



MAX-PLANCK-GESELLSCHAFT



Theory of Anomalous Couplings in Effective Field Theory (EFT)

Nicolas Greiner
Max-Planck-Institut für Physik, München



Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

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Motivation



- July 4, 2012: New particle found! (Compatible with SM Higgs)

Besides that, no sign of new physics!



Next steps:

- Try to measure Higgs couplings as precise as possible.
(look for deviations from SM Higgs)
- Continue search for new physics.
But what to look for ? SUSY? Extra dimensions ? Little Higgs ? ...

General approach:

Try to parametrize deviations from SM in a model-independent way



Effective Field Theory



Which features should an extension of the SM have ?

- Extension should satisfy S-Matrix axioms (unitary, analyticity).
- Symmetries of the SM should be respected:
 - Lorentz invariance
 - $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry
- Should be possible to recover SM in an appropriate limit.
- Extension should be general enough to capture any physics beyond SM, but also give some guidance where to look for new physics.
- Should be possible to calculate radiative corrections to SM interactions in the extended theory.
- Should be possible to calculate radiative corrections in the new interactions in the extended theory



Effective Field Theory



This features can be realized by an effective quantum field theory [Weinberg '79]

Construction:

- Add additional operators to the SM Lagrangian. (SM contains operators up to dim 4
→ coupling constants dimensionless)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

- Operators are constructed by defining particle content, e.g: $\mathcal{O}_{WW} = \phi^\dagger \hat{W}^{\mu\nu} \hat{W}_{\mu\nu} \phi$
- Coupling constants inverse powers of mass, mass scale Λ .
- Operators are suppressed if accessible energy low compared to mass scale.
→ Lower dimensional operators more important.
(relevant: dim 6, for complete list, see [Buchmueller, Wyler '86])



Effective Field Theory



Important properties of the effective theory:

- Low energy effective theory ($s < \Lambda^2$).
- Λ : Scale of new physics.
- Fields defined in operator: Particles present at low energies.
- Recover Standard Model in the limit $\Lambda \rightarrow \infty$.

EXAMPLE: Fermi theory of weak interaction / Z'

Z' boson: $\mathcal{O} = \frac{c}{M_{Z'}^2} \bar{\psi} \psi \bar{\psi} \psi$

At low energies: Four fermions present, $\Lambda = M_{Z'}$



Effective Field Theory



- **Strategy:** Write down all possible Dimension 6 operators and calculate their contribution to QGCs (TGCs respectively)
Only consider combinations of **(SM) Higgs** field and **electroweak gauge bosons**.

11 CP-even operators

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D_\mu \Phi)$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{DW} = Tr([D_\mu, \hat{W}_{\nu\rho}][D^\mu, \hat{W}^{\nu\rho}])$$

$$\mathcal{O}_{DB} = -\frac{g'^2}{2} (\partial_\mu B_{\nu\rho}) (\partial^\mu B^{\nu\rho})$$

$$\mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi)$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3} (\Phi^\dagger \Phi)^3$$

$$\mathcal{O}_{WWW} = Tr[\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu]$$

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D^\nu \Phi)$$

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D^\nu \Phi)$$

7 CP-odd operators

$$\mathcal{O}_{\bar{W}W} = \Phi^\dagger \tilde{\hat{W}}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{\bar{W}} = (D_\mu \Phi)^\dagger \hat{\tilde{W}}^{\mu\nu} (D^\nu \Phi)$$

$$\mathcal{O}_{\bar{B}B} = \Phi^\dagger \tilde{\hat{B}}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{\bar{B}} = (D_\mu \Phi)^\dagger \hat{\tilde{B}}^{\mu\nu} (D^\nu \Phi)$$

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

$$\mathcal{O}_{D\bar{W}} = Tr([D_\mu, \hat{W}_{\nu\rho}][D^\mu, \hat{W}^{\nu\rho}])$$

$$\mathcal{O}_{\bar{W}WW} = Tr[\tilde{\hat{W}}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu]$$

