Chiral methods at the electroweak scale

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(based on collaborations with G. Buchalla, A. Celis, M. Jung and C. Krause)

Before the Higgs

- Scalar sector in the electroweak theory either linearly or nonlinearly realized. Based on analogies with LσM vs NLσM in the strong interactions.

- Very early EFT-oriented steps in the pure gauge sector [Longhitano'80; Appelquist+Bernard'80]. Steady production of results in 80's and 90's but not systematic and mostly Technicolor-oriented.

- Failure of Technicolor led to some discouragement. Steps towards UV completion hard but there is life after Technicolor...

- Return of the EFT approach [Nyffeler et al'99; Hirn+Stern'03; Bernard+Passemar+Oertel+Stern'07; Buchalla+OC'12] and resonance models prompted by the LHC [OC+Isidori+Kamenik'09; Pich+Sanz-Cillero+Rosell'11].

- Notice the amount of ChPT practitioners involved...

After the Higgs

- Higgs discovery at the LHC confirms the Standard Model as an excellent low-energy approximation to the electroweak interactions up to roughly 10%.

- This precision is unable to single out the nature of the Higgs. We can assume it to be part of a fundamental weak doublet (SM) or take it as a physical pseudo-Goldstone that acquired mass.

- Nonlinear EFT is not only still a valid framework, but the one we should first test at the LHC: generically bigger effects (easy to rule out) and general framework to test the Higgs hypothesis. Assuming the existence of a mass gap, the most general model-independent way of parametrizing effects through EFT at the EW scale. Most conservative and least biased EFT choice.

- Technicolor is no longer the incarnation of it, but vacuum misalignment mechanism [Georgi+Kaplan'84; Agashe+Pomarol'05;...].

- Where and how to look for signatures of a nonstandard Higgs?

EFTs at the EW scale: the standard case

- The Higgs is in a weak doublet.
- The theory is renormalizable and new physics is decoupled.
- Expansion in canonical dimensions:

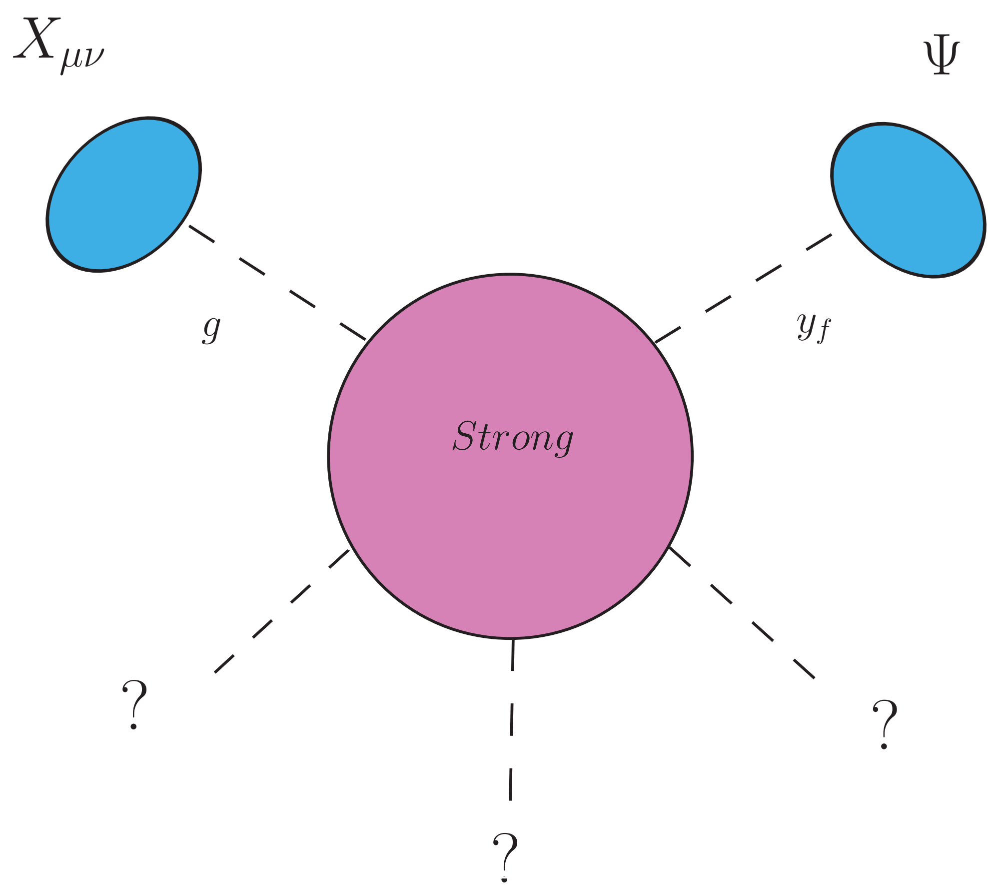
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{L}_{d=6}$$

- Examples: [Buchmueller et al'86;Grzadkowski et al'10]

