Lecture 3

Testing the Electroweak Standard Model

Testing the Electroweak Standard Model

- Couplings of gauge bosons to fermions

- Gauge boson self-couplings

- Higgs boson couplings:
  - to fermions
  - to gauge bosons
  - to itself

Gauge Boson Self Couplings

Evidence of the Non Abelian caracter of the EW theory

From $$\mathcal{L}_{\mathrm{GB}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

with $$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g\epsilon^{abc} A^b_\mu A^c_\nu$$

and going from $(A^a_\mu, B_\mu) \to (W^\pm, A_\mu, Z^0_\mu)$ we obtain the triple gauge couplings (TGC)

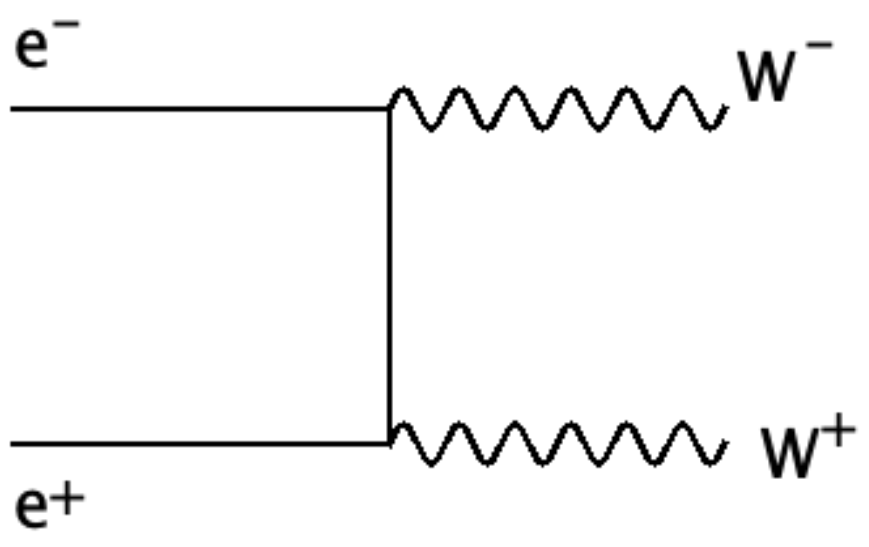
$$\mathcal{L}_{WWV} = i g_{WWV} \left[\left(W^\dagger_{\mu\nu} W^\mu - W_{\mu\nu} W^{\mu\dagger} \right) + W^\dagger_\mu W_\nu V^{\mu\nu} \right]$$

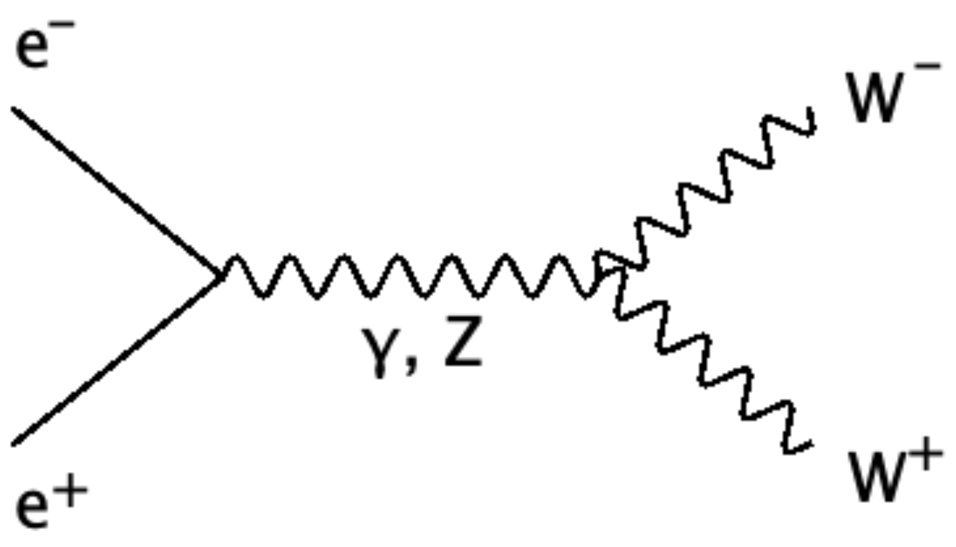
for $V = \gamma, Z^0$ with $g_{WW\gamma} = -e$ $\quad g_{WWZ} = -e \cot\theta_W$

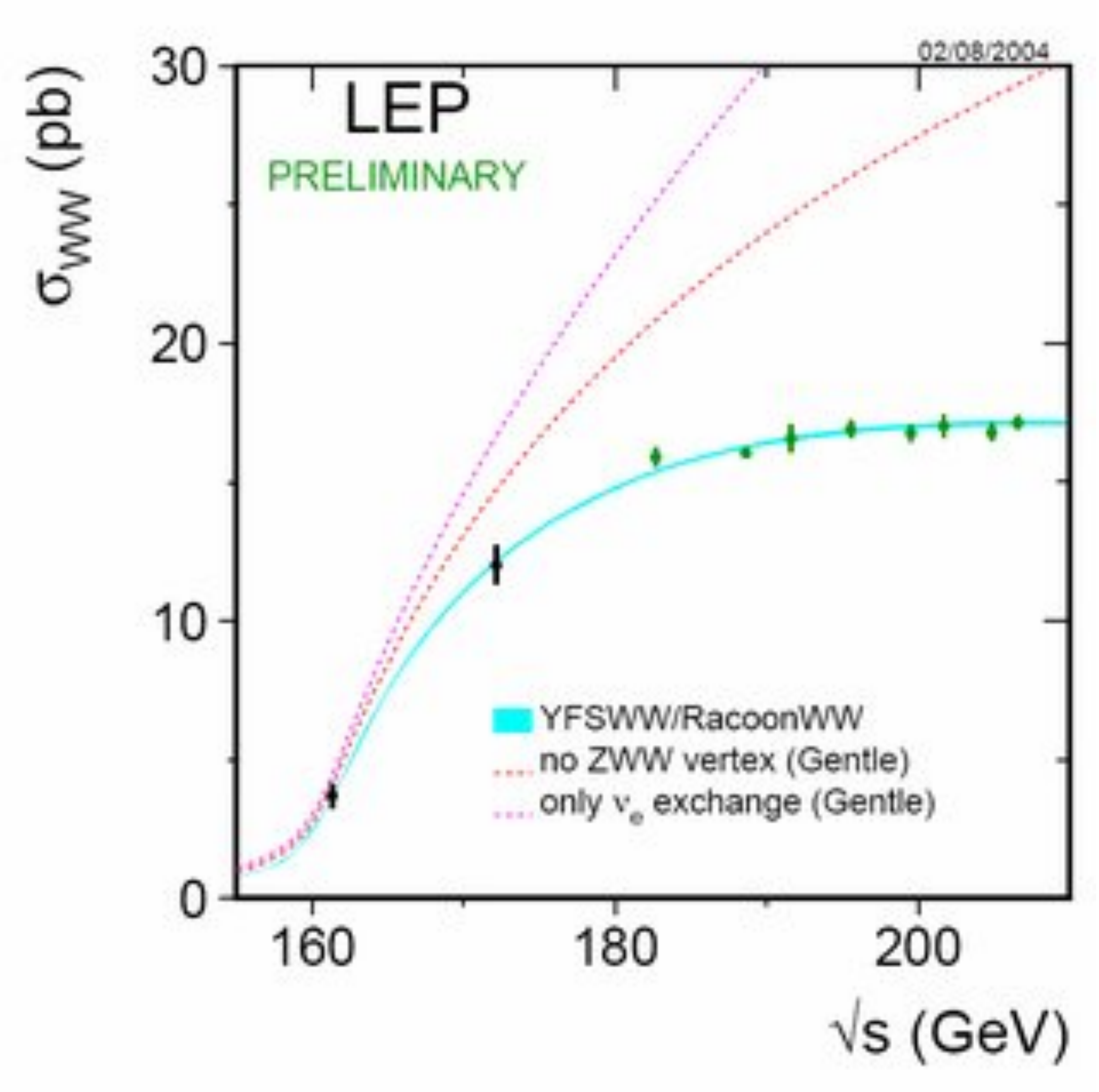
and $$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu \qquad V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

