Vector Boson Scattering at 100 TeV pp Collider

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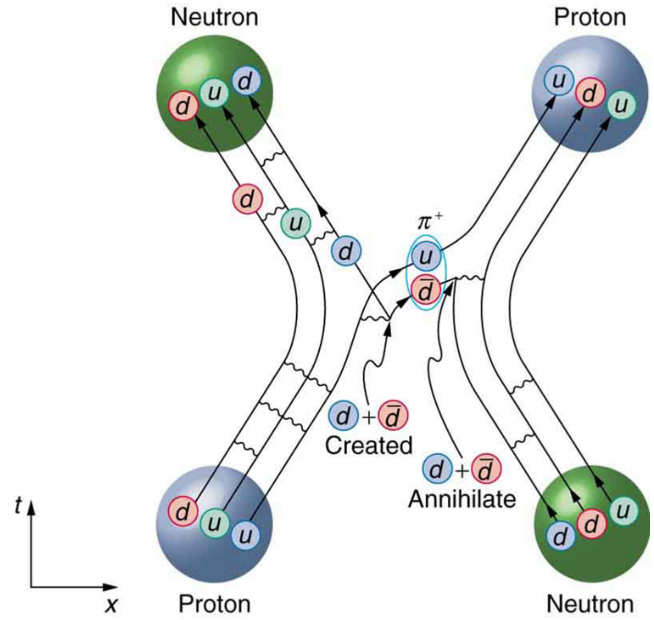

100 TeV Workshop
Fermilab – August 26, 2014

Questions from Snowmass 2013 Workshop

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

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

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Answer: A lot

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

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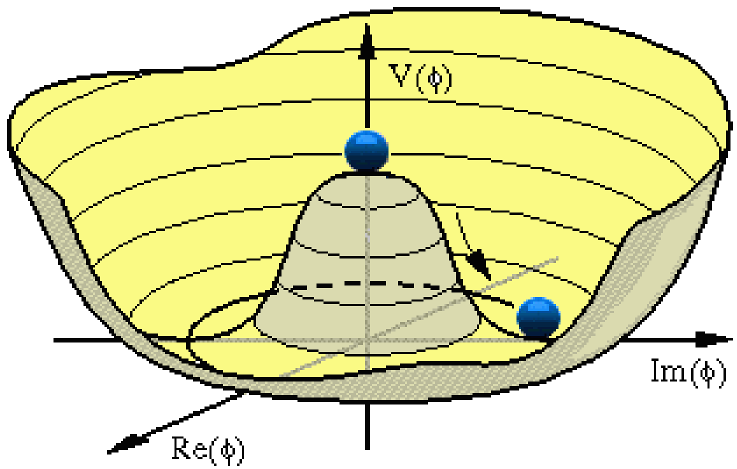
Do theories exist where we expect to naturally have SM-like precision measurements, but large deviations in the TGCs & QGCs?

Answer: yes

Spontaneous Symmetry Breaking of Gauge Symmetry

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



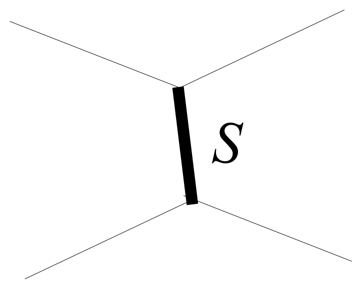
- Phase transition → vacuum state possesses non-trivial quantum numbers

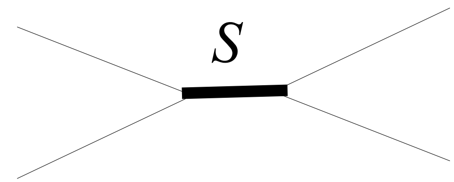
- Dynamical origin of this phase transition is not known

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

A Toy Model for BSM extension

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





$[\Box - m_s^2]^{-1} \sim m_s^{-2}[1 + \Box/m_s^2]$

- For energies << m_S, induces effective field theory operators:
  - Dimension-4: $(f/m_S)^2\left(\phi^\dagger\phi\right)^2$
  - 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
  - alters VBS compared to SM

A Toy Model for BSM extension

- Consider a term coupling the Higgs to a singlet scaler S: $f\,\phi^\dagger\phi S$
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  - Dimension-6: $O_{\phi d} = (f^2/m_S^4)\ |\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$
  - 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)

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

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Coupling modifications

Pure gauge →

	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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Coupling modifications

