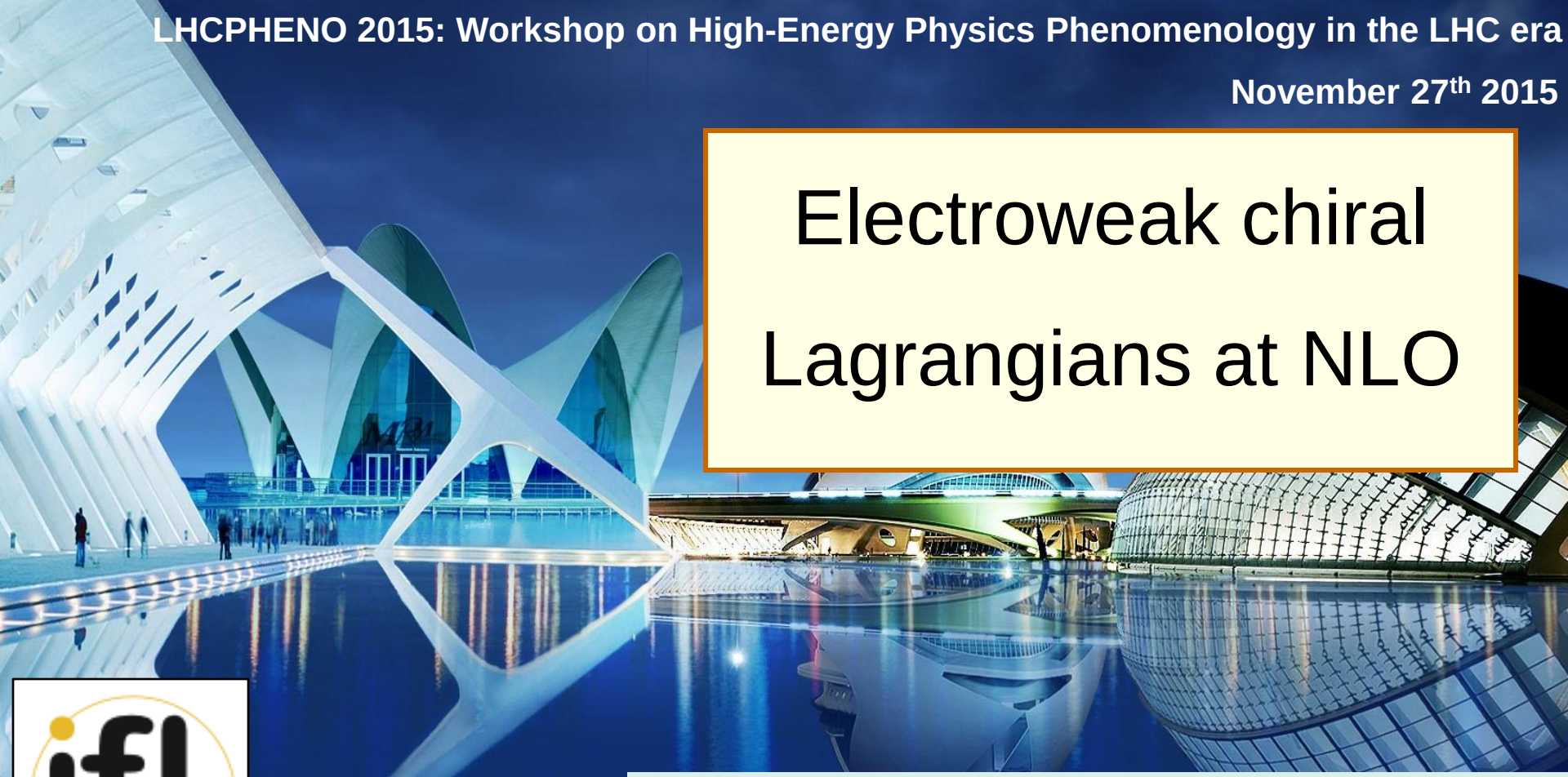
LHCPHENO 2015: Workshop on High-Energy Physics Phenomenology in the LHC era

November 27th 2015

Electroweak chiral Lagrangians at NLO



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OUTLINE

1) Introduction: Higgs EW Non-linear EFT's (ECLh)

- The importance of loops in precision analysis:

  NLO tree diagrs. ~ NLO loop diagrs. in ECLh

2) NLO 1-loop in the eff-action Γ: scalar boson loops

- 1-loop UV-divergences of Γ^{1loop}
- Renormalization and RGE

3) Observables: Full NLO (tree + loop-running + loop-finite)

Introduction

Motivation*

What?

- **Non-linear Higgs EFT**: *EW Chiral Lagrangian with a light Higgs (ECLh)*

[inspired by models where **h** is another (pseudo) Goldstone;
(linear ⊂ non-linear)]

- **UV-divergences at NLO** induced by scalar boson ($h+\pi^a$) 1-loop diagrams
- **Remaining NLO contributions** discussedin this talk

Why?

- Many BSM models show this non-linear realization (e.g. compositeness)
- 1-loop corrections in this framework will be needed:

NLO tree diagrs. ~ NLO loop diagrs. in non-linear models (!!!)
[Full NLO result in the EFT ➔ NLO tree + NLO loop]

How?

- Starting point: non-linear LO Lagrangian $\mathcal{L}_{O(p2)}$
- Path integral computation of the effective action ∞'s: *Bg. field method:*

- Schwinger-DeWitt proper-time representation + heat kernel expansion

* F.-K. Guo, P.D. Ruiz-Femenia, SC '15

Remember, remember... *

Goldstone boson ⟶ Non-linearity

Multiplets after SSB G→H ⟶ Unbroken group H

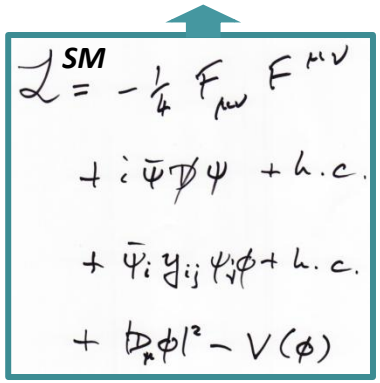
[e.g. Isospin multiplets $\rho^{0,\pm} \neq a_1^{0,\pm}$]

* CCWZ: Coleman et al., Phys.Rev. 177 (1969) 2239; Callan et al., Phys.Rev. 177 (1969) 2247

‘CHIRAL’ expansion in ECLh

- EFT Lagrangian at LO and NLO in chiral exp. *

$$\mathcal{L}_{ECLh} = \mathcal{L}_{p^2} + \mathcal{L}_{p^4} + \dots$$



Examples of BSM terms:

$$\mathcal{L}_{p^2}^{\rm BSM} = \frac{(a-1)\,h}{2v}\mathrm{Tr}\{D_\mu U^\dagger D^\mu U\} + \dots$$

$$\mathcal{L}_{p^4}^{\rm BSM} = \frac{i}{2}(a_2 - a_3)\,\mathrm{Tr}\{f_+^{\mu\nu}[u_\mu, u_\nu]\} + \mathcal{F}_{X\psi\psi}\,\mathrm{Tr}\{f_{+\,\mu\nu} d^\mu J_V^\nu\} + \dots$$

which leads to a chiral expansion in the sctatering

$$\mathcal{M} \sim \underbrace{\frac{p^2}{v^2}}_{\text{LO (tree)}} + \underbrace{\left(c_{k,n}^r \right)}_{\text{NLO (tree)}} \frac{p^4}{v^4} - \underbrace{\left(\frac{\Gamma_{k,n}}{16\pi^2} \ln \frac{p}{\mu} + \dots \right)}_{\text{NLO (1-loop)}} \frac{p^4}{v^4}$$

Finite pieces from loops (amplitude dependent)*

Typical tree suppression
$\sim 1/M_R^2$
(other states)

Typical loop suppression
$\sim 1/(16\pi^2 v^2)$
(non-linearity)

* Weinberg ‘79
* Manohar,Georgi, NPB234 (1984) 189
* Urech ’95
* Georgi,Manohar NPB234 (1984) 189
* Buchalla,Catà,Krause ‘13
* Hirn,Stern ‘05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149
* Pich,Rosell,Santos,SC, forthcoming

- **NLO suppression wrt LO:**

  - NLO tree-level ➔ Suppressed by $c_k\, p^2 / v^2 \sim p^2 / M_R^2$

  - NLO 1-loop ➔ Suppressed by $\Gamma_k\, p^2 / (16\pi^2 v^2)$ *

*Beyond NDA:

- Deviation in $\mathcal{L}_2$ from SM [Guo,Ruiz-Femenia,SC '15] ➔ 0 deviat. in SM
- Curvature in the SO(4) SU(2)xSU(2)R Higgs space [Alonso,Jenkins,Manohar '15] ➔ 0 curvat. in SM

Importance for future BSM analyses

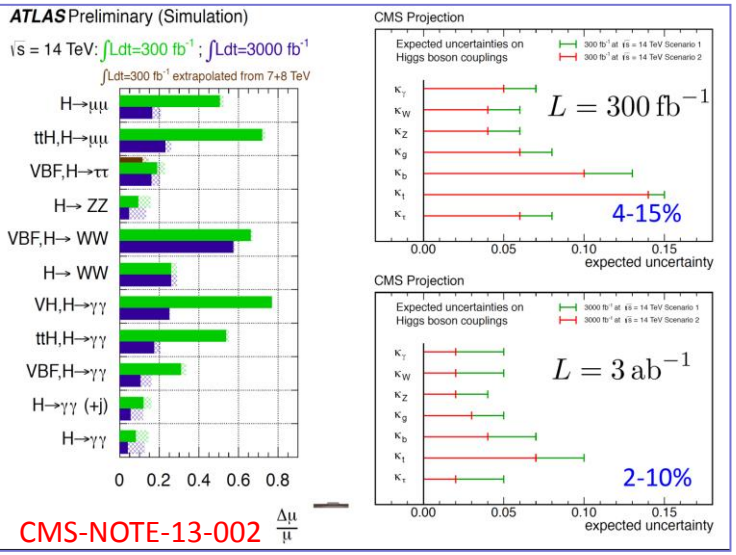
κ-framework:*

$\sigma = \sigma_{SM}\ \kappa_j^{\,2}$

(tree-level rescaling; up to details)

- Fine for low precision
- Not enough for high precision:
  $\kappa_j \neq 1$ ➔ Strong implications in loops
- **Use QFT:**
  - Model building
  - **EFT:**
    * Not just a parametrization;
    * ∞ # of obs. with finite # of couplings
    * It tells you the info YOU CAN ACTUALLY SEE

[See analysis of EFT vs. κ-framew. *]



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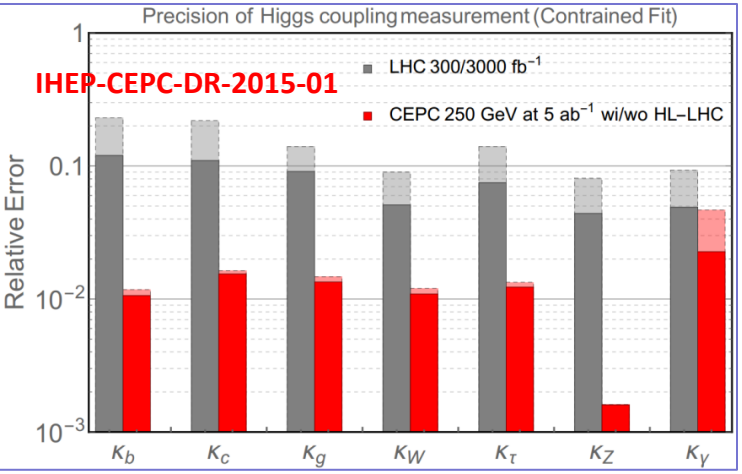


ILC-REPORT-2013-040	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$				
$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	250 fb^{-1} at 250 GeV (-0.8,+0.3)		500 fb^{-1} at 500 GeV (-0.8,+0.3)		1 ab^{-1} at 1 TeV (-0.8,+0.2)
mode	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$
$h \to b\bar{b}$	1.1%	10.5%	1.8%	0.66%	0.47%
$h \to c\bar{c}$	7.4%	-	12%	6.2%	7.6%
$h \to gg$	9.1%	-	14%	4.1%	3.1%
$h \to WW^*$	6.4%	-	9.2%	2.6%	3.3%
$h \to \tau^+\tau^-$	4.2%	-	5.4%	14%	3.5%
$h \to ZZ^*$	19%	-	25%	8.2%	4.4%
$h \to \gamma\gamma$	29-38%	-	29-38%	20-26%	7-10%
$h \to \mu^+\mu^-$	100%	-	-	-	32%

*Buchalla,Catà,Celis,Krause '15

There are two kinds of people...

LINEAR HIGGS vs. Non-linear Higgs

- **Linear Higgs models** [complex doublet Φ *-or bifundamental repr.* -] *

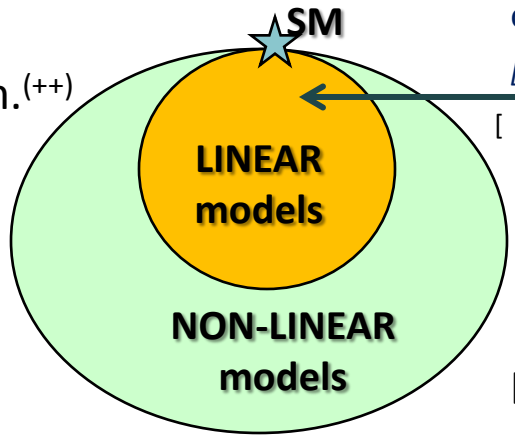
  (SUSY, 2HDM...)

  →Low-energy power counting in canonical-dim.(+)

- **Non-linear Higgs models** [singlet h + non-linear Goldstones U(π); missaligned] (x)

  (MCHM, dilaton, TC-like theories...) (**)

  →Low-energy power counting in chiral-dim.(++)



Perfect alignment of (h,π^1,π^2,π^3) into an 4-plet

[or $\Phi = (v+h)\,U(\pi)$, if preferred]

[**geometrical interpretation:*****
flat curvature
in the Higgs space metric $g_{ij}(\pi,h)$]

[M.Trott's picture ©]

* Jenkins,Manohar,Trott and later Alonso, JHEP 1310 (2013) 087; 1401 (2014) 035; 1404 (2014) 159

(+) Manohar,Jenkins,Trott, [1309.0819]

(x) Apelquist,Bernard '80
(x) Longhitano '80, '81
(x) G.F. Giudice, C. Grojean, A. Pomarol and R. Rattazzi, JHEP 06 (2007) 045
(x) Buchalla ,Cata, JHEP 1207 (2012) 101
(x) Alonso et al., PLB722 (2013) 330

** See the rev. Contino,1005.4269.
(++) Weinberg, Physica A 96 (1979) 327
(++) Georgi,Manohar NPB234 (1984) 189
(++) Buchalla,Catà,Krause, PLB 731 (2014) 80
(++) Hirn,Stern, PRD 73 (2006) 056001
(++) Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149
*** Alonso,Jenkins,Manohar, [1511.00724]

• **SM:**

1) **Gauge sym. group GSM= $SU(2)_L$ x $U(1)_Y$** *(and QCD)*

2) **EW Sym. Breaking (EWSB) G → H_{SM}= $U(1)_{EM}$**

Irrelevant in our main analysis here

• **Custodial extension of the SM:**

1) **G = $SU(2)_L$ x $SU(2)_R$ x $U(1)_{B-L}$ ⊃ G_{SM}**

2) **EW Spont. Sym. Breaking G/H with H= $SU(2)_{L+R}$ x $U(1)_{B-L}$ ⊃ H_{SM}**

3) **Break Custodial through spurions:** (external classical auxiliary fields)

- **Gauge fields: spurions l_μ, r_μ, X_μ**

  (only some components are physical dof)

$$\ell_\mu = -\frac{g}{2} W_\mu^a \sigma^a \,, \qquad r_\mu = -\frac{g'}{2} B_\mu \sigma^3 \,,$$

- **Yukawas: spurion Y → diag(y_t,y_b) , etc.**

$$Y = \hat{y}_t P_+ + \hat{y}_b P_-$$

• **Classification according to the chiral scaling $O(p^d)$ at low energies:**

$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_4 + \quad \ldots$$

• **Lowest order Lagrangian:***

$$\mathcal{L}_2 = \frac{v^2}{4}\mathcal{F}_C\langle\, u_\mu u^\mu \,\rangle + \frac{1}{2}(\partial_\mu h)^2 - \mathbf{v^2\,V} + \mathcal{L}_{YM} + i\bar{\psi}\not{D}\psi - v^2\langle\, J_S \,\rangle\,,$$

where $\psi_{R,L} = P_{R,L}\psi$ with $\psi = (t,b)^T$

$$u_\mu = iu_R^\dagger(\partial_\mu - ir_\mu)u_R - iu_L^\dagger(\partial_\mu - i\ell_\mu)u_L\,,$$

$$\Gamma_\mu = \frac{1}{2}u_R^\dagger(\partial_\mu - ir_\mu)u_R + \frac{1}{2}u_L^\dagger(\partial_\mu - i\ell_\mu)u_L\,,$$

$\nabla_\mu \cdot = \partial_\mu + [\Gamma_\mu, \cdot]$

$$f_\pm^{\mu\nu} = u_L^\dagger \ell^{\mu\nu} u_L \pm u_R^\dagger r^{\mu\nu} u_R\,,$$

$$r_{\mu\nu} = \partial_\mu r_\nu - \partial_\nu r_\mu - i[r_\mu, r_\nu]\,, \qquad (R \leftrightarrow L)\,,$$

$\bar{\psi}_m\psi_n = -\psi_n\bar{\psi}_m$

$$J_S = J_{YRL} + J_{YRL}^\dagger\,, \qquad J_P = i(J_{YRL} - J_{YRL}^\dagger)$$

$P_{R,L} = (1 \pm \gamma^5)/2$

$$J_{YRL} = -\frac{1}{\sqrt{2}v}u_R^\dagger Y\, \mathrm{Tr}_D\{\psi_R\bar{\psi}_L\}u_L\,,$$

• Convenient Goldstone tensors when computing 1-loop div. [as noted by Bijnens,Colangelo,Ecker] (equivalent but simpler than the U, V_μ, etc. notation)

* G.F. Giudice, C. Grojean, A. Pomarol and R. Rattazzi, JHEP 06 (2007) 045
* Buchalla ,Cata, JHEP 1207 (2012) 101
* Alonso et al., PLB722 (2013) 330

• Counting:*

$$\partial_\mu,\ m_h,\ g^{(\prime)}v,\ \lambda_q v \sim \mathcal{O}(p)$$
$$\frac{\chi}{v},\ u_{L,R} \sim \mathcal{O}(p^0) \quad (\text{with } \chi = \text{boson field})$$
$$\frac{\psi}{v} \sim \mathcal{O}(p^{\frac{1}{2}}) \quad (\text{with } \psi = \text{fermion field})$$

h,π^a,W^a,B

quarks, leptons

$$\begin{aligned} \mathcal{F}_C &\sim \mathcal{O}(p^0) \\ u_\mu &\sim \mathcal{O}(p) \\ r_{\mu\nu},\ \ell_{\mu\nu},\ f_\pm^{\mu\nu} &\sim \mathcal{O}(p^2) \\ J_S,\ J_P,\ \Gamma_S,\ \Gamma_P &\sim \mathcal{O}(p^2) \\ V &\sim \mathcal{O}(p^2) \end{aligned}$$

$$\mathcal{F}_C[h/v] = 1 + 2ah/v + bh^2/v^2 + \ldots$$

(other notation $a=\kappa_W=c_W=\omega$)

$\mathcal{O}(p^0)$ $\mathcal{O}(p)$

, so you can check that every term in the LO Lagrangian $\mathcal{L}_2$ is O(p²):

$$\mathcal{L}_2 = \frac{v^2}{4}\mathcal{F}_C\langle u_\mu u^\mu\rangle + \frac{1}{2}(\partial_\mu h)^2 - \mathbf{v^2}\,\mathbf{V}$$
$$+\mathcal{L}_{YM} + i\bar{\psi}\not{D}\psi - v^2\langle J_S\rangle,$$

$\mathcal{O}(p^2)$

* Manohar,Georgi, NPB234 (1984) 189
* Hirn,Stern '05
* Buchalla,Catà,Krause '13
* Delgado,Dobado,Herrero,SC, JHEP 1407 (2014) 149
* Pich,Rosell,Santos,SC, forthcoming

NLO effective action at 1-loop:

UV divergences

Info about the QFT from the fluctuations

- Loops of EW Goldstones & Higgs ➔ Fluctuations*

$$u_{R,L} = \bar{u}_{R,L}\, \exp\{\pm i \mathcal{F}_C^{-1/2}\, \Delta/(2v)\}\,, \qquad \Delta = \Delta^a \sigma^a$$

$$h = \bar{h} + \epsilon\,,$$

$$\vec{\eta}^T = (\Delta^a, \epsilon)$$

$$u_L = u_R^\dagger = \exp\{i\pi^a\sigma^a/(2v)\}$$

$$\mathcal{L}_2 = \mathcal{L}_2^{\mathcal{O}(\eta^0)} + \mathcal{L}_2^{\mathcal{O}(\eta^1)} + \mathcal{L}_2^{\mathcal{O}(\eta^2)} + \mathcal{O}(\eta^3)$$

Tree-level | EoM | 1-loop | Higher loops

O(η) fluctuations: EoM

- Equations of motion (EoM):

$$\nabla^\mu u_\mu = 2J_P - u_\mu \partial^\mu (\ln \mathcal{F}_C)\,,$$
$$\partial^2 h/v = \frac{1}{4}\mathcal{F}_C' \langle\, u_\mu u^\mu \,\rangle - V' - \langle\, J_S' \,\rangle$$

,with the pseudoscalar density $J_P = i(J_{YRL} - J_{YRL}^\dagger)$

O(η²) fluctuations: 1-loop corrections

- The UV-divergences are given by the 1/(d-4) pole: *

Seeley-DeWitt coefficient $\mathrm{Tr}\{a_2(x)\}$

$$S^{1\ell} = -\frac{\mu^{d-4}}{16\pi^2(d-4)}\int \mathrm{d^dx\,Tr}\left\{\frac{1}{12}[d_\mu,d_\nu]\,[d^\mu,d^\nu] + \frac{1}{2}\Lambda^2\right\} + \text{finite}$$
$$= -\frac{\mu^{d-4}}{16\pi^2(d-4)}\int \mathrm{d^dx}\sum_k \Gamma_k\,\mathcal{O}_k + \text{finite}$$

$\equiv \Lambda_\infty$

't Hooft, NPB 62 (1973) 444; Ramond, Front. Phys. 74 (1989) 1; DeWitt, Int. Ser. Monogr. Phys. 114 (2003) 1;D. V. Vassilevich, Phys. Rept. 388 (2003) 279
A. O. Barvinsky and G. A. Vilkovisky, Phys. Rept. 119 (1985) 1; C. Lee, T. Lee and H. Min, PRD 39 (1989) 1681; R. D. Ball, Phys. Rept. 182 (1989) 1

This is the quadratic fluctuation before make-up

$$\mathcal{L}^{\mathcal{O}(\Delta^2)} = -\frac{1}{4}\langle\, \Delta\nabla^2\Delta\,\rangle + \frac{1}{16}\langle\, [u_\mu,\Delta]\,[u^\mu,\Delta]\,\rangle$$
$$+\left[\frac{\mathcal{F}_C^{-\frac{1}{2}}\mathcal{K}}{8}\left(\frac{\partial^2 h}{v}\right)+\frac{\Omega}{16}\left(\frac{\partial_\mu h}{v}\right)^2\right]\langle\,\Delta^2\,\rangle+\frac{1}{2\mathcal{F}_C}\langle\,\Delta^2 J_S\,\rangle,$$
$$\mathcal{L}^{\mathcal{O}(\epsilon^2)} = -\frac{1}{2}\epsilon\left[\partial^2-\frac{1}{4}\mathcal{F}_C''\langle\,u_\mu u^\mu\,\rangle+V''+\langle\,J_S''\,\rangle\right]\epsilon\,,$$
$$\mathcal{L}^{\mathcal{O}(\epsilon\Delta)} = -\frac{1}{2}\epsilon\mathcal{F}_C'\,\langle\,u_\mu\nabla^\mu(\mathcal{F}_C^{-\frac{1}{2}}\Delta)\,\rangle+\mathcal{F}_C^{-\frac{1}{2}}\epsilon\langle\,\Delta J_P'\,\rangle$$

with $\mathcal{K}=\mathcal{F}_C^{-1/2}\mathcal{F}_C'$ and $\Omega=2\mathcal{F}_C''/\mathcal{F}_C-(\mathcal{F}_C'/\mathcal{F}_C)^2$

- The previous result comes from the Gaussian integration:

$$S^{1\ell} = \frac{i}{2}\mathrm{tr}\,\log\left(d_\mu d^\mu+\mathbf{\Lambda}\right) = -\frac{\mu^{d-4}}{16\pi^2(d-4)}\int \mathrm{d^dx}\langle\,\frac{1}{12}[d_\mu,d_\nu][d^\mu,d^\nu]+\frac{1}{2}\mathbf{\Lambda}^2\,\rangle+\text{finite}$$

Types of ∞'s, types of c.t.'s

- Not all ∞'s need new operators

- In general ,the 1-loop divergences have the structure

$$\mathcal{L}^{1\ell,\,\infty} = \mathcal{L}_2^{1\ell,\,\infty} + \mathcal{L}_4^{1\ell,\,\infty} + \quad \ldots$$

$$\mathcal{L}_2^{1\ell,\,\infty} = -\mathbf{\Lambda}_\infty \Big\{ \ldots$$

$$\mathcal{L}_4^{1\ell,\,\infty}|_{\rm ferm} = -\mathbf{\Lambda}_\infty \Big\{ \ldots$$

$\mathcal{L}_4$ divergences (NLO): bosonic operators*

c_k	Operator $\mathcal{O}_k$	Γ_k	$\Gamma_{k,0}$
c_1	$\frac{1}{4}\langle f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu}\rangle$	$\frac{1}{24}(\mathcal{K}^2-4)$	$-\frac{1}{6}(1-a^2)$
(c_2-c_3)	$\frac{i}{2}\langle f_+^{\mu\nu}[u_\mu,u_\nu]\rangle$	$\frac{1}{24}(\mathcal{K}^2-4)$	$-\frac{1}{6}(1-a^2)$
c_4	$\langle u_\mu u_\nu\rangle\langle u^\mu u^\nu\rangle$	$\frac{1}{96}(\mathcal{K}^2-4)^2$	$\frac{1}{6}(1-a^2)^2$
c_5	$\langle u_\mu u^\mu\rangle^2$	$\frac{1}{192}(\mathcal{K}^2-4)+\frac{1}{128}\mathcal{F}_C^2\Omega^2$	$\frac{1}{8}(a^2-b)^2+\frac{1}{12}(1-a^2)^2$
c_6	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle u_\nu u^\nu\rangle$	$\frac{1}{16}\Omega(\mathcal{K}^2-4)-\frac{1}{96}\mathcal{F}_C\Omega^2$	$-\frac{1}{6}(a^2-b)(7a^2-b-6)$
c_7	$\frac{(\partial_\mu h)(\partial_\nu h)}{v^2}\langle u^\mu u^\nu\rangle$	$\frac{1}{24}\mathcal{F}_C\Omega^2$	$\frac{2}{3}(a^2-b)^2$
c_8	$\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4}$	$\frac{3}{32}\Omega^2$	$\frac{3}{2}(a^2-b)^2$
c_9	$\frac{(\partial_\mu h)}{v}\langle f_-^{\mu\nu} u_\nu\rangle$	$\frac{1}{24}\mathcal{F}_C^{\frac{1}{2}}\mathcal{K}\Omega$	$-\frac{1}{3}a(a^2-b)$
c_{10}	$\frac{1}{2}\langle f_+^{\mu\nu} f_{+\,\mu\nu} + f_-^{\mu\nu} f_{-\,\mu\nu}\rangle$	$-\frac{1}{48}(\mathcal{K}^2+4)$	$-\frac{1}{12}(1+a^2)$

* Guo,Ruiz-Femenia,SC,'15

- **In general:** $\mathcal{F}_C[h/v] = 1 + 2ah/v + bh^2/v^2 + \ldots \qquad (\mathcal{K}^2-4) = 4(a-1)+\ldots \qquad \Omega = 4(b-a^2)+\ldots$

- **SM:** a very special case $\mathcal{F}_C[h/v] = (1+h/v)^2, \qquad (\mathcal{K}^2-4) = \Omega = 0$

• And now the geometric connection to this result * provided by *** (going beyond NDA):

$$\mathcal{R}_4 = \left(1 - v^2 (F')^2\right) F^2 \quad = \quad \left(1 - \mathcal{K}^2/4\right) \mathcal{F}_C \,,$$

$$\mathcal{R}_2 = \left(1 - v^2 (F')^2\right) - \frac{v^2 F'' F}{(N_\varphi - 1)} \quad = \quad \left(1 - \mathcal{K}^2/4\right) - \frac{\mathcal{F}_C \Omega}{8} \,,$$

$$\mathcal{R}_0 = 2\mathcal{F}_C^{-1} \mathcal{R}_2 - \mathcal{F}_C^{-2} \mathcal{R}_4 \,,$$

$$F = \mathcal{F}_C^{1/2}$$

$$N_\varphi = 3$$

* Guo,Ruiz-Femenia,SC,'15

*** Alonso,Jenkins,Manohar, [1511.00724]

Renormalization

- **Divergent operators in the eff-action**

$$\mathcal{L}^{1\ell,\infty} = \sum_k \left(-\Lambda_\infty \, \Gamma_k \right) \mathcal{O}_k$$

require the same operator in the Lagrangian to be renormalized,

$$\mathcal{L}^{\rm ct} = \sum_k c_k \, \mathcal{O}_k$$

fulfilling the renormalization condition

$$c_k = c_k^r + \Lambda_\infty \Gamma_k$$

$$c_{k,n} = c_{k,n}^r + \Lambda_\infty \Gamma_{k,n}$$

$$\frac{\partial c_{k,n}^r}{\partial \ln \mu} = -\frac{\Gamma_{k,n}}{16\pi^2}$$

But just, remember, remember...

$$\Gamma_k[h/v] = \sum_n \Gamma_{k,n} (h/v)^n / n!$$

$$c_k[h/v] = \sum_n c_{k,n} (h/v)^n / n!$$

Full NLO for given observables:

NLO-tree

+ NLO-loop-running

+ NLO-loop-finite

- First estimate:

  tree-level Resonance tree-level EFT estimate at NLO

- True prediction:

  full tree+1loop resonance full NLO prediction

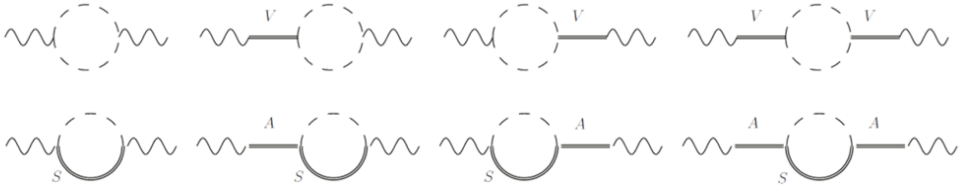
  μ scale uncertainty: **removed**
  chiral logs: **matched**
  full NLO EFT: **matched**

Example of RχT ⇔χPT tree-level* and one-loop matching**

*Ecker,Gasser,Pich,de Rafael, NPB 321 (1989) 311
*Cirigliano et al., NPB753 (2006) 139

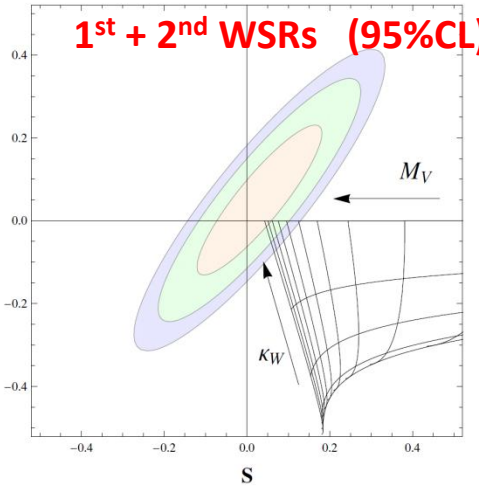
** Catà and Peris, Phys. Rev. D 65 (2002) 056014
** Pich,Rosell,SC, JHEP 0408 (2004) 042
…

EXAMPLE 1: *, (x) S-parameter



V,A resonances + 1-loop + 2 WSRs

$$S = -16\pi \left[\underbrace{a_1^r(M_V)}_{\text{Tree} \approx -2\times 10^{-3}} + \underbrace{\frac{\kappa_W^2 - 1}{192\pi^2}}_{\text{loop} \approx -6\times 10^{-5}} \left(\ln \frac{M_V^2}{m_h^2} + \frac{5}{6} \right) \right]$$



$M_V > 4$ TeV

$0.94 < a=\kappa_W < 1$

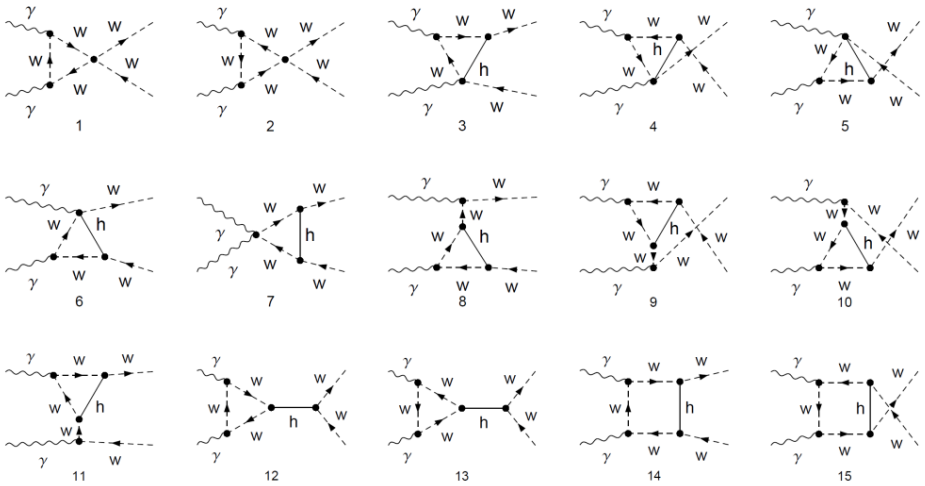
Small splitting due to constraints from WSRs

$$\kappa_W = M_V^2/M_A^2$$

EXAMPLE 2: * γγ→Z_LZ_L, γγ→W_LW_L

(only charged shown here)

$$A_{\text{NLO}}^{\gamma\gamma\to\omega\omega} = \frac{1}{v^2}\left[2\kappa_W c_\gamma^r + \underbrace{8(a_1^r - a_2^r + a_3^r)}_{\text{tree} \approx 0.5\times 10^{-3}} + \underbrace{\frac{\kappa_W^2 - 1}{8\pi^2}}_{\text{loop} \approx -1.5\times 10^{-3}} \right]$$

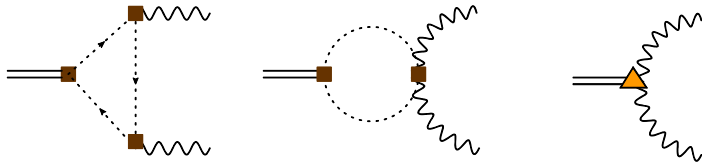


+24 more

* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

(x) Pich,Rosell and SC, JHEP 1208 (2012) 106; PRL 110 (2013) 181801

EXAMPLE 3: *,(+) $\Gamma(h\to\gamma\gamma)$

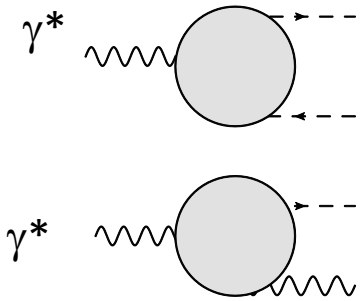


$$\Gamma(h\to\gamma\gamma)=\Gamma(h\to\gamma\gamma)^{\rm SM}\left(8\pi^2 c_\gamma^r+0+a\right)^2$$

Finite tree

Finite 1-loop

EXAMPLE 4: * EM form-factors $\langle W_L^+W_L^-|J_{EM}^\mu|0\rangle$ and $\langle h\gamma|J_{EM}^\mu|0\rangle$



$$\mathcal{F}_{\gamma^* ww}=1+\frac{2q^2(a_3^r-a_2^r)}{v^2}+\frac{(1-a^2)q^2}{96\pi^2v^2}\left(-\ln\frac{-q^2}{\mu^2}+\frac{8}{3}\right)$$

$$\mathcal{F}_{\gamma^* h\gamma}=-2c_\gamma^r+0+0$$

OTHERS:

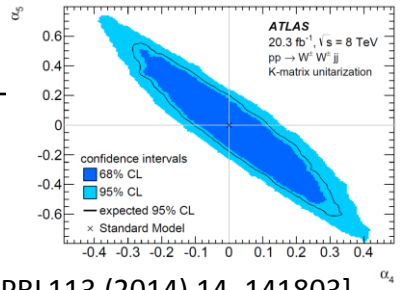
gg→ZZ Azatov,Grojean,Paul,Salvioni, Zh.Eksp.Teor.Fiz. 147 (2015) 410, J.Exp.Theor.Phys. 120 (2015) 354

$\Gamma(h\to Z\gamma)$ Azatov, Contino,Di Iura,Galloway, PRD88 (2013) 7, 075019

WW, ZZ, hh scat. Espriu,Yencho, PRD 87 (2013) 055017; ←

Espriu,Mescia, Yencho, PRD88 (2013) 055002;

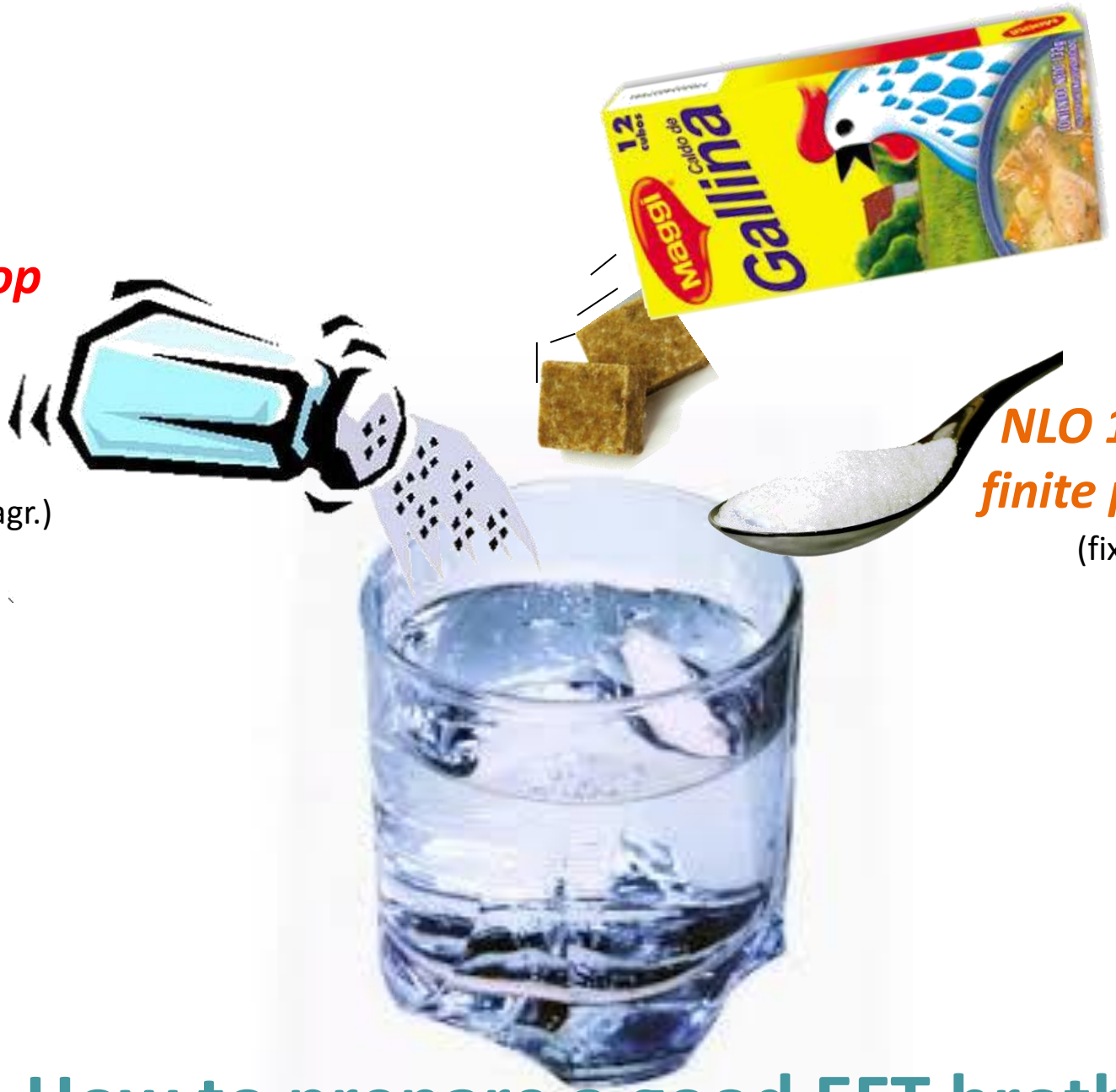
Delgado,Dobado,Llanes-Estrada, JHEP1402 (2014) 121;



[ATLAS, PRL113 (2014) 14, 141803]

* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

Conclusions



NLO
Tree-level
(modelling;
e.g., Resonances)

NLO 1-loop
running
(fixed by LO Lagr.)

NLO 1-loop
finite pieces
(fixed by LO Lagr.)

How to prepare a good EFT broth?

Modifying your LO non-linear action ➔ Consequences at NLO

- RG invariant couplings:
  - $\gamma\gamma \rightarrow ZZ, Z\gamma, \gamma\gamma$ *
  - $\gamma\gamma, Z\gamma \rightarrow h, hh, hhh\ldots$ **
  - $gg \rightarrow h, hh, hhh\ldots$

- Check of the running in previous analyses
  - $\gamma\gamma \rightarrow W^+W^-$ *
  - WW, ZZ, hh scattering (x)

- Other important effects:
  - Generation of logs with 4-fermion operators $J_{S,P}{}^2$!!! *(Flavour??)*
  - Modiffications to Higgs potential

- Fermion and gauge boson loops under calculation

* $\gamma\gamma \rightarrow ZZ$, $h \rightarrow \gamma\gamma$, $h \rightarrow \gamma\gamma^*$: Delgado,Dobado,Herrero,SC,'2014

** $h \rightarrow Z\gamma$ Azatov, Contino,Di Iura,Galloway, PRD88 (2013) 7, 075019

(x) Espriu,Mescia,Yencho '13
(x) Delgado,Dobado,Llanes-Estrada '13