Tested first at LEP 2 in W pair production

$$e^+e^- \to W^+W^-$$







TGC further tested

Allow for anomalous TGCs:

$$\mathcal{L}_{WWV} = i g_{WWV} \left[g_1^V \left(W^{\dagger}_{\mu\nu} W^{\mu} - W_{\mu\nu} W^{\mu\dagger} \right) V^{\nu} + \kappa_V \, W^{\dagger}_{\mu} W_{\nu} V^{\mu\nu} + i \frac{\lambda_V}{M_W^2} W^{\dagger}_{\rho\mu} W^{\mu}_{\nu} V^{\nu\rho} \right]$$

In the SM $\quad g_1^V = 1 = \kappa_V \quad \text{and} \quad \lambda_V = 0$

Already from LEP data we have:

$$g_1^V = 0.984^{+0.018}_{-0.020} \qquad \kappa_V = 0.982 \pm 0.042 \qquad \lambda_V = -0.022 \pm 0.019$$

TGC and Quartic Couplings further tested at the LHC

Taken from G. Monchenault, *Annu. Rev. Nucl. Part. Sci. 2017. 67:19–44*

Table 1 Observed 95%-CL limits on $WW\gamma$ and WWZ anomalous trilinear gauge boson couplings

	Channel	95%-CL interval	Experiment	$\sqrt{s}$ (TeV)	Luminosity (fb^{-1})	Reference
$\Delta\kappa_\gamma$	LEP combined	[−0.099, +0.066]	LEP	0.2	0.7	115
	D0 combined	[−0.16, +0.25]	D0	1.96	8.6	132
	$W\gamma$	[−0.41, +0.46]	ATLAS	7	4.6	63
	$W\gamma$	[−0.38, +0.29]	CMS	7	5.0	64
	WW	[−0.21, +0.22]	CMS	7	4.9	71
	$WW+WZ$	[−0.21, +0.22]	ATLAS	7	4.6	93
	$WW+WZ$	[−0.11, +0.14]	CMS	7	5.0	94
	WW	[−0.12, +0.17]	ATLAS	8	20.3	72
	WW	[−0.13, +0.095]	CMS	8	19.4	73
λ_γ	LEP combined	[−0.059, +0.017]	LEP	0.2	0.7	115
	D0 combined	[−0.036, +0.044]	D0	1.96	8.6	132
	$W\gamma$	[−0.065, +0.061]	ATLAS	7	4.6	63
	$W\gamma$	[−0.050, +0.037]	CMS	7	5.0	64
	WW	[−0.048, +0.048]	CMS	7	4.9	71
	$WW+WZ$	[−0.039, +0.040]	ATLAS	7	4.6	93
	$WW+WZ$	[−0.038, +0.030]	CMS	7	5.0	94
	WW	[−0.019, +0.019]	ATLAS	8	20.3	72
	WW	[−0.024, +0.024]	CMS	8	19.4	73
Δg_1^Z	LEP combined	[−0.054, +0.021]	LEP	0.2	0.7	115
	D0 combined	[−0.034, +0.084]	D0	1.96	8.6	132
	WW	[−0.039, +0.052]	ATLAS	7	4.6	70
	WW	[−0.095, +0.095]	CMS	7	4.9	71
	$WW+WZ$	[−0.055, +0.071]	ATLAS	7	4.6	93
	WW	[−0.016, +0.027]	ATLAS	8	20.3	72
	WW	[−0.047, +0.022]	CMS	8	19.4	73
	WZ	[−0.19, +0.29]	ATLAS	8	20.3	78
	WZ	[−0.28, +0.40]	CMS	8	19.6	79
$\Delta\kappa_Z$	WZ	[−0.19, +0.30]	ATLAS	8	20.3	78
	WZ	[−0.29, +0.30]	CMS	8	19.6	79
λ_Z	WZ	[−0.016, +0.016]	ATLAS	8	20.3	78
	WZ	[−0.024, +0.021]	CMS	8	19.6	79

Anomalous TGC and Quartic couplings enter in EFT analysis

See lectures by John Ellis

Electroweak Precision Tests

- Measurements of the electroweak couplings of fermions with great precision
- This precision must be matched by the theoretical predictions. It requires to go well beyond leading order (tree level) in perturbative calculations

- The electroweak theory is defined by 3 parameters (ignoring the fermion Yukawas)

$$g, g' \quad \text{and} \quad v$$

From them we can predict observables

- But if we need loop calculations do we need to worry about divergences, renormalization. etc. ?

Renormalization (See I.L19 to I.L25)

Consider a real scalar field with lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi_0\partial^\mu\phi_0 - \frac{1}{2}m_0^2\phi_0^2 - \frac{\lambda_0}{4!}\phi_0^4$$

(ϕ_0, m_0, λ_0) are the un-renormalized parameters

Define renormalized parameters as

$$\phi = Z_\phi^{-1/2}\,\phi_0 \qquad m^2 \equiv m_0^2 Z_\phi - \delta m^2 \qquad \lambda \equiv \lambda_0 Z_\phi^2 - \delta\lambda$$

Then using $Z_\phi = 1 + \delta Z_\phi$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

⟵ Renormalized lagrangian

$$+\frac{1}{2}\delta Z_\phi\,\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\delta m^2\phi^2 - \frac{\delta\lambda}{4!}\phi^4$$

