arXiv:1409.1571

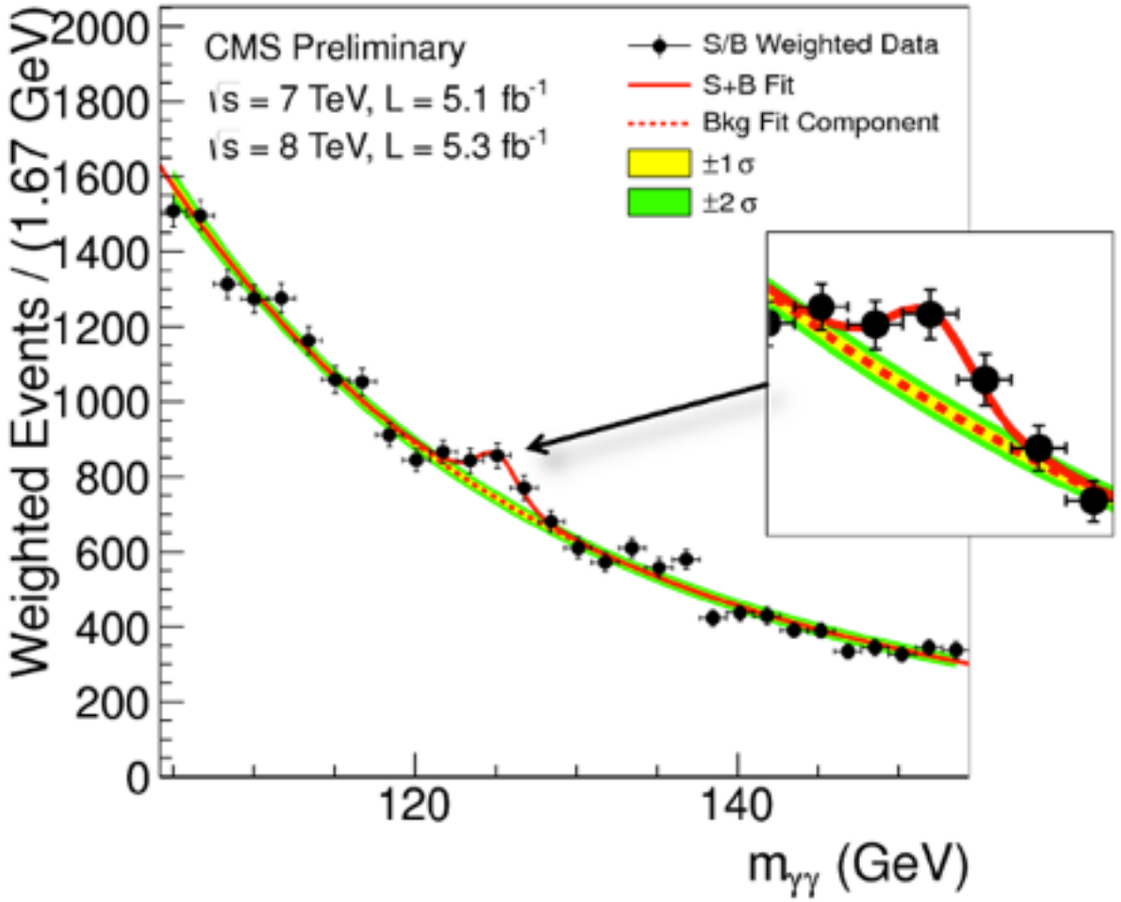
On the renormalization of the Electroweak chiral Lagrangian with a Higgs

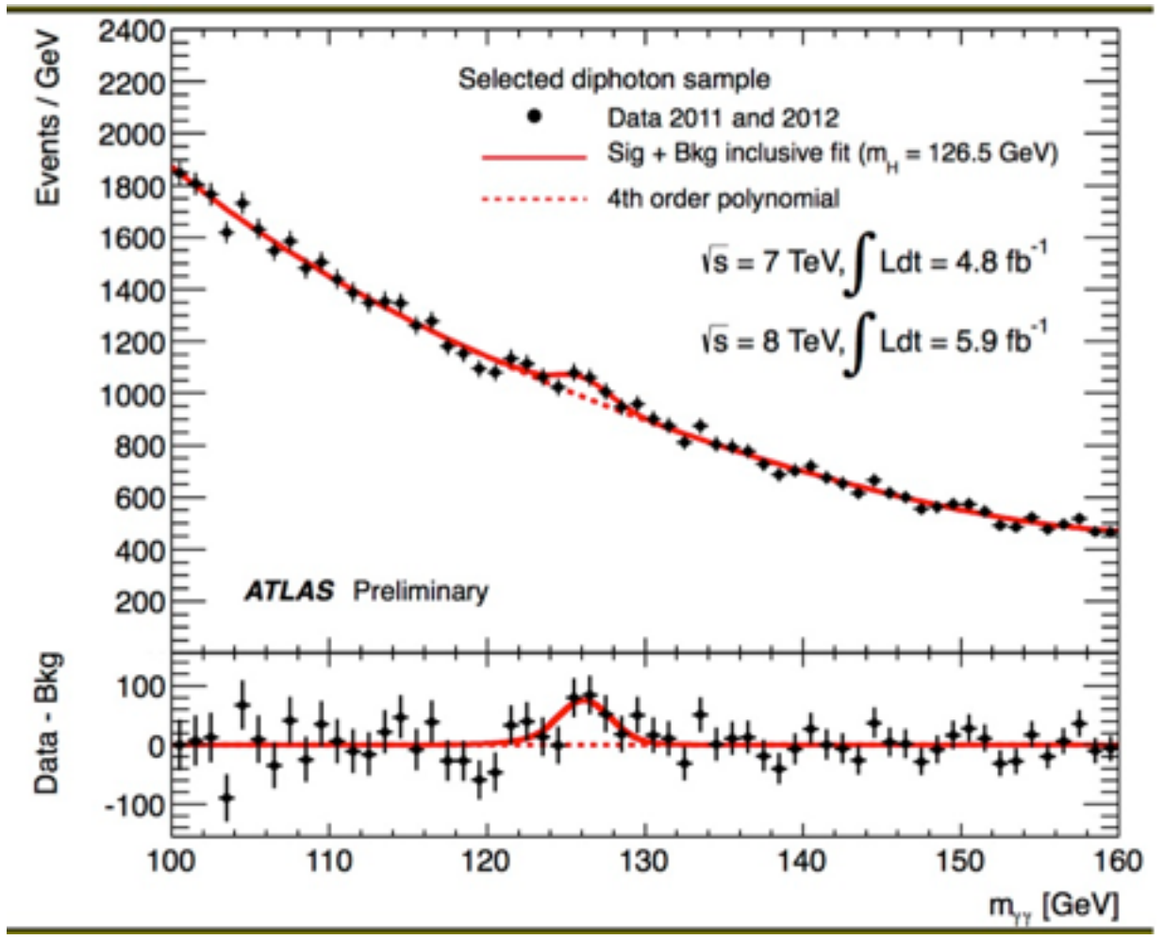
Pedro A N Machado

in collaboration with

B Gavela, K Kanshin, S Saa, S Rigolin

What is this bump?





Is it the SM Higgs?

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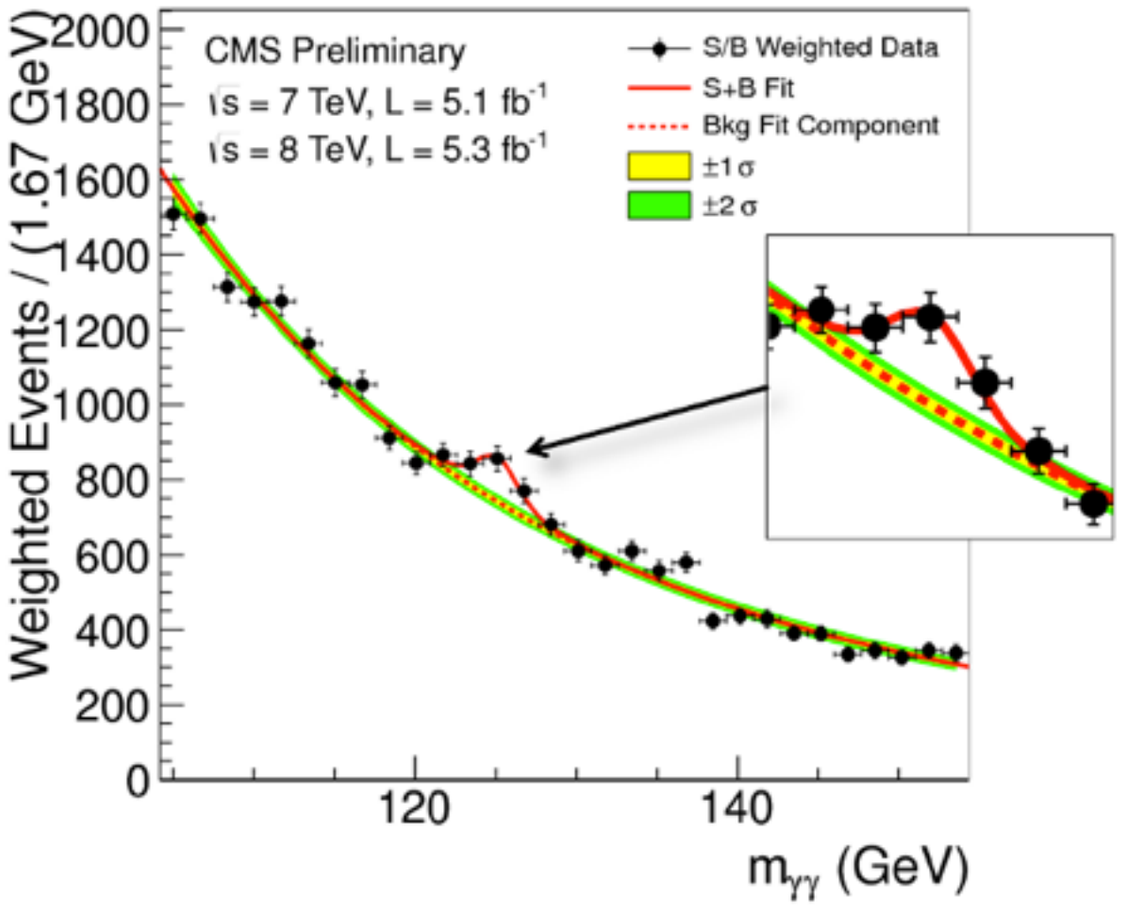

