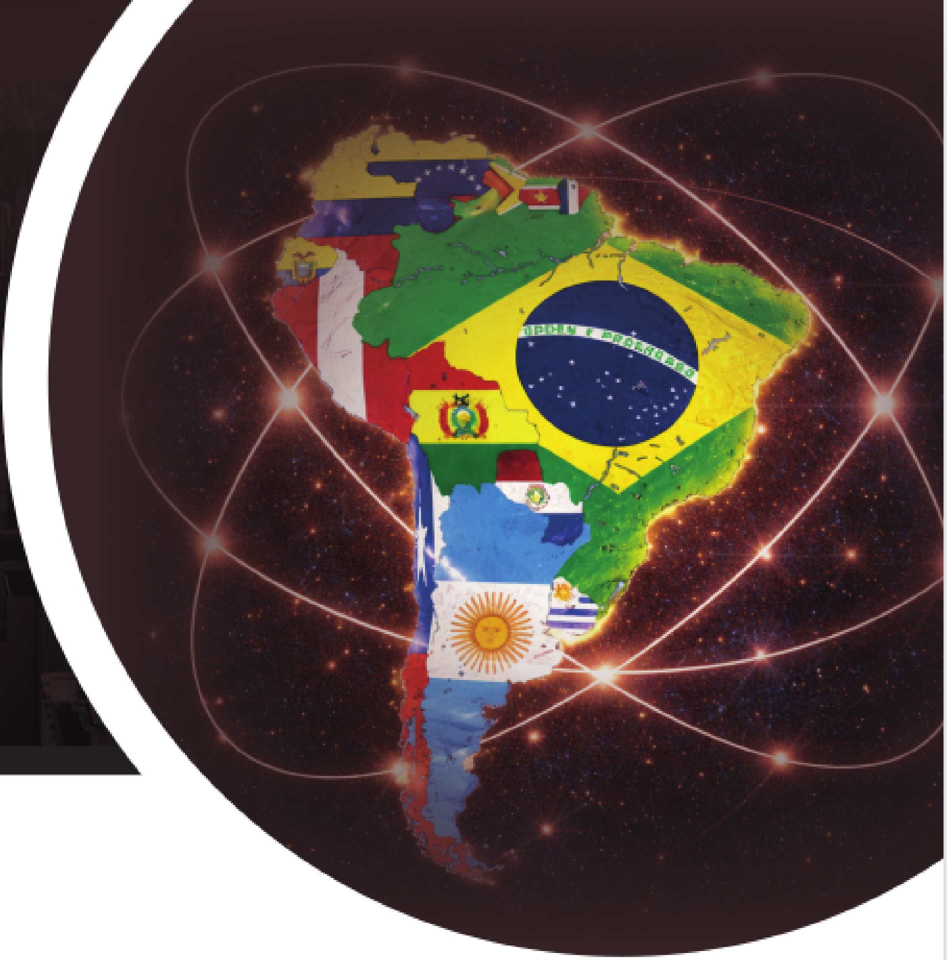
ICTP SAIFR | International Centre for Theoretical Physics South American Institute for Fundamental Research

PHENOEXP WORKSHOP



August 10 – 12, 2026
at IFT-UNESP, São Paulo, Brazil

EW and Higgs Theory
SM and Beyond

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BSM - Theory

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The Argentine national government has repeatedly insulted the Brasilian government and people, generating a diplomatic crisis.

It has completely cut funding for research and higher education, and has brutally reduced salaries.

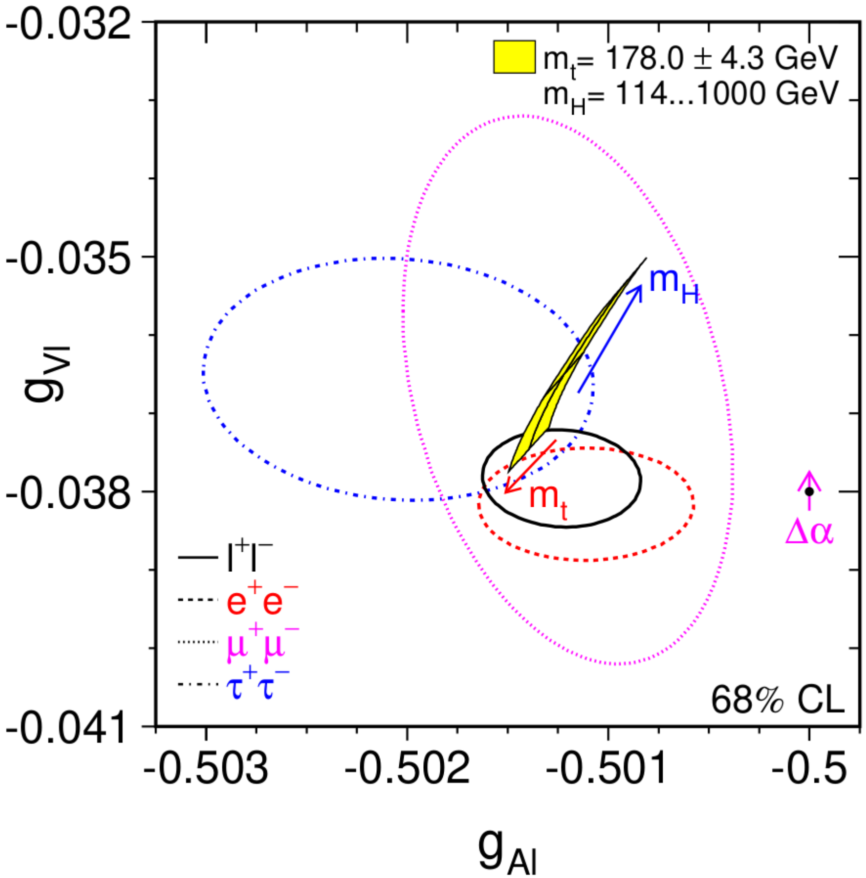
Today Brasil is helping Argentine science far more than the Argentine government itself.

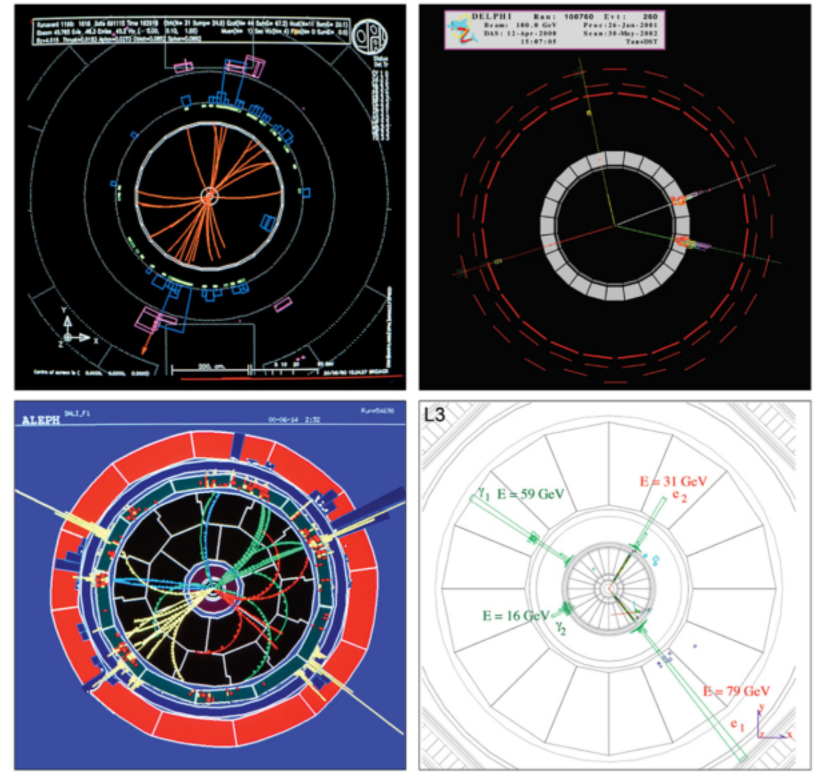
That government does not represent me, as well as an increasingly large portion of the Argentine people.

I have no doubt that the only desirable future for Argentina is built together with Brazil, and with all of Latin America.

EW precision at LEP and SLD

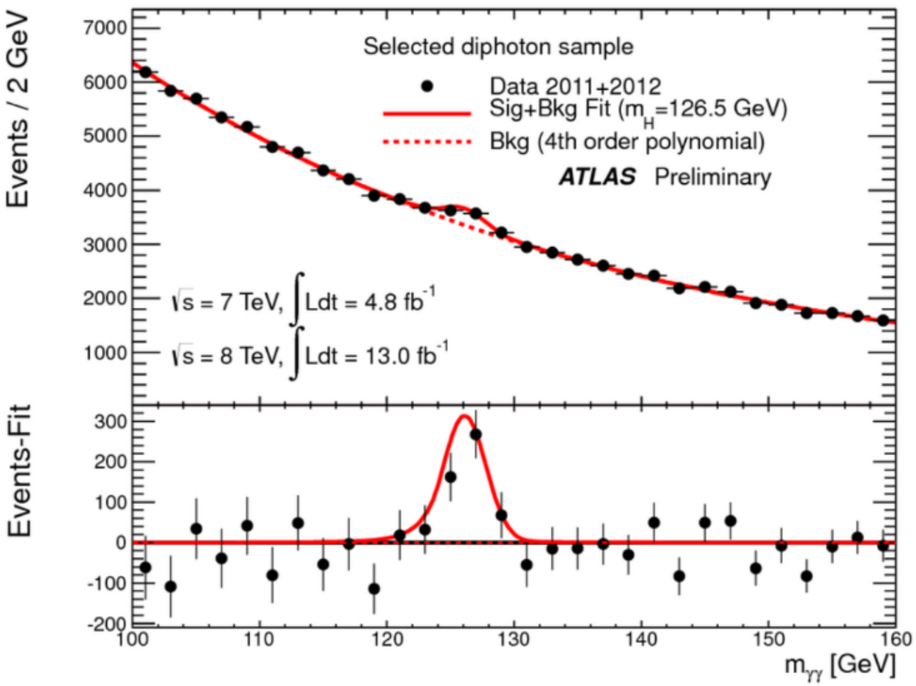
Z pole and beyond

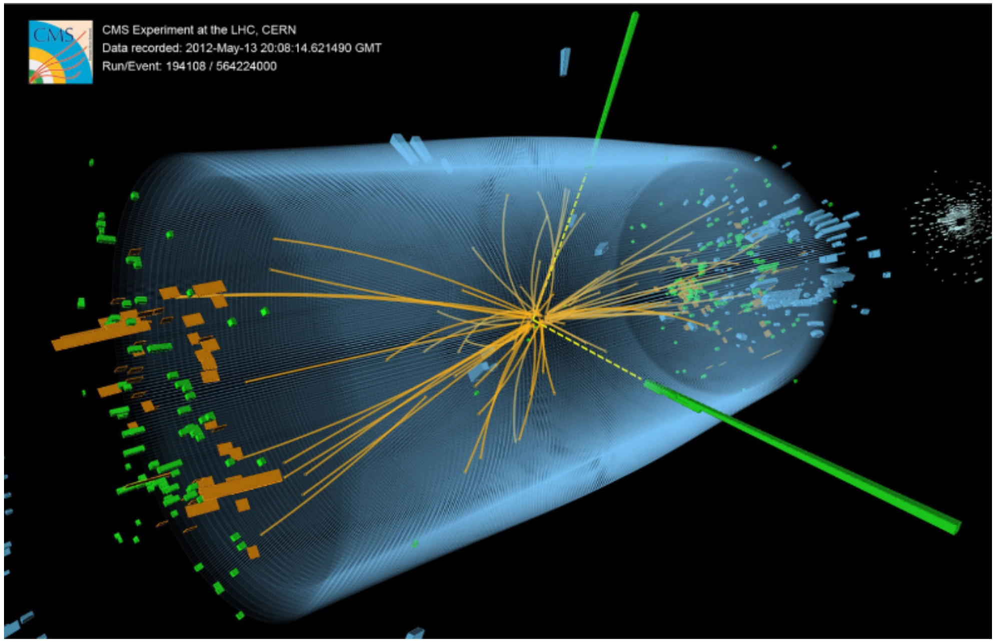




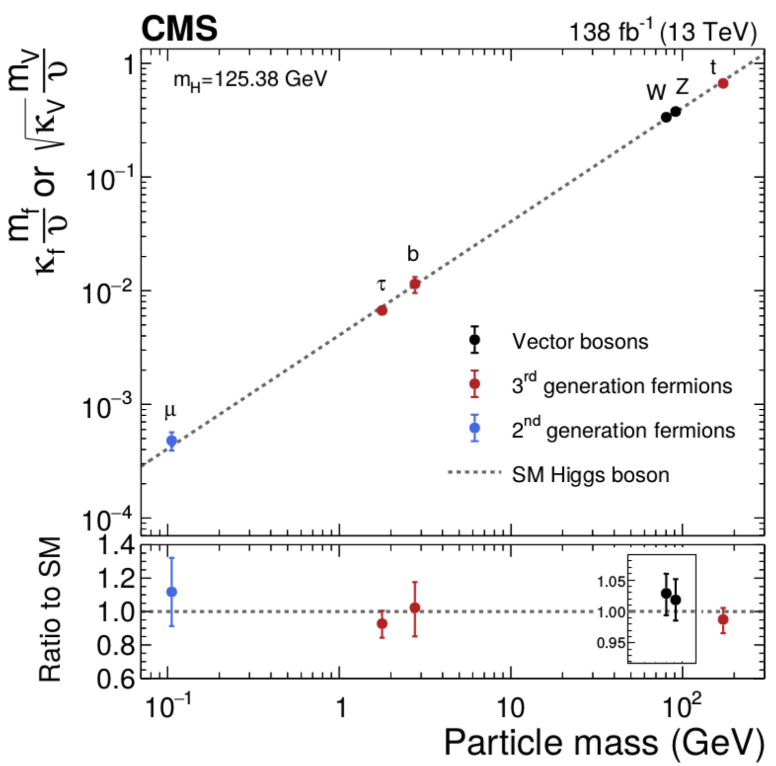
SU(2)$_L$xU(1)$_Y$ at work!

