Precision Frontier Panel Discussion

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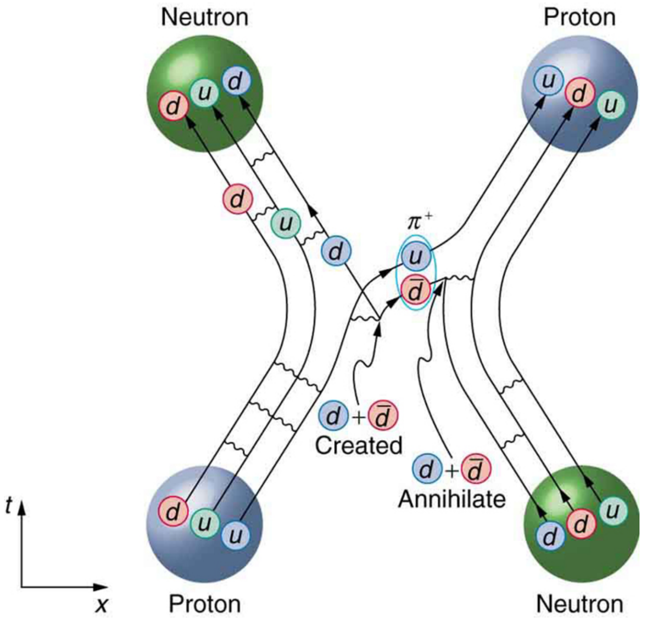

Snowmass Workshop
Minneapolis – August 1, 2013

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Answer: A lot

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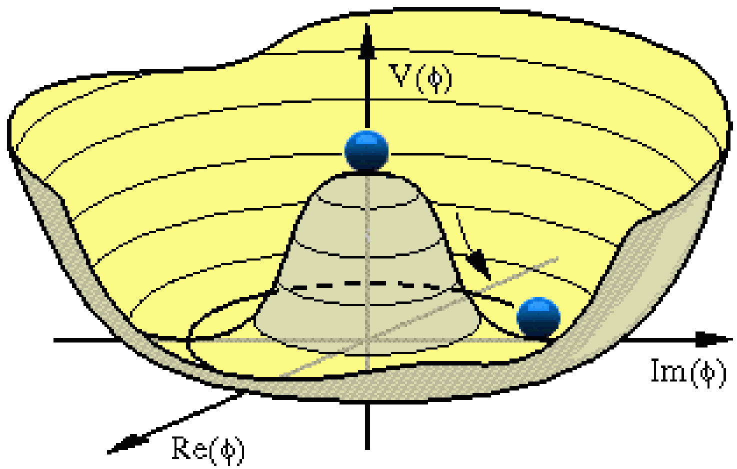
Do theories exist where we expect to naturally have SM-like precision measurements, but large deviations in the TGCs & QGCs?

Answer: yes

Spontaneous Symmetry Breaking of Gauge Symmetry

- The Higgs potential in the SM is a parameterization that respects certain rules of QFT



- Phase transition → vacuum state possesses non-trivial quantum numbers

- Dynamical origin of this phase transition is not known (see Peskin's talk on Tuesday)

- Broadly speaking, underlying dynamics may be
  - Weakly coupled (e.g. Supersymmetry)
  - Strongly coupled

A Toy Model for BSM Extension of Higgs Sector

- Consider a term coupling the Higgs to a singlet scaler *S*: $f\,\phi^\dagger \phi S$
- Via *S* exchange, can mediate scattering process: $\phi\phi \to \phi\phi$

- For energies << m_S, induces effective field theory operators:
  - Dimension-4: $(f/m_S)^2\,(\phi^\dagger\phi)^2$
  - Dimension-6: $O_{\phi d} = (f^2/m_S^4)\;\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$
  - This is one of the operators predicted in strongly-interacting light Higgs models
    - Alternate mechanism to SUSY for ensuring light Higgs boson

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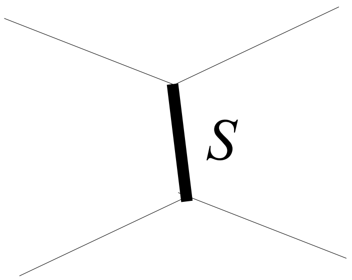