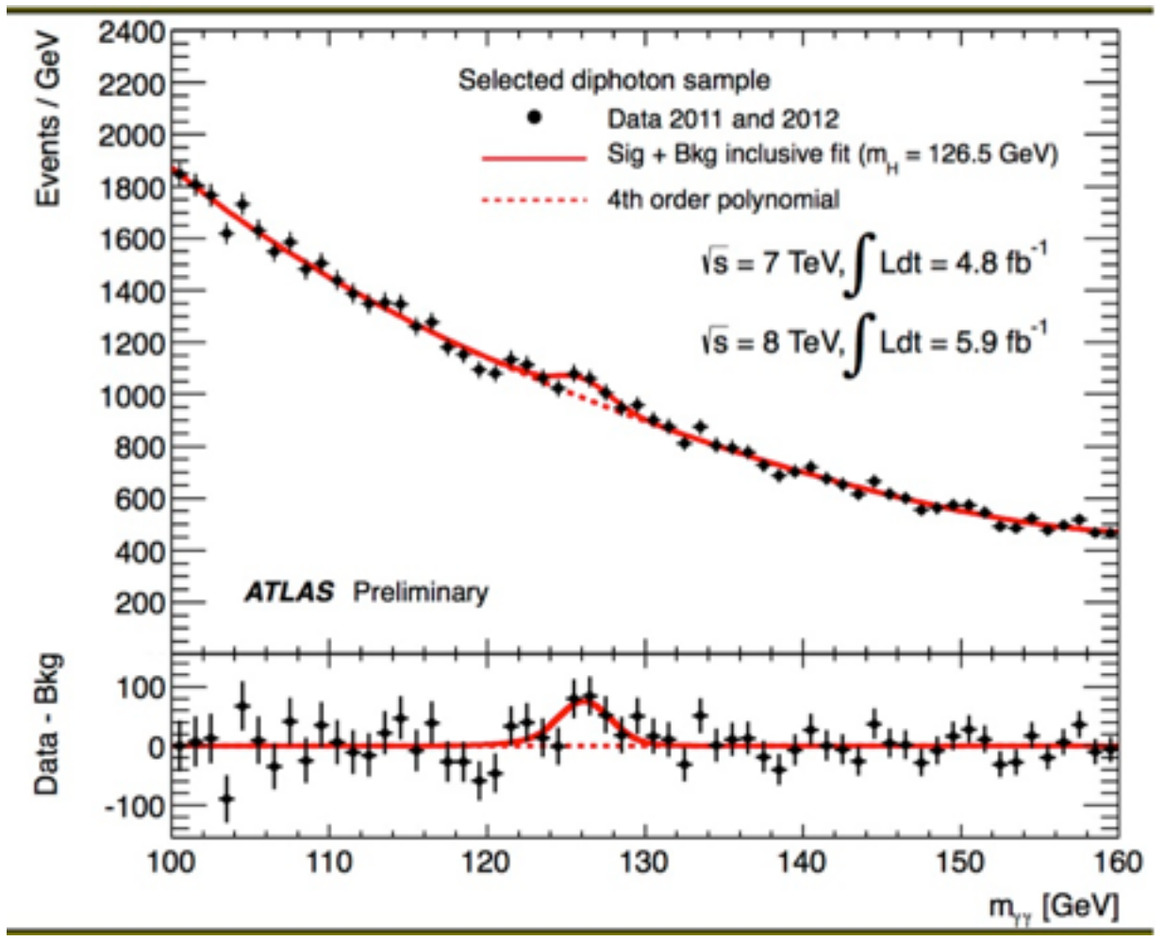

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Is it an elementary particle?

Are the Yukawas fundamental interactions?

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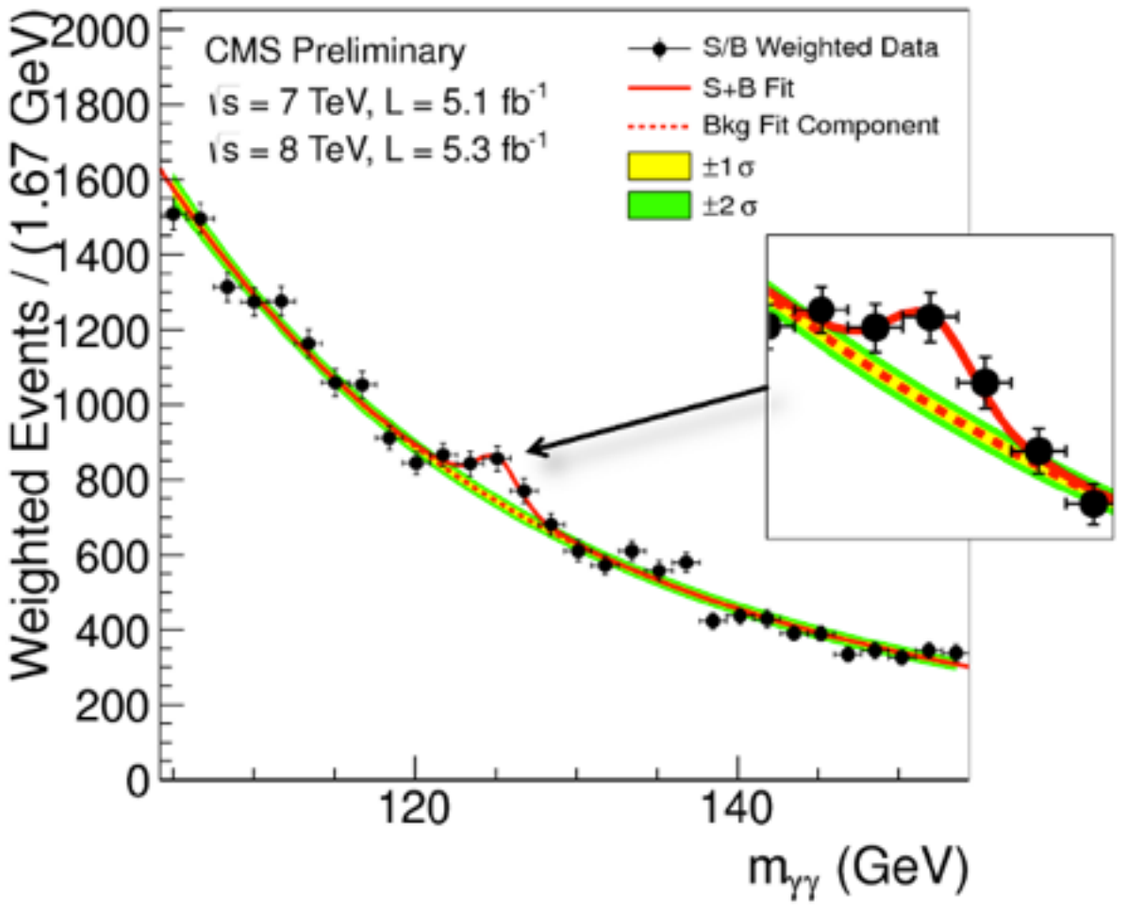

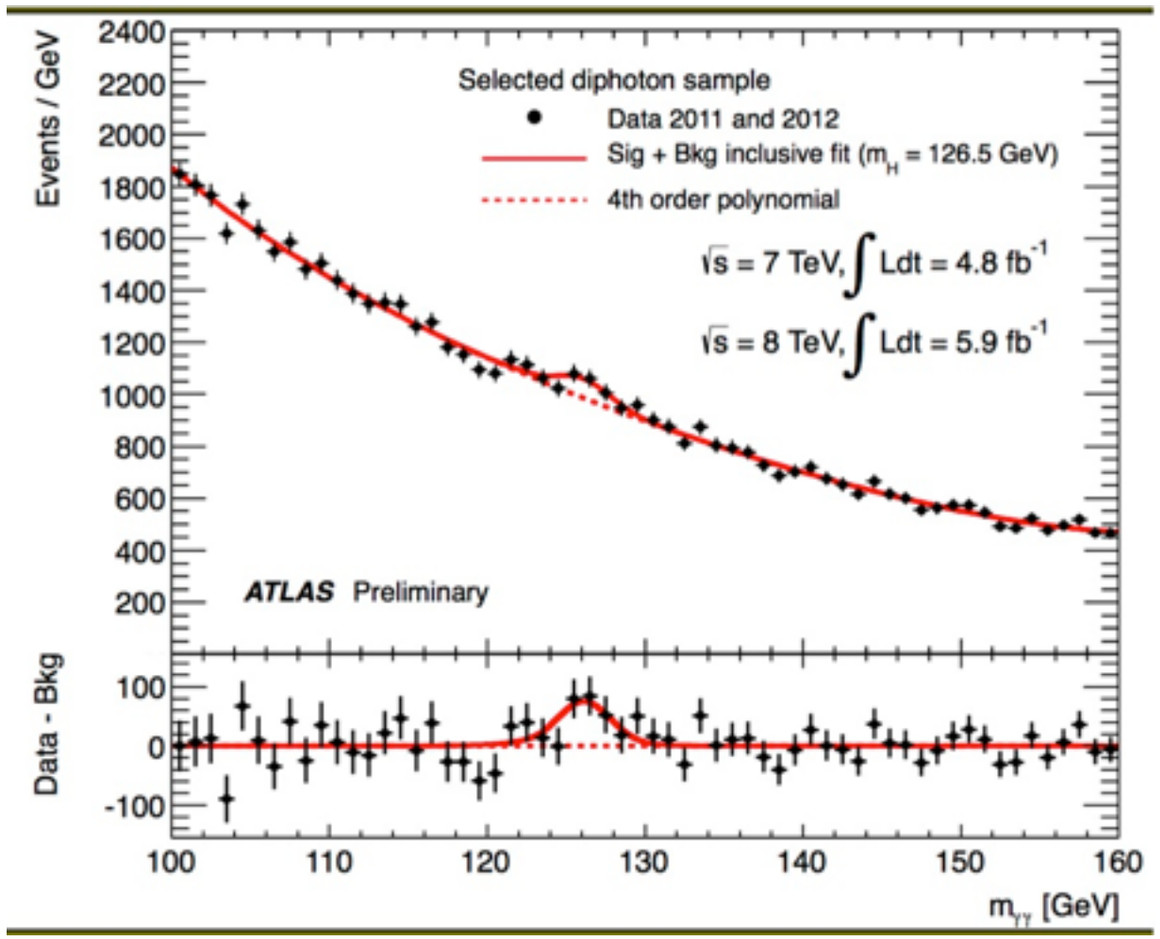

Is it the SM Higgs?

