DETERMINING THE PHYSICAL IMPACT OF OPERATORS IN EFFECTIVE FIELD THEORIES

Luca Merlo

based on:
B. Gavela, E. Jenkins, A. Manohar & LM,
Analysis of General Power Counting Rules in Effective Field Theory,
arXiv: 1601.07551

Invisibles' Webinar, February 23rd, 2016

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Milan, 21st of August 2021

Motivations: which rule?

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Physica 96A (1979) 327–340 © North-Holland Publishing Co.

PHENOMENOLOGICAL LAGRANGIANS*

STEVEN WEINBERG

Motivations: which rule?

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Nuclear Physics B234 (1984) 189–212
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CHIRAL QUARKS AND THE NON-RELATIVISTIC QUARK MODEL*

Aneesh MANOHAR and Howard GEORGI

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Physics Letters B 726 (2013) 697–702

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Naive dimensional analysis counting of gauge theory amplitudes and anomalous dimensions

Elizabeth E. Jenkins [a], Aneesh V. Manohar [a], Michael Trott [b,*]

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On the power counting in effective field theories

Gerhard Buchalla [a,*], Oscar Catà [a,b,c], Claudius Krause [a]

Motivations: predictions in HEFT

SMEFT: constructed with

$$\Phi(x) = \frac{v+h}{\sqrt{2}} e^{i\sigma_a \pi^a(x)/v} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

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Higgs: h

Singlet

GBs: $\mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v}$

$\mathbf{U}(x) \to L\, \mathbf{U}(x) R^\dagger$

Independent!!

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- Being h a singlet: generic functions of h $\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \ldots$

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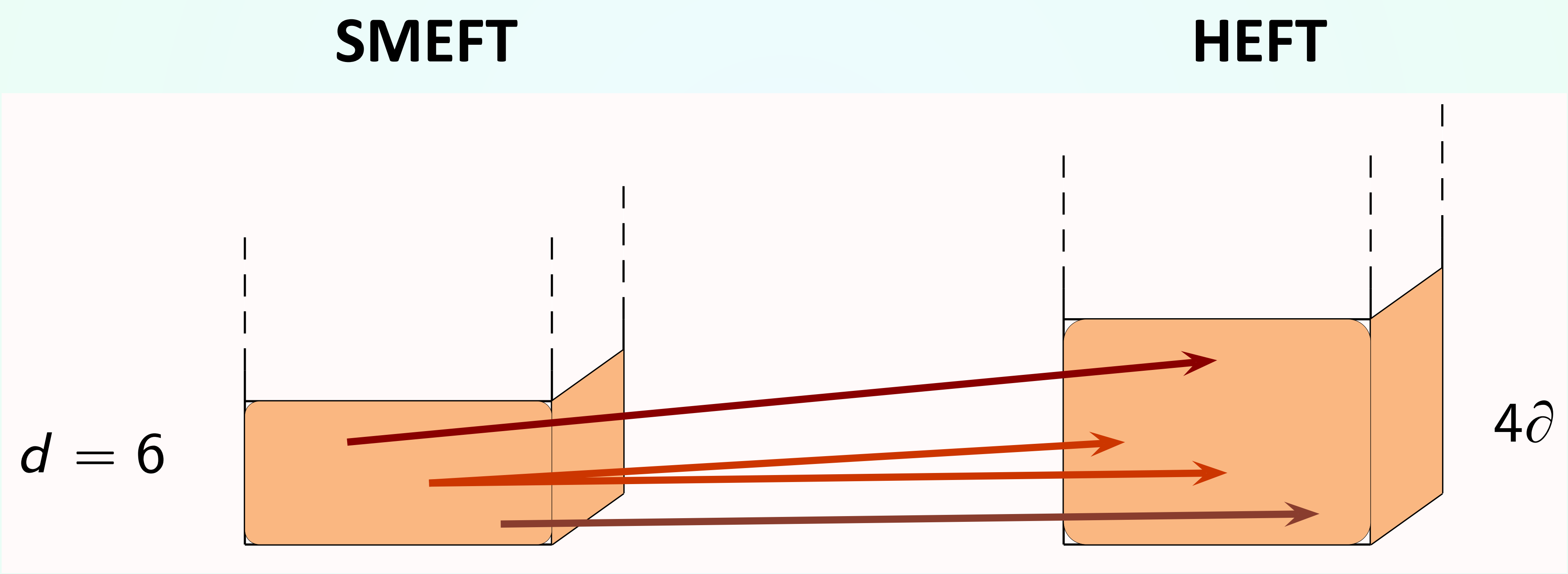
Independent!!

- Being h a singlet: generic functions of h $\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \ldots$
- Being $\mathbf{U}(x)$ **vs.** h independent, many more operators can be constructed

Decorrelations

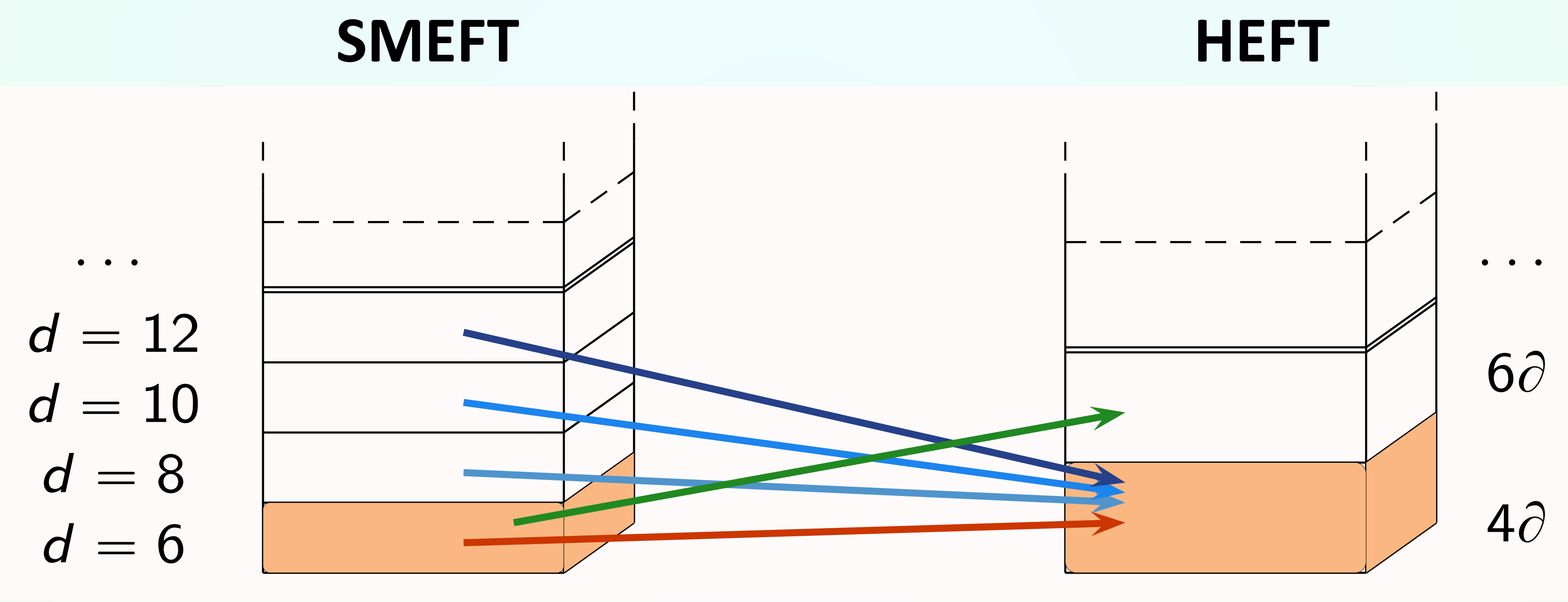
- Investigate on the signals of decorrelations: due to the nature of the chiral expansion vs. the linear one, and due to $\mathcal{F}_i(h) \neq \left(1+\frac{h}{v}\right)^2$



Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014)
Brivio,Eboli,Gavela,Gonzalez-Garcia,LM&Rigolin, JHEP 1412 (2014)
Brivio,Gavela,LM,Mimasu,No,Rey&Sanz, arXiv:1511.0109

New Signals

- Study the anomalous signal present in the chiral description, but absent in the linear one



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Content

- Why and how EFTs
- The master formulas for operator counting and cross sections
- SMEFT
- χPT
- HEFT

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Why to use an EFT?

It is convenient

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The observables considered are measured in a determined energy range

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Only on relevant contributions at that energy
Calculations are easier
Benefits in the renormalisation procedure
Accidental (approximate) symmetries

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<u>Top-down approach</u> from the full theory to the EFT: i.e.

- EFT applied to B physics;
- QCD chiral perturbation theory for pions;
- etc...

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Use of the known particles and known interactions to infer the symmetries and the nature of the full theory.

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Use of the known particles and known interactions to infer the symmetries and the nature of the full theory.

Bottom-up approach from the EFT to the full theory (with some luck): i.e.

- Fermi theory;
- Higgs effective theories;
- etc…

How to construct an EFT?

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Spectrum ✚ **Symmetries**

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Construct ALL possible operators with the fields of the given spectrum and invariant under the chosen symmetries.

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Construct ALL possible operators with the fields of the given spectrum and invariant under the chosen symmetries.

✚ **Power counting**

↓

Reduces the number of operators at each order of the expansion(s), organises the hierarchy among the operators, sets the validity of the EFT.

How to construct an EFT?