Higgs production at LHC





Higgs precision



Motivations

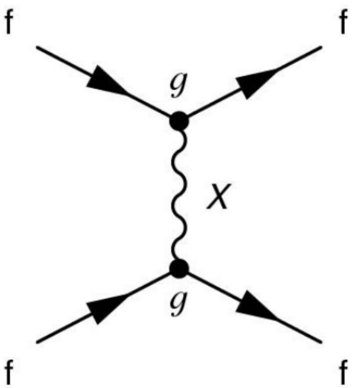
- ✓ Up to which scale is valid the SM?
- ✓ Is the new scalar the SM Higgs boson?
- ✓ What should be tested?, which mechanisms?
- ✓ Reasons for New Physics?
- ✓ Where do we look for NP?

Summary

- The SM: EW precision tests
- The SM: Higgs
  - EW symmetry breaking
  - Couplings
  - Flavor
- Higgs production and decay modes
- LHC results
- New Physics in Higgs sector
  - Motivations
  - Parametrization
  - Searches

The SM: EW precision tests

LEP+SLD measured $e^+e^- \longrightarrow f\bar{f}$ with high precision

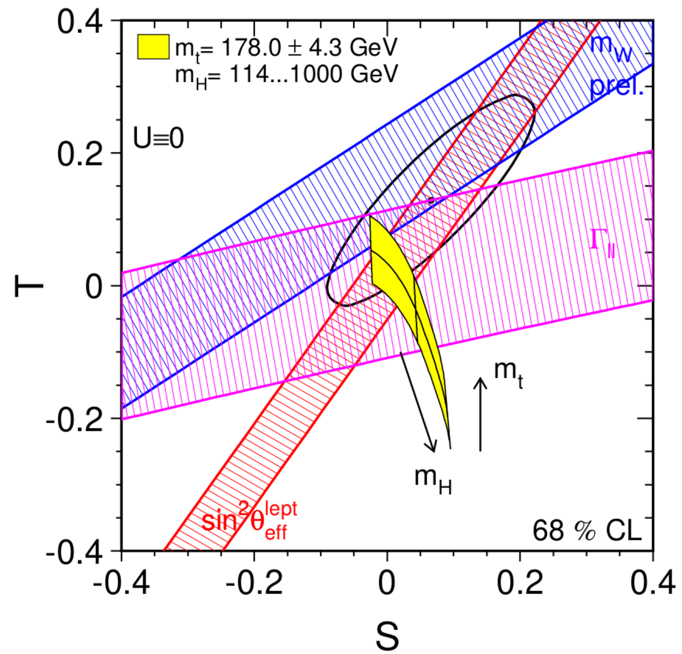


★ Universal effects: Vector Boson self-energies (Peskin-Takeuchi '91)

$$\Pi_V(q) = \Pi_V(0) + \Pi'_V(0)q^2 + \ldots; \quad V = W, B$$

		Adim. form factors	custodial	$SU(2)_L$
S	$=$	$16\pi\Pi'_{W_3B}(0)$	$+$	$-$
T	$=$	$\frac{4\pi}{s^2c^2M_Z^2}[\Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)]$	$-$	$-$
U	$=$	$16\pi[\Pi'_{W_3W_3}(0) - \Pi'_{W^+W^-}(0)]$	$-$	$-$

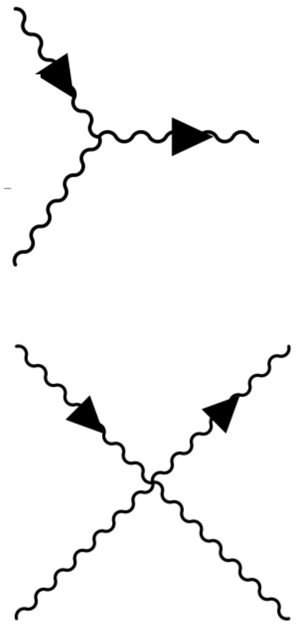
U usually suppressed compared with T



★ Non-universal effects: $Zb\bar{b}$

The SM: EW precision tests

LEP+SLD+LHC: triple/quartic gauge boson coupling

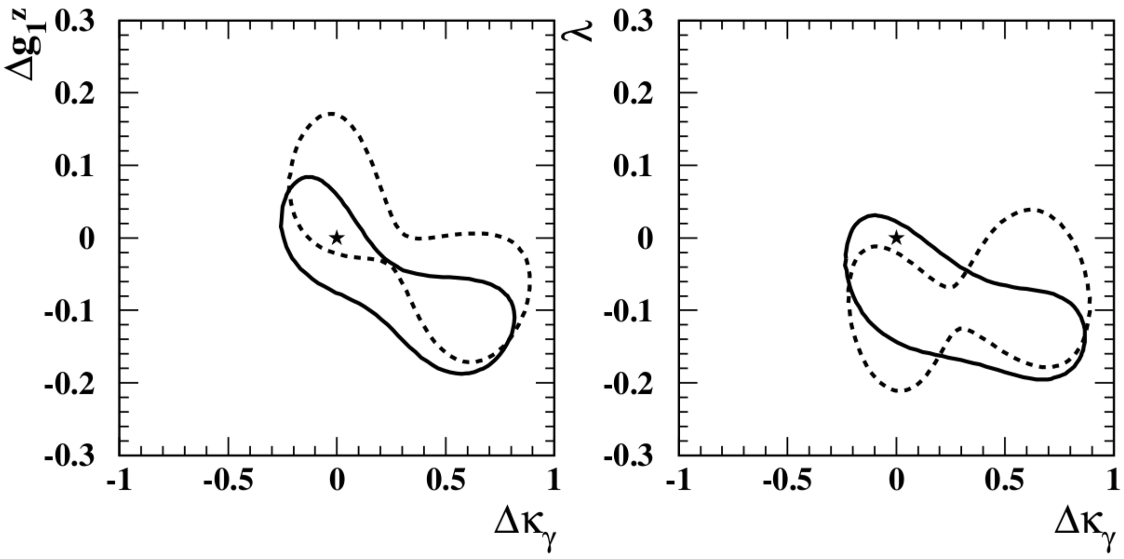


★ Lorentz, $U(1)_{em}$, C and P invariance:

$$g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \frac{\lambda^V}{m_W^2}W_\mu^{+\nu}W_\nu^{-\rho}V_\rho^\mu + \kappa^V W^+_\mu W^-_\nu V^{\mu\nu}$$

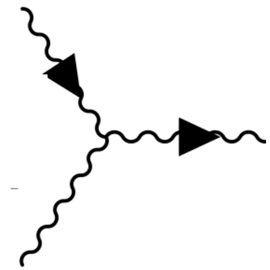
SM – SU(2)xU(1) gauge: $g_1^z = \kappa_z = \kappa_\gamma = 1$ and $\lambda_z = \lambda_\gamma = 0$

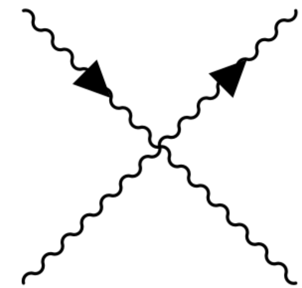
OPAL (LEP)



The SM: EW precision tests

LEP+SLD+LHC: triple/quartic gauge boson coupling



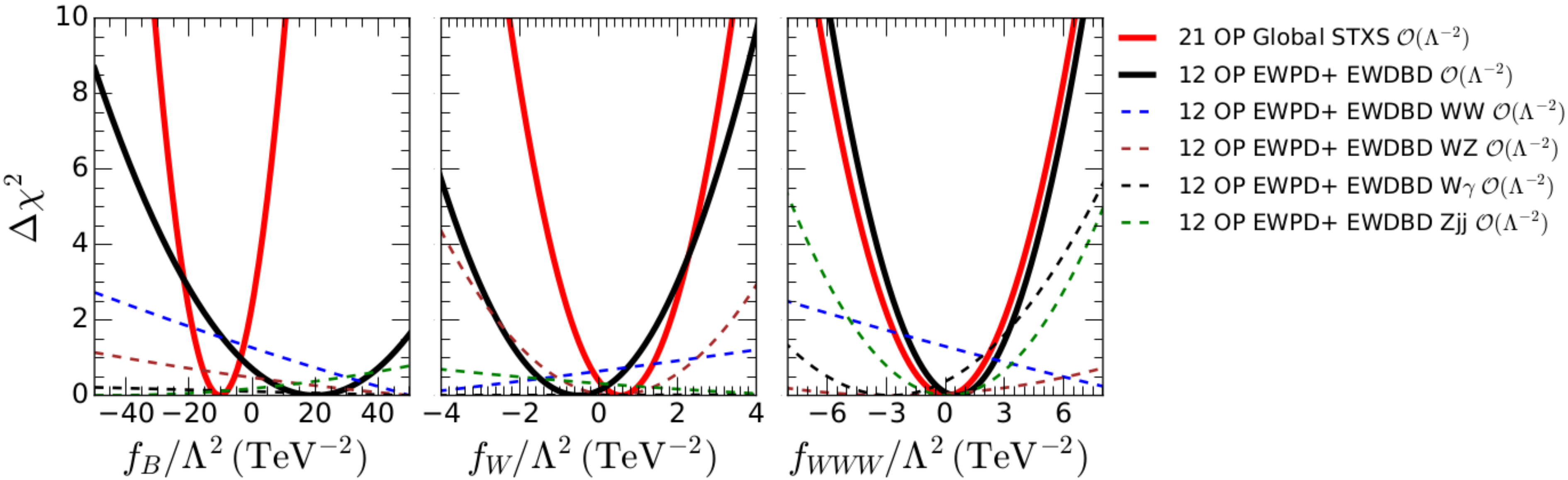


★ $SU(2)_L xU(1)_Y$: SM + Higher dim operators (Eboli et al '21)

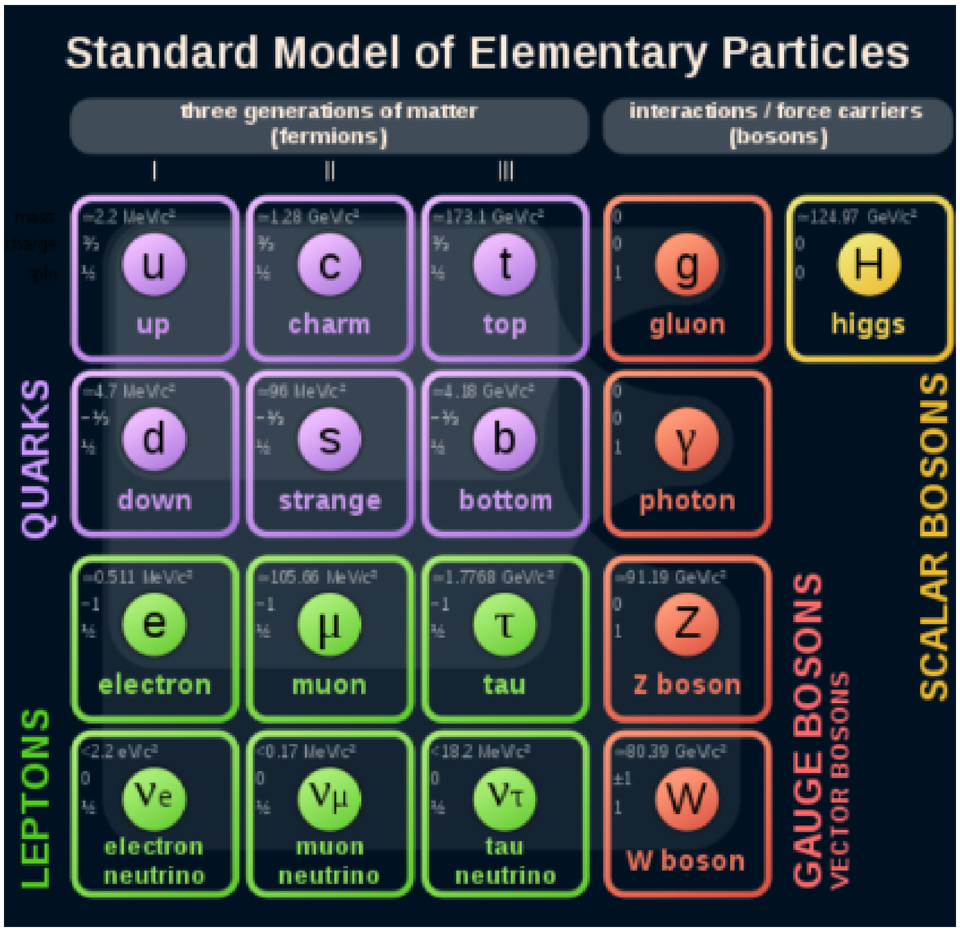
$\mathcal{O}_{BW} = \Phi^\dagger \widehat{B}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi$	$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi)$	$\mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right)$
$\mathcal{O}_{B} = (D_\mu \Phi)^\dagger \widehat{B}^{\mu\nu} (D_\nu \Phi)$	$\mathcal{O}_{W} = (D_\mu \Phi)^\dagger \widehat{W}^{\mu\nu} (D_\nu \Phi)$	$\mathcal{O}_{WWW} = \mathrm{Tr}[\widehat{W}_\mu^\nu \widehat{W}_\nu^\rho \widehat{W}_\rho^\mu]$
$\mathcal{O}_{GG} = \Phi^\dagger \Phi \, G^a_{\mu\nu} G^{a\mu\nu}$	$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$	$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$

(and fermionic operators)

LHC Run 2 (Eboli et al '21)



The SM: Higgs



- ✓ **Only spin 0 field**
- ✓ **Non-gauge interactions**
- ✓ **Origin of masses**
- ✓ **Unitarity**
- ✓ **Breaking of flavor symmetry**
- ✓ **...**