$\psi^2\varphi^2 D$	
$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

EFT for generic EWSB

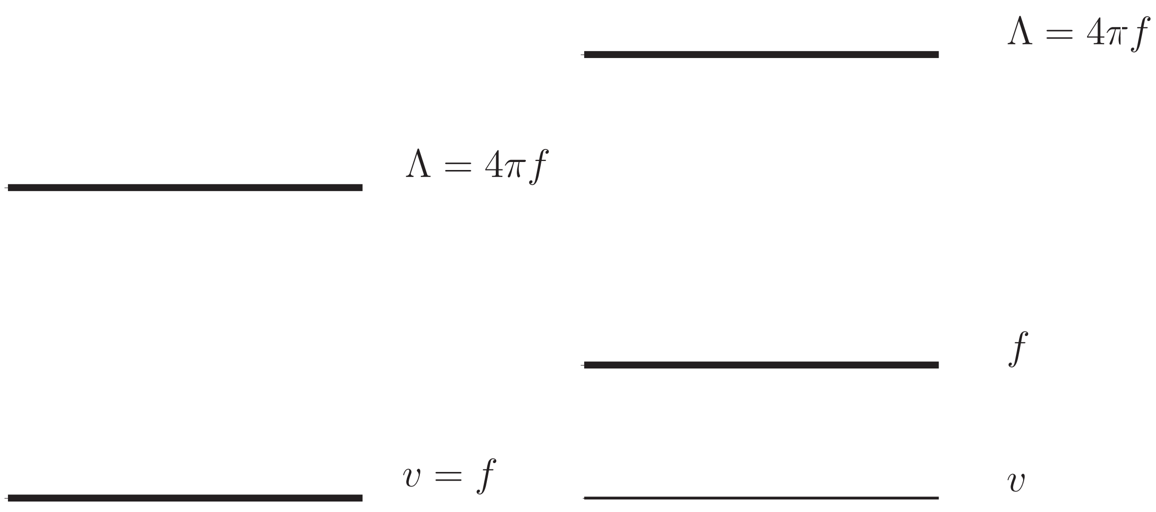


- Combination of strong and weak sectors makes the theory complicated (similar to ChPT coupled to QED). Multiscale problem: v, f, Λ_W. Essential to be able to decouple the strong sector ($v \neq f$), otherwise SM cannot be a limiting case.

- Framework has to reduce to a ChPT-like theory when weak couplings are switched off.

Dynamical picture: Vacuum misalignment mechanism

- Interpolating scenario between nondecoupling (composite) and decoupling (fundamental) interactions.

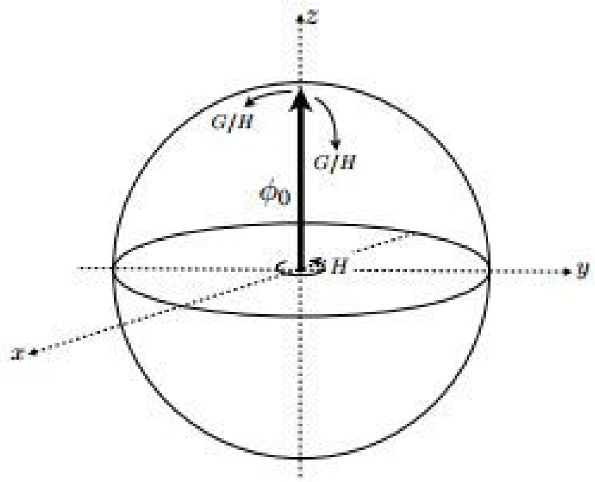


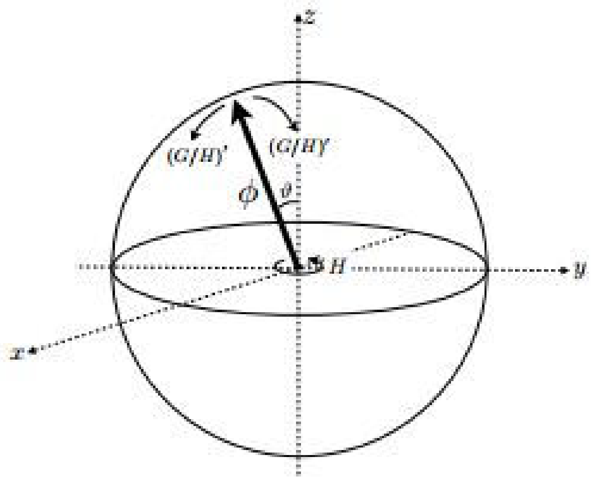
- The transition can be gauged with the parameter $\xi = \dfrac{v^2}{f^2}$:
  - $\xi \to 1$: purely nondecoupling limit.
  - $0 < \xi < 1$: heavy states and h balanced out to achieve unitarization.
  - $\xi \to 0$: decoupling (SM) limit, heavy states pushed up in energy.

Dynamical picture: Vacuum misalignment mechanism

- $G \to H_1 \supset G_{SM}$ at the scale f, generating Goldstones and a scalar.

- Explicit breaking of G_{SM} by Yukawa interactions generates a (loop-induced) Higgs potential. True vacuum tilted away from $SU(2)_L \times U(1)_Y$. [Georgi et al'84]





- Decoupling of v and f with Higgs as pNGB. Early alternative to technicolor.

- Most popular cosets: $SO(5)/SO(4)$, $SO(6)/SO(5)$. [Agashe,Pomarol,...]

EFT for generic EWSB

MULTISCALE EXPANSION:

$$\ell = \frac{f^2}{\Lambda^2}; \qquad \xi = \frac{v^2}{f^2}; \qquad d = \frac{v^2}{\Lambda_W^2}$$

- Strong χPT-like limit: $f \sim v << \Lambda_W$. Loop expansion with $\mathcal{L}_{LO} \neq \mathcal{L}_{SM}$.
- Strong-dominated dynamics: $v < f << \Lambda_W$. Hybrid expansion (ℓ, ξ).
- Weak-dominated dynamics: $\Lambda_W < f$. Dimensional expansion.
- Pure Standard Model: $f, \Lambda_W \to \infty$.

At present, $\xi \sim 10^{-1}$ while $\ell \sim 10^{-2}$. Strong-dominated dynamics still a possibility.

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EFT for generic EWSB

MAIN ASSUMPTIONS:

- **Strongly-coupled dynamics** at the scale $f < \Lambda_W$ triggering EWSB [Longhitano'80,81; Appelquist et al'80,93]. Natural strong cutoff of the theory: (dynamically generated) $\Lambda_S \sim 4\pi f \sim (5-10)$ TeV. Weak cutoffs Λ_W can exist but assumed subdominant.

- **Minimal EWSB pattern**: $SU(2)_L \times SU(2)_R \to SU(2)_V$ with $SU(2)_L \times U(1)_Y$ gauged. Most general with the minimal particle content (3 Goldstone bosons to account for the longitudinal modes of the W and Z). Collected in a nonlinear realization inside $U(x) \to g_L U(x) g_R^\dagger$. (Setting similar to $n_f = 2$ ChPT but Goldstones unphysical)

- **Light scalar** h as a SM singlet (pGB of a more general symmetry group) [Ferruglio'93; Contino et al.'10]. It can always be tuned to the SM Higgs but comprises more general scenarios.