Spectrum + **Symmetries** + **Power counting**

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$\downarrow$

Easy: all the particles lighter than a reference energy scale Λ

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DEPENDS ON THE DATA CONSIDERED

How to construct an EFT?

Spectrum + **Symmetries** + **Power counting**

<u>Easy</u>: all the particles lighter than a reference energy scale Λ

<u>Hard</u>: based on some rigorous method but with some freedom.

<u>Medium</u>: convenience vs. necessity

EFT for B physics: the residual symmetry after integrating out Z and W is QCDxEM

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DEPENDS ON THE DATA CONSIDERED

Basics

Independently of the specific spectrum or symmetries, let's identify common aspects of the fundamental building blocks in EFTs.

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<u>Canonical mass dimensions in 4 space-time dimensions:</u>

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$$\left.\begin{array}{l} D_\mu \equiv \partial_\mu + gA_\mu \\ X_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu, A_\nu] \end{array}\right\} \longrightarrow \begin{array}{l} [A] = 1 \\ [g] = 0 \end{array}$$

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not the end of the story!!

- A generic interaction vertex i constructed out of the building blocks has the form

$$\partial^{N_{p,i}}\phi^{N_{\phi,i}}A^{N_{A,i}}\psi^{N_{\psi,i}}\Lambda^{N_{\Lambda,i}}g^{N_{g,i}}y^{N_{y,i}}\lambda^{N_{\lambda,i}}(4\pi)^{N_{4\pi,i}}$$

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The $N_{a,i}$ are NOT independent, but they should give $d=4$:

$$\longrightarrow \quad 4 = N_{p,i} + N_{\phi,i} + N_{A,i} + \frac{3}{2} N_{\psi,i} + N_{\Lambda,i}$$

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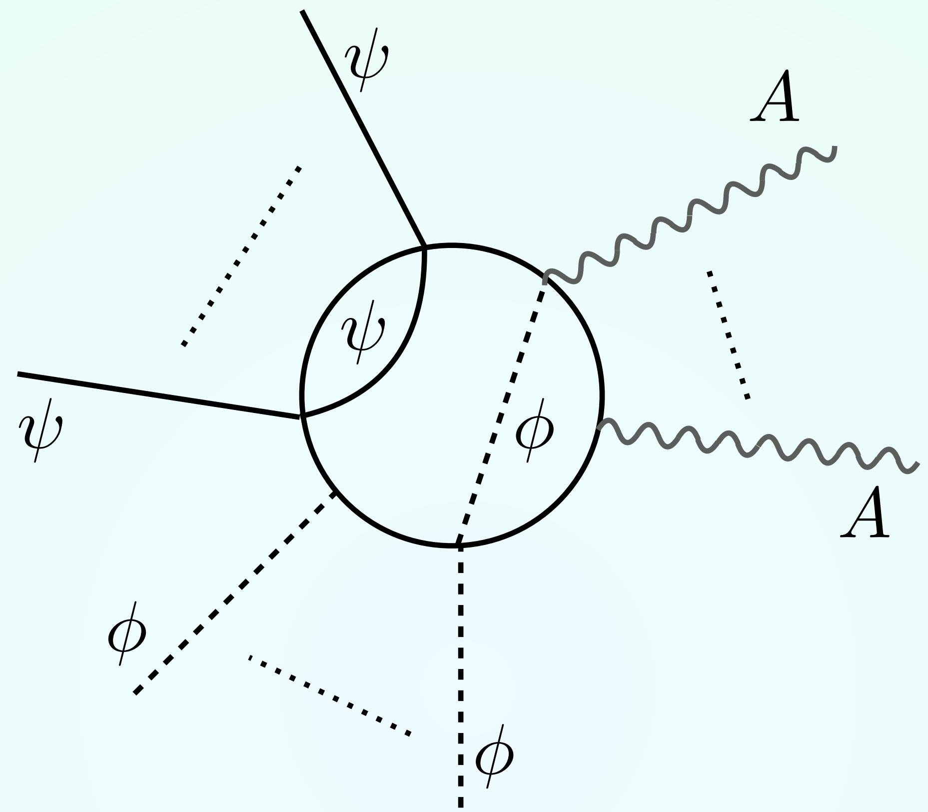
$$(\bar\psi\psi)^2 \longrightarrow \begin{cases} N_\psi = 4 \\ N_p = 0 = N_\phi = N_A \end{cases} \longrightarrow N_\Lambda = -2 \longrightarrow \frac{(\bar\psi\psi)^2}{\Lambda^2}$$

- An arbitrary connected diagram with insertions of the generic vertex will have an amplitude of the same form of the vertex but the N_a undergo some conditions



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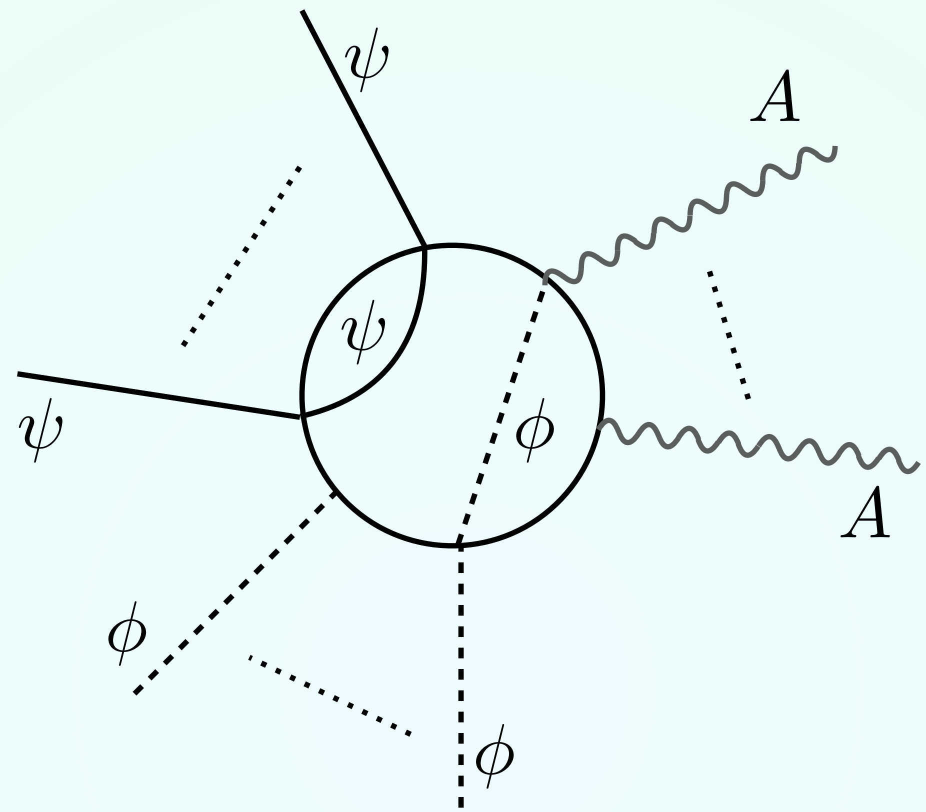

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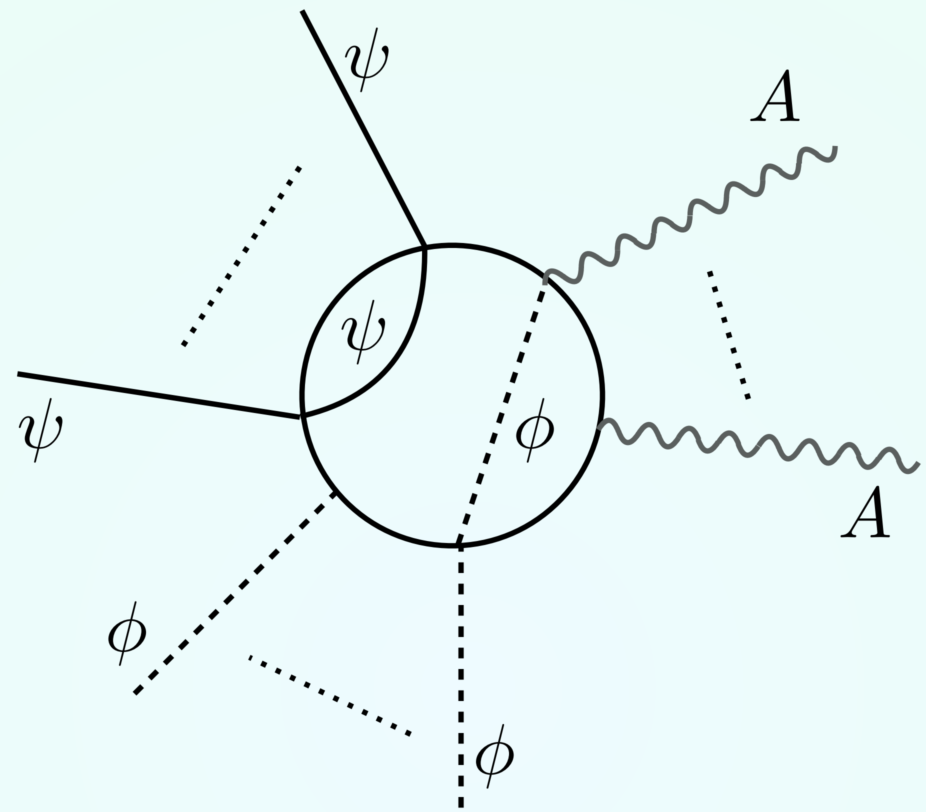

