TGC & QGC: With a Light Higgs Boson

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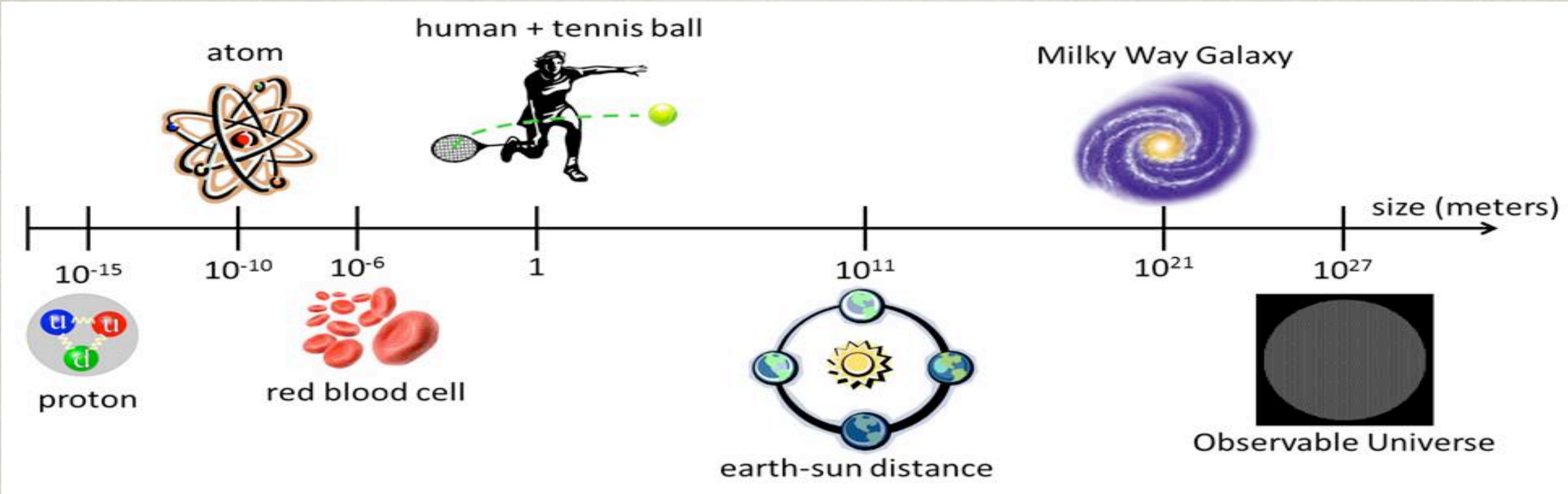
Physics Is Defined at a Scale



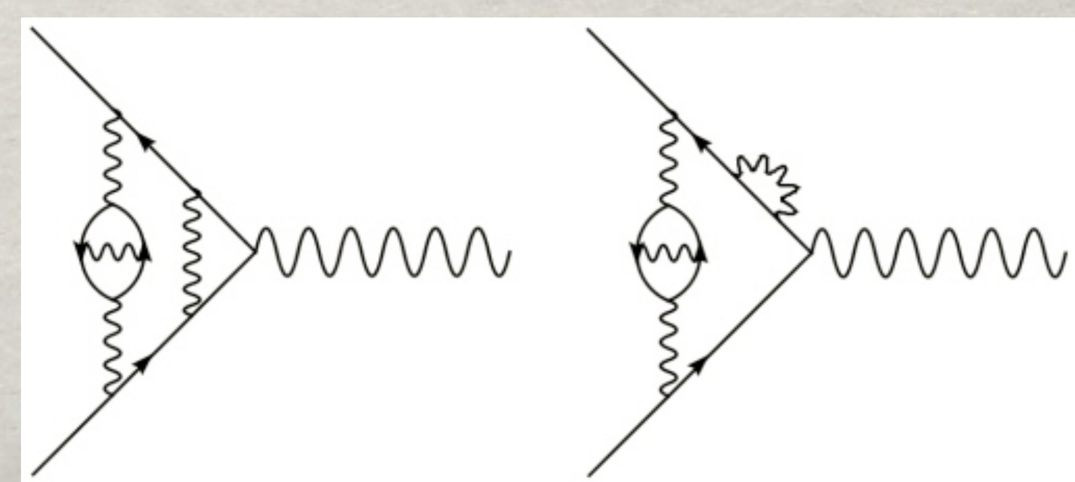
At (very) low energies:

QED: $U(1)_{em}$ gauge theory,
the most accurate theory in science
Anomalous magnetic dipole moment (g-2):

$$a_e = 0.00115965218073(28)$$

$$\Rightarrow \alpha^{-1} = 137.035999173(35)$$

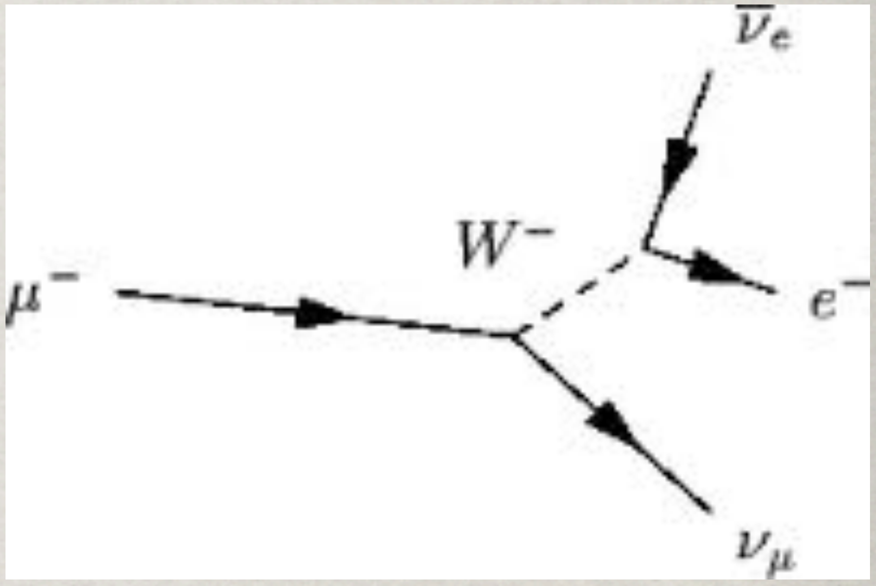
$$a_\mu = 0.00116592080(63)$$



* # Weak force well measured at low energy:

Charged current: W± $-\frac{G_F}{\sqrt{2}}\,\bar{p}\mathcal{O}n\;\bar{e}\mathcal{O}'\nu$

Neutral current: Z^0 $-\frac{G_F}{\sqrt{2}}\,\bar{\nu}_\mu\mathcal{O}\nu_\mu\;\bar{e}\mathcal{O}'e$



$$G_\mu = 1.1663787(6)\times 10^{-5}\ \mathrm{GeV}^{-2}$$

$$\Rightarrow v = 1/(\sqrt{2}G_\mu)^{1/2} = 246.22\ \mathrm{GeV}.$$

Which defines a new physical scale: The EW Scale.

