Building models from the bottom up

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with

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LHC 😕 ⟶ The era of EFT

SMEFT: General parametrization of heavy new physics under mild assumptions

Buchmuller, Wyler '85 , … , Grzadkowski, Iskrzynski, Misiak, Rosiek, '10   2682 cit. each!

However…   [see talk by Manuel Drees]

- Just a parametrization ⟶ no obvious insight
- Lots of independent parameters
- Bad high-energy behaviour
- Limited range of validity

We need UV completions!

- Look for perturbative completions
- Stay as general as possible
- But concentrate on leading effects

↓

BSMEFT

- D.o.f.: SM plus spin 0, 1/2, 1
- Symmetries: Poincaré + SM gauge SU(3)xSU(2)xU(1)

Spin 0

$S \in (1,1)_0$
$S_1 \in (1,1)_1$
$S_2 \in (1,1)_2$
$\varphi \in (1,2)_{\frac{1}{2}}$
$\Xi_0 \in (1,3)_0$
$\Xi_1 \in (1,3)_1$
$\Theta_1 \in (1,4)_{\frac{1}{2}}$
$\Theta_3 \in (1,4)_{\frac{3}{2}}$

$\omega_1 \in (3,1)_{-\frac{1}{3}}$
$\omega_2 \in (3,1)_{\frac{2}{3}}$
$\omega_4 \in (3,1)_{-\frac{4}{3}}$
$\Pi_1 \in (3,2)_{\frac{1}{6}}$
$\Pi_7 \in (3,2)_{\frac{7}{6}}$
$\zeta \in (3,3)_{-\frac{1}{3}}$

$\Omega_1 \in (6,1)_{\frac{1}{3}}$
$\Omega_2 \in (6,1)_{-\frac{2}{3}}$
$\Omega_4 \in (6,1)_{\frac{4}{3}}$
$\Upsilon \in (6,3)_{\frac{1}{3}}$

$\Phi \in (8,2)_{\frac{1}{2}}$

Spin 1/2

$N \in (1,1)_0$
$E \in (1,1)_{-1}$
$\Delta_1 \in (1,2)_{-\frac{1}{2}}$
$\Delta_3 \in (1,2)_{-\frac{3}{2}}$
$\Sigma \in (1,3)_0$
$\Sigma_1 \in (1,3)_{-1}$

$U \in (3,1)_{\frac{2}{3}}$
$D \in (3,1)_{-\frac{1}{3}}$
$Q_1 \in (3,2)_{\frac{1}{6}}$
$Q_5 \in (3,2)_{-\frac{5}{6}}$
$Q_7 \in (3,2)_{\frac{7}{6}}$
$T_1 \in (3,3)_{-\frac{1}{3}}$
$T_2 \in (3,3)_{\frac{2}{3}}$

New multiplets with sizable effects

del Aguila, Bowick, de Blas, Chala, MPV, Santiago, '82-'14

Spin 1

$\mathcal{B} \in (1,1)_0$
$\mathcal{B}_1 \in (1,1)_1$
$\mathcal{W} \in (1,3)_0$
$\mathcal{W}_1 \in (1,3)_1$
$\mathcal{L}_1 \in (1,2)_{\frac{1}{2}}$
$\mathcal{L}_3 \in (1,2)_{-\frac{3}{2}}$

$\mathcal{U}_2 \in (3,1)_{\frac{2}{3}}$
$\mathcal{U}_5 \in (3,1)_{\frac{5}{3}}$
$\mathcal{Q}_1 \in (3,2)_{\frac{1}{6}}$
$\mathcal{Q}_5 \in (3,2)_{-\frac{5}{6}}$
$\mathcal{X} \in (3,3)_{\frac{2}{3}}$

$\mathcal{Y}_1 \in (\bar{6},2)_{\frac{1}{6}}$
$\mathcal{Y}_5 \in (\bar{6},2)_{-\frac{5}{6}}$

$\mathcal{G} \in (8,1)_0$
$\mathcal{G}_1 \in (8,1)_1$
$\mathcal{H} \in (8,3)_0$

Renormalizable BSM interactions

$$
\begin{aligned}
&(\kappa_{\mathcal{S}})_r \mathcal{S}_r \phi^\dagger \phi + (\lambda_{\mathcal{S}})_{rs} \mathcal{S}_r \mathcal{S}_s \phi^\dagger \phi + (\kappa_{\mathcal{S}^3})_{rst} \mathcal{S}_r \mathcal{S}_s \mathcal{S}_t \\
&+ \left\{ (y_{\mathcal{S}_1})_{rij} \mathcal{S}_{1r}^\dagger \bar{l}_{Li} i\sigma_2 l^c_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ (y_{\mathcal{S}_2})_{rij} \mathcal{S}_{2k}^\dagger \bar{e}_{Ri} e^c_{Rj} + \text{h.c.} \right\} \\
&+ \left\{ (y^e_\varphi)_{rij} \varphi_r^\dagger \bar{e}_{Ri} l_{Lj} + (y^d_\varphi)_{rij} \varphi_r^\dagger \bar{d}_{Ri} q_{Lj} + (y^u_\varphi)_{rij} \varphi_r^\dagger i\sigma_2 \bar{q}^T_{Li} u_{Rj} \right. \\
&\quad \left. + (\lambda_\varphi)_r \left(\varphi_r^\dagger \phi\right)\left(\phi^\dagger \phi\right) + \text{h.c.} \right\} \\
&+ (\kappa_\Xi)_r \phi^\dagger \Xi^a_r \sigma^a \phi + (\lambda_\Xi)_{rs} \left(\Xi^a_r \Xi^a_s\right)\left(\phi^\dagger \phi\right) \\
&+ \frac{1}{2}(\lambda_{\Xi_1})_{rs} \left(\Xi^{a\dagger}_{1r} \Xi^a_{1s}\right)\left(\phi^\dagger \phi\right) + \frac{1}{2}(\lambda'_{\Xi_1})_{rs} f_{abc} \left(\Xi^{a\dagger}_{1r} \Xi^b_{1s}\right)\left(\phi^\dagger \sigma^c \phi\right) \\
&+ \left\{ (y_{\Xi_1})_{rij} \Xi^{a\dagger}_{1r} \bar{l}_{Li} \sigma^a i\sigma_2 l^c_{Lj} + (\kappa_{\Xi_1})_r \Xi^{a\dagger}_{1r} \left(\tilde{\phi}^\dagger \sigma^a \phi\right) + \text{h.c.} \right\} \\
&+ \left\{ (\lambda_{\Theta_1})_r \left(\phi^\dagger \sigma^a \phi\right) C^I_{a\beta} \tilde{\phi}_\beta \epsilon_{IJ} \Theta^J_{1r} + \text{h.c.} \right\} \\
&+ \left\{ (\lambda_{\Theta_3})_r \left(\phi^\dagger \sigma^a \tilde{\phi}\right) C^I_{a\beta} \tilde{\phi}_\beta \epsilon_{IJ} \Theta^J_{3r} + \text{h.c.} \right\} \\
&+ \left\{ (y^{ql}_{\omega_1})_{rij} \omega^\dagger_{1r} \bar{q}^c_{Li} i\sigma_2 l_{Lj} + (y^{qq}_{\omega_1})_{rij} \omega^{A\dagger}_{1r} \epsilon_{ABC} \bar{q}^B_{Li} i\sigma_2 q^{cC}_{Lj} \right. \\
&\quad \left. + (y^{eu}_{\omega_1})_{rij} \omega^\dagger_{1r} \bar{e}^c_{Ri} u_{Rj} + (y^{du}_{\omega_1})_{rij} \omega^{A\dagger}_{1r} \epsilon_{ABC} \bar{d}^B_{Ri} u^{cC}_{Rj} + \text{h.c.} \right\} \\
&+ \left\{ (y_{\omega_2})_{rij} \omega^{A\dagger}_{2r} \epsilon_{ABC} \bar{d}^B_{Ri} d^{cC}_{Rj} + \text{h.c.} \right\} \\
&+ \left\{ (y^{ed}_{\omega_4})_{rij} \omega^{A\dagger}_{4r} \bar{e}^c_{Ri} d_{Rj} + (y^{uu}_{\omega_4})_{rij} \omega^{A\dagger}_{4r} \epsilon_{ABC} \bar{u}^B_{Ri} u^{cC}_{Rj} + \text{h.c.} \right\} \\
&+ \left\{ (y_{\Pi_1})_{rij} \Pi^\dagger_{1r} i\sigma_2 \bar{l}^T_{Li} d_{Rj} + \text{h.c.} \right\} \\
&+ \left\{ (y^{lu}_{\Pi_7})_{rij} \Pi^\dagger_{7r} i\sigma_2 \bar{l}^T_{Li} u_{Rj} + (y^{eq}_{\Pi_7})_{rij} \Pi^\dagger_{7r} \bar{e}_{Ri} q_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ (y^{ql}_\zeta)_{rij} \zeta^{a\dagger}_r \bar{q}^c_{Li} i\sigma_2 \sigma^a l_{Lj} + (y^{qq}_\zeta)_{rij} \zeta^{a\dagger}_r \epsilon_{ABC} \bar{q}^B_{Li} \sigma^a i\sigma_2 q^{cC}_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ (y^{ud}_{\Omega_1})_{rij} \Omega^{AB\dagger}_{1r} \bar{u}^{c(A|}_{Ri} d^{|B)}_{Rj} + (y^{qq}_{\Omega_1})_{rij} \Omega^{AB\dagger}_{1r} \bar{q}^{c(A|}_{Li} i\sigma_2 q^{|B)}_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ (y_{\Omega_2})_{rij} \Omega^{AB\dagger}_{2r} \bar{d}^{c(A|}_{Ri} d^{|B)}_{Rj} + \text{h.c.} \right\} \\
&+ \left\{ (y_{\Omega_4})_{rij} \Omega^{AB\dagger}_{4r} \bar{u}^{c(A|}_{Ri} u^{|B)}_{Rj} + \text{h.c.} \right\} \\
&+ \left\{ (y_\Upsilon)_{rij} \Upsilon^{AB\dagger}_r \bar{q}^{c(A|}_{Li} i\sigma_2 \sigma^a q^{|B)}_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ (y^{qu}_\Phi)_{rij} \Phi^{A\dagger}_r i\sigma_2 \bar{q}^T_{Li} T_A u_{Rj} + (y^{dq}_\Phi)_{rij} \Phi^{A\dagger}_r \bar{d}_{Ri} T_A q_{Lj} + \text{h.c.} \right\} \\
&+ (\lambda_{\mathcal{S}\Xi})_{rs} \mathcal{S}_r \Xi^a_s \left(\phi^\dagger \sigma^a \phi\right) + (\kappa_{\mathcal{S}\Xi})_{rst} \mathcal{S}_r \Xi^a_s \Xi^a_t \\
&+ (\kappa_{\mathcal{S}\Xi_1})_{rst} \mathcal{S}_r \Xi^{a\dagger}_{1s} \Xi^a_{1t} + \left\{ (\lambda_{\mathcal{S}\Xi_1})_{rs} \mathcal{S}_r \Xi^{a\dagger}_{1s} \left(\tilde{\phi}^\dagger \sigma^a \phi\right) + \text{h.c.} \right\} \\
&+ \left\{ (\kappa_{\mathcal{S}\varphi})_{rs} \mathcal{S}_r \varphi^\dagger_s \phi + (\kappa_{\Xi\varphi})_{rs} \Xi^a_r (\varphi^\dagger_s \sigma^a \phi) + (\kappa_{\Xi_1\varphi})_{rs} \Xi^{a\dagger}_{1r} \left(\tilde{\varphi}^\dagger_s \sigma^a \phi\right) + \text{h.c.} \right\} \\
&+ (\kappa_{\Xi\Xi_1})_{rst} f_{abc} \Xi^a_r \Xi^{b\dagger}_{1s} \Xi^b_{1t} + \left\{ (\lambda_{\Xi_1\Xi})_{rs} f_{abc} \Xi^{a\dagger}_{1r} \Xi^b_s \left(\tilde{\phi}^\dagger \sigma^c \phi\right) + \text{h.c.} \right\} \\
&+ \left\{ (\kappa_{\Xi\Theta_1})_{rs} \Xi^a_r C^I_{a\beta} \tilde{\phi}_\beta \epsilon_{IJ} \Theta^J_{1s} + (\kappa_{\Xi_1\Theta_1})_{rs} \Xi^{a\dagger}_{1r} C^I_{a\beta} \phi_\beta \epsilon_{IJ} \Theta^J_{1s} \right. \\
&\quad \left. + (\kappa_{\Xi_1\Theta_3})_{rs} \Xi^{a\dagger}_{1r} C^I_{a\beta} \tilde{\phi}_\beta \epsilon_{IJ} \Theta^J_{3s} + \text{h.c.} \right\},
\end{aligned}
$$