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depend on external and <u>internal legs</u>

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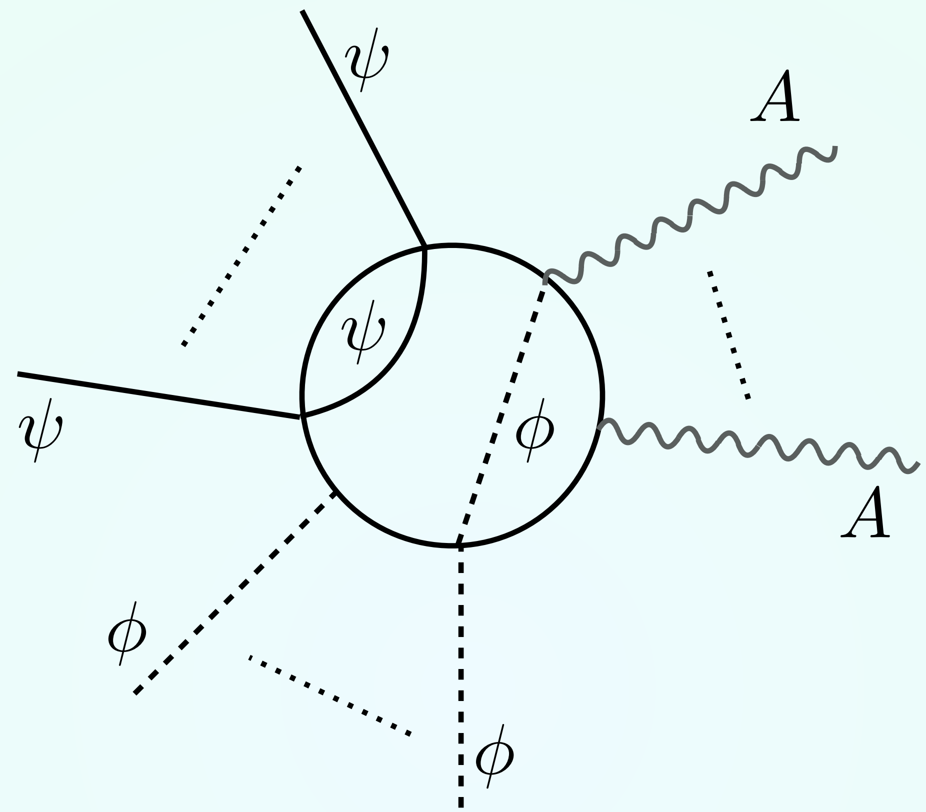

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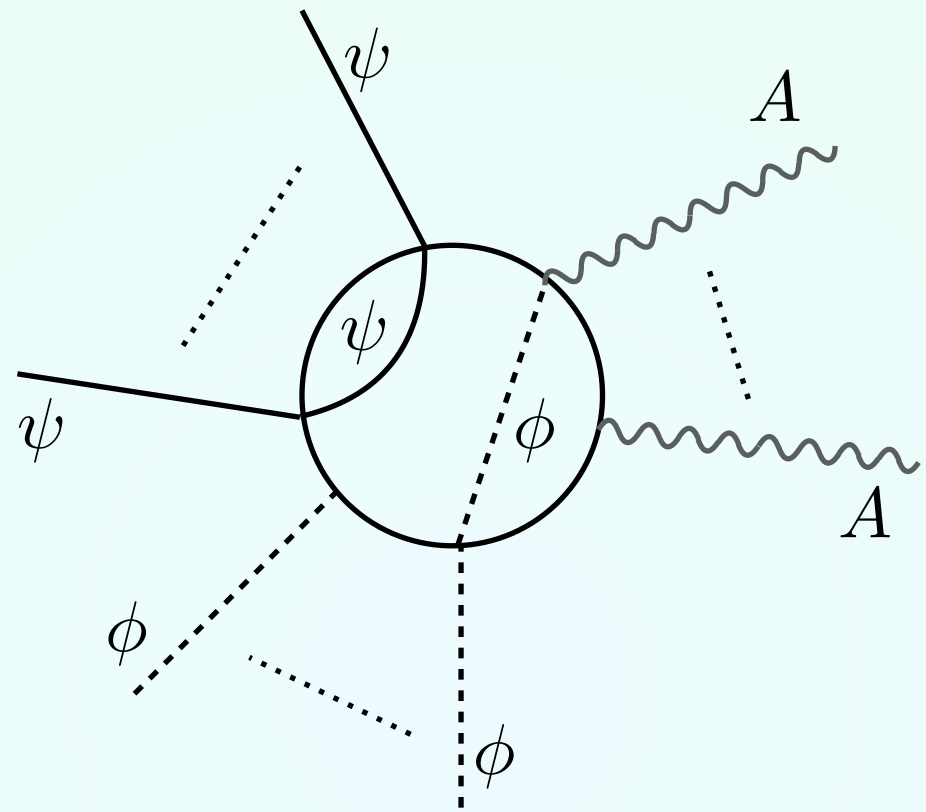

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depends on the "external" 4π and on the number of loops

$$N_{4\pi} = \sum_i N_{4\pi,i} - 2L$$

When we have an operator, only the **external** legs, and not the internal, are relevant!

→ Eliminate the dependence from the internal legs

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$$4 = N_{p,i} + N_{\phi,i} + N_{A,i} + \frac{3}{2}N_{\psi,i} + N_{\Lambda,i}$$

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→ Eliminate the dependence from the internal legs

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only 6 relations are independent

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$$N_{\chi,i} \equiv N_{p,i} + \frac{1}{2}N_{\psi,i}$$

$$N_\chi \equiv N_p + \frac{1}{2}N_\psi$$

$$\boxed{N_\chi - 2 = \sum_i (N_{\chi,i} - 2) + 2L}$$

$$\boxed{N_a = \sum_i N_{a,i}}$$

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$$N_{\chi,i} \equiv N_{p,i} + \frac{1}{2}N_{\psi,i}$$

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$$N_{F_i} \equiv N_{\phi_i} + N_{A_i} + N_{\psi_i}$$

$$N_F \equiv \sum_i (N_{F_i} - 2) - (2L - 2)$$

$$\boxed{N_\chi - 2 = \sum_i (N_{\chi,i} - 2) + 2L}$$

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$$\boxed{N_{4\pi} = N_F - N_g - N_y - 2N_\lambda - 2}$$

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$$N_{F_i} \equiv N_{\phi_i} + N_{A_i} + N_{\psi_i}$$

$$N_F \equiv \sum_i (N_{F_i} - 2) - (2L - 2)$$

$$\boxed{N_\chi - 2 = \sum_i (N_{\chi,i} - 2) + 2L}$$

$$\boxed{N_a = \sum_i N_{a,i}}$$

$$\boxed{N_{4\pi} = N_F - N_g - N_y - 2N_\lambda - 2}$$

equivalent to say that:

$$\{\phi, A, \psi\} \to 4\pi\{\phi, A, \psi\}$$

$$\{g, y, \sqrt{\lambda}\} \to \frac{1}{4\pi}\{g, y, \sqrt{\lambda}\}$$

$$\mathcal{L} \to \frac{1}{(4\pi)^2}\mathcal{L}$$

$$\partial^{N_p}\phi^{N_\phi}A^{N_A}\psi^{N_\psi}\Lambda^{N_\Lambda}g^{N_g}y^{N_y}\lambda^{N_\lambda}(4\pi)^{N_{4\pi}}$$

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Master Formula

$$\frac{\Lambda^4}{16\pi^2}\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{4\pi\,\phi}{\Lambda}\right]^{N_\phi}\left[\frac{4\pi\,A}{\Lambda}\right]^{N_A}\left[\frac{4\pi\,\psi}{\Lambda^{3/2}}\right]^{N_\psi}\left[\frac{g}{4\pi}\right]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}\left[\frac{\lambda}{16\pi^2}\right]^{N_\lambda}$$

Each operator in the effective Lagrangian should be written according to this normalisation.

Compare with:
Manohar&Georgi 1984
Luty 1997
Cohen,Kaplan&Nelson 1997

Consequences

$$\frac{\Lambda^4}{16\pi^2}\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{4\pi\,\phi}{\Lambda}\right]^{N_\phi}\left[\frac{4\pi\,A}{\Lambda}\right]^{N_A}\left[\frac{4\pi\,\psi}{\Lambda^{3/2}}\right]^{N_\psi}\left[\frac{g}{4\pi}\right]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}\left[\frac{\lambda}{16\pi^2}\right]^{N_\lambda}$$

- The master formula can be generalised to masses and cubic couplings:

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$$k\phi^3 \quad\Downarrow\quad \left[\frac{k}{4\pi\Lambda}\right]^{N_k}$$

Consequences

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- Covariant derivative homogeneous in power counting of Λ and 4π (not of N_χ)

$$\frac{D}{\Lambda}=\frac{\partial}{\Lambda}+i\left[\frac{g}{4\pi}\right]\left[\frac{4\pi A}{\Lambda}\right]=\frac{\partial+igA}{\Lambda}$$

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- Equation of Motion is homogeneous in power counting of Λ and 4π (not of N_χ): i.e. consider the SM Higgs doublet

$$\Box H+m^2H+\lambda(H^\dagger H)H+y\bar{\psi}\psi=0$$

all the terms scale as $\frac{4\pi}{\Lambda^3}$.

