Effective Field Theories for Multiboson Interactions

Jürgen R. Reuter, DESY

@ BNL in stabler vacuum ... & the discovery of a doublet

@ BNL in stabler vacuum ... & the discovery of a doublet

@ BNL in stabler vacuum ... & the discovery of a doublet

Setting the stage for Weak Interactions

- Discovery of a light Higgs boson leaves still open questions:

  1. Nature of Electroweak Symmetry Breaking
  2. Higgs boson potential, all the way like the Standard Model!?
  3. Does it fulfill the US-fermion/Europe-boson rule?
  4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
  5. How do EW vector bosons scatter? (true heart of weak interactions)
  6. Is there something related to the Little Hierarchy problem (strong or weak)

- What do we know about W, Z bosons?

Setting the stage for Weak Interactions

- Discovery of a light Higgs boson leaves still open questions:

  1. Nature of Electroweak Symmetry Breaking
  2. Higgs boson potential, all the way like the Standard Model!?
  3. Does it fulfill the US-fermion/Europe-boson rule?
  4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
  5. How do EW vector bosons scatter? (true heart of weak interactions)
  6. Is there something related to the Little Hierarchy problem (strong or weak)

- What do we know about *W*, *Z* bosons?

E. Rutherford, *Phil. Mag., 1899, (47), ser. 5, 109*

virtual *W*: 1899

VIII. *Uranium Radiation and the Electrical Conduction produced by it.* By E. Rutherford, *M.A., B.Sc., formerly 1851 Science Scholar, Coutts Trotter Student, Trinity College, Cambridge; McDonald Professor of Physics, McGill University, Montreal**.

THE remarkable radiation emitted by uranium and its compounds has been studied by its discoverer, Becquerel, and the results of his investigations on the nature and properties of the radiation have been given in a series of papers in the *Comptes Rendus*†. He showed that the radiation, continuously emitted from uranium compounds, has the power of passing through considerable thicknesses of metals and other opaque substances; it has the power of acting on a photographic plate and of discharging positive and negative electrification to an equal degree. The gas through which the radiation passes is made a temporary conductor of electricity and preserves its power of discharging electrification for a short time after the source of radiation has been removed.

The results of Becquerel showed that Röntgen and uranium radiations were very similar in their power of penetrating solid bodies and producing conduction in a gas exposed to them; but there was an essential difference between the two types of radiation. He found that uranium radiation could be refracted and polarized, while no definite results showing

* Communicated by Prof. J. J. Thomson, F.R.S.

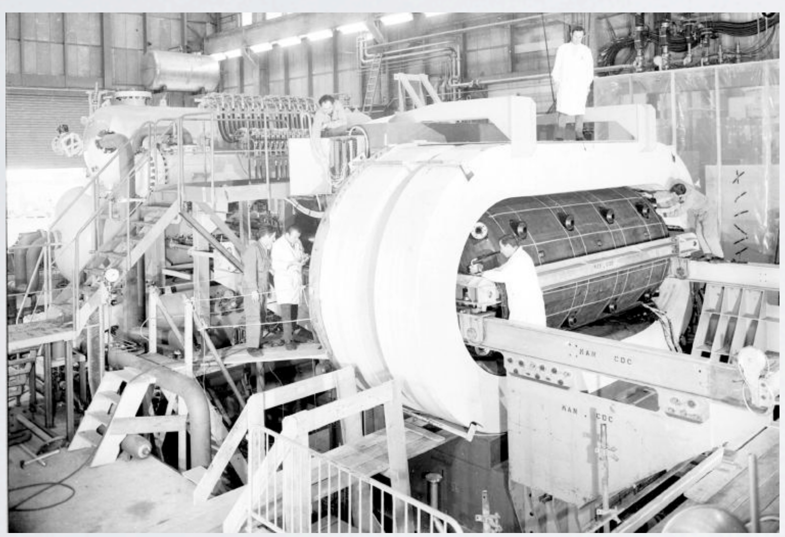
† *C. R.* 1896, pp. 420, 501, 559, 689, 762, 1086; 1897, pp. 438, 800.

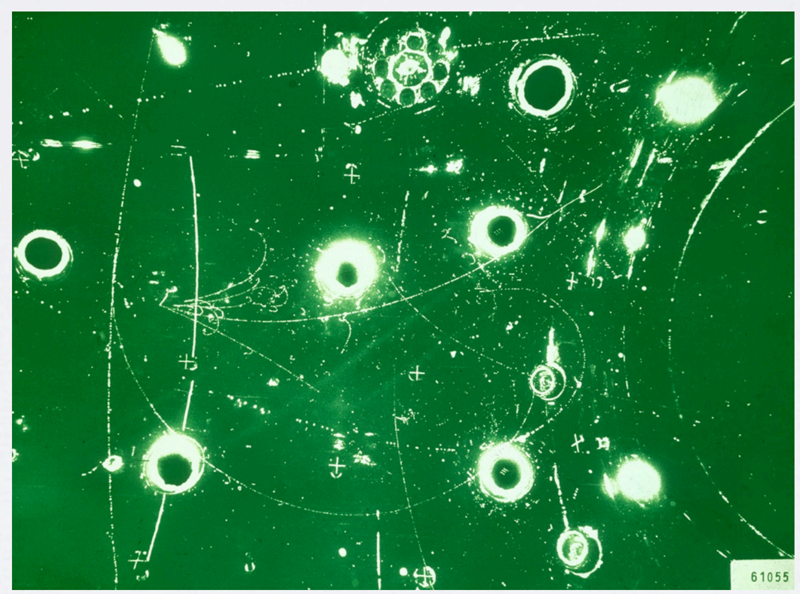
Setting the stage for Weak Interactions

- Discovery of a light Higgs boson leaves still open questions:

  1. Nature of Electroweak Symmetry Breaking
  2. Higgs boson potential, all the way like the Standard Model!?
  3. Does it fulfill the US-fermion/Europe-boson rule?
  4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
  5. How do EW vector bosons scatter? (true heart of weak interactions)
  6. Is there something related to the Little Hierarchy problem (strong or weak)

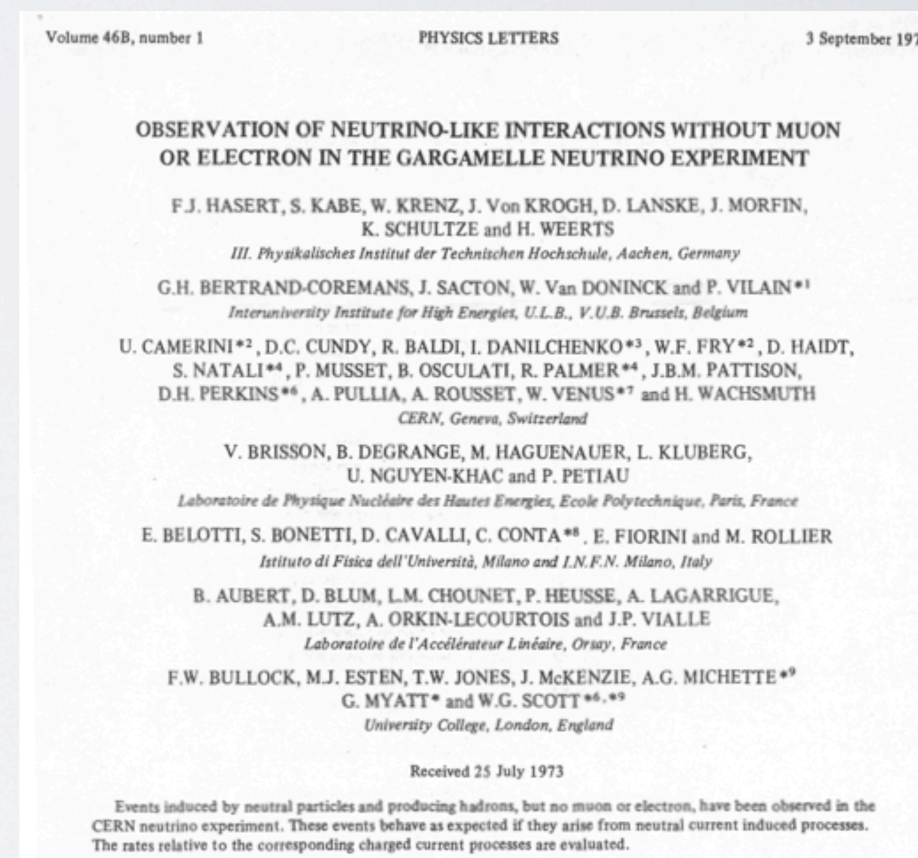
- What do we know about *W*, *Z* bosons?





F. Hasert et al., *Phys. Lett. B46 (1973), 38*

virtual *Z*: 1973



Volume 46B, number 1 PHYSICS LETTERS 3 September 1973

OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

F.J. HASERT, S. KABE, W. KRENZ, J. Von KROGH, D. LANSKE, J. MORFIN, K. SCHULTZE and H. WEERTS
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

G.H. BERTRAND-COREMANS, J. SACTON, W. Van DONINCK and P. VILAIN *1
Interuniversity Institute for High Energies, U.L.B., V.U.B. Brussels, Belgium

U. CAMERINI *2, D.C. CUNDY, R. BALDI, I. DANILCHENKO *3, W.F. FRY *2, D. HAIDT, S. NATALI *4, P. MUSSET, B. OSCULATI, R. PALMER *4, J.B.M. PATTISON, D.H. PERKINS *6, A. PULLIA, A. ROUSSET, W. VENUS *7 and H. WACHSMUTH
CERN, Geneva, Switzerland

V. BRISSON, B. DEGRANGE, M. HAGUENAUER, L. KLUBERG, U. NGUYEN-KHAC and P. PETIAU
Laboratoire de Physique Nucléaire des Hautes Energies, Ecole Polytechnique, Paris, France

E. BELOTTI, S. BONETTI, D. CAVALLI, C. CONTA *8. E. FIORINI and M. ROLLIER
Istituto di Fisica dell'Università, Milano and I.N.F.N. Milano, Italy