$$
\begin{aligned}
&(\lambda_N)_{ri} \bar{N}_{Rr} \tilde{\phi}^\dagger l_{Li} + (\lambda_E)_{ri} \bar{E}_{Rr} \phi^\dagger l_{Li} \\
&+ (\lambda_{\Delta_1})_{ri} \bar{\Delta}_{1Lr} \phi e_{Ri} + (\lambda_{\Delta_3})_{ri} \bar{\Delta}_{3Lr} \tilde{\phi} e_{Ri} \\
&+ \frac{1}{2}(\lambda_\Sigma)_{ri} \bar{\Sigma}^a_{Rr} \tilde{\phi}^\dagger \sigma^a l_{Li} + \frac{1}{2}(\lambda_{\Sigma_1})_{ri} \bar{\Sigma}^a_{1Rr} \phi^\dagger \sigma^a l_{Li} \\
&+ (\lambda_{N\Delta_1})_{rs} \bar{N}^c_{Rr} \phi^\dagger \Delta_{1Rs} + (\lambda_{E\Delta_1})_{rs} \bar{E}_{Lr} \phi^\dagger \Delta_{1Rs} \\
&+ (\lambda_{E\Delta_3})_{rs} \bar{E}_{Lr} \tilde{\phi}^\dagger \Delta_{3Rs} + \frac{1}{2}(\lambda_{\Sigma\Delta_1})_{rs} \bar{\Sigma}^{ca}_{Rr} \tilde{\phi}^\dagger \sigma^a \Delta_{1Rs} \\
&+ \frac{1}{2}(\lambda_{\Sigma_1\Delta_1})_{rs} \bar{\Sigma}^a_{1Lr} \phi^\dagger \sigma^a \Delta_{1Rs} + \frac{1}{2}(\lambda_{\Sigma_1\Delta_3})_{rs} \bar{\Sigma}^a_{1Lr} \tilde{\phi}^\dagger \sigma^a \Delta_{3Rs} + \text{h.c.}
\end{aligned}
$$

$$
\begin{aligned}
&(\lambda_U)_{ri} \bar{U}_{Rr} \tilde{\phi}^\dagger q_{Li} + (\lambda_D)_{ri} \bar{D}_{Rr} \phi^\dagger q_{Li} \\
&+ (\lambda^u_{Q_1})_{ri} \bar{Q}_{1Lr} \tilde{\phi} u_{Ri} + (\lambda^d_{Q_1})_{ri} \bar{Q}_{1Lr} \phi d_{Ri} \\
&+ (\lambda_{Q_5})_{ri} \bar{Q}_{5Lr} \tilde{\phi} d_{Ri} + (\lambda_{Q_7})_{ri} \bar{Q}_{7Lr} \phi u_{Rj} \\
&+ \frac{1}{2}(\lambda_{T_1})_{ri} \bar{T}^a_{1Rr} \phi^\dagger \sigma^a q_{Li} + \frac{1}{2}(\lambda_{T_2})_{ri} \bar{T}^a_{2Rr} \tilde{\phi}^\dagger \sigma^a q_{Li} \\
&+ (\lambda_{UQ_1})_{rs} \bar{U}_{Lr} \tilde{\phi}^\dagger Q_{1Rs} + (\lambda_{UQ_7})_{rs} \bar{U}_{Lr} \phi^\dagger Q_{7Rs} \\
&+ (\lambda_{DQ_1})_{rs} \bar{D}_{Lr} \phi^\dagger Q_{1Rs} + (\lambda_{DQ_5})_{rs} \bar{D}_{Lr} \tilde{\phi}^\dagger Q_{5Rs} \\
&+ \frac{1}{2}(\lambda_{T_1Q_1})_{rs} \bar{T}^a_{1Lr} \phi^\dagger \sigma^a Q_{1Rs} + \frac{1}{2}(\lambda_{T_1Q_5})_{rs} \bar{T}^a_{1Lr} \tilde{\phi}^\dagger \sigma^a Q_{5Rs} \\
&+ \frac{1}{2}(\lambda_{T_2Q_1})_{rs} \bar{T}^a_{2Lr} \tilde{\phi}^\dagger \sigma^a Q_{1Rs} + \frac{1}{2}(\lambda_{T_2Q_7})_{rs} \bar{T}^a_{2Lr} \phi^\dagger \sigma^a Q_{7Rs} + \text{h.c.}
\end{aligned}
$$

