

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

Motivations: which rule?

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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

Motivations: which rule?

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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,*}

Motivations: which rule?

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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

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

Independent!!

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■ Being h a singlet: generic functions of h

$$\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \dots$$

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Independent!!

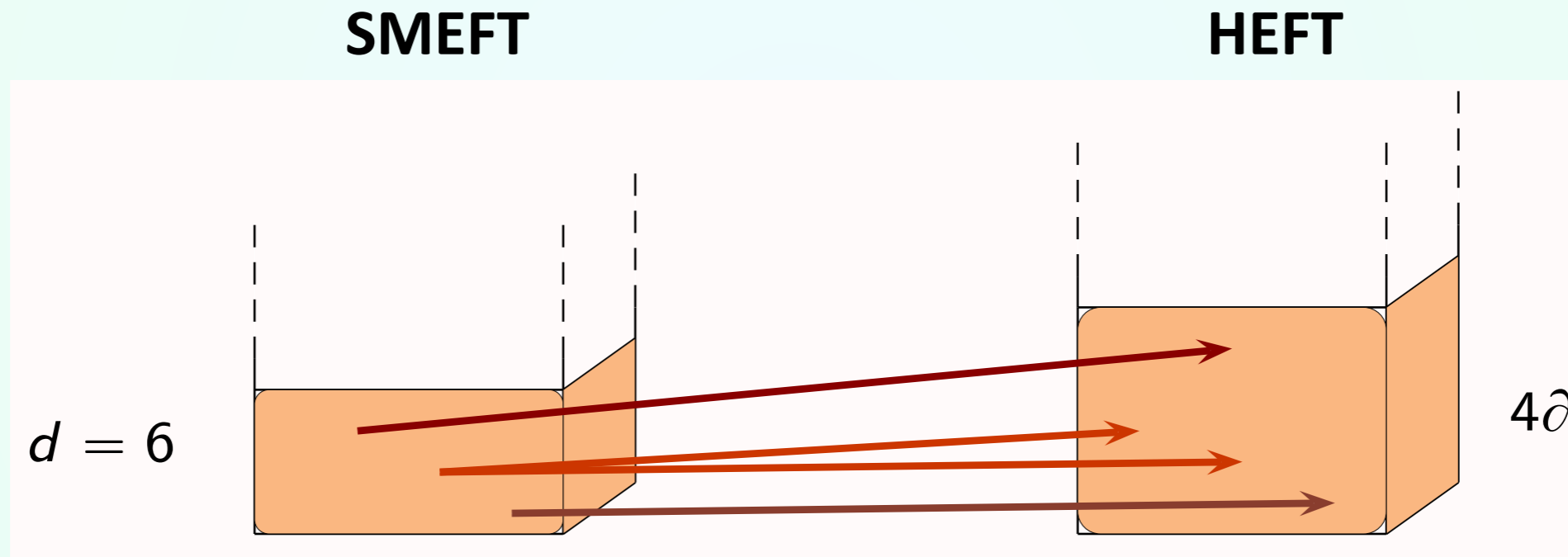
Being h a singlet: generic functions of h

$$\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \dots$$

Being **$\mathbf{U}(x)$ vs. h** independent, many more operators can be constructed

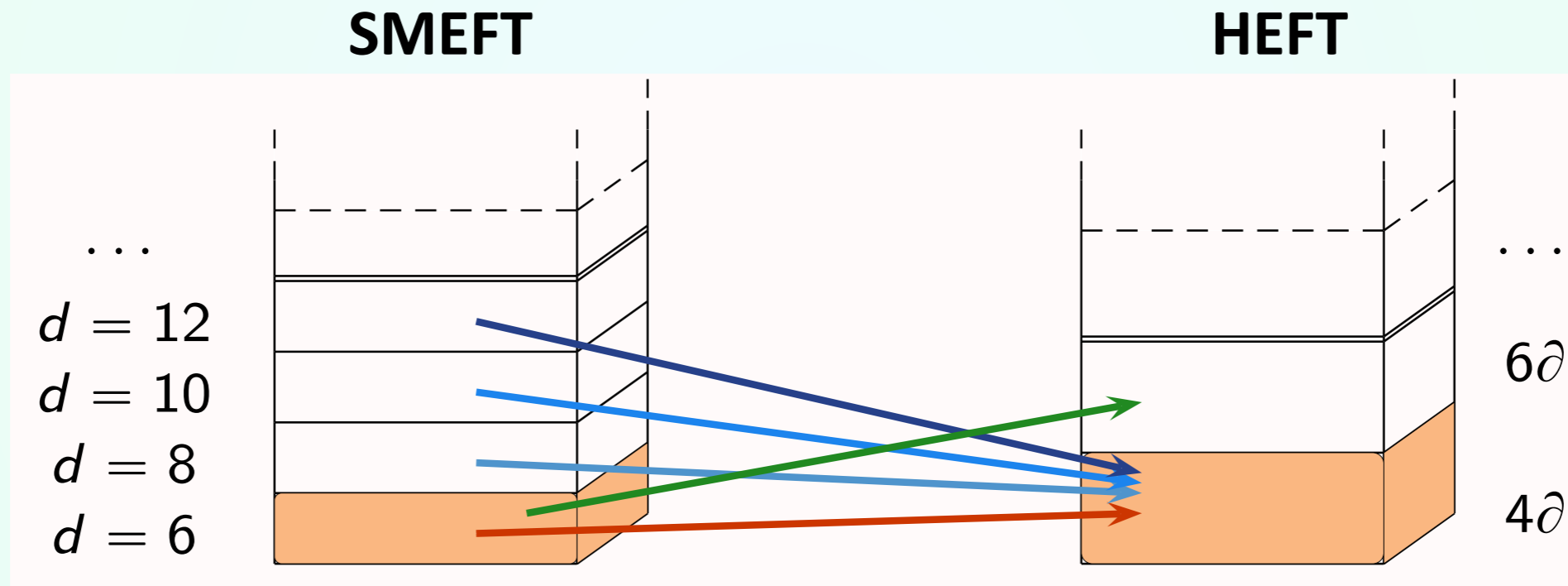
Decorrelations

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



New Signals

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



Content

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

Why to use an EFT?

It is convenient

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The observables considered are measured in a determined energy range



Only on relevant contributions at that energy

Calculations are easier

Benefits in the renormalisation procedure

Accidental (approximate) symmetries

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Top-down approach 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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Bottom-up approach from the EFT to the full theory
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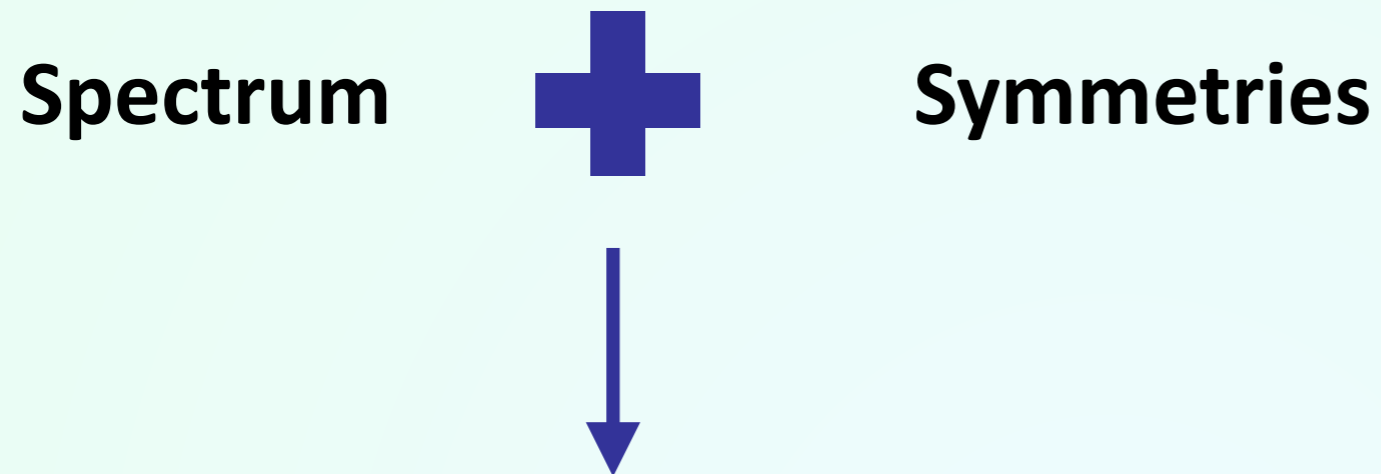
- Fermi theory;
- Higgs effective theories;
- etc...

How to construct an EFT?

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Spectrum  **Symmetries**

How to construct an EFT?



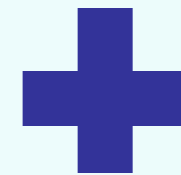
Construct ALL possible operators with the fields of the given spectrum and invariant under the chosen symmetries.

How to construct an EFT?

Spectrum  **Symmetries**



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**

How to construct an EFT?

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



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

How to construct an EFT?

Spectrum + Symmetries + Power counting



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Medium: convenience vs. necessity

How to construct an EFT?

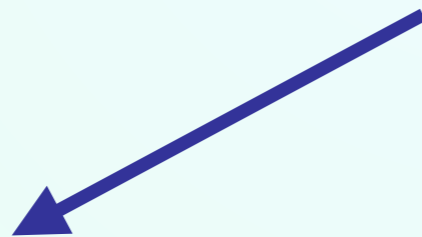
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EFT for B physics: the residual symmetry after integrating out Z and W is QCDxEM

How to construct an EFT?

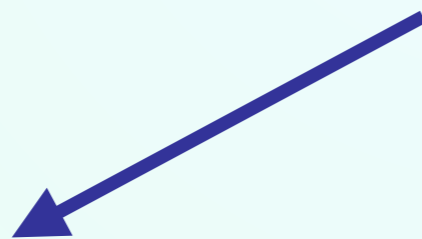
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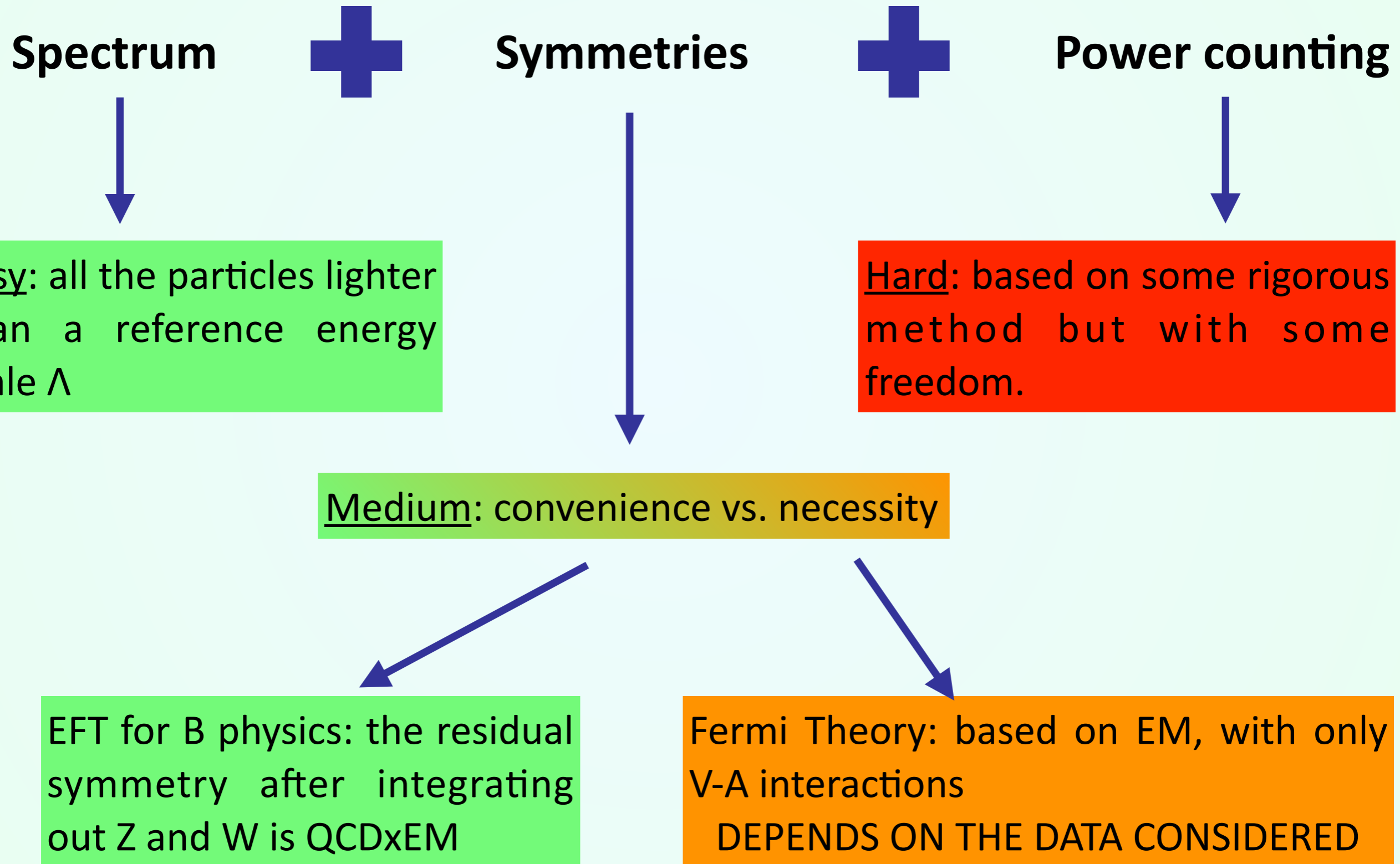


EFT for B physics: the residual symmetry after integrating out Z and W is QCDxEM



Fermi Theory: based on EM, with only V-A interactions
DEPENDS ON THE DATA CONSIDERED

How to construct an EFT?