* # Near the EW scale:

QED + weak currents ➔ $SU(2)_L \otimes U(1)_Y$ gauge theory

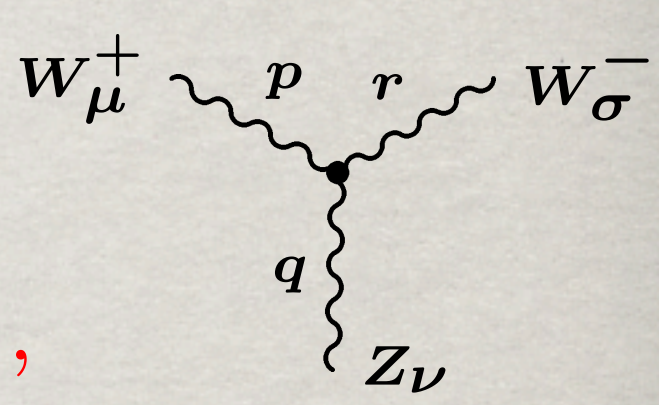
α, G_F ➔ g_1, g_2, v [trade to M_Z, $\alpha(M_Z)$, G_F]

* # At higher energies → new physics!?

The Yang-Mills Gauge Theory

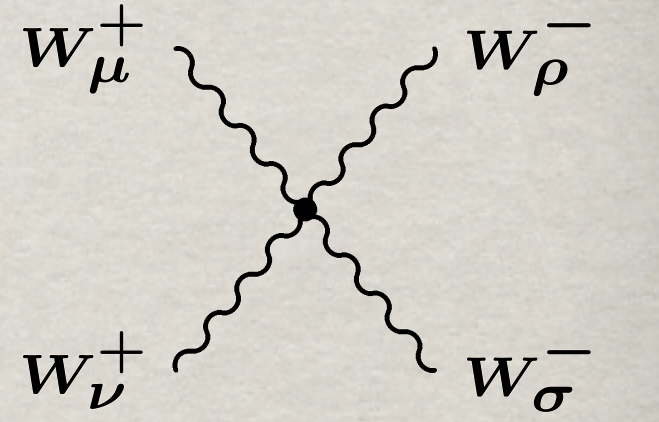
Non-Abelian local gauge theory $\mathrm{SU}(2)$

$$
\begin{aligned}
\mathcal{L}_{W3} &= -ig(\partial_\rho W^3_\nu) W^+_\mu W^-_\sigma [g^{\rho\mu} g^{\nu\sigma} - g^{\rho\sigma} g^{\nu\mu}] \\
&\quad -ig(\partial_\rho W^+_\mu) W^3_\nu W^-_\sigma [g^{\rho\sigma} g^{\mu\nu} - g^{\rho\nu} g^{\mu\sigma}] \\
&\quad -ig(\partial_\rho W^-_\sigma) W^3_\nu W^+_\mu [g^{\rho\nu} g^{\mu\sigma} - g^{\rho\mu} g^{\nu\sigma}],
\end{aligned}
$$



$$
\mathcal{L}_{W4} = \frac{g^2}{4} \left[W^+_\mu W^+_\nu W^-_\sigma W^-_\rho \mathcal{Q}^{\mu\nu\rho\sigma} - 2 W^+_\mu W^3_\nu W^3_\sigma W^-_\rho \mathcal{Q}^{\mu\rho\nu\sigma} \right]
$$

$$
\mathcal{Q}_{\mu\nu\rho\sigma} \equiv 2 g_{\mu\nu} g_{\rho\sigma} - g_{\mu\rho} g_{\nu\sigma} - g_{\mu\sigma} g_{\nu\rho}.
$$



Transversely polarized gauge bosons:

$$
\epsilon^\mu_T = (0, \cos\theta\cos\phi, \cos\theta\sin\phi, \sin\theta)
$$

$$
\mathcal{A}_{W_T W_T}(2 \to 2) \sim \mathcal{O}(g^2)
$$

Well behaved, well predicted!

But, W/Z are massive!

Longitudinally polarized gauge bosons:

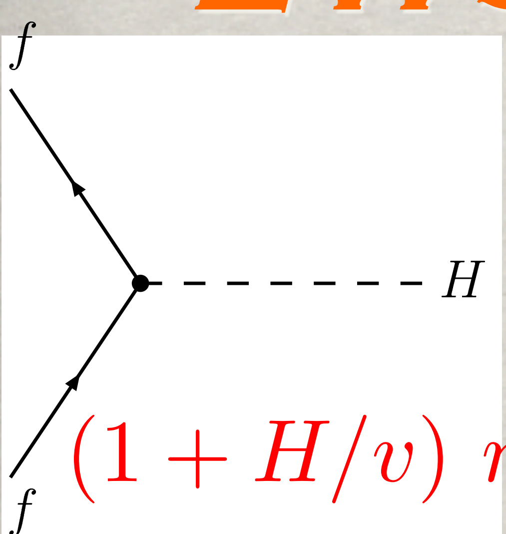
$\epsilon_L^\mu \approx p^\mu / M_W$ at $M_W/E \ll 1.$ Model-independent!

