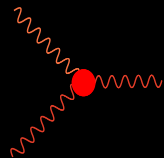
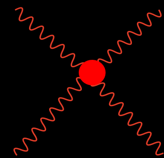
Trilinear and Quartic Gauge Boson Couplings



at the LHC



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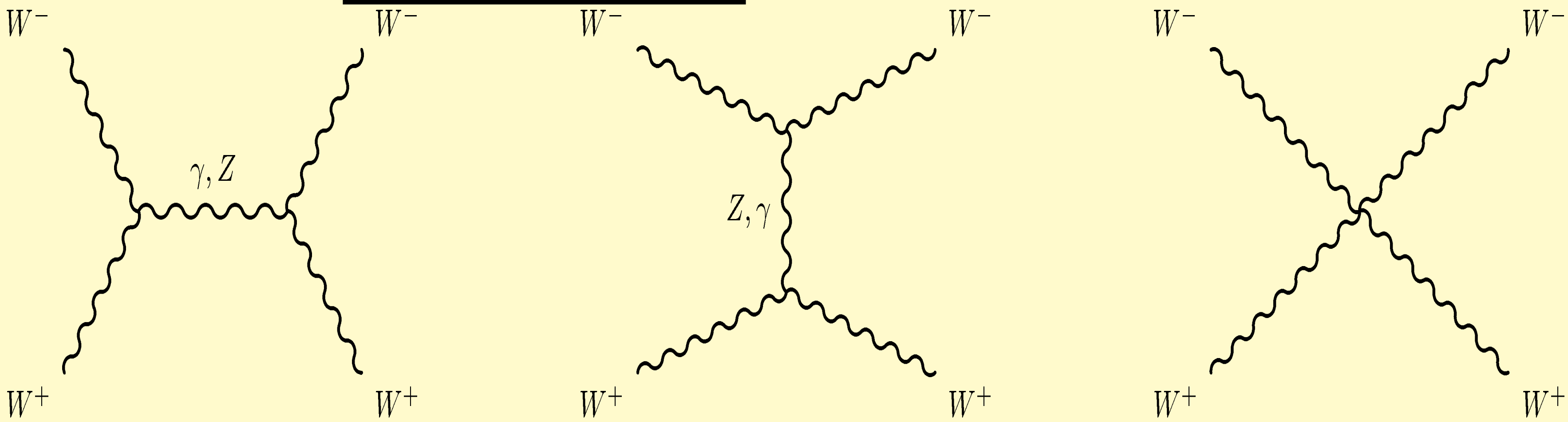
OUTLINE

- Vector bosons self-couplings and the symmetry breaking connection
- Gauge Invariance and the Hierarchy of couplings: Higgs *vs* Higgsless description
- Present indirect limits as a yardstick for a meaningful future measurement/constraint
- Important channels. Outlook. Conclusions

Self-couplings: the Higgs and Symmetry Breaking Connection

$W_L^+ W_L^- \to W_L^+ W_L^-$ *Without Higgs*



If $g_{VVVV} \neq g_{VVV}^2 \Longrightarrow \mathcal{M}_{LLLL} \propto E_W^4$

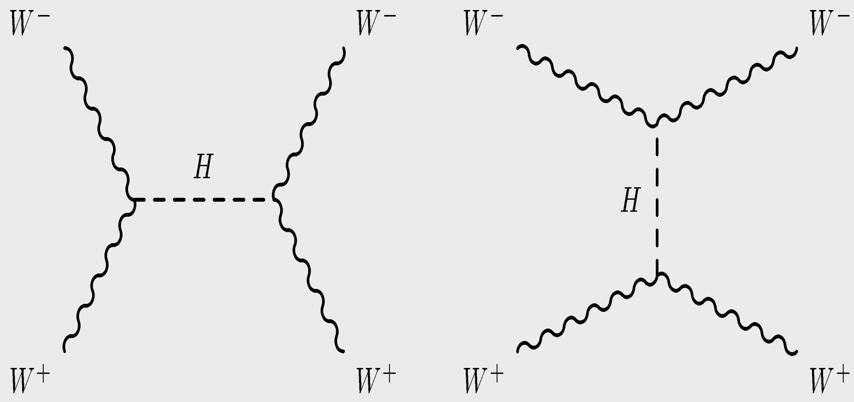
In the SM $\mathcal{M}_{LLLL} \sim \sqrt{2} G_F u \propto E_W^2$

Unitarity without Higgs requires $\sqrt{s_{WW}} \leq 1.2\mathrm{TeV}$

Slight departure of the vector bosons self-couplings from SM values is enhanced at high energies

Higgs and Delayed Unitarity

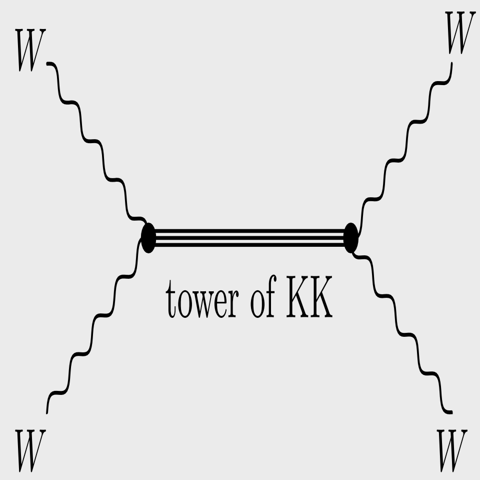
Higgs in SM



$$\mathcal{M}_{LLLL} \sim -\sqrt{2} G_F M_H^2 \left(\frac{s}{s - M_H^2} + \frac{t}{t - M_H^2} \right)$$