Basics

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

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Canonical mass dimensions in 4 space-time dimensions:

For the generalisation to d dimensions of all the formulae that follow see:

B. Gavela, E. Jenkins, A. Manohar & LM, arXiv: 1601.07551

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$$i\bar{\psi}\not{D}\psi \quad \text{should be} \quad d = 4 \quad \longrightarrow \quad \begin{array}{l} [\partial] = 1 \\ [\psi] = 3/2 \end{array}$$

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$\partial_\mu\phi\partial^\mu\phi$	should be	$d = 4$	\longrightarrow	$[\phi] = 1$
$X_{\mu\nu}X^{\mu\nu}$	should be	$d = 4$	\longrightarrow	$[X_{\mu\nu}] = 2$
$D_\mu \equiv \partial_\mu + gA_\mu$	}		\longrightarrow	$[A] = 1$
$X_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu, A_\nu]$				$[g] = 0$
$m\bar{\psi}\psi$	should be	$d = 4$	\longrightarrow	$[m] = 1$
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$\longrightarrow \mathcal{L}_{\text{eff}} \sim \Lambda^4 \mathcal{L} \left(\frac{\partial}{\Lambda}, \frac{\psi}{\Lambda^{3/2}}, \frac{\phi}{\Lambda}, \frac{X_{\mu\nu}}{\Lambda^2} \right)$

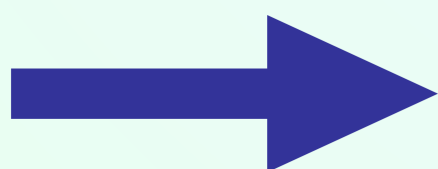
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not the end of the story!!

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

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

$N_{a,i}$ refers to the number of such field/coupling appearing in the vertex

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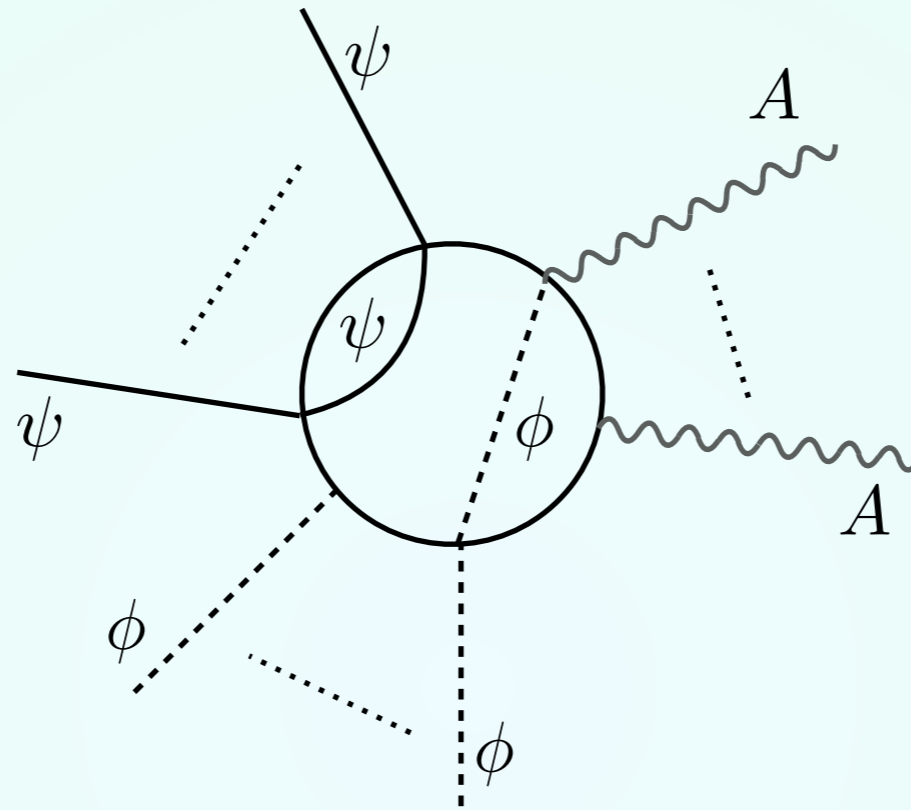
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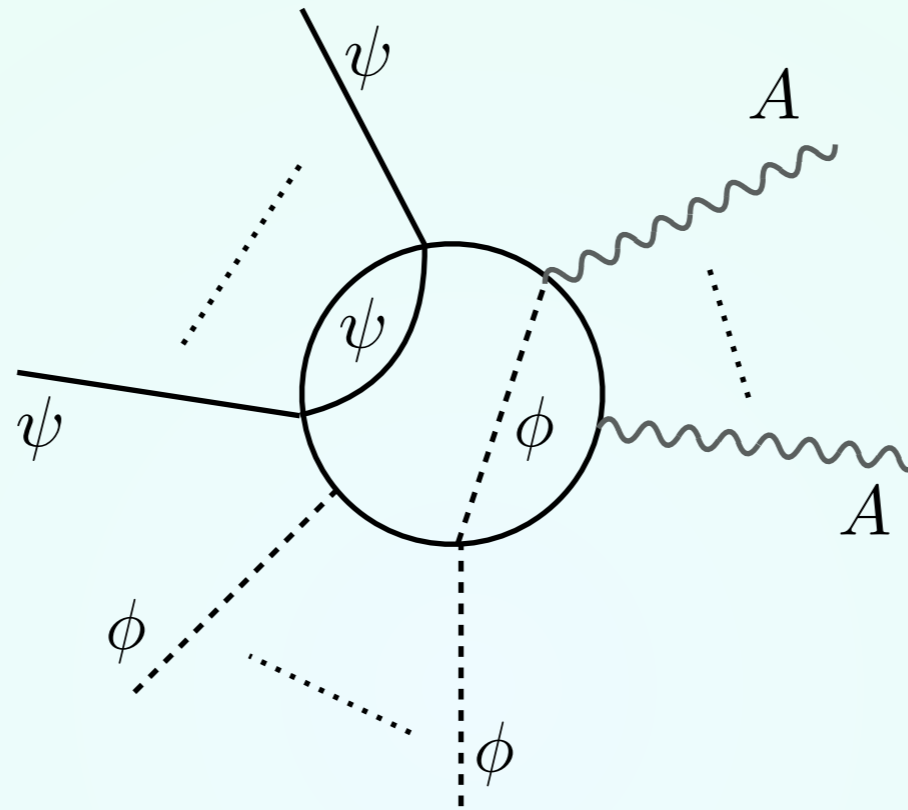
$$(\bar{\psi}\psi)^2 \longrightarrow \begin{cases} N_\psi = 4 \\ N_p = 0 = N_\phi = N_A \end{cases} \longrightarrow N_\Lambda = -2 \longrightarrow \frac{(\bar{\psi}\psi)^2}{\Lambda^2}$$

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

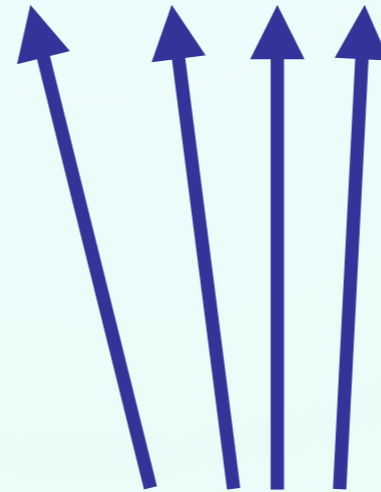


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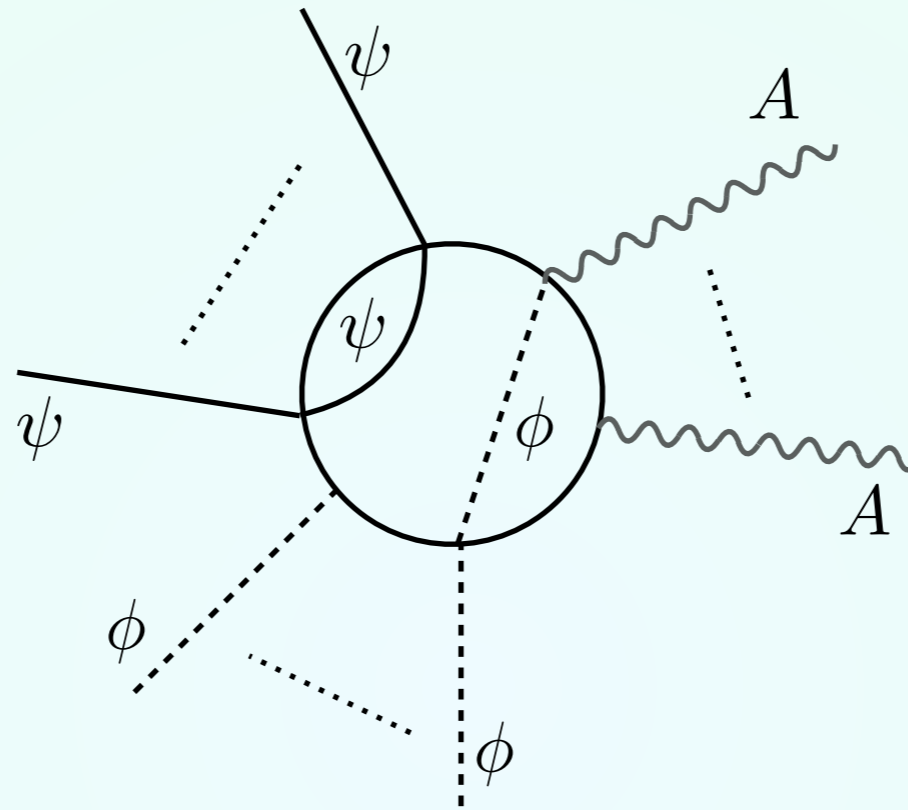


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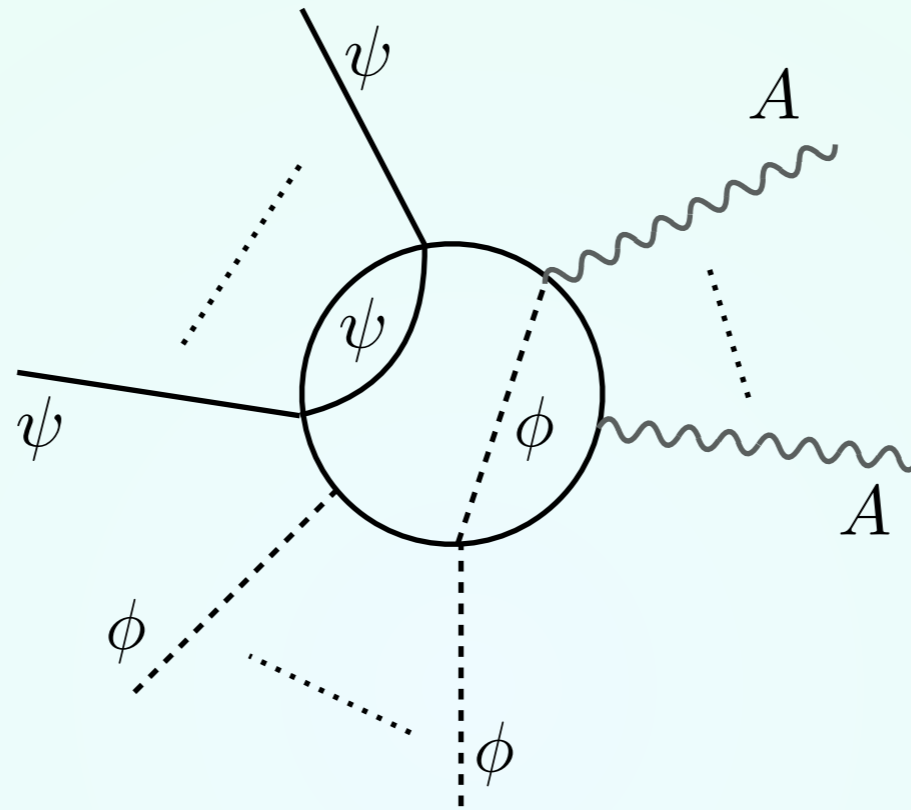


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depend on external and internal legs

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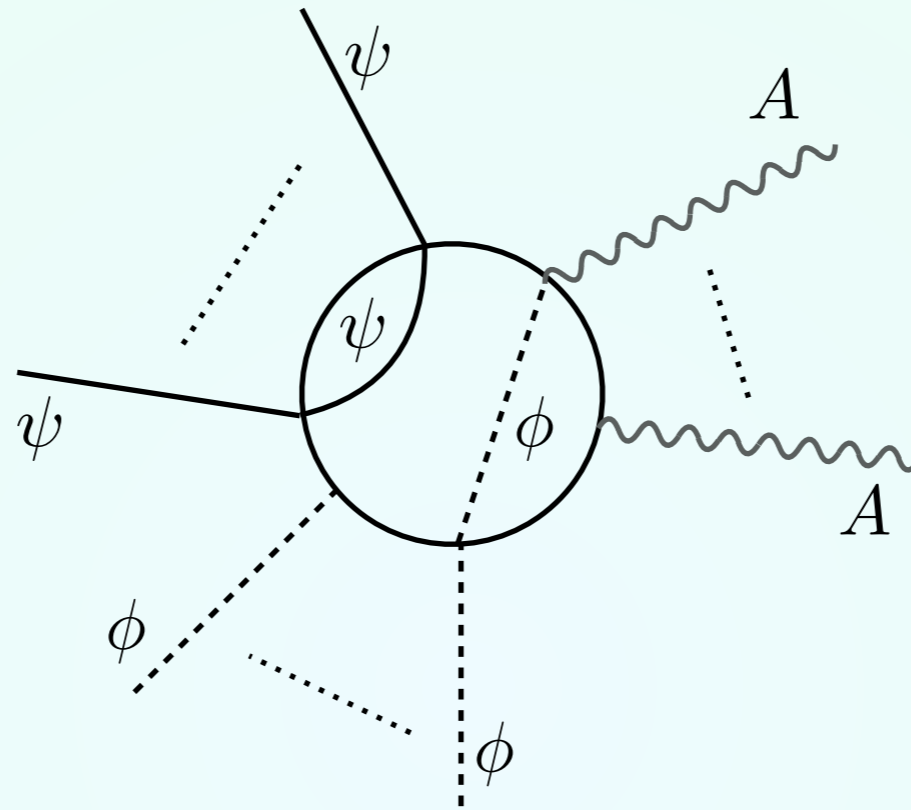
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depends on external momenta and internal legs (propagators brings momenta)