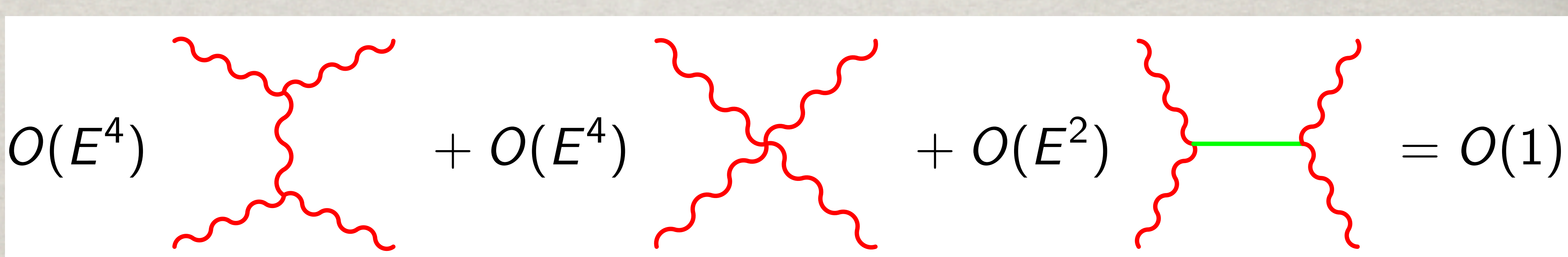
Thus lead to "bad high energy behavior":

$$A(f\bar{f} \to W_L W_L) \sim m_f \sqrt{s}/v^2$$
$$A(W_L W_L \to W_L W_L) \sim \epsilon_{1L}\cdot\epsilon_{2L}\ \epsilon_{3L}\cdot\epsilon_{4L}$$

Naively, $A(W_L W_L \to W_L W_L) \sim g^2 (p^2)^2/M_W^4 \sim g^2 s^2/M_W^4,$

EWSB & The Higgs Boson:





$(1 + H/v)\ m_f \bar{\psi}_f \psi_f$ Model-dependent! $(v+H)^2\ g^2 V^\mu V_\mu$

* Consistent perturbative theory up to TeV,…M_{pl} (?)

The Parameterizations for New Physics

Triple Gauge-boson Couplings (TGC)

(1) A conventional parameterization: (Hagiwara et al., 1986)

Most general structure of Lorentz, EM gauge invariance.

$$\begin{aligned}\frac{\mathcal{L}_V}{g_V} &= ig_1^V\left(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\ &+ i\frac{\lambda_V}{m_W^2}W^\dagger_{\lambda\mu}W^\mu{}_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) \\ &+ g_5^V\epsilon^{\mu\nu\lambda\rho}\left(W^\dagger_\mu\partial_\lambda W_\nu - \partial_\lambda W^\dagger_\mu W_\nu\right)V_\rho \\ &+ i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{m_W^2}W^\dagger_{\lambda\mu}W^\mu{}_\nu\tilde{V}^{\nu\lambda}.\end{aligned}$$

Pros:

- General
- Historical

Cons:

- Power counting unclear
- Violate unitarity (soon)
- Not gauge invariant

In the SM at tree level:

$$g_1^V = \kappa_V = 1,$$
$$\lambda_V = \tilde{\lambda}_V = \tilde{\kappa}_V = g_4^V = g_5^V = 0.$$

Deviations from the SM often called "anomalous couplings".
(The operators: g_5^Z is P-odd, $g_4^V,\ \tilde{\lambda}_V,\ \tilde{\kappa}_V$ are CP-odd, $\lambda's$ dim-6.)

How large do we expect the deviations to be? See later ...

(2). Non-linear realization of gauge symmetry:

$$\mathcal{L}_0 = \frac{(h+v)^2}{2} Tr[D^\mu U^\dagger D^\mu U], \quad U = exp(i\omega^i \tau^i / v)$$

$$\mathcal{L}_4 = \ell_4 (\frac{v}{\Lambda})^2 [Tr V^\mu V^\nu]^2, \quad V^\mu = (D^\mu U) U^\dagger,$$

$$\mathcal{L}_5 = \ell_5 (\frac{v}{\Lambda})^2 [Tr V^\mu V_\mu]^2.$$

Appelquist, Bernard, 1980
Longitano, 1980

Another convention: $\alpha_{4,5} = \ell_{4,5} (v/\Lambda)^2$.

"Naturally speaking", $\Lambda \sim 4\pi v, \quad \ell_{4,5} \sim \mathcal{O}(1)$.

Remarks: This is equivalent to integrate out h (as a heavy singlet), which is inappropriate in light of the Higgs discovery.

(3). Linear realization of gauge symmetry:

$$\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$$

Buchmuller, Wyler, 1986
Leung, Love, Rao, 1986
Hagiwara et al. 1993
Grzadkowski et al. 2010

B-L conserving, CP even: 59 operators at dim-6.

e.g. Higgs & TGC:

$$\begin{aligned}
&\mathcal{O}_{GG} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu}\ , \quad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi\ ,\\
&\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi,\quad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right)\ ,\\
&\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger\Phi)(\bar{L}_i\Phi e_{R_j})\ ,\quad \mathcal{O}_{d\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\Phi d_{Rj})\ ,\\
&\mathcal{O}_W = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi)\ ,\quad \mathcal{O}_B = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi)\ ,\\
&\mathcal{O}_{WWW} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^\mu_\rho]\ . \qquad (3)
\end{aligned}$$

$$\begin{aligned}
&\Delta\kappa_\gamma = \frac{g^2v^2}{8\Lambda^2}\Big(f_W + f_B\Big)\,,\ \lambda_\gamma = \lambda_Z = \frac{3g^2M_W^2}{2\Lambda^2}f_{WWW}\ ,\\
&\Delta g_1^Z = \frac{g^2v^2}{8c^2\Lambda^2}f_W\,,\ \Delta\kappa_Z = \frac{g^2v^2}{8c^2\Lambda^2}\Big(c^2 f_W - s^2 f_B\Big)\,. \quad (5)
\end{aligned}$$

"Naturally speaking", $\Lambda \sim 4\pi v,\quad f_n \sim \mathcal{O}(1),\quad \Delta\kappa \sim 10^{-3}.$

Eboli et al., 2006, 2012.