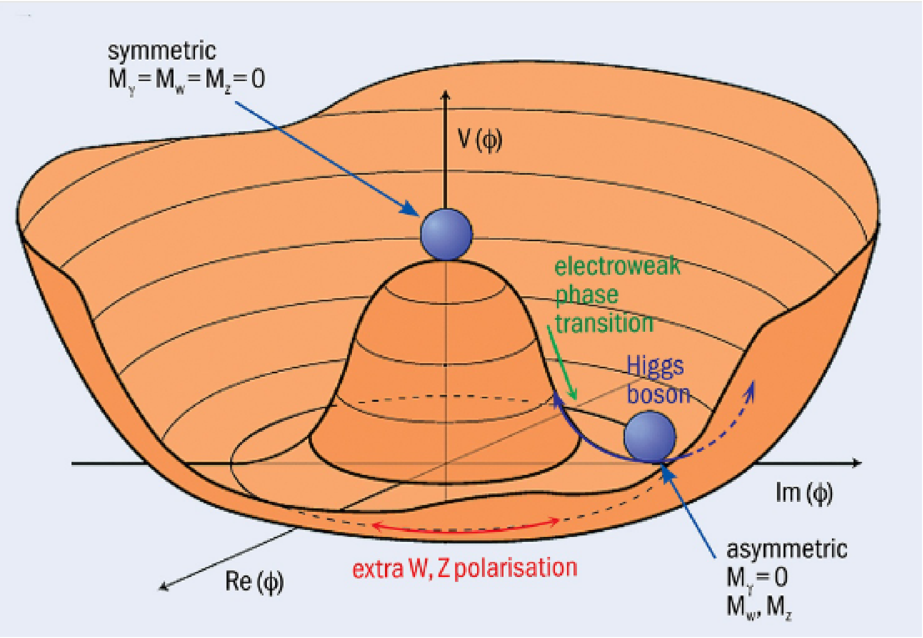
The SM: Higgs

★ Potential

$$\mathcal{L} \supset -\frac{m_h^2}{2}h^2 - \lambda_3^{SM} v h^3 - \lambda_4^{SM} h^4,$$

$$\lambda_3^{SM} = \frac{m_h^2}{2v^2}, \qquad \lambda_4^{SM} = \frac{m_h^2}{8v^2},$$

EW symmetry breaking
(custodial sym SU(2)^2 → SU(2))



★ H kinetic term $\quad |D_\mu H|^2 \supset \frac{1}{4} g^2 v^2 W_\mu^+ W^{\mu-} + \frac{1}{8} v^2 (g W_\mu^3 - g' B_\mu)(g W^{\mu 3} - g' B^\mu)$

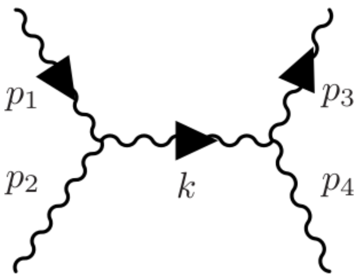
W & Z masses + interactions

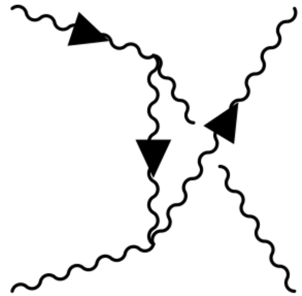
★ Yukawa int $\quad Y_{ij}\,\bar{\psi}_i H \psi_j = \frac{Y_{ij} v}{\sqrt{2}} \bar{\psi}_i \psi_j + \frac{Y_{ij}}{\sqrt{2}} h\, \bar{\psi}_i \psi_j$

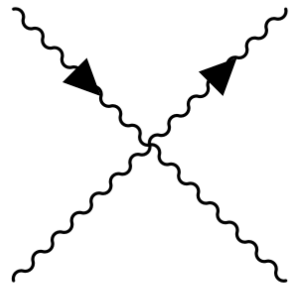
Masses + abscence of Higgs mediated FCNC

The SM: Higgs

UV regulator: unitarity

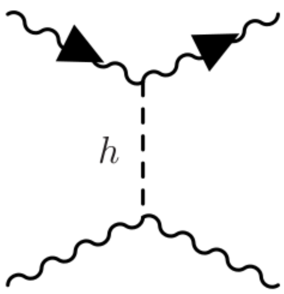






unitarity violation

$$\mathcal{M}_{EW}(W_L Z_L \to W_L Z_L) = -\frac{m_Z^2}{4m_W^4} e^2 \cot^2\theta_w (s+u) + \mathcal{O}(1) = \frac{t}{v^2} + \mathcal{O}(1)$$



$$\mathcal{M}_h \quad = -\frac{t}{v^2} + \mathcal{O}(1)$$

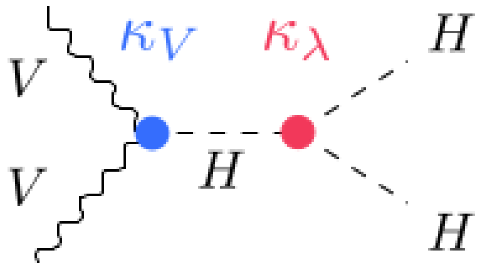
H unitarizes the Amplitude

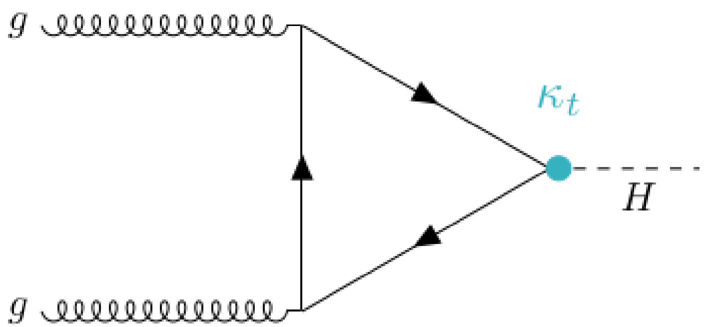
Theoretical bounds on the Higgs couplings

Kappa framework: modification of couplings only

$$\kappa_f = \frac{y_f}{y_f^{\rm SM}}, \qquad \kappa_V = \frac{g_V}{g_V^{\rm SM}}, \qquad \kappa_\lambda = \frac{\lambda_{H^3}}{\lambda_{H^3}^{\rm SM}}, \qquad \kappa_{g/\gamma} = \frac{c_{g/\gamma}}{c_{g/\gamma}^{\rm SM}}$$

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$



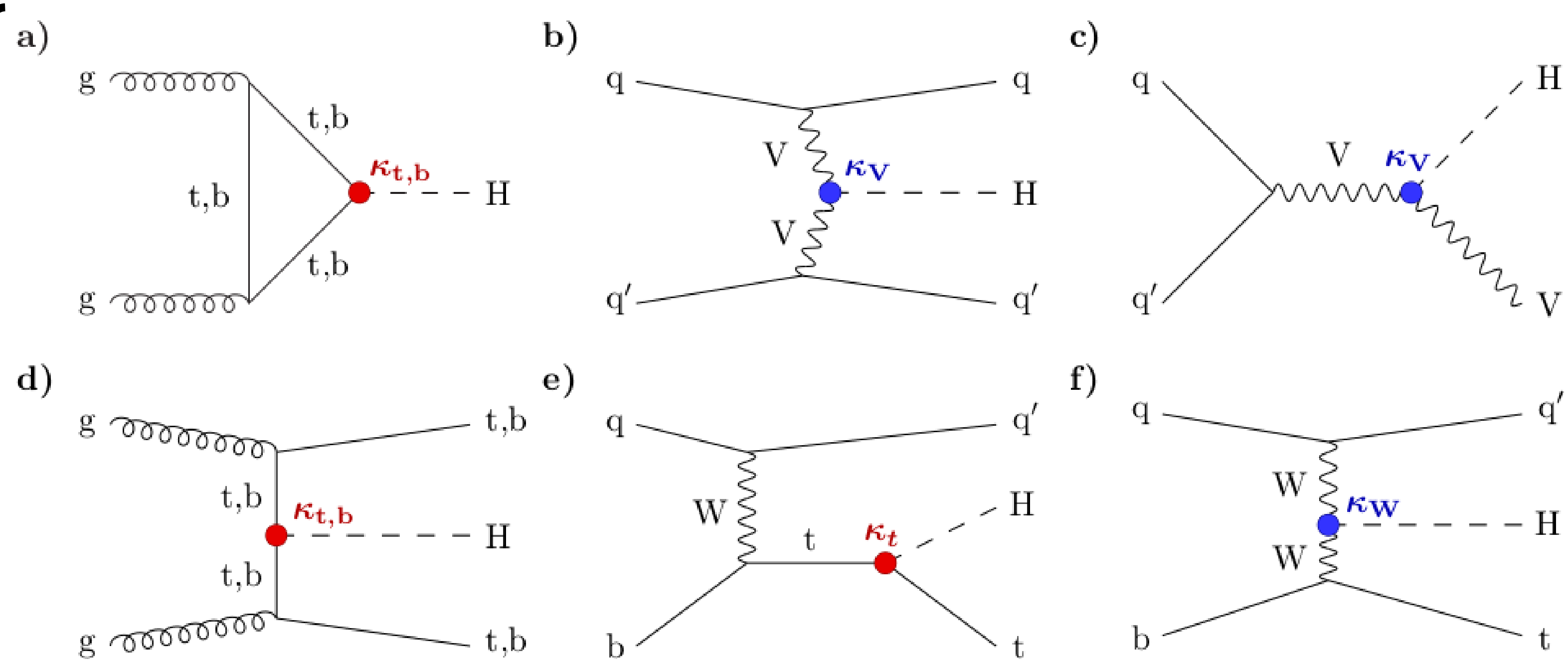


Bounds

perturbativity	$\vert\kappa_\lambda\vert \lesssim 6$	$\vert\lambda_{H^4}/\lambda_{H^4}^{\rm SM}\vert \lesssim 65$	(Nardechia et al '16)
unitarity	$\vert\kappa_\lambda\vert \lesssim 6.5$		(Nardechia et al '17)
single H production	$-4.7 < \kappa_\lambda < 12.6$		(McCullough, Haisch et al '16, Grojean et al '19, ...)

Higgs production at LHC

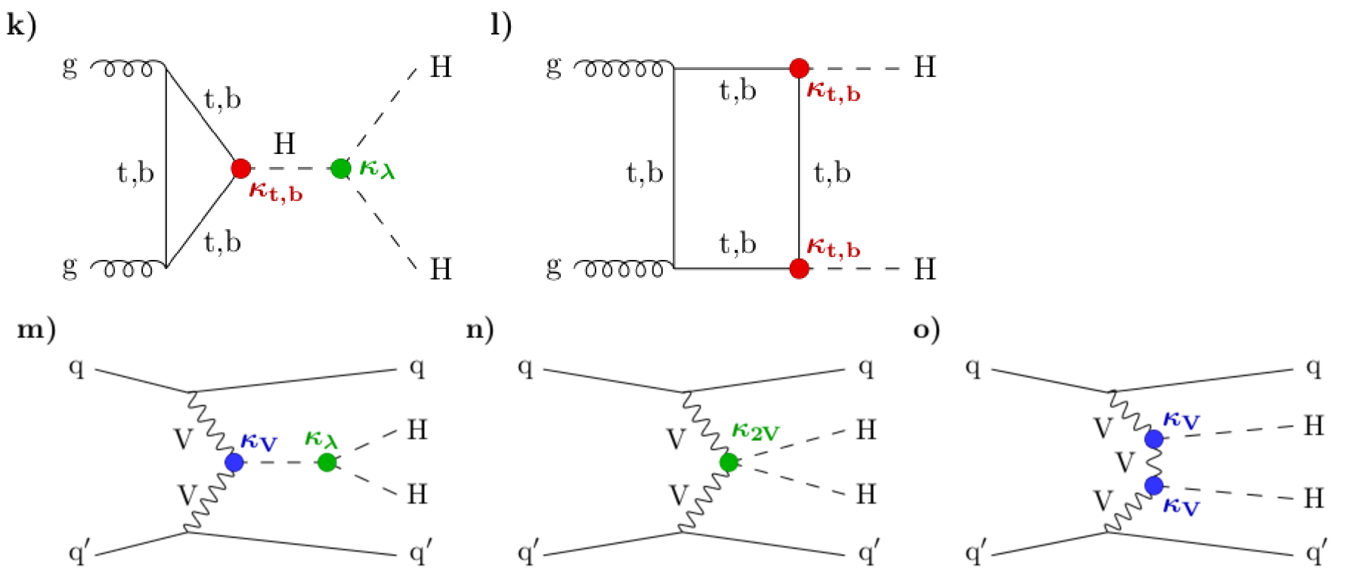
Single production



Double production

Gluon fusion

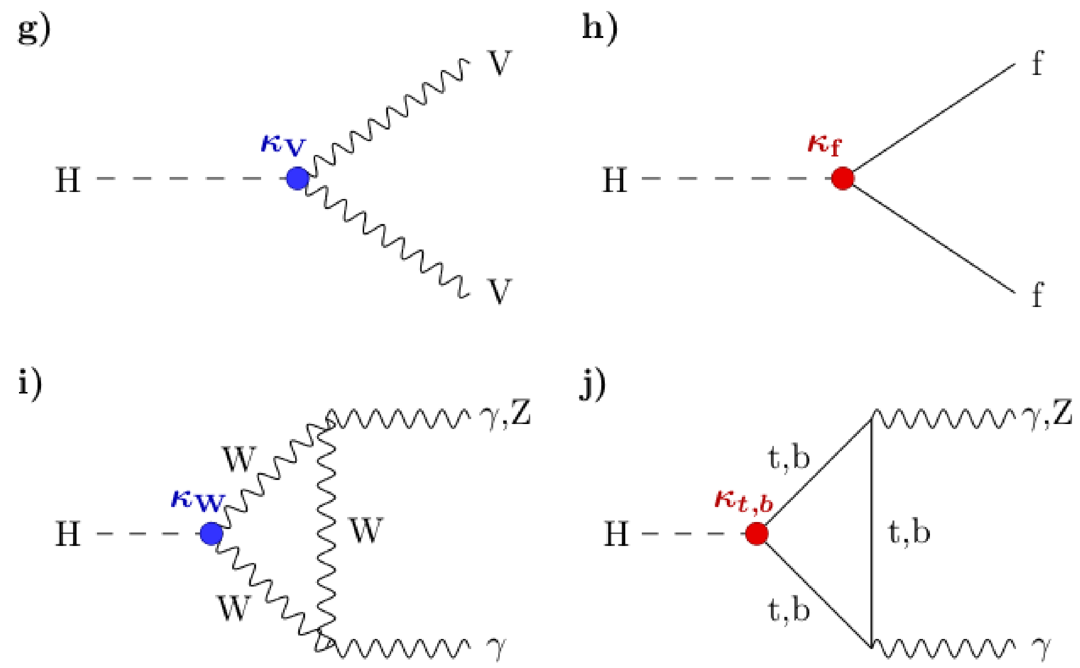
Vector boson fusion



Higgs decay

Tree level

Loop level

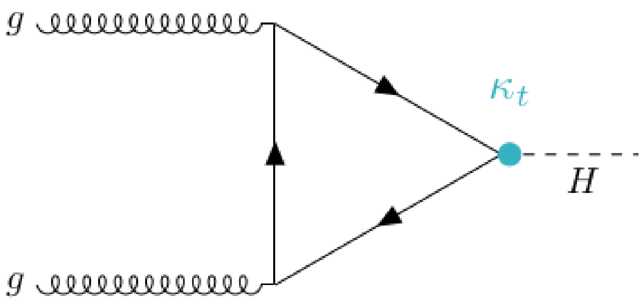


BRs of two Higgses

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- Multi particle final states: simulations
- Showering + Hadronization: model dependence
- Hadronic initial state: PDF dependence

