\,V_{il}^{\star}\,V_{jk}^{\star}\right) \approx A^2\lambda^6\,\eta$$

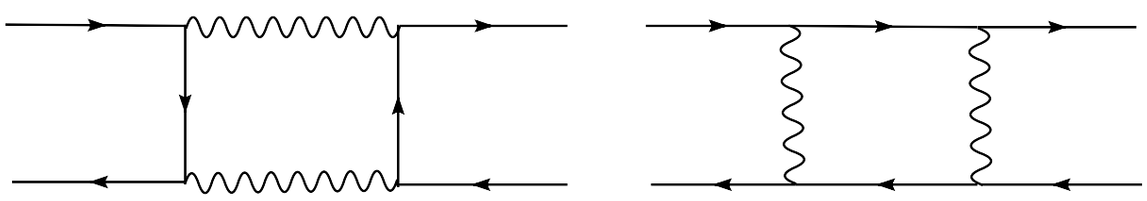
$$(i \neq j, l \neq k)$$

CP violation tiny in SM! (but seen)

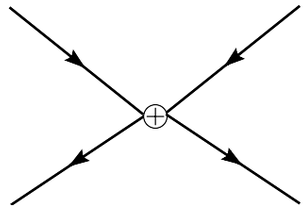
$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\,\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\,\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

- Exp facts that: $\lambda \sim 0.22$ Flavour violation, and CP violation could have been larger, but pattern works.

Flavour Symmetry



VS



Recall SM contribution to meson mixing:

$$\mathcal{A}_{SM} \sim \frac{m_t^2}{16\,\pi^2 v^4}\,(V_{3i}^{\star}\,V_{3j})^2 \langle \bar{M}|(\bar{d}_L^i\,\gamma^\mu\,d_L^j)^2|M\rangle$$

SM PATTERN has GIM suppression,
CKM suppression , and loop suppression

$\lambda \sim 0.2$ so $\lambda^8 \sim 10^{-6}$ $\lambda^4 \sim 10^{-3}$

Integrate out your desired NP states/sector

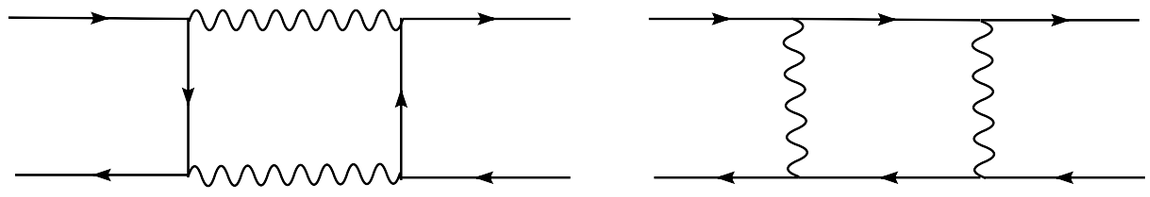
$$O_{ij} = \frac{c_{ij}}{\Lambda^2}\,(\bar{Q}_L^i\,\gamma^\mu\,Q_L^j)^2$$

- Extra flavour violation for TeV scale BSM - experimentally challenging
- Flavour breaking in these operators proportional to

$$(g_u^\dagger\,g_u) \to V_Q\,(g_u^\dagger\,g_u)\,V_Q^\dagger \qquad \left(g_d^\dagger\,g_d\right) \to V_Q\,\left(g_d^\dagger\,g_d\right)\,V_Q^\dagger$$

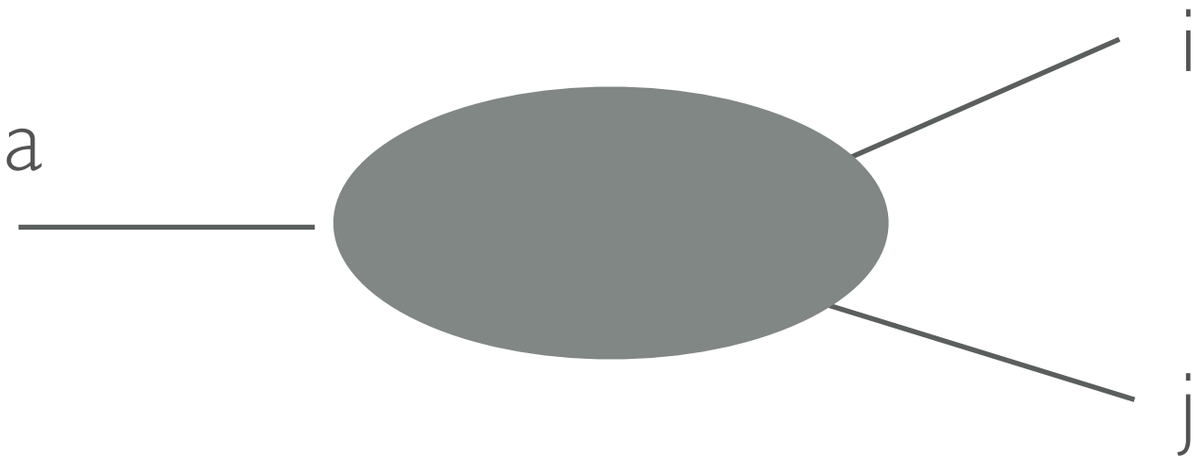
as up and down not simultaneously diagonalized

Flavour Symmetry



$$\mathcal{A}_{SM} \sim \frac{m_t^2}{16\,\pi^2 v^4}\,(V_{3i}^{\star}\,V_{3j})^2 \langle \bar{M}|(\bar{d}_L^i\,\gamma^\mu\,d_L^j)^2|M\rangle$$

- Flavour symmetry controls 2-2 scattering/mixing in SM



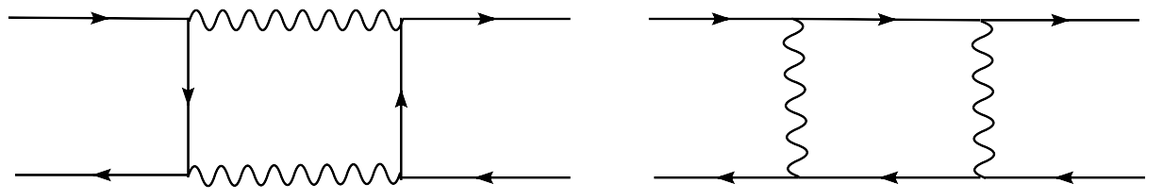
- Flavour symmetry also controls 1-2decay in SM

$$\mathcal{A}_{SM}^{a,ij} + \mathcal{A}_{SMEFT}^{a,ij}$$

- CKM based flavour violation of specific form,
  CP violation from Jarlskov invariant (three generations) of SM
  And related GIM mechanism summing over 3 generations

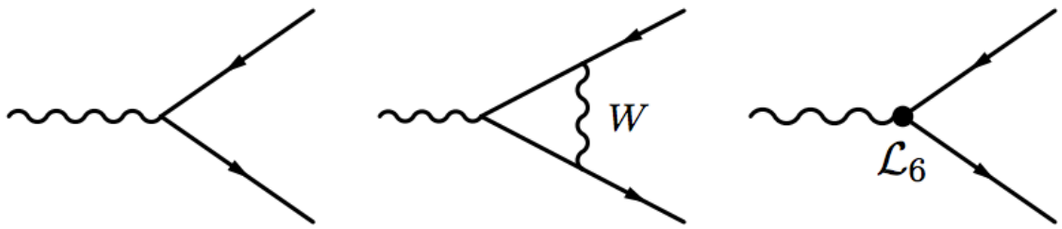
- No flavour changing neutral currents at tree level

Flavour Symmetry



$$\mathcal{A}_{SM} \sim \frac{m_t^2}{16\,\pi^2 v^4}\,(V_{3i}^{\star}\,V_{3j})^2 \langle \bar{M}|(\bar{d}_L^i\,\gamma^\mu\,d_L^j)^2|M\rangle$$

- Flavour symmetry controls 2-2 scattering/mixing in SM



- Flavour symmetry also controls 1-2decay in SM

$$\mathcal{A}_{SM}^{a,ij} + \mathcal{A}_{SMEFT}^{a,ij}$$

$$\mathcal{A}_{ik}^{h} \simeq \frac{3\bar{v}_T\,\bar{g}_2^3}{16^2\,\pi^2\,\hat{m}_W}\,\bar{\psi}_i\,\left[y_i\,V_{ik}^{\dagger}\,V_{kj}\frac{m_k^2}{\hat{m}_W^2}P_L + y_j\,V_{kj}^{\dagger}\,V_{ik}\frac{m_k^2}{\hat{m}_W^2}P_R\right]\,\psi_j, + \cdots$$

$$\mathcal{A}_{ik}^{Z} \simeq -\frac{3\sqrt{\bar{g}_1^2+\bar{g}_2^2}\,\bar{g}_2^2\,V_{jk}^{\star}\,V_{ji}}{32\,\pi^2}\frac{m_j^2}{m_W^2}\bar{\psi}_k\,\gamma^\mu\,P_L\,\psi_i\,\epsilon_\mu^Z + \cdots,$$

SM Symmetry breaking in general controls parameter appearance

- SM flavour symmetry breaking (even before any assumption in SMEFT) Already projects out parameters.

$$|\mathcal{A}^{a,ij}_{SM} + \mathcal{A}^{a,ij}_{SMEFT}|^2 = |\mathcal{A}^{a,ij}_{SM} + \frac{\mathcal{A}^{a,ij}_{SMEFT,6}}{\Lambda^2} + \frac{\mathcal{A}^{a,ij}_{SMEFT,8}}{\Lambda^4} + \cdots|^2$$

$$= |\mathcal{A}^{a,ij}_{SM}|^2 + \mathcal{A}^{a,ij}_{SM}\,\frac{\mathcal{A}^{a,ij}_{SMEFT,6}}{\Lambda^2} + |\frac{\mathcal{A}^{a,ij}_{SMEFT,6}}{\Lambda^2}|^2 + \mathcal{A}^{a,ij}_{SM}\,\frac{\mathcal{A}^{a,ij}_{SMEFT,8}}{\Lambda^4} + \text{h.c} + \cdots$$

SM Symmetry breaking pattern squared

SM Symmetry breaking pattern X $\mathcal{L}^{(6)}$ sym breaking

$\mathcal{L}^{(6)}$ sym breaking pattern squared

SM Symmetry breaking pattern X $\mathcal{L}^{(8)}$ sym breaking

LO SMEFT = dim 6 shifts

- Warsaw basis: 1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC}\widetilde{G}^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\tilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\tilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

6 gauge dual ops

28 non dual operators

25 four fermi ops

---

59 + h.c. operators

NOTATION:

$$\widetilde{X}_{\mu\nu} = \tfrac{1}{2}\varepsilon_{\mu\nu\rho\sigma}X^{\rho\sigma} \quad (\varepsilon_{0123} = +1)$$

$$\widetilde{\varphi}^j = \varepsilon_{jk}(\varphi^k)^\star \qquad \varepsilon_{12} = +1$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi \equiv i\varphi^\dagger\left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$$

$$\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi \equiv i\varphi^\dagger\left(\tau^I D_\mu - \overleftarrow{D}_\mu\tau^I\right)\varphi$$

LO SMEFT = dim 6 shifts

- Four fermion operators: 1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek

$8:(\bar{L}L)(\bar{L}L)$		$8:(\bar{R}R)(\bar{R}R)$		$8:(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$		$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Count the parameters in the SMEFT

In Warsaw basis arXiv:1008.4884 (SMEFT standard basis)

$$\frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6$$

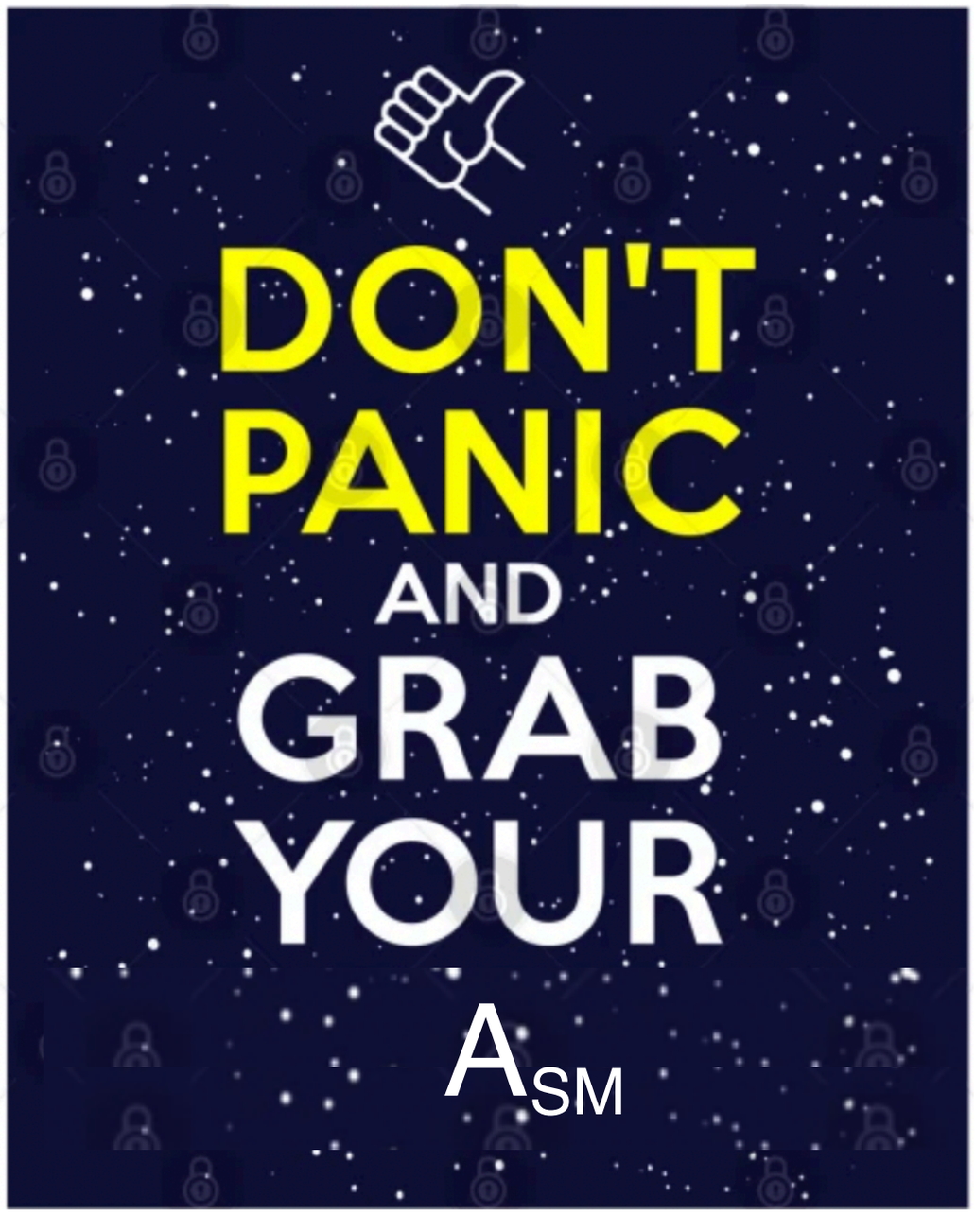
Class		$N_{\rm op}$	CP-even			CP-odd		
			n_g	1	3	n_g	1	3
1	g^3X^3	4	2	2	2	2	2	2
2	H^6	1	1	1	1	0	0	0
3	H^4D^2	2	2	2	2	0	0	0
4	$g^2X^2H^2$	8	4	4	4	4	4	4
5	$y\psi^2H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6	$gy\psi^2XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7	ψ^2H^2D	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
ψ^4	$8:(\overline{L}L)(LL)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
	$8:(\overline{R}R)(\overline{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
	$8:(\overline{L}L)(\overline{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
	$8:(\overline{L}R)(\overline{R}L)$	1	n_g^4	1	81	n_g^4	1	81
	$8:(\overline{L}R)(\overline{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
	8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total		59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

2499

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

Considering 2499



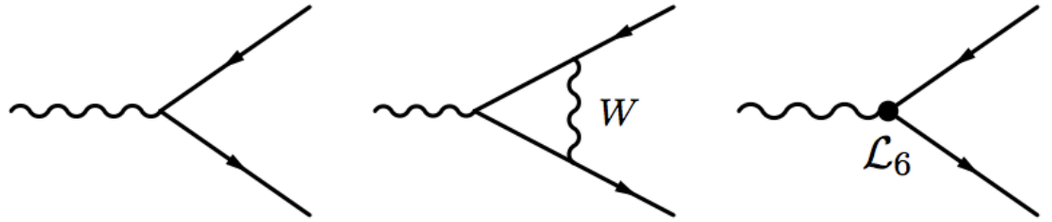
.. are there too many parameters?