Gauge & Higgs couplings

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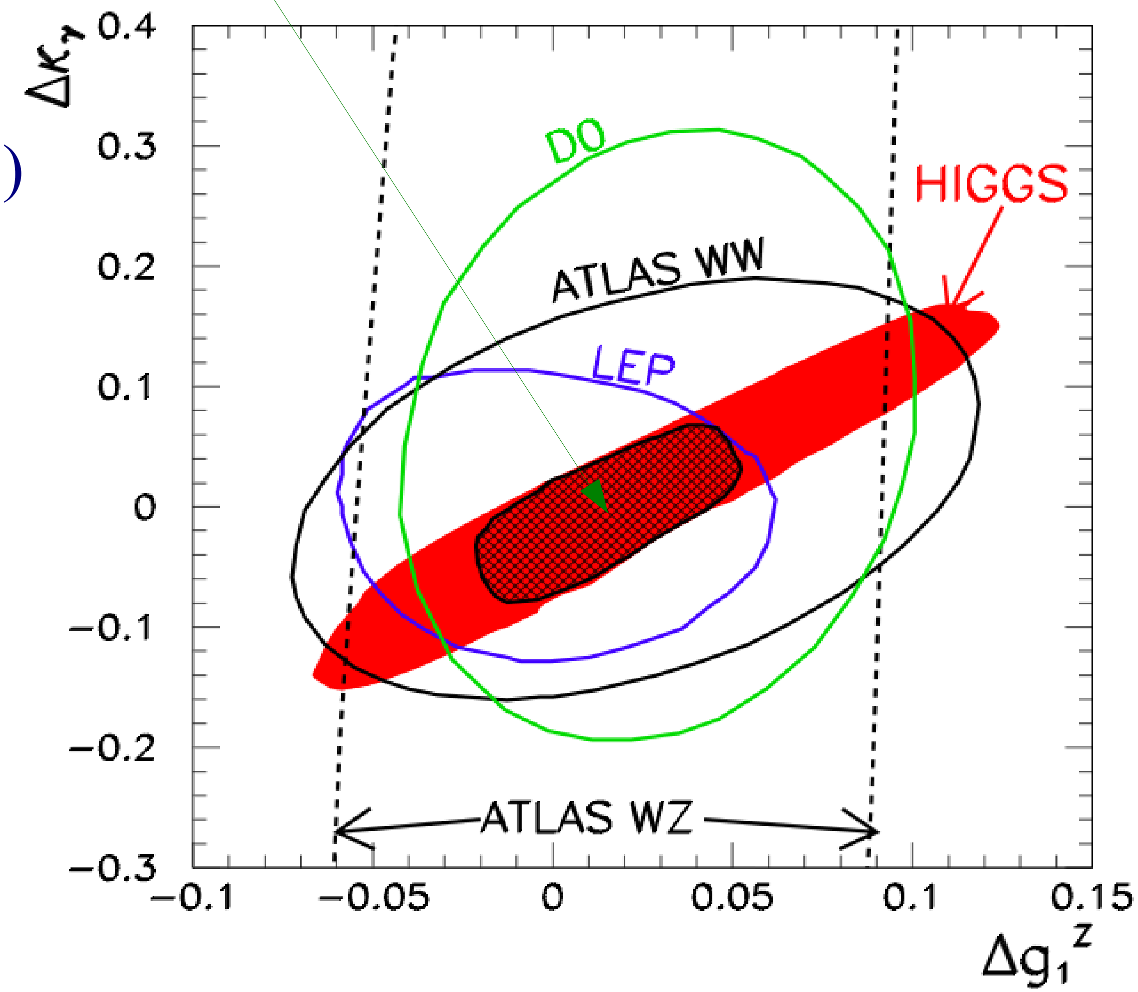
$\mathcal{O}_{\phi d}$			x	x		
$\mathcal{O}_{\phi W}$			x	x	x	x
$\mathcal{O}_{\phi B}$				x	x	x

Higgs couplings

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

$\propto (O_W + O_B)$

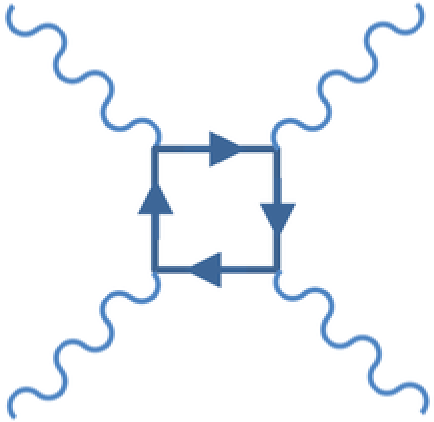


$\propto O_W$

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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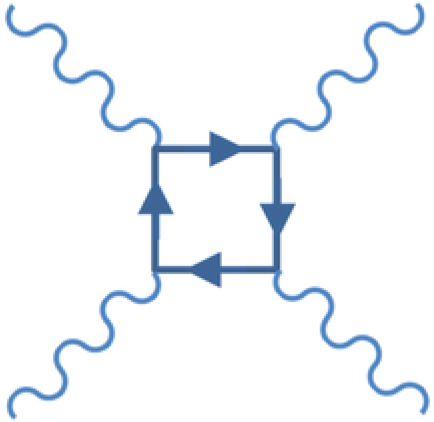