⟵ Counter-Terms

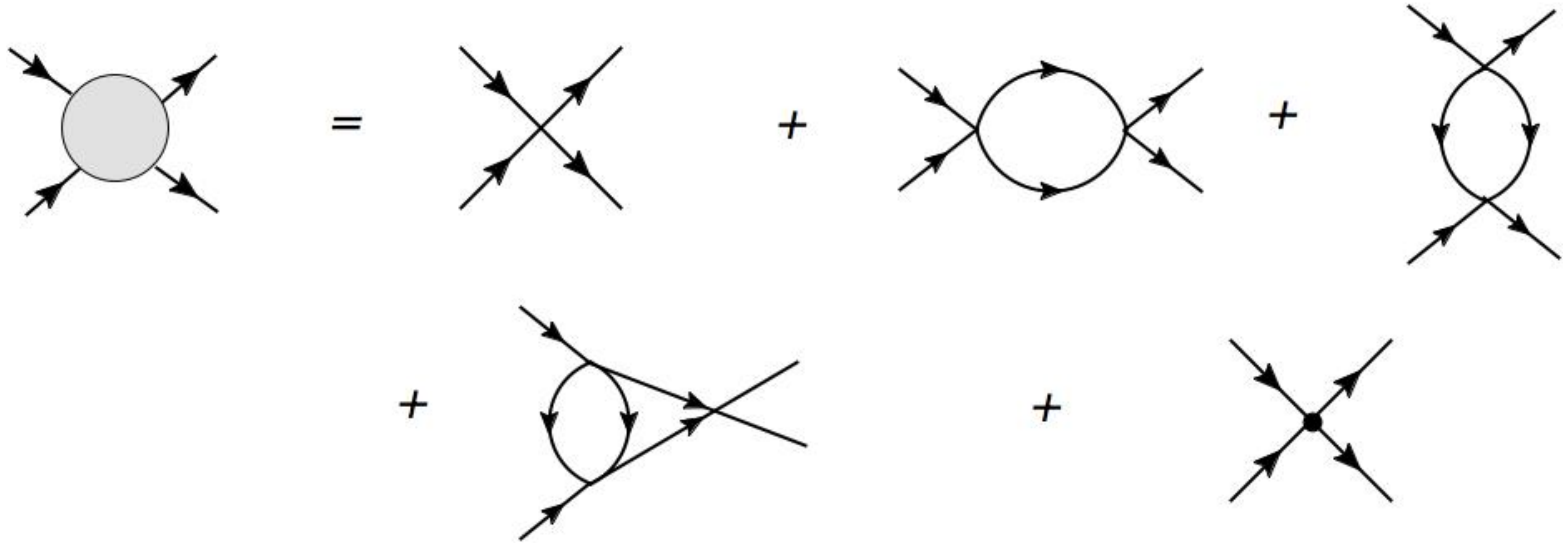
The CTs generate additional Feynman rules

- A renormalizable theory has a *finite* number of CTs

- The CTs are computed in perturbation theory by imposing *renormalization conditions*

These are input. E.g. m^2 is the pole in propagator, with residue = 1 fixes δm^2 and δZ_ϕ

But to fix $\delta\lambda$ we need a “measurement"



$$i\mathcal{A}(p_1, p_2 \to p_3, p_4) = -i\lambda + \Gamma(s) + \Gamma(t) + \Gamma(u) - i\delta\lambda$$

Choose a kinematic point to impose $i\mathcal{A}(s_0, t_0, u_0) = -i\lambda \implies \boxed{\Gamma(s_0) + \Gamma(t_0) + \Gamma(u_0) - i\delta\lambda = 0}$

Fixes $\delta\lambda$ ↑

Back to Electroweak Precision Tests

Since the theory is renormalizable zeroth order “natural relations” (from the classical lagrangian) are not affected by the shift in the parameters (i.e. by the counter-terms).

These relations are affected by quantum corrections. But these must be finite.

They constitute important tests of the quantum field theory.

E.g.: $\frac{M_W^2}{M_Z^2} = \cos^2\theta_W$ receives finite quantum corrections from loops

E.g. if we ignore corrections to vertices involving external (light) fermions then

$$= \Pi_{VV'}(q^2)\, g^{\mu\nu} - \Delta_{VV'}(q^2)\, q^\mu q^\nu$$

Will depend on the parameters of the theory (including m_h and m_t through loops)

$$\rho = 1 + \frac{\Pi_{ZZ}(0)}{M_Z^2} - \frac{\Pi_{WW}(0)}{M_W^2}$$

The finite quantum corrections change the tree level form of decay widths, cross sections, asymmetries, …

Global fits to these data result in predictions for the electroweak SM

Global fit of Z pole observables
From RPP Summary

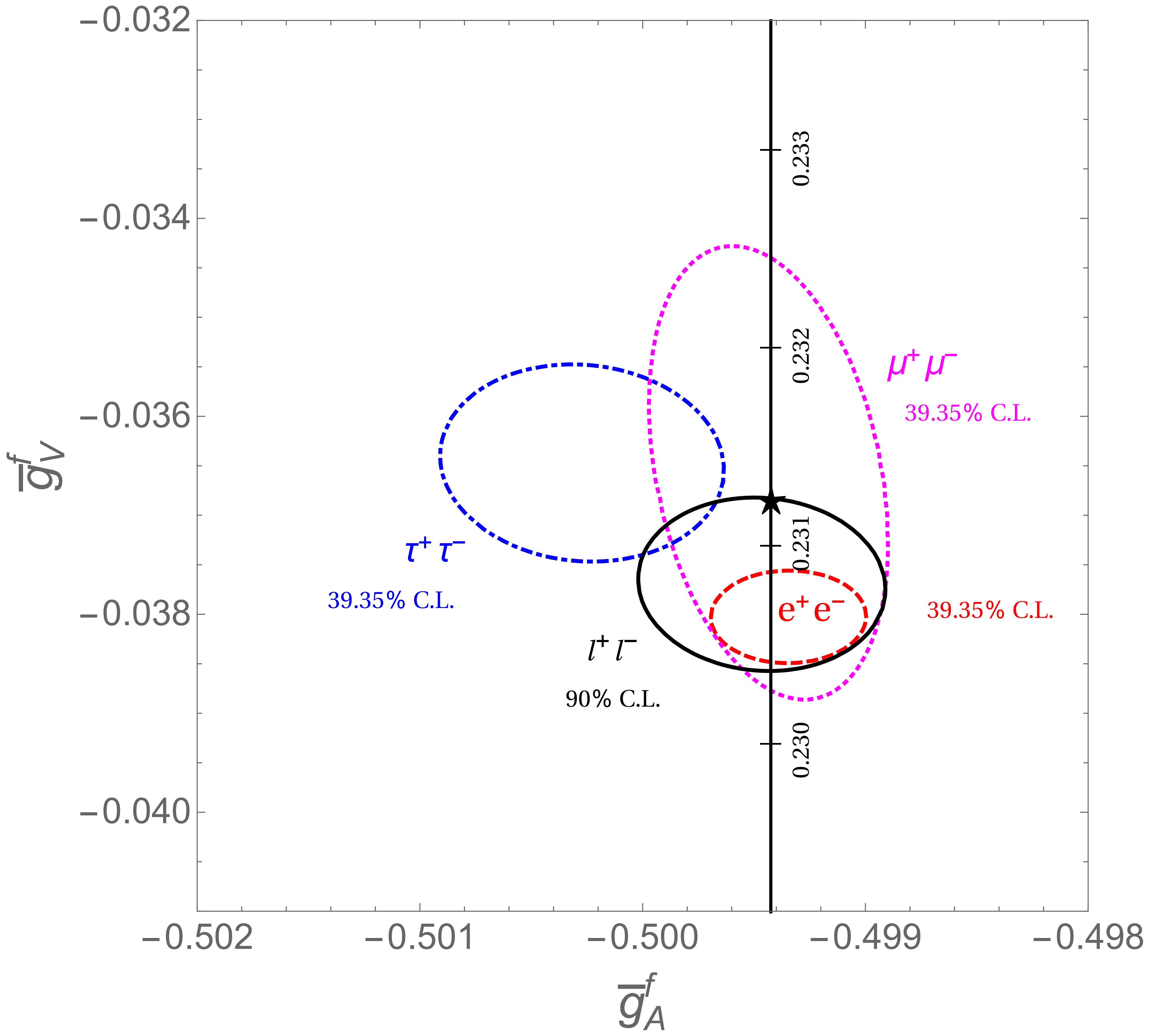
Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1884 ± 0.0020	-0.4
Γ_Z [GeV]	2.4952 ± 0.0023	2.4942 ± 0.0008	0.4
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7411 ± 0.0008	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.44 ± 0.04	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.959 ± 0.008	—
σ_{had}[nb]	41.541 ± 0.037	41.481 ± 0.008	1.6
R_e	20.804 ± 0.050	20.737 ± 0.010	1.3
R_μ	20.785 ± 0.033	20.737 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.782 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21582 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01618 ± 0.00006	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1030 ± 0.0002	-2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0001	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1031 ± 0.0002	-0.5
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23154 ± 0.00003	0.7
	0.23148 ± 0.00033		-0.2
	0.23104 ± 0.00049		-1.0
A_e	0.15138 ± 0.00216	0.1469 ± 0.0003	2.1
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6677 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