$$
\begin{aligned}
&(g^l_{\mathcal{B}})_{rij} \mathcal{B}^\mu_r \bar{l}_{Li} \gamma_\mu l_{Lj} + (g^q_{\mathcal{B}})_{rij} \mathcal{B}^\mu_r \bar{q}_{Li} \gamma_\mu q_{Lj} + (g^e_{\mathcal{B}})_{rij} \mathcal{B}^\mu_r \bar{e}_{Li} \gamma_\mu e_{Lj} \\
&+ (g^d_{\mathcal{B}})_{rij} \mathcal{B}^\mu_r \bar{d}_{Li} \gamma_\mu d_{Lj} + (g^u_{\mathcal{B}})_{rij} \mathcal{B}^\mu_r \bar{u}_{Li} \gamma_\mu u_{Lj} + \left\{ (g^\phi_{\mathcal{B}})_r \mathcal{B}^\mu_r \phi^\dagger i D_\mu \phi + \text{h} \right. \\
&+ \left\{ (g^{du}_{\mathcal{B}_1})_{rij} \mathcal{B}^{\mu\dagger}_{1r} \bar{d}_{Ri} \gamma_\mu u_{Rj} + (g^\phi_{\mathcal{B}_1})_r \mathcal{B}^{\mu\dagger}_{1r} i D_\mu \phi^T i\sigma_2 \phi + \text{h.c.} \right\} \\
&+ \frac{1}{2}(g^l_{\mathcal{W}})_{rij} \mathcal{W}^{\mu a}_r \bar{l}_{Li} \sigma^a \gamma_\mu l_{Lj} + \frac{1}{2}(g^q_{\mathcal{W}})_{rij} \mathcal{W}^{\mu a}_r \bar{q}_{Li} \sigma^a \gamma_\mu q_{Lj} \\
&+ \left\{ \frac{1}{2}(g^\phi_{\mathcal{W}})_r \mathcal{W}^{\mu a}_r \phi^\dagger \sigma^a i D_\mu \phi + \text{h.c.} \right\} \\
&+ \left\{ \frac{1}{2}(g_{\mathcal{W}_1})_r \mathcal{W}^{\mu a\dagger}_{1r} i D_\mu \phi^T i\sigma_2 \sigma^a \phi + \text{h.c.} \right\} \\
&+ (g^q_{\mathcal{G}})_{rij} \mathcal{G}^{\mu A}_r \bar{q}_{Li} \gamma_\mu T_A q_{Lj} + (g^u_{\mathcal{G}})_{rij} \mathcal{G}^{\mu A}_r \bar{u}_{Li} \gamma_\mu T_A u_{Rj} + (g^d_{\mathcal{G}})_{rij} \mathcal{G}^{\mu A}_r \bar{d}_{R} \\
&+ \left\{ (g_{\mathcal{G}_1})_{rij} \mathcal{G}^{A\mu\dagger}_{1r} \bar{d}_{Ri} T_A \gamma_\mu u_{Rj} + \text{h.c.} \right\} \\
&+ \frac{1}{2}(g_{\mathcal{H}})_{rij} \mathcal{H}^{\mu a A}_r \bar{q}_{Li} \gamma_\mu \sigma^a T_A q_{Lj} \\
&+ \left\{ (\gamma_{\mathcal{L}_1})_r \mathcal{L}^\dagger_{1r\mu} D^\mu \phi + \text{h.c.} \right\} \\
&+ i(g^B_{\mathcal{L}_1})_{rs} \mathcal{L}^\dagger_{1r\mu} \mathcal{L}_{1s\nu} B^{\mu\nu} + i(g^W_{\mathcal{L}_1})_{rs} \mathcal{L}^\dagger_{1i\mu} \sigma^a \mathcal{L}_{1j\nu} W^{a\,\mu\nu} \\
&+ i(g^{\tilde{B}}_{\mathcal{L}_1})_{rs} \mathcal{L}^\dagger_{1r\mu} \mathcal{L}_{1s\nu} \tilde{B}^{\mu\nu} + i(g^{\tilde{W}}_{\mathcal{L}_1})_{rs} \mathcal{L}^\dagger_{1r\mu} \sigma^a \mathcal{L}_{1s\nu} \tilde{W}^{a\,\mu\nu} \\
&+ (h^{(1)}_{\mathcal{L}_1})_{rs} \left(\mathcal{L}^\dagger_{1r\mu} \mathcal{L}^\mu_{1s}\right)\left(\phi^\dagger \phi\right) + (h^{(2)}_{\mathcal{L}_1})_{rs} \left(\mathcal{L}^\dagger_{1r\mu} \phi\right)\left(\phi^\dagger \mathcal{L}^\mu_{1s}\right) \\
&+ \left\{ (h^{(3)}_{\mathcal{L}_1})_{rs} \left(\mathcal{L}^{1\dagger}_{1r\mu} \phi\right)\left(\mathcal{L}^{\dagger\mu}_{1s} \phi\right) + \text{h.c.} \right\} \\
&+ \left\{ (g_{\mathcal{L}_3})_{rij} \mathcal{L}^{\mu\dagger}_{3r} \bar{e}^c_{Ri} \gamma_\mu l_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ (g^{ed}_{\mathcal{U}_2})_{rij} \mathcal{U}^{\mu\dagger}_{2r} \bar{e}_{Ri} \gamma_\mu d_{Rj} + (g^{lq}_{\mathcal{U}_2})_{rij} \mathcal{U}^{\mu\dagger}_{2r} \bar{l}_{Li} \gamma_\mu q_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ (g_{\mathcal{U}_5})_{rij} \mathcal{U}^{\mu\dagger}_{5r} \bar{e}_{Ri} \gamma_\mu u_{Rj} + \text{h.c.} \right\} \\
&+ \left\{ (g^{ul}_{\mathcal{Q}_1})_{rij} \mathcal{Q}^{\mu\dagger}_{1r} \bar{u}^c_{Ri} \gamma_\mu l_{Lj} + (g^{dq}_{\mathcal{Q}_1})_{rij} \mathcal{Q}^{A\mu\dagger}_{1r} \epsilon_{ABC} \bar{d}^B_{Ri} \gamma_\mu i\sigma_2 q^{cC}_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ (g^{dl}_{\mathcal{Q}_5})_{rij} \mathcal{Q}^{\mu\dagger}_{5r} \bar{d}^c_{Ri} \gamma_\mu l_{Lj} + (g^{eq}_{\mathcal{Q}_5})_{rij} \mathcal{Q}^{\mu\dagger}_{5r} \bar{e}^c_{Ri} \gamma_\mu q_{Lj} \right. \\
&\quad \left. + (g^{uq}_{\mathcal{Q}_5})_{rij} \mathcal{Q}^{A\mu\dagger}_{5r} \epsilon_{ABC} \bar{u}^B_{Ri} \gamma_\mu q^{cC}_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ \frac{1}{2}(g_{\mathcal{X}})_{rij} \mathcal{X}^{a\mu\dagger}_r \bar{l}_{Li} \gamma_\mu \sigma^a q_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ \frac{1}{2}(g_{\mathcal{Y}_1})_{rij} \mathcal{Y}^{AB\mu\dagger}_{1r} \bar{d}^{(A|}_{Ri} \gamma_\mu i\sigma_2 q^{c|B)}_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ \frac{1}{2}(g_{\mathcal{Y}_5})_{rij} \mathcal{Y}^{AB\mu\dagger}_{5r} \bar{u}^{(A|}_{Ri} \gamma_\mu i\sigma_2 q^{c|B)}_{Lj} + \text{h.c.} \right\} \\
&+ \left\{ (\zeta_{\mathcal{L}_1\mathcal{B}})_{rs} \left(\mathcal{L}^\dagger_{1r\mu} \phi\right) \mathcal{B}^\mu_s + (\zeta_{\mathcal{L}_1\mathcal{B}_1})_{rs} \tilde{\mathcal{L}}^\dagger_{1r\mu} \phi \mathcal{B}^{\mu\dagger}_{1s} \right. \\
&\quad \left. + (\zeta_{\mathcal{L}_1\mathcal{W}})_{rs} \left(\mathcal{L}^\dagger_{1r\mu} \sigma^a \phi\right) \mathcal{W}^{a\mu}_s + (\zeta_{\mathcal{L}_1\mathcal{W}_1})_{rs} \tilde{\mathcal{L}}^\dagger_{1r\mu} \sigma^a \phi \mathcal{W}^{a\mu\dagger}_{1s} + \text{h.c.} \right\},
\end{aligned}
$$