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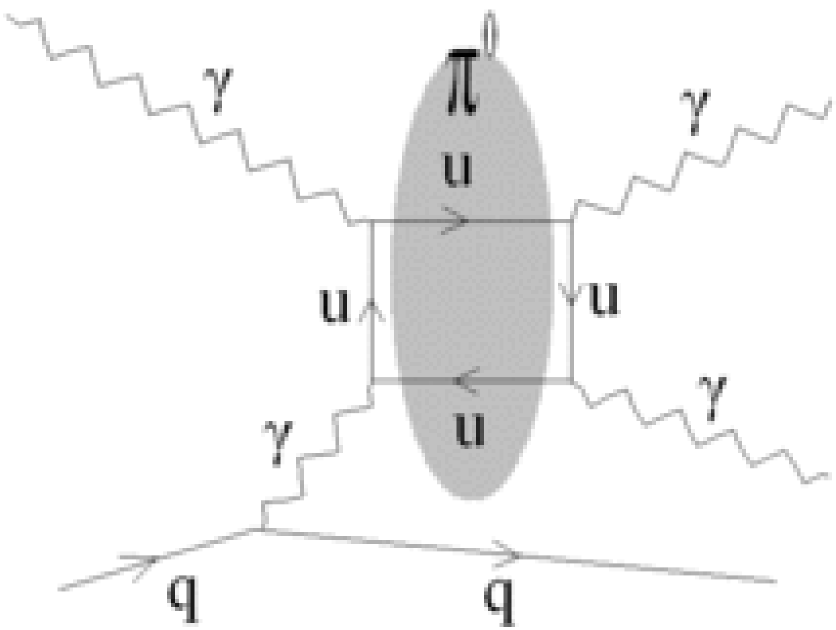
  – Second term can be re-written in terms of

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

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

Another Analogy – Primakoff Production of π^0

- Primakoff production by photon interacting with strong nuclear EM field



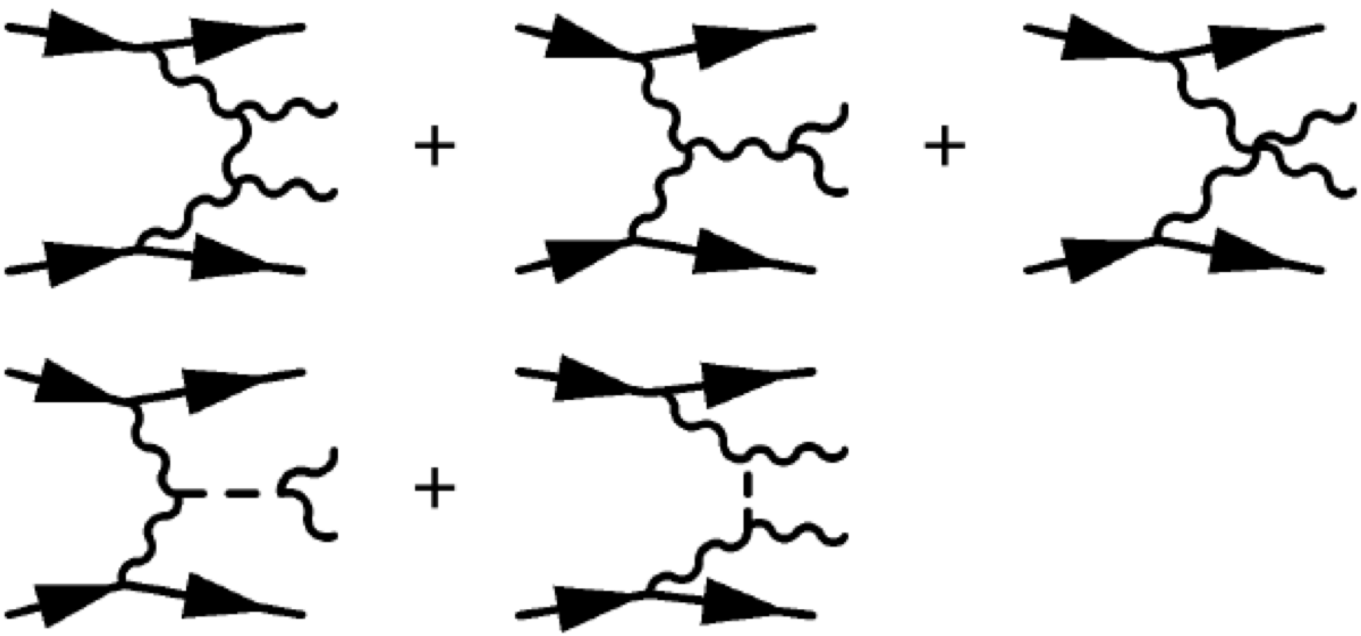
  - Therefore following operators can describe scalar resonance production in VBS