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Are the Yukawas fundamental interactions?

Whatever that is,
how can it be used
to probe/understand
BSM physics?

some problems and puzzles

Hierarchy problem

$$\delta m_H^2 \propto \frac{y^2}{16\pi^2}\Lambda_{UV}^2$$

some problems and puzzles

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New physics at high scale – Fine tuning

Is it a problem? Or is it a puzzle?

some problems and puzzles

Flavour puzzle

How can the same mechanism explain the top and the electron masses?

Moreover, flavour physics generically push up the scale of new physics a lot

some problems and puzzles

Flavour puzzle

How can the same mechanism explain the top and the electron masses?

Moreover, flavour physics generically push up the scale of new physics a lot

Are the Yukawas fundamental fields? Is there a flavour symmetry?

some problems and puzzles

Neutrino masses problem

Neutrinos oscillate, so they have mass

Mimicking the charged fermion sector, the right handed neutrino allows for a Majorana mass, which can lead to a see-saw mechanism

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Neutrino masses problem

Neutrinos oscillate, so they have mass

Mimicking the charged fermion sector, the right handed neutrino allows for a Majorana mass, which can lead to a see-saw mechanism

The origin of neutrino masses and the nature of neutrinos is unknown

some problems and puzzles

The hierarchy puzzle is present for any scalar particle
and it is reflected on its mass, particularly the higgs mass

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Neutrino masses might require new physics at very high scales
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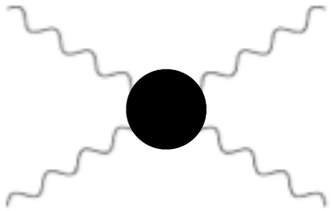
There is something special about scalars...

some problems and puzzles

Why do we need a higgs?

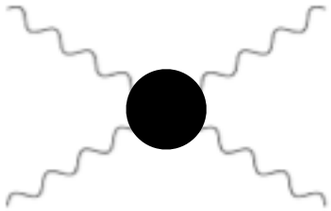


In WW scattering, the longitudinal modes amplitudes grow with energy eventually violating unitarity

The SM higgs contribution moderate this growth in such a way that unitarity is preserved

some problems and puzzles

Why do we need a higgs?



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The SM higgs contribution moderate this growth in such a way that unitarity is preserved

Deviations from the SM higgs may imply loss of unitarity, unless there is new physics to moderate the energy growth

some problems and puzzles

Vacuum stability

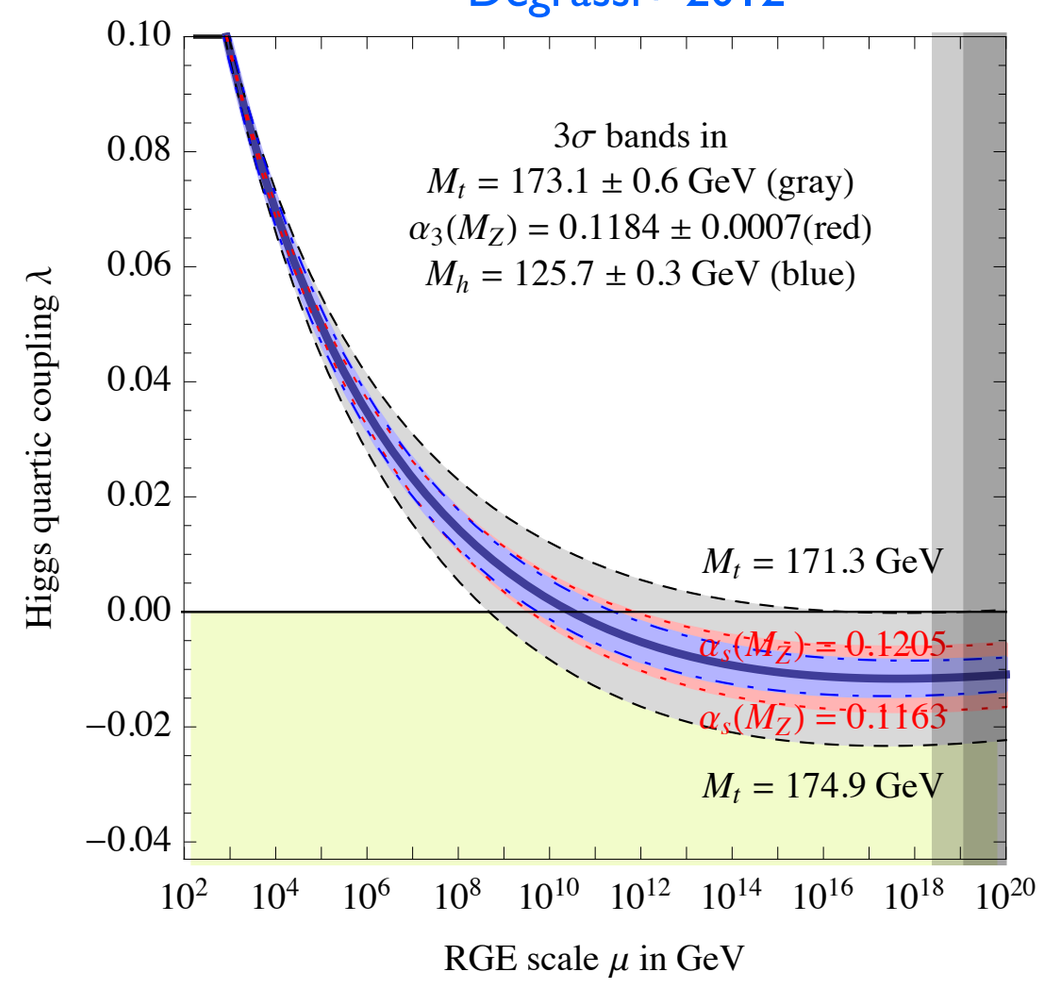
Having a scalar in the theory allows for a scalar potential which gets quantum corrections

In principle we can see up to which point we can extrapolate our theory

Meta-stability region up to the Planck scale

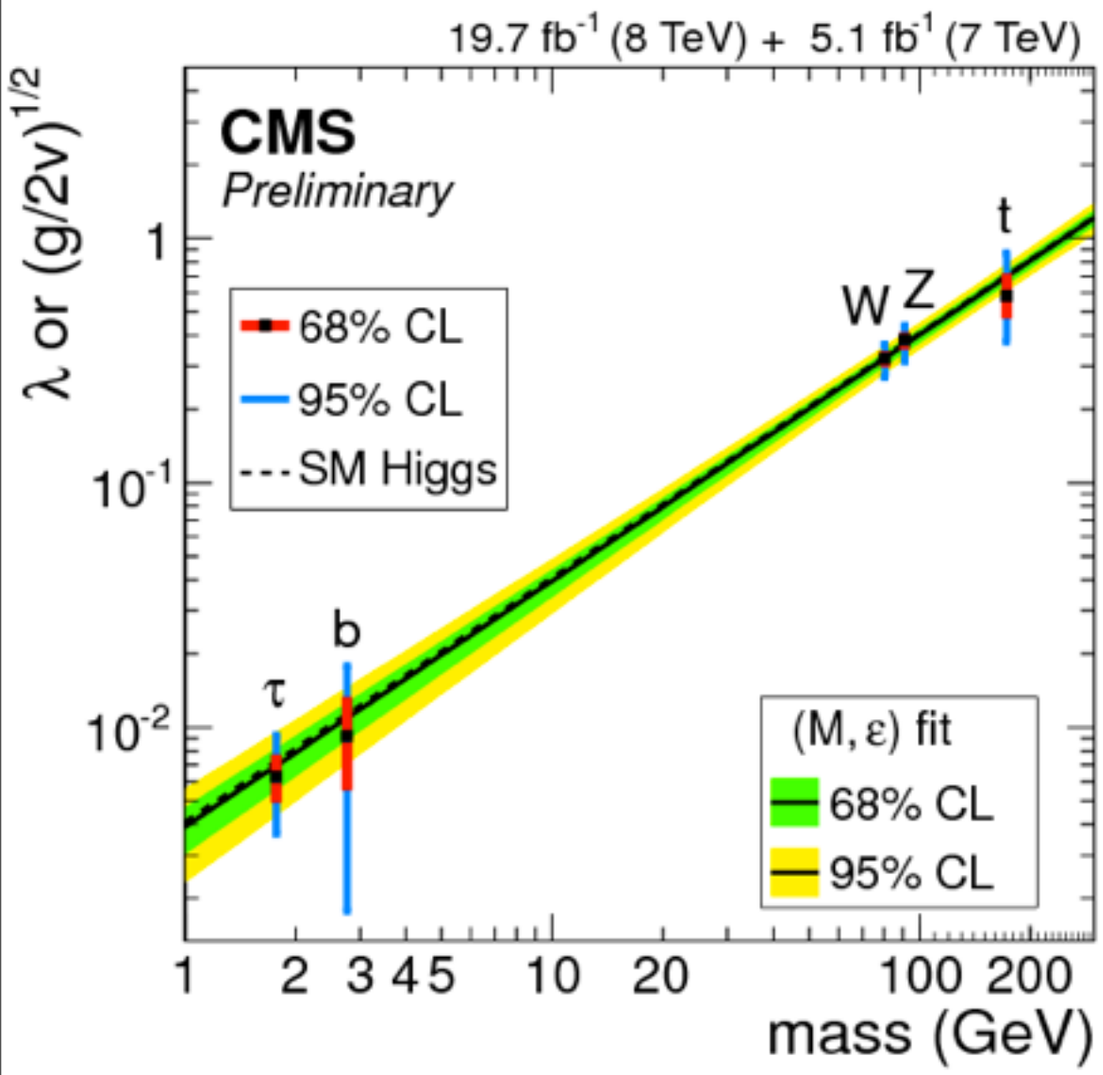
It does not tell much...