- **Soft custodial symmetry breaking**: T-parameter contribution at NLO.

- Gauge bosons weakly coupled to the strong sector.

EFTs at the EW scale: the generic case

- Higgs not necessarily a doublet: h as singlet, EW Goldstones inside U.
- The theory is nonrenormalizable and new operators required to absorb divergences.
- Expansion in loops, or analogously in chiral dimensions [Buchalla+OC+Krause'14]

$$[\partial_\mu]_\chi = 1, \quad [\varphi]_\chi = [h]_\chi = 0, \quad [X_{\mu\nu}]_\chi = 1, \quad [\psi_{L,R}]_\chi = \frac{1}{2}, \quad [g]_\chi = [y]_\chi = 1$$

- Leading order Lagrangian: [Contino et al.'10; Buchalla+OC+Krause'13]

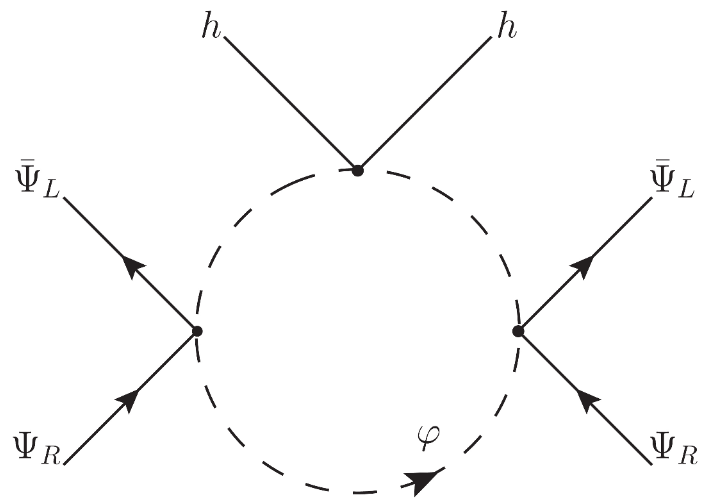
$$\mathcal{L}_{(\chi=2)} = -\frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\sum_j \bar{f}_j \not{D} f_j + \frac{1}{2}\partial_\mu h \partial^\mu h$$
$$+ \frac{v^2}{4}\langle D_\mu U D^\mu U^\dagger\rangle f_U(h) - v\left[\bar{\psi} f_\psi(h) U P_\pm \psi + \text{h.c.}\right] - V(h)$$

with

$$f_U(h) = 1 + \sum_j a_j^U \left(\frac{h}{v}\right)^j; \quad f_\psi(h) = Y_\psi + \sum_j Y_\psi^{(j)} \left(\frac{h}{v}\right)^j; \quad V(h) = \sum_{j\geq 2} a_j^V \left(\frac{h}{v}\right)^j$$

Some reflections on power-counting

- Decoupling EFTs: dimensional counting ($1/\Lambda^2$ expansion).
- Non-decoupling EFTs: loop counting ($f^2/\Lambda^2 \sim 1/(16\pi^2)$ expansion).
- In some simplified cases strongly-coupled EFTs can be cast as a dimensional expansion, *e.g.* pure ChPT (expansion in derivatives).
- When weakly and strongly-coupled sectors mix (as is the case here), the picture gets complicated. Basic requirements of a power-counting: Homogeneity of the LO Lagrangian and essential nondecoupling divergences.



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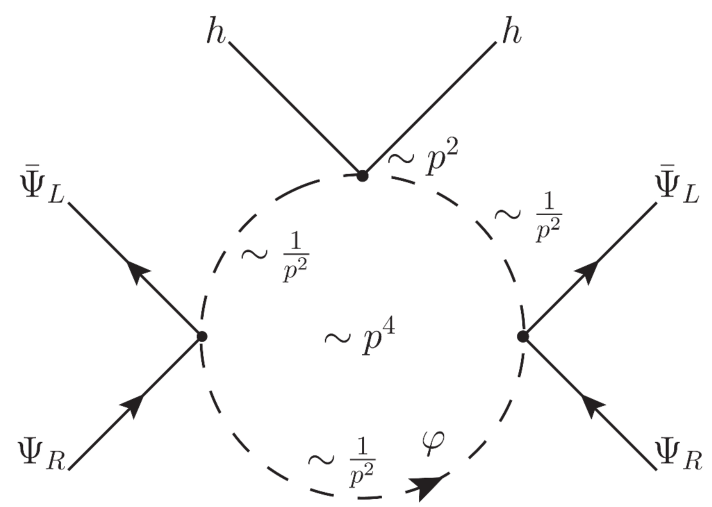

Organizing the expansion: general power-counting

The **degree of divergence** of every diagram is [Buchalla+OC'12;Buchalla+OC+Krause'13]

$$\Delta = \frac{p^d}{\Lambda^{2L}}\left[(yv)^{\nu_f}\left(\frac{\Psi}{v}\right)^F\right]\left[(gv)^{\nu_g}\left(\frac{X_{\mu\nu}}{v}\right)^G\right]\left[v^2\left(\frac{\varphi}{v}\right)^B\right]\left[(hv)^{2\nu_h}\left(\frac{h}{v}\right)^H\right]$$

where

$$d = 2L + 2 - \frac{F}{2} - G - 2\nu_h - \nu_f - \nu_g$$

- Bounded from above: number of counterterms finite (consistency check).
- The divergences of the theory do not differentiate between Goldstone bosons (h or U).
- In the absence of fermions and gauge bosons one recovers the familiar χPT formula:

$$\Delta = v^2 \frac{p^d}{\Lambda^{2L}}\left(\frac{\varphi}{v}\right)^B, \qquad d = 2L + 2$$

- The loop expansion is not simply a derivative expansion:

$$2L + 2 = d + \frac{F}{2} + G + 2\nu_h + \nu_f + \nu_g$$

- Chiral dimensions are the natural dimensions for loop expansions. Unique and consistent prescription.

Operators at NLO

Operator building at every order: assemble building blocks (U, ψ, X and derivatives) in accordance with the power-counting formula.