- Number of parameters convolution of power counting

$$\langle\rangle \sim O^0_{SM} + \frac{f_1(s,t,u)}{M^2_{heavy}} + \frac{f_2(s,t,u)}{M^4_{heavy}} + \cdots$$

<u>+ numerical suppression due to interference with SM and resonance domination, or not</u>

- EX - flavour indicies for neutral currents:



$$\mathcal{A}^h_{ik} \simeq \frac{3\bar{v}_T\,\bar{g}_2^3}{16^2\,\pi^2\,\hat{m}_W}\,\bar{\psi}_i\,\left[y_i\,V^\dagger_{ik}\,V_{kj}\,\frac{m_k^2}{\hat{m}_W^2}P_L + y_j\,V^\dagger_{kj}\,V_{ik}\,\frac{m_k^2}{\hat{m}_W^2}P_R\right]\,\psi_j, + \cdots$$

$$\mathcal{A}^Z_{ik} \simeq -\frac{3\sqrt{\bar{g}_1^2+\bar{g}_2^2}\,\bar{g}_2^2\,V^\star_{jk}\,V_{ji}}{32\,\pi^2}\,\frac{m_j^2}{m_W^2}\bar{\psi}_k\,\gamma^\mu\,P_L\,\psi_i\,\epsilon^Z_\mu + \cdots,$$

This IR SM physics projects out parameters.

Leading "WHZ pole parameters"

Case	CP even	CP odd	WHZ Pole parameters
General SMEFT ($n_f = 1$)	53 [10]	23 [10]	~ 23
General SMEFT ($n_f = 3$)	1350 [10]	1149 [10]	~ 46
$U(3)^5$ SMEFT	~ 52	~ 17	~ 24
MFV SMEFT	~ 108	-	~ 30

Brivio, Jiang, MT https://arxiv.org/abs/1709.06492

- So long as a measurement is dominated by a near on-shell region of phase space of a narrow boson (like W,Z,H) many other parameters suppressed by

$$\left(\frac{\Gamma_B\, m_B}{\bar{v}_T^2}\right) \frac{\{\mathrm{Re}(C), \mathrm{Im}(C)\}}{g_{SM}\, C_i}, \qquad \left(\frac{\Gamma_B\, m_B}{p_i^2}\right) \frac{\{\mathrm{Re}(C), \mathrm{Im}(C)\}}{g_{SM}\, C_k},$$

Measurement/facility design can DEFINE a subset of SMEFT parameters in a fit

Field redefinition invariance

SMEFT requires a GLOBAL approach

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

- The operators are defined in a BASIS, fixed by SM field redefinitions.

$$\mathcal{L}_{B'} = -\frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - g_1 \, \mathrm{y}_\psi \, \overline{\psi} \not{B}' \psi + (D^\mu H)^\dagger (D_\mu H) + \mathcal{C}_B (H^\dagger \overleftrightarrow{D}^\mu H)(D^\nu B_{\mu\nu}),$$
$$+ \mathcal{C}_{BH} (D^\mu H)^\dagger (D^\nu H) B'_{\mu\nu} + C^{(1)}_{\substack{Hl \\ tt}} Q^{(1)}_{\substack{Hl \\ tt}} + C_{\substack{He \\ tt}} Q_{\substack{He \\ tt}} + C^{(1)}_{\substack{Hq \\ tt}} Q^{(1)}_{\substack{Hq \\ tt}} + C_{\substack{Hu \\ tt}} Q_{\substack{Hu \\ tt}},$$
$$+ C_{\substack{Hd \\ tt}} Q_{\substack{Hd \\ tt}} + C_{HB} Q_{HB} + C_T (H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}^\mu H).$$

Over complete set of ops depending on B^μ

1706.08945 I. Brivio, MT

- Perform a field redefinition $B'_\mu \to B_\mu + b_2 \frac{H^\dagger i \overleftrightarrow{D}_\mu H}{\Lambda^2}$ then $\mathcal{L}_{B'} - g_1 \, b_2 \Delta B$

<u>The physics is not changed by this choice of path integral variable.</u>

SMEFT requires a GLOBAL approach

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

- CHOOSE $b_2 = \mathcal{C}_B$ THEN

$$\mathcal{L}_{B'} = -\frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - g_1 \, \mathsf{y}_\psi \, \overline{\psi} \not{B}' \psi + (D^\mu H)^\dagger (D_\mu H) + \mathcal{C}_B (H^\dagger \overleftrightarrow{D^\mu} H)(D^\nu B_{\mu\nu}),$$
$$+ \mathcal{C}_{BH} (D^\mu H)^\dagger (D^\nu H) B'_{\mu\nu} + C^{(1)}_{\substack{Hl \\ tt}} Q^{(1)}_{\substack{Hl \\ tt}} + C_{\substack{He \\ tt}} Q_{\substack{He \\ tt}} + C^{(1)}_{\substack{Hq \\ tt}} Q^{(1)}_{\substack{Hq \\ tt}} + C_{\substack{Hu \\ tt}} Q_{\substack{Hu \\ tt}},$$
$$+ C_{\substack{Hd \\ tt}} Q_{\substack{Hd \\ tt}} + C_{HB} Q_{HB} + C_T (H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}^\mu H).$$

Non-redundant set of ops depending on B^μ

1706.08945 I. Brivio, MT

- BUT terms that remain SHIFTED $\mathcal{L}_B - g_1 \, b_2 \Delta B$

$$\Delta B = \mathsf{y}_l Q^{(1)}_{\substack{Hl \\ tt}} + \mathsf{y}_e Q_{\substack{He \\ tt}} + \mathsf{y}_q Q^{(1)}_{\substack{Hq \\ tt}} + \mathsf{y}_u Q_{\substack{Hu \\ tt}} + \mathsf{y}_d Q_{\substack{Hd \\ tt}}, \quad + \mathsf{y}_H (Q_{H\Box} + 4 Q_{HD}) + \frac{1}{g_1} B^{\mu\nu} \partial_\mu (H^\dagger i \overleftrightarrow{D}_\nu H).$$

EWPD, diboson, Higgs data all modified globally

Z,W couplings

$$\mathcal{Q}_{Hl}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$$
$$\mathcal{Q}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{Hq}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$$
$$\mathcal{Q}_{Hq}^{(3)} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$$
$$\mathcal{Q}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$$
$$\mathcal{Q}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$

Top data

$$\mathcal{Q}^{(1)}_{qq\,prst} = (\bar{q}_p\gamma^\mu q_r)(\bar{q}_s\gamma_\mu q_t),$$
$$\mathcal{Q}^{(3)}_{qq\,prst} = (\bar{q}_p\gamma^\mu \tau^I q_r)(\bar{q}_s\gamma_\mu \tau_I q_t),$$
$$\mathcal{Q}_{uu\,prst} = (\bar{u}_p\gamma^\mu u_r)(\bar{u}_s\gamma_\mu u_t),$$
$$\mathcal{Q}^{(1)}_{ud\,prst} = (\bar{u}_p\gamma^\mu u_r)(\bar{d}_s\gamma_\mu d_t),$$
$$\mathcal{Q}^{(8)}_{ud\,prst} = (\bar{u}_p\gamma^\mu T^A u_r)(\bar{d}_s\gamma_\mu T^A d_t),$$
$$\vdots$$

Bhabha scattering

$$\mathcal{Q}_{ee} = (\bar{e}\gamma^\mu e)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{le} = (\bar{l}\gamma^\mu l)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{ll} = (\bar{l}_p\gamma^\mu l_p)(\bar{l}_r\gamma^\mu l_r)$$

$$\mathcal{Q}_W = \varepsilon_{ijk} W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$$

TGC/multi-boson

Field redefinitions are WHY a global SMEFT is needed

$$\mathcal{Q}_{HD} = (D_\mu H^\dagger H)(H^\dagger D^\mu H)$$
$$\mathcal{Q}_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{Q}^{(3)}_{Hl} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$$
$$\mathcal{Q}'_{ll} = (\bar{l}_p\gamma^\mu l_r)(\bar{l}_r\gamma^\mu l_p)$$

input quantities

B anomalies

$$\mathcal{Q}^{(1)}_{lq\,iisb} = (\bar{\ell}_i\gamma^\mu \ell_i)(\bar{s}\gamma_\mu b),$$
$$\mathcal{Q}^{(3)}_{lq\,iisb} = (\bar{\ell}_i\,\tau^I\,\gamma^\mu \ell_i)(\bar{s}\,\tau_I\,\gamma_\mu b).$$

We are looking for few % to 10's% effects in SMEFT.

$$\mathcal{Q}_{Hbox} = (H^\dagger H)\,\Box\,(H^\dagger H)$$
$$\mathcal{Q}_{HG} = (H^\dagger H) G^a_{\mu\nu} G^{a\mu\nu}$$
$$\mathcal{Q}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{Q}_{HW} = (H^\dagger H) W^i_{\mu\nu} W^{i\mu\nu}$$
$$\mathcal{Q}_{uH} = (H^\dagger H)(\bar{q}\tilde{H}u)$$
$$\mathcal{Q}_{dH} = (H^\dagger H)(\bar{q}Hd)$$
$$\mathcal{Q}_{eH} = (H^\dagger H)(\bar{q}e)$$
$$\mathcal{Q}_G = \varepsilon_{abc} G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho$$
$$\mathcal{Q}_{uG} = (\bar{q}\sigma^{\mu\nu} T^a \tilde{H}u) G^a_{\mu\nu}$$

H processes

Z,W couplings

$$\mathcal{Q}_{Hl}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$$
$$\mathcal{Q}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{Hq}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$$
$$\mathcal{Q}_{Hq}^{(3)} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$$
$$\mathcal{Q}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$$
$$\mathcal{Q}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$

Top data

$$\mathcal{Q}^{(1)}_{qq\,prst} = (\bar{q}_p\gamma^\mu q_r)(\bar{q}_s\gamma_\mu q_t),$$
$$\mathcal{Q}^{(3)}_{qq\,prst} = (\bar{q}_p\gamma^\mu \tau^I q_r)(\bar{q}_s\gamma_\mu \tau_I q_t),$$
$$\mathcal{Q}_{uu\,prst} = (\bar{u}_p\gamma^\mu u_r)(\bar{u}_s\gamma_\mu u_t),$$
$$\mathcal{Q}^{(1)}_{ud\,prst} = (\bar{u}_p\gamma^\mu u_r)(\bar{d}_s\gamma_\mu d_t),$$
$$\mathcal{Q}^{(8)}_{ud\,prst} = (\bar{u}_p\gamma^\mu T^A u_r)(\bar{d}_s\gamma_\mu T^A d_t),$$
$$\vdots$$

Bhabha scattering

$$\mathcal{Q}_{ee} = (\bar{e}\gamma^\mu e)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{le} = (\bar{l}\gamma^\mu l)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{ll} = (\bar{l}_p\gamma^\mu l_p)(\bar{l}_r\gamma^\mu l_r)$$

$$\mathcal{Q}_W = \varepsilon_{ijk} W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$$

TGC/multi-boson

But measurement design and kinematics reduce parameters

$$\mathcal{Q}_{HD} = (D_\mu H^\dagger H)(H^\dagger D^\mu H)$$
$$\mathcal{Q}_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{Q}^{(3)}_{Hl} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$$
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H processes

We are looking for few % to 10's% effects in SMEFT.

Such field redefinitions preserve the symmetries of the theory. So symmetry is still a good guide to parameter counts/exp.

Field redefinition invariance = field space geometry

geoSMEFT preview.

Field coord. invariance leads to field space geometry

geoSMEFT

- Field coordinate choice invariance in amplitudes
- Mathematical quantities: metrics, Curvature, tensors of INTERACTION TERMS (field spaces)

$$\mathcal{L}_{SMEFT} = \frac{1}{2} h_{IJ}(\phi)(D_\mu \phi)^I (D_\mu \phi)^J - \frac{1}{4} g_{AB}(\phi) \mathcal{W}^A_{\mu\nu} W^{B,\mu\nu} + \cdots$$

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{bmatrix} \qquad \mathcal{W}^A = (W^1, W^2, W^3, B)$$

General Relativity.

- Space-time coordinate general covariance
- Mathematical quantities: metrics, Curvature, tensors for SPACE TIME

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

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In general terms: G. A. Vilkovisky, Nucl. Phys. B234 (1984) 125.