Consequences

$$\frac{\Lambda^4}{16\pi^2}\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{4\pi\,\phi}{\Lambda}\right]^{N_\phi}\left[\frac{4\pi\,A}{\Lambda}\right]^{N_A}\left[\frac{4\pi\,\psi}{\Lambda^{3/2}}\right]^{N_\psi}\left[\frac{g}{4\pi}\right]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}\left[\frac{\lambda}{16\pi^2}\right]^{N_\lambda}$$

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$$\frac{\partial_{\{\mu}}{\Lambda},\frac{4\pi A_{\nu\}}}{\Lambda}+\frac{g}{4\pi}\left[\frac{4\pi A_\mu}{\Lambda},\frac{4\pi A_\nu}{\Lambda}\right]=\frac{4\pi X_{\mu\nu}}{\Lambda^2}$$

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$\longrightarrow$ Doubts on how to weight $X_{\mu\nu}$:

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Tuning!!

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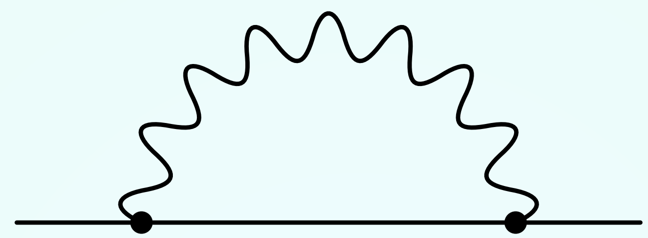

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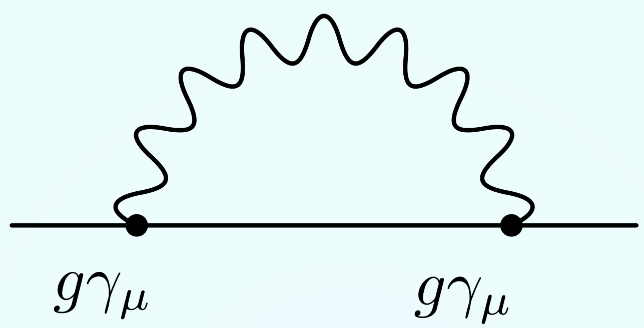

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$$\frac{g^2}{(4\pi)^2} i\bar{\psi}\not{\partial}\psi$$

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master formula

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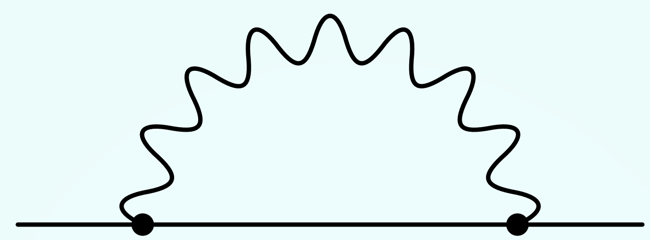

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$(m = 0)$

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<u>Master Formula for Cross Sections</u>

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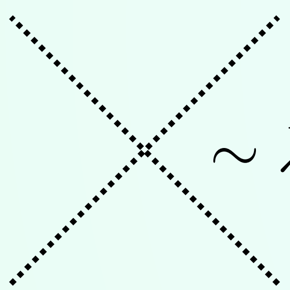

$\sim \lambda$

$$\longrightarrow$$

$$\begin{aligned}\sigma &\sim \frac{1}{E^2}\rho\,|\mathcal{M}|^2\\ &\sim \frac{1}{E^2}\frac{1}{16\pi}\lambda^2\\ &\sim \frac{\pi(4\pi)^2}{E^2}\left(\frac{\lambda}{(4\pi)^2}\right)^2\end{aligned}$$

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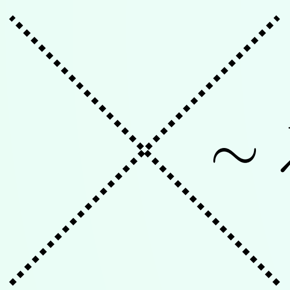 $\sim \lambda$ $\longrightarrow$

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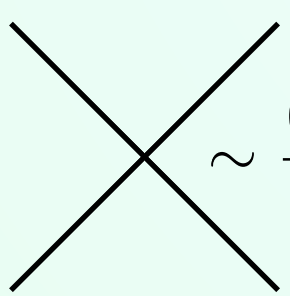 $\sim \frac{(4\pi)^2}{\Lambda^2}$ $\longrightarrow$

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The Physical Impact

$$\sigma \sim \frac{\pi(4\pi)^2}{E^2}\left(\frac{E^2}{\Lambda^2}\right)^{-N_\Lambda}\left[\frac{g}{4\pi}\right]^{2N_g}\left[\frac{y}{4\pi}\right]^{2N_y}\left[\frac{\lambda}{(4\pi)^2}\right]^{2N_\lambda}$$

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$$d = 6 \begin{cases} \dfrac{(4\pi)^4}{\Lambda^2}\phi^6 \\ \\ \dfrac{(4\pi)^2}{\Lambda^2}(\phi\partial_\mu\phi)^2 \end{cases}$$

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$$\sigma \sim \frac{\pi(4\pi)^2}{E^2}\left(\frac{E^2}{\Lambda^2}\right)^{-N_\Lambda}\left[\frac{g}{4\pi}\right]^{2N_g}\left[\frac{y}{4\pi}\right]^{2N_y}\left[\frac{\lambda}{(4\pi)^2}\right]^{2N_\lambda}$$

<u>There ONLY dependence is on Λ</u>

$\Rightarrow$ The hierarchy between the size of cross sections only depends on Λ, and not on the number of derivates!!

$$d = 6 \begin{cases} \dfrac{(4\pi)^4}{\Lambda^2}\phi^6 & \longrightarrow \quad 2\phi \to 4\phi \\[2ex] \dfrac{(4\pi)^2}{\Lambda^2}(\phi\partial_\mu\phi)^2 & \longrightarrow \quad 2\phi \to 2\phi \end{cases}$$

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- Processes with *different* number of particles/derivatives can have *same* cross sections: same number of Λ

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SMEFT

The Standard Model Effective Field Theory (SMEFT): assuming B and L conservation

[Buchmuller&Wyler 1984]
[Gradkoski,Iskrzynski,Misiak&Rosiek 2010]

Operator	d	N_χ	NDA Form
H^2	2	0	$\Lambda^2 H^2$
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H^4	4	0	$(4\pi)^2\, H^4$
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$\psi^2 D$	4	2	$\psi^2 D$	$\longleftrightarrow$ $i\bar{\psi}\not{D}\psi$
$H^2 D^2$	4	2	$H^2 D^2$	$\longleftrightarrow$ $D_\mu H^\dagger D^\mu H$
X^2	4	2	X^2	$\longleftrightarrow$ $\mathrm{Tr}\,(W_{\mu\nu} W^{\mu\nu})$
H^6	6	0	$\frac{(4\pi)^4}{\Lambda^2}\, H^6$	
$\psi^2 H^3$	6	1	$\frac{(4\pi)^3}{\Lambda^2}\, \psi^2 H^3 2$	
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$X^2 H^2$	6	2	$\frac{(4\pi)^2}{\Lambda^2}\, X^2 H^2$	$\frac{(4\pi)^2}{\Lambda^2} \mathrm{Tr}\,(W_{\mu\nu} W^{\mu\nu})\, (H^\dagger H)$
$\psi^2 X H$	6	2	$\frac{(4\pi)^2}{\Lambda^2}\, \psi^2 X H$	
$\psi^2 H^2 D$	6	2	$\frac{(4\pi)^2}{\Lambda^2}\, \psi^2 H^2 D$	$\frac{(4\pi)^2}{\Lambda^2} \bar{\psi} \gamma_\mu \psi (H^\dagger D^\mu H)$
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$$\mathcal{L} = \mathcal{L}^{d\leq 4} + \mathcal{L}^{d=6} + \mathcal{L}^{d=8} + \ldots$$

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<u>independently of number of loops!!</u>

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χPT

- Chiral Perturbation Theory (χPT) has been used for low-energy QCD: considering only *u* and *d* quarks and neglecting their mass

<u>Chiral Symmetry $SU(2)_L \times SU(2)_R$:</u>

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \to \Omega_L \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{pmatrix} u_R \\ d_R \end{pmatrix} \to \Omega_R \begin{pmatrix} u_R \\ d_R \end{pmatrix} \qquad \Omega_{L,R} \in SU(2)_{L,R}$$

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- As $q - \bar{q}$ pairs are energetically cheap, the QCD vacuum will contain condensates:

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<u>Chiral Symmetry spontaneous breaking $\langle \bar{q} q \rangle \neq 0$:</u>

$$SU(2)_L \times SU(2)_R \to SU(2)_{\text{diag}} \longrightarrow$$ 3 Goldstone bosons $\vec{\pi}$

$$U \equiv e^{2i\vec{\pi}\cdot\vec{\sigma}/f} \qquad U \to \Omega_L^\dagger U \Omega_R$$

- The pion Lagrangian is written as

$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_4 + \dots \quad \text{(+ soft breaking part)}$$

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$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_4 + \ldots$$ (+ soft breaking part)

$$\frac{\Lambda^4}{16\pi^2}\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{4\pi\phi}{\Lambda}\right]^{N_p}$$

$$\Lambda = 4\pi\, f$$

f scale of the pions

$$\mathcal{L}_2 = \frac{f^2}{4}\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right)$$

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$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_4 + \ldots$$ (+ soft breaking part)

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<u>Does N_χ determine the physical impact of operators in χPT?</u>

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The same operator gives two cross sections with different suppression and therefore N_χ cannot be useful to determine the ordering of the physical impact

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The ordering in Λ coincides with N_χ only for processes with same number of external fields.