Lepton couplings to Z

From g_L^f and g_R^f $\longrightarrow$ $$\begin{cases} \bar{g}_V^f = \sqrt{\rho_f}(t_f^3 - \kappa_f 2Q_f \sin^2\theta_W) \\ \bar{g}_A^f = \sqrt{\rho_f}\, t_f^3 \end{cases}$$

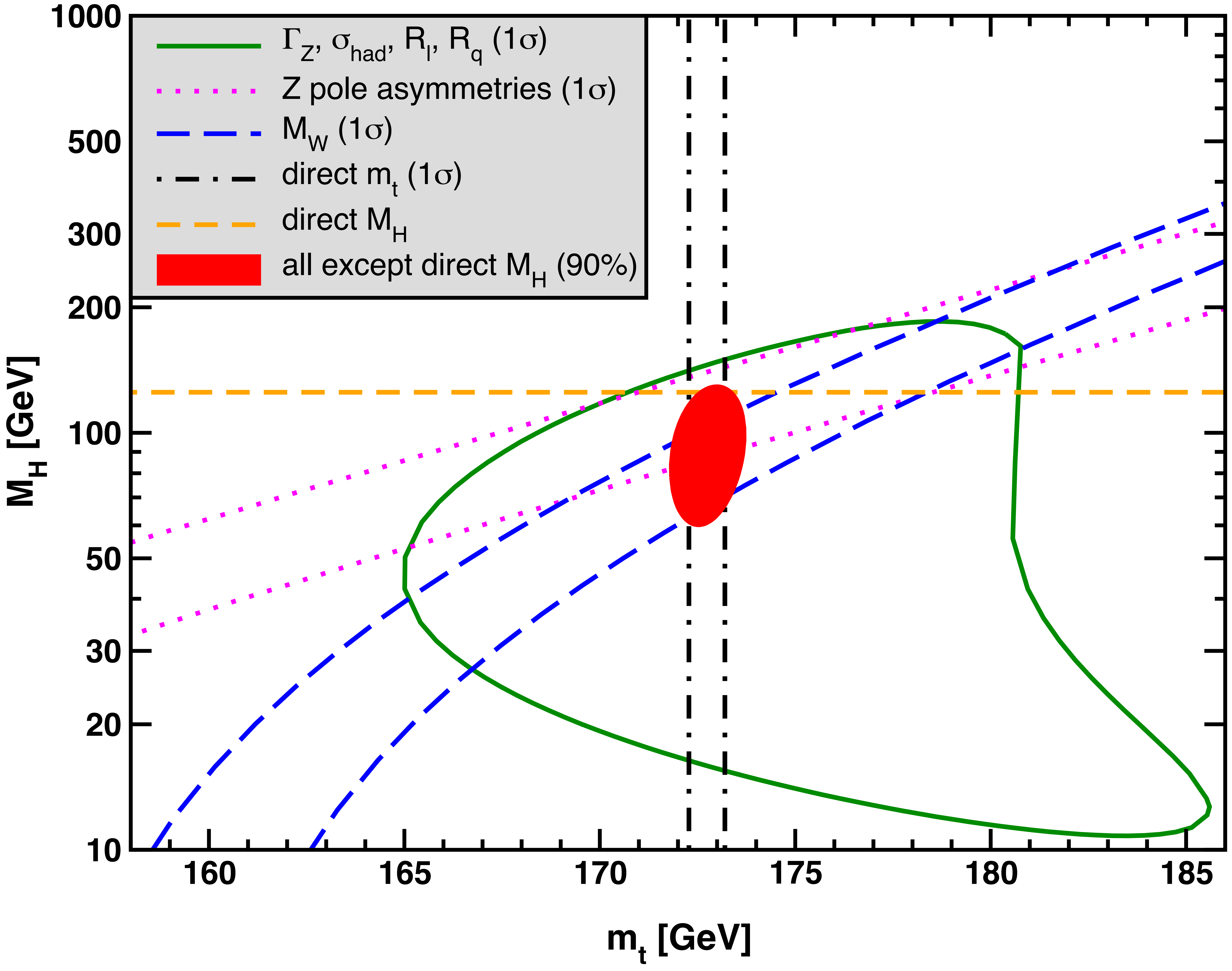
Here ρ_f, κ_f encode quantum corrections (=1 at tree level)

Extracted from Z pole decays to leptons and asymmetries from LEP and SLD data



Sensitivity to the Higgs quantum corrections

From the log dependence on m_h in the quantum corrections



$$\Rightarrow \quad m_h = (90^{+17}_{-16})\ \mathrm{GeV}$$

The Standard Model Higgs

$$\mathcal{L}_{\rm EW} = (D_\mu\Phi)^\dagger D^\mu\Phi - V(\Phi^\dagger\Phi) + \mathcal{L}_{HF} + \mathcal{L}_{GF} + \mathcal{L}_{GB}$$

Higgs couplings to gauge bosons — to itself — to fermions

Using $\Phi(x) = \begin{pmatrix} 0 \\ \frac{v+h(x)}{\sqrt{2}} \end{pmatrix}$ (unitary gauge)

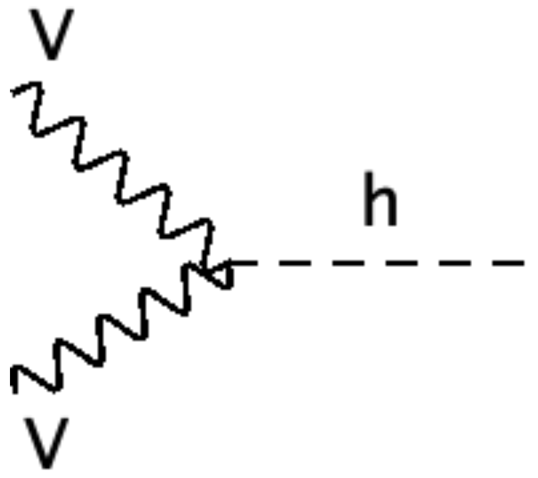
Coupling to Gauge Bosons:

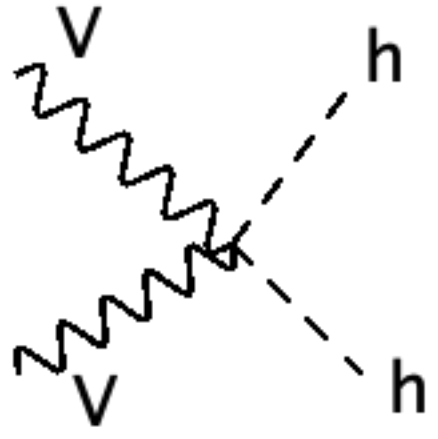
$$\mathcal{L}_{hWW} = \left[g_{hWW}h + \frac{g_{hhWW}}{2!}h^2\right] W_\mu^- W^{+\mu}$$

$$\mathcal{L}_{hZZ} = \left[\frac{g_{hZZ}}{2!}h + \frac{g_{hhZZ}}{(2!)^2}h^2\right] Z_\mu Z^\mu$$

$$g_{hWW} = \frac{2M_W^2}{v} \qquad g_{hZZ} = \frac{2M_Z^2}{v}$$

$$g_{hhWW} = \frac{2M_W^2}{v^2} \qquad g_{hhZZ} = \frac{2M_Z^2}{v^2}$$



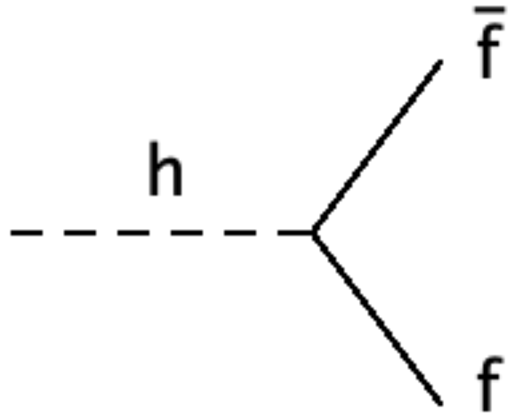


- Triple coupling tested in Higgs decays to both $\gamma\gamma$ and VV^* at the LHC
- g_{hhVV} accessible in double Higgs production

Higgs Couplings to Fermions

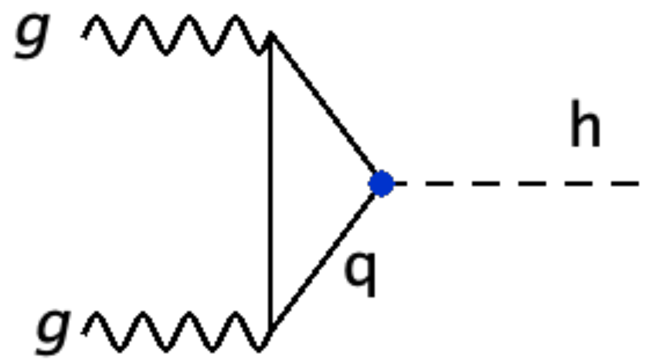
$$-\mathcal{L}_{HF} = \lambda_u^{ij}\,\bar{q}_{L,i}\tilde{\Phi}u_{R,j} + \lambda_d^{ij}\,\bar{q}_{L,i}\Phi d_{R,j} + \lambda_e^{ij}\,\bar{\ell}_{L,i}\Phi\ell_{R,j}$$

But the couplings $\lambda_f^{ij} = \frac{M_f^{ij}}{v}$ are simultaneously diagonalized with the mass matrices