Unitarity implies $M_H \leq \frac{4\pi\sqrt{2}}{3G_F} \sim 700\text{GeV}$

Extra-dim with special boundary cdts



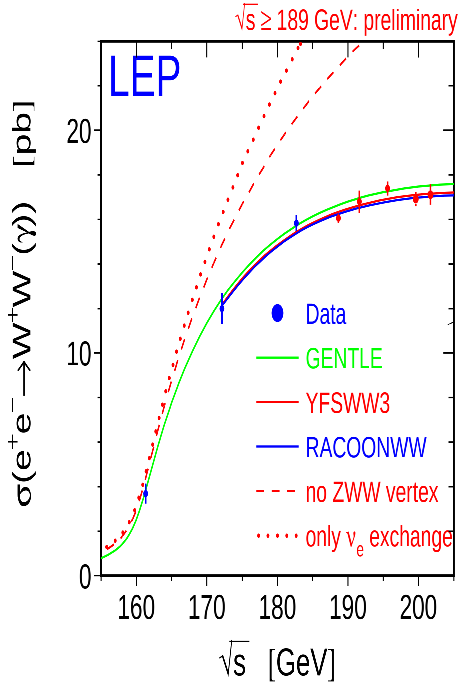
Unitarity is delayed up to a few TeV

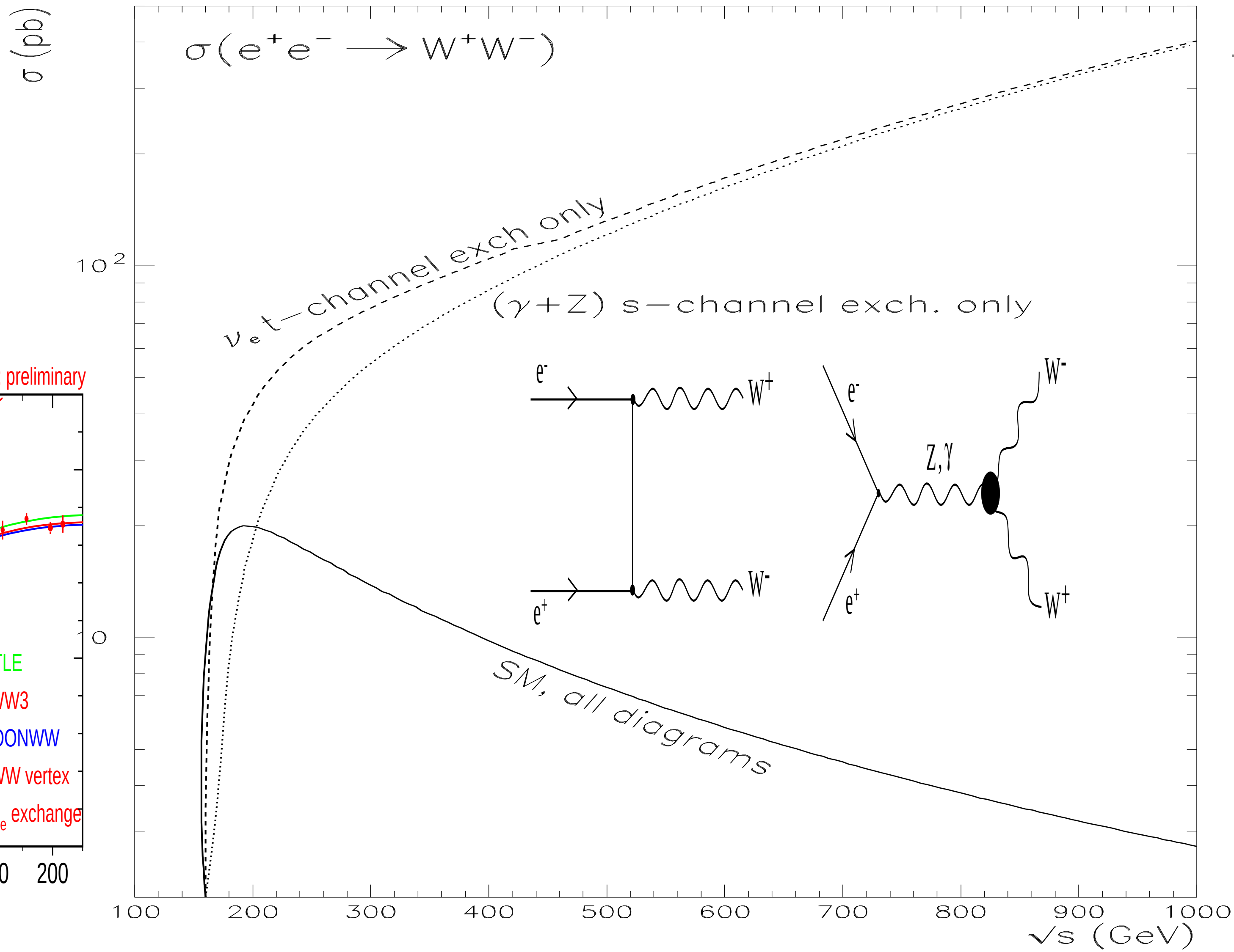
cancellation from underlying

5-d gauge symmetry.