Only 5 linear independent

$$\mathcal{O}_{B\bar{W}} = -2\mathcal{O}_{\bar{B}} - \mathcal{O}_{\bar{B}B}$$

$$\mathcal{O}_{\bar{W}} = \mathcal{O}_{\bar{B}} - \frac{1}{2}\mathcal{O}_{\bar{W}W} + \frac{1}{2}\mathcal{O}_{\bar{B}B}$$

Definitions:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

$$D_\mu = \partial_\mu + g \frac{i}{2} W_\mu^a \sigma^a + g' \frac{i}{2} B_\mu$$

$$\hat{B}_{\mu\nu} = i \frac{g'}{2} B_{\mu\nu}, \hat{W}_{\mu\nu} = i \frac{g}{2} \sigma^a W_{\mu\nu}^a$$

$$\tilde{\hat{W}}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} W^{\rho\sigma}$$

Notation/parametrization
not unique, use
[\[Hagiwara,Ishihara,Szalapski,
Zeppenfeld '92\]](#)



Effective Field Theory



Some operators do not / not only contribute to TGCs or QGCs

- $\mathcal{O}_{\Phi,2,3}$: only contribute to Higgs wavefunction and Higgs potential
→ can be neglected!
- \mathcal{O}_{DB} : no gauge couplings, anomalous running of α_{QED}
→ strongly constrained!
- $\mathcal{O}_{\Phi,1}, \mathcal{O}_{BW}, \mathcal{O}_{DW}$: Contribute to T,S,U parameter [Peskin,Takeuchi '91]
→ strongly constrained!

$$\alpha S \equiv 4e^2 [\Pi'_{33}(0) - \Pi'_{3Q}(0)] ,$$

$$\Pi_{AA} = e^2 \Pi_{QQ}, \quad \Pi_{ZA} = \frac{e^2}{sc} (\Pi_{3Q} - s^2 \Pi_{QQ}) ,$$

$$\alpha T \equiv \frac{e^2}{s^2 c^2 m_Z^2} [\Pi_{11}(0) - \Pi_{33}(0)] ,$$

$$\Pi_{ZZ} = \frac{e^2}{s^2 c^2} (\Pi_{33} - 2s^2 \Pi_{3Q} + s^4 \Pi_{QQ}) ,$$

$$\alpha U \equiv 4e^2 [\Pi'_{11}(0) - \Pi'_{33}(0)] .$$

$$\Pi_{WW} = \frac{e^2}{s^2} \Pi_{11} .$$



Effective Field Theory



- Which Operators contribute to which Vertices ?

	\mathcal{O}_{WWW}	\mathcal{O}_{WW}	\mathcal{O}_W	\mathcal{O}_{BB}	\mathcal{O}_B	$\mathcal{O}_{\tilde{B}}$	$\mathcal{O}_{\tilde{B}B}$	$\mathcal{O}_{\tilde{W}W}$	$\mathcal{O}_{\tilde{W}WW}$	$\mathcal{O}_{\tilde{D}W}$
WWZ	×		×		×	×			×	×
WWA	×		×		×	×			×	×
ZZH		×	×	×		×	×	×		
WWH		×	×						×	
AAH		×		×				×	×	
AZH		×	×	×	×	×	×	×		
WWWW	×		×						×	×
WWZZ	×		×						×	×
WWAA	×								×	×
WWAZ	×		×						×	×
WWHH		×	×					×		
ZZHH		×	×	×	×	×	×	×		
AZHH		×	×	×	×	×	×	×		
AAHH		×		×				×		



Alternative: Anomalous couplings



Vertices as starting point: [Gaemers,Gounaris '79]

- Lagrangian approach (for TGC, also for QGC):

$$\begin{aligned}\mathcal{L} = & ig_{WWV} \left(g_1^V (W_{\mu\nu}^+ W^{-\mu} - W^{+\mu} W_{\mu\nu}^-) V^\nu + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W_\mu^{\nu+} W_\nu^{-\rho} V_\rho^\mu \right. \\ & + ig_4^V W_\mu^+ W_\nu^- (\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V \epsilon^{\mu\nu\rho\sigma} (W_\mu^+ \partial_\rho W_\nu^- - \partial_\rho W_\mu^+ W_\nu^-) V_\sigma \\ & \left. + \tilde{\kappa}_V W_\mu^+ W_\nu^- \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W_\mu^{\nu+} W_\nu^{-\rho} \tilde{V}_\rho^\mu \right)\end{aligned}$$

$$V = \gamma, Z; W_{\mu\nu}^\pm = \partial_\mu W_\nu^\pm - \partial_\nu W_\mu^\pm, V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