Modern uptake:

1002.2730 Burgess, Lee, Trott
1511.00724 Alonso, Jenkins, Manohar
1605.03602 Alonso, Jenkins, Manohar
1803.08001 Helset, Paraskevas, Trott.
1909.08470 Corbett, Helset, Trott

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Field coord. invariance leads to field space geometry

$$\mathcal{L}_{SMEFT} = \frac{1}{2} h_{IJ}(\phi)(D_\mu \phi)^I (D_\mu \phi)^J - \frac{1}{4} g_{AB}(\phi) \mathcal{W}^A_{\mu\nu} W^{B,\mu\nu} + \cdots$$

- Dimensionless expansion into operator bases $\tilde{C}_i = \frac{\langle H^\dagger H \rangle}{\Lambda^2} C_i$

$$\sqrt{h}^{IJ} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 - \frac{1}{4}\tilde{C}_{HD} & 0 \\ 0 & 0 & 0 & 1 + \tilde{C}_{H\Box} - \frac{1}{4}\tilde{C}_{HD} \end{bmatrix}$$

$$\sqrt{g}^{AB} = \begin{bmatrix} 1 + \tilde{C}_{HW} & 0 & 0 & 0 \\ 0 & 1 + \tilde{C}_{HW} & 0 & 0 \\ 0 & 0 & 1 + \tilde{C}_{HW} & -\frac{\tilde{C}_{HWB}}{2} \\ 0 & 0 & -\frac{\tilde{C}_{HWB}}{2} & 1 + \tilde{C}_{HB} \end{bmatrix}$$

(Small perturbations so positive semi-definite matrix and unique square root)

- Geometric field space quantities are useful (True independent of mass dimension of ops) Amp. perturb. are:

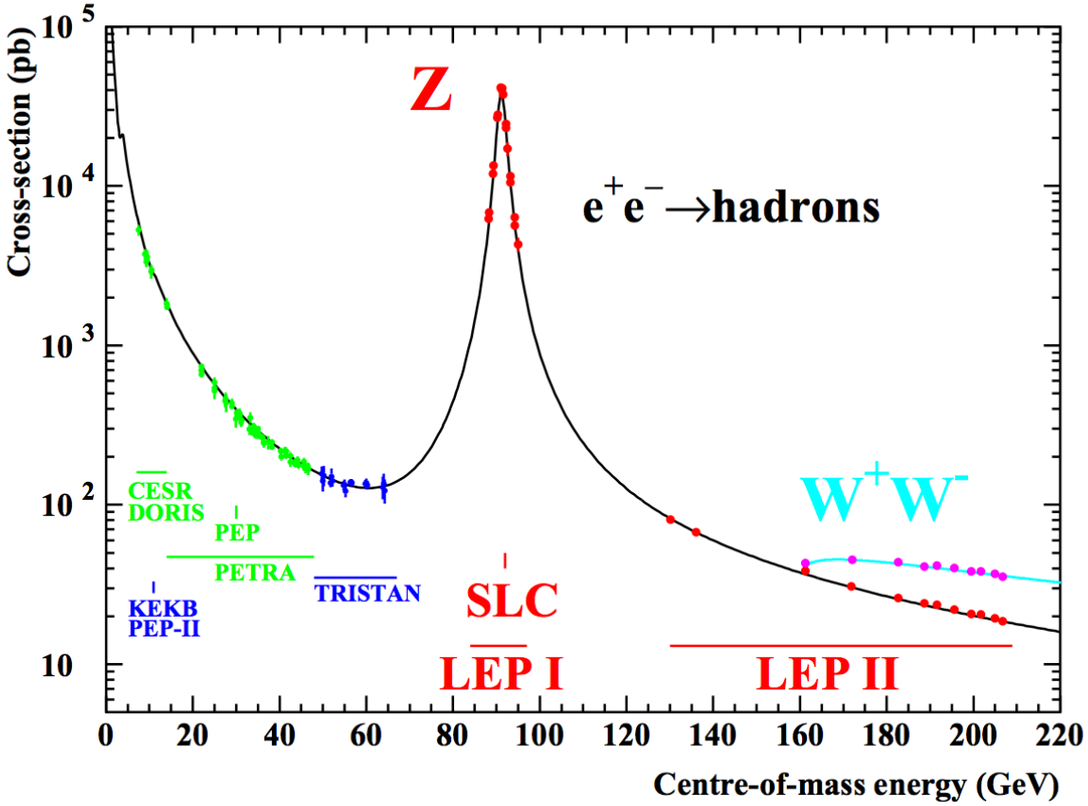
$$\mathcal{A} \simeq \mathcal{A}_{SM} + \langle \mathcal{O} \rangle_1 N_1 + \langle \mathcal{O} \rangle_2 N_2 + \cdots$$

Fun. of 4 vectors (kinematics)

Defined by field space geometries

LEP as a SMEFT example

We want to interpret LEP EWPD measurements



- EWPD is a scan through the Z pole

$\sim 40\, pb^{-1}$ off peak data

$\sim 155\, pb^{-1}$ on peak data

Simultaneous PO fit to

$$\sigma^{Z}_{\bar{f}f} = \sigma^{peak}_{\bar{f}f} \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

Peak shape is fit to:

$$\sigma^{peak}_{\bar{f}f} = \frac{\sigma^{0}_{\bar{f}f}}{R_{QED}} \qquad \sigma^{0}_{\bar{f}f} = \frac{12\pi\,\Gamma_{ee}\,\Gamma_{\bar{f}f}}{m_Z^2\,\Gamma_Z^2} \qquad R^0_\ell = \frac{\Gamma_{had}}{\Gamma_\ell}$$

Parameters extracted: $\left(m_Z^2, \Gamma_Z, R^0_\ell, \sigma^0_{had}\right)$ subsequently $A^i_{FB}, \Gamma_{Z\to f}$

Muon decay

- Decay of $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ measured far below the W pole.

- Probes the effective lagrangian $\hat{v}_T = \dfrac{1}{2^{1/4}\sqrt{\hat{G}_F}},$

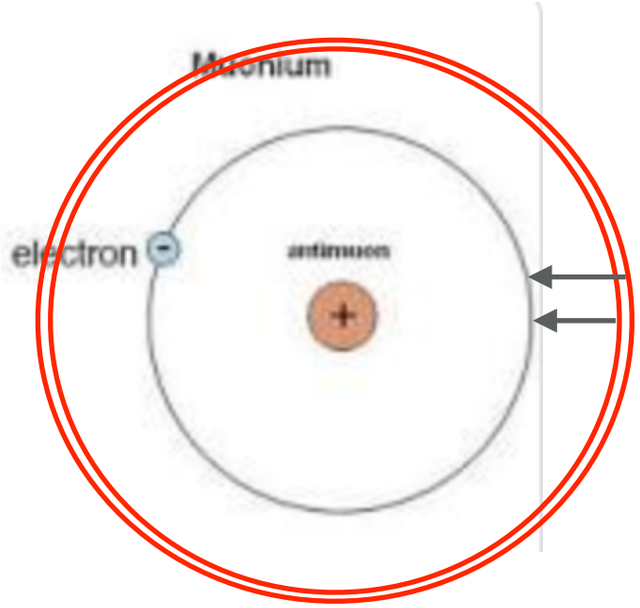
$$\mathcal{L}_{G_f} = \frac{-4G_F}{\sqrt{2}} \left(\bar{\nu}_\mu \gamma^\mu P_L \mu\right) \left(\bar{e} \gamma_\mu P_L \nu_e\right)$$

Through the total decay width $\Gamma = \dfrac{G_F^2\, m_\mu^5}{192\pi^3}$

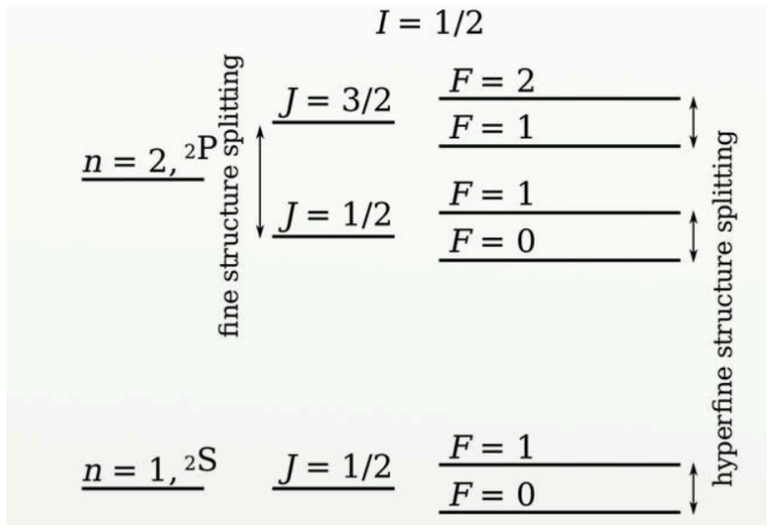
Need the mass of the muon to determine G_F

Muon mass/Electron mass

- Muon electron mass ratio can be measured in muonium



Spin-orbit interaction perturbs Hamiltonian leeds to Zeeman hyperfine splitting

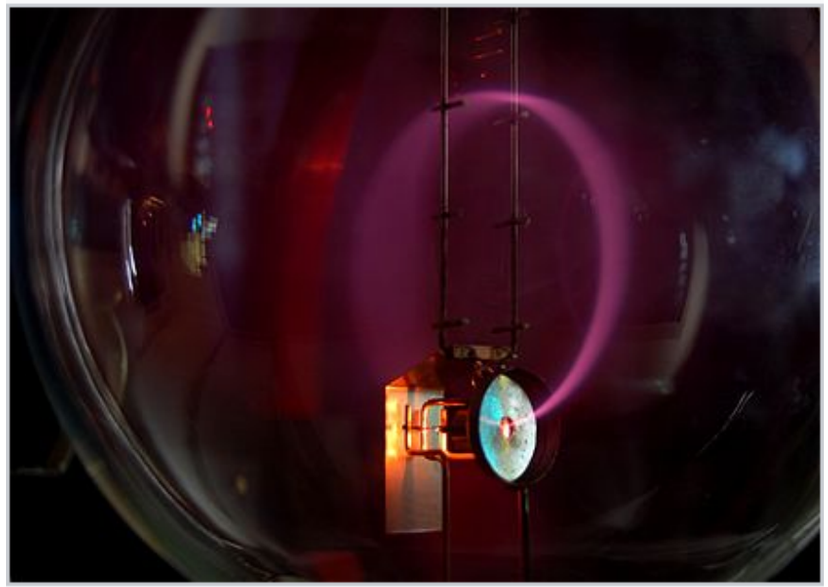


Allows an extraction of ratio m_μ/m_e

- Then we need to know the electron mass! How to we get it?

Electron mass/charge

- Motion of electron in a magnetic field gives mass/charge ratio

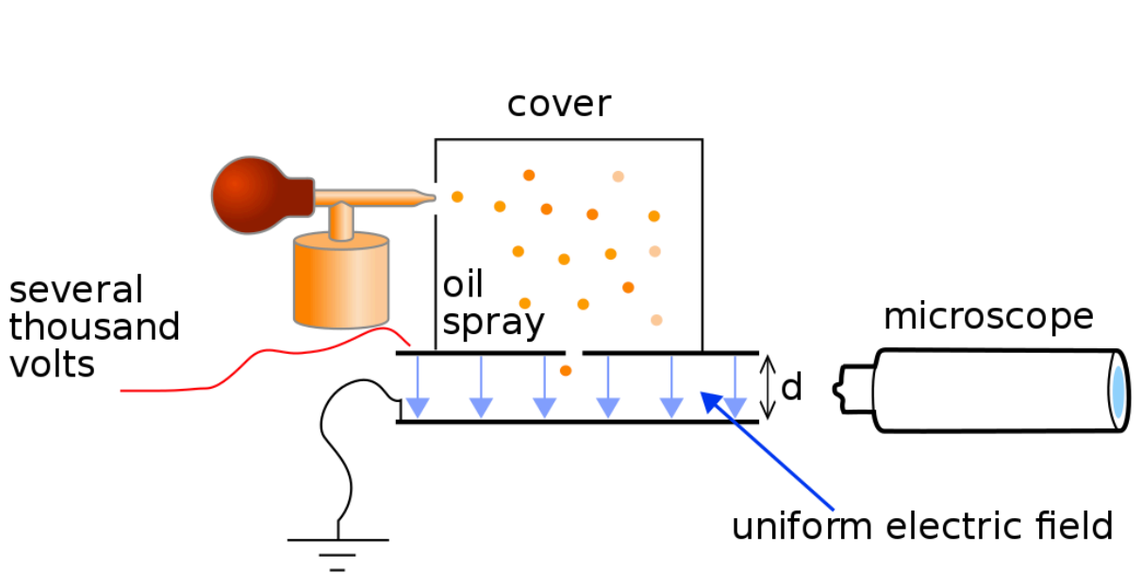


$$\mathbf{F} = Q(\mathbf{E} + \mathbf{v} \times \mathbf{B}),$$

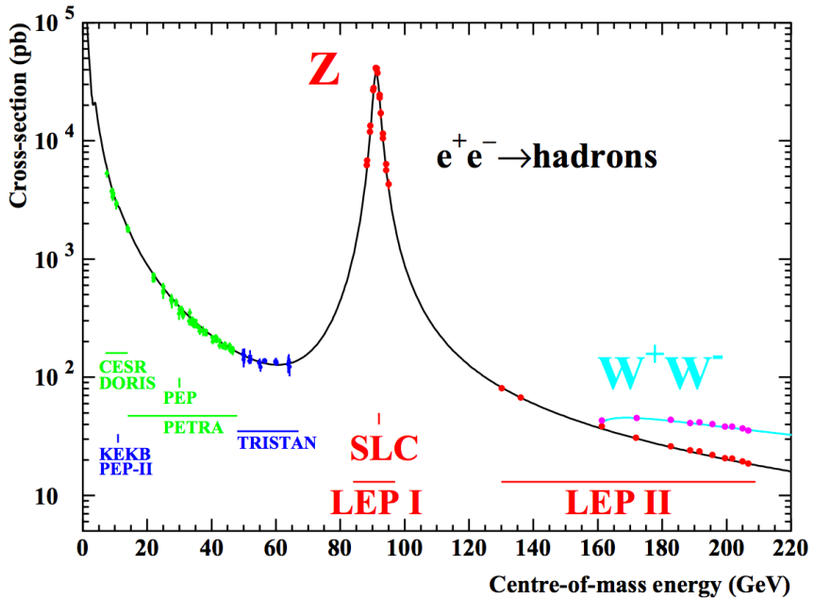
$$\mathbf{F} = m\mathbf{a} = m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}$$

$$\left(\frac{m}{Q}\right)\mathbf{a} = \mathbf{E} + \mathbf{v} \times \mathbf{B}.$$

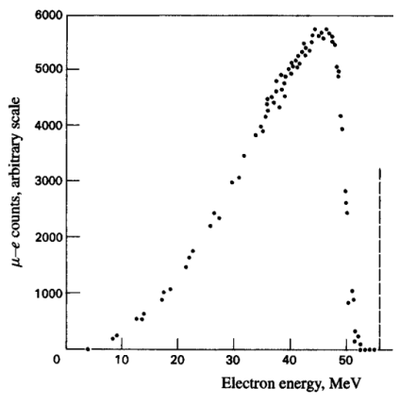
- Oil drop experiment can be used to extract the charge of the electron.