- expect some collective modes to effectively affect the self-interaction of the gauge bosons
- watch out for the longitudinal modes

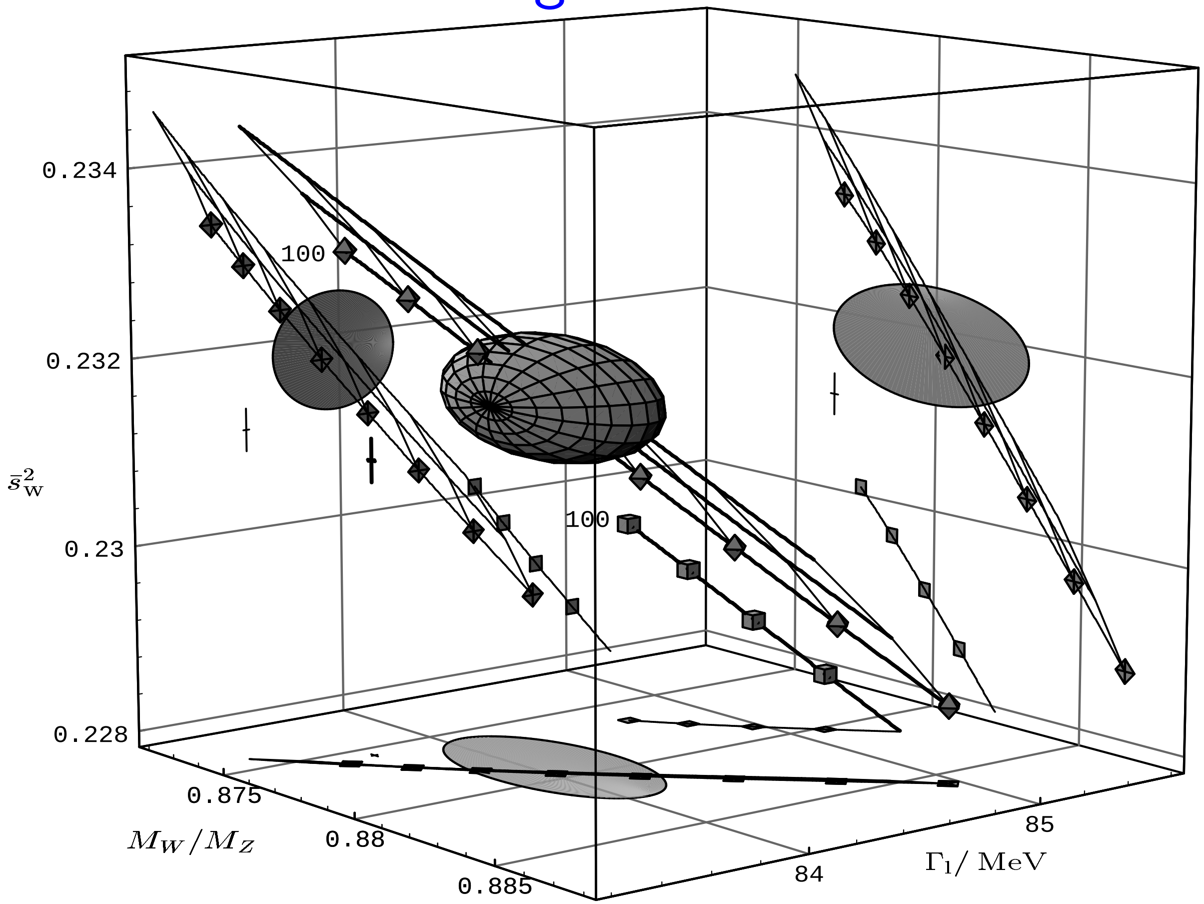
Gauge Invariance: $g_{ffV} = g_{VVV}$





- LEP legacy: We know that WWV can not deviate too much (10%) from SM gauge value.
- But slightest deviations are revealed at higher energies (LHC?)

Gauge Invariance: Indirect Limits



Dittmaier, Schildknecht and Weiglein 1996.

Origin of VVVV and VVV: Gauge Invariance, Symmetry Breaking. I. SM

$$\bullet\ \mathcal{L}_{\rm Gauge} = -\frac{1}{2}\left[{\rm Tr}(\boldsymbol{W}_{\mu\nu}\boldsymbol{W}^{\mu\nu}) + {\rm Tr}(\boldsymbol{B}_{\mu\nu}\boldsymbol{B}^{\mu\nu})\right] \text{ GI kinetic term}$$

$$\boldsymbol{W}_{\mu\nu} = \frac{1}{2}\left(\partial_\mu \boldsymbol{W}_\nu - \partial_\nu \boldsymbol{W}_\mu + \frac{i}{2} \boxed{g[\boldsymbol{W}_\mu, \boldsymbol{W}_\nu]}\right) = \frac{\tau^i}{2}\left(\partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\epsilon^{ijk}W^j_\mu W\right.$$

$$\boldsymbol{B}_{\mu\nu} = \frac{1}{2}\left(\partial_\mu B_\nu - \partial_\nu B_\mu\right)\tau_3 \qquad \boldsymbol{B}_\mu = \tau_3 B_\mu$$

- $\mathcal{L}_{\rm Gauge}$ describes transverse states (field strength)
- longitudinal states, $Z^L_\mu \propto \partial_\mu \phi_3$ $\quad \epsilon^L_\mu = \boxed{\frac{k_\mu}{M_Z}} - M_Z \frac{s_\mu}{s.k}$ do not contribute much to $\mathcal{L}_{\rm Gauge}$
- BUT to the mass and Symmetry Breaking Lagrangian
- $\mathcal{L}_M = M_W^2 W^+_\mu W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \subset \mathcal{L}_{H,M=SB} = (\mathcal{D}_\mu\Phi)^\dagger(\mathcal{D}_\mu\Phi) - \boxed{\lambda\left[\Phi^\dagger\Phi - \frac{\mu^2}{2\lambda}\right]^2}$
- Self interacting Goldstone Bosons $\equiv$ Self-interacting $V_L V_L \to V_L V_L$
- Symmetry Breaking has a custodial $SU(2)$ symmetry $\rightarrow$ $\rho = 1$