Renormalizable BSM interactions

$$
\begin{aligned}
&(\lambda_{\mathcal{S}E})_{rsi}\mathcal{S}_r\bar{E}_{Ls}e_{Ri} + (\lambda_{\mathcal{S}\Delta_1})_{rsi}\mathcal{S}_r\bar{\Delta}_{1Rs}l_{Li}\\
&+ (\lambda_{\mathcal{S}U})_{rsi}\mathcal{S}_r\bar{U}_{Ls}u_{Ri} + (\lambda_{\mathcal{S}D})_{rsi}\mathcal{S}_r\bar{D}_{Ls}d_{Ri} + (\lambda_{\mathcal{S}Q_1})_{rsi}\mathcal{S}_r\bar{Q}_{1Rs}q_{Li}\\
&+ (\lambda_{\Xi\Delta_1})_{rsi}\Xi_r^a\bar{\Delta}_{1Rs}\sigma^a l_{Li} + (\lambda_{\Xi\Sigma_1})_{rsi}\Xi_r^a\bar{\Sigma}_{1Ls}^a e_{Ri}\\
&+ (\lambda_{\Xi Q_1})_{rsi}\Xi_r^a\bar{Q}_{1Rs}\sigma^a q_{Li} + (\lambda_{\Xi T_1})_{rsi}\Xi_r^a\bar{T}_{1Ls}^a d_{Ri} + (\lambda_{\Xi T_2})_{rsi}\Xi_r^a\bar{T}_{2Ls}^a u_{Ri}\\
&+ (\lambda_{\Xi_1\Delta_3})_{rsi}\Xi_{1r}^{a\dagger}\bar{\Delta}_{3Rs}\sigma^a l_{Li} + (\lambda_{\Xi_1\Sigma})_{rsi}\Xi_{1r}^{a\dagger}\bar{\Sigma}_{Rs}^{c\ a}e_{Ri}^c\\
&+ (\lambda_{\Xi_1 Q_5})_{rsi}\Xi_{1r}^{a\dagger}\bar{Q}_{5Rs}\sigma^a q_{Li} + (\lambda_{\Xi_1 Q_7})_{rsi}\Xi_{1r}^a\bar{Q}_{7Rs}\sigma^a q_{Li}\\
&+ (\lambda_{\Xi_1 T_1})_{rsi}\Xi_{1r}^{a\dagger}\bar{T}_{1Ls}^a u_{Ri} + (\lambda_{\Xi_1 T_2})_{rsi}\Xi_{1r}^a\bar{T}_{2Ls}^a d_{Ri} + \text{h.c.}\,,
\end{aligned}
$$

$$
\begin{aligned}
&(\delta_{\mathcal{B}\mathcal{S}})_{rs}\mathcal{B}_{r\mu}D^\mu\mathcal{S}_s + (\delta_{\mathcal{W}\Xi})_{rs}\mathcal{W}_{r,\mu}D^\mu\Xi_s\\
&+ \left\{(\delta_{\mathcal{L}^1\varphi})_{rs}\mathcal{L}_{1r\mu}^{1\dagger}D^\mu\varphi_s + (\delta_{\mathcal{W}^1\Xi_1})_{rs}\mathcal{W}_{1r\mu}^{1\dagger}D^\mu\Xi_{1s} + \text{h.c.}\right\}\\
&+ (\varepsilon_{\mathcal{S}\mathcal{L}_1})_{rst}\mathcal{S}_r\mathcal{L}_{1s\mu}^\dagger\mathcal{L}_{1t}^\mu + (\varepsilon_{\Xi\mathcal{L}_1})_{rst}\Xi_r^a\mathcal{L}_{1s\mu}^\dagger\sigma^a\mathcal{L}_{1t}^\mu\\
&+ \left\{(\varepsilon_{\Xi_1\mathcal{L}_1})_{rst}\Xi_{1i}^a\mathcal{L}_{1s\mu}^\dagger\sigma^a\tilde{\mathcal{L}}_{1t}^\mu + \text{h.c.}\right\}\\
&+ \Big\{(g_{\mathcal{S}\mathcal{L}_1})_{rs}\phi^\dagger\left(D_\mu\mathcal{S}_r\right)\mathcal{L}_{1s}^\mu + (g'_{\mathcal{S}\mathcal{L}_1})_{rs}\left(D_\mu\phi\right)^\dagger\mathcal{S}_r\mathcal{L}_{1s}^\mu\\
&\quad + (g_{\Xi\mathcal{L}_1})_{rs}\phi^\dagger\sigma^a\left(D_\mu\Xi_r^a\right)\mathcal{L}_{1s}^\mu + (g'_{\Xi\mathcal{L}_1})_{rs}\left(D_\mu\phi\right)^\dagger\sigma^a\Xi_r^a\mathcal{L}_{1s}^\mu\\
&\quad + (g_{\Xi_1\mathcal{L}_1})_{rs}\tilde{\phi}^\dagger\sigma^a\left(D_\mu\Xi_{1r}^a\right)^\dagger\mathcal{L}_{1s}^\mu + (g'_{\Xi_1\mathcal{L}_1})_{rs}\left(D_\mu\tilde{\phi}\right)^\dagger\sigma^a\Xi_{1r}^{a\dagger}\mathcal{L}_{1s}^\mu + \text{h.c.}\Big\}
\end{aligned}
$$

$$
\begin{aligned}
&(z_{N\mathcal{L}_1})_{rsi}\bar{N}_{Rr}^c\gamma^\mu\tilde{\mathcal{L}}_{1s\mu}^\dagger l_{Li} + (z_{E\mathcal{L}_1})_{rsi}\bar{E}_{Lr}\gamma^\mu\mathcal{L}_{1s\mu}^\dagger l_{Li}\\
&+ (z_{\Delta_1\mathcal{L}_1})_{rsi}\bar{\Delta}_{1Rr}\gamma^\mu\mathcal{L}_{1s\mu}e_{Ri} + (z_{\Delta_3\mathcal{L}_1})_{rsi}\bar{\Delta}_{3Rr}\gamma^\mu\tilde{\mathcal{L}}_{1s\mu}e_{Ri}\\
&+ (z_{\Sigma\mathcal{L}_1})_{rsi}\bar{\Sigma}_{Rr}^{c\ a}\gamma^\mu\tilde{\mathcal{L}}_{1s\mu}^\dagger\sigma^a l_{Li} + (z_{\Sigma_1\mathcal{L}_1})_{rsi}\bar{\Sigma}_{1Lr}^a\gamma^\mu\mathcal{L}_{1s\mu}^\dagger\sigma^a l_{Li}\\
&+ (z_{U\mathcal{L}_1})_{rsi}\bar{U}_{Lr}\gamma^\mu\tilde{\mathcal{L}}_{1s\mu}^\dagger q_{Li} + (z_{D\mathcal{L}_1})_{rsi}\bar{D}_{Lr}\gamma^\mu\mathcal{L}_{1s\mu}^\dagger q_{Li}\\
&+ (z_{Q_1\mathcal{L}_1}^u)_{rsi}\bar{Q}_{1Rr}\gamma^\mu\tilde{\mathcal{L}}_{1s\mu}u_{Ri} + (z_{Q_1\mathcal{L}_1}^d)_{rsi}\bar{Q}_{1Rr}\gamma^\mu\mathcal{L}_{1s\mu}d_{Ri}\\
&+ (z_{Q_5\mathcal{L}_1})_{rsi}\bar{Q}_{5Rr}\gamma^\mu\tilde{\mathcal{L}}_{1s\mu}d_{Ri} + (z_{Q_7\mathcal{L}_1})_{rsi}\bar{Q}_{7Rr}\gamma^\mu\mathcal{L}_{1s\mu}u_{Ri}\\
&+ (z_{T_1\mathcal{L}_1})_{rsi}\bar{T}_{1Lr}^a\gamma^\mu\mathcal{L}_{1s\mu}^\dagger\sigma^a q_{Li} + (z_{T_2\mathcal{L}_1})_{rsi}\bar{T}_{2Lr}^a\gamma^\mu\tilde{\mathcal{L}}_{1s\mu}^\dagger\sigma^a q_{Li} + \text{h.c.}\,.
\end{aligned}
$$

+ ...