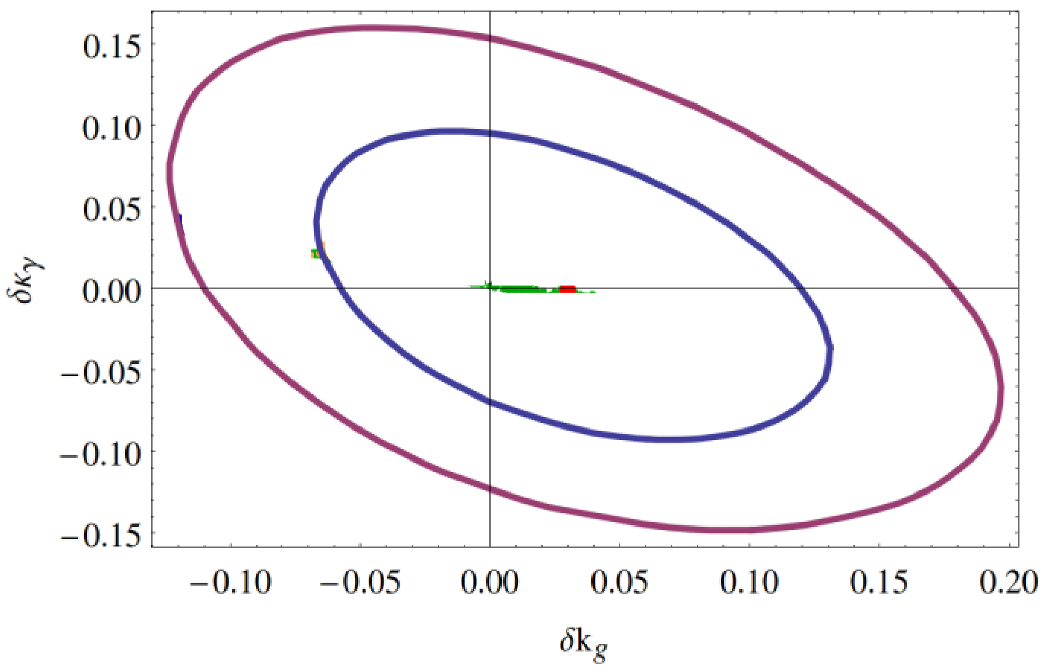
Single Higgs poduction



All colored particles in the loop

$$\mathcal{A} \simeq \sum_i \frac{y_i}{m_i} \,, \qquad m_i \gg m_h$$

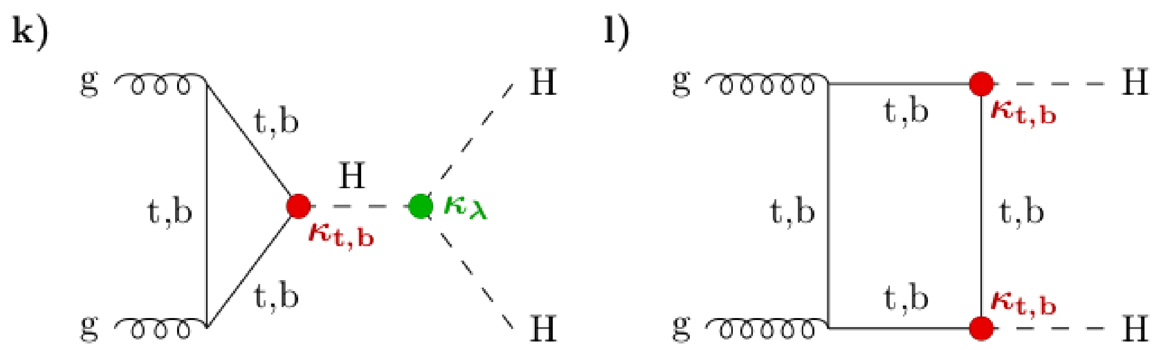
Dominated by the top (bottom)



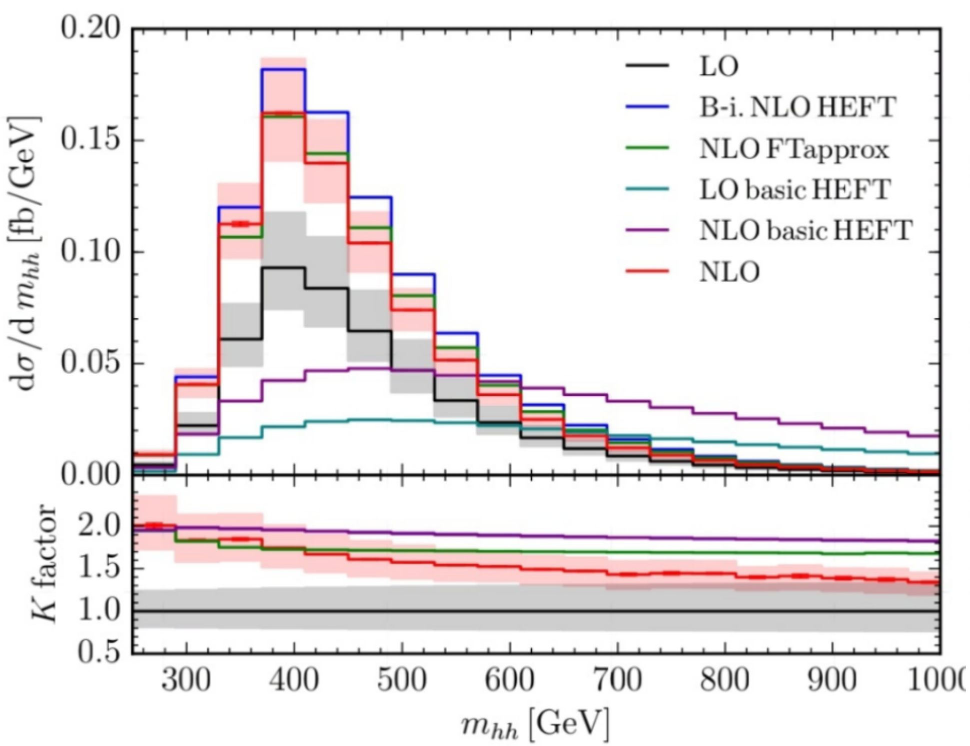
No deviations observed within ~ 10%

Di Higgs production in gluon fusion

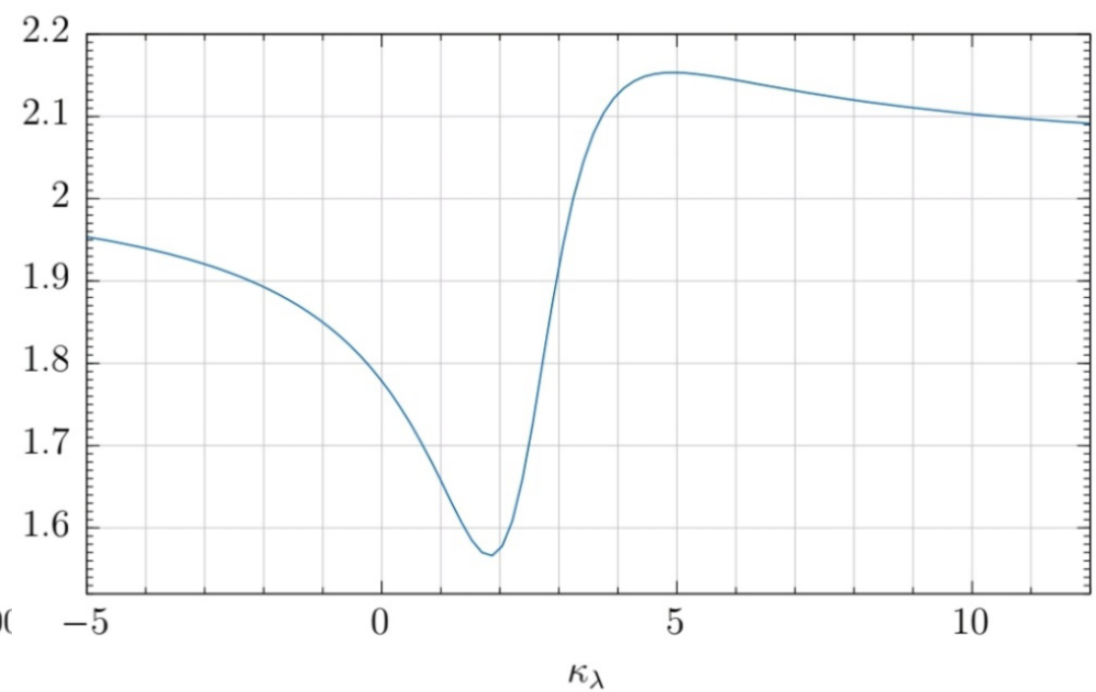
Test of the Higgs cubic coupling



Radiative corrections



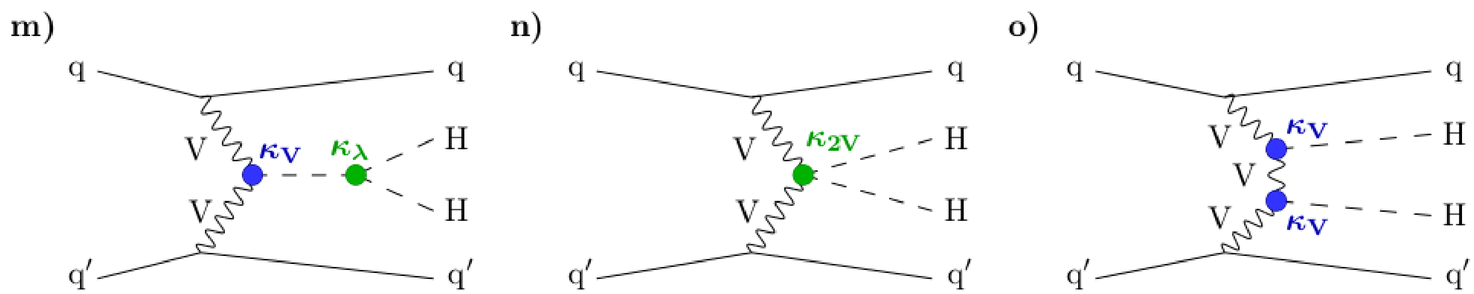
Dependence of k-factor with cubic coupling



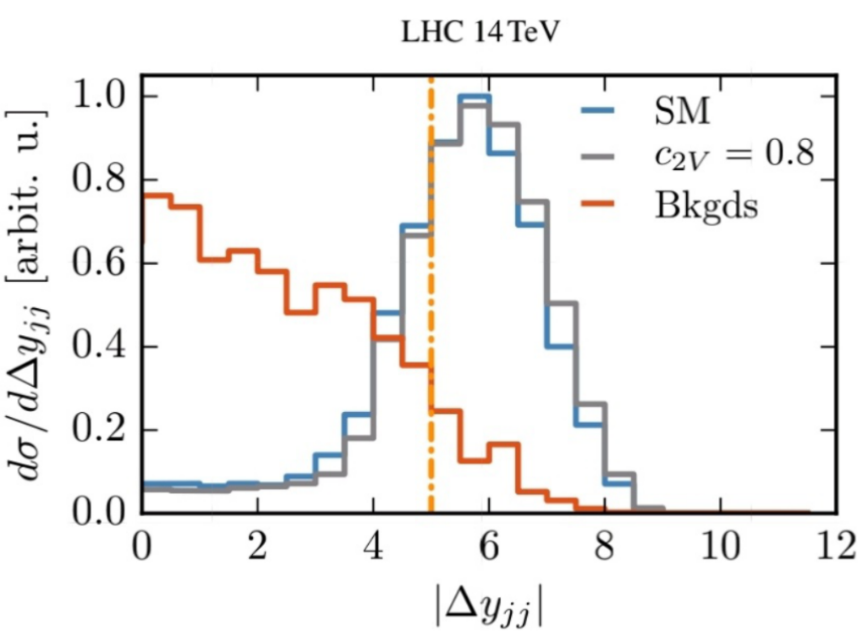
(LHC Higgs Working Group, see talk by Daniel)

Di Higgs production in vector boson fusion

Test of the Higgs cubic coupling



Test of unitarity $$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(\kappa_{2V} - \kappa_V^2)$$



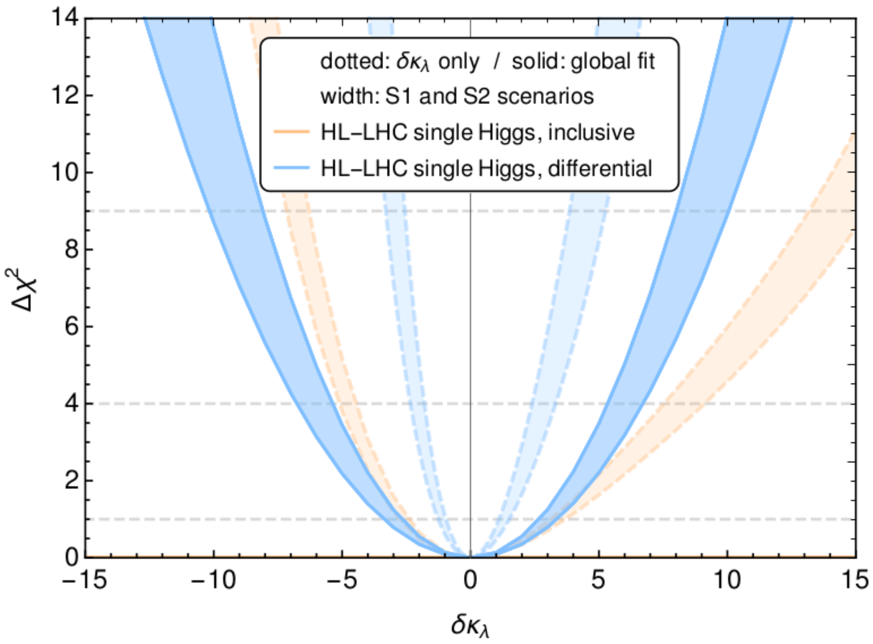
		Cross-sections (fb)			
		Acceptance	VBF	Higgs reco.	m_{hh} cut
14 TeV	Signal SM	0.011	0.0061	0.0039	0.0020
	Signal $c_{2V} = 0.8$	0.035	0.020	0.017	0.011
	Bkgd (total)	1.3×10^5	4.9×10^3	569	47
100 TeV	Signal SM	0.22	0.15	0.11	0.033
	Signal $c_{2V} = 0.8$	3.4	2.7	1.9	1.6
	Bkgd (total)	1.9×10^6	1.9×10^5	9.5×10^3	212