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depend on external and internal legs

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

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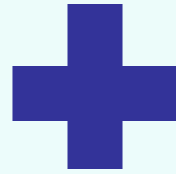
$$N_{4\pi} = \sum_i N_{4\pi,i} - 2L$$

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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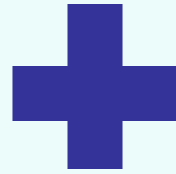
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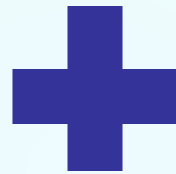
→ Imposing the theory identity $V - I + L = 1$

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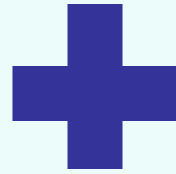


→ Imposing that the total dimension is 4

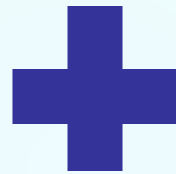
$$4 = N_{p,i} + N_{\phi,i} + N_{A,i} + \frac{3}{2}N_{\psi,i} + N_{\Lambda,i}$$

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→ Imposing that the total dimension is 4

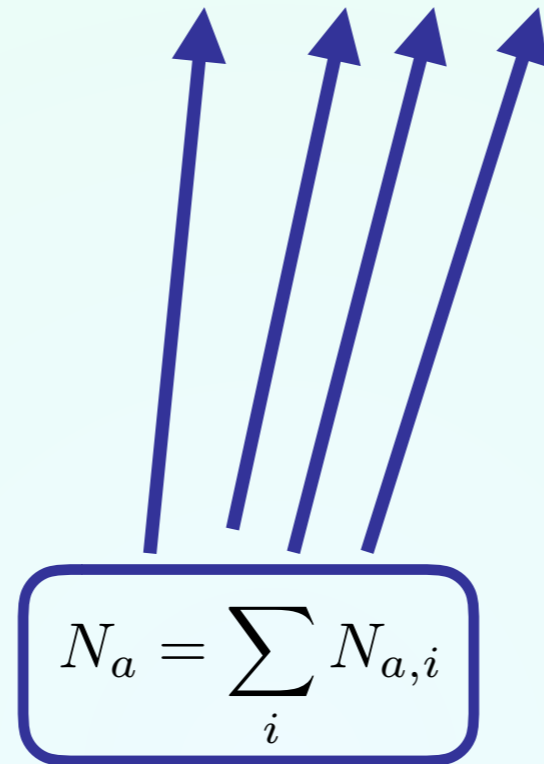
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only 6 relations are independent

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

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

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

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equivalent to say that:

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

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

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

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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:

$$m_\phi^2 \phi^2$$



$$\left[\frac{m_\phi^2}{\Lambda^2} \right]^{N_{m_\phi}}$$

$$m_\psi \bar{\psi} \psi$$



$$\left[\frac{m_\psi}{\Lambda} \right]^{N_{m_\psi}}$$

$$k\phi^3$$



$$\left[\frac{k}{4\pi\Lambda} \right]^{N_k}$$

Consequences

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

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

Consequences

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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

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

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

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$$\frac{\Lambda^4}{(4\pi)^2} \times \frac{\partial_\mu 4\pi\phi}{\Lambda} \frac{\partial^\mu 4\pi\phi}{\Lambda} \quad \rightarrow \quad \partial_\mu\phi\partial^\mu\phi$$

Consequences

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$$\begin{aligned} \frac{\Lambda^4}{(4\pi)^2} \times i \frac{4\pi\bar{\psi}}{\Lambda^{3/2}} \frac{\not{\partial}}{\Lambda} \frac{4\pi\psi}{\Lambda^{3/2}} &\rightarrow i\bar{\psi}\not{\partial}\psi \\ \frac{\Lambda^4}{(4\pi)^2} \times \frac{\partial_\mu 4\pi\phi}{\Lambda} \frac{\partial^\mu 4\pi\phi}{\Lambda} &\rightarrow \partial_\mu\phi\partial^\mu\phi \\ \frac{\Lambda^4}{(4\pi)^2} \times \frac{4\pi X_{\mu\nu}}{\Lambda^2} \frac{4\pi X^{\mu\nu}}{\Lambda^2} &\rightarrow X_{\mu\nu}X^{\mu\nu} \end{aligned}$$

Comparison with the old NDA

What is different wrt the well-known NDA master formula?

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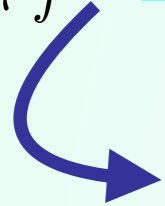
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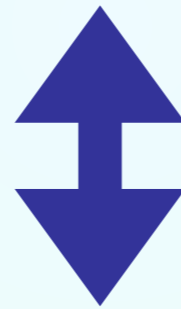
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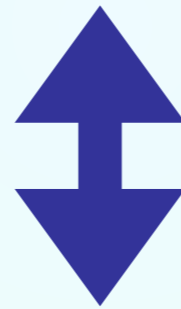
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→ Doubts on how to weight $X_{\mu\nu}$:

$$f^2 \Lambda^2 \times \frac{X_{\mu\nu}}{\Lambda^2} \frac{X^{\mu\nu}}{\Lambda^2} \rightarrow \frac{1}{4\pi^2} X_{\mu\nu} X^{\mu\nu}$$

Tuning!!

Why to use the Master Formula

- It is a convenient tool to avoid computing loop amplitudes explicitly:

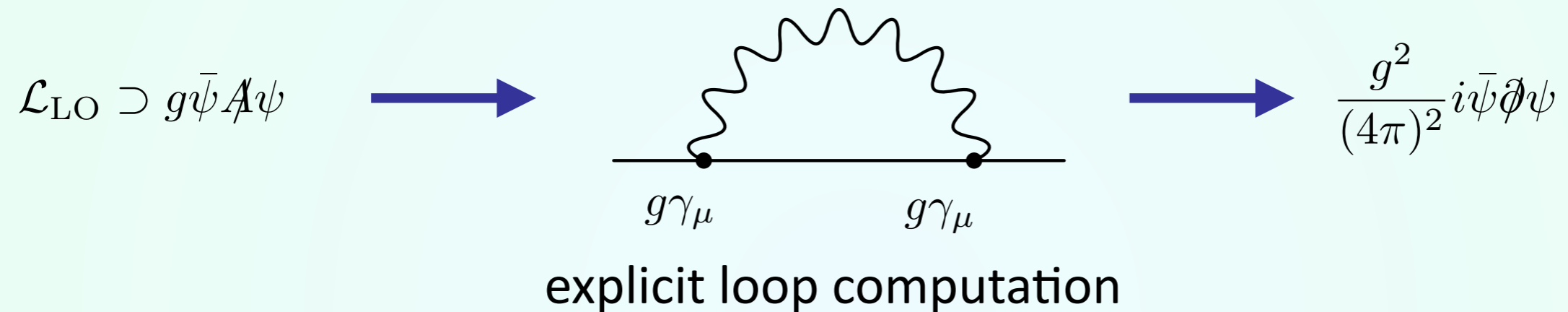
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$$\mathcal{L}_{\text{LO}} \supset g \bar{\psi} \not{A} \psi$$

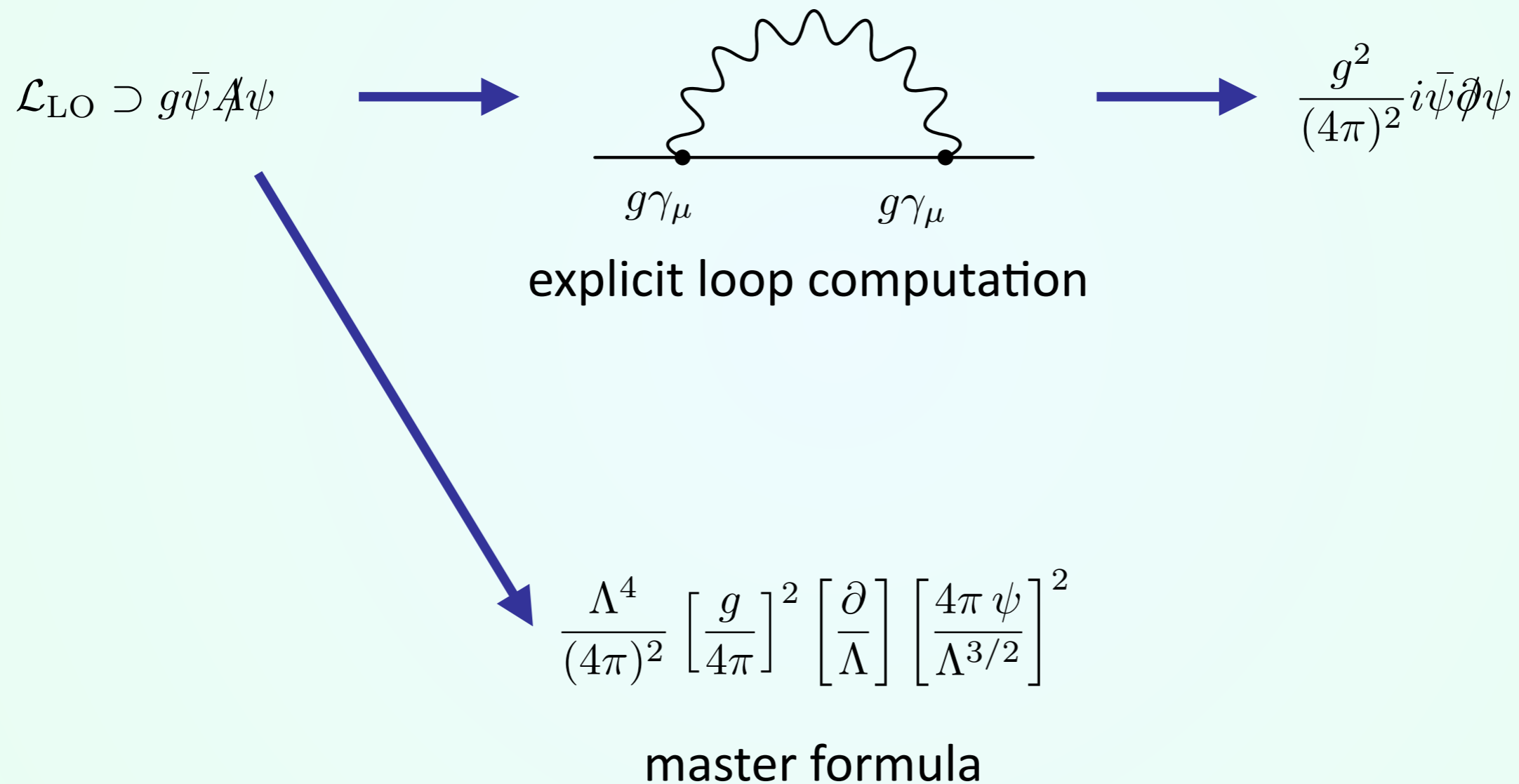
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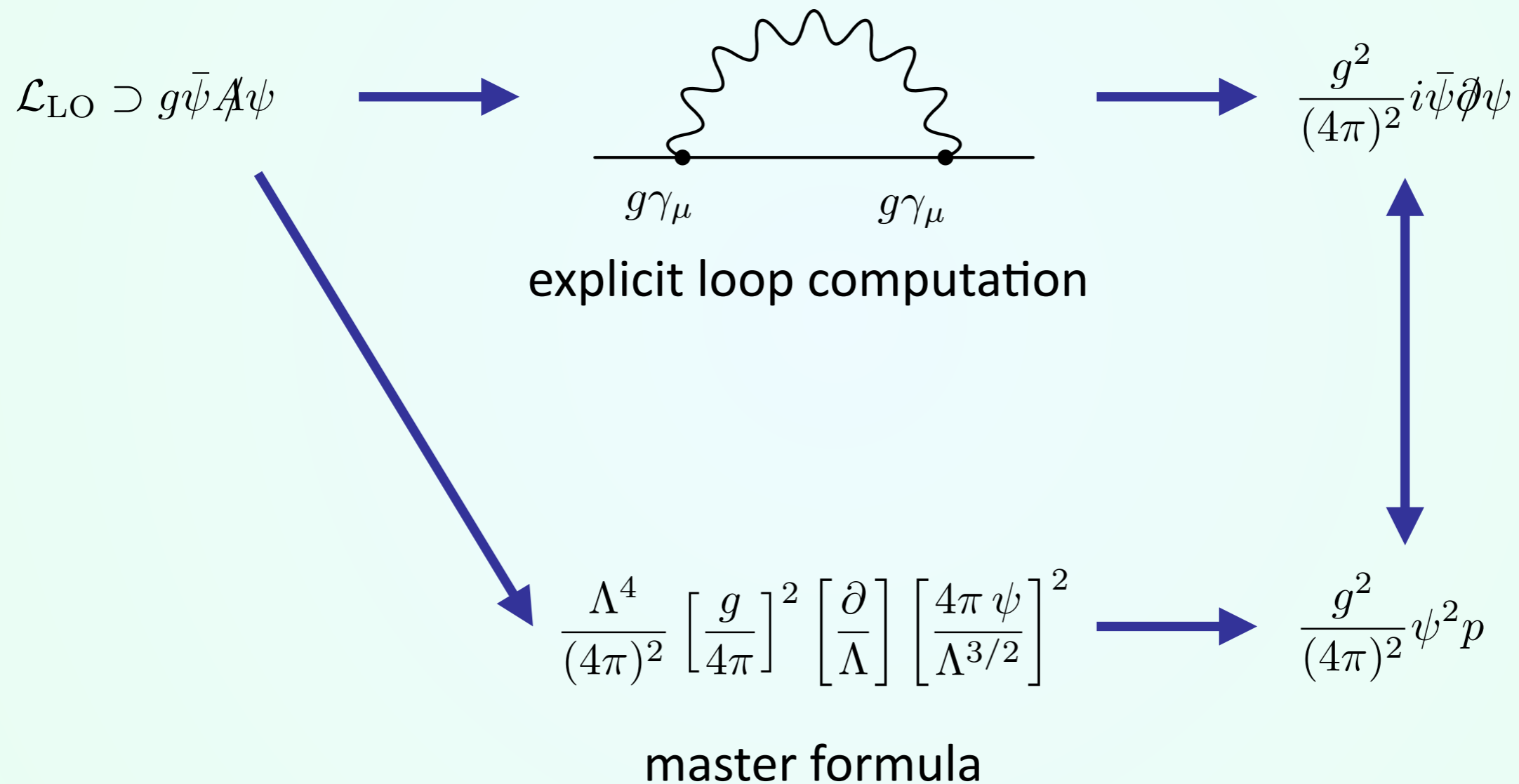
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Master Formula for Cross Sections