- NLO: 6 classes, denoted as X^2U, XUD^2, UD^4, ψ^2UD, ψ^2UD^2 and ψ^4U.

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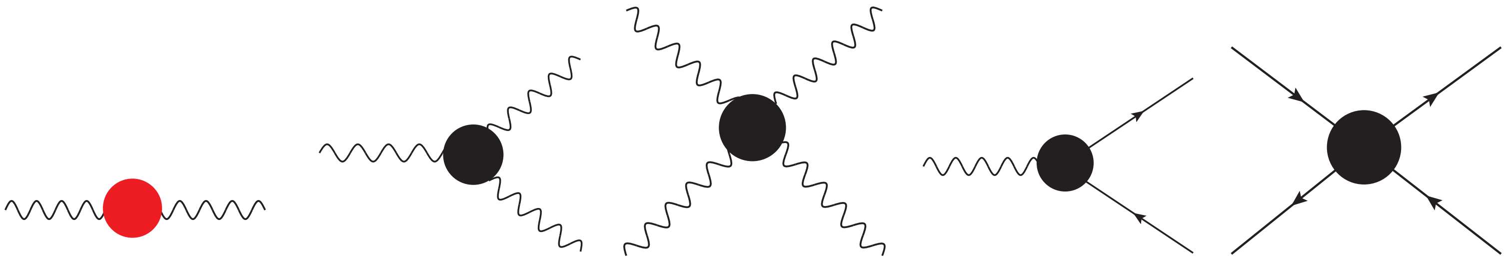

$\mathcal{O}_{XU1} = g'gB_{\mu\nu}\langle W^{\mu\nu}\tau_L\rangle \quad \mathcal{O}_{XU4} = g'g\epsilon_{\mu\nu\lambda\rho}\langle\tau_L W_{\mu\nu}\rangle B^{\lambda\rho} \quad \mathcal{O}_{XU2} = g^2\langle W^{\mu\nu}\tau_L\rangle^2$

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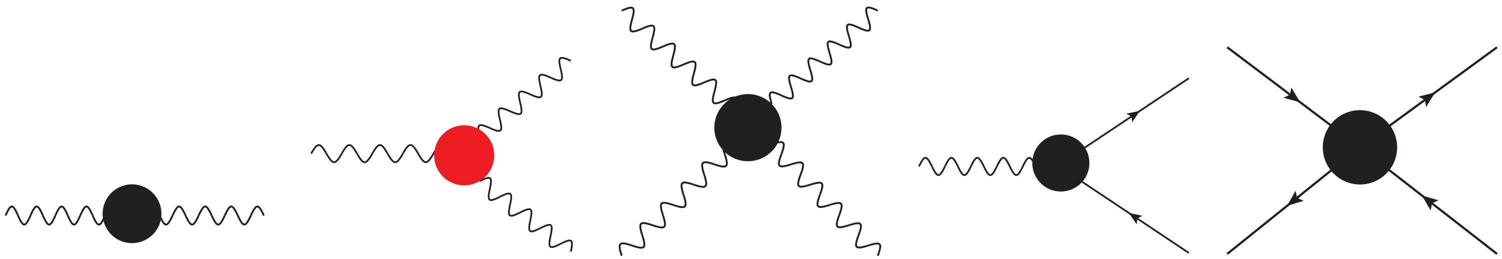

$\mathcal{O}_{XU7} = ig' B_{\mu\nu}\langle\tau_L[L^\mu, L^\nu]\rangle \quad \mathcal{O}_{XU8} = ig\langle W_{\mu\nu}[L^\mu, L^\nu]\rangle \quad \mathcal{O}_{XU9} = ig\langle W_{\mu\nu}\tau_L\rangle\langle\tau_L[L^\mu, L^\nu]\rangle$

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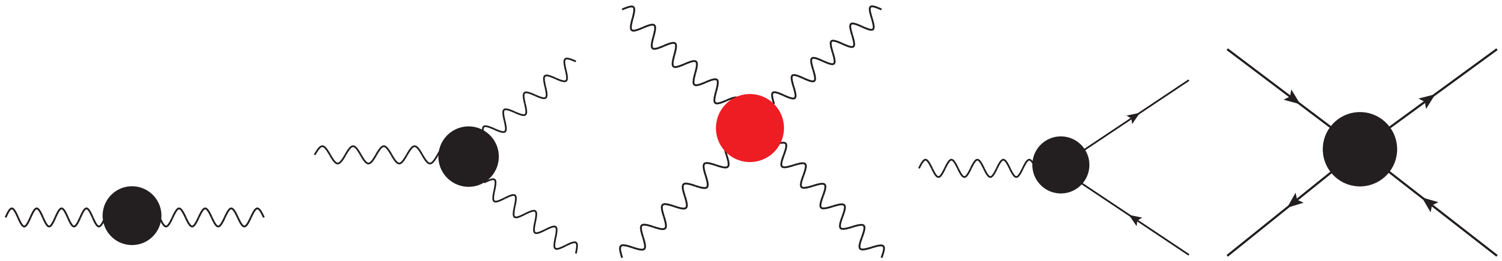

$$\mathcal{O}_{D1} = \langle L_\mu L^\mu \rangle \langle L_\nu L^\nu \rangle \qquad \mathcal{O}_{D5} = \langle \tau_L L^\mu \rangle \langle \tau_L L_\nu \rangle \langle L_\mu L^\nu \rangle$$

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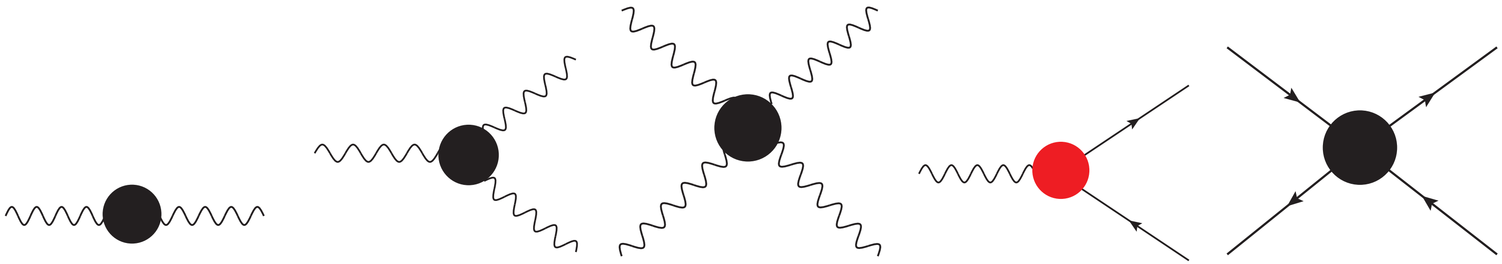