Quartic couplings w/o modifying triple couplings at dim-8:

$$\frac{f_0}{\Lambda^4}\left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]\times\left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\frac{f_1}{\Lambda^4}\left[(D_\mu\Phi)^\dagger D^\mu\Phi\right]\times\left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

leading to interactions like

$$\mathcal{O}_0^{WW} = g^{\alpha\beta}g^{\gamma\delta}\left[W^+_\alpha W^-_\beta W^+_\gamma W^-_\delta\right] , \qquad \mathcal{O}_1^{WW} = g^{\alpha\beta}g^{\gamma\delta}\left[W^+_\alpha W^+_\beta W^-_\gamma W^-_\delta\right] ,$$
$$\mathcal{O}_0^{WZ} = g^{\alpha\beta}g^{\gamma\delta}\left[W^+_\alpha Z_\beta W^-_\gamma Z_\delta\right] , \qquad \mathcal{O}_1^{WZ} = g^{\alpha\beta}g^{\gamma\delta}\left[W^+_\alpha W^-_\beta Z_\gamma Z_\delta\right] ,$$
$$\mathcal{O}_0^{ZZ} = \mathcal{O}_1^{ZZ} \equiv \mathcal{O}^{ZZ} = g^{\alpha\beta}g^{\gamma\delta}\left[Z_\alpha Z_\beta Z_\gamma Z_\delta\right] ,$$

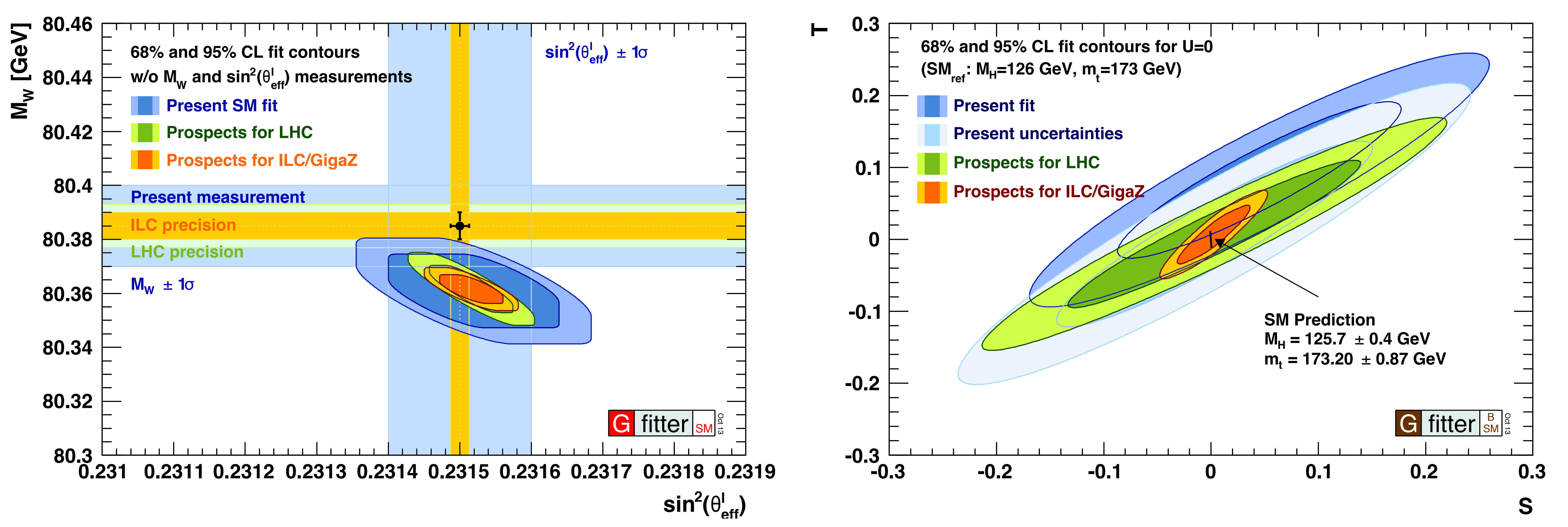
"Naturally speaking",
dim-8 operators should be suppressed by

$$(v/\Lambda)^2 \sim 1/16\pi^2.$$

The Test of EW Theory

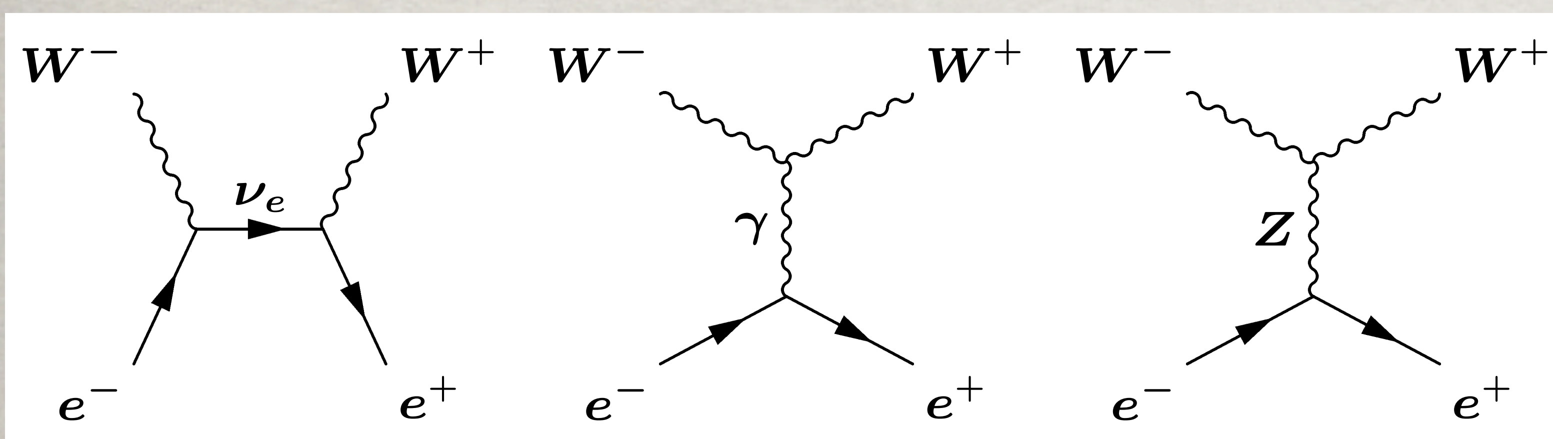
Precision EW physics stared at LEP-I:
(and on ...)