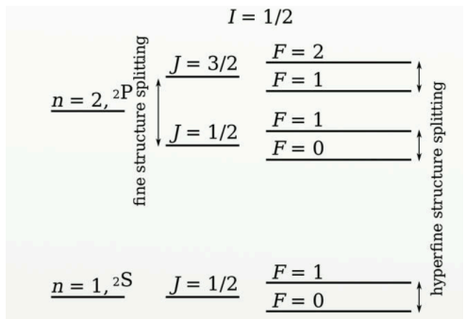


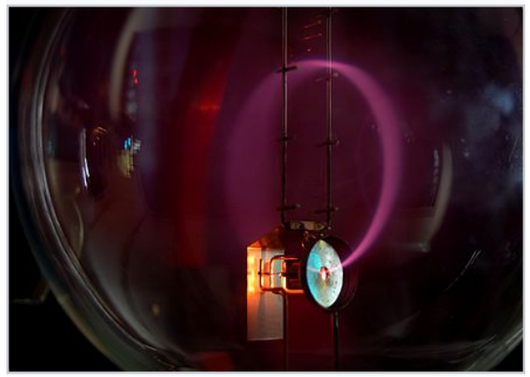
How do we know the SM EW sector input parameters?

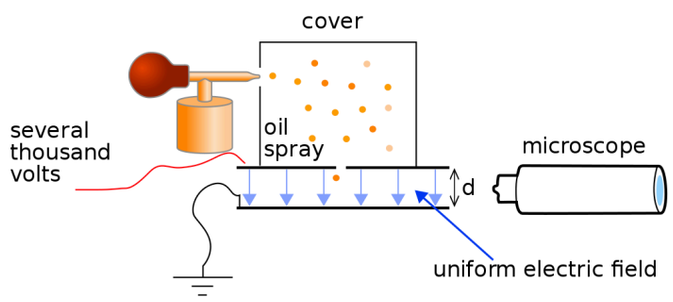


$$(m_Z^2, \Gamma_Z, R_\ell^0, \sigma_{had}^0)$$



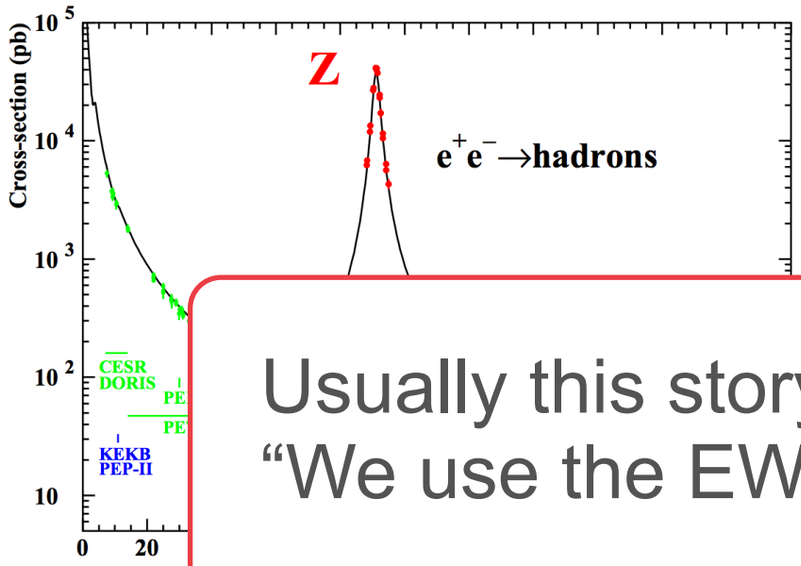






$$(G_F, \alpha_{ew}, m_e, m_\mu)$$

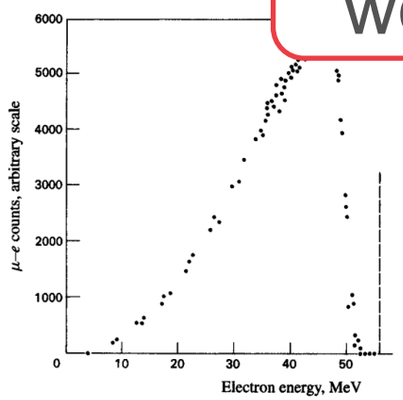
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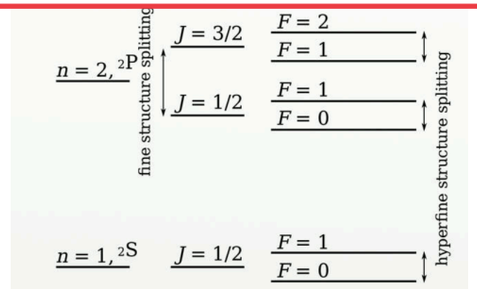


$$\left(m_Z^2, \Gamma_Z, R_\ell^0, \sigma_{had}^0\right)$$

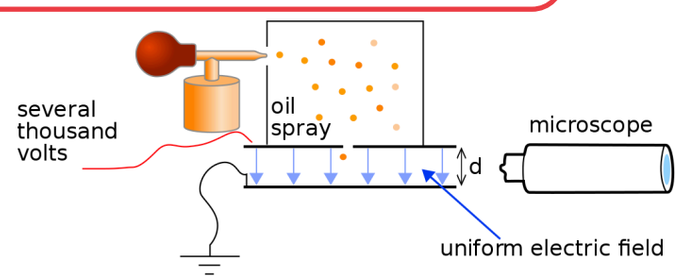
Usually this story is just boiled down to
"We use the EW input parameter scheme $\left(G_F, \alpha_{ew}, m_Z\right)$"

Now we want to know how does the EWPD pattern work using these inputs.









$$\left(G_F, \alpha_{ew}, m_e, m_\mu\right)$$

SM, usual approach to EWPD

- This is a multi-scale problem

$\hat{\alpha}$ $p^2 \simeq 0$

$\hat{G}_F$ $p^2 \simeq m_\mu^2$

$\hat{M}_Z$ $p^2 \simeq m_Z^2$

$$\hat{e} = \sqrt{4\pi\hat{\alpha}_{ew}}, \qquad \hat{v}_T = \frac{1}{2^{1/4}\sqrt{\hat{G}_F}},$$

$$\hat{g}_1 = \frac{\hat{e}}{c_{\hat{\theta}}}, \qquad \hat{g}_2 = \frac{\hat{e}}{s_{\hat{\theta}}},$$

$$s^2_{\hat{\theta}} = \frac{1}{2}\left[1 - \sqrt{1 - \frac{4\pi\hat{\alpha}}{\sqrt{2}\hat{G}_F\hat{M}_Z^2}}\right], \qquad \hat{M}_W^2 = \hat{M}_Z^2 c^2_{\hat{\theta}},$$

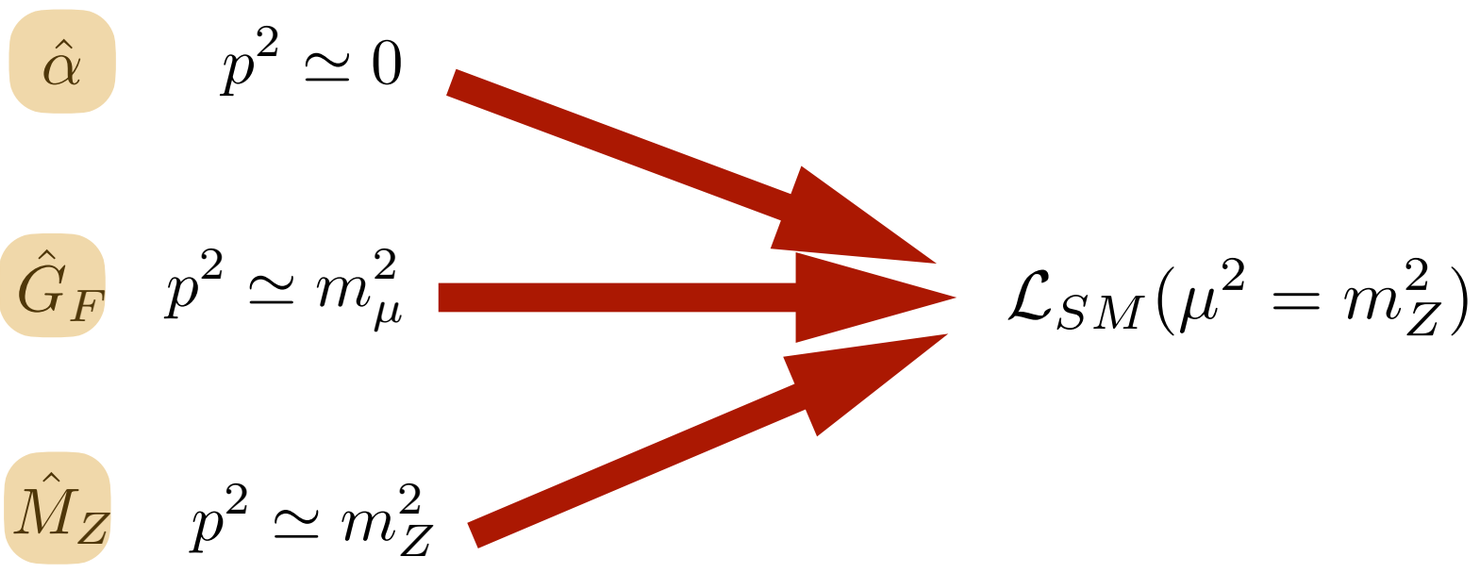
$$\hat{g}_Z = -\frac{\hat{g}_2}{c_{\hat{\theta}}},$$

Compare to LEP data:

Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
$\hat{m}_Z$[GeV]	91.1875 ± 0.0021	[19]	-	-
M_W[GeV]	80.385 ± 0.015	[49]	80.365 ± 0.004	[50]
Γ_Z[GeV]	2.4952 ± 0.0023	[19]	2.4942 ± 0.0005	[48]
R_ℓ^0	20.767 ± 0.025	[19]	20.751 ± 0.005	[48]
R_c^0	0.1721 ± 0.0030	[19]	0.17223 ± 0.00005	[48]
R_b^0	0.21629 ± 0.00066	[19]	0.21580 ± 0.00015	[48]
σ_h^0 [nb]	41.540 ± 0.037	[19]	41.488 ± 0.006	[48]
A_{FB}^ℓ	0.0171 ± 0.0010	[19]	0.01616 ± 0.00008	[32]
A_{FB}^c	0.0707 ± 0.0035	[19]	0.0735 ± 0.0002	[32]
A_{FB}^b	0.0992 ± 0.0016	[19]	0.1029 ± 0.0003	[32]

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$\hat{M}_Z$ $p^2 \simeq m_Z^2$

Then Z decay widths are predicted as:

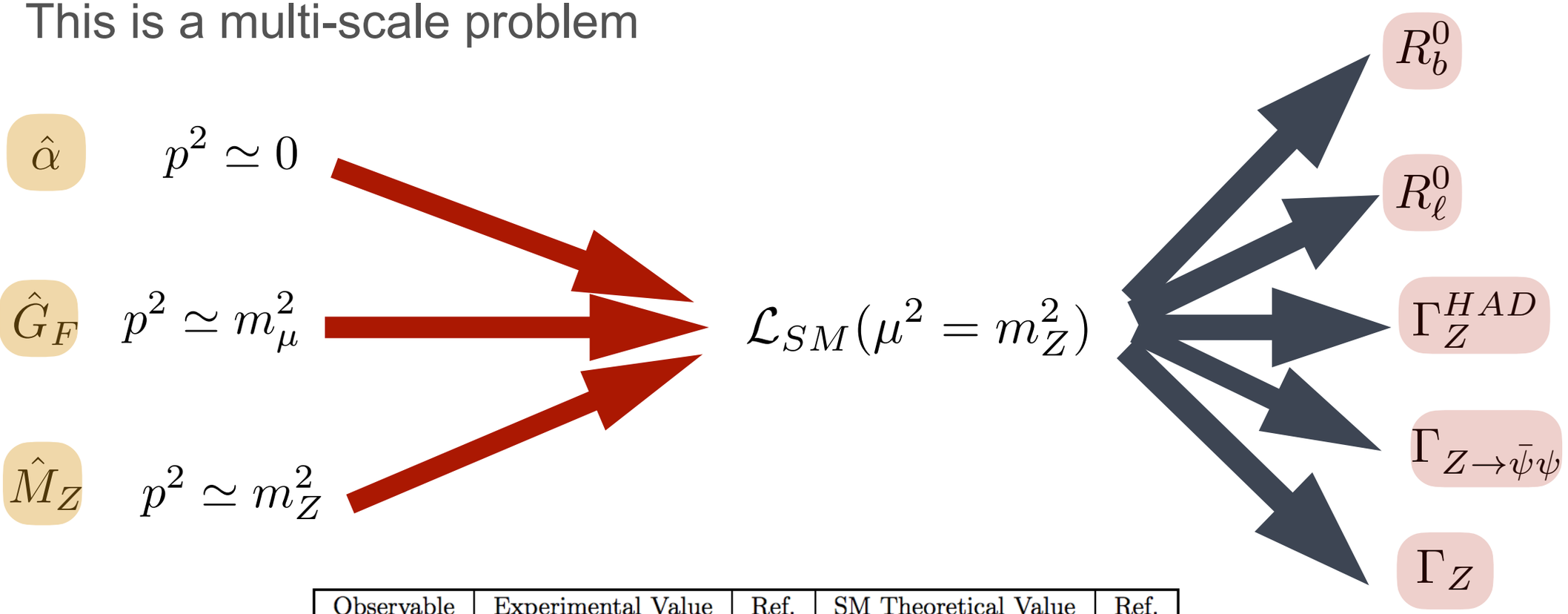
$$\Gamma\left(Z \to \psi\bar{\psi}\right) = \frac{\sqrt{2}\,\bar{G}_F \bar{M}_Z^3\, N_C^\psi}{3\pi}\left(|\bar{g}_V^\psi|^2 + |\bar{g}_A^\psi|^2\right)$$

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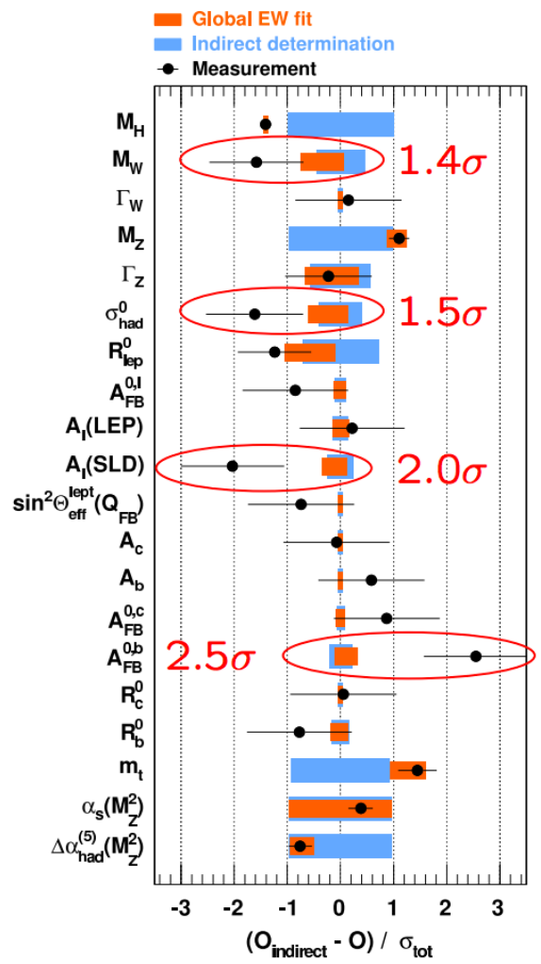
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Does EWPD already rule out C's in SMEFT?