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

Operator coefficients contain information on mass and coupling of new scalar resonance

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

Effective Field Theory Operators

- All dimension-6 and dimension-8 operators have been catalogued

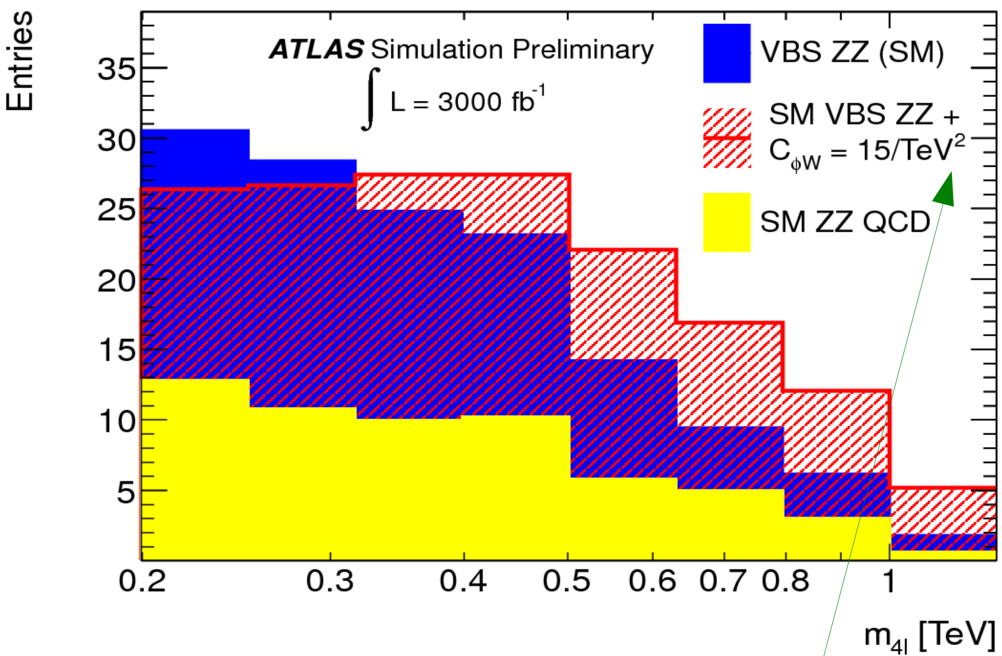
$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j$$

- VBS processes have the potential for
  - measuring new physics parameterized by higher-dimension operators
  - Differentiating between different operators using
    - Direct measurement of energy-dependence
    - different channels
  - Dimension-8 operators tested:

$$\begin{aligned}
\mathcal{O}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{O}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{O}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{O}_{T,1} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]
\end{aligned}$$