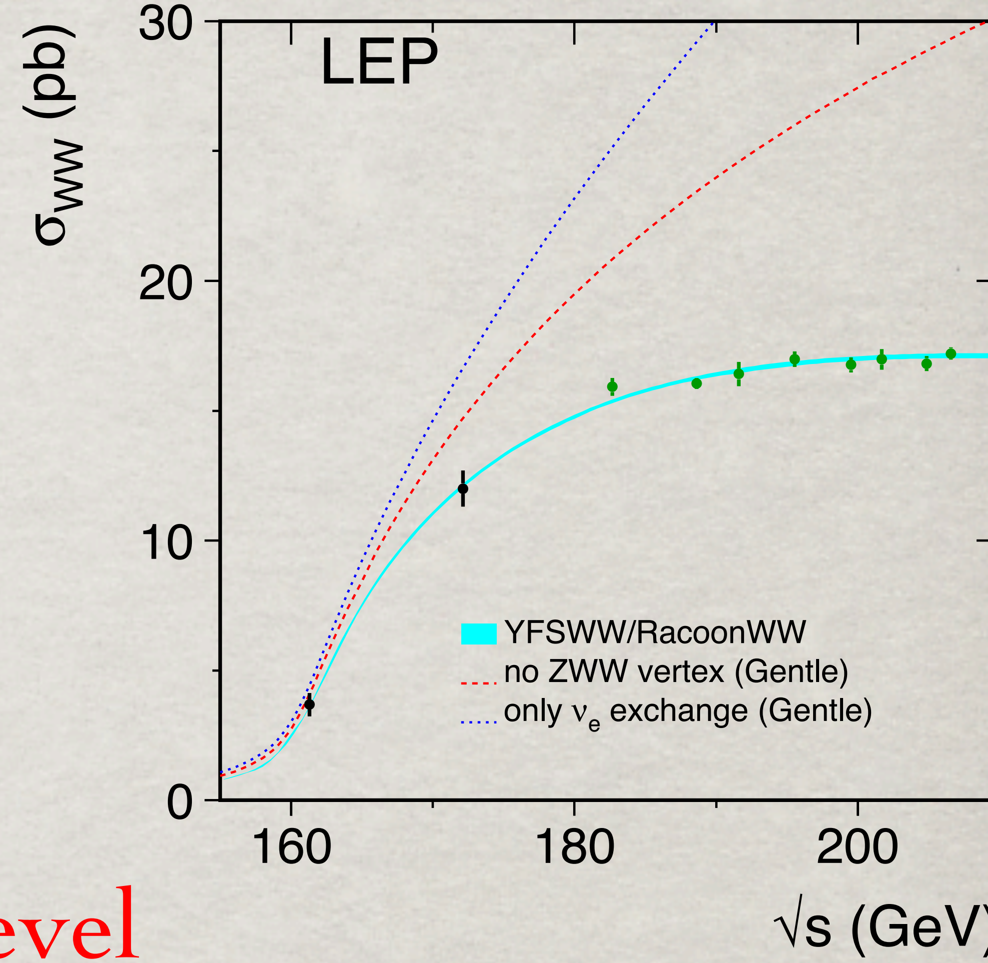
arXiv:1310.6708



"Custodial SU(2)c symmetry"
(only broken by g_Y & m_U-m_D)

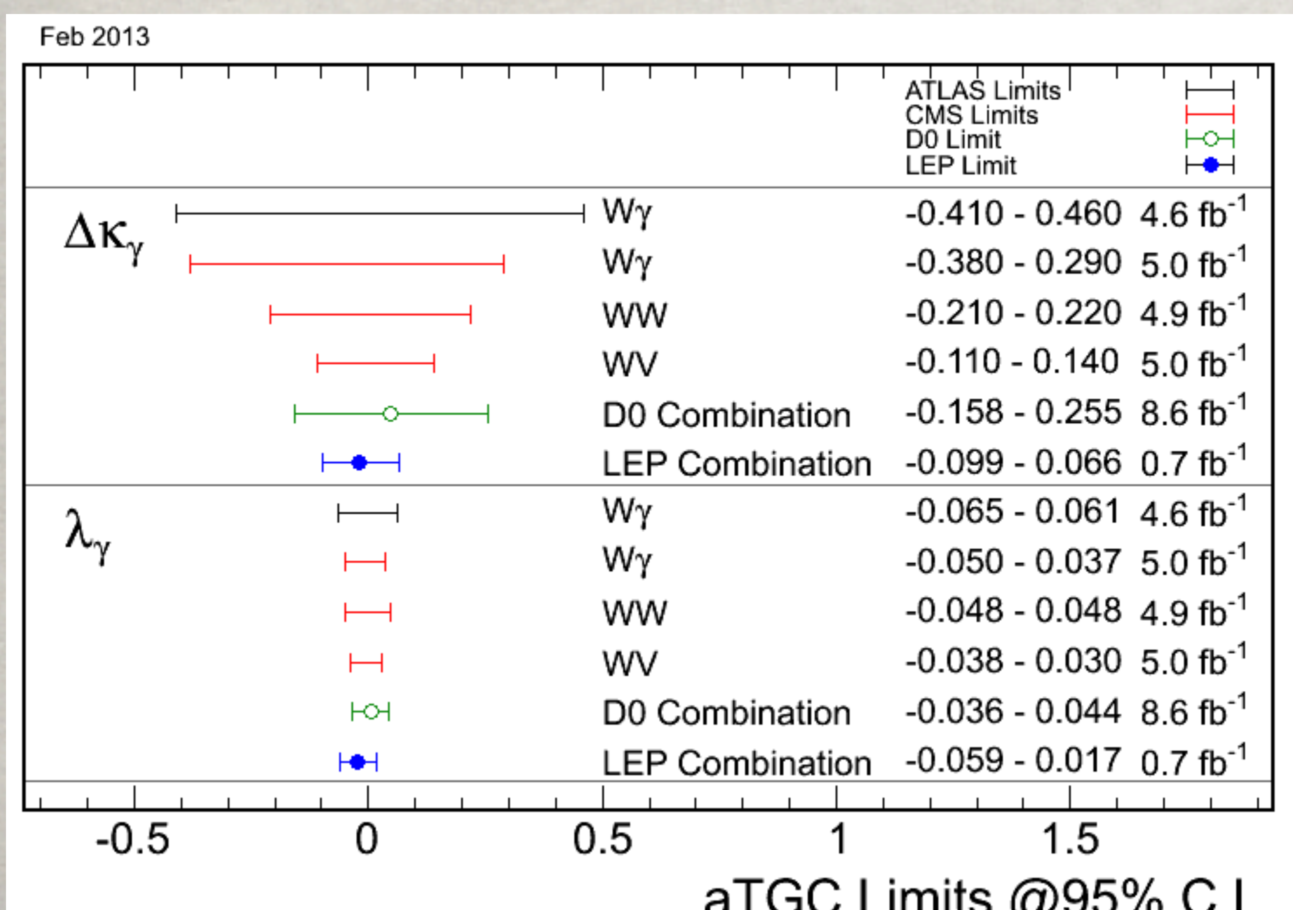
At LEP-II: (and on …)