Gauge invariance of Mass and SB: Covariant Derivatives

Origin of VVVV and VVV: Gauge Invariance, Symmetry Breaking. II. SM without Higgs

kinetic term still there but mass and longitudinals through a system of Goldstones without the Higgs (still gauge invariant): Non-Linear realisation of SB

$$\Sigma = exp(\frac{i\omega^i\tau^i}{v}) \;\; (v = 246\; GeV \text{ is the vev}) \;\; \text{and} \;\; \mathcal{D}_\mu\Sigma = \partial_\mu\Sigma + \frac{i}{2}\left(g\boldsymbol{W}_\mu\Sigma - g'B_\mu\Sigma\tau_3\right)$$

$$\mathcal{L}_M = \frac{v^2}{4}\mathrm{Tr}(\mathcal{D}^\mu\Sigma^\dagger\mathcal{D}_\mu\Sigma) \equiv -\frac{v^2}{4}\mathrm{Tr}\left(\mathcal{V}_\mu\mathcal{V}^\mu\right) \quad \text{with} \;\; \mathcal{V}_\mu = \left(\mathcal{D}_\mu\Sigma\right)\Sigma^\dagger$$

Hierarchy of Operators: Most important effects

- POST-LEP 1&2: The SM is a gauge invariant (GI) theory with a custodial SU(2) symm.
- as in QED any deviation should be parameterized as a (higher order) GI operators
- This approach defines a hierarchy of couplings and order of magnitude for deviations

QED example

$$\mathcal{L}^{QED}_{eff.} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\beta_1}{m^2}\frac{e^2}{16\pi^2}\left(F_{\mu\nu}\Box F^{\mu\nu} + \frac{\epsilon_2}{m^2}F_{\mu\nu}\Box^2 F^{\mu\nu}\right)$$
$$+ \frac{1}{m^4}\frac{e^4}{16\pi^2}\left(\beta_2(F_{\mu\nu}F^{\mu\nu})^2 + \beta_3(F_{\mu\nu}\tilde{F}^{\mu\nu})^2\right) + \ldots\ldots + \mathcal{L}_{gauge\ fixing}$$

SM need to describe new physics of longitudinal modes

decide about Linear (with Higgs) or Non-Linear (without Higgs) of Symm. Breaking

Operators for W Physics

Linear Realisation , Light Higgs	Non Linear-Realisation , No Higgs
$\mathcal{L}_B = ig' \frac{\epsilon_B}{\Lambda^2} (\mathcal{D}_\mu \Phi)^\dagger B^{\mu\nu} \mathcal{D}_\nu \Phi$	$\mathcal{L}_{9R} = -ig' \frac{L_{9R}}{16\pi^2} \mathrm{Tr}(\boldsymbol{B}^{\mu\nu} \mathcal{D}_\mu \Sigma^\dagger \mathcal{D}_\nu \Sigma)$
$\mathcal{L}_W = ig \frac{\epsilon_W}{\Lambda^2} (\mathcal{D}_\mu \Phi)^\dagger (2 \times \boldsymbol{W}^{\mu\nu})(\mathcal{D}_\nu \Phi)$	$\mathcal{L}_{9L} = -ig \frac{L_{9L}}{16\pi^2} \mathrm{Tr}(\boldsymbol{W}^{\mu\nu} \mathcal{D}_\mu \Sigma \mathcal{D}_\nu \Sigma^\dagger)$
$\mathcal{L}_\lambda = \frac{2i}{3} \frac{L_\lambda}{\Lambda^2} g^3 \mathrm{Tr}(\boldsymbol{W}_{\mu\nu} \boldsymbol{W}^{\nu\rho} \boldsymbol{W}^{\mu}{}_{\rho})$	— — — — — —
— — — — — — — — — — — —	$\mathcal{L}_1 = \frac{L_1}{16\pi^2} \left(\mathrm{Tr}(D^\mu \Sigma^\dagger D_\mu \Sigma)\right)^2 \equiv \frac{L_1}{16\pi^2} \mathcal{O}_1$ $\mathcal{L}_2 = \frac{L_2}{16\pi^2} \left(\mathrm{Tr}(D^\mu \Sigma^\dagger D_\nu \Sigma)\right)^2 \equiv \frac{L_2}{16\pi^2} \mathcal{O}_2$

$W^+W^-Z, W^+W^-\gamma$ couplings

$$
\begin{aligned}
\Delta\kappa_\gamma &= \frac{e^2}{s_w^2}\frac{v^2}{4\Lambda^2}(\epsilon_W+\epsilon_B) = \frac{e^2}{s_w^2}\frac{1}{32\pi^2}\left(L_{9L}+L_{9R}\right) \\
\Delta\kappa_Z &= \frac{e^2}{s_w^2}\frac{v^2}{4\Lambda^2}(\epsilon_W-\frac{s_w^2}{c_w^2}\epsilon_B) = \frac{e^2}{s_w^2}\frac{1}{32\pi^2}\left(L_{9L}-\frac{s_w^2}{c_w^2}L_{9R}\right) \\
\Delta g_1^Z &= \frac{e^2}{s_w^2}\frac{v^2}{4\Lambda^2}(\frac{\epsilon_W}{c_w^2}) = \frac{e^2}{s_w^2}\frac{1}{32\pi^2}\left(\frac{L_{9L}}{c_w^2}\right) \\
\lambda_\gamma &= \lambda_Z = \left(\frac{e^2}{s_w^2}\right) L_\lambda \frac{M_W^2}{\Lambda^2}
\end{aligned}
$$