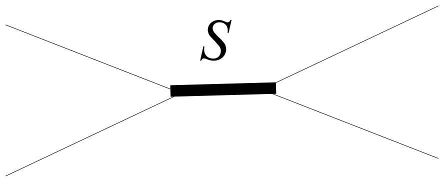

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  - Observing a deviation in gauge and Higgs couplings consistent with this model would immediately point to model parameter values for *f* and m_S

Examples from Strongly Interacting Light Higgs models

Effective Field Theory Operators provide a general parameterization of new physics at a high mass scale

Especially useful to parameterize new strong dynamics

(see Low *et al*, JHEP 1004:126 (2010), Giudice *et al*, JHEP06, 045 (2007) and references therein)

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

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Coupling modifications

Pure gauge → ($\mathcal{O}_{WWW}$)

	ZWW	AWW	HWW	HZZ	HZA	HAA
$\mathcal{O}_{WWW}$	x	x				
$\mathcal{O}_{W}$	x	x	x	x	x	
$\mathcal{O}_{B}$	x	x		x	x	
$\mathcal{O}_{\phi d}$			x	x		
$\mathcal{O}_{\phi W}$			x	x	x	x
$\mathcal{O}_{\phi B}$				x	x	x

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Gauge & Higgs couplings → ($\mathcal{O}_{W}$, $\mathcal{O}_{B}$)

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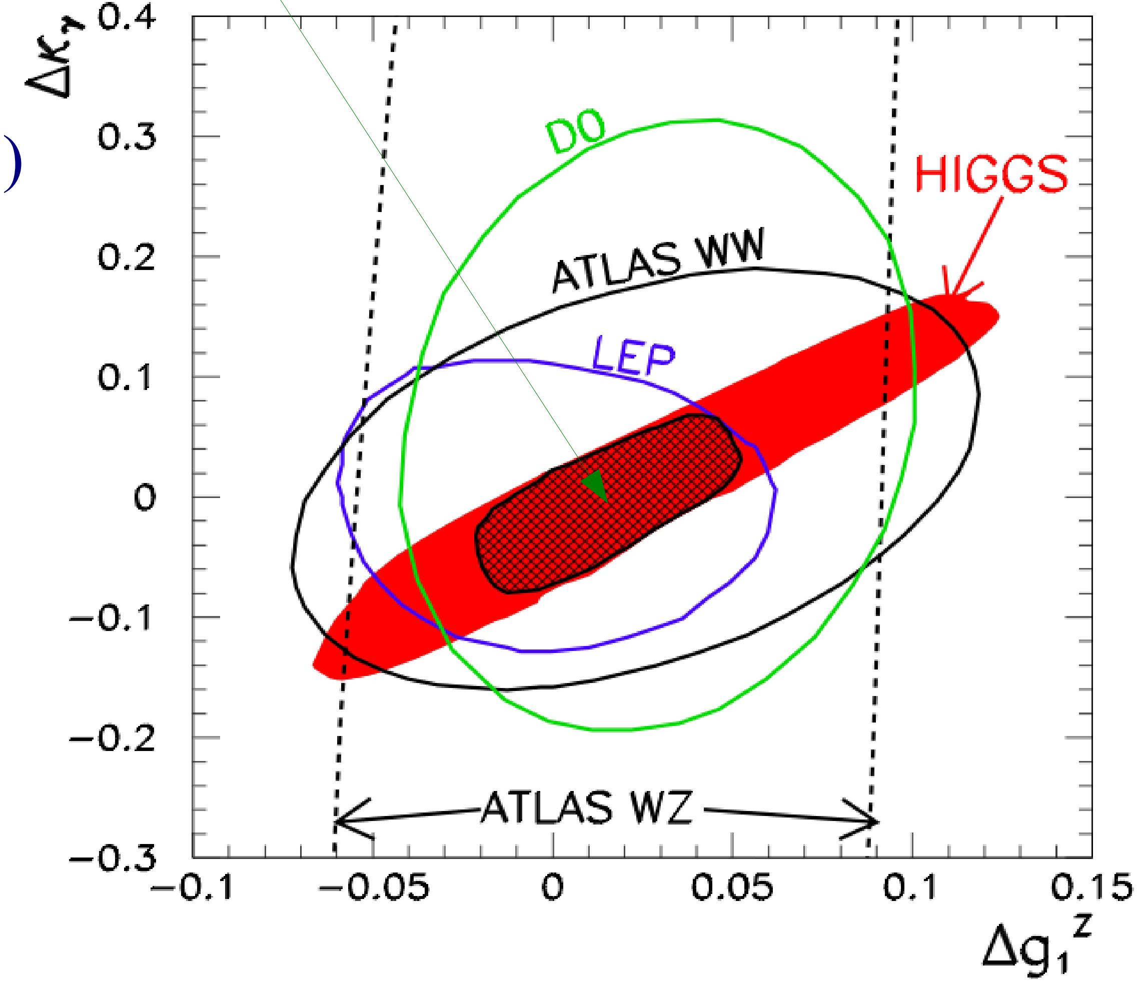
$\mathcal{O}_{\phi B}$				x	x	x