B. AUBERT, D. BLUM, L.M. CHOUNET, P. HEUSSE, A. LAGARRIGUE, A.M. LUTZ, A. ORKIN-LECOURTOIS and J.P. VIALLE
Laboratoire de l'Accélérateur Linéaire, Orsay, France

F.W. BULLOCK, M.J. ESTEN, T.W. JONES, J. McKENZIE, A.G. MICHETTE *9 G. MYATT * and W.G. SCOTT *6, *9
University College, London, England

Received 25 July 1973

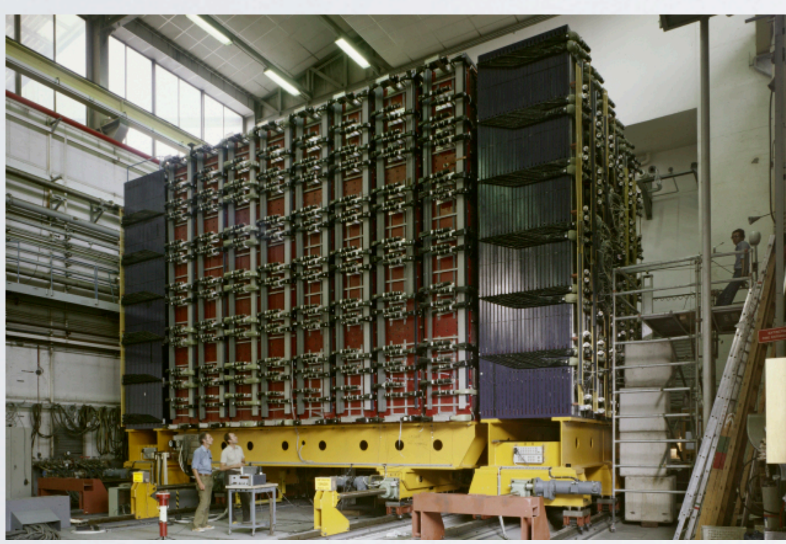
Events induced by neutral particles and producing hadrons, but no muon or electron, have been observed in the CERN neutrino experiment. These events behave as expected if they arise from neutral current induced processes. The rates relative to the corresponding charged current processes are evaluated.

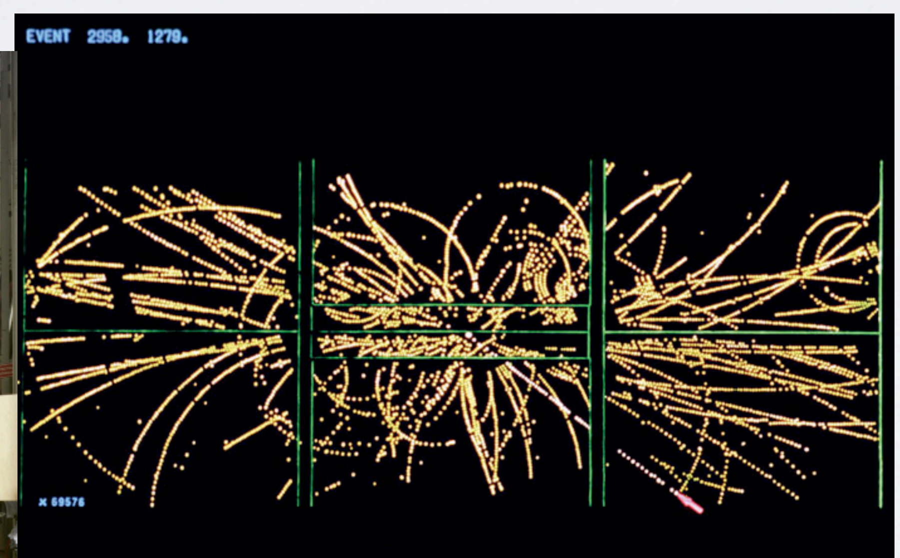
Setting the stage for Weak Interactions

- Discovery of a light Higgs boson leaves still open questions:

  1. Nature of Electroweak Symmetry Breaking
  2. Higgs boson potential, all the way like the Standard Model!?
  3. Does it fulfill the US-fermion/Europe-boson rule?
  4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
  5. How do EW vector bosons scatter? (true heart of weak interactions)
  6. Is there something related to the Little Hierarchy problem (strong or weak)

- What do we know about W, Z bosons?





G. Arnison et al., *Phys. Lett. B6 (1983), 398*

real W and Z: 1982

Volume 126B, number 5 PHYSICS LETTERS 7 July 1983

EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c^2 AT THE CERN SPS COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

G. ARNISON [j], A. ASTBURY [j], B. AUBERT [b], C. BACCI [i], G. BAUER [l], A. BÉZAGUET [d], R. BÖCK [d], T.J.V. BOWCOCK [f], M. CALVETTI [d], P. CATZ [b], P. CENNINI [d], S. CENTRO [d], F. CERADINI [d,i], S. CITTOLIN [d], D. CLINE [l], C. COCHET [k], J. COLAS [b], M. CORDEN [c], D. DALLMAN [d,l], D. DAU [2], M. DeBEER [k], M. DELLA NEGRA [b,d], M. DEMOULIN [d], D. DENEGRI [k], A. Di CIACCIO [i], D. DiBITONTO [d], L. DOBRZYNSKI [g], J.D. DOWELL [c], K. EGGERT [a], E. EISENHANDLER [f], N. ELLIS [d], P. ERHARD [a], H. FAISSNER [a], M. FINCKE [2], G. FONTAINE [g], R. FREY [h], R. FRÜHWIRTH [l], J. GARVEY [c], S. GEER [g], C. GHESQUIÈRE [g], P. GHEZ [b], K. GIBONI [a], W.R. GIBSON [f], Y. GIRAUD-HÉRAUD [g], A. GIVERNAUD [k], A. GONIDEC [b], G. GRAYER [j], T. HANSL-KOZAŇECKA [a], W.J. HAYNES [j], L.O. HERTZBERGER [3], C. HODGES [h], D. HOFFMANN [a], H. HOFFMANN [d], D.J. HOLTHUIZEN [3], R.J. HOMER [c], A. HONMA [f], W. JANK [d], G. JORAT [d], P.I.P. KALMUS [f], V. KARIMÄKI [e], R. KEELER [f], I. KENYON [c], A. KERNAN [h], R. KINNUNEN [e], W. KOZANECKI [h], D. KRYN [d,g], F. LACAVA [i], J.-P. LAUGIER [k], J.-P. LEES [b], H. LEHMANN [a], R. LEUCHS [a], A. LÉVÊQUE [k,d], D. LINGLIN [b], E. LOCCI [k], J.-J. MALOSSE [k], T. MARKIEWICZ [d], G. MAURIN [d], T. McMAHON [c], J.-P. MENDIBURU [g], M.-N. MINARD [b], M. MOHAMMADI [l], M. MORICCA [i], K. MORGAN [h], H. MUIRHEAD [4], F. MULLER [d], A.K. NANDI [j], L. NAUMANN [d], A. NORTON [d], A. ORKIN-LECOURTOIS [g], L. PAOLUZI [i], F. PAUSS [d], G. PIANO MORTARI [i], E. PIETARINEN [e], M. PIMIÄ [e], A. PLACCI [d], J.P. PORTE [d], E. RADERMACHER [a], J. RANSDELL [h], H. REITHLER [a], J.-P. REVOL [d], J. RICH [k], M. RIJSSENBEEK [d], C. ROBERTS [j], J. ROHLF [d], P. ROSSI [d], C. RUBBIA [d], B. SADOULET [d], G. SAJOT [g], G. SALVI [f], G. SALVINI [i], J. SASS [k], J. SAUDRAIX [k], A. SAVOY-NAVARRO [k], D. SCHINZEL [d], W. SCOTT [j], T.P. SHAH [j], M. SPIRO [k], J. STRAUSS [l], J. STREETS [c], K. SUMOROK [d], F. SZONCSO [l], D. SMITH [h], C. TAO [3], G. THOMPSON [f], J. TIMMER [d], E. TSCHESLOG [a], J. TUOMINIEMI [e], B. Van EIJK [3], J.-P. VIALLE [d], J. VRANA [g], V. VUILLEMIN [d], H.D. WAHL [l], P. WATKINS [c], J. WILSON [c], C. WULZ [l], G.Y. XIE [d], M. YVERT [b] and E. ZURFLUH [d]

Aachen [a] – Annecy (LAPP) [b] – Birmingham [c] – CERN [d] – Helsinki [e] – Queen Mary College, London [f] – Paris (Coll. de France) [g] – Riverside [h] – Rome [i] – Rutherford Appleton Lab. [j] – Saclay (CEN) [k] – Vienna [h] Collaboration

Received 6 June 1983

We report the observation of four electron–positron pairs and one muon pair which have the signature of a two-body decay of a particle of mass ~95 GeV/c^2. These events fit well the hypothesis that they are produced by the process $\bar{p} + p \to Z^0 + X$ (with $Z^0 \to \ell^+ + \ell^-$), where Z^0 is the Intermediate Vector Boson postulated by the electroweak theories as the mediator of weak neutral currents.