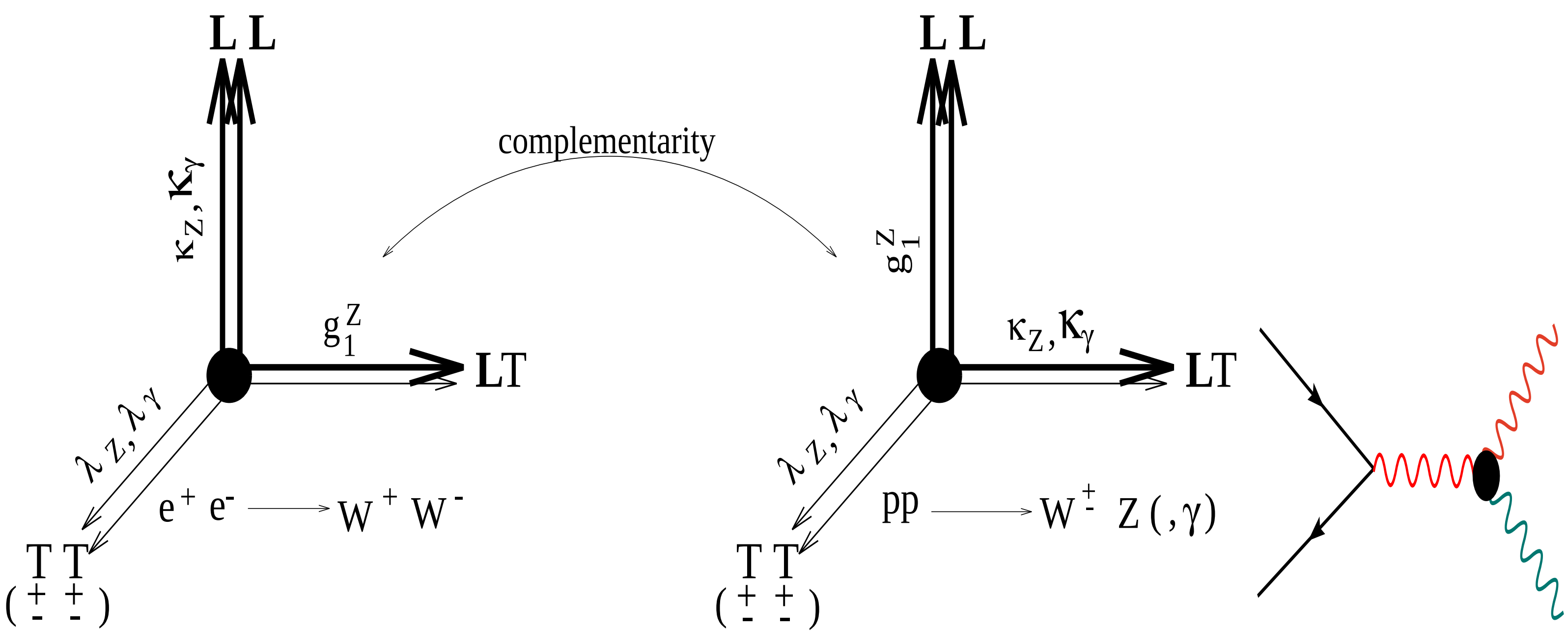
• At this order no $\mathcal{C}$ violating tri-linear couplings in particular no $ZZZ, ZZ\gamma, Z\gamma\gamma$ couplings. These appear at higher orders. Should not receive high priority.