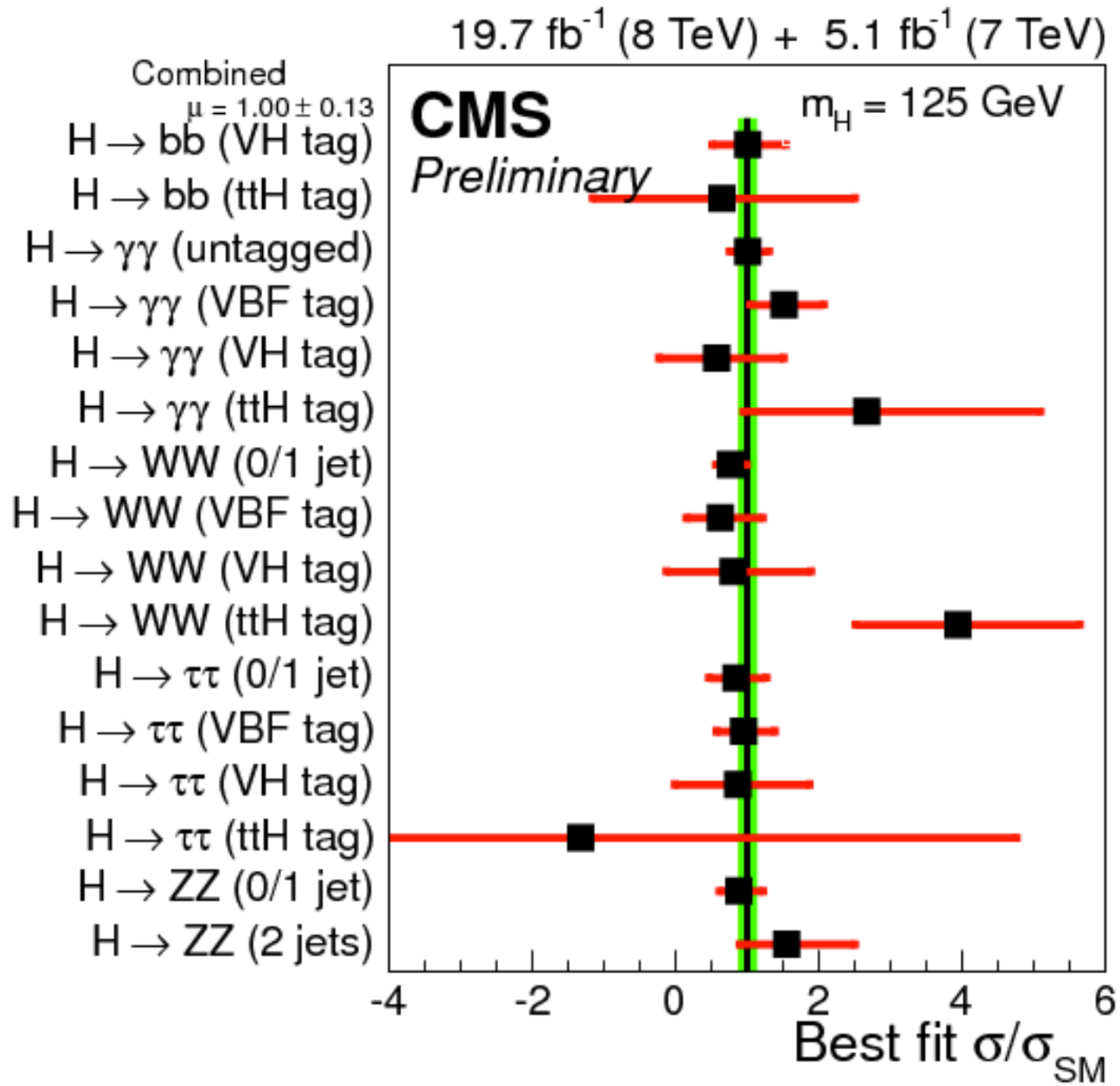
Degrassi+ 2012



Experimental data

Higgs couplings



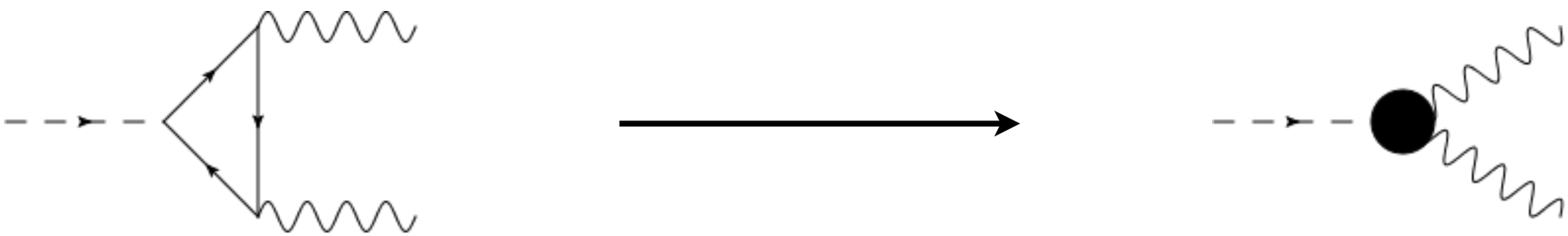


Linear effective field theory

There is a gap between EW and new physics scales

The higgs is the SM one

New physics is supposed to be integrated out



Buchmuller Wyler 1986
Grzadkowski + 2010

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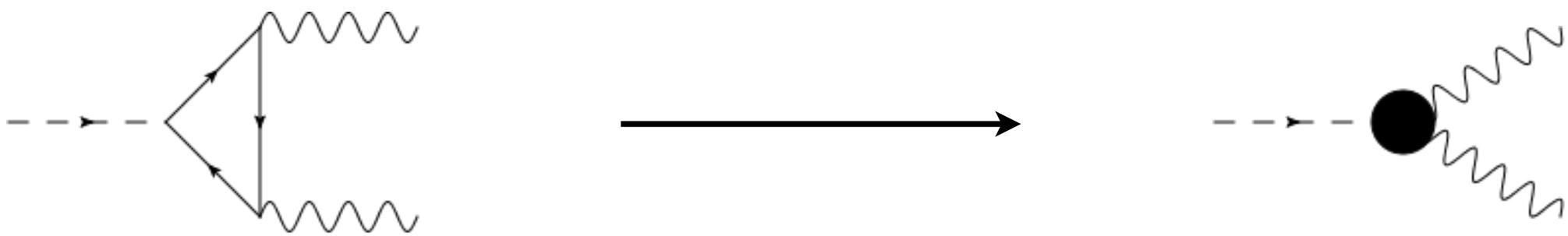

As we do not know which new physics is there, we write all possible operators and suppress them using a <u>dimensional counting</u>

$$\mathcal{L} = L_4 + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \dots$$

Buchmuller Wyler 1986
Grzadkowski + 2010

Linear effective field theory

What is this counting?

The counting reflects which is the expansion we think it makes sense

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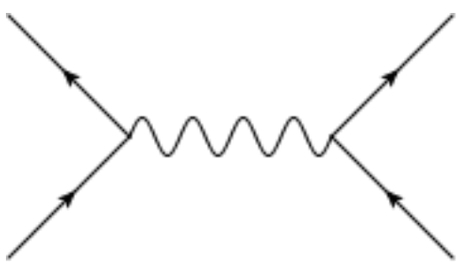
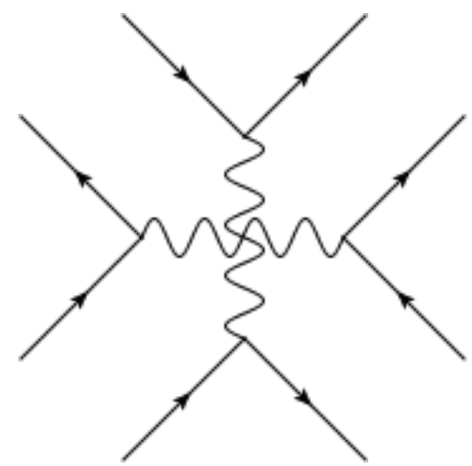


$\psi\psi\psi\psi/\Lambda^2$

>>>



$(8\ \psi s)/\Lambda^8$

But there are other possibilities (low energy QCD, for instance)

Non-linear higgsless theory

We only need 3 degrees of freedom to give mass to W and Z

Non-linear sigma model with f = v

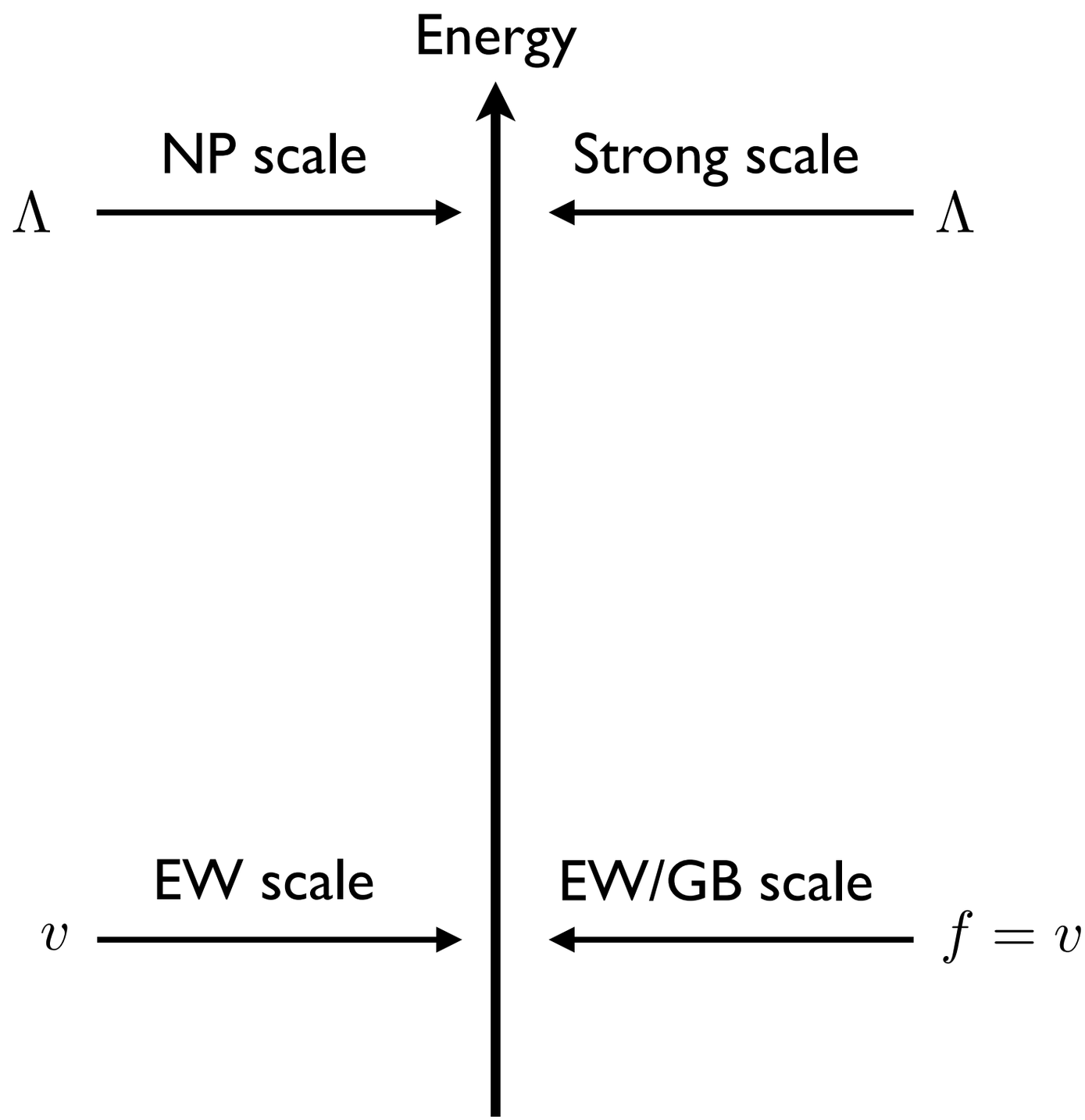
Fermion masses could come from a strong sector condensate