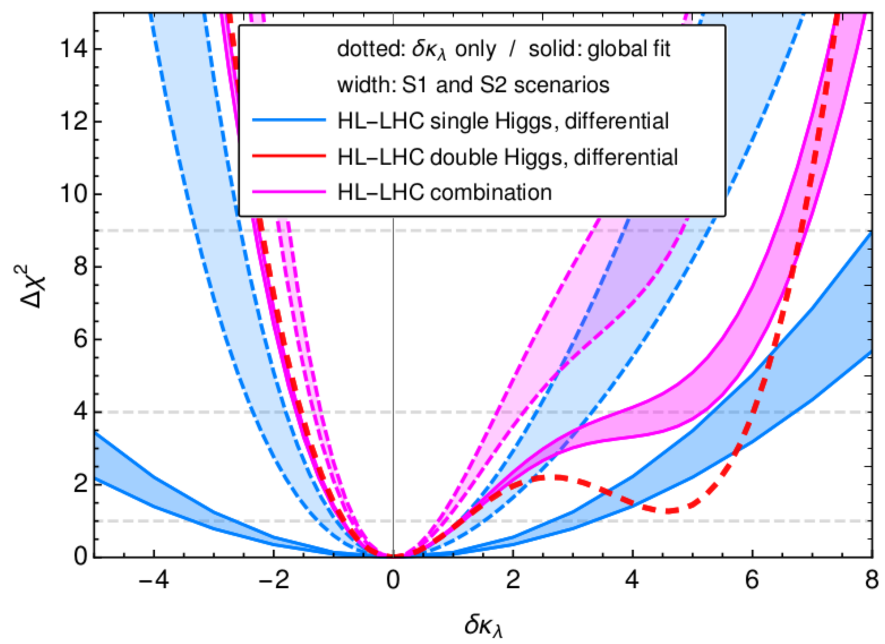
(Contino et al ’16)

Bounds on the Higgs couplings

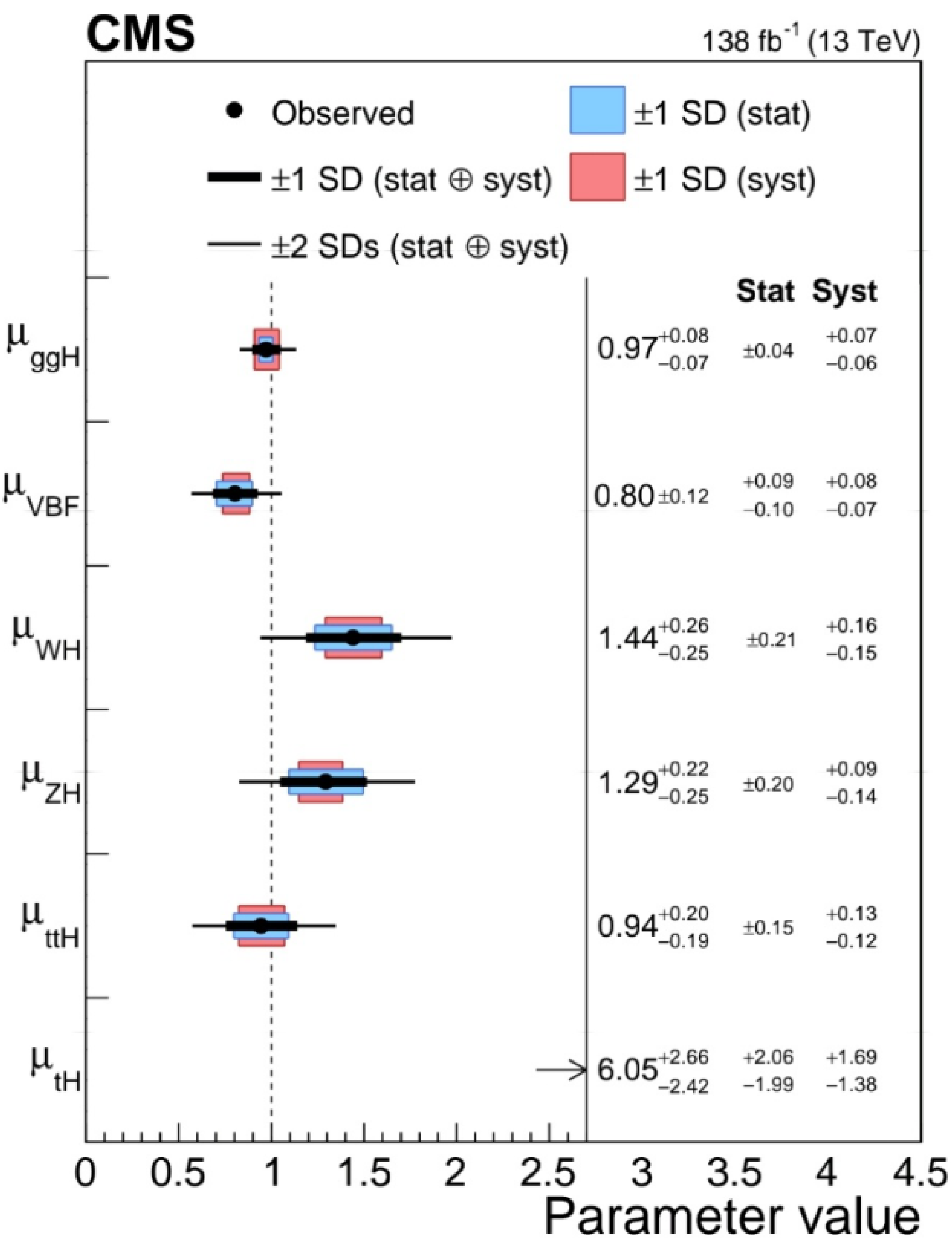
Combination of single and double H production

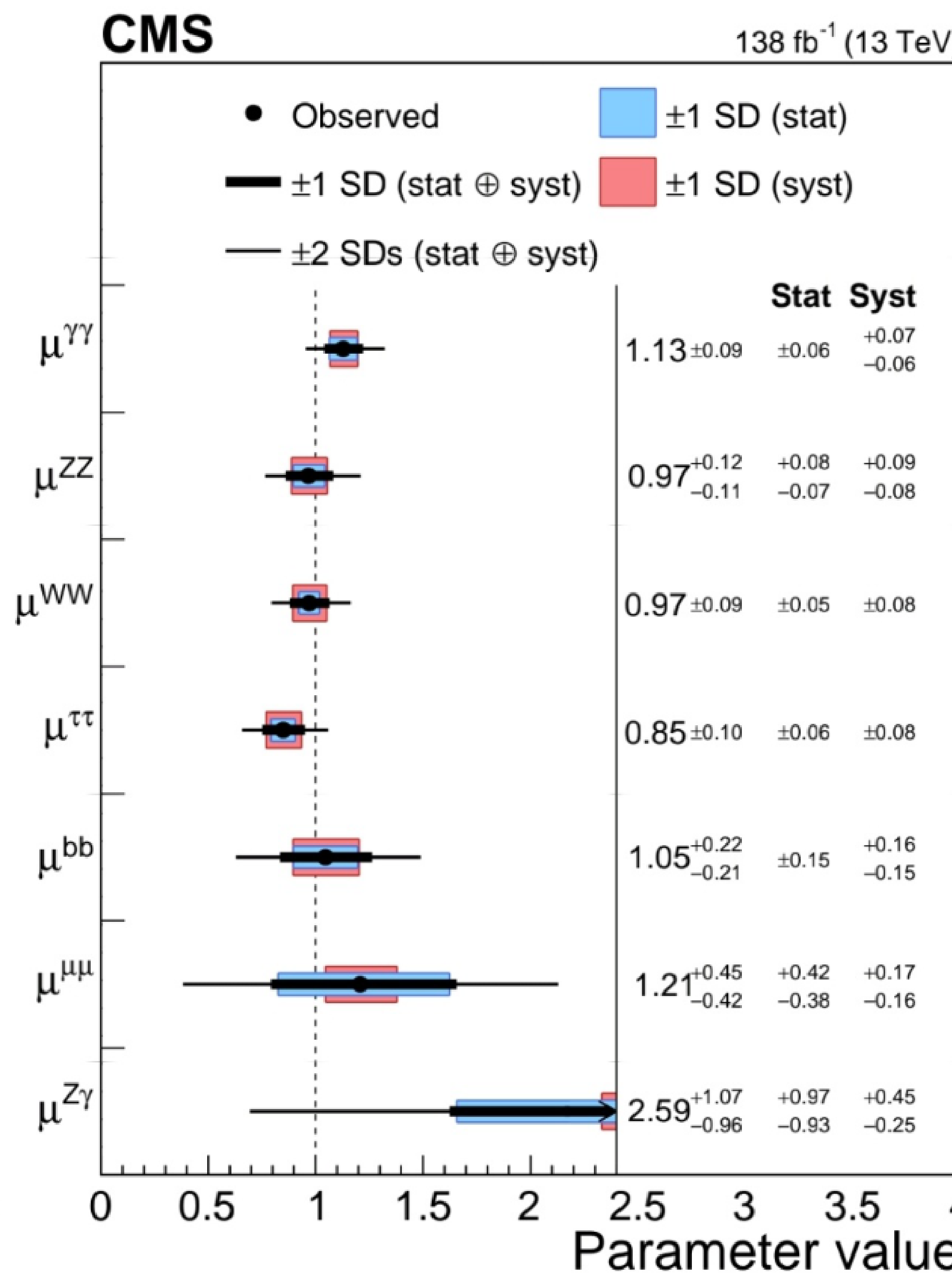
δκλ from HL-LHC projections (Grojean et al ‘19)





Higgs results from LHC



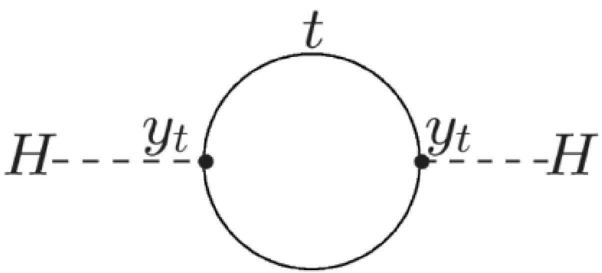


(see Marissilva, Hernán, Thiago’s talks)

Beyond the Standard Model

The hierarchy problem

Elementary Higgs: dim(H^2)=2 ➡ quadratic sensitivity to cut-off



$$\Rightarrow \quad \delta m_H^2 \simeq -\frac{3}{4\pi^2} y_t^2 \Lambda^2$$

m_H ~ 100 GeV

⬇

cut-off ~ TeV

The SM Higgs potential

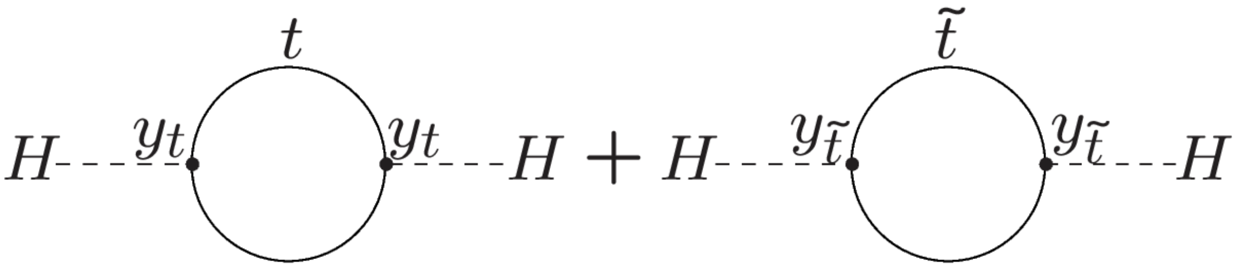
suffers the Planck-Weak hierarchy problem

does not explain the origin of EWSB

suffers instabilities (quartic)

It is just a “good” parametrization of EWSB ➡ **Eff. theory**

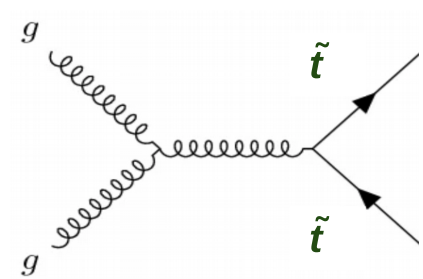
Solving the hierarchy problem



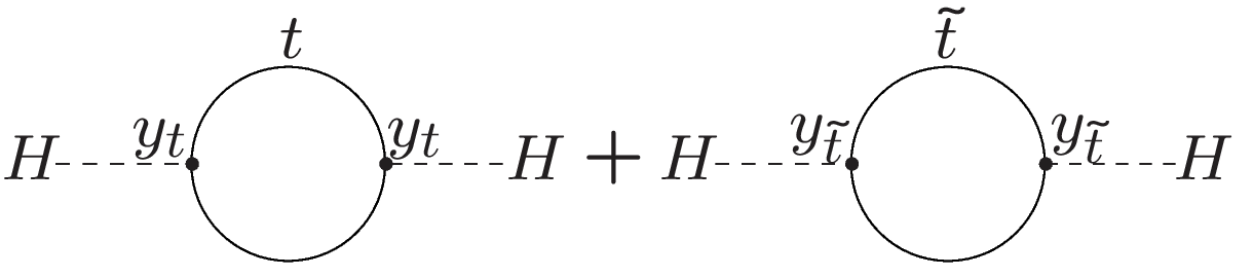
Ex: SUSY, Composite Higgs, Little Higgs, ...

top partner with color

★ **Direct signal: QCD production of $\tilde{t}\,\tilde{t}$**
Bounds depend on BRs: $m_{\tilde{t}}$>1.4 TeV



Solving the hierarchy problem



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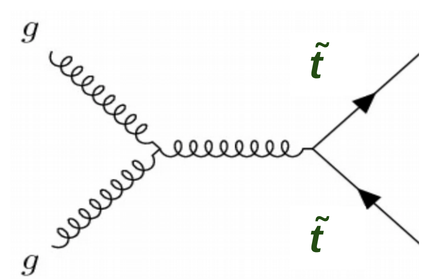
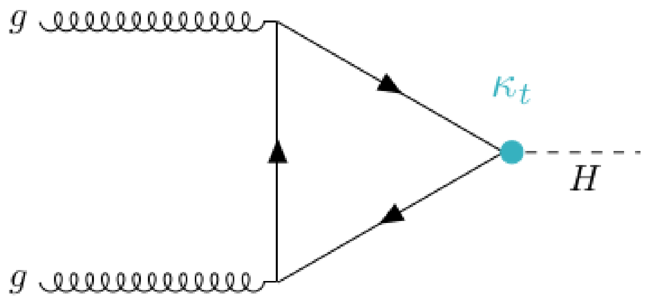


- **Indirect signal:**

What's in the loop?