VBS Studies using Forward Tagged Jets

ZZ → leptons

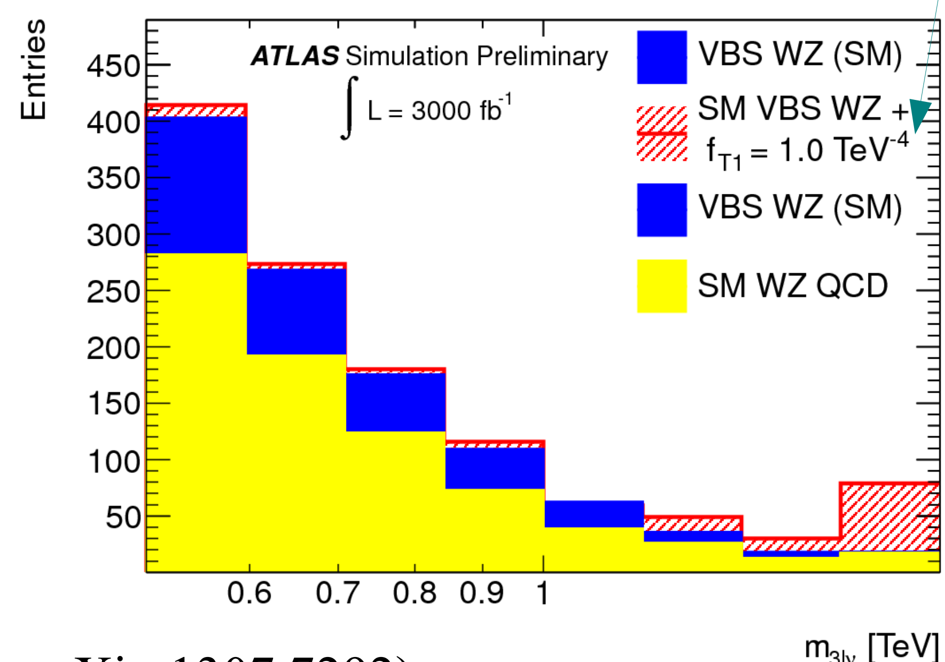


$p_T^j > 50$ GeV

$m_{jj} > 1$ TeV

dim-8 operator coefficient implies sensitivity to strong dynamics at TeV-scale

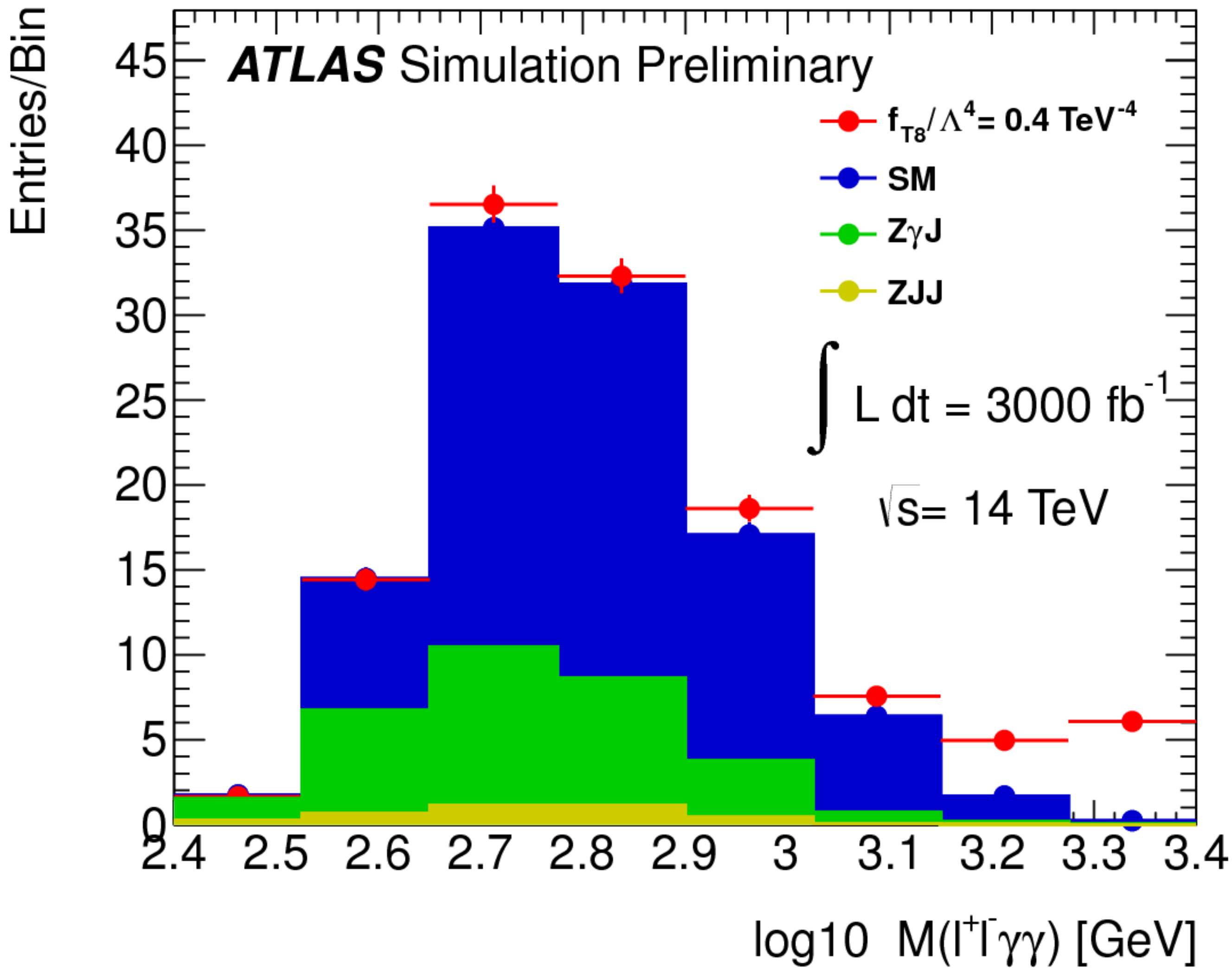
WZ → leptons



Threshold of interest for dim-6 operator coefficient $< v^{-2} \sim 16\ \mathrm{TeV}^{-2}$