In fact, there is no need to have a doublet – EWSB could be realized non-linearly

Most simple technicolor is severely constrained by EWPT

Weinberg 1979, Susskind 1979,
Dimopoulos Susskind 1979,
Callan Coleman Wess Zumino 1980,
Kaplan Georgi 1984,
Peskin Takeuchi 1990,
Holdom Terning 1990,
Golden Randall 1991

Comparison between linear and non-linear



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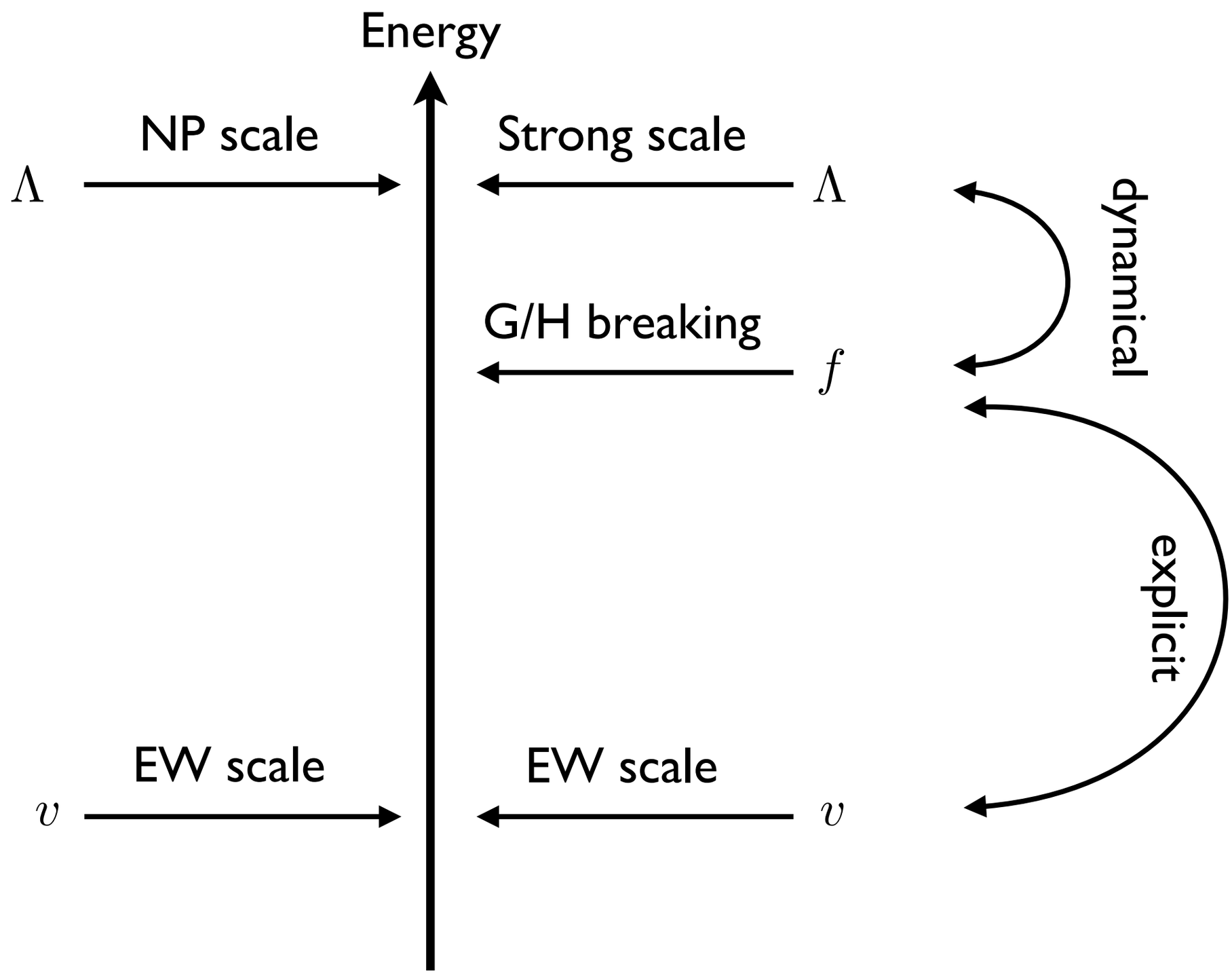

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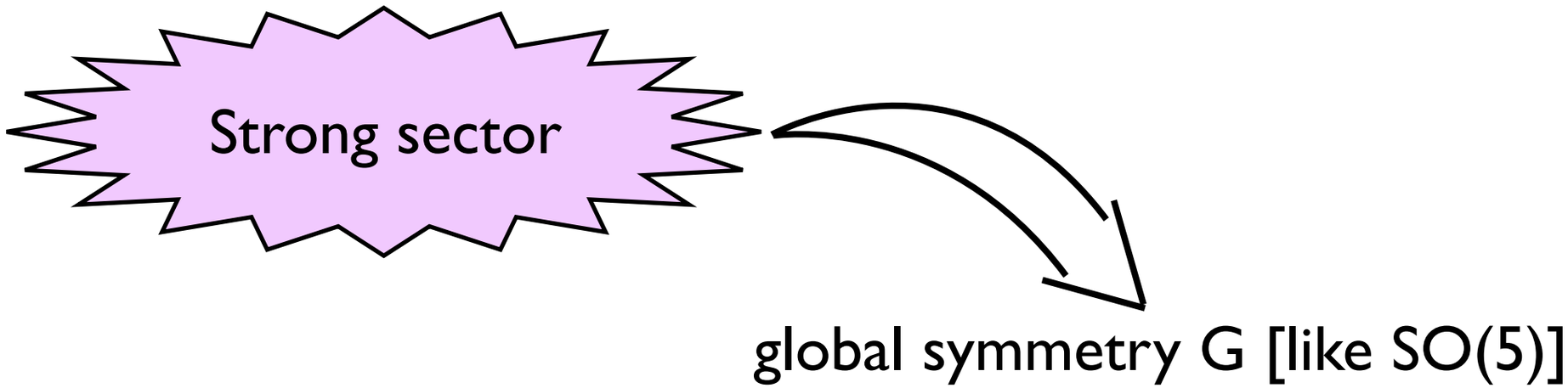
Strong sector

Comparison between linear and non-linear



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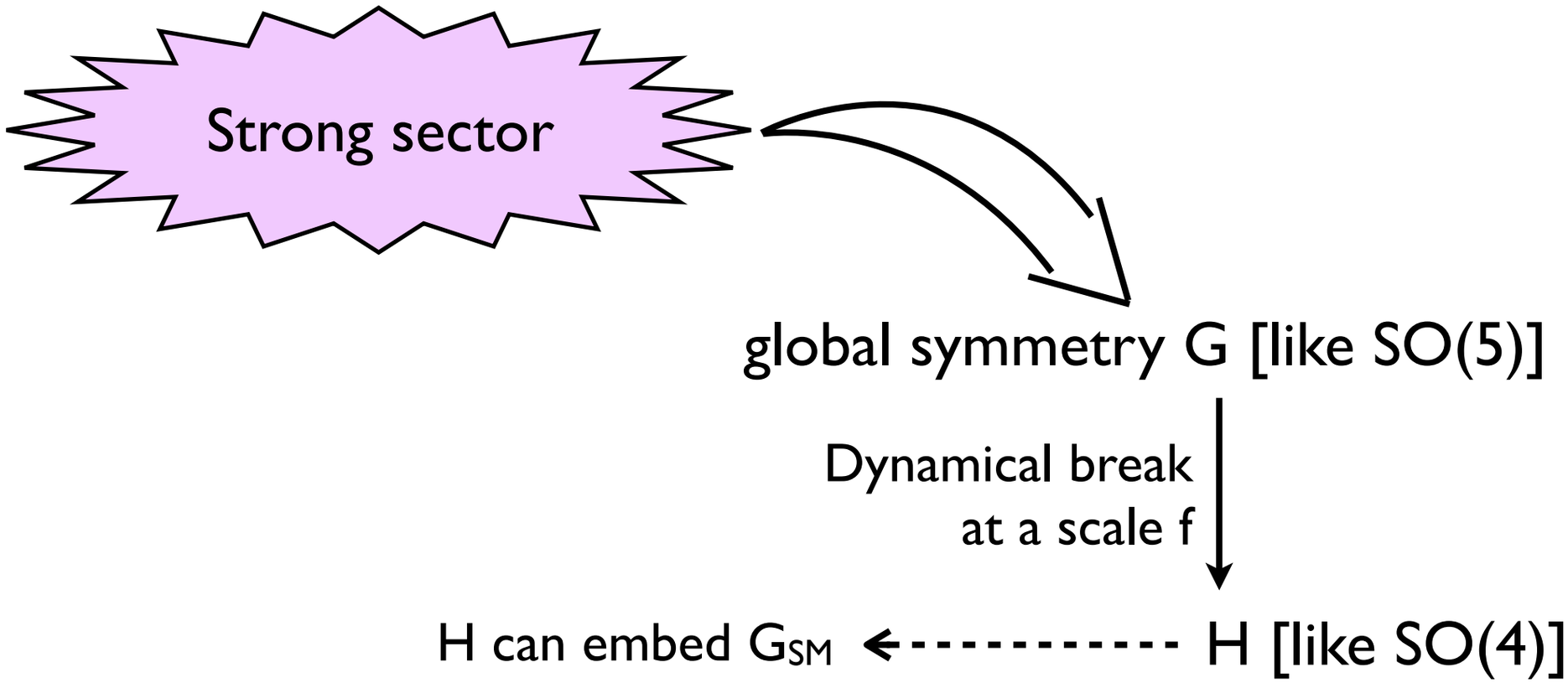