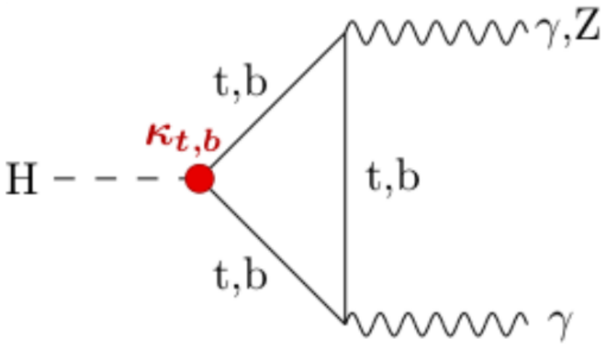
What's in the loop?

★ **Single Higgs production in gluon fusion**



All colored particles in the loop

$$\mathcal{A} \simeq \sum_i \frac{y_i}{m_i} \ , \qquad m_i \gg m_h$$



All EW particles in the loop

$$\mathcal{A} \simeq \sum_i \frac{y_i}{m_i} \ , \qquad m_i \gg m_h$$

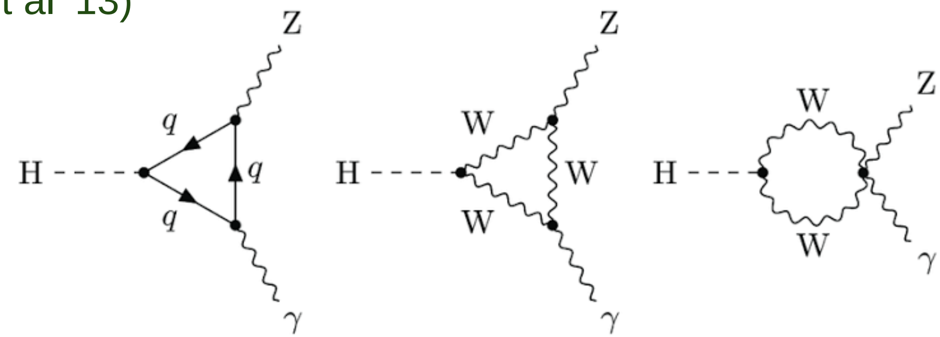
Only 10% corrections alowed

What’s in the loop?

★ **Higgs → Z γ in Composite Higgs** (Contino et al ‘13)

WC-operators compatible with shift-sym
unlike Higgs production operators

Large corrections without P_{LR} sym

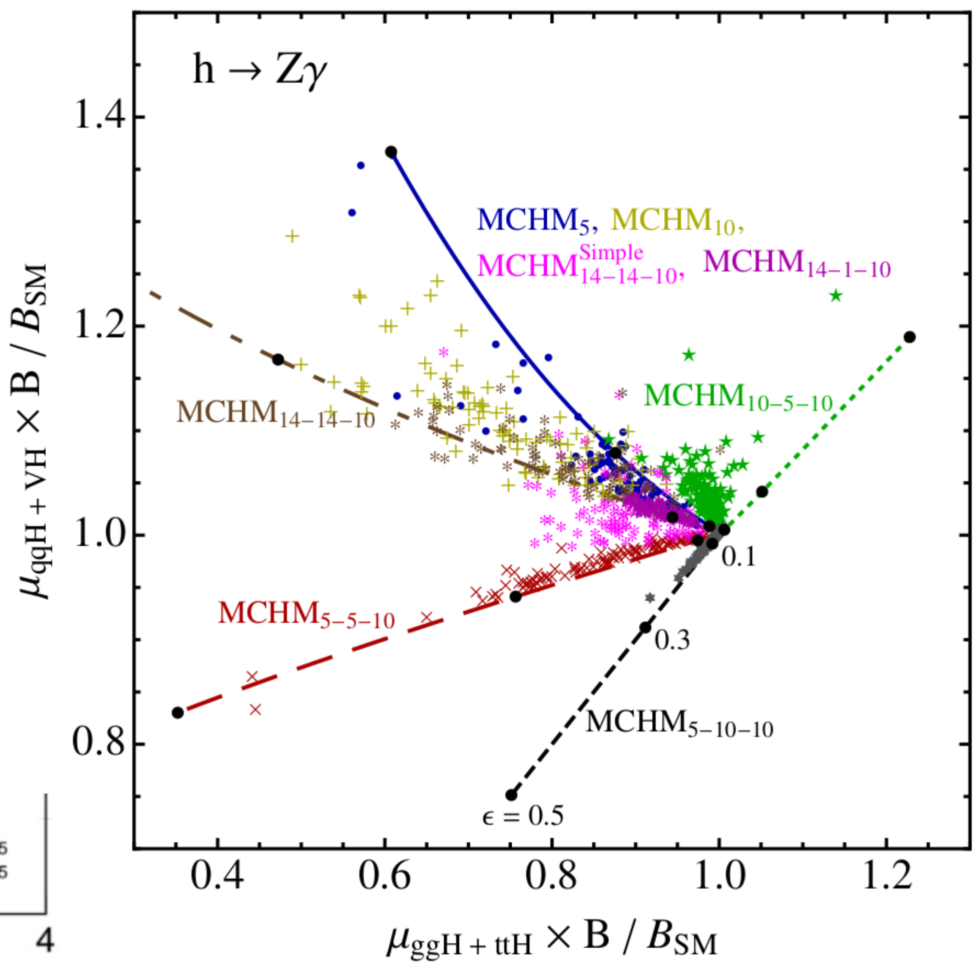


MCHM (Carena, Ponton, DR, ‘13)

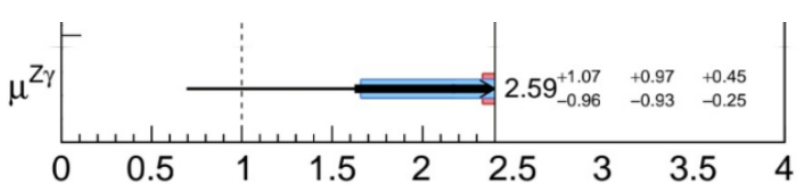
H = pNGB of SO(5)/SO(4) of a
composite sector

keep P_{LR} sym for $Zb\bar{b}$

distinguish fermion representations



CMS

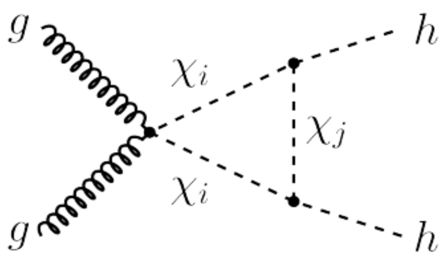


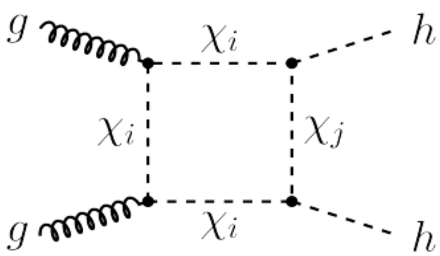
What's in the loop?

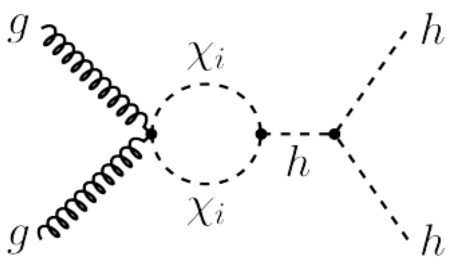
(DR, Epele, Medina, Mileo, Szynkman '22, '23, '25)

★ Di Higgs production → disentangling colored states

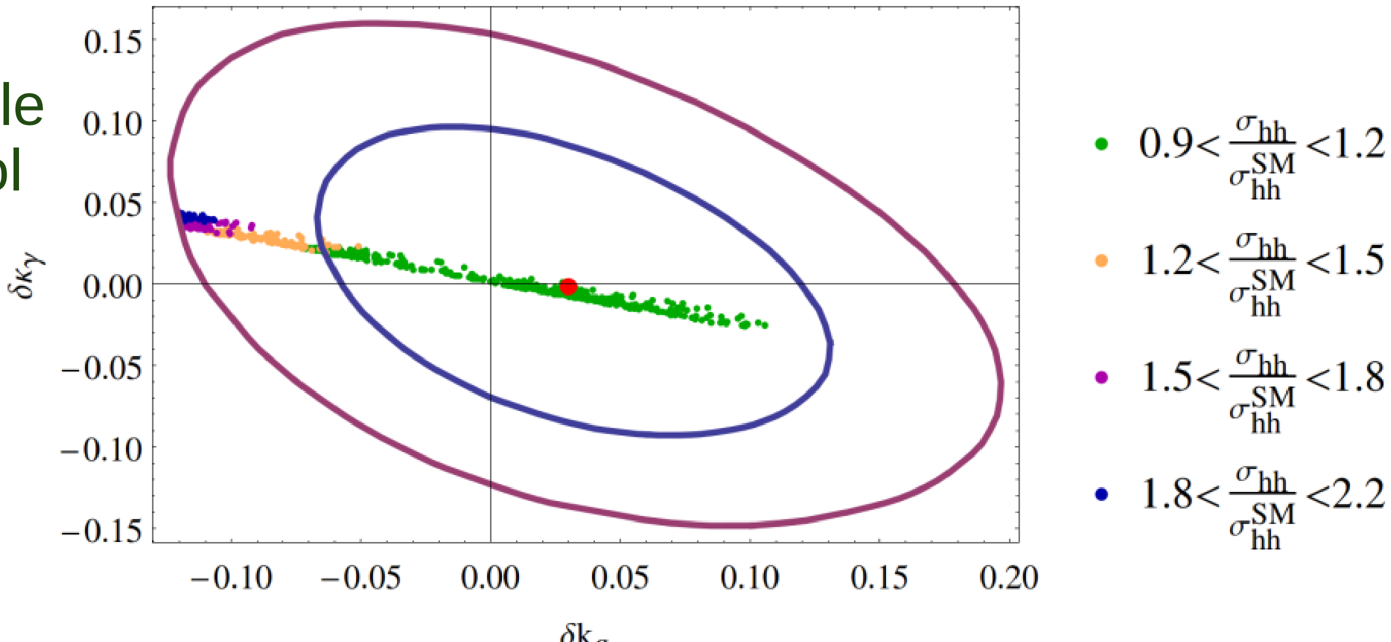
ex: s-fermions / scalar leptoquarks





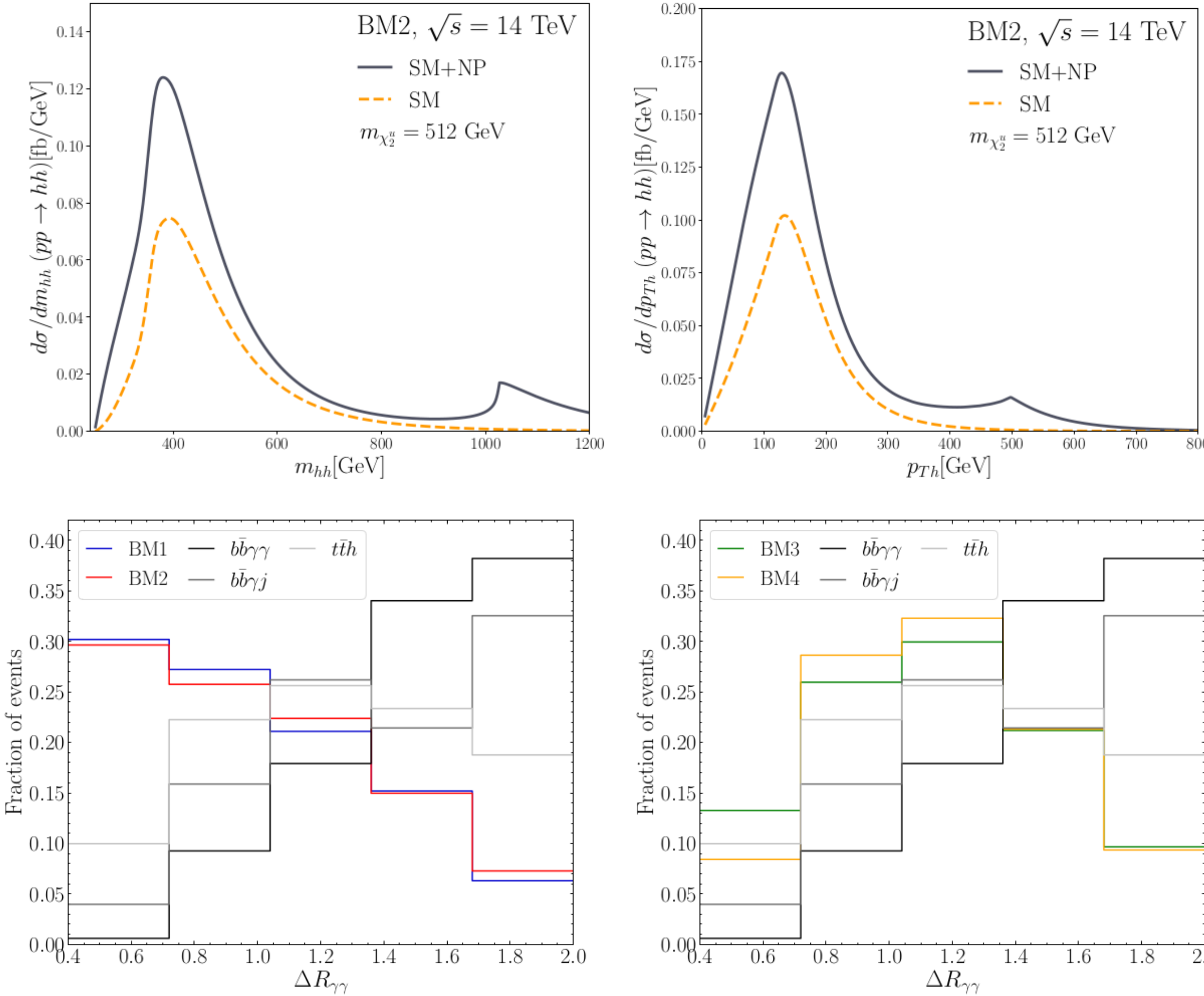


Corrections in single Higgs under control



What's in the loop?