HEFT

Grinstein & Trott, PRD 76 (2007)
Azatov, Contino & Galloway JHEP 1204 (2012)
Alonso, Gavela, LM, Rigolin & Yepes, JHEP 1206 (2012)
Alonso, Gavela, LM, Rigolin & Yepes, PLB 722 (2013)
Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)
Buchalla, Catà & Krause, NPB 880 (2014)
Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM, Rigolin & Yepes, JHEP 1410 (2014)

$$\boxed{\Phi(x) = \frac{v+h}{\sqrt{2}} e^{i\sigma_a \pi^a(x)/v} \begin{pmatrix} 0 \\ 1 \end{pmatrix}}$$

Higgs: h

Singlet

GBs: $\mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v}$

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Independent!!

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Primary Dimension

$$\mathbf{U} = 1 + \ldots \qquad N_\chi = 0 \qquad d_p = 0$$

$$\mathbf{T} = \sigma_3 \qquad N_\chi = 0 \qquad d_p = 0$$

$$\mathbf{V}_\mu = \frac{2i}{f}\partial_\mu \mathbf{\Pi} + \frac{2i}{f}\left[\mathbf{\Pi}, gA_\mu\right] + \frac{gv}{f}B_\mu \qquad N_\chi = 1 \qquad d_p = 2$$

HEFT basis

Assuming B and L conservation, and no BSM custodial breaking

Operator	d_p	N_χ	NDA form
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
$\psi^2 D$	4	2	$\psi^2 D$
$(\partial h)^2$	4	2	$(\partial h)^2$
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

HEFT basis

Assuming B and L conservation, and no BSM custodial breaking

Operator	d_p	N_χ	NDA form	
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$	$\longleftrightarrow$ $\Lambda\bar{\psi}_L\mathbf{U}\psi_R\mathcal{F}_{\psi^2\mathbf{U}}(h)$
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$	
$\psi^2 D$	4	2	$\psi^2 D$	$\longleftrightarrow$ $i\bar{\psi}\not{D}\psi$
$(\partial h)^2$	4	2	$(\partial h)^2$	
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$	$\longleftrightarrow$ $\frac{\Lambda^2}{(4\pi)^2}\mathrm{Tr}\,(\mathbf{V}_\mu\mathbf{V}^\mu)\,\mathcal{F}_{\mathbf{V}^2}(h)$
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$	
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$	
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$	
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$	$\longleftrightarrow$ $\frac{1}{4\pi}\mathrm{Tr}\,(W_{\mu\nu}\,[\mathbf{V}^\mu,\mathbf{V}^\nu])\,\mathcal{F}_{X\mathbf{V}^2}(h)$
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$	
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$	
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$	
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$	
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$	
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$	
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$	$\longleftrightarrow$ $\frac{1}{(4\pi)^2}\mathrm{Tr}\,(\mathbf{V}^\mu\mathbf{V}^\mu)^2\,\mathcal{F}_{\mathbf{V}^4}(h)$

Primary Dimension d_p

Operator	d_p	N_χ	NDA form
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
$\psi^2 D$	4	2	$\psi^2 D$
$(\partial h)^2$	4	2	$(\partial h)^2$
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

Primary Dimension d_p

d_p counts the dimensions of the leading interacting term

Operator	d_p	N_χ	NDA form
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
$\psi^2 D$	4	2	$\psi^2 D$
$(\partial h)^2$	4	2	$(\partial h)^2$
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

Primary Dimension d_p

d_p counts the dimensions of the leading interacting term

$\updownarrow$

d_p counts the number of scales, explicit and implicit

Operator	d_p	N_χ	NDA form
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
$\psi^2 D$	4	2	$\psi^2 D$
$(\partial h)^2$	4	2	$(\partial h)^2$
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

Primary Dimension d_p

d_p counts the dimensions of the leading interacting term

↕

d_p counts the number of scales, explicit and implicit

$$\sigma \sim \frac{\pi(4\pi)^2}{E^2}\left(\frac{E^2}{\Lambda^2}\right)^{-N_\Lambda}$$

The physical impact on cross sections is ordered by d_p

Operator	d_p	N_χ	NDA form
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
$\psi^2 D$	4	2	$\psi^2 D$
$(\partial h)^2$	4	2	$(\partial h)^2$
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

d_p is orthogonal to the ordering for renormalisation:

Operator	d_p	N_χ	NDA form
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
$\psi^2 D$	4	2	$\psi^2 D$
$(\partial h)^2$	4	2	$(\partial h)^2$
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

d_p is orthogonal to the ordering for renormalisation:

	Operator	d_p	N_χ	NDA form
LO	$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
	X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
	$\psi^2 D$	4	2	$\psi^2 D$
	$(\partial h)^2$	4	2	$(\partial h)^2$
	$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
	$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
	$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
	ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
	$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
	X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
	$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
	$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
	$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
	$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
	$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
	$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

d_p is orthogonal to the ordering for renormalisation:

	Operator	d_p	N_χ	NDA form
LO	$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
LO	X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
LO	$\psi^2 D$	4	2	$\psi^2 D$
LO	$(\partial h)^2$	4	2	$(\partial h)^2$
LO	$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
NLO	$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
NLO	$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
NLO	ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
NLO	$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
NLO	X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
NLO	$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
NLO	$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
NLO	$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
NLO	$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
NLO	$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
NLO	$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

Operators necessary to absorbed divergent contributions arising from the 1-loop renorm. of LO Lag

+

Operators encoding NP contributions with the same physical impact

Disentangling the Higgs Nature

$$\Phi(x) = \frac{v+h}{\sqrt{2}} e^{i\sigma_a \pi^a(x)/v} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Higgs: h

Singlet

GBs: $\mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v}$

$\mathbf{U}(x) \to L\,\mathbf{U}(x) R^\dagger$

Independent!!

- Being h a singlet: generic functions of h $\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \ldots$
- Being $\mathbf{U}(x)$ **vs.** h independent, many more operators can be constructed

Disentangling the Higgs Nature

Operator	d_p	N_χ	NDA form	SMEFT
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$	4
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$	4
$\psi^2 D$	4	2	$\psi^2 D$	4
$(\partial h)^2$	4	2	$(\partial h)^2$	4
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$	4
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$	6, 8
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$	6
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$	6
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$	6, 8
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$	6
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$	6
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$	8
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$	8
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$	8
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$	8
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$	8, 10

$\longleftrightarrow$ Linear sibling

Disentangling the Higgs Nature

Operator	d_p	N_χ	NDA form	SMEFT
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$	4
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$	4
$\psi^2 D$	4	2	$\psi^2 D$	4
$(\partial h)^2$	4	2	$(\partial h)^2$	4
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$	4
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$	6, 8
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$	6
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$	6
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$	6, 8
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$	6
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$	6
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$	8
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$	8
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$	8
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$	8
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$	8, 10

$\longleftrightarrow$ Linear sibling

$(\partial h)^2,\ \mathbf{V}^2 \longleftrightarrow D_\mu H^\dagger D^\mu H$

Disentangling the Higgs Nature

Operator	d_p	N_χ	NDA form	SMEFT
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$	4
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$	4
$\psi^2 D$	4	2	$\psi^2 D$	4
$(\partial h)^2$	4	2	$(\partial h)^2$	4
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$	4
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$	6, 8
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$	6
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$	6
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$	6, 8
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$	6
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$	6
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$	8
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$	8
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$	8
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$	8
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$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$	6
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$	6
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X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$	6
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$	8
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$\longleftrightarrow$ Linear sibling

$(\partial h)^2,\ \mathbf{V}^2 \longleftrightarrow D_\mu H^\dagger D^\mu H$

$\epsilon^{\mu\nu\rho\lambda}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}(h)$

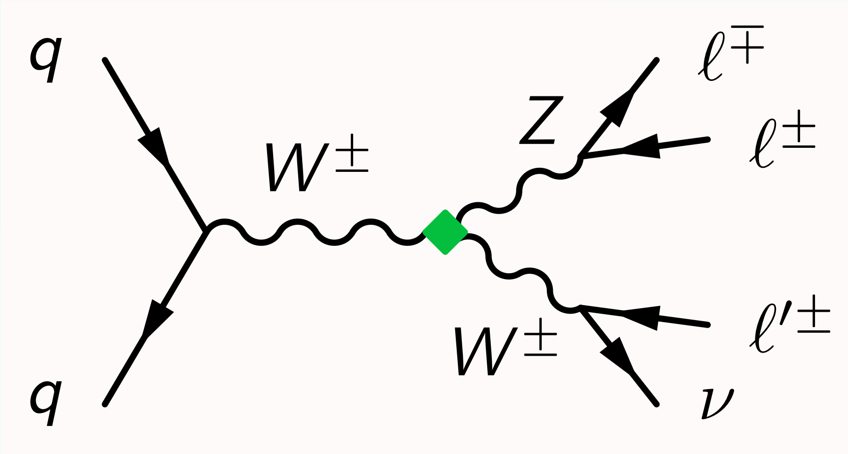
$\varepsilon^{\mu\nu\rho\lambda}\,(\Phi^\dagger D_\mu\Phi)\,(\Phi^\dagger\sigma_i D_\nu\Phi)\,W^i_{\rho\lambda}$

$$\epsilon^{\mu\nu\rho\lambda}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}(h)$$