Current status of electroweak precision tests

A. Freitas
University of Pittsburgh
HEFT 2017



Surprisingly good agreement:
$\chi^2/\text{d.o.f.} = 18.1/14$ ($p = 20\%$)

Most quantities measured with
1%–0.1% precision

A few interesting deviations:

M_W	$(\sim 1.4\sigma)$
σ^0_{had}	$(\sim 1.5\sigma)$
A_ℓ(SLD)	$(\sim 2\sigma)$
A^b_{FB}	$(\sim 2.5\sigma)$
$(g_\mu - 2)$	$(\sim 3\sigma)$

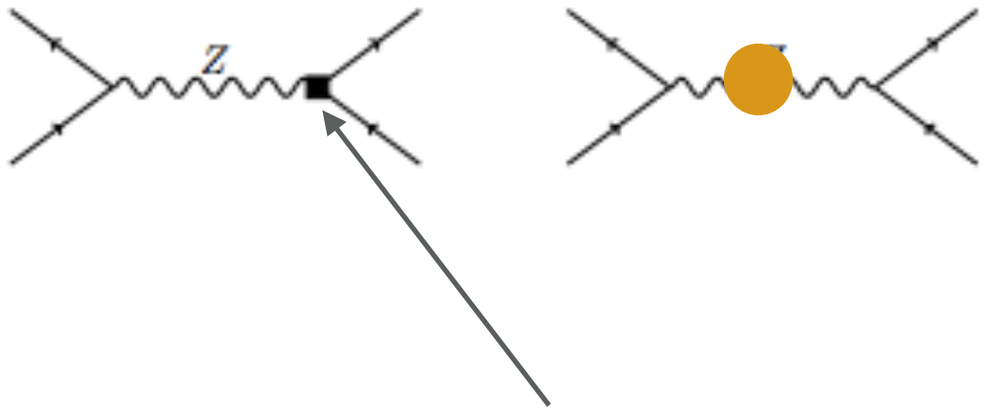
GFitter coll. '14

https://conference.ippp.dur.ac.uk/event/590/session/8/contribution/24/material/slides/0.pdf

- No discovery of new physics - but not exactly SM like.
- Tension on percent level effects, and pulls on most precise observables. :)

Global constraints on dim 6-update

- The old paradigm of ST was based on the idea that the effects of physics undiscovered should give mass to the W,Z, like the higgs



- The idea is that you have small vertex corrections (like in the case of the SM higgs) and large 2 point effects.

- Unfortunately this is *not a field redefinition invariant distinction*, so if really is assuming restricted UV (like a Higgs)

- Now that we found a Higgs like scalar, this is no longer appropriate to assume in general - need SMEFT analysis

Recall S,T Definitions

- When considering BSM physics, non SM effects on the mass relationship is parameterised as

$$\hat{\alpha}(M_Z)\,T \equiv \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

Large BSM contributions to the T parameter need to be avoided.

For quite a few years the standard approach to EWPD was S,T fits

$$\frac{\hat{\alpha}(M_Z)}{4\,\hat{s}_Z^2\,\hat{c}_Z^2}\,S \equiv \frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} - \frac{\hat{c}_Z^2 - \hat{s}_Z^2}{\hat{c}_Z\,\hat{s}_Z}\frac{\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$

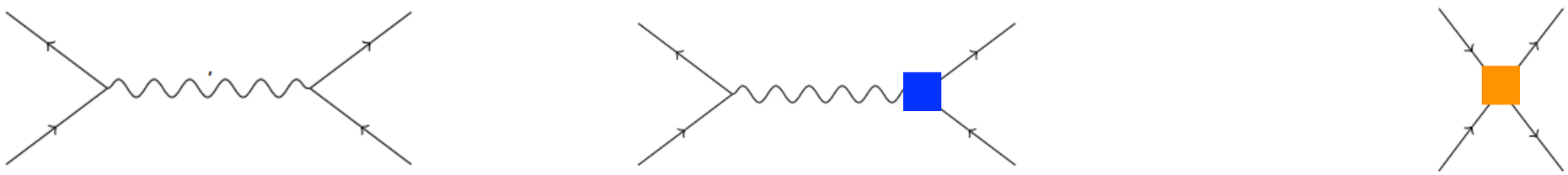
(S violates custodial symmetry too ….
but does not contribute to ρ at tree level)

SMEFT Muon decay

- Decay of $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ still measured far below the W pole.

- Still probes the effective lagrangian

$$\mathcal{L}_{G_F} = -\frac{4\mathcal{G}_F}{\sqrt{2}} \left(\bar{\nu}_\mu \gamma^\mu P_L \mu\right) \left(\bar{e} \gamma_\mu P_L \nu_e\right)$$



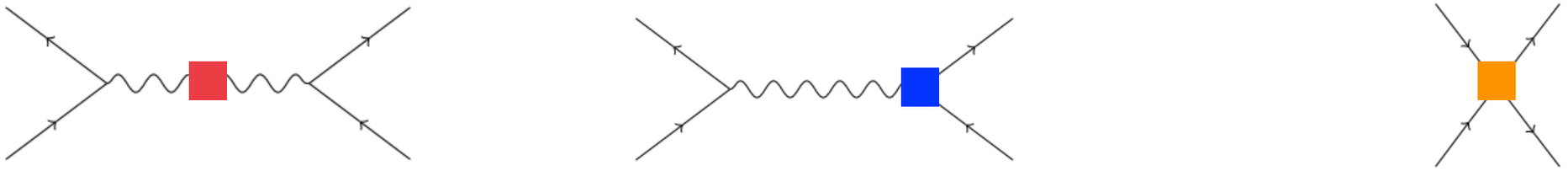
So now $$-\frac{4\mathcal{G}_F}{\sqrt{2}} = -\frac{2}{v_T^2} + \left(C_{\substack{ll \\ \mu ee \mu}} + C_{\substack{ll \\ e\mu\mu e}}\right) - 2\left(C^{(3)}_{\substack{Hl \\ ee}} + C^{(3)}_{\substack{Hl \\ \mu\mu}}\right)$$

$$\delta G_F$$

SMEFT EWPD

- For measurements of LEPI near Z pole data and W mass at LO:

$$Q_{HWB}, Q_{HD}, \quad Q_{H\ell}^{(1)}, Q_{H\ell}^{(3)}, Q_{Hq}^{(1)}, Q_{Hq}^{(3)}, Q_{He}, Q_{Hu}, Q_{Hd}, \quad Q_{\ell\ell}$$

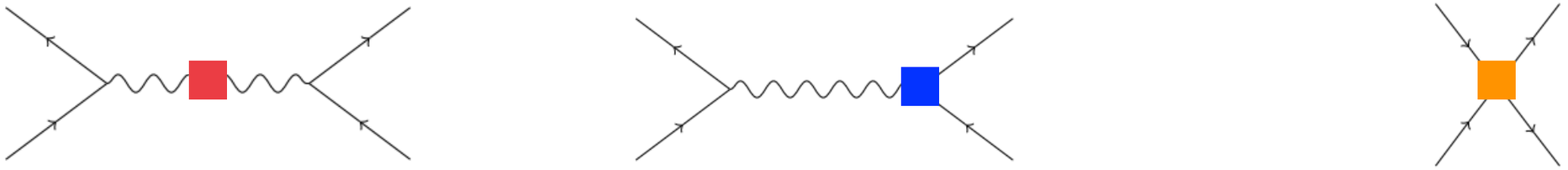


- Relevant four fermion operator at LO is introduced due to $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ As used to extract G_F and all other four fermion ops neglected.
- Some basis dependence in this, but $\mathcal{O}(10) \ll 76$ as $\Gamma_{W,Z}/M_{W,Z} \ll 1$

SMEFT EWPD

- EWPD is essentially solved in closed form with geoSMEFT now.

$$Q_{HWB}, Q_{HD}, Q^{(1)}_{H\ell}, Q^{(3)}_{H\ell}, Q^{(1)}_{Hq}, Q^{(3)}_{Hq}, Q_{He}, Q_{Hu}, Q_{Hd}, Q_{\ell\ell}$$



The observables are

$$\bar{\Gamma}_i = \frac{\sqrt{2}\,\hat{G}_F\,\hat{m}_Z^3\,N_c}{6\,\pi}\left(|g_{eff}^{\mathcal{Z},i,L}|^2 + |g_{eff}^{\mathcal{Z},i,R}|^2\right), \qquad \bar{\Gamma}_{had} = \bar{\Gamma}_u + \bar{\Gamma}_d + \bar{\Gamma}_c + \bar{\Gamma}_s + \bar{\Gamma}_b,$$

$$\bar{R}_{c,b} = \frac{\bar{\Gamma}_{c,b}}{\bar{\Gamma}_{had}}, \qquad \bar{R}_\ell = \frac{\bar{\Gamma}_{had}}{\bar{\Gamma}_\ell},$$

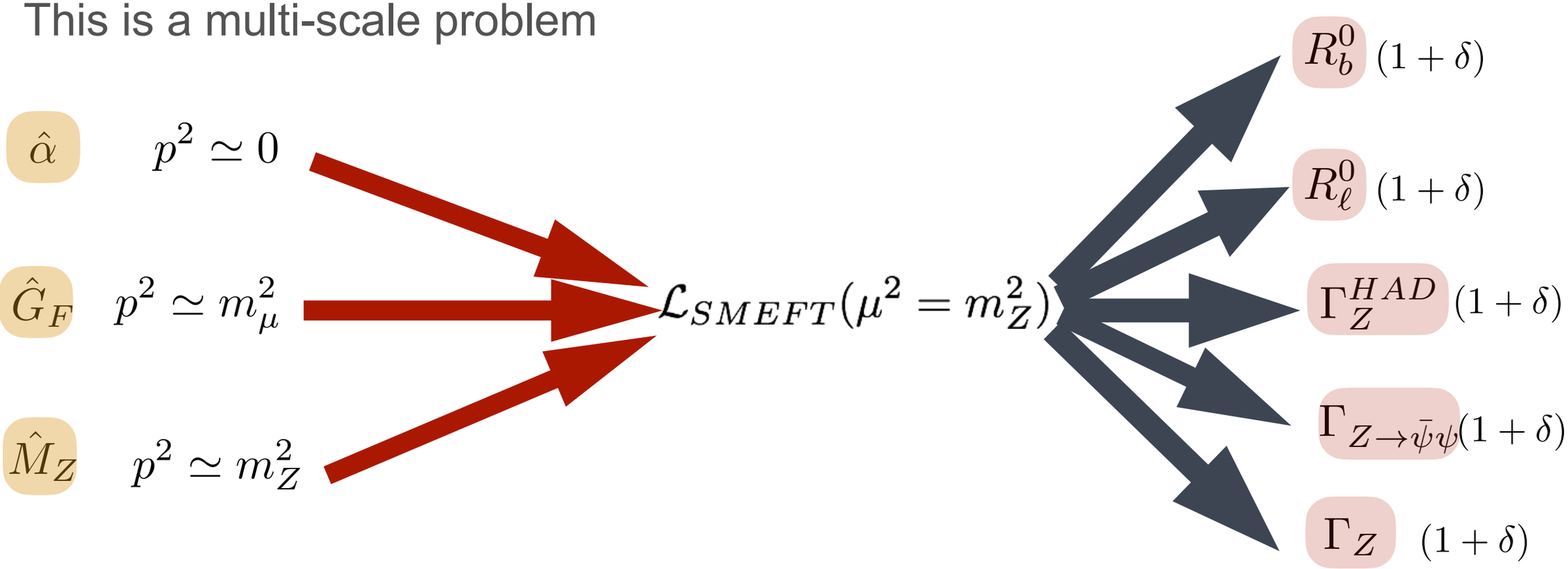
$$\bar{\sigma}^0_{had} = \frac{12\,\pi}{\hat{m}_Z^2}\,\frac{\bar{\Gamma}_e\,\bar{\Gamma}_{had}}{\bar{\Gamma}_Z^2}, \qquad \bar{A}^{0,f}_{FB} = \frac{3}{4}\,\bar{A}_e\,\bar{A}_f,$$

where

$$\bar{A}_i = \frac{(g_{eff}^{\mathcal{Z},i_L} - g_{eff}^{\mathcal{Z},i_R})(g_{eff}^{\mathcal{Z},i_L} + g_{eff}^{\mathcal{Z},i_R})}{(g_{eff}^{\mathcal{Z},i_L})^2 + (g_{eff}^{\mathcal{Z},i_R})^2}.$$

Leading order (LO) SMEFT analysis

- This is a multi-scale problem



- Lagrangian parameters inferred from inputs now corrected by local contact operators

$$\sqrt{2\langle H^\dagger H\rangle} \sim 246\,\text{GeV}$$

$$\delta\kappa = \bar{\kappa} - \hat{\kappa}$$

ex:
$$\delta g_1 = \bar{g}_1 - \hat{g}_1 = \frac{\hat{g}_1}{2c_{2\hat{\theta}}}\left[s_{\hat{\theta}}^2\left(\sqrt{2}\delta G_F + \frac{\delta m_Z^2}{\hat{m}_Z^2}\right) + c_{\hat{\theta}}^2\, s_{2\hat{\theta}}\bar{v}_T^2 C_{HWB}\right],$$

$$\delta s_\theta^2 = s_{\bar{\theta}}^2 - s_{\hat{\theta}}^2 = 2c_{\hat{\theta}}^2 s_{\hat{\theta}}^2\left(\frac{\delta g_1}{\hat{g}_1} - \frac{\delta g_2}{\hat{g}_2}\right) + \bar{v}_T^2\frac{s_{2\hat{\theta}}c_{2\hat{\theta}}}{2}C_{HWB}.$$