• For LHC fits and measurements better to switch to the L_i parameters

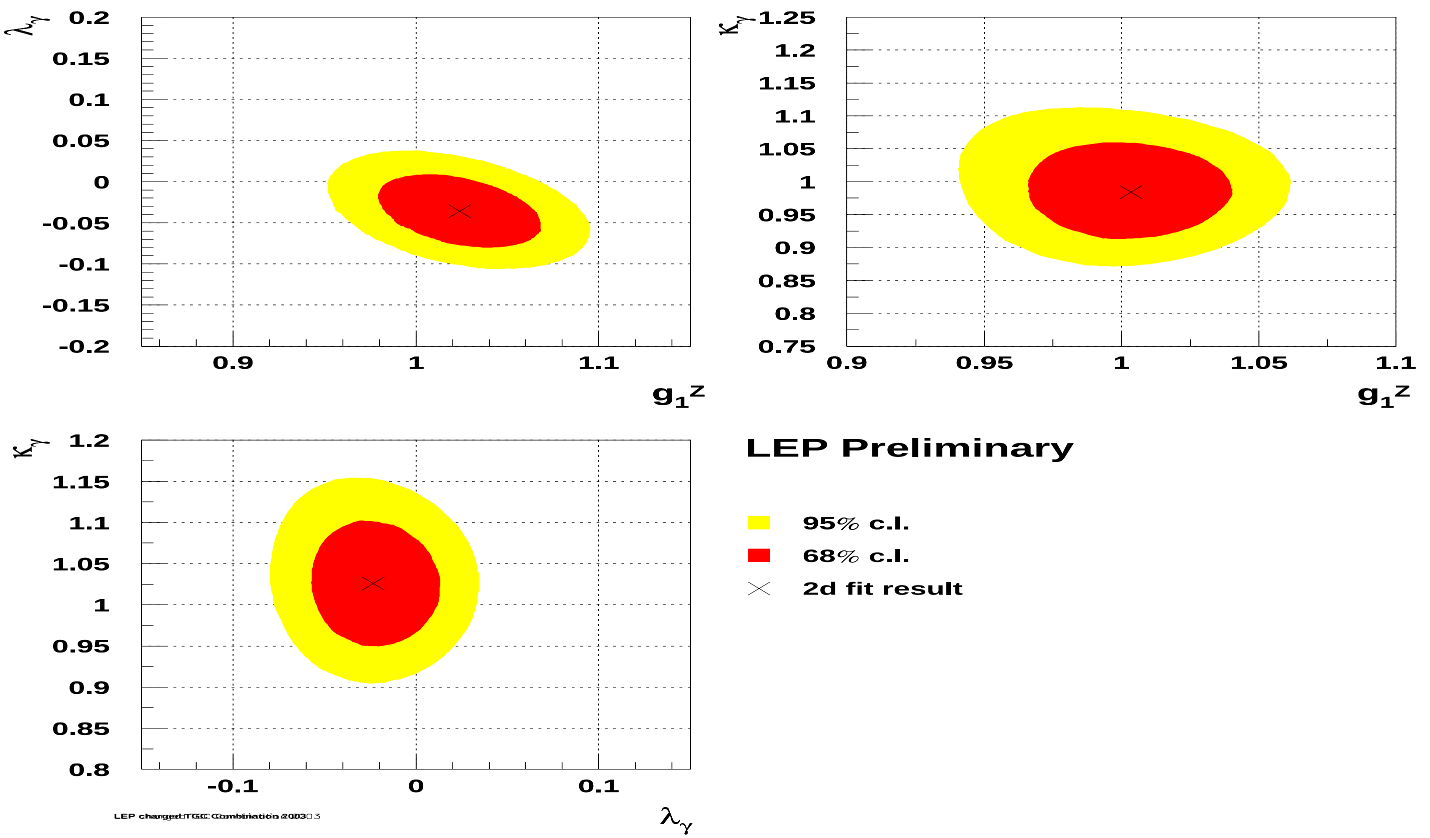
Pheno of tri-linear couplings

$$
\begin{aligned}
\mathcal{L}_{WWV} = -ie \Bigg\{ & \Bigg[A_\mu \left(W^{-\mu\nu} W^+_\nu - W^{+\mu\nu} W^-_\nu \right) + \overbrace{(1+\Delta\kappa_\gamma)}^{\kappa_\gamma} F_{\mu\nu} W^{+\mu} W^{-\nu} \Bigg] \\
& + \frac{c_W}{s_W} \Bigg[\overbrace{(1+\Delta g_1^Z)}^{g_1^Z} Z_\mu \left(W^{-\mu\nu} W^+_\nu - W^{+\mu\nu} W^-_\nu \right) + \overbrace{(1+\Delta\kappa_Z)}^{\kappa_Z} Z_{\mu\nu} W^{+\mu} W^{-\nu} \Bigg] \\
& + \frac{1}{M_W^2} \left(\lambda_\gamma F^{\nu\lambda} + \lambda_Z \frac{c_W}{s_W} Z^{\nu\lambda} \right) W^+_{\lambda\mu} W^{-\mu}{}_\nu \Bigg\}
\end{aligned}
$$

No $ZZZ, ZZ\gamma, Z\gamma\gamma$ (higher order)



Current direct limits as a guide



$5-10\%$ accuracy $\Longrightarrow |L_9| \sim 50$

$\mathcal{L}_{WWV_1V_2}$

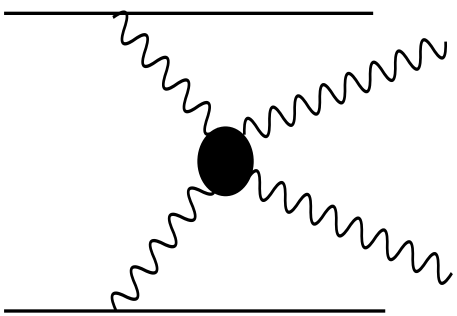
$$
\begin{aligned}
- \quad & e^2 \Big\{ \big(A_\mu A^\mu W^+_\nu W^{-\nu} - A^\mu A^\nu W^+_\mu W^-_\nu \big) \\
+ \quad & 2\frac{c_w}{s_w}(1+\frac{l_{9l}}{c_w^2}) \Big(A_\mu Z^\mu W^+_\nu W^{-\nu} - \frac{1}{2} A^\mu Z^\nu (W^+_\mu W^-_\nu + W^+_\nu W^-_\mu) \Big) \\
+ \quad & \frac{c_w^2}{s_w^2}(1+\frac{2l_{9l}}{c_w^2} - \frac{l_-}{c_w^4}) \big(Z_\mu Z^\mu W^+_\nu W^{-\nu} - Z^\mu Z^\nu W^+_\mu W^-_\nu \big) \\
+ \quad & \frac{1}{2s_w^2}(1+2l_{9l}-l_-) \big(W^{+\mu} W^-_\mu W^{+\nu} W^-_\nu - W^{+\mu} W^+_\mu W^{-\nu} W^-_\nu \big) \\
- \quad & \frac{l_+}{2s_w^2} \big((3W^{+\mu} W^-_\mu W^{+\nu} W^-_\nu + W^{+\mu} W^+_\mu W^{-\nu} W^-_\nu \big) \\
+ \quad & \frac{2}{c_w^2} \; \big(Z_\mu Z^\mu W^+_\nu W^{-\nu} + Z^\mu Z^\nu W^+_\mu W^-_\nu \big) + \frac{1}{c_w^4} Z_\mu Z^\mu Z_\nu Z^\nu \Big) \Big\} \\
& \text{with} \quad l_{9l} = \frac{e^2}{32\pi^2 s_w^2} L_{9L} \quad ; \quad l_\pm = \frac{e^2}{32\pi^2 s_w^2}(L_1 \pm L_2)
\end{aligned}
$$

No Anomalous $WW\gamma\gamma$, No $V_1V_2\gamma\gamma$

New $ZZZZ$, New $WWWW$ and $WWZZ$ structures.

Best probed in WW scattering ($L_{1,2}$) $\Longrightarrow$ $\Longrightarrow$

(higher order structures see Bélanger et al.,)



Catch 22: Contribution to 2-point functions?.....!

◇ I only listed operators giving contribution to VVV and $VVVV$ but...