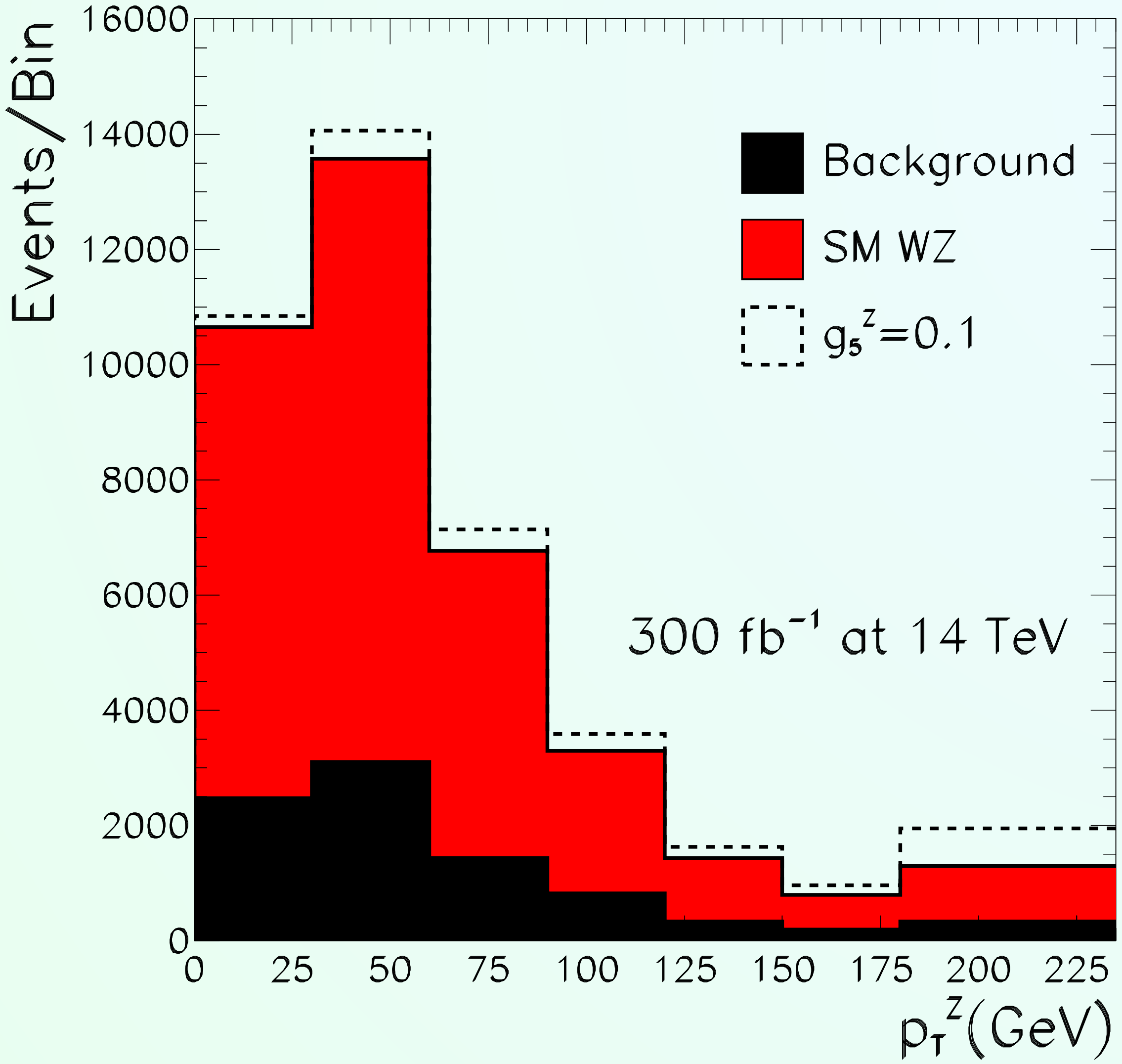
Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014)

Signals expected in the chiral basis, but not in the linear one (d=8)

$$g_5^Z\,\varepsilon^{\mu\nu\rho\lambda}\partial_\mu W^+_\nu W^-_\rho Z_\lambda \mathcal{F}_{14}(h)$$



number of expected events (WZ production) with respect to the Z p_T



@95% CL:

present $g_5^Z \in [-0.08, 0.04]$

LHC(7+8+14) $g_5^Z \in [-0.033, 0.028]$

Conclusions

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- The primary dimension counting:
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  - is orthogonal to the renormalisation ordering(s)
- To disentangle the Higgs nature:
  - the presence of new signals
  - decorrelation signals (not discussed here)
  - …

and the primary dimension can tell which are the most promising couplings. Relevant for phenomenology!!

Conclusions

- Use EFT is convenient and sometimes necessary. Many different counting can be defined.

- Th
  - ons
  -

Thanks

- To disentangle the Higgs nature:
  - the presence of new signals
  - decorrelation signals (not discussed here)
  - …

  and the primary dimension can tell which are the most promising couplings. Relevant for phenomenology!!

Backup

Comparison with Buchalla *et al.*

Buchalla, Catà & Krause, NPB 894 (2015)

Counting based on derivatives

Naively expected at LO, as they are $N_\chi = 2$

$$\widetilde{N}_\chi \equiv \underbrace{N_p + \frac{N_\psi}{2}}_{N_\chi} + N_g + N_y + 2N_\lambda$$

Use one single parameter when naturally there are many!

AD HOC ASSUMPTIONS

$\bar\psi\psi \times \{g, y\}$

$X_{\mu\nu} \times g$

otherwise 4 fermions at LO

	Operator	d_p	N_χ	NDA form
LO	$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
	X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
	$\psi^2 D$	4	2	$\psi^2 D$
	$(\partial h)^2$	4	2	$(\partial h)^2$
	$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
NLO	$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
	$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
	ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
	$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
NNLO	X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
	$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
NLO	$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
	$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
	$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
	$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
	$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

Alternative $F_{\mu\nu}$ Normalisation

- Canonical normalisation of the gauge field strength kinetic terms as

$$X_{\mu\nu}X^{\mu\nu}$$

$$\frac{\Lambda^4}{16\pi^2}\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{4\pi\,\phi}{\Lambda}\right]^{N_\phi}\left[\frac{4\pi\,A}{\Lambda}\right]^{N_A}\left[\frac{4\pi\,\psi}{\Lambda^{3/2}}\right]^{N_\psi}\left[\frac{g}{4\pi}\right]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}\left[\frac{\lambda}{16\pi^2}\right]^{N_\lambda}$$

- Alternatively

$$\frac{1}{g^2}X_{\mu\nu}X^{\mu\nu}$$

$$\frac{\Lambda^4}{16\pi^2}\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{4\pi\,\phi}{\Lambda}\right]^{N_\phi}\left[\frac{A}{\Lambda}\right]^{N_A}\left[\frac{4\pi\,\psi}{\Lambda^{3/2}}\right]^{N_\psi}[g]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}\left[\frac{\lambda}{16\pi^2}\right]^{N_\lambda}$$

$\bar{\psi}_L\gamma^\mu \mathbf{V}_\mu \psi_L$ & $\bar{\psi}_L\gamma^\mu \left[\mathbf{T},\mathbf{V}_\mu\right]\psi_L$ in MFV

Alonso, Gavela, LM, Rigolin & Yepes, JHEP 1206 (2012)
Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)

It is easier to read the interaction vertices in the unitary gauge:

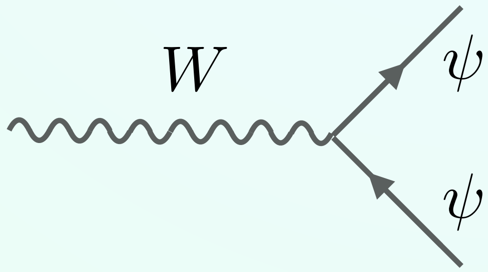
$$\mathcal{L}^f_{\chi=4} = -\frac{g}{\sqrt{2}}\left[W^+_\mu \bar{U}_L\gamma^\mu[a_W(1+\beta_W\, h/v) + i a_{CP}(1+\beta_{CP}\, h/v)]\times \right.$$

$$\left. \times\left(\mathbf{y}_U^2 V + V\mathbf{y}_D^2\right) D_L + \text{h.c.}\right] +$$