Higgs couplings { $\mathcal{O}_{\phi d}$, $\mathcal{O}_{\phi W}$, $\mathcal{O}_{\phi B}$ }

Combined Fit to Higgs and Anomalous Gauge Couplings

- Illustrates the complementary of approaches to new physics via deviations of Higgs-to-gauge and gauge-gauge couplings
  - Combined fit provides significantly tighter constraints

$\propto (O_W + O_B)$

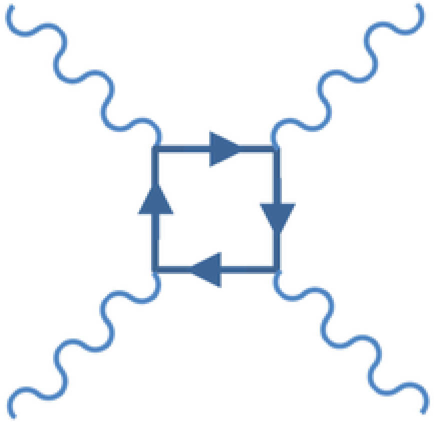


$\propto O_W$

Corbett *et al.*, arXiv:1304.1151

Another Toy Model – for Dimension-8 Operators

- Consider the analogy with light-by-light scattering via electron loop



- Euler-Heisenberg effective lagrangian at low energies

$$\mathcal{L} = \frac{1}{2}\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{2\alpha^2}{45m^4}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + 7\left(\mathbf{E}\cdot\mathbf{B}\right)^2\right]$$

Another Toy Model – for Dimension 8 Operators

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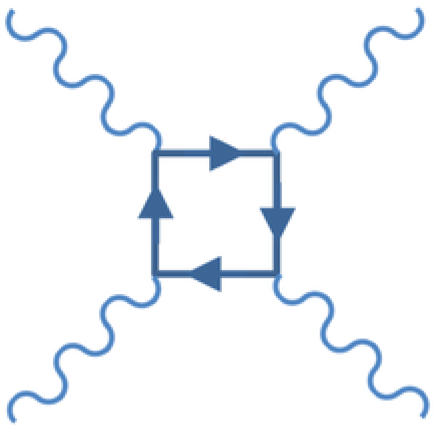