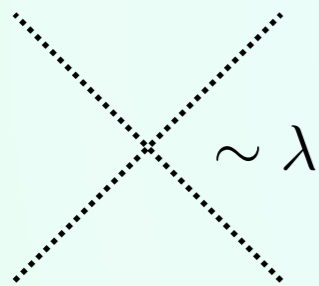
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Master Formula for Cross Sections



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



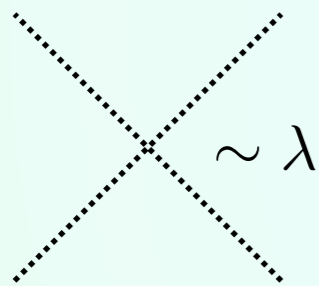
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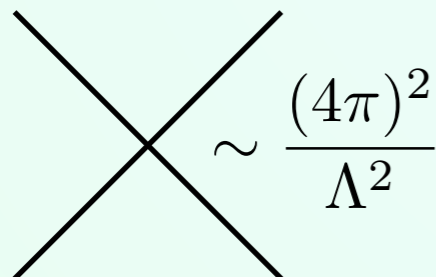
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Master Formula for Cross Sections



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



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

The Physical Impact

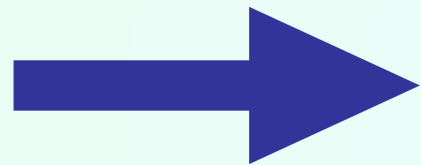
$$\sigma \sim \frac{\pi(4\pi)^2}{E^2} \left(\frac{E^2}{\Lambda^2} \right)^{-N_\Lambda} \left[\frac{g}{4\pi} \right]^{2N_g} \left[\frac{y}{4\pi} \right]^{2N_y} \left[\frac{\lambda}{(4\pi)^2} \right]^{2N_\lambda}$$

There ONLY dependence is on Λ

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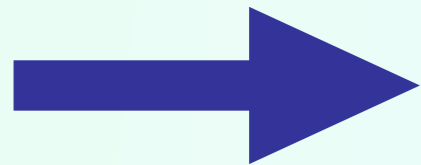


The hierarchy between the size of cross sections only depends on Λ , and not on the number of derivatives!!

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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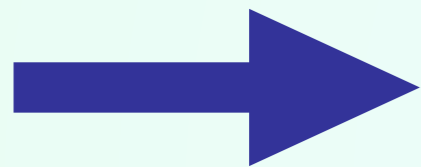
The hierarchy between the size of cross sections only depends on Λ , and not on the number of derivatives!!

$$d = 6 \left\{ \begin{array}{l} \frac{(4\pi)^4}{\Lambda^2} \phi^6 \\ \frac{(4\pi)^2}{\Lambda^2} (\phi \partial_\mu \phi)^2 \end{array} \right.$$

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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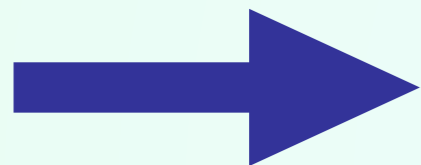
The hierarchy between the size of cross sections only depends on Λ , and not on the number of derivatives!!

$$d = 6 \left\{ \begin{array}{l} \frac{(4\pi)^4}{\Lambda^2} \phi^6 \quad \longrightarrow \quad 2\phi \rightarrow 4\phi \\ \frac{(4\pi)^2}{\Lambda^2} (\phi \partial_\mu \phi)^2 \quad \longrightarrow \quad 2\phi \rightarrow 2\phi \end{array} \right.$$

The Physical Impact

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

There ONLY dependence is on Λ



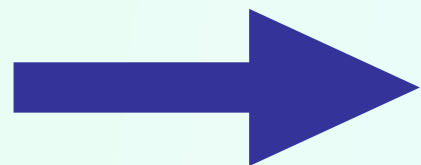
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The Physical Impact

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

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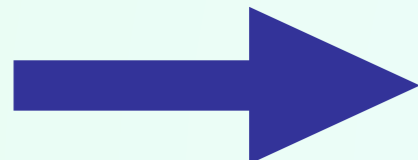
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$$\begin{array}{l}
 d = 6 \left\{ \begin{array}{l} \frac{(4\pi)^4}{\Lambda^2} \phi^6 \quad \longrightarrow \quad 2\phi \rightarrow 4\phi \\ \frac{(4\pi)^2}{\Lambda^2} (\phi \partial_\mu \phi)^2 \quad \longrightarrow \quad 2\phi \rightarrow 2\phi \end{array} \right. \quad \longrightarrow \quad \sigma \sim \frac{\pi(4\pi)^2}{E^2} \left(\frac{E^2}{\Lambda^2}\right)^2 \\
 \\
 d = 8 \left\{ \begin{array}{l} \frac{(4\pi)^6}{\Lambda^4} \phi^8 \\ \frac{(4\pi)^2}{\Lambda^4} (\phi \square \phi)^2 \end{array} \right.
 \end{array}$$

The Physical Impact

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There ONLY dependence is on Λ

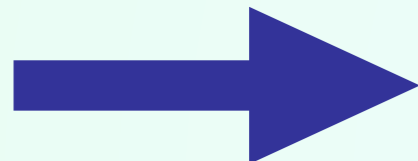
 The hierarchy between the size of cross sections only depends on Λ , and not on the number of derivatives!!

$$\begin{array}{l}
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 \\
 d = 8 \left\{ \begin{array}{l} \frac{(4\pi)^6}{\Lambda^4} \phi^8 \quad \longrightarrow \quad 2\phi \rightarrow 6\phi \\ \frac{(4\pi)^2}{\Lambda^4} (\phi \square \phi)^2 \quad \longrightarrow \quad 2\phi \rightarrow 2\phi \end{array} \right.
 \end{array}$$

The Physical Impact

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

There ONLY dependence is on Λ

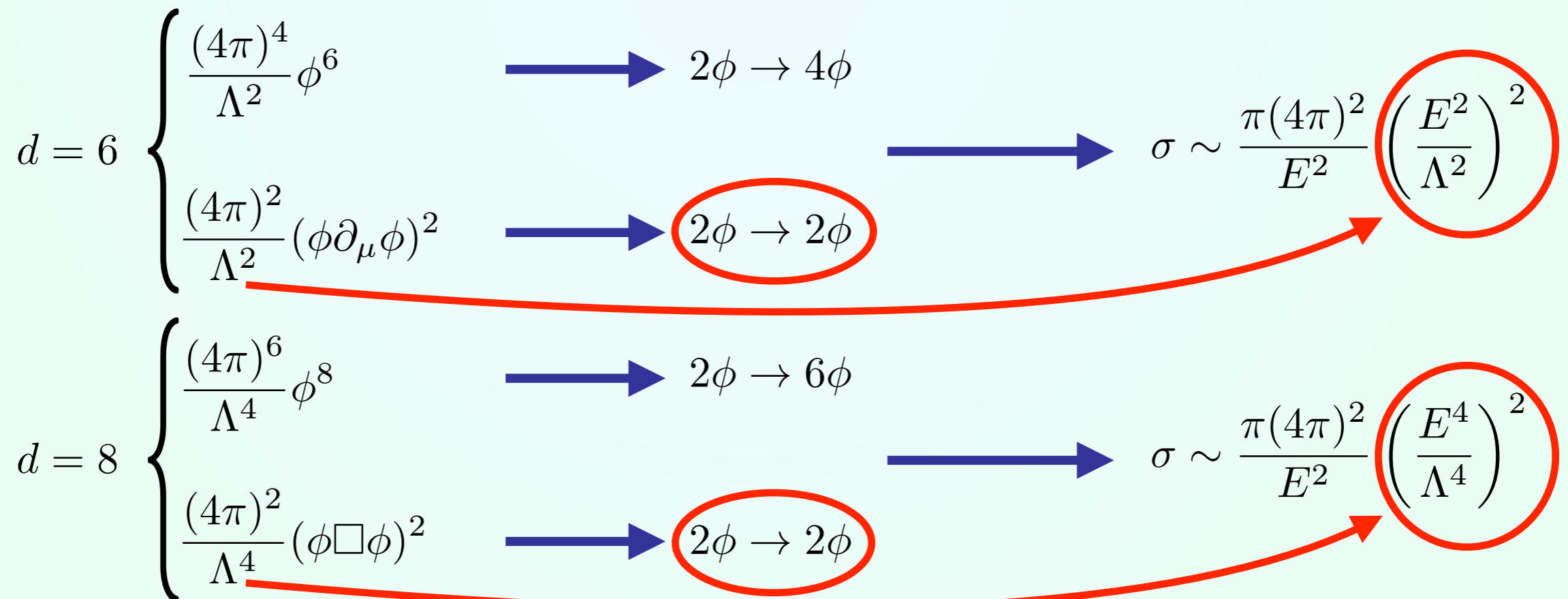
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$$\begin{array}{l}
 d = 6 \left\{ \begin{array}{l} \frac{(4\pi)^4}{\Lambda^2} \phi^6 \quad \longrightarrow \quad 2\phi \rightarrow 4\phi \\ \frac{(4\pi)^2}{\Lambda^2} (\phi \partial_\mu \phi)^2 \quad \longrightarrow \quad 2\phi \rightarrow 2\phi \end{array} \right. \longrightarrow \sigma \sim \frac{\pi(4\pi)^2}{E^2} \left(\frac{E^2}{\Lambda^2}\right)^2 \\
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$$\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}$$

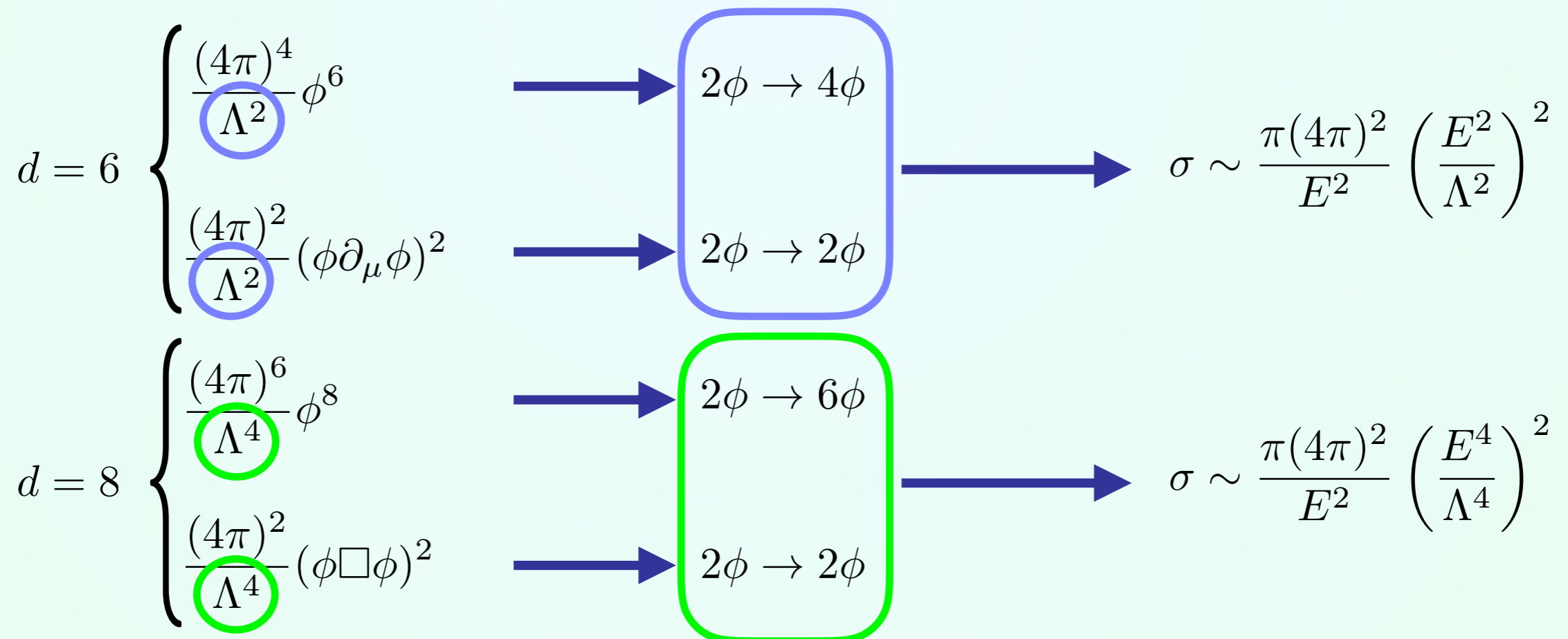
- Processes with *same* number of particles can have *different* cross sections: the difference is ruled by Λ