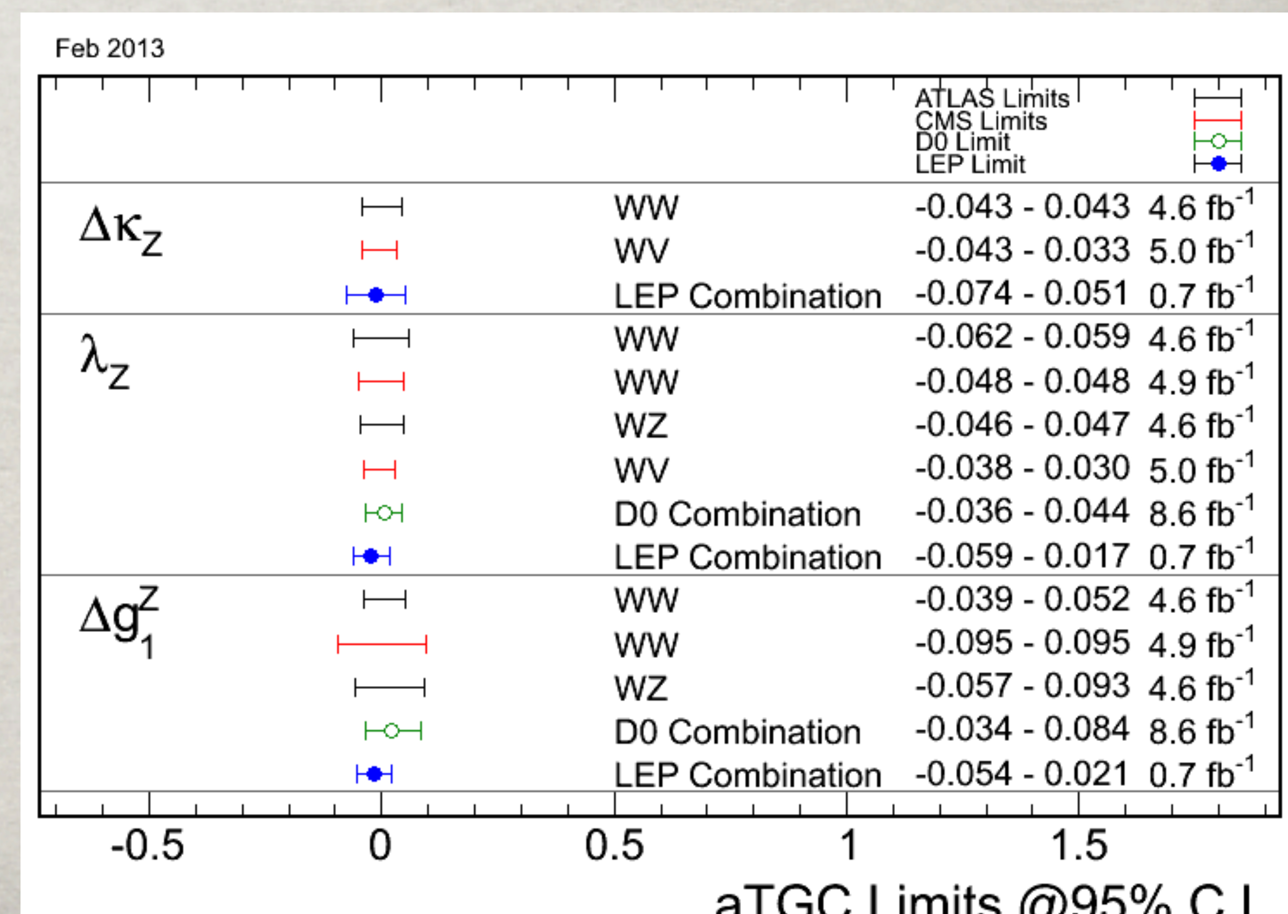




Anomalous triple gauge-boson couplings: (aTGC)