22, '23, '25)

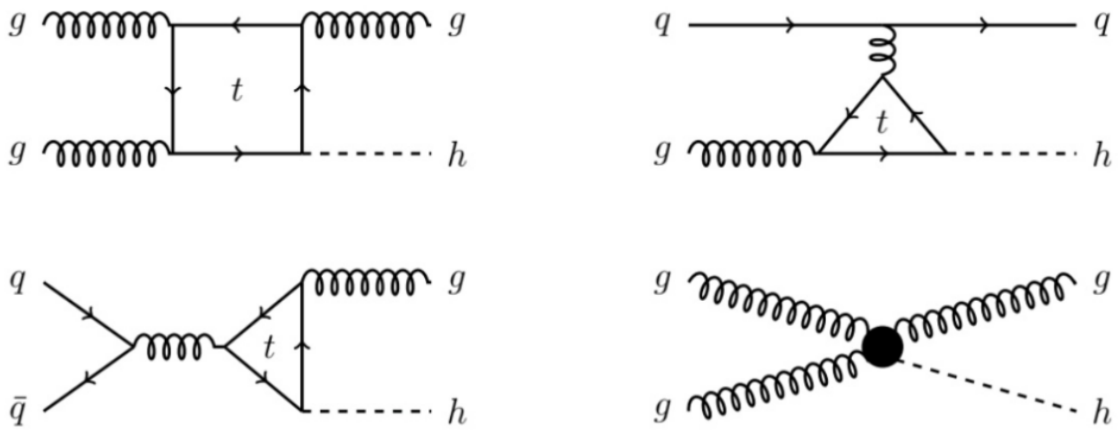


More ...

Boosted Higgs production

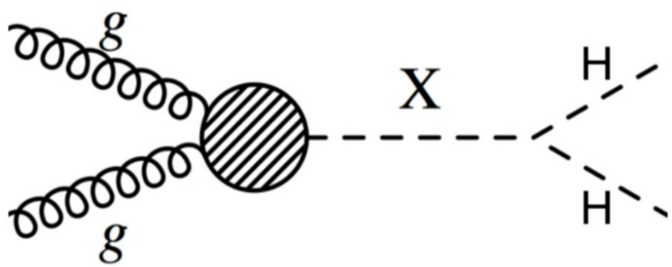
What’s in the loop?

(Sanz et al’13)

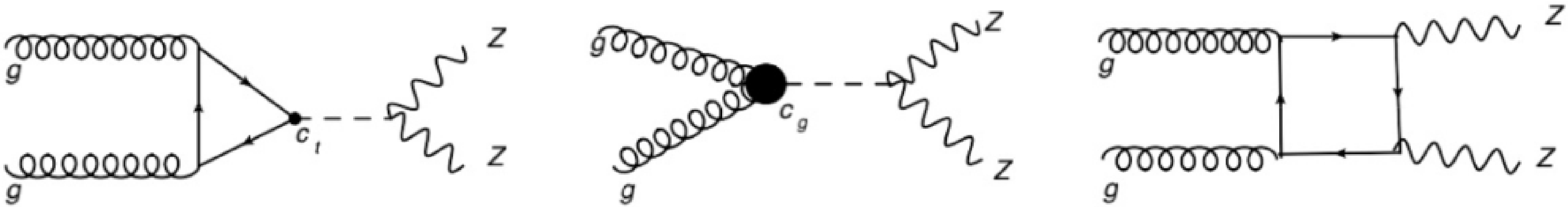


Resonant di-Higgs prod.

New bosons



Off-shell Higgs prod., Break degeneracy (Grojean et al ‘13, ‘15)



An example for EW precision

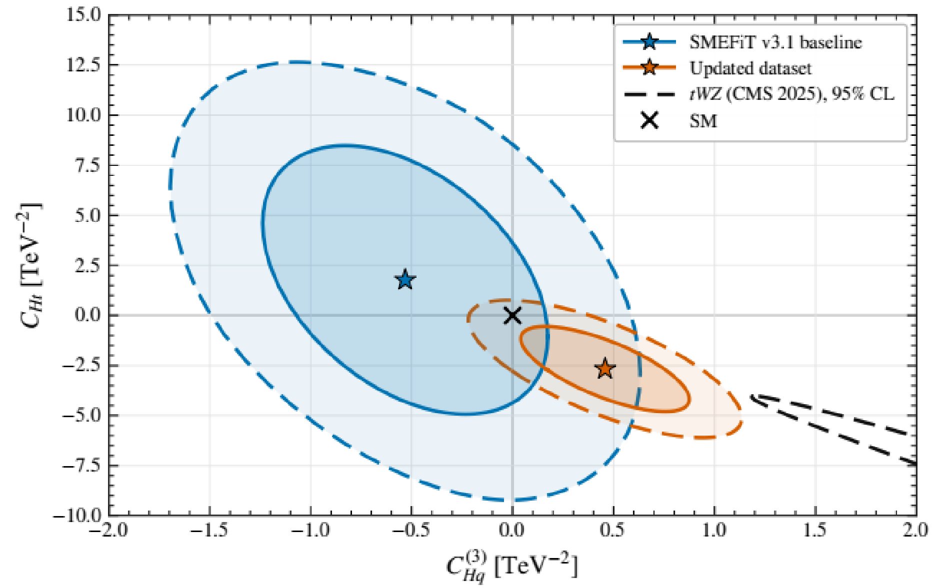
ttZ and tWZ at LHC: CMS 2025 - 200 fb^{-1} run2+run3, ATLAS 2024 – 140 fb^{-1} run2

★ EFT interpretation: main operators

$$\mathcal{O}_{Hq}^{(3)} = \left(H^\dagger i \overleftrightarrow{D}_\mu^I H\right)\left(\bar{q}_L \gamma^\mu \tau^I q_L\right) \qquad \delta g_L^{Wtb} = \frac{v^2}{\Lambda^2} C_{Hq}^{(3)}$$

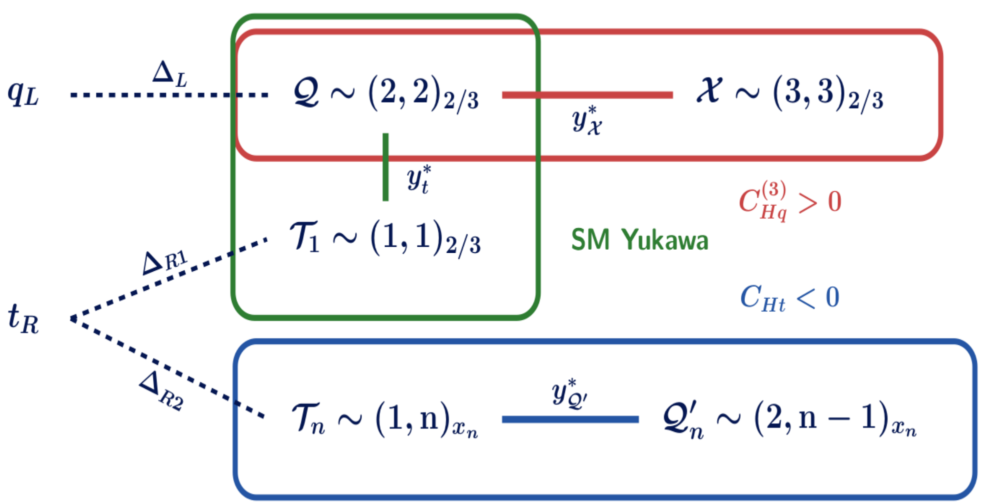
$$\mathcal{O}_{Hq}^{(1)} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_L \gamma^\mu q_L\right) \xrightarrow{\text{EWSB}} \delta g_L^{Zt\bar{t}} = -\frac{v^2}{2\Lambda^2}\left(C_{Hq}^{(1)} - C_{Hq}^{(3)}\right)$$

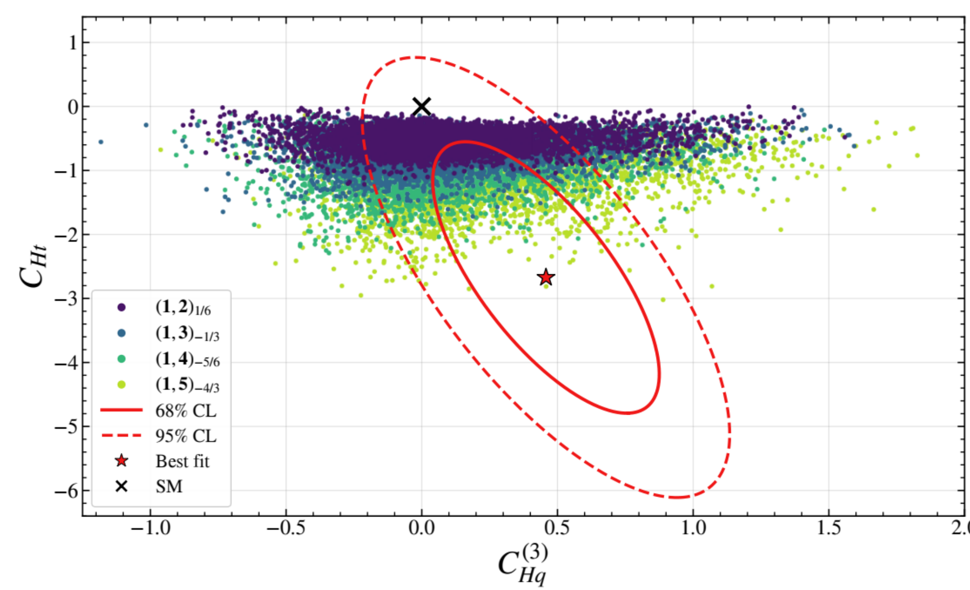
$$\mathcal{O}_{Ht} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{t}_R \gamma^\mu t_R\right) \qquad \delta g_R^{Zt\bar{t}} = -\frac{v^2}{2\Lambda^2} C_{Ht}$$



★ UV Theory interpretation: new vector like QUARKS + custodial sym

(Fernandez, DR, wp)





Conclusions

- The succes of the SM: EW sym and Higgs mechanism at work!
  - How can we test them at LHC?
  - How can we look for New Physics at LHC?
  - Can we look for direct NP?
  - Can we measure WC of EFT?

- Goal: to test V(h)

  What's in the loop?
  - di-Higgs production
  - boosted Higgs production
  - precision single Higgs

- EW and top physics
  - multi top
  - ttV, tVV
  - flavor violation

- The hierarchy problem is alive, new ideas?
  - Supersymmetry
  - Composite Higgs
  - Extra dimensions
  - ...

Muito Obrigado!

A more general Higgs

Generic singlet of custodial symmetry $\Sigma = e^{i\sigma^a \pi^a / v}$

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2c_V \frac{h}{v} + c_{2V}\frac{h^2}{v^2} + \ldots\right]$$
$$- m_i\, \bar{\psi}_{Li}\, \Sigma \left(1 + c_\psi \frac{h}{v} + \ldots\right) \psi_{Ri} + \mathrm{h.c.}\,,$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + c_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right) h^4 + \ldots$$

SM: h is a component of an
elementary doublet

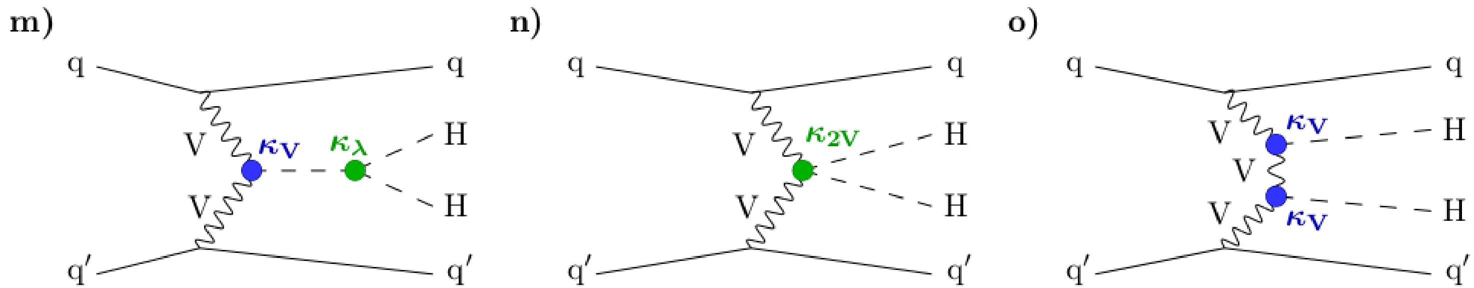
$$H = \Sigma \begin{pmatrix} 0 \\ v+h \end{pmatrix}\,, \qquad c_i = 1$$