The Physical Impact

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

- Processes with *same* number of particles can have *different* cross sections: the difference is ruled by Λ
- Processes with *different* number of particles/derivatives can have *same* cross sections: same number of Λ



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	$\Lambda^2 H^2$
ψ^2	3	1	$\Lambda \psi^2$
H^4	4	0	$(4\pi)^2 H^4$
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X^2	4	2	X^2
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$X^2 H^2$	6	2	$\frac{(4\pi)^2}{\Lambda^2} X^2 H^2$
$\psi^2 X H$	6	2	$\frac{(4\pi)^2}{\Lambda^2} \psi^2 X H$
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\longleftrightarrow
 \longleftrightarrow
 \longleftrightarrow

$i\bar{\psi} \not{D} \psi$
 $D_\mu H^\dagger D^\mu H$
 $\text{Tr}(W_{\mu\nu} W^{\mu\nu})$

SMEFT

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$\psi^2 X H$	6	2	$\frac{(4\pi)^2}{\Lambda^2} \psi^2 X H$
$\psi^2 H^2 D$	6	2	$\frac{(4\pi)^2}{\Lambda^2} \psi^2 H^2 D$
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$\psi^2 D$	\longleftrightarrow	$i\bar{\psi} \not{D} \psi$
$H^2 D^2$	\longleftrightarrow	$D_\mu H^\dagger D^\mu H$
X^2	\longleftrightarrow	$\text{Tr} (W_{\mu\nu} W^{\mu\nu})$
$X^2 H^2$	\longleftrightarrow	$\frac{(4\pi)^2}{\Lambda^2} \text{Tr} (W_{\mu\nu} W^{\mu\nu}) (H^\dagger H)$
$\psi^2 H^2 D$	\longleftrightarrow	$\frac{(4\pi)^2}{\Lambda^2} \bar{\psi} \gamma_\mu \psi (H^\dagger D^\mu H)$

SMEFT

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

SMEFT

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

$$\mathcal{L} = \mathcal{L}^{d \leq 4} + \mathcal{L}^{d=6} + \mathcal{L}^{d=8} + \dots$$

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SMEFT

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

$$\mathcal{L} = \mathcal{L}^{d \leq 4} + \mathcal{L}^{d=6} + \mathcal{L}^{d=8} + \dots$$

The Λ expansion determines the physical impact of the operators and it coincides with the ordering of the operators due to renormalisation:

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SMEFT

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$$\text{LO} \begin{cases} \mathcal{L}^{d \leq 4} \\ \text{n-loop with } \mathcal{L}^{d \leq 4} \text{ vertices} \end{cases}$$

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SMEFT

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$$\begin{array}{l} \text{LO} \\ \text{NLO} \end{array} \left\{ \begin{array}{l} \mathcal{L}^{d \leq 4} \\ \text{n-loop with } \mathcal{L}^{d \leq 4} \text{ vertices} \\ \mathcal{L}^{d=6} \\ \text{n-loop with 1 } \mathcal{L}^{d=6} \text{ vertex} \end{array} \right.$$

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SMEFT

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

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$$\begin{array}{l} \text{LO} \\ \text{NLO} \\ \text{NNLO} \end{array} \left\{ \begin{array}{l} \mathcal{L}^{d \leq 4} \\ \text{n-loop with } \mathcal{L}^{d \leq 4} \text{ vertices} \\ \mathcal{L}^{d=6} \\ \text{n-loop with 1 } \mathcal{L}^{d=6} \text{ vertex} \\ \mathcal{L}^{d=8} \\ \text{n-loop with 1 } \mathcal{L}^{d=8} \text{ vertex} \\ \text{n-loop with 2 } \mathcal{L}^{d=6} \text{ vertices} \end{array} \right.$$

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SMEFT

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

$$\mathcal{L} = \mathcal{L}^{d \leq 4} + \mathcal{L}^{d=6} + \mathcal{L}^{d=8} + \dots$$

The Λ expansion determines the physical impact of the operators and it coincides with the ordering of the operators due to renormalisation:

$$\begin{array}{l} \text{LO} \\ \text{NLO} \\ \text{NNLO} \end{array} \left\{ \begin{array}{l} \mathcal{L}^{d \leq 4} \\ \text{n-loop with } \mathcal{L}^{d \leq 4} \text{ vertices} \\ \mathcal{L}^{d=6} \\ \text{n-loop with 1 } \mathcal{L}^{d=6} \text{ vertex} \\ \mathcal{L}^{d=8} \\ \text{n-loop with 1 } \mathcal{L}^{d=8} \text{ vertex} \\ \text{n-loop with 2 } \mathcal{L}^{d=6} \text{ vertices} \end{array} \right.$$

independently of number of loops!!

Operator	d	N_χ	NDA Form
H^2	2	0	$\Lambda^2 H^2$
ψ^2	3	1	$\Lambda \psi^2$
H^4	4	0	$(4\pi)^2 H^4$
$\psi^2 H$	4	1	$(4\pi) \psi^2 H$
$\psi^2 D$	4	2	$\psi^2 D$
$H^2 D^2$	4	2	$H^2 D^2$
X^2	4	2	X^2
H^6	6	0	$\frac{(4\pi)^4}{\Lambda^2} H^6$
$\psi^2 H^3$	6	1	$\frac{(4\pi)^3}{\Lambda^2} \psi^2 H^3$
$H^4 D^2$	6	2	$\frac{(4\pi)^2}{\Lambda^2} H^4 D^2$
$X^2 H^2$	6	2	$\frac{(4\pi)^2}{\Lambda^2} X^2 H^2$
$\psi^2 X H$	6	2	$\frac{(4\pi)^2}{\Lambda^2} \psi^2 X H$
$\psi^2 H^2 D$	6	2	$\frac{(4\pi)^2}{\Lambda^2} \psi^2 H^2 D$
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2} \psi^4$
X^3	6	3	$\frac{(4\pi)}{\Lambda^2} X^3$

χ PT

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

Chiral Symmetry $SU(2)_L \times SU(2)_R$:

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

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Chiral Symmetry spontaneous breaking $\langle \bar{q}q \rangle \neq 0$:

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

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

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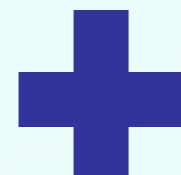
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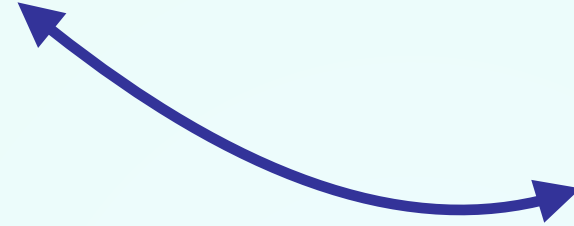
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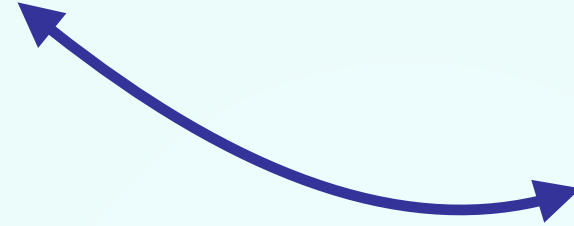
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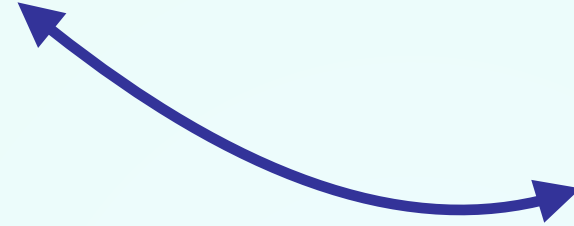

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→ The ordering in Λ coincides with N_χ only for processes with same number of external fields.

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)

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

Higgs: h

Singlet

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

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

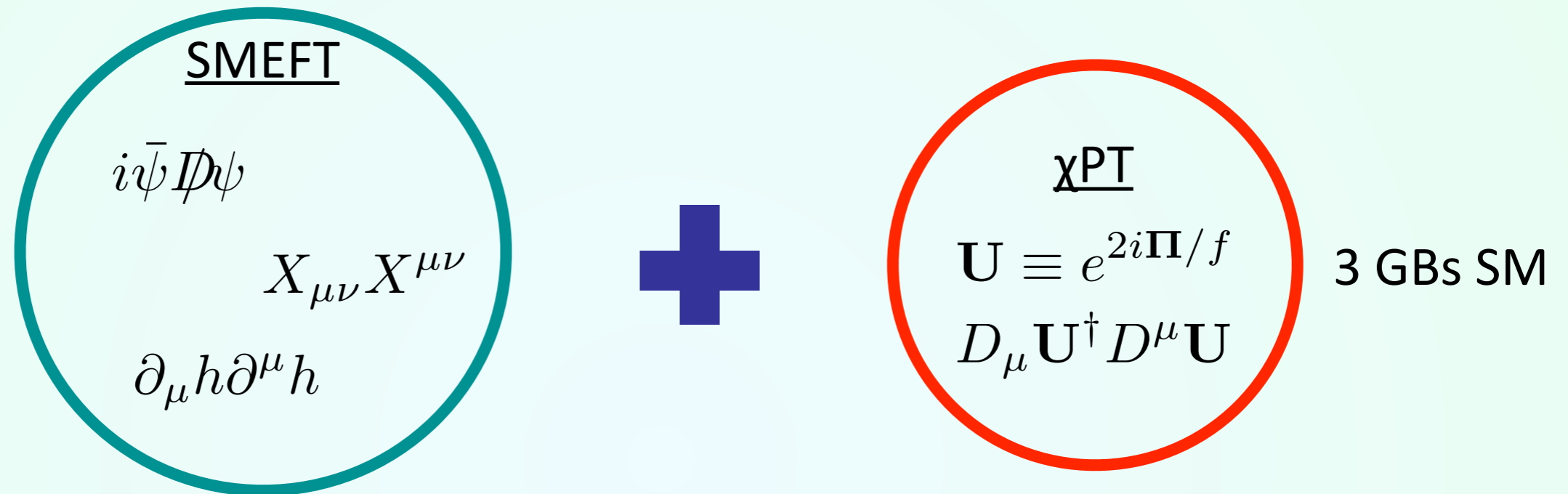
Independent!!

HEFT

The Higgs Effective Field Theory (HEFT) is a fusion of SMEFT and χ PT

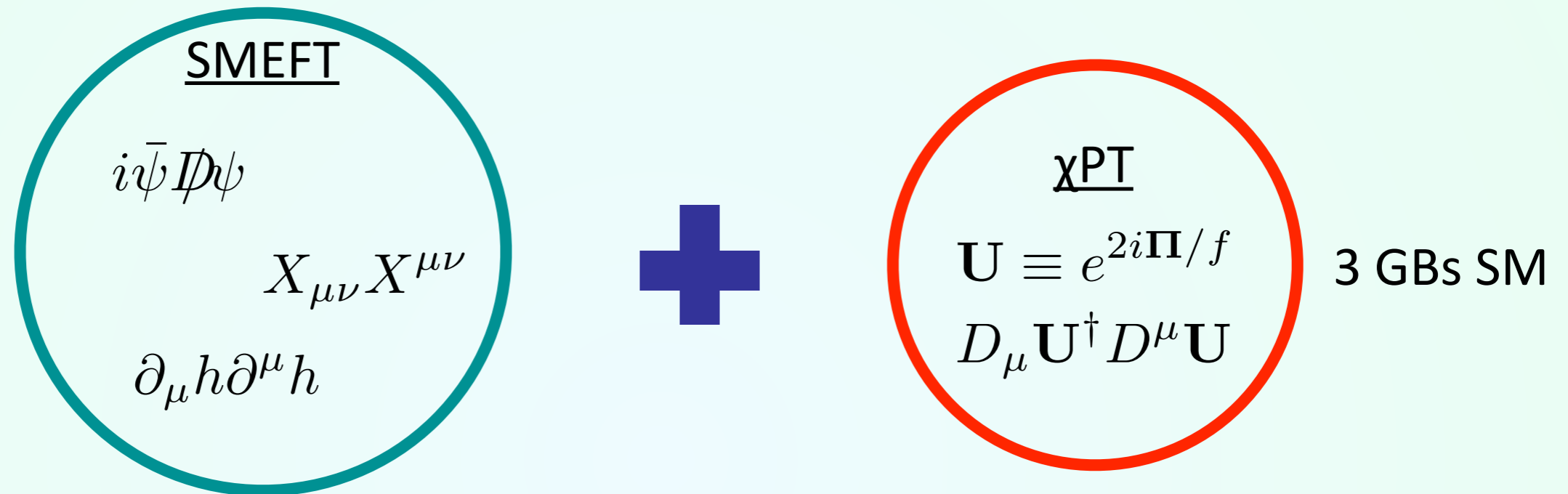
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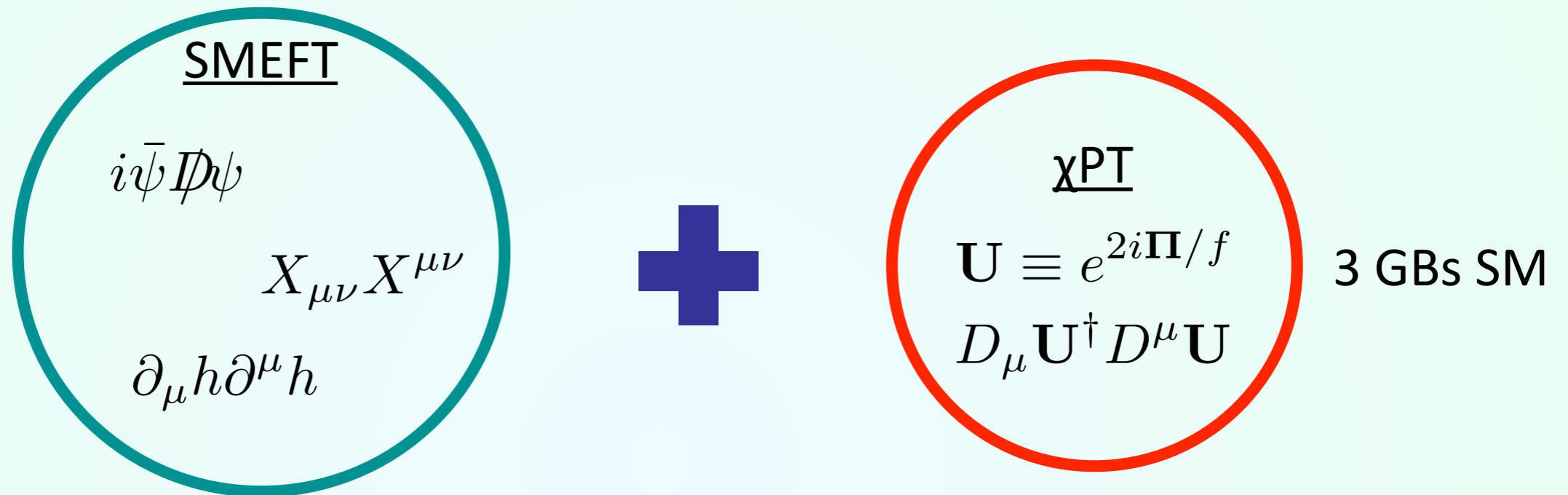
The Higgs Effective Field Theory (HEFT) is a fusion of SMEFT and χ PT