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

Complementarity of VBS and Triboson production



Anomalous Zγγ production at high mass also very sensitive to "T" operators

=> Comparison of VBS and triboson production is another powerful capability for characterizing the new physics

VBS and Tribosons at 100 TeV pp Collider

Parameter	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	pileup	5σ [TeV^{-4}]	95% CL [TeV^{-4}]
$f_{T,1}/\Lambda^4$	14	300	50	0.2 (0.4)	0.1 (0.2)
$f_{T,1}/\Lambda^4$	14	3000	140	0.1 (0.2)	0.06 (0.1)
$f_{T,1}/\Lambda^4$	14	3000	0	0.1 (0.2)	0.06 (0.1)
$f_{T,1}/\Lambda^4$	100	1000	40	0.001 (0.001)	0.0004 (0.0004)
$f_{T,1}/\Lambda^4$	100	3000	263	0.001 (0.001)	0.0008 (0.0008)
$f_{T,1}/\Lambda^4$	100	3000	0	0.001 (0.001)	0.0008 (0.0008)

Table 1-25. *In $pp \to W^\pm W^\pm + 2j \to \ell\nu\ell\nu + 2j$ processes, 5σ-significance discovery values and 95% CL limits are shown for coefficients the higher-dimension operator, $f_{T,1}/\Lambda^4$, for different machine scenarios without the UV cut and with the UV cut in parenthesis. Pileup refers to the number of pp interactions per crossing.*

Parameter	dim.	Luminosity [fb^{-1}]	14 TeV	33 TeV	100 TeV
c_{WWW}/Λ^2 [TeV^{-2}]	6	300	4.8 (8)	-	-
		1000	-	-	1.3 (1.5)
		3000	2.3 (2.5)	1.7 (2.0)	0.9 (1.0)
$f_{T,0}/\Lambda^4$ [TeV^{-4}]	8	300	1.2	-	-
		1000	-	-	0.004
		3000	0.6	0.05	0.002

Table 1-26. *In the $pp \to WWW \to 3\ell + 3\nu$ process, the 5σ-significance discovery values are shown for the coefficients of higher order operators. The values in parentheses are obtained with the UV bound applied. pp colliders at $\sqrt{s} = 14$, 33 and 100 TeV are studied.*

Conclusions

VBS and triboson production is dramatically more sensitive to new physics at higher beam energy

Dimension-8 operators are probed much more strongly than Dimension-6 operators (due to stronger growth of amplitude with energy)

For dimension-8 operator coefficients of order ~ 1:

HL-LHC probes energy scale $\Lambda \sim 1.6$ TeV

VLHC (100 TeV) probes $\Lambda \sim 6$ TeV (with $3ab^{-1}$)

High energy pp colliders probe dimension-8 operators much more sensitively than lepton colliders

Complication with EFT Approach

EFT approach valid and results easy to interpret when $m_{VV} << \Lambda$

Safe to use at lepton colliders

Hadron colliders can probe $m_{VV} \sim \Lambda$

Observation of resonances more likely than EFT description?

To preserve generality offered by EFT operators, intermediate solution may be to preserve unitarity by imposing ad-hoc prescription:

eg. K-matrix unitarization (adds no parameters)

Agreement and implementation of some unitarization scheme would facilitate studies immensely

technical problem for K-matrix method in MADGRAPH

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 electroweak precision observables, Higgs and gauge boson processes can pick out certain models and associated mass scales.

THANK YOU

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Electroweak Report posted at:

http://snowmass2013.org/tiki-index.php?page=Precision+Study+of+Electroweak+Interactions

and arXiv:1310.6708

Backup

Program of VBS and Triboson Measurements

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Table 5: 5σ-significance discovery values and 95% CL limits for coefficients of higher-dimension electroweak operators. Λ_{UV} is the unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1} of integrated luminosity.