Effective and More Effective Descriptions

First Effective Field Theory for Single EW Boson

Fermi theory: $$\mathcal{L}_{eff.} = \frac{c_F}{v^2} \cdot \overline{\Psi}_d \gamma^\mu (1-\gamma^5) \Psi_u \times \overline{\Psi}_u \gamma_\mu (1-\gamma^5) \Psi_d$$

- Contains known degrees of freedom
- Describes the measured interactions
- Includes a high new physics scale v
- Contains coefficients parameterizing (unknown) new interactions

Effective and More Effective Descriptions

First Effective Field Theory for Single EW Boson

Fermi theory: $$\mathcal{L}_{eff.} = \frac{c_F}{v^2} \cdot \overline{\Psi}_d \gamma^\mu (1-\gamma^5) \Psi_u \times \overline{\Psi}_u \gamma_\mu (1-\gamma^5) \Psi_d$$

- Contains known degrees of freedom
- Describes the measured interactions
- Includes a high new physics scale v
- Contains coefficients parameterizing (unknown) new interactions

Different physics necessitates usage of different operator bases

Talk ⟶ M. Sekulla

- $K^0 - \overline{K}^0, D^0 - \overline{D}^0, B^0 - \overline{B}^0$ mixing
- K^0, D^0, B^0 semileptonic decays
- $\nu - \nu'$ oscillations

$$\begin{aligned} \mathcal{L}_1 &= \tfrac{c_F}{v^2} \cdot \overline{\Psi}_L \gamma^\mu \Psi_L \times \overline{\Psi}_L \gamma_\mu \Psi_L \\ \text{vs.} \quad \mathcal{L}_2 &= \tfrac{c'_F}{v^2} \cdot \overline{\Psi'}_L \gamma^\mu \Psi_L \times \overline{\Psi'}_L \gamma_\mu \Psi'_L \\ \text{vs.} \quad \mathcal{L}_3 &= \tfrac{c''_F}{v^2} \cdot \overline{\Psi}_L \Gamma^\mu \Psi_L \times \overline{\Psi}_L \Gamma_\mu \Psi_L \end{aligned}$$

Effective and More Effective Descriptions

First Effective Field Theory for Single EW Boson

Fermi theory: $$\mathcal{L}_{eff.} = \frac{c_F}{v^2} \cdot \overline{\Psi}_d \gamma^\mu (1-\gamma^5) \Psi_u \times \overline{\Psi}_u \gamma_\mu (1-\gamma^5)\Psi_d$$

- ✦ Contains known degrees of freedom
- ✦ Describes the measured interactions
- ✦ Includes a high new physics scale *v*
- ✦ Contains coefficients parameterizing (unknown) new interactions

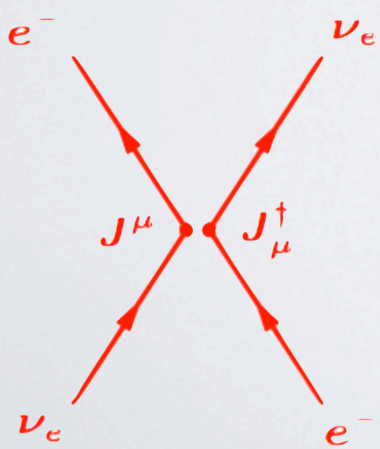
Different physics necessitates usage of different operator bases

Talk $\longrightarrow$ M. Sekulla

- $K^0 - \overline{K}^0, D^0 - \overline{D}^0, B^0 - \overline{B}^0$ mixing
- K^0, D^0, B^0 semileptonic decays
- $\nu - \nu'$ oscillations

$$\mathcal{L}_1 = \frac{c_F}{v^2} \cdot \overline{\Psi}_L \gamma^\mu \Psi_L \times \overline{\Psi}_L \gamma_\mu \Psi_L$$
vs. $$\mathcal{L}_2 = \frac{c'_F}{v^2} \cdot \overline{\Psi'}_L \gamma^\mu \Psi_L \times \overline{\Psi'}_L \gamma_\mu \Psi'_L$$
vs. $$\mathcal{L}_3 = \frac{c''_F}{v^2} \cdot \overline{\Psi}_L \Gamma^\mu \Psi_L \times \overline{\Psi}_L \Gamma_\mu \Psi_L$$

Effective theory leads to invalidity / unitarity violation at higher energies



$$\sigma(e^- \nu_e \to e^- \nu_e) \longrightarrow \sim \frac{s}{\pi v^2}$$

S-wave unitarity demands: $\sqrt{s} \lesssim 500\,\text{GeV}$

Talk $\longrightarrow$ W. Kilian

Remark about EFTs of the 1970/1980s

- SppS: discovery of *W*, *Z* (on-shell)
- SLC/LEP: proof of non-Abelian weak structure, failure to find (very) light Higgs
- Measurement of longitudinal *W*s: $ee \to WW$ (LEP), $t \to Wb$ (Tevatron)
- Using all known d.o.f., parameterizing all possible interactions

Building blocks for EFT:

$$\psi \quad , \quad \mathbf{W}_\mu \quad , \quad \mathbf{B}_\mu \quad , \quad \Sigma = \exp\left[\frac{-i}{v}\mathbf{w}\boldsymbol{\tau}\right]$$

SM fermions — weak bosons — hypercharge boson — longitudinal d.o.f.

Remark about EFTs of the 1970/1980s

- SppS: discovery of W, Z (on-shell)
- SLC/LEP: proof of non-Abelian weak structure, failure to find (very) light Higgs
- Measurement of longitudinal Ws: $ee \to WW$ (LEP), $t \to Wb$ (Tevatron)
- Using all known d.o.f., parameterizing all possible interactions

Building blocks for EFT:

$$\psi \quad , \quad \mathbf{W}_\mu \quad , \quad \mathbf{B}_\mu \quad , \quad \Sigma = \exp\left[\frac{-i}{v}\mathbf{w}\boldsymbol{\tau}\right]$$

SM fermions — weak bosons — hypercharge boson — longitudinal d.o.f.

Minimal Lagrangian describing measurements at SLC / LEP [II] / Tevatron

$$\mathcal{L}_{\text{pre-LHC}} = \sum_\psi \overline{\psi}(i\not{D})\psi - \frac{1}{2g^2}\text{tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] - \frac{1}{2g'^2}\text{tr}\left[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\right] + \frac{v^2}{4}\text{tr}\left[(\mathbf{D}_\mu\Sigma)(\mathbf{D}^\mu\Sigma)\right]$$

with the following useful definitions:

$$\mathbf{D}_\mu = \partial_\mu + \frac{i}{2}g\boldsymbol{\tau}^I W^I_\mu + \frac{i}{2}g' B_\mu \boldsymbol{\tau}^3$$

$$\mathbf{W}_{\mu\nu} = \frac{i}{2}g\boldsymbol{\tau}^I(\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon_{IJK}W^J_\mu W^K_\nu)$$

$$\mathbf{B}_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu)\boldsymbol{\tau}^3$$

Remark about EFTs of the 1970/1980s

- SppS: discovery of W, Z (on-shell)
- SLC/LEP: proof of non-Abelian weak structure, failure to find (very) light Higgs
- Measurement of longitudinal Ws: $ee \to WW$ (LEP), $t \to Wb$ (Tevatron)
- Using all known d.o.f., parameterizing all possible interactions

Building blocks for EFT:

$$\psi \quad , \quad \mathbf{W}_\mu \quad , \quad \mathbf{B}_\mu \quad , \quad \Sigma = \exp\left[\frac{-i}{v}\mathbf{w}\boldsymbol{\tau}\right]$$

SM fermions — weak bosons — hypercharge boson — longitudinal d.o.f.

Minimal Lagrangian describing measurements at SLC / LEP [II] / Tevatron

$$\mathcal{L}_{\text{pre-LHC}} = \sum_\psi \overline{\psi}(i\not{D})\psi - \frac{1}{2g^2}\text{tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] - \frac{1}{2g'^{\,2}}\text{tr}\left[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\right] + \frac{v^2}{4}\text{tr}\left[(\mathbf{D}_\mu\Sigma)(\mathbf{D}^\mu\Sigma)\right]$$

with the following useful definitions:

$$\mathbf{D}_\mu = \partial_\mu + \frac{i}{2}g\boldsymbol{\tau}^I W^I_\mu + \frac{i}{2}g' B_\mu \boldsymbol{\tau}^3$$

$$\mathbf{W}_{\mu\nu} = \frac{i}{2}g\boldsymbol{\tau}^I(\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon_{IJK}W^J_\mu W^K_\nu)$$

$$\mathbf{B}_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu)\boldsymbol{\tau}^3$$

Electroweak Chiral Lagrangian

Remark about EFTs of the 1970/1980s

- SppS: discovery of W, Z (on-shell)
- SLC/LEP: proof of non-Abelian weak structure, failure to find (very) light Higgs
- Measurement of longitudinal Ws: $ee \to WW$ (LEP), $t \to Wb$ (Tevatron)
- Using all known d.o.f., parameterizing all possible interactions

Building blocks for EFT:

$$\psi \quad , \quad \mathbf{W}_\mu \quad , \quad \mathbf{B}_\mu \quad , \quad \Sigma = \exp\left[\frac{-i}{v}\mathbf{w}\boldsymbol{\tau}\right]$$

SM fermions — weak bosons — hypercharge boson — longitudinal d.o.f.

Minimal Lagrangian describing measurements at SLC / LEP [II] / Tevatron

$$\mathcal{L}_{\text{pre-LHC}} = \sum_\psi \overline{\psi}(i\not{D})\psi - \frac{1}{2g^2}\text{tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] - \frac{1}{2g'^2}\text{tr}\left[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\right] + \frac{v^2}{4}\text{tr}\left[(\mathbf{D}_\mu\Sigma)(\mathbf{D}^\mu\Sigma)\right]$$

with the following useful definitions:

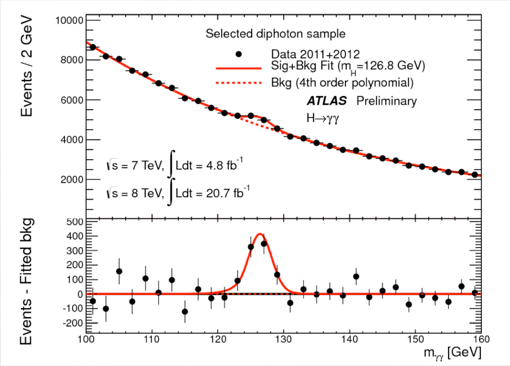
$$\mathbf{D}_\mu = \partial_\mu + \frac{i}{2}g\boldsymbol{\tau}^I W^I_\mu + \frac{i}{2}g' B_\mu \boldsymbol{\tau}^3$$

$$\mathbf{W}_{\mu\nu} = \frac{i}{2}g\boldsymbol{\tau}^I(\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon_{IJK}W^J_\mu W^K_\nu)$$

$$\mathbf{B}_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu)\boldsymbol{\tau}^3$$

Electroweak Chiral Lagrangian

Ruled out by LHC data (Higgs discovery)



Parameterizing SM deviations

★ Specific models (SUSY, Compositeness, Little Higgses, 2HDM, Modified Higgses, Xdim, ...)