BSMEFT

Dictionary ↕

SMEFT

de Blas, Criado, MPV, Santiago '17

Guedes, Olgoso '24 SOLD

Bottom-up (outdated) example

LHCb anomalies → $\mathcal{O}^{\ell}_{ij} = (\bar{s}\gamma^{\mu}P_i b)(\bar{\ell}\gamma_{\mu}P_j\ell)$

$$\left\{ \overset{(3,3)_{-\frac{1}{3}}}{\zeta}, \; \overset{(1,1)_0}{\mathcal{B}}, \; \overset{(1,3)_0}{\mathcal{W}}, \; \overset{(3,1)_{\frac{2}{3}}}{\mathcal{U}_2}, \; \overset{(3,3)_{\frac{2}{3}}}{\mathcal{X}} \right\}$$

0 1 1 1 1

We can also use BSMEFT without any reference to SMEFT

New spin 1 particles represented by Proca fields

↓

$\mathscr{L}_{\rm BSMEFT}$ is an effective theory also at $D \leq 4$ level

It breaks down at $E \sim \dfrac{M_V}{\Delta g}$

This talk: UV completion of $\mathscr{L}_{\rm BSMEFT}$

Outline

- High-energy limit and the emergence of gauge invariance

  Cornwall, Levin, Tiktopoulos ‘74

  Benincasa, Cachazo ´07, Arkani-Hamed, Huang, Huang, ´17

- Building the SM from the bottom up

- (Next-to) Minimal UV completions

  - Examples

  - The landscape of UV completions

Perturbativity at high energies (HE): $\mathscr{M}_n^{\text{tree}} \lesssim E^{4-n}$

Scattering amplitudes with massive particles:

good HE behaviour $\Longrightarrow$ well-defined massless limit

Massive spin 1 $\left\{ \begin{array}{lcl} + & \xrightarrow{\text{HE}} & h = +1 \\ - & \longrightarrow & h = -1 \\ L & \longrightarrow & h = 0 \end{array} \right.$

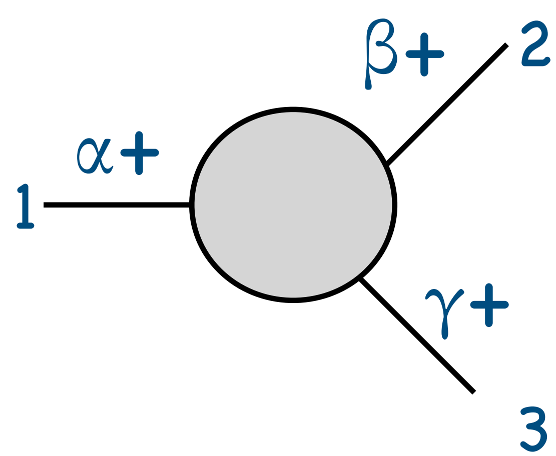
$h = +1$, $h = -1$ } CPT "massless spin 1"

$h = 0$: scalar :)

Match amplitudes -> couplings of massive spin 1
directly related to couplings of massless spin 1 and Goldstones

Scattering amplitudes of massless spin 1 particles

- Hilbert space inner product + factorization $\Longrightarrow$ Positive-definite bilinear form (metric) $g_{\alpha\beta}$

- Poincaré 

$= f_{\alpha\beta\gamma} \frac{[12]^3}{[13][23]}$ • CPT

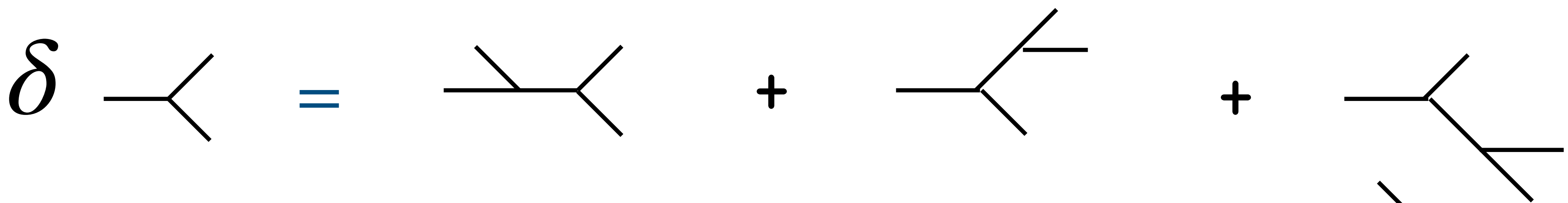
$\Longrightarrow$ Coupling $f_{\alpha\beta\gamma}$ totally antisymmetric

- Define generators $f^{\alpha}_{\beta\gamma} := g^{\alpha\eta} f_{\eta\beta\gamma}$ that transform amplitudes as tensors: $\delta_\gamma A_{\alpha\beta\ldots} = f^{\eta}_{\gamma\alpha} A_{\eta\beta\ldots} + f^{\eta}_{\gamma\beta} A_{\alpha\eta\ldots} + \ldots$

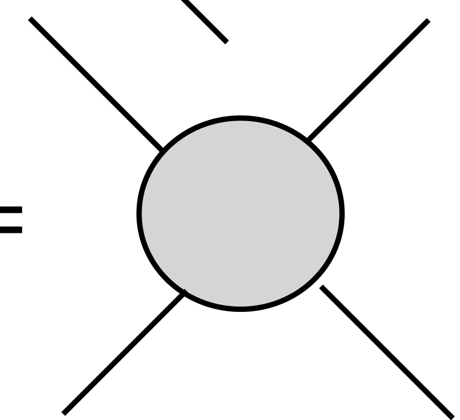
- $f_{\alpha\beta\gamma}$ totally antisymmetric $\Longrightarrow \delta_\gamma g_{\alpha\beta} = 0$ invariant metric

Scattering amplitudes of massless spin 1 particles

- $\delta_\eta f_{\alpha\beta\gamma} = f^\kappa_{\eta\alpha} f_{\kappa\beta\gamma} + f^\kappa_{\eta\beta} f_{\alpha\kappa\gamma} + f^\kappa_{\eta\gamma} f_{\alpha\beta\kappa}$



Factorization channels of single $A_{\alpha\beta\gamma\eta} =$



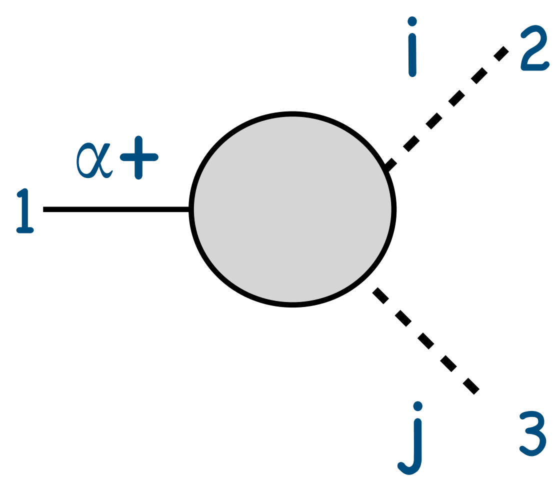
Locality + Unitarity $\Longrightarrow \delta_\eta f_{\alpha\beta\gamma} = 0$ Jacobi identity

- So, $f^\alpha_{\beta\gamma}$ are the structure constants of a Lie algebra

- Invariant positive-definite metric $\Longrightarrow$ semisimple $\oplus$ abelian

Scattering amplitudes of massless spin 1 particles with spin 0 and spin 1/2 particles

- For scalars (similar for fermions)



$$= T^{\alpha}_{ij} \frac{[12][13]}{[23]}$$

antisymmetric under $i \leftrightarrow j$

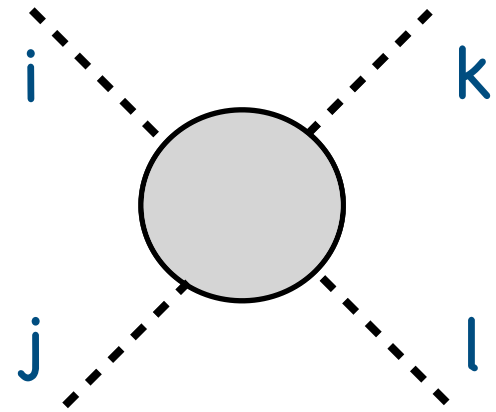
- Use T^{α}_{ij} as generators of transformations of amplitudes with scalars: $\delta_\gamma A_{ij\ldots} = T^{\gamma}_{ik} A_{kj\ldots} + T^{\gamma}_{jk} A_{ik\ldots} + \ldots$

- Locality + unitarity (factorization) $\Longrightarrow \delta_\gamma T^{\alpha}_{ij} = 0$

Scattering amplitudes of spin 0 and spin 1/2 particles

Also invariant in theories with spin 1 particles:

$A_{ijkl} =$

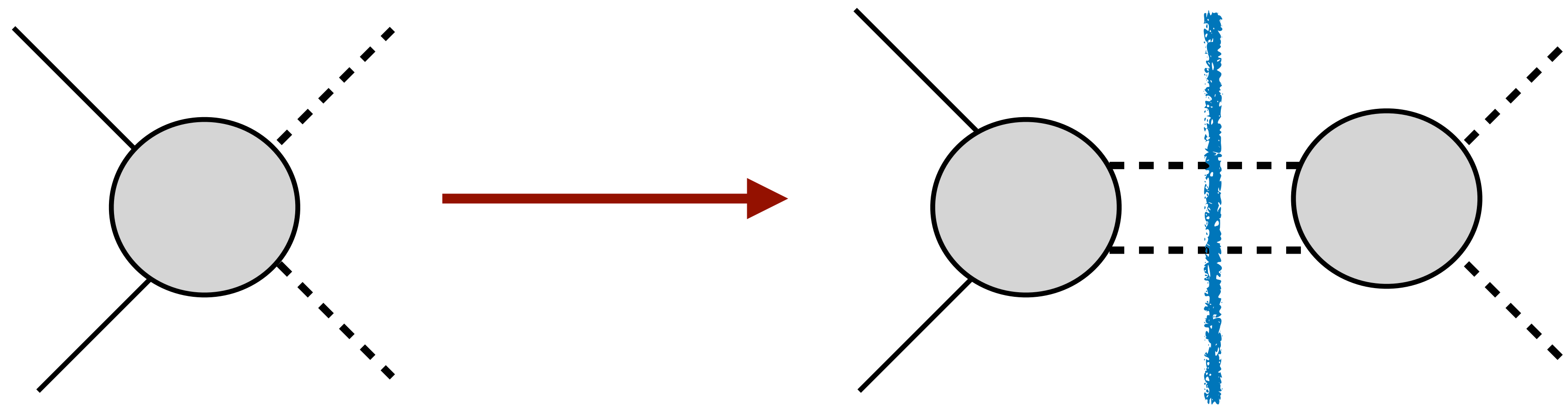


$= \lambda_{ijkl}$ + non local

- Locality + unitarity (factorization) $\Longrightarrow \delta_\gamma \lambda_{ijkl} = 0$

Non local and beyond tree level

Generalized unitarity method

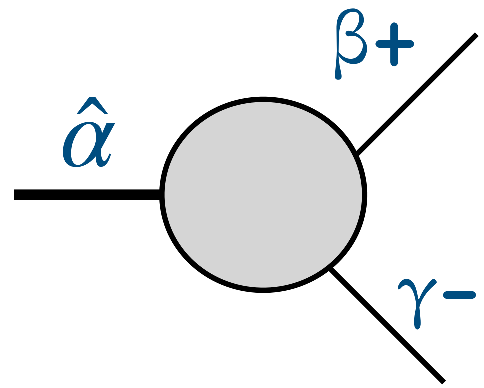


Ignoring kinematics, this is a tensor built out of invariant tensors. Hence, all amplitudes are invariant.

The transformations δ_η generate a (point-like) symmetry group of the S matrix

Notation:

hatted indices -> massive spin 1 (or their HE incarnation)
unhatted (normal) indices -> massless spin 1
capital indices -> arbitrary

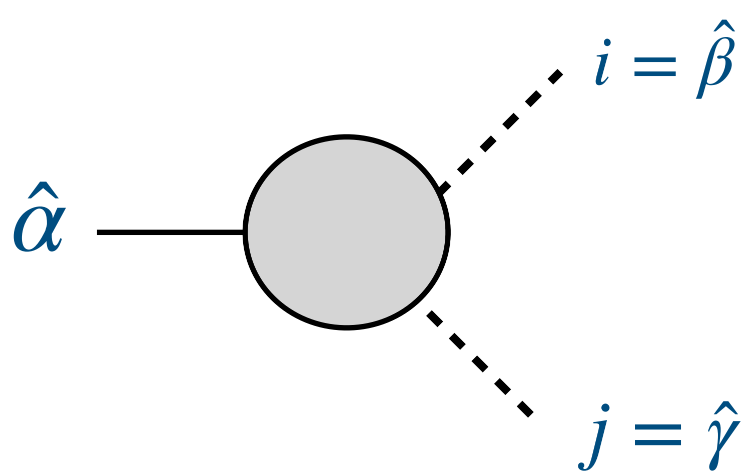
- 

= 0 (Yang's theorem)

Hence, $f_{\hat{\alpha}\beta\gamma} = 0$

The generators associated to massless spin 1 particles span a subalgebra

- $\delta_\eta M_{\mathscr{A}\mathscr{B}} = 0$

- $\delta_{\hat{\eta}}$ 

$= 0$ may require $k \notin \{\hat{\alpha}, \hat{\beta}, \dots\}$ → physical Higgses

From particles to fields

Introduce interpolating fields; in particular vector fields A^a

$\langle\alpha|A^a|0\rangle = e^a_\alpha$ (I'm keeping Lorentz indices, space-time coordinates, helicities and polarization vectors implicit)

$g^{ab} = \langle 0|A^a A^b|0\rangle = e^{\alpha a} e^{\beta b}\langle\alpha|\beta\rangle = g_{ab} e^{\alpha a} e^{\beta b}$

LSZ: $\langle 0|\alpha\beta\gamma\ldots\rangle = e_{\alpha a} e_{\beta b} e_{\gamma c}\ldots\langle 0|A^a A^b A^c\ldots|0\rangle|_{\text{on-shell}}$

$g^{ab}, f_{abc} := e_{\alpha a} e_{\beta b} e_{\gamma c} f^{\alpha\beta\gamma}$ and other couplings inherit invariance properties of amplitudes

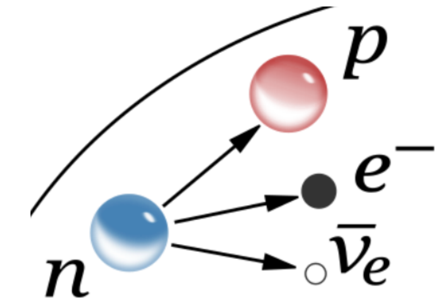
Choosing field basis with $e_{\hat{\alpha} a} = e^{\hat{a}}_{\alpha} = 0$ we also have subalgebra property for massless fields

Global symmetry must be promoted to local symmetry

Building the EW SM from the bottom up

1933

- Fermi theory of beta decay
- Electromagnetism



- At HE, $\mathscr{M}_F \sim G_F E^2$

- Intermediate vector bosons $W^{\pm}$ with mass

$$M_W^2 = \frac{g^2}{4\sqrt{2}G_F} \lesssim (120\ \mathrm{GeV})^2$$

Great, now we have a perturbative theory at energies foreseen before the end of this century

Well, not quite: at HE we have e.g. $\mathscr{M}(\nu\bar{\nu}W^+W^-) \sim G_F E^2$

Keep going and impose good massless limit

$a \in \{0\}$ $\longrightarrow$ γ

$\hat{a} \in \{+,-\}$ (or $\hat{a} \in \{1,2\}$) $\longrightarrow$ $W^{\pm}$

$i \in \{\nu, e\}$ (and $i \in \{p, n\}$)

- $f_{0+-} = -ie$, antisymmetric (in {1,2} basis)

$\delta_D f_{ABC} \overset{?}{=} 0$ Yes (even if no freedom)

Spin 1 sector OK

- $T^0 = e\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$, $T^+ = \frac{g}{\sqrt{2}}\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, $T^- = \frac{g}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$

$\delta_D T^A_{ij} \overset{?}{=} 0$ No! This is the reason for the bad HE behaviour

$[T^+, T^-] = \frac{g^2}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \neq eT^0$

Keep going and impose good massless limit

$a \in \{0\}$ → γ

$\hat{a} \in \{+,-\}$ (or $\hat{a} \in \{1,2\}$) → $W^{\pm}$

$i \in \{\nu, e\}$ (and $i \in \{p, n\}$)

- $f_{0+-} = -ie$, antisymmetric (in {1,2} basis)

$\delta_D f_{ABC} \overset{?}{=} 0$ Yes (even if no freedom)

Spin 1 sector OK

- $T^0 = e\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}, \quad T^+ = \frac{g}{\sqrt{2}}\begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix}, \quad T^- = \frac{g}{\sqrt{2}}\begin{pmatrix}0 & 0\\ 1 & 0\end{pmatrix}$

$\delta_{\hat{a}} T^A_{ij} \overset{?}{=} 0$ No! This is the reason for the bad HE behaviour

$$[T^+, T^-] = \frac{g^2}{2}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix} \neq eT^0 + if_{+-\hat{a}'}T^{\hat{a}'} \qquad (\delta_0 f_{+-\hat{a}} = 0)$$

Minimal extension: one extra neutral vector boson Z

(we need $M_Z \lesssim \frac{M_W}{g}$)

$a \in \{0\}$ → γ

$\hat{a} \in \{+,-,\hat{0}\}$ (or $\hat{a} \in \{1,2,\hat{0}\}$) → $W^{\pm}, Z$

$i \in \{\nu, e\}$ (and $i \in \{p, n\}$)

- $\delta_{\hat{a}} f_{ABC} \stackrel{?}{=} 0$ yes for any $i f_{+-\hat{0}} =: f$
- $\delta_{\hat{a}} T^A_{ij} \stackrel{?}{=} 0$ yes iff $T^{\hat{0}} = \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}$ with the relations

$$g^2 = 2fa; \quad g^2 = 2(e^2 - fb); \quad a - b = f$$

defining $\cos\theta := \frac{f}{g}$ we get the SM:

$$g^2 = e^2 + f^2, \qquad T^{\hat{0}} = \frac{g}{\cos\theta}\left(\frac{\sigma_3}{2} - \sin^2\theta\, Q\right)$$

So, in 1933 we could have already guessed the existence of the W boson, the existence of the Z boson and the form of their couplings to fermions. We could also have put bounds on the boson masses by assuming perturbative couplings.