$\bar{\psi}_L\gamma^\mu \mathbf{V}_\mu \psi_L$

$\bar{\psi}_L\gamma^\mu \left[\mathbf{T},\mathbf{V}_\mu\right]\psi_L$

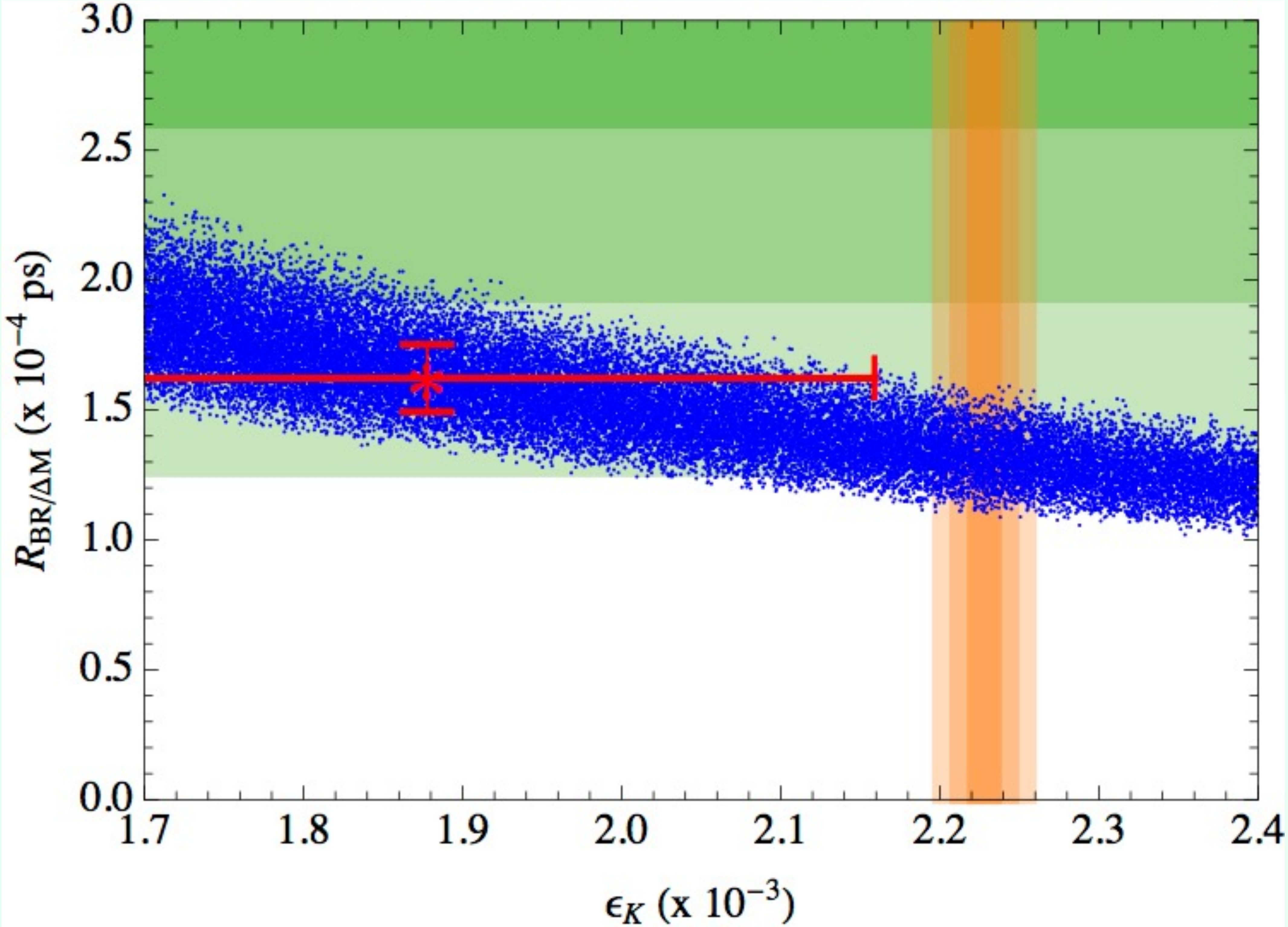
$a_{W,CP} \longrightarrow$



$\longrightarrow$

$$\begin{cases} B^+ \to \tau^+\nu \\ \text{meson oscillations} \\ A^b_{sl} \\ \bar{B} \to X_s\gamma \end{cases}$$

$$R_{BR/\Delta M} \equiv BR(B^+ \to \tau^+ \nu)/\Delta M_{B_d}$$



SM values:

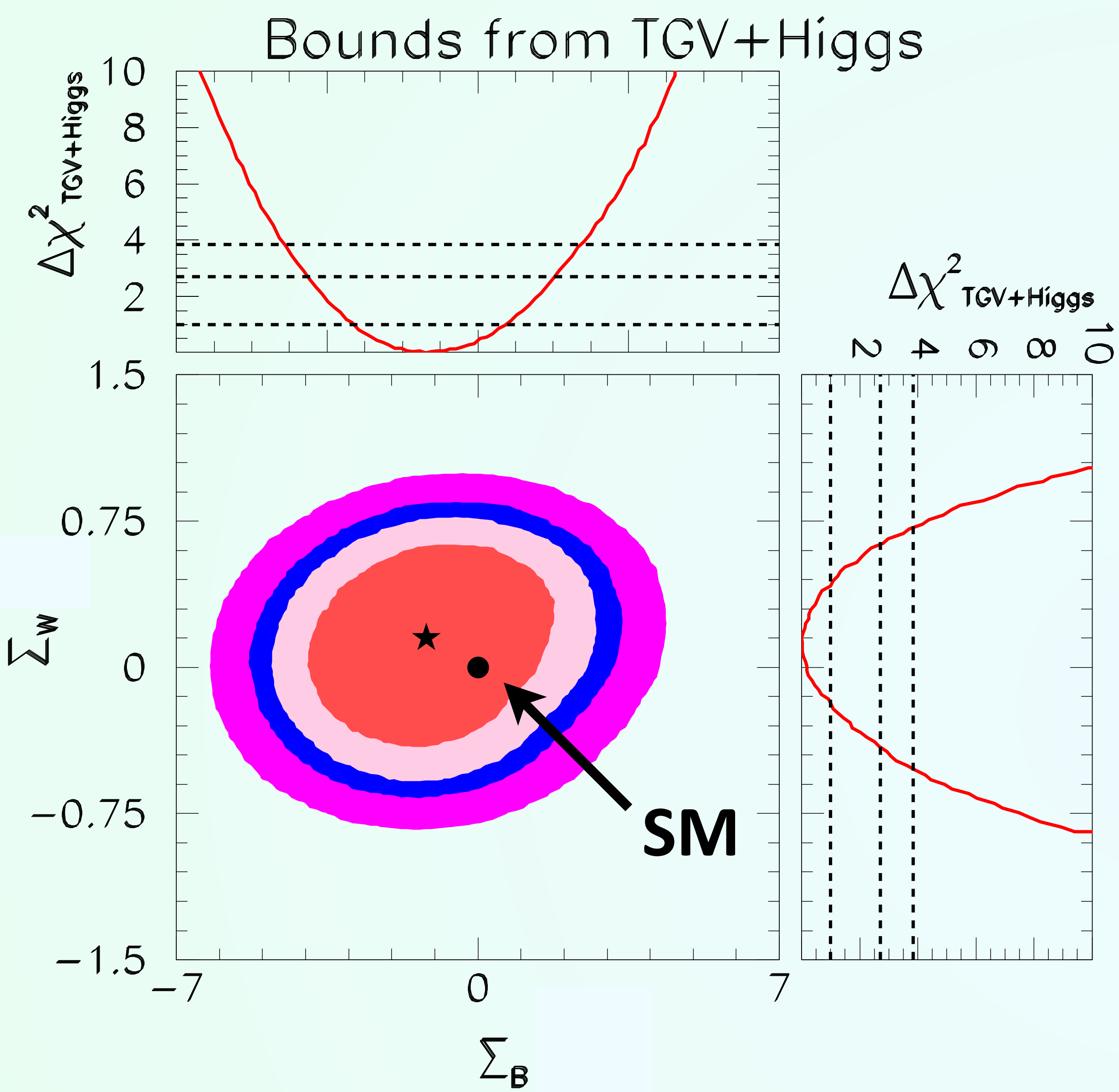
$$\epsilon_K \simeq (1.88 \pm 0.3) \times 10^{-3}$$

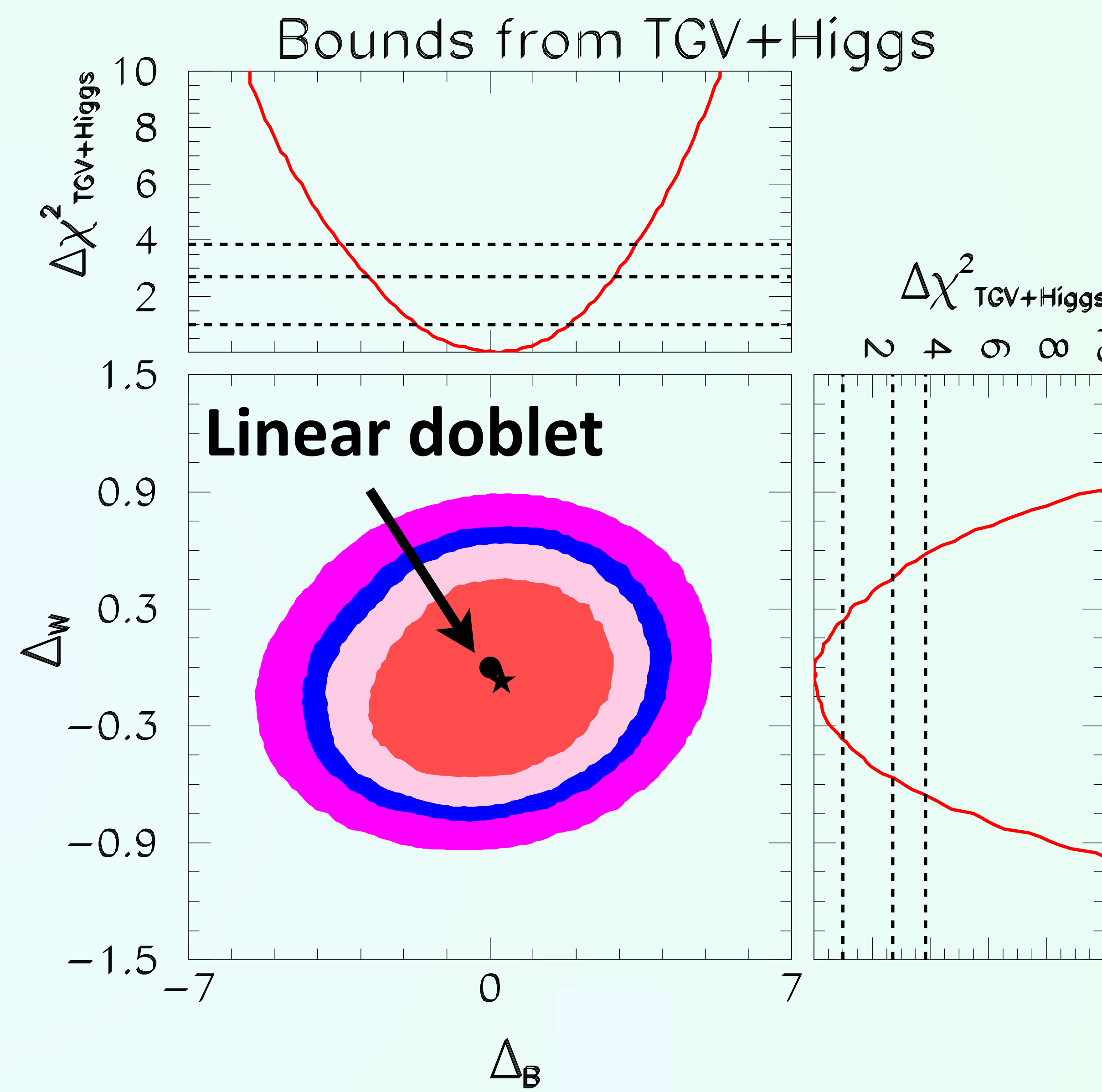
$$R_{BR/\Delta M} \simeq (1.62 \pm 0.13) \times 10^{-4}$$