5% level

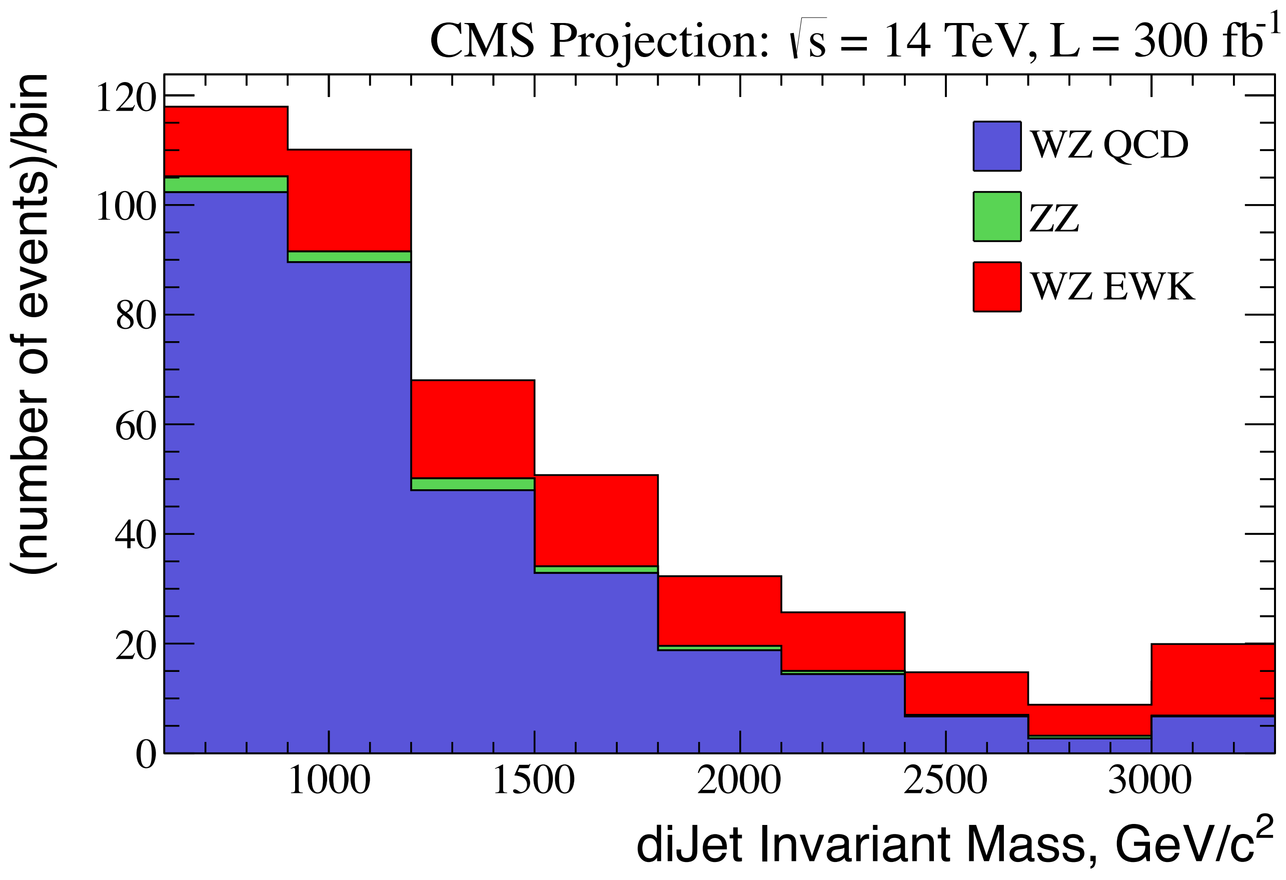




Longitudinal W's sensitive to new physics.
Crucial: observe the SM $W_L W_L$ scattering:

Duric (CMS)