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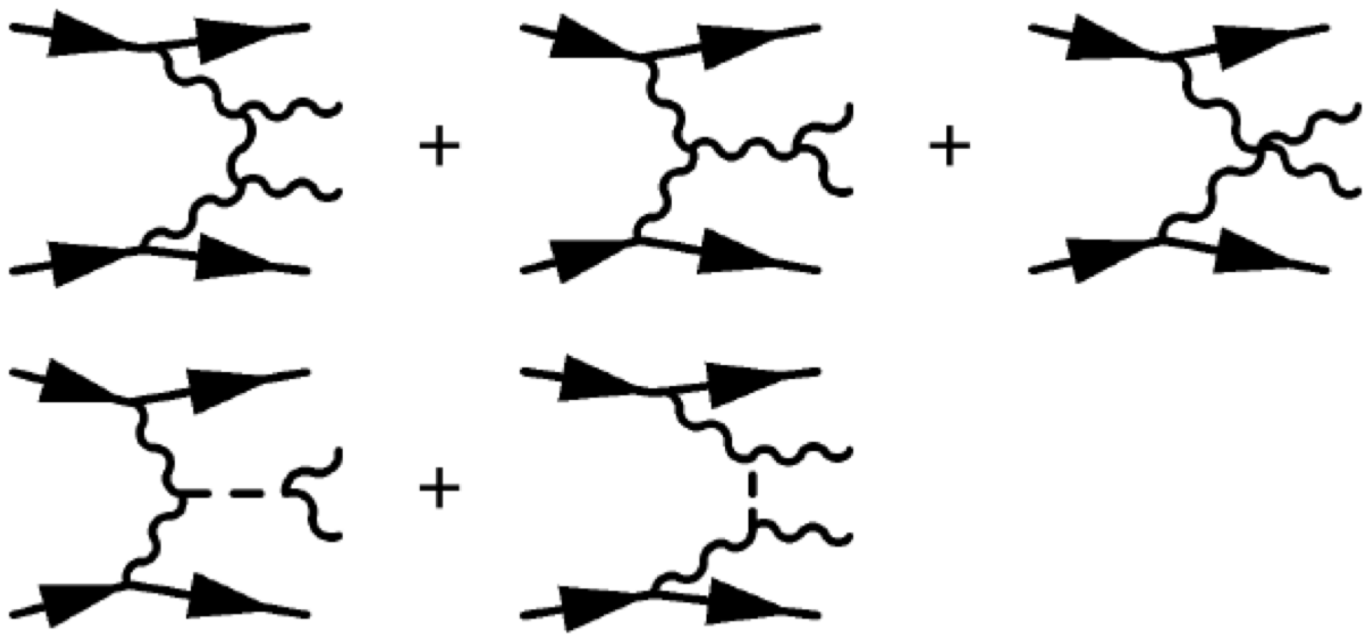
  - Second term can be re-written in terms of

$$F_{\mu\rho}F^{\mu\sigma}F^{\nu\rho}F_{\nu\sigma} \qquad \left(F_{\mu\nu}F^{\mu\nu}\right)^2$$

Operator coefficients contain information on mass and coupling of new dynamical degrees of freedom

Vector Boson Scattering

- This is a key process accessible for the first time at LHC



Vector Boson Scattering is intimately connected with EWSB

Provides a unique method of exploring the possibility of strong dynamics

Effective Field Theory Operators at Dimension-8

- All dimension-6 and dimension-8 operators involving SM boson fields have been catalogued