We can also infer from the UV invariance the existence of at least one physical Higgs, with couplings proportional to masses

Now let's follow the same procedure to find UV completions of effective BSM theories. We work in the EW symmetric phase, so the 12 SM gauge fields play the role of the photon and the hypothetical extra vector bosons play the role of the W

The general method

- Work in basis with antisymmetric structure constants (in this basis we no longer distinguish upper and lower indices)
- In the vector sector we know f_{abc} and $f_{ab\hat{c}} = 0$
- By the assumption of a certain collection of vector multiplets with certain SM transformations we (almost) know $f_{a\hat{b}\hat{c}}$
- The unkowns are then $f_{\hat{a}\hat{b}\hat{c}}$
- The invariance of $f_{\hat{a}\hat{b}\hat{c}}$ gives rise to non-trivial Jacobi equations

$$f_{\hat{a}\hat{b}\hat{e}}f_{\hat{c}d\hat{e}} + f_{\hat{a}\hat{c}\hat{e}}f_{d\hat{b}\hat{e}} + f_{\hat{a}d\hat{e}}f_{\hat{b}\hat{c}\hat{e}} = 0 \quad \rightarrow \quad \text{LINEAL}$$

$$f_{\hat{a}\hat{b}e}f_{\hat{c}\hat{d}e} + f_{\hat{a}\hat{b}\hat{e}}f_{\hat{c}\hat{d}\hat{e}} + (\text{perms.}) = 0 \quad \rightarrow \quad \text{QUADRATIC}$$

In the cases in which the closure condition

$$f_{\hat{a}\hat{b}e}f_{\hat{c}\hat{d}e} + \text{perms}\,. = 0$$

is satisfied, there is a trivial solution $f_{\hat{a}\hat{b}\hat{c}} = 0$, which corresponds to a symmetric coset space.
This does not preclude the existence of non-trivial solutions.
Furthermore, the closure may not be satisfied.

- Solve the equations
- Proceed analogously with fermion and scalar couplings

Examples

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

$$\mathscr{L}_{\text{int}} = \frac{\kappa}{2}\mathscr{W}_1 \phi^T \epsilon\tau D\phi + \text{h.c.}$$

(contributes to the T parameter)

Similar discussion

But $T^{\hat{a}}_{ij}$ antisymmetric under $i \leftrightarrow j$ implies $\kappa = 0$ and thus $\mathscr{W}_1$ irrelevant for phenomenology. Same for $\mathscr{L}_1$

Fonseca '22

de Blas, Criado, MPV, Santiago '17

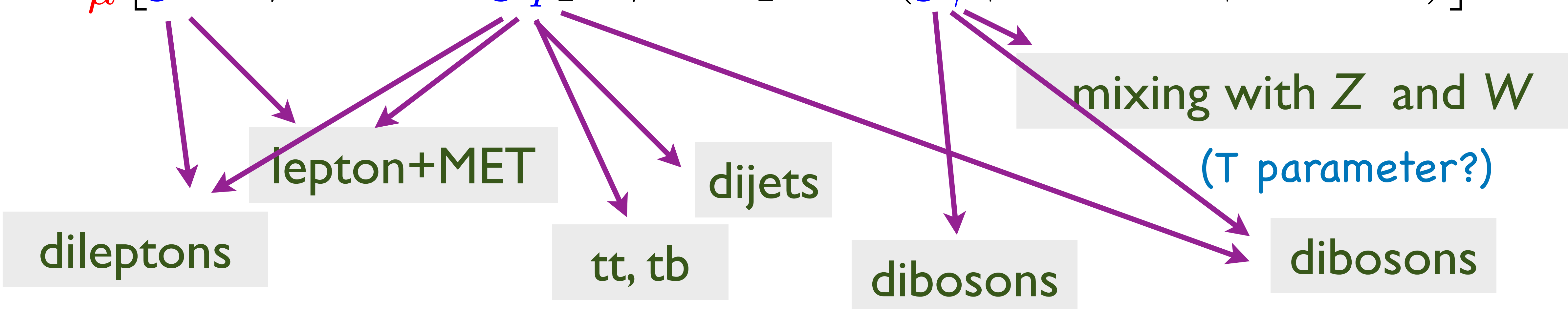
Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

$\mathcal{W}$ { Charged $W'^{\pm}$, Neutral Z'

de Blas, Lizana, MPV, 2012

Pappadopulo, Thamm, Torre, Wulzer, 2014

$$\mathcal{W}^a_\mu\left[g_l\bar{l}_L\gamma^\mu\sigma_a l_L+g_q\bar{q}_L\gamma^\mu\sigma_a q_L+\left(g_\phi\phi^\dagger\sigma_a iD^\mu\phi+\text{h.c.}\right)\right]$$



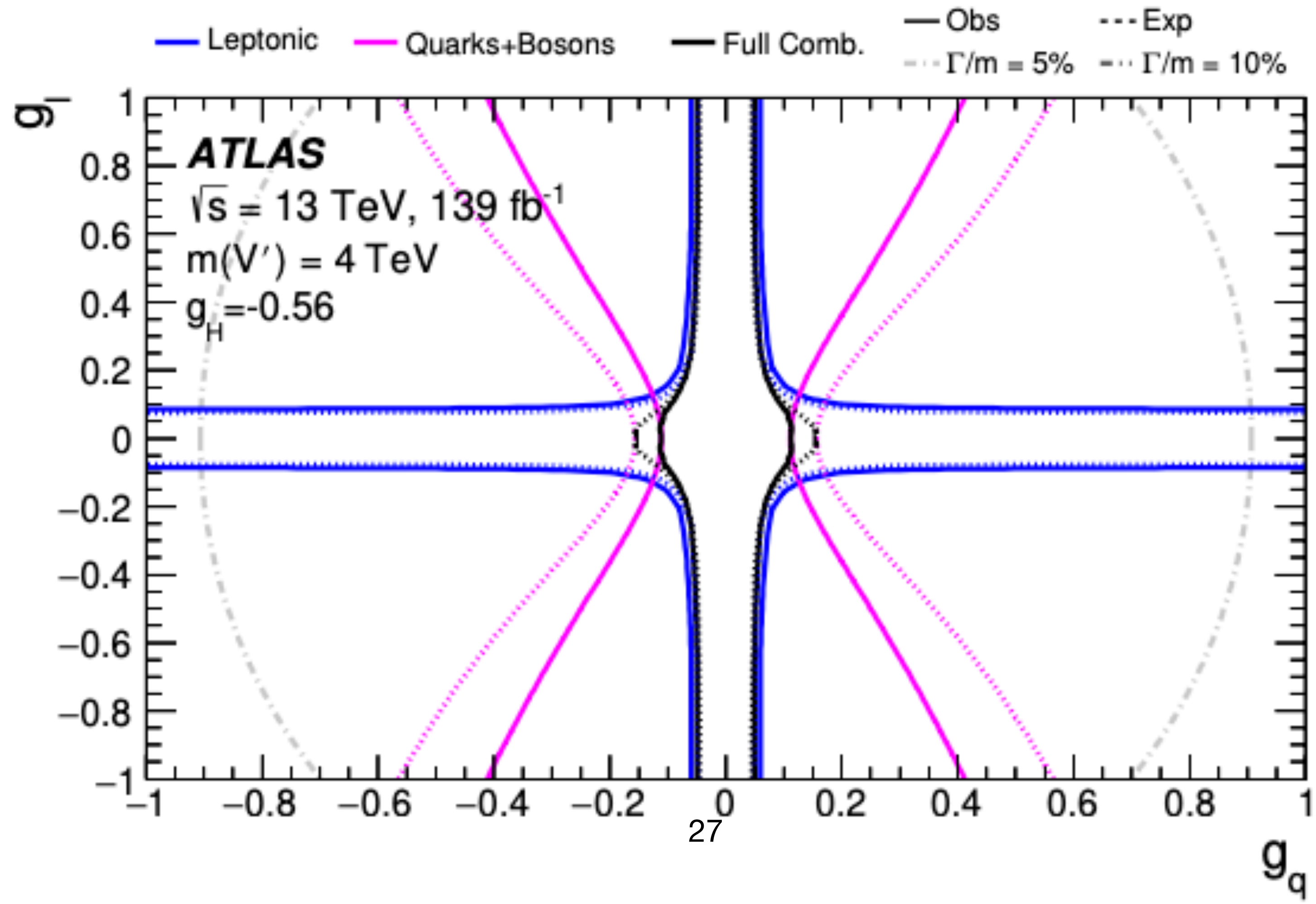
Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