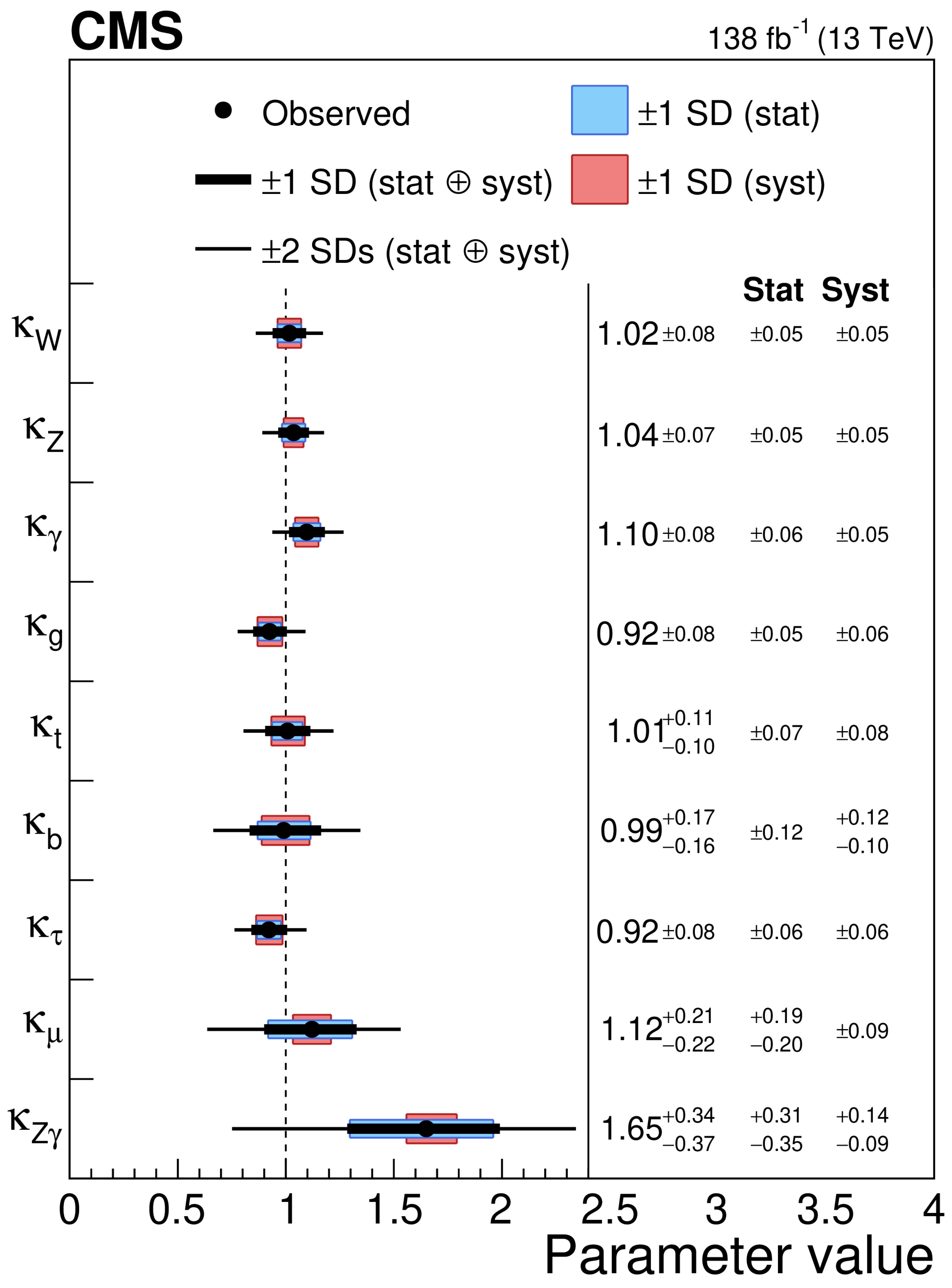
$\frac{m_f}{v}$ are flavor diagonal

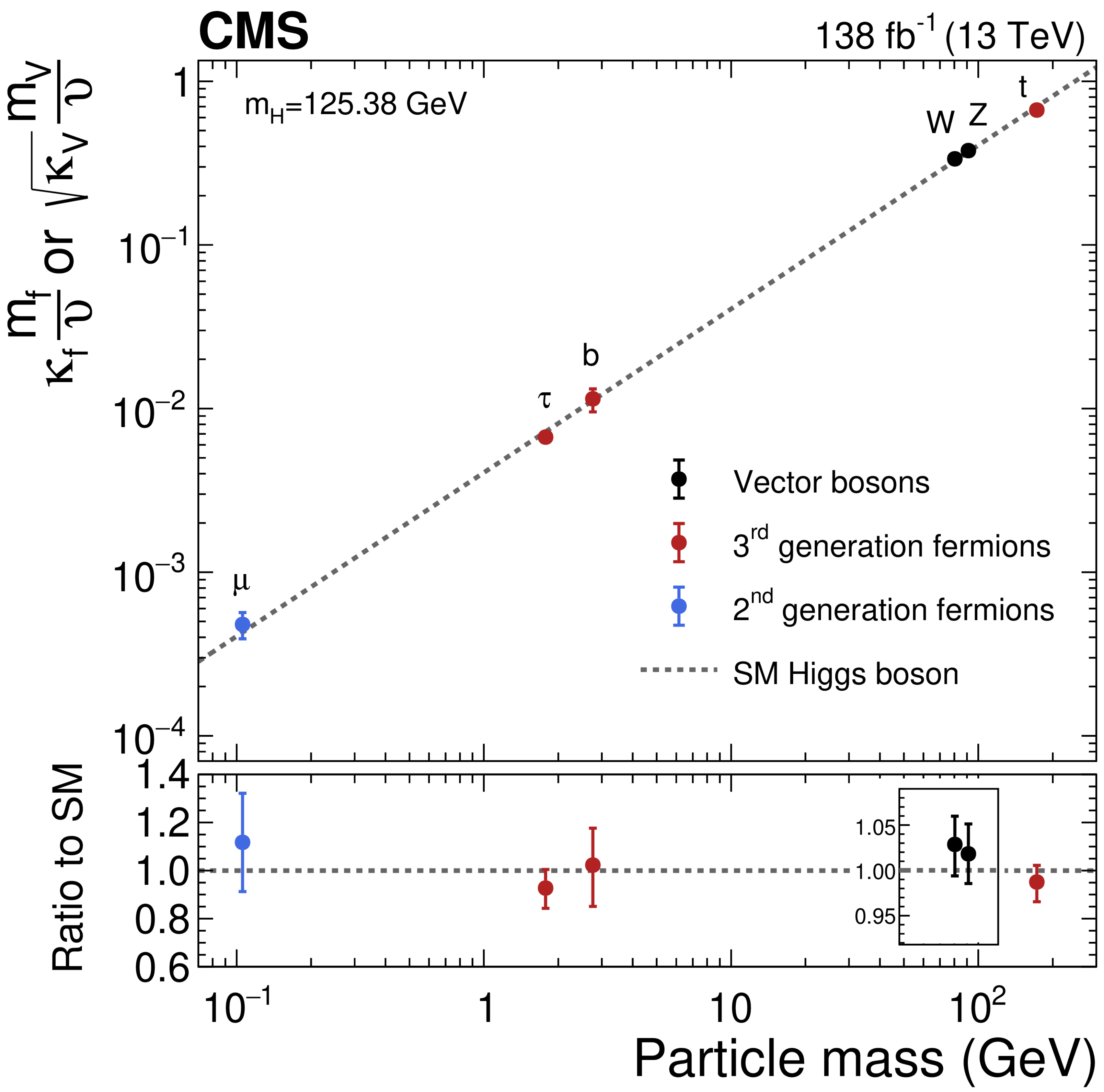
Experimentally accessible:

- λ_t enters in production through ggF loop


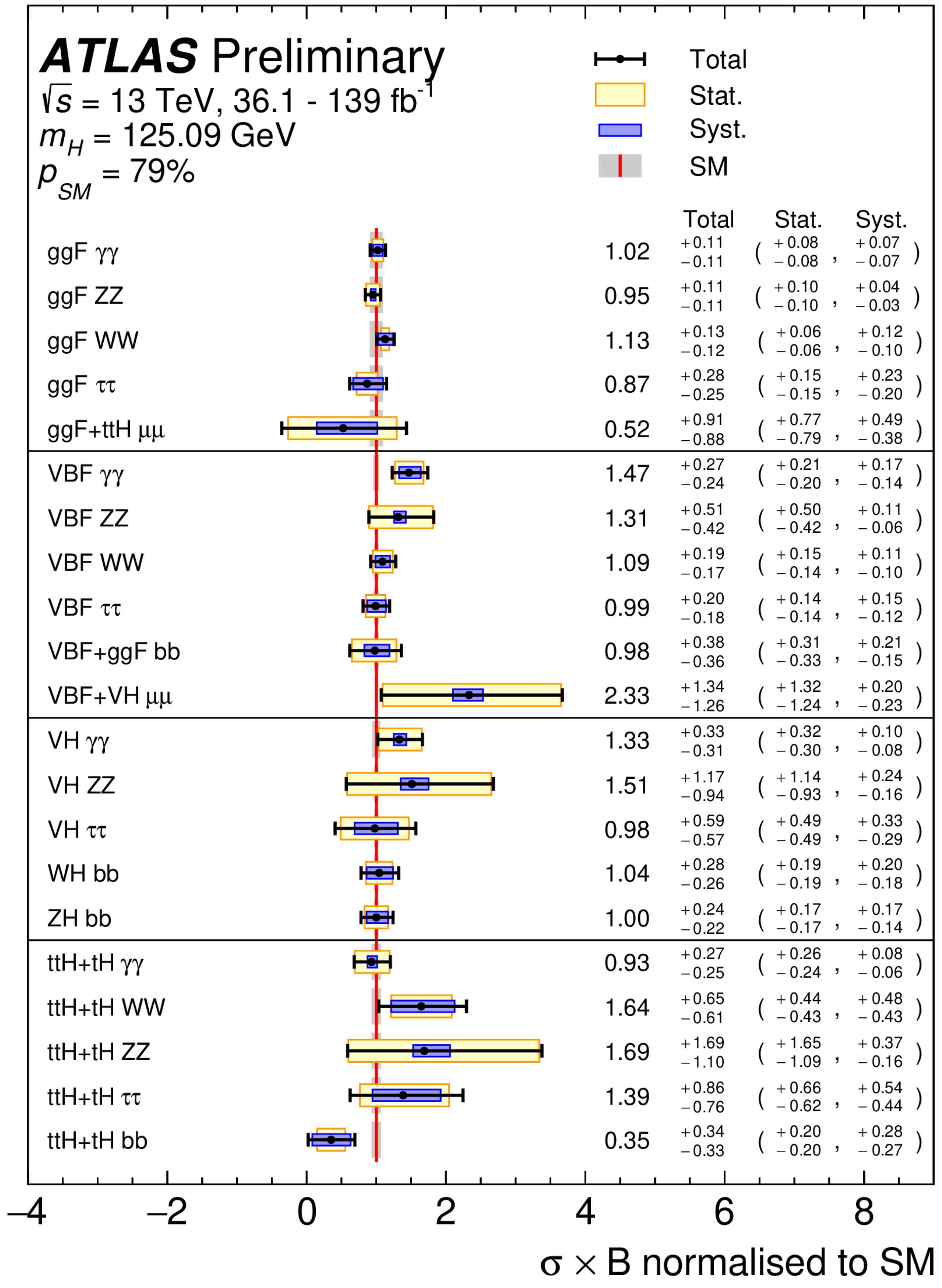
and $t\bar{t}h$
- λ_b ggF+VH+$t\bar{t}h$
- λ_τ VH+VBF+ggF
- λ_μ ggF+VBF