Note:

- Not necessarily gauge invariant, need to impose

$$g_1^\gamma = 1 \quad g_4^\gamma = g_5^\gamma = 0$$

- Additional terms can be generated by adding derivatives ∂_μ

→ Would get another factors M_W^{-1} , as this is the only scale in the theory.



Alternative: Anomalous couplings



- Vertex function approach:

$$\begin{aligned}\Gamma_V^{\alpha\beta\mu} = & f_1^V (q - \bar{q})^\mu g^{\alpha\beta} - \frac{f_2^V}{M_W^2} (q - \bar{q})^\mu P^\alpha P^\beta + f_3^V (P^\alpha g^{\mu\beta} - P^\beta g^{\mu\alpha}) \\ & + i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho} (q - \bar{q})_\rho \\ & - f_6^V \epsilon^{\mu\alpha\beta\rho} P_\rho - \frac{f_7^V}{m_W^2} (q - \bar{q})^\mu \epsilon^{\alpha\beta\rho\sigma} P_\rho (q - \bar{q})_\sigma\end{aligned}$$

P, q, \bar{q} four momenta of V, W^-, W^+

- Momentum space analogue of Lagrangian approach.
- Coefficients f_i^V are form factors that depend on P^2 , but functional form $f_i^V(P^2)$ is arbitrary.
- W-boson charge and gauge invariance require $f_1^\gamma(0) = 1, f_4^\gamma, f_5^\gamma \sim P^2$
- Sometimes vertex- and Lagrangian approach are mixed by treating $g^V, \kappa_V, \Lambda_V, \dots$ as form factors (but Lagrangian is in position space)



Effective Theory vs. Anomalous Couplings



Transitions between effective field theory and anomalous coupling

Start with the operators contributing to trilinear couplings [Hagiwara,Ishihara,Szalapski,Zeppenfeld '92]

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

→ Relations between approaches can be derived:

$$\begin{aligned}g_1^Z &= 1 + c_W \frac{m_Z^2}{2\Lambda^2} & f_1^Y &= 1 + c_{WWW} \frac{3g^2 P^2}{4\Lambda^2} \\ \kappa_\gamma &= 1 + (c_W + c_B) \frac{m_W^2}{2\Lambda^2} & f_1^Z &= 1 + c_W \frac{m_Z^2}{\Lambda^2} - c_{WWW} \frac{3g^2 P^2}{4\Lambda^2} \\ \kappa_Z &= 1 + (c_W - c_B \tan^2 \theta_W) \frac{m_W^2}{2\Lambda^2} & f_2^Y &= f_2^Z = c_{WWW} \frac{3g^2 m_W^2}{2\Lambda^2} \\ \lambda_\gamma &= \lambda_Z = c_{WWW} \frac{3g^2 m_W^2}{2\Lambda^2} & f_3^Y &= 2 + (c_B + c_W) \frac{m_W^2}{2\Lambda^2} + c_{WWW} \frac{3g^2 m_W^2}{2\Lambda^2} \\ g_4^V &= g_5^V = 0 & f_3^Z &= 2 + (c_W(1 + \cos^2 \theta_W) - c_B \sin^2 \theta_W) \frac{m_Z^2}{2\Lambda^2} + c_{WWW} \frac{3g^2 m_W^2}{2\Lambda^2} \\ \tilde{\kappa}_\gamma &= c_{\tilde{W}} \frac{m_W^2}{2\Lambda^2} & f_4^Y &= f_5^V = 0 \\ \tilde{\kappa}_Z &= -c_{\tilde{W}} \tan^2 \theta_W \frac{m_W^2}{2\Lambda^2} & f_6^Y &= +c_{\tilde{W}} \frac{m_W^2}{2\Lambda^2} - c_{\tilde{W}WW} \frac{3g^2 m_W^2}{2\Lambda^2} \\ \tilde{\lambda}_\gamma &= \tilde{\lambda}_Z = c_{\tilde{W}WW} \frac{3g^2 m_W^2}{2\Lambda^2} & f_6^Z &= -c_{\tilde{W}} \tan^2 \theta_W \frac{m_W^2}{2\Lambda^2} - c_{\tilde{W}WW} \frac{3g^2 m_W^2}{2\Lambda^2} \\ && f_7^Y &= f_7^Z = -c_{\tilde{W}WW} \frac{3g^2 m_W^2}{4\Lambda^2}\end{aligned}$$