The corrections depend on the scheme choice

Strong input scheme dependence in SMEFT

$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2}\tilde{C}_{HD} + \frac{2^{3/4}\sqrt{\pi\hat{\alpha}}\,\hat{M}_Z}{\hat{G}_F^{1/2}}\tilde{C}_{HWB},$$

$$\begin{aligned}
\delta s_\theta^2 &= 0.17\tilde{C}_{HD} + 0.79\tilde{C}_{HWB} + 0.76\tilde{C}_{Hl}^{(3)} - 0.34\tilde{C}'_{ll},\\
\frac{\delta\Gamma_Z}{\Gamma_Z^{SM}} &= -0.82\tilde{C}_{HWB} - 0.67\tilde{C}_{HD} - 0.19\tilde{C}_{Hl}^{(1)} - 2.06\tilde{C}_{Hl}^{(3)} - 0.19\tilde{C}_{He}\\
&\quad + 0.47\tilde{C}_{Hq}^{(1)} + 1.61\tilde{C}_{Hq}^{(3)} + 0.26\tilde{C}_{Hu} - 0.19\tilde{C}_{Hd} + 1.35\tilde{C}'_{ll}\\
\frac{\delta\alpha}{2\,\hat{\alpha}} &= 0,\\
\frac{\delta M_W^2}{\hat{M}_W^2} &= -\frac{s_{2\hat{\theta}}}{4\,c_{2\hat{\theta}}}\left(\frac{c_{\hat{\theta}}}{s_{\hat{\theta}}}\tilde{C}_{HD} + \frac{s_{\hat{\theta}}}{c_{\hat{\theta}}}2\sqrt{2}\,\delta G_F + 4\tilde{C}_{HWB}\right),\\
\frac{\delta\Gamma_W}{\Gamma_W^{SM}} &= -3.97\tilde{C}_{HWB} - 1.80\tilde{C}_{HD} - 3.52\tilde{C}_{Hl}^{(3)} + 1.33\tilde{C}_{Hq}^{(3)} + 2.10\tilde{C}'_{ll}\,.
\end{aligned}$$

$\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\begin{aligned}
\delta m_Z^2 &= \frac{\hat{M}_Z^2}{2}\tilde{C}_{HD} + 2\,\hat{M}_Z\,\hat{M}_W\sqrt{1-\frac{\hat{M}_W^2}{\hat{M}_Z^2}}\tilde{C}_{HWB},\\
\delta s_\theta^2 &= -0.39\tilde{C}_{HD} - 0.42\tilde{C}_{HWB},\\
\frac{\delta\Gamma_Z}{\Gamma_Z^{SM}} &= 0.46\tilde{C}_{HWB} - 0.07\tilde{C}_{HD} - 0.18\tilde{C}_{Hl}^{(1)} - 1.37\tilde{C}_{Hl}^{(3)} - 0.18\tilde{C}_{He}\\
&\quad + 0.47\tilde{C}_{Hq}^{(1)} + 1.61\tilde{C}_{Hq}^{(3)} + 0.24\tilde{C}_{Hu} - 0.18\tilde{C}_{Hd} + \tilde{C}'_{ll},\\
\frac{\delta\alpha}{2\,\hat{\alpha}} &= -\frac{\delta G_F}{\sqrt{2}} + \frac{\delta m_Z^2}{\hat{M}_Z^2}\frac{\hat{M}_W^2}{2\,(\hat{M}_W^2-\hat{M}_Z^2)} - \tilde{C}_{HWB}\frac{\hat{M}_W}{\hat{M}_Z}\sqrt{1-\frac{\hat{M}_W^2}{\hat{M}_Z^2}},\\
\frac{\delta M_W^2}{\hat{M}_W^2} &= 0,\\
\frac{\delta\Gamma_W}{\Gamma_W^{SM}} &= \frac{4}{3}\left(\tilde{C}_{Hq}^{(3)} - \tilde{C}_{Hl}^{(3)}\right) + \tilde{C}'_{ll}.
\end{aligned}$$

- Completely expected from decoupling theorem. ***UV physics preserving SM symmetries being absorbed into measured low scale parameters now.***

Strong input scheme dependence in SMEFT

$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2}\tilde{C}_{HD} + \frac{2^{3/4}\sqrt{\pi\hat{\alpha}}\,\hat{M}_Z}{\hat{G}_F^{1/2}}\tilde{C}_{HWB},$$

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$$\frac{\delta\alpha}{2\,\hat{\alpha}} = 0,$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = -\frac{s_{2\hat{\theta}}}{4\,c_{2\hat{\theta}}}\left(\frac{c_{\hat{\theta}}}{s_{\hat{\theta}}}\tilde{C}_{HD} + \frac{s_{\hat{\theta}}}{c_{\hat{\theta}}}2\sqrt{2}\,\delta G_F + 4\tilde{C}_{HWB}\right),$$

$$\frac{\delta\Gamma_W}{\Gamma_W^{SM}} = -3.97\tilde{C}_{HWB} - 1.80\tilde{C}_{HD} - 3.52\tilde{C}_{Hl}^{(3)} + 1.33\tilde{C}_{Hq}^{(3)} + 2.10\tilde{C}'_{ll}\,.$$

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$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2}\tilde{C}_{HD} + 2\,\hat{M}_Z\,\hat{M}_W\sqrt{1-\frac{\hat{M}_W^2}{\hat{M}_Z^2}}\tilde{C}_{HWB},$$

$$\delta s_\theta^2 = -0.39\tilde{C}_{HD} - 0.42\tilde{C}_{HWB},$$

$$\frac{\delta\Gamma_Z}{\Gamma_Z^{SM}} = 0.46\tilde{C}_{HWB} - 0.07\tilde{C}_{HD} - 0.18\tilde{C}_{Hl}^{(1)} - 1.37\tilde{C}_{Hl}^{(3)} - 0.18\tilde{C}_{He} + 0.47\tilde{C}_{Hq}^{(1)} + 1.61\tilde{C}_{Hq}^{(3)} + 0.24\tilde{C}_{Hu} - 0.18\tilde{C}_{Hd} + \tilde{C}'_{ll},$$

$$\frac{\delta\alpha}{2\,\hat{\alpha}} = -\frac{\delta G_F}{\sqrt{2}} + \frac{\delta m_Z^2}{\hat{M}_Z^2}\frac{\hat{M}_W^2}{2\,(\hat{M}_W^2-\hat{M}_Z^2)} - \tilde{C}_{HWB}\frac{\hat{M}_W}{\hat{M}_Z}\sqrt{1-\frac{\hat{M}_W^2}{\hat{M}_Z^2}},$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = 0,$$

$$\frac{\delta\Gamma_W}{\Gamma_W^{SM}} = \frac{4}{3}\left(\tilde{C}_{Hq}^{(3)} - \tilde{C}_{Hl}^{(3)}\right) + \tilde{C}'_{ll}.$$

Significant input parameter dependence on symmetry preserving
New physics effects being absorbed into numerical input parameters.

Global constraints on dim 6.

Global SMEFT analysis on 103 observables (pre LHC data).

arXiv:1502.02570, 1508.05060 Berthier, Trott

Comprehensive global fit of pre-LHC data in SMEFT

- LEP pole data + all these measurements below with clear theory errors

B $2 \to 2$ **scattering observables at LEP, Tristan, Pep, Petra.**
- B.1 $\ell^+ \ell^- \to f \bar{f}$ near and far from the Z pole.
  - B.1.1 Forward-Backward Asymmetries for u, d, ℓ
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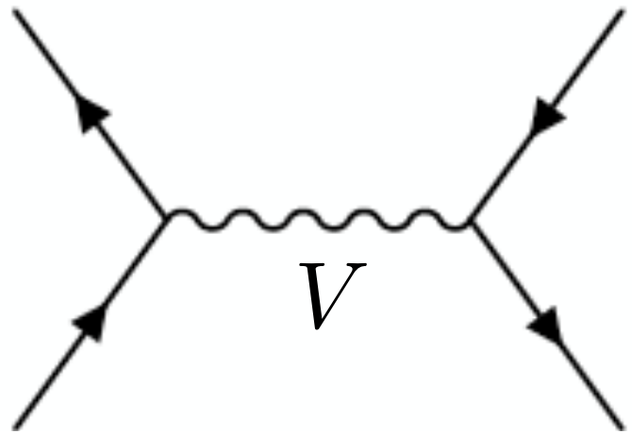
D Universality in β decays

Despite all this, 2 unconstrained directions in wilson coefficient space. (first identified by Han and Skiba)

- Global data analysis of data from PEP, PETRA, TRISTAN, SpS, Tevatron, SLAC, LEPI and LEP II

Recall field redefinitions lead to OP basis

- Flat directions is due to an EOM based invariance in the SMEFT and field redefinitions.



arXiv:1701.06424 Reparameterization! Ilaria Brivio, MT

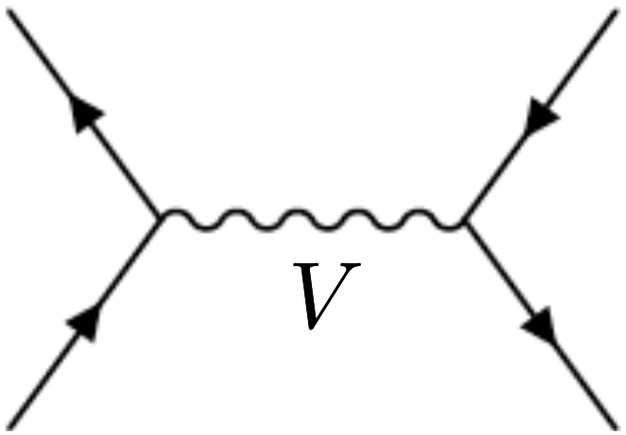
$$(V, g) \leftrightarrow \left(V'\,(1+\epsilon), g'\,(1-\epsilon)\right),$$

$\bar{\psi}\psi \to \bar{\psi}\psi$ scattering has a reparamatrization invariance

$$\mathcal{L}_{V\psi_i} = \frac{1}{2}\,m_V^2\,V^\mu\,V_\mu - \frac{1}{4}V^{\mu\,\nu}V_{\mu\,\nu} - g\,\bar{\psi}_i\gamma^\mu\psi_j V_\mu - g\,\kappa\,\bar{\psi}_k\gamma^\mu\psi_l V_\mu + \cdots .$$

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These terms invariant under shift

This term changes!

- BUT! The LSZ formula corrects out the non-normalized kinetic terms, so no physical effect.

SMEFT reparameterization invariance

- This is why at one scale, you can get rid of the effect of the operators

$$H^\dagger H B^{\mu\nu} B_{\mu\nu}, \quad H^\dagger H W^{\mu\nu} W_{\mu\nu}$$

$$\langle \mathsf{y}_h\, g_1^2 Q_{HB}\rangle_{S_R} \to \frac{g_1^2\,\bar{v}_T^2}{4\,\Lambda^2}\, B^{\mu\nu}\, B_{\mu\nu}, \quad \langle g_2^2 Q_{HW}\rangle_{S_R} \to \frac{g_2^2\,\bar{v}_T^2}{2\,\Lambda^2}\, W_I^{\mu\nu}\, W^I_{\mu\nu}.$$

$\bar{\psi}\psi \to \bar{\psi}\psi$

- via $B \to \mathcal{B}(1 + C_{HB} v^2), \qquad g_1 \to \bar{g}_1(1 - C_{HB} v^2)$

  Which leaves $B\, g_1 \to \mathcal{B}\, \bar{g}_1$ invariant.

- LEP data also can't see what is EOM equivalent to these operators in $\bar{\psi}\psi \to \bar{\psi}\psi$

$$\langle \mathsf{y}_h\, g_1^2 Q_{HB}\rangle_{S_R} = \Big\langle \sum_{\substack{\psi_\kappa = u,d,\\ q,e,l}} \mathsf{y}_k\, g_1^2\, \overline{\psi}_\kappa\, \gamma_\beta \psi_\kappa\, (H^\dagger\, i \overleftrightarrow{D}_\beta H) + \frac{g_1^2}{2}\,(Q_{H\Box} + 4 Q_{HD}) - \frac{1}{2} g_1\, g_2\, Q_{HWB}\Big\rangle_{S_R},$$

$$\langle\, g_2^2 Q_{HW}\rangle_{S_R} = \langle g_2^2\, (\bar{q}\,\tau^I \gamma_\beta q + \bar{l}\,\tau^I \gamma_\beta l)\, (H^\dagger\, i \overleftrightarrow{D}^I_\beta H) + 2\, g_2^2\, Q_{H\Box} - 2\, g_1\, g_2\, \mathsf{y}_h\, Q_{HWB}\rangle_{S_R}.$$

This is a smoking gun of geoSMEFT rescaling!

GeoSMEFT and flat directions

- As soon as people started to use the full SMEFT - immediately data analysis indicated a hidden structure pointing to the importance of field space understanding.

Key early analysis going in right direction: Han,Skiba 0412166

They found flat directions in LEP data. We now know due an invariance.

Weak eigenstates

Mass eigenstate

$$\hat{\mathcal{W}}^{A,\nu} = \sqrt{g}^{AB} U_{BC} \hat{\mathcal{A}}^{C,\nu},$$
$$\hat{\alpha}^{A} = \sqrt{g}^{AB} U_{BC} \hat{\beta}^{C},$$
$$\hat{\phi}^{J} = \sqrt{h}^{JK} V_{KL} \hat{\Phi}^{L},$$

1909.08470 Corbett, Helset, Trott

$\hat{\alpha} \cdot \hat{\mathcal{W}} = \hat{\beta} \cdot \hat{\mathcal{A}}$
Play a role?



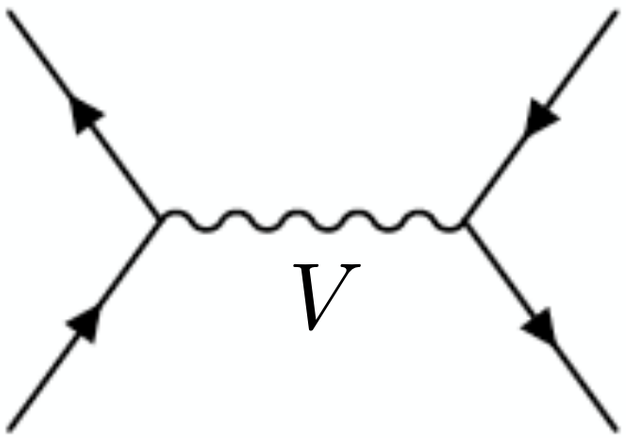
Field space metrics

Rotations

EWPD flat directions

- Flat directions due the invariance, fundamentally its $\hat{\alpha}\cdot\hat{\mathcal{W}}=\hat{\beta}\cdot\hat{\mathcal{A}}$





arXiv:1701.06424 Reparameterization! Ilaria Brivio, MT

$$(V,g)\leftrightarrow\left(V'\left(1+\epsilon\right),g'\left(1-\epsilon\right)\right),$$

$\bar{\psi}\psi\to\bar{\psi}\psi$ scattering has a reparamatrization invariance

- Flat directions in many data sets project onto EOM equivalents to what cancels in the invariant $\hat{\alpha}\cdot\hat{\mathcal{W}}=\hat{\beta}\cdot\hat{\mathcal{A}}\quad\left(\tilde{C}_{HB},\tilde{C}_{HW}\right)$

$$w_1^{\alpha}=-w_B-2.59\,w_W \qquad w_1^{m_W}=-w_B-2.48\,w_W$$

$$w_2^{\alpha}=-w_B+4.31\,w_W, \qquad w_2^{m_W}=-w_B+4.40\,w_W.$$

be careful and keep all operators!