Conclusions:

1) factor of 2-3 improvement in sensitivity with HL-LHC upgrade

2) single-channel sensitivities pushed into the TeV-scale if new dynamics is strongly-coupled to Higgs and vector bosons

3) a powerful method of probing models of strongly-interacting light Higgs

4) model-independent tests of BSM dynamics

Example Test of Unitarization by Higgs

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi d}/\Lambda^2$ at 14 TeV	6	WZ	1.9	29 TeV^{-2}	17 TeV^{-2}	15 TeV^{-2}	8.7 TeV^{-2}

Conclusion:

We are not really testing unitarization by SM Higgs until operator < 16 TeV^{-2}

$$O_{\phi d} = \frac{c_{\phi d}}{M_S^2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)$$

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Single-channel tests of unitarization achievable with HL-LHC

LHC and ILC Comparison for Anomalous Trilinear Gauge Couplings

- equivalent to dimension-6 operator coefficients

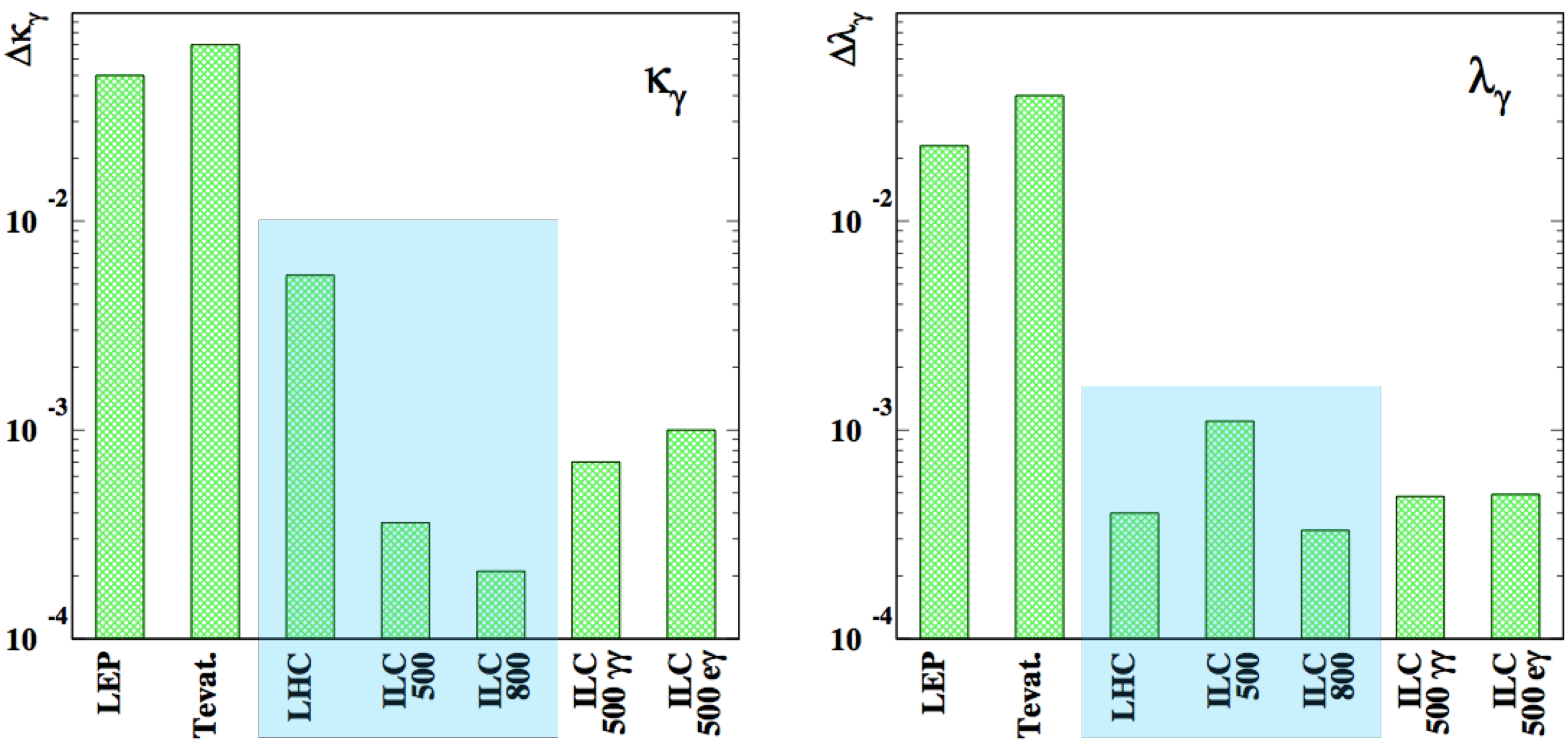