$$a_W, a_{CP} \in [-1, 1]$$

$$a_Z^d \in [-0.1, 0.1]$$

Decorrelations





$$\Sigma_B = 4(2c_2 + a_4) \to f_B \xi \qquad \Delta_B = 4(2c_2 - a_4) \to 0$$

$$\Sigma_W = 2(2c_3 - a_5) \to f_W \xi \qquad \Delta_W = 2(2c_3 + a_5) \to 0$$

Data: Tevatron D0 and CDF Collaborations and LHC, CMS, and ATLAS Collaborations at 7 TeV and 8 TeV for final states $\gamma\gamma$, W^+W^-, ZZ, $Z\gamma$, $b\bar{b}$, and $\tau\bar{\tau}$

Example of Decorrelation

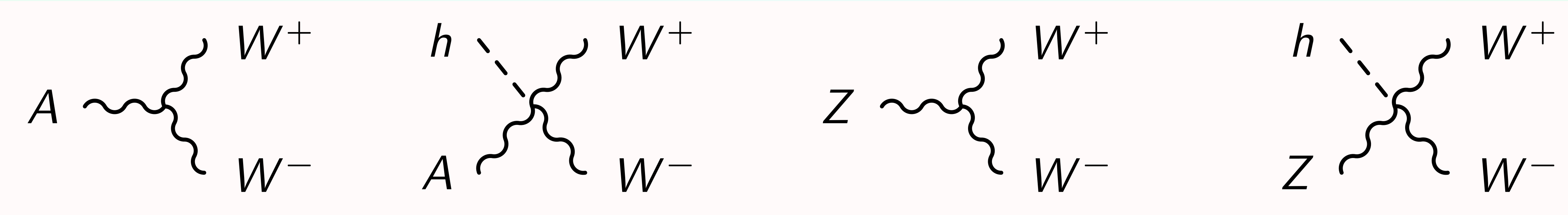
Correlations present in the linear basis are absent in the chiral basis

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

Example of Decorrelation

Correlations present in the linear basis are absent in the chiral basis

$$\mathcal{O}_B = \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{8\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2$$
$$- \frac{eg}{4\cos\theta_W} A_{\mu\nu} Z^\mu \partial^\nu h (v+h) + \frac{e^2}{4\cos^2\theta_W} Z_{\mu\nu} Z^\mu \partial^\nu h (v+h)$$



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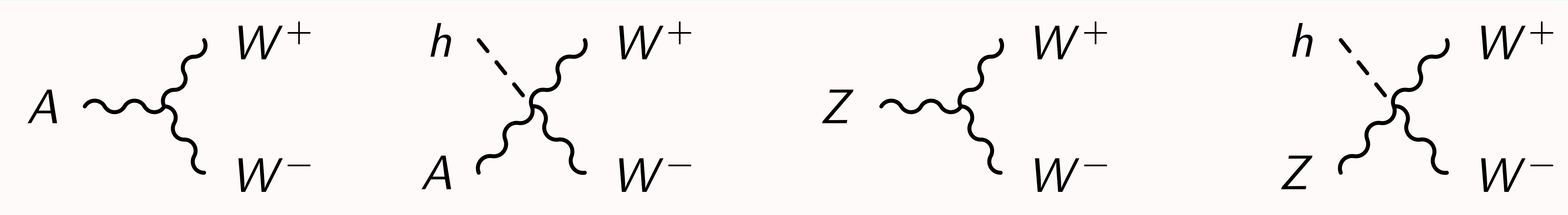
$$- \frac{eg}{4\cos\theta_W} A_{\mu\nu} Z^\mu \partial^\nu h (v+h) + \frac{e^2}{4\cos^2\theta_W} Z_{\mu\nu} Z^\mu \partial^\nu h (v+h)$$

$$\Rightarrow \quad \mathcal{O}_B = \frac{v^2}{16} \mathcal{P}_2(h) + \frac{v^2}{8} \mathcal{P}_4(h) \quad \text{with} \quad \mathcal{F}_i(h) = \left(1 + \frac{h}{v}\right)^2$$

$$\mathcal{P}_2(h) = 2ieg^2 A_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h) - 2\frac{ie^2 g}{\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h)$$

$$\mathcal{P}_4(h) = -\frac{eg}{\cos\theta_W} A_{\mu\nu} Z^\mu \partial^\nu \mathcal{F}_4(h) + \frac{e^2}{\cos^2\theta_W} Z_{\mu\nu} Z^\mu \partial^\nu \mathcal{F}_4(h)$$



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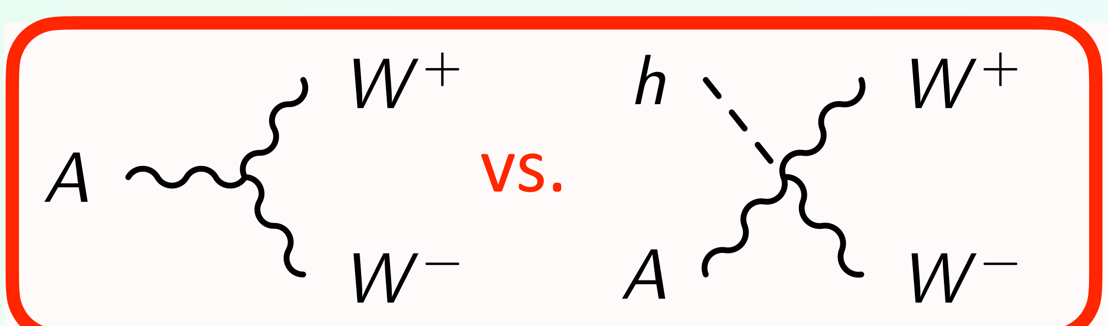
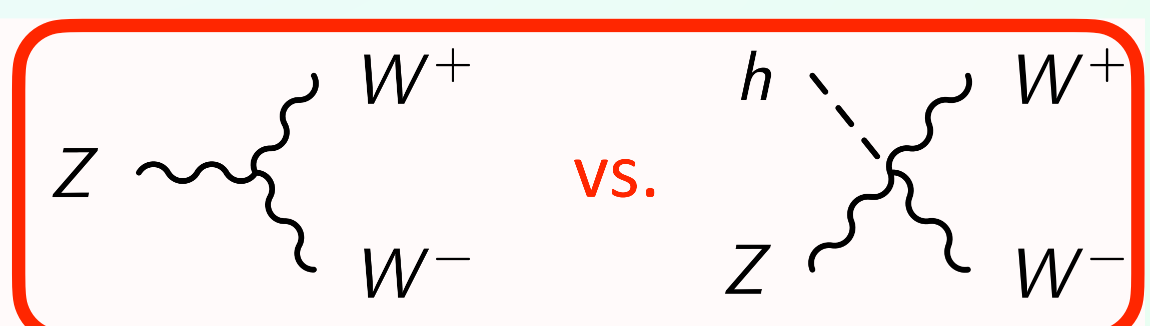
due to the decorrelation in the $\mathcal{F}_i(h)$ functions: i.e.

[see also Isidori&Trott, 1307.4051]





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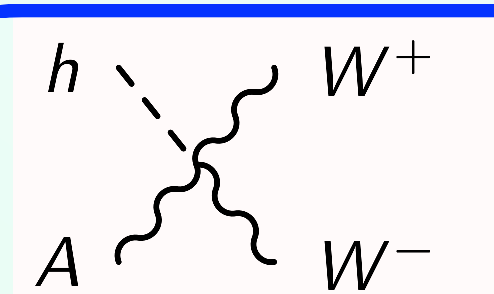
due to the nature of the chiral operators (different c_i coefficients): i.e.



vs.