Effective Theory vs. Anomalous Couplings



Relations between different couplings:

$$\Delta g_1^Z = \Delta \kappa_Z + \tan^2 \theta_W \Delta \kappa_\gamma$$

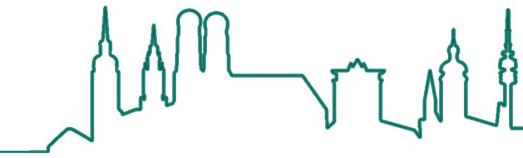
$$\Delta g_1^Z = g_1^Z - 1, \Delta \kappa_{\gamma,Z} = \kappa_{\gamma,Z} - 1$$

$$0 = \tilde{\kappa}_Z + \tan^2 \theta_W \tilde{\kappa}_\gamma$$

- Effective field theory approach leads to simplifications (due to restriction to dim 6).
- Transition between the approaches work only if coupling constants are not modified to form factors !
- In anomalous couplings approach there is no relation between TGCs and QGCs !



Dimension 8 operators



- All previous statements made for Dim-6 operators also hold for Dim-8 operators.
- Only from Dim-8 on there are operators that contribute to QGC but not TGC.
- That does not imply that there are no Dim-8 operators contributing to TGC.
- Dim-8 operators stronger suppressed than Dim-6 operators.
If both contribute equally, higher dim. Operators can not be neglected.
→ EFT approach breaks down!

$$\begin{aligned}\mathcal{L}_{S,0} &= \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] \\ \mathcal{L}_{S,1} &= \left[(D_\mu \Phi)^\dagger D^\alpha \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\beta \Phi \right] \\ \mathcal{L}_{M,0} &= \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] \\ \mathcal{L}_{M,1} &= \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right] \\ \mathcal{L}_{M,2} &= [B_{\mu\nu} B^{\mu\nu}] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] \\ \mathcal{L}_{M,3} &= [B_{\mu\nu} B^{\nu\beta}] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right] \\ \mathcal{L}_{M,4} &= \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi \right] \times B^{\beta\nu} \\ \mathcal{L}_{M,5} &= \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi \right] \times B^{\beta\mu} \\ \mathcal{L}_{M,6} &= \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\nu \Phi \right] \\ \mathcal{L}_{M,7} &= \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi \right] \\ \mathcal{L}_{T,0} &= \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \text{Tr} \left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right] \\ \mathcal{L}_{T,1} &= \text{Tr} \left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right] \\ \mathcal{L}_{T,2} &= \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right] \\ \mathcal{L}_{T,3} &= \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\nu\alpha} \right] \times B_{\beta\nu} \\ \mathcal{L}_{T,4} &= \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\alpha\mu} \hat{W}^{\beta\nu} \right] \times B_{\beta\nu} \\ \mathcal{L}_{T,5} &= \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta} \\ \mathcal{L}_{T,6} &= \text{Tr} \left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu} \\ \mathcal{L}_{T,7} &= \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha} \\ \mathcal{L}_{T,8} &= B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \\ \mathcal{L}_{T,9} &= B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}\end{aligned}$$



Current limits (TGC)