Renormalisation is different between SMEFT and χ PT:

HEFT

The Higgs Effective Field Theory (HEFT) is a fusion of SMEFT and χ PT

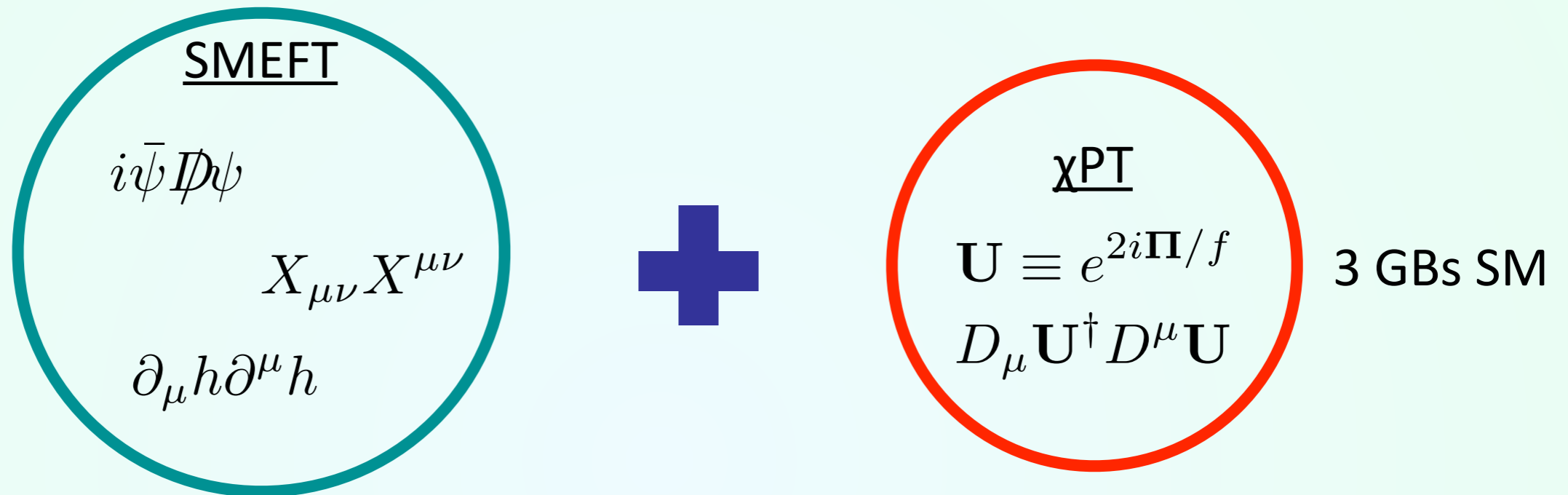


Renormalisation is different between SMEFT and χ PT:

SMEFT	Tree	1 loop	2 loop
LO	LO	LO	LO
NLO	NLO $\frac{1}{\Lambda^2}$	NLO $\frac{1}{\Lambda^2}$	NLO $\frac{1}{\Lambda^2}$
NNLO	NNLO $\frac{1}{\Lambda^4}$	NNLO $\frac{1}{\Lambda^4}$	NNLO $\frac{1}{\Lambda^4}$

HEFT

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Renormalisation is different between SMEFT and χ PT:

SMEFT	Tree	1 loop	2 loop	χ PT	Tree	1 loop	2 loop
LO	LO	LO	LO	LO	LO	NLO $\frac{1}{\Lambda^2}$	NNLO $\frac{1}{\Lambda^4}$
NLO	NLO $\frac{1}{\Lambda^2}$	NLO $\frac{1}{\Lambda^2}$	NLO $\frac{1}{\Lambda^2}$	NLO	NLO $\frac{1}{\Lambda^2}$	NNLO $\frac{1}{\Lambda^4}$...
NNLO	NNLO $\frac{1}{\Lambda^4}$	NNLO $\frac{1}{\Lambda^4}$	NNLO $\frac{1}{\Lambda^4}$	NNLO	NNLO $\frac{1}{\Lambda^4}$

How to merge the two theories??

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■ Building blocks:

$$\mathbf{V}_\mu \equiv (\mathbf{D}_\mu \mathbf{U}) \mathbf{U}^\dagger$$

$$\mathbf{V} \rightarrow L \mathbf{V} L^\dagger$$

$$L \in SU(2)_L$$

$$\mathbf{T} \equiv \mathbf{U} \sigma_3 \mathbf{U}^\dagger$$

$$\mathbf{T} \rightarrow L \mathbf{T} L^\dagger$$

$$\psi_{L,R}$$

$$A_\mu \quad X_{\mu\nu}$$

$$h \quad \text{singlet of SM syms: arbitrary} \quad \mathcal{F}(h) = \sum_{i=0} a_i \left(\frac{h}{f} \right)^i$$

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■ Leading interacting terms: expanding the fields

$$\mathbf{U} = 1 + \dots$$

$$\mathbf{T} = \sigma_3$$

$$\mathbf{V}_\mu = \frac{2i}{f} \partial_\mu \mathbf{\Pi} + \frac{2i}{f} [\mathbf{\Pi}, g A_\mu] + \frac{gv}{f} B_\mu$$

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$$h \quad \text{singlet of SM syms: arbitrary} \quad \mathcal{F}(h) = \sum_{i=0} a_i \left(\frac{h}{f} \right)^i$$

■ Leading interacting terms: expanding the fields

$$\mathbf{U} = 1 + \dots \quad N_\chi = 0$$

$$\mathbf{T} = \sigma_3 \quad N_\chi = 0$$

$$\mathbf{V}_\mu = \frac{2i}{f} \partial_\mu \mathbf{\Pi} + \frac{2i}{f} [\mathbf{\Pi}, g A_\mu] + \frac{gv}{f} B_\mu \quad N_\chi = 1$$

How to merge the two theories??

■ Building blocks:

$$\mathbf{V}_\mu \equiv (\mathbf{D}_\mu \mathbf{U}) \mathbf{U}^\dagger$$

$$\mathbf{V} \rightarrow L \mathbf{V} L^\dagger$$

$$L \in SU(2)_L$$

$$\mathbf{T} \equiv \mathbf{U} \sigma_3 \mathbf{U}^\dagger$$

$$\mathbf{T} \rightarrow L \mathbf{T} L^\dagger$$

$$\psi_{L,R}$$

$$A_\mu \quad X_{\mu\nu}$$

$$h \quad \text{singlet of SM syms: arbitrary} \quad \mathcal{F}(h) = \sum_{i=0} a_i \left(\frac{h}{f}\right)^i$$

■ Leading interacting terms: expanding the fields

$$\mathbf{U} = 1 + \dots$$

$$N_\chi = 0 \quad d = 0, 1, 2, \dots$$

$$\mathbf{T} = \sigma_3$$

$$N_\chi = 0 \quad d = 0, 1, 2, \dots$$

$$\mathbf{V}_\mu = \frac{2i}{f} \partial_\mu \mathbf{\Pi} + \frac{2i}{f} [\mathbf{\Pi}, g A_\mu] + \frac{gv}{f} B_\mu$$

$$N_\chi = 1 \quad d = 1, 2, 3, \dots$$

How to merge the two theories??

■ Building blocks:

$$\mathbf{V}_\mu \equiv (\mathbf{D}_\mu \mathbf{U}) \mathbf{U}^\dagger$$

$$\mathbf{V} \rightarrow L \mathbf{V} L^\dagger$$

$$L \in SU(2)_L$$

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$$\mathbf{T} \rightarrow L \mathbf{T} L^\dagger$$

$$\psi_{L,R}$$

$$A_\mu \quad X_{\mu\nu}$$

$$h \quad \text{singlet of SM syms: arbitrary} \quad \mathcal{F}(h) = \sum_{i=0} a_i \left(\frac{h}{f} \right)^i$$

■ Leading interacting terms: expanding the fields

$$\mathbf{U} = 1 + \dots$$

$$N_\chi = 0$$

$$d_p = 0$$

$$\mathbf{T} = \sigma_3$$

$$N_\chi = 0$$

$$d_p = 0$$

$$\mathbf{V}_\mu = \frac{2i}{f} \partial_\mu \mathbf{\Pi} + \frac{2i}{f} [\mathbf{\Pi}, g A_\mu] + \frac{gv}{f} B_\mu$$

$$N_\chi = 1$$

$$d_p = 2$$

Primary Dimension

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	$\frac{\Lambda^2}{(4\pi)^2} \text{Tr} (\mathbf{V}_\mu \mathbf{V}^\mu) \mathcal{F}_{\mathbf{V}^2}(h)$
$\psi^2 \mathbf{V}$	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	$\frac{1}{4\pi} \text{Tr} (W_{\mu\nu} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{X \mathbf{V}^2}(h)$
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	$\frac{1}{(4\pi)^2} \mathbf{V}^2 \partial^2 \mathcal{F}_{\mathbf{V}^2 \partial^2}(h)$	\longleftrightarrow	$\frac{1}{(4\pi)^2} \text{Tr} (\mathbf{V}^\mu \mathbf{V}^\mu)^2 \mathcal{F}_{\mathbf{V}^4}(h)$
\mathbf{V}^4	8	4	$\frac{1}{(4\pi)^2} \mathbf{V}^4 \mathcal{F}_{\mathbf{V}^4}(h)$		

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	$\Lambda \psi^2 \mathbf{U} \mathcal{F}_{\psi^2 \mathbf{U}}(h)$
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$\psi^2 \mathbf{V}$	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

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:

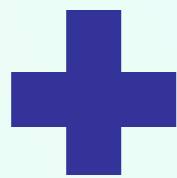
Operator	d_p	N_χ	NDA form
$\psi^2 \mathbf{U}$	3	1	$\Lambda \psi^2 \mathbf{U} \mathcal{F}_{\psi^2 \mathbf{U}}(h)$
X^2	4	2	$X^2 \mathcal{F}_{X^2}(h)$
$\psi^2 D$	4	2	$\psi^2 D$
$(\partial h)^2$	4	2	$(\partial h)^2$
\mathbf{V}^2	4	2	$\frac{\Lambda^2}{(4\pi)^2} \mathbf{V}^2 \mathcal{F}_{\mathbf{V}^2}(h)$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

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



Operators encoding NP contributions with the same physical impact

	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	$\frac{1}{4\pi} X \mathbf{V}^2 \mathcal{F}_{X \mathbf{V}^2}(h)$
	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	$\frac{1}{(4\pi)^2} \mathbf{V}^4 \mathcal{F}_{\mathbf{V}^4}(h)$

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

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

Independent!!