SMEFT reparameterization invariance

- Flat directions discovered in the 2 to 2 scattering data set project onto these EOM equivalent combinations of operators

$$w_1^\alpha = -w_B - 2.59\, w_W \qquad w_2^\alpha = -w_B + 4.31\, w_W.$$

be careful and keep all operators!

- Input scheme independent.
- Must combine data sets in a well defined SMEFT, so no matter what operator basis you choose you get consistent results

B $2 \to 2$ scattering observables at LEP, Tristan, Pep, Petra.
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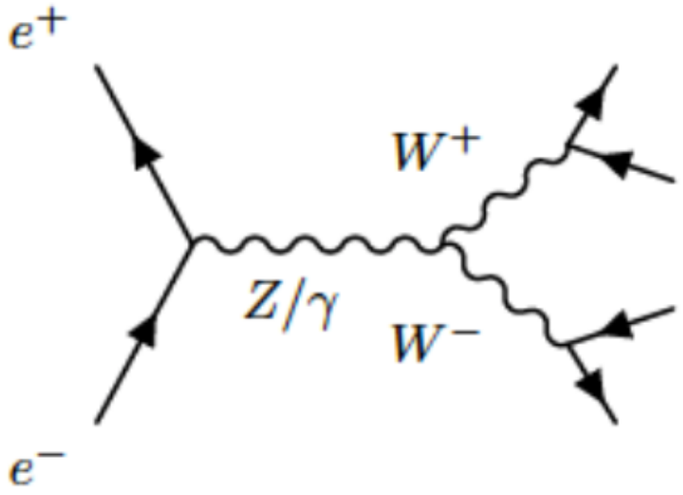
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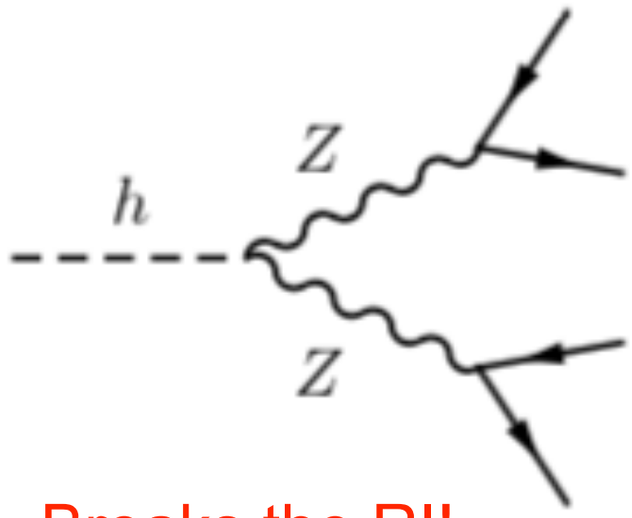
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Breaks the RI!



Breaks the RI!

LHC is the machine to measure a ton of these events

SMEFT reparameterization invariance

- Flat directions discovered in the 2 to 2 scattering data set project onto these EOM equivalent combinations of operators

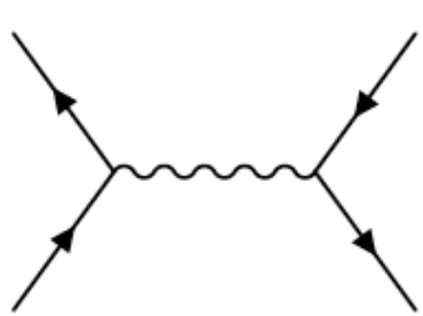
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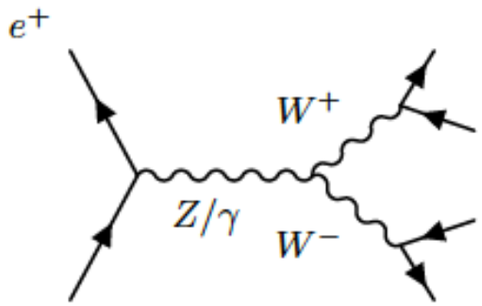
- Input scheme independent.
- Must combine data sets in a well defined SMEFT, so no matter what operator basis you choose you get consistent results

Not as precisely measured.

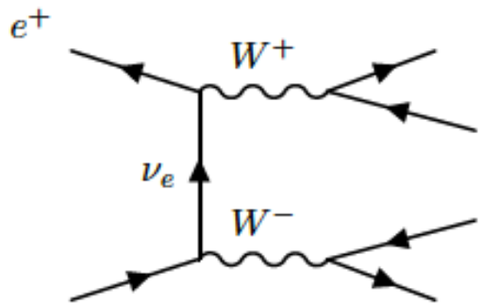
So weaker constraints



RI not broken



Breaks the RI!

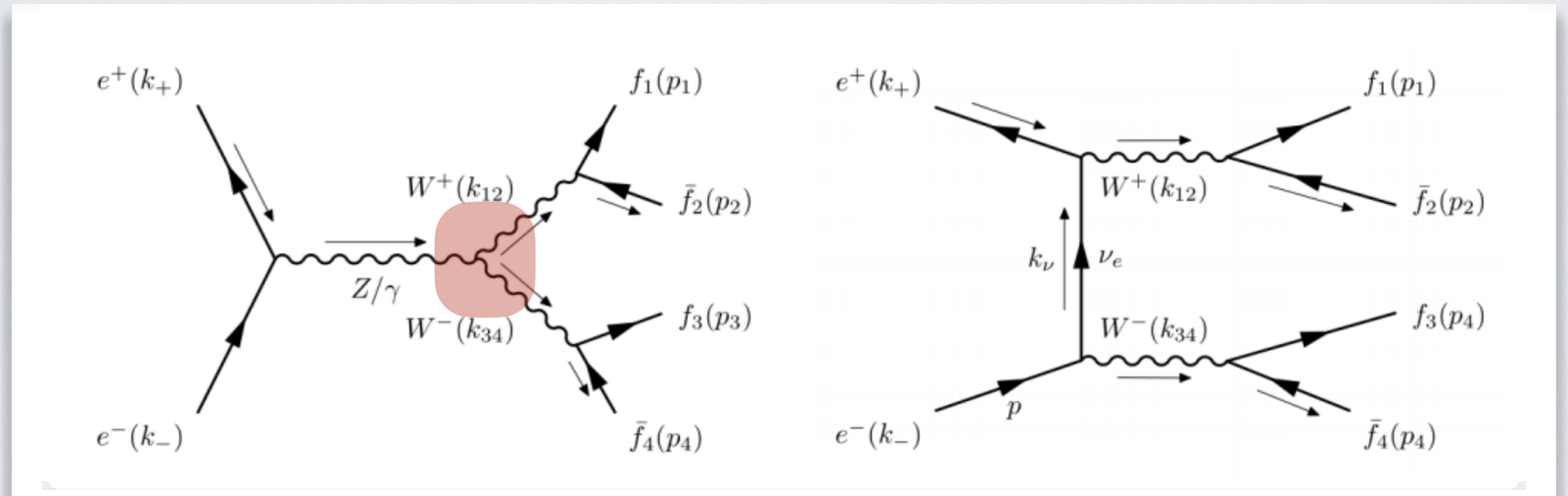


RI not broken

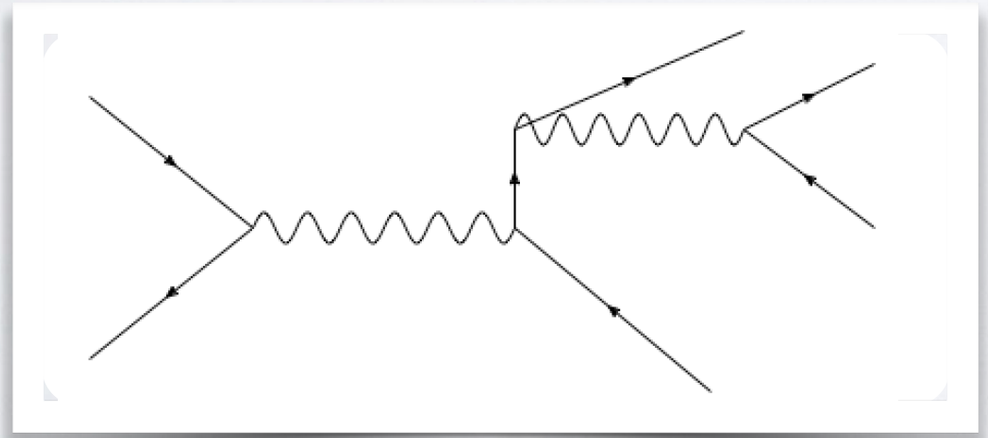
This channel dominant at LEP2

Subtleties due to intermediate unstable states

- It is well known from LEPI/LEPII times that you have to be careful defining the process that involves the off shell TGC verticies



- A difference of gauge fixing terms (axial and feynman gauge) added to the diagrams above generates diagrams like



W. Beenakker and A. Denner, Standard model predictions for W pair production in electron - positron collisions, Int. J. Mod. Phys. A9 (1994) 4837–4920. (and many other refs)

This is the known distinction between “CC03” and “CC11” diagrams.

Global constraints on dim 6-update

- We have performed an analysis of this form. Fit with 177 obs now (1606.06693 Bjorn, Berthier, MT). Key is to add the “TGC data” in the SMEFT correctly.
- Interesting subtlety is how these processes are defined, in a double pole approximation around the resonances:

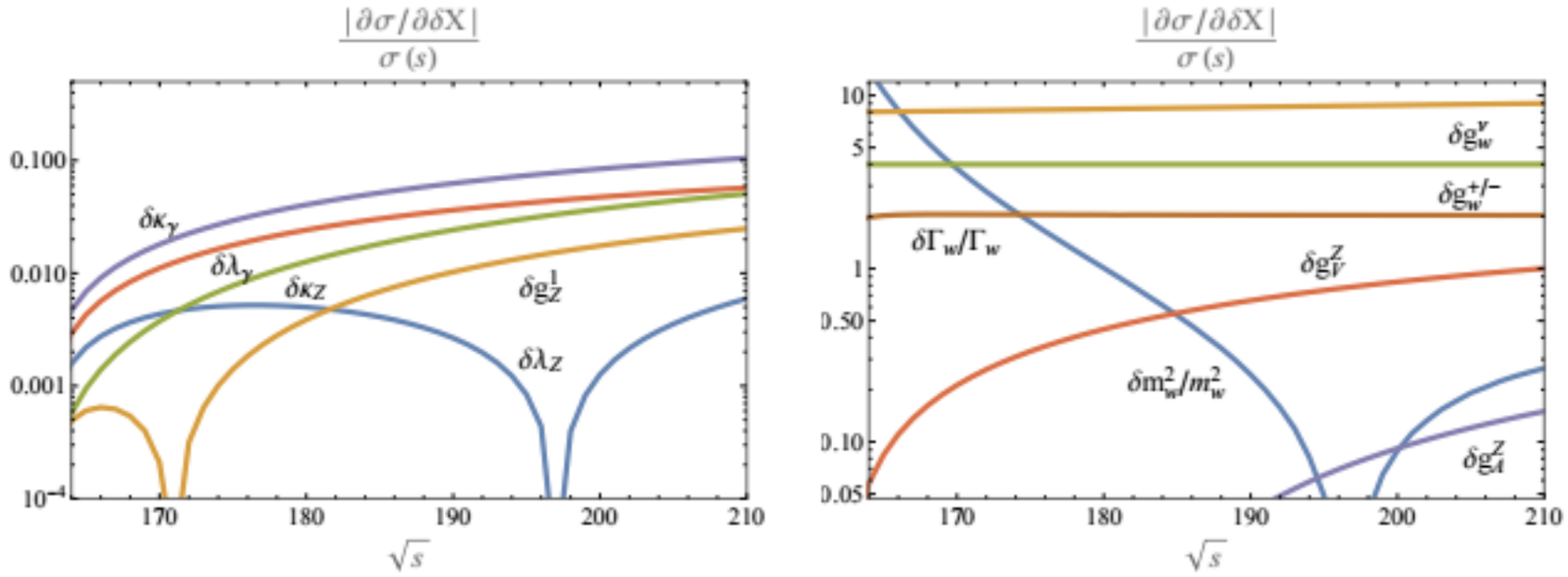
$$\mathcal{A}(s_{12},s_{34}) = \frac{1}{s_{12}-\bar{m}_W^2}\frac{1}{s_{34}-\bar{m}_W^2}\mathrm{DR}[s_{12},s_{34},\Omega] + \frac{1}{s_{12}-\bar{m}_W^2}\mathrm{SR}_1[s_{12},s_{34},d\Omega],$$
$$+ \frac{1}{s_{34}-\bar{m}_W^2}\mathrm{SR}_2[s_{12},s_{34},d\Omega] + \mathrm{NR}[s_{12},s_{34},d\Omega].$$

Need to include $\frac{\delta m_W^2}{\hat{m}_W^2} = \frac{c_{\hat{\theta}} s_{\hat{\theta}}}{(c_{\hat{\theta}}^2 - s_{\hat{\theta}}^2)\, 2\sqrt{2}\hat{G}_F}\left[4\, C_{HWB} + \frac{c_{\hat{\theta}}}{s_{\hat{\theta}}} C_{HD} + 4\frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} C_{Hl}^{(3)} - 2\frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} C_{ll})\right].$