- LEP-Bounds on TGC (no QGC) [Aihara,Barklow,Baur,Busenitz,Errede,Fuess,Han,London '95]

$$\Delta g_1^Z = -0.033 \pm 0.031,$$

$$\Delta \kappa_\gamma = 0.056 \pm 0.056,$$

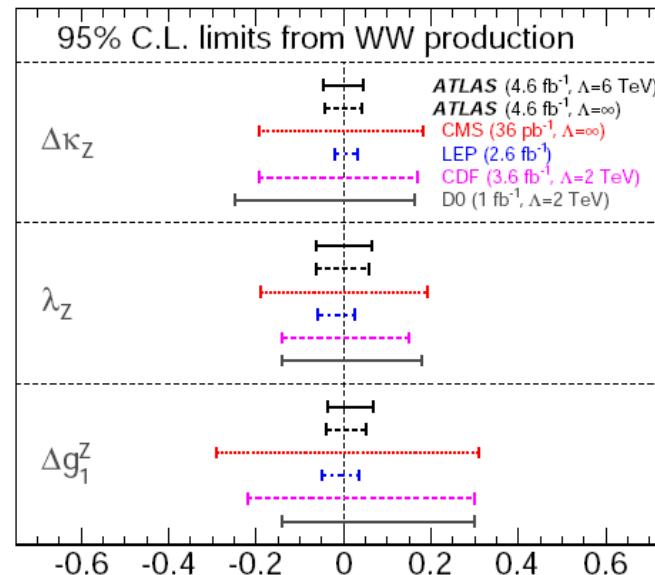
$$\Delta \kappa_Z = -0.0019 \pm 0.044,$$

$$\lambda_\gamma = -0.036 \pm 0.034,$$

$$\lambda_Z = 0.049 \pm 0.045.$$

- LHC Bounds:

[Atlas, arxiv:1210.2979]





Unitarity in the SM



- Famous SM example: longitudinal WW → WW scattering

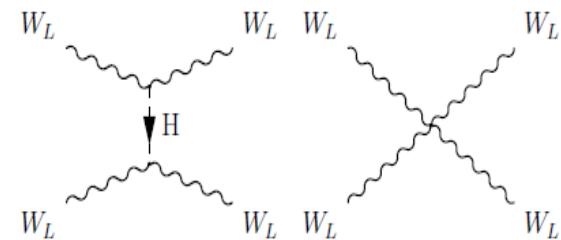
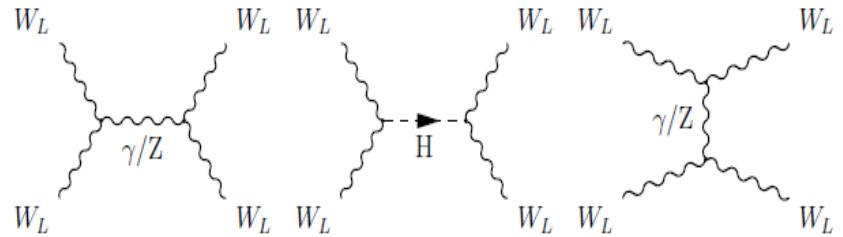
- Longitudinal polarization:

$$\lim_{k \rightarrow \infty} \epsilon_k^\mu(k) = \frac{k^\mu}{m} + \mathcal{O}\left(\frac{m}{E}\right)$$

- For each diagram: $|\mathcal{M}|^2 \sim k^8$
 - Adding photon, Z and 4W vertex:

$$|\mathcal{M}|^2 \sim k^4$$

- Summing all diagrams: $|\mathcal{M}|^2 \sim k^0$



- In SM unitarity is preserved by gauge cancellations.
- Adding additional terms (dim 6 operators) spoils cancellations



Unitarity



Effective Field theory:

- Dimension 6 operators yield amplitudes $\sim \frac{s}{\Lambda^2}$.
- Will eventually violate unitarity → But then the theory is useless (low energy effective theory), should not be applied anymore!

Alternative Anomalous Couplings approach:

- Yields amplitudes $\sim \frac{s}{M_W^2}$.
- Leads to unitarity violation → Use vertex function and choose form factors such that they decrease at high energies (also done with lagrangian, hard to justify).
→ Valid up to arbitrary energies.

IMPORTANT:

- Measurement will NEVER violate unitarity!
- Effective theory that fits data will not violate unitarity → No need for form factors!