- Could give strong signals in VBS (presumably Little Higgses, Compositeness, Xdim ....)
- Could give faint signals in VBS (presumably SUSY, 2HDM [Higgs data!], ...)
- Up to parametric uncertainties precise predictions from the models (new independent couplings)
- Mostly even beyond tree level predictable
- Analysis has to be repeated for each and every model, introduces new parameters

Parameterizing SM deviations

★ Specific models (SUSY, Compositeness, Little Higgses, 2HDM, Modified Higgses, Xdim, ...)

- Could give strong signals in VBS (presumably Little Higgses, Compositeness, Xdim ....)
- Could give faint signals in VBS (presumably SUSY, 2HDM [Higgs data!], ...)
- Up to parametric uncertainties precise predictions from the models (new independent couplings)
- Mostly even beyond tree level predictable
- Analysis has to be repeated for each and every model, introduces new parameters

★ Anomalous Couplings

- Usually first "model-independent" proposal
- At the moment applied by HXSWG (but under debate)
- Only modifications of SM couplings or introduction of new (Lorentz) structures ?
- Allows fits of coupling strengths
- Possible deviations difficult to interpret in terms of quantum field theory, unitarity!!

Parameterizing SM deviations

★ Specific models (SUSY, Compositeness, Little Higgses, 2HDM, Modified Higgses, Xdim, ...)

- Could give strong signals in VBS (presumably Little Higgses, Compositeness, Xdim ....)
- Could give faint signals in VBS (presumably SUSY, 2HDM [Higgs data!], ...)
- Up to parametric uncertainties precise predictions from the models (new independent couplings)
- Mostly even beyond tree level predictable
- Analysis has to be repeated for each and every model, introduces new parameters

★ Anomalous Couplings

- Usually first "model-independent" proposal
- At the moment applied by HXSWG (but under debate)
- Only modifications of SM couplings or introduction of new (Lorentz) structures ?
- Allows fits of coupling strengths
- Possible deviations difficult to interpret in terms of quantum field theory, unitarity!!

★ Form factors

- Similar approach to anomalous couplings, partially resums perturbative series
- (Almost) completely general and model-independent
- Needs parameterizations, violates gauge invariance, unitarity ad-hoc curable (new parameters)

Parameterizing SM deviations

★ Specific models (SUSY, Compositeness, Little Higgses, 2HDM, Modified Higgses, Xdim, ...)

- Could give strong signals in VBS (presumably Little Higgses, Compositeness, Xdim ....)
- Could give faint signals in VBS (presumably SUSY, 2HDM [Higgs data!], ...)
- Up to parametric uncertainties precise predictions from the models (new independent couplings)
- Mostly even beyond tree level predictable
- Analysis has to be repeated for each and every model, introduces new parameters

★ Anomalous Couplings

- Usually first "model-independent" proposal
- At the moment applied by HXSWG (but under debate)
- Only modifications of SM couplings or introduction of new (Lorentz) structures ?
- Allows fits of coupling strengths
- Possible deviations difficult to interpret in terms of quantum field theory, unitarity!!

★ Form factors

- Similar approach to anomalous couplings, partially resums perturbative series
- (Almost) completely general and model-independent
- Needs parameterizations, violates gauge invariance, unitarity ad-hoc curable (new parameters)

★ Effective Field Theory

- (Almost) model-independent, consistent calculation of perturbative corrections (power counting !?)
- Depends on (possibly) many free parameters
- Requires decoupling of New Physics
- Range of applicability strongly depends on couplings and scales (unitarity issue)

The Rationale of Effective Field Theories

- SM contains all dim 2- and dim 4-operators "relevant" for low-energy physics:
  (no fermions or QCD here)

$$\mathcal{L}_{EW} = -\frac{1}{2}\mathrm{tr}\,[W_{\mu\nu}W^{\mu\nu}] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

- Add all higher-dimensional operators consisting of SM fields/consistent with SM symmetries

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots\right]}$$

S. Weinberg, 1979

- $v \ll \Lambda$: new physics scale; $c_i^{(d)}$: dimensionless Wilson coefficient
- Unique (up to flavor) combinations dim 5 operator: Majorana mass term (violates *L*)
- All odd operators involve fermions, all dim 5 and dim 7 violate *B* and/or *L*
- Validity of EFT assumes $E \ll \Lambda$

The Rationale of Effective Field Theories

- SM contains all dim 2- and dim 4-operators "relevant" for low-energy physics:
  (no fermions or QCD here)

$$\mathcal{L}_{EW} = -\frac{1}{2}\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

- Add all higher-dimensional operators consisting of SM fields/consistent with SM symmetries

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots \right]$$

S. Weinberg, 1979

- $v \ll \Lambda$: new physics scale; $c_i^{(d)}$: dimensionless Wilson coefficient
- Unique (up to flavor) combinations dim 5 operator: Majorana mass term (violates *L*)
- All odd operators involve fermions, all dim 5 and dim 7 violate *B* and/or *L*
- Validity of EFT assumes $E \ll \Lambda$

, such a general Lagrangian has no specific dynamical content beyond the general principles of analyticity, unitarity, cluster decomposition, Lorentz invariance, and chirality, so that when it is used to calculate *S*-matrix elements, it yields the most general matrix elements consistent with these general principles, provided that all terms of all orders in all couplings , are included.

S. Weinberg, 1979

The Rationale of Effective Field Theories

- SM contains all dim 2- and dim 4-operators "relevant" for low-energy physics:
  (no fermions or QCD here)

$$\mathcal{L}_{EW} = -\frac{1}{2}\mathrm{tr}\,[W_{\mu\nu}W^{\mu\nu}] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

- Add all higher-dimensional operators consisting of SM fields/consistent with SM symmetries

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots \right]$$

S. Weinberg, 1979

- $v \ll \Lambda$: new physics scale; $c_i^{(d)}$: dimensionless Wilson coefficient
- Unique (up to flavor) combinations dim 5 operator: Majorana mass term (violates *L*)
- All odd operators involve fermions, all dim 5 and dim 7 violate *B* and/or *L*
- Validity of EFT assumes $E \ll \Lambda$

> , such a general Lagrangian has no specific dynamical content beyond the general principles of analyticity, unitarity, cluster decomposition, Lorentz invariance, and chirality, so that when it is used to calculate *S*-matrix elements, it yields the most general matrix elements consistent with these general principles, provided that all terms of all orders in all couplings , are included.

S.Weinberg, 1979

- Unitarity plays important role: allows to determine coefficients of poles

Li/Pagels, 1971; Lehmann, 1972

Effective Field Theories: Higher-dimensional operators

- Must include all dim 6 operators from SM fields Buchmüller/Wyler, 1986
- Redundancy of operators $\Longrightarrow$ minimal set of operators (in principle)

  1. Equations of motion: $D_\mu \mathbf{W}^{\mu\nu} = \Phi^\dagger (D^\nu \Phi) - (D^\nu \Phi)^\dagger \Phi + \ldots$
  2. Gauge symmetry: $[D_\mu, D_\nu]\, \Phi \propto \mathbf{W}_{\mu\nu} \Phi$
  3. Integration by parts: $\left(\Phi^\dagger \Phi\right) \Box \left(\Phi^\dagger \Phi\right) \longrightarrow \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$

- Further reduction by use of discrete / horizontal symmetries

  1. *B* and *L* conservation (excludes 5 operators per generation)
  2. Flavor symmetries (assumption: Minimal Flavor Violation)
  3. *CP* symmetry

- Assuming *B* and *L* conservation: number of operators (without ν_R)

Effective Field Theories: Higher-dimensional operators

- Must include all dim 6 operators from SM fields — Buchmüller/Wyler, 1986
- Redundancy of operators $\Longrightarrow$ minimal set of operators (in principle)

    1. Equations of motion: $D_\mu \mathbf{W}^{\mu\nu} = \Phi^\dagger (D^\nu \Phi) - (D^\nu \Phi)^\dagger \Phi + \ldots$
    2. Gauge symmetry: $[D_\mu, D_\nu]\, \Phi \propto \mathbf{W}_{\mu\nu} \Phi$
    3. Integration by parts: $(\Phi^\dagger \Phi) \Box (\Phi^\dagger \Phi) \longrightarrow \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)$

- Further reduction by use of discrete / horizontal symmetries

    1. *B* and *L* conservation (excludes 5 operators per generation)
    2. Flavor symmetries (assumption: Minimal Flavor Violation)
    3. *CP* symmetry

- Assuming *B* and *L* conservation: number of operators (without ν_R)

    - 1 dim-2 operator + 15 dim-4 operators
    - 59 dim-6 operators for 1 generation
    - 2499 dim-6 operators for 3 generations — Alonso/Jenkins/Manohar/Trott, 2013

Effective Field Theories: Higher-dimensional operators

- Must include all dim 6 operators from SM fields   Buchmüller/Wyler, 1986
- Redundancy of operators $\Longrightarrow$ minimal set of operators (in principle)

   1. Equations of motion: $D_\mu \mathbf{W}^{\mu\nu} = \Phi^\dagger (D^\nu \Phi) - (D^\nu \Phi)^\dagger \Phi + \ldots$
   2. Gauge symmetry: $[D_\mu, D_\nu] \Phi \propto \mathbf{W}_{\mu\nu} \Phi$
   3. Integration by parts: $(\Phi^\dagger \Phi) \square (\Phi^\dagger \Phi) \longrightarrow \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)$

- Further reduction by use of discrete / horizontal symmetries

   1. *B* and *L* conservation (excludes 5 operators per generation)
   2. Flavor symmetries (assumption: Minimal Flavor Violation)
   3. *CP* symmetry

- Assuming *B* and *L* conservation: number of operators (without ν_R)

   - 1 dim-2 operator + 15 dim-4 operators
   - 59 dim-6 operators for 1 generation
   - 2499 dim-6 operators for 3 generations   Alonso/Jenkins/Manohar/Trott, 2013

- No unique basis exists (more in a second)
- Well-known in *B* physics: different experimental measurements constrain different operators

   interpretation of limits in terms of New Physics $\Longrightarrow$ Theorists

Effective Field Theories: Operator Bases

No unique basis exists

- "HISZ" basis: no fermionic operators — Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993
- "GIMR" basis: first minimal complete basis — Grzadkowski/Iskrzyński/Misiak/Rosiek, 2010
- "SILH" basis: complete basis — Giudice/Grojean/Pomarol/Ratazzi, 2007; Elias-Miró et al, 2013
- Dim. 8 operators: — Eboli et al., 2006; Kilian/JRR/Sekulla, 2014

Effective Field Theories: Operator Bases

No unique basis exists

- "HISZ" basis: no fermionic operators — Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993
- "GIMR" basis: first minimal complete basis — Grzadkowski/Iskrzyński/Misiak/Rosiek, 2010
- "SILH" basis: complete basis — Giudice/Grojean/Pomarol/Ratazzi, 2007; Elias-Miró et al, 2013
- Dim. 8 operators: — Eboli et al., 2006; Kilian/JRR/Sekulla, 2014

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi)G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi})G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi)\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi)G_{\mu\nu}^A$	$\mathcal{O}_{\Phi l}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi)W_{\mu\nu}^I$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi})W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi)W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi)B_{\mu\nu}$	$\mathcal{O}_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi)W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi})B_{\mu\nu}$	$\mathcal{O}_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi)B_{\mu\nu}$	$\mathcal{O}_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud}d)$

+ 25 four-fermion operators — Grzadkowski et al.