$\mathcal{O}_{\psi V7} = i\bar{l}\gamma^{\mu}l\ \langle\tau_L L_{\mu}\rangle$ $\quad \mathcal{O}_{\psi V8} = i\bar{l}\gamma^{\mu}\tau_L l\ \langle\tau_L L_{\mu}\rangle$ $\quad \mathcal{O}_{\psi V10} = i\bar{e}\gamma^{\mu}e\ \langle\tau_L L_{\mu}\rangle$

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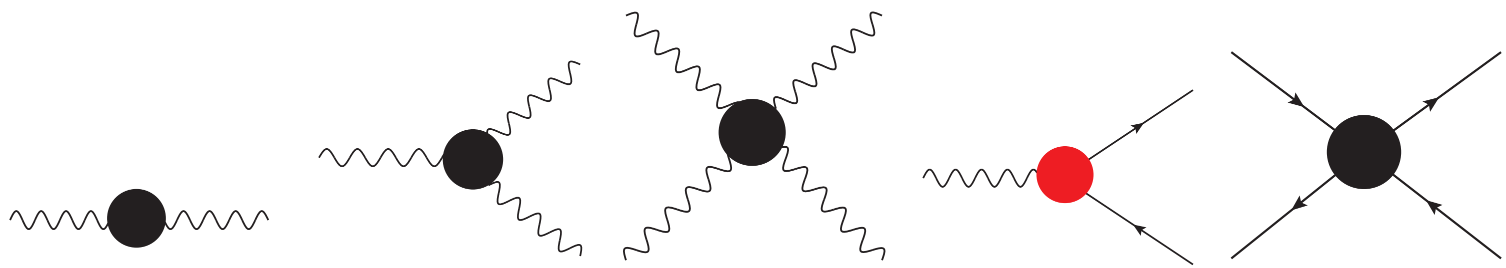

$$\mathcal{O}_{\psi S7} = \bar{l}UP\_l\ \langle L^\mu L_\mu \rangle \quad \mathcal{O}_{\psi S8} = \bar{l}UP\_l\ \langle \tau_L L_\mu \rangle^2$$

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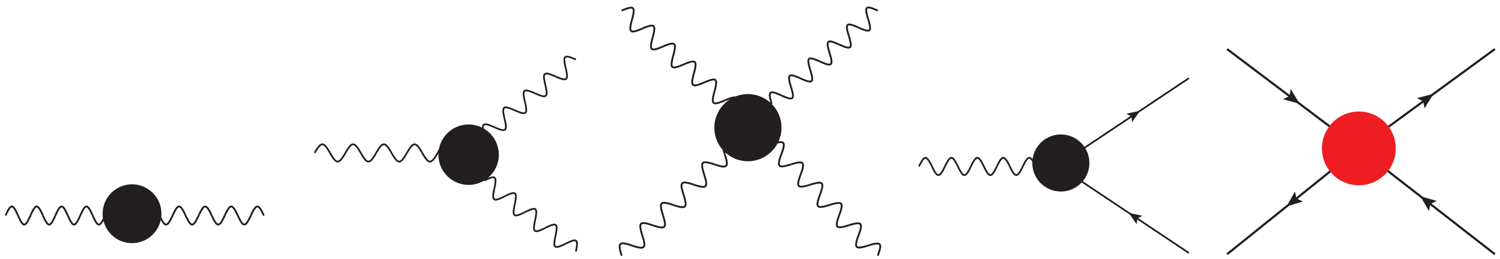
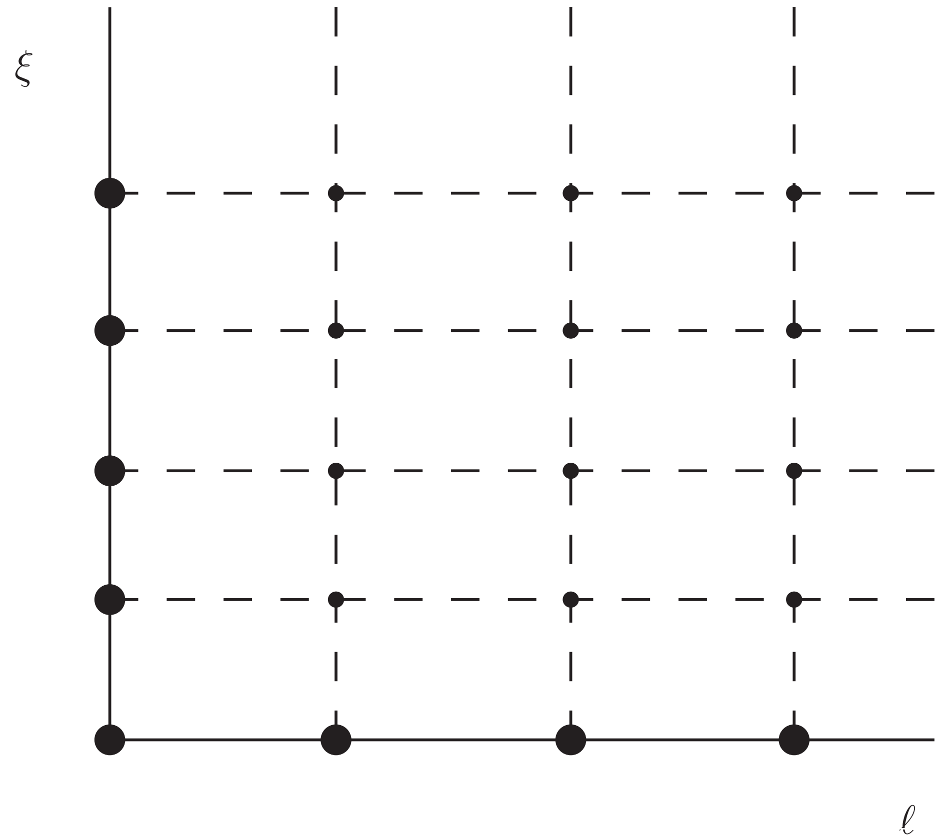


$$\mathcal{O}_{LR8} = \bar{l}\gamma_\mu l \bar{e}\gamma^\mu e \quad \mathcal{O}_{FY10} = \bar{l}UP\_l\bar{l}UP\_l$$