◇ A general approach would also include contributions to 2-point function (see QED example)

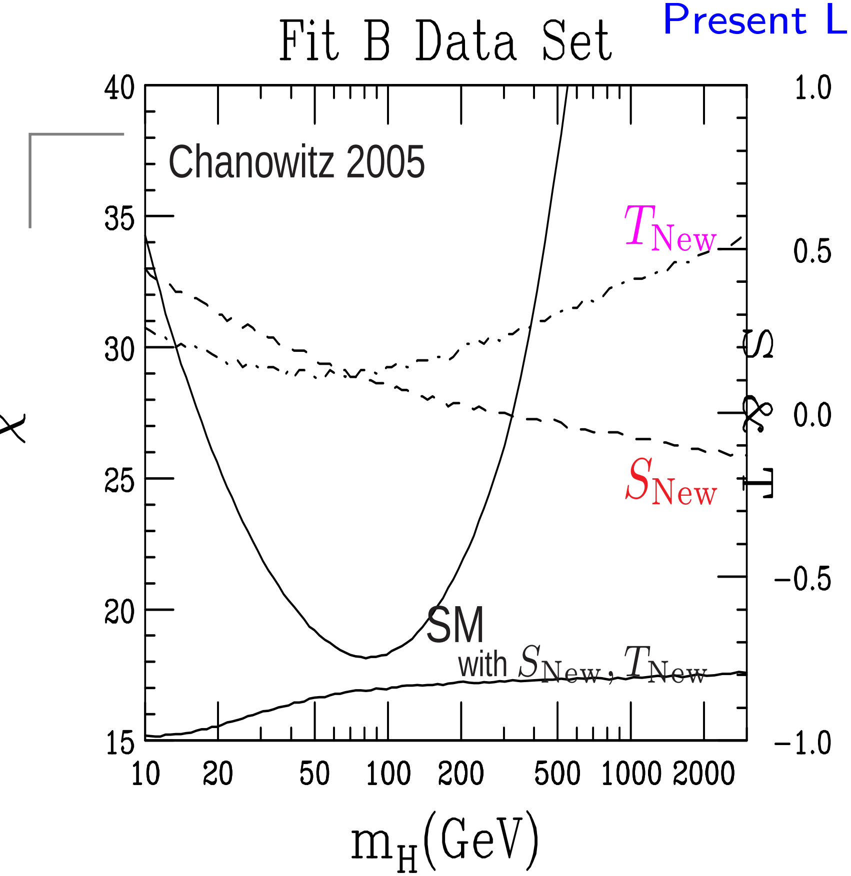
$$\mathcal{L}_{WB} = gg' \frac{\epsilon_{WB}}{\Lambda^2} \left(\Phi^\dagger \times \boldsymbol{W}^{\mu\nu} \Phi\right) B_{\mu\nu}$$

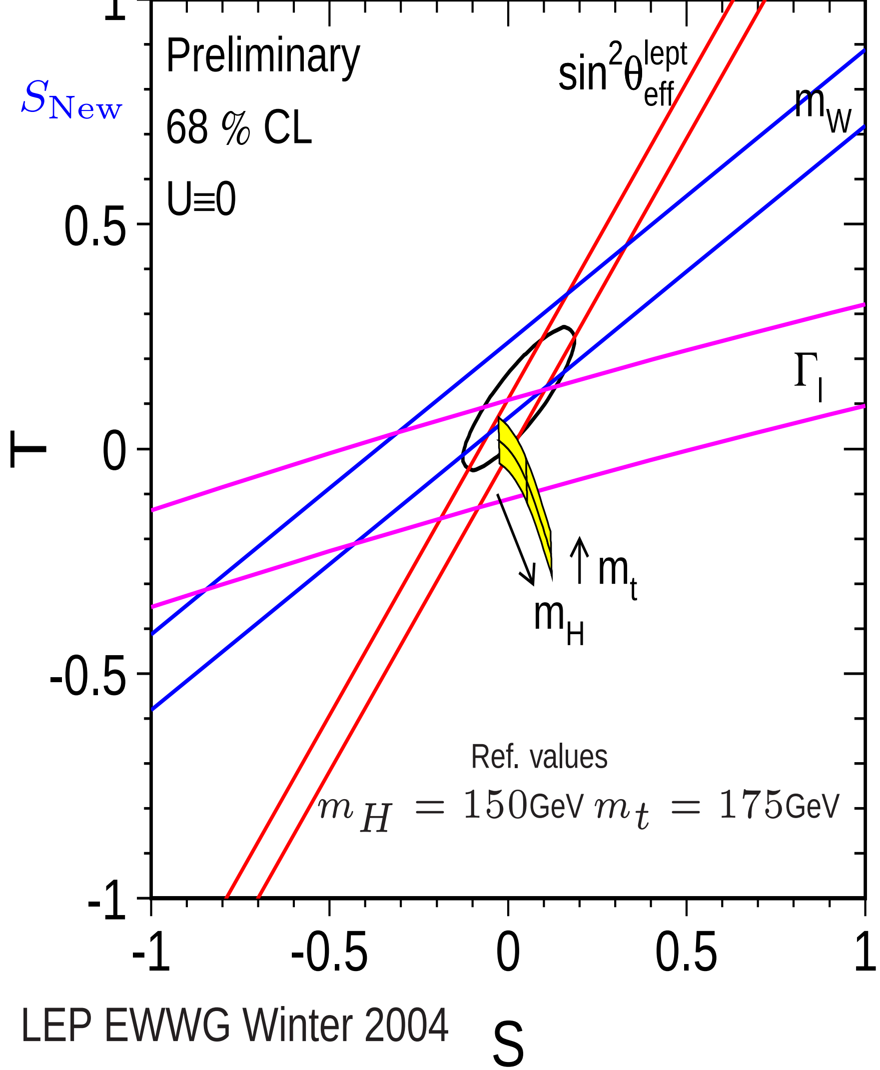
$$\mathcal{L}_{10} = gg' \frac{L_{10}}{16\pi^2} \mathrm{Tr}(\boldsymbol{B}^{\mu\nu} \Sigma^\dagger \boldsymbol{W}^{\mu\nu} \Sigma) \longrightarrow L_{10} = -\pi S_{\mathrm{New}} \simeq \frac{4\pi s_W}{\alpha} \epsilon_3$$