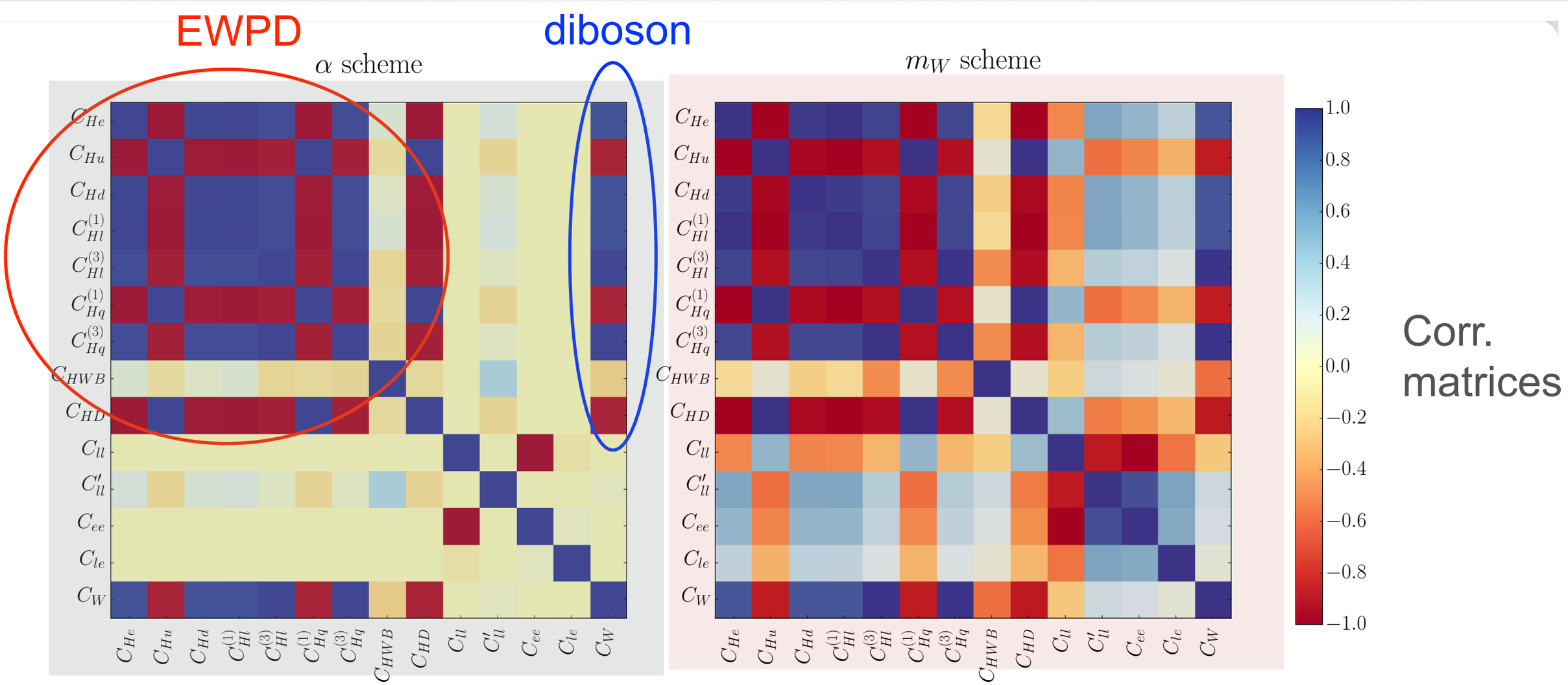
when fixing $s_{12} = s_{34} = \bar{m}_W^2$ the shift of the pole in the SMEFT itself.

Global constraints on dim 6-update

- Shifts in the $e^+e^- \to 4f$ cross section and angular data



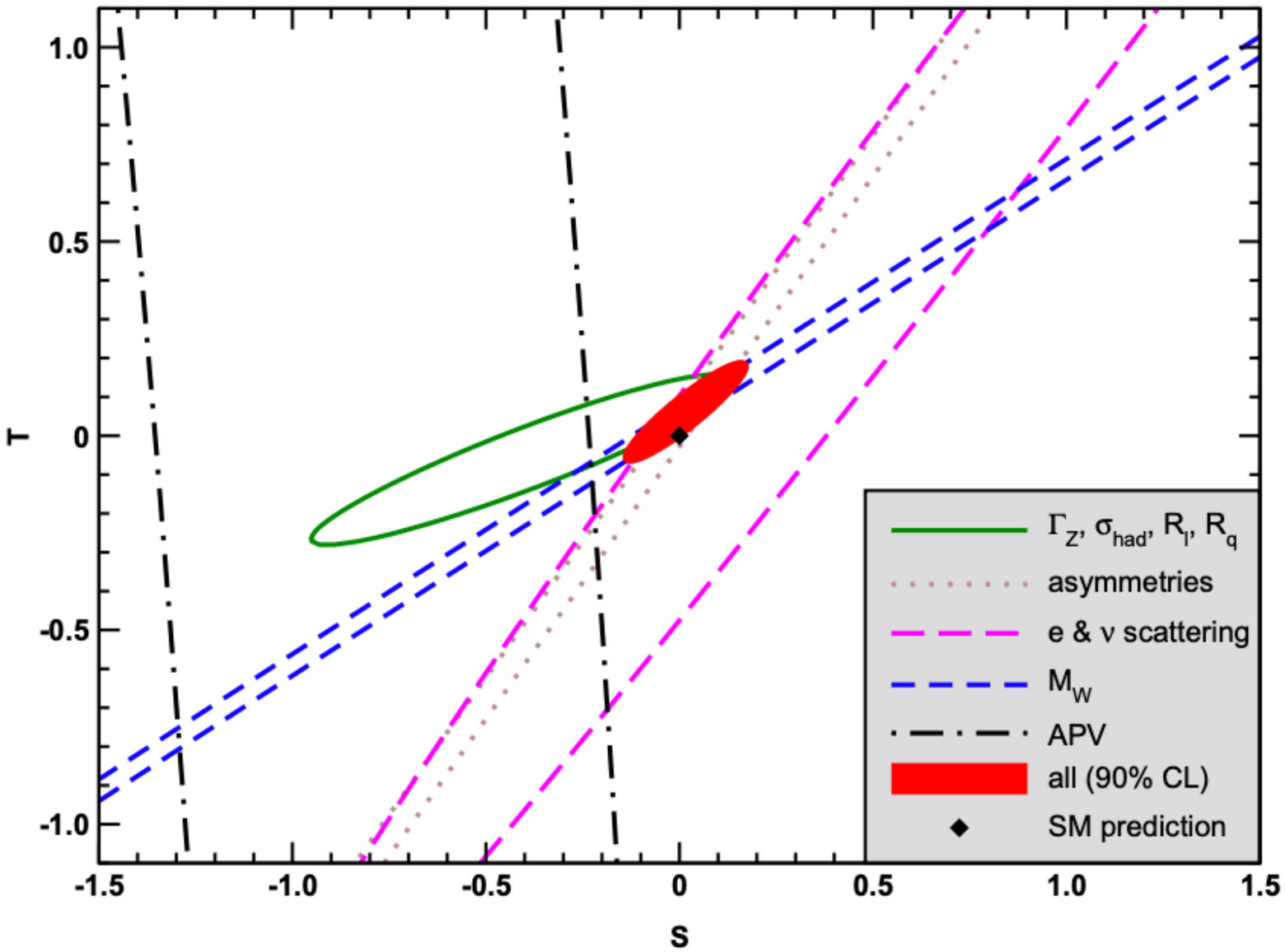
What emerges as global constraints?



- Correlation matrices in a likelihood for the SMEFT

$$L(C) = \frac{1}{\sqrt{(2\pi)^n |V|}} \exp\left(-\frac{1}{2}\left(\hat{O} - \bar{O}\right)^T V^{-1} \left(\hat{O} - \bar{O}\right)\right),$$

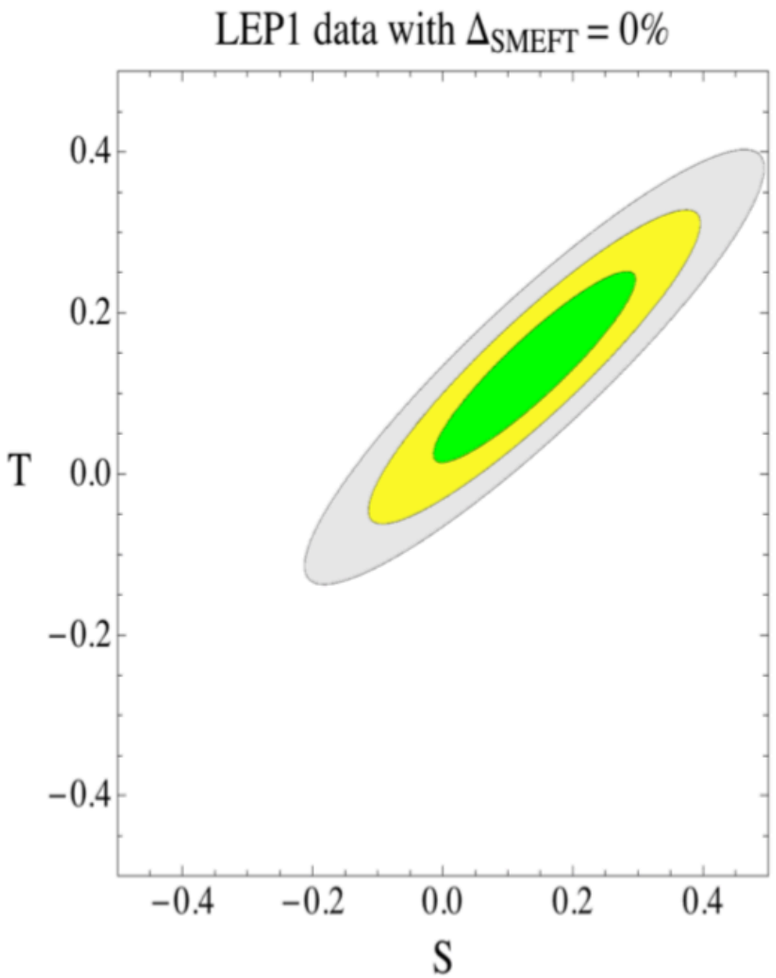
Old school EWPD analysis

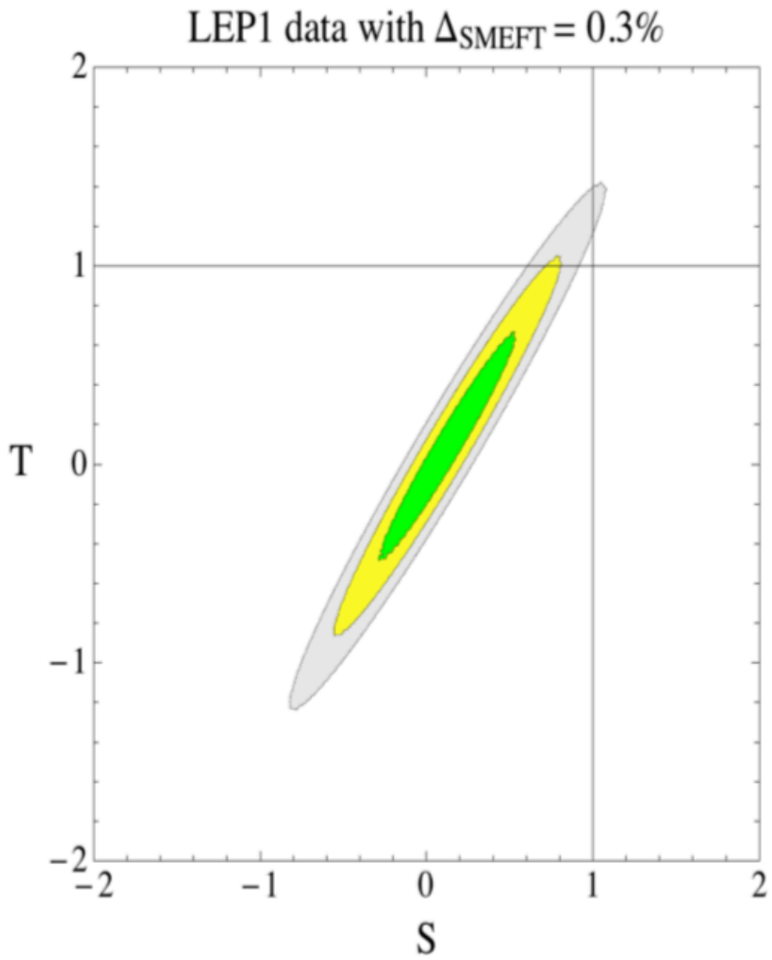


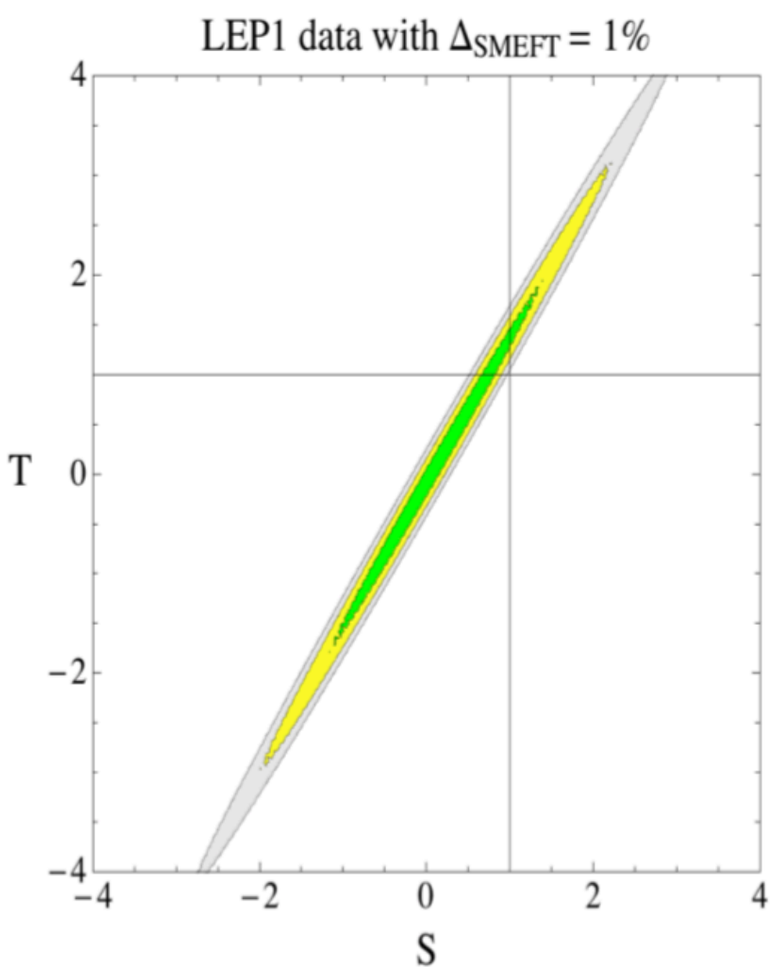
- Careful with interpretation, if hypothesis testing SM - OK!
- NOT a proper general constraint for arbitrary new physics sectors.

Comparison to S,T fit.

$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme results







- Other parameters just set To 0.
- Other parameters set to 0 and a theory error introduced to take into account approximation.