Searching for New Physics with Electroweak Effective Operators

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May 7, 2012

The Challenge

- We believe there is new physics at some higher energy scale
- Each BSM theory has its own set of parameters
- We would like a single, model-independent framework for parametrizing indirect effects of new physics

Effective Field Theory: An Introduction

- At sufficiently low energies, new physics can be integrated out and treated perturbatively

- The resulting Lagrangian will contain terms of dimension greater than four, suppressed by inverse powers of the energy scale of new physics

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_i c_i \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_j c_j \mathcal{O}_j^{(6)} + \cdots$$

Extending the Standard Model

- We need to extend the standard model in a way that will handle all possible low-energy effects of new physics while maintaining gauge invariance

- A complete basis comprises 59 dimension-six operators (there is only one dimension-five operator)

- Here, we will focus on operators involving electroweak bosons

Selected Dimension-Six Electroweak Operators

$$
\begin{aligned}
\mathcal{O}_{WWW} &= \epsilon_{IJK} W_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu} \\
\mathcal{O}_{WB} &= (\phi^\dagger \tau^I \phi) W_{\mu\nu}^{I} B^{\mu\nu} \\
\mathcal{O}_{\phi}^{(3)} &= (\phi^\dagger D_\mu \phi)(D^\mu \phi^\dagger \phi) \\
\mathcal{O}_{\phi W} &= \frac{1}{2} (\phi^\dagger \phi) W_{\mu\nu}^{I} W^{I\mu\nu} \\
\mathcal{O}_{\phi B} &= \frac{1}{2} (\phi^\dagger \phi) B_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{W} &= (D_\mu \phi)^\dagger \tau^I W^{I\mu\nu} (D_\nu \phi) \\
\mathcal{O}_{B} &= (D_\mu \phi)^\dagger B^{\mu\nu} (D_\nu \phi)
\end{aligned}
$$

Anomalous Couplings

- The anomalous couplings approach involves writing down interaction terms with no regard for gauge invariance

$$\mathcal{L} = ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2}W^{+\nu}_\mu W^{-\rho}_\nu V_\rho{}^\mu + \cdots\right)$$

- Alternatively, we can move to momentum space and write down a vertex function

$$\Gamma^{\mu\nu\rho} = f_1^V(p^2,q^2)\left\{p^\nu\eta^{\mu\rho} - q^\mu\eta^{\nu\rho} + (q-p)^\rho\eta^{\mu\nu}\right\} + f_2^V(p^2,q^2)\left\{(p+q)^\nu\eta^{\mu\rho} - (p+q)^\mu\eta^{\nu\rho}\right\} + \dots$$

where f_1^V and f_2^V are functions of momentum and are called form factors

Unitarity

- S-matrix unitarity and partial wave analysis imply a bound on the amplitude of any 2-to-2 inelastic scattering process

$$\sum_{\lambda_3,\lambda_4} \int dPS_2 \, |T^{in}|^2 \leq 24\pi$$

- Higher-dimensional operators may add terms to $|T^{in}|^2$ which grow like s/Λ^2, possibly violating unitarity at high energies

Unitarity, cont'd

- In the anomalous couplings approach, form factors are constructed so as prevent unitarity violation at arbitrarily high energies
- An effective field theory will not violate unitarity at energies less than Λ and has nothing to say about energies above Λ
- We are interested in energies for which there is data; data does not violate unitarity

Tree-Level Cross Section

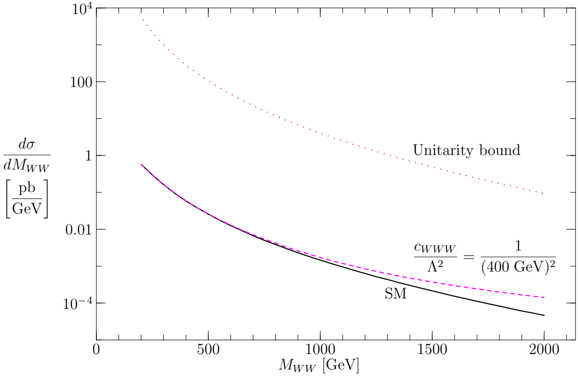
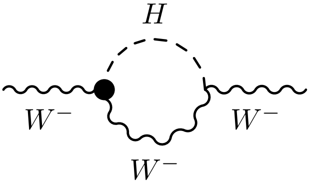
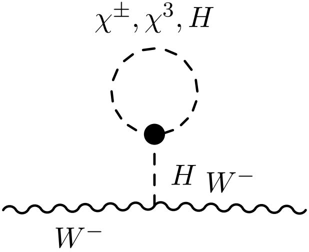
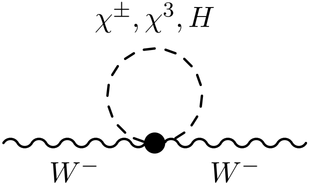


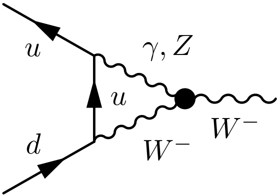
Figure: Cross section versus invariant mass for the process $pp \to W^+W^-$ at the LHC. The pink dashed curve includes the dimension-six operator O_{WWW}.

Loop-Level Effects









Summary

- Effective field theory is a model-independent framework for studying indirect effects of physics beyond the standard model
- Unlike the anomalous couplings approach, it preserves $SU(3) \times SU(2) \times U(1)$ gauge symmetry and provides a framework for handling divergences
- Unitarity violation is not a concern in effective field theory, and form factors are not needed