Extraction of Higgs Couplings





Extraction of Higgs Couplings



Parameter	(a) $B_{i.} = B_{u.} = 0$	(b) $B_{i.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	0.99 ± 0.06	$0.96^{+0.04}_{-0.05}$
κ_W	1.06 ± 0.06	$1.00^{+0.00}_{-0.03}$
κ_b	0.87 ± 0.11	0.81 ± 0.08
κ_t	0.92 ± 0.10	0.90 ± 0.10
κ_μ	$1.07^{+0.25}_{-0.30}$	$1.03^{+0.23}_{-0.29}$
κ_τ	0.92 ± 0.07	0.88 ± 0.06
κ_γ	1.04 ± 0.06	1.00 ± 0.05
$\kappa_{Z\gamma}$	$1.37^{+0.31}_{-0.37}$	$1.33^{+0.29}_{-0.35}$
κ_g	$0.92^{+0.07}_{-0.06}$	$0.89^{+0.07}_{-0.06}$
$B_{i.}$	-	< 0.09 at 95% CL
$B_{u.}$	-	< 0.16 at 95% CL

Higgs Self Couplings

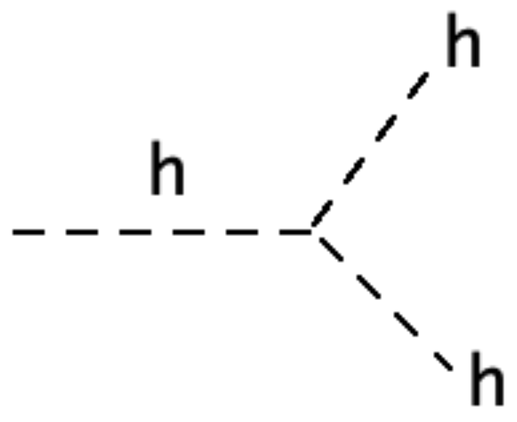
From the Higgs potential

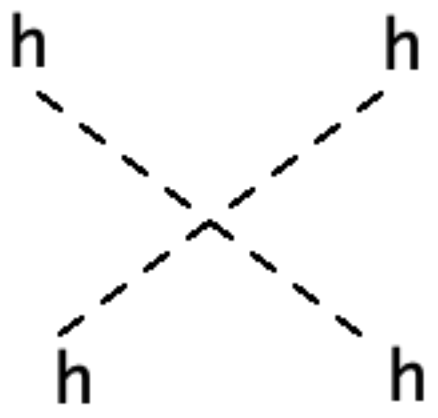
$$V(\Phi^\dagger\Phi) = -m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$ and using $$v = \sqrt{\frac{m^2}{\lambda}}$$ from minimization

$$\mathcal{L}_h = -\frac{1}{2}m_h^2\, h^2 - \frac{g_{h^3}}{3!}\, h^3 - \frac{g_{h^4}}{4!}$$

with $$\begin{cases} m_h = \sqrt{2\lambda}\, v \\ g_{h^3} = \dfrac{3m_h^2}{v} \\ g_{h^4} = \dfrac{3m_h^2}{v^2} \end{cases}$$

Require experimental access to (at least) double Higgs production





Fundamental question: is the coupling extracted from the measurement of m_h really the Higgs self-coupling ? We will begin attacking this question at the HL-LHC.

Fundamental Test of the SM Higgs Sector

From $m_h \simeq 125\,\mathrm{GeV}$

using $m_h = \sqrt{2\lambda}\,v$ and $v \simeq 246\,\mathrm{GeV}$ from fits to EW data