- Being h a singlet: generic functions of h

$$\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \dots$$

- 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	\longleftrightarrow Linear sibling
$\psi^2 \mathbf{U}$	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	

Disentangling the Higgs Nature

Operator	d_p	N_χ	NDA form	SMEFT	\longleftrightarrow Linear sibling
$\psi^2 \mathbf{U}$	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	} $\longleftrightarrow D_\mu H^\dagger D^\mu H$
\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	

Disentangling the Higgs Nature

Operator	d_p	N_χ	NDA form	SMEFT	Linear sibling
$\psi^2 \mathbf{U}$	3	1	$\Lambda \psi^2 \mathbf{U} \mathcal{F}_{\psi^2 \mathbf{U}}(h)$	4	\longleftrightarrow
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	} $\longleftrightarrow D_\mu H^\dagger D^\mu H$
\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	
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$\psi^2 \mathbf{V}^2 \mathbf{U}$	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	

Disentangling the Higgs Nature

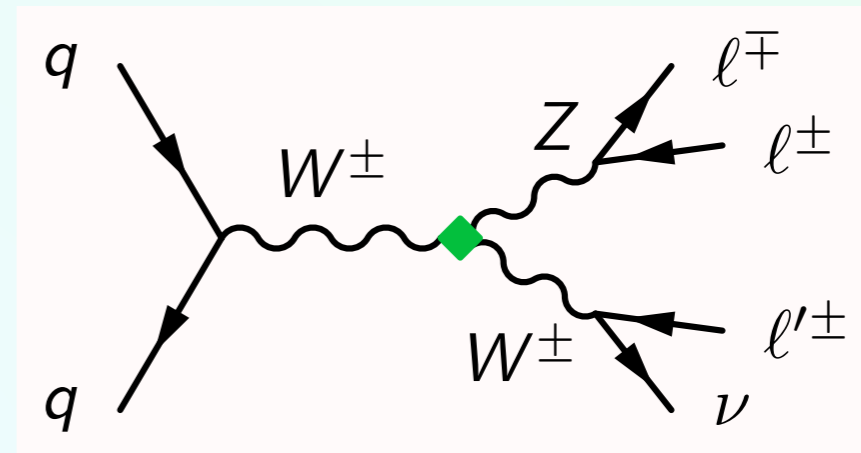
Operator	d_p	N_χ	NDA form	SMEFT	Linear sibling
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$\psi^2 D$	4	2	$\psi^2 D$	4	
$(\partial h)^2$	4	2	$(\partial h)^2$	4	} $\longleftrightarrow D_\mu H^\dagger D^\mu H$
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X^3	6	3	$\frac{(4\pi)}{\Lambda^2} X^3 \mathcal{F}_{X^3}(h)$	6	
<div style="border: 2px solid orange; padding: 10px; display: flex; justify-content: space-around;"> <div style="text-align: center;"> $\epsilon^{\mu\nu\rho\lambda} \text{Tr}(\mathbf{T} \mathbf{V}_\mu) \text{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$ </div> <div style="text-align: center;"> $\epsilon^{\mu\nu\rho\lambda} (\Phi^\dagger D_\mu \Phi) (\Phi^\dagger \sigma_i D_\nu \Phi) W_{\rho\lambda}^i$ </div> </div>					
$\psi^2 \mathbf{U} \partial^2$	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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$$\epsilon^{\mu\nu\rho\lambda} \text{Tr}(\mathbf{T}\mathbf{V}_\mu) \text{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$

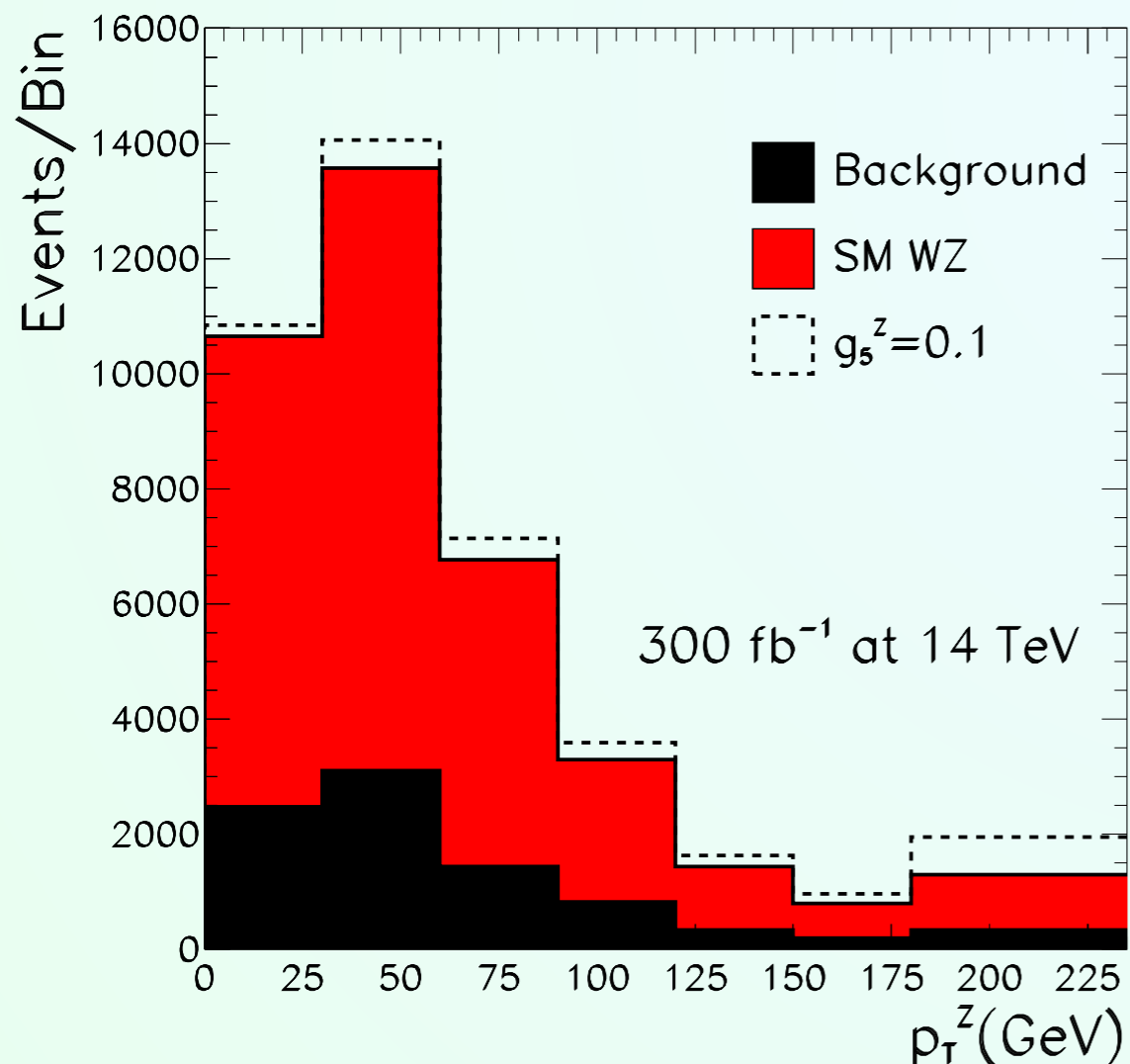
Brivio, Corbett, Eboli, Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM&Rigolin, JHEP 1403 (2014)

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

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



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

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Conclusions

- Use EFT is convenient and sometimes necessary. Many different counting can be defined.
 - The primary dimension counting:
 - measures the physical impact in terms of cross sections
 - 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

Thanks

ons

- 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 $N_\chi = 2$

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

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

LO

NLO

NNLO

NLO

Operator	d_p	N_χ	NDA form
$\psi^2 \mathbf{U}$	3	1	$\Lambda \psi^2 \mathbf{U} \mathcal{F}_{\psi^2 \mathbf{U}}(h)$
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$(\partial h)^2$	4	2	$(\partial h)^2$
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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	$\frac{1}{(4\pi)^2} \mathbf{V}^4 \mathcal{F}_{\mathbf{V}^4}(h)$

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

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



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

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

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

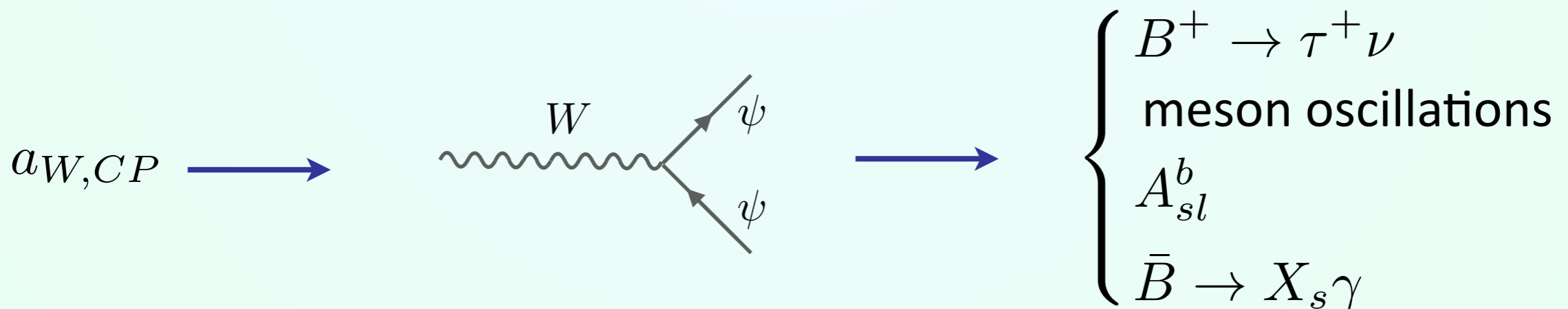
Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)

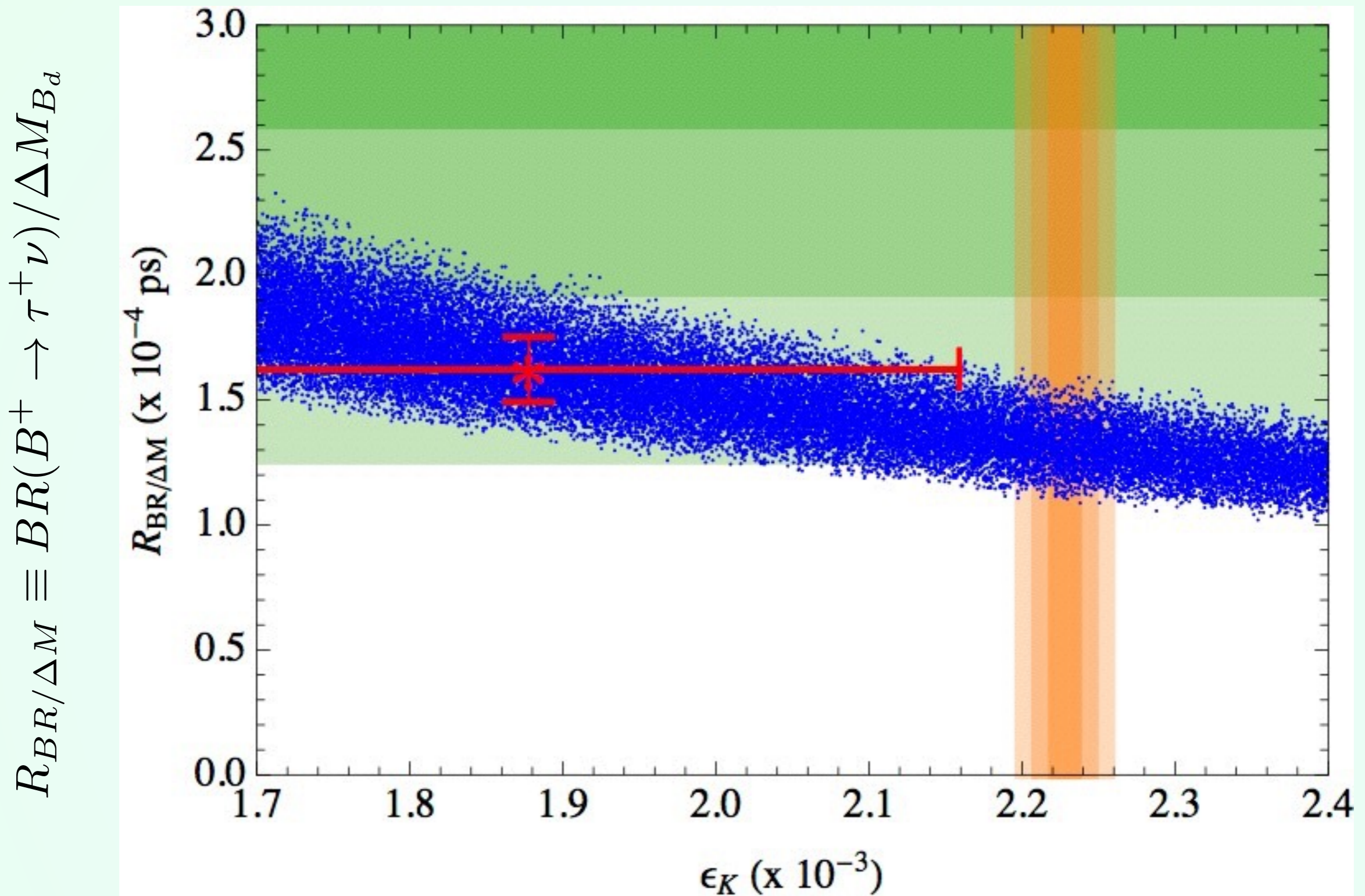
It is easier to read the interaction vertices in the unitary gauge:

$$\mathcal{L}_{\chi=4}^f = -\frac{g}{\sqrt{2}} \left[W_\mu^+ \bar{U}_L \gamma^\mu [a_W (1 + \beta_W h/v) + ia_{CP} (1 + \beta_{CP} h/v)] \times \right. \\ \left. \times (\mathbf{y}_U^2 V + V \mathbf{y}_D^2) D_L + \text{h.c.} \right] +$$

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

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





SM values:

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

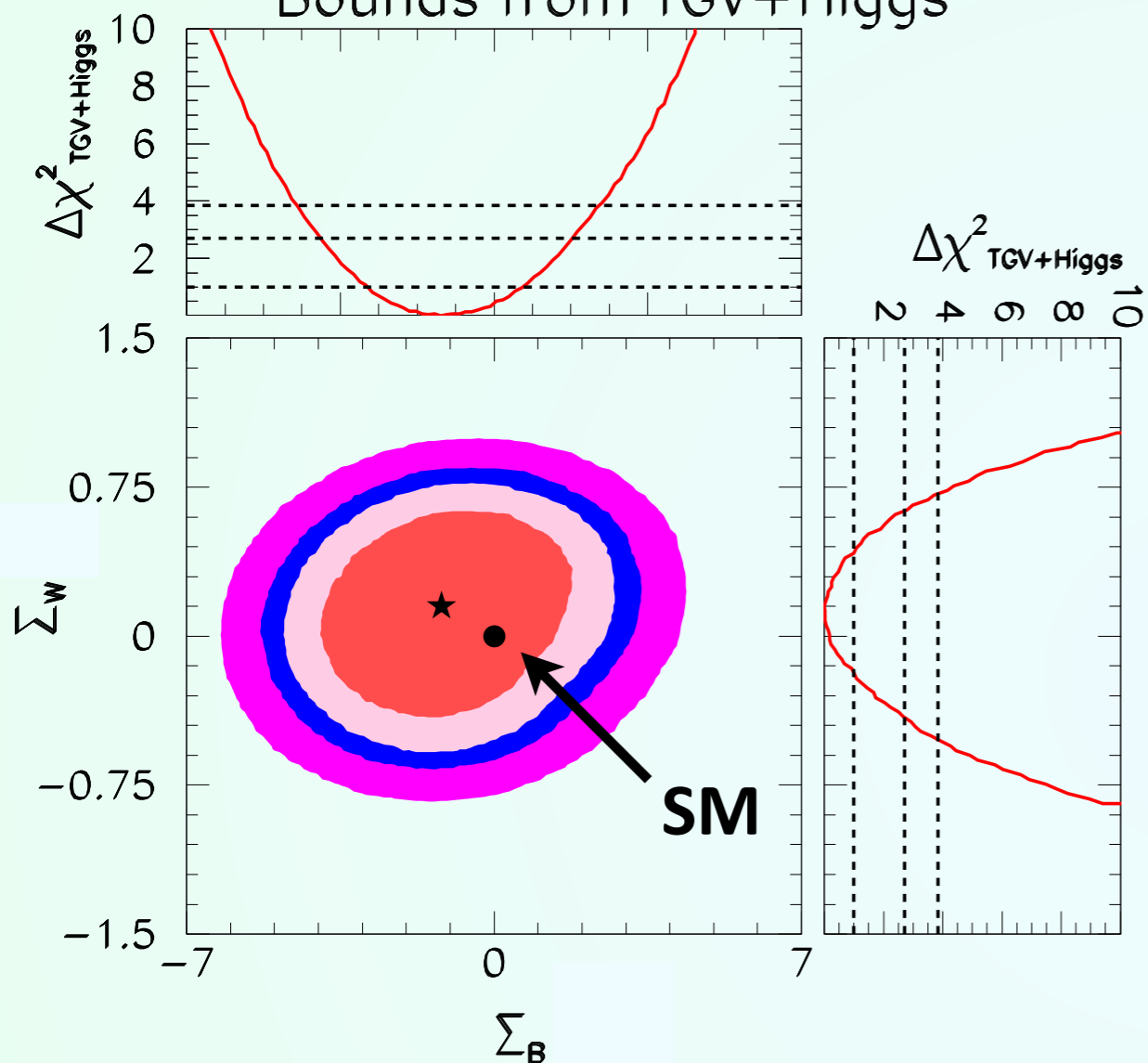
$$R_{BR/\Delta M} \simeq (1.62 \pm 0.13) \times 10^{-4}$$

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

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

Decorrelations

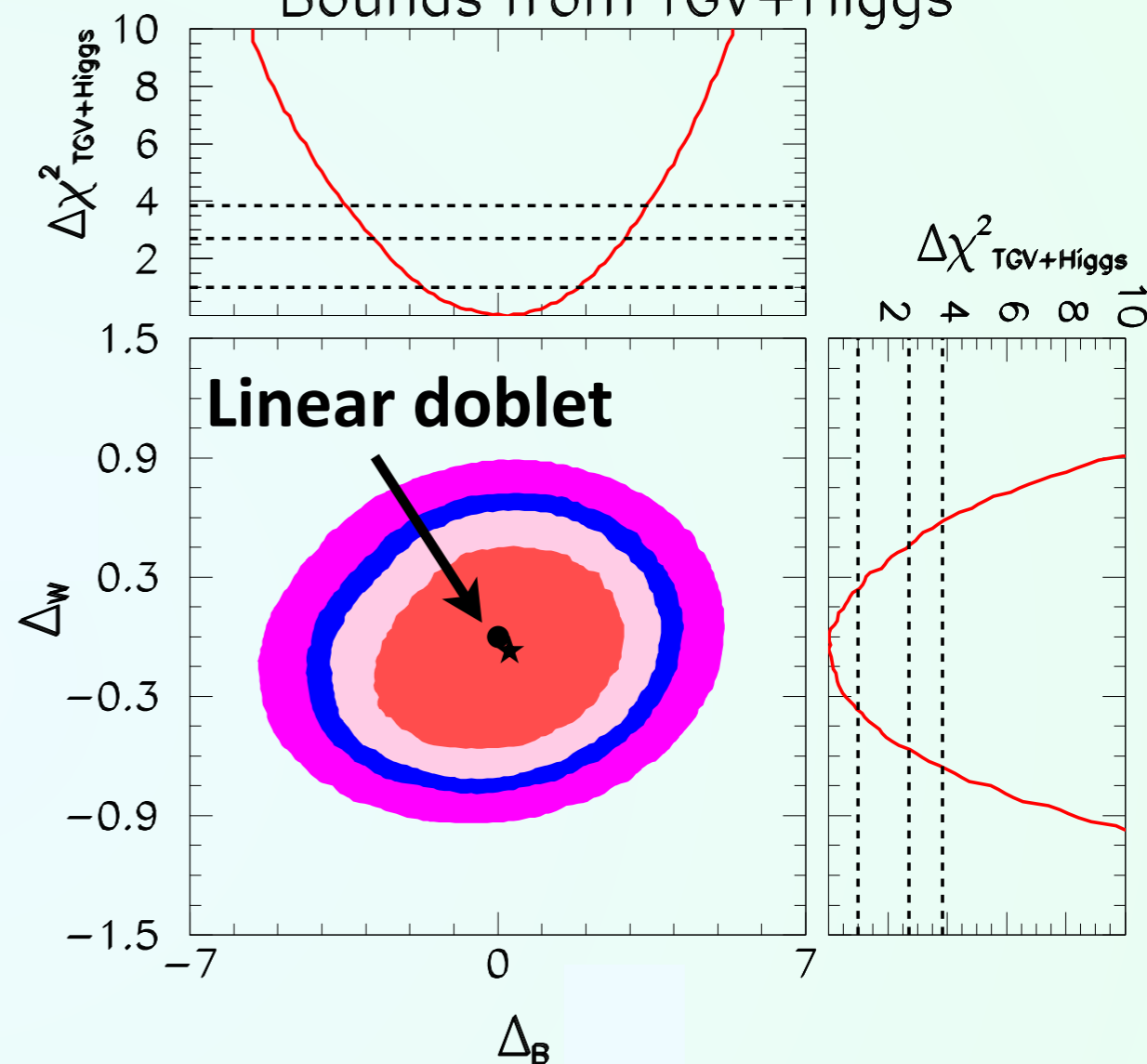
Bounds from TGV+Higgs



$$\Sigma_B = 4(2c_2 + a_4) \rightarrow f_B \xi$$

$$\Sigma_W = 2(2c_3 - a_5) \rightarrow f_W \xi$$

Bounds from TGV+Higgs



$$\Delta_B = 4(2c_2 - a_4) \rightarrow 0$$

$$\Delta_W = 2(2c_3 + a_5) \rightarrow 0$$

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 $\tau\tau^-$

Example of Decorrelation

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

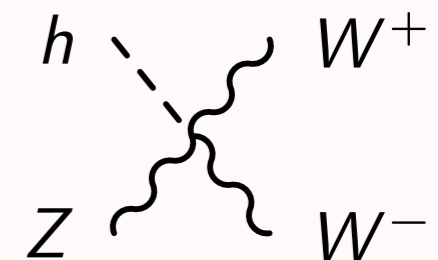
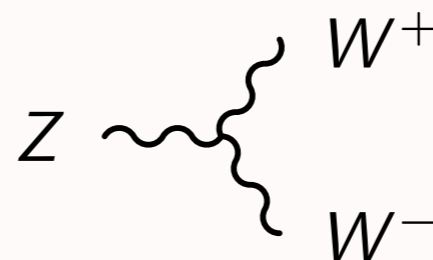
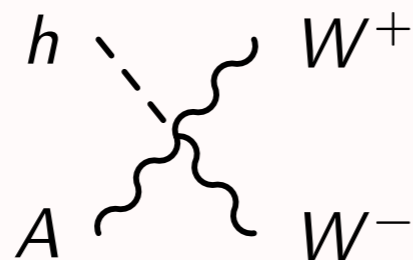
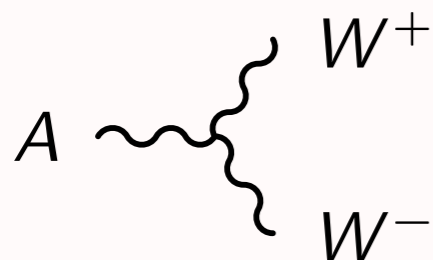
$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

Example of Decorrelation

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

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

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



Example of Decorrelation

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

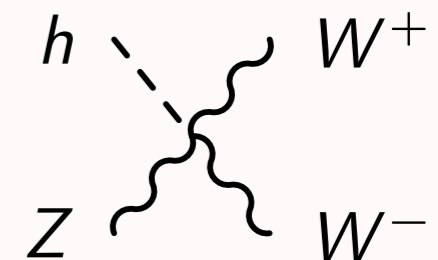
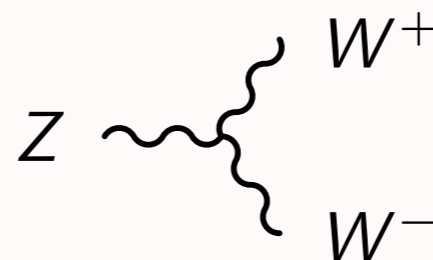
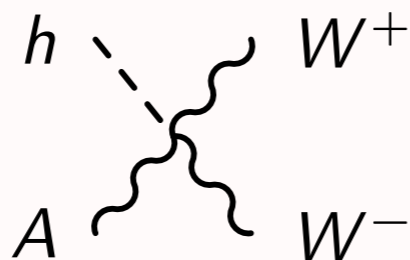
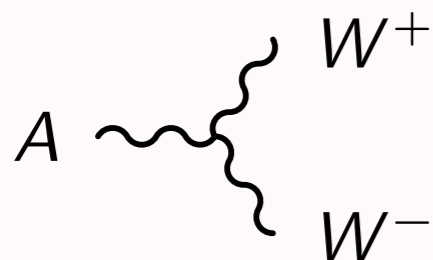
$$\mathcal{O}_B = \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2g}{8 \cos \theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2$$

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

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

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

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



Example of Decorrelation

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

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

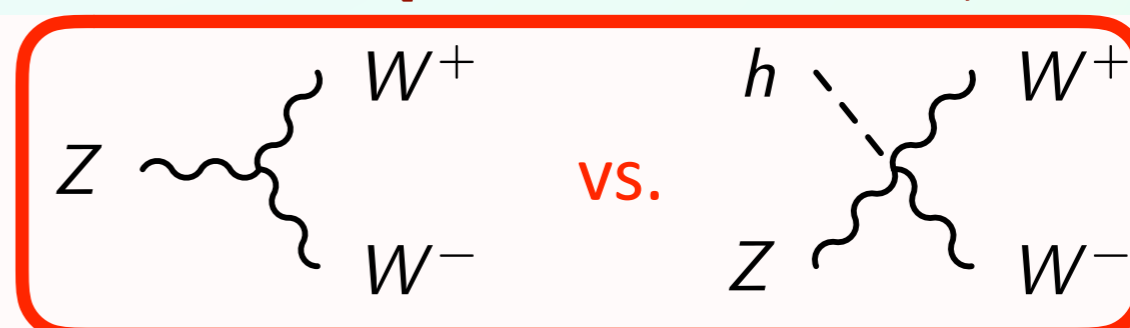
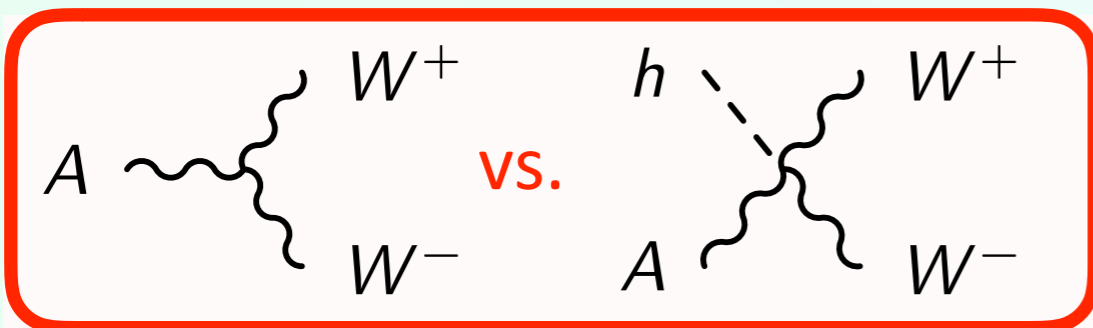
➔ $\mathcal{O}_B = \frac{v^2}{16} \mathcal{P}_2(h) + \frac{v^2}{8} \mathcal{P}_4(h)$ with $\mathcal{F}_i(h) = \left(1 + \frac{h}{v}\right)^2$

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

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

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

[see also Isidori&Trott, 1307.4051]



Example of Decorrelation

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

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

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

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

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

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

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