Unitarity in EFT



Remember:

- Low energy effective theory only valid below scale Λ .
- If $s \approx \Lambda^2$: Higher dimensional operators are no longer suppressed
→ Approach no longer useful.
- For Z' example: If $s \approx M_{Z'}^2$:
Effective theory has to be replaced by a theory which contains Z' as low energy content.
- If measurement leads to dim 6 coupling constants not compatible with zero:
→ Replace EFT by full theory that can explain the measurement.



Unitarity in EFT



How do we know up to which energy the EFT is valid ??

→ Unitarity bound can be calculated!

- Partial wave decomposition: [Jacob,Wick '59]

$$\langle \theta \phi \lambda_c \lambda_d | T(E) | 00 \lambda_a \lambda_b \rangle = 16\pi \sum_J (2J+1) \langle \lambda_c, \lambda_d | T^J(E) | \lambda_a, \lambda_b \rangle e^{i(\lambda-\mu)\phi} d_{\lambda\mu}^J(\theta)$$

$$\lambda = \lambda_a - \lambda_b \quad \mu = \lambda_c - \lambda_d \quad d_{00}^l(\theta) = P_l(\cos \theta)$$

- Unitarity requires (for all partial waves): $|T^J| \leq 1$
- 0th partial wave:

$$P_0 = \int_{-1}^1 \mathcal{M} d(\cos \theta) = \int_0^\pi \mathcal{M} \sin \theta d\theta$$

- Leads to energy-dependent unitarity bounds, e.g. [Gounaris,Layssac,Paschalis,Renard '95]

$$\frac{f_W}{\Lambda^2} \leq \frac{31}{s}$$



Experimental Searches



- Low energy experiments (up to LEP-II)
 - ✓ Very precise results /observables → **Strong constraints**
 - ✗ Many operators not constrained, basically **no direct constraints** on QGCs
- LHC era (14Tev):
 - Effects of dim 6 operators grow with energy
 - ✓ Tails of distributions promising (pT, invariant masses, etc.)
 - ✗ Enough events left ?
 - Tree-level vs. loop induced :
 - Operator can contribute **directly** to tree-level process
 - Operator can contribute **indirectly** through loop processes (anomalous running, contribution to masses, etc)
 - ➔ **In general:** Contributions to tree level processes lead to stronger constraints !



Experimental Searches



- Difference between measurement and SM prediction determines maximal size of BSM contribution
- For given observable X , theoretical prediction given by

$$X_{\text{th}} = X_{\text{SM}} + \sum_i C_i X_i^{\text{dim}6}$$

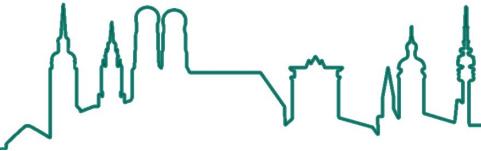
Calculate χ^2 :

$$\chi^2 = \sum_X \frac{(X_{\text{th}} - X_{\text{exp}})^2}{\sigma_X^2} = \sum_X \frac{(X_{\text{SM}} - X_{\text{exp}} + \sum_i C_i X_i^{\text{dim}6})^2}{\sigma_X^2}$$

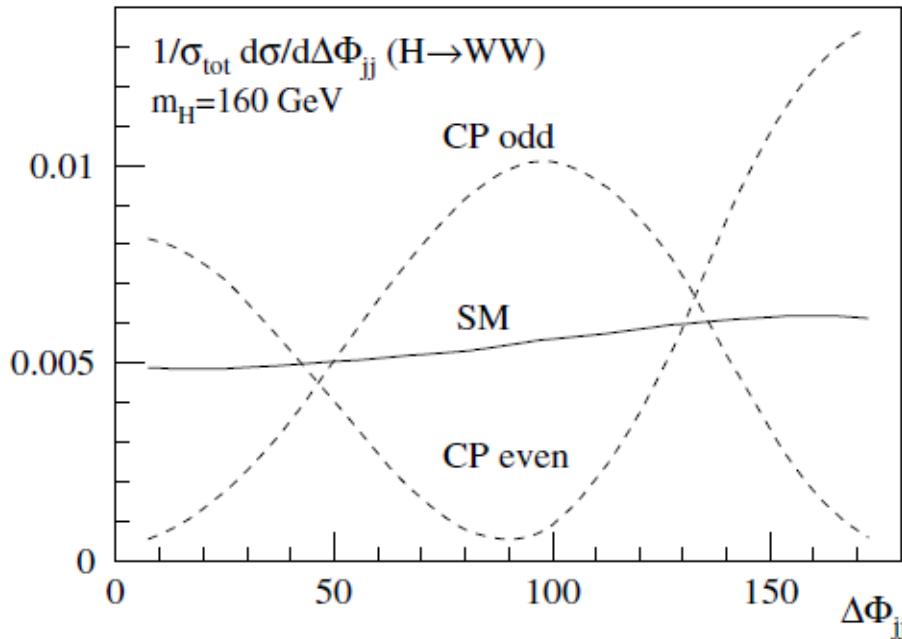
- Minimizing χ^2 leads to a fit for the coefficients C_i .
If coefficients not consistent with zero: **NEW PHYSICS!**
- Useful for EW precision observables also for loop-induced effects.