Effective Field Theories: Operator Bases

No unique basis exists

- "HISZ" basis: no fermionic operators — Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993
- "GIMR" basis: first minimal complete basis — Grzadkowski/Iskrzyński/Misiak/Rosiek, 2010
- "SILH" basis: complete basis — Giudice/Grojean/Pomarol/Ratazzi, 2007; Elias-Miró et al, 2013
- Dim. 8 operators: — Eboli et al., 2006; Kilian/JRR/Sekulla, 2014

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}'_6 = (\Phi^\dagger\Phi)^3$	$\mathcal{O}'_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\,\Gamma_e e\Phi)$	$\mathcal{O}'_G = f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
$\mathcal{O}'_\Phi = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$	$\mathcal{O}'_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}'_{\widetilde{G}} = f^{ABC}\widetilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
$\mathcal{O}'_T = (\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)$	$\mathcal{O}'_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}'_W = \varepsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
		$\mathcal{O}'_{\widetilde{W}} = \varepsilon^{IJK}\widetilde{W}^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}'_{DW} = \left(\Phi^\dagger\tau^I i\overleftrightarrow{D^\mu}\Phi\right)(D^\nu W_{\mu\nu})^I$	$\mathcal{O}'_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi})G^A_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi l} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}'_{DB} = \left(\Phi^\dagger i\overleftrightarrow{D^\mu}\Phi\right)(\partial^\nu B_{\mu\nu})$	$\mathcal{O}'_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi)G^A_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi l} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}'_{D\Phi W} = i(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)W^I_{\mu\nu}$	$\mathcal{O}'_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi)W^I_{\mu\nu}$	$\mathcal{O}'_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}'_{D\Phi\widetilde{W}} = i(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\widetilde{W}^I_{\mu\nu}$	$\mathcal{O}'_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi})W^I_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi q} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}'_{D\Phi B} = i(D^\mu\Phi)^\dagger(D^\nu\Phi)B_{\mu\nu}$	$\mathcal{O}'_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi)W^I_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi q} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}'_{D\Phi\widetilde{B}} = i(D^\mu\Phi)^\dagger(D^\nu\Phi)\widetilde{B}_{\mu\nu}$	$\mathcal{O}'_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}'_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}'_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi})B_{\mu\nu}$	$\mathcal{O}'_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}'_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)B_{\mu\nu}\widetilde{B}^{\mu\nu}$	$\mathcal{O}'_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud} d)$
$\mathcal{O}'_{\Phi G} = \Phi^\dagger\Phi G^A_{\mu\nu}G^{A\mu\nu}$		
$\mathcal{O}'_{\Phi\widetilde{G}} = \Phi^\dagger\Phi G^A_{\mu\nu}\widetilde{G}^{A\mu\nu}$	Giudice et al. / Contino at al.	+(25-2) four-fermion operators

Effective Field Theories: Operator Bases

No unique basis exists

- "HISZ" basis: no fermionic operators — Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993
- "GIMR" basis: first minimal complete basis — Grzadkowski/Iskrzyński/Misiak/Rosiek, 2010
- "SILH" basis: complete basis — Giudice/Grojean/Pomarol/Ratazzi, 2007; Elias-Miró et al, 2013
- Dim. 8 operators: — Eboli et al., 2006; Kilian/JRR/Sekulla, 2014

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}'_6 = (\Phi^\dagger\Phi)^3$	$\mathcal{O}'_{e\Phi} = (\Phi^\dagger\Phi)(\bar{l}\,\Gamma_e e\Phi)$	$\mathcal{O}'_G = f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$
$\mathcal{O}'_\Phi = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$	$\mathcal{O}'_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}'_{\widetilde{G}} = f^{ABC}\widetilde{G}^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$
$\mathcal{O}'_T = (\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)$	$\mathcal{O}'_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}'_W = \varepsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$
		$\mathcal{O}'_{\widetilde{W}} = \varepsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$

$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}'_{DW} = \left(\Phi^\dagger\tau^I i\overleftrightarrow{D^\mu}\Phi\right)(D^\nu W_{\mu\nu})^I$	$\mathcal{O}'_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi})G^A_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi l} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}'_{DB} = \left(\Phi^\dagger i\overleftrightarrow{D^\mu}\Phi\right)(\partial^\nu B_{\mu\nu})$	$\mathcal{O}'_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi)G^A_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi l} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{l}\gamma^\mu\tau^I l)$
$\mathcal{O}'_{D\Phi W} = i(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)W^I_{\mu\nu}$	$\mathcal{O}'_{eW} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi)W^I_{\mu\nu}$	$\mathcal{O}'_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}'_{D\Phi\widetilde{W}} = i(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\widetilde{W}^I_{\mu\nu}$	$\mathcal{O}'_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi})W^I_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi q} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}'_{D\Phi B} = i(D^\mu\Phi)^\dagger(D^\nu\Phi)B_{\mu\nu}$	$\mathcal{O}'_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi)W^I_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi q} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}'_{D\Phi\widetilde{B}} = i(D^\mu\Phi)^\dagger(D^\nu\Phi)\widetilde{B}_{\mu\nu}$	$\mathcal{O}'_{eB} = (\bar{l}\sigma^{\mu\nu}\Gamma_e e\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}'_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}'_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi})B_{\mu\nu}$	$\mathcal{O}'_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}'_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)B_{\mu\nu}\widetilde{B}^{\mu\nu}$	$\mathcal{O}'_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi)B_{\mu\nu}$	$\mathcal{O}'_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud}d)$
$\mathcal{O}'_{\Phi G} = \Phi^\dagger\Phi G^A_{\mu\nu}G^{A\mu\nu}$		
$\mathcal{O}'_{\Phi\widetilde{G}} = \Phi^\dagger\Phi G^A_{\mu\nu}\widetilde{G}^{A\mu\nu}$	Giudice et al. / Contino at al.	$+$(25-2) four-fermion operators

More in Marco's talk

Operators and Multi(EW)-boson Physics (I)

Operators and Multi(EW)-boson Physics (I)

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\partial\Phi} = \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$$
$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger\Phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}]$$
$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu}$$

Operators and Multi(EW)-boson Physics (I)

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\begin{aligned} \mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}] \\ \mathcal{O}_{W} &= (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \\ \mathcal{O}_{B} &= (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) \end{aligned}$$

$$\begin{aligned} \mathcal{O}_{\partial\Phi} &= \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right) \\ \mathcal{O}_{\Phi W} &= \left(\Phi^\dagger \Phi\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}] \\ \mathcal{O}_{\Phi B} &= \left(\Phi^\dagger \Phi\right) B^{\mu\nu} B_{\mu\nu} \end{aligned}$$

Dimension-6 operators for Multiboson physics (CP-violating)

$$\begin{aligned} \mathcal{O}_{\widetilde{W}W} &= \Phi^\dagger \widetilde{W}_{\mu\nu} W^{\mu\nu} \Phi \\ \mathcal{O}_{\widetilde{B}B} &= \Phi^\dagger \widetilde{B}_{\mu\nu} B^{\mu\nu} \Phi \end{aligned}$$

$$\begin{aligned} \mathcal{O}_{\widetilde{W}WW} &= \mathrm{Tr}[\widetilde{W}_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}] \\ \mathcal{O}_{\widetilde{W}} &= (D_\mu \Phi)^\dagger \widetilde{W}^{\mu\nu} (D_\nu \Phi) \end{aligned}$$

Operators and Multi(EW)-boson Physics (I)

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\partial\Phi} = \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$$
$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger\Phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}]$$
$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu}$$

Dimension-6 operators for Multiboson physics (CP-violating)

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger\widetilde{W}_{\mu\nu}W^{\mu\nu}\Phi$$
$$\mathcal{O}_{\tilde{B}B} = \Phi^\dagger\tilde{B}_{\mu\nu}B^{\mu\nu}\Phi$$

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}[\widetilde{W}_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$
$$\mathcal{O}_{\widetilde{W}} = (D_\mu\Phi)^\dagger\widetilde{W}^{\mu\nu}(D_\nu\Phi)$$

Affect the following electroweak couplings:

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{W}$	✓	✓	✓	✓	✓		✓	✓	✓	
$\mathcal{O}_{B}$	✓	✓		✓	✓					
$\mathcal{O}_{\Phi d}$			✓	✓						
$\mathcal{O}_{\Phi W}$			✓	✓	✓	✓				
$\mathcal{O}_{\Phi B}$				✓	✓	✓				
$\mathcal{O}_{\tilde{W}WW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{\tilde{W}}$	✓	✓	✓	✓	✓					
$\mathcal{O}_{\tilde{W}W}$			✓	✓	✓	✓				
$\mathcal{O}_{\tilde{B}B}$				✓	✓	✓				

Operators and Multi(EW)-boson Physics (I)

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}]$$
$$\mathcal{O}_{W} = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$$
$$\mathcal{O}_{B} = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{\partial\Phi} = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$$
$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger \Phi\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}]$$
$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger \Phi\right) B^{\mu\nu} B_{\mu\nu}$$