◇ LEP-Tevatron precision EW physics implies strong constraint on $S_{\mathrm{New}}(L_{10})$ and consequently on the other operators

◇ This constraint could be considered as a yardstick for future measurements

Present Limit on $S_{\rm New}$





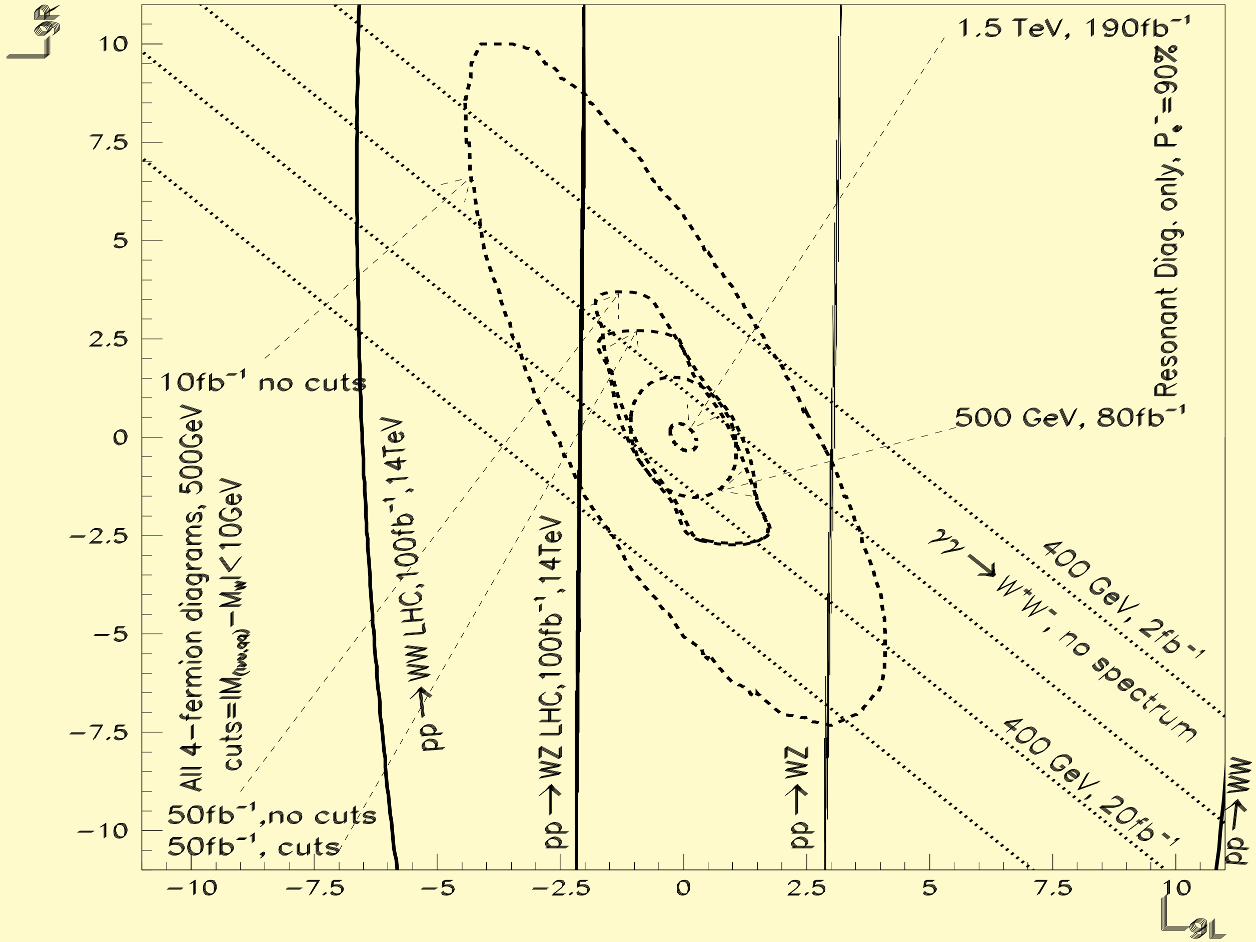
For $M_H = 1$TeV need $S_{\rm New} = -0.07$ and $T_{\rm New} = +0.3 \Longrightarrow$ Constraint $L_{10} < 1$

future L_i measurements of this order! $L_i \sim 1$

unless some global symmetry makes $L_{10} = 0$ ($SU(2)_A$?)

Future measurements I.

The S, T, U Post-LEP



From WW scattering $L_{1,2} \sim 1$@ LHC

Future measurements and Conclusions.

- Especially if Higgs not found precision measurements of (longitudinal) vector bosons self-couplings is crucial
- Update simulations in the channels $pp \to WZ, W\gamma(WW?)$ including NLO (MCFM)
- $pp \to (W, Z)X$ (VV fusion to single V): worth it?
- Can more be done to optimize $WW \to WW$?
- Quartic through $pp \to WWZ, ZZZ, .$ though falls like $1/\hat{s}$ could it help? combined with WW fusion?
- work out in detail consequences of some extra-dim models, (Little Higgs?)...

...could constitute a nice subgroup at Les Houches 2005....

Official deadline for registration TOMORROW

http://lappweb.in2p3.fr/conferences/LesHouches/Houches2005/application.html