WZ scattering discovery possibilities

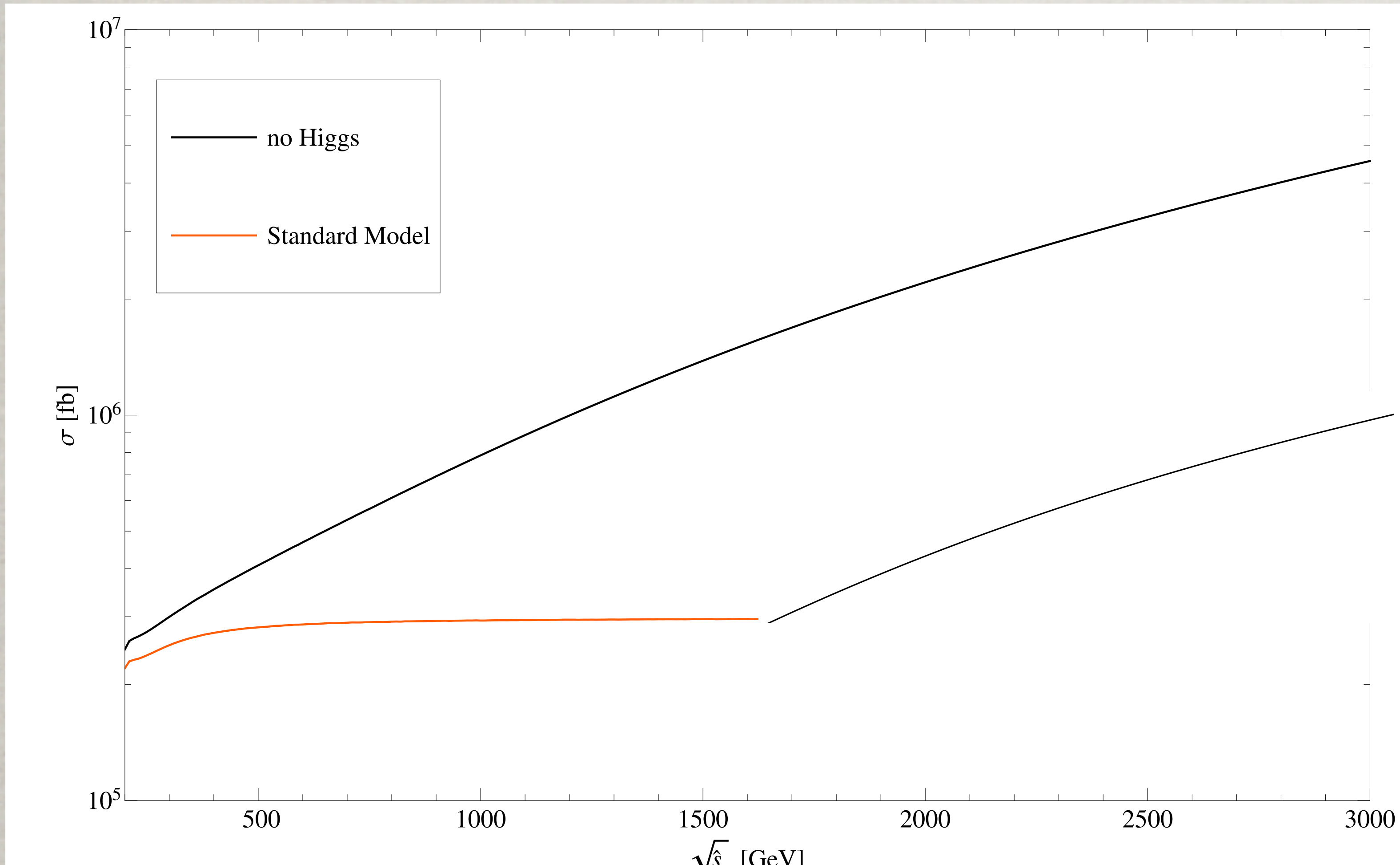


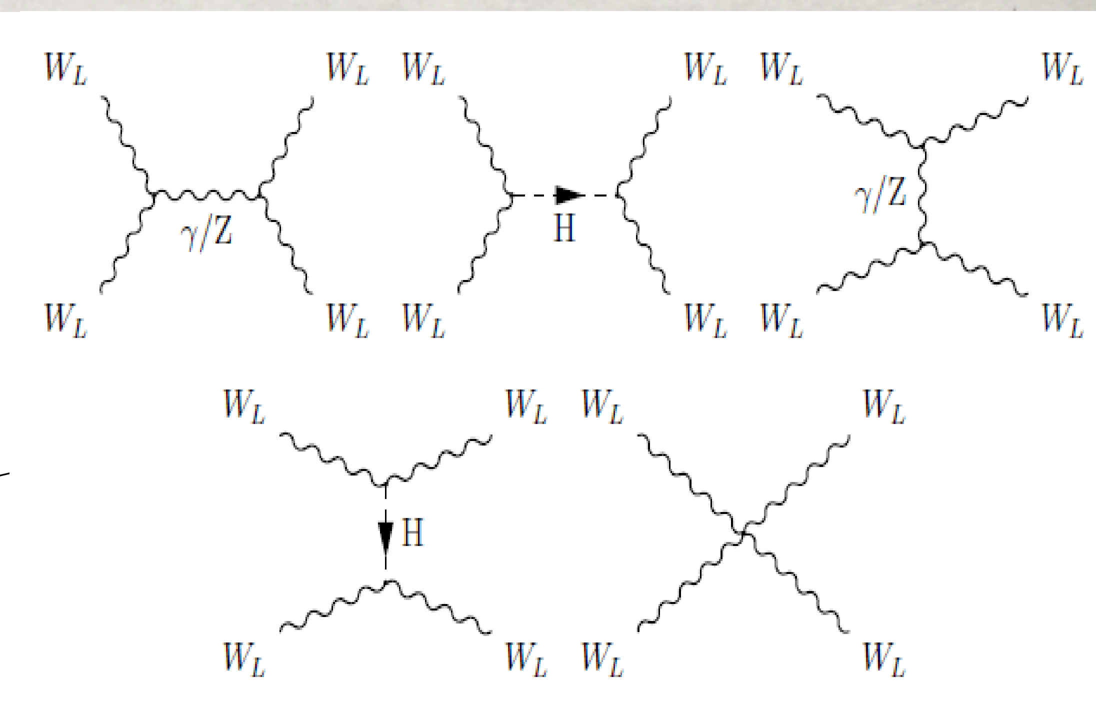
- WZ scattering inhanced in high dijet mass region
- Counting experiment in M(jet1,jet2)>1.2 TeV region
- 5σ discovery expected with integrated luminosity of 185 fb^{-1}

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFTR13006

- The existence of a light, weakly coupled Higgs boson unitarize the amplitude:





- New physics still possible, but be "delayed"

~ $(g^2/16\pi^2)\ s/v^2$

- For 1 TeV new physics **$(v/1\ \mathrm{TeV})^2$ ~ 6%!**

Representative examples:
Different channels are sensitive to different physics:

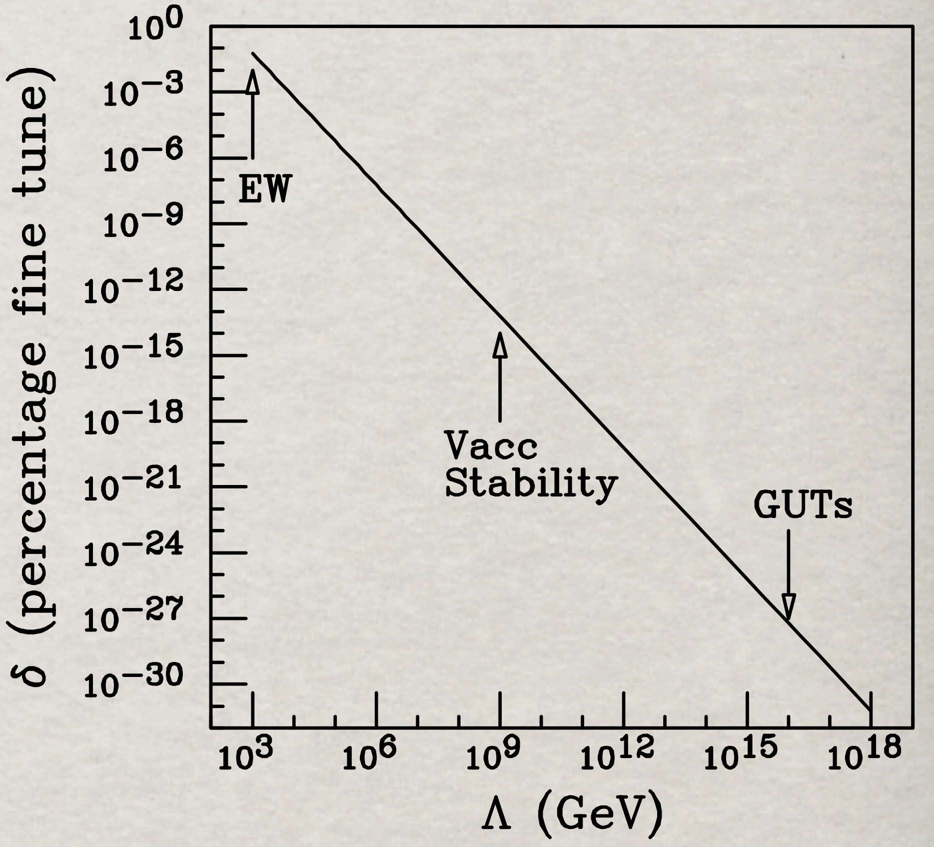
I	0	1	2
$J = 0$	σ^0	.	$\phi^{--}, \phi^-, \phi^0, \phi^+, \phi^{++}$
1	.	ρ^-, ρ^0, ρ^+	.
2	f^0	.	$t^{--}, t^-, t^0, t^+, t^{++}$
...	...	...	...

- $I = 0$: resonant in W^+W^- and ZZ scattering
- $I = 1$: resonant in W^+Z and W^-Z scattering
- $I = 2$: resonant in W^+W^+ and W^-W^- scattering

Type of resonance	LHC 300 fb^{-1}		LHC 3000 fb^{-1}	
	5	95% CL	5	95% CL
scalar	1.8 TeV	2.0 TeV	2.2 TeV	3.3 TeV
vector	2.3 TeV	2.6 TeV	2.9 TeV	4.4 TeV
tensor f	3.2 TeV	3.5 TeV	3.9 TeV	6.0 TeV

Overall

* With the Higgs discovery, EW theory is healthier than ever, valid from EW scale possibly to M_{PL}



But the Higgs sector fine-tuned: need more understanding.

- Gauge/Higgs weakly coupled, e.g. TGC etc. SM-like.

$W_L W_L$ still robust test for EWSB: compositeness … But sensitivity delayed: $g_\rho/4\pi$.

* Perhaps, it's more likely to observe resonant states:

$W^{\pm\prime}$, Z'; $H^\pm$, A^0; …

than aTGC ($W^{\pm\prime}$, Z'), aQGC (Higgs-like)