Experimental Searches



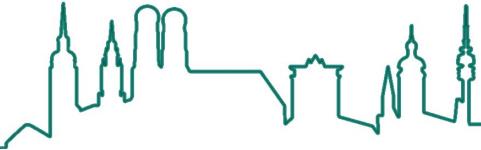
- CP-structure influences observables
Example: Azimuthal angle of tagging jets in VBF signature
[Plehn,Rainwater,Zeppenfeld '02]



- Example: Higgs production (and decay) in VBF.
Anomalous couplings change distribution according to underlying CP properties.
- Effect big enough to be detected ??



Experimental Searches



Various other approaches for experimental searches:

- Kinematic methods (for review, e.g. [\[Barr,Lester, '10\]](#))
Uses kinematical information, no knowledge about underlying model required.
Works for small number of events.
- Matrix Element Method
Makes use of all events in sample. Works very well if underlying model is well understood (ideally for both signal and background), and only set of parameters needs to be determined.

$$P(\mathbf{x}|\boldsymbol{\alpha}) = \int d\mathbf{y} P_\alpha(\mathbf{y}) W(\mathbf{x}, \mathbf{y})$$

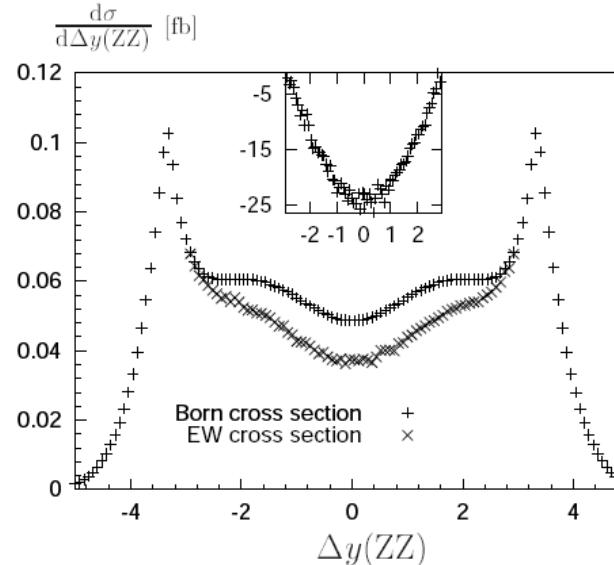
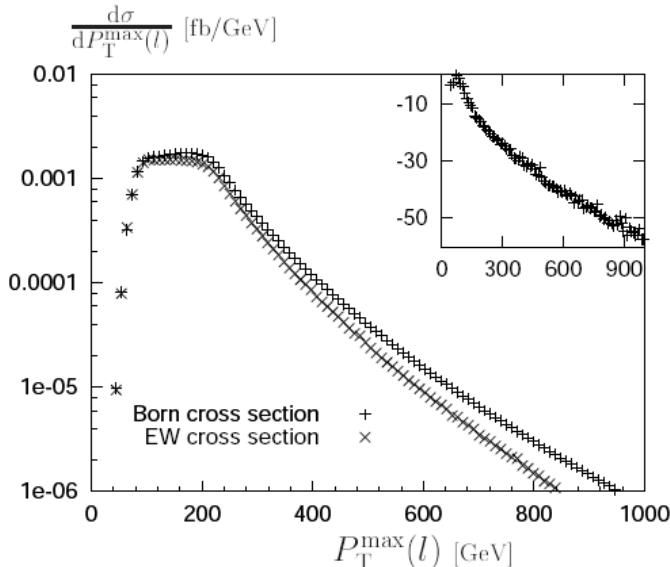
$$P(\mathbf{x}|\boldsymbol{\alpha}) = \frac{1}{\sigma_\alpha} \int d\Phi(\mathbf{y}) dq_1 dq_2 f_1(q_1) f_2(q_2) |M_\alpha|^2(\mathbf{y}) W(\mathbf{x}, \mathbf{y})$$