$\mathcal{W}$ { Charged $W'^{\pm}$ / Neutral Z' }

de Blas, Lizana, MPV, 2012

Pappadopulo, Thamm, Torre, Wulzer, 2014

$$\mathcal{W}^a_\mu\left[g_l \bar{l}_L\gamma^\mu\sigma_a l_L + g_q \bar{q}_L\gamma^\mu\sigma_a q_L + (g_\phi \phi^\dagger\sigma_a iD^\mu\phi + \text{h.c.})\right]$$



ATLAS ‘24

- The antisymmetry of the coset generators implies $\mathrm{Im}(g_\phi) = 0$
  Then, it does not contribute to the T parameter

- $a \in \{1,2,3\}$ W $\quad \hat{a} \in \{\hat{1},\hat{2},\hat{3}\}$ $\mathscr{W}$

- Invariance and antisymmetry imply (linear equations)

$$f_{abc} = g\epsilon_{abc}, \quad f_{\hat{a}\hat{b}c} = g\epsilon_{abc}, \quad f_{\hat{a}\hat{b}\hat{c}} = C\epsilon_{abc}$$

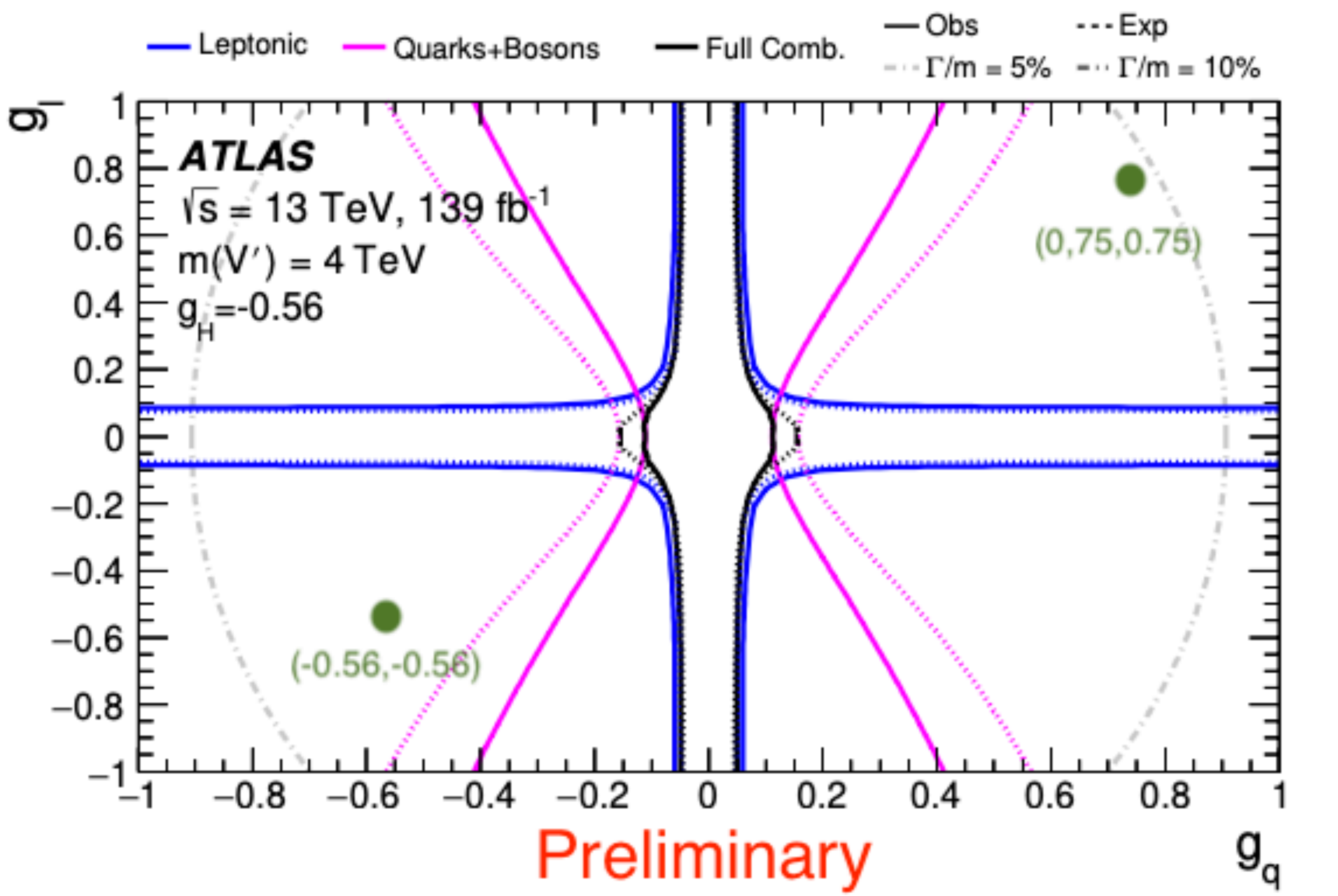
- Closure condition satisfied, so C=0 is a solution. But non-linear equations are satisfied for any C

- Invariance of fermion and scalar generators imply

$$C = \cot\varphi - \tan\varphi$$
$$g_l, g_q, g_\phi \in \{-g\tan\varphi, g\cot\varphi\}$$

for some angle φ

So, the parameter space of the model in the universal case is reduced from four to two



Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

$\mathscr{B}_1$ is a W′ that couples to RH fermions. Its completion is completely analogous to the completion of the W boson in the SM: a Z′ boson is required, the form of the fermion generators is fixed and there are relations among couplings. At the end of the day, this reduces to a LR model.

$\mathscr{U}_2$ is a leptoquark. Its completion involves a partial unification. Consistency of fermion couplings requires at least a Z′ boson and extending the fermions with a RH neutrino. In this way, we rediscover Pati-Salam.

In all cases flavour strongly constrained

The landscape of UV completions

In this approach, model building reduces to solving algebraic equations.

This task is amenable to automation :)

But solving exactly a large system of quadratic equations can take too much time and memory :(

So, brute force not sufficient

The only consistent minimal cases with only one vector irrep and no extra fermions or scalars turn out to be the SM-like irreps:
$\mathscr{B}, \mathscr{W}, \mathscr{G}$
So, we scan over non-minimal cases as well

A glimpse at the scan in progress

U2 + B0 + N

```
(aux data) Length[fabcToUse]: 1

[Vectors] There are solution.

[Fermions] nullTensor: SparseArray[ Specified elements: 51 149
                                    Dimensions: {19, 19, 16, 16} ]
                                    Data not saved. Save now

[Fermions] Linear part: done. (Length[solLinear]=1)

[Fermions] Quadratic part: done. (Length[solLinearQuadratic]=24)

[Fermions] There are solutions.

[Scalars] nullTensor: SparseArray[ Specified elements: 2832
                                   Dimensions: {19, 19, 4, 4} ]
                                   Data not saved. Save now

[Scalars] Linear part: done. (Length[solLinear]=1)

[Scalars] Quadratic part: done. (Length[solLinearQuadratic]=1)

[Scalars] There are solutions.
```

In conclusion,

- The existence of perturbative completions puts strong limits on EFT with heavy vector bosons.

- Classical top-down gauge model building continuous to hold up well. It can be used to find the UV completions. Knowing the group offers many advantages. It involves embeddings, branching rules, Slansky,...

- Bottom-up model building is an equivalent pheno-motivated work flow. It involves algebraic equations, fast computers, Renato,... (This approach can also be used for global symmetries not involving vector bosons)

- A combination of both approaches (such as using group theory once a group has been determined from the equations) seems helpful