Approaching the decoupling limit

Graphically, tilted double expansion: [Buchalla+OC+Krause'14]



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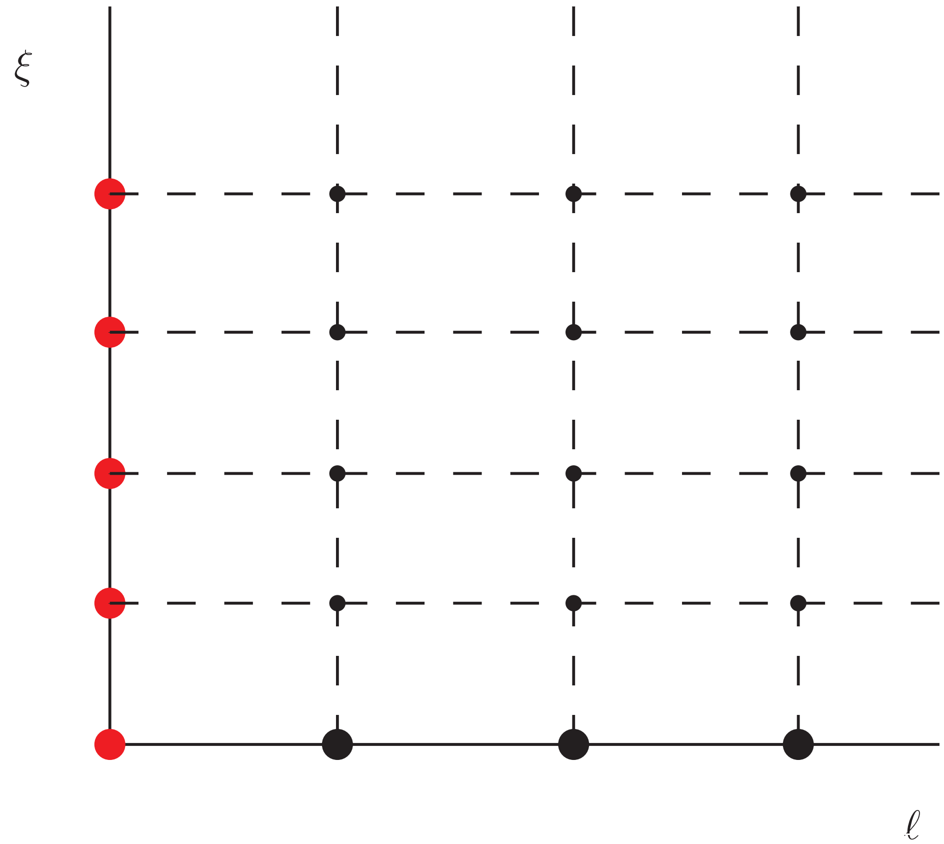

- $\mathcal{L}_{LO}$ amounts to a resummation of the ξ expansion.

Approaching the decoupling limit

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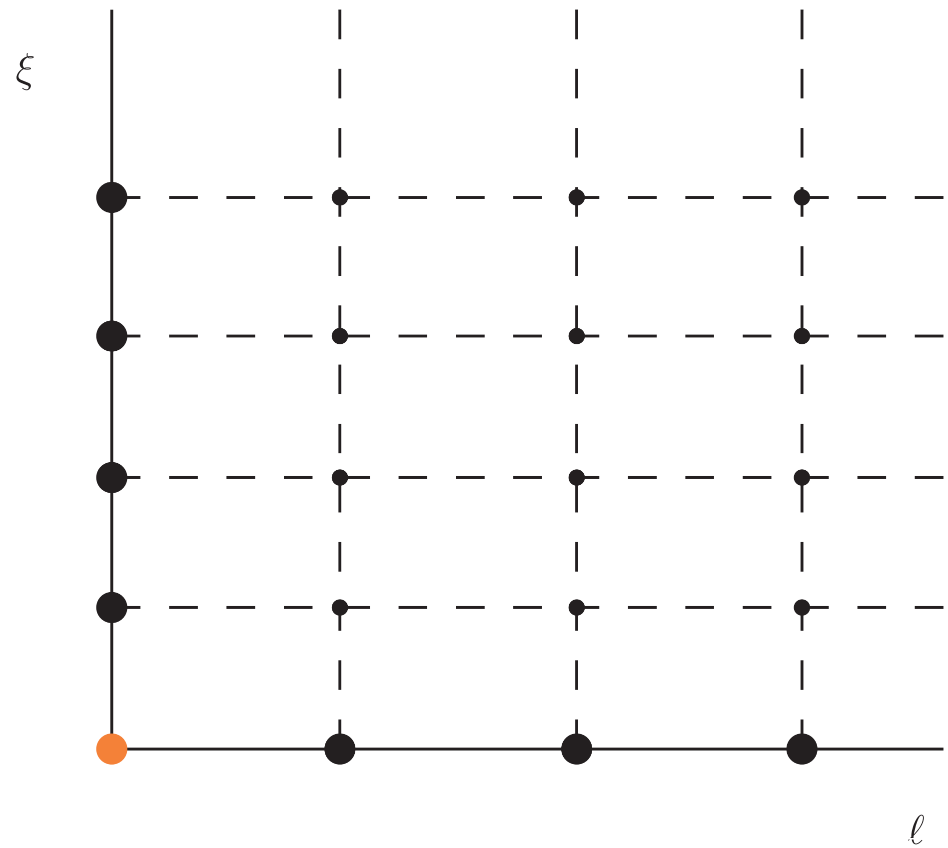

- $\mathcal{L}_{SM}$ must be recovered from $\mathcal{L}_{LO}$ when $\xi \to 0$.

Approaching the decoupling limit

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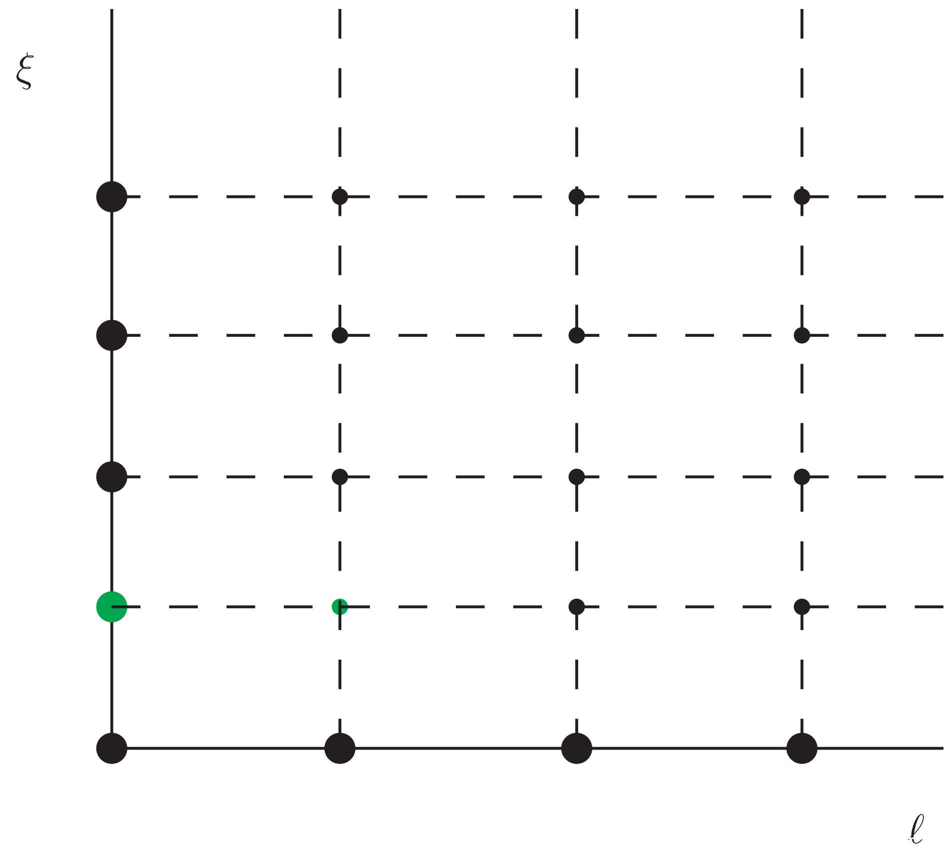

- $\mathcal{L}_{SILH}$ is an early attempt at a double expansion. However, currently $\mathcal{L}_{LO}(\xi^2)$ is in general more important than $\mathcal{L}_{NLO}(\xi)$:

$$\xi = \frac{v^2}{f^2}; \qquad \frac{\xi}{16\pi^2} = \frac{v^2}{f^2}\left(\frac{f^2}{\Lambda^2}\right); \qquad \xi^2 = \frac{v^2}{f^2}\left(\frac{v^2}{f^2}\right)$$

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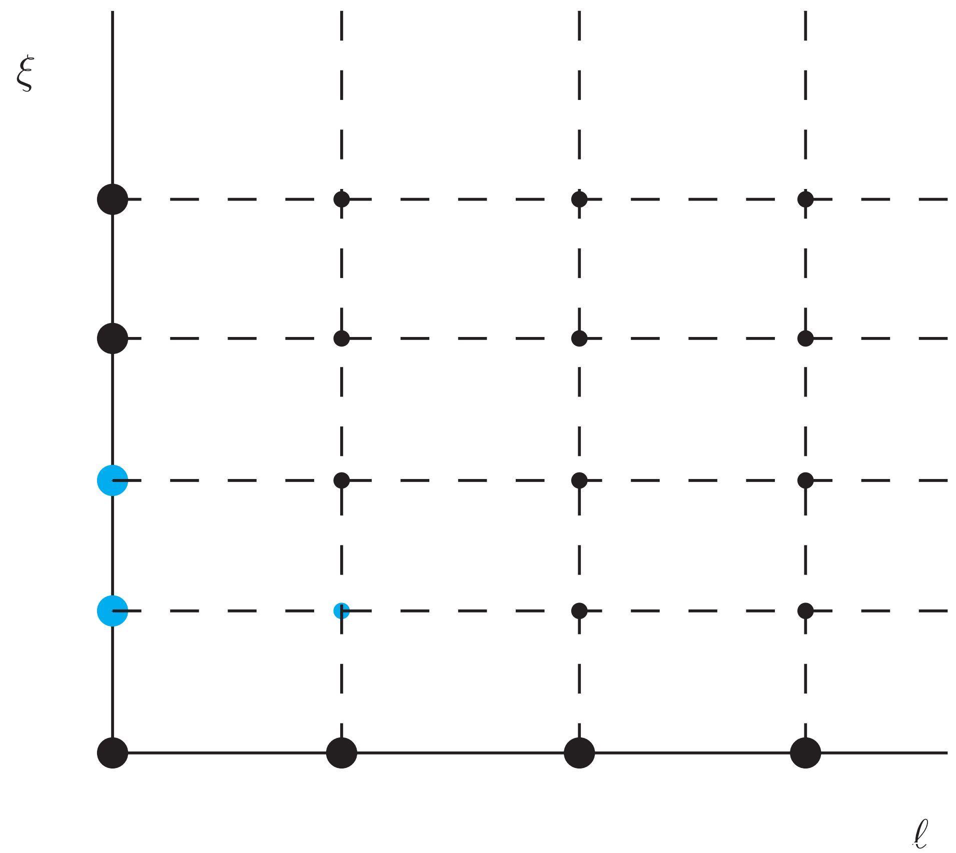


- $\mathcal{L}$ is the consistent expansion. In practice, additional decorrelations compared to $\mathcal{L}_{SILH}$. Phenomenological impact needs to be explored.

EFT fitting strategies at the LHC

STRATEGY 1: Assume

- The Standard Model is the leading-order description at low energies.
- The theory is renormalizable and so new physics is decoupled.
- The Higgs a fundamental scalar in a $SU(2)$ doublet.

Then deviations come from the $1/\Lambda^2$ suppressed $d = 6$ operators.

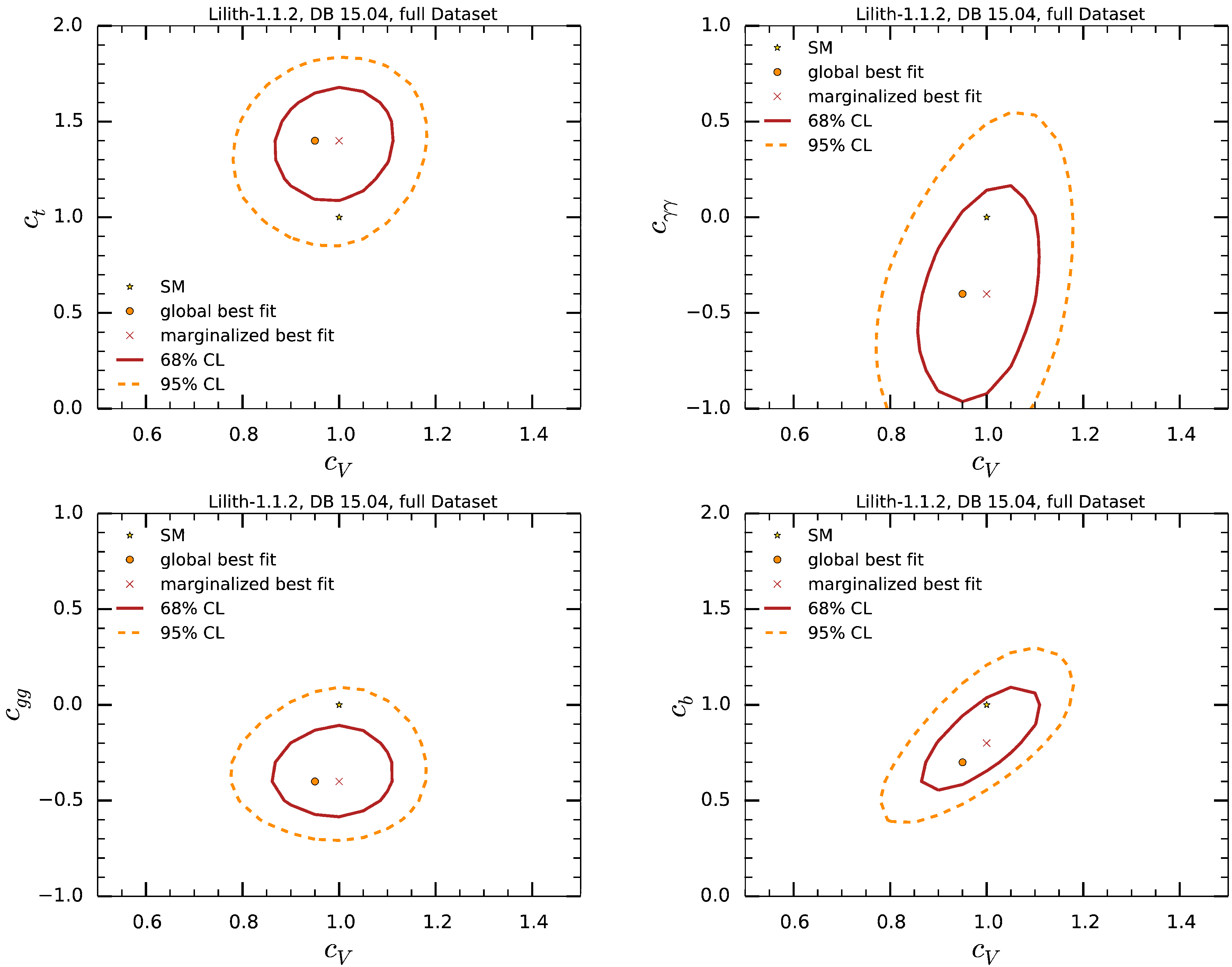
STRATEGY 2: Assume [Buchalla+OC+Celis+Krause'15]

- Basically nothing.

Experiment is allowing right now deviations in the SM couplings around 10%. The biggest effects are still described by the nonlinear EFT at LO. Fit to experimental data with only 6 parameters:

$$\mathcal{L} = c_V \left(m_W^2 W_\mu W^\mu + \frac{1}{2} Z_\mu Z^\mu \right) \frac{h}{v} - \sum_{f=t,b,\tau} c_f y_f \bar{f} f h + c_{gg} \frac{g_s^2}{16\pi^2} G_{\mu\nu} G^{\mu\nu} \frac{h}{v} + c_{\gamma\gamma} \frac{e^2}{16\pi^2} F_{\mu\nu} F^{\mu\nu} \frac{h}{v}$$

Jumping to Strategy 1 is premature...



Lilith-1.1.2, DB 15.04, full Dataset
SM
global best fit
marginalized best fit
68% CL
95% CL
c_V
c_t
$c_{\gamma\gamma}$
c_{gg}
c_b

Summary

- EFTs are the right tool to extract unbiased information from experimental data. Important to pick the most generic one allowed by current status of experiments.

- At present, strong dynamics still allowed. The most conservative fitting procedure is to consider $\mathcal{L}_{LO} \neq \mathcal{L}_{SM}$. Very few parameters, ideal for the LHC (discovery machine). Justification and systematic extension of the so-called κ-formalism.

- Flavor physics may have a saying in determining the nature of the Higgs boson, especially if multi-Higgs processes turn out to be not so decisive at the LHC, as recently hinted at: learning about the Higgs without the Higgs... [OC+Jung'15]