Missing SM contributions



- Missing higher order corrections from the SM can fake new physics.
- Most important contribution typically NLO QCD
K-factor in general not constant, rescaling of LO result with global K-factor not sufficient, deviations in particular in tails of distribution.
- Also electroweak corrections can be sizeable.
Example: Electroweak corrections to gauge boson pair production
[\[Accomondo,Denner,Kaiser '04\]](#)

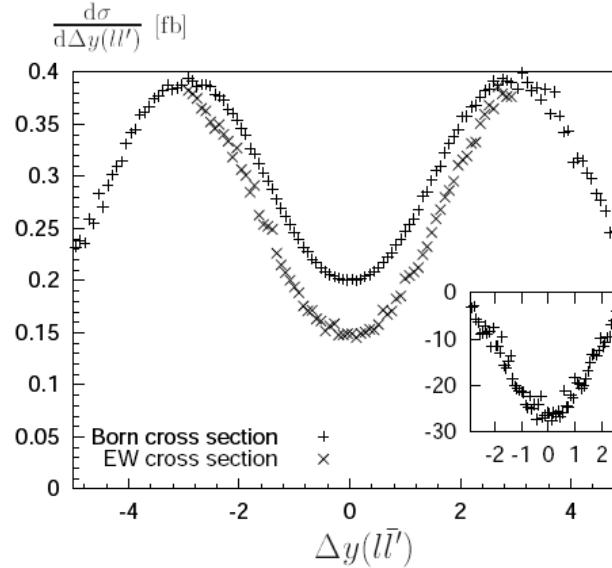
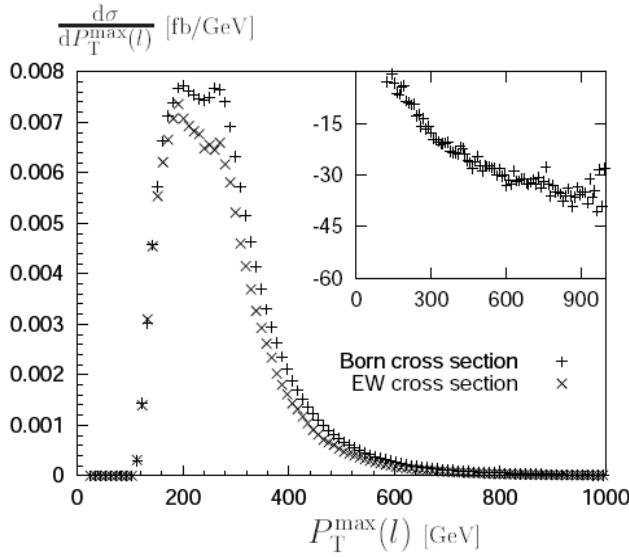


**ZZ-pair
production**



MAX-PLANCK-GESELLSCHAFT

Missing SM contributions



WW-pair
production

- Considerable contributions due to NLO EW corrections.
- Sizeable distortion of distributions.



Precise determination of anomalous couplings requires precise knowledge of SM contribution (at least NLO QCD and EW)!



Summary



- EFT provides a model independent approach to BSM physics.
- EFT low energy theory, only valid well below new physics scale Λ .
- Connection between TGCs and QGCs due to gauge symmetry.
- Effects of higher dim. Operators grow with energy → Tails of distributions interesting.
- Growing contribution leads to unitarity violation → EFT not valid, has to be replaced by UV completed model.