Composite Higgs: h in a doublet but

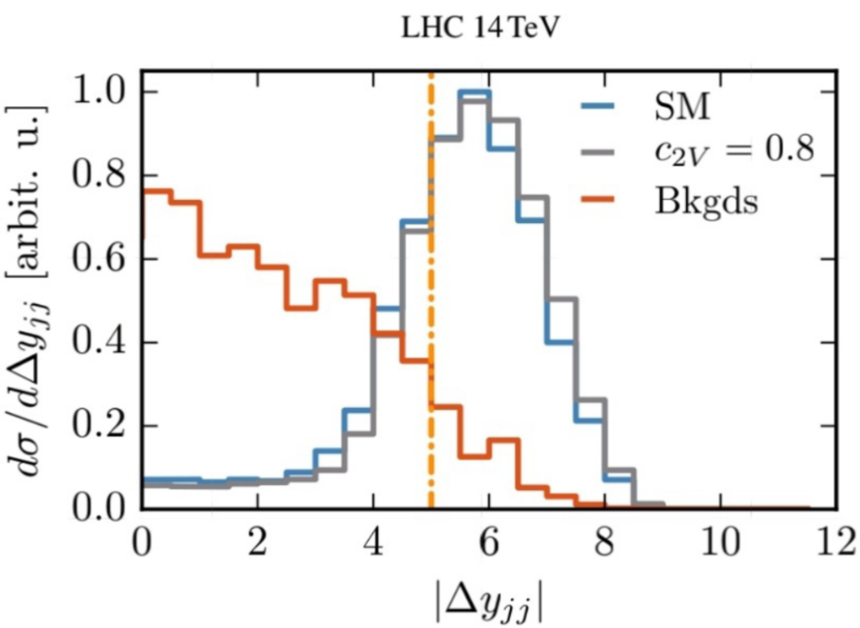
$$\begin{cases} c_V = \sqrt{1-\xi} \\ c_{2V} = 1 - 2\xi \\ c_\psi = f_\psi(\xi) \end{cases} \qquad \xi \equiv v^2/f^2$$

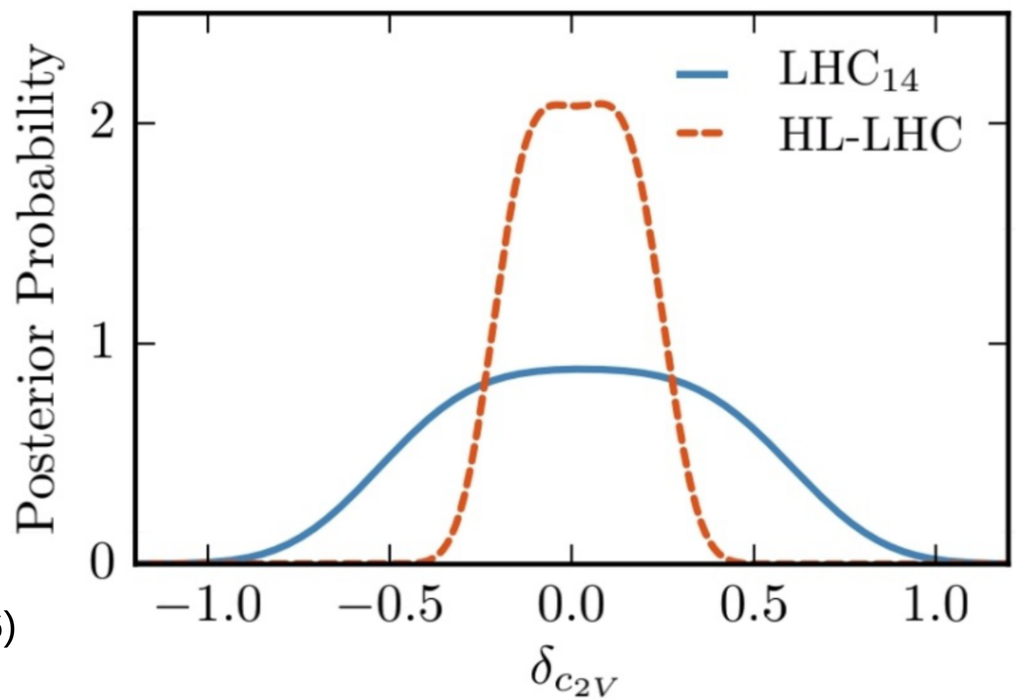
Di Higgs production in vector boson fusion

Test of the Higgs cubic coupling



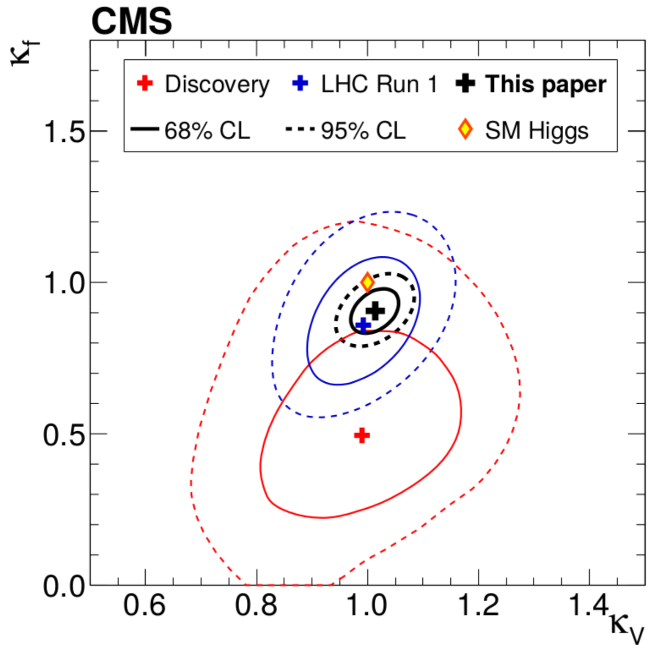
Test of unitarity $\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(\kappa_{2V} - \kappa_V^2)$

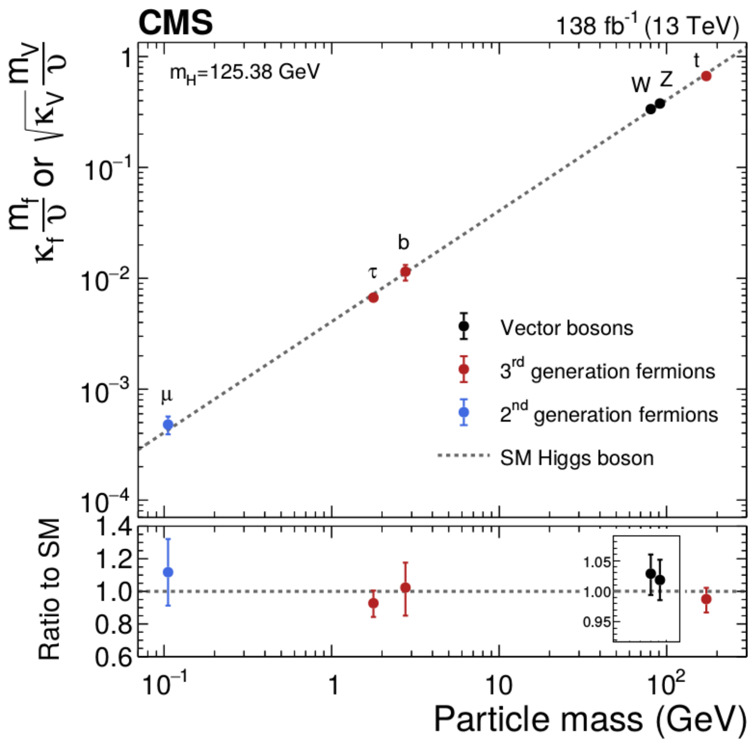


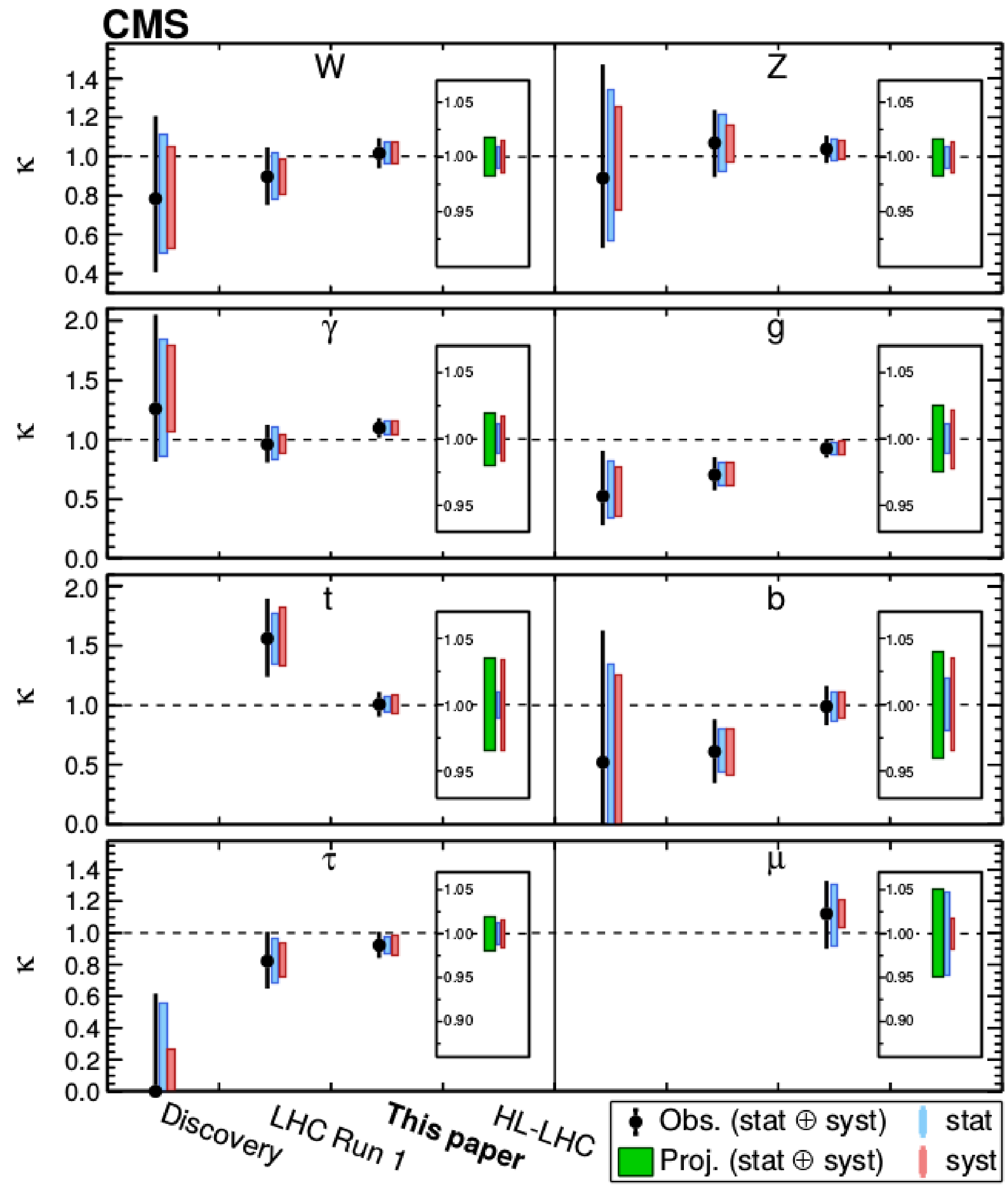


(Contino et al ’16)

Higgs results from LHC







(see Marissilva, Hernán, Thiago's talks)

Beyond the Standard Model

(Non exhaustive list, see BSM talks by Andre and Hernán)

Experimental motivations

- Neutrino masses (neutrino Right, New scalars, LFV, …)
- Matter/antimatter asymmetry
- Dark matter
- Accelerated expansion of the universe (Dark energy)

Theoretical motivations

- Quantization of gravity
- Higgs potential (hierarchy problem v_{EW}/M_{pl}, triviality of λ_H)
- Strong CP problem
- Landau pole of $U(1)_Y$
- Flavor structure, gauge unification, ...

SCALE OF NEW PHYSICS?

Beyond the Standard Model

Two usual approaches

UV theory

- Description of new d.o.f. and interactions
- Luckily with a QFT of elementary particles in a Lagrangean

SM effective field theory (EFT)

- Using only the SM fields and gauge symmetries
- Adding higher dimensional operators, ordered by dimensions
- Very general, but 2499 operators (usually O(10) enough)

The little hierarchy problem

Higher dimensional operators at the NP scale

(Barbieri et al, Peskin et al, Isidori et al)

$$\mathcal{L}_{eff} = \Lambda_1^{-2}(\bar{e}\gamma_\mu e)^2 + \Lambda_2^{-2} W^a_{\mu\nu} B_{\mu\nu} H^\dagger \tau^a H + \ldots$$

EW precision measurements no deviations → cut-off ~ 10 TeV

Operator	Bounds on Λ in TeV ($c_{\mathrm{NP}}=1$)		Bounds on c_{NP} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

Flavor measurements “almost” no deviations

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Flavor measurements “almost” no deviations → **cut-off ~ 10 – 10^5 TeV**

The little hierarchy problem

Higher dimensional operators at the NP scale

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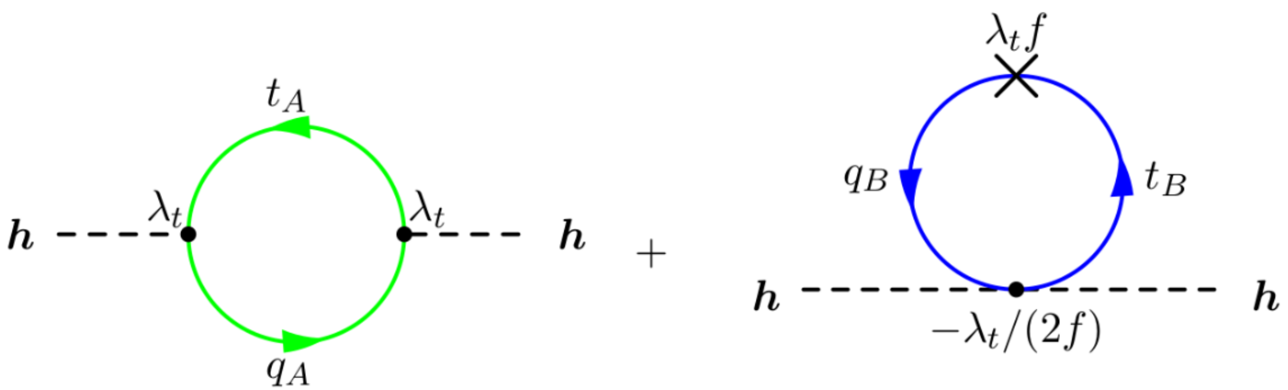
Flavor measurements "almost" no deviations → Highly non-generic couplings

A light Higgs without colored partners

★ **Mirror Twin Higgs**
(Burdman et al '14)

SM neutral top partners



- ✓ No new particles in the loops of Higgs production
- ✓ Universal corrections of Higgs couplings

★ **Folded susy for LEP paradox**
(Burdman et al '06)

colorless top partners

Susy + global symmetries (extra dim) at work

Postpone hierarchy problem by one loop

Collider signals: hard leptons and miss-E