Dimension-6 operators for Multiboson physics (CP-violating)

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger \widetilde{W}_{\mu\nu} W^{\mu\nu} \Phi$$
$$\mathcal{O}_{\tilde{B}B} = \Phi^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu} \Phi$$

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}[\widetilde{W}_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}]$$
$$\mathcal{O}_{\widetilde{W}} = (D_\mu \Phi)^\dagger \widetilde{W}^{\mu\nu} (D_\nu \Phi)$$

Affect the following electroweak couplings:

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{W}$	✓	✓	✓	✓	✓		✓	✓	✓	
$\mathcal{O}_{B}$	✓	✓		✓	✓					
$\mathcal{O}_{\Phi d}$			✓	✓						
$\mathcal{O}_{\Phi W}$			✓	✓	✓	✓				
$\mathcal{O}_{\Phi B}$				✓	✓	✓				
$\mathcal{O}_{\tilde{W}WW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{\tilde{W}}$	✓	✓	✓	✓	✓					
$\mathcal{O}_{\tilde{W}W}$			✓	✓	✓	✓				
$\mathcal{O}_{\tilde{B}B}$				✓	✓	✓				

connected to Higgs physics

Operators and Multi(EW)-boson Physics (II)

Dimension-8 operators for Multiboson physics

$$
\begin{aligned}
\mathcal{O}_{S,0} &= \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] \\
\mathcal{O}_{S,1} &= \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right]
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_{T,0} &= \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot \mathrm{Tr}\left[W_{\alpha\beta} W^{\alpha\beta} \right] \\
\mathcal{O}_{T,1} &= \mathrm{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \cdot \mathrm{Tr}\left[W_{\mu\beta} W^{\alpha\nu} \right] \\
\mathcal{O}_{T,2} &= \mathrm{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \cdot \mathrm{Tr}\left[W_{\beta\nu} W^{\nu\alpha} \right] \\
\mathcal{O}_{T,5} &= \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot B_{\alpha\beta} B^{\alpha\beta} \\
\mathcal{O}_{T,6} &= \mathrm{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \cdot B_{\mu\beta} B^{\alpha\nu} \\
\mathcal{O}_{T,7} &= \mathrm{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \cdot B_{\beta\nu} B^{\nu\alpha} \\
\mathcal{O}_{T,8} &= B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \\
\mathcal{O}_{T,9} &= B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_{M,0} &= \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] \\
\mathcal{O}_{M,1} &= \mathrm{Tr}\left[W_{\mu\nu} W^{\nu\beta} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right] \\
\mathcal{O}_{M,2} &= \left[B_{\mu\nu} B^{\mu\nu} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] \\
\mathcal{O}_{M,3} &= \left[B_{\mu\nu} B^{\nu\beta} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right] \\
\mathcal{O}_{M,4} &= \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\mu \Phi \right] \cdot B^{\beta\nu} \\
\mathcal{O}_{M,5} &= \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\nu \Phi \right] \cdot B^{\beta\mu} \\
\mathcal{O}_{M,6} &= \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\nu} D^\mu \Phi \right] \\
\mathcal{O}_{M,7} &= \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu \Phi \right]
\end{aligned}
$$

Operators and Multi(EW)-boson Physics (II)

Dimension-8 operators for Multiboson physics

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\begin{aligned}
\mathcal{O}_{T,0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] \\
\mathcal{O}_{T,1} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] \\
\mathcal{O}_{T,2} &= \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right] \\
\mathcal{O}_{T,5} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{O}_{T,6} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{O}_{T,7} &= \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{O}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{O}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}_{M,0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{O}_{M,1} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{O}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{O}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{O}_{M,4} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \cdot B^{\beta\nu} \\
\mathcal{O}_{M,5} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \cdot B^{\beta\mu} \\
\mathcal{O}_{M,6} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right] \\
\mathcal{O}_{M,7} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right]
\end{aligned}$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

Operators and Multi(EW)-boson Physics (II)

Dimension-8 operators for Multiboson physics

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \cdot B^{\beta\nu}$$

$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \cdot B^{\beta\mu}$$

$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right]$$

$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right]$$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right]$$

$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$						✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

- Dim. 8 generate aQGCs, no aTGCs
- generate neutral quartic couplings

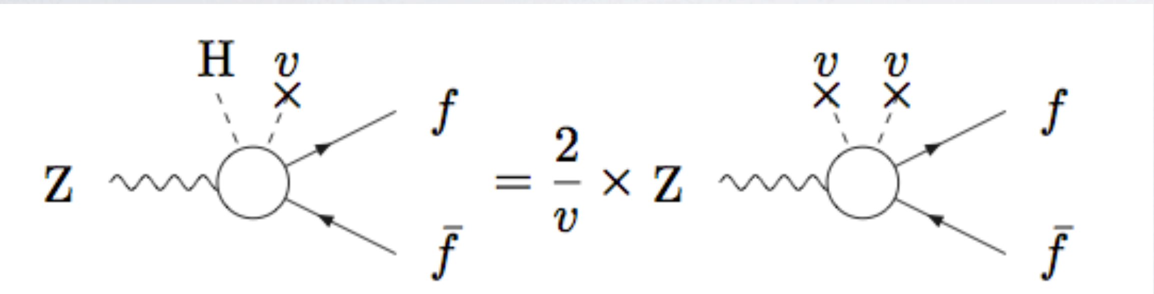
General Procedure using EFTs

- Use all experimental observables $\Longrightarrow$ global fit to all Wilson coefficients
- Would-be optimal approach
- Too many independent variables $\Longrightarrow$ needs staged fitting
- Need for simplifying assumptions
- Try to find minimal "physically well motivated" operator basis
- Experimental bias: consider only LHC-accessible operators
- Cross check from low-energy physics (flavor / EDMs / EWPO etc. / Higgs!)
- Explore full structure of EW Higgs doublet:

General Procedure using EFTs

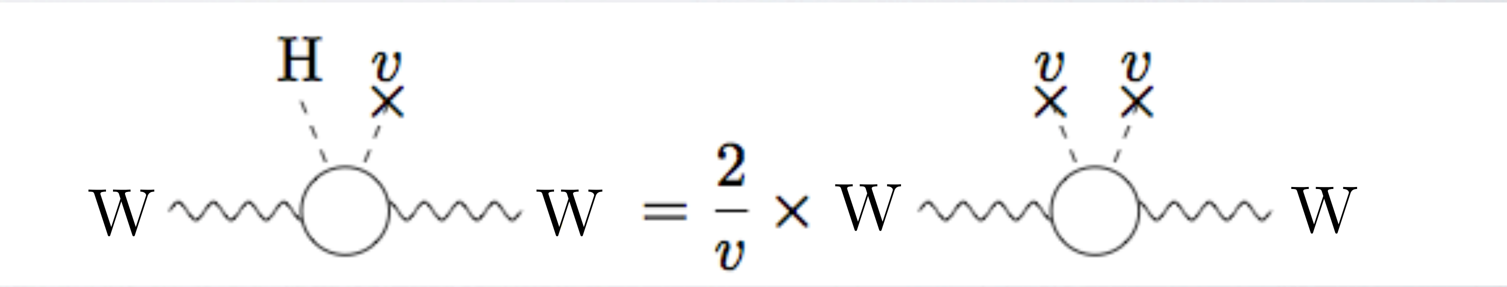
- Use all experimental observables $\Longrightarrow$ global fit to all Wilson coefficients
- Would-be optimal approach
- Too many independent variables $\Longrightarrow$ needs staged fitting
- Need for simplifying assumptions
- Try to find minimal "physically well motivated" operator basis
- Experimental bias: consider only LHC-accessible operators
- Cross check from low-energy physics (flavor / EDMs / EWPO etc. / Higgs!)
- Explore full structure of EW Higgs doublet:

$$\mathcal{O}_{\Phi f} = (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\,(\overline{f}\gamma^\mu f)$$



Effects in $H \to Zff$ related to $Z \to ff \Longrightarrow$ constrained by SLC/LEP

$$\mathcal{O}_{\Phi W} = (\Phi^\dagger \Phi) W_{\mu\nu} W^{\mu\nu}$$



visible in Higgs physics: $H \to WW$

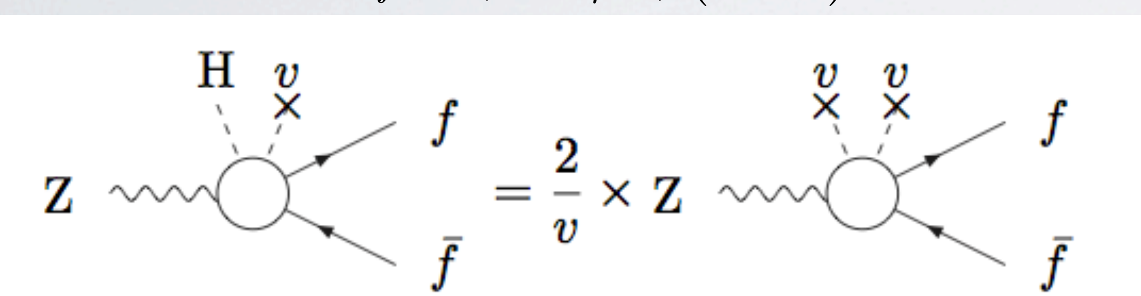
redefines only SM parameters $\Longrightarrow$ no experimental constraints