We arrive at

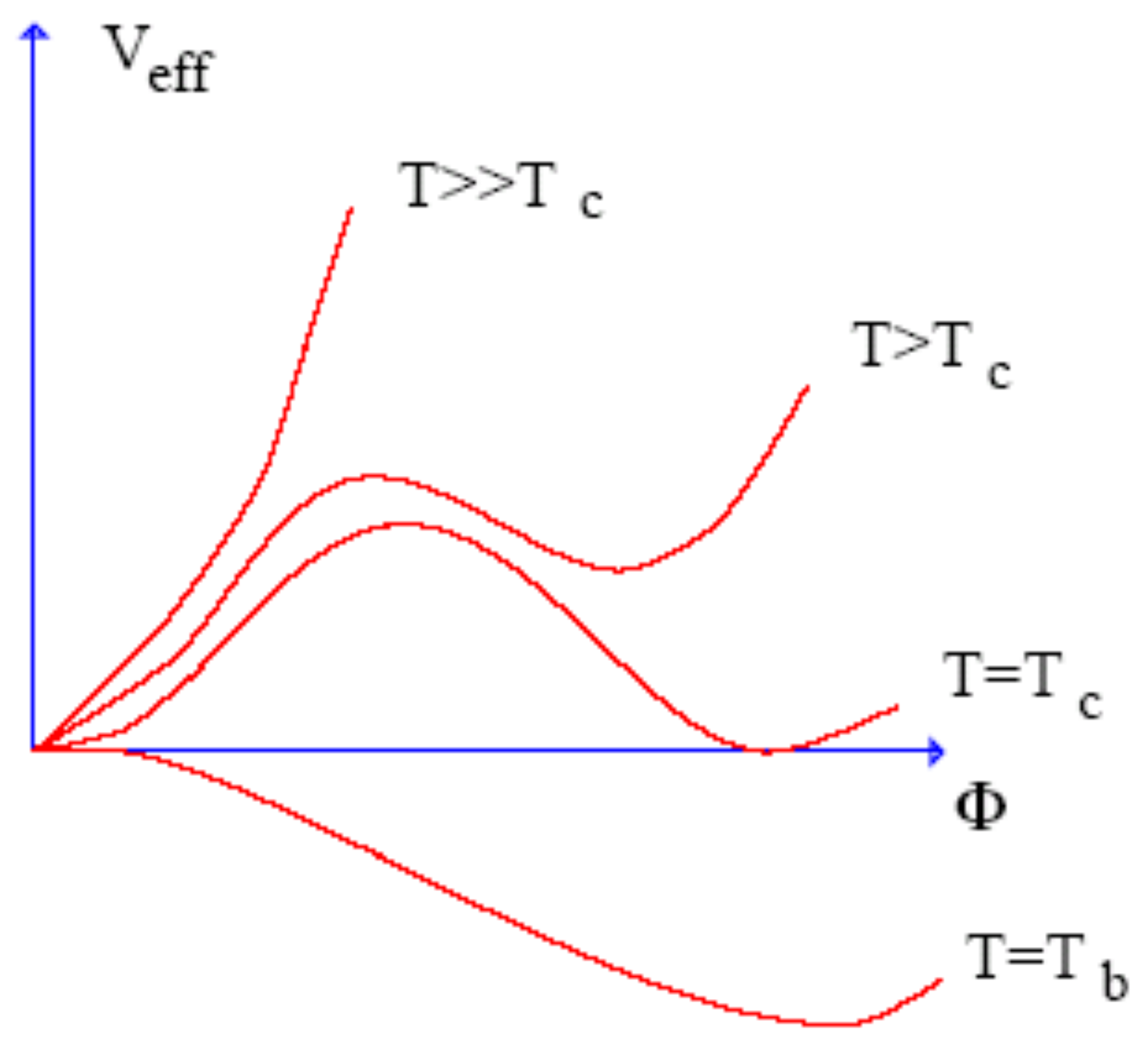
$$\lambda \simeq 0.13$$

Measurements of λ in multi-Higgs production directly test the shape of the Higgs potential

Other Possible Consequence of the Shape of the Higgs Potential

The Electroweak Phase Transition

- It happens during the history of the universe, as it cools down $T_{\rm EWPT} \simeq 150 \quad {\rm GeV}$



- If a barrier develops ⟶ first order phase transition

  This would lead to bubble formation ⟶ gravity waves !

- LISA will have sensitivity to these GW

- But, in the SM PT is not strong enough!

  Higgs too heavy ! Actually, only a crossover.

New physics affecting the Higgs potential could change this !

The Electroweak Standard Model and the Future

- It is a very successful theory:

  As a gauge theory $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\rm EM}$

  It is tested with great precision interactions of fermions and gauge bosons self-interactions

- The mechanism of spontaneous gauge symmetry breaking (ABEH) has been established

  The Higgs field is responsible for electroweak symmetry breaking

  The remnant Higgs boson has the interactions predicted by this mechanism

  although more precision is desirable in the Higgs sector, in all Higgs couplings

Questions not answered by the SM

- The origin of dark matter

  The SM contains no viable candidate for DM. More than 80% of the matter in the universe appears to be "dark".

- The origin of the baryon asymmetry:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

The interactions in $\mathcal{L}_{\rm SM}$ respect baryon and lepton numbers. These are global $U(1)_B$ and $U(1)_L$
Violated at the quantum level by non-perturbative effects (sphalerons)

But to generate η we also need (Sakharov):

- CP violation (more than provided by CKM !) X
- Out of equilibrium dynamics. E.g. strong first order EW phase transition X

Questions raised by the SM

- The origin of the Higgs sector and the electroweak scale

$$\mathcal{L}_{\rm EW} = \left(D_\mu \Phi\right)^\dagger D^\mu \Phi - V(\Phi^\dagger \Phi) + \mathcal{L}_{HF} + \mathcal{L}_{GF} + \mathcal{L}_{GB}$$

with $V(\Phi^\dagger\Phi) = -m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$

$m\,(\text{or} \;\; m_h \;\; \text{or} \;\; v)$: only energy scale in all of the SM

- Where does it come from ?

- Other scales are generated by interactions. E.g. $\Lambda_{\rm QCD}$

- Only other fundamental scale is in Gravity: $M_P \simeq 10^{19}~\text{GeV}$

Plus $\Lambda_{\rm CC} \simeq 10^{-3}~\text{eV}$

- Is the electroweak scale natural ?

The energy scale in $V(\Phi^\dagger\Phi) = -m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$

i.e. coefficient of $\Phi^\dagger\Phi$ or m_h^2 have large (quadratic) sensitivity to the UV

Quantum corrections to the Higgs mass

$$\Delta m_h^2 \simeq \frac{c}{16\pi^2}\Lambda^2$$

with c coming from SM loops from GB, top, Higgs

This is not the case for fermions (chiral symm.) or gauge bosons (gauge symm.). Only log sensitivity to Λ

Renormalization condition is tuned: $(m_h^2)_{\text{phys.}} = \Delta m_h^2 + \delta m_h^2$

But, in principle, this is not a problem in QFT: we tune the RC to the physical Higgs mass.

Once this is done, $m_h^2(\mu)$ runs logarithmically.

But what if the Higgs couples to a heavy state with mass $M \gg m_h$?

This will give a contribution with a large mass threshold

$$\frac{Y_M^2}{16\pi^2} M^2 \ln \mu^2$$

This would force us to tune the RG running at the UV (above M) so we get the right Higgs mass in the IR

The existence of this heavy state coupled to the Higgs reintroduces the large tuning to still $(m_h)_{\rm phys.}$

So, even if we do not mind tuned renormalization conditions, we need no heavy particles coupled to the Higgs to avoid the quadratic UV sensitivity.

- Is the Higgs boson an elementary particle ?

    Spontaneous Symmetry Breaking appears in other physical systems

    Superfluidity, Superconductivity, Hadron physics

    Scalars are composite states (or collective excitations)

    “Radial” excitations (like the Higgs boson) are typically heavy (at the cutoff)

    Scalars that are light are (pseudo) Nambu-Goldstone bosons

Could the Higgs be a (pseudo) NGB from a spontaneously broken global symmetry ?

Could this be the reason why it is “light" ? Just as $m_\pi \ll 1 \ \text{GeV}$

If the Higgs boson is composite what are the experimental signals of this ?

- Why are fermion masses (Yukawa couplings) so different ?

  Why $\lambda_t \simeq 1 \qquad \lambda_u \simeq 10^{-5}$

- What is the nature of neutrino masses ?

  Since RH neutrinos would have no gauge couplings no need for them in the SM

  But without ν_R neutrino masses require a Majorana mass

  In the SM this needs a dim 5 operator $\frac{c}{\Lambda}\,[\bar{L}\tilde{\Phi}\tilde{\Phi}\bar{L}^c] \Longrightarrow$ new physics from Λ

  See lectures by Renata Funchal

- Is parity violation fundamental ? Or it is the result of some new dynamics ?

Conclusions

- The Electroweak Standard Model is an extremely successful description of nature.
- It answers many fundamental questions
  - How do we describe the weak and electromagnetic interactions in a unified gauge theory ?
  - What is the mechanism that allows to have masses compatible with $SU(2)_L \times U(1)_Y$?
- But it poses many questions in the process:
  - What is the origin of the electroweak symmetry breaking scale ? Why $v \simeq 246\ \mathrm{GeV}$?
  - Is the Higgs boson an elementary scalar ?
  - Why are fermion Yukawa couplings so different ? Is there new dynamics behind flavor ?
  - What is the nature of neutrino masses ?
  - Parity violation ?
- It also leave many other questions untouched (e.g. dark matter, baryogenesis,…)

Outlook

Experiments were crucial in building the Standard Model

There are again central to guide us to push the frontier of fundamental physics

Precision tests of the electroweak sector, particularly the Higgs, at the LHC

Measuring the shape of the Higgs potential seems to require higher energies

Neutrino experiments will help answer some of these questions

Precision low energy/flavor experimental tests

Dark Matter detection (direct, indirect, …)