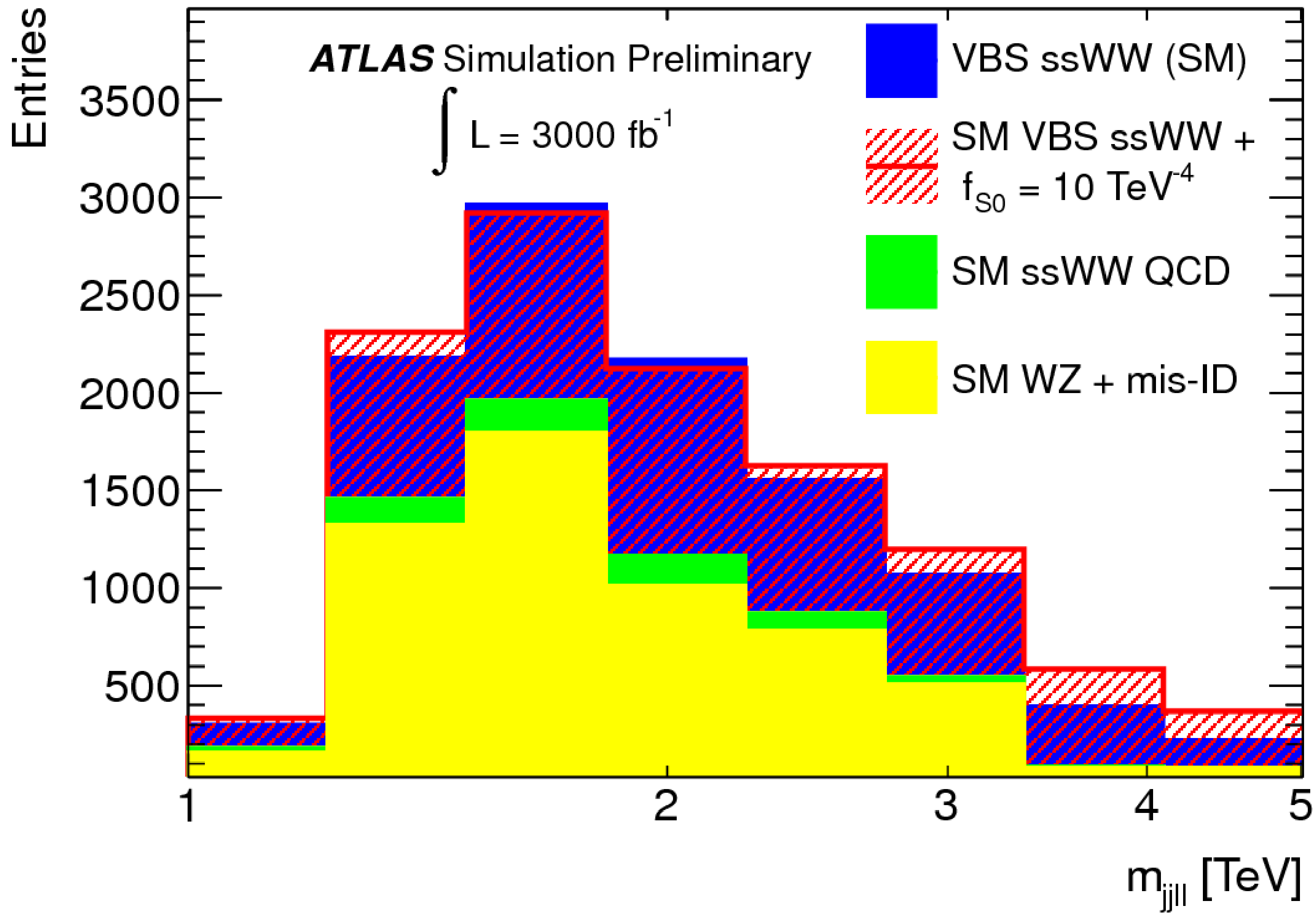
Figure 1-22. *Comparison of $\Delta\kappa_\gamma$ and $\Delta\lambda_\gamma$ at different machines. For LHC and ILC three years of running are assumed (LHC: 300 fb^{-1}, ILC $\sqrt{s} = 500$ GeV: 500 fb^{-1}, ILC $\sqrt{s} = 800$ GeV: 1000 fb^{-1}). If available the results from multi-parameter fits have been used. Taken from Ref. [193, 194].*

Generally, ILC probes dimension-6 operators, through diboson production, much better than LHC

Hadron vs Lepton Colliders

- ILC1000 vs LHC sensitivity to higher-dimension operators in VBS and multi-boson production:
  - ILC more sensitive to dimension-6 operators through diboson production (clean environment, sensitivity through interference with SM)
  - LHC more sensitive (by 1-2 orders of magnitude) to dimension-8 operators compared to ILC1000, as probed by VBS and triboson production

VBS Study using same-sign WW → leptons



Stronger SM interference for “S0” operator → different kinematic dependence