$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j$$

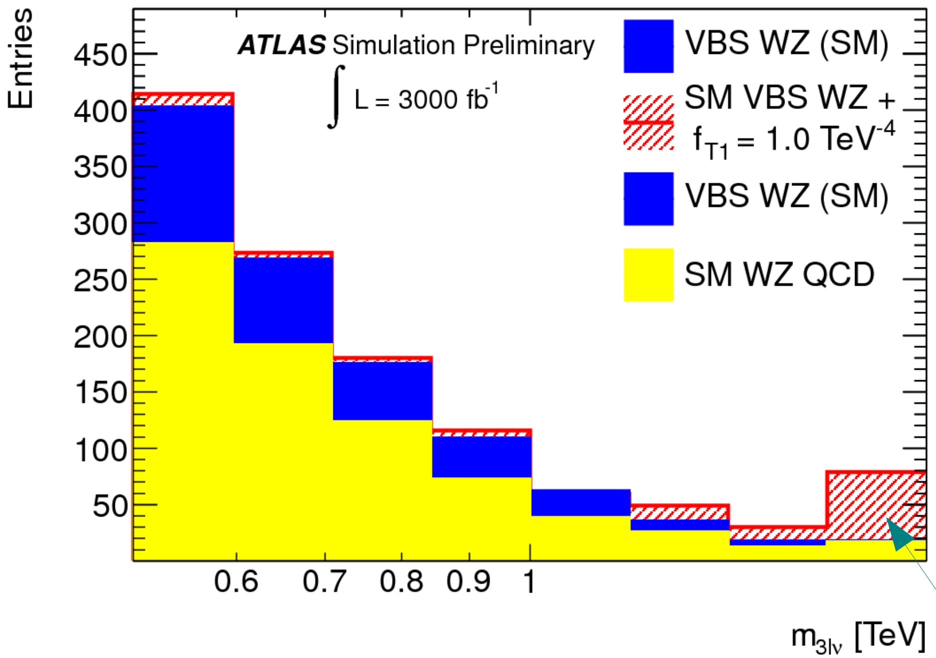
- Examples of dimension-8 operators

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

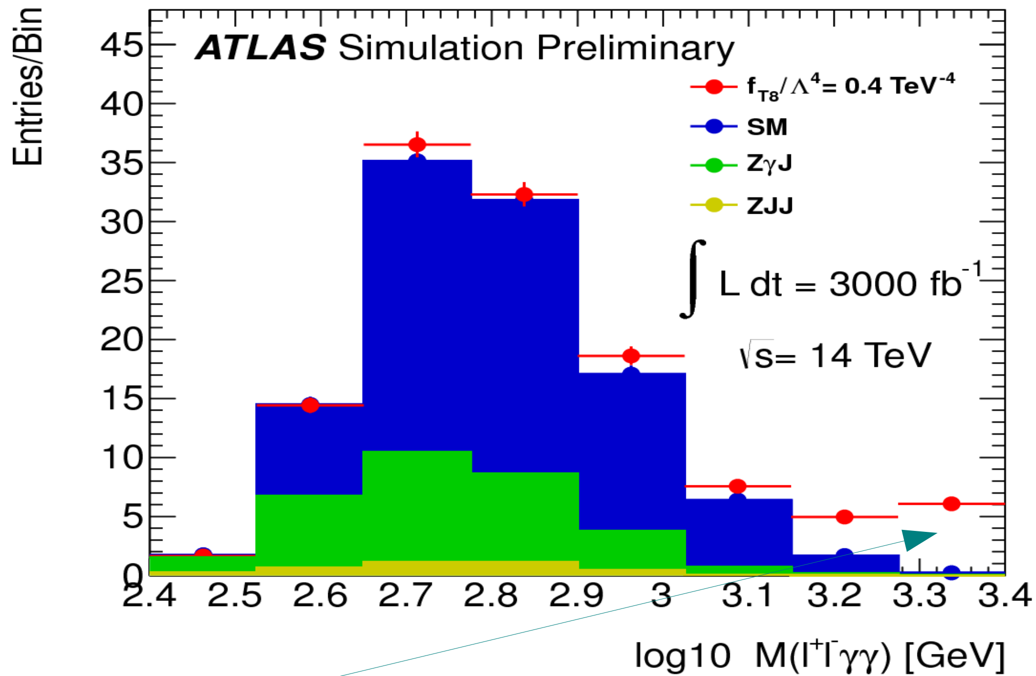
- Dimension-8 operators only affect vector boson scattering and triboson production
  - These processes open up a new and unique window on new dynamics in the EWSB sector

Studies of Multi-boson Scattering

vector boson scattering
WZ → leptons



triboson production
Zγγ



Potential signals imply sensitivity to strong dynamics at TeV-scale

(ATL-PHYS-PUB-2013-006, ATLAS White Paper arXiv:1307.7292)

EF12. What do we gain from measurements of gauge couplings, trilinear (TGC) & quartic (QGC), in light of other precision electroweak data?

Answer: A lot, because heavy gauge bosons and Higgs boson are inextricably linked. Gauge couplings contain complementary and independent information to other electroweak measurements

Do theories exist where we expect to naturally have SM-like precision measurements, but large deviations in the TGCs & QGCs?

Answer: yes, individual models eg. Littlest Higgs etc. predict specific values for coefficients of specific higher-dimension operators.

Observing a certain pattern of deviations in gauge boson processes electroweak precision observables, Higgs and gauge boson processes can pick out certain models and associated mass scales.