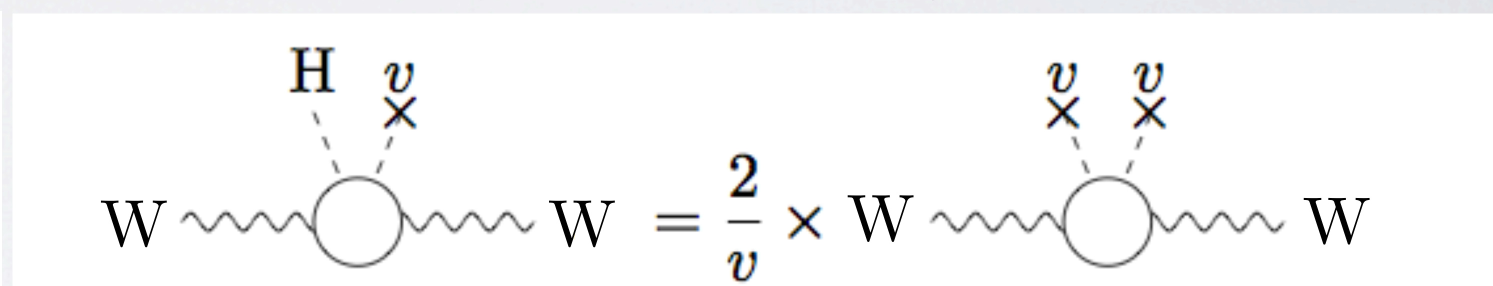
General Procedure using EFTs

- Use all experimental observables $\Longrightarrow$ global fit to all Wilson coefficients
- Would-be optimal approach
- Too many independent variables $\Longrightarrow$ needs staged fitting
- Need for simplifying assumptions
- Try to find minimal "physically well motivated" operator basis
- Experimental bias: consider only LHC-accessible operators
- Cross check from low-energy physics (flavor / EDMs / EWPO etc. / Higgs!)
- Explore full structure of EW Higgs doublet:

$$\mathcal{O}_{\Phi f} = (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\,(\bar{f}\gamma^\mu f)$$

$$\mathcal{O}_{\Phi W} = (\Phi^\dagger \Phi) W_{\mu\nu} W^{\mu\nu}$$





Effects in $H \to Zff$ related to $Z \to ff \Longrightarrow$ constrained by SLC/LEP

visible in Higgs physics: $H \to WW$

redefines only SM parameters $\Longrightarrow$ no experimental constraints

- Often use *vev*-subtracted operators: $\mathcal{O}(\Phi^\dagger\Phi) \longrightarrow \mathcal{O}'(\Phi^\dagger\Phi - v^2)$
- EFT allows to systemically calculate higher-order corrections

$\to$ Talks by A. Karlberg, K. Ellis, S. Kallweit

Higgs Effective Field Theory (HEFT)

- ⋆ Assumption: MFV, fermionic dipole operators vanish (except for top)
- ⋆ Neglect *CP*-odd operators (no interference with SM contributions
- ⋆ Only operators considered that affect Higgs @ tree level
- ⋆ 59 operators reduced to 18 operators:

Elias-Miró/Espinosa/Massó/Pomarol, 2013;
Pomarol/Riva, 2014; Gupta/Pomarol/Riva, 2014

  - ✳ 7 Wilson coefficients constrained by EWPO (0.1%)
  - ✳ 3 Wilson coefficients constrained by aTGC (1%)
  - ✳ 8 Wilson coefficients can be independently constrained by Higgs physics

Higgs Effective Field Theory (HEFT)

- ★ Assumption: MFV, fermionic dipole operators vanish (except for top)
- ★ Neglect *CP*-odd operators (no interference with SM contributions
- ★ Only operators considered that affect Higgs @ tree level
- ★ 59 operators reduced to 18 operators:

Elias-Miró/Espinosa/Massó/Pomarol, 2013; Pomarol/Riva, 2014; Gupta/Pomarol/Riva, 2014

  - ✳ 7 Wilson coefficients constrained by EWPO (0.1%)
  - ✳ 3 Wilson coefficients constrained by aTGC (1%)
  - ✳ 8 Wilson coefficients can be independently constrained by Higgs physics

g_s	$(\Phi^\dagger\Phi)G_{\mu\nu}G^{\mu\nu}$	$\Rightarrow$	Hgg coupling	constrained at ‰ level
g_1	$(\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\Rightarrow$	$H\gamma\gamma$ coupling	constrained at ‰ level
g_2	$(\Phi^\dagger\Phi)W_{\mu\nu}W^{\mu\nu}$	$\Rightarrow$	$H\gamma Z$ coupling	to be constrained
M_W	$(\Phi^\dagger D^\mu\Phi)(\Phi^\dagger D^\mu\Phi)$	$\Rightarrow$	HVV coupling	constrained
M_H	$(\Phi^\dagger\Phi)^3$	$\Rightarrow$	HHH coupling	to be constrained
m_f	$(\Phi^\dagger\Phi)(\overline{f}\Gamma_f f\Phi)$	$\Rightarrow$	Hff coupling	constrained $(f = t, b, \tau)$

Bounds are given for $\Lambda \equiv M_W$!!! (i.e. for $\kappa_{gg}\frac{M_W^2}{\Lambda^2}$)

Higgs Effective Field Theory (HEFT)

- ⋆ Assumption: MFV, fermionic dipole operators vanish (except for top)
- ⋆ Neglect *CP*-odd operators (no interference with SM contributions
- ⋆ Only operators considered that affect Higgs @ tree level
- ⋆ 59 operators reduced to 18 operators:

Elias-Miró/Espinosa/Massó/Pomarol, 2013; Pomarol/Riva, 2014; Gupta/Pomarol/Riva, 2014

  - ✳ 7 Wilson coefficients constrained by EWPO (0.1%)
  - ✳ 3 Wilson coefficients constrained by aTGC (1%)
  - ✳ 8 Wilson coefficients can be independently constrained by Higgs physics

g_s	$(\Phi^\dagger\Phi)G_{\mu\nu}G^{\mu\nu}$	$\Rightarrow$	Hgg coupling	constrained at ‰ level
g_1	$(\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\Rightarrow$	$H\gamma\gamma$ coupling	constrained at ‰ level
g_2	$(\Phi^\dagger\Phi)W_{\mu\nu}W^{\mu\nu}$	$\Rightarrow$	$H\gamma Z$ coupling	to be constrained
M_W	$(\Phi^\dagger D^\mu\Phi)(\Phi^\dagger D^\mu\Phi)$	$\Rightarrow$	HVV coupling	constrained
M_H	$(\Phi^\dagger\Phi)^3$	$\Rightarrow$	HHH coupling	to be constrained
m_f	$(\Phi^\dagger\Phi)(\bar{f}\Gamma_f f\Phi)$	$\Rightarrow$	Hff coupling	constrained $(f = t, b, \tau)$

Bounds are given for $\Lambda \equiv M_W$!!! (i.e. for $\kappa_{gg}\frac{M_W^2}{\Lambda^2}$)

- ⋆ Linear RGE running for Wilson coefficients of dim-6 operators:

$$c_i(\mu) = \left(\delta_{ij} + \gamma_{ij}^{(0)}\frac{\{\alpha,\alpha/s_w^2,\alpha_s\}}{4\pi}\log\left(\frac{\mu}{\Lambda}\right)\right)c_j(\Lambda)$$

How to get EFTs from New Physics

- Consider effects from heavy states by using (known) low-energy d.o.f.s

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy.

H. Georgi, 1993

How to get EFTs from New Physics

- Consider effects from heavy states by using (known) low-energy d.o.f.s

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy.

H. Georgi, 1993

- Integrating out heavy d.o.f.s marginalizes over details of short-distance interactions
- Toy Example: two interacting scalar fields φ, Φ

Path integral

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\;\exp\left[i\int dx\left(\frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}\Phi(\Box + M^2)\Phi - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi\right)\right]$$

How to get EFTs from New Physics

- Consider effects from heavy states by using (known) low-energy d.o.f.s

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy.

H. Georgi, 1993

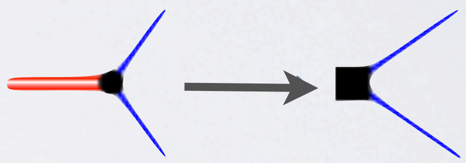
- Integrating out heavy d.o.f.s marginalizes over details of short-distance interactions
- Toy Example: two interacting scalar fields φ, Φ

Path integral

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\ \exp\left[i\int dx\left(\tfrac{1}{2}(\partial\varphi)^2 - \tfrac{1}{2}\Phi(\Box + M^2)\Phi - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi\right)\right]$$

Completing the square (Gaussian integration)

$$\Phi' = \Phi + \frac{\lambda}{M^2}\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2 \qquad \Longrightarrow$$



How to get EFTs from New Physics

- Consider effects from heavy states by using (known) low-energy d.o.f.s

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy.

H. Georgi, 1993

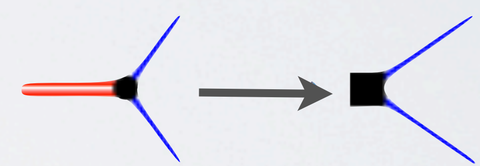
- Integrating out heavy d.o.f.s marginalizes over details of short-distance interactions
- Toy Example: two interacting scalar fields φ, Φ

Path integral

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\;\exp\left[i\int dx\left(\tfrac{1}{2}(\partial\varphi)^2 - \tfrac{1}{2}\Phi(\Box + M^2)\Phi - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi\right)\right]$$

Completing the square (Gaussian integration)

$$\Phi' = \Phi + \frac{\lambda}{M^2}\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2 \qquad \Longrightarrow$$

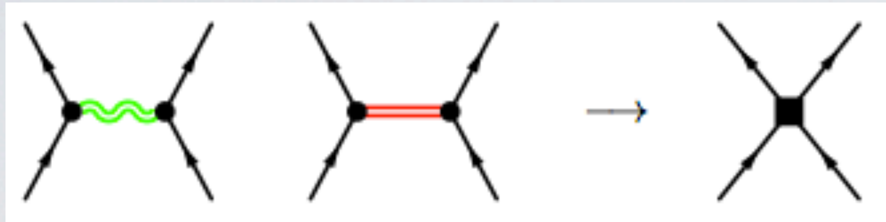


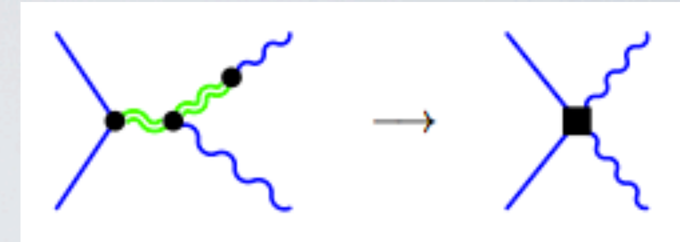
In the Lagrangian remove the high-scale d.o.f.s:

$$\frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi \quad = \quad \underbrace{-\frac{1}{2}\Phi'(M^2 + \partial^2)\Phi'}_{\text{Irrelevant normalization of the path integral}} + \underbrace{\frac{\lambda^2}{2M^2}\varphi^2\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2}_{\text{Tower of higher and higher-dim. operators of light fields}}$$

Generation of Higher-dimensional Operators

$$\mathcal{O}_{JJ}^{(I)} = \frac{1}{\Lambda^2}\mathrm{tr}\left[J^{(I)}\cdot J^{(I)}\right]$$





$$\mathcal{O}'_{WW} = -\frac{1}{\Lambda^2}\frac{1}{2}(\Phi^\dagger\Phi - v^2/2)\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right]$$

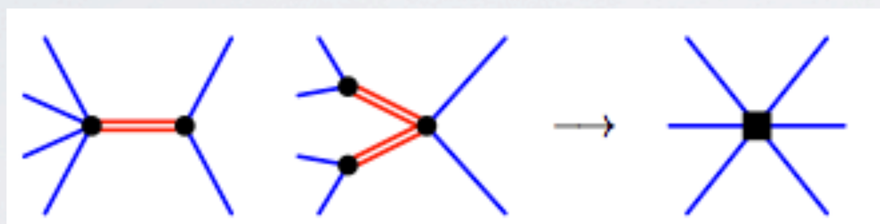
$$\mathcal{O}_B = \frac{1}{\Lambda^2}\frac{i}{2}(D_\mu\Phi)^\dagger(D_\nu\Phi)B^{\mu\nu}$$

$$\mathcal{O}'_{BB} = -\frac{1}{F^2}\frac{1}{4}(\Phi^\dagger\Phi - v^2/2)B_{\mu\nu}B^{\mu\nu}$$

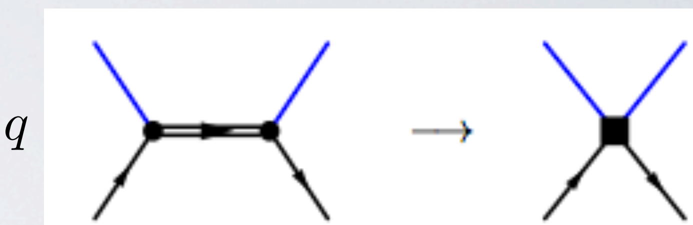
$$\mathcal{O}'_{\Phi,1} = \tfrac{1}{\Lambda^2}\left((D\Phi)^\dagger\Phi\right)\cdot\left(\Phi^\dagger(D\Phi)\right) - \tfrac{v^2}{2}|D\Phi|^2$$

$$\mathcal{O}'_{\Phi\Phi} = \tfrac{1}{\Lambda^2}(\Phi^\dagger\Phi - v^2/2)\,(D\Phi)^\dagger\cdot(D\Phi)$$

$$\mathcal{O}'_{\Phi,3} = \frac{1}{\Lambda^2}\frac{1}{3}(\Phi^\dagger\Phi - v^2/2)^3$$



$$\mathcal{O}_{Vq} = \frac{1}{\Lambda^2}\overline{q}\Phi(\not{D}\Phi)q$$

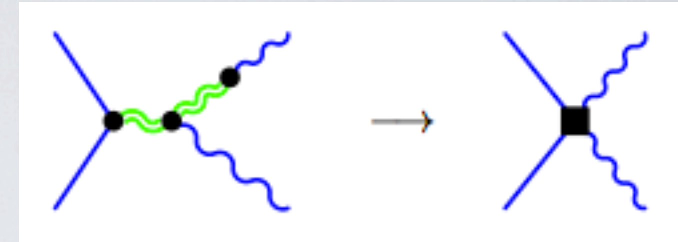


Couplings of new states to the longitudinal / transversal diboson system

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs singlet?)	ω^0 (γ'/Z' ?)	f^0 (Graviton ?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$a^\pm, a^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

Generation of Higher-dimensional Operators

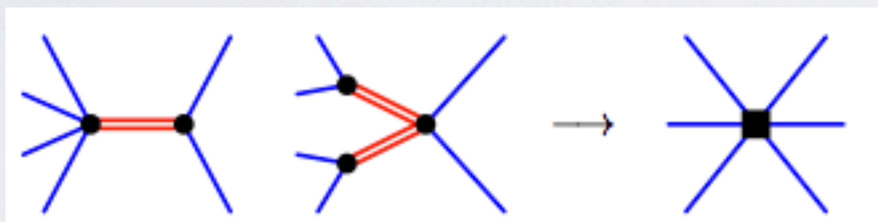
$$\mathcal{O}^{(I)}_{JJ} = \frac{1}{\Lambda^2}\mathrm{tr}\left[J^{(I)} \cdot J^{(I)}\right]$$



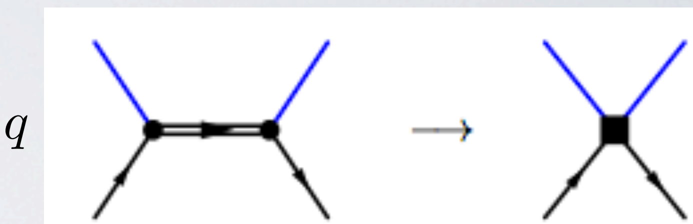
$$\mathcal{O}'_{WW} = -\frac{1}{\Lambda^2}\frac{1}{2}(\Phi^\dagger\Phi - v^2/2)\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right]$$
$$\mathcal{O}_{B} = \frac{1}{\Lambda^2}\frac{i}{2}(D_\mu\Phi)^\dagger(D_\nu\Phi)B^{\mu\nu}$$
$$\mathcal{O}'_{BB} = -\frac{1}{F^2}\frac{1}{4}(\Phi^\dagger\Phi - v^2/2)B_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}'_{\Phi,1} = \tfrac{1}{\Lambda^2}\left((D\Phi)^\dagger\Phi\right)\cdot\left(\Phi^\dagger(D\Phi)\right) - \tfrac{v^2}{2}|D\Phi|^2$$
$$\mathcal{O}'_{\Phi\Phi} = \tfrac{1}{\Lambda^2}(\Phi^\dagger\Phi - v^2/2)\,(D\Phi)^\dagger\cdot(D\Phi)$$

$$\mathcal{O}'_{\Phi,3} = \frac{1}{\Lambda^2}\frac{1}{3}(\Phi^\dagger\Phi - v^2/2)^3$$



$$\mathcal{O}_{Vq} = \frac{1}{\Lambda^2}\overline{q}\Phi(\not{D}\Phi)q$$



Couplings of new states to the longitudinal / transversal diboson system

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs singlet?)	ω^0 (γ'/Z' ?)	f^0 (Graviton ?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$a^\pm, a^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

Different power counting for weakly and strongly interacting theories

$$\frac{c_i}{\Lambda} \sim \frac{g}{4\pi\Lambda} \quad \text{vs.} \quad \frac{c_i}{\Lambda} \sim \frac{g}{\Lambda}$$

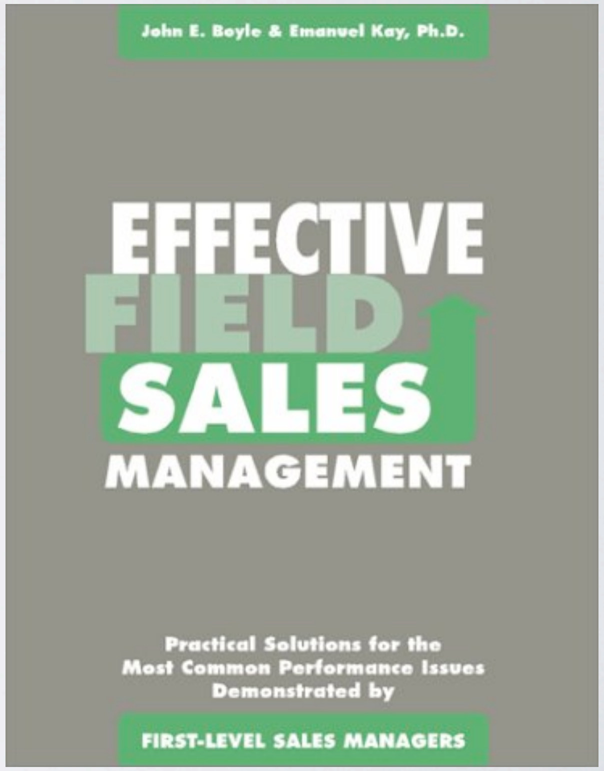
→ Talks by P. Meade, W. Kilian

Conclusions / Summary

- Effective Field Theory provides *a* (!) [not *the*] consistent framework for SM deviations
- Provides powerful tool for fixed energy range [e.g. LHC Higgs production @ threshold]
- Very well-defined (and limited) range of applicability
- Accounts for access to New Physics in the VBS and Di-/Triboson channels
- Big Overlap with Higgs Effective Field Theories (HEFT) $\Longrightarrow$ Cross-Fertilization
- Tasks: operator bases, subsets for initial fits, unitarization, combination with Higgs/EWPO data
- Provide the appropriate tools
- Always compare to specific models
- Make use of simplified models
- Make sure that actual limits are meaningful and comparable

Conclusions / Summary

- ✦ Effective Field Theory provides *a* (!) [not *the*] consistent framework for SM deviations
- ✦ Provides powerful tool for fixed energy range [e.g. LHC Higgs production @ threshold]
- ✦ Very well-defined (and limited) range of applicability
- ✦ Accounts for access to New Physics in the VBS and Di-/Triboson channels
- ✦ Big Overlap with Higgs Effective Field Theories (HEFT) $\Longrightarrow$ Cross-Fertilization
- ✦ Tasks: operator bases, subsets for initial fits, unitarization, combination with Higgs/EWPO data
- ✦ Provide the appropriate tools
- ✦ Always compare to specific models
- ✦ Make use of simplified models
- ✦ Make sure that actual limits are meaningful and comparable



whatever approach ....

whatever approach .... always get the correct ellipses