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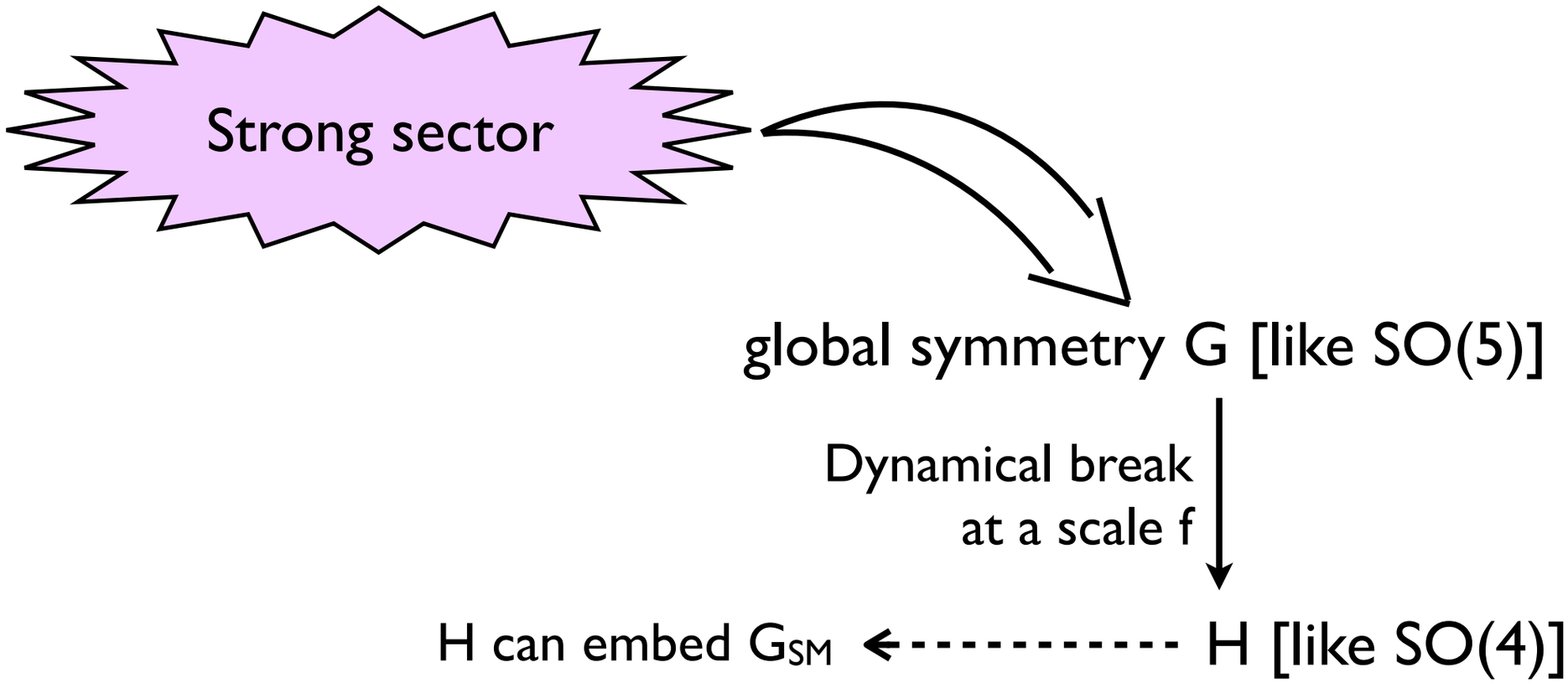
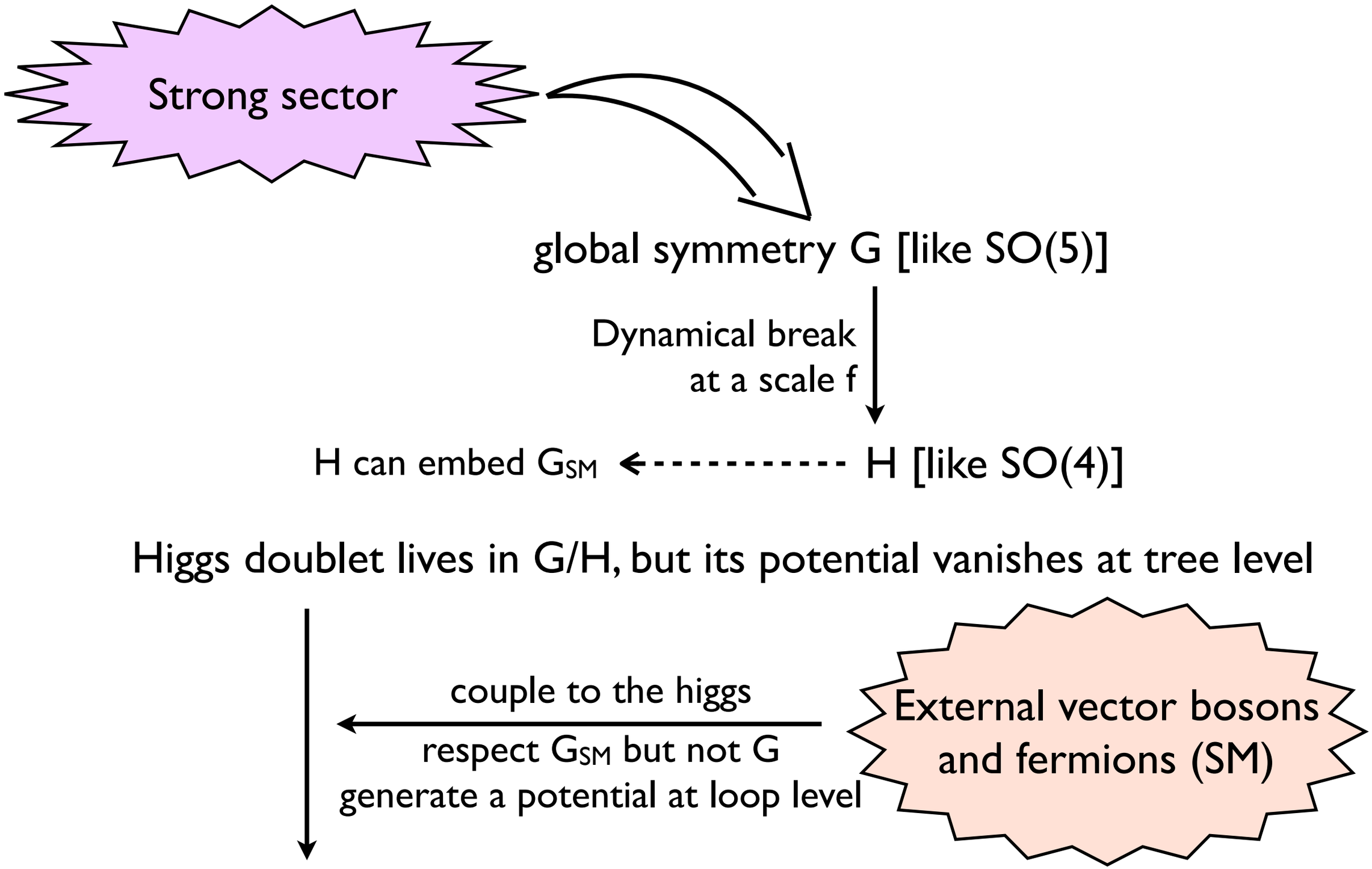


Higgs doublet lives in G/H, but its potential vanishes at tree level

Comparison between linear and non-linear



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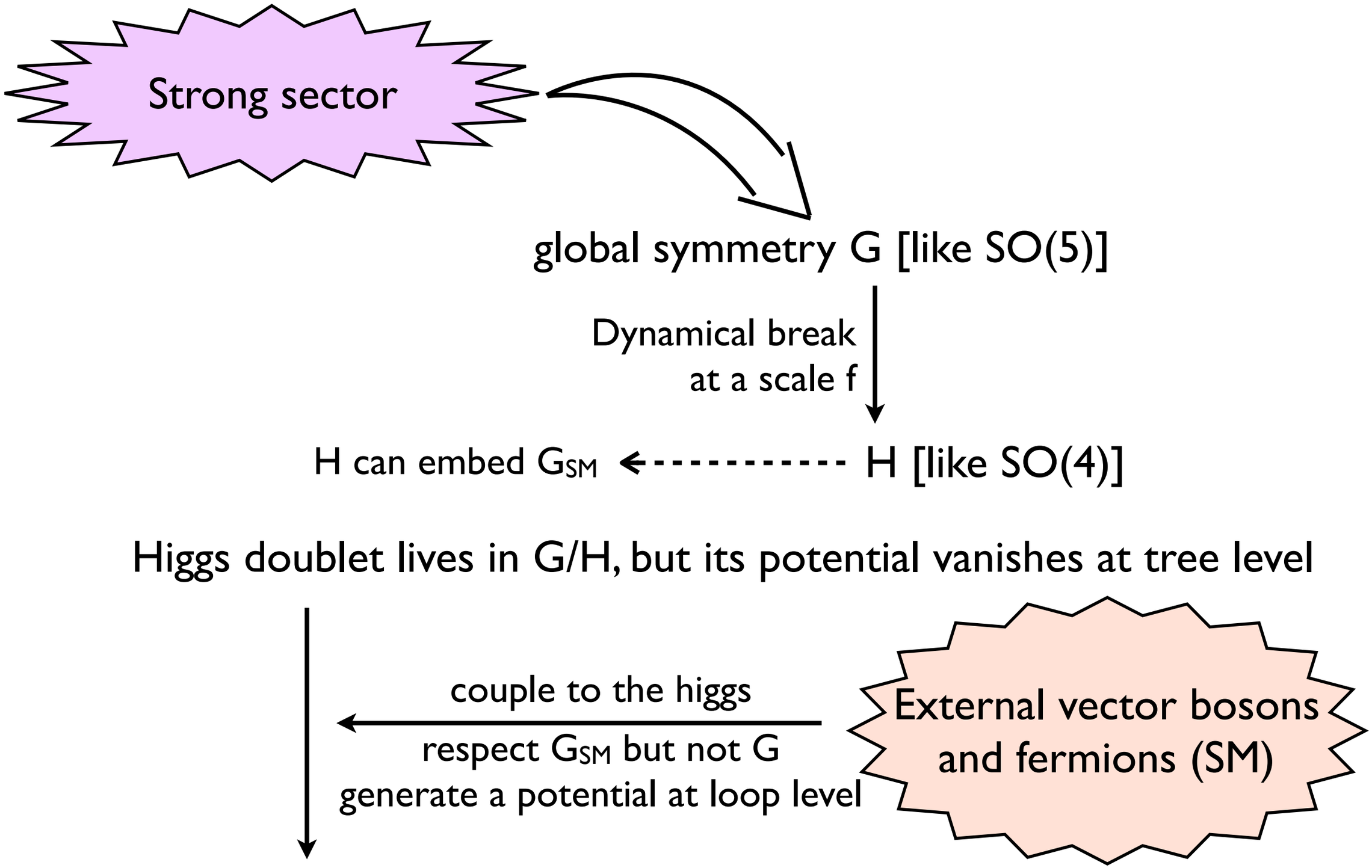

see Contino's TASI lecture 1005.4269 for an introduction

Non-linear higgsless theory

Defining the non-linear theory

$$SU(2)_L \times U(1)_Y$$

$$UU^\dagger = U^\dagger U = 1 \qquad U \to LUR^\dagger$$

$$V_\mu = (D_\mu U)U^\dagger \qquad T = U\tau^3 U^\dagger$$

h is a singlet

Non-linear higgsless theory

$$U = \exp(i\vec{\pi} \cdot \vec{\tau}/f)$$

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$$(2\pi)^4 \delta^4(\Sigma p_i)\left(\frac{\pi}{f}\right)^A \left(\frac{\psi}{f\sqrt{\Lambda}}\right)^B \left(\frac{gG_\mu}{\Lambda}\right)^C \left(\frac{p}{\Lambda}\right)^D f^2\Lambda^2$$

Georgi Manohar 1984

$$f < \Lambda < 4\pi f$$

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Write down all invariant operators, expand in derivatives

Non-linear higgs EFT

$$\mathcal{L}_0 = -V(h)$$

F(h) are polynomial functions of h/v

$$\mathcal{F}_i(h) = 1 + 2a_i h/v + b_i h^2/v^2$$

$$\mathcal{L}_2 = \frac{1}{2}\partial_\mu h \partial^\mu h \; \mathcal{F}_H(h) - \frac{v^2}{4}\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu] \; \mathcal{F}_C(h)$$

$$\vdots$$

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$$\vdots$$

$$(\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2 \, c_6 \mathcal{F}_6(h)$$

$$\mathrm{Tr}[\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu] \frac{\partial^\nu h}{v} c_{10} \mathcal{F}_{10}(h)$$

$$\frac{\Box h \Box h}{v^2} c_{\Box H} \mathcal{F}_{\Box H}(h)$$

$$\vdots$$

Appelquist Bernard PRD 1980
Longhitano PRD 1980
Longhitano NPB 1981
Appelquist Wu PRD 1993
Feruglio IJMP 1993
Alonso et al PLB 2013
Buchala et al NPB 2014

Non-linear higgs EFT

There has been a lot of activity in this field

Full gauge-higgs basis
Alonso et al PLB 2013
Gavela et al 1406.6367

Distinguishing the linear and the non-linear scenarios
Brivio et al JHEP 2014

Full basis including fermions
Buchalla et al NPB 2014

(1-loop) signals at collider
Delgado et al JHEP 2014

Unitarity constraints
Delgado et al 1408.1193
Espriu Mescia PRD 2014
Espriu Mescia Yencho PRD 2013

Effective Lagrangian for generic symmetry cosets
Alonso et al 1409.1589

Why bothering renormalizing it? (Off-shell???)

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Theoretical consistency

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The chiral Lagrangian is renormalizable order by order

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It is long known that the off-shell renormalization of the nonlinear sigma model displays apparent chiral non-invariant divergencies (NID)
It has been shown that the NIDs are unphysical
We would like to do the same for the EW chiral Lagrangian

Charap 1970, Appelquist Bernard 1981, Kazakov+ 1977, Honerkamp 1972, ...

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Future phenomenology

The RGEs may be useful when comparing future higgs data at different energies

see for instance Alonso+ 2013

Renormalization

SETUP

only the h – π sector of the Lagrangian (longitudinal modes of gauge bosons)

g, g' = 0

no custodial breaking terms

renormalization up to 4 legs

<u>General U matrix parametrization</u>

Off-shell amplitudes

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$$\boxed{\mathbf{U} = 1 - \frac{\boldsymbol{\pi}^2}{2v^2} - \left(\eta + \frac{1}{8}\right)\frac{\boldsymbol{\pi}^4}{v^4} + \frac{i\boldsymbol{\tau}\boldsymbol{\pi}}{v}\left(1 + \eta\frac{\boldsymbol{\pi}^2}{v^2}\right) + O(\boldsymbol{\pi}^5)}$$

$$\eta = 0 \;\Rightarrow\; \mathbf{U} = \sqrt{1 - \boldsymbol{\pi}^2/v^2} + i\boldsymbol{\tau}\boldsymbol{\pi}/v$$

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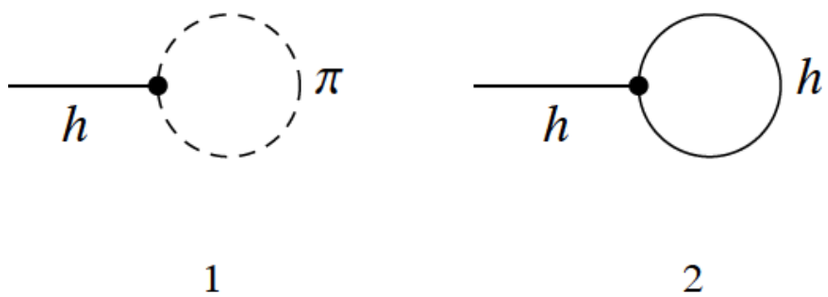
All physical quantities are independent of η

Weinberg 1968

Renormalization

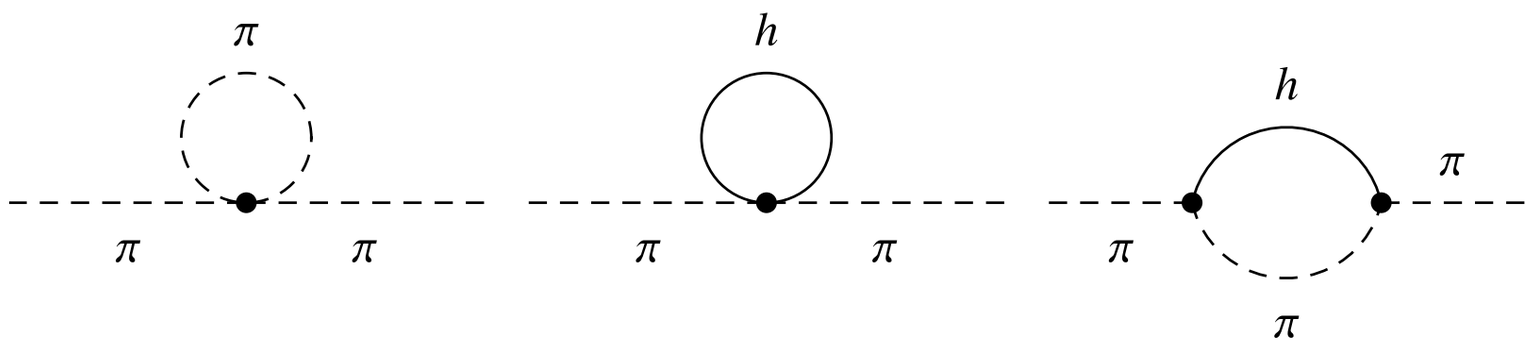
1-point function



Boring... just get a source counterterm to cancel the tadpole

Renormalization

2-point function



$$\Pi^{ij}_{\rm div}(p^2) = \left[p^2 \left(a_C^2 - b_C \right) \frac{m_h^2}{v^2} + p^4 \frac{a_C^2}{v^2} \right] \delta_{ij}$$

$$\Pi^{ij}_{ctr}(p^2) = \left[p^2 \delta_\pi - p^4 \frac{4}{v^2} \left(\delta c_9 - \frac{\delta v^2}{v^2} \right) \right] \delta_{ij}$$

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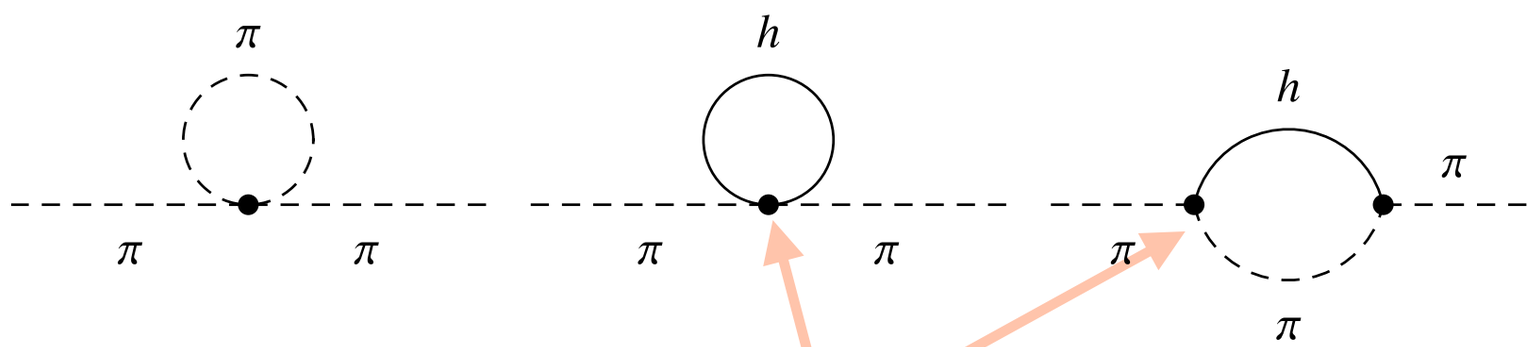

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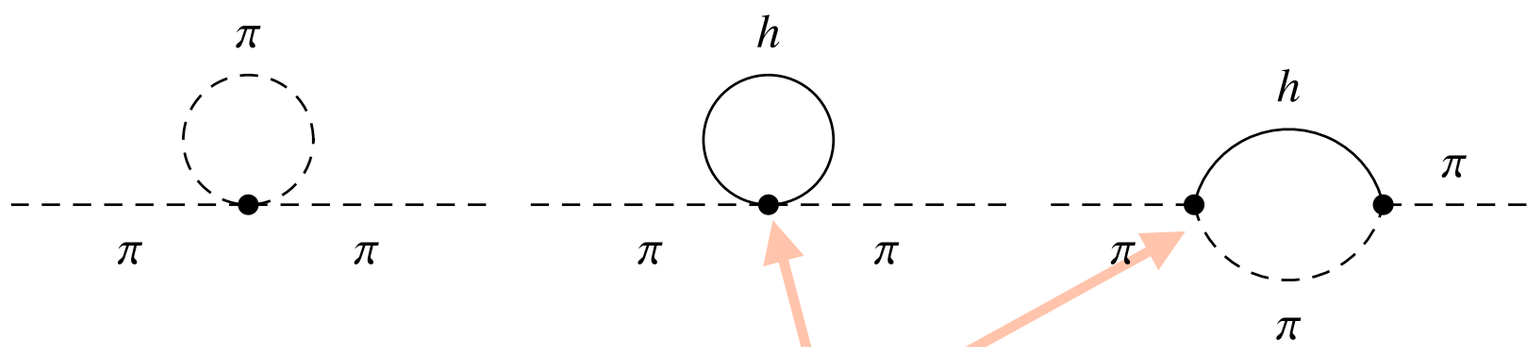

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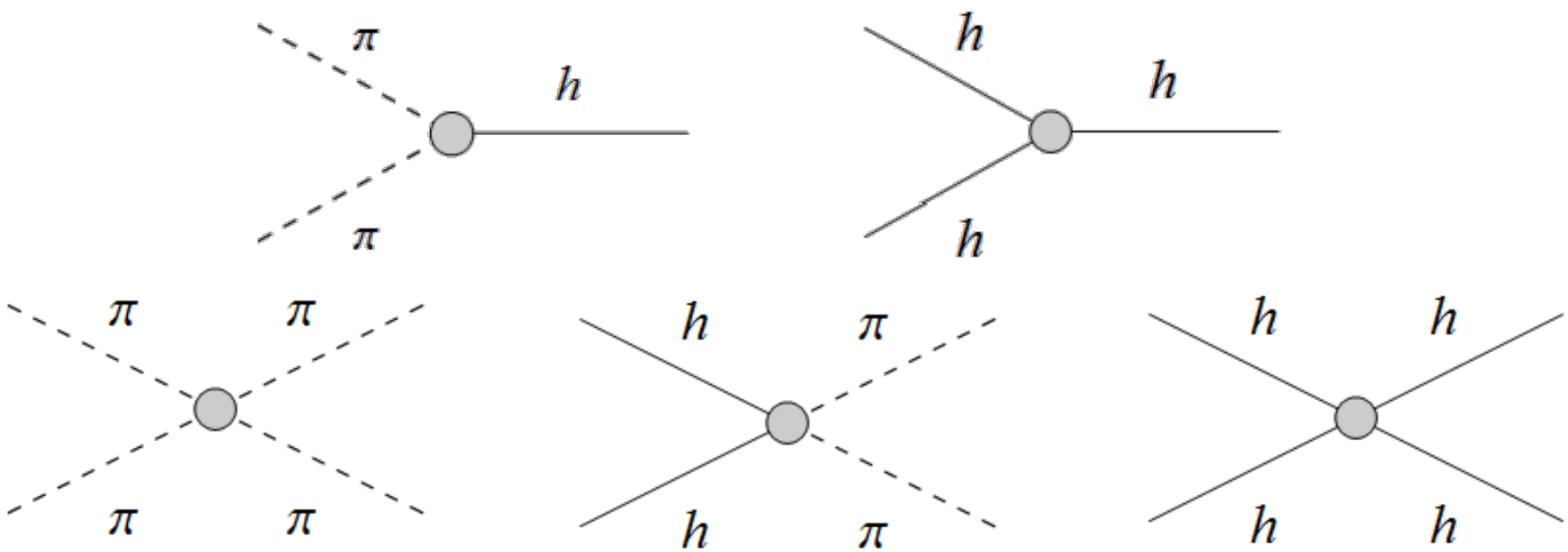
$$\Box\pi\Box\pi$$

Renormalization

3- and 4-point functions



I am not going to write down all formulas, ok?

Renormalization

3- and 4-point functions

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In fact, we get ALL $h - \pi$ invariant operators in L_4

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In fact, we get ALL $h - \pi$ invariant operators in L_4

We agree with Georgi-Manohar NDA

We find explicitly that physical quantities do not depend on η

Renormalization

3- and 4-point functions

Due to the off-shell renormalization, we expect a long list of required operators
In fact, we get ALL $h - \pi$ invariant operators in L_4

We agree with Georgi-Manohar NDA

We find explicitly that physical quantities do not depend on η

There are apparent non-invariant divergencies involving the higgs

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$$-\left(\frac{3}{2}-5\eta\right) a_C \Delta_\varepsilon\, \boldsymbol{\pi}\Box\boldsymbol{\pi}\Box h$$

$$-(2a_C^2-b_C)\left(\frac{3}{2}-5\eta\right)\frac{\Delta_\varepsilon}{v^4}\,\boldsymbol{\pi}\Box\boldsymbol{\pi}\, h\Box h$$

$$-(a_C^2-b_C)\left(\frac{3}{2}-5\eta\right)\frac{\Delta_\varepsilon}{v^4}\,\boldsymbol{\pi}\Box\boldsymbol{\pi}\,\partial_\mu h\partial^\mu h$$

$$+2a_C^2\left(\frac{3}{2}-5\eta\right)\frac{\Delta_\varepsilon}{v^4}\,\boldsymbol{\pi}\partial_\mu\boldsymbol{\pi}\,\partial^\mu h\Box h$$

$$-\left(9\eta^2+5\eta+\frac{3}{4}\right)\frac{\Delta_\varepsilon}{v^4}\,(\boldsymbol{\pi}\Box\boldsymbol{\pi})^2,$$

$$-\left[1+4\eta+\left(\frac{1}{2}+\eta\right)a_C^2\right]\frac{\Delta_\varepsilon}{v^4}\,(\boldsymbol{\pi}\Box\boldsymbol{\pi})(\partial_\mu\boldsymbol{\pi}\partial^\mu\boldsymbol{\pi}),$$

$$-2\eta^2\frac{\Delta_\varepsilon}{v^4}\,\boldsymbol{\pi}^2(\Box\boldsymbol{\pi})^2,$$

$$-2\eta\left(a_C^2-1\right)\frac{\Delta_\varepsilon}{v^4}\,(\Box\boldsymbol{\pi}\partial_\mu\boldsymbol{\pi})(\boldsymbol{\pi}\partial^\mu\boldsymbol{\pi}).$$

These terms do not respect chiral invariance!!! How do we deal with it?

Dealing with the non-invariant divergencies

There are many methods to deal with the NIDs

Proper quantization using the Hamiltonian formalist
which yields non-covariant Feynman rules

Gerstein Jackiw Weinberg Lee 1971

Modified background field method

Honerkamp 1972
Kazakov Pervushin Pushkin 1976

Field redefinition

Appelquist Bernard 1981

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Hence, if we redefine the π field

$$\pi \to \pi f(\pi, \partial_\mu \pi, h, \partial_\mu h, \dots), \quad f(0) = 1$$

in such a way that

$$\mathcal{L}(\pi, \partial_\mu \pi, h, \partial_\mu h) \to \mathcal{L}(\pi, \partial_\mu \pi, h, \partial_\mu h) + \Delta\mathcal{L}$$

the ΔL term in the Lagrangian is not physical

Dealing with the non-invariant divergencies

With this redefinition

$$\pi_i \to \pi_i \left(1 + \frac{\alpha_1}{2v^4}\boldsymbol{\pi}\Box\boldsymbol{\pi} + \frac{\alpha_2}{2v^4}\partial_\mu\boldsymbol{\pi}\partial^\mu\boldsymbol{\pi} + \frac{\beta}{2v^3}\Box h + \frac{\gamma_1}{2v^4}h\Box h + \frac{\gamma_2}{2v^4}\partial_\mu h\partial^\mu h\right)$$
$$+ \frac{\alpha_3}{2v^4}\Box\pi_i(\boldsymbol{\pi}\boldsymbol{\pi}) + \frac{\alpha_4}{2v^4}\partial_\mu\pi_i(\boldsymbol{\pi}\partial^\mu\boldsymbol{\pi})$$

we can absorb all NIDs

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With this redefinition

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$$+ \frac{\alpha_3}{2v^4}\Box\pi_i(\boldsymbol{\pi}\boldsymbol{\pi}) + \frac{\alpha_4}{2v^4}\partial_\mu\pi_i(\boldsymbol{\pi}\partial^\mu\boldsymbol{\pi})$$

we can absorb all NIDs

Therefore, chiral symmetry is never broken:
the non-invariant terms are actually "zero" (inside a path integral)

This should be equivalent to use the equations of motion
(but a bit more elegant, in my opinion)

RGEs

$$16\pi^2 \frac{d}{d\ln\mu}\lambda = \lambda\left[26 a_H \frac{\mu_3}{v} + \left(14 b_H - 82 a_H^2\right)\frac{m_h^2}{v^2}\right] - \frac{3}{2}\lambda^2 + 12\left(b_H - 6a_H^2\right)\frac{\mu_3^2}{v^2}$$
$$+ 48 a_H\left(8a_H^2 - 3b_H\right)\mu_3\frac{m_h^2}{v^3} - 6\left(80a_H^4 - 48 b_H a_H^2 + 3b_H^2\right)\frac{m_h^4}{v^4}\,.$$

$$16\pi^2 \frac{d}{d\ln\mu} b_H = b_H\left[20 a_H \frac{\mu_3}{v} - \frac{3}{2}\lambda + \left(-a_C^2 + b_C - 87 a_H^2\right)\frac{m_h^2}{v^2}\right]$$
$$- 42\frac{\mu_3}{v}a_H^3 + \frac{13}{2}\lambda a_H^2 + \left(7b_H^2 + 120 a_H^4\right)\frac{m_h^2}{v^2}\,.$$

$$16\pi^2 \frac{d}{d\ln\mu} c_6 = -\frac{1}{24}\left[2 + 2a_C^4 + 3b_C^2 - a_C^2\left(-8 + 6b_C\right)\right]$$

Although in the SM limit the RGEs for BSM operators do not vanish,
BSM contributions cancel when calculating physical quantities!

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Off-shell one loop renormalization of the h – π non-linear